Constraints on the parameters of radiatively decaying dark matter from the dark matter halos of the Milky Way and Ursa Minor

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ABSTRACT

Aims. We improve the earlier restrictions on parameters of the dark matter (DM) in the form of a sterile neutrino.

Methods. The results were obtained from non-observing the DM decay line in the X-ray spectrum of the Milky Way (using the recent XMM-Newton PN blank sky data). We also present a similar constraint coming from the recent XMM-Newton observation of Ursa Minor – dark, X-ray quiet dwarf spheroidal galaxy.

Results. The new Milky way data improve on (by as much as the order of magnitude at masses ~ 3.5 keV) existing constraints. Although the observation of Ursa Minor has relatively poor statistics, the constraints are comparable to those recently obtained using observations of the Large Magellanic Cloud or M31. This confirms a recent proposal that dwarf satellites of the MW are very interesting candidates for the DM search and dedicated studies should be made to this purpose.

Key words. Galaxy: halo – Galaxies: individual: Ursa Minor – Cosmology: dark matter – X-rays:galaxies

1. Introduction

This past year has seen a lot of activity, devoted to searching for the decay signals of the DM particle in X-ray spectra of various astrophysical objects (Boyarsky et al. 2006a,b,c; Riemer-Sørensen et al. 2006; Watson et al. 2006; Riemer-Sørensen et al. 2006, e.g.). It was noticed long ago by Dodelson & Widrow (1994) that a right-handed neutrino with masses in the keV range presents a viable warm dark matter (WDM) candidate. Such a particle possesses a specific radiative decay channel, so one can search for its decay line in the X-ray spectra of astrophysical objects (Dolgov & Hansen 2002; Abazajian et al. 2001b).

Recently, the interest in the sterile neutrino as a DM candidate has been greatly revitalized. First, the discovery of neutrino oscillations (see e.g. Strumia & Vissani 2006 for a review) strongly suggest the existence of right-handed neutrinos. Probably the easiest way to explain the data on oscillations is by adding several right-handed, or sterile, neutrinos to the Standard Model. It has been demonstrated recently in Asaka et al. (2005) and Asaka & Shaposhnikov (2005) that a simple extension of the Standard Model by three singlet fermions with masses smaller than the electroweak scale (dubbed the νMSM in Asaka et al. 2005) allows accommodation of the data on neutrino masses and mixings, allows baryon asymmetry of the Universe to be explained, and provides a candidate for the dark matter particle in the form of the lightest of the sterile neutrinos¹.

Secondly, warm DM with the mass of particle in keV range can ease the problem of the dark halo structures in comparison with the cold dark matter scenario Bode et al. (2001); Goerdt et al. (2006). By determining the matter power spectrum from the Lyman-α forest data from SDSS Seljak et al. (2006) and Viel et al. (2006) argue that the mass of the DM particles should be in the range > 10 keV (≥ 14 keV in the case of Seljak et al. 2006). As this method gives direct bounds for the free-streaming length of the neutrinos, the bounds on the mass of the DM particle depend on the momentum distribution function of the sterile neutrinos and, therefore, on their production mechanism. The results quoted above are claimed for the simplest Dodelson-Widrow model (1994).

At the same time, studies of the Fornax dwarf spheroidal galaxy (Goerdt et al. 2006; Strigari et al. 2006) disagree with the predictions of CDM models and suggest lower mass than in Seljak et al. (2006) and Viel et al. (2006) for the DM particle MDM ~ 2 keV. This result agrees with the earlier studies

¹ The νMSM does not explain the unconfirmed results of the LSND experiment (Aguilar et al. 2001). There are other models that try to account for it by introducing a sterile neutrino with the mass around 1 eV. There are also models that explain not all, but only some of these phenomena (e.g. LSND and DM, but not the baryon asymmetry as e.g. in de Gouvea 2005). We do not give any review here. We would like to stress that, although our work is motivated by the recent results on the νMSM, our method and results do not rely on any particular model.
of [Hansen et al. (2002) and Viel et al. (2005)], which used a different dataset. For other interesting applications of the sterile neutrinos with the mass ~ few keV see e.g. Kusenko (2006b), Biermann & Kusenko (2006), Stasielak et al. (2006), Kusenko (2006a), and Hidaka & Fuller (2006).

