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Where to find a dark matter sterile neutrino?

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We propose a strategy of how to look for dark matter (DM) particles possessing a radiative decay channel and derive constraints on their parameters from observations of X-rays from our own Galaxy and its dwarf satellites. When applied to the sterile neutrinos in keV mass range, it allows a significant improvement of restrictions to its parameters, as compared with previous works.

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Introduction. It was noticed long ago that a sterile neutrino with the mass in the keV range appears to be a viable DM candidate [1]. Moreover, being a *warm* DM, sterile neutrino ease the tension between observations and predictions of the *cold* DM model on small scales. The interest to this scenario is revitalized since the discovery of neutrino oscillations (see e.g. [2] for review). Indeed, one of the simplest ways to explain this data is to add to the Standard Model several (at least two) gauge singlet fermions – right handed, or *sterile* neutrinos. It has been demonstrated recently [3] that a simple extension of the Standard Model by three singlet fermions with masses smaller than the electroweak scale, dubbed the νMSM in [3], allows to accommodate the data on neutrino masses and mixings (with the exception of the LSND anomaly), provides a candidate for DM particle in the form of sterile neutrino, and allows to explain baryon asymmetry of the Universe. The simplicity of the model, the similarity of its quark and lepton right-handed sectors, together with a considerable number of phenomena it can simultaneously describe, forces us to take this model seriously and thus provides additional motivations for study of keV mass range sterile neutrino as a DM candidate.

The sterile neutrino has a radiative decay channel, emitting a photon with energy $E = m_s/2$ (m_s being the mass of sterile neutrino). Parametrically, the decay width is proportional to $m_s^5 \sin^2 2\theta$ [4], where θ is the mixing angle between active and sterile neutrino.

If such a neutrino is a main ingredient of the DM, it is potentially detectable in various X-ray observations. The most obvious candidates include diffuse extragalactic X-ray background (XRB) [5, 6, 7, 8]; clusters of galaxies [6, 9, 10]; galaxies [6], including our own.

The aim of the present Letter is to discuss the best strategy to search for a DM sterile neutrino and to derive the constraints on its properties. Although we concentrate on sterile neutrino, the constraints we get can be applied to any DM candidate with a radiative two-body decay channel in a keV range. We analyze various types of astrophysical objects and show that the strongest constraints on sterile neutrino are coming from neutrino decays in the Milky Way halo and in particular in the halo dwarf galaxies. These objects were not considered previously in this context. The existing XMM Newton and HEAO-1 data allow us to improve over previous constraints, highlighting the potential of new optimal cites for the searches of the signal from the sterile neutrino decay.

Dark matter halo of the Milky Way (MW). Energy flux produced by the DM decay from a given direction into a solid angle $\Omega_{\rm fov} \ll 1$ is given by

$$F = \frac{\Gamma\Omega_{\rm fov}}{8\pi} \int\limits_{\text{line of sight}} \rho_{\rm DM}(r)dr\ , \qquad (1)$$

where Γ is the radiative decay width of sterile neutrino. To determine the MW contribution into the flux (1), one needs to know the distribution of the DM in the halo.

Mass distribution within MW has been modeled by many authors. Characteristics which are relevant for our study are tightly constrained by the wealth of detailed data available for this system. As a reference we will choose the mass distribution derived recently in [11], where physically interesting models were selected by imposing additional constraints based on a theory of halo formation. At large r the halo density can be described by the Navarro-Frenk-White (NFW) profile $\rho_{\rm NFW}(r) = \frac{M_{\rm vir}}{4\pi\alpha}\frac{1}{r(r_s+r)^2}$. The MW halo parameters of favorite models obtained in [11] correspond to $M_{\rm vir} = 1.0\times10^{12}M_\odot$, $r_s = 21.5$ kpc and numerical constant $\alpha \simeq 1.64$.

In the region of r relevant for our study the halo density can be also approximated by the isothermal profile

$$\rho_{\rm halo} = \frac{v_h^2}{4\pi G_N}\frac{1}{r_c^2+r^2}, \qquad (2)$$

where v_h corresponds to contribution of the DM halo into the Galactic rotation curve in its flat part, $v_h \approx 170$ km/s, see e.g. [11].

