Indications for a Nonzero Lepton Asymmetry from Extremely Metal-Poor Galaxies

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The recent measurement of helium-4 from the near-infrared spectroscopy of extremely metal-poor galaxies by the Subaru Survey may point to a new puzzle in the early Universe. We exploit this new helium measurement together with the percent-level determination of primordial deuterium, to assess indications for a nonvanishing lepton asymmetry during the big bang nucleosynthesis era, paying particular attention to the role of uncertainties in the nuclear reaction network. A cutting-edge Bayesian analysis focused on the role of the newly measured extremely metal-poor galaxies, jointly with information from the cosmic microwave background, suggests the existence of a nonzero lepton asymmetry at around the 2σ level, providing a hint for cosmology beyond lambda cold dark matter. We discuss conditions for a large total lepton asymmetry to be consistently realized in the early Universe.

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Introduction.—Cosmological observations from the early Universe provide an invaluable probe of physics beyond the standard model (BSM). Observations of the cosmic microwave background (CMB), epitomized by the Planck mission [1] and further developed, e.g., by the ACT [2] and SPT [3] collaborations, paint a picture of a universe dominated by nonbaryonic dark energy and dark matter, well-described by the lambda cold dark matter (ΛCDM) model [4–6]. Equipped with the CMB inference of the small cosmological baryonic abundance, $\Omega_B \sim 4\%$, the theory of big bang nucleosynthesis (BBN) within the standard model (SM) of particle physics is highly predictive, and confronted with accurate measurements of primeval elements such as the mass density fraction of helium-4, Y_P, and the relative abundance of deuterium to hydrogen, D/H, offers important constraints on new physics (NP) [7–10] active during the first few minutes of the Universe [11–14].

At present, measurements of deuterium in quasar absorption spectra provide the best proxy for the determination of a primordial abundance. The most recent measurements from damped Lyman-α systems achieve better than 1% precision [15–17], yielding a weighted average of $\mathrm{D/H} \times 10^5 = 2.547 \pm 0.025$ [18]. This remarkable precision appears to be in tension with the SM at about the 2σ level [19], although this remains under debate [20,21] in light of the uncertainties on the key nuclear reactions involved. This highlights the primary importance of assessing the impact of uncertainties in the nuclear network rates on the predictions from BBN [22]. A notable recent advance in this direction is the improved determination of the $\mathrm{D}(p,\gamma)^3\mathrm{He}$ rate by the LUNA Collaboration [23], which has an important impact on BBN constraints from primordial deuterium on various NP scenarios [24].

The recent near-infrared observation of 10 extremely metal-poor galaxies (EMPGs) by the Subaru Survey [25] points to even more puzzling mysteries. Spectroscopic observations of EMPGs provide a crucial input to the inference of Y_P because they host the gas of nebulae resembling extraordinarily pristine environments that allow for a more accurate extrapolation of the helium density to zero metallicity. Combined with the pre-existing data from 3 EMPGs and 51 metal-poor galaxies [26] and measurements of the He λ10830 infrared emission line (relevant for parameter-degeneracy breaking [27]), 5 (out of 10) Subaru EMPGs yield a determination of primordial helium-4 of $Y_P = 0.2370^{+0.0034}_{-0.0033}$, in sharp contrast with the Particle Data Group (PDG) value $Y_P = 0.245 \pm 0.003$ [18], and well below the SM prediction [19–21], naively a 3σ-level discrepancy.

Reference [25] took the first steps toward an interpretation of this "helium anomaly" in terms of a BSM fit where the standard theory has been extended by extrarelativistic degrees of freedom, ΔN_{eff}, as well as a nonzero electron neutrino asymmetry, ξ_{ν_e}, while simply anchoring $\Omega_B h^2$ to the most precise determination derived by Planck [1].

In this Letter, we revise the inference of a lepton asymmetry ξ_ν in the early Universe, as well as on ΔN_{eff}

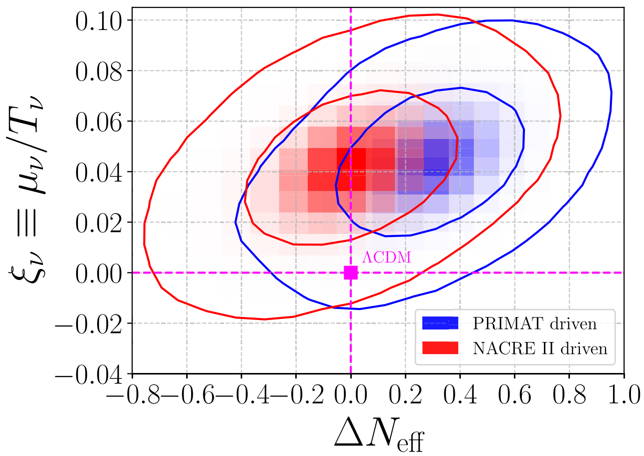

FIG. 1. 68% and 95% two-dimensional probability distribution of the primordial chemical potential of neutrinos, μ_ν, normalized to the neutrino temperature T_ν, and the number of extrarelativistic degrees of freedom in the early Universe, $\Delta N_{\rm eff}$, from a state-of-the-art analysis of BBN and CMB data. The red and blue contours indicate the results for two different sets of nuclear uncertainties; magenta lines the ΛCDM prediction.

