7 keV sterile neutrino Dark Matter in extended seesaw framework

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The appearance of a 3.5 keV photon line in the X-ray spectra of Andromeda galaxy and other galaxy clusters including the Perseus galaxy can be interpreted as the signal of a 7 keV sterile neutrino dark matter candidate as one of the plausible explanations. We present here a novel framework of extended seesaw mechanism where the lightest sterile neutrino neutrino acts as a Dark Matter candidate and its decay into a photon and an ordinary neutrino can explain the appearance of the X-ray signal with energy 3.5 keV. For implementing the idea, we add two different types of neutral fermion singlets \((S_L, N_R)\) to the SM light neutrino \(\nu_L\) so that the light neutrino mass is governed by the generic linear seesaw formula. We discuss the complementarity constraints on the model parameters including sterile-active neutrino mixing angle within the extended seesaw framework. Favorably, this framework can be embedded in a SO(10) grand unified theory.

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INTRODUCTION

Dark Matter (DM), which occupies 25% of the total energy density of our present universe, still remains a mystery from particle physics point of view. Though its exploration seems quite difficult with a limited knowledge about its properties, a pretty good number of papers including ref. [1] have brought the issue little closer to our reach. The observation of an excess 3.5 keV photon line in the X-ray spectra of Andromeda galaxy and many other galaxy clusters by XMM-Newton X-ray Space observatory [2, 3] has made the topic afresh since the possibility of its appearance due to the decay of DM can not be exactly denied. This weak line has created much noise in the astro-particle world recently with the observed flux and best fit energy peak being at,

\[
\Phi_\gamma = 4 \pm 0.8 \times 10^{-6} \text{ photons cm}^{-2} \text{sec}^{-1} \\
E_\gamma = 3.57 \pm 0.02 \text{ keV}
\]

(1)

The aftermath of this finding brings Dark Matter into the plot since no other atomic transition in thermal plasma can account for this intensity. The potential candidates responsible for giving such a result can be a sterile neutrino dark matter \([4, 11]\), axions or axion like particles \([12, 16]\), axinos \([17, 19]\), gravitino as decaying dark matter \([20, 22]\), moduli \([23, 25]\), Magnetic dipolar dark matter \([26, 32]\), and others \([33-35]\).

We humbly look for a possible explanation of the origin of this monochromatic 3.5 keV photon line with a 7 keV sterile neutrino dark matter as the prime tool within an extended seesaw framework. The decay of this sterile neutrino dark matter into a photon and an ordinary neutrino can explain the appearance of the X-ray signal with energy 3.51 keV. The paper is sketched as follows. In Sec.II, we discuss briefly the extended linear seesaw framework and provide correct picture of masses and mixing with the ordinary neutrinos in the one generation case. In Sec.III, we extend the study in a three generation picture using the consistent model parameters resulting lightest sterile neutrino mass around 7 keV and active-sterile mixing angle around \(10^{-5}\). We present the status of keV sterile neutrino dark matter including the stability issue and relic abundance in Sec.IV with the existing experimental constraints. Towards the end, we summarize our results and conclude the work.

FRAMEWORK ACCOMMODATING 7 KEV DARK MATTER

We have added two extra neutral fermions \(N_i, S_i\), \(i=1,2,3\) that are singlets under SM gauge group \(SU(2)_L \times U(1)_Y\) to the usual SM leptons

\[
\ell_L = \left( \begin{array}{c} \nu_\alpha \\ e_\alpha \end{array} \right)_L , \ e_\alpha R,
\]

where \(\alpha = e, \mu, \tau\) represents a flavour/generation index. The extra fermions being neutral and singlets under SM gauge group, can have Majorana mass terms (i.e. \(M_R\) for \(N\) and \(M_\mu\) for \(S\)) in the interaction Lagrangian. A notable feature of the model is that, the mass term for RH heavy neutrino \((M_R)\) is purposely larger than other mass terms present in the model.

