Opening New Windows on *Dark Matter in* the X-ray Sky

Kerstin Perez

ACP Winter Workshop

March 24, 2022

* Focusing on work from my group, but see references throughout!

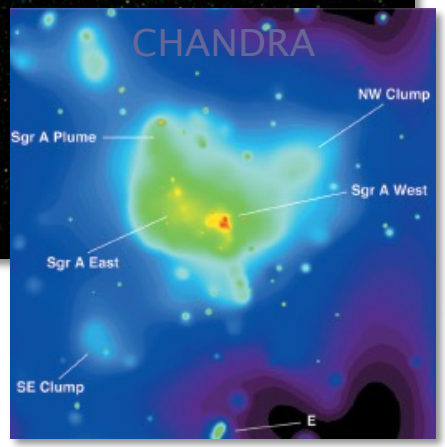
*** Photo from 33 km up in the air!**
Prototype GAPS balloon flight, June 2012

The sky from low to high-energy

Optical, IR, UV:

Stars and gas

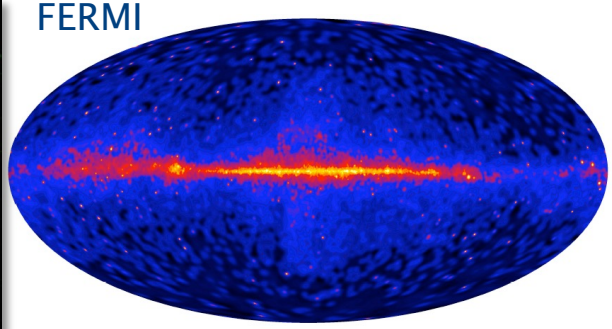
X-rays:



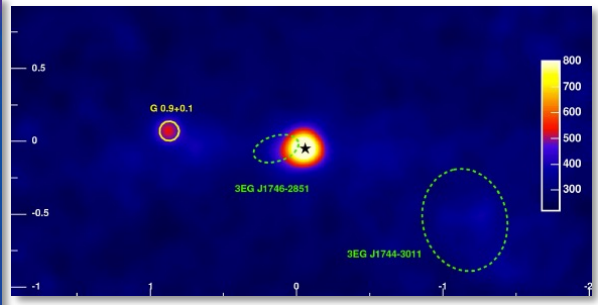
Accreting black holes, white dwarfs, neutron stars; supernovae, very hot gas, scattering by cosmic rays

Gamma-rays:

