



Classe di Scienze
Corso di perfezionamento in
Fisica
XXXIV ciclo

Interstellar dust in galaxies in the Epoch of Reionization

Settore Scientifico Disciplinare **FIS/05**

Candidata
dr.ssa Laura Sommovigo

Relatore
Prof. Andrea Ferrara

Co-supervisione
Dr. Stefano Carniani

Anno accademico 2022–2023

A mia Nonna

“There are places where you cannot see the stars, for all the rubbish. For years astrophysicists have been racking their brains over the reason for the great difference in the amounts of cosmic dust in various galaxies. The answer, I think, is quite simple: the higher a civilization is, the more dust and refuse it produces.

This is a problem more for janitors than for astrophysicists.”

– Stanislaw Lem (from: “Memoirs of a Space Traveler”, 1957) –

Contents

1	General Introduction	11
1.1	Basics of Λ CDM cosmology	11
1.2	Cosmic thermal history	13
1.3	Galaxies at the EoR: theory and observations	14
1.3.1	Selection techniques	14
1.3.2	Global characterization	15
2	Dust	23
2.1	The ISM	23
2.2	Interstellar dust	25
2.2.1	Extinction	26
2.2.2	A physical grain model	28
2.2.3	Infrared emission	29
2.3	Dusty ISM in galaxies at the EoR	30
2.3.1	ALMA and the “dust budget crisis”	31
2.3.2	Dust production mechanisms in the high- z Universe	31
2.3.3	The importance of constraining the dust temperature	33
2.3.4	Interpretation of latest dust observations at high- z	35
2.3.5	Open questions	36
3	A new method to derive the dust temperature	41
3.1	The [C II]-based method	41
3.1.1	Dust-to-gas ratio	41
3.1.2	[C II]-to-total gas mass conversion factor	42
3.1.3	Determining the dust temperature T_d	43
3.2	Local testing of the [C II]-based method	45
3.3	Application of the [C II]-based method at high z	46
3.3.1	Determining the dust mass at high- z	49
3.4	Molecular gas content	51
3.4.1	Molecular gas fraction cosmic evolution	51
3.5	Summary	52
3.6	Accurate T_d determination in a $z \sim 7$ galaxy	54
3.6.1	Data description	54
3.6.2	Comparing traditional SED fitting and the [C II]-based method	55
3.6.3	Implications	56
4	Determining the dust properties of REBELS galaxies	57
4.1	Application of the [C II]-based method to REBELS galaxies	57
4.1.1	Dust temperatures at $z \sim 7$	60
4.1.2	Dust masses at $z \sim 7$	60
4.1.3	IR emission at $z \sim 7$	61

4.2	Dust temperature evolution	62
4.2.1	Physical origin of the $T_d - z$ relation	64
4.2.2	Comparison with observations at $0 \lesssim z \lesssim 8$	65
4.3	Summary	66
5	Extending the analysis to ALPINE galaxies	69
5.1	Application of the [C II]-based method to ALPINE galaxies	69
5.2	Dust temperatures at $z \sim 5$	70
5.2.1	Cosmic T_d evolution	71
5.3	Dust masses at $z \gtrsim 5$	73
5.3.1	Implications for dust production at high- z	75
5.4	IR luminosities and total SFR at $z \sim 5$	76
5.5	Summary	79
6	Warm dust at high-z: theoretical model and implications	83
6.1	Comparing ALMA observations to simulated spectra at $z \sim 7$	83
6.2	Warm dust in high- z GMCs	86
6.2.1	A physical model for GMCs	86
6.3	Star formation and H II regions	87
6.3.1	GMC dispersal	89
6.4	Dust model	91
6.4.1	Radiation pressure in dusty H II regions	92
6.5	Dust temperature in GMCs	92
6.5.1	Uniform cloud	94
6.5.2	Radiation pressure-modified density profile	95
6.6	Infrared emission from GMCs	98
6.7	Implications for high- z observations	100
6.7.1	Obscured UV emission	100
6.7.2	IRX- β relation	101
6.7.3	Dust mass estimates	101
6.8	Summary	102
7	Early JWST results on galaxies at Cosmic Dawn	105
7.1	Preliminary considerations	106
7.2	Dust ejection scenario	108
7.3	Dust spatial segregation scenario	111
7.4	Summary	112
8	Summary and Future Developments	115
	List of Figures	167
	List of Tables	169
	Acronyms	171

Abstract

We are living in the golden age of extra-galactic astrophysics. The construction of the sub-millimetre (sub-mm) interferometer [ALMA](#), and the successful operation of the [JWST](#), have marked a giant leap forward in terms of the amount and quality of extra-galactic data. Simultaneously, the rapidly increasing computational power of modern supercomputers allows us to develop and run increasingly detailed numerical simulations [1, 2], bridging the gap between cosmological [3, 4, 5, 6] and sub-galactic scale physics (e.g. [7, 8]).

Before the advent of new generation sub-mm interferometers, the early Universe ($z > 4$) was believed to be nearly dust and metals free. Surprisingly, ALMA observations have revealed the presence of copious dust [FIR](#) continuum emission in galaxies when the Universe was only ~ 600 Myr old [9, 10, 11, 12]. Dust thermal FIR emission is produced by interstellar dust grains heated by the [UV](#) and optical radiation coming from young stars [13, 14, 15].

Due to the stringent time constraints imposed by the age of the Universe and of the dominant stellar populations at $z > 5$, short-lived [SN](#) have been appointed as the dominant dust production mechanism at these high redshifts [16, 17, 18]. However, the amount of dust which is spared in a SN reverse shock is highly debated, and some theoretical works suggest SN dust yields which are in tension with the measured dust-to-stellar mass ratios [9, 19, 20, 21]. This tension between high- z FIR data and theory aggravated the so-called “dust budget crisis” in the early Universe [22]. Crucially, the poor understanding of the mechanisms responsible for the dust and metals build-up at high- z has been hindering the progress of galaxy evolution studies.

The inferred large dust masses (M_d) for high- z galaxies are often dependent on the cold dust temperatures ($T_d \sim 25\text{K}$, see [23] *assumed* in their FIR continuum fitting procedure. The lack of knowledge on T_d (due to the few or even single available ALMA data) casts large uncertainties on the derived IR luminosity (L_{FIR}) and obscured [SFR](#) of high- z galaxies.

Several works based on sub-mm and radio serendipitous detections of UV dark systems have suggested that we might have been severely underestimating the contribution of the dust-obscured star formation to the cosmic [SFRD](#) [24] at $z > 4$ ([25, 26, 27]). The main uncertainties complicating this assessment come from i) the few and sparse observations of individual high- z galaxies FIR spectra and ii) our very biased view of star-forming galaxies at early epochs, mostly limited to UV-selected massive objects (which are hardly representative of the whole galaxy population). A consensus on the evolution of the obscured and total SFRD at high- z is yet to be reached. Other works based on high- z UV-selected targets or the extrapolation from lower- z blank field sub-mm observations report a steep decrease in the obscured SFRD at $z > 4 - 6$ [28, 21, 29]. Crucially, the SFRD is a commonly used benchmark for galaxy formation and mass assembly models. Therefore, getting it right is paramount if we hope to constrain our models of galaxy formation.

Open questions: The fundamental open questions motivating my research are:

- How do the physical conditions (e.g. density, temperature, radiation intensity) in early galaxies SF regions impact interstellar dust properties?
- What are the production mechanisms responsible for the dust/metals build-up in the early universe?
- What is the contribution of the obscured sources/star formation to the cosmic SFRD beyond cosmic noon at $z \gtrsim 5$?

A possible solution to the “dust budget crisis” in the early universe, is that high- z galaxies host warm/hot dust. Indeed, hotter T_d can produce the same observed FIR flux without implying such large dust masses. This hypothesis seems to be supported by state-of-the-art cosmological zoom-in simulations at high- z (see e.g. [30, 31, 32, 33, 34, 6, 35, 8, 7]). Some of these works [30, 32] find that in early galaxies most of the FIR emission comes from a few UV-opaque GMC where dust temperatures as hot as $\sim 100\text{K}$ ($\sim 4\times$ higher than typically measured in the local universe) can be reached. Unfortunately, GMCs are not resolved in these simulations due to the demanding computational time required to run them.

To further investigate these small scales, Sommovigo+20 (**hereafter LS+20**) zoomed in on the star-forming GMCs within a $z \sim 8$ simulated galaxy from the state-of-the-art SERRA simulation suite [8]. We developed a sub-grid analytical model to predict gas and dust properties and model the FIR continuum emission. We found that in high- z GMCs dust is warmer due to the compact structure (high internal pressure and gas column density) of the clouds. This compactness also delays the clouds dispersal by stellar feedback, thus $\sim 40\%$ of the total UV radiation emitted by newly born stars remains obscured. This might question our understanding of dust obscuration at high- z , which is based on the simplistic assumption of the co-spatiality of UV and IR emission.

To overcome the observational limitations in constraining high- z galaxies dust properties (namely the temperature T_d , mass M_d , and IR luminosity L_{FIR}), in **LS+21** we pioneered a new method which relies on a single ALMA band observation per each source. We use the [C II] $158\mu\text{m}$ emission-line luminosity as a proxy for the dust mass, and the underlying continuum to constrain the dust temperature.

In **LS+22a,b** we applied this new method to interpret the observations from two recent, ambitious ALMA large programs, which have ventured to trace the cold gas and dust emission in numerous galaxies approaching the EoR: **ALPINE** ($z = 4 - 6$, [36, 37]) and **REBELS** ($z = 6 - 9$, [38]). We stress that due to observation time constraints, most REBELS and ALPINE targets were observed in a single ALMA band around the [C II] emission. Thus, the dust properties of individual galaxies could not be inferred using traditional **SED** fitting techniques.

We find that the dust-to-stellar mass ratios inferred for most ALPINE and REBELS sources are consistent with SN dust production constraints (assuming dust yields $\sim 0.1 M_\odot$ per SN event). This might hint that the “dust budget crisis” in the early universe is not as severe as initially thought. However, the large uncertainties on these galaxies stellar masses (> 1 dex, [39]) and the limited number (and biased nature) of sources, are currently preventing us from reaching definitive conclusions. We note that the obscured SFR fraction of the UV-bright galaxies targeted both in REBELS and ALPINE is on average $\gtrsim 50\%$, reinforcing the importance of properly correcting for dust obscuration even at high- z at least in the most massive systems ($M_\star > 10^9 M_\odot$).

Further, in **LS+22a,b** we find that the average dust temperature is nearly the same in REBELS and ALPINE galaxies ($T_d \sim 45 - 50 \text{ K}$), and it is $\sim 2\times$ warmer than that observed in most local main-sequence galaxies. A positive trend between T_d and redshift did already appear in the analysis of stacked ALMA and Herschel data in the range $z = 0 - 5$ (e.g. [40, 41, 42]). However, different stacking procedures result in very different (empirically derived) $T_d - z$ relations (see [43]). The largest discrepancies arise at the high- z end ($z > 4$), where isolating low- z interlopers in the stacks and/or correcting for the bias towards the brightest sources becomes more challenging.

To clarify this issue and address the lack of physical understanding for these reported $T_d - z$ trends, in **LS+22a** we produced a physical model for the cosmic evolution of T_d . Using a simple energy conservation argument, we showed that the dust temperature anti-correlates with the total gas depletion time ($t_{\text{dep}} = M_{\text{gas}}/\text{SFR}$).

Due to the higher cosmological accretion rate, t_{dep} decreases at early times (see also [23, 44]), thus implying a mild increase of T_{d} with redshift, which changes our understanding of star formation conditions in the early universe.

Finally, we conclude this by showing a preliminary analysis of early JWST pioneer observation of $z > 10$ galaxy candidates from Ziparo+23 [45]. JWST observations – albeit affected by several uncertainties due to calibration issues and uncertain photometric redshifts – seem to highlight an excess of UV bright, massive (stellar mass $M_{\star} \sim 10^{8-9}$) and very blue (UV slope $\beta_{\text{UV}} \sim -2.6$) systems at this extraordinarily high- z (e.g. [46, 47, 48, 49, 50, 51]). Our favoured explanation is that such extremely early galaxies undergo tumultuous star formation episodes, which due to their very compact sizes (~ 100 pc), result in strong radiation pressure-driven winds which devoid the galaxies of a large fraction of their simultaneously produced dust and metals.

Chapter 1

General Introduction

Over the last few decades, our understanding of the Universe has majorly improved thanks to the advent of new-generation multi-wavelength telescopes which are pushing the observational frontier increasingly backwards in time (well within the first billion years of the life of the Universe). Simultaneously, the rapidly increasing computational power of modern supercomputers allows us to develop and run increasingly detailed numerical simulations, bridging the gap between cosmological and sub-galactic scale physics for the first time.

In this Introduction, we review the basic concepts of cosmology and astrophysics which are fundamental for the understanding of this thesis and its broader scientific context.

1.1 Basics of Λ CDM cosmology

Cosmological models built on [GR](#), are based on a basic assumption known as the “Cosmological Principle”. This principle states that, on large enough scales, the Universe is homogeneous and isotropic. The appropriate metric for space-time in such a Universe is the Friedman-Robertson-Walker ([FRW](#)) metric. Using this metric we can compute the distance (ds , here in spherical coordinates) between any two events as:

$$ds^2 = -c^2 dt^2 + a(t)^2 \left[\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right]. \quad (1.1)$$

The parameter k quantifies the curvature of space-time, which can be $\pm 1, 0$, while $a(t)$ is the so-called “expansion factor”. This expansion factor corresponds to the ratio of the physical separation between two events at fixed coordinates (“comoving coordinates”). By convention, $a(t = t_0) = 1$ at present time and $a(t = 0) = 0$.

The evidence that the factor $a(t)$ is an increasing function of cosmic time came from pioneer extra-galactic observations in the 1920s. At that time, Hubble observed that galaxies beyond the Local Group are moving away from us with velocities v proportional to their distances R , according to the “Hubble law” $v = \dot{a}/a R$ [\[52\]](#). The ratio $\dot{a}/a$ is known as the Hubble parameter $H(t)$, and its value at the present day is denoted by H_0 . Hubble’s observations provided us with the first evidence that our Universe is expanding.

We now know that the evolution of the Universe is tightly connected to that of the expansion factor $a(t)$. In a homogeneous and isotropic Universe, filled by a perfect fluid with density ρ and pressure p , $a(t)$ evolves according to the “Friedmann equations”:

$$\begin{cases} \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3} \rho - \frac{kc^2}{a^2} \\ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left(\rho + \frac{3p}{c^2} \right) \end{cases} \quad (1.2)$$

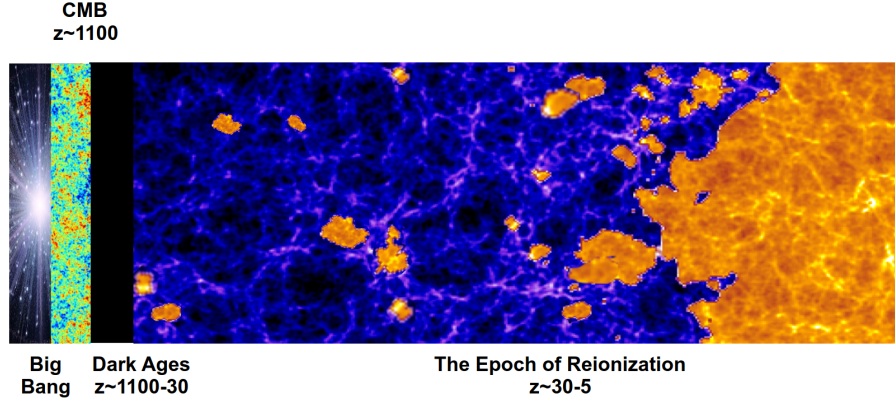


Figure 1.1: Schematic view of the thermal history of the Universe, focusing on its first billion years of age (Figure 1 in [56]).

which were derived by Friedmann (1922) from Einstein’s GR field equations. Substituting the $H(t)$ in these equations, one can relate the expansion of the Universe to the matter-energy density ρ and the space-time curvature. At present epoch (when $a = 1$) we can re-write the first equation in 1.2 as:

$$kc^2 = H_0^2(\Omega_0 - 1) , \quad (1.3)$$

where we have defined the density parameter $\Omega_0 = \rho_0/\rho_{crit,0}$. The critical present density $\rho_{crit,0} = 3H_0^2/(8\pi G)$ is that required to make the topology of the Universe flat ($k = 0$). By assigning the values of the density parameter, curvature, and H_0 , we can completely define a cosmological model.

The standard cosmological model (also known as Λ CDM cosmology) is flat and it features three main energy components which contribute together to Ω_0 . In order of crescent weight, these components are i) radiation, with $\Omega_{r,0} \approx 10^{-4}$; ii) (dark and baryonic) matter, with $\Omega_{m,0} = 0.3089 \pm 0.0062$; and iii) dark energy, with $\Omega_{\Lambda,0} = 0.6911 \pm 0.0062$. The aforementioned values have been measured to extraordinary precision by the Planck Collaboration [53, 54, 55]. They also provided us with the an accurate measurement of H_0 , amounting to $H_0 = 100 h \text{ kms}^{-1}\text{Mpc}^{-1}$ with $h = 0.6774 \pm 0.0046$. We will adopt this cosmological model throughout this whole thesis.

As a byproduct, the expansion of the Universe provides us also with an alternative measure of distance in space-time, the so-called “redshift”. Suppose that a stationary source (located at the position R_1) emits two photons, one at t_1 and the other at $t_1 + \delta t_1$. These photons are received by us at t_0 and $t_0 + \delta t_0$. Using that light follows a null geodesic, $ds = 0$, we can write the ratio between the two time intervals as $\delta t_1/\delta t_0 = a(t_1)/a(t_0)$ (assuming that $\delta t_{1,0} \ll a/\dot{a}$). We can think of the t_1 and $t_1 + \delta t_1$ (t_0 and $t_0 + \delta t_0$) events as the separation of peaks of an electromagnetic wavefront with frequency $\nu_1 \propto 1/\delta t_1$ ($\nu_0 \propto 1/\delta t_0$). Then, the ratio between the emitted and the received photon frequency corresponds to $\nu_0/\nu_1 = a(t_1)/a(t_0) < 1$, i.e. the photon is received at a frequency lower than that at which it was emitted. In other words, within an expanding universe also electromagnetic waves propagating in space-time are stretched, that is redshifted. The amount of the redshift z is defined as:

$$z = \frac{\nu_1 - \nu_0}{\nu_0} . \quad (1.4)$$

Because of the constancy of the speed of light, an object’s redshift can be used to infer its distance with respect to our Galaxy at the present day.

1.2 Cosmic thermal history

In the following, we review the major events in the Universe’s early history according to the big bang standard model and most recent observational findings (see Fig. 1.1 for a schematic representation).

In the standard model of cosmology, the Universe initiated about 13.7 billion years ago from a singularity called the “Big Bang” (BB) where all the fundamental interactions (gravity, electromagnetic, weak and strong interactions) were unified. Currently, it is not possible to explain how the BB originated nor what happened in the first instants of life of the Universe. It is widely accepted that the Universe underwent an inflationary phase very early on in its life. This rapid, exponential expansion flattened any initial space-time curvature, generating a flat geometry and uniform conditions across a region far greater than our current horizon. Inflation is also responsible for sourcing the nearly scale-invariant primordial density perturbations that have grown into today’s large-scale structures. As of now, there is no consensus on the mechanism that made the Universe inflate. Astronomical observations put little constraints on the numerous inflationary models available in the literature, which all rely on non-standard physics.

As the Universe expanded, it undoubtedly cooled down, passing through several symmetry breaking phase transitions (grand unification theory, electroweak, hadrosynthesis). Already a few minutes after the BB, as the temperature declined to $\sim 10^9$ K, nuclear fusion reactions produced a few light elements more massive than hydrogen – such as deuterium, helium, and lithium – in abundances which are measurable today in regions unaltered by star formation. This process is known as the “Big Bang Nucleosynthesis”.

At this stage, the Universe was still in a plasma state. Only about 2×10^5 years after the BB, the temperature of the Universe dropped below 13.6 eV, so free electrons started recombining with protons to form neutral hydrogen atoms. This epoch is known as the “Recombination” epoch (redshift $z \sim 1100$). As soon as the dense fog of free electrons was depleted, the Universe became transparent to relic radiation, which is observed today as the CMB. The CMB spectrum has been measured by several satellites such as COBE, WMAP, and Planck [53, 55]. It is a black-body spectrum with an average temperature $T_{\text{CMB}} = 2.72548 \pm 0.00057\text{K}$ [57] and fluctuations of the order of $\sim 10^{-5}$ K [53]. These little temperature variations reflect the density inhomogeneities caused by the quantum fluctuations not erased at the end of Inflation. Noticeably, the CMB radiation provides us with the earliest picture of the Universe available so far, dating back to when the Universe was only ~ 0.38 Myr old.

After recombination and decoupling, the Universe was transparent to radiation but no stars had formed yet. The only photons in the Universe were those of the CMB and 21cm occasional radio emissions by hydrogen atoms. This period, raging from $z \sim 1100$ to $z \sim 30$, is commonly referred to as “The Dark Ages”. At this stage, the small inhomogeneities in the dark matter density field present during the Recombination epoch started growing via gravitational instability, giving rise to highly nonlinear structures, i.e. collapsed haloes. Still, most of the baryons at these redshifts resided in the diffuse gas in the IGM.

The collapsed haloes formed potential wells within which baryons could fall. If the mass of the halo was large enough (i.e. the potential well was deep enough), the gas would be able to dissipate its energy, cool via atomic or molecular transitions and fragment. This produced conditions appropriate for the condensation of gas and the formation of the first stars, putting an end to the Dark Ages. The first stars are referred to as Population III stars. Population III stars were likely very massive (up to $M_{\star} \leq 10^3 M_{\odot}$, [58]) and thus short-lived (few million years, [58]). Their feedback on the environment, namely the dispersion of heavy elements in the surrounding gas, further facilitated atomic and molecular cooling, igniting subsequent star formation processes in galaxies.

The first population of stars and galaxies generated copious UV radiation through

nuclear reactions. An early population of accreting black holes (quasars) and the decay or annihilation of dark matter particles might also have generated some amount of UV light. Crucially, the UV photons with energies > 13.6 eV started ionizing the hydrogen atoms in the surrounding IGM. This process is known as “Cosmic Reionization” [59, 60, 61], and it is the second major change in the ionization state of hydrogen in the Universe (after Recombination).

According to our current understanding, Reionization started shortly after the first structures formed, likely around $z \approx 30$. The EoR is of immense importance in the study of structure formation. It is a direct consequence of the formation of the first structures and luminous sources in our Universe. Further, it affects subsequent structure formation out to the present day.

In the last twenty years, new-generation telescopes have allowed us to probe the EoR in increasing detail, providing detections of numerous galaxies as early as $z \sim 9 - 10$ [62, 50, 63, 49, 51, 47, 64, 65, 66, 48]. Gaining insight into such extraordinarily early structures has been possible thanks to refined selection techniques and state-of-the-art facilities such as the HST, Subaru, VLT, Spitzer, Keck and ALMA [67, 68]. Last December, the launch and successful operation of the JWST marked another major step towards our understanding of the first generations of galaxies in our Universe. We review the state of the art of EoR galaxies observations and theoretical models in the following.

1.3 Galaxies at the EoR: theory and observations

Although many aspects of the process are still largely unknown, there is a large consensus that Reionization was predominantly powered by photons emitted by stars within small galaxies in $10^{8-9} M_{\odot}$ dark matter halos [69, 70, 71].

Identifying the Reionization sources with available instrumentation has represented one of the most intense areas of activity in observational cosmology in the last two decades (see [72, 67, 73] for recent reviews). In the following, we review the main detection techniques and our current physical understanding of EoR galaxies properties.

1.3.1 Selection techniques

Two methods have proved most effective in distinguishing extreme redshift galaxies amid the much more numerous and brighter low-redshift systems in the sky.

- The first method, the so-called Lyman-break technique, selects Lyman Break Galaxies (LBGs) via the abrupt drop (the “Lyman break”) in their UV continuum emission beyond $912 \text{ \AA}$ (rest-frame) due to the absorption of LyC photons by the neutral ISM gas. Beyond $z > 5 - 6$, as we approach the EoR, the Lyman Break shifts to $1216 \text{ \AA}$, as lower wavelengths photons are absorbed both by the ISM and intervening (increasingly neutral) IGM. The strength of the Lyman-break selection technique resides in the possibility of applying it to imaging with broad-band filters. This allowed us to gather extraordinarily large samples (thousands) of high-redshift galaxies candidates. Recently, thanks to the Advanced Camera for Surveys (ACS) and the Wide Field Camera3 (WFC3) onboard the HST, and now NIRCAM on JWST, it has become possible to detect LBG candidates as early as $z > 10$ [49, 51, 50, 74, 47, 75, 76]. It is important to mention that low- z dusty galaxies (due to a combination of dust reddening and nebular lines) may mimic the Lyman drop in high-redshift galaxies. Therefore, spectroscopic confirmation of the candidates is paramount (for the highest redshift spectroscopically confirmed candidates see [75, 77, 78]).
- The second method selects Lyman Alpha Emitters (LAEs) via the detection of the bright Ly α recombination line at $1216 \text{ \AA}$, which is produced by HI atoms in the

galaxies ISM. With the advent of genuinely wide-field CCD imaging cameras on 8–m class telescopes, narrow-band searches for LAEs have proved successful in uncovering large samples of galaxies up to $z \sim 8$ (e.g. [79, 80, 81, 82, 83]). Unfortunately, the Ly α selection is bound to be inefficient at redshifts $z > 7$. The reason is that Ly α has an extremely high optical depth against neutral hydrogen. Thus at such early epochs, the fairly neutral IGM prohibitively attenuates the Ly α line.

As previously mentioned, spectroscopic confirmation of candidate high- z galaxies is crucial. This task is particularly challenging for $z > 5$ galaxies as the rest-frame optical emission lines commonly used at low- z (such as H α , H β , [O III] $\lambda\lambda$ 4959,5007, and [O II] $\lambda\lambda$ 3726, 3729) are redshifted to near-IR where ground based facilities have limited sensitivity and HST has no wavelength coverage. To overcome this limitation, the JWST has been designed to detect such lines in galaxies out to $z \sim 10$ thanks to the addition of high-sensitivity long wavelength channels (up to $\sim 5\mu\text{m}$, observer frame). So far, JWST has detected optical emission lines in several HST-selected galaxies out to $z = 8 - 10$ enabling pioneer studies on their ISM properties[84, 85]. Spectroscopic confirmation of JWST-selected candidates via optical emission lines has been achieved for a handful of sources out to $z \sim 10$ [75, 77, 78].

Before the JWST, nebular emission lines, such as CIII] $\lambda\lambda$ 1907,1909 (Stark et al., 2015a), [OIII]+H β (Smit et al., 2014) and CIV] λ 1548Å [86], detectable with HST out to $z > 7$, have been successfully been used as alternatives. Far infrared (FIR) fine structure lines, such as [C II] $158\mu\text{m}$ [87, 88, 89, 90, 83, 91, 92, 93] and [O III] $88\mu\text{m}$ [94, 95, 96, 97, 9] detectable with ALMA out to similarly high- z , have also been widely used for spectroscopic confirmation as well as probing early galaxies ISM properties (see also [98] for a recent review).

In particular, the [C II] $158\mu\text{m}$ line is the dominant coolant of the neutral atomic gas in the ISM [99], making it one of the brightest FIR lines in most galaxies [100]. Further, [C II] has been proved to be connected to the SFR of local [101, 102] and high- z galaxies [89, 103, 104, 95, 83, 105, 91, 106, 92, 107]. Over the last few years, three ambitious ALMA large programs have ventured to observe the [C II] line emission in hundreds of galaxies beyond $z = 4$. The ALPINE program [36, 37] has provided us with the first large sample (122 sources) of spectroscopically confirmed star-forming galaxies at $4 < z < 6$ [36]. Out of the whole sample, 2/3 has been detected in [C II] (and 1/3 in the dust continuum [41]; more on this in the next Section). Afterwards, the REBELS survey [38] targeted 40 of the brightest UV-selected galaxies at $z = 6.5 - 9$, scanning for both [C II] and [O III] line emission. So far, they have obtained 15 [C II](Schouws in prep.), 2 [O III][21] (and 13 dust continuum [108]) detections. Finally, the latest survey probing FIR lines at high- z is CRISTAL (PI: Herrera-Camus), a large program which proposes to follow up 19 of the initial ALPINE targets to obtain high-resolution [C II](and dust continuum) maps. In this case, the purpose is to do an unprecedentedly detailed ISM study for galaxies at such early epochs, moving past the spectroscopic confirmation and/or broad galactic properties assessment.

1.3.2 Global characterization

Combined efforts with the aforementioned techniques have been amazingly successful, and they have allowed us grasp the physical characteristics of EoR galaxies. Further, we are probing the evolution of the cosmic star formation rate density and the consequent stellar mass build-up out to unprecedentedly early epochs, gaining key insight into the process of galaxy evolution from its earliest stages. A key ingredient in galaxy evolution models, which is interconnected with all the aforementioned global characterizations of early systems, is the progressive dust (and metal) enrichment of the Universe. We will

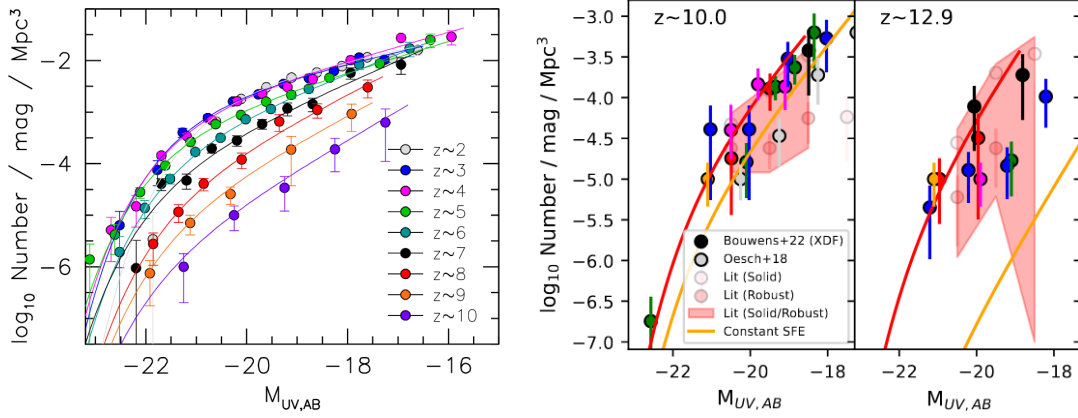


Figure 1.2: **Left Panel:** UV LFs in the redshift range $z = 2 - 9$ compiled by Bouwens+21 (Fig. 5 in [109]) based on their comprehensive blank-field searches with HST. The best-fit Schechter LFs are also shown (solid lines). **Right panel:** Latest, preliminary compilation of UV LF at $z = 10$ and $z = 12.9$ by Bouwens+22 [110] based on the candidate galaxies identified in the combined HST+JWST data set over the HUDF (adapted from Fig. 6 in [110]; see also [49, 51, 66, 63, 76]). The variation resulting from considering only the “robust” candidates (where the cumulative probability of candidates lying at $z > 5.5$ exceeds 99% based on NIRCcam photometry analysis) vs. all the literature candidates is shown by the pink shaded area.

discuss this topic, central to the work presented in this thesis, in the next Chapter.

UV luminosity function

Luminosity Functions (LFs), which describe the number density of galaxies as a function of their luminosity/magnitude, are regarded as one of the best ways to outline the changing demographics of galaxies in the Universe across cosmic time. The most commonly adopted parametrization of the UV LF is through the Schechter function, according to which we can write the number of galaxies as a function of luminosity:

$$\frac{dn}{dL} = \phi(L) = \frac{\phi_*}{L_*} \left(\frac{L}{L_*} \right)^\alpha e^{-L/L_*} \quad (1.5)$$

where the free parameters ϕ_*, L_* represent the characteristic number density and luminosity, and α the faint-end slope. The function ϕ is often expressed in terms of the UV AB magnitude instead of the luminosity, substituting $\phi(M_{UV})dM_{UV} = \phi(L)d(-L)$ and $M_{UV} = M_{UV*} - 2.5 \log(L/L_*)$, where M_{UV*} is the characteristic magnitude of the exponential drop-off (the “knee”) of the LF.

Over the last decade, space and ground-based surveys probing non-cluster extragalactic fields (e.g. the Hubble Ultra Deep Field, Hubble Frontier Field and CANDELS fields) have allowed us to accurately map the UV LF out to $z \sim 10$ (e.g. [111, 109], see the Upper panel of Fig. 1.2) in the broad magnitude range $M_{UV} \in [-17; -23]$. JWST observations with NIRCcam probing these same fields, are now providing new observational constraints at $z > 10$ for $-22 \lesssim M_{UV} \lesssim -18$ (e.g. [49, 51, 76, 63, 66, 76]). At $z = 10 - 15$ different works infer substantially different (several dex) LF estimates [49, 76, 51, 63, 66]. This is not surprising given the small number of (hardly secure) sources in the $z > 10$ selection and the limited cosmological volume probed by these first JWST observations.

At $z < 10$ the abundant observations provide us with a more coherent picture. There is a general agreement that the faint-end of the UV LF steepens (from $\alpha \sim -1.5$ at $z \sim 2$ to $\alpha \sim -2.4$ at $z = 10$) with increasing z [112, 109]. This has relevant implications for the EoR (fainter, more abundant galaxies are believed to be mainly responsible for the Reionization of the Universe, see e.g. [73]). Disentangling the effects of the remaining two free parameters (ϕ_*, M_{UV*}) on the UV LF evolution remains more challenging. A

progressive brightening of the bright end of the LF is observed up to $z \sim 5$ (from $M_{\text{UV}*} \sim -20.3$ at $z = 2$ to $M_{\text{UV}} - 21.1$ at $z \sim 5$), with a subsequent halt between $z \sim 5 - 10$. Theoretical works agree on interpreting this effect as the result of a genuine increase in the UV luminosity (and thus star formation rate) of most massive LBGs at earlier epochs (e.g. [113]). The characteristic density appears to rapidly decrease at earlier times (~ 3 order of magnitude drop from $z = 2$ to $z = 10$). We caution that observational biases due to samples incompleteness, magnification uncertainties, and estimated size-luminosity relation can significantly impact these results.

The UV LF has been modelled in a number of ways, ranging from abundance matching (between galaxies and their dark matter halos, e.g. [114] to semi-analytics [115, 116] to hydrodynamic simulations [5, 117, 118, 119, 120]. Interestingly, despite the wide variety of approaches followed and the parameters used, most of these models are in reasonable agreement with the data out to $z \sim 9$. This consistency is likely driven by the degenerate effect that a number of physical processes have on the UV LF. For instance, SN and UV background feedback decrease the gas content of low-mass dark matter halos, virtually increasing their star formation efficiency; the large dust content of most massive halos reduces their observed UV luminosity; the assembly history impacts the amount of gas retained by a galaxy at a given halo mass.

At pioneering, extremely high-redshift, significant tension between theoretical models predictions and preliminary JWST data seems to arise. In particular, observations have reported an excess of bright galaxies ($M_{\text{UV}} < -18$) at $z > 10$ [121, 122, 123, 124]. Several explanations have been proposed, ranging from questioning the Λ CDM cosmology [122, 123], down to more conservative ones suggesting higher SF efficiency for galaxies at $z > 10$ [121, 110] or no dust obscuration in such high- z massive systems due to efficient dust ejection [124, 45]. It is worth mentioning that considering only “robust” $z > 10$ candidates (where the cumulative probability of candidates lying at $z > 5.5$ exceeds 99% based on NIRCcam photometry analysis) reduces the tension with theoretically predicted UV LFs ([76, 110], see Fig. 1.2). Further, even for the “robust” candidates, the uncertainties on the photometric redshifts, strongly affect their estimated UV magnitudes and number counts. Overall, we can agree that the evolution of the UV LF $z \gtrsim 10$ is still extremely uncertain, emphasizing the need for spectroscopy and deeper NIRCcam and optical imaging to obtain reliable results [110].

IR luminosity function

About half of all the luminous power from stars and active galactic nuclei (AGN) that make up the extra-galactic background is emitted in the FIR and submillimetre (sub-mm), as a result of re-radiation of dust heated by UV and optical photons [127, 128, 129, 130]. Thus, it is of the utmost importance to complement UV LF studies with (rest-frame) FIR ones out to the highest redshifts.

In the past decade, significant progress has been made thanks to a succession of breakthrough space-based and ground-based instruments, namely the Spitzer [131] and Herschel [132] space telescopes, the radio interferometer VLA [133, 134], single-dish submillimetre telescopes such as JCMT [135], IRAM [136], ASTE [137], APEX [138], and SPT [139], and earlier sub-mm interferometers such as SMA [140] and PdBI/NOEMA [141]. Together, these facilities have enabled the IR LF out to $z \sim 5$ [142, 143, 125]. Extending such studies at earlier epochs has proven extremely difficult. Herschel – the only instrument probing rest-frame FIR wavelengths at $z > 5$ before ALMA – is prohibitively limited by its relatively low sensitivity (only bright sub-mm galaxies, SMGs, are detectable at this high- z) and by the confusion resulting from blending multiple sources within the same telescope beam [144].

The advent of the high-sensitivity, high-resolution sub-mm interferometer ALMA al-

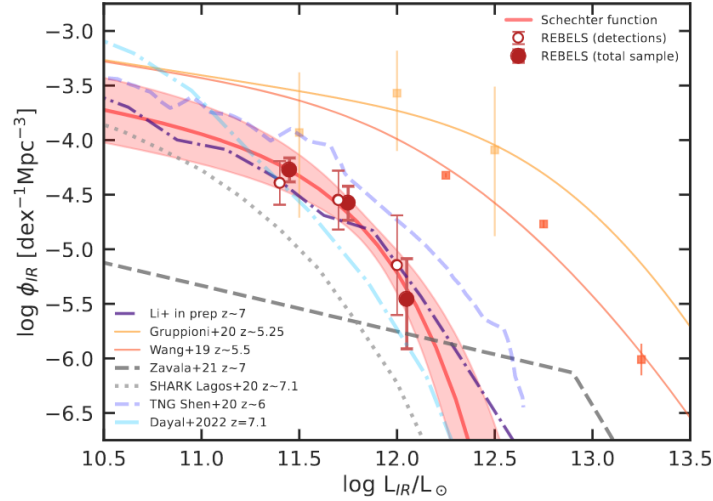


Figure 1.3: Total IR LF inferred by the REBELS collaboration relying on their rest-frame $158 \mu\text{m}$ continuum detections and upper limits at $z \sim 7$ (red points and curve, this is Fig. 3 in [29]). The rest of the lines show both theoretical and observational IRLF studies in several fields. The dark grey line represents the $z \sim 7$ IRLF predicted based on backwards modelling combined with the data from the ALMA SMGs survey MORA (among others, [28]). The yellow line and dots indicate the IRLF at $z \sim 5$ inferred by the ALPINE collaboration based on their rest-frame $158 \mu\text{m}$ serendipitous detections [26]. The orange symbols show the results previously obtained based on the Herschel COSMOS catalogue [125]. Theoretical predictions from the TNG simulations at $z \sim 6$ (light purple dashed line, [126]) and semi-analytical models DELPHI (cyan dashed line, [20]) and SHARK (grey dotted lines, [116]) at $z \sim 7$ are also shown.

lowed us for the first time to detect individual LBGs as early as $z \sim 8.3$ [11, 9]. Since then, increasingly large samples of FIR-emitting star-forming galaxies as early as $z \sim 7$ have been collected [108]; noticeably, some high- z sources detected with ALMA are UV-dark [145, 26], meaning that they were completely missed by previous studies based on HST data. Unfortunately, deep, blind, large sky area observations with ALMA are not feasible. This complicates the assessment of the statistical relevance of the undeniably biased samples now available at $z > 5$ [26, 146, 28, 21].

The recent ALMA large program ALPINE has provided us with a surprisingly large number (56) of serendipitous detections at the same redshift as the (120) survey UV-selected targets, at $z = 4 - 6$. Based on these findings, the ALPINE collaboration has attempted to extend the IR LF out to $z \sim 6$, finding little evolution in (ϕ_*, L_*) between $z = 2.5$ and $z = 6$ (in contrast with previous assessments based on Herschel data, [125]). They also found a surprisingly flat faint-end slope of the IRLF across all redshifts ($\alpha \sim 1.2$). The limited number and biased nature of the selected sources (likely found within an overdense region) together with the little range of IR luminosities spanned (especially in the highest redshift bin $z = 4.5 - 6$) leave room for large uncertainties. A more recent work based on a compilation of the results of several Herschel and ALMA surveys (including MORA, the first ALMA blank-field survey searching SMGs at 2 mm) and backwards-evolution modelling, attempted at extending IR LF studies to $z \sim 7$ [28]. They inferred a very steep decrease in the characteristic number density of the IR LF at high- z ($\phi_* \propto (1 + z)^{-6.5}$), which is in contrast with the results from ALPINE serendipitous detections.

The first direct constraint on the IRLF at $z \sim 7$ has very recently been provided by the REBELS collaboration [29]. They use the UV LF as a proxy to derive the effective volume of their 42 $z \sim 7$ UV-selected targets, and the $158 \mu\text{m}$ continuum flux-to-IR luminosity conversion factor derived by [147] to quantify the targets L_{IR} (using both the 16 detections and the remaining upper limits). The resulting IR LF is well reproduced by a Schechter function with a characteristic luminosity of $\log(L_*/L_\odot) = 11.6 \pm 0.15$, and a significantly (~ 1 dex) lower normalization than that inferred at $z \sim 5$ by the ALPINE collaboration

([26], see also [125]). This result suggests a rapid evolution of the IRLF from $z = 4 - 5$ to $z = 7$. It is worth mentioning, that the IRLF derived from REBELS $z \sim 7$ data, is an order of magnitude higher than that extrapolated from lower- z studies by [28], emphasizing the importance of directly constraining the obscured SFR out to high- z .

The relatively slow progress on the observational side (mostly due to the limited power of available instruments) has been hampering also the progress of theoretical models of IR LF at high- z . Hydrodynamical simulations [118, 6, 126] and semi-analytical models [115, 116] struggle in reproducing the flatness of the IR LF suggested by ALPINE serendipitous detections, predicting a sharper drop in the number density of sources with $L_{\text{IR}}/L_{\odot} > 10^{11.5}$, which is consistent with latest REBELS results (albeit differences in the normalization constants). It is important to mention that unlike in UV LF studies, different theoretical works predict IR LF which can differ by ~ 2 order of magnitude both at the faint ($L_{\text{IR}}/L_{\odot} < 10^{11}$) and at the bright ($(L_{\text{IR}}/L_{\odot} > 10^{12})$) end at $z > 5$. The theoretical hurdle stems from the difficulty in bridging the gap between large cosmological volumes required to statistically investigate very massive ($M_{\star}/M_{\odot} > 10^{11}$) and thus rare sources such as SMGs, and the physical processes happening on ISM physics scales. Such processes cannot be treated on-the-fly in cosmological simulations, but they greatly impact the output IR luminosity-to-halo mass ratio. In fact, halo/stellar mass to IR luminosity scaling relations are hardly understood in the high- z Universe, hampering the predictive power of semi-analytical/numerical nearly as much as simulations.

Stellar mass density

Another fundamental galaxy property is the stellar mass, $M_{\star}$, as it gives us insight into the past star formation activity within a source. However, accurately constraining $M_{\star}$ for high- z galaxies from broad-band data is highly non-trivial. Indeed, the estimate depends on several assumptions on the Initial Mass Function (IMF), the strength of nebular emission, the star formation history (SFH), the stellar metallicity and dust extinction. This strongly affects the rest-frame UV and visible emission (observer frame $0.1 - 0.8 \mu\text{m}$) probed by HST, while it is milder at longer NIR-to-MIR wavelengths (observer frame $0.6 - 28.8 \mu\text{m}$) probed by JWST NIRCAM and MIRI. JWST data will hopefully allow us to break the degeneracy between SFH, dust and metallicity and improve our constraints on galaxies stellar masses out to $z \sim 10$. As a reference, note that assuming a given metallicity and dust attenuation curve, different SFH assumptions (constant vs. non-parametric), can result in variations in $M_{\star}$ up to 1dex.

Albeit these caveats, broad-band HST and Spitzer data have been used to probe the stellar mass density (SMD, i.e. stellar mass per unit cosmological volume) as high as $z = 5 - 10$ and down to a limiting UV magnitude of $M_{\text{UV}} = -18$ [148, 149, 150, 67]. Different works apply different procedures, and only some account for the impact of nebular emission [149, 67, 42]. Nevertheless, there is a general agreement that the SMD decreases at $z \gtrsim 4$ as $(1 + z)^{-0.36}$, although the error bars and paucity of data preclude strong conclusions beyond $z \sim 8$.

Theoretical works, based on semi-analytical [113] or semi-numerical models [151], and hydrodynamical cosmological simulations [152, 56], agree with one another and with observations within the (broad) 1σ uncertainties. We conclude that at $z > 5$ small, faint galaxies ($M_{\text{UV}} > -18$) contain most ($\sim 75\%$ at $z \sim 6.5$, and up to $\sim 90\%$ at $z \sim 9$) of the total stellar mass in the Universe as they strongly outnumber more massive systems. This crucially implies that most of the stellar content of the early Universe is embedded in sources which were not detectable (and still have not been detected) until the advent of the JWST, which promises to extend stellar mass estimates down to $M_{\text{UV}} \sim -14$.

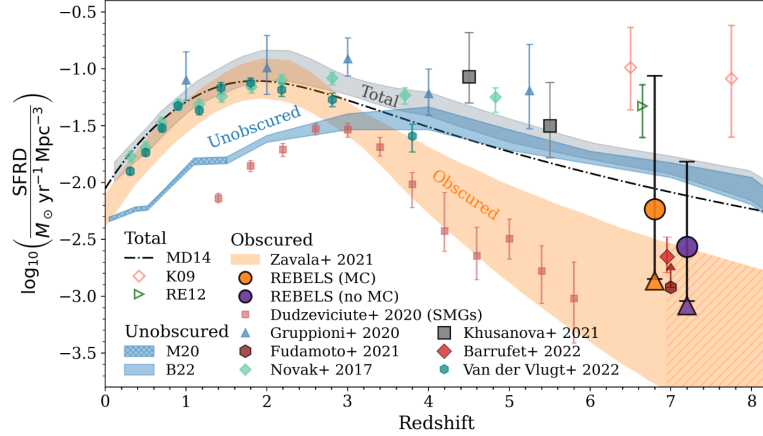


Figure 1.4: Constraints on the dust-obscured $z \sim 7$ cosmic star formation density from the REBELS collaboration (Fig. 6 in [21]). Same-colour triangles indicate the lower limits obtained from considering only the REBELS stellar mass range $10^{8.8} < M_*/M_\odot < 10^{10.8}$. The points are slightly offset from $z = 7$ for visual clarity. Several SFRD measurements and compilations from the literature are also shown, divided into total, unobscured and obscured SFRD measurements. At $z \lesssim 1.5$ we show the unobscured SFRD from Moutard et al. [153], and at $z > 2$ from Bouwens et al. [76] in blue. The dust-obscured and total SFRD inferred by Zavala et al. [28] are overplotted in orange and grey, respectively. Obscured SFRD constraints inferred from several far-infrared and radio observations at $z < 6$ are shown as filled symbols (see the legend, [25, 26, 154, 145]). Total SFRD constraints based on gamma-ray bursts studies are represented by empty symbols ([155, 156], denoted K09 and RE12 in the legend).

Cosmic star formation rate density

The cosmic star formation rate density (SFRD or CSFRD) is inferred by integrating the UV LFs at each given epoch and converting the UV luminosity into a SFR in order to derive the evolution of the SFR per unit volume across cosmic time. An important, and non-trivial, step in this procedure is that of accounting for dust attenuation to properly convert the observed L_{UV} into the intrinsic SFR.

Since the first compilation by Madau & Dickinson [24], several works have investigated the SFRD, mostly relying on the HUDF surveys and the CLASH lensing surveys data [153, 42, 76]. It has been established that the SFRD reaches its maximum around a redshift of $z \sim 1 - 3$, and has since been declining up to the present day, as galaxies progressively consume their gas-reservoir entering a nearly quiescent phase. At low redshift ($z \lesssim 4$), the SFRD is dominated by dust-obscured star formation [157, 142, 26, 112, 25, 158, 28]. At earlier epochs, unobscured star formation progressively takes over due to the increasingly younger ages, and scarce dust content of most abundant star-forming galaxies [24, 42, 154, 28]. However, direct observations of dust at $z \gtrsim 5$ are still scarce, thus the importance of obscured star formation at these high redshifts remains highly debated.

Some works based on sub-mm to radio data have suggested that we might have underestimated the contribution of the obscured SFR [159, 21, 29] and/or of optically/UV dark sources [25, 26, 27, 145] at $z > 4$. This would result in a flatter SFRD at this high- z end with respect to that inferred from UV-based studies. However, different works find quantitatively, vastly different results (e.g. the inferred obscured SFRD at $z \sim 5 - 7$ varies from $\sim 10\%$ [29, 21, 28] up to $\sim 80\%$ of the un-obscured SFRD [26]), mostly due to the little and biased rest-frame FIR data available at the high- z end. This requires the employ of backward modelling and/or non-trivial completeness evaluations, which hampers a consistent comparison between the derivations from different groups.

On the theoretical side, the challenges in modelling the SFRD at high- z are the same as mentioned for the IR LF, i.e. the necessity of cosmological volumes to probe SMGs and, at the same time, proper treatment of ISM physics which majorly impact obscured

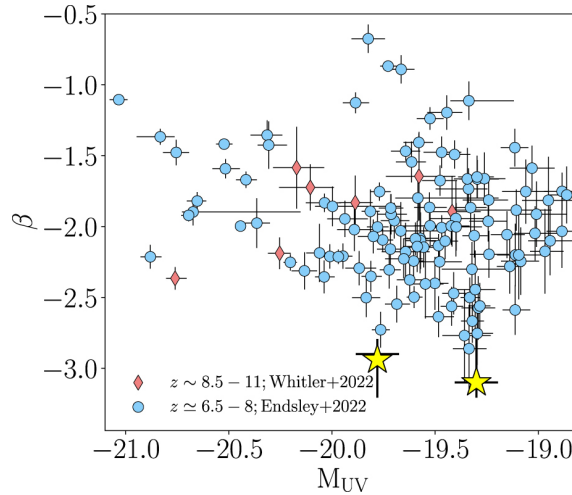


Figure 1.5: Recent compilation of measured UV slopes as a function of MUV for $z > 7$ HST and JWST detected galaxies (Fig. 6 in [46], for details on the galaxies sample see [165, 65]). Two objects identified with extremely blue UV slopes are highlighted as yellow stars.

SF quantification. Semi-analytical models [115, 20, 116] and hydrodynamical simulations [5, 117, 118, 119, 120] predict slightly different slopes for the z -evolution of the SFRD, but they are all in accord with UV-based studies and struggle in reproducing the flatness of the SFRD predicted by some sub-mm to radio wavelengths studies at $z > 4$. The theoretical challenge is represented by bridging the gap between the large cosmological scales required to account for bright and massive, and thus rare sources such as SMGs and the sub-galactic scale physics involved in the treatment of dust-obscuration of star formation in “normal” galaxies [160].

Preliminary results from JWST NIRCcam indicate that (similarly – and rightly so – to the UV LF) the SFRD at $z > 8$ might lie significantly in excess of the constant star formation efficiency (SFE) models, by factors of $\times 2 - 6$. Interpretation of these results is unclear, and it is an open question whether the new results indicate the SFE of galaxies is indeed more efficient or if the IMF of (luminous) galaxies is very different at early times. Noticeably, the first deep NIRCcam observations also revealed the existence of UV-undetected, dusty galaxies at $z > 6$. The contribution to the SFRD from these high- z dusty galaxies is inferred to be as large as $\log(\text{SFRD}/\text{M}_{\odot}\text{yr}^{-1}\text{Mpc}^{-3}) \sim -3$ at $z \sim 7$ [161]. This result implies that so-far undetected sources might contribute as much as the bright REBELS galaxy sample to the SFRD at $z = 7$, reinforcing the importance of properly accounting for dust obscuration out to the EoR. Future spectroscopic and deeper imaging observations, combined with likewise theoretical efforts will shed light on the evolution of the SFRD at $z > 8$.

A simultaneous effort needs to be put into the construction of new sub-mm instruments capable of producing wide sky-area, blind surveys aimed at probing the obscured SFRD beyond cosmic noon ($z > 3$). Blind surveys – albeit limited to the bright SMGs – are now starting to be carried out/advocated for at increasingly high redshift with ALMA ($z > 2$, see e.g. the MORA survey, [162, 28]), which however is limited both in the area and sensitivity for such endeavours. Proposed instruments for the upcoming decade include the 50m Atacama Large Aperture Submillimeter Telescope (AtLAST, [163]) and Large Sub-mm Telescope (LST, [164]). These instruments would allow us to achieve an order-of-magnitude increase in survey speed, thus enabling mapping $\gg 2$ deg areas of the sky at a $\lesssim 5 - 10$ arcsec resolution, emulating the capabilities of state-of-the-art UV and optical telescopes.

Ultraviolet slopes

It is common to parameterize galaxies UV continuum flux F_λ , in the wavelength range $1600\text{\AA} \leq \lambda \leq 2500\text{\AA}$, in terms of a power law index β [13]:

$$F_\lambda \propto \lambda^\beta. \quad (1.6)$$

This index β is referred to as the UV slope; its departure from the negative, intrinsic galaxy value (for the MW $\beta_i = -2.6$ [166]) provides us with a direct constraint on dust attenuation. Positive, i.e. “red”, β are typically seen in dusty, evolved galaxies, whereas metal/dust-poor, young galaxies (e.g. local dwarfs) are typically characterised by “blue” $\beta \sim \beta_i$ [167, 67, 168].

As expected due to their young ages and relatively low metallicity, most galaxies at $z \sim 7$ observed with the HST WFC3 camera have been inferred to have blue UV slopes $\beta \sim -2$ [169, 170, 171, 172, 173]. Thanks to JWST Nircam these results have already been confirmed and extended out to $z \sim 11$ in a statistically large sample of UV bright galaxies [46] (see Fig. 1.5). Interestingly, some of the new $z = 7-11$ candidate sources show extreme β values, as low as $\beta_{\text{UV}} \lesssim -3$ [47, 62, 46, 50], implying negligible dust content and nebular emission [167]. This evidence is somewhat puzzling considering the large stellar masses ($M_\star > 10^9 M_\odot$) and low, but not primordial metallicities ($Z \simeq 0.1 Z_\odot$, [48]) of such systems. We caution that some of these extremely blue values might be spuriously produced by an observational bias and/or calibration issues [174].

Based on the measured blue β_{UV} , little-to-no dust correction was applied in UV luminosity functions and SFRD studies at high- z [175, 176]. However, recent ALMA large programs following up UV bright systems ($-22 \lesssim M_{\text{UV}} \lesssim -20$) at $z = 4-7$, have shown that in some cases, galaxies showing blue UV slopes ($\beta \lesssim -2$) have strong dust continuum emission [177, 178]. This is possible in sources where the UV and IR photons trace spatially separated regions of the galaxies, as we will discuss in Chapter 5-6. Understanding whether this “spatially-segregated” ISM morphology is frequent in EoR systems is crucial, as it would have severe consequences on LF and SFRD estimates.

Chapter 2

Dust

The interstellar medium is a crucial component of galaxies. It is responsible for fueling the stars which are the galaxies' dominant sources of energy. While most of the present-day galaxies' mass is in the form of dark matter particles, it is the baryons (accounting for $\sim 10\%$ of the total galaxy mass, [179]) that determine their visible appearance.

In the earliest evolutionary stages, the ISM gas accounts for all the baryons in a galaxy. As galaxies evolve, the interstellar medium is gradually converted into stars. Processes such as cosmic accretion, galaxy mergers, stellar winds and outflows also strongly affect the stellar-to-gas mass ratios. Understanding the properties of the interstellar medium holds the key to several open questions concerning galaxy evolution. In particular, we will focus on a key component of the ISM, the interstellar dust. Despite accounting for only $\lesssim 1\%$ of the total ISM mass [180], dust majorly shapes the emission spectra of galaxies across all redshifts.

2.1 The ISM

In any galaxy the space among stars is not empty, it is filled with:

- **Interstellar gas:** ions, atoms and molecules in the gas phase. Most of the gas is hydrogen, 10% is helium, and the remaining 0.1% is constituted by other elements such as oxygen, carbon and nitrogen;
- **Interstellar dust:** small (mainly less than $1\mu\text{m}$ in size), solid, metallic (carbonaceous or silicates) particles mixed with the interstellar gas;
- **Cosmic rays:** ions and electrons with ultra-relativistic kinetic energies far greater than thermal (up to 10^{21} eV);
- **Interstellar radiation field:** radiation field resulting from stellar emission, re-processing of starlight by dust grains, CMB radiation, free-free emission the interstellar plasma, synchrotron radiation from relativistic electrons and gamma rays emitted in nuclear transitions and decays.

We might also add two other components, the interstellar magnetic field and the gravitational field, resulting respectively from the electric currents in the ISM and the mass stored in the whole galaxy.

The gas in the ISM spans a wide range of temperatures, densities, and ionization states. It is typically classified according to the following characteristic states, or “phases”:

- **Coronal gas:** gas that has been shock-heated to $T > 10^{5.5}$ K by blastwaves racing outward from supernovae explosions. The gas is collisionally ionized, with ions such

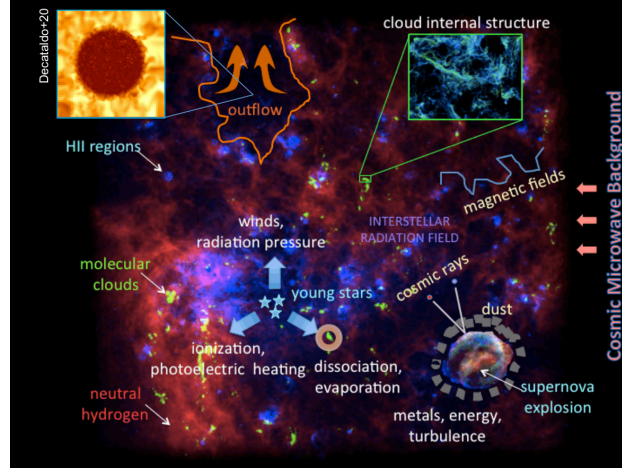


Figure 2.1: Schematic representation of the interstellar medium and its components. Credits: courtesy of Andrea Ferrara

as OVI. Most of it has low number density $n_{\text{H}} \sim 4 \times 10^{-3} \text{ cm}^{-3}$ and in a Milky Way-like kind of galaxy it fills nearly half of the volume of the galactic disk ([179]). The coronal gas cools down on time scales of the order of $\sim \text{Myr}$ through expansion and X-ray emission. It is often referred to as a “hot ionized medium” (HIM).

- **HII gas:** gas where hydrogen has been photoionized by UV photons from young hot stars (typically massive O-stars). The photoionized gas temperature is around $T \sim 10^4 \text{ K}$ and it may be dense material from a nearby cloud (in which case the ionized gas is called an H II region) or lower density intercloud medium (referred to as diffuse HII). The number densities range is: $0.3 \text{ cm}^{-3} < n_{\text{H}} < 10^4 \text{ cm}^{-3}$ ([179]). The extended low-density photoionized region is called “warm ionized medium” (WIM), and it contains more mass than its denser more visible counterpart. It cools down through free-free, fine structure and optical line emission and it has been observed thanks to the latter and its thermal radio continuum emission.
- **Warm HI:** predominantly atomic gas whose temperature is around $T \sim 10^{3.7} \text{ K}$. Its density is around $n_{\text{H}} \sim 0.6 \text{ cm}^{-3}$ and it generally fills a significant fraction of the volume of the disk of the host galaxy. It cools through optical and fine structure line emission, and it is observed in particular thanks to HI 21 cm, optical and UV emission and absorption. It is often referred to as the “warm neutral medium” (WNM).
- **Cool HI:** predominantly atomic gas whose temperature is around $T \sim 10^2 \text{ K}$ with density $n_{\text{H}} \sim 30 \text{ cm}^{-3}$ filling $\sim 1\%$ of the total ISM volume. It is often referred to as the “cold neutral medium” (CNM) and it is observed through analogous processes as the WNM. Its cooling proceeds through fine structure line emission.
- **Diffuse molecular gas:** similar to the cool HI clouds, but with sufficiently large densities (and column densities) so that self-shielding allows a copious formation of H_2 molecules. Its temperature is around 50 K and the density amounts to $n_{\text{H}_2} \sim 100 \text{ cm}^{-3}$. Its main cooling channels are fine-structure emission lines. It is typically traced by optical, HI 21 cm and UV absorption lines and in emission through HI 21 cm and CO 2.6 mm ($n = 1 \rightarrow n = 0$ transition).
- **Dense molecular gas:** gravitationally bound clouds that have achieved $10^3 \text{ cm}^{-3} < n_{\text{H}} < 10^6 \text{ cm}^{-3}$. These clouds are often dark, i.e. the gaseous component fails to emit. Indeed, the first excited state for H_2 is found at 172 K , a temperature that is almost never reached in these clouds (where $10 \text{ K} < T < 50 \text{ K}$). The first allowed

transition for a homo-nuclear molecule is a quadrupole transition, which is much fainter than a dipole and thus hardly observable ([181]). Heavier molecules, such as CO, are employed as dense molecular gas tracers. Indeed, the spacing between energetic levels decreases with the atoms' mass ($\Delta E \propto \omega = \sqrt{k/m}$), thereby facilitating the transitions (e.g. one of the most commonly observed lines is the CO 2.6 mm). Another crucial tracer is the dust thermal emission. Dust grains absorb the UV light coming from newly formed hot stars, and re-emit it thermally in the far infrared. With respect to UV radiation, the FIR is more likely to be detected since it is rarely absorbed by the intervening gas along the line of sight.

These phases in reality are not clearly distinct from one another due to the ISM being a highly turbulent medium. Turbulence in the ISM is driven by a number of different physical processes including thermal instability, supernova feedback and the inflow of gas onto the galaxy disk.

In terms of chemical abundances, the interstellar gas is primarily constituted by H and He ($\sim 99\%$ of the ISM mass) persisting from the Big Bang Nucleosynthesis. Only a few additional heavy elements (or “metals”), from carbon to uranium, resulting from the inflow of gas previously processed in stars and stellar explosions. The abundance of heavy elements in the ISM (e.g. C, O, Mg, Si, and Fe) is a monotonically decreasing function of the distance from the galactic centre. All together the heavy elements contribute to the ISM mass is $\sim 1\%$. Nevertheless, in many cases, it is crucial for the chemistry, ionization state and temperature of the gas, and heavy elements also provide valuable observable diagnostics. In the following, we focus on that related to metals locked into dust grains.

2.2 Interstellar dust

Interstellar dust was long regarded by astronomers as a troublesome interstellar “fog” which prevented an accurate mapping of star-forming regions. Thanks to the advances in ultraviolet and infrared astronomy, laboratory astrophysics and theoretical modelling, we now know that dust plays a vital role in the evolution of galaxies. Besides accounting for $\sim 30\%$ of the total Galactic luminosity via their thermal emission [182], dust grains actively participate in the baryonic cycle of gas and dust from the ISM into stars and vice-versa.

Dust grains form during the late evolutionary stages of massive stars, in the atmosphere of Asymptotic Giant Branch (AGB) and Wolf-Rayet stars, in planetary nebulae, and within the ejecta of Novae and Supernovae (SNe). They are then released into the diffuse ISM, and throughout the process, they interact with hot, shocked gas, stellar radiation and cosmic rays. As a result, dust grains can undergo destruction via sputtering (impacting against gas atoms), vaporization/sublimation or grain-grain collisions [183]. When confined regions of the diffuse ISM (e.g. due to shock compression, gravitational instability or agglomeration of proto-clouds [184]) form Giant Molecular Clouds (GMCs), dust grains get dragged into these dense structures. There, they can undergo growth via the accretion of ice mantles or coagulation [185, 182]. GMCs collapse leading to the birth of new stars, which will ultimately produce more dust grains and eject them in the ISM via stellar winds or SNe explosions.

Dust also plays an active role in star formation processes. Dust grains absorb UV and optical light coming from young stars, and thermally re-emit it at MIR-to-FIR wavelengths [185, 13, 14, 15, 186]. Dust thermal emission provides collapsing GMCs with an effective cooling channel, thereby allowing star formation to take place. Further, dust IR emission provides us with an effective probe for star formation, crucially complementing the UV and optical data probing optically thin regions. Dust grains also contribute to the formation and storage of molecules in dense clouds. Indeed, grain surfaces constitute a site for

the formation of H_2 and dust shields molecules from photodissociating stellar radiation [182, 186].

The first observational evidence of the existence of interstellar dust came from the obscuration of starlight [187]. Even a naked-eye view of the sky from a dark site on a clear night reveals dark patches in the Milky Way. These apparent dark regions are not devoided of stars but are the result of obscuration by dusty clouds intervening along our line of sight. This obscuration tends to be greater at shorter wavelengths. Thus, the stellar radiation crossing a dusty media gets both attenuated and reddened; this process is referred to as “extinction”, and it is physically motivated by the scattering and absorption of UV photons by sub-micron dust grains.

Dust grains span a wide range of sizes, from molecules to particles as large as $\sim 0.2 \mu\text{m}$ [186]. In terms of chemical composition, most grains appear to be either silicates or carbonaceous materials (mostly graphite, amorphous carbon and polycyclic aromatic hydrocarbons, PAHs) [182, 186].

Astrophysical phenomena – other than the aforementioned wavelength-dependent extinction – that provide us with direct constraints on dust spatial distribution, grains sizes and composition include i) the spectroscopic features observed in extinction (or in emission where dust is sufficiently hot) such as the prominent $2175\text{\AA}$ “bump”; ii) the polarization of (initially unpolarized) stellar radiation; iii) reflection nebulae (opaque dust clouds which become visible due to the scattering of starlight by dust grains), iv) x-ray haloes around x-ray point sources located behind interstellar dust clouds, and iii) the infrared continuum emission resulting from dust grains heated by starlight.

2.2.1 Extinction

The extinction is most reliably determined using the pair method. The pair method consists in comparing the spectra of two stars of the same spectral class, one being reddened and the other having negligible foreground dust. Via this comparison one can measure the dust extinction A_λ as a function of wavelength (obtaining a so-called extinction curve):

$$A_\lambda = 2.5 \log (F_\lambda^i / F_\lambda), \quad (2.1)$$

where F_λ (F_λ^i) is the attenuated (intrinsic) flux. A widely used parameter to describe the extinction curve in the optical regime is the total-to-selective extinction ratio R_V :

$$R_V = \frac{A_V}{A_B - A_V}, \quad (2.2)$$

where A_V, A_B represent the extinction A_λ in the V (540 nm) and B (442 nm) bands. The value of R_V is directly related to the size of dust grains. Very large grains would produce grey extinction, thus $R_V \rightarrow \infty$. On the other hand, very small grains (grain size $a \ll 0.44 \mu\text{m}$) undergoing Rayleigh scattering against optical photons (so that $A_\lambda \propto \lambda^{-4}$), would produce $R_V \sim 1$.

In the following, we review the observational constraint on the extinction curves of our Galaxy and of two satellites, obtained by applying the pair method.

Milky Way The mean MW extinction curve, obtained by averaging over several sightlines, is shown in Fig. 2.2. It is characterized by a rapid rise in A_λ/A_V from IR to far UV wavelengths and a broad absorption feature at $2175\text{\AA}$ ($\lambda^{-1} = 4.6 \mu\text{m}^{-1}$). Measurements of R_V vary depending on the sightline, ranging from 2.1 [191] to 5.8 [192, 193], with the average value being $R_V = 3.1$. Larger R_V are inferred for sightlines intersecting dense clouds. This evidence suggests that dust grains have larger sizes in denser regions, likely due to grain growth or coagulation [186].

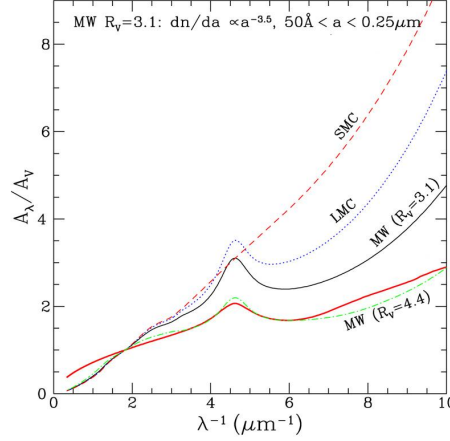


Figure 2.2: Interstellar extinction curves (adapted from Fig. 2 in [188]) of the Milky Way ($R_V = [3.1, 4.4]$, black solid and green dotted dashed line, respectively), SMC (red dashed line), and LMC (black dotted line). Also plotted is the empirical extinction curve for AGNs derived by Maiolino+10 [189] (red solid line, see also [190]) produced by a mixture of interstellar silicate and graphite grains similar to that proposed for the MW by Draine and collaborators [15, 180]. Their inferred MW grain size distribution dn/da is also reported at the top.

Dust extinction can be further characterised via the extinction per unit H atom. Using Lyman- α and molecular absorption lines to determine the hydrogen column density (N_H) in the diffuse ISM, pioneer studies in the 80s [194] found:

$$\frac{N_H}{A_B - A_V} = 5.8 \times 10^{21} \text{ cm}^{-2} \quad (2.3)$$

$$\frac{A_V}{N_H} = 5.3 \times 10^{-22} \text{ cm}^{-2}. \quad (2.4)$$

$$(2.5)$$

where the average value $R_V \sim 3.1$ is used to infer A_V/N_H . In dense clouds, the A_V/N_H ratio is hard to quantify due to the difficulty in measuring N_H . It has been shown that beyond the I band (806 nm i.e. $\lambda^{-1} < 1.2 \mu\text{m}^{-1}$), the MW extinction curve is virtually independent of R_V [192]. Thus, the $A_I/N_H = 2.6 \times 10^{-22} \text{ cm}^{-2}$ measured in the diffuse ISM likely holds also for dense regions.

Magellanic Clouds Our knowledge of the dust extinction laws in other galaxies is still fairly limited. So far, the pair method has been successfully applied to two satellites of the MW, the Small and Large Magellanic Cloud (SMC and LMC). Noticeably, the SMC extinction curve has been used as a template to quantify dust attenuation in high-redshift sources due to its younger stellar age(s) and lower metallicity compared to the MW ($Z_{\text{SMC}} < 0.1 Z_\odot$ [186]). These characteristics are supposed to make it a better high- z galaxy analogue.

In the SMC, the extinction curves of most sightlines display a nearly linear ($A_\lambda \propto \lambda^{-1}$), steep rise from visual to Far UV (FUV) wavelengths and no 2175Å bump [195, 196]. The LMC extinction curve is characterized by a weak 2175Å bump and a strong FUV rise [197, 198], appearing as an intermediate between the SMC and MW curve (see Fig. 2.2). The extinction normalization is more uncertain for Magellanic Clouds than for the MW. For the LMC, $A_V/N_H = 1.2 \times 10^{-22} \text{ cm}^{-2}$ has been inferred taking $R_V = 2.6$ [186]. For the SMC, $A_V/N_H = 6.2 \times 10^{-23} \text{ cm}^{-2}$ is derived considering $R_V = 2.87$ [199]. The lower A_V/N_H values measured in the Magellanic clouds are consistent with their low metal content, around $\sim 10\%$ of the MW value. As in our Galaxy, regional variations are observed both in the SMC and LMC extinction curves.

