

# Axion cold dark matter: status after Planck and BICEP2

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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, the full dataset implies that the axion mass  $m_a = 82.2 \pm 1.1 \mu\text{eV}$  (corresponding to the Peccei-Quinn symmetry being broken at a scale  $f_a = (7.54 \pm 0.10) \times 10^{10} \text{ GeV}$ ), or  $m_a = 76.6 \pm 2.6 \mu\text{eV}$  ( $f_a = (8.08 \pm 0.27) \times 10^{10} \text{ GeV}$ ) when we allow for a non-standard effective number of relativistic species  $N_{\text{eff}}$ . We also find a  $2\sigma$  preference for  $N_{\text{eff}} > 3.046$ . The limit on the sum of neutrino masses is  $\sum m_\nu < 0.25 \text{ eV}$  at 95% CL for  $N_{\text{eff}} = 3.046$ , or  $\sum m_\nu < 0.47 \text{ eV}$  when  $N_{\text{eff}}$  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  $dn_s/d\ln k$  are allowed to vary does not change significantly the axion mass-energy density constraints. However, in the case of the full dataset exploited here, there is a preference for a non-zero tensor index or scalar running, driven by the different tensor amplitudes implied by the Planck and BICEP2 observations.

Dark matter axions with mass in the  $70 - 80 \mu\text{eV}$  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  $\nu \simeq 20 \text{ GHz}$ . This is out of the reach of current experiments like ADMX (limited to a maximum frequency of a few GHzs), but is, on the other hand, within the reach of the upcoming ADMX-HF experiment, that will explore the  $4 - 40 \text{ GHz}$  frequency range and then being sensitive to axions masses up to  $\sim 150 \mu\text{eV}$ .

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## I. INTRODUCTION

In the past few years, a great deal of observational evidence has accumulated in support of the  $\Lambda\text{CDM}$  cosmological model, that is to date regarded as the “standard model” of cosmology. One of the great puzzles related to the  $\Lambda\text{CDM}$  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 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  $\Lambda\text{CDM}$  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 analyse 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  $U(1)_{\text{PQ}}$ , that is spontaneously broken at the Peccei-Quinn (PQ) scale  $f_a$ . 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 non-thermal 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 axion-like particles produced non-thermally, as they were postulated as natural candidates for the cold dark matter component [16–20]. The history of axions start at the PQ scale  $f_a$ . For temperatures between this scale and the QCD phase transition  $\Lambda_{\text{QCD}}$ , the axion is, for practical purposes, a massless particle. When the universe's temperature approaches  $\Lambda_{\text{QCD}}$ , the axion acquires a mass via instanton effects. The effective potential  $V$  for the axion field  $a(x)$  is generated through non-perturbative QCD effects [21] and, setting the color anomaly  $N = 1$ , it may be written as

$$V(a) = f_a^2 m_a^2(T) \left[ 1 - \cos\left(\frac{a}{f_a}\right) \right], \quad (1)$$

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

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0, \quad (2)$$

where the axion temperature-dependent mass is [21]

$$m_a(T) = \begin{cases} C m_a(T=0) (\Lambda_{\text{QCD}}/T)^4 & T \gtrsim \Lambda_{\text{QCD}} \\ m_a(T=0) & T \lesssim \Lambda_{\text{QCD}} \end{cases} \quad (3)$$

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

$$m_a \simeq 6.2 \mu\text{eV} \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{-1}. \quad (4)$$

The axion is effectively massless at  $T \gg \Lambda_{\text{QCD}}$ , as it 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

$$f_a > \left( \frac{H_I}{2\pi} \right), \quad (5)$$

is satisfied, the initial misalignment angle  $\theta_i$  should be identical in the whole observable universe, with a variance given by

$$\langle \sigma_\theta^2 \rangle = \left( \frac{H_I}{2\pi f_a} \right)^2, \quad (6)$$

and corresponding to quantum fluctuations in the massless axion field

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

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

$$\Delta_a(k) = k^3 |\delta_a^2| / 2\pi^2 = \frac{H_I^2}{\pi^2} \theta_i^2 f_a^2. \quad (8)$$

