Mon. Not. R. Astron. Soc. **368,** L6–L9 (2006) doi:10.1111/j.1745-3933.2006.00145.x

The infrared glow of the first stars

Ruben Salvaterra,[1⋆] Manuela Magliocchetti,[2] Andrea Ferrara[2] and Raffaella Schneider[3,4]

[1] *Dipartimento di Fisica e Matematica, Universitá dell'Insubria, Via Valleggio 11, 22100 Como, Italy*
[2] *SISSA/International School for Advanced Studies, Via Beirut 4, 34100 Trieste, Italy*
[3] *Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy*
[4] *'Enrico Fermi' Centre, Via Panisperna 89/A, 00184 Roma, Italy*

Accepted 2006 January 13. Received 2006 January 12; in original form 2005 December 15

ABSTRACT

Kashlinsky et al. find a significant cosmic infrared background fluctuation excess on angular scales $\gtrsim$50 arcsec that cannot be explained by instrumental noise or local foregrounds. The excess has been tentatively attributed to emission from primordial, very massive (Population III, hereafter PopIII) stars formed $\leqslant$ 200 Myr after the Big Bang. Using an evolutionary model motivated by independent observations and including various feedback processes, we find that PopIII stars can contribute <40 per cent of the total background intensity ($\nu J_\nu \sim$ 1–2 nW m^{-2} sr^{-1} in the 0.8–8 μm range) produced by all galaxies (hosting both PopIII and PopII stars) at $z \geqslant 5$. The infrared fluctuation excess is instead very precisely accounted for by the clustering signal of galaxies at $z \geqslant 5$, predominantly hosting PopII stars with masses and properties similar to the present ones.

Key words: galaxies: clusters: general – cosmology: observations – cosmology: theory – large-scale structure of Universe – infrared: galaxies.

1 INTRODUCTION

Observations of the infrared background provide important information on the emission of cosmic luminous sources throughout the history of the Universe. It has been suggested (Santos, Bromm & Kamionkowski 2003; Salvaterra & Ferrara 2003) that a large fraction of the measured near-infrared (1–10 μm) cosmic background (NIRB) arises from redshifted Lyα line photons and nebular emission produced by the first very massive metal-free stars. This hypothesis, however, is very demanding in terms of the required conversion efficiency of baryons into stars (Madau & Silk 2005). A large NIRB contribution from such stars has more recently been rejected by the paucity ($\leqslant$3) of $z \sim 10$ candidate sources in *Hubble Space Telescope* ultradeep observations (Salvaterra & Ferrara 2005). Nevertheless, a more modest contribution from very high-redshift galaxies, the clustering of which should leave a distinct signature on small-scale angular fluctuations of the background light (Magliocchetti, Salvaterra & Ferrara 2003; Kashlinsky et al. 2004; Cooray et al. 2004), is still possible.

Kashlinsky et al. (2005) have recently found significant NIRB fluctuations in deep exposure data obtained with the *Spitzer* Infrared Array Camera (IRAC) (Fazio et al. 2004a,b) in four channels (3.6, 4.5, 5.8 and 8 μm), after Galactic stars and galaxies bright enough to be individually resolved by the instrument have been carefully subtracted. With the exception of only the 8-μm channel, the shape and amplitude of the power spectrum cannot be reproduced by either contributions from intervening dusty, Galactic neutral hydrogen gas (cirrus) or from local interplanetary dust (zodiacal light). Ordinary galaxies ($z \lesssim 5$) produce fluctuations due to their clustering and shot noise. The faint flux limits ($\geqslant$0.3 μJy) of *Spitzer* data allow their residual clustering contribution to be pushed below the level of the excess signal at relatively large ($\gtrsim$50 arcsec) angular scales (Kashlinsky et al. 2005). The shot noise component, estimated directly from galaxy counts, fits the observed fluctuations at smaller angular scales, and rapidly fades away at larger angles. The residual large-scale signal has been ascribed by Kashlinsky et al. (2005) as coming from very distant ($z \geqslant 5$) sources provided their total flux contribution is >1 nW m^{-2} sr^{-1}. The aim of this Letter is to show that this is indeed the case.

The layout of the paper is as follows: in Section 2 we will briefly describe the adopted model, while in Section 3 we provide predictions for the NIRB intensity and fluctuations and compare the latter with the results of Kashlinsky et al. (2005). Section 4 summarizes our conclusions.

