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STERILE NEUTRINOS IN THE MILKY WAY: OBSERVATIONAL CONSTRAINTS

Signe Riemer-Sørensen,[1] Steen H. Hansen,[2] and Kristian Pedersen[1]
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ABSTRACT

We consider the possibility of constraining decaying dark matter by looking out through the Milky Way halo. Specifically, we use *Chandra* blank sky observations to constrain the parameter space of sterile neutrinos. We find that a broad band in parameter space is still open, leaving the sterile neutrino as an excellent dark matter candidate.

Subject headings: dark matter — elementary particles — neutrinos — X-rays: diffuse background

1. INTRODUCTION

The particle nature of the dark matter remains a mystery. This is contrasted with the firmly established dark matter abundance, which has been measured using the cosmic microwave background and large-scale structure observations (Spergel et al. 2006; Seljak et al. 2005).

A wide range of dark matter particle candidates have been proposed, including axions, the lightest supersymmetric particle, and sterile neutrinos. Recently, sterile neutrinos have gained renewed interest, since theoretical considerations have shown them to be a natural part of a minimally extended standard model, the νMSM. This νMSM, which is the standard model extended with only three sterile neutrinos, manages to explain the masses of the active neutrinos (Asaka et al. 2005), the baryon asymmetry of the universe (Asaka & Shaposhnikov 2005), and the abundance of dark matter (Dodelson & Widrow 1994).

Arguably, one of the most appealing aspects of sterile neutrinos as dark matter candidates is that they will very likely be either detected or rejected during the next couple of years. This is because the sterile neutrinos decay virtually at rest into a photon and an active neutrino, producing a sharp decay line at $E = m_s/2$ (here m_s is the mass of the sterile neutrinos in natural units), where $c = \hbar = k_{\rm B} = 1$ (Dolgov & Hansen 2002). This photon line can now be searched for in cosmic high-energy data of the background radiation (for recent studies, see Mapelli & Ferrara 2005 and Boyarsky et al. 2005), toward massive structures like galaxy clusters (Abazajian et al. 2001; Boyarsky et al. 2006a) or toward dark matter structures with a very low fraction of baryons (Hansen et al. 2002).

The sterile neutrino was originally introduced in order to alleviate discrepancies between the theory of cold dark matter structure formation and observations (Dodelson & Widrow 1994; Dolgov & Hansen 2002), which indicated that the dark matter particle should be warm. Traditionally, "warm" means that the mass of the dark matter particle should be in the keV range, in order to suppress the formation of small-scale structures. While other solutions have been found for some of these problems, other uses have been found for sterile neutrinos, e.g., as an explanation for the peculiar velocities of pulsars (Kusenko & Segre 1997; Fuller et al. 2003), for synthesizing early star formation (Biermann & Kusenko 2006), and, as mentioned above, as an explanation for the masses of the active neutrinos and the baryon asymmetry (Asaka et al. 2005; Asaka & Shaposhnikov 2005). Also, constraints on double-β decays have been derived (Bezrukov 2005).

Here we will follow the idea of Hansen et al. (2002) and look for a decay line toward a region with very few baryons. Specifically, we will study X-ray "blank" regions in the sky with no known X-ray sources. By doing so, we will search for a signal from the dark matter halo of our own Galaxy. We will see that the signal is very low for photons with energies of the order 0.1–10 keV, which allows us to exclude a part of the sterile neutrino parameter space.

2. X-RAY DATA ANALYSIS

We have analyzed a 0.3–9 keV spectrum extracted from many combined *Chandra* ACIS-S3 blank sky observations[3] (shown in Fig. 1) using CIAO 3.3[4] and have fitted spectral models with the spectral fitting package Xspec (Arnaud 1996).

The line features at 1.74, 2.1–2.2, and 7.48 keV are Si Kα, the Au M$\alpha\beta$ complex, and Ni Kα respectively, originating from the fluorescence of material in the telescope and focal plane (i.e., they are seen in spectra obtained when ACIS-S3 is stowed and not pointing at the sky[5]). However, a decay line from dark matter could "hide" under these prominent lines. In this case the decay line should be redshifted by a factor of $1 + z$, where z is the redshift of the dark matter emitter. Dark matter concentrations located at different distances should thus give rise to lines at different observed energies. In order to test for this, we extracted spectra from ACIS-S3 data of two galaxy clusters, A383 and A478, at redshifts $z = 0.1883$ and 0.0881, respectively. We optimized the ratio between expected dark matter signal and emission from hot intracluster gas by extracting spectra from the cluster outskirts. The X-ray emission from hot intracluster gas is proportional to the gas density squared, whereas the emission of photons from dark matter is directly proportional to the dark matter density. Hence, in the cluster outskirts, the gas surface brightness falls off with projected cluster-centric distance b as $S_{\rm gas} \propto b^{-3}$ (assuming a typical β-model), whereas the dark matter surface brightness is expected to fall off as $S_{\rm DM} \propto b^{-1}$ (assuming an isothermal sphere that is a good approximation; Pointecouteau et al. 2005). Specifically, we have extracted spectra from an outer radial bin, defined by optimizing the ratio of matter in the field of view (proportional to the signal from decaying dark matter) to the X-ray emission from the intracluster gas ("noise") described by a β-profile. The outer radius was chosen as the radius with an optimal ratio

