

Axion Hot Dark Matter Bounds

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We derive cosmological limits on two-component hot dark matter consisting of neutrinos and axions. We restrict the large-scale structure data to the safely linear regime, excluding the Lyman- α forest. We derive Bayesian credible regions in the two-parameter space consisting of m_a and $\sum m_\nu$. Marginalizing over $\sum m_\nu$ provides $m_a < 1.02$ eV (95% C.L.). In the absence of axions the same data and methods give $\sum m_\nu < 0.63$ eV (95% C.L.).

1 Introduction

The masses of the lightest particles are best constrained by the largest cosmic structures. The well-established method of using cosmological precision data to constrain the cosmic hot dark matter fraction [1, 2] has been extended to hypothetical low-mass particles, notably to axions, in several papers [3, 4, 5, 6, 7]. If axions thermalize after the QCD phase transition, their number density is comparable to that of one neutrino family. Neutrino mass limits are in the sub-eV range so that axion mass limits will be similar and therefore of interest to experiments like CAST [8] or the Tokyo axion helioscope [9] that search for axions in the mass range around 1 eV. We here summarize our detailed limits on axions that were derived from the latest sets of cosmological data, including WMAP (5 years). Numerically our latest limit on m_a [7] is almost identical to one that some of us have derived several years ago [4]. The main difference is that in the older paper the Lyman- α data were used that we now consider “too dangerous” in that they are prone to systematic errors. So, the latest data, that are safely in the linear regime, now do as well as the older data where Lyman- α was included.

2 Axions

The Peccei-Quinn solution of the CP problem of strong interactions predicts the existence of axions, low-mass pseudoscalars that are very similar to neutral pions, except that their mass and interaction strengths are suppressed by a factor of order f_π/f_a , where $f_\pi \approx 93$ MeV is the pion decay constant, and f_a the axion decay constant or Peccei-Quinn scale [10]. In more detail, the axion mass is

$$m_a = \frac{z^{1/2}}{1+z} \frac{f_\pi m_\pi}{f_a} = \frac{6.0 \text{ eV}}{f_a/10^6 \text{ GeV}}, \quad (1)$$

where $z = m_u/m_d$ is the mass ratio of up and down quarks. A value $z = 0.56$ was often assumed, but it could vary in the range 0.3–0.6 [11]. A large range of f_a values is excluded

by experiments and by astrophysical and cosmological arguments [12]. Axions with a mass of order $10 \mu\text{eV}$ could well be the cold dark matter of the universe [13] and if so will be found eventually by the ongoing ADMX experiment, provided that $1 \mu\text{eV} < m_a < 100 \mu\text{eV}$ [14].

In addition, a hot axion population is produced by thermal processes [15, 16]. Axions attain thermal equilibrium at the QCD phase transition or later if $f_a \lesssim 10^8 \text{ GeV}$, erasing the cold axion population produced earlier and providing a hot dark matter component instead. If axions do not couple to charged leptons (“hadronic axions”) the main thermalization process in the post-QCD epoch is [15] $a + \pi \leftrightarrow \pi + \pi$. The axion–pion interaction is given by a Lagrangian of the form [15] $\mathcal{L}_{a\pi} = (C_{a\pi}/f_\pi f_a) (\pi^0 \pi^+ \partial_\mu \pi^- + \pi^0 \pi^- \partial_\mu \pi^+ - 2\pi^+ \pi^- \partial_\mu \pi^0) \partial_\mu a$. In hadronic axion models, the coupling constant is [15] $C_{a\pi} = (1 - z)/[3(1 + z)]$. Based on this interaction, the axion decoupling temperature in the early universe was calculated in Ref. [4], where all relevant details are reported. In Fig. 1 we show the relic axion density as a function of f_a .

