



7 keV sterile neutrino dark matter from split flavor mechanism



Hiroyuki Ishida^a, Kwang Sik Jeong^{b,*}, Fuminobu Takahashi^{a,c}

^a Department of Physics, Tohoku University, Sendai 980-8578, Japan

^b Deutsches Elektronen Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany

^c Kavli IPMU, TODIAS, University of Tokyo, Kashiwa 277-8583, Japan

ARTICLE INFO

Article history:

Received 28 February 2014

Accepted 21 March 2014

Available online 26 March 2014

Editor: J. Hisano

ABSTRACT

The recently discovered X-ray line at about 3.5 keV can be explained by sterile neutrino dark matter with mass, $m_s \simeq 7$ keV, and the mixing, $\sin^2 2\theta \sim 10^{-10}$. Such sterile neutrino is more long-lived than estimated based on the seesaw formula, which strongly suggests an extra flavor structure in the seesaw sector. We show that one can explain both the small mass and the longevity based on the split flavor mechanism where the breaking of flavor symmetry is tied to the breaking of the $B - L$ symmetry. In a supersymmetric case we find that the 7 keV sterile neutrino implies the gravitino mass about 100 TeV.

© 2014 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/3.0/>). Funded by SCOAP³.

1. Introduction

Roughly a quarter of the Universe consists of dark matter. In spite of extensive dark matter searches conducted so far, its nature remains unknown. If dark matter is made of as-yet-unknown species of particles, they must be cold and very long-lived. The required longevity, however, does not guarantee the absolute stability of dark matter; it may decay into the standard model (SM) particles, enabling us to probe the nature of dark matter through indirect dark matter search.

Recently an unidentified X-ray line at about 3.5 keV in the XMM-Newton X-ray observatory data of various galaxy clusters and the Andromeda galaxy was reported independently by two groups [1,2]. While there are a variety of systematic uncertainties that can affect the observed line energy and flux, it is interesting that such X-ray line can be explained by sterile neutrino dark matter [3–8], a long-sought dark matter candidate, with mass about 7 keV.

The sterile neutrino dark matter with mass in the keV range is known to decay radiatively into a photon and an active neutrino, producing a narrow X-ray line. The lifetime depends on its mass and the mixing with active neutrinos. For the mass of 7 keV, the observed X-ray line can be explained by the mixing angle, $\sin^2 2\theta \sim 7 \times 10^{-11}$ [1,2], which is just below the previously known X-ray bound. Such small mass and mixing can be partially understood by the split seesaw mechanism [9] or a simple Froggatt–Nielsen (FN) type flavor model [10]. In these scenarios, the seesaw

formula [11] remains intact even in the presence of large mass hierarchy in the right-handed (sterile) neutrinos:

$$(m_\nu)_{\alpha\beta} = \lambda_{I\alpha} \lambda_{I\beta} \frac{v^2}{M_I}, \quad (1)$$

where $v \equiv \langle H^0 \rangle \simeq 174$ GeV is the vacuum expectation value (VEV) of the Higgs field, $\lambda_{I\alpha}$ denotes the Yukawa coupling of the right-handed neutrino N_I with the lepton doublet L_α and the Higgs field, and M_I is the mass of the right-handed neutrino N_I . The point is that both the neutrino Yukawa coupling $\lambda_{I\alpha}$ and the right-handed neutrino mass M_I are suppressed by either a geometrical factor or flavor charge in such a way that the suppression factors are canceled out in the above seesaw formula. This is because the suppression mechanism is independent of the $U(1)_{B-L}$ breaking. The observed X-ray flux (as well as the previously known X-ray bound), however, requires that the sterile neutrino dark matter should be more long-lived than estimated based on the above seesaw formula.¹ The observed X-ray line therefore strongly suggests an extra flavor structure in the seesaw sector.

