Sterile Neutrino/Dark Fermion Dark Matter: Searches in the X-Ray Sky, the Nuclear Physics Laboratory and in Galaxy Formation

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Abstract The possibility of dark matter being a particle involved in the generation of neutrino mass has been of interest for over 25 years. Sterile neutrinos—or in the contemporary parlance—dark fermions, are among the simplest and most cited particles which can provide a mechanism for neutrino mass. If one particle of this class has a small mixing, it can be quasi-thermally or nonthermally produced in the early Universe, affect cosmological structure formation, and be detected by X-ray telescopes or laboratory nuclear experiments. A candidate line was detected in 2014, and I review the status of the line and its implications for galaxy formation, proposals for future observations, and laboratory detection.

1 Introduction

One of the most significant discoveries in the past two decades in particle physics was that neutrinos have mass and oscillate between flavor states [1]. The presence of mass requires a mass generation mechanism, and many mechanisms have been proposed [2]. One of the simplest and prevalent mechanisms has been the introduction of Majorana and Dirac type mass terms into the Standard Model Lagrangian:

$$\mathcal{L} \supset -h_{\alpha i} L_\alpha N_i \varphi - \frac{1}{2} M_{ij} N_i N_j + H.c., \tag{1}$$

where $h_{\alpha i}$ are the Yukawa couplings for the flavor states $\alpha = e, \mu, \tau$ and $M_{ij} = M_{ji}$ $(i, j = 1, 2, ...)$ are the Majorana masses. The extra particles involved in this mechanism were labeled "sterile neutrinos" due to the lack of their involvement in Standard Model interactions. In a sense, the introduction of these sterile neutrinos was one of the first instances of invoking dark fermion fields to solve a problem in

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particle physics. In the contemporary parlance, they would be referred to as "dark fermions" from a "hidden sector" and I interchanged these names below.

This mechanism can be embedded in what is described as the seesaw mechanism, where the smallness of neutrino mass is due to the generation of Majorana masses

$$m_{ij} = \frac{\lambda_{ij}\langle H\rangle^2}{M_N} \sim \frac{m_D^2}{M_N}. \tag{2}$$

For M_N large, $m_{ij} \ll m_D$, providing small neutrino masses, as observed relative to charged lepton masses. The high-scale completion of this mechanism determines the type of seesaw mechanism [3]. The relation in Eq. (1) can be considered simply phenomenologically, and this is dubbed the "new Standard Model" or "neutrino Standard Model" (νSM) [4] or the "neutrino Minimal Standard Model" (νMSM) [5]. In this mechanism, there are only two "heavy" M_N required to produce the observed atmospheric and solar oscillation mass scales. If there is a symmetry in flavor between the "dark sector" fermions (sterile neutrinos) and the Standard Model fermions, we get an extra M_N for free. This dark fermion (sterile neutrino) can have arbitrary mass and mixings, except for where there are constraints on sterile neutrino mixings. In fact, the mixing for this dark fermion (sterile neutrino) can be arbitrarily small, since the lightest mass eigenstate, m_α of the neutrinos may be arbitrarily small

$$\theta \sim \sqrt{\frac{m_\alpha}{M_N}} \ll 1. \tag{3}$$

The arbitrarily small mixing angle is of interest because production and the candidate signals in X-ray indicate mixing angles of order 10^{-7}–10^{-10}. Note that the simplest models of this form cannot accommodate both dark fermions (sterile neutrinos) being dark matter as well as a short baseline neutrino [5]. More complicated models can accommodate both [6].

2 Sterile Neutrino/Dark Fermion Dark Matter: Production and Indirect Detection

It was realized in 1992 that such an extra dark fermion could be dark matter [7], via scattering induced production in mixing with an active neutrino—dubbed the Dodelson-Widrow case. In 1998, this was extended to use a Mikheyev-Smirnov-Wolfenstein resonant production method in universes that could have a nontrivial lepton asymmetry in active neutrinos—dubbed the Shi-Fuller case [8]. Nonresonant Dodelson-Widrow production occurs at temperatures of approximately 100 MeV, where above that temperature the scattering rate to Hubble expansion rate decreases with increasing temperatures as $\Gamma/H \propto T^{-9}$ and below that temperature, the rate of production decreases again as $\Gamma/H \propto T^3$. In the resonant Shi-Fuller case, there can still be some production via the nonresonant production, but the production is enhanced by resonance at higher temperature due to the presence of lepton asymmetry. Therefore, the Shi-Fuller case can produce the requisite total dark matter density with even smaller mixing angles.

