New BBN limits on Physics Beyond the Standard Model from $^4$He

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Abstract

A recent analysis of the $^4$He abundance determined from observations of extragalactic HII regions indicates a significantly greater uncertainty for the $^4$He mass fraction. The derived value is now in line with predictions from big bang nucleosynthesis when the baryon density determined by WMAP is assumed. Based on this new analysis of $^4$He, we derive constraints on a host of particle properties which include: limits on the number of relativistic species at the time of BBN (commonly taken to be the limit on neutrino flavors), limits on the variations of fundamental couplings such as $\alpha_{em}$ and $G_N$, and limits on decaying particles.
1 Introduction

Big bang nucleosynthesis (BBN) is one of the most sensitive available probes of physics beyond the standard model. The concordance between the observation-based determinations of the light element abundances of D, $^3$He, $^4$He, and $^7$Li [1], and their theoretically predicted abundances reflects the overall success of the standard big bang cosmology. Many departures from the standard model are likely to upset this agreement, and are tightly constrained [2].

The $^4$He abundance, in particular, has often been used as a sensitive probe of new physics. This is due to the fact that nearly all available neutrons at the time of BBN end up in $^4$He and the neutron-to-proton ratio is very sensitive to the competition between the weak interaction rate and the expansion rate. For example, a bound on the number $g_*$ of relativistic degrees of freedom (at the time of BBN), commonly known as the limit on neutrino flavors, $N_\nu$, is derived through its effect on the expansion rate, $H \propto \sqrt{g_*}$ [3]. However, because the calculated $^4$He abundance increases monotonically with baryon density (parameterized by the baryon-to-photon ratio, $\eta \equiv n_b/n_\gamma$), a meaningful limit on $N_\nu$ requires both a lower bound to $\eta$ and an upper bound to the primordial $^4$He mass fraction, $Y_p$ [4]. Indeed, for a fixed upper limit to $Y_p$, the upper limit to $N_\nu$ can be a sensitive function of the lower limit to $\eta$, particularly if $\eta$ is small [4, 5].

The recent all-sky, high-precision measurement of microwave background anisotropies by WMAP [6] has opened the possibility for new precision analyses of BBN. Among the cosmological parameters determined by WMAP, the baryon density has been derived with unprecedented precision. The WMAP best fit assuming a varying spectral index is $\Omega_B h^2 = 0.0224 \pm 0.0009$ which is equivalent to $\eta_{10,CMB} = 6.14 \pm 0.25$, where $\eta_{10} = 10^{10}\eta$. This result is sensitive mostly to WMAP alone but does include CMB data on smaller angular scales [7], Lyman $\alpha$ forest data, and 2dF redshift survey data [8] on large angular scales. This result is very similar to the corresponding value obtained from combining WMAP with SDSS data and other CMB measurements, which gives $\Omega_B h^2 = 0.0228^{+0.0010}_{-0.0008}$ [9] and corresponds to $\eta_{10} = 6.25^{+0.27}_{-0.22}$. Using the WMAP data to fix the baryon density, one can make quite accurate predictions for the light element abundances [10–13]. At the WMAP value for $\eta$, the $^4$He abundance is predicted to be [13]:

$$Y_p = 0.2485 \pm 0.0005$$

On the other hand, accurate $^4$He abundances have been and continue to be difficult to obtain. It is recognized that there are many potential sources of systematic uncertainties in the derived $^4$He abundance [14, 15]. As a result there exists a wide range of derived
primordial $^4$He abundances which have typically been relatively low compared with (1). Recently, a reanalysis [16] of the $^4$He data [17,18] has led to a significant enlargement in the statistical uncertainty as well as a potential shift in the mean value. A representative result of that analysis is

$$Y_p = 0.2495 \pm 0.0092$$

(2)

Conservatively, it would be difficult to exclude any value of $Y_p$ inside the range $0.232 - 0.258$.

Because much of the previous work was based on relatively low values of $Y_p$, tension between the value of $\eta$ inferred from either D/H or WMAP, and $^4$He gave rise to very tight constraints on $N_\nu$ and on other particle properties. In light of the newly suggested range for $Y_p$ [16], it is important to reexamine the constraints on physics beyond the standard model.

