

High-Energy Astronomy Searches for Particle Dark Matter

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Abstract

X-ray astronomy remains one of the most sensitive probes of new nuclear and particle physics connected to the nature of dark matter and the origin of neutrino masses. As the leading model for neutrino mass generation, sterile neutrinos are also a likely candidate for cosmological and astrophysical dark matter. Due to the presence of a higher-order-loop process, sterile neutrinos may radiatively decay, producing soft to hard X-ray photons. We present the physics behind the signal, an analysis of an optimal detector, as well as the limiting sensitivity of the Resolve instrument aboard the *XRISM* telescope. We also review the classes of models that reside in the parameter space that are probed by X-ray astronomy

Introduction

The mechanism that produces dark matter (DM) in the early Universe often ties it to our Standard Model particles, leading to a possibility for detection of dark matter radiative decay or annihilation via astronomical observations. Sterile neutrinos are the leading model for neutrino mass generation and are also a likely candidate for cosmological and astrophysical DM. It was shown by Abazajian, Fuller & Tucker (2001) that radiative decay of sterile neutrino DM could be detected by current and future X-ray observatories.

The signal of DM decay from an astronomical object, including dwarf galaxies and clusters of galaxies, is given by the DM decay rate into photons for a given decay channel, Γ , and photon spectrum dN_λ/dE ,

$$\frac{d\Phi_\lambda}{dE d\Omega} = \Gamma \frac{\mathcal{D}_{\text{obj}}}{4\pi m_\chi} \frac{dN_\lambda}{dE}, \quad (1)$$

$$\mathcal{D}_{\text{obj}} = \frac{1}{\Delta\Omega} \int \rho_{\text{obj}}(r_{\text{obj}}) dx d\Omega, \quad (2)$$

evaluated toward an astronomical body with DM density profile ρ_{obj} . In these equations, m_χ is the DM particle mass, x is the line-of-sight distance, and R_\odot is the distance from the Galactic Center to the Sun. This expression can be generalized for diffuse emission from the Milky Way DM halo, and can have a subdominant contribution from extragalactic sources. The spectrum of DM decay, in the case of a two-body decay, is a monochromatic line with dispersion given only by the DM velocity. Constraints from DM decay are shown in Fig. 1.

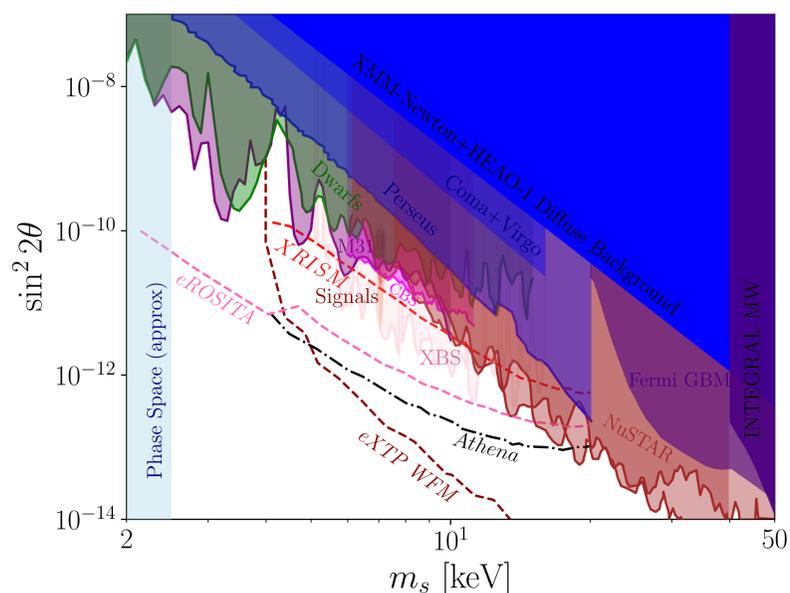


Figure 1: Sterile neutrino DM parameter space and X-ray astronomy constraints. Models for the production of sterile neutrinos to be the full DM fill the entire parameter space. This is based on a previous figure in Abazajian (2017), wherein all the constraint and signal regions are defined.