It has been argued in Boyarsky et al. (2006c) and Riemer-Sørensen et al. (2006) that the preferred targets for observations are objects from the local halo, including our own Milky Way and its satellites. In particular, Boyarsky et al. (2006c) showed that the best observational targets are the dwarf spheroidals (Ursa Minor, Draco, etc). Indeed, these objects are X-ray quiet, while at the same time one expects the DM decay signal from them, comparable to what comes from galaxy clusters. Because at the time of writing of Boyarsky et al. (2006c) no public data were available for these dwarf spheroidals, the observations of the core of Large Magellanic Cloud (LMC) were used to produce the strongest restrictions on parameters of the sterile neutrino. It was stressed in Boyarsky et al. (2006c) that other dwarf satellite galaxies should be studied as well, in order to minimize uncertainties related to the DM modeling in each single object. In this paper we continue studies of the dwarf satellites of the MW by analyzing the data from XMM-Newton observation of Ursa Minor and confirm the restrictions of Boyarsky et al. (2006c).

It was also shown in Boyarsky et al. (2006c) that the improvement of the results from MW DM halo can be achieved by using longer exposure data (notably, longer exposure of the closed filter observations). In this paper, we improve our restrictions, coming from the MW DM halo by using the blank sky dataset with better statistics from Nevalainen et al. (2005).

2. DM with radiative decay channel

Although throughout this paper we are talking mostly about the sterile neutrino DM, the results can be applied to any DM particle that possesses the monoenergetic radiative decay channel, emits photon of energy $E_γ$, and has a decay width $\Gamma$. In the case of the sterile neutrino (with mass below that of an electron), the radiative decay channel is into photon and active neutrino [Pal & Wolfenstein (1982)]. As the mass of an active neutrino is much lower than keV, $E_γ = M_{\nu}$ in this case. The width $\Gamma$ of radiative decay can be expressed (Pal & Wolfenstein 1982; Barger et al., 1995) in terms of mass $M_\nu$ and mixing angle $\theta$ via

$$\Gamma = \frac{9\alpha G_f^2 \sin^2 2\theta}{1024\pi} M_\nu^5 \approx 1.38 \times 10^{-22} \sin^2(2\theta) \left[ \frac{M_\nu}{\text{keV}} \right]^5 \text{sec}^{-1}.$$  \(\text{Eq. (1)}\)

(The notation $\sin^2(2\theta)$ is used traditionally, although in all realistic cases $\theta \ll 1$). The flux of the DM decay from a given direction is given by

$$F_{DM} = \frac{E_γ}{M_\nu} \int_{\text{cones}} \frac{\rho_{DM}(r)}{4\pi D_L} \sin^2(2\theta) \, d^3r.$$ \(\text{Eq. (2)}\)

Here $D_L$ is the luminous distance between the observer and the center of the observed object, $\rho_{DM}(r)$ is the DM density, and the integration is over the DM distribution inside the (truncated) cone – solid angle, spanned by the field of view (FoV) of the X-ray satellite. If the observed object is far then Eq. (2) can be simplified:

$$F_{DM} = \frac{M_{DM} \Gamma_{\nu}}{4\pi D_L^2 M_\nu}.$$ \(\text{Eq. (3)}\)

where $M_{DM}$ is the mass of DM within a telescope’s field of view (FoV). Equation (3) can be rewritten again as

$$F_{DM} = 6.38 \times 10^6 \left[ \frac{M_{DM}}{10^{10} M_\odot} \right] kpc^{-2} \times \text{sin}^2(2\theta) \left[ \frac{M_\nu}{\text{keV}} \right]^5 \text{keV}^{-1} \text{cm}^{-2} \text{sec}^{-1}.$$ \(\text{Eq. (4)}\)

In the absence of a clearly detectable line, one can put an upper limit on the flux of DM from the astrophysical data, which will lead via Eq. (4) to the restrictions of parameters of the sterile neutrino $M_\nu$ and $\theta$.

