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CAN THE EXCESS IN THE Fe xxvi Lyγ LINE FROM THE GALACTIC CENTER PROVIDE EVIDENCE FOR 17 keV STERILE NEUTRINOS?

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ABSTRACT

Sterile neutrinos (or right-handed neutrinos) are a plausible warm dark matter candidate. We find that the excess of the intensity in the 8.7 keV line (at the energy of the Fe xxvi Lyγ line) in the spectrum of the Galactic center observed by *Suzaku* cannot be explained by standard ionization and recombination processes. We suggest that the origin of this excess is via decays of sterile neutrinos with a mass of 17.4 keV. The estimated value of the mixing angle $\sin^2(2\theta) = (4.4 \pm 2.2) \times 10^{-12}$ lies in the allowed region of the mixing angle for a dark matter sterile neutrino with a mass of 17–18 keV.

Key words: dark matter – line: identification – neutrinos

1. INTRODUCTION

Several astrophysical observations, including indications of central cores in low mass galaxies and the sparcity of Milky Way satellites, have revived interest in sterile neutrinos as a warm dark matter candidate. Electroweak singlet sterile neutrinos with masses in the few keV range naturally arise in many extensions of the Standard Model and could be produced in the early universe through non-resonant oscillations with active neutrino species (Barbieri & Dolgov 1991; Dodelson & Widrow 1994). The experimentally established phenomenon of neutrino oscillations requires neutrinos to have non-zero mass, and sterile neutrinos are a natural warm dark matter candidate. Sterile neutrinos with masses in the few keV range could also be produced from Higgs decays (Kusenko 2006; Petraki & Kusenko 2008) or directly from the decay of a very light inflaton (Shaposhnikov & Tkachev 2006).

Direct constraints on masses and mixing angles are obtained both from the Lyman alpha forest power spectrum and X-ray observations of the radiative decay channel, the latter providing a photon with energy $E = m_s c^2/2$, where m_s is the sterile neutrino mass. X-ray observations of the local dwarf Willman 1 have shown marginal evidence for a 5 keV sterile neutrino (Loewenstein & Kusenko 2010). The inferred mixing angle lies in a narrow range for which neutrino oscillations can produce all of the dark matter.

Constraints from the Lyα forest power spectrum and X-ray observations seem to rule out sterile neutrinos produced via the Barbieri–Dolgov mechanism as a dark matter candidate (Seljak et al. 2006; Viel et al. 2006). Comparing the number of Milky way satellites within the 0–50 kpc bin based on the Aquarius simulations with the observed number of Milky Way satellites, Polisensky & Ricotti (2010) find that the thermal warm dark particle mass equals 3.2 keV if the number of satellites derived from the corrected observations is equal to the number of dark matter haloes and if Willman 1 is excluded from the observed set. This value of a thermal warm dark particle mass has the equivalent effect to the mass of a sterile neutrino of 17.8 keV, produced from the decay of a very light inflaton.

In fact, if sterile neutrinos provide a significant fraction of the dark matter, the Galactic center (GC) provides a more attractive environment than the Willman 1 dwarf galaxy to search for radiative decay signals. If the sterile neutrino mass is indeed around 17 keV, we expect an X-ray line near 8.5 keV. The diffuse X-ray emission from the GC using the X-ray imaging spectrometer on *Suzaku* was analyzed by Koyama et al. (2007a), who detect the 8.7 keV line corresponding to Fe xxvi Lyγ. We have reanalyzed the data on hydrogen-like (hereafter H-like) iron line strengths and find that there is an unexpected excess in the 8.7 keV line from the GC in the *Suzaku* data that cannot be explained by means of standard ionization and recombination processes. We propose an explanation of the excess in the 8.7 keV line in terms of 17.4 keV neutrino decays.