2 THE MODEL

Schneider et al. (2005) have presented a scenario for the formation of galaxies in a concordance Λ cold dark matter (ΛCDM) cosmological model[1] which includes a self-consistent treatment of two key

⋆E-mail: salvaterra@mib.infn.it

[1] We adopt a ΛCDM cosmological model with parameters $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $\Omega_B = 0.04$, $n = 1$ and $\sigma_8 = 0.9$, which lies within the experimental errorbars of *WMAP* experiment (Spergel et al. 2003).

© 2006 The Authors. Journal compilation © 2006 RAS

Downloaded from https://academic.oup.com/mnrasl/article/368/1/L6/959271 by Scuola Normale Superiore Biblioteca user on 03 December 2025

feedback processes: (i) *radiative feedback*, suppressing star formation in H_2-cooling haloes and the formation of low-mass galaxies due to the effects of ultraviolet background radiation approaching the reionization epoch, and (ii) *chemical feedback*, which controls the transition from metal-free stars (Population III, hereafter PoPIII) to ordinary stars (PopII) through the progressive enrichment of star-forming gas with heavy elements released by supernova explosions (Schneider et al. 2002, 2004, 2005; Bromm et al. 2001). Chemical feedback propagates through the hierarchy of galaxy mergers from progenitors to their descendants so that, at each redshift, existing haloes which are allowed to form stars are classified as PopII (PopIII) galaxies depending on whether the halo itself or any of its progenitors have (have not) already experienced an episode of star formation.

Within this model we can compute the comoving specific emissivity, ϵ_ν, which is given by

$$\epsilon_\nu(z) = \int_z^\infty \mathrm{d}z' l_\nu(t_{z,z'}) \times \int_{M_{\min}(z')}^{M_{\max}(z')} M_\star \frac{\mathrm{d}^2 n}{\mathrm{d}M_\mathrm{h}\,\mathrm{d}z'}(M_\mathrm{h}, z')\,\mathrm{d}M_\mathrm{h}, \quad (1)$$

where $\mathrm{d}^2n/\mathrm{d}M_\mathrm{h}\,\mathrm{d}z$ is the formation rate of haloes of total (dark + baryonic) mass M_h with corresponding stellar mass $M_\star$, and $M_{\min}(z)$ is the minimum mass of haloes [corresponding to a virial temperature of 10^4 K, i.e. $M_{\min}(z) \sim 10^8\,\mathrm{M}_\odot\,(1+z/10)^{-3/2}$] allowed to form stars at redshift z; $M_{\max}(z)$ is the maximum mass of haloes, which depends on the details of their merging history (see Schneider et al. 2005); and $l_{\nu(t_{z,z'})}$ is the template specific luminosity for a stellar population of age $t_{z,z'}$ (time elapsed between redshift z' and z). Following the results of Schneider et al. (2005), both PopII and PopIII stars are assumed to form according to a Salpeter Initial Mass Function (IMF) with an efficiency $f_\star = 0.1$. The emission properties of PopII stars are taken from the GALAXEV library (masses in the range 0.1–100 $\mathrm{M}_\odot$, metallicity $Z = 10^{-2}\,\mathrm{Z}_\odot$; Bruzual & Charlot 2003) and those of PopIII stars are based on the synthesis model for metal-free stars of Schaerer (1–100 $\mathrm{M}_\odot$, $Z = 0$; Schaerer 2002).

A set of independent observational constraints can be accommodated within this model (Schneider et al. 2005): the number counts of dropout galaxies at $z \sim 6$ (i-dropouts; Bouwens et al. 2005b) and at $z \sim 10$ (J-dropouts; Bouwens et al. 2005a), and the value of the optical depth for Thomson scattering $\tau_\mathrm{e} = 0.16 \pm 0.04$ measured by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) satellite (Kogut et al. 2003). Indeed, the predicted surface density of i-dropouts at a limiting magnitude of $i = 28$ is $\sim$5 arcmin^{-2} (observed value $\sim$4.7 arcmin^{-2}; Bouwens et al. 2005b). The model is also consistent with the three candidate dropouts at $z \sim 10$ reported by Bouwens et al. (2005a). Moreover, the large value of τ_e can be matched with standard values of the ionizing photon escape fraction from galaxies ($f_\mathrm{esc} \leqslant 0.2$) and gas clumping factor $C \sim 10$, resulting in a reionization redshift of 13.2 (Schneider et al. 2005).