Designing an Optimal X-ray Observatory for Dark Matter Detection

The two components of an X-ray observatory and its instrumentation that have greatest leverage to optimize a DM X-ray telescope are its field of view and energy resolution, for a fixed exposure and detector effective area. The latter two variables are usually limited by time-allocation and launch.

Field of View

The sensitivity of observations on the sky for DM emission is given by the signal-to-noise ratio of DM photons to those photons emitted by foreground or background astronomical sources FOV, i.e., $\text{SNR} = S/\sqrt{B}$, where S is the count in signal photons, and B is the astronomical and/or instrumental background. For a diffuse signal such as DM, $S \propto \text{FOV}$, approximately. The background flux from the sky scales similarly, $B \propto \text{FOV}$, but since the noise goes as the square-root, the SNR can be enhanced by many orders of magnitude by exposing an observatory's detector to order-one fractions of the sky, relative to pointed observatories such as *Chandra*, *XMM-Newton* or *XRISM*. This is the reason for the very high sensitivity of the optics-free *eXTP WFM*, as well as the high sensitivity of *eROSITA*, as shown in Fig. 1.

Energy Resolution

A higher resolution spectrometer stacks DM-decay line photons into an arbitrarily narrow energy bin, as long as that bin is larger than the intrinsic width of the line. Meanwhile, the foreground/background emission count in the bin decreases with the bin size. This provides the greatly enhanced sensitivity of *XRISM* and *Athena/NewAthena*, as shown in Fig. 1. Our results find that existing technology can increase X-ray sensitivity to DM decay by orders of magnitude, with a relatively small mission (García-Escudero et al., in prep.).

Current Constraints, Signals, and Forecast Sensitivity of *XRISM*

DM halos in astronomical objects such as a field galaxy, dwarf galaxy, or cluster of galaxies are particle reservoirs. A dark matter halo of mass M_{DM} in any of these environments will be composed of $N = M_{\text{DM}}/m_\chi$ dark matter particles of rest mass m_χ . If Γ_γ is the dark matter particle decay rate

into photons of energy E_γ , then the total associated X-ray luminosity is $\mathcal{L} \approx (E_\gamma/m_\chi)M_{\text{DM}}\Gamma_\gamma$. As described above, the sensitivity of observations on the sky for DM emission is given by the signal-to-noise ratio of DM signal photons to those foreground/background photons emitted by astronomical sources in the FOV, plus any instrumental background.

As an approximation, we can estimate the flux onto an X-ray detector, following a parallel calculation as in Abazajian et al. (2001), but for the Resolve instrument on board *XRISM* instead of ACIS onboard *Chandra* X-ray mission. We can place two limits: a $2\text{-}\sigma$ detectability and a more stringent $4\text{-}\sigma$ requisite to produce a matter decay detection. The count level required to overcome the background at $4\text{-}\sigma$ is $C_L \approx 4\sqrt{B}/t$, and we calculate the commensurate limit at $2\text{-}\sigma$. Using Resolve's data, the detectable flux is $F_{-14}^{\text{det}} \approx 7.9 \cdot 10^{-2} t_5^{-1/2}$, where $F_{-14} \equiv F/(10^{-14} \text{ erg cm}^{-2} \text{ sec}^{-1})$ is the flux associated with the line and $t_5 \equiv t/(10^5 \text{ sec})$ is the observation time in seconds. For low surface brightness sources, a standard observation with an integration time of 100,000 sec ($t_5 = 1$), Resolve can detect a flux $\approx 8 \times 10^{-16} \text{ erg cm}^{-2} \text{ sec}^{-1}$. Note that the reduction of the grasp by the closed aperture door aboard *XRISM* will limit the particle mass range and require longer exposures, but will not overwhelmingly degrade its sensitivity to DM indirect detection. Importantly, the ultimate sensitivities that we have determined for *XRISM* are much greater than other forecasts (Dessert et al., 2023), as optimization strategies that reduce foregrounds/backgrounds can greatly enhance *XRISM*'s sensitivity.

