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2017 J. Phys.: Conf. Ser. 841 012002

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# Sterile neutrinos with non-standard secret interactions imprints on Cosmic Microwave Background anisotropies

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**Abstract.** Short baseline laboratory (SBL) anomalies have shown preference for light sterile neutrinos with eV masses. These particles, if confirmed, would be produced in the early universe and would add their contribution to the relativistic energy density basically increasing the effective number of extra relativistic species ( $N_{\text{eff}}$ ). It has been shown that when the matter potential produced by the sterile interactions becomes smaller than the vacuum oscillation frequency, sterile neutrinos are plentifully produced by the scattering effects in the sterile neutrino sector. This behaviour, however, leads to a  $\Delta N_{\text{eff}} \simeq 1$  which is in tension at  $3 - 5\sigma$  with the actual constraints given by the latest Cosmic Microwave Background radiation (CMB) observations. In order to avoid the thermalization of eV sterile neutrinos in the early universe, secret interactions between the sterile and active sectors mediated by a massive vector boson ( $M_X < M_W$ ) have been proposed. In particular, interactions mediated by a gauge boson having  $M_X < 10$  MeV would suppress the sterile neutrino production for  $T > 0.1$  eV and seem to save the cosmological constraints coming from big-bang nucleosynthesis (BBN) and mass bounds. In this framework, cosmological observations represent a powerful tool to constrain neutrino physics complementary to laboratory experiments. In particular, observations of the CMB have the potential to constrain the properties of relic neutrinos, as well as of additional light relic particles in the universe. In this work we present the effects of the strength of the interaction on the neutrino fluid perturbations and on the CMB anisotropies power spectrum.

## 1. Introduction

The standard cosmological picture predicts the existence of a thermal background of relic neutrinos with  $T_{\nu 0} = 1.9$  K; present cosmological data provide a  $10\sigma$  evidence for the presence of this background. Moreover, cosmological data are so precise that can go further, constraining several properties of the cosmic neutrino background. From a theoretical point of view the thermal history of neutrinos is well established: they are kept in equilibrium with the cosmological fluid by weak interactions until the temperature of the primordial fluid falls below  $T \sim 1$  MeV and, since the decoupling happens when neutrinos are ultrarelativistic, they preserve a thermal spectrum. The energy contribution of the standard three neutrino families is taken into account into the relativistic content through the effective degrees of freedom  $N_{\text{eff}}$  whose standard value is 3.046 [1]. The radiation energy density of the universe reads:

$$\rho_r = \rho_\gamma + \rho_\nu = \left(1 + \frac{7}{8} \left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\text{eff}}\right) \rho_\gamma. \quad (1)$$



Thus in the standard cosmological model the only free parameters are the masses of the three eigenstates. Although this simple picture is perfectly consistent with the observed data there are still some open questions: starting from the absolute scale and the hierarchy of the masses, passing through the Majorana or Dirac nature of these particles and the mass generation mechanism, investigating the reason of the existence of only three active neutrino families and so on. Luckily present-day cosmological data are good enough to allow the study of several non-standard models and to test more complicated scenarios such as non-standard interactions between neutrinos or hidden sterile eigenstates.

The existence of an extra neutrino eigenstate is hinted in short-baseline neutrino experiments [2, 3], in particular laboratory data suggest a sterile neutrino mass of the order of 1 eV and active-sterile mixing angle  $\theta_{as} \simeq 0.1$ . The production of this new state in the primordial universe would lead to an increase in the extra-relativistic energy content  $\Delta N_{\text{eff}} \simeq 1$  in tension with the actual bounds coming from the Planck experiment [4] and with other cosmological bounds [5, 6, 7]. In order to avoid this behaviour several mechanisms have been proposed in the literature, e.g. scenarios with large primordial neutrino asymmetries [8, 9] or with low-reheating temperature [10].