Potential limits from D/H have been discussed recently [10, 12, 13], and we will just quote those results below in comparison with the results derived here. At present, it is not possible to use $^7$Li to obtain constraints. This is due to 1) the large uncertainty in the BBN prediction of the $^7$Li abundance, and 2) to the current discrepancy between the BBN prediction and the observational determination of the $^7$Li abundance (see e.g. [10–13, 19]).

## 2 The $^4$He Abundance

The $^4$He abundance has had a somewhat checkered history over the last decade. Of the modern determinations, the work of Pagel et al. [20] established the analysis techniques that others were soon to follow [21]. Their value of $Y_p = 0.228 \pm 0.005$ was significantly lower than that of a sample of 45 low metallicity HII regions, observed and analyzed in a uniform manner [17], with a derived value of $Y_p = 0.244 \pm 0.002$. An analysis based on the combined available data as well as unpublished data yielded an intermediate value of $0.238 \pm 0.002$ with an estimated systematic uncertainty of $0.005$ [22]. An extended data set including 89 HII regions obtained $Y_p = 0.2429 \pm 0.0009$ [18]. However, the recommended value is based on the much smaller subset of 7 HII regions, finding $Y_p = 0.2421 \pm 0.0021$. As seen in table 6 of [18], changing the assumed value of the equivalent width of He absorption for one of the observed He wavelengths by 0.1 Å changes the derived abundance significantly to $Y_p = 0.2444 \pm 0.0020$. This change of $\Delta Y_p = 0.0023$, is indicative of the importance of systematic errors.

$^4$He abundance determinations depend on a number of physical parameters associated with the HII region in addition to the overall intensity of the He emission line. These include the temperature, electron density, optical depth and degree of underlying absorption. A self-consistent analysis may use multiple $^4$He emission lines to determine the He abundance,
the electron density and the optical depth. In [17], five He lines were used, underlying He absorption was assumed to be negligible and temperatures based on OIII observations were used.

A very accurate helium abundance for the HII region NGC 346 in the Small Magellanic Cloud was derived with a value of \( Y_p = 0.2345 \pm 0.0026 \) [23]. Knowing that the OIII temperatures are systematically high, they use the He I emission lines to solve for the electron temperature. Recently, the spectra of five metal poor HII regions - NGC 346 and four regions reported in [17] have been reanalyzed [24]. After considering the effects of additional physical processes (e.g., collisional excitation of the Balmer lines), a higher determination of \( Y_p = 0.239 \pm 0.002 \) was found.

The question of systematic uncertainties was addressed in some detail in [14]. It was shown that there exist severe degeneracies inherent in the self-consistent method, particularly when the effects of underlying absorption are taken into account. A sixth He line was proposed to test for the presence of underlying He absorption. However, even in the six-line method, one can not escape the degeneracies present in the solutions. In particular, solutions with no absorption and high density are often indistinguishable (i.e., in a statistical sense they are equally well represented by the data) from solutions with underlying absorption and a lower density. In the latter case, the He abundance is systematically higher. These degeneracies are markedly apparent when the data is analyzed using Monte-Carlo methods which generate statistically viable representations of the observations. When this is done, not only are the He abundances found to be higher, but the uncertainties are also found to be significantly larger than in a direct self-consistent approach.

In [16], the Monte-Carlo method was applied to seven of the highest quality observations from the sample in [17]. As expected, systematically higher He abundances were found, with significantly larger uncertainties. The results of a regression (to zero metallicity) led to the primordial He abundance given in Eq. (2). With this value of \( Y_p \) (particularly with the stated uncertainty), there is clearly no discrepancy between He observations and BBN predictions of \( Y_p \) at the WMAP value for \( \eta \). It was stressed however, that although this method found higher He abundances, one could not exclude the lower abundances found by other methods.

### 3 Standard BBN

Key to BBN analysis is an accurate determination of BBN theory uncertainties, which are dominated by the errors in nuclear cross section data. To this end, several groups have
determined reaction rate representations and uncertainties. Smith, Kawano and Malaney [25] presented the first detailed error budget for BBN, generally assuming constant relative errors. In more recent work [26], uncertainties were propagated based on available nuclear data into the light element predictions. The NACRE collaboration presented a larger focus nuclear compilation [27], meant to update the previous astrophysical standard [28]. However, their “high” and “low” limits are not defined rigorously as 1 or 2 sigma limits (see [29, 30] for its impact on BBN). In an attempt to increase the rigor of the NACRE errors, we reanalyzed [29] the data using NACRE cross section fits defining a “sample variance” which takes into account systematic differences between data sets.

