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A robust upper limit on N_{eff} from BBN, circa 2011

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ABSTRACT

We derive here a robust bound on the effective number of neutrinos from constraints on primordial nucleosynthesis yields of deuterium and helium. In particular, our results are based on very weak assumptions on the astrophysical determination of the helium abundance, namely that the minimum effect of stellar processing is to keep constant (rather than increase, as expected) the helium content of a low-metallicity gas. Using the results of a recent analysis of extragalactic HII regions as *upper limit*, we find that $\Delta N_{\mathrm{eff}} \leqslant 1$ at 95% C.L., quite independently of measurements on the baryon density from cosmic microwave background anisotropy data and of the neutron lifetime input. In our approach, we also find that primordial nucleosynthesis alone has no significant preference for an effective number of neutrinos larger than the standard value. The $\sim 2\sigma$ hint sometimes reported in the literature is thus driven by CMB data alone and/or is the result of a questionable regression protocol to infer a *measurement* of primordial helium abundance.

1. Introduction

Historically, the helium abundance has played an important role for establishing the "hot big bang" cosmological model, see for example [1]. Primordial nucleosynthesis, most often referred to as big bang nucleosynthesis (BBN), helped building confidence in the overall credibility of cosmology as a science. Nowadays, in the era of "precision cosmology", it is clearly no more question to prove that the bulk of ^{4}He is primordial, also in view of the indirect (but clean) detection of a non-vanishing ^{4}He mass fraction Y_p from CMB data, see [2,3].

The basic pillars of the hot big bang model have found many confirmations and have been subject to several important cross-checks, leading to the so-called concordance (or standard) model of cosmology. In the last two decades, BBN has thus mostly turned into a probe of physics/cosmology beyond the standard model (see [4,5] for recent reviews). Moving forward in this direction has been however hampered by the systematics in the determination of light nuclei abundances, since one has no access to truly primordial environments, i.e. prior to the first generation of stars and nucleosynthetic events: any inference thus relies to some extent on astrophysical models. In particular for the case of ^{4}He, despite the more and more careful analyses undertaken over the past decade, very different conclusions can be sometimes found on the inferred Y_p, see e.g. [6–8]. Without entering the issues related to the analysis of spectroscopic data, from a particle physics perspective one may wonder what is the most profitable way to use the results of these analyses for constraining new physics, while maintaining some robustness and independence from the regression protocol.

In fact, we believe that for a largest fraction of the particle astrophysics community it is more important to obtain reliable constraints than inferring primordial abundances. In this spirit, here we propose a simple and robust approach to the use of ^{4}He data for constraining the effective number of neutrinos, N_{eff}, by far the most widely used BBN-related quantity used to parameterize new physics. This Letter is structured as follows: in Section 2 we outline our minimal assumptions in using the data; in Section 3 we present our results; in Section 4 we discuss our findings and assumptions and conclude.

2. Procedure

For ^{4}He, we use here the abundances inferred in nine metal-poor, extragalactic HII regions in [8] (see also [7]). Differently from the usual practice, we do not perform a regression to zero metallicity, since our aim is to derive an upper bound to ^{4}He. Hence, we fit the yields to a constant abundance Y_0, obtaining

$$\langle Y_0 \rangle \pm \sigma_0 = 0.2581 \pm 0.0025 \text{ (68\% C.L.)} \quad (1)$$

which also implies

$$Y_0 < 0.2631 \quad \text{at 95\% C.L.} \quad (2)$$

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Assuming that no information is available on the lower-limit of ^{4}He, one can parametrize the likelihood function for Y_p as a flat+semi-gaussian shape

$$\ell(Y_p) \propto \Theta\big(\langle Y_0\rangle - Y_p\big) + \Theta\big(Y_p - \langle Y_0\rangle\big)\exp\left[-\frac{(Y_p - \langle Y_0\rangle)^2}{2\sigma_0^2}\right]. \tag{3}$$

We argue here that this is conservative and robust. In fact, Eq. (2) is a strict upper limit to the primordial value Y_p under *the sole assumption* that $dY/dZ \geqslant 0$, i.e. that the *average*[1] effect of stellar processing is to increase the helium content of a low-metallicity gas. By now, there is some empirical evidence of this trend (positive derivative) even in the few high-quality objects analyzed in [7,8]. However, assuming $dY/dZ =$ constant is a much stronger assumption, usually justified empirically since the seventies as the simplest possible fit [9] (see also [10]), but subject to the obvious risk of extrapolation errors.

