AXIS Can Access Dark Matter Decays

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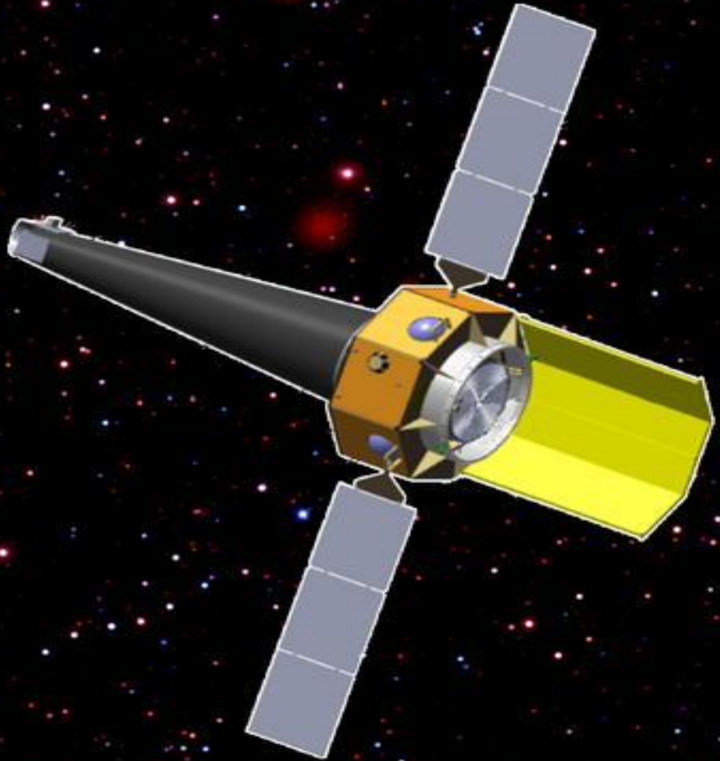
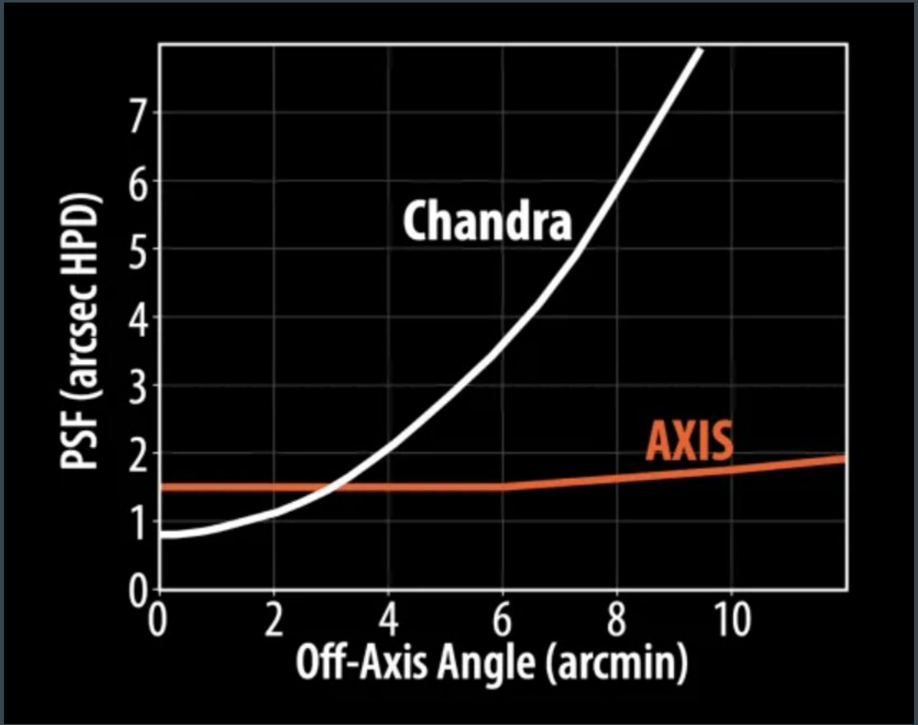


