Constraining Dark Matter Decays at the keV Scale with the NuSTAR Observatory

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TeVPA – Kingston, ON
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Based mostly on arXiv:2207.04572 (BMR, *et al*)

Outline

- Sterile-neutrino dark matter
- NuSTAR as a dark-matter observatory
- Updated NuSTAR constraints on sterile neutrinos

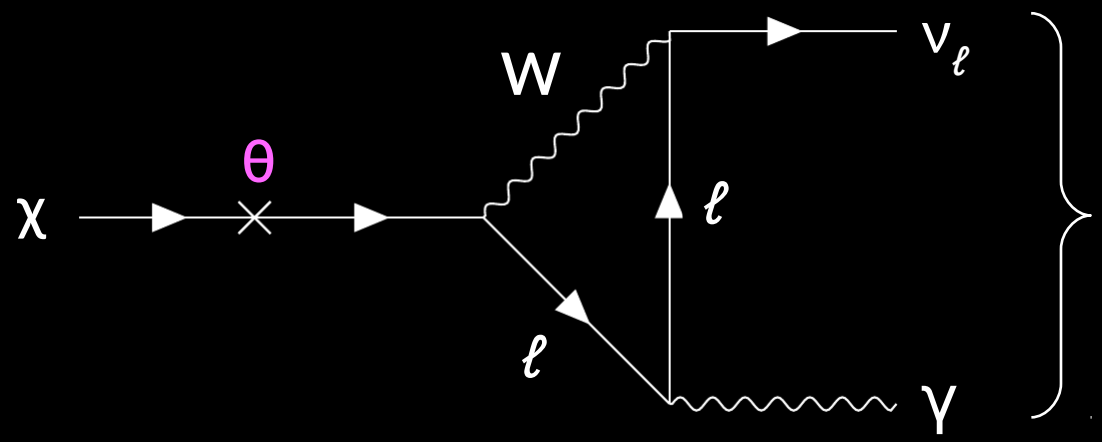
Sterile-neutrino DM

Many BSM theories introduce additional sterile (heavy, RH) neutrinos with cosmologically long lifetimes.

– e.g., the Neutrino Minimal Standard Model (νMSM, e.g., 0503065, 0612182)

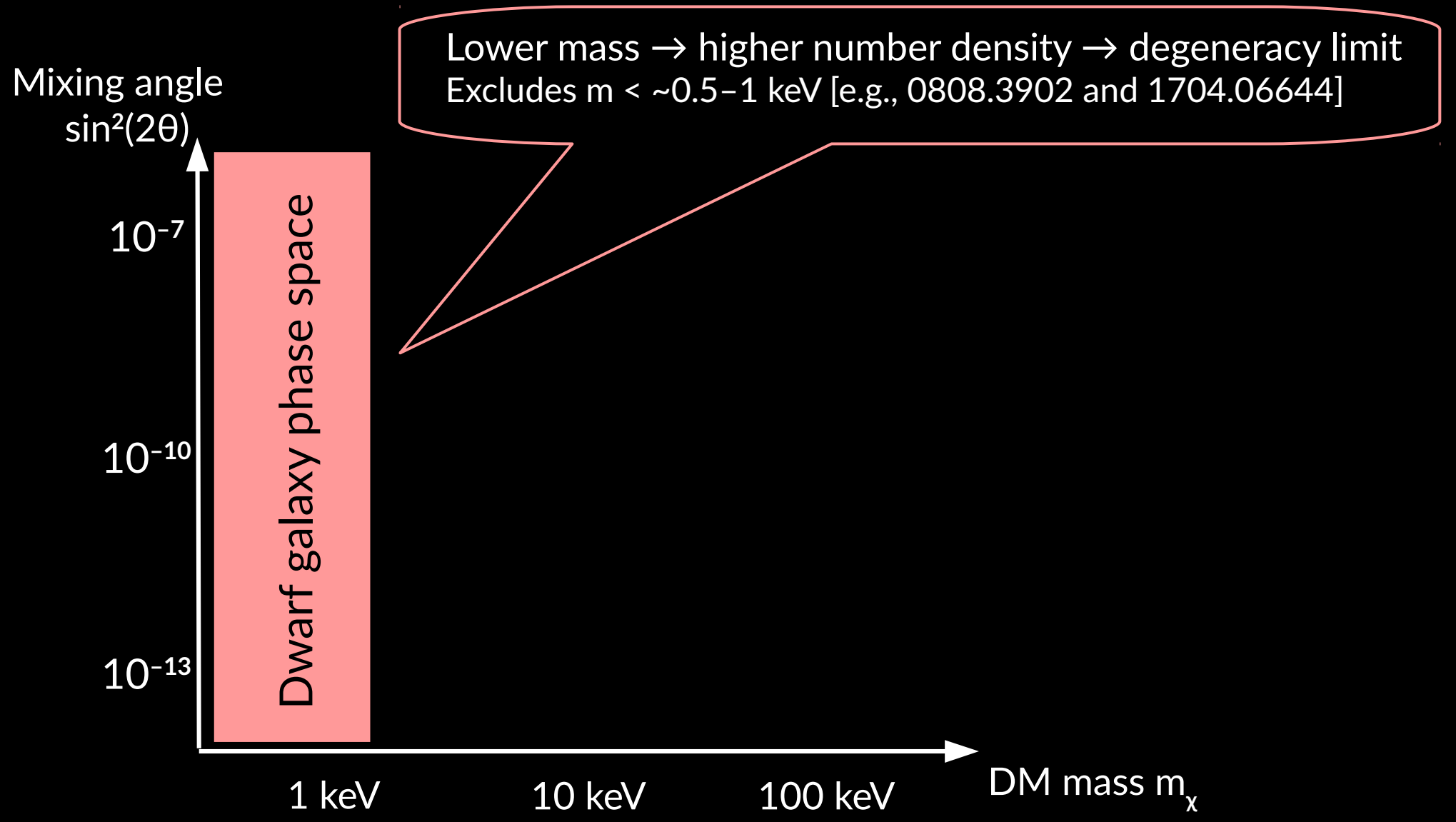
keV-scale sterile neutrinos are an ideal DM candidate!

– keV mass range → x-ray photons ($E_\gamma = m_\chi/2$)



Decay rate ∝ $\sin^2(2\theta)\, m^5$

The sterile-neutrino landscape



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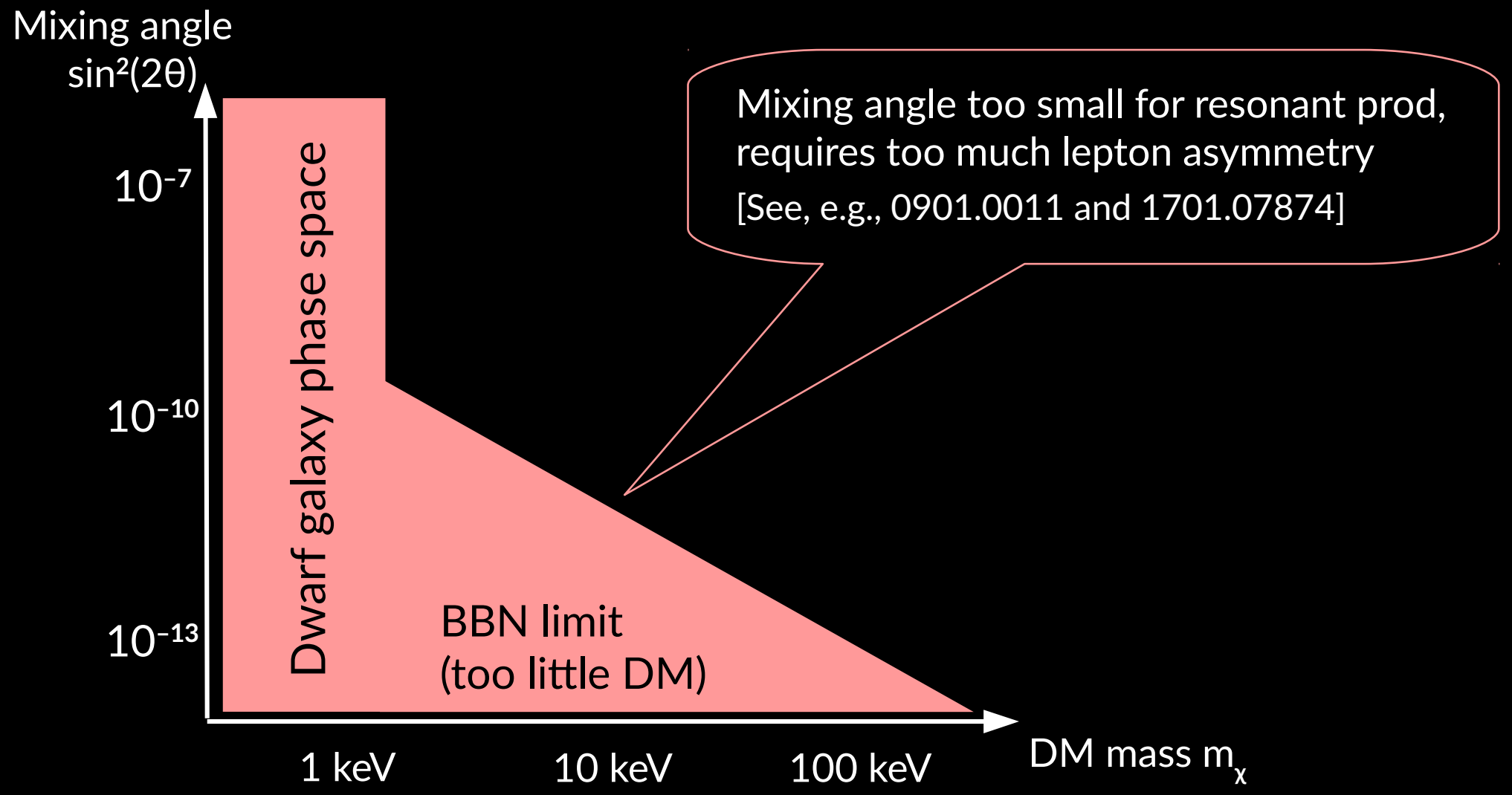
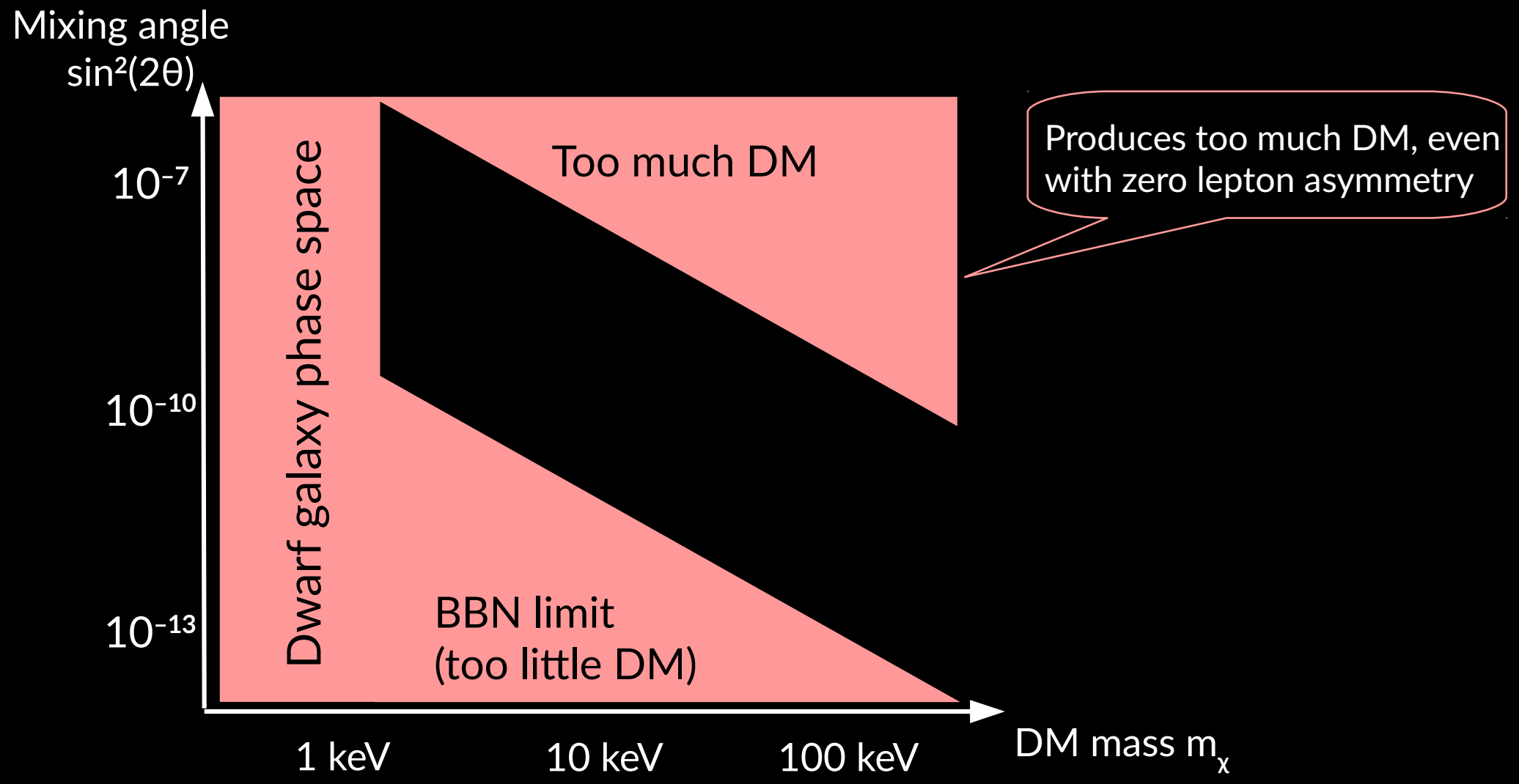