2. THE EXCESS IN THE 8.7 keV LINE FROM THE GALACTIC CENTER AND ITS ORIGIN

Diffuse X-ray emission from the GC is produced by a high temperature plasma in the inner 20 pc of the GC ($\sim$ 7 keV). The most pronounced features in the emission lines are Fe i Kα at 6.4 keV, and the K-shell lines 6.7 and 6.9 keV from the helium-like (Fe xxv Kα) and H-like (Fe xxvi Lyα) ions of iron, respectively. For the first time, the Fe xxvi Lyγ at 8.7 keV was detected by *Suzaku* (Koyama et al. 2007a). The observed line intensities by *Suzaku* are listed in Table 2 of Koyama et al. (2007a). We list below the most important lines (for our analysis) taken from the paper by Koyama et al. (2007a). The measured intensities of the H-like iron ion lines (90% confidence level) are $I_{\mathrm{Ly}\alpha} = 1.66^{+0.09}_{-0.11} \times 10^{-4}$ photons (cm^2 s)$^{-1}$, $I_{\mathrm{Ly}\beta} = 2.29^{+1.35}_{-1.31} \times 10^{-5}$ photons (cm^2 s)$^{-1}$, and $I_{\mathrm{Ly}\gamma} = 1.77^{+0.62}_{-0.56} \times 10^{-5}$ photons (cm^2 s)$^{-1}$.

The measured ratio of the Fe xxvi Lyβ to Fe xxvi Lyα lines equals 0.138 ± 0.059 and is in agreement with the theoretical value of ≈ 0.12 at gas temperatures 5–15 keV (see line list[4]). We note that the measured intensity of the Fe xxvi Lyγ = $1.77^{+0.62}_{-0.56} \times 10^{-5}$ photons (cm^2 s)$^{-1}$ iron line has a significant excess above the value derived from the MEKAL model [1] and the measured intensity $I_{\mathrm{Ly}\alpha}$ of the Fe xxvi Lyα line. The ratio of the Fe xxvi Lyγ to Fe xxvi Lyα lines $\approx$0.035 in the gas temperature range 5 and 15 keV is from a theoretical model (see Mewe & Gronenschild 1981). Therefore, the expected value of the intensity in the Fe xxvi Lyγ line

[4] http://www.sron.nl/divisions/hea/spex/version1.10/line/index.html

is $0.035 \times I_{\mathrm{Ly}\alpha} = 5.8^{+0.4}_{-0.4} \times 10^{-6}$ photons $(\mathrm{cm}^2\ \mathrm{s})^{-1}$ and is much smaller than the measured intensity by *Suzaku*. The excess intensity in the 8.7 keV line equals $\approx (1.2 \pm 0.6) \times 10^{-5}$ photons $(\mathrm{cm}^2\ \mathrm{s})^{-1}$. Koyama et al. remark that the ratios of the strongest lines are consistent with emission from a 5–7 keV plasma in collisional ionization equilibrium (CIE). Their only comments on the Fe XXVI Lyγ line are that it is tentatively identified and that the Lyγ/Lyα intensity ratio is consistent with the other line ratios. Note that the Ly γ detection is not a point of emphasis in Koyama et al. (2007a) and the value of the 8.7 keV line to Lyα intensity ratio, derived under the assumption that Fe XXV Kα, Fe XXVI Lyα, and the 8.7 keV line are totally produced via charge exchange (CX), should be 0.4 (see, e.g., Figure 2 for run IJ from Wargelin et al. 2005) and is much higher than the ratio observed by *Suzaku*.

To demonstrate that this excess cannot be explained by ionization and recombination processes, we calculate the ratio of the fully stripped (Fe XXVII) ion fraction to the H-like (Fe XXVI) ion fraction using the ratio of the intensities of the Fe XXVI Lyγ to Lyα lines as a function of temperature T. The ratio $r_{\gamma\alpha}$ of the Fe XXVI Lyγ to Fe XXVI Lyα line intensities is given by

$$r_{\gamma\alpha} = \frac{E_\gamma(T) N_{\mathrm{Fe\,XXVI}} + R_\gamma(T) N_{\mathrm{Fe\,XXVII}}}{E_\alpha(T) N_{\mathrm{Fe\,XXVI}} + R_\alpha(T) N_{\mathrm{Fe\,XXVII}}}, \qquad (1)$$

where E_γ and E_α are the impact excitation rate coefficients, and R_γ and R_α are the rate coefficients for the contribution from recombination to the Lyγ and Lyα spectral lines, respectively. Rate coefficients are taken from Mewe & Gronenschild (1981).