Before the discovery of the 3.5 keV X-ray line, the present authors showed in Ref. [16] that both the small mass and the small mixing just below the X-ray bound can be achieved in the split flavor mechanism; we introduce two $B - L$ Higgs fields, one of which is charged under single discrete flavor symmetry. The point is that the VEV of the $B - L$ Higgs leads to both breaking of the $U(1)_{B-L}$ symmetry and the flavor symmetry. In this letter we revisit the split flavor mechanism in light of the recent discovery of

* Corresponding author.

E-mail addresses: h_ishida@tuhep.phys.tohoku.ac.jp (H. Ishida), kwangsik.jeong@desy.de (K.S. Jeong), fumi@tuhep.phys.tohoku.ac.jp (F. Takahashi).

<http://dx.doi.org/10.1016/j.physletb.2014.03.044>

0370-2693/© 2014 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/3.0/>). Funded by SCOAP³.

¹ It is known that, if the sterile neutrino comprises all the dark matter, its contribution to the light neutrino mass should be negligible to satisfy the X-ray bounds [12,13].

the unidentified X-ray line at 3.5 keV, and show that the observed X-ray line can be nicely explained in the split flavor mechanism. In particular, we examine carefully the model parameters by taking account of numerical coefficients of order unity, while those numerical coefficients were set to be unity in Ref. [16] for simplicity. In a supersymmetric case we will study the implications for supersymmetry breaking scale and show that the gravitino mass about 100 TeV is favored by the observed X-ray line.

2. 7 keV sterile neutrino in the split flavor mechanism

The interactions relevant to the seesaw mechanism read

$$-\mathcal{L} = \lambda_{I\alpha} \bar{N}_I L_\alpha H + \frac{1}{2} \kappa_I M \bar{N}_I^c N_I + \text{h.c.}, \quad (2)$$

for M being the $B - L$ breaking scale. Here N_I ($I = 1, 2, 3$), L_α ($\alpha = e, \mu, \tau$), and H are the right-handed neutrino, lepton doublet, and Higgs scalar, respectively. The right-handed neutrino masses are given by $M_I = \kappa_I M$.

We are interested in the case where N_1 is much lighter than N_i ($i = 2, 3$), and couples more weakly to the lepton doublet and Higgs scalar than N_i . To parameterize such hierarchical structures in the right-handed neutrino sector, let us introduce the suppression factors²:

$$\kappa_1 = x^2 \kappa, \quad |\lambda_{1\alpha}| = x_\alpha \lambda, \quad (3)$$

with $x_\alpha \lesssim x$ for x and x_α much smaller than unity. Here κ and λ are the typical values of κ_i and the Yukawa couplings $\lambda_{i\alpha}$, respectively. The active neutrinos obtain tiny masses of the order,

$$m_{\text{seesaw}} \equiv \frac{\lambda^2 v^2}{\kappa M}, \quad (4)$$

through the seesaw mechanism. To generate phenomenologically viable neutrino masses, one needs $m_{\text{seesaw}} \sim 0.1$ eV, implying M around 10^{15} GeV for κ and λ of order unity.

After electroweak symmetry breaking, N_1 mixes with the active neutrinos due to the coupling $\lambda_{1\alpha}$. The mixing angle is given by

$$\theta^2 \equiv \sum_\alpha \frac{|\lambda_{1\alpha}|^2 v^2}{M_1^2} = \epsilon^2 \frac{m_{\text{seesaw}}}{M_1}, \quad (5)$$

where we have defined

$$\epsilon^2 \equiv \frac{\sum_\alpha x_\alpha^2}{x^2}. \quad (6)$$

The decay mixing angle of the sterile neutrino dark matter is estimated to be

$$\sin^2 2\theta \simeq 0.6 \times 10^{-10} \left(\frac{\epsilon}{10^{-3}} \right)^2 \left(\frac{m_{\text{seesaw}}}{0.1 \text{ eV}} \right) \left(\frac{m_s}{7 \text{ keV}} \right)^{-1}, \quad (7)$$