[1] Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark.
[2] University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland.

[3] See http://cxc.harvard.edu/contrib/maxim.
[4] See http://cxc.harvard.edu/ciao.
[5] See http://cxc.harvard.edu/proposer/POG/html/node1.html.

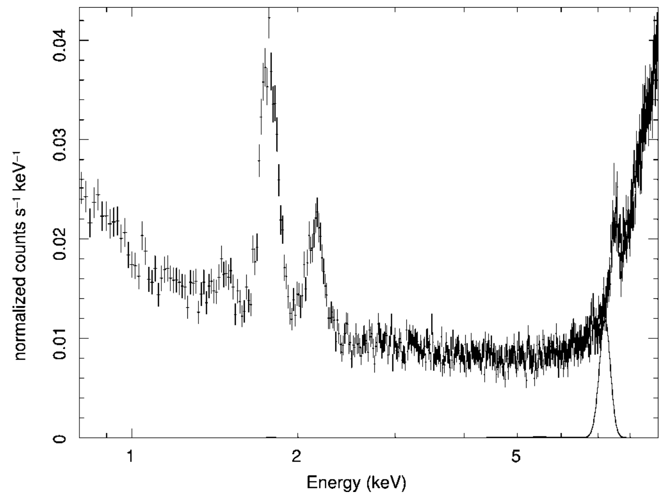

FIG. 1.—Blank sky ACIS-S3 spectrum (i.e., a view through the Milky Way halo). Also shown is the maximal single Gaussian emission line from decaying dark matter at a specific energy (here shown at $E = 7.2$ keV), as discussed in § 2.

(which is very close to the edge of the ACIS-S3 chip), and the inner radius was chosen so that the signal-to-noise ratio had a value of half the optimal value. No obvious line features were detected at the corresponding redshifted energies.[6]

We then proceeded to firmly constrain the flux from any dark matter decay line in the full energy interval spanned by the blank sky spectrum. The blank sky spectrum was well fitted (reduced $\chi^2 = 1.1$ for 540 degrees of freedom) by a composite model consisting of an exponential plus a power law plus four Gaussians for the most prominent lines. A hypothetical monoenergetic emission line in the spectrum was represented by a Gaussian, centered at the line energy and with a width, σ, given by the instrument spectral resolution: $\sigma \approx 0.1$ keV for 0.3 keV $\leq E < 6.0$ keV and $\sigma \approx 0.15$ keV for 6.0 keV $\leq E < 8.0$ keV.[7] (The velocity of the halo dark matter produces negligible line broadening, $v/c \sim 10^{-3}$ to 10^{-4}). For each energy in steps of 0.05 keV, we defined a Gaussian with the instrumental width and maximum at the model value of the fit to the broadband spectrum. The flux of this Gaussian was then calculated, providing an upper limit of emission from decaying dark matter at the given energy. This is a model-independent and very conservative analysis, since any X-ray emitters within the field of view, and background, contribute to the extracted spectrum. If we instead only allowed the decay signal from potential decaying dark matter to produce a bump above the "baseline" spectrum, then we could improve the bounds by a large factor (Boyarsky et al. 2005). However, this approach would depend sensitively on the robustness of modeling the background and emissions from sources contributing to the baseline spectrum.

3. DECAY RATE OF STERILE NEUTRINOS IN THE MILKY WAY HALO

The amount of dark matter from our Galaxy within the observed field of view is only a minute fraction of the total mass of the halo. We use the model for the Milky Way presented in Klypin et al. (2002), namely, an Navarro-Frenk-White dark matter profile with $M_{\rm vir} = 10^{12}\ M_\odot$, virial radius $r_{\rm vir} = 258$ kpc, concentration $c = 12$ (virial radius over scale radius), and solar distance $R_\odot = 8$ kpc. We then integrate out through the Milky Way halo to find the expected signal. Changing the details of this model does not significantly affect our results (e.g., changing the inner density slope between -1 and zero, or changing the outer slope between -3 and -4, changes the predicted signal by less than a factor of 2). There is also an uncertainty, possibly as large as a factor of 2, arising from using the value of $M_{\rm vir} = 10^{12}\ M_\odot$.

