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Discovery Potential for Decaying Dark Matter and Faint X-ray Sources with XRISM

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Astrophysical emission lines arising from particle decays can offer unique insights into the nature of dark matter (DM). Using dedicated simulations with background and foreground modeling, we comprehensively demonstrate that the recently launched XRISM space telescope with powerful X-ray spectroscopy capabilities is particularly well-suited to probe decaying DM, such as sterile neutrinos and axion-like particles, in the mass range of few to tens of keV. We analyze and map XRISM's DM discovery potential parameter space by considering Milky Way Galactic DM halo, including establishing an optimal line-of-sight search, as well as dwarf galaxies where we identify Segue 1 as a remarkably promising target. We demonstrate that with only 100 ks exposure XRISM/Resolve instrument is capable of probing the underexplored DM parameter window around few keV and testing DM couplings with sensitivity that exceeds by two orders existing Segue 1 limits. Further, we demonstrate that XRISM/Xtend instrument sensitivity enables discovery of the nature of faint astrophysical X-ray sources, especially in Segue 1, which could shed light on star-formation history. We discuss implications for decaying DM searches with improved detector energy resolution in future experiments.

Keywords: cosmic X-ray background — X-rays: diffuse background — dark matter

Decaying Dark Matter

- For keV-scale sterile neutrino DM dominant decays are $\nu_s \to \nu_a + \gamma$, resulting in monochromatic X-ray photons with energies $E_\gamma = m_s/2$. The channel decay rate is

$$\Gamma_{\nu_s \to \gamma\nu_a} = 1.38 \times 10^{-32} \left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5 \mathrm{s}^{-1}$$

(Shrock 1974; Pal & Wolfenstein 1982)

- For keV-scale pseudoscalar ALPs $m_a \ll m_e$ compared to electron mass m_e and the decays proceed via $a \to 2\gamma$. Neglecting loop contributions from ALP-electron couplings, the rate is

$$\Gamma_{a \to \gamma\gamma} = 7.56 \times 10^{-31} \left(\frac{g_{a\gamma\gamma}}{10^{-17}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_a}{1\ \mathrm{keV}}\right)^3 \mathrm{s}^{-1}$$

Langhoff et al, Irreducible Axion Background, PRL, 129, 241101 (2022)

Galactic Halo

- We model DM density distribution of the Galactic DM halo using Navarro-Frenk-White (NFW) profile (Navarro et al. 1996)

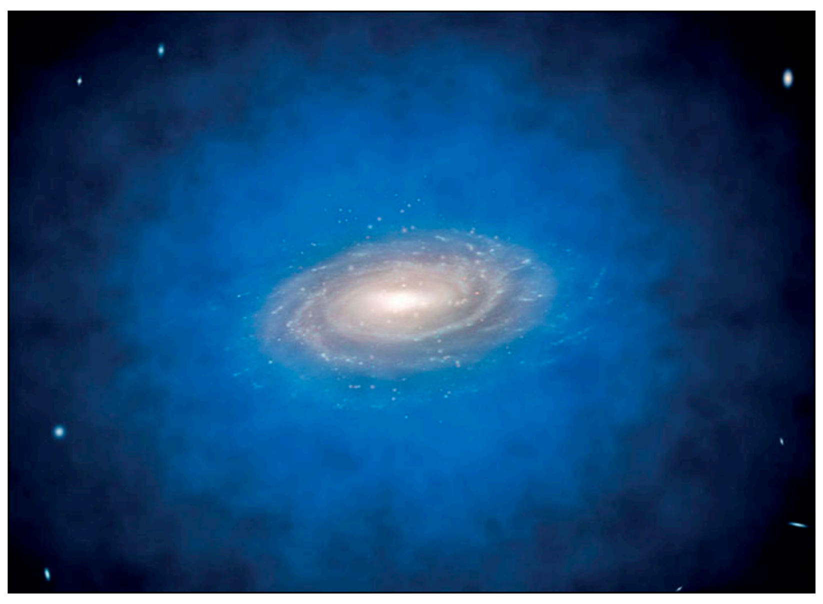
$$\rho_{\mathrm{DM}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

with $\rho_s = 6.6 \times 10^6\ M_\odot/\mathrm{kpc}^3$ and $r_s = 19.1$ kpc.

