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Bounds on 3+1 active-sterile neutrino oscillations in very low reheating scenarios

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In the 3+1 neutrino scheme with an additional state, we consider the thermalisation of neutrinos in the early Universe in the so-called very low reheating scenarios. This process could be incomplete due to the lack of interactions, leading to a reduced contribution of neutrinos to the cosmological energy density of radiation. We calculate this contribution, usually measured in terms of the parameter effective number of neutrino species ($N_{\rm eff}$), taking into account the full 4×4 neutrino mixing matrix, as a function of the reheating temperature $T_{\rm rh}$.

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While most of the data from neutrino oscillation experiments nicely fit into a three-neutrino scenario (see e.g. the global fit in [1]), there remain a few experimental results that this simplest scheme can not describe. The existence of a fourth neutrino state, a gauge singlet insensitive to weak interactions but with non-zero mixing with the active neutrinos, is a well-motivated solution to these so-called anomalies (see e.g. [2]). This would require a new mass state at the eV scale and a small mixing with the three active neutrinos, the 3+1 scheme, although this is not an optimal solution due to the tension between the anomalies in the appearance sector and disappearance measurements, as shown by global analyses of short-baseline data [3].

A well-known consequence of this kind of active-sterile oscillations in cosmology is that, if these conversions are effective in the early Universe before neutrino decoupling, the new sterile state could be populated while the active neutrinos keep an equilibrium energy distribution. This thermalisation of the sterile neutrinos is complete for the range of mixing parameters that could explain the anomalies [4], thus in strong tension with the available cosmological data, in particular on the anisotropies of the cosmic microwave background radiation (CMB) from the Planck satellite [5]. The production of sterile states through oscillations before neutrino decoupling would also modify the outcome of Big Bang Nucleosynthesis (BBN).

One way to alleviate this would be to suppress the thermalisation of the sterile states, introducing either new neutrino interactions, large primordial lepton asymmetries or non-standard cosmological scenarios. Among the latter, here we consider the so-called very low reheating Universe, in which the start of the radiation-dominated era that arises from the decay products of a massive particle is significantly delayed with respect to the standard case, down to cosmic temperatures $\sim \mathcal{O}(1)$ MeV. In such a scenario, the thermalisation of the neutrino background could be incomplete due to the lack of interactions, modifying its contribution to the cosmological energy density of radiation (parameterised by the effective number of neutrino species, $N_{\rm eff}$) and their influence on BBN [6–8]. The production of sterile states in the 3+1 case would be reduced for MeV reheating temperatures, relaxing the cosmological bounds as shown in [9] in the 1+1 case with the `LASAGNA` code.

We have revisited the problem of sterile neutrino thermalisation for MeV reheating temperatures with the full oscillation paradigm of the 3+1 scheme, extending the analysis in [8]. For the first time, we consider the effect of all mixing angles, fixing those exclusive of active neutrinos to the values obtained in global-fit analyses but leaving the three active-sterile angles as free parameters. The evolution of neutrinos is obtained with a modified version of the `FortEPiaNO` code [4, 10] and the bounds on active-sterile parameters and the reheating temperature will be computed using the latest available cosmological data, including a BBN analysis using the `PArthENoPE` code [11].

The 3+1 scheme includes four neutrino states with masses m_i ($i = 1, 2, 3, 4$) that lead to three different squared-mass differences. Two of them, Δm^2_{21} and Δm^2_{31}, are the usual mass parameters of the 3ν case, while Δm^2_{41} is an additional mass splitting from the presence of one sterile state. This framework also requires a mixing matrix described by six mixing angles (three standard mixing angles θ_{12}, θ_{13} and θ_{23}, plus three new mixing angles θ_{14}, θ_{24} and θ_{34}). Up to ten complex phases exist, but seven are unphysical, leading to two extra CP violating phases, additional to the one existing in the 3ν case. For simplicity, we will fix all CP violating phases to zero, so that the standard parameterisation in the 3+1 scheme corresponds to a 4×4 mixing matrix U, where the entries of the fourth column are related to the active-sterile mixing angles as follows: $|U_{e4}|^2 = \sin^2\theta_{14}, \left|U_{\mu 4}\right|^2 = \cos^2\theta_{14}\sin^2\theta_{24}, |U_{\tau 4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$ and

$|U_{s4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34}$. We also consider that the active-sterile mixings are small enough to avoid modifying the values of the elements related only to the three flavour states.

