Journal of Physics: Conference Series **598** (2015) 012029 doi:10.1088/1742-6596/598/1/012029

Cosmological bounds on active-sterile neutrino mixing after Planck data

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Abstract. Light sterile neutrinos can be produced by oscillations with active neutrinos in the early universe. Their properties can be constrained by their contribution as extra-radiation, parametrized in terms of the effective number of neutrino species $N_{\rm eff}$, and to the universe energy density today $\Omega_\nu h^2$. Both these parameters have been measured to quite a good precision by the Planck satellite experiment. We use these results to update the bounds on the parameter space of (3+1) sterile neutrino scenarios, with an active-sterile neutrino mass squared splitting in the range $(10^{-5} - 10^{2})\,{\rm eV}^2$. For the first time we take into account the possibility of two non-vanishing active-sterile mixing angles. We find that the mass and mixing parameter space is severely constrained. In particular sterile neutrinos with $m \sim \mathcal{O}(1)$ eV are strongly disfavoured by neutrino mass bound.

1. Introduction

In recent years a renewed attention has been devoted to low-mass sterile neutrinos (m ∼1 eV), after intriguing but controversial hints coming from laboratory oscillation experiments. Many analyses have been performed to explain the anomalies in scenarios with one (dubbed "3+1") or two ("3+2") eV sterile neutrinos [1, 2]. In this context, cosmological observations represent an important tool, being sensitive to the number of neutrinos and to their mass at eV scale. Indeed, sterile neutrinos can be produced by oscillations with the active ones in the early universe participating, if sufficiently light, to the radiation content, parametrized in terms of $N_{\rm eff}$, leaving possible traces on different cosmological observables. Moreover they can contribute to the energy density in the universe today. The Big Bang Nucleosynthesis (BBN) marginally allows one fully thermalized sterile neutrino. The Cosmic Microwave Background (CMB) measurements have shown a preference for extra radiation which has been reduced over the years. Moreover, even a single extra thermalized sterile neutrino with mass $m \sim 1$ eV appears to be inconsistent with mass bounds from CMB and LSS data. A recent and important contribution in determining the *dark* radiation content in the early universe and in constraining the neutrino mass bound is represented by the first data release of the Planck experiment providing, in combination with WMAP, Baryon Acoustic Oscillation and high multipole CMB data, $N_{\rm eff} = 3.30 \pm 0.27$ at 68 % C.L. [3]. Given this partially contradictory situation it is necessary to assess the sterile abundance through the flavor evolution of the active-sterile neutrino ensemble. In particular, motivated by the recent data release of the Planck experiment, we performed an extensive scan of the sterile neutrino parameter space in a 3+1 model, with the sterile mass splitting $\Delta m^2_{\rm st}$ in the range $(10^{-5} - 10^{2})\,\mathrm{eV}^2$ and considering for the first time the possibility of two non-vanishing active-sterile mixing angles. Once more we confirm the tension between the cosmological data and the mass and mixing suggested by the laboratory hints.

2. Setup of the (3+1) flavor evolution

We consider one single light sterile neutrino ν_s, which mixes with the active neutrino states ν_e, ν_μ, ν_τ. In our study we fix the values of the three active mixing angles to the current best-fit from global analysis of the different active neutrino oscillation data, $\sin^2\theta_{12} = 0.307$, $\sin^2\theta_{23} = 0.398$, and $\sin^2\theta_{13} = 0.0245$. Concerning the active-sterile mixing angles we choose as representative range $10^{-5} \leq \sin^2\theta_{i4} \leq 10^{-1}$ (i=1,2,3).

The solar and the atmospheric mass-square differences are given by $\Delta m^2_{21} = m^2_2 - m^2_1 = 7.54 \times 10^{-5}\ \mathrm{eV}^2$ and $|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.43 \times 10^{-3}\ \mathrm{eV}^2$, respectively. Concerning the sterile mass-square difference, we consider the following range $10^{-5} \leq \Delta m^2_{41}/\mathrm{eV}^2 \leq 10^2$.

The neutrino (antineutrino) ensemble in the early universe plasma, is described in terms of a 4×4 momentum-averaged density matrix ρ ($\bar{\rho}$). The evolution equation for neutrino ensemble is given by:

$$\mathrm{i}\,\frac{d\rho}{dt} = [\Omega_{\mathrm{vac}}, \rho] + [\Omega_{\mathrm{mat}}, \rho] + [\Omega_{\nu-\nu}, \rho] + C[\rho]\,, \tag{1}$$

and a similar expression holds for the antineutrino matrix $\bar{\rho}$. The first term on the right-hand-side of Eq. (1) represents the vacuum term, the second and the third ones describe refractive interactions, in particular we have the ordinary matter term and the neutrino-neutrino one, respectively. Remarkably, the matter term can induce Mikheyeev-Smirnov-Wolfenstein (MSW)-like resonances when it becomes of the same order of the neutrino mass-squared splitting. In the sterile sector resonances are associated with the three different active-sterile mass splittings Δm^2_{4i} and with the different θ_{i4} mixing angles. Finally, the last term in the right-hand-side of Eq. (1) is the collisional term.