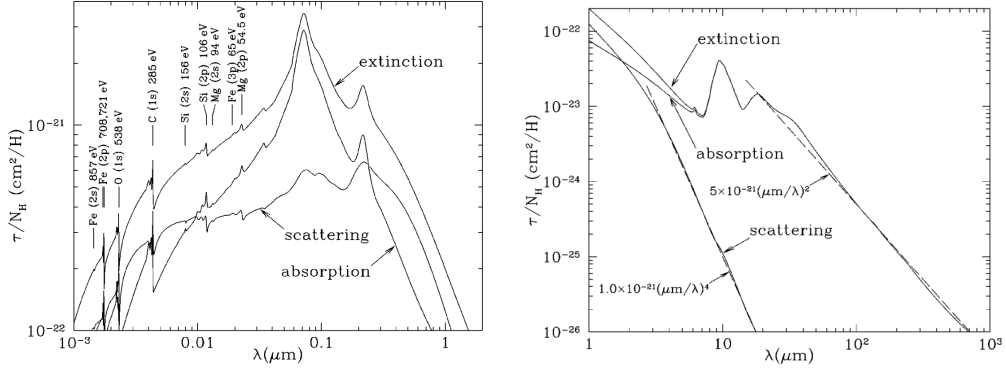


Figure 2.3: **Left panel:** Extinction and scattering calculated for the MW dust model by Draine and collaborators [15] with $R_V = 3.1$ and grains abundances reduced by a factor 0.93 (Fig. 9 in [186]). The shown wavelengths span the UV to visible range, $\lambda = 0.001 - 1 \mu\text{m}$. **Right panel:** Same as the left panel but at FIR wavelengths, $\lambda = 1 - 1000 \mu\text{m}$ (Fig. 10 in [186]). The dashed line shows the best-fitting power-law relation reported in eq. 2.6.

Other galaxies In galaxies where individual stars cannot be resolved, other approaches other than the pair method can be applied to derive effective extinction curves, which are typically referred to as attenuation curves [200]. For instance, Calzetti et al. [14] used the spectra of 39 local starburst galaxies to define an average attenuation curve, obtained by assuming a simple dust screen geometry for all the galaxies in the sample ($F_\lambda = e^{-\tau_\lambda} F_{\lambda_0}$). This attenuation law is grey, i.e. it is flatter than the MW, LMC or SMC extinction curves, and it completely lacks the $2175 \text{ \AA}$ feature. A clear interpretation of this result is still lacking due to the various degenerate effects that can impact the obtained attenuation curve. These effects include the assumed dust geometry, intrinsic galaxy properties such as metallicity, specific SFR, and stellar mass (which change from source to source in the sample), and – implicitly – microscopic grain properties (chemical composition, and grain size distribution).

In the last few years, several works have applied the method introduced by Calzetti et al. to study large galaxy samples out to intermediate redshifts $z \sim 1 - 3$ [201, 202, 203, 204, 205, 206, 207]. Latest local studies, analysing unprecedentedly large samples of sources (e.g. 230000 galaxies in [208]), find that even at $z = 0$ attenuation curves exhibit a very wide range of slopes, with a strong dependence on the galaxies’ optical opacity (opaque galaxies have shallower curves), and thus indirectly on their stellar mass. A wide range of UV bump amplitudes is measured, from none to Milky Way (MW)-like, with an average strength $\sim 1/3$ that of the MW bump. Notably, local analogs of high-redshift galaxies have an average curve that is somewhat steeper than the SMC curve, with a modest UV bump. The analysis of 218 SFGs at $z = 1.4 - 2.6$ from the comprehensive MOSDEF survey [201] has shown the presence of a positive correlation between the galaxies’ stellar mass and metallicity and their attenuation curve slope and UV bump strength (i.e. more massive and metallic galaxies show steeper attenuation curves with more pronounced UV bumps, up to $\sim 3\times$ stronger than the MW one [209, 207]). Further progress will soon be possible thanks to JWST NIRSpec and NIRCам which will allow us to extend such studies out to the EoR (see e.g. [210]) at least for the most massive galaxies.

2.2.2 A physical grain model

Since the 2000s, based on several, independent observational probes of interstellar dust emission properties, precise, physically motivated dust models have been developed [211, 185, 15]. There is a general consensus that interstellar dust is constituted by a mixture of carbonaceous (graphite and PAHs) and silicate dust grains [211, 185, 15, 180]. Both

grain components are predicted to have a power-law grain size distributions $dn/da \propto a^{-3.5}$ truncated at a minimum (maximum) size of $a = 0.005 \mu\text{m}$ ($a = 0.25 \mu\text{m}$, see e.g. [182, 186]). The 2175Å absorption feature is now believed to result from the $\pi \rightarrow \pi^*$ electron transition in C-C bonds within large PAH molecules (containing $20 - 10^5$ C atoms, [15]). Thus, dust models now assume small carbonaceous grains ($a < 0.010 \mu\text{m}$, [186]) to be PAH molecules, which naturally transition to graphite grains at larger sizes. The LMC and SMC extinction curves are also easily reproduced with minor changes in the mixture of carbonaceous and silicate grains. In particular, the lack of PAHs/graphite grains with radii $a \leq 0.01 \mu\text{m}$ is required to avoid the onset of the 2175Å bump for the SMC [15, 186].

The dielectric functions of graphite, PAHs and “astrosilicates” have been estimated by Draine and collaborators ([15, 180], hereafter WD01). The derived extinction and scattering cross sections per H nucleon (τ_λ/N_H) at wavelengths $10^{-3} < \lambda < 10^3 \mu\text{m}$ are shown in Fig. 2.3. Noticeably, at $\lambda \geq 20 \mu\text{m}$, the extinction/absorption can be approximated by a power law:

$$\tau_\lambda/N_H = 5 \times 10^{-21} \left(\frac{\lambda}{\mu\text{m}} \right)^{-\beta_d} \text{ cm}^2 \quad (2.6)$$

where $\beta_d = 2$ is the dust emissivity index. This parameter quantifies the deviation of dust emission from a perfect black body to a grey body.

2.2.3 Infrared emission

The byproduct of dust extinction is the grains’ thermal re-emission of starlight at MIR-to-FIR wavelengths. Because the heating by starlight photons is quantized and stochastic, the temperature of a dust grain is expected to be time-dependent. Dust grains with radii $a > 0.2 \mu\text{m}$ can be approximated as having a steady temperature (T_d). Their emission is that of a grey body, i.e. an imperfect black body whose deviation from the Planck function B_λ is quantified by the emissivity $k_\lambda \propto \tau_\lambda/N_H$ (see eq. 2.6). Galaxies FIR emission results from the combination of several grey body spectra associated with different dust components.

The notion of temperature for very small grains ($a \leq 50 \text{ \AA}$), such as the PAH molecules, is more problematic. These grains are small enough that the time-averaged vibrational energy is smaller/comparable to the energy of the photons that heat the grains. Stochastic heating by absorption of starlight, therefore, results in transient temperature spikes during which much of the energy deposited by the starlight photon is reradiated at MIR/short FIR wavelengths ($1 \lesssim \lambda/\mu\text{m} \lesssim 20$, [212, 180]).

Within the MW, observations of the diffuse ISM at galactic latitudes $b \geq 20^\circ$ provide a particularly clean test for dust models. Indeed, there we have good estimates for the intensity of the radiation field heating the dust and the observed 21 cm emission provides us with accurate gas column densities estimates. Assuming a dust-to-gas ratio D , we can then quantify the column density of dust, and thus its optical depth. Although the surface brightness of the infrared emission is low, it has been detected by the IR telescopes IRAS and COBE after averaging over large areas of the sky. Infrared emission from dust in the SMC has also been measured by IRAS [213], COBE ([214]) and ISO [215].

Silicate-graphite-PAHs dust models are able to reproduce the observed IR spectra of both the MW [15, 186] and the SMC [216], with little modifications in the grain mixture (reduced PAHs abundance, $\lesssim 3\%$ of the SMC interstellar C abundance). According to the most commonly used WD01 model [15], in the MW $\sim 20\%$ of the absorbed starlight energy is reradiated by PAHs at $\lambda < 12 \mu\text{m}$ following temperature spikes due to individual photons’ absorption. Most (2/3) of the IR emission comes from $a \geq 0.1 \mu\text{m}$ silicate-graphite grains that are maintained at a nearly steady temperature $\sim 15 - 20 \text{ K}$ by the interstellar radiation field [186].

2.3 Dusty ISM in galaxies at the EoR

Before the advent of new generation sub-mm interferometers, direct observations of the dust emission in individual high-redshift ($z > 5$) LBGs were not attainable. As discussed in Sec. 1.3.2, previously available instruments probing mm and sub-mm wavelengths were prohibitively confusion-limited at high-redshift [217]. Only extremely bright sub-mm galaxies (SMGs) were detectable [218], but such rare and massive sources are hardly representative of the population of high-redshift star-forming galaxies. Thus, to quantify dust obscuration of star formation in “normal” star-forming galaxies, indirect methods based on rest-frame UV data were initially applied.

The IRX- β relation (introduced by Meurer+99, [13]) was routinely used to quantify the correction for dust attenuation in UV luminosity functions and SFRD studies out to $z \sim 10$ [175, 167, 112, 109]. The IRX- β relation connects the infrared excess (IRX) of galaxies:

$$\text{IRX} = L_{\text{FIR}}/L_{\text{UV}} \quad (2.7)$$

with their UV slope β , so that by measuring the latter and a galaxy UV luminosity L_{UV} (at rest-frame 1500Å) one can indirectly infer the FIR luminosity L_{FIR} (the integrated luminosity between rest-frame 8–1000 μm). In this way, a galaxy total, intrinsic luminosity $L_{\text{tot},i} = L_{\text{FIR}} + L_{\text{UV}}$ and SFR ($\text{SFR} \propto L_{\text{tot},i}$ [219]) can be quantified also in the absence of any (rest-frame) FIR data. Under the assumption of UV and FIR emission being co-spatial, and with a simple dust screen geometry approximation ($L_{\lambda} = e^{-\tau_{\lambda}} L_{\lambda}^i$), the analytic deviation of the IRX- β relation is pretty straightforward. We can write:

$$\text{IRX} = \frac{1 - e^{-\tau_{1500}}}{e^{-\tau_{1500}}} \quad (2.8)$$

$$\beta - \beta_i = -2.24 \ln \left(\frac{e^{-\tau_{1600}}}{e^{-\tau_{2500}}} \right) \quad (2.9)$$

where $(\tau_{1500}, \tau_{1600}, \tau_{2500})$ represent the dust optical depths at $\lambda = (1500, 1600, 2500)\text{Å}$. Given a dust model (MW, SMC or Calzetti), the ratios between the optical depths at different wavelengths are fixed, and IRX can be written explicitly as a function of β manipulating eq. 2.8.

A recent analysis of a large, heterogeneous sample of ~ 5000 galaxies, spanning the redshift range $0 \lesssim z \lesssim 5$ (with most sources being located at $z < 3.5$), confirmed that an average IRX- β relation (albeit slightly redder than the one initially inferred by Meurer+99 [13]) can be recovered out to $z \sim 3.5$ [220]. The little scatter around the average relation that appears when looking at stacked galaxy samples validates the use of the IRX- β relation to quantify the average dust attenuation in the galaxy population at a given epoch.

Since most high- z galaxies display blue UV slopes $\beta \sim -2$ (see Sec. 1.3.2), close to the intrinsic MW value ($\beta_i = -2.16$, [166]) the early Universe was assumed to be nearly dust (and metals) free. Indeed, in the absence of dust, $\tau_{\lambda} \rightarrow 0$, thus $\text{IRX} \rightarrow 0$ and $\beta \rightarrow \beta_i$. However, an accurate, physical interpretation of the IRX- β relation goes beyond the simple relations shown in eq. 2.8. In reality, dust geometry can significantly differ from a dust screen, and dust-to-gas ratios and dust optical depth vary in different galactic regions (e.g. diffuse ISM vs. molecular clouds). Further, variations in the SFH, stellar age and metallicity strongly impact β_i , regardless of dust attenuation [167, 221, 222, 223, 168, 35]. Disentangling these effects is far from trivial, and their combination can explain the large deviations from the average IRX- β relation (e.g. $\Delta \text{IRX} \sim 2$ dex at a given β) that are observed in individual local and low- z sources [220, 224, 225, 226]. This complicates the assessment of the effect of dust obscuration in individual galaxies at high- z . We will discuss this further in Sec. 2.3.4.

2.3.1 ALMA and the “dust budget crisis”

With the advent of ALMA in the 2010s, the paradigm of the dust-free early Universe was soon called into question. ALMA observations showed that “normal” (UV bright, non-lensed) star-forming galaxies as early as $z \sim 8.3$ [11, 9, 12, 10] (within ~ 600 Myr of the age of the Universe) can have strong dust continuum emission, with monochromatic fluxes $\sim 100 \mu\text{Jy}$ at rest-frame $88 \mu\text{m}$ (corresponding to $L_{\text{FIR}} \sim 10^{11} L_{\odot}$ for $T_{\text{d}} = 40$ K and dust emissivity index $\beta_{\text{d}} = 1.5$, [9]). Recently, ALMA large programs exploiting band 6 and 7 capabilities, namely ALPINE ($z = 5 - 6$, [36, 37]) and REBELS ($z = 6 - 9$, [38]), have provided us for the first time with relatively large samples of FIR continuum emitting LBGs at $z \sim 5 - 7$ (totalling 30 detections). Within these two surveys a few (8 at $z \gtrsim 5$, and 2 at $z \sim 7$) serendipitous, UV-dark (i.e. completely dust-obscured) sources have also been detected, with the highest redshift spectroscopically confirmed one being located at $z = 7.35$ [145]. ALMA has also provided us with the detection of the highest redshift Dusty Star-Forming Galaxy (DSFG, a dust-obscured system with $\text{SFR} \gtrsim 100 - 1000 M_{\odot}/\text{yr}$) to date at $z = 6.91$ [227, 96]. This source is part of the SPT sample of strongly lensed DSFGs, which includes 12 other systems at $z > 5$ ($\sim 50\%$ of the spectroscopically confirmed DSFGs at these high-redshifts, [228, 229]).

The analysis of pioneer ALMA high- z observations unveiled the presence of some tension between $z < 3.5$ and $z > 5$ data, both in terms of the IRX- β relation and in the measured dust-to-stellar mass ratios. The first studies investigating the IRX- β relation at high- z , consistently found that $z > 5$ LBGs presented a strong IRX deficit (up to ~ 2 dex) compared to lower- z analogues ([89, 112, 230], see the left panel in Fig. 2.5). In these works, a cold dust temperature $T_{\text{d}} \sim 25 - 30$ K (consistent with that measured in the MW, [186]) was initially assumed to convert the monochromatic flux – measured in a single ALMA band at rest-frame $158 \mu\text{m}$ for each target – into the corresponding FIR luminosity. Under this cold dust temperature assumption, uncomfortably large dust masses (dust-to-stellar mass ratios $M_{\text{d}}/M_{\star} \gg 10^{-3}$) were required to reproduce the bright FIR fluxes observed in several $z \geq 5$ galaxies [89, 231, 11, 9, 232]. These large dust masses were in tension with theoretical dust production constraints implied by the young age (few 100s Myr) of the dominant stellar population, and of the Universe itself, at $z > 5$ [233, 9, 232]. This problem is referred to as the “dust budget crisis” in the early Universe. This term was coined in the context of dusty SMGs, where tension with dust production models already arises at $z > 1$ [234, 22].

2.3.2 Dust production mechanisms in the high- z Universe

To understand the origin of the aforementioned theoretical dust production constraints (and thus of the whole “dust budget crisis” at high- z), we briefly review the main mechanisms which (are believed to) contribute to the dust build-up in the early Universe. These include Supernovae (SN), AGB stars, and grain growth in the ISM.

Supernovae On short times-scales ($\ll$ Gyr) the most efficient production mechanism is core-collapse SN (SNII). SNII represent the ultimate fate of massive stars ($M_{\star} > 8 M_{\odot}$), which explode in less than 30 Myr [235]. Dust synthesis occurs in SNII ejecta in less than a decade due to the rapidly evolving physical conditions of the outflowing gas. There the formation of dust grains proceeds through nucleation and condensation phases (see [236] for a recent review). The nucleation phase comprises chemical reactions which lead to the synthesis of molecules and small clusters, which later condense into macroscopic dust grains once the cluster “critical size” is exceeded. Classical Nucleation Theory (CNT, [237]) provided the backbone for the earliest studies on dust formation in SN [16, 238, 17]. An alternative formalism is provided by Kinetic Nucleation Theory (KNT, [239, 240, 241]),

which has the main advantage of not relying on steady-state conditions, which are unlikely in such dynamic environments [242]. Latest studies find that about 30% of all the gas in the SNII ejecta is in molecular form after a few years of the explosion and that $\sim 1/3$ of these molecules/molecular clusters (i.e. 3 – 10% of the total ejecta mass) condense into dust grains [236]. Thus, typical SNII (type IIp) in the mass range $\sim 8 - 25 M_{\odot}$, are predicted to produce dust yields between $y_d = 0.02 - 1 M_{\odot}$ [16, 238, 243, 236, 244, 245]. For a given Initial Mass Function (IMF), SFH, metallicity, and stellar age the rate of supernovae per unit stellar mass (ν_{SN}) is fixed (e.g. $\nu_{\text{SN}} = (53 M_{\odot})^{-1}$ for a Salpeter IMF $1 - 100 M_{\odot}$, continuous SFH, stellar age $\sim 100 \text{ Myr}$, and $Z = 0.004$ [246]). Multiplying ν_{SN} by the galaxy’s stellar mass and the predicted dust yield per each SN event y_d , one obtains a constraint on the producible dust-to-stellar mass ratio (e.g. $M_d/M_{\star} \lesssim 10^{-3}$ for the average $y_d \sim 0.1 M_{\odot}$).

There is clear observational evidence for the production of dust in supernovae thanks to MIR and sub-mm observations of SN remnants in the local Universe. However, the measured dust yields vary greatly, ranging from $10^{-6} M_{\odot}$ [247, 248, 249] to $0.7 M_{\odot}$ [250, 251, 252]. These large variations can be explained by the different ages of the remnants (which imply variations both in the dust temperatures and masses, [253]) and the wavelength range probed by observations (e.g. the MIR traces only the warm dust component, possibly resulting in an underestimation of the SN dust yields). As a result, quantifying the net production of dust by SN has proven quite challenging, with different theoretical works predicting vastly different efficiencies of dust destruction (from $\sim 42\%$ to 90% of the newly formed dust, see e.g. [254, 255, 256, 244]) due to sputtering in the SN reverse shock. There is a general consensus that dust destruction processes mostly affect small grains ($a < 0.25 - 0.5 \mu\text{m}$, see e.g. [17, 256]) and older SNe remnants, where the reverse shock post-processing of the ejecta has already taken place [252, 257, 258].

AGB stars Dust is also produced in the late evolutionary stage of low-to-intermediate mass stars ($0.8 - 8 M_{\odot}$), during the asymptotic giant branch (AGB) phase. This is a thermally pulsating phase, characterised by a large mass loss rate ($10^{-7} - 10^{-4} M_{\odot}/\text{yr}$, [259]). Dust grains can via condensation in the outflowing gas, in the cool, dense outer layers of the circumstellar envelopes (in the so-called “dust formation zone”) [260, 261, 262, 263]. Given the relatively low stellar masses of AGB stars, their evolutionary timescales are significantly longer than SNe, being comparable to the Age of the Universe at $z > 6$ (e.g. a $M_{\star} \sim 1.6 M_{\odot}$ star has a lifetime of $\sim 900 \text{ Myr}$). For this reason, although AGB stars are believed to be the main dust producers in the local and low- z Universe, their contribution to dust production at the EoR is most likely sub-dominant (provided that the SN reverse shock spares $y_d > 0.003 M_{\odot}$ of dust per SN event, [254, 18, 264, 265, 266, 20, 178]).

Grain growth Finally, galaxies’ dust mass can also increase via the accretion of gas-phase metals onto solid grains, in the cold and dense phases of the ISM [254, 267, 268, 269, 270, 271, 20, 272]. equation. Some works have proposed early ($z \sim 10 - 12$), and very efficient (timescales $\sim 0.2 - 0.3 \text{ Myr}$) grain growth as a possible solution to the dust budget crisis in the early universe [269, 270, 273, 271, 274]. However, studies focused on dust grains chemistry, have argued that this rapid grain growth scenario is highly unlikely [275, 276]. At these high redshifts, the CMB sets a high-temperature floor for dust grains ($T_{\text{CMB}} > 16 \text{ K}$ at $z > 6$). Accounting for this effect, together with the dust grains’ high Coulomb barrier and the diffuse ISM low gas density, results in much ($\gtrsim 10\times$) slower accretion rates than those required to significantly impact high- z galaxies’ dust content. Non-star forming, cold molecular clouds might offer more favourable conditions for grain growth thanks to their higher gas density. However, Ferrara et al. [275] have argued that there the rapid formation of icy mantels, prevents silicate molecules from getting in close

contact. These results, question the impact of grain growth in the dust build-up at $z > 6$ (see also [20]).

2.3.3 The importance of constraining the dust temperature

It is important to stress that the puzzling M_d and IRX estimates initially inferred for ≥ 5 LBGs were heavily dependent on the cold dust temperatures *assumed* in the FIR continuum spectral energy density (SED) fitting procedure. At these high redshifts, an assumption on T_d is often required as most dust continuum observations (typically relying on ALMA bands 6,7) scarcely probe a narrow wavelength range far from the FIR emission peak [112, 230, 277, 278, 9]. This issue is exacerbated in ALMA large surveys such as ALPINE and REBELS, where only a single continuum data point (at rest-frame $158 \mu\text{m}$, underlying the [C II] emission line) is available for each target [41, 108]

Due to the nearly arbitrary assumption on T_d , all the dust and galaxy properties inferred from SED fitting are highly uncertain. These quantities include M_d , L_{FIR} , and thus – indirectly – IRX and the dust-obscured star formation rate $\text{SFR}_{\text{FIR}}/\text{M}_{\odot}\text{yr}^{-1} = 10^{-10} L_{\text{FIR}}/L_{\odot}$ [219]. L_{FIR} is obtained by integrating over wavelength/frequency the grey body function:

$$k_{\lambda} B_{\lambda} \propto \lambda^{-\beta_d} \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda k_B T_d)} - 1}, \quad (2.10)$$

where the normalization of k_{λ} and β_d depend on the dust model, c is the speed of light, h is the Planck constant, and k_B is the Boltzmann constant. We can then write:

$$L_{\text{FIR}} \propto \int_{8\mu\text{m}}^{1000\mu\text{m}} M_d k_{\lambda} B_{\lambda} d\lambda \propto M_d T_d^{4+\beta_d}. \quad (2.11)$$

According to most commonly adopted MW and SMC dust models $\beta_d \sim 2$ [15, 180], thus a few tens of K of difference in T_d can produce either i) the same FIR luminosity with an order of magnitude smaller dust mass, or ii) an order of magnitude higher L_{FIR} and thus IRX at fixed β , L_{UV} . This simple computation shows the importance of accurately probing high- z galaxies' dust temperatures.

The analysis of stacked FIR spectra, obtained by combining Spitzer, Herschel and ALMA data, provided us with the first indication of the presence of warmer dust temperatures in high- z LBGs. Indeed, several studies spanning the broad redshift range $0 \leq z \leq 6$, inferred the presence of a tight positive correlation between T_d and redshift [291, 292, 293, 40, 43]. Interestingly, different works find discrepant results. Some works suggest a linearly increasing $T_d - z$ trend based on stacked SEDs fitting results in the redshift range $z = 0 - 5$ [40, 41], coupled with a few individual detections at $z \gtrsim 5$ [42]. Other observational works based both on stacked data and individual DFGS detections predict a much milder (or even no) evolution [292, 291, 229, 294]. On the simulations side, [32] find a substantial flattening in the increase of T_d at $z \gtrsim 4$ based on SED fitting procedure applied to the FIRE simulations at $z = 2 - 6$; on the other hand, a steeper than linear $T_d - z$ evolution is inferred from the FLARES simulations at $z = 5 - 10$ [6]. Most recently, similarly hot dust temperatures ($T_d > 60 \text{ K}$ at $z > 5$), increasing quadratically with redshift have been inferred by [43] based on the latest release of the COSMOS2020 catalogue [295]. Thanks to the new COSMOS2020 data, the authors have been able to extend stacked FIR SEDs studies up to $z \sim 10$ for the first time. However, the reliability of stacking results at $z \gg 4$ is somewhat uncertain, as distinguishing low- z interlopers and/or correcting for the bias towards the brightest sources becomes more challenging [43]. An additional complication is related to the vastly different PSFs and sensitivity of the instruments (Spitzer, Herschel, SCUBA2 and ALMA) whose data are used to produce the stacked SEDs in the broad observed wavelength range $10 - 1000 \mu\text{m}$.

Measured dust temperatures for LBGs at $z > 5$ available in the literature. We note that for the literature data, we always show the result derived from single-temperature optically thin grey-body fitting in the most recent reference. **References:** 1 [10], 2 [9], 3 [12], 4 [279], 5 [278], 6 [277], 7 [280], 8 [281], 9 [231], 10 [93], 11 [282], 12 [283, 284], 13 [89], 14 [19], 15 [285].

ID	# <i>Det.</i>	# <i>Up Lim</i>	β_d	T_d [K]	z	Ref.
MACS0416-Y1	1	2	2	> 80	8.31	1, 2
A2744-YD4	1	1	2	> 55	7.88	3, 4, 15
B14-65666	2	-	1.5	48 – 61	7.15	5, 6
A1689-zD1	4	-	1.61	47^{+15}_{-9}	7.133	7, 8, 9
J1211-0118	2	1	1.5	38^{+34}_{-12}	6.0295	10
J0217-0208	2	1	1.5	25^{+19}_{-5}	6.204	10
HZ10	3	-	2.15	46^{+16}_{-8}	5.657	11, 12, 13
HZ4	3	-	2.01	57^{+67}_{-17}	5.544	11, 12, 13
HZ9	3	-	2.01	49^{+29}_{-11}	5.541	11, 12, 13
HZ6	3	-	1.6	41^{+18}_{-7}	5.293	11, 12, 13
COS-3018555981	1	1	1.5	29^{+9}_{-5}	6.8540	14
UVISTA-Z-001	2	-	1.5	59^{+41}_{-20}	7.0611	14
UVISTA-Z-019	1	1	1.5	47^{+40}_{-17}	6.7544	14
REBELS 12	1	1	2	41^{+64}_{-14}	7.3459	15
REBELS 25	2	-	2	34^{+6}_{-6}	7.3065	15
REBELS 38	2	-	2	32^{+7}_{-5}	7.5770	15

It is thus fundamental to complement stacked SED studies with the observations of individual sources in multiple ALMA bands. Albeit expensive, and thus so far limited to a few sources (16 LBGs and 15 DSFGs at $z > 5$, see Table 2.1), such observations can give us clearer insight on high- z galaxies' ISM and dust emission properties. Rather than clarifying the T_d -related issues, the latest ALMA observations have further highlighted the complexity and variety of dust properties at the high- z end. On one hand, $T_d > 60 - 80$ K have been inferred for the only two galaxies observed in multiple ALMA bands at $z \sim 8$ [12, 10]. Warm dust temperatures $T_d \sim 40 - 60$ K have also been measured in 10 of the $z = 5 - 7$ “normal” galaxies detected with ALMA in multiple bands [278, 282, 93, 280, 19, 285], albeit with large uncertainties $\gtrsim \pm 10$ K due to the aforementioned observational limitations. At the same time, very cold temperatures $T_d < 30$ K compatible to that found in the local Universe have also been measured in other two $z = 6 - 7$ SFGs [19, 93]. The samples so far are too scarce, and probe similarly massive ($M_\star/M_\odot = 10^9 - 10^{10}$) and bright SFGs ($M_{UV} = [-20; -22]$), thus individuating a trend of the dust temperatures with some intrinsic galaxy property (e.g. $M_\star$, SFR or stellar age), has proven extremely challenging.

DSFGs observations at $z > 5$ indicate that the majority of these sources are characterised by $T_d \sim 50 - 55$ K ([229, 296, 297], for the few cold T_d exceptions see [298]). However, the presence of a warm/hot dust component is characteristic of most DSFGs across all redshifts [299, 300, 301, 302, 303], as evidenced by the excess of emission at rest-frame MIR wavelengths observed in several of these sources [304, 305, 306, 307, 308, 309, 310, 311, 312, 229]. This is expected due to the large gas column densities and thus efficient

dust heating achieved within dense and highly star-forming DSFGs ISM ($N_{\text{H}} > 10^{22} \text{ cm}^{-2}$, sufficient to achieve optically thick IR emission, see eq. 2.6). Nevertheless, a positive T_{d} -redshift trend has been identified by the SPT collaboration within their large –albeit biased– sample of (81) DSFGs, spanning the redshift range $z = 2 - 7$ [229].

Before reviewing the state of the art of theoretical models for dust in high- z galaxies, we pause for a remark. Within the high- z galaxy community, different groups often use different FIR continuum SED fitting procedures. This can result in vastly different T_{d} estimates for the same source, especially given the few and poorly distributed data points available for most high- z LBGs. Differences as large as $\sim 10 - 20 \text{ K}$ can result from adopting i) different dust models (resulting in variations in the dust emissivity index $1.5 \lesssim \beta_{\text{d}} \lesssim 2$ and dust absorption normalization coefficient, see e.g. [19, 285]) and/or ii) adopting fitting functions deviating from a single-temperature, optically thin grey-body approximation (for a detailed discussion see [32]). A frequently employed alternative is the modified black body, which features a grey body function at long FIR wavelengths and with a power-law fit at MIR wavelengths [282, 19, 285]. This fitting formula better reproduces FIR continuum SEDs in the presence of optically thick dust emission and/or a hot dust component [218, 312]. Applying this fitting formula to high- z LBGs requires assumptions on the MIR portion of their spectra, which are not testable with currently available instruments.

2.3.4 Interpretation of latest dust observations at high- z

In light of the latest T_{d} measurements, the tension between $z \lesssim 3.5$ and $z > 5$ data has significantly reduced both in terms of the IRX- β relation and the dust production constraints. This effect is particularly striking at the highest-redshift end, i.e. for the two $z \sim 8$ LBGs detected in the dust continuum with ALMA, YD4 and Y1 (see Tab). Due to their hot dust temperatures, the dust masses inferred for these $M_{\star} \sim 10^8 - 10^9 M_{\odot}$ galaxies are $M_{\text{d}} < 10^5 - 10^6 M_{\odot}$ [12, 10]. These values are consistent even with the most stringent Supernovae dust yields constraints of $y_{\text{d}} < 0.1 M_{\odot}/\text{SN}$, thus they do not require non-stellar dust production mechanisms ([313], see Chapter 5).

To overcome ALMA observational limitations at high- z , alternative methods for the derivation of $T_{\text{d}}, M_{\text{d}}$ have been proposed [314, 177, 315]. These methods rely on a single FIR continuum observation by combining it with UV and/or FIR lines measurements. Recently, two of these methods have been exploited to constrain the IR properties of the $z = 5 - 7$ UV bright, massive galaxies ($M_{\text{UV}} < -20$, $M_{\star} > 10^9 M_{\odot}$) from the ALMA large programs ALPINE and REBELS [177, 147, 178]. The emerging picture is that high- z massive galaxies have relatively warm dust $T_{\text{d}} = 40 - 50 \text{ K}$, implying a significant fraction of obscured SFR, from 20% – 90% (for a detailed discussion see Chapter 4-5) The inferred dust-to-stellar mass ratios are mostly consistent with theoretical dust production constraints (assuming a SN dust yield $Y_{\text{d}} \sim 0.1 M_{\odot}/\text{SN}$, see the right panel in Fig. 2.5), although a few outliers require an extreme scenario with no dust destruction and very efficient growth. Interestingly, the dust to stellar mass relation appears flatter at $z \sim 7$ than at $z \sim 5$ [178]. This might be due to observational bias, or a hint of an evolution in the dust and metal production between these two epochs. Further observations, broadening the parameter space probed at $z \sim 7$ will clarify this issue.

Several theoretical works based on cosmological, cosmological zoom-in simulations [30, 32, 35, 6] and semi analytical models [221, 313, 315, 147, 316], predict the emergence of warm/hot dust temperatures in high- z SFGs. Behrens et al. [30] produced an exceptionally high-resolution ($\sim 30 \text{ pc}$) simulation of a $z \sim 8$ galaxy mirroring the properties of the observed source YD4. They showed that in their simulated galaxy, the UV emission comes from the diffuse ISM ($\sim \text{kpc}$ scale), whereas most of the FIR emission comes from a few, UV-opaque star-forming patches (of the same scale as GMCs both in mass and size)

where (few but extremely IR bright) dust grains attain temperatures as hot as $T_d \sim 100$ K. Similar results have been found in other cosmological high- z galaxies' simulations, which rely on different hydrodynamic codes (e.g. different versions of RAMSES [30, 8], GADGET [233, 6], and GIZMO [34, 32, 35]).

To investigate the sub-galactic scales further, Sommovigo+20 [313] zoomed in on the star-forming GMCs within one of the $z \sim 8$ simulated galaxies from the SERRA suite (presented in [8]), producing a semi-analytical model for the dust and gas properties (see Chapter 6). Sommovigo+20 find that in high- z GMCs dust is warmer ($T_d \gtrsim 60$ K) due to their compact structure, characterised by higher internal pressure and larger gas column densities than local clouds. The high- z GMCs compactness also delays their dispersal by stellar feedback, thus $\sim 40\%$ of the total UV radiation emitted by newly born stars remains obscured.

The emergence of spatial separation between UV and IR emitting regions in high- z galaxies questions our understanding of dust obscuration at high- z . Theoretical studies based on semi-analytical models [168, 223] and cosmological simulations [222, 32, 34, 35, 6, 8] have shown that due to a patchy ISM morphology, IRX up to ~ 100 can be found also in $z > 5$ galaxies with relatively blue UV slopes $\beta \sim -1.5$. This effect seems to be prominent in lower mass galaxies ($M_\star < 10^9 M_\odot$, [8]), which are hardly probed by current observations. If confirmed, this would imply that the obscured SFR fraction in high- z galaxies which have not been followed up with ALMA might be severely underestimated. For instance, thanks to unique ALMA band 9 follow-up observations of an EoR SFG, it has been shown that the lensed $M_\star \sim 10^9 M_\odot$ galaxy zD1 (at $z = 7.1$) has $> 85\%$ of its SFR obscured by dust despite being UV-selected. Also, a few galaxies within the ALPINE and REBELS survey, have been predicted to show a spatially segregated ISM morphology, based on their peculiar UV to IR flux ratio, which is not reproducible with a single-phase optically thin ISM where dust, gas and stars are uniformly mixed [177, 178].

On the other hand, the presence of cold dust and (molecular) gas reservoirs, which are shielded from the diffuse ISM radiation field, can produce IRX values > 2 dex lower at a given β [221]. Constraining such a cold dust/gas component is similarly challenging for $z > 5$ observations, due to both the lack of direct HI tracers (at least before JWST) and the confusion due to the background CMB emission (which at these high redshifts $T_{\text{CMB}} \gtrsim 17$ K). For the few $z \sim 6 - 7$ sources whose dust temperature have been tentatively (at most 2 ALMA detections are available) measured to be as cold as $T_{\text{CMB}} = 25 - 30$ K, the inferred dust-to-stellar mass ratios remain in tension with theoretical dust production constraints. Indeed, a maximally efficient dust production is required, with grain growth on timescales $\ll 10$ Myr, no SN reverse shock destruction, nor dust ejection [289, 20, 19]. It is worth noting that the assumption of different SFH in the optical to NIR fitting for these galaxies can result in up to ~ 1 dex larger stellar masses [46], due to the presence of an older stellar population together with a more recent SF burst (see also [233]). JWST NIRspec follow-up observations will clarify this issue, shedding light on the eventual necessity of extreme dust production scenarios in a few peculiar sources.

2.3.5 Open questions

Despite the amazing, and fast-paced progress that has been possible in the last few years thanks to the exploitation of facilities such as ALMA, and now JWST, several open questions on high- z galaxies dust remain open.

It is paramount to constrain the dust temperature of high- z galaxies, in order to properly quantify their IR luminosity and obscured SFR. However, in order to do so ALMA band 9 observations and even shorter wavelengths should be probed [32, 280, 315]. Only then we can probe the peak of FIR emission and verify whether the hot dust temperature component predicted by high-resolution hydro simulations [30, 34, 32, 6, 8] is ubiquitous in

EoR star-forming galaxies. Very recently, the first spatially resolved (on kpc scales) dust continuum emission map of a $z \sim 7$ strongly lensed galaxy zdl [231, 281, 280] has been produced thanks to deep ALMA observations [317]. A preliminary analysis has shown the presence of dust temperature gradients > 40 K within this EoR source, with dust temperatures up to ~ 60 K being reached in the central star-forming region. Despite the large uncertainties due to the lensing model and the narrow FIR wavelength coverage, these results are extremely promising. Further progress will hopefully be possible thanks to instruments such as the proposed ORIGIN [318] and SPICE (previously SPIRIT, see e.g. [319]) space telescopes. These instruments are designed to cover the observational window interposed between the JWST and ALMA, at $30 - 300$ μm . They aim at achieving $\gg 3$ orders of magnitude higher sensitivity than previous instruments such as Herschel and Spitzer. This would finally allow us to probe the rest-frame MIR-IR emission of individual high- z SFGs.

At the same time, to address the open question of how much the obscured SFR contributes to the total SFRD beyond cosmic noon, we should be able to mimic rest-frame optical and UV deep blank field observations at mm and sub-mm wavelengths. Only then we can quantify properly our bias towards UV bright objects in the early universe, due to their long-standing UV-based identification. Achieving this goal might be possible in the upcoming decade thanks to proposed instruments such as the 50m Atacama Large Aperture Submillimeter Telescope (AtLAST, [163]) and the Large Sub-mm Telescope (LST, [164]). These ground-based telescopes are being designed to map $\gg 2$ deg areas of the sky at a $\lesssim 5 - 10$ arcsec resolution, emulating the capabilities of state-of-the-art UV and optical telescopes such as HST and JWST.

On the theoretical side, an urgent improvement in the treatment of dust in simulations and SAMs is needed. Hydro, high-resolution simulations have the key advantage of providing us with the full dust temperature PDF, and FIR spectra of galaxies out to arbitrarily high redshift, and down to stellar masses and UV magnitudes which are not probed by current observations. However, it has been shown that sub-galactic scale physics (e.g. stellar feedback, radiation pressure in HII regions) strongly impacts the output galaxy spectra, and dust temperature profiles inferred even in the highest resolution hydro simulations [313]. Physical sub-grid models, and/or more sophisticated stellar and SN feedback needs to be included in future cosmological simulations, especially for the largest cosmological boxes ($\gg 100$ Mpc) used for LF and SFRD studies.

Further, dust destruction, production and growth processes are rarely modelled in hydro simulations. Dust is typically included in post-processing adopting a linear scaling with the metallicity, and accounting for dust destruction due to thermal sputtering by adding a coarse gas temperature threshold in the dust-to-metal scaling. A more refined treatment is needed to address the long-lasting question of which mechanisms are responsible for the dust build-up in the early Universe.

Finally, both in theoretical works and in data analysis, local/low-redshift templates for dust emission properties are typically used. An open question is whether such templates properly reproduce the emitting properties of dust in the very high- z galaxies ISM. FIR lines studies have shown that high- z galaxies have i) extraordinarily high $[\text{O III}]/[\text{C II}]$ line ratios [95, 107, 93, 285], and ii) extended $[\text{C II}]$ emission (at $> \text{kpc}$ scales, [320, 321, 322]) with respect to local analogues. Various interpretations have been proposed in the literature, but there is a general consensus that such emission properties likely depend on high- z galaxies hard UV fields, turbulent ISM, lower average gas metallicity and/or C over O ratios [323, 324, 325, 326, 31, 8, 33, 7, 327, 255, 328, 329]. These galaxy properties, might affect dust grains composition and size distribution (see e.g. [275]), possibly resulting in a deviation of emitting properties with respect to local templates. Attenuation curve studies on numerous, individual SFGs out to the EoR, which will be possible with the JWST,

might shed light on this open issue. The first analysis of an $z = 6.91$ JWST-detected source has shown the presence of a strong 2175 Å bump [210], likely indicating the presence of PAHs and thus early metal enrichment in the observed galaxy.

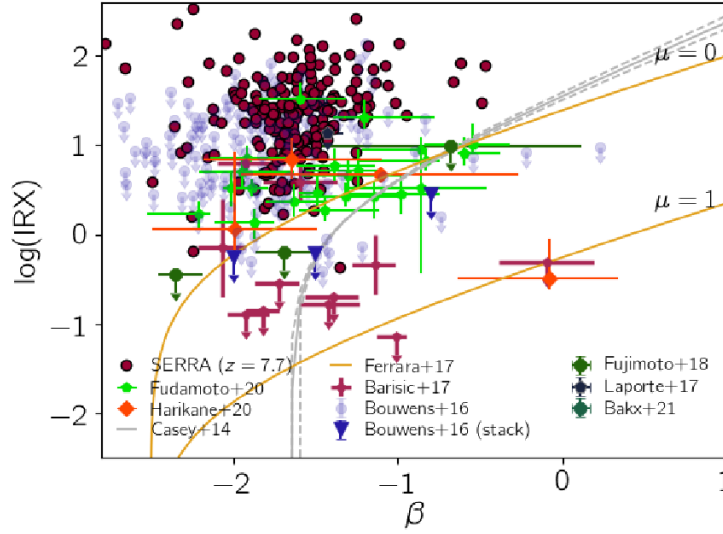


Figure 2.4: IRX- β relation for $z > 5$ galaxies compared with SERRA simulated galaxies (Fig. 11 in [8]). Data points refer to upper limits [112, 286] and detections [230, 11, 287, 93, 280], assuming dust temperatures in the range 25 – 50 K in the lack of direct constraints from SED fitting. Also shown is the empirical IRX- β relation inferred for local galaxies [218], and that is expected from one of the semi-analytical models mentioned in the text [221]. For the latter, the two limiting cases in which the ISM molecular fraction is either $\mu = 0$ (fully atomic) or $\mu = 1$ (fully molecular) are shown.

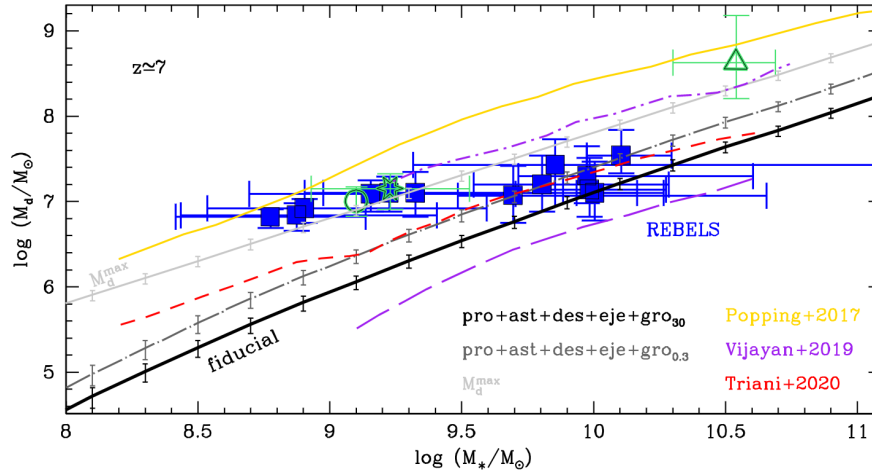


Figure 2.5: The dust mass as a function of stellar mass at $z \sim 7$ (Fig. A1 in [20]). The solid blue points show data from REBELS [38] where the stellar [288] and dust masses [147] have been re-scaled to a Salpeter IMF with $0.1 - 100 M_{\odot}$. The other points show observational data for A1689-zD1 (empty star, [231, 280]), for B14-65666 (empty circle, [278]) and for SPT0311-58 (empty triangle, [229]). The solid black, dot-dashed grey and solid grey lines (along with 1σ error bars) show results from the DELPHI semi-analytical model [115, 20] for the fiducial case (including dust production, astration, destruction, ejection and growth on a timescale of 30 Myr), a grain growth time-scale of 0.3 Myr and the “maximal dust mass” case (with saturated grain growth and no destruction), respectively. These are compared to the results from three other semi-analytic models: The solid yellow line shows the fiducial model by Popping+17 [273], the violet dashed and dot-dashed lines show the fiducial model and upper limits from Vijayan+19 [289], and the red line shows the fiducial results from Triani+20 [290]. Expect a few outliers which require the maximal dust mass production scenario, (M_d, M_*) estimates inferred from $z \sim 7$ data are consistent with theoretical predictions.

Chapter 3

A new method to derive the dust temperature

At $z \geq 5$ most of the sources observed with ALMA, when detected in dust continuum, have only a single (or very few) data-point at FIR wavelengths [112, 230, 277, 278, 9]. Consequently, $T_{\text{d,SED}}$ is assumed a priori in the fitting to reduce the degrees of freedom. The lack of knowledge of $T_{\text{d,SED}}$ results in very large uncertainties on the derived galaxy properties, such as M_{d} , the far-infrared luminosity L_{FIR} , and obscured star formation rate (SFR, [313]). Further observations in a larger number of ALMA bands would ameliorate the problem, but not necessarily solve it. Indeed, MIR wavelengths remain inaccessible to ALMA. Nevertheless, the inclusion of ALMA band 7 – 8 – 9 data would improve the results significantly for galaxies at $z \gtrsim 5$. At these redshifts, these bands sample the SED at shorter wavelengths, closer to the FIR emission peak.

Here we intend to overcome current observational limitations by combining dust continuum measurements with the widely observed fine-structure transition of singly ionized carbon [C II] at $158 \mu\text{m}$. This line is the dominant coolant of the neutral atomic gas in the ISM [99], making it one of the brightest FIR lines in most galaxies [100]. Moreover, [C II] has been proved to be connected to the SFR of local [101, 102] and high- z galaxies [89, 103, 104, 95, 83, 91, 105, 91, 278, 92, 107].

We propose a novel method for the dust temperature computation using L_{CII} as a proxy for the total gas mass, and therefore for M_{d} given a dust-to-gas ratio. Our method breaks the degeneracy between M_{d} and $T_{\text{d,SED}}$ in the SED fitting. This allows us to constrain $T_{\text{d,SED}}$ with a single continuum data point. As a byproduct of our method, we provide an interpretation of the empirical relation found by [330] between M_{H_2} and L_{CII} . We also derive a more general relation connecting the *total* gas mass M_{gas} with L_{CII} . Joining the two we can also study the evolution of the molecular gas fraction $M_{\text{gas}}/M_{\text{H}_2}$ with redshift.

3.1 The [C II]-based method

Before introducing our method, we discuss two key ingredients, i.e. the dust-to-gas ratio D and the conversion factor $\alpha_{\text{CII}} = M_{\text{gas}}/L_{\text{CII}}$. Multiplying L_{CII} by the product $D \cdot \alpha_{\text{CII}}$ we infer M_{d} . We can then constrain $T_{\text{d,SED}}$ using a single continuum data point.

3.1.1 Dust-to-gas ratio

Several studies [331, 180, 332, 333] have shown that D scales linearly with metallicity, with little scatter, down to $Z \lesssim 0.1 Z_{\odot}$:

$$D = D_{\text{MW}} \left(\frac{Z}{Z_{\odot}} \right), \quad (3.1)$$

where $D_{\text{MW}} = 1/162$ is the Milky Way dust-to-gas ratio [334]. We adopt eq. 3.1 as our fiducial choice, since almost all the galaxies to which we apply our method, have metallicities $\gtrsim 0.2 Z_{\odot}$. Hence, they are mostly unaffected by deviations¹ from this linear scaling that might occur at $Z \lesssim 0.1 Z_{\odot}$.

Moreover, the ideal targets of our method are the galaxies observed in current high- z ALMA surveys (such as e.g. ALPINE, PI: Le Fèvre, and REBELS, PI: Bouwens), which are massive (stellar mass $M_{\star} \simeq 10^{10} M_{\odot}$), dusty, and evolved sources. From numerical simulations galaxies at $z \sim 6$ with similar stellar masses ($10^9 < M_{\star} < 10^{11}$) are expected to have $Z \gtrsim 0.1 Z_{\odot}$ [338, 339]. This is also confirmed, albeit with considerable uncertainties (relative errors up to $\sim 80\%$), by several studies which analyse FIR lines (such as [N II], [N III], [C II], C III] and [O III]) observations at $z \gtrsim 6 - 8$ to derive Z [340, 278, 92, 9, 341, 10, 255].

Current estimates of Z at high redshift will be significantly ameliorated thanks to forthcoming ALMA observations and to the James Webb Space Telescope (JWST) spectroscopy. Indeed, JWST will detect several optical nebular lines (such as H β , H α , [N II], [O II] and [O III]) out to $z \sim 10$. This will allow us to reduce the relative errors associated with Z down to $\sim 35\%$ even at very high- z [342, 343, 344], improving also our knowledge of the dust-to-gas ratios.

3.1.2 [C II]-to-total gas mass conversion factor

The [C II] conversion factor, α_{CII} , expresses the specific [C II] emission efficiency per unit *total* (i.e. atomic + molecular) gas mass. To investigate the relation between total L_{CII} and M_{gas} , we use the following empirical relations²:

$$\Sigma_{\text{SFR}} = 10^{-6.99} \Sigma_{\text{CII}}^{0.93} \quad (\text{De Looze relation}) \quad (3.2)$$

$$\Sigma_{\text{SFR}} = 10^{-12} \kappa_s \Sigma_{\text{gas}}^{1.4} \quad (\text{Kennicutt – Schmidt relation}) \quad (3.3)$$

$$\Sigma_{\text{gas}} = \alpha_{\text{CII}} \Sigma_{\text{CII}} \quad (\text{conversion relation}) \quad (3.4)$$

The first relation has been inferred by ([101], hereafter DL) from the Dwarf Galaxy Survey (DGS) sample of local galaxies³. The second one is the Kennicutt–Schmidt relation ([219], hereafter KS). The “burstiness parameter” κ_s quantifies the single source deviations (upwards for starbursts, and downwards for quiescent galaxies, see [345, 327]) from the average relation. Finally, eq. 3.4 is equivalent to the definition $\alpha_{\text{CII}} = M_{\text{gas}}/L_{\text{CII}}$ under the assumption that [C II] is spatially extended as the gas.

We combine eq. 3.2–3.4 into the following one,

$$\alpha_{\text{CII}} = \frac{11.3}{\kappa_s^{5/7}} \Sigma_{\text{SFR}}^{-0.36} \frac{M_{\odot}}{L_{\odot}}. \quad (3.5)$$

This relation shows that satisfying the DL and KS relations at the same time implies that α_{CII} cannot be constant. It must depend on the SFR and its mode (burst vs. quiescent). At a fixed SFR, galaxies with large κ_s values (starbursts) have a lower α_{CII} and therefore can produce a larger [C II] luminosity per unit gas mass. The same is true if κ_s is fixed and the SFR is larger. In high star formation regimes the more efficient [C II] emission might depend on a more intense radiation field or higher gas density [327, 31].

¹At very low metallicities ($Z \lesssim 0.1 Z_{\odot}$), deviations from the linear relation have been suggested [335, 336, 334, 337]. For instance, [334] find a steeper $D - Z$ relation in their sample of local galaxies. However, the deviation is driven especially by the fewer, widely scattered data at $Z \leq 0.1 Z_{\odot}$.

²We adopt the standard units used for these quantities: surface star formation [$M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$], [C II] luminosity [$L_{\odot} \text{ kpc}^{-2}$], and gas density [$M_{\odot} \text{ kpc}^{-2}$]

³For details on the DGS sample see Sec. 3.2

Modification at high- z

As we approach the Epoch of Reionization (EoR) a precise assessment of the KS relation becomes very difficult. H I is not observable at $z \geq 4$, and typical H₂ tracers (CO and dust) suffer from severe limitations⁴. Hence Σ_{gas} is not reliably measurable. So far there is considerable evidence that FIR-detected galaxies at $z > 5$ are strong UV emitters⁵ with large SFRs, i.e. they are most likely starbursts ($\kappa_s \gg 1$, see e.g. [341], Vallini in prep.).

The validity of the DL relation might also be questioned at high- z . Most studies agree that this relation is still valid at $z > 4$, although its scatter is ~ 2 times larger than the local one [91, 105, 348, 349]. However, in extreme cases (SFR < 30 – 50 M_⊙/yr or $z > 8$) high- z sources have been found to deviate more than 2σ from the local DL relation, being systematically below the latter [104, 90, 350, 348, 12].

Recently, [107] showed that EoR galaxies lay on a slightly different (w.r.t. the one in eq. 3.2) DL relation appropriate for starburst/H II-like galaxies⁶:

$$\Sigma_{\text{SFR}} = 10^{-7.06} y^2 \Sigma_{\text{CII}} \quad (\text{DeLooze relation/starbursts}). \quad (3.6)$$

once the obscured fraction of the SFR is appropriately included in Σ_{SFR} . The factor $y = r_{\text{CII}}/r_{\star}$ is introduced since there is growing evidence that at $z > 4$ [C II] emission is more extended than UV emission ($1.5 \lesssim y \lesssim 3$ at $z > 4$, see e.g. [95, 105, 83, 348, 320, 321, 322, 107]). The origin of such an extended [C II] structure is still debated. Current explanations range from emission by a) outflow remnants in the Circum Galactic Medium (CGM, [87, 323, 351, 320, 352, 322]), b) CGM gas illuminated by the galaxies strong radiation field [95, 91, 321]), to c) actively accreting satellites [326, 105, 348].

By combining eq. 3.6 with eqs. 3.3 and 3.4, we derive the high- z conversion factor

$$\alpha_{\text{CII,hz}} = \frac{32.47}{\kappa_s^{5/7}} y^2 \Sigma_{\text{SFR}}^{-0.29} \frac{M_{\odot}}{L_{\odot}}. \quad (3.7)$$

Using the DL relation for starbursts, independently on the chosen factor y , results in a rescaling upwards of α_{CII} at high- z with respect to $z \simeq 0$. The dependence on Σ_{SFR} and κ_s is almost unchanged. Additionally, at a fixed SFR and κ_s , galaxies with lower y (less extended [C II] emission) have a lower α_{CII} , i.e. a larger [C II] luminosity per unit gas mass.

3.1.3 Determining the dust temperature T_d

We assume an optically thin, single-temperature, grey-body approximation. The dust continuum flux F_{ν} observed against the CMB at rest-frame frequency ν can be written as [346, 328]

$$F_{\nu} = g(z) M_d \kappa_{\nu} [B_{\nu}(T'_{\text{d,SED}}) - B_{\nu}(T_{\text{CMB}})], \quad (3.8)$$

where $g(z) = (1+z)/d_L^2$, d_L is the luminosity distance to redshift z , κ_{ν} is the dust opacity, B_{ν} is the black-body spectrum, and $T_{\text{CMB}}(z)$ is the CMB temperature⁷ at redshift z .

⁴Observing CO transitions becomes challenging due to the larger cosmological distance of sources, and lower contrast against the Cosmic Microwave Background (CMB, [346]). This also makes dust emission observations more difficult at high- z . This is particularly true in the presence of cold dust nearly in equilibrium with the CMB [346]. Most importantly, the impossibility of simultaneously constraining M_d and $T_{\text{d,SED}}$ due to the few available data points, results in very large uncertainties on M_d , and therefore M_{H_2} .

⁵This might, however, be due to an observational bias. Indeed, most high- z ALMA targets have been selected from UV observations (i.e. by construction they are strong UV emitters). There are few exceptions represented by the (sub)mm-selected targets, as in the surveys ASPECS [347] and SPT [228].

⁶Which is also provided in [101]

⁷ $T_{\text{CMB}}(z) = T_{\text{CMB},0}(1+z)$, with $T_{\text{CMB},0} = 2.7255$ K [57]

At wavelengths $\lambda > 20\mu\text{m}$, κ_ν can be approximated as [186]

$$\kappa_\nu = \kappa_* \left(\frac{\nu}{\nu_*} \right)^\beta. \quad (3.9)$$

where the choice of (κ_*, ν_*, β) depends on the assumed dust properties. We consider Milky Way-like dust (following the WD01 model), for which standard values are $(\kappa_*, \nu_*, \beta) = (10.41 \text{ cm}^2\text{g}^{-1}, 1900 \text{ GHz}, 2.03)$, see [177]. We also account for the fact that the CMB acts as a thermal bath for dust grains, setting a lower limit for their temperature. We correct $T_{\text{d,SED}}$ for this effect, following the prescription⁸ by [346].

Eq. 3.8 has two parameters, M_d and $T_{\text{d,SED}}$. [C II] observations can be used to determine M_d :

$$M_d = DM_{\text{gas}} = D \alpha_{\text{CII}} L_{\text{CII}}. \quad (3.10)$$

We substitute in eq. 3.8 and specialize to the [C II] line frequency $\nu_0 = 1900.54 \text{ GHz}$. We thus introduce the [C II]-based dust temperature $T_{\text{d,CII}}$, defined as the solution of

$$F_{\nu_0} = g(z) D \alpha_{\text{CII}} L_{\text{CII}} \kappa_{\nu_0} [B_{\nu_0}(T_{\text{d,CII}}) - B_{\nu_0}(T_{\text{CMB}})]. \quad (3.11)$$

We can re-write this equation in a more compact form, yielding the explicit expression for $T_{\text{d,CII}}$:

$$T_{\text{d,CII}} = \frac{T_0}{\ln(1 + f^{-1})}. \quad (3.12)$$

where $T_0 = h_p \nu_0 / k_B = 91.86 \text{ K}$ is the temperature corresponding to the [C II] transition energy (k_B and h_p are the Boltzmann and Planck constants). We have defined:

$$f = \mathcal{B}(T_{\text{CMB}}) + A^{-1} \tilde{F}_{\nu_0}, \quad (3.13)$$

where $\mathcal{B}(T_{\text{CMB}}) = [\exp(T_0/T_{\text{CMB}}) - 1]^{-1}$. The non-dimensional continuum flux $\tilde{F}_{\nu_0}$ and the constant A are defined as

$$\begin{aligned} \tilde{F}_{\nu_0} &= \frac{\lambda_0^2 F_{\nu_0}}{2k_B T_0} = 0.98 \times 10^{-16} \left(\frac{F_{\nu_0}}{\text{mJy}} \right), \\ A &= g(z) \alpha_{\text{CII}} D L_{\text{CII}} k_0 = 5.2 \times 10^{-24} \left[\frac{g(z)}{g(6)} \right] \left(\frac{L_{\text{CII}}}{L_\odot} \right) \left(\frac{\alpha_{\text{CII}}}{M_\odot/L_\odot} \right) D. \end{aligned} \quad (3.14)$$

Clearly, if $\tilde{F}_{\nu_0}/A \gg \mathcal{B}(T_{\text{CMB}})$ the CMB effects on dust temperature become negligible.

Eq. 3.12 can be used to compute T_{CII} using a single 1900 GHz observation (which provides both L_{CII} and F_{ν_0}) once one has an estimate for the two parameters D (Sec. 3.1.1) and α_{CII} (Sec. 3.1.2).

Numerical implementation

Writing explicitly the expressions for D and α_{CII} in eq. 3.14, we can show that $T_{\text{d,CII}}$ is ultimately a function of the following parameters $(\kappa_s, z, F_{\nu_0}, Z, \Sigma_{\text{SFR}}, L_{\text{CII}})$. For local galaxies, all these quantities are well constrained by observations. In practice we solve eq. 3.12 performing a random sampling of these parameters around the measured values, within the uncertainties. Differently, at high- z κ_s is largely unknown⁹. Hence we consider a broad random uniform distribution for this parameter.

To constrain $T_{\text{d,CII}}$ at high- z , we add the following physical conditions:

⁸ $T'_{\text{d,SED}} = \{T_{\text{d,SED}}^{4+\beta} + T_{\text{CMB},0}^{4+\beta} [(1+z)^{4+\beta} - 1]\}^{1/(4+\beta)}$. In the following, we drop the apex from the dust temperature symbol for better readability. It is then intended we always refer to the *CMB-corrected* dust temperature.

⁹At high- z we also introduce the parameter y . This is often well constrained by observations.

ID	Galaxy	ν_2 [GHz]	F_{ν_2} [Jy]	d_L [Mpc]	F_{ν_0} [Jy]	Z [$Z_\odot$]	$\log \Sigma_{\text{SFR}}$ [$\text{M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$]	$\log L_{\text{CII}}$ [$\text{L}_\odot$]	κ_s	$T_{\text{d,SED}}$ [K]	$T_{\text{d,CII}}$ [K]
0	UGC4483 ^a	4285	0.109 ± 0.007	3.2	0.081 ± 0.029	0.053	−3.041	4.119	0.1	31.0 ^{+5.0} _{−2.0}	32.0 ^{+7.0} _{−7.0}
1	VII Zw 403 ^a	4285	0.493 ± 0.026	4.5	0.260 ± 0.037	0.083	−2.621	4.994	0.3	34.0 ^{+2.0} _{−1.0}	30.0 ^{+4.0} _{−3.0}
2	NGC 1569 ^a	4285	42.600 ± 2.100	3.1	39.700 ± 4.800	0.190	−1.721	6.669	3.1	29.0 ^{+1.0} _{−1.0}	34.0 ^{+2.0} _{−1.0}
3	II Zw 40 ^a	4285	5.580 ± 0.280	12.1	3.140 ± 0.431	0.309	−0.818	6.586	0.9	33.0 ^{+2.0} _{−1.0}	43.0 ^{+7.0} _{−11.0}
4	NGC 4214 ^a	4285	20.400 ± 1.020	2.9	23.400 ± 2.820	0.331	−3.054	5.977	0.4	28.0 ^{+1.0} _{−1.0}	27.0 ^{+3.0} _{−3.0}
5	UM 448 ^a	4285	4.040 ± 0.203	87.8	2.850 ± 0.345	0.380	−0.957	8.281	0.8	31.0 ^{+1.0} _{−1.0}	37.0 ^{+6.0} _{−8.0}
6	NGC1140 ^a	4285	3.430 ± 0.172	20	4.050 ± 0.487	0.436	−2.096	7.169	0.1	27.0 ^{+1.0} _{−1.0}	26.0 ^{+3.0} _{−3.0}
7	LARS2 ^b	4285	0.080 ± 0.011	131.4	0.121 ± 0.014	0.309	−2.901	7.230	0.1	26.0 ^{+1.0} _{−1.0}	24.0 ^{+7.0} _{−3.0}
8	LARS3 ^b	4285	9.306 ± 0.008	138.7	4.745 ± 0.019	0.468	−1.444	9.190	2.7	34.0 ^{+1.0} _{−1.0}	24.0 ^{+3.0} _{−4.0}
9	LARS8 ^b	2998	4.322 ± 0.027	169.6	3.346 ± 0.034	0.589	−1.850	9.550	1.1	24.0 ^{+2.0} _{−2.0}	18.0 ^{+2.0} _{−2.0}
10	LARS9 ^b	4285	1.147 ± 0.017	208.7	1.306 ± 0.027	0.427	−0.425	9.170	0.3	25.0 ^{+2.0} _{−2.0}	28.0 ^{+5.0} _{−6.0}
11	LARS12 ^b	4285	0.104 ± 0.004	473.8	0.062 ± 0.004	0.398	−2.021	8.580	5.1	33.0 ^{+1.0} _{−1.0}	20.0 ^{+3.0} _{−3.0}
12	LARS13 ^b	4283	0.506 ± 0.003	701.1	0.286 ± 0.003	0.575	−1.333	9.250	4.5	33.0 ^{+1.0} _{−1.0}	25.0 ^{+3.0} _{−3.0}
13	NGC4631 ^c	3409	31.11	6.2	34.23	0.50	−3.18	6.91	0.4	24.0 ^{+3.0} _{−2.0}	22.0 ^{+3.0} _{−3.0}
14	NGC3627 ^c	3409	20.68	9.3	17.40	1.77	−2.85	6.46	0.7	27.0 ^{+3.0} _{−3.0}	23.0 ^{+4.0} _{−4.0}
15	NGC2146 ^c	3409	137.93	12.9	229.17	0.98	−2.03	8.28	0.1	21.0 ^{+2.0} _{−2.0}	25.0 ^{+3.0} _{−3.0}
16	NGC3938 ^c	3409	30.41	17.9	38.72	2.10	−2.98	6.80	0.1	23.0 ^{+2.0} _{−2.0}	31.0 ^{+6.0} _{−7.0}
17	M83 ^c	3409	135.78	7.4	111.93	1.23	−2.87	7.37	0.5	27.0 ^{+4.0} _{−3.0}	21.0 ^{+3.0} _{−3.0}
18	M82 ^c	3409	1117.00	2.9	614.57	2.75	−1.56	7.38	5.9	32.0 ^{+3.0} _{−4.0}	21.0 ^{+3.0} _{−3.0}

Properties of galaxies included in our benchmark local sample. For the data without specified uncertainty, we consider a 20% relative error as a conservative choice. **References:**^a[354, 101, 355, 356], ^b[357], and ^c[358, 359, 360, 361, 362].

1. M_d does not exceed the largest dust mass producible by supernovae (SNe), $M_{d,\text{max}}$. To quantify $M_{d,\text{max}}$ we take a metal yield constraint $y_Z < 2 \text{ M}_\odot$ per SN, and assume that all the produced metals are later included in dust grains. Then:

$$M_{d,\text{max}} = y_Z \nu_{\text{SN}} M_\star \quad (3.15)$$

where $\nu_{\text{SN}} = (53 \text{ M}_\odot)^{-1}$ is the number of SNe per solar mass of stars formed for a standard Salpeter 1-100 $\text{M}_\odot$ IMF [246].

2. $\text{SFR}_{\text{FIR}} \sim 10^{-10} L_{\text{FIR}}$ [219], does not exceed the total measured SFR. This directly relates to the dust mass and temperature as $L_{\text{FIR}} = M_d (T_{\text{d,CII}}/6.73)^6$ [353].

$T_{\text{d,CII}}$ solutions not satisfying 1. and 2. are discarded. These conditions result in a lower (upper) cut for very cold (hot) dust temperatures corresponding to unphysically large dust masses (FIR luminosity and SFR). This allows us to effectively constrain $T_{\text{d,CII}}$ at high- z despite the lack of information on κ_s .

3.2 Local testing of the [C II]-based method

We have selected 19 local galaxies for which the needed data are available: (a) κ_s , (b) redshift, (c) metallicity, (d) total SFR and Σ_{SFR} , (e) total L_{CII} , (f) at least two FIR continuum detections, one of which at ν_0 . These galaxies are drawn from the following catalogs¹⁰:

- Dwarf Galaxy Survey (DGS, [101, 365, 366]): targeting a total of 50 local dwarf galaxies, whose [C II], [O I] and [O III] line emission are mapped with the Herschel Space Observatory;
- Lyman Alpha Reference Sample (LARS, [367, 368]): consisting of 14 low-redshift ($z = 0.03 - 0.2$) mildly starbursting systems observed in multiple bands with HST. This sample was intended as a local laboratory for the study of $\text{Ly}\alpha$, which is one of the dominant lines used to characterise high- z sources;

¹⁰Other local samples, such as KINGFISH [363] and GOALS surveys [364], lack one of the required data (total [C II] luminosity and metallicity, respectively).

Galaxy	z	F_{ν_0} [mJy]	Z [$Z_{\odot}$]	$\log \Sigma_{\text{SFR}}$ [$\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$]	L_{CII} [$10^8 L_{\odot}$]	κ_s	$y = r_{\text{CII}}/r_*$	$M_{\star}$ [$10^8 M_{\odot}$]
SPT0418-47 ^a	4.23	3.30 ± 0.30	$0.30 - 1.30$	1.72	19.9 ± 1.5	9	1.5	120.0 ± 15.0
B1465666 ^b	7.15	0.13 ± 0.03	0.40 ± 0.30	1.32	11.0 ± 1.4	–	1.4 ± 0.4	7.7
MACS0416-Y1 ^c	8.31	< 0.02	0.20 ± 0.16	1.16	1.4 ± 0.2	–	1.2 ± 0.4	2.0

Properties of our high- z template sample of galaxies. We underline that for the data where the uncertainty is not given we consider a 30% relative error which is a conservative choice given the other available data. **References:**^a[369, 370, 229, 371]. Here we show the intrinsic values, which are obtained by dividing by the magnification factor of the source $\mu = 32.7$ [370]; ^b[278], and ^c[10].

- The complete database of the Herschel/Photoconductor Array Camera and Spectrometer (PACS, [358]): a coherent database of spectroscopic observations of FIR fine-structure lines (in the range $10 - 600 \mu\text{m}$) collected from the Herschel/PACS spectrometer archive for a local sample of 170 Active Galactic Nuclei (AGNs), 20 starburst, and 43 dwarf galaxies.

The selected galaxies and their properties are reported in Tab. 3.1. Hereafter we refer to these galaxies as the *local sample*.

The DL relation (eq. 3.2) has been derived from a portion of this same sample and therefore is nearly satisfied by construction. The galaxies in the local sample also follow the KS relation with a scatter consistent with that of local spirals and starbursts ($0.1 \leq \kappa_s \leq 5.9$, see Fig. 3.1, left panel).

We compare the value of α_{CII} resulting from eq. 3.5 with the ratio $M_{\text{gas}}/L_{\text{CII}}$ derived from observations (Fig. 3.1, right panel). We find $0.7 \leq \log \alpha_{\text{CII}} \leq 3.2$. The predicted α_{CII} are consistent with the data at $< 1.5\sigma$, although there are significant uncertainties.

Finally, we compare $T_{\text{d,CII}}$ and the dust temperature deduced from traditional SED fitting ($T_{\text{d,SED}}$). For the local sample galaxies we infer $T_{\text{d,SED}}$ from the following equation:

$$\frac{F_{\nu_1}}{F_{\nu_2}} = \frac{\kappa_{\nu_1}[B_{\nu_1}(T_{\text{d,SED}}) - B_{\nu_1}(T_{\text{CMB}})]}{\kappa_{\nu_2}[B_{\nu_2}(T_{\text{d,SED}}) - B_{\nu_2}(T_{\text{CMB}})]}. \quad (3.16)$$

where we consider¹¹ $\nu_1 = 1900 \text{ GHz}$ and $\nu_2 = (4285, 3409) \text{ GHz}$, corresponding to $\lambda_2 = (70, 88) \mu\text{m}$. This method based on the continuum fluxes ratio is equivalent to the single temperature grey-body SED fitting, hence the obtained dust temperature is $T_{\text{d,SED}}$.

To produce $T_{\text{d,CII}}$ we consider a flat distribution for the burstiness parameter $0.1 \lesssim \kappa_s \lesssim 5.9$, where the range is derived from gas masses and SFR measurements for the single sources (see Tab. 3.1). The temperature comparison is shown in Fig. 3.2. We find that $T_{\text{d,CII}}$ and $T_{\text{d,SED}}$ are consistent within a 20% uncertainty in $\sim 90\%$ of the sources (precisely, all but galaxies ID11, ID18). The two discrepant sources are the most bursty ones in the sample, with an inferred $\kappa_s \sim 5$. Considering $\kappa_s \sim 5$ in these two cases (rather than the aforementioned flat distribution) would allow us to correctly recover $T_{\text{d,SED}}$ within 20% uncertainty. Nevertheless, we have preferred to consider a flat distribution for κ_s to be more consistent with a general application at high- z , where this parameter is almost always unconstrained.

3.3 Application of the [C II]-based method at high z

We now apply our method to high- z galaxies. We have collected a small (3 galaxies) sample for which the properties b)-f) are measured. The high- z sample contains:

- SPT 0418-47 [228, 372]: a strongly lensed Dusty Star-Forming Galaxy (DSFG) at redshift $z = 4.225$;

¹¹We select these frequencies to avoid PAH contamination present at wavelengths $\lesssim 20 \mu\text{m}$. For ID10 we take $\nu_2 = 2998 (100 \mu\text{m})$ since observations at the above-mentioned frequencies are not available.