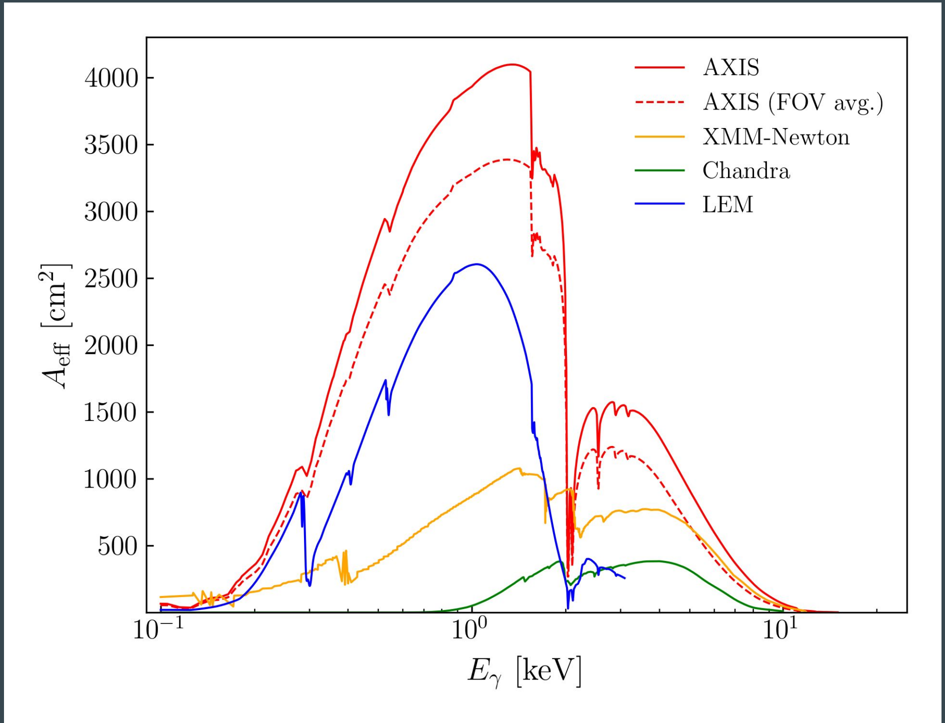
What is AXIS?

- Advanced X-ray Imaging Satellite
- Physics goal is to study SMBHs, galaxy evolution, explosive phenomena
- One of two proposals under consideration by NASA (decision in 2026)
- $5 million in funding for mission concept study

Why is it important?

- Large effective area (4x larger than XMM-Newton below 2 keV)
- High spatial resolution (6x lower FOV-avg PSF than Chandra)
- Lower backgrounds due to improved detector technology



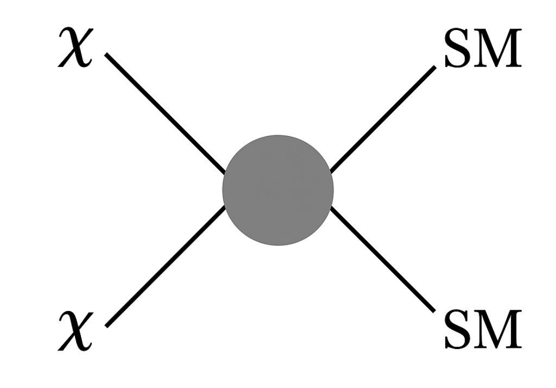


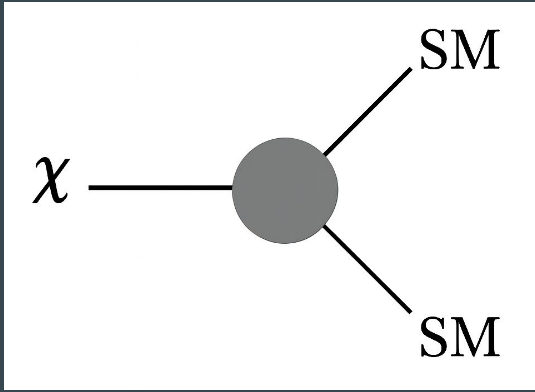
https://axis.umd.edu/researchers/mission

What particle physics can we do with AXIS?

Dark Matter Detection

- Collider searches, direct detection, indirect detection (“make it, shake it, break it”)
- First two methods restricted to terrestrial experiments
- Indirect detection can utilize space-based telescopes
- Annihilation harder to detect, focus on long-lived DM decays instead ($\chi \to f\gamma$)
- Decays produce characteristic line signals at E=m/2





Galactic Photon Flux

$$\left(\frac{d\phi}{dE_\gamma}\right)_{\text{gal}} = \frac{1}{4\pi m\tau}\frac{dN_\gamma}{dE_\gamma}\int_{\Delta\Omega} d\Omega \int_{\text{LOS}} ds\,\rho(r)$$

D. Hooper (*Proc. Sci.* **TASI2018** , 010 (2019))

Galactic Photon Flux

instrument

$$\left(\frac{d\phi}{dE_\gamma}\right)_{\rm gal} = \frac{1}{4\pi m \tau}\frac{dN_\gamma}{dE_\gamma}\int_{\Delta\Omega} d\Omega \int_{\rm LOS} ds\, \rho(r)$$

particle physics

astrophysics

Only a single power of DM density profile (unlike annihilations)

D. Hooper (*Proc. Sci.* **TASI2018** , 010 (2019))

DM Density Profiles

Navarro-Frenk-White (NFW)

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}$$

- Benchmark profile
- Emerged from collisionless CDM simulations
- Invalid close to the galactic center (divergent)

