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All-sky Limits on Sterile Neutrino Galactic Dark Matter

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Dark matter sterile neutrinos radiatively decaying in the Milky Way, which can be tested with searches for almost monochromatic photons in the X-ray cosmic spectrum. We analyse the data of the SRG/ART-XC telescope operated for two years in the all-sky survey mode. With no significant hints in the Galactic diffuse X-ray spectrum we explore models with sterile neutrino masses in the 12-40 keV range and exclude corresponding regions of sterile-active neutrino mixing. We also discuss the limits that can be obtained in the framework of the correlation analysis and data from SRG mission.

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1. Introduction

The nature of dark matter is one of the most pressing issues in modern fundamental physics. As is known, dark matter reveals itself only through gravitational interaction, and today there is not enough confirmed data revealing the non-gravitational nature of dark matter. However, there continues to be an active search for dark matter particles that could potentially be detected beyond gravitational interactions alone. One of these particles are the so-called sterile neutrinos [1–3]. These particles appear in many extensions of the Standard Model of particle physics and are used to explain various anomalies that currently cannot be explained within the Standard Model. Sterile neutrinos cannot be directly detected in modern experiments, however, due to the fact that sterile neutrinos can mix with active neutrinos or decay into active neutrinos and photons, they can be detected by observations of active neutrinos or traces of such decays in astrophysical observations. For example, traces of such decays, previously observed in X-ray spectra at an energy near 3.5 keV, were discussed in [4, 5] and [6–8]. Thus, searches for the monochromatic line in cosmic X-rays, presumably driven by sterile neutrino decays, remain useful and promising for revealing the nature of dark matter or setting even more stringent constraints on the parameters of sterile neutrino decays.

Here we focus on specific candidates for dark matter particles, namely sterile neutrinos, which, due to mixing with active neutrinos, can decay into an active neutrino (electron, muon, or tau neutrino) and a photon

$$\nu_s \longrightarrow \nu_{e,\mu,\tau} + \gamma. \tag{1}$$

The decay width of a sterile neutrino in this process is given by the following expression [9, 10]

$$\Gamma_{\nu_s} = \frac{9}{1024}\frac{\alpha}{\pi^4}G_F^2 m_{\nu_s}^5 \sin^2 2\theta = 1.36\times 10^{-22}\left(\frac{m_{\nu_s}}{1\text{keV}}\right)^5 \sin^2 2\theta \quad \text{s}^{-1}, \tag{2}$$

where m_{ν_s} is the mass of the sterile neutrino, θ is the mixing angle between active and sterile neutrino, where we do not distinguish between the mass and flavor eigenstates at small mixing angles. In this two-particle decay, the energy of the emitted photon is $E_\gamma = m_{\nu_s}/2$, and the sterile neutrinos that form galactic dark matter produce a monochromatic photon spectrum with a width on the order of the speed of dark matter particles in the galaxy.

We consider constraints on the parameters of decaying sterile neutrinos that can be obtained in X-ray observations of the Milky Way by the SRG mission telescopes. Namely, we demonstrate constraints on the parameters of such particles, which were obtained by the SRG/ART-XC telescope in the sterile neutrino mass range of 12 - 40 keV during a two-year all-sky survey.

2. Galactic dark matter constraints

In July 2019, the space observatory Spektr - Roentgen - Gamma (SRG) [11] was launched. SRG mission is X-ray observatory was designed to obtain a deep X-ray map of the Universe in a wide energy range from ~ 0.2 to 30 keV, with two X-ray telescopes SRG/ART – XC [12] and SRG/eROSITA [13] on board. The characteristics of the SRG observatory make it an excellent tool for studying decay traces from sterile neutrinos in the keV mass range.

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Assuming that sterile neutrinos form galactic dark matter, we can estimate the photon flux from sterile neutrino decays in the Galaxy as follows:

$$F_\gamma = \frac{1}{7.88\times10^{-4}}\left(\frac{S_{DM}}{\mathrm{M_\odot pc^{-2}}}\right)\left(\frac{2E_\gamma}{1\,\mathrm{keV}}\right)^4 \sin^2(2\theta)\quad \frac{\mathrm{cts}}{\mathrm{cm^2\ s}}.$$

The value of S_{DM} can be calculated in various ways, taking into account the specific type of dark matter density distribution profile. We consider the case when the distribution of dark matter density in the halo depends only on the absolute radius - the vector from the center of the halo to a given point. In this case, in galactic coordinates (b, l), the quantity S_{DM} has the form

$$S_{DM} = \int_{b_1}^{b_2}\int_{l_1}^{l_2}\int_0^{R_{cut}} \frac{\rho_{DM}(r)}{z^2} z^2 \sin\left(\frac{\pi}{2} - b\right) \mathrm{d}z\mathrm{d}b\mathrm{d}l, \tag{3}$$

where (b_1, b_2), (l_1, l_2) are the integration limits that determine the size of the selected area in the sky, R_{cut} is the cutoff scale, which usually corresponds to the virial radius. Note that the result of integration weakly depends on the upper limit if it is equal to or slightly larger than the virial radius. z is the distance along the line of sight from the observer to a given object, $\rho_{DM}(r)$ is the dark matter density profile, $r = \sqrt{z^2 + r_{g.c.}^2 - 2r_{g.c.}z\cos b\cos l}$ is where $r_{g.c.}$ is the distance from the observer to the center of the Milky Way.

