Probing nuclear rates with Planck and BICEP2

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Big-bang nucleosynthesis (BBN) relates key cosmological parameters to the primordial abundance of light elements. In this paper, we point out that the recent observations of cosmic microwave background anisotropies by the Planck satellite and by the BICEP2 experiment constrain these parameters with such a high level of accuracy that the primordial deuterium abundance can be inferred with remarkable precision. For a given cosmological model, one can obtain independent information on nuclear processes in the energy range relevant for BBN, which determine the eventual ^{2}H/H yield. In particular, assuming the standard cosmological model, we show that a combined analysis of Planck data and of recent deuterium abundance measurements in metal-poor damped Lyman-alpha systems provides independent information on the cross section of the radiative capture reaction $d(p,\gamma)^3$He converting deuterium into helium. Interestingly, the result is higher than the values suggested by a fit of present experimental data in the BBN energy range (10–300 keV), whereas it is in better agreement with *ab initio* theoretical calculations, based on models for the nuclear electromagnetic current derived from realistic interactions. Due to the correlation between the rate of the above nuclear process and the effective number of neutrinos $N_{\rm eff}$, the same analysis points out a $N_{\rm eff} > 3$ as well. We show how this observation changes when assuming a nonminimal cosmological scenario. We conclude that further data on the $d(p,\gamma)^3$He cross section in the few hundred keV range, which can be collected by experiments like LUNA, may either confirm the low value of this rate, or rather give some hint in favor of next-to-minimal cosmological scenarios.

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I. INTRODUCTION

Big-bang nucleosynthesis (BBN, see e.g. Ref. [1] for a recent overview) offers one of the most powerful methods to test the validity of the cosmological model around the MeV energy scale. Two key cosmological parameters enter BBN computations, the energy density in baryons, $\Omega_b h^2$, and the effective neutrino number, $N_{\rm eff}$, defined such that the energy density of relativistic particles at BBN is given by

$$\rho_{\rm rel} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right), \tag{1}$$

where ρ_γ is the cosmic microwave background (CMB) photon energy density, given today by $\rho_{\gamma,0} \approx 4.8 \times 10^{-34}$ g cm^{-3}.

Recent measurements of CMB anisotropies obtained by the Planck satellite are in very good agreement with the theoretical predictions of the minimal ΛCDM cosmological model. They significantly reduce the uncertainty on the parameters of this model, and provide strong bounds on its possible extensions [2]. Assuming a given cosmological scenario and standard BBN dynamics, it is now possible to infer indirectly from Planck data the abundance of primordial nuclides with exquisite precision. For example, assuming ΛCDM, the Planck constraint on the baryon density, $\Omega_b h^2 = 0.02207 \pm 0.00027$, can be translated into a prediction for the primordial deuterium fraction using the public BBN code PArthENoPE [3,4],

$$^2\text{H/H} = (2.65 \pm 0.07) \times 10^{-5} \quad (68\%\,\text{C.L.}). \tag{2}$$

This constraint is competitive with the most recent and precise direct observations. Recently, the authors of Ref. [5] (see also Ref. [6]) presented a new analysis of all known deuterium absorption-line systems, including some new data from very metal-poor Lyman-alpha systems at redshift $z = 3.06726$ (visible in the spectrum of the quasar QSO SDSS J1358 + 6522) and at redshift $z = 3.04984$ (seen in QSO SDSS J1419 + 0829). Their result

$$^2\text{H/H} = (2.53 \pm 0.04) \times 10^{-5} \quad (68\%\,\text{C.L.}), \tag{3}$$

is smaller than the (indirect, model-dependent) cosmological determination from CMB data, but with a comparable uncertainty.

These two deuterium abundance determinations, while broadly consistent, are off by about two standard deviations. This small tension might well be the result of small experimental systematics, either in Planck or in astrophysical deuterium measurements. However, the point of this paper is to underline that current BBN calculations could also be plagued by systematics in the experimental determination of nuclear rates. As explained in the following, the main uncertainty for standard BBN calculations of ^{2}H comes from the rate of the radiative capture reaction $d(p,\gamma)^3$He. A recent review of the experimental status for this process can be found in Ref. [7]. The low-energy limit of its cross section $\sigma(E)$ [or equivalently, of the corresponding astrophysical factor $S(E)$ [8]] is well known thanks to the results of the underground experiment LUNA [9]. However, during BBN, the relevant energy range in the center of mass is rather around $E \simeq 30$–300 keV. For such energies, the uncertainty on the cross section is at the level of 6–10% when fitting $S(E)$ with a polynomial expression. This translates into a theoretical error on the primordial ^{2}H/H ratio of the order of 2% (for a fixed value of the baryon density and $N_{\rm eff}$), comparable to the experimental error in the above cosmological determination (2) or astrophysical determination (3).

Recently, a reliable *ab initio* nuclear theory calculation of this cross section has been performed in Refs. [10–12]. The uncertainty on this prediction can be conservatively estimated to be also of the order of 7% [13]. However, the theoretical result is systematically larger than the best-fit value derived from the experimental data in the BBN energy range. By plugging the theoretical estimate of the cross section into a BBN code one finds that more deuterium is destroyed for the same value of the cosmological baryon density, and thus the predicted primordial ^{2}H abundance results to be smaller [13]. Interestingly, the theory-indicated cross section could be a way to reconcile the slightly different values of ^{2}H/H measured in astrophysical data and predicted by Planck. Indeed, the result quoted in Eq. (2) using the public BBN code PArthENoPE [3] relies on a value of the cross section $d(p,\gamma)^3$He inferred from nuclear experimental data [the default value for the $d(p,\gamma)^3$He rate used in the code was calculated in Ref. [14], and agrees at the 1.4% level with the best-fit result of Ref. [7]].

