Recombining WMAP: Constraints on ionizing and resonance radiation at recombination

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We place new constraints on sources of ionizing and resonance radiation at the epoch of the recombination process using the recent cosmic microwave background temperature and polarization spectra coming from the Wilkinson Microwave Anisotropy Probe (WMAP). We find that non-standard recombination scenarios are still consistent with the current data. In light of this we study the impact that such models can have on the determination of several cosmological parameters. In particular, the constraints on curvature and baryon density appear to be weakly affected by a modified recombination scheme. However, it may affect the current WMAP constraints on inflationary parameters such as the spectral index n_s and its running. Physically motivated models, such as those based on primordial black holes or super heavy dark matter decay, are able to provide a good fit to the current data. Future observations in both temperature and polarization will be needed to more stringently test these models.

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I. INTRODUCTION

The recent measurements of the cosmic microwave background (CMB) flux provided by the Wilkinson Microwave Anisotropy Probe (WMAP) mission [1] have truly marked the beginning of the era of precision cosmology. In particular, the position and amplitude of the detected oscillations in the angular power spectrum of the CMB are in spectacular agreement with the expectations of the standard model of structure formation, based on primordial adiabatic and nearly scale invariant perturbations [2]. Assuming this model of structure formation, an *indirect* but accurate measurement of several cosmological parameters has been reported [3] in agreement with those previously indicated (see, e.g. [4] and [5]).

However, beside a full confirmation of the previous scenario (with a sensible reduction of the error bars) the WMAP data set is also hinting towards a modification of the standard picture in several aspects [3]. In particular, the low CMB quadrupole [6,7] possible scale dependence of the spectral index [8,9], high optical depth (see, e.g. [10–12]) possible deviations from flatness [13] and dark energy [14] have already produced a wide interest. Further, the relatively high χ^2 per degree of freedom of the fiducial model suggests systematics and/or new physics could be considered.

It is therefore timely, with the increased precision of the CMB data set to further test the standard scenario and to investigate possible deviations. Here we investigate possible deviations in the mechanism to which CMB anisotropies are highly dependent: the process of recombination.

The recombination process can be modified in several ways. For example, one could use a model independent, phenomenological approach such as in [15] where models are specified by the position and width of the recombination surface in redshift space. Here we will instead focus on theoretically motivated mechanisms based on extra sources of ionizing and resonance radiation at recombination (see, e.g. [16]). While the method we adopt will be general enough to cover most of the models of this kind, we remind the reader that there are several other ways in which to modify recombination, like, for instance, by having a time-varying fine-structure constant [17]. In our analysis, we will not cover the constraints on these models from WMAP as they have been recently investigated in [18].

Following the seminal papers [19,20] detailing the recombination process, further refinements to the standard scenario were developed [21], allowing predictions at the accuracy level found in data from the WMAP satellite and the future Planck satellite [22,23]. With this level of accuracy it becomes conceivable that deviations from standard recombination maybe be detectable [16,24,25].

The paper proceeds as follows. In Sec. II we review models which can produce deviations from the standard recombination scenario. In Sec. III we describe how these deviations might affect the CMB temperature and polarization power spectra and conduct a likelihood analysis using the recent CMB data from WMAP. In particular, we will study the impact that a modified recombination scheme can have on several cosmological parameters. In Sec. IV we draw together the implications of the analysis, placing constraints on current theories of recombination.

II. BEYOND STANDARD RECOMBINATION

In the standard recombination model [19,20] the net recombination rate is given by

$$-\left.\frac{dx_e}{dt}\right|_{std}=C\left[a_c n x_e^2-b_c(1-x_e)\exp\left(-\frac{\Delta B}{k_B T}\right)\right] \quad (1)$$

where x_e is the ionization fraction, a_c and b_c are the effective recombination and photo-ionization rates for principle quantum numbers $\geqslant 2$, and ΔB is the difference in binding energy between the first and second energy levels. In addition to the single Ly-α transition with wavelength λ_α, there is also two-photon decay from the meta-stable $2s$ level, with decay rate Λ_{1s2s}. The contribution of this process is reflected in the parameter C,

$$C=\frac{1+K\Lambda_{1s2s}n_{1s}}{1+K(\Lambda_{1s2s}+b_c)n_{1s}}, \quad K=\frac{\lambda_\alpha^3}{8\pi H(z)}. \quad (2)$$

The standard hydrogen recombination scenario can be simply extended in two ways with the addition of Ly-α and ionizing photons [16].

