PROCEEDINGS OF SCIENCE

Cosmological radiation density and neutrino NSI with electrons

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Non-standard interactions (NSI) between neutrinos and electrons modify the decoupling of neutrinos from the cosmic plasma. These interactions have two effects on the overall picture: (i) they alter neutrino oscillations though matter effects and (ii) they modify the scattering and annihilation processes involving neutrinos and electrons and positrons. We address the role of different NSI in the decoupling process and study how they impact the determination of the effective number of neutrinos, $N_{\rm eff}$. We examine the existing degeneracies between NSI parameters and we compare the expected sensitivity from future cosmological surveys with the current limits from terrestrial experiments. We also comment on the apparent phenomenological similarities between NSI and some scenarios where Lorentz invariance is not preserved, and we discuss the robustness of the NSI limits derived from cosmological observations.

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1. Introduction to neutrino decoupling

In the early Universe, neutral current and charged current weak interaction mantained neutrinos in thermal equilibrium with the rest of the cosmic plasma. However, as the Universe expanded, the rate of the interactions between neutrinos and the plasma decreased faster than the Hubble rate, and at temperatures around 1 MeV, these interactions stopped being efficient. As a result, neutrinos were no longer in equilibrium with electrons and photons and their evolution decoupled from the rest of the cosmic plasma. Once the temperature dropped below the mass of the electron, only electron-positron annihilations into photons were favoured, leading to a increase in the temperature of photons.

This complicated process has been studied in detail in the literature, taking into account the distributions of the different species and including neutrino interactions, as described in the Standard Model. In addition, finite temperature corrections to Quantum Electrodynamics (QED) and the effect of neutrino oscillations have also been incorporated in the calculations.

The radiation density of the Universe after electron-positron annihilation is given by

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

where $\rho_\gamma$and ρ_ν denote the energy density of photons and neutrinos respectively. The parameter $N_{\rm eff}$ has been introduced in order to quantify the ratio between the energy density in the form of photons and other relativistic species. This parameter, $N_{\rm eff}$, is the so-called *effective number of neutrinos*. Recent calculations yield a value of $N_{\rm eff} = 3.0440 \pm 0.0002$ [1, 2]. These are in good agreement with the experimental results $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ at 95% C.L. [3], derived from the combination of the measurements of the anisotropies in the cosmic microwave background with other cosmological datasets.

Any deviations from the theoretical value could be pointing towards the existence of additional relativistic degrees of freedom or new physics in the neutrino sector, beyond flavour oscillations. Given the projected sensitivities of future CMB observatories, CMB-S4 and Simons Observatory, to $N_{\rm eff}$, $\sigma(N_{\rm eff}) = 0.02 - 0.03$ [4] and $\sigma(N_{\rm eff}) = 0.05 - 0.07$ [5] respectively, beyond the Standard Model scenarios altering the neutrino sector can be studied. We revisit the impact of neutrino non-standard interactions with electrons in the process of neutrino decoupling and outline the synergies and differences between non-standard interactions and some forms of Lorentz invariance violation in the neutrino sector.

2. Neutrino non-standard interactions with electrons

Neutrino non-standard interactions (NSI) are a common prediction of many mass models. They are generally studied in the framework of Effective Field Theories and parametrised in terms of four fermion operators. In this work, we focus on the case of neutral current NSI with electrons and positrons only. Hence, the effective Lagrangian which parametrises the interactions between electrons and neutrinos is

$$\mathcal{L} = -2\sqrt{2}G_F \left[\left(\bar{\nu}_e \gamma_\mu P_L e\right)\left(\bar{e}\gamma_\mu P_L \nu_e\right) + \sum_{\alpha,X} g_X \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\alpha\right)\left(\bar{e}\gamma_\mu P_X e\right) \right.$$
$$\left. + \sum_{\alpha,\beta X} \varepsilon^X_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\alpha\right)\left(\bar{e}\gamma_\mu P_X e\right) \right] , \quad (2)$$

where the first two terms correspond to the charged current and neutral current electron-neutrino interactions in the Standard Model respectively, and the third term accounts for NC-NSI. The Greek subindices α and β indicate the neutrino flavour, G_F is the Fermi constant and $X = \{L, R\}$, so that P_X are the two chiral projectors. Standard Model neutral current interactions depend on the coefficients $g_L = \sin^2\theta_W - 1/2$ and $g_R = \sin^2\theta_W$, whereas for the strength of the NC-NSI are parametrised in terms of the dimensionless coefficients $\varepsilon^X_{\alpha\beta}$.

