PROCEEDINGS OF SCIENCE

Neutrino decoupling in standard and non-standard scenarios

Pablo Martínez Miravé[a,b,*]

[a] *Instituto de Física Corpuscular (CSIC-Universitat de València)*
Parc Científic UV, C/ Catedrático José Beltrán, 2, 46980 Paterna, Spain

[b] *Niels Bohr International Academy and DARK, Niels Bohr Institute, University of Copenhagen*
Blegdamsvej 17, 2100, Copenhagen, Denmark

E-mail: pablo.mirave@nbi.ku.com

We discuss the phenomenology of neutrino decoupling in the early universe in standard and non-standard scenarios. We review how the effective number of neutrino species in the early universe ($N_{\rm eff}$) is calculated in the three-neutrino case, which gives Neff=3.044, and show how this result can change when one considers non-standard properties such as non-standard interactions between neutrinos and electrons and a non-unitary three-neutrino mixing matrix.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08_01.09.2023
University of Vienna

[*]Speaker

https://pos.sissa.it/

PoS(TAUP2023)245

1. Introduction

In the early universe, when the temperature dropped below O(MeV), electroweak interactions keeping neutrinos coupled to the cosmic plasma stopped being effective. Then, neutrinos started free-streaming, forming the so-called cosmic neutrino background.

The contribution of such neutrinos to the radiation energy content of the universe is generally parametrised in terms of the effective number of neutrinos $N_{\rm eff}$, which relates the ratio between the radiation energy density in the form of photons, ρ_γ, and neutrino, ρ_ν, shortly after neutrino decoupling. The theoretical prediction for the Standard Model of particle physics is expected to be $N_{\rm eff} \simeq 3$. Such prediction is in good agreement with the recent determination of the parameter from Planck 2018 (TT, TE, EE + lowE + lensing + BAO) at 95% C.L., $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$. In the years to come, Simons Observatory [1] and CMB-S4 [2], could significantly improve this measurement to $\sigma(N_{\rm eff}) = 0.02 - 0.03$. With such unprecedented precision, it will be possible to test some non-standard scenarios of neutrino decoupling [3, 4].

2. Neutrino decoupling in the standard scenario

For three neutrino families, departures from $N_{\rm eff} = 3$ are due to neutrino Standard-Model interactions and finite-temperature corrections to Quantum Electrodynamics (QED). Besides that, one can include the effects of neutrino flavour oscillations, which also result in subleading contributions. At present, detailed calculations taking into account such effects yield a benchmark value of $N_{\rm eff} = 3.0440 \pm 0.0002$ [5–7]. The dominant sources of uncertainties in this calculations are related to the numerical solution procedure, the uncertainty in the determination of the solar mixing angle $\sin^2\theta_{12}$ [8], and radiative corrections in $e^+e^- \longleftrightarrow \nu\bar{\nu}$ cross-section [9].

3. Neutrino decoupling in non-standard scenarios

3.1 Non-unitary three neutrino mixing

In many extensions of the SM accounting for neutrino masses, the particle content is extended to include heavy neutral leptons (HNL). In those cases, the lepton mixing matrix is enlarged to include the mixing between the three light neutrinos and the $n-3$ HNLs. Then, the 3×3 lepton mixing matrix, N, is no longer unitary and it can be parameterised as as

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U\,, \tag{1}$$

where U is the usual unitary parametrisation of the lepton mixing matrix in terms of three mixing angles and one CP phase. Then, departures from unity in the diagonal elements or from zero in the off-diagonal ones would indicate a non-unitary three-neutrino mixing.

At low energies and considering that only the three light states lie below the energy scale of interest for neutrino decoupling, the Lagrangian accounting for charged-current (CC) and neutral-

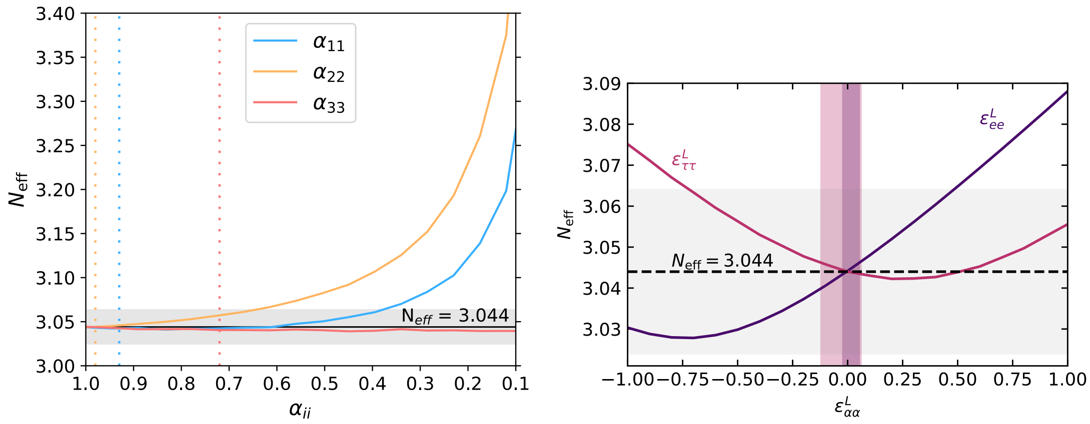

Figure 1: Left panel: Predicted value of $N_{\rm eff}$ as a function of the diagonal α_{ii} parameters. The black line corresponds to the standard benchmark value and the grey band is the expected sensitivity from CMB-S. Right panel: Predicted value of $N_{\rm eff}$ for non-zero values of the NSI parameters ε^L_{ee} and $\varepsilon^L_{\tau\tau}$. Vertical bands correspond to limits from terrestrial experiments.

