

# Underground detections of an extra gauge interacting sterile neutrino dark matter

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**Abstract.** We show that decay products from sterile neutrino dark matter in extra  $U(1)$  models are detectable in both direct dark matter detection experiments and neutrino telescope. The sterile neutrino dark matter interacts with a light gauge boson and decays into neutrinos. Those neutrinos could scatter off nuclei with a large enough recoil energy in direct dark matter detection experiments as WIMPs do.

## 1. Introduction

The total amount of material in our Universe has been measured by a variety of methods. These provide compelling evidence that dark matter (DM) is the dominant component of non-relativistic matter in the Universe. Many candidates for DM in models beyond the standard model (SM) of particle physics have been proposed. Among them, sterile neutrino is an interesting DM candidate if its lifetime is long enough, since it is massive and electrically neutral. For a recent review, see Ref. [1] for example. The introduction of sterile neutrinos is highly motivated to explain non-vanishing neutrino masses by the so called seesaw mechanism with gauge singlet right-handed (RH) neutrinos [2, 3, 4, 5]. The RH neutrino extension of the SM seems to be simple and economical from the viewpoint of the simultaneous explanation of tiny neutrino masses and DM. This model is called the  $\nu$ MSM [6, 7].

Gauge singlet sterile neutrinos as dark matter could be generated in the early Universe by the so-called Dodelson-Widrow (DW) mechanism through the mixing between active and sterile neutrinos [8, 9]. However, the stringent X-ray background limit now excludes the sufficient mixing for the DW mechanism [10, 11].

This brought us to consider other mechanisms to generate the sufficient amount of sterile neutrinos. One way is a nonthermal production, sometime called “freeze-in mechanism”, of sterile neutrino DM. For example, if RH neutrinos have interactions through an extra  $U(1)$  gauge interaction, the sterile neutrino DM can be generated nonthermally [12, 13, 14].

Sterile neutrino DM has been probed by astrophysical observations such as X-ray background as mentioned above. In addition to the X-ray signal, an extra  $U(1)$  interacting sterile neutrino



may decay into a lighter neutrino and the extra gauge boson, followed by the decay of the extra gauge boson into a pair of neutrinos. This decay mode opens a new possibility to probe sterile neutrino DM. We show that detection of light neutrinos as the decay product is possible with the Super-Kamiokande (SK) and future experiments of direct dark matter detection [15].

## 2. Model

We consider the extension of the SM by imposing extra  $U(1)$  gauge symmetry, such as  $U(1)_{B-L}$  [16, 17, 18] or  $U(1)_R$  [19] gauge symmetry, where  $B$  and  $L$  are the baryon and lepton number, and  $R$  represents right-handed chirality, respectively. The fermion sector of the SM has to be extended with three RH neutrinos  $\nu_R$  for anomaly cancelation. We introduce one complex scalar  $S$  charged under the extra  $U(1)$  symmetry. After the scalar fields develop the vacuum expectation values (VEVs), the masses of the gauge bosons and fermions are generated. The mass of the extra gauge boson  $X$  is approximately given by

$$m_X^2 \simeq q_S^2 g_X^2 v_S^2, \quad (1)$$

where  $v_S$  is the VEV of  $S$ ,  $g_X$  is the gauge coupling constant of  $U(1)_X$ , and  $q_S$  is the extra  $U(1)_X$  charge of  $S$ . For the exact formula, see for example Ref. [15, 20]. Masses and mixings of light neutrinos can be reproduced by the type-I seesaw mechanism with two RH neutrinos. We identify the remaining RH neutrino, suppose  $\nu_{R_1}$ , as the DM sterile neutrino  $\nu_s$  with tiny active-sterile mixing,  $\theta$ ,

$$\nu_s = \nu_{R_1} + \sin \theta U_{1\alpha} \nu_{L\alpha}^c, \quad (2)$$

where  $U$  is the MNS matrix [21]. The superscript  $c$  stands for charge conjugation, and the index  $\alpha$  runs over  $e$ ,  $\mu$ , and  $\tau$ .