3. Restrictions from the blank sky observation

3.1. Modeling the DM halo of the MW

As shown in the previous section, one needs to know the distribution of the DM to obtain the restrictions on parameters of the sterile neutrino. In the case of nearby objects (including our own Galaxy and dwarf satellites from the local halo), the DM distribution can be deduced e.g. by using the rotation curves of the stars in the galaxy. Here we follow the analysis of Boyarsky et al. (2006c). Various DM profiles, used to fit observed velocity distributions, differ the most in the center of a distribution. In the case of the MW we choose, as in Boyarsky et al. (2006c), to use the observations away from the center, to minimize this uncertainty. In particular, in Refs. Klypin et al. (2002); Battaglia et al. (2005) it was shown that the DM halo of the MW can be described by the Navarro-Frenk-White (NFW) profile (Navarro et al. 1997)

$$\rho_{NFW}(r) = \frac{\rho_s r_s^2}{r(r + r_s)^2},$$ \(\text{Eq. (5)}\)

with parameters, given in Table 1. The relation between virial parameters and $\rho_s$, $r_s$ are given in the Appendix A. Quoted halo parameters provide DM decay flux (from the directions with $\phi > 90^\circ$) consistent within ~ 5% with the one, given by Eqs. (6)–(7). Only “maximal disk” models in Klypin et al. (2002) would provide 30 – 50% weaker restrictions; however, these models are highly implausible, see Klypin et al. (2002). Similarly, taking the lower limit for the virial mass of Battaglia et al. (2005), one would obtain 25% weaker restrictions than the ones, presented in this paper.

To compare the results from different (e.g. cuspy and cored) profiles, we can also describe the DM distribution in the MW via an isothermal profile:

$$\rho_{iso}(r) = \frac{\rho_{iso} v_0^2}{4 \pi G N} \frac{1}{r^2 + r_s^2}.$$ \(\text{Eq. (6)}\)

The DM flux from a given direction $\phi$ into the solid angle $\Omega_{\text{fov}} \ll 1$, measured by an observer on Earth (distance $r_0 \approx 8 \text{kpc}$ from the galactic center), is given by

$$F_{iso}^{DM}(\phi) = \frac{L_0}{R} \left( \frac{\pi}{2} + \arctan \left( \frac{\cos \phi}{\sqrt{r_0^2 + r_s^2}} \right) \right), \quad \cos \phi \geq 0$$

$$= \frac{L_0}{R} \arctan \left( \frac{r_0 \cos \phi}{r_s} \right), \quad \cos \phi < 0.$$ \(\text{Eq. (7)}\)

1 According to Klypin et al. (2002), the choice of e.g. the Moore profile (Ghigna et al. 2000) or a generalization thereof, as compared to the NFW profile, would change the results by $\lesssim 1\%$ for $r < 3 \text{kpc}$. As we are using observations away from the center, this difference is completely negligible, so we choose to use the NFW profile.

2 When quoting results of Klypin et al. (2002), we do not take the effects of baryon compression on DM into account. While these effects make DM distribution in the core of the MW denser, they are hard to compute precisely. Thus the values we adopt give us a conservative lower bound on the estimated DM signal.
Here $L_0 = \frac{\sqrt{M_{\odot}v_0^2}}{32\pi G} \rho_0$ and $R = \sqrt{r_0^2 + r_0^2 \sin^2 \phi}$. Angle $\phi$ is related to the galactic coordinates $(b, l)$ via
\[
\cos \phi = \cos b \cos l.
\] (8)

Thus, the galactic center corresponds to $\phi = 0^\circ$, and the anti-center $\phi = 180^\circ$ and the direction perpendicular to the galactic plane to $\phi = 90^\circ$.

