PROCEEDINGS OF SCIENCE

Constraining Particle Dark Matter with eROSITA Early Data

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Many well motivated dark matter (DM) particle candidates can decay into detectable X-ray photons. We analyze eROSITA Final Equatorial Depth Survey (eFEDS) from eROSITA early data release to search for unexplained X-ray lines that could indicate DM signal. Having discovered no extra line, we set limits on DM decay rate in mass range between 1.8-18 keV, and constrain the parameter space of two DM particles: sterile neutrino and axion-like particles. Finally we also study the projected sensitivity of eROSITA full sky search, showing that eROSITA all-sky survey is expected to set the most stringent limits in the soft X-ray band.

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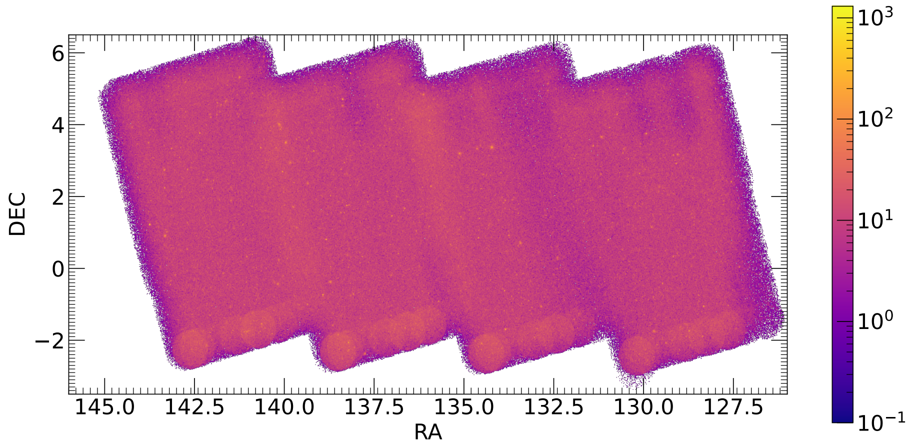

Figure 1: Sky image of eFEDS observations, shown in Galactic coordinates. The x and y axes are in degrees. Each pixel is 64″ wide. The color bar shows number of photons in each pixel.

1. Introduction

Dark Matter (DM) study remains a popular field in today's physics community. In indirect DM detection, the myriad of search methods included the entire electromagnetic spectrum, neutrinos and gravitational waves [1]. In this work, we look for a spectral line originated from the decay of keV scale DM particle in X-ray. This search method garnered attention back in 2014, when a study looked at Galaxy cluster observed by XMM-Newton and found a unexplained line at 3.5 keV [2]. However the line was not seen in the latest studies [3]. To offer a more through investigation on the subject, more sensitive instruments are needed for X-ray DM search.

2. Modeling DM Decay Line

If DM particles decay, they will leave a signature in astrophysical observation. Usually it is manifested as a bump on (mostly) smooth astrophysical background. The model of such DM signal only depends on the decay rate (Γ), the mass of the DM particle (m_χ), the single decay spectrum of the theoretical particle model ($\frac{dN}{dE}$, which we take as a delta function centered at one half the original particle energy $\delta(E - m_\chi/2)$), the field of view size of the survey (Ω), and column density of DM in the field of view (characterized by D-factor $\mathcal{D} = \int_{\text{los}} dl \rho_{\text{DM}} \left(r(\psi, l)\right)$).

$$\frac{dF}{dE} = \frac{\Gamma}{4\pi m_\chi} \frac{dN}{dE} \cdot \int d\Omega \cdot \mathcal{D} \tag{1}$$

3. eROSITA Instrument and Data

eROSITA is a joint German-Russian collaboration launched in 2019, onboard SRG satellite currently in the Lagrangian Point L2. Its four year mission, is to provide the next generation all-sky X-ray survey. eROSITA has seven telescope modules (TMs), arranged like a honeycomb. It has competitive energy resolution and also effective area [4].

