Detection of Dark Matter Decay in the X-ray

Submitted to the Astro2010 Decadal
Cosmology and Fundamental Physics Science Frontier Panel

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1. Introduction

The nature of dark matter remains one of the most significant unsolved problems in cosmology and particle astrophysics. The first indication of the presence of what was dubbed "dark matter" was by Fritz Zwicky, who in 1933 suggested a dark matter component to clusters of galaxies to explain the high mass-to-light ratios required by measurements of high velocity dispersions of component galaxies. It was then found that the rotation curves of galaxies also required a dark matter component. The formation of large-scale structure measured by galaxy surveys and the cosmic microwave background (CMB) also has required the presence of dark matter. In fact, the abundance of dark matter has been precisely determined by observations of anisotropies in the CMB (Komatsu et al. 2008), and from the growth of cosmological structure in the clustering of galaxies (Tegmark et al. 2004). The fundamental nature of the dark matter, however, remains unknown.

One natural candidate is a fermion that has no standard model interactions other than a coupling to the standard neutrinos through their mass generation mechanism (Dodelson & Widrow 1994; Shi & Fuller 1999). Due to their lack of interactions and association with the neutrino sector, such fermions are referred to as sterile neutrinos. One prominent search for sterile neutrinos was the MiniBooNE experiment, which searched for oscillations consistent with a form of sterile neutrino indicated an oscillation interpretation of the Liquid Scintillator Neutrino Detector (LSND) results, at a mass scale of $m_s \sim 1$ eV and mixing of $sin^2 2\theta \sim 10^{-2}$. MiniBooNE found evidence against such a sterile neutrino interpretation for LSND Aguilar-Arevalo et al. (2007), which is very far from the mass and mixing scale required for dark matter sterile neutrinos, $m_s \sim 1$ keV and mixing $sin^2 2\theta \lesssim 10^{-7}$.

Observations are consistent with sterile neutrinos as the dark matter for a limited mass range for the standard production mechanism. The most stringent constraints come from X-ray observations and observations small scale cosmological structure (Abazajian & Koushiappas 2006). In this allowed range of masses, the sterile neutrino has a non-negligible thermal velocity component, and is therefore a warm dark matter (WDM) candidate, but for higher particle masses, can behave as a cold dark matter (CDM) particle candidate. Much work has been done on oscillation production of this dark matter candidate, which ties its production mechanism and primordial density with its decay rate and detectability (Abazajian et al. 2001a; Abazajian & Fuller 2002; Asaka et al. 2006). Other production mechanisms have the sterile neutrino production method separate from the physics of their decay, and therefore could lie in any part of the detectable parameter space (Kusenko 2006; Shaposhnikov & Tkachev 2006). As shown below, *IXO* can detect this dark matter candidate in the entire favored region of parameter space or rule it out, using techniques proven by current and past observations.

The prevalent ansatz of an absolute CDM component in galaxy formation is not strictly valid even for one of the most cited CDM candidate, a supersymmetric neutralino. The damping scale at which thermal velocities of the dark matter cut off the growth of gravitationally bound structures is completely unknown below the galactic scale. One principal challenge to the CDM paradigm is the order of magnitude over-prediction of the observed satellites in galaxy-sized halos such as the Milky Way (Klypin et al. 1999; Moore et al. 1999). Warm dark matter suppresses dwarf galaxy formation, which may occur through fragmentation of larger structures. Semi-analytic galaxy formation modeling has found that the number of dwarf galaxies formed in satellite halos may be suppressed due to the reionization, stellar feedback within halos, and/or tidal stripping of satellites (Bullock et al. 2000). Whether a minor or major suppression of small mass halos is beneficial or detrimental to the suppression of dwarf galaxy formation remains unsolved.

Four more problems in the CDM paradigm may benefit from the reduction of power on small scales from WDM. First is the reduction of the prevalence of halos in low-density voids in N-body simulations of CDM structure formation, consistent the apparent dearth of massive galaxies within voids in local galaxy surveys (Peebles 2001). The second is the relatively low concentrations of galaxies observed in rotation curves compared to what is predicted from the ΛCDM power spectrum (Dalcanton & Hogan 2001), which can be relieved by a reduction of the initial power spectrum of density fluctuations at small scales (Zentner & Bullock 2002). The third is the “angular-momentum” problem of CDM halos, where gas cools at very early times into small mass halos and leads to massive low-angular momentum gas cores in galaxies, which can be alleviated by the hindrance of gas collapse and angular momentum loss through the delay of small halo formation in a WDM scenario (Dolgov & Sommer-Larsen 2001). The fourth problem is the formation of disk-dominated or pure-disk galaxies in CDM models, which is impeded by bulge formation due to the high merger accretion rate history in CDM models, but may be alleviated with WDM (Governato et al. 2004).