In Boitavsky et al. (2006c), the following parameters of isothermal profile were chosen: $v_0 = 170$ km/sec and $r_c = 4$ kpc. One can easily check (using Table 1 and Eqs. (A.3)–(A.6) in Appendix A) that, in the directions $\phi \geq 90^\circ$, the difference in predicted DM fluxes between the NFW model with parameters, given in Table 1 and isothermal model with parameters just quoted are completely negligible (less than 5%).

### 3.2. XMM-Newton PN blank sky data

To examine the Milky Way halo, we used the double-filtered, single+double event XMM-Newton PN blank sky data from Nevalainen et al. (2005), which is a collection of 18 blank sky observations (see Table 2 in Nevalainen et al. 2005 for their observation IDs, positions, and exposures). The exposure time of the co-added observations is 547 ks. We used a combination of closed-filter observations from Nevalainen et al. (2005) (total exposure time 145 ks) to model the background of XMM-Newton PN instrument separately. The data has been filtered using SAS expression “flag=0”, which rejects the data from bad pixels and CCD gap regions. After removing the brightest point sources, the total accumulation area is 603 arcmin².

Based on the $>10$ keV band count rates of the blank sky and the closed filter data, we normalized the closed-filter spectrum by a factor of 1.07 before subtracting it from the blank sky spectrum. The remaining sky-background spectrum consists mainly of the Galactic emission and the cosmic X-ray background (CXB) due to unresolved extragalactic point sources. We modeled the Galactic emission by a non-absorbed MEKAL model with Solar abundances. For the CXB emission, we used a power-law model modified at the lowest energies by Galactic absorption with the value of $N_H$ fixed to its exposure-weighted average over all blank sky observations ($N_H = 1.3 \times 10^{20}$ cm$^{-2}$).

The variable Galactic emission and geocoronal Solar wind-charge exchange emission (see e.g. Wargelin et al. 2004) complicate the modeling at the lowest energies. The remaining calibration uncertainties further complicate the analysis in the lowest energies (see e.g. Nevalainen et al. 2006). Thus, we omitted the channels below 0.6 keV. At energies above 7 keV, the particle background dominates and the total flux is very sensitive to the background normalization. We thus excluded channels above 7 keV.

The data are not well-described in the 1.45–1.55 and 5.8–6.3 keV bands with the above model. These deviations probably originate from the variability of the instrumental Al and Fe line emission. In order to minimize the effect of the instrumental problems, we excluded these bands when finding the best-fit sky background model (see below). Also, to account for possibly remaining calibration inaccuracies, we added a systematic uncertainty of 5% of the model value in each bin in quadrature to the statistical uncertainties.

We binned the spectrum using a bin size of 1/3 of the energy resolution and fitted the data using models and channels as described above. The best-fit (reduced $\chi^2 = 1.03$ for 153 degrees of freedom) model agrees with the data within the uncertainties (see Fig. 1), yielding a photon index of $1.50\pm0.02$ at 1 $\sigma$ confidence level (see Fig. 1), consistent with similar analyses based on Chandra (Hickox & Markevitch 2006) and XMM-Newton instrument (De Luca & Molendi 2004). The best-fit temperature

### Table 1. Best-fit parameters of NFW model of the MW DM halo.

| References | $M_{\text{vir}} [M_\odot]$ | $r_{\text{vir}}$ [kpc] | Concentration | $r_c$ [kpc] | $\rho_c [M_\odot/kpc^3]$ |
|------------|-----------------|-----------------|----------------|-------------|-----------------|
| Klypin et al. (2002), favored models (A₁ or B₁) | $1.0 \times 10^{12}$ | 258 | 12 | 21.3 | $4.9 \times 10^8$ |
| Battaglia et al. (2005) | $0.8^{+1.1}_{-0.2} \times 10^{12}$ | 255 | 18 | 14.2 | $11.2 \times 10^8$ |
of the MEKAL component used to model the Galactic emission is $0.19 \pm 0.01$ keV, consistent with e.g. Hickox & Markevitch (2006).