FERMI

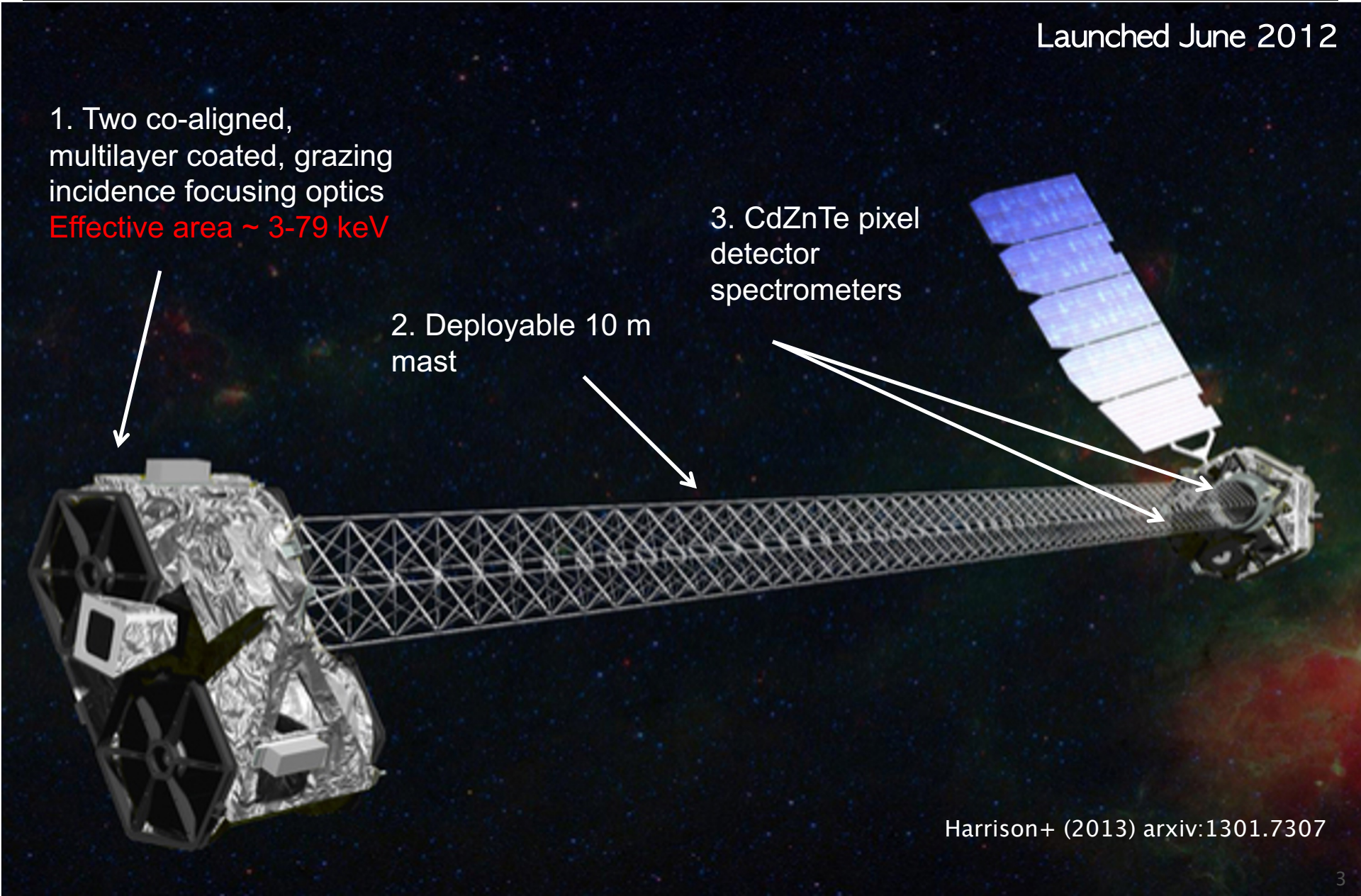


HESS



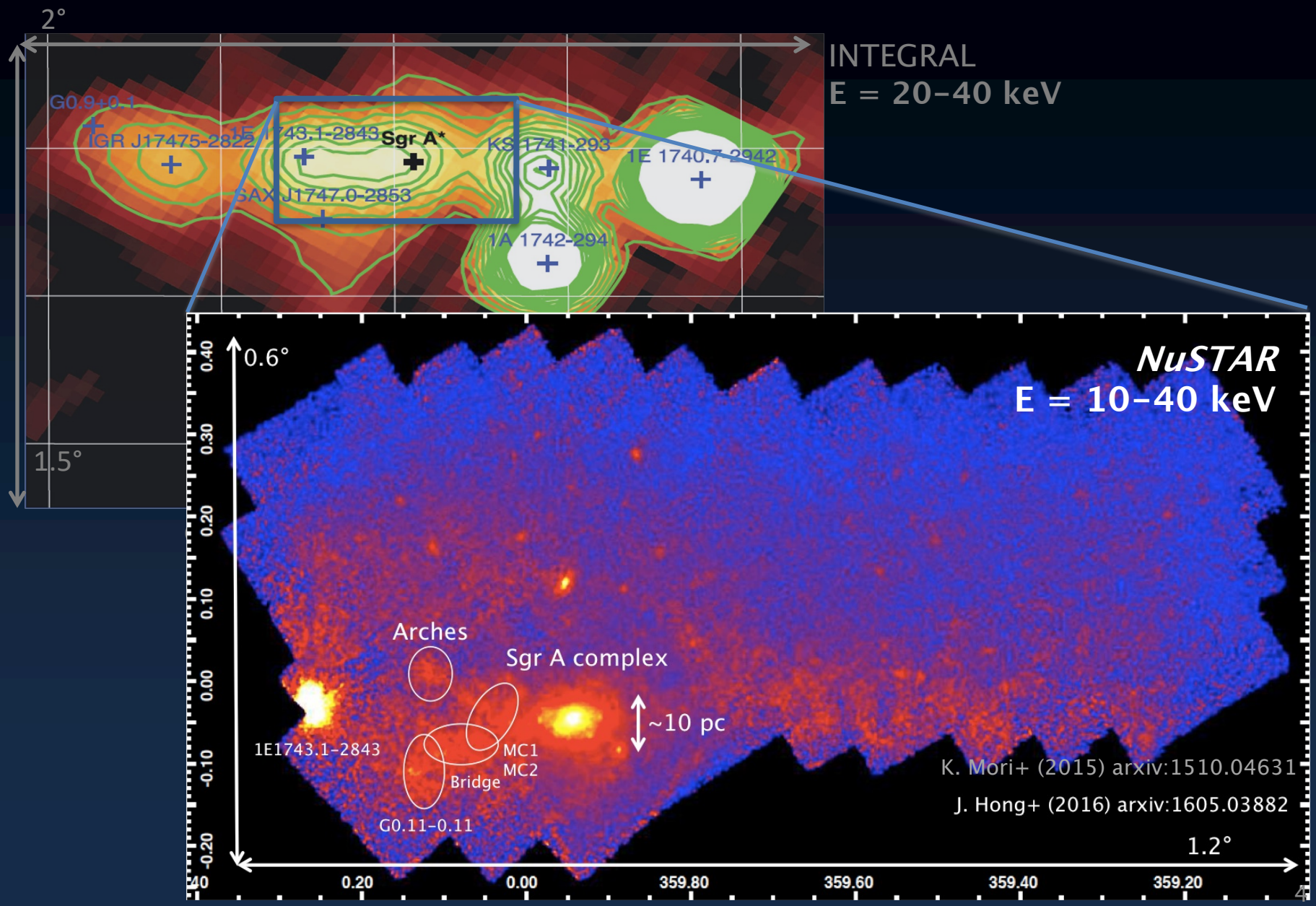
Pulsars, supernovae, active galactic nuclei