Further data on this crucial cross section in the relevant energy range might be expected from experiments such as LUNA. While waiting for such measurements one can find out to which extent the deuterium measurement of Ref. [5] can be made even more compatible with Planck predictions when the rate of the reaction $d(p,\gamma)^3$He is treated as a free input parameter. We will address this issue assuming different cosmological models: the minimal ΛCDM model, ΛCDM plus extra radiation, a non-spatially flat universe, etc. This simple exercise points out that, remarkably, present CMB data are powerful enough to provide information on nuclear rates. Moreover, we will see that our results give independent support to the theoretical calculation of Ref. [12]. Of course, this close interplay between astrophysical observations and nuclear physics is not new. It is worth recalling the role that the solar neutrino problem played in the quest for a more accurate solar model, and the impact of this question on experimental efforts for measuring specific nuclear cross sections.

The paper is organized as follows. In the next section, we discuss in more detail the nuclear rates which are most relevant for the determination of the primordial deuterium abundance and its theoretical error. We introduce a simplified way to parametrize the level of uncertainty still affecting the $d(p,\gamma)^3$He reaction rate, found to be sufficient for our analysis. In Sec. III, we describe our method for fitting cosmological and astrophysical data. We present our results in Sec. IV, and discuss their implications in Sec. V.

II. THE PRIMORDIAL DEUTERIUM AS A FUNCTION OF COSMOLOGICAL PARAMETERS AND NUCLEAR RATES

As is well known, the theoretical value of the primordial ^{2}H/H abundance is a rapidly decreasing function of the baryon density parameter $\Omega_b h^2$. If we consider a slightly more general cosmological model with extra radiation, it grows as $N_{\rm eff}$ increases. Finally, this value depends on the cross section of a few leading nuclear processes, responsible for the initial deuterium production and its subsequent processing into $A = 3$ nuclei. More precisely, the calculation depends on the thermal rate of such processes, obtained by convolving their energy-dependent cross section $\sigma(E)$ with the thermal energy distribution of incoming nuclei during BBN. The four leading reactions are listed in Table I. Note that the uncertainties reported in the Table, like all other results quoted in this paper, unless otherwise stated, are calculated with a version of PArthENoPE where the $d(p,\gamma)^3$He reaction rate is updated to the best-fit determination of Ref. [7].

TABLE I. List of the leading reactions and corresponding rate symbols controlling the deuterium abundance after BBN. The last column shows the error on the ratio ^{2}H/H coming from experimental (or theoretical) uncertainties in the cross section of each reaction, for a fixed baryon density $\Omega_b h^2 = 0.02207$.

Reaction	Rate symbol	$\sigma_{^2\rm H/H} \times 10^5$
$p(n,\gamma)^2$H	R_1	± 0.002
$d(p,\gamma)^3$He	R_2	± 0.062
$d(d,n)^3$He	R_3	± 0.020
$d(d,p)^3$H	R_4	± 0.013

In the past, BBN calculations were based on the experimental determination of the cross section of nuclear processes, measured in laboratory experiments. The situation has changed recently, since detailed theoretical calculations are now available, at least for some reactions. For example, this is the case for the cross section of the neutron-proton fusion reaction $p(n,\gamma)^2$H, for which a very accurate result could be derived using pionless effective field theory, with a theoretical error below the percent level [15,16] (see e.g. Ref. [14] for further details). Using PArthENoPE, one can propagate this error to the primordial deuterium abundance. The resulting uncertainty is very small, $\sigma_{^2\mathrm{H/H}} = 0.002 \times 10^{-5}$, i.e. of the order of 0.1% (for $\Omega_b h^2$ fixed at the Planck best-fit value).

The cross sections of dd fusion reactions, $d(d,n)^3$He and $d(d,p)^3$H, are still determined using experimental data. They have been measured in the 100 keV range with a 1–2% uncertainty [17]. This leads to a propagated uncertainty on the deuterium primordial abundance at most of the order of 1%; see Table I.

The main source of uncertainty is presently due to the radiative capture process $d(p,\gamma)^3$He converting deuterium into helium. The present experimental status for the corresponding astrophysical factor $S(E)$ (where E is the center-of-mass energy) was reviewed in Ref. [7]. As we already mentioned, when fitting a polynomial expression for $S(E)$ to the raw data, now dominated by the LUNA results [9], one finds that the uncertainty at 68% C.L. grows from 6% in the low-energy limit to 19% around 1 MeV. In the energy range relevant for BBN, the uncertainty is in the range 6–10%, which gives an error on the primordial deuterium abundance of order $\sigma_{^2\mathrm{H/H}} = 0.062 \times 10^{-5}$, as reported in Table I. This uncertainty is comparable to the experimental error estimated by Ref. [5], and dominates the error budget. In addition, the best-fit value of $S(E)$ inferred from the data in the range 30 keV $\le E \le$ 300 keV is lower than the theoretical result of Refs. [10,12] by about 1σ. This difference may have an impact on the concordance of Planck results for the baryon density with the deuterium abundance measured by Ref. [5].

Using PArthENoPE with the best-fit experimental cross section for the $d(p,\gamma)^3$He reaction, one can check that the best-fit value of the astrophysical determination of the deuterium abundance, $^2\mathrm{H/H} = 2.53 \times 10^{-5}$ [5], corresponds to $\Omega_b h^2 = 0.02269$. However, in the case of the minimal cosmological model (i.e. the spatially flat ΛCDM model, with no extra relativistic species and $N_{\mathrm{eff}} = 3.046$ [18]), we have seen that Planck data yield $\Omega_b h^2 = 0.02207 \pm 0.00027$ (68% C.L.). Hence there is a moderate 2σ tension, which could be relaxed either by assuming a more complicated cosmological model compatible with higher values of the baryon density, or by adopting the theoretical value of the $d(p,\gamma)^3$He cross section [12]. In the latter case, if we stick to the ΛCDM model, the same range for the baryon density leads to

$$^2\mathrm{H/H} = (2.58 \pm 0.07) \times 10^{-5}, \tag{4}$$

in nice agreement with the astrophysical determination at the 1σ level. In other words, increasing the $d(p,\gamma)^3$He thermal rate has the same effect as increasing the cosmological baryon fraction.

