NEUTRINO DECOUPLING IN STANDARD AND NON-STANDARD SCENARIOS

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Based on [1][2][3][4][in preparation]

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Neutrino decoupling

Neutrinos are present in the early Universe. They interact with the thermal plasma thanks to interactions with electron/positron pairs.
At the time weak interactions become inefficient and they are unable to maintain neutrinos in equilibrium with the thermal plasma, when the photons had a **temperature** of approximately **2 MeV**, the neutrino fluid decouples. From such moment, neutrinos free-stream in the universe until today.
Shortly after neutrino decoupling, electrons and positrons start to become non-relativistic, and transfer they entropy to the photon fluid. Since neutrino decoupling does not occur instantaneously, however, neutrinos with high energy receive a fraction of this entropy. As a consequence, the neutrino distribution function slightly deviates from the equilibrium Fermi-Dirac, and the comoving energy density of neutrinos increases a little bit. Since electron neutrinos have stronger interactions with the thermal plasma, moreover, they are heated more than the muon and tau neutrinos, so that the distortion to the momentum distribution function is not the same for the various neutrino flavors, although oscillations partly equilibrate the differences.
The increase in the neutrino energy density, which can be computed numerically, depends on several factors: the strength of the interaction with electrons and other neutrinos, how fast neutrino oscillations redistribute the energy amongst the different neutrino flavors, what is the expansion rate of the universe at neutrino decoupling.

Effective number of relativistic species ($N_{\rm eff}$)

The expansion rate at neutrino decoupling depends on the amount of relativistic particles, which are commonly expressed in terms of the effective number of relativistic species, $N_{\rm eff}$, defined as

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

where ρ_γ is the photon energy density while ρ_i represents the energy density of the relativistic species different from photons, including neutrinos.
$N_{\rm eff}$ measures the number of neutrino-like species that were present in the early universe. If only standard neutrinos exist, and their decoupling is instantaneous, $N_{\rm eff}$ is by definition equal to three.
In case the energy density of neutrinos is altered (either by non-instantaneous decoupling or non-standard properties), $N_{\rm eff}$ can differ from three even if only three neutrino families exist.
Most importantly, if there are additional relativistic particles, usually grouped under the name **dark radiation** for the lack of electromagnetic interaction, $N_{\rm eff}$ can be much larger than three.

Note:
an additional contribution to $N_{\rm eff}$ can arise from new species (e.g. sterile neutrinos, thermal axions) or different phenomena (e.g. evaporation of primordial black holes).

The amount of radiation affects the expansion rate of the universe, which in turn alters the Big Bang Nucleosynthesis (BBN) abundances and the Cosmic Microwave Background (CMB) spectrum.

$N_{\rm eff}$ measurements

Note: independent but similar results emerge from current BBN observations.

The Planck observations of the CMB spectrum can be exploited to put constraints on $N_{\rm eff}$ [5], see figure 1.
The **strongest CMB bound** is $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ at 95% CL, confirming the presence of approximately three neutrino-like species. **Future experiments** are expected to reach a sensitivity on $N_{\rm eff}$ at the level of **0.02** [6].

