Contribution ID: **306** Type: **Oral report**

Revisiting primordial neutrino asymmetries, spectral distortions and cosmological constraints with full neutrino transport

The primordial neutrino asymmetries leave significant imprints on the evolution of the universe and can therefore be constrained by cosmological observations of Big Bang Nucleosynthesis (BBN), the Cosmic Microwave Background (CMB), and Large Scale Structure (LSS).
In this paper, we present a systematic study of the implications and corresponding constraints of the primordial neutrino asymmetries under a precise and accurate treatment of neutrino decoupling.
For the neutrino decoupling process, we solve the full quantum kinetic equations (QKEs) for neutrinos and antineutrinos, which are derived from the closed-time-path (CTP) formalism, and evaluate the resulting effective number of neutrinos $N_{\rm eff}$ and the spectral distortions for neutrinos and antineutrinos.
We then study the implications of the primordial neutrino asymmetries on the BBN, CMB and LSS using the resulting neutrino density matrices from the QKEs.
In comparison with the traditional treatments using the Fermi-Dirac distribution for neutrinos, we find that the actual density matrices are important to obtain accurate results of the implications, especially for the helium abundance in the BBN and the free-streaming effects of massive neutrinos.
We also find the dependence of the Baryon Acoustic Oscillations (BAO) on the primordial neutrino asymmetries, suggesting its potential to constrain the primordial neutrino asymmetries.
This is confirmed by the MCMC analysis with the data from EMPRESS, Planck and BOSS. We find that the combined constraint on the neutrino degeneracy parameter from EMPRESS, Planck and BOSS is $\xi_\nu = 0.024^{+0.012}_{-0.013}$, deviating from zero by $1.8\,\sigma$, which is $0.4\,\sigma$ smaller than the constraint without the BOSS data.

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Track Classification: 中微子物理、粒子天体物理与宇宙学