The sterile-neutrino landscape



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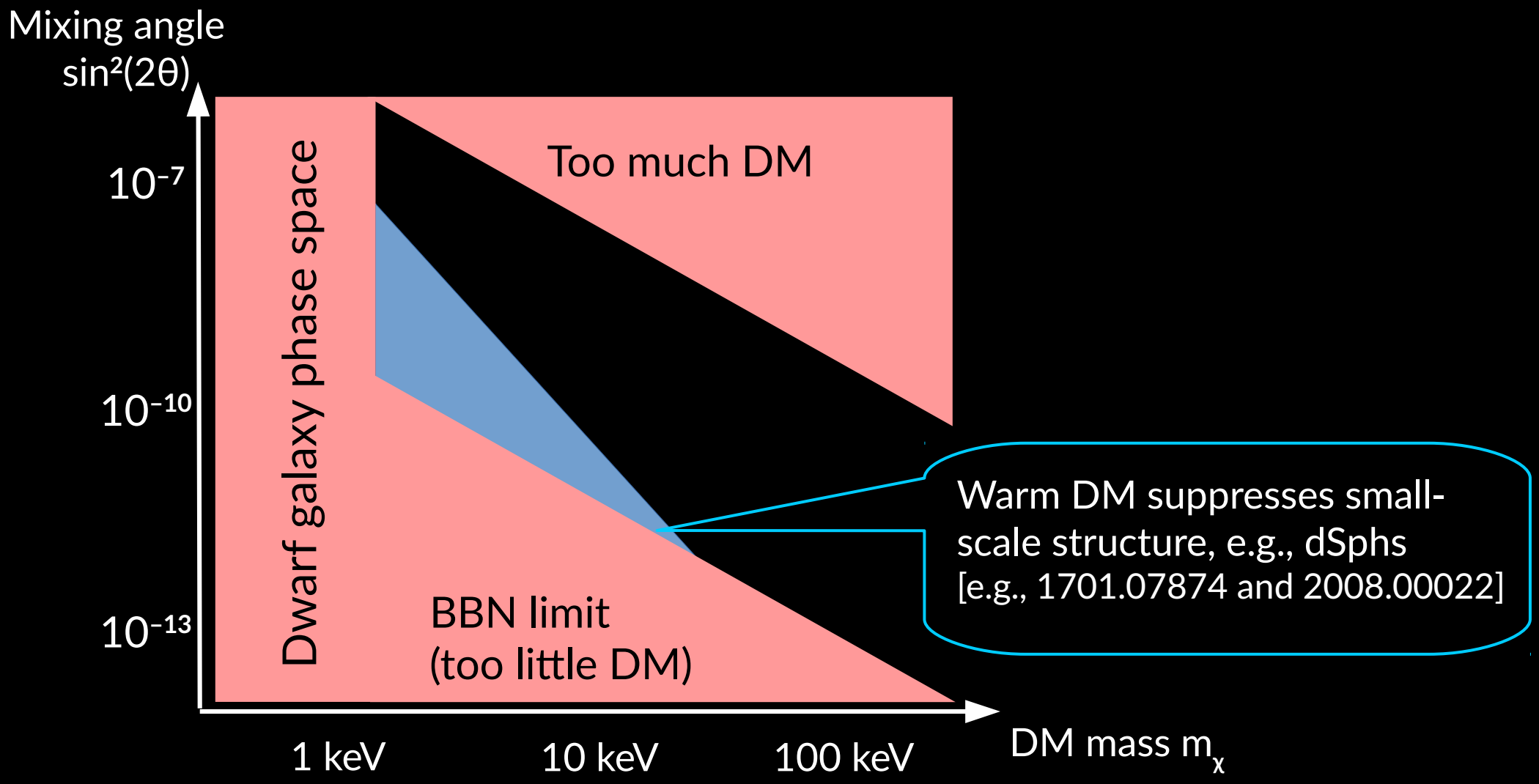
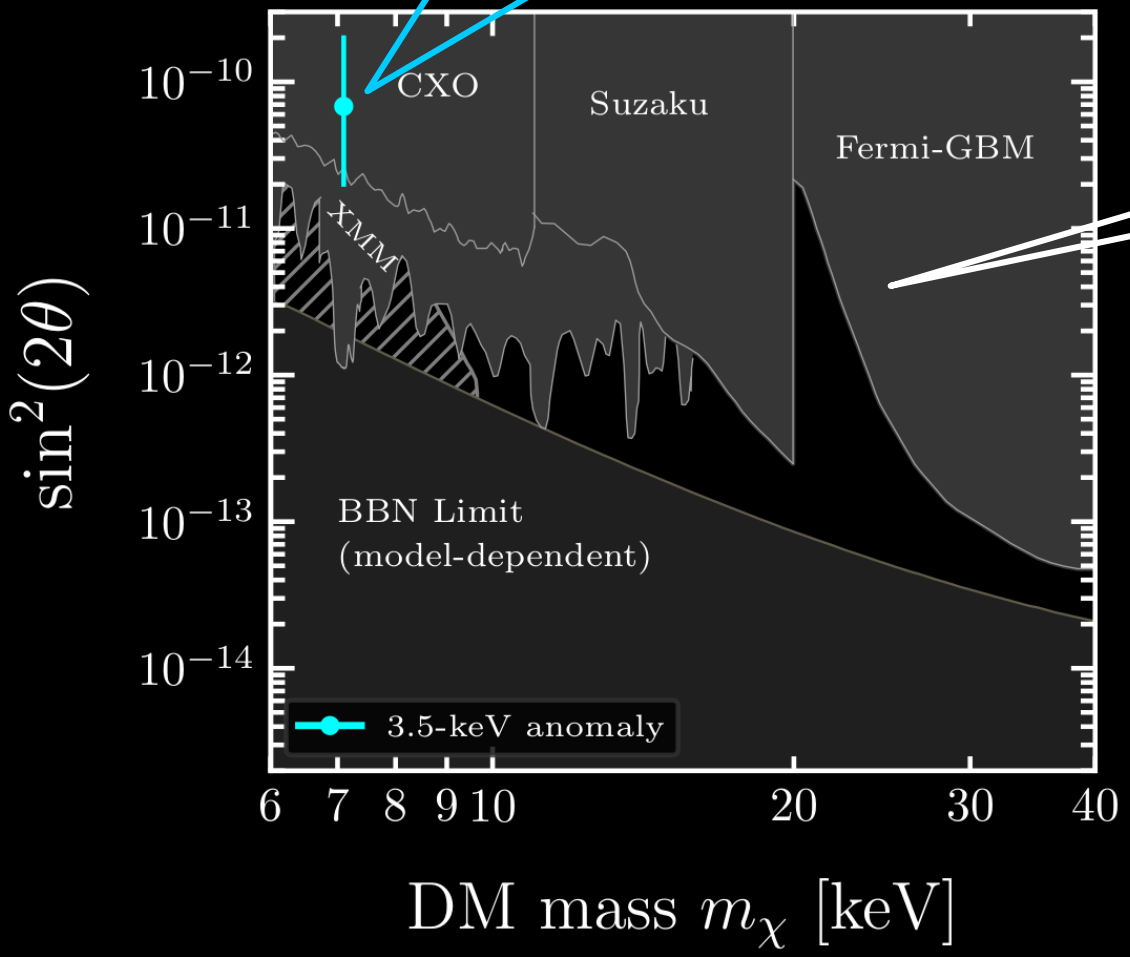


The sterile-neutrino landscape

Possible detection?
[1402.2301, 1402.4119]

Model-independent x-ray limits
[see, e.g., list in 2207.04572]