The blank sky spectrum was extracted from the full angular opening of the *Chandra* ACIS-S3 chip, which is 8′.4, corresponding to a mass within the field of view of $M_{\rm fov} = 1.5 \times 10^{-7} M_{\rm vir}$ at a mean luminosity distance of $D_L = 35$ kpc, derived from the model mentioned above.

The luminosity from decaying sterile neutrinos is $\mathcal{L} = E_\gamma N \Gamma_\gamma$, where E_γ is the energy of the photons, N is the number of sterile neutrino particles in the field of view ($N = M_{\rm fov}/m_s$), and Γ_γ is the decay rate. The flux at a luminosity distance, D_L, is

$$F = \frac{\mathcal{L}}{4\pi D_L^2} = \frac{E_\gamma N \Gamma_\gamma}{4\pi D_L^2}. \qquad (1)$$

The observed flux, F, at a given energy ($E_\gamma = m_s/2$) yields a conservative upper limit on the flux from decaying sterile neutrinos, so equation (1) can be rewritten as

$$\Gamma_\gamma \leq \frac{8\pi F D_L^2}{M_{\rm fov}}. \qquad (2)$$

From the blank sky flux, an upper limit on the decay rate has been derived as a function of line energy and plotted in Figure 2.

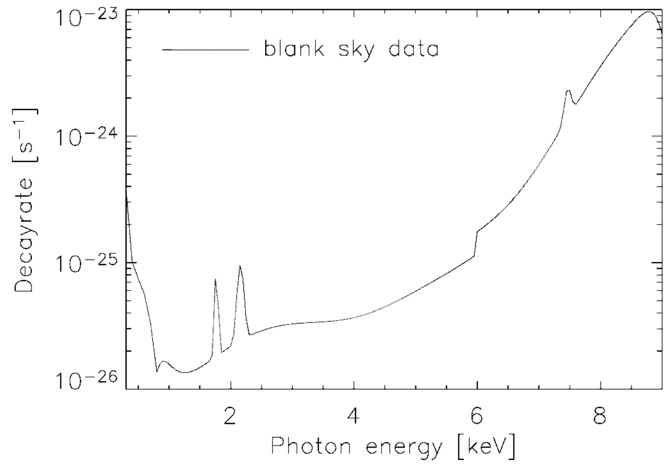

FIG. 2.—Dark matter decay rate as function of photon energy. The solid line is the upper limit from the *Chandra* blank sky observations looking out through the Milky Way halo.

4. CONFRONTING THE MODEL WITH DATA

The neutrinos can decay via various channels, with the dominating one being $\nu_s \rightarrow \nu_a + l + l$, where l is any light fermion, and the lifetime of the sterile neutrinos is given by (Barger et al. 1995; Dolgov et al. 2000)

$$\tau = \frac{1}{\Gamma_{\rm tot}} = \frac{f(m_s) \times 10^{20}}{(m_s/{\rm keV})^5 \sin^2(2\theta)}\ {\rm s}, \qquad (3)$$

where $\sin^2(2\theta)$ is the mixing angle with the active neutrino,

[6] After finishing this analysis, a related paper appeared (Boyarsky et al. 2006a) in which an analysis using exactly this method of looking at the outer cluster region was made.

[7] See http://acis.mit.edu/acis/spect/spect.html.

and $f(m_s)$ takes into account the open decay channels so that for $m_s < 1$ MeV, where only the neutrino channel is open, $f(m_s) = 0.86$. A wide range of effects from neutrinos decaying into photons has been discussed for many years (Sciama 1982).

The mixing angle is given by (Dolgov 2002, eqs. [209] and [210])

$$\sin^2(2\theta) \approx 6.7 \times 10^{-8} \left(\frac{A}{6.7 \times 10^{-8}}\right) \left(\frac{\mathrm{keV}}{m_s}\right)^2 \left(\frac{\Omega_{\mathrm{DM}}}{0.3}\right) \times \left(\frac{h}{0.65}\right)^2 \left(\frac{S}{1}\right) \left(\frac{g_*(T_{\mathrm{produced}})}{10.75}\right)^{3/2}, \quad (4)$$