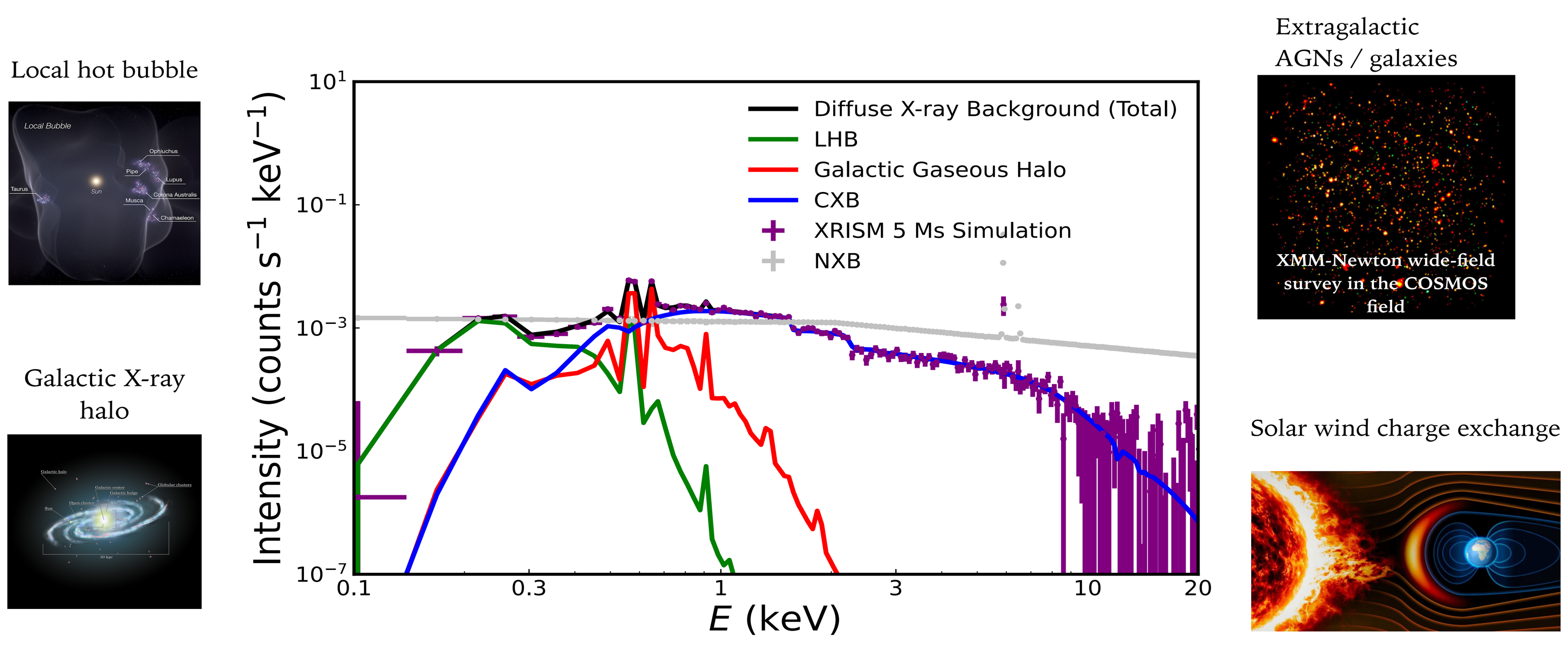
- Finite velocity dispersion of the Milky Way DM in the Galactic frame will result in Doppler broadening

$$f(E,r) = \frac{4}{m_s}\frac{\int_0^\infty ds \rho_{\mathrm{DM}}(r) f(v(E),r)}{\int_0^\infty ds \rho_{\mathrm{DM}}(r)}$$

