PHYSICAL REVIEW D **90,** 043534 (2014)

Axion cold dark matter: Status after Planck and BICEP2

Eleonora Di Valentino,[1] Elena Giusarma,[1] Massimiliano Lattanzi,[2] Alessandro Melchiorri,[1] and Olga Mena[3]

[1]*Physics Department and INFN, Università di Roma "La Sapienza", Ple Aldo Moro 2, Rome 00185, Italy*

[2]*Dipartimento di Fisica e Science della Terra, Università di Ferrara and INFN, sezione di Ferrara, Polo Scientifico e Tecnologico–Edficio C Via Saragat 1, Ferrara I-44122, Italy*

[3]*IFIC, Universidad de Valencia-CSIC, Valencia 46071, Spain*

(Received 19 May 2014; published 26 August 2014)

We investigate the axion dark matter scenario (ADM), in which axions account for all of the dark matter in the Universe, in light of the most recent cosmological data. In particular, we use the Planck temperature data, complemented by WMAP E-polarization measurements, as well as the recent BICEP2 observations of B-modes. Baryon acoustic oscillation data, including those from the baryon oscillation spectroscopic survey, are also considered in the numerical analyses. We find that, in the minimal ADM scenario and for $\Lambda_{\rm QCD} = 200$ MeV, the full data set implies that the axion mass $m_{\rm a} = 82.2 \pm 1.1$ μeV [corresponding to the Peccei-Quinn symmetry being broken at a scale $f_{\rm a} = (7.54 \pm 0.10) \times 10^{10}$ GeV], or $m_{\rm a} = 76.6 \pm 2.6$ μeV $[f_{\rm a} = (8.08 \pm 0.27) \times 10^{10}$ GeV] when we allow for a nonstandard effective number of relativistic species $N_{\rm eff}$. We also find a 2σ preference for $N_{\rm eff} > 3.046$. The limit on the sum of neutrino masses is $\sum m_\nu < 0.25$ eV at 95% C.L. for $N_{\rm eff} = 3.046$, or $\sum m_\nu < 0.47$ eV when $N_{\rm eff}$ is a free parameter. Considering extended scenarios where either the dark energy equation-of-state parameter w, the tensor spectral index n_t, or the running of the scalar index $dn_s/d\ln k$ is allowed to vary does not change significantly the axion mass-energy density constraints. However, in the case of the full data set exploited here, there is a preference for a nonzero tensor index or scalar running, driven by the different tensor amplitudes implied by the Planck and BICEP2 observations. We also study the effect on our estimates of theoretical uncertainties, in particular the imprecise knowledge of the QCD scale $\Lambda_{\rm QCD}$, in the calculation of the temperature-dependent axion mass. We find that in the simplest ADM scenario the Planck + WP data set implies that the axion mass $m_{\rm a} = 63.7 \pm 1.2$ μeV for $\Lambda_{\rm QCD} = 400$ MeV. We also comment on the possibility that axions do not make up for all the dark matter, or that the contribution of string-produced axions has been grossly underestimated; in that case, the values that we find for the mass can conservatively be considered as lower limits. Dark matter axions with mass in the 60–80 μeV (corresponding to an axion-photon coupling $G_{a\gamma\gamma} \sim 10^{-14}$ GeV^{-1}) range can, in principle, be detected by looking for axion-to-photon conversion occurring inside a tunable microwave cavity permeated by a high-intensity magnetic field, and operating at a frequency $\nu \simeq 15$–20 GHz. This is out of the reach of current experiments like the axion dark matter experiment (limited to a maximum frequency of a few GHzs), but is, on the other hand, within the reach of the upcoming axion dark matter experiment-high frequency experiment that will explore the 4–40 GHz frequency range and then be sensitive to axion masses up to ~160 μeV.

DOI: 10.1103/PhysRevD.90.043534 PACS numbers: 98.80.-k, 95.85.Sz, 98.70.Vc, 98.80.Cq

I. INTRODUCTION

In the past few years, a great deal of observational evidence has accumulated in support of the ΛCDM cosmological model, which is to date regarded as the standard model of cosmology. One of the great puzzles related to the ΛCDM model, however, is the nature of the dark matter (DM) component that, according to the recent Planck observations [1–3], makes up roughly 27% of the total matter-energy content of the Universe. A well-motivated DM candidate is the axion that was first proposed by Peccei and Quinn [4] to explain the strong charge parity (CP) problem, i.e., the absence of CP violation in strong interactions.

Here, we consider the hypothesis that the axion accounts for all the DM present in the Universe. We put this axion dark matter (ADM) scenario under scrutiny using the most recent cosmological data, in particular the observations of cosmic microwave background (CMB) temperature [1–3] and polarization anisotropies (including the recent BICEP2 detection of B-mode polarization [5,6]) and of baryon acoustic oscillations (BAO) [7–11]. The ADM model has also been revisited by other authors [12,13] in light of BICEP2 data, and our analyses in the minimal ΛCDM scenario agree with these previous works. However, in order to assess the robustness of the cosmological constraints presented in the literature, as well as the tension between BICEP2 and Planck measurements of the tensor-to-scalar ratio, here we also consider extensions of the simplest ADM model. The effects of additional relativistic degrees of freedom, of neutrino masses, of a dark energy equation-of-state parameter and of a free-tensor spectral index are carefully explored.

The paper is structured as follows. Section II introduces axions in cosmology and derives the excluded scenarios after BICEP2 data. Section III describes the analysis method and the data used to analyze the ADM models that survive after applying BICEP2 bounds on gravitational waves and Planck isocurvature constraints. In Sec. IV we present our main results and we draw our conclusions in Sec. V.

II. AXION COSMOLOGY

In order to solve the strong CP problem dynamically, Peccei and Quinn postulated the existence of a new global $U(1)$ (quasi) symmetry, often denoted $U(1)_{\rm PQ}$, that is spontaneously broken at the Peccei-Quinn (PQ) scale $f_{\rm a}$. The spontaneous breaking of the PQ symmetry generates a pseudo–Nambu-Goldstone boson, the axion, which can be copiously produced in the Universe's early stages, both via thermal and nonthermal processes. Thermal axions with sub-eV masses contribute to the hot dark matter component of the Universe, as neutrinos, and the cosmological limits on their properties have been recently updated and presented in Refs. [14,15].

Here we focus on axionlike particles produced nonthermally, as they were postulated as natural candidates for the cold dark matter component [16–20]. The history of axions starts at the PQ scale $f_{\rm a}$. For temperatures between this scale and the QCD phase transition $\Lambda_{\rm QCD}$, the axion is, for practical purposes, a massless particle. When the Universe's temperature approaches $\Lambda_{\rm QCD}$, the axion acquires a mass via instanton effects. The effective potential V for the axion field $a(x)$ is generated through nonpertubative QCD effects [21] and, setting the color anomaly $N = 1$, it may be written as

$$V(a) = f_{\rm a}^2 m_{\rm a}^2(T)\left[1 - \cos\left(\frac{a}{f_{\rm a}}\right)\right], \tag{1}$$

where the axion mass is a function of temperature. Introducing the misalignment angle $\theta \equiv a/f_{\rm a}$, the field evolves according to the Klein-Gordon equation on a flat Friedmann-Robertson-Walker background:

$$\ddot{\theta} + 3H\dot{\theta} + m_{\rm a}^2(T)\theta = 0, \tag{2}$$

where the axion temperature-dependent mass is [21]

$$m_{\rm a}(T) = \begin{cases} C m_{\rm a}(T=0)(\Lambda_{\rm QCD}/T)^4 & T \gtrsim \Lambda_{\rm QCD} \\ m_{\rm a}(T=0) & T \lesssim \Lambda_{\rm QCD}, \end{cases} \tag{3}$$

where $C \simeq 0.018$ is a model dependent factor, see Refs. [21,22], $\Lambda_{\rm QCD} \simeq 200$ MeV and the zero-temperature mass $m_{\rm a}(T=0)$ is related to the PQ scale:

$$m_{\rm a} \simeq 6.2\ \mu\text{eV}\left(\frac{f_{\rm a}}{10^{12}\ \text{GeV}}\right)^{-1}. \tag{4}$$

The axion is effectively massless at $T \gg \Lambda_{\rm QCD}$, as can be seen from Eq. (3).