Even if one could model the metallicity evolution of the observed systems reliably, it is unclear to what extent the *pre-galactic* value of Y should coincide with its *primordial* value Y_p. Actually, it has been proven since longtime that the bulk of ^{4}He must be primordial (see e.g. [11] for a short historical overview), and by now there is a positive (albeit indirect) detection of a non-vanishing Y_p from CMB data, see [2,3]. However, it is a different issue to prove that no extra production of ^{4}He has taken place since early times *at a level comparable to the current error* on its determination, i.e. at the percent level. In fact, "What is the helium enrichment by the first stellar generations?" was a question already posed in the seminal paper [12]. In the last decade, several models have been proposed where such a production does take place at an appreciable level ($\Delta Y \simeq 10^{-3}$–10^{-2}), see for example [13,14]. This is perhaps not surprising, given that the yet undiscovered generation of stars known as PopIII forming in the pristine metal-free gas should generate some chemical enrichment. It is worth remembering that currently observed "metal-poor" samples have metal contents many orders of magnitude above the expectations from BBN [15]. When using the late universe determinations of Y as measurements of its primordial value, a systematics error is committed, difficult to quantify precisely since it depends on astrophysical modeling of pre-galactic times. Again, this extra problem is avoided in our conservative procedure. Notice that our upper bound of Eq. (2) is close but slightly more stringent than what is found at 2σ in [8], $Y_p < 0.2639$, since only seven of the nine determinations were used there. The small difference shows however that a minor change in the choice of objects would not change the following results appreciably, which is another hint in favor of their robustness. It is more involved to compare with the results of the group of Izotov et al., which does not present fits assuming $dY/dZ = 0$. For illustration, the *measurement* quoted in [6], based on a linear regression method whose robustness we question here, yielded $Y_p = 0.2565 \pm 0.0010$ (1σ stat.) ± 0.0050 (syst.). On the other hand, we note that fitting to a constant the 10 determinations reported in Table 4 of [16], as suggested here, one obtains $Y_0 = 0.2555 \pm 0.0016$, i.e. $Y < 0.2587$ at 95% C.L. When rescaling the above value upwards by 2% due to some improved atomic corrections as argued in [6], one finds a value remarkably consistent with the above determinations of the upper limit. We take this exercise as an indication that our results are not sensitive to the different analysis codes and protocols, at least when the same and most updated atomic data are used.

[1] Note that short periods of evolution with $dY/dZ < 0$ would not alter the conclusion, hence the requirement is less restrictive that the inequality $dY/dZ \geqslant 0$ taken at face value.

For ^{2}H, following the analysis in [4], as the best estimate of the primordial deuterium yield one may use

$$\big({}^2\text{H/H}\big)_p = 2.87^{+0.22}_{-0.21} \quad \text{at 68\% C.L.,} \tag{4}$$

which is based on a conservative analysis of seven (relatively) reliable absorption spectra of clouds at high redshifts, on the light of background quasars. Detailed studies [10] suggest that the depletion due to stellar activity in these early systems is negligible and thus the above range can be considered a faithful estimate of the primordial value. Yet, we shall also show one example based on the minimal assumption

$$\big({}^2\text{H/H}\big)_p > 2.45 \times 10^{-5} \quad \text{at 95\% C.L.,} \tag{5}$$

which is agnostic on an eventual depletion of ^{2}H in an early chemical evolutionary phase. In this case, a semi-gaussian+flat likelihood function similar to what done for Helium in Eq. (3) is constructed. Even in this case, very similar results follow on the upper limit on $N_{\rm eff}$.

Concerning the BBN predictions, we used nuclide yields based on the code described in [17], also including the uncertainties due to nuclear reactions extensively described in [18].

Finally, one may (or may not) impose the CMB measurement of the baryon fraction [2]

$$\omega_b = \Omega_b h^2 = 0.02250 \pm 0.00056 \quad \text{at 68\% C.L.} \tag{6}$$

We checked that significantly relaxing the above range (say, by one order of magnitude) does not affect the upper limit on $N_{\rm eff}$ appreciably. Note that for consistency we consider the value for ω_b inferred in a ΛCDM + $N_{\rm eff}$ model (i.e. where $N_{\rm eff}$ is allowed to vary), although using the best-fit in a ΛCDM model would make no quantitative difference.

For illustration, in one case we shall also consider the impact of the Y_p measurement from CMB data (WMAP 7 yrs plus small scale results of the Atacama Cosmology Telescope [3]), assuming the additional measurement (gaussian error)

$$Y_p = 0.313 \pm 0.044 \quad \text{at 68\% C.L.} \tag{7}$$

3. Results

With the ingredients described above we constructed two-dimensional likelihood functions in the ω_b–$N_{\rm eff}$ plane, then marginalized over the parameter ω_b, which is not of interest here. The results of our analysis are thus encoded in the 1-dimensional likelihoood functions $\mathcal{L}(N_{\rm eff})$, whose integrals are normalized to 1. These functions are shown in Fig. 1 and relevant numerical quantities are summarized in Table 1. We define $N_{\rm eff}^{\rm min}$ and $N_{\rm eff}^{\rm max}$ such that

$$\int_{N_{\rm eff}^{\rm min}}^{7} \mathcal{L}(x)\,dx = 0.95, \qquad \int_0^{N_{\rm eff}^{\rm max}} \mathcal{L}(x)\,dx = 0.95, \tag{8}$$

and the parameter $L(N_{\rm eff} \leqslant N_{\rm eff}^{\rm SM})$ in Table 1 as

$$L\big(N_{\rm eff} \leqslant N_{\rm eff}^{\rm SM}\big) = \int_0^{N_{\rm eff}^{\rm SM}} \mathcal{L}(x)\,dx. \tag{9}$$

When remembering that the standard model expectation for $N_{\rm eff}$ is about 3.046 [19], we see that in all cases we get a bound $\Delta N_{\rm eff} \leqslant 1$. The reason why it is slightly more stringent when using deuterium as a "measurement" of ω_b instead of CMB (third line) is that it favors a slightly smaller value for the baryon fraction.