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Data-constrained reionization and its effects on cosmological parameters

S. Pandolfi,[1,2,3] A. Ferrara,[4] T. Roy Choudhury,[5] A. Melchiorri,[3] and S. Mitra[5]

[1]*Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark*
[2]*Physics Department and ICRA, Universitá di Roma "La Sapienza", Piazzale Aldo Moro 2, 00185, Rome, Italy*
[3]*Physics Department and INFN, Universitá di Roma "La Sapienza", Piazzale. Aldo Moro 2, 00185, Rome, Italy*
[4]*Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy*
[5]*Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211019 India*

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We perform an analysis of the recent WMAP7 data considering physically motivated and viable reionization scenarios with the aim of assessing their effects on cosmological parameter determinations. The main novelties are: (i) the combination of cosmic microwave background data with astrophysical results from quasar absorption line experiments; (ii) the joint variation of both the cosmological and astrophysical [governing the evolution of the free electron fraction $x_e(z)$] parameters. Including a realistic, data-constrained reionization history in the analysis induces appreciable changes in the cosmological parameter values deduced through a standard WMAP7 analysis. Particularly noteworthy are the variations in $\Omega_b h^2 = 0.02258^{+0.00057}_{-0.00056}$ [WMAP7 (Sudden)] vs $\Omega_b h^2 = 0.02183 \pm 0.00054$ [WMAP7 + ASTRO (CF)] and the new constraints for the scalar spectral index, for which WMAP7 + ASTRO (CF) excludes the Harrison-Zel'dovich value $n_s = 1$ at $>3\sigma$. Finally, the electron-scattering optical depth value is considerably decreased with respect to the standard WMAP7, i.e. $\tau_e = 0.080 \pm 0.012$. We conclude that the inclusion of astrophysical data sets, allowing to robustly constrain the reionization history, in the extraction procedure of cosmological parameters leads to relatively important differences in the final determination of their values.

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I. INTRODUCTION

It is well-known from a large set of astrophysical observables that after primordial recombination (which occurred at a redshift of $z \sim 1100$), the Universe "reionized" at a redshift $z > 6$. It is common practice in cosmic microwave background (CMB) studies to parametrize the reionization as an instantaneous process occurring at some redshift z_r, with $4 < z_r < 32$, and to marginalize over z_r when deriving constraints on the other cosmological parameters. In the absence of any precise astrophysical model of the reionization process, the electron ionization fraction $x_e(z)$ is parametrized by z_r in the following way: $x_e(z) = 1$ for $z \ll z_r$ [possibly $x_e(z) = 1.08$ or $x_e(z) = 1.16$ for $z < 3$ in order to take into account the first and second helium ionization] and $x_e(z) < 2 \times 10^{-4}$ for $z > z_r$ in order to join the ionization fraction value after the recombination. In the following, we will refer to this parametrization as "sudden" or "instantaneous" reionization. With this choice of parametrization there exists a one-to-one relation between the redshift of sudden reionization z_r and the electron scattering optical depth τ_e. The most recent constraints on the optical depth that come from the analysis of the Wilkinson Microwave Anisotropy Probe team on their seven-year data (WMAP7), in which it is assumed a sudden reionization scenario, is $\tau_e = 0.088 \pm 0.015$. However, as already noticed, e.g. in Ref. [1], and further emphasized by our previous works ([2,3]), the assumption of a general reionization scenario could affect the extraction of the constraints of cosmological parameters. In particular, we studied the effects of noninstantaneous reionization on the two principal inflationary parameters (the scalar spectral index of primordial perturbations n_s and the tensor-to-scalar ratio parameter r) and on the optical depth τ_e. The method used in the above-cited works to describe a general reionization scenario, developed in Ref. [1], is based on a principal-components (PC) analysis of the reionization history, $x_e(z)$. PCs provide a complete basis for describing the effects of reionization on the large-scale E-mode polarization spectrum. Following Ref. [1], one can treat $x_e(z)$ as a free function of redshift by decomposing it into its principal components:

$$x_e(z) = x_e^f(z) + \sum_\mu m_\mu S_\mu(z), \tag{1}$$

where the principal components $S_\mu(z)$ are the eigenfunctions of the Fisher matrix describing the dependence of the polarization spectra on $x_e(z)$; the m_μ are the PC amplitudes for a particular reionization history, and $x_e^f(z)$ is the WMAP *fiducial* model for which the Fisher matrix is computed and from which the PCs are obtained. The fiducial model has a constant free electron fraction $x_e = 0.15$ over the range $6 < z < 30$, and there are 95 redshift bins of a constant width $dz = 0.25$. The amplitude of eigenmode μ for a perturbation around the fiducial reionization history $\delta x_e(z) \equiv x_e(z) - x_e^f(z)$ is

$$m_\mu = \frac{1}{z_{\max} - z_{\min}} \int_{z_{\min}}^{z_{\max}} dz S_\mu(z) \delta x_e(z). \qquad (2)$$

In Refs. [2,3], we made use of the publicly available $S_\mu(z)$ functions and varied the amplitudes m_μ for the first five eigenfunctions (i.e. for $\mu = 1, \ldots, 5$). The principal components were computed only in the range of redshifts $z \in [6\text{–}30]$.

In what follows, we refer to this parametrization of reionization as the "PC" reionization. Since the ionization fraction is bounded in $0 < x_e(z) < 1$ (neglecting helium reionization and the small residual ionized fraction after recombination) in the range of redshifts in which PCs are defined, it is necessary to impose some limits on the amplitudes of the eigenmodes of Eq. (2) to let the reionization fraction be within these limits, if only for the definition of reionization fraction. In Ref. [1], the authors find the ranges of values for the amplitudes m_μ compatible with $x_e(z) \in [0, 1]$ for all the redshifts in range of interest. In Refs. [2,3], we performed a Monte Carlo–Markov-chains analysis assuming a flat prior on (only) the ranges of values of the amplitudes m_μ whose linear combination with the function S_μ gives a $x_e(z)$ in the allowed range. These values are reported in left part of Table I and are labeled "PC bounds".

However, these limits for the values of the PC amplitudes are a necessary but not sufficient condition for the reionization fraction to lie in $0 < x_e(z) < 1$. In fact, as noticed also by Ref. [1], if any m_μ violates those bounds, $x_e(z)$ is guaranteed to be unphysical in some redshift range, but the opposite is not true because the full reionization history depends on the linear combinations of the product of the amplitudes times their corresponding PC principal component. Indeed, even if all the amplitudes m_μ satisfy the bounds reported in Table I, $x_e(z)$ could assume an unphysical value for some redshifts. To overcome this potential problem, we have added in the version of the COSMOMC package used in Refs. [2,3] the condition that the value of $x_e(z)$ computed at each step of a Markov chain must be in the range $0 < x_e(z) < 1$ for every z. In these studies, this was the only "physicality" condition imposed on the possible reionization history. However, experimental data gathered in the last few years can be used to discard at least some of the possible $x_e(z)$ histories on well-understood (astro)physical grounds. It is now possible to use reionization histories that are physically motivated and tested with known probes of the reionization epoch, such as the Gunn-Peterson optical depth, or the distribution in redshift of the Lyα emitters.

TABLE I. Ranges of variation for the amplitudes of the principal component, in the case of the principal components and in the case of the 99% c.l. reconstructed amplitudes of the present analysis (see text for details).