(defined at the last scattering), paying attention to the details of a joint likelihood analysis of BBN and CMB data as recently carefully formulated in [13,14]. Our key result is given in Fig. 1 [28]. We perform a Bayesian analysis taking into account the theory uncertainties pivotal for unbiased conclusions based on the use of the new public code for state-of-the-art investigations of (BSM) physics in the early Universe—PRYMORDIAL—presented in a companion paper [29].

Primordial lepton asymmetries.—Electric charge neutrality of the early Universe does not allow for a large primordial asymmetry in the charged lepton sector, which is constrained to be (at most) of the order of the baryon-to-photon ratio $\eta_B \equiv n_B/n_\gamma \sim \mathcal{O}(10^{-10})$ [30,31]. Nevertheless, a large cosmic asymmetry can be hidden in the neutrino sector [32]

$$\eta_L \equiv \frac{1}{n_\gamma}\sum_{i=e,\mu,\tau}(n_{\nu_i}-n_{\bar{\nu}_i}) \simeq \frac{\pi^2}{33\zeta(3)}(\xi_{\nu_e}+\xi_{\nu_\mu}+\xi_{\nu_\tau}), \qquad (1)$$

where n_γ is the photon number density, n_{ν_i} the flavor i neutrino density, and $\xi_{\nu_i} \equiv \mu_{\nu_i}/T_{\nu_i}$ are the "degeneracy parameters" defined as the chemical potential for each neutrino normalized to its temperature, which encode the relevant lepton asymmetries today. Equation (1) assumes $T_{\nu_i}/T_\gamma = (4/11)^{1/3}$, which is a good approximation given the modest impact of noninstantaneous neutrino decoupling and tiny departures from the Fermi-Dirac distributions in relativistic freeze-out [33–35]. It is further relevant that nonzero neutrino chemical potentials play a marginal role in SM neutrino decoupling [36,37].

Equation (1) further implements the condition $|\xi_{\nu_i}| < 1$, as $\mathcal{O}(1)$ degeneracy parameters were probed by early-stage CMB observations about two decades ago [38,39], and now are robustly [40–42] ruled out (irrespective of the lepton flavor [43,44]). In fact, a nonzero chemical potential for the i-flavored neutrino would yield a contribution to the total radiation density (relative to photons) of

$$\frac{\Delta\rho_{\rm rad}}{\rho_\gamma} \simeq \frac{15}{4\pi^2}\left(\frac{4}{11}\right)^{4/3}\xi_{\nu_i}^2 \qquad (2)$$

and would increase the expansion rate of the Universe, resulting in a positive shift of $N_{\rm eff}$ that would delay the time of matter-radiation equality that is tightly constrained by the CMB acoustic peaks.

From the Planck constraint on $N_{\rm eff}$ adopting the likelihood analysis including TTTEEE and low-ℓ measurements, as well as baryonic acoustic oscillations (BAO) and lensing data, and assuming a flat prior on Y_P, one may derive a simple upper bound on the degeneracy parameters purely driven by the CMB. In particular, for $N_{\rm eff} = 2.97 \pm 0.29$ (68% probability interval) [1,45], considering the SM prediction $N_{\rm eff} = 3.044$ (known better than the per-mille level) [33–35], the 1σ upper bound is

$$\xi_{\nu_e}^2 + \xi_{\nu_\mu}^2 + \xi_{\nu_\tau}^2 \lesssim 0.5, \qquad (3)$$

implying the conservative constraint $|\xi_{\nu_i}| \lesssim 0.71$, valid for each flavor individually (see also Ref. [46]). Since the onset of neutrino oscillations is expected to occur around $T_\nu \sim 10$ MeV, flavor equilibration in the muon-tau sector is predicted to be complete by the time of neutrino decoupling ($T_\nu \sim 2$ MeV) [47,48], and the conservative CMB bound of Eq. (3) becomes slightly tighter for the second and third generation ν asymmetries:

$$|\xi_{\nu_{\mu,\tau}}| \lesssim 0.5. \qquad (4)$$

BBN can place stronger constraints on the electron-neutrino asymmetry (by about an order of magnitude [32,49]) largely because an electron-neutrino asymmetry at the time of BBN affects the β equilibrium of weak interactions controlling the neutron-proton conversion [50]. A positive (negative) value of ξ_{ν_e} acts through the equilibrium reactions $n\nu_e \leftrightarrow pe^-$, $p\bar{\nu}_e \leftrightarrow ne^+$, and neutron decay to reduce (enhance) the neutron-to-proton ratio

$$(n_n/n_p)|_{\rm eq} \simeq \exp(-\mathcal{Q}/T_\gamma - \xi_{\nu_e}), \qquad (5)$$

where $\mathcal{Q} \equiv m_n - m_p = 1.293$ MeV is the neutron-proton mass difference. While light primordial abundances like deuterium are particularly sensitive to Ω_B, from Eq. (5) it follows that helium-4, which depends crucially on the amount of neutrons at the time where deuterium is no longer photodissociated [30,31], can be regarded as a sensitive "primordial leptometer."

