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Cosmological radiation density with non-standard neutrino physics

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Many extended models of particle physics that explain non-zero neutrino masses also include non-standard interactions (NSI) of these elusive particles with other fermions. The NSIs that modify the collisions between neutrinos and electrons have an impact on the process of neutrino decoupling in the early universe, leading to a different contribution to the radiation energy density, parameterised by the effective number of neutrinos, $N_{\rm eff}$. We have performed an analysis of the influence of non-universal and flavour-changing NSI on $N_{\rm eff}$, both for one-parameter and multi-parameter choices. In comparison with current constraints from terrestrial experiments, cosmology is less sensitive to NSI parameters, but future cosmological observations could provide competitive and complementary bounds for some combinations of NSI couplings.

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The experimental evidence for non-zero neutrino masses and mixing calls for new physics beyond the Standard Model (SM) of fundamental particles and forces. Many extended theoretical models predict the existence of non-standard interactions (NSI) of neutrinos, that could leave their imprint in a variety of experiments. Combining all available data, there is no evidence for the presence of NSI and the corresponding bounds can be derived (see e.g. the review [1]). Non-zero NSI could also affect astrophysical and cosmological scenarios and we have recently considered their implications on the decoupling process of neutrinos in the early universe [2]. Earlier cosmological analyses of the effect of NSI include [3, 4], but only for particular choices of the NSI parameters.

1. Neutrino non-standard interactions with electrons

In order to study the decoupling of relic neutrinos, only neutral-current neutrino non-standard interactions (NC-NSI) with electrons will be considered. The effective Lagrangian including NSI and SM interaction reads $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{NSIe}$, where we have defined

$$\mathcal{L}_{SM} = -2\sqrt{2}\,G_F \left[(\overline{\nu}_e \gamma^\mu P_L e)\,(\overline{e}\gamma_\mu P_L \nu_e) + \sum_{X,\alpha} g_X\,(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\alpha)\,(\overline{e}\gamma_\mu P_X e) \right], \tag{1a}$$

$$\mathcal{L}_{NSIe} = -2\sqrt{2}\,G_F \sum_{\alpha,\beta} \varepsilon^X_{\alpha\beta}\,(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\,(\overline{e}\gamma_\mu P_X e)\,. \tag{1b}$$

Here G_F is the Fermi constant and the index $X = \{L, R\}$, so that P_X denotes the chiral projectors $P_{R,L} = (1 \pm \gamma_5)/2$. The strength of the (neutral current) weak interactions is set by the couplings $g_L = \sin^2\theta_W - 1/2$ and $g_R = \sin^2\theta_W$, with θ_W being the weak mixing angle. Greek indices refer to the different flavours: $\alpha, \beta = e, \mu, \tau$. In $\mathcal{L}_{NSIe}$, the dimensionless coefficients $\varepsilon^X_{\alpha\beta}$ parametrise the strength of the interaction between flavours α and β. Non-standard interactions can be further classified from the point of view of the symmetries of the SM. For non-zero values of $\varepsilon^X_{\alpha\beta}$, with $\alpha \neq \beta$, lepton flavour symmetry is no longer conserved and, consequently, they are often referred as *flavour-changing NSI*. In the case of $\alpha = \beta$, if the difference $\varepsilon^X_{\alpha\alpha} - \varepsilon^X_{\beta\beta} \neq 0$, lepton flavour universality does not hold anymore and such interactions are called *non-universal NSI*.

The current bounds on neutrino non-standard interactions with electrons, derived considering only one non-zero parameter at a time, are summarised in Table 1 for non-universal and flavour-changing NSI. They rely on the detailed analysis of neutrino oscillation experiments and on cross-section measurements performed in scattering experiments, but they are also complemented by the study of several observables at LEP (see ref. [2] for details).