From Equation (1), the ratio of the Fe XXVII to Fe XXVI ionic fractions is

$$\frac{N_{\mathrm{Fe\,XXVII}}}{N_{\mathrm{Fe\,XXVI}}} = \frac{E_\gamma(T) - r_{\gamma\alpha} E_\alpha(T)}{r_{\gamma\alpha} R_\alpha(T) - R_\gamma(T)}. \qquad (2)$$

Note that we do not assume CIE. For the best-fit value of the intensity ratio of the Lyγ to Lyα iron lines $(1.77 \times 10^{-5}/(1.66 \times 10^{-4}) \approx 0.107)$ found by Koyama et al. (2007a), we find that the ratio of the Fe XXVII ion fraction to the Fe XXVI ion fraction lies in the range $(-40, -20)$ when the electron temperature is in the range (5 keV, 15 keV). Since the ratio of the Fe XXVII to Fe XXVI ion fractions cannot be negative, we conclude that the excess cannot be explained by ionization and recombination processes.

To verify that the excess in the Fe XXVI Lyγ line intensity cannot be explained by a multi-temperature model with temperatures outside the 5–15 keV range while the Fe XXVI Lyβ/Lyα intensity ratio is consistent with line emission produced by a CIE plasma, we show the line intensity ratios of Fe XXVI Lyγ/Lyα (dashed line) and Fe XXVI Lyβ/Lyα (solid line; taken from Mewe et al. 1985) in the temperature range of 1–54 keV in Figure 1, assuming a CIE plasma. The lower bounds on the Fe XXVI Lyγ/Lyα and Lyβ/Lyα intensity ratios found by Koyama et al. (2007a) are shown by dash-dotted and dotted lines, respectively. Since the lower observational bound on the Fe XXVI Lyγ/Lyα intensity ratio is much higher than the theoretical Fe XXVI Lyγ/Lyα intensity ratio in this temperature range, a multi-temperature model cannot explain the excess in the Fe XXVI Lyγ line intensity. The ratio of the Fe XXVII to Fe XXVI ion fractions is positive when the condition

$$\min(E_\gamma/E_\alpha, R_\gamma/R_\alpha) < r_\gamma < \max(E_\gamma/E_\alpha, R_\gamma/R_\alpha) \qquad (3)$$

is fulfilled (see Equation (2)) and this condition is not fulfilled for the best-fit value of the Fe XXVI Lyγ/Lyα intensity ratio found by *Suzaku*. However, the similar condition on the Lyβ/Lyα intensity ratio is fulfilled for the best-fit value found by *Suzaku*, since the recombination rate ratio R_β/R_α is $\simeq$0.2 in the 5–15 keV temperature range (Mewe & Gronenschild 1981).

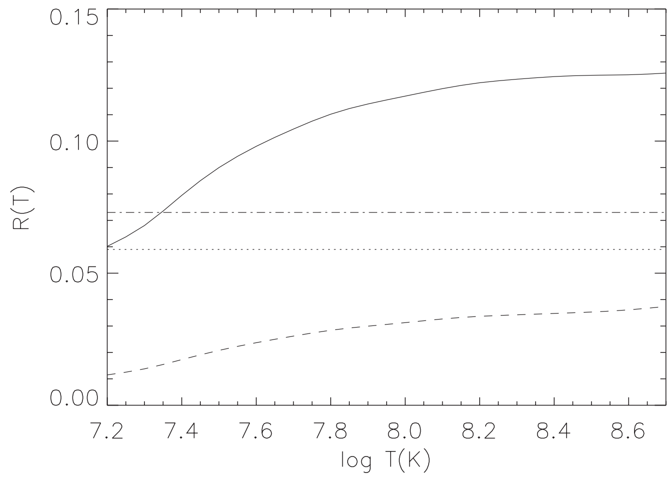

Figure 1. Line flux ratios of Fe XXVI Lyγ/Lyα and Fe XXVI Lyβ/Lyα in the temperature range of 1–54 keV, and lower observational bounds on these flux ratios observed by *Suzaku*.

