Indications for a Nonzero Lepton Asymmetry in the Early Universe

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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 non-vanishing lepton asymmetry during the Big Bang Nucleosynthesis (BBN) era, paying particular attention to the role of uncertainties in the nuclear reaction network. A cutting-edge Bayesian analysis of BBN data 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 ΛCDM. We discuss conditions for a large total lepton asymmetry to be consistently realized in the Early Universe.

I. 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 that is dominated by non-baryonic dark energy and dark matter, well-described by the 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, $D/H$, offers important constraints on New Physics (NP) [7–10] active during the first few minutes of the lifetime 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-$\alpha$ systems achieve better than 1% precision [15–17], yielding a weighted average of $D/H \times 10^5 = 2.547 \pm 0.025$ [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 plaguing our understanding of the key nuclear reactions involved. This highlights the primary importance to assess the impact of uncertainties in the nuclear reaction rates on the predictions from BBN [22]. A notable recent advance in this direction is the improved determination of the $D(p,\gamma)^3$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 which 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 $\lambda$10830 infrared emission line (relevant for parameter-degeneracy breaking [27]), the 10 Subaru EMPGs yield a determination of primordial

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{68% and 90% joint probability distribution of the primordial chemical potential of neutrinos, $\mu_\nu$, normalized to the neutrino temperature $T_\nu$, and the number of extra relativistic degrees of freedom in the Early Universe, $\Delta N_{\text{eff}}$, 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 adopted in the analysis as explained in the text. Magenta dashed lines highlight the ΛCDM prediction.}
\end{figure}
helium-4 of $Y_P = 0.2379^{+0.0031}_{-0.0030}$ in sharp contrast with the PDG value $Y_P = 0.245 \pm 0.003$ [18], and well below the SM prediction [19–21], naively a 3σ-level discrepancy.

Ref. [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 extra-relativistic degrees of freedom, $\Delta N_{\text{eff}}$, as well as a nonzero electron neutrino asymmetry, $\xi_{\nu_e}$, while simply anchoring $\Omega_B h^2$ to the most precise determination derived by Planck [1]. In view of the situation depicted for both helium and deuterium, in this Letter we revise the inference of a lepton asymmetry $\xi_{\nu_i}$ in the Early Universe, as well as on $\Delta N_{\text{eff}}$, paying attention to the details of a joint likelihood analysis of BBN and CMB data as recently carefully formulated in [13, 14]. To this aim, we perform a Bayesian analysis and comment on the possible NP implications.

II. 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 $\eta_B \equiv n_B/n_\gamma \sim \mathcal{O}(10^{-10})$ [29, 30]. Nevertheless, a large cosmic asymmetry can be hidden in the neutrino sector [31]:

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

where $n_\gamma$ is the photon number density, $n_{\nu_i}$ 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. Eq. (1) assumes $T_{\nu_i}/T_\gamma = (4/11)^{1/3}$, which is a good approximation given the modest impact of non-instantaneous neutrino decoupling and tiny departures from the Fermi-Dirac distributions in relativistic freeze-out [32–34]. It is further relevant that non-zero neutrino chemical potentials play a marginal role in SM neutrino decoupling [35, 36].

Eq. (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 [37, 38], and now are robustly [39] ruled out (irrespective of the lepton flavor [40, 41]). In fact, a nonzero chemical potential for the $i$-flavored neutrino would yield a contribution to the total radiation density (relative to photons) of

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

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

From the Planck constraint on $N_{\text{eff}}$ adopting the likelihood analysis including TTTEEE and low-$\ell$ 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 $N_{\text{eff}} = 2.97 \pm 0.29$ (68% probability interval) [1, 42], considering the SM prediction $N_{\text{eff}} = 3.044$ (known better than the per-mille level) [32–34], the 1σ upper-bound is:

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

implying the conservative constraint $|\xi_{\nu_i}| \lesssim 0.71$, valid for each flavor individually (see also Ref. [43]). Since the onset of neutrino oscillations is expected to occur around $T_\nu \sim 10$ MeV, flavor equilibration in the quark-neutral sector is predicted to be complete by the time of neutrino decoupling ($T_\nu \sim 2$ MeV) [44, 45], and the conservative CMB bound of Eq. (3) becomes slightly tighter for the 2nd and 3rd generation $\nu$ asymmetries:

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

BBN can place stronger constraints on the electron-neutrino asymmetry (by about an order of magnitude [31, 46]) largely because an electron-neutrino asymmetry at the time of BBN affects the $\beta$ equilibrium of weak interactions controlling the neutron-proton conversion. A positive (negative) value of $\xi_{\nu_e}$ acts through the equilibrium reactions $n_{\nu_e} \leftrightarrow p e^-, p \bar{\nu}_e \leftrightarrow n e^+$ and neutron decay to reduce (enhance) the neutron-to-proton ratio:

$$(n_n/n_p)|_{\text{eq}} \simeq \exp \left( -\frac{Q}{T_\gamma} - \xi_{\nu_e} \right) , \quad (5)$$

where $Q \equiv m_n - m_p = 1.293$ MeV is the neutron-proton mass difference. While light primordial abundances like deuterium are particularly sensitive to $\Omega_B h^2$ from the CMB yields the precise determination: $\xi_{e\nu} = 0.001 \pm 0.016$, 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. [48] indicates that
the degree to which full flavor equilibration is realized during the BBN era sensitively depends on the PMNS mixing angle $\theta_{13}$ and on the initially generated values of the degeneracy parameters. In the following, we revisit the determination of $\xi_\nu$ in light of the newly measured helium-4 mass fraction from EMPGs as reported in Ref. [25]. While $\xi_\nu = \xi_{\nu_e,\nu_\tau}$ may be achieved in the Early Universe, one should bear in mind that the conservative interpretation of our main finding in Fig. 1 applies in Ref. [25]. While ensured helium-4 mass fraction from EMPGs as reported during the BBN era sensitively depends on the PMNS the degree to which full flavor equilibration is realized

\[ \mu \]

rates integrating over nucleon thermal distributions with QED [57, 58] corrections, as well as finite-temperature beyond the Born approximation [55], namely including $\ell + BAO + lensing Planck run varying also $Y_P, N_{\text{eff}}$ [1, 42] and also retrieving correlations in $C_{\text{BBN}}$ from [70]. The BBN likelihood of our study corresponds to:

\[ \log L_{\text{BBN}} = -\frac{1}{2} \sum_X \left( \frac{X^{\text{th}} - X}{\sigma_X} \right)^2 , \]

where $X = \{Y_P, D/H\}$, and we use the measurements: $Y_P = 0.2379(31)$ [25], $D/H = 0.00002547(25)$ [18].

The parameters we infer are varied according to uniform priors: $-2 \leq \Delta N_{\text{eff}} \leq 2$, $-0.2 \leq \xi_\nu \leq 0.2$, $1 \leq (\eta_B \times 10^{10}) \leq 10$ (using $\eta_B \times 10^{10} \approx 273.748 \Omega_B h^2$). 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. [71], varying a total of 12 additional nuisance parameters.

We perform an MCMC analysis via the \texttt{emcee} [72] 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 $T S_{\text{ cosm }}$, we also compute for each scenario the Information Criterion [73, 74] $I C \equiv -2 \log \hat{L}_{\text{BBN}} + 2k - 1$, $k$ being the number of BSM parameters and accounting for the CMB information as an extra constraint in the fit. Then, we evaluate the

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. [60] (plus $^3$He($p, \gamma$)$^4$He, taken from [61]), yielding state-of-the-art predictions for $Y_P$ and D/H. In particular, for the radiative neutron capture rate we adopt the MCMC result of Ref. [62], while in the treatment of the other 10 key reactions we distinguish two approaches:

- **PRIMAT driven**: Nuclear rates are implemented according to the statistical determination of Refs [63–68], i.e. following theoretical ab-initio energy modeling tuned to datasets for which an estimate of systematic errors is available [19, 22, 47].

- **NACRE II driven**: Nuclear rates are interpolated from the updated NACRE compilation [69], comprising charged-particle-induced reactions; for $^7$Be($n, p$)$^7$Li we use the LUNA result reported in [23]; for $^7$Be($n, p$)$^7$Li we adopt the baseline of Ref. [46].