In my collaboration with Fuller and Patel, we explored the full parameter space of mixing, mass, and lepton number, where the latter is what connects the two mechanisms of Dodelson-Widrow and Shi-Fuller [9]. (As the lepton number approaches zero, Shi-Fuller becomes Dodelson-Widrow.) We included the effects of the quark-hadron transition that occurs during peak production of the dark matter in much of the parameter space. That work also explored all of the constraints on the dark fermion/sterile neutrino dark matter, including structure formation constraints due to the "warmness" of the dark matter, the cosmic microwave background spectral distortions due to decay, big bang nucleosynthesis, the diffuse X-ray background, and supernova cooling. The strongest constraint was found by Abazajian, Fuller, and Patel to be likely from X-ray emission as observed in relatively local structures like galaxies and clusters of galaxies observed by the contemporary X-ray telescopes *Chandra* and *XMM-Newton*. This is due to the radiative decay of the dark fermion/sterile neutrino, which has no GIM suppression:

$$\Gamma_\gamma(m_s, \sin^2 2\theta) \approx 1.36 \times 10^{-30}\,\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\,\mathrm{keV}}\right)^5, \tag{4}$$

for the Majorana case. This decay was first pointed out and calculated by Shrock [10] and independently by Pal & Wolfenstein [11], and for the Majorana case by [12]. The level of constraints from *Virgo Cluster XMM-Newton* observations were explored in Abazajian et al. [13]. In that work, we also explored future sensitivities by the at the time proposed *Constellation-X* mission, as well as pointing out that an equivalent exposure to that large mission "could be obtained by a stacking analysis of the spectra of a number of similar clusters." In the subsequent thirteen years, there was a long history of searches for the line in X-ray data, with no conclusive evidence (for a review, see [14]).

In 2014, Bulbul et al. [15] used a stack of 73 clusters to search for dark matter decay lines, and discovered a $\approx 5\sigma$ line in the sample, in several subsamples, with both detectors aboard *XMM-Newton*. They also saw evidence for the line in *Chandra* observations of the *Perseus* Cluster. This detection was followed up in several searches, with evidence for the line from Andromeda [16], the Milky Way Galactic Center (with *XMM-Newton*) [17], with *SUZAKU* X-ray Space Telescope data toward Perseus [18], in 8 more clusters at $>2\sigma$ significance [19], and in *NUSTAR* [20] and *Chandra* [21] deep fields' exposure to the Milky Way Galactic Halo, as shown in Fig. 1.

The line was not detected in claimed sensitive observations of stacked galaxies, though the systematic uncertainties in the continuum were of order the signal [22]. It was also not detected in MOS observations of Draco, though the authors of the analysis state the observations do not exclude a dark matter decay interpretation [23].

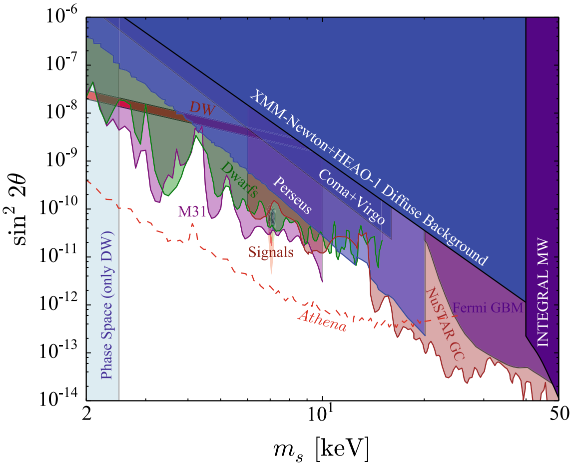

Fig. 1 The full parameter space for sterile neutrino dark matter is shown, for the case where it comprises all of the dark matter. Constraints arise from M31 Horiuchi et al. [24], as well as stacked dwarfs [25]. Also shown are constraints from the diffuse X-ray background [26], and individual clusters "Coma+Virgo" [27]. At higher masses, we show the limits from Fermi GBM [28] and INTEGRAL [29]. The signals near 3.55 keV from M31 and stacked clusters are also shown [15, 16]. The vertical mass constraint only directly applies to the Dodelson-Widrow model being all of the dark matter, labeled "DW," which is now excluded as all of the dark matter. We also show forecast sensitivity of the planned *Athena X-ray Telescope* [30]. This figure is from Ref. [14]