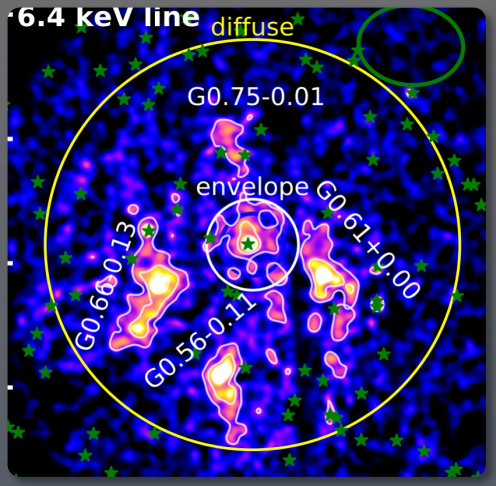
NuSTAR: first *focusing high-energy* X-ray telescope



Focus on the Galactic Center

- High density of *both* astrophysical X-rays and dark matter

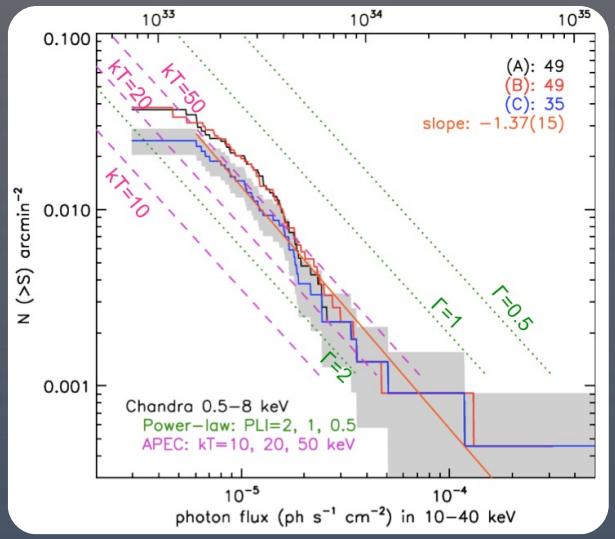




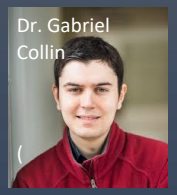
New!