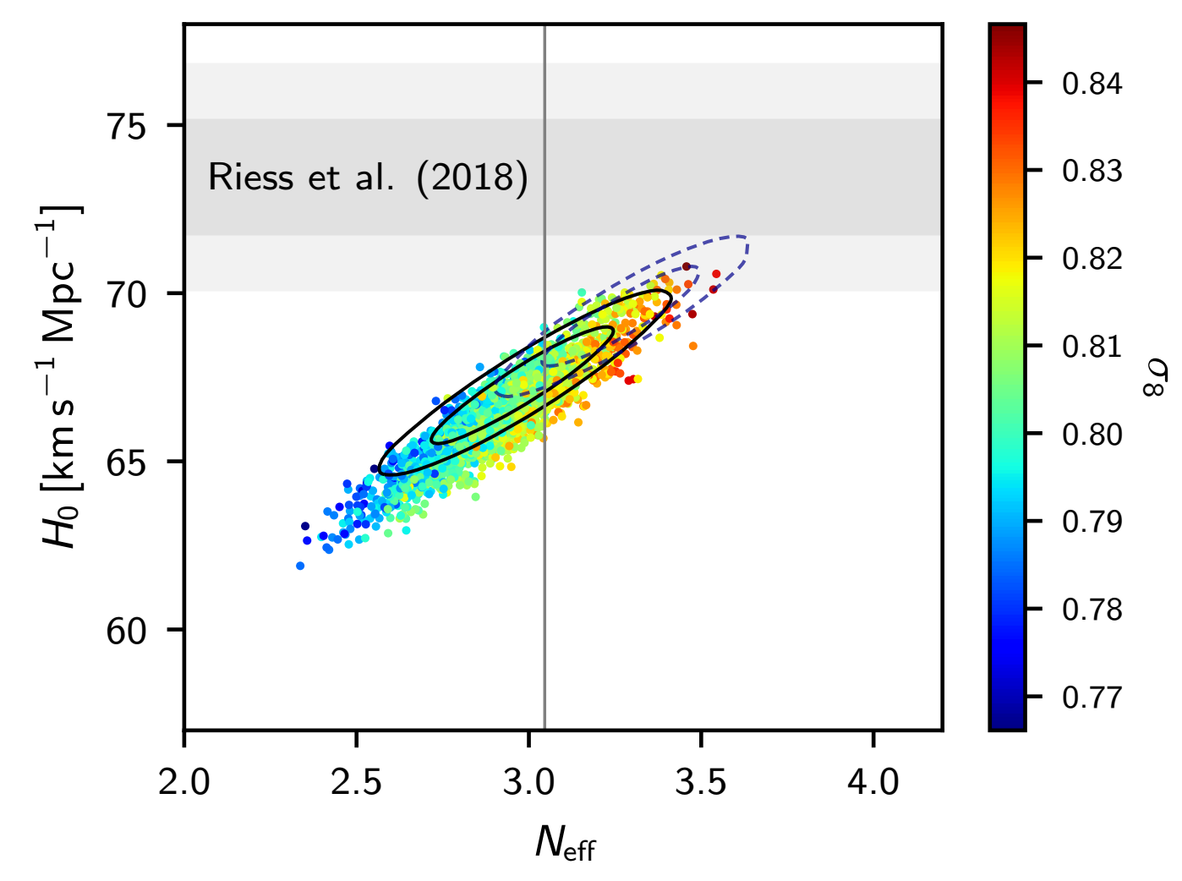

Fig. 1: $N_{\rm eff}$ constraints from Planck 2018.

Standard neutrino decoupling: $N_{\rm eff} = 3.044$ [1]