Of particular interest recently for models of WDM are the possible indications of the presence of cores in local group dwarf galaxies, inferred from the positions of central stellar globular clusters (Goerdt et al. 2006) and radial stellar velocity dispersions (Wilkinson et al. 2006). For example, for the Fornax dwarf spheroidal galaxy to be consistent with a packed phase space density of the WDM, as a sterile neutrino, the sterile neutrino particle mass must be between 0.5 and 1.2 keV (Strigari et al. 2006; Abazajian & Koushiappas 2006). Conversely, this places a robust limit—the Tremaine-Gunn bound—on the mass and phase space of the dark matter particle from observed dynamics in galaxy centers (Tremaine & Gunn 1979).

There are three other interesting physical effects when sterile neutrinos have parameters such that they are created as the dark matter in the non-resonant production mechanism. First, asymmetric sterile neutrino emission from a supernova core can assist in producing the observed large pulsar velocities above 1000 km s^{-1} (Kusenko & Segre 1999; Kusenko et al. 2008). The parameter space overlaps that of the non-resonant production mechanism (Fig. 1). Second, the slow radiative decay of the sterile neutrino dark matter in the standard production mechanism can augment the ionization fraction of the primordial gas at high-redshift (high-z) (Biermann & Kusenko 2006). This can lead to an enhancement of molecular hydrogen formation and star formation. This has significant consequences on the formation of the first stars and quasars, leading to earlier formation of massive gas systems, stars and quasars than expected in WDM or even canonical CDM models. This remains an open question, but it does indicate that the reionization epoch is not a elementary constraint on WDM models (O'Shea & Norman 2006). Third, the sterile neutrino may enhance the heating of the shock in core-collapse Type-II supernovae, alleviating the problems of (Hidaka & Fuller 2007).

The potentially beneficial effects of the suppression of cosmological small-scale structure in WDM models like sterile neutrinos can also lead to observational conflicts if the suppression extends to excessively high mass and length scales. The suppression scale monotonically decreases with increasing sterile neutrino particle mass. One of the best direct measures of clustering at small scales is the clustering observed in intervening gas along the line-of-sight to a quasar, known as the Lyman-α forest (Narayanan et al. 2000). Statistically-consistent constraints allowing freedom in all cosmological parameters and constraints from the CMB, galaxy clustering, and a measurement of clustering in the Lyman-α forest gives a lower limit for the sterile neutrino dark matter particle mass as $m_s > 1.7$ keV (95% CL) (Abazajian 2006). Seljak et al. (2006) describe a much more stringent constraint when directly using high-z flux power spectra from the Sloan Digital Sky Survey (SDSS) and other higher-resolution flux power spectra, $m_s > 14$ keV (95% CL). This limit only applies to the specific non-resonant oscillation production model of Dodelson & Widrow (1994) and not to other production methods such as non-zero lepton number L cosmologies. Moreover, the analysis and interpretation of the Lyman-α forest is complicated by many aspects. The theoretical interpretation of the flux power spectrum is complicated by the thermal state of the gas as a function of redshift, the presence of metal lines in the forest, and the limitations of hydrodynamical simulations in the forest modeling (e.g. Jena et al. 2005).

There remains considerable interest in the potential benefits of WDM in galaxy and sub galaxy-scale structure formation, and sterile neutrinos are the most natural candidate. Therefore, there is still considerable interest in searching for the dark matter decay line in the X-ray.

2. Detectability by X-ray Observations

Because the sterile neutrino dark matter candidate is mixed with one or more active neutrinos, there exists are radiative decay mode of the dark matter particle to the lighter neutrino and an X-ray photon. Abazajian et al. (2001b) was the first to propose the use of X-ray observations to detect this signature radiative decay. Since the mixing angle required for production of the sterile neutrino dark matter is such that $\theta^2 \lesssim 10^{-6}$, the coupling is inaccessible to any current methods of searches for neutral leptons via so-called kink-searches in beta-decay experiments. However, the same mass-generation mechanism that couples the sterile neutrino to the active neutrinos for their production causes a radiative decay mode that can be detected by X-ray observatories. For the Majorana neutrino case, the decay rate is (Pal & Wolfenstein 1982)

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

where m_s is the mass eigenstate most closely associated with the sterile neutrino, and θ is the mixing angle between the sterile and active neutrino. The decay of a nonrelativistic sterile neutrino into two (nearly) massless particles produces a line at energy $E_\gamma = m_s/2$. The radiative decay time is orders of magnitude greater than the age of the universe (which is necessary for a viable dark matter candidate) but the number of particles in the field of view of the *Chandra* or *IXO* observatories is approximately $\sim 10^{70}$, which makes this decay even at very low rates detectable by these observatories.