The PQ symmetry breaking can occur before or after inflation. If there was an inflationary period in the Universe after or during the PQ phase transition, there will exist, together with the standard adiabatic perturbations generated by the inflaton field, axion isocurvature perturbations associated to quantum fluctuations in the axion field. In this scenario, i.e., when the condition

$$f_{\rm a} > \left(\frac{H_I}{2\pi}\right) \tag{5}$$

is satisfied, the initial misalignment angle θ_i should be identical in the whole observable Universe, with a variance given by

$$\langle \sigma_\theta^2 \rangle = \left(\frac{H_I}{2\pi f_{\rm a}}\right)^2, \tag{6}$$

and corresponding to quantum fluctuations in the massless axion field

$$\langle \delta_a^2 \rangle = \left(\frac{H_I}{2\pi}\right)^2, \tag{7}$$

where H_I is the value of the Hubble parameter during inflation. These quantum fluctuations generate an axion isocurvature power spectrum

$$\Delta_a(k) = k^3|\delta_a^2|/2\pi^2 = \frac{H_I^2}{\pi^2}\theta_i^2 f_{\rm a}^2. \tag{8}$$

The Planck data, combined with the nine-year polarization data from WMAP [23] constrain the primordial isocurvature fraction (defined as the ratio of the isocurvature perturbation spectrum to the sum of the adiabatic and isocurvature spectra) to be [24]

$$\beta_{\rm iso} < 0.039, \tag{9}$$

at 95% C.L. and at a scale $k = 0.05\ \text{Mpc}^{-1}$. This limit can be used to exclude regions in the parameter space of the PQ scale and the scale of inflation H_I, since they are related via

$$H_I = 0.96 \times 10^7\ \text{GeV}\left(\frac{\beta_{\rm iso}}{0.04}\right)^{1/2}\left(\frac{\Omega_{\rm a}}{0.120}\right)^{1/2} \times \left(\frac{f_{\rm a}}{10^{11}\ \text{GeV}}\right)^{0.408}, \tag{10}$$

where $\Omega_{\rm a}$ is the axion mass-energy density. In this scenario, in which the PQ symmetry is not restored after inflation, and therefore the condition $f_a > (\frac{H_I}{2\pi})$ holds, and assuming that the dark matter is made of axions produced by the misalignment mechanism [25], Planck data has set a 95% C.L. upper bound on the energy scale of inflation [24],

$$H_I \leq 0.87 \times 10^7 \text{ GeV}\left(\frac{f_a}{10^{11}\text{ GeV}}\right)^{0.408}. \qquad (11)$$

Very recently the BICEP2 collaboration has reported 6σ evidence for the detection of primordial gravitational waves, with a tensor-to-scalar ratio $r = 0.2^{+0.07}_{-0.05}$, pointing to inflationary energy scales of $H_I \sim 10^{14}$ GeV [5,6]. These scales would require a value for f_a that lies several orders of magnitude above the Planck scale and consequently nullifies the axion scenario in which the PQ is broken during inflation. We conclude that, if future CMB polarization experiments confirm the BICEP2 findings, the axion scenario in which the PQ symmetry is broken during inflation will be ruled out, at least in its simplest form. This conclusion could be circumvented in a more complicated scenario (see e.g. Ref. [26] for a proposal in this direction) but we shall not consider this possibility here.

There exists however another possible scenario in which the PQ symmetry is broken after inflation, i.e.

$$f_a < \left(\frac{H_I}{2\pi}\right), \qquad (12)$$

In this second axion cold dark matter scheme, there are no axion isocurvature perturbations since there are not axion quantum fluctuations. On the other hand, there will exist a contribution to the total axion energy density from axionic string decays. We briefly summarize these two contributions (misalignment and axionic string decays) to $\Omega_a h^2$. The misalignment mechanism will produce an initial axion number density which reads

$$n_a(T_1) \simeq \frac{1}{2} m_a(T_1) f_a^2 \langle f(\theta_i)\theta_i^2\rangle, \qquad (13)$$

where T_1 is defined as the temperature for which the condition $m_a(T_1) = 3H(T_1)$ is satisfied, and $f(\theta_i)$ is a function related to anharmonic effects, linked to the fact that Eq. (2) has been obtained assuming that the potential, Eq. (1), is harmonic. The value of $f(\theta_i)\theta_i^2$ is an average of a uniform distribution of all possible initial values:

$$\langle \theta_i^2 f(\theta_i)\rangle = \frac{1}{2\pi}\int_{-\pi}^{\pi} \theta_i^2 f(\theta_i) d\theta_i = 8.77, \qquad (14)$$

considering the analytic expression for $f(\theta_i)$ provided by Ref. [27]. If anharmonic effects are neglected (i.e., $f(\theta_i) = 1$), the factor quoted above should be replaced by the standard $\pi^2/3$, changing the cold dark matter axion population and consequently the cosmological constraints here presented, as we will shortly see.

The mass-energy density of axions today related to misalignment production is obtained via the product of the ratio of the initial axion number density to entropy density times the present entropy density, times the axion mass m_a, and reads [27]

$$\Omega_{a,\text{mis}} h^2 = \begin{cases} 0.236\langle \theta_i^2 f(\theta_i)\rangle \left(\frac{f_a}{10^{12}\text{ GeV}}\right)^{7/6} & f \lesssim \hat{f}_a \\ 0.0051\langle \theta_i^2 f(\theta_i)\rangle \left(\frac{f_a}{10^{12}\text{ GeV}}\right)^{3/2} & f \gtrsim \hat{f}_a, \end{cases} \qquad (15)$$

where $\hat{f}_a = 9.91 \times 10^{16}$ GeV.

If we now consider the recent BICEP2 results, the value of f_a, which, in this second scenario, should be always smaller than the inflationary energy scale, will always be smaller than $\hat{f}_a$ and, therefore, the misalignment axion cold dark matter energy density is

$$\Omega_{a,\text{mis}} h^2 = 2.07\left(\frac{f_a}{10^{12}\text{ GeV}}\right)^{7/6}. \qquad (16)$$

As previously stated, there will also be a contribution from axionic string decays and other axion topological-defect decays, as domain walls, $\Omega_{a,\text{dec}} h^2$. The total (axion) cold dark matter density $\Omega_a h^2$ is the sum of the misalignment and topological-defect decay contributions [28] [12]:

$$\Omega_a h^2 = 2.07(1 + \alpha_{\text{dec}})\left(\frac{f_a}{10^{12}\text{ GeV}}\right)^{7/6}, \qquad (17)$$

where α_{dec} is the ratio $\alpha_{\text{dec}} = \Omega_{a,\text{dec}}/\Omega_{a,\text{mis}}$ between the two contributions. Following Ref. [27], and considering $\alpha_{\text{dec}} = 0.164$ [29] so that [30]

$$\Omega_a h^2 = 2.41\left(\frac{f_a}{10^{12}\text{ GeV}}\right)^{7/6}. \qquad (18)$$

In the following we will quote our results on m_a for the case $\alpha_{\text{dec}} = 0.164$. However, the CMB is actually only sensitive to $\Omega_a h^2 \propto (1 + \alpha_{\text{dec}}) m_a^{-7/6}$; therefore limits on m_a for an arbitrary value of α_{dec} can be obtained from the ones reported in the following section by means of the rescaling:

$$m_a \longrightarrow m_a' = m_a\left[\frac{(1 + \alpha_{\text{dec}})}{(1 + 0.164)}\right]^{6/7}. \qquad (19)$$