An alternative approach introduces a Fermi-like non-standard interaction between active and sterile eigenstates mediated by a massive gauge boson  $X$ , with  $M_X \ll M_W$  [11, 12, 13]. The strength of the non-standard secret interaction  $G_X$  drives the collisional rate and as long as the universe expands the matter potential generated by the secret coupling declines leading to a resonance in the sterile neutrino sector. This translates into a sterile production due to the combination of the resonant Mikheyev-Smirnov-Wolfenstein effect [14, 15] and non-resonant Dodelson-Widrow production [16]. Considering a coupling constant  $g_X \leq 10^{-2}$  and for masses of the mediator larger or of the order of 10 eV, the sterile production would have a considerable effect on the light elements production during the Big Bang Nucleosynthesis (BBN). Assuming smaller values of the mediator mass, sterile neutrinos would still be produced at  $T \ll 0.1$  MeV [17]. Mirizzi et al. in [18] have shown that in a certain region of the parameter space ( $g_X$ - $M_X$ ) where the mass of the mediator is smaller enough to allow the sterile production after the neutrino decoupling, the process of flavour equilibration is fast and produces a sizeable  $\nu_s$  abundance. In addition this mechanism reduces the effective number of neutrinos to  $N_{\text{eff}} \simeq 2.7$  at matter radiation equality (see Sec. 2 for further details) [17, 18].

The existence of a possible window for this secret interaction which allows the presence of a sterile eigenstate without adding a tension in the extra-relativistic energy content is tempting. Aim of this paper is to investigate a secret Fermi-like interaction considering a scenario with 3 active massive neutrinos, having  $\sum_i m_{\nu_i} = 0.06$  eV and one light  $m_{\nu_s} \sim 1$  eV sterile neutrino.

## 2. The model

The existence of a fourth sterile neutrino eigenstate requires the extension of the standard 3 neutrino families scenario to a  $3 + 1$  active-sterile neutrino mixing scenario. The active-sterile flavour evolution is described in [19, 8]. Since the flavour equilibration happens when neutrinos have a temperature  $T < M_X$ , we can consider the low energy approximation for the non-standard interaction, i.e. the effective strength of the interaction takes the form:

$$G_X = \frac{\sqrt{2}}{8} \frac{g_X^2}{M_X^2}. \quad (2)$$

The collisional rate of the interaction  $\Gamma_X$  is calculated using the relaxation time approximation [20] and describes a strong collisional effect that would bring the system towards a quick flavour equilibrium among the different neutrino species. The effective production rate  $\Gamma$  is the product of the average probability of conversion between active and sterile neutrinos  $\langle P(\nu_a \rightarrow \nu_s) \rangle$  with the collisional rate:

$$\Gamma_X = G_X^2 T_\nu^5 \frac{p}{\langle p \rangle} \frac{n_s}{n_a}, \quad (3)$$

where  $n_s$  and  $n_a$  are the densities in number of sterile and active neutrinos, while  $p$  and  $\langle p \rangle$  are the momentum and the average momentum respectively.

It is possible to constrain the secret interaction using different cosmological observables. In [17] the authors perform a study on deuterium primordial abundances  $^2H/H$  for a coupling constant  $g_X \gtrsim 10^{-2}$  and masses of the mediator  $M_X \gtrsim 10$  MeV, thus excluding a large part of the parameter space. Alteration in the production of light elements during BBN is due to a larger value of  $N_{\text{eff}}$  and to the spectral distortion of electron neutrinos when active-sterile oscillations occur close to the neutrino decoupling. Taking smaller values of the mediator mass the sterile production is suppressed before the neutrino decoupling and this choice leaves unchanged the BBN dynamics, but at temperatures less than 1 MeV sterile neutrinos are still in a collisional regime, due to their secret self-interactions. Neglecting the contribution of the resonance and considering only a pure collisional production, the average probability of conversion takes the form:

$$\langle P(\nu_a \rightarrow \nu_s) \rangle \simeq \frac{1}{2} \sin^2 \theta_{as}. \quad (4)$$

In this framework even a small population of sterile neutrinos can generate a large scattering rate at relatively low temperatures for sufficiently large values of the coupling constant  $G_X$ . In particular if  $G_X > 10^8 G_F$ , where  $G_F$  is the Fermi constant, the decoupling of the non-standard interaction would take place at redshift  $z \sim 5 \times 10^4$ , which means a temperature of a few tens eV; this implies the following energy density equilibration. Going from an initial energy density to a final one [7]:

$$\rho_\nu^{in} = 3 \cdot \frac{7}{8} \left( \frac{4}{11} \right)^{\frac{4}{3}} \rho_\gamma \rightarrow \rho_\nu^{fin} = 4 \left( \frac{3}{4} \right)^{\frac{4}{3}} \cdot \frac{7}{8} \left( \frac{4}{11} \right)^{\frac{4}{3}} \rho_\gamma. \quad (5)$$

The consequence of this behaviour is a reduction in the energy density of the neutrino sector which translates into a slightly lower value for the effective number of neutrino families with respect to the standard value:

$$N_{\text{eff}} = 4 \cdot \left( \frac{3}{4} \right)^{\frac{4}{3}} = 2.7. \quad (6)$$

In this work, we want to study this model (we will refer to it as the  $(3+1)\nu$  model) looking at the effect of the interaction on cosmological neutrino perturbations and consequently CMB temperature anisotropies. We will include the effect of the interaction in the density and pressure perturbations inside the neutrino fluid, this modifies the CMB angular power spectrum (APS) by increasing the power mainly at high multipoles i.e. at small angular scales (see Sec. 3).

