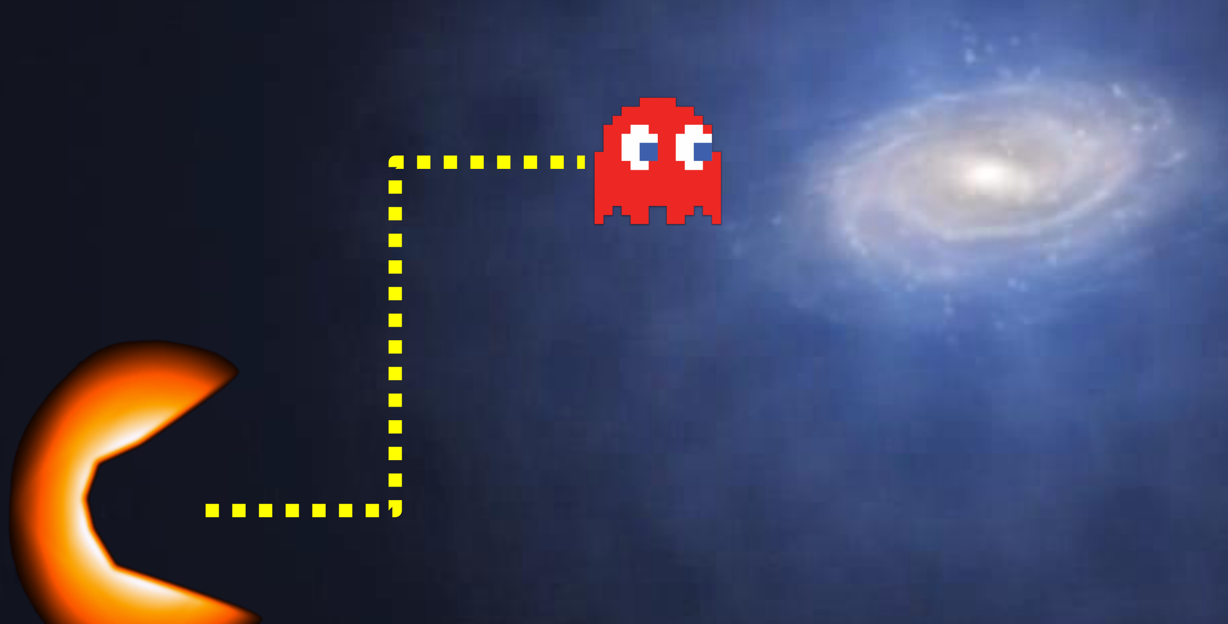
Scanning the Sky for Sterile Neutrino Dark Matter

Kerstin Perez (MIT)



CERN Neutrino Cross-Talk Seminar

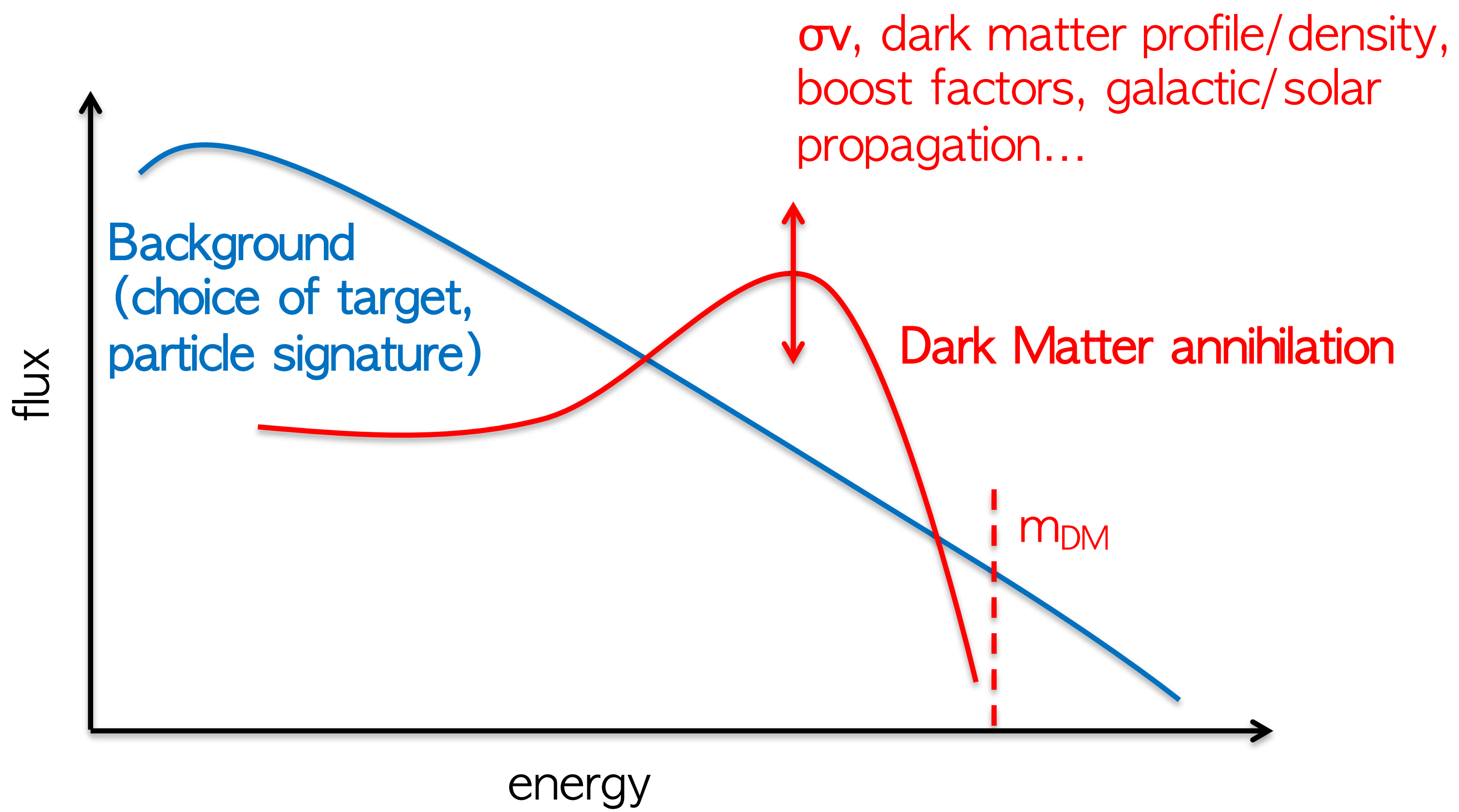
May 8, 2020

Overview

- *Scanning the sky:* Astrophysical searches for dark matter
- Sterile neutrinos as dark matter
- X-ray searches for sterile neutrinos
    - Ex: *NuSTAR as a large-aperture dark matter telescope*
- Onwards!

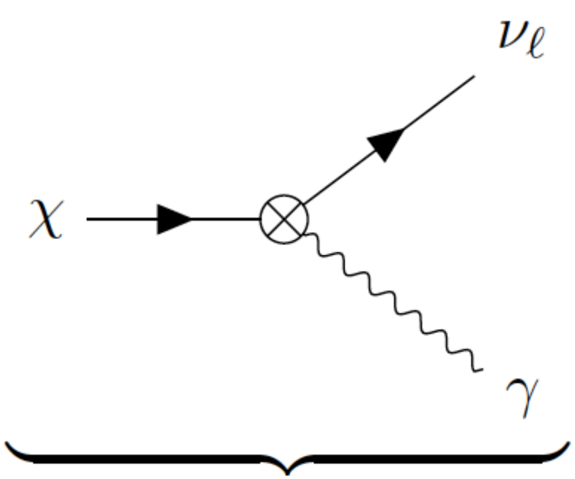
The challenge of astroparticle searches…

Common challenge = minimize/constrain astrophysical background, maximize predicted dark matter signal

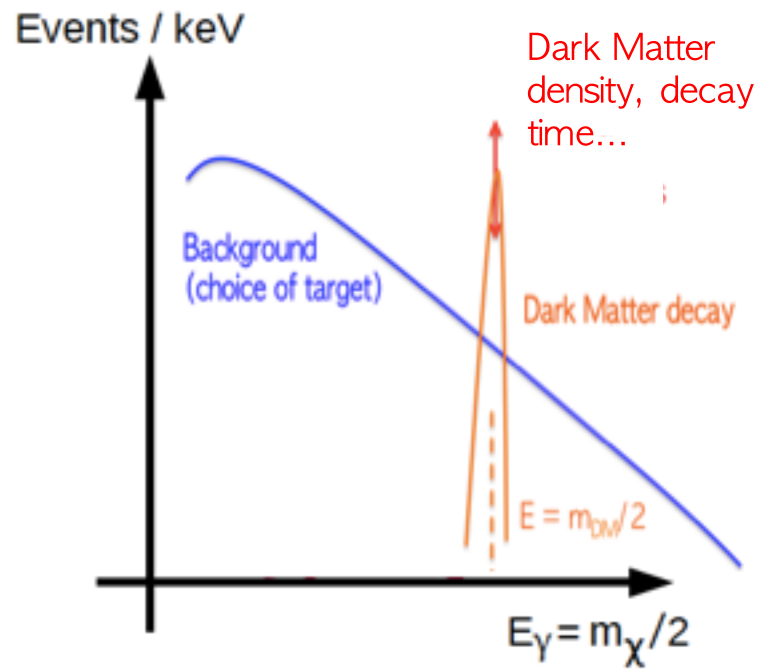


Decay lines: a "smoking gun" signature

Sterile neutrino dark matter decay can provide a clear line signature



Decay rate $\propto m_\chi^5 \sin^2 2\theta$



Target objects with high dark matter density, low astrophysical background

Decay lines: a “smoking gun” signature

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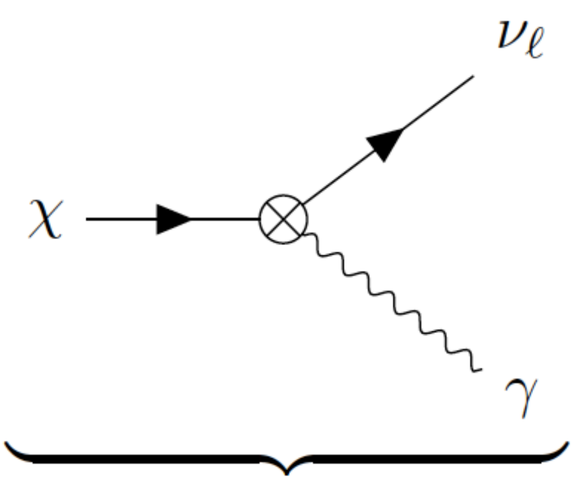

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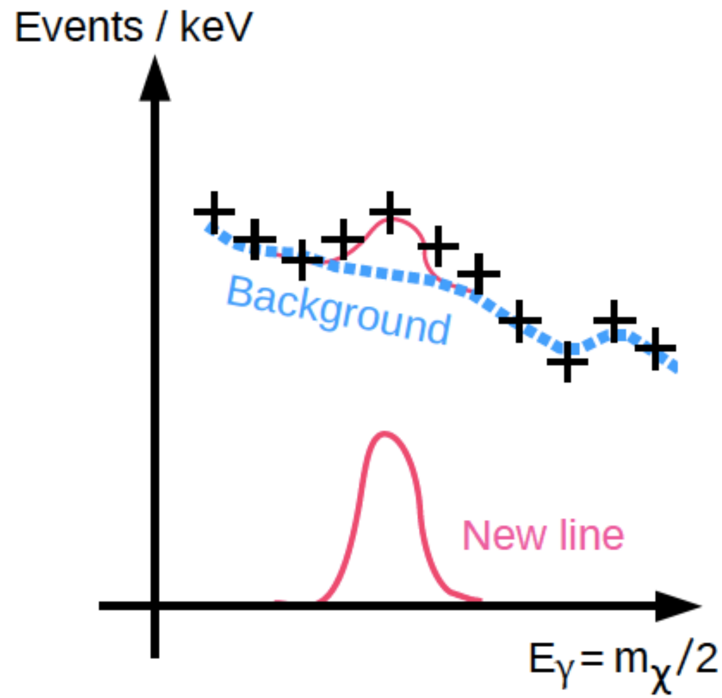

Target objects with high dark matter density, low astrophysical background

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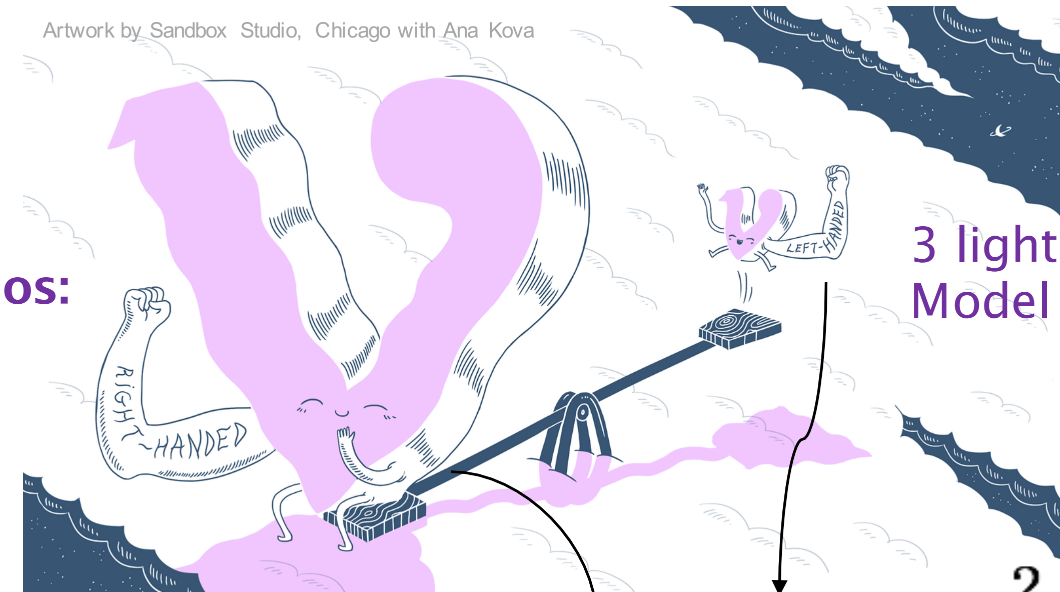
Sterile neutrinos can solve the mass puzzle



3 *sterile* neutrinos:
interact via neutrino oscillations

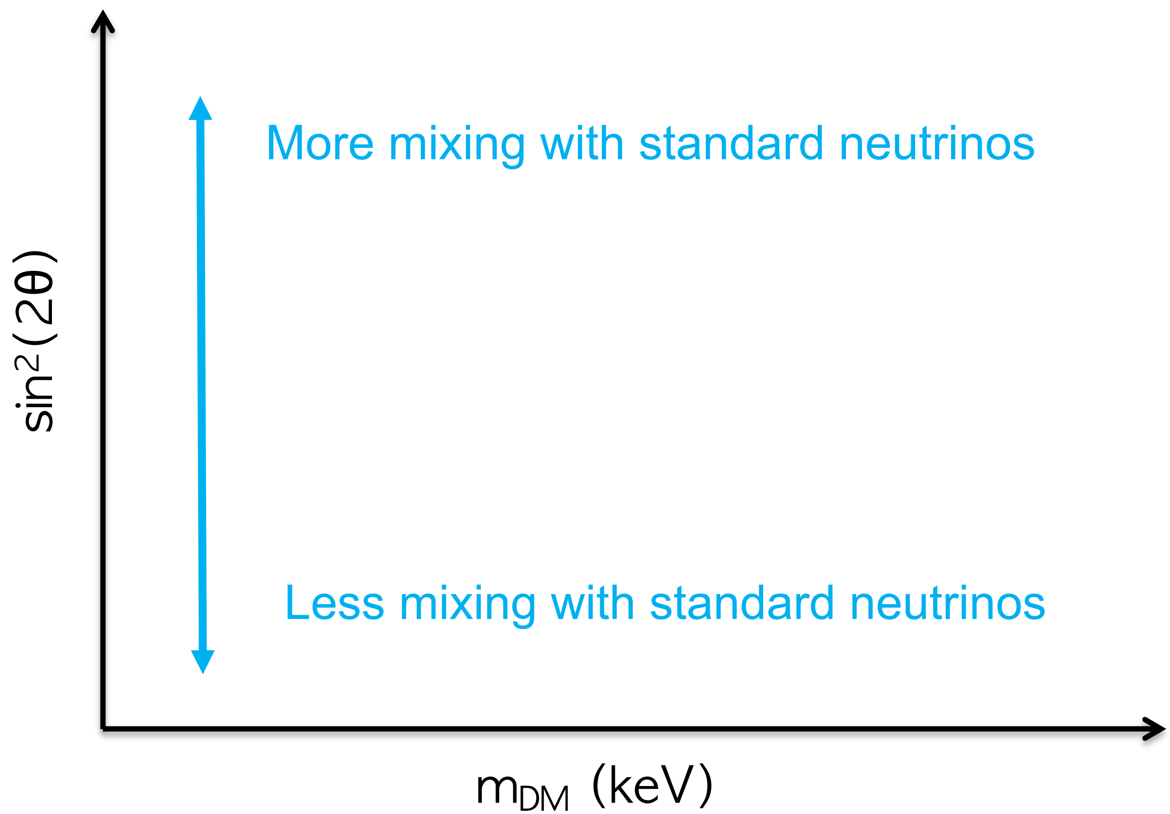
3 light Standard Model neutrinos

$$M_\nu \sim \frac{m_D^2}{M_R}$$

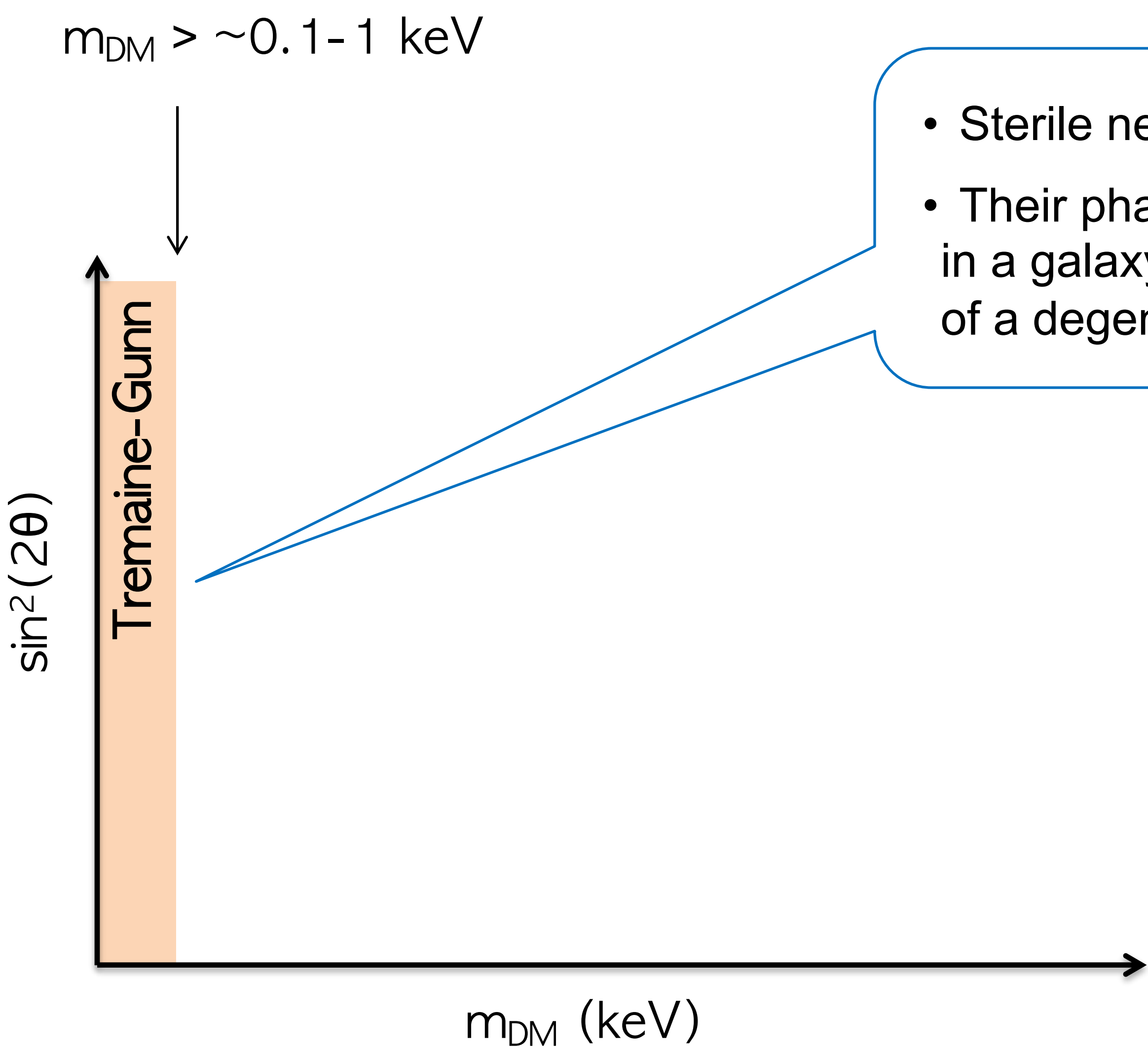
Neutino Minimal Standard Model (νMSM)

