Towards Testing Sterile Neutrino Dark Matter with SRG Mission

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We investigate the prospects of the SRG mission in searches for the keV-scale mass sterile neutrino dark matter radiatively decaying into active neutrino and photon. The ongoing all-sky X-ray survey of the SRG space observatory with data acquired by the ART-XC and eROSITA telescopes can provide a possibility to fully explore the resonant production mechanism of the dark matter sterile neutrino, which exploits the lepton asymmetry in the primordial plasma consistent with cosmological limits from the Big Bang Nucleosynthesis. In particular, it is shown that at the end of the four year all-sky survey, the sensitivity of the eROSITA telescope near the 3.5 keV line signal reported earlier can be comparable to that of the XMM-Newton with all collected data, which will allow to carry out another independent study the possible sterile neutrino decay signal in this area. In the energy range below ≈ 2.4 keV, the expected constraints on the model parameters can be significantly stronger than those obtained with XMM-Newton. From ART-XC data, in the energy range approximately from 5 to 20 keV, it can be possible to get more stringent constraints than those obtained with NuSTAR so far. We conclude that the SRG mission has a very high potential in testing the sterile neutrino dark matter hypothesis.

I. INTRODUCTION

The recently launched Spectrum-Roentgen-Gamma space observatory (Spektr-RG or SRG, [1]), carrying two X-ray telescopes on board, ART-XC [2,6] and eROSITA [7,8], is expected to contribute considerably to cosmology by investigating cosmic large scale structure properties associated with galaxy clusters [7,10], providing a major improvement in cosmological constraints as compared to the results from earlier X-ray, Sunyaev-Zeldovich and optical galaxy cluster surveys, e.g., [11-13]. While these studies can further refine the parameters of Standard Cosmological Model (presently, ΛCDM), the SRG has also high potential in testing specific particle physics models of dark energy and dark matter. Notably, dark matter particles decaying or annihilating with keV-scale photons in the final state can be probed with eROSITA (energy range 0.2–10 keV) and ART-XC (4–30 keV) X-ray telescopes aboard SRG.

In this paper we concentrate on a particular candidate of dark matter — sterile neutrinos — unstable because of mixing with active neutrinos and consequently exhibiting a two-body radiative decay into active neutrino (electron, muon or tau neutrino) and photon

$$\nu_s \rightarrow \nu_e, \mu, \tau + \gamma$$

with decay rate [14]

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

(2)

where $m_s$ is the sterile neutrino mass, and $\theta$ is the sterile-active mixing angle. The outgoing photon energy is $E_\gamma = m_s/2$, and for sterile neutrinos forming galactic dark matter the expected photon spectrum is highly monochromatic with width of order the velocity of the dark matter particles in the galaxy, i.e. $\nu \sim 10^{-4} - 10^{-3}$. This suggests a signature in the galactic photon spectrum to be searched for by the X-ray telescopes.

Sterile neutrinos are Majorana fermions, singlet with respect to the gauge group of the Standard Model of particle physics (SM). The introduction of sterile neutrinos into particle physics is motivated primarily by their contribution to the active neutrino masses coming (after electroweak symmetry breaking) from Yukawa-type interactions with the SM Higgs doublet and lepton doublets. To provide all the three active neutrinos with masses, one needs at least three sterile neutrinos, but the lightest (or fourth, fifth, etc) can be sufficiently feebly coupled and hence long-lived to form dark matter, see Refs. [15, 16] for a review. Naturally, this strong physical motivation makes the model very attractive phenomenologically [17] and the suggested signature has been exploited by X-ray telescopes to explore the relevant part of model parameter space $(m_s, \theta)$. The absence of monochromatic photons of a given frequency implies an upper limit on the mixing angle at the sterile neutrino mass equal to the double photon frequency provided by eq. (2). The latest results are from NuSTAR experiment, see Fig. [1]

As a component being in thermal equilibrium with pri-
FIG. 1. Constraints on the parameters of sterile neutrinos adopted from Ref. [18]. The green color indicates the allowed region of sterile neutrino parameters space consistent with both X-ray searches and cosmological limits from Big Bang Nucleosynthesis. The red color shows the energy range \( E_\gamma = m_s/2 \) covered by the eROSITA telescope; the blue shows the energy range covered by the ART-XC telescope; the purple refers the overlapping region of the energy ranges of these two telescopes.

