

Cosmological constraints on thermal relic axions and axion-like particles

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Abstract. Cosmological precision data can be used to set very strict constraints on axions and axion-like particles (ALPs) produced thermally in the big bang. We briefly review the known bounds and propose two new constraints for axions and ALPs decaying in the early universe, based upon the concomitant dilution of baryon and neutrino densities, using WMAP7 and other cosmological data.

1. Cosmology of decaying axions and ALPs

The axion is a pseudo Nambu-Goldstone boson arising from the spontaneous breaking of the global axial Peccei-Quinn $U(1)$ symmetry proposed to solve the strong CP problem [1]. The effective lagrangian relevant for this work includes only their coupling to photons

$$\mathcal{L}_{\text{eff}}^a = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a^2 - a \frac{g_{a\gamma}}{4} F^{\mu\nu} \tilde{F}_{\mu\nu}. \quad (1)$$

Considering couplings to electrons and other leptons changes only slightly our conclusions. The mass and the photon coupling are calculable in chiral perturbation theory as [1],

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6 \text{ eV} \left(\frac{10^6 \text{ GeV}}{f_a} \right) \quad (2)$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - \frac{2}{3} \frac{m_u + 4m_d}{m_d + m_u} \right) \equiv \frac{1.9 \alpha \delta}{2\pi f_a}. \quad (3)$$

and are related to each other via δ , a free $\mathcal{O}(1)$ parameter. The two-photon coupling allows for the decay $a \rightarrow \gamma\gamma$, at the rate

$$\Gamma_{a\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi}. \quad (4)$$

The two photon coupling allows axions to thermalize in the early universe via the Primakoff process $q^\pm + \gamma \leftrightarrow q^\pm + a$. However, at some temperature axions decouple. Additional axion interactions with pions or electrons can lower the decoupling temperature, but are not relevant for this discussion. This thermal axion population behaves as hot dark matter, which is currently disfavoured, implying the constraint $m_a < 0.7 \text{ eV}$ [2].

The axion lifetime $\tau = \Gamma_{a\gamma\gamma}^{-1} \sim 10^{24} \text{ s} (\text{eV}/m_a)^5 \delta^{-2}$ becomes shorter than the age of the universe if the mass exceeds $\sim 20 \text{ eV}$ and the above bound loses its meaning. We have therefore explored the possibility that, above a certain mass, the axion could disappear from the universe without leaving any observable trace [3]. Still, the decay of axions would affect BBN, the neutrino temperature, and the CMB. The exquisite precision of cosmological data sets permits us to constrain the axion parameters. All in all, we found that axions are allowed by cosmology to have $m_a > 300 \text{ keV}$ [3].

These cosmological limits become even more interesting in the case of axion-like particles (ALPs): pseudo-scalars having properties similar to the axion one except the relation between the mass and the photon coupling, which are now free to span the whole parameter space [4]. In a recent paper [5], we have extended to ALPs the cosmological axion bounds we found in [3]. The summary of the constraints we found is in Fig. 1, together with some other relevant cosmological and astrophysical bounds.

The most interesting bounds arise because of the entropy released during the decay. As the decay products are photons (and in some axion models also electrons), *this entropy is shared only among the species in thermal equilibrium with the electromagnetic radiation*. If axions or ALPs decay when inverse reactions are efficient, $\gamma\gamma \rightarrow a$, they do it in local thermal equilibrium (LTE). This is the case if ALPs decay when the temperature exceeds greatly their mass. The rise in entropy follows from entropy conservation by counting the relevant relativistic degrees of freedom g_{*S} before and after the disappearance, like one usually does for the e^\pm annihilation. For instance, if axions or ALPs decay affects only photons, the photon entropy is increased by a factor $(2 + 1)/2 = 3/2$.