The extra contributions can be related to the baryon number density through the efficiency functions ε_α and ε_i, respectively,

$$\frac{dn_\alpha}{dt}=\varepsilon_\alpha(z)H(z)n, \quad \frac{dn_i}{dt}=\varepsilon_i(z)H(z)n \quad (3)$$

where $H(z)$ and n are the Hubble expansion parameter and mean baryon density (neutral H and protons), respectively. We leave photons produced by two-body interactions, for example of annihilation of weakly interacting massive particles (WIMPs), with $dn_i/dt=\sigma_{WIMP}n_{WIMP}^2$ for future investigation.

The addition of extra Ly-α and ionization photons in Eq. (3) adjusts the recombination rate from the standard model in Eq. (1)

$$-\frac{dx_e}{dt}=-\left.\frac{dx_e}{dt}\right|_{std}-C\varepsilon_i H-(1-C)\varepsilon_\alpha H. \quad (4)$$

There is a range of physical mechanisms which could generate additional photons; we review them briefly here, see [25] and references therein for a fuller discussion and derivations.

In general ε_α and ε_i are functions of redshift, dependent upon the particle decay model that is being employed, and the size of the decay lifetime, t_x in comparison to the lifetime of the universe t_0.

Primordial black hole (PBH) decay [26] at the moment of recombination can be described by a model of the form

$$\varepsilon_j=c_j\zeta^{-3/2}\exp-\zeta^{-3/2}, \quad \zeta=\frac{1+z}{1+z_{dec}} \quad (5)$$

where j can be α or i and z_{dec} is the redshift of photon decoupling. The authors of [25] use $c_\alpha\approx 0.3$ and $c_i\approx 0.13$; however, these values are dependent on assumptions about the PBH mass and number density distributions, which in turn rely on the nature of the inflationary spectrum [27] and the possibility of accretion [28].

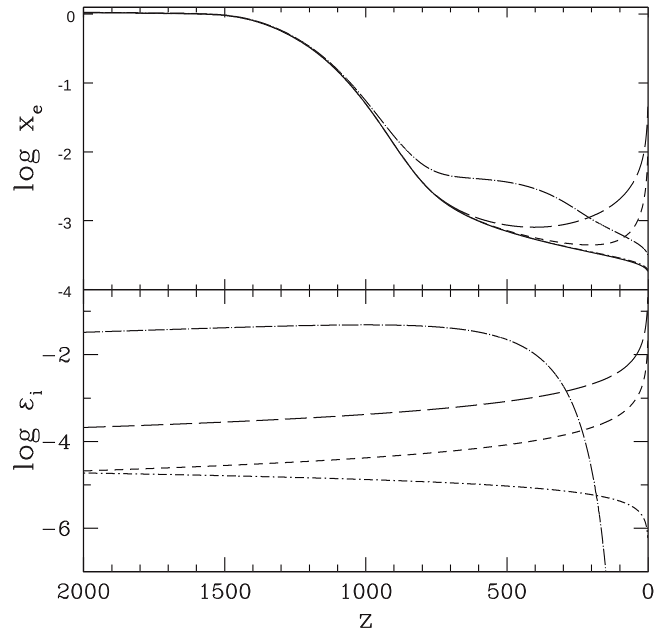

FIG. 1. Evolution of ε_i, characterizing the number density of extra ionizing photons added during the recombination epoch (bottom panel) and the evolution of the associated ionization fraction x_e (top panel) for the WMAP best fit, fiducial case (full line, $\varepsilon_i=0$) and for sample models, described in the text: PBH decay with coefficients as in [25] (dot–long dash), topological defect particle release (dot–short dash), short-lived SHDM decay with $\Theta=10^5$ (short dash), and $\Theta=10^6$ (long dash) corresponding to $z(t_x)\sim 4$ and 5, respectively. The ionization fraction for the topological defect model lies almost on top of the fiducial case. The parameter measuring additional resonance photons, ε_α, is of the same order as ε_i in each of these models.