The Planck data, combined with the 9-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]

$$\beta_{\text{iso}} < 0.039, \quad (9)$$

at 95% CL 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

$$H_I = 0.96 \times 10^7 \text{ GeV} \left( \frac{\beta_{\text{iso}}}{0.04} \right)^{1/2} \left( \frac{\Omega_a}{0.120} \right)^{1/2} \left( \frac{f_a}{10^{11} \text{ GeV}} \right)^{0.408}, \quad (10)$$

where  $\Omega_a$  is the axion mass-energy density. In this scenario, in which the PQ symmetry is not restored after inflation, and therefore the condition  $f_a > \left(\frac{H_I}{2\pi}\right)$  holds, and assuming that the dark matter is made of axions produced by the misalignment mechanism [39], Planck data has set a 95% CL upper bound on the energy scale of

inflation [24]

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

Very recently the BICEP2 collaboration has reported  $6\sigma$  evidence for the detection of primordial gravitational waves, with a tensor to scalar ratio  $r = 0.2_{-0.05}^{+0.07}$ , pointing

to inflationary energy scales of  $H_I \sim 10^{14}$  GeV [5, 6]. These scale would require a value for  $f_a$  which 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 polarisation 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. [25] 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

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

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 summarise 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

$$n_a(T_1) \simeq \frac{1}{2} m_a(T_1) f_a^2 \theta_i^2 \quad (13)$$

where  $T_1$  is defined as the temperature for which the condition  $m_a(T_1) = 3H(T_1)$  is satisfied. 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 [26]

$$\Omega_{a,\text{mis}} h^2 = \begin{cases} 0.236 \langle \theta_i^2 f(\theta_i) \rangle \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} & f \lesssim \hat{f}_a \\ 0.0051 \langle \theta_i^2 f(\theta_i) \rangle \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{3/2} & f \gtrsim \hat{f}_a \end{cases} \quad (14)$$

where  $\hat{f}_a = 9.91 \times 10^{16}$  GeV 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  $\theta_i^2$  is an average of a uniform distribution of all possible initial values:

$$\langle \theta_i^2 f(\theta_i) \rangle = \frac{1}{2\pi} \int_{-\pi}^{\pi} \theta_i^2 f(\theta_i) d\theta_i. \quad (15)$$

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

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

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

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

where  $\alpha_{\text{dec}}$  is the ratio  $\alpha_{\text{dec}} = \Omega_{a,\text{dec}}/\Omega_{a,\text{mis}}$  between the two contributions.

Following Ref. [26], we consider  $\alpha_{\text{dec}} = 0.164$  so that [40]

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

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  $\alpha_{\text{dec}}$  can be obtained from the ones reported in the following section by means of the rescaling:

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

### III. METHOD

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

$$\{\omega_b, \theta_s, \tau, n_s, \log[10^{10} A_s], r, m_a\}, \quad (20)$$

where  $\omega_b \equiv \Omega_b h^2$  is the physical baryon density,  $\theta_s$  the ratio of the sound horizon to the angular diameter distance at decoupling,  $\tau$  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  $m_a$  is the axion mass. The latter sets the density of cold dark matter  $\Omega_c h^2 \equiv \Omega_a h^2$  through Eq. (17). All the quantities characterising the primordial scalar and tensor spectra (amplitudes, spectral indices, possibly running) are evaluated at the pivot wave number  $k_0 = 0.05 \text{ Mpc}^{-1}$ . In the baseline model we assume flatness, purely adiabatic initial conditions, a total neutrino mass  $\sum m_\nu = 0.06 \text{ eV}$  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  $\Delta N_{\text{eff}}$  sterile massive neutrino species, characterised by a sterile neutrino

mass  $m_s^{\text{eff}}$ , is also analysed. 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 [29] 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` [30] 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 9-year polarization data from WMAP [23].

The likelihood functions associated to these datasets are estimated and combined using the likelihood code distributed by the Planck collaboration, described in Ref. [3], and publicly available at Planck Legacy Archive[41]. We use Planck TT data up to a maximum multipole number of  $\ell_{\text{max}} = 2500$ , and WMAP 9-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  $6\sigma$  significance. This B-mode excess is much higher than known systematics and expected foregrounds, being the spectrum well fitted with a tensor-to-scalar ratio  $r = 0.2_{-0.05}^{+0.07}$ . 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] datasets, as well as the most recent and most accurate BAO measurements to date, arising from the 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  $k_0 = 0.05 \text{ Mpc}^{-1}$ . 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  $m_a = 81.5 \pm 1.6 \mu\text{eV}$  ( $m_a = 82.0 \pm 1.5 \mu\text{eV}$ ) from Planck, WP (+BICEP2) data, corresponding to a cold dark matter energy density of  $\Omega_a h^2 = 0.1194 \pm 0.0027$  ( $\Omega_a h^2 = 0.1186 \pm 0.026$ ). When adding BAO measurements, the former value translates into  $m_a = 82.2 \pm 1.0 \mu\text{eV}$ . Therefore, the inclusion of BAO data reduces mildly the error on  $m_a$ .