J. F. Navarro et al. (*Astrophys. J.* **462**, 563-575 (1996))

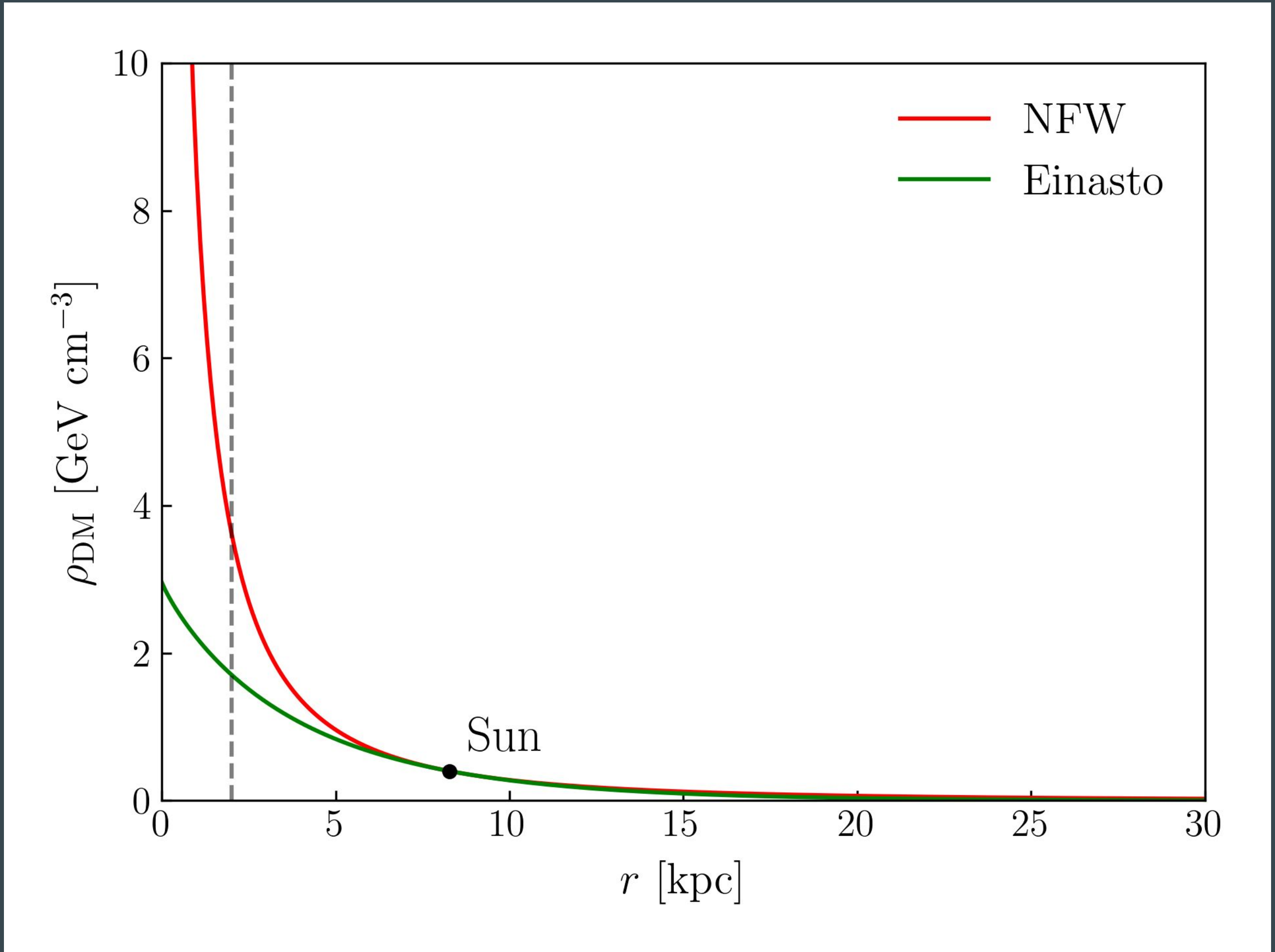
Einasto

$$\rho_{\mathrm{Ein}}(r) = \rho_0 \exp[-(r/r_s)^\alpha]$$

- Originally for stellar density distributions
- Later applied to high-resolution CDM simulations

J. Einasto (*Trudy Inst. Astrofiz. Alma-Ata* **5**, 87-100 (1965))

DM density in inner ~2 kpc poorly understood



10
8
6
4
2
0
0
5
10
15
20
25
30
$\rho_{\rm DM}$ [GeV cm^{-3}]
r [kpc]
NFW
Einasto
Sun

Extragalactic Photon Flux

AXIS FOV

$$\left(\frac{d\phi}{dE_\gamma}\right)_{\mathrm{EG}} = \frac{\Omega_{\mathrm{c}}\rho_{\mathrm{crit}}}{2\pi H_0 m^2 \tau}\sqrt{\frac{2E_\gamma}{m}}\frac{\Delta\Omega}{\sqrt{\Omega_{\mathrm{m}} + \Omega_\Lambda (2E_\gamma/m)^3}}$$