We then evaluated the level of possible DM flux above the background model allowed by the statistical and systematic uncertainties in each channel. For this, we modified the above best-fit model by adding a narrow (width = 1 eV) Gaussian line to it. We then re-fitted the data, fixing the Gaussian centroid for each fit to the central energy of a different channel. In these fits we fixed the above continuum model parameters to the best-fit values and thus the Gaussian normalization parameter is the only free parameter. We used the fits to find the upper $3\sigma$ uncertainty of the Gaussian normalization, i.e. the allowed DM flux. Note that here we included the channels 1.45–1.55 and 5.8–6.3 keV (excluded above when defining the sky background model). The background is oversubtracted in the channels at 1.45-1.55 keV and ~6.0 keV (see Fig. 1), which would formally require negative normalization for the Gaussian. However, we forced the normalization to be positive and thus obtained conservative upper limits in these energies.

Finally, we converted the upper bound obtained for the flux per energy bin to the restrictions on $M_s$ and $\sin^2 \theta$, using Eqs. (1), (7) (we use exposure weighted average of DM fluxes (Eq. 7) from all the observations, constituting the blank sky dataset). This corresponds to the average "column density" 1.22 $\times$ 10$^{28}$ keV/cm$^2$. The results are shown in Fig. 2.

At energies above $E = 5$ keV, the instrumental background of PN dominates over the sky background (c.f. Nevalainen et al. 2005). Therefore, the accuracy of the co-added closed filter spectrum in predicting the particle background in the blank sky observations becomes essential. We estimate this accuracy using the variability of the individual closed-filter spectra in the 0.8-7.0 keV band Nevalainen et al. 2005 and propagate it by varying the normalization of closed filter data by $\pm 5\%$ and repeating the above analysis. This leads to a factor of 3 change in the results at $M_s \sim 14$ keV (see Fig. 3). Therefore, for $E \geq 5$ keV we choose the more conservative normalization (see Fig. 7 below).

4. Restrictions from observations of Ursa Minor

It was argued in Boyarsky et al. (2006c) that dwarf satellite galaxies should provide the best restrictions, based on their high concentration of DM and low X-ray signal. At the moment of writing of Boyarsky et al. (2006c), no public data on preferred dwarf satellites were available, therefore the observation of core of LMC were used as a demonstration. Recently, the Ursa Minor dwarf (UMi) was observed with XMM-Newton (obs IDs: 0301690201, 0301690301, 0301690401, 0301690501, observed in August-September 2005). Unfortunately, most of these observations are strongly contaminated by background flares and the observations have very small exposure times. Below we present the analysis of only one observation (obsID: 0301690401), which "suffered" the least from background contamination.

4.1. DM modeling for UMi

The DM distribution in UMi has a cored profile (see e.g. Kleva et al. 2003; Wilkinson et al. 2006; Gilmore et al. 2004, 2007). We adopt the following parameters of isothermal profile (6) for UMi: $v_h = 23$ km/sec, $r_c = 0.1$ kpc (see e.g. Wilkinson et al. 2006). We adopt the distance to UMi $D_L =$ 7

$^7$ We are very grateful to Prof. T. Maccarone for sharing this data with us before it became publicly available through the XMM data archive.

$^8$ As discussed in Section 3.1 the estimates for DM flux do not vary significantly if one uses NFW instead of the isothermal DM density profile. In the case of UMi, the cored (isothermal) profile will clearly produce a more conservative estimate than will the cuspy NFW profile. Indeed, taking NFW parameters for UMi from the recent paper Wu (2007) gives a ~ 20% higher estimate for the DM mass within the FoV.