where $g_*(T_{\mathrm{produced}})$ is the number of relativistic degrees of freedom at the temperature at which the sterile neutrinos are produced. For neutrino masses of $m_s \approx$ keV, the neutrinos are produced near the QCD phase transition (Dodelson & Widrow 1994), making the distribution somewhat nonthermal (Dolgov & Hansen 2002). The value of g_* for such neutrinos is very conservatively considered to be between 10.75 and 20, depending on the details of the QCD phase transition. Here we will use $g_*(T_{\mathrm{produced}}) = 15$ as a reference value, corresponding to the degrees of freedom at the production peak. A numerical calculation, including the details of the QCD phase transition, quantum damping, and the presence of thermal muons (Abazajian 2006), has confirmed that the choice of $g_* = 15$ is in rough agreement with the analytical results presented by Dolgov (2002). It should, however, be kept in mind that the exact details of the QCD phase transition may change the production by a factor of a few (T. Asaka et al. 2006, in preparation; D. Semikoz et al. 2006, in preparation). S is a free parameter that takes into account that additional entropy may be produced after the sterile neutrinos have been created (Asaka et al. 2006). This parameter was suggested to be in the range between 1 and 100 (Asaka et al. 2006). A is a constant, depending on which active neutrino the sterile neutrinos are assumed to mix with. It takes the values $A_{s,e} = 6.7 \times 10^{-8}$ for ν_s mixing with ν_e and $A_{s,\mu} = 4.8 \times 10^{-8}$ for $\nu_{\mu,\tau}$. The sterile neutrinos are assumed to account for all dark matter, i.e., $\Omega_{\mathrm{DM}} = 0.30$, and the Hubble parameter at the present time, H_0, is given as $h = H_0/(100\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$.

Barger et al. (1995) derived the branching ratio for the radiative decay, $\nu_s \rightarrow \nu_\alpha + \gamma$, to be $\Gamma_\gamma/\Gamma_{\mathrm{tot}} = (27\alpha)/(8\pi) \approx 1/128$. Now the lifetime can be rewritten as

$$\tau = 10^{26}\ \mathrm{s} \left(\frac{E}{\mathrm{keV}}\right)^{-3} \left(\frac{g_*}{15}\right)^{-3/2} \left(\frac{\Omega_{\mathrm{DM}}}{0.3}\right)^{-1} \left(\frac{h}{0.7}\right)^{-2} \times \left(\frac{f(m_s)}{0.86}\right) \left(\frac{A}{6.7 \times 10^{-8}}\right)^{-1} \left(\frac{1}{S}\right). \quad (5)$$

An upper limit on the decay rate is constrained from equation (2), and

$$\tau = \frac{1}{\Gamma_{\mathrm{tot}}} \approx \frac{1}{128\Gamma_\gamma}. \quad (6)$$

The lower limit on the lifetime from the data and the model predictions are plotted in Figure 3 for various values of S and g_*. We see from Figure 3 that the blank sky data (*solid red line*) is at least 1 order of magnitude less restrictive than the simplest sterile model predictions (*hatched region*). Models with significant entropy production, $S \approx 30$, are excluded in the mass range 4.2 keV $< m_s <$ 7 keV. For $S > 100$, we exclude 2 keV $< m_s <$ 16 keV. These constraints are more restrictive than the ones obtained for the Coma Cluster periphery (Boyarsky et al. 2006a) for masses less than approximately 8 keV.

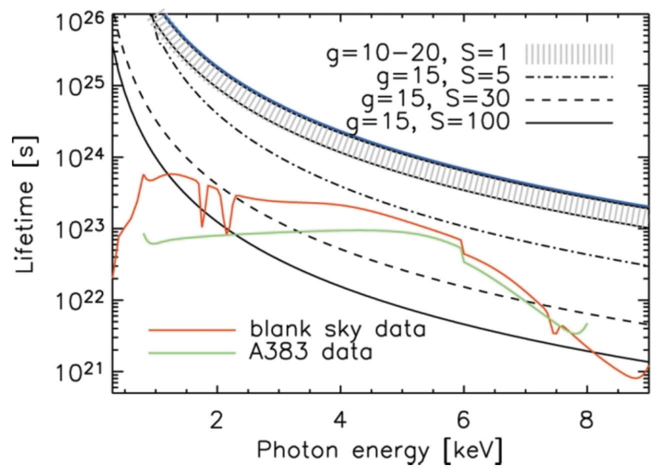

FIG. 3.—Lifetime constrained from the flux of the *Chandra* blank sky data (*red line*) and A383 (*green line*). The νMSM prediction for $S = 1$ and $g_* = 10$–20 (*hatched region*) and several variations of S and g_* (*black lines*) have been overplotted. The solid blue line is the relation from Abazajian (2006).

