

Dark radiation candidates after Planck data

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Recent Cosmic Microwave Background (CMB) results from the Planck satellite, combined with previous CMB data and Hubble constant measurements from the Hubble Space Telescope, provide a constraint on the effective number of relativistic degrees of freedom $3.62_{-0.48}^{+0.50}$ at 95% CL. These new measurements of N_{eff} provide a unique opportunity to place limits on models containing relativistic species at the decoupling epoch. Here we review the bounds or the allowed parameter regions in sterile neutrino models, hadronic axion models as well as on extended dark sectors with additional light species based on the latest Planck CMB observations.

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I. INTRODUCTION

Recent Cosmic Microwave Background (CMB) measurements from the Planck satellite, combined with other cosmological data sets, have provided new constraints on the effective number of relativistic degrees of freedom N_{eff} , defined in terms of the energy density of the total radiation component as

$$\rho_{\text{rad}} = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_{\gamma}, \quad (1)$$

where ρ_{γ} is the current energy density of the CMB. In the standard scenario, the expected value is $N_{\text{eff}} = 3.046$, corresponding to the three active neutrino contribution and considering effects related to non-instantaneous neutrino decoupling and QED finite temperature corrections to the plasma. Planck data [1], combined with measurements of the Hubble constant H_0 from the Hubble Space Telescope (HST) [2] give the constraint $N_{\text{eff}} = 3.83 \pm 0.54$ at 95% CL. When low multipole polarization measurements from the Wilkinson Microwave Anisotropy Probe (WMAP) 9 year data release [3] and high multipole CMB data from both the Atacama Cosmology Telescope (ACT) [4] and the South Pole Telescope (SPT) [5, 6] are added in the analysis, the constraint on N_{eff} is $3.62_{-0.48}^{+0.50}$ at 95% CL [1]. These bounds indicate the presence of an extra dark radiation component at the $\sim 2.4\sigma$ confidence level. Different cosmological analyses carried out previously to Planck data release including SPT data-only have shown a similar evidence [7–9], see also Refs. [3, 10–28] for constraints on the dark radiation abundances exploiting different cosmological scenarios, data sets and/or analysis techniques. In addition, the presence of an extra dark radiation component will help enormously in the agreement on the value of the Hubble constant extracted from CMB Planck data and the value of H_0 measured by the HST team [1]. Even if the discrepancy between the CMB and the astrophysical measurements of H_0 can be alleviated in the context of *Hubble bubble* models [29], in which we, observers, are living inside a local underdensity, it is mandatory to analyse carefully the constraints

from Planck data on any physical mechanism which could provide $\Delta N_{\text{eff}} \sim 0.6$.

The simplest scenario to explain the extra dark radiation $\Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046$ arising from cosmological data analyses includes extra sterile neutrino species, since there is no fundamental symmetry in nature forcing a definite number of right-handed (sterile) neutrino species. Therefore, sterile neutrinos are allowed in the Standard Model fermion content. However, there are other possibilities which are as well closely related to minimal extensions to the standard model of elementary particles, as thermal axions, or extended dark sectors with additional relativistic species. New Planck data provide a unique opportunity to place limits (or find the favoured regions) on the different parameters which describe the three models listed above or any other model containing new light species, see Ref. [30]. It is the aim of this paper to carefully study these limits. Namely, in the case of sterile neutrino models, the constraints on N_{eff} from recent Planck data can set upper bounds on the sterile neutrino mixing parameters for sterile neutrino masses $m \lesssim 0.3$ eV, see Ref. [31] for a recent study. We shall focus here on the so-called (3+1) neutrino mass models [32]. In the hadronic axion model [33, 34], one can explore, as a function of the axion mass m_a (being $m_a \lesssim 0.3$ eV) if the axion abundance (parameterized in terms of ΔN_{eff}) agrees with Planck findings. Models containing a dark sector with light species that eventually decouples from the standard model will also contribute to N_{eff} , as, for instance, asymmetric dark matter models (see e.g. Refs. [35, 36] and references therein), or extended weakly-interacting massive particle models (see the recent work presented in Ref. [37]). We will follow the expressions from Ref. [36], in which the authors have followed a general approach to describe the dark sector structure, including both light and heavy relativistic degrees of freedom in the dark sector at the time of decoupling. While the former correspond to the number of degrees of freedom that ultimately constitute the dark radiation sector, the latter correspond to relatively heavy degrees of freedom that will turn non-relativistic and heat the dark radiation fluid. We derive here the constraints on the number of light and heavy degrees of

freedom of the dark sector as a function of its decoupling temperature from the standard model sector.