R. Essig et al. (*J. High Energ. Phys.* **2013**, 193 (2013))

Backgrounds

Galactic

- Non X-ray background (NXB)
  - Charged particles interacting with detector
- Soft X-ray background (SXB)
  - Emission from hot gas (Local Hot Bubble and Hot Halo)
  - Energy range: 0.1 - 1 keV
  - Subdominant contribution

D. McCammon et al. (*Astrophys. J.* **576**, 188-203 (2002))

Extragalactic

- Cosmic X-ray background (CXB)
  - Primarily due to distant AGNs
  - Spectrum is a power law above 1 keV
  - Strongly attenuated below 1 keV

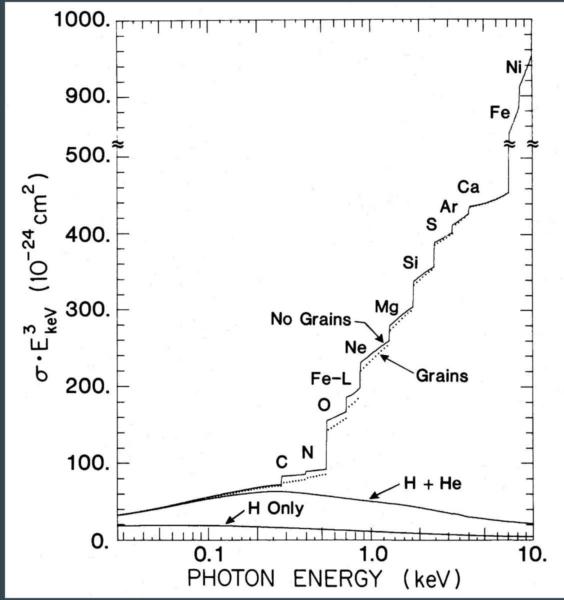
R. F. Mushotsky et al. (*Nature* **404**, 459-464 (2000))
R. C. Hickox, M. Markevitch (*Astrophys. J.* **645**, 95-114, (2006))

Attenuation

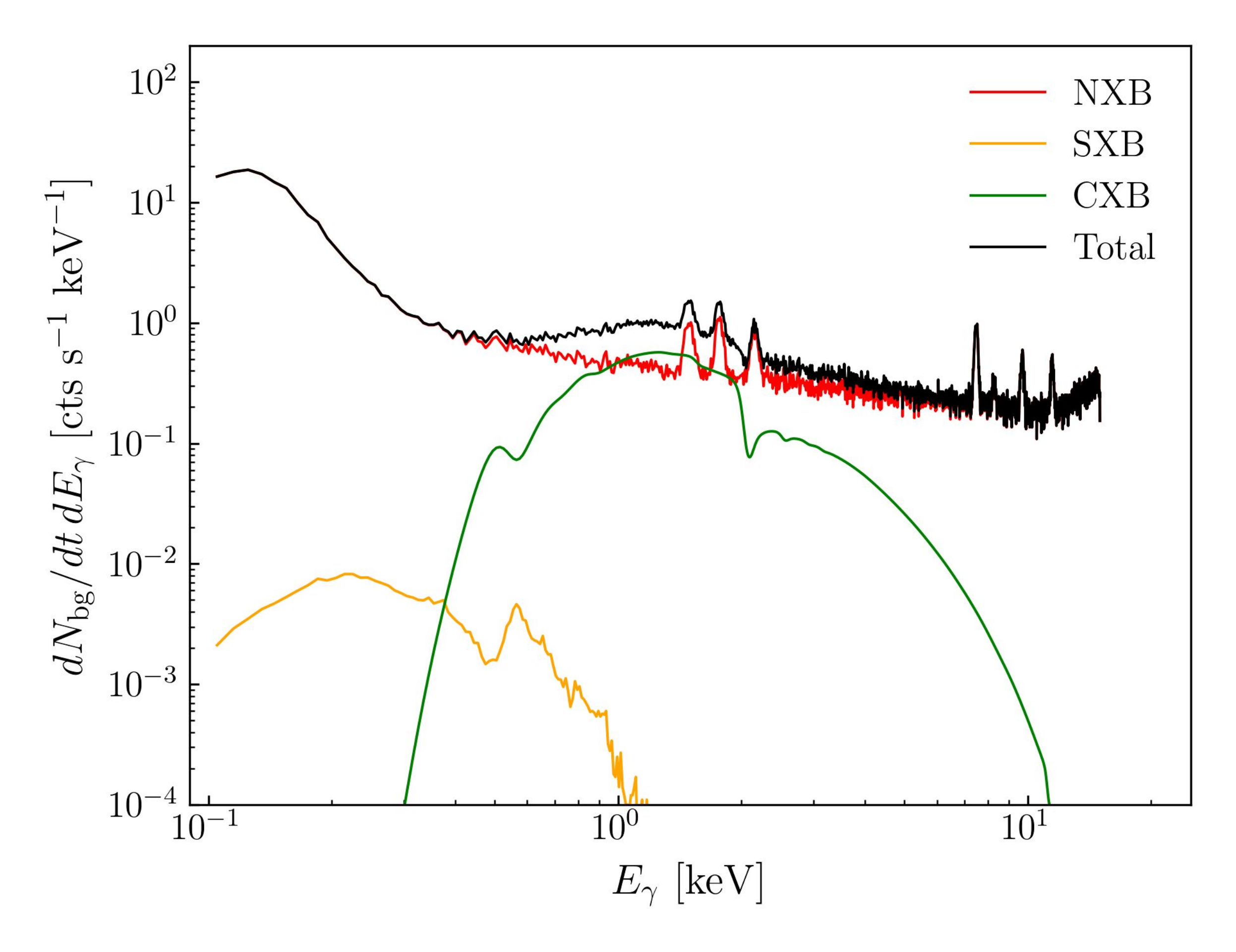
- Signal (galactic and EG) and background (CXB) strongly attenuated below 1 keV
- Primarily due to neutral H (but also other elements)