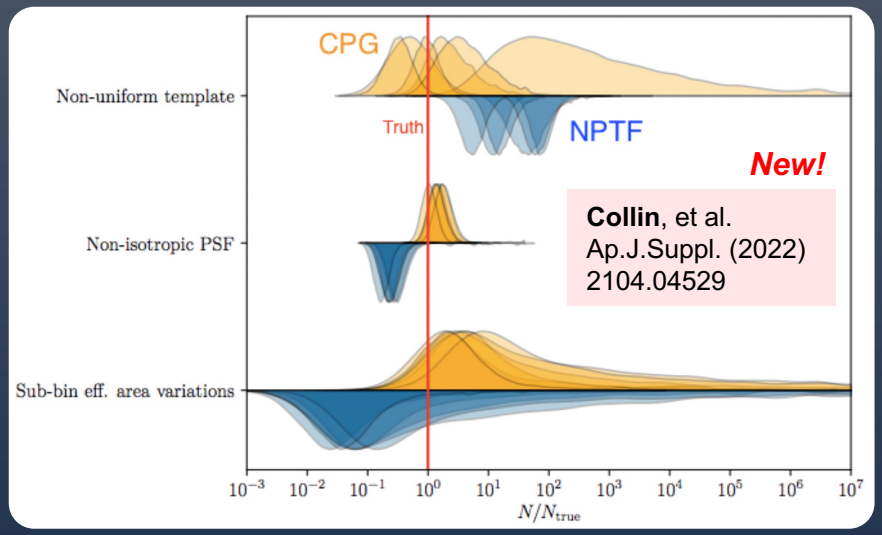
Rogers, et al. Submitted Ap.J. (2021) 2108.13399

Tracing X-ray, cosmic-ray injection in molecular clouds



Improved statistical method to disentangle faint point-source populations from diffuse (particle) backgrounds





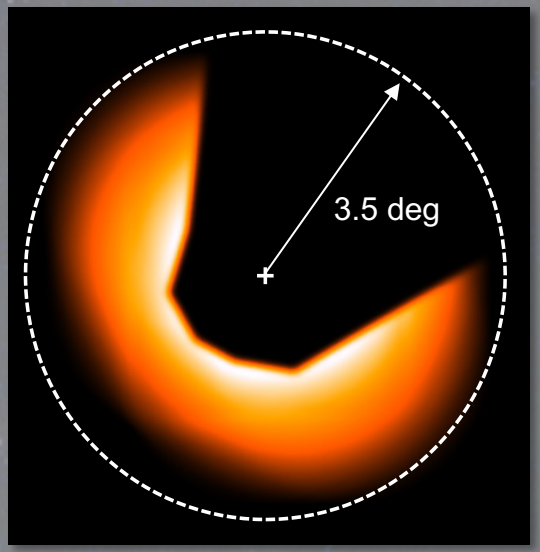
New!