mordial plasma in the early Universe, the sterile neutrino making all dark matter is not suitable, because of the same (qualitatively) problems with cosmic structure formation, as active neutrinos have. However, they can be produced non-thermally by active neutrinos oscillating in the primordial plasma, that works with relatively small mixing. Note, that the simplest case, where the mixing is in one-to-one correspondence with the relic sterile neutrino abundance [19], has been already excluded [16]. Nevertheless, for the efficient production of sterile neutrino in the early Universe much smaller mixing (below upper X-ray limits on \( 2 \)) is still sufficient in cosmological models with lepton asymmetry in the primordial plasma [20] or physical model extensions, see, e.g., Refs. [21–23] for scalars coupled to sterile neutrinos. Along with particle physics motivations, these model extensions are supported by a feature at near 3.5 keV, that claimed to be observed in spectra of several dark matter dominated astrophysical objects [e.g., 10, 24, 25] (see, however, 20, 28). Therefore, hunts for a monochromatic line in cosmic X-rays, presumably initiated by decays [1], remain worthwhile and promising as to reveal the nature of dark matter. In this paper we estimate the sensitivity of SRG telescopes to the models with sterile neutrino dark matter.

If dark matter consists of the decaying sterile neutrinos, then we expect to observe correlated signal fluxes from various dark matter dominated astronomical objects. In this paper, we consider the Galactic Center (GC), the Andromeda Galaxy (M31), and the Draco dwarf Galaxy (DdG) as possible sources of the monochromatic photons. This choice is motivated by investigations based on analysis of previous generation X-ray telescopes, which found them as most prospective sources of the monochromatic line and scrutinize their dark matter structure.

II. EXPECTED SIGNAL

Assuming that the sterile neutrinos form (a part of) galactic dark matter, we can estimate the photon flux from decays [1] in a nearby source as follows,

\[
F_{DM} = \frac{1}{4\pi} \frac{\Gamma_\gamma}{m_s} S_{DM}. \tag{3}
\]

Here \( S_{DM} \) is the sterile neutrino dark matter column density along the line of sight in the given field of view (FOV) [20, 30]

\[
S_{DM} = \int_0^{2\pi} \int_0^{\psi_r} \int_{l_{min}}^{l_{max}} \rho_{DM}(r(l, \psi)) l^2 \sin \theta d\phi d\psi dl, \tag{4}
\]

where \( \psi_r \) is the FOV radius of telescope, \( \rho_{DM}(r(l, \psi)) \) is the dark matter density profile and \( r(l, \psi) = \sqrt{R_{GC}^2 - 2R_{GC}l \cos \psi + l^2} \), \( R_{GC} \) is the galactic center distance for Milky Way (MW) or dark halo center distance for other far objects (nearby galaxies or galaxy clusters), \( l \) is the distance along the line of sight \( ^1 \) see Fig. 2. Thus, the photon flux from the sterile neutrino decays

\[ ^1 \text{For MW we set } l_{min} = 0 \text{ and } l_{max} \approx R_{GC} + R_{vir} \text{ and for other far objects we set } l_{min} \approx R_{GC} - R_{vir} \text{ and } l_{max} \approx R_{GC} + R_{vir}. \text{ Multiplying } R_{vir} \text{ by factor of two in these formulas changes the expected flux by less than one per cent for M31 and about ten per cent for DdG.} \]
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\[ 1 \]

\( F_{DM} = \frac{1}{7.882 \times 10^{-4}} \left( \frac{S_{DM}}{\text{M}_{\odot}\text{pc}^{-2}} \right) \]
\[ \times \left( \frac{2E}{1 \text{ keV}} \right)^{4} \sin^{2}2\theta \times \frac{\text{cts}}{\text{cm}^{2} \text{s}}. \]  

To evaluate the signal flux, we need to know the dis-

tribution density of dark matter for each object, source

of the photons, under study. This quantity is neither

fixed from the theory, nor directly measured, and so has

many uncertainties. However, they are not so dramatic

for the decay signal, as compared to the annihilation

do dark matter particles, which signal is proportional

to squared dark matter density. In our study, for MW

and for M31, we use the standard NFW profile: \( \rho(r) = \rho_{s}/(r/r_{s})^{2} \) \[31\]. For MW, we use the param-

eters given in Ref. \[32\], where the values of the scale

density and scale radius are \( \rho_{s} = 10.5 \times 10^{-3}\text{M}_{\odot}\text{pc}^{-3} \)

and \( r_{s} = 20 \text{kpc} \), respectively, \( R_{GC} = 8 \text{kpc} \) and \( R_{\text{vir}} = 200 \text{kpc} \) \[33\]. For the M31 halo, we use the parameter values from \[34\], where \( \rho_{s} = 11.0 \times 10^{-3}\text{M}_{\odot}\text{pc}^{-3} \)