The NFW density profiles and (2) produce identical fluxes from the direction of the Galactic anti-center if $r_c \approx 4$ kpc, giving $\int_{r_\odot}^\infty \rho_{\rm halo}\, dr \approx 0.7\times10^{22}$ GeV/cm^2. They also follow closely each other in the range 3 kpc $< r <$ 80 kpc (difference being less than 5%). Therefore, in estimates of the flux from directions which are outside of 20° circle around the Galactic center both NFW and (2) give the same results.

The halo density profile is less certain in the region $r < r_\odot$. In [11] two distinct types of models were considered, with and without exchange of angular momentum between DM and baryons. In the model without momentum exchange the DM density profile at $r < 10$ kpc diverges even faster than NFW profile. In the model with angular momentum exchange the DM density profile at 2 kpc $< r <$ 10 kpc is less singular and rather resembles the isothermal sphere Eq. (2) with $r_c \approx 4$ kpc, but the DM density is larger at $r < 2$ kpc as compared to the isothermal sphere. Therefore, one can use Eq. (2) with $r_c = 4$ kpc as a lower limit on the DM density when calculating fluxes from DM decays, and, therefore, for putting a conservative bound on the sterile neutrino mixing angle (e.g. the halo density at the Sun position in the model Eq. (2) is 0.25 GeV/cm^3, which is smaller than the accepted value 0.3 GeV/cm^3 [12]). Utilizing the NFW profile at all r can only strengthen the bounds.

In the model Eq. (2) the DM flux from the direction (b, l) (in galactic coordinates) into the solid angle $\Omega_{\rm fov} \ll 1$, measured by an observer on Earth is given by

$$F_{\rm MW}(\phi) = \frac{L_0}{R} \times \begin{cases} \frac{\pi}{2} + \arctan\left(\frac{r_\odot \cos\phi}{R}\right), & 0 \le \phi \le \frac{\pi}{2} \\ \arctan\left(\frac{R}{r_\odot |\cos\phi|}\right), & \frac{\pi}{2} < \phi \le \pi \end{cases}, \tag{3}$$

where $L_0 \equiv \frac{\Gamma \Omega_{\rm fov} v_h^2}{32\pi^2 G_N}$, $R = \sqrt{r_c^2 + r_\odot^2 \sin^2\phi}$, and $\cos\phi = \cos b \cos l$. For example, $F_{\rm MW}(90^\circ)/F_{\rm MW}(180^\circ) \simeq 1.52$.

Search for a preferred observation. Let us compare the Galaxy contribution to the DM decay flux, computed above, with those of other astrophysical objects.

(i) XRB. Although the DM has a very narrow radiative decay width, the cosmological DM decay contribution to the XRB gets significantly broaden due to the contributions from various red shifts. The resulting differential flux for $E < m_s/2$ is given by

$$\frac{d^2 F_{\rm XRB}}{dE\, d\Omega} = \frac{\Gamma}{4\pi H_0 m_s} \frac{\rho^0_{\rm DM}(2E)^{3/2}}{\sqrt{8E^3\Omega_\Lambda + \Omega_m m_s^3}}, \tag{4}$$

where $\rho^0_{\rm DM} = 1.2 \times 10^{-6}\,{\rm GeV/cm^3}$ is the average DM density in the Universe, Ω_Λ and Ω_m are the cosmological constant and matter contributions to the density of the Universe. The paper [5] looked at restrictions from XRB, assuming that DM is uniform up to very small z. This question was further addressed in [6, 7] and finally the most stringent constraint in the $(\sin^2 2\theta, m_s)$ plane from XRB was obtained recently in [8].

One can compare flux (4), integrated over all E with the galactic contribution: $F_{\rm MW}/F_{\rm XRB} = \mathcal{R}\, r_c H_0$, where $\mathcal{R} \sim \rho^0_{\rm MW}/\rho^0_{\rm DM} \sim 10^6$ is *overdensity* of the Galaxy as compared to the average density of DM in the universe. With $r_c \sim 4$ kpc, one arrives to the conclusion that $F_{\rm MW}/F_{\rm XRB} \sim 1$, i.e. Galactic contribution is *comparable* with the total DM decay flux from all red shifts.