Collin, et al. Ap.J.Suppl. (2022) 2104.04529

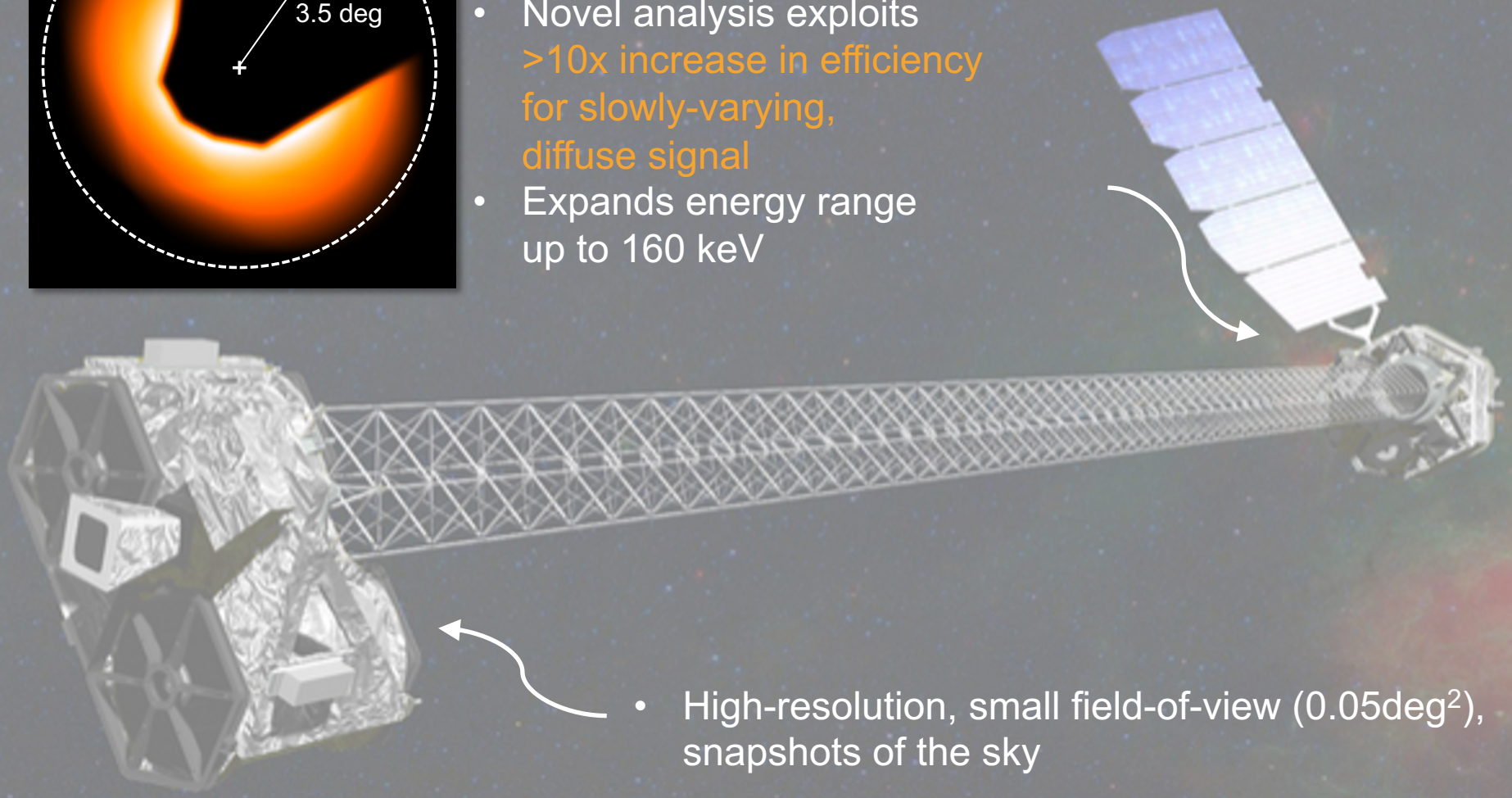
Constraining stellar remnant populations in galactic nuclei

Perez+ Nature (2015)
Hong+ (2016) 1605.03882
Hailey, Mori, Perez+ (2016)
Perez, Krivonos, Wik (2019)

Adapting NuSTAR as a *large-aperture DM telescope*



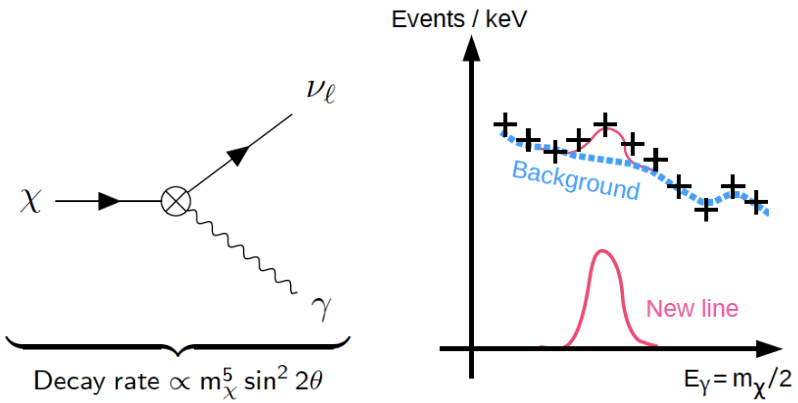
- "0-bounce" photons that bypass the optics are typically a major background
- Novel analysis exploits >10x increase in efficiency for slowly-varying, diffuse signal
- Expands energy range up to 160 keV