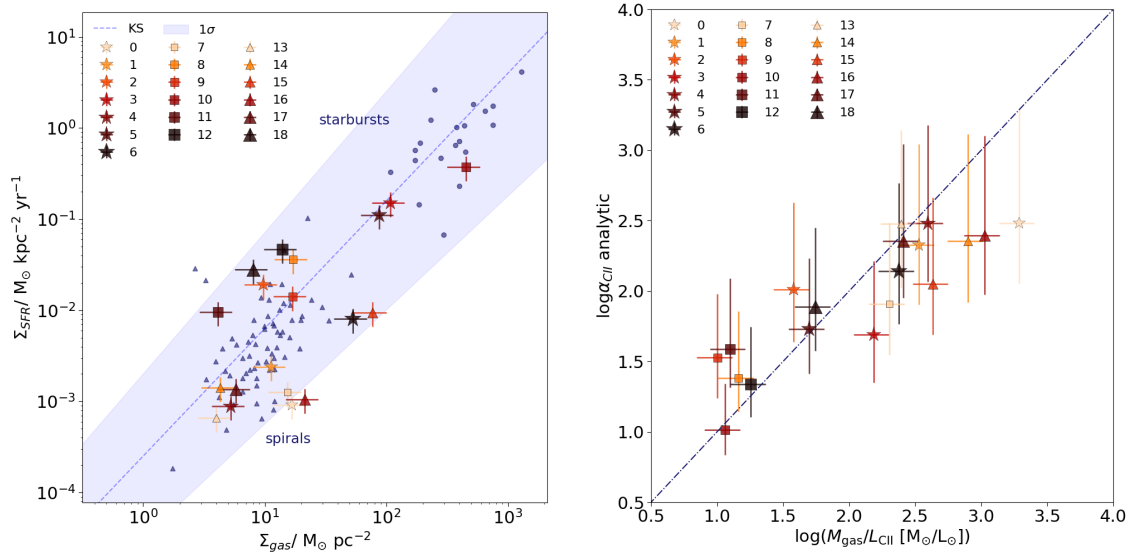


Figure 3.1: **Left panel:** Measured Σ_{SFR} vs. Σ_{gas} of our local sample. We associate each galaxy with an ID number which will be used in the following plots. The dashed blue line represents the KS relation (eq. 3.3) and the blue-shaded region its intrinsic scatter. Also shown for reference are a number of local spirals (black triangles, [219]) and starbursts (black stars, [219]). We distinguish each galaxy in our local sample with a different colour and identify them in the legend with their IDs as in Tab. 3.1. We also differentiate the three sub-samples with different shapes: a (star), b (square), and c (triangle, all references are the same as in Tab. 3.1). We note galaxies in the local sample are consistent with errors with the KS relation. **Right panel:** [C II] conversion factor computed from eq. 3.5 vs. the observed $\log(M_{\text{gas}}/L_{\text{CII}})$ for the same galaxies as in the left panel. The solid symbols correspond to the value of α_{CII} obtained considering for each galaxy the κ_s value computed from the measured Σ_{SFR} and Σ_{gas} . The dotted dashed black line is the bisector, i.e. it represents the relation $\log \alpha_{\text{CII}} = \log(M_{\text{gas}}/L_{\text{CII}})$. The fact that the points lay within $\lesssim 1.5\sigma$ from the bisector shows that eq. 3.5 gives a good estimate of the observed gas mass-to-[C II] luminosity ratio.

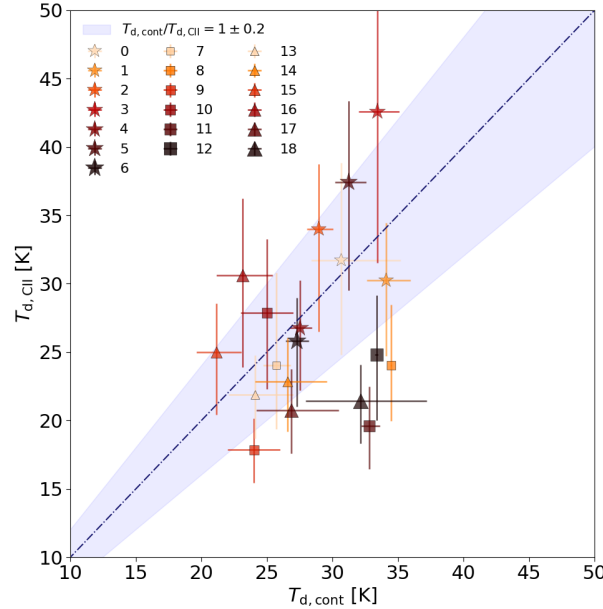


Figure 3.2: Comparison between $T_{\text{d,CII}}$ (from eq. 3.12) and $T_{\text{d,SED}}$ (from eq. 3.16) in our local template sample of galaxies (see Tab. 3.1 for the properties of each galaxy corresponding to the ID in legend). The dotted dashed grey line represents the relation $T_{\text{d,CII}} = T_{\text{d,SED}}$ and the shaded area a deviation from the equality of $\pm 20\%$.

- B1465666 [278]: a Lyman Break Galaxy (LBG) at $z = 7.15$
- MACS0416-Y1 [9, 10]: an LBG at $z \sim 8.31$

The properties of these galaxies are summarized in Tab. 3.2. These sources are UV-selected, highly star-forming (yet not extreme as $\text{SFR} \lesssim 500 \text{ M}_\odot/\text{yr}$), do not host AGN, and are presumably main sequence high- z galaxies.

For all these sources the parameter $y = r_{\text{CII}}/r_\star$ has been estimated [371, 278, 10]. Moreover, [371] provided a constraint on Σ_{gas} for SPT 0418-47. Hence, we can also derive the burstiness parameter for this galaxy finding $\kappa_s \sim 9$. Due to the uncertainty in the gas mass derivation, in the computation we consider a Gaussian distribution centred around this value with a $\sigma \sim 2$ (i.e. we allow for values in the range $3 \lesssim \kappa_s \lesssim 15$, consistent with previous works e.g. [341]).

For the remaining two galaxies κ_s is unknown, hence we need to define a broader distribution of possible values for this parameter. High redshift UV selected sources are strong UV emitters by construction, highly star-forming, and consequently they are expected to be starburst with $\kappa_s > 1$. Both locally and at intermediate redshift, values up to $\kappa_s \approx 100$ have been observed in such galaxies [373]. Recently, [341] for the mildly star-bursting COS-3018 at $z = 6.854$ found $\kappa_s \sim 3$, applying the [C II]-emission model given in [327]. Applying the same method to B1465666 and MACS0416-Y1 Vallini in prep. finds very large values $30 \lesssim \kappa_s \lesssim 140$. Hence, we conservatively choose a random uniform distribution in the range $10 < \kappa_s < 100$ for these two sources.

Using eq. 3.7 we compute the coefficient $\alpha_{\text{CII,hz}}$. We find, $\alpha_{\text{CII,hz}} = 7_{-1}^{+2}$ for SPT 0418-47, which is perfectly consistent with the recent estimate by [371] of $M_{\text{gas}}/L_{\text{CII}} \sim \alpha_{\text{CII,hz}} = 7 \pm 1$. We derive $\alpha_{\text{CII,hz}} = 2_{-1}^{+2}$ for B14-65666, and $\alpha_{\text{CII,hz}} = 2_{-1}^{+2}$ for MACS0416-Y1. We note that these values are lower than the average α_{CII} values found locally ($z \sim 0$, see e.g. Fig. 3.1). This might indicate a trend of less efficient [C II] emission per unit gas mass at higher redshift.

We now compare the $T_{\text{d,CII}}$ estimated by our model with the $T_{\text{d,SED}}$ from the SEDs. We summarise our findings and compare them with literature data in Tab. 3.3. For SPT 0418-47 we derive $T_{\text{d,CII}} = 50_{-5}^{+3} \text{ K}$ that is consistent, within the error, with the $T_{\text{d,SED}}$ from the SED fitting by [372] ($T_{\text{d,SED}} = 45 \pm 2 \text{ K}$). Recently [229] derived a slightly higher dust temperature $T_{\text{d,SED}} = 58 \pm 11 \text{ K}$ for this source, which is still consistent with our result¹². Although the uncertainty of our $T_{\text{d,CII}}$ is larger than the one of $T_{\text{d,SED}}$ this is somewhat expected. The SED for SPT 0418-47 is well-constrained, featuring data points on both sides of the FIR spectrum. On the other hand, the metallicity of the source is very uncertain, $0.3 \leq Z/Z_\odot \leq 1.3$ and this affects directly the error on our $T_{\text{d,CII}}$.

For B14-65666 we find $T_{\text{d,CII}} = 61_{-15}^{+16} \text{ K}$. This value is consistent with $T_{\text{d,SED}} = 48 - 61 \text{ K}$ which is inferred considering $1.5 < \beta < 3.0$ [278]. For MACS0416-Y1 [9, 10] we consider the upper limit on F_{ν_0} recently derived by [10]. Interestingly $T_{\text{d,CII}}$ in eq. 3.12 decreases with $f \propto F_{\nu_0}$. Hence, for this galaxy we provide an upper limit for the [C II] derived dust temperature: $T_{\text{d,CII}} \leq 82_{-19}^{+16} \text{ K}$. Very hot dust temperatures $T_{\text{d,CII}} > 120 \text{ K}$ are excluded thanks to the condition on SFR_{FIR} (see Sec. 3.1.3)¹³. This result is particularly relevant as [10] obtained only a lower limit for the dust temperature $T_{\text{d,SED}} \gtrsim 80 \text{ K}$. By combining

¹²[229] left $\lambda_\star = 100 \mu\text{m}$ as an additional free parameter in the SED fitting [374], which resulted in a larger ($\times 4$) uncertainty alongside a raise in the dust temperature. The fewer FIR data currently available at very high- z do not allow for the application of a similar fitting procedure on a large scale. Hence, at the current stage, a simpler grey body (as in [372]) with little variation in the dust properties is uniformly applied, leading to pretty consistent $T_{\text{d,SED}}$ derivations for different sources.

¹³Without the condition on SFR_{FIR} dust temperatures as large as $T_{\text{d,CII}} \gtrsim 130 \text{ K}$ would be reached. In part, this is a consequence of the very large uncertainty ($\sim 80\%$) on the already low metallicity of this galaxy ($Z = 0.2 Z_\odot$). Indeed for a fixed flux F_{ν_0} , $T_{\text{d,CII}}$ diverges as the metallicity $Z \rightarrow 0$ as this is equivalent to $M_d \rightarrow 0$, see eq. 3.10.

Galaxy	$\alpha_{\text{CII,hz}}$	$T_{\text{d,SED}}$ [K]	$T_{\text{d,CII}}$ [K]	M_{d} [$10^6 M_{\odot}$]	y_{d} [$M_{\odot}/\text{SN}$]
SPT0418-47 ^a	7 ± 1	$45 - 58$	—	110^{+10}_{-20}	—
This work	7^{+2}_{-1}	—	50^{+3}_{-5}	118^{+30}_{-20}	0.5 ± 0.1
B1465666 ^b	—	$48 - 61$	—	$6.5 - 13.2$	—
This work	2^{+2}_{-1}	—	61^{+16}_{-15}	$6.8^{+5.4}_{-2.4}$	$0.5^{+0.3}_{-0.1}$
MACS0416Y1 ^c	—	≥ 80	—	$0.2 - 0.6$	—
This work	2^{+2}_{-1}	—	$\leq 82^{+16}_{-19}$	$0.6^{+0.4}_{-0.2}$	0.2 ± 0.1

Comparison between predicted (“This work”) and published properties of galaxies in our high- z sample. We underline that the dust temperature estimates taken from the literature are obtained through SED fitting, while our predictions correspond to $T_{\text{d,CII}}$. **References:**^a[372, 369, 370, 229, 371]. Here we show the intrinsic values, which are obtained by dividing by the magnification factor of the source $\mu = 32.7$ [370]; ^b[278], and ^c[10].

the two results we can constrain the dust temperature of MACS0416-Y1 in the range $T_{\text{d,SED}} \sim 80 - 98$ K.

In conclusion, with our method, we can provide dust temperature estimations comparably accurate as that obtained from the traditional SED fitting with multiple bands data out to $z = 8.31$. This is very encouraging, as for the single high- z sources targeted by large programs, only single band measurements are generally available. Hence, commonly used SED fitting is not applicable without some underlying restrictive assumption on $T_{\text{d,SED}}$. Our method can be used in these cases to improve the accuracy of the interpretation of FIR observations and derive dust and galaxies’ properties.

3.3.1 Determining the dust mass at high- z

Our method also provides reliable estimates of the dust masses of distant galaxies. Once α_{CII} has been determined, it is straightforward to derive M_{d} using eq. 3.10. As already discussed, we discard the solutions for which $M_{\text{d}} > M_{\text{d,max}}$, which is computed in eq. 3.15.

For SPT0418-47 we find $M_{\text{d}} = 1.2^{+0.3}_{-0.2} \times 10^8 M_{\odot}$, a value perfectly consistent with that obtained from SED fitting $M_{\text{d}} = 1.1^{+0.1}_{-0.2} \times 10^8 M_{\odot}$. For B14-65666 we find $M_{\text{d}} = 6.8^{+5.4}_{-2.4} \times 10^6 M_{\odot}$. This is also consistent with the result obtained from SED fitting by [278]. They find $6.5 < M_{\text{d}}/10^6 M_{\odot} < 13.2$ with $1.5 \leq \beta \leq 2$. In the case of MACS0416-Y1 we find $M_{\text{d}} = 0.6^{+0.4}_{-0.2} \times 10^6 M_{\odot}$. This is consistent with the result obtained from SED fitting by [10]. They find $M_{\text{d}} = 0.2 - 0.6 \times 10^6 M_{\odot}$ for $70 \text{ K} < T_{\text{d,SED}} < 130 \text{ K}$, and $\beta = 2$.

We also compute the dust yield per SN, y_{d} , required to produce the above dust masses, which are consistent with previous estimates in the literature. We use the formula in [313]: $y_{\text{d}} = M_{\text{d}}/M_{\star}\nu_{\text{SN}}$, where $\nu_{\text{SN}} = (53 M_{\odot})^{-1}$ is the number of SNe per solar mass of stars formed [246]. For all the three sources it is $y_{\text{d}} \lesssim 1 M_{\odot}$ (see Tab. 3.3 for the value of y_{d} in each galaxy), i.e. within the allowed range given in the latest SNe dust production studies by [18]. They find that up to $y_{\text{d}} \leq 1.1 M_{\odot}$ per SN can be produced, where the exact value depends on the amount of dust which is destroyed during the explosion ($1.1 M_{\odot}$ corresponds to the extreme case of no dust destruction).

The presence of warmer dust ($T_{\text{d,SED}} \gtrsim 50$ K) in these high- z sources alleviates the large dust mass requirements set by the observed FIR luminosity. This is particularly relevant in the context of early galaxies. Allowing for lower dust masses prevents invoking super efficient dust production by stellar sources, which is difficult to reconcile with both data and theoretical models [313].

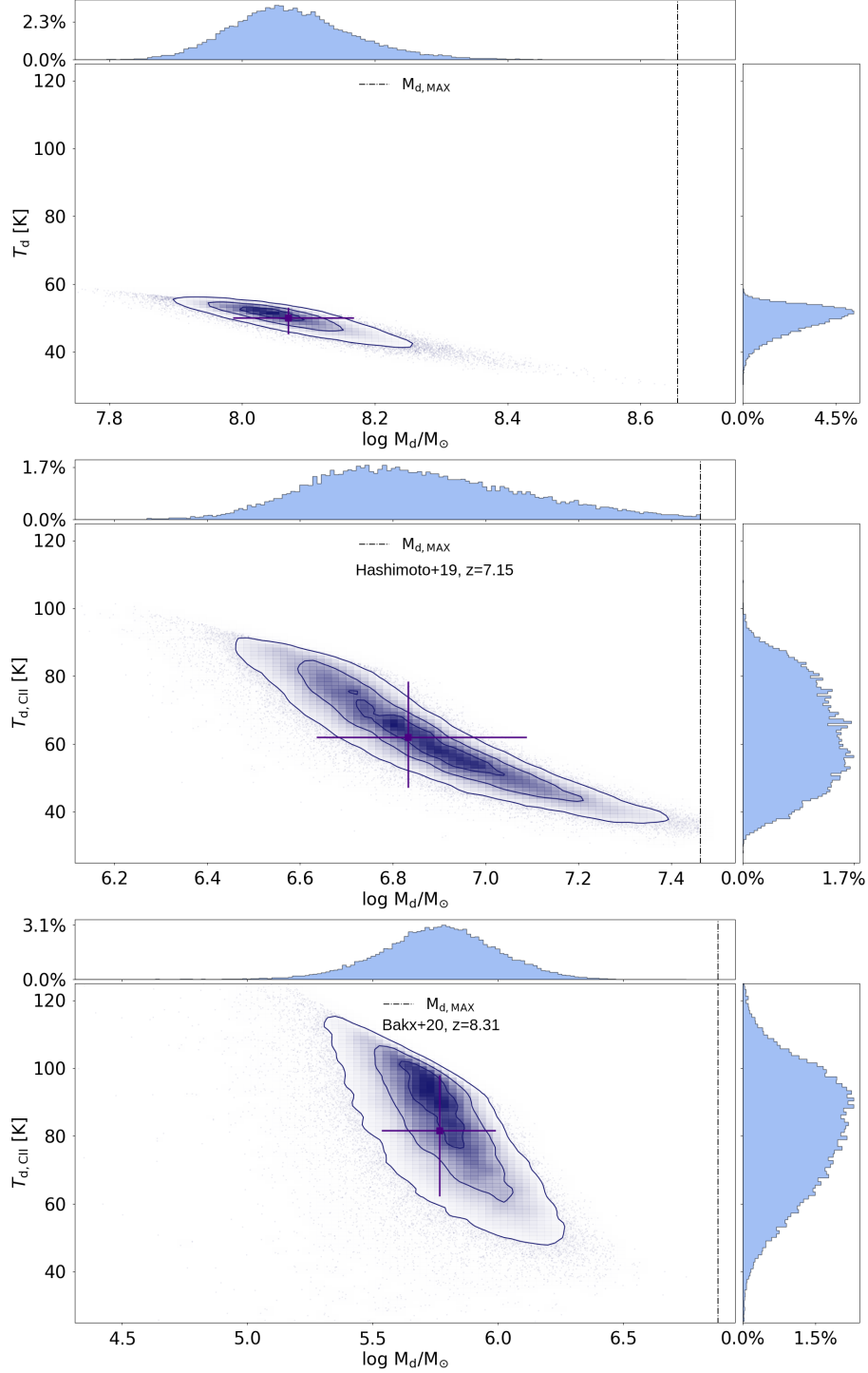


Figure 3.3: Recovered distribution of $T_{d,\text{CII}}$ as a function of M_d for the galaxies in our high- z template sample (same order as in Tab. 3.2). The contours show the (16, 50, 84) percentiles of the distribution. The median value is represented by the purple square (alongside its 16 and 84 percentiles marked by the error bars). We also show the temperature (right) and mass (top) PDFs. The upper limit on the dust mass, computed through eq. 3.15, is shown by the vertical black dot-dashed line in each panel.

3.4 Molecular gas content

Besides providing a reliable determination of the dust temperature, our method offers a physical interpretation of the [330] relation. To show this, we parallel the analysis in Sec. 3.1.2. Here we substitute the KS relation with the following expression linking the star formation and molecular gas surface density Σ_{H_2} [181]¹⁴:

$$\Sigma_{\text{SFR}} = 10^{-9} \frac{\Sigma_{\text{H}_2}}{t_{\text{depl}}}. \quad (3.17)$$

where t_{depl} is the depletion time. Combining eq. 3.17 with the DL relation and the definition of the molecular conversion factor, $\alpha_{\text{CII,mol}} = \Sigma_{\text{H}_2}/\Sigma_{\text{CII}}$, we find

$$\alpha_{\text{CII,mol}} = \frac{t_{\text{depl}}}{3.3 \times 10^{-2}} \Sigma_{\text{SFR}}^{-0.075}. \quad (3.18)$$

The dependence of $\alpha_{\text{CII,mol}}$ on Σ_{SFR} is extremely weak, in contrast with $\alpha_{\text{CII}} \propto \Sigma_{\text{SFR}}^{-0.3}$ (total gas conversion coefficient¹⁵, see Sec. 3.1.2). We can understand this result in physical terms as both H_2 and $[\text{C II}]$ emission trace closely ongoing star formation. Since both Σ_{H_2} and Σ_{CII} scale almost linearly with Σ_{SFR} , their ratio is virtually independent of this quantity. Instead, the total gas reservoir is less sensitive to star formation (see eq. 3.3). Therefore in the ratio $\Sigma_{\text{gas}}/\Sigma_{\text{CII}}$ the dependence on Σ_{SFR} does not cancel out.

Most recent results by [375] suggest that t_{depl} is nearly constant above redshift $z > 2$, and then increases slightly from $t_{\text{depl}} \sim 0.4$ Gyr at $z \sim 2$, to $t_{\text{depl}} \sim 0.7$ Gyr at $z = 0$. Substituting these values in eq. 3.18, we find $\alpha_{\text{CII,mol}} = (12 - 21) \Sigma_{\text{SFR}}^{-0.075}$. This result is compatible with the measurement of $M_{\text{H}_2}/L_{\text{CII}} = 31^{+31}_{-16} \text{ M}_\odot/L_\odot$ derived by [330] in a sample of galaxies at $z \sim 0 - 6$. Recently, [376] found this $M_{\text{H}_2}/L_{\text{CII}}$ ratio to hold also in the $[\text{C II}]$ -detected galaxies at $z \sim 4 - 6$ targeted by the ALPINE survey, albeit with some uncertainties¹⁶.

On average, previous works indicated longer depletion times $t_{\text{depl}} \sim [0.5, 2]$ Gyr both in local and high- z galaxies [377, 378, 373, 379, 380, 381, 293, 382, 383, 384, 385, 376]. Nevertheless, the observed scatter in t_{depl} is within measurement errors by [330]. The variation of $\alpha_{\text{CII,mol}}$ is significantly smaller than that of α_{CII} . Already within our limited sample of 23 galaxies, α_{CII} varies by nearly two orders of magnitude due to its strong dependence on Σ_{SFR} and κ_s (see Fig. 3.1).

3.4.1 Molecular gas fraction cosmic evolution

Armed with the expressions for α_{CII} (eq. 3.5) and $\alpha_{\text{CII,mol}}$ (eq. 3.18) we intend to study the redshift evolution of the ratio $\alpha_{\text{CII,mol}}/\alpha_{\text{CII}} = \Sigma_{\text{H}_2}/\Sigma_{\text{gas}}$. To this aim, since $\alpha_{\text{CII}} \propto \Sigma_{\text{SFR}}^{-0.3}$, we need to provide a qualitative prescription for the redshift evolution of the average $\bar{\Sigma}_{\text{SFR}}(z)$ in normal galaxies.

We consider the cosmic SFR comoving density, ψ , derived by [24] in the range $z = 0.01 - 8$. We combine ψ with the evolution of the effective radius, $r_\star \approx r_e = 6.9 \times (1+z)^{1.2} \text{ kpc}$, derived by [386] for a HST sample of $\sim 19,000$ galaxies at $z = 0 - 10$ to obtain $\bar{\Sigma}_{\text{SFR}}(z) = \psi/\pi r_e^2$, and the corresponding expression for $\alpha_{\text{CII}}(z)$ from eq. 3.5.

For simplicity, in computing $\alpha_{\text{CII}}(z)$ we consider $\kappa_s = 1$ as on average we expect most local and low- z galaxies to lie on the KS-relation¹⁷. In parallel to the result shown in Sec.

¹⁴We adopt the standard units used for these quantities: $\Sigma_{\text{SFR}} [\text{M}_\odot \text{ kpc}^{-2} \text{ yr}^{-1}]$, $t_{\text{depl}} [\text{Gyr}]$, and in eq. 3.18, $\alpha_{\text{CII,mol}} [\text{M}_\odot/L_\odot]$.

¹⁵The exponent -0.3 is an average value between the -0.36 and -0.29 found in eq. 3.5, 3.7.

¹⁶More precisely, [376] find a good agreement between molecular gas masses derived from $[\text{C II}]$ luminosities (using the relation by [330]), dynamical masses, and rest-frame $850 \mu\text{m}$ luminosities (extrapolated from the rest-frame $158 \mu\text{m}$ continuum).

¹⁷If $\kappa_s > 1$ the $\Sigma_{\text{H}_2}/\Sigma_{\text{gas}}$ curve is shifted upwards, as we are reducing $\Sigma_{\text{gas}} \propto \alpha_{\text{CII}} \propto \kappa_s^{-5/7}$, without affecting Σ_{H_2} . Hence, at higher redshift deviations are expected to occur due to the burstiness of galaxies.

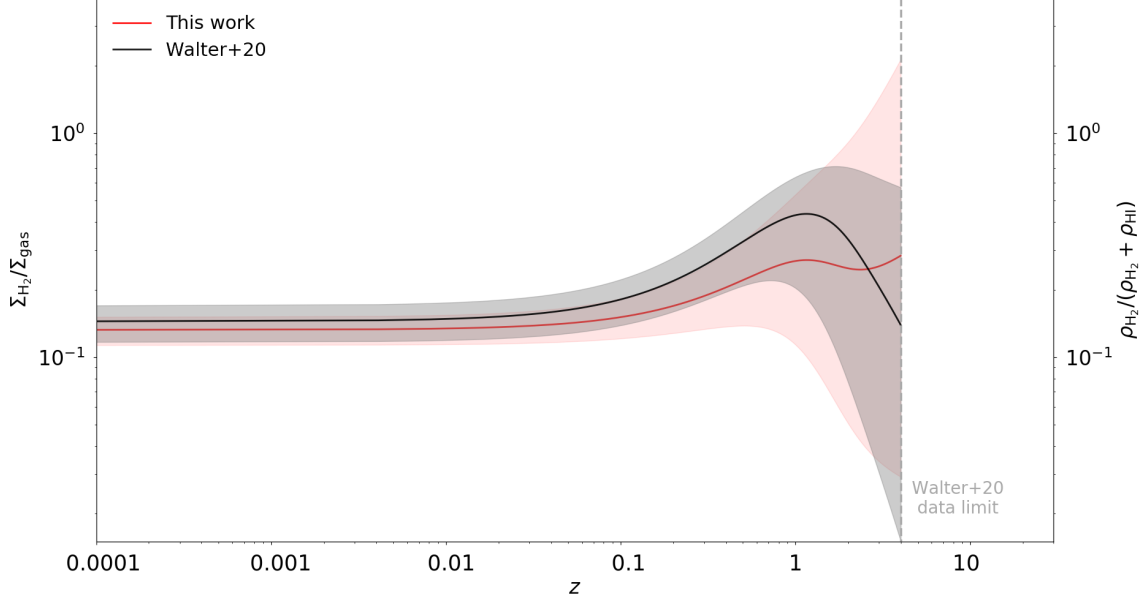


Figure 3.4: Redshift evolution of the molecular gas fraction $f_{\text{H}_2}(z) = \Sigma_{\text{H}_2}/\Sigma_{\text{gas}}$. The red line represents our fiducial estimate. The black line shows the $\rho_{\text{H}_2}/(\rho_{\text{H}_2} + \rho_{\text{HI}})$ trend observed by [375]; the vertical grey dashed line refers to the highest redshift considered in their analysis. For sake of the comparison here, we consider the same $t_{\text{depl}}(z)$ as in [375].

3.4, we write $\alpha_{\text{CII,mol}}(z) = (12 - 21) \bar{\Sigma}_{\text{SFR}}^{-0.075}$. We can then compute the ratio:

$$f_{\text{H}_2}(z) \equiv \Sigma_{\text{H}_2}/\Sigma_{\text{gas}} = \alpha_{\text{CII,mol}}/\alpha_{\text{CII}} \sim \left(\frac{\bar{\Sigma}_{\text{SFR}}}{\text{M}_{\odot} \text{kpc}^{-2} \text{yr}^{-1}} \right)^{0.225} \quad (3.19)$$

The redshift evolution of the molecular fraction in galaxies has been experimentally determined by [375] from observations¹⁸ of molecular, ρ_{H_2} , and atomic, ρ_{HI} , gas densities at $z \lesssim 4$. In Fig. 3.4 we show the comparison of $f_{\text{H}_2}(z)$ with the observed redshift evolution of the empirical $\rho_{\text{H}_2}/(\rho_{\text{HI}} + \rho_{\text{H}_2})$ ratio.

The two approaches yield a pretty consistent evolution trend, albeit they are both affected by large uncertainties. We find that on average $f_{\text{H}_2}(z)$ increases by a factor of ~ 2 from $z = 0.01$ to $z = 1$, in agreement with the trend found by [375] ($\sim 1.7 - 3.6$). However, at $z > 1$ the two trends might be different, as we predict a possible further increase in $f_{\text{H}_2}(z)$. This can be due to (a) a further increase in the $M_{\text{H}_2}/M_{\text{gas}}$, and/or (b) an increase in the ratio $r_{\text{gas}}/r_{\text{H}_2}$ ratio. The first case seems to be disfavoured by theoretical studies (see e.g. [391]), as both the H_2 and H I evolution become steeper with redshift at fixed stellar mass. The second possibility is instead suggested by recent works showing the presence of $[\text{C II}]$ emission at high- z around $\times 1.5 - 3$ times more extended than the stellar (and possibly molecular) mass [95, 105, 83, 348, 320, 321, 322, 107]. Clarifying this uncertainty is crucial as the assumption that $f_{\text{H}_2} \approx 1$ at high- z is widely used to derive molecular gas masses from dynamical [373, 378, 376] and dust [23, 376] masses.

3.5 Summary

We have proposed a novel method to derive the dust temperature in galaxies, based on the combination of continuum and $[\text{C II}]$ line emission measurements, which breaks the SED

¹⁸The H I density is obtained by combining measurements of H I emission in the local universe [387] with quasar absorption lines at higher z [388]; $\rho_{\text{H}_2}(z)$ determination is based on CO and FIR dust continuum data [389, 44, 390, 68].

fitting degeneracy between dust mass and temperature. The method allows constraining T_d from a single band observation at 1900 GHz (rest-frame). We conveniently provide analytic expressions in eq. 3.12 for a direct application.

Besides, the same method offers a physical explanation for the empirical relation found by [330] between [C II] luminosity and molecular gas. We also derive the relation between total gas surface density and [C II] surface brightness, $\Sigma_{\text{gas}} = \alpha_{\text{CII}} \Sigma_{\text{CII}}$. By combining such relations we predict the redshift evolution of the molecular gas fraction defined here as $\Sigma_{\text{H}_2}/\Sigma_{\text{gas}}$.

We summarise our main findings below:

- **Dust temperature from [C II] data at high- z :** using a single band observation, with our method, we can constrain the dust temperature as well as with the commonly used SED fitting in multiple bands. We recover dust temperatures consistent with literature data (within 1σ) out to redshift $z = 8.31$;
- **Gas-to-[C II] luminosity relation:** the total gas conversion coefficient α_{CII} strongly depends on the SFR surface density ($\sim \Sigma_{\text{SFR}}^{1/3}$) and the burstiness of galaxies (see eq. 3.5). When computing the analogous conversion factor for the molecular gas $\alpha_{\text{CII,mol}}$, we find that the dependence on Σ_{SFR} nearly cancels out, hence $\alpha_{\text{CII,mol}} \approx \text{const.}$ (see eq. 3.18);
- **Molecular gas fraction:** we find that $f_{\text{H}_2}(z)$ on average increases with z by a factor ≈ 2 from $z = 0.01$ to $z = 1$. This is consistent with the trend observed by [375]. We predict a possible further increase at $z > 1$. This could be caused by a rise of the H_2 content, and/or a change in the relative extension of H_2 and H I gas.

Assuming a dust temperature, as usually done in high- z galaxy observations analysis, introduces large uncertainties on the derived dust masses, infrared luminosities, and star formation rates (see also e.g. [313] for a detailed discussion). Our method can improve the reliability of the interpretation of [C II] and continuum observations from ALMA and NOEMA. This is particularly relevant in the context of recent ALMA large programs targeting [C II] emitters at high- z , such as ALPINE [36, 392, 41, 349], REBELS (PI: Bouwens), and others. With future instruments such as JWST, providing more accurate metallicity measurements, it will be possible to improve current estimates of the dust-to-gas ratios at high- z . This will further enhance the precision of our dust temperature determinations.

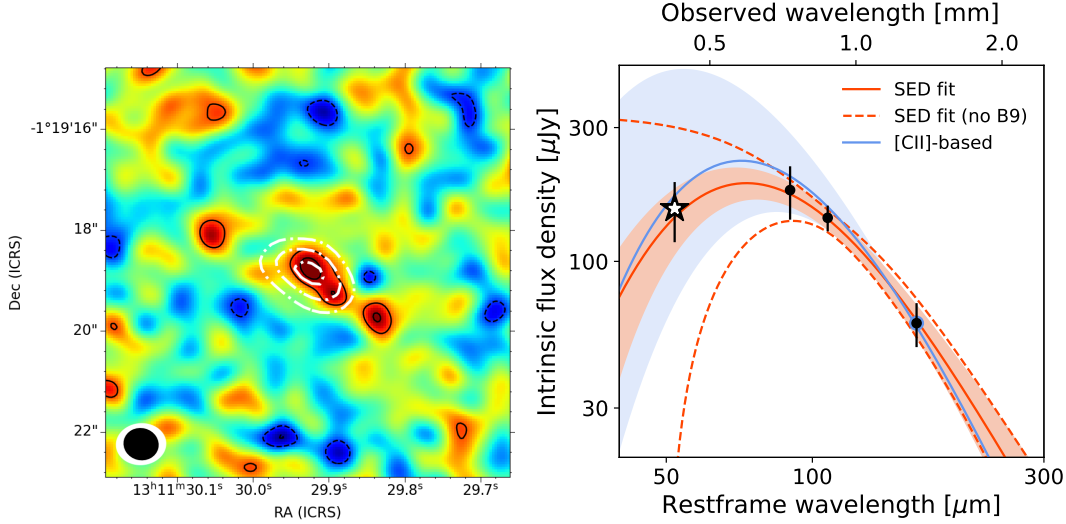


Figure 3.5: **Left panel:** The tapered band 9 data (*background and black contours*; drawn at -3 , -2 , 2 and 3σ) is shown against the band 8 continuum emission (*white contours*; drawn at 5 , 7 and 10σ). The continuum emissions appear co-spatial, and we find a 4.6σ dust detection in band 9. **Right panel:** We fit a modified black-body (*red line and fill*) to the observed data points of A1689-zD1, including the band 9 data point (*star*). The [C II]-based spectrum (*blue line and fill*) is fit solely to the 158μ m continuum data point (*blue*), and it predicts a consistent galaxy spectrum, providing confidence in the [C II]-based method for this specific source even at 50μ m rest-frame. For comparison, the *dashed red lines* show the spread in SEDs fitted without band 9 data, which results in a twice larger error in dust temperature, and a sixfold increase in the error in dust mass.

3.6 Accurate T_d determination in a $z \sim 7$ galaxy

Before proceeding to the application of this new method to galaxies where multiple ALMA data are not available, we want to review the additional test and analysis that we have performed focusing on a peculiar $z \sim 7$ galaxy, A1689-zD1. In Bakx, Sommovigo et al. [280] we combined the existing ALMA observations reported in [231], [281] and [393] with archival band 9 data from (Program ID: 2019.1.01778.S, P.I. D. Watson), see Table 3.4, to obtain one of the best constrained FIR SED of an EoR star-forming galaxy to date. This SED (shown in Fig. 3.5) features 4 continuum detections, with ALMA band-9 crucially probing the shorter wavelength side of the FIR emission peak. This allows us to accurately constrain A1689-zD1 dust properties (M_d, T_d, β_d), making it the best candidate for further testing our [C II]-based method for the derivation of T_d .

3.6.1 Data description

We briefly review the literature and new observations of the target in the following. The galaxy A1689-zD1 was identified in [394] as a bright ($m_{AB} \sim 25$) $z > 7$ galaxy. Due to the foreground galaxy cluster (A1689; [395]), it is magnified¹⁹ by $\mu \simeq 9.3$ [281]. Its intrinsic UV magnitude indicates it is a sub- L^* galaxy representing the bulk of galaxies at $z = 7$ [396]. Band 6 observations at 1.3 mm by [231] reported the first detection of dust beyond redshift 7, and indicated an intrinsic star-formation rate of $\sim 12 M_\odot \text{yr}^{-1}$. Notably, the estimated dust mass of this *normal* galaxy (assuming 35 K) was found in tension to star-formation history and dust production estimates in [18].

In the following, we use the newly-derived [C II] luminosity reported in Knudsen et al. in prep., which is $(6.1 \pm 0.7) \times 10^8 L_\odot$, and their value for spectroscopic redshift, $z_{\text{spec}} = 7.13$. For the band 9 [397] data, the source was observed for 95 min. in baselines ranging from

¹⁹While μ is high, there is only little shear, and we do not account for any differential lensing effects in this paper

Continuum and fitting properties of A1689-zD1

	λ [mm]	$F_{\nu}^{\text{int}} [\mu\text{Jy}]^{\dagger}$	Reference
Band 9	0.427	154 ± 37	This work
Band 8	0.728	180 ± 39	[393]
Band 7	0.873	143 ± 15	[281]
Band 6	1.33	60 ± 11	[231]
	SED fit	[C II]-based	SED fit (no B9)
T_d [K]	42_{-7}^{+13}	40_{-7}^{+13}	38_{-13}^{+35}
β_d	$1.61_{-0.75}^{+0.60}$	$2.03^{\ddagger}$	$1.78_{-0.97}^{+0.55}$
M_d [$10^7 M_{\odot}$] †	$1.7_{-0.7}^{+1.3}$	$2.0_{-1.0}^{+1.8}$	$2.4_{-1.9}^{+11}$
L_{FIR} [$10^{11} L_{\odot}$] †	$1.9_{-0.4}^{+0.5}$	$2.2_{-1.0}^{+4.1}$	$1.5_{-0.6}^{+3.0}$
$\log_{10} \text{IRX}$	$1.0_{-0.1}^{+0.1}$	$1.0_{-0.3}^{+0.5}$	$0.8_{-0.2}^{+0.5}$
$M_d/\text{SN} [M_{\odot}]^{\dagger}$	$0.4_{-0.1}^{+0.3}$	$0.6_{-0.3}^{+0.6}$	$0.8_{-0.7}^{+3.0}$

Notes: † Corrected for the magnification assuming $\mu = 9.3$ from [281]. ‡ β_d is fixed to 2.03.

14 to 312 m. The lower and upper sidebands covered the contiguous frequency ranges of 690.4 to 697.6 and of 706.5 to 713.6 GHz. We assume a typical flux accuracy of 10%. The continuum image is produced with CASA pipeline version 5.6.1-8 [398], using natural weighting, a taper of 0.5 arcseconds, and excluding any channels within 1000 km/s of the [O III] $52\mu\text{m}$ emission at 711.4 GHz. Figure 3.5 shows the resulting image with a 0.61 by 0.67 arcsecond beam with a beam position angle of 75 degrees, with an r.m.s. level of $210 \mu\text{Jy beam}^{-1}$. Using CASA's IMFIT routine, we spatially integrate the emission using a 2D Gaussian profile. This results in a flux of 1.43 ± 0.31 mJy ($\sim 4.6\sigma$; excluding calibration flux), with an apparent (or lensed) beam-deconvolved size of 0.81 ± 0.26 by 0.38 ± 0.22 arcsec at a position angle of 44 ± 38 degrees. The emission appears co-spatial to the UV-emission seen in [281], although we leave further discussion of this to Knudsen et al. in prep.

3.6.2 Comparing traditional SED fitting and the [C II]-based method

Figure 3.5 shows the modified black body (eq. 8 in [315]) fitted to the continuum points reported in Table 3.4. We use equations 12 and 18 from [399] to account for the heating of dust by and decreasing contrast against the CMB, respectively. We approximate the dust mass absorption coefficient (κ_{ν}) as $\kappa_{\star}(\nu/\nu_{\star})^{\beta_d}$, with $(\kappa_{\star}, \nu_{\star})$ as $(10.41 \text{ cm}^2/\text{g}, 1900 \text{ GHz})$ from [186]. We use the emcee MCMC-fitting routine and allow M_d , T_d and β_d to vary freely using flat priors, resulting in a magnification-corrected dust mass of $1.7_{-0.7}^{+1.3} \times 10^7 M_{\odot}$, a dust temperature of 42_{-7}^{+13} K and a β_d of $1.61_{-0.75}^{+0.60}$. We note that the spectrum appears well-represented by a single modified black body. For comparison, we also fit the spectral energy distribution (SED) without band 9 data, with an upper limit on β_d of 2.5 to ensure convergence and find significantly larger errors across the board. If we take a fiducial $\beta_d = 1.8$ (e.g., [400, 282]), we find a more accurate dust temperature of 39_{-5}^{+4} K, however, there is no improvement on the error of dust mass ($2.0_{-0.7}^{+1.4} \times 10^7 M_{\odot}$) nor luminosity ($1.7_{-0.4}^{+0.5} \times 10^{11} L_{\odot}$). The accuracy of these later parameters thus depends solely on observational uncertainties, indicating that we fully trace the dust emission in this source.

We use the novel method proposed in [315] to derive the dust temperature in galaxies, based on the combination of 1900 GHz continuum and the overlying [C II] line emission. We find a dust temperature $T_d = 40_{-7}^{+13}$ K and mass of $M_d = 2.0_{-1.0}^{+1.8} \times 10^7 M_{\odot}$. These values are obtained assuming a wide range of values for the metallicity $Z = 0.2 - 1 Z_{\odot}$, and the burstiness parameter $\kappa_s = 1 - 50$ [325].

The dust temperature and mass estimates from the [C II]-based method agree with the results from the direct SED fitting, which adds confidence to the method from [315]. As shown in Table 3.4, band 9 observations reduce the uncertainty in the dust temperature by $\sim 50\%$, which translates to a much-improved estimate on the far-infrared luminosity and dust mass estimate.

3.6.3 Implications

Our band 9 observations confirm that A1689-zD1 has a very large obscured fraction of the SFR around $\sim 85\%$ ($\text{SFR}_{\text{obs}} = 33 \pm 9 \text{ M}_{\odot}\text{yr}^{-1}$, whereas²⁰ $\text{SFR}_{\text{UV}} = 5.7 \pm 0.3 \text{ M}_{\odot}\text{yr}^{-1}$), even though it was selected to be UV-bright. The dust-obscured ratio is higher than the 61% found for the typically more-massive ALPINE survey [36, 37, 392, 41, 159] at $z = 5.5$, although this 61% is expected to decrease with higher redshift. Albeit extreme, our dust-obscured ratio is in line with recent results (both theoretical and observational) suggesting that we might have been underestimating the dust-obscured contribution to the total SFR in $z > 4$ galaxies [401, 26]. On the other hand, some studies of similarly massive, UV-bright sources at very high- z ($z \sim 7$; e.g., [38, 402]) have so far failed to detect dust continuum at $158 \mu\text{m}$ in half of their sources, even though their average stellar mass is similar to those of A1689-zD1. These undetected sources might have low dust contents, but that does not guarantee low obscured star-formation fractions, since it is possible that this dust is warm and is mainly emitting at wavelengths shorter than the currently observed ones (mainly $158 \mu\text{m}$ rest-frame). In fact, while the continuum around $158 \mu\text{m}$ of MACS0416-Y1 [9, 10] has yet to be seen, its spectrum is indicative of a similar obscured fraction to A1689-zD1 (i.e., 94 to 85% for $\beta_d = 1.5$ to 2), even though Y1's UV-observed stellar mass is one order of magnitude lower than A1689-zD1.

The selection towards UV-bright sources might also bias towards lower fractions of obscured-to-total star-formation rate. With the discovery of so-called optically-dark galaxies (e.g., [403, 404, 405, 125, 406, 407, 408, 409, 27, 410, 411, 412, 413, 414]), we know of the existence of galaxies without detections in optical wavelengths at high redshift. These sources, by definition, have exceedingly high obscured fractions and might well account for a substantial fraction of the SFRD at high redshift [415, 26, 28]. The typical obscured star-formation rate fraction across all $z > 7$ galaxies might thus be higher than predicted by UV-selected samples alone, with for example [26] predicting an increase in SFRD of 17% at $z = 5$ by this population.

Due to the largely obscured fraction of the SFR in A1689-zD1, one might naively expect that this galaxy also contains an exceedingly large dust mass. Instead, the dust mass derived from SED fitting implies a dust yield of $y_d = 0.4^{+0.3}_{-0.1} \text{ M}_{\odot}$ per SN. This estimate is almost an order of magnitude more accurate than the one derived without band 9 data, and most importantly, it is consistent with the latest SN dust production constraints by [18] based on the expected number of SNe given its stellar mass estimate. They find at most a $y_d = 1.1 \text{ M}_{\odot}$ per SN, derived in the extreme case of no dust destruction/ejection. We note that SN yield is still highly debated, with other works suggesting that dust destruction processes might only spare $0.1 \text{ M}_{\odot}$ per SN [251, 416, 256]. In this extreme case, inter-stellar medium grain growth [269, 270] or more exotic dust production mechanisms might well be required at $z > 7$, such as dust produced in supershells [417] or in the wake of Wolf-Rayet stars [418].

²⁰derived using the magnification-corrected $L_{\text{UV}}/10^{10} L_{\odot} = 2.28 \pm 0.1$ [278], and the UV luminosity-to-unobscured SFR conversion factor in [24].

Chapter 4

Determining the dust properties of REBELS galaxies

The method that we introduced in the previous section can be exploited in the context of recent ALMA large programs targeting [C II] emitters at $z \gtrsim 5$, such as the very recent “*Reionization Era Bright Emission Line Survey*” (REBELS; PI: Bouwens, [38]). REBELS studied 40 of the brightest known galaxies at $z > 6.5$ identified over a 7 deg^2 area of the sky, systematically scanning for bright ISM-cooling lines, [C II] $158\mu\text{m}$ and [O III] $88\mu\text{m}$, and dust-continuum emission [145].

REBELS galaxies are UV-selected sources at redshift $z = 6.5 - 7.7$; they are luminous galaxies ($-21.3 \lesssim M_{\text{UV}} \lesssim -22.5$) with stellar masses¹ in the range $10^9 \lesssim M_{\star}/M_{\odot} \lesssim 10^{10}$, and relatively high SFRs around $20 \lesssim \text{SFR}/M_{\odot}\text{yr}^{-1} \lesssim 200$ [38].

Here we apply our method [315] to the 13 REBELS targets detected both in continuum (3σ) and in [C II] (5σ) at $z = 6.5 - 8.5$ (for the sources properties see Table 4.1). They represent the first statistical sample of continuum detections at such early epochs, featuring a four-fold increase of the size of the previously available galaxy sample.

Constraining the dust temperatures and masses of REBELS galaxies is crucial for a better understanding of SF obscuration and dust production in these early galaxies. Moreover, our analysis on the REBELS sample can investigate for the first time the reported cosmic dust temperature evolution [421, 292, 293, 40, 282, 42] into the Epoch of Reionization. In particular, the eventual flattening in the $T_{\text{d}}(z)$ evolution would be more robustly identified at the high ($z \approx 7$) redshift of the REBELS sample.

4.1 Application of the [C II]-based method to REBELS galaxies

We use our method to derive T_{d} (hereafter we drop the [C II] subscript for simplicity) for the 13 REBELS galaxies that are detected both in [C II] and in the continuum at 1900 GHz. In this work we always refer to this sub-sample of the survey targets. The observed properties of these sources are summarized in Table 4.1. For the data analysis we refer to the dedicated papers by [108] (FIR continuum fluxes), [422] ([C II] luminosities), and [288] (stellar masses).

For some of the REBELS sources the UV half-light radius has been measured by [423], who find on average $r_{\star} = 1.3 \pm 0.8 \text{ kpc}$. [423] caution that the large sizes $r_{\star} > 1 \text{ kpc}$ are

¹derived from rest-frame UV SED fitting by [288] using BEAGLE [419]. The authors adopt a constant Star Formation History (SFH), $0.2 Z_{\odot}$ metallicity, a [14] dust extinction law, and a [420] $0.1 - 300 M_{\odot}$ initial mass function. Note that the correction on the given $M_{\star}$ values, required to be consistent with a Salpeter $1 - 100 M_{\odot}$ IMF (used in the rest of the paper), is well within their uncertainties and does not affect significantly our results. We caution that using a non-parametric prescription for the SFH might result in $M_{\star}$ values up to a factor $\sim \times 3$ larger (for a detailed discussion on this point see [39]). Implications on the results presented here are discussed in the text.

On the left: Measured REBELS galaxies properties, respectively: redshift z , stellar mass $\log M_\star$, [C II] luminosity L_{CII} , and 1900 GHz continuum flux F_{1900} (not CMB-corrected). For the data analysis we refer to the dedicated papers by [108] (F_{1900}), [422] (z, L_{CII} , see also [38]), and [288] ($M_\star$). **On the right:** Predicted REBELS galaxies properties, respectively: [C II]-to-total gas conversion factor α_{CII} (eq. 3.7), dust temperature T_d and mass M_d , IR luminosity $\log L_{\text{FIR}}$, SN dust yield y_d and obscured SFR, $\text{SFR}_{\text{FIR}}[\text{M}_\odot\text{yr}^{-1}] = 10^{-10} L_{\text{FIR}}[L_\odot]$ [219]. Please note that the galaxy names in the text are abbreviated as REBxx for conciseness.

Measured			ID#	Predicted						
z	$\log M_\star$	L_{CII}	F_{1900}		α_{CII}	T_d	$\log M_d$	$\log L_{\text{FIR}}$	y_d	SFR_{FIR}
	$[\text{M}_\odot]$	$[10^8 L_\odot]$	$[\mu\text{Jy}]$			$[\text{K}]$	$[\text{M}_\odot]$	$[L_\odot]$	$[\text{M}_\odot]$	$[\text{M}_\odot\text{yr}^{-1}]$
6.496	$9.2^{+0.9}_{-1.0}$	6.9 ± 0.4	67 ± 13	REB05	5^{+4}_{-2}	43^{+15}_{-9}	$7.14^{+0.31}_{-0.3}$	$11.37^{+0.5}_{-0.32}$	$0.51^{+0.52}_{-0.26}$	23^{+51}_{-12}
6.749	$9.0^{+0.6}_{-0.7}$	7.4 ± 0.9	101 ± 20	REB08	5^{+3}_{-2}	50^{+17}_{-11}	$7.17^{+0.25}_{-0.25}$	$11.83^{+0.5}_{-0.36}$	$0.74^{+0.58}_{-0.33}$	68^{+147}_{-39}
7.346	$8.9^{+0.9}_{-0.7}$	10.1 ± 1.9	87 ± 24	REB12	4^{+2}_{-1}	49^{+16}_{-9}	$7.19^{+0.22}_{-0.26}$	$11.79^{+0.49}_{-0.33}$	$0.93^{+0.6}_{-0.41}$	62^{+130}_{-33}
7.084	$8.7^{+0.8}_{-0.7}$	3.7 ± 0.5	60 ± 15	REB14	6^{+3}_{-2}	52^{+15}_{-10}	$6.95^{+0.22}_{-0.23}$	$11.67^{+0.44}_{-0.34}$	$0.87^{+0.59}_{-0.36}$	47^{+84}_{-25}
7.675	$9.5^{+0.6}_{-0.7}$	10.8 ± 0.7	53 ± 10	REB18	4^{+5}_{-2}	39^{+12}_{-7}	$7.30^{+0.34}_{-0.32}$	$11.29^{+0.4}_{-0.21}$	$0.34^{+0.4}_{-0.18}$	19^{+30}_{-7}
7.370	$8.8^{+0.7}_{-0.7}$	8.7 ± 1.7	71 ± 20	REB19	3^{+2}_{-1}	50^{+16}_{-9}	$7.09^{+0.19}_{-0.24}$	$11.74^{+0.48}_{-0.32}$	$1.05^{+0.57}_{-0.45}$	55^{+110}_{-28}
7.307	$9.9^{+0.2}_{-0.2}$	15.9 ± 0.4	260 ± 22	REB25	5^{+5}_{-2}	55^{+15}_{-14}	$7.55^{+0.32}_{-0.22}$	$12.45^{+0.43}_{-0.45}$	$0.24^{+0.27}_{-0.1}$	284^{+480}_{-184}
7.090	$9.7^{+0.3}_{-0.3}$	6.1 ± 0.6	51 ± 10	REB27	5^{+7}_{-2}	41^{+13}_{-9}	$7.14^{+0.37}_{-0.32}$	$11.25^{+0.48}_{-0.3}$	$0.15^{+0.2}_{-0.08}$	18^{+37}_{-9}
6.685	$9.6^{+0.2}_{-0.2}$	5.5 ± 0.9	56 ± 13	REB29	6^{+7}_{-2}	42^{+16}_{-10}	$7.11^{+0.37}_{-0.32}$	$11.27^{+0.53}_{-0.35}$	$0.16^{+0.22}_{-0.09}$	19^{+44}_{-10}
6.729	$9.6^{+0.4}_{-0.4}$	7.9 ± 0.6	60 ± 17	REB32	5^{+6}_{-2}	39^{+15}_{-9}	$7.21^{+0.35}_{-0.32}$	$11.22^{+0.51}_{-0.31}$	$0.24^{+0.31}_{-0.13}$	17^{+37}_{-9}
6.577	$9.6^{+0.7}_{-1.3}$	16.8 ± 1.3	163 ± 23	REB38	4^{+4}_{-2}	46^{+18}_{-11}	$7.45^{+0.32}_{-0.3}$	$11.89^{+0.55}_{-0.38}$	$0.39^{+0.43}_{-0.2}$	77^{+195}_{-45}
6.845	$8.6^{+0.6}_{-0.6}$	7.9 ± 1.4	80 ± 16	REB39	3^{+1}_{-1}	58^{+15}_{-9}	$6.95^{+0.13}_{-0.19}$	$11.98^{+0.4}_{-0.29}$	$1.3^{+0.46}_{-0.45}$	95^{+145}_{-46}
7.365	$9.5^{+0.5}_{-1.0}$	4.9 ± 1.0	48 ± 13	REB40	6^{+7}_{-3}	43^{+17}_{-10}	$7.07^{+0.37}_{-0.32}$	$11.34^{+0.54}_{-0.34}$	$0.21^{+0.27}_{-0.11}$	22^{+54}_{-12}

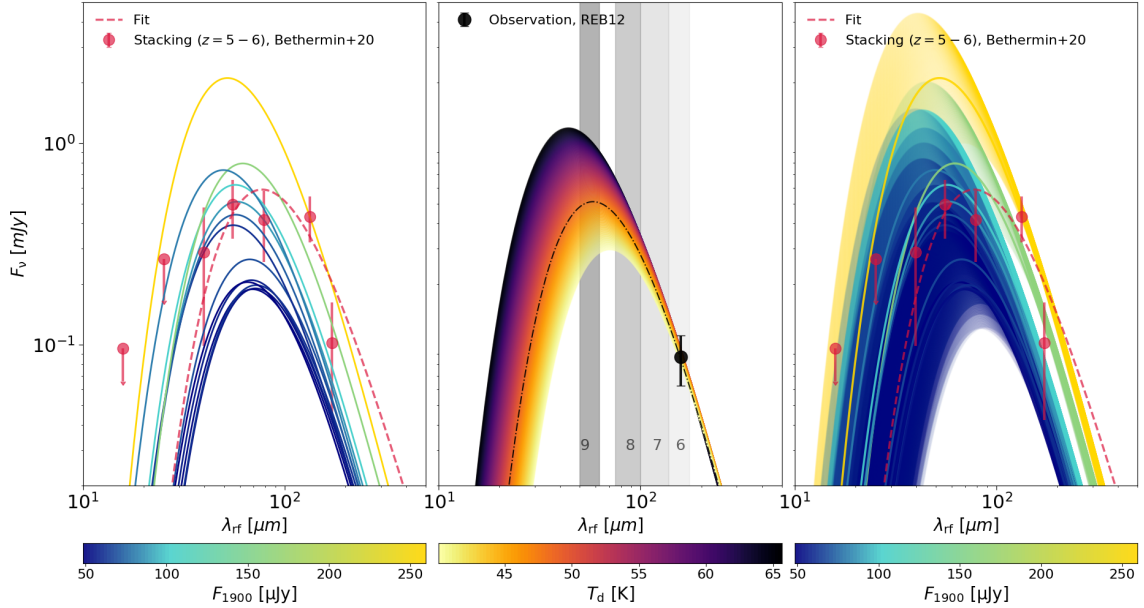


Figure 4.1: **Left panel:** FIR SEDs obtained using the median (T_d, M_d) derived for REBELS galaxies (see Table 4.1 for the source details). The lines are colour-coded depending on their 1900 GHz flux (see colorbar). The red points are obtained by [41] for the ALPINE galaxies in the redshift interval $z = 5 - 6$ through stacking. The red dashed line is the best fit to these points (corresponding to $T_d \sim 42$ K); **Center:** Variation in the SED of a single source (REBELS-12) due to the $1 - \sigma$ uncertainty in (T_d, M_d) around the median values. The lines are colour coded according to the corresponding dust temperature (see colorbar). The dashed black curve shows the SED for the median $T_d \sim 46$ K. The black point is the continuum observation at 1900 GHz. The shaded grey regions mark the ALMA bands 6 to 9.; **Right:** Variation of the SEDs of all the REBELS galaxies due to the uncertainty in (T_d, M_d) of each source. This plot can be interpreted as the combination of the left and central panels. Here we are showing the median FIR SEDs and their variation due to uncertainty on (M_d, T_d) for all the REBELS galaxies. The colour coding, the red points and red dashed line are the same as in the left panel.

due to multiple components, with individual clumps being less extended $r_\star \sim 0.2 - 1.0$ kpc. This is in agreement with the theoretical findings by [177], who predicts sub-kpc sizes for most REBELS galaxies. In light of this, we consider star-forming/dust emitting regions of REBELS galaxies to be uniformly randomly distributed in the range $0.2 \text{ kpc} \lesssim r_\star \lesssim 1.1 \text{ kpc}$.

We then consider the [C II] emitting regions to be $1.5 \lesssim y \lesssim 3$ times more extended than the UV emitting ones, as indicated by previous observations of galaxies at $z \gtrsim 4$ [95, 105, 83, 348, 320, 321, 322, 107].

The burstiness parameter of REBELS galaxies is unknown. High- z UV selected sources are expected to be highly star forming and UV emitting by construction [424]. Both locally and at intermediate redshift, values up to $\kappa_s \approx 100$ have been observed in such galaxies [373]. Recently, [341] found for the mildly star-bursting COS-3018 at $z = 6.854$ a value of $\kappa_s \sim 3$, applying the [C II]-emission model given in [327]. Applying the same method on 11 bright UV selected galaxies² at $z = 6 - 9$, [325] find values as large as $10 \lesssim \kappa_s \lesssim 80$. For the REBELS galaxies we choose a random uniform distribution in the range $1 \lesssim \kappa_s \lesssim 50$ inline with the independent derivation in [177] which suggests that these sources are not extreme starbursts.

For the metallicity, which is also unconstrained by current data, we assume a broad uniform random distribution in the range $0.3 - 1 Z_\odot$. This general assumption is validated by numerical simulations of galaxies at $z \sim 6$ with similar stellar masses $10^9 < M_\star < 10^{11}$ [338, 339], and several observational studies which analyse FIR lines (such as [N II], [N III], [C II], and [O III]) at $z \gtrsim 6-8$ to derive Z [340, 278, 370, 9, 341, 10, 255]. Current estimates of Z at high redshift will be significantly improved thanks to forthcoming ALMA observations and to the JWST spectroscopy³.

We pause for a quick summary: the physical properties needed for the application of our method are $(\kappa_s, z, F_{\nu_0}, Z, \Sigma_{\text{SFR}}, L_{\text{CII}}, y)$. For REBELS galaxies all these properties are constrained by observations, with the exception of (y, κ_s, Z) . For these three parameters, for each individual REBELS galaxy, we assume uniform random distributions in the broad ranges $1.5 \lesssim y \lesssim 3$, $1 \lesssim \kappa_s \lesssim 50$, and $0.3 < Z/Z_\odot < 1$, as motivated in the previous paragraphs.

Using eq. 3.7 we compute the [C II]-to-total gas conversion coefficient α_{CII} for all REBELS galaxies. Individual values are given in Table 4.1, the average is $\langle \alpha_{\text{CII}} \rangle = 5.3^{+0.8}_{-1.2}$. We note that this value is lower than the values we find in local galaxies ([315], $10 \lesssim \alpha_{\text{CII}} \lesssim 10^3$ at $z \sim 0$). Interestingly, we find low $\alpha_{\text{CII}} < 7$ also in the other $z > 4$ sources analysed in [315] (SPT0418-47 at $z = 4.225$, B14-65666 at $z = 7.15$, and MACS0416-Y1 at $z = 8.31$). This might indicate that at fixed [C II] luminosity high- z galaxies have a lower gas content (for a detailed discussion see e.g. [327]).

We conclude with a remark. The *total* gas-to-[C II] conversion factor computed here $\alpha_{\text{CII}} = \Sigma_{\text{gas}}/\Sigma_{\text{CII}}$ is different by construction from the empirical *molecular*-to-[C II] conversion factor $\alpha_{\text{CII,mol}} = \Sigma_{\text{H}_2}/\Sigma_{\text{CII}} = 31^{+31}_{-16}$ derived⁴ in [330]. The ratio of the two conversion factors corresponds to $\alpha_{\text{CII,mol}}/\alpha_{\text{CII}} = f_{\text{H}_2} (r_{\text{gas}}/r_{\text{H}_2})^2 \approx f_{\text{H}_2} y^2$ (under the reasonable assumption that $r_{\text{CII}} \sim r_{\text{gas}}$ and $r_{\text{H}_2} \sim r_\star$), where $f_{\text{H}_2} = M_{\text{H}_2}/M_{\text{gas}}$ is the molecular gas fraction. Since $f_{\text{H}_2} < 1$ by definition, the empirical result $\alpha_{\text{CII,mol}} \sim 31$ can be reconciled with the REBELS galaxies average value of $\langle \alpha_{\text{CII}} \rangle = 5.3$ for $y > 2.4$.

We proceed to compute M_d and T_d for all our targets. The results are summarised in Table 4.1, and discussed in detailed in the following dedicated Sections.

²In particular: MACS1149-JD1 [97], A2744-YD4 [11], MACS416-Y1 [9, 10], SXDF-NB1006-2 [94], B14-65666 [278], BDF3299 [95], J0121 J0235, J1211 [93]. See also Table 3.2, Fig. 4.3.

³JWST will provide observations of optical nebular lines (such as H β , H α , [N II], [O II] and [O III]), which are reliable metallicity tracers, out to $z \sim 10$ [342, 343, 344].

⁴In [315] we derive an analytical formula also for $\alpha_{\text{CII,mol}} \approx 30.3 t_{\text{depl,H}_2}/\text{Gyr}$, finding consistent values with [330] under the assumption of a molecular gas depletion time $t_{\text{depl,H}_2} = 0.4 - 0.7 \text{ Gyr}$ [375].

4.1.1 Dust temperatures at $z \sim 7$

We find the median T_d of REBELS galaxies to vary in the range between 39 K and 58 K with REBELS-39 (REBELS-18,32) being the galaxy with the warmest (coldest) dust. The median values are associated with large uncertainties (up to $\sim 35\%$) due to the lack of knowledge on the metallicity and burstiness of REBELS galaxies. Considering such uncertainties, the range widens to 30 K – 73 K (where the lower limit is set by the condition on the dust masses and the upper one by that on the obscured SFRs, see Chapter 3). Note that these large uncertainties on T_d are often comparable with the ones derived in the literature from traditional SED fitting using 2 – 3 data points at FIR wavelengths (see Table 3.2 where we compare T_d values obtained from our method vs. SED fitting for several $z > 5$ galaxies). Further ALMA observations in bands 8–9 will help us significantly in constraining T_d at high- z by sampling the SEDs closer to the FIR emission peak (see central panel of Fig. 4.1).

Overall we find an average dust temperature of $\langle T_d \rangle = 47 \pm 6$ K. This value is in agreement with the independent derivation in [177], where they find $\langle T_d \rangle = (52 \pm 12)$ K. The physical model presented in [177] relies on 1900 GHz continuum, and UV data (instead of [C II] used here) to derive the physical properties of individual REBELS galaxies, such as their $(T_d, M_d, L_{\text{FIR}}, \text{SFR})$, assuming a given attenuation curve.

The average value $\langle T_d \rangle \simeq 47$ K is close to the dust temperature derived by [41] from the mean stacked SED of ALPINE sources (and analogs in the COSMOS field) in the redshift interval $z = 5 - 6$ ($T_d = 43 \pm 5$ K). For the lower redshift bin at $z = 4 - 5$, where they have $3\times$ more sources (analogs included), [41] produce two different mean stacked SEDs dividing the considered sources depending on their SFR. For the galaxies with lower SFR ($\text{SFR} > 10 \text{ M}_\odot/\text{yr}$) they find $T_d = 41 \pm 1$ K, while for the higher star forming galaxies ($\text{SFR} > 100 \text{ M}_\odot/\text{yr}$) they find $T_d = 47 \pm 2$ K.

Since most REBELS galaxies have $\text{SFR} \lesssim 100 \text{ M}_\odot/\text{yr}$ (both from the DL relation, and from the independent analysis of rest-frame UV and IR data performed in [177]), they overall appear to have similar dust temperatures to the lower redshift ALPINE galaxies. We discuss this point in detail in the dedicated Section 4.2.

4.1.2 Dust masses at $z \sim 7$

We find the median dust masses of REBELS sources to vary in the range $6.95 \leq \log(M_d/M_\odot) \leq 7.55$, REBELS-25 (REBELS-14,39) being the galaxy with the largest (lowest) dust mass. This is not surprising as REBELS-25 also has the largest stellar mass $M_\star \sim 10^{10} \text{ M}_\odot$ and continuum emission $F_{1900} = 260 \pm 22 \mu\text{Jy}$ in the sample. Overall we find an average dust mass around $\langle M_d \rangle = (1.63 \pm 0.73) \times 10^7 \text{ M}_\odot$. This value is consistent with an independent derivation in [177] ($\langle M_d \rangle = (1.3 \pm 1.1) \times 10^7 \text{ M}_\odot$), although they find a larger scatter in the dust masses values.

We also compute the dust yield per SN, y_d , required to produce REBELS galaxies' dust masses. We use: $y_d = M_d/M_\star \nu_{\text{SN}}$, where $\nu_{\text{SN}} = (53 \text{ M}_\odot)^{-1}$ is the number of SNe per solar mass of stars formed [246] assuming a Salpeter 1 – 100 $\text{M}_\odot$ IMF. For all (but two of) the REBELS sources we find $y_d \lesssim 1 \text{ M}_\odot$ (see Table 4.1 for the value of y_d in each galaxy), which is quite consistent with the latest constraints on SNe dust production by [18]. They find that up to $y_d = 1.1 \text{ M}_\odot$ of dust per SN can be produced, where the exact value depends on the amount of dust which is destroyed/ejected during the SN explosion ($1.1 \text{ M}_\odot$ corresponds to the case of no dust destruction/ejection).

We note that SN yield is still highly debated, with some works suggesting that dust destruction processes might only spare $\lesssim 0.1 \text{ M}_\odot$ per SN [252, 416, 256]. In this extreme case, inter-stellar medium grain growth or more exotic dust production mechanisms might be required [269, 270, 273, 322].

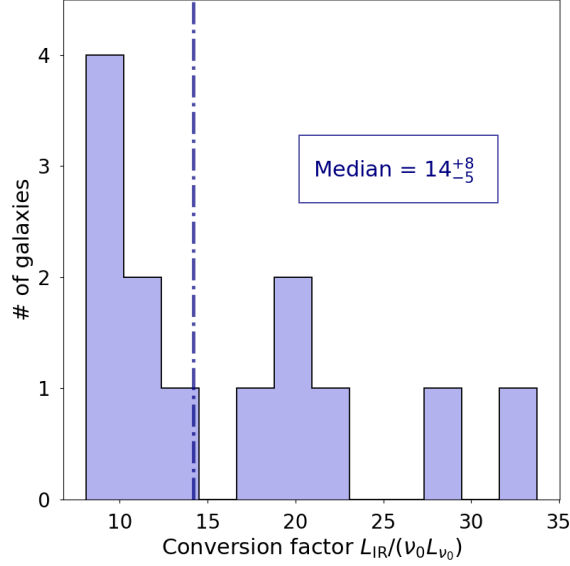


Figure 4.2: Conversion factor from the monochromatic luminosity $\nu_0 L_{\nu_0}$ at 1900 GHz to the total IR luminosity L_{FIR} for the REBELS galaxies. We also show the median (blue line) value.

It is worth mentioning that the increase by a factor ~ 3 of the stellar masses possibly resulting from a non parametric SFH prescription would have a relevant impact in this context. In fact, as explained in Chapter 3, the dust masses remain mostly unaffected. This implies, by definition, a reduction by the same factor ~ 3 in the SN dust yield. As a result, we would find an average value of $\langle y_d \rangle \sim 0.23 M_\odot$ for the REBELS sources, consistent even with stringent SN dust production constraints.

For a detailed discussion, we refer to [20] where they use the semi-analytical galaxy formation model DELPHI to investigate the dust build up and content of average $z \sim 7$ galaxies. The processes accounted for include SNe dust production, grain growth, astration, shock destruction, and ejection in outflows. The DELPHI model general predictions are then compared to the dust masses derived here for individual REBELS galaxies, finding a good agreement (within $1 - \sigma$) in most (77%) cases.

4.1.3 IR emission at $z \sim 7$

In Fig. 4.1 we show the FIR SEDs obtained for the REBELS galaxies considering a single-temperature grey body approximation and the dust masses and temperatures in Table 4.1. In the left panel, we show the FIR SEDs obtained using the median (T_d, M_d) values of each source. We can see that the flux at the peak of emission changes within a factor $\times 10$, with a variation in the peak wavelength of emission $50 \mu\text{m} \leq \lambda_{\text{peak}} \leq 73 \mu\text{m}$. Interestingly, almost all the λ_{peak} values that we predict lay within the range observable with ALMA, albeit in band-10 for the hottest sources.

Here we focus on REBELS-12 (central panel of Fig. 4.1), whose M_d and T_d are close to the average values in the sample. For REBELS-12 cold dust temperatures $T_d < 30$ K are disfavoured as they would result in very large dust masses $M_d \gg 10^7 M_\odot$, and very low κ_s values that are unexpected for a strongly UV-emitting high- z source. Very hot dust temperatures ($T_d > 80$ K) are similarly unlikely as they would result in very large IR luminosities, and consequently unreasonably large obscured SFRs (for REBELS-12 $\text{SFR}_{\text{FIR}} > 500 M_\odot/\text{yr}$). These are hard to reconcile with the generally blue UV slopes β observed in most REBELS galaxies (e.g. $\beta = -1.99$ for REBELS-12).

F_{1900} to total IR luminosity conversion

Using eq. 4.3 we can compute the IR luminosities of all the REBELS galaxies. We find that their IR luminosities vary in the range $1.7 \times 10^{11} L_{\odot} \lesssim L_{\text{FIR}} \lesssim 2.8 \times 10^{12} L_{\odot}$, which corresponds to obscured SFRs in the range $\sim 17 - 285 M_{\odot}/\text{yr}$ (assuming the conversion factor given in Table 4.1). Interestingly, the most IR luminous REBELS (REBELS-25) classifies as an Ultra-Luminous InfraRed Galaxy (ULIRG, with $L_{\text{FIR}} > 10^{12} L_{\odot}$, see e.g. [425]) despite being UV selected. This peculiar source will be discussed in detail in [426].

Combining these values with the total star formation rates derived using the DL relation for starbursts we find that on average $\langle \text{SFR}_{\text{FIR}}/\text{SFR} \rangle = 53\%$ (in agreement with the independent derivation in [402, 177, 20]), implying that REBELS galaxies are on average relatively UV-transparent sources. The only exceptions are represented by REBELS-8, REBELS-14, REBELS-25 and REBELS-39 for which we find $\text{SFR}_{\text{FIR}} \gtrsim \text{SFR}$, i.e. the SFR deduced from [C II] is exceeded (barely, only by 6%, in the case of REBELS-8). Interestingly these sources include 2 (REBELS-8, and the peculiar REBELS-25) of the 4 galaxies for which the UV-to-IR emission model in [177] fails to find a solution for (T_d, M_d) (using the same dust model adopted here, i.e. MW-like dust). In fact, these galaxies have very large IR-to-UV flux ratios compared to their UV slopes. This might indicate that their UV and IR emitting regions are spatially segregated (see [177] for a detailed discussion).

We can provide a conversion factor from the galaxies' monochromatic luminosity νL_{ν} at any frequency to their total L_{FIR} (for a discussion on the application of such conversion factor see e.g. [392, 42]). The monochromatic luminosity at 1900 GHz can be written as:

$$\nu_0 L_{\nu_0} = 2.92 \times 10^{11} \left[\frac{g(6)}{g(z)} \right] \left(\frac{F_{\nu_0}}{\text{mJy}} \right) L_{\odot} \quad (4.1)$$

where $g(z)$ is defined in eq. 3.14. The results for the conversion factor $L_{\text{FIR}}/\nu_0 L_{\nu_0}$ are shown in Fig. 4.2.

