24. Big Bang Nucleosynthesis

Revised August 2025 by B.D. Fields (Astronomy, Illinois U.; Physics, Illinois U.), P. Molaro (INAF-OATS Trieste; IFPU) and S. Sarkar (Rudolf Peierls, Oxford U.).

24.1 Abstract

Big-Bang nucleosynthesis (BBN) offers the deepest reliable probe of the early Universe, being based on well-understood Standard Model physics [1]. Predictions of the abundances of the light elements, D, ^{3}He, ^{4}He, and ^{7}Li, synthesized at the end of the *first three minutes*, are in good overall agreement with the primordial abundances inferred from observational data, thus validating the standard hot Big-Bang cosmology (see [2–5] for reviews). This is particularly impressive given that these abundances span nine orders of magnitude – from ^{4}He/H~ 0.08 down to ^{7}Li/H$\sim 10^{-10}$ (ratios by number). Thus BBN provides powerful constraints on possible deviations from the standard cosmology, and on new physics beyond the Standard Model [6–9].

24.2 Theory

The synthesis of the light elements is sensitive to physical conditions in the early radiation-dominated era at a temperature $T \sim 1$ MeV, corresponding to an age $t \sim 1$ s. At higher temperatures, weak interactions were in thermal equilibrium, thus fixing the ratio of the neutron and proton number densities to be $n/p = \mathrm{e}^{-Q/T}$, where $Q = 1.293$ MeV is the neutron-proton mass difference. As the temperature dropped, the neutron-proton inter-conversion rate per nucleon, $\Gamma_{n\leftrightarrow p} \sim G_{\mathrm{F}}^2 T^5$, fell faster than the Hubble expansion rate, $H \sim \sqrt{g_* G_{\mathrm{N}}}\, T^2$, where g_* counts the number of relativistic particle species determining the energy density in radiation (see 'Big Bang Cosmology' — Sec. 22 of this *Review*). This resulted in departure from chemical equilibrium (*freeze-out*) at $T_{\mathrm{fr}} \sim (g_* G_{\mathrm{N}}/G_{\mathrm{F}}^4)^{1/6} \simeq 1$ MeV. The neutron fraction at this time, $n/p = \mathrm{e}^{-Q/T_{\mathrm{fr}}} \simeq 1/6$, is thus sensitive to every known physical interaction, since Q is determined by both strong and electromagnetic interactions while T_{fr} depends on the weak as well as gravitational interactions. Moreover, the sensitivity to the Hubble expansion rate affords a probe of, *e.g.,* the number of relativistic neutrino species [10]. After freeze-out, the neutrons were free to β-decay, so the neutron fraction dropped to $n/p \simeq 1/7$ by the time nuclear reactions began. A simplified analytic model of freeze-out yields the n/p ratio to an accuracy of $\sim 1\%$ [11, 12].

The rates of these reactions depend on the density of baryons (strictly speaking, nucleons), which is usually expressed normalized to the relic blackbody photon density as $\eta \equiv n_b/n_\gamma$. As we shall see, all the light-element abundances can be explained with $\eta_{10} \equiv \eta \times 10^{10}$ in the range 6.040 ± 0.118. With n_γ fixed by the present CMB temperature 2.7255 K (see 'Cosmic Microwave Background' — Sec. 29 of this *Review*), this can be stated as the allowed range for the baryon mass density today, $\rho_{\mathrm{b}} = (4.2 \pm 0.1) \times 10^{-31}\ \mathrm{g\,cm^{-3}}$, or as the baryonic fraction of the critical density, $\Omega_{\mathrm{b}} = \rho_b/\rho_{\mathrm{crit}} \simeq \eta_{10} h^{-2}/274 = (0.02205 \pm 0.00043)h^{-2}$, where $h \equiv H_0/100\ \mathrm{km\,s^{-1}\,Mpc^{-1}} \simeq 0.7$ is the present Hubble parameter (see 'The Cosmological Parameters' — Sec. 25 of this *Review*).

The nucleosynthesis chain begins with the formation of deuterium in the process $p(n,\gamma)$D. However, photo-dissociation by the high number density of photons delays production of deuterium (and other complex nuclei) until well after T drops below the binding energy of deuterium, $\Delta_{\mathrm{D}} = 2.23$ MeV. The quantity $\eta^{-1}\mathrm{e}^{-\Delta_{\mathrm{D}}/T}$, *i.e.,* the number of photons per baryon above the deuterium photo-dissociation threshold, falls below unity at $T \simeq 0.1$ MeV; nuclei can then begin to form without being immediately photo-dissociated again. Only 2-body reactions, such as D$(p,\gamma)^3$He and ^{3}He$(\mathrm{D},p)^4$He are important because the density by this time has become rather low – comparable to that of air!

Nearly all neutrons end up bound in the most stable light element ^{4}He. Heavier nuclei do not form in any significant quantity both because of the absence of stable nuclei with mass number 5 or 8 (which impedes nucleosynthesis via n^4He, p^4He or ^{4}He^{4}He reactions), and the large Coulomb barriers for reactions such as ^{3}He(^{4}He, γ)^{7}Li and ^{3}He(^{4}He, γ)^{7}Be. Hence the primordial mass fraction of ^{4}He, $Y_{\rm p} \equiv \rho(^4{\rm He})/\rho_{\rm b}$, can be estimated by the simple counting argument

$$Y_{\rm p} = \frac{2(n/p)}{1+n/p} \simeq 0.25\,, \tag{24.1}$$

where strictly speaking this gives the baryon fraction in ^{4}He, which is what we will quote throughout. This differs slightly from the mass fraction due to small binding energy corrections.

There is little sensitivity here to the actual nuclear reaction rates for the production of ^{4}He. Nuclear rates are, however, critically important in determining the other 'left-over' abundances: D and ^{3}He at the level of a few times 10^{-5} by number relative to H, and ^{7}Li/H at the level of about 10^{-10} (when η_{10} is in the range 1–10). These values can be understood in terms of approximate analytic arguments [12, 13].

The elemental abundances shown in Fig. 24.1 as a function of η_{10} were calculated using an updated version [14] of the Wagoner code [1]; other versions [15–18] too are publicly available. The ^{4}He curve includes small corrections due to radiative processes at zero and finite temperatures [19], non-equilibrium neutrino heating during $e^{\pm}$ annihilation [20], and finite nucleon mass effects [21]; the range primarily reflects the 2σ uncertainty in the neutron lifetime. The spread in the curves for D, ^{3}He, and ^{7}Li corresponds to the 2σ uncertainties in nuclear cross sections, as estimated by Monte Carlo methods [22–25]. The input nuclear data have been carefully reassessed [2, 14, 22–32], leading to improved precision for the abundance predictions. In particular, the uncertainty in ^{7}Li/H at interesting values of η has been reduced recently by a factor ~ 2, a consequence of a similar reduction in the error budget [33] for the dominant mass-7 production channel ^{3}He(^{4}He, γ)^{7}Be. Polynomial fits to the predicted abundances and the error correlation matrix have been given in refs. [24, 34]. The boxes in Fig 24.1 show the observationally inferred primordial abundances with their associated uncertainties, as discussed below.

The nuclear reaction cross sections important for BBN have all been measured at the relevant energies. Recently however there have been substantial advances in the precision of light element observations (e.g., D/H) and in the determination of cosmological parameters (e.g., from *Planck*). This motivates corresponding improvement in BBN predictions and thus in the key reaction cross sections. Recent measurements of D(p, γ)^{3}He by the LUNA collaboration have significantly improved the precision of D/H predictions [35]. Even so, the nuclear uncertainties still leave D/H prediction errors larger than those of the observations [14, 31, 32]. The D(D, n)^{3}He and D(D, p)^3H reactions now not only dominate the uncertainty budget, but they can give significantly different D/H predictions depending on whether one uses just the empirical determination of the cross sections, or also uses theory to guide the functional form. Clearly, more experimental data is needed.

An additional experimental parameter important in determining the light element abundances is the neutron lifetime, τ_n, which normalizes (the inverse of) $\Gamma_{n\leftrightarrow p}$. Its value has been revised downwards to $\tau_n = 878.4 \pm 0.5$ s (see *N* Baryons Listing).