The extended seesaw mechanism featuring similar mass matrices for Dirac neutrino and up-quark can give interesting results since type I seesaw contribution is exactly canceled out here and can be accessible to LHC. Thus we have chosen here an extended Linear seesaw framework woven with the addition of a large Lepton number violating mass term \(M_R\) to the minimal linear seesaw scheme \([36, 42]\) where the lightest sterile neutrino \(S_{\text{lightest}}\) acts as a Dark Matter candidate. We present below the interaction Lagrangian, masses and mixing of the framed model and examine whether it results 7 keV sterile neutrino dark matter with adequate mixing with the active neutrinos to be able to account for the unidentified 3.5 keV X-ray line.

The relevant interaction Lagrangian for extended linear seesaw framework having both the lepton number violating Majorana mass terms for \(N\) and \(S\) with \(\mu = 0\) is as follows,

\[
-\mathcal{L}_{\text{mass}} = M_D \overline{\nu}_L N_R + M_L \overline{\nu}_L S_L \\
+ M_S \overline{\nu}_L S_R + \frac{1}{2} M_R \overline{N}_R N_R^* N^*_R \text{ h.c.} \tag{2}
\]
where $M_D$ is the Dirac neutrino mass matrix connecting $\nu_L - N_R$, $M$ is the heavy $N - S$ mixing matrix, $M_L$ is the lepton number violating $\nu - S$ mixing matrix and $M_R$ is the large Majorana mass matrix for heavy RH neutrinos $N_R$. After the electroweak symmetry breaking, one can write down the full $(9 \times 9)$ neutrino mass matrix in the $(\nu_L, N_R, S_L)$ basis as,  

$$ \mathcal{M} = \begin{pmatrix} 0 & M_D & M_L \\ M_D^T & M_R & M_T \\ M_L^T & M_T & 0 \end{pmatrix}, \quad (3) $$

The allowed hierarchy between different neutral fermion mass matrices is $M_R > M, M_D \gg M_L$. Since the lepton number violating term for heavy RH neutrinos is heavier than the other mass scales, it is eventually integrated out from the Lagrangian resulting in 

$$ -\mathcal{L}_{\text{eff}} = \left( M_D \frac{1}{M_R} M_D^T - M_D M^{-1} M_L^T - M_L M^{-1} M_D^T \right)_{\alpha \beta} \nu_{\alpha}^T \nu_{\beta} + \left( M_D \frac{1}{M_R} M_D^T \right)_{\alpha j} (\bar{\nu}_\alpha S_j + \bar{S}_j \nu_\alpha) + \left( M \frac{1}{M_R} M_D^T \right)_{i j} S_i^T S_j, \quad (4) $$

which, in the $(\nu, s)$ basis, gives the $6 \times 6$ mass matrix

$$ \mathcal{M}_{\text{eff}} = \left( M_D M_R^{-1} M_D^T + M_D M^{-1} M_L^T + M_L M^{-1} M_D^T \right)_{\alpha \beta} \nu_{\alpha}^T \nu_{\beta} + \left( M_D M_R^{-1} M_D^T \right)_{\alpha j} (\bar{\nu}_\alpha S_j + \bar{S}_j \nu_\alpha) + \left( M D M_R^{-1} M_D^T \right)_{i j} S_i^T S_j, $$

An unique feature of extended linear seesaw mechanism, with desired mass hierarchy $M_R > M, M_D \gg M_L, \mu$ is that the type-I seesaw contribution to light neutrino masses is exactly canceled out, and the mass formula for light neutrinos (with $\mu = 0$) becomes 

$$ m_\nu = -M_D M^{-1} M_L^T - M_L M^{-1} M_D^T. \quad (5) $$

The mass formula for heavy RH neutrinos and heavy sterile neutrinos are

$$ M_S \sim -M M_R^{-1} M_D^T \quad (6) \quad M_N \sim M_R + \cdots, \quad (7) $$

For a case study, we have considered the model parameters as presented in Table I. Using these model parameters one can find the light neutrino mass through extended linear seesaw contribution to be $m_\nu = (M_D/M)M_L = 0.1 \text{ eV}$ for $10 \text{ keV}$ mass for $M_L$.