Since the initial proposal of the search of the radiative decay line in clusters of galaxies, field galaxies, and the cosmic X-ray background by Abazajian et al. (2001b), many groups have conducted follow-up searches for the signature decay in the cosmic X-ray background (Boyarsky et al. 2006a), clusters of galaxies (Watson et al. 2006), dwarf galaxies (Boyarsky et al. 2006c), the Andromeda galaxy (Watson et al. 2006) and the Milky Way (Riemer-Sorensen et al. 2006). No detections of candidate lines have yet been found, but upper limits to the decay flux in lines have been made, and have led to upper limits to the particle mass of the sterile neutrino dark matter in the standard production mechanism. The best current constraint is that from an analysis of *XMM-Newton* X-ray observations of the Andromeda galaxy by Watson et al. (2006), with the constraint at the level of $m_s < 3.5$ keV (95% CL). Constraints from Milky Way observations are comparable in strength (Boyarsky et al. 2007), as well as constraints from *Suzaku* observations of Ursa Minor (Loewenstein et al. 2008). Many of the current X-ray constraints on the parameter space of sterile neutrino dark matter parameters are shown in Fig. 1.

3. Sensitivity of the *IXO* Telescope and Detectors

IXO has very significant technical advantages to the detection of a dark matter decay line over current observatories such as *Chandra*, *XMM-Newton*, or *Suzaku*. The advantages come from three factors: (1) the significantly larger collecting area of*IXO*, (2) the enhanced energy resolution of the *IXO* microcalorimeter detectors, and (3) lower background of the *IXO* spectral and imaging system.