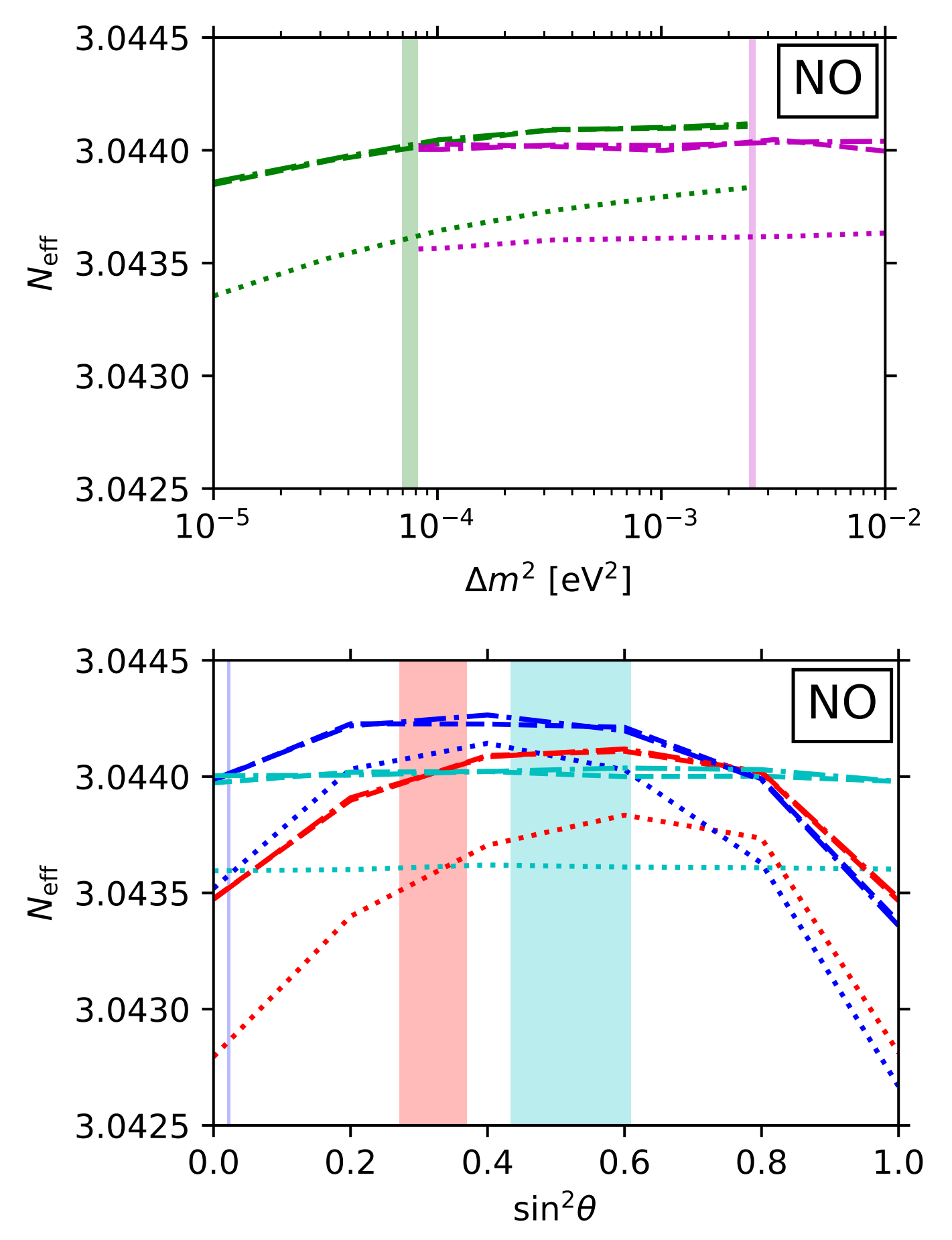

Fig. 2: Dependence of $N_{\rm eff}$ on the mixing parameters in the three-neutrino case. Vertical bands represent current terrestrial constraints at 3σ for each parameter [7].

When we consider the decoupling of neutrinos in the standard scenarios, we have to solve a set of coupled differential equations that govern the evolution of the neutrino density matrix. The 3×3 density matrix has real diagonal elements representing the momentum distribution functions of the neutrino states and complex off-diagonal elements describing the coherence of the system. Such matrix is discretized in the neutrino momentum in order to obtain the full momentum dependence of the process. The differential equations that give the density matrix evolution take into account the presence of universe expansion, vacuum oscillations, matter potentials, neutrino-neutrino and electron-neutrino interactions. The latter, in particular, describe how part of the entropy is transferred from the electron-positron fluid to neutrinos, at the time of the electron non-relativistic transition.
The full calculation of neutrino decoupling in the early universe has reached nowadays a significant precision. When the full equations are solved, the **most precise value obtained to date** is given by [1, 8, 9]

$$N_{\rm eff} = 3.0440 \pm 10^{-4}\,, \qquad (2)$$

where the error represents the uncertainty arising from the allowed range for neutrino oscillation parameters, as shown in figure 2, and the discretization of the neutrino momentum.