Since then, new data and techniques have become available, motivating new compilations. Within the last year, several new BBN compilations have been presented [11–13], the latter being one of the most rigorous and exhaustive efforts to determine reliable rate representations and meaningful uncertainties and we adopt this compilation here.

To compare theory with observations, we will adopt the $^4$He results discussed in §2. For brevity, we will simply adopt the D observations discussed in [31]. We use the D abundance constraints based on the best five measurements of D/H in QSO absorption line systems

$$d/h_a = (2.78 \pm 0.29) \times 10^{-5}$$

BBN is tested with the comparison between light element abundance observations, BBN theory predictions, and the subsequent allowed ranges of baryon density, which has now been independently measured by CMB anisotropy experiments [10]. One way to perform this test is to use the CMB range of $\eta$ as an input to the BBN calculation, and to compute the resulting ranges in the light elements. This procedure is illustrated in Figure 1. As is well known, the agreement with D is excellent. The $^4$He overlap is also essentially perfect, though the larger uncertainty in $^4$He renders this agreement a less powerful test, and the near-coincidence of central values is fortuitous. Nevertheless, the new $^4$He analyses does bring this nuclide in good agreement with the CMB and D. This consistency was not guaranteed and marks a success of BBN and of cosmology.

4 Beyond the Standard Model

For several cases of interest, it will be useful to define a dimensionless cosmic “speed-up” factor $\xi = H_{\text{new}}/H_{\text{std}}$, where $H = \dot{a}/a$ is the Hubble expansion rate; $\xi = 1$ then represents the unperturbed case. The expansion rate itself is given by the Friedmann equation, which for a flat universe is $H^2 = (8\pi/3) G_N \rho$, where $\rho$ is the total mass-energy density. Thus the
Figure 1: Likelihood distributions for light element abundances. The dark (blue) shaded regions are the BBN predictions given the CMB-determined $\eta$ values. The light (yellow) shaded regions correspond to the light element observations: the new $Y_p$ and world average of $D/H_A$ values of eq. 3 are represented by the yellow regions.

The speed-up factor evolves as $\xi = \sqrt{(G_N\rho)_{\text{new}}/(G_N\rho)_{\text{std}}}$. For the case of a radiation-dominated universe, we have $\rho \propto g_* T^4$, where $g_* = 2 + 7/2 + 7N_\nu/4$ counts the relativistic degrees of freedom in photons, $e^\pm$ pairs, and $N_\nu$ neutrino species.

4.1 Constraints on $N_\nu$

We first consider the canonical extension of standard BBN, in which there are $N_\nu$ effectively massless ($m_\nu \ll 1$ MeV) left-handed neutrino species. The increase in the speed-up factor is

$$\xi = \sqrt{1 + 7\delta N_\nu/43}, \quad (4)$$

where $\delta N_\nu = N_\nu - 3$. This in turn changes the weak freezeout temperature and ultimately affects all of the light elements. Until recently, the effect on the $^4\text{He}$ abundance was the only measurable consequence, but $D/H$ measurements are now sufficiently accurate that $D/H$ also
has an important sensitivity to $N_\nu$ [32].

For a fixed value of $\eta_{10} = 6.14 \pm 0.25$ and the He abundance given in \(Y_p\), we show the likelihood distribution for $N_\nu$ by the shaded region in Fig. 2. Also shown for comparison are the likelihood distribution based the WMAP value of $\eta$ using D/H alone, $Y_p$ and D/H, and the result based on BBN alone. Despite the increased uncertainty in the He abundance, it still provides the strongest constraint on $N_\nu$. D/H is nonetheless becoming competitive in its ability to set limits on $N_\nu$.