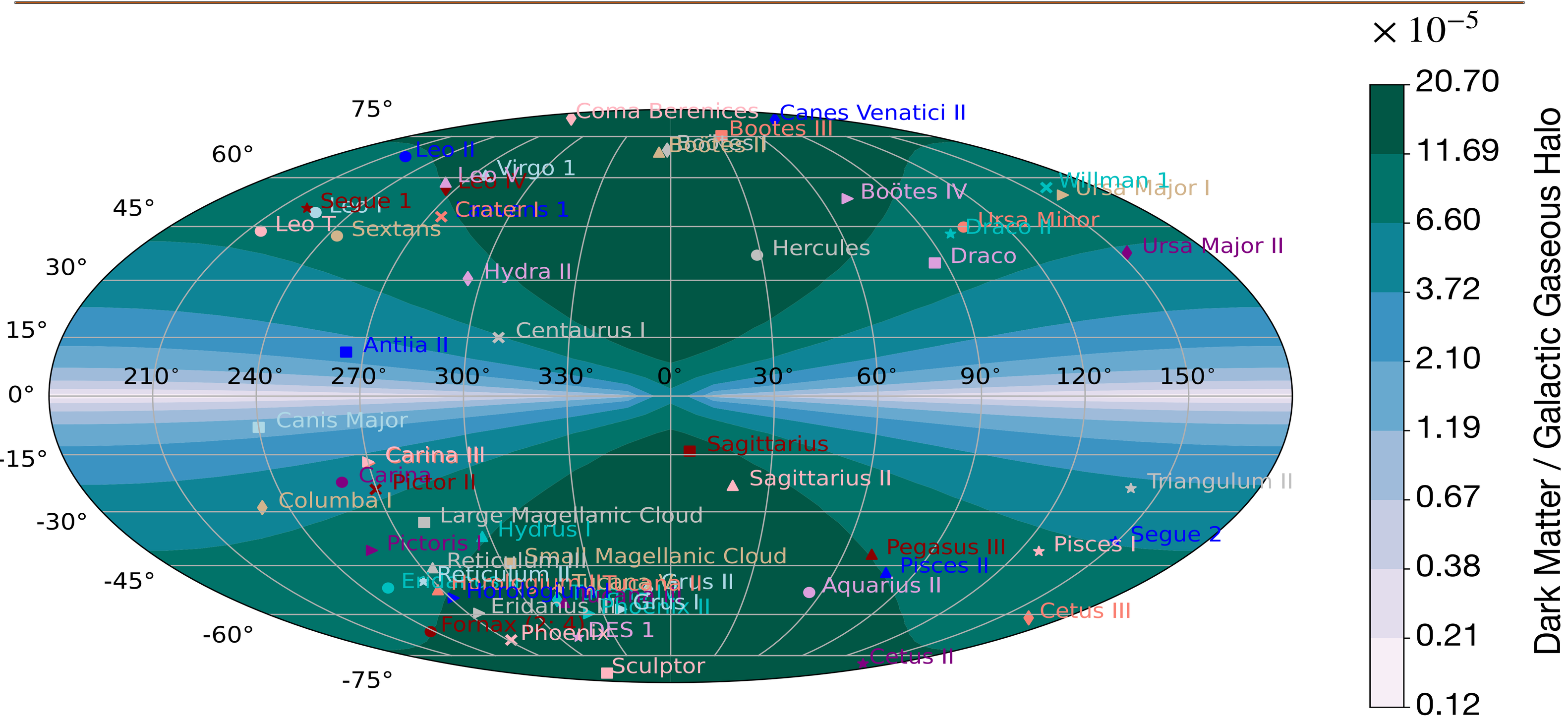
where the f(v(E), r) is the DM velocity distribution projected along the line-of-sight under the assumption of a homogeneous and isotropic DM velocity distribution for a collisionless DM species in gravitational equilibrium with a gravitational potential (Dehnen et al. 2006)