where $m_s \simeq M_1$ denotes the mass of the sterile neutrino N_1 . Thus ϵ should be around 10^{-3} if the sterile neutrino dark matter is responsible for the observed X-ray line around 3.5 keV. One is however led to $x \sim x_\alpha$, i.e. $\epsilon \sim 1$, in the simple FN model or the split seesaw mechanism. This implies that either all the three components of $\lambda_{1\alpha}$ are less than 10^{-3} of the expected, or the sterile neutrino mass M_1 is heavier by a factor of 10^6 than the expected, or a combination of these two. If x_α/x takes a value of order unity randomly as in the neutrino mass anarchy [17,18], it would require

a fine-tuning of order $\epsilon^3 \sim 10^{-9}$. We call this fine-tuning problem as the longevity problem [16].

Taken at face value, the longevity problem strongly suggests an extra flavor structure in the seesaw sector. The split flavor mechanism [16] provides a natural way to explain both $m_s \simeq 7$ keV and $\epsilon \sim 10^{-3}$ simultaneously.³ Before going into the details of the model, let us briefly summarize how this is achieved. The suppression mechanism is implemented by extending the seesaw sector to include two (or more) $B - L$ Higgs fields, one of which is charged under discrete flavor symmetry. Most important, the breaking of flavor symmetry is tied to the breaking of the $B - L$ symmetry. Then one is led to

$$\epsilon \sim \frac{M}{M_{Pl}} \sim 10^{-3} \left(\frac{M}{10^{15} \text{ GeV}} \right), \quad (8)$$

in non-supersymmetric models. Here $M_{Pl} \simeq 2.435 \times 10^{18}$ GeV is the reduced Planck scale. In what follows, we will take M around 10^{15} GeV assuming that κ_i and the Yukawa couplings $\lambda_{i\alpha}$ are order unity.⁴ Then the above relation tells that the observed X-ray line can naturally be explained by the sterile neutrino dark matter. As will be shown later, $m_s \simeq 7$ keV is obtained for appropriate $B - L$ Higgs VEVs.

On the other hand, in supersymmetric models, one can consider discrete flavor symmetry or discrete R symmetry. The sterile neutrino mass is given by

$$m_s \sim m_{3/2} \left(\frac{M}{M_{Pl}} \right)^3, \quad (9)$$

for both cases, with $m_{3/2}$ being the gravitino mass. The ϵ parameter can be collectively written as

$$\epsilon \sim \left(\frac{m_{3/2} M_{Pl}^3}{M^4} \right)^{\pm \frac{1}{2}} \frac{M}{M_{Pl}}, \quad (10)$$

where the minus sign in the exponent applies when $\lambda_{1\alpha}$ mainly receives supersymmetric contribution in the case of discrete R symmetry, and the plus sign is for the other cases. These relations show that, for $m_{3/2} \sim 10^5$ GeV and $M \sim 10^{15}$ GeV, the sterile neutrino has the right properties to be the origin of the X-ray line.

2.1. Non-supersymmetric case

The seesaw sector includes two $B - L$ Higgs fields Φ and Φ' , and three right-handed neutrinos N_i . Let us take the charge assignment,

	Φ	Φ'	N_1	N_i	L_α	H
U(1) _{B-L}	2	-6	-1	-1	-1	0
Z_4	0	-1	1	0	0	0

Then the U(1)_{B-L} and flavor symmetry constrain the seesaw sector interactions as

$$-\Delta\mathcal{L} = \frac{1}{2} \kappa_i \Phi \bar{N}_i^c N_i + \lambda_i \bar{N}_i L H + \frac{1}{2} \tilde{\kappa} \frac{(\Phi^5 \Phi'^2)^*}{M_{Pl}^6} \bar{N}_1^c N_1 + \tilde{\lambda}_\alpha \frac{(\Phi^3 \Phi')^*}{M_{Pl}^4} \bar{N}_1 L_\alpha H + \text{h.c.}, \quad (11)$$

³ In Ref. [16] we adopted $m_s \sim 10$ keV and $\epsilon \sim 10^{-3}$ as reference values, which are surprisingly close to the observed ones.