5. OTHER CONSTRAINTS

The simplest models with $S = 1$ are bounded from below, $m_s > 2$ keV, using Lyα observations (Viel et al. 2005), and possibly even $m_s > 14$ keV according to a recent analysis (Seljak et al. 2006). These constraints are weakened when allowing for $S > 1$ (Asaka et al. 2006), since additional entropy dilutes the momentum of the sterile neutrinos.

Upper limits on the sterile neutrino mass are derived from the flux of the diffuse photon background (Dolgov & Hansen 2002) and are of the order $m_s < 15$ keV for $S = 1$ (Mapelli & Ferrara 2005; Boyarsky et al. 2005). These bounds are strengthened for $S > 1$, since the sterile neutrinos then will decay faster.

A strict lower bound on the sterile neutrino mass arises because big bang nucleosynthesis allows for only approximately 0.3 additional relativistic neutrino species to be populated at ~MeV temperatures. This lower bound is approximately $m_s > 50$ eV. Instead, the Tremain-Gunn bound, when applied to dwarf speroidals, gives $m_s > 0.5$ keV (Tremaine & Gunn 1979; Lin & Faber 1983).

The strong claim of an upper mass limit presented in Abazajian et al. (2001) underestimated the flux from the Virgo Cluster by 2 orders of magnitude and is unreliable (for details see Boyarsky et al. 2006a).

Comparing these existing bounds with our findings, we conclude that a broad band in neutrino parameter space is still open, as shown in Figure 4. Taking the results of Seljak et al. (2006) into account, only masses above approximately 5 keV are allowed. Ignoring the results of Seljak et al. (2006), another band opens in parameter space, for small masses and large entropy production.

6. CONCLUSIONS

We have used *Chandra* blank sky observations, i.e., looking out through the Milky Way halo, to search for a possible decay line from dark matter particles. No obvious decay line was identified.

The blank sky 0.3–9 keV X-ray flux is used to constrain the parameter space of sterile neutrinos, predicted to decay at rest

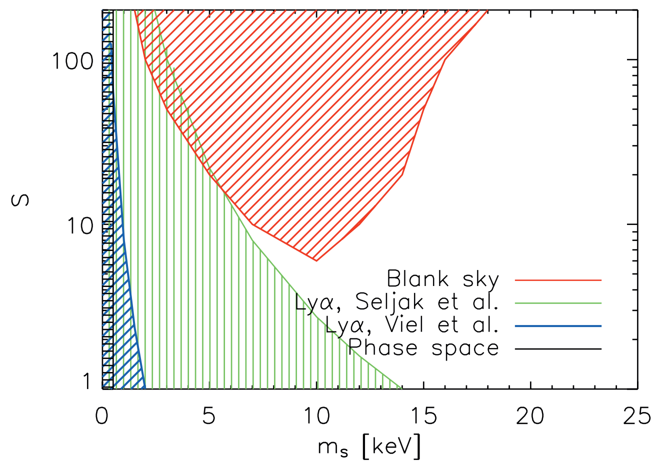

FIG. 4.—The $m_s - S$ parameter space with constraints from *Chandra* blank sky data (*red diagonal lines*; this Letter), Lyα observations (*blue diagonal lines* [conservative analysis by Viel et al. 2005] *and green vertical lines* [ambitious analysis by Seljak et al. 2006]), and Tremaine-Gunn bound $m_s > 0.5$ keV (*black vertical lines*).

to a detectable photon and an active neutrino. We find that the entropy production must be limited, $S < 100$ for the mass range, 2 keV $< m_s <$ 16 keV, and even $S < 10$ for masses near m_s = 10 keV.

This leaves a wide allowed parameter space, and the sterile neutrino is therefore still a viable dark matter candidate. If all Lyα constraints are considered, then it appears that either the sterile neutrino is rather massive or its momenta are diluted by the entropy production, rendering it a cold dark matter candidate. If some of the Lyα constraints are relaxed, then there is a broad allowed band for smaller masses where the sterile neutrino is still a warm dark matter candidate.

Our analysis is conservative and assumes that the entire blank sky signal at a given energy is arising from a decaying neutrino. By looking for decay lines above the expected blank sky emission, the results obtained here may be improved significantly.

Note added in manuscript.—After finishing this Letter, we became aware of an independent analysis in which the possibility of measuring decaying dark matter particles from our Galaxy, using blank sky observations with *XMM-Newton*, was considered (Boyarsky et al. 2006b). The conclusions reached in that paper are qualitatively similar to ours.

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