In a similar approach, the limits obtained on m_a when neglecting anharmonic effects can also be obtained from the values presented in the next section as

$$m''_{\rm a} = m_{\rm a} \times \left(\frac{\pi^2/3}{8.77}\right)^{6/7} = m_{\rm a} \times 0.43. \qquad (20)$$

III. METHOD

The basic ADM scenario analyzed here is described by the following set of parameters:

$$\{\omega_{\rm b}, \theta_s, \tau, n_s, \log[10^{10}A_s], r, m_{\rm a}\}, \qquad (21)$$

where $\omega_{\rm b} \equiv \Omega_{\rm b}h^2$ is the physical baryon density, θ_s is the ratio of the sound horizon to the angular diameter distance at decoupling, τ is the reionization optical depth, A_s and n_s are, respectively, the amplitude and spectral index of the primordial spectrum of scalar perturbations, r is the ratio between the amplitude of the spectra of tensor and scalar perturbations and finally $m_{\rm a}$ is the axion mass. The latter sets the density of cold dark matter $\Omega_{\rm c}h^2 \equiv \Omega_{\rm a}h^2$ through Eq. (17). All the quantities characterizing the primordial scalar and tensor spectra (amplitudes, spectral indices, possibly running) are evaluated at the pivot wave number $k_0 = 0.05\ {\rm Mpc}^{-1}$. In the baseline model we assume flatness, purely adiabatic initial conditions, a total neutrino mass $\sum m_\nu = 0.06$ eV and a cosmological constant–like dark energy ($w = -1$). We also assume, unless otherwise noted, that the inflation consistency condition $n_T = -r/8$ between the tensor amplitude and spectral index holds.

Extensions to the baseline model described above are also explored. We start by considering the effective number of relativistic degrees of freedom and the sum of neutrino masses, first separately and then jointly, as additional parameters. A model with $\Delta N_{\rm eff}$ sterile massive neutrino species, characterized by a sterile neutrino mass $m_s^{\rm eff}$, is also analyzed. Then we proceed to add the equation-of-state parameter w of dark energy to the baseline model. Finally, we also study the effect of having more freedom in the inflationary sector, by letting the running of the scalar spectral index vary or by relaxing the assumption of the inflation consistency.

We use the CAMB Boltzmann code [31] to evolve the background and perturbation equations, and derive posterior distributions for the model parameters from current data using a Monte Carlo Markov chain (MCMC) analysis based on the publicly available MCMC package COSMOMC [32] that implements the Metropolis-Hastings algorithm.

A. Cosmological data

We consider the data on CMB temperature anisotropies measured by the Planck satellite [2,3] supplemented by the nine-year polarization data from WMAP [23].

The likelihood functions associated to these data sets are estimated and combined using the likelihood code distributed by the Planck collaboration, described in Ref. [3], and publicly available at Planck Legacy Archive [33]. We use Planck TT data up to a maximum multipole number of $\ell_{\rm max} = 2500$, and WMAP nine-year polarization data (WP) up to $\ell = 23$ [23].

Very recently, the BICEP2 collaboration has reported evidence for the detection of B-modes in the multipole range $30 < \ell < 150$ after three seasons of data taking in the South Pole [5,6] with 6σ significance. This B-mode excess is much higher than known systematics and expected foregrounds, the spectrum being well fitted with a tensor-to-scalar ratio $r = 0.2^{+0.07}_{-0.05}$. Notice however that when foregrounds are taken into account, subtraction of different foreground models makes the best-fit value for r move in the range 0.12–0.21. In the following we shall nevertheless assume that the BICEP2 signal is entirely of cosmological origin. The likelihood data from the BICEP2 collaboration has been included in our MCMC analyses accordingly to the latest version of the COSMOMC package.

We also use BAO measurements, namely the SDSS Data Release 7 [8,9], WiggleZ survey [10] and 6dF [11] data sets, as well as the most recent and most accurate BAO measurements to date, arising from the Baryonic Oscillation Spectroscopic Survey (BOSS) Data Release 11 (DR11) results [7].

IV. RESULTS

Here we present the results for the allowed axion mass ranges in the scenario which would survive once the BICEP2 findings concerning the tensor to scalar ratio and, consequently, the energy scale associated to inflation, are confirmed by ongoing and near future searches of primordial B modes. In this case, the PQ symmetry should be broken after inflation. We shall restrict ourselves to such scenario in the following.

Tables I and II depict the results for the different cosmologies explored in this study, for two possible data combinations: (a) Planck temperature data + WMAP polarization (WP) and (b) Planck temperature data, WP and BICEP2 measurements. The constraints on the tensor to scalar ratio are quoted for a reference scale of $k_0 = 0.05\ {\rm Mpc}^{-1}$. For the sake of simplicity, we do not show here all the results with the BAO measurements included in the numerical analyses. We shall quote the values of the cosmological parameters resulting from the analyses with BAO data included only in the cases in which these values notably differ from the results obtained without considering BAO measurements.

In the standard ADM model we find $m_{\rm a} = 81.5 \pm 1.6\ \mu$eV ($m_{\rm a} = 82.0 \pm 1.5\ \mu$eV) from Planck, WP (+BICEP2) data, corresponding to a cold dark matter energy density of $\Omega_{\rm a}h^2 = 0.1194 \pm 0.0027$ ($\Omega_{\rm a}h^2 = 0.1186 \pm 0.026$). Notice that the mean values obtained here can be estimated by equating Eq. (18) to the total dark matter energy density inferred from cosmological observations. Therefore, in mixed axion-cold dark matter schemes (see e.g. Ref. [34] for an implementation of this possible scenario), the required axion cold dark matter will be smaller, implying higher mean values for $m_{\rm a}$.

TABLE I. Constraints at 68% confidence level on cosmological parameters from our analysis for Planck + WP, except for the upper bounds on the neutrino mass and on the tensor-to-scalar ratio, which refer to 95% C.L. upper limits.

Parameter	ADM + r	ADM + r + $N_{\rm eff}$	ADM + r + $\sum m_\nu$	ADM + r+ $\sum m_\nu + N_{\rm eff}$	ADM + r+ $m_s^{\rm eff} + N_{\rm eff}$	ADM + r + w	ADM + r + n_t	ADM + r + $dn_s/d\ln k$
$\Omega_{\rm b}h^2$	0.02204 ± 0.00028	0.02261 ± 0.00043	0.02189 ± 0.00033	0.02245 ± 0.00047	0.02246 ± 0.00039	0.02208 ± 0.00028	0.02211 ± 0.00029	0.02229 ± 0.00031
$\Omega_{\rm a}h^2$	0.1194 ± 0.0027	0.1280 ± 0.0054	0.1203 ± 0.0029	0.1277 ± 0.0054	0.1275 ± 0.0055	0.1192 ± 0.0026	0.1206 ± 0.0030	0.1198 ± 0.0027
θ	1.04127 ± 0.00064	1.04053 ± 0.00072	1.04097 ± 0.00070	1.04039 ± 0.00073	1.04040 ± 0.00074	1.04132 ± 0.00063	1.04117 ± 0.00063	1.04133 ± 0.00064
τ	0.089 ± 0.013	0.097 ± 0.015	0.089 ± 0.013	0.096 ± 0.015	0.096 ± 0.014	0.089 ± 0.013	0.089 ± 0.013	0.100 ± 0.016
n_s	0.9614 ± 0.0075	0.991 ± 0.018	0.9576 ± 0.0088	0.985 ± 0.019	0.982 ± 0.018	0.9617 ± 0.0073	0.9615 ± 0.0074	0.9572 ± 0.0080
$\log[10^{10}A_s]$	3.086 ± 0.025	3.122 ± 0.033	3.086 ± 0.025	3.119 ± 0.033	3.119 ± 0.032	3.087 ± 0.024	3.149 ± 0.026	3.114 ± 0.031
H_0[km/s/Mpc]	67.4 ± 1.2	73.2 ± 3.5	64.5 ± 3.3	70.4 ± 4.7	70.2 ± 3.4	84 ± 10	67.0 ± 1.2	67.5 ± 1.2
r	< 0.12	< 0.19	< 0.13	< 0.19	< 0.18	< 0.13	< 0.93	< 0.23
$m_{\rm a}(\mu{\rm eV})$	81.5 ± 1.6	76.8 ± 2.8	81.0 ± 1.6	77.0 ± 2.7	77.1 ± 2.9	81.6 ± 1.5	80.8 ± 1.7	81.3 ± 1.6
$N_{\rm eff}$	(3.046)	3.79 ± 0.41	(3.046)	3.71 ± 0.41	3.72 ± 0.37	(3.046)	(3.046)	(3.046)
$\sum m_\nu$(eV)	(0.06)	(0.06)	< 0.97	< 0.83	(0.06)	(0.06)	(0.06)	(0.06)
w	(-1)	(-1)	(-1)	(-1)	(-1)	-1.50 ± 0.31	(-1)	(-1)
$m_s^{\rm eff}$(eV)	(0)	(0)	(0)	(0)	< 0.87	$< (0)$	(0)	(0)
n_t	(0)	(0)	(0)	(0)	(0)	(0)	2.19 ± 0.87	(0)
$dn_s/d\ln k$	(0)	(0)	(0)	(0)	(0)	(0)	(0)	-0.022 ± 0.011

