Forecast on lepton asymmetry from future CMB experiments

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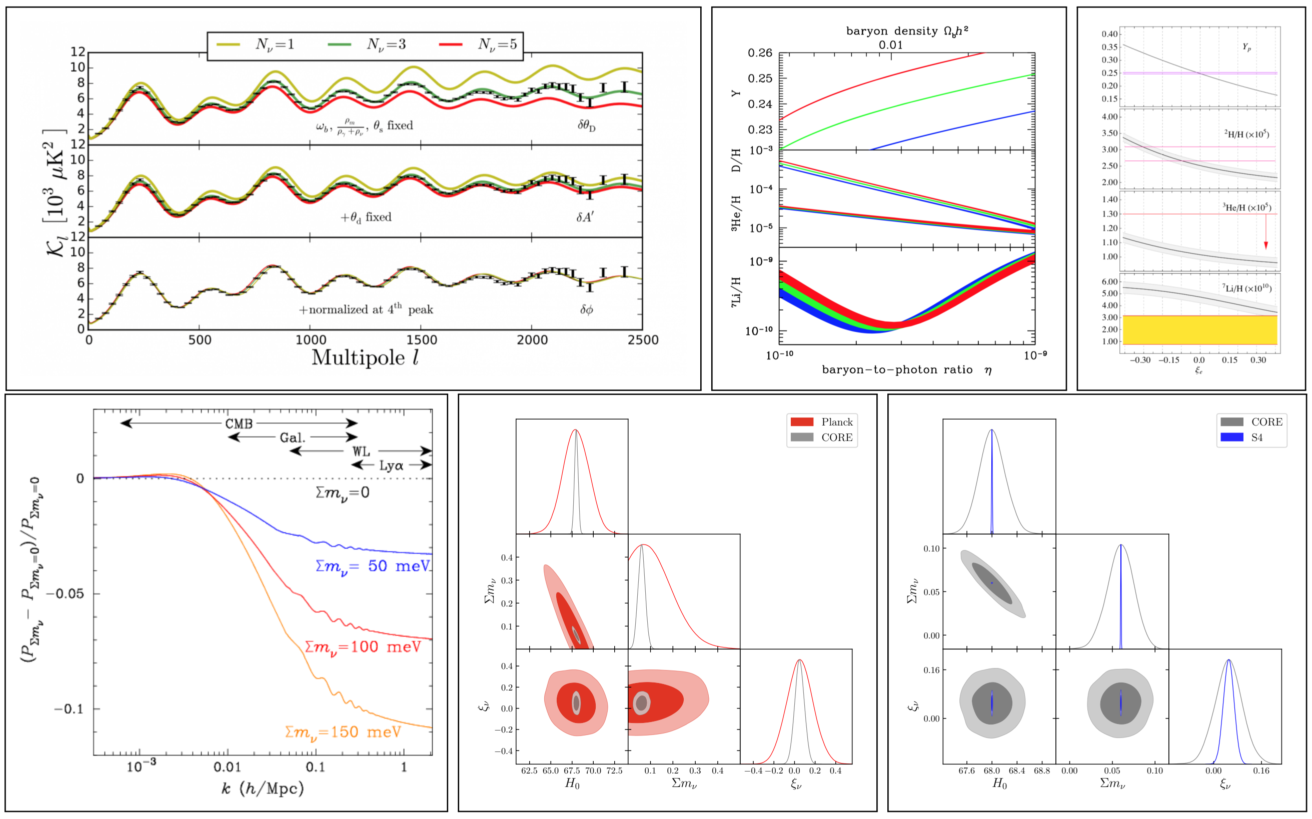
1. Introduction

- The lepton asymmetry of the Universe, represented by neutrinos and antineutrinos, is nowadays one of the most weakly constrained cosmological parameter. 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 the neutrinos on antineutrinos or vice versa and have consequences in the early Universe phase transitions, cosmological magnetic fields and dark matter relic density. Other effects can be considered as changes in the decoupling temperature of Cosmic Neutrino Background $C\nu B$, the time equivalence between the energy densities of radiation and matter, the production of primordial light elements at BBN **(Fig 1. Top-Center and Right)** and the expansion rate of the Universe, i.e.
- 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)**.

Figure 1.



2. Cosmological neutrino propierties

- Unlike CMB, the $C\nu B$ has not yet been detected directly, however, indirect measures were established using CMB as well as estimations from the primordial abundances of light elements. Recently, Follin 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 Σm_ν and the effective number $N_{\rm eff}$. The up dated constraint on the neutrino mass scale is $\Sigma m_\nu < 0.12$ eV at 95 percent C.L. from the final full-mission Planck 2018. $N_{\rm eff} = 3.046$ and any excess over this value can be parameterized through $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$, which in principle is assumed to be some excess of the number of relativistic relics degrees of freedom.
- The lepton asymmetry is usually parameterized by the so-called degeneracy parameter $\xi_\nu = \mu_\nu/T_{\nu 0}$, where μ_ν is the neutrino chemical potential and $T_{\nu 0} \approx 1.9K$ is the current temperature of the relic neutrino. If the neutrinos are Majorana particles they must have $\mu_\nu = 0$, and if $\mu_\nu \neq 0$, neutrinos are Dirac fermions thus, evidence on 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 ρ_r as

$$\rho_r = (\rho_\gamma + \rho_\nu) = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)\rho_\gamma, \qquad (1)$$

where $\rho_\nu = 10^4 h^2 \Omega_\nu eV cm^{-3}$ and $\Omega_\nu = \rho_\nu/\rho_{cri}$ is the neutrino energy density in units of critical density and

$$\rho_{\nu_i} + \rho_{\bar\nu_i} = T_\nu^4 \int \frac{d^3q}{2(\pi)^3} E_{\nu_i}(f_{\nu_i}(q) + f_{\bar\nu_i}(q)) \qquad (2)$$

where $E^2_{\nu_i} = q^2 + a^2 m_{\nu_i}$ is one flavor neutrino/antineutrino energy and $q = ap$ is the comoving momentum. The functions f_{ν_i}, $f_{\bar\nu_i}$ are the Fermi-Dirac phase space distributions given by

$$f_{\nu_i}(q) = \frac{1}{e^{E_{\nu_i}/T_\nu - \xi_\nu} + 1}, f_{\bar\nu_i}(q) = \frac{1}{e^{E_{\bar\nu_i}/T_\nu + \xi_{\bar\nu}} + 1}, \qquad (3)$$