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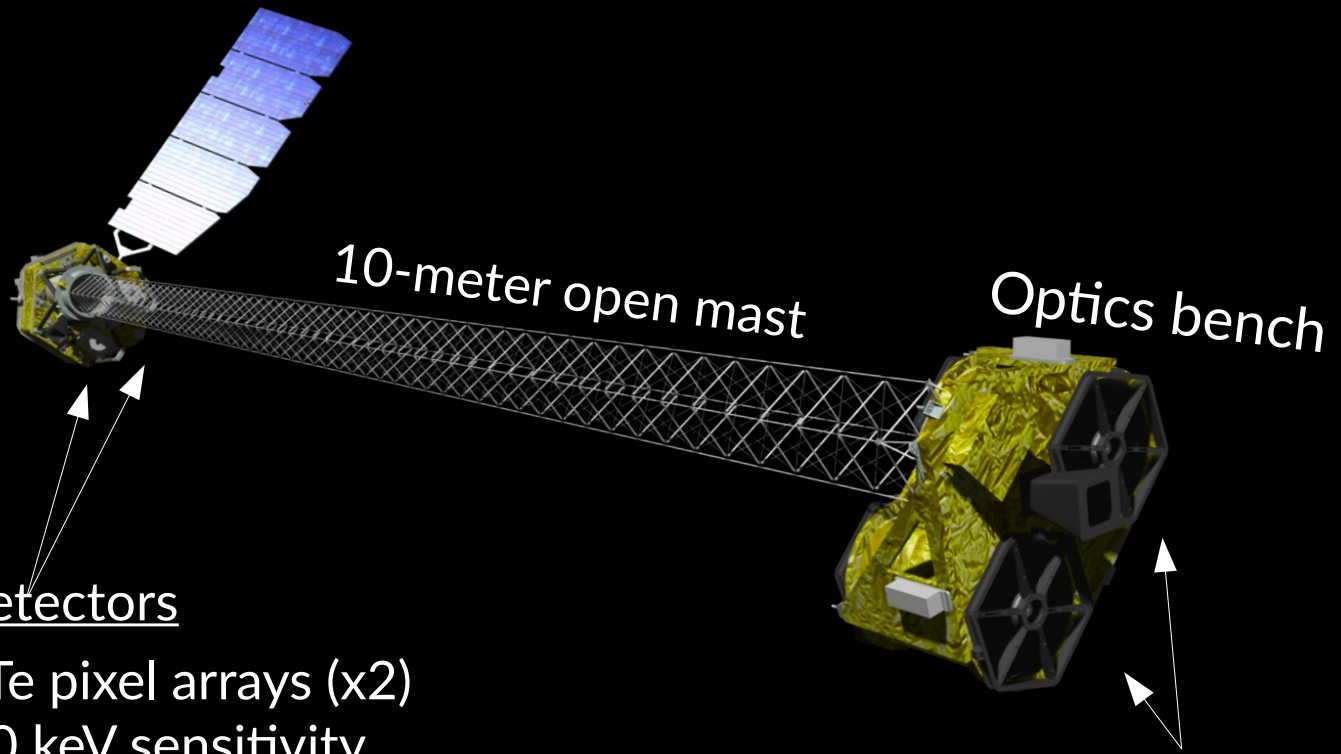
The NuSTAR telescope

First high-energy (E > 10 keV) focusing telescope (large collecting area) in orbit!



X-ray detectors

- CdZnTe pixel arrays (x2)
- 3–160 keV sensitivity
- 13 cm^2 per array

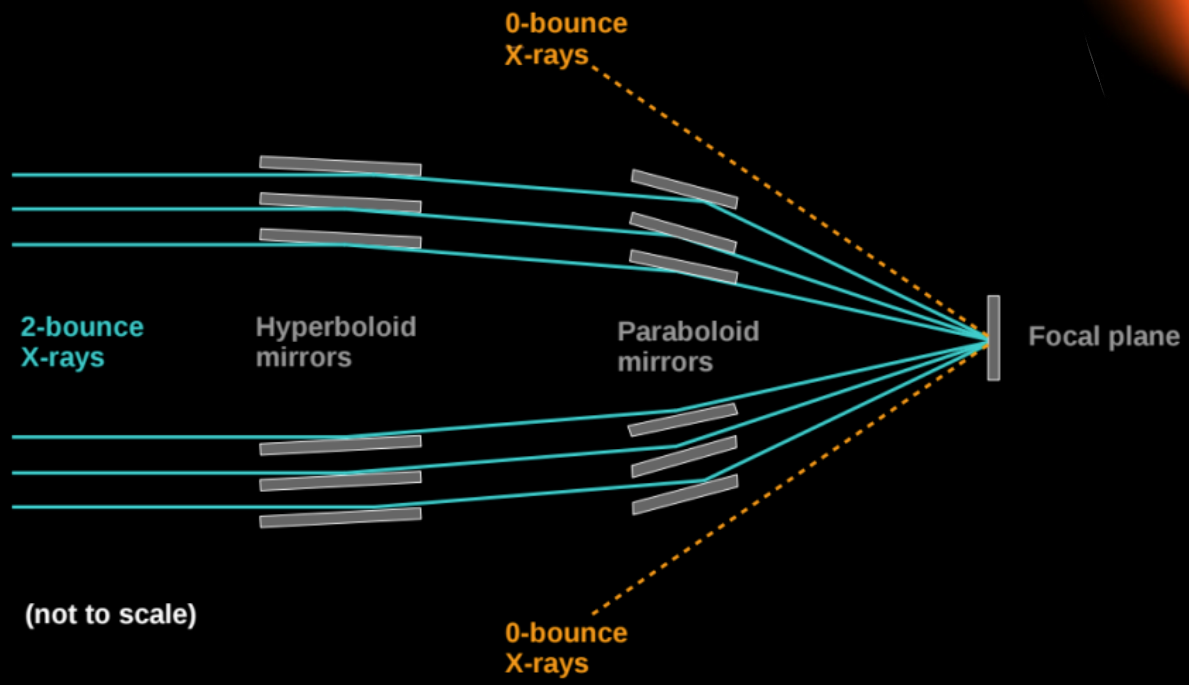
Focusing optics

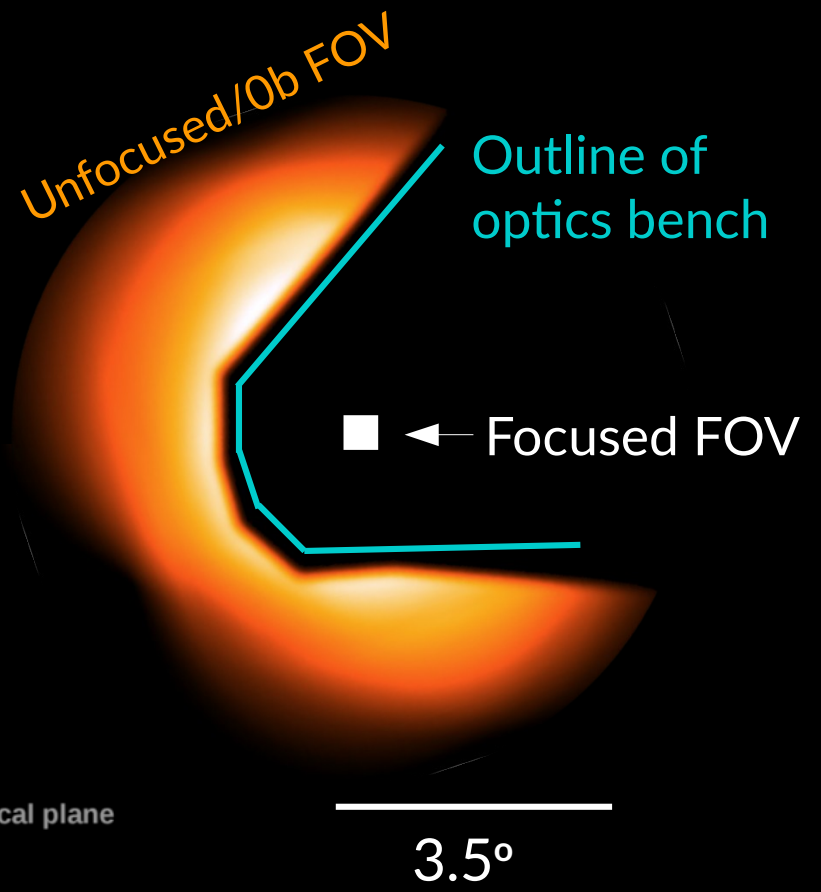
- Grazing-incidence optics (x2)
- Small solid angle (~0.05 deg^2)
- 3–79 keV reflectance

NuSTAR as a DM observatory

A major NuSTAR background is unfocused (0-bounce) photons bypassing the mirrors.