In Ref. [51] a combined analysis of the helium and deuterium PDG values together with a Gaussian prior on $\Omega_B h^2$ from the CMB yields the precise determination $\xi_\nu = 0.001 \pm 0.016$, consistent with zero. By assuming full equilibration of lepton flavor asymmetries due to neutrino oscillations, this inference is more stringent than the bound outlined in Eq. (4). Nevertheless, a recent state-of-the-art investigation in Ref. [52] indicates that the degree to which full flavor equilibration is realized during the BBN era sensitively depends on the Pontecorvo-Maki-Nakagawa-Sakata mixing angle θ_{13} and on the initially generated values of the degeneracy parameters. In the following, we revisit the determination of ξ_ν in light of the newly measured helium-4 mass fraction from EMPGs as reported in Ref. [25]. While $\xi_\nu = \xi_{\nu_{e,\mu,\tau}}$ may be achieved in the early Universe, one should bear in mind that the conservative interpretation of our main finding in Fig. 1 applies only to $\xi_\nu = \xi_{\nu_e}$, i.e., the primordial electron-neutrino asymmetry probed by BBN via β equilibrium, Eq. (5).

Methodology.—Our computation of BBN abundances via the PRYMORDIAL [29] code, proceeds through three main steps: (1) solving for the thermal background, (2) computing neutron-proton conversion, and (3) evaluating the final primordial abundances.

For (1), we base our computation on the approach proposed in [53] and further developed in [37] (see also [54]). It consists in solving the Boltzmann equations for the electron-photon plasma and neutrinos assuming a thermal distribution for the species, including next-to-leading order QED corrections for the plasma [55] as well as non-instantaneous decoupling effects for the neutrino sector [37]. For our purposes, it suffices to describe the neutrino sector by a common temperature T_ν, yielding the SM prediction $N_{\rm eff} = 3.045$, differing from the most refined prediction in [33–35] only at the per-mille level, well within current and future observational sensitivity [56–58]. A nonzero chemical potential for neutrinos would influence our analysis of the thermal background via Eq. (2). If full neutrino equilibration is achieved, we find *a posteriori* a contribution to the radiation density that would be totally negligible. Nevertheless, in our BSM analysis we also account for the possibility of a nonzero lepton asymmetry $|\xi_{\nu_{\mu,\tau}}| \gg |\xi_{\nu_e}|$ by varying $\Delta N_{\rm eff}$ (a valid interpretation of $\Delta N_{\rm eff}$ in the scenario where such a shift is mainly driven by a nonvanishing muon-tau chemical potential). Note that from our bound in Eq. (4), a muon-tau neutrino asymmetry can induce a maximal shift $\Delta N_{\rm eff} \sim 0.1$.

Moving to (2), we compute $n \leftrightarrow p$ matrix elements beyond the Born approximation [59], namely including isospin-breaking contributions like finite-mass [60] and QED [61,62] corrections, as well as finite-temperature effects [63], following the implementation carried out in [51]. Most importantly, we evaluate weak-interaction rates integrating over nucleon thermal distributions with chemical potential $\mu_Q \equiv \mu_n - \mu_p = -\mu_{\nu_e} \neq 0$.

Finally, regarding (3), we proceed evolving the abundances according to the network of thermonuclear reactions comprising the main processes listed in Table 1 of Ref. [64] (plus $^3{\rm He}(p,\gamma)^4{\rm He}$, taken from [65]), yielding state-of-the-art predictions for Y_P and D/H. In particular, for the radiative neutron capture rate we adopt the Markov chain Monte Carlo result of Ref. [66], while in the treatment of the other 10 key reactions we distinguish two approaches: PRImordial MATter (PRIMAT) driven: Nuclear rates are implemented according to the statistical determination of Refs. [67–72], i.e., following theoretical *ab initio* energy modeling tuned to datasets for which an estimate of systematic errors is available [19,22,51]. NACRE II driven: Nuclear rates are interpolated from the updated Nuclear Astrophysics Compilation of REaction rates (NACRE) compilation [73], comprising charged-particle-induced reactions [74]; for $D(p,\gamma)^3{\rm He}$ we use the LUNA Collaboration result reported in [23]; for $^7{\rm Be}(n,p)^7{\rm Li}$ we adopt the baseline of Ref. [49].