2. Impact of non-standard interactions on the effective number of neutrinos

It is well known that weak interactions keeping neutrinos in equilibrium with the primeval plasma become ineffective at a temperature of $\mathcal{O}$(MeV), when they decouple and constitute the cosmological neutrino background. This process is nowadays well understood, and the percent deviations of the neutrino energy distributions from a thermal spectrum have been very precisely calculated [5–7], including all relevant effects: neutrino collisions with SM interactions, finite-temperature corrections to quantum electrodynamics (QED) and flavour neutrino oscillations. The

Parameter and 90% C.L range	Origin
-0.021 < ε^L_{ee} < 0.052	Neutrino oscillations
-0.07 < ε^R_{ee} < 0.08	Neutrino scattering
-0.03 < $\varepsilon^L_{\mu\mu}, \varepsilon^R_{\mu\mu}$ < 0.03	Neutrino scattering and accelerator data
-0.12 < $\varepsilon^L_{\tau\tau}$ < 0.06	Neutrino oscillations
-0.98 < $\varepsilon^R_{\tau\tau}$ < 0.23 -0.25 < $\varepsilon^R_{\tau\tau}$ < 0.43	Neutrino oscillations Neutrino scattering and accelerator data
-0.13 < $\varepsilon^L_{e\mu}, \varepsilon^R_{e\mu}$ < 0.13	Neutrino scattering and accelerator data
-0.33 < $\varepsilon^L_{e\tau}$ < 0.33	Neutrino scattering and accelerator data
-0.28 < $\varepsilon^R_{e\tau}$ < -0.05 & 0.05 < $\varepsilon^R_{e\tau}$ < 0.28 -0.19 < $\varepsilon^R_{e\tau}$ < 0.19	Neutrino scattering and accelerator data Neutrino scattering
-0.10 < $\varepsilon^L_{\mu\tau}, \varepsilon^R_{\mu\tau}$ < 0.10	Neutrino scattering and accelerator data

Table 1: Current bounds on NSI parameters for 1 degree of freedom (90% C.L.). See Ref. [2] for details.

corresponding value of the effective number of neutrinos is found to be $N_{\rm eff} = 3.044$, where $N_{\rm eff}$ is a parameter related to the cosmological density of radiation ($\rho_{\rm rad}$) that quantifies the ratio of energy densities of neutrino-like relics to photons (ρ_γ),

$$\rho_{\rm rad} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right) . \tag{2}$$

Measurements of the cosmological microwave background (CMB) anisotropies by Planck, combined with other cosmological data, constrain $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ at 95% C.L. [8]. Such value severely restricts the possible existence of additional relativistic particles.

Non-standard interactions with electrons, the only charged leptons that are still abundant at MeV cosmological temperatures, would modify the thermal contact of neutrinos with the QED plasma and change their momentum spectra, leading to values of $N_{\rm eff}$ different from the standard one. The effect of NSI enters the calculation of the neutrino thermalisation in the early universe in two different ways: (i) through the matter effects that alter neutrino oscillations in the dense electromagnetic plasma, and (ii) through the collision integrals that encode the scattering and annihilation between neutrinos and electrons. In [7], it was shown that neutrino oscillations change $N_{\rm eff}$ in less than 0.001, much below the expected experimental sensitivity of the incoming generation of cosmological observations. Consequently, we expect the impact of NSI through matter effects to be much smaller than the modification they cause on the interactions of neutrinos with electrons.

In our calculation, we used the density matrix formalism, where the diagonal elements of the neutrino density matrix are the momentum distribution functions of the different neutrino flavours, and the off-diagonal elements implement the coherence of the system. This is the proper way to solve the evolution of neutrinos including oscillations with time-dependent vacuum and matter terms, as well as interactions in the primeval plasma. All the expressions for the kinetic equations and collision integrals, modified in order to include the presence of NSI, are listed in ref. [2].

All the results we discuss in the following are obtained using the Fortran code `FortEPiaNO` (Fortran-Evolved Primordial Neutrino Oscillations[1]) [7, 9]. We adopt numerical settings that allow an estimated precision at the level of $\lesssim 5 \times 10^{-4}$ on the final $N_{\rm eff}$, enough to study the effect of NSI.