- Two heavy (>100 GeV) sterile neutrinos explain atmospheric and solar neutrino oscillations
- A third lighter (keV-scale) sterile neutrino can account for dark matter
  → decay would give an *X-ray line*

The sterile neutrino landscape



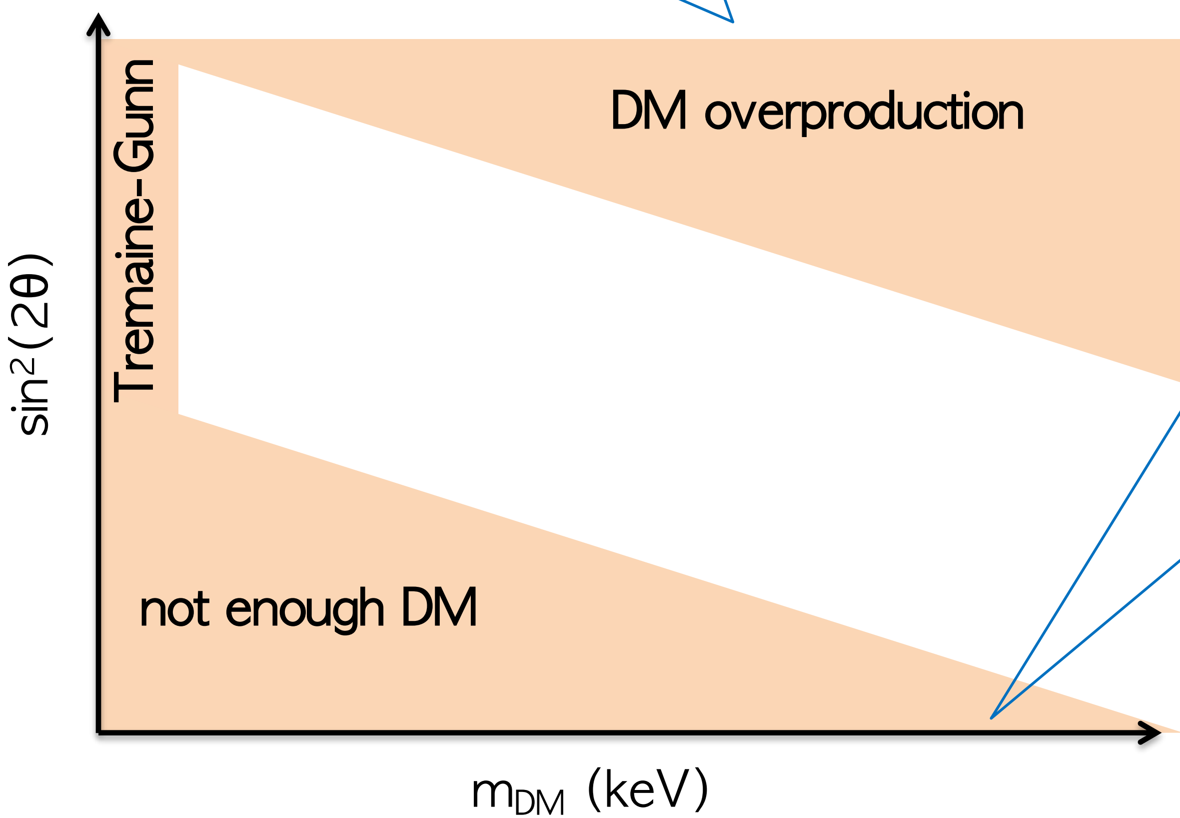
The sterile neutrino landscape



- Sterile neutrinos are fermions
- Their phase-space distribution in a galaxy cannot exceed that of a degenerate Fermi gas

The sterile neutrino landscape

- Large mixing angles will produce too much dark matter in the early universe

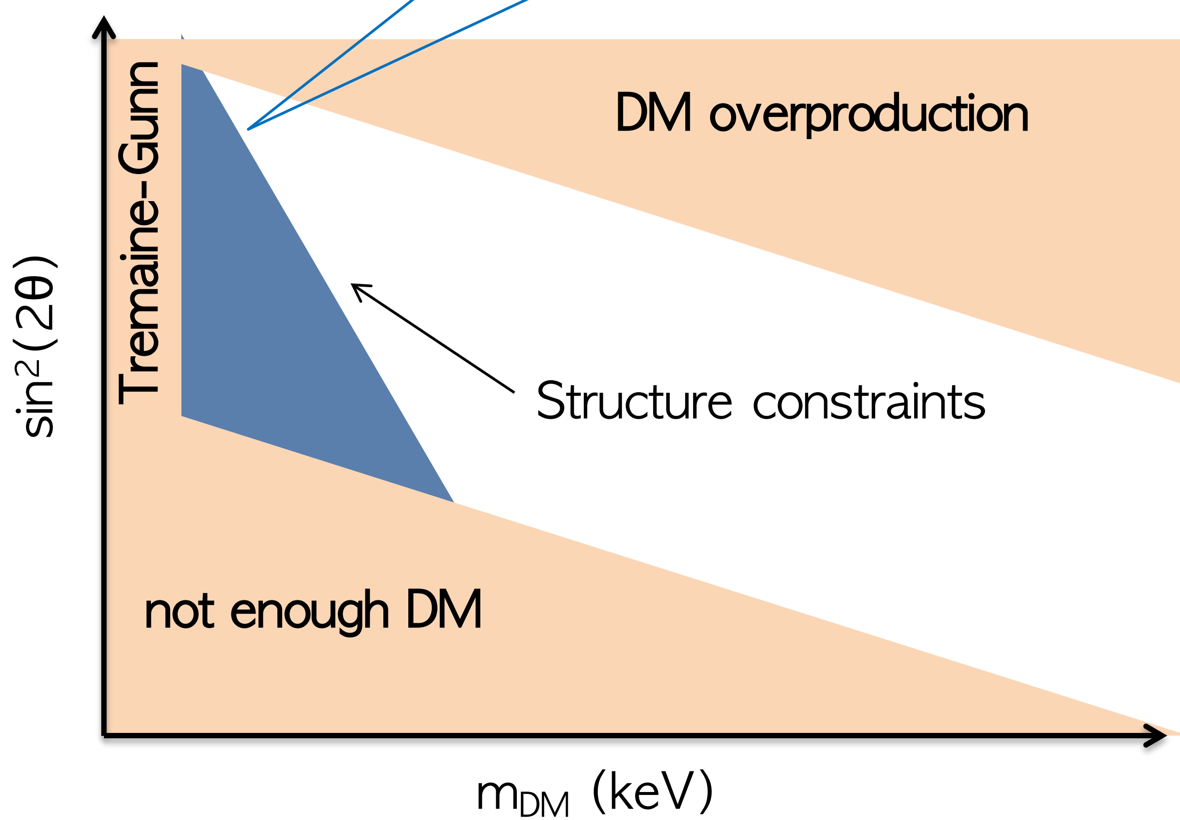


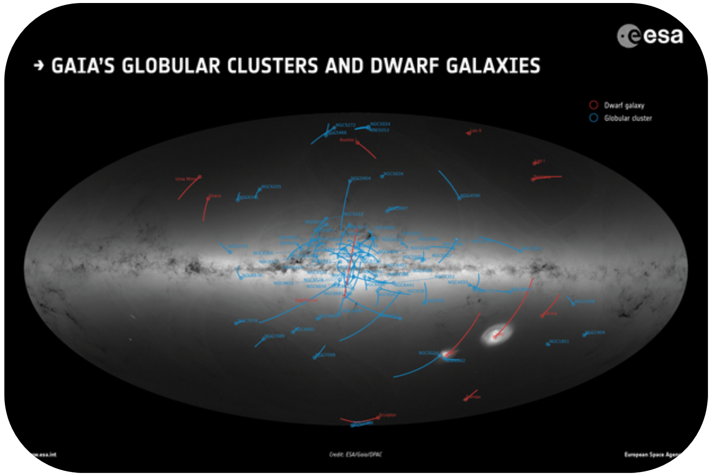
- Small mixing angles require resonant production due to high lepton asymmetry in the early universe
- Minimum lepton asymmetry consistent with Big Bang Nucleo-synthesis sets limit*

** if sterile neutrinos are all of dark matter*

The sterile neutrino landscape

- Require number of predicted dwarf satellites be *at least* as many as are detected





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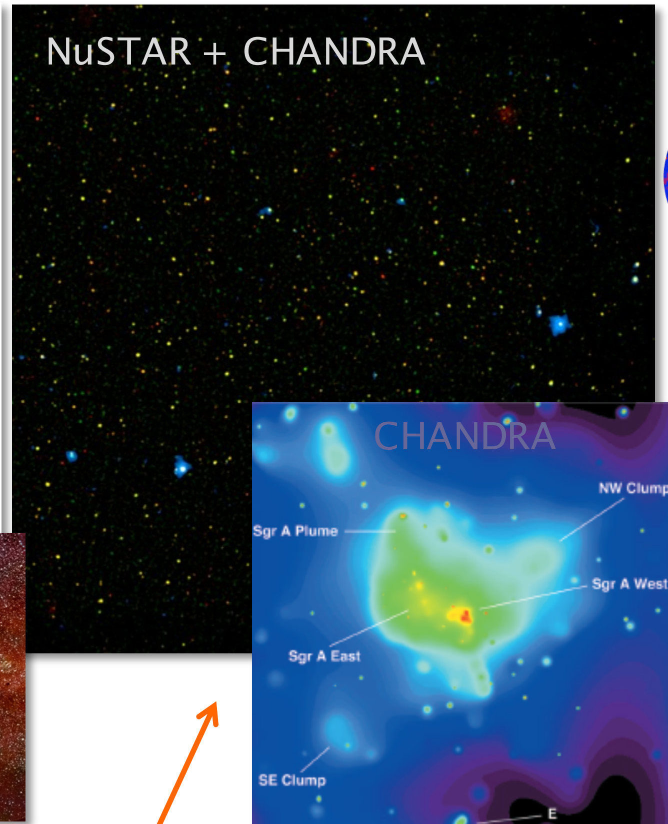
From low to high-energy

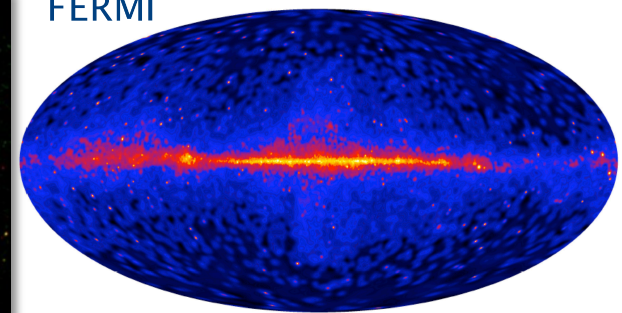
Optical, IR, UV:

X-rays:

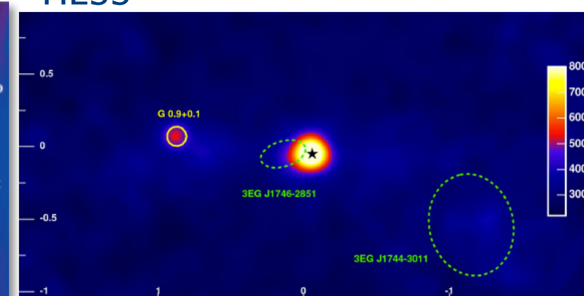


Gamma-rays:

FERMI



HESS

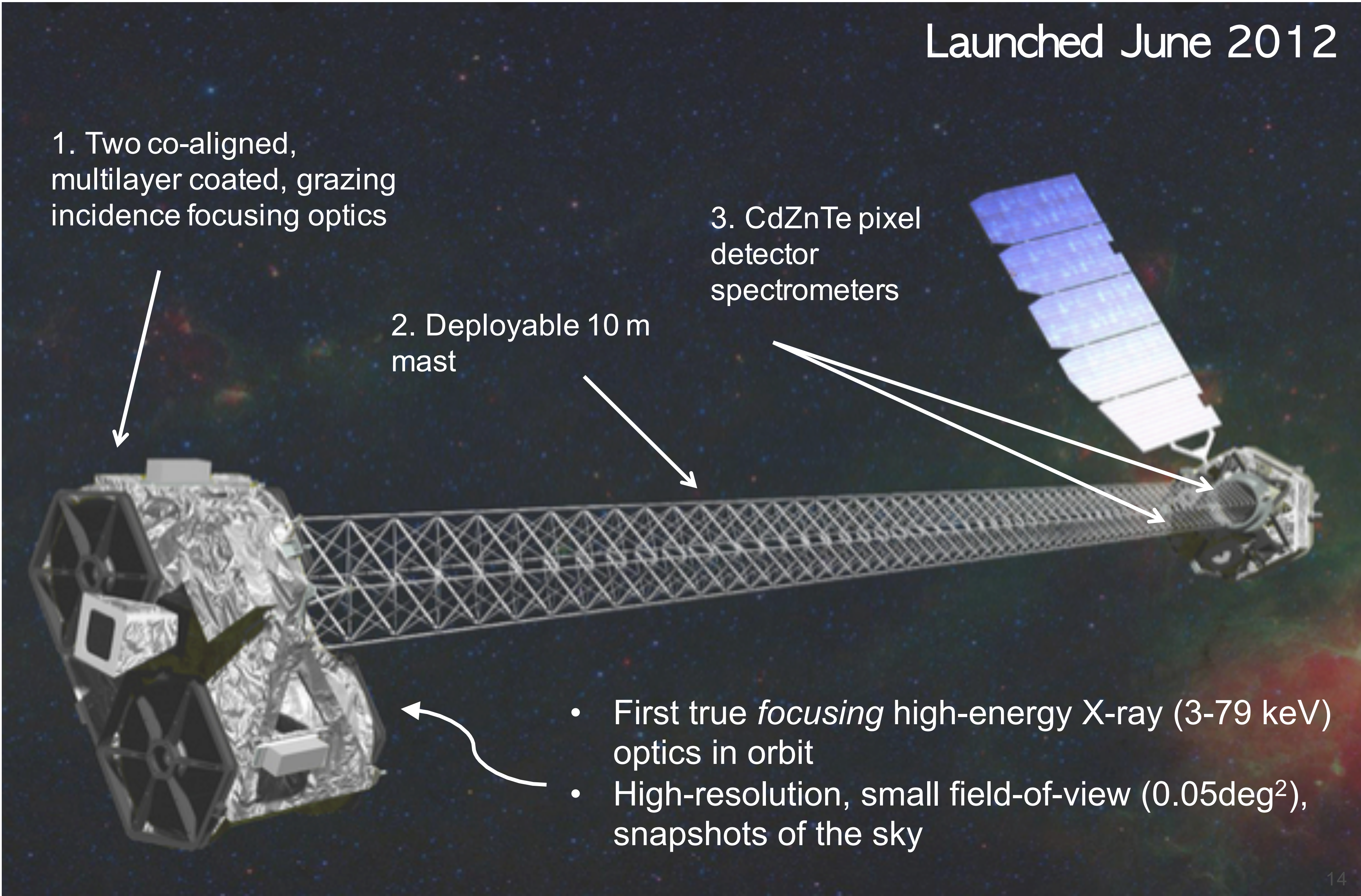


Stars and gas

Accreting black holes, white dwarfs, neutron stars; supernovae, very hot gas, scattering by cosmic rays

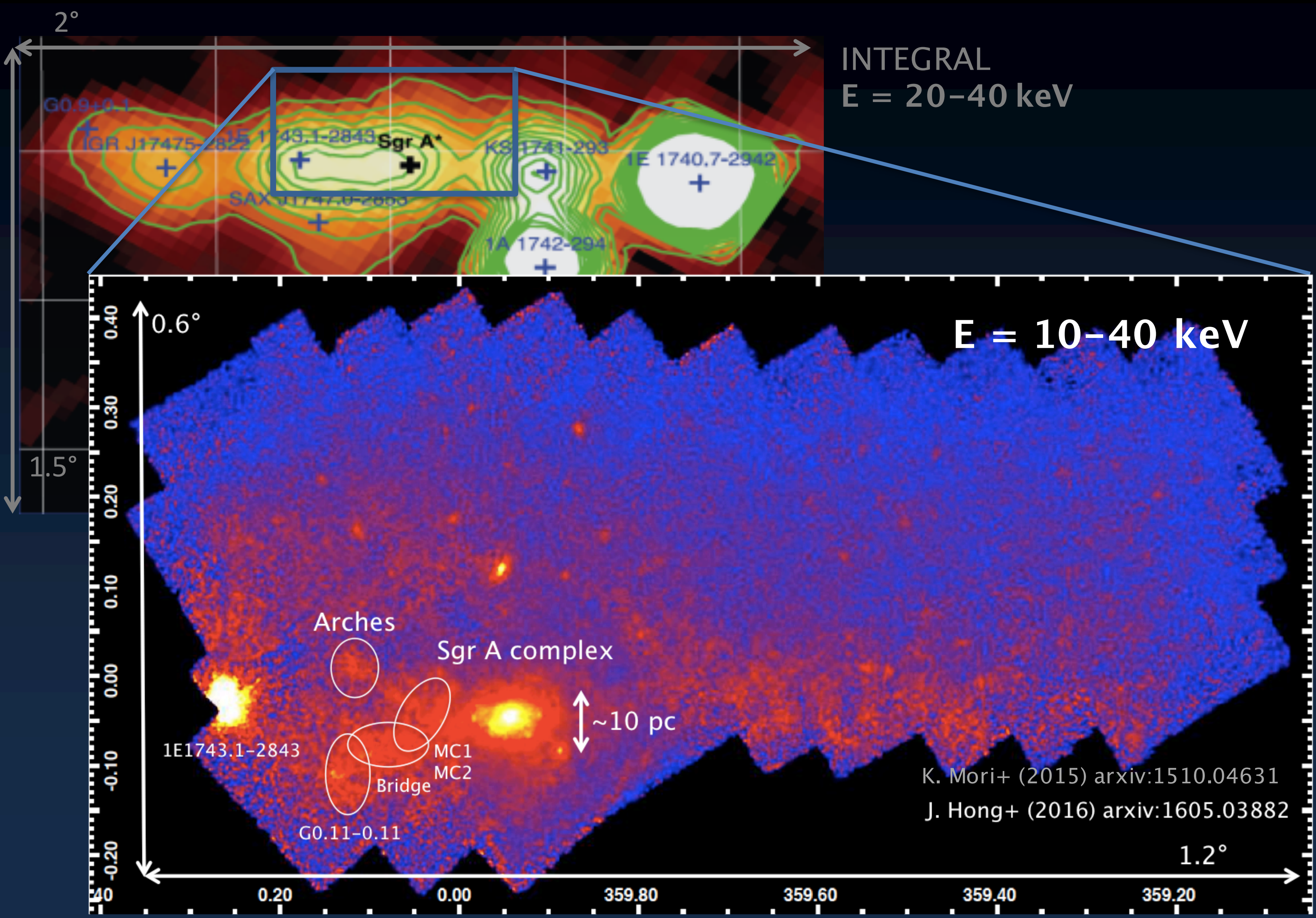
Pulsars, supernovae, active galactic nuclei

NuSTAR: first *focusing* high-energy X-ray telescope

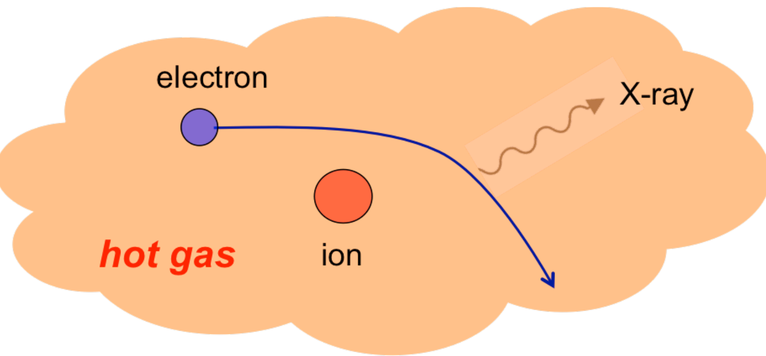


- First true *focusing* high-energy X-ray (3-79 keV) optics in orbit
- High-resolution, small field-of-view (0.05deg^2), snapshots of the sky