We perform a Bayesian analysis of early Universe data constructing the cosmological test statistic

$$\mathrm{TS}_{\rm cosmo} \equiv -2(\log \mathcal{L}_{\rm CMB} + \log \mathcal{L}_{\rm BBN}); \tag{6}$$

the CMB likelihood explicitly reads

$$\log \mathcal{L}_{\rm CMB} = -\frac{1}{2}\Delta\vec{v}^T \mathcal{C}_{\rm CMB}^{-1}\Delta\vec{v}, \tag{7}$$

with $\Delta\vec{v} \equiv \vec{v}^{\rm th} - \vec{v}$, $\vec{v} = (Y_P, \Omega_B h^2, N_{\rm eff})^T$, using mean and standard-deviation values from the TTTEEE + *low-ℓ* + BAO + lensing Planck run varying also Y_P, $N_{\rm eff}$ [1,45] and also retrieving correlations in $\mathcal{C}_{\rm CMB}$ from [75]. The BBN likelihood of our study corresponds to

$$\log \mathcal{L}_{\rm BBN} = -\frac{1}{2}\sum_X \left(\frac{X^{\rm th} - X}{\sigma_X}\right)^2, \tag{8}$$

where $X = \{Y_P, {\rm D/H}\}$, and we use the measurements: $Y_P = 0.2370(34)$ [25], ${\rm D/H} = 0.000\,025\,47(25)$ [18].

The parameters we infer are varied according to uniform priors: $-2 \le \Delta N_{\rm eff} \le 2$, $-0.2 \le \xi_\nu \le 0.2$, $1 \le (\eta_B \times 10^{10}) \le 10$ (using $\eta_B \times 10^{10} \simeq 273.748\ \Omega_B h^2$). We marginalize over the neutron lifetime and the adopted nuclear uncertainties. From the PDG analysis [18] we assign the Gaussian prior $\tau_n = (879.4 \pm 0.6)$ s to the neutron lifetime. For the uncertainties in the nuclear rates, we assign log-normal distributions following the method detailed in Ref. [76], varying a total of 12 additional nuisance parameters.

We perform a Markov chain Monte Carlo analysis via the EMCEE [77] package, using 60 walkers with 2100 steps each, discarding the first 700 steps of each walker as burn-in. From the best-fit values minimizing $\mathrm{TS}_{\rm cosmo}$ we also compute for each scenario the information criterion (IC)

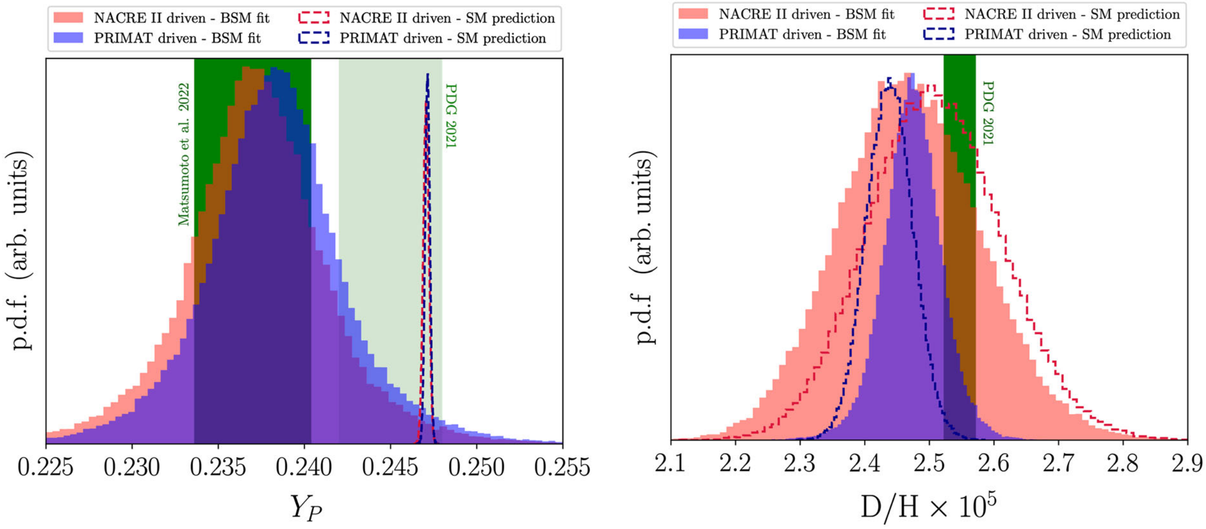

FIG. 2. Probability density function (p.d.f.) for the primordial light elements analyzed in this Letter. In the left panel, the p.d.f. for helium-4, Y_P, as precisely predicted in the SM according to two different sets of nuclear uncertainties and adopting the determination of the cosmological baryon-to-photon ratio from the fit of CMB data within ΛCDM (color code similar to Fig. 1). In the same panel, the outcome from the joint fit to BBN and CMB likelihoods in the BSM scenario where ξ_ν and $\Delta N_{\rm eff}$ are consistently allowed to differ from their ΛCDM limit. In the right panel, the same set of p.d.f.s is shown for the deuterium. In both panels, vertical dark green bands correspond to the 1σ interval for the BBN measurements employed in the analysis. In the left one, the PDG 2021 recommended value for helium-4 is also reported, in agreement with the SM prediction.