24.3 Observations: the Light Element Abundances

BBN theory predicts the universal abundances of D, ^{3}He, ^{4}He, and ^{7}Li, which are essentially fixed by $t \sim 180$ s. However, these abundances are *inferred* from observations made at much later epochs, after stellar nucleosynthesis has begun. Stars produce heavier elements such as C, N, O, and Fe (collectively referred to as "metals"), and the ejecta from stellar processes can alter the light element abundances from their primordial values. To obtain measurements that more closely reflect the primordial composition, one must identify astrophysical environments with low metallicity, where stellar processing has been minimal.

BBN is the only significant source of deuterium, which is entirely destroyed when cycled through stars [36]. Thus, any detection of D provides a lower limit to the primordial abundance D/H|p, and correspondingly, an upper limit on the baryon-to-photon ratio η_{10}. The best proxy for the primordial D abundance is its measurement in distant, chemically unprocessed environments, where stellar processing (astration) is minimal [36, 37]. These measurements have become possible with the advent of large-aperture telescopes; yet, despite nearly three decades of observational effort, only 12 high-precision determinations are currently available, as listed in Table 24.1 [38–44].

High-resolution spectra reveal the presence of deuterium in high-redshift, low-metallicity quasar absorption systems through its isotope-shifted Lyman-α absorption lines. However, these features are often partially obscured or contaminated by intervening hydrogen in the Lyman-α forest. In a few damped Lyman-α (DLA) systems, deuterium absorption has been resolved in higher-order transitions of the Lyman series. Recent determinations [39, 41] and re-analyses [42–44] have significantly improved the precision of deuterium abundance measurements compared to earlier studies. The observed D/H ratio exhibits no correlation with metallicity, redshift, or the neutral hydrogen column density $N(\mathrm{HI})$ $(= \int_{\mathrm{los}} n_{\mathrm{HI}}\ ds)$ integrated along the line of sight through the absorber. The metallicities of these absorption systems range from $(0.001 - 0.03)\times$ the Solar value, and the level of deuterium astration is estimated to be between 0.1% and 1% [37]. In contrast, within the Milky Way, DI/HI measurements show an anti-correlation with metal abundance, suggesting that a fraction of interstellar deuterium is depleted onto dust grains [46].

However, in the absorbers where deuterium is measured, the dust content is small, as implied by Solar proportions of the abundances of refractory and non-refractory elements. Thus, the neutral atomic ratio DI/HI $\equiv$ D/H should match the underlying isotope ratio, and be truly representative of the primordial value D/H|p. The weighted mean of the 12 most precise and recent measurements in Table 24.1 is $\mathrm{D/H}|_{\mathrm{p}} \times 10^6 = (25.08 \pm 0.27)$. It is worth noting that earlier determinations by [47–51] are also consistent with this mean value. However, the ones listed in Table 24.1 yield $\chi^2/(N-1) = 1.160$, indicating that some uncertainties may be underestimated. We therefore increase the uncertainty by a factor $S = \sqrt{\chi^2/(N-1)} = 1.08$, and the recommended value for the abundance of primordial deuterium is:

$$\mathrm{D/H}|_{\mathrm{p}} \times 10^6 = 25.08\ (\pm 0.27 \times S) = 25.08\ (\pm 0.29). \tag{24.2}$$

The primordial ^{4}He abundance is best determined through recombination emission lines of He and H in the most metal-poor extragalactic HII (ionized) regions, *viz.* blue compact galaxies, generally found at low redshift. There is now a large body of data on ^{4}He and CNO in these galaxies, with over 1000 such systems in the Sloan Digital Sky Survey alone [54]. These data confirm that the stellar contribution to the helium abundance is positively correlated with metal production, so extrapolation to zero metallicity gives the primordial ^{4}He abundance Y_{p}. However, HII regions are complex systems and several physical parameters enter in the He/H determination, notably the electron density and temperature, as well as reddening. Thus, systematic effects dominate the uncertainties in the abundance determination [55, 56]. A major step forward has been the inclusion of the He $\lambda 10830$ infrared emission line which shows a strong dependence on the electron density and is thus useful to break the degeneracy with the temperature, allowing for a more robust helium abundance determination. In recent works the underlying ^{4}He stellar absorption, and/or the newly derived values of the HeI-recombination and H-excitation-collisional coefficients are adressed and the ^{4}He abundances have increased significantly. Some recent results are reported in Table 24.2.

There is a reassuring convergence towards the value of $Y_{\mathrm{p}} = 0.245$ between detailed analyses of specific extragalactic HII regions with other (statistically more significant) analyses of many

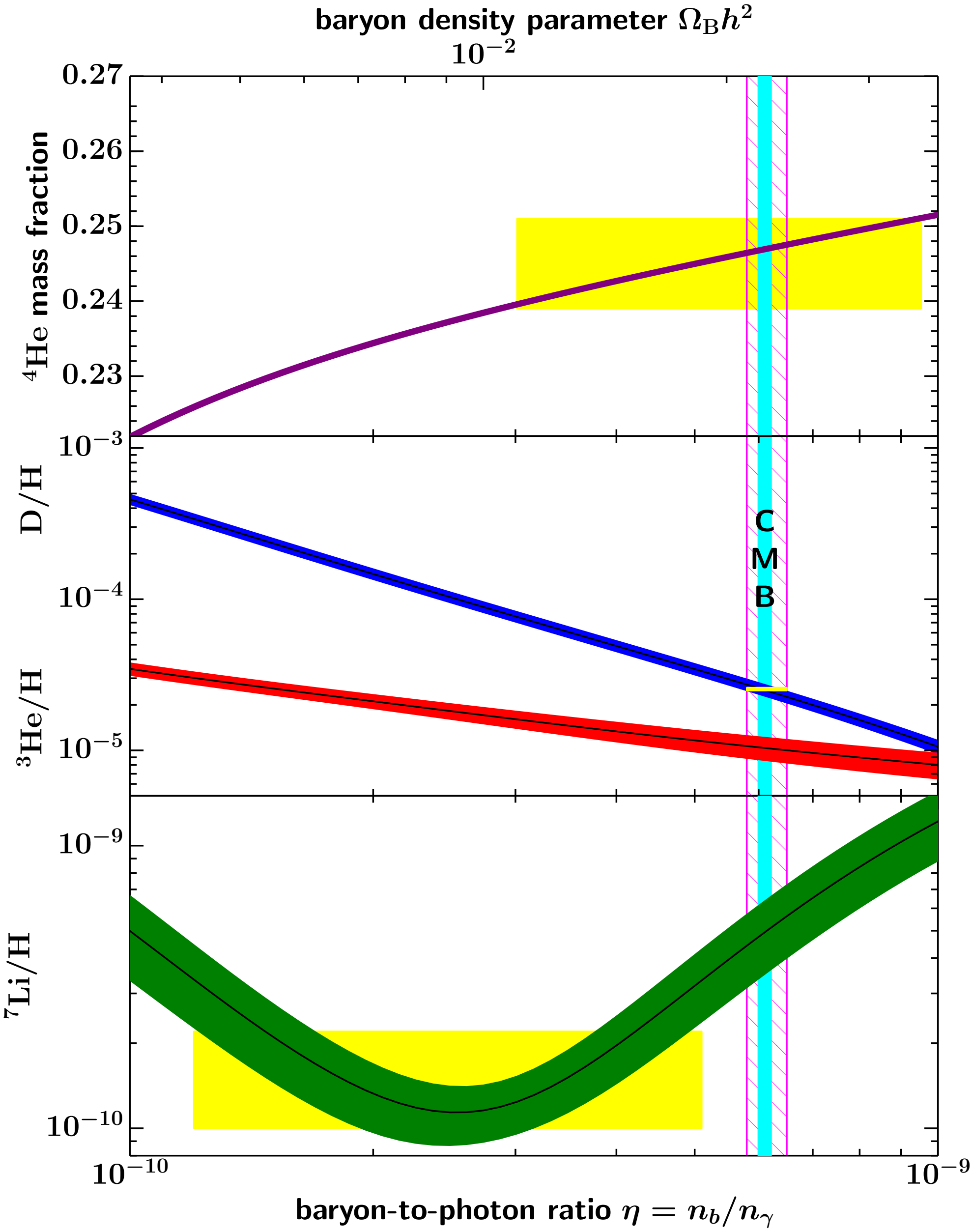

Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [45]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).

systems. Thus our recommended ^{4}He abundance is:

$$Y_p = 0.245 \pm 0.003. \tag{24.3}$$

Table 24.1: D/H measurements. For systems with multiple measurements we used the most recent one which is generally more precise.