Electromagnetic cascades from general particle decay can be described by the parametrization [25]

$$\varepsilon_{\alpha,i}\sim\frac{10^{-8}}{\Omega_b^0 h^2}\Theta[z(t_x)](1+z)^r, \quad (6)$$

with $r=1/2$ for particle release from topological defects, $r=-1$ for the decay of super heavy dark matter (SHDM), and where the normalization is the EGRET energy density [29], although one could imagine using a code such as DARKSUSY [30] to get a more precise normalization value. The proportionality constant $\Theta[z(t_x)]$ reflects an alteration required for decay time dependence in the normalization of SHDM scenarios. For short-lived SHDM with $t_x<t_0$, $\Theta[z(t_x)]\sim\exp[(1+z[t_x])^{3/2}]$ and equals 1 for all other cases. Short-lived SHDM can therefore have substantially higher values for $\epsilon_{i,\alpha}$.

Note that in both particle and BH decay the models predict $\epsilon_i\sim\epsilon_\alpha$. We demonstrate the size and evolution of ϵ_i for scenarios described above in Fig. 1.

The combined effect on reionization from mechanisms such as those described above would obviously require a sum over contributions from all sources. Our aim is to find an upper limit on the overall contribution, independent of source, and as such we adopt a simple parametrization using constant, effective values for ε_i and ε_α.

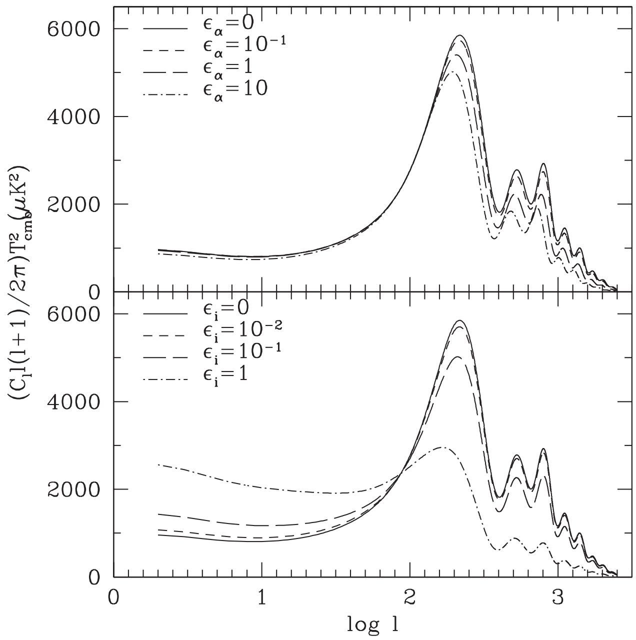

FIG. 2. CMB TT spectra for various values of ε_α (top) and ε_i (bottom) showing the increasing suppression and shift of the peaks as one increases the number of extra resonance and ionizing photons, respectively, in comparison to the WMAP best fit fiducial model with $\varepsilon_i=\varepsilon_\alpha=0$ (full line). Spectra are normalized to C_{87}.

In Figs. 2 and 3 we plot the temperature (TT) and temperature-polarization cross-correlation (TE) power spectra for several values of ε_α and ε_i. Qualitatively, increasing ε_α broadens the epoch of recombination and lowers the redshift when the optical depth drops through unity. Delaying recombination increases the angular diameter distance at last scattering and therefore shifts the first peak to lower l. The delay also increases the optical depth, suppressing the height of the peaks in comparison to the low l plateau and decreasing the ratio of the second to first peaks.