However, for a modern X-ray instrument with good spectral resolution $\Delta E \ll m_s$ (e.g. XMM-Newton) one should compare contributions from the Galaxy and from uniform cosmological distribution into XRB within ΔE. The ratio $F_{\rm MW}/F_{\rm XRB}$ then gets enhanced by the factor $E/\Delta E$ which is $10 \div 50$ for EPIC cameras on board of XMM-Newton, i.e. for XMM the Galactic signal is 1 to 2 orders of magnitude *stronger* than the contribution from uniform distribution of DM in the universe.

(ii) Clusters. Let us now analyze the flux enhancement from Coma and Virgo clusters of galaxies [6, 10]. The DM distribution in these clusters can be approximated by *isothermal β-model* [13, 14]

$$\rho_{\rm cluster}(r) = \rho^0_{\rm cluster} \frac{3 + (r/r_{\rm cluster})^2}{(1 + (r/r_{\rm cluster})^2)^2}. \tag{5}$$

Integrating it according to Eq. (1) and using the fact that the Coma cluster is located perpendicularly to the Galactic plane, and has core radius $r_{\rm cluster} \simeq 0.3$ Mpc and central density $\rho^0_{\rm Coma} = 10^{-2}\,{\rm GeV/cm^3}$ (see e.g. [10] for discussion), we get $F_{\rm MW}(90^\circ)/F_{\rm Coma} \approx 0.25$. Similar estimate for the center of the Virgo cluster ($\rho^0_{\rm Virgo} \simeq 2.3\,{\rm GeV/cm^3}$, $r_{\rm cluster} \approx 10$ kpc) shows that Galactic contribution is $\sim 10\%$. Therefore, one could conclude that clusters are preferable objects for DM detection [6, 9].

These results have been recently reanalyzed by [10], where it was shown that the actual restriction from clusters is only by about a factor of 3–4 (in θ^2 for given m_s) better than those from XRB. The reason for such a modest improvement is the following. The detection of the DM decay line in galaxy clusters is complicated by the fact that most of them show strong emission precisely in keV range. Indeed, the virial theorem immediately tells us that the temperature of the intercluster medium is $T_{\rm gas} \sim G_N\, m_p\, \mathcal{R} \rho^0_{\rm DM} d^2$, where d is characteristic size. For overdensity $\mathcal{R} \sim 10^3$ and size $d \sim 1$ Mpc, the temperature $T_{\rm gas}$ is always in the keV range, which makes it hard to detect a DM decay line against a strong X-ray continuum.

(iii) Dwarf galaxies. There should be an enhancement of the flux in directions of dwarf spheroidal galaxies, which are satellites of the MW. Promising satellites with large mass to light ratio are Draco and Ursa Minor. Density profiles of both galaxies can be modeled by the isothermal sphere with $v_h \approx 22$ km/s and $r_c \approx 100$ pc [15]. This gives for the contribution to the flux from the dwarf galaxy (along the line which passes through the core of the satellite) $\int \rho\, dr \approx 3.3 \times 10^{22}\,{\rm GeV/cm^2}$.

Contribution of the Galaxy halo flux in directions of both satellites $\approx 1.0 \times 10^{22}\,{\rm GeV/cm^2}$. Therefore, in directions of both satellites the 4-fold local enhancement of the flux is expected, while the total flux matches the flux from the central region of the MW and the flux from clusters. The advantage of observing the dwarf satellites, as compared to clusters or to the Galactic center, is lower level of X-ray background contamination and clear signature of the signal, namely, local flux enhancement within single field of view of X-ray telescope.

Therefore, we see that the local DM halo (especially dwarf satellite galaxies) can provide *the strongest restriction* on the parameters of the sterile neutrino as DM candidates.

Restrictions from local halo DM contribution.

