Constraints on millicharged particles from Planck

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We revisit cosmic microwave background (CMB) constraints on the abundance of millicharged particles based on the Planck data. The stringent limit $\Omega_{\text{mcp}} h^2 < 0.001$ (95\% CL) may be set using the CMB data alone if millicharged particles participate in the acoustic oscillations of baryon-photon plasma at the recombination epoch. The latter condition is valid for a wide region of charges and masses of the particles. Adding the millicharged component to aCDM shifts preferred scalar spectral index of primordial perturbations to somewhat larger values as compared to minimal model, even approaching Harrison-Zeldovich spectrum under some assumptions.

I. INTRODUCTION

The nature of dark matter is unknown. Suggested particle candidates range from massive gravitons, through axions, sterile neutrino, wimps, mirror matter, wimpzillas, and up to primordial black holes (for a recent reviews see e.g. [1]), with the common requirement that they should interact rather weakly. In particular, the dark matter constituents cannot carry electric charge comparable to that of electrons, unless they are extremely heavy. This does not preclude though the intriguing possibility of electrically millicharged particles and corresponding models were discussed extensively in the past.

Millicharged particles have electric charge $e' = \epsilon e$, where $e$ is the electron charge and $\epsilon \ll 1$. They can be either bosons or fermions. Nothing prevents their ad hoc introduction into the theory, nevertheless, they appear naturally in a wide class of models. Consider e.g. a model with a hidden gauge sector. It may contain a $U(1')$ gauge group. The corresponding ‘dark photon’ field $A_{\mu}'$ may have a kinetic mixing, $\frac{1}{2} F_{\mu
u}' F^{\mu
u}$, to ‘our’ photon $A_{\mu}$ [2]. This mixing makes shadow charge carriers to be millicharged with respect to our world. Moreover, these charge carriers can be ‘mirror’ replicas of our electrons and protons. This opens up a possibility of dark matter being the ‘mirror world’ which is a shadow sector with particles having strong and electroweak interactions similar to the ordinary particles. The mirror world may have different weak and strong scales [3], or microphysics in it can be exactly identical to the Standard Model, see a review [4] and references therein. The existence of models with natural appearance of millicharged particles grants them close attention.

Bounds on parameters of millicharged particles are derived from direct laboratory tests as well as from cosmological and astrophysical observations. These bounds are strongly sensitive to the mass range of particles involved. In what follows we will call millicharged particles as X-particles.

If $X$-particles are lighter than an electron, $m_X < m_e$, the best particle physics limit comes from the data on invisible decay mode of ortho-postionin into $XX$, according to which $\epsilon < 3.4 \cdot 10^{-5}$ [5]. For very light particles, $m_X < 1$ keV, the reactor experiments give stronger bound $\epsilon < 10^{-5}$ [6]. For $m_X > m_e$ the direct bounds were obtained in Ref. [7]. For $m_X = 1$ MeV they yield $\epsilon < 4.1 \times 10^{-5}$ while the bounds become weaker for heavier $X$-particles, up to $\epsilon < 5.8 \times 10^{-4}$ for $m_X = 100$ MeV. For $X$-particles heavier than 100 MeV electric charges $e' \sim 10^{-2} \epsilon$ are allowed, while for $m_X > 1$ GeV they can be as large as $\epsilon = 0.1$.

Stellar evolution provides very restrictive limits on $\epsilon$, see Refs. [8,9], but they are unapplicable if $m_X > 10$ keV. On the other hand millicharged particles may survive late time annihilation by forming bound states with protons and $\alpha$-particles. Therefore terrestrial searches result in the constraint $\epsilon < 0.01$ for $m_X > 1$ GeV [10].

The presence of millicharged particles in the early Universe during the epoch of big bang nucleosynthesis (BBN) influences the standard cosmological picture in several respects. In particular, both the expansion rate of the Universe and baryon-to-photon ratio can be significantly altered during BBN and this is dangerous [9]. The impact of such particles on BBN is discussed in Ref [11], with the conclusion that the BBN upper bound on the charge of light millicharged particles can be avoided assuming non-zero lepton asymmetry.