Parameter	PC Bounds	Astrophysical Bounds
m_1	$[-0.1236, 0.7003]$	$[-0.1229, -0.0866]$
m_2	$[-0.6165, 0.2689]$	$[-0.2594, 0.0002]$
m_3	$[-0.3713, 0.5179]$	$[0.0763, 0.2941]$
m_4	$[-0.4729, 0.3817]$	$[-0.2107, -0.1080]$
m_5	$[-0.3854, 0.4257]$	$[0.0418, 0.1319]$

In this work, we adopt the results of a well-tested semianalytical reionization model proposed in Refs. [4,5] (in what follows, we will refer to this model as the "Choudhury-Ferrara model"). This model takes into account a large number of parameters and physical processes that are involved in modeling reionization, including (e.g.) the radiative and chemical feedbacks of the first sources of ionizing light on the evolution of the intergalactic medium (IGM), and we constrain the model by comparing it with a variety of observational data, such as the redshift evolution of Lyman Limit Systems (LLS), the IGM temperature and the cosmic star formation density. Thus, we will be able to build up an ensemble of reionization histories that is more robust from both the theoretical and the observational point of view, rather than rely on purely phenomenological, albeit model-independent, parameterization schemes as the PCs. In the present work, the CF model is properly modified to let the cosmological parameters free to vary (see Sec. II for details on the adopted settings).

We will combine the CF model with a standard Λ cold dark matter cosmological model, and we perform a Monte Carlo– Markov-chains analysis of the joint CMB and reionization data. We will thus be able to test the impact of considering a detailed physical model for reionization on the constraints of the cosmological parameters, and conversely to test the dependence of the CF model on the underlying cosmological model.

At the end of such analysis, we will moreover derive the subsequent constraints on the amplitudes of the reionization principal components m_μ [applying directly Eq. (2)]. By construction then, these limits on the values of amplitudes of the principal components will be compatible and constrained both by the CMB and by the astrophysical probes of the reionization process.

The main objectives of the present work are then:

(i) Verify the impact of considering a data-constrained and realistic reionization model on the determination cosmological parameters.

(ii) Verify the impact on the constraints of the reionization parameters produced by variations of the cosmological parameters, i.e. refraining from fixing them *a priori* from the most updated best-fit values of the WMAP experiment.

(iii) Obtain the PC amplitudes m_μ from the allowed reionization histories.

As such an analysis with combined cosmological parameters characterizing the background evolution of the Universe and astrophysical parameters modeling the reionization history has not yet been made, it is worthwhile to explore their mutual implications on the extraction of the constraints of the two ensemble of parameters.

II. ANALYSIS

The details of the CF model are summarized in Ref. [6]; in the present work, we assume the following settings:

(i) We consider here a flat ΛCDM cosmology described by a set of cosmological parameters:

$$\{\Omega_m, \Omega_b h^2, h, \sigma_8, n_s\}, \tag{3}$$

where Ω_m is the total matter density relative to the critical density, $\Omega_b h^2$ is the baryonic matter density, h is the reduced Hubble parameter $H_0 = 100h$ km Mpc^{-1} s^{-1}, σ_8 is the rms density fluctuation in spheres of radius $8h^{-1}$ Mpc and n_s is the scalar spectral index of primordial perturbations. We want to stress that these cosmological parameters are considered here as free parameters, so that they are not assumed *a priori*, as in Ref. [6].

(ii) The CF reionization model contains three additional free parameters. These are $\epsilon_{\mathrm{II,III}} = [\epsilon_* f_{\mathrm{esc}}]_{\mathrm{II,III}}$, the product of the star-forming efficiency (fraction of baryons within collapsed haloes going into stars) ϵ_* and the fraction of photons escaping into the IGM f_{esc} for PopII and PopIII stars; the normalization λ_0 of the ionizing photons' mean free path (see Ref. [6] for details). In what follows, we refer to these three parameters as the "astrophysical" parameters, to distinguish them from the five "cosmological" ones described in the previous point.

(iii) The ranges of variation adopted for the three free astrophysical parameters are $\epsilon_{\mathrm{II}} \in [0; 0.02]$, $\epsilon_{\mathrm{III}} \in [0; 0.1]$, $\lambda_0 \in [1; 10]$.

(iv) The observational data used to compute the likelihood analysis are (i) the photo-ionization rates Γ_{PI} obtained using Lyα forest Gunn-Peterson optical depth observations and a large set of hydrodynamical simulations [7] and (ii) the redshift distribution of LLS $\mathrm{d}N_{\mathrm{LL}}/\mathrm{d}z$ in the redshift range of $0.36 < z < 6$ [8]. The data points are obtained using a large sample of quasi-stellar-object spectra. For details, see Ref. [9].