QSO	$z_{\rm em}$	$z_{\rm abs}$	$\log N((\rm HI))$	[X/H]	$(\rm D/H) \times 10^6$	Ref
SDSS J1419+0829	3.03	3.049	20.392±0.003	-1.92[O/H]	25.06 ± 0.52	[38]
HS 0105+1619	2.65	2.536	19.426±0.006	-1.77[O/H]	25.76 ± 1.54	[38]
QSO B0913+0715	2.78	2.618	20.312±0.008	-2.40[O/H]	25.29 ± 1.05	[38]
SDSS J1358+0349	2.89	2.853	20.524±0.006	-2.80[O/H]	26.18 ± 0.72	[39]
SDSS J1358+6522	3.17	3.067	20.495±0.008	-2.33[O/H]	25.82 ± 0.71	[38]
SDSS J1558−0031	2.82	2.702	20.75±0.03	-1.55[O/H]	24.04 ± 1.44	[38]
PKS 1937−1009	3.78	3.256	18.09±0.03	-1.87[O/H]	24.49 ± 2.80	[40]
QSO J1444+2919	2.66	2.437	19.983±0.010	-2.04[O/H]	$19.68^{+3.3}_{-2.8}$	[41]
PKS 1937−1009	3.78	3.572	17.925±0.006	-2.52[O/H]	26.08 ± 1.02	[52]
QSO 1009+2956	2.63	2.504	17.362±0.005	-2.50[Si/H]	$24.77^{+4.1}_{-3.5}$	[43]
QSO 1243+307	2.55	2.525	19.761±0.026	-2.77[O/H]	23.88 ± 0.82	[44]
QSO J1332+0052	3.51	3.42	19.304±0.004	-1.71[O/H]	23.88 ± 0.77	[53]
Weighted mean, with $S = 1.08$					25.08 ± 0.29	

Table 24.2: Recent primordial ^{4}He measurements in extragalactic HII regions.

$Y_{\rm p}(^4\rm He)$	$\pm 1\sigma_{\rm stat}$	$\pm 1\sigma_{\rm sys}$	$\pm 1\sigma_{\rm tot}$	# systems	Ref
0.2453	0.0034			16	[57]
0.2451	0.0019	0.0018	0.0026	1	[58]
0.243	0.005			16	[59]
0.2462	0.0022			120	[60]
0.2436	0.0040			54	[61]
0.2448	0.0027	0.0018	0.0033	7	[62]
0.2448			0.0033	17	[63]

The central value is close to the mean/weighted average of the values in Table 24.2, however we caution that combining these partially overlapping data sets is not straightforward. The uncertainty reflects the combined statistical and systematic errors, with the latter, estimated to be ±0.002 [62], being dominant.

The best-suited objects for determining the primordial abundance of ^{7}Li are metal-poor stars in the Galactic halo, which exhibit metallicities as low as 10^{-6} of the Solar value [64]. Observations have long shown that ^{7}Li does not vary significantly among halo dwarfs with metallicities $\lesssim 1/30$ of Solar — the *Spite plateau* [65–69]. However, more recent observations show an increase in Li depletion in metal-poor stars [70–72]. The reason for this increased scatter at low metallicity remains unknown and prevents a reliable derivation of the primordial ^{7}Li abundance by extrapolation to zero metallicity [71, 72].

To estimate the primordial ^{7}Li abundance, we restrict the analysis to stars with metallicities in the range $-3.5 < [\rm Fe/H] < -1.5$ [69, 72], where no scatter beyond the observational uncertainties is observed. Lower metallicity stars show a strong contamination of Carbon enriched stars [73]. This yields:

$$\mathrm{Li/H}|_{\mathrm{p}} = (1.45 \pm 0.25) \times 10^{-10}. \quad (24.4)$$

Strictly speaking, the inferred primordial ^{7}Li abundance should be regarded as a *lower bound* rather than a direct measurement. This is because ^{7}Li in Population II stars may have been partially destroyed through mixing of the outer stellar layers with the hotter interior [74]. Such processes are constrained by the lack of significant scatter in ^{7}Li as a function of T_{eff}, yet a significant depletion may still have occurred [75]. Stellar determinations of Li abundances typically sum the contributions from both ^{6}Li and ^{7}Li isotopes. However, high-precision measurements indicate that $^6\mathrm{Li}\ /\ ^7\mathrm{Li} < 0.05$, confirming that ^{7}Li overwhelmingly dominates [76].

The primordial abundance of ^{3}He has the poorest observational determination of all of the light nuclides. The only data available come from the Solar system and from solar-metallicity HII regions in the Galaxy [77]. Therefore, inferring the primordial ^{3}He abundance is problematic, compounded by the fact that stellar nucleosynthesis models for ^{3}He are in conflict with observations. Consequently, we consider it inappropriate to use ^{3}He (and also D+^{3}He) as a cosmological probe.

24.4 Concordance, Dark Matter, and the CMB

We now use the observed light element abundances to test the theory. We first consider standard BBN, which is based on Standard Model physics alone, so $N_\nu = 3$ and the only free parameter is the baryon-to-photon ratio η. (The implications of BBN for physics beyond the Standard Model will be considered below). Thus, any abundance measurement determines η, and additional measurements overconstrain the theory and thereby provide a consistency check.

While the η ranges spanned by the boxes in Fig 24.1 do not all overlap, they are all within a factor ~ 2 of each other. In particular, the lithium abundance corresponds to η values that are inconsistent with that of the (now very precise) D/H abundance as well as the less-constraining ^{4}He abundance. This discrepancy marks the *lithium problem.* The problem could simply reflect difficulty in determining the primordial lithium abundance, or could hint at a more fundamental omission in the theory. The possibility that lithium reveals new physics is addressed in detail in the next section. If however we exclude the lithium constraint because its inferred abundance suffers from systematic uncertainties, then D/H and ^{4}He are in agreement. The concordant η range is essentially determined by D/H, and yields [78]

$$(\eta_{10})_{\mathrm{SBBN}} = 6.040 \pm 0.118 \ , \quad (24.5)$$

where the errors are 1σ. Despite the lithium problem, the overall concordance remains remarkable: using only well-established microphysics we can extrapolate back to $t \sim 1$ s to predict light element abundances spanning nine orders of magnitude, in approximate agreement with observation. This is a major success for the standard cosmology, and inspires confidence in extrapolation back to such early times.

This concordance provides a measure of the baryon content:

$$(\Omega_{\mathrm{b}}\mathrm{h}^2)_{\mathrm{SBBN}} = 0.02205 \pm 0.00043 \ , \quad (24.6)$$

where again errors are 1σ, a result that plays a key role in our understanding of the matter budget of the Universe. First of all $\Omega_{\mathrm{b}} \ll 1$, *i.e.*, baryons cannot close the Universe [79]. Furthermore, the cosmic density of (optically) luminous matter is $\Omega_{\mathrm{lum}} \simeq 0.0024\mathrm{h}^{-1}$ [80], so that $\Omega_{\mathrm{b}} \gg \Omega_{\mathrm{lum}}$: most baryons are optically dark, probably in the form of a diffuse intergalactic medium [81]. Finally, given that $\Omega_{\mathrm{m}} \sim 0.3$ (see the 'Dark Matter' and 'Cosmological Parameters' reviews), we infer that most matter in the Universe is not only dark, but also takes some non-baryonic (more precisely, non-nucleonic) form.

The BBN prediction for the cosmic baryon density can be tested through precision measurements of CMB temperature fluctuations (see the 'Cosmic Microwave Background' review). One can determine η from the amplitudes of the acoustic peaks in the CMB angular power spectrum [82], making it possible to compare two measures of η using very different physics, at two widely separated epochs. In the standard cosmology, there is no change in η between BBN and CMB decoupling, thus, a comparison of $\eta_{\rm BBN}$ and $\eta_{\rm CMB}$ is a key test. Agreement would endorse the standard picture, while disagreement could point to new physics during/between the BBN and CMB epochs.