This is illustrated in Fig. 1 where the likelihood function $\mathrm{L}(\Omega_b h^2, R_2)$

$$\mathrm{L}(\Omega_b h^2, R_2) = \exp\left(-\frac{(^2\mathrm{H/H_{th}}(\Omega_b h^2, R_2) - {}^2\mathrm{H/H_{ex}})^2}{\sigma_{\mathrm{ex}}^2}\right), \tag{5}$$

is plotted vs baryon density in two different scenarios. The indices "th" and "ex" refer to the theoretical value of ^{2}H/H and to the experimental result of Ref. [5], respectively. The solid line corresponds to $R_2^{\mathrm{ex}}(T)$ obtained by using the best fit of experimental values for the $d(p,\gamma)^3$He cross section, while the dashed line relies on the theoretical prediction of the same cross section [12], whose corresponding rate is denoted by $R_2^{\mathrm{th}}(T)$. The latter brings the agreement with the Planck ΛCDM value of $\Omega_b h^2$ from the 2σ to the 1σ level. Note that, in calculating those likelihoods, we only included the experimental error on astrophysical measurements of the deuterium fraction, $\sigma_{\mathrm{ex}} = 0.05$. Indeed, our purpose is to show what the baryon probability could look like after a future measurement campaign of the $d(p,\gamma)^3$He astrophysical factor, assuming a small uncertainty and two different central values for this measurement. If the theoretical calculation of Ref. [12] was experimentally confirmed, the likelihood profile would shift to the dashed curve.

In the next section, we will generalize this study to nonminimal cosmological scenarios. The aim is to see whether, by combining CMB and BBN data, we can grasp some robust information on the value of the thermal rate R_2

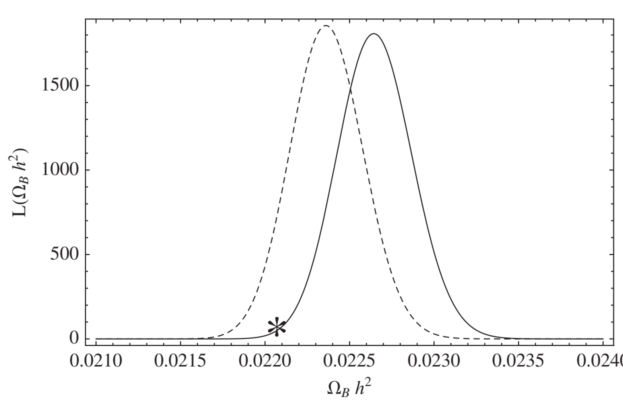

FIG. 1. The likelihood $\mathrm{L}(\Omega_b h^2)$, assuming the astrophysical determination of the primordial deuterium abundance ^{2}H/H by Cooke *et al.* [5], adopting either the experimental best-fit $R_2^{\mathrm{ex}}(T)$ (solid) or *ab initio* calculation $R_2^{\mathrm{th}}(T)$ (dashed) [12]. The star shows the Planck best-fit value of $\Omega_b h^2$ in the minimal ΛCDM model.

preferred by cosmology. To this end, it is enough to parametrize the generic $R_2(T)$ in terms of an overall rescaling factor A_2, namely $R_2(T) = A_2 R_2^{\rm ex}(T)$, and use it in PArthENoPE. This approximation may sound too simplistic, since the thermal rate is a function of the temperature. We notice that, for example, the ratio of the baseline fit of R_2 used in PArthENoPE and the one which is found starting from the calculation of Ref. [12] is not simply a constant as temperature varies in the BBN range and monotonically decreases. This variation is at the level of 1%. The main point however, is the net effect on deuterium. Indeed, we have checked that the theoretical estimate $R_2^{\rm th}$ gives a primordial deuterium which is the same obtained by a constant rescaling of the experimental rate by a constant factor $R = 1.05$ *in the whole range for* $\Omega_b h^2$ of interest, from 0.021 up to 0.023, the difference between the two results for ^{2}H/H being at worst of order 0.1%. Hence, the use of a constant rescaling factor A_2 is reliable enough for our purpose, and offers the advantage of limiting the number of extra free parameters to one.

Assuming this ansatz, we introduce the baryon likelihood function, $\mathrm{L}(\Omega_b h^2, A_2)$, through

$$\mathrm{L}(\Omega_b h^2, A_2) = \exp\left(-\frac{(^2\mathrm{H}/\mathrm{H}_{\rm th}(\Omega_b h^2, A_2) - {}^2\mathrm{H}/\mathrm{H}_{\rm ex})^2}{\sigma_{\rm ex}^2 + \sigma_{\rm th}^2}\right), \tag{6}$$

where the theoretical value is a function of the baryon density and the $d(p,\gamma)^3$He thermal rate rescaling factor A_2, and again we use the experimental value and its squared uncertainty; see Eq. (3). Finally, $\sigma_{\rm th}^2$ is the squared propagated error on the deuterium yield due to the present experimental uncertainty on R_2.

III. DATA ANALYSIS METHOD

Our main data set consists in the Planck public data release of March 2013 [19], based on Planck temperature completed by WMAP9 polarization at low ℓ. We also consider the recent B-mode polarization data from the BICEP2 experiment [20]. In this respect, we include the five bandpowers of the BB spectrum and the window functions provided by the BICEP2 collaboration (http://bicepkeck.org/). We perform a likelihood analysis of this data set following the method of Hamimeche and Lewis [21].

We combine these two CMB data sets (referred as Planck + WP and Planck + WP + BICEP2, respectively) with the deuterium abundance likelihood function $\mathrm{L}(\Omega_b h^2, A_2)$ (referred as BBN).

Occasionally, we will also include the direct measurement of the Hubble constant by Ref. [22] (referred as HST), and information on baryon acoustic oscillations by SDSS-DR7 at redshift $z = 0.35$ [23], by SDSS-DR9 at $z = 0.57$ [24], and by WiggleZ at $z = 0.44, 0.60, 0.73$ [25] (referred all together as BAO).