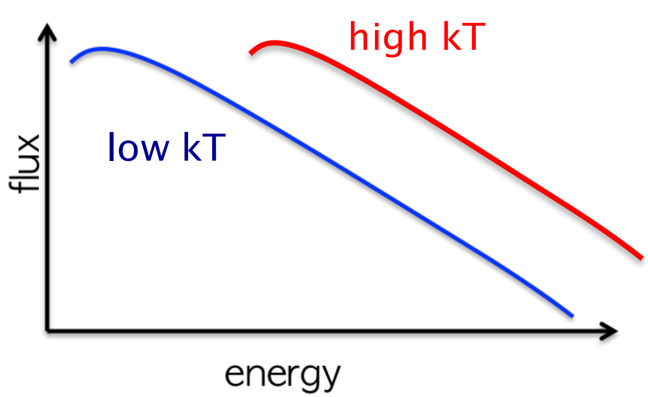
NuSTAR's view of the Galactic Center:



How to make an X-ray



A thermal bremsstrahlung spectrum
(kT ~ keV)



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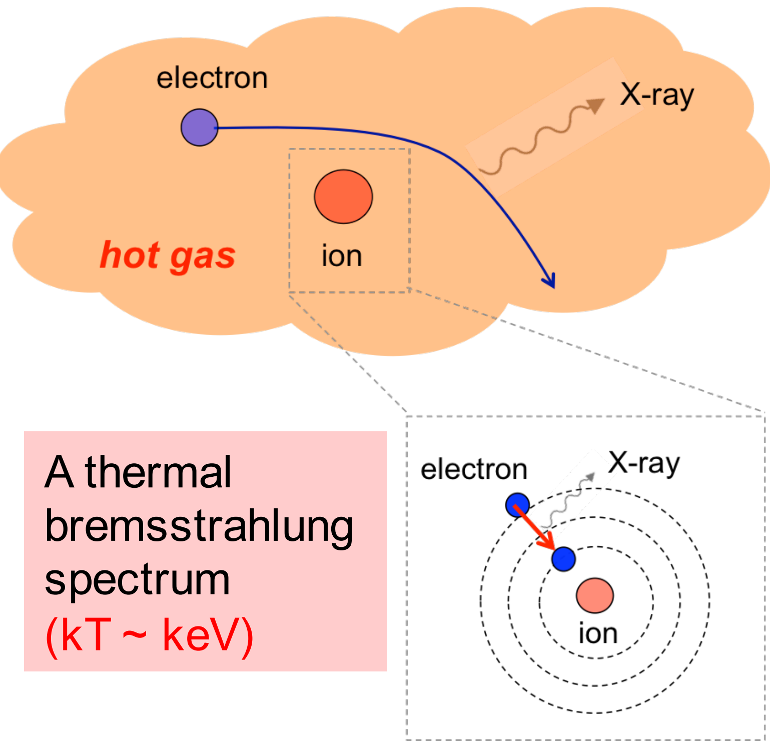

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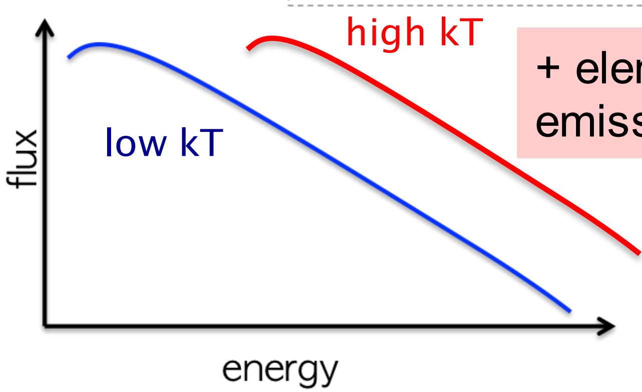

+ elemental emission ***lines***

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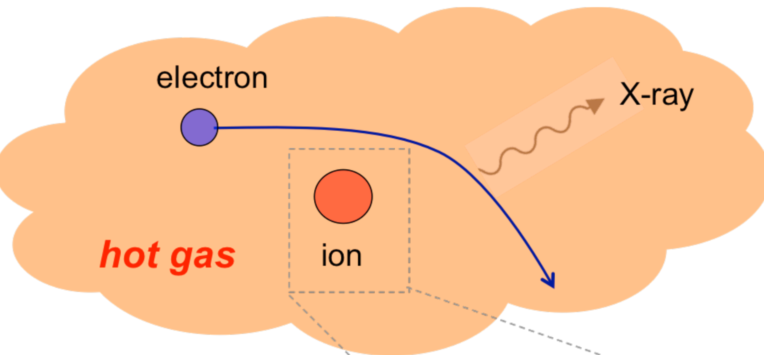

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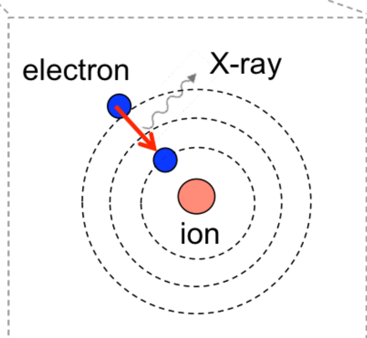
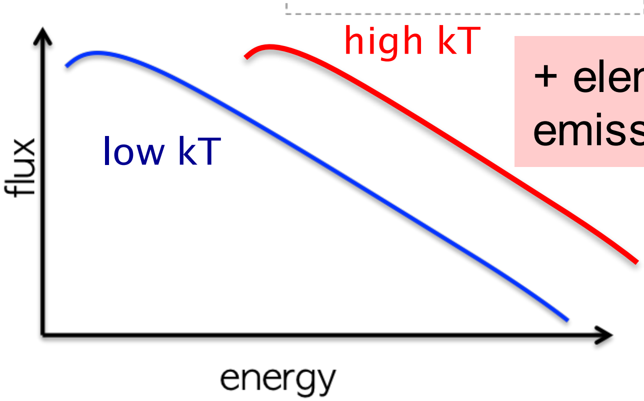




+ elemental emission ***lines***

Accreting stellar remnant binary systems

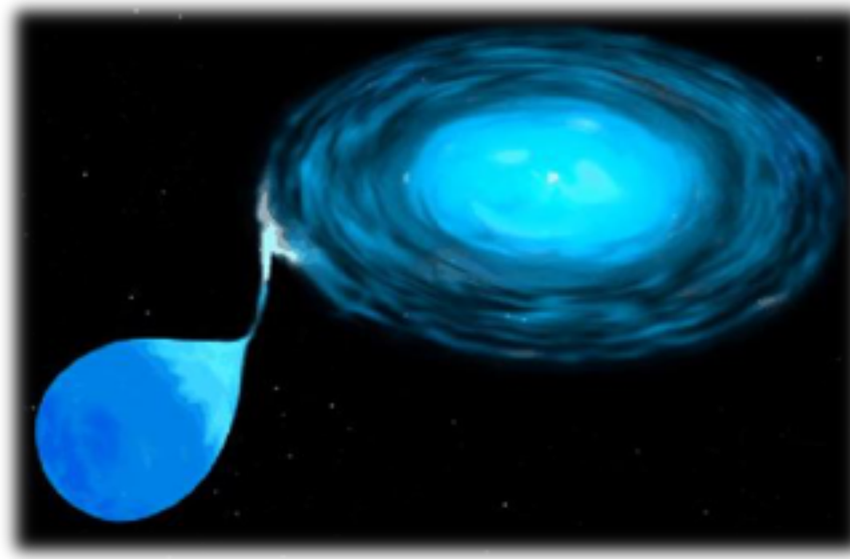
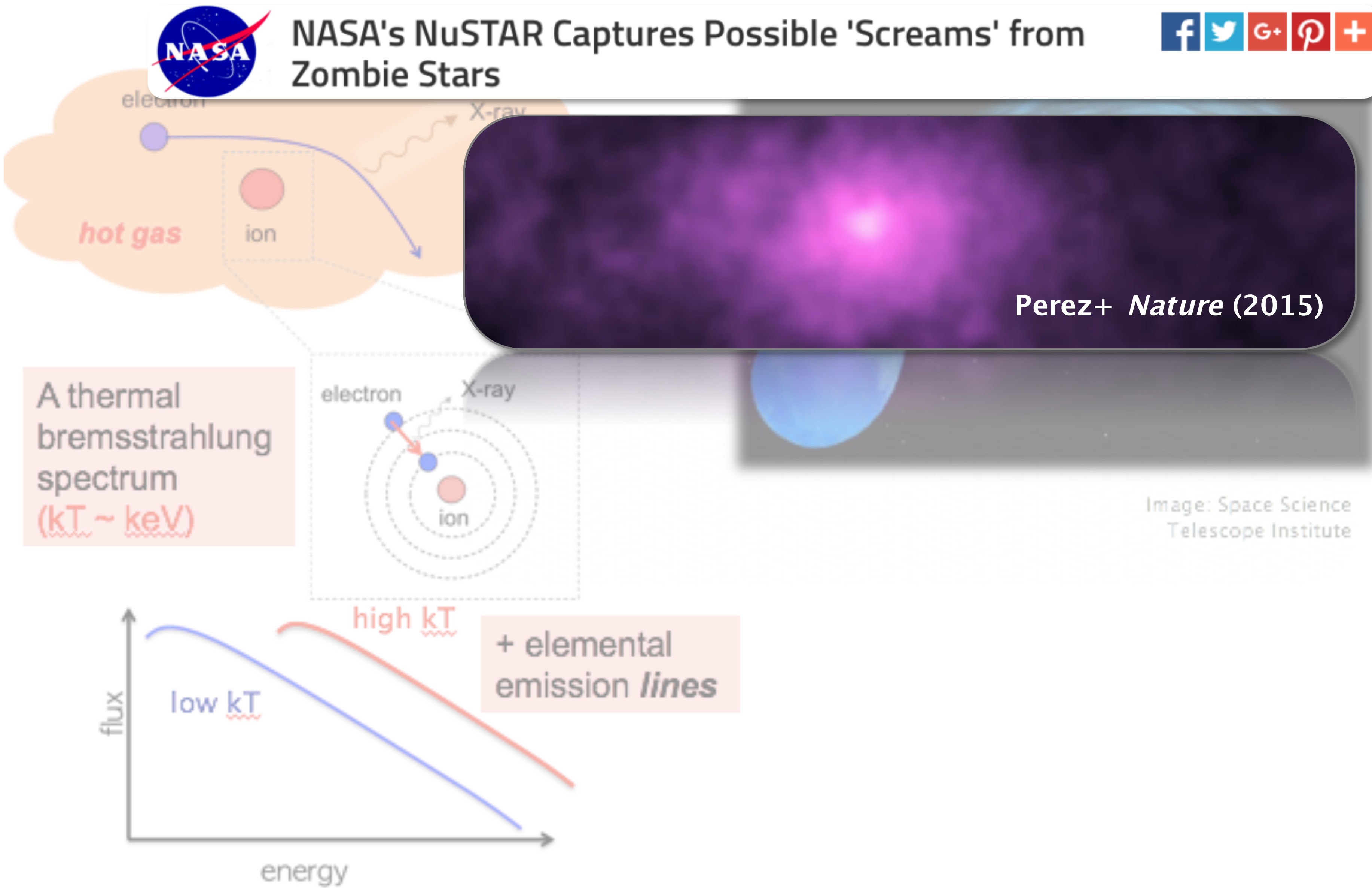


Image: Space Science Telescope Institute

How to make an X-ray



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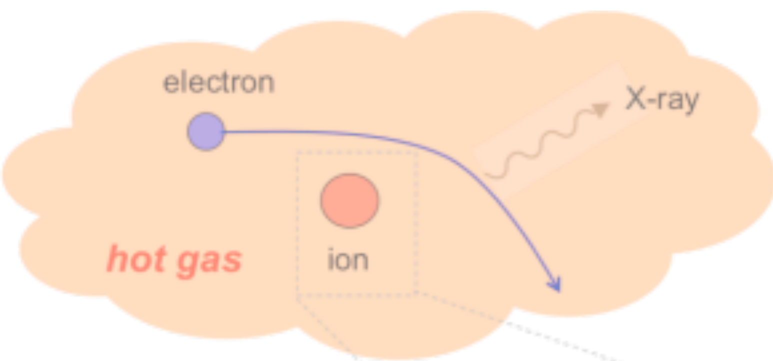

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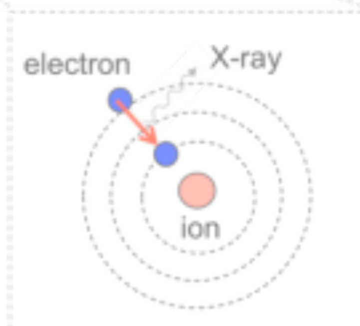

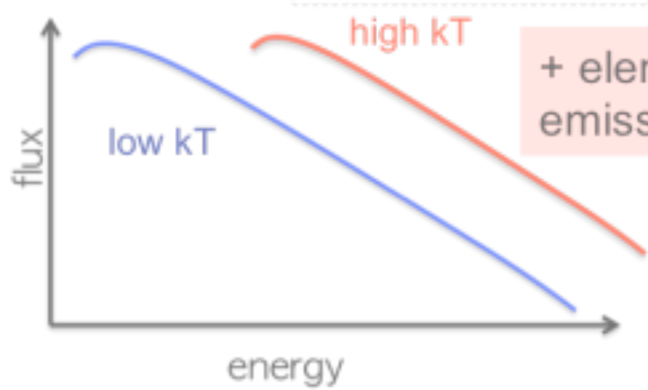

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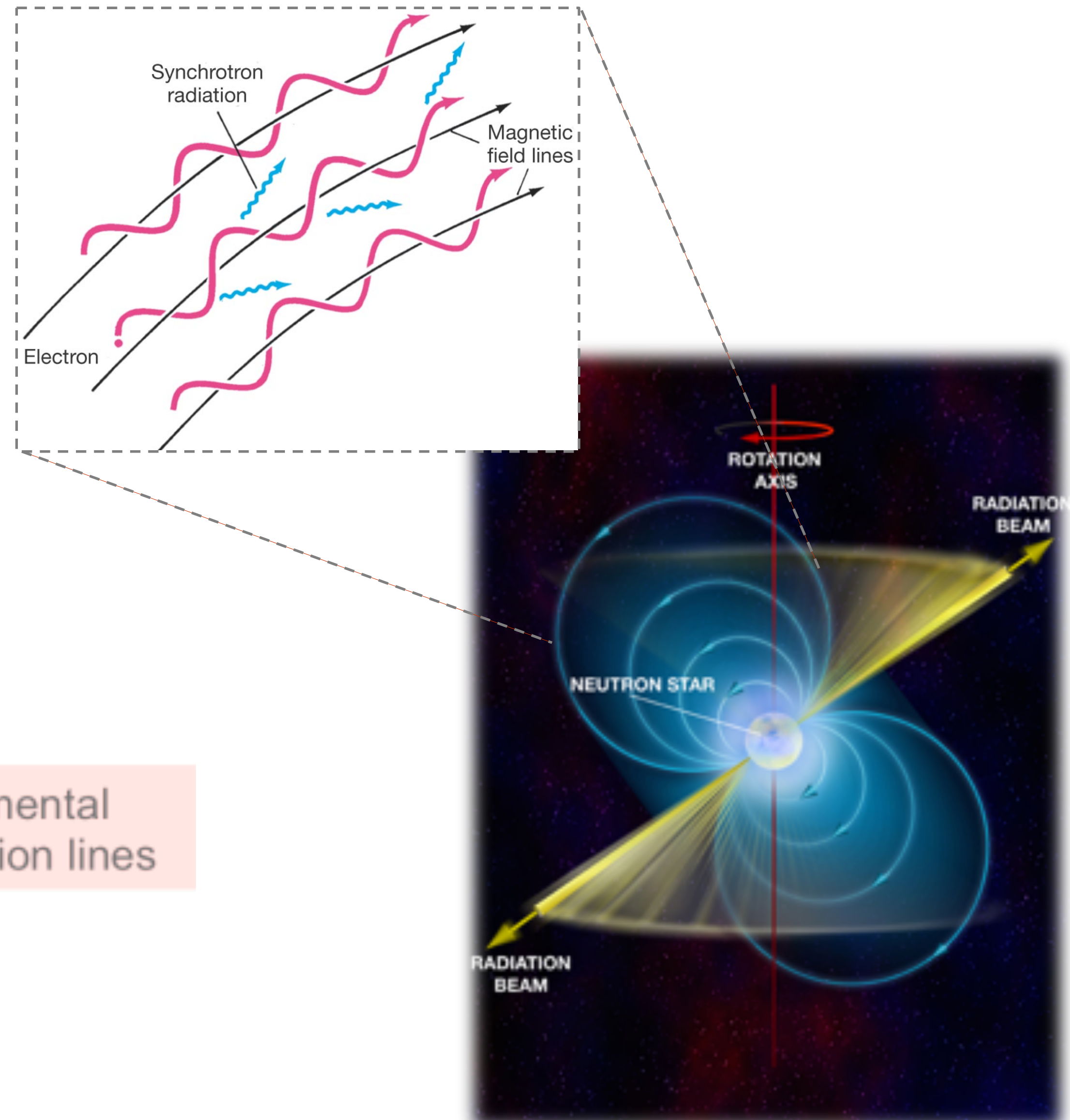

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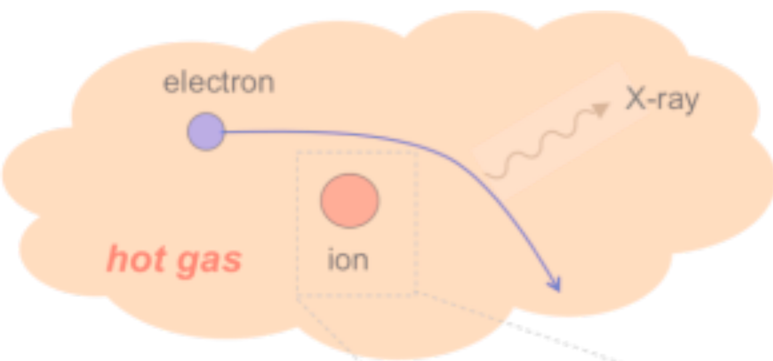

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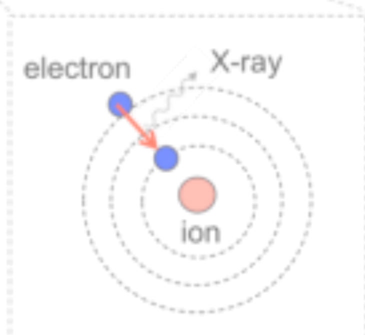

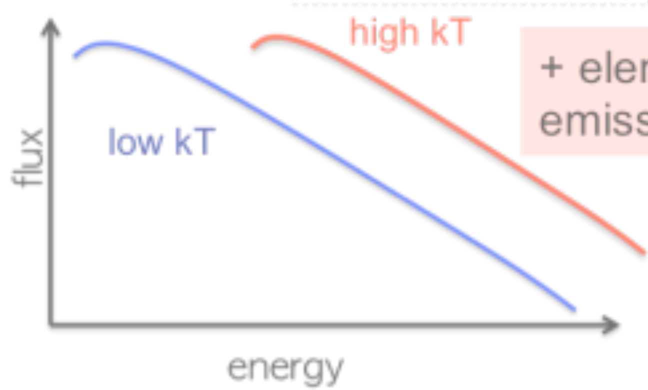

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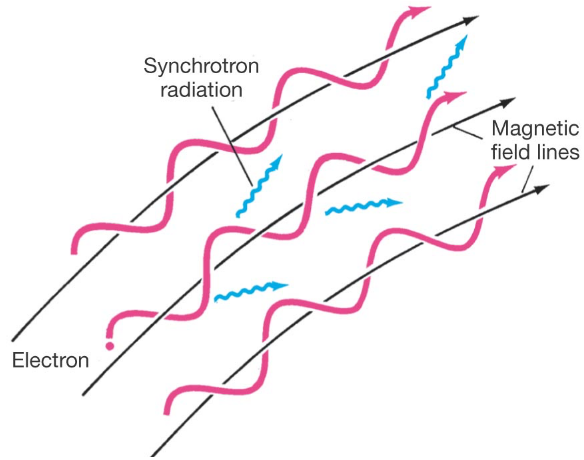
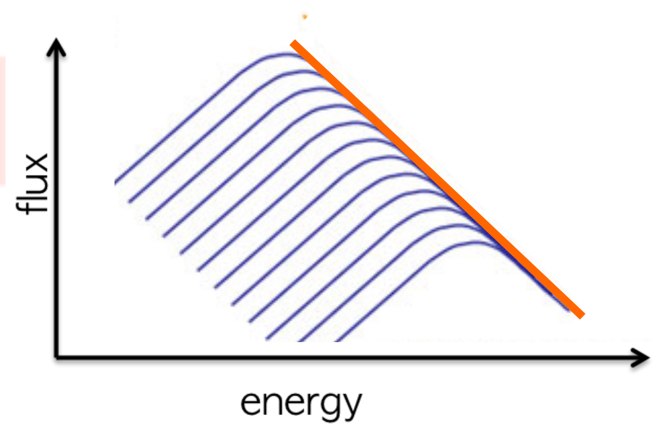