$$I_{\text{att.}}(\ell, b, E_\gamma) = I(\ell, b, E_\gamma) \times e^{-N_{\text{H}}(\ell,b)\sigma(E_\gamma)}$$

$$\sigma(E_\gamma) \sim E_\gamma^{-2.4}$$



R. Morrison, D. McCammon (*Astrophys. J.* **270**, 119-122 (1983))

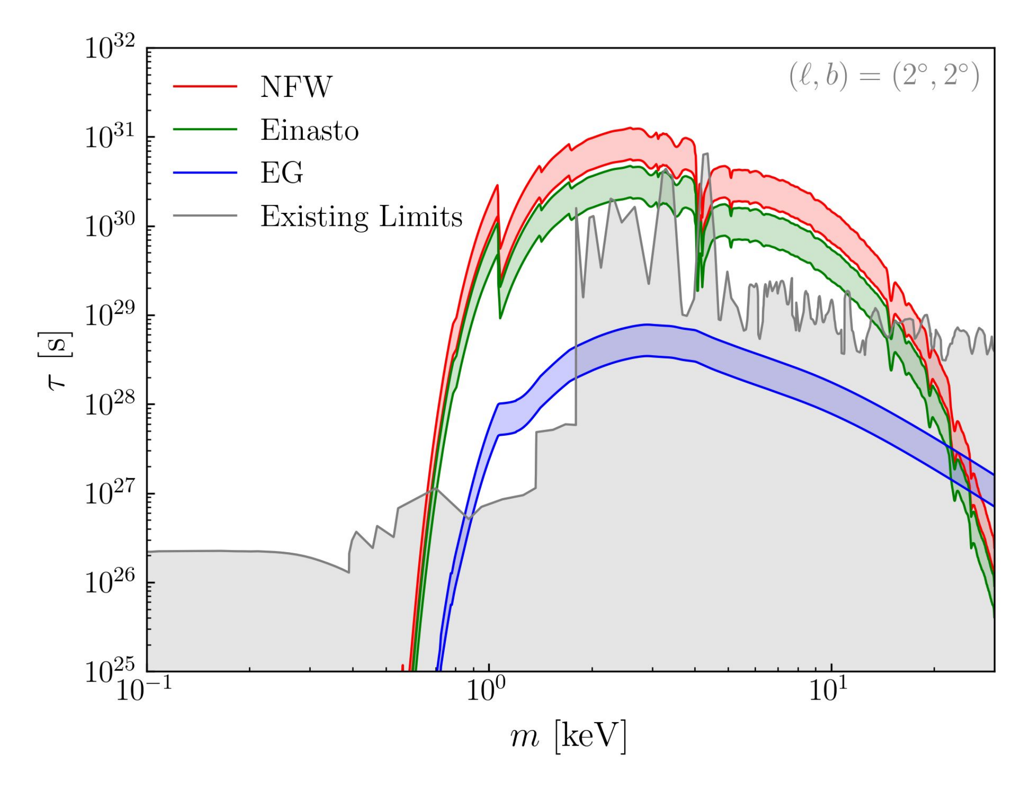

NXB
SXB
CXB
Total
$dN_{\rm bg}/dt\,dE_\gamma$ [cts s^{-1} keV^{-1}]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
10^{0}
10^{1}
E_γ [keV]

Forward Modeling

- Raw photon flux must be *forward modeled*
  - Effective area
  - Quantum efficiency
  - Filters
  - Energy redistribution
  - Exposure time
  - Field of view
- Instrument response files provided by AXIS collaboration

Results (DM Lifetime)

- Up to an order of magnitude improvement compared to existing limits (mainly from XMM-Newton)!
- Primarily due to increase in effective area and spatial resolution
- Dips in plot due to shape of effective area curve and absorption edges