3 NIRB INTENSITY AND FLUCTUATIONS

The model presented in Section 2 (referred to as model C in Schneider et al. 2005) allows one to compute the NIRB intensity J_{ν_0} from $z \geqslant 5$ galaxies seen at frequency ν_0 by an observer at redshift $z_0 = 0$. This can be done in a fashion similar to Salvaterra & Ferrara (2003) as:

$$J_{\nu_0}(z_0) = \frac{(1+z_0)^3}{4\pi} \int_{z_0}^\infty \epsilon_\nu(z) \mathrm{e}^{-\tau_\mathrm{eff}(\nu_0, z_0, z)} \frac{\mathrm{d}l}{\mathrm{d}z}\,\mathrm{d}z, \quad (2)$$

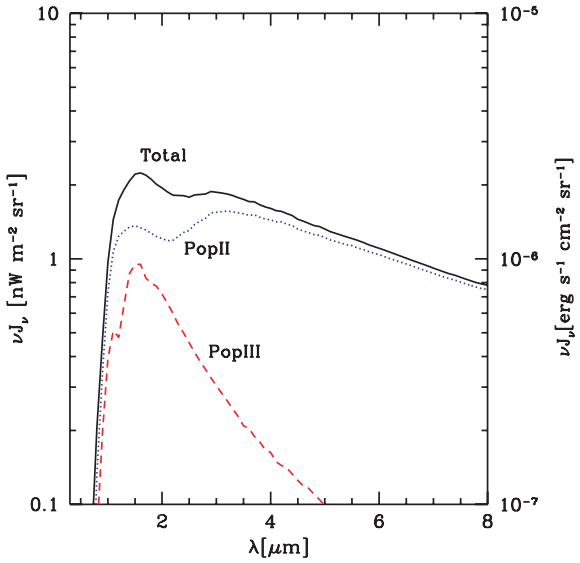

Figure 1. Infrared background from sources at $z \geqslant 5$ in the wavelength range 0.3–8 μm. The dotted (dashed) line shows the contribution of PopII (PopIII) galaxies. The sum of the two components is denoted by the solid line. The sharp drop below 0.8 μm is due to the absorption of the intergalactic medium for $\lambda < \lambda_{\mathrm{Ly}\alpha}$ in the emitter rest frame.

where $\nu = \nu_0(1+z)/(1+z_0)$, $\mathrm{d}l/\mathrm{d}z$ is the proper line element, $\tau_\mathrm{eff}(\nu_0, z_0, z)$ is the effective optical depth at ν_0 of the intergalactic medium between redshift z_0 and z (see section 2.2 of Salvaterra & Ferrara 2003 for a full description of the IGM modelling) and $\epsilon_\nu(z)$ is provided by equation (1). Our results are shown in Fig. 1. The background intensity, $\nu J_\nu \sim 1-2$ nW m^{-2} sr^{-1}, is almost constant in the 0.8–8 μm range. PopII galaxies dominate the NIRB in the entire wavelength range, while PopIII galaxies contribute at most 40 per cent of the total intensity (at $\lambda \sim 1.5$ μm), via their strong Lyα line emission. We have checked that the sources responsible for such emission are too faint to be resolved and identified at the *Spitzer* magnitude limit in all four channels. The total contribution of all galaxies at $z \geqslant 5$ is 1.55, 1.45, 1.07 and 0.74 nW m^{-2} sr^{-1} in the 3.6-, 4.5-, 5.8- and 8.0-μm IRAC bands, respectively, representing a substantial fraction ($\sim$10–20 per cent) of the total NIRB intensity estimated from integration of *Spitzer* galaxy number counts (Fazio et al. 2004b).

The angular correlation function of intensity fluctuations δJ due to inhomogeneities in the space distribution of unresolved sources (i.e. with fluxes fainter than some threshold S_d) is defined as:

$$C(\theta) = \langle \delta J(\theta', \phi')\, \delta J(\theta'', \phi'') \rangle, \quad (3)$$

where (θ', ϕ') and (θ'', ϕ'') identify two positions on the sky separated by an angle θ. The above expression can be written as the sum of two terms, C_P and C_C, the first one due to Poisson noise (i.e. fluctuations given by randomly distributed objects), and the second one owing to source clustering. It can be shown that the shot noise contribution originating from $z \geqslant 5$ galaxies is negligible, so we only concentrate on fluctuations which stem from the clustering of these sources, i.e. we assume $C(\theta) \equiv C_\mathrm{C}$.