Power-law spectrum
Flux ~ $E^{-\Gamma}$



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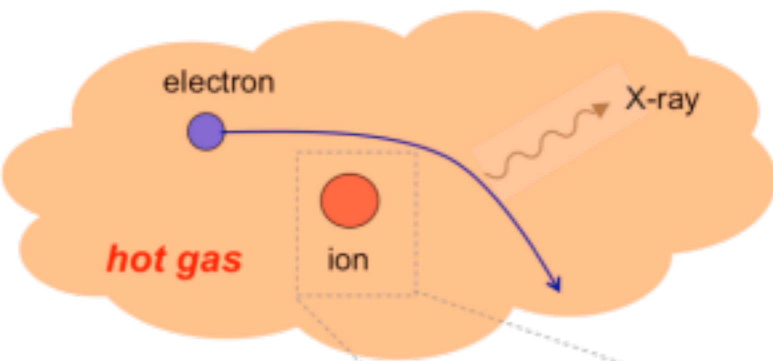

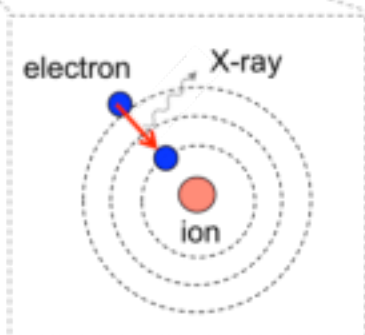

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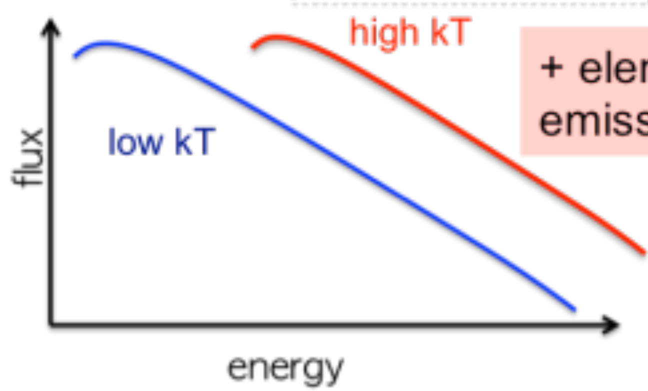

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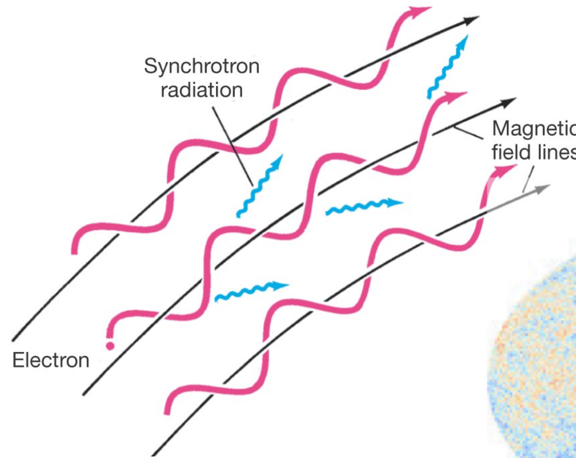

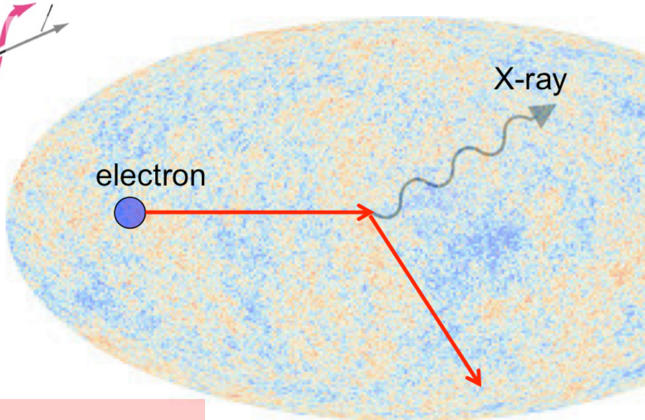

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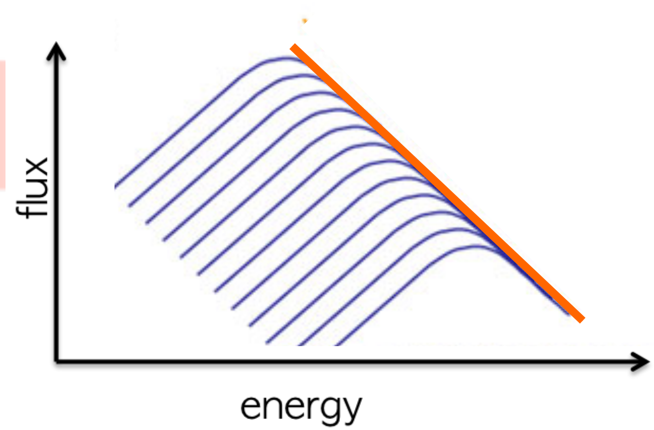
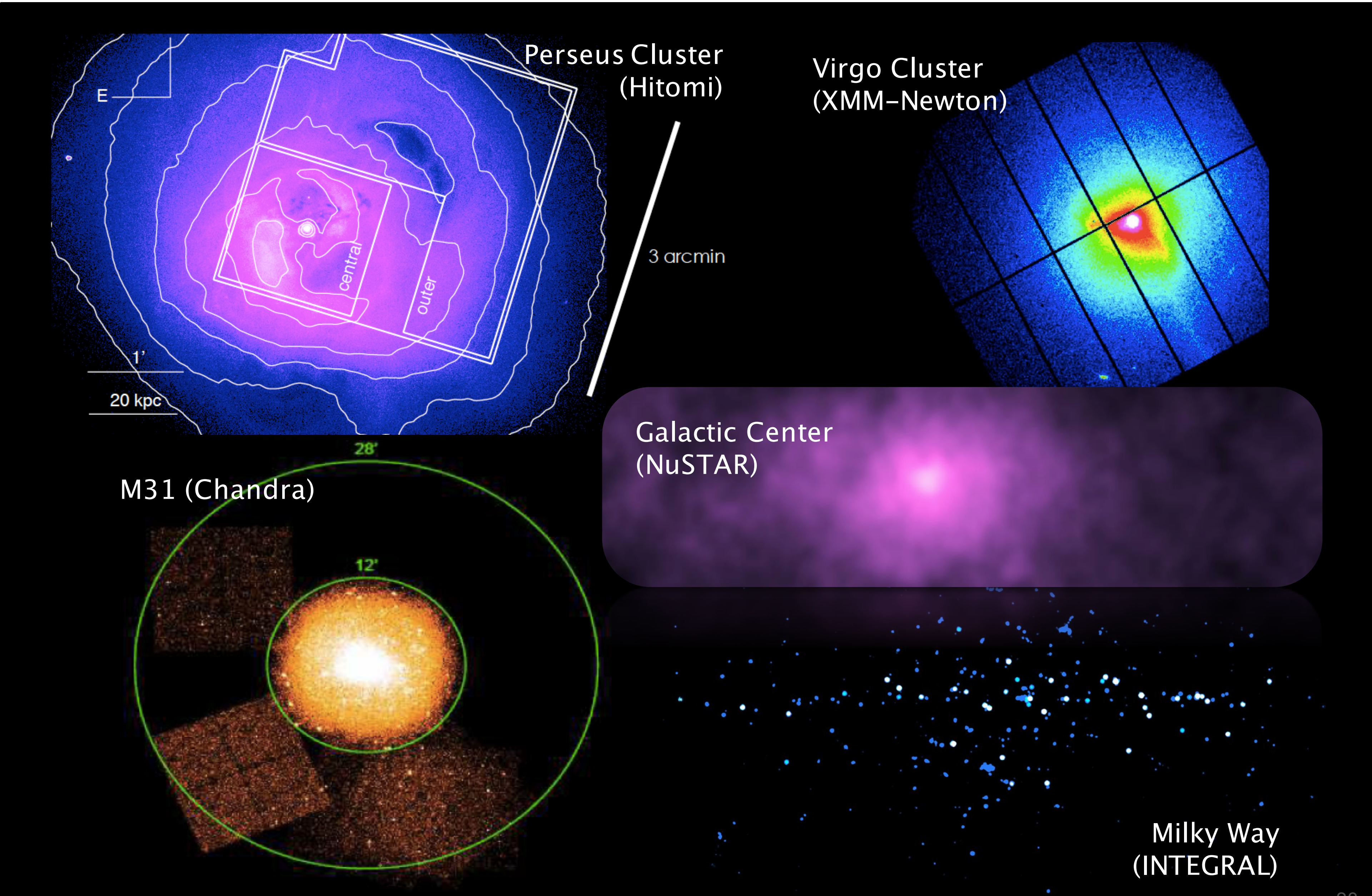
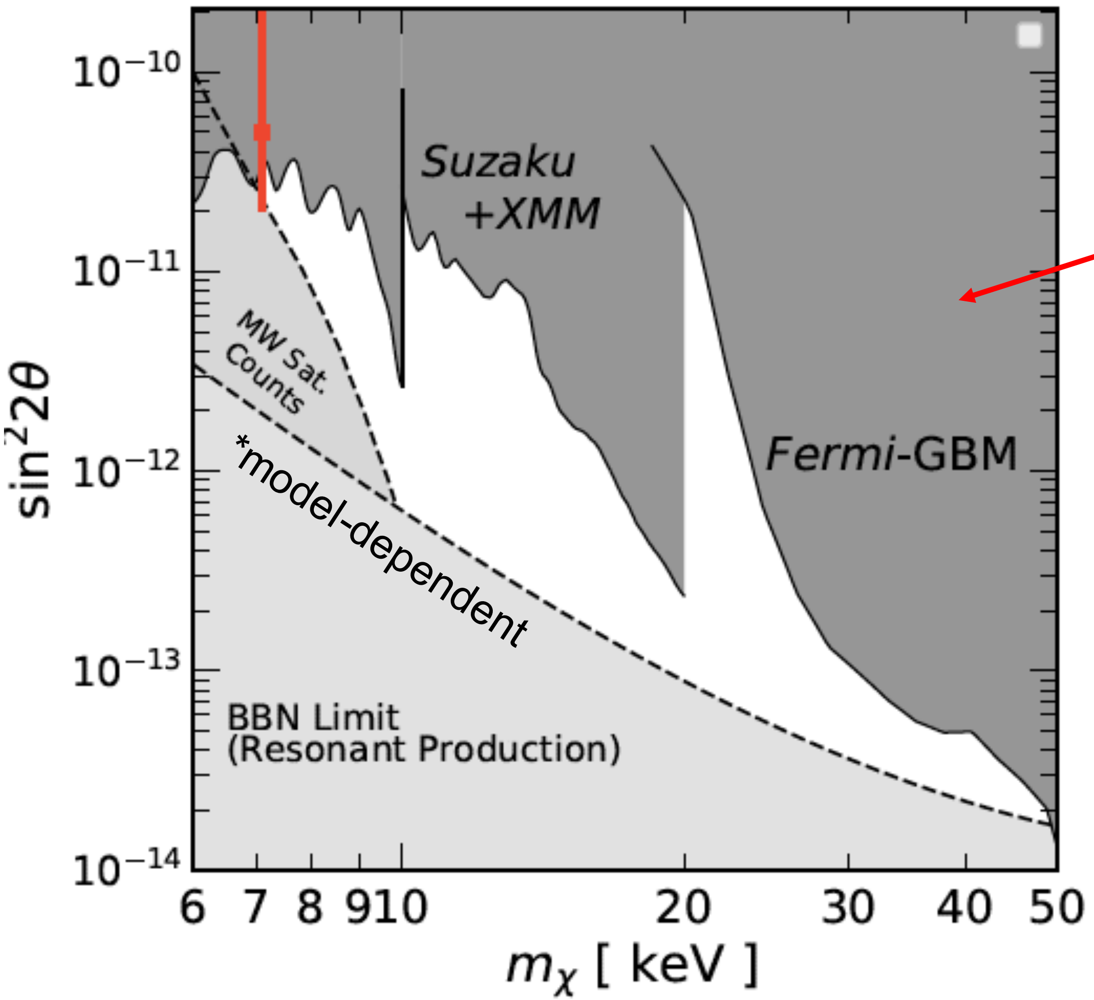


X-rays leading the hunt for sterile neutrinos



A narrowing window…

Only a narrow window remains in which sterile neutrinos (in the simplest models) can constitute all of dark matter



*model-*In*dependent search method

Abazajian, Fuller & Patel 2001; Abazajian 2005

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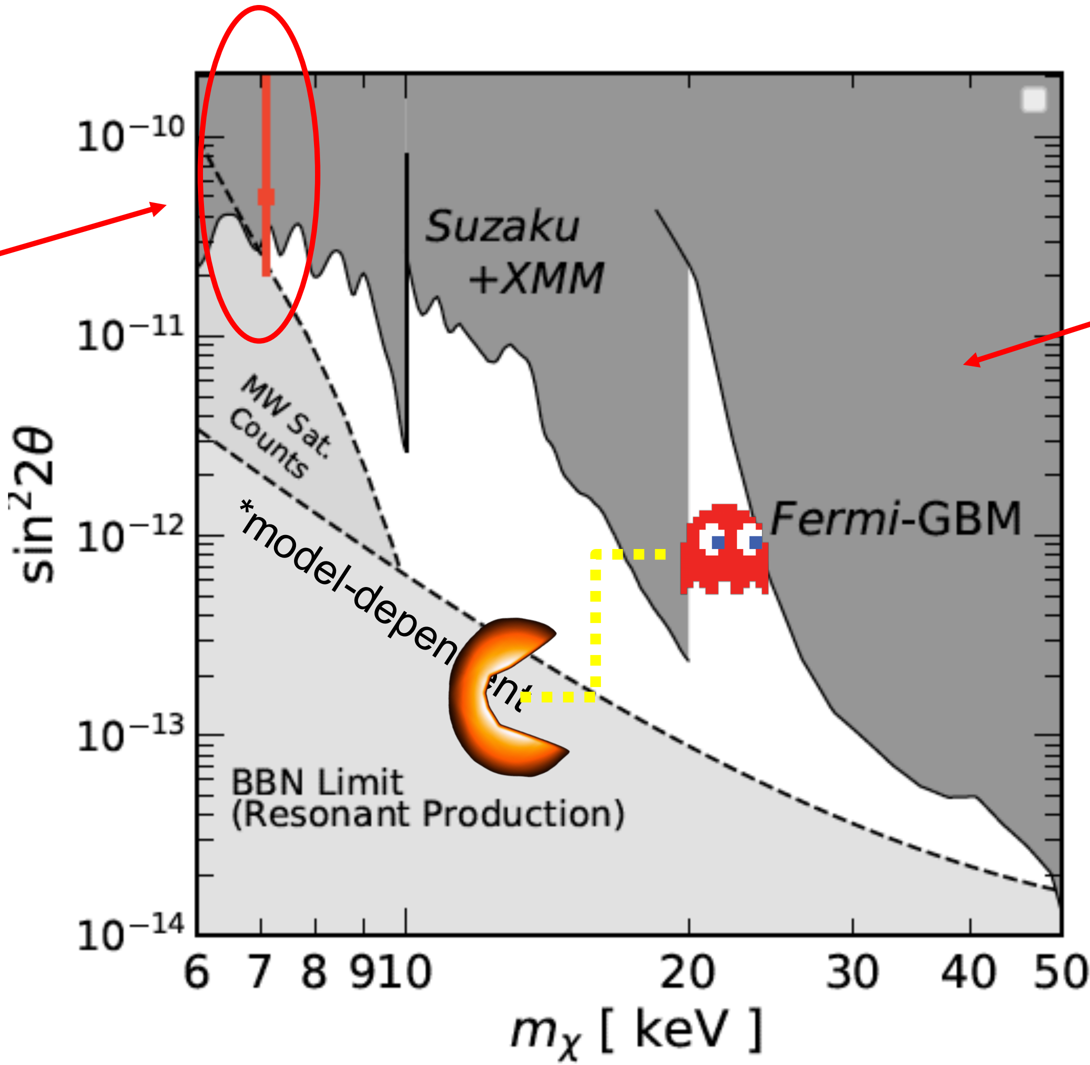
A possible detection?
→ *see Ben's talk*



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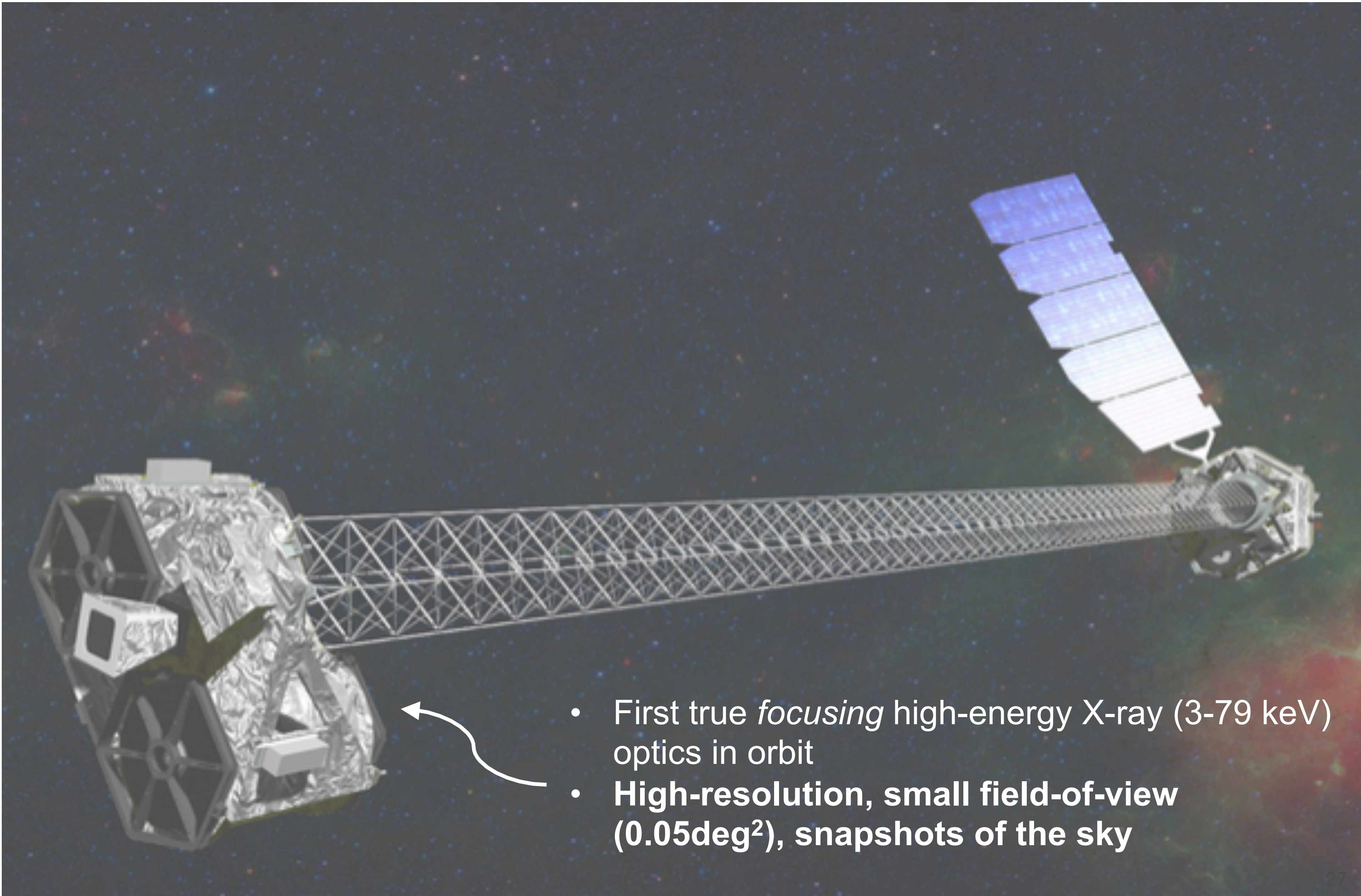
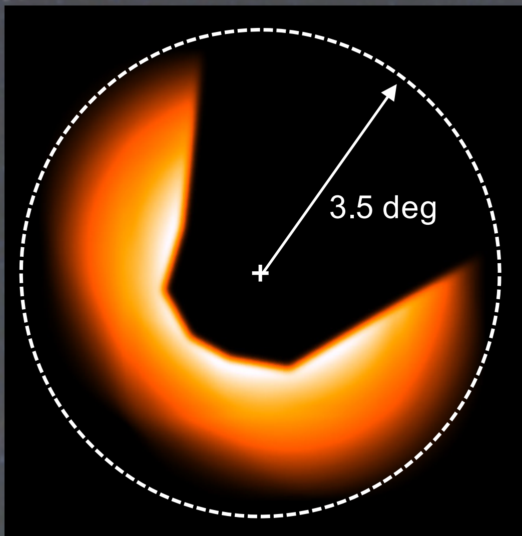
Adapting NuSTAR as a *large-aperture DM telescope*