- Different areas of the detector "see" different solid angles Ω_{0b} on the sky





NuSTAR as a DM observatory

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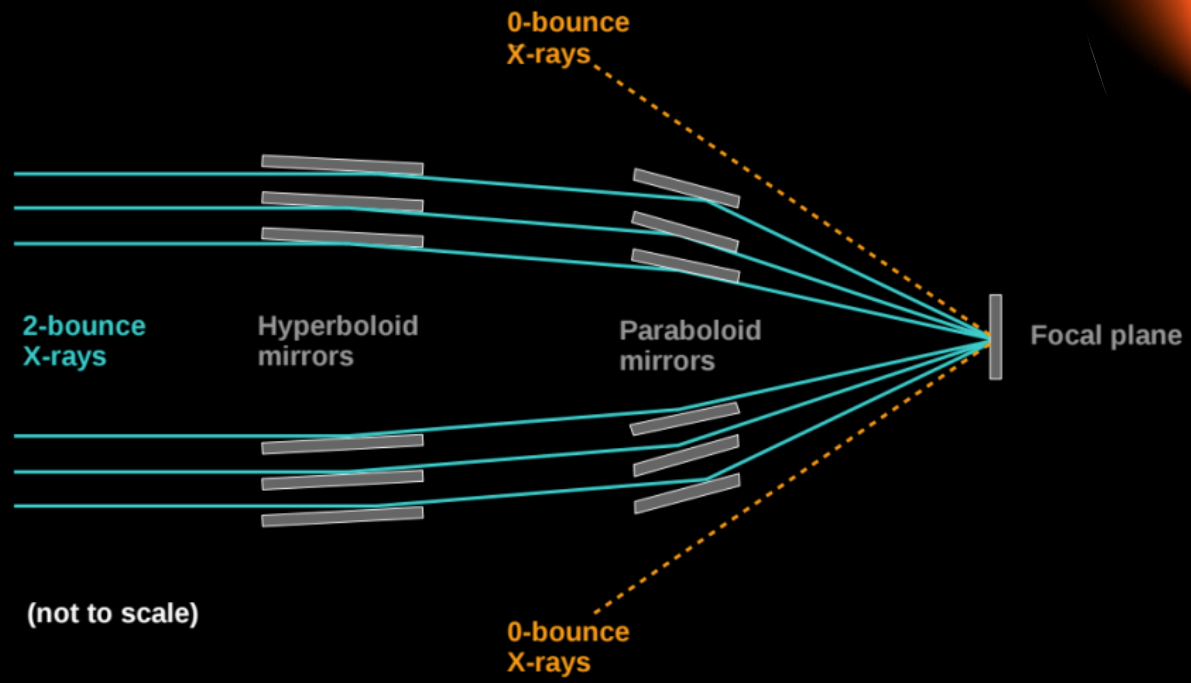
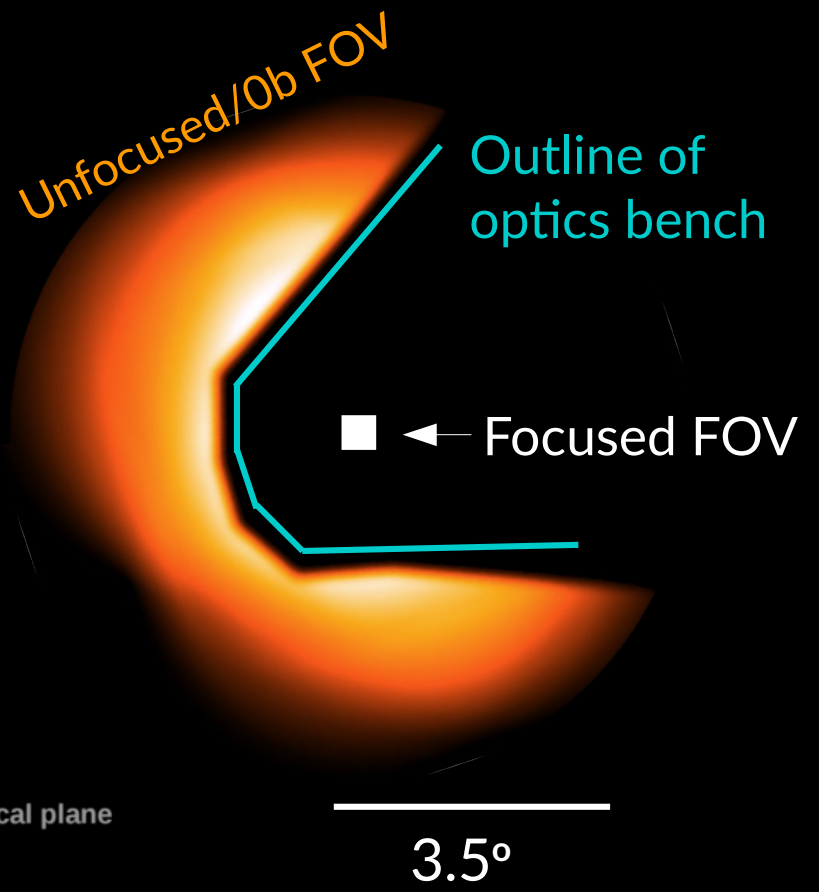
- Different areas of the detector "see" different solid angles Ω_{0b} on the sky

For diffuse sources (e.g., DM!) there are 10x more unfocused photons than focused!

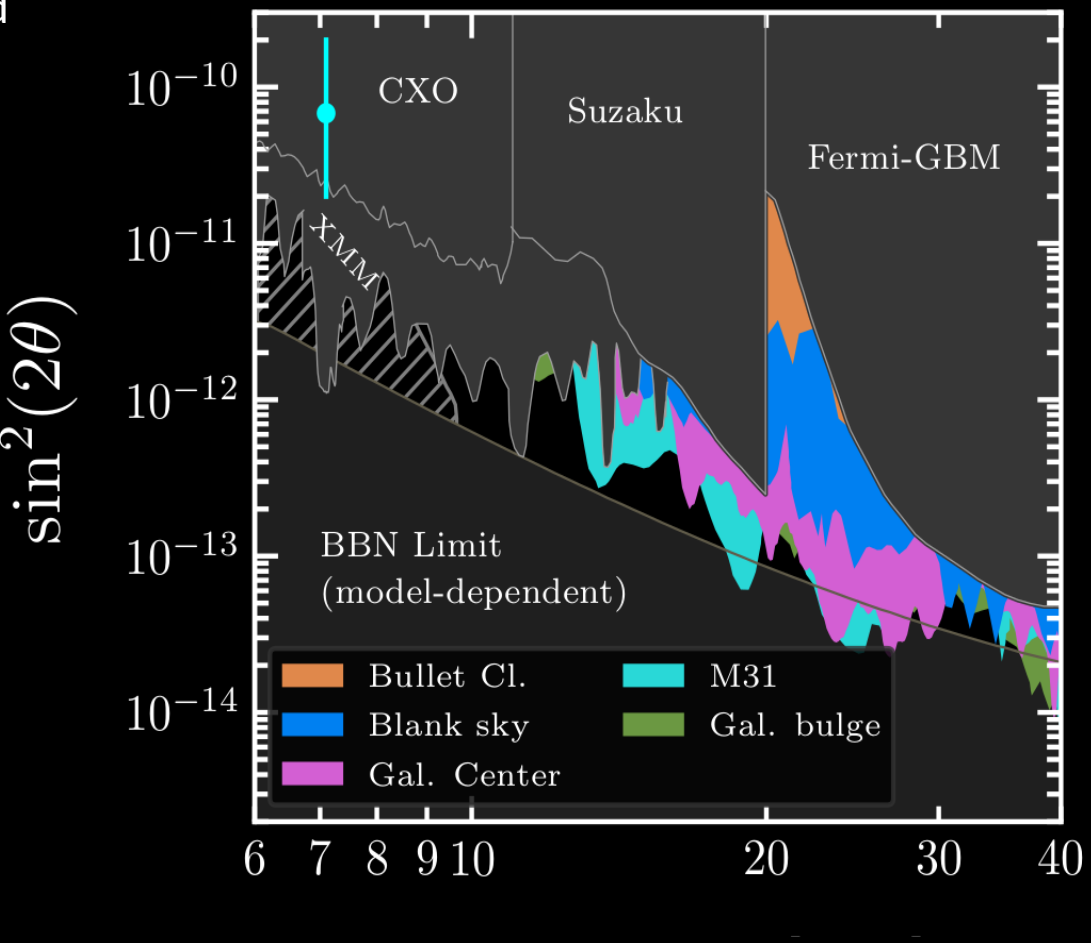




NuSTAR as a DM observatory

First NuSTAR sterile-neutrino search used data from Bullet Cluster [1507.01378]
- Limited by cluster x-ray background and large distance (z ~ 0.3)

Followed by several 0-bounce analyses exploiting large 0-bounce solid angle:
- MW blank-sky [1607.07328]
- MW Galactic Ctr. [1609.00667]
- M31 galaxy [1901.01262]
- MW Galactic bulge [1908.09037]

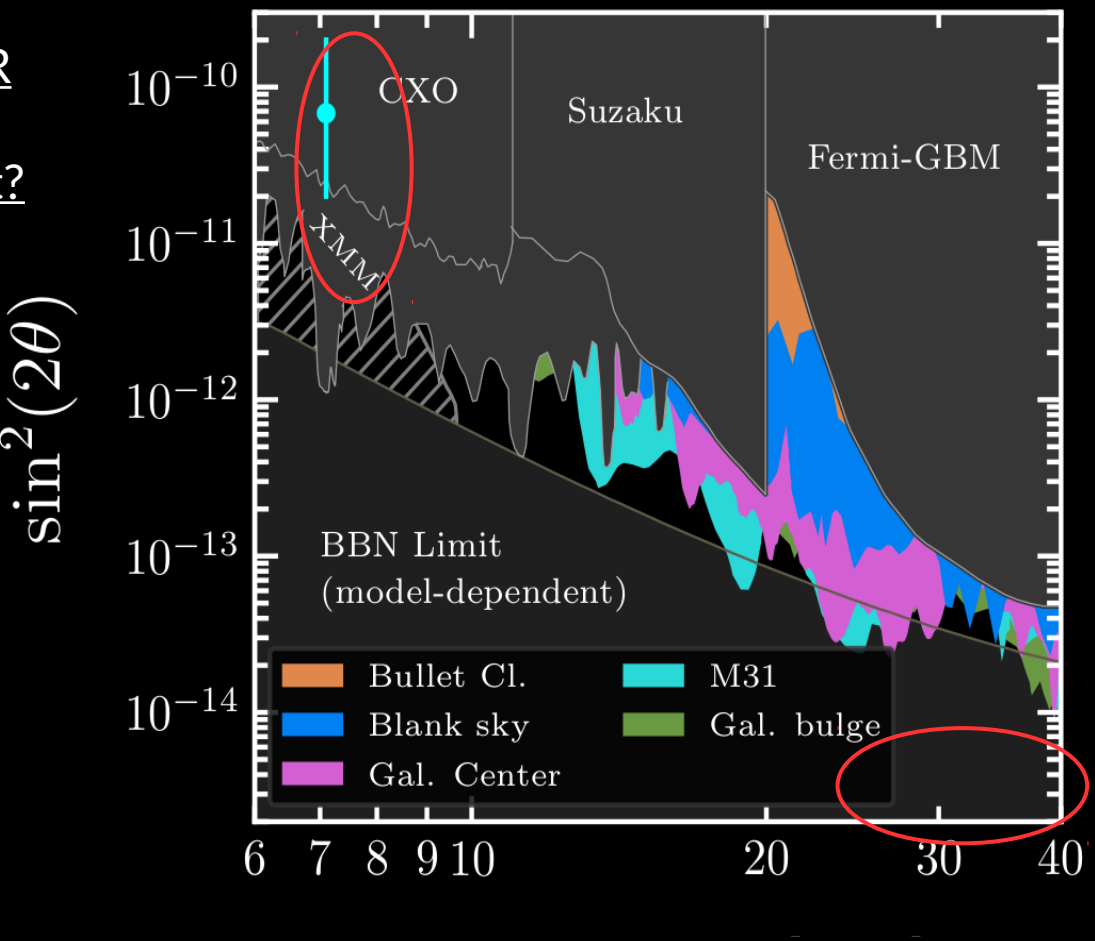


NuSTAR as a DM observatory

Additional work was needed to realize the full potential of NuSTAR's observation catalog:

- Background lines (solar + internal detector) limit sensitivity to DM decay lines. NuSTAR background model includes a 3.5-keV line, observed in Earth-occulted data. What is it?

- High-statistics blank-sky observations reveal issues modeling the detector continuum background for energies ~10–20 keV.



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Updated NuSTAR results

Our new preprint contains two independent analyses [2207.04572]:

- Novel “spatial-gradient” method applied to ~7 Ms blank-sky data
- Traditional parametric analysis with improved background model (~20 Ms data)

Long-Exposure NuSTAR Constraints on Decaying Dark Matter in the Galactic Halo

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The spatial-gradient method

NuSTAR photons have different spatial geometries on the detectors!