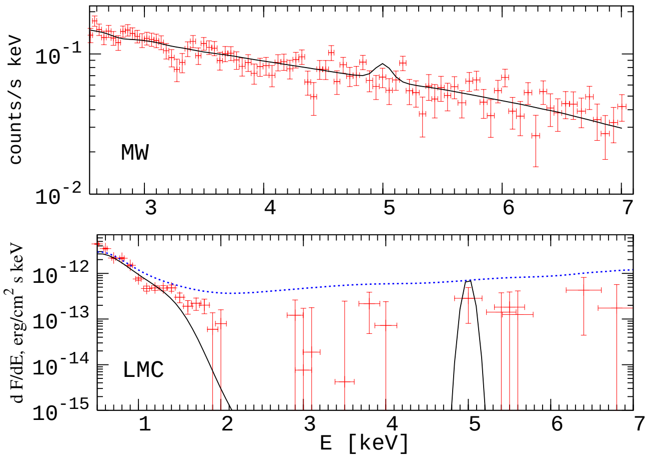

FIG. 1: Upper panel: Method used to obtain restrictions on DM decay in MW from blank sky XRB observations. The data is fitted by a power law (reduced $\chi^2 = 1.07$ for 82 d.o.f.) and `XSPEC v11.3.2` is used to put a 3σ limit on the presence of DM line (via command `"error <line norm> 9.0"`).
Lower Panel: Method used to obtain restrictions from LMC. Flux rapidly decreases for $E \gtrsim 2$ keV, most of the data points at higher energies are zero within statistical uncertainty. The solid green line is the sum of the total flux plus 3σ per energy bin. At $E \gtrsim 2$ keV the bound is dominated by errors and therefore can be improved significantly by increasing statistics.

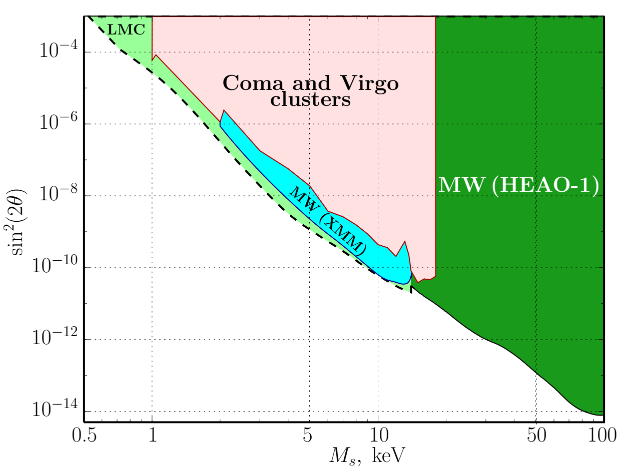

FIG. 2: 3σ restrictions on DM decay line from Milky way halo (XMM and HEAO-1 observations). Dashed line: total flux + 3σ restriction from LMC. Also shown the previous strongest limit from the clusters of galaxies [10].

We have analyzed XMM blank sky observations of [16] (exposure time $\sim$ 200 ksec), taking into account MW contribution and putting a 3σ bound on the DM line flux in the region $1\,\text{keV} < E < 7\,\text{keV}$ (FIG. 1). The exclusion plot in the region $m_s > 6$ keV was obtained by using the HEAO-1 measurements of XRB [17]. As spectral resolution of HEAO-1 is about 25%, the resulting correction due to MW is not so drastic as compared to the results of Ref. [8].

Unfortunately, X-ray observations of Draco and Ursa Minor dwarfs are not available currently. However, approximately the same signal is expected from the Large Magellanic Clouds (LMC) albeit with larger uncertainties. Using isothermal sphere, with the following halo parameters, $v_h \approx 50$ km/s and $r_c \approx 1$ kpc [18], we obtain $\int \rho\, dr \approx 2.8 \times 10^{22}$ GeV/cm^2 for the LMC contribution, while MW halo contribution in the direction of LMC is again $\approx 1.0 \times 10^{22}$ GeV/cm^2 (the use of the NFW profile gives even larger value for flux).

Therefore, as an illustration we have processed one of the observations of the LMC (XMM obs ID: 0127720201, exposure $\sim$ 20 ksec). Subtracting the blank sky background [16], one sees that the flux is zero within statistical uncertainty for $E \gtrsim 2$ keV. Similar reduction of the background is expected for dwarf satellites. In this situation we put an upper limit on the flux of the DM decay line, by demanding it to be smaller than total flux plus its 3σ error in an energy bin equal to spectral resolution, see Fig.1. One can see that increasing the exposure time, one can significantly lower the restriction especially in the region $E \gtrsim 2$ keV.

Discussion. In this paper, we have shown that the best objects for the search of the DM with radiative decay channel is the MW halo, including dwarf satellite galaxies (e.g. Draco and Ursa Minor). To illustrate this, we put the strongest restrictions on parameters of sterile neutrino *(i)* searching for the MW DM decay signal in the blank sky XRB; *(ii)* using LMC observations. One can see that improving statistics one can significantly improve bounds from such objects. Our analysis also shows that improvement of the spectral resolution of X-ray instruments (even by means of decreasing imaging capabilities) is crucial to continue the search of DM decay line.