(v) In order to make the analysis self-consistent, the WMAP7 constraint on the total electron scattering optical depth τ_e is not considered in this analysis. This prevents a possible incoherence in our analysis: WMAP7 constraints on τ_e have been obtained using the assumption of instantaneous reionization at $z = z_r$. Once this idealized evolution of $x_e(z)$ is dropped (this paper), the value of τ_e must be a byproduct of the new analysis rather than being inserted artificially as an external constraint into it. Moreover, as already pointed out in Ref. [6], the CMB polarization spectra are sensitive to the shape of the reionization history, and considering a more general reionization scenario could lead to a tighter optical depth constraint than derived by WMAP7 [2].

(vi) Finally, we impose the prior that reionization should be completed by $z = 5.8$ to match the flux data of Lyα and Lyβ forest. Indeed, the spectra of quasars below redshift $z = 5.8$ do not show the Gunn-Peterson trough, indicating that the intergalactic medium is entirely ionized by that redshift [10].

With these hypotheses, we have then modified the Boltzmann CAMB code [11] to incorporate the CF model and performed a Monte Carlo–Markov-chains analysis based on an adapted version of the publicly available MCMC package COSMOMC [12]. Our basic data set is the seven–yr WMAP data [13] (temperature and polarization), on top of which we add two astrophysical data sets, i.e. the LLS redshift evolution, dN_{LL}/dz of Ref. [8], and the Gunn-Peterson optical depth measurements presented in Ref. [7]. To extract the constraints on free parameters from such a combined data set, we consider a total likelihood function $L \propto \exp(-\mathcal{L})$ made up by two parts:

$$\mathcal{L} = \frac{1}{2}\sum_{\alpha=1}^{N_{\mathrm{obs}}}\left[\frac{\mathcal{J}_\alpha^{\mathrm{obs}} - \mathcal{J}_\alpha^{\mathrm{th}}}{\sigma_\alpha}\right]^2 + \mathcal{L}', \tag{4}$$

where $\mathcal{L}'$ refers to the WMAP7 likelihood function and is computed using the routine supplied by the WMAP team; $\mathcal{J}_\alpha$ represents the set of N_{obs} observational points referring to Gunn-Peterson optical depth LLS distribution data; finally, σ_α are the corresponding observational error bars.

The Monte Carlo–Markov-chain convergence diagnostics are done on 4 chains applying the Gelman and Rubin "variance of chain mean"/"mean of chain variances" R statistic for each parameter. We considered the chains to be converged at $R - 1 < 0.03$.

III. RESULTS

The results of the MCMC analysis described above are summarized in Table II, where we list the marginalized posterior probabilities at 95% confidence level (c.l.) errors on the free cosmological and astrophysical parameters. We also report the constraints for two derived parameters: the electron scattering optical depth τ_e and reionization redshift z_r, to be intended as the redshift at which the reionization is 99% complete. In Table III, we show the 68% c.l. constraints obtained by the WMAP team for the standard 6-parameter ΛCDM model ["WMAP7 (Sudden)"] and the constraints obtained on the cosmological parameters from the present analysis ["WMAP7 + ASTRO (CF)"].

As we can see from Table III, the results of our work mildly differ from the WMAP7 (Sudden) results for the parameters of the standard ΛCDM model. The most sensitive parameter for the presence of the astrophysical data sets (LLS and Gunn-Peterson data) is $\Omega_b h^2$ whose mean values in the two cases differ by more than a standard deviation from each other. It is important to note that

TABLE II. Mean and 95% c.l. constraints on the cosmological, astrophysical and derived parameters obtained with WMAP7 + ASTRO data set with the reionization parametrized with the CF model of reionization (WMAP + ASTRO (CF).