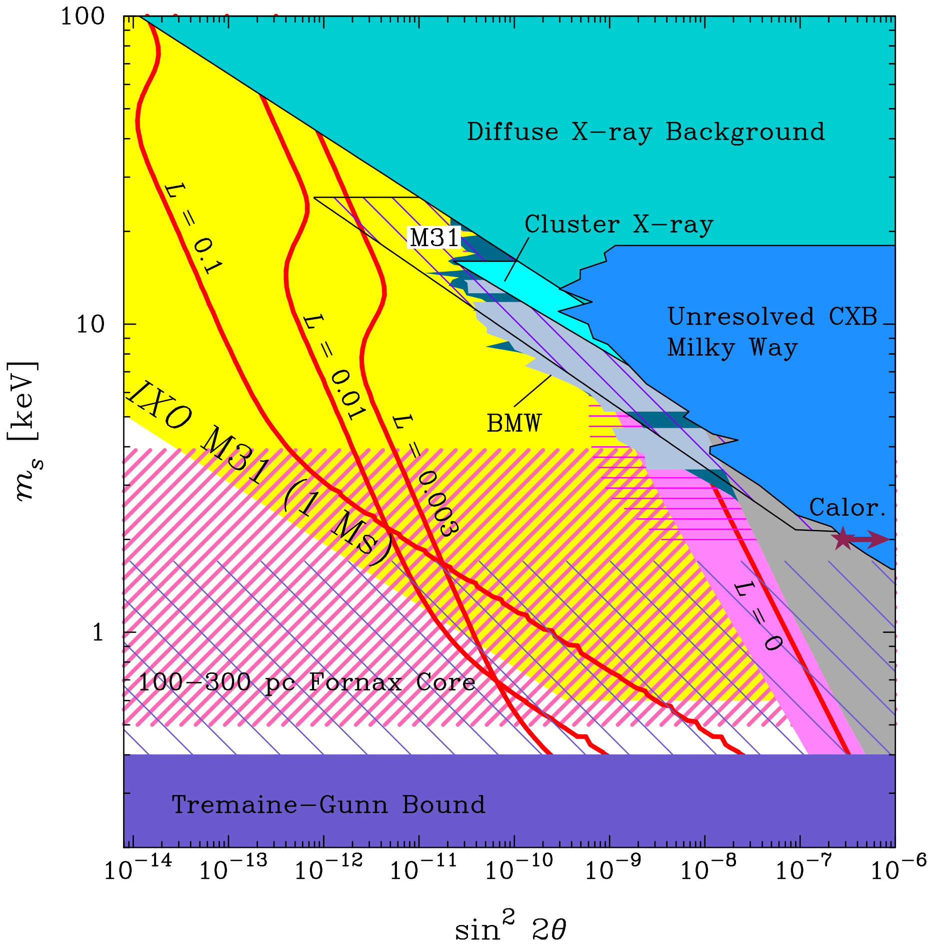

Fig. 1.— Full parameter space constraints for the sterile neutrino production models, assuming sterile neutrinos constitute the dark matter. Favored regions are in red/magenta colors, disfavored and excluded regions are in blue/turquoise colors. The strongly favored region of a horizontal band of the mass scale consistent with producing a 100 - 300 pc core in the Fornax dwarf galaxy (Strigari et al. 2006). The favored parameters consistent with pulsar kick generation are in horizontal hatching (Kusenko et al. 2008). Contours labeled with lepton number $L = 0$, $L = 0.003$, $L = 0.01$, $L = 0.1$ are dark matter production predictions for constant comoving density of $\Omega_s = 0.24$ for $L = 0$, and $\Omega_s = 0.3$ for non-zero lepton number L universes (Abazajian & Fuller 2002). The minimal standard production prediction is that of $L = 0$. The grey region to the right of $L = 0$ over-produces the dark matter. Constraints from X-ray observations include the diffuse X-ray background (turquoise) (Boyarsky et al. 2006a), from XMM-Newton observations of the Coma and Virgo clusters (light blue) (Boyarsky et al. 2006b), the Milky Way (labeled BMW) (Boyarsky et al. 2007), and Ursa Minor using Suzaku (dark blue) (Loewenstein et al. 2008). The diagonal wide-hatched region is the constraint from *XMM-Newton* observations of M31 (Watson et al. 2006). Also shown is the best current constraint from *Chandra*, from observations of contributions of dark matter X-ray decay in the cosmic X-ray background through the CDFN and CDFS (medium blue, "Unresolved CXB Milky Way"). Also shown is an estimate of the sensitivity of a 1 Ms observation of M31 with *IXO* (yellow). This extends into the entire favored parameter space of interest where all production models can place the dark matter candidate. The region at $m_s < 0.4$ keV is ruled out by a conservative application of the Tremaine-Gunn bound (Bode et al. 2001), and $m_s < 1.7$ keV is disfavored by conservative application of constraints from the Lyman-α forest.

The primary advantage for this application of *IXO* over that of current observatories is its collecting area, which increases the sensitivity of the detection by a factor of approximately 75 times relative to *Chandra*. The second advantage is the planned microcalorimetric energy resolution of 2.5 eV, which enhances the sensitivity of the decay line over background relative to that aboard *Chandra* by a factor of approximately 8.9. The third advantage is the planned significant reduction of background radiation in the spectral and imaging system, which enhances the sensitivity to a line feature by a factor of approximately 12 times relative to *Chandra*.[1]

In detail, it can be shown that the background count rate in a line of 2.5 eV in *IXO* is approximately $B \approx 1.9{\times}10^{-5} t_5$ counts in an integration time of $t_5 = t/(10^5\ \mathrm{s})$. The count rate in a line is $C_L = 2.3 \times 10^{-2} F_{-14}$ counts s^{-1} for a line of flux $F_{-14} \equiv F/(10^{-14}$ ergs cm^{-2} s^{-1}. The count level sensitivity for a 4σ line is then $C_L = 4\sqrt{B}/t$, or the detectable flux is $F^{\rm det}_{-14} \approx 9.3 \times 10^{-6} t_5^{-1/2}$.

The sensitivity detailed here is a several order of magnitude improvement to line detection from currently operational X-ray observatories. The sensitivity in parameter space of *IXO* to a sterile neutrino-like dark matter particle is shown in Fig. 1 relative to current constraints. As shown in the figure, the entire favored region is within reach for *IXO*. In summary, *IXO* would detect this dark matter particle if it exists within any of the favored parameter space (colored red/magenta), or exclude it entirely, which presents a tremendous opportunity for particle astrophysics and cosmology within our lifetime.

