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Active-sterile neutrino oscillations in the early universe with dynamical neutrino asymmetries

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Abstract

In the last recent years different anomalies observed in short-baseline neutrino oscillation experiments seem to point towards the existence of light sterile neutrinos. These sterile neutrinos can also be produced in the early universe by oscillations of the active neutrinos and can affect different cosmological observables. In order to quantify the abundance of sterile neutrinos, we perform a detailed study of the flavor evolution in (3 + 1) and (2 + 1) oscillation schemes, in presence of dynamical primordial neutrino asymmetries L. We find that for $|L| \lesssim 10^{-4}$ eV sterile neutrinos would be completely thermalized creating a tension with the cosmological data. An asymmetry of $|L| \gtrsim 10^{-3}$ is then required in order to suppress the sterile production and to reconcile them with cosmology.

Keywords: Non-standard-model neutrinos; Neutrino mass and mixing; Cosmology.

1. Introduction

The 3-flavors active neutrino scenario has described with success nearly all the results of the oscillation experiments. However in the last recent years some anomalies emerged that cannot be explained in this scenario. In particular, the $\bar{\nu}_e$ appearance signals in LSND and MiniBoone experiments, the $\bar{\nu}_e$ and ν_e disappearance signals revealed by the Reactor and the Gallium Anomaly can be described in terms of light ($m \sim O(1\,\text{eV})$) sterile neutrinos mixing with the active ones [1] . In this context, scenarios with one (“3+1”) or two (“3+2”) sub-eV sterile neutrinos have been proposed to fit the different data [2].

Sterile neutrinos produced in the early universe can contribute as extra radiation to the non electromagnetic energy density which is usually expressed in terms of the effective numbers of thermalized neutrino species N_{eff}. This number can be constrained from the Big-Bang Nucleosynthesis (BBN), Cosmic Microwave Background (CMB) and from the Large Scale Structure (LLS): current observational data show a preference for N_{eff} larger then the standard value ~ 3 (see [3] for details). However, it is not simple to link the laboratory neutrinos with the cosmological extra radiation. Indeed, the mass and mixing parameters preferred by experimental anomalies lead to the production and thermalization of 1 or 2 sterile neutrinos in the Early Universe. At this regard, 2 extra d.o.f are too many for the BBN [4] and already 1 eV sterile neutrino is too heavy for the CMB and LSS [5].

A way to reconcile the eV sterile neutrino interpretation of the short-baseline anomalies with the cosmological observations is to suppress the sterile neutrino thermalization in the early universe, reducing their possible excess in extra-radiation. To this end it was proposed to introduce a primordial asymmetry between neutrinos and antineutrinos $L = n_\nu - n_{\bar{\nu}}/n_\gamma$ [6, 7]. This would contribute with an additional “matter term potential” in the active-sterile neutrino equations of motion. If sufficiently large, one expects this term to *block* the active-sterile flavor conversions via the in-medium suppression of the mixing angle. On the contrary, this term can

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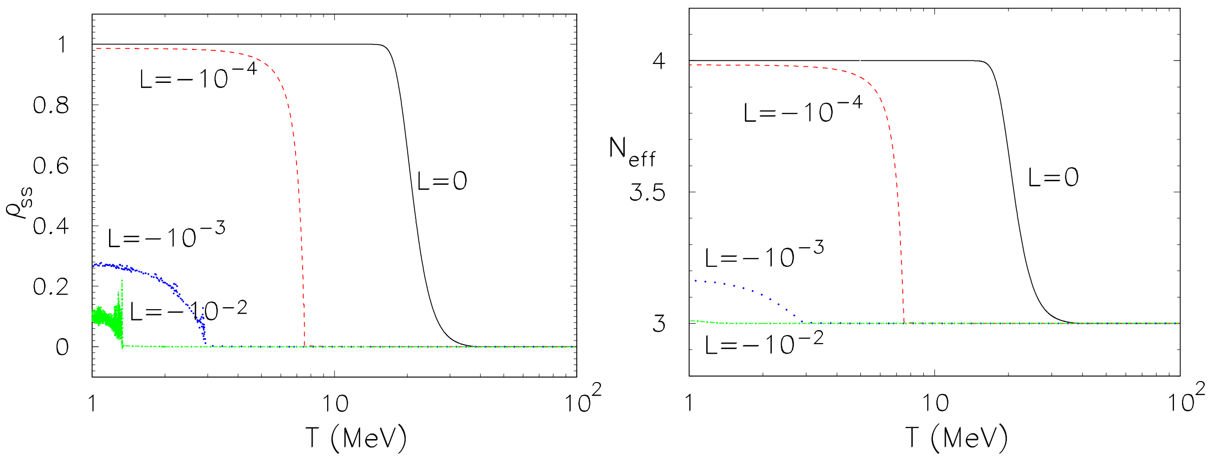