Light sterile neutrino (LSN) [2]

The process of neutrino decoupling is slightly different when one considers an additional neutrino state. We consider sterile neutrinos, i.e. right-handed fermions that are singlets in the standard model (thus they have no electroweak interactions) but can oscillate into standard (active) neutrinos. Through oscillations between active and sterile neutrinos, the new state can be brought in full equilibrium with the active states. If this happens, $N_{\rm eff}$ is expected to be close to 4. In case oscillations are not efficient enough, however, the sterile neutrino may not be produced in the early universe and $N_{\rm eff} \simeq 3.044$.
In the specific case of a light sterile neutrino (LSN) with a mass splitting $\Delta m^2_{41} \simeq 1$ eV^2 with respect to active neutrino flavors, the new state becomes non-relativistic approximately at the time of CMB decoupling, and thus fully contributes to radiation in the early universe. Heavier states ($m_4 \gtrsim 1$ keV) may be non-relativistic already at BBN, thus they cannot be considered as radiation, but rather as warm dark matter candidates.
For LSNs, the oscillations with the new state start earlier than those driven by active mass splittings. For larger Δm^2_{41}, oscillations have more time to bring the sterile neutrino in equilibrium. Larger mixing angles also contribute to a faster thermalization of the additional state. Figure 3 also shows that **oscillations** driven by the mixing between the fourth mass state and the different flavor neutrinos ($|U_{e4}|^2$, $|U_{\mu4}|^2$, $|U_{\tau4}|^2$) **act in parallel**, and it is sufficient to have any one of them larger than 10^{-3}, together with $\Delta m^2_{41} \simeq 1$ eV^2, for having the LSN fully thermalized ($N_{\rm eff} \simeq 4.05$). Such large value of $N_{\rm eff}$ is disfavored by CMB and BBN measurements, thus penalizing a significant fraction of the sterile neutrino parameter space.