⁴ It is straightforward to suppress $\kappa_{i\alpha}$ and $\lambda_{i\alpha}$ by assigning additional FN flavor charges on N_i . Our results are not changed even in this case.

² We use a slightly different notation from Ref. [16] to examine more precisely the properties of the sterile neutrino dark matter.

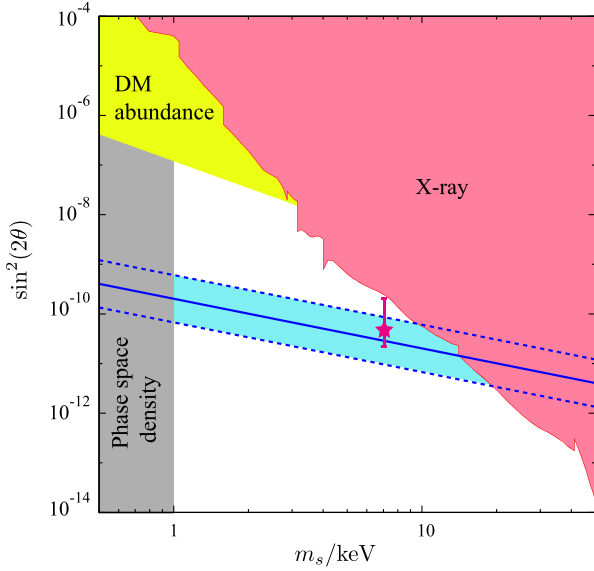


Fig. 1. Properties of the sterile neutrino dark matter. The solid (blue) line shows the relation (14) between the mass and the mixing induced by the split flavor mechanism in non-supersymmetric case. The upper and lower dotted (blue) lines correspond to the cases of three times larger and smaller values of $\sin^2 2\theta$, respectively. The red star represents the values of the mass and the mixing that can explain the observed X-ray line. The shaded regions denoted by X-ray and DM abundance are excluded by the X-ray observations [6] and the dark matter overproduction by the Dodelson–Widrow mechanism [14]. We also show the region excluded by phase-space density [15]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where we have assumed that the cut-off scale of the model is the Planck scale. For the coupling constants of order unity, the model gives

$$\epsilon \sim \frac{M}{M_{Pl}}. \quad (12)$$

Under the assumption that there is no additional structure in the coupling constants, we take the couplings of N_1 to be

$$\frac{|\tilde{\lambda}_\alpha|^2}{\tilde{\kappa}} = \frac{\lambda^2}{\kappa}. \quad (13)$$

Then it follows

$$m_s \simeq 4.8 \text{ keV} \times \tilde{\kappa} r^2 \left(\frac{M}{10^{15} \text{ GeV}} \right)^7, \quad (14)$$

$$\sin^2 2\theta \simeq 0.3 \times 10^{-10} \left(\frac{m_s}{7 \text{ keV}} \right)^{-1} \left(\frac{m_{\text{seesaw}}}{0.1 \text{ eV}} \right) \left(\frac{M}{10^{15} \text{ GeV}} \right)^2,$$

taking $\langle \Phi \rangle = M$ and $\langle \Phi' \rangle = rM$. The $B - L$ Higgs fields would generally have VEVs of a similar size, giving $r \sim 1$. Thus the sterile neutrino dark matter has the right mass and mixing to account for the observed X-ray line. Note that the relation between the mass and the mixing angle is independent of r .

Fig. 1 shows the relation (14) between the mixing and the mass of the sterile neutrino dark matter. To take account of the uncertainty in the relation between couplings, we show as dotted (blue) lines the results for cases with a numerical factor of 3 and 1/3 multiplied with the RHS of Eq. (13). The shaded (light blue) region between the dotted lines represents the prediction of our model, which satisfies various observational bounds. We show the bounds from the non-detection of the X-ray line, the dark matter overproduction, and phase-space density, together with the values suggested by the 3.5 keV X-ray line. We can see that our model can naturally explain the observed X-ray line at 3.5 keV.