The other extreme possibility is that the temperature is smaller than the mass when axions or ALPs decay, which implies far out-of-equilibrium decay. In this case the energy density in scalars can even dominate the universe expansion thrusting in a huge amount of entropy. In this case, one finds [6]

$$\frac{S_f}{S_i} \sim \frac{m_a R}{\sqrt{m_{\text{Pl}} \Gamma_{a\gamma\gamma}}} \quad (5)$$

where R is the number of ALPs per photon before the decay. Solving the Boltzmann equations we exactly calculated the entropy emitted during the decay and how this influences the thermodynamics of the other species.

2. Number of effective neutrinos

If axions or ALPs decay after the decoupling of neutrinos, the latter can not be heated by the radiation released and the final ratio T_ν/T_γ would be lower than the standard value $(4/11)^{1/3}$. The number of effective neutrinos is defined as

$$N_{\text{eff}} = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_\nu}{\rho_\gamma} \quad (6)$$

to measure the neutrino energy density. From WMAP7, the 7th release of the SSDS and the measurement of H_0 by the HST, we obtained the following limits on N_{eff} [3]

$$N_{\text{eff}} > \begin{cases} 2.70 & \text{at 68\% C.L.} \\ 2.39 & \text{at 95\% C.L.} \\ 2.11 & \text{at 99\% C.L.} \end{cases} \quad (7)$$

assuming a prior $N_{\text{eff}} < 3$ because we assume only 3 standard neutrinos and in the ALP decay scenario sketched the ALP decay can only increase ρ_γ , i.e. lower N_{eff} . We plot our results in Fig. 2 in the ALP mass and lifetime plane. Axion models with $\delta = 1$ lie along the steep line labelled KSVZ.

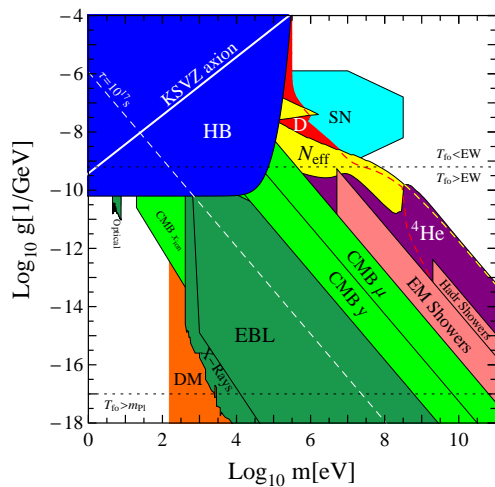


Figure 1. Summary of ALP bounds in the mass-coupling plane. The ALP relic density exceeds the observed value in the region labelled DM. EBL, Optical and X-Rays regions are excluded by the non observation of photons from relic ALP decay. The black-body spectrum of CMB would be unacceptably distorted by ALP decays in the regions labelled CMB. N_{eff} , D, Showers and He are described in the text. SN and HB are astrophysical bounds. See [5] for details.

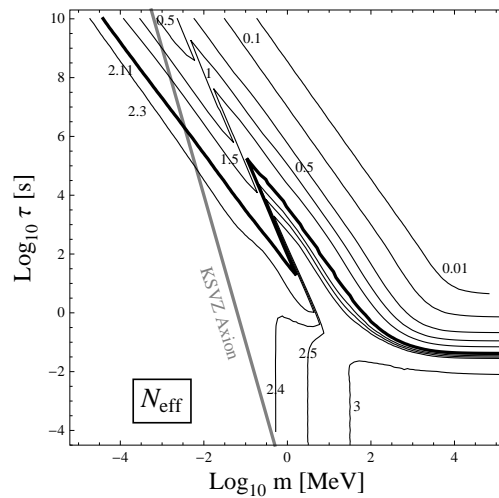
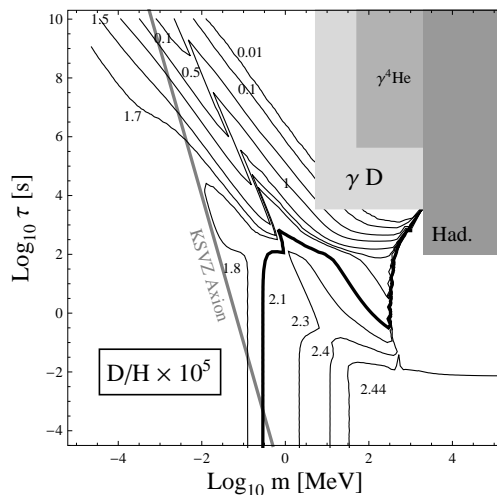
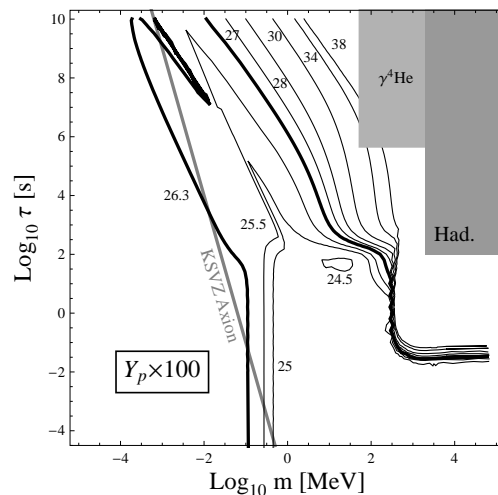