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

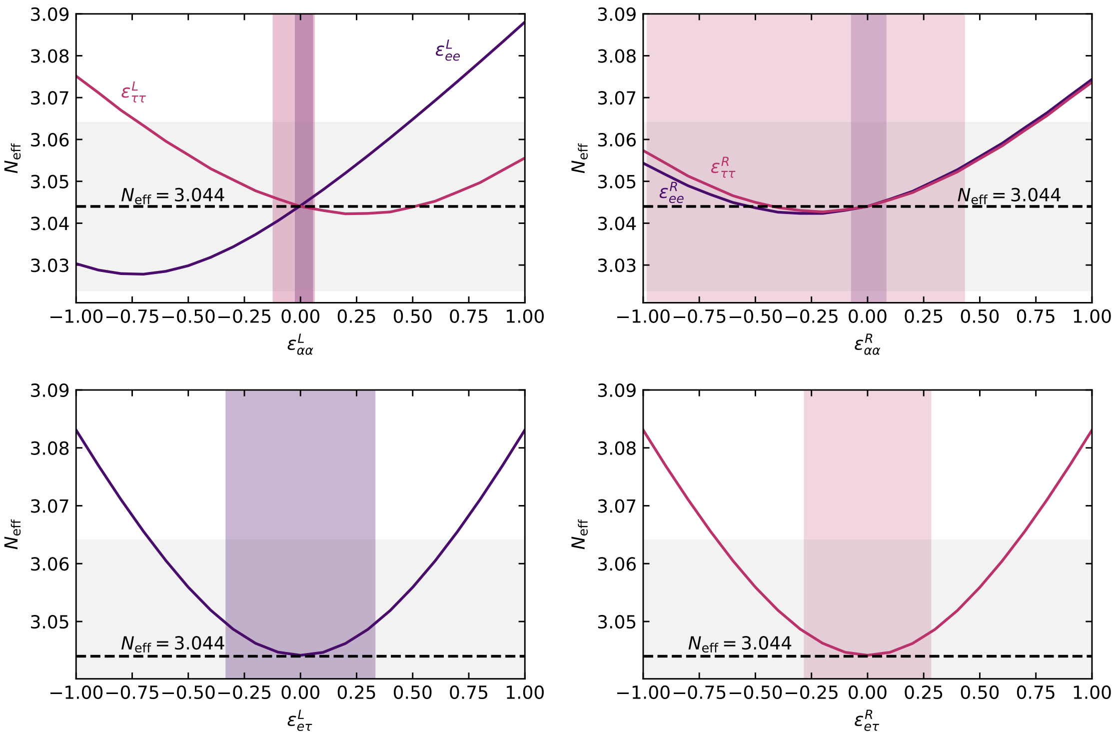

Figure 1: Values of $N_{\rm eff}$ for non-zero NSI parameters: diagonal $\varepsilon^{L,R}_{\alpha\alpha}$, for $\alpha = \{e, \tau\}$ (upper panels), and flavour-changing $\varepsilon^L_{e\tau}$ and $\varepsilon^R_{e\tau}$ (bottom panels). The shaded vertical regions are 90% C.L. bounds from Table 1. The standard value of $N_{\rm eff}$ is indicated by a dashed line, together with a shaded region corresponding to ± 0.02 (1σ sensitivity from future cosmological observations).

Concerning non-universal NSI, we present in Figure 1 the values of $N_{\rm eff}$ predicted in the presence of non-zero $\varepsilon^L_{\alpha\alpha}$ or $\varepsilon^R_{\alpha\alpha}$, with $\alpha = e, \tau$. In the upper left panel, one can see that for negative values of ε^L_{ee} the value of $N_{\rm eff}$ decreases with respect to the SM prediction, since the strength of the coupling is reduced. The minimum, expected for $\varepsilon^L_{ee} = -\tilde{g}_L = -\frac{1}{2} - \sin^2\theta_W$, is visible on the left of the plot. For the $\varepsilon^L_{\tau\tau}$ parameter, the minimum is located at $\varepsilon^L_{\tau\tau} = -g_L = \frac{1}{2} - \sin^2\theta_W$, and it varies more slowly across the displayed range. The trend observed in the case of the R couplings is different: for both ε^R_{ee} and $\varepsilon^R_{\tau\tau}$, the minimum value of $N_{\rm eff}$ is clearly more similar for the two parameters, and it is close to $\varepsilon^R_{\alpha\alpha} = -g_R = -\sin^2\theta_W$. The small difference between the effect of the two parameters ε^R_{ee} and $\varepsilon^R_{\tau\tau}$ at large negative values arises from the mixed terms, proportional to $g_L g_R$ in the SM, since the left coupling of neutrinos to electrons or taus is different. As a conclusion, we find that minima are found where they were expected from the argument of the shift in the coupling. Thus, the exact value of the oscillation parameters is not playing a major role.

From the figure, one can see that only large negative values of ε^L_{ee} would lead to an effective number of neutrinos considerably smaller than 3.044. In spite of being experimentally constrained, this is one of the few scenarios that can lead to a value of $N_{\rm eff}$ smaller than the SM prediction.