2.2. Supersymmetric case

The split flavor mechanism can be straightforwardly generalized to the supersymmetric case. In contrast to the non-supersymmetric case, there are two important effects. One is the holomorphic nature of the superpotential, and the other is the supersymmetry breaking effects represented by the gravitino mass.

To cancel anomalies, we assign the $B - L$ charges to the left-handed chiral superfields as

	Φ	Φ'	N_1	N_i	L_α	H_u
$U(1)_{B-L}$	-2	2	1	1	-1	0

where H_u is the up-type Higgs doublet superfield. The $U(1)_{B-L}$ is broken along the D -flat direction

$$|\Phi|^2 = |\Phi'|^2 = M^2, \quad (15)$$

which is lifted by supersymmetry breaking effects associated with higher dimensional operators or radiative corrections.

Small ϵ is obtained by imposing flavor symmetry under which Φ' and N_1 transform non-trivially. Let us consider Z_6 flavor symmetry with⁵

	Φ	Φ'	N_1	N_i	L_α	H_u
Z_6	0	1	1	0	0	0

which allows the conventional superpotential terms for N_i

$$W = \frac{1}{2} \Phi N_1 N_i + N_i L_\alpha H_u, \quad (16)$$

while the relevant interactions of N_1 come from the following Kähler potential

$$\Delta K = \frac{\Phi'^*}{M_{Pl}} N_1 N_i + \frac{1}{2} \frac{(\Phi \Phi'^2)^*}{M_{Pl}^3} N_1 N_1 + \text{h.c.}, \quad (17)$$

in which we have dropped coupling constants of order unity. For $M \gg m_{3/2}$, the effective action for the seesaw sector is obtained by replacing the $B - L$ Higgs fields by their VEVs. From ΔK , one obtains

$$\Delta W_{\text{eff}} = \frac{1}{2} \tilde{\kappa} \frac{m_{3/2} M^3}{M_{Pl}^3} N_1 N_1 + \tilde{\lambda}_\alpha \frac{m_{3/2}}{M_{Pl}} N_1 L_\alpha H_u, \quad (18)$$

for $m_{3/2} M_{Pl} \ll M^2$, after redefining the heavy right-handed neutrinos to remove the mixing terms with N_1 . The above implies

$$\epsilon \sim \frac{\sqrt{m_{3/2} M_{Pl}}}{M}. \quad (19)$$

The detailed properties of the sterile neutrino dark matter depend on the supersymmetry breaking scale. Taking the coupling constants to be (13), we find

$$m_s \simeq 6.9 \text{ keV} \times \tilde{\kappa} \left(\frac{m_{3/2}}{10^5 \text{ GeV}} \right) \left(\frac{M}{10^{15} \text{ GeV}} \right)^3,$$

$$\sin^2 2\theta \simeq 0.4 \times 10^{-10} \left(\frac{m_s}{7 \text{ keV}} \right)^{-1} \left(\frac{m_{\text{seesaw}}}{0.1 \text{ eV}} \right) \times \left(\frac{m_{3/2}}{10^5 \text{ GeV}} \right) \left(\frac{M}{10^{15} \text{ GeV}} \right)^{-2}. \quad (20)$$

Hence the sterile neutrino can explain the X-ray line for $m_{3/2}$ around 10^5 GeV and M around 10^{15} GeV .

⁵ Our results can be straightforwardly applied to the case of Z_k with $k \geq 6$.