Parameter	Mean	95% c.l. limits
Ω_m	0.2733	[0.2260, 0.3305]
$\Omega_b h^2$	0.2184	[0.0208, 0.0229]
h	0.6984	[0.6553, 0.7422]
n_s	0.9579	[0.9330, 0.9838]
σ_8	0.7941	[0.7434, 0.8491]
$\epsilon_{\rm II}$	0.0037	[0.0016, 0.0067]
$\epsilon_{\rm III}$	0.0165	[0.0000, 0.0398]
λ_0	3.0152	[1.0000, 5.1739]
τ_e	0.0803	[0.0625, 0.1042]
z_r	6.7469	[5.8563, 8.2000]

even when considering a complex reionization history implying three new parameters, the errors remain practically the same as in the standard case.

Table III reports the results obtained in Ref. [2] for the WMAP7 data set with the PC reionization [“WMAP7 (PC)”]. This method produces two main differences with respect to the WMAP7 + ASTRO (CF) case: the first is related to the constraints obtained for n_s. In Ref. [2], the constraints for the scalar spectral index were compatible with $n_s = 1$, i.e. the Harrison-Zel’dovich primordial power spectrum, when instead WMAP7 + ASTRO (CF) excludes the value $n_s = 1$ at $>3\sigma$. The second difference concerns τ_e in the two cases: for WMAP7 (PC), this quantity is in the range $\tau_e = 0.093 \pm 0.010$, while the WMAP + ASTRO (CF) case gives a mean value lower by $>1 - \sigma$, i.e. $\tau_e = 0.080 \pm 0.012$.

This is made more clear in Fig. 1, where we show the two-dimensional 68% and 95% c.l. constraints in the $(\Omega_h^2 - \tau_e)$ plane in the cases WMAP7 (Sudden) and WMAP7 + ASTRO (CF).

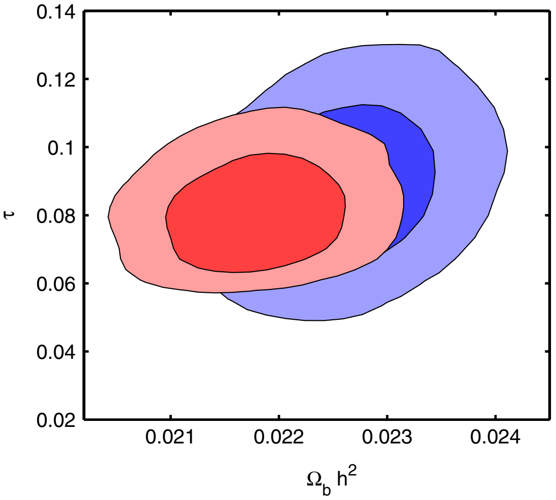

FIG. 1 (color online). Two-dimensional 68% (darker regions) and 95% (lighter regions) c.l. constraints on the $(\Omega_h^2 - \tau_e)$ plane in the WMAP (Sudden) case (blue, bottom layer) and in the WMAP + ASTRO (CF) case (red, top layer).

Note that in the WMAP7 (PC) case, we did not consider constraints on the σ_8 parameter, so in Table III, the corresponding value is missing.

There is a caveat in comparing the constraints obtained on z_r. Indeed, in the WMAP7 (Sudden) case, z_r is the redshift of reionization, if the Universe was reionized instantaneously from the neutral state to the fully ionized state at z_r [13]. In the more realistic, extended reionization scenarios considered here instead, z_r is defined as the redshift at which the IGM is 99% reionized by volume. With this clarification in mind, WMAP7 + ASTRO (CF) results predict $5.8 < z_r < 8.2$ at 95% c.l. (see Table II).

TABLE III. Comparison of the one-dimensional 68% c.l. posterior probability constraints on the cosmological parameters obtained in three cases: (i) Ref. [13], with the WMAP7-only data set and sudden reionization [first column, WMAP7 (Sudden)]: (ii) Ref [2], with the WMAP7-only data set and PC reionization [second column, WMAP7 (PC)] (iii) the present work, with WMAP7 and two additional astrophysical data sets, namely, the LLS redshift evolution, dN_{LL}/dz of Ref. [8] and the Gunn-Peterson optical depth measurements presented in Ref. [7] [third column, WMAP7 + ASTRO (CF)].