For the data analysis method, we will use indifferently the publicly available Monte Carlo Markov chain packages CosmoMC [26] (http://cosmologist.info/cosmomc/) and Monte Python [27] (http://montepyhton.net), which rely on the Metropolis-Hastings algorithm for exploring the parameter space, and on a convergence diagnostic based on the Gelman and Rubin statistics. We use the latest version of the two codes (April 201a), which include the support for the Planck Likelihood Code v1.0 (see http://www.sciops.esa.int/wikiSI/planckpla/) and implement an efficient sampling of the parameter space using a fast/slow parameter decorrelation [28]. We checked that the results from the two codes were identical. To evaluate the deuterium abundance produced during the big-bang nucleosynthesis, we use the PArthENoPE code, minimally modified in order to account for the global rescaling factor A_2.

We will first consider the Planck + WP data set assuming the minimal ΛCDM model with six free parameters: the density of baryons and cold dark matter $\Omega_b h^2$ and $\Omega_c h^2$, the ratio θ of the sound horizon to the angular diameter distance at decoupling, the optical depth to reionization τ, the amplitude A_S of the primordial scalar fluctuation spectrum at $k = 0.05\ \mathrm{Mpc}^{-1}$, and the spectral index n_S of this spectrum. We extend this list of free parameters to include the rescaling factor A_2, affecting only the determination of the primordial deuterium abundance. For this model, we consider purely adiabatic initial conditions, we impose spatial flatness, we fix the effective number

TABLE II. Constraints on cosmological parameters (at the 68% confidence level) in the case of the minimal ΛCDM model.

Parameter	Planck + WP + BBN	Planck + WP + BBN + BAO
$\Omega_b h^2$	0.02202 ± 0.00028	0.02209 ± 0.00025
$\Omega_c h^2$	0.1200 ± 0.0026	0.1188 ± 0.0017
θ	1.04129 ± 0.00063	1.04144 ± 0.00058
τ	0.089 ± 0.013	0.091 ± 0.013
n_s	0.9599 ± 0.0073	0.9625 ± 0.0058
$\log[10^{10} A_s]$	3.089 ± 0.025	3.089 ± 0.025
H_0[km/s/Mpc]	67.2 ± 1.2	67.74 ± 0.78
A_2	1.155 ± 0.082	1.138 ± 0.076

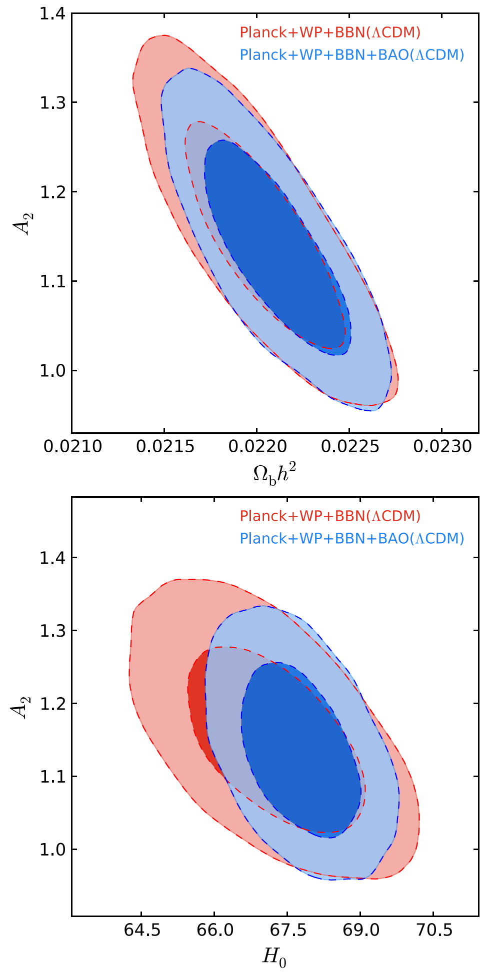

FIG. 2 (color online). Two-dimensional contour plots in the $\Omega_b h^2$ vs A_2 (top panel) and H_0 vs A_2 (bottom panel) planes, showing preferred parameter regions at the 68% and 95% confidence levels in the case of the minimal ΛCDM model.

of neutrinos to its standard value $N_{\rm eff} = 3.046$ [18], and we consider the sum of neutrino masses to be 0.06 eV as in Ref. [2].

Subsequently, we will study several extensions of the minimal ΛCDM model, with extra free parameters: the neutrino effective number $N_{\rm eff}$, the spatial curvature of the Universe parametrized by $\Omega_k = 1 - \Omega_c - \Omega_b - \Omega_\Lambda$, and the amplitude of the lensing power spectrum $A_{\rm L}$ [29].

Finally, we consider a ΛCDM + r framework where we allow for the possibility for a gravitational-wave background with tensor-to-scalar amplitude ratio r. In this case we include the BICEP2 data set, assuming the B-mode signal claimed by this experiment to be the genuine signature of primordial inflationary tensor modes. Since the amplitude of tensor modes measured by BICEP2 is in tension with the upper limit on r coming from the Planck experiment, we also consider two further extensions that could in principle solve the tension: an extra number of relativistic particles parametrized by $N_{\rm eff}$ (see e.g. Ref. [30]) and a running of the spectral index $dn_S/dlnk$ [20].

IV. RESULTS

In Table II, we report our results for the parameters of the minimal ΛCDM model (plus the nuclear rate parameter A_2 and the derived cosmological parameter H_0), using the data combinations Planck + WP + BBN and PLANCK + WP + BBN + BAO.

As expected from the discussion of Secs. I and II, we find that the data provides an indication for A_2 being greater than 1, roughly at the level of two standard deviations, even when adding the BAO data set. We can also check explicitly in Fig. 2 (top panel) that there is a clear anticorrelation between A_2 and $\Omega_b h^2$: in order to improve the agreement between Planck data and deuterium abundance measurements, one needs either a value of the nuclear rate rescaling factor A_2 higher than 1, or a value of the baryon density larger than the Planck mean value. This could be expected, since deuterium is a decreasing function of both the R_2 rate and the baryon density Ω_b. The lower panel of Fig. 2 also shows an interesting correlation between A_2 and the Hubble constant H_0. Letting A_2 vary yields a lower value for the Hubble constant in a combined Planck + WP + BBN analysis.