The method adopted here is similar to that presented in Magliocchetti et al. (2003), whereby angular fluctuations are

© 2006 The Authors. Journal compilation © 2006 RAS, MNRAS **368,** L6–L9

Downloaded from https://academic.oup.com/mnrasl/article/368/1/L6/959271 by Scuola Normale Superiore Biblioteca user on 03 December 2025

obtained by means of the expression:

$$C(\theta) = \left(\frac{1}{4\pi}\right)^2 \int_{z_0}^{\infty} \mathrm{d}z \, \frac{\epsilon_\nu^2(z)}{(1+z)^2} \, \mathrm{e}^{-2\tau_{\rm eff}} \left(\frac{\mathrm{d}x}{\mathrm{d}z}\right) \times \int_{-\infty}^{\infty} \mathrm{d}u \; \xi_g(r, z), \quad (4)$$

where $x = l(1+z)$ is the comoving coordinate, $r = (u^2 + x^2\theta^2)^{1/2}$ (for a flat universe and in the small angle approximation) and ϵ_ν is defined as in Section 2.

The spatial two-point correlation function of a class of galaxies 'g', $\xi_g(r, z)$, in general results from a complicated interplay between the clustering properties of the underlying dark matter and physical processes associated to the formation of such galaxies (see e.g. Magliocchetti & Porciani 2003). However, the sources we are considering in this work are small enough (typical dark matter masses around 10^9–$10^{10}\,\mathrm{M}_\odot$ for $z \simeq 5$, values which rapidly decrease when moving to higher redshifts; see Schneider et al. 2005 for further details) and set at high enough redshifts to ensure that – if present – their sub-halo behaviour falls into angular scales which are too small to be detected. We can therefore safely assume a one-to-one correspondence between haloes and galaxies and write $\xi_g(r, z) = \xi(r, z) b_{\rm eff}^2(z)$, where $\xi(r, z)$ is the mass-mass correlation function (evaluated by following the Peacock & Dodds 1996 approach up to 100 Mpc comoving) and $b_{\rm eff}(z)$ the bias associated to all dark matter haloes massive enough to host a galaxy at redshift z. This latter quantity was then obtained respectively for PopII and PopIII galaxies by integrating the function $b(M_{\rm h}, z)$ – representing the bias of individual haloes of mass $M_{\rm h}$ – opportunely weighted by the number density of such sources $\mathrm{d}\,n/\mathrm{d}\,M_{\rm h}(M_{\rm h}, z)\, f(M_{\rm h}, z)$ as:

$$b_{\rm eff}(z) = \frac{\int_{M_{min}(z)}^{M_{\rm max}(z)} \mathrm{d}M_{\rm h} \; b(M_{\rm h}, z) \; \frac{\mathrm{d}n}{\mathrm{d}M_{\rm h}}(M_{\rm h}, z) \; f(M_{\rm h}, z)}{\int_{M_{\rm min}(z)}^{M_{\rm max}(z)} \mathrm{d}M_{\rm h} \; \frac{\mathrm{d}n}{\mathrm{d}M_{\rm h}}(M_{\rm h}, z) \; f(M_{\rm h}, z)}, \quad (5)$$

where $\mathrm{d}n/\mathrm{d}M_{\rm h}(M_{\rm h}, z)$ is the Sheth & Tormen (1999) mass function of the dark matter haloes, $f(M_{\rm h}, z)$ is the fraction of haloes that at any mass and redshift host a PopII (PopIII) galaxy and $M_{\rm min}(z)$, $M_{\rm max}(z)$ are the limiting mass values for such haloes to host either a PopII or a PopIII source (see Section 2).

The above prescriptions then allow one to estimate $C(\theta)$, i.e. the contribution from the clustering of unresolved $z \geqslant 5$ (PopII and PopIII) galaxies to the background fluctuations at different wavelengths. An important feature to mention about the resulting $C(\theta)$ is that – independent of the considered frequency and only due to the high redshift of the sources being examined – it features a sharp drop at around 300 arcsec beyond which it rapidly approaches zero. This implies that signals on scales larger than the above value, such as those detected by some experiments (e.g. Hauser & Dwek 2001; Matsumoto et al. 2005), have to rely on the presence of a more local population of unresolved sources.