The suppression mechanism is successfully implemented also by a discrete R symmetry. There are many different ways to assign the discrete R charges. Here we consider a simple case with⁶

	Φ	Φ'	N_1	N_i	L_α	H_u
Z_{5R}	0	4	3	1	1	0

Then the interactions of N_i are again given by (16). The relevant interactions of N_1 come from the following Kähler and superpotentials after $B - L$ breaking,

$$\begin{aligned}\Delta K &= \frac{\Phi'^*}{M_{Pl}} N_1 N_i + \frac{\Phi^2 \Phi'}{M_{Pl}^3} N_1 N_1 + \text{h.c.}, \\ \Delta W &= \frac{(\Phi \Phi')^2}{M_{Pl}^4} N_1 L_\alpha H_u,\end{aligned}\quad (21)$$

where order unity coefficients have been omitted. At energy scales below M , one finds the effective superpotential

$$\Delta W_{\text{eff}} = \frac{1}{2} \tilde{\kappa} \frac{m_{3/2} M^3}{M_{Pl}^3} N_1 N_1 + \tilde{\lambda}_\alpha \left(s \frac{m_{3/2}}{M_{Pl}} + \frac{M^4}{M_{Pl}^4} \right) N_1 L_\alpha H_u, \quad (22)$$

for $m_{3/2} M_{Pl} \ll M^2$. Here the constant s is generally order unity. If the neutrino Yukawa coupling of N_1 to $L_\alpha H_u$ is dominated by the supersymmetry breaking contribution, the properties of the sterile neutrino are same as in the previous case. So, we here focus on the case that the effective Yukawa coupling is dominated by the supersymmetric contribution $\sim (M/M_{Pl})^4$. This is the case for s around or slightly smaller than unity in the parameter region with $m_{3/2} \sim 10^5$ GeV and $M \sim 10^{15}$ GeV. From the effective superpotential, ϵ is then estimated to be

$$\epsilon \sim \left(\frac{m_{3/2}}{M_{Pl}} \right)^{-1/2} \left(\frac{M}{M_{Pl}} \right)^3, \quad (23)$$

for the coupling constants of order unity. Let us take $\tilde{\kappa}$ and $\tilde{\lambda}_\alpha$ to be (13) assuming no extra structure. Then the mass and mixing angle of the sterile neutrino dark matter are given by

$$\begin{aligned}m_s &\simeq 6.9 \text{ keV} \times \tilde{\kappa} \left(\frac{m_{3/2}}{10^5 \text{ GeV}} \right) \left(\frac{M}{10^{15} \text{ GeV}} \right)^3, \\ \sin^2 2\theta &\simeq 0.2 \times 10^{-10} \left(\frac{m_s}{7 \text{ keV}} \right)^{-1} \left(\frac{m_{\text{seesaw}}}{0.1 \text{ eV}} \right) \\ &\quad \times \left(\frac{m_{3/2}}{10^5 \text{ GeV}} \right)^{-1} \left(\frac{M}{10^{15} \text{ GeV}} \right)^6.\end{aligned}\quad (24)$$

Note that the sterile neutrino mass has the same dependence on $m_{3/2}$ and M as in the case of Z_6 flavor symmetry, while the mixing angle has different dependence.

In both cases considered above, the gravitino mass close to 100 TeV is favored by the observed X-ray line. Such heavy gravitino mass is consistent with the SM-like Higgs boson of mass near 126 GeV [19,20].

3. Discussion and conclusions

So far we have focused on the small mass and mixing of the sterile neutrino dark matter suggested by the recently discovered 3.5 keV X-ray line, and have shown that these properties can be naturally realized in the split flavor mechanism. In order to ex-

plain the observations, we need to generate a right amount of the sterile neutrinos. Thermal production through mixings with active neutrinos, however, is inefficient for such small mixing angle, unless there is a large lepton asymmetry. Another possibility is through thermal production through $U(1)_{B-L}$ gauge interactions at high temperature [5,16,21]; the abundance of the sterile neutrino is given by

$$\begin{aligned}\Omega_{\text{DM}} h^2 &\sim 0.2 \left(\frac{g_*}{106.75} \right)^{\frac{3}{2}} \left(\frac{m_s}{7 \text{ keV}} \right) \\ &\quad \times \left(\frac{M}{10^{15} \text{ GeV}} \right)^{-4} \left(\frac{T_R}{5 \times 10^{13} \text{ GeV}} \right)^3,\end{aligned}\quad (25)$$

