Axion reionization during dark ages

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Axion-like particles (ALPs) with a two-photon vertex are hypothetical particles predicted in many extensions of the Standard Model. Pseudoscalar ALPs couple with photons through the following effective Lagrangian [1]

$$\mathcal{L}_{a\gamma} = -\frac{1}{8} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a \,, \tag{1}$$

where a is the ALP field with mass m_a, $F^{\mu\nu}$ the electromagnetic field-strength tensor, and $g_{a\gamma}$ the ALP-photon coupling. As a consequence of this coupling, ALPs and photons do oscillate into each other in an external magnetic field. The photon-ALP evolution for a particle moving in the z direction is described by a Shrödinger-like equation of the kind $i\partial_t \Psi = \mathcal{H} \cdot \Psi$, where $\Psi = (A_x, A_y, a)^T$ and

$$\mathcal{H} = \left[\begin{array}{ccc} k - i\frac{\Gamma}{2} & 0 & \frac{1}{2} g_{a\gamma} B_x \\ 0 & k - i\frac{\Gamma}{2} & \frac{1}{2} g_{a\gamma} B_y \\ \frac{1}{2} g_{a\gamma} B_x & \frac{1}{2} g_{a\gamma} B_y & -\frac{m_a^2}{2E} \end{array} \right] . \tag{2}$$

Here m_a is the ALP mass, E the ALP energy (that can depend by z due to cosmological redshift) and Γ is the absorption rate due to incoherent scattering of photons on atoms and electrons. In a cosmological context, the factor k contains two components, one (negative) due plasma effect (which is proportional to the electron density) and the other (positive) is due to a nonlinear coherent scattering of the photon on the photons of the Cosmic Microwave Background (CMB) [2]. In the following we assume $m_a/E \ll k$ and thus negligible.

In the (string-inspired) scenario in Ref. [3], a non-thermal background of very light ($m_a < 10^{-10}$ eV) ALPs (Cosmic Axion-like Background, CAB) with energy is generated by the decay of primordial scalar particles called Moduli. The total decay rate of moduli (into ALPs and SM particles) during the post-inflation epoch is given by [4]

$$\Gamma_\Phi \sim \frac{1}{4\pi} \frac{m_\Phi^3}{M_{\rm pl}^2} \quad , \tag{3}$$

where $M_{\rm pl} = 2.4 \times 10^{18}$ GeV is the Planck mass, $m_\Phi \sim \mathcal{O}$(PeV) is the modulus mass. The SM particles from moduli decays would rapidly thermalize. Moduli can also decay into light states from the hidden sector, like ALPs, with initial energy $\varepsilon_{\rm a} = m_\Phi/2$ and decay rate given by $\Gamma_{\rm a} = B_{\rm a}\Gamma_\Phi$ with B_a the branching ratio in ALPs. If these ALPs are weakly coupled to SM, they do not thermalize and remain till now as dark radiation, with typical energy today $\varepsilon_{\rm a} \sim \mathcal{O}(100)$ eV for moduli masses $m_\Phi \sim 10^6$ GeV. This ALPs background can be detected by conversion in astrophysical magnetic fields, for example in galaxy clusters [5] or in Milky Way [6].

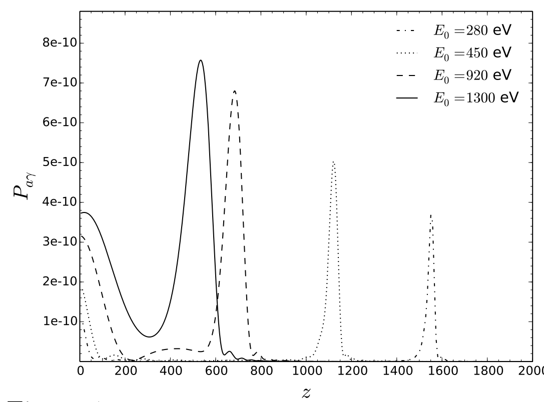

Figure 1. Conversion probability $P_{a\gamma}$ in function of the redshift z for different representative energies of the ALP spectrum for $g_{a\gamma} B = 10^{-17}$GeV^{-1}nG.

ALPs can be converted into photons by the primordial Intergalactic Magnetic Field. Although this field has not been measured yet, there are many indication of its existence, with today strength $B < 1$ nG. Typically, this magnetic field is not uniform but has a turbulent stochastic structure. A good approximation for practical purposes is a cell-like structure with a constant random magnetic field in each cells of coherence length l while the correlation of the magnetic fields between different cells is zero. However, we remark that this model is unrealistic because the condition $\nabla \cdot \mathbf{B} = 0$ cannot be satisfied on the boundary of cells.

In this case the conversion of ALPs into photons after the recombination phase induced by primordial magnetic field can reionize the neutral hydrogen thus increasing the opacity of the Universe to CMB. In fact, due to redshift, the energy and the density of ALPs are more and

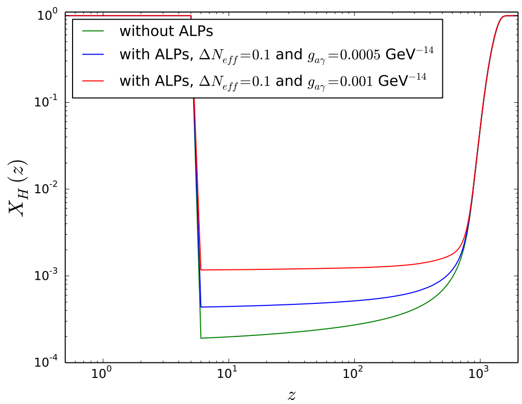

Figure 2. Fraction of ionized hydrogen $X_{\rm H}$ (normalized to 1 for full ionization) in function of redshift z without and with ALP conversions for two values of $g_{a\gamma}B = 10^{-17}\text{GeV}^{-1}\text{nG}$. We assume $\Delta N_{\rm eff} = 0.1$.