TABLE II. Constraints at 68% confidence level on cosmological parameters from our analysis for Planck + WP + BICEP2, except for the bounds on the neutrino mass, which refer to 95% C.L. upper limits.

Parameter	ADM + r	ADM + r + $N_{\rm eff}$	ADM + r + $\sum m_\nu$	ADM + r+ $\sum m_\nu + N_{\rm eff}$	ADM + r + $m_s^{\rm eff} + N_{\rm eff}$	ADM + r + w	ADM + r + n_t	ADM + r + $dn_s/d\ln k$
$\Omega_{\rm b}h^2$	0.02202 ± 0.00028	0.02285 ± 0.00043	0.02193 ± 0.00032	0.02276 ± 0.00046	0.02272 ± 0.0043	0.02207 ± 0.00028	0.02202 ± 0.00029	0.02234 ± 0.00031
$\Omega_{\rm a}h^2$	0.1186 ± 0.0026	0.1313 ± 0.0057	0.1191 ± 0.0028	0.1312 ± 0.0059	0.1257 ± 0.0015	0.1183 ± 0.0025	0.1192 ± 0.0026	0.1193 ± 0.0027
θ	1.04138 ± 0.00063	1.04032 ± 0.00071	1.04118 ± 0.00067	1.04023 ± 0.00073	1.04020 ± 0.00075	1.04143 ± 0.00062	1.04129 ± 0.00065	1.04141 ± 0.00064
τ	0.089 ± 0.013	0.101 ± 0.015	0.090 ± 0.013	0.101 ± 0.015	0.104 ± 0.016	0.090 ± 0.013	0.089 ± 0.013	0.104 ± 0.016
n_s	0.9649 ± 0.0074	1.0057 ± 0.0173	0.9628 ± 0.0083	1.0032 ± 0.0184	1.004 ± 0.0175	0.9654 ± 0.0073	0.9611 ± 0.0074	0.1004 ± 0.0150
$\log[10^{10}A_s]$	3.084 ± 0.025	3.136 ± 0.034	3.085 ± 0.025	3.135 ± 0.034	3.134 ± 0.033	3.085 ± 0.025	3.149 ± 0.025	3.123 ± 0.031
H_0[km/s/Mpc]	67.7 ± 1.2	76.0 ± 3.6	65.9 ± 2.8	74.5 ± 4.3	73.6 ± 3.9	87.1 ± 9.1	67.5 ± 1.2	67.7 ± 1.2
r	0.166 ± 0.036	0.180 ± 0.037	0.168 ± 0.035	0.183 ± 0.038	0.183 ± 0.038	0.168 ± 0.035	0.172 ± 0.047	0.194 ± 0.040
$m_{\rm a}(\mu{\rm eV})$	82.0 ± 1.5	75.3 ± 2.8	81.6 ± 1.6	75.3 ± 2.8	75.3 ± 2.9	82.1 ± 1.5	81.6 ± 1.5	81.5 ± 1.6
$N_{\rm eff}$	(3.046)	4.13 ± 0.43	(3.046)	$4.08. \pm 0.44$	4.08 ± 0.42	(3.046)	(3.046)	(3.046)
$\sum m_\nu$(eV)	(0.06)	(0.06)	< 0.78	< 0.58	(0.06)	(0.06)	(0.06)	(0.06)
w	(-1)	(-1)	(-1)	(-1)	(-1)	-1.57 ± 0.26	(-1)	(-1)
$m_s^{\rm eff}$(eV)	(0)	(0)	(0)	(0)	< 0.63	$< (0)$	(0)	(0)
n_t	(0)	(0)	(0)	(0)	(0)	(0)	1.66 ± 0.51	(0)
$dn_s/d\ln k$	(0)	(0)	(0)	(0)	(0)	(0)	(0)	-0.0278 ± 0.0099

Neglecting anharmonic effects in the axion potential will shift the mean values roughly by a half. If we consider as well BAO measurements, the former value translates into $m_a = 82.2 \pm 1.0\ \mu$eV. Therefore, the inclusion of BAO data reduces mildly the error on m_a. Notice that the value of m_a that we obtain in the standard ADM model after considering BICEP2 data, $m_a = 81.5 \pm 1.6\ \mu$eV, is in perfect agreement with the value obtained by Ref. [12], where it is found that $m_a = 71 \pm 2\ \mu\text{eV}(1 + \alpha_{\text{dec}})$, after applying Eq. (19), which provides the correct rescaling of our bounds for an arbitrary α_{dec}.

When allowing N_{eff} to be a free parameter to extend the minimal ADM scenario to scenarios in which additional relativistic species are present, we find that $m_a = 76.8 \pm 2.8\ \mu$eV and $N_{\text{eff}} = 3.79 \pm 0.41$ for Planck + WP, and $m_a = 75.3 \pm 2.8\ \mu$eV and $N_{\text{eff}} = 4.13 \pm 0.43$ after combining Planck data with WP and BICEP2 measurements. When BAO data sets are included in the analysis, the former values are translated into $m_a = 76.6 \pm 2.6\ \mu$eV and $N_{\text{eff}} = 3.69 \pm 0.30$. Therefore, there exists from CMB data a 2–3σ evidence for extra radiation species. The higher value of N_{eff} found when considering tensor modes and BICEP2 simultaneously was first found in Ref. [15], where it was also pointed out that the tension between the tensor-to scalar ratio r extracted by Planck and WP data and the value of r found by BICEP2 data is less evident when $N_{\text{eff}} > 3$. The reason for this is because, if the value of $N_{\text{eff}} > 3$, the power in the CMB damping tail is suppressed. This can be compensated by a higher scalar spectral index n_s which in turn, will reduce the power at large scales. This power reduction at small multipoles can be compensated by increasing the tensor to scalar ratio r, and the overall result is a positive correlation between N_{eff} and r. This effect is illustrated in Fig. 1, where the left panel depicts the strong positive correlation between N_{eff} and n_s and the left panel shows the relation between n_s and r. Concerning exclusively CMB data, a larger value of N_{eff} can be compensated with a larger value of r (and viceversa), being the degeneracy among these two parameters mildly broken when considering as well BAO data in the MCMC analysis. Thus the preference for $N_{\text{eff}} > 3$, already present in the Planck data, is further increased by the inclusion of the BICEP2 likelihood that assigns a large probability to the $r \simeq 0.2$ region.

