1. Introduction

The lepton asymmetry of the Universe, represented by neutrinos and antineutrinos, is nowadays one of the most weakly constrained cosmological parameters. Although the baryon asymmetry is well measured from cosmic microwave background (CMB), the lepton asymmetry could be larger by many orders of magnitude and not of the same order as expected by the Big Bang Nucleosynthesis (BBN).

The lepton asymmetry can be considered as an excess of the neutrinos on antineutrinos or vice versa and have consequences in the early Universe phase transition, cosmological magnetic fields and dark matter relic density. Other effects can be considered as changes in the decoupling temperature of Cosmic Neutrino Background CνB, the time equivalence between the energy densities of radiation and matter, and the production of primordial light elements at BBN (Fig 1. Top-Left and Right). The degeneracy parameter.

These changes can affect the evolution of the matter density perturbations in the Universe, which has effects not only on the CMB anisotropies, but also on the formation, evolution, and distribution of the large-scale structure (LSS) of the Universe, in different hierarchies (Fig 1. Down-Left).

2. Cosmological neutrino properties

Unlike CMB, the CνB has not been detected directly, however, indirect measures were established using CMB as well as estimations from the primordial abundances of light elements. Recently, Folini et al. (2015) interpreting data from damping of acoustic oscillations of the CMB, demonstrated a detection of a temporal phase shift is generated by neutrino perturbations (Fig 1. Top-Left).

The main parameters that characterize the neutrinos are the total mass Σmν and the effective number Nν. The up dated constraint on the neutrino mass scale is Σmν < 0.12 eV at 95 percent C.L. from the final full-season Planck 2018, Nν = 3.846 and any excess over this value can be parameterized through ΔNν = Nν − 3.846, which in principle is assumed to be some excess of the number of relativistic relics degree of freedom.

The lepton asymmetry is usually parameterized by the so-called degeneracy parameter ξν = νT/νl, where νl is the neutrino chemical potential and Tν ∼ 1.9K is the current temperature of the relic neutrino. If the neutrinos are Majorana particles they must have ρν = 0, and if ρν ≠ 0, neutrinos are Dirac fermions, this being as the null hypothesis is necessary to help to solve this question.

3. Cosmic neutrino background

Relativistic neutrinos contribute to the total energy density of radiation ρν as

\[ \rho_\nu = (\rho_\nu + \rho_{\bar{\nu}}) = \frac{1}{2} \sum \Omega_{\nu_i} \rho_{\nu_i} \]

where \( \rho_{\nu_i} = 9.6 \times 10^{-5} T_{\nu_i}^4 \text{eV}^3 \text{cm}^{-3} \) and \( \Omega_{\nu_i} = \frac{\rho_{\nu_i}}{\rho_{\gamma}} \) is the neutrino energy density in units of critical density and

\[ \rho_\nu + \rho_{\bar{\nu}} = T^4 \int \frac{d^3k}{(2\pi)^3} E_{\nu_i}(f_{\nu_i} + f_{\bar{\nu}_i}) \]

where \( E_{\nu_i} = m^2_{\nu_i} + q^2 m_\gamma \) is the mirror neutrino and antineutrino energy and \( q = m_\gamma \) is the comoving momentum. The functions \( f_{\nu_i}, f_{\bar{\nu}_i} \) are the Fermi-Dirac phase space distributions given by

\[ f_{\nu_i} = \frac{1 - e^{-\frac{E_{\nu_i}}{T}}}{1 + e^{-\frac{E_{\nu_i}}{T}}} \]

and

\[ f_{\bar{\nu}_i} = \frac{1 - e^{-\frac{E_{\bar{\nu}_i}}{T}}}{1 + e^{-\frac{E_{\bar{\nu}_i}}{T}}} \]

At the early Universe, we assumed neutrinos-antineutrinos are produced in thermal and chemical equilibrium. Their equilibrium distribution functions have been frozen from the time of decoupling to the present.