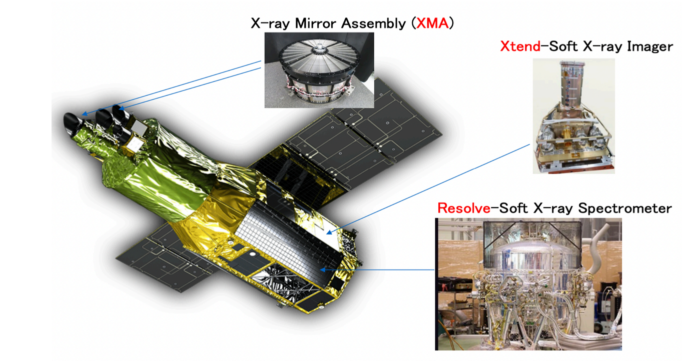
X-ray background



Optimization of linesights



XRISM Resolve/Xtend



Resolve spectrometer is equipped with an X-ray microcalorimeter array of 6x6 pixels at the focus of the X-ray mirror assembly (XMA), which is capable of non-dispersive high-resolution (ΔE≦7 eV) spectroscopy and limited imaging of 3′ x 3′ field of view in the soft X-ray (0.3-12 keV) band with a large effective area of ≧210 cm².

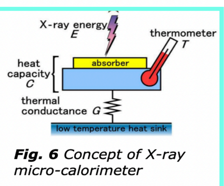


Fig. 6 *Concept of X-ray micro-calorimeter*

Xtend is a telescope system which consists of an X-ray mirror assembly (XMA) and an X-ray CCD camera (SXI) [5]. It has an imaging-spectroscopic capability with a wide FoV (38x38 arcmin²) and a medium energy resolution (E/ΔE~35@6 keV, based on the performance of Hitomi/SXI [7]) in the soft X-ray band (0.4-13 keV). It is a successor of Suzaku/XRT+XIS and Hitomi/SXT+SXI (**Table 3**).

Table 1 *Key parameters and performance requirement of the XRISM observatory (Tashiro et al. 2018)*

Parameters	Resolve	Xtend
X-ray mirrors	Conically approximated Wolter I optics (203 nested)	
Focal length	5.6 m	
Angular resolution	≤ 1.7 arcmin (HPD*1)	
Detector technology	X-ray micro-calorimeter	X-ray CCD
Effective area	≥210 cm² @ 6keV, ≥160 cm² @ 1keV	≥300 cm² @ 6 keV
Field of View	≥ 2.9 x 2.9 arcmin²	≥ 30 x 30 arcmin²
Energy range	0.3 – 12 keV	0.4 – 12 keV
Absolute energy scale	≤ 2 eV	–
Energy resolution	≤ 7 eV FWHM @ 6keV	≤ 250 eV @ 6keV (EOL)
Non X-ray background	≤ 2 x 10^{-3} c/s/keV/array	≤ 1 x 10^{-6} c/s/keV/arcmin² (in 5–10 keV)
Time tagging accuracy	≤ 1 ms	–

*1 Half Power Diameter

Dwarf Galaxies

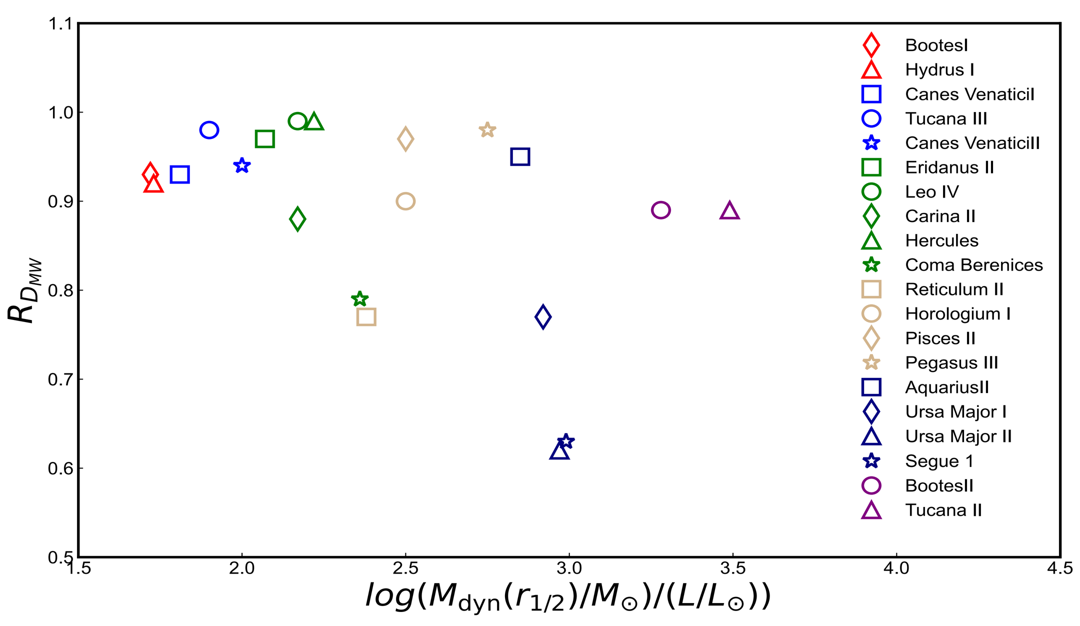
- The D-factor accounts for the distribution of DM in an astrophysical system to determine the strength of the emission signal from decaying DM