When allowing  $N_{\text{eff}}$  to be a free parameter to extend the minimal ADM scenario to scenarios in which additional relativistic species are present, we find that  $m_a = 76.8 \pm 2.8 \mu\text{eV}$  and  $N_{\text{eff}} = 3.79 \pm 0.41$  for Planck+WP, and  $m_a = 75.3 \pm 2.8 \mu\text{eV}$  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  $m_a = 76.6 \pm 2.6 \mu\text{eV}$  and  $N_{\text{eff}} = 3.69 \pm 0.30$ . Therefore, there exists from CMB data a  $2 - 3\sigma$  evidence for extra radiation species. The higher value of  $N_{\text{eff}}$  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  $N_{\text{eff}}$  and  $r$ . This effect is illustrated in Fig. 1, where the left panel depicts the strong positive correlation between  $N_{\text{eff}}$  and  $n_s$  and the left panel shows the relation between  $n_s$  and  $r$ . Concerning exclusively CMB data, a larger value of  $N_{\text{eff}}$  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  $N_{\text{eff}}$  results in a smaller axion mass (and in a larger associated error) due to the well-known

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

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% CL upper limits.

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

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% CL upper limits.

existing correlation between  $N_{\text{eff}}$  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 Tabs. 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  $N_{\text{eff}}$  and  $m_a$ . The large degeneracy between  $N_{\text{eff}}$  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  $N_{\text{eff}}$  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,  $m_a = 81.6 \pm 1.6 \mu\text{eV}$  after combining Planck data with WP and BICEP2 measurements, while  $m_a = 82.4 \pm 1.1 \mu\text{eV}$  when BAO data sets are also considered. However, in this  $\Lambda\text{CDM}$  plus

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,  $\sum m_\nu < 0.25 \text{ eV}$ , 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  $\Delta N_{\text{eff}}$  massless species. The numerical results without BAO data are presented in the fifth column of Tabs. 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  $N_{\text{eff}}$  cosmology, finding, from CMB data, evidence for extra dark radiation species at more than  $2\sigma$ . 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  $\sum m_\nu - N_{\text{eff}}$  degeneracy: we find a 95% CL bound of  $\sum m_\nu < 0.47 \text{ eV}$  from the combination of Planck data with WP, BICEP2 and BAO measurements. Notice that, as in the case of the ADM