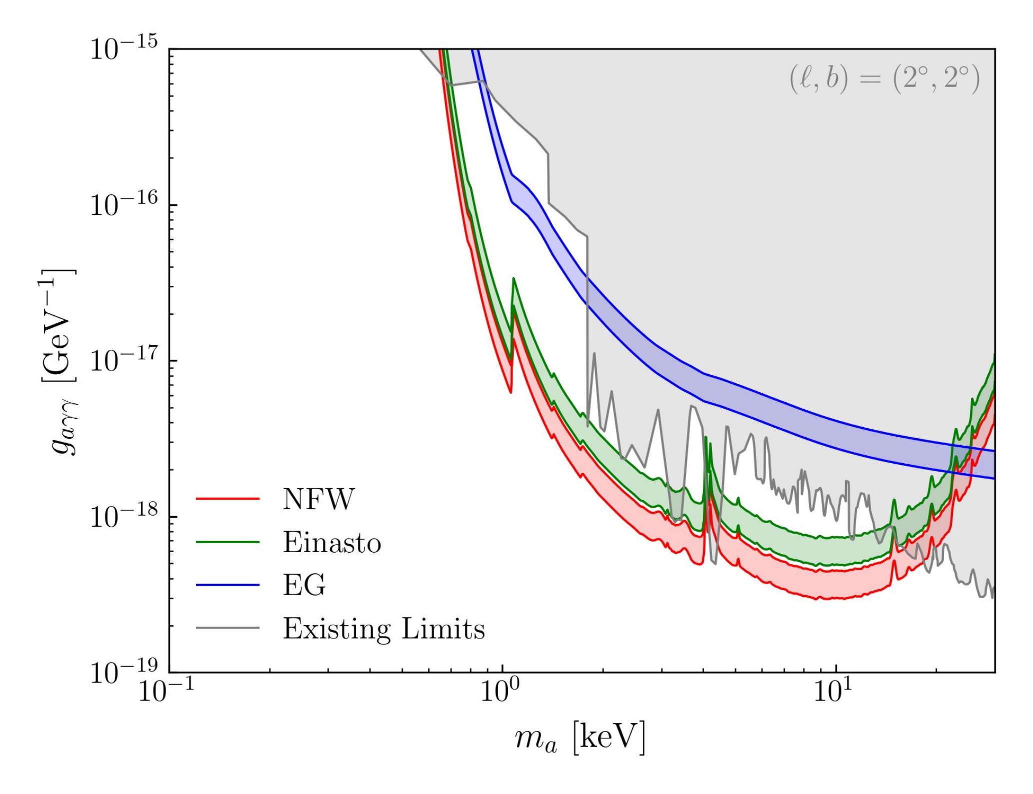


Existing limits obtained from Ciaran O'Hare: https://cajohare.github.io/AxionLimits/

Results (ALPs)

- ALPs decay into two photons
- Lifetime expression allows us to constrain diphoton coupling

$$\tau = \frac{64\pi}{g_{a\gamma\gamma}^2 m_a^3}$$

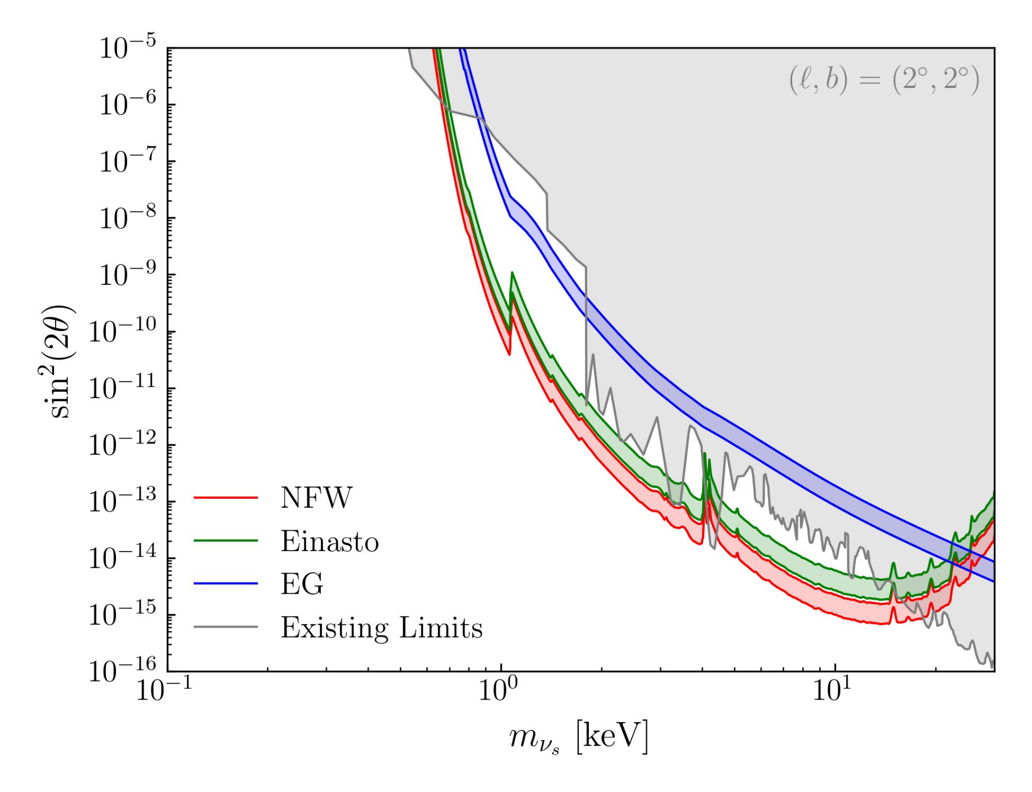


Results (Sterile Neutrinos)