The analysis described in the Cosmic Microwave Background review (Sec.29), based on *Planck* TT, TE, EE + lowE data and lensing, yields [83]:

$$(\Omega_{\rm b}{\rm h}^2)_{\rm CMB} = 0.02237 \pm 0.00015; \tag{24.7}$$

which corresponds to [84]

$$(\eta_{10})_{\rm CMB} = 6.12 \pm 0.04\ . \tag{24.8}$$

This result depends weakly on the primordial helium abundance, and the fiducial *Planck* analysis uses BBN theory to fix $Y_{\rm p}(\eta)$. Without BBN theory, the *Planck* TT, TE, EE + lowE data plus lensing give $\Omega_{\rm b}{\rm h}^2 = 0.02230 \pm 0.00021$, corresponding to $\eta_{10} = 6.104 \pm 0.058$. As shown in Fig. 24.1, this CMB estimate of the baryon density (narrow vertical band) is consistent with the BBN range, *i.e.*, in good agreement with the value inferred from high-redshift D/H measurements and local ^{4}He determinations; together these observations span diverse environments from redshifts $z \sim 1000$ to the present. Combining the CMB and BBN sharpens the baryon measures to $\eta_{10} = 6.115 \pm 0.038$ and $\Omega_{\rm b}h^2 = 0.02233 \pm 0.00014$ [78].

The ^{4}He abundance is proportional to the n/p ratio when the weak-interaction rate falls behind the Hubble expansion rate at $T_{\rm fr} \sim 1$ MeV. The presence of additional neutrino flavors (or of any other relativistic species) at this time increases g_*, hence the expansion rate, leading to a larger value of $T_{\rm fr}$, n/p, and therefore $Y_{\rm p}$ [10,85]. In the Standard Model at $T = 1$ MeV, $g_* = 5.5 + \frac{7}{4}N_\nu$, where N_ν is the *effective* number of (nearly) massless neutrino flavors. The helium curves in 24.1 were computed taking $N_\nu = 3$; small corrections for non-equilibrium neutrino heating [20] are included in the thermal evolution and lead to an effective $N_\nu = 3.044$ compared to assuming instantaneous neutrino freezeout (see 'Big Bang Cosmology' — Sec. 22 of this *Review*). The computed ^{4}He abundance scales as $\Delta Y_{\rm p} \simeq 0.013 \Delta N_\nu$ [11]. Clearly the central value for N_ν from BBN will depend on η, which is independently determined (with weaker sensitivity to N_ν) by the adopted D or ^{7}Li abundance. For example, if the best value for the observed primordial ^{4}He abundance is 0.249, then, for $\eta_{10} \sim 6$, the central value for N_ν is very close to 3. A maximum likelihood analysis on η and N_ν based on ^{4}He and D abundances nearly identical to those above finds the (correlated) 68% CL ranges to be $\eta_{10} = 6.088 \pm 0.054$ and [45,78,86]

$$N_\nu = 2.898 \pm 0.141 \tag{24.9}$$

which is consistent with the Standard Model. Identical results are obtained using a simpler method to extract such bounds based on χ^2 statistics, given a set of input abundances [87]. Very recently, the *Atacama Cosmology Telescope* and *South Pole Telescope* have each released new cosmological parameters arising from their most recent data, reporting $N_{\rm eff} = 2.86 \pm 0.13$ [88] and $N_{\rm eff} = 2.83 \pm 0.13$ [89], respectively. We look forward to joint analyses of these data with *Planck* that will sharpen the BBN/CMB interplay.

The CMB damping tail is sensitive to the primordial ^{4}He abundance independently of both BBN and local ^{4}He measurements [90]. The *Planck* analysis using TT, TE, EE+lowE and lensing but not the BBN $Y_{\rm p}(\eta)$ relation gives a ^{4}He mass fraction $0.239^{+0.024}_{-0.025}$, and nucleon fraction $Y_{\rm p} = 0.240^{+0.24}_{-0.25}$, both at 95% CL [83]. This is consistent with the HII region helium abundance determination. Moreover, this value is consistent with the Standard ($N_\nu = 3$) BBN prediction for Y_p with the *Planck*-determined baryon density. This concordance represents a successful CMB-only test of BBN.

The precision determination of the baryon density using the CMB motivates using this as an input to BBN calculations. Within the context of the Standard Model, BBN then becomes a zero-parameter theory, and the light element abundances are completely determined to within the uncertainties in η_CMB and the BBN theoretical errors. Comparison with the observed abundances then can be used to test the astrophysics of post-BBN light element evolution [91]. Alternatively, one can consider possible physics beyond the Standard Model (*e.g.*, which might change the expansion rate during BBN) and then use all of the abundances to test such models; this is discussed in 24.6 below.

24.5 The Lithium Problem and its Possible Resolution

As shown in Fig. 24.1, stellar Li/H measurements are inconsistent with the D/H (and CMB) constraints, given the quoted error budgets. For example, the primordial value from [45]

$$\mathrm{Li/H}|_\mathrm{p} = (4.72 \pm 0.7) \times 10^{-10} \tag{24.10}$$

exceeds the prediction of eq. 24.4 by a factor of 3.3, corresponding to a 4.4σ discrepancy. The universality of this problem is underscored by the fact that stars accreted into the Milky Way billions of years ago from external galaxies exhibit the same Li abundances as native stars [92–94]. The question then becomes pressing as to whether this mismatch comes from systematic errors in the observed abundances, and/or uncertainties in stellar astrophysics or nuclear inputs, or whether there might be new physics at work [9]. Nuclear inputs (cross sections) for BBN reactions are constrained by extensive laboratory measurements; to increase ^{7}Be destruction requires enhancement of otherwise subdominant processes that can be attained by missed resonances in a few reactions such as $^7\mathrm{Be}(d,p)2\alpha$ if the compound nuclear state properties are particularly favorable [30, 95–97]. However, experimental searches have now closed off these possibilities [98–100], making a *nuclear fix* increasingly unlikely.

Alternatively, lithium may be destroyed *in situ* within stars over their lifetimes. Depletion mechanisms include diffusion, rotational mixing, and pre-main-sequence burning. While these effects are real, reducing Li to the required levels generally demands some degree of fine-tuned stellar parameters or *ad hoc* mechanisms [101–104]. Diffusive models, for instance, predict both a dispersion in Li abundances and a downturn at the hot end of the Spite plateau. Additional turbulence must then be invoked to suppress diffusion and restore the observed uniformity [103].

Large surveys provide new insight. The GALAH project, which measured Li abundances for over 100,000 field stars, finds that warm stars with $-1.0 \le [\mathrm{Fe/H}] \le -0.5$ form a plateau consistent with BBN predictions. This suggests that more metal-poor stars—now evolved beyond observability—may once have had higher Li abundances as well [105]. Pre-main-sequence depletion has also been proposed as a viable mechanism [102, 106].

Recent ^{6}Li measurements have added an important dimension. Because BBN produces negligible ^{6}Li [107], this isotope arises from later cosmic-ray interactions—fusion reactions such as $^4\mathrm{He} + {}^4\mathrm{He} \to {}^{6,7}\mathrm{Li} + \cdots$ and spallation on CNO nuclei, e.g. $p_\mathrm{cr} + {}^{16}\mathrm{O} \to {}^{6,7}\mathrm{Li}, {}^9\mathrm{Be}, {}^{10,11}\mathrm{B} + \cdots$. Thus ^{6}Li is co-produced with Be and B, both observed in metal-poor stars, implying that ^{6}Li must have been present at their birth. Early reports of ^{6}Li detections [108–110] suggested limited ^{7}Li depletion, since ^{6}Li is more fragile. However, recent work places strong upper limits on ^{6}Li/H in key plateau stars [111], removing the ^{6}Li-based objection for the absence of stellar depletion. Indeed, cosmic-ray production models can quantify the expected ^{6}Li levels, and the observed absence of ^{6}Li today implies significant depletion—enough that ^{7}Li destruction may also be sufficient to reconcile observations with BBN predictions [112]. This strengthens the case for stellar depletion as the leading resolution to the lithium problem [101–104, 113]. Future ^{6}Li detections or limits, together with refined models, will be critical for testing this scenario.