The paper is organised as follows. Section presents the constraints on the sterile neutrino mixing parameters in the $(3+1)$ neutrino mass models. In Section III we briefly review the thermal axion model and illustrate the constraints on its mass and its coupling parameter arising from Planck measurements on N_{eff} . Section analyses the implications from Planck data on extended dark sectors models. Finally, we draw our conclusions in Sec. V.

II. LIGHT STERILE NEUTRINO MODELS

A number of studies in the literature have been devoted to compute constraints on the light sterile massive neutrino thermal abundances [7, 10, 38–42]. However, the extra sterile neutrinos do not necessarily need to feature thermal abundances, depending dramatically their contribution to the mass-energy density of the universe on the flavour mixing processes operating at the decoupling period. Such a study was carried out firstly in Ref. [43], where the authors computed the constraints on the sterile neutrino masses and abundances arising from a joint analysis of short baseline oscillation and cosmological data. More recently, the authors of Ref. [31] have shown that the constraints on N_{eff} from recent Planck data can set upper bounds on the sterile neutrino mixing angles. We benefit here from the approximated expressions provided in Ref. [43] to explore the constraints on the sterile neutrino mixing parameters arising from Planck results. The approximate expressions derived in Ref. [43] are valid here, as we are assuming small mixing both between the active and heavy sectors and between the sterile and light neutrino sectors. In other words, if the flavor neutrinos ν_α , $\alpha = e, \mu, \tau, s$ (where s refers to the fourth sterile neutrino) are related to the massive base ν_i , $i = 1, 2, 3, 4$, through a 4×4 unitary matrix which U :

$$\nu_\alpha = U_{\alpha i} \nu_i, \quad (2)$$

we are assuming that $|U_{a4}|, |U_{js}| \ll 1$, with $a = e, \mu, \tau$ and $j = 1, 2, 3$. In this case, sterile neutrinos never reach complete thermalization and their abundances are much lower than the thermal one. The sterile neutrino contributes to the energy density of the Universe with [43]:

$$\Omega_s h^2 \simeq 7 \times 10^{-5} \left(\frac{\Delta m_{41}^2}{\text{eV}^2} \right) \sum_a \frac{g_a}{\sqrt{C_a}} \left(\frac{U_{a4}}{10^{-2}} \right)^2 \quad (3)$$

with $a = e, \mu, \tau$ and Δm_{41}^2 is taken here as the squared mass of the extra sterile neutrino, assuming $m_1 \simeq 0$. The constants C_a ($C_e \sim 0.61$ and $C_{\mu, \tau} \sim 0.17$, respectively) are related to the effective potential describing the interactions of neutrinos with the medium. The constants $g_e \simeq 3.6$ and $g_\mu = g_\tau \simeq 2.5$ are the coefficients of the damping factor. The contribution from the extra sterile

neutrino to the effective number of relativistic degrees of freedom reads:

$$\Delta N_{\text{eff}} = \frac{\Omega_s h^2}{\frac{7}{8} \left(\frac{4}{11} \right)^{\frac{4}{3}} \Omega_\gamma h^2}, \quad (4)$$

and therefore, using the Planck measurements of ΔN_{eff} it is possible to set constraints on the sterile neutrino mixing parameters, for a given value of the sterile neutrino mass m_4 , provided that $m_4 \lesssim 0.3$ eV. We allow for an electron (U_{e4}) and muon ($U_{\mu 4}$) flavor content of the sterile neutrino, setting $U_{\tau 4} = 0$.

Figure 1, left (right) panel, shows the 95% CL constraints on the $(|U_{e4}|, |U_{\mu 4}|)$ plane arising from the Planck constraints, $N_{\text{eff}} = 3.62_{-0.48}^{+0.50}$ ($N_{\text{eff}} = 3.83 \pm 0.54$), for two possible values of the sterile neutrino mass, $m_s = 0.2$ and 0.3 eV. Larger values of the sterile neutrino mass will not be relativistic at decoupling and therefore they can not be tested exploiting the measured value of N_{eff} by Planck: a full Montecarlo analysis would be needed, analysis which will be carried out elsewhere [44]. Notice that the relatively large values of the sterile neutrino mixing parameters preferred by short baseline oscillation data in $(3+1)$ models are excluded here for $0.1 \lesssim m_s \lesssim 0.3$ eV. We find $U_{e4} < 0.07$ and $U_{\mu 4} < 0.06$ at the 95% CL for the former range of sterile neutrino masses. For lower sterile neutrino masses $m_s < 0.1$ eV, higher mixing parameters are allowed, but such a low sterile neutrino mass is highly disfavored by oscillation analyses. For instance, the best fit point to appearance short baseline data in $(3+1)$ models is found at $\Delta m_{41}^2 = 0.15$ eV², being $U_{e4} = 0.39$ and $U_{\mu 4} = 0.39$ [45]. This region of parameters is, however, highly disfavoured by recent Planck measurements. Nevertheless one should keep in mind that the analysis presented here is in the context of $(3+1)$ models, which have been shown to be inadequate to fit global data sets and one should use instead $(3+2)$ or $(3+3)$ models [45].