We find a median value of $L_{\text{FIR}}/\nu_0 L_{\nu_0} = 14_{-5}^{+8}$ (where both $L_{\text{FIR}}, \nu_0 L_{\nu_0}$ are in solar luminosity units). This range is consistent with the one obtained in [42] at $z \sim 7$ using a simple modified black body with $\beta_d = 1.6$, and a dust temperature derived from a linear fit of currently available dust temperature data vs. redshift. It is worth noting that they consider $T_d = 54$ K at $z = 7$, which is warmer than the temperatures derived here for the REBELS galaxies. We will discuss this point in detail in the following Section 4.2.

4.2 Dust temperature evolution

In the last few years, several works have suggested the presence of a trend of increasing dust temperature with redshift in star-forming galaxies detected in the UV-to-IR rest-frame wavelength range [157, 292, 300, 293, 40].

In particular, [40] fitted stacked SEDs to a complete sample of main-sequence galaxies in the CANDELS fields, and derived the linear relation $T_d = 32.9 + 4.6(z - 2)$, shown in the inset of Fig. 4.3. Compared to those for individual sources, stacked SEDs (a) reduce the scatter introduced in the relation by different intrinsic galaxy properties, and (b) allow to extend the relation up to $z \sim 4$. The above trend is also consistent with the stacked SED fitting results produced for ALPINE galaxies by [41] at $4 < z < 6$ (also shown in the inset). In this case, a stacking procedure was necessary since ALPINE galaxies are individually detected only in a single band at restframe 1900 GHz. Hence it would be impossible to constrain their T_d with ordinary SED-fitting.

More recently, T_d obtained from stacked SEDs at $z < 6$ has been combined with the T_d derived for individual galaxies detected in multiple bands at $z \gtrsim 5$. Two studies reached somewhat discordant conclusions. While [32, 282] deduce a flattening of $T_d - z$ relation at $z > 4$, [42] confirm the trend with little modification in the slope. Either trend is yet to

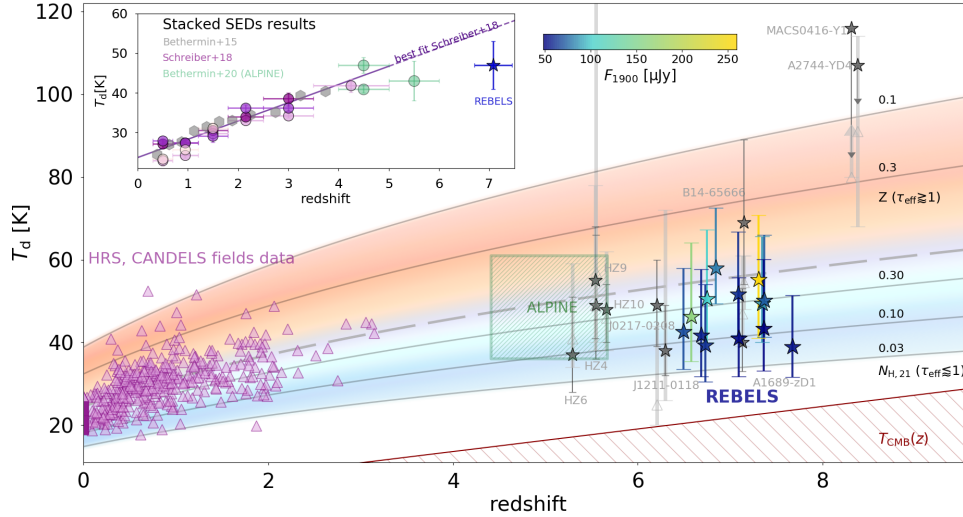


Figure 4.3: **Main panel:** We unpack the low- z stacked SEDs into the single detections (purple triangles). These are the UV-to-IR normal star-forming galaxies detected in the HRS and CANDELS fields [40]. We add the individual UV-selected galaxies at $z \gtrsim 5$ for which T_d estimates are available (see Table 3.2 for the details and references of the sources). We also show the T_d values obtained with our method for REBELS and ALPINE continuum detected galaxies (respectively, stars and green hatched rectangle). REBELS galaxies are colour-coded according to their F_{1900} (see colorbar). The coloured region shows the T_d -redshift evolution that we derive analytically in eq. 4.4-4.12 (for an increasing effective optical depth τ_{eff} from blue to red). We find that on average T_d raises with redshift due to the decreasing gas depletion time at higher- z , as $T_d(z) \propto t_{\text{dep}}^{-1/6}$. The grey dashed line represents the relation given in eq. 4.4 which can be written explicitly as $T_d = 24.5 (1 + 1.5 z)^{1/6} [\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/12}$ assuming (τ_{eff}, Z) equal unity. We can also explain the scatter in measured T_d at a given redshift. In the UV-transparent approximation ($\tau_{\text{eff}} \lesssim 1$) the scatter depends solely on the column density $N_{\text{H},21} = N_{\text{H}}/10^{21} \text{ cm}^{-2}$ (see solid lines and associated labels). In the UV-obscured approximation ($\tau_{\text{eff}} \gtrsim 1$) the scatter depends only on the metallicity Z (see solid lines and associated labels; note that Z is in solar units). **Inset panel:** T_d values obtained from stacked SEDs fitting in the redshift range $0 \lesssim z \lesssim 6$ (grey, purple and green points, from [293, 40, 41], respectively). The purple line shows the linear best fit obtained by [40] at $z \lesssim 4$. The blue star corresponds to the average temperature $T_d = (47 \pm 6) \text{ K}$ derived here for the REBELS galaxies.

be explained by a physical model. Previous theoretical works suggested that warmer dust temperatures at high- z might depend on the dust geometry, with most of the dust in high- z galaxies being located in compact, young star-forming regions, where the dust heating is particularly efficient [30, 32, 313]. Other works [300, 338, 118, 427] have suggested that the increasing $T_d(z)$ trend together with the flattening at $z \sim 4$ are correlated to the specific star formation rate increase with redshift and its subsequent plateau at $z \sim 4$ [428, 429]. Finally, the lower dust-to-metal ratio predicted for early galaxies from simulations at $z \gtrsim 5$ [430, 30, 427, 431] could also motivate the presence of hot dust at high- z . In fact, a lower dust content results in warmer dust temperatures for a given L_{FIR} . This is physically motivated by the fact that a lower amount of dust is exposed to the same radiation field, thus being more efficiently heated.

Our analysis of the REBELS sample can clarify the issue of the $T_d(z)$ evolution in a unique way for two reasons: (a) REBELS continuum detections double the number of previously known sources at $z \gtrsim 5$; (b) possible deviations from the linear trend are more robustly identified at the higher ($z \approx 7$) redshift of the REBELS sample.

Extrapolating the [40] relation to $z = 7$ gives $T_d = (56 \pm 4) \text{ K}$, i.e. a slightly warmer temperature than found here, $T_d \sim 47 \text{ K}$. This does not come as a surprise, as there is no special physical motivation to expect a linearly increasing T_d trend. It is therefore crucial to develop a simple but physical theoretical framework against which observations of individual UV-to-FIR detected galaxies in the range $0 \lesssim z \lesssim 8.5$ can be compared and interpreted. This is our goal in the next Section.

4.2.1 Physical origin of the $T_d - z$ relation

Under the assumption that FIR and UV emitting regions are co-spatial, L_{FIR} is equal to the absorbed fraction of the intrinsic UV luminosity, L_{1500} :

$$L_{\text{FIR}} = (1 - e^{-\tau_{\text{eff}}})L_{1500} = (1 - e^{-\tau_{\text{eff}}})\mathcal{K}_{1500}\text{SFR}. \quad (4.2)$$

In the previous equation, τ_{eff} is the galaxy effective dust attenuation optical depth at 1500 Å, which directly relates to the transmissivity, $\tau_{\text{eff}} = -\ln T$. The transmissivity is defined as the ratio of the observed-to-intrinsic UV luminosity, i.e. $T = 1$ ($T = 0$) for a fully transparent (obscured) galaxy. Note that, depending on the relative dust and star distributions, τ_{eff} might significantly differ from the physical UV optical depth, τ_{1500} . Hence, a large transmissivity does not directly imply a low physical optical depth. The conversion factor for (a) continuous star formation at the age of 150 Myr, (b) Salpeter IMF in the range 1-100 $M_\odot$, (c) metallicity $Z = 1/3 Z_\odot$ is $\mathcal{K}_{1500} \equiv L_{1500}/\text{SFR} = 1.174 \times 10^{10} L_\odot/(M_\odot\text{yr}^{-1})$ [177].

Combining the following relation [177, 147]:

$$L_{\text{FIR}} = \left(\frac{M_d}{M_\odot}\right) \left(\frac{T_d}{8.5 \text{ K}}\right)^{4+\beta_d} L_\odot, \quad (4.3)$$

which is valid for the Milky Way (MW) dust model adopted here, eq. 4.2, and recalling that $M_d = DM_g$, it follows that

$$T_d = 29.7 \left[\frac{(1 - e^{-\tau_{\text{eff}}})}{Z} \left(\frac{\text{Gyr}}{t_{\text{dep}}} \right) \right]^{1/(4+\beta_d)} \text{ K} \quad (4.4)$$

where $\beta_d = 2.03$ and Z is in solar units. We have introduced the *total* gas depletion time $t_{\text{dep}} = M_g/\text{SFR}$, which we derive in the following from cosmological arguments. Eq. 4.4 shows that the dust temperature is larger in optically thick, low metallicity systems with a short depletion time.

Let us express M_g and SFR of a galaxy in terms of its total (dark + baryonic) halo mass, M , and mean dark matter accretion rate, $\langle dM/dt \rangle$:

$$M_g = f_b M - M_\star \quad (4.5)$$

$$\text{SFR} = \epsilon_\star f_b \left\langle \frac{dM}{dt} \right\rangle \quad (4.6)$$

where $\epsilon_\star$ is the star formation efficiency, and $f_b = \Omega_B/\Omega_M$ is the (cosmological) baryon fraction in the halo. By integrating eq. 4.6 and substituting it into eq. 4.5 we obtain

$$M_g = f_b M (1 - \epsilon_\star) \quad (4.7)$$

Numerical simulations [432, 433, 434] provide the following fit to the mean halo accretion rate, as a function of redshift and halo mass, $M_{12} = M/10^{12} M_\odot$,

$$\left\langle \frac{dM}{dt} \right\rangle = 69.3 M_{12} f'(z) E(z) M_\odot\text{yr}^{-1}, \quad (4.8)$$

with

$$f'(z) = -0.24 + 0.75(1+z); \quad E(z) = [\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}. \quad (4.9)$$

By combining the previous equations t_{dep} takes the form

$$t_{\text{dep}}(z) = t_{\text{d},0} [f'(z)E(z)]^{-1}, \quad (4.10)$$

where the timescale $t_{d,0} = 14.4(1 - \epsilon_\star)/\epsilon_\star$ Gyr is fixed so that $t_{\text{dep}}(z = 0) = 2$ Gyr as approximately measured in local galaxies, including the MW [377, 435, 436].

According to eq. 4.10, the depletion time decreases with redshift as $(1 + z)^{-5/2}$ as a result of the higher cosmological accretion rate at early times⁵. This point is crucial as, barring variations of the optical depth and metallicity (see below), the redshift evolution of T_d is governed by the gas depletion time in galaxies. From the result above, and using eq. 4.4, it follows that

$$T_d \propto (1 + z)^{5/2(4+\beta_d)} \approx (1 + z)^{0.42}. \quad (4.11)$$

As we will see shortly, this trend matches perfectly the observed one.

On top of the above overall increasing trend of dust temperature, at fixed redshift scatter is introduced by variations of τ_{eff} and Z in individual galaxies. It is useful to separately discuss two asymptotic regimes, i.e. the optically thin ($1 - e^{-\tau_{\text{eff}}} \approx \tau_{\text{eff}}$), and optically thick ($1 - e^{-\tau_{\text{eff}}} \approx 1$) one. In these two limits eq. 4.4 becomes

$$\begin{cases} T_d = 29.4 [N_{\text{H},21} f'(z) E(z)]^{1/6.03} \text{ K} & \tau_{\text{eff}} \lesssim 1 (T \gtrsim 37\%), \\ T_d = 29.6 \left[\frac{f'(z) E(z)}{Z} \right]^{1/6.03} \text{ K} & \tau_{\text{eff}} \gtrsim 1 (T \lesssim 37\%); \end{cases} \quad (4.12)$$

we have used eq. 3.1 to write $\tau_{\text{eff}}/Z = \sigma_{\text{ext}} N_{\text{H}}$, where $N_{\text{H}} = 10^{21} N_{\text{H},21} \text{ cm}^{-2}$ is the effective gas column density⁶ of the galaxy, and $\sigma_{\text{ext}} = 0.96 \times 10^{-21} \text{ cm}^2$ is the extinction cross-section appropriate for the adopted dust model. Eq. 4.12 is graphically displayed in Fig. 4.3, where it is also compared with available data.

Interpreting eq. 4.12 is straightforward. First, for optically thin galaxies (for which UV transmissivity $T \gtrsim 37\%$) T_d depends solely on N_{H} , with larger column densities producing warmer dust. Quantitatively, for a $z = 0$ source with $N_{\text{H},21} = 1$, corresponding to a ratio $\tau_{\text{eff}}/Z = 0.96$, we predict $T_d = 26.5$ K. Second, dust in obscured sources (for which $T \lesssim 37\%$) is warmer; this is not surprising, as a larger obscuration results in more efficient dust heating. Third, among obscured sources, T_d is higher in metal-poor systems. This is because a lower metallicity implies a smaller dust content, which for fixed L_{FIR} results in warmer temperatures.

Locally, given the observed (N_{H}, Z) scatter in individual sources, our model predicts variations as large as $\Delta T_d \approx 25$ K. We finally note that, if the (N_{H}, Z) range does not evolve with time, the scatter at $z = 0$ gets amplified at earlier times by the redshift dependence of T_d , reaching $\Delta T_d \approx 55$ K at $z = 8$.

4.2.2 Comparison with observations at $0 \lesssim z \lesssim 8$

We now compare our theoretical predictions with dust temperature estimates available in the literature for UV-detected sources at $0 \lesssim z \lesssim 8$.

We recover the dust temperatures of individual UV-to-IR detected galaxies whose stacked SEDs in the redshift range $0 \lesssim z \lesssim 3$ are used in the analysis by [40]. We then add all the UV-selected galaxies at $z \gtrsim 5$ for which dust temperature estimates are available in the literature (see Table 3.2 for details of the sources). We apply the method used here to derive T_d for these galaxies, finding values consistent (within $1 - \sigma$) with SED

⁵While t_{dep} is fundamentally unknown at high- z , the *molecular* gas depletion time, $t_{\text{dep,H}_2} = M_{\text{H}_2}/\text{SFR}$, has been studied up to $z \lesssim 5$ via CO and dust observations [437, 375, 44]. For instance, [44] suggest a mild evolution of $t_{\text{dep,H}_2}$ time with redshift for main-sequence galaxies, $t_{\text{dep,H}_2} \propto (1 + z)^{-0.98 \pm 0.1}$. Assuming such $t_{\text{dep,H}_2}(z)$ evolution (instead of the one given in eq. 4.10), does not qualitatively affect our results. In fact, T_d would still increase with redshift due to the shorter depletion times. However, the different evolution slightly modifies the predicted $(N_{\text{H},21}, Z)$ values shown in Figure.

⁶As in general, $\tau_{\text{eff}} < \tau_{1500}$, N_{H} should be intended as a lower limit to the actual mean column density in the galaxy.

fitting results (see Table 3.2 for the detailed comparison). Finally, we apply our method to individual ALPINE galaxies detected simultaneously in [C II] and continuum. We find their median dust temperatures to vary in the range $35 \text{ K} \lesssim T_d \lesssim 60 \text{ K}$, which is consistent with the stacked SEDs fitting results in [41] ($40 \text{ K} \leq T_d \leq 49 \text{ K}$). A detailed analysis of ALPINE galaxies will be presented in Chapter 5.

The complete collection of T_d values is shown in Fig. 4.3 as a function of redshift. We stress that we consistently compare dust temperatures obtained by fitting individual galaxy SEDs; moreover, the same method is applied to *all* high- z sources. This avoids the confusion arising from comparing intrinsically different quantities such as dust temperatures obtained from stacked SEDs, and/or peak dust temperatures:

$$T_{\text{peak}} = 2.898 \times 10^3 (\lambda_{\text{peak}}/\mu\text{m})^{-1}, \quad (4.13)$$

defined via Wien's displacement law. The physical interpretation of T_{peak} might be unclear for $z > 5$ galaxies. Indeed currently available data at these redshifts hardly trace the peak of FIR emission. Moreover, when a different SED fitting function other than the optically thin grey body is used, T_{peak} can significantly differ from T_d . In fact, the assumptions made for the MIR (rest-frame) portion of the spectra affect T_{peak} [282], and the validity of such assumptions cannot be tested as no currently available instrument probes MIR wavelengths at $z > 5$.

We find that our predictions are in agreement with the data. Fitting all the dust temperatures with a single power law: $T_d(z) = az^\alpha + b$, we find $\alpha = (0.58 \pm 0.04)$, which is close to the value 0.42 given in eq. 4.11. The slight difference is due to the fact that T_d does not depend uniquely on redshift, as discussed in detail in the previous section (see eq. 4.12). Hence fitting all the data with a single power-law is misleading.

The additional dependence on the column density (for optically thin sources), and metallicity (for optically thick sources) is responsible for the scatter in the measured temperatures at a given redshift. At $z \simeq 0.3$ variations as large as $\Delta T_d = 22 \text{ K}$ are observed [40], which is perfectly consistent with our predictions ($\Delta T_d \simeq 25 \text{ K}$ in the local Universe).

The amplification of the dust temperature scatter at high- z that we predict (if the N_{H}, Z range does not evolve) is also consistent with data. In the narrow redshift range $7.6 \lesssim z \lesssim 8.3$ variations as large as $\Delta T_d = 53 \text{ K}$ are observed (we predicted $\Delta T_d \simeq 55 \text{ K}$ at $z = 8$).

At one extreme there are galaxies hosting very hot dust such as MACS0416-Y1 and A2744-YD4 ($T_d > 80 \text{ K}$ [10], and $T_d = 90 \pm 20 \text{ K}$ [11, 30, 285], respectively). On the other, there are galaxies such as REBELS-18 and J1211-0118 that show more moderate dust temperatures, possibly closer to local sources ($T_d = 39^{+12}_{-7} \text{ K}$ and $T_d = 38^{+16}_{-8} \text{ K}$ [314], respectively).

Our physical model suggests that MACS0416-Y1 and A2744-YD4 are more heavily obscured than most currently observed high- z galaxies. Larger $\tau_{\text{eff}} > 1$ combined with low metallicities $Z/Z_\odot \lesssim 0.3$ can explain the very hot dust temperatures found in these two galaxies.

We explain the colder dust temperatures found in REBELS-18 and J1211-0118 with lower effective optical depths $\tau_{\text{eff}} < 1$, i.e. larger UV transmissivity (ultimately resulting in less efficient dust heating). For these galaxies, we predict mean gas column densities around $0.3 \times 10^{20} \text{ cm}^{-2} \lesssim N_{\text{H}} \lesssim 1.0 \times 10^{20} \text{ cm}^{-2}$.

4.3 Summary

We have applied a novel method [315] to derive the dust temperature to 13 $z \approx 7$ galaxies part of the ALMA Large Program REBELS. Our method combines the continuum and super-imposed [C II] line emission measurements, thus breaking the SED fitting degeneracy

between dust mass and temperature. This allows us to constrain T_d from a single-band restframe observation at 1900 GHz, and to derive dust masses, IR luminosities, and the obscured SFR. Moreover, since REBELS targets constitute the first significant sample of continuum detected sources at $z \sim 7$ (for which T_d estimates are available), we can extend the reported T_d -redshift relation [421, 292, 293, 40, 282, 42] into the Epoch of Reionization.

We summarize below our main findings:

- **Dust temperature and mass:** the median T_d values for REBELS galaxies vary in the range 39 – 58 K, with $\sim 35\%$ associated uncertainty. The median dust masses are in the narrow range $(0.9 - 3.6) \times 10^7 M_\odot$. Dust production from SNe alone in most cases (85%) can generate such dust masses assuming a dust yield $\lesssim 1 M_\odot$ per SN;
- **IR luminosities and L_{1900} -to- L_{FIR} conversion at $z \sim 7$:** REBELS galaxies IR luminosities vary in the range $1.7 \times 10^{11} L_\odot \lesssim L_{\text{FIR}} \lesssim 2.8 \times 10^{12} L_\odot$, which corresponds to obscured SFRs around $\sim 17 - 285 M_\odot/\text{yr}$. We also derive their average conversion factor $L_{\text{FIR}} = 14^{+8}_{-5} L_{1900}$, where $L_{1900} = \nu_0 L_{\nu_0}$, with $\nu_0 = 1900$ GHz. This value is consistent with an extrapolation of the empirical fitting formula of [42] to $z \approx 7$;
- **Dust temperature cosmic evolution:** we produce a *new physical model* (see eq. 4.4-4.12) that motivates the dust temperature increase with redshift. Such trend is an imprint of the decreasing gas depletion time towards high- z , $t_{\text{dep}} \propto (1+z)^{5/2}$. We show that $T_d \propto t_{\text{dep}}^{-1/6}$, or $T_d \approx (1+z)^{0.42}$;
- **Dust temperature scatter at a given redshift:** on top of the $T_d - z$ trend, we can also physically motivate the scatter in the measured T_d values at a given redshift. We find that in UV-transparent galaxies (UV transmissivity $\gtrsim 37\%$) the scatter in T_d depends solely on the column density N_H , with larger N_H corresponding to hotter dust. Instead, in UV-obscured galaxies the scatter in T_d depends only on the metallicity Z , with lower Z implying hotter dust.

A very hot dust component, implying a large obscured SFR, can coexist with a steep UV slope in the presence of *spatial segregation* of IR and UV emitting regions. This possibility has been suggested by theoretical studies and simulations in some $z \sim 7 - 8$ sources [30, 32, 34, 313, 6]. Such scenario is also supported by some observations; for instance [438, 439, 95, 11, 277, 440] find significant spatial offset between their ALMA and HST data. High-resolution ALMA follow-up observations of REBELS galaxies are required in order to make a step forward (see also [108, 177] for a discussion on this point).

JWST will also provide us with much more accurate metallicity measurements at $z \gtrsim 5$, improving current estimates of the dust-to-gas ratios at high- z . Finally, further ALMA observation at shorter wavelengths in band 7–8–9, will allow us to reduce the uncertainties in current dust temperature estimates at $z \gtrsim 5$ by sampling galaxies SEDs closer to the FIR emission peak.

Chapter 5

Extending the analysis to ALPINE galaxies

The ALMA large program ALPINE (PI: Le Fevre, [36, 41, 37]) provided us with the most abundant sample of FIR continuum detected galaxies at high- z (23 at $z \sim 5$), featuring precise stellar masses $M_\star$ determinations thanks to the wealth of photometric data points available for individual targets. Interestingly, dust-to-stellar mass ratios as large as $M_d/M_\star = 0.002\text{--}0.056$ have been inferred for ALPINE galaxies [232]. Such large dust yields at these early epochs are in tension with theoretical predictions, adding to the so-called “dust budget crisis” [22]. It is important to stress that these dust masses measurements are heavily dependent on the cold dust temperatures ($T_d = 25$ K for ALPINE galaxies) *assumed* in the FIR SED-fitting procedure.

Here we intend to investigate the individual dust and FIR emission properties of the numerous $z \sim 5$ ALPINE galaxies. We are able to do so despite the availability of the single ALMA band-6 measurement thanks to the new method to derive T_d presented in Chapter 3.

With our analysis, we can infer the dust masses of ALPINE [C II] and continuum detected sources without the need to rely on an assumption on T_d . We can compare these new results with theoretical dust production constraints at $z \sim 5$. Moreover, we can study individual galaxies T_d , L_{FIR} and SFR_{FIR} , providing a complementary view to stacked FIR SEDs analysis [41]. Deriving ALPINE galaxies T_d also provides a fundamental anchoring to the $T_d - z$ evolution recently extended in the Epoch of Reionization (EoR) thanks to the REBELS galaxies study at $z \sim 7$ ([147], for details on the REBELS survey see [38]). ALPINE continuum-detected galaxies are almost ~ 2 times more numerous than REBELS ones, and span a wider SFR and $M_\star$ range (see Fig. 5.2), thus constituting a less biased sample with respect to REBELS galaxies (which in turn have the advantage of probing higher- z , where empirical $T_d - z$ relations differ the most). Consistent analysis and thorough comparison of both samples are crucial to solidify our understanding of dust properties at high- z .

5.1 Application of the [C II]-based method to ALPINE galaxies

We aim at deriving the dust masses and temperatures (M_d, T_d) of the 21 ALPINE galaxies detected both in [C II] and in continuum¹ at rest-frame 1900 GHz. The physical properties needed for the application of our method are all constrained by observations² (see Tab.

¹We do not consider 2 out of the 23 [C II] and continuum detected ALPINE sources, as their UV sizes, $r_\star$, and/or stellar masses $M_\star$ were not constrained.

²Measurements of r_{CII} are provided by [321] for all ALPINE sources except the galaxy VC 5101209780, which was left out due to its signal-to-noise ratio $\text{SNR} < 5$. For this source, we measure the [C II] radius

5.1 for all galaxies measured properties used in this work), with the exception of (κ_s, Z) .

The burstiness parameter κ_s and metallicity Z of ALPINE galaxies are unknown, thus a broad range of values is assumed for each quantity. Values as large as $\kappa_s \simeq 100$ have been observed in star-forming galaxies both locally and at intermediate-redshift [373]. By applying the [C II]-emission model given in [327] on 12 bright UV-selected galaxies at $z = 6 - 9$, [341, 325] found that κ_s values spanning the range $\sim 3 - 80$. Based on these findings, for ALPINE galaxies we choose a random uniform distribution in the range $1 \lesssim \kappa_s \lesssim 80$.

For the metallicity, we assume a uniform random distribution of values in the range $0.3 - 1 Z_\odot$. This is based on numerical simulations results for galaxies at $z \lesssim 6$ with similar stellar masses as ALPINE galaxies $10^9 < M_\star/M_\odot < 10^{11}$ [338, 339], and several observational studies which analyse FIR lines (such as [N II], [N III], [C II], [O II] and [O III]) to infer Z in galaxies up to $z \sim 6-8$ [340, 278, 370, 9, 341, 10, 255, 441]. In particular, [442] infer an average metallicity $Z/Z_\odot \sim 0.5$ for 10 ALPINE galaxies based on their measured [O II]-to-CII ratios. Better constraints on galaxies metallicities out to $z \sim 10$ will be available soon thanks to the JWST spectroscopic observations of rest-frame optical nebular lines (such as H β , H α , [N II], [O II] and [O III], [343, 344, 84]).

We can now compute the [C II]-to-total gas conversion coefficient α_{CII} for the ALPINE sources using eq. 3.7. We find on average $\langle \alpha_{\text{CII}} \rangle = 8_{-5}^{+3}$, which is consistent with our previous findings for $z > 4$ galaxies [315, 147]. Note that in local sources we find much larger conversion factors, up to $\alpha_{\text{CII}} \lesssim 10^3$. This might suggest that for a given [C II] luminosity high- z galaxies have a lower gas content (or that for a given gas content they have higher [C II] emission; for a detailed discussion see e.g. [327]). For the comparison with the empirical *molecular*-to-[C II] conversion factor $\alpha_{\text{CII,mol}} = \Sigma_{\text{H}_2}/\Sigma_{\text{CII}} = 31_{-16}^{+31}$ derived in [330] we refer to [147] (Sec. 3).

We can now estimate M_d and T_d for all the targets, and thus L_{FIR} and SFR_{FIR} . The results are reported in Tab. 5.2, and discussed in detail in the following Sections.

5.2 Dust temperatures at $z \sim 5$

We find the dust temperatures of ALPINE galaxies to lay within the wide range $25 - 60$ K, with an average value around $\langle T_d \rangle = 48 \pm 8$ K. The relative error associated to the individual sources T_d is around $\Delta T_d/T_d \sim 30\%$, with the dominant contributions to this uncertainty coming from the metallicity and burstiness parameter. Albeit large, this $\Delta T_d/T_d$ is comparable to that obtained from traditional SED fitting at similarly high- z when multiple FIR data are available [93, 278, 277]. Among the ALPINE targets, there are two galaxies, DC 494057 and DC 848185 (HZ4 and HZ6 from [89]), for which ALMA bands 6, 7, and 8 observations are available thanks to dedicated follow-up observations by [282]. For both sources, the T_d values derived with our method are consistent with traditional SED fitting results within less than $\lesssim 20\%$ uncertainty.

In [41] the authors attempt at constraining the average T_d of ALPINE galaxies by fitting the stacked, single-dish FIR data from a photometric sample similar to ALPINE at $z = 4 - 6$. The stacked targets in [41] are selected to resemble ALPINE galaxies in stellar mass, $M_\star > 3 \times 10^{10} M_\odot$, and star formation rate, $\text{SFR} > 10 M_\odot/\text{yr}$ (derived from optical and near-infrared SED fitting). They are divided in two redshift bins at $z = 4 - 5$ (5749 sources)

in this work. We retrieve the ALMA continuum-subtracted, integrated [C II] line map (from the ALPINE website, <http://alpine.ipac.caltech.edu>) and exploit the CASA task `imfit` software. We fit the [C II] map with a 2D elliptical Gaussian model and measure the beam-deconvolved FWHMs in arcseconds. We then infer r_{CII} from the mean of the beam-deconvolved major and minor axes. The result is given in Tab. 5.1. We have checked that this procedure gives r_{CII} estimates consistent with the ones provided by [321], where available.

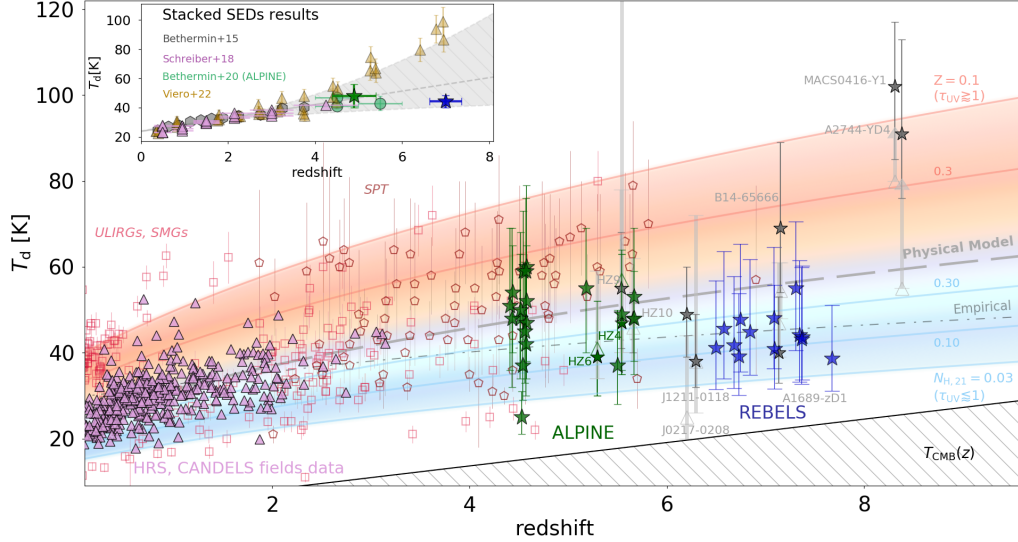


Figure 5.1: **Main panel:** Dust temperature T_d as a function of redshift for star-forming galaxies in the range $z = 0 - 8$ (updated version of Fig. 2 in [147]). The purple triangles represent the UV-to-IR normal star-forming galaxies detected in the HRS and CANDELS fields studied in [40], which have comparable $M_\star$ to ALPINE and REBELS galaxies ($10^{9.5} \leq M_\star/M_\odot \leq 10^{11.5}$). The maroon and red empty symbols represent respectively the sub-mm galaxies observed at $z \lesssim 2$ [299, 300, 301, 302, 303] and at $z = 2 - 4$ (SPT sample, [229]). The grey points show the individual UV-selected galaxies at $z > 5$ for which T_d estimates are available thanks to multiple FIR continuum observations. Both the T_d values obtained with our method and with traditional SED fitting are shown (respectively as stars and triangles; we note that in all cases the two estimates are consistent within $1 - \sigma$, for further details see [147]). Finally, in green and blue we show the results obtained with our method for individual ALPINE and REBELS galaxies, respectively. The coloured region shows the T_d -redshift evolution that we derive analytically in [147] (for an increasing effective UV optical depth τ_{UV} from blue to red). We find that on average T_d raises with redshift due to the decreasing gas depletion time $t_{\text{dep}} = M_g/\text{SFR}$ at higher- z , as $T_d(z) \propto t_{\text{dep}}^{-1/6}$. This dependence is shown by the grey dashed line for $t_{\text{dep}} \propto (1+z)^{-2.5}$ – derived from numerical simulations – implying $T_d \propto (1+z)^{0.4}$. For comparison, we also show the $T_d - z$ relation we would predict based on the empirical evolution $t_{\text{dep},H_2} \propto (1+z)^{-1.5}$ inferred by [44] for main-sequence galaxies (grey dotted-dashed line). **Inset panel:** T_d values obtained from stacked SEDs fitting in the redshift range $0 \lesssim z \lesssim 8$ (grey, purple, green and yellow points, from [293, 40, 41, 43], respectively). The grey hatched area shows the different $T_d - z$ trends empirically derived in these works, with the lower (upper) bound being set by [32] ([43]). The linear $T_d - z$ relation derived by [40] is also shown. The green (blue) star corresponds to the average temperature derived here for ALPINE (REBELS) galaxies.

and $z = 5 - 6$ (1883 sources). We find that most (all but 3) of the individual ALPINE galaxies FIR SEDs are bracketed by the stacked SEDs. In fact, by fitting the stacked SEDs with the same dust model adopted for the individual galaxies³ we find $T_d = 37 - 54$ K, consistent (albeit slightly lower) with the range of dust temperatures obtained with our method. This consistency between SEDs of individual continuum-detected sources and stacked data is encouraging as stacking is widely used to extend star-forming galaxies IR emission studies out to $z \gtrsim 4$ [293, 40, 41, 43].

5.2.1 Cosmic T_d evolution

Recently, several works have alluded to the presence of a cosmic evolution of the dust temperature in star-forming galaxies [421, 292, 291, 293, 40, 37, 32, 42, 229]. In most of these studies, the average T_d at a given epoch is derived by fitting stacked data, including observations at wavelengths shorter than $\lambda \lesssim 350 \mu\text{m}$ from the Herschel space observatory. Herschel was the only instrument probing these MIR-to-FIR wavelengths, which are crucial

³We consider Milky Way-like dust, for which standard values for the dust opacity $\kappa_\nu = \kappa_\star(\nu/\nu_\star)^{\beta_d}$ are $(\kappa_\star, \nu_\star, \beta_d) = (10.41 \text{ cm}^2\text{g}^{-1}, 1900 \text{ GHz}, 2.03)$, from [15, 186].

to obtain stringent constraints on T_d . However, Herschel cannot detect individual galaxies at $z \gtrsim 2$ because of confusion [421, 300], thus requiring to rely on stacking at higher- z .

Interestingly, different works find discrepant results (see inset panel in Fig. 5.1). Some works suggest a linearly increasing $T_d - z$ trend based on stacked SEDs fitting results in the redshift range $z = 0 - 5$ [40], coupled with a few individual detections at $z \gtrsim 5$ [42]. Other works predict a much milder evolution [292, 291, 229]; in particular, [32] find a substantial flattening in the increase of T_d at $z \gtrsim 4$ based on SED fitting procedure applied to the FIRE simulations at $z = 2 - 6$. This flattening in the $T_d - z$ evolution is consistent with individual galaxies peak dust temperatures ($T_{\text{peak}} \sim 2.9 \times 10^3 (\lambda_{\text{peak}}/\mu\text{m})^{-1}$) measured at $z \sim 4 - 5$ by [282]. However, T_{peak} can significantly differ from T_d depending on the adopted SED fitting function. In fact, [282] finds $T_d > T_{\text{peak}}$ ($\delta T_d \sim 13$ K on average), consistently with our derivation (see Sec. 5.2). It is worth mentioning that the only two $z \sim 8$ ALMA-detected sources host hot dust with temperatures $T_d = 90 - 100$ K [30, 10, 12], possibly questioning such scenario. We stress that for these 2 galaxies we are able to uniquely derive T_d by combining the [C II] luminosity information with the rest-frame $88 \mu\text{m}$ continuum flux⁴. These hot dust temperatures at $z \sim 8$ are consistent with the results by [43], where they exploit the recently released COSMOS2020 catalogue [295] to extend stacked SEDs studies up to unprecedentedly high- z ($z \sim 10$). The reliability of these stacking results at $z \gg 4$ is somewhat uncertain, as individuating low- z interlopers and/or correcting for the bias towards the brightest sources becomes more challenging (see the discussion in [43]). We caution that [43] find a nearly constant number of very massive sources (~ 60 at $M_\star \gtrsim 10^{11} M_\odot$) in their stacked bins at $z = 3.5 - 4$ and $z = 8 - 10$, which is in contrast with the predictions from the stellar mass function. In fact, extrapolating abundance matching results [443] and observations [444] at $z \leq 8$ and $M_\star \leq 3 \times 10^{10} M_\odot$, we would expect a > 2 orders of magnitude (odm) drop in the number density of $M_\star \gtrsim 10^{11} M_\odot$ sources from $z = 4$ to $z > 8$. Semi-analytical models such as DELPHI [20] agree with this prediction, with a steep drop in the number density (7 odm) at the high-mass end ($M_\star = 4 \times 10^{10} M_\odot$) from $z = 4$ to $z = 10$. Upcoming JWST observations will allow us to extend the census of massive systems at $z > 8$, testing these predictions [445, 446, 447].

Thanks to our method, for the first time we constrain T_d in a large number of sources (40) at $z \gtrsim 4$, thus adding fundamental and highly complementary information from individual galaxies analysis to stacked SED results. At $z = 4.9$, the mean redshift of [C II] and continuum detected ALPINE galaxies, we find an average $\langle T_d \rangle = 48 \pm 8$ K, whereas $\langle T_d \rangle = 44 \pm 4$ K for the 13 [C II] and continuum-detected REBELS galaxies at $z \sim 7$ [38, 108]. We note that this value for REBELS galaxies $\langle T_d \rangle$ is slightly lower than the one reported in [147] ($T_d = 47 \pm 7$ K). We have updated the stellar masses of REBELS galaxies to the latest values by [39], obtained by assuming a non-parametric star-formation history (SFH, instead of constant SF). A non-parametric SFH results in an increase in $M_\star$ up to one order of magnitude for galaxies with large specific SFR⁵. Larger $M_\star$ imply slightly larger dust M_d and lower T_d to reproduce the same observed F_{1900} .

The comparable average T_d in ALPINE and REBELS galaxies, whose main difference is the redshift of the sources⁶, questions the validity of the simple, linearly increasing $T_d - z$ trend suggested by [40, 42] (predicting an increase from $T_d \sim 46$ K at $z = 4.9$ to 56 K at $z = 7$). On the other hand, the flattening in the $T_d - z$ trend at $z > 4$ inferred by [292, 32] seems too extreme (they predict colder temperatures, $T_d \sim 37$ K at $z = 4.9$ and $T_d \sim 39$ K at $z = 7$). The largest discrepancy is with the preliminary results by [43], whose

⁴From traditional SED fitting only a lower limit on $T_d > 50, 80$ K is obtained [10, 12], see Appendix B in [147].

⁵This increase in $M_\star$ is due to the presence of a significant old stellar population that is out-shined by the recent star formation (SF) burst

⁶REBELS galaxies stellar masses and SFRs are similar -albeit spanning a narrower range- to that of ALPINE galaxies, being $9 \lesssim \log(M_\star/M_\odot) \lesssim 10$ and $20 \lesssim \text{SFR}/M_\odot\text{yr}^{-1} \lesssim 200$.

best fitting $T_d - z$ relation features a sharp increase in T_d at $z \gtrsim 5$ reaching $T_d \sim 87$ K at $z = 7$ (almost $\times 2$ higher than the average dust temperature we find in REBELS galaxies at the same redshift). A possible caveat is that both ALPINE and REBELS sources are UV-selected as the brightest sources at their respective redshift, thus constituting a biased sample, possibly skewed toward colder dust temperatures [448]. JWST will allow us to probe relatively UV-faint galaxies also at $z \geq 5$; by following-up JWST observations with ALMA, we will investigate also UV-faint high- z galaxies dust properties, possibly reducing the current observational bias.

In [147] we produced a model aimed at physically motivating the cosmic evolution of the dust temperature. Assuming FIR and UV emission to be co-spatial, from simple conservation of energy argument, we show that T_d anti-correlates with the *total* gas depletion time as $T_d \propto t_{\text{dep}}^{-1/6}$. The increase of the cosmological accretion rate at early times [432, 433, 434], results in high- z galaxies being more efficiently star forming, thus implying shorter t_{dep} at high- z . As a result, we predict a mild increase of T_d with redshift as:

$$T_d \propto t_{\text{dep}}^{-1/6} \approx (1+z)^{0.42}. \quad (5.1)$$

where the adopted $t_{\text{dep}} - z$ evolution ($t_{\text{dep}} \propto (1+z)^{-2.5}$) is taken from numerical simulations [432, 433, 434] due to the lack of observational constraints on the atomic gas content of high- z galaxies. The *molecular* gas depletion time, $t_{\text{dep,H}_2} = M_{\text{H}_2}/\text{SFR}$, has been indirectly studied up to $z \sim 6$ relying on CO and dust observations [375, 44, 376]. For main-sequence galaxies, different works consistently infer an evolution of $t_{\text{dep,H}_2}$ with redshift around $t_{\text{dep,H}_2} \propto (1+z)^{-1.5}$ [44]. Adopting such empirical $t_{\text{dep,H}_2}(z)$ relation, would imply a milder - but still significant- cosmic T_d evolution $T_d \propto (1+z)^{0.25}$. This is also shown in Fig. 5.1.

On top of the $T_d - z$ trend, [147] showed that the scatter in the measured T_d values at a given redshift can be explained by the variation of a few key individual galaxies properties, namely the optical depth τ_{UV} , metallicity and column density $N_{\text{H}} \sim 10^{21} \tau_{\text{UV}}/Z \text{ cm}^{-2}$. The results derived in this paper for individual ALPINE galaxies are consistent with the predictions from our physical model, as shown in Fig. 5.1. Due to the different redshifts of the ALPINE and REBELS samples, we expected a minor mean temperature variation $|\langle T_{d,\text{REB}} \rangle - \langle T_{d,\text{ALP}} \rangle|/\langle T_{d,\text{ALP}} \rangle \sim 14\%$. However, such variation is comparable to the $1 - \sigma$ error associated with $\langle T_d \rangle$ in the two samples.

The slightly warmer T_d of ALPINE galaxies with respect to REBELS galaxies could be explained by larger UV optical depths, implying a more efficient dust heating. This prediction is qualitatively confirmed by the measured average UV slopes $\langle \beta_{\text{UV}} \rangle$ for the two samples. In fact, $\langle \beta_{\text{UV}} \rangle$ is redder in ALPINE galaxies (-1.4 ± 0.5) than in REBELS galaxies (-1.8 ± 0.3), implying a larger dust-obscuration (as a reference, we remind the intrinsic UV slope⁷ amounts to $\beta_{\text{int}} = -2.406$, [177]). Our prediction of warmer dust temperatures in more UV-obscured systems is also confirmed by the comparison with sub-millimetre galaxies studies at $z \lesssim 6$ (see Fig. 5.1). In fact, on average sub-mm galaxies host warmer dust than UV-transparent galaxies [282], reaching values around $T_d \sim 40$ K in the local Universe [299, 300, 301, 302, 303], and $T_d \sim 60$ K at $z \sim 5$ [229]⁸.

5.3 Dust masses at $z \gtrsim 5$

We derive the dust masses for our sample of the ALPINE galaxies finding them to vary within the range $6.77 < \log(M_d/M_\odot) < 8.41$, with the average value being $\langle \log(M_d/M_\odot) \rangle =$

⁷The quoted intrinsic UV slope is obtained from STARBUST99 [449], assuming continuous star formation, Salpeter IMF $1 - 100 M_\odot$, metallicity $Z = 1/3 Z_\odot$, and stellar age 150 Myr.

⁸We caution that the SED-fitting procedure used in [229] for SPT galaxies is different with respect to the one adopted here, which assumes an optically thin grey-body emission. Nevertheless, when testing our method on the only SPT galaxy with available metallicity measurements (SPT 0418-47), we found consistent results with [229] within $1 - \sigma$ [315].

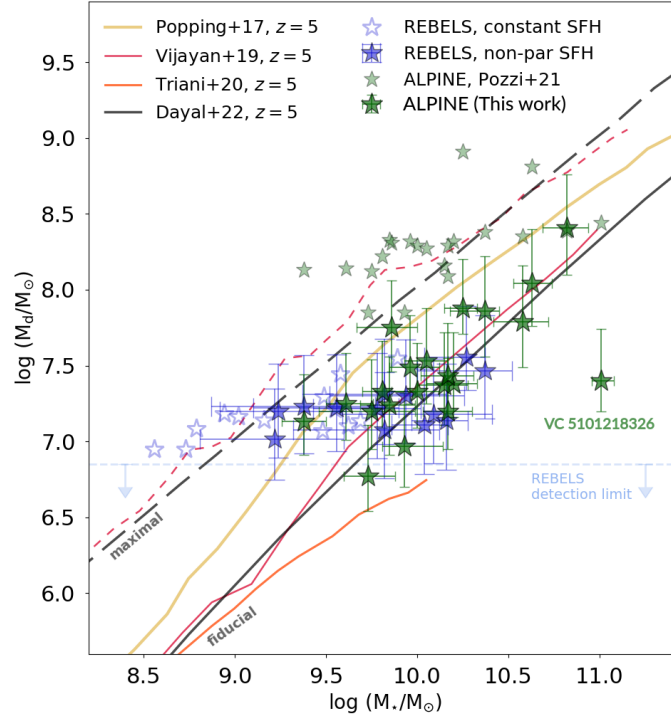


Figure 5.2: Dust mass M_d as a function of stellar mass M_* . The solid green stars show the M_d values that we derive for ALPINE galaxies, whereas the transparent ones were obtained by [232] assuming $T_d = 25$ K. The blue stars (empty stars) represent REBELS galaxies, where M_* is inferred assuming a non-parametric SFH (constant SF, [39]). The solid lines show the fiducial predictions at $z \sim 5$ from semi-analytical models such as DELPHI [115, 20], Santa Cruz in yellow [273], Dusty Sage in orange [290], and L-Galaxies in red [289]. The dashed lines show the maximal predictions of the corresponding models, assuming no dust destruction or ejection, and saturated grain growth. We find that all but one ALPINE galaxies are consistent with theoretical predictions. This is not true for higher- z REBELS galaxies (particularly under the assumption of constant SF), whose $M_d - M_*$ relation appears flat; possible explanations are discussed in the text (see also [20]). The dashed blue line shows the M_d detection threshold for the REBELS program assuming a non-detection flux limit of $42 \mu\text{Jy}$ and $T_d = 48$ K.

7.47 ± 0.37 . This value is a factor ~ 7 lower than the values reported in [232] for these same galaxies. [232] assume a very cold dust temperature of 25 K, to derive the dust masses from the continuum fluxes F_{1900} . They state that this value (which is close to $T_{\text{CMB}}(z = 6)$) should correspond to the mass-weighted dust temperature of typical $z \sim 6$ galaxies. However, by analysing an average simulated galaxy at $z \sim 6$ from the SERRA simulation suite [31, 8], in [315] we found that the mass-weighted dust temperature and T_d derived from fitting the simulated spectra (using mock continuum observations in ALMA band 6, 7, and 8 or our method) actually correspond, and are $\gg T_{\text{CMB}}$ ($T_d \sim 60$ K, see also [8] for an extended discussion). The temperatures that we infer for ALPINE galaxies are similarly warm, $T_d \sim 48$ K, with a single exception represented by the galaxy VC 5180966608 for which we infer $T_d = 25$ K. This cold dust results from the peculiar, and likely unreliable, [C II]-to-UV size ratio measured for this galaxy. In fact, from eq. 3.7-3.10 it follows that $M_d \propto y^2 = (r_{\text{CII}}/r_*)^2$, resulting in a much larger dust mass for VC 5180966608, whose $y = 10$, with respect to the other galaxies in the ALPINE sample, where on average $\langle y \rangle \sim 3$. This massive dust content ($\log(M_d/M_\odot) = 8.41$), coupled with a relatively low continuum flux ($F_{1900} = 462 \mu\text{Jy}$), results in the exceptionally cold dust temperature derived for this galaxy. However, the [C II] size of VC 5180966608 is flagged as unreliable by [321] due to its complicated morphology. In fact, in the latest analysis by [450] VC 5180966608 is classified as a merger; treating it as a single source might have led us to misinterpret its properties. Upcoming deeper ALMA [C II] observations and higher

resolution FIR continuum data from the CRISTAL large program (PI: Herrera-Camus) will allow us to further investigate this hypothesis.

The lower dust masses that we infer for ALPINE galaxies have important implications in terms of the comparison with theoretical dust production constraints at $z \sim 5$. We discuss this in detail in the following Section.

5.3.1 Implications for dust production at high- z

We begin by computing the dust yield y_d per SN which would be required to produce the dust masses derived in this work for ALPINE galaxies. This is $y_d/M_\odot = M_d/(\nu_{\text{SN}}M_\star)$, where $\nu_{\text{SN}} = (53 M_\odot)^{-1}$ is the rate of SNe per solar mass of stars formed assuming a Salpeter $1 - 100 M_\odot$ IMF [246]. We find that on average $\langle y_d \rangle = 0.15 \pm 0.09 M_\odot$, which is consistent with the SN dust production constraints by [18]. However, other works suggest that the dust yield spared in a SN blast is as low as $\lesssim 0.1 M_\odot$ [252, 416, 256].

To investigate dust production further, in Fig. 5.2 we compare the dust-to-stellar mass relation that we find for ALPINE galaxies with predictions from semi-analytical dust production models at $z \sim 5$. We include the DELPHI model [115, 20], the Santa Cruz model [273], Dusty Sage [290], and L-Galaxies [289], which (mostly) cover the ALPINE stellar mass range $M_\star = 10^9 - 10^{11} M_\odot$. All these models include varying prescriptions for gas cooling, star formation, SN feedback, chemical enrichment and key dust processes, namely dust formation, astration, destruction in SNe shocks, ejection in outflows, and grain growth. The DELPHI model does not include the contribution of AGB stars to dust production, which is likely sub-dominant due to the long timescales required for such dust production mechanism ($\gtrsim 150$ Myr) and the conflicting young stellar ages of $z \gtrsim 5$ galaxies (e.g. [18, 451, 264, 20]).

Our results are consistent (within $1 - \sigma$) with DELPHI and L-Galaxies theoretical predictions, with the Santa Cruz model favouring slightly larger dust masses (for nearly 50% of the sample). The slope of the $M_d - M_\star$ relation is consistent with our results in all four models. Therefore, it is not necessary to invoke unphysical scenarios with no dust destruction or ejection, and saturated grain growth. Moreover, dust production from SNe described by the DELPHI model is able to reproduce the inferred dust masses for most of the ALPINE galaxies (72% within $1 - \sigma$ and the remaining ones within $1.5 - \sigma$), confirming that the contribution to dust production from AGB stars in ALPINE galaxies is subdominant. The most discrepant galaxy is VC 5101218326, for which we predict a surprisingly low dust mass $M_d = 10^{7.4} M_\odot$, roughly one order of magnitude below theoretical predictions given the galaxy large stellar mass $M_\star = 10^{11} M_\odot$. This source is one of the two most peculiar sources in the ALPINE sample in terms of its dust properties and will be discussed in detail in the following Section.

Finally, we compare our results for the dust-to-stellar mass ratios in ALPINE galaxies, with the ones obtained for the REBELS sources with the same method [147, 20]. By using the larger $M_\star$ values derived for REBELS galaxies assuming a non-parametric SFH instead of constant SF [39], the discrepancy with theoretical models is reduced (none of the sources exceeds the maximal dust production constraints). In fact, for less massive objects ($\log(M_\star/M_\odot) \leq 10^{9.5}$) the increase in $M_\star$ can be as large as 1 dex, while M_d is marginally affected (30% variation). However, differently from ALPINE galaxies, in the higher- z REBELS sample, we do not recover the $M_d - M_\star$ correlation predicted by analytical models (independently from the assumed SFH). In fact, REBELS galaxies dust masses appear to be independent from their stellar masses. ALPINE galaxies are more massive than REBELS objects, and overall cover a larger range of $M_\star$ values. This might indicate that flatness of the $M_d - M_\star$ trend found for REBELS galaxies largely depends on an observational bias due to the limited range of stellar masses probed by this survey⁹.

⁹In Fig. 5.2 we show the M_d detection threshold for the REBELS program assuming a non-detection

Further ALMA observations probing the dust content of galaxies in a wider stellar mass range both at $z = 7$ and $z = 5$, will confirm whether we are witnessing an evolution in the dust-to-stellar mass relation between these two epochs. This could imply that also the mass-metallicity relation (to whom our dust-to-stellar mass relation is directly connected as we assume $D \propto Z$) breaks down at $z > 6$.

5.4 IR luminosities and total SFR at $z \sim 5$

We compute the IR luminosities using eq. 4.3. We find that ALPINE galaxies' IR luminosities vary in the range $1.7 \times 10^{11} L_{\odot} \lesssim L_{\text{FIR}} \lesssim 8.7 \times 10^{12} L_{\odot}$. Among the 21 galaxies analyzed here, as many as 8 have IR luminosities comparable to Ultra-Luminous InfraRed Galaxies¹⁰ (ULIRGs, i.e. $L_{\text{FIR}} > 10^{12} L_{\odot}$, see [425]). This finding is quite surprising as ALPINE galaxies are selected as UV-brightest sources in the given redshift range $z = 4 - 6$. Our results suggest that a large fraction of their star formation is dust-obscured, which is consistent with stacking results by [392] (suggesting that on average 45% of SFR is obscured at $z = 5 - 6$).

The inferred IR luminosities correspond to obscured SFRs in the range $\text{SFR}_{\text{FIR}} \sim 17 - 878 M_{\odot}/\text{yr}$ (assuming the conversion factor given in Table 5.2). The largest value for $\text{SFR}_{\text{FIR}} = 878 M_{\odot}/\text{yr}$ is found in the galaxy DC 873756, the least UV-bright galaxy among the FIR continuum detected ALPINE sources. Its UV magnitude ($M_{\text{UV}} = -20.9$) corresponds to a monochromatic luminosity at $1500 \text{ \AA}$ around $L_{\text{UV}} = 10^{10.7} L_{\odot}$, implying an unattenuated¹¹ $\text{SFR}_{\text{UV}} = 4 M_{\odot}/\text{yr}$. Compared to its surprisingly large SFR_{FIR} , this implies that more than 99% of the SFR in DC 873756 is obscured¹². These results are highly in contrast with UV-to-optical SED-fitting results by [37], who derive a total, dust-corrected $\text{SFR}_{\text{SED}} = 5_{-2}^{+10} M_{\odot}/\text{yr}$. Using only UV-to-optical data the total SFR of DC 873756 was underestimated by more than two orders of magnitude¹³.

In order to understand the nature of this discrepancy and whether DC 873756 represents an isolated case, in Fig. 5.3 we compare the SFR derived from UV-to-optical SED-fitting with $\text{SFR}_{\text{UV}} + \text{SFR}_{\text{FIR}}$ for all the ALPINE sources considered here. We find that in most cases (80%) the two methods give consistent results within $1 - \sigma$. The uncertainties on SFR_{FIR} are very large (see Tab. 5.2) due to the strong dependence of this quantity on T_d ($\text{SFR}_{\text{FIR}} \propto L_{\text{FIR}} \propto T_d^6$), which is only constrained within $\pm 10 \text{ K}$. There are 4 outliers (DC 539609, VC 5100969402, DC 873756, VC 5101218326); for these sources the ratio¹⁴ between the UV-to-optical SED-derived SFR and that obtained from our method is $< 1/3$. In all these sources strong FIR continuum emission ($\text{SFR}_{\text{FIR}} > 100 M_{\odot}/\text{yr}$) coexists with blue UV slopes $\beta_{\text{UV}} < -1$, which would, in contrast, suggest low dust obscuration. These 4 galaxies are highlighted in Fig. 5.3, with the two most extreme cases being the galaxies DC 873756 and VC 5101218326. We note that if we do not include these two sources in the SFR_{SED} vs. $\text{SFR}_{\text{UV}} + \text{SFR}_{\text{FIR}}$ linear fit we recover a slope which is perfectly consistent with the bisector 1.1 ± 0.4 (albeit the large scatter), whereas if we include them we find -0.1 ± 0.1 .

One possible scenario to explain these peculiar galaxies is that they host Active Galac-

flux limit of $42 \mu\text{Jy}$ [108] and the average dust temperature $T_d = 47 \pm 7 \text{ K}$.

¹⁰For comparison, only one ULIRG-like galaxy, REBELS-25, is found among the 13 REBELS galaxies ([147, 108], see also [426] for a detailed analysis of the source).

¹¹ $\text{SFR}_{\text{UV}} = L_{\text{UV}}/\mathcal{K}_{1500}$, where the conversion coefficient $\mathcal{K}_{1500} = 1.174 \times 10^{10} L_{\odot}/(M_{\odot}\text{yr}^{-1})$ is taken from [177].

¹²Following the same procedure, we infer obscured SFR fractions in the range $\sim 60 - 90\%$ for the remaining ALPINE galaxies.

¹³We note that a milder correction to account for the obscured SFR fraction was already applied by [349] to some ALPINE galaxies; due to the lack of constraints on individual galaxies IR luminosities, they relied on the dust temperature derived by [41] from stacking.

¹⁴This discrepancy is larger than what can be explained by the different assumptions on the IMF in the two derivations (here we assume a Salpeter $1 - 100 M_{\odot}$, whereas [37] adopt a Chabrier).

tic Nuclei (AGN). Indeed, [452] show that AGN can emit significantly not only at MIR but also at FIR wavelengths. Thus, not accounting for AGN contribution, results in an overestimation of the host galaxy L_{FIR} and obscured SFR_{FIR} . However, this scenario seems unlikely based on these ALPINE galaxies' optical-to-UV spectra, which do not show any peculiar features with respect to the other sources in the sample. Nevertheless, whether AGN could contribute to the FIR emission of the most massive ALPINE galaxies such as VC 5101218326 (whose $M_{\star} = 10^{11} M_{\odot}$ is the largest among all ALPINE galaxies) is still an open question (Barchiesi et al. in prep., Shen et al. in prep, [453]). A clue for the interpretation of these outliers comes from computing their molecular index [177]:

$$I_{\text{m}} = \frac{(F_{1900}/F_{\text{UV}})}{(\beta_{\text{UV}} - \beta_{\text{int}})} \quad (5.2)$$

where $\beta_{\text{int}} = -2.406$ for the MW. Assuming the interstellar medium (ISM) to be described by a single zone model, where dust and stars are uniformly mixed¹⁵, [177] obtains the following analytical expression for $I_{\text{m}} \sim 7062 x e^{-3x^{1/6}}$, where $x = Zt_{\text{dep}}/(\beta - \beta_{\text{int}})$. This expression has a maximum $I_{\text{m}}^* \simeq 1120$ (located at $x = 64$). Indeed, F_{1900} and thus I_{m} can be increased by raising either the dust mass or the temperature. However, increasing T_{d} requires larger effective optical depths $(\beta_{\text{UV}} - \beta_{\text{int}})$ (see also Sec. 5.2.1), which are excluded in a relatively transparent single zone medium. It is possible to raise M_{d} while keeping $(\beta_{\text{UV}} - \beta_{\text{UV,int}})$ low, but this implies pushing the dust temperatures progressively closer to T_{CMB} , thus preventing F_{1900} , and hence I_{m} , to increase indefinitely. Interestingly, we find that the only galaxies in the ALPINE sample for which $I_{\text{m}} > I_{\text{m}}^*$ are the outliers in Fig. 5.3 (see also Tab. 5.2 for the I_{m} value of each source), with the largest value $I_{\text{m}} = 6752$ corresponding to the most peculiar galaxy DC 873756.

These large I_{m} values¹⁶ can be achieved only if the FIR and UV emitting regions are spatially decoupled [177]. In this scenario, the observed strong FIR continuum emission in these peculiar ALPINE galaxies comes from optically thick, star-forming clumps (likely, giant molecular complexes), whereas the small UV optical depth (i.e. blue β_{UV}) traces the diffuse, interclump gas component in which young stars are embedded after they disperse their natal cloud [168]. This scenario, referred to as “spatial-segregation” of UV and IR emission has been proposed by other theoretical works focusing on sources at the EoR [30, 32, 313, 8, 20]. Current ALMA observations do not probe the ISM morphology down to such scales ($\ll 1$ kpc).

High-resolution observations at sub-kpc scales for both the UV (see e.g. $\propto 100$ pc resolution images of $z = 6 - 8$ galaxies by [454]) and the dust continuum (also including shorter-wavelengths ALMA bands 8 and 9) of the ALPINE spatially-segregated galaxies will help us clarify the morphology of their ISM. An immediate improvement will be provided by upcoming high-resolution ALMA band 7 observations within the CRISTAL large program (PI: Herrera-Camus) and by JWST, whose pointings include 2 of these 4 peculiar sources. So far, a significant spatial offset between ALMA and HST data has been observed in some $z > 5$ star-forming galaxies [438, 95, 11, 108, 277]. At lower redshift, spatial segregation has been invoked to motivate the blue β_{UV} slopes found in some $z \sim 2$ dusty star-forming galaxies (DSFGs, [218]), which strongly deviate from the local IRX- β relation (where $\text{IRX} = L_{\text{FIR}}/L_{\text{UV}}$). Similarly, the IRX excess observed in some $z \sim 2$ starbursts [455] and $z \sim 4.5$ sub-mm galaxies [456] has been associated with spatially decoupled UV and IR emission in resolved ALMA and HST maps.

¹⁵And UV and IR emission are co-spatial.

¹⁶ $I_{\text{m}} > I_{\text{m}}^*$ are also measured in a few REBELS galaxies (4 out of the 14 continuum detected sources).

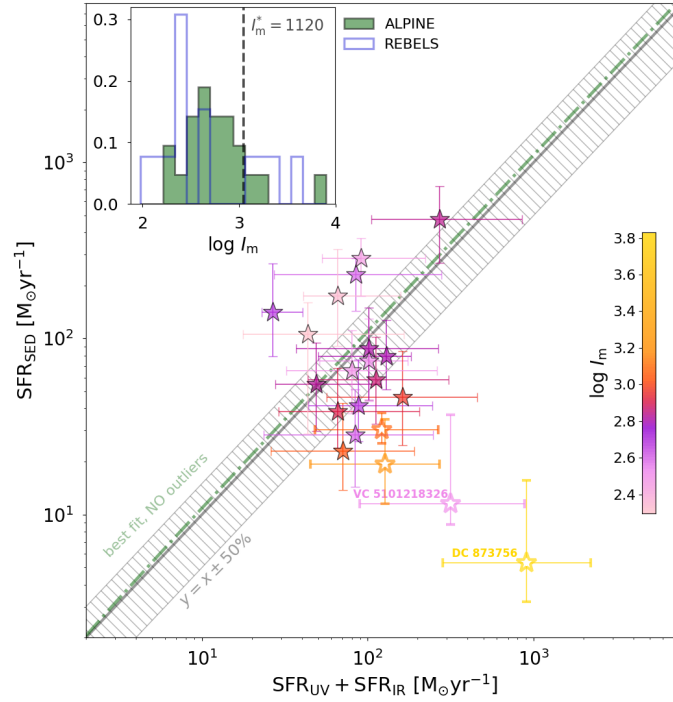


Figure 5.3: **Main panel:** Total SFR inferred for ALPINE galaxies through dust-corrected optical-to-UV SED fitting, SFR_{SED} [37] vs. that obtained from the UV and IR luminosities multiplied by the corresponding calibration factors, $\text{SFR}_{\text{UV}} + \text{SFR}_{\text{IR}}$. The dashed area shows the area around the bisector $\pm 50\%$ uncertainty. The light green symbols represent the most peculiar sources in the sample, for which $\text{SFR}_{\text{FIR}} > 100 \text{ M}_{\odot}/\text{yr}$, largely deviating from the SFR deduced from optical-to-UV data $\text{SFR}_{\text{SED}} < 30 \text{ M}_{\odot}/\text{yr}$. The green dotted dashed line shows the slope of the best-fitting linear relation obtained when excluding these outliers, consistent with the bisector. **Inset panel:** Distribution of the molecular index $I_m = (F_{1900}/F_{\text{UV}})/(\beta_{\text{UV}} - \beta_{\text{int}})$ among the ALPINE continuum detected galaxies. The vertical dashed line shows the upper limit $I_m^* = 1120$ obtained in a single-phase ISM model, where UV and IR emission are cospatial. This limit is exceeded in 3 among the 21 ALPINE galaxies considered here, which correspond to the outliers in the main plot (but one). We speculate that these peculiar galaxies have spatially segregated UV and IR emission.

5.5 Summary

In this Chapter, we studied the dust continuum emission properties of the Far Infrared (FIR) continuum detected $z = 5$ galaxies from the ALMA Large Program ALPINE [36, 37]. To derive their dust temperature T_d using the single available FIR continuum observation (at rest-frame $158 \mu\text{m}$), we apply the method presented in [315]. This method relies on the combination of the dust continuum flux with the overlying [C II] emission line luminosity; L_{CII} serves as a proxy for the dust mass M_d , breaking the degeneracy between M_d and T_d in the FIR SED fitting procedure.

Having constrained T_d and M_d for all the ALPINE galaxies, we can uniquely derive dust-temperature-dependent properties such as the IR luminosity L_{FIR} and obscured SFR fraction SFR_{FIR} . Providing this insight for ALPINE galaxies is fundamental as they constitute the most abundant sample of dusty star-forming galaxies at $z > 4$. Moreover, using the results from [147], we can compare them with the higher- z REBELS galaxies [38], consistently investigating the cosmic evolution of dust properties in an unprecedentedly large number of sources from $z \sim 5$ to $z \sim 7$.

We summarize below our findings:

- The dust temperatures for ALPINE galaxies vary within the range $25 - 60 \text{ K}$. The average value $\langle T_d \rangle = 48 \pm 8 \text{ K}$ is consistent with the result from stacked SED fitting by [41]. It also matches the predictions from the physical model for the cosmic T_d evolution by [147], which finds a mild increase in the dust temperature with redshift $T_d \propto (1 + z)^{0.4}$;
- Dust masses for ALPINE galaxies are in the $0.6 - 25.1 \times 10^7 M_\odot$ range. Due to the ~ 2 times warmer T_d that we infer for ALPINE galaxies, M_d are 7 times lower than previously reported by [232]. Thus, the resulting dust yields $\langle M_d/M_\star \rangle = 2 \times 10^{-3}$ are now consistent with theoretical dust production constraints at $z \sim 5$. In particular, we do not need to invoke extreme scenarios, e.g. saturated grain growth or no dust destruction, which might instead be needed at $z \sim 7$ for a few peculiar REBELS galaxies [20].
- The linear $M_d - M_\star$ relation predicted by theoretical models is consistent with our results, differently from what is found at $z \sim 7$ for REBELS galaxies where it appears flat. This might be evidence of a rapid evolution of the $M_d - M_\star$ relation at $z > 5$. However, probing a wider stellar mass range at both redshifts is needed to completely exclude that this is due to an observational bias;
- We find 8 ALPINE sources with $L_{\text{FIR}} > 10^{12} L_\odot$, comparable to Ultra-Luminous InfraRed Galaxies (ULIRGs). Among these 8 ULIRGs-like sources, there are 4 extreme systems where $\text{SFR}_{\text{FIR}} > 100 M_\odot/\text{yr}$, exceeding by a factor > 3 the total SFR deduced from UV-to-optical SED fitting. These outliers are the only sources showing large molecular index values $I_m = (F_{1900}/F_{\text{UV}})/(\beta_{\text{UV}} - \beta_{\text{int}}) > 1120$, the critical value for a single phase ISM [177]. We thus predict that these outliers are spatially-segregated systems, where FIR emission comes from clumpy giant molecular clouds whereas the UV arises from the diffuse, UV transparent ISM.

High-resolution observations at sub-kpc scales for both the UV (such as [454] and the dust continuum (also including shorter-wavelengths ALMA bands 8 and 9) of the ALPINE spatially-segregated galaxies will help us clarify the morphology of their ISM. An immediate improvement will be provided by upcoming high-resolution ALMA band 7 observations within the CRISTAL large program (PI: Herrera-Camus) and by JWST, whose pointings include 2 of these 4 peculiar sources.

Measured properties of the 21 [C II] and continuum detected ALPINE galaxies together with adopted relative errors ($[z, L_{\text{CII}}, F_{1900}]$ from [41], $[M_{\star}, M_{\text{UV}}, \beta_{\text{UV}}]$ from [37], and $[r_{\text{CII}}, r_{\star}]$ from [321]). The value of r_{CII} derived in this work is marked with a *. We also show the molecular index value I_{m} (see eq. 5.2) directly derived from the data.

[C II] AND CONTINUUM DETECTED ALPINE GALAXIES: DATA									
name	z	L_{CII}	F_{1900}	$\log M_{\star}$	r_{CII}	$r_{\star}$	M_{UV}	β_{UV}	I_{m}
		$[10^8 L_{\odot}]$	$[\mu\text{Jy}]$	$[M_{\odot}]$	$[\text{kpc}]$	$[\text{kpc}]$	$[\text{mag}]$		
CG 32	4.4105	8.2 ± 0.8	230 ± 65	$9.75^{+0.24}_{-0.29}$	1.94 ± 0.3	0.91 ± 0.13	-21.274	-0.859157	397
DC 396844	4.5424	11.5 ± 1.0	346 ± 69	$9.86^{+0.14}_{-0.19}$	2.56 ± 0.33	0.58 ± 0.2	-21.665	-1.38062	658
DC 417567	5.6700	3.1 ± 0.5	201 ± 60	$9.81^{+0.18}_{-0.11}$	2.07 ± 0.58	0.65 ± 0.20	-22.919	-1.86659	320
DC 422677	4.4381	4.2 ± 0.7	375 ± 123	$9.85^{+0.14}_{-0.16}$	1.10 ± 0.50	0.58 ± 0.14	-21.634	-1.2423	624
DC 488399	5.6704	10.8 ± 0.5	252 ± 32	$10.20^{+0.13}_{-0.15}$	1.32 ± 0.16	0.47 ± 0.32	-22.058	-1.88283	913
DC 493583	4.5134	4.3 ± 0.6	235 ± 81	$9.61^{+0.15}_{-0.11}$	1.89 ± 0.51	0.64 ± 0.17	-21.765	-2.01243	1051
DC 494057(HZ4)	5.5448	7.2 ± 0.5	179 ± 30	$10.15^{+0.13}_{-0.15}$	2.48 ± 0.25	0.88 ± 0.16	-22.373	-1.87832	466
DC 539609	5.1818	4.9 ± 0.6	187 ± 54	$9.38^{+0.12}_{-0.12}$	1.65 ± 0.43	0.77 ± 0.16	-22.357	-2.20637	1179
DC 683613	5.5420	7.8 ± 0.7	245 ± 54	$10.17^{+0.14}_{-0.15}$	1.82 ± 0.33	0.57 ± 0.24	-21.428	-1.3048	729
DC 848185(HZ6)	5.2931	16.0 ± 0.95	319 ± 50	$10.37^{+0.08}_{-0.19}$	3.47 ± 0.25	0.9 ± 0.3	-22.54	-1.14217	277
DC 881725	4.5777	6.87 ± 0.63	349 ± 90	$9.96^{+0.16}_{-0.11}$	2.26 ± 0.33	0.67 ± 0.21	-21.553	-1.20243	634
VC 5100822662	4.5205	7.86 ± 0.65	210 ± 38	$10.17^{+0.13}_{-0.14}$	2.59 ± 0.37	1.32 ± 0.33	-21.891	-1.31549	303
VC 5100969402	4.5785	5.23 ± 0.55	327 ± 99	$10.00^{+0.12}_{-0.14}$	1.62 ± 0.33	0.59 ± 0.15	-21.53	-1.94423	1583
VC 5100994794	4.5802	5.57 ± 0.51	117 ± 36	$9.73^{+0.15}_{-0.13}$	1.86 ± 0.32	1.63 ± 0.35	-21.342	-1.62524	398
VC 5101209780	4.5701	7.31 ± 1.56	311 ± 112	$10.05^{+0.12}_{-0.12}$	$3.25 \pm 0.72^*$	1.00 ± 0.24	-22.143	-1.91506	803
VE 530029038	4.4298	6.9 ± 0.8	125 ± 58	$9.93^{+0.21}_{-0.12}$	2.76 ± 0.65	1.96 ± 0.14	-21.95	-1.4904	197
DC 552206	5.5016	15.2 ± 1.1	285 ± 73	$10.58^{+0.14}_{-0.16}$	3.41 ± 0.35	0.96 ± 0.64	-22.642	-0.977538	211
DC 818760	4.5613	43.0 ± 1.7	1077 ± 130	$10.63^{+0.11}_{-0.10}$	2.59 ± 0.16	0.75 ± 0.17	-22.225	-0.548038	679
DC 873756	4.5457	36.2 ± 1.3	1354 ± 76	$10.25^{+0.08}_{-0.10}$	2.36 ± 0.11	1.08 ± 0.43	-20.869	-1.59125	6752
VC 5101218326	4.5739	18.3 ± 0.8	462 ± 79	$11.01^{+0.07}_{-0.05}$	2.37 ± 0.15	1.46 ± 0.32	-22.345	-0.86014	315
VC 5180966608	4.5296	13.7 ± 1.1	419 ± 84	$10.82^{+0.12}_{-0.13}$	5.10 ± 0.42	0.59 ± 0.24	-21.743	-0.826991	479

Predicted properties of the 21 [C II] and continuum detected ALPINE galaxies, respectively: [C II]-to-total gas conversion factor α_{CII} (eq. 3.7), dust temperature T_d and mass M_d , IR luminosity $\log L_{\text{FIR}}$, SN dust yield y_d and obscured SFR, $\text{SFR}_{\text{FIR}}[M_\odot \text{yr}^{-1}] = 10^{-10} L_{\text{FIR}}[L_\odot]$ [219].