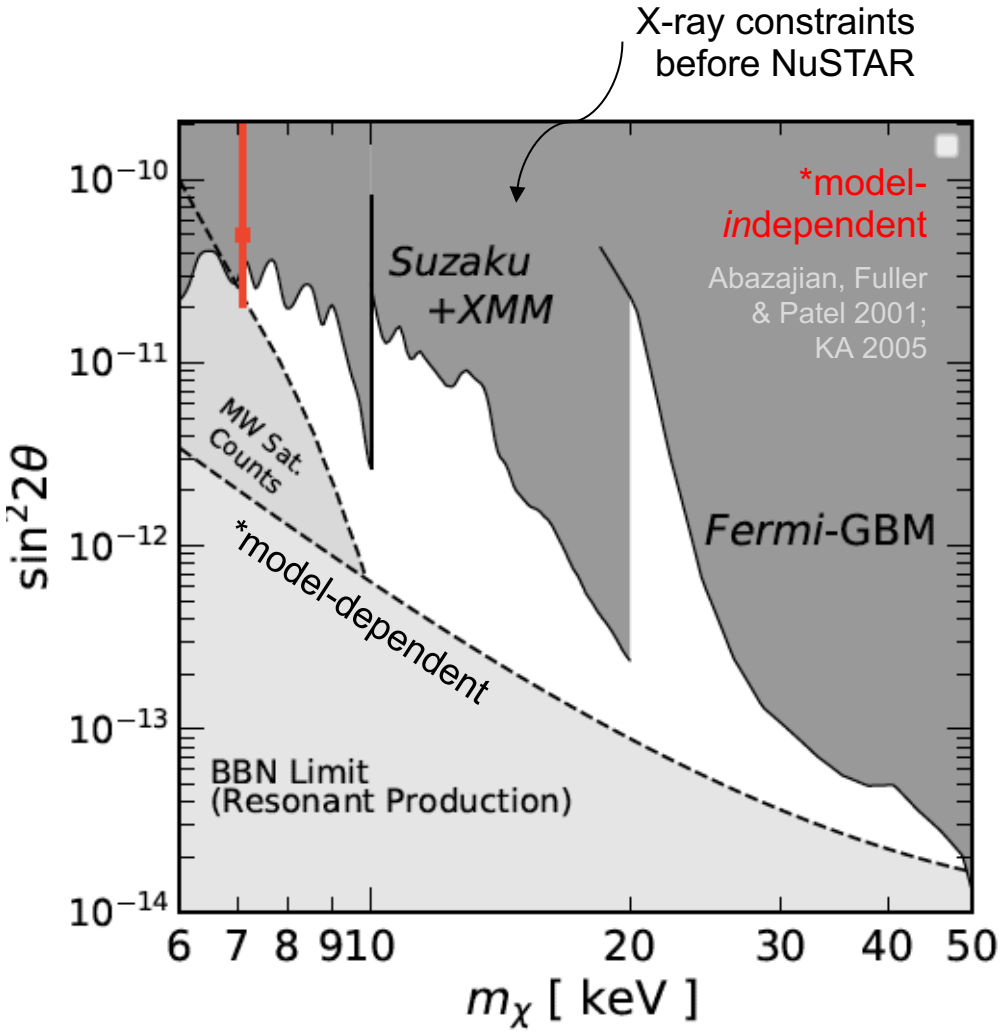


- High-resolution, small field-of-view (0.05deg^2), snapshots of the sky

X-rays from sterile neutrino dark matter

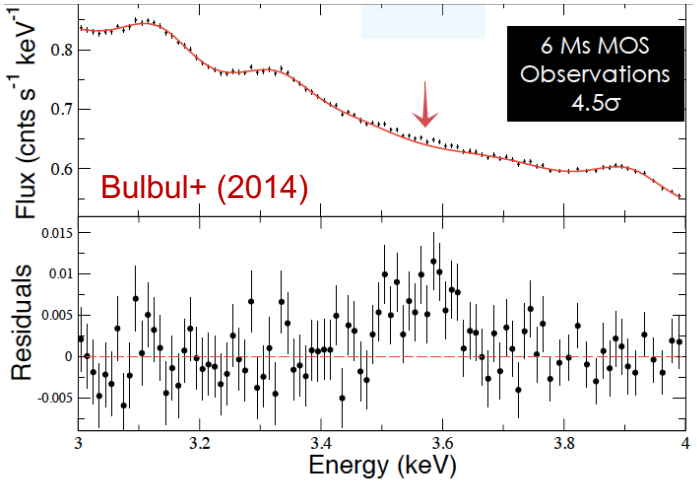
- **Sterile neutrinos** are a candidate for **keV-mass dark matter**, motivated by neutrino mass and mixing
- Can decay to a neutrino and a photon with $E_{photon} = m_{DM} / 2$