current (NC) interactions between neutrinos, electrons and positrons reads

$$\mathcal{L}_{\rm NU} = -\,2\sqrt{2}G_F \sum_{i,j}^{3} \sum_{X=L,R} \left[\left(\delta_{XL}(N^\dagger)_{ie}N_{ej} + g_X(N^\dagger N)_{ij}\right)(\bar{\nu}_i\gamma^\mu P_L\nu_j)(\bar{e}\gamma_\mu P_X e)\right] . \quad (2)$$

Here, the subindex $X = \{L,\ R\}$ denotes the chirality of the projector, P_X, G_F is the Fermi constant, g_X are the SM coefficients, and the Latin subindices indicate the neutrino mass eigenstate. Notice here that, in the presence of a non-unitary three-neutrino mixing matrix, the strength and flavour structure of both CC and NC interactions are modified and hence, one would expect the predictions for $N_{\rm eff}$ to change accordingly.

In the left panel of Figure 1, we display the dependence on the predicted value of $N_{\rm eff}$ when the diagonal parameters are allowed to vary individually. The observed departures from the benchmark value are mainly due to the changes in the interaction rates of scattering and annihilation processes involving neutrinos, electrons and positrons. Then, it is possible to derive current limits from Planck (sensitivity projections for CMB-S4 at 90% C.L. :

$$\alpha_{11} > 0.07\ (0.29) \qquad \text{and} \qquad \alpha_{22} > 0.15\ (0.50)\,. \quad (3)$$

3.2 Non-standard interactions between neutrinos and electrons

Neutrino non-standard interactions (NSI) are also a common prediction from many neutrino mass models or scenarios involving light mediators. The effect of neutral-current NSIs with electrons can be studied from the following Lagrangian:

$$\mathcal{L}_{\rm NSIe} = -2\sqrt{2}G_F \sum_X \sum_{\alpha,\beta} \varepsilon^X_{\alpha\beta} \left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{e}\gamma_\mu P_X e\right) . \quad (4)$$

Here, the Greek subindices indicate the flavour of the neutrinos involved and we have introduced the dimensionless coefficients $\varepsilon^X_{\alpha\beta}$ which are related to the strength of the interaction. Non-standard interactions can either increase or decrease the interaction rate between neutrinos and the rest of the cosmic plasma, resulting in an earlier or delayed decoupling. This can be seen in Figure 1, where we show how the predicted N_{eff} changes as a function of the value of two NSI parameters.

4. Discussion

In the forthcoming years, the precision expected from cosmological observations would allow us to determine precisely the contribution of neutrinos to the radiation energy density of the universe in the MeV era. Such achievement would open the door to further study of neutrino properties from cosmology using a complementary approach to terrestrial experiments. In particular, an accurate measurement of N_{eff} would allow to test the standard scenario of neutrino decoupling and test it against other non-standard possibilities, including the existence of non-standard neutrino interactions with electrons or the non-unitarity of the three-neutrino mixing matrix.

Acknowledgements

This work has been supported by the Spanish fellowship FPU18/04571(MICIU) and the Spanish grants PID2020-113775GB-I00 (AEI/10.13039/501100011033) and CIPROM/2021/054 (Generalitat Valenciana). The work of P.M.M. is supported by the Danmarks Frie Forskningsfonds (Project No. 8049-00038B).

References

[1] P. Ade *et al.* [Simons Observatory], JCAP **02** (2019), 056 doi:10.1088/1475-7516/2019/02/056 [arXiv:1808.07445 [astro-ph.CO]].

[2] K. N. Abazajian *et al.* [CMB-S4], [arXiv:1610.02743 [astro-ph.CO]].

[3] S. Gariazzo, P. Martínez-Miravé, O. Mena, S. Pastor and M. Tórtola, JCAP **03** (2023), 046 doi:10.1088/1475-7516/2023/03/046 [arXiv:2211.10522 [hep-ph]].

[4] P. F. de Salas, S. Gariazzo, P. Martínez-Miravé, S. Pastor and M. Tórtola, Phys. Lett. B **820** (2021), 136508 doi:10.1016/j.physletb.2021.136508 [arXiv:2105.08168 [hep-ph]].

[5] J. J. Bennett, G. Buldgen, P. F. De Salas, M. Drewes, S. Gariazzo, S. Pastor and Y. Y. Y. Wong, JCAP **04** (2021), 073 doi:10.1088/1475-7516/2021/04/073 [arXiv:2012.02726 [hep-ph]].

[6] J. Froustey, C. Pitrou and M. C. Volpe, JCAP **12** (2020), 015 doi:10.1088/1475-7516/2020/12/015 [arXiv:2008.01074 [hep-ph]].

[7] K. Akita and M. Yamaguchi, JCAP **08** (2020), 012 doi:10.1088/1475-7516/2020/08/012 [arXiv:2005.07047 [hep-ph]].

[8] P. F. de Salas, D. V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. A. Ternes, M. Tórtola and J. W. F. Valle, JHEP **02** (2021), 071 doi:10.1007/JHEP02(2021)071 [arXiv:2006.11237 [hep-ph]].

[9] M. Cielo, M. Escudero, G. Mangano and O. Pisanti, [arXiv:2306.05460 [hep-ph]].