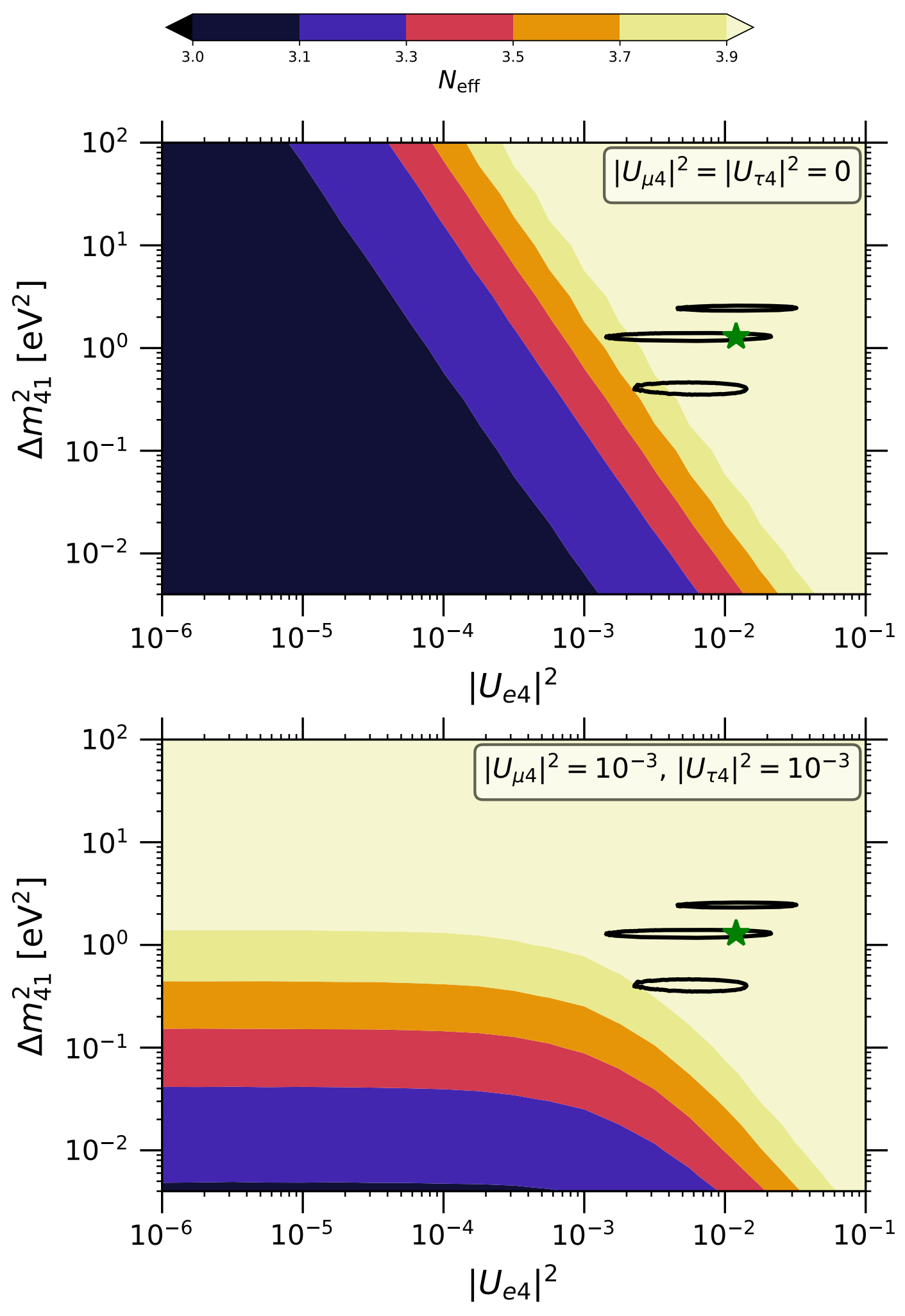

Fig. 3: $N_{\rm eff}$ as a function of active-sterile mixing parameters. Circles indicate the preferred regions from [10].

Non-Standard Interactions (NSI) [3]

