Cosmological axion bounds

Steen Hannestad[1], *Jan Hamann*[1], *Alessandro Mirizzi*[2], *Georg G. Raffelt*[3], *Yvonne Y. Y. Wong*[4]

[1] Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark
[2] Institut für theoretische Physik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany
[3] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, D-80805 München, Germany
[4] Institut für Theoretische Physik E, RWTH Aachen University, D-52056 Aachen, Germany

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We discuss current cosmological constraints on axions, as well as future sensitivities. Bounds on axion hot dark matter are discussed first, and subsequently we discuss both current and future sensitivity to models in which axions play the role as cold dark matter, but where the Peccei-Quinn symmetry is not restored during reheating.

The Peccei-Quinn (PQ) mechanism provides a simple explanation for the smallness of the QCD Θ parameter [1]. A consequence of this is the existence of axions, low mass pseudoscalars similar to pions, except that their mass and coupling strength are suppressed by a factor f_π/f_a, where $f_\pi \simeq 93$ MeV and f_a is the PQ scale. The axion mass is given by the relation

$$m_a = \frac{z^{1/2}}{1+z}\frac{f_\pi m_\pi}{f_a} = \frac{6\,\mathrm{eV}}{f_a/10^6\,\mathrm{GeV}}, \tag{1}$$

where $z \equiv m_u/m_d \sim 0.3-0.6$. Thus, there is a tight relation between m_a and f_a, known as the axion line. Axions couple to photons with a coupling $g_{a\gamma}$ of order $g_{a\gamma} \sim \frac{\alpha}{f_a}$ and are therefore in principle detectable even if f_a is much larger than the electroweak energy scale. A large number of direct detection experiments use this coupling to photons to search for axions, and are described in detail elsewhere in these proceedings.

Astrophysics also provides a stringent bound on the axion-photon coupling (see [2] for a thorough discussion). The most restrictive bound comes from constraints on the horizontal branch (HB) lifetime of globular cluster stars. If an additional source of energy loss from the core is present, the core Helium burning phase can be shortened to a point where the predicted number of HB stars in a globular cluster is in conflict with observations. The bound from this argument roughly corresponds to $g_{a\gamma} \lesssim 10^{-10}\,\mathrm{GeV}^{-1}$.

While this bound is formally very stringent, it is also model dependent, and it is possible to construct models with an axion photon coupling much smaller than the normally predicted α/f_a. However, in this case cosmology provides an important lower bound on f_a coming from the unavoidable coupling of axions to quarks. In this case, the main thermalisation mechanism is axion-pion conversion, $a\pi \leftrightarrow \pi\pi$. Provided that $f_a \lesssim \mathrm{few} \times 10^7$ GeV axions couple sufficiently strongly to thermalise completely after the QCD phase transition at $T \sim 150$ MeV. If this is the case axions automatically provide a source of hot dark matter because they will have masses in the eV range.

Therefore, cosmological constraints on light neutrinos can be also be applied to axions in this range. The current upper bound on the axion mass is of order 0.5-1 eV [3, 4], corresponding to $f_a \gtrsim 10^7$ GeV. Fig. 1, taken from [4], shows the bound on m_a and $\sum m_\nu$ simultaneously.

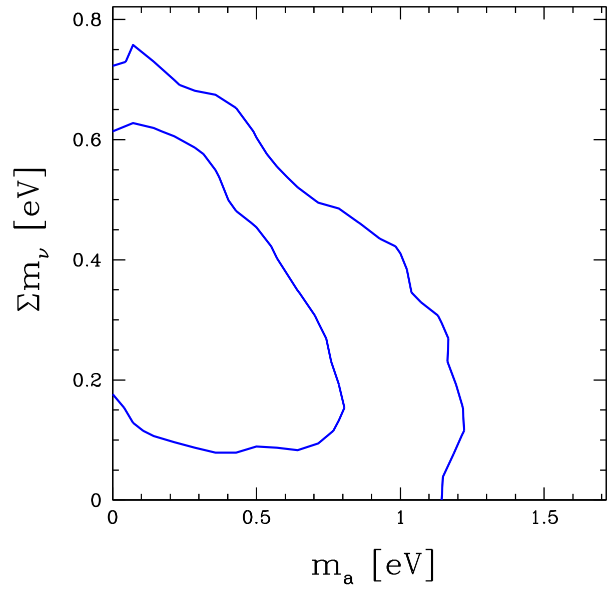

Figure 1: 68% and 95% contours in the $\sum m_\nu$-m_a plane (taken from Ref. [4]).