Sufficient abundance of millicharged particles in the "late" Universe (not necessarily making the whole of dark matter) may lead to a profound cosmological consequences also. These implications may be even ‘useful’. E.g., in the Ref. [12] it has been suggested that the diff-
ference in electromagnetic drag forces on electrons and protons from the millicharged matter during the process of galaxies formation may explain the long standing puzzle of the origin of seeds for galactic and cluster magnetic fields.

On the other hand, if millicharged particles have sufficiently strong coupling to baryons and participate in the acoustic oscillations of baryon-photon plasma at the recombination epoch [13] then the power spectrum of Cosmic Microwave Background (CMB) radiation anisotropies is affected in several ways. For $l \lesssim 1000$ the contribution of millicharged particles is degenerate with that of baryonic matter. Using this fact, and employing nucleosynthesis data on baryon abundance together with WMAP CMB spectrum, a strong limit on cosmological abundance of millicharged particles was obtained in Ref. [14]. At $l \gtrsim 1000$ millicharged particles lead to direct additional suppression of the spectrum. Recent Planck satellite data [15] are precise at high multipoles up to $l \sim 2500$. Therefore, Planck spectra can be used to look for this effect of additional suppression. The aim of the present paper is to consider corresponding CMB anisotropy limits on millicharged particles in view of the Planck data.

II. CMB CONSTRAINTS ON MILlichARGED MATTER ABUNDANCE

Millicharged particles scatter off electrons and protons at the recombination epoch. It was shown that if the velocity transfer rate of this process exceeds the expansion rate of the Universe, the millicharged particles behave similar to baryons until recombination [13]. The tight coupling condition is given by [14]:

$$\Gamma_{mcp}(\Omega_b + \Omega_{mcp})H^{-1} \gtrsim 250,$$

(1)

where $\Omega_b$ and $\Omega_{mcp}$ are baryon and X-particles abundances correspondingly, $H$ is the Hubble parameter and $\Gamma_{mcp}$ is a velocity transfer rate at recombination. The latter is given by the following equation:

$$\Gamma_{mcp} = \frac{4\sqrt{2}\pi^2 \alpha^2 e^2 \rho_{crit}}{3m_X m_p T^{3/2}} |\ln \theta_D| (\sqrt{\mu_{X,e}} + \sqrt{\mu_{X,p}}),$$

(2)

where $\mu_{X,e(p)}$ is the reduced mass of a millicharged particle and electron (proton), $\alpha$ is the fine structure constant, $T$ is a temperature, $\rho_{crit}$ is the critical density at recombination and $\theta_D = \sqrt{2\pi\alpha m_{e}}/T^{2} m_{e}$ is the Debye angle. The tight coupling condition given by Eq. (1) is valid in the broad region of the parameter space

$$c^2 \gtrsim 5 \cdot 10^{-11} \text{GeV}^{-1}/\text{m} = \frac{m_X}{\sqrt{\mu_{X,e} + \sqrt{\mu_{X,p}}}}.$$  

(3)

Unlike baryons, millicharged particles do not contribute to the plasma opacity at the recombination since the Compton process is suppressed by the fourth power of the charge. Therefore the photon mean free path before recombination is longer if a fraction of baryons is replaced by millicharged particles and high multipoles of the CMB spectrum get suppressed. Consequently, as proposed in [13], an accurate determination of high CMB multipoles should result in strong limits on the millicharged particles. The Planck collaboration has recently published [15] high-quality measurements of the CMB spectrum up to $l \sim 2500$. In this note we use the Planck data on CMB to set a limit on the abundance of millicharged particles. We assume that the millicharged particles are stable and that the tight coupling condition holds.

We numerically solve the linearized kinetic equations for the primordial plasma in synchronous gauge with CAMB [16]. The millicharged component and the corresponding equations are added to CAMB similarly to the modification of CMBFAST [17] performed in Ref. [14].