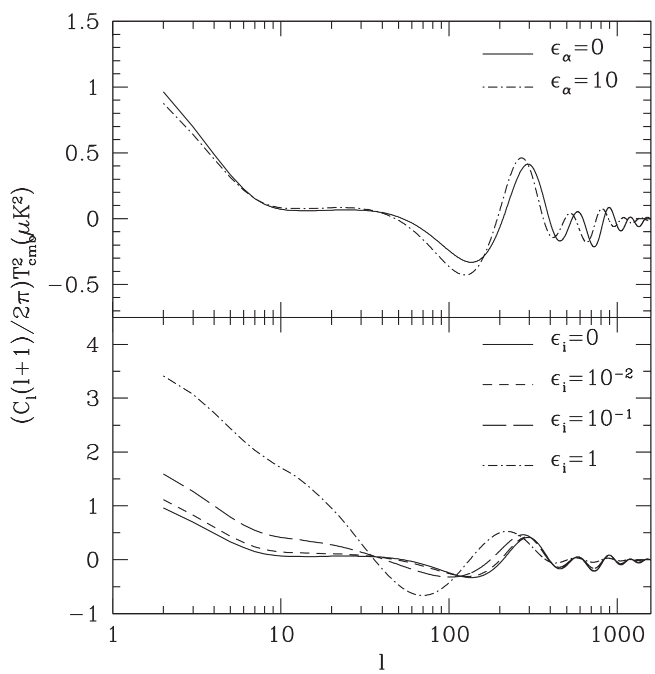

FIG. 3. CMB TE spectra for various values of ε_α (top) and ε_i (bottom) against a fiducial case with $\varepsilon_\alpha=\varepsilon_i=0$ (full line). In each case a reionization redshift of $z_{ri}=7$ is used for comparison.

Increasing ε_i introduces a plateau in ionization fraction, preventing a trend towards full recombination. Boosting the number density of ionizing photons increases the optical depth significantly more than a similar increase in Ly-α photons, resulting in a pronounced suppression on the first peak height. Subsequently we would expect much tighter constraints on ε_i from the TT and TE spectra.

It is interesting to note that introducing a large extra ionizing component can give a large cross-correlation on large scales, similar to that generated by early reionization. However, it is unable to account for both the TT and TE observations simultaneously because of the peak suppression in the TT spectrum.

III. LIKELIHOOD ANALYSIS

Our analysis method is based on the computation of a likelihood distribution over a grid of precomputed theoretical models. We restrict our analysis to a flat, adiabatic, Λ-CDM model template computed with a modified version of CMBFAST [31], sampling the parameters as follows: $\Omega_{cdm}h^2 \equiv \omega_{cdm}=0.05,\ldots,0.25$ in steps of 0.01, $\Omega_b h^2 \equiv \omega_b =0.009,\ldots,0.030$ in steps of 0.001 and $h=0.55,\ldots,0.85$ in steps of 0.05. The value of the cosmological constant Λ is determined by the flatness condition. Our choice of the above parameters is motivated by big bang nucleosynthesis bounds on ω_b (both from D [32] and ^{4}He$+^7$Li [33]), from supernovae [34] and galaxy clustering observations (see, e.g. [35,36]). From the grid above we only consider models with the age of the universe $t_0>11$ Gyrs. We vary the spectral index of the primordial density perturbations within the range $n_s=0.8,\ldots,1.2$, we allow for a possible (instantaneous) reionization of the intergalactic medium by varying the reionization redshift $5<z_{ri}<25$ and we allow a free rescaling of the fluctuation amplitude by a pre-factor of the order of C_{87}, in units of $C_{87}^{NORM}=1.9\ \mu K^2$. Finally, we let ε_α and ε_i vary as follows: $10^{-4}<\varepsilon_\alpha<10^2$ and $<10^{-4}<\varepsilon_i<10^2$ in logarithmic steps.

The theoretical models are compared with the recent temperature and temperature-polarization WMAP data using the publicly available likelihood code [10,37].