Finally, interstellar lithium measurements in low-metallicity systems provide a stellar depletion-free probe. In the Small Magellanic Cloud, interstellar Li/H has been measured at levels consistent with Galactic halo stars [114,115]. Additional such measurements in other metal-poor environments would be highly valuable in disentangling primordial and stellar contributions.

It remains possible that the lithium problem points to new physics. Nucleosynthesis models in which the baryon-to-photon ratio is inhomogeneous can alter abundances for a given $\eta_{\rm BBN}$, but will overproduce ^{7}Li [116]. Entropy generation by some non-standard process could have decreased η between the BBN era and CMB decoupling, however the lack of spectral distortions in the CMB rules out any significant energy injection up to a redshift $z \sim 10^7$ [117]. The most intriguing resolution of the lithium problem thus involves new physics during BBN [7–9]

We summarize the general features of such solutions here, and later consider examples in the context of specific particle physics models. Many proposed solutions introduce perturbations to light-element formation during BBN; while all element abundances may suffer perturbations, the interplay of ^{7}Li and D is often the most important *i.e.* observations of D often provide the strongest constraints on the allowed perturbations to ^{7}Li. In this connection it is important to note that the new, very precise determination of D/H will significantly constrain the ability of such models to ameliorate or solve the lithium problem.

A well studied class of models invokes the injection of suprathermal hadronic or electromagnetic particles due to decays of dark matter particles. The effects are complex and depend on the nature of the decaying particles and their branchings and spectra. However, the models that most successfully solve the lithium problem generally feature non-thermal nucleons, which dissociate all light elements. Dissociation of even a small fraction of ^{4}He introduces a large abundance of free neutrons, which quickly thermalize. The thermal neutrons drive the $^7{\rm Be}(n,p)^7{\rm Li}$ conversion of ^{7}Be. The resulting ^{7}Li has a lower Coulomb barrier relative to ^{7}Be and is readily destroyed via $^7{\rm Li}(p,\alpha)^4{\rm He}$ [118, 119]]. But ^{4}He dissociation also produces D directly as well as via nonthermal neutron $n(p,\gamma)d$ reactions. This introduces a tension between Li/H reduction and D/H enhancement that becomes increasingly restrictive with the increasing precision of deuterium observations. Indeed, this now forces particle injection scenarios to make very small ^{7}Li perturbations — far short of the level needed. An exception is a recent model wherein MeV-scale decays by construction avoid ^{4}He dissociation and associated D/H overproduction, instead *borrowing* neutrons by dissociating only deuterons [120].

Another important class of models retains the standard cosmic particle content, but changes their interactions via time variations in the fundamental constants [121–127]. Here too, the details are model-dependent, but scenarios that solve or alleviate the lithium problem often feature perturbations to the deuteron binding energy. A weaker D binding leads to the D bottleneck being overcome later, so that element formation commences at a lower temperature and lower density. This leads in turn to slower nuclear rates that freeze out earlier. The net result is a *higher* final D/H, due to less efficient processing into ^{4}He, but also *lower* Li, due to suppressed production via $^3{\rm He}(\alpha,\gamma)^7{\rm Be}$.

The *cosmological lithium problem* remains an unresolved issue in BBN. Nevertheless, the remarkable concordance between the CMB and the D (as well as ^{4}He) abundance, is a non-trivial success, and provides important constraints on the early Universe.

24.6 Beyond the Standard Model

Given the simple physics underlying BBN, it is remarkable that it still provides the most effective test for the cosmological viability of ideas concerning physics beyond the Standard Model. Although baryogenesis and inflation must have occurred at higher temperatures in the early Universe, we do not as yet have 'standard models' for these, so BBN still marks the boundary between the established and the speculative in Big Bang cosmology. It might appear possible to push the boundary back to the quark-hadron transition at $T \sim \Lambda_{\rm QCD}$, or electroweak symmetry breaking at $T \sim 1/\sqrt{G_{\rm F}}$; however, so far no observable relics of these epochs have been identified, either theoretically or observationally. Thus, although the Standard Model provides a precise description of physics up to the Fermi scale, cosmology cannot be traced in detail before the BBN era.

The CMB power spectrum in the damping tail is independently sensitive to N_ν (*e.g.* [128]). The CMB value $N_\nu^{\rm CMB}$ probes the cosmic radiation content at (re)combination, so a discrepancy would imply new physics or astrophysics. Indeed, observations by the South Pole Telescope implied $N_\nu^{\rm CMB} = 3.85 \pm 0.62$ [129], prompting discussion of *dark radiation* such as sterile neutrinos [130]. However, *Planck* 2018 results give $N_\nu^{\rm CMB} = 2.92^{+0.36}_{+0.37}$, 95% CL, when using Planck TT, TE, EE+lowE, a result quite consistent with 3 Standard Model neutrinos [83] (and adjusting for the CMB's measurement of $N_{\rm eff} = 3.044$ due to neutrino heading effects [131–133]). Indeed, the BBN and CMB constraints on N_ν are independent and of similar precision, so that it is now possible to limit any *change* in this parameter (and/or the baryon-to-photon ratio) between nucleosynthesis and recombination [78]. This can, for example, constrain models with late particle decays, or with early dark energy.

Just as one can use the measured helium abundance to place limits on g_* [85, 122, 134–136], any changes in the strong, weak, electromagnetic, or gravitational coupling constants, arising *e.g.*, from the dynamics of new dimensions, can be similarly constrained [137], as can any speed-up of the expansion rate in, *e.g.*, scalar-tensor theories of gravity [138].

The limits on N_ν can be translated into limits on other types of particles or particle masses that would affect the expansion rate of the Universe during nucleosynthesis. For example, consider *sterile* neutrinos with only right-handed interactions of strength $G_{\rm R} < G_{\rm F}$. Such particles would decouple at higher temperature than (left-handed) neutrinos, so their number density ($\propto T^3$) relative to neutrinos would be reduced by any subsequent entropy release, *e.g.*, due to annihilations of massive particles that become non-relativistic between the two decoupling temperatures. Thus, (relativistic) particles with less than full strength weak interactions contribute less to the energy density than particles that remain in equilibrium up to the time of nucleosynthesis [139]. If we impose $N_\nu < 4$ as an illustrative constraint, then the three right-handed neutrinos must have a temperature $3(T_{\nu_{\rm R}}/T_{\nu_{\rm L}})^4 < 1$. Since the temperature of the decoupled $\nu_{\rm R}$ is determined by entropy conservation (see 'Big Bang Cosmology' — Sec. 22 of this *Review*), $T_{\nu_{\rm R}}/T_{\nu_{\rm L}} = [(43/4)/g_*(T_{\rm d})]^{1/3} < 0.76$, where $T_{\rm d}$ is the decoupling temperature of the $\nu_{\rm R}$. This requires $g_*(T_{\rm d}) > 24$, so decoupling must have occurred at $T_{\rm d} > 140$ MeV. The decoupling temperature is related to $G_{\rm R}$ through $(G_{\rm R}/G_{\rm F})^2 \sim (T_{\rm d}/3\,{\rm MeV})^{-3}$, where 3 MeV is the decoupling temperature for $\nu_{\rm L}$s. This yields a limit $G_{\rm R} \lesssim 10^{-2} G_{\rm F}$. The above argument sets lower limits on the masses of new Z' gauge bosons to which right-handed neutrinos would be coupled in models of superstrings [140], or extended technicolour [141]. Similarly a Dirac magnetic moment for neutrinos, which would allow the right-handed states to be produced through scattering and thus increase g_*, can be significantly constrained [142], as can any new interactions for neutrinos that have a similar effect [143–145]. Right-handed states can be populated directly by helicity-flip scattering if the neutrino mass is large enough, and this property has been used to infer a bound of $m_{\nu_\tau} \lesssim 1$ MeV (taking $N_\nu < 4$) [146]. If there is mixing between active and sterile neutrinos then the effect on BBN is more complicated [147, 148].