As seen from the Table II, the extended linear seesaw mechanism consistently results 7 keV lightest sterile neutrino dark matter for all choices of the model parameters and the active-sterile neutrino mixing at order of $10^{-5}$. Thus, the framework not only holds an answer for the 3.5 keV X-ray line as observed by XMM-Newton X-ray Space observatory but also agrees with the oscillation data.

| $M_D$ ($\text{GeV}$) | $M$ ($\text{GeV}$) | $\theta_{SV} \simeq M_D/M$ | $M_R$ ($\text{GeV}$) | $|M_S| \simeq M^2/M_R$ |
|---------------------|------------------|--------------------------|-------------------|---------------------|
| 1                   | $10^5$           | $10^{-5}$                 | $10^{15}$         | 7 keV               |
| 0.1                 | $10^4$           | $10^{-5}$                 | $10^{13}$         | 7 keV               |
| 0.01                | $10^3$           | $10^{-5}$                 | $10^{11}$         | 7 keV               |
| 0.001              | $10^2$           | $10^{-6}$                 | $10^{9}$          | 7 keV               |

TABLE I: Input model parameters within extended seesaw mechanism examined for one generation case in order to yield 7 keV sterile neutrino dark matter mass and sterile-active neutrino mixing of the order of $10^{-5}$.

### NUMERICAL RESULTS:

We present here a numerical study of masses and mixing within extended linear seesaw framework with $\nu_i, N_i, S_i$ $i=1,2,3$ where the model parameters may have Left-Right symmetric origin or $SO(10)$ origin. In such extended seesaw scheme both the sterile neutrinos have Majorana mass (where $S$ has mass of the order $M^2/M_R$ and $N$ has mass of the order $M_R$) and their admixture with the ordinary neutrinos is suppressed by the factors, $M_D/M$ and $M_D/M_R$ for $S - \nu$ and $N - \nu$ cases, respectively. Contrary to the case of canonical seesaw where the GUT scale right-handed neutrino mass (equivalent to seesaw scale) makes the model inaccessible to current accelerator experiments, here the mass of $M$ can be much smaller since the light neutrino mass formula involves $(M_D/M), M_L$ and the sub-eV scale of light neutrinos can be consistently addressed by suitably adjusting the small lepton number violating term $M_L$ even with EW scale of $M$.

The Dirac-neutrino mass matrix is an arbitrary complex matrix in the present case, but there is a possibility that $M_D$ can be similar to the charged lepton mass matrix $M_\ell$ ($M_D$ is similar to the up-type quark mass matrix $M_u$) originating from left-right model (high scale Pati-Salam symmetry or $SO(10)$ GUT) [43]. The other $N - S$ mixing mass matrix $M$, in principle, can take any form, but we have considered it to be diagonal for the sake of simplicity. However, the diagonal elements can be constrained from the existing experimental bound on unitarity violation in the lepton sector. Similarly, we consider here the diagonal structure for $M_R$ though both diagonal and general form of $M_R$ is possible when this extended seesaw framework will be embedded in a $SO(10)$ GUT model.

A. $M_D \simeq M_u$ signifying its origin of high scale Pati-Salam symmetry or $SO(10)$ GUT:

Within high scale Pati-Salam symmetry relating quarks and leptons with each other or in $SO(10)$ GUT models, it is found that the Dirac neutrino mass matrix is similar to the up-type quark mass matrix. Using the running masses $(m_u, m_c, m_t) = (0.00233, 1.275, 160) \text{ GeV}$ and Cabbibo-Kobayashi-Maskawa mixing matrix, $V_{CKM}$ [44], the Dirac
neutrino mass matrix is structured to be,
\[
M_D(\text{GeV}) \approx M_{\text{diag}} = V_{\text{CKM}} \tilde{M}_a V_{\text{CKM}}^T
\]
\[
= \begin{pmatrix}
0.06 & 0.3 - 0.02i & 0.55 - 0.53i \\
0.30 - 0.02i & 1.48 - 0.0i & 6.53 - 0.001i \\
0.55 - 0.5i & 6.534 - 0.0009i & 159.7
\end{pmatrix} . \tag{8}
\]

