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# The masses of active neutrinos in the $\nu$MSM from X-ray astronomy

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In an extention of the Standard Model by three relatively light right-handed neutrinos (the $\nu$MSM model) the role of the dark matter particle is played by the lightest sterile neutrino. We demonstrate that the observations of the extragalactic X-ray background allow to put a strong upper bound on the mass of the lightest active neutrino and predict the absolute values of the mass of the two heavier active neutrinos in the $\nu$MSM, provided that the mass of the dark matter sterile neutrino is larger than 1.8 keV.

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Recently a simple extention of the Minimal Standard Model (MSM) by three relatively light (with the Majorana masses smaller than the electroweak scale) right-handed neutrinos was suggested [1, 2]. The model (dubbed $\nu$MSM) allows simultaneous explanation of neutrino oscillations and baryon asymmetry of the universe and proposes the candidate for the dark matter – the lightest long-lived sterile neutrino. Unlike traditional see-saw mechanism [3], the tiny values of the active neutrino masses in this model are related to the small Yukawa coupling constants between sterile neutrinos and left-handed leptonic doublets. Small Yukawas are essential for the explanation of dark matter: the lightest sterile neutrino with the mass of a few keV can be sufficiently long-lived [4, 5]. In addition to this, small Yukawa couplings are crucial for baryogenesis in the $\nu$MSM, leading to coherence in the oscillations of sterile neutrinos [6, 2]. Moreover, they are required by some models, explaining pulsar kick velocities [7].

The Lagrangian of the $\nu$MSM has the following form:

$$\begin{aligned}\mathcal{L}_{\nu\mathrm{MSM}} &= \mathcal{L}_{\mathrm{MSM}} + i\bar{N}^I \partial\!\!\!/ N_I - \\ &- \left(\bar{L}_\alpha M^D_{\alpha I} N_I + \frac{1}{2} M_I \bar{N}^c_I N_I + \mathrm{h.c.}\right). \qquad (1)\end{aligned}$$

In Eq. (2) we fixed the basis in which the sterile neutrino Majorana mass matrix $M_I$ is diagonal (fields $N_I$ denote right-handed neutrinos, $I = 1, 2, 3$), whereas the Dirac mass matrix providing the mixing between left-handed $L_\alpha$ and right-handed neutrinos is $M^D_{\alpha I} \equiv F_{\alpha I}\langle\Phi\rangle$, where $\alpha = \{e, \mu, \tau\}$ is the active neutrino flavor, $F_{\alpha I}$ is a set of Yukawa couplings, and $\langle\Phi\rangle \simeq 174$ GeV is the Higgs vacuum expectation value. The sterile neutrino with $I = 1$ is supposed to be the lightest one.

It was pointed out in [1] that a prediction of the absolute values of the masses of active neutrinos can be made, provided that the only source of the sterile neutrino production in the early universe is their mixing with active neutrinos. Assuming that the initial concentration (say, at temperatures greater than 1 GeV) of sterile neutrinos were zero, one can estimate [4, 5, 8] the sterile neutrino abundance $\Omega_s$ and identify it with that of the dark matter $\Omega_{DM}$. The abundance is proportional to the square of the Dirac mass and depends only weakly on the sterile neutrino Majorana mass in the keV region [4, 5, 8]. With the use of these results the constraint on the parameters of the $\nu$MSM can be written as [1]:

$$\sum_{\alpha=e,\mu,\tau} |M^D_{\alpha 1}|^2 = m_0^2, \qquad (2)$$

where $m_0^2 = \mathcal{O}(0.1\,\mathrm{eV})^2$ with an uncertainty of, say, factor of a few, coming from the poor knowledge of the dynamics of the hadronic plasma at the temperature of the sterile neutrino production. The restrictions from the observations of the cosmic microwave background and the matter power spectrum inferred from Lyman-$\alpha$ forest data [9, 10] gives a constraint (see also [11] for a most recent study):

$$M_1 > 2\ \mathrm{keV}. \qquad (3)$$

Similarly to Eq. (2) this constraint assumes that the sterile neutrino was produced in active-sterile neutrino oscillations and plays a role of so-called warm dark matter

(WDM). A weaker, but an assumption-free lower bound on the mass of the lightest sterile neutrino

$$M_1 \gtrsim 0.5 \text{ keV} \tag{4}$$

comes from the application of Tremaine-Gunn arguments [12] to the dwarf spheroidal galaxies [13]. Now, since $M_1$ from (3), (4) is much larger than $m_0$, the see-saw formula [3] for active neutrino masses

$$M^\nu = -\left(M^D\right)^T \; M_I^{-1} \, M^D \tag{5}$$

is valid. The analysis of Eq. (5) reveals [1] that the constraint (2) together with (3) leads to an upper bound on the lightest neutrino mass, $m_\nu < m_0^2/M_1 \simeq \mathcal{O}(10^{-5})$ eV. Now, since this bound is much smaller than $\sqrt{\Delta m^2_{\rm sol}} \simeq \simeq 10^{-2}$ eV, where $\Delta m^2_{\rm sol}$ is the solar mass square difference, the masses of other two active neutrinos should be given by

$$m_2 = \sqrt{\Delta m^2_{\rm sol}}, \quad m_3 = \sqrt{\Delta m^2_{\rm atm}} \tag{6}$$

or by

$$m_1 \approx m_2 = \sqrt{\Delta m^2_{\rm atm}}, \;\; m_1^2 - m_2^2 = \Delta m^2_{\rm sol}, \tag{7}$$

if the hierarchy is inverted[1)]. In numbers [14]

$$\begin{aligned} \Delta m^2_{\rm sol} &= (7.2 - 8.9)\cdot 10^{-5} \text{ eV}^2, \\ \Delta m^2_{\rm atm} &= (1.7 - 3.3)\cdot 10^{-3} \text{ eV}^2. \end{aligned} \tag{8}$$