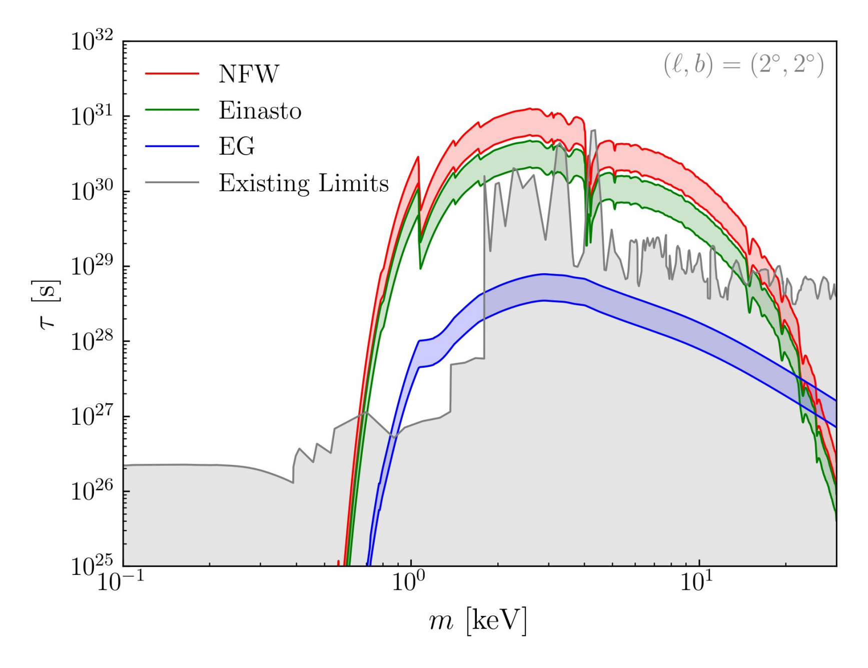
- Sterile neutrinos can decay into activate neutrinos via mixing ($\nu_s \to \nu\gamma$)
- Lifetime expression allows us to constrain mixing angle

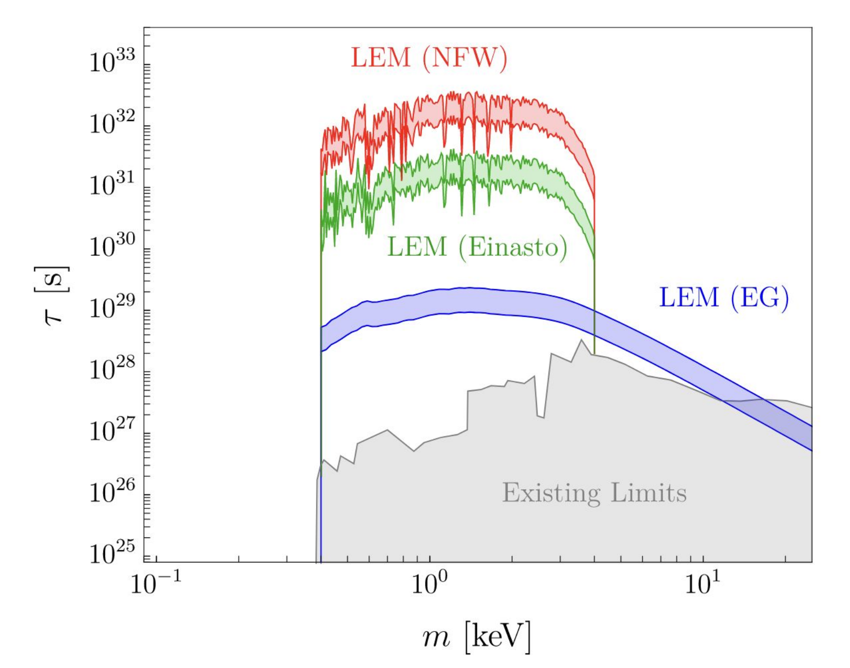
$$\Gamma_\gamma = \frac{9\alpha_{\rm EM} G_F^2 \sin^2(2\theta) m_{\nu_s}^5}{1024\pi^4}$$

$$\tau = \frac{{\rm Br}(\nu_s \to \nu\gamma)}{\Gamma_\gamma}$$



How does AXIS compare with LEM?