Figure 2. Isocontours of N_{eff} , as a function of the ALP mass m and the lifetime τ . The excluded region lies above the thick black line. LTE decay (lower-left corner) produces no bound for N_{eff} . In the upper-right corner the decay is out-of-equilibrium and during ALP domination: ν s are almost washed out. Decreasing τ the bound becomes less severe: it completely disappears for τ shorter than the ν freeze-out [5]. For the KSVZ axion $m_a \gtrsim 3$ keV is allowed at 99% C.L. [3].



(a) Deuterium



(b) Helium

Figure 3. Deuterium to proton abundances ratio (left) and helium mass fraction (right) from BBN in the decaying ALP cosmology, as in Fig. 2. The LTE decay (lower-left corner) case is enough to exclude masses below 300 keV at 99% C.L. because of D underproduction, also for the KSVZ axion [3]. Massive ALPs dissociate nuclei through EM and hadronic cascades and are excluded in the grey regions. BBN happens in a low N_{eff} universe for $\tau < 100$ s, which generally translates into helium overproduction. For shorter lifetimes ($\tau \sim 0.1 - 100$ s) the decay produces charged pions that enhance the neutron-to-proton ratio at BBN, resulting in a high D/H and He mass fraction [5].

3. Primordial nucleosynthesis

The photons emitted in ALP decays decrease the baryon to photon ratio η_B , which is well measured from CMB to be $\eta_B^{\text{CMB}} = 6.23 \times 10^{-10}$. This value agrees with what is inferred from standard BBN. If a relic population decays before the CMB release but after BBN it means BBN happened with a higher η_B , i.e. $\sim (S_f/S_i)\eta_B^{\text{CMB}}$. The LTE value $S_f/S_i = 3/2$ is enough to create a disagreement between BBN simulations and the observation of primordial elements. ALPs with longer lifetimes decay increasingly out-of-equilibrium and rise the tension, unless a decrease in R compensates the growth of $(\Gamma_{a\gamma\gamma})^{-1/2}$, c.f. Eq. (5). The sharp features of our results correspond indeed to the large decrease in R when ALPs decouple around the QCD phase transition. Deuterium is the most affected nucleus in a high η_B BBN, where it can be more efficiently processed into heavier elements: it is the best observable to test S_f/S_i . Values of $D/H < 2.2 \times 10^{-5}$ are presently excluded at 99% C.L., which allows only axions with mass larger than 300 keV [3]. The results for the ALP case are plotted in Figs. 3. Higher mass ALPs initiate EM and hadronic showers, which dissociate nuclei. Also ALPs decays produce charged pions, whose presence alters the neutron/proton equilibrium. In general, they enhance n_n/n_p , which can even reach values ~ 1 . This translates into high He and D/H yields [5]. The N_{eff} , D and He limits are presently the most constraining ones for shorter ALP lifetimes.

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