The errors correspond to 99% confidence level range of $2.58\sigma$. Clearly, the predictions (6), (7) remain in force provided the mass of the lightest neutrino is smaller than the error bar in the solar neutrino mass difference, namely for (99% C.L.)

$$m_\nu < 3\cdot 10^{-3} \text{eV}. \tag{9}$$

In fact, the results (2) and (3) are not universal and do depend on the details of universe evolution above the temperature of Big Bang Nucleosynthesis (BBN). In particular, they are sensible to the universe content at the time of sterile neutrino production and on particle physics well beyond the electroweak scale. For example, a substantial lepton asymmetry may lead to enhancement of the production of the sterile neutrinos [15]. If the reheating temperature of the universe is just above the nucleosynthesis scale [16] the consideration leading to Eq. (2) is not applicable at all. If the sterile neutrino has large enough coupling to inflaton it will be created right after inflation rather than at small temperatures. The reheating of the universe between the moment of the sterile neutrino production and nucleosynthesis due to late phase transitions or due to hypothetical heavy particle decays would dilute the concentration of the sterile neutrinos and decrease their momentum, leading to smaller free streaming lengths at the onset of structure formation.

In this note we consider the question whether a *robust* prediction (which does not depend on the uncertainties discussed above) can be made for active neutrino masses in the $\nu$MSM provided all 100% of the dark matter in the universe is associated with sterile neutrino.

Our analysis is based on the astrophysical constraint coming from the analysis of the X-ray background derived in [17] (for earlier works see [5, 18]). In the $\nu$MSM the lightest sterile neutrino can decay into active neutrino and photon with the width given by a trivial generalization of Pal and Wolfenstein formula [19, 20]:

$$\Gamma_\gamma = \frac{9\,\alpha_{\rm em}\, G_F^2\, M_1^3}{256\,\pi^4} \sum_{\alpha=e,\mu,\tau} |M^D_{\alpha 1}|^2. \tag{10}$$

The increase of the Dirac neutrino mass $|M^D_{\alpha 1}|^2$ (notice that exactly the same combination appears in Eq. (2)) would lead to the increase of the X-ray flux from the sterile neutrino dark matter. Clearly, the astrophysical constraints on this flux would lead to the limit on $m_0$, and, therefore to the prediction of active neutrino masses if $m_0$ happens to be small enough.

The corresponding bound on $m_0$ can be found from ref. [17]. As we have shown in this paper, a non-observation of a peculiar feature in the X-ray background associated with the decays of dark matter sterile neutrino implies that[2)]

$$\Omega_s \sin^2(2\theta) < 3\cdot 10^{-5}\left(\frac{M_1}{\rm keV}\right)^{-5}, \tag{11}$$

where $\Omega_s$ is the dark matter abundance. This equation describes an empirical fit to the corresponding exclusion region coming from the analysis of the HEAO-1 and XMM missions and is valid at $M_1 > 1$ keV (see [17] and references therein). In the limit $m_0 \ll M_1$, one gets an upper bound on the lightest active neutrino mass $m_\nu < m_0^2/M_1$. Combined with Eq. (1), this can be recast into the constraint on $m_\nu$:

$$m_\nu < 3.4\cdot 10^{-2}\left(\frac{0.22}{\Omega_s}\right)\left(\frac{\rm keV}{M_1}\right)^4 \text{ eV}. \tag{12}$$

[1)]The same conclusion is true if the bound (4) is taken.

[2)]Sterile neutrino mass $M_1$ was denoted by $m_s$ in [17], mixing angle $\theta$ is defined via $\tan 2\theta \equiv 2m_0/M_1$.

The weakest limit on the mass of the lightest active neutrino comes from the region of smaller sterile neutrino masses. One can see that for $\Omega_s = 0.22$ and

$$M_1 > 1.8\ \text{keV} \tag{13}$$

the condition (9) is satisfied. In other words, the prediction of active neutrino masses (6), (7), made in [1] is robust if the mass of dark matter sterile neutrino is large enough.

In conclusion, we have demonstrated that in the $\nu$MSM the astronomical observations of the X-ray background allow to put severe constraints on the mass of the lightest sterile neutrino and to make a prediction of the masses of other active neutrinos, independently on assumptions on the evolution of the early universe above the BBN temperatures, provided the mass of dark matter neutrino is larger than 1.8 keV. For smaller masses $M_1$, admitted by the constraint (4), the predictions (6), (7) are not in general valid.

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