Parameter	WMAP7 (Sudden)	WMAP7 (PC)	WMAP7 + ASTRO (CF)
Ω_m	0.266 ± 0.029	0.243 ± 0.032	0.273 ± 0.027
$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02321 ± 0.00076	0.02183 ± 0.00054
h	0.710 ± 0.025	0.735 ± 0.033	0.698 ± 0.023
n_s	0.963 ± 0.014	0.994 ± 0.023	0.958 ± 0.013
σ_8	0.801 ± 0.030	$\cdots$	0.794 ± 0.027
τ_e	0.088 ± 0.015	0.093 ± 0.010	0.080 ± 0.012
z_r [a]	10.5 ± 1.2	$\cdots$	6.7 ± 0.6

[a] The z_r parameter has a different definition in the different reionization scenarios (see text for details).

TABLE IV. Comparison between the mean value and the 95% c.l posterior constraints between the present work WMAP7 + ASTRO (CF) and the CF model, Ref. [6] (CF).

Parameter	WMAP7 + ASTRO (CF) Mean	WMAP7 + ASTRO (CF) 95% c.l. limits	CF Mean	CF 95% c.l. limits
ϵ_{II}	0.0037	[0.0016, 0.0067]	0.003	[0.001, 0.005]
ϵ_{III}	0.0165	[0.0000, 0.0398]	0.020	[0.0000, 0.043]
λ_0	3.0152	[1.0000, 5.1739]	5.310	[2.317, 9.474]
τ_e	0.0803	[0.0625, 0.1042]	$\equiv 0.088 \pm 0.015$	$\equiv 0.088 \pm 0.015$
z_r	6.7469	[5.8563, 8.2000]	6.762	[5.800, 7.819]

Understanding the parameter shifts with respect to WMAP7 (Sudden) is relatively complex. A physical interpretation could be the following. Having released the instantaneous reionization history hypothesis results in a lower e.s. optical depth, as the ionized fraction can linger for a finite time span on intermediate values. However, as reionization is gradual and starts at earlier redshifts, where recombination is enhanced by the differentially larger density, the value of Ω_b has to be smaller to compensate. The same is probably true also for the smaller scalar spectra index, which implies a small, albeit non-negligible, power spectrum cut at the lowest masses not to exceed the decreased τ_e.

In Table IV, we report the 95% c.l. posterior probability constraints for the reionization parameters ϵ_{II}, ϵ_{III} and λ_0 obtained in the present work [in the WMAP7 + ASTRO (CF) case, cosmological parameters are free to vary] compared to those obtained in Ref. [6] in which the cosmological parameters were fixed to the WMAP7 best-fit values (CF case). Figure 2 shows the comparison between the best-fit model for the $x_e(z)$ evolution for the two cases of WMAP7 + ASTRO (CF) and CF. For the WMAP7 + ASTRO (CF) case, full hydrogen reionization is not only achieved earlier than in the CF model, but the evolution is faster, resulting in an initially lower $x_e(z)$ above $z = 8$. These differences are entirely induced by the fact that we have now allowed the cosmological parameters to vary together with the astrophysical ones, but they are relatively small. The fact that the astrophysical parameters do not show much dependence on cosmology is understandable because the cosmological parameters affect the reionization process mostly through structure formation. The next obvious step is to include large-scale structure information in the analysis. In conclusion, including astrophysical data sets in the analysis seems to lead to relatively important effects on the extraction of the cosmological parameters.