In Fig. 4 we plot the likelihood contours in the ε_α-ε_i plane showing the 2σ and 3σ contours. As we can see there is no strong correlation between the two parameters.

Marginalizing over all the remaining nuisance parameters we obtain the following constraints: $\varepsilon_\alpha<10^{0.5}$ and $\varepsilon_i<10^{-1.2}$ at 95% C.L.

As we can see, despite the high precision of the WMAP data, substantial modifications to the recombination process might be present. In Table I we demonstrate this for models discussed in Sec. II. Ionizing photons from PBH decay are still in good agreement with the data, to within 1σ. Similarly, assuming the normalization prescription given in [25], long lived SHDM particles are not constrained well by the

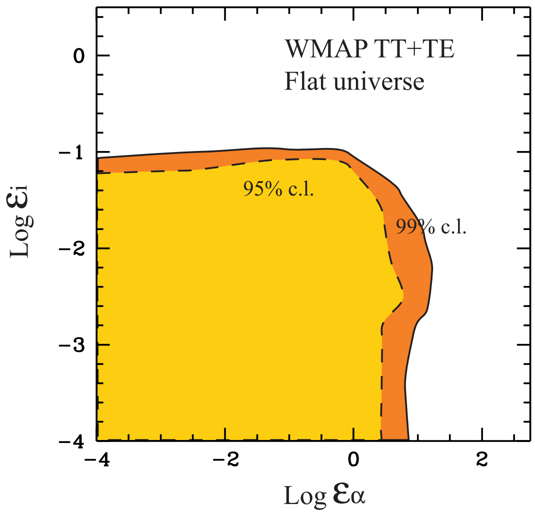

FIG. 4. Likelihood contour plot in the ε_α-ε_i plane showing the 2σ and 3σ contours.

data; however, there is a sharp cutoff in the likelihood for particles that would decay on time scales shorter than $t(z=6)$.

Since a modified recombination scheme can still be in agreement with the data, it is interesting to study the impact these modifications might have on the constraints of several parameters determined in the standard analysis. In Fig. 5 we demonstrate the benefits of having both the TT and TE spectra available in breaking potential degeneracies with spatial curvature. With pre-WMAP uncertainties in the TT spectrum peak heights relative to the plateau, a ''degeneracy'' between curvature and ε_α existed [16]. A non-zero value of ε_α can shift the TT spectrum peak positions in an open model so that they have a similar fiducial Λ-CDM case. However the accuracy of WMAP data over the first and second peaks now allows such an open model to be distinguished by the peak suppression produced by increasing ε. Moreover, the reionization peak is strongly suppressed in the open scenario so the two scenarios are further differentiated by the inclusion of TE data.

In Fig. 6 we probe degeneracies that are less easily distinguished; projecting the constraints on ε_α and ε_i in function of the baryon density, the spectral index and its running $dn_s/d\ln k$ at $k_0=0.05h$ Mpc^{-1}. As we can see, the constraints on ω_b are weakly affected by our simple modifica-

TABLE I. Difference in χ^2 from the best fit standard recombination model for a range of non-standard recombination scenarios discussed in Sec. II, using WMAP TT and TE data. For the SHDM models we consider a range of decay lifetimes, t_x, measured in terms of the lifetime of the universe at a redshift, $z(t_x)$.

			$\Delta\chi^2$
PBH	$c_a=0.3$,	$c_i=0.13$	1.9
SHDM	$\Theta\leqslant 10^7$,	$z<5.3$	$\leqslant 0.3$
	$\Theta=10^8$,	$z=6.0$	8.7
	$\Theta=10^9$,	$z=6.5$	3757