The larger value of N_{eff} results in a smaller axion mass (and in a larger associated error) due to the well-known existing correlation between N_{eff} and $\Omega_a h^2$ (that is, the cold dark matter energy density) when considering only CMB data, since it is possible to increase both to leave the redshift of matter-radiation equality unchanged. This effect can be clearly noticed from the results depicted in Tables I and II, where the value of $\Omega_a h^2$ is about $\sim 2\sigma$ larger than the value found in the minimal scenario with no extra dark radiation species. The error on the $\Omega_a h^2$ cosmological parameter is also larger. Given that $\Omega_a h^2$ is inversely proportional to m_a, this results in an anticorrelation between N_{eff} and m_a. The large degeneracy between N_{eff} and $\Omega_c h^2 \equiv \Omega_a h^2$ also drives the large value of H_0 found in this case. The degeneracy is partly broken by the inclusion of BAO information: when the BAO data sets are considered, both H_0 and N_{eff} are closer to their ADM + r values, being $H_0 = 71.7 \pm 1.9$ and $N_{\text{eff}} = 3.69 \pm 0.30$ respectively.

We also consider a model in which the active neutrino mass is a free parameter. In this case, $m_a = 81.6 \pm 1.6\ \mu$eV after combining Planck data with WP and BICEP2 measurements, while $m_a = 82.4 \pm 1.1\ \mu$eV when BAO data sets are also considered. However, in this ΛCDM plus

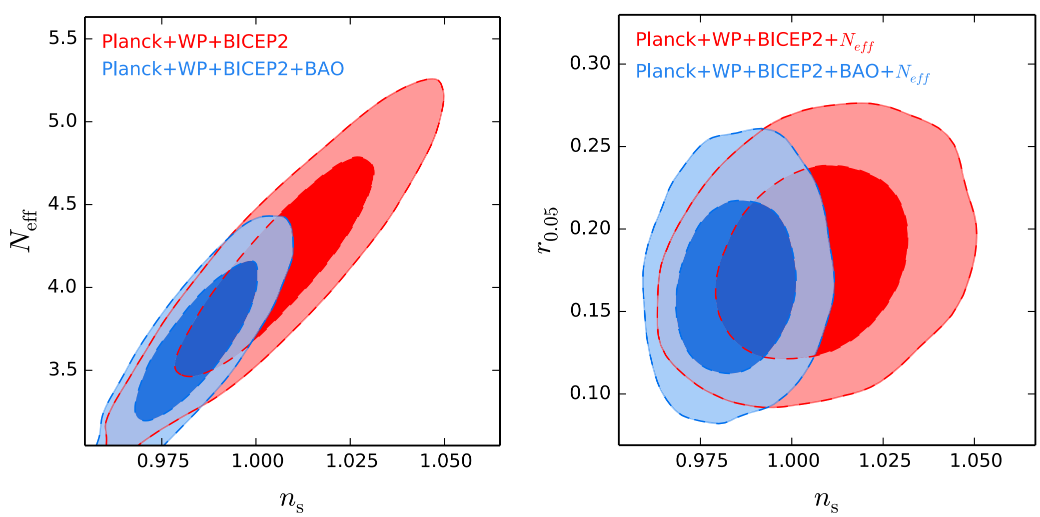

FIG. 1 (color online). Left panel: the red contours show the 68% and 95% C.L. allowed regions from the combination of Planck data, WP and BICEP2 measurements in the (n_s, N_{eff}) plane. The blue contours depict the constraints after the BAO data sets are added in the analysis. Right panel: as in the left panel but in the (n_s, r) plane.

massive neutrino scenario, the neutrino mass bounds are unaffected when considering tensors and BICEP2 data. Indeed, the 95% CL bound on the total neutrino mass we get after considering all the data explored in this paper, $\sum m_\nu < 0.25$ eV agrees perfectly with the one found when neither tensors nor BICEP2 data are included in the analyses [15]. We have also explored here the case in which the three massive active neutrinos coexist with $\Delta N_{\rm eff}$ massless species. The numerical results without BAO data are presented in the fifth column of Tables I and II. The values obtained for the axion mass and for the number of relativistic degrees of freedom in this scenario are very close to the ones reported above for the $N_{\rm eff}$ cosmology, finding, from CMB data, evidence for extra dark radiation species at more than 2σ. When considering the full data set exploited here, including BAO measurements, the bound on the neutrino mass becomes less stringent than in the three massive neutrino scenario due to the strong $\sum m_\nu$-$N_{\rm eff}$ degeneracy: we find a 95% C.L. bound of $\sum m_\nu < 0.47$ eV from the combination of Planck data with WP, BICEP2 and BAO measurements. Notice that, as in the case of the ADM plus $N_{\rm eff}$ relativistic degrees of freedom model, the mass of the axion is smaller and the value of the Hubble constant is larger than in the standard ADM scenario. The reason for that is due to the large existing degeneracy between $\Omega_{\rm a}h^2$ and $N_{\rm eff}$ when considering CMB data only: notice the higher value of $\Omega_{\rm a}h^2$ in Tables I and II, when compared to its value in the standard ADM + r scenario.

The last neutrino scenario we analyze here is the case in which there are $\Delta N_{\rm eff}$ sterile massive neutrino species, characterized by a mass $m_s^{\rm eff}$, which, for instance, in the case of a thermally distributed sterile neutrino state, reads

$$m_s^{\rm eff} = (T_s/T_\nu)^3 m_s = (\Delta N_{\rm eff})^{3/4} m_s, \qquad (22)$$

where T_s, T_ν are the current temperature of the sterile and active neutrino species, respectively, and m_s is the true sterile neutrino mass. We recall however that the parametrization in terms of $\Delta N_{\rm eff}$ and $m_s^{\rm eff}$ is more general, and also includes, among others, the case of a Dodelson-Widrow sterile neutrino (in which case $m_s^{\rm eff} = \Delta N_{\rm eff} m_s$). For this particular case we have fixed the mass of the three light neutrino species $\sum m_\nu = 0.06$ eV, i.e., the minimum value indicated by neutrino oscillation data. In this case, we find an axion mass, a number of neutrino species and an effective sterile neutrino mass of $m_{\rm a} = 75.3 \pm 2.9$ μeV, $N_{\rm eff} = 4.08 \pm 0.42$ and $m_s^{\rm eff} < 0.63$ eV at 95% C.L. ($m_{\rm a} = 76.5 \pm 2.6$ μeV, $N_{\rm eff} = 3.82 \pm 0.32$ and $m_s^{\rm eff} < 0.51$ eV at 95% C.L.) before (after) the combination of Planck, WP and BICEP2 measurements with BAO results. As previously explained and as expected, the mean values for $N_{\rm eff}$ are considerably larger than those found in the absence of BICEP2 data. Concerning the bounds on the effective sterile neutrino mass, the values are mildly shifted when the BICEP2 measurements are addressed due to the anticorrelation between $N_{\rm eff}$ and $m_s^{\rm eff}$, being that the 95% C.L. constraints on the neutrino mass constraints are tighter when considering BICEP2 data. Our findings agree with the recent results presented in Refs. [35–37], which also include BICEP2 data. Note that the mean value of the cold dark matter density, made by axions, is, again, larger than what is found in the standard ADM + r scenario.

The next scenario explored here is a wCDM model with a free, constant, dark energy equation-of-state parameter w. Both the values of the axion masses and the value of the tensor-to-scalar ratio r are very close to their values in the ADM model. However, when the BAO data are not considered, the equation-of-state parameter is different from -1 at ~95% C.L. ($w = -1.57 \pm 0.26$), and we also find a very large value for $H_0 = 87.1 \pm 9.1$ km/s/Mpc. The addition of BAO constraints makes both the value of the Hubble constant H_0 and of the dark energy equation of state w much closer to their expected values within a minimal ΛCDM scenario, the values of these two parameters being $w = -1.12 \pm 0.12$ and $H_0 = 70.5 \pm 2.8$ km/s/Mpc, respectively. This illustrates the highly successful constraining power of BAO data concerning dark energy measurements.