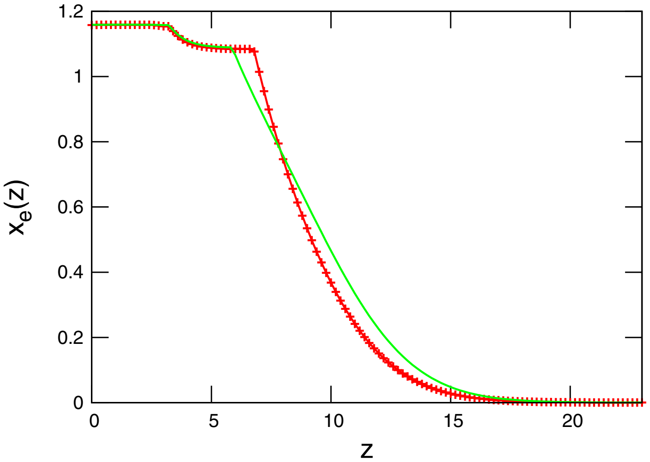

FIG. 2 (color online). Ionization histories for the best-fit model for the two cases WMAP7 + ASTRO (CF) (red dotted solid curve) and CF (green solid curve) [6].

PC amplitude reconstruction

For each reionization history allowed by the MCMC likelihood analysis, we use Eq. (2) to reconstruct the amplitudes of the first five PC amplitudes, m_μ, with $\mu = 1 \dots 5$. By construction now, the amplitudes m_μ not only fulfill the necessary physicality conditions (see Sec. I), but also they are compatible with the additional astrophysical data sets considered in this analysis, i.e. the Lyα Gunn-Peterson test and the LLS redshift distribution.

In Fig. 3, we show the two-dimensional 68% and 99% c.l constraints for the amplitudes m_μ obtained here compared with those obtained in Ref. [2] for which we show the two-dimensional 68% and 95% c.l. distributions for each of the cases considered. We choose to report the 99% c.l. instead of the usual 95% c.l. limits to be as conservative as possible in showing the reionization histories allowed by the MCMC likelihood analysis. The color (layer) code is the following: in pink (top layer), there is the case WMAP7 + ASTRO (CF) considered in the present work. In the background, there are the cases considered in Ref. [2]: in blue is the WMAP7 case (bottom layer); in red (next layer up) is the case called "CMB all" (i.e. WMAP7 + ACBAR+ BICEP + QUAD + BOOMERanG); the green (next layer) is CMB All + LRG − 7 and the yellow (next layer) is simulated Planck data. Reference [2] considered an ensemble of CMB data sets along with WMAP7, and also we forecasted future constraints from the Planck experiment,