and \( r_{s} = 16.5 \text{kpc}, \) \( R_{GC} = 780 \text{kpc} \) and \( R_{\text{vir}} = 207 \text{kpc} \) \[35\]. The matter density distribution in Draco galaxy is well

described by \( \rho(r) = \rho_{s}/(r/r_{s})^{\gamma}(1 + (r/r_{s})^{\alpha})^{(\beta-\gamma)/\alpha} \), with parameters \( \rho_{s} = 18.2 \times 10^{-3}\text{M}_{\odot}\text{pc}^{-3}, \) \( r_{s} = 3.72 \text{kpc}, \)

and \( (\alpha, \beta, \gamma) = (2.01, 6.34, 0.71) \) and \( R_{GC} = 76 \text{kpc}, \) \( R_{\text{vir}} = 1.87 \text{kpc} \) \[36\].

Using the latest constraints on the parameters of ster-

eile neutrinos presented in \[18, 37\], we estimate the possi-

ble signal flux from these objects, and also evaluate the

ecessary time of observation of these objects by \( \text{SRG} \)

to strengthen the existing constraints, and to check the

dark matter explanation of the 3.5 keV line.

III. SRG-X-RAY TELESCOPES

The Spectrum-Roentgen-Gamma (\( \text{SRG}, \[1\] \)) is a Rus-

sian X-ray observatory created with participation of Ger-

many, launched in July, 2019 and designed to produce

deep X-ray map of the Universe in a wide, 0.2–30 keV, energy range. Its scientific payload consists of two X-

ray telescopes — \( \text{ART-XC} \) \[2–5\] and \( \text{eROSITA} \) \[7, 8\],

build in Russia and Germany respectively. A map of the large scale structure of the Universe including more than

a hundred thousand clusters of galaxies will be outlined.

At the end of the main survey mission (four years of op-

eration), the telescope will be switched to the pointed

observations of selected objects (two years), which will

allow one to explore the most interesting X-ray sources

in more detail. In particular, using these data, it will

be possible to use the spectra of various astrophysical

objects to search for the peak signature of dark matter

radiative decays.

The \( \text{SRG} \) observatory revolves with a six-month pe-

riod around the second Lagrange point (L2) of the Sun –

Earth system, located at the distance of approximately

1.5 million km from Earth, in an elliptical non-closed or-

bit with 0.75 million km and 0.25 million km semiaxes.

In the survey mode the telescope pointing axis is con-

tinuously rotated approximately around the direction to

Earth and Sun, therefore, due to this observing strategy

the entire celestial sphere is covered during six month

period, and eight full scans of the celestial sphere will

be performed at the main four year stage of operation. The

full field of view of the \( \text{eROSITA} \) telescope is 0.8 deg\(^2\) and

for \( \text{ART-XC} \) is around 2 deg\(^2\) (in telescope+concentrator

mode, see \[5\]). This means that the total average expo-

sure time for any part of the sky will be about 2500 s and

6100 s (uncorrected for vignetting). Note that by the end

of the survey mission, the largest exposure is expected in

the region of the ecliptic poles, since for each revolution

the telescope axis passes near these poles.

In the survey mode, the most important parameter

characterising the ability to cover a large part of the sky

is “grasp”, which is defined as the product of the effective

area of the telescope and the angular area of its field

of view corrected for vignetting. Grasps for \( \text{eROSITA} \)

and \( \text{ART-XC} \) telescopes on board \( \text{SRG} \) observatory are

shown in Fig. \[3\] in comparison with those of \( \text{XMM-Newton} \)

\[39\] and \( \text{NuSTAR} \) \[40\] telescopes, currently used to

search for sterile neutrino dark matter radiative decay

signatures. The grasp for \( \text{XMM-Newton} \) was calculated

using PN, MOS1 and MOS2 effective area and vignetting

taken from \( \text{XMM-Newton Users Handbook} \). The grasp

for \( \text{NuSTAR} \) shown in Fig. \[3\] is calculated for a stray-light

aperture, used in case of \( \text{NuSTAR} \) data for the sterile

neutrino DM decay searches. The lower and upper

curves represent average \( \text{NuSTAR} \) side aperture (or stray-light)

grass inferred from the \( \text{NuSTAR} \) observations in the GC

\[35\] and Bulge \[18\], where the most recent DM decay

constraints were achieved. The average \( \text{NuSTAR} \) grasp

is multiplied by the energy-dependent efficiency for pho-
tons to pass through the NuSTAR detector beryllium shield. The difference in the NuSTAR grasp estimations is mainly explained by a strong stray-light contamination of bright sources in the GC. In the Galactic Bulge observations, NuSTAR stray-light aperture contamination from the X-ray background is minimised, however the expected DM signal is also lower compared to that from the GC due to the smaller amount of DM integrated over the line of sight. Note that the total effective exposure available for the NuSTAR DM studies in the GC [5] and Bulge [18] is ≈200 and ≈100 ks, respectively.