Very recently, the authors of Ref. [38] extracted the tensor spectral index from the BICEP2 measurements. The standard inflationary paradigm predicts a small, negative, tensor spectral index. More concretely, the inflation consistency relation implies that $n_T \simeq -r/8$. We shall relax this constraint here, leaving n_T as a free parameter. We rule out a scale invariant tensor spectrum with 3σ significance when considering CMB data only. The addition of BAO measurements does not change these results significantly; see Fig. 2. As expected, the axion mass constraints are unaffected by the presence of a free n_T. The value of the tensor-to-scalar ratio we find is $r = 0.172 \pm 0.047$ using the Planck + WP + BICEP2 data set. The fact that the data support a nonzero spectral index for tensors also implies that r strongly depends on the scale k_0. The corresponding 95% C.L. limit on $r_{0.002} \equiv r(k = 0.002\ {\rm Mpc}^{-1})$ is $r_{0.002} < 0.055$ for the Planck + WP + BICEP2 data sets; see Fig. 2, right panel.

The latest extended scenario considered is the one with a running of the scalar spectral index $n_{\rm run} = dn_s/d\ln k$. This minimal extension was first addressed in the context of a ΛCDM scenario by the BICEP2 collaboration, in order to relax the discrepancy between their measurements of the tensor-to-scalar ratio r and the limits on the same quantity arising from Planck data [5,6]. The reason for that is due to the degeneracy between the running and the scalar spectral index: a negative running of the spectral index can be compensated with a larger scalar spectral index, which will decrease the CMB temperature power spectra at large scales. This lowering effect at low multipoles can be compensated with a higher tensor contribution to the

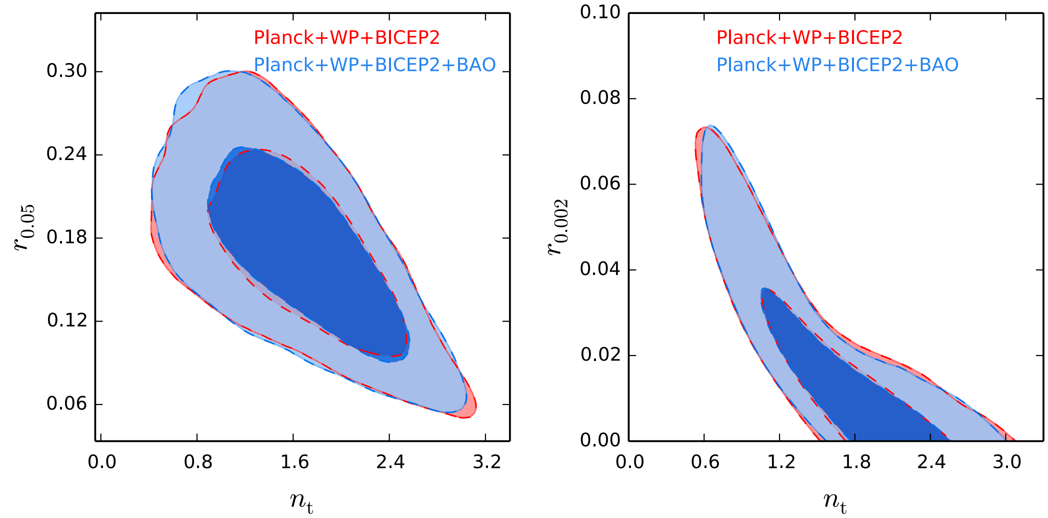

FIG. 2 (color online). Left panel: the red contours show the 68% and 95% CL allowed regions from the combination of Planck data, WP and BICEP2 measurements in the $(n_t, r_{0.05})$ plane, referring these limits to a scale of $k_0 = 0.05\ \mathrm{Mpc}^{-1}$. The blue contours depict the constraints after the BAO data sets are added in the analysis. Right panel: as in the left panel but for a scale $k_0 = 0.002\ \mathrm{Mpc}^{-1}$.

temperature fluctuations (by increasing r). The former degeneracies are depicted in Fig. 3. The BICEP2 collaboration reports $dn_s/d\ln k = -0.022 \pm 0.010$ at 68% C.L., whose absolute value is smaller than what we find in the context of the ADM scenario, $dn_s/d\ln k = -0.028 \pm 0.010$ at 68% C.L.

Finally, we briefly comment on how the results reported in this section are affected by theoretical uncertainties. These can be broadly divided into two classes: those due to the imprecise knowledge of the fraction of dark matter provided by misalignment-produced axions, and uncertainties in the $m_a - \Omega_{\mathrm{a,mis}}$ relation. Concerning the former, we have assumed so far that $\Omega_{\mathrm{dm}} = (1+\alpha_{\mathrm{dec}}) \times \Omega_{\mathrm{a,mis}} = 1.164 \times \Omega_{\mathrm{a,mis}}$; however, one could consider the possibility that axions do not make up for the totality of dark matter, or that the contribution of axions produced by string decays (parametrized by α_{dec}) is larger than expected. In fact, there is still some controversy about the magnitude of the string radiation contribution to the total axion density, as some numerical studies find it to be the dominant mechanism (see e.g. Ref. [39]) while in other cases it is found to be comparable or subdominant with respect to the misalignment mechanism (like in Ref. [29], from which we took our reference value $\alpha_{\mathrm{dec}} = 0.164$). We have already commented at the end of Sec. II on the effect of changing the ratio between misalignment- and string decay–produced axions.

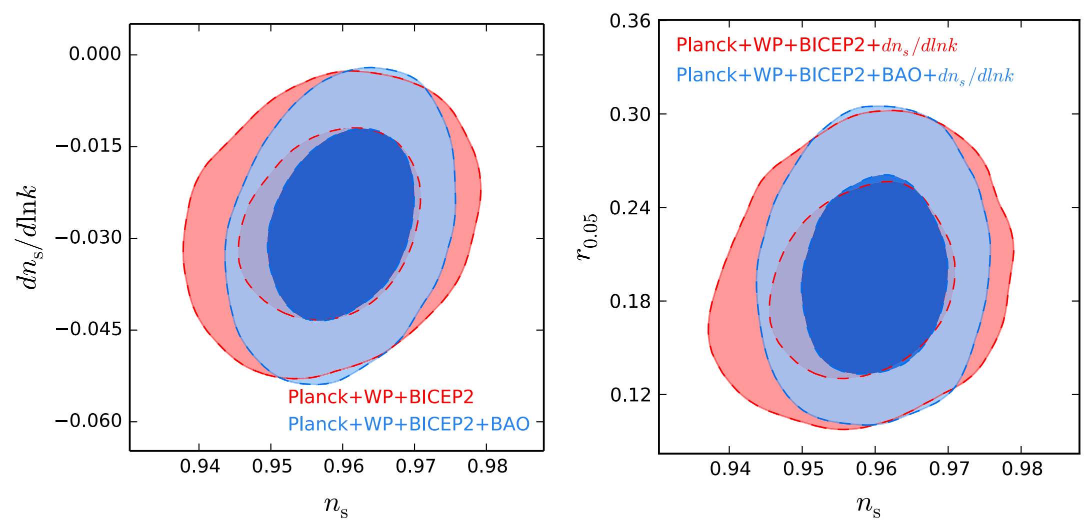

FIG. 3 (color online). Left panel: the red contours show the 68% and 95% C.L. allowed regions from the combination of Planck data, WP and BICEP2 measurements in the $(n_s, dn_s/d\ln k)$ plane. The blue contours depict the constraints after the BAO data sets are added in the analysis. Right panel: as in the left panel but in the (n_s, r) plane.

TABLE III. 68% confidence level constraints on the axion mass considering differing values of the $\Lambda_{\rm QCD}$ scale, for the ADM + r scenario and the Planck + WP data set. The first row corresponds to our Eq. (15) (Eq. (34) of Ref. [27]) while the remaining rows correspond to Eq. (30) of Ref. [40].