Figure 3 shows the joint limits on $\eta$ and $N_\nu$ based on D and $^4$He. We see that the $^4$He contours are nearly horizontal, which arises from the weak (logarithmic) sensitivity of $Y_p$ to $\eta$, as opposed to a stronger, linear sensitivity to $\delta N_\nu$. Thus $^4$He by itself is a poor baryometer but an excellent probe of nonstandard physics. On the other hand, the D/H contours have a steep slope, indicating a strong sensitivity to $\eta$ which is the origin of the D/H power as a baryometer. The non-vertical nature of the slope does however indicate a correlation between the D/H sensitivity to $\eta$ and $N_\nu$. Thus by combining D and $^4$He we can expect to arrive at strong constraints on both parameters. Numerical results appear in Table I where we see that these light elements alone constrain $\eta$ to within about 10%, and fix $N_\nu$ to within about 20%, both at 1\(\sigma\). Note that the contour ellipses in Figure 3 have a
Figure 3: a) BBN-only constraints on $\eta$ and $N_\nu$. The thickest (thinnest) curves correspond to $1\sigma$ ($3\sigma$) limits. The nearly vertical (blue) curves are limits due to D/H, nearly horizontal (red) curves are for $^4$He, and the closed (black) contours combine both. b) As in a), with the CMB $\eta$ information included.

Slight positive tilt, corresponding to a small positive correlation between $\eta$ and $N_\nu$.

Also appearing in Table I, we have shown the 95% upper confidence limits placed on the effective neutrino number, $\delta N_{\nu,\text{max}}$, assuming that $N_\nu > 3.0$ or $\delta N_{\nu} > 0.0$. The constraints presented suggest a robust upper bound of 1.6 with 95% confidence. We next introduce the CMB information on $\eta$; this tests the overall consistency, but as we have already shown, the agreement is good for the standard $N_\nu = 3$ case. Note that CMB anisotropies also have some sensitivity to $N_\nu$, though this is at the moment significantly weaker than the light element sensitivity. We do not use this additional information, which would slightly strengthen the constraints on $N_\nu$, but would not affect the $\eta$ limits (where the CMB impact is largest) due to the independence of the CMB limits on $\eta$ and $N_\nu$ [33].

Figure 3b shows the impact of the CMB on the $\eta$ and $N_\nu$ constraints. We see that the dominant effect is that the CMB narrows and steepens the combined contours; this
Table 1: The table shows constraints placed on $N_\nu$ and $\eta$ by various combinations of observations. Shown are the 68% confidence limits determined by marginalizing the 2-D likelihood distribution $L(\eta, N_\nu)$. Also shown are the 95% upper limits on $\delta N_\nu = N_\nu - 3$, given that $\delta N_\nu > 0$.

| Observations                  | $\eta_{10} \equiv 10^{10} \eta$ | $N_\nu$     | $\delta N_{\nu,\text{max}}$ |
|-------------------------------|----------------------------------|-------------|-----------------------------|
| $Y_p + D/H_A$                 | $5.94^{+0.36}_{-0.50}$           | $3.14^{+0.70}_{-0.65}$ | 1.59                        |
| $Y_p + \eta_{\text{CMB}}$    | $6.14 \pm 0.25$                  | $3.08^{+1.14}_{-1.04}$ | 1.63                        |
| $D/H_A + \eta_{\text{CMB}}$  | $6.16 \pm 0.25$                  | $3.24^{+0.61}_{-0.57}$ | 2.78                        |
| $Y_p + D/H_A + \eta_{\text{CMB}}$ | $6.10^{+0.24}_{-0.22}$          | $3.24^{+0.61}_{-0.57}$ | 1.44                        |

reflects the very tight CMB constraint on $\eta$. Table 1 shows the impact of the CMB on the $\eta$ and $N_\nu$ constraints. The resulting precision on $\eta$ is roughly doubled, to about a 4% (!) measurement, dominated by the CMB contribution but for which the D/H contribution is not negligible. The precision of the $N_\nu$ constraint remains essentially the same, reflecting both the dominance of $Y_p$ in determining $N_\nu$, as well as the near-independence of $Y_p$ on $\eta$.

In [16], it was noted that the primordial value of the $^4$He abundance based on a regression with respect to O/H was only marginally statistically more significant than a weighted mean which yields $Y_p = 0.252 \pm 0.003$. This result is also obtained using a Bayesian analysis in which the sole prior is the increase in $^4$He in time [34]. The combination of the $^4$He abundance based on the mean value and the CMB value for $\eta$ gives $N_\nu = 3.27 \pm 0.24$ with a 95% upper limit $\delta N_{\nu,\text{max}} = 0.7$. Recall, the constraint on $\delta N_{\nu,\text{max}}$ assumes $N_\nu > 3$ or $\delta N_\nu > 0$.