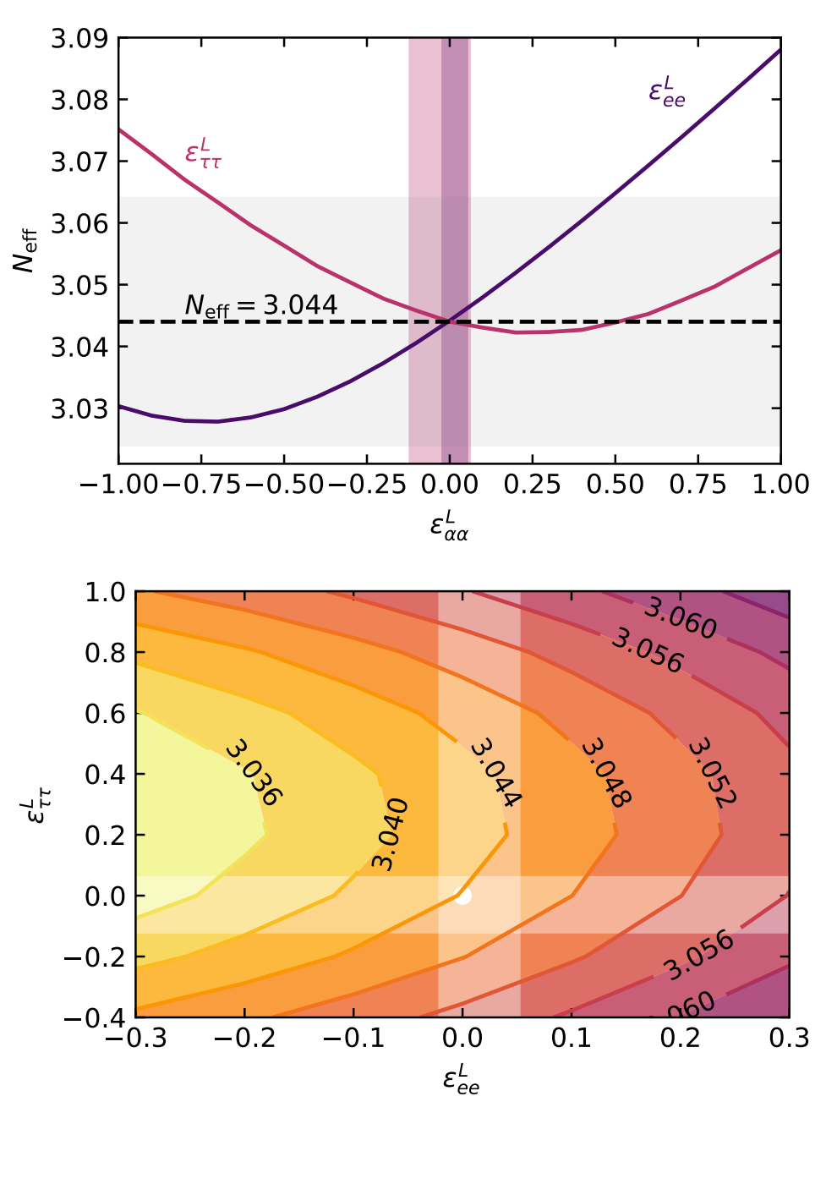

Fig. 4: Dependence of $N_{\rm eff}$ on some NSI parameters. Vertical colored bands represent current terrestrial bounds, while gray bands show future CMB constraints on $N_{\rm eff}$.

When one considers new theories beyond the standard model of particle physics, it is common to find scenarios where neutrinos have additional interactions with electrons, with an effective Lagrangian that at low energies takes the form [11]

$$\mathcal{L}' \propto G_F \sum_{\alpha,\beta} \epsilon^{L,R}_{\alpha\beta} (\bar\nu_\alpha \gamma^\mu P_L \nu_\beta)(\bar e \gamma_\mu P_{L,R} e)\,. \qquad (3)$$

Phenomenologically, such new interactions are parameterized by a set of coefficients $\epsilon^{L,R}_{\alpha\beta}$. These coefficients can be constrained by studying the interactions of neutrinos with the medium at terrestrial experiments, but they also affect neutrino decoupling in the early universe. Although their impact on early universe observables may be limited, we shall study the complementarity between terrestrial and cosmological probes.

When considering neutrino decoupling, the $\epsilon^{L,R}_{\alpha\beta}$ coefficients have two different effects: on one hand, they modify the oscillation pattern through matter potentials, because neutrino interactions with the dense fluid of electrons are altered. On the other hand, the entropy transfer from electron to neutrino can be more efficient in presence of large NSI. Figure 4 shows the impact of some selected $\epsilon^{L,R}_{\alpha\beta}$ coefficients on $N_{\rm eff}$, either varying only one (upper panel) or two parameters at each time. As we can see from the upper panel, even future cosmological bounds, represented by the gray horizontal band, are not as constraining as current terrestrial ones (vertical colored bands). Future cosmological measurements, however, may explore parameter degeneracies that are not available at terrestrial experiments, thus representing an interesting complementary probe.

Non-Unitarity (NU) [4]

The presence of heavy sterile neutrino states may affect the process of neutrino decoupling even if such states are not relativistic in the early universe. This arises from the fact that if the full $N \times N$ mixing matrix is unitary, the 3×3 section that corresponds to active neutrino oscillations is not. As a consequence, the oscillation probabilities are altered and the evolution of the neutrino energy density is not the same as in the unitary case.
The non-unitary mixing matrix can be expressed in terms of the α coefficients:

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U\,, \qquad (4)$$

where U is the standard 3×3 unitary mixing matrix.
In the NU case, moreover, one has to take into account that the measurements of the Fermi constant G_F, which governs the strength of neutrino interactions, actually probe a combination of the α coefficients:

$$G_F^\mu = G_F \sqrt{\alpha_{11}^2\,(\alpha_{22}^2 + |\alpha_{21}|^2)} \qquad (5)$$

where $G_F^\mu = 1.1663787(6)10^{-5}$ GeV^{-2} [12]. Using the proper G_F value alters significantly the importance of collision terms, generating the effect on $N_{\rm eff}$, testable by future CMB bounds, that can be see in the upper right panel of fig. 5.

