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CMB neutrino mass bounds and reionization

Maria Archidiacono,[1,2] Asantha Cooray,[2] Alessandro Melchiorri,[1] and Stefania Pandolfi[3]

[1] *Physics Department and INFN, Università di Roma "La Sapienza," Piazzale Aldo Moro 2, Rome 00185, Italy*

[2] *Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, California 92697, USA*

[3] *ICRA and INFN, Università di Roma "La Sapienza," Piazzale Aldo Moro 2, Rome 00185, Italy*

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Current cosmic microwave background bounds on the sum of the neutrino masses assume a sudden reionization scenario described by a single parameter that determines the onset of reionization. We investigate the bounds on the neutrino mass in a more general reionization scenario based on a principal component approach. We found the constraint on the sum of the neutrino masses from cosmic microwave background data can be relaxed by ~40% in a generalized reionization scenario. Moreover, the amplitude of the rms mass fluctuations σ_8 is also considerably lower providing a better consistency with the low amplitude of the Sunyaev-Zel'dovich signal recently found by the South Pole Telescope.

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I. INTRODUCTION

The high precision measurements of cosmic microwave background (hereafter, CMB) anisotropies made by the WMAP satellite have provided not only a wonderful confirmation of the standard model of cosmological structure formation but also relevant information on key parameters in particle physics. One example is the sum of the neutrino masses and the neutrino mass hierarchy.

The most recent data release from WMAP after seven years of observations presented a bound on the total neutrino mass of $\Sigma m_\nu < 1.3$ eV at the 95% C.L. [1]. This bound is approximately a factor of 5 better than the current laboratory experimental upper limit inferred from a combination of beta-decay experiments and neutrino oscillation data (see e.g. [2]). The CMB bound on neutrino masses is also considered the most conservative limit from cosmology. Indeed, including information from galaxy clustering and luminosity distance data, the constraint can be further improved to $\Sigma m_\nu < 0.55$ eV at 95% C.L. [1], while a limit of $\Sigma m_\nu < 0.28$ eV at 95% C.L. can be obtained by including redshift-dependent halo bias-mass relations [3].

It is however important to be aware of the theoretical modeling behind the constraint based on cosmological measurements. A model of structure formation based on dark matter, adiabatic primordial fluctuations and dark energy is assumed and the removal of one of these assumptions can in principle affect the CMB limit. For example, the inclusion of isocurvature perturbations [4], dark energy [1] or modified gravity [5] can all relax the CMB upper limit on the neutrino masses.

In this Brief Report we investigate another possible theoretical caveat that could affect the CMB bound on the sum of the neutrino masses, i.e. the modeling of the reionization epoch. It is often assumed in the current cosmological data analysis that reionization is a sudden event at redshift $z = z_{\rm re}$, i.e. this process is usually described by a single parameter with the free electron fraction x_e increasing from $\sim 10^{-4}$ up to 1 for redshifts $z < z_{\rm re}$ (~ 1.08 for $z < 3$ when taking into account helium reionization). While this scenario can properly describe several reionization scenarios, it obviously cannot describe more complex reionization scenarios as, for example, double or not-monotone reionization. Given our current ignorance about the thermal history of the universe at redshifts $z \geq 6$ it is important to consider all the possible reionization scenarios allowed by data when deriving the most conservative constraint on a cosmological parameter such as the sum of the neutrino masses.

Here, we indeed assume a more general reionization model following the principal components method suggested by Mortonson and Hu [6] and we derive constraints on the neutrino mass in this different theoretical framework. It has been shown recently [7] that a general reionization scenario can drastically alter the conclusions on inflationary parameters as the scalar spectral index n, putting its value in better agreement with the expectations of a Harrison-Zel'dovich [8], $n = 1$, spectrum. So it is definitely timely to investigate what kind of impact a general reionization scenario can have on the current CMB neutrino bound. The paper is organized as follows: In Sec. II we briefly describe the reionization parametrization assumed and the decomposition in principal components. We also describe the data analysis method. In Sec. III we present the results of our analysis, and in Sec. IV we discuss our conclusions.