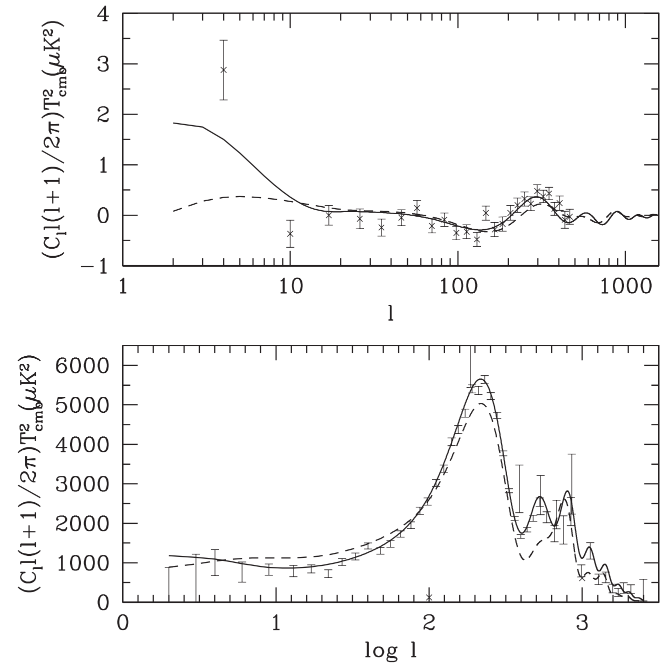

FIG. 5. Figures demonstrating how a potential degeneracy between flat and spatially curved scenarios with non-zero ε_α is broken with WMAP TT and TE spectra. A WMAP best fit fiducial model with $z_{ri}=17$ and $\Omega_K=0$ (full line) is shown against a model with $\Omega_K=0.6$ and $\varepsilon_\alpha=10^3$ and $z_{ri}=17$ (dashed line) that prior to the WMAP data release had some degeneracy with the standard scenario. In particular note how the addition of the TE spectrum strongly breaks the degeneracy, since the open model has a strongly suppressed reionization peak.

tions to the recombination process. The value of $\omega_b=0.023\pm0.001$ is unaffected by the inclusion of ε_α or ε_i. This can be explained by the high precision measurements of Sachs-Wolfe plateau and the first two acoustic peaks made by the WMAP satellite, which breaks the degeneracy between ω_b and ε_i found in Seager *et al.* Increasing ε_α or ε_i, however, can have an important impact on the determination of n_s. Namely, a modified recombination will have effects similar to those of an early reionization process, lowering the small scale anisotropies and allowing greater values of n_s to be in agreement with the data.

Finally, it is interesting to study the correlation with a possible running of the spectral index. In Peiris *et al.* [8], a $\sim 2\sigma$ evidence for a negative running of the spectral index has been found. This is not expected in most common inflationary scenarios and several mechanisms have been proposed to explain the effect (see, e.g. [9]). However, as we can see from the plots at the bottom of Fig. 6, a delayed recombination will in general not solve this problem, but it will enhance it towards a more negative running (in the plots we assume $n_s=0.93$). A possible solution might come from a speeding up of recombination rather than delay, through having concentrations of baryons in high density, low mass clouds, for example [24]. The accelerated recombination, because of the resultant premature reduction in the ionization fraction, can be parametrized by an effective $\epsilon_\alpha<0$ with $\epsilon_i\geqslant 0$ still. As we see in Fig. 7, negative values of ϵ_α are more