where T_R is the reheating temperature of the Universe after inflation. At such high reheating temperature, a right amount of the baryon asymmetry can be created through thermal leptogenesis [22] by the two heavy right-handed neutrinos [23,24]. Non-thermal production may also work; see e.g. Ref. [25]. Alternatively, if the $B - L$ symmetry is restored after inflation, the sterile neutrino N_1 will be thermalized through the $B - L$ gauge interactions. If there is a late-time entropy production of $\mathcal{O}(10^2)$, its thermal abundance can be reduced so that it can explain the dark matter abundance [9]. In this case we need to introduce small explicit breaking of the discrete symmetry to make domain walls annihilate before dominating the Universe.

In this letter we have revisited the split flavor mechanism in light of the recent discovery of the X-ray line at 3.5 keV in the XMM-Newton X-ray observatory data of various galaxy clusters and the Andromeda galaxy. In particular, the required small mixing angle, $\sin^2 2\theta \sim 7 \times 10^{-11}$, implies that the sterile neutrino dark matter is more long-lived than estimated based on the seesaw formula, which strongly suggests an extra flavor structure in the seesaw sector. Note that the seesaw formula holds in the split seesaw mechanism or the simple FN flavor model. In the split flavor mechanism we introduce two $B - L$ Higgs fields, one of which is charged under discrete flavor symmetry. Most important, the breaking of flavor symmetry is tied to the breaking of the $B - L$ symmetry. We have shown in both non-supersymmetric and supersymmetric scenarios that the 7 keV sterile neutrino with mixing $\sin^2 2\theta \sim 7 \times 10^{-11}$ can be realized easily. The suppression of the mixing angle, namely, the longevity of the sterile neutrino dark matter with respect to the expectation based on the seesaw formula, is due to the mild hierarchy between the $U(1)_{B-L}$ breaking scale and the Planck scale. In the supersymmetric scenarios, the small mixing is partially due to the smallness of the gravitino mass compared to the Planck scale; the gravitino mass around 100 TeV is favored by the observed X-ray line, which is consistent with the SM-like Higgs boson with 126 GeV mass.

Acknowledgements

This work was supported by Scientific Research on Innovative Areas (No. 24111702 [FT], No. 21111006 [FT], and No. 23104008 [FT]), Scientific Research (A) (No. 22244030 and No. 21244033) [FT], and JSPS Grant-in-Aid for Young Scientists (B) (No. 24740135) [FT], and Inoue Foundation for Science [HI and FT]. This work was also supported by World Premier International Center Initiative (WPI Program), MEXT, Japan [FT].

References

- [1] E. Bulbul, M. Markevitch, A. Foster, R.K. Smith, M. Loewenstein, S.W. Randall, arXiv:1402.2301 [astro-ph.CO].
- [2] A. Boyarsky, O. Ruchayskiy, D. Iakubovskiy, J. Franse, arXiv:1402.4119 [astro-ph.CO].

⁶ Even though the R -parity is broken in the case of Z_{5R} symmetry, the lightest supersymmetric particle (LSP) remains stable due to the residual Z_{2B-L} symmetry [16]. Its thermal relic abundance can be suppressed for the Wino-like LSP, or in the presence of late-time entropy production.