Figure 1: (3 + 1) scenario. Left panel: Evolution of the density matrix element ρ_{ss} in function of the temperature T for different initial neutrino asymmetries. We consider $L_e = L_\mu = L_\tau$. Right panel: Evolution of the effective number of degrees of freedom $N_{\rm eff}$.

also generate Mikheev-Smirnov-Wolfenstein (MSW)-like resonant flavor conversions among active and sterile neutrinos, *enhancing* their production. In order to assess which of the two effects dominates the flavor evolution we perform a study of the kinetic equations for active-sterile neutrino oscillations in the early universe, including more then one active neutrinos and considering different choices of primordial asymmetries. We find that for $|L| \gtrsim 10^{-3}$ one reaches the goal of significantly reduce the sterile neutrino thermalization, making the effect on $N_{\rm eff}$ less and less prominent. On the other hands, these large values of the L can have an impact on BBN.

These results are based on our work [8], to which we address the interested reader for further details.

2. Analysis of active-sterile neutrino flavor evolution and results

The evolution equations in the early universe for the 4×4 density matrices ϱ ($\bar\varrho$), describing the neutrino (antineutrino) system, are the following [9]:

$$\mathrm{i}\,\frac{d\varrho_{\mathbf{p}}}{dt} = [\Omega_{\mathbf{p}}, \varrho_{\mathbf{p}}] + C[\varrho_{\mathbf{p}}, \bar\varrho_{\mathbf{p}}]\,, \quad (1)$$

and similar for the antineutrino matrices $\bar\varrho_{\mathbf{p}}$. The first term on the right-hand side of Eq. (1) describes flavor oscillations,

$$\Omega_{\mathbf{p}} = \frac{\mathsf{M}^2}{2p} + \sqrt{2}\,G_{\rm F}\left(-\frac{8p}{3m_{\rm W}^2}\,\mathsf{E} + \varrho - \bar\varrho\right), \quad (2)$$

where the neutrino mass matrix M includes the mixing parameters that characterizes the vacuum term of oscillations. In our calculations we have fixed both mass-squared differences and the mixing angles to the best-fit values for the active and sterile sectors (see [8]). The terms proportional to the Fermi constant G_F encode the matter effects in the neutrino oscillations. In particular, the term E_ℓ is related to the energy density of e^- and e^+, while the $\nu - \nu$ interaction term is proportional to the neutrino asymmetry L. This latter term makes the EoMs non-linear and is the main numerical challenge in dealing with this physical system. In order to simplify the numerical complexity of this problem we make use of the average momentum approximation in which all the neutrinos share the common thermal average $p_{\rm ave} = 3.15\ T$. With this approximation $\varrho_{\mathbf{p}} \to \rho$. Finally, the last term corresponds to the collision term, proportional to G_F^2.

For the (“3+1”) scenario, in the left panel of Fig.1 we show the evolution of the diagonal component of the density matrix ρ_{ss} for sterile neutrinos (i. e. the sterile neutrino abundance) in function of the temperature T for different initial lepton asymmetries, namely, $L = 0$ (solid curve), $L = -10^{-4}$ (dashed curve), $L = -10^{-3}$ (dotted curve), and $L = -10^{-2}$ (dashed-dotted curve). In the absence of lepton asymmetries, sterile neutrinos are copiously produced at $T \sim 30$ MeV until they reach $\rho_{ss} = 1$. Instead, including a nonzero initial L, the effect is to suppress the sterile neutrino production as long as the asymmetric term is larger than the vacuum term. However, due to their opposite dependence on the temperature, these two terms eventually cross and sterile neutrinos are then produced resonantly. Increasing