Secret neutrino interactions: a pseudoscalar model

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Abstract. Neutrino oscillation experiments point towards the existence of additional mostly sterile neutrino mass eigenstates in the eV mass range. At the same time, such sterile neutrinos are disfavoured by cosmology (Big Bang Nucleosynthesis, Cosmic Microwave Background and Large Scale Structure), unless they can be prevented from being thermalised in the early Universe. To this aim, we introduce a model of sterile neutrino secret interactions mediated by a new light pseudoscalar: The new interactions can accomodate sterile neutrinos in the early Universe, providing a good fit to all the up to date cosmological data.

1. Introduction

Neutrinos deeply affect the cosmological observables, such as the Cosmic Microwave Background and the power spectrum of matter fluctuations. Thanks to these fingerprints cosmology can detect the cosmic neutrino background and constrain the number of neutrino species and the neutrino mass sum with greater precision than current laboratory experiments. However cosmological bounds are model dependent, therefore complementary results from earth based neutrino experiment are essential to provide robust constraints.

In this framework the case of sterile neutrinos represents an open question. Indeed in the last decade oscillation data have been providing hints of the existence of one (or more) sterile neutrinos in the eV mass range [2, 3, 4], while the latest Planck results [1] rule out additional neutrino species at high significance.

Here, we present a pseudoscalar model of secret interactions which satisfies all the cosmological constraints on sterile neutrinos. For a more detailed discussion of this model we refer the reader to the papers of Refs. [5, 6].

2. Model framework and early Universe phenomenology

The new non-standard Lagrangian term describing the secret interaction between sterile neutrinos and pseudoscalars is given by

$$\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4. \tag{1}$$

where ϕ is the pseudoscalar ($m_\phi << 1$ eV) and g_s is the coupling strength.

The main limit on g_s comes from the supernova bounds and it turns out to be roughly $g_s < 10^{-4}$ [7].

We postulate that the pseudoscalars are thermally produced at very high temperatures and that they thermalize sterile neutrinos through incoherent processes such as $\phi\phi \leftrightarrow \bar{\nu}_s\nu_s$ at $T \sim 1$ GeV (assuming $g_s \sim 10^{-4}$). At temperatures higher than 200 MeV, the dark fluid decouples from the plasma, thus, it does not get the entropy released by the QCD phase transition, i.e. $T_\phi = 0.47T_\gamma$. As a result, when neutrino oscillations become efficient, the Universe already contains a low temperature fluid of sterile neutrinos and pseudoscalars.

The new interactions of the fluid contribute to the Quantum Kinetic Equations (QKE) through an additional matter-like potential

$$V_s(p_s) = \frac{g_s^2}{8\pi^2 p_s} \int pdp \left(f_\phi + f_s\right) \tag{2}$$

where f_ϕ is the Bose-Einstein distribution for the pseudoscalar and f_s is the distribution for the sterile neutrinos. The new potential suppresses the neutrino in medium mixing angle, delaying the sterile neutrino production until after the collisional decoupling of the standard neutrinos (~ 1 MeV). As a consequence, when sterile neutrinos are produced, their phase space distribution shows some non-thermal features, i.e. sterile neutrinos are not fully thermalized. As we can see from Fig. 1, the partial thermalization occurs for $g_s > 10^{-6}$ and leads to a lower value of the sterile neutrino energy density, parameterized as $\delta N_{\rm eff}$, in the early Universe, which is compatible with Big Bang Nucleosynthesis bounds [10].

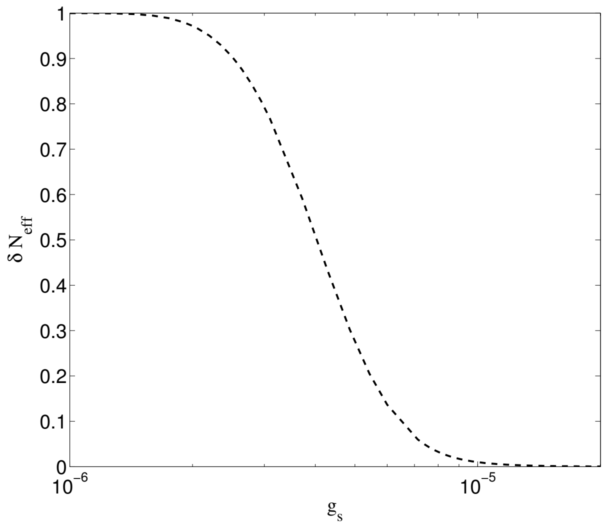

Figure 1. The contribution of a sterile neutrino to the energy density in terms of $\delta N_{\rm eff}$ as a function of the coupling. The figure is obtained by solving the QKE with a modified version of the public code LASAGNA [8], in a 1+1 framework with sterile neutrino mixing parameter $\sin^2 2\theta = 0.05$ and $m_{\rm s} = 1$ eV.

3. Late time phenomenology

The scattering rate for pseudoscalars and sterile neutrinos is proportional to the temperature $\Gamma \sim g_s^4 T$, therefore, if $g_s > 10^{-6}$, sterile neutrinos in the eV mass range recouple (i.e. $\Gamma > H$, where H is the expansion rate of the Universe) before they go non-relativistic and before photon decoupling.