BBN limits on the cosmic expansion rate constrain supersymmetric scenarios in which the neutralino or gravitino are very light, so that they contribute to g_* [149]. A gravitino in the mass range $\sim 10^{-4} - 10$ eV will affect the expansion rate of the Universe similarly to a light neutralino (which is however now probably ruled out by collider data, especially the decays of the Higgs-like boson). The net contribution to N_ν then ranges between 0.74 and 1.69, depending on the gravitino and slepton masses [150].

The limit on the expansion rate during BBN can also be translated into bounds on the mass/lifetime of non-relativistic particles that decay during BBN. This results in an even faster speed-up rate, and typically also changes the entropy [151–153]. If the decays include Standard Model particles, the resulting electromagnetic [154] [91, 140, 155] and/or hadronic [156, 157] cascades can strongly perturb the light elements, which leads to even stronger constraints. Such arguments have been applied to rule out an MeV mass for ν_τ, which decays during nucleosynthesis [158].

Decaying-particle arguments have proved very effective in probing supersymmetry. Light-element abundances generally are complementary to accelerator data in constraining SUSY parameter space, with BBN reaching to values kinematically inaccessible to the LHC. Much recent interest has focused on the case in which the next-to-lightest supersymmetric particle is metastable and decays during or after BBN. The constraints on unstable particles discussed above imply stringent bounds on the allowed abundance of such particles [118]; if the metastable particle is charged (*e.g.*, the stau), then it is possible for it to form atom-like electromagnetic bound states with nuclei, and the resulting impact on light elements can be quite complex [8, 95, 159]. Moreover, SUSY decays can destroy ^{7}Li and/or produce ^{6}Li, leading to a possible supersymmetric solution to the lithium problems noted above [160] (see [7] for a review).

These arguments impose powerful constraints on supersymmetric inflationary cosmology [91, 140, 155–157], particularly thermal leptogenesis [161]. These limits can be evaded only if the gravitino is massive enough to decay before BBN, i.e., $m_{3/2} \gtrsim 50$ TeV [162] (which would be unnatural), or if it is in fact the lightest supersymmetric particle and thus stable [140, 155, 163, 164]. Similar constraints apply to moduli – very weakly coupled fields in string theory that obtain an electroweak-scale mass from supersymmetry breaking [165].

Finally, we mention that BBN places powerful constraints on the possibility that there are new large dimensions in nature, perhaps enabling the scale of quantum gravity to be as low as the electroweak scale [166]. Thus, Standard Model fields may be localized on a *brane*, while gravity alone propagates in the *bulk*. It has been further noted that the new dimensions may be non-compact, even infinite [167], and the cosmology of such models has attracted considerable attention. The expansion rate in the early Universe can be significantly modified, so BBN is able to set interesting constraints on such possibilities [168, 169].

References

[1] R. V. Wagoner, W. A. Fowler and F. Hoyle, Astrophys. J. **148**, 3 (1967).

[2] D. N. Schramm and M. S. Turner, Rev. Mod. Phys. **70**, 303 (1998), [arXiv:astro-ph/9706069].

[3] G. Steigman, Ann. Rev. Nucl. Part. Sci. **57**, 463 (2007), [arXiv:0712.1100].

[4] F. Iocco *et al.*, Phys. Rept. **472**, 1 (2009), [arXiv:0809.0631].

[5] R. H. Cyburt *et al.*, Rev. Mod. Phys. **88**, 015004 (2016), [arXiv:1505.01076].

[6] S. Sarkar, Rept. on Prog. in Phys. **59**, 1493 (1996).

[7] K. Jedamzik and M. Pospelov, New J. Phys. **11**, 105028 (2009), [arXiv:0906.2087].

[8] M. Pospelov and J. Pradler, Ann. Rev. Nucl. Part. Sci. **60**, 539 (2010), [arXiv:1011.1054].

[9] B. D. Fields, Ann. Rev. Nucl. Part. Sci. **61**, 47 (2011), [arXiv:1203.3551].

[10] P.J.E. Peebles, Phys. Rev. Lett. **16**, 411 (1966).

[11] J. Bernstein, L. S. Brown and G. Feinberg, Rev. Mod. Phys. **61**, 25 (1989).

[12] S. Mukhanov, Int. J. Theor. Phys. **143**, 669 (2004).

[13] R. Esmailzadeh, G. D. Starkman and S. Dimopoulos, Astrophys. J. **378**, 504 (1991).

[14] T.-H. Yeh, K. A. Olive and B. D. Fields, JCAP **03**, 046 (2021), [arXiv:2011.13874].

[15] L. Kawano, Technical report (1992), URL `https://ui.adsabs.harvard.edu/abs/1992STIN...9225163K`.

[16] A. Arbey *et al.*, Comput. Phys. Commun. **248**, 106982 (2020), [arXiv:1806.11095].

[17] R. Consiglio *et al.*, Computer Physics Communications **233**, 237 (2018), [arXiv:1712.04378].

[18] A.-K. Burns, T. M. P. Tait and M. Valli, Eur. Phys. J. C **84**, 1, 86 (2024), [arXiv:2307.07061].

[19] S. Esposito *et al.*, Nucl. Phys. **B568**, 421 (2000), [arXiv:astro-ph/9906232].

[20] S. Dodelson and M. S. Turner, Phys. Rev. **D46**, 3372 (1992).

[21] D. Seckel (1993), [hep-ph/9305311].

[22] R. H. Cyburt, B. D. Fields and K. A. Olive, New Astron. **6**, 215 (2001), [arXiv:astro-ph/0102179].

[23] M. S. Smith, L. H. Kawano and R. A. Malaney, Astrophys. J. Suppl. **85**, 219 (1993).

[24] G. Fiorentini *et al.*, Phys. Rev. **D58**, 063506 (1998), [arXiv:astro-ph/9803177].

[25] A. Coc *et al.*, Astrophys. J. **744**, 158 (2012), [arXiv:1107.1117].

[26] R. H. Cyburt, B. D. Fields and K. A. Olive, JCAP **0811**, 012 (2008), [arXiv:0808.2818].

[27] K. M. Nollett and S. Burles, Phys. Rev. **D61**, 123505 (2000), [arXiv:astro-ph/0001440].

[28] R. H. Cyburt, Phys. Rev. **D70**, 023505 (2004), [arXiv:astro-ph/0401091].

[29] P. D. Serpico *et al.*, JCAP **0412**, 010 (2004), [arXiv:astro-ph/0408076].

[30] R. N. Boyd *et al.*, Phys. Rev. **D82**, 105005 (2010), [arXiv:1008.0848].

[31] C. Pitrou *et al.*, Mon. Not. Roy. Astron. Soc. **502**, 2, 2474 (2021), [arXiv:2011.11320].

[32] O. Pisanti *et al.*, JCAP **04**, 020 (2021), [arXiv:2011.11537].

[33] R.H. Cyburt and B. Davids, Phys. Rev. **C78**, 012 (2008).

[34] S. Burles, K. M. Nollett and M. S. Turner, Astrophys. J. **552**, L1 (2001), [arXiv:astro-ph/0010171].

[35] V. Mossa *et al.*, Nature **587**, 7833, 210 (2020).

[36] R. I. Epstein, J. M. Lattimer and D. N. Schramm, Nature **263**, 198 (1976).

[37] F. van de Voort *et al.*, Mon. Not. Roy. Astron. Soc. **477**, 1, 80 (2018), [arXiv:1704.08254].

[38] R. Cooke *et al.*, Astrophys. J. **781**, 1, 31 (2014), [arXiv:1308.3240].

[39] R. J. Cooke *et al.*, Astrophys. J. **830**, 2, 148 (2016), [arXiv:1607.03900].

[40] S. Riemer-Sørensen *et al.*, Mon. Not. Roy. Astron. Soc. **447**, 3, 2925 (2015), [arXiv:1412.4043].

[41] S. A. Balashev *et al.*, Mon. Not. Roy. Astron. Soc. **458**, 2, 2188 (2016), [arXiv:1511.01797].

[42] S. Riemer-Sørensen *et al.*, Mon. Not. Roy. Astron. Soc. **468**, 3, 3239 (2017), [arXiv:1703.06656].

[43] E. O. Zavarygin *et al.*, Mon. Not. Roy. Astron. Soc. **477**, 4, 5536 (2018), [arXiv:1706.09512].