3 Galaxy Formation

There has been considerable interest in this candidate because of the "warmness" of sterile neutrino dark matter, which may alleviate problems in galaxy formation, namely the central density or *Too Big To Fail* problem [32, 33]. This was explored in ranges of the parameter space of the signal, showing how sterile neutrino/dark fermion dark matter could be differentiated from thermal warm dark matter in dark matter only simulations [34, 35], as well as recent full hydrodynamic simulations [36]. It should be emphasized that the fraction of dark matter need not by 100% in order to produce the candidate line but could be as little as 7×10^{-4} in low reheating universe scenarios [14]. In the case of a small fraction of the dark matter being the signal producing sterile neutrino/dark fermion, the dynamics of galaxy formation would be dominated by the predominant form of dark matter, whether it is cold dark matter, self-interacting dark matter, or anything else (Fig. 2).

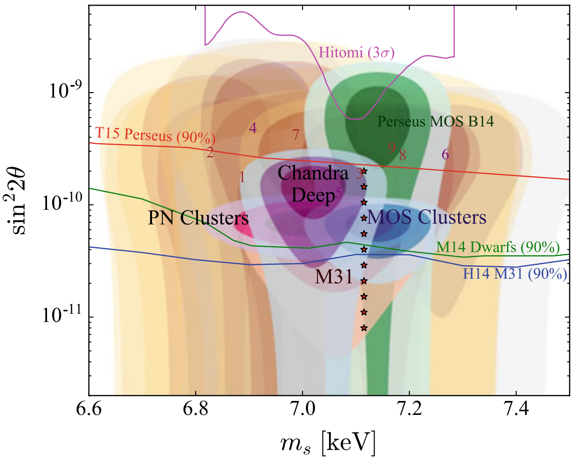

Fig. 2 X-ray line detections consistent with sterile neutrino dark matter are shown here. The dark colored regions are 1, 2 and 3 σ from the MOS (blue) and PN (red) stacked clusters by Bulbul et al. [15], the Bulbul et al. core-removed Perseus cluster (green), and M31 (orange) from Boyarsky et al. [16]. Also shown are the 1 and 2σ regions of the detection in the Galactic Center (GC) [17] as well as the $>2\sigma$ line detections in 1. Abell 85; 2. Abell 2199; 3. Abell 496 (MOS); 4. Abell 496 (PN); 5. Abell 3266; 6. Abell S805; 7. Coma; 8. Abell 2319; 9. Perseus by Iakubovskyi et al. [19]. Numbers in the plot mark the centroid of the regions, with MOS detections in orange and PN in purple. We also show, in purple, the region consistent with the signal in *Chandra* Deep Field observations, with errors given by the flux uncertainty, i.e., not including dark matter profile uncertainties [21]. The lines show constraints at the 90% level from *Chandra* observations of M31 (14) [24], stacked dwarf galaxies (M14) [25], and Suzaku observations of Perseus (T15) [31]. Stars mark models studied in Ref. [32]. This figure is from Ref. [14]

4 The Future

Several follow-up observations and experiments are planned. On the laboratory experiment side, the KArlsruhe TRItium Neutrino (KATRIN) experiment has sensitivities down to mixing angles of $\sim 10^{-8}$ at $m_s \approx 7\,\text{keV}$ [37], and the atom trap experiment Heavy Unseen Neutrinos from Total Energy-momentum Reconstruction (HUNTER) aims to be even more sensitive via energy-momentum reconstruction of K-capture ^{131}Cs [38].

Future searches on the sky include the *Micro-X* and *XQC* sounding rocket experiments, which can be sensitive to the signal parameter space, with campaigns that could occur from the southern hemisphere in the summer of 2019 [39]. Large missions such as *ATHENA* [30] and the *X-ray Surveyor* will be very sensitive to the candidate signal parameter space, but are a decade or more away from launch (2028 launch for *ATHENA* and later for *X-ray Surveyor*). Sooner would be the replacement mission for *Hitomi*, the X-ray Recovery Mission (*XARM*), which is scheduled for launch in March 2021, and would be sensitive to the velocity broadening of the line [15].

A very exciting development that was initiated by this Symposium was the proposal for a CUBESAT mission by a team at Fermi National Accelerator Laboratory led by S. Timpone, and presented by Roni Harnik at the Symposium. The mission would use newly designed CCDs from Fermilab that are sensitive to 3.5 keV photons on a CUBESAT in order to search for the line from exposure to a large fraction of the sky. Such an experiment is roughly estimated to have $\sim 20\sigma$ sensitivity to the 3.5 keV signal, with a mere 90 min exposure. I was able to connect the instrumentalist team at Fermilab with space mission specialists at Jet Propulsion Lab, led by Olivier Doré, to help draft a more robust proposal to NASA for funding what would be an exceedingly high-impact CUBESAT mission.