$^9$ For the detailed studies of mass distribution in dwarf spheroidals, see Gilmore et al. (2004). We are grateful to Prof. G. Gilmore for sharing the numbers with us before their paper became available. The statistical uncertainty in determining these numbers is below 10%. The systematic uncertainties are much harder to estimate. One of the major sources of the systematic errors comes from violation of the main assumptions of the method: deviation from equilibrium and from the spherical distribution of matter in a galaxy. In other known examples it provides a factor of 2 uncertainty, which should be a conservative estimate in the case of UMi, as it is rather spherical. Another typical uncertainty – determination of the mass of the stars – is not important for UMi, as it has a very high mass-to-light ratio.
is small (filtering around the quiescent level). Thus we accepted the data from all instants after the initial 2 ks, and we approximated the background method to channels below 2 keV.

In our case, the radius of FoV is 13.9’, which corresponds to \( r_{\text{fov}} = 0.27 \) kpc (i.e. about \( 3r_c \)). Therefore

\[
M_{\text{DM}}^{\text{fov}} = \frac{\pi v^2}{2G_N} \left( \sqrt{r_{\text{fov}}^2 + r_c^2} - r_c \right). \tag{9}
\]

In our case, the hydrogen column density in the direction of Ursa Minor is \( 66 \) kpc (Mateo 1998). The DM mass within the circular FoV with the radius \( r_{\text{fov}} \), centered at the center of the galaxy is given by

\[
M_{\text{DM}}^{\text{fov}} = 3.3 \times 10^7 M_\odot \quad \text{for} \quad r_{\text{fov}} = 0.27 \text{ kpc}. \tag{10}
\]

Using Eqs. \text{(10)} and \text{(3)}, one can compute the expected DM flux from UMi:

\[
F_{\text{DM}} = 4.79 \times 10^{-5} \text{ keV/cm}^2 \cdot \text{sec} \cdot \text{keV}^{-1} \cdot \sin^2(2\theta). \tag{11}
\]

### 4.2. PN data analysis

We processed the Ursa Minor observation 0301690401 using epchain version 8.56 and filtered the event file with SAS expressions “PATTERN<=4” and “FLAG==0”. We applied the blank sky-based XMM-Newton background method of Nevalainen et al. (2005) for Ursa Minor. The > 10 keV band light curve from the full FOV (FIG. 4) shows that the count rate in observation 0301690401 (excluding first 2 ks) exceeds that of the blank sky quiescent average by 25%. This level is higher, but close to what is used in the blank sky accumulation (± 20% filtering around the quiescent level). Thus we accepted the data from all instants after the initial 2 ks, and we approximated the background uncertainties with those in Nevalainen et al. (2005).

The hydrogen column density in the direction of Ursa Minor is small (\( \sim N_H = 2 \times 10^{20} \text{ cm}^{-2} \)) and consistent with the variation in the blank sky sample. Thus we can also apply the blank sky background method to channels below 2 keV.

As noted in the above XMM-Newton blank sky study, the > 10 keV band-based scaling of the background only works up to a factor of 1.1, beyond which the background prediction becomes worse. Furthermore, the correlation of background rates in the > 10 keV band is very poor with the rates below 2 keV band. Thus, in order to achieve the best possible background prediction accuracy, we scaled the blank sky background spectrum by a factor of 1.1 at channels above 2 keV, and we applied no background scaling at lower energies.

We removed this scaled background spectrum from the Ursa Minor spectrum (see FIG. 5). As shown in Nevalainen et al. (2005), the background accuracy is worse at lower energies. We used those estimates to propagate the background uncertainties at 1 \( \sigma \) confidence level to our results by examining how the results change when varying the 0.8–2.0 keV and 2.0–7.0 keV band background by 15% and 10%, respectively.