- [3] A.D. Dolgov, S.H. Hansen, *Astropart. Phys.* 16 (2002) 339, arXiv:hep-ph/0009083.
- [4] A. Boyarsky, O. Ruchayskiy, M. Shaposhnikov, *Annu. Rev. Nucl. Part. Sci.* 59 (2009) 191, arXiv:0901.0011 [hep-ph].
- [5] A. Kusenko, *Phys. Rep.* 481 (2009) 1, arXiv:0906.2968 [hep-ph].
- [6] K.N. Abazajian, M.A. Acero, S.K. Agariwalla, A.A. Aguilar-Arevalo, C.H. Albright, S. Antusch, C.A. Argüelles, A.B. Balantekin, et al., arXiv:1204.5379 [hep-ph].
- [7] M. Drewes, *Int. J. Mod. Phys. E* 22 (2013) 1330019, arXiv:1303.6912 [hep-ph].
- [8] A. Merle, *Int. J. Mod. Phys. D* 22 (2013) 1330020, arXiv:1302.2625 [hep-ph].
- [9] A. Kusenko, F. Takahashi, T.T. Yanagida, *Phys. Lett. B* 693 (2010) 144, arXiv:1006.1731 [hep-ph].
- [10] C.D. Froggatt, H.B. Nielsen, *Nucl. Phys. B* 147 (1979) 277.
- [11] T. Yanagida, in: O. Sawada, A. Sugamoto (Eds.), *Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe*, Tsukuba, Japan, Feb. 13–14, 1979, p. 95 (KEK report KEK-79-18);
T. Yanagida, Horizontal symmetry and masses of neutrinos, *Prog. Theor. Phys.* 64 (1980) 1103;
M. Gell-Mann, P. Ramond, R. Slansky, in: D.Z. Freedman, P. van Nieuwenhuizen (Eds.), *Supergravity*, North-Holland, Amsterdam, 1979, Print-80-0576 (CERN);
See also P. Minkowski, *Phys. Lett. B* 67 (1977) 421.
- [12] T. Asaka, S. Blanchet, M. Shaposhnikov, *Phys. Lett. B* 631 (2005) 151, arXiv:hep-ph/0503065.
- [13] A. Boyarsky, A. Neronov, O. Ruchayskiy, M. Shaposhnikov, *JETP Lett.* 83 (2006) 133, arXiv:hep-ph/0601098.
- [14] S. Dodelson, L.M. Widrow, *Phys. Rev. Lett.* 72 (1994) 17, arXiv:hep-ph/9303287.
- [15] A. Boyarsky, O. Ruchayskiy, D. Iakubovskiy, *J. Cosmol. Astropart. Phys.* 0903 (2009) 005, arXiv:0808.3902 [hep-ph].
- [16] H. Ishida, K.S. Jeong, F. Takahashi, *Phys. Lett. B* 731 (2014) 242, arXiv:1309.3069 [hep-ph].
- [17] L.J. Hall, H. Murayama, N. Weiner, *Phys. Rev. Lett.* 84 (2000) 2572, arXiv:hep-ph/9911341.
- [18] N. Haba, H. Murayama, *Phys. Rev. D* 63 (2001) 053010, arXiv:hep-ph/0009174.
- [19] G. Aad, et al., ATLAS Collaboration, *Phys. Lett. B* 716 (2012) 1, arXiv:1207.7214 [hep-ex].
- [20] S. Chatrchyan, et al., CMS Collaboration, *Phys. Lett. B* 716 (2012) 30, arXiv:1207.7235 [hep-ex].
- [21] S. Khalil, O. Seto, *J. Cosmol. Astropart. Phys.* 0810 (2008) 024, arXiv:0804.0336 [hep-ph];
G. Gelmini, S. Palomares-Ruiz, S. Pascoli, *Phys. Rev. Lett.* 93 (2004) 081302, arXiv:astro-ph/0403323;
G. Gelmini, E. Osoba, S. Palomares-Ruiz, S. Pascoli, *J. Cosmol. Astropart. Phys.* 0810 (2008) 029, arXiv:0803.2735 [astro-ph].
- [22] M. Fukugita, T. Yanagida, *Phys. Lett. B* 174 (1986) 45.
- [23] T. Endoh, S. Kaneko, S.K. Kang, T. Morozumi, M. Tanimoto, *Phys. Rev. Lett.* 89 (2002) 231601, arXiv:hep-ph/0209020.
- [24] M. Raidal, A. Strumia, *Phys. Lett. B* 553 (2003) 72, arXiv:hep-ph/0210021.
- [25] K. Petraki, A. Kusenko, *Phys. Rev. D* 77 (2008) 065014, arXiv:0711.4646 [hep-ph].