[44] R. J. Cooke, M. Pettini and C. C. Steidel, Astrophys. J. **855**, 2, 102 (2018), [arXiv:1710.11129].

[45] B. D. Fields *et al.*, JCAP **2020**, 3, 010 (2020), [arXiv:1912.01132].

[46] J. L. Linsky *et al.*, Astrophys. J. **647**, 1106 (2006), [arXiv:astro-ph/0608308].

[47] M. Pettini and D. V. Bowen, Astrophys. J. **560**, 41 (2001), [arXiv:astro-ph/0104474].

[48] S. D'Odorico, M. Dessauges-Zavadsky and P. Molaro, Astron. Astrophys. **368**, L21 (2001), [arXiv:astro-ph/0102162].

[49] M. Fumagalli, J. M. O'Meara and J. X. Prochaska, Science **334**, 1245 (2011), [arXiv:1111.2334].

[50] P. Noterdaeme *et al.*, Astron. Astrophys. **542**, L33 (2012), [arXiv:1205.3777].

[51] R. Srianand *et al.*, Mon. Not. Roy. Astron. Soc. **405**, 3, 1888 (2010), [arXiv:1002.4620].

[52] F. Guarneri *et al.*, Mon. Not. Roy. Astron. Soc. **529**, 2, 839 (2024), [arXiv:2402.05586].

[53] P. A. Kislitsyn *et al.*, Mon. Not. Roy. Astron. Soc. **528**, 3, 4068 (2024), [arXiv:2401.12797].

[54] Y. I. Izotov, T. X. Thuan and N. G. Guseva, Mon. Not. Roy. Astron. Soc. **445**, 1, 778 (2014), [arXiv:1408.6953].

[55] Y. I. Izotov *et al.*, Astrophys. J. **527**, 757 (1999), [arXiv:astro-ph/9907228].

[56] K. A. Olive and E. D. Skillman, Astrophys. J. **617**, 29 (2004), [arXiv:astro-ph/0405588].

[57] E. Aver *et al.*, JCAP **2021**, 3, 027 (2021), [arXiv:2010.04180].

[58] M. Valerdi *et al.*, Astrophys. J. **876**, 2, 98 (2019), [arXiv:1904.01594].

[59] V. Fernández *et al.*, Mon. Not. Roy. Astron. Soc. **487**, 3, 3221 (2019), [arXiv:1905.09215].

[60] O. A. Kurichin *et al.*, Mon. Not. Roy. Astron. Soc. **502**, 2, 3045 (2021), [arXiv:2101.09127].

[61] T. Hsyu *et al.*, Astrophys. J. **896**, 1, 77 (2020), [arXiv:2005.12290].

[62] M. Valerdi, A. Peimbert and M. Peimbert, Mon. Not. Roy. Astr. Soc. **505**, 3, 3624 (2021), [arXiv:2105.12260].

[63] E. Aver *et al.*, Mon. Not. Roy. Astr. Soc. **510**, 1, 373 (2022), [arXiv:2109.00178].

[64] D. S. Aguado *et al.*, Astrophys. J. Lett. **874**, 2, L21 (2019), [arXiv:1904.04892].

[65] M. Spite and F. Spite, Nature **297**, 483 (1982).

[66] E. Vangioni-Flam *et al.*, New Astron. **4**, 245 (1999), [arXiv:astro-ph/9811327].

[67] S. G. Ryan *et al.*, Astrophys. J. **530**, L57 (2000), [arXiv:astro-ph/9905211].

[68] P. Bonifacio and P. Molaro, Mon. Not. Roy. Astron. Soc. **285**, 847 (1997), [arXiv:astro-ph/9611043].

[69] A. M. Matas Pinto *et al.*, Astron. Astrophys. **654**, A170 (2021), [arXiv:2110.00243].

[70] P. Bonifacio *et al.*, Astron. Astrophys. **462**, 851 (2007), [arXiv:astro-ph/0610245].

[71] W. Aoki *et al.*, Astrophys. J. **698**, 1803 (2009), [arXiv:0904.1448].

[72] L. Sbordone *et al.*, Astron. Astrophys. **522**, A26 (2010), [arXiv:1003.4510].

[73] P. Bonifacio *et al.*, Astron. & Astrophys. Rev. **33**, 1, 2 (2025), [arXiv:2504.06335].

[74] M. H. Pinsonneault *et al.*, Astrophys. J. **574**, 398 (2002), [arXiv:astro-ph/0105439].

[75] S. Borisov, N. Prantzos and C. Charbonnel, Astron. Astrophys. **691**, A142 (2024), [arXiv:2410.01880].

[76] R. Cayrel *et al.*, Astron. Astrophys. **473**, L37 (2007), [arXiv:0708.3819].

[77] D. S. Balser and T. M. Bania, Astrophys. J. **156**, 6, 280 (2018), [arXiv:1810.09422].

[78] T.-H. Yeh *et al.*, JCAP **10**, 046 (2022), [arXiv:2207.13133].

[79] H. Reeves *et al.*, Astrophys. J. **179**, 909 (1973).

[80] M. Fukugita and P. J. E. Peebles, Astrophys. J. **616**, 643 (2004), [arXiv:astro-ph/0406095].
[81] R. Cen and J. P. Ostriker, Astrophys. J. **514**, 1 (1999), [arXiv:astro-ph/9806281].
[82] G. Jungman *et al.*, Phys. Rev. **D54**, 1332 (1996), [arXiv:astro-ph/9512139].
[83] Planck Collaboration *et al.*, Astron. & Astrophys. **641**, A6 (2020), [arXiv:1807.06209].
[84] P. A. R. Ade *et al.* (Planck), Astron. Astrophys. **594**, A13 (2016), [arXiv:1502.01589].
[85] G. Steigman, D. N. Schramm and J. E. Gunn, Phys. Lett. **B66**, 202 (1977), [,159(1977)].
[86] B. D. Fields *et al.*, JCAP **2020**, 11, E02 (2020).
[87] E. Lisi, S. Sarkar and F. L. Villante, Phys. Rev. **D59**, 123520 (1999), [hep-ph/9901404].
[88] E. Calabrese *et al.*, arXiv e-prints arXiv:2503.14454 (2025), [arXiv:2503.14454].
[89] F. Ge *et al.* (SPT-3G), Phys. Rev. D **111**, 8, 083534 (2025), [arXiv:2411.06000].
[90] R. Trotta and S. H. Hansen, Phys. Rev. **D69**, 023509 (2004), [arXiv:astro-ph/0306588].
[91] R. H. Cyburt, B. D. Fields and K. A. Olive, Phys. Lett. **B567**, 227 (2003), [arXiv:astro-ph/0302431].
[92] P. Molaro, G. Cescutti and X. Fu, Mon. Not. Roy. Astron. Soc. **496**, 3, 2902 (2020), [arXiv:2006.00787].
[93] J. D. Simpson *et al.*, Mon. Not. Roy. Astron. Soc. (2021).
[94] D. S. Aguado *et al.*, Mon. Not. Roy. Astron. Soc. **500**, 1, 889 (2021), [arXiv:2007.11003].
[95] R. H. Cyburt *et al.*, JCAP **1305**, 014 (2013), [arXiv:1303.0574].
[96] N. Chakraborty, B. D. Fields and K. A. Olive, Phys. Rev. **D83**, 063006 (2011), [arXiv:1011.0722].
[97] C. Broggini *et al.*, JCAP **1206**, 030 (2012), [arXiv:1202.5232].
[98] P. D. O'Malley *et al.*, Phys. Rev. **C84**, 042801 (2011).
[99] F. Hammache *et al.*, Phys. Rev. **C88**, 6, 062802 (2013), [arXiv:1312.0894].
[100] M. W. Paris *et al.*, Nucl. Data Sheets **120**, 184 (2014), [arXiv:1304.3153].
[101] P. Molaro *et al.*, Memorie della Soc. Astronomica Italiana Supp. **22**, 233 (2012).
[102] X. Fu *et al.*, Mon. Not. Roy. Astron. Soc. **452**, 3, 3256 (2015), [arXiv:1506.05993].
[103] O. Richard, G. Michaud and J. Richer, Astrophys. J. **619**, 538 (2005), [arXiv:astro-ph/0409672].
[104] A. J. Korn *et al.*, Nature **442**, 657 (2006), [arXiv:astro-ph/0608201].
[105] X. Gao *et al.*, Mon. Not. Roy. Astron. Soc. **497**, 1, L30 (2020), [arXiv:2006.05173].
[106] C. T. Nguyen *et al.*, Astron. Astrophys. **696**, A136 (2025), [arXiv:2408.05039].
[107] D. Thomas *et al.*, Astrophys. J. **406**, 569 (1993), [arXiv:astro-ph/9206002].
[108] V. V. Smith, D. L. Lambert and P. E. Nissen, Astrophys. J. **408**, 262 (1993).
[109] L. M. Hobbs and J. A. Thorburn, Astrophys. J. Lett. **428**, L25 (1994).
[110] R. Cayrel *et al.*, Astron. Astrophys. **343**, 923 (1999), [arXiv:astro-ph/9901205].
[111] E. X. Wang *et al.*, Mon. Not. Roy. Astron. Soc. **509**, 1, 1521 (2021), [arXiv:2110.03822].
[112] B. D. Fields and K. A. Olive, JCAP **10**, 078 (2022), [arXiv:2204.03167].
[113] S. Borisov *et al.*, Astron. Astrophys. **690**, A245 (2024), [arXiv:2403.15534].
[114] J. C. Howk *et al.*, Nature **489**, 7414, 121 (2012), [arXiv:1207.3081].
[115] P. Molaro *et al.*, Astron. Astrophys. **690**, A38 (2024), [arXiv:2407.10818].

