Cosmological axion and neutrino mass constraints from Planck 2015 temperature and polarization data

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A B S T R A C T

Axions currently provide the most compelling solution to the strong CP problem. These particles may be copiously produced in the early universe, including via thermal processes. Therefore, relic axions constitute a hot dark matter component and their masses are strongly degenerate with those of the three active neutrinos, as they leave identical signatures in the different cosmological observables. In addition, thermal axions, while still relativistic states, also contribute to the relativistic degrees of freedom, parameterized via $N_{\rm eff}$. We present the cosmological bounds on the relic axion and neutrino masses, exploiting the full Planck mission data, which include polarization measurements. In the mixed hot dark matter scenario explored here, we find the tightest and more robust constraint to date on the sum of the three active neutrino masses, $\sum m_\nu < 0.136$ eV at 95% CL, as it is obtained in the very well-known linear perturbation regime. The Planck Sunyaev–Zeldovich cluster number count data further tightens this bound, providing a 95% CL upper limit of $\sum m_\nu < 0.126$ eV in this very same mixed hot dark matter model, a value which is very close to the expectations in the inverted hierarchical neutrino mass scenario. Using this same combination of data sets we find the most stringent bound to date on the thermal axion mass, $m_a < 0.529$ eV at 95% CL.

1. Introduction

The axion field arises as a solution to solve the strong CP problem in Quantum Chromodynamics [1–3]. The axion is the Pseudo-Nambu–Goldstone associated to a new global $U(1)_{PQ}$ (Peccei–Quinn) symmetry that is spontaneously broken at an energy scale f_a. In the early universe, axions can be produced via thermal or non thermal processes. While in the former the axion contributes as an extra hot thermal relic (together with three active neutrinos), in the latter the axion could be the cold dark matter component. In the following, we shall focus on the thermal axion scenario. In order to compute the present thermal axion relic density, the most relevant process is the axion–pion interaction, $\pi + \pi \rightarrow \pi + a$. The characteristic parameter for the thermal axion is f_a, the axion coupling constant, that canbe related to the axion mass by

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{R}}{1+R} = 0.6 \text{ eV} \frac{10^7 \text{ GeV}}{f_a}, \qquad (1)$$

where the up-to-down quark masses ratio is taken as $R = 0.553 \pm 0.043$, and $f_\pi = 93$ MeV is the pion decay constant.

Thermal axions, while still relativistic, will increase the amount of radiation in the universe, contributing to the effective number of relativistic degrees of freedom $N_{\rm eff}$. In the standard cosmological Λ-CDM model with three active neutrino species, we expect $N_{\rm eff} = 3.046$ [4], where the 0.046 takes into account corrections for the non-instantaneous neutrino decoupling from the primor-

dial plasma. An extra $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$ modifies the damping tail of the Cosmic Microwave Background (CMB) temperature angular power spectrum, changing two important scales at recombination, the sound horizon and the Silk damping, as well as also the primordial abundances of the light elements predicted by Big Bang Nucleosynthesis. When thermal axions become non-relativistic particles, they will affect the different cosmological observables in an analogous way to that of massive neutrinos, i.e. by increasing the amount of the (hot) dark matter density in our universe. Axions will suppress the structure formation at scales smaller than its free-streaming scale, favouring clustering only at large scales. Thermal axions will also leave an imprint on the CMB temperature anisotropies, via the early integrated Sachs–Wolfe effect. Therefore, a large degeneracy between the axion mass and the total neutrino mass is expected [5]. Several papers in the literature have provided cosmological constraints on the thermal axion mass in different cosmological scenarios, see e.g. Refs. [5–11].

In light of the recent Planck 2015 temperature and polarization data [12], it is timely to compute the changes on the existing bounds on the thermal axion mass, including the case in which massive neutrinos are present. Our results are obtained using the Monte Carlo Markov Chains (MCMC) package CosmoMC [13], with CAMB (Code for Anisotropies in the Microwave Background) [14] as solver for the Boltzman equations. In the mixed hot dark matter scenario, in which both axion and neutrino masses are allowed to freely vary, we find the tightest and more robust constraint to date on the sum of the three active neutrino masses, $\sum m_\nu < 0.156$ eV at 95% CL, as it only relies on the (very well-known) linear perturbation regime.