Given the fact that our results depend on the underlying cosmological model, it is interesting to investigate whether extensions of the standard ΛCDM model could bring the value of A_2 back into better agreement with the current

TABLE III. Constraints on cosmological parameters (at the 68% confidence level) in the case of the extended ΛCDM model with extra relativistic degrees of freedom.

Parameter	Planck + WP + BBN	Planck + WP + BBN + HST	Planck + WP + BBN + BAO
$\Omega_b h^2$	0.02241 ± 0.00042	0.02261 ± 0.00031	0.02233 ± 0.00029
$\Omega_c h^2$	0.1263 ± 0.0055	0.1281 ± 0.0049	0.1251 ± 0.0051
τ	0.096 ± 0.015	0.099 ± 0.014	0.094 ± 0.013
n_s	0.979 ± 0.017	0.988 ± 0.011	0.974 ± 0.010
$\log[10^{10} A_s]$	3.117 ± 0.034	3.128 ± 0.030	3.109 ± 0.029
H_0[km/s/Mpc]	71.0 ± 3.2	72.8 ± 2.0	70.1 ± 1.9
$N_{\rm eff}$	3.56 ± 0.40	3.76 ± 0.27	3.43 ± 0.30
A_2	1.29 ± 0.15	1.33 ± 0.14	1.26 ± 0.14

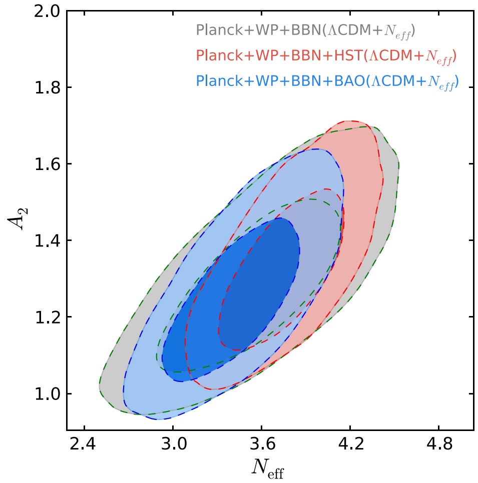

FIG. 3 (color online). Two-dimensional contour plots in the $N_{\rm eff}$ vs A_2 plane, showing preferred parameter regions at the 68% and 95% confidence levels in the case of the extended ΛCDM model with extra relativistic degrees of freedom.

experimental determination of $R_2(T)$ (corresponding by definition to $A_2 = 1$).

In Table III, we report the constraints when a variation in the neutrino effective number $N_{\rm eff}$ is allowed (to account, e.g. for extra relativistic degrees of freedom, or for nonstandard physics in the neutrino sector). Even in that case, we can see that the combined Planck + WP + BBN and Planck + WP + BBN + BAO analyses show a preference for $A_2 > 1$ at roughly the 2σ level, even if the central value and error bar for A_2 are almost doubled. When the direct measurement of the Hubble parameter is included (case Planck + WP + BBN + HST), the indication for $A_2 > 1$ is even stronger, at the 2.5σ level. We can conclude that the preference for a large $d(p,\gamma)^3$He reaction rate is robust against the extension of the minimal cosmological model to a free $N_{\rm eff}$.

It is interesting to note that in Table III, the preferred value for the neutrino effective number $N_{\rm eff}$ is always larger than the standard value 3.046. As reported in Sec. 6.4.4 of Ref. [2], the "standard" Planck + WP + BBN analysis (assuming $A_2 = 1$) gives $N_{\rm eff} = 3.02 \pm 0.27$ (68% C.L.), while the CMB-only result is $N_{\rm eff} = 3.36 \pm 0.34$ (to be precise, in these results, the CMB data set includes high-ℓ data from ACT and SPT, but the same trend is observed with only Planck + WP). With the present analysis, it becomes clear that this shift of $N_{\rm eff}$ towards its standard value is mostly driven by the low experimental value of R_2. When A_2 is let free, the preference for $N_{\rm eff} > 3.046$ persists even when deuterium measurements are included. This can also be checked in Fig. 3, where we report the two-dimensional likelihood contours in the $N_{\rm eff}$ vs A_2 plane for the three different data sets: Planck + WP + BBN, Planck + WP + BBN + HST, and Planck + WP + BBN + BAO. A correlation between A_2 and $N_{\rm eff}$ is clearly present: large values of A_2 remain compatible with Planck + WP + BBN data, provided that at the same time $N_{\rm eff}$ is larger than 3. Such considerations reinforce the motivations for a future experimental campaign to collect further data on the $d(p,\gamma)^3$He cross section in the few hundred keV range. Notice that for $A_2 = 1.05$, corresponding to the theoretical result of Ref. [12] a standard value of $N_{\rm eff}$ is allowed at 68% C.L. If experiments would confirm the theoretical result $R_2^{\rm th}(T)$ in the BBN energy range, the overall agreement of CMB and BBN data for a standard number of relativistic degrees of freedom would improve with respect to the $A_2 = 1$ case. This does not hold if the HST measurement of H_0 is included in the analysis.

In Table IV we report the constraints on A_2 for further extensions of the minimal ΛCDM model, using the Planck + WP + BBN. We tried to vary the curvature parameter Ω_k, despite the fact that $\Omega_k \neq 0$ is difficult to explain from a theoretical point of view, and is almost excluded when BAO data is also included. With free spatial curvature and without BAO data, the evidence for $A_2 > 1$ is slightly weaker. Finally, we considered the case of a free CMB lensing amplitude parameter $A_{\rm L}$. Strictly speaking,

TABLE IV. Constraints on cosmological parameters (at the 68% confidence level) for several extensions of the ΛCDM model, with free parameters $(N_{\rm eff}, A_{\rm L}, \Omega_k)$. We vary at most two of these extra parameters at the same time, and fix the other ones to their standard model value, indicated above between squared brackets.