We have checked that the theoretical ratio of the Lyγ to Lyα iron lines fluxes at a temperature of 7 keV taken from Mewe & Gronenschild (1981) is in agreement with other plasma emission models, such as APEC,[5] the newest version of MEKAL, and new results for effective collision strengths (Ballance et al. 2002) and radiative rates (Aggarwal et al. 2008).

A more physically acceptable explanation of the excess is that of sterile neutrino decays, under the assumption that sterile neutrinos constitute a significant fraction of dark matter.

3. RADIATIVE DECAYS OF STERILE NEUTRINOS

The sterile neutrino possesses a radiative decay channel decaying to an active neutrino and a photon with energy $E = m_s c^2/2$. Since the excess in the 8.7 keV line corresponds to a sterile neutrino mass of 17.4 keV, we now estimate the mixing angle $\sin^2(2\theta)$ and decay rate for such a sterile neutrino.

Using the excess in the 8.7 keV line intensity equal to $I_{\mathrm{excess}} \approx (1.2 \pm 0.6) \times 10^{-5}$ photons $(\mathrm{cm}^2\ \mathrm{s})^{-1}$ and the definition of the energy flux $F_s = I_{\mathrm{excess}} \times E$, we find that the value of the energy flux excess in the 8.7 keV line equals $(10.4 \pm 5.2) \times 10^{-5}$ keV $(\mathrm{cm}^2\ \mathrm{s})^{-1}$.

Decays of sterile neutrinos in the dark matter halo of the Milky Way are a promising way to explain the possible excess in the 8.7 keV line. The amount of dark matter within the *Suzaku* field of view (FOV; see Figure 1 of Koyama et al. 2007a) is only a minute fraction of the dark matter halo mass of the Milky Way. The Milky Way halo density is described by a Navarro–Frenk–White (NFW) profile with the dark matter halo parameters taken from Klypin et al. (2002). This model yields a mass within the FOV of $M_{\mathrm{fov}} \simeq 2.5 \times 10^6\, M_\odot$.

The decay flux into a solid angle Ω (within the FOV) is given by (see, e.g., Boyarsky et al. 2008)

$$F_s = \int_\Omega \frac{\rho_{\mathrm{NFW}}(\vec{r})}{4\pi(\vec{r}_0 - \vec{r})^2} \frac{\Gamma c^2}{2} d^3\vec{r}, \qquad (4)$$

[5] http://cxc.harvard.edu/atomdb/

where $|\vec{r}_0| = 8.5$ kpc is the distance to the GC. The decay rate Γ is given by (e.g., Boyarsky et al. 2008)

$$\Gamma = 1.38 \times 10^{-22} \sin^2(2\theta) \left(\frac{m_s}{1\,\text{keV}}\right)^5 \text{s}^{-1}. \quad (5)$$

To estimate the value of the mixing angle, we use the inferred value of $m_s = 17.4$ keV and the value of the energy flux excess. Then, from Equation (4) the value of the mixing angle is

$$\sin^2(2\theta) = (4.4 \pm 2.2) \times 10^{-12}. \quad (6)$$

Using Equation (5), we derive the constraint on the decay rate:

$$\Gamma = (9.7 \pm 4.8) \times 10^{-28}\,\text{s}^{-1}. \quad (7)$$

Note that the derived values of the mixing angle and decay rate lie in the allowed region for a dark matter sterile neutrino with a mass of 17–18 keV (see den Herder et al. 2009).

For a mass of 17.4 keV and a mixing angle of $\sin^2(2\theta) = (4.4 \pm 2.2) \times 10^{-12}$, neutrino oscillations produce a small contribution of sterile neutrinos (<1%) to the total density of dark matter (see Dodelson & Widrow 1994 and Equation (6.9) from Abazajian et al. 2001). The rest of the dark matter could consist of sterile neutrinos produced from Higgs decays (Kusenko 2006; Petraki & Kusenko 2008), or directly from the decay of a very light inflaton (Shaposhnikov & Tkachev 2006). This production rate is independent of the mixing angle, while the radiative decay is controlled by the mixing angle and the mass. Sterile neutrinos are still capable of accounting for a substantial fraction, if not all, of the dark matter.