II. ANALYSIS METHOD

We adopt the method, developed in Ref. [6], based on principal components that provide a complete basis for describing the effects of reionization on large-scale E-mode polarization. Following Ref. [6], one can parametrize the reionization history as a free function of redshift by decomposing $x_e(z)$ into its principal components:

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

where the principal components, $S_\mu(z)$, are the eigenfunctions of the Fisher matrix that describes the dependence of the polarization spectra on $x_e(z)$ (again, see Ref. [6]), m_μ are the amplitudes of the principal components for a particular reionization history, and $x_e^f(z)$ is the WMAP fiducial model at which the Fisher matrix is computed and from which the principal components are obtained. In what follows we used the publicly available $S_\mu(z)$ functions and varied the amplitudes m_μ for $\mu = 1, \ldots, 5$ for the first five eigenfunctions. The eigenfunctions are computed in 95 bins from redshift $z_{\rm min} = 6$ to redshift $z_{\rm max} = 30$ with $x_e(z) = 1.08$ for $z < 3$, $x_e(z) = 1.0$ for $3 \leq z < 6$, and $x_e(z) = 10^{-4}$ for $z \geq 30$. Hereafter we refer to this method as the MH (Mortonson-Hu) case.

We have then modified the Boltzmann CAMB code [9] incorporating the generalized MH reionization scenario as in [6] and extracted cosmological parameters from current data using a Monte Carlo Markov chain analysis based on the publicly available package COSMOMC [10].

We consider here a flat Λ-cold dark matter universe described by a set of cosmological parameters

$$\{\omega_b, \omega_c, \omega_\nu, \Theta_s, n, \log[10^{10}A_s]\}, \quad (2)$$

where $\omega_b \equiv \Omega_b h^2$ and $\omega_c \equiv \Omega_c h^2$ are the physical baryon and cold dark matter densities relative to the critical density, ω_ν is the physical energy density in massive neutrinos, Θ_s is the ratio of the sound horizon to the angular diameter distance at decoupling, A_s is the amplitude of the primordial spectrum, and n is the scalar spectral index. We assume 3 degenerate, massive neutrinos with the same mass:

$$m_\nu = 30.8 \text{ eV} \times \omega_\nu. \quad (3)$$

In what follows we will use as standard parameter the value $\Sigma m_\nu = 3m_\nu$.

The extra parameters needed to describe the reionization are the five amplitudes of the eigenfunctions for the MH case and one single common parameter, the optical depth τ, for the sudden reionization case.

Our basic data set is the seven-year WMAP data [1] (temperature and polarization) with the routine for computing the likelihood supplied by the WMAP team.

III. RESULTS

In Table I we compare the constraints on several cosmological parameters in the case of standard or MH reionization scenario. As we can see from the table, the CMB constraint on the neutrino mass is weakened by ~40% when a more general reionization scenario is considered. This is not simply due to an increase in the parameter space but also due to degeneracies present between the cosmological parameters. Considering the MH reionization scenario renders values of the spectral index n in better agreement with the Harrison-Zel'dovich $n = 1$ value (see [7]). This changes the relative amplitude of the peaks in the CMB angular spectrum and makes models with higher neutrino mass more consistent with the WMAP data. Introducing a neutrino mass has indeed the effect of decreasing the gravitational potential at recombination, increasing the small scale CMB anisotropy.[1] This can be counterbalanced by decreasing the value of the spectral index n as clearly shown by the anticorrelation in the n-Σm_ν plane. A general reionization scenario brings higher values of n in agreement with observations, immediately resulting in a better compatibility of larger neutrino masses. It is worth noticing that, while in the standard reionization scenario Harrison-Zel'dovich spectra are excluded at about 3 standard deviations when massive neutrinos are included in the analysis, in the MH case the $n = 1$ spectra are well consistent with the data and inside the 1σ C.L. also with $\Sigma m_\nu \sim 0.5$ eV.

TABLE I. 95% C.L. errors on cosmological parameters in the case of sudden reionization and MH reionization. The upper limit on the neutrino mass is relaxed by ~43%.