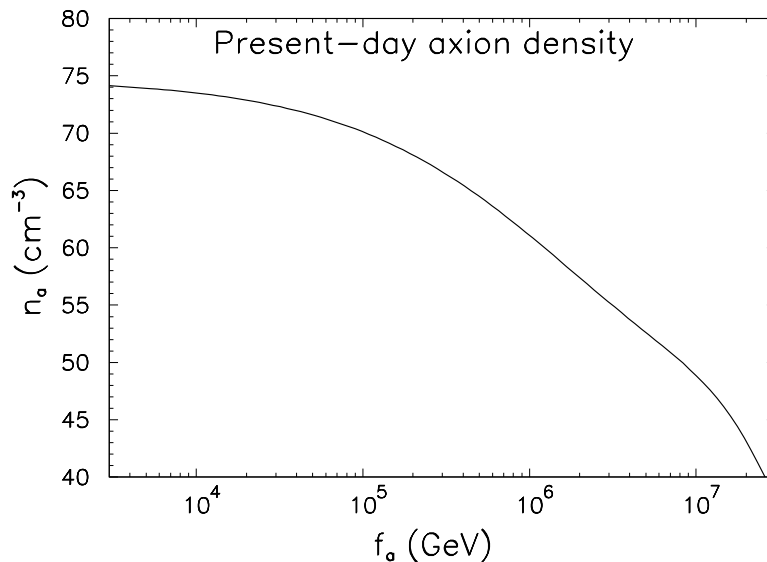


Figure 1: Axion relic density.

3 Cosmological model and data

We consider a cosmological model with vanishing spatial curvature and adiabatic initial conditions, described by six free parameters, the dark-matter density $\omega_{\text{dm}} = \Omega_{\text{dm}} h^2$, the baryon density $\omega_b = \Omega_b h^2$, the Hubble parameter $H_0 = h \, 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the optical depth to reionization τ , the amplitude of the primordial scalar power spectrum $\ln(10^{10} A_s)$, and its spectral index n_s . In addition we allow for a nonzero sum of neutrino masses $\sum m_\nu$ and a nonvanishing axion mass m_a which also determines the relic density shown in Fig. 1 by the standard relation between m_a and f_a . We show the priors on our parameters in Ref. [6].

We use the 5-year release of the WMAP cosmic microwave data [17, 18] that we analyze using version 3 of the likelihood calculation package provided by the WMAP team on the LAMBDA homepage [19], following closely the analyses of references [20, 21]. For the large-

scale galaxy power spectra we use $P_g(k)$ inferred from the luminous red galaxy (LRG) sample of the Sloan Digital Sky Survey (SDSS) [22, 23] and from the Two-degree Field Galaxy Redshift Survey (2dF) [24]. We only use data safely in the linear regime where a scale-independent bias is likely to hold true. For 2dF this is $k_{\text{max}} \sim 0.09 \, h \, \text{Mpc}^{-1}$ (17 bands) and for SDSS-LRG $k_{\text{max}} \sim 0.07 \, h \, \text{Mpc}^{-1}$ (11 bands). We do not use Lyman- α data at all. The baryon acoustic oscillation peak was measured in the SDSS luminous red galaxy sample [25]. We use all 20 points in the two-point correlation data and the corresponding analysis procedure [25]. We use the SN Ia luminosity distance measurements of provided by Davis et al. [26].

4 Results

We use standard Bayesian inference techniques and explore the model parameter space with Monte Carlo Markov Chains (MCMC) generated using the publicly available COSMOMC package [27, 28]. We find the 68% and 95% 2D marginal contours shown in Fig. 2 in the parameter plane of $\sum m_\nu$ and m_a . Marginalizing over $\sum m_\nu$ provides $m_a < 1.02 \, \text{eV}$ (95% C.L.). In the absence of axions the same data and methods give $\sum m_\nu < 0.63 \, \text{eV}$ (95% C.L.). These axion mass limits are nicely complementary to the search range of the CAST experiment [8] and the Tokyo helioscope [9] that can reach to 1 eV or somewhat above. While the hot dark matter limits are not competitive with the SN 1987A limits, it is intriguing that cosmology alone now provides both an upper and a lower limit for the allowed range of axion parameters.

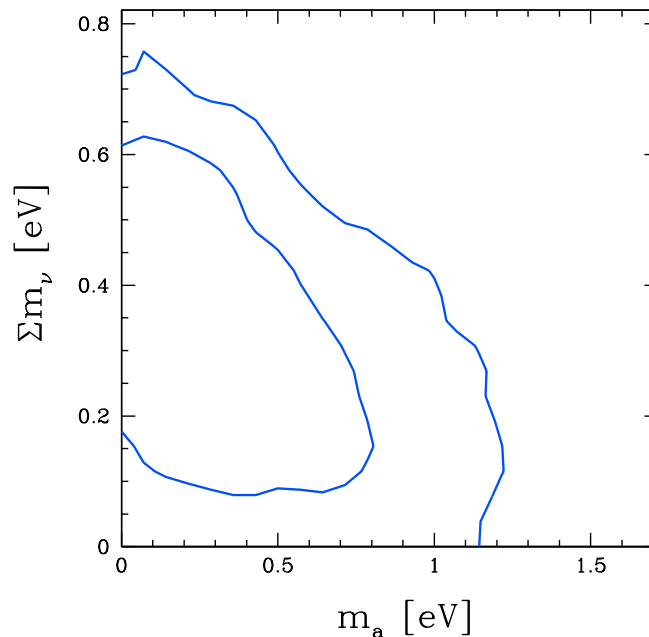


Figure 2: 2D marginal 68% and 95% contours in the $\sum m_\nu - m_a$ plane.