2. Thermal axion cosmological model

The scenario we analyze here is the ΛCDM model, with both axions and neutrinos as extra hot thermal relics. We describe this scenario by the following set of parameters:

$$\{\omega_b, \omega_c, \Theta_s, \tau, m_a, \sum m_\nu, n_s, \log[10^{10}A_s]\}, \qquad (2)$$

where $\omega_b \equiv \Omega_b h^2$ is the baryon matter energy density, $\omega_c \equiv \Omega_c h^2$ the cold dark matter energy density, Θ_s is the ratio between the sound horizon and the angular diameter distance at decoupling, τ is the reionization optical depth, m_a is the axion mass in eV and $\sum m_\nu$ the sum of three active neutrino masses in eV. We consider also the inflationary parameters, the scalar spectral index n_s and the amplitude of the primordial spectrum A_s. We use flat priors for all the parameters, as listed in Table 1. Notice that the standard extra radiation density will change, as the presence of a thermal axion will increase the value of the effective number of relativistic degrees of freedom in the following way:

$$\Delta N_{\text{eff}} = \frac{4}{7}\left(\frac{3}{2}\frac{n_a}{n_\nu}\right)^{4/3}, \qquad (3)$$

where n_a is the axion number density and n_ν is the present neutrino plus antineutrino number density per flavor. The current axion number density is a function of the axion decoupling temperature T_D, that is a function of the axion mass m_a. For the details related to the calculation of the axion decoupling temperature, we refer the reader to Ref. [10], where it can be seen that:

$$n_a = \frac{g_{\star S}(T_0)}{g_{\star S}(T_D)} \times \frac{n_\gamma}{2}, \qquad (4)$$

in which $g_{\star S}$ refers to the number of *entropic* degrees of freedom and n_γ is the present photon density ($n_\gamma = 410.5 \pm 0.5 \text{ cm}^{-3}$). At the current temperature, $g_{\star S}(T_0) = 3.91$.

Table 1
Priors for the parameters used in the MCMC analyses.

Parameter	Prior
$\Omega_b h^2$	[0.005, 0.1]
$\Omega_{\text{cdm}} h^2$	[0.001, 0.99]
Θ_s	[0.5, 10]
τ	[0.01, 0.8]
m_a (eV)	[0.1, 3]
$\sum m_\nu$ (eV)	[0.06, 3]
n_s	[0.9, 1.1]
$\log[10^{10}A_s]$	[2.7, 4]

3. Datasets

Our baseline data set consists of the recent Planck 2015 satellite CMB temperature and polarization measurements [12,15,16]. We consider a combination of the likelihood at $30 \leq \ell \leq 2500$ using TT, TE and EE power spectra and the Planck low-ℓ multipole likelihood in the range $2 \leq \ell \leq 29$. We refer to this combination as *Planck TT,TE,EE+lowP*, following the nomenclature of Ref. [15]. We also include the new Planck 2015 lensing likelihood, [17], constructed from measurements of the power spectrum of the lensing potential, referring to it as *lensing*. Concerning Planck catalogs, we make use of the Sunyaev–Zeldovich second cluster catalog [18,19] (denoted as *SZ* in what follows), which consists of 439 clusters with their corresponding redshifts and with a signal-to-noise ratio $q > 6$. We also consider additional datasets to the Planck satellite measurements, as a gaussian prior on the Hubble constant $H_0 = 73.8 \pm 2.4$ km/s/Mpc, according with the measurements of the Hubble Space Telescope, [20]. We refer to this data set as *HST*. We also include measurements of the large scale structure of the universe in their geometrical form, i.e. in the form of Baryon Acoustic Oscillations (BAO). In particular, we use the 6dFGS, SDSS-MGS and BOSS DR11 measurements of D_V/r_d^2 [21–23], referring to the combination of all of them as *BAO*. We shall also consider large scale structure measurements in their full matter power spectrum form, as provided by WiggleZ survey [24], and denoted as *MPK*. Tomographic weak lensing surveys provide a powerful tool to constrain the mass distribution in the universe, and therefore we shall also exploit in our analyses the constraint on the relationship between σ_8 and Ω_m of $\sigma_8(\Omega_m/0.27)^{0.46} = 0.774 \pm 0.040$ provided by the Canada–France–Hawaii Telescope [25], CFHTLenS. This last measurement is referred to as *WL*.

4. Results

Table 2 summarises the results from our MCMC analyses in the mixed hot dark matter scenario revisited here. Notice that Planck temperature and polarization measurements (*TT*, *TE*, *EE* and *lowP*) set 95% CL upper bounds of $\sum m_\nu < 0.441$ eV and $m_a < 2.09$ eV respectively. The bounds on the thermal axion mass are similar to those obtained in the case in which only axion masses are considered, albeit for that case the value of the σ_8 parameter is always higher than the one shown here, as only one hot relic suppresses the small-scale clustering. Nevertheless the deviation of σ_8 is not significant (about half sigma away from the value illustrated in Table 2). Furthermore, neutrino oscillation experiments have provided compelling evidence for the existence of neutrino masses and therefore neutrinos must be added as massive particles. The addition of CMB lensing measurements from the Planck satellite weakens the neutrino mass bounds, as discussed in [15]: the lensing reconstruction data prefers lensing amplitudes lower than the standard prediction, and this favours higher neutrino masses, as the presence of those will smooth the lensing power spectrum.