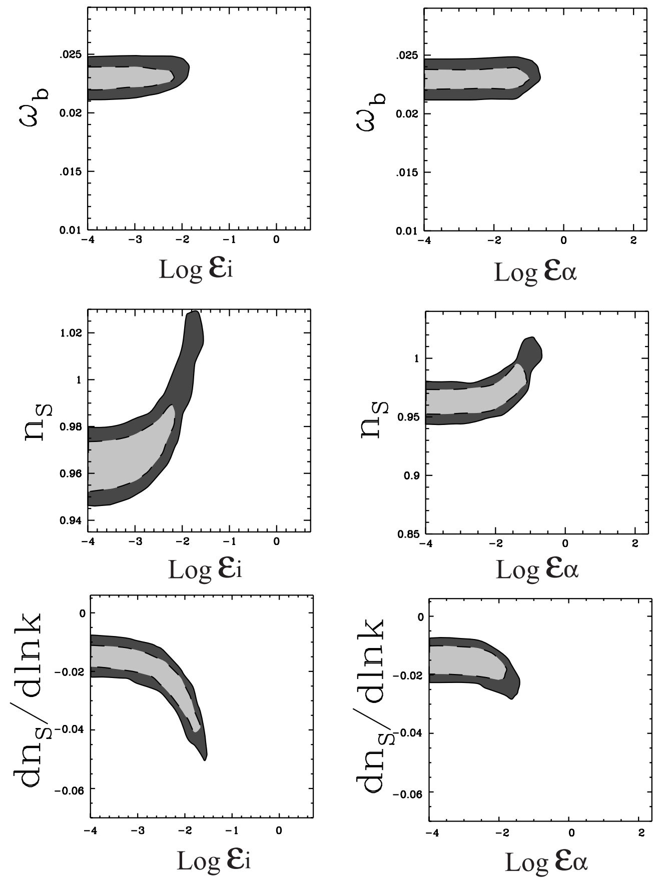

FIG. 6. Correlations between ε_α and ε_i with several cosmological parameters. The redshift of reionization is fixed at $z_{ri}=12$ and the Hubble parameter is $h=0.68$. One can see that while the baryon density is robust to alterations in ε_α and ε_i, both the scalar spectral index and its running are sensitive.

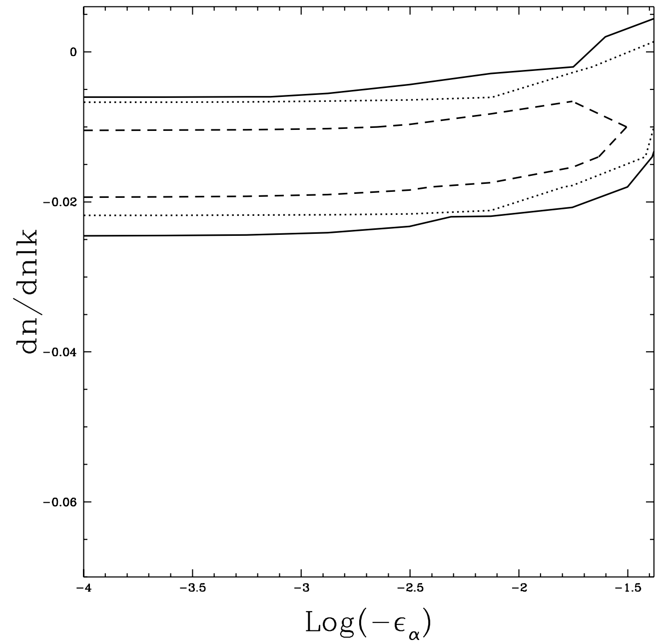

FIG. 7. Correlation between a negative ε_α and a running of the spectral index $dn/dlnk$ at $k=0.05hMpc^{-1}$. The redshift of reionization is fixed at $z_{ri}=12$, the Hubble parameter is $h=0.68$, $n_s=0.93$ and $\varepsilon_i=0$.

consistent with a zero running, although they are likely not sufficient to fully explain the observed phenomenon.

IV. CONCLUSIONS

We have probed the upper bounds that can be placed on the contribution of extra Ly-α and ionizing photon-producing sources through their effect on recombination and subsequently on the CMB TT and TE spectra. We have found that, adopting a simple parametrization using constant, effective values for ε_α and ε_i, the WMAP data contraints $\varepsilon_\alpha < 10^{0.5}$ and $\varepsilon_i < 10^{-1.2}$ at the 95% level.

We have found that the WMAP data are able to break many of the worrying degeneracies between ε_α, ε_i and the more standard cosmological parameters. In particular, the constraints on the curvature and baryon density appear to be weakly affected by a modified recombination scheme. However, it may affect the current WMAP constraints on inflationary parameters like the spectral index n_s and its running.

Physically motivated models, like those based on primordial black hole or super heavy dark matter decay, are able to provide a good fit to the current data. Future observations in both temperature and polarization, from the next WMAP release and the Planck satellite [25], will be needed if we are to more stringently test these models.

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