[C II] AND CONTINUUM DETECTED ALPINE GALAXIES: RESULTS						
name	α_{CII}	T_d	$\log M_d$	y_d	$\log L_{\text{FIR}}$	SFR_{FIR}
		[K]	$[M_\odot]$	$[M_\odot/\text{SN}]$	$[L_\odot]$	$[M_\odot/\text{yr}]$
CG 32	4^{+5}_{-2}	51^{+18}_{-15}	$7.20^{+0.34}_{-0.25}$	$0.15^{+0.18}_{-0.07}$	$11.87^{+0.54}_{-0.56}$	75^{+182}_{-54}
DC 396844	12^{+11}_{-5}	37^{+12}_{-8}	$7.75^{+0.31}_{-0.29}$	$0.41^{+0.43}_{-0.2}$	$11.6^{+0.45}_{-0.33}$	40^{+73}_{-21}
DC 417567	16^{+19}_{-6}	48^{+11}_{-13}	$7.33^{+0.33}_{-0.24}$	$0.18^{+0.2}_{-0.08}$	$11.9^{+0.29}_{-0.46}$	79^{+75}_{-51}
DC 422677	9^{+11}_{-5}	54^{+11}_{-14}	$7.24^{+0.32}_{-0.33}$	$0.13^{+0.14}_{-0.07}$	$12.11^{+0.16}_{-0.47}$	128^{+58}_{-84}
DC 488399	5^{+6}_{-2}	53^{+16}_{-15}	$7.38^{+0.34}_{-0.22}$	$0.08^{+0.1}_{-0.03}$	$12.2^{+0.47}_{-0.5}$	157^{+308}_{-108}
DC 493583	10^{+11}_{-4}	48^{+15}_{-14}	$7.25^{+0.33}_{-0.24}$	$0.23^{+0.26}_{-0.1}$	$11.79^{+0.45}_{-0.54}$	61^{+111}_{-44}
DC 494057 (HZ4)	8^{+9}_{-3}	47^{+16}_{-12}	$7.37^{+0.35}_{-0.26}$	$0.09^{+0.11}_{-0.04}$	$11.83^{+0.5}_{-0.45}$	68^{+145}_{-44}
DC 539609	6^{+7}_{-2}	55^{+14}_{-15}	$7.13^{+0.31}_{-0.22}$	$0.30^{+0.31}_{-0.12}$	$12.0^{+0.36}_{-0.53}$	101^{+132}_{-71}
DC 683613	8^{+10}_{-3}	49^{+15}_{-13}	$7.43^{+0.35}_{-0.24}$	$0.10^{+0.12}_{-0.04}$	$12.01^{+0.48}_{-0.48}$	102^{+206}_{-68}
DC 848185 (HZ6)	11^{+13}_{-5}	39^{+13}_{-9}	$7.86^{+0.36}_{-0.3}$	$0.16^{+0.21}_{-0.08}$	$11.86^{+0.48}_{-0.34}$	73^{+145}_{-40}
DC 881725	11^{+12}_{-4}	47^{+14}_{-13}	$7.49^{+0.34}_{-0.24}$	$0.18^{+0.22}_{-0.08}$	$11.96^{+0.46}_{-0.49}$	91^{+172}_{-62}
VC 5100822662	5^{+5}_{-2}	50^{+18}_{-14}	$7.2^{+0.35}_{-0.25}$	$0.06^{+0.07}_{-0.02}$	$11.86^{+0.54}_{-0.52}$	72^{+178}_{-51}
VC 5100969402	9^{+11}_{-4}	52^{+13}_{-14}	$7.33^{+0.32}_{-0.24}$	$0.11^{+0.13}_{-0.05}$	$12.06^{+0.33}_{-0.53}$	116^{+133}_{-81}
VC 5100994794	2^{+3}_{-1}	60^{+19}_{-19}	$6.77^{+0.34}_{-0.23}$	$0.06^{+0.07}_{-0.02}$	$11.87^{+0.48}_{-0.64}$	75^{+153}_{-58}
VC 5101209780	11^{+13}_{-4}	42^{+16}_{-12}	$7.53^{+0.35}_{-0.28}$	$0.16^{+0.2}_{-0.08}$	$11.72^{+0.55}_{-0.5}$	52^{+135}_{-36}
VE 530029038	3^{+4}_{-1}	48^{+21}_{-16}	$6.97^{+0.35}_{-0.27}$	$0.06^{+0.07}_{-0.03}$	$11.5^{+0.66}_{-0.69}$	31^{+113}_{-25}
DC 552206	10^{+12}_{-4}	37^{+13}_{-9}	$7.79^{+0.37}_{-0.3}$	$0.09^{+0.12}_{-0.04}$	$11.66^{+0.48}_{-0.34}$	45^{+93}_{-25}
DC 818760	6^{+7}_{-2}	45^{+16}_{-12}	$8.04^{+0.36}_{-0.28}$	$0.14^{+0.17}_{-0.06}$	$12.38^{+0.53}_{-0.45}$	240^{+575}_{-154}
DC 873756	5^{+5}_{-1}	59^{+14}_{-16}	$7.88^{+0.32}_{-0.17}$	$0.22^{+0.24}_{-0.07}$	$12.94^{+0.38}_{-0.55}$	878^{+1233}_{-628}
VC 5101218326	3^{+3}_{-1}	59^{+17}_{-18}	$7.40^{+0.34}_{-0.2}$	$0.01^{+0.02}_{-0.0}$	$12.48^{+0.46}_{-0.59}$	303^{+569}_{-225}
VC 5180966608	47^{+54}_{-21}	25^{+6}_{-4}	$8.41^{+0.35}_{-0.31}$	$0.20^{+0.26}_{-0.1}$	$11.23^{+0.22}_{-0.12}$	17^{+11}_{-4}

Chapter 6

Warm dust at high- z : theoretical model and implications

Numerical simulations are a crucial complementary tool to astronomical observations. Large scale structure formation and galaxy evolution across cosmic time has been investigated via large-volume simulations, both dark matter only [457] and including baryons [152, 4, 458]. Zoom-in simulations – which focus on individual haloes extracted from the large boxes – have been used to capture the internal properties and dynamics of galaxies in their large-scale environment, by consistently following the star formation history and feedback processes driving the chemical evolution of high- z galaxies [326, 459, 460, 461]. Such theoretical studies have identified some important differences between early and local galaxies, providing a physical explanation and broader context to observational findings. Pristine systems tend to have more compact sizes, higher specific SFR, and a more turbulent ISM than their local analogues [462, 463, 326, 31, 8, 33, 7, 273, 20].

Hydrodynamical simulations [30, 32, 33, 31, 8, 464] can be post-processed with physically-rich radiative transfer computations to investigate the relation between intrinsic galaxy properties, and observables such as atomic line and continuum emission across the whole electromagnetic spectrum. Following this approach, Behrens et al. [30] pointed out that most of the FIR emission in early systems (at $z \sim 8$) appears to come from a few massive, UV-opaque, star-forming complexes – in brief Giant Molecular Clouds (GMC) – while the UV flux mostly arises from a diffuse ISM component with relatively low optical depth. GMC scales are not resolved further in cosmological simulations due to the demanding computational times required by the most detailed ones (in terms of considered physical processes, and resolution, see e.g. [465, 30, 32, 118, 7, 8]).

SAMs, analogous to the ones used in the previous Chapters to interpret high- z galaxies observations (3-5), can be employed as sub-grid models for cosmological simulations to account for small-scale (here GMC scale) physics and facilitate the understanding of the key physical processes shaping complex simulations outputs. In this Chapter, we discuss the results obtained in this context in Sommovigo+20,21 [315, 313].

6.1 Comparing ALMA observations to simulated spectra at $z \sim 7$

The [C II]-based method developed in Chapter 3 can reliably determine the dust temperature in a galaxy for which only a *single* simultaneous observation for the [C II] line and underlying continuum is available. This value corresponds to the canonical temperature, $T_{\text{d,SED}}$, that one would normally define from fitting the SED with a single temperature grey body formula. As already mentioned, $T_{\text{d,SED}}$ does not necessarily correspond to the physical dust temperature which instead is distributed according to a given Probability Distribution Function (PDF, [30, 313]). Hence, it is instructive to understand the relation

Galaxy	z	F_{ν_0} [μJy]	Z [$Z_\odot$]	$\log \Sigma_{\text{SFR}}$ [$\text{M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$]	L_{CII} [$10^8 L_\odot$]	κ_s	$y = r_{\text{CII}}/r_\star$	$M_\star$ [$10^9 \text{ M}_\odot$]
Zinnia	6.6847	2.81	0.07	2.56	2.05	4.29	1.00*	2.19

Properties of our high- z simulated galaxy Zinnia (serra05:s46:h0643). We note that the parameter $y = r_{\text{CII}}/r_\star = 1.0$ is selected by definition, i.e. we only consider the emission coming from the central ~ 1.5 kpc region.

Galaxy	$\alpha_{\text{CII,hz}}$	$T_{\text{d,SED}}$ [K]	M_{d} [$10^5 \text{ M}_\odot$]	y_{d} [$10^{-3} \text{ M}_\odot/\text{SN}$]
Zinnia	8.9	62 ± 2	2.0 ± 0.8	-
This work	8.76 ± 0.07	63.4 ± 0.5	1.94 ± 0.03	4.67 ± 0.06

Comparison between the properties predicted with our method (“This work”), and derived through a single temperature grey body fitting of the simulated flux in ALMA band 6,7,8 of galaxy Zinnia. In the SED fitting procedure, we keep the dust emissivity index fixed at $\beta = 2.0$, as in our analytical method and consider a 1% uncertainty on all the galaxy properties derived from the simulation and listed in Tab. 6.1. We underline that our predictions correspond to $T_{\text{d,CII}}$.

among $T_{\text{d,SED}}$ and the PDF properties.

In the context of theoretical studies, i.e. both analytical models and simulations, the dust temperature PDF is actually available. Various weighting procedures can be applied to this PDF, and then the average can be compared to the observational results. In particular, the most commonly adopted are the mass- (M-weighted) and luminosity-weighted (L-weighted; $L \propto M_{\text{d}} T_{\text{d}}^{4+\beta}$). The M-weighted temperature traces the most abundant cold temperature component; instead, the L-weighted is biased towards hotter but less massive dust component present in star-forming regions where it is efficiently heated by the UV emission from newborn stars, see e.g. [30, 313]. Neither of them is traced by $T_{\text{d,SED}}$. Indeed cold dust nearly in equilibrium with the CMB is not observable in emission; hot dust (if present) emits mainly in the MIR, where it is largely responsible for distortions of the single temperature grey body (see e.g. [307, 312]).

At high- z such distortion is not observable, as only the long-wavelength part of the SED spectra is currently accessible with ALMA (bands 6,7, and 8). However, locally, where the whole SED is well sampled, it has been observed and studied by e.g. [307] within $z \sim 0$ sub-millimetre galaxies. In light of these considerations, the most appropriate and clean choice when comparing theoretical results with observations is to perform a single temperature grey-body fit to the simulated SEDs in order to consistently obtain $T_{\text{d,SED}}$. In Fig. 6.1 we show the result of applying this procedure to the SED of the simulated $z \sim 6.7$ galaxy Zinnia from the SERRA simulation suite.

Full details on SERRA simulations are given in Pallottini+22 [8] and can be summarized as follows. Simulations zoom in on the evolution of $M_\star \sim 10^{10} \text{ M}_\odot$ galaxies from $z = 100$ to $z = 6$ with a mass (spatial) resolution of the order of $10^4 \text{ M}_\odot$ (30 pc at $z = 6$). [C II] emission is obtained by post-processing using grids of CLOUDY [466] models accounting for the internal structure of molecular clouds [324, 31]. Additionally, SKIRT [467, 468] is used to obtain UV and dust continuum emission, with a setup similar to [30].

The main properties of Zinnia are summarised in Tab. 6.1. We proceed to compute and compare the following temperatures:

- T_{d} : dust temperature obtained from fitting the full (i.e. MIR and FIR) galaxy SED with a single-T grey body;
- $T_{\text{d,SED}}^{3\text{p}}$: dust temperature obtained from fitting the galaxy SED at the frequencies

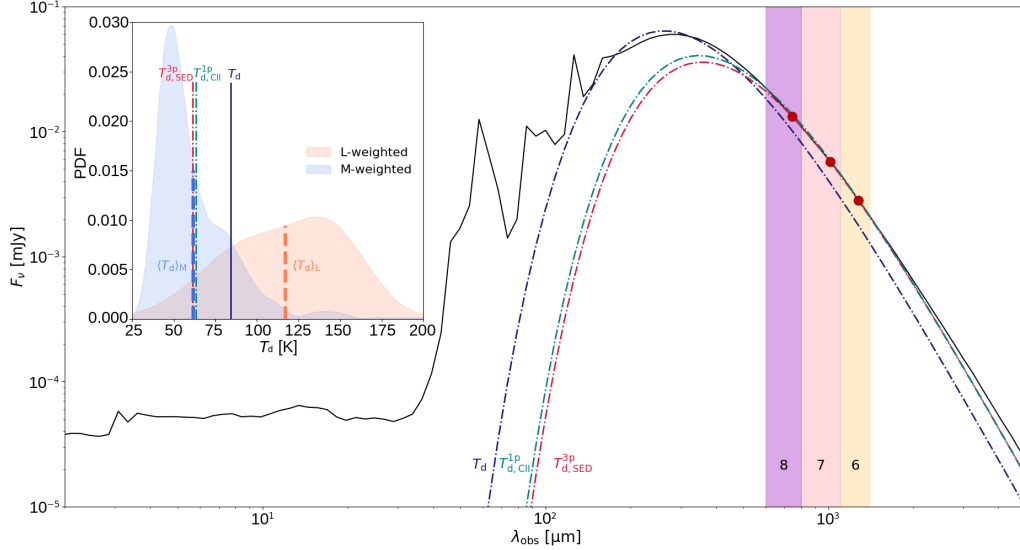


Figure 6.1: SED for the simulated galaxy Zinnia (serra05:s46:h0643, black solid line) extracted from the SERRA simulation suite. The dotted-dashed lines show the curves obtained through a single temperature grey body fitting of the SED, with the two following methods: (a) a canonical SED fitting performed considering the three red “data points” in ALMA bands 6, 7, 8 (red line, $T_{\text{d,SED}}^{3\text{p}}$); (b) same as (a) but considering the full (i.e. MIR and FIR) galaxy SED (blue line, T_{d}); (c) the method presented in this work; it uses a single continuum observation and the [C II] emission (green line, $T_{\text{d,CII}}^{1\text{p}}$). The shaded regions mark the ALMA bands 6 to 8. *Subplot*: comparison among the above dust temperatures values, the luminosity- (orange), and mass-weighted (blue) dust temperature PDFs derived for Zinnia. The PDFs mean values ($\langle T_{\text{d}} \rangle_{\text{L}}$ and $\langle T_{\text{d}} \rangle_{\text{M}}$) are indicated by dashed lines. See the text for a detailed discussion.

corresponding to ALMA band 6, 7, 8 with a single-T grey-body;

- $T_{\text{d,CII}}^{1\text{p}}$: dust temperature obtained with our method combining a single continuum data at 1900 GHz (rest-frame) with the [C II] line emission data, as described in Sec. 3.3;
- $\langle T_{\text{d}} \rangle_{\text{M}}$: M-weighted dust temperature;
- $\langle T_{\text{d}} \rangle_{\text{L}}$: L-weighted dust temperature.

We underline that in all these computations, as in the rest of the paper, we keep the dust emissivity index fixed to $\beta_{\text{d}} = 2.0$. Such an assumption is reasonable as this is close to the emissivity index retrieved from the simulation ($\beta_{\text{d}} = 1.7 - 2$, see [30] for the Radiative Transfer details). Hence, the free parameters in the fitting procedure are the dust temperature and dust mass ($40 \text{ K} \leq T_{\text{d}} \leq 200 \text{ K}$, and $10^3 \text{ M}_{\odot} \leq M_{\text{d}} \leq 10^7 \text{ M}_{\odot}$).

All these temperatures are compared in the subplot in the upper left corner of Fig. 6.1. Our method gives a dust temperature value $T_{\text{d,CII}}^{1\text{p}} = 63.4 \pm 0.5 \text{ K}$, consistent with the result that one obtains with the usual SED-fitting technique using three points corresponding to the available ALMA bands at this redshift, $T_{\text{d,SED}}^{3\text{p}} = 62 \pm 2 \text{ K}$. For this galaxy, the value of $T_{\text{d,SED}}^{3\text{p}} \sim T_{\text{d,CII}}^{1\text{p}}$ is also consistent with the M-weighted temperature, $\langle T_{\text{d}} \rangle_{\text{M}} = 61 \text{ K}$. Instead, both $\langle T_{\text{d}} \rangle_{\text{L}} = 117 \text{ K}$ and $T_{\text{d}} = 84 \text{ K}$ are larger than the previous values as they are more sensitive to the small amount of dust with physical temperatures up to 150 K (see the L-weighted PDF in the subplot of Fig. 6.1).

This comparison shows that the single-T approximation often used might lead to a misinterpretation of the physical properties of the galaxy depending directly on T_{d} . Moreover, whenever theoretical studies and observations are compared, it is necessary to pay particular attention to the definition of the dust temperature used and to the fitting procedure. We suggest that a uniform, meaningful comparison is best performed using either $T_{\text{d,SED}}^{3\text{p}}$

or, as we propose here, $T_{\text{d,CII}}^{1p}$, when only a single measurement is available. It is very reassuring that the two procedures yield essentially the same result. These quantities can be also easily derived from the simulated spectrum, and readily compared with data. In the future, we intend to extend this analysis to the whole SERRA galaxy sample.

6.2 Warm dust in high-z GMCs

In the previous section we discussed the presence of a hot dust component ($T_{\text{d}} > 100$ K) in the $z \sim 6.8$ simulated galaxy Zinnia. This hot dust contributes little to the galaxy dust budget, but dominates the IR emission, resulting in a large difference (~ 50 K) between the L-weighted and M-weighted dust temperatures. This occurrence is observed in several SERRA galaxies [30, 8], where most of the FIR emission comes from the little hot dust located in UV-opaque, star-forming Giant Molecular Clouds (GMCs).

GMC scales ($\lesssim 30$ pc) are unresolved in galaxy's numerical simulations due to the demanding computational times that the most detailed ones (in terms of considered physical processes, and resolution) require [469, 468, 470, 467, 465, 30, 32, 118]. To investigate this further, in Sommovigo+20 [313] we presented a SAM for dust physical and emission properties in local and high- z GMCs. We refer to [221] for a complementary treatment including the diffuse ISM.

6.2.1 A physical model for GMCs

We model GMCs as homogeneous spheres of densities ρ and radius R , characterised by a turbulent velocity with a 3D r.m.s. velocity dispersion σ and pressure p . We assume supersonic turbulence, ($\sigma \gg c_s$, the sound speed of the gas). This simplification is supported by numerical simulation results showing that the ISM of high- z galaxies is highly turbulent [471, 326]. The density ρ can then be written as $\rho = p/\sigma^2$, neglecting the thermal pressure. Assuming that GMCs have mass M , we introduce the virial parameter

$$\alpha_{\text{vir}} = \frac{5\sigma^2 R}{3fGM}, \quad (6.1)$$

where f is a geometrical factor related to the cloud internal density profile. For spherical clouds with a radial density profile $\rho \propto r^{-\gamma}$ it is $f = (1 - \gamma/3)/(1 - 2\gamma/5)$. We assume $f = 1$ for our homogeneous cloud and $\alpha_{\text{vir}} = 5/3$, which is consistent with local observations [472] and simulations of GMCs [473].

The cloud mass, radius, and total hydrogen column density (N_H) can be written as

$$M = \frac{1}{2} \frac{\sigma^4}{\sqrt{G^3 p}} \quad (6.2a)$$

$$R = \frac{1}{2} \frac{\sigma^2}{\sqrt{Gp}} \quad (6.2b)$$

$$N_H = \frac{1}{2\mu m_p} \sqrt{\frac{p}{G}}, \quad (6.2c)$$

where R is the Jeans length, $\mu = 2$ is the mean molecular weight of the gas (we consider only H_2), and m_p is the proton mass. The cloud gas number density can be expressed as $n = \rho/\mu m_p$. Relations among the different quantities that enter in our calculations can be visualised in Fig. 6.2, where we also report the normalised σ -distribution in GMCs found in zoom-in simulations of a typical, simulated high- z galaxy from [31] and [474], Freesia. A comparison between the Milky Way (MW) and Freesia is summarised in Tab. 6.3.

Galaxy	M_{halo} [$10^{11} M_{\odot}$]	$M_{\star}$ [$10^9 M_{\odot}$]	SFR [$M_{\odot}/\text{yr}$]	z	Ref.
MW	10^{+3}_{-2}	60.8 ± 11.4	1.65 ± 0.19	0	(1)
Freesia	0.59	4.2	11.5 ± 1.8	8	(2)

Properties of the Milky Way and simulated high- z galaxy, Freesia. Data taken from (1) [479, 480], and (2) [31].

We note that the r.m.s. dispersion retrieved from this simulation (for further details see [474]¹, and also [328]) spans a range $1 \lesssim \sigma_{\text{kms}} \lesssim 30$, where $\sigma_{\text{kms}} = \sigma/(\text{km s}^{-1})$, and has a median value $\sigma_{\text{kms}} = 15.76$, which is on average higher than what expected from MW-like galaxies at low redshift ($\sigma_{\text{kms}} \sim 5$, see observations by e.g. [475, 476, 472], and simulations by e.g. [477, 473]). Derived GMC pressures in high- z clouds are comparable to those found in the Galactic centre, i.e. $6 \lesssim \log \tilde{p} \lesssim 8$, where $\tilde{p} = p/k_B \text{ cm}^{-3} \text{ K}$, with k_B being the Boltzmann constant. Simulations [31], in agreement with observations [478], also find that the effective radii of galaxies at $z = 6$ are < 1 kpc. In order to exclude unphysically large GMC sizes in our model, we only consider the $p - \sigma$ parameter space satisfying $R < 1$ kpc (i.e. we cut off the white region in Fig. 6.2), corresponding to $\sigma_{\text{kms}} < (p/k_B)^{1/4}$. With these assumptions, our model includes GMC masses in the range $2 \leq \log(M/M_{\odot}) \leq 8$.

6.3 Star formation and H II regions

To determine the *physical* dust temperature in GMCs we need to estimate the star formation rate (SFR), and the associated flux of UV photons heating the dust grains. In addition, it is important to study the effects of H II regions both on GMC dispersal and density structure as a result of the dynamical effects occurring during the H II region evolution. We consider all the stars to be located in the centre of our GMCs.

The SFR can be estimated by assuming a Schmidt-Kennicutt [481, 219] relation,

$$\text{SFR} = \epsilon_{\text{ff}} \frac{M}{t_{\text{ff}}} = \frac{1}{2} \epsilon_{\text{ff}} \frac{\sigma^3}{G} = 10^{-5.9} \sigma_{\text{kms}}^3 M_{\odot} \text{yr}^{-1}, \quad (6.3)$$

where we use the relations given in eq. 6.2 for the cloud mass; $t_{\text{ff}} \propto 1/\sqrt{G\rho}$ is the cloud free-fall time, and $\epsilon_{\text{ff}} \approx 0.01$ is the amount of gas converted in stars within t_{ff} . For the latter value we consider the average computed by [482], who analysed a variety of GMCs observed within the MW. Note that in our model the SFR does not depend on pressure, but only on σ .

In the absence of feedback impairing the star-forming ability of the cloud, eq. 6.3 implies a gas depletion time for the GMC equal to $t_{\text{dep}} \equiv M/\text{SFR}$, or²

$$t_{\text{dep, Myr}} = \frac{t_{\text{ff}}}{\epsilon_{\text{ff}}} = 10.5 \sigma_{\text{kms}} \tilde{p}_8^{-1/2}, \quad (6.4)$$

where $\tilde{p}_8 = \tilde{p}/10^8$. Massive stars produce ionising ($h\nu > 13.6$ eV) photons which create an H II region around the star-forming site. The size of the ionised bubble is set by recombination-ionisation equilibrium, and it is equal to the Strömgren radius R_S :

$$R_S = (3\dot{N}_i/4\pi n_e^2 \alpha_B)^{1/3}, \quad (6.5)$$

¹Data for σ from the simulation are retrieved as a H₂ mass-weighted PDF on a cell by cell basis. For the first moment of the distribution, there are almost no differences with respect to the extraction of data on a cloud by-cloud basis, as shown in [474].

²In this paper we adopt the notation $Y_x = Y/10^x$

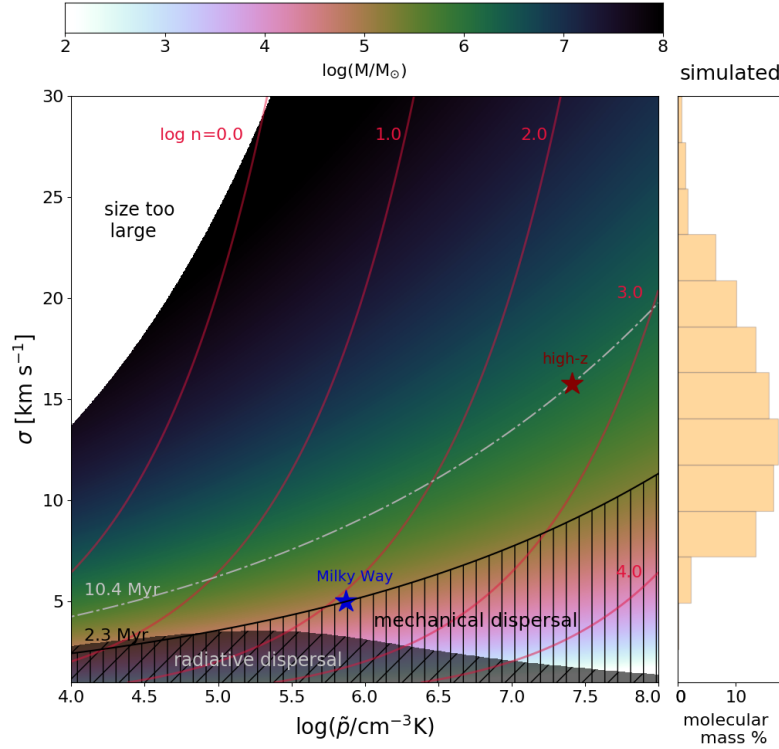


Figure 6.2: Overview of GMC properties: phase-space diagram of pressure versus dispersion for molecular clouds with masses between $10^2 M_\odot$ and $10^8 M_\odot$. The white region corresponds to clouds that have a size larger than 1 kpc. Red lines indicate those clouds with number density $\log n = 0.0, 1.0, 2.0, 3.0$, and 4.0 . The grey region shows the clouds dispersed by the expansion of the H II regions (radiative dispersal) before 4 Myr, while the hatched region indicates those clouds dispersed by either SN explosion or stellar winds (mechanical dispersal) before 2.3 Myr. The blue and brown star marks correspond to a typical GMC in the Milky Way (MW, $\sigma = 5 \text{ km s}^{-1}$, $\tilde{p} = 10^{5.87} \text{ cm}^{-3} \text{ K}$, [477], Decataldo in prep.) and high- z galaxies ($\sigma = 15.76 \text{ km s}^{-1}$, $\tilde{p} = 10^{7.41} \text{ cm}^{-3} \text{ K}$, [31]), respectively. The grey dashed line represents the mechanical dispersal time for typical high- z GMCs ($t_{d,\text{Myr}} = 10.4$) and the black one for the MW-like clouds ($t_{d,\text{Myr}} = 2.3$). In the right vertical panel we report the normalised distribution of the σ in GMCs found in a zoom-in simulation of a typical high- z galaxy [31, Freesia, see].

which is reached after approximately a recombination time,

$$t_r = (n_e \alpha_B)^{-1}. \quad (6.6)$$

In the previous expressions, $\dot{N}_i$ is the ionising photon rate, n_e is the electron number density, and $\alpha_B(T = 10^4 \text{ K}) = 2.6 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ the case-B hydrogen recombination coefficient. As for gas densities $n_e > 1 \text{ cm}^{-3}$, $t_r < 2 \times 10^4 \text{ yr}$, which is much shorter than the evolutionary timescale of the massive stars driving the H II region, we can safely assume that the Strömgen sphere forms instantaneously.

We consider that star formation proceeds in a continuous mode, according to a Salpeter single power-law Initial Mass Function (IMF) with a stellar mass range $1 - 100 M_\odot$. We assume a metallicity $Z = 0.5 Z_\odot$. We then use the population synthesis code Starburst99 [449] and the Geneva tracks [483] to derive the ionising photon rate conversion, $\dot{N}_i = \eta_i \text{ SFR}/M_\odot \text{ yr}^{-1}$, with $\eta_i = 10^{53.4}$. With these assumptions we find

$$R_S = 0.14 \sigma^{7/3} p^{-2/3} = 3.7 \times 10^{-3} \sigma_{\text{kms}}^{7/3} \tilde{p}_8^{-2/3} \text{ pc}. \quad (6.7)$$

Therefore, the H II region size decreases for increasing GMC pressure, shrinking to (sub-)pc scales when $\tilde{p}_8 \gtrsim 1$ (for $\sigma_{\text{kms}} \sim 15$, namely the one of our high- z cloud).

The overpressurised, ionised region begins to expand into the surrounding gas after a sound crossing time, $t_c = R_S/c_i$, where $c_i \approx 10 \text{ km s}^{-1}$ is the sound speed in the

ionised gas. Stated differently, the ionisation front makes a transition from R-type to D-type. It is straightforward to show that the condition $t_r < t_c$ is equivalent to $c_i < n_e \alpha_B (3\dot{N}_i / 4\pi n_e^2 \alpha_B)^{1/3} \sim 43 n^{1/3} \sigma_{\text{kms}} \text{ km s}^{-1}$. Hence, we conclude that the R-type phase always precedes the D-type, under realistic conditions.

6.3.1 GMC dispersal

As H II regions expand, they inject kinetic energy and might ultimately destroy the cloud by dispersing it. In addition to radiation, massive stars produce stellar winds, and ultimately supernova explosions. In the following, we provide separate estimates for these effects in terms of their ability to disrupt the cloud and quench star formation. The timescale on which GMC dispersal occurs is crucial to predict the FIR dust luminosity, as will be discussed in Sec. 6.6.

Dispersal by H II regions

The expansion of the H II region, formed around newly born stars can lead to the dispersal of the cloud. This occurs via two distinct processes: (a) if the Strömgren radius exceeds the GMC radius, $R_S > R$, the ionisation front (IF) is density-bounded and the cloud undergoes essentially free-expansion in the lower pressure diffuse ISM, rapidly dispersing. The timescale for the dispersal is approximately equal to the H II region sound crossing time $t_c = R_S / c_i$; (b) if $R_S < R$, the GMC can still be dispersed during the subsequent D-type expansion of the front, starting at t_c .

By using eq. 6.5, we first determine the conditions for which R_S exceeds the GMC radius, which is given by eq. 6.2. We find that R_S is always smaller than the GMC radius for our assumed values of p and σ . In fact, the condition $R_S > R$:

$$\frac{R_S}{R} = \frac{0.28 \sigma^{7/3} / p^{2/3}}{\sigma^2 / \sqrt{Gp}} > 1 \quad (6.8)$$

implies $n \ll 1 \text{ cm}^{-3}$, corresponding to a cloud radius $> \text{kpc}$ for fixed σ and p , i.e. exceeding the size of a typical galaxy at $z \approx 6$ [478].

Once the IF reaches R_S it makes a transition to a D-type front, in which the warm, ionised gas starts to expand, driving a shock into the surrounding neutral gas. To describe this process we follow the approach by [484]. Assuming that (i) the shock is isothermal, (ii) the gas in the ionised region is uniform and in photo-ionisation equilibrium, we can write the velocity of the IF at radius r as:

$$\frac{1}{c_i} \frac{dr}{dt} = \left(\frac{R_S}{r} \right)^{3/4} - C \left(\frac{r}{R_S} \right)^{3/4}, \quad (6.9)$$

where $C = (c_s^2 + \sigma^2) / (c_i^2 + \sigma^2)$ and c_i , c_s are the sound speeds in ionised and neutral gas, respectively. Note that when $C = 0$ the solution by [485] is recovered, and the H II region expands forever. With the boundary condition $r(t = 0) = R_S$, eq. 6.9 can be integrated analytically to obtain:

$$t' = \frac{1}{3C^{7/6}} [q(y) - q(1)] \quad (6.10a)$$

with $y = r/R_S$, $t' = t \sqrt{c_i^2 + \sigma^2} / R_S$, and

$$\begin{aligned} q = & -12 C^{1/6} y^{1/4} + 2 \sqrt{3} \arctan \left(\frac{\sqrt{3} C^{1/6} y^{1/4}}{1 - C^{1/3} y^{1/2}} \right) + \\ & + \ln \left[\frac{(C^{1/3} y^{1/2} + C^{1/6} y^{1/4} + 1)(C^{1/6} y^{1/4} + 1)^2}{(C^{1/3} y^{1/2} - C^{1/6} y^{1/4} + 1)(C^{1/6} y^{1/4} - 1)^2} \right]. \end{aligned} \quad (6.10b)$$

We now determine the stalling radius (r_e) where the H II region expansion stops. The surviving clouds are those for which $r_e < R$. Those not fulfilling this condition are (radiatively) dispersed over the timescale $t'(r_e/R_S)$ given by eq. 6.10a. In Fig. 6.2 we identify GMCs with $t < 4$ Myr as the black hatched region. From the above analysis we conclude that H II regions can only disperse relatively small, $M \leq 10^5 M_\odot$, weakly turbulent ($\sigma < 5$ km/s) clouds.

Dispersal by stellar winds and supernovae

Supernova (SN) explosions and stellar winds can disperse GMCs by accelerating gas to speeds exceeding the cloud escape velocity, v_e . The number of supernovae produced by a given SFR at time t can be written as

$$N_{\text{SN}}(t) = \Theta(t - t_{\text{SN}}) \nu_{\text{SN}} \text{SFR } t = 0.02 \sigma_{\text{kms}}^3 t_{\text{Myr}} \Theta(t - t_{\text{SN}}), \quad (6.11)$$

where $\nu_{\text{SN}} = (53 M_\odot)^{-1}$ is the number of SNe per solar mass of stars formed [246]; the Heaviside function, $\Theta(t - t_{\text{SN}})$, accounts for the mass-dependent delay between the onset of star formation and the SN explosion. We consider as a lower limit $t_{\text{SN}} \sim 3$ Myr, which roughly corresponds to the lifetime of a $100 M_\odot$ star [486], i.e. the largest mass in our IMF range. The energy released in kinetic form is then

$$E_{\text{SN}}(t) = f_{\text{SN}} E_0 N_{\text{SN}}(t) = 2 \times 10^{48} \sigma_{\text{kms}}^3 t_{\text{Myr}} \Theta(t - t_{\text{SN}}) \text{ erg}. \quad (6.12)$$

We have assumed a kinetic-to-total energy efficiency $f_{\text{SN}} \approx 0.1$ and a standard SN explosion energy of $E_0 = 10^{51}$ erg.

Before the SN explosion, a large amount of kinetic energy is also produced by stellar winds of massive stars,

$$E_{\text{w}}(t) \simeq \frac{1}{3} E_{\text{SN}} = 0.67 \times 10^{48} \sigma_{\text{kms}}^3 t_{\text{Myr}}, \quad (6.13)$$

where the ratio of 1/3 with respect to the SN explosion energy is taken from Starburst99. The total mechanical energy is thus $E = E_{\text{SN}} + E_{\text{w}}$.

Using eq. 6.2, the escape velocity of GMCs can be written as a function of σ as:

$$v_e^2 = \frac{2GM}{R} = 2\sigma^2. \quad (6.14)$$

For the dispersal condition, we require that the kinetic energy is sufficient to accelerate the GMC gas mass to v_e , i.e. $E \geq 0.5 M v_e^2$. This condition defines a dispersal time t_d , at which the cloud becomes unbound, and its gas returns to the diffuse phase. Using the above relations we find

$$t_{d,\text{Myr}} = \frac{t_{d',\text{Myr}}}{\Theta(t_{d',\text{Myr}} - t_{\text{SN,Myr}}) + 1/3}, \quad (6.15)$$

where $t_{d',\text{Myr}} = 1.94 \times 10^{-3} \sigma_{\text{kms}}^3 \tilde{p}_8^{-1/2}$ would be the dispersal time assuming that SNe explode at $t_{\text{SN}} = 0$. Thus, for the expected pressure in high- z galaxies ($\tilde{p} \simeq 3 \times 10^7$), GMCs with $\sigma_{\text{kms}} \leq 15.76$ are dispersed in ≤ 10.4 Myr, while in the MW ($\tilde{p} \simeq 7 \times 10^5$) typical GMCs with $\sigma_{\text{kms}} \leq 5$ are dispersed in ≈ 2.3 Myr. However, MW clouds can last for 17 Myr if we consider $\sigma_{\text{kms}} \approx 10$, i.e. for clouds with $M \sim 10^6 M_\odot$ at the typical MW pressure. Our estimates are consistent with the recent cosmological zoom-in simulations of MW-like galaxies by [487]. The authors measure the lifetimes of GMCs with masses above $\geq 10^5 M_\odot$, finding average values below 7 Myr, with less than 1% of clouds living longer than 20 Myr.

Before dispersal at time t_d (eq. 6.15), dust in the GMC efficiently reprocesses the UV light of the stars into FIR emission. When the GMC is finally dispersed, the dust is ejected into

the diffuse ISM on much larger scales, thus drastically decreasing its UV optical depth and quenching the FIR emission.

The fraction of GMC gas converted into stars ($f_* = M_*/M$) before dispersal can be derived by combining eqs. 6.4 and 6.15:

$$f_* = \frac{t_d}{t_{\text{dep}}} = \frac{1.8 \times 10^{-4} \sigma_{\text{kms}}^2}{\Theta(t_{d,\text{Myr}} - t_{\text{SN,Myr}}) + 1/3}. \quad (6.16)$$

Thus, f_* vary from about 1.4% for a MW-like cloud to 3.2% for GMCs in high- z galaxies. This is yet another consequence of the higher turbulence level predicted for these systems. Since the GMC mass fraction converted into stars is low, we assume that the cloud density does not change with time due to star-formation activity. We note that these are lower limits for the number of stars formed since we are considering the average free-fall time, neglecting the likely presence of local density inhomogeneities (“clumps”, see e.g. [477]). These structures may contribute significantly to star formation on very short time scales since $t_{\text{ff}} \propto \rho^{-1/2}$.

The above estimates can be seen as a rough approximation as some unwarranted assumptions have been made. First, eq. 6.8 neglects radiative losses which are likely to occur during the blastwave evolution. Second, off-centre SNe might induce blisters which are not described by our simple geometry. Finally, the stochastic sampling of the IMF might result in values of ν_{SN} which are different from the average one assumed here. Despite these simplifications, eq. 6.15 provides some useful guidance for the problem at hand, although we leave a more refined treatment to future work.

6.4 Dust model

Following [15], we model dust grains as constituted by a mixture of silicate and carbonaceous grains with a relative mass ratio $\approx 11 : 1$ [186, 180]. Grains are assumed to be spherical with radii in the range $10^{-3} \mu\text{m} < a < 1 \mu\text{m}$ and with a size distribution given by WD01:

$$\frac{dN^j}{da} \frac{1}{N_{\text{H}}} = \frac{C_s}{a} \left(\frac{a}{a_{\text{t,s}}} \right)^{\alpha_s} F(a, \beta_s, a_{\text{t,s}}) G(a, a_{\text{t,s}}, a_{\text{c,s}}), \quad (6.17a)$$

where $(C_s, a_{\text{t,s}}, a_{\text{c,s}}, \alpha_s, \beta_s)$ are five parameters used to fit the observed extinction curves. In particular, we adopt the extinction curve appropriate for the MW with $R_V = A_V/(A_B - A_V) = 3.1$ where A_B and A_V are the extinctions measured in the B (4400 Å) and V (5500 Å) spectral bands, respectively. In general, the Small Magellanic Cloud (SMC) is considered a fair local analogue for high- z galaxies because of its low metallicity. Nevertheless, there is no conclusive evidence that high- z dust should be SMC-like [190, 488, 273, 30, 277]. For this reason, and to allow a direct comparison with local GMCs, we adopt a MW-like dust grain-size distribution and extinction curve. Moreover, we present results only for silicate grains since the contribution of carbonaceous grains is found to be negligible. We neglect the effect of coagulation and grain growth by accretion of gas-phase metals occurring in dense environments, which might result in larger grains.

Under these assumptions, the functions $F(a, \beta_s, a_{\text{t,s}})$ and $G(a, a_{\text{t,s}}, a_{\text{c,s}})$ take the following form:

$$F = \begin{cases} 1 + \beta_s \left(\frac{a}{a_{\text{t}}} \right) & \beta_s \geq 0 \\ \left[1 - \beta_s \left(\frac{a}{a_{\text{t}}} \right) \right]^{-1} & \beta_s < 0 \end{cases} \quad (6.17b)$$

$$G = \begin{cases} 1 & 3.5 \text{ Å} < a < a_{\text{t,s}} \\ e^{-[(a-a_{\text{t,s}})/a_{\text{c,s}}]^3} & a > a_{\text{t,s}} \end{cases} \quad (6.17c)$$

6.4.1 Radiation pressure in dusty H II regions

So far we have considered H II regions only in relation to their eventual dispersal of the GMCs. However, H II regions can also modify the dust and gas spatial distribution. For instance, radiation pressure from the internal sources, drags both dust and gas outwards (more or less efficiently depending on the strength of the radiation field), resulting in lower central densities. We now intend to modify our previous assumption of a uniform GMC gas/dust density profile by taking into account this effect. We follow the approach by [489], which assumes that the dust-to-gas ratio remains constant throughout evolution. This is equivalent to assuming that dust is well coupled to the gas so that the radiation pressure acting on the dust directly determines the gas motion. This assumption is valid once the grains approach their terminal velocities (i.e. negligible acceleration). For gas densities $n > 10 \text{ cm}^{-3}$, and grain sizes in the range $10^{-3} \mu\text{m} \leq a \leq 1 \mu\text{m}$, the time needed for grains to approach their terminal velocity – see eq. 28 in [489], is a few tens of years³. This is much shorter than the timescales of interest here. So we conclude that grains can be safely assumed to be perfectly coupled to the gas.

We can then assume that the gas is in dynamical equilibrium so that the force per unit volume from radiation pressure is balanced by the pressure gradient:

$$n\sigma_d \frac{[L_n e^{-\tau} + L_i \phi(r)]}{4\pi r^2 c} + \alpha_B n^2 \frac{\langle h\nu_i \rangle}{c} - \frac{dp}{dr} = 0 \quad (6.18a)$$

where σ_d the dust scattering and absorption cross-section per H nucleus averaged over the radiation field. $L_i \phi(r)$ is the power in ionising photons ($h\nu_i \geq 13.6 \text{ eV}$) crossing a sphere of radius r , and L_n the one in non-ionising photons (the central cluster UV luminosity is then equal to $L_n + L_i = L_{\text{UV}}$). The function $\phi(r)$ and the dust absorption optical depth at the distance r (integrated over wavelength) $\tau(r)$ are determined by the differential equations:

$$\frac{d\phi}{dr} = -\frac{1}{N_i} \alpha_B n^2 4\pi r^2 - n\sigma_d \phi, \quad (6.18b)$$

$$\frac{d\tau}{dr} = n\sigma_d, \quad (6.18c)$$

with boundary conditions $\phi(0) = 1$, and $\tau(0) = 0$. Following the computation by [489], we numerically solve the system eqs. 6.18, fixing the pressure at the edge of the H II region, p , and N_i to the corresponding values for the MW and high- z clouds.

The resulting⁴ density profile $n(r)/n$, normalised to our homogeneous Jeans cloud density n , is shown in the upper panel of Fig. 6.4 for the high- z GMC. The (normalised) dust number density drops almost to zero for distances $\log x < -1.2$, and reaches ≈ 3 at the Strömgen radius R_S ; outside the H II region the dust profile remains unaffected with respect to the uniform cloud case.

6.5 Dust temperature in GMCs

We now compute the dust temperature, T_d , by balancing the dust photoheating rate⁵, $\dot{E}_+$, with the emission rate, $\dot{E}_-$. To this aim, we consider GMCs to be constituted by a

³More precisely, for the largest (slowest) grains in the two clouds we find $\tau_{\text{drag,MW}} = 43 \text{ yr}$, and $\tau_{\text{drag,hz}} = 11 \text{ yr}$

⁴The above density profiles refer to a steady-state solution of the equations. Hence we have to ensure that the timescale to reach such a configuration is shorter than, for instance, the lifetime of massive stars. We compute the grain velocity due to radiation pressure, $v(r)$, by solving the momentum equation, $(L_{\text{UV}}/4\pi r^2 c)\pi a^2 Q_{\text{abs}} = m_g v(dv/dr)$, where $m_g = (4\pi/3)\delta_g a^3$ is the mass of a grain of bulk density is $\delta_g \approx 3 \text{ g cm}^{-3}$. We estimate the transient timescale as $\Delta t \approx R_S/v(R_S)$, finding $\Delta t \ll 1 \text{ Myr}$. Hence, we can safely assume that the steady-state solution is instantaneously reached.

⁵We neglect collisional heating.

series of concentric shells of dust and gas of radius $r = xR$, with a fixed dust-to-gas ratio $D = 0.01$. We then compute the temperature of a dust grain located in the shell at radius x , $T_d(x, a)$, for different values of the grain size in the range $10^{-3} \mu\text{m} < a < 1 \mu\text{m}$. We adopt the internal radiation field provided by newly formed stars, F_{int} , as the only UV radiation source. For the photoheating rate, we get

$$\dot{E}_+ = \int_{100\text{\AA}}^{4000\text{\AA}} \pi a^2 Q_{\text{abs}}(\lambda, a) (1 - e^{-\tau_{\text{shell}}}) F_{\text{int}} d\lambda, \quad (6.19a)$$

$$F_{\text{int}} = \frac{L_\lambda}{\pi(xR)^2} e^{-\tau_\lambda}. \quad (6.19b)$$

The integral runs over the range $100 \text{ \AA} < \lambda < 4000 \text{ \AA}$ since the UV flux out of this range contributes negligibly to grain heating in actively star-forming systems [490]. L_λ is the specific luminosity of the central cluster; using the SFR of our clouds (eq. 6.3) we can write $L_{1500\text{\AA}} = \eta_{1500\text{\AA}} \text{ SFR}$ and compute $\eta_{1500\text{\AA}}$ using Starburst99 (see Sec. 6.3 for the detailed assumptions). We find that $\eta_{1500\text{\AA}}$ increases with the cloud lifetime, ranging from $10^{41.8} \text{ erg s}^{-1}/\text{M}_\odot \text{ yr}^{-1}$ at 0.4 Myr of the cloud age, to $10^{43.1} \text{ erg s}^{-1}/\text{M}_\odot \text{ yr}^{-1}$ at 10 Myr. The dust optical depth can be written as:

$$\tau_\lambda = [\tau_\lambda]_0^R = \int_0^R n(r) dr \int_{a_{\text{min}}}^{a_{\text{max}}} \pi a^2 Q_{\text{abs}}(\lambda, a) \frac{dN}{da}(a) da. \quad (6.20)$$

Within a shell at radius r , and width $2dr$, the optical depth is $\tau_{\text{shell}} = [\tau_\lambda]_{r-dr}^{r+dr}$. dN/da is the grain size distribution given in eq. 6.17, and $n(r)$ is the number density of the cloud, which is either uniform, or is computed via eq. 6.18a when taking into account the effect of radiation pressure.

The grain radiates energy at a rate given by:

$$\dot{E}_- = 4\pi \int_0^\infty \frac{4}{3} \pi a^3 \delta_g B_\lambda(T_d) k_\lambda d\lambda, \quad (6.21)$$

where B_λ is the Planck function and $k_\lambda(\lambda)$ the opacity per unit mass, which can be well approximated by a power law (for $\lambda > 20 \mu\text{m}$) as in [186]:

$$k_\lambda(\lambda) = k_* \left(\frac{\lambda}{\text{cm}} \right)^{-\beta_d} \quad (6.22)$$

the constant of proportionality in the MW extinction curve corresponds to $k_* = 2.47 \times 10^{-3} \text{ cm}^2/\text{g}$. Estimates of the power slope found in literature span the range $1 \leq \beta_d \leq 2.5$ [491, 492, 493, 494, 495, 496]; here we adopt $\beta_d = 2$ as in [186]. The equilibrium temperature⁶ $T_d(a, \beta, \Sigma_\lambda)$ can be then obtained by imposing $\dot{E}_+ = \dot{E}_-$. Furthermore, we take into account the effect of the Cosmic Microwave Background (CMB) acting as a thermal bath. We always correct the dust temperature [499]:

$$T'_d = \{T_d^{4+\beta_d} + T_0^{4+\beta_d} [(1+z)^{4+\beta_d} - 1]\}^{1/(4+\beta_d)}, \quad (6.23)$$

where $T_0 = 2.73 \text{ K}$ is the CMB temperature at $z = 0$.

In Fig. 6.3 we show the results for T_d with/without the effects of radiation pressure on the dust density, for the typical grain radius $a = 0.1 \mu\text{m}$. We compare dust temperatures for the prototypical MW and high- z GMC (blue and brown star in Fig. 6.2, respectively) at 0.4 Myr of stellar age, i.e. well before stellar feedback effects start to play a role. In the following, we analyse separately the results for uniform clouds and the case including radiation pressure due to UV radiation.

⁶Very small grains might undergo stochastic temperature fluctuations [497, 498]. We neglect this effect in the paper, although we recognise that it might influence the observed emission under certain conditions.

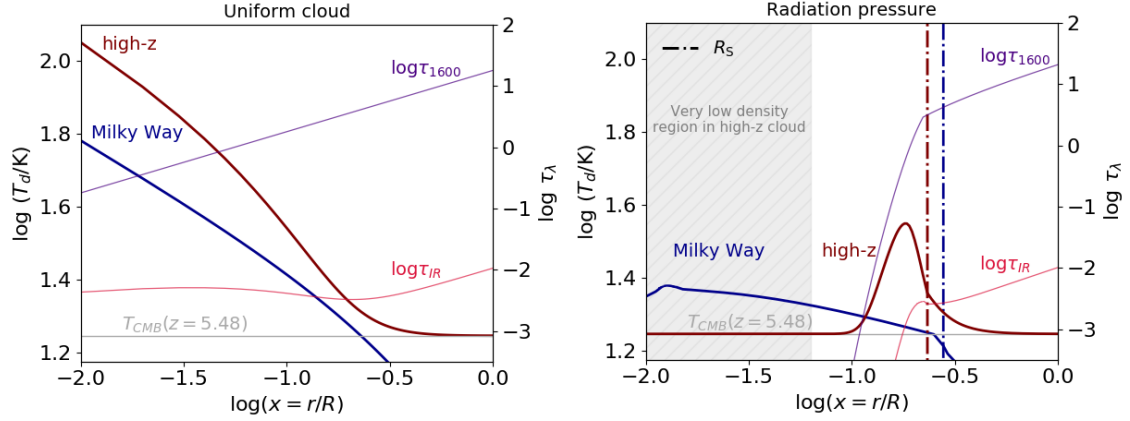


Figure 6.3: Dust temperature vs. normalised distance from the centre of the cloud for typical grains with radius $a = 0.1 \mu\text{m}$. *Left panel:* Case of a uniform GMC in which radiation pressure effects have been neglected. Blue and brown lines show the dust temperature profiles for a MW-like and high- z GMC, respectively. The properties of the two GMCs are the same as those marked as blue and brown stars in Fig. 6.2, and the stellar age is 0.4 Myr. The thin lines show respectively the values of the optical depth at $1600\text{\AA}$ (purple) impinging on dust grains at various distances from the centre of the cloud, and at the optical depth corresponding to the IR peak wavelength of emission λ_{peak} (red, see text) for the high- z GMC. *Right:* as the left panel, but the model takes into account the radiation pressure. The dashed-dotted lines represent the location of the boundary of the H II region in the MW and high- z like cloud.

6.5.1 Uniform cloud

In the left panel of 6.3, we show that in the central region of uniform clouds ($\log x < -1$), dust is warmer by $\Delta T_d \sim 50 \text{ K}$ in high- z GMCs with respect to MW ones. The higher pressure of high- z GMCs results in larger N_H and τ values; radiation is more efficiently absorbed in the vicinity of the source, and therefore dust becomes warmer⁷. To show this more quantitatively, we have plotted in Fig. 6.3 the optical depth $\tau_{1600\text{\AA}}$ as a function of x . The dust mass heated by the internal source is essentially that contained within a radius, r_d , such that $\tau_{1600\text{\AA}}(r_d) = 1$. For clouds with higher p , r_d decreases accordingly because of the higher column density (see eq. 6.2), resulting in higher dust temperatures. This finding provides the physical basis to interpret the simulation results by [30]. The authors, in fact, noticed that the galaxy regions with the highest dust temperature, which contribute to most of the FIR radiation, are optically thick.

Differences between early and local GMCs are also seen in the external layers ($\log x \gtrsim -0.5$). Due to the absorption of the UV radiation within the cloud, and in the absence of an external radiation field (such as the interstellar radiation field), T_d drops at the surface of the cloud down to the CMB temperature. The CMB acts as a thermal bath, setting a temperature floor for the dust around 20 K at $z \gtrsim 6$ (see eq. 6.23). This effect is sub-dominant in the central regions of the GMC, where dust reaches higher temperatures $T_d \gg T_{\text{CMB}}$. In Fig. 6.3 we computed the CMB correction for $z = 5.48$, i.e. the mean redshift of the [89] sample.

We can understand these results in simple physical terms. Let us assume that the amount of dust heated by the internal radiation field is that contained within r_d , the distance at which the dust optical depth is $\tau_{1600\text{\AA}} \approx 1$. For a gas of solar metallicity ($Z = Z_\odot$) and dust-to-gas ratio $\mathcal{D} = \mathcal{D}_\odot = 0.01$, the condition $\tau_{1600\text{\AA}} = 1$ is reached for a column density $N_1 = 1.4 \times 10^{21} \text{ cm}^{-2}$. By using eq. 6.2, we find that the dust content within r_d is

$$M_d(r_d) = \mathcal{D}(\mu m_p)^3 N_1^3 \frac{\sigma^4}{p^2}. \quad (6.24)$$

⁷Although the higher SFR in the high- z cloud results in a larger F_{int} , this does not imply a higher T_d . We show below (eq. 6.25) that the dust temperature in the GMC is virtually independent of the SFR.

As the UV light is completely absorbed by dust within r_d and re-emitted at FIR wavelengths, we can write $L_{\text{FIR}} \sim L_{1500\text{\AA}} = 10^{2.9} \sigma_{\text{kms}}^3 L_{\odot}$. We can finally derive the dust temperature by adapting to our dust model the formula from [500],

$$T_d = 3.24 \left(\frac{L_{\text{FIR}}/L_{\odot}}{M_d/M_{\odot}} \right)^{1/6} \text{ K} = 122 \tilde{p}_8^{1/3} \sigma_{\text{kms}}^{-1/6} \text{ K}. \quad (6.25)$$

This result shows that star-forming GMCs at higher pressure contain hotter dust. For example, for a pressure $p/k_B = 10^{7.41} \text{ erg cm}^{-3} \text{ K}$, and $\sigma_{\text{kms}} = 15.76$ (typical of high- z simulated galaxies, [31]), we find $T_d \sim 50 \text{ K}$, in good agreement with the numerical result in Fig. 6.3. Although velocity dispersion modifies the dust temperature as well, its effect is less relevant than pressure. As already mentioned, T_d is virtually independent of SFR: as $\sigma \propto \text{SFR}^{1/3}$, from eq. 6.25 we deduce $T_d \propto \text{SFR}^{-1/18}$. Hence pressure is the primary factor controlling dust temperature. Thus, the physical explanation for the higher T_d in high-pressure environments is related to the limited amount of dust required to block the UV radiation. Dust located outside r_d cools to the CMB temperature as the flux from the stars is largely blocked.

So far we have assumed that the GMC is optically thin with respect to the FIR radiation. We motivate such choice by showing in Fig. 6.3 the optical depth τ_{FIR} at the peak wavelength of emission, computed from Wien's law: $\lambda_{\text{peak}} T_d(x) = 0.29 \text{ cm K}$. We find that $\tau_{\text{FIR}} \ll 1$, i.e. dust is optically thin with respect to its FIR emission, even at this very high density. Indeed, we can understand this by considering the optical depth at $100 \mu\text{m}$ from [186]: $\tau_{100 \mu\text{m}}/N_H = 5.07 \times 10^{-25}$, hence⁸ in order to have $\tau_{100 \mu\text{m}} = 1$, $N_H = 1.9 \times 10^{24} \text{ cm}^{-2}$. Using eq. 6.2, we can compute the pressure needed to reach such a value in our GMCs and we find $\tilde{p}_8 = 64$ which is outside the considered range. If these high pressures were to be reached, dust might become optically thick to FIR emission as well [501, 502].

6.5.2 Radiation pressure-modified density profile

Next, we consider dust temperature variations associated with the density redistribution induced by radiation pressure on dust described in Sec. 6.4.1. The obtained profiles of the dust temperature as a function of the distance are shown in the right panel of Fig. 6.3. By comparing with the uniform cloud (left panel), we see that the inclusion of radiation pressure decreases T_d : for the high- z (MW) cloud T_d spans the range $17 - 40 \text{ K}$ ($2.73 - 25 \text{ K}$). The lower T_d in both cases is associated with the fact that dust is pushed to larger distances from the UV source where the flux is more geometrically diluted. We note that the resulting central region devoid of dust is much wider in the high- z GMC, where it extends up to $\log x = -1.2$ (see the grey hatched region). In the MW cloud, this region is much smaller, $\log x \sim -3$. This is due to the larger UV luminosity resulting from the higher SFR, in turn, associated with larger dispersion in the high- z GMC ($\text{SFR} \propto \sigma^3$, see eq. 6.3). In both cases (high- z and MW clouds) the external layers are unaffected by the presence of the internal sources since the emitted radiation has already been absorbed within the cloud. Hence, no appreciable differences with respect to the uniform density case are found at large distances (in the absence of the external interstellar radiation field). The dust temperature depends also on grain size, a , as shown in Fig. 6.4 in the case of the high- z cloud. We can isolate the terms related to the grain size in the photoheating and emission rates (eq. 6.21 and 6.19b), and find that $T_d \propto [Q_{\text{abs}}(\lambda, a)/a]^{1/6}$. The dependence of T_d on wavelength and grain radius is non-monotonic. Blueward of $\lambda = 1500 \text{ \AA}$ smaller grains are more efficiently heated; at longer wavelengths $2000 \text{ \AA} < \lambda < 3500 \text{ \AA}$, intermediate grains with $a \sim 0.1 \mu\text{m}$ have the highest Q_{abs} value. This has a noticeable effect on the dust grains temperatures at different radii in the GMC.

⁸As a reference, the column density at the surface of our typical high- z cloud is $N_H = 3.7 \times 10^{22} \text{ cm}^{-2}$.

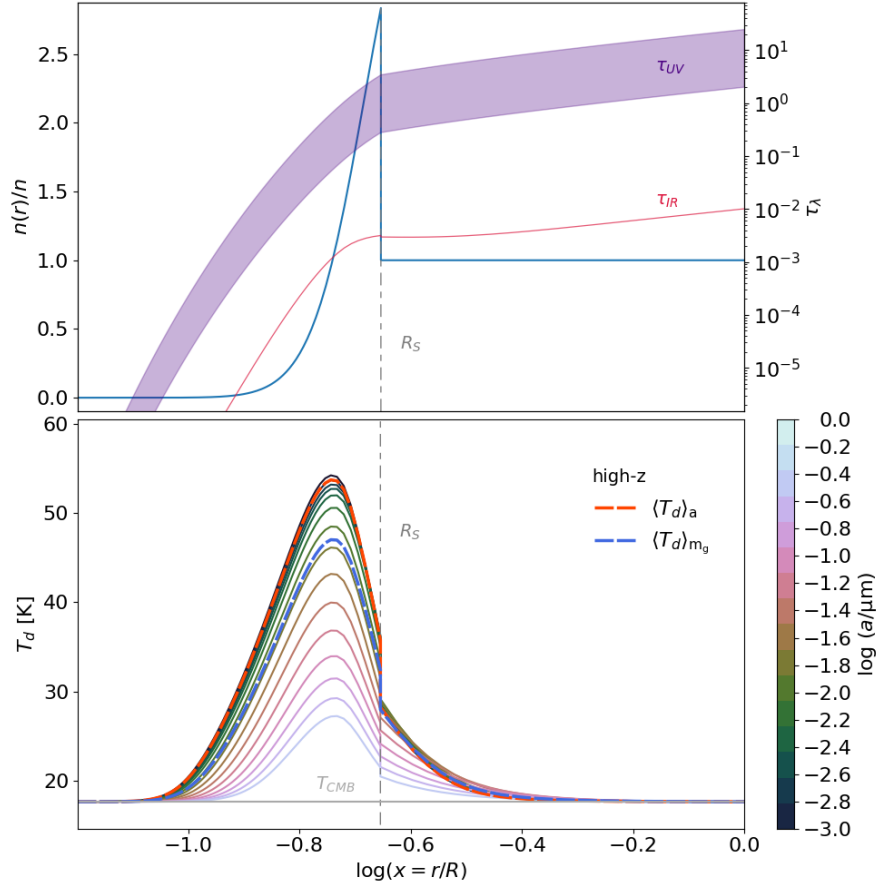


Figure 6.4: *Upper panel:* Dust density modified by the radiation pressure in the high- z GMC as a function of the normalised distance x from the centre. We also show the dust optical depth to UV radiation in the wavelength range $1500 \text{ \AA} < \lambda < 3100 \text{ \AA}$ (purple shaded region, computed via eq. 6.20), along with the dust IR optical depth (red solid line) at the peak emission wavelength. *Bottom:* Grain temperature for the high- z GMC as a function of radial distance from the centre and for different grain radii, colour-coded in the colourbar. The dashed line shows the size-averaged temperature, $\langle T_d \rangle_a$. We consider a cluster stellar age 0.4 Myr.

While within the H II region the photo-heating rate is dominated by short-wavelength UV radiation with $\lambda < 2000 \text{ \AA}$, radiation with longer wavelengths ($\lambda \gtrsim 3000 \text{ \AA}$) takes over in the external neutral layers. As a result, near the centre of the cloud ($\log x < -0.6$), the small grains, $a \sim 10^{-3} \mu\text{m}$, are the hottest, reaching $T_d > 50 \text{ K}$. At the GMC surface, instead, intermediate-size grains, $a \sim 0.1 \mu\text{m}$, attain the highest temperatures. These trends are clearly visible in the bottom panel of Fig. 6.4, where we also show the size-averaged temperature $\langle T_d \rangle_a$ and grain mass-averaged temperature $\langle T_d \rangle_{m_g}$ (averaged over $dN/da \times 4\pi a^2 da$). At the surface of the cloud, independently of the grain size, the dust temperature converges to the CMB temperature due to the very high optical depth (see the purple shaded region in fig. 6.4 for the dependence of the grain size-averaged UV optical depth on the distance from the centre of the cloud).

We pause here for a remark. We considered the same continuous SFR described in Sec. 6.3 also in the radiation pressure modified density profile treatment. This is clearly an approximation since the reduction in the central density of the cloud (shown in the upper panel of Fig. 6.4) actually affects the SFR, which is proportional to gas density. However, star formation is distributed all over the cloud, and not just in its centre (as shown also by recent fully resolved simulations, see Decataldo in prep.). Therefore, the average SFR over the whole cloud will not necessarily change considerably, despite the local density drop. Although this approximation over the SFR has been introduced, we prefer to include

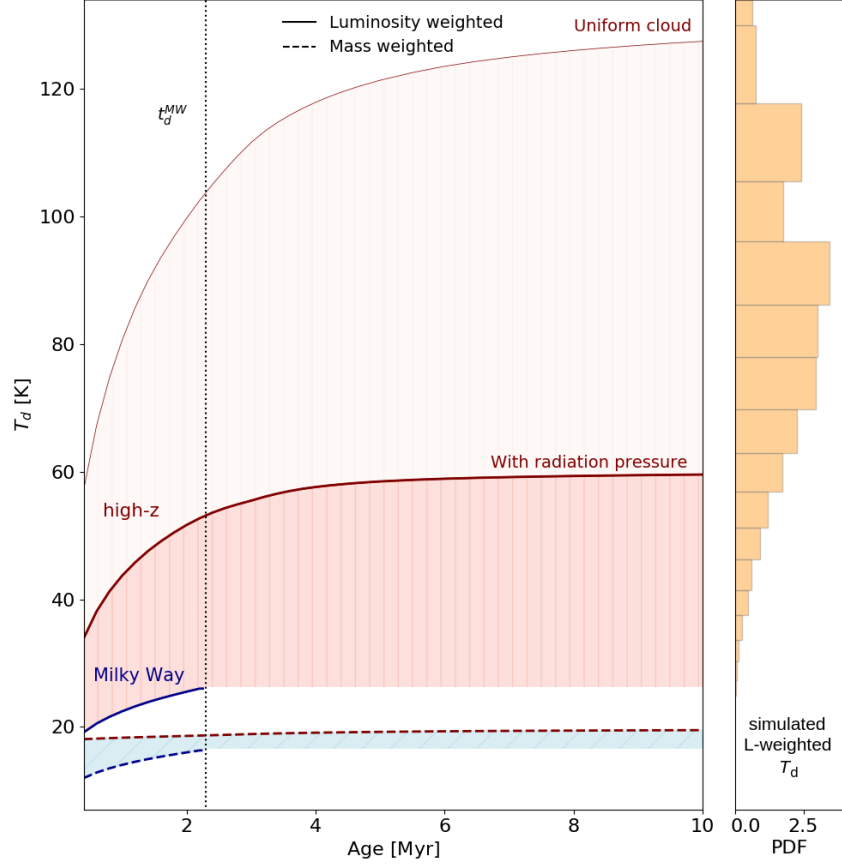


Figure 6.5: Mass weighted $\langle T_d \rangle_M$ (dashed line) and luminosity weighted $\langle T_d \rangle_L$ (solid line) dust temperatures at various ages of the cluster and host GMC (see Sec. 6.5.2). The blue line corresponds to the MW cloud, while the brown one to the high- z cloud, already described in Fig. 6.2. For the thick lines we always consider the effect of radiation pressure, and we account for the stellar emission evolution until the dispersal of the clouds, which happens at different times in the two cases (see Sec. 6.3.1). The thin brown line corresponds to the uniform high- z cloud case, instead. The grey dotted line represents the dispersal time of the MW cloud. The vertical panel shows the normalised distribution of the luminosity-weighted dust temperatures in the simulations by [30].

radiation pressure in our models, since we have shown that it alters considerably our predictions on dust temperatures. Moreover, we underline that our main goal is to give a lower limit for the dust temperature in GMCs, and to show how this lower bound evolves from low to high- z . The radiation pressure case gives a lower temperature value with respect to the homogeneous case, and yet a higher T_d with respect to what so far assumed at high- z .

Mass- and luminosity- weighted dust temperature

From the above results, we can compute the mass-weighted, $\langle T_d \rangle_M$, and luminosity-weighted, $\langle T_d \rangle_L$, dust temperature as a function of the age of the stellar cluster accounting for the associated evolution of the UV luminosity (taken from Starburst99 with the usual assumptions on the SFR and metallicity, see Sec. 6.3). We compute T_d in the time interval $0 - t_{d, \text{Myr}}$, where $t_{d, \text{Myr}}$ is the GMC lifetime against dispersal caused by feedback processes (Sec. 6.3.1). As usual, in Fig. 6.5 we compare high- z and MW GMCs.

For the high- z cloud, most of the dust mass is in thermal equilibrium with the CMB, $\langle T_d \rangle_M^{\text{hi-}z} \sim T_{\text{CMB}}$. However, a small fraction of the dust located near the UV source is much hotter and contributes strongly to the luminosity-weighted temperature. Indeed, we find $\langle T_d \rangle_L^{\text{hi-}z} \sim 60 \text{ K} \gg \langle T_d \rangle_M^{\text{hi-}z}$ at 10 Myr of the central cluster stellar age. The luminosity-

weighted temperature is of particular importance as it represents a good proxy for the dust temperature that would be inferred from the SED fitting of the source. Neglecting the effects of radiation pressure, would lead to even higher temperatures, $\langle T_d \rangle_L^{\text{hi-z}} \sim 100$ K. This is because more dust would be found in the proximity of the source (at $\log x < -1$), as already discussed (see Sec. 6.5.2). The MW GMC is instead much colder, with $\langle T_d \rangle_M^{\text{MW}} \leq 15$ K and $\langle T_d \rangle_L^{\text{MW}} < 30$ K. This is because at $z = 0$ (i) the CMB temperature sets a much lower floor for T_d , and (ii) the more diffuse structure of the cloud results in a less efficient dust heating (see Sec. 6.5.1). We will return to this point in the following Section.

6.6 Infrared emission from GMCs

We predict the infrared luminosity of our star-forming GMCs by using the above grain mass-averaged temperature $\langle T_d \rangle_{\text{mg}}$ (blue dashed line in Fig. 6.4), and weighting the contribution of each shell by its dust mass, $m_{\text{d,shell}}$:

$$L_\lambda^i = \frac{8\pi hc^2}{\lambda^5} \frac{k_\lambda}{M_d} \int_0^1 \frac{m_{\text{d,shell}}(x)}{\exp(hc/k_B \langle T_d \rangle_{\text{mg}} \lambda) - 1} dx. \quad (6.26)$$

The comparison between the high- z and MW cloud is shown in Fig. 6.6 at the stellar age of 0.4 Myr. As expected, the IR emission from the high- z cloud is ~ 30 times stronger due to its higher star formation rate, entailing a stronger UV field within the cloud. In fact, the SFR in the two GMCs differs by a factor $\approx 30\times$ ($\text{SFR}^{\text{hi-z}} = 4.8 \times 10^{-3} \text{ M}_\odot \text{yr}^{-1}$ vs. $\text{SFR}^{\text{MW}} = 1.5 \times 10^{-4} \text{ M}_\odot \text{yr}^{-1}$). Note that the different T_d shifts the emission peak from $100 \mu\text{m}$ (MW) to $\sim 47 \mu\text{m}$ at high- z .