Non-standard interactions are generally separated in two categories according to the physics they relate to. When $\varepsilon_{\alpha\alpha} - \varepsilon_{\beta\beta} \neq 0$ for $\alpha \neq \beta$, flavour universality of the interactions is no longer present and consequently, $\varepsilon_{\alpha\alpha}$ are often referred to as non-universal NSI coefficients. Alternatively, when $\varepsilon^X_{\alpha\beta}$ for $\alpha \neq \beta$, lepton flavour symmetry is broken. Hence, these coefficients account for the so-called flavour-changing NSI.

Non-standard interactions modify the cross-section of the processes involving neutrinos as well as neutrino propagation from the source to the detector. As a result, their presence could manifest in scattering experiments and also they could alter neutrino oscillations through matter effects. Terrestrial experiments are sensitive to this scenario and set limits on the strength of NSI with electrons and quarks. For a review on the existing limits, see [6].

3. Non-standard interactions and N$_{\text{eff}}$

Neutrino non-standard interactions with electrons can also change the picture of neutrino decoupling due to two different effects. Firstly, the alter the cross section of the scattering and annihilation processes involving neutrinos, electrons and positrons. This fact is encoded in the collisional terms that appear in Boltzmann kinetic equations. The standard cross section of these processes are proportional to the coefficients g_L^2, g_R^2 or $g_L g_R$. However, when one considers additional non-standard interactions, the following shifts are introduced in the coefficients:

$$g_L^2 \longrightarrow \left(g_L + \varepsilon^L_{\alpha\alpha}\right)^2 + \sum_{\beta\neq\alpha} |\varepsilon^L_{\alpha\beta}|^2 , \quad (3)$$

$$g_R^2 \longrightarrow \left(g_R + \varepsilon^R_{\alpha\alpha}\right)^2 + \sum_{\beta\neq\alpha} |\varepsilon^R_{\alpha\beta}|^2 , \quad (4)$$

$$g_L g_R \longrightarrow \left(g_L + \varepsilon^L_{\alpha\alpha}\right)\left(g_R + \varepsilon^R_{\alpha\alpha}\right) + \sum_{\beta\neq\alpha} |\varepsilon^L_{\alpha\beta}||\varepsilon^R_{\alpha\beta}| . \quad (5)$$

Secondly, NSI modify neutrino propagation and give rise to a generalised matter potential in the Hamiltonian. This term is the same that appears when studying the effect of NSI in propagation at oscillation experiments.

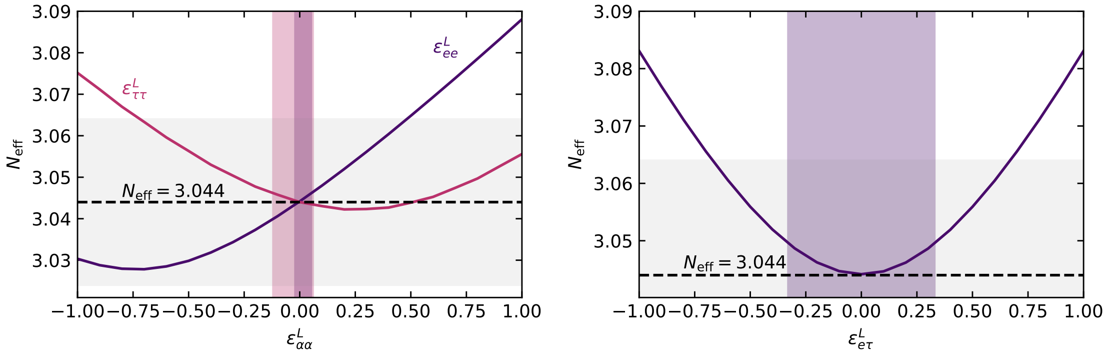

Figure 1: Values of $N_{\rm eff}$ in the presence of non-standard interactions. The left panel corresponds to non-universal NSI, with the effect of a non-zero ε^L_{ee} in purple and that of a non-zero $\varepsilon^L_{\tau\tau}$ in pink. The right panel corresponds to flavour changing NSI, in particular, a non-zero $\varepsilon^L_{e\tau}$. The value of $N_{\rm eff} = 3.044$ expected in the absence of NSI is indicated by the black dashed line. The horizontal grey-shaded region corresponds to ± 0.02 which is the expected sensitivity from future cosmological observations. The vertical coloured bands are the current terrestrial limits at 90% C.L. Both panels are adapted from Figures in [9] and reproduced with the authorisation of the original authors.