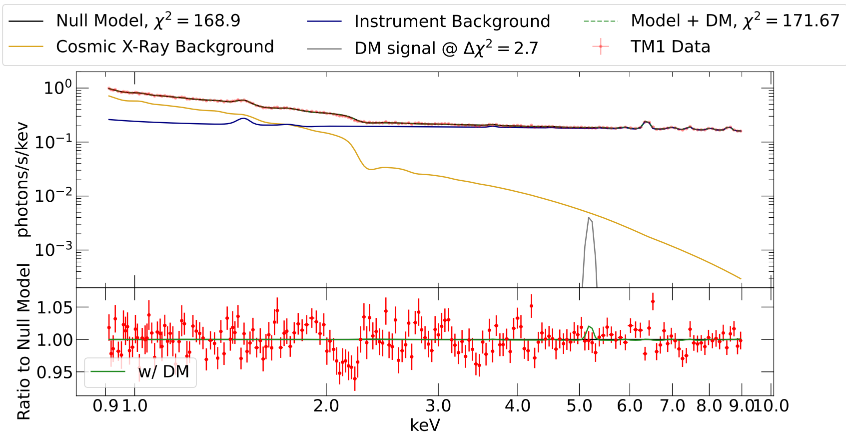

Figure 2: eFEDS TM1 data and our models. The data points are shown in red dots. The total blank sky model, astrophysical background, and instrument background are shown in black, gold, and blue lines. We also show a fiducial DM signal at 5 keV and a model with said signal, in grey and green lines. The bottom panel shows the ratio of data to null model (red dots), and the ratio of model with DM to null model (green).

The eROSITA data we used here is released in 2021, known as eROSITA Early Data Release (eROSITA EDR).[1] Among all the available data, the observation with the largest continuous area and longest observation time is called eROSITA Field Equatorial Depth Survey (eFEDS), shown in figure 1. Specifically, it has 360 ks of observation on an area of 140 deg^2, divided into four rectangles. For details about eFEDS, see table 1 in [5]. We perform spectra extraction and skymap creation with analysis software provided by eROSITA collaboration, eRASS[2].

We also check the impact of the point sources with eRASS. We use a “cheese mask" to remove all the point sources documented by eROSITA collaboration, and compare the spectrum before and after the point source removal. We found removing all the point sources does not change the spectrum shape, mainly due to eFEDS pointing direction being away from Galactic center.

It was discovered that eROSTIA has “light leak" in low energy. Between 0.2 to 1 keV there are 2 telescope modules that have been contaminated and the spectra modified (see [4] for detailed discussion). To deal with this issue, we take the convenient approach by ignoring spectral energy range below 0.9 keV for all TMs.

4. Constructing Blank Sky Spectrum

Our blank sky spectrum can be divided into two categories. The first one is instrumental background, which comes from high particles interacting the internal elements the telescope. It's modeled by a continuum and 14 Gaussian lines. The model parameters are based on spectrum taken with camera lenses shut off. The second category is diffuse X-ray background from astrophysical sources, following previous eFEDS analysis [6], and other X-ray DM searches [7–9]. It's based on previous X-ray studies, and modeled as the addition of two absorbed XSPEC [10] models: `apec` and

[1] https://erosita.mpe.mpg.de/edr/eROSITAObservations/
[2] https://erosita.mpe.mpg.de/edr/DataAnalysis/

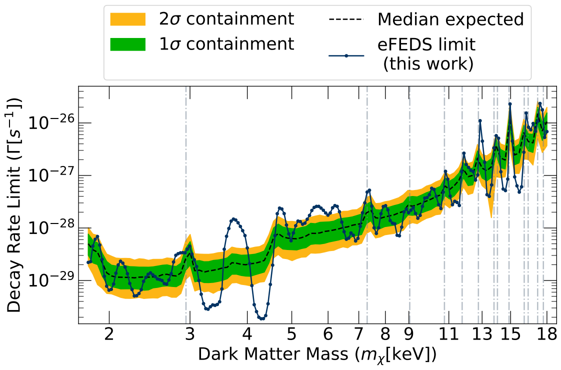

Figure 3: Our constraint on DM decay rate, obtained from eFEDS. We also show our power constrained 1σ and 2σ regions. Grey dash-dotted lines mark the energies at which our null model has a Gaussian line.

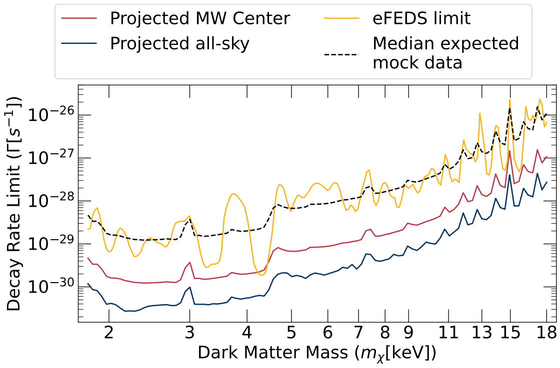

Figure 4: Projected sensitivities of eROSITA future data surveys. We show the constraint obtained from eFEDS in gold and the median from mock data in dashed black line, same as figure 3, for comparison. The projected limits from Milky way center is in red and all-sky is in blue.

an absorbed `powerlaw`, representing the X-ray from local group and diffuse sources respectively. In the end, we can produce a best fit model with $\chi_0^2/d.f. \approx 1$.

5. Dark Matter Line Search and Constraint

We search for potential DM signature by injecting a fiducial signal and check if the model with signal can produce a better fit than null model. We could not find a fit consistent with DM detection.