Finally, we can move to the calculation of the power spectrum $P(q)$ originating from the above fluctuations,

$$P(q) = 2\pi \int_0^{\infty} C(\theta) J_0(\theta, q) \theta \, \mathrm{d}\theta, \quad (6)$$

where J_0 is the zeroth-order Bessel function.

In order to compare our predictions with the Kashlinsky et al. (2005) results, $P(q)$ has been evaluated in the 3.6, 4.5, 5.8 and 8 μm IRAC bands. Our findings are summarized in Fig. 2, where the dotted lines represent the fluctuations originating from PopII galaxies, the dashed lines those due to PopIII sources, and the dot–dashed curves indicate the shot-noise contribution from galaxies fainter than the limiting magnitude as estimated by Kashlinsky et al. (2005). It is clear from the plot that at the lowest frequencies the contribution of $z \geqslant 5$ galaxies can provide an excellent fit to the observed fluctuations; in particular it dominates over the shot-noise component at all angular scales greater than ∼50 arcsec. At 5.8 μm, their importance is reduced but the presence of $z \geqslant 5$ sources is still required to properly account for the amplitude of the signal at the largest probed scales. Finally, high-redshift galaxies and shot noise alone cannot reproduce the power spectrum at 8 μm, where the cirrus probably becomes the dominant component (Kashlinsky et al. 2005).

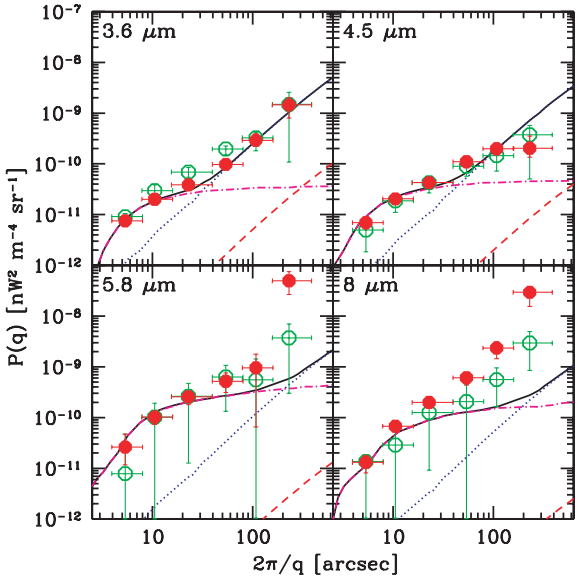

Figure 2. Power spectrum of fluctuations in the IRAC bands. Different symbols show data of different observed fields (Kashlinsky et al. 2005): filled circles corresponds to the QSO 1700 field, open circles to Extended Groth Strip (EGS). Data are averaged over wide bins to increase the signal-to-noise ratio. The errors are $N_q^{-1/2}$, where N_q is the number of Fourier elements at the given q-bin. Dotted (dashed) lines show the contribution from PopII (PopIII) galaxies. Dot–dashed lines show the contribution of shot noise from remaining galaxies fainter than the limiting magnitude (Kashlinsky et al. 2005). The solid line is the sum of the different components.

As a last point it is worth mentioning that, as expected within the present scenario, the contribution of PopIII galaxies is negligible in all IRAC bands; the amplitude of their signal is in fact ∼50 times lower than that of PopII galaxies in the most favorable case (3.6 μm), while the PopIII-to-PopII contribution ratio can go as low as 10^{-3} at the highest frequency probed by IRAC.

4 CONCLUSIONS

Using a physically motivated, observationally tested model of the early Universe (Schneider et al. 2005), we compute the expected background radiation in the NIR by sources that were forming when the Universe was <1 Gyr old. We find that the background intensity, $\nu J_\nu \sim 1$–2 nW m^{-2} sr^{-1}, is almost constant in the 0.8–8 μm range. PopII galaxies dominate the NIRB in the entire wavelength range, while PopIII galaxies contribute at most 40 per cent of the total intensity (at $\lambda \sim 1.5$ μm), via their strong Lyα line emission. Finally, we found that the infrared fluctuation excess on angular scales $\geqslant$50 arcsec detected by *Spitzer*/IRAC (Kashlinsky et al. 2005) is accounted very for precisely by the clustering signal of galaxies at

Downloaded from https://academic.oup.com/mnrasl/article/368/1/L6/959271 by Scuola Normale Superiore Biblioteca user on 03 December 2025

$z \geqslant 5$ that are predominantly hosting stars with masses and properties similar to the present ones.