To estimate the signal flux, we need to know the dark matter density distribution for each object that is the source of the photons under study. This quantity is not fixed and is not measured directly, so there are significant uncertainties in estimates of the distribution of dark matter density in galaxies. To describe the distribution of dark matter density in the Milky Way galaxy, we use the standard NFW profile [14]

$$\rho(r) = \frac{\rho_s}{(r/r_s)\,(1 + r/r_s)^2} \tag{4}$$

and the parameters given in [15]: $\rho_s = 10.5\times10^{-3}$ $\mathrm{M_\odot pk^{-3}}$ and $r_s = 20$ kpc, $r_{g.c.} = 8$ kpc. Since, as noted above, there is a noticeable scatter in estimates of dark matter density profiles, it is worth illustrating the uncertainties in the geometric factor S_{DM} associated with the dispersion of the dark matter density profile. In [16] we present various dark matter density profiles for the Milky Way galaxy and show variations in the profile depending on model parameters.

In the work [16] the sensitivity of the SRG/eROSITA and SRG/ART-XC telescopes was assessed to search for traces of the decay of sterile neutrinos and expected constraints on the parameters of sterile neutrinos that can be obtained by observing the center of the Milky Way in a cone were obtained with a very wide opening angle. The work [17] improved the search strategy presented in [16] using survey operation mode to get rid of the possibly time-dependent isotropic X-ray background.

The main idea of searching for traces of decay is as follows. In the energy range of the ART-XC telescope (6 – 30 keV) there are two sources of diffuse X-ray radiation. The first contribution is CXB and the second is GRXE. The first contribution is fairly uniform across the sky, but has temporal variations, and the second contribution is cut out. There is also an internal background of the telescope. Thus, in order to get rid of short-term fluctuations of the detector parameters, we subtract the normalized X-ray fluxes in the direction towards the center of the Milky Way with a cone opening angle of 60 deg^2 ($\Omega^{in} \sim 9040$ deg^2) and the rest of the sky beyond these 60 deg^2

($\Omega^{out} \sim 27600$ deg^2). We perform the same operation for the dark matter contribution towards the center and anti-center. And we will study the contribution of the difference in signals from dark matter in both directions to this background difference (for more details, see [17]). For this purpose, data collected by ART-XC from December 12, 2019 to December 19, 2021 is used, which produces four complete all-sky X-ray maps in the energy range 6-20 keV. As follows from the results of the analysis, we do not find a convincing signal from traces of the decay of sterile neutrinos and set limits for the masses of sterile neutrinos in the range from 12 keV to 40 keV. The results of our analysis, together with current constraints on the parameters of sterile neutrinos, are presented in Fig. 1 and in [17].

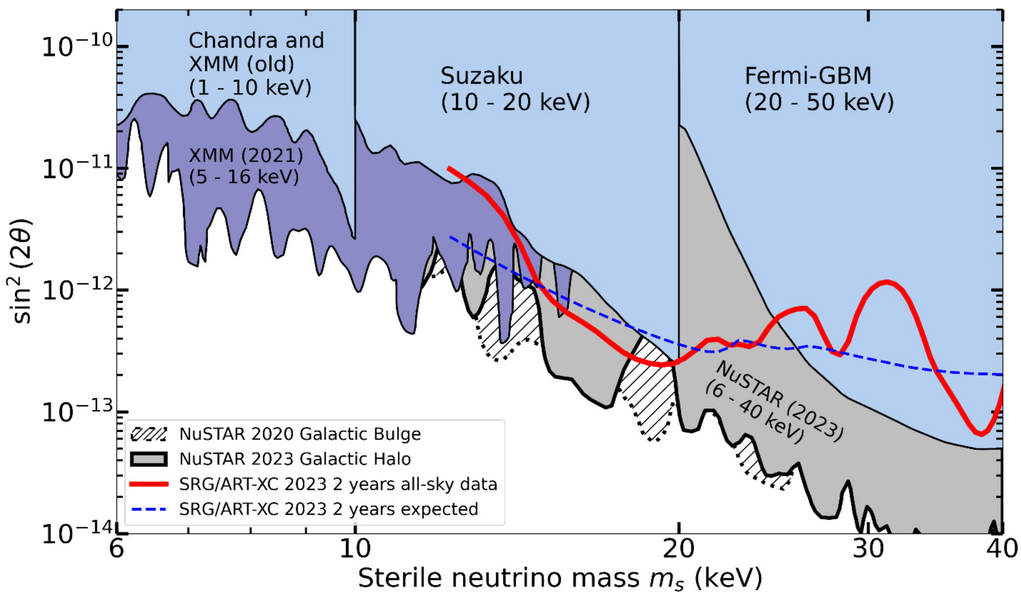

Figure 1: Upper limits on mixing (95%,C.L.) from 2 years of data taking at ART-XC in the survey mode are depicted with red solid line and previous X-ray constraints [17]. The blue dashed line refers to the expected 2-year sensitivity of ART-XC. Note, that the expected sensitivity does not contain statistical fluctuations observed in real data. Black solid line with gray shading show limits recently obtained with the NuSTAR in the Galactic halo [18]. And black dotted line with hatching show limits obtained in Galactic bulge [19] with NuSTAR.