We proceed to set the upper limit constraint on DM Decay lifetime consistent with null observation. It is set by gradually increasing decay rate until the model with a DM signal produces $\chi^2 - \chi_0^2 = 2.71$. We call this decay rate one sided 95% lower limit on DM decay rate. See figure 2 for an example of fiducial signal, and see the solid blue line on figure 3 our result lower limit on DM decay rate.

To increase the confidence in our result, we perform a Monte Carlo test. We generate a thousand mock data sets based on the null model, allowing Poisson error. From these 1000 data sets we generate 1000 mock limits, and record where 68% and 92% of them fall into. These correspond to our 1σ and 2σ containment respectively. As shown on figure 3, in most of the energy range, our limit falls within 2σ containment, but there are a few places that it does not. Firstly, our DM signal is degenerate with the internal Gaussian lines, and the limit becomes untrustworthy in those energies. Secondly, between DM mass 4 to 6 keV our limit goes below 2σ range. We believe that it is due to the poorness of our model. This artifact in modeling comes from effective area extracted from eSASS provided by eROSITA collaboration, where there's a sharp drop and small rise between 2 to 3 keV. As more eROSITA studies emerge and calibration gets better, we expect this feature to go away.

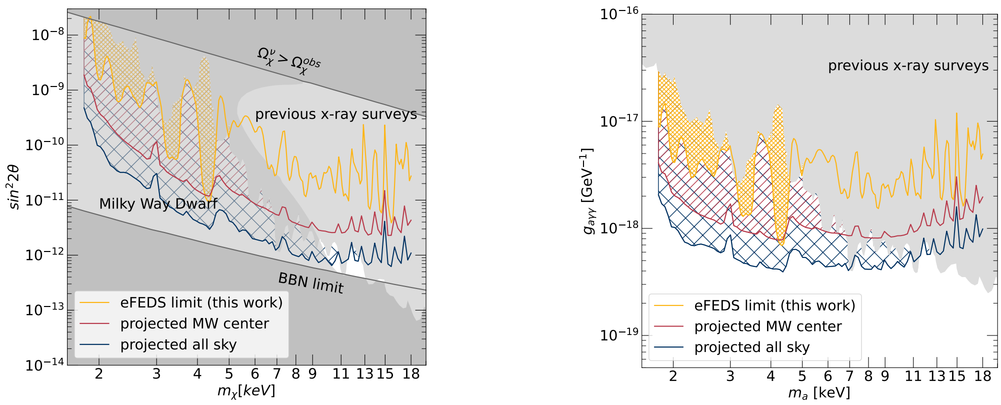

Figure 5: Our constraint on DM decay lifetime converted to two specific models, compared to existing constraints. *Left:* current and future eROSITA constraints on sterile neutrino DM mixing angle as a function of mass. *Right:* ditto, but for ALP-photon coupling.

6. Projection for Future Survey

Based on the result from early data, we project how eROSITA will perform in DM search once all-sky survey results are available. We generate a mock sky with `healpy`[3] [11, 12]. Each patch on the mock sky has roughly the same area as eFEDS. For every one of them, we calculate DM density in the field of view, and projected DM limit. We then statistically combine them to produce the all-sky projection. Figure 4 shows that the improvement is about factor of three and factor of ten for eROSITA Milky Way Center and for all-sky observation, respectively.

7. Sterile Neutrino and Axion-like Particle Parameter Space Constraint

We convert our DM decay rate limit into two specific models: sterile neutrino axion-like particles, shown in figure 5. The parameters determine sterile neutrino decay rate are mass and mixing angle $\sin^2 2\theta$ [23, 24]:

$$\Gamma_{\nu_s \to \nu\gamma} = 1.38 \times 10^{-32}\,\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_\chi}{\mathrm{keV}}\right)^5 . \tag{2}$$

For ALP, the parameters are mass and photon coupling strength $g_{a\gamma\gamma}$ [25]:

$$\Gamma_{a\to\gamma\gamma} \simeq 5 \times 10^{-29} \left(\frac{m_a}{7\mathrm{keV}}\right)^3 \left(\frac{f_a}{5 \times 10^{14}\mathrm{GeV}}\right)^{-2} \mathrm{s}^{-1}. \tag{3}$$

Compared to previous X-ray surveys [3, 13–22] our limit improves the most improving in the lower energy regime. For neutrino minimal standard model, which is also constrained by Dwarf galaxy count and BBNS, the improved energy range has already been ruled out. But for ALP and non-thermally produced DM models, eROSITA can provide good limit.

[3]http://healpix.sourceforge.net

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8. Conclusion

We have demonstrated the potential of eROSITA in DM search. By using early data release, we improved the limit on DM decay rate in some energy range. With the full data release coming up very soon, we can produce better limits in keV scale DM search.

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