### 3. Results

In the cosmological framework neutrino perturbations are evolved through the Boltzmann equation and we adopt the same notation of [21]:

$$\frac{\partial \Psi}{\partial \tau} + i \frac{q(\vec{k} \cdot \hat{n})}{\epsilon} \Psi + \frac{d \ln f_0}{d \ln q} \left[ \dot{\phi} - i \frac{q(\vec{k} \cdot \hat{n})}{\epsilon} \Psi \right] = \frac{1}{f_0} \hat{C}[f], \quad (7)$$

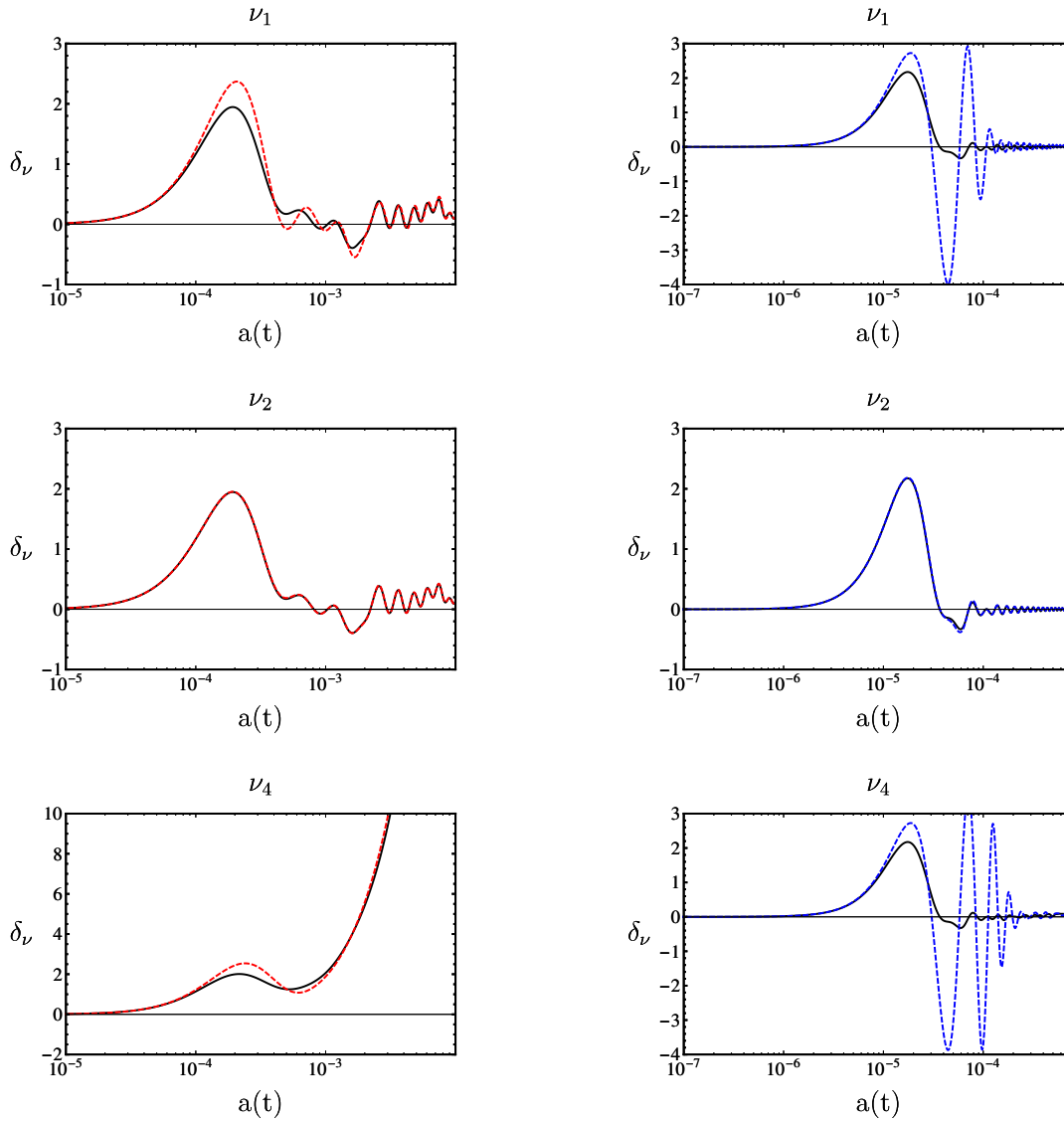
where  $\tau$  is the conformal time,  $f$  is the distribution function of neutrinos and  $\Psi$  is the perturbation. The right hand side of the equation is the collisional term which consists in a complicated integral involving specific scattering terms for the considered processes. Its calculation would be too demanding from a computational point of view and generally excessively sophisticated for the purpose of this study. Thus, as said before, we use the relaxation time approximation where:

$$\hat{C}[f] \simeq a \Gamma \delta f. \quad (8)$$

Inside this collisional term,  $2 \leftrightarrow 2$  processes are taken into account and the most generic form of the scattering rate can be written as:

$$\Gamma = \begin{bmatrix} \sin^2 \theta_{as} & 0 & 0 & \sin \theta_{as} \cos \theta_{as} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \sin \theta_{as} \cos \theta_{as} & 0 & 0 & \cos^2 \theta_{as} \end{bmatrix} G_X^2 T^5, \quad (9)$$

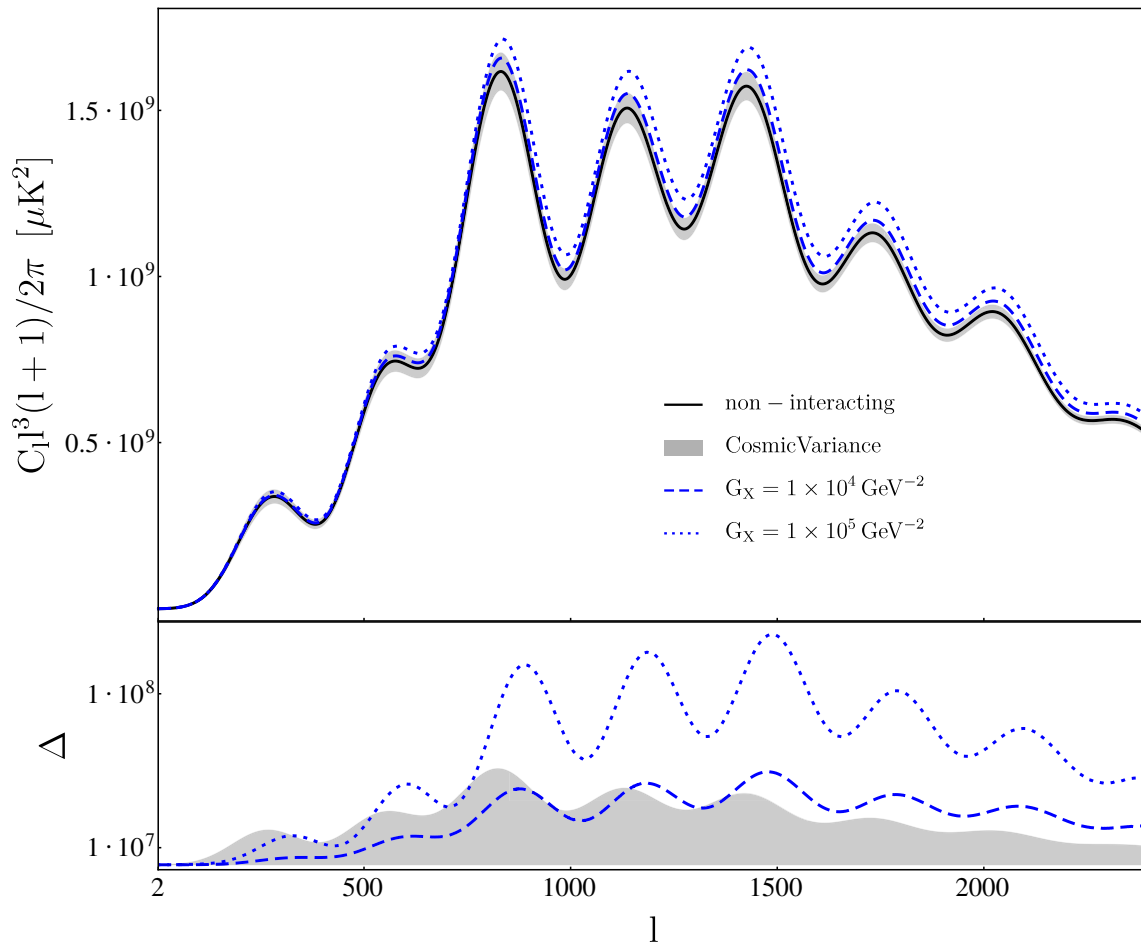
where we considered the mass basis in order to evolve the perturbations inside the public code CAMB [22, 23], basically considering the sterile state as a superposition of neutrino mass eigenstates  $\nu_1$  and  $\nu_4$ . In Figure 1 it is possible to appreciate the effects of the interaction on the density perturbations  $\delta_\nu = \delta\rho_\nu/\rho_\nu$  (the first order of Boltzmann hierarchy) for different perturbation wave numbers.