Moreover, we fit the above IR spectra to compare the recovered temperature with the luminosity-weighted dust temperature from the model. As discussed in the Introduction, the two should correspond. Nevertheless, this sanity check is important since dust temperature in our model has a distribution depending on the grain size and position within the GMC. In the fitting procedure, we use a single temperature grey body function $B_\lambda(T_d)k_\lambda$, with k_λ as in eq. 6.22. We leave β_d and T_d as free parameters (in the range $1.5 < \beta_d < 2.5$, and $10 \text{ K} \leq T_d \leq 70 \text{ K}$). The recovered temperatures are consistent with $\langle T_d \rangle_L$ for both the MW and high- z cloud:

$$T_{\text{d,fit}}^{\text{MW}} = 19 \pm 1 \text{ K} \quad T_{\text{d,fit}}^{\text{hi-z}} = 40 \pm 2 \text{ K} \quad (6.27a)$$

where the corresponding values for the luminosity-weighted temperatures are:

$$\langle T_d \rangle_L^{\text{MW}} = 19 \text{ K} \quad \langle T_d \rangle_L^{\text{hi-z}} = 37 \text{ K} \quad (6.27b)$$

We have repeated the fitting procedure also for the high- z cloud at 10 Myr of stellar age: we find $T_{\text{d,fit}}^{\text{hi-z}} = 62 \pm 3 \text{ K}$, consistent with our $\langle T_d \rangle_L^{\text{hi-z}} = 60 \text{ K}$. This is particularly interesting and useful, as $T_{\text{d,fit}}$ represents the temperature generally used for extrapolating IR luminosity.

Another quantity of interest that can be deduced from our model is the FIR luminosity per unit mass of gas in the GMC. We integrate the FIR luminosity over wavelength and divide by the mass of the cloud, and for the high- z GMC at the end of its lifetime (10.4 Myr) we find:

$$\frac{L_{\text{FIR}}}{M} \sim 10 \text{ L}_\odot / \text{M}_\odot. \quad (6.28a)$$

This value exceeds by $\sim 10\times$ the one we find in our MW cloud, where we have at the end of its lifetime (2.3 Myr):

$$L_{\text{FIR}}/M \sim 1 \text{ L}_\odot / \text{M}_\odot. \quad (6.28b)$$

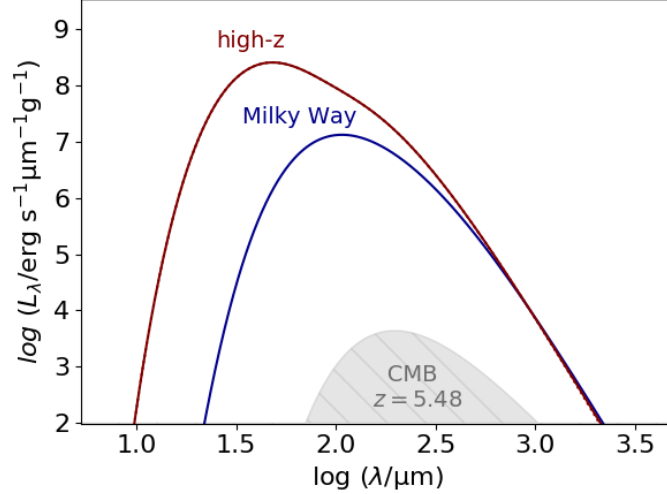


Figure 6.6: Specific luminosity per unit wavelength of the high- z cloud (brown line) and MW cloud (blue line) at the stellar age of 0.4 Myr. We also show as a comparison the CMB specific luminosity at redshift $z = 5.48$ (grey line). The latter is important because, at such redshift, dust emission is observed against it, hence the intensity of the CMB must be subtracted out.

This value is consistent with the average value observed in MW GMCs in which the H II region is obscured [503].

As a caveat, we warn that so far we have discussed the intrinsic luminosity of our clouds. In order to compute the observed luminosity, one would need to account for the fact that dust emission is observed against the CMB; hence, the latter must be subtracted out [221, as in]. However, as $\langle T_d \rangle_L \gg T_{\text{CMB}}$ in our clouds, such correction is negligible, as it can be realised from an inspection of Fig. 6.6 where the dust and CMB spectra are compared.

Our results show a colder mass-weighted, but consistent luminosity-weighted dust temperature with respect to simulations by [32]. We also confirm that mass-weighted dust temperatures are in general significantly lower than luminosity-weighted ones. Indeed, at redshift $z = 6$ they find that the bulk of the dust mass is as cold as $\langle T_d \rangle_M = 30.7$ K, while from SED fitting they find the equivalent temperature to be around $T_{\text{d,eqv}} \sim 45 - 50$ K. These modest quantitative differences are not surprising as in this work they are considering very compact systems, optically thick to IR, which is not the case of our clouds (see discussion at the end of Sec. 6.5.1). Moreover, our GMCs are not exposed to an external radiation field, thus approaching the surface dust temperature reaches the CMB temperature (and also $\langle T_d \rangle_M \sim T_{\text{CMB}}$). Nevertheless, this sort of bi-modality in the dust temperature is in accord with the results of our model (see Fig. 6.5), and we find a physical motivation for this behaviour as extensively described in Sec. 6.5.2.

The dust temperature distribution that we infer within our high- z GMC, is also consistent with the findings by [233]. At redshift $z \sim 6$, they find that in the outer low-density regions of their simulated galaxies, a large amount of dust is in thermal equilibrium with the CMB. Instead, for more centrally-concentrated dust the temperature increases up to ~ 100 K due to a stronger UV flux.

We conclude this Section by comparing our results also with the simulations by [30], where the average $\langle T_d \rangle_L = 91 \pm 23$ K at $z = 8.38$ [11]. We underline that, even at the remarkably high resolution (≈ 30 pc) of their simulations, dust temperature effects related to the radiation pressure in H II regions included here, cannot yet be properly treated (see also discussion in [31, 504]). This explains the hotter dust temperatures found in their simulations, which lie in between the two curves corresponding to the two models (homogeneous and with a density profile due to radiation pressure, see the vertical panel in Fig. 6.5).

In conclusion, all our results indicate that the dust temperature increases with redshift. This is confirmed also by recent observations [32, 10, see e.g.]. This evidence is not accounted for in most observations, which usually assume $T_d = 35 - 45$ K at $z > 5$. This conclusion bears important implications that we are going to discuss next.

6.7 Implications for high- z observations

The conclusion reached so far, namely that dust is on average warmer at early cosmic times, entails a number of important implications that we briefly discuss here.

6.7.1 Obscured UV emission

At redshift $5 \leq z \leq 10$ the Star Formation Rate Density (SFRD) is usually probed in the rest-frame UV [505, 112, 170], but at the moment there is no consensus on the obscured fraction of UV emission at these early epochs. Clearly, not taking into account obscuration, can lead to underestimating the star formation rate in early structures. Interestingly, we find that UV photons emitted by newly-born stars are completely absorbed within our high- z GMCs up to the time of dispersal, t_d , when the gas is removed by stellar feedback. This feature is not appreciably modified by the inclusion of radiation pressure and the subsequent formation of a low-density cavity in the central regions of the GMC. Hence, the unobscured UV emission observed in high- z galaxies should come from clouds that have already been dispersed (see sec. 6.3.1), either due to mechanical or radiative processes (Sec. 6.4). In short, the obscured fraction depends on cloud lifetimes.

To get a rough estimate of the fraction of obscured UV emission within our typical high- z GMC, we integrate the UV luminosity at $1500 \text{ \AA}$ for continuous star formation until t_d ⁹. After the cloud is dispersed, all the UV photons leak away. We can then compute the ratio between obscured UV photons (those produced before t_d) and all the produced UV photons:

$$f_{\text{UV,obscured}} = \frac{\int_0^{t_d, \text{Myr}} L_{1500\text{\AA}}(t) dt}{\int_0^{100 \text{ Myr}} L_{1500\text{\AA}}(t) dt} \quad (6.29)$$

where the upper limit of 100 Myr is indicative of the time at which the UV emission from the past star formation episodes becomes negligible. We find that $f_{\text{UV,obscured}} \simeq 0.42$, i.e. almost half of the energy in the UV produced by star formation in our high- z GMC is obscured. Note that in our MW cloud, this fraction is much lower, around $f_{\text{UV,obscured}} \simeq 0.18$, basically due to the shorter lifetime of the cloud. Our finding is consistent with recent high- z observations.

So far, dust obscuration has been observed at $z \sim 7$ by [277] in six bright LBGs. They were able to obtain a 5σ detection of the highest redshift galaxy targeted, but no detection of the five remaining sources. From a stacking analysis, they determined the average FIR luminosity of the sample to be $L_{\text{FIR}} \sim 2 \times 10^{11} L_\odot$. Then, converting this observed FIR luminosity into a star-formation rate, they found that $\approx 50\%$ of the total SFR is obscured by dust. Moreover, [282] recently observed that within their UV-selected sample, massive galaxies ($\log(M_\star/M_\odot) > 10$) at $z \sim 5 - 6$ exhibit an obscured fraction of star formation of $\sim 45\%$. Together these results indicate a rapid build-up of dust during the epoch of Reionization.

⁹In practice we approximate the continuous SFR with a series of subsequent bursts, and the resulting $f_{\text{UV,obscured}}$ converges considering more than 20 bursts.

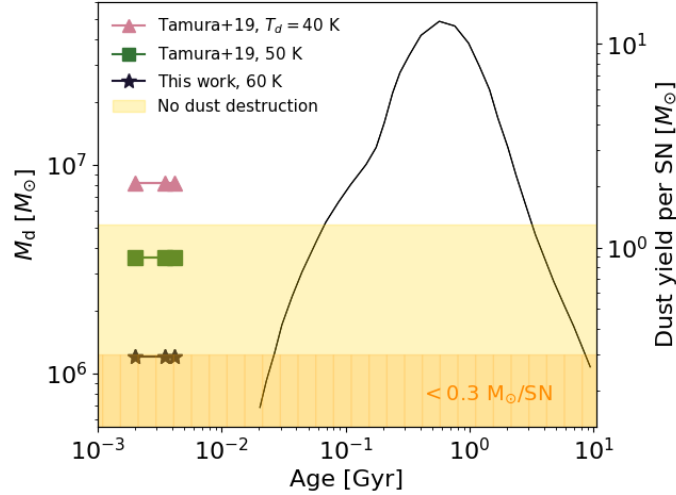


Figure 6.7: Time evolution of dust mass predicted in a dust formation model [267, 506] as a function of galaxy age with an initial gas mass of $M_{\text{gas}} = 2 \times 10^{10} M_{\odot}$ and a star formation time scale of $\tau_{\text{SFH}} = 0.3$ Gyr. This plot is adapted from [9, Fig. 6, lower right panel]. The symbols correspond to the best-fitting parameters of the physical properties of MACS0416Y1 ($z = 8.31$) estimated through [14], MW, and SMC extinction laws (from right to left). Each colour and shape corresponds to a different assumption for the dust temperature T_d , as shown by the legend. On the y-axis, we also show which would be the dust yield per SN event depending on the computed dust mass, and so on the assumed dust temperature (see text). The yellow-shaded region corresponds to the maximum theoretical dust yield without dust destruction in SNe explosions, and the hatched orange region to the upper limit assuming $T_d = 60$ K.

6.7.2 IRX- β relation

In Chapter 2 we introduced the empirical IRX- β relation, which is used to correct for dust obscuration in UV-selected galaxies at $z > 5$. This relation is confirmed to hold up to $z \sim 2 - 3$, but it is yet unclear whether it applies at higher redshift where a large scatter is present in the data [230, 225]. On average, high- z galaxies are shown to have low IRX and lie below the local relation [89, 112]. However, as discussed in Chapter 2, this conclusion is heavily dependent on the dust temperature assumption for the SEDs of dust emission, which is generally set in $T_d < 35$ K. This might lead to a severe underestimate of the high- z galaxies FIR luminosity (see the re-analysis of the sample by [89] performed by [230]). As already pointed out by [112], the tension with the local relation would be alleviated by warmer dust, with $T_d = 45 - 50$ K. In addition, even if the bulk of the dust remained cold (~ 35 K), a moderate fraction of warm dust is already sufficient to affect the SEDs (see the discussion in Sec. 6.5.2), reducing the apparent flux on the Rayleigh-Jeans tail at fixed L_{FIR} [312]. This scenario is consistent with our conclusion on dust temperature in high- z GMCs, where due to the large turbulent velocities and consequent high SFR, dust attains temperatures as high as $T_d \simeq 60$ K. The resulting increase in FIR luminosity, and consequently in IRX parameter, is as large as 1.4 dex (computed using eq. 6.25) with respect to considering $T_d = 35$ K. This is sufficient to shift the IRX faint galaxies back on the local relation. As a final remark, we notice that the IRX- β relation implicitly assumes that FIR and UV emitting regions are co-spatial. However, if dust completely absorbs the radiation emitted by stars within GMCs, as suggested here, FIR and UV emitting regions might actually be spatially segregated [30].

6.7.3 Dust mass estimates

Higher dust temperatures imply that a smaller dust amount can produce the same FIR luminosity, see eq. 6.25. This would alleviate the problem of a super-efficient dust production by stellar sources which is very hard to reconcile with available data and theoretical

results; see discussion in e.g. [9] for the galaxy MACS0416Y1 at $z = 8.31$ (whose $90\ \mu\text{m}$ continuum is observed).

For instance given L_{FIR} , assuming $T_{\text{d}} = 60\ \text{K}$, which is the maximum value derived for our high- z GMC (when the radiation pressure effect is included), would result in a dust mass reduction by a factor $\Delta M_{\text{d}} = (50/60)^{4+\beta_{\text{d}}} = 0.33$ with respect to the value suggested by [9] who took $T_{\text{d}} = 50\ \text{K}$. The power $4+\beta_{\text{d}} = 6$ is derived from the integration of the greybody function (eq. 6.25). This result is shown graphically in Fig. 6.7, where we compare the dust mass estimates for MACS0416Y1 resulting from three different assumptions for the dust temperature, $T_{\text{d}} = (40, 50, 60)\ \text{K}$.

We can also compute the dust mass per SN event produced for these three cases, by using the stellar mass computed by [9], $M_{\star} \sim 2 \times 10^8\ M_{\odot}$:

$$\text{Dust yield per SN} = \frac{M_{\text{d}}}{M_{\star} \nu_{\text{SN}}}, \quad (6.30)$$

where ν_{SN} (see eq. 6.11) is the number of SNe per solar mass of stars formed. We obtain that for $T_{\text{d}} = 50\ \text{K}$, which is the most optimistic case considered by [9], around $\sim 1\ M_{\odot}$ of dust should be produced in each SNe explosion. This value exceeds the most recent constraints on SN dust yields by [18] when we allow for some dust destruction during SNe explosions. Moreover, for the most frequently assumed value of the dust temperature $T_{\text{d}} = 40\ \text{K}$, we get $2\ M_{\odot}$ of dust yield per SN event, which exceeds even the less stringent constraints available (i.e. with no dust destruction, see the yellow shaded region in Fig. 6.7). Instead, if we consider $T_{\text{d}} = 60\ \text{K}$, dust yield drops to a modest $0.3\ M_{\odot}$, a value more in line with current data.

We also note that recent observations of MACS0416Y1, indicate the presence of warmer dust in this galaxy. [10] fail to detect continuum emission at $160\ \mu\text{m}$ (rest frame) down to $18\ \mu\text{Jy}$. This non-detection places strong limits on the dust spectrum, given the observed continuum emission at longer wavelengths $850\ \mu\text{m}$ [9]. In particular, it suggests an unusually warm dust component $T_{\text{d,L}} > 80\ \text{K}$ (90% confidence limit) considering an emissivity index $\beta_{\text{d}} = 2$. This would further decrease the required dust masses, with a reduction factor of 0.06 with respect to the value deduced by [9].

6.8 Summary

In this Chapter, we have developed a detailed model for dust temperature and associated Far Infrared (FIR) emission within star-forming Giant Molecular Clouds (GMC). We emphasise the difference between local and high- z GMCs, which is connected mainly to the larger pressure (p) and the turbulent velocity (σ) within early galaxies. These differences have two crucial effects: the star formation rate, which we showed to depend only on σ^3 , is ~ 30 times larger in high- z clouds, and the optical depth to Ultra Violet (UV) is ~ 10 times higher due to the increase in the cloud column density, which depends on $p^{1/2}$. We have also analysed the effects of UV radiation for the formation of H II regions and radiation pressure – in short radiative feedback – which, along with mechanical feedback from stellar winds and SNe, determine the cloud dispersal time scale.

Our main findings are summarised as follows:

- **Dust temperature in star forming GMCs:** in high- z clouds dust is warmer than in local ones, reaching $T_{\text{d}} = 60\ \text{K}$. This results from (i) the more compact structure of GMCs, and (ii) the more turbulent nature of early galaxies;
- **Clouds lifetimes:** star formation (and associated UV emission) is heavily obscured within the very compact high- z clouds. Due to their compact nature, these structures also survive longer (about $\sim 4\times$) than local clouds to H II region expansion, stellar winds and SNe. Their lifetimes are $\sim 10\ \text{Myr}$.

- **Infrared emission from star-forming GMCs:** high- z clouds are intense FIR emitters, with a luminosity-to-dust mass ratio of $\sim 10 L_{\odot}/M_{\odot}$, which is 10 times higher than the value of our reference MW cloud.

These results have some very significant implications. The unobscured UV emission observed in high- z galaxies mainly comes from clouds that have already been dispersed and hence depend on cloud lifetimes. This may lead to a spatial separation between the UV, which arises from the diffuse ISM, and the FIR emission, associated with compact clouds. Our scenario seems to be supported by simulations [30, 32, 34, 6, 8] and observations [438, 439, 440, 108], which find a significant spatial offset between ALMA and HST data. The spatial offset between UV and FIR might lead to questioning the significance of the IRX- β relation at high redshift. In any case, the higher dust temperatures predicted here would reduce the tension between local and high- z IRX- β relation, shifting the early IRX faint galaxies back on the local relation. Warmer dust also reduces the problem of insufficient dust production due to star formation in early times (< 0.1 Gyr). Indeed, the dust yield produced per SN event within our clouds is in agreement with the most updated SN efficiency constraints.

Finally, warmer dust produces a strong interstellar FIR radiation field pervading the galaxy, and hence GMCs. This “background” might affect FIR emission lines, such as the fine-structure [C II]158 μm line in two ways by (1) altering the population levels of C^+ , and (2) decreasing the line-to-continuum contrast of [C II]. These two effects might possibly be responsible for the observed [C II] deficit in luminous FIR emitting galaxies ($L_{\text{FIR}} > 10^{11} L_{\odot}$). In addition, it could induce significant spatial variations in the [C II]/FIR ratio as hinted by recent observations of high- z starbursts [507].

Given the relevant implications that warm/hot dust may have for galaxy formation at early epochs, it is of utmost importance to measure dust temperature in high- z galaxies. This will become possible in the near future by means of infrared observatories such as ORIGINS [318] or SPICE [319].

Chapter 7

Early JWST results on galaxies at Cosmic Dawn

We conclude this Thesis with a preliminary study of dust in $z > 10$ galaxies based on the ground-breaking observations obtained over the first ~ 5 months of operation of the JWST.

In this limited span of time, the JWST has already unveiled tens of bright ($M_{\text{UV}} \sim -21$), massive and blue galaxy candidates at unprecedentedly high redshift ($z > 10$, [62, 50, 63, 49, 51, 47, 64, 65, 66, 48]). Even more strikingly, [508, 74] reported the detection of ~ 20 sources potentially located at $z > 11$, some of which show extremely bright $M_{\text{UV}} \lesssim -23$. The first spectroscopically confirmed galaxies (4) around $z \sim 11$ have been reported by [509, 77]. For these sources, the photometric and spectroscopic redshifts only differ by $\leq 3\%$, which is very promising for the numerous other JWST-detected candidates with photometric $z \geq 10$. The unexpected abundance of such super-early “blue monsters” is challenging the predicting power of standard theoretical models [115, 20, 114, 121, 122, 123].

Thanks to the JWST data, it has become possible to extend UV Luminosity Function (LF) studies up to $z \simeq 14$. [49, 63] find a minimal evolution of the bright end of the UV LF between $z = 7$ and $z = 14$. These results are in contrast with the extrapolation of $z \simeq 7$ LFs [112], which would predict a sharp drop in the number density of sources at $M_{\text{UV}} \lesssim -21$. Such a discrepancy can be reconciled in at least two alternative ways. The first solution invokes a much higher star formation efficiency ($\epsilon_* \simeq 0.1 - 0.3$, [121, 510]) with respect to lower- z systems. This would imply that JWST is probing relatively small, and thus abundant, halos ($M_h \sim 10^{9-10} M_\odot$), featuring surprisingly large stellar masses.

A possibly simpler hypothesis is that galaxies at $z > 10$ are essentially unattenuated by dust [124]. Indeed, a drastic drop in the dust optical depth results in much brighter galaxies, virtually compensating for the lower abundance of their host halos.

As already hinted, most of the observed sources at $z \gtrsim 10$ [50, 64, 47, 51, 49] are characterised by blue UV slopes, in the range $-2.0 \lesssim \beta \lesssim -2.6$. At face value, this evidence supports the hypothesis that early galaxies suffer very little obscuration. Indeed, from the SED-fitting analysis of 15 gravitationally lensed $z = 10 - 16$ galaxies behind the galaxy cluster SMACS J0723.3-7327, [48] found an upper limit to dust attenuation of $A_V < 0.02$. On the other hand, most JWST-detected galaxies appear to be relatively massive ($M_* = 10^{8-9} M_\odot$), and metal-enriched as indicated by their (a) blue ($\beta \gtrsim -2.6$), but not ultra blue¹ ($\beta \simeq -3$) UV spectral slopes [39, 174, 48, 49, 51]; (b) low, but not primordial metallicities, $Z \simeq 0.1 Z_\odot$ [48].

These two sets of evidences seem to point in opposite directions. While from the high stellar mass/moderate metallicity one would expect a consistently high dust content, the

¹A moderately red β slope can be produced by either dust attenuation or nebular emission even starting from a metal-free (Pop III), very blue stellar population, see [511].

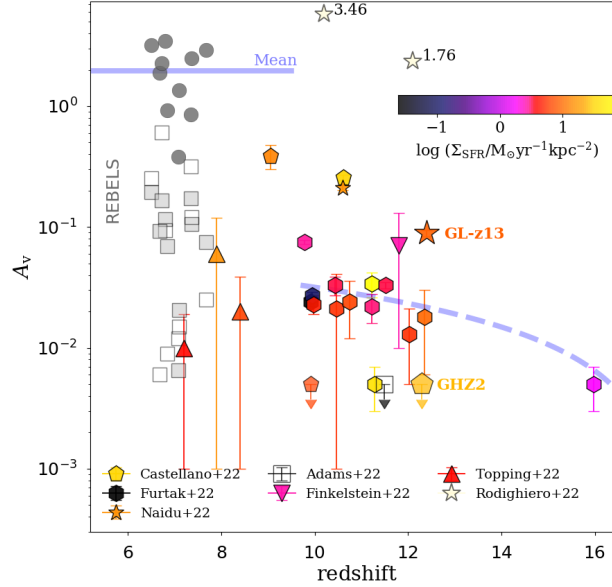


Figure 7.1: Dust attenuation, A_V , as a function of redshift for JWST-detected galaxies ($z > 9.5$, [50, 47, 51, 48, 49, 509, 46]) compared to ALMA and HST-detected galaxies from the REBELS survey [38]. JWST-detected galaxies are colour-coded according to their SFR surface density Σ_{SFR} (when available). We also show the two $z > 10$ JWST-detected sources from [512], which feature surprisingly large A_V (their $\log \Sigma_{\text{SFR}}$ values are also shown). The blue dashed curve shows the best-fitting $A_V - z$ relation at $z > 9.5$; the solid one represents the mean A_V for ALMA-detected REBELS galaxies inferred by consistently modelling both their UV and FIR emission [177]. For comparison, also shown are the A_V values for the same galaxies derived from UV-to-NIR SED fitting only, and assuming either a constant (empty squares, Stefanon et al., in prep) or non-parametric (grey squares, [39]) star formation history.

extremely low dust optical depth (e.g. $A_V \approx 0.01$) implies either very low dust content or attenuation.

Here we propose two alternative solutions to reconcile the above tension: (a) dust ejection by radiation pressure, or (b) dust spatial segregation with respect to the UV emitting regions. These two scenarios carry very different implications for the FIR continuum emission that can be tested with ALMA observations.

7.1 Preliminary considerations

The JWST discovery of a large number of super-early, massive galaxies at $z > 10$ represents a theoretical challenge for most structure formation models. A possible solution [124] involves an extremely low attenuation of UV light by dust in these systems, which almost exactly compensates for the increasing shortage of their host halos, and keeps their observed abundance constant with redshift.

Importantly, this hypothesis is supported by the surprisingly little attenuation, and frequent blue colours of these objects [48]. For example, Maisie’s galaxy at $z \approx 12$ [51] has $A_V = 0.06$; SMACS-z12a ($z = 12.03$) has extremely steep UV spectral slope, $\beta = -2.71$ [64]. GHZ2 ($z = 12.35$) shows a very blue slope $\beta = -3.00 \pm 0.12$ [47, 62] based on the updated photometry based on the latest NIRCcam calibration files; this value is in contrast with the one initially inferred by [513] for the same source (there referred to as GL-z13 as in [49]) $\beta = -2.4 \pm 0.13$. In the rest of the work we show the predictions obtained for both values of β inferred for this source. Even more surprisingly, the galaxy 10234 at $z = 11.49$ [50] is the bluest with a $\beta \approx -3.35$ that is even reminiscent of peculiar stellar populations².

²We warn that at least some of these extremely blue values might be spuriously produced by an obser-

Such decreasing trend of A_V with redshift is clearly seen in Fig. 7.1, where we have also collected, for comparison, data at $z \approx 7$ from the ALMA Large Program REBELS [38]. Where available, we show A_V obtained from SED fitting [48, 46, 51]. For the other sources, we derive the dust attenuation from the observed UV slope using the standard relation $A_V = 0.41 \tau_{1500}$ (assuming MW dust, [177]), where $\tau_{1500} \simeq (\beta - \beta_{\text{int}})$ in the optically-thin limit. We assume an intrinsic UV slope $\beta_{\text{int}} = -2.616$ [166]; in the few cases where $\beta < \beta_{\text{int}}$ we assign an upper limit for $A_V \sim 0.005$ (which corresponds to the lowest value measured in $z > 10$ JWST-detected galaxies, see [48]).

Although a decreasing dust content could be expected at early epochs as a result of the lower cosmic stellar mass³ density, $\Omega_*(z = 8) \approx 10^{-3} \Omega_*(z = 0)$ [444], the result remains puzzling.

A simple calculation serves to illustrate the problem. To fix ideas, consider the galaxies GHZ2/GLz13 and GLz11 [49, 47], whose mean stellar mass is $M_* = 10^{9.2} M_\odot$. If $\nu_{\text{SN}} = (52.89 M_\odot)^{-1}$ supernovae (SNe) are produced per stellar mass formed, assuming a Salpeter $1 - 100 M_\odot$ initial mass function, and each of them yields $y_d \gtrsim 0.1 M_\odot$ of dust [177], then we would expect a dust mass $M_d \gtrsim 3 \times 10^6 M_\odot$ to be present in the system⁴. This corresponds to a dust-to-stellar mass ratio of $\gtrsim 1/529$, about a factor $\approx 2\times$ larger than in the Milky Way (MW).

By further assuming that $\approx 10\%$ of the baryonic fraction, $f_b = \Omega_b/\Omega_m$, of their halos ($M \approx 10^{11.3} M_\odot$, [124]) cools in the disk, we find a gas-to-stellar ratio of $M_g/M_* = 2.1$. This corresponds to a gas fraction $f_g = M_g/(M_g + M_*) = 0.68$, and a dust-to-gas ratio $D \approx 0.001$, i.e. 6 times lower than in the MW. As [334] have shown that $D \propto D_{\text{MW}}(Z/Z_\odot)$ in the range $0.1 < Z/Z_\odot < 0.5$ expected for JWST galaxy candidates [514, 84], $D = 0.001$ is a reasonable choice. Although uncertain, in the following we will use these values for f_g and D as an educated guess for the super-early galaxy population.

Assuming a spherical system with an effective radius r_e , the dust optical depth at $1500 \text{ \AA}$ is

$$\tau_{1500} = \frac{\sigma_{1500}}{4\pi r_e^2 m_p D_\odot} M_d, \quad (7.1)$$

where $\sigma_{1500} = 1.3 \times 10^{-21} (D/D_\odot)$ is the dust extinction cross section, m_p is the proton mass, and $D_\odot = 1/162$ is the MW dust-to-gas ratio. Eq. 7.1 numerically yields

$$\tau_{1500} \gtrsim 6.25 \left(\frac{M_d}{3 \times 10^6 M_\odot} \right) \left(\frac{\text{kpc}}{r_e} \right)^2. \quad (7.2)$$

As at these high redshifts, $r_e \approx 0.5 \text{ kpc}$ for a galaxy with stellar mass $M_* \approx 10^9 M_\odot$ [8, 50], the above calculations show that we should expect these massive galaxies to be heavily obscured, i.e. $\tau_{1500} \approx 25$. How do we overcome this apparently conflicting result? There are two possibilities that we will explore in sequence in the next two Sections.

The first solution is that the dust produced by the SNe on very short time scales (typically, $5 - 10 \text{ Myr}$ after the onset of the star formation activity) is ejected into the intergalactic medium at a rate exceeding its production rate. Evacuation can take place, for example, via the strong radiation pressure exerted by the observed UV-emitting stars. Of course, it is necessary to clarify if and under what conditions such a process can effectively work. An alternative explanation involves spatial segregation between the UV-emitting regions and the dust. This UV-dust continuum displacement is relatively common in lower redshift ($z \approx 6 - 7$) galaxies, as shown by a number of observations and models [91, 277, 515, 516,

vational bias, pushing measurements towards artificially blue β values for faint sources near the detection threshold [174].

³Stars, and in particular SNe [16] are the main dust factories for cosmic ages $\lesssim 1 \text{ Gyr}$.

⁴Note that this argument neglects dust growth in the interstellar medium. Although likely negligible [275], the above value then represents a strong lower limit on y_d .

108]. In this case, the freshly produced dust remains in the system, but it only marginally attenuates the UV light emitted by stars.

Remarkably, these two scenarios make distinct predictions concerning the dust continuum luminosity of the JWST-detected galaxies typically measured at 158 μm restframe wavelength. While ejection entails a very low F_{158} flux, due to the lack of significant amounts of dust in the galaxy, the spatial segregation scenario predicts that these systems might be noticeable FIR emitters. In the following we quantify these statements and provide further arguments.

7.2 Dust ejection scenario

We explore the possibility that dust is ejected via a galactic outflow driven by UV radiation pressure on grains⁵, assuming a disk galaxy. The radiation pressure is given by

$$p_r = (1 - e^{-\tau_{1500}}) \frac{\mathcal{F}_{\text{bol}}}{c}, \quad (7.3)$$

where c is the speed of light. Following [327], we write the bolometric flux⁶ ($\text{erg cm}^{-2} \text{s}^{-1}$) as $\mathcal{F}_{\text{bol}} = 5 \Sigma_{\text{SFR}} [M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}]$ ⁷, where Σ_{SFR} is the disk star formation rate (SFR) per unit area. The gravitational pressure of the gas at the disk mid-plane is instead

$$p_g = \frac{\pi}{2} G \frac{\Sigma_g^2}{f_g}, \quad (7.4)$$

where G is the gravitational constant, and Σ_g is the gas surface density.

To drive an outflow, the radiation pressure must overcome the gravity pressure. By imposing that the Eddington ratio, $\lambda_E = p_r/p_g > 1$, we then derive the necessary condition for an outflow to develop as a function of Σ_{SFR} , and burstiness parameter, κ_s , implicitly defined [327] by the following expression:

$$\Sigma_{\text{SFR}} = 10^{-12} \kappa_s \Sigma_g^{1.4}. \quad (7.5)$$

Physically, κ_s quantifies deviations from the local [345] Kennicutt-Schmidt relation.

The behavior of λ_E with Σ_{SFR} for various κ_s values is shown in Fig. 7.2. The grey area identifies the region of the parameter space in which an outflow is expected ($\lambda_E > 1$). Independently of Σ_{SFR} , there is a limiting value, $\kappa_s^* \simeq 3.3$, below which outflows cannot be launched. This is obtained by imposing $\lambda = 1$, and solving for Σ_{SFR} and κ_s . A solution always exists for $\kappa_s > 3.3$; below that threshold, no solution can be found.

By combining eq. 7.3 and 7.4 we find that outflows can occur, for $\kappa_s > \kappa_s^*$ and $D = 0.001$, in the Σ_{SFR} range

$$0.32 \kappa_s^{-5/2} \leq \Sigma_{\text{SFR}} \leq 4.3 \times 10^{-3} \kappa_s^{10/3}. \quad (7.6)$$

The trend of the Eddington ratio can be understood as follows. In the optically thin regime, $p_r \sim \tau_{1500} \Sigma_{\text{SFR}} \sim \Sigma_g \Sigma_{\text{SFR}}$; hence $\lambda_E \sim \Sigma_{\text{SFR}}^{2/7}$, having used the KS relation (eq. 7.5). In the optically thick regime ($\tau_{1500} \gg 1$), it is instead $\lambda_E \sim \Sigma_{\text{SFR}}^{-3/7}$. Thus, λ_E has a maximum located at $\tau_{1500} \approx 1$, depicted by the red dots in Fig. 7.2.

The condition $\lambda_E > 1$ is not sufficient to guarantee that dust is fully evacuated. To complete the dust clearing process, the dust ejection rate $\dot{\Sigma}_w$ must exceed the dust production rate

⁵We assume perfect dynamical coupling between dust and gas.

⁶This expression is valid for a stellar population with a $1 - 100 M_{\odot}$ Salpeter IMF, $Z = 0.5 Z_{\odot}$ at age of 10 Myr.

⁷This relation implies a number of ionizing photons per unit SFR, $N_i = 10^{53.4}$, obtained from the population synthesis code STARBURST99 by assuming an average age of 100 Myr, and a standard Salpeter IMF. In the metallicity range discussed in Sec. 7.1, N_i can vary within a factor < 3 .

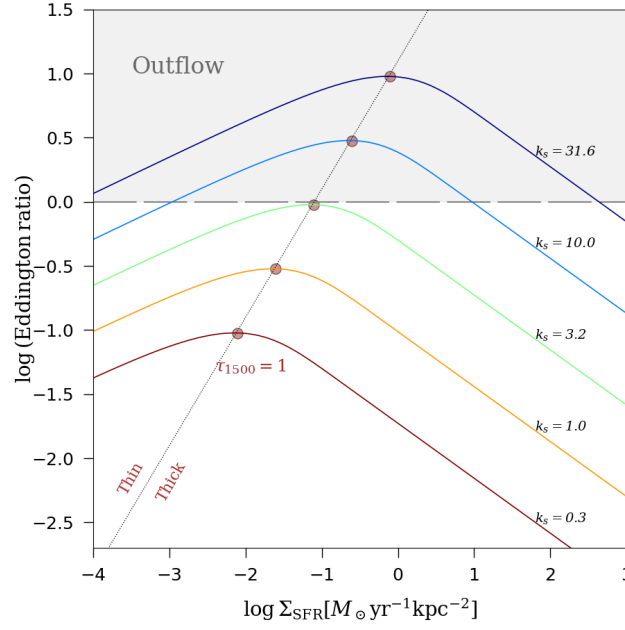


Figure 7.2: Eddington ratio, $\lambda_E \equiv p_r/p_g$, as a function of Σ_{SFR} . Curves corresponds to different κ_s values, as indicated. Outflows develop in the grey region where $\lambda_E > 1$. Red dots mark the locus $\tau_{1500} = 1$, which maximises λ_E . The grey dotted line separates optically thin/thick regimes.

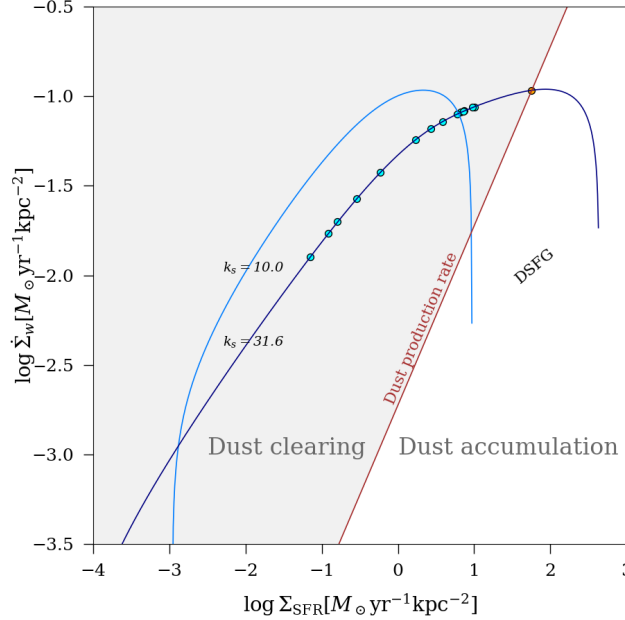


Figure 7.3: Dust outflow rate, $\dot{\Sigma}_w$, as a function of Σ_{SFR} for $z = 11.5$, assuming $y_d = 0.1 M_\odot$. Shown are two curves corresponding to $\kappa_s = (10, 31.6)$ for which radiatively-driven outflows can occur in the displayed Σ_{SFR} range. When the curves are located in the “dust clearing” region, the dust ejection rate is faster than the production rate (red curve) and the galaxy is cleared; in the opposite case (white region) dust accumulates as a result of a too slow ejection rate. Shown for comparison, arbitrarily assuming $\kappa_s = 31.6$ appropriate for the starburst nature of these galaxies, are the almost dust-free $z > 10$ candidates reported by [48] (cyan points), and the obscured ($A_V = 2.5$) galaxy by [512] at $z = 12.1$ (orange), for which an effective radius of 0.5 kpc has been assumed to compute Σ_{SFR} .

$\dot{\Sigma}_\pi$. In the super-Eddington regime ($p_r > p_g$), the radiation pressure accelerates the gas to a velocity v (perpendicular to the disk) given by momentum conservation:

$$\Sigma_g \frac{dv}{dt} = p_r - p_g. \quad (7.7)$$

The gas velocity at the disk scale height H is then

$$v_\infty = \sqrt{\frac{2H}{\Sigma_g}(p_r - p_g)}, \quad (7.8)$$

with a gas outflow rate, $\dot{\Sigma}_g$, given by

$$\dot{\Sigma}_g v_\infty = (p_r - p_g), \quad (7.9)$$

while the gas scale height can be expressed as

$$H = \frac{\sigma^2}{\pi G \Sigma} \quad (7.10)$$

where σ is the turbulent r.m.s. velocity dispersion, which is related to the SFR by $\sigma = \Sigma_{\text{SFR}}/\zeta^2$, with $\zeta = 0.041(1+z)^{3/2}f_g$, representing the rotational frequency of a galaxy hosted by a dark matter halo of mass M_h (Ferrara, in prep.).

Finally, $\Sigma = \Sigma_g/f_g$ is the total (gas+stars) mass surface density. By combining the last two expressions we obtain the dust ejection rate⁸

$$\dot{\Sigma}_w = \frac{1}{2} v_\infty \frac{\Sigma_g}{H} D. \quad (7.11)$$

The dust production rate can be derived from the SFR surface density as:

$$\dot{\Sigma}_\pi = y_d v_{\text{SN}} \Sigma_{\text{SFR}}. \quad (7.12)$$

In principle, two mechanisms can destroy dust. These are: (a) destruction by the reverse shock processing the SN ejecta; (b) destruction of pre-existing ISM dust by the SN shock. We implicitly account for (a) by adopting a dust net yield/SN of $y_d = 0.1 M_\odot$, corresponding to the destruction of $\sim 90\%$ of the dust freshly produced by the SN [416, 18, 256]. For simplicity, however, we do not include the effects of (b). Neglecting this effect is a conservative assumption, as adding ISM dust destruction would result in a lower Σ_{SFR} threshold for the dust clearing regime. Also, dust destruction due to thermal sputtering is inefficient at $T \lesssim 10^5$ K. As it is likely that only a small fraction of the galaxy volume is filled with hotter gas, this effect is expected to be small, as indeed recently found by [517]. Fig. 7.3 shows the outflow rate as a function of Σ_{SFR} . The blue (purple) curve represents the case $\kappa_s = 10$ ($\kappa_s = 31.6$). The dust production rate (red curve) separates the two regimes of dust clearing and dust accumulation. In the clearing region (grey shaded area) the dust ejection rate overcomes its production rate, and dust is efficiently evacuated into the circumgalactic medium. Outside that region, dust ejection becomes inefficient, and dust accumulates in the galaxy.

The majority ($\sim 60\%$) of JWST super-early sources show a very blue ($\beta < -2$) UV slope, which might result from dust ejection. As we have seen, ejection requires specific conditions highlighted in Fig. 7.2 which might not be met by all high- z galaxies. [512] studied a sample of very red galaxies ($A_V \sim 5$) which are detected in the F444 band, but missed in F200. Remarkably, they find two strongly dust-attenuated galaxies at $z > 10$, thus confirming that dust accumulation is active also at these very early epochs. We warn that the identification of the observed break as a standard Lyman-break can be misinterpreted as dusty star-forming lower redshift ($z < 7$) interlopers⁹.

⁸As $\dot{\Sigma}_w \propto D$, the normalization of the curves in Fig. 7.3 may vary by a factor ≈ 3 due to uncertainties in metallicity measurements.

⁹[518] and [519] presented similar cases in which an extremely high redshift ($z \sim 12 - 17$) candidate has a second interpretation with a lower redshift ($z = 5$) solution.

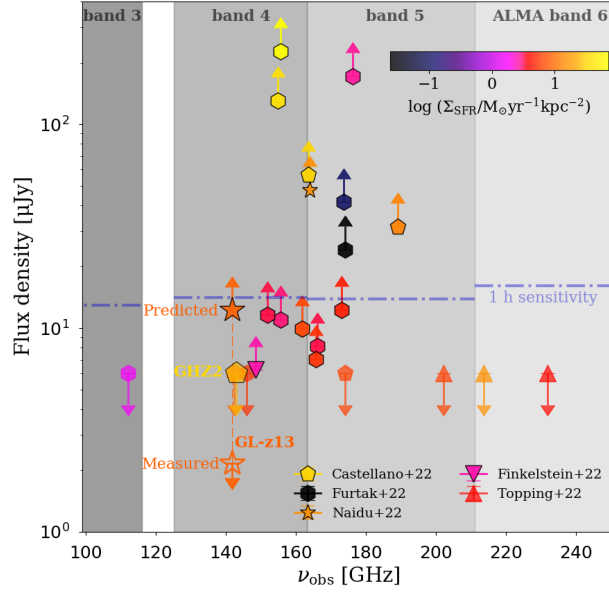


Figure 7.4: Predicted FIR continuum flux at rest-frame $158\ \mu\text{m}$ as a function of the corresponding observed frequency ν_{obs} for the $z > 9.5$ galaxies detected so far with JWST [64, 49, 51, 509]. The galaxies are colour-coded according to their Σ_{SFR} as in Fig. 7.1. The lower limits for F_{IR} shown here are obtained as described in Sec. 7.3, under the assumption of all the sources being spatially segregated. For sources with $\beta < \beta_{\text{int}}$, an upper limit for F_{IR} is fixed at the minimum value of the sample ($\sim 6\ \mu\text{Jy}$). The ALMA bands in which F_{IR} would be measured are also shown, alongside the sensitivity reached with 1 hour of observation. For GHZ2/GL-z13 we show the upper limit for the $158\ \mu\text{m}$ continuum flux inferred by rescaling the 3σ upper limit measured by [513] at rest-frame $88\ \mu\text{m}$ (assuming $T_d = 50\ \text{K}$ and MW dust).

7.3 Dust spatial segregation scenario

We now discuss an alternative scenario to explain the low A_V observed in $z \gtrsim 10$ galaxies, which involves the “spatial segregation” of stellar (optical-to-UV) and dust continuum (infrared, IR) emitting regions [30, 313, 178, 177, 8, 20]. In this scenario, the UV radiation mostly comes from the transparent diffuse interstellar medium (ISM), hosting either little or cold dust. The dust-obscured SFR is instead located in giant molecular clouds (GMCs), strongly emitting at IR wavelengths.

[177] introduced a quantitative measure of the ISM morphology of the ISM, the molecular index I_m . This is defined as:

$$I_m = \frac{(F_{\text{IR}}/F_{\text{UV}})}{(\beta - \beta_{\text{int}})}, \quad (7.13)$$

where F_{IR} (F_{UV}) is the monochromatic flux at rest-frame $158\ \mu\text{m}$ ($1500\ \text{\AA}$). For a single zone, optically-thin ISM, [177] obtains an analytical expression for I_m which shows a maximum¹⁰ at $I_m^* \simeq 1120$.

Under the assumption that the nearly dust-unattenuated super-early galaxies observed with JWST are spatially segregated systems ($I_m > I_m^*$), we can make a testable prediction on their F_{IR} . Inverting eq. 7.13, from the observed F_{UV} we infer a lower limit to their F_{IR} . This is shown in Fig. 7.4. Thanks to the very high- z of the considered sources,

¹⁰The presence of a maximum value for I_m in an optically-thin medium has a straightforward physical explanation. F_{IR} , and thus I_m , can be increased by raising either the dust temperature, T_d , or mass, M_d . However, increasing T_d requires a larger A_V , which is excluded in an optically-thin medium. Raising M_d while keeping A_V low is possible, but it implies pushing T_d progressively closer to the CMB temperature. This prevents F_{IR} , and thus I_m , to increase indefinitely. Hence, $I_m > I_m^*$ values can only be attained in a multi-phase ISM, where UV and IR emission are essentially decoupled. This is the case of spatially-segregated sources.

their rest-frame $158\mu\text{m}$ continuum emission is redshifted at > 1 mm wavelengths, traced by the sensitive ($\approx 13 \mu\text{Jy}$ in 1 hr of observation) ALMA bands 3, 4, 5 and 6. We predict $F_{\text{IR}} > 6 \mu\text{Jy}$ for all of the considered sources with $\beta > -2.616$; thus, a few hours of observations with ALMA would suffice to test the validity of the spatially segregated scenario. This is a noticeable example of the leap forward in terms of high- z galaxies characterisation that will soon be possible thanks to ALMA and JWST synergy. For the sources where the inferred UV slope is bluer than the assumed intrinsic one, the previously described method to predict F_{IR} cannot be applied. In these cases, however, we do expect an extremely low dust content, and thus negligible FIR emission, consistent with the dust ejection scenario.

[513] and [272] performed deep spectroscopic and continuum ALMA observation of the $z \approx 12$ galaxy GHZ2/GL-z13 [47, 49], searching for [O III] line emission at rest-frame $88\mu\text{m}$ (see also [520, 521, 522]). They fail to detect the $88\mu\text{m}$ dust continuum emission from this source, obtaining a 3σ upper limit of $< 13.8 \mu\text{Jy}$.

Assuming a dust temperature of 50 K, we can rescale this value to obtain an upper limit on the continuum flux at $158 \mu\text{m}$, $F_{\text{IR}} < 2 \mu\text{Jy}$ (open orange star in Fig. 7.4). Such F_{IR} value is $\times 6$ smaller than the lower limit ($F_{\text{IR}} \geq 12 \mu\text{Jy}$, orange star in Fig. 7.4) we predict for this source when considering $\beta = -2.4$ [513]. We note that if we consider the most extreme $\beta = -3$ inferred by [47, 62] for this same source, we can only provide a qualitative upper limit on $F_{\text{IR}} < 6 \mu\text{Jy}$, which is consistent with the ALMA non-detection. We interpret this result as an indication that this galaxy is dust-cleared by an outflow.

As a final remark, the spatially segregated, multi-phase ISM scenario is also disfavoured by the very compact size of GHZ2/GL-z13 (≈ 100 pc, [513]). Further ALMA observations of the other super-early galaxies will make our prediction more robust.

7.4 Summary

To explain the puzzling evidence reported by JWST Early Release Science surveys for “blue monsters”, i.e. super-early ($z > 10$), massive galaxies showing very blue spectra ($\beta \approx -2.6$) and little dust attenuation ($A_V \lesssim 0.02$), we have proposed two distinct scenarios.

Dust ejection. In the first scenario, A_V is small as a major fraction of the dust content is ejected from the galaxy by UV radiation pressure produced by newly born, massive stars. This process requires that the galaxy is in a starburst phase ($\kappa_s > \kappa_s^* = 3.3$), and that the dust ejection rate exceeds its production one by SN. Such a condition is shown in Fig. 7.3. Galaxies with very large SFR surface density can instead accumulate dust and become significantly obscured, perhaps explaining the recent detection of $A_V \approx 5$ galaxies in the same JWST data [512].

Dust spatial segregation. The alternative scenario involves spatial segregation of dust (mostly located in opaque GMCs) with respect to transparent UV-emitting regions. This scenario can explain the blue spectra colours, and at the same time, it makes it possible to predict the FIR continuum emission from these sources using eq. 7.13, once the slope β is known.

Although both scenarios provide a physical explanation for the blue colours of the observed galaxies, they make distinct predictions concerning the FIR dust continuum flux observed by e.g. ALMA. If most of the dust is ejected in the circumgalactic medium, both its density and temperature drop dramatically, making its detection virtually impossible. On the other hand, the segregation scenario should result in (rest-frame) $158 \mu\text{m}$ fluxes $F_{\text{IR}} > 6 \mu\text{Jy}$ for most sources, which are detectable by ALMA in bands 3, 4, 5, and 6 in a few hours.

Recently, [513, 272] reported results from continuum ALMA observations towards GHZ2, one of the brightest and most robust candidates at $z > 10$, identified in the GLASS-

JWST Early Release Science Program [523]. They obtained an upper limit for the flux at (restframe) $88\ \mu\text{m}$ flux of $13\ \mu\text{Jy}$. This non-detection favours the ejection scenario, and it implies a stringent upper limit on the dust mass $< 6.5 \times 10^6 M_\odot$, assuming a dust temperature of 50 K.

If the dust is indeed efficiently ejected during the starburst phase of (some of) the super-early galaxies, such outflow might also carry a significant fraction of the gas to which grains are likely to be tightly dynamically coupled. These galaxies might then also retain a very limited amount of gas. This fact has two important consequences: (a) the escape fraction of ionizing photons could be very high; (b) the production of nebular lines can be highly suppressed. It is then tantalising to interpret the non-detection of $[\text{O III}]88\mu$ line in GHZ2/GL-z13 [513] in this physical framework (see [329] for a detailed discussion). Noticeably, [521, 522] also attempted at observing the $[\text{O III}]88\mu$ line for two JWST $z > 10$ galaxy candidates (HD1, GHZ1) without any success.

Chapter 8

Summary and Future Developments

The main goal of my PhD Research has been to improve our understanding of dust properties and their impact on the spectral energy distribution of galaxies at the Epoch of Reionization. I have worked on semi-analytical models developed to interpret astronomical observations in the restframe optical, UV and FIR regime, as well as cosmological simulations outputs. I will review the main conclusions of this Thesis in the following.

A new method to constrain T_d in high- z galaxies ALMA observations have unequivocally revealed the presence of dust in the first generations of galaxies in the Universe. However, the dust temperature T_d remains mostly unconstrained due to the few available FIR continuum data for individual galaxies at redshift $z > 5$. This introduces large uncertainties in the estimates of several physical properties, namely the dust masses M_d , infrared luminosities L_{IR} , and obscured star formation rate.

To overcome these observational limitations, in Chapter 3 we introduce a new method to constrain T_d – and T_d -dependent properties – which relies on combining the observations of continuum emission at $158 \mu\text{m}$ with that of the far-infrared [C II] line emitted at the same wavelength. By breaking the $M_d - T_d$ degeneracy, with our method we can reliably constrain multiple dust properties with a single dust continuum observation, uniquely exploiting ALMA and NOEMA large data samples on high- z [C II] emitters.

As a byproduct of this method, we also provide a physical interpretation of the empirical relation recently found between *molecular* gas mass and [C II] luminosity. We derive an analogous relation linking the *total* gas surface density and [C II] surface brightness. By combining the two, we predict the cosmic evolution of the surface density ratio $\Sigma_{\text{H}_2}/\Sigma_{\text{gas}}$. We find for the first time that $\Sigma_{\text{H}_2}/\Sigma_{\text{gas}}$ increases with redshift, which is compatible with current observations at $0 < z < 4$.

Determination of dust properties in a sample of EoR galaxies In Chapter 4 we apply our new method for determining dust properties to a sample of $z \approx 7$ galaxies part of the ALMA Large Program REBELS. We stress that REBELS galaxies constitute the first statistical sample of dusty galaxies at the Epoch of Reionization (EoR), featuring two serendipitous detections of completely dust-obscured systems as early as $z \sim 7$.

We find their dust temperatures to be around $30 \text{ K} < T_d < 60 \text{ K}$, and their dust masses to vary within the narrow range $M_d = (0.9 - 3.6) \times 10^7 M_\odot$. Given the large stellar masses of most REBELS galaxies, $M_\star = 10^9 - 10^{10.5} M_\odot$, their dust content is consistent with dust production constraints from SNe, except a few outliers (see the next paragraph).

Noticeably, our analysis allows us to extend for the first time the reported $T_d(z)$ relation into the EoR. We produce a *new physical model* that explains the increasing $T_d(z)$ trend with the decrease of the total gas depletion time, $t_{\text{dep}} = M_g/\text{SFR}$, induced by the higher cosmological accretion rate at early epochs; this hypothesis yields $T_d \propto (1+z)^{0.4}$. The model

also explains the observed T_d scatter at a fixed redshift. We find that dust is warmer in obscured sources, as a larger obscuration result in more efficient dust heating. For UV-transparent (obscured) galaxies, T_d only depends on the gas column density (metallicity), $T_d \propto N_H^{1/6}$ ($T_d \propto Z^{-1/6}$). We predict that high- z galaxies (e.g. MACS0416-Y1, A2744-YD4) with estimated $T_d \gg 60$ K, are significantly obscured, low-metallicity systems. In fact, T_d is higher in metal-poor systems due to their smaller dust content, which for fixed L_{IR} results in warmer temperatures.

Implications for dust production and SFR obscuration at high- z In Chapter 5 we extend the analysis performed on REBELS sources to the $z = 4-6$ targets of the ALPINE survey. ALPINE [C II] and continuum detected galaxies are almost ~ 2 times more numerous than REBELS ones, and span a wider SFR and $M_\star$ range, thus constituting a less biased sample with respect to REBELS galaxies, which in turn have the advantage of pioneering higher redshifts.

We find that the dust masses of ALPINE galaxies are in the $0.6 - 25.1 \times 10^7 M_\odot$ range. Due to the ~ 2 times warmer T_d that we *infer* for ALPINE galaxies, our estimated M_d are 7 times lower than previously reported in the literature (where $T_d = 25$ K was assumed, consistently with local measurements). Thus, the dust yields $\langle M_d/M_\star \rangle = 2 \times 10^{-3}$ that we infer are inline with theoretical dust production constraints at $z \sim 5$. In particular, we do not need to invoke extreme scenarios, such as saturated grain growth or no dust destruction, which might instead be needed at $z \sim 7$ for a few peculiar REBELS galaxies. For ALPINE galaxies we recover the linear $M_d - M_\star$ relation predicted by theoretical models, differently from what is found at $z \sim 7$ where this relation appears flat. We speculate that this might be evidence of a rapid evolution in the dust/metals-to-stellar mass ratios between the two epochs. Probing a wider stellar mass range at both redshifts is needed to rule out observational bias.

Despite ALPINE galaxies being selected as UV bright, we find that 38% have $L_{\text{IR}} \geq 10^{12} L_\odot$, comparable to UltraLuminous IR Galaxies (ULIRGs). Relying on ultraviolet-to-optical SED fitting, the SFR was underestimated by up to 2 orders of magnitude in 4 of these 8 ULIRGs-like galaxies. We conclude that these 4 peculiar sources should be characterised by a two-phase interstellar medium structure with “spatially-segregated” FIR and ultraviolet emitting regions.

Further insights from high-resolution hydrodynamical simulations In Chapter 6 we investigate the impact of high- z galaxies ISM properties on dust emission by combining semi-analytical models with hydrodynamical simulations. We show that the limited wavelength coverage allowed by ALMA observations provides us with a biased view of dust in $z > 6$ galaxies. In the galaxies from the SERRA simulation suite, most of the IR luminosity comes from a hot dust component ($T_d \sim 100$ K), mainly emitting at short FIR and MIR wavelengths which would be missed by ALMA. This hot dust is found to be located in UV opaque un-resolved patches of the simulations, i.e. within Giant Molecular Clouds (GMCs).

To investigate this further, we develop an analytical and physically-motivated model for dust temperature and FIR emission within star-forming GMCs. We find that in high- z GMCs dust is warmer ($T_d \gtrsim 60$ K) than in local clouds. This is due to the more compact GMC structure induced by the higher gas pressure and turbulence characterising early galaxies. The high- z GMCs compactness also delays their dispersal by stellar feedback, implying that $\sim 40\%$ of the total UV radiation emitted by newly born stars remains obscured.

The dearth of dust at Cosmic Dawn We conclude with a preliminary study of early JWST data on $z > 10$ galaxies in Chapter 7. We aim at physically motivating the discovery of a population of super-early (redshift $z > 10$) relatively massive ($M_{\star} = 10^{8-9} M_{\odot}$) and evolved galaxies (metallicity $Z \approx 0.1 Z_{\odot}$), whose blue UV spectra ($\beta \simeq -2.6$) and very small dust attenuation ($A_V \lesssim 0.02$) challenge theoretical models.

To solve the puzzle we propose two solutions in which dust is either ejected by radiation pressure or segregated with respect to UV-emitting regions. We clarify the conditions for which the two scenarios apply and show that they can be discriminated by ALMA observations. In particular, the recent non-detections of the $88\mu\text{m}$ dust continuum in some of these $z > 10$ galaxy candidates seem to favour the dust ejection scenario.

Future prospects In the near future, we will extend the work presented here by exploiting upcoming JWST and ALMA observations and newly developed cosmological simulations. We intend to exploit the analytical model for GMC-scale physics discussed in Chapter 6 as a sub-grid model for cosmological simulations of high- z galaxies (such as the SERRA simulations). The aim is to improve our treatment of SNe and stellar feedback and produce more realistic synthetic spectra and emission maps in preparation for high-resolution images of EoR galaxies from JWST and ALMA. We will investigate the occurrence of spatial separation between UV and IR emission across cosmic time, and how it relates to the evolution of intrinsic properties of SF regions and GMCs in a wide variety of sources. Apart from high resolution, the JWST follow-ups of HST-detected EoR galaxies will provide us with more stringent constraints on their SFR, stellar masses, ages, and possibly initial mass function (thanks to additional data at optical-to-NIR wavelengths). The detection of optical nebular lines (e.g. $H\beta$, $H\alpha$, [NII], [OII] and [OIII]) will also provide us with constraints for the metallicity of galaxies out to $z \sim 10$. By combining this information with the dust mass estimates we have inferred (or can infer) with the [C II]-based method presented in Chapter 3, we can study for the first time how dust-to-gas ratios change between local and high-redshift galaxies in statistically large samples.

Having a handle on early galaxies stellar and metals content, IMF and SFR, one can reliably model SN (and/or AGBs) dust production, astration, destruction, and ejection, as well as grain growth. Comparing improved theoretical predictions with the growing number of measured dust-to-metals and dust-to-stellar mass ratios, we might finally be able to shed light on the mechanisms responsible for the dust and metals build-up in the very early Universe. Crucially, understanding the process of enrichment of heavy metals in early sources is a key point for galaxy evolution models.

Thanks to JWST data, we will also be able to probe the attenuation curves of galaxies beyond the local and low- z Universe (see e.g. [210]). This will mark a significant improvement in our dust models, which currently consist solely of (nearly) arbitrarily favoured local templates (e.g. Milky Way, Small or Large Magellanic Cloud extinction curves). Attenuation curves give us insight into the chemical composition and sizes of dust grains, which are key quantities for the determination of dust opacity and the overall obscuration of star formation.

Our ultimate goal is to produce a self-consistent, physically motivated model for the obscured SFRD beyond Cosmic Noon, filling in the evolutionary gap between the EoR systems and their descendants at later epochs. Only a multi-scale approach achievable with the combination of SAMs and cosmological simulations will allow us to bridge the gap between large volumes required to statistically investigate very massive ($M_{\star} \sim 10^{11} M_{\odot}$) and thus rare sources such as SMGs, and the physical processes happening on sub-galactic scales that cannot be treated on-the-fly in cosmological simulations.

This work is timely, as JWST deep field observations are allowing us to extend UV luminosity function studies out to $z > 10$, urging us to provide reliable models for dust

correction at these unprecedentedly early epochs. Parallel progress at longer wavelengths is hindered by the difficulty in emulating UV deep, large sky-area surveys with current sub-mm interferometers. Nevertheless, blind surveys – albeit limited to the FIR brightest and more massive systems (i.e. SMGs) – are now starting to be carried out/advocated for at increasingly high redshift [162].

By the end of this decade, we will hopefully welcome new sub-mm instruments such as the 50m Atacama Large Aperture Submillimeter Telescope (AtLAST) and Large Sub-mm Telescope (LST). These instruments promise to achieve an order-of-magnitude increase in survey speed, thus enabling mapping $\gg \text{deg}^2$ areas of the sky at a $\leq 5\text{--}10$ arcsec resolution, emulating UV studies developed over the last decade.

Ultimately, this is an unbelievably exciting time to be working on high- z galaxies, and I personally look forward to the amazing science that our community will be able to produce in the upcoming years.

Additional Works

This appendix contains the abstracts of additional published papers developed during the PhD, but not included in the present Thesis. The order of appearance is chronological.

1. **Ferrara, Sommovigo et al. 2022 [177]:** We analyse FIR dust continuum measurements for 14 galaxies (redshift $z \approx 7$) in the ALMA REBELS Large Program to derive their physical properties. Our model uses three input data, i.e. (a) the UV spectral slope, β , (b) the observed UV continuum flux at $1500\text{\AA}$, F_{1500} , (c) the observed continuum flux at $\approx 158\mu\text{m}$, F_{158} , and considers Milky Way (MW) and SMC extinction curves, along with different dust geometries. We find that REBELS galaxies have $28 - 90.5\%$ of their star formation obscured; the *total* (UV+IR) star formation rates are in the range $31.5 < \text{SFR}/(M_{\odot}\text{yr}^{-1}) < 129.5$. The sample-averaged dust mass and temperature are $(1.3 \pm 1.1) \times 10^7 M_{\odot}$ and 52 ± 11 K, respectively. However, in some galaxies dust is particularly abundant (REBELS-14, $M'_d \approx 3.4 \times 10^7 M_{\odot}$), or hot (REBELS-18, $T'_d \approx 67$ K). The dust distribution is compact (< 0.3 kpc for 70% of the galaxies). The inferred dust yield per supernova is $0.1 \leq y_d/M_{\odot} \leq 3.3$, with 70% of the galaxies requiring $y_d < 0.25 M_{\odot}$. Three galaxies (REBELS-12, 14, 39) require $y_d > 1 M_{\odot}$, which is likely inconsistent with pure SN production, and might require dust growth via accretion of heavy elements from the interstellar medium. With the SFR predicted by the model and a MW extinction curve, REBELS galaxies detected in [C II] nicely follow the local $L_{\text{CII}} - \text{SFR}$ relation, and are approximately located on the Kennicutt-Schmidt relation. The sample-averaged gas depletion time is of $0.11 y_p^{-2}$ Gyr, where y_p is the ratio of the gas-to-stellar distribution radius. For some systems a solution simultaneously matching the observed $(\beta, F_{1500}, F_{158})$ values cannot be found. This occurs when the index $I_m = (F_{158}/F_{1500})/(\beta - \beta_{\text{int}})$, where β_{int} is the intrinsic UV slope, exceeds $I_m^* \approx 1120$ for a MW curve. For these objects we argue that the FIR and UV emitting regions are not co-spatial, questioning the use of the IRX- β relation.
2. **Dayal, Ferrara, Sommovigo et al. 2022 [20]:** We include a fully coupled treatment of metal and dust enrichment into the Delphi semi-analytic model of galaxy formation to explain the dust content of 13 Lyman Break Galaxies (LBGs) detected by the Atacama Large millimetre Array (ALMA) REBELS Large Program at $z \approx 7$. We find that the galaxy dust mass, M_d , is regulated by the combination of SNII dust production, astration, shock destruction, and ejection in outflows; grain growth (with a standard timescale $\tau_0 = 30$ Myr) plays a negligible role. The model predicts a dust-to-stellar mass ratio of $\sim 0.07 - 0.1\%$ and a UV-to-total star formation rate relation such that $\log(\psi_{\text{UV}}) = -0.05 [\log(\psi)]^2 + 0.86 \log(\psi) - 0.05$ (implying that 55-80% of the star formation is obscured) for REBELS galaxies with stellar mass $M_* = 10^9 - 10^{10} M_{\odot}$. This relation reconciles the intrinsic UV luminosity of LBGs with their observed luminosity function at $z = 7$. However, **2 out of the 13 systems show dust-to-stellar mass ratios** ($\sim 0.94 - 1.1\%$) that are up to $18\times$ larger than expected from the *fiducial* relation. Due to the physical coupling between dust and metal enrichment, even decreasing τ_0 to very low values (0.3 Myr) only increases the dust-to-stellar mass ratio by a factor ~ 2 . Given that grain growth is not a viable explanation for such

high observed ratios of the dust-to-stellar mass, we propose alternative solutions.

3. **Bouwens ... Sommovigo et al. 2021 [38]:** The Reionization Era Bright Emission Line Survey (REBELS) is a cycle-7 ALMA Large Program (LP) that is identifying and performing a first characterization of many of the most luminous star-forming galaxies known in the $z > 6.5$ universe. REBELS is providing this probe by systematically scanning 40 of the brightest UV-selected galaxies identified over a 7 deg^2 area for bright [C II] $158 \mu\text{m}$ and [O III] $88 \mu\text{m}$ lines and dust-continuum emission. Selection of the 40 REBELS targets was done by combining our own and other photometric selections, each of which is subject to extensive vetting using three completely independent sets of photometry and template-fitting codes. Building on the observational strategy deployed in two pilot programs, we are increasing the number of massive interstellar medium (ISM) reservoirs known at $z > 6.5$ by $\sim 4\text{--}5\times$ to > 30 . In this manuscript, we motivate the observational strategy deployed in the REBELS program and present initial results. Based on the first-year observations, 18 highly significant $\gtrsim 7\sigma$ [C II] $158 \mu\text{m}$ lines have already been discovered, the bulk of which (13/18) also show $\gtrsim 3.3\sigma$ dust-continuum emission. These newly discovered lines more than triple the number of bright ISM-cooling lines known in the $z > 6.5$ universe, such that the number of ALMA-derived redshifts at $z > 6.5$ rival Ly α discoveries. An analysis of the completeness of our search results versus star formation rate (SFR) suggests an $\sim 79\%$ efficiency in scanning for [C II] $158 \mu\text{m}$ when the $\text{SFR}_{\text{UV*IR}}$ is $> 28 \text{ M}_{\odot}/\text{yr}$. These new LP results further demonstrate ALMA's efficiency as a "redshift machine", particularly in the Epoch of Reionization.
4. **Pallottini ... Sommovigo et al. 2022 [8]:** We introduce SERRA, a suite of zoom-in high-resolution ($1.2 \times 10^4 \text{ M}_{\odot}$, $\approx 25 \text{ pc}$ at $z = 7.7$) cosmological simulations including non-equilibrium chemistry and on-the-fly radiative transfer. The outputs are post-processed to derive galaxy ultraviolet (UV) + far-infrared (FIR) continuum and emission line properties. Results are compared with available multiwavelength data to constrain the physical properties [e.g. star formation rates (SFRs), stellar/gas/dust mass, metallicity] of high-redshift $6 \lesssim z \lesssim 15$ galaxies. This flagship paper focuses on the $z = 7.7$ sub-sample, including 202 galaxies with stellar mass $10^7 \text{ M}_{\odot} \lesssim M_{\star} \lesssim 5 \times 10^{10} \text{ M}_{\odot}$, and specific star formation rate ranging from $\text{sSFR} \sim 100 \text{ Gyr}^{-1}$ in young, low-mass galaxies to $\sim 10 \text{ Gyr}^{-1}$ for older, massive ones. At this redshift, SERRA galaxies are typically bursty, i.e. they are located above the Schmidt-Kennicutt relation by a factor $\kappa_s = 3.03^{+4.9}_{-1.8}$, consistent with recent findings for [O III] and [C II] emitters at high z . They also show relatively large InfraRed eXcess ($\text{IRX} = L_{\text{FIR}}/L_{\text{UV}}$) values as a result of their compact/clumpy morphology effectively blocking the stellar UV luminosity. Note that this conclusion might be affected by insufficient spatial resolution at the molecular cloud level. We confirm that early galaxies lie on the standard [C II]–SFR relation; their observed $L_{[\text{OIII}]} / L_{[\text{CII}]} \sim 1 - 10$ ratios can be reproduced by a part of the SERRA galaxies without the need of a top-heavy initial mass function and/or anomalous C/O abundances. [O I] line intensities are similar to local ones, making ALMA high- z detections challenging but feasible ($\sim 6 \text{ h}$ for an SFR of $50 \text{ M}_{\odot} \text{ yr}^{-1}$).
5. **Fudamoto ... Sommovigo et al. 2022 [524]:** We present the average [C II] $158 \mu\text{m}$ emission line sizes of UV-bright star-forming galaxies at $z \sim 7$. Our results are derived from a stacking analysis of [C II] $158 \mu\text{m}$ emission lines and dust continua observed by the Atacama Large Millimeter/submillimeter Array (ALMA), taking advantage of the large program Reionization Era Bright Emission Line Survey. We find that the average [C II] emission at $z \sim 7$ has an effective radius r_e of $2.2 \pm 0.2 \text{ kpc}$. It is $\geq 2\times$ larger than the dust continuum and the rest-frame UV emission, in agreement with recently reported measurements for $z \leq 6$ galaxies. Additionally, we compared the average [C II] size with $4 < z < 6$ galaxies observed by the ALMA Large Program to INvestigate [C II] at Early times (ALPINE). By analyzing [C II] sizes of $4 < z < 6$ galaxies in two redshift bins, we find an average [C II]

size of $r_{\text{e}} = 2.2 \pm 0.2$ kpc and $r_e = 2.5 \pm 0.2$ kpc for $z \sim 5.5$ and $z \sim 4.5$ galaxies, respectively. These measurements show that star-forming galaxies, on average, show no evolution in the size of the [C II] 158 μm emitting regions at redshift between $z \sim 7$ and $z \sim 4$. This finding suggests that the star-forming galaxies could be morphologically dominated by gas over a wide redshift range.