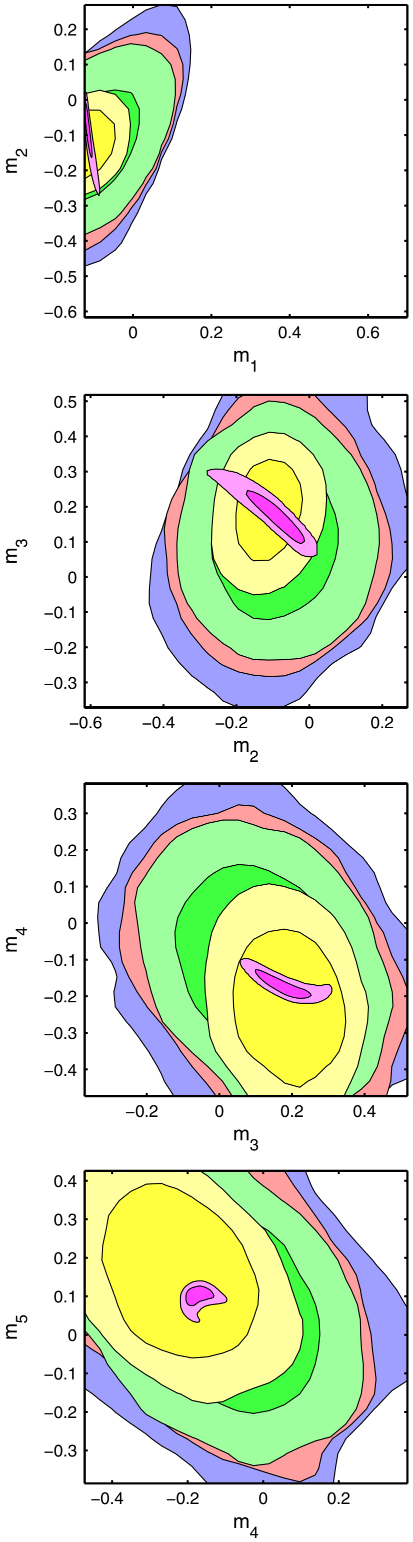

FIG. 3 (color online). 68% and 99% reconstructed c.l. constraints for the values of the PC amplitudes computed from CF model and Eq. (2) (top layer, pink). Background contours refer to 68% and 95% c.l. constraints obtained in Ref. [2] with the PC reionization for WMAP7 (bottom layer, blue), WMAP7 + QUAD + ACBAR + BICEP (CMB All, next layer up, red), CMB All + LRG − 7 (next layer, green) and simulated Planck data (next layer, yellow), respectively.

simulating a set of mock data with a fiducial model given by the best-fit WMAP5 model with the following experimental noise:

$$N_\ell = \left(\frac{w^{-1/2}}{\mu\text{K} - \text{rad}}\right)^2 \exp\left[\frac{\ell(\ell+1)(\theta_{\text{FWHM}}/\text{rad})^2}{8\ln 2}\right], \tag{5}$$

where $w^{-1/2}$ is the temperature noise level (a factor $\sqrt{2}$ larger for polarization noise) and θ is the beam size. For the Planck mission, we use $w^{1/2} = 58\mu K$ and $\theta_{\text{FWHM}} = 7.1'$ equivalent to expected sensitivity of the 143 GHz channel.

The region spanned by PC amplitude values is much smaller than that allowed by when the PC bounds only are imposed. The 99% c.l. constraints values are reported in the right part of the Table I (“astrophysical bounds”). As seen from Table I, the amplitudes of all the principal components (except for m_2) obtained with the above procedure are constrained at 99% c.l. to take a definite sign, negative for m_1 and m_4 and positive for m_3 and m_5. Moreover, even if the 99% c.l. upper bound of m_2 is positive, this second amplitude is mostly constrained to be always negative. These results are in qualitative agreement with Ref. [2], where we also found the same amplitude signature, albeit with errors large enough that the 95% c.l. bounds encompass values of both possible signs.

IV. CONCLUSIONS

With the aim of constraining the evolution of cosmic reionization, we have extended previous work based on the use of principal components analysis. The main novelty of the present work is represented on one hand by complementing available CMB data with additional astrophysical results from quasar absorption line experiments, such as the Gunn-Peterson test and the redshift evolution of Lyman Limit Systems. In addition, we have for the first time explored the effects of a joint variation of both the cosmological (Ω_m, $\Omega_b h^2$, h, σ_8, n_s) and astrophysical (ϵ_{II}, ϵ_{III}, λ_0, see Sec. II for their physical meaning) parameters. Note that, differently from the vastly used approach in the literature, we do not impose *a priori* any bound on the electron scattering optical depth τ_e, which instead we calculate *a posteriori*. This is to prevent a possible incoherence in the calculation, as the WMAP determination of such quantity is based on the assumption of an instantaneous reionization which we do not make here.

Including a realistic (i.e physically motivated) reionization history in the analysis induces mild changes in the cosmological parameter values deduced through a standard WMAP7 analysis. Particularly noteworthy are the variations in $\Omega_b h^2 = 0.02258^{+0.00057}_{-0.00056}$ (WMAP7 (Sudden)) vs $\Omega_b h^2 = 0.02183 \pm 0.00054$ (WMAP7 + ASTRO (CF)) and the new constraints for the scalar spectral index, for which WMAP7 + ASTRO (CF) excludes the

Harrison-Zel'dovich value $n_s = 1$ at $>3\sigma$. Finally, the e.s. optical depth values are considerably decreased with respect to the standard WMAP7, i.e. $\tau_e = 0.080 \pm 0.012$. We conclude that inclusion of astrophysical data sets, allowing us to robustly constrain the reionization history, in the extraction procedure of cosmological parameters leads to relatively important differences in the final determination of their values.

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