Consequently, from the radiative decay flux expression for DM in the halo,

$$F \approx 10^{-17} \text{ erg cm}^{-2} \text{ sec}^{-1} \left(\frac{D_L}{1 \text{ Mpc}} \right)^{-2} \left(\frac{M_{\text{DM}}}{10^{11} M_\odot} \right) \left(\frac{\sin^2 2\theta}{10^{-10}} \right) \left(\frac{m_s}{1 \text{ keV}} \right)^5. \quad (3)$$

we use the calculation Resolve's detectable flux and $(M_{\text{DM}}/D_L^2) = 10^9 M_\odot/\text{Mpc}^2$ to place constraints on the mass mixing angle parameter space shown on Fig. 2. **As shown, *XRISM*'s ultimate sensitivity is much greater than any existing or near-term proposed observatory.**

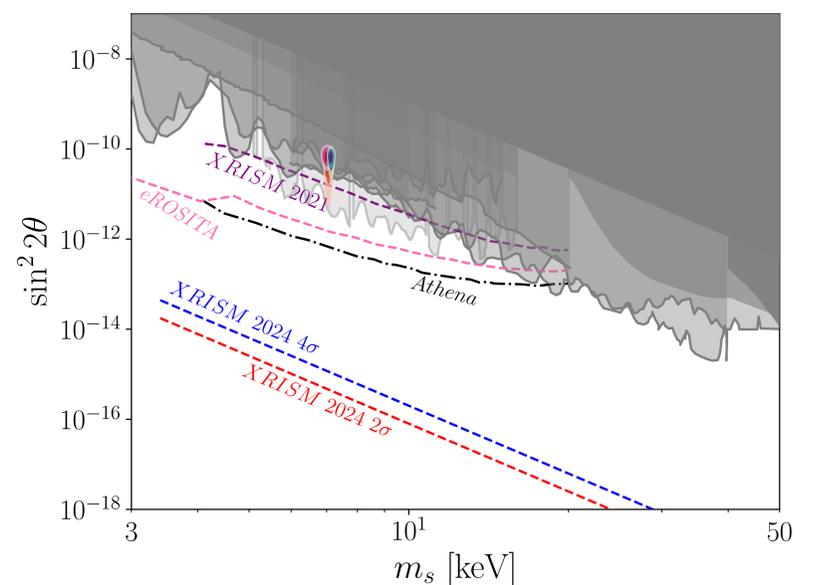


Figure 2: Shown here is the *XRISM* sensitivity line for dwarf galaxies from previous work (*XRISM* 2021), relative to our forecasts for the $2\text{-}\sigma$ and $4\text{-}\sigma$ potential optimistic case of Resolve instrument aboard *XRISM* mission.

Warm Dark Matter

Importantly, the parameter space in Figs. 1 & 2 is also tested as warm DM (WDM). There is recent 3σ evidence for WDM from Lyman- α forest observations (B. Villaseñor et al., 2023). Mapping structure formation sensitivity accurately in this parameter space requires robust linear growth calculations, like those in Vogel & Abazajian (2022) (Vogel et al., in prep.).

Detection of an unidentified line at 3.5 keV

Bulbul et al. (2014) reported a high-significance, $4\sigma - 5\sigma$, detection in stacked observations of 73 clusters with the MOS and PN spectrometers aboard *XMM-Newton*, as well as a consistent signal from the Perseus cluster of galaxies observed with the *Chandra* telescope. Boyarsky et al. (2014) found a consistent signal from the Andromeda galaxy as well as Perseus using data from the *XMM-Newton* satellite. There has been significant scrutiny of the results as well as follow-up observations that see commensurate signals in other astronomical observations (Abazajian 2017), and several observations do not see the line with deep exposures, as shown in Fig. 1 (Sicilian et al., 2020; Foster et al., 2021). Constraints from Dessert et al. (2020) are not adopted here, as the limits are a factor of ~ 20 weaker than claimed, which was acknowledged within that work, and in subsequent comments, e.g., Abazajian (2020). We also do not show limits from Foster et al. as that work does not include instrumental and on-sky lines present at 3.3 and 3.7 keV in their stated limits. The *XRISM* Observatory will have great sensitivity to this line, as discussed above, and would also potentially resolve the DM velocity broadening of the line (Bulbul et al.).

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