III. THERMAL AXION MODEL

Here we first briefly review the origin of axions. Quantum Chromodynamics (QCD) respects CP symmetry, despite the existence of a natural, four dimensional, Lorentz and gauge invariant operator which violates CP. This CP violating-term will induce a non-vanishing neutron dipole moment, d_n . However, the constraint on the dipole moment $|d_n| < 3 \times 10^{-26}$ ecm [46] requires the CP term contribution to be negligible. Why is CP not broken in QCD? This is known the so-called *strong CP problem*. The most elegant and promising solution to the strong CP problem was provided by Peccei and Quinn [47], by adding a new global $U(1)_{PQ}$ symmetry, which is spontaneously broken at an energy scale f_a , generating a new spinless particle, the axion. The axion mass is inversely proportional to the axion coupling constant f_a

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{R}}{1+R} = 0.6 \text{ eV} \frac{10^7 \text{ GeV}}{f_a}, \quad (5)$$

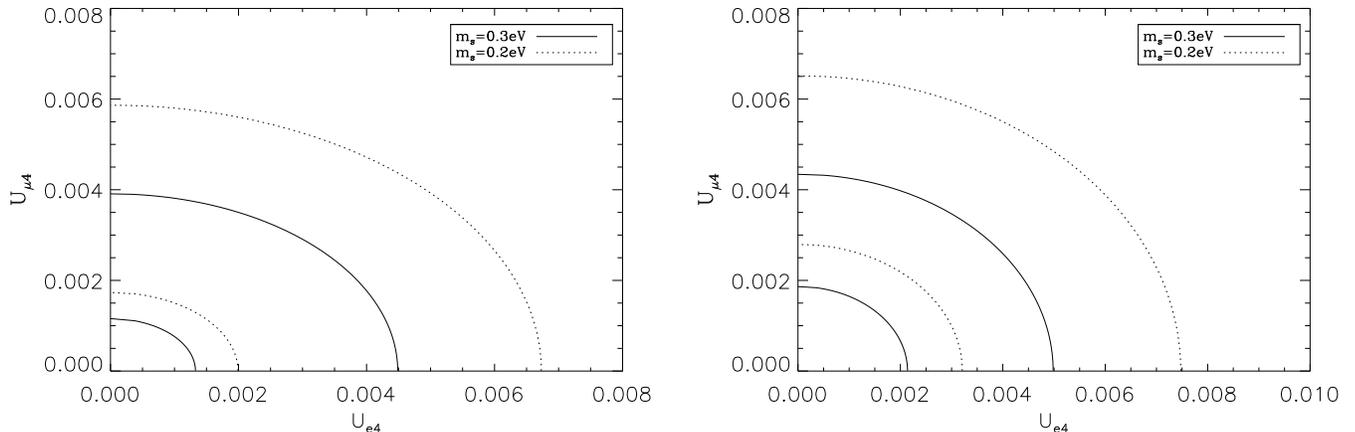


FIG. 1. The left (right) panel illustrates the 95% CL allowed regions in the $(|U_{e4}|, |U_{\mu 4}|)$ plane arising from the Planck measurements of the effective number of relativistic degrees of freedom $N_{\text{eff}} = 3.62^{+0.50}_{-0.48}$ ($N_{\text{eff}} = 3.83 \pm 0.54$) for two values of the sterile neutrino mass.

where $R = 0.553 \pm 0.043$ is the up-to-down quark masses ratio and $f_\pi = 93$ MeV is the pion decay constant. Axions can be produced via thermal or non-thermal processes the early universe, providing a possible (sub)dominant (hot) dark matter candidate. Here we focus on *hadronic axion models* such as the KSVZ model [33, 34].