Of course, all constraints on the sterile neutrino mixing angle, derived from X-ray observations, suffer from the uncertainties in the DM profiles. However, in our analysis we tried to be as conservative as possible. Namely, we present only the results coming from the study of directions which are away of the Galactic center. In this case the most relevant parameter, which influences the line of sight integral Eq. (1) is v_h, corresponding to the contribution of the DM halo to the Galactic rotation curve at large distances, away form the core. The total (DM plus baryons) rotational curve is measured directly. Although the subtraction of the baryon contribution is model dependent, this dependence is weakest for the directions opposite to the Galactic center.

Moreover, we have found, quite remarkably, that the line of sight integral Eq. (1) is roughly the same for all studied DM dominated objects, from cosmological background to clusters of galaxies to dwarfs satellites. This suggests that the expected DM decay signal should be roughly the same for all of them. Better constrains are obtained for the objects whose X-ray background is lower. This makes dwarf satellites more suitable as compared to clusters. In addition, in the most DM dominated satellites, such as Draco and Ursa Minor, not only the X-ray background is lower, but uncertainties due to subtraction of baryonic component from the galactic rotational curve are also minimized. The restrictions, based on the different (types of) objects, further minimize these uncertainties.

The limits we derived here allow to strengthen the bounds on sterile neutrinos in different models of particle physics, shed light on the possible mechanisms of their production in the early universe, and constrain different astrophysical phenomena that might be related to their existence.

(i) In the Standard Model with addition of just one sterile neutrino (assuming the absence of sterile neutrinos above the temperature ~ 1 GeV and charge neutrality of the plasma) the relic abundance of sterile neutrinos can be expressed through m_s and θ [1]. This relation (quite uncertain, since the sterile neutrinos are mainly produced at temperatures $\mathcal{O}(150)$ MeV, exactly where the description of the strongly interacting plasma is most complicated [20]) allows one to find, potentially, an upper limit on the sterile neutrino mass in this particular scenario. Taking as a rough estimate the computation of [9] and our X-ray constraints we arrive to an upper bound $m_s \lesssim 3$ keV. This may be contrasted with the lower bound on the mass of sterile neutrino (derived in the same model with the same assumptions) coming from the analysis of the Ly-α forest data [21]: $m_s > 2$ keV [22], $m_s > 1.7$ keV [23] leaving a very limited allowed mass range for a sterile neutrino. If a more recent result of [24], $m_s > 14$ keV is proven to be correct, and uncertainties related to poor knowledge of QCD at the relevant range of temperatures happen to be not substantial, this scenario will be ruled out by cosmological and astrophysical observations. The same conclusion is true [25] for the νMSM if the same assumptions about the initial state are taken for granted. This would make the production mechanisms of the sterile neutrinos related to inflation [26] or large lepton asymmetries [27] more important.

(ii) The X-ray observations allow to predict the masses of active neutrinos in the νMSM. In [19] was shown, that the XRB limits of [8] imply that the lightest active neutrino must have a mass $m_\nu < 3 \times 10^{-3}$, provided $m_s > 1.8$ keV. In case of normal hierarchy two other masses are given by the observed mass square differences $\sqrt{\Delta m^2_{\rm solar}} \simeq (8.5 - 9.5) \times 10^{-3}$ eV and $\sqrt{\Delta m^2_{\rm atm}} \simeq 0.04 - 0.06$ eV. (In the case of inverted hierarchy masses of both neutrinos are $\sqrt{\Delta m^2_{\rm atm}}$). With the improved bound, derived in this paper, this result is true for even smaller sterile neutrino masses, $m_s > 1.3$ keV.

(iii) Our constraints, combined with those of [24], put severe bounds on explanation of pulsar kick velocities by dark matter sterile neutrinos, proposed in [28] and on the mechanism of early reionization by radiative decays of sterile neutrinos, suggested in [29].

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Note added. After finishing this paper we became aware of an independent analysis, where the possibility of measuring decaying DM particles from our Galaxy, using Chandra blank sky data, was considered [30]. The conclusions, reached in that paper on MW, are similar to ours.

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