G. Krnjaic, E. Pinetti (*Phys. Rev. D* **109**, 095027 (2024))

How does AXIS compare with LEM?

- AXIS energy resolution is ~ 70 eV (FWHM at 1 keV) compared to ~ 2 eV for LEM
  - Main driver of difference in sensitivity
- Comparable effective areas
- Attenuation not accounted for in previous analysis
  - Signal region of interest typically above 1 keV, where absorption cross-section is small
- Existing limits updated with XMM-Newton data
- Both proposals competitive in constraining DM lifetimes

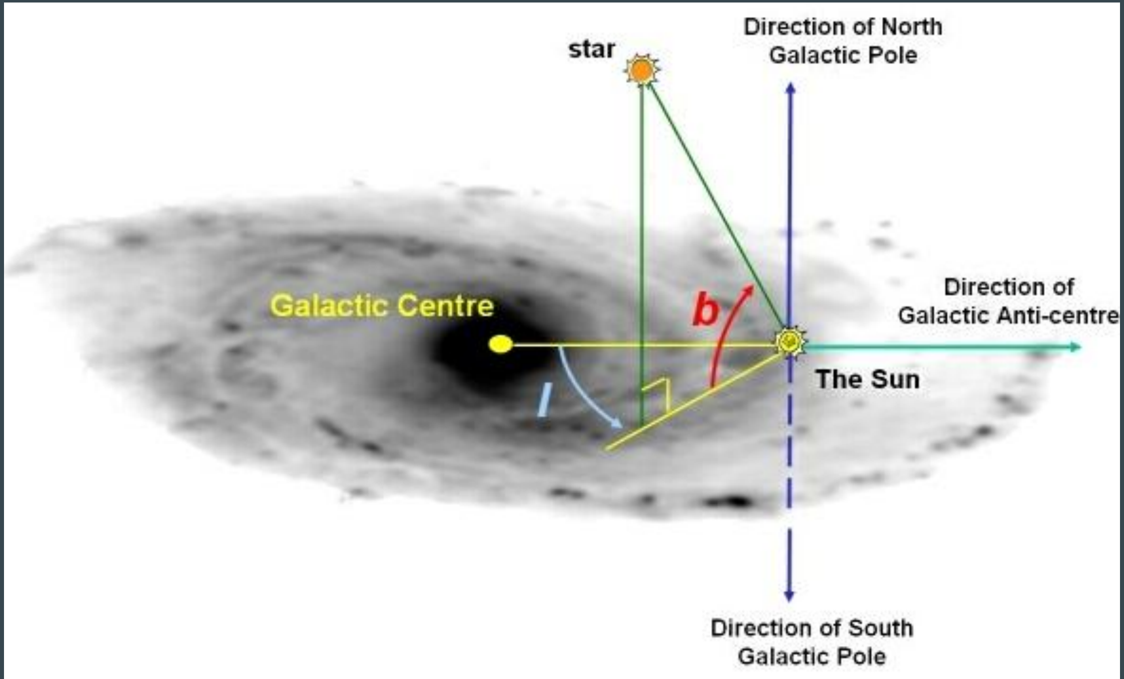
Conclusion and Outlook

- AXIS is one of two proposals submitted to NASA for a next generation X-ray telescope
- Significant improvements in effective area and spatial resolution compared to XMM-Newton and Chandra
- Look for DM decays rather than annihilations
- Galactic and extragalactic backgrounds from NXB, SXB and CXB
- AXIS can place tighter constraints on DM lifetime than previous X-ray telescopes (up to an order of magnitude improvement!)
- Similar to other proposals (e.g. LEM)
- Exciting prospects for DM indirect detection in the early 2030s!

Backup Slides

Galactic Coordinate System

- Line-of-sight coordinate: s
- Galactic longitude: l
- Galactic latitude: b



https://astronomy.swin.edu.au/cosmos/G/Galactic+Coordinate+System

Coding Pipeline

1. Compute backgrounds
2. Compute DM signal contributions
3. Construct chi-squared test statistic (observed events obey Poisson statistics)
4. Compute DM lifetime constraint as a function of DM mass at 2 and 5 sigma
    - Efficient computation leverages the fact that $\chi^2 \propto \tau^{-2}$
5. Additionally reinterpret results in the context of axion-like particles (ALPs) and sterile neutrinos
    - ALPs: constraint on axion-photon coupling
    - Sterile neutrinos: constraint on mixing angle

Sterile to Active Branching Ratio

- Comparison between tree- and loop-level diagrams for sterile neutrino decay
- Dominant decay mode is mediated by a virtual Z boson
  - Tree-level diagram with three-body final state
  - Two weak vertices
- Sterile to active diagram is achieved through mixing
  - Loop-level diagram with two-body final state
  - Two week vertices
  - One EM vertex
- Loop factor: ~0.01, EM vertex: ~0.01, three- vs two-body phase space: ~0.01

$$\mathrm{Br}(\nu_s \to \nu\gamma) \sim 0.01$$