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

4. Neutrino asymmetry

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

$$\eta_\nu \equiv \frac{n_{\nu_i} - n_{\bar\nu_i}}{n_\gamma} = \frac{1}{12\zeta(3)} \sum_i y_{\nu 0}\left(\pi^2 \xi_{\nu_i} + \xi^3_{\nu_i}\right), \qquad (4)$$

where $n_{\nu_i}(n_{\bar\nu_i})$ is the neutrino (antineutrino) number density, n_γ is the photon number density, $\zeta(3) \approx 1.20206$, and $y^{1/3}_{\nu 0} = T_{\nu 0}/T_{\gamma 0}$ is the ratio of neutrino and photons temperature to the present, where $T_{\gamma 0}$ is the temperature of the CMB ($T_{\gamma 0} = 2.726K$).

Is well known that the impact of the leptonic asymmetry increase the radiation energy density with the form, $N_{\rm eff} = 3.046 + \Delta N^{\xi_\nu}_{\rm eff}$, where $\Delta N^{\xi_\nu}_{\rm eff}$ is due to the leptonic asymmetry induced via equation

$$\Delta N^{\xi_\nu}_{\rm eff} = \frac{60}{7}\left(\frac{\xi_\nu}{\pi}\right)^2 + \frac{30}{7}\left(\frac{\xi_\nu}{\pi}\right)^4, \qquad (5)$$

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

5. Methodology

We use public Boltzmann CLASS and Monte Python codes in the present work, where we introduced the ξ_ν corrections on $N_{\rm eff}$. Also we have used CLASS to compute the theoretical CMB angular power spectra C_l^{TT}, C_l^{TE}, C_l^{EE} 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_l^{PP}.

Experi	Beam	Power noise	$l_{\rm min}$	$l_{\rm max}$	$f_{\rm sky}$
CORE	6.0	2.5	2	3000	0.7
S4	3.0	1.0	50	3000	0.4

Table 1. Experimental specifications for CORE and S4.

We have assumed the set of the cosmological parameters: $\{100\omega_{\rm b}, \omega_{\rm cdm}, H_0, \ln 10^{10}A_s, n_s, \tau_{\rm reio}, \sum m_\nu, \xi_\nu\}$: baryon density, cold dark matter density, Hubble constant, amplitude and slope of the primordial spectrum, optical depth to reionization, neutrino mass scale and the degeneracy parameter. **Fig 1. Down-Center and Right**, show 1-D marginalized distribution and 2-D regions at 68 % CL and 95 % CL, for some parameters taking into account Planck, CORE and S4 experiments.

6. Main results

Parameter	Fiducial value	σ(CORE)	σ(S4)
$10^2\omega_b$	2.22	0.000057	0.00012
ω_{cdm}	0.11919	0.00037	0.0000093
H_0	68.0	0.32	0.0088
$\ln 10^{10}A_s$	3.0753	0.0056	0.0035
n_s	0.96229	0.0022	0.0054
$\tau_{\rm reio}$	0.055	0.0028	0.00025
$\sum m_\nu$	0.06	0.024	0.00053
ξ_ν	0.05	0.071	0.027

Table 2. Summary of the observational constraints from both CORE and S4 experiments. The notation σ(CORE) and σ(S4), represents the 68 % CL estimation on the fiducial values.

- With CMB-S4, we find $\xi_\nu = 0.05 \pm 0.027$ (± 0.043) at 68 % CL (95 % CL). These constraints can rule out the null hypothesis up to 2σ CL on ξ_ν. In this perspective the neutrinos can be Dirac particles against the null hypothesis and no Majorana.
- For neutrino mass scale, we find $0.021 < \sum m_\nu \lesssim 0.1$ eV and $0.05913 < \sum m_\nu \lesssim 0.061$ eV at 95 % CL for CORE and S4, respectively, thus, unfavorable to inverted hierarchy scheme mass in both cases.
- We note that $\Delta N^{\xi_\nu}_{\rm eff} = 0.002 \pm 0.019$ (± 0.030) for Planck $\Delta N^{\xi_\nu}_{\rm eff} = 0.0022 \pm 0.0083$ (± 0.013), CORE and $\Delta N^{\xi_\nu}_{\rm eff} = 0.0022 \pm 0.0045$ (± 0.0059) S4..

7. Summary and Conclusions

- In this work, we have derived new constraints relative 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 $N_{\rm eff}$ where, as expected, we noticed the existence of very small corrections on $\Delta N_{\rm eff}$, 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 $\sum m_\nu$, where the mass scale for both, CORE and CMB-S4 configurations, are well bound to $\sum m_\nu < 0.1$ eV at 95 percent CL, therefore, favoring a normal hierarchy scheme ($m_1 \ll m_2 < m_3$) within the perspective adopted here.

Bibliography: Based on "Bonilla A., Nunes R. C., Abreu E. M. C., 2019, MNRAS, 485, 2486, arXiv:1810.06356v2" and all references therein.

Acknowledgments: The authors wish to thank the financial support of **CAPES** and **CNPq**.