	WMAP7	
Parameter	(Sudden Reionization)	(MH Reionization)
$\Omega_b h^2$	$0.0221^{+0.0012}_{-0.0012}$	$0.0226^{+0.0015}_{-0.0014}$
$\Omega_c h^2$	$0.117^{+0.013}_{-0.013}$	$0.115^{+0.017}_{-0.017}$
θ_s	$1.038^{+0.005}_{-0.005}$	$1.039^{+0.006}_{-0.005}$
n	$0.955^{+0.032}_{-0.033}$	$0.975^{+0.0448}_{-0.0434}$
H_0	$65.7^{+7.6}_{-8.2}$	$66.0^{+10.2}_{-9.0}$
Ω_Λ	$0.674^{+0.091}_{-0.134}$	$0.675^{+0.112}_{-0.148}$
Σm_ν	<1.15 eV	<1.66 eV

In Fig. 1 we show the constraints on the Σm_ν vs n plane, while in Fig. 2 we show the constraints on the Σm_ν vs σ_8 plane. The filled contours assume MH reionization while the empty contours assume standard, sudden, reionization. As we can see, MH reionization allows for values of the spectral index n closer to 1 (as already pointed out in [7]), for a larger neutrino mass and for a lower σ_8 amplitude. It is interesting to note that a neutrino mass can in principle accommodate lower values of σ_8 with CMB data. When MH reionization is assumed, even lower values of σ_8 are consistent with CMB data. A low value of $\sigma_8 \sim 0.77$ is preferred by the recent detection of the diffuse Sunyaev-Zel'dovich effect by the South Pole Telescope [11] experiment.

Moreover, correlations exist with the matter density Ω_m, as we show in Fig. 3, and (even if less pronounced) with the baryon physical density $\Omega_b h^2$, as we show in Fig. 4.

[1]The effect of neutrino mass on CMB lensing for the WMAP data is negligible.

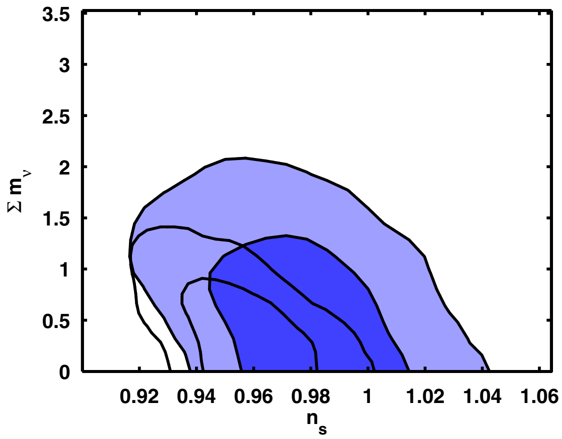

FIG. 1 (color online). Constraints on the Σm_ν vs n plane. The filled contours assume MH reionization while the empty contours assume standard, sudden, reionization.

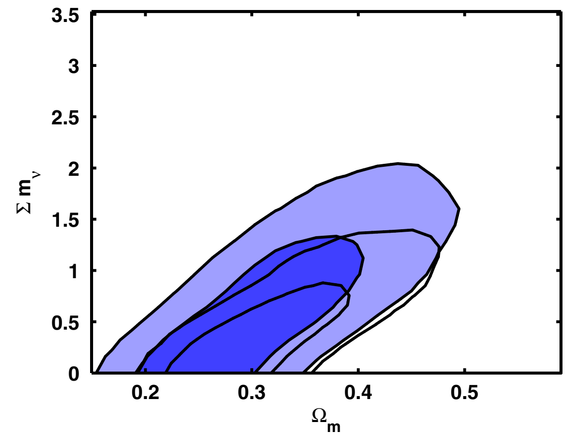

FIG. 3 (color online). Constraints on the Σm_ν vs Ω_m plane. The filled contours assume MH reionization while the empty contours assume standard, sudden, reionization.