For axion thermalization purposes, only the axion-pion interaction will be relevant. To compute the axion decoupling temperature T_D we follow the usual freeze out condition

$$\Gamma(T_D) = H(T_D). \quad (6)$$

The average rate $\pi + \pi \rightarrow \pi + a$ is given by [48]:

$$\Gamma = \frac{3}{1024\pi^5} \frac{1}{f_a^2 f_\pi^2} C_{a\pi}^2 I, \quad (7)$$

where

$$C_{a\pi} = \frac{1 - R}{3(1 + R)}, \quad (8)$$

is the axion-pion coupling constant [48], and

$$I = n_a^{-1} T^8 \int dx_1 dx_2 \frac{x_1^2 x_2^2}{y_1 y_2} f(y_1) f(y_2) \times \int_{-1}^1 d\omega \frac{(s - m_\pi^2)^3 (5s - 2m_\pi^2)}{s^2 T^4}, \quad (9)$$

where $n_a = (\zeta_3/\pi^2) T^3$ is the number density for axions in thermal equilibrium, $f(y) = 1/(e^y - 1)$ denotes the pion distribution function, $x_i = |\vec{p}_i|/T$, $y_i = E_i/T$ ($i = 1, 2$), $s = 2(m_\pi^2 + T^2(y_1 y_2 - x_1 x_2 \omega))$, and we assume a common mass for the charged and neutral pions, $m_\pi = 138$ MeV.

We have numerically solved the freeze out equation Eq. (6), obtaining the axion decoupling temperature T_D versus the axion mass m_a (or, equivalently, versus

the axion decay constant f_a). From the axion decoupling temperature, we can compute the current axion number density, related to the present photon density $n_\gamma = 410.5 \pm 0.5 \text{ cm}^{-3}$ via

$$n_a = \frac{g_{*S}(T_0)}{g_{*S}(T_D)} \times \frac{n_\gamma}{2}, \quad (10)$$

where g_{*S} refers to the number of *entropic* degrees of freedom. At the current temperature, $g_{*S}(T_0) = 3.91$. The deviation from the expected value of N_{eff} is 3.046 due to the presence of a thermal hadronic axion is given by

$$\Delta N_{\text{eff}} = \frac{\rho_a}{\rho_\nu} = \frac{4}{3} \left(\frac{3 n_a}{2 n_\nu} \right)^{\frac{4}{3}}, \quad (11)$$

being n_ν the current neutrino number density. Figure 2 illustrates the expected ΔN_{eff} as a function of the thermal axion mass. Axions with masses $m_a \lesssim 0.3$ eV are still relativistic at the decoupling epoch and is precisely in this range of values the ones in which CMB N_{eff} measurements can constrain the hadronic axion model.

If we assume the $N_{\text{eff}} = 3.83 \pm 0.54$, see the right panel of Fig. 2, which corresponds to the value arising from the combination of Planck data and HST measurements, the thermal axion model is disfavoured at the 2σ CL, since axion masses larger than 0.4 eV are excluded by cosmology [49–51] while axions with masses $m_a < 0.4$ eV do not seem to provide the appropriate amount of dark radiation, considering Planck and HST data sets exclusively. However, when other data sets are also added in the analysis, as for instance, WMAP polarization data plus high multipole data from both ACT and SPT, N_{eff} turns out to be $3.62^{+0.50}_{-0.48}$ and therefore the hadronic axion model with $m_a \lesssim 0.4$ eV is perfectly compatible with the value measured of N_{eff} (see the left panel of Fig. 2).