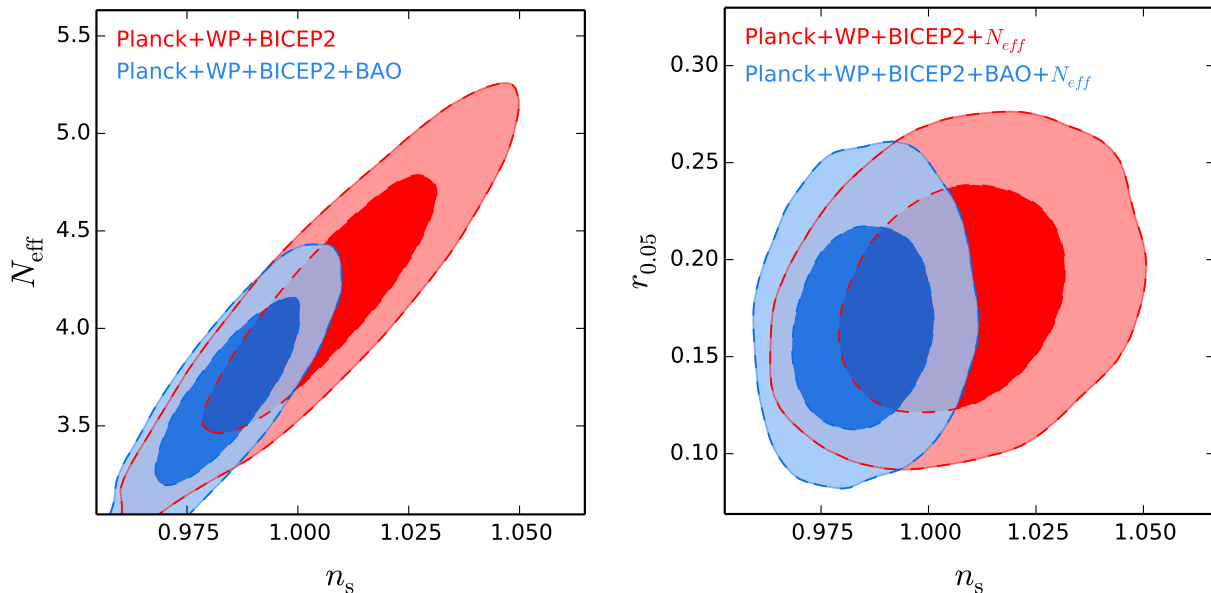


FIG. 1: Left panel: the red contours show the 68% and 95% CL allowed regions from the combination of Planck data, WP and BICEP2 measurements in the  $(n_s, N_{\text{eff}})$  plane. The blue contours depict the constraints after the BAO data sets are added in the analysis. Right panel: as in the left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

plus  $N_{\text{eff}}$  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  $\Lambda$ CDM scenario. The reason for that is due to the large existing degeneracy between  $\Omega_a h^2$  and  $N_{\text{eff}}$  when considering CMB data only: notice the higher value of  $\Omega_a h^2$  in Tabs. I and II, when compared to its value in the standard  $\Lambda$ CDM+ $r$  scenario.

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

$$m_s^{\text{eff}} = (T_s/T_\nu)^3 m_s = (\Delta N_{\text{eff}})^{3/4} m_s, \quad (21)$$

where  $T_s$ ,  $T_\nu$  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 parameterization in terms of  $\Delta N_{\text{eff}}$  and  $m_s^{\text{eff}}$  is more general, and also includes, among others, the case of a Dodelson-Widrow sterile neutrino (in which case  $m_s^{\text{eff}} = \Delta N_{\text{eff}} m_s$ ). 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  $m_a = 75.3 \pm 2.9 \mu\text{eV}$ ,  $N_{\text{eff}} = 4.08 \pm 0.42$  and  $m_s^{\text{eff}} < 0.63$  eV at 95% CL ( $m_a = 76.5 \pm 2.6 \mu\text{eV}$ ,  $N_{\text{eff}} = 3.82 \pm 0.32$  and  $m_s^{\text{eff}} < 0.51$  eV at 95% CL) before (after) the combination of Planck, WP and BICEP2 measurements with BAO results. As previously explained and as expected, the mean values for  $N_{\text{eff}}$  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  $N_{\text{eff}}$  and  $m_s^{\text{eff}}$ , being the 95% CL constraints on the neutrino mass constraints tighter when considering BICEP2 data. Our findings agree with the recent results presented in Refs. [31–33], 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  $\Lambda$ CDM+ $r$  scenario.

The next scenario explored here is a  $w$ CDM 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  $\Lambda$ CDM model. However, when the BAO data are not considered, the equation-of-state parameter is different from  $-1$  at  $\sim 95\%$  CL ( $w = -1.57 \pm 0.26$ ), and we also find a very large value for  $H_0 = 87.1 \pm 9.1$  km/s/Mpc. The addition of BAO constraints make 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  $\Lambda$ CDM scenario, being the values of these two parameters  $w = -1.12 \pm 0.12$  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. [34] have 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 constrain here, leaving  $n_T$  as a free pa-

parameter. We rule out a scale invariant tensor spectrum with  $3\sigma$  significance when considering CMB data only. The addition of BAO measurements does not change significantly these results, 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 dataset. The fact that the data support a non-zero spectral index for tensors also implies that  $r$  strongly depends on the scale  $k_0$ . The corresponding 95% CL limit on  $r_{0.002} \equiv r(k = 0.002 \text{ Mpc}^{-1})$  is  $r_{0.002} < 0.055$  for the Planck+WP+BICEP2 datasets, see Fig. 2, right panel.

The latest extended scenario considered is the one with a running of the scalar spectral index  $n_{\text{run}} = dn_s/d \ln k$ . This minimal extension was firstly addressed in the context of a  $\Lambda$ CDM 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 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% CL, 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% CL.