Alternatively, it is possible to constrain the parameter space of decaying (annihilating) dark matter from a correlation analysis of various signatures [20, 21], [22, 23], [24–28]. For this purpose, an approach is used based on the study of auto and cross - correlation angular power spectrum of various signatures across the sky. As part of this analysis, for each signature pair (DM - DM, Galaxies - Galaxies, DM - Galaxies), a nonlinear power spectrum is calculated (We use the HaloModel and HOD model for these calculations), and then the auto and cross – correlation angular power spectrum are calculated for all signature pairs. The resulting model spectrum is then compared with the measured correlation spectrum, taking into account uncertainties from the X-ray background and the contribution of uncertainties from given signatures. Thus, correlations are sought between the power spectra of various structures and photons caused by the decays of sterile neutrinos.

Following the analysis presented in [22, 23], we show that our expected constraints are in good agreement with the results of previous work for the eROSITA telescope [22, 23]. We also demonstrate the expected limits on the parameters of sterile neutrinos that can be obtained from the ART-XC telescope. The results of our analysis are presented in Fig.2 and [29]. We also note that the presented expected constraints within the framework of the correlation analysis for the eROSITA telescope are roughly consistent with the constraints presented in [30].

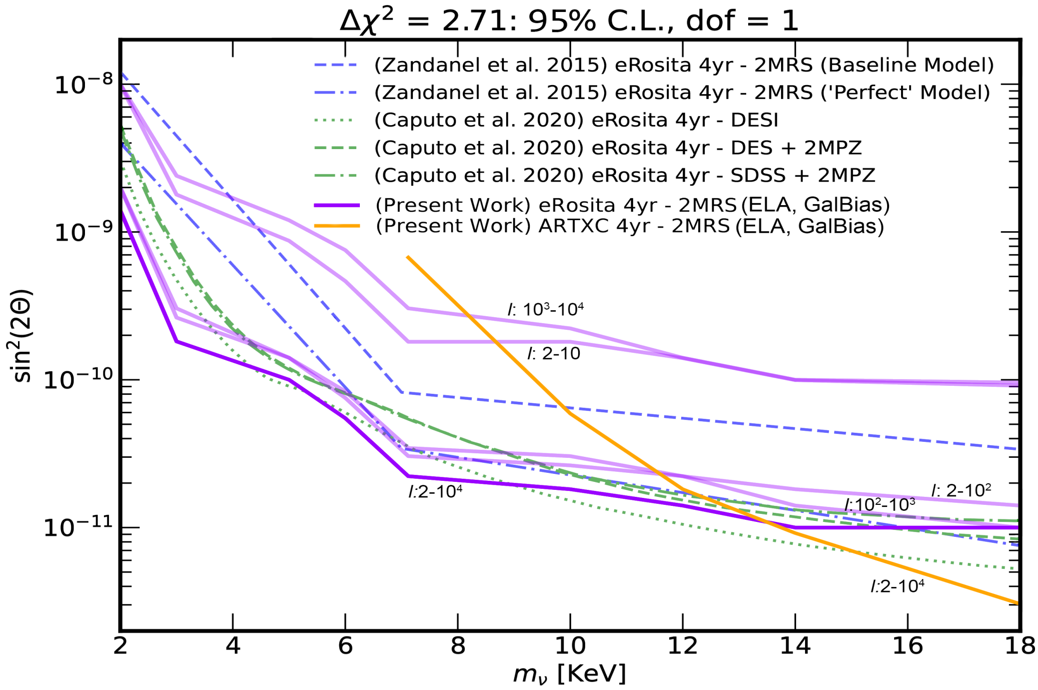

Figure 2: Expected constraints on the parameters of sterile neutrinos obtained in the framework of our analysis for various ranges of multipoles [29]. The purple line corresponds to the constraints for the eROSITA telescope (the translucent purple lines show the contributions to the constraints for different ranges of multipoles). The yellow line corresponds to the ART-XC telescope. For comparison, the constraints from the works [22, 23] are presented. The observation time is 4 years in the full sky survey mode.

3. Conclusion

The presented galactic constraints on the parameters of sterile neutrinos in the mass region of several keV, as well as current constraints from other X-ray observations, impose strong limits.

Taking into account new data that can be obtained after 4 years of observations during SRG/ART-XC mission, collected data from the SRG/eROSITA, and the high exposure data of the NuSTAR telescope, we hope to significantly improve the constraints on the parameters of sterile neutrinos in the near future.

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