In all cases the preferred values for $N_\nu$ are consistent with $N_\nu = 3$, and in many cases are much closer to $N_\nu = 3$ than 1σ. This restates the overall consistency among standard BBN theory, D and $^4$He observations, and CMB anisotropies. It also constrains departures from this scenario. Our combined limit using BBN + light elements + CMB limit is:

$$ 2.67 \leq N_\nu \leq 3.85 $$

at 68% CL.

4.2 Constraints on the Variation of Fundamental Constants

As noted earlier, BBN also placed interesting limits on possible variations of fundamental constants. Indeed, almost every fundamental parameter can be constrained by BBN if it affects either the expansion rate of the Universe, the weak interaction rates prior to nucleosynthesis, or of course the nuclear rates themselves. As quantitative examples of the
constraints which can be derived, we focus here solely on variations of Newton’s constant and the fine-structure constant. Here, we simply note that many other constraints have been considered in the past (for a recent review see: [35]).

4.2.1 Newton’s Constant, $G_N$

Strictly speaking, it makes no sense to consider the variation of a dimensionful constant such as $G_N$ (see e.g. [36]). We include the discussion here for the purposes of comparison with previous constraints. We also note that the limit set here could be interpreted as a limit on the gravitational coupling between two protons ($G_N m_p^2$) in a framework where we have chosen $m_p$ (and all other particle masses) to be constant. Early constraints [37] on $G_N$ relied mainly on $^4$He abundance observations. Recently, the D/H abundance was used [38] in conjunction with the WMAP determination of $\eta$ to set a limit on $\Delta G_N/G_{N,0}$ of about 20\% from the time of BBN. Assuming a simple power law dependence $G_N \sim t^{-x}$, $x$ was constrained to the range $-0.004 < x < 0.005$ implying $-4 \times 10^{-13} \text{yr}^{-1} < \dot{G}_{N,0}/G_{N,0} < 3 \times 10^{-13} \text{yr}^{-1}$. The use of D/H was motivated in part by the previously discrepant value for $Y_p$.

Although the uncertainty in the $^4$He abundance has been argued to be significantly larger than past values (0.009 vs 0.002) [16], the resulting bounds on $G_N$ are still interesting. The limit on $\delta N_\nu$ of $-0.60 < \delta N_\nu < 0.82$ from the $Y_p + \text{CMB}$ constraint, can be translated directly to a bound on the speed-up factor: $0.949 < \xi < 1.062$. Any variation in $G_N$ can be expressed through $\xi$

$$-0.10 < \frac{\Delta G_N}{G_{N,0}} = \xi^2 - 1 < 0.13 \quad (6)$$

or perhaps more simply put, the limit on the variation in $G_N$ can always be related directly to the limit on $N_\nu$ through

$$\frac{\Delta G_N}{G_{N,0}} = \frac{7}{43} \delta N_\nu \quad (7)$$

If one makes the common assumption that $G_N \sim t^{-x}$, we obtain, $-0.0029 < x < 0.0032$ and $-2.4 \times 10^{-13} \text{yr}^{-1} < \dot{G}_{N,0}/G_{N,0} < 2.1 \times 10^{-13} \text{yr}^{-1}$ (using $t_0 = 13.7 \pm 0.2 \text{ Gyr}$ [6], and $t_{BBN} \sim 100 \text{ sec}$). Thus despite the increased uncertainty in $Y_p$, the $^4$He abundance still provides the strongest possible constraint on $G_N$.

4.2.2 The Fine-Structure Constant, $\alpha$

There has been a great deal of activity surrounding possible variations of the fine-structure constant, motivated largely by a reported observational analysis of quasar absorption systems which has been interpreted as a variation in $\alpha$ [39]. We note that other observations using
similar methods [40] have not confirmed the variation in \( \alpha \), and other interpretations based on the nucleosynthesis of heavy Mg isotopes in the absorbers may also explain the data [41]. Other constraints from the CMB [42], the Oklo reactor [43, 44], and meteoritic abundances [44, 45] have also been derived. Once again, our goal here is to update the BBN bound on variations in \( \alpha \) using the newly derived value of \( Y_p \).