## 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 non-thermally in the early Universe through the misalignment mechanism and the decay of axionic strings, and its mass is inversely proportional to the scale  $f_a$  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 seem 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 Data Release 11 (DR11). We find that, in

the minimal ADM scenario, the largest dataset implies  $m_a = 82.2 \pm 1.1 \mu\text{eV}$ , corresponding to  $f_a = (7.54 \pm 0.10) \times 10^{10} \text{ GeV}$ . These values change to  $m_a = 76.6 \pm 2.6 \mu\text{eV}$  and  $f_a = (8.08 \pm 0.27) \times 10^{10} \text{ GeV}$  when we consider a model with an additional number of relativistic degrees of freedom  $N_{\text{eff}}$ . In that case, we also find that a non-standard value for  $N_{\text{eff}}$  is preferred at more than 95% CL. We find similar results for  $m_a$  and  $N_{\text{eff}}$  if we also allow the neutrino mass to vary. For what concerns the latter parameter, we obtain  $\sum m_\nu < 0.25 \text{ eV}$  at 95% CL for the Planck+WP+BICEP2+BAO dataset if we fix  $N_{\text{eff}} = 3.046$ ; the constraint is degraded to  $\sum m_\nu < 0.47 \text{ eV}$  when  $N_{\text{eff}}$  is allowed to vary, due to the strong degeneracy between these two parameters. The case of  $\Delta N_{\text{eff}}$  sterile massive neutrino species, characterised by a mass  $m_s^{\text{eff}}$ , has also been analysed and the constraints on the axion mass are very similar to those previously quoted. We find  $N_{\text{eff}} = 4.08 \pm 0.42$  and  $m_s^{\text{eff}} < 0.63 \text{ eV}$  at 95% CL from the combination of Planck, WP and BICEP2 measurements, finding evidence for extra dark radiation species at more than  $2\sigma$ .

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  $n_{\text{run}}$  of the scalar spectral index. In none of these extended models the results for  $m_a$  change significantly. The BICEP2 data, however, drive a preference for non-zero tensor spectral index or non-zero scalar running in the corresponding models.

The search for axion dark matter is also the target of laboratory experiments like the Axion Dark Matter eXperiment (ADMX) [35], that 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  $\nu \simeq 20 \text{ GHz}$ . ADMX has been operating in the range  $0.3 - 1 \text{ GHz}$ , thus being able to exclude DM axions in the mass range between  $1.9$  and  $3.53 \mu\text{eV}$  [36, 37]. ADMX is currently undergoing an upgrade that will extend its frequency range up to a few GHzs (i.e., masses in the  $10 \mu\text{eV}$  range) [38], which is unfortunately still not enough to detect DM axions in the mass range implied by cosmological observations [42], if the PQ symmetry is broken after inflation (as implied by the recent BICEP2 data). However, a second, smaller experiment called ADMX-HF is currently being built, that will allow to probe the  $4 - 40 \text{ GHz}$  range [38], thus being in principle sensitive to axion masses in the  $\sim 100 \mu\text{eV}$  range, allowing to directly test the ADM scenario, at least in its simplest implementation.

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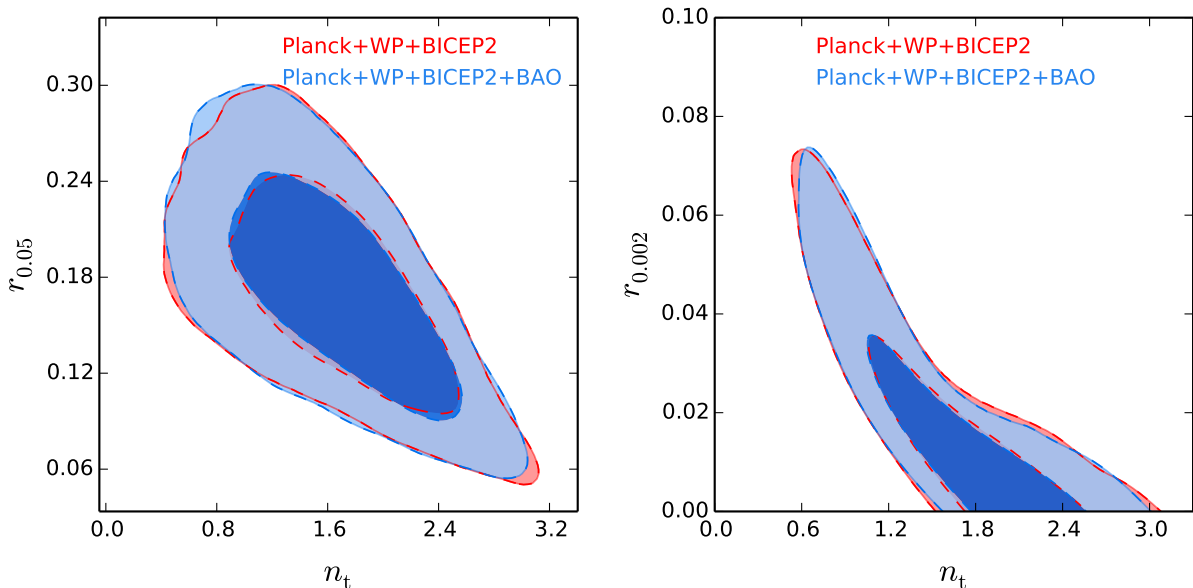


