PROCEEDINGS OF SCIENCE

Photon to axion conversion during BBN

Manuel Masip

Departamento de Física Teórica y del Cosmos
Universidad de Granada, 18071 Granada, Spain

E-mail: masip@ugr.es

We discuss the cosmology of an axion-like particle associated to the generation of neutrino masses: an axion-like majoron or ALM. In particular, we consider the possibility that at the end of BBN a fraction of the CMB photons converts into majorons that then decay into neutrinos during recombination. We show that this could define an interesting variation of the ΛCDM model where *(i)* the increase in N_{eff} relaxes the so called H_0 tension; *(ii)* the larger baryon to photon ratio after BBN provides a better agreement of the deuterium abundance with CMB observables; and *(iii)* the sudden drop in the CMB temperature interrupts the synthesis of lithium and beryllium alleviating the so called lithium problem.

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1. Introduction

We find two reasons to consider variations of the standard cosmology. On one hand, ΛCDM works extremely well, but precisely this underlines a few anomalies or *tensions* currently present in some observations. In particular, the best fit of CMB observables is obtained for an expansion rate H_0 and a baryon to photon ratio η_{10} (see [1, 2] and references therein)

$$H_0 = 67.71 \pm 0.44 \ \frac{\text{km}}{\text{s Mpc}} , \qquad \eta_{10} \equiv 10^{10} \frac{n_b}{n_\gamma} = 6.14 \pm 0.04 \, . \tag{1}$$

However, this H_0 is 5σ smaller than the one deduced from supernovas calibrated on CEPHEIDS, the so called H_0 tension. As for η_{10}, the CMB value seems to be 2σ larger than the one implying the right deuterium abundance from BBN. In addition, the data on primordial lithium suggests a much smaller value of η_{10}, defining a 9.5σ discrepancy. Although not fully established, these observational anomalies could mean something.

On the other hand, in the neutrino sector some basic question have no answer yet. Are ν's Dirac particles with purely EW masses, just like the rest of standard fermions? Or are these masses introducing a new scale in physics, like beta decays were revealing the EW scale more than 100 years ago? This second possibility seems the most likely: the first one has to justify why the Yukawa couplings are so small and also what protects the right handed neutrino from a large mass, as it is non chiral under the standard model symmetry. It seems more natural that neutrinos are Majoranas getting their mass through the dim-5 Weinberg operator, $\frac{1}{\Lambda_\nu} HHLL$, with $\Lambda_\nu \approx 10^{15}$ GeV. But then there are still two different ways to explain this $(10^{15}\,\text{GeV})^{-1}$ coupling. One is the seesaw mechanism, that justifies it with a very large scale for the new physics: a 10^{10} GeV sterile neutrino with regular Yukawa couplings will define a minimal scenario with just the Weinberg operator and no extra fields at low energies. There is, however, a second possibility that assumes that the new physics is not at 10^{10} GeV but at the TeV. In that case one needs to suppress the Wilson coefficient in the operator, and the natural way to do it is using approximate symmetries that may imply extra light fields, in particular, an axion like majoron (ALM).

2. ALM model

Let us briefly review the model proposed in [1, 2]. It is an extension of the SM with three (2-component) fermion singlets (N, N^c, n), several complex scalar singlets s_i, and a global $U(1)$ symmetry with the charges Q_X given in Table 1. The model is valid below a cut off scale $\Lambda \approx 10$ TeV, so we include higher dimensional operators suppressed by inverse powers of Λ. Then we assume that a linear combination of scalar singlets gets a VEV $v_X \approx$ TeV, and that its flavor is along

	$(\nu\ e)$	e^c	N	N^c	n	$(h^+\ h^0)$	$s_1,\ s_2,\ s_3,\ s_4\ \ldots$
Q_X	$+1$	-1	-2	-1	0	0	$1,\ 2,\ 3,\ 4,\ \ldots$
Z_3	α	α^*	α	α^*	1	1	$\alpha,\ \alpha^*,\ 1,\ \alpha,\ \ldots$

Table 1: Charges under the global symmetry and discrete Z_3 symmetry ($\alpha^3 = 1$).

s_3 with a small component ϵ along s_4. The charge 3 of the main component in the VEV leaves the vacuum still invariant under a phase shift of angle $2\pi/3$, implying the residual Z_3 symmetry given also in Table 1. This discrete symmetry protects the neutrinos and implies a TeV Dirac mass for (N, N^c), but to generate the Weinberg operator one needs to break it with the small VEV component along s_4. Neutrino masses appear then with the right value, two of them through an inverse seesaw and the third one through the usual seesaw, whereas the (pseudo) Goldstone boson ϕ associated to the breaking of the global symmetry has couplings $\lambda_{\nu_i} \approx m_{\nu_i}/v_X$ to neutrinos. In summary, the ALM model includes a light pseudo scalar ϕ with a benchmark mass $m_\phi = 0.5$ eV and couplings to photons $g_{\phi\gamma\gamma} = 1.46 \times 10^{-11}$ GeV^{-1} and to the heaviest neutrino family $\lambda_{\nu_3} = 6.8 \times 10^{-14}$. This is an axion that decays relatively fast ($\tau_\phi \approx 10^{12}$ s) into neutrinos, not into photons.