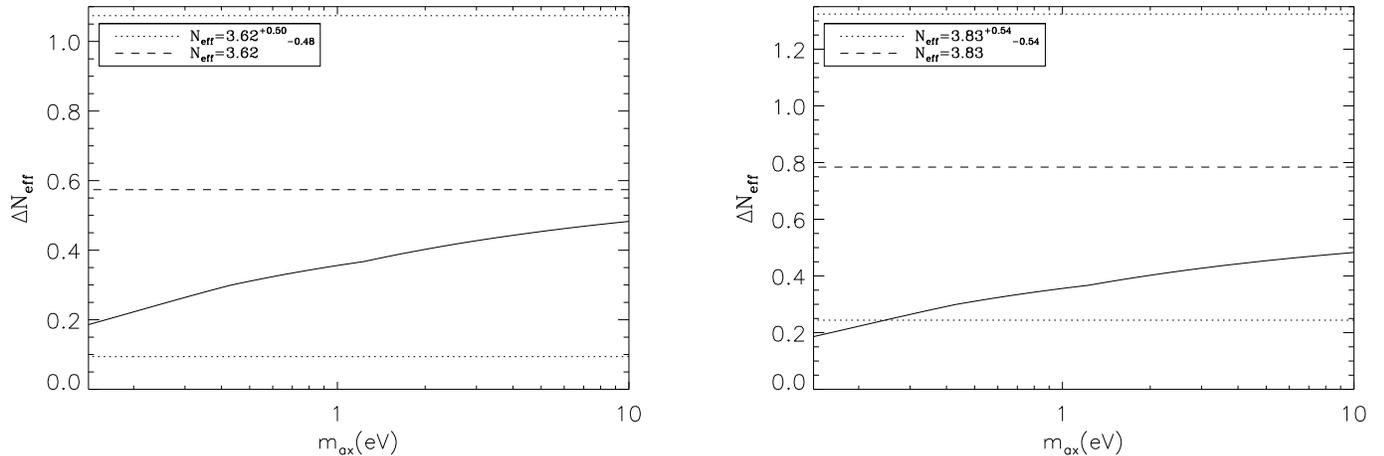


FIG. 2. ΔN_{eff} as a function of the thermal axion mass (in eV). The left (right) panel illustrates the constraint $N_{\text{eff}} = 3.62^{+0.50}_{-0.48}$ ($N_{\text{eff}} = 3.83 \pm 0.54$).

IV. EXTENDED DARK SECTOR MODELS

Any model containing a dark sector with relativistic degrees of freedom that eventually decouples from the standard model sector will contribute to N_{eff} . An example of these models is the so-called asymmetric dark matter scenario, which, in general, contains extra radiation degrees of freedom produced by the annihilations of the thermal dark matter component. We follow here the general approach of Ref. [36], in which the dark sector contains both light (g_ℓ) and heavy (g_h) relativistic degrees of freedom at the temperature of decoupling T_D from the standard model. For high decoupling temperature, $T_D > \text{MeV}$, the contribution to the effective number of relativistic degrees of freedom reads [36]

$$\Delta N_{\text{eff}} = \frac{13.56}{g_{\star S}(T_D)^{\frac{4}{3}}} \frac{(g_\ell + g_h)^{\frac{4}{3}}}{g_\ell^{\frac{1}{3}}}, \quad (12)$$

where $g_{\star S}(T_D)$ is calculated using the approximated expression given in Ref. [52]. If the dark sector decouples at lower temperatures ($T_D < \text{MeV}$), there are two possibilities for the couplings of the dark sector with the standard model: either the dark sector couples to the electromagnetic plasma or it couples to neutrinos. In the second case, which is the one we illustrate here,

$$N_{\text{eff}} = \left(3 + \frac{4}{7} \frac{(g_h + g_\ell)^{\frac{4}{3}}}{g_\ell^{\frac{1}{3}}}\right) \left(\frac{3 \times \frac{7}{4} + g_H + g_h + g_\ell}{3 \times \frac{7}{4} + g_h + g_\ell}\right)^{\frac{4}{3}}, \quad (13)$$

being g_H the number of degrees of freedom that become non relativistic between Big Bang Nucleosynthesis and the dark sector decoupling period.

As firstly illustrated in Ref. [36], it is possible to use the measured value of N_{eff} to find the required heavy degrees of freedom heating the light dark sector plasma

g_h as a function of the dark sector decoupling temperature T_D for a fixed value of g_ℓ . Figure 3, left (right) panel, illustrates the 2σ required ranges for g_h using $N_{\text{eff}} = 3.62^{+0.50}_{-0.48}$ ($N_{\text{eff}} = 3.83 \pm 0.54$), for $g_H = 0$. Notice that at decoupling temperatures $T_D > \text{MeV}$, the standard model relativistic degrees of freedom will be heated, requiring therefore heating in the dark sector to enhance the value of ΔN_{eff} . On the other hand, at low decoupling temperatures, the number of the required heavy degrees of freedom g_h decreases as ΔN_{eff} does. Indeed, for the case of $N_{\text{eff}} = 3.62^{+0.50}_{-0.48}$ ($N_{\text{eff}} = 3.83 \pm 0.54$), having extra heavy degrees of freedom is highly (mildly) disfavoured. This is because at low temperatures, the photon background can not get extra heating from standard model particles and therefore an extra heating in the dark sector will increase dramatically the value of N_{eff} .