[78,79] $\mathrm{IC} \equiv -2 \log \hat{\mathcal{L}}_{\rm BBN} + 2(k-1)$, k being the number of BSM parameters and accounting for the CMB information as an extra constraint in the fit. Then, we evaluate the IC difference with respect to the SM prediction of the primordial light abundances within a given approach: $\Delta\mathrm{IC} \sim \mathcal{O}(1)$ [$\sim\mathcal{O}(10)$] provides positive (strong) support in favor of NP beyond ΛCDM according to the canonical scales of evidence [80].

Results.—In Fig. 1, we report the main result of our study: the 68% and 95% probability region for the primordial lepton asymmetry ξ_ν and the extrarelativistic degrees of freedom $\Delta N_{\rm eff}$ as determined by $\mathrm{TS}_{\rm cosmo}$, Eq. (6), corresponding to the two approaches to thermonuclear rates described in the previous section. From the ΛCDM limit highlighted in the same figure, we can conclude that a BSM fit to a dataset that includes the newly measured EMPGs by Subaru [25] favors at present a nonvanishing asymmetry in the neutrino sector.

In Fig. 1 we also observe that, dependent on the approach to nuclear uncertainties, a shift of $N_{\rm eff}$ of $\mathcal{O}(1)$ can be simultaneously favored by current cosmological data. Note that the size of the shift in the number of relativistic degrees of freedom can be interpreted within the 68% probability region as the result of a large neutrino asymmetry in the muon-tau sector in case flavor equilibration has not been fully realized.

To further investigate the different outcome from each approach, we show in Fig. 2 the posterior probability density function (p.d.f.) for the BBN observables Y_P and D/H. We report both the result from the BSM fit varying both ξ_ν and $N_{\rm eff}$ as well as the one from the SM prediction, obtained fixing the BSM parameters to 0 and replacing the CMB likelihood with the Gaussian prior, $\Omega_B h^2 = 0.02242 \pm 0.00014$, from the ΛCDM Planck analysis (TTTEEE+ low-ℓ + BAO + lensing) [1,45]. In the same figure, we also highlight with vertical dark green bands the measurements adopted in our BBN analysis via Eq. (8), and report the PDG 2021 value $Y_P = 0.245(3)$ [18], in optimal agreement with the analysis of Ref. [73] that comprises the set studied also in [25] without the new EMPGs from Subaru.

Figure 2 neatly highlights two tensions in the limit where BSM physics is not accounted for. First, a discrepancy at the 3σ level between the SM prediction of Y_P and the newly inferred helium-4 mass-fraction value, regardless of the approach taken for the thermonuclear reactions; the tension is fully driven by the new measurement delivered by Ref. [25], while the overall significance also depends on the precision obtained for the inference of the cosmological baryon abundance within ΛCDM. Second, a tension of about 2σ significance between the SM prediction of D/H and the PDG 2021 recommended measurement [18] when the PRIMAT driven approach is taken for the analysis of the key thermonuclear reactions involved, in line with recent discussions in the literature [22].

From Fig. 2, it is clear that a shift of $\Delta N_{\rm eff}$ is required together with $\xi_\nu \neq 0$ only when the PRIMAT driven approach is considered, in order to address the discrepancy consequently present in the fit in relation to the observed primordial deuterium abundance. In the same figure it is also evident how the PDG 2021 recommended

TABLE I. 68% probability interval for the posterior distribution of the main observables and parameters in the scenarios considered in this work. For the BSM fits, improvement with respect to the SM is given by $\Delta IC > 0$; see text for more details.

Scenario	Approach	Y_P	$D/H \times 10^5$	$\Delta N_{\rm eff}$	ξ_ν	$\eta_B \times 10^{10}$	ΔIC
SM prediction	PRIMAT driven	0.247 15(14)	2.439(36)	⋯	⋯	6.137(38)	⋯
	NACRE II driven	0.247 06(16)	2.51(10)	⋯	⋯	6.137(38)	⋯
$\Delta N_{\rm eff}$ BSM fit	PRIMAT driven	0.2472(13)	2.472(45)	0.02(20)	⋯	6.091(66)	2
	NACRE II driven	0.2455(15)	2.46(11)	−0.26(23)	⋯	6.093(67)	0
$(\Delta N_{\rm eff}, \xi_\nu)$ BSM fit	PRIMAT driven	0.2383(42)	2.474(46)	0.29(23)	0.044(20)	6.119(65)	8
	NACRE II driven	0.2372(43)	2.47(11)	0.00(23)	0.041(21)	6.114(68)	5

measurement of the helium-4 mass fraction is in perfect agreement with the SM prediction, and our inference for a nonzero degeneracy parameter ξ_ν is the consequence of adopting the new Y_P measurement [25].