In the collisional regime, sterile neutrinos and pseudoscalars are not free-streaming, but rather behave as a single fluid with no anisotropic stress. Such neutrino perturbations induce an enhancement of the monopole term in the acoustic peaks of the power spectrum of the Cosmic Microwave Background temperature anisotropies. If not only sterile neutrinos but also active neutrinos were strongly interacting, then the resulting CMB temperature power spectrum would not be compatible with measurements [9]. Therefore the new interactions must be confined to the sterile sector.

Later on, when sterile neutrinos go non relativistic, they annihilate into pseudoscalars, while the inverse process becomes kinematically prohibited. The annihilations transfer energy to the fluid, whose temperature starts decreasing less rapidly than in a standard fully relaivistic fluid, leading to an increase in the energy density. During this process the pressure of the combined fluid also drops relative to its energy density because of the temporary non negligible value of the sterile neutrino rest mass.

We plug the above phenomenology into a Boltzmann solver (`CAMB` [15]) and we run a Markov Chain Monte Carlo (`CosmoMC` [16]) to fit various cosmological data to our model.

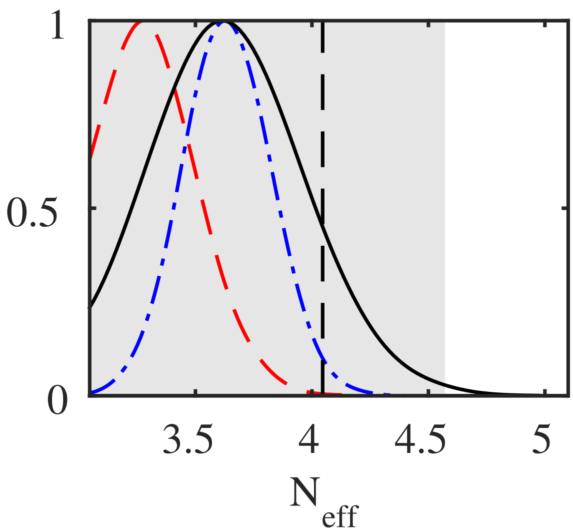

Figure 2. 1D marginalized posterior of $N_{\rm eff}$. The baseline dataset include only Planck 2015 CMB data (PlanckTT+lowP, black/solid line), red/dashed line refers to PlanckTT+lowP+Baryonic Acoustic Oscillations [11, 12, 13, 14] and blue/dot-dashed line to PlanckTT+lowP+ prior on the Hubble constant from Hubble Space Telescope measurements [17]. The partial thermalization of pseudoscalars and sterile neutrinos in the early Universe can make one sterile neutrino consistent with a value of $N_{\rm eff}$ between 3.046 and 4.57 (grey shaded region), depending on g_s (in particular, $N_{\rm eff} = 3.046$ corresponds to no thermalization at high temperatures); while the ΛCDM model has to be consistent with one fully thermalized additional degree of freedom ($N_{\rm eff} = 4.046$, black/dotted vertical line) in order to account for one sterile neutrino with a significant amount of mixing.

Fig. 2 shows the one-dimensional marginalized posterior of the total energy density in neutrinos. Here we stress that if the only non-standard physics is the addition of a sterile neutrino with the mass and mixing needed to explain the short baseline data, the expectation is that the additional species is almost fully thermalised in the early universe, leading to $N_{\rm eff} \sim 4$. On the contrary, in the pseudoscalar model, the expectation is that $3.046 \leq N_{\rm eff} \leq 4.57$ with $N_{\rm eff} \sim 3$ corresponding to no thermalization at all (i.e. $g_s > 10^{-5}$) and the case $N_{\rm eff} \sim 4.57$

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corresponding to the full thermalization (i.e. $g_s < 10^{-6}$).

The χ^2 analysis shows that the pseudoscalar model provides a χ^2 comparable to ΛCDM and way better than ΛCDM with a one-eV fully thermalized sterile neutrino.

Finally, the crucial point which distinguishes the pseudoscalar model from other models of neutrino self-interactions [18, 19, 20, 21, 22] is the possibility to accomodate the mass limits from large scale structure [24] in a simple way[1]. Indeed, the annihilations will deplete the abundance of sterile states in the cosmic neutrino background, which will eventually end up being close to zero when the fluid will freeze out ($\Gamma = H$). Thus, strongly interacting neutrinos will not cause any suppression of the matter power spectrum on small scales, which occurs in the case of free-streaming massive neutrinos. In conclusion, in the pseudoscalar model, the mass of the mostly sterile mass eigenstate can evade the large scale structure bounds on the neutrino mass sum.

4. Discussion

If the eV sterile neutrino interpretation of short-baseline data turns out to be true, cosmology is faced with a very serious challenge. Taken at face value such a model is excluded by CMB and large scale structure data at least at the 5σ level. With this in mind it is clear that accommodating eV sterile neutrinos requires addition of new physics either in cosmology or in the neutrino sector. The model discussed here provides a simple and elegant way of reconciling eV sterile neutrinos with precision cosmology. It could well be possible to test details of the model with the greatly enhanced precision of future cosmological surveys such as Euclid.

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[1] Ref. [23] pointed out that secret interactions mediated by a massive vector boson can satisfy all cosmological constraints, provided that the mass and the coupling are such that sterile neutrinos either never recouple with active neutrinos or remain collisional until matter-radiation equality.

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