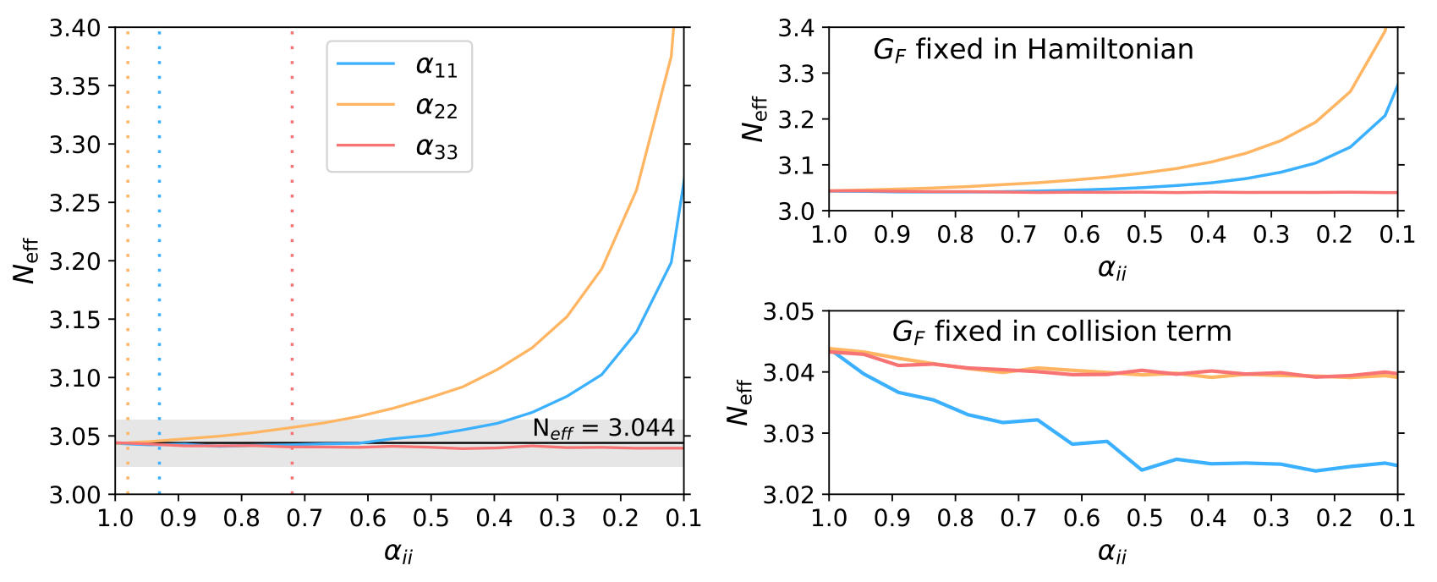

Fig. 5: Dependence of $N_{\rm eff}$ on NU parameters. The horizontal gray band represents future CMB constraints, while vertical lines show current terrestrial lower limits.

Low-reheating scenarios (in prep.)

Most of the scenarios discussed until now only allow to increase $N_{\rm eff}$ with respect to the standard value. Reducing $N_{\rm eff}$ to values smaller than three may require non-trivial modifications of the cosmological evolution.
A non-standard scenario that allows $N_{\rm eff} < 3$ emerges when the inflaton, the scalar field responsible for inflation, decays very late, at temperatures $T_{\rm rh}$ of the order of $\lesssim 10$ MeV. In such **low-reheating** scenarios, the inflaton decays electromagnetically into standard model particles except from neutrinos. Weak interactions with electrons are then expected to produce neutrinos, but if there is not enough time to populate their momentum distribution before decoupling, the neutrino contribution to the radiation energy density may be smaller than the standard one. When considering three neutrinos, in particular, $N_{\rm eff}$ starts to deviate from 3.044 if $T_{\rm rh} \lesssim 7$ MeV, see the preliminary figure 6, left panel. Notice that $T_{\rm rh} \lesssim 3$ MeV, corresponding to $N_{\rm eff} \lesssim 2$, would significantly modify the BBN processes.
Low-reheating scenarios can be studied when we consider three active and one LSN as well. Considering $\Delta m^2_{41} \simeq 1$ eV^2 and $|U_{e4}|^2 \sim 0.01$, for which we would have $N_{\rm eff} \simeq 4.05$ without low reheating, it is sufficient to have $T_{\rm rh} \lesssim 10$ MeV to reduce the total $N_{\rm eff}$ by preventing active-sterile neutrino oscillation to fully thermalize the sterile state. By selecting the appropriate $T_{\rm rh}$, it is possible to **accomodate the presence of the LSN** while satisfying cosmological constraints on $N_{\rm eff}$. As we can see from the right panel of figure 6, for $\Delta m^2_{41} \simeq 1$ eV^2 and $|U_{e4}|^2 \sim 0.01$, $N_{\rm eff}$ is approximately 3 if we consider $T_{\rm rh} \simeq 5$ MeV.