We report in Table I the 68% probability interval for the scenarios discussed so far as well as the one for the BSM fit where only $\Delta N_{\rm eff}$ is considered. Looking at the ΔIC values, we conclude that a joint analysis of BBN + CMB data provides mild to strong evidence for a scenario with nonvanishing lepton asymmetry. Moreover, within the NACRE II approach no notable support from data is found for the presence of extrarelativistic degrees of freedom in the early Universe, whereas a scenario where only $\Delta N_{\rm eff}$ is varied may be slightly preferred by data over the SM in the case of the PRIMAT driven approach, partially ameliorating a potential "deuterium anomaly."

Discussion and outlook.—Our study based on the addition of the newly observed EMPGs [25] to the original sample of Ref. [26] suggests that today's total lepton asymmetry, Eq. (1), is large, $\eta_L \gg \eta_B$, ranging from $\sim 10^{-2}$ to $\sim 1/4$, depending on the details of the neutrino sector.

There are common factors that any successful explanation of a large η_L must share. At temperatures above the scale of electroweak symmetry restoration, electroweak sphalerons equilibrate $B + L$ such that the final total lepton and baryon asymmetries differ by a $\mathcal{O}(1)$ factor [81,82]. Thus, for a difference of orders of magnitude between η_L and η_B to persist, it must either be generated after the sphalerons become inactive (in the SM, at the electroweak phase transition around temperatures of order 100 GeV) or the individual flavor asymmetries must be distributed such that the net L is much smaller than the individual asymmetries [83]. The latter scenario would point to flavor-dependent NP in the lepton sector, with possible interesting implications for the smallness of η_B as well; see for instance [83–86].

Because equilibration of neutrino species depends both on imprecisely determined mixing parameters and the assumed initial asymmetry in each flavor [52], mapping the inferred neutrino asymmetries during BBN into the space of consistent initial conditions at some earlier time is an interesting inverse problem; it also requires assumptions on the interpretation of the inference carried out here for $\Delta N_{\rm eff}$, and it is beyond the scope of this work. Several examples of theories capable of generating a sufficiently large and persistent lepton-flavored neutrino asymmetry via variations of the Affleck-Dine mechanism [87] exist in the literature [83,88–90].

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[1] N. Aghanim *et al.* (Planck Collaboration), Astron. Astrophys. **641**, A6 (2020); **652**, C4(E) (2021).
[2] S. Aiola *et al.* (ACT Collaboration), J. Cosmol. Astropart. Phys. 12 (2020) 047.
[3] D. Dutcher *et al.* (SPT-3G Collaboration), Phys. Rev. D **104**, 022003 (2021).
[4] D. Baumann, D. Green, J. Meyers, and B. Wallisch, J. Cosmol. Astropart. Phys. 01 (2016) 007.
[5] E. Komatsu, Nat. Rev. Phys. **4**, 452 (2022).
[6] C. L. Chang *et al.*, arXiv:2203.07638.
[7] S. Sarkar, Rep. Prog. Phys. **59**, 1493 (1996).
[8] G. Steigman, Annu. Rev. Nucl. Part. Sci. **57**, 463 (2007).
[9] F. Iocco, G. Mangano, G. Miele, O. Pisanti, and P. D. Serpico, Phys. Rep. **472**, 1 (2009).
[10] M. Pospelov and J. Pradler, Annu. Rev. Nucl. Part. Sci. **60**, 539 (2010).
[11] P. D. Serpico and G. G. Raffelt, Phys. Rev. D **70**, 043526 (2004).
[12] C. Boehm, M. J. Dolan, and C. McCabe, J. Cosmol. Astropart. Phys. 08 (2013) 041.
[13] N. Sabti, J. Alvey, M. Escudero, M. Fairbairn, and D. Blas, J. Cosmol. Astropart. Phys. 01 (2020) 004.
[14] C. Giovanetti, M. Lisanti, H. Liu, and J. T. Ruderman, Phys. Rev. Lett. **129**, 021302 (2022).

[15] R. J. Cooke, M. Pettini, K. M. Nollett, and R. Jorgenson, Astrophys. J. **830**, 148 (2016).

[16] S. Riemer-Sørensen, S. Kotuš, J. K. Webb, K. Ali, V. Dumont, M. T. Murphy, and R. F. Carswell, Mon. Not. R. Astron. Soc. **468**, 3239 (2017).

[17] R. J. Cooke, M. Pettini, and C. C. Steidel, Astrophys. J. **855**, 102 (2018).

[18] P. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020), and 2021 update.

[19] C. Pitrou, A. Coc, J.-P. Uzan, and E. Vangioni, Mon. Not. R. Astron. Soc. **502**, 2474 (2021).