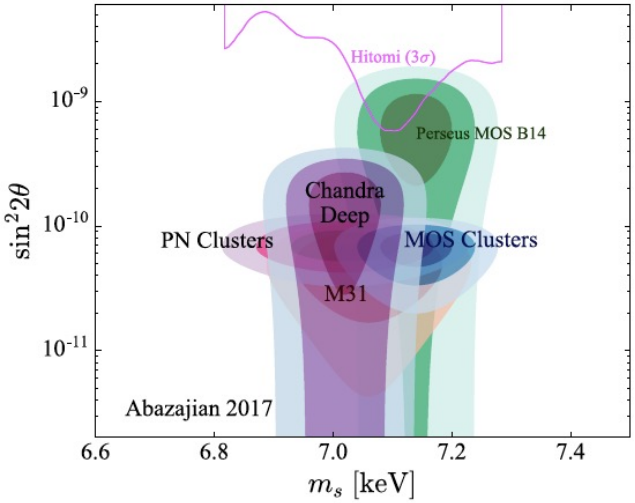


Current status: the "3.5 keV line"?

1. A faint line detected in XMM-Newton spectra of stacked galaxy clusters



2. Line consistent with observations using **many instruments and astrophysical regions**



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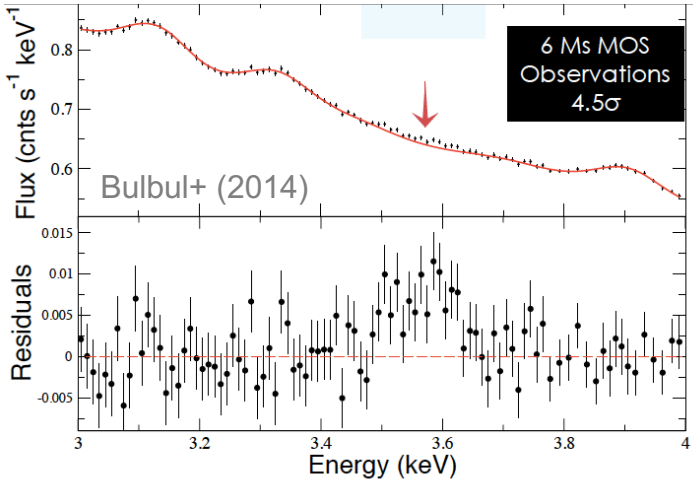

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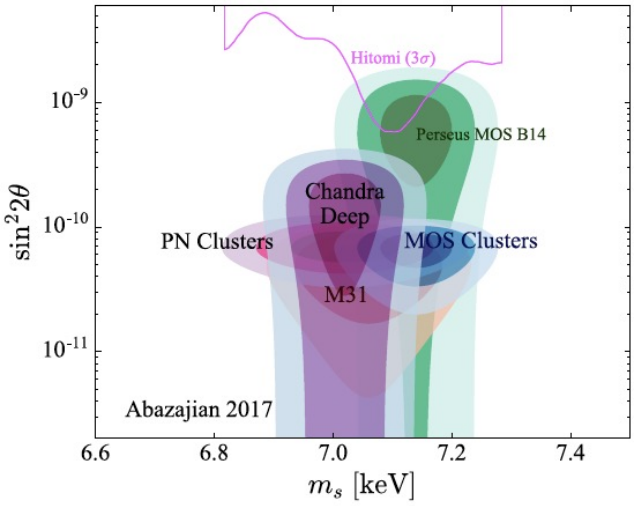
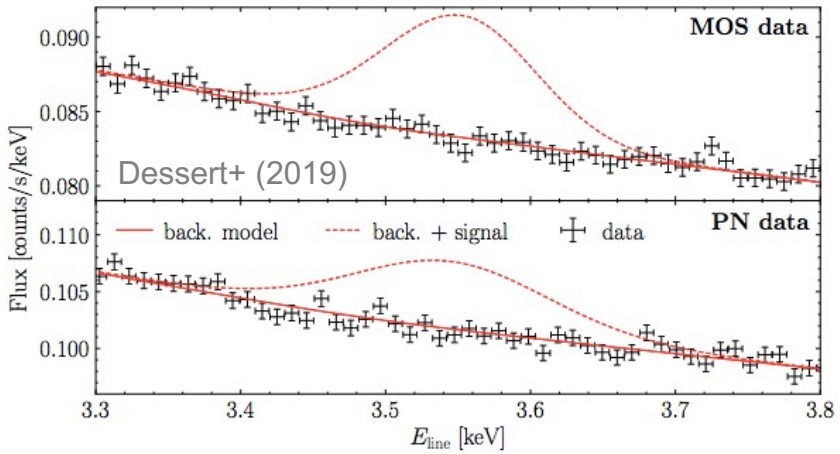