6. **Heintz ... Sommovigo et al. 2022 [525]:** The neutral atomic gas content of individual galaxies at large cosmological distances has until recently been difficult to measure due to the weakness of the hyperfine HI 21 cm transition. Here we estimate the H I gas mass of a sample of main-sequence star-forming galaxies at $z \sim 6.5$ -7.8 surveyed for [C II] 158 μm emission as part of the Reionization Era Bright Emission Line Survey (REBELS), using a recent calibration of the [C II]-to-H I conversion factor. We find that the H I gas mass excess in galaxies increases as a function of redshift, with an average of $M_{\text{HI}}/M_{\star} \sim 10$, corresponding to H I gas mass fractions of $f_{\text{HI}} = M_{\text{HI}}/(M_{\star} + M_{\text{HI}}) = 90\%$, at $z \sim 7$. Based on the [C II] 158 μm luminosity function (LF) derived from the same sample of galaxies, we further place constraints on the cosmic H I gas mass density in galaxies (ρ_{HI}) at this redshift, which we measure to be $\rho_{\text{HI}} = 7.1^{+6.4}_{-3.0} \times 10^6 M_{\odot} \text{Mpc}^{-3}$. This estimate is substantially lower by a factor of ~ 10 than that inferred from an extrapolation of damped Ly α absorber (DLA) measurements and largely depends on the exact [C II] LF adopted. However, we find this decrease in ρ_{HI} to be consistent with recent simulations and argue that this apparent discrepancy is likely a consequence of the DLA sight lines predominantly probing the substantial fraction of H I gas in high- z galactic halos, whereas [C II] traces the H I in the ISM associated with star formation. We make predictions for this buildup of neutral gas in galaxies as a function of redshift, showing that at $z \geq 5$, only $\sim 10\%$ of the cosmic H I gas content is confined in galaxies and associated with the star-forming ISM.
7. **Inami ... Sommovigo et al. 2022 [108]:** We report 18 dust continuum detections ($> 3.3\sigma$) at ~ 88 and 158 μm out of 49 ultraviolet (UV)-bright galaxies ($M_{\text{UV}} < -21.3$ mag) at $z > 6.5$, observed by the Cycle-7 Atacama Large Millimeter/submillimeter Array (ALMA) Large Program, Reionization-Era Bright Emission Line Survey (REBELS) and its pilot programs. This has more than tripled the number of dust continuum detections known at $z > 6.5$. Out of these 18 detections, 12 are reported for the first time as part of REBELS. In addition, 15 of the dust continuum detected galaxies also show a [C II]_{158 μm} emission line, providing us with accurate redshifts. We anticipate more line emission detections from six targets (including three continuum-detected targets) where observations are still ongoing. We estimate that all of the sources have an infrared (IR) luminosity (L_{IR}) in a range of $3 - 8 \times 10^{11} L_{\odot}$, except for one with $L_{\text{IR}} = 1.5^{+0.8}_{-0.5} \times 10^{12} L_{\odot}$. Their fraction of obscured star formation is significant at ~ 50 per cent, despite being UV-selected galaxies. Some of the dust continuum detected galaxies show spatial offsets (~ 0.5 -1.5 arcsec) between the rest-UV and far-IR emission peaks. These separations could imply spatially decoupled phases of obscured and unobscured star formation, but a higher spatial resolution observation is required to confirm this. REBELS offers the best available statistical constraints on obscured star formation in UV-luminous galaxies at $z > 6.5$.
8. **Topping ... Sommovigo et al. 2022 [39]:** We present specific star formation rates (sSFRs) for 40 ultraviolet (UV)-bright galaxies at $z \sim 7$ -8 observed as part of the Reionization Era Bright Emission Line Survey (REBELS) Atacama Large Millimeter/submillimeter Array (ALMA) large programme. The sSFRs are derived using improved star formation rate (SFR) calibrations and spectral energy distribution (SED)-based stellar masses, made possible by measurements of far-infrared (FIR) continuum emission and [C II]-based spectroscopic redshifts. The median sSFR of the sample is $18^{+7}_{-5} \text{Gyr}^{-1}$, significantly larger than literature measurements lacking constraints in the FIR, reflecting the larger obscured SFRs derived from the dust continuum relative to that implied by the UV+optical SED.

We suggest that such differences may reflect spatial variations in dust across these luminous galaxies, with the component dominating the FIR distinct from that dominating the UV. We demonstrate that the inferred stellar masses (and hence sSFRs) are strongly dependent on the assumed star formation history in reionization-era galaxies. When large sSFR galaxies (a population that is common at $z > 6$) are modelled with non-parametric star formation histories, the derived stellar masses can increase by an order of magnitude relative to constant star formation models, owing to the presence of a significant old stellar population that is outshined by the recent burst. The [C II] line widths in the largest sSFR systems are often very broad, suggesting dynamical masses capable of accommodating an old stellar population suggested by non-parametric models. Regardless of these systematic uncertainties among derived parameters, we find that sSFRs increase rapidly toward higher redshifts for massive galaxies ($9.6 < \log(M_\star/M_\odot) < 9.8$), evolving as $(1+z)^{1.70.3}$, broadly consistent with expectations from the evolving baryon accretion rates.

9. **Endsley ... Sommovigo et al. 2022 [526]:** Recent work has shown that UV-luminous reionization-era galaxies often exhibit strong Lyman-alpha emission despite being situated at redshifts where the IGM is thought to be substantially neutral. It has been argued that this enhanced Ly α transmission reflects the presence of massive galaxies in overdense regions which power large ionized bubbles. An alternative explanation is that massive galaxies shift more of their Ly α profile to large velocities (relative to the systemic redshift) where the IGM damping wing absorption is reduced. Such a mass-dependent trend is seen at lower redshifts, but whether one exists at $z \sim 7$ remains unclear owing to the small number of existing systemic redshift measurements in the reionization era. This is now changing with the emergence of [C II]-based redshifts from ALMA. Here, we report MMT/Binospec Ly α spectroscopy of eight UV-bright ($M_{UV} \sim -22$) galaxies at $z \sim 7$ selected from the ALMA REBELS survey. We detect Ly α in four of eight galaxies and use the [C II] systemic redshifts to investigate the Ly α velocity profiles. The Ly α lines are significantly redshifted from systemic (average velocity offset = 223 km s^{-1}) and broad (FWHM $\sim 300\text{-}650 \text{ km s}^{-1}$), with two sources showing emission extending to $\sim 750 \text{ km s}^{-1}$. We find that the broadest Ly α profiles are associated with the largest [C II] line widths, suggesting a potential link between the Ly α FWHM and the dynamical mass. Since Ly α photons at high velocities transmit efficiently through the $z \sim 7$ IGM, our data suggest that velocity profiles play a significant role in boosting the Ly α visibility of the most UV-luminous reionization-era galaxies.
10. **Algera ... Sommovigo et al. 2023 [21]:** Cosmic dust is an essential component shaping both the evolution of galaxies and their observational signatures. How quickly dust builds up in the early Universe remains an open question that requires deep observations at (sub-)millimetre wavelengths to resolve. Here, we use Atacama Large Millimeter Array observations of 45 galaxies from the Reionization Era Bright Emission Line Survey (REBELS) and its pilot programs, designed to target [C II] and dust emission in UV-selected galaxies at $z \sim 7$, to investigate the dust content of high-redshift galaxies through a stacking analysis. We find that the typical fraction of obscured star formation $f_{\text{obs}} = \text{SFR}_{\text{IR}}/\text{SFR}_{\text{UV+IR}}$ depends on stellar mass, similar to what is observed at lower redshift, and ranges from $f_{\text{obs}} \sim 0.3 - 0.6$ for galaxies with $\log M_\star/M_\odot = 9.4\text{-}10.4$. We further adopt the $z \sim 7$ stellar mass function from the literature to extract the obscured cosmic star formation rate density (SFRD) from the REBELS survey. Our results suggest only a modest decrease in the SFRD between $3 \leq z \leq 7$, with dust-obscured star formation still contributing ~ 30 per cent at $z \sim 7$. While we extensively discuss potential caveats, our analysis highlights the continued importance of dust-obscured star formation even well into the epoch of reionization.
11. **Algera ... Sommovigo et al. 2023b [285]:** We present new ALMA Band 8 (rest-frame $90 \mu\text{m}$) observations of three massive ($M_\star \approx 10^{10} M_\odot$) galaxies at $z \approx 7$ previously detected

in [CII]158 μ m and underlying dust continuum emission in the Reionization Era Bright Emission Line Survey (REBELS). We detect the dust continuum emission of two of our targets in Band 8 (REBELS-25 and REBELS-38), while REBELS-12 remains undetected. Through modified blackbody fitting we determine cold dust temperatures ($T_{\text{dust}} \approx 30\text{--}35$ K) in both of the dual-band detected targets, given a fiducial model of optically thin emission with $\beta = 2.0$. Their dust temperatures are lower than most $z \sim 7$ galaxies in the literature, and consequently their dust masses are higher ($M_{\text{dust}} \approx 10^8 M_{\odot}$). Nevertheless, these large dust masses are still consistent with predictions from models of dust production in the early Universe. In addition, we target and detect [OIII]88 μ m emission in both REBELS-12 and REBELS-25, and find $L_{\text{[OIII]}}/L_{\text{[CII]}}$ ratios of approximately unity, low compared to the $L_{\text{[OIII]}}/L_{\text{[CII]}} \gtrsim 2 - 10$ observed in the known $z \gtrsim 6$ population thus far. We argue the lower line ratios are due to a comparatively weaker ionizing radiation field resulting from the less starbursty nature of our targets. This low burstiness supports the cold dust temperatures and below average [OIII] $\lambda\lambda 4959, 5007 + \text{H}\beta$ equivalent widths of REBELS-25 and REBELS-38, compared to the known high-redshift population. Overall, this provides evidence for the existence of a massive, dust-rich galaxy population at $z \approx 7$ which has previously experienced vigorous star formation, but is currently forming stars in a steady, as opposed to bursty, manner.

12. **Pizzati ... Sommovigo et al. 2023 [527]:** ALMA observations have revealed that many high redshift galaxies are surrounded by extended (10 – 15 kpc) [C II]-emitting halos which are not predicted by even the most advanced zoom-in simulations. Using a semi-analytical model, in a previous work we suggested that such halos are produced by starburst-driven, catastrophically cooling outflows. Here, we further improve the model and compare its predictions with data from 7 star-forming ($10 \lesssim \text{SFR}/M_{\odot} \text{ yr}^{-1} \lesssim 100$) galaxies at $z = 4 - 6$, observed in the ALPINE survey. We find that (a) detected [C II]halos are a natural by-product of starburst-driven outflows; (b) the outflow mass loading factors are in the range $4 \lesssim \eta \lesssim 7$, with higher η values for lower-mass, lower-SFR systems, and scale with stellar mass as $\eta \propto M_{*}^{-0.36}$, consistently with the momentum-driven hypothesis. Our model suggests that outflows are widespread phenomena in high- z galaxies. However, in low-mass systems the halo extended [C II]emission is likely too faint to be detected with the current levels of sensitivity.
13. **Kohandel ... Sommovigo et al. 2023 [329]:** Recent attempts to detect [OIII] 88 μ m emission from super-early ($z > 10$) galaxy candidates observed by JWST have been unsuccessful. Non-detections can be either due to wrong photometric redshifts, or to the faintness of the line in such early systems. By using zoom-in simulations, we show that, if the redshift of these galaxies is confirmed, they are faint, and mostly fall below the local metal-poor [OIII] – SFR relation as a result of their low ionization parameter, $U_{\text{ion}} \lesssim 10^{-3}$. Such low U_{ion} values are found in galaxies that are in an early assembly stage, and whose stars are still embedded in high-density natal clouds. However, the most luminous galaxy in our sample ($\log[L_{\text{[OIII]}}/L_{\odot}] = 8.4$, $U_{\text{ion}} \approx 0.1$) could be detected by ALMA in only 2.8 hrs.
14. **Barrufet ... Sommovigo et al. 2023 [29]:** We present the first observational infrared luminosity function (IRLF) measurement in the Epoch of Reionization (EoR) based on a UV-selected galaxy sample with ALMA spectroscopic observations. Our analysis is based on the ALMA large program Reionization Era Bright Emission Line Survey (REBELS), which targets 42 galaxies at $z = 6.4 - 7.7$ with [CII] 158 μ m line scans. 16 sources exhibit a dust detection, 15 of which are also spectroscopically confirmed through the [CII] line. The IR luminosities of the sample range from $\log L_{\text{IR}}/L_{\odot} = 11.4$ to 12.2. Using the UVLF as a proxy to derive the effective volume for each of our target sources, we derive IRLF estimates, both for detections and for the full sample including IR luminosity upper limits. The resulting IRLFs are well reproduced by a Schechter function with the characteristic luminosity of $\log L_{*}/L_{\odot} = 11.6^{+0.2}_{-0.1}$. Our observational results are in broad agreement with

the average of predicted IRLFs from simulations at $z \sim 7$. Conversely, our IRLFs lie significantly below lower redshift estimates, suggesting a rapid evolution from $z \sim 4$ to $z \sim 7$, into the reionization epoch. The inferred obscured contribution to the cosmic star-formation rate density at $z \sim 7$ amounts to $\log(\text{SFRD}/M_\odot/\text{yr}/\text{Mpc}^3) = -2.66^{+0.17}_{-0.14}$ which is at least $\sim 10\%$ of UV-based estimates. We conclude that the presence of dust is already abundant in the EoR and discuss the possibility of unveiling larger samples of dusty galaxies with future ALMA and JWST observations.

15. **Ferrara ... Sommovigo et al. 2023 [528]:** Quasar outflows might either quench (negative) or enhance (positive feedback) star formation in galaxies located in the quasar environment. The possible outcome depend on 4 parameters: the quasar (σ) and satellite (σ_*) halo velocity dispersion, their relative distance, d , and satellite disk radius, r_d . We find that: (i) small satellites with $\sigma_* < 164 \sigma_{200}^{2/3} \text{ km s}^{-1}$ have their star formation quenched; (ii) in larger satellites, star formation, and hence UV/FIR luminosity, is instead boosted by $> 80\%$ in a burst with typical duration of $5 - 10 \text{ Myr}$, if the following positive feedback criterion is met: $d/r_d < 15(Q/\eta)^{1/2} \sigma_{200}$, where $Q \approx 1$ is the satellite disk Toomre parameter; the disruption parameter must be $\eta > 1$ to prevent complete satellite gas removal. We compare our predictions with ALMA data finding that observed satellites of $z \simeq 6$ QSOs on average form stars at a $3\times$ higher rate with respect to field galaxies at the same redshift. Further tests of the model are suggested.

I want to mention one more project which has not resulted in any scientific publication but has employed a significant amount of my time over the past year. Together with two other PhD students at Scuola Normale Superiore (Carmen Baiano and Francesca d'Elia), we have designed a project called “**ISPIRA**” (i.e. INSPIRE, see [link](#)). The acronym stands for “INclusion in Science: a Possibility of Identification and REpresentation”. ISPIRA aims to motivate more girls to consider a career in scientific fields. In Italy STEM disciplines are still strongly male-dominated. As a reference, over the past ten years, 80% of the applicants for scientific disciplines at Scuola Normale Superiore have been males (while for humanities the average is stably ~ 50%).

With ISPIRA we aimed to tackle the lack of diversity in STEM through scientific outreach, approaching it with a unique and modern spin. We organized a series of interactive lectures for teenage students in local secondary schools. Each lecture was held by a young female researcher from our institution and revolved around a hot scientific topic related to the speaker's research interests. Apart from communicating science, each speaker explained why they decided to become a researcher, how they became fascinated with their field of study and what has been their personal journey. The – often historically overlooked – impact of female researchers in each speaker's area of competence was also highlighted.

With ISPIRA we aimed to provide young students with relatable role models, interacting in a less formal, and more personal context than a typical orientation day (which has the additional drawback of happening at a much later stage in students' education). We wanted to communicate our passion for science and normalize the idea of female researchers for all the students attending (independently from their gender). To be able to do that, all of us speakers attended a 10-hour workshop held by a communications expert which helped us identify new ways to present scientific content, instead of the classic oral presentation with some visual aid. Researchers from all genders/fields were encouraged to participate in the workshop and the preparation of lectures for the students.

The first-year pilot of the project ISPIRA received 4600 euros in funding from the Italian government program for a broader impact on society. So far we held 56 lectures (involving more than one thousand students) within Tuscany. I am proud to say that ISPIRA has recently been selected as a permanent part of the European Gender Equality Plan at Scuola Normale Superiore. I strongly believe that projects such as ISPIRA are key to achieving a more inclusive, equal and diverse scientific community, which is paramount for the progress of science itself.



Bibliography

- [1] Somerville, R. S. & Davé, R. Physical Models of Galaxy Formation in a Cosmological Framework. *ARA&A* **53**, 51–113 (2015).
- [2] Vogelsberger, M., Marinacci, F., Torrey, P. & Puchwein, E. Cosmological simulations of galaxy formation. *Nature Reviews Physics* **2**, 42–66 (2020).
- [3] Vogelsberger, M. *et al.* Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe. *MNRAS* **444**, 1518–1547 (2014).
- [4] Pillepich, A. *et al.* Simulating galaxy formation with the IllustrisTNG model. *MNRAS* **473**, 4077–4106 (2018).
- [5] Wilkins, S. M. *et al.* The properties of the first galaxies in the BlueTides simulation. *Monthly Notices of the Royal Astronomical Society* **469**, 2517–2530 (2017). URL <https://doi.org/10.1093/mnras/stx841>.
- [6] Vijayan, A. P. *et al.* First Light And Reionisation Epoch Simulations (FLARES) III: The properties of massive dusty galaxies at cosmic dawn. *arXiv e-prints* arXiv:2108.00830 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021arXiv210800830V>.
- [7] Katz, H. RAMSES-RTZ: non-equilibrium metal chemistry and cooling coupled to on-the-fly radiation hydrodynamics. *MNRAS* **512**, 348–365 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.512..348K>.
- [8] Pallottini, A. *et al.* A survey of high- z galaxies: SERRA simulations. *arXiv e-prints* arXiv:2201.02636 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220102636P>.
- [9] Tamura, Y. *et al.* Detection of the Far-infrared [O III] and Dust Emission in a Galaxy at Redshift 8.312: Early Metal Enrichment in the Heart of the Reionization Era. *ApJ* **874**, 27 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...874...27T>.
- [10] Bakx, T. J. L. C. *et al.* ALMA uncovers the [CII] emission and warm dust continuum in a $z = 8.31$ Lyman break galaxy. *MNRAS* **493**, 4294–4307 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.493.4294B>.
- [11] Laporte, N. *et al.* Dust in the Reionization Era: ALMA Observations of a $z \sim 8.38$ Gravitationally Lensed Galaxy. *ApJL* **837**, L21 (2017). URL <http://adsabs.harvard.edu/abs/2017ApJ...837L..21L>.
- [12] Laporte, N. *et al.* The absence of [CII] $158 \mu\text{m}$ in spectroscopically confirmed galaxies at $z > 8$. *Monthly Notices of the Royal Astronomical Society: Letters* **487**, L81–L85 (2019). URL <https://doi.org/10.1093/mnrasl/slz094>.

- [13] Meurer, G. R., Heckman, T. M. & Calzetti, D. Dust absorption and the ultraviolet luminosity density at $z \sim 3$ as calibrated by local starburst galaxies. *The Astrophysical Journal* **521**, 64 (1999).
- [14] Calzetti, D. *et al.* The dust content and opacity of actively star-forming galaxies. *The Astrophysical Journal* **533**, 682 (2000).
- [15] Weingartner, J. C. & Draine, B. Dust grain-size distributions and extinction in the milky way, large magellanic cloud, and small magellanic cloud. *The Astrophysical Journal* **548**, 296 (2001).
- [16] Todini, P. & Ferrara, A. Dust formation in primordial Type II supernovae. *MNRAS* **325**, 726–736 (2001). URL <https://ui.adsabs.harvard.edu/abs/2001MNRAS.325..726T>.
- [17] Bianchi, S. & Schneider, R. Dust formation and survival in supernova ejecta. *MNRAS* **378**, 973–982 (2007). URL <https://ui.adsabs.harvard.edu/abs/2007MNRAS.378..973B>.
- [18] Leńniewska, A. & Michałowski, M. J. Dust production scenarios in galaxies at $z \sim 6-8.3$. *A&A* **624**, L13 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019A&A...624L..13L>.
- [19] Witstok, J. *et al.* Dual constraints with ALMA: new [O III] 88- μ m and dust-continuum observations reveal the ISM conditions of luminous LBGs at $z \sim 7$. *MNRAS* **515**, 1751–1773 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.515.1751W>.
- [20] Dayal, P. *et al.* The ALMA REBELS survey: the dust content of $z \sim 7$ Lyman break galaxies. *MNRAS* **512**, 989–1002 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.512..989D>.
- [21] Algera, H. S. B. *et al.* The ALMA REBELS survey: the dust-obscured cosmic star formation rate density at redshift 7. *MNRAS* **518**, 6142–6157 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023MNRAS.518.6142A>.
- [22] Rowlands, K. *et al.* The dust budget crisis in high-redshift submillimetre galaxies. *MNRAS* **441**, 1040–1058 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014MNRAS.441.1040R>.
- [23] Scoville, N. *et al.* Ism masses and the star formation law at $z = 1$ to 6: Alma observations of dust continuum in 145 galaxies in the cosmos survey field. *The Astrophysical Journal* **820**, 83 (2016).
- [24] Madau, P. & Dickinson, M. Cosmic Star-Formation History. *ARA&A* **52**, 415–486 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014ARA&A...52..415M>.
- [25] Novak, M. *et al.* The VLA-COSMOS 3 GHz Large Project: Cosmic star formation history since $z \sim 5$. *A&A* **602**, A5 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017A&A...602A...5N>.
- [26] Gruppioni, C. *et al.* The ALPINE-ALMA [CII] survey. The nature, luminosity function, and star formation history of dusty galaxies up to $z \sim 6$. *A&A* **643**, A8 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...643A...8G>.

- [27] Talia, M. *et al.* Illuminating the Dark Side of Cosmic Star Formation Two Billion Years after the Big Bang. *ApJ* **909**, 23 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021ApJ...909...23T>.
- [28] Zavala, J. A. *et al.* The Evolution of the IR Luminosity Function and Dust-obscured Star Formation over the Past 13 Billion Years. *ApJ* **909**, 165 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021ApJ...909..165Z>.
- [29] Barrufet, L. *et al.* The alma rebels survey: The first infrared luminosity function measurement at $z \sim 7$ (2023). [2303.11321](https://arxiv.org/abs/2303.11321).
- [30] Behrens, C., Pallottini, A., Ferrara, A., Gallerani, S. & Vallini, L. Dusty galaxies in the Epoch of Reionization: simulations. *MNRAS* **477**, 552–565 (2018). URL <http://adsabs.harvard.edu/abs/2018MNRAS.477..552B>.
- [31] Pallottini, A. *et al.* Deep into the structure of the first galaxies: SERRA views. *MNRAS* **487**, 1689–1708 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.487.1689P>.
- [32] Liang, L. *et al.* On the dust temperatures of high redshift galaxies. *MNRAS* **2072** (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.tmp.2072L>.
- [33] Katz, H. *et al.* Probing cosmic dawn with emission lines: predicting infrared and nebular line emission for ALMA and JWST. *MNRAS* **487**, 5902–5921 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.487.5902K>.
- [34] Ma, X. *et al.* Dust attenuation, dust emission, and dust temperature in galaxies at $z > 5$: a view from the FIRE-2 simulations. *MNRAS* **487**, 1844–1864 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.487.1844M>.
- [35] Liang, L. *et al.* The IRX- β relation of high-redshift galaxies. *MNRAS* **502**, 3210–3241 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.502.3210L>.
- [36] Le Fèvre, O. *et al.* The ALPINE-ALMA [CII] survey. Survey strategy, observations, and sample properties of 118 star-forming galaxies at $4 < z < 6$. *A&A* **643**, A1 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...643A...1L>.
- [37] Faisst, A. L. *et al.* The ALPINE-ALMA [CII] Survey: Multiwavelength Ancillary Data and Basic Physical Measurements. *ApJS* **247**, 61 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJS..247...61F>.
- [38] Bouwens, R. J. *et al.* Reionization Era Bright Emission Line Survey: Selection and Characterization of Luminous Interstellar Medium Reservoirs in the $z > 6.5$ Universe. *arXiv e-prints* arXiv:2106.13719 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021arXiv210613719B>.
- [39] Topping, M. W. *et al.* The ALMA REBELS Survey: specific star formation rates in the reionization era. *MNRAS* **516**, 975–991 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.516..975T>.
- [40] Schreiber, C. *et al.* Dust temperature and mid-to-total infrared color distributions for star-forming galaxies at $0 < z < 4$. *A&A* **609**, A30 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018A&A...609A...30S>.
- [41] Bethermin, M. *et al.* The ALPINE-ALMA [CII] Survey: data processing, catalogs, and statistical source properties. *arXiv e-prints* arXiv:2002.00962 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200200962B>.

- [42] Bouwens, R. *et al.* The ALMA Spectroscopic Survey Large Program: The Infrared Excess of $z = 1.5$ -10 UV-selected Galaxies and the Implied High-redshift Star Formation History. *ApJ* **902**, 112 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...902..112B>.
- [43] Viero, M. P., Sun, G., Chung, D. T., Monceli, L. & Condon, S. S. The early Universe was dust-rich and extremely hot. *MNRAS* **516**, L30–L34 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.516L..30V>.
- [44] Tacconi, L. J., Genzel, R. & Sternberg, A. The Evolution of the Star-Forming Interstellar Medium Across Cosmic Time. *ARA&A* **58**, 157–203 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ARA&A...58..157T>.
- [45] Ziparo, F., Ferrara, A., Sommovigo, L. & Kohandel, M. Blue monsters. Why are JWST super-early, massive galaxies so blue? *MNRAS* **520**, 2445–2450 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023MNRAS.520.2445Z>.
- [46] Topping, M. W. *et al.* Searching for Extremely Blue UV Continuum Slopes at $z = 7 - 11$ in JWST/NIRCam Imaging: Implications for Stellar Metallicity and Ionizing Photon Escape in Early Galaxies. *arXiv e-prints* arXiv:2208.01610 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220801610T>.
- [47] Castellano, M. *et al.* Early results from GLASS-JWST. III: Galaxy candidates at $z \sim 9$ -15. *arXiv e-prints* arXiv:2207.09436 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220709436C>.
- [48] Furtak, L. J. *et al.* Constraining the physical properties of the first lensed $z \sim 10 - 16$ galaxy candidates with JWST. *arXiv e-prints* arXiv:2208.05473 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220805473F>.
- [49] Naidu, R. P. *et al.* Two Remarkably Luminous Galaxy Candidates at $z \approx 10$ -12 Revealed by JWST. *ApJL* **940**, L14 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022ApJ...940L..14N>.
- [50] Adams, N. J. *et al.* Discovery and properties of ultra-high redshift galaxies ($9 < z < 12$) in the JWST ERO SMACS 0723 Field. *arXiv e-prints* arXiv:2207.11217 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220711217A>.
- [51] Finkelstein, S. L. *et al.* A Long Time Ago in a Galaxy Far, Far Away: A Candidate $z \sim 14$ Galaxy in Early JWST CEERS Imaging. *arXiv e-prints* arXiv:2207.12474 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220712474F>.
- [52] Hubble, E. A relation between distance and radial velocity among extra-galactic nebulae. *Proceedings of the National Academy of Sciences* **15**, 168–173 (1929).
- [53] Planck Collaboration *et al.* Planck 2015 results. XIII. Cosmological parameters. *A&A* **594**, A13 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016A&A...594A..13P>.
- [54] Planck Collaboration *et al.* Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth. *A&A* **596**, A107 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016A&A...596A.107P>.
- [55] Planck Collaboration, Aghanim, N. & ... Planck 2018 results. VI. Cosmological parameters. *arXiv e-prints* arXiv:1807.06209 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018arXiv180706209P>.

- [56] Dayal, P. & Ferrara, A. Early galaxy formation and its large-scale effects. *Phys. Rep.* **780**, 1–64 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018PhR...780...1D>.
- [57] Fixsen, D. J. The Temperature of the Cosmic Microwave Background. *ApJ* **707**, 916–920 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009ApJ...707..916F>.
- [58] Loeb, A. *How Did the First Stars and Galaxies Form?* (2010). URL <https://ui.adsabs.harvard.edu/abs/2010hdfs.book....L>.
- [59] Madau, P., Haardt, F. & Rees, M. J. Radiative Transfer in a Clumpy Universe. III. The Nature of Cosmological Ionizing Sources. *ApJ* **514**, 648–659 (1999). URL <https://ui.adsabs.harvard.edu/abs/1999ApJ...514..648M>.
- [60] Gnedin, N. Y. Effect of Reionization on Structure Formation in the Universe. *ApJ* **542**, 535–541 (2000). URL <https://ui.adsabs.harvard.edu/abs/2000ApJ...542..535G>.
- [61] Barkana, R. & Loeb, A. In the beginning: the first sources of light and the reionization of the universe. *Physics Reports* **349**, 125–238 (2001).
- [62] Santini, P. *et al.* Early results from GLASS-JWST. XI: Stellar masses and mass-to-light ratio of $z > 7$ galaxies. *arXiv e-prints* arXiv:2207.11379 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220711379S>.
- [63] Donnan, C. T. *et al.* The evolution of the galaxy UV luminosity function at redshifts $z = 8 - 15$ from deep JWST and ground-based near-infrared imaging. *MNRAS* **518**, 6011–6040 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023MNRAS.518.6011D>.
- [64] Atek, H. *et al.* Revealing galaxy candidates out to $z \sim 16$ with jwst observations of the lensing cluster smacs0723 (2022). URL <https://arxiv.org/abs/2207.12338>.
- [65] Whitler, L. *et al.* On the ages of bright galaxies ~ 500 Myr after the Big Bang: insights into star formation activity at z_{rsim15} with JWST. *arXiv e-prints* arXiv:2208.01599 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220801599W>.
- [66] Harikane, Y. *et al.* A Comprehensive Study on Galaxies at $z \sim 9-17$ Found in the Early JWST Data: UV Luminosity Functions and Cosmic Star-Formation History at the Pre-Reionization Epoch. *arXiv e-prints* arXiv:2208.01612 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220801612H>.
- [67] Stark, D. P. Galaxies in the first billion years after the big bang. *Annual Review of Astronomy and Astrophysics* **54**, 761–803 (2016). URL <https://doi.org/10.1146/annurev-astro-081915-023417>.
- [68] Hodge, J. A. & da Cunha, E. High-redshift star formation in the Atacama large millimetre/submillimetre array era. *Royal Society Open Science* **7**, 200556 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020RSOS...700556H>.
- [69] Choudhury, T. R., Ferrara, A. & Gallerani, S. On the minimum mass of reionization sources. *MNRAS* **385**, L58–L62 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008MNRAS.385L..58C>.

- [70] Mitra, S., Choudhury, T. R. & Ferrara, A. Cosmic reionization after Planck. *MNRAS* **454**, L76–L80 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015MNRAS.454L..76M>.
- [71] Robertson, B. E., Ellis, R. S., Furlanetto, S. R. & Dunlop, J. S. Cosmic Reionization and Early Star-forming Galaxies: A Joint Analysis of New Constraints from Planck and the Hubble Space Telescope. *ApJL* **802**, L19 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015ApJ...802L..19R>.
- [72] Dunlop, J. S. A Deep ALMA Image of the Hubble Ultra Deep Field. *The Messenger* **166**, 48–52 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016Msngr.166..48D>.
- [73] Dayal, P. & Ferrara, A. Early galaxy formation and its large-scale effects. *Phys. Rep.* **780**, 1–64 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018PhR...780...1D>.
- [74] Yan, H. *et al.* Webb’s PEARLS: Bright 1.5–2.0 micron Dropouts in the Spitzer/IRAC Dark Field. *arXiv e-prints* arXiv:2209.04092 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220904092Y>.
- [75] Curtis-Lake, E. *et al.* Spectroscopic confirmation of four metal-poor galaxies at $z=10.3$ – 13.2 . *arXiv e-prints* arXiv:2212.04568 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv221204568C>.
- [76] Bouwens, R. J. *et al.* Evolution of the UV LF from $z\sim 15$ to $z\sim 8$ Using New JWST NIRCам Medium-Band Observations over the HUDF/XDF. *arXiv e-prints* arXiv:2211.02607 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv221102607B>.
- [77] Bunker, A. J. *et al.* JADES NIRSpec Spectroscopy of GN-z11: Lyman- α emission and possible enhanced nitrogen abundance in a $z = 10.60$ luminous galaxy. *arXiv e-prints* arXiv:2302.07256 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023arXiv230207256B>.
- [78] Arrabal Haro, P. *et al.* Spectroscopic verification of very luminous galaxy candidates in the early universe. *arXiv e-prints* arXiv:2303.15431 (2023).
- [79] Ouchi, M. *et al.* The subaru/xmm-newton deep survey (sxds). iv. evolution of $\text{Ly}\alpha$ emitters from $z= 3.1$ to 5.7 in the 1 deg² field: Luminosity functions and agn. *The Astrophysical Journal Supplement Series* **176**, 301 (2008).
- [80] Taniguchi, Y. *et al.* The subaru deep field project: Lyman α emitters at a redshift of 6.6. *Publications of the Astronomical Society of Japan* **57**, 165–182 (2005).
- [81] Kashikawa, N. *et al.* Completing the census of $\text{Ly}\alpha$ emitters at the reionization epoch. *The Astrophysical Journal* **734**, 119 (2011).
- [82] Matthee, J. *et al.* The CALYMHA survey: Ly α escape fraction and its dependence on galaxy properties at $z = 2.23$. *MNRAS* **458**, 449–467 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016MNRAS.458..449M>.
- [83] Matthee, J. *et al.* ALMA Reveals Metals yet No Dust within Multiple Components in CR7. *ApJ* **851**, 145 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017ApJ...851..145M>.

- [84] Curti, M. *et al.* The chemical enrichment in the early Universe as probed by JWST via direct metallicity measurements at $z \sim 8$. *arXiv e-prints* arXiv:2207.12375 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220712375C>.
- [85] Cameron, A. J., Katz, H., Rey, M. P. & Saxena, A. Nitrogen enhancements 440 Myr after the Big Bang: super-solar N/O, a tidal disruption event or a dense stellar cluster in GN-z11? *arXiv e-prints* arXiv:2302.10142 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023arXiv230210142C>.
- [86] Stark, D. P. *et al.* Spectroscopic detection of C IV λ 1548 in a galaxy at $z = 7.045$: implications for the ionizing spectra of reionization-era galaxies. *MNRAS* **454**, 1393–1403 (2015).
- [87] Maiolino, R. *et al.* The assembly of ‘normal’ galaxies at $z \sim 7$ probed by ALMA. *Monthly Notices of the Royal Astronomical Society* **452**, 54–68 (2015). URL <https://doi.org/10.1093/mnras/stv1194>.
- [88] Willott, C. J., Carilli, C. L., Wagg, J. & Wang, R. Star Formation and the Interstellar Medium in $z > 6$ UV-luminous Lyman-break Galaxies. *ApJ* **807**, 180 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015ApJ...807..180W>.
- [89] Capak, P. *et al.* Galaxies at redshifts 5 to 6 with systematically low dust content and high [cii] emission. *Nature* **522**, 455 (2015).
- [90] Knudsen, K. K. *et al.* [CII] emission in $z \sim 6$ strongly lensed, star-forming galaxies. *MNRAS* **462**, L6–L10 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016MNRAS.462L...6K>.
- [91] Carniani, S., Maiolino, R., Smit, R. & Amorin, R. Alma detection of extended [cii] emission in himiko at $z = 6.6$. *The Astrophysical Journal Letters* **854**, L7 (2018).
- [92] Smit, R. *et al.* Rotation in [CII]-emitting gas in two galaxies at a redshift of 6.8. *Nature* **553**, 178–181 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018Natur.553..178S>.
- [93] Harikane, Y. *et al.* Large Population of ALMA Galaxies at $z > 6$ with Very High [O III] $88 \mu\text{m}$ to [CII] $158 \mu\text{m}$ Flux Ratios: Evidence of Extremely High Ionization Parameter or PDR Deficit? *ApJ* **896**, 93 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...896...93H>.
- [94] Inoue, A. K. *et al.* Detection of an oxygen emission line from a high-redshift galaxy in the reionization epoch. *Science* **352**, 1559–1562 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016Sci...352.1559I>.
- [95] Carniani, S. *et al.* Extended ionised and clumpy gas in a normal galaxy at $z = 7.1$ revealed by ALMA. *A&A* **605**, A42 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017A&A...605A..42C>.
- [96] Marrone, D. P. *et al.* Galaxy growth in a massive halo in the first billion years of cosmic history. *Nature* **553**, 51–54 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018Natur.553...51M>.
- [97] Hashimoto, T. *et al.* The onset of star formation 250 million years after the Big Bang. *Nature* **557**, 392–395 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018Natur.557..392H>.

- [98] Hodge, J. A. & da Cunha, E. High-redshift star formation in the alma era (2020). [2004.00934](https://arxiv.org/abs/2004.00934).
- [99] Wolfire, M. G., McKee, C. F., Hollenbach, D. & Tielens, A. G. G. M. Neutral atomic phases of the interstellar medium in the galaxy. *The Astrophysical Journal* **587**, 278–311 (2003). URL <https://doi.org/10.1086%2F368016>.
- [100] Stacey, G. J. *et al.* The 158 Micron [CII] Line: A Measure of Global Star Formation Activity in Galaxies. *ApJ* **373**, 423 (1991). URL <https://ui.adsabs.harvard.edu/abs/1991ApJ...373..423S>.
- [101] de Looze, I. *et al.* The applicability of far-infrared fine-structure lines as star formation rate tracers over wide ranges of metallicities and galaxy types. *A&A* **568**, A62 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014A&A...568A..62D>.
- [102] Herrera-Camus, R. *et al.* [c II] 158 μ m EMISSION AS a STAR FORMATION TRACER. *The Astrophysical Journal* **800**, 1 (2015). URL <https://doi.org/10.1088%2F0004-637x%2F800%2F1%2F1>.
- [103] Bowler, R. A. A. *et al.* The galaxy luminosity function at $z \sim 6$ and evidence for rapid evolution in the bright end from $z \sim 7$ to 5. *MNRAS* **452**, 1817–1840 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015MNRAS.452.1817B>.
- [104] Pentericci, L. *et al.* TRACING THE REIONIZATION EPOCH WITH ALMA: [cii] EMISSION IN $z \sim 7$ GALAXIES. *The Astrophysical Journal* **829**, L11 (2016). URL <https://doi.org/10.3847%2F2041-8205%2F829%2F1%2F111>.
- [105] Carniani, S. *et al.* Kiloparsec-scale gaseous clumps and star formation at $z = 5$ –7. *MNRAS* **478**, 1170–1184 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.478.1170C>.
- [106] Harikane, Y. *et al.* SILVERRUSH. V. Census of Ly α , [O III] λ 5007, H α , and [CII] 158 μ m Line Emission with 1000 LAEs at $z = 4.9$ –7.0 Revealed with Subaru/HSC. *ApJ* **859**, 84 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...859..84H>.
- [107] Carniani, S. *et al.* Missing [C II] emission from early galaxies. *arXiv e-prints* arXiv:2006.09402 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200609402C>.
- [108] Inami, H. *et al.* The ALMA REBELS Survey: Dust Continuum Detections at $z > 6.5$. *MNRAS* (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.tmp.1725I>.
- [109] Bouwens, R. J. *et al.* New Determinations of the UV Luminosity Functions from $z = 9$ to 2 Show a Remarkable Consistency with Halo Growth and a Constant Star Formation Efficiency. *AJ* **162**, 47 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021AJ....162...47B>.
- [110] Bouwens, R. *et al.* UV Luminosity Density Results at $z > 8$ from the First JWST/NIRCam Fields: Limitations of Early Data Sets and the Need for Spectroscopy. *arXiv e-prints* arXiv:2212.06683 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv221206683B>.
- [111] Oesch, P. A., Bouwens, R. J., Illingworth, G. D., Labbé, I. & Stefanon, M. The Dearth of $z \sim 10$ Galaxies in All HST Legacy Fields—The Rapid Evolution of the

- Galaxy Population in the First 500 Myr. *ApJ* **855**, 105 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...855..1050>.
- [112] Bouwens, R. J. *et al.* ALMA Spectroscopic Survey in the Hubble Ultra Deep Field: The Infrared Excess of UV-Selected $z = 2$ -10 Galaxies as a Function of UV-Continuum Slope and Stellar Mass. *ApJ* **833**, 72 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ApJ...833...72B>.
- [113] Dayal, P., Ferrara, A. & Dunlop, J. S. The physics of the fundamental metallicity relation. *MNRAS* **430**, 2891–2895 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013MNRAS.430.2891D>.
- [114] Behroozi, P. *et al.* The Universe at $z > 10$: predictions for JWST from the UNIVERSEMACHINE DR1. *MNRAS* **499**, 5702–5718 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.499.5702B>.
- [115] Dayal, P., Ferrara, A., Dunlop, J. S. & Pacucci, F. Essential physics of early galaxy formation. *MNRAS* **445**, 2545–2557 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014MNRAS.445.2545D>.
- [116] Lagos, C. d. P. *et al.* Physical properties and evolution of (sub-)millimetre-selected galaxies in the galaxy formation simulation shark. *Monthly Notices of the Royal Astronomical Society* **499**, 1948–1971 (2020). URL <https://doi.org/10.1093/mnras/staa2861>.
- [117] Vogelsberger, M. *et al.* High-redshift JWST predictions from IllustrisTNG: dust modelling and galaxy luminosity functions. *Monthly Notices of the Royal Astronomical Society* **492**, 5167–5201 (2020). URL <https://doi.org/10.1093/mnras/staa137>.
- [118] Ma, X. *et al.* Dust attenuation, dust emission, and dust temperature in galaxies at $z \geq 5$: a view from the FIRE-2 simulations. *MNRAS* **487**, 1844–1864 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.487.1844M>.
- [119] Vijayan, A. P. *et al.* First Light And Reionization Epoch Simulations (FLARES) - II: The photometric properties of high-redshift galaxies. *MNRAS* **501**, 3289–3308 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.501.3289V>.
- [120] Dawoodbhoy, T. *et al.* Cosmic Variance and the Inhomogeneous UV Luminosity Function of Galaxies During Reionization. *arXiv e-prints* arXiv:2302.08523 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023arXiv230208523D>.
- [121] Mason, C. A., Trenti, M. & Treu, T. The brightest galaxies at Cosmic Dawn. *arXiv e-prints* arXiv:2207.14808 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220714808M>.
- [122] Boylan-Kolchin, M. Stress Testing Λ CDM with High-redshift Galaxy Candidates. *arXiv e-prints* arXiv:2208.01611 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220801611B>.
- [123] Lovell, C. C., Harrison, I., Harikane, Y., Tacchella, S. & Wilkins, S. M. Extreme Value Statistics of the Halo and Stellar Mass Distributions at High Redshift: are JWST Results in Tension with Λ CDM? *arXiv e-prints* arXiv:2208.10479 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220810479L>.

- [124] Ferrara, A., Pallottini, A. & Dayal, P. On the stunning abundance of super-early, massive galaxies revealed by jwst (2022a). URL <https://arxiv.org/abs/2208.00720>.
- [125] Wang, T. *et al.* A dominant population of optically invisible massive galaxies in the early Universe. *Nature* **572**, 211–214 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019Natur.572..211W>.
- [126] Shen, X. *et al.* High-redshift predictions from IllustrisTNG - III. Infrared luminosity functions, obscured star formation, and dust temperature of high-redshift galaxies. *MNRAS* **510**, 5560–5578 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.510.5560S>.
- [127] Fixsen, D. J., Dwek, E., Mather, J. C., Bennett, C. L. & Shafer, R. A. The Spectrum of the Extragalactic Far-Infrared Background from the COBE FIRAS Observations. *ApJ* **508**, 123–128 (1998). URL <https://ui.adsabs.harvard.edu/abs/1998ApJ..508..123F>.
- [128] Hauser, M. G. *The Cosmic Infrared Background: COBE Lifts the Veil*, Vol. 193 of *American Astronomical Society Meeting Abstracts*, 62.02 (1998). URL <https://ui.adsabs.harvard.edu/abs/1998AAS...193.6202H>.
- [129] Hauser, M. G. & Dwek, E. The Cosmic Infrared Background: Measurements and Implications. *ARA&A* **39**, 249–307 (2001). URL <https://ui.adsabs.harvard.edu/abs/2001ARA&A..39..249H>.
- [130] Dole, H. *et al.* The cosmic infrared background resolved by Spitzer. Contributions of mid-infrared galaxies to the far-infrared background. *A&A* **451**, 417–429 (2006). URL <https://ui.adsabs.harvard.edu/abs/2006A&A...451..417D>.
- [131] Werner, M. W. *et al.* The Spitzer Space Telescope Mission. *ApJS* **154**, 1–9 (2004). URL <https://ui.adsabs.harvard.edu/abs/2004ApJS..154....1W>.
- [132] Pilbratt, G. L. *et al.* Herschel Space Observatory. An ESA facility for far-infrared and submillimetre astronomy. *A&A* **518**, L1 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010A&A...518L...1P>.
- [133] Thompson, A. R., Clark, B. G., Wade, C. M. & Napier, P. J. The Very Large Array. *ApJS* **44**, 151–167 (1980). URL <https://ui.adsabs.harvard.edu/abs/1980ApJS..44..151T>.
- [134] Perley, R. A., Chandler, C. J., Butler, B. J. & Wrobel, J. M. The Expanded Very Large Array: A New Telescope for New Science. *ApJL* **739**, L1 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011ApJ...739L...1P>.
- [135] Robson, I., Holland, W. S. & Friberg, P. Celebrating 30 years of science from the James Clerk Maxwell Telescope. *Royal Society Open Science* **4**, 170754 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017RSOS....470754R>.
- [136] Baars, J. W. M., Wilson, T. & Downes, D. The 30-m Millimeter Radio Telescope. Performance and Observational Results. *Mitteilungen der Astronomischen Gesellschaft Hamburg* **68**, 35 (1987). URL <https://ui.adsabs.harvard.edu/abs/1987MitAG..68...35B>.
- [137] Ezawa, H., Kawabe, R., Kohno, K. & Yamamoto, S. Oschmann, J., Jacobus M. (ed.) *The Atacama Submillimeter Telescope Experiment (ASTE)*. (ed.Oschmann,

- J., Jacobus M.) *Ground-based Telescopes*, Vol. 5489 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 763–772 (2004). URL <https://ui.adsabs.harvard.edu/abs/2004SPIE.5489..763E>.
- [138] Güsten, R. *et al.* The Atacama Pathfinder EXperiment (APEX) - a new sub-millimeter facility for southern skies -. *A&A* **454**, L13–L16 (2006). URL <https://ui.adsabs.harvard.edu/abs/2006A&A...454L..13G>.
- [139] Carlstrom, J. E. *et al.* The 10 Meter South Pole Telescope. *Publ. Astr. Soc. Pac.* **123**, 568 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011PASP..123..568C>.
- [140] Ho, P. T. P., Moran, J. M. & Lo, K. Y. The Submillimeter Array. *ApJL* **616**, L1–L6 (2004). URL <https://ui.adsabs.harvard.edu/abs/2004ApJ...616L...1H>.
- [141] Guilloteau, S. *et al.* The IRAM interferometer on Plateau de Bure. *A&A* **262**, 624 (1992). URL <https://ui.adsabs.harvard.edu/abs/1992A&A...262..624G>.
- [142] Gruppioni, C. *et al.* The Herschel PEP/HerMES luminosity function - I. Probing the evolution of PACS selected Galaxies to $z \simeq 4$. *MNRAS* **432**, 23–52 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013MNRAS.432...23G>.
- [143] Koprowski, M. P. *et al.* The evolving far-IR galaxy luminosity function and dust-obscured star formation rate density out to $z \sim 5$. *MNRAS* **471**, 4155–4169 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.471.4155K>.
- [144] Dole, H., Lagache, G. & Puget, J. L. Predictions for Cosmological Infrared Surveys from Space with the Multiband Imaging Photometer for SIRTf. *ApJ* **585**, 617–629 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003ApJ...585..617D>.
- [145] Fudamoto, Y. *et al.* Normal, dust-obscured galaxies in the epoch of reionization. *Nature* **597**, 489–492 (2021). URL <http://dx.doi.org/10.1038/s41586-021-03846-z>.
- [146] Loiacono, F. *et al.* The ALPINE-ALMA [C II] survey. Luminosity function of serendipitous [C II] line emitters at $z \sim 5$. *A&A* **646**, A76 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A&A...646A..76L>.
- [147] Sommovigo, L. *et al.* The ALMA REBELS Survey: cosmic dust temperature evolution out to $z \sim 7$. *MNRAS* **513**, 3122–3135 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.513.3122S>.
- [148] González, V. *et al.* Evolution of galaxy stellar mass functions, mass densities, and mass-to-light ratios from $z \sim 7$ to $z \sim 4$. *The Astrophysical Journal Letters* **735**, L34 (2011).
- [149] Labbé, I. *et al.* The spectral energy distributions of $z \sim 8$ galaxies from the irac ultra deep fields: Emission lines, stellar masses, and specific star formation rates at 650 myr*. *The Astrophysical Journal Letters* **777**, L19 (2013). URL <https://dx.doi.org/10.1088/2041-8205/777/2/L19>.
- [150] Oesch, P. A. *et al.* PROBING THE DAWN OF GALAXIES AT $z \sim 9$ –12: NEW CONSTRAINTS FROM HUDF12/XDF AND CANDELS DATA. *The Astrophysical Journal* **773**, 75 (2013). URL <https://doi.org/10.1088/0004-637x/773/1/75>.
- [151] Mutch, S. J. *et al.* Dark-ages reionization and galaxy formation simulation - III. Modelling galaxy formation and the epoch of reionization. *MNRAS* **462**, 250–276 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016MNRAS.462..250M>.

- [152] Schaye, J. *et al.* The EAGLE project: simulating the evolution and assembly of galaxies and their environments. *MNRAS* **446**, 521–554 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015MNRAS.446..521S>.
- [153] Moutard, T. *et al.* UV and U-band luminosity functions from CLAUDS and HSC-SSP – I. Using four million galaxies to simultaneously constrain the very faint and bright regimes to $z \sim 3$. *Monthly Notices of the Royal Astronomical Society* **494**, 1894–1918 (2020). URL <https://doi.org/10.1093/mnras/staa706>.
- [154] Dudzevičiūtė, U. *et al.* An ALMA survey of the SCUBA-2 CLS UDS field: physical properties of 707 sub-millimetre galaxies. *MNRAS* **494**, 3828–3860 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.494.3828D>.
- [155] Kistler, M. D., Yüksel, H., Beacom, J. F., Hopkins, A. M. & Wyithe, J. S. B. The Star Formation Rate in the Reionization Era as Indicated by Gamma-Ray Bursts. *ApJL* **705**, L104–L108 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009ApJ...705L.104K>.
- [156] Robertson, B. E. & Ellis, R. S. Connecting the Gamma Ray Burst Rate and the Cosmic Star Formation History: Implications for Reionization and Galaxy Evolution. *ApJ* **744**, 95 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ApJ...744..95R>.
- [157] Magnelli, B. *et al.* Evolution of the dusty infrared luminosity function from $z = 0$ to $z = 2.3$ using observations from Spitzer. *A&A* **528**, A35 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011A%26A...528A..35M>.
- [158] Dunlop, J. S. *et al.* A deep ALMA image of the Hubble Ultra Deep Field. *MNRAS* **466**, 861–883 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.466..861D>.
- [159] Khusanova, Y. *et al.* The ALPINE-ALMA [CII] survey. Obscured star formation rate density and main sequence of star-forming galaxies at $z > 4$. *A&A* **649**, A152 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A&A...649A.152K>.
- [160] Hayward, C. C. *et al.* How to distinguish starbursts and quiescently star-forming galaxies: the ‘bimodal’ submillimetre galaxy population as a case study. *Monthly Notices of the Royal Astronomical Society* **424**, 951–970 (2012). URL <https://doi.org/10.1111/j.1365-2966.2012.21254.x>.
- [161] Barrufet, L. *et al.* Unveiling the Nature of Infrared Bright, Optically Dark Galaxies with Early JWST Data. *arXiv e-prints* arXiv:2207.14733 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220714733B>.
- [162] Casey, C. M. *et al.* Mapping Obscuration to Reionization with ALMA (MORA): 2 mm Efficiently Selects the Highest-redshift Obscured Galaxies. *ApJ* **923**, 215 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021ApJ...923..215C>.
- [163] Klaassen, P. D. *et al.* Marshall, H. K., Spyromilio, J. & Usuda, T. (eds) *The Atacama Large Aperture Submillimeter Telescope (AtLAST)*. (eds Marshall, H. K., Spyromilio, J. & Usuda, T.) *Ground-based and Airborne Telescopes VIII*, Vol. 11445 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 114452F (2020). URL <https://ui.adsabs.harvard.edu/abs/2020SPIE11445E..2FK.2011.07974>.

- [164] Kohno, K. *et al.* Zmuidzinas, J. & Gao, J.-R. (eds) *Large format imaging spectrograph for the Large Submillimeter Telescope (LST)*. (eds Zmuidzinas, J. & Gao, J.-R.) *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy X*, Vol. 11453 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 114530N (2020). URL <https://ui.adsabs.harvard.edu/abs/2020SPIE11453E..ONK.2102.08280>.
- [165] Endsley, R. *et al.* A JWST/NIRCam Study of Key Contributors to Reionization: The Star-forming and Ionizing Properties of UV-faint $z \sim 7 - 8$ Galaxies. *arXiv e-prints* arXiv:2208.14999 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220814999E>.
- [166] Reddy, N. A. *et al.* The HDUV Survey: A Revised Assessment of the Relationship between UV Slope and Dust Attenuation for High-redshift Galaxies. *ApJ* **853**, 56 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...853...56R>.
- [167] Dunlop, J. S. in *Observing the first galaxies* 223–292 (Springer, 2013).
- [168] Faisst, A. L. *et al.* Are High-redshift Galaxies Hot? Temperature of $z > 5$ Galaxies and Implications for Their Dust Properties. *ApJ* **847**, 21 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017ApJ...847...21F>.
- [169] McLure, R. *et al.* Galaxies at $z = 6 - 9$ from the wfc3/ir imaging of the hubble ultra deep field. *Monthly Notices of the Royal Astronomical Society* **403**, 960–983 (2010).
- [170] Finkelstein, S. L. *et al.* Candels: The evolution of galaxy rest-frame ultraviolet colors from $z = 8$ to 4. *The Astrophysical Journal* **756**, 164 (2012).
- [171] Dunlop, J. *et al.* A critical analysis of the ultraviolet continuum slopes (β) of high-redshift galaxies: no evidence (yet) for extreme stellar populations at $z > 6$. *Monthly Notices of the Royal Astronomical Society* **420**, 901–912 (2012).
- [172] Bouwens, R. *et al.* Uv-continuum slopes of $> 4000 z = 4 - 8$ galaxies from the hufd/xd, hufd09, ers, candels-south, and candels-north fields. *The Astrophysical Journal* **793**, 115 (2014).
- [173] Bhatawdekar, R. & Conselice, C. J. UV Spectral Slopes at $z = 6 - 9$ in the Hubble Frontier Fields: Lack of Evidence for Unusual or Population III Stellar Populations. *ApJ* **909**, 144 (2021).
- [174] Cullen, F. *et al.* The ultraviolet continuum slopes (β) of galaxies at $z = 8 - 15$ from JWST and ground-based near-infrared imaging. *arXiv e-prints* arXiv:2208.04914 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220804914C>.
- [175] Bouwens, R. J., Illingworth, G. D., Franx, M. & Ford, H. Uv luminosity functions at $z \sim 4, 5$, and 6 from the hubble ultra deep field and other deep hubble space telescope acs fields: Evolution and star formation history. *The astrophysical journal* **670**, 928 (2007).
- [176] Bouwens, R. *et al.* Ultraviolet luminosity functions from 132 $z \sim 7$ and $z \sim 8$ lyman-break galaxies in the ultra-deep hufd09 and wide-area early release science wfc3/ir observations. *The Astrophysical Journal* **737**, 90 (2011).
- [177] Ferrara, A. *et al.* The ALMA REBELS Survey. Epoch of Reionization giants: Properties of dusty galaxies at $z \sim 7$. *MNRAS* **512**, 58–72 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.512...58F>.

- [178] Sommovigo, L. *et al.* A new look at the infrared properties of $z \approx 5$ galaxies. *MNRAS* **517**, 5930–5941 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.517.5930S>.
- [179] Draine, B. T. *Physics of the interstellar and intergalactic medium* Vol. 19 (Princeton University Press, 2010).
- [180] Draine, B. T. & Li, A. Infrared Emission from Interstellar Dust. IV. The Silicate-Graphite-PAH Model in the Post-Spitzer Era. *ApJ* **657**, 810–837 (2007). URL <https://ui.adsabs.harvard.edu/abs/2007ApJ...657..810D>.
- [181] Krumholz, M. R. *Notes on star formation* (2015).
- [182] Li, A. & Greenberg, J. M. Pirronello, V., Krelowski, J. & Manicò, G. (eds) *In dust we trust: an overview of observations and theories of interstellar dust.* (eds Pirronello, V., Krelowski, J. & Manicò, G.) *Solid State Astrochemistry*, Vol. 120, 37–84 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003ssac.proc...37L.astro-ph/0204392>.
- [183] Tielens, A. G. G. M. Greenberg, J. M. & Li, A. (eds) *The destruction of interstellar dust.* (eds Greenberg, J. M. & Li, A.) *Formation and Evolution of Solids in Space*, Vol. 523 of *NATO Advanced Study Institute (ASI) Series C*, 331 (1999). URL <https://ui.adsabs.harvard.edu/abs/1999ASIC...523..331T>.
- [184] Chevance, M. *et al.* The Molecular Cloud Lifecycle. *Space Science Reviews* **216**, 50 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020SSRv...216...50C>.
- [185] Draine, B. *Interstellar extinction in the infrared*, Vol. 290 (1989).
- [186] Draine, B. Interstellar dust grains. *Annual Review of Astronomy and Astrophysics* **41**, 241–289 (2003). URL <https://doi.org/10.1146/annurev.astro.41.011802.094840>.
- [187] Trumpler, R. J. Absorption of Light in the Galactic System. *Publ. Astr. Soc. Pac.* **42**, 214 (1930). URL <https://ui.adsabs.harvard.edu/abs/1930PASP...42..214T>.
- [188] Li, A. Dust in Active Galactic Nuclei. *arXiv e-prints* arXiv:0808.4117 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008arXiv0808.4117L>.
- [189] Maiolino, R., Marconi, A. & Oliva, E. Dust in active nuclei. II. Powder or gravel? *A&A* **365**, 37–48 (2001). URL <https://ui.adsabs.harvard.edu/abs/2001A&A...365...37M>.
- [190] Gallerani, S. *et al.* The extinction law at high redshift and its implications. *A&A* **523**, A85 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010A&A...523A...85G>.
- [191] Welty, D. E. & Fowler, J. R. Ultraviolet, optical, and infrared observations of the high-latitude molecular cloud toward hd 210121. *The Astrophysical Journal* **393**, 193–205 (1992).
- [192] Cardelli, J. A., Clayton, G. C. & Mathis, J. S. The relationship between infrared, optical, and ultraviolet extinction. *The Astrophysical Journal* **345**, 245–256 (1989).
- [193] Fitzpatrick, E. L. Correcting for the effects of interstellar extinction. *Publications of the Astronomical Society of the Pacific* **111**, 63 (1999).
- [194] Bohlin, R., Savage, B. & Drake, J. A survey of interstellar H I from $\text{I} \alpha$ absorption measurements 2 (1977).

- [195] Bouchet, P., Lequeux, J., Maurice, E., Prevot, L. & Prevot-Burnichon, M. The visible and infrared extinction law and the gas-to-dust ratio in the small magellanic cloud. *Astronomy and Astrophysics* **149**, 330–336 (1985).
- [196] Prevot, M., Lequeux, J., Maurice, E., Prévot, L. & Rocca-Volmerange, B. The typical interstellar extinction in the small magellanic cloud. *Astronomy and Astrophysics* **132**, 389–392 (1984).
- [197] Koornneef, J. & Code, A. D. Ultraviolet interstellar extinction in the Large Magellanic Cloud using observations with the international ultraviolet explorer. *ApJ* **247**, 860–868 (1981).
- [198] Nandy, K., Morgan, D. H., Willis, A. J., Wilson, R. & Gondhalekar, P. M. Interstellar extinction in the Large Magellanic Cloud. *MNRAS* **196**, 955–966 (1981).
- [199] Gordon, K. D. & Clayton, G. C. Starburst-like Dust Extinction in the Small Magellanic Cloud. *ApJ* **500**, 816–824 (1998). URL <https://ui.adsabs.harvard.edu/abs/1998ApJ...500..816G>.
- [200] Calzetti, D., Kinney, A. L. & Storchi-Bergmann, T. Dust Extinction of the Stellar Continua in Starburst Galaxies: The Ultraviolet and Optical Extinction Law. *ApJ* **429**, 582 (1994). URL <https://ui.adsabs.harvard.edu/abs/1994ApJ...429..582C>.
- [201] Reddy, N. A. *et al.* The mosdef survey: Measurements of balmer decrements and the dust attenuation curve at redshifts $z \sim 1.4$ -2.6. *The Astrophysical Journal* **806**, 259 (2015). URL <https://dx.doi.org/10.1088/0004-637X/806/2/259>.
- [202] Zeimann, G. R. *et al.* The dust attenuation curve versus stellar mass for emission line galaxies at $z \sim 2$. *The Astrophysical Journal* **814**, 162 (2015). URL <https://dx.doi.org/10.1088/0004-637X/814/2/162>.
- [203] Scoville, N. *et al.* Dust attenuation in high redshift galaxies: “diamonds in the sky”. *The Astrophysical Journal* **800**, 108 (2015). URL <https://dx.doi.org/10.1088/0004-637X/800/2/108>.
- [204] Salmon, B. *et al.* Breaking the curve with candels: A bayesian approach to reveal the non-universality of the dust-attenuation law at high redshift. *The Astrophysical Journal* **827**, 20 (2016). URL <https://dx.doi.org/10.3847/0004-637X/827/1/20>.
- [205] Tress, M. *et al.* shards: constraints on the dust attenuation law of star-forming galaxies at $z \sim 2$. *Monthly Notices of the Royal Astronomical Society* **475**, 2363–2374 (2018). URL <https://doi.org/10.1093/mnras/stx3334>.
- [206] Battisti, A. J., da Cunha, E., Shivaei, I., Calzetti, D. & collaboration), C. The strength of the 2175 Å feature in the attenuation curves of galaxies at $0.1 \lesssim z \lesssim 3$. *The Astrophysical Journal* **888**, 108 (2020). URL <https://dx.doi.org/10.3847/1538-4357/ab5fdd>.
- [207] Shivaei, I. *et al.* Infrared Spectral Energy Distributions and Dust Masses of Sub-solar Metallicity Galaxies at z 2.3. *ApJ* **928**, 68 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022ApJ...928...68S>.
- [208] Salim, S., Boquien, M. & Lee, J. C. Dust Attenuation Curves in the Local Universe: Demographics and New Laws for Star-forming Galaxies and High-redshift Analogs. *ApJ* **859**, 11 (2018).

- [209] Shivaiei, I. *et al.* The MOSDEF Survey: The Variation of the Dust Attenuation Curve with Metallicity. *ApJ* **899**, 117 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...899..117S>.
- [210] Witstok, J. *et al.* Carbonaceous dust grains within galaxies seen in the first billion years of cosmic time. *arXiv e-prints* arXiv:2302.05468 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023arXiv230205468W>.
- [211] Mathis, J. S., Rumpl, W. & Nordsieck, K. H. The size distribution of interstellar grains. *The Astrophysical Journal* **217**, 425–433 (1977).
- [212] Greenberg, J. M. in *Interstellar Grains* (eds Middlehurst, B. M. & Aller, L. H.) *Nebulae and Interstellar Matter* 221 (1968). URL <https://ui.adsabs.harvard.edu/abs/1968nim...book..221G>.
- [213] Schwering, P. & Israel, F. A catalog of iras sources in the magellanic clouds (1990).
- [214] Stanimirovic, S. *et al.* Cool dust and gas in the small magellanic cloud. *Monthly Notices of the Royal Astronomical Society* **315**, 791–807 (2000).
- [215] Boulanger, F. *et al.* *Small dust particles as seen by iso*, Vol. 455, 91 (2000).
- [216] Li, A. & Draine, B. Infrared emission from interstellar dust. iii. the small magellanic cloud. *The Astrophysical Journal* **576**, 762 (2002).
- [217] Jin, S. *et al.* “super-deblended” dust emission in galaxies. ii. far-ir to (sub)millimeter photometry and high-redshift galaxy candidates in the full cosmos field. *The Astrophysical Journal* **864**, 56 (2018). URL <https://dx.doi.org/10.3847/1538-4357/aad4af>.
- [218] Casey, C. M., Narayanan, D. & Cooray, A. Dusty star-forming galaxies at high redshift. *Phys. Rep.* **541**, 45–161 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014PhR...541...45C>.
- [219] Kennicutt, J., Robert C. The Global Schmidt Law in Star-forming Galaxies. *ApJ* **498**, 541–552 (1998). URL <https://ui.adsabs.harvard.edu/abs/1998ApJ...498..541K>.
- [220] Casey, C. M. *et al.* Are dusty galaxies blue? insights on uv attenuation from dust-selected galaxies. *The Astrophysical Journal* **796**, 95 (2014). URL <https://dx.doi.org/10.1088/0004-637X/796/2/95>.
- [221] Ferrara, A., Hirashita, H., Ouchi, M. & Fujimoto, S. The infrared-dark dust content of high redshift galaxies. *MNRAS* **471**, 5018–5024 (2017). URL <https://ui.adsabs.harvard.edu/#abs/2017MNRAS.471.5018F>.
- [222] Narayanan, D., Conroy, C., Davé, R., Johnson, B. D. & Popping, G. A Theory for the Variation of Dust Attenuation Laws in Galaxies. *ApJ* **869**, 70 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...869...70N>.
- [223] Popping, G., Puglisi, A. & Norman, C. A. Dissecting the $\text{irx-}\beta$ dust attenuation relation: exploring the physical origin of observed variations in galaxies. *Monthly Notices of the Royal Astronomical Society* **472**, 2315–2333 (2017).
- [224] Coppin, K. E. *et al.* The scuba-2 cosmology legacy survey: the submillimetre properties of lyman-break galaxies at $z=3-5$. *Monthly Notices of the Royal Astronomical Society* **446**, 1293–1304 (2015).

- [225] Fudamoto, Y. *et al.* The dust attenuation of star-forming galaxies at $z \geq 3$ and beyond: New insights from ALMA observations. *Monthly Notices of the Royal Astronomical Society* **472**, 483–490 (2017).
- [226] Koprowski, M. P. *et al.* A direct calibration of the IRX- β relation in Lyman-break Galaxies at $z = 3$ –5. *MNRAS* **479**, 4355–4366 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.479.4355K>.
- [227] Strandet, M. L. *et al.* The Redshift Distribution of Dusty Star-forming Galaxies from the SPT Survey. *ApJ* **822**, 80 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ApJ...822...80S>.
- [228] Weiß, A. *et al.* ALMA redshifts of millimeter-selected galaxies from the SPT survey: the redshift distribution of dusty star-forming galaxies. *The Astrophysical Journal* **767**, 88 (2013).
- [229] Reuter, C. *et al.* The Complete Redshift Distribution of Dusty Star-forming Galaxies from the SPT-SZ Survey. *arXiv e-prints* arXiv:2006.14060 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200614060R>.
- [230] Barisic, I. *et al.* Dust properties of $z \geq 5.5$ galaxies: New HST/WFC3 near-IR observations. *The Astrophysical Journal* **845**, 41 (2017).
- [231] Watson, D. *et al.* A dusty, normal galaxy in the epoch of reionization. *Nature* **519**, 327–330 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015Natur.519..327W>.
- [232] Pozzi, F. *et al.* The ALPINE-ALMA [CII] survey. Dust mass budget in the early Universe. *A&A* **653**, A84 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A&A...653A..84P>.
- [233] Arata, S., Yajima, H., Nagamine, K., Li, Y. & Khochfar, S. Radiative properties of the first galaxies: rapid transition between UV and Infrared bright phases. *MNRAS* **488**, 1825 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.tmp.1825A>.
- [234] Morgan, H. L. & Edmunds, M. G. Dust formation in early galaxies. *Monthly Notices of the Royal Astronomical Society* **343**, 427–442 (2003). URL <https://doi.org/10.1046/j.1365-8711.2003.06681.x>.
- [235] Matteucci, F. & Greggio, L. Relative roles of type I and II supernovae in the chemical enrichment of the interstellar gas. *A&A* **154**, 279–287 (1986). URL <https://ui.adsabs.harvard.edu/abs/1986A&A...154..279M>.
- [236] Sarangi, A., Matsuura, M. & Micelotta, E. R. Dust in Supernovae and Supernova Remnants I: Formation Scenarios. *Space Science Reviews* **214**, 63 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018SSRv..214...63S>.
- [237] Feder, J., Russell, K. C., Lothe, J. & Pound, G. M. Homogeneous nucleation and growth of droplets in vapours. *Advances in Physics* **15**, 111–178 (1966). URL <https://ui.adsabs.harvard.edu/abs/1966AdPhy..15..111F>.
- [238] Schneider, R., Ferrara, A. & Salvaterra, R. Dust formation in very massive primordial supernovae. *MNRAS* **351**, 1379–1386 (2004). URL <https://ui.adsabs.harvard.edu/abs/2004MNRAS.351.1379S>.

- [239] Nozawa, T., Kozasa, T., Umeda, H., Maeda, K. & Nomoto, K. Dust in the Early Universe: Dust Formation in the Ejecta of Population III Supernovae. *ApJ* **598**, 785–803 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003ApJ...598..785N>.
- [240] Nozawa, T. *et al.* Hunt, L. K., Madden, S. C. & Schneider, R. (eds) *Evolution of newly formed dust in Population III supernova remnants and its impact on the elemental composition of Population II.5 stars.* (eds Hunt, L. K., Madden, S. C. & Schneider, R.) *Low-Metallicity Star Formation: From the First Stars to Dwarf Galaxies*, Vol. 255, 254–259 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008IAUS..255..254N>. 0809.4369.
- [241] Nozawa, T. & Kozasa, T. Formulation of Non-steady-state Dust Formation Process in Astrophysical Environments. *ApJ* **776**, 24 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...776...24N>.
- [242] Donn, B. & Nuth, J. A. Does nucleation theory apply to the formation of refractory circumstellar grains? *ApJ* **288**, 187–190 (1985). URL <https://ui.adsabs.harvard.edu/abs/1985ApJ...288..187D>.
- [243] Nozawa, T. *et al.* Formation and Evolution of Dust in Type IIb Supernovae with Application to the Cassiopeia A Supernova Remnant. *ApJ* **713**, 356–373 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...713..356N>.
- [244] Ferrara, A. & Peroux, C. Late-time cosmic evolution of dust: solving the puzzle. *MNRAS* **503**, 4537–4543 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.503.4537F>.
- [245] Sarangi, A. Formation, distribution, and IR emission of dust in the clumpy ejecta of Type II-P core-collapse supernovae, in isotropic and anisotropic scenarios. *A&A* **668**, A57 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022A&A...668A..57S>.
- [246] Ferrara, A. & Tolstoy, E. The role of stellar feedback and dark matter in the evolution of dwarf galaxies. *Monthly Notices of the Royal Astronomical Society* **313**, 291–309 (2000). URL <https://doi.org/10.1046/j.1365-8711.2000.03209.x>.
- [247] Kotak, R. *et al.* Dust and The Type II-Plateau Supernova 2004et. *ApJ* **704**, 306–323 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009ApJ...704..306K>.
- [248] Inserra, C. *et al.* The Type IIP SN 2007od in UGC 12846: from a bright maximum to dust formation in the nebular phase. *MNRAS* **417**, 261–279 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.417..261I>.
- [249] Gallagher, S. C., Everett, J. E., Keating, S. K., Hill, A. R. & Deo, R. P. Chartas, G., Hamann, F. & Leighly, K. M. (eds) *Looking for the Wind in the Dust.* (eds Chartas, G., Hamann, F. & Leighly, K. M.) *AGN Winds in Charleston*, Vol. 460 of *Astronomical Society of the Pacific Conference Series*, 199 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ASPC..460..199G>. 1201.5018.
- [250] Gomez, H. L. *et al.* A Cool Dust Factory in the Crab Nebula: A Herschel Study of the Filaments. *ApJ* **760**, 96 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ApJ...760...96G>.
- [251] Matsuura, M. *et al.* A Stubbornly Large Mass of Cold Dust in the Ejecta of Supernova 1987A. *ApJ* **800**, 50 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015ApJ...800...50M>.