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References

- [1] J. Lesgourgues and S. Pastor, Phys. Rept. **429** (2006) 307 [arXiv:astro-ph/0603494].
- [2] S. Hannestad, Ann. Rev. Nucl. Part. Sci. **56** (2006) 137 [arXiv:hep-ph/0602058].
- [3] S. Hannestad and G. Raffelt, JCAP **0404** (2004) 008 [arXiv:hep-ph/0312154].
- [4] S. Hannestad, A. Mirizzi and G. Raffelt, JCAP **0507** (2005) 002 [arXiv:hep-ph/0504059].
- [5] A. Melchiorri, O. Mena and A. Slosar, Phys. Rev. D **76**, 041303 (2007) [arXiv:0705.2695].
- [6] S. Hannestad, A. Mirizzi, G. G. Raffelt and Y. Y. Y. Wong, JCAP **0708**, 015 (2007) [arXiv:0706.4198].
- [7] S. Hannestad, A. Mirizzi, G. G. Raffelt and Y. Y. Y. Wong, JCAP **0804**, 019 (2008) [arXiv:0803.1585].
- [8] S. Andriamonje *et al.* [CAST Collaboration], JCAP **0704**, 010 (2007) [arXiv:hep-ex/0702006].
- [9] Y. Inoue, Y. Akimoto, R. Ohta, T. Mizumoto, A. Yamamoto and M. Minowa, arXiv:0806.2230 [astro-ph].
- [10] R. D. Peccei, Lect. Notes Phys. **741** (2008) 3 [arXiv:hep-ph/0607268].
- [11] W. M. Yao *et al.* [Particle Data Group], J. Phys. G **33** (2006) 1.
- [12] G. G. Raffelt, Lect. Notes Phys. **741** (2008) 51 [arXiv:hep-ph/0611350].
- [13] P. Sikivie, Lect. Notes Phys. **741** (2008) 19 [arXiv:astro-ph/0610440].
- [14] S. J. Asztalos, *et al.*, Ann. Rev. Nucl. Part. Sci. **56** (2006) 293.
- [15] S. Chang and K. Choi, Phys. Lett. B **316** (1993) 51 [arXiv:hep-ph/9306216].
- [16] E. Massó, F. Rota and G. Zsembinski, Phys. Rev. D **66** (2002) 023004 [arXiv:hep-ph/0203221].
- [17] G. Hinshaw *et al.*, arXiv:0803.0732 [astro-ph].
- [18] M. R. Nolta *et al.*, arXiv:0803.0593 [astro-ph].
- [19] Legacy Archive for CMB Data Analysis (LAMBDA), <http://lambda.gsfc.nasa.gov>
- [20] J. Dunkley *et al.* [WMAP Collaboration], arXiv:0803.0586 [astro-ph].
- [21] E. Komatsu *et al.*, arXiv:0803.0547 [astro-ph].
- [22] W. J. Percival *et al.*, Astrophys. J. **657** (2007) 645 [arXiv:astro-ph/0608636].
- [23] M. Tegmark *et al.*, Phys. Rev. D **74** (2006) 123507 [arXiv:astro-ph/0608632].
- [24] S. Cole *et al.* [2dFGRS Coll.], Mon. Not. Roy. Astron. Soc. **362** (2005) 505 [arXiv:astro-ph/0501174].
- [25] D. J. Eisenstein *et al.* [SDSS Collaboration], Astrophys. J. **633** (2005) 560 [arXiv:astro-ph/0501171]; see also <http://cmb.as.arizona.edu/~eisenste/acousticpeak>
- [26] T. M. Davis *et al.*, Astrophys. J. **666** (2007) 716 [arXiv:astro-ph/0701510].
- [27] A. Lewis and S. Bridle, Phys. Rev. D **66** (2002) 103511 [arXiv:astro-ph/0205436]
- [28] A. Lewis, Homepage, <http://cosmologist.info>