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

\[ T S_{\text{ cosm }} = -2(\log L_{\text{CMB}} + \log L_{\text{BBN}}) ; \]

the CMB likelihood explicitly reads:

\[ \log L_{\text{CMB}} = -\frac{1}{2} \Delta \vec{v}^T C_{\text{CMB}}^{-1} \Delta \vec{v} , \]

with $\Delta \vec{v} = \vec{v}^{\text{th}} - \vec{v}$, $\vec{v} = (Y_P, \Omega_B h^2, N_{\text{eff}})^T$, using mean and standard-deviation values from the TTTEEE + low-$\ell$ + BAO + lensing Planck run varying also $Y_P, N_{\text{eff}}$ [1, 42] and also retrieving correlations in $C_{\text{CMB}}$ from [70].

For 1) we base our computation on the approach proposed in [49] and further developed in [36] (see also [50]). It consists in solving the Boltzmann equations for the electron-photon plasma and neutrinos assuming a thermal distribution for the species, including NLO QED corrections for the plasma [51] as well as non-instantaneous decoupling effects for the neutrino sector [36]. For our purposes, it suffices to describe the neutrino sector by a common temperature $T_\nu$, yielding the SM prediction $N_{\text{eff}} = 3.045$, differing from the most refined prediction in [32–34] only at the per-mille level, well within current and future observational sensitivity [52–54]. A non-zero 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 non-zero lepton asymmetry $|\xi_{\nu_e}| \gg |\xi_{\nu_\tau}|$ by varying $\Delta N_{\text{eff}}$. Note that from our bound in Eq. (4), a muon-tau neutrino asymmetry can induce a maximal shift $\Delta N_{\text{eff}} \sim 0.1$.

Moving to 2), we compute $n \leftrightarrow p$ matrix elements beyond the Born approximation [55], namely including isospin-breaking contributions like finite-mass [56] and QED [57, 58] corrections, as well as finite-temperature effects [59], following the implementation carried out in [47]. Most importantly, we evaluate weak-interaction rates integrating over nuclear thermal distributions with chemical potential $\mu_Q \equiv \mu_n - \mu_p = -\mu_{\nu_\tau} \neq 0$. We perform an MCMC analysis via the \texttt{emcee} [72] 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 $T S_{\text{ cosm }}$, we also compute for each scenario the Information Criterion [73, 74] $I C \equiv -2 \log \hat{L}_{\text{BBN}} + 2k - 1$, $k$ being the number of BSM parameters and accounting for the CMB information as an extra constraint in the fit. Then, we evaluate the
The determination of the cosmological baryon-to-photon ratio from the fit of CMB data within \( \Lambda \) p.d.f. for helium-4, \( Y_p \)

\[ \Delta \xi \]

**FIG. 2.** Probability density function (p.d.f.) for the primordial light elements analyzed in this study. In the left panel, the p.d.f. for helium-4, \( Y_P \), as precisely predicted in the SM according to two different set of nuclear uncertainties and adopting the determination of the cosmological baryon-to-photon ratio from the fit of CMB data within \( \Lambda \)CDM (color code similar to Figure 1). In the same panel, the outcome from the joint fit to BBN and CMB likelihoods in the BSM scenario where \( \xi \) and \( \Delta N_{\text{eff}} \) are consistently allowed to differ from their \( \Lambda \)CDM 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 1\( \sigma \) 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.

\[ IC \]

difference with respect to the SM prediction of the primordial light abundances within a given approach: \( \Delta IC \sim O(1) (\sim O(10)) \) provides positive (strong) support in favor of NP beyond \( \Lambda \)CDM according to the canonical scales of evidence [75].

**IV. RESULTS**

In Figure 1 we report the main result of our study: the 68% and 90% probability region for the primordial lepton asymmetry \( \xi \) and the extra-relativistic degrees of freedom \( \Delta N_{\text{eff}} \) as determined by TS\(_{\text{cosmo}}\), Eq. (6), corresponding to the two approaches to thermonuclear rates described in the previous section. From the \( \Lambda \)CDM 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], while the overall significance also depends on the precision obtained for the inference of the cosmological baryon abundance within \( \Lambda \)CDM; a shift of \( \xi \) and \( N_{\text{eff}} \) 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 \( \Lambda \)CDM Planck analysis (TTTEEE + low-\( \ell \) + BAO + lensing) [1, 42]. 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. [69] 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:

- A discrepancy at the 3\( \sigma \) 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 \( \Lambda \)CDM;

- A tension of about 2\( \sigma \) 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 ther-
mononuclear reactions involved, in line with recent discussions in the literature [22].