We compute the evolution of the neutrino density matrix ϱ according to

$$\frac{d}{dx}\varrho(y) = \sqrt{\frac{3M_{\rm Pl}^2}{8\pi\rho}}\left\{\frac{-ix^3}{m_e^3}\left[\frac{\mathbb{M}_F}{2y} - \frac{2\sqrt{2}G_F y m_e^2}{x^6}\left(\frac{\mathbb{E}_l + \mathbb{P}_l}{m_W^2} + \frac{4\mathbb{E}_\nu}{3m_Z^2}\right), \varrho\right] + \frac{m_e^3}{x^4}\mathcal{I}(\varrho)\right\} \tag{6}$$

where we have introduced the comoving variables $x = m_e a$, $y = pa$ and $z = T_\gamma a$, which depend on the electron mass m_e, the neutrino momentum p, the photon temperature T_γ, and the scale factor a. In equation 6, ρ denotes the total energy density of the universe, $M_{\rm Pl}$ is the Planck mass, m_Z and m_W are the masses of the Z and W bosons respectively and . In addition, $\mathbb{M}_F$ is the neutrino mass matrix in the flavour basis, $\mathbb{E}_l$, $\mathbb{P}_l$ and $\mathbb{E}_\nu$ are the energy density and pressure of charged leptons and neutrinos. Finally, $\mathcal{I}(\varrho)$ accounts for the collision integrals. For more details, see [9]

To perform the calculation, we use the publicly available code `ForEPiaNO` [1] [7]. For a more detailed discussion of the formalism and the procedure employed to compute the evolution of the density matrix, we refer the reader to Refs. [2, 7]. In our calculations we take the values of the oscillation parameters from [8] and the same numerical settings as in [9].

We start by studying the impact of one non-zero NSI parameter at a time. From the left panel of Figure 1, one can see that non-universal NSI either increase or decrease the value of $N_{\rm eff}$ with respect to the prediction of the Standard Model. The situation of smaller $N_{\rm eff}$ corresponds to the case in which NSI cancel out the contribution of the weak interactions, leading to an earlier decoupling of neutrinos. One can see that this corresponds to the case of $\varepsilon^L_{ee} = -(1 + g_L) \sim -0.72$ and $\varepsilon^L_{\tau\tau} = -g_L \sim 0.28$. One can see that non-universal NSI can also enhance the interactions between neutrinos and electrons, delaying neutrino decoupling and resulting in a higher value of $N_{\rm eff}$. On the other hand, the impact of flavour-changing NSI is illustrated in the right panel of Figure 1. One can see that for all non-zero values of the NSI parameter $\varepsilon^L_{e\tau}$, one would expect a

[1] https://bitbucket.org/ahep_cosmo/fortepiano_public

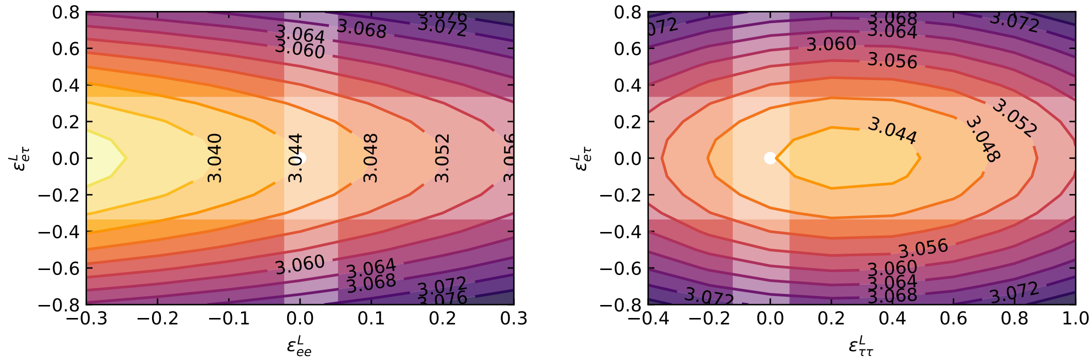

Figure 2: Isocontours of N_{eff} when two NSI parameters are allowed to vary simultaneously. The left panel shows the interplay between ε^L_{ee} and $\varepsilon^L_{e\tau}$, and the right panel shows the combined effect of $\varepsilon^L_{\tau\tau}$ and $\varepsilon^L_{e\tau}$. The white point corresponds to the standard case, where NSI are absent and $N_{\text{eff}} = 3.044$ in the absence of NSI. The white shaded bands are the 95% C.L. limits derived in terrestrial experiments varying one parameter at a time. Both panels are adapted from Figures in [9] and reproduced with the authorisation of the original authors.

higher value of N_{eff}. This is a consequence of lepton flavour conservation in the SM. Since these NSI introduce additional flavour-changing interactions, the interaction rate between electrons and neutrinos increases and neutrinos decouple later than in the standard picture.