## 3. Sterile neutrino dark matter

### 3.1. Cosmological abundance

We consider the case of a very small extra gauge coupling  $g_X$  and mass spectrum  $2m_{\nu_s} > m_X$ . For a very small  $g_X$ ,  $\nu_s$  never reaches thermal equilibrium. The DM abundance can be explained by a so-called freeze-in mechanism, where DM are produced through scattering processes from the thermal bath. The abundance of the sterile neutrino  $\nu_s$  DM is estimated by solving the Boltzmann equation

$$\frac{dn_{\nu_s}}{dt} + 3Hn_{\nu_s} = \sum_{i,j} \langle \sigma v(ij \rightarrow \nu_s \nu_s) \rangle n_i n_j, \quad (3)$$

where  $n_{\nu_s}$  is the number density of DM sterile neutrino  $\nu_s$ ,  $H$  is the Hubble parameter,  $\langle \sigma v \rangle$  is the thermal averaged product of the cross section and the relative velocity for production processes and  $n_{i(j)}$  is the thermal abundance of a SM particle in initial states [13].

### 3.2. Constraints

**3.2.1. The  $X$  boson mass** One stringent constraint on a light gauge boson comes from the  $e-\nu$  scattering experiments such as GEMMA [22], BOREXINO [23] and TEXONO [24]. Various beam dump experiments such as CHARM [25, 26] and NOMAD [27] and electron colliders such as KLEO [28] and BABAR [29] constrain wide range of the  $X$  boson mass for  $m_X > 2m_e$  where  $X$  decays into an electron and positron pair [30]. Lighter mass region of  $m_X \lesssim 0.3$  MeV

is constrained by the stellar cooling in globular clusters [31, 32, 33]. The unconstrained mass ranges of the  $X$  boson are summarized as

$$0.3 \text{ MeV} \lesssim m_X < 1 \text{ MeV}, \quad (4)$$

$$100 \text{ MeV} \lesssim m_X, \quad (5)$$

for  $g_X = \mathcal{O}(10^{-6})$  [13].

*3.2.2. Lifetime and cosmic ray background bound* For the mass spectrum  $m_{\nu_s} > m_X$ , the sterile neutrino mainly decays into one neutrino and the  $X$  boson through active-sterile mixing, followed by the decay of  $X$ . Since its rate is proportional to the squared of the mixings as

$$\Gamma(\nu_s \rightarrow X\nu) \propto g_X^2 \sin^2 \theta \frac{m_{\nu_s}^3}{m_X^2}, \quad (6)$$

the lifetime can be long enough for a very small mixing  $\theta$ . If the  $X$  boson is heavier than  $2m_e$ , the lifetime of  $\nu_s$  decay into  $\nu$  and  $X$  has to be longer than  $10^{27}$  second [34]. In this case, we will not observe signals we will discuss in following due to the too long lifetime. Thus, for our interest, we will examine the mass range (4) only and will take  $m_X = 0.5$  MeV. In the following analysis, we use the lifetime  $\tau$  as an input parameter instead of the mixing  $\theta$ .

In addition, the constraints from X-ray background is more stringent for sterile neutrino DM than that from the lifetime compared with the age of the Universe. The decay rate by the SM processes is given as [35]

$$\Gamma(\nu_s \rightarrow \gamma\nu) = \frac{9\alpha_{\text{em}}G_F^2}{256\pi^4} m_{\nu_s}^5 \sin^2 \theta, \quad (7)$$

with  $\alpha_{\text{em}} = e^2/(4\pi)$ ,  $G_F$  being the Fermi constant and  $e$  being the fundamental electric charge. This constraint can be avoided for a sufficiently small  $\theta$ .