FIG. 2: Left panel: the red contours show the 68% and 95% CL allowed regions from the combination of Planck data, WP and BICEP2 measurements in the  $(n_t, r_{0.05})$  plane, referring these limits to a scale of  $k_0 = 0.05 \text{ Mpc}^{-1}$ . The blue contours depict the constraints after the BAO data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

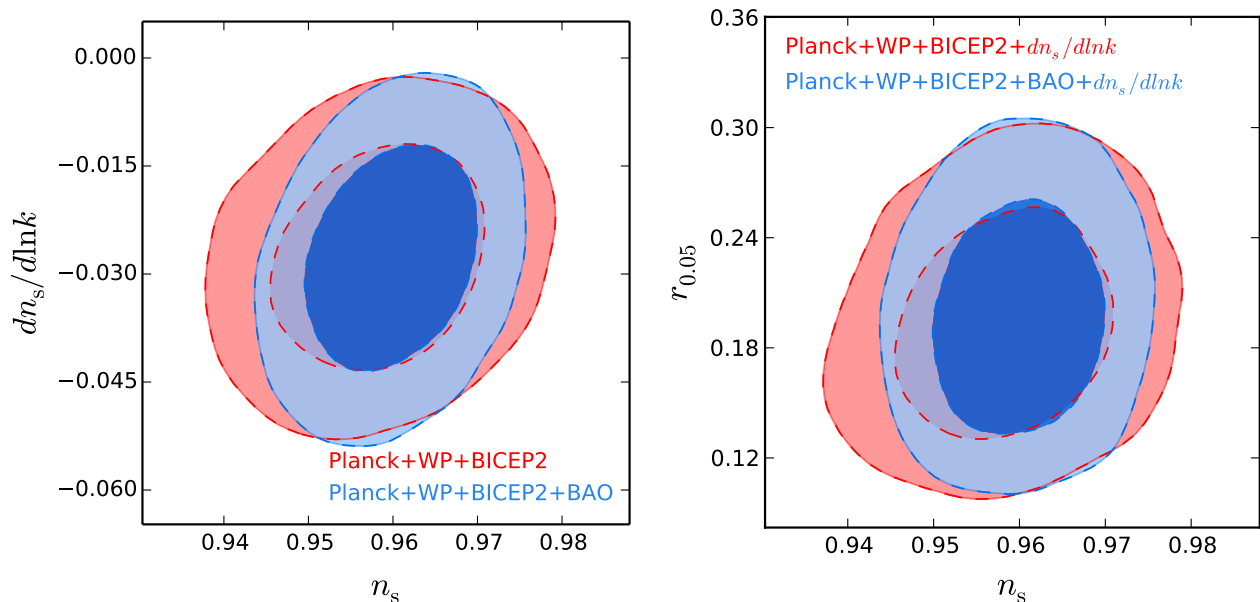


FIG. 3: Left panel: the red contours show the 68% and 95% CL allowed regions from the combination of Planck data, WP and BICEP2 measurements in the  $(n_s, dn_s/d\ln k)$  plane. The blue contours depict the constraints after the BAO data sets are added in the analysis. Right panel: as in the left panel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

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- [40] A value for the axionic string decays fractional contribution larger than the one used here has been recently reported in Ref. [27]. 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.
- [41] <http://pla.esac.esa.int/pla/aio/planckProducts.html>
- [42] This is still true even if one assumes  $\alpha_{\text{dec}} \simeq 0$ , that corresponds, for a given of  $\Omega_a h^2$ , 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.