Using this Dirac neutrino mass matrix, diagonal structure of \(N-S\) mixing matrix \(M = \text{diag}(8.4 \times 10^3, 10^5, 10^6)\) GeV, and heaviest RH neutrino mass matrix \(M_R = \text{diag}(10^{13}, 2 \times 10^{13}, 5 \times 10^{13})\) GeV, we can derive the sterile-active neutrino mass matrix as
\[
\tilde{M}_S = (7 \text{ keV}, 0.5 \text{ MeV}, 20 \text{ MeV})
\]
\[
\theta_\nu = 10^{-6} \times \begin{pmatrix}
7.94 & 0.302 - 0.22i & 0.55 - 0.53i \\
35.3 - 2.62i & 14.8 & 6.53 - 0.001i \\
65.4 - 63.1i & 65.3 - 0.009 & 159
\end{pmatrix} \tag{9}
\]

Notably, the presence of a large number of intermediate symmetry breaking steps from \(SO(10)\) to SM affects the value of \(M_D \approx M_a\) [43-46]. As discussed in Ref. [46], a particular form of \(M_D\) including RG Corrections is
\[
M_D = \begin{pmatrix}
0.02 & 0.098 - 0.016i & 0.146 - 0.385i \\
0.098 + 0.016i & 0.6319 & 4.88 + 0.003i \\
0.146 + 0.385i & 4.884 - 0.003i & 117.8
\end{pmatrix} \text{ GeV} . \tag{10}
\]

Assuming \(M\) to be diagonal for the sake of simplicity, \(M = \text{diag}(M_1, M_2, M_3) \approx \text{diag}(3 \times 10^3, 10^5, 5 \times 10^6)\) GeV and heaviest RH neutrino mass matrix \(M_R \approx \text{diag}(M_{R1}, M_{R2}, M_{R3}) \approx \text{diag}(1.25 \times 10^{12}, 2 \times 10^{13}, 5 \times 10^{13})\) GeV, the sterile neutrino mass eigenvalues for \(S\) is found to be \(\tilde{M}_S = (7 \text{ keV}, 0.5 \text{ MeV}, 12.5 \text{ MeV})\) and corresponding sterile-active neutrino mixing is of the order \(10^{-6}\).

### B. Dirac neutrino mass matrix is similar to charged lepton mass matrix \((M_D \approx M_L)\):

The Dirac neutrino mass matrix can be similar to charged lepton mass matrix as expected from Left-Right symmetric theory [43] and when we are working in a basis where charged lepton mass matrix is already diagonal it becomes, \(M_D \approx M_L = \text{diag}(m_e, m_\mu, m_\tau)\). Assuming diagonal structure of \(M = \text{diag}(50, 10000, 100000)\) GeV and \(|M_R| \geq 3.35 \times 10^8\) GeV (inverted pattern of heavy neutrinos mass matrix \(M_R\) of any general form) along with \(M_D \approx M_L\) the estimated value of the sterile neutrino mass eigenvalues becomes \(\tilde{M}_S = (7 \text{ keV}, 0.5 \text{ MeV}, 2 \text{ GeV}, 50 \text{ GeV})\) and corresponding sterile-active neutrino mixing of the order \(10^{-6}\).

### 3.51 KEV X-RAY LINE SIGNAL

Sterile neutrinos should mix slightly with active neutrinos in order to rationalize their origin in the early universe. Possibly, this mixing causes the active neutrinos to oscillate to sterile ones which further increases the flock of sterile neutrinos and backs the relic abundance of DM. In the nick of time, the same mixing causes a sterile neutrino \((S_1)\) to decay into a light active neutrino plus a monochromatic photon line of energy \(E_{\gamma} = m_S/2\). The analytic formula for the decay width of this process as presented in Fig. [1] is,
\[
\Gamma_{S_1 \rightarrow \nu \gamma} = \frac{9\alpha G_F^2}{1024\pi^2} m_S^5 , \tag{11}
\]
where \(\alpha\) is the fine structure constant for electromagnetic interaction, \(G_F\) is the universal Fermi coupling constant, \(m_S \approx M_{DM}\) is the mass of the sterile neutrino dark matter.