$\Lambda_{\rm QCD}$[MeV]	$m_a[\mu{\rm eV}]$
200	81.5 ± 1.6
320	75.6 ± 1.4
380	69.0 ± 1.3
440	63.7 ± 1.2

However, we could take a step further and take the very conservative view that we know nothing about the fraction of dark matter provided by misalignment-produced axions. In this case we can still note that

$$\Omega_{\rm a,mis} \leq \Omega_{\rm a} \leq \Omega_{\rm dm}, \quad (23)$$

from which it readily follows that the values reported in the tables (divided by a factor $1.164^{6/7} \simeq 1.14$ to consider only the misaligment contribution to the total Ω) can be considered as lower bounds on the axion mass. In other words, we can put conservative lower limits to the axion mass by requiring only that the density of misalignment-produced axions does not exceed the total dark matter density. For example, in the case of the minimal ADM + r scenario, using the value reported in Table I we get $m_a \geq 81.5\ \mu{\rm eV} \times 1.164^{-6/7} = 71.5\ \mu{\rm eV}$.

The second source of uncertainty is the $m_a - \Omega_{\rm a,mis}$ relation. The axion abundance depends, among others, on the details of the QCD phase transition through the temperature-dependent axion mass. Detailed calculations of the axion abundance, together with the relevant fitting formulas, have been presented e.g. in Refs. [40,41]; in particular, the expressions derived there explicitly account for the dependence of $\Omega_{\rm a,mis}$ on the QCD scale $\Lambda_{\rm QCD}$. We have run additional chains for the basic ADM + r scenario, substituting Eq. (16) (that assumes $\Lambda_{\rm QCD} = 200$ MeV) with the $m_a - \Omega_{\rm a,mis}$ relation derived by Bae, Huh, and Kim [40] considering three different values for $\Lambda_{\rm QCD}$, namely $\Lambda_{\rm QCD} = 320$, 380, 440 MeV (see. Eq. (30) of Ref. [40]). The results for the Planck + WP data set are shown in Table III. We see that the value of the axion mass required to explain the observed dark matter density decreases down to $63.7 \pm 1.2\ \mu{\rm eV}$ when the QCD scale is increased up to 440 MeV. We get very similar shift for the Planck + WP + BICEP data set. Another uncertain parameter that enters the $m_a - \Omega_{\rm a,mis}$ relation is the anharmonicity factor $f(\theta)$. As observed at the end of Sec. II, the value of the axion mass scales as $\langle\theta_i^2 f(\theta_i)\rangle^{6/7}$.

V. CONCLUSIONS

The exact nature of dark matter is still an open issue, involving both particle physics and cosmology. A well-motivated candidate for the role of DM is the axion, the pseudo–Nambu-Goldstone boson associated to the breaking of the PQ symmetry, proposed to explain the absence of CP violation in strong interactions. The axion can be created nonthermally in the early Universe through the misalignment mechanism and the decay of axionic strings, and its mass is inversely proportional to the scale $f_{\rm a}$ at which the PQ symmetry is broken. This can happen, in principle, either before or after the end of inflation; however, the large value of the tensor-to-scalar ratio implied by the recent BICEP2 observations seems to exclude the first possibility, as it would imply the presence of a large isocurvature component in the primordial perturbations, far above the current observational limits.

We have presented here the constraints on the axion dark matter scenario, in which the PQ symmetry is broken after inflation, using the most precise CMB data available to date (including the recent BICEP2 on the spectrum of B-modes), as well as the recent and most precise distance BAO constraints to date from the BOSS (DR11). We find that, in the minimal ADM scenario, the largest data set implies $m_{\rm a} = 82.2 \pm 1.1\ \mu{\rm eV}$, corresponding to $f_{\rm a} = (7.54 \pm 0.10) \times 10^{10}$ GeV. These values change to $m_{\rm a} = 76.6 \pm 2.6\ \mu{\rm eV}$ and $f_{\rm a} = (8.08 \pm 0.27) \times 10^{10}$ GeV when we consider a model with an additional number of relativistic degrees of freedom $N_{\rm eff}$. In that case, we also find that a nonstandard value for $N_{\rm eff}$ is preferred at more than 95% C.L. We find similar results for $m_{\rm a}$ and $N_{\rm eff}$ if we also allow the neutrino mass to vary. For what concerns the latter parameter, we obtain $\sum m_\nu < 0.25$ eV at 95% C.L. for the Planck + WP + BICEP2 + BAO data-set if we fix $N_{\rm eff} = 3.046$; the constraint is degraded to $\sum m_\nu < 0.47$ eV when $N_{\rm eff}$ is allowed to vary, due to the strong degeneracy between these two parameters. The case of $\Delta N_{\rm eff}$ sterile massive neutrino species, characterized by a mass $m_s^{\rm eff}$, has also been analyzed and the constraints on the axion mass are very similar to those previously quoted. We find $N_{\rm eff} = 4.08 \pm 0.42$ and $m_s^{\rm eff} < 0.63$ eV at 95% C.L. from the combination of Planck, WP and BICEP2 measurements, finding evidence for extra dark radiation species at more than 2σ.

We have also addressed other extensions to the baseline ADM model, by considering, one at a time, the dark energy equation-of-state parameter w, the tensor spectral index n_T and the running $n_{\rm run}$ of the scalar spectral index. In none of these extended models do the results for $m_{\rm a}$ change significantly. The BICEP2 data, however, drive a preference for nonzero tensor spectral index or nonzero scalar running in the corresponding models.

We have also investigated the effect of theoretical uncertainties like those related to the precise calculation of the temperature-dependent mass, in particular to the value of the QCD scale $\Lambda_{\rm QCD}$. We have found that the axion mass required to explain all the dark matter content of the Universe in the simplest ADM scenario shifts down to

$63.7 \pm 1.2\ \mu\text{eV}$ (for the Planck + WP dataset) when $\Lambda_{\text{QCD}} = 440$ MeV.

The search for axion dark matter is also the target of laboratory experiments like the axion dark matter experiment (ADMX) [42], which uses a tunable microwave cavity positioned in a high magnetic field to detect the conversion of axions into photons. This is enhanced at a resonant frequency $\nu = m_a/2\pi$; for the typical masses found in our study, this corresponds to a frequency $\nu \simeq 15$–20 GHz. ADMX has been operating in the range 0.3–1 GHz, thus being able to exclude DM axions in the mass range between 1.9 and 3.53 μeV [43,44]. The ADMX is currently undergoing an upgrade that will extend its frequency range up to a few GHzs (i.e., masses in the 10 μeV range) [45], which is unfortunately still not enough to detect DM axions in the mass range implied by cosmological observations [46], if the PQ symmetry is broken after inflation (as implied by the recent BICEP2 data). However, a second, smaller experiment called axion dark matter experiment (ADMX) HF (high frequency) is currently being built that will allow probing of the 4–40 Ghz range [45], thus being in principle sensitive to axion masses approximately in the 16–160 μeV range, allowing it to directly test the ADM scenario, at least in its simplest implementation.

Finally, we remark that the values of the axion mass found in our analysis correspond to an axion-photon coupling constant $G_{a\gamma\gamma}$ in the 10^{-14} GeV^{-1} range (or larger if we interpret our results on the mass as lower limits), the exact value depending on the electromagnetic and color anomalies associated with the axial current associated with the axion.

ACKNOWLEDGMENTS

M. L. is supported by Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) through the PRIN grant *Galactic and extragalactic polarized microwave emission'* (Contract No. PRIN 2009XZ54H2-002). Part of this work was carried out while M. L. was visiting the Instituto de Física Corpuscular in Valencia, whose hospitality is kindly acknowledged, supported by the grant *Giovani ricercatori* of the University of Ferrara, financed through Grants No. *Fondi 5x1000 Anno 2010* and No. *Fondi Unicredit 2013*. O. M. is supported by the Consolider Ingenio Grant No. CSD2007-00060, by PROMETEO/2009/116, by the Spanish Ministry Science Grant No. FPA2011-29678 and by the ITN Invisibles Grant No. PITN-GA-2011-289442. We thank A. Ringwald for useful comments on a first version of the draft.