If the PQ scale is much higher, axions never thermalise in the early universe, and their presence is caused solely by non-thermal production. During the QCD epoch of the early universe, a non-thermal mechanism produces axions as nonrelativistic coherent field oscillations that can play the role of cold dark matter [5]. In terms of the initial "misalignment angle" $\Theta_{\rm i} = a_{\rm i}/f_a$ relative to the CP-conserving minimum of the axion potential, the cosmic axion density is [6]

$$\omega_a = \Omega_a h^2 \simeq 0.195\, \Theta_{\rm i}^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.184} . \qquad (2)$$

If $\Theta_{\rm i}^2$ is of order unity, axions provide the dark matter of the universe if $f_a \sim 10^{12}$ GeV ($m_a \sim 10\ \mu$eV).

One may also consider axions in another range beyond the classical cosmological window. In a scenario where the PQ symmetry is not restored during or after inflation, a single value $-\pi < \Theta_{\rm i} < +\pi$ determines the axion density in our Hubble volume. It is possible that $\Theta_{\rm i} \ll 1$, allowing for $f_a \gg 10^{12}$ GeV. This "anthropic axion window" is motivated because the PQ mechanism presumably is embedded in a greater framework. In particular, the PQ symmetry emerges naturally in many string scenarios, where f_a is naturally high (see also [7]).

An interesting signature of such a high f_a is the presence of primordial isocurvature fluctuations that can show up in future data. When axions acquire a mass during the QCD epoch, axion field fluctuations from the de Sitter expansion during inflation become dynamically relevant in the form of isocurvature fluctuations that are uncorrelated with the adiabatic fluctuations inherited by all other matter and radiation from the inflaton field. The isocurvature amplitude depends on both f_a and H_I, the Hubble parameter during inflation, so observational limits on isocurvature fluctuations exclude certain regions in this parameter space [8, 9]. Since there is no trace of isocurvature fluctuations in existing data, perhaps a more interesting question is the remaining window for axions to show up in future data.

Now going into slightly more detail, when the PQ symmetry breaks at some large temperature $T \sim v_\mathrm{PQ}$, the relevant Higgs field will settle in a minimum corresponding to $\Theta_\mathrm{i} = a_\mathrm{i}/f_a$, where $-\pi \leq \Theta_\mathrm{i} \leq +\pi$. We assume that this happens before cosmic inflation, so throughout our observable universe we have the same initial condition except for fluctuations imprinted by inflation itself. The cosmic energy density in axions is given by Eq. (2) with Θ_i^2 replaced by $\langle\Theta^2\rangle_\mathrm{i} = \Theta_\mathrm{i}^2 + \sigma_\Theta^2$, where $\sigma_\Theta^2 = H_I^2/(4\pi^2 f_a^2)$ is the inflation-induced variance, with H_I the Hubble parameter during inflation. All cosmologically viable models have $\Theta_\mathrm{i}^2 \gg \sigma_\Theta^2$. Assuming that all of the cold dark matter consists of axions, according to current cosmological data $\omega_\mathrm{a} = \omega_\mathrm{c} = 0.109 \pm 0.004$. Assuming σ_Θ is small, one finds $\Theta_\mathrm{i} = 0.748 \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)^{0.592}$ as a unique relationship between the initial misalignment angle and the axion decay constant.

As mentioned, axion-induced isocurvature fluctuations are uncorrelated with the adiabatic fluctuations inherited by other matter and radiation components from the inflaton, and the isocurvature fraction, α, of the total fluctuation power spectrum is given by [10]

$$\alpha \simeq 7.5 \times 10^{-3} \left(\frac{2.4 \times 10^{-9}}{A_\mathrm{S}}\right) \left(\frac{0.109}{\omega_\mathrm{c}}\right) \left(\frac{H_I}{10^7\ \mathrm{GeV}}\right)^2 \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)^{0.816}, \qquad (3)$$

where $A_\mathrm{S} = \mathcal{P}(k = k_0)$ is the amplitude of the total primordial scalar power spectrum at the pivot scale $k_0 = 0.002\ \mathrm{Mpc}^{-1}$.