From Figure 2, it is clear that a shift of $\Delta N_{\text{eff}}$ 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 measurement of the helium-4 mass fraction is in perfect agreement with the SM prediction, and our inference for a nonzero degeneracy parameter $\xi_{\nu}$ 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 $\Delta N_{\text{eff}}$ is considered. Looking at the $\Delta IC$ values, we conclude that a joint analysis of BBN + CMB data provides mild to strong evidence for a scenario with non-vanishing lepton asymmetry. Moreover, within the NACRE II approach no notable support from data is found for the presence of extra relativistic degrees of freedom in the Early Universe, whereas a scenario where only $\Delta N_{\text{eff}}$ 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.

| Scenario | Approach | $Y_{P} \times 10$ | D/H $\times 10^{5}$ | $\Delta N_{\text{eff}}$ | $\xi_{\nu}$ | $\eta_{B} \times 10^{10}$ | $\Delta IC$ |
|----------|----------|-------------------|-------------------|------------------|------------|-----------------|----------|
| SM prediction | PRIMAT driven | 2.4715(14) | 2.439(36) | – | – | 6.137(38) | – |
| | NACRE II driven | 2.4706(16) | 2.51(10) | – | – | 6.137(38) | – |
| $\Delta N_{\text{eff}}$ BSM fit | PRIMAT driven | 2.472(11) | 2.471(44) | 0.02(18) | – | 6.096(64) | 2 |
| | NACRE II driven | 2.453(14) | 2.46(11) | -0.28(23) | – | 6.088(67) | 0 |
| ($\Delta N_{\text{eff}},\xi_{\nu}$) BSM fit | PRIMAT driven | 2.393(38) | 2.475(44) | 0.27(24) | 0.039(18) | 6.120(67) | 8 |
| | NACRE II driven | 2.383(41) | 2.47(11) | -0.01(27) | 0.036(19) | 6.114(65) | 5 |

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.

V. DISCUSSION AND OUTLOOK

We find that the new measurement of primeval helium including 10 additional EMPGs by the Subaru Survey leads to a tantalizing hint for a large total lepton asymmetry of primordial origin. From Eq. (1) today’s value $\eta_{L} \gg \eta_{B}$, and ranges from $\sim 0.01$ to $\sim 0.26$, depending on the details of neutrino oscillations in the Early Universe as well as on the initial value for the neutrino degeneracy parameters. Such a finding would require a cosmology dramatically different from the one inferred extrapolating the SM, and thus hints toward BSM physics.

While it is possible to imagine many types of NP which could generate such a situation, there are common factors that any successful explanation 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 $O(1)$ factor [76, 77]. Thus, for a difference of orders of magnitude between $\eta_{L}$ and $\eta_{B}$ 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 [78]. The latter scenario would point to flavor-dependent NP in the lepton sector, with possible interesting implications for the smallness of $\eta_{B}$ as well, see for instance [78–81].

Because equilibration of neutrino species depends both on imprecisely determined mixing parameters and the assumed initial asymmetry in each flavor [48], mapping the inferred neutrino asymmetries during BBN into the space of consistent initial conditions at some earlier time is an interesting inverse problem; it requires also assumptions on the interpretation of the inference carried out here for $\Delta N_{\text{eff}}$, 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 [82] exist in the literature [78, 83–85].

Looking forward, our study highlights the combined power of BBN and CMB data to provide a key glimpse of an early epoch of the Universe. Making the most of its opportunity requires more work, to improve the treatment of nuclear physics inputs and measurements of the primordial abundances. If the current indications of a large total lepton asymmetry $\eta_{L}$ survives further scrutiny, it provides important clues towards our understanding of the Universe in its early stages, offering at the same time a quite privileged view on BSM physics.

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