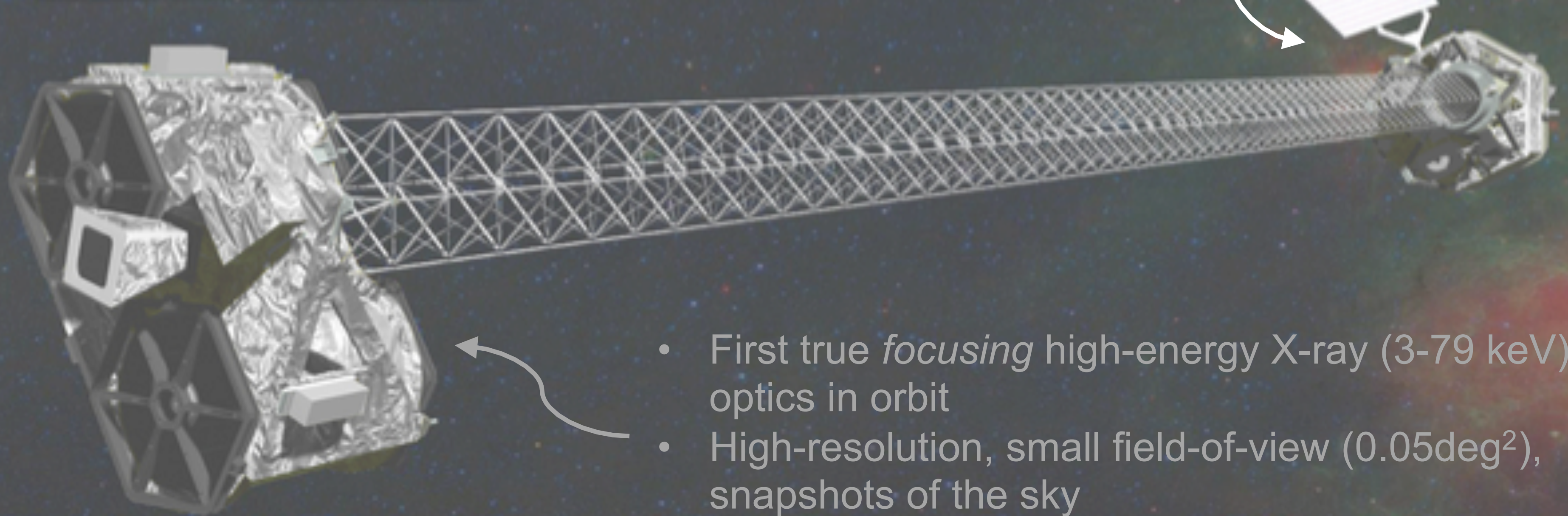


- First true *focusing* high-energy X-ray (3-79 keV) optics in orbit
- **High-resolution, small field-of-view ($0.05 deg^2$), snapshots of the sky**

Adapting NuSTAR as a *large-aperture DM telescope*



- "0-bounce" photons that bypass the optics are typically a major background
- Novel analysis exploits **>10x increase in collection efficiency for slowly-varying, diffuse signal**



- First true *focusing* high-energy X-ray (3-79 keV) optics in orbit
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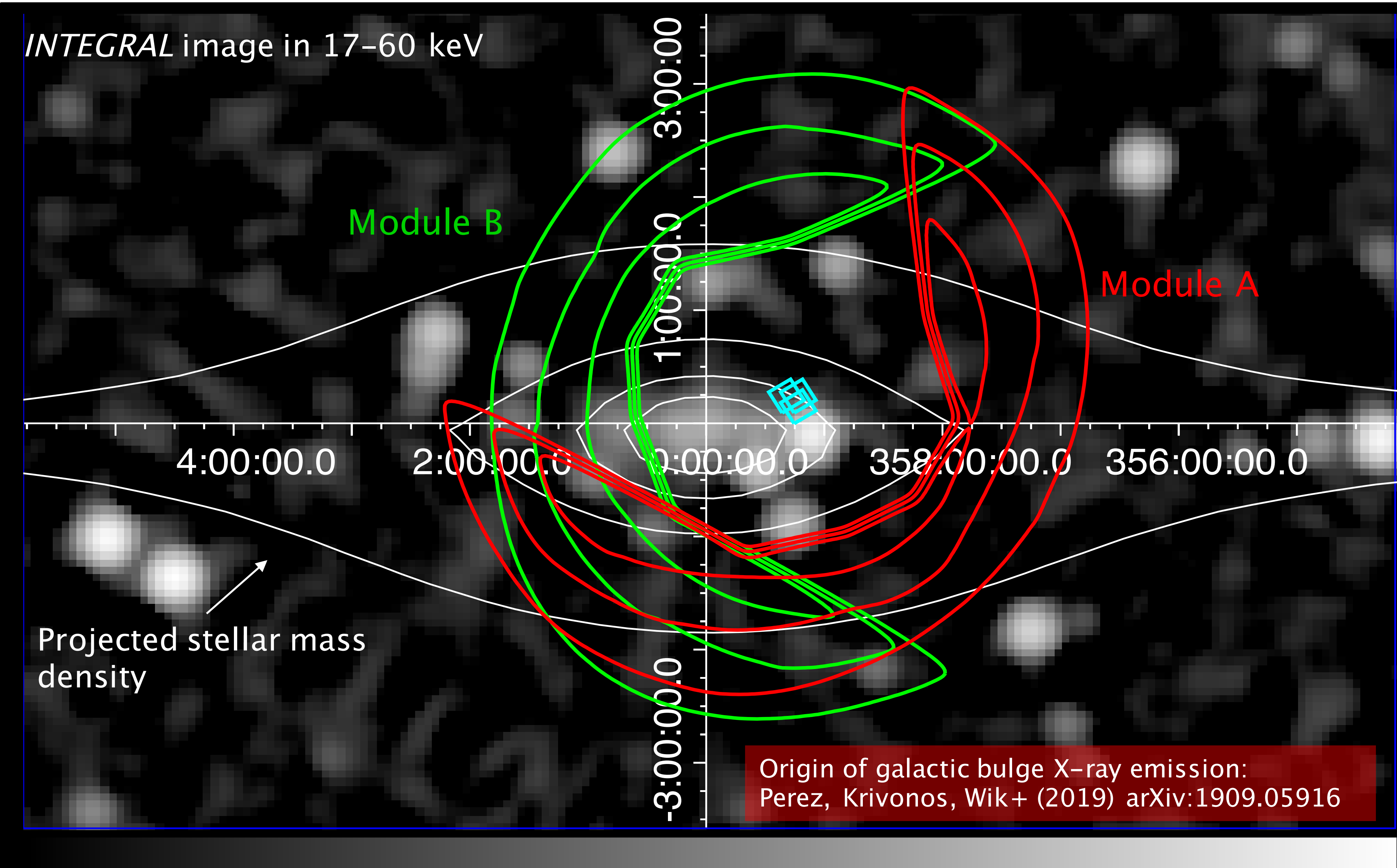
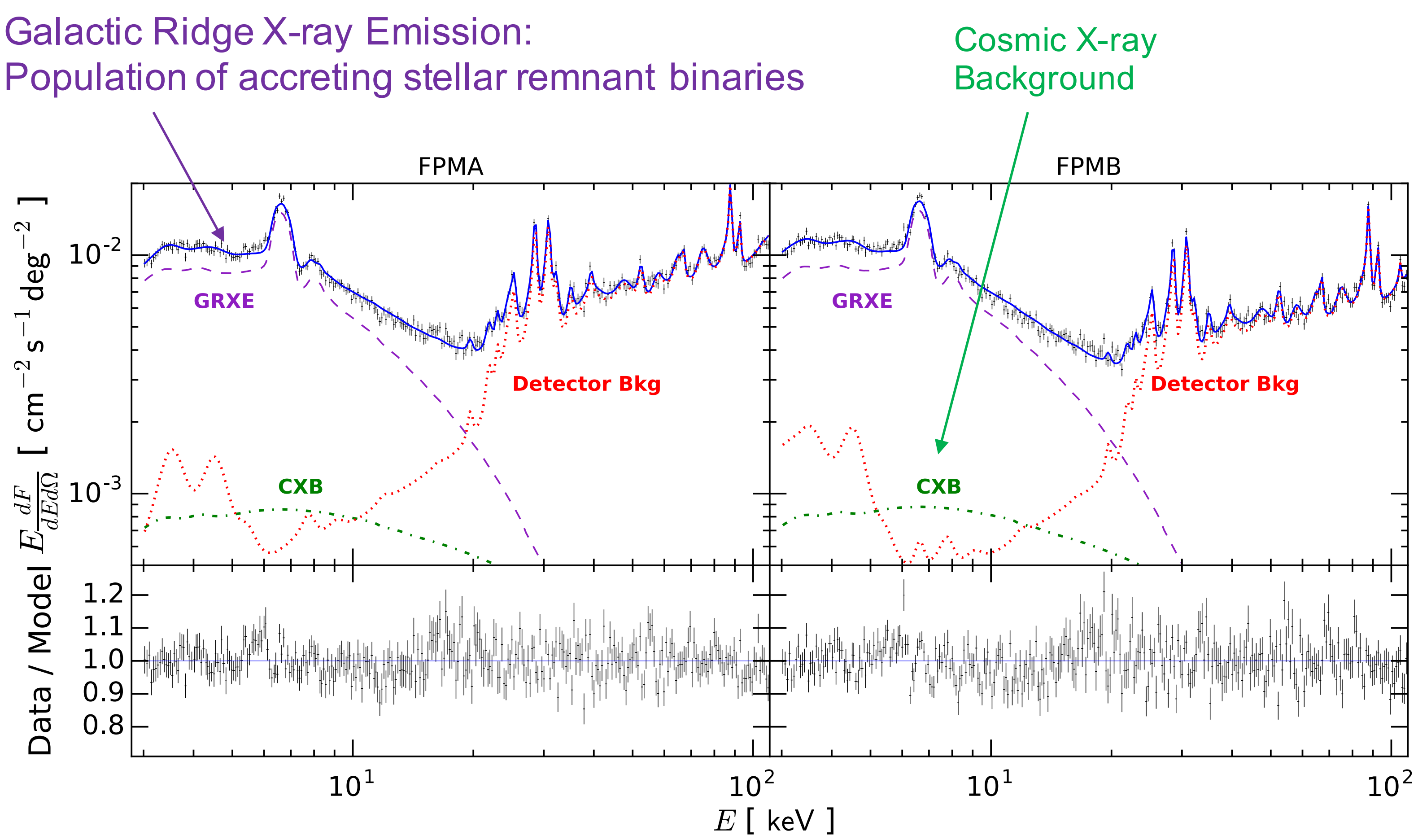
NuSTAR's *NEW* "view" of the Galactic Center



We detect a line! (OK, lots of them…)

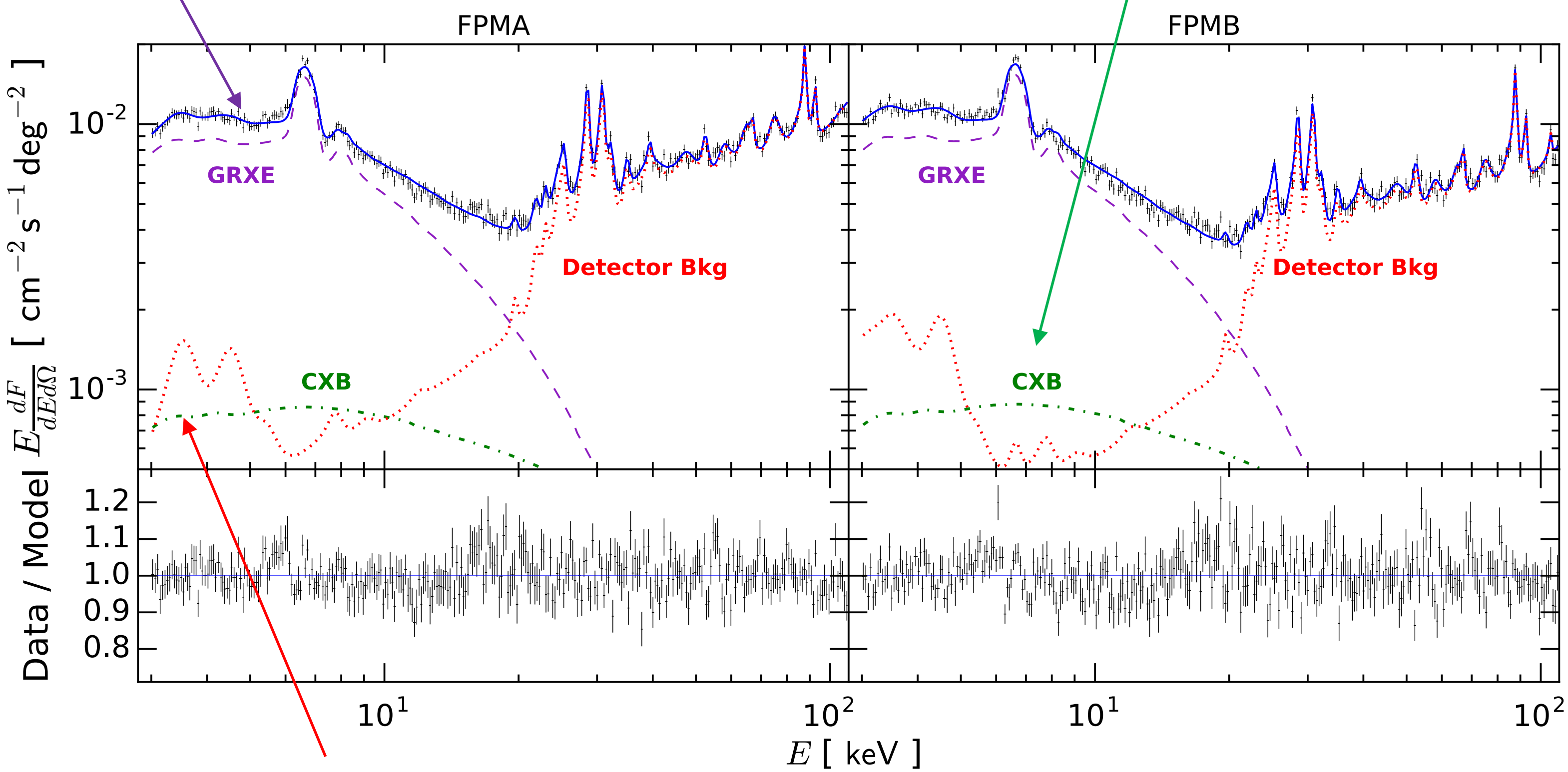


- No *unidentified* X-ray lines
- Set line flux limits: how much DM flux could we add without breaking the spectral fit?
- Conservative method: allow DM line to assume full strength of any known line

We detect a line! (OK, lots of them…)

Galactic Ridge X-ray Emission:
Population of accreting stellar remnant binaries

Cosmic X-ray
Background



A 3.5 keV
(***background***) signal

- Set line flux limits: how much DM flux could we add without breaking the spectral fit?
- Conservative method: allow DM line to assume full strength of any known line

New *leading* sterile neutrino constraints

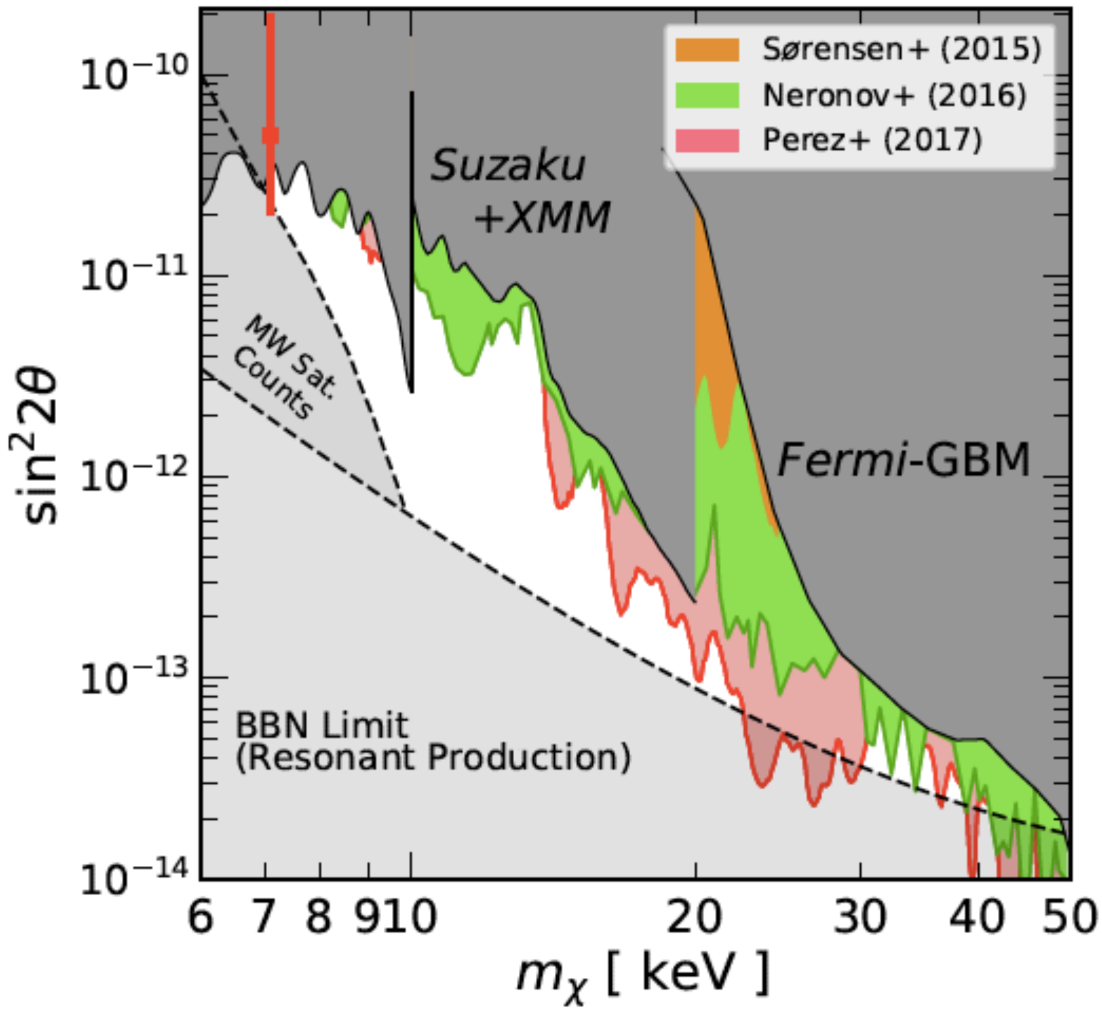
NuSTAR Galactic center

Total exposure: 0.4 Ms

(+) Large DM density
(+) Large sensitivity from unfocused FOV

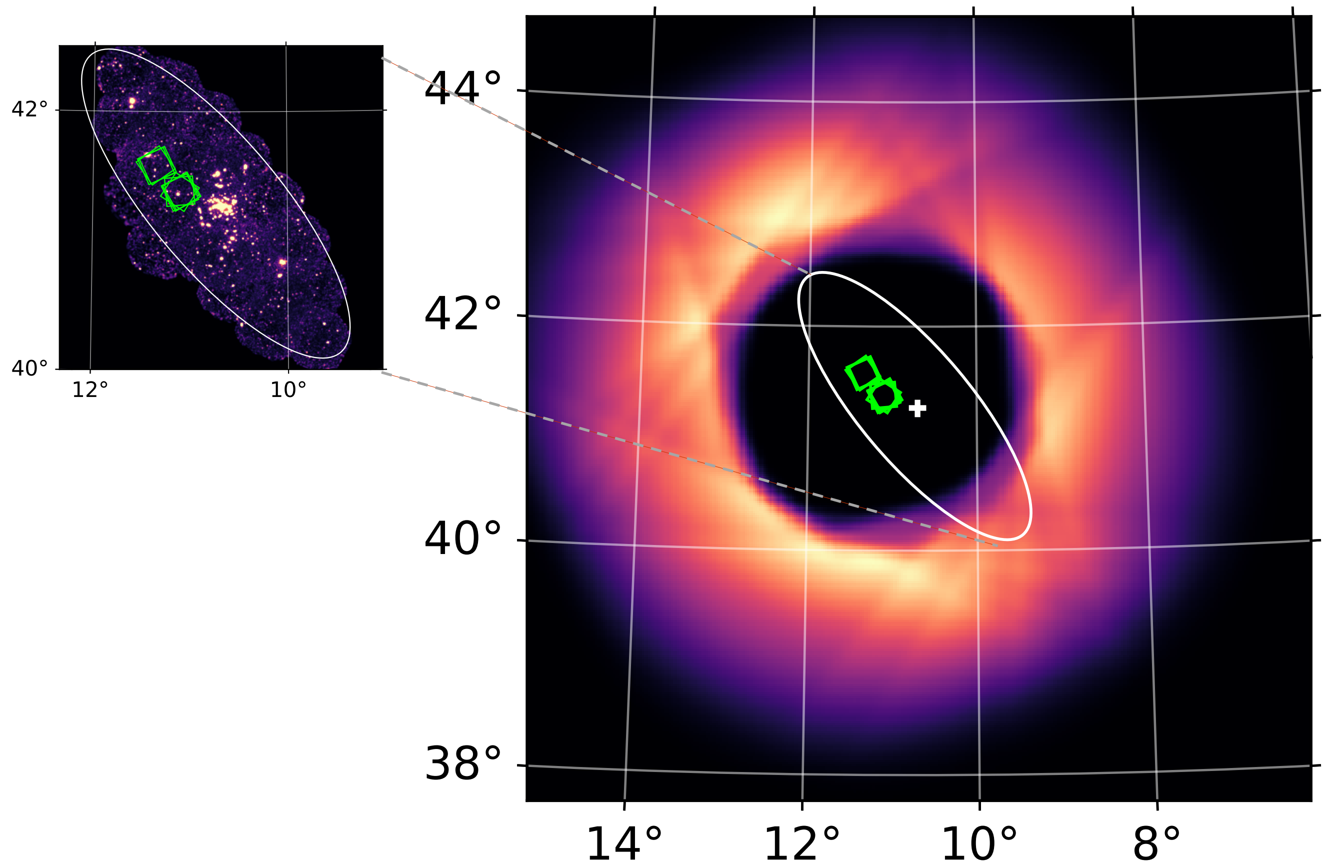
(–) Galactic ridge emission incl. bright Fe lines
(–) Removing point sources reduces effective area