Two additional points are worth noticing: (i) very massive stars ($M \geqslant 100\,\mathrm{M}_{\odot}$) do not need to be invoked to explain NIRB fluctuations and reionization history; (ii) because of their small contribution [$P(q) \leqslant 10^{-10}$ nW^2 m^{-4} sr^{-1}] to the observed power spectrum in all channels, extracting the signal of the (very) first PopIII stars is extremely challenging. Future instruments (such as the James Webb Space Telescope) will be able to directly identify these sources up to $z = 10$ or above. Finally, the intensity of the NIRB provided by $z \geqslant 5$ galaxies falls short of accounting for the excess measured by the *Infrared Telescope in Space* (*IRTS*; Matsumoto et al. 2005) and Diffuse Infrared Background Experiment (DIRBE; Hauser & Dwek 2001) experiments. The origin of this component remains very puzzling (Salvaterra & Ferrara 2005) and might require either a revision of current model of zodiacal light subtraction or the existence of a large population of faint galaxies located at $z \simeq 2$–3 (or both). Important insights on these issues are expected from the upcoming Cosmic Infrared Background Experiment (CIBER; Bock et al. 2005), which will be able to simultaneously measure the total NIRB intensity and fluctuation power spectrum in the poorly known wavelength range 0.8–2 μm. Such an instrument, in addition, will allow a clear separation of the cosmological signal from local foregrounds (i.e. zodiacal light).

REFERENCES

Bock J. et al., 2005, New Astron. Reviews., in press, astro-ph/0510587

Bouwens R. J., Illingworth G. D., Thompson R. I., Franx M., 2005a, ApJ, 624, L5

Bouwens R. J., Illingworth G. D., Blakeslee J. P., Franx M., 2005b, ApJ, in press, astro-ph/0509641

Bromm V., Ferrara A., Coppi P. S., Larson R. B., 2001, MNRAS, 328, 969

Bruzual G., Charlot S., 2003, MNRAS, 344, 1000

Cooray A., Bock J., Keating B., Lange A., Matsumoto T., 2004, ApJ, 606, 611

Fazio G. G. et al., 2004a, ApJS, 154, 10

Fazio G. G. et al., 2004b, ApJS, 154, 39

Hauser M. G., Dwek E., 2001, ARA&A, 39, 249

Kashlinsky A., Arendt R., Gardner J. P., Mather J., Moseley S. H., 2004, ApJ, 608, 1

Kashlinsky A., Arendt R. G., Mather J., Moseley S. H., 2005, Nat, 438, 45

Kogut A. et al., 2003, ApJS, 148, 161

Madau P., Silk J., 2005, MNRAS, 359, L37

Magliocchetti M., Porciani C., 2003, MNRAS, 346, 186

Magliocchetti M., Salvaterra R., Ferrara A., 2003, MNRAS, 342, L25

Matsumoto T. et al., 2005, ApJ, 626, 31

Peacock J. A., Dodds S. J., 1996, MNRAS, 280, L19

Salvaterra R., Ferrara A., 2003, MNRAS, 339, 973

Salvaterra R., Ferrara A. 2006, MNRAS, 367, L11

Santos M., Bromm V., Kamionkowski M., 2003, MNRAS, 336, 1082

Schaerer D., 2002, A&A, 382, 28

Schneider R., Ferrara A., Natarajan P., Omukai K., 2002, ApJ, 571, 30

Schneider R., Ferrara A., Salvaterra R., Omukai K., Bromm V., 2004, Nat, 422, 869

Schneider R., Salvaterra R., Ferrara A., Ciardi B. 2005, MNRAS, submitted, astro-ph/0510685

Sheth R. K., Tormen G., 1999, MNRAS, 308, 119

Spergel D. N. et al., 2003, ApJS, 148, 175

This paper has been typeset from a TEX/LATEX file prepared by the author.

Downloaded from https://academic.oup.com/mnrasl/article/368/1/L6/959271 by Scuola Normale Superiore Biblioteca user on 03 December 2025