If we assume that only \( \alpha \) is allowed to vary (i.e., we assume that all other fundamental parameters are held fixed), the dominant contribution to a change in \( Y_p \) comes from the variation in the neutron-proton mass difference, \( Q = m_n - m_p \) [46]. The \(^4\)He abundance can be estimated simply from the ratio of the neutron-to-proton number densities, \( n/p \), by assuming that essentially all free neutrons are incorporated into \(^4\)He. The neutron-to-proton ratio at weak freezeout is \((n/p)_f \sim e^{-Q/T_f}\), modulo free neutron decay, where \( T_f \) is the temperature at which the weak interaction rate for interconverting neutrons and protons falls below the expansion rate of the Universe.

Variations in \( Q \) leads to a variation in \( Y_p \) given approximately by

\[
\frac{\Delta Y}{Y} \approx -\frac{\Delta Q}{Q}
\]

One can write the nucleon mass difference as

\[
Q \sim a\alpha \Lambda_{QCD} + bv
\]

where \( a \) and \( b \) are dimensionless constants giving the relative contributions from the electromagnetic and weak interactions. In [47], \( v \) is the standard model Higgs expectation value. A discussion on the contributions to \( Q \) can be found in [47]. The constants \( a \) and \( b \) are chosen so that at present the two terms contribute -0.8 MeV and 2.1 MeV respectively. Eqs. [8] and [9] can be combined to give

\[
\frac{\Delta Y}{Y} \approx 0.6 \frac{\Delta \alpha}{\alpha}
\]

Thus the current uncertainty in the observational determined value of \( Y_p \) leads to a bound of \(|\Delta \alpha/\alpha| < 0.06\). If changes in \( \alpha \) are correlated to changes in other gauge or Yukawa couplings, this limit improves (in a model dependent way) by about 2 orders of magnitude [48].

4.3 Limits on Decaying Particles

An exotic scenario often considered is that of late-decaying particles \((\tau_X \sim 10^8 \text{ sec})\) [49]. The particles are assumed to decay electromagnetically, meaning that the decays inject electromagnetic radiation into the early universe. If the decaying particle is abundant enough
or massive enough, the injection of electromagnetic radiation can photo-erode the light elements created during primordial nucleosynthesis. The theories we have in mind are generally supersymmetric, in which the gravitino and neutralino are the next-to-lightest and lightest supersymmetric particles, respectively, but the constraints hold for any decay producing electromagnetic radiation. We thus constrain the abundance of such a particle given its mean lifetime $\tau_X$. The abundance is constrained through the parameter $\zeta_X \equiv 2E_{inj}n_X/n_\gamma$. We can see there is a degeneracy between the relative abundance $n_X/n_\gamma$ and the injected energy $E_{inj}$. Specific theories can relate the lifetime with the mass of the decaying particle and thus the injected energy $E_{inj}$, however, we will restrict ourselves to the general case.

The constraint placed by the $^4$He abundance comes from its lower limit, as this scenario destroys $^4$He. The maximum value our abundance parameter can take is proportional to the $^4$He constraint, $\zeta_{X,max}(^4\text{He}) \propto (Y_{BBN} - Y_{min})/Y_{BBN}$. Here $Y_{BBN}$ is the predicted $^4$He abundance given $\eta$ and $Y_{min}$ is the minimum allowed value from observations. Using $Y_{min} = 0.232$, we find:

$$\zeta_X(^4\text{He}) < 2.1 \times 10^{-10} \text{ GeV} \left( \frac{\eta_0}{6.14} \right) \left( \frac{\tau_X}{10^8 \text{ sec}} \right)^{1/4} \text{ for } \tau_X > 10^8 \text{ sec}$$

(11)

However, in this scenario the limits on the tertiary production of $^6$Li provide stronger constraints on late-decaying particles, with $\zeta_X < 5.1 \times 10^{-12} \text{ GeV}$ following the same scalings with $\eta_0$ and $\tau_X$ as $^4$He.