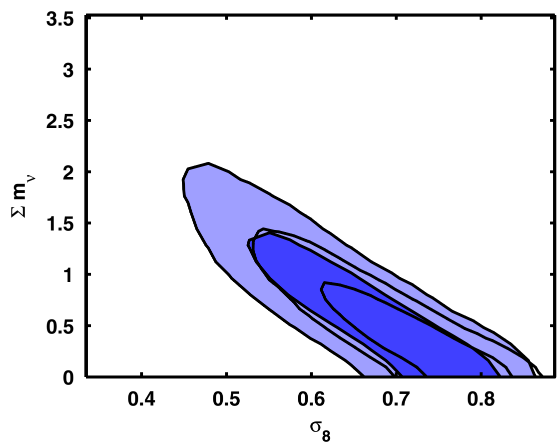

FIG. 2 (color online). Constraints on the Σm_ν vs σ_8 plane. The filled contours assume MH reionization while the empty contours assume standard, sudden, reionization.

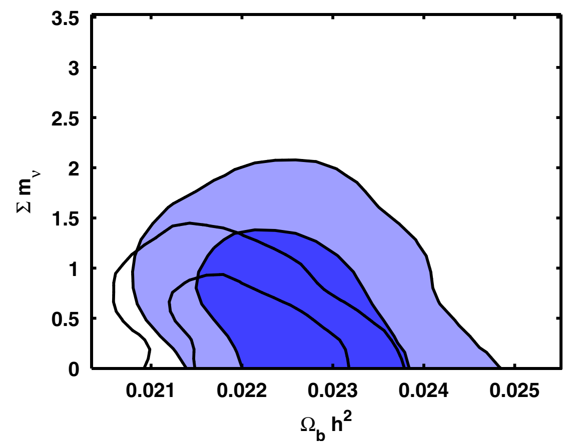

FIG. 4 (color online). Constraints on the Σm_ν vs $\Omega_b h^2$ plane. The filled contours assume MH reionization while the empty contours assume standard, sudden, reionization.

IV. CONCLUSIONS

In conclusion, the details of the reionization processes in the late universe are not very well known. In the absence of a precise, full redshift evolution of the ionization fraction during the reionization period, a simple parametrization, with a single parameter z_r, has become the standard reionization scheme in numerical analyses. However, more general reionization scenarios are certainly plausible and their impact on the cosmological constraints should be carefully explored.

In this Brief Report we have investigated the stability of the CMB constraints on neutrino masses in generalized reionization scenarios. We have found that a more general treatment of reionization could potentially weaken the current CMB upper limit on Σm_ν by $\sim$40%. Cosmological information from baryonic acoustic oscillations, for example, can be added in order to reduce the uncertainty on the neutrino mass. However the lack of knowledge on dark energy and the assumption made with regard to the equation of state could again affect the neutrino mass limit with large-scale structure data. Future data expected from the Planck [12] satellite on large angular scale CMB polarization will help in clarifying the thermal history of the Universe and in ruling out exotic reionization scenarios that are still in agreement with present-day observations with WMAP.

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[1] E. Komatsu *et al.*, arXiv:1001.4538; D. Larson *et al.*, 1001.4635 [Astrophys. J. Suppl. Ser. (to be published)].
[2] G. L. Fogli *et al.*, Phys. Rev. D **78**, 033010 (2008).
[3] F. De Bernardis, P. Serra, A. Cooray, and A. Melchiorri, Phys. Rev. D **78**, 083535 (2008).
[4] C. Zunckel and P. G. Ferreira, J. Cosmol. Astropart. Phys. 08 (2007) 004.
[5] T. Giannantonio, M. Martinelli, E. Menegoni, A. Cooray, A. Melchiorri (unpublished).
[6] M. J. Mortonson and W. Hu, Astrophys. J. **686**, L53 (2008).
[7] S. Pandolfi, A. Cooray, E. Giusarma, E. W. Kolb, A. Melchiorri, O. Mena, and P. Serra, Phys. Rev. D **81**, 123509 (2010).
[8] E. R. Harrison, Phys. Rev. D **1**, 2726 (1970); Y. B. Zel'dovich, Mon. Not. R. Astron. Soc. **160**, 1P (1972); P. J. E. Peebles and J. T. Yu, Astrophys. J. **162**, 815 (1970).
[9] A. Lewis, A. Challinor, and A. Lasenby, Astrophys. J. **538**, 473 (2000).
[10] A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002).
[11] M. Lueker *et al.*, Astrophys. J. **719**, 1045 (2010).
[12] Planck Collaboration, arXiv:astro-ph/0604069.