V. CONCLUSIONS

Recent Cosmic Microwave Background measurements from the Planck satellite, combined with measurements of the Hubble constant from the Hubble Space Telescope (HST) have provided the constraint $N_{\text{eff}} = 3.83 \pm 0.54$ at 95% CL. If low multipole polarization measurements from the Wilkinson Microwave Anisotropy Probe 9 year data release and high multipole CMB data from both the Atacama Cosmology Telescope and the South Pole Telescope are added in the analysis, the constraint on N_{eff} is $3.62^{+0.50}_{-0.48}$ at 95% CL. These bounds indicate the presence of an extra dark radiation component at the $\sim 2\sigma$ confidence level and can be exploited to set limits on any model containing extra dark radiation species, as sterile neutrino models, hadronic axion scenarios or extended dark sector schemes.

Within the (3+1) sterile neutrino scenario, we find that

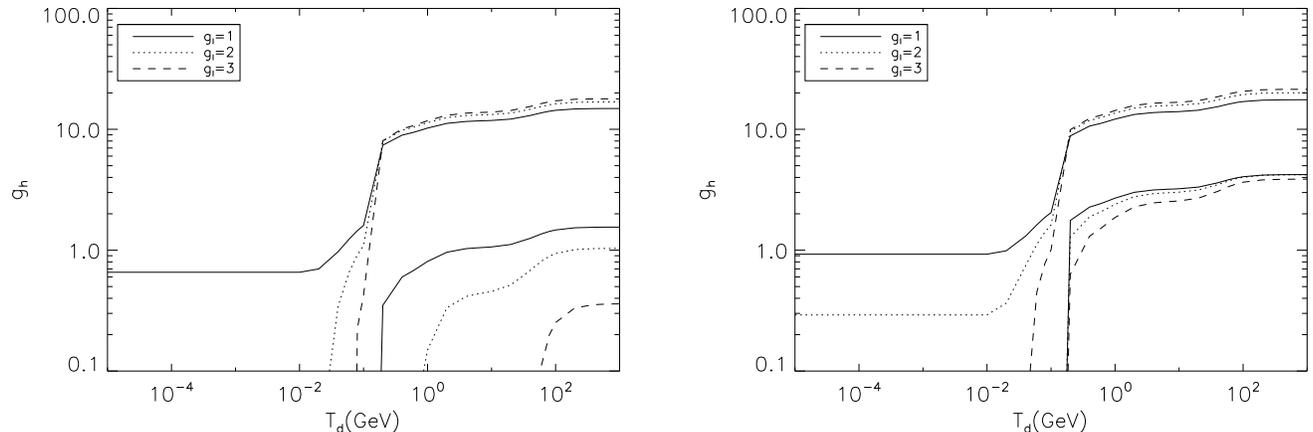


FIG. 3. The left (right) panel shows the 2σ required ranges for the number of heavy degrees of freedom heating the dark sector g_h using $N_{\text{eff}} = 3.62^{+0.50}_{-0.48}$ ($N_{\text{eff}} = 3.83 \pm 0.54$) for several values of g_l , the light degrees of freedom of the dark sector.

the relatively large values of the sterile neutrino mixing parameters preferred by short baseline oscillation data in $(3+1)$ models are excluded here for $0.1 \lesssim m_s \lesssim 0.3$ eV. For lower sterile neutrino masses $m_s < 0.1$ eV, higher mixing parameters are allowed, but such a low sterile neutrino mass is highly disfavoured by oscillation analyses. However, other sterile neutrino models, as the $(3+2)$ or the $(3+3)$ scenarios, may provide a much better fit to both cosmological measurements and short baseline data. In the context of the hadronic axion model, the constraint $N_{\text{eff}} = 3.83 \pm 0.54$ disfavours the former model at the 2σ CL. On the other hand, the axion model studied here with $m_a \lesssim 0.4$ eV is perfectly compatible with cosmological data when lower values of N_{eff} are considered, as those obtained when other data sets are analysed together with Planck data. Concerning models with a dark

sector with light species that eventually decouples from the standard model, as, for instance, asymmetric dark matter models, having extra heavy degrees of freedom in the dark sector is highly (mildly) disfavoured for the case of $N_{\text{eff}} = 3.62^{+0.50}_{-0.48}$ ($N_{\text{eff}} = 3.83 \pm 0.54$). Future Planck polarization data will help in cornering dark radiation models.