$$D_{\mathrm{DG}} = \int_{\Delta\Omega} d\Omega \int dl \rho_{\mathrm{DM}}(r(l,\Omega))$$

where Ω is the solid angle of the chosen field of view and l is the distance along the line-of-sight.

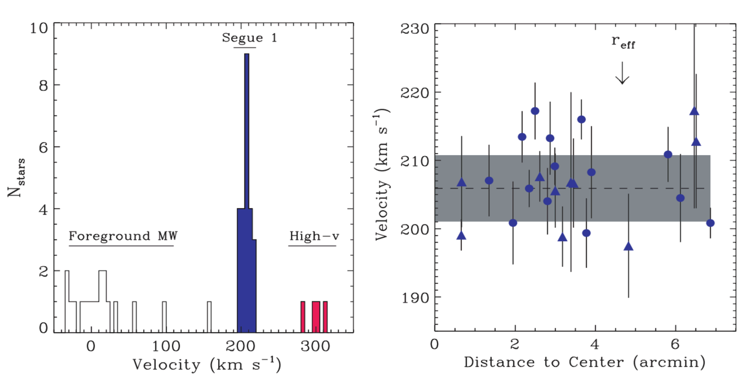
- The D-factor ratio of the Milky Way to a given DG can be found from

$$R_{D_{\mathrm{MW}}} = \frac{D_{\mathrm{MW}}}{D_{\mathrm{MW}} + D_{\mathrm{DG}}}$$

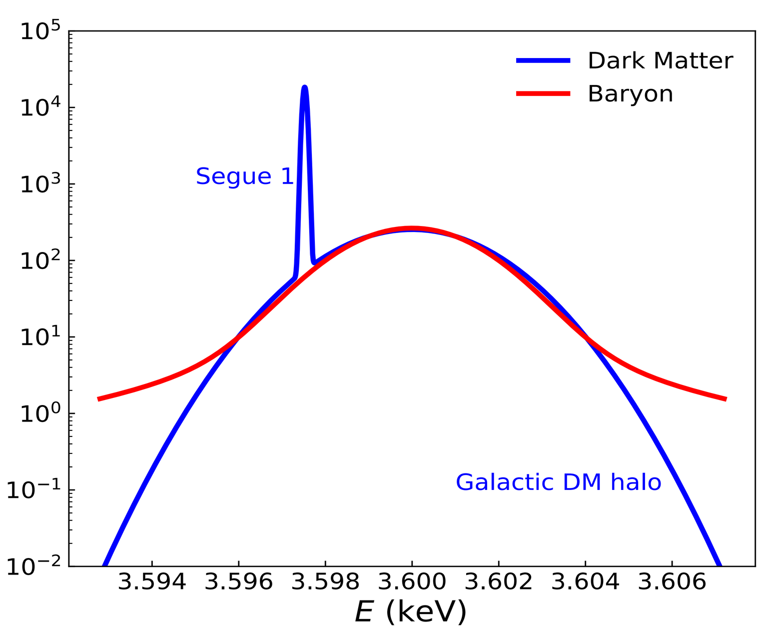


Segue 1 dwarf galaxy

- An unevolved fossil galaxy from the early Universe (Frebel et al, ApJ, 786:74, 19pp, 2014)
- Internal stellar kinematics suggest that Segue 1 is highly dark-matter dominated
- Small half-light radius ~ 4 arcmin
- Internal velocity dispersion $4.3 \pm 1.2\ km/s$



(Geha et al, ApJ, 692:1464-1475, 2009)



DM Sensitivity Forecast