Parameter	Planck + WP + BBN	Planck + WP + BBN	Planck + WP + BBN	Planck + WP + BBN
$\Omega_b h^2$	0.02242 ± 0.00035	0.02301 ± 0.00051	0.02227 ± 0.00032	0.02261 ± 0.00042
$\Omega_c h^2$	0.1169 ± 0.0030	0.1245 ± 0.0055	0.1185 ± 0.0027	0.1241 ± 0.0053
θ	1.04179 ± 0.00067	1.04112 ± 0.00078	1.04153 ± 0.00065	1.04104 ± 0.00079
τ	0.087 ± 0.013	0.094 ± 0.015	0.087 ± 0.013	0.092 ± 0.015
n_s	0.9687 ± 0.0085	0.996 ± 0.018	0.9640 ± 0.0075	0.981 ± 0.015
$\log[10^{10} A_s]$	3.078 ± 0.025	3.111 ± 0.034	3.081 ± 0.025	3.105 ± 0.033
H_0[km/s/Mpc]	68.8 ± 1.4	74.3 ± 3.6	56.7 ± 5.4	5905 ± 6.4
$N_{\rm eff}$	[3.046]	3.73 ± 0.40	[3.046]	3.50 ± 0.36
$A_{\rm L}$	1.21 ± 0.12	1.25 ± 0.13	[1]	[1]
Ω_k	[0]	[0]	-0.035 ± 0.023	-0.035 ± 0.023
A_2	1.067 ± 0.086	1.21 ± 0.14	1.100 ± 0.084	1.21 ± 0.14

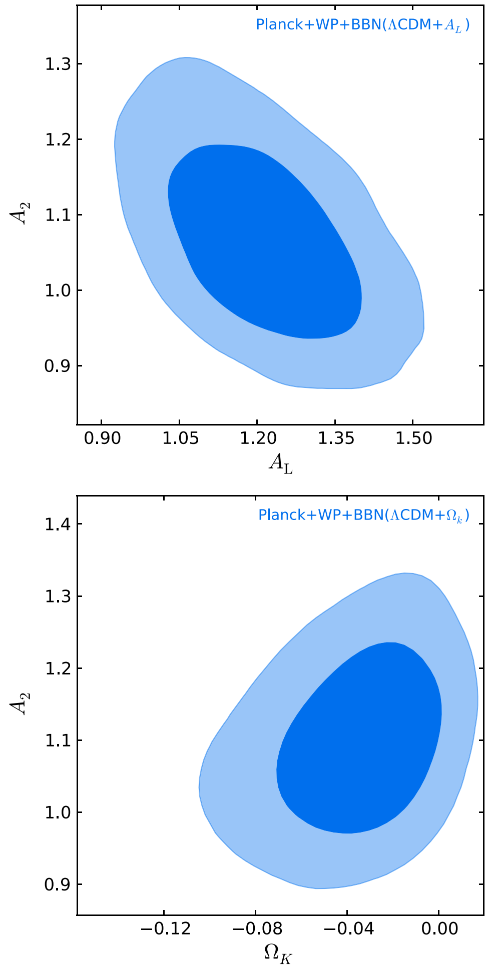

FIG. 4 (color online). Two-dimensional contour plots in the $A_{\rm L}$ vs A_2 (top panel) and Ω_k vs A_2 (bottom panel) planes showing probabilities at the 68% and 95% confidence levels.

this is not a physical extension of the ΛCDM model. The Planck data prefers $A_{\rm L} > 1$, but as such, this result has no physical interpretation. It could be caused by a small and not yet identified systematic error affecting the Planck data (see the discussion in Ref. [2]), or alternatively, it may account in some approximate way for a nonstandard growth rate of large-scale structures after recombination. We can see in Table IV that when $A_{\rm L}$ is left free, the A_2 parameter is well compatible with 1. Our results for the joint confidence limits on A_2 vs Ω_k and A_2 vs $A_{\rm L}$ are shown in Fig. 4.

In summary, Planck + WP + BBN data consistently indicate that $A_2 > 1$ [suggesting a $d(p,\gamma)^3$He reaction rate closer to theoretical predictions than to experimental results] in the minimal ΛCDM model, as well as in a model with free $N_{\rm eff}$. The evidence for $A_2 > 1$ goes away when either Ω_k or $A_{\rm L}$ are promoted as free parameters (with $N_{\rm eff} = 3.046$), but these scenarios are less theoretically motivated. Incidentally, Table IV also shows that with a free Ω_k or $A_{\rm L}$, and at the same time a free $N_{\rm eff}$, the evidence for $A_2 > 1$ persists.

Finally, we have considered the Planck + WP + BICEP2 + BBN data set as stated in the previous section. In Table V we report the constraints using this data set, allowing for a gravitational-wave background with tensor-to-scalar ratio $r_{0.05}$ at scales of $k = 0.05$ Mpc^{-1}. As we can see the indication for $A_2 > 1$ is still present in this case. Allowing for a variation in $N_{\rm eff}$ provides even further evidence for $A_2 > 1$ at more than two standard deviations. It is however interesting that when a running of the primordial spectral index is considered, A_2 is now compatible with 1 at the level of 1 standard deviation. In Fig. 5 we show the two-dimensional contour plots from the Planck + WP + BICEP2 + BBN data set in the $r_{0.05}$ vs A_2 (top panel), $N_{\rm eff}$ vs A_2 (center panel) and $dn_s/dlnk$ vs A_2 (bottom panel) planes showing probabilities at the 68% and 95% confidence levels. As we can see, while there is essentially no degeneracy between A_2 and $r_{0.05}$, a degeneracy is clearly present between A_2 and $N_{\rm eff}$ and $dn_s/dlnk$.

In summary, the BICEP2 data set, when combined with the Planck data, provides an evidence either for a larger

TABLE V. Constraints on cosmological parameters (at the 68% confidence level) for the Planck + WP + BICEP2 data set, with free parameters ($r_{0.05}$, $N_{\rm eff}$, $dn_s/dlnk$). We vary at most two of these extra parameters at the same time, and fix the other ones to their standard model value, indicated above between squared brackets.