### 4.3. Ursa Minor data and restrictions on the sterile neutrino parameters

The X-ray spectrum of UMi is similar to that of LMC: above 2 keV the flux is zero within statistical limits (see FIG. 5). (Of course, the data set has rather low statistics: after the cleaning of flares the UMi observation only contains 7 ks). Therefore, for such data, we utilized the “total flux” method. Namely, we restricted the DM flux in the given energy bin to be bounded correspondingly. The solid black line represents the 3 \( \sigma \) upper bound on total flux in a given energy bin, which we use to put the limit on DM parameters.

The restriction of results (at least for energies above \( 2 \text{ keV} \)) is roughly a factor of \( \sqrt{100 \text{ ks}/7 \text{ ks}} \approx 3.77 \).
5. Results

5.1. Restrictions from the blank sky data

By analyzing the blank sky data set with better statistics, we improved on the previous results of Boyarsky et al. (2006c), Riemer-Sørensen et al. (2006), Watson et al. (2006) (by as much as the factor of 10 for $M_s \approx 3.5$ keV and by the negligible amount for $M_s \gtrsim 11$ keV). The result is shown in Fig. 7 in red solid line. The best previous bounds are also shown: bound from LMC (Boyarsky et al. 2006c) with a blue short-dashed line and bound from M31 (Watson et al. 2006) with a dotted magenta line. We see that in the region $3.5$ keV $\lesssim M_s \lesssim 11$ keV the new blank sky data improves on previous results. These results can be converted (using Eq. (1)) into restrictions on the decay rate $\Gamma$ of any DM particle, that possesses radiative decay channel and emits a photon $E_\gamma$ (see FIG. 8). Our results provide more than an order of magnitude improvement over similar restrictions derived in Riemer-Sørensen et al. (2006) (which used the Chandra blank sky background), as one can clearly see by comparing FIG. 8 with FIG. 2 in Riemer-Sørensen et al. (2006), where the exclusion plot is above $\Gamma = 10^{-26}$ sec$^{-1}$ line for all energies. (In Riemer-Sørensen et al. (2006) the restriction were made, based on the total flux of Chandra satellite, without subtraction of the instrumental background, which explains a much weaker restrictions).

The empirical fit to the MW data is given by the following expression:

$$\sin^2(2\theta) \lesssim 2.15 \times 10^{-7} \left( \frac{M_s}{\text{keV}} \right)^{-3.45}.$$  \hspace{1cm} (12)

5.2. Restrictions from Ursa Minor dwarf

Restrictions from XMM observation of UMi are shown in FIG. 7 by the green long-dashed line. These results are slightly weaker than LMC or M31 results, which is due to the very low statistics of the UMi observation. Improvement of the statistics should lead to improvement of the current bound (as shown on the FIG. 6). These results confirm the recent claims (Boyarsky et al., 2006c) that dwarfs of the local halo are promising candidates for the DM-decay line search and, as such, should be studied dedicately.

In searching for the DM signatures, it is important to understand that the uncertainties of the DM modeling for any given object can be large, and therefore it is important to study many objects of given type, as well as many different types of objects (where DM distributions are deduced by independent methods). To this end, although UMi data does not provide any improvement over existing bounds, it makes those bounds more robust as the existence of DM in UMi is deduced by independent observations, and the rotation curves of UMi are measured quite well, since it has less perturbed dynamics, compared to e.g. LMC.

6. Discussion

In this paper we continued to search for the best astrophysical objects, from the point of view of restricting parameters of DM particles with the radiative decay channel. Several comments are in order here.

(1) Although throughout this paper we have spoken about the sterile neutrinos and restricted their parameters (namely, mass, and mixing angle), the constraints can be readily converted into any other DM candidate that possesses a radia-
tive decay channel. Then the restrictions are formulated on the decay rate $\Gamma$ as a function of energy of the emitted photon $E_\gamma$. The results then can be presented in the form of an exclusion plot, presented in FIG. 8.