One can see that the behaviour found is completely consistent with the expected shifts in the coefficients presented in (3), (4) and (5). This shows the idea that the main contribution of NSI to the neutrino decoupling comes from the annihilation and scattering processes between neutrinos and electrons.

It is interesting to explore the interplay between two non-zero NSI parameters. The results from some of the numerical calculations are shown in Figure 2 in the form of isocontours of N_{eff}. The elliptical shapes found can be well understood in the light of the shifts that NSI introduce in the coefficients g_L^2, g_R^2 and $g_L g_R$. These results also illustatrate the feasibility of an analysis where more than one NSI parameter is allowed to be non-zero. This is not always the case in terrestrial experiments since not all combinations of NSI parameters are accessible.

Notice that although the expected constraints from future cosmological observations are not really competitive with those from terrestrial probes of NSI, they would provide an independent confirmation of the existing limits.

4. Non-standard interactions vs Lorentz invariance violation

The Standard Model Extension (SME) [10–12] is an extension of the Standard Model Lagrangian that allows for Lorentz and CPT violation while preserving the $SU(2) \times U(1) \times SU(3)$ symmetries of the Standard Model. Among the many new operators that are included in the SME, one can find the following CPT-odd renormalisable terms [13, 14],

$$\mathcal{L}_{\text{LIV}} = -\frac{1}{2}\left(a^{\mu}_{\alpha\beta}\bar{\psi}_{\alpha}\gamma_{\mu}\psi_{\beta} + b^{\mu}_{\alpha\beta}\bar{\psi}_{\alpha}\gamma_{\mu}\gamma_5\psi_{\beta}\right), \tag{7}$$

where ψ_α is a Dirac fermion of flavour α. In the context of neutrinos, these terms are of interest since they can alter neutrino propagation. In particular, the observable effect in left-handed neutrinos is controlled by the combination

$$(a_L)^{\mu}_{\alpha\beta} = (a^{\mu} + b^{\mu})_{\alpha\beta} \ . \tag{8}$$

The coefficients corresponding to $\mu = 1, 2, 3$ break rotational invariance. Consequently, they are generally neglected and studies commonly focus on the isotropic ($\mu = 0$) LIV term. As a result, one finds that, for non-zero $a^0_{\alpha\beta}$ (which we will denote $a_{\alpha\beta}$ for simplicity), neutrino propagation would be modified and the effect can be captured in the following effective Hamiltonian,

$$H_{LIV} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix} , \tag{9}$$

which is formally equally to the effective Hamiltonian induced by NSI [15], after identifying

$$a_{\alpha\beta} \longleftrightarrow \sqrt{2} G_F (\epsilon^L_{\alpha\beta} - \varepsilon^R_{\alpha\beta}) N_e(x) \tag{10}$$

where $N_e(x)$ is the electron number density in the medium. In spite of the similarity in the form, they correspond to two very different physical pictures and it is important to clarify the conceptual difference. NSI are exotic form of matter effects altering neutrino propagation (as well as cross sections) and in order to manifest, neutrino propagation has to occur in a medium. Conversely, isotropic CPT-odd Lorentz invariance violation alter neutrino propagation in vacuum too and do not depend on the properties of the medium.

Having this in mind, it is possible to translate the existing bounds on NSI into limits on these LIV coefficients as long as one takes into account the underlying assumptions in the number density of electrons that were made when deriving the bounds. Also, these argument only applies to constraints on NSI parameters derived by studying the effect in propagation but not in scattering experiments. Finally, it is important to point out that the limits on NSI derived from cosmology, since they come mainly from the change in the interaction rate between neutrinos and electrons, are basically independent of possible signatures of Lorentz invariance violation. Hence, cosmology provides a complementary tool to disentangle NSI and LIV effects, which may not be possible with oscillation data only.

5. Discussion

In these proceedings, we have presented a state-of-the -art calculation of the impact of neutrino NSI with electrons in the process of neutrino decoupling. We have shown the effect that non-standard and flavour-changing NSI would have in the overall picture and justified it according to the change they would induce in the interaction rates between neutrinos and electrons/positrons. We have illustrated this point with accurate calculations of the cosmological parameter N_{eff}.

We have commented on the projected sensitivity to this scenario from forthcoming cosmological observatories and outline the complementarity between these limits and the existing terrestrial probes.

Finally, the similarities and differences between non-standard interactions and some forms of Lorentz invariance violation have been outlined, emphasising the conceptual difference and clarify how cosmological probes of NSI would not be affected by these forms of LIV, hence providing robust limits.

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