The process of neutrino decoupling in the early Universe is not completely instantaneous. This implies that some deviations from equilibrium appear in the neutrino distribution functions. Moreover, it has been previously shown that neutrino oscillations become effective at temperatures of O (MeV), when the process of neutrino decoupling takes place. Therefore, in order to properly study neutrino decoupling, we need to consider the evolution of the 4×4 neutrino density matrix [4], $\varrho(p,t)$, whose diagonal terms are the distribution functions of flavour neutrinos with momentum p, while the off-diagonal terms take complex values but vanish for zero mixing. Since we neglect any potential neutrino asymmetry, neutrinos and antineutrinos share the same density matrix.

The evolution of the neutrino density matrix is obtained by solving the integro-differential set of Boltzmann equations, see e.g. [4], that must be solved simultaneously with the continuity equation for the total energy density of radiation ρ_R and total pressure P_R of the relativistic plasma, that includes the electromagnetic components γ, $e^\pm$, $\mu^\pm$ (in equilibrium with a temperature T_γ) and the neutrino states. 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.

When these differential equations are evolved simultaneously, one can obtain the final energy density of neutrinos and compare it with that of photons. It is convenient to express the amount of radiation associated to neutrinos in terms of the well known effective number of relativistic species, $N_{\rm eff} \equiv 8/7\,(11/4)^{4/3}\,(\sum\rho_{\nu_i}/\rho_\gamma)$. In the standard case, the recommended value is $N_{\rm eff} = 3.044$ (see e.g. [10]), slightly enhanced from 3 because of the small entropy transfer from $e^\pm$ annihilation to neutrinos in the non-instantaneous decoupling. In the 3+1 framework, the final value of $N_{\rm eff}$ depends on the mixing parameters with the sterile neutrino and it can be as large as $N_{\rm eff} \approx 4$ if the oscillations are efficient enough to guarantee a full thermalisation of the new neutrino. This value, however, is in tension with the bounds set from cosmological observations (see e.g. [12]).

Here we consider a simple scenario of reheating which occurs at very low temperatures, as in [8], where the Universe is initially in a matter-domination stage, arising from the energy density of a massive scalar field, which we consider to be the inflaton. Photons are almost absent in this phase, but the scalar decays into standard-model (relativistic) particles other than neutrinos quickly populate the radiation components. Neutrinos are populated via weak interactions with charged leptons and may reach equilibrium if the inflaton decay occurs early enough. In case the decay starts too late, the neutrino fluid cannot reach equilibrium with the rest of the relativistic particles, so that the final $N_{\rm eff}$ is smaller than in the standard case. In order to compute the evolution of the Universe within a low-reheating scenario, the equations previously discussed must be modified, as shown in [8], including the reheating temperature $T_{\rm rh}$, which is just a different way of referring to the decay rate of the massive particle: $\Gamma_\phi = 3H(T_{\rm rh})$, where H is the Hubble factor.

Let us now present some of our results. As a benchmark point, we consider the active-sterile mixing parameters as follows: $\Delta m^2_{41} = 1\,{\rm eV}^2$, $|U_{\tau4}|^2 = 0.01$, $|U_{e4}|^2 = |U_{\mu4}|^2 = 0$. Such combination can be considered as a representative value and serves the purpose of showing the effect of low-reheating scenarios in presence of light sterile neutrinos. Since from the cosmological point of view all the active-sterile mixing channels are practically equivalent, having $|U_{\tau4}|^2 = 0.01$ and the other elements equal to zero is almost the same as considering $|U_{e4}|^2 = 0.01$ only, but the former choice allows to avoid all terrestrial bounds, since constraints on $|U_{\tau4}|^2$ are much weaker than those

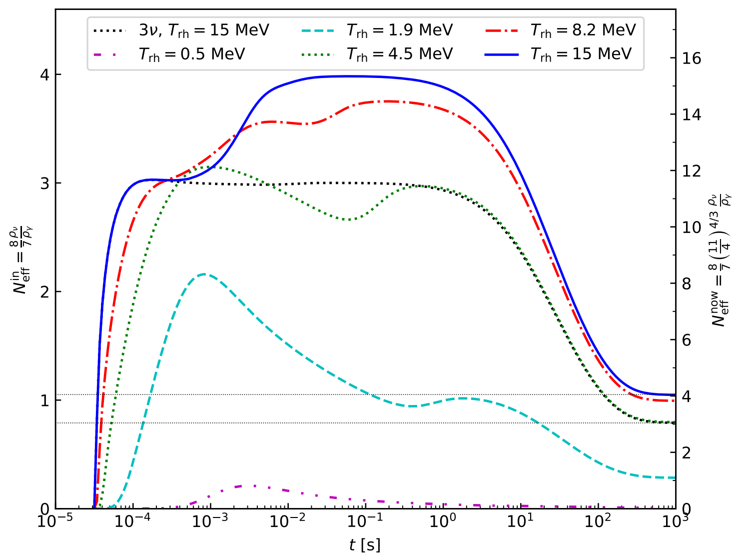

Figure 1: Time evolution of $N_{\rm eff}$ in the 3+1 case for the benchmark values of the mixing parameters and different values of $T_{\rm rh}$. The black dotted line corresponds to $T_{\rm RH} = 15\,$MeV in the standard 3ν scheme. $N_{\rm eff}$ is defined before (left y axis) and after (right y axis) $e^\pm$ annihilation.

on $|U_{e4}|^2$ or $|U_{\mu4}|^2$. We want to remark the fact that, given the current available observations, a valid global solution of the short-baseline anomalies seems difficult to obtain.