### 3.3. Detection of neutrinos from sterile neutrino DM decay

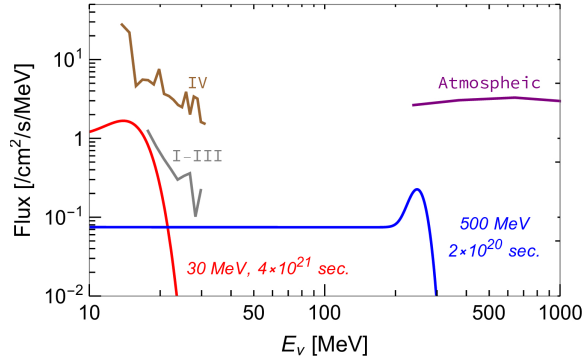
The flux of light active neutrino has two sources. One comes from the sterile neutrino decay  $d\phi^{\nu_s}/dE_\nu$  and the others, we call the background, include solar, atmospheric and diffuse supernova neutrinos  $d\phi^{\text{bkg}}/dE_\nu$ . The resultant flux is given by

$$\frac{d\phi}{dE_\nu} = \frac{d\phi^{\text{bkg}}}{dE_\nu} + \frac{d\phi^{\nu_s}}{dE_\nu}, \quad (8)$$

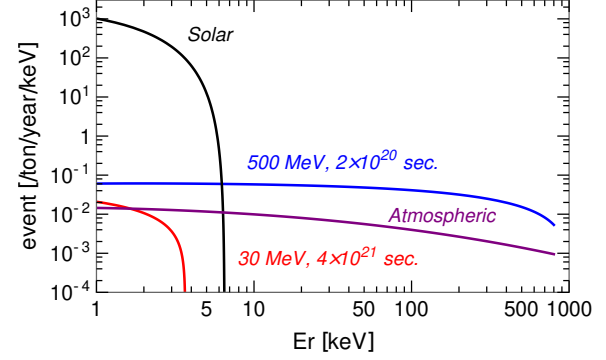
$$\frac{d\phi^{\nu_s}}{dE_\nu} = \frac{dN}{dE_\nu} \frac{J}{4\pi\tau_{\nu_s}m_{\nu_s}}, \quad (9)$$

$$J = \int_{\text{l.o.s}} ds \rho_{\text{DM}} d\Omega, \quad (10)$$

where  $J$  is the  $J$  factor of the decay of the DM with the integration of the DM mass density  $\rho_{\text{DM}}$  along the line of sight (l.o.s) and the solid angle  $\Omega$ . The value  $J = 7 \times 10^{22}$  GeV/cm<sup>2</sup> is taken for the whole Milky Way galaxy halo [36]. For the decays of the sterile neutrino DM and the  $X$  boson, the energy spectrum of the generated neutrino  $dN/dE_\nu$  depends on the mass spectrum. If the mass of  $\nu_s$  and  $X$  are degenerate, one is given by  $E_\nu = m_{\nu_s} - m_X$  and the other is given by  $E_\nu \simeq m_X/2$ . On the other hand, if the  $X$  boson is much lighter than  $\nu_s$ , one is given by  $E_\nu \simeq m_{\nu_s}/2$  and the others from from the  $X$  boson decay form "the box-shape" spectrum [37, 38, 39] as  $dN/dE_\nu \simeq 2/m_{\nu_s}$  for  $m_X^2/(2m_{\nu_s}) < E_\nu < m_{\nu_s}/2$ .



**Figure 1.** The flux of benchmark points of sterile neutrino DM decay and bounds from DSN searches and the measurement of atmospheric neutrino at the SK.



**Figure 2.** The nucleus recoil energy spectrum of solar and atmospheric neutrino as well as that of neutrinos generated by the sterile neutrino DM decay.

Figure 1 shows the limits on the neutrino flux by SK and predicted neutrino flux for some benchmark points of sterile neutrino DM. The limits come from the null results in diffuse supernova neutrino (DSN) from SK I/II/III data (gray) [40], SK IV (brown) [41] and the measurement of atmospheric neutrino (purple) [42]. The red and blue curves are predicted neutrino spectrum for benchmark points and the values associated with each curves stand for the mass and the lifetime of the sterile neutrino DM. The spectrum with one sharp peak originated from  $E_\nu \simeq m_{\nu_s}/2$  and continuous component from the  $X$  decay is a prediction of the model.