4. Neutrino asymmetry

The neutrino degeneracy parameter is conserved and if it (ξν) remains constant, finite and non-zero after decoupling, then could lead to an asymmetry on the neutrinos and antineutrinos, which is usually parameterized as

\[ \rho_\nu = \frac{n_{\nu} - n_{\bar{\nu}}}{n_\gamma} \]

where \( n_{\nu}(n_{\bar{\nu}}) \) is the neutrino (antineutrino) number density, \( n_\gamma \) is the photon number density, \( (\xi_\nu) \approx 1.2 \times 10^{-3}, \)

\[ \text{and} \ \frac{e_{\nu}}{e_{\gamma}} = \frac{T_{\nu}}{T_{\gamma}} \]

Within is known that the impact of the lepton asymmetry increase the radiation energy density with the form:

\[ \Omega_{\nu} = 3.046 + \Delta\Omega_{\nu} \]

\[ \Delta\Omega_{\nu} \text{ is due to the leptonic asymmetry induced via equation} \]

\[ \Delta\Omega_{\nu} = \frac{60}{T_c^2} (\frac{\xi_\nu}{\xi_{\nu,0}})^2 \approx \frac{30}{T_c^2} (\frac{\xi_\nu}{\xi_{\nu,0}})^2 \]

where \( i = 1, 2 \) only (two massless neutrino states). In what follows, let us impose expected sensitivities on \( \xi_\nu \).

5. Methodology

We use public Boltzmann CLASS and Monte Python codes in the present work, where we introduced the \( \xi_\nu \) corrections on \( \Omega_{\nu} \). Also we have used CLASS to compute the theoretical CMB angular power spectra \( C_{\ell}^{TT}, C_{\ell}^{EE}, C_{\ell}^{TE} \) for temperature, cross temperature, polarization and polarization. Together with the primary anisotropy signal, we have also taken into account informations from CMB weak lensing, considering the power spectrum of the CMB lensing potential \( C_{\ell}^{\phi\phi} \).

6. Main results

| Parameter | Value | (CORE) | (S4) |
|-----------|-------|--------|------|
| η_{ee} | 0.1919 | 0.0037 | 0.0003 |
| H_{0} | 69 | 2.25 |
| ln(10A_{s}) | 3.0753 | 0.0056 | 0.0003 |
| n_{s} | 0.9622 | 0.0022 | 0.0004 |
| θ_{s} | 0.6935 | 0.0028 | 0.0002 |
| Σm_{ν} | 0.06 | 0.0124 | 0.0003 |
| ξ_{ν} | 0.05 | 0.071 | 0.027 |

7. Summary and Conclusions

In this work, we have derived new constraints relevant to the lepton asymmetry through the degeneracy parameter by using the CMB angular power spectrum from the Planck data and future CMB experiments like CORE and CMB-S4.

We have analyzed the impact of a lepton asymmetry on \( \Omega_{\nu} \) where, as expected, we noticed the existence of very small corrections on \( \Delta N_{\nu} \), but corrections that can not negligible at the level of CMB-S4 experiments.

Within this cosmological scenario, we have also investigated the neutrino mass scale in combination with the cosmological lepton asymmetry.

We have found strong limits on \( \Sigma m_{\nu} \), where the scale mass for both, CORE and CMB-S4 configurations, are well bound to be \( m_{\nu} = 0.1 \text{eV} \) at 95 percent C.L, therefore, favoring a normal hierarchy scheme mass in both cases.

We note that \( \Delta N_{\nu} = 0.0032 \pm 0.0194 \) for Planck for CORE and S4, respectively, thus, unfavorable to inverted hierarchy scheme mass in both cases.

Bibliography:
Based on [Bonilla A., Nunes R. C., Abreu E. M. C., 2019, MNRAS, 485, 2489, arXiv:1810.05656v2] and all references therein.

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