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- [1] P. A. R. Ade *et al.* [Planck Collaboration], arXiv:1303.5076 [astro-ph.CO].
- [2] A. G. Riess, L. Macri, S. Casertano, H. Lampeitl, H. C. Ferguson, A. V. Filippenko, S. W. Jha and W. Li *et al.*, *Astrophys. J.* **730**, 119 (2011) [Erratum-ibid. **732**, 129 (2011)] [arXiv:1103.2976 [astro-ph.CO]].
- [3] G. Hinshaw, D. Larson, E. Komatsu, D. N. Spergel, C. L. Bennett, J. Dunkley, M. R. Nolte and M. Halpern *et al.*, arXiv:1212.5226 [astro-ph.CO].
- [4] J. L. Sievers, R. A. Hlozek, M. R. Nolte, V. Acquaviva, G. E. Addison, P. A. R. Ade, P. Aguirre and M. Amiri *et al.*, arXiv:1301.0824 [astro-ph.CO].
- [5] Z. Hou, C. L. Reichardt, K. T. Story, B. Follin, R. Keisler, K. A. Aird, B. A. Benson and L. E. Bleem *et al.*, arXiv:1212.6267 [astro-ph.CO].
- [6] K. T. Story, C. L. Reichardt, Z. Hou, R. Keisler, K. A. Aird, B. A. Benson, L. E. Bleem and J. E. Carlstrom *et al.*, arXiv:1210.7231 [astro-ph.CO].
- [7] M. Archidiacono, E. Giusarma, A. Melchiorri, O. Mena and , arXiv:1303.0143 [astro-ph.CO].
- [8] E. Calabrese, R. e A. Hlozek, N. Battaglia, E. S. Battistelli, J. R. Bond, J. Chluba, D. Crichton and S. Das *et al.*, arXiv:1302.1841 [astro-ph.CO].
- [9] E. Di Valentino, S. Galli, M. Lattanzi, A. Melchiorri, P. Natoli, L. Pagano, N. Said and , arXiv:1301.7343 [astro-ph.CO].
- [10] E. Giusarma, R. de Putter and O. Mena, arXiv:1211.2154 [astro-ph.CO].
- [11] G. Mangano, A. Melchiorri, O. Mena, G. Miele and A. Slosar, *JCAP* **0703**, 006 (2007) [astro-ph/0612150].
- [12] J. Hamann, S. Hannestad, G. G. Raffelt and Y. Y. Y. Wong, *JCAP* **0708**, 021 (2007) [arXiv:0705.0440 [astro-ph]].
- [13] B. A. Reid, L. Verde, R. Jimenez and O. Mena, *JCAP* **1001**, 003 (2010) [arXiv:0910.0008 [astro-ph.CO]].