We describe the prospect of the signals from the sterile neutrino decay in direct DM detection experiments. The event rate of recoils is expressed as

$$\frac{dR}{dE_r} = N_T \int_{E_\nu^{\min}}^{E_\nu^{\max}} \frac{d\phi}{dE_\nu} \frac{d\sigma}{dE_r} dE_\nu, \quad (11)$$

where  $N_T$  is the number of the total target particles such as nucleus or electrons,  $d\sigma/dE_r$  is the differential cross section with respect to the recoil energy [43],  $E_\nu^{\max}$  is the maximal energy in the neutrino flux, and  $E_\nu^{\min}$  is the minimal energy of neutrinos to generate a given recoil energy  $E_r$ . The expected event rate with its spectrum in nucleus recoil scattering off a Xenon nucleus is shown in Fig. 2. In this plot, the benchmark points are the same as in Fig. 1. The black and purple curves represent the contribution of what is known as the neutrino floor induced by the solar and atmospheric neutrino, respectively. Some parameter sets predict more neutrino flux than the background. Thus, these light neutrinos may be detected by future experiments of direct dark matter detection [44, 45, 46].

#### 4. Conclusion

We have examined the possibility of indirect research on sterile DM neutrinos. An extra  $U(1)$  interacting sterile neutrino DM, at the tree level, can decay into three lighter neutrinos via on-shell the extra gauge boson decaying into two neutrinos. If  $m_{\nu_s}$  is of the order of tens MeV, the produced neutrinos are of sufficient energy to be detected in the SK and direct DM detection experiments. If the lifetime is shorter than about  $10^{21}$  second, the expected event rate in direct DM searches is larger than those by atmospheric neutrinos. Similarly, those neutrinos would be detected by the SK experiment as a by-product of DSN neutrino searches.