Perez, Ng, Beacom+ (2017)



M31 (Andromeda Galaxy)

- M31 is our closest galaxy neighbor, at ~785 kpc
- 0-bounce NuSTAR field-of-view extends over DM halo, avoids astrophysical disk



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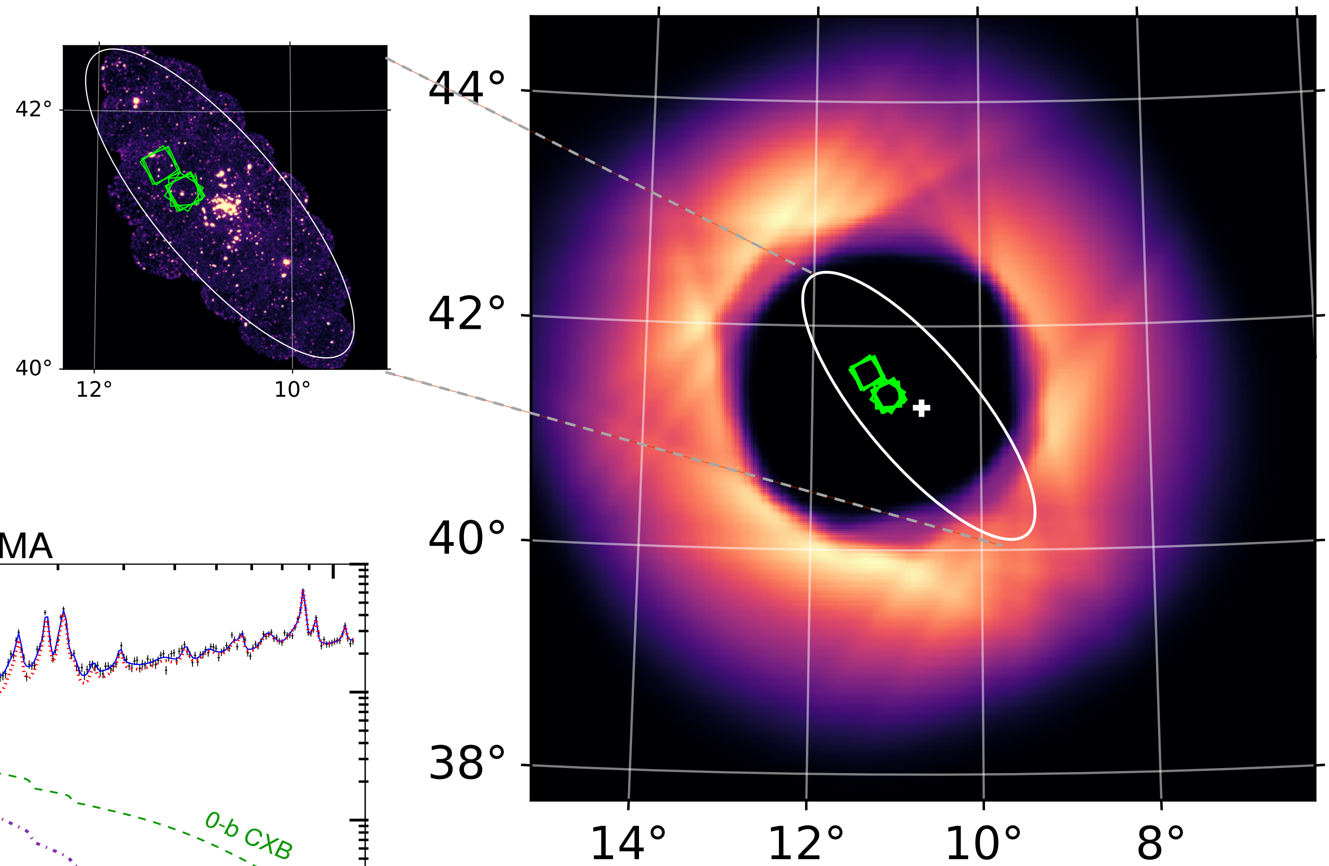
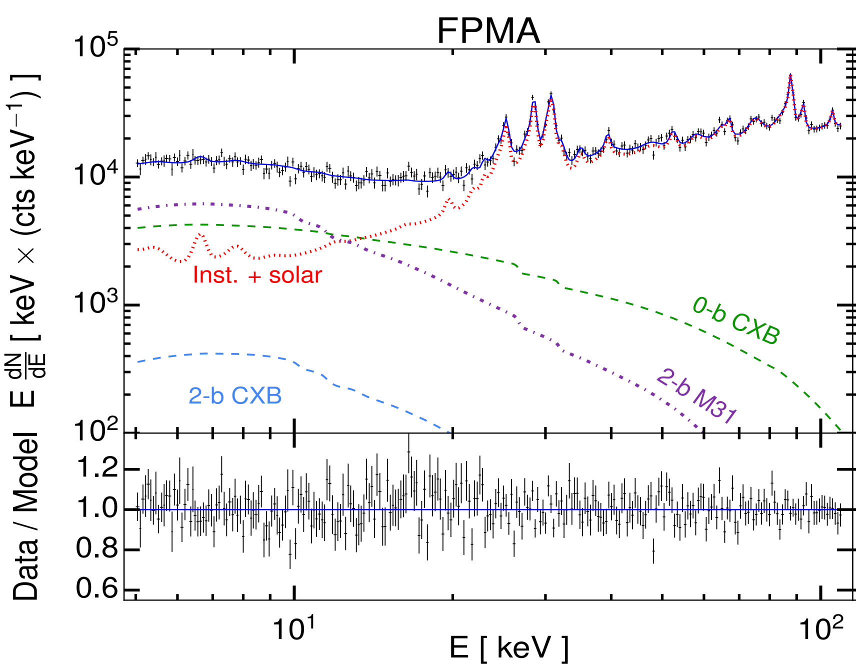




1. Much lower astrophysical background
2. No Fe emission lines at ~6 keV

→ *Improved sterile neutrino constraints!*

New *leading* low-mass constraints

Ng, Roach, Perez+ (2019) 1901.01262

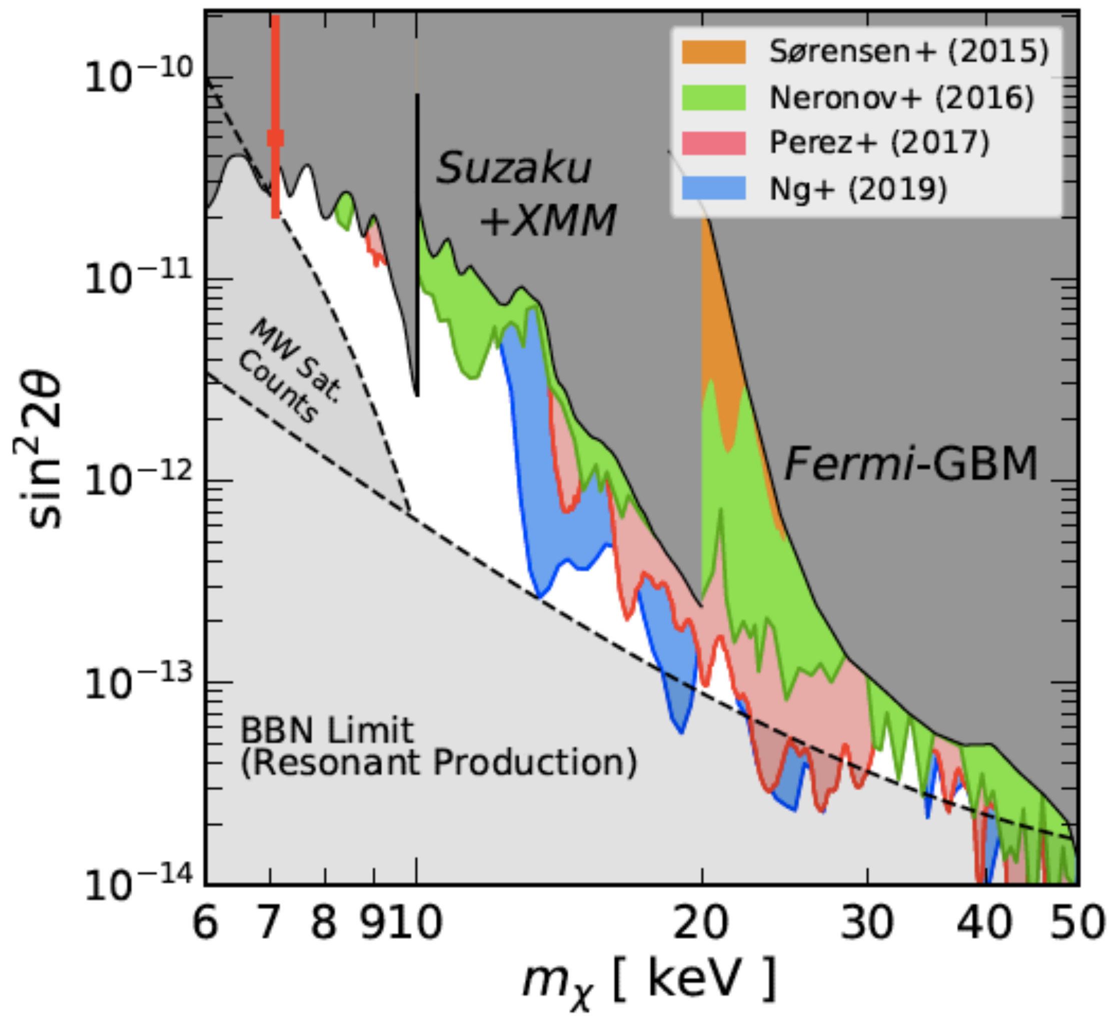
NuSTAR M31

Total exposure: 1.2 Ms

(+) No Fe emission lines
(+) 0-bounce FOV covers most of halo; focused FOV covers core of DM profile

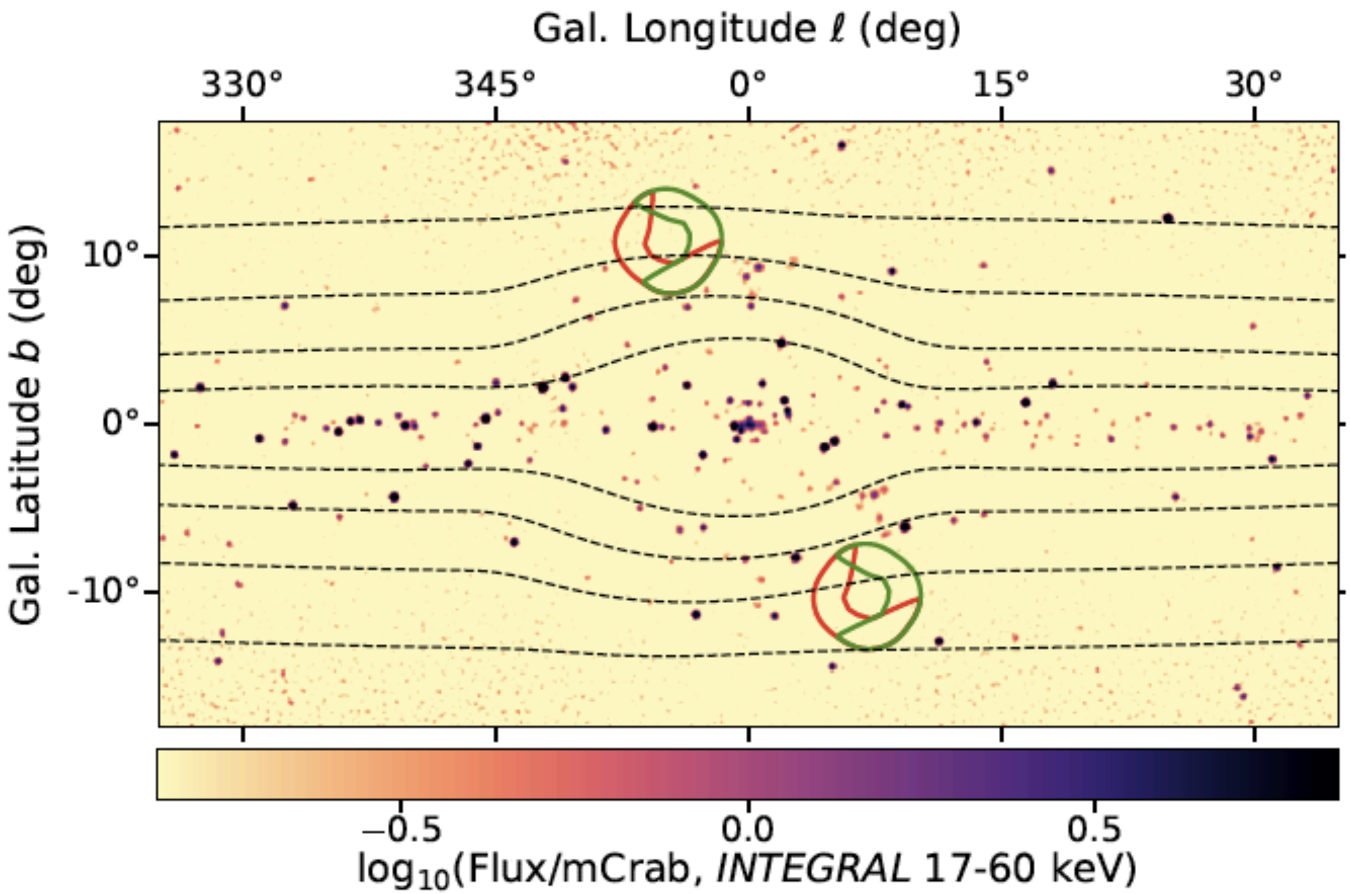
(–) Still don't understand background at E < 5 keV (m < 10 keV)

Reduce available parameter space by ~1/3



Back to the Galactic Center...

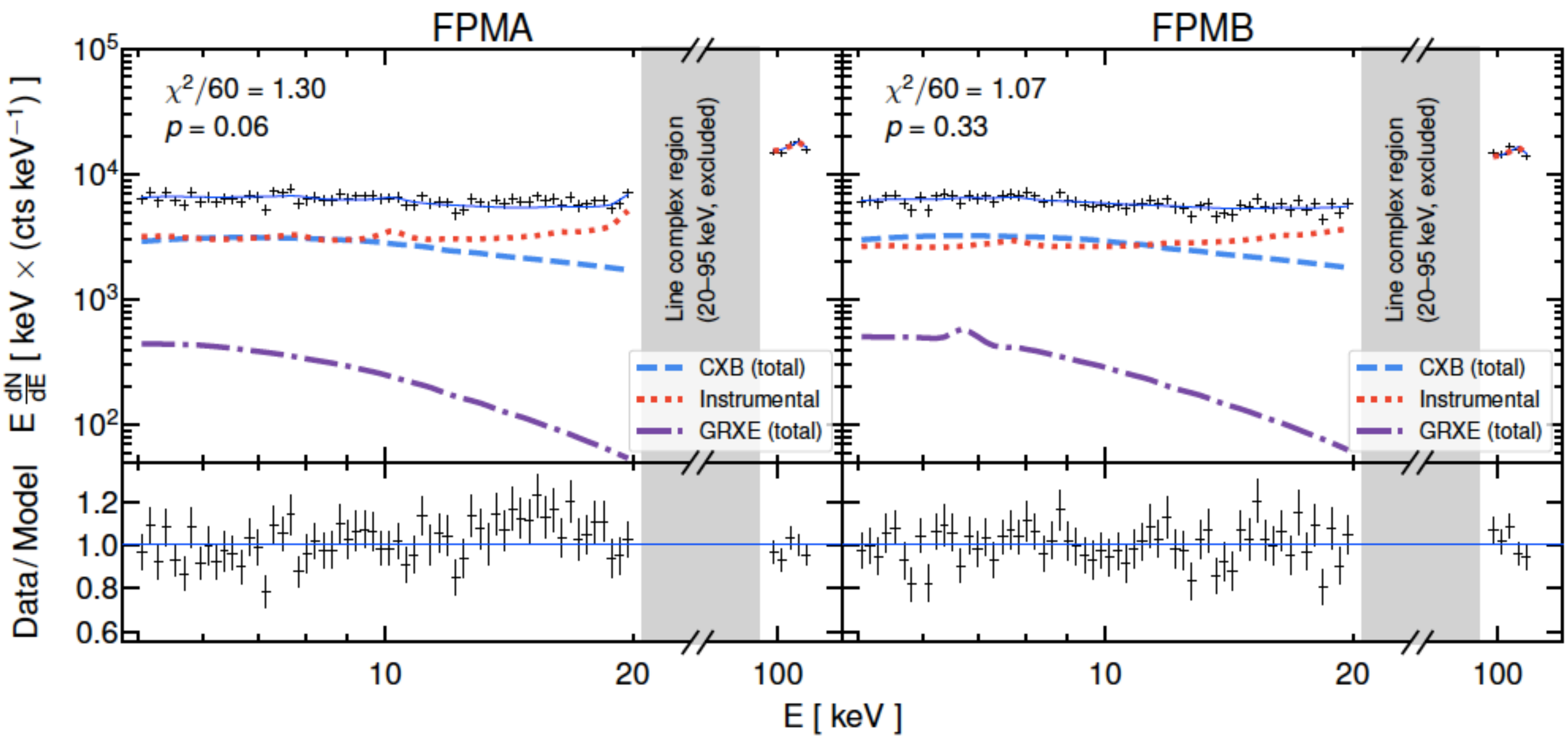
(+) minimal point-source and Galactic ridge emission
(+) remaining near the center of the DM halo



INTEGRAL map from Krivonos+ 2017, arXiv:1704.03364

Low astro emission reveals instrumental background

Good fit quality, but we are starting to see ***systematic deviations from the NuSTAR background model*** due to low astrophysical emission.



New *leading* low-mass constraints

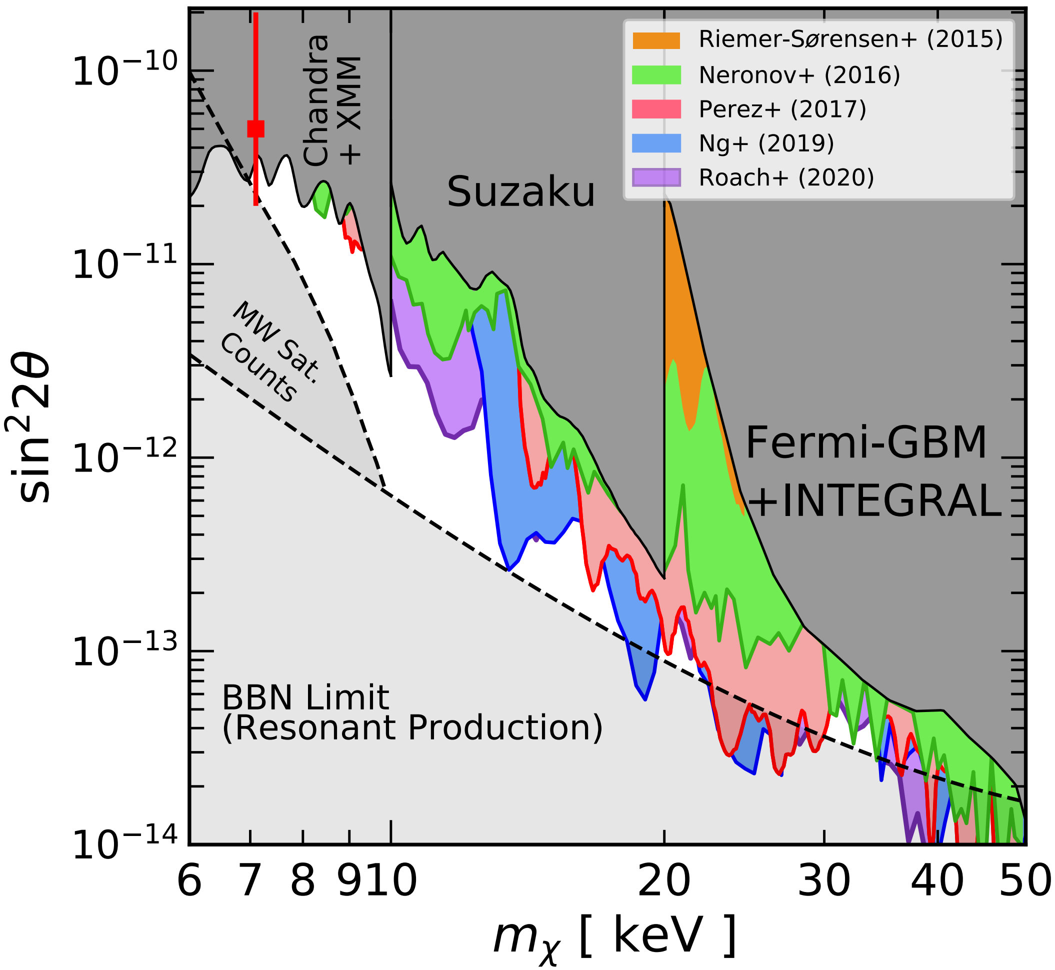
NuSTAR Galactic bulge

Total exposure: 0.2 Ms

Continues to fill in the Fe-line sensitivity gap from the Galactic center survey (Perez+ 2017)

Surpasses limits from blank-sky survey (Neronov+ 2016) using <3% of the exposure time

Roach, Ng, Perez+ (2020) 1908.09037



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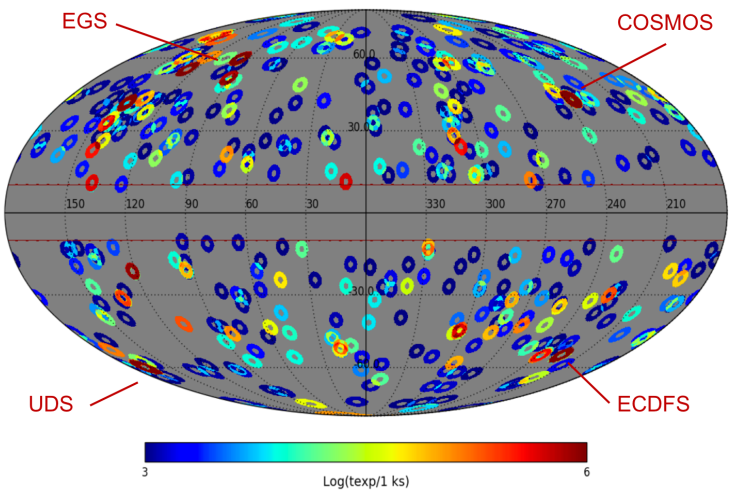
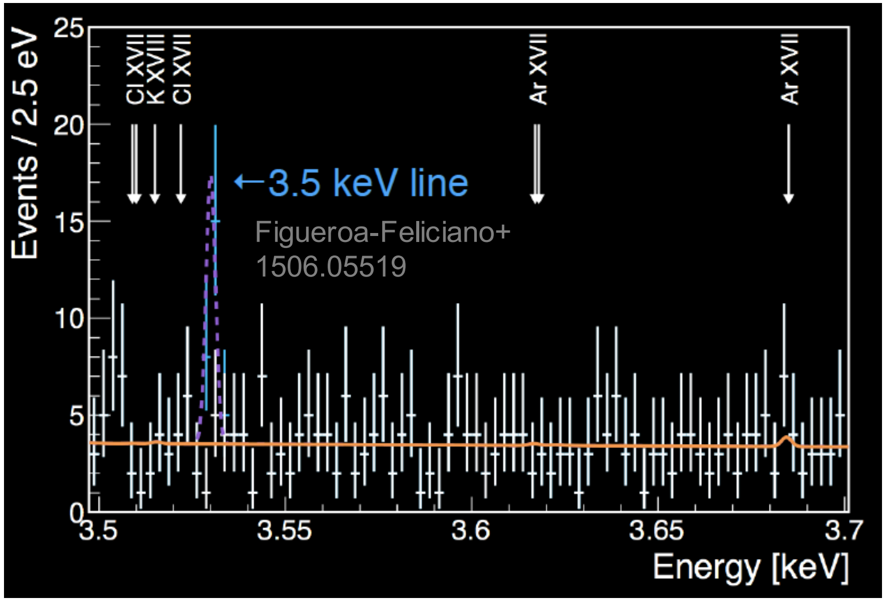
- Sterile neutrinos as dark matter
- X-ray searches for sterile neutrinos
  - Ex: *NuSTAR as a large-aperture dark matter telescope*
- Onwards!

Towards closing the sterile neutrino window?

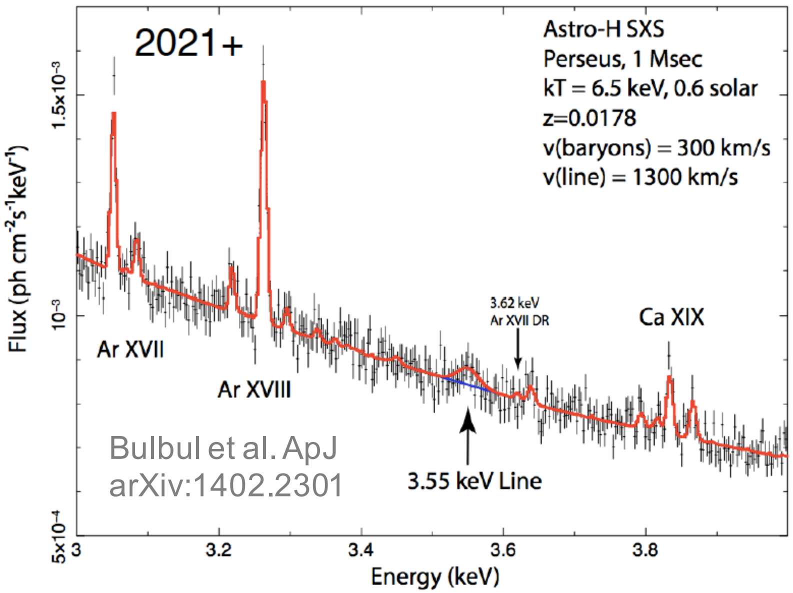


>50 Ms (!) NuSTAR catalog allows for ***improved instrumental background mode***l, increased sensitivity especially at low mass

Prospects for Micro-X rocket:



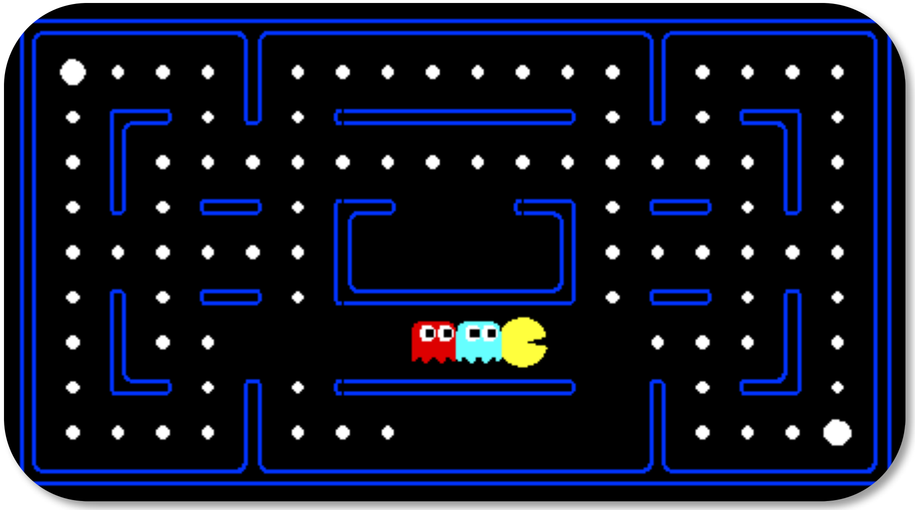
Prospects for XRISM Satellite:



Conclusions

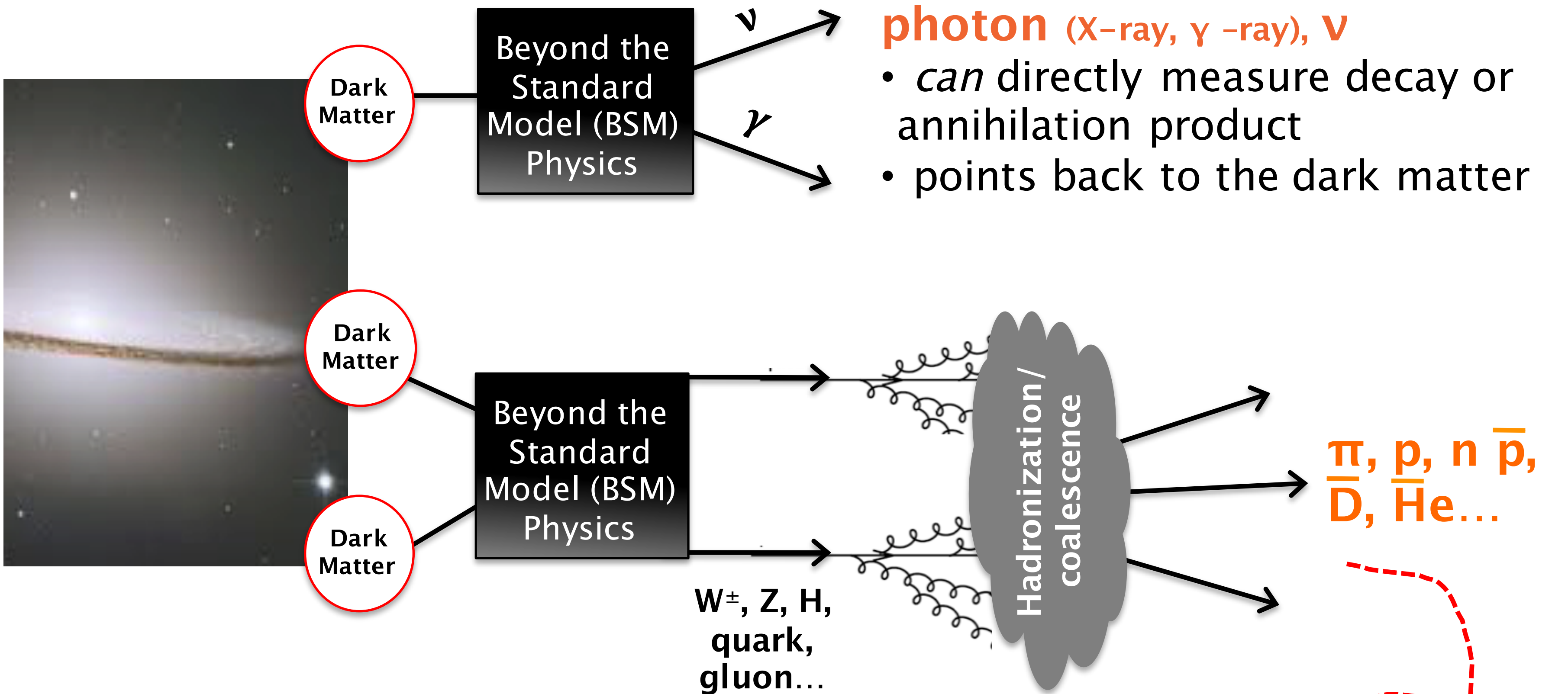
- Sterile neutrinos are among the best-motivated dark matter candidates
- Astrophysical X-ray searches provide the best chance of detection
- Adapting the NuSTAR instrument as a large-aperture dark matter telescope has increased sensitivity by over an order of magnitude
- In the coming decade…

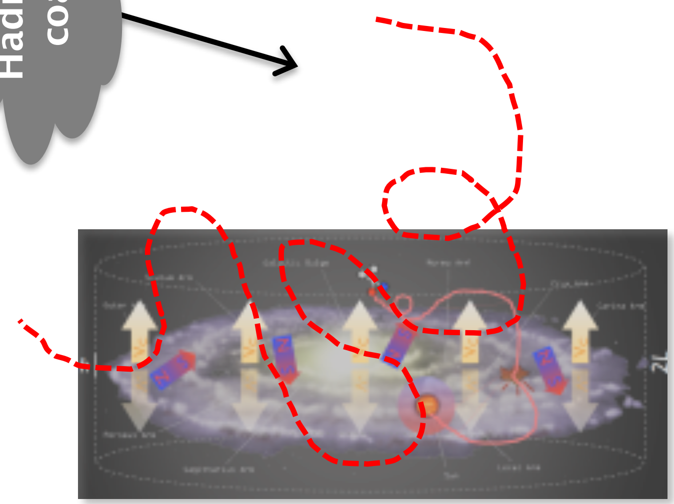
OR?



BACKUP

Scanning the sky for dark matter

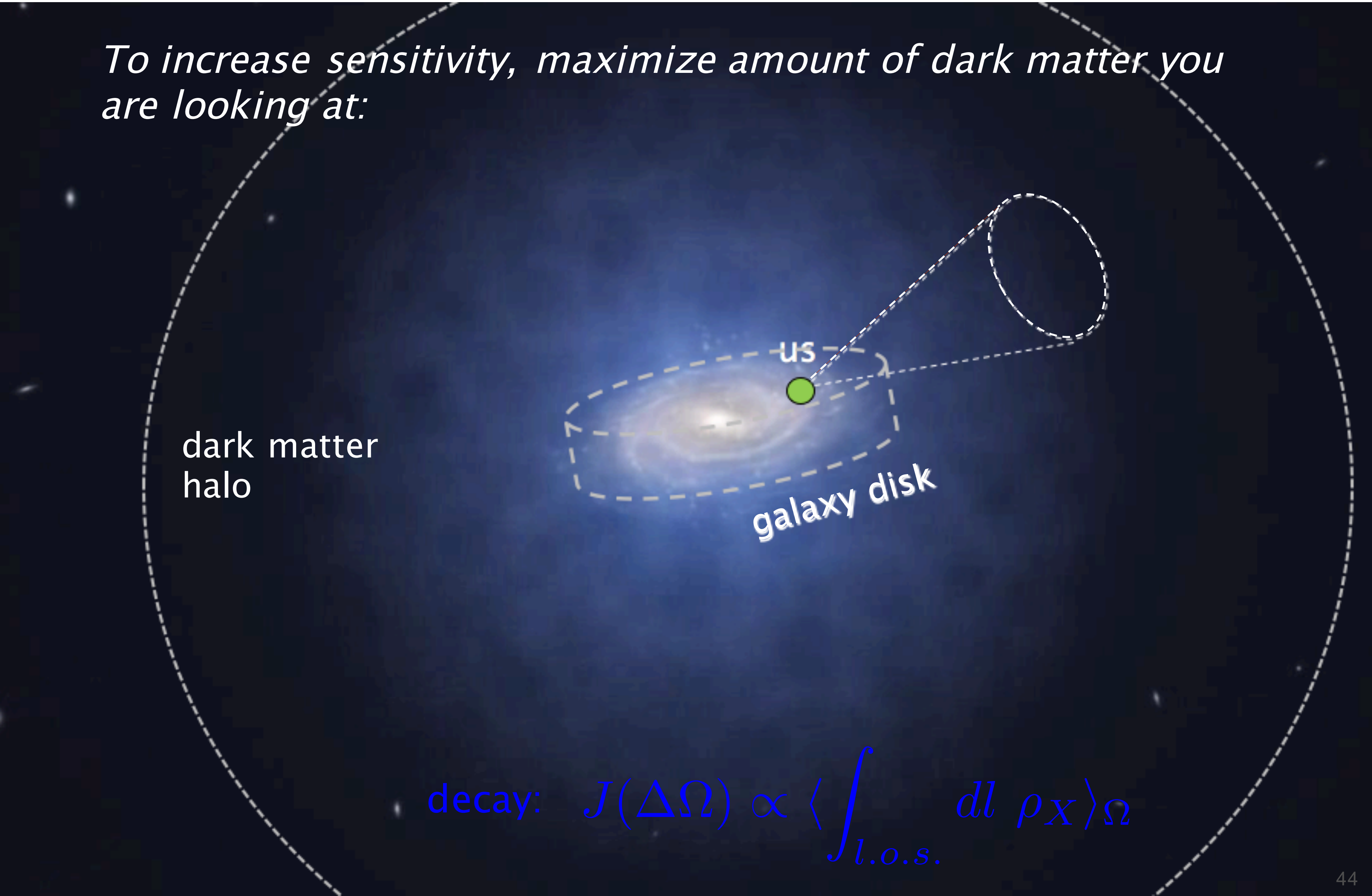




- For p̄, D̄, H̄e… additional uncertainties from **hadronization, nuclear coalescence.**
- For any charged particle, need precise modelling of **galactic and solar propagation.**

How much dark matter?

To increase sensitivity, maximize amount of dark matter you are looking at:



decay: $J(\Delta\Omega) \propto \langle \int_{l.o.s.} dl \ \rho_X \rangle_\Omega$

Maximizing your sterile neutrino signal

$$F = \frac{\Gamma}{4\pi m_{DM}} \frac{M_{DM}^{fov}}{D_L^2}$$

The particle physics:
- Flux increases with increasing **DM decay rate Γ**

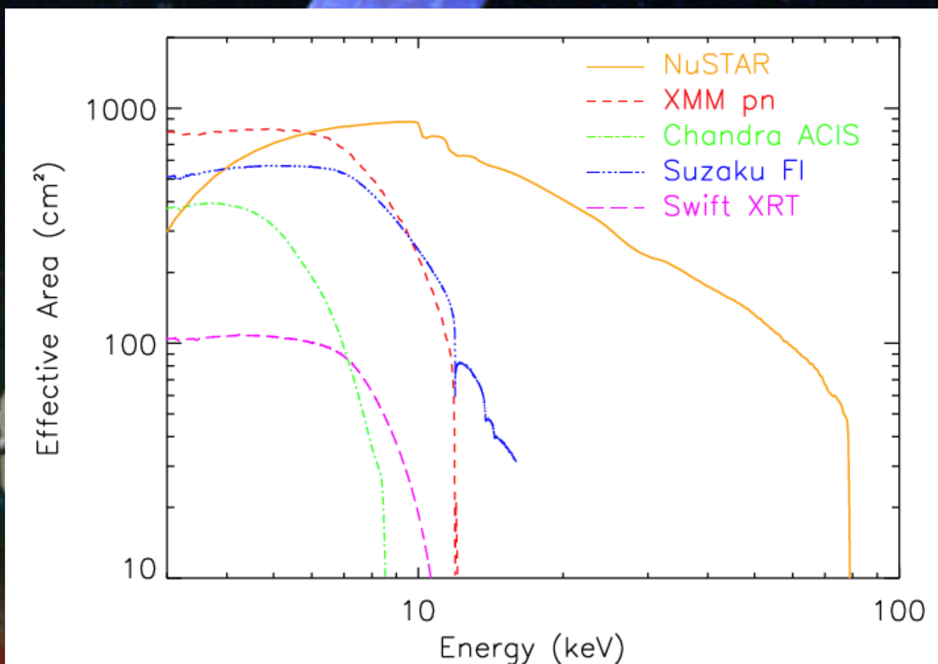
$$\Gamma = 1.38 \times 10^{-32}\,\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_\chi}{\mathrm{keV}}\right)^5$$

The astrophysics:
- Flux increases with increasing **DM mass in the field-of-view**, i.e. higher *J*-factor, larger field-of-view

The instrument/observation:
- Flux increases with increasing exposure time, effective area, FOV, energy resolution

$$S/N \propto J\sqrt{t_{exp} A_{eff} \Omega_{fov}}/\sqrt{\Delta E}$$

NuSTAR: first focusing *high-energy* X-ray telescope



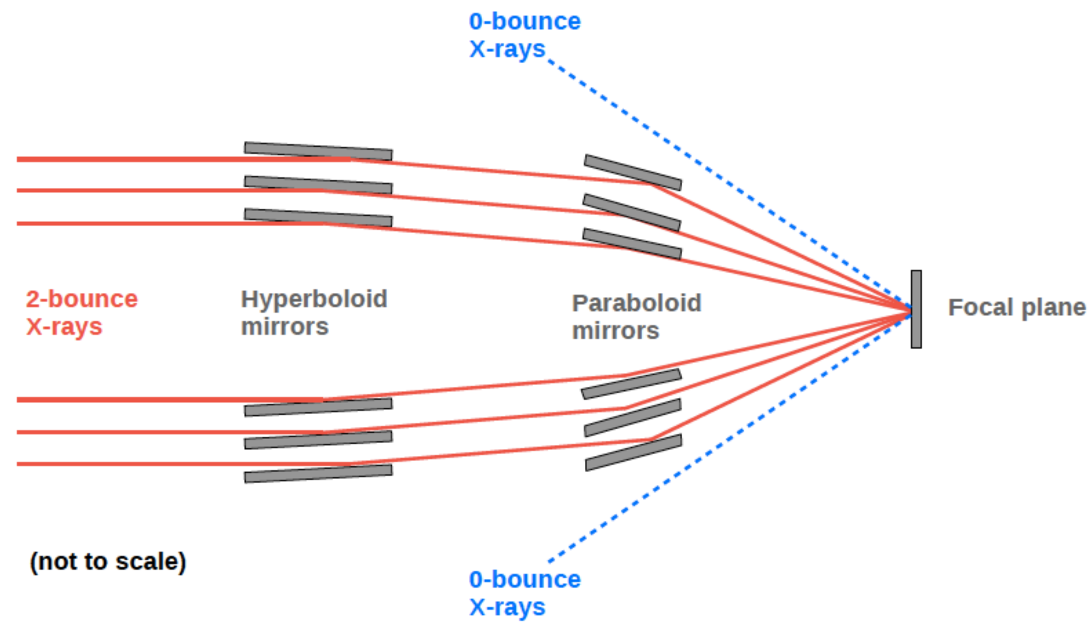
Harrison+ (2013)
arxiv:1301.7307

- **Energy Band:** 3–79 keV
- **Angular Resolution:**
  58" (HPD), 18" (PSF)
- **Field-of-view:** 12' x 12'
- **Energy resolution (FWHM):**
  0.4 keV at 6 keV,
  0.9 keV at 60 keV
- **Temporal resolution**: 0.1 ms
- **Maximum Flux Rate:** 10k ct/s
- **ToO response:** <24 hours

NuSTAR as a *large-aperture DM telescope*

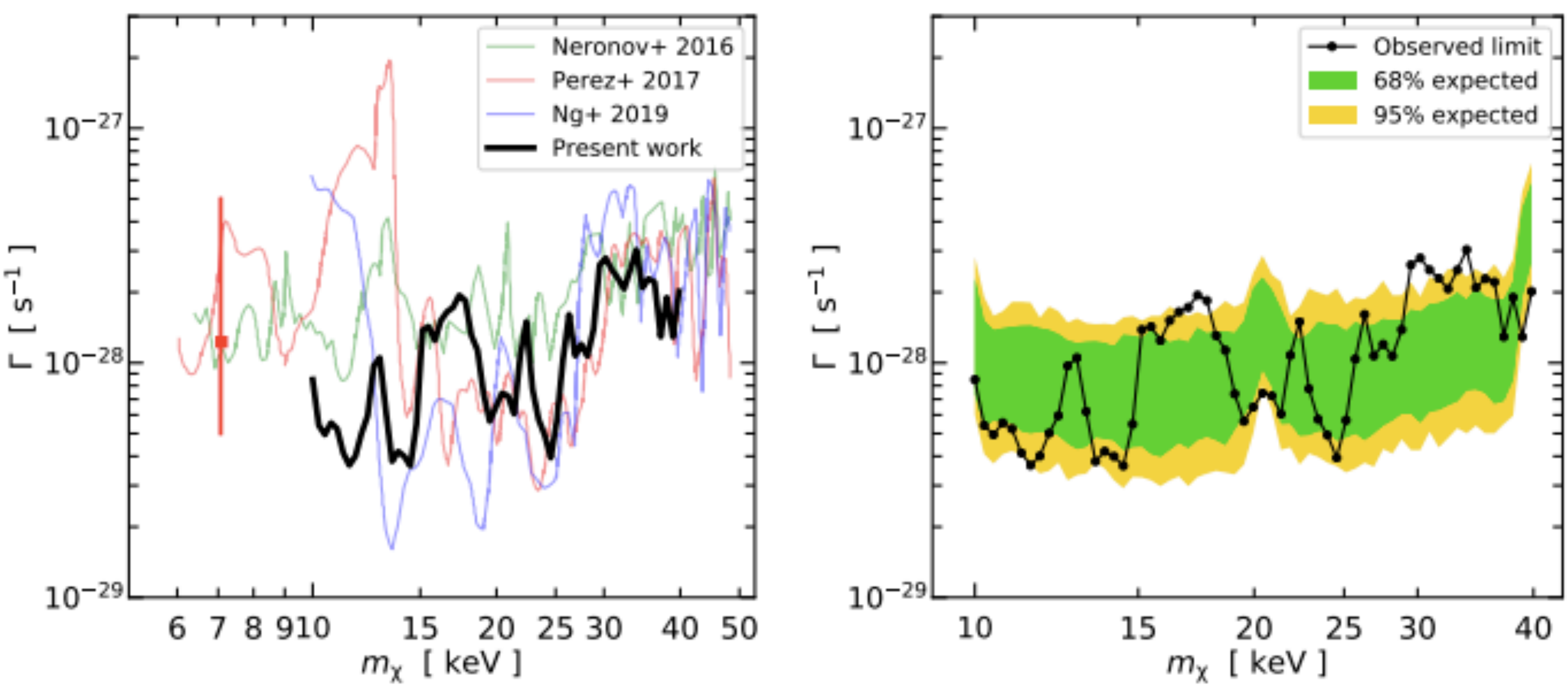
- Aperture-stops block unfocused X-rays from reaching the detectors
- But shielding is not complete → source of ***stray-light*** or ***0-bounce*** background

- 2-bounce (focused): $A_{\rm eff}(E) \lesssim 200~{\rm cm}^2$ (avg), FOV $\sim 0.05~{\rm deg}^2$
- 0-bounce (unfocused): $A_{\rm eff} \sim 13~{\rm cm}^2$, FOV $\sim 4.5~{\rm deg}^2$



- **Increases collection efficiency for a slowly-varying, diffuse dark matter signature *by over an order of magnitude***

Limited by statistical, not systematic deviations



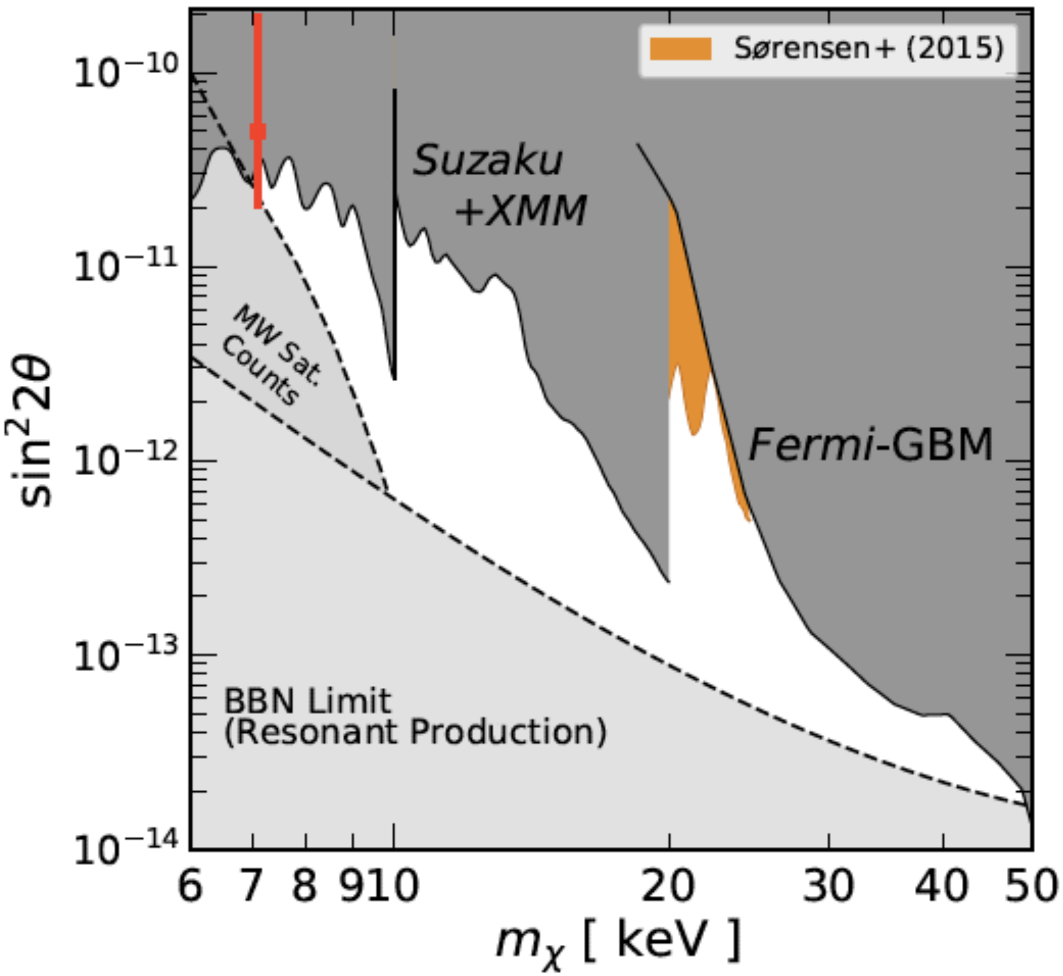
“0-bounce” technique allows leap-forward in sensitivity

NuSTAR Bullet Cluster

Total exposure: 0.6 Ms

(+) Huge DM mass in FOV

(–) Large astro. background
(–) **DM in focused FOV only**
(–) 3.5-keV line redshifted out of NuSTAR acceptance



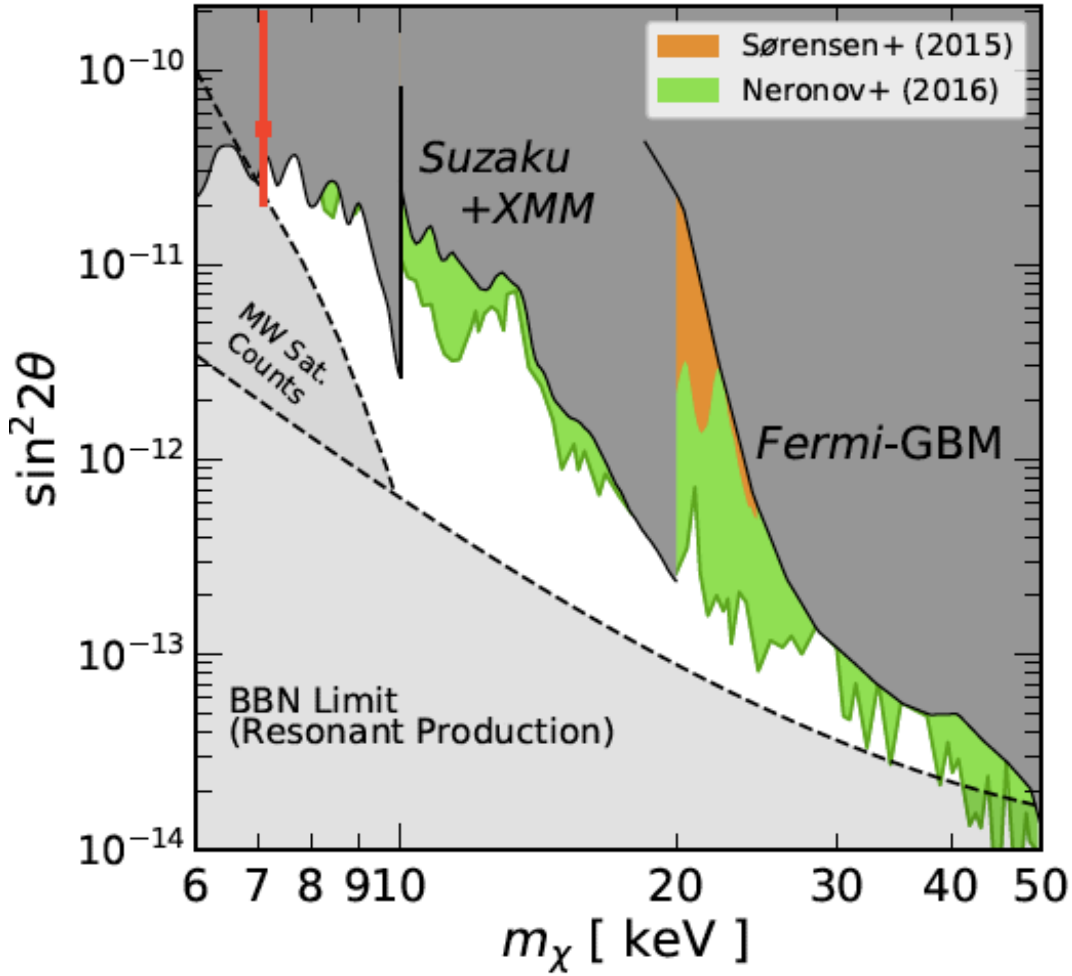
“0-bounce” technique allows leap-forward in sensitivity

NuSTAR Blank-sky

Total exposure: 7.5 Ms

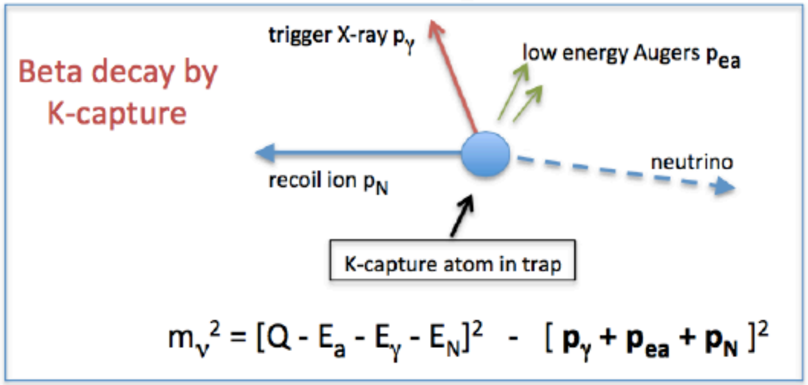
(+) Long exposure
(+) Low astro. background
(+) **Large sensitivity from unfocused FOV**

(–) Low DM density



Direct detection

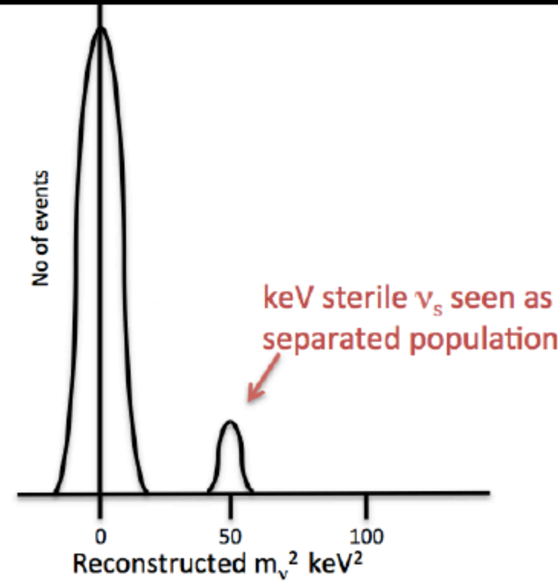
Laboratory Method: full kinematic reconstruction of K-capture nuclear decay



Original studies: Finocchiaro & Shrock 1992

CACHE (Cesium Atomic-electron Capture with Heavy neutrino Emission)

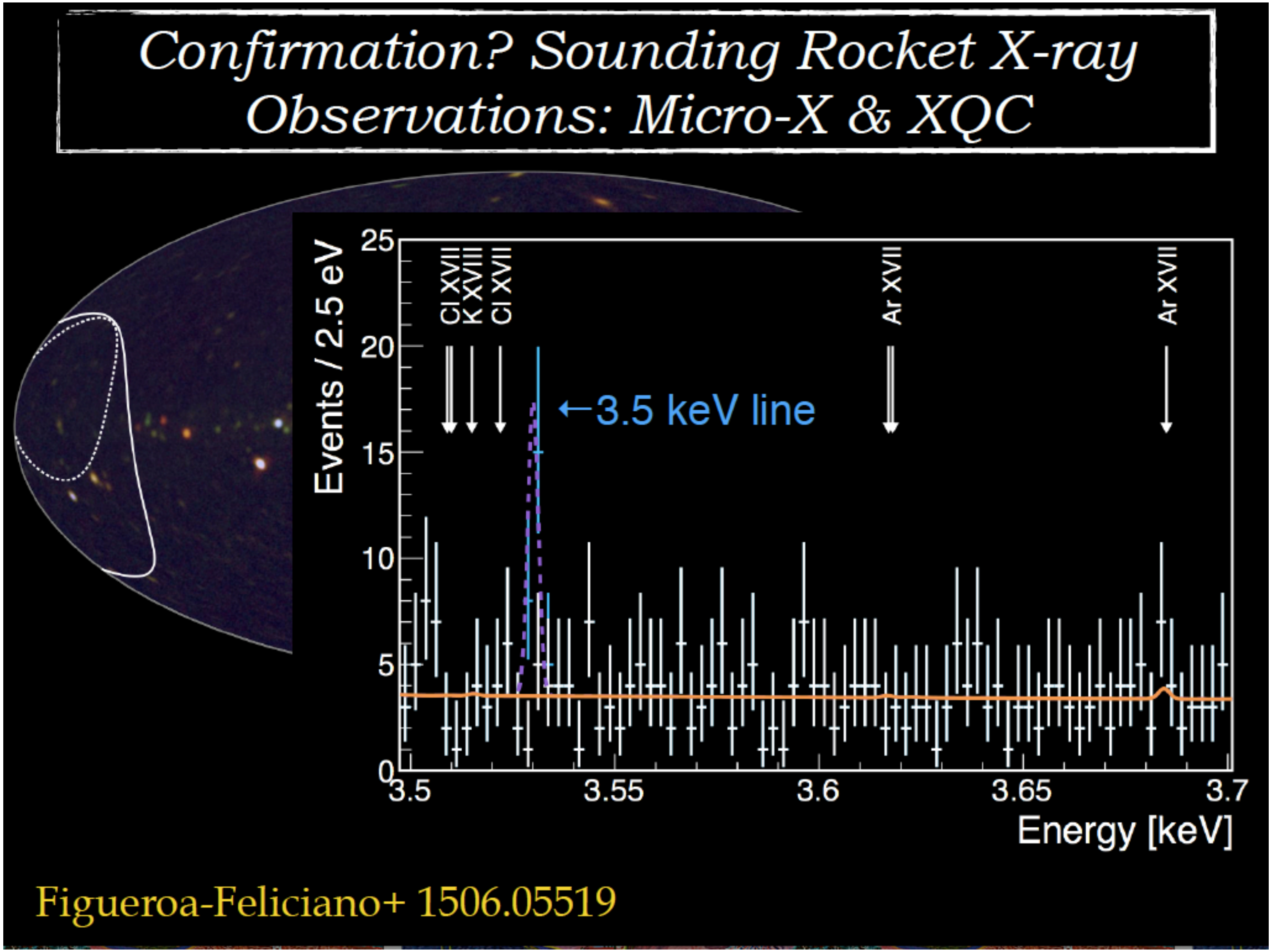
^{131}Cs Ion trap proposal:
Peter Smith+ arXiv:1705.06876



High precision time of flight measurements needed to achieve 6σ separation from zero mass peak

Recent studies show this may now be feasible

3.5 keV Prospects with Micro-X



3.5 keV Prospects with XARM