An additional decay contribution of comparable strength comes from a point-like source if a cusp of dark matter develops around the central black hole. The dark matter cusp mass is constrained observationally by stellar orbit measurements and is taken to be $3 \times 10^6\,M_\odot$ within the central 0.001 pc. Such a cusp is naturally produced via adiabatic contraction of dark matter around the black hole within its sphere of influence, about 3 pc for the Milky Way black hole (Gondolo & Silk 1999; Zhao & Silk 2005). Typically about as much mass is captured in the spike as is in the central black hole and with a density profile of $\rho \propto r^{-9/4}$ or even steeper. Sterile neutrinos could form such a dark matter cusp, although the spike density is limited by phase space considerations for non-degenerate neutrinos (Tremaine & Gunn 1979) as well as by dynamical heating and regeneration (cf. Merritt et al. 2007). Using the values of the velocity dispersion for the Milky Way of 100 km s^{-1} (Merritt & Ferrarese 2001) and a sterile neutrino mass of 17.4 keV, we find a limit on the density $\rho_{cr} < 1.4 \times 10^9\,M_\odot\,(\text{pc}^3)^{-1}$ that would be required for a point-like source.

4. DISCUSSION

To confirm an X-ray line flux from decays of a keV scale sterile neutrino, instrumental and observational uncertainties should be taken into account. Our analysis of the excess in the Fe XXVI Lyγ line from the GC has uncertainties caused by the fact that lines in the crowded energy interval of (6.0–9.0) keV are barely resolved from each other with *Suzaku*. The Fe XXVI Lyα line is blended with the Fe I Kβ line, and to estimate the Fe XXVI Lyγ intensity from the Fe XXVI Lyα intensity, we need to precisely determine the Fe XXVI Lyα intensity. Fortunately, the Fe I Kβ intensity can be found from the Fe I Kα intensity, since the Fe I Kα line is not blended with other lines. The best-fit flux ratio of Fe I Kβ to Fe I Kα (Table 2 in Koyama et al. 2007a) equals 0.16 and is high compared to the theoretical prediction of ≈0.125 for this ratio (Kaastra & Mewe 1993). The Fe I Kβ line intensity should therefore be equal to 5.4×10^{-5} photons (cm^2 s)$^{-1}$, and then the Fe XXVI Lyα line intensity equals 1.81×10^{-4} photons (cm^2 s)$^{-1}$. We now find from the predicted ratio of the Fe XXVI Lyγ to Fe XXVI Lyα lines that the Fe XXVI Lyγ line intensity should be 6.3×10^{-6} photons (cm^2 s)$^{-1}$. Hence, the excess of the intensity in the 8.7 keV line equals $(1.1 \pm 0.6) \times 10^{-5}$ photons (cm^2 s)$^{-1}$. Therefore, the uncertainty in the Fe I Kβ line intensity is not sufficient to explain the excess in the 8.7 keV line.

Other uncertainties of our analysis arise from a possible contribution of CX to the 8.7 keV line intensity. In the Fe XXV spectrum produced via CX, the Kα emission feature dominates, and the Kα centroid is at 6.666 keV (Wargelin et al. 2005). Using the observed and theoretical values of the Kα centroid taken from Koyama et al. (2007a) and the MEKAL code, respectively, we find that the upper limit for a possible contribution of the CX process to the total Fe XXV Kα line intensity equals 7%. To find an upper limit for the contribution of CX in Fe XXVI ions to the intensity at 8.7 keV, we use the constraint on the line intensities from transitions of the captured electron from the levels with $n \geqslant 7$, which give such a contribution. From Table 3 of Wargelin et al. (2005), we find that the total intensity from this contribution is less than 15% of the Fe XXV Kα line intensity produced by CX in Fe XXVI. Therefore, the contribution from these transitions to the intensity of the line at 8.7 keV is less than 5.3×10^{-6} photons (cm^2 s^{-1})$^{-1}$ and can provide a possible explanation of the excess in the Fe XXVI Lyγ line. On the other hand, in the Fe XXVI spectrum produced via CX, the main features are the Lyα line and the high-n Lyman peak at 9.2 keV. Measurements of Koyama et al. (2007a) give an upper limit of 9×10^{-6} photons (cm^2 s^{-1})$^{-1}$ for the high-n Lyman peak. A possible contribution of Fe XXVI ions produced via the CX process is determined by transitions of the captured electron from the fourth level to the first level. The line intensity from this transition is one order of magnitude smaller than that of the high-n Lyman peak, because the level with the largest capture probability for single-electron transfer is ≈12 (see Janev & Winter 1985). Therefore, any possible contribution to the excess in the 8.7 keV line from CX of Fe XXVII ions is not significant. Note that Koyama et al. (2007b) have not detected any strong line at 8.7 keV from the giant molecular cloud Sgr B2, which contains the bulk of the molecular hydrogen.