![Fig. 1: Feynman diagram for two body radiative decay of sterile neutrino dark matter into a ordinary neutrino plus a monochromatic photon line with energy 3.51 keV.](image1)

Elseways, the sterile neutrino decays into three ordinary neutrinos as shown in Fig. [2] with the decay rate,
\[
\Gamma_{S_1 \rightarrow 3\nu} = \frac{4G_F^2}{384\pi^2} \sin^2(2\theta) m_S^5 , \tag{12}
\]

![Fig. 2: Feynman diagram for sterile neutrino decay \(S \rightarrow \nu_e \nu_x \bar{\nu}_x\) via neutral current interactions.](image2)

For observed 3.5 keV X-ray line signal, it is calculated that the decay rate for sterile neutrino dark matter to \(\nu\) and a photon is \(\sim 3.3 \times 10^{-52}\) GeV. Using the PDG values \(\alpha_{em} = 1/127.94\), \(G_F = 1.1662 \times 10^{19}\) GeV and sterile-active neutrino mixing of the order of \(10^{-10}\), the dominant decay mode \(S \rightarrow 3\nu\) with a keV mass sterile neutrino dark matter results,
\[
\Gamma_{S_1 \rightarrow 3\nu} \approx 1.43 \times 10^{-53} \left( \frac{\sin^2(2\theta)}{10^{-10}} \right) \left( \frac{m_S}{\text{keV}} \right)^5 \text{ GeV} , \tag{13}
\]
while for radiative two body decay yields

$$\Gamma_{S_1 \to \nu + \gamma} \simeq 9.47 \times 10^{-56} \left( \frac{\sin^2 2\theta}{10^{-10}} \right) \left( \frac{m_{S_1}}{\text{keV}} \right)^5 \text{ GeV.} \quad (14)$$


![Graph](image)

**FIG. 3:** Estimation of life-time of decaying dark matter $\tau_{DM}$ wrt dark matter mass $M_{DM}$

The mass and mixing of a sterile neutrino should be indeed tiny to make itself a viable DM candidate which survives much longer than the universe. We demonstrate here how the stability of the sterile neutrino dark matter of 7 keV is fulfilled with a life-time $\tau_{DM} \simeq 6.2 \times 10^{27}$ secs as shown in Fig. 3. With $\sin^2 2\theta \simeq 10^{-10}$ and 7 keV sterile neutrino mass, the life-time for 3-body three level decay can be written as

$$\tau_{S_1 \to 3\nu} \simeq 4.5 \times 10^{28} \left( \frac{10^{-10}}{\sin^2 2\theta} \right) \left( \frac{\text{keV}}{m_{S_1}} \right)^5 \text{ sec}, \quad (15)$$

and that for a radiative 2-body decay as

$$\tau_{S_1 \to \nu + \gamma} \simeq 6.9 \times 10^{30} \left( \frac{10^{-10}}{\sin^2 2\theta} \right) \left( \frac{\text{keV}}{m_{S_1}} \right)^5 \text{ sec}, \quad (16)$$

which assures us that a sterile neutrino dark matter with mass $m_{S_1} = 2E_r = 7$ keV can easily satisfy the stability criteria. Some other experiments on X-ray signal with different energy (around keV) put a constraint on sterile-active neutrino mixing as [47].

$$\sin^2 2\theta \leq 1.2 \times 10^{-5} \left( \frac{m_{S_1}}{\text{keV}} \right)^{-5} \quad (17)$$

At present, predicting the exact relic density of dark matter is another necessity of a DM model. In case of cold dark matter, it is assumed that its relic abundance increases by thermal freezing-out mechanism based on the thermally averaged effective DM annihilation cross section at the time of freeze-out. However, relic abundance of keV mass dark matter is supported by specific production mechanisms which involve more engaging calculations. One such mechanism is Dodelson-Widrow mechanism [48] which provides the formula for relic density of DM as,

$$\Omega_{S}\hbar^2 \simeq 0.3 \left( \frac{\sin^2 2\theta}{10^{-10}} \right) \left( \frac{m_{S_1}}{100 \text{ keV}} \right)^2, \quad (18)$$

Few more works have also determined the relic abundance of a 10 keV sterile neutrino DM to be,

$$\Omega_{S}\hbar^2 \simeq 10^{-7} \left( \frac{m_{S_1}}{10\text{ keV}} \right) \left( \frac{T_R}{5 \text{ MeV}} \right)^3 \quad (19)$$

with a presupposition that the universe after being inflated never attained a temperature above few MeV [49-51].