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## References

- [1] Boyarsky A, Drewes M, Lasserre T, Mertens S and Ruchayskiy O 2019 *Prog. Part. Nucl. Phys.* **104** 1–45 (Preprint 1807.07938)
- [2] Minkowski P 1977 *Phys. Lett. B* **67** 421–428
- [3] Yanagida T 1979 *Conf. Proc. C* **7902131** 95–99
- [4] Gell-Mann M, Ramond P and Slansky R 1979 *Conf. Proc. C* **790927** 315–321 (Preprint 1306.4669)
- [5] Mohapatra R N and Senjanovic G 1980 *Phys. Rev. Lett.* **44** 912
- [6] Asaka T, Blanchet S and Shaposhnikov M 2005 *Phys. Lett. B* **631** 151–156 (Preprint hep-ph/0503065)
- [7] Asaka T and Shaposhnikov M 2005 *Phys. Lett. B* **620** 17–26 (Preprint hep-ph/0505013)
- [8] Dodelson S and Widrow L M 1994 *Phys. Rev. Lett.* **72** 17–20 (Preprint hep-ph/9303287)
- [9] Dolgov A and Hansen S 2002 *Astropart. Phys.* **16** 339–344 (Preprint hep-ph/0009083)
- [10] Asaka T, Laine M and Shaposhnikov M 2006 *JHEP* **06** 053 (Preprint hep-ph/0605209)
- [11] Yuksel H, Beacom J F and Watson C R 2008 *Phys. Rev. Lett.* **101** 121301 (Preprint 0706.4084)
- [12] Khalil S and Seto O 2008 *JCAP* **10** 024 (Preprint 0804.0336)
- [13] Kaneta K, Kang Z and Lee H S 2017 *JHEP* **02** 031 (Preprint 1606.09317)
- [14] Biswas A and Gupta A 2016 *JCAP* **09** 044 [Addendum: JCAP 05, A01 (2017)] (Preprint 1607.01469)
- [15] Seto O and Shimomura T 2020 *Phys. Lett. B* **811** 135880 (Preprint 2007.14605)
- [16] Davidson A 1979 *Phys. Rev. D* **20** 776
- [17] Mohapatra R N and Marshak R 1980 *Phys. Rev. Lett.* **44** 1316–1319 [Erratum: Phys.Rev.Lett. 44, 1643 (1980)]
- [18] Marshak R and Mohapatra R N 1980 *Phys. Lett. B* **91** 222–224
- [19] Jung S, Murayama H, Pierce A and Wells J D 2010 *Phys. Rev. D* **81** 015004 (Preprint 0907.4112)
- [20] Seto O and Shimomura T 2021 *JHEP* **04** 025 (Preprint 2006.05497)
- [21] Maki Z, Nakagawa M and Sakata S 1962 *Prog. Theor. Phys.* **28** 870–880
- [22] Beda A, Brudanin V, Egorov V, Medvedev D, Pogosov V, Shevchik E, Shirchenko M, Starostin A and Zhitnikov I 2013 *Phys. Part. Nucl. Lett.* **10** 139–143
- [23] Agostini M *et al.* (BOREXINO) 2018 *Nature* **562** 505–510
- [24] Deniz M *et al.* (TEXONO) 2010 *Phys. Rev. D* **82** 033004 (Preprint 1006.1947)
- [25] Bergsma F *et al.* (CHARM) 1986 *Phys. Lett. B* **166** 473–478
- [26] Gninenko S 2012 *Phys. Lett. B* **713** 244–248 (Preprint 1204.3583)
- [27] Astier P *et al.* (NOMAD) 2001 *Phys. Lett. B* **506** 27–38 (Preprint hep-ex/0101041)
- [28] Anastasi A *et al.* 2015 *Phys. Lett. B* **750** 633–637 (Preprint 1509.00740)
- [29] Lees J *et al.* (BaBar) 2014 *Phys. Rev. Lett.* **113** 201801 (Preprint 1406.2980)
- [30] Lindner M, Queiroz F S, Rodejohann W and Xu X J 2018 *JHEP* **05** 098 (Preprint 1803.00060)
- [31] Grifols J and Masso E 1986 *Phys. Lett. B* **173** 237–240
- [32] Harnik R, Kopp J and Machado P A 2012 *JCAP* **07** 026 (Preprint 1202.6073)
- [33] Bilmis S, Turan I, Aliev T, Deniz M, Singh L and Wong H 2015 *Phys. Rev. D* **92** 033009 (Preprint 1502.07763)
- [34] Boudaud M, Lavalle J and Salati P 2017 *Phys. Rev. Lett.* **119** 021103 (Preprint 1612.07698)
- [35] Pal P B and Wolfenstein L 1982 *Phys. Rev. D* **25** 766
- [36] Buch J, Buen-Abad M A, Fan J and Leung J S C 2020 *JCAP* **10** 051 (Preprint 2006.12488)
- [37] Ibarra A, Lopez Gehler S and Pato M 2012 *JCAP* **07** 043 (Preprint 1205.0007)
- [38] Agashe K, Franceschini R and Kim D 2013 *Phys. Rev. D* **88** 057701 (Preprint 1209.0772)
- [39] Boddy K K, Dienes K R, Kim D, Kumar J, Park J C and Thomas B 2016 *Phys. Rev. D* **94** 095027 (Preprint 1606.07440)
- [40] Bays K *et al.* (Super-Kamiokande) 2012 *Phys. Rev. D* **85** 052007 (Preprint 1111.5031)
- [41] Zhang H *et al.* (Super-Kamiokande) 2015 *Astropart. Phys.* **60** 41–46 (Preprint 1311.3738)
- [42] Richard E *et al.* (Super-Kamiokande) 2016 *Phys. Rev. D* **94** 052001 (Preprint 1510.08127)
- [43] Freedman D Z 1974 *Phys. Rev. D* **9** 1389–1392
- [44] Aalbers J *et al.* (DARWIN) 2016 *JCAP* **11** 017 (Preprint 1606.07001)
- [45] Aalseth C *et al.* 2018 *Eur. Phys. J. Plus* **133** 131 (Preprint 1707.08145)
- [46] Akerib D *et al.* (LUX-ZEPLIN) 2020 *Phys. Rev. D* **101** 052002 (Preprint 1802.06039)