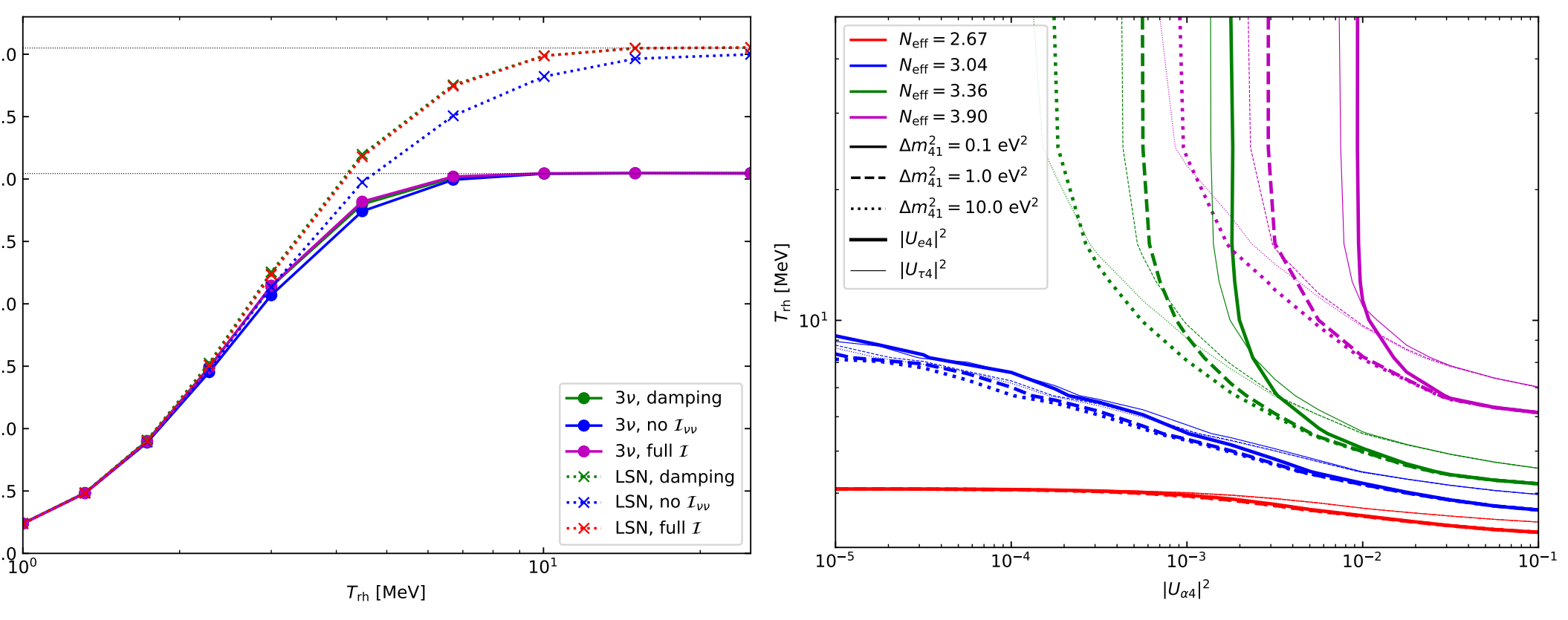

Fig. 6: Variation of $N_{\rm eff}$ in presence of low-reheating scenarios. *Left panel:* comparison of the three-neutrino and LSN cases. *Right panel:* $N_{\rm eff}$ at different $T_{\rm rh}$, Δm^2_{41} and $|U_{e4}|^2$ or $|U_{\tau4}|^2$.

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We numerically solve the equations with `FortEPiaNO`,
https://bitbucket.org/ahep_cosmo/fortepiano_public.

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