[1] P. A. R. Ade *et al.* (Planck Collaboration), arXiv:1303.5076 [Astron. Astrophys. (to be published)].
[2] P. A. R. Ade *et al.* (Planck Collaboration), arXiv:1303.5062.
[3] P. A. R. Ade *et al.* (Planck Collaboration), arXiv:1303.5075.
[4] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977).
[5] P. A. R. Ade *et al.* (BICEP2 Collaboration), Phys. Rev. Lett. **112**, 241101 (2014).
[6] P. A. R. Ade *et al.* (BICEP2 Collaboration), arXiv:1403.4302.
[7] L. Anderson, E. Aubourg, S. Bailey, F. Beutler, V. Bhardwaj, M. Blanton, A. S. Bolton, J. Brinkmann *et al.*, arXiv:1312.4877.
[8] W. J. Percival *et al.* (SDSS Collaboration), Mon. Not. R. Astron. Soc. **401**, 2148 (2010).
[9] N. Padmanabhan, X. Xu, D. J. Eisenstein, R. Scalzo, A. J. Cuesta, K. T. Mehta, and E. Kazin, Mon. Not. R. Astron. Soc. **427**, 2132 (2012).
[10] C. Blake, E. Kazin, F. Beutler, T. Davis, D. Parkinson, S. Brough, M. Colless, C. Contreras *et al.*, Mon. Not. R. Astron. Soc. **418**, 1707 (2011).
[11] F. Beutler, C. Blake, M. Colless, D. H. Jones, L. Staveley-Smith, L. Campbell, Q. Parker, W. Saunders, and F. Watson, Mon. Not. R. Astron. Soc. **416**, 3017 (2011).
[12] L. Visinelli and P. Gondolo, Phys. Rev. Lett. **113**, 011802 (2014).
[13] D. J. E. Marsh, D. Grin, R. Hlozek, and P. G. Ferreira, Phys. Rev. Lett. **113**, 011801 (2014).
[14] M. Archidiacono, S. Hannestad, A. Mirizzi, G. Raffelt, and Y. Y. Y. Wong, J. Cosmol. Astropart. Phys. 10 (2013) 020.
[15] E. Giusarma, E. Di Valentino, M. Lattanzi, A. Melchiorri, and O. Mena, Phys. Rev. D **90**, 043507 (2014).
[16] J. Preskill, M. B. Wise, and F. Wilczek, Phys. Lett. **120B**, 127 (1983).
[17] L. F. Abbott and P. Sikivie, Phys. Lett. **120B**, 133 (1983).
[18] M. Dine and W. Fischler, Phys. Lett. **120B**, 137 (1983).
[19] M. S. Turner and F. Wilczek, Phys. Rev. Lett. **66**, 5 (1991).
[20] D. H. Lyth and E. D. Stewart, Phys. Rev. D **46**, 532 (1992).
[21] D. J. Gross, R. D. Pisarski, and L. G. Yaffe, Rev. Mod. Phys. **53**, 43 (1981).
[22] P. Fox, A. Pierce, and S. D. Thomas, arXiv:hep-th/0409059.
[23] C. L. Bennett, D. Larson, J. L. Weiland, N. Jarosik, G. Hinshaw, N. Odegard, K. M. Smith, R. S. Hill *et al.*, Astrophys. J. Suppl. Ser. **208**, 20 (2013).
[24] P. A. R. Ade *et al.* (Planck Collaboration), arXiv:1303.5082.
[25] An additional relevant mechanism of axion production that we will shortly see is via the decay of axionic strings. However, in this particular scenario such contribution will be negligible, since strings and other defects are diluted after the inflationary stage.

[26] T. Higaki, K. S. Jeong, and F. Takahashi, Phys. Lett. B **734**, 21 (2014).
[27] L. Visinelli and P. Gondolo, Phys. Rev. D **80**, 035024 (2009).
[28] For the values of f_a considered here, and relevant for the axion cold dark matter scenario, $f_a \sim 10^{11}$ GeV, axions will decouple when the number of relativistic degrees of freedom includes all the standard model particles, their current number density being highly suppressed and their contribution to $\Delta N_{\mathrm{eff}} \sim 0.03$ [15,47], a deviation which is currently unobservable and may be at reach in future surveys such as Euclid [48].
[29] P. Sikivie, Lect. Notes Phys. **741**, 19 (2008).
[30] A value for the topological-defect decays fractional contribution larger than the one used here has been recently reported in Ref. [49]. This value is obtained by combining the observed value of $\Omega_c h^2$ with estimates of the axion mass based on the Josephson effect.
[31] A. Lewis, A. Challinor, and A. Lasenby, Astrophys. J. **538**, 473 (2000).
[32] A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002).
[33] T. Basse, O. E. Bjaelde, J. Hamann, S. Hannestad, and Y. Y. Y. Won, http://pla.esac.esa.int/pla/aio/planckProducts.html.
[34] H. Baer, A. Lessa, S. Rajagopalan, and W. Sreethawong, J. Cosmol. Astropart. Phys. 06 (2011) 031.
[35] C. Dvorkin, M. Wyman, D. H. Rudd, and W. Hu, arXiv:1403.8049.
[36] J.-F. Zhang, Y.-H. Li, and X. Zhang, arXiv:1403.7028.
[37] M. Archidiacono, N. Fornengo, S. Gariazzo, C. Giunti, S. Hannestad, and M. Laveder, J. Cosmol. Astropart. Phys. 06 (2014) 031.
[38] M. Gerbino, A. Marchini, L. Pagano, L. Salvati, E. Di Valentino, and A. Melchiorri, arXiv:1403.5732.
[39] R. A. Battye and E. P. S. Shellard, Phys. Rev. Lett. **73**, 2954 (1994); **76**, 2203 (1996).
[40] K. J. Bae, J.-H. Huh, and J. E. Kim, J. Cosmol. Astropart. Phys. 09 (2008) 005.
[41] O. Wantz and E. P. S. Shellard, Phys. Rev. D **82**, 123508 (2010).
[42] S. J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L. J. Rosenberg, G. Rybka *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **656**, 39 (2011).
[43] S. J. Asztalos, R. F. Bradley, L. Duffy, C. Hagmann, D. Kinion, D. M. Moltz, L. J. Rosenberg, P. Sikivie *et al.*, Phys. Rev. D **69**, 011101 (2004).
[44] S. J. Asztalos *et al.* (ADMX Collaboration), Phys. Rev. Lett. **104**, 041301 (2010).
[45] K. van Bibber and G. Carosi, in *Proceedings of the 8th Patras Workshop on Axions, WIMPs and WISPs, Hyatt Regency Chicago, Chicago IL USA, 2012*, http://axion-wimp2012.desy.de/.
[46] This is still true even if one assumes $\alpha_{\mathrm{dec}} \simeq 0$, which corresponds, for a given $\Omega_a h^2$, to the smallest value of the axion mass. We also note that it does not help either if axions only make up for part of the total DM content of the Universe. In fact, since $\Omega_a h^2 \propto m_a^{-6/7}$, having $\Omega_a h^2 < \Omega_c h^2$ would just shift the resonant frequency to even higher values.
[47] A. Salvio, A. Strumia, and W. Xue, J. Cosmol. Astropart. Phys. 01 (2014) 011.
[48] T. Basse, O. E. Bjaelde, J. Hamann, S. Hannestad, and Y. Y. Y. Wong, J. Cosmol. Astropart. Phys. 05 (2014) 021.
[49] C. Beck, arXiv:1403.5676.