- [14] E. Komatsu *et al.* [WMAP Collaboration], *Astrophys. J. Suppl.* **192**, 18 (2011) [arXiv:1001.4538 [astro-ph.CO]].
- [15] Y. I. Izotov and T. X. Thuan, *Astrophys. J.* **710**, L67 (2010) [arXiv:1001.4440 [astro-ph.CO]].
- [16] J. Hamann, S. Hannestad, J. Lesgourgues, C. Rampf and Y. Y. Y. Wong, *JCAP* **1007**, 022 (2010) [arXiv:1003.3999 [astro-ph.CO]].
- [17] Z. Hou, R. Keisler, L. Knox, M. Millea and C. Reichardt, arXiv:1104.2333 [astro-ph.CO].
- [18] R. Keisler *et al.*, arXiv:1105.3182 [astro-ph.CO].
- [19] T. L. Smith, S. Das and O. Zahn, *Phys. Rev. D* **85**, 023001 (2012) [arXiv:1105.3246 [astro-ph.CO]].
- [20] J. Dunkley, R. Hlozek, J. Sievers, V. Acquaviva, P. A. R. Ade, P. Aguirre, M. Amiri and J. W. Appel *et al.*, *Astrophys. J.* **739**, 52 (2011) [arXiv:1009.0866 [astro-ph.CO]].
- [21] M. Archidiacono, E. Calabrese and A. Melchiorri, arXiv:1109.2767 [astro-ph.CO].
- [22] J. Hamann, *JCAP* **1203**, 021 (2012) [arXiv:1110.4271 [astro-ph.CO]].
- [23] K. M. Nollett and G. P. Holder, arXiv:1112.2683 [astro-ph.CO].
- [24] A. Smith, M. Archidiacono, A. Cooray, F. De Bernardis, A. Melchiorri and J. Smidt, *Phys. Rev. D* **85**, 123521 (2012) [arXiv:1112.3006 [astro-ph.CO]].
- [25] M. Archidiacono, E. Giusarma, A. Melchiorri and O. Mena, *Phys. Rev. D* **86**, 043509 (2012) [arXiv:1206.0109 [astro-ph.CO]].
- [26] M. C. Gonzalez-Garcia, V. Niro and J. Salvado, arXiv:1212.1472 [hep-ph].
- [27] R. Diamanti, E. Giusarma, O. Mena, M. Archidiacono, A. Melchiorri and , arXiv:1212.6007 [astro-ph.CO].
- [28] S. M. Feeney, H. V. Peiris, L. Verde and , arXiv:1302.0014 [astro-ph.CO].
- [29] V. Marra, L. Amendola, I. Sawicki and W. Valkenburg, arXiv:1303.3121 [astro-ph.CO].
- [30] C. Brust, D. E. Kaplan, M. T. Walters and , arXiv:1303.5379 [hep-ph].
- [31] A. Mirizzi, G. Mangano, N. Saviano, E. Borriello, C. Giunti, G. Miele, O. Pisanti and , arXiv:1303.5368 [astro-ph.CO].
- [32] S. M. Bilenky, C. Giunti, W. Grimus and , *Eur. Phys. J. C* **1**, 247 (1998) [hep-ph/9607372]. V. D. Barger, T. J. Weiler, K. Whisnant and , *Phys. Lett. B* **427**, 97 (1998) [hep-ph/9712495].
- [33] J. E. Kim, *Phys. Rev. Lett.* **43**, 103 (1979).
- [34] M. A. Shifman, A. I. Vainshtein, V. I. Zakharov and , *Nucl. Phys. B* **166**, 493 (1980).
- [35] M. Blennow, B. Dasgupta, E. Fernandez-Martinez, N. Rius and , *JHEP* **1103**, 014 (2011) [arXiv:1009.3159 [hep-ph]].
- [36] M. Blennow, E. Fernandez-Martinez, O. Mena, J. Redondo and P. Serra, *JCAP* **1207**, 022 (2012) [arXiv:1203.5803 [hep-ph]].
- [37] U. Franca, R. A. Lineros, J. Palacio and S. Pastor, arXiv:1303.1776 [astro-ph.CO].
- [38] E. Giusarma, M. Corsi, M. Archidiacono, R. de Putter, A. Melchiorri, O. Mena, S. Pandolfi, *Phys. Rev. D* **83**, 115023 (2011). [arXiv:1102.4774 [astro-ph.CO]].
- [39] J. Hamann, S. Hannestad, G. G. Raffelt, Y. Y. Y. Wong, *JCAP* **1109**, 034 (2011). [arXiv:1108.4136 [astro-ph.CO]].
- [40] E. Giusarma, M. Archidiacono, R. de Putter, A. Melchiorri and O. Mena, *Phys. Rev. D* **85**, 083522 (2012) [arXiv:1112.4661 [astro-ph.CO]].
- [41] S. Joudaki, K. N. Abazajian and M. Kaplinghat, *Phys. Rev. D* **87**, 065003 (2013) [arXiv:1208.4354 [astro-ph.CO]].
- [42] S. Riemer-Sorensen, D. Parkinson, T. M. Davis and C. Blake, *Astrophys. J.* **763**, 89 (2013)
- [43] A. Melchiorri, O. Mena, S. Palomares-Ruiz, S. Pascoli, A. Slosar and M. Sorel, *JCAP* **0901**, 036 (2009) [arXiv:0810.5133 [hep-ph]].
- [44] E. Giusarma *et al.*, in preparation.
- [45] J. M. Conrad, C. M. Ignarra, G. Karagiorgi, M. H. Shaevitz and J. Spitz, *Adv. High Energy Phys.* **2013**, 163897 (2013) [arXiv:1207.4765 [hep-ex]].
- [46] C. A. Baker *et al.*, *Phys. Rev. Lett.* **97**, 131801 (2006) [arXiv:hep-ex/0602020].
- [47] R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977); R. D. Peccei and H. R. Quinn, *Phys. Rev. D* **16**, 1791 (1977).
- [48] S. Chang and K. Choi, *Phys. Lett. B* **316**, 51 (1993)
- [49] S. Hannestad, A. Mirizzi and G. Raffelt, *JCAP* **0507**, 002 (2005) [hep-ph/0504059].
- [50] S. Hannestad, A. Mirizzi, G. G. Raffelt and Y. Y. Y. Wong, *JCAP* **0708**, 015 (2007) [arXiv:0706.4198 [astro-ph]].
- [51] A. Melchiorri, O. Mena and A. Slosar, *Phys. Rev. D* **76**, 041303 (2007) [arXiv:0705.2695 [astro-ph]].
- [52] O. Wantz and E. P. S. Shellard, *Phys. Rev. D* **82**, 123508 (2010) [arXiv:0910.1066 [astro-ph.CO]].