3. Cosmological bounds: results

In our investigation we use as benchmark the Planck joint constraints for extra radiation and mass. In particular, the first quantity we are exploiting to constrain the sterile neutrino parameter space is the overall non electromagnetic radiation content, parametrized via N_{eff},

$$N_{\mathrm{eff}} = \frac{1}{2}\mathrm{Tr}(\rho + \bar{\rho})\ \ . \tag{2}$$

Our bounds are given comparing this number with the one measured by Planck experiment, $N_{\mathrm{eff}} < 3.80$ at 95 % C.L. [3]. Since neutrinos with mass larger then 1 eV would be not relativistic anymore at the CMB decoupling, we cannot use radiation constraints. However, mass bounds become very important through the neutrino contribution to the energy density in the Universe. Assuming the existence of a massive sterile neutrino together with two massless active neutrinos and one very light (i.e. m 0.06 eV), the second quantity is

$$\Omega_\nu h^2 = \frac{1}{2}\frac{\sqrt{\Delta m^2_{41}} \cdot (\rho_{ss} + \overline{\rho}_{ss})}{94.1\ \ \mathrm{eV}}\ \ . \tag{3}$$

The constraint on the neutrino energy density is $\Omega_\nu h^2 \leq 0.0045$ at 95 % C.L, coming from the Planck+ BAO bound on the effective sterile mass $m_s^{\mathrm{eff}} \leq 0.42$ eV. In Fig. 1 we present our exclusion plot in the planes $(\Delta m^2_{41}, \sin^2\theta_{14})$ for different values of the other mixing angle $\sin^2\theta_{24}$. In according to the analysis for the laboratory anomalies, $\sin^2\theta_{34}$ is fixed to zero. The excluded regions from N_{eff} are those on the right or at the exterior of the black contours, while

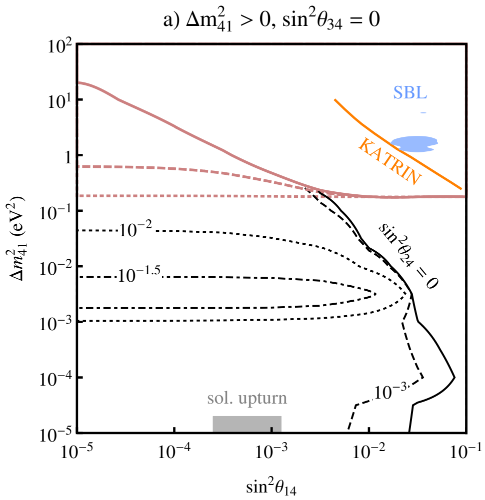

Figure 1. Exclusion plots for the active-sterile neutrino mixing parameter space from $N_{\rm eff}$ (black curves) and $\Omega_\nu h^2$ (red curves) at 95 % C.L.

the ones from $\Omega_\nu h^2$ are above the red contours. We discuss at first the bound on $N_{\rm eff}$. The most conservative limit corresponds to $\sin^2\theta_{24} = 0$, where for $\Delta m^2_{41} > 10^{-2}$ eV^2 the exclusion contour is a straight line in this plane. We cut the bound at $\Delta m^2_{41} \sim 10^{-1}$ eV^2, since for higher masses sterile neutrinos would almost be non-relativistic at the CMB epoch. Increasing the value of $\sin^2\theta_{24}$, the constraint on the parameter space becomes stronger. Large values of $\sin^2\theta_{24}$ would dominate the sterile neutrino production excluding regions otherwise permitted. Finally, we represent with a rectangle in the lower part of the plot, the region of parameters corresponding to a light sterile neutrino suggested to solve the problem of the upturn of the solar neutrino spectrum. We realize that this region is excluded if $\sin^2\theta_{24} > 10^{-3}$. We address the reader to our publication [4] for more details.

Passing now to the bounds from $\Omega_\nu h^2$, again the most conservative limit is for $\sin^2\theta_{24} = 0$. The bound becomes more stringent increasing the value of $\sin^2\theta_{24}$. In particular, for $\sin^2\theta_{24} \geq 10^{-2}$, $\Delta m^2_{41} \geq 10^{-1}$ eV^2 is excluded independently on the value of $\sin^2\theta_{14}$, since sterile neutrinos would be always produced with thermal abundances. For comparison, we also show the slice at $\sin^2\theta_{24} = 10^{-2}$ of the 95 % C.L., for the allowed region obtained from the global analysis of short-baseline oscillation data [1] (filled region in the up right part of the plot denoted by SBL). We observe that it is completely ruled out by the cosmological bound from $\Omega_\nu h^2$. A possible escape route could be represented by the suppression of the sterile neutrino production [5].

Acknowledgments

N.S. acknowledges support from the European Union FP7 ITN INVISIBLES (Marie Curie Actions, PITN- GA-2011- 289442).

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