### 4.4 Other Bounds

Models of neutrino masses with new right-handed interactions are also subject to the constraint from $^4$He. If we assume right-handed neutrinos are present and are light enough ($< 1 \text{ MeV}$) to count as extra relativistic degrees of freedom during BBN, they are subject to the constraint on $\delta N_\nu < 1.60$. Assuming there are 3 standard model neutrinos and 3 right-handed neutrinos, we can relate the limit on $\delta N_\nu$ to the temperature ratio of right-handed to left-handed neutrino temperatures: $\delta N_\nu = 3(T_{\nu_R}/T_{\nu_L})^4$ [50]. We find $T_{\nu_R}/T_{\nu_L} < 0.85$ with 95% confidence. In order to change this ratio from unity, right-handed neutrinos must decouple before epochs of entropy release, generally due to particle annihilation. To accommodate the constraint on the temperature ratio, $\nu_R$ must decouple at least before the annihilation epoch of pions, if not before the quark-hadron transition, with $T_{\text{dec}} > 140 \text{ MeV}$.

As a consequence, right-handed interactions governed by some new mass scale $M_R$, can also be constrained. Requiring that these interactions decouple before the pion annihilation...
epoch and recalling that $T_{\text{dec}}$ scales as $M_{W_R}^4$, we find that:

$$M_{W_R} > 3.3 \text{ TeV} \left( \frac{T_{\text{dec}}}{140 \text{ MeV}} \right)^{3/4}$$

(12)

Note this constraint is stronger than limits currently set by high-precision electroweak constraints ($M_{W_R} > 715 \text{ GeV}$ [51]). For recent analyses of models of this type, see [52].

BBN can also constrain the presence of vacuum energy during nucleosynthesis, via the expansion speedup provided by the additional energy density. The presence of vacuum energy during BBN is motivated both by considerations of dark energy [53, 54] as well as inflation. The new vacuum energy component is typically modelled as some scalar field $\phi$. The evolution of the scalar field is controlled by its potential as well as the Friedmann equation. However, for an important class of models, there is a “tracker” solution which is an attractor, and leads the vacuum energy density to be proportional to the dominant radiation density [53]. In this case, the vacuum energy acts essentially as an extra neutrino species, with

$$\Omega_\phi(1 \text{ MeV}) = \frac{\rho_\phi}{\rho_{\text{rad}} + \rho_\phi} = \frac{7\delta N_\nu/4}{10.75 + 7\delta N_\nu/4}$$

(13)

Using our limit $\delta N_\nu < 1.60$, we find that $\Omega_\phi(1 \text{ MeV}) < 0.21$. For the case of an exponential potential $V(\phi) = M_{Pl}^4 e^{-\phi/M_{Pl}}$, this constraints the coupling $\lambda = 2/\sqrt{\Omega_\phi} > 4.4$.

5 Summary

A new and detailed assessment [16] of the observed primordial $^4\text{He}$ abundance, and its uncertainties, has important implications for cosmology and BBN generally, and for early universe and particle physics in particular. The observed $^4\text{He}$ abundance is now found to be consistent with the $\eta$ value given by D, leaving $^7\text{Li}$ alone in discordance. Moreover, both D and now $^4\text{He}$ are consistent with the precision $\eta$ range determined by recent observations of CMB anisotropies. The newfound $^4\text{He}$ agreement arises primarily because the new and more detailed error budget is also larger than previous estimates. Nevertheless, with $^4\text{He}$ in concordance, it now rejoins D and the CMB as a probe of physics beyond the Standard Model.

We have surveyed the impact of the new $^4\text{He}$ analysis on nonstandard physics. The classic neutrino counting argument is found to give relaxed though non-trivial limits to $\delta N_\nu$ (eq. 5 and Table 1). We find that D and $^4\text{He}$ observations each make similar contributions to these limits. Thus, if one of these observations can be significantly improved, it will dominate our ability to probe exotica.
These limits immediately translate to tighter constraints on variation of the fundamental constants. They also constrain the presence of vacuum energy (in the “tracker” regime) during BBN. Finally, we note that the new $^4\text{He}$ limit on decaying particle scenarios remains weaker than the constraints placed by $^6\text{Li}$; with a factor $\sim 2$ improvement in precision, $^4\text{He}$ would be competitive.

We thus urge continued effort to (realistically!) improve the precision of the observations of primordial abundances. A sharpening in either D or $^4\text{He}$ will immediately tighten the limits we place here. And of course, the outstanding problem with $^7\text{Li}$ continues to demand explanation.

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