**Figure 1.** Density perturbations as function of the universe scale factor  $a(t)$  for the  $(3+1)\nu$  model for two different wave numbers, left column  $k = 0.05 \text{ Mpc}^{-1}$ , right column  $k = 0.5 \text{ Mpc}^{-1}$ , in case of no interaction (black solid line) and in case of interaction mediated by a coupling constant  $G_X = 10^5 G_F$  (colored dashed line).

Out of the horizon the physics is unchanged and the evolution is dominated by the metric perturbation. As the mode enters the horizon it starts to oscillate and from this moment on the dynamic is influenced by micro-physics, thus the larger the magnitude of the interaction the

larger the effects on the oscillations of the density perturbations. Considering the interacting cases, the blue dashed line refers to the mode  $k = 0.5 \text{ Mpc}^{-1}$  which crosses the horizon at approximately  $z \sim \text{few} \times 10^5$ , the mode  $k = 0.05 \text{ Mpc}^{-1}$  (red dashed line) enters the horizon at a redshift an order of magnitude lower, this translates into a greater effect. Notice that the intensity of the effect depends also on the probability of conversion which is greater for  $\nu_s - \nu_s$  due to the  $\cos^2 \theta_{as}$  dependency. The corresponding effect on the temperature anisotropies power spectrum is an increase of the power over all the multipoles, especially on small angular scales as expected from the perturbation analysis which revealed a greater impact of the interaction on scales that enter the horizon at early times with respect the photon recombination.



**Figure 2.** Upper panel: theoretical angular power spectrum for the  $(3+1)\nu$  model and for two different values of the coupling constant  $G_X$ , the blue dashed line is obtained setting  $G_X = 1 \times 10^4 \text{ GeV}^{-2}$ , the blue dotted one represents the case  $G_X = 1 \times 10^5 \text{ GeV}^{-2}$ . The black solid one is the  $3+1$  non-interacting case ( $G_X = 0$ ) with the corresponding cosmic variance (grey filled area). In the lower panel we show the corresponding differences among the interacting and non interacting cases. The line-style notation is the same in the two panels. In order to underline the effect of the interaction all the spectra have been obtained starting from the same set of cosmological parameters for the best-fit [4] of the non-interacting case.

In Figure 2 it is possible to appreciate the impact of the interaction on the main observable of the CMB framework. The upper panel shows the APS for the  $(3+1)\nu$  model in case of no interaction and for two different values of the coupling constant  $G_X = 10^4 \text{ GeV}^{-2}$  and  $G_X = 10^5 \text{ GeV}^{-2}$  respectively. In the bottom panel we present the difference of the two interacting cases with respect to the non-interacting one.

#### 4. Conclusions

We have shown the effects of a non-standard Fermi-like interaction among three active and one light sterile neutrinos in the primordial universe framework; we studied their impact on the perturbations and, thus, on the angular power spectrum of the CMB. When the interaction is dominant, if neutrinos are tightly coupled their anisotropic stress is suppressed and eventually vanishes, thus the damping of density perturbation due to neutrino free streaming is no more effective and the neutrino fluid undergoes acoustic oscillations. Since the fluid starts to oscillate when the wavelength of a perturbation enters the horizon and the interaction is stronger at early times, the effect is greater on small scales. Considering an interaction strength  $10^9 \div 10^{10}$  times greater than the standard Fermi weak interaction, the impact on the CMB APS is, over all the multipoles, larger than the theoretical uncertainty given by the cosmic variance. This translates into a quantifiable effect that can balance the presence of a sterile massive neutrino eigenstate suggested by the SBL anomalies. Therefore, the model can be tested against available CMB data in a future work.

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