On the physics theory side, Alex Kusenko and I started a new project at the Symposium which studies a number of production mechanisms besides Dodelson-Widrow and Shi-Fuller, which could be responsible for the decay line and be all of or a fraction of the dark matter. These models include production by the decay of a gauge singlet in the Higgs sector [40], and mechanisms in the split seesaw model [41]. This collaboration is ongoing thanks to the Symposium.

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References

1. C. Patrignani et al., Chin. Phys. C **40**(10), 100001 (2016). https://doi.org/10.1088/1674-1137/40/10/100001
2. A. de Gouvêa, Ann. Rev. Nucl. Part. Sci. **66**, 197 (2016). https://doi.org/10.1146/annurev-nucl-102115-044600
3. R.N. Mohapatra, A.Y. Smirnov, Ann. Rev. Nucl. Part. Sci. **56**, 569 (2006). https://doi.org/10.1146/annurev.nucl.56.080805.140534
4. A. de Gouvea, Phys. Rev. D **72**, 033005 (2005). https://doi.org/10.1103/PhysRevD.72.033005
5. T. Asaka, S. Blanchet, M. Shaposhnikov, Phys. Lett. B **631**, 151 (2005). https://doi.org/10.1016/j.physletb.2005.09.070
6. D. Borah, Phys. Rev. D **94**(7), 075024 (2016). https://doi.org/10.1103/PhysRevD.94.075024
7. S. Dodelson, L.M. Widrow, Phys. Rev. Lett. **72**, 17 (1994). https://doi.org/10.1103/PhysRevLett.72.17
8. X.D. Shi, G.M. Fuller, Phys. Rev. Lett. **82**, 2832 (1999). https://doi.org/10.1103/PhysRevLett.82.2832
9. K. Abazajian, G.M. Fuller, M. Patel, Phys. Rev. D **64**, 023501 (2001). https://doi.org/10.1103/PhysRevD.64.023501
10. R. Shrock, Phys. Rev. D **9**, 743 (1974). https://doi.org/10.1103/PhysRevD.9.743
11. P.B. Pal, L. Wolfenstein, Phys. Rev. D **25**, 766 (1982). https://doi.org/10.1103/PhysRevD.25.766
12. V.D. Barger, R.J.N. Phillips, S. Sarkar, Phys. Lett. B **352**, 365 (1995). https://doi.org/10.1016/0370-2693(95)00486-5, https://doi.org/10.1016/0370-2693(95)00831-5. [Erratum: Phys. Lett. B356,617(1995)]
13. K. Abazajian, G.M. Fuller, W.H. Tucker, Astrophys. J. **562**, 593 (2001). https://doi.org/10.1086/323867