We show in Figure 1 the time evolution of $N_{\rm eff}$ for different reheating temperatures. As we can see, $N_{\rm eff}$ rapidly grows from 0 at the beginning of the evolution, when neutrinos are populated from weak interactions with the thermal plasma. If $T_{\rm rh}$ is small, even in the 3ν case weak interactions cannot bring neutrinos to the same equilibrium temperature as photons, and $N_{\rm eff}$ remains (potentially much) smaller than 3 for very small reheating temperatures. Since these values of $N_{\rm eff}$ are incompatible with cosmology, and BBN is completely spoiled by such extreme scenarios, we restrict ourselves to $T_{\rm rh} > 3$ MeV. For the 3+1 scenario, the blue line in Figure 1 clearly shows the moment when active-sterile oscillations bring the new neutrino state into equilibrium, well after the inflaton decay. In such case, thermalisation is complete ($T_{\rm rh} \gtrsim 8$ MeV) and $N_{\rm eff}$ can reach a value of 4.05 [4]. If $T_{\rm rh}$ decreases, any value between 0 and such number can be produced. In particular, notice how $T_{\rm rh} \simeq 4.5$ MeV gives $N_{\rm eff} \simeq 3$, mimicking the three-neutrino case.

Instead, we show in Figure 2 the iso-$N_{\rm eff}$ contours as a function of the reheating temperature and the mixing matrix element $|U_{e4}|^2$ (thick lines) or $|U_{\tau4}|^2$ (thin lines), for three different values of Δm^2_{41}. It is interesting to note that, when the reheating temperature is very small, the active-sterile mixing angle has almost no impact on the final value of $N_{\rm eff}$, and it does not matter if there are three or four neutrino states: there is no time to produce sterile neutrinos because active neutrinos are populated very late, when active-sterile oscillations generated by the Δm^2_{41} are not effective anymore. Secondly, when $T_{\rm rh}$ is above 10 MeV, its impact is significantly reduced, but it can still have some when large mass splittings Δm^2_{41} are considered. This is a consequence of the fact that oscillations corresponding to higher Δm^2_{41} take place earlier in time, and therefore they could be not effective when $T_{\rm rh}$ is in the intermediate range.

In a forthcoming paper (T. Brinckmann et al., in preparation) we will show how to employ

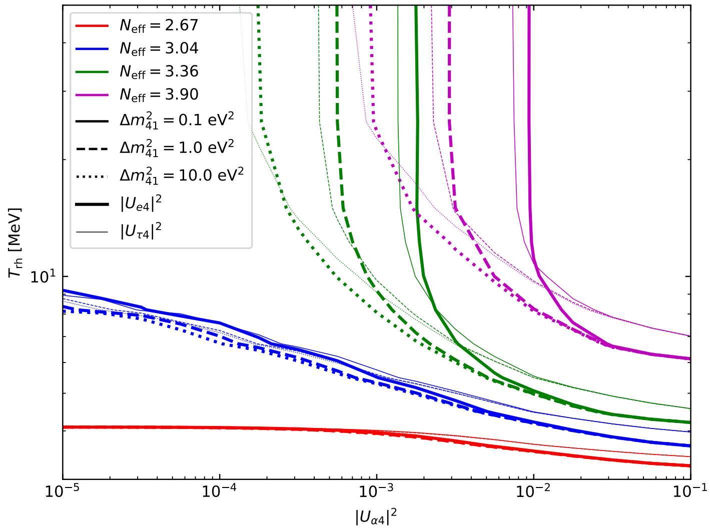

Figure 2: Variation of $N_{\rm eff}$ as a function of $|U_{e4}|^2$ (thick lines) or $|U_{\tau 4}|^2$ (thin lines) for three selected values of Δm^2_{41} (0.1 eV^2 in solid, 1 eV^2 in dashed and 10 eV^2 in dotted style), in the 3+1 case with low reheating temperatures $T_{\rm rh}$ from 3 to 50 MeV. The colors indicate different values of $N_{\rm eff}$.

our results on the dependence of $N_{\rm eff}$ to constrain the reheating temperature and the active-sterile mixing parameters by means of cosmological observations such as BBN and CMB.

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