Parameter	Planck + WP + BICEP2 + BBN	Planck + WP + BICEP2 + BBN	Planck + WP + BICEP2 + BBN
$\Omega_b h^2$	0.02209 ± 0.00028	0.02286 ± 0.00044	0.02236 ± 0.00031
$\Omega_c h^2$	0.1184 ± 0.0027	0.1300 ± 0.0058	0.1195 ± 0.0027
θ	1.04146 ± 0.00063	1.04050 ± 0.00073	1.04144 ± 0.00063
τ	0.088 ± 0.012	0.100 ± 0.015	0.101 ± 0.015
n_s	0.9663 ± 0.0072	1.004 ± 0.018	0.9593 ± 0.0080
$\log[10^{10} A_s]$	3.082 ± 0.024	3.131 ± 0.034	3.115 ± 0.031
H_0[km/s/Mpc]	67.9 ± 1.2	75.5 ± 3.7	67.7 ± 1.2
$r_{0.05}$	0.134 ± 0.045	0.153 ± 0.040	0.163 ± 0.040
$N_{\rm eff}$	[3.046]	4.04 ± 0.44	[3.046]
$dn_s/dlnk$	[0]	[0]	-0.0256 ± 0.0097
A_2	1.145 ± 0.081	1.40 ± 0.17	1.080 ± 0.079

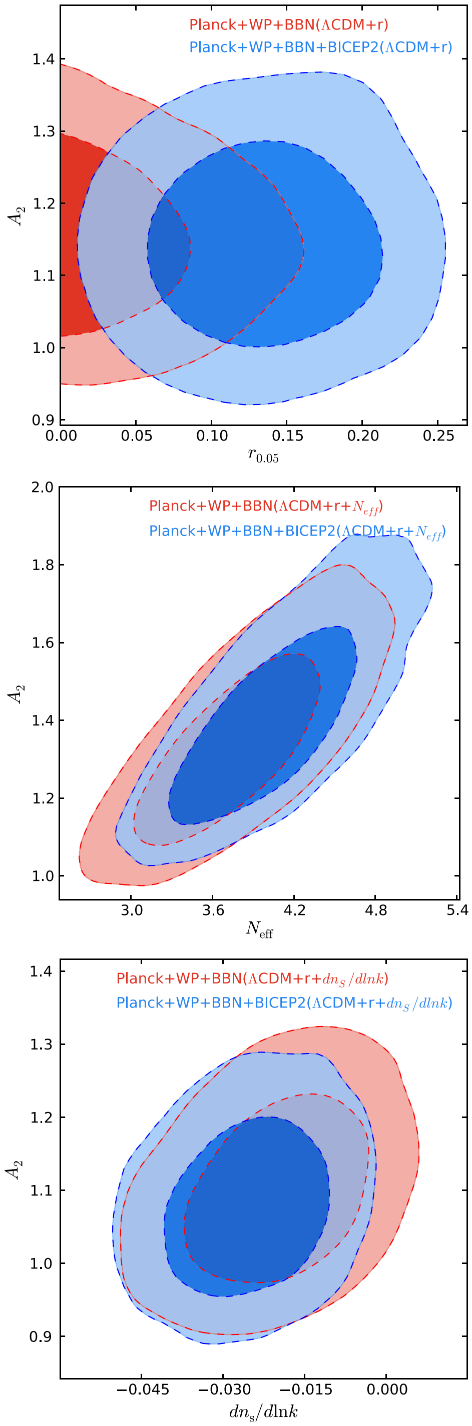

FIG. 5 (color online). Two-dimensional contour plots from the Planck + WP + BICEP2 + BBN dataset in the r vs A_2 (top panel), $N_{\rm eff}$ vs A_2 (center panel) and $dn_s/dlnk$ vs A_2 (bottom panel) planes showing probabilities at the 68% and 95% confidence levels.

$N_{\rm eff}$, or for a negative running of the spectral index $dn_s/dlnk$. In the first case a value of A_2 strictly larger than 1 is needed in order to be in agreement with BBN. In the second case, when running is considered, A_2 is well compatible with 1. A precise measurement of A_2 from laboratory experiments could in principle help in a significative way in discriminating between these two scenarios.

V. CONCLUSIONS

In this work, we have shown that a combined analysis of Planck CMB data and of recent deuterium abundance measurements in metal-poor damped Lyman-alpha systems provides some piece of information on the radiative capture reaction $d(p,\gamma)^3$He, converting deuterium into helium. The value of the rate for this process represents the main source of uncertainty to date in the BBN computation of the primordial deuterium abundance within a given cosmological scenario, parametrized by the baryon density $\Omega_b h^2$ and effective neutrino number $N_{\rm eff}$. The corresponding cross section has not been measured yet with a sufficiently low uncertainty and normalization errors in the BBN center-of-mass energy range, 30–300 keV. In addition to that, the best fit of available data appears to be systematically lower than the detailed theoretical calculation presented in Ref. [12]. Both of these issues should be addressed by performing new dedicated experimental campaigns. We think that an experiment such as LUNA at the underground Gran Sasso Laboratories may give an answer to this problem in a reasonably short time.

In fact, with the present underground 400-kV LUNA accelerator [31] it is possible to measure the ^{2}H$(p,\gamma)^3$He cross section in the $20 < E_{\rm cm}(\rm keV) < 260$ energy range with an accuracy better than 3%, i.e. considerably better than the 9% systematic uncertainty estimated in Ref. [32]. This goal can be achieved by using the large BGO detector already used in Ref. [33]. This detector ensures a detection efficiency of about 70% and a large angular coverage for the photons emitted by the ^{2}H$(p,\gamma)^3$He reaction. The accurate measurement of the ^{2}H$(p,\gamma)^3$He absolute cross section may be accomplished with the study of the angular distribution of emitted γ rays by means of a large Ge(Li) detector [34,35], in order to compare the data with *ab initio* calculations.