– Technique validated using CXB measurements [2011.11469]

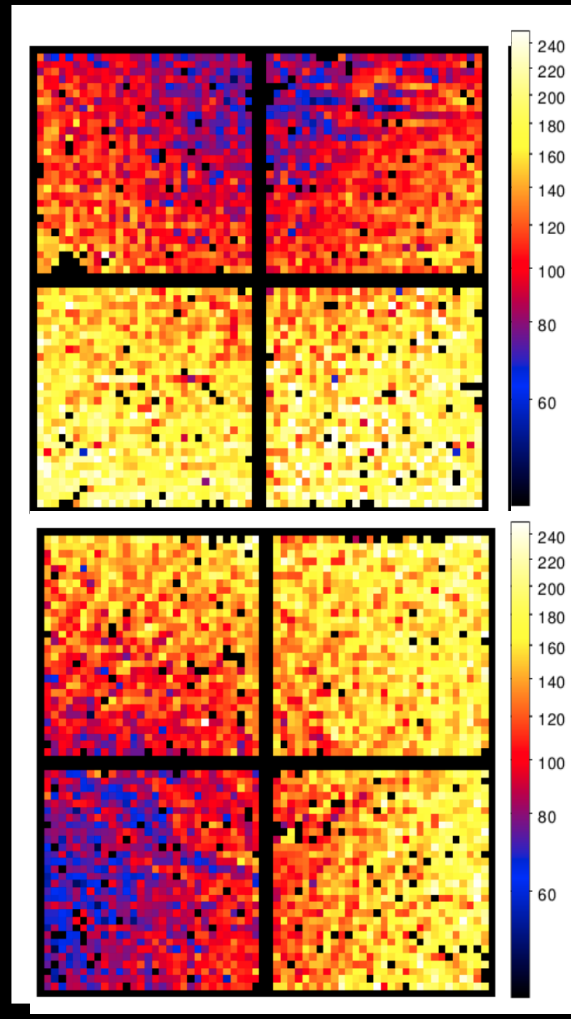
$$N_{i,\mathrm{model}} \sim \left(\frac{dN}{dt}\right) T_{\mathrm{obs}} + \left(\frac{dF}{d\Omega}\right) A_{\mathrm{pix}} \Omega_{0\mathrm{b}} T_{\mathrm{obs}}$$

Spatially ~flat background

“Pac man” shaped sky intensity

DET-A

DET-B



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Spatially ~flat background

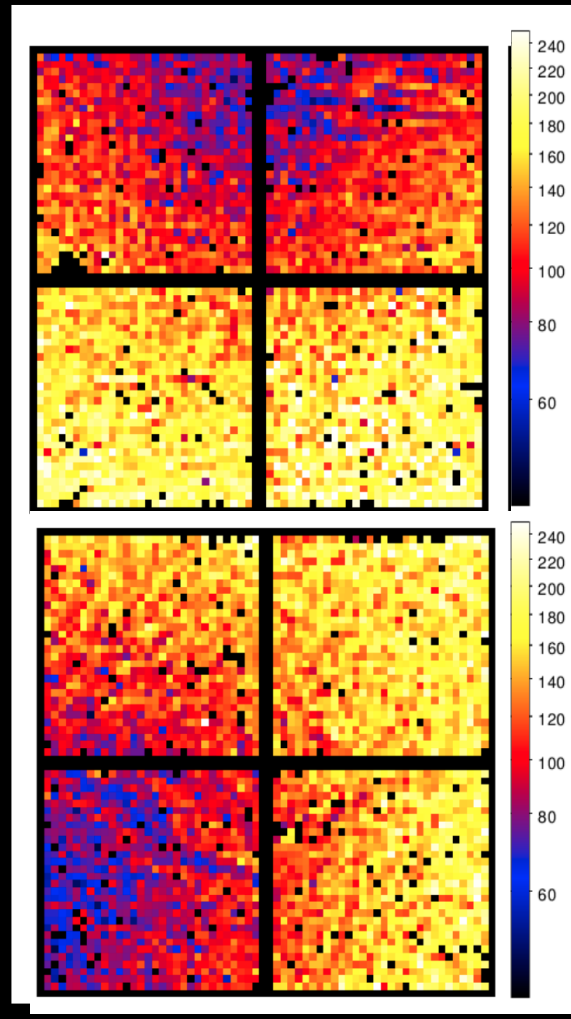
"Pac man" shaped sky intensity

$$\mathcal{L} = \prod_i \mathrm{Pois}(N_{i,\mathrm{obs}}, N_{i,\mathrm{model}})$$