From Fig. 3 we see that the grasp of SRG/eROSITA telescope significantly supersedes that of XMM-Newton at the energies below ≈2.2 keV. At higher energies the grasps of the telescopes aboard SRG are comparable to those of XMM-Newton and NuSTAR. Therefore, the main difference in DM decay flux constraints at these energies between SRG/eROSITA and SRG/ART-XC telescopes as compared to XMM-Newton and NuSTAR, will arise due to the difference in exposures used to observe the source. As we show below, in cases of observations of the dark matter halo of our Galaxy, with the SRG telescopes it will be possible to collect the data with much higher exposures than what were used to constrain the sterile neutrino DM from XMM-Newton and NuSTAR data.

For the reliable signal detection, it is necessary to know the energy dependence of the background flux. Estimates of the expected number of events for the eROSITA and ART-XC telescopes obtained by modelling the background signal and ground calibrations, as well as based on observational data from earlier missions are presented in [3, 5]. The background of SRG/eROSITA telescope is dominated by Cosmic X-ray Background (CXB) all over the sky and, additionally, by the Galactic Ridge X-ray Emission [41–44] when pointed towards Galactic plane and bulge. For the estimates below we adopt the results of eROSITA background calculations from Ref. [8], taking into account actual particle background level measured in-orbit [5], which appears to be approximately 4 times higher than that predicted before the launch. Additionally, we calculated the contribution from the Galactic Ridge X-ray Emission based on the near-infrared stellar mass model from Ref. [10] and 3–20 keV Galactic ridge X-ray emissivity per unit stellar mass from Ref. [11]. The background flux for the ART-XC telescope is dominated by charged particle background in L2, which was estimated to be between $10^{-3}$ and $10^{-2}$ cts s$^{-1}$ cm$^{-2}$ keV$^{-1}$ before the launch of the SRG see e.g. [17]. In the calculations below we adopt the flat particle background spectrum, with the spectral flux density equal to the average of the two estimates above, $5 \times 10^{-3}$ cts s$^{-1}$ cm$^{-2}$ keV$^{-1}$ [5], which appears to be very close to the actual ART-XC background measured in orbit [11, 6].

We also assume that the sterile neutrino DM decay flux is detected in a bandwidth equal to the energy resolution FMHM of the corresponding telescope, which are taken from [8] for SRG/eROSITA and from [3] for SRG/ART-XC and are summarized in Table I.

| Field of view (FOV) [deg$^2$] | eROSITA | ART-XC |
|-----------------------------|---------|--------|
| 0.31                        | 0.3 - 2.0 |
| 1.7                        | 0.3 - 2.0 |
| 2.0                        | 0.3 - 2.0 |

* FOV [deg$^2$]: Telescope 0.31, Concentrator 1.7, Full 2.0 [3, 5].

IV. EXPECTED CONSTRAINTS ON THE DARK MATTER DECAY FLUX

The existing constraints on the parameters of sterile neutrinos, presented in Ref. [18], can be used to estimate the ranges of possible signal flux from decays of resonantly produced dark matter sterile neutrino to be observed by the SRG mission. For this purpose, we calculate the photon flux from decays of sterile neutrinos in the central part of MW, in M31 and Draco. For the center of the Galaxy we calculate the signal flux in the cone of radius corresponding to 1.5° and 60° respectively. For M31 the cone radius refers to 1.5° and for Draco galaxy we estimate the signal flux within a cone of radius 0.25° from its center.
Figures 4 and 5 show possible signal fluxes which can be obtained with the eROSITA and ART-XC telescopes from observations of the GC, M31 and Draco. For the eROSITA observation of GC with radius of 60°, we cut the central part of 2.5° radius and the Galactic disc of ±1.5°. Using these data, we can estimate the observation time required to strengthen the existing limits (in terms of the standard deviation $\sigma$) if the expected flux is not detected:

$$T = \left[ \frac{F_{\text{DM}} \text{GRASP}(E)/\Omega + F_{\text{BG}}}{F_{\text{DM}}^2 \text{GRASP}(E)/\Omega^2} \right] \times \sigma^2, \quad (6)$$

where GRASP$(E)/\Omega$ is the ratio of GRASP to the angular size of the source. If we observe a region equal to the field of view of the telescope ($\Omega \cong \text{FOV}$), then this ratio is the effective area (EA) of the telescope. The $F_{\text{BG}}$ here is the background in a bandwidth corresponding to the telescope energy resolution. The energy resolution of eROSITA telescope remains almost constant, 2.3%, over the entire observation energy range [8]. The energy dependence of ART-XC telescope energy resolution is taken from [3].