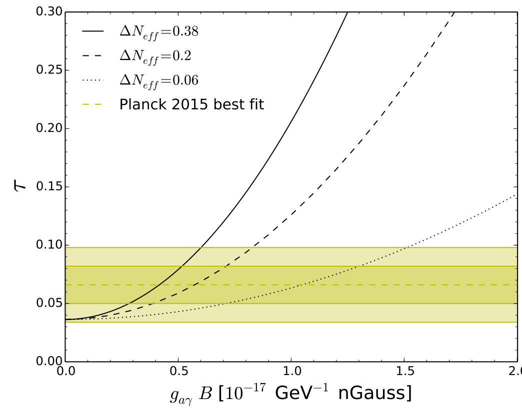

Figure 3. Optical depth τ in presence of ALP for $\Delta N_{\rm eff} = 0.38$ (continuous curve), $\Delta N_{\rm eff} = 0.2$ (dashed curve) and $\Delta N_{\rm eff} = 0.06$ (dotted curve) in function of $g_{a\gamma}B$. The horizontal bands represent the 1σ (dark) and 2σ (light) range for τ measured from Planck.

more increasing with increasing redhift leading to an efficient conversion of ALPs into photons and subsequent scattering on neutral hydrogen and helium.

Since we expect that a very small conversion probability ($P_{a\gamma} \sim 10^{-9}$) is sufficient to give an important effect on reionization, we can expand photon-ALP evolution Eq. (2) at first order of $g_{a\gamma}B$. The solution is

$$P_{a\to\gamma}(t) = \frac{g_{a\gamma}^2}{2}\int_0^t ds\,\tilde{\varepsilon}_\perp(k(s))e^{-\int_s^t du\,\Gamma(u)}\,, \qquad (4)$$

where $\tilde{\varepsilon}_\perp(k)$ is the Fourier transform of the correlation function $\mathcal{C}(\zeta) = \langle B_x(z)B_x(z+\zeta)\rangle$ along the line-of-sight. In particular, for a cell-like structure $\tilde{\varepsilon}_\perp(k) = \frac{1}{2}\langle B_T^2\rangle\, l\,\text{sinc}^2\left(\frac{kl}{2}\right)$, with $\text{sinc}(x) = \sin x/x$ and $\langle B_T^2\rangle$ the variance of the transverse magnetic field on all cells.

In Fig. 1 we show the conversion probability $P_{a\gamma}$ for $g_{a\gamma}B = 10^{-17}\text{GeV}^{-1}\text{nG}$ obtained from Eq. (4) as function of the redshift z. We realize that the probability has a typical resonant behavior, being peaked at redshift for which $k = 0$. We also note that for the values of the different parameters $P_{a\gamma} < 10^{-9}$.

The total optical depth encountered by the CMB photons as they travel to us from the surface of last scattering is given by

$$\tau = \int_0^\infty X_H(z)n_H^0(1+z)^3\sigma_T\left|\frac{dt}{dz}\right|dz\ , \qquad (5)$$

where $X_H(z)$ is the fraction of ionized hydrogen and n_H^0 the present number density of hydrogen atoms and σ_T is the Thomson cross section. It is then clear that this observable is sensitive to the number of extra ionizations of neutral Hydrogen or Helium atoms at $z < 1000$ induced by ALP-photon conversions. Since the optical depth is well measured by Planck, this set a strong limit on the product $g_{a\gamma}B$: $g_{a\gamma}B < \mathcal{O}(10^{-18})$ GeV^{-1}nG, depending on te quantity of extra-radiation induced by the ALPs background (and parameterized by an effective extra number of neutrinos $\Delta N_{\rm eff}$).

In Fig. 2 the fraction of ionized hydrogen $X_{\rm H}$ (normalized to 1 for full ionization) in function of redshift z without and with ALP conversions for different values of $g_{a\gamma}B$ is shown [7]. After $z > 3$ all hydrogen is reionized by UV light produced by stars. In Fig. 3 by [7] we show the optical depth τ as a function of $g_{a\gamma}B$ for different values of $\Delta N_{\rm eff}$. Horizontally we show the 2σ band of τ from Planck observations: $\tau_{\rm obs} = 0.066 \pm 0.016$. We can see that, also in the presence of a subleading content of ALP extra-radiation the bound is really impressive

$$g_{a\gamma}B < \mathcal{O}(10^{-18})\,\text{GeV}^{-1}\,\text{nG}\ \ . \qquad (6)$$

Of course this limit cannot be regarded as a bound on photon-ALP coupling *tout court*. In fact, it is valid only in this particular scenario of moduli decay and imply that cosmic magnetic fields are non-zero at the epoch reionization.

REFERENCES

1. G. Raffelt and L. Stodolsky, Phys. Rev. D **37**, 1237 (1988).
2. A. Dobrynina, A. Kartavtsev and G. Raffelt, Phys. Rev. D **91**, 083003 (2015)
3. M. Cicoli, J. P. Conlon and F. Quevedo, Phys. Rev. D **87** (2013) 043520.
4. J. P. Conlon and M. C. D. Marsh, JHEP **1310**, 214 (2013)

5. S. Angus, J. P. Conlon, M. C. D. Marsh, A. J. Powell and L. T. Witkowski, JCAP **1409**, no. 09, 026 (2014)
6. M. Fairbairn, Phys. Rev. D **89**, no. 6, 064020 (2014)
7. C. Evoli, M. Leo, A. Mirizzi and D. Montanino, arXiv:1602.08433 [astro-ph.CO].