We extend the spatially-flat six-parameter $\Lambda$CDM cosmology [18] with one additional parameter: the present abundance of millicharged particles $\Omega_{mcp} h^2$. We start with assumption that neutrinos are effectively massless, i.e. the mass of one neutrino is $m_\nu = 0.06 \text{eV}$, and the effective number of neutrinos is $n_\nu = 3.046$. The parameter space is explored using the Markov Chain Monte-Carlo technique with the COSMOMC (March 2013) package [19]. The Planck likelihood code [plc-1.0] is used [20] in conjunction with the fast-slow sampling method [21]. The latter technique performs an efficient sampling over the subclass of “fast” parameters which do not require to recalculate the CMB transfer functions (e.g., the overall normalization of the spectrum and the Planck calibration parameters).

We generated 10 Markov chains with a total of $3 \times 10^5$ samples using a covariance matrix supplied with COSMOMC. The marginalized likelihood in the $\Omega_{mcp} h^2$ - $\Omega_b h^2$ plane of parameters is shown in Figure 1. Left panel corresponds to the above quoted fixed values for the number and mass of neutrinos.

We arrive at the following upper limit

$$\Omega_{mcp} h^2 < 0.001 \text{ (95\% CL)}$$

(4)

An approximate degeneracy in the parameter space is seen in Fig. 1 namely, larger $\Omega_{mcp} h^2$ leads to a smaller $\Omega_b h^2$. The degeneracy agrees with that predicted in [14] based on hypothetical CMB measurements up to $l = 1600$. Planck measures CMB spectrum up to higher multipoles and hence the limit is stronger than expected. Note that Planck provides much more precise CMB data than WMAP and, as expected, the Big Bang nucleosynthesis data [22] don’t help to improve the constraints.

To test the robustness of the result we relaxed the number of effective neutrinos and the mass of one neutrino. We generated ten new Markov chains with a total of $1 \times 10^5$ samples. The marginalized likelihood in $\Omega_{mcp} h^2$ - $\Omega_b h^2$ plane of parameters is shown in Fig. 1 right panel. Likelihoods for $\Omega_{mcp} h^2$ versus $m_\nu$ and $n_\nu$ are shown in
Precision results of the Planck mission lead to the conclusion that the power-law index of the spectrum of scalar primordial perturbations in the standard cosmological (aka ΛCDM) and Standard particle physics models is restricted to the value \( n_s = 0.9603 \pm 0.0073 \) \[18\], which is about 6σ away from scale invariant Harrison-Zeldovich spectrum. At the face value this would mean also that in this simplest setup many models of inflation are disfavored \[23\] with respect to e.g. \( R^2 \) \[24\] or Higgs \[24\] models of inflation. This result is of great importance for cosmology. Therefore, it should be inspected how this conclusion holds with respect to the possible extensions of the Standard Model of particle physics.

In the presence of millicharged matter the higher multipoles of the CMB spectrum are additionally suppressed, which clearly should change the derived value of \( n_s \). To quantify this we plot in Fig. 3 the marginalized likelihood of parameters in the \( \Omega_{\text{mcp}} h^2 - n_s \) plane. Left panel in this Figure corresponds to the case of ‘3 massless’ neutrinos. We see that, indeed, with the increase of \( \Omega_{\text{mcp}} h^2 \) the value of \( n_s \) increases, pushing it out from \( R^2 \) inflation into the range predicted by other models, such as the spontaneously broken SUSY model of Ref. \[26\].

Relaxing the constraints on the number of neutrinos widens the allowed range for \( n_s \) even further, and now even the Harrison-Zeldovich spectrum is not ruled out, see Fig. 3, right panel. However, the preferred value of \( n_s \) does not depend upon \( \Omega_{\text{mcp}} h^2 \).
We find that the cosmological abundance of millicharged particles is strongly constrained by the Planck data, $\Omega_{\text{mcp}} h^2 < 0.001$. The mechanism for generation of galactic magnetic seed fields, proposed in [12], is not ruled out by this limit. The precise value of the limit depends upon the particle physics model assumed. E.g. the maximally allowed value for the abundance, at the level of 4 light neutrinos, while it can be achieved if only 3 ‘massless’ neutrinos are present.

In addition, the abundance of millicharges is partially degenerate with the power-law index of primordial scalar perturbations, $n_s$. Existence of millicharge particles reopens the possibility for some inflationary scenario, such as the spontaneously broken SUSY model of inflations, which would be excluded under minimal assumptions.

**IV. CONCLUSIONS**

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