**V. CONCLUSIONS AND OUTLOOK**

In this paper, we examined the capabilities of the SRG mission to detect a signal from the dark matter formed by sterile neutrinos, which can decay into active neutrino and photon. We have estimated the potential signal fluxes which can be detected during the SRG mis-
Observation time [Ms] for GC 1 telescopes for GC 1.

FIG. 6. The observation time for ART-XC and eROSITA telescopes for GC 1.5° and 60° radius cone required to fully explore the dark matter sterile neutrino model with resonant production mechanism (exclusion at 2σ confidence level). The horizontal dashed line on the left panel shows the exposure obtained in SRG/ART-XC GC survey, the similar line on right panel shows the exposure to be collected in four year SRG all-sky survey with both eROSITA and ART-XC.

The exposure time in a wide 60° radius cone towards the Galactic Center (GC), is to be compared to the exposure which will be obtained in SRG all-sky survey. It is currently planned that all the sky will be surveyed by SRG during four years in total. Therefore, 60° radius cone centered on the GC will be surveyed for approximately one year during this survey (≈30 Ms, shown as the horizontal dashed line on the right panel of Fig. 6). These data will allow one to place stronger than 2-σ bounds on the lowest possible dark matter decay signal at the photon energies between 6.5 keV and 12.5 keV with ART-XC and at the photon energies below 6 keV with eROSITA. Thus, our estimates imply that it will be possible to obtain even stronger constraints on the parameters of sterile neutrinos in the corresponding mass range using the SRG/ART-XC and SRG/eROSITA all-sky survey data.

In particular, to detect at 5-σ level the 7 keV dark matter sterile neutrino with mixing of about sin²2θ ∼ 5 × 10⁻¹¹ (invited to explain the anomalous 3.5 keV line [24, 25]), it takes only ~25 ks and 0.4 Ms of observations near GC and in wide angle around GC respectively. The eROSITA sensitivity at 3.5 keV is approximately similar to that of XMM-Newton, as expected, see e.g. [28], also Fig. 3. Confronting these exposures with SRG mission time scale one concludes, that the constraints to be obtained by the eROSITA telescope near the 3.5 keV line signal reported earlier can be comparable to that obtained from XMM-Newton data, which will provide with another independent study of the possible sterile neutrino decay signal in this mass range.

At the photon energies below approximately 2.4 keV the SRG/eROSITA sensitivity in wide angle observations is higher than that of XMM-Newton. Therefore eROSITA data from a wide cone around GC yields a new independent prob of the region of the DM sterile neutrino parameter space, previously disfavored from the Milky Way satellite counts [18], not from X-ray observations. This may be important, since both methods may have their own unknown systematics. Likewise, if dark matter particles decay, it happens in each galaxy and all the time, so the expected X-ray signal from unresolved astrophysical sources at cosmological distances suffers from redshifting and correlates with the Cosmic Structure. The sensitivity of the eROSITA to the corresponding observables in the X-ray diffuse all-sky map has been studied in Refs. [49, 50]. Similar investigation is en-
visaged for ART-XC. As a kind of intermediate approach, one can use the stacked spectra of resolved astrophysical sources to search for the decay signature.

The data of X-ray surveys which are carried out with ART-XC and eROSITA telescopes aboard SRG space observatory will give a possibility to fully explore the dark matter sterile neutrino model with resonant production in the early Universe. The presence of overlapping areas in the energy ranges of the eROSITA and ART-XC telescopes will further improve the overall sensitivity to the parameters of sterile neutrinos. The SRG mission has high potential for verifying the dark matter sterile neutrino hypothesis within the minimal extensions of the SM like νMSM [51], where no additional ingredients are introduced in the model to change the neutrino dynamics at the production epoch. There still be a room for the models with sterile neutrino forming only a fraction of dark matter. To conclude, the SRG mission has a very high potential for testing the sterile neutrino dark matter hypothesis.

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