It is also interesting to see the interplay between the NSI parameters once two of them are allowed to vary simultaneously, as shown in Figure 2. The iso-$N_{\rm eff}$ contours presented in the plots are ellipses, as one can predict from the shift in the couplings entering the collisions. Again, this

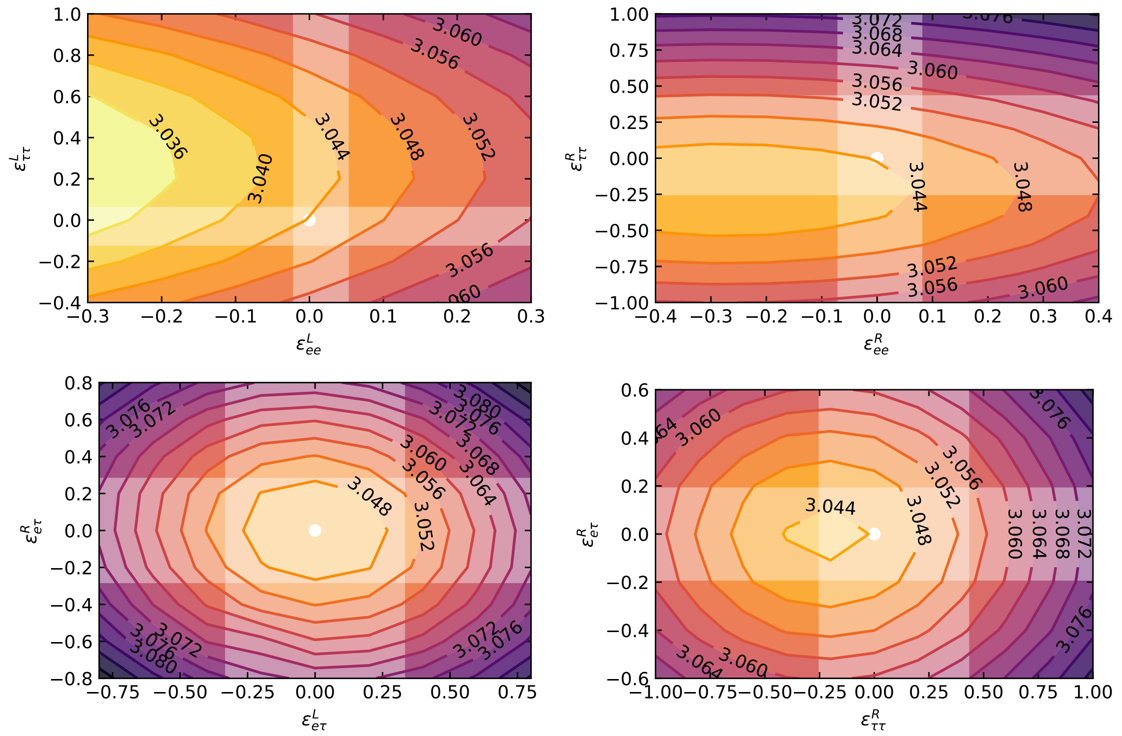

Figure 2: Values of $N_{\rm eff}$ when two NSI parameters are varied simultaneously: ε^L_{ee}- $\varepsilon^L_{\tau\tau}$ (upper left), ε^R_{ee}- $\varepsilon^R_{\tau\tau}$ (upper right), $\varepsilon^L_{e\tau}$- $\varepsilon^R_{e\tau}$ (bottom left) and $\varepsilon^R_{\tau\tau}$- $\varepsilon^R_{e\tau}$ (bottom right). White-shaded regions correspond to the 90% C.L. experimental bounds obtained varying one parameter at a time, extracted from [1].

confirms the fact that the impact of NSI on collisions dominates over its effect on oscillations. To illustrate it, one can consider that, along the line for which $\varepsilon^L_{\alpha\alpha} = -\varepsilon^R_{\alpha\alpha}$, the vectorial component of the NSI cancels out, leaving oscillations unchanged. The change in the value of $N_{\rm eff}$, therefore, arises exclusively from the shift in the value of the axial coupling entering the collision term.

From Figures 1 and 2 we can also see that next-generation cosmological observations, which are expected to determine $N_{\rm eff}$ with an error that could be as small as ± 0.02 [10], will be able to constrain non-universal NSI to the same order of magnitude of current laboratory experiments, in particular for the $\varepsilon^R_{\tau\tau}$ parameter. Remember, however, that constraints from cosmology are indirect and, therefore, much more model-dependent than laboratory results.