Further uncertainty in the 8.7 keV line is caused by uncertainties in the continuum spectrum. In fact Koyama et al. suggest that the temperature based on fitting the continuum (≃15 keV) is not consistent with the ≃6.5 keV plasma temperature deduced from the ratios of the brightest emission lines. Their preferred model for the continuum is a 6.5 keV thermal plasma with an additional power law that provides a hard tail. To check how the excess in the 8.7 keV line intensity depends on a continuum profile, we fit the X-ray spectrum in the energy range (5.5 keV, 11.5 keV), obtained from the 15 keV thermal continuum model with Gaussian lines (taken from Koyama et al. 2007a), with a model including a 6.5 keV plasma, a power-law component with the power-law index $\Gamma = 1.4$, and Gaussian lines. We found that the best-fit 8.7 keV line intensity in this case is higher by 10% compared to that obtained from the 15 keV continuum model. Although this change does not change our conclusion on the 8.7 keV line excess, a more detailed analysis of the continuum profile in the X-ray spectrum of the GC is required.

5. CONCLUSIONS

We find that there is an excess in the intensity in the 8.7 keV line observed from the GC over the theoretical value expected for the intensity in the Fe XXVI Lyγ line. This intensity excess equals $(1.2 \pm 0.6) \times 10^{-5}$ photons $(\mathrm{cm}^2\ \mathrm{s})^{-1}$, where the errors are at the 90% confidence level. We show that this excess cannot be explained by means of standard ionization and recombination processes. We suggest that a physically acceptable explanation of the intensity excess in the 8.7 keV line observed by *Suzaku* toward the GC is due to decays of sterile neutrinos in a halo of dark matter around the Milky Way. A dark matter mass in the *Suzaku* FOV analyzed by Koyama et al. (2007a), containing only $\simeq 2.5 \times 10^6\, M_\odot$, suffices to produce a significant flux $(1.2 \pm 0.6) \times 10^{-5}$ photons $(\mathrm{cm}^2\ \mathrm{s})^{-1}$ via decays of sterile neutrinos. We find that about 30% of the flux comes from the central region, subtending of order 40 pc, and that most of the flux comes from outer regions of the dark matter halo. We consequently conclude that a narrow band map at the 8.7 keV line should be fairly uniform in both the square regions of the FOV shown in Koyama et al. (2007a, Figure 2). This provides us with an addition test of the sterile neutrino decay interpretation of the 8.7 keV line flux excess, since the iron line fluxes are significantly stronger from the square region of FOV at low longitude than at high longitude (see Figures 1 and 2 of Koyama et al. 2007a). Additional observational data is required to perform this test.

We estimated the mixing angle of $\sin^2(2\theta) = (4.4 \pm 2.2) \times 10^{-12}$ from the excess in the intensity and the decay rate is found to be $\Gamma = (9.7 \pm 4.8) \times 10^{-28}\ \mathrm{s}^{-1}$. These values lie in the allowed region of the mixing angle and decay rate parameter space for a dark matter sterile neutrino with a mass of 17–18 keV. Sterile neutrinos in this region of parameter space can contribute significantly to dark matter if they are produced from the Higgs decays or from the decay of a very light inflaton. The neutrino mass limits from Lyα forest considerations (Seljak et al. 2006; Viel et al. 2006) and from the numbers of Milky Way satellites (Polisensky & Ricotti 2010) are comfortably within range of a sterile neutrino mass of 17–18 keV (Shaposhnikov & Tkachev 2006). Such neutrinos would be virtually indistinguishable from cold dark matter except in the lowest mass dwarf galaxies where cores would be formed. High resolution X-ray observations could potentially reveal a point-like line source of comparable strength to the *Suzaku* line excess if a cusp is present around the central black hole.