Our study shows that, interestingly, the combined analysis of Planck and deuterium abundance data returns a larger rate A_2 for this reaction than the best fit computed in Ref. [7], where the authors exploited the available experimental information on the $d(p,\gamma)^3$He cross section. On the other hand Planck is in better agreement with *ab initio* theoretical calculations. More precisely, when the reaction rate A_2 is chosen to match its present determination, Planck predicts a value of the primordial deuterium abundance in 2σ tension with its direct astrophysical determination. When the same reaction rate A_2 is assumed instead to match theoretical calculations, the two values of the primordial deuterium abundance agree at the 1σ level. We have shown that this conclusion holds in the minimal ΛCDM cosmological model, as well as when allowing for a free effective neutrino number. In the latter case, the global likelihood analysis of astrophysical and cosmological data shows a direct correlation between A_2 and $N_{\rm eff}$, so that higher values for A_2 are in better agreement with non-standard scenarios with extra relativistic degrees of freedom.

Finally, we have shown that the inclusion of the new BICEP2 data set also points towards a larger value for A_2, especially when $N_{\rm eff}$ is left free to vary. However, a running of the spectral index could bring the value of A_2 back into agreement with 1 even when the BICEP2 data set is considered.

New experimental data on the $d(p,\gamma)^3$He reaction rate will therefore have a significant impact on the knowledge of $N_{\rm eff}$ and of $dn_s/dlnk$ as well.

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[1] F. Iocco, G. Mangano, G. Miele, O. Pisanti, and P. D. Serpico, Phys. Rep. **472**, 1 (2009).
[2] P. A. R. Ade *et al.* (Planck Collaboration), arXiv:1303.5076.
[3] O. Pisanti, A. Cirillo, S. Esposito, F. Iocco, G. Mangano, G. Miele, and P. D. Serpico, Comput. Phys. Commun. **178**, 956 (2008).
[4] In this paper we use a version of PArthENoPE where the $d(p,\gamma)^3$He reaction rate is updated to the best-fit experimental determination (see Sec. II). The deuterium fraction given by the public version of PArthENoPE is slightly different, but the change in the central value is at the level of 4 per mille, only.
[5] R. Cooke, M. Pettini, R. A. Jorgenson, M. T. Murphy, and C. C. Steidel, Astrophys. J. **781**, 31 (2014).
[6] M. Pettini and R. Cooke, Mon. Not. R. Astron. Soc. **425**, 2477 (2012).
[7] E. G. Adelberger *et al.*, Rev. Mod. Phys. **83**, 195 (2011).
[8] We recall that the energy-dependent cross section $\sigma(E)$ is related to the energy-dependent astrophysical factor $S(E)$ through $\sigma(E) = S(E)e^{-2\pi\eta}/E$, where η is the Sommerfeld factor.
[9] C. Casella *et al.* (LUNA Collaboration), Nucl. Phys. **A706**, 203 (2002)
[10] M. Viviani, A. Kievsky, L. E. Marcucci, S. Rosati, and R. Schiavilla, Phys. Rev. C **61**, 064001 (2000).
[11] L. E. Marcucci, K. M. Nollett, R. Schiavilla, and R. B. Wiringa, Nucl. Phys. **A777**, 111 (2006).
[12] L. E. Marcucci, M. Viviani, R. Schiavilla, A. Kievsky, and S. Rosati, Phys. Rev. C **72**, 014001 (2005).
[13] K. M. Nollett and G. P. Holder, arXiv:1112.2683.
[14] P. D. Serpico, S. Esposito, F. Iocco, G. Mangano, G. Miele, and O. Pisanti, J. Cosmol. Astropart. Phys. 12 (2004) 010.
[15] G. Rupak, Nucl. Phys. **A678**, 405 (2000).
[16] J. W. Chen and M. J. Savage, Phys. Rev. C **60**, 065205 (1999)
[17] D. S. Leonard, H. Karwowski, C. Brune, B. Fisher, and E. Ludwig, Phys. Rev. C **73**, 045801 (2006).
[18] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, and P. D. Serpico, Nucl. Phys. **B729**, 221 (2005).
[19] P. A. R. Ade *et al.* (Planck Collaboration), arXiv:1303.5075.
[20] P. A. R. Ade *et al.* (BICEP2 Collaboration), Phys. Rev. Lett. **112**, 241101 (2014).
[21] S. Hamimeche and A. Lewis, Phys. Rev. D **77**, 103013 (2008).
[22] A. G. Riess, L. Macri, S. Casertano, H. Lampeitl, H. C. Ferguson, A. V. Filippenko, S. W. Jha, W. Li, and R. Chornock, Astrophys. J. **730**, 119 (2011); **732**, 129(E) (2011).
[23] 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).
[24] L. Anderson *et al.*, Mon. Not. R. Astron. Soc. **427**, 3435 (2012).
[25] C. Blake *et al.*, Mon. Not. R. Astron. Soc. **415**, 2892 (2011).
[26] A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002).
[27] B. Audren, J. Lesgourgues, K. Benabed, and S. Prunet, J. Cosmol. Astropart. Phys. 02 (2013) 001.
[28] A. Lewis, Phys. Rev. D **87**, 103529 (2013).
[29] E. Calabrese, A. Slosar, A. Melchiorri, G. F. Smoot, and O. Zahn, Phys. Rev. D **77**, 123531 (2008).
[30] E. Giusarma, E. Di Valentino, M. Lattanzi, A. Melchiorri, and O. Mena, arXiv:1403.4852 [Phys. Rev. D (to be published)]; J.-F. Zhang, Y.-H. Li, and X. Zhang, arXiv:1403.7028 [Phys. Rev. Lett. (to be published)]; C. Dvorkin, M. Wyman, D. H. Rudd, and W. Hu, arXiv:1403.8049 [Phys. Rev. D (to be published)].
[31] A. Formicola *et al.* (LUNA collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **507**, 609 (2003).
[32] L. Ma, H. Karwowski, C. Brune, Z. Ayer, T. Black, J. Blackmon, E. Ludwig, M. Viviani, A. Kievsky, and R. Schiavilla, Phys. Rev. C **55**, 588 (1997).
[33] C. Casella *et al.* (LUNA collaboration), Nucl. Phys. **A706**, 203 (2002).
[34] M. Anders *et al.* (LUNA collaboration), Eur. Phys. J. A **49**, 28 (2013).
[35] M. Anders *et al.* (LUNA collaboration), Phys. Rev. Lett. (to be published).