14. K.N. Abazajian, Phys. Rept. **711–712**, 1 (2017). https://doi.org/10.1016/j.physrep.2017.10.003
15. E. Bulbul, M. Markevitch, A. Foster, R.K. Smith, M. Loewenstein, S.W. Randall, Astrophys. J. **789**, 13 (2014). https://doi.org/10.1088/0004-637X/789/1/13
16. A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse, Phys. Rev. Lett. **113**, 251301 (2014). https://doi.org/10.1103/PhysRevLett.113.251301
17. A. Boyarsky, J. Franse, D. Iakubovskyi, O. Ruchayskiy, Phys. Rev. Lett. **115**, 161301 (2015). https://doi.org/10.1103/PhysRevLett.115.161301
18. O. Urban, N. Werner, S.W. Allen, A. Simionescu, J.S. Kaastra, L.E. Strigari, Mon. Not. Roy. Astron. Soc. **451**(3), 2447 (2015). https://doi.org/10.1093/mnras/stv1142
19. D. Iakubovskyi, E. Bulbul, A.R. Foster, D. Savchenko, V. Sadova, preprint, arXiv:1508.05186 [astro-ph.HE] (2015)
20. A. Neronov, D. Malyshev, D. Eckert, Phys. Rev. D **94**(12), 123504 (2016). https://doi.org/10.1103/PhysRevD.94.123504
21. N. Cappelluti, E. Bulbul, A. Foster, P. Natarajan, M.C. Urry, M.W. Bautz, F. Civano, E. Miller, R.K. Smith, Astrophys. J. **854**(2), 179 (2018). https://doi.org/10.3847/1538-4357/aaaa68
22. M.E. Anderson, E. Churazov, J.N. Bregman, Mon. Not. Roy. Astron. Soc. **452**(4), 3905 (2015). https://doi.org/10.1093/mnras/stv1559
23. O. Ruchayskiy, A. Boyarsky, D. Iakubovskyi, E. Bulbul, D. Eckert, J. Franse, D. Malyshev, M. Markevitch, A. Neronov, Mon. Not. Roy. Astron. Soc. **460**(2), 1390 (2016). https://doi.org/10.1093/mnras/stw1026
24. S. Horiuchi, P.J. Humphrey, J. Onorbe, K.N. Abazajian, M. Kaplinghat, S. Garrison-Kimmel, Phys. Rev. D **89**(2), 025017 (2014). https://doi.org/10.1103/PhysRevD.89.025017
25. D. Malyshev, A. Neronov, D. Eckert, Phys. Rev. D **90**, 103506 (2014). https://doi.org/10.1103/PhysRevD.90.103506
26. A..Boyarsky, A. Neronov, O. Ruchayskiy, M. Shaposhnikov, Mon. Not. Roy. Astron. Soc. **370**, 213 (2006). https://doi.org/10.1111/j.1365-2966.2006.10458.x
27. A. Boyarsky, A. Neronov, O. Ruchayskiy, M. Shaposhnikov, Phys. Rev. D **74**, 103506 (2006). https://doi.org/10.1103/PhysRevD.74.103506
28. K.C.Y. Ng, S. Horiuchi, J.M. Gaskins, M. Smith, R. Preece, Phys. Rev. D **92**(4), 043503 (2015). https://doi.org/10.1103/PhysRevD.92.043503
29. A. Boyarsky, D. Malyshev, A. Neronov, O. Ruchayskiy, Mon. Not. Roy. Astron. Soc. **387**, 1345 (2008). https://doi.org/10.1111/j.1365-2966.2008.13003.x
30. A. Neronov, D. Malyshev, Phys. Rev. D **93**(6), 063518 (2016). https://doi.org/10.1103/PhysRevD.93.063518
31. T. Tamura, R. Iizuka, Y. Maeda, K. Mitsuda, N.Y. Yamasaki, Publ. Astron. Soc. Jpn. **67**, 23 (2015). https://doi.org/10.1093/pasj/psu156
32. T. Venumadhav, F.Y. Cyr-Racine, K.N. Abazajian, C.M. Hirata, Phys. Rev. D **94**(4), 043515 (2016). https://doi.org/10.1103/PhysRevD.94.043515
33. K.N. Abazajian, Phys. Rev. Lett. **112**(16), 161303 (2014). https://doi.org/10.1103/PhysRevLett.112.161303
34. S. Horiuchi, B. Bozek, K.N. Abazajian, M. Boylan-Kolchin, J.S. Bullock, S. Garrison-Kimmel, J. Onorbe, Mon. Not. Roy. Astron. Soc. **456**(4), 4346 (2016). https://doi.org/10.1093/mnras/stv2922
35. B. Bozek, M. Boylan-Kolchin, S. Horiuchi, S. Garrison-Kimmel, K. Abazajian, J.S. Bullock, Mon. Not. Roy. Astron. Soc. **459**(2), 1489 (2016). https://doi.org/10.1093/mnras/stw688
36. B. Bozek, et al., Mon. Not. Roy. Astron. Soc. **483**(3), 4086 (2019). https://doi.org/10.1093/mnras/sty3300
37. N.M.N. Steinbrink, J.D. Behrens, S. Mertens, P.C.O. Ranitzsch, C. Weinheimer, Eur. Phys. J. C **78**(3), 212 (2018). https://doi.org/10.1140/epjc/s10052-018-5656-9
38. P.F. Smith, New J. Phys. **21**(5), 053022 (2019). https://doi.org/10.1088/1367-2630/ab1502
39. E. Figueroa-Feliciano et al., Astrophys. J. **814**(1), 82 (2015). https://doi.org/10.1088/0004-637X/814/1/82

40. K. Petraki, A. Kusenko, Phys. Rev. D **77**, 065014 (2008). https://doi.org/10.1103/PhysRevD.77.065014
41. A. Kusenko, F. Takahashi, T.T. Yanagida, Phys. Lett. B **693**, 144 (2010). https://doi.org/10.1016/j.physletb.2010.08.031