[20] O. Pisanti, G. Mangano, G. Miele, and P. Mazzella, J. Cosmol. Astropart. Phys. 04 (2021) 020.

[21] T.-H. Yeh, K. A. Olive, and B. D. Fields, J. Cosmol. Astropart. Phys. 03 (2021) 046.

[22] C. Pitrou, A. Coc, J.-P. Uzan, and E. Vangioni, Nat. Rev. Phys. **3**, 231 (2021).

[23] V. Mossa *et al.*, Nature (London) **587**, 210 (2020).

[24] N. Sabti, J. Alvey, M. Escudero, M. Fairbairn, and D. Blas, J. Cosmol. Astropart. Phys. 08 (2021) A01.

[25] A. Matsumoto *et al.*, Astrophys. J. **941**, 167 (2022).

[26] T. Hsyu, R. J. Cooke, J. X. Prochaska, and M. Bolte, Astrophys. J. **896**, 77 (2020).

[27] E. Aver, K. A. Olive, and E. D. Skillman, J. Cosmol. Astropart. Phys. 07 (2015) 011.

[28] While the methodology developed in this work stands out as a robust recipe for an advanced statistical analysis of Early Universe data, the measurement published in [25], focus of the present study, strongly depends on the emission-line data modeling. Further scrutiny on the corresponding systematics of the measurement is warranted for the future.

[29] A.-K. Burns, T. M. P. Tait, and M. Valli, PRYMORDIAL: The first minutes beyond the Standard Model in a few seconds (to be published).

[30] E. W. Kolb and M. S. Turner, *The Early Universe* (CRC Press, Boca Raton, 1990), Vol. 69.

[31] V. A. Rubakov and D. S. Gorbunov, *Introduction to the Theory of the Early Universe: Hot Big Bang Theory* (World Scientific, Singapore, 2017).

[32] V. Simha and G. Steigman, J. Cosmol. Astropart. Phys. 08 (2008) 011.

[33] K. Akita and M. Yamaguchi, J. Cosmol. Astropart. Phys. 08 (2020) 012.

[34] J. Froustey, C. Pitrou, and M. C. Volpe, J. Cosmol. Astropart. Phys. 12 (2020) 015.

[35] J. J. Bennett, G. Buldgen, P. F. De Salas, M. Drewes, S. Gariazzo, S. Pastor, and Y. Y. Y. Wong, J. Cosmol. Astropart. Phys. 04 (2021) 073.

[36] E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, and A. Vlasenko, Phys. Rev. D **93**, 083522 (2016).

[37] M. Escudero Abenza, J. Cosmol. Astropart. Phys. 05 (2020) 048.

[38] W. H. Kinney and A. Riotto, Phys. Rev. Lett. **83**, 3366 (1999).

[39] J. Lesgourgues and S. Pastor, Phys. Rev. D **60**, 103521 (1999).

[40] I. M. Oldengott and D. J. Schwarz, Europhys. Lett. **119**, 29001 (2017).

[41] A. Bonilla, R. C. Nunes, and E. M. C. Abreu, Mon. Not. R. Astron. Soc. **485**, 2486 (2019).

[42] S. Kumar, R. C. Nunes, and P. Yadav, J. Cosmol. Astropart. Phys. 09 (2022) 060.

[43] K. N. Abazajian, J. F. Beacom, and N. F. Bell, Phys. Rev. D **66**, 013008 (2002).

[44] E. Castorina, U. Franca, M. Lattanzi, J. Lesgourgues, G. Mangano, A. Melchiorri, and S. Pastor, Phys. Rev. D **86**, 023517 (2012).

[45] N. Aghanim *et al.* (Planck Collaboration), https://wiki.cosmos.esa.int/planck-legacy-archive/images/4/43/Baseline-params-table-2018–68 pc-v2.pdf (2019).

[46] G. Barenboim, W. H. Kinney, and W.-I. Park, Eur. Phys. J. C **77**, 590 (2017).

[47] A. D. Dolgov, S. H. Hansen, S. Pastor, S. T. Petcov, G. G. Raffelt, and D. V. Semikoz, Nucl. Phys. **B632**, 363 (2002).

[48] S. Pastor, T. Pinto, and G. G. Raffelt, Phys. Rev. Lett. **102**, 241302 (2009).

[49] B. D. Fields, K. A. Olive, T.-H. Yeh, and C. Young, J. Cosmol. Astropart. Phys. 03 (2020) 010; 11 (2020) E02.

[50] K. Kohri, M. Kawasaki, and K. Sato, Astrophys. J. **490**, 72 (1997).

[51] C. Pitrou, A. Coc, J.-P. Uzan, and E. Vangioni, Phys. Rep. **754**, 1 (2018).

[52] J. Froustey and C. Pitrou, J. Cosmol. Astropart. Phys. 03 (2022) 065.

[53] M. Escudero, J. Cosmol. Astropart. Phys. 02 (2019) 007.