(2) Clearly, if one could relate parameters of the sterile neutrino with their relic abundance $\Omega_\nu$, this would allow one to put an upper limit on the mass of the sterile neutrino. Unfortunately, such a computation is strongly model-dependent. In Dolgov & Hansen (1994), Dolgov & Hansen (2002), Abazajian et al. (2001a), Abazajian (2006), the relic abundance of the sterile neutrinos was computed in a simple model with only one sterile neutrino, assuming the absence of the sterile neutrinos above the temperatures $\sim 1$ GeV. Yet, even the computation in this simplest model is subject to a number of uncertainties (Shi & Fuller 1998, Boyarsky et al. 2006a, Asaka et al. 2006a, Asaka et al. 2006b, Shaposhnikov & Tkachev 2000). In particular, in Dolendo & Widrow (1994), Dolgov & Hansen (2002), Abazajian et al. (2001a), Abazajian (2006), two assumptions were made: (i) the absence of heavy particles, whose decay can dilute the relic abundance, (ii) the absence of lepton asymmetries. In addition, simplifying assumptions about dynamics of hadrons at temperatures $O(150) \text{ MeV}$ were used. Recently, Asaka et al. (2007) performed this computation from the first principles, showing that the uncertainty due to QCD effects (between minimal and maximal values of $\sin^2(2\theta)$ for given $M_\nu$) is about a factor of 8.

Taking away the assumptions about the absence of the sterile neutrinos above the temperatures $\sim 1$ GeV makes any mixing angle possible. For example, the DM neutrinos can be created due to the inflaton decay Shaposhnikov & Tkachev (2006). Therefore, in this work we chose not to derive an upper bound on the mass of the sterile neutrino.

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Appendix A: Determining parameters of NFW profile

Using data on rotation curves, one usually obtains the following parameters of DM distribution (see e.g. Klypin et al. 2002):

- virial mass $M_{\text{vir}}$, virial radius $r_{\text{vir}}$, and concentration parameter $C$.
- The following relation with the parameters of NFW profile (5) $r_s$ and $\rho_s$:

$$r_s = \frac{r_{\text{vir}}}{C}; \quad \rho_s = \frac{M_{\text{vir}}}{4\pi r_s^3 f(C)},$$

where in terms of function $f(x)$

$$f(x) = \log(1 + x) - \frac{x}{1 + x},$$

one obtains the mass within the radius $r$:

$$M(r) = M_{\text{vir}} \frac{r(r/r_s)}{f(C)}.$$

If DM distribution in the Milky Way is described by the NFW model (as in Battaglia et al. 2005, Klypin et al. 2002), the flux from a direction $\phi$ is given by

$$F_{\text{NFW}}(\phi) = \frac{\Gamma M_{\text{tot}}}{8\pi} \int_0^{\infty} dz P_{\text{NFW}} \sqrt{\frac{r_s^2 + z^2 - 2r_s z \cos \phi}{r_s^2}}$$

(notations are the same as in Eqs. (7)–(8)). Let us consider two cases, when the integral in (A.4) can be easily computed. Namely, we have for $\phi = 180^\circ$

$$F_{\text{NFW}}(180^\circ) = \frac{\Gamma M_{\text{tot}}}{8\pi} \rho_{\text{tot}} r_s \left[ \log(1 + \frac{r_s}{r_0}) - \frac{r_s}{r_0} + \frac{r_s}{r_0^2} \right],$$

and for $\phi = 90^\circ$

$$F_{\text{NFW}}(90^\circ) = \frac{\Gamma M_{\text{tot}}}{8\pi} \rho_{\text{tot}} r_s \left[ -1 - \log \frac{r_s}{r_0} + \frac{r_s}{r_0^2} \left( \frac{3}{2} \log \left( \frac{r_s}{r_0} - \frac{5}{4} \right) \right) \right] + O\left( \frac{r_0^2}{r_s^2} \right).$$

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