Suzaku has advantages which permit us to analyze X-ray spectra for searching an X-ray line in the 8–9 keV range from sterile neutrino decays. The effective area of *Suzaku* at these energies is much higher than that of *Chandra* and the background level of the *Suzaku*/XIS-FI is much lower than that of the *XMM-Newton*/EPIC-MOS (e.g., Yamaguchi et al. 2006). The background level of the *XMM-Newton*/EPIC-PN is lower than that of EPIC-MOS, however the background spectrum of the *XMM-Newton*/EPIC-PN has very strong emission lines from Ni, Cu, Zn above 7 keV. Therefore, *Suzaku*/XIS is a more promising instrument for a detection of an X-ray line from sterile neutrino decays. Observations of other objects, such as nearby dwarf spheroidals (Segue 1 is a better target) which have no hot plasma backgrounds, by *Suzaku* are required to confirm our tentative identification of the 8.7 keV line produced from sterile neutrino decays.

REFERENCES

Abazajian, K., Fuller, G. M., & Patel, M. 2001, Phys. Rev. D., 64, 023501

Aggarwal, K. M., Hamada, K., Igarashi, A., Jonauskas, V., Keenan, F. P., & Nakazaki, S. 2008, A&A, 879, 879

Ballance, C. P., Badnell, N. R., & Berrington, K. A. 2002, J. Phys. B.: At. Mol. Opt. Phys., 35, 1095

Barbieri, R., & Dolgov, A. 1991, Nucl. Phys. B, 349, 743

Boyarsky, A., Ruchayskiy, O., & Markevitch, M. 2008, ApJ, 673, 752

den Herder, J.-W., Boyarsky, A., & Ruchayskiy, O. 2009, arXiv:0906.1788

Dodelson, S., & Widrow, L. M. 1994, Phys. Rev. Lett., 72, 17

Gondolo, P., & Silk, J. 1999, Phys. Rev. Lett., 83, 1719

Janev, R. K., & Winter, H. 1985, Phys. Rep., 117, 265

Kaastra, J. S., & Mewe, R. 1993, A&AS, 97, 443

Klypin, A., Zhao, H., & Somerville, R. S. 2002, ApJ, 573, 597

Koyama, K., et al. 2007a, PASJ, 59, 245

Koyama, K., et al. 2007b, PASJ, 59, 221

Kusenko, A. 2006, Phys. Rev. Lett., 97, 241301

Loewenstein, M., & Kusenko, A. 2010, ApJ, 714, 652

Merritt, D., & Ferrarese, L. 2001, ApJ, 547, 140

Merritt, D., Harfst, S., & Bertone, G. 2007, Phys. Rev. D, 75, 043517

Mewe, R., & Gronenschild, E. H. B. M. 1981, A&AS, 45, 11

Mewe, R., Gronenschild, E. H. B. M., & van den Oord, G. H. J. 1985, A&AS, 62, 197

Petraki, K., & Kusenko, A. 2008, Phys. Rev. D, 77, 065014

Polisensky, E., & Ricotti, M. 2010, arXiv:1004.1459

Seljak, U., Makarov, A., McDonald, P., & Trac, H. 2006, Phys. Rev. Lett., 97, 191303

Shaposhnikov, M., & Tkachev, I. 2006, Phys. Lett. B, 639, 414

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

Viel, M., Lesgourgues, J., Haehnelt, M. G., Matarrese, S., & Riotto, A. 2006, Phys. Rev. Lett., 97, 1301

Wargelin, B. J., Beiersdorfer, P., Neill, P. A., Olson, R. E., & Scofield, J. H. 2005, ApJ, 634, 687

Yamaguchi, H., et al. 2006, Proc. SPIE, 6266, 626642

Zhao, H., & Silk, J. 2005, Phys. Rev. Lett., 95, 011301