[54] X. Chu, J.-L. Kuo, and J. Pradler, Phys. Rev. D **106**, 055022 (2022).

[55] J. J. Bennett, G. Buldgen, M. Drewes, and Y. Y. Y. Wong, J. Cosmol. Astropart. Phys. 03 (2020) 003; 03 (2021) A01.

[56] P. Ade *et al.* (Simons Observatory Collaboration), J. Cosmol. Astropart. Phys. 02 (2019) 056.

[57] K. Abazajian *et al.* (CMB-S4 Collaboration), in *Proceedings of the 2022 Snowmass Summer Study* (2022), arXiv: 2203.08024.

[58] S. Aiola *et al.* (CMB-HD Collaboration), arXiv:2203.05728.

[59] A. Sirlin, Phys. Rev. **164**, 1767 (1967).

[60] L. S. Brown and R. F. Sawyer, Phys. Rev. D **63**, 083503 (2001).

[61] A. Czarnecki, W. J. Marciano, and A. Sirlin, Phys. Rev. D **70**, 093006 (2004).

[62] A. N. Ivanov, R. Höllwieser, N. I. Troitskaya, M. Wellenzohn, and Y. A. Berdnikov, Phys. Rev. D **95**, 033007 (2017).

[63] R. E. Lopez, M. S. Turner, and G. Gyuk, Phys. Rev. D **56**, 3191 (1997).

[64] C. Iliadis and A. Coc, Astrophys. J. **901**, 127 (2020).

[65] P. D. Serpico, S. Esposito, F. Iocco, G. Mangano, G. Miele, and O. Pisanti, J. Cosmol. Astropart. Phys. 12 (2004) 010.

[66] S. Ando, R. H. Cyburt, S. W. Hong, and C. H. Hyun, Phys. Rev. C **74**, 025809 (2006).

[67] P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, and E. Vangioni-Flam, At. Data Nucl. Data Tables **88**, 203 (2004).

[68] C. Iliadis, K. Anderson, A. Coc, F. Timmes, and S. Starrfield, Astrophys. J. **831**, 107 (2016).

[69] A. Iñesta Gómez, C. Iliadis, and A. Coc, Astrophys. J. **849**, 134 (2017).

[70] R. S. de Souza, C. Iliadis, and A. Coc, Astrophys. J. **872**, 75 (2019).

[71] R. S. de Souza, S. R. Boston, A. Coc, and C. Iliadis, Phys. Rev. C **99**, 014619 (2019).
[72] J. Moscoso, R. S. de Souza, A. Coc, and C. Iliadis, Astrophys. J. **923**, 49 (2021).
[73] Y. Xu, K. Takahashi, S. Goriely, M. Arnould, M. Ohta, and H. Utsunomiya, Nucl. Phys. **A918**, 61 (2013).
[74] In particular, for the key reactions $\mathrm{D}(d,n)^3\mathrm{He}$ and $\mathrm{D}(d,p)^3\mathrm{H}$ we either interpolate rates and corresponding uncertainties from the NACRE II numerical database or from the outcome of the Bayesian analysis of Ref. [68].
[75] N. Aghanim *et al.* (Planck Collaboration), https://wiki.cosmos.esa.int/planck-legacy-archive/index.php/Cosmological-Parameters (2019).
[76] A. Coc, J.-P. Uzan, and E. Vangioni, J. Cosmol. Astropart. Phys. 10 (2014) 050.
[77] D. Foreman-Mackey, D. W. Hogg, D. Lang, and J. Goodman, Publ. Astron. Soc. Pac. **125**, 306 (2013).
[78] H. Akaike, IEEE Trans. Autom. Control **19**, 716 (1974).
[79] A. Gelman, J. Hwang, and A. Vehtari, arXiv:1307.5928.
[80] R. E. Kass and A. E. Raftery, J. Am. Stat. Assoc. **90**, 773 (1995).
[81] S. Y. Khlebnikov and M. E. Shaposhnikov, Nucl. Phys. **B308**, 885 (1988).
[82] J. A. Harvey and M. S. Turner, Phys. Rev. D **42**, 3344 (1990).
[83] J. March-Russell, H. Murayama, and A. Riotto, J. High Energy Phys. 11 (1999) 015.
[84] H. K. Dreiner and G. G. Ross, Nucl. Phys. **B410**, 188 (1993).
[85] J. Shu, T. M. P. Tait, and C. E. M. Wagner, Phys. Rev. D **75**, 063510 (2007).
[86] P.-H. Gu, Phys. Rev. D **82**, 093009 (2010).
[87] I. Affleck and M. Dine, Nucl. Phys. **B249**, 361 (1985).
[88] A. Casas, W. Y. Cheng, and G. Gelmini, Nucl. Phys. **B538**, 297 (1999).
[89] J. McDonald, Phys. Rev. Lett. **84**, 4798 (2000).
[90] M. Kawasaki and K. Murai, J. Cosmol. Astropart. Phys. 08 (2022) 041.