But with the above relations it seems clear that for both the cases the allowed range of $\sin^2 2\theta$ and $m_{S_1}$ (from the recent X-ray observation) hardly validates the relic abundance of sterile neutrinos. Whereas, in order to justify the fact that dark matter (DM) contributes 25% to the total energy density of the present universe, its relic abundance should be $\Omega_{DM}\hbar^2 = 0.119$. In this regard, the Shi-Fuller mechanism [52] predicts an acceptable value with a 7 keV sterile neutrino dark matter. In addition to this, one may also go through refs. [53, 54] for the exact calculations relating to relic abundance.

**CONCLUSION**

We have shown how a 7 keV sterile neutrino dark matter and the corresponding sterile-active mixing angle $\simeq 10^{-5}$ can be accommodated successfully in an extended seesaw framework with simple addition of two types of sterile fermions to the minimal particle content of Standard Model. The radiative decay of the 7 keV sterile neutrino dark matter into the SM light neutrino plus a monochromatic photon can easily explain the recent unidentified 3.5 keV X-ray line signal as observed by XMM-Newton Telescope. The numerical results of the framed model stands parallel to the oscillation data explaining the sub-eV scale of light neutrino masses. More significant a point; this framework having high scale heavy neutrinos with masses $> 10^9$ GeV can ably answer another vital issue of particle physics called matter-antimatter asymmetry of our present Universe.

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[1] G. Bertone, D. Hooper and J. Silk, *Particle Dark Matter: Evidence, Candidates and Constraints*, Phys. Rept. 405 (2005) 279-390; arXiv:0404175 [hep-ph].
K. Nakayama, F. Takahashi, and T. T. Yanagida,
3.5 keV X-ray Line Signal from Decay of
3.5 keV X-ray line signal
arXiv:1403.1733.

H. M. Lee, S. C. Park, and W.-I. Park,
7 keV axion dark matter decay
Phys. Rev. D89 (2014) 113004, [arXiv:1403.2727].

T. Tsuyuki, Neutrino masses, leptogenesis, and sterile neutrino dark matter,
arXiv:1403.5053.

F. Bezrukov and G. Gorbunov, Relic Gravity Waves and 7 keV Dark Matter from a GeV scale inflaton,
arXiv:1403.4638.

K. P. Modak, 3.5 keV X-ray Line Signal from Decay of
7 keV Axion-like particle dark matter
Phys. Rev. Lett. 112 (2014) 161303, [arXiv:1403.0954].

S. Baek and H. Okada, 7 keV Dark Matter as X-ray Line Signal
in Radiative Neutrino Model,
arXiv:1403.1710.

B. Shuve and I. Yavin, A Dark Matter Progenitor: Light Vector Boson Decay into (Sterile) Neutrinos,
Phys.Rev. D89 (2014) 135004, [arXiv:1403.0954].

K. Nakayama, F. Takahashi, and T. T. Yanagida,
3.5 keV X-ray line signal
Phys.Lett. B734 (2014) 178182, [arXiv:1403.7390].

D. P. Finkbeiner and N. Weiner, An X-Ray Line from eXciting Dark Matter,
arXiv:1402.6671.

C. E. Asai, T. Hambye, and T. Scarpa, Can a millicharged dark matter particle emit an observable gamma-ray line?,
arXiv:1403.1280.

M. T. Frandsen, F. Sannino, I. M. Shoemaker, and O. Svendsen,
X-ray Lines from Dark Matter: The Good, The Bad, and The Unlikely,
JCAP 1405 (2014) 033, [arXiv:1403.1570].