- [252] Bocchio, M. *et al.* Dust grains from the heart of supernovae. *A&A* **587**, A157 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016A&A...587A.157B>.
- [253] Niculescu-Duvaz, M. *et al.* Dust masses for a large sample of core-collapse supernovae from optical emission line asymmetries: dust formation on 30-year time-scales. *MNRAS* **515**, 4302–4343 (2022).
- [254] Valiante, R., Schneider, R., Salvadori, S. & Bianchi, S. The origin of the dust in high-redshift quasars: the case of SDSS J1148+5251. *MNRAS* **416**, 1916–1935 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.416.1916V>.
- [255] Jones, T. *et al.* The Mass-Metallicity Relation at $z=8$: Direct-Method Metallicity Constraints and Near-Future Prospects. *arXiv e-prints* arXiv:2006.02447 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200602447J>.
- [256] Slavin, J. D., Dwek, E., Mac Low, M.-M. & Hill, A. S. The Dynamics, Destruction, and Survival of Supernova-formed Dust Grains. *ApJ* **902**, 135 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...902..135S>.
- [257] Micelotta, E. R., Dwek, E. & Slavin, J. D. Dust destruction by the reverse shock in the Cassiopeia A supernova remnant. *A&A* **590**, A65 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016A&A...590A..65M>.
- [258] Micelotta, E. R., Matsuura, M. & Sarangi, A. Dust in Supernovae and Supernova Remnants II: Processing and Survival. *Space Science Reviews* **214**, 53 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018SSRv...214...53M>.
- [259] Vassiliadis, E. & Wood, P. R. Evolution of Low- and Intermediate-Mass Stars to the End of the Asymptotic Giant Branch with Mass Loss. *ApJ* **413**, 641 (1993). URL <https://ui.adsabs.harvard.edu/abs/1993ApJ...413..641V>.
- [260] Ferrarotti, A. S. & Gail, H. P. Composition and quantities of dust produced by AGB-stars and returned to the interstellar medium. *A&A* **447**, 553–576 (2006). URL <https://ui.adsabs.harvard.edu/abs/2006A&A...447..553F>.
- [261] Valiante, R., Schneider, R., Bianchi, S. & Andersen, A. C. Stellar sources of dust in the high-redshift Universe. *MNRAS* **397**, 1661–1671 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009MNRAS.397.1661V>.
- [262] Nanni, A., Bressan, A., Marigo, P. & Girardi, L. Evolution of thermally pulsing asymptotic giant branch stars - II. Dust production at varying metallicity. *MNRAS* **434**, 2390–2417 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013MNRAS.434.2390N>.
- [263] Schneider, R., Valiante, R., Ventura, P., dell’Agli, F. & di Criscienzo, M. Kerschbaum, F., Wing, R. F. & Hron, J. (eds) *Dust in the Early Universe and the Contribution of AGB Stars*. (eds Kerschbaum, F., Wing, R. F. & Hron, J.) *Why Galaxies Care about AGB Stars III: A Closer Look in Space and Time*, Vol. 497 of *Astronomical Society of the Pacific Conference Series*, 369 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015ASPC..497..369S>.
- [264] Nanni, A., Burgarella, D., Theulé, P., Côté, B. & Hirashita, H. The gas, metal, and dust evolution in low-metallicity local and high-redshift galaxies. *A&A* **641**, A168 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...641A.168N>.

- [265] Liu, H.-M. & Hirashita, H. Expected dust grain-size distributions in galaxies detected by ALMA at $z > 7$. *MNRAS* **490**, 540–549 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.490..540L>.
- [266] Burgarella, D. *et al.* Observational and theoretical constraints on the formation and early evolution of the first dust grains in galaxies at $5 < z < 10$. *A&A* **637**, A32 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...637A..32B>.
- [267] Asano, R. S., Takeuchi, T. T., Hirashita, H. & Nozawa, T. What determines the grain size distribution in galaxies? *Monthly Notices of the Royal Astronomical Society* **432**, 637–652 (2013). URL <https://doi.org/10.1093/mnras/stt506>.
- [268] Hirashita, H. & Voshchinnikov, N. V. Effects of grain growth mechanisms on the extinction curve and the metal depletion in the interstellar medium. *MNRAS* **437**, 1636–1645 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014MNRAS.437.1636H>.
- [269] Mancini, M. *et al.* The dust mass in $z > 6$ normal star-forming galaxies. *MNRAS* **451**, L70–L74 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015MNRAS.451L..70M>.
- [270] Michałowski, M. J. Dust production 680–850 million years after the Big Bang. *A&A* **577**, A80 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015A&A...577A..80M>.
- [271] Ginolfi, M. *et al.* Where does galactic dust come from? *MNRAS* **473**, 4538–4543 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.473.4538G>.
- [272] Popping, G. An upper limit on [OIII] 88 μ m and 1.2 mm continuum emission from a JWST $z \approx 12 - 13$ galaxy candidate with ALMA. *arXiv e-prints* arXiv:2208.13072 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220813072P>.
- [273] Popping, G., Somerville, R. S. & Galametz, M. The dust content of galaxies from $z = 0$ to $z = 9$. *MNRAS* **471**, 3152–3185 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.471.3152P>.
- [274] Graziani, L. *et al.* The assembly of dusty galaxies at $z \geq 4$: statistical properties. *MNRAS* **494**, 1071–1088 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.494.1071G>.
- [275] Ferrara, A., Viti, S. & Ceccarelli, C. The problematic growth of dust in high-redshift galaxies. *MNRAS* **463**, L112–L116 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016MNRAS.463L.112F>.
- [276] Ceccarelli, C., Viti, S., Balucani, N. & Taquet, V. The evolution of grain mantles and silicate dust growth at high redshift. *MNRAS* **476**, 1371–1383 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.476.1371C>.
- [277] Bowler, R. A. A., Bourne, N., Dunlop, J. S., McLure, R. J. & McLeod, D. J. Obscured star formation in bright $z \sim 7$ Lyman-break galaxies. *MNRAS* **481**, 1631–1644 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.481.1631B>.
- [278] Hashimoto, T. *et al.* Big Three Dragons: A $z = 7.15$ Lyman-break galaxy detected in [O III] 88 μ m, [CII] 158 μ m, and dust continuum with ALMA. *Pub. Astron. Soc. Japan* **71**, 71 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019PASJ...71...71H>.

- [279] Morishita, T. *et al.* Early results from GLASS-JWST. XVIII: A spectroscopically confirmed protocluster 650 million years after the Big Bang. *arXiv e-prints* arXiv:2211.09097 (2022).
- [280] Bakx, T. J. L. C. *et al.* Accurate dust temperature determination in a $z = 7.13$ galaxy. *arXiv e-prints* arXiv:2108.13479 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021arXiv210813479B>.
- [281] Knudsen, K. K. *et al.* A merger in the dusty, $z = 7.5$ galaxy A1689-zD1. *MNRAS* **466**, 138–146 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.466..138K>.
- [282] Faisst, A. L. *et al.* ALMA Characterises the Dust Temperature of $z \sim 5.5$ Star-Forming Galaxies. *arXiv e-prints* arXiv:2005.07716 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200507716F>.
- [283] Pavesi, R. *et al.* Alma reveals weak [n ii] emission in “typical” galaxies and intense starbursts at $z = 5-6$. *The Astrophysical Journal* **832**, 151 (2016).
- [284] Pavesi, R., Riechers, D. A., Faisst, A. L., Stacey, G. J. & Capak, P. L. Low Star Formation Efficiency in Typical Galaxies at $z = 5-6$. *ApJ* **882**, 168 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...882..168P>.
- [285] Algera, H. *et al.* Cold Dust and Low [OIII]/[CII] Ratios: an Evolved Star-forming Population at Redshift 7. *arXiv e-prints* arXiv:2301.09659 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023arXiv230109659A>.
- [286] Fujimoto, S., Ouchi, M., Shibuya, T. & Nagai, H. Demonstrating a New Census of Infrared Galaxies with ALMA (DANCING-ALMA). I. FIR Size and Luminosity Relation at $z = 0-6$ Revealed with 1034 ALMA Sources. *ApJ* **850**, 83 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017ApJ...850...83F>.
- [287] Fudamoto, Y. *et al.* A3COSMOS: the dust attenuation of star-forming galaxies at $z = 2.5-4.0$ from the COSMOS-ALMA archive. *MNRAS* **491**, 4724–4734 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.491.4724F>.
- [288] Stefanon, L. & al., in prep. **0**, 0–0 (2022).
- [289] Vijayan, A. P. *et al.* Detailed dust modelling in the L-GALAXIES semi-analytic model of galaxy formation. *MNRAS* **489**, 4072–4089 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.489.4072V>.
- [290] Triani, D. P., Sinha, M., Croton, D. J., Pacifici, C. & Dwek, E. The origin of dust in galaxies across cosmic time. *MNRAS* **493**, 2490–2505 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.493.2490T>.
- [291] Viero, M. P. *et al.* HerMES: The Contribution to the Cosmic Infrared Background from Galaxies Selected by Mass and Redshift. *ApJ* **779**, 32 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...779...32V>.
- [292] Magnelli, B. *et al.* The deepest Herschel-PACS far-infrared survey: number counts and infrared luminosity functions from combined PEP/GOODS-H observations. *A&A* **553**, A132 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013A&A...553A.132M>.

- [293] Béthermin, M. *et al.* Evolution of the dust emission of massive galaxies up to $z = 4$ and constraints on their dominant mode of star formation. *A&A* **573**, A113 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015A&A...573A.113B>.
- [294] Drew, P. M. & Casey, C. M. No Redshift Evolution of Galaxies' Dust Temperatures Seen from $0 < z < 2$. *ApJ* **930**, 142 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022ApJ...930..142D>.
- [295] Weaver, J. R. *et al.* COSMOS2020: A Panchromatic View of the Universe to z 10 from Two Complementary Catalogs. *ApJS* **258**, 11 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022ApJS..258...11W>.
- [296] Riechers, D. A. *et al.* POLYCYCLIC AROMATIC HYDROCARBON AND MID-INFRARED CONTINUUM EMISSION IN at $z > 4$ SUBMILLIMETER GALAXY. *The Astrophysical Journal* **786**, 31 (2014). URL <https://doi.org/10.1088/0004-637x/786/1/31>.
- [297] Riechers, D. A. *et al.* COLDz: A High Space Density of Massive Dusty Starburst Galaxies ~ 1 Billion Years after the Big Bang. *ApJ* **895**, 81 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...895...81R>.
- [298] Jin, S. *et al.* Discovery of four apparently cold dusty galaxies at $z = 3.62\text{--}5.85$ in the cosmos field: Direct evidence of cosmic microwave background impact on high-redshift galaxy observables. *The Astrophysical Journal* **887**, 144 (2019). URL <https://dx.doi.org/10.3847/1538-4357/ab55d6>.
- [299] Yang, M., Greve, T. R., Dowell, C. D. & Borys, C. 350 micron Observations of Ultraluminous Infrared Galaxies at Intermediate Redshifts. *ApJ* **660**, 1198–1208 (2007). URL <https://ui.adsabs.harvard.edu/abs/2007ApJ...660.1198Y>.
- [300] Magdis, G. E. *et al.* A FAR-INFRARED SPECTROSCOPIC SURVEY OF INTERMEDIATE REDSHIFT (ULTRA) LUMINOUS INFRARED GALAXIES. *The Astrophysical Journal* **796**, 63 (2014). URL <https://doi.org/10.1088/0004-637x/796/1/63>.
- [301] Huang, J.-S. *et al.* HerMES: SPECTRAL ENERGY DISTRIBUTIONS OF SUBMILLIMETER GALAXIES AT $z > 4$. *The Astrophysical Journal* **784**, 52 (2014). URL <https://doi.org/10.1088/0004-637x/784/1/52>.
- [302] Chapman, S. C., Blain, A. W., Smail, I. & Ivison, R. J. A Redshift Survey of the Submillimeter Galaxy Population. *ApJ* **622**, 772–796 (2005). URL <https://ui.adsabs.harvard.edu/abs/2005ApJ...622..772C>.
- [303] Clements, D. L. *et al.* HERUS: the far-IR/submm spectral energy distributions of local ULIRGs and photometric atlas. *Monthly Notices of the Royal Astronomical Society* **475**, 2097–2121 (2017). URL <https://doi.org/10.1093/mnras/stx3227>.
- [304] Dunne, L. & Eales, S. A. The SCUBA Local Universe Galaxy Survey – II. 450micron data: evidence for cold dust in bright IRAS galaxies. *Monthly Notices of the Royal Astronomical Society* **327**, 697–714 (2001). URL <https://doi.org/10.1046/j.1365-8711.2001.04789.x>.
- [305] Blain, A. W., Barnard, V. E. & Chapman, S. C. Submillimetre and far-infrared spectral energy distributions of galaxies: the luminosity—temperature relation and consequences for photometric redshifts. *Monthly Notices of the Royal Astronomical Society* **338**, 733–744 (2003). URL <https://doi.org/10.1046/j.1365-8711.2003.06086.x>.

- [306] Kovács, A. *et al.* FAR-INFRARED PROPERTIES OF SPITZER-SELECTED LUMINOUS STARBURSTS. *The Astrophysical Journal* **717**, 29–39 (2010). URL <https://doi.org/10.1088/0004-637x/717/1/29>.
- [307] Casey, C. M. Far-infrared spectral energy distribution fitting for galaxies near and far. *MNRAS* **425**, 3094–3103 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012MNRAS.425.3094C>.
- [308] Dale, D. A. *et al.* HERSCHEL FAR-INFRARED AND SUBMILLIMETER PHOTOMETRY FOR THE KINGFISH SAMPLE OF NEARBY GALAXIES. *The Astrophysical Journal* **745**, 95 (2012). URL <https://doi.org/10.1088/0004-637x/745/1/95>.
- [309] Galametz, M. *et al.* Mapping the cold dust temperatures and masses of nearby KINGFISH galaxies with Herschel. *Monthly Notices of the Royal Astronomical Society* **425**, 763–787 (2012). URL <https://doi.org/10.1111/j.1365-2966.2012.21667.x>.
- [310] Kirkpatrick, A. *et al.* GOODS-HERSCHEL: IMPACT OF ACTIVE GALACTIC NUCLEI AND STAR FORMATION ACTIVITY ON INFRARED SPECTRAL ENERGY DISTRIBUTIONS AT HIGH REDSHIFT. *The Astrophysical Journal* **759**, 139 (2012). URL <https://doi.org/10.1088/0004-637x/759/2/139>.
- [311] da Cunha, E. *et al.* AN ALMA SURVEY OF SUB-MILLIMETER GALAXIES IN THE EXTENDED CHANDRA DEEP FIELD SOUTH: PHYSICAL PROPERTIES DERIVED FROM ULTRAVIOLET-TO-RADIO MODELING. *The Astrophysical Journal* **806**, 110 (2015). URL <https://doi.org/10.1088/0004-637x/806/1/110>.
- [312] Casey, C. M. *et al.* An analysis of ALMA deep fields and the perceived dearth of high- z galaxies. *The Astrophysical Journal* **862**, 78 (2018). URL <https://doi.org/10.3847/2F1538-4357/2Faacd11>.
- [313] Sommovigo, L. *et al.* Warm dust in high- z galaxies: origin and implications. *MNRAS* **497**, 956–968 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.497..956S>.
- [314] Inoue, A. K., Hashimoto, T., Chihara, H. & Koike, C. Radiative equilibrium estimates of dust temperature and mass in high-redshift galaxies. *Monthly Notices of the Royal Astronomical Society* **495**, 1577–1592 (2020). URL <https://doi.org/10.1093/mnras/staa1203>.
- [315] Sommovigo, L. *et al.* Dust temperature in ALMA [CII]-detected high- z galaxies. *MNRAS* **503**, 4878–4891 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.503.4878S>.
- [316] Hirashita, H. & Chiang, I.-D. Analytic models of dust temperature in high-redshift galaxies. *MNRAS* **516**, 1612–1623 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.516.1612H>.
- [317] Akins, H. B. *et al.* ALMA Reveals Extended Cool Gas and Hot Ionized Outflows in a Typical Star-forming Galaxy at $z = 7.13$. *ApJ* **934**, 64 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022ApJ...934...64A>.
- [318] Meixner, M. *et al.* Origins Space Telescope Mission Concept Study Report. *arXiv e-prints* arXiv:1912.06213 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019arXiv191206213M>.

- [319] Leisawitz, D. *et al.* *The Space Interferometer for Cosmic Evolution (SPICE) Far-IR Probe*, Vol. 55 of *American Astronomical Society Meeting Abstracts*, 160.04 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023AAS...24116004L>.
- [320] Fujimoto, S. *et al.* First Identification of 10 kpc [CII] 158 μ m Halos around Star-forming Galaxies at $z = 5-7$. *ApJ* **887**, 107 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...887..107F>.
- [321] Fujimoto, S. *et al.* The ALPINE-ALMA [CII] Survey: Size of Individual Star-Forming Galaxies at $z=4-6$ and their Extended Halo Structure. *arXiv e-prints* arXiv:2003.00013 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200300013F>.
- [322] Ginolfi, M. *et al.* The ALPINE-ALMA [CII] survey: Star-formation-driven outflows and circumgalactic enrichment in the early Universe. *A&A* **633**, A90 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...633A..90G>.
- [323] Vallini, L., Gallerani, S., Ferrara, A., Pallottini, A. & Yue, B. On the [CII]-SFR Relation in High Redshift Galaxies. *ApJ* **813**, 36 (2015). URL <http://adsabs.harvard.edu/abs/2015ApJ...813...36V>.
- [324] Vallini, L., Ferrara, A., Pallottini, A. & Gallerani, S. Molecular cloud photoevaporation and far-infrared line emission. *MNRAS* **467**, 1300–1312 (2017). URL <http://adsabs.harvard.edu/abs/2017MNRAS.467.1300V>.
- [325] Vallini, L., Ferrara, A., Pallottini, A., Carniani, S. & Gallerani, S. High [O III]/[CII] surface brightness ratios trace early starburst galaxies. *MNRAS* **505**, 5543–5553 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.505.5543V>.
- [326] Pallottini, A. *et al.* Zooming on the internal structure of $z \approx 6$ galaxies. *MNRAS* **465**, 2540–2558 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.465.2540P>.
- [327] Ferrara, A. *et al.* A physical model for [CII] line emission from galaxies. *MNRAS* **489**, 1–12 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.489....1F>.
- [328] Kohandel, M. *et al.* Kinematics of $z \geq 6$ galaxies from [CII] line emission. *MNRAS* **487**, 3007–3020 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.487.3007K>.
- [329] Kohandel, M. *et al.* Interpreting ALMA non-detections of JWST super-early galaxies. *arXiv e-prints* arXiv:2212.02519 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv221202519K>.
- [330] Zanella, A. *et al.* The [CII] emission as a molecular gas mass tracer in galaxies at low and high redshifts. *MNRAS* **481**, 1976–1999 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.481.1976Z>.
- [331] James, A., Dunne, L., Eales, S. & Edmunds, M. G. SCUBA observations of galaxies with metallicity measurements: a new method for determining the relation between submillimetre luminosity and dust mass. *MNRAS* **335**, 753–761 (2002). URL <https://ui.adsabs.harvard.edu/abs/2002MNRAS.335..753J>.
- [332] Galliano, F., Dwek, E. & Charnial, P. Stellar Evolutionary Effects on the Abundances of Polycyclic Aromatic Hydrocarbons and Supernova-Condensed Dust in Galaxies. *ApJ* **672**, 214–243 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008ApJ...672..214G>.

- [333] Leroy, A. K. *et al.* THE CO-TO-h2conversion FACTOR FROM INFRARED DUST EMISSION ACROSS THE LOCAL GROUP. *The Astrophysical Journal* **737**, 12 (2011). URL <https://doi.org/10.1088%2F0004-637x%2F737%2F1%2F12>.
- [334] Rémy-Ruyer, A. *et al.* Gas-to-dust mass ratios in local galaxies over a 2 dex metallicity range. *A&A* **563**, A31 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014A&A...563A..31R>.
- [335] Galliano, F., Madden, S. C., Jones, A. P., Wilson, C. D. & Bernard, J. P. ISM properties in low-metallicity environments. III. The spectral energy distributions of II Zw 40, He 2-10 and NGC 1140. *A&A* **434**, 867–885 (2005). URL <https://ui.adsabs.harvard.edu/abs/2005A&A...434..867G>.
- [336] Galametz, M. *et al.* Probing the dust properties of galaxies up to submillimetre wavelengths. II. Dust-to-gas mass ratio trends with metallicity and the submm excess in dwarf galaxies. *A&A* **532**, A56 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011A&A...532A..56G>.
- [337] De Vis, P. *et al.* A systematic metallicity study of DustPedia galaxies reveals evolution in the dust-to-metal ratios. *A&A* **623**, A5 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019A&A...623A...5D>.
- [338] Ma, X. *et al.* The origin and evolution of the galaxy mass-metallicity relation. *MNRAS* **456**, 2140–2156 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016MNRAS.456.2140M>.
- [339] Torrey, P. *et al.* The evolution of the mass-metallicity relation and its scatter in IllustrisTNG. *MNRAS* **484**, 5587–5607 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.484.5587T>.
- [340] Pereira-Santaella, M., Rigopoulou, D., Farrah, D., Lebouteiller, V. & Li, J. Far-infrared metallicity diagnostics: application to local ultraluminous infrared galaxies. *Monthly Notices of the Royal Astronomical Society* **470**, 1218–1232 (2017). URL <https://doi.org/10.1093/mnras/stx1284>.
- [341] Vallini, L., Ferrara, A., Pallottini, A., Carniani, S. & Gallerani, S. Star formation law in the EoR from [CII] and C III] lines. *MNRAS* (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.tmpL..44V>.
- [342] Wright, S. A. *et al.* Tracing the evolution and distribution of metallicity in the early universe. *The Astronomy and Astrophysical Decadal Survey, Science White paper* (2010).
- [343] Maiolino, R. & Mannucci, F. De re metallica: the cosmic chemical evolution of galaxies. *The Astronomy and Astrophysics Review* **27** (2019). URL <http://dx.doi.org/10.1007/s00159-018-0112-2>.
- [344] Chevallard, J. *et al.* Simulating and interpreting deep observations in the Hubble Ultra Deep Field with the JWST/NIRSpec low-resolution ‘prism’. *MNRAS* **483**, 2621–2640 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.483.2621C>.
- [345] Heiderman, A., Evans, N. J., Allen, L. E., Huard, T. & Heyer, M. THE STAR FORMATION RATE AND GAS SURFACE DENSITY RELATION IN THE MILKY WAY: IMPLICATIONS FOR EXTRAGALACTIC STUDIES. *The Astrophysical Journal* **723**, 1019–1037 (2010). URL <https://doi.org/10.10882F0004-637x2F7232F22F1019>.

- [346] Da Cunha, E. *et al.* On the effect of the cosmic microwave background in high-redshift (sub-) millimeter observations. *The Astrophysical Journal* **766**, 13 (2013).
- [347] Walter, F. *et al.* ALMA Spectroscopic Survey in the Hubble Ultra Deep Field: Survey Description. *ApJ* **833**, 67 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ApJ...833...67W>.
- [348] Matthee, J. *et al.* Resolved UV and [CII] Structures of Luminous Galaxies within the Epoch of Reionization. *ApJ* **881**, 124 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...881..124M>.
- [349] Schaerer, D. *et al.* The ALPINE-ALMA [CII] survey. No or weak evolution in the [CII]-SFR relation over the last 13 Gyr. *arXiv e-prints* arXiv:2002.00979 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200200979S>.
- [350] Bradač, M. *et al.* ALMA [CII] 158 μ m Detection of a Redshift 7 Lensed Galaxy behind RXJ1347.1-1145. *ApJL* **836**, L2 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017ApJ...836L...2B>.
- [351] Gallerani, S. *et al.* ALMA suggests outflows in $z \sim 5.5$ galaxies. *Monthly Notices of the Royal Astronomical Society* **473**, 1909–1917 (2017). URL <https://doi.org/10.1093/mnras/stx2458>.
- [352] Pizzati, E. *et al.* Outflows and extended [CII] haloes in high-redshift galaxies. *Monthly Notices of the Royal Astronomical Society* **495**, 160–172 (2020). URL <https://doi.org/10.1093/mnras/staa1163>.
- [353] Hahn, O. & Abel, T. Multi-scale initial conditions for cosmological simulations. *Monthly Notices of the Royal Astronomical Society* **415**, 2101–2121 (2011). URL <https://doi.org/10.1111/j.1365-2966.2011.18820.x>.
- [354] Nilson, P. Uppsala General Catalogue of Galaxies, 1973, Acta Universitatis Upsalienis, Nova Regiae Societatis Upsaliensis, Series v: a Vol. *Nova Acta Regiae Soc. Sci. Upsaliensis Ser. V* 0 (1973). URL <https://ui.adsabs.harvard.edu/abs/1973UGC...C...0000N>.
- [355] Engelbracht, C. W. *et al.* Metallicity Effects on Dust Properties in Starbursting Galaxies. *ApJ* **678**, 804–827 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008ApJ...678..804E>.
- [356] Cormier, D. *et al.* The Herschel Dwarf Galaxy Survey. II. Physical conditions, origin of [CII] emission, and porosity of the multiphase low-metallicity ISM. *A&A* **626**, A23 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019A&A...626A..23C>.
- [357] Puschnig, J. *et al.* The Lyman Alpha Reference Sample XI: Efficient Turbulence Driven Ly α Escape and the Analysis of IR, CO and [CII]158 μ m. *arXiv e-prints* arXiv:2004.09142 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200409142P>.
- [358] Fernandez-Ontiveros, J. *et al.* Vizier online data catalog: Fir spectra of agns from herchel (fernandez-ontiveros+, 2016). *VizieR Online Data Catalog* **222** (2016).
- [359] Leroy, A. K. *et al.* The Star Formation Efficiency in Nearby Galaxies: Measuring Where Gas Forms Stars Effectively. *AJ* **136**, 2782–2845 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008AJ....136.2782L>.

- [360] Caldú-Primo, A. & Cruz-González, I. *Massive Star Formation in Two Spiral Galaxies: NGC 3938 and NGC 3184; Multiwavelength Analysis*, Vol. 34 of *Revista Mexicana de Astronomía y Astrofísica Conference Series*, 115–116 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008RMxAC..34..115C>.
- [361] Jarrett, T. H., Chester, T., Cutri, R., Schneider, S. E. & Huchra, J. P. The 2MASS Large Galaxy Atlas. *AJ* **125**, 525–554 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003AJ....125..525J>.
- [362] Groves, B. A. *et al.* DUST CONTINUUM EMISSION AS a TRACER OF GAS MASS IN GALAXIES. *The Astrophysical Journal* **799**, 96 (2015). URL <https://doi.org/10.1088%2F0004-637x%2F799%2F1%2F96>.
- [363] Kennicutt, R. C. *et al.* KINGFISH—Key Insights on Nearby Galaxies: A Far-Infrared Survey with Herschel: Survey Description and Image Atlas. *Publ. Astr. Soc. Pac.* **123**, 1347 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011PASP..123.1347K>.
- [364] Chu, J. K. *et al.* The Great Observatories All-Sky LIRG Survey: Herschel Image Atlas and Aperture Photometry. *ApJS* **229**, 25 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017ApJS..229...25C>.
- [365] Madden, S. C. *et al.* An Overview of the Dwarf Galaxy Survey (PASP, 125, 600, [2013])—Corrigendum. *Publ. Astr. Soc. Pac.* **126**, 1079 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014PASP..126.1079M>.
- [366] Madden, S. C. *et al.* Tracing the total molecular gas in galaxies: [CII] and the CO-dark gas. *arXiv e-prints* arXiv:2009.00649 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200900649M>.
- [367] Hayes, M. *et al.* THE LYMAN ALPHA REFERENCE SAMPLE. II. HUBBLE SPACE TELESCOPE IMAGING RESULTS, INTEGRATED PROPERTIES, AND TRENDS. *The Astrophysical Journal* **782**, 6 (2014). URL <https://doi.org/10.10882F0004-637x2F7822F12F6>.
- [368] Östlin, G. *et al.* THE $\text{Ly}\alpha$ REFERENCE SAMPLE. i. SURVEY OUTLINE AND FIRST RESULTS FOR MARKARIAN 259. *The Astrophysical Journal* **797**, 11 (2014). URL <https://doi.org/10.10882F0004-637x2F7972F12F11>.
- [369] Bothwell, M. S. *et al.* ALMA observations of atomic carbon in $z \sim 4$ dusty star-forming galaxies. *MNRAS* **466**, 2825–2841 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.466.2825B>.
- [370] De Breuck, C. *et al.* A dense, solar metallicity ISM in the $z = 4.2$ dusty star-forming galaxy SPT 0418-47. *A&A* **631**, A167 (2019).
- [371] Rizzo, F. *et al.* A dynamically cold disk galaxy in the early Universe. *Nature* **584**, 201–204 (2020). URL <https://doi.org/10.1038/s41586-020-2572-6>.
- [372] Strandet, M. *et al.* The redshift distribution of dusty star-forming galaxies from the spt survey. *The Astrophysical Journal* **822**, 80 (2016).
- [373] Daddi, E. *et al.* DIFFERENT STAR FORMATION LAWS FOR DISKS VERSUS STARBURSTS AT LOW AND HIGH REDSHIFTS. *The Astrophysical Journal* **714**, L118–L122 (2010). URL <https://doi.org/10.1088%2F2041-8205%2F714%2F1%2F118>.

- [374] Spilker, J. *et al.* Alma imaging and gravitational lens models of south pole telescope—selected dusty, star-forming galaxies at high redshifts. *The Astrophysical Journal* **826**, 112 (2016).
- [375] Walter, F. *et al.* The Evolution of the Baryons Associated with Galaxies Averaged over Cosmic Time and Space. *arXiv e-prints* arXiv:2009.11126 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020arXiv200911126W>.
- [376] Dessauges-Zavadsky, M. *et al.* The alpine-alma [cii] survey: Molecular gas budget in the early universe as traced by [cii] (2020). 2004.10771.
- [377] Bigiel, F. *et al.* The Star Formation Law in Nearby Galaxies on Sub-Kpc Scales. *AJ* **136**, 2846–2871 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008AJ...136.2846B>.
- [378] Genzel, R. *et al.* A study of the gas–star formation relation over cosmic time*. *Monthly Notices of the Royal Astronomical Society* **407**, 2091–2108 (2010). URL <https://doi.org/10.1111/j.1365-2966.2010.16969.x>.
- [379] Leroy, A. K. *et al.* Molecular Gas and Star Formation in nearby Disk Galaxies. *AJ* **146**, 19 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013AJ....146..19L>.
- [380] Sargent, M. T. *et al.* Regularity Underlying Complexity: A Redshift-independent Description of the Continuous Variation of Galaxy-scale Molecular Gas Properties in the Mass-star Formation Rate Plane. *ApJ* **793**, 19 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014ApJ...793...19S>.
- [381] Genzel, R. *et al.* Combined CO and Dust Scaling Relations of Depletion Time and Molecular Gas Fractions with Cosmic Time, Specific Star-formation Rate, and Stellar Mass. *ApJ* **800**, 20 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015ApJ...800...20G>.
- [382] Dessauges-Zavadsky, M. *et al.* Molecular gas content in strongly lensed $z \sim 1.5$ –3 star-forming galaxies with low infrared luminosities. *A&A* **577**, A50 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015A&A...577A..50D>.
- [383] Schinnerer, E. *et al.* GAS FRACTION AND DEPLETION TIME OF MASSIVE STAR-FORMING GALAXIES AT $z \sim 3.2$: NO CHANGE IN GLOBAL STAR FORMATION PROCESS OUT TO $z > 3$. *The Astrophysical Journal* **833**, 112 (2016). URL <https://doi.org/10.3847/2F1538-4357/2F833/2F1/2F112>.
- [384] Scoville, N. *et al.* Evolution of interstellar medium, star formation, and accretion at high redshift. *The Astrophysical Journal* **837**, 150 (2017). URL <https://doi.org/10.3847/2F1538-4357/2Faa61a0>.
- [385] Saintonge, A. *et al.* xCOLD GASS: The complete IRAM 30 m legacy survey of molecular gas for galaxy evolution studies. *The Astrophysical Journal Supplement Series* **233**, 22 (2017). URL <https://doi.org/10.3847/2F1538-4365/2Faa97e0>.
- [386] Shibuya, T., Ouchi, M. & Harikane, Y. MORPHOLOGIES OF $\sim 190,000$ GALAXIES AT $z = 0$ –10 REVEALED WITH HST LEGACY DATA. i. SIZE EVOLUTION. *The Astrophysical Journal Supplement Series* **219**, 15 (2015). URL <https://doi.org/10.1088/2F0067-0049/2F219/2F2/2F15>.

- [387] Zwaan, M. A., Meyer, M. J., Staveley-Smith, L. & Webster, R. L. The HIPASS catalogue: Ω_{HI} and environmental effects on the HI mass function of galaxies. *Monthly Notices of the Royal Astronomical Society: Letters* **359**, L30–L34 (2005). URL <https://doi.org/10.1111/j.1745-3933.2005.00029.x>.
- [388] Prochaska, J. X. & Wolfe, A. M. On the (Non)Evolution of H I Gas in Galaxies Over Cosmic Time. *ApJ* **696**, 1543–1547 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009ApJ...696.1543P>.
- [389] Carilli, C. L. & Walter, F. Cool Gas in High-Redshift Galaxies. *ARA&A* **51**, 105–161 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ARA&A...51..105C>.
- [390] Péroux, C. & Howk, J. C. The Cosmic Baryon and Metal Cycles. *ARA&A* **58**, an-nurev (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ARA&A...5821820P>.
- [391] Davé, R., Rafieferantsoa, M. H., Thompson, R. J. & Hopkins, P. F. MUFASA: Galaxy star formation, gas, and metal properties across cosmic time. *MNRAS* **467**, 115–132 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.467..115D>.
- [392] Fudamoto, Y. *et al.* The ALPINE-ALMA [CII] survey. Dust attenuation properties and obscured star formation at $z \sim 4.4\text{--}5.8$. *A&A* **643**, A4 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...643A...4F>.
- [393] Inoue, A. K., Hashimoto, T., Chihara, H. & Koike, C. Radiative equilibrium estimates of dust temperature and mass in high-redshift galaxies. *MNRAS* **495**, 1577–1592 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.495.1577I>.
- [394] Bradley, L. D. *et al.* Discovery of a Very Bright Strongly Lensed Galaxy Candidate at $z \approx 7.6$. *ApJ* **678**, 647–654 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008ApJ...678..647B>.
- [395] Struble, M. F. & Rood, H. J. A Compilation of Redshifts and Velocity Dispersions for ACO Clusters. *ApJS* **125**, 35–71 (1999). URL <https://ui.adsabs.harvard.edu/abs/1999ApJS...125...35S>.
- [396] Ono, Y. *et al.* Great Optically Luminous Dropout Research Using Subaru HSC (GOLDRUSH). I. UV luminosity functions at $z \sim 4\text{--}7$ derived with the half-million dropouts on the 100 deg² sky. *Pub. Astron. Soc. Japan* **70**, S10 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018PASJ...70S..10O>.
- [397] Baryshev, A. M. *et al.* The ALMA Band 9 receiver. Design, construction, characterization, and first light. *A&A* **577**, A129 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015A&A...577A.129B>.
- [398] McMullin, J. P., Waters, B., Schiebel, D., Young, W. & Golap, K. *CASA Architecture and Applications*, Vol. 376 of *Astronomical Society of the Pacific Conference Series*, 127 (2007). URL <https://ui.adsabs.harvard.edu/abs/2007ASPC...376..127M>.
- [399] da Cunha, E. *et al.* On the Effect of the Cosmic Microwave Background in High-redshift (Sub-)millimeter Observations. *ApJ* **766**, 13 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...766...13D>.
- [400] Casey, C. M. Far-infrared spectral energy distribution fitting for galaxies near and far. *MNRAS* **425**, 3094–3103 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012MNRAS.425.3094C>.

- [401] Novak, M. *et al.* The VLA-COSMOS 3 GHz Large Project: Cosmic star formation history since $z \sim 5$. *A&A* **602**, A5 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017A&A...602A...5N>.
- [402] Schouws, S. *et al.* Significant Dust-Obscured Star Formation in Luminous Lyman-break Galaxies at $z \sim 7 - 8$. *arXiv e-prints* arXiv:2105.12133 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021arXiv210512133S>.
- [403] Simpson, J. M. *et al.* An ALMA Survey of Submillimeter Galaxies in the Extended Chandra Deep Field South: The Redshift Distribution and Evolution of Submillimeter Galaxies. *ApJ* **788**, 125 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014ApJ...788..125S>.
- [404] Franco, M. *et al.* GOODS-ALMA: 1.1 mm galaxy survey. I. Source catalog and optically dark galaxies. *A&A* **620**, A152 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018A&A...620A.152F>.
- [405] Hatsukade, B. *et al.* ALMA twenty-six arcmin² survey of GOODS-S at one millimeter (ASAGAO): Source catalog and number counts. *Pub. Astron. Soc. Japan* **70**, 105 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018PASJ...70..105H>.
- [406] Yamaguchi, Y. *et al.* ALMA 26 arcmin² Survey of GOODS-S at 1 mm (ASAGAO): Near-infrared-dark Faint ALMA Sources. *ApJ* **878**, 73 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...878...73Y>.
- [407] Williams, C. C. *et al.* Discovery of a Dark, Massive, ALMA-only Galaxy at $z \sim 5-6$ in a Tiny 3 mm Survey. *ApJ* **884**, 154 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...884..154W>.
- [408] Algera, H. S. B. *et al.* A Multiwavelength Analysis of the Faint Radio Sky (COSMOS-XS): the Nature of the Ultra-faint Radio Population. *ApJ* **903**, 139 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...903..139A>.
- [409] Romano, M. *et al.* The ALPINE-ALMA [CII] Survey: on the nature of an extremely obscured serendipitous galaxy. *MNRAS* **496**, 875–887 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020MNRAS.496..875R>.
- [410] Toba, Y. *et al.* Search for Optically Dark Infrared Galaxies without Counterparts of Subaru Hyper Suprime-Cam in the AKARI North Ecliptic Pole Wide Survey Field. *ApJ* **899**, 35 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...899..35T>.
- [411] Umehata, H. *et al.* ALMA Deep Field in SSA22. A near-infrared-dark submillimeter galaxy at $z = 4.0$. *A&A* **640**, L8 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...640L...8U>.
- [412] Zhou, L. *et al.* GOODS-ALMA: Optically dark ALMA galaxies shed light on a cluster in formation at $z = 3.5$. *A&A* **642**, A155 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...642A.155Z>.
- [413] Shibuya, T. *et al.* Galaxy Morphologies Revealed with Subaru HSC and Super-Resolution Techniques I: Major Merger Fractions of L-UV $\sim$ 3-15 L-UV* Dropout Galaxies at $z \sim 4-7$. *arXiv e-prints* arXiv:2106.03728 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021arXiv210603728S>.

- [414] Smail, I. *et al.* An ALMA survey of the S2CLS UDS field: optically invisible sub-millimetre galaxies. *MNRAS* **502**, 3426–3435 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.502.3426S>.
- [415] Alcalde Pampliega, B. *et al.* Optically Faint Massive Balmer Break Galaxies at $z > 3$ in the CANDELS/GOODS Fields. *ApJ* **876**, 135 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...876..135A>.
- [416] Matsuura, M. *et al.* SOFIA mid-infrared observations of Supernova 1987A in 2016 - forward shocks and possible dust re-formation in the post-shocked region. *MNRAS* **482**, 1715–1723 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.482.1715M>.
- [417] Martínez-González, S., Silich, S. & Tenorio-Tagle, G. Dust grain growth at high redshift: starburst-driven CMB-dark supershells. *MNRAS* **507**, 1175–1183 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.507.1175M>.
- [418] Lau, R. M. *et al.* Revealing Efficient Dust Formation at Low Metallicity in Extragalactic Carbon-rich Wolf-Rayet Binaries. *ApJ* **909**, 113 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021ApJ...909..113L>.
- [419] Chevallard, J. & Charlot, S. Modelling and interpreting spectral energy distributions of galaxies with beagle. *Monthly Notices of the Royal Astronomical Society* **462**, 1415–1443 (2016). URL <https://doi.org/10.1093/mnras/stw1756>.
- [420] Chabrier, G. The Galactic Disk Mass Function: Reconciliation of the Hubble Space Telescope and Nearby Determinations. *ApJL* **586**, L133–L136 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003ApJ...586L.133C>.
- [421] Magdis, G. E. *et al.* The Evolving Interstellar Medium of Star-forming Galaxies since $z = 2$ as Probed by Their Infrared Spectral Energy Distributions. *ApJ* **760**, 6 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ApJ...760....6M>.
- [422] Schouws, S. & al., in prep. **0**, 0–0 (2022).
- [423] Bowler, R. A. A., Dunlop, J. S., McLure, R. J. & McLeod, D. J. Unveiling the nature of bright $z \sim 7$ galaxies with the Hubble Space Telescope. *MNRAS* **466**, 3612–3635 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.466.3612B>.
- [424] Dayal, P., Dunlop, J. S., Maio, U. & Ciardi, B. Simulating the assembly of galaxies at redshifts $z = 6$ –12. *MNRAS* **434**, 1486–1504 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013MNRAS.434.1486D>.
- [425] Lonsdale, C. J., Farrah, D. & Smith, H. E. *Ultraluminous Infrared Galaxies*, 285 (2006). URL <https://ui.adsabs.harvard.edu/abs/2006asup.book..285L>.
- [426] Hygate, A. & al., in prep. **0**, 0–0 (2022).
- [427] Shen, X. *et al.* High redshift JWST predictions from IllustrisTNG: III. Infrared luminosity functions, obscured star formation and dust temperature of high-redshift galaxies. *arXiv e-prints* arXiv:2104.12788 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021arXiv210412788S>.
- [428] Tomczak, A. R. *et al.* The $\text{sfr}-m_*$ relation and empirical star formation histories from zfourge at $0.5 < z < 4$. *The Astrophysical Journal* **817**, 118 (2016). URL <https://doi.org/10.3847/0004-637x/817/2/118>.

- [429] Santini, P. *et al.* The star formation main sequence in the Hubble space Telescope Frontier fields. *The Astrophysical Journal* **847**, 76 (2017). URL <https://doi.org/10.3847/1538-4357/aa8874>.
- [430] Aoyama, S. *et al.* Galaxy simulation with dust formation and destruction. *MNRAS* **466**, 105–121 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.466..105A>.
- [431] Pallottini, A. *et al.* A survey of high- z galaxies: SERRA simulations. *arXiv e-prints* arXiv:2201.02636 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220102636P>.
- [432] Fakhouri, O., Ma, C.-P. & Boylan-Kolchin, M. The merger rates and mass assembly histories of dark matter haloes in the two Millennium simulations. *Monthly Notices of the Royal Astronomical Society* **406**, 2267–2278 (2010). URL <https://doi.org/10.1111/j.1365-2966.2010.16859.x>.
- [433] Dekel, A. & Krumholz, M. R. Steady outflows in giant clumps of high- z disc galaxies during migration and growth by accretion. *Monthly Notices of the Royal Astronomical Society* **432**, 455–467 (2013). URL <https://doi.org/10.1093/mnras/stt480>.
- [434] Correa, C. A., Wyithe, J. S. B., Schaye, J. & Duffy, A. R. The accretion history of dark matter haloes - II. The connections with the mass power spectrum and the density profile. *MNRAS* **450**, 1521–1537 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015MNRAS.450.1521C>.
- [435] Leroy, A. K. *et al.* THE STAR FORMATION EFFICIENCY IN NEARBY GALAXIES: MEASURING WHERE GAS FORMS STARS EFFECTIVELY. *The Astronomical Journal* **136**, 2782–2845 (2008). URL <https://doi.org/10.1088/0004-6256/136/6/2782>.
- [436] Genzel, R. *et al.* A study of the gas-star formation relation over cosmic time. *MNRAS* **407**, 2091–2108 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010MNRAS.407.2091G>.
- [437] Tacconi, L. J. *et al.* PHIBSS: Unified Scaling Relations of Gas Depletion Time and Molecular Gas Fractions. *ApJ* **853**, 179 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...853..179T>.
- [438] Hodge, J. A. *et al.* Evidence for a Clumpy, Rotating Gas Disk in a Submillimeter Galaxy at $z = 4$. *ApJ* **760**, 11 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ApJ...760...11H>.
- [439] Hodge, J. A. *et al.* Kiloparsec-scale Dust Disks in High-redshift Luminous Submillimeter Galaxies. *ApJ* **833**, 103 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ApJ...833..103H>.
- [440] Bowler, R. A. A., Cullen, F., McLure, R. J., Dunlop, J. S. & Avison, A. The discovery of rest-frame UV colour gradients and a diversity of dust morphologies in bright $z \sim 7$ Lyman-break galaxies. *MNRAS* (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.tmp.3413B>.
- [441] Ucci, G. *et al.* Astraeus V: The emergence and evolution of metallicity scaling relations during the Epoch of Reionization. *arXiv e-prints* arXiv:2112.02115 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021arXiv211202115U>.

- [442] Vanderhoof, B. N. *et al.* The ALPINE-ALMA [C II] survey: Investigation of 10 galaxies at z 4.5 with [O II] and [C II] line emission - ISM properties and [O II]-SFR relation. *MNRAS* **511**, 1303–1316 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.511.1303V>.
- [443] Behroozi, P., Wechsler, R. H., Hearin, A. P. & Conroy, C. UNIVERSEMACHINE: The correlation between galaxy growth and dark matter halo assembly from $z = 0$ –10. *MNRAS* **488**, 3143–3194 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.488.3143B>.
- [444] Song, M. *et al.* The Evolution of the Galaxy Stellar Mass Function at $z = 4$ –8: A Steepening Low-mass-end Slope with Increasing Redshift. *ApJ* **825**, 5 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ApJ...825....5S>.
- [445] Castellano, M. *et al.* Early results from GLASS-JWST. III: Galaxy candidates at $z \sim 9$ –15. *arXiv e-prints* arXiv:2207.09436 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220709436C>.
- [446] Naidu, R. P. *et al.* Two Remarkably Luminous Galaxy Candidates at $z \approx 11$ – 13 Revealed by JWST. *arXiv e-prints* arXiv:2207.09434 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220709434N>.
- [447] Labbe, I. *et al.* A very early onset of massive galaxy formation. *arXiv e-prints* arXiv:2207.12446 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220712446L>.
- [448] Chen, Y. Y., Hirashita, H., Wang, W.-H. & Nakai, N. A simple numerical experiment on the dust temperature bias for Lyman break galaxies at $z \gtrsim 5$. *MNRAS* **509**, 2258–2268 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.509.2258C>.
- [449] Leitherer, C. *et al.* Starburst99: synthesis models for galaxies with active star formation. *The Astrophysical Journal Supplement Series* **123**, 3 (1999).
- [450] Romano, M. *et al.* The ALPINE-ALMA [CII] survey. The contribution of major mergers to the galaxy mass assembly at $z \sim 5$. *A&A* **653**, A111 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A&A...653A.111R>.
- [451] Liu, H.-M. & Hirashita, H. Expected dust grain-size distributions in galaxies detected by ALMA at $z > 7$. *MNRAS* **490**, 540–549 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.490..540L>.
- [452] Di Mascia, F. *et al.* Is the star-formation rate in z 6 quasars overestimated? *MNRAS* **518**, 3667–3674 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023MNRAS.518.3667D>.
- [453] Faisst, A. L. *et al.* ALPINE: A Large Survey to Understand Teenage Galaxies. *arXiv e-prints* arXiv:2206.03510 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220603510F>.
- [454] Chen, Z. *et al.* JWST/NIRCam Observations of Stars and HII Regions in $z \approx 6$ – 8 Galaxies: Properties of Star Forming Complexes on 150 pc Scales. *arXiv e-prints* arXiv:2207.12657 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220712657C>.
- [455] Elbaz, D. *et al.* Starbursts in and out of the star-formation main sequence. *A&A* **616**, A110 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018A&A...616A.110E>.

- [456] Gómez-Guijarro, C. *et al.* Starburst to Quiescent from HST/ALMA: Stars and Dust Unveil Minor Mergers in Submillimeter Galaxies at $z \sim 4.5$. *ApJ* **856**, 121 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...856..121G>.
- [457] Springel, V. *et al.* Simulations of the formation, evolution and clustering of galaxies and quasars. *Nature* **435**, 629–636 (2005).
- [458] Davé, R. *et al.* SIMBA: Cosmological simulations with black hole growth and feedback. *MNRAS* **486**, 2827–2849 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.486.2827D>.
- [459] Hopkins, P. F. *et al.* FIRE-2 simulations: physics versus numerics in galaxy formation. *Monthly Notices of the Royal Astronomical Society* **480**, 800–863 (2018). URL <https://doi.org/10.1093/mnras/sty1690>.
- [460] Lupi, A., Bovino, S., Capelo, P. R., Volonteri, M. & Silk, J. The natural emergence of the correlation between H_2 and star formation rate surface densities in galaxy simulations. *MNRAS* **474**, 2884–2903 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.474.2884L>.
- [461] Rosdahl, J. *et al.* The SPHINX cosmological simulations of the first billion years: the impact of binary stars on reionization. *MNRAS* **479**, 994–1016 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.479..994R>.
- [462] González-López, J. *et al.* SEARCH FOR [c II] EMISSION IN $z = 6.5$ –11 STAR-FORMING GALAXIES. *The Astrophysical Journal* **784**, 99 (2014). URL <https://doi.org/10.1088/0004-637x/784/2/99>.
- [463] Genzel, R. *et al.* Strongly baryon-dominated disk galaxies at the peak of galaxy formation ten billion years ago. *Nature* **543**, 397–401 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017Natur.543..397G>.
- [464] Lovell, C. C. *et al.* First Light And Reionization Epoch Simulations (FLARES) - I. Environmental dependence of high-redshift galaxy evolution. *MNRAS* **500**, 2127–2145 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.500.2127L>.
- [465] Ceverino, D., Glover, S. C. O. & Klessen, R. S. Introducing the FirstLight project: UV luminosity function and scaling relations of primeval galaxies. *MNRAS* **470**, 2791–2798 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017MNRAS.470.2791C>.
- [466] Ferland, G. J. *et al.* The 2017 Release Cloudy. *Revista Mexicana de Astronomía y Astrofísica* **53**, 385–438 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017RMxAA..53..385F>.
- [467] Baes, M. & Camps, P. SKIRT: The design of a suite of input models for Monte Carlo radiative transfer simulations. *Astronomy and Computing* **12**, 33–44 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015A&C....12...33B>.
- [468] Camps, P. & Baes, M. SKIRT: An advanced dust radiative transfer code with a user-friendly architecture. *Astronomy and Computing* **9**, 20–33 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015A&C.....9...20C>.
- [469] Gordon, K. D. *et al.* Dust emission features in ngc 7023 between 0.35 and 2.5 microns: Extended red emission (0.7 microns) and two new emission features (1.15 and 1.5 microns). *The Astrophysical Journal* **544**, 859 (2000).

- [470] Bianchi, S. Dust extinction and emission in a clumpy galactic disk. An application of the radiative transfer code TRADING. *A&A* **490**, 461–475 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008A&A...490..461B>.
- [471] Vallini, L. *et al.* CO line emission from galaxies in the Epoch of Reionization. *MNRAS* **473**, 271–285 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.473..271V>.
- [472] Heyer, M., Krawczyk, C., Duval, J. & Jackson, J. M. RE-EXAMINING LARSON'S SCALING RELATIONSHIPS IN GALACTIC MOLECULAR CLOUDS. *The Astrophysical Journal* **699**, 1092–1103 (2009). URL <https://doi.org/10.1088%2F0004-637x%2F699%2F2%2F1092>.
- [473] Grisdale, K., Agertz, O., Renaud, F. & Romeo, A. B. Physical properties and scaling relations of molecular clouds: the effect of stellar feedback. *MNRAS* **479**, 3167–3180 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018MNRAS.479.3167G>.
- [474] Leung, T. K. D., Pallottini, A., Ferrara, A. & Mac Low, M.-M. Dynamical Properties of Molecular Cloud Complexes in Galaxies at the Epoch of Reionization. *arXiv e-prints* arXiv:1907.02972 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019arXiv190702972L>.
- [475] Larson, R. B. Turbulence and star formation in molecular clouds. *Monthly Notices of the Royal Astronomical Society* **194**, 809–826 (1981).
- [476] Rosolowsky, E. & Blitz, L. Giant molecular clouds in m64. *The Astrophysical Journal* **623**, 826 (2005).
- [477] Semenov, V. A., Kravtsov, A. V. & Gnedin, N. Y. How Galaxies Form Stars: The Connection between Local and Global Star Formation in Galaxy Simulations. *ApJ* **861**, 4 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...861....4S>.
- [478] Shibuya, T. *et al.* What is the Physical Origin of Strong Ly α Emission? II. Gas Kinematics and Distribution of Ly α Emitters. *ApJ* **788**, 74 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014ApJ...788...74S>.
- [479] Licquia, T. C. & Newman, J. A. IMPROVED ESTIMATES OF THE MILKY WAY'S STELLAR MASS AND STAR FORMATION RATE FROM HIERARCHICAL BAYESIAN META-ANALYSIS. *The Astrophysical Journal* **806**, 96 (2015). URL <https://doi.org/10.10882F0004-637x2F8062F12F96>.
- [480] Xue, X. X. *et al.* The milky way's circular velocity curve to 60 kpc and an estimate of the dark matter halo mass from the kinematics of ~ 2400 SDSS blue horizontal-branch stars. *The Astrophysical Journal* **684**, 1143–1158 (2008). URL <https://doi.org/10.10862F589500>.
- [481] Schmidt, M. The Rate of Star Formation. *ApJ* **129**, 243 (1959). URL <https://ui.adsabs.harvard.edu/abs/1959ApJ...129..243S>.
- [482] Krumholz, M. R. & Tan, J. C. Slow star formation in dense gas: evidence and implications. *The Astrophysical Journal* **654**, 304 (2007).
- [483] Schaerer, D., Charbonnel, C., Meynet, G., Maeder, A. & Schaller, G. Grids of Stellar Models - Part Four - from 0.8-SOLAR-MASS to 120-SOLAR-MASSSES at Z=0.040. *A&A Supp.* **102**, 339 (1993). URL <https://ui.adsabs.harvard.edu/abs/1993A%26AS...102..339S>.

- [484] Raga, A., Cantó, J. & Rodríguez, L. Analytic and numerical models for the expansion of a compact hii region. *Monthly Notices of the Royal Astronomical Society: Letters* **419**, L39–L43 (2012).
- [485] Dyson, J. & Williams, D. The physics of the interstellar medium (manchester (1980).
- [486] Schaerer, D. & de Koter, A. Combined stellar structure and atmosphere models for massive stars. III. Spectral evolution and revised ionizing fluxes of O3-B0 stars. *A&A* **322**, 598–614 (1997). URL <https://ui.adsabs.harvard.edu/abs/1997A&A...322..598S>.
- [487] Benincasa, S. M. *et al.* Live Fast, Die Young: GMC lifetimes in the FIRE cosmological simulations of Milky Way-mass galaxies. *arXiv e-prints* arXiv:1911.05251 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019arXiv191105251B>.
- [488] Stratta, G., Gallerani, S. & Maiolino, R. Is GRB 050904 at $z = 6.3$ absorbed by dust? *A&A* **532**, A45 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011A&A...532A...45S>.
- [489] Draine, B. T. On Radiation Pressure in Static, Dusty H II Regions. *ApJ* **732**, 100 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011ApJ...732..100D>.
- [490] Buat, V. & Xu, C. Star formation and dust extinction in disk galaxies. comparison between the uv non-ionizing and the fir emissions. *Astronomy and Astrophysics* **306**, 61 (1996).
- [491] Hildebrand, R. H. The determination of cloud masses and dust characteristics from submillimetre thermal emission. *QJRAS* **24**, 267–282 (1983). URL <https://ui.adsabs.harvard.edu/abs/1983QJRAS...24..267H>.
- [492] Dunne, L. *et al.* The SCUBA Local Universe Galaxy Survey — I. First measurements of the submillimetre luminosity and dust mass functions. *Monthly Notices of the Royal Astronomical Society* **315**, 115–139 (2000). URL <https://doi.org/10.1046/j.1365-8711.2000.03386.x>.
- [493] Dupac, X. *et al.* Inverse temperature dependence of the dust submillimeter spectral index. *A&A* **404**, L11–L15 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003A&A...404L...11D>.
- [494] Désert, F. X. *et al.* Submillimetre point sources from the Archeops experiment: very cold clumps in the Galactic plane. *A&A* **481**, 411–421 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008A&A...481..411D>.
- [495] Paradis, D., Bernard, J. P. & Mény, C. Dust emissivity variations in the Milky Way. *A&A* **506**, 745–756 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009A&A...506..745P>.
- [496] Planck Collaboration, Ade, P. A. R., Aghanim, N. & Arnaud, e. a. Planck early results. XIX. All-sky temperature and dust optical depth from Planck and IRAS. Constraints on the “dark gas” in our Galaxy. *A&A* **536**, A19 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011A&A...536A...19P>.
- [497] Guhathakurta, P. & Draine, B. T. Temperature Fluctuations in the Interstellar Grains. I. Computational Method and Sublimation of Small Grains. *ApJ* **345**, 230 (1989). URL <https://ui.adsabs.harvard.edu/abs/1989ApJ...345..230G>.

- [498] Draine, B. T. & Li, A. Infrared Emission from Interstellar Dust. I. Stochastic Heating of Small Grains. *ApJ* **551**, 807–824 (2001). URL <https://ui.adsabs.harvard.edu/abs/2001ApJ...551..807D>.
- [499] Da Cunha, E. *et al.* On the effect of the cosmic microwave background in high-redshift (sub-) millimeter observations. *The Astrophysical Journal* **766**, 13 (2013).
- [500] Dayal, P., Hirashita, H. & Ferrara, A. Detecting Lyman alpha emitters in the submillimetre. *Monthly Notices of the Royal Astronomical Society* **403**, 620–624 (2010). URL <https://doi.org/10.1111/j.1365-2966.2009.16164.x>.
- [501] Conley, A. *et al.* DISCOVERY OF a MULTIPLY LENSED SUBMILLIMETER GALAXY IN EARLY HerMESHERSCHEL/SPIRE DATA. *The Astrophysical Journal* **732**, L35 (2011). URL <https://doi.org/10.1088%2F2041-8205%2F732%2F2%2F135>.
- [502] da Cunha, E. *et al.* AN ALMA SURVEY OF SUB-MILLIMETER GALAXIES IN THE EXTENDED CHANDRA DEEP FIELD SOUTH: PHYSICAL PROPERTIES DERIVED FROM ULTRAVIOLET-TO-RADIO MODELING. *The Astrophysical Journal* **806**, 110 (2015). URL <https://doi.org/10.1088%2F0004-637x%2F806%2F1%2F110>.
- [503] Scoville, N. Z. & Good, J. C. The far-infrared luminosity of molecular clouds in the Galaxy. *ApJ* **339**, 149–162 (1989). URL <https://ui.adsabs.harvard.edu/abs/1989ApJ...339..149S>.
- [504] Decataldo, D., Pallottini, A., Ferrara, A., Vallini, L. & Gallerani, S. Photoevaporation of Jeans-unstable molecular clumps. *MNRAS* **487**, 3377–3391 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.487.3377D>.
- [505] Oesch, P. *et al.* The bright end of the ultraviolet luminosity function at $z \sim 8$: New constraints from candels data in goods-south. *The Astrophysical Journal* **759**, 135 (2012).
- [506] Nozawa, T., Asano, R. S., Hirashita, H. & Takeuchi, T. T. Evolution of grain size distribution in high-redshift dusty quasars: integrating large amounts of dust and unusual extinction curves. *Monthly Notices of the Royal Astronomical Society: Letters* **447**, L16–L20 (2014).
- [507] Oteo, I. *et al.* Witnessing the Birth of the Red Sequence: ALMA High-resolution Imaging of [CII] and Dust in Two Interacting Ultra-red Starbursts at $z = 4.425$. *ApJ* **827**, 34 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ApJ...827..340>.
- [508] Windhorst, R. A. *et al.* Webb’s PEARLS: Prime Extragalactic Areas for Reionization and Lensing Science: Project Overview and First Results. *arXiv e-prints* arXiv:2209.04119 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220904119W>.
- [509] Robertson, B. E. *et al.* Discovery and properties of the earliest galaxies with confirmed distances (2022). URL <https://arxiv.org/abs/2212.04480>.
- [510] Inayoshi, K., Harikane, Y., Inoue, A. K., Li, W. & Ho, L. C. A lower bound of star formation activity in ultra-high redshift galaxies detected with jwst: Implications for stellar populations and radiation sources (2022). URL <https://arxiv.org/abs/2208.06872>.

- [511] Bouwens, R. J. *et al.* Discovery of $z \sim 8$ Galaxies in the Hubble Ultra Deep Field from Ultra-Deep WFC3/IR Observations. *ApJL* **709**, L133–L137 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...709L.133B>.
- [512] Rodighiero, G. *et al.* JWST unveils heavily obscured (active and passive) sources up to $z \sim 13$. *arXiv e-prints* arXiv:2208.02825 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220802825R>.
- [513] Bakx, T. J. L. C. *et al.* Deep ALMA redshift search of a $z \sim 12$ GLASS-JWST galaxy candidate. *arXiv e-prints* arXiv:2208.13642 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220813642B>.
- [514] Tacchella, S. *et al.* JWST NIRCam+NIRSpec: Interstellar medium and stellar populations of young galaxies with rising star formation and evolving gas reservoirs. *arXiv e-prints* arXiv:2208.03281 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220803281T>.
- [515] Cochrane, R. K. *et al.* Predictions for the spatial distribution of the dust continuum emission in $1 < z < 5$ star-forming galaxies. *MNRAS* **488**, 1779–1789 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019MNRAS.488.1779C>.
- [516] Zanella, A. *et al.* Early galaxy growth: mergers or gravitational instability? *MNRAS* **500**, 118–137 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.500..118Z>.
- [517] Nath, B. B., Vasiliev, E. O., Drozdov, S. A. & Shchekinov, Y. A. Dust-free starburst galaxies at redshifts $z > 10$. *arXiv e-prints* arXiv:2211.12378 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv221112378N>.
- [518] Naidu, R. P. *et al.* Schrodinger’s Galaxy Candidate: Puzzlingly Luminous at $z \approx 17$, or Dusty/Quenched at $z \approx 5$? *arXiv e-prints* arXiv:2208.02794 (2022b). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220802794N>.
- [519] Zavala, J. A. *et al.* A dusty starburst masquerading as an ultra-high redshift galaxy in JWST CEERS observations. *arXiv e-prints* arXiv:2208.01816 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022arXiv220801816Z>.
- [520] Fujimoto, S. *et al.* Alma fir view of ultra high-redshift galaxy candidates at $z \sim 11$ –17: Blue monsters or low- z red interlopers? (2022). URL <https://arxiv.org/abs/2211.03896>.
- [521] Kaasinen, M. *et al.* To see or not to see a $z \sim 13$ galaxy? that is the question (2022). URL <https://arxiv.org/abs/2210.03754>.
- [522] Yoon, I. *et al.* Alma observation of a $z \gtrsim 10$ galaxy candidate discovered with jwst (2022). URL <https://arxiv.org/abs/2210.08413>.
- [523] Treu, T. *et al.* The GLASS-JWST Early Release Science Program. I. Survey Design and Release Plans. *ApJ* **935**, 110 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022ApJ...935..110T>.
- [524] Fudamoto, Y. *et al.* The ALMA REBELS Survey: Average [C II] $158 \mu\text{m}$ Sizes of Star-forming Galaxies from $z = 7$ to $z = 4$. *ApJ* **934**, 144 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022ApJ...934..144F>.

- [525] Heintz, K. E. *et al.* The ALMA REBELS Survey: The Cosmic H I Gas Mass Density in Galaxies at $z \sim 7$. *ApJL* **934**, L27 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022ApJ...934L..27H>.
- [526] Endsley, R. *et al.* The REBELS ALMA Survey: efficient Ly alpha transmission of UV-bright $z \sim 7$ galaxies from large velocity offsets and broad line widths. *MNRAS* **517**, 5642–5659 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022MNRAS.517.5642E>.
- [527] Pizzati, E. *et al.* [C II] Haloes in ALPINE galaxies: smoking-gun of galactic outflows? *MNRAS* **519**, 4608–4621 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023MNRAS.519.4608P>.
- [528] Ferrara, A., Zana, T., Gallerani, S. & Sommovigo, L. The feedback of quasars on their galactic environment. *MNRAS* **520**, 3089–3096 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023MNRAS.520.3089F>.

List of Figures

1.1	Schematic representation of the cosmic thermal history	12
1.2	UV Luminosity Functions at $z = 2 - 13$	16
1.3	IR Luminosity Function at $z \sim 7$	18
1.4	Cosmic star formation rate density at $z = 0 - 7$	20
1.5	UV slopes of galaxies at $z > 7$	21
2.1	Schematic representation of the ISM	24
2.2	Measured extinction curves at $z \sim 0$	27
2.3	Predicted Milky Way extinction curve	28
2.4	IRX- β relation at $z > 5$	39
2.5	Dust-to-stellar mass relation at $z \sim 7$	39
3.1	Kennicutt-Schmidt relation	47
3.2	Comparison of $T_{\text{d,CII}}$ and $T_{\text{d,SED}}$ in our local sample	47
3.3	Inferred $T_{\text{d,CII}}$ and M_{d} in our high- z sample	50
3.4	Molecular gas fraction evolution	52
3.5	A1689-zD1 ALMA band-9 emission map and FIR SED	54
4.1	REBELS galaxies FIR SEDs	58
4.2	L_{1900} -to- L_{FIR} conversion factor at $z \sim 7$	61
4.3	$T_{\text{d}} - z$ evolution out to $z \sim 7$	63
5.1	$T_{\text{d}} - z$ evolution out to $z \sim 7$: update	71
5.2	Dust-to-stellar mass relation at $z \geq 5$	74
5.3	Comparison of the SFR derived with and without ALMA data	78
6.1	SED of the simulated galaxy Zinnia	85
6.2	Overview of GMCs physical properties	88
6.3	T_{d} profiles in the local and high- z GMCs	94
6.4	T_{d} profile in the high- z GMC including radiation pressure	96
6.5	Average T_{d} evolution with stellar age in the local and high- z GMCs	97
6.6	FIR luminosity of the local and high- z GMCs	99
6.7	Dust build-up as a function of galaxy age and T_{d} at $z \sim 8$	101
7.1	Dust attenuation for JWST-detected galaxies at $z > 9.5$	106
7.2	Eddington ratio as a function of Σ_{SFR} and κ_{s}	109
7.3	Dust outflow rate for starburst galaxies	109
7.4	Predicted FIR continuum flux for JWST-detected $z > 9.5$ galaxies	111

List of Tables

2.1	Measured T_d in LBGS at $z > 5$	34
3.1	Our local test sample properties	45
3.2	Our high- z sample properties	46
3.3	Comparison of T_d and $T_{d,\text{CII}}$ in the high- z sample	49
3.4	Measured and inferred properties of the $z \sim 7$ galaxy A1689-zD1	55
4.1	REBELS galaxies measured and predicted properties	58
5.1	ALPINE galaxies measured properties	80
5.2	ALPINE galaxies predicted properties	81
6.1	Physical properties of the simulated high- z galaxy Zinnia	84
6.2	Intrinsic vs. inferred (via SED fitting procedures) properties of Zinnia	84
6.3	Comparison between the MW and simulated high- z galaxy Freesia physical properties	87

Acronyms

AGB Asymptotic Giant Branch. [25](#), [170](#)

ALMA Atacama Large Millimeter/Submillimeter Array. [7](#), [170](#)

ALPINE ALMA Large Program to INvestigate [C II] at Early times. [8](#), [170](#)

BB Big Bang. [13](#), [170](#)

CDM Cold Dark Matter. [12](#), [170](#)

CMB Cosmic Microwave Background radiation. [13](#), [170](#)

CNM Cold Neutral Medium. [24](#), [170](#)

COBE Cosmic Background Explorer. [13](#), [170](#)

DL De Looze. [42](#), [170](#)

EoR Epoch of Reionization. [8](#), [170](#)

FIR Far Infrared radiation. [7](#), [170](#)

FRW Friedman Robertson Walker. [11](#), [170](#)

GMC Giant Molecular Clouds. [8](#), [170](#)

GR General Relativity. [11](#), [170](#)

HIM Hot Ionized Medium. [24](#), [170](#)

HST Hubble Space Telescope. [14](#), [170](#)

IGM InterGalactic Medium. [13](#), [170](#)

ISM Interstellar Medium. [14](#), [170](#)

JWST James Webb Space Telescope. [7](#), [170](#)

KS Kennicutt–Schmidt. [42](#), [170](#)

LAE Lyman Alpha Emitters. [14](#), [170](#)

LBG Lyman Break Galaxies. [14](#), [170](#)

LF Luminosity Function. [16](#), [170](#)

LMC Large Magellanic Cloud. [27](#), [170](#)

Ly α the Lyman-alpha transition. [14](#), [170](#)

MORA Mapping Obscuration to Reionization with ALMA. [18](#), [170](#)

MOSDEF MOSFIRE Deep Evolution Field. [28](#), [170](#)

MW Milky Way. [22](#), [170](#)

REBELS Reionization Era Bright Emission Line Survey. [8](#), [170](#)

SED Spectral Energy Distribution. [8](#), [170](#)

SFG Star Forming Galaxy. [170](#)

SFR Star Formation Rate. [7](#), [170](#)

SFRD Star Formation Rate Density. [7](#), [170](#)

SMC Small Magellanic Cloud. [27](#), [170](#)

SN Supernovae. [7](#), [170](#)

UV Ultraviolet radiation. [7](#), [170](#)

VLT Very Large Telescope. [14](#), [170](#)

WD01 Weingartner & Draine. [29](#), [170](#)

WIM Warm Ionized Medium. [24](#), [170](#)

WMAP Wilkinson Microwave Anisotropy Probe. [13](#), [170](#)

WNM Warm Neutral Medium. [24](#), [170](#)

Acknowledgments

I thank my supervisor and mentor Andrea Ferrara, without whom none of this work would have been possible. Over the past four years he has been my guide and an inspiring example of the scientist I hope one day to become. I admire his genuine enthusiasm for all forms of science and discoveries; it is rare and refreshing to see such passion in someone at his career level. I hope to be able to maintain the same drive and thirst for knowledge without allowing daily routine and growing commitments to numb it down.

I thank my co-supervisor Stefano Carniani for constantly pushing me and trying to take me to the observers' dark side. He made me curious about aspects I would have – wrongly – overlooked and it is thanks to him that I have written my first observational proposal. It did not get accepted, but I am not giving up anytime soon.

I thank Andrea Pallottini (aka Pallo) for slowing down my publications. Without him, they would have been far less accurate. From him, I have learnt a great deal about being precise in writing and scientific thinking, if not in coding.

I want to thank the REBELS collaboration for being such a stimulating environment, where I have been able to broaden my scientific expertise and grow as a researcher, with the example and guidance of some of the world-leading experts in the field.

I want to thank three professors who have had a great impact on my education and personal growth, Andrei Mesinger, Pratika Dayal, and Simona Gallerani. I want to thank Andrei and Pratika for their constant support and encouragement, especially throughout the dreadful application process, and Simona for her fundamental help with ISPIRA.

There are several other people I need to acknowledge for their help throughout these ~ five years. Livia Vallini is both someone I look up to and a friend. I hope one day I will make slides half as beautiful as hers. Fabio Vito and Viola Allevato have both had the misfortune of sharing the office with me. I thank them for helping me greatly with important decisions, always in their own unique style and with much-needed laughter and levity. I thank Eva Ntormousi and Fabio del Sordo for reminding us all that one can be socially engaged and also an excellent scientist. Thanks to Michele Ginolfi for probing that not all capable and successful young scientists have to be sharks.

I want to thank the people that have been my travelling companions. Fabio di Mascia, with whom I have shared nearly all frustrating and happy moments, Yuxiang Qin, who is the most motivational colleague and friend I could ever ask for. Thanks to Mahsa Kohandel and Davide Decataldo for being patient with me, especially at the beginning, and to David Prelogovic and Ivan Nikolic for making “distribucija” and “kolega” words that make me smile.

I want to thank all the PhDs and Researchers – particularly Carmen Baiano and Francesca D'Elia – involved in ISPIRA who have donated their precious time to our project, with enthusiasm and commitment.

Thanks to Nicola for sharing with me both Zip and our birthday. Thanks to Sonali for being my emotional support housemate. I hope one day we will write our book “How to survive your PhD”. Thanks to Giada for having been there for and with me for so long and to Eugenia for her golden retriever energy. Thanks to Meri for always being late with me.

Thanks to my family for teaching me the importance of culture and for always having my back. To my mum for pushing me, to my dad for his kindness, and to my sister for relieving my stress with her presence alone.

Many thanks also to Luna, Stella and Aida, who have made many of my days happier albeit messier.

Infine grazie a Zip per esserci da sempre. Grazie per essere così diverso da me, perchè non ti fai trascinare dal mio pessimismo quando sono giù di morale, perchè non mi riporti coi piedi per terra quando mi entusiasmo più o meno a caso. Grazie per capirmi senza bisogno che mi spieghi, per aver fatto sembrare bella pure la pandemia.