3. Cosmological evolution: H_0

In the early universe the ALM ϕ decouples at $T \approx 500$ GeV and its abundance is negligible at the beginning of BBN, once all the entropy in the SM heavier particles has been transferred to photons, electrons and neutrinos. The key event in its cosmological evolution occurs at $\overline{T} \approx 26$ keV, when a fraction of CMB photons converts into majorons [3]. This possibility rests on two basic observations. First, photons in a medium get a mass that can be expressed in terms of the refractive index. This *plasmon* mass is proportional to the number of free electrons (not bound in nuclei),

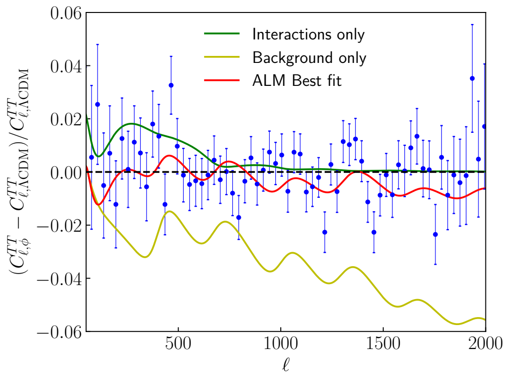
$$n_e(T) \approx 4 \left(\frac{m_e T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_e}{T}\right) + 0.88\, \eta_B\, n_\gamma(T)\,. \tag{2}$$

Second, in the presence of a background magnetic field $\vec{B}$ the photon polarization parallel to $\vec{B}$ mixes with the axion. We will then assume a primordial magnetic field with (today) a strength around 3 nG and coherence of 1 Mpc, changing direction from dominion to dominion.

Since the photon mass changes fast with the expansion, there will be a point when it coincides with the axion mass and implies resonant oscillations similar to the ones in the MSW effect for neutrinos. We obtain that at $\overline{T} = 26$ keV 4.4% of the CMB photons carrying 6.3% of ρ_γ go into majorons. This brings a sudden 1.6% drop in the photon temperature of the universe with two main consequences: *(i)* $N_{\rm eff}$, expressing the total amount of decoupled radiation (includes both majorons and neutrinos), increases from 3 to 3.6; and *(ii)* the baryon to photon ratio increases a 4.7% respect to its value at the beginning of BBN. Notice that, although no baryons nor neutrinos are produced, the reduction in the number of photons increases their relative number at $T < \overline{T}$.

After the conversion photons re-thermalize and the universe evolves down to temperatures $T \approx m_\phi = 0.5$ eV (around recombination), where two important effects take place [4]. First majorons become non relativistic, they evolve more like matter and increase their energy density relative to ρ_γ, defining $N_{\rm eff} = 3.8$ once they decay. Second, majoron decays and inverse decays become effective and put in thermal contact majorons and neutrinos, reducing the free streaming of the dark radiation and providing consistency with CMB observables.

We have used `CLASS` and `MontePython` to obtain the cosmological parameters (in Fig. 1) that provide the best fit to CMB+BAO observables both in ΛCDM and the ALM model. We find a similar goodness of the fit in both models (see in Fig. 2 the differential TT power spectrum for illustration) [2]. Most important, the value of the Hubble constant that we obtain in the ALM



Parameter	ΛCDM	ALM
$100\,\Omega_b h^2$	2.242 ± 0.015	2.295 ± 0.014
$\Omega_{\rm cdm} h^2$	0.119 ± 0.001	0.129 ± 0.001
$100\,\theta_s$	1.0420 ± 0.0003	1.0407 ± 0.0003
$\ln\left(10^{10} A_s\right)$	3.046 ± 0.015	3.062 ± 0.016
n_s	0.967 ± 0.004	0.991 ± 0.004
$\tau_{\rm reio}$	0.055 ± 0.008	0.056 ± 0.008
H_0 [km/s/Mpc]	67.71 ± 0.44	71.4 ± 0.5

Figure 1: Differential TT power spectrum (left) and cosmological parameters in the ALM model (right).

model, $H_0 = (71.42 \pm 0.50)$ km/s/Mpc, is consistent (within 1.8σ) with the one from supernova observations calibrated with CEPHEIDS, versus a 5.6σ discrepancy in ΛCDM.