REFERENCES

Abazajian, K. 2006, Phys. Rev., D73, 063513, astro-ph/0512631

Abazajian, K., Fuller, G. M., & Patel, M. 2001a, Phys. Rev., D64, 023501, astro-ph/0101524

Abazajian, K., Fuller, G. M., & Tucker, W. H. 2001b, Astrophys. J., 562, 593, astro-ph/0106002

Abazajian, K. & Koushiappas, S. M. 2006, Phys. Rev., D74, 023527, astro-ph/0605271

Abazajian, K. N. & Fuller, G. M. 2002, Phys. Rev., D66, 023526, astro-ph/0204293

Aguilar-Arevalo, A. A. et al. 2007, Phys. Rev. Lett., 98, 231801, arXiv:0704.1500

Asaka, T., Laine, M., & Shaposhnikov, M. 2006, JHEP, 06, 053, hep-ph/0605209

Biermann, P. L. & Kusenko, A. 2006, Phys. Rev. Lett., 96, 091301, astro-ph/0601004

Bode, P., Ostriker, J. P., & Turok, N. 2001, Astrophys. J., 556, 93, astro-ph/0010389

Boyarsky, A., Neronov, A., Ruchayskiy, O., & Shaposhnikov, M. 2006a, Mon. Not. Roy. Astron. Soc., 370, 213, astro-ph/0512509

—. 2006b, Phys. Rev., D74, 103506, astro-ph/0603368

[1]Scientific and technological design goal data is from `http://ixo.gsfc.nasa.gov/` and the *IXO* Science Team Meeting January 28-29, 2009.

Boyarsky, A., Neronov, A., Ruchayskiy, O., Shaposhnikov, M., & Tkachev, I. 2006c, Phys. Rev. Lett., 97, 261302, astro-ph/0603660

Boyarsky, A., Nevalainen, J., & Ruchayskiy, O. 2007, Astron. Astrophys., 471, 51, astro-ph/0610961

Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2000, Astrophys. J., 539, 517, astro-ph/0002214

Dalcanton, J. J. & Hogan, C. J. 2001, Astrophys. J., 561, 35, astro-ph/0004381

Dodelson, S. & Widrow, L. M. 1994, Phys. Rev. Lett., 72, 17, hep-ph/9303287

Dolgov, A. D. & Sommer-Larsen, J. 2001, Astrophys. J., 551, 608

Goerdt, T., Moore, B., Read, J. I., Stadel, J., & Zemp, M. 2006, Mon. Not. Roy. Astron. Soc., 368, 1073, astro-ph/0601404

Governato, F. et al. 2004, Astrophys. J., 607, 688, astro-ph/0207044

Hidaka, J. & Fuller, G. M. 2007, Phys. Rev., D76, 083516, arXiv:0706.3886

Jena, T. et al. 2005, Mon. Not. Roy. Astron. Soc., 361, 70, astro-ph/0412557

Klypin, A. A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, Astrophys. J., 522, 82, astro-ph/9901240

Komatsu, E. et al. 2008, arXiv:0803.0547

Kusenko, A. 2006, Phys. Rev. Lett., 97, 241301, hep-ph/0609081

Kusenko, A., Mandal, B. P., & Mukherjee, A. 2008, Phys. Rev., D77, 123009, arXiv:0801.4734

Kusenko, A. & Segre, G. 1999, Phys. Rev., D59, 061302, astro-ph/9811144

Loewenstein, M., Kusenko, A., & Biermann, P. L. 2008, arXiv:0812.2710

Moore, B. et al. 1999, Astrophys. J., 524, L19, astro-ph/9907411

Narayanan, V. K., Spergel, D. N., Dave, R., & Ma, C.-P. 2000, Astrophys. J., 543, L103, astro-ph/0005095

O'Shea, B. W. & Norman, M. L. 2006, Astrophys. J., 648, 31, astro-ph/0602319

Pal, P. B. & Wolfenstein, L. 1982, Phys. Rev., D25, 766

Peebles, P. J. E. 2001, astro-ph/0101127

Riemer-Sorensen, S., Hansen, S. H., & Pedersen, K. 2006, Astrophys. J., 644, L33, astro-ph/0603661

Seljak, U., Makarov, A., McDonald, P., & Trac, H. 2006, Phys. Rev. Lett., 97, 191303, astro-ph/0602430

Shaposhnikov, M. & Tkachev, I. 2006, Phys. Lett., B639, 414, hep-ph/0604236

Shi, X.-d. & Fuller, G. M. 1999, Phys. Rev. Lett., 82, 2832, astro-ph/9810076

Strigari, L. E. et al. 2006, Astrophys. J., 652, 306, astro-ph/0603775

Tegmark, M. et al. 2004, Phys. Rev., D69, 103501, astro-ph/0310723

Tremaine, S. & Gunn, J. E. 1979, Phys. Rev. Lett., 42, 407

Watson, C. R., Beacom, J. F., Yuksel, H., & Walker, T. P. 2006, Phys. Rev., D74, 033009, astro-ph/0605424

Wilkinson, M. I. et al. 2006, astro-ph/0602186

Zentner, A. R. & Bullock, J. S. 2002, Phys. Rev., D66, 043003, astro-ph/0205216