[10] considered several different current and future data sets in order to constrain α: 1) Current data: WMAP plus auxiliary data sets. 2) Planck: Simulated TT, TE and EE spectra up to $\ell = 2000$ from the Planck satellite [11]. 3) CVL: Simulated, noiseless TT, TE and EE spectra up to $\ell = 2000$. Roughly equivalent to the projected CMBPol experiment [12].

Data set 1 gives $\alpha < 0.09$ at 95% confidence, consistent with the findings of Komatsu et al. [9]. For the future experiments and if no isocurvature signal shows up, we forecast 95%-credible upper limits of $\alpha < 0.042$ for Planck and $\alpha < 0.017$ for CVL.

The constraints and sensitivity forecasts on the isocurvature fraction α can be translated into axion parameters using equation (3). It can we written in the form

$$H_I = 3.5 \times 10^7\ \mathrm{GeV} \left(\frac{\alpha}{0.09}\right)^{1/2} \left(\frac{\omega_\mathrm{c}}{0.109}\right)^{1/2} \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{0.408}, \qquad (4)$$

where the present upper bound on α has been used as a benchmark. Assuming axions are the dark matter, this constraint is shown in Fig. 2 with a line marked $\alpha = 0.09$. In this plot, taken from [10], we also show the relationship between f_a and Θ_i as dashed lines. Future sensitivities to α from Planck and CVL are shown labelled with the appropriate α values.

In conclusion, axions have a number of potentially very important consequences for cosmology, depending entirely on the value of the PQ symmetry breaking scale.

For low values of the breaking scale, axions are thermalised in the early universe and can act as a hot dark matter component. Such scenarios can be constrained by current observations of large scale structure, and while these constraints are formally much less stringent than astrophysical bounds using the axion-photon coupling, they are also less model dependent.

At intermediate scales, $f_a \sim 10^{12}$ GeV, axions may naturally act as a CDM candidate.

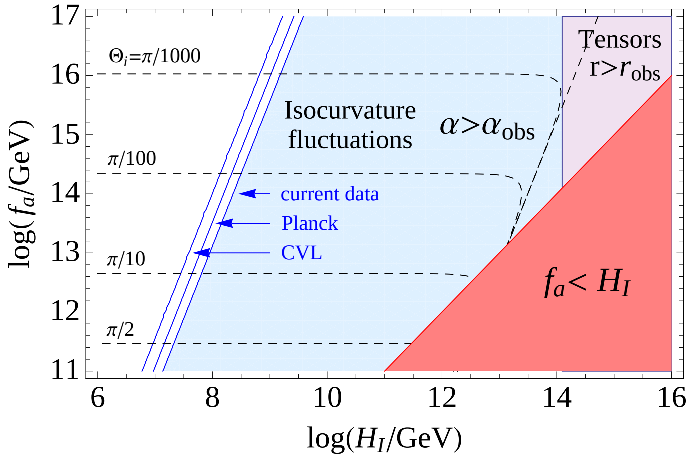

Figure 2: Exclusion and sensitivity regions in the plane of H_I (Hubble rate during inflation) and f_a (axion decay constant), assuming axions are all of the dark matter. The isocurvature exclusion region based on current data is shown in light blue. The sensitivity forecasts for Planck and CVL are also indicated. The dashed lines indicate the required Θ_i for a given f_a to obtain the full amount of axion dark matter. We also show the region of excessive tensor modes and the region $f_a < H_I$ where our late-inflation scenario is not applicable.

At the other end of the scale, a very high value of the PQ scale may also provide axion cold dark matter, but in this case there may be additional observational signatures in the form of axion isocurvature fluctuations. Such an isocurvature component could plausible be observed by future CMB experiments, and would provide a very interesting new window on both axion physics and early universe cosmology.

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