[116] K. Jedamzik and J. B. Rehm, Phys. Rev. **D64**, 023510 (2001), [arXiv:astro-ph/0101292].

[117] D. J. Fixsen *et al.*, Astrophys. J. **473**, 576 (1996), [arXiv:astro-ph/9605054].

[118] M. Kawasaki, K. Kohri and T. Moroi, Phys. Rev. **D71**, 083502 (2005), [arXiv:astro-ph/0408426].

[119] K. Jedamzik, Phys. Rev. **D70**, 063524 (2004), [arXiv:astro-ph/0402344].

[120] A. Goudelis, M. Pospelov and J. Pradler, Phys. Rev. Lett. **116**, 21, 211303 (2016), [arXiv:1510.08858].

[121] J. D. Barrow, Phys. Rev. **D35**, 1805 (1987).

[122] B. A. Campbell and K. A. Olive, Phys. Lett. **B345**, 429 (1995), [hep-ph/9411272].

[123] L. Bergstrom, S. Iguri and H. Rubinstein, Phys. Rev. **D60**, 045005 (1999), [arXiv:astro-ph/9902157].

[124] V. V. Flambaum and E. V. Shuryak, Phys. Rev. **D65**, 103503 (2002), [hep-ph/0201303].

[125] A. Coc *et al.*, Phys. Rev. **D76**, 023511 (2007), [arXiv:astro-ph/0610733].

[126] J. C. Berengut *et al.*, Phys. Rev. **D87**, 8, 085018 (2013), [arXiv:1301.1738].

[127] C. J. A. P. Martins, Astron. Astrophys. **646**, A47 (2021), [arXiv:2012.10505].

[128] Z. Hou *et al.*, Phys. Rev. **D87**, 083008 (2013), [arXiv:1104.2333].

[129] R. Keisler *et al.*, Astrophys. J. **743**, 28 (2011), [arXiv:1105.3182].

[130] J. Hamann *et al.*, Phys. Rev. Lett. **105**, 181301 (2010), [arXiv:1006.5276].

[131] K. Akita and M. Yamaguchi, JCAP **2020**, 8, 012 (2020), [arXiv:2005.07047].

[132] J. Froustey, C. Pitrou and M. C. Volpe, JCAP **2020**, 12, 015 (2020), [arXiv:2008.01074].

[133] J. J. Bennett *et al.*, JCAP **04**, 073 (2021), [arXiv:2012.02726].

[134] F. S. Accetta, L. M. Krauss and P. Romanelli, Phys. Lett. **B248**, 146 (1990).

[135] K. M. Nollett and R. E. Lopez, Phys. Rev. **D66**, 063507 (2002), [arXiv:astro-ph/0204325].

[136] C. Bambi, M. Giannotti and F. L. Villante, Phys. Rev. **D71**, 123524 (2005), [arXiv:astro-ph/0503502].

[137] E. W. Kolb, M. J. Perry and T. P. Walker, Phys. Rev. **D33**, 869 (1986).

[138] A. Coc *et al.*, Phys. Rev. **D73**, 083525 (2006), [arXiv:astro-ph/0601299].

[139] K. A. Olive, D. N. Schramm and G. Steigman, Nucl. Phys. **B180**, 497 (1981).

[140] J. R. Ellis *et al.*, Phys. Lett. **167B**, 457 (1986).

[141] L. M. Krauss, J. Terning and T. Appelquist, Phys. Rev. Lett. **71**, 823 (1993), [hep-ph/9305265].

[142] J. A. Morgan, Phys. Lett. **102B**, 247 (1981).

[143] E. W. Kolb, M. S. Turner and T. P. Walker, Phys. Rev. **D34**, 2197 (1986).

[144] J. A. Grifols and E. Masso, Mod. Phys. Lett. **A2**, 205 (1987).

[145] K. S. Babu, R. N. Mohapatra and I. Z. Rothstein, Phys. Rev. Lett. **67**, 545 (1991).

[146] A. D. Dolgov, S. H. Hansen and D. V. Semikoz, Nucl. Phys. **B524**, 621 (1998), [hep-ph/9712284].

[147] K. Enqvist, K. Kainulainen and M. J. Thomson, Nucl. Phys. **B373**, 498 (1992).

[148] A. D. Dolgov, Phys. Rept. **370**, 333 (2002), [hep-ph/0202122].

[149] J. A. Grifols, R. N. Mohapatra and A. Riotto, Phys. Lett. **B400**, 124 (1997), [hep-ph/9612253].

[150] H. K. Dreiner *et al.*, Phys. Rev. **D85**, 065027 (2012), [arXiv:1111.5715].
[151] K. Sato and M. Kobayashi, Prog. Theor. Phys. **58**, 1775 (1977).
[152] D. A. Dicus *et al.*, Phys. Rev. **D17**, 1529 (1978).
[153] R. J. Scherrer and M. S. Turner, Astrophys. J. **331**, 19 (1988), [Astrophys. J.331,33(1988)].
[154] D. Lindley, Mon. Not. Roy. Astron. Soc. **188**, 15P (1979).
[155] J. R. Ellis *et al.*, Nucl. Phys. **B373**, 399 (1992).
[156] M. H. Reno and D. Seckel, Phys. Rev. **D37**, 3441 (1988).
[157] S. Dimopoulos *et al.*, Nucl. Phys. **B311**, 699 (1989).
[158] S. Sarkar and A. M. Cooper-Sarkar, Phys. Lett. **148B**, 347 (1984).
[159] M. Kawasaki, K. Kohri and T. Moroi, Phys. Lett. **B649**, 436 (2007), [hep-ph/0703122].
[160] K. Jedamzik *et al.*, JCAP **0607**, 007 (2006), [hep-ph/0512044].
[161] S. Davidson *et al.*, Phys. Rev. **466**, 105 (2008).
[162] S. Weinberg, Phys. Rev. Lett. **48**, 1303 (1982).
[163] R. H. Cyburt *et al.*, Phys. Rev. **D67**, 103521 (2003), [arXiv:astro-ph/0211258].
[164] M. Bolz, A. Brandenburg and W. Buchmuller, Nucl. Phys. **B606**, 518 (2001), [Erratum: Nucl. Phys.B790,336(2008)], [hep-ph/0012052].
[165] G. D. Coughlan *et al.*, Physics Letters B **131**, 1-3, 59 (1983).
[166] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Rev. **D59**, 086004 (1999), [hep-ph/9807344].
[167] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999), [hep-ph/9905221].
[168] J. M. Cline, C. Grojean and G. Servant, Phys. Rev. Lett. **83**, 4245 (1999), [hep-ph/9906523].
[169] P. Binetruy *et al.*, Phys. Lett. **B477**, 285 (2000), [hep-th/9910219].