4. BBN: deuterium, helium, lithium

Let us finally focus on BBN [5]. We see in Fig. 1-right that in the ALM model the baryon density is significantly larger than in ΛCDM. Is this consistent with the primordial deuterium abundance? Actually, in ΛCDM the value of η_{10} preferred by BBN is even smaller than the one dictated by CMB observables, a 2σ deviation that is illustrated in Fig. 2-left. However, this large value of η_{10} in the ALM model is during recombination: at temperatures above $\overline{T} = 26$ keV (*i.e.*, before the conversion of photons into majorons) it was a 5% smaller. We show in Fig. 2-right that the value of η_{10} preferred by CMB+BAO data in the ALM model is in perfect agreement with the one preferred by the observed deuterium and ^{4}He abundances.

We have also studied if the sudden cooling of the universe at $\overline{T} = 26$ keV could interrupt the synthesis of Li+Be and solve the lithium problem (ΛCDM predicts 3 times more primordial Li than observed). We find that this may only happen in generalized scenarios where the photon to axion conversion *(i)* takes place at a higher temperature, $\overline{T} \approx 50$ keV, and *(ii)* a larger fraction of CMB

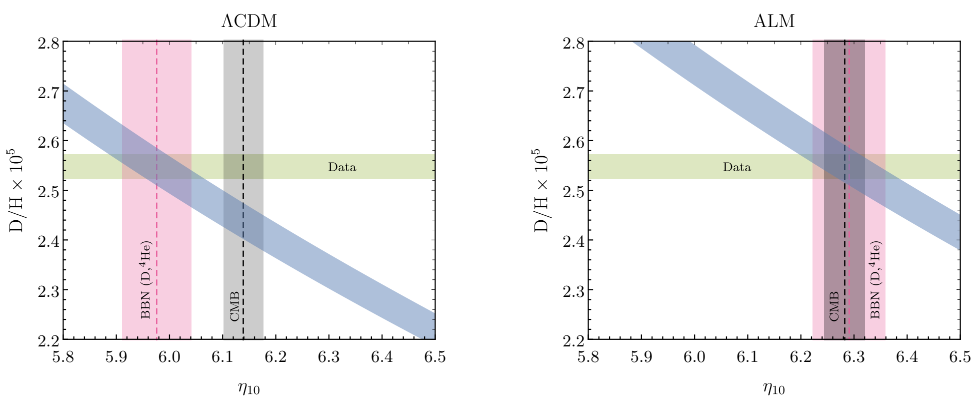


Figure 2: Deuterium abundance for different values of η_{10} in ΛCDM (left) and the ALM model (right).

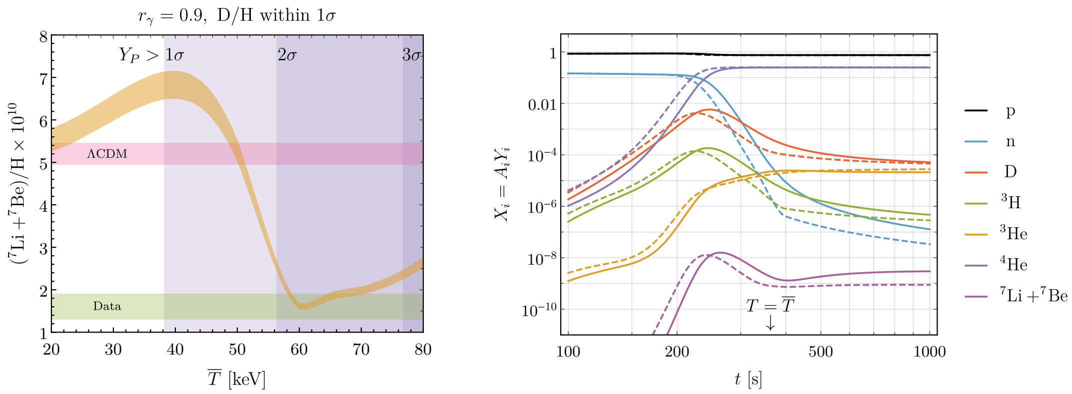


Figure 3: (Li+Be)/H for an ALM model with $r_\gamma = 0.9$, different values of $\overline{T}$ and a value of η_{10} giving the D abundance within 1σ. Primordial abundances at different times in ΛCDM (solid) and that ALM model.

energy is converted into axions, $r_\gamma \approx 0.9$. One might expect that, for example, in models with a larger global symmetry and multiple pseudo-Goldstone bosons. In any case, Fig. 3-left shows that such a model could reproduce the observed Li abundance consistently with the D (at 1σ) and ^{4}He (at 2σ) abundances. It would require (see Fig. 3-right) a large value of η_{10} so that BBN starts earlier than in ΛCDM. The model implies a slight excess of products and a deficit of reactives, but the sudden cooling halts the late production of Li+Be and solves the problem.

To conclude, although none of the current tensions in cosmology have won general acceptance, we find remarkable that such a variation of the standard cosmology is observationally viable. In the near future the quality and the quantity of the probes will only improve, eventually separating ΛCDM from variations like the ALM model discussed here.

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