NSI leading to flavour-changing processes can lead to higher values of $N_{\rm eff}$, because they increase the strength of the interactions involving neutrinos and electrons. Also, the effect on the collisions is independent of the sign of $\varepsilon^X_{\alpha\beta}$ and, hence, one expects the contours to be symmetric with respect to $\varepsilon^X_{\alpha\beta} = 0$ (see the bottom panels of Figure 1). Notice that future CMB constraints would be able to constrain the flavour-changing NSI parameters to a similar level than terrestrial experiments, particularly for the R component. We repeated the same exercise also considering the $\varepsilon^L_{e\mu}$, $\varepsilon^L_{\mu\tau}$ and $\varepsilon^R_{e\mu}$, $\varepsilon^R_{\mu\tau}$ parameters. The results are not shown in the figure because the dependence of $N_{\rm eff}$ on these NSI couplings is practically indistinguishable from the effect of the corresponding $\varepsilon^L_{e\tau}$ or $\varepsilon^R_{e\tau}$ parameters. This is expected, since the effect of the flavour-changing NSI parameters is significantly different from one another only if the neutrino density matrix differs from the identity matrix multiplied by the neutrino momentum distribution. Given the fact that the three neutrino flavours have almost the same momentum distribution function, apart from small corrections, and that the off-diagonal components of the neutrino density matrix are always very small, all the flavour-changing NSI parameters are expected to affect $N_{\rm eff}$ in the same way.

The interplay between two flavour-changing NSI components or between non-universal and flavour-changing NSI terms can give rise to degeneracies, as shown in Figure 2. Actually, considering several non-zero NSI parameters can lead to a value of $N_{\rm eff}$ significantly larger than 3.044. For instance, for $\varepsilon^L_{\tau\tau} = -0.60$, $\varepsilon^R_{\tau\tau} = -0.36$, $\varepsilon^L_{e\tau} = 0.132$, $\varepsilon^R_{e\tau} = -0.80$, $\varepsilon^L_{\mu\tau} = \varepsilon^R_{\mu\tau} = 0.52$, one obtains $N_{\rm eff} = 3.10$. Such a large deviation from the prediction in the absence of NSI could be tested by future determinations of $N_{\rm eff}$ with a significance around 2–3σ. The values of the parameters needed to reach such a significant deviation from $N_{\rm eff} = 3.044$ are excluded by terrestrial experiments with a very high confidence level, although constraints are commonly derived varying one parameter at a time, therefore not taking into account the degeneracies between the various parameters.

In conclusion, taking into account the forecasted sensitivity on $N_{\rm eff}$ from forthcoming CMB observations, future cosmological bounds on NSI parameters are not expected to be, in general, competitive with present constraints from terrestrial experiments. However, a sensitivity of $\sigma(N_{\rm eff}) = 0.02 - 0.03$ [10] could constrain non-universal NSI (e.g. $\varepsilon^R_{\tau\tau}$) to the same level as current laboratory experiments, or could bound some particular combinations of two (or more) NSI parameters leading to $N_{\rm eff} \simeq 3.08$ or larger. In any case, cosmological observations provide an independent and complementary test on the existence of non-standard interactions of neutrinos with electrons.

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References

[1] Y. Farzan and M. Tórtola, Front. in Phys. **6** (2018) 10 [arXiv:1710.09360].

[2] P.F. de Salas *et al.*, Phys. Lett. B **820** (2021) 136508 [arXiv:2105.08168].

[3] G. Mangano *et al.*, Nucl. Phys. B **756** (2006) 100-116 [arXiv:hep-ph/0607267].

[4] P.F. de Salas and S. Pastor, JCAP **07** (2016) 051 [arXiv:1606.06986].

[5] K. Akita and M. Yamaguchi, JCAP **08** (2020) 012 [arXiv:2005.07047].

[6] J. Froustey, C. Pitrou and M. C. Volpe, JCAP **12** (2020) 015 [arXiv:2008.01074].

[7] J.J. Bennett *et al.*, JCAP **04** (2021) 073 [arXiv:2012.02726].

[8] Planck Collaboration, Astron. Astrophys. **641** (2020) A6 [arXiv:1807.06209].

[9] S. Gariazzo, P.F. de Salas and S. Pastor, JCAP **07** (2019) 014 [arXiv:1905.11290].

[10] K.N. Abazajian *et al.* [CMB-S4 Collaboration], arXiv:1610.02743.