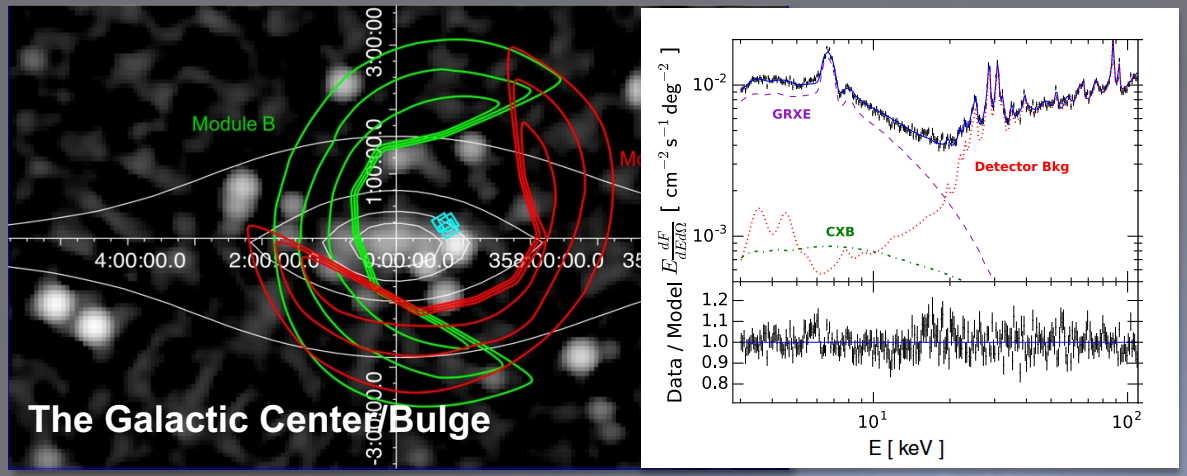
3. Ruled out with **HEP statistical methods?**

- Statistically combining limits from 30(!) Ms of XMM-Newton blank-sky data
  Dessert+ Science (2021)
- 547(!!) Ms of XMM-Newton blank-sky data, non-parametric background modelling technique Foster+ PRL (2021)



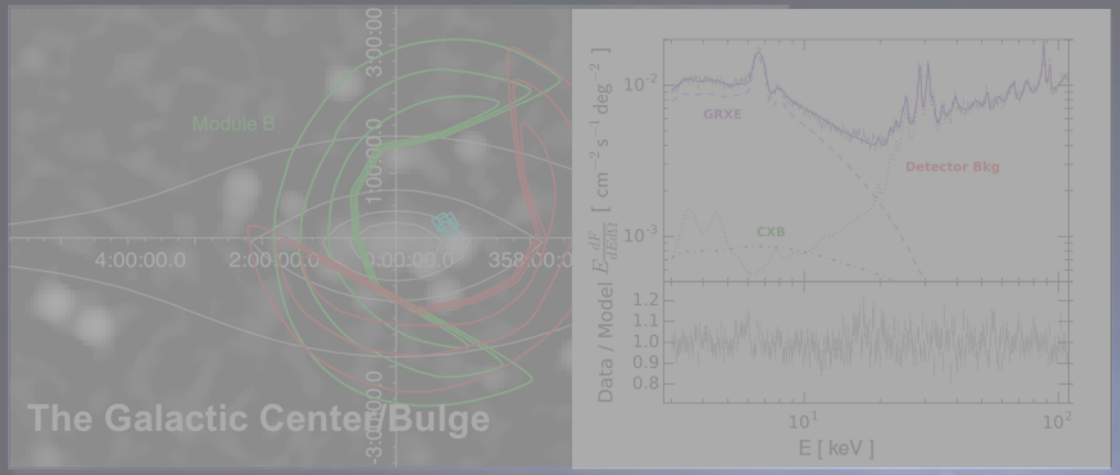
Looking forward to new observatories!

Perez, Ng, Beacom+ (2017)