Minimize in each energy bin → $d^2F/dEd\Omega$

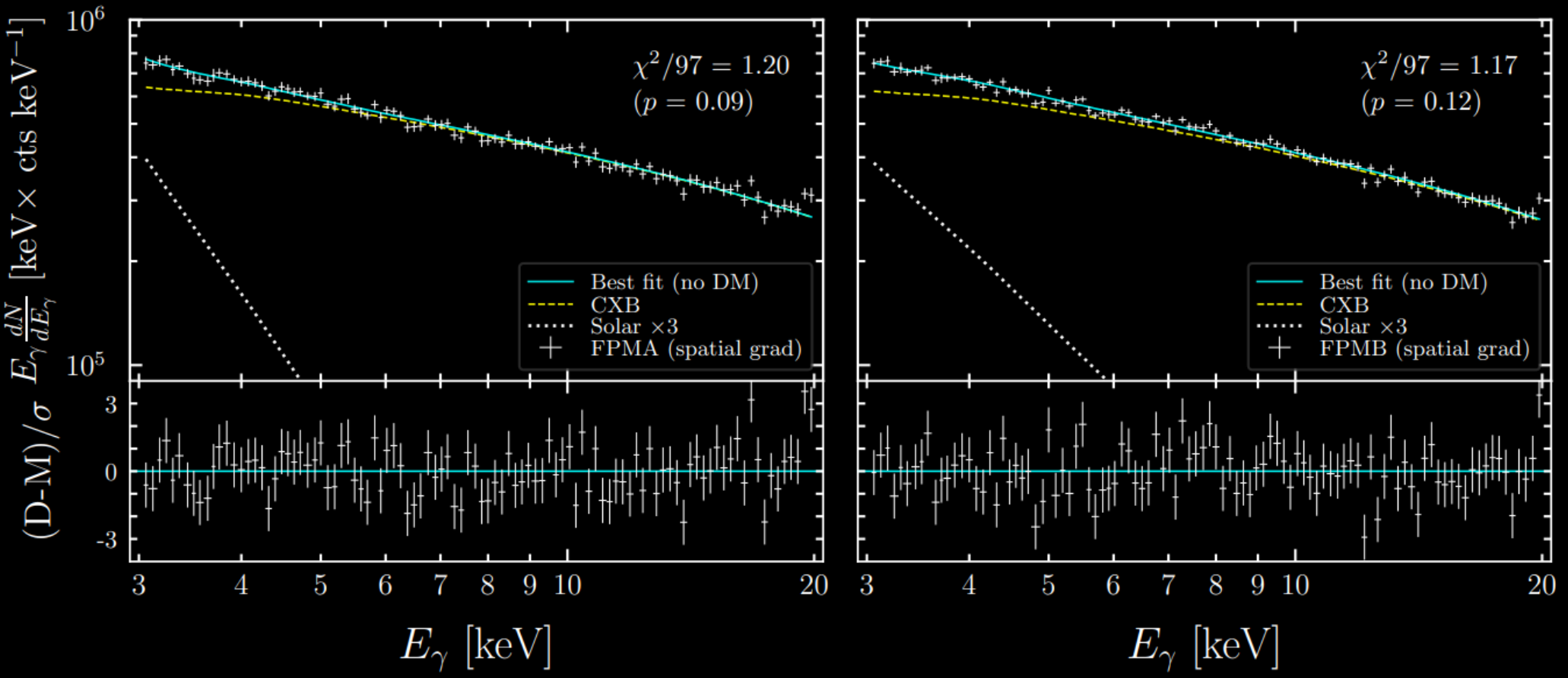
DET-A

DET-B



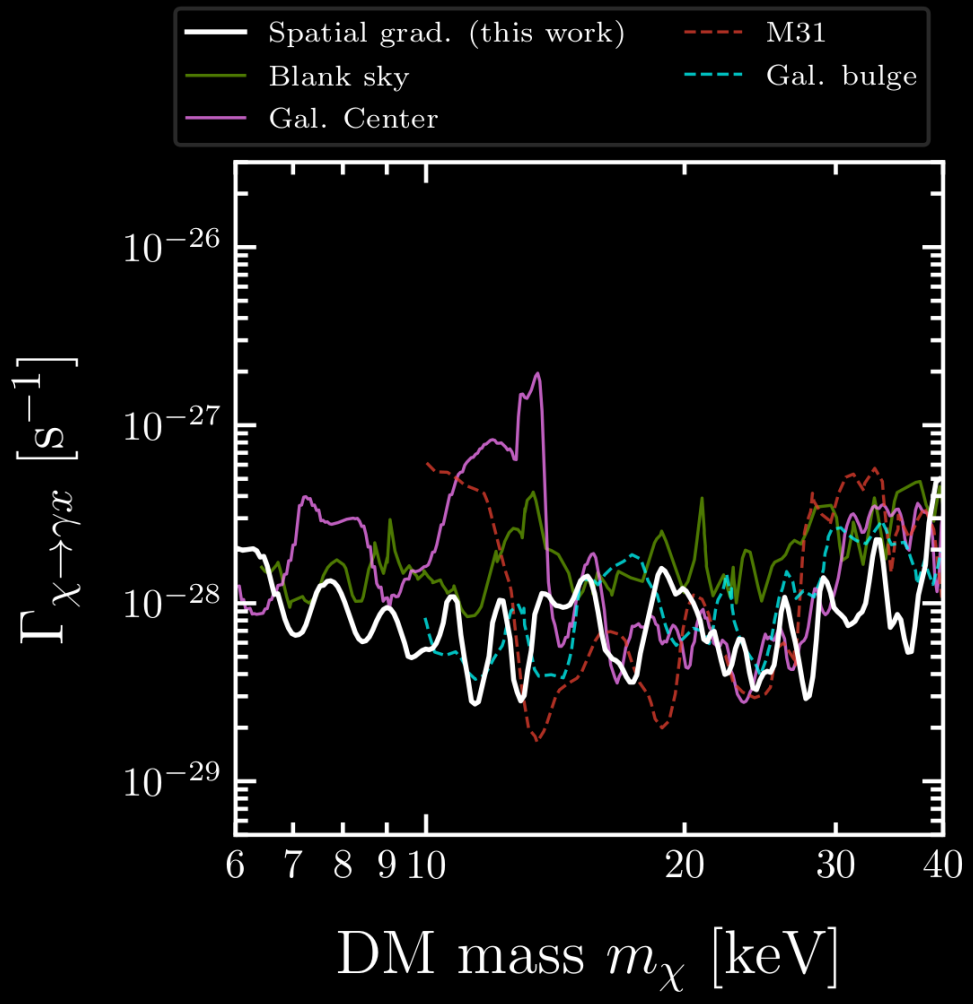
The spatial-gradient method

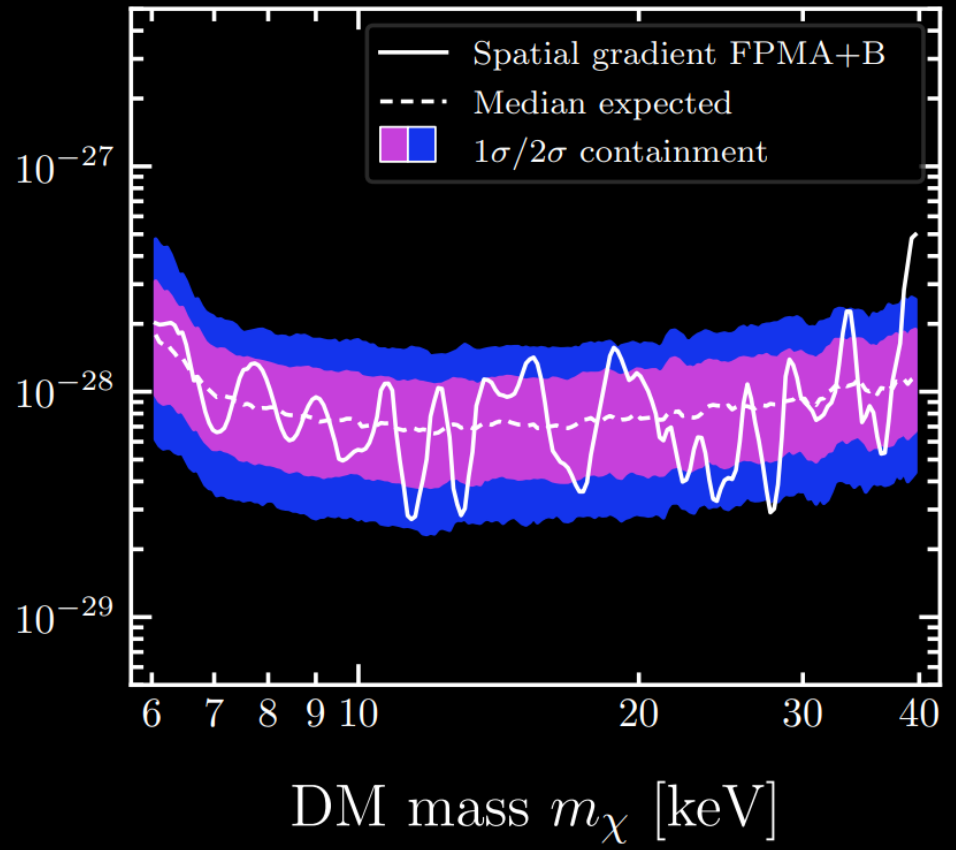
For the first time, we use the geometry of NuSTAR photons to reject detector backgrounds (especially lines!) on a pixel-by-pixel basis!



The spatial-gradient method

→ We don't see the 3.5-keV line! This suggests it's a detector feature, not astrophysical.

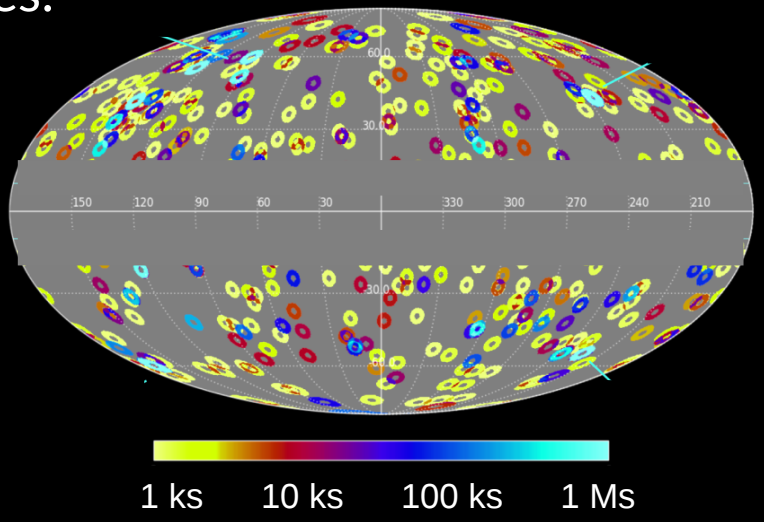


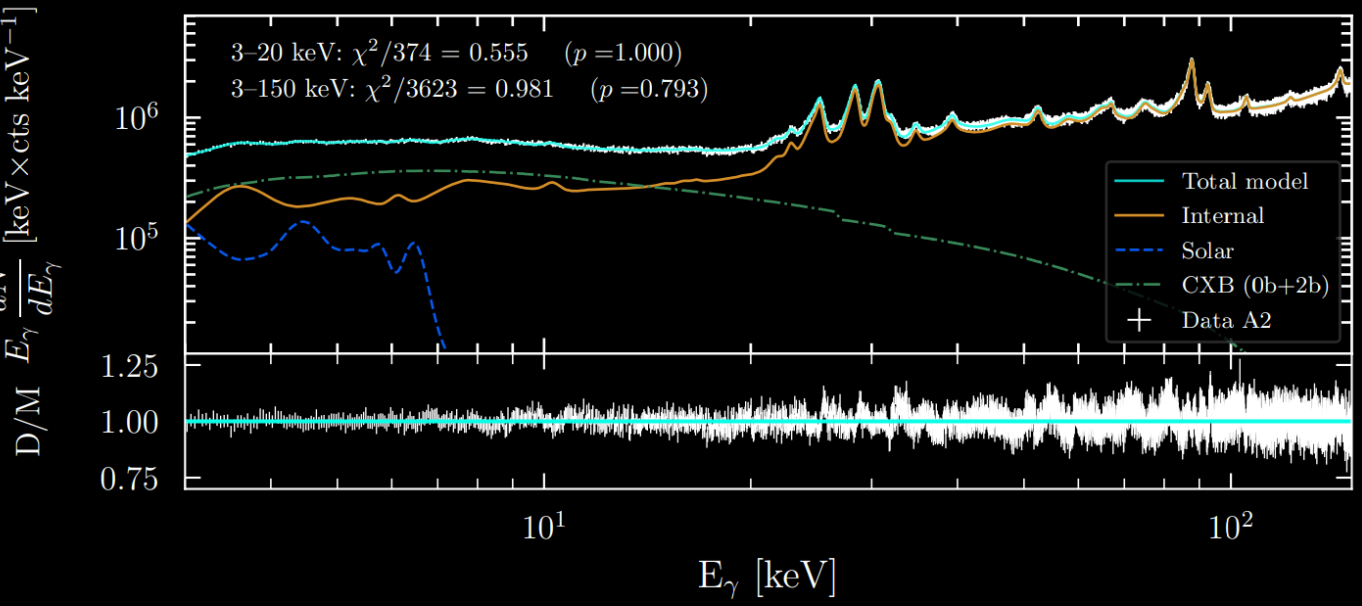


The parametric method

Two huge differences from previous NuSTAR analyses:

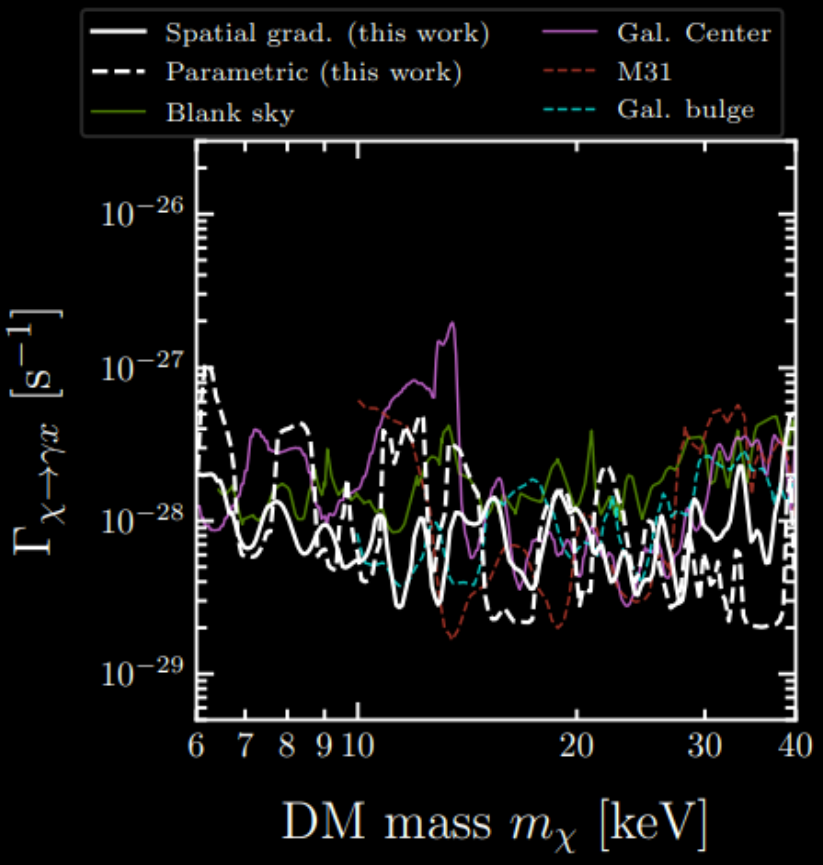
- Extract and model spectra from each detector chip independently (each has slightly different bkgd)
- Use much more data (20 Ms/detector!)
- Scan energy range 3–20 keV (mass range 6–40 keV)

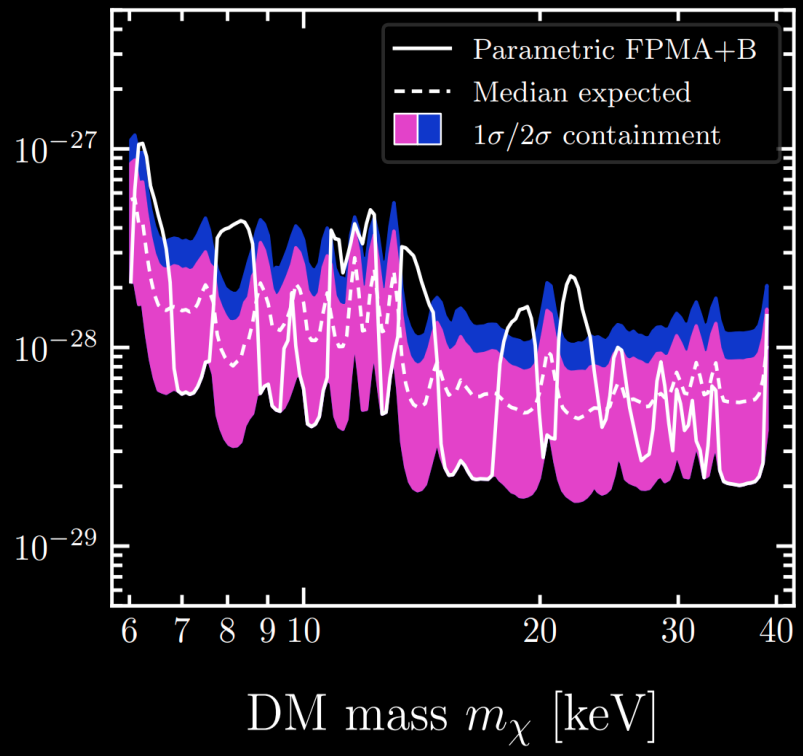




The parametric method

- Leads to similar constraints as spatial-gradient method (useful consistency check)
- High statistics and improved background model → strong constraints for masses 30–40 keV
- We have a 3.5-keV line in the background model, but it's much wider than expected for DM (artifact of detector absorption/response rather than real line?)