R. Allahverdi, B. Dutta, and Y. Gao, keV Photon Emission from
Light Nonthermal Dark Matter,
arXiv:1403.5717.

J. M. Cline, Y. Farzan, Z. Liu, G. D. Moore, and W. Xue,
3.5 keV X-rays as the 21 cm line of dark atoms, and a link to light sterile neutrinos,
Phys.Rev. D89 (2014) 121302, [arXiv:1404.3729].

H. Okada and T. Toma, The 3.55 keV X-ray Line Signal
from Excited Dark Matter in Radiative Neutrino Model,
arXiv:1404.4795.

H. M. Lee, Magnetic dark matter for the X-ray line at 3.55 keV,
arXiv:1404.5446.

S. F. Queiroz and K. Sinha, The Poker Face of the Majoron
Dark Matter Model: LUX to keV line,
Phys.Lett. B735 (2014) 6974, [arXiv:1404.1400].

E. Dudas, L. Heurtier, and Y. Mambrini, Generating X-ray lines
from annihilating dark matter,
arXiv:1404.1927.

K. Babu and R. N. Mohapatra, 7 keV Scalar Dark Matter and
the Anomalous Galactic X-ray Spectrum,
Phys.Rev. D89 (2014) 115011, [arXiv:1404.2220].

M. Malinsky, J.C. Romao and J.W.F. Valle, Phys. Rev. Lett. 95, 161801 (2005).

E. Akhmedov et al., Phys. Lett. B 368, 270 (1996);
arXiv:9507275 [hep-ph].

E. Akhmedov et al., Phys. Rev. D 53, 2759 (1996);
arXiv:9509255 [hep-ph].

P. -H. Gu and U. Sarkar, Phys. Lett. B 694, 226 (2010)
arXiv:1007.2323 [hep-ph].

H. Zhang and S. Zhou, Phys. Lett. B 685 (2010) 297
arXiv:0912.2661 [hep-ph].

M. Hirsch, S. Morisi and J. W. F. Valle, Phys. Lett. B 679, 454
[arXiv:0905.3056 [hep-ph]].

S.K. Kang and C.S. Kim, Phys. Lett. B 646, 248 (2007);
arXiv:0607.072 [hep-ph].

J. C. Pati and A. Salam, Phys. Rev. D 10 (1974) 275; R. N. Mohapatra and J. C. Pati, Phys.Rev. D 11 (1975) 2558; G. Senjanovic and R. N. Mohapatra, Phys. Rev. D 12 (1975) 1502.

C. Amsler et al. (Particle Data Group), Phys. Lett. B667, 1 (2008).

P.S Bhupal Dev and R.N. Mohapatra, Phys. Rev. D 81 (2010) 013001; arXiv:0910.3924 [hep-ph].

R. L. Awasthi, M. K. Parida and S. Patra, JHEP 1308, 122 (2013);

A. Y. Smirnov and R. Zukanovich Funchal, Sterile neutrinos: Direct mixing effects versus induced mass matrix of active neutrinos,
Phys. Rev. D 74, 013001 (2006) [hep-ph/0603009];
A. Boyarskii, O. Ruchayskiy and M. Shaposhnikov, The Role of sterile neutrinos in cosmology and astrophysics
Ann. Rev. Nucl. Part. Sci. 59, 191 (2009) [arXiv:0901.0011 [hep-ph]].
[52] X. Shi, G.M. Fuller, A New Dark Matter Candidate: Non-thermal Sterile Neutrinos, Phys. Rev. Lett. 82 (1999) 2832-2835; arXiv:9810076 [astro-ph].

[53] K. Abazajian, G.M. Fuller and M. Patel Sterile Neutrino Hot, Warm, and Cold Dark Matter, Phys. Rev. D 64 (2001) 023501.

[54] Kevork N. Abazajian, Resonantly Produced 7 keV sterile neutrino dark matter models and the properties of Milky way Satellites, Phys. Rev. Lett 112, 161303 (2014); arXiv:1403.0954 [hep-ph].