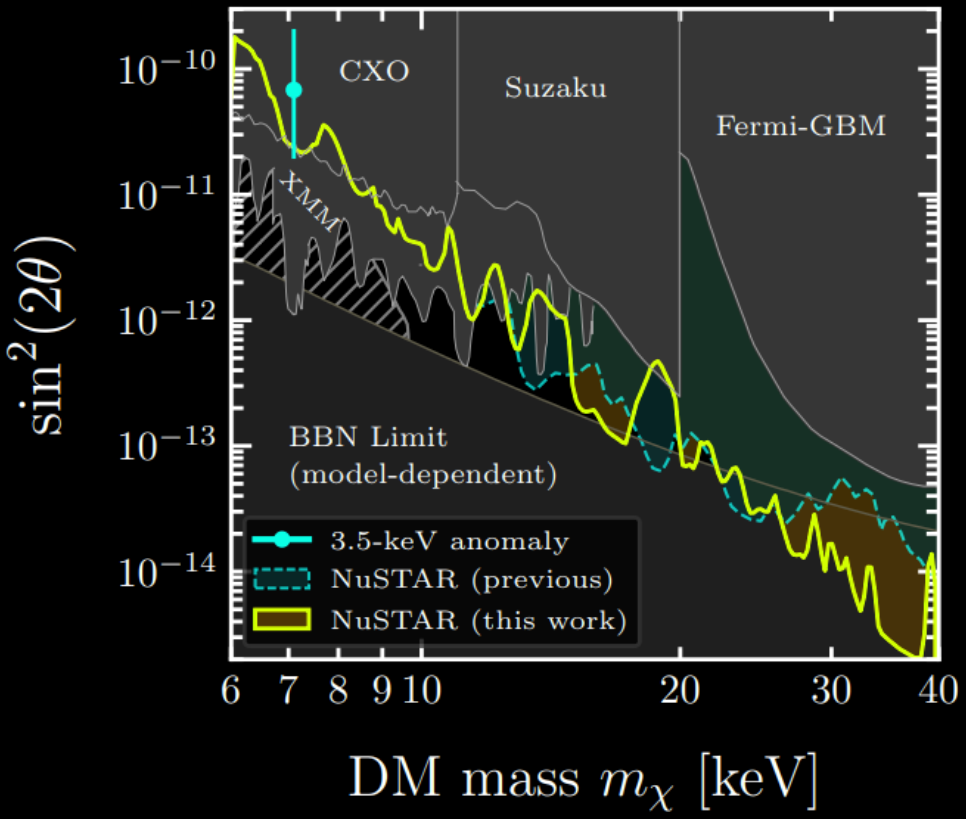
Conclusions

- NuSTAR has been essential for constraining the sterile-neutrino parameter space down to (and below) the BBN limit!

- We strongly disfavor a DM origin of the 3.5-keV line in the MW halo using two Independent analysis techniques!

- New/upcoming instruments (eROSITA, Micro-X, XRISM, Athena) are needed!
  - see A. Dekker's talk in this track at 15:00 Wed!

- *Not much room left for sterile-neutrino DM to hide (at least in the simplest models)*



Thank you!!

Backup Material

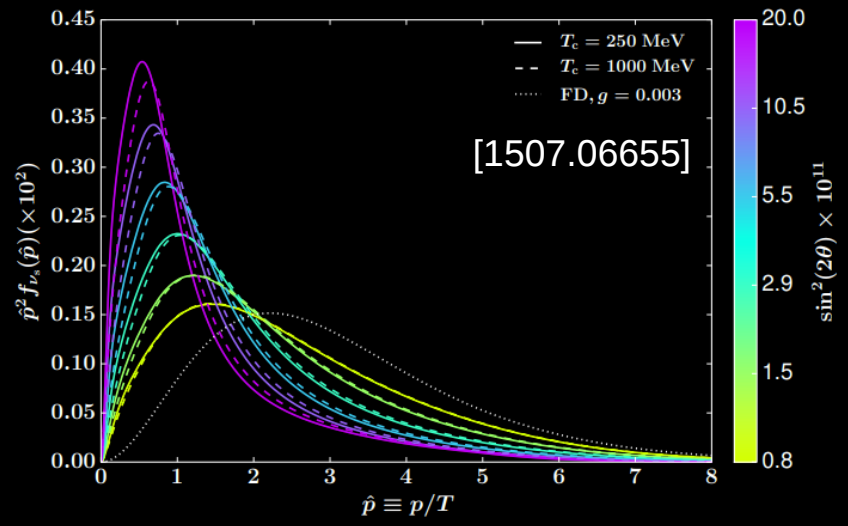
Resonant production

If there is a primordial lepton asymmetry (leptons vs anti-leptons), matter effects can enhance the sterile-neutrino production rate [Shi-Fuller mechanism].

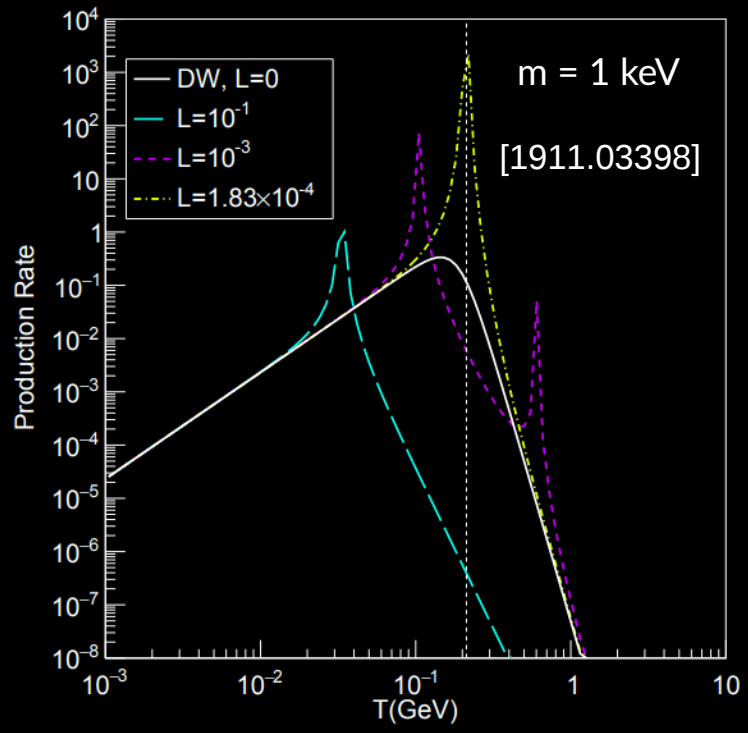
→ Lepton asymmetry constrained mainly by BBN yields of D and ^{4}He [0506162]

The location/amplitude of these resonances depends on the mass, mixing angle, and lepton asymmetry.

→ Also affects the sterile neutrino momentum spectrum, and hence structure formation.

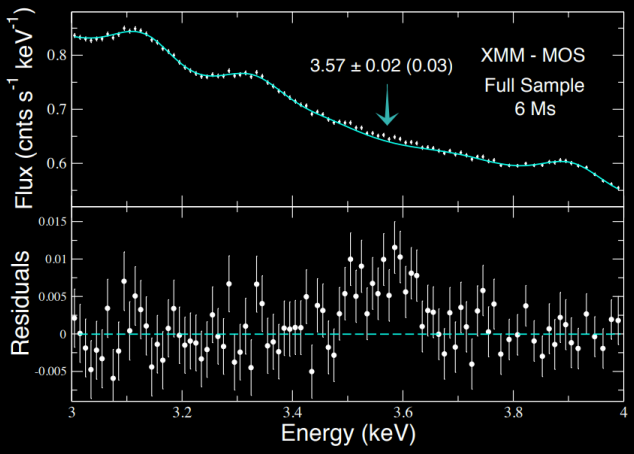


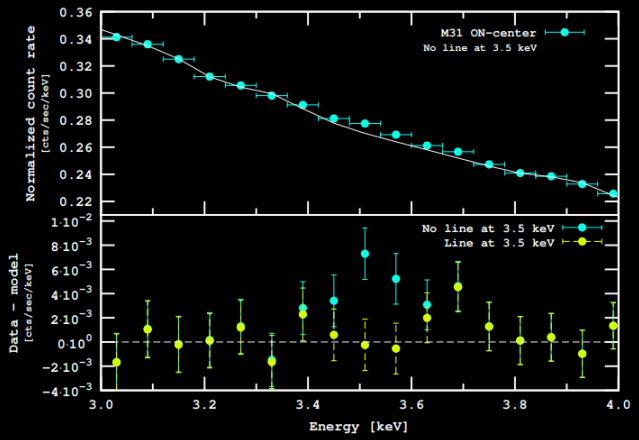
(b) sterile neutrino PSDs at $T = 10$ MeV

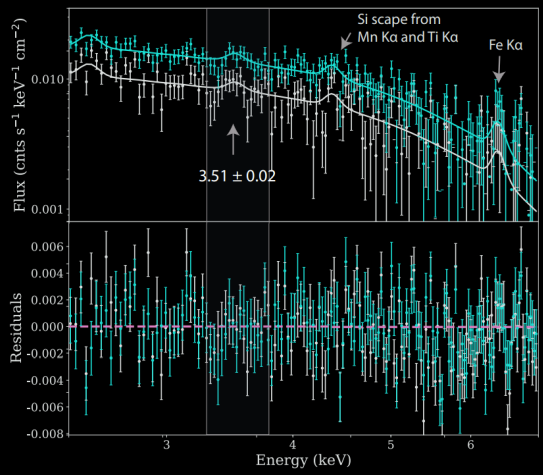


The 3.5-keV line

Line observed by XMM in galaxy clusters [1402.2301] and M31 + Perseus [1402.4119], and (maybe) by CXO in MW halo [1701.07932].
Inferred mixing angle $\sin^2(2\theta) \sim (0.2 \text{ to } 2) \times 10^{-10}$, including DM density uncertainties

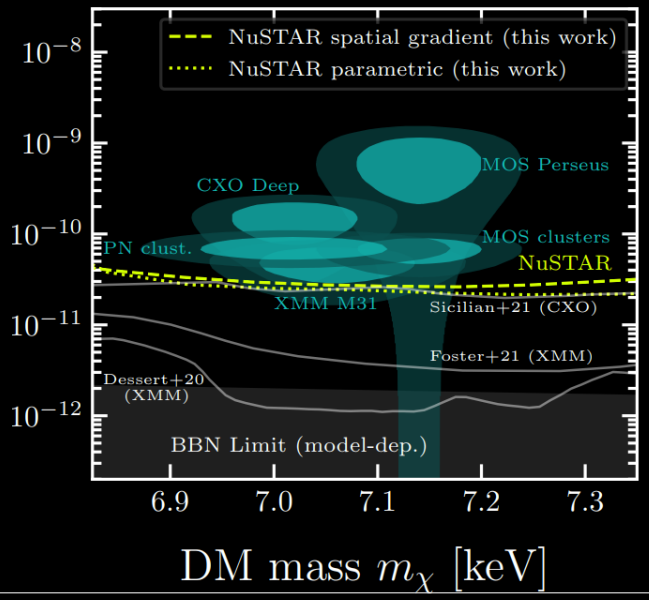






However, not observed by …

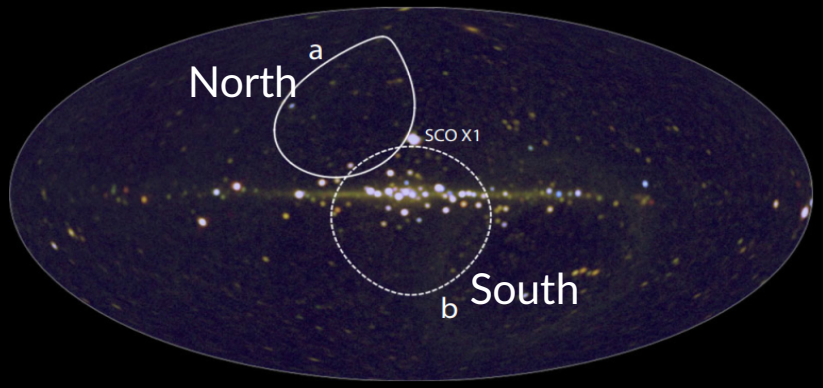
- CXO [MW halo, 2008.02283]
- XMM [clusters, 2006.13955]
- HaloSat [MW halo, 2105.12252]
- NuSTAR [MW halo, 2207.04572]
- XMM [MW halo, 1812.06976, 2102.02207]
  - ~ applied new HEP statistical techniques
  - ~ see discussion in 2004.06170, 2004.06601, 2006.03974

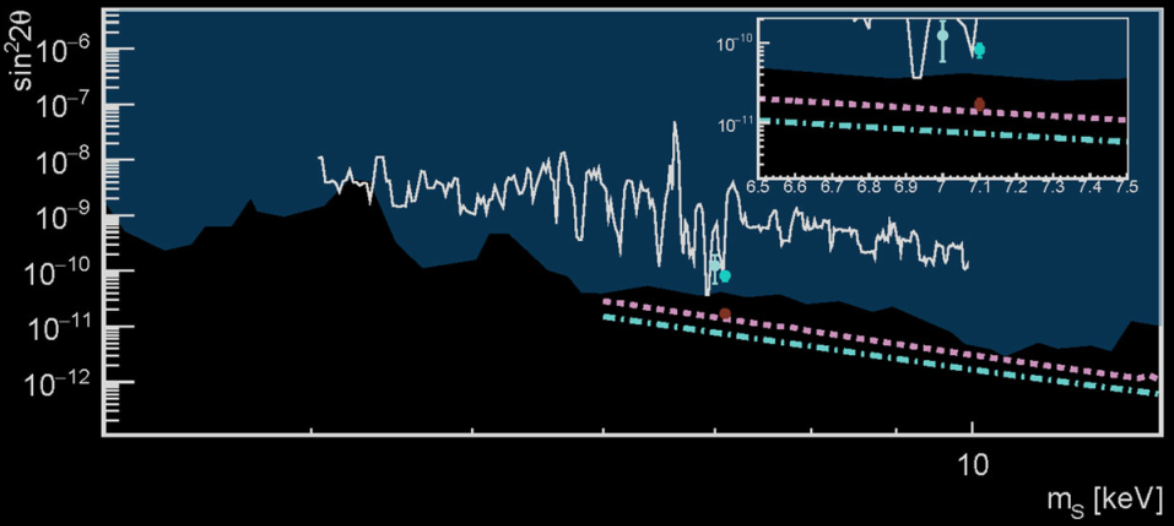


New instruments

Micro-X

- Sounding rocket, expected launch Q3 2022!!
- A ~ 1 cm^2, FOV ~ 10^3 deg^2 [~20x NuSTAR]
- FWHM ~ 4 eV
- Expected >3 sigma detection in ~600 seconds, even for $\sin^2(2\theta) \sim 2 \times 10^{-11}$ [1908.09010]

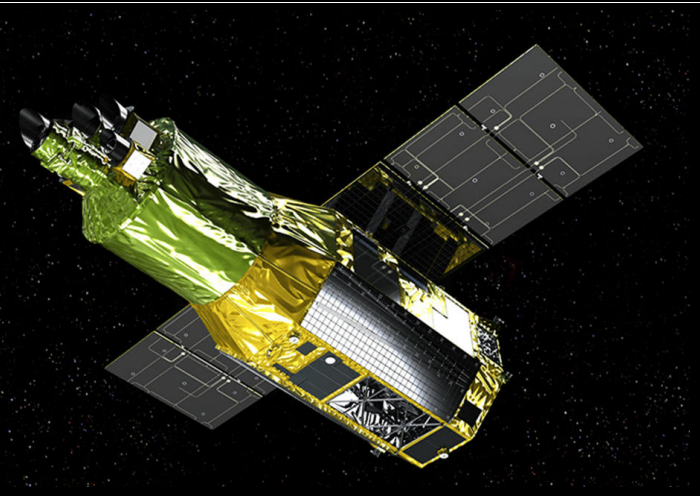




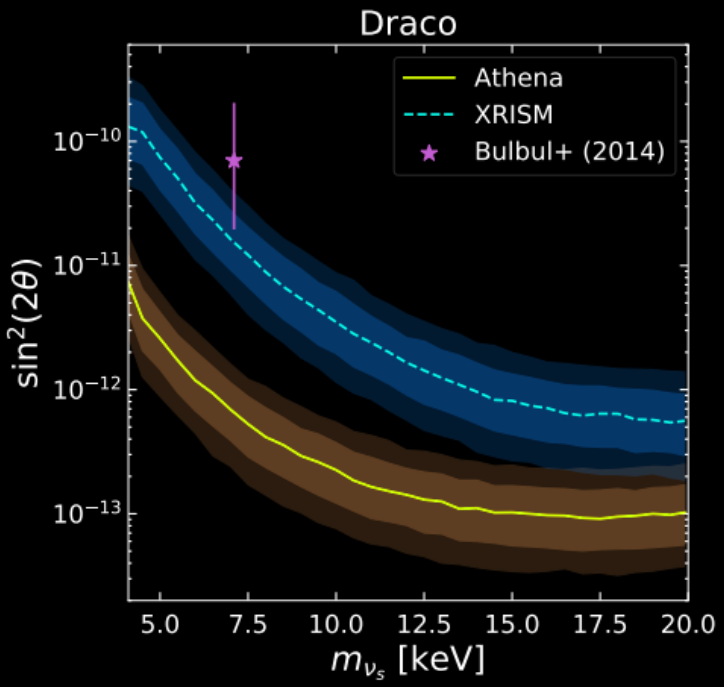
New instruments

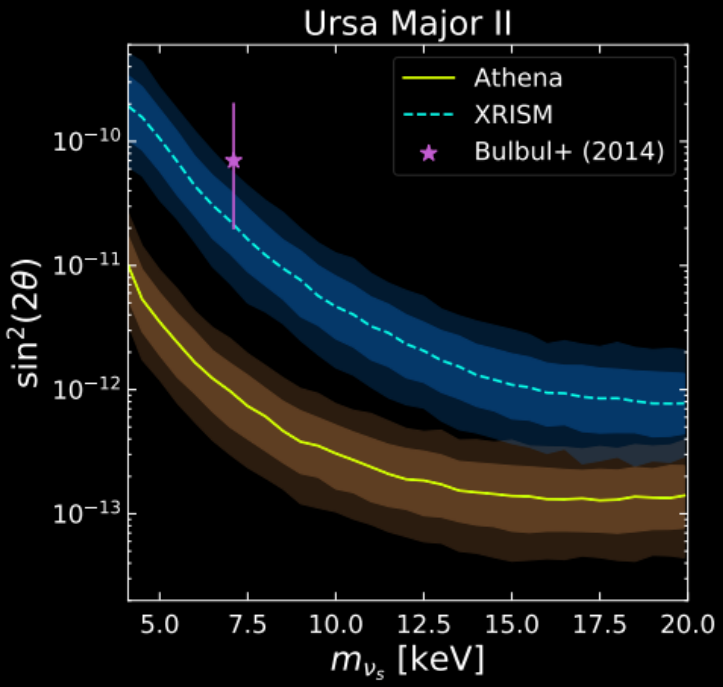
XRISM [Resolve instrument]

- JAXA satellite, expected launch ~2023
- Replacement for lost Astro-H (Hitomi)
- A ~ 200 cm^2 @ 3.5 keV, FOV ~ 0.002 deg^2
- FWHM ~ 7 eV
- Will require few ~Ms exposures of MW dSphs to fully constrain 3.5-keV line [e.g., 2103.13242]



[JAXA]

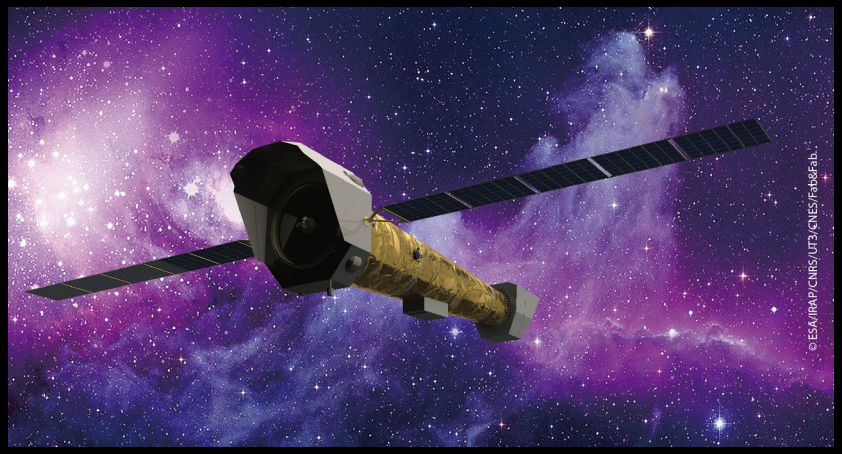




New instruments

Athena [X-IFU instrument]

- ESA satellite, expected launch ~2030s
- A ~ 4000 cm^2 @ 3.5 keV, FOV ~ 0.005 deg^2
- FWHM ~ 3 eV
- Will require few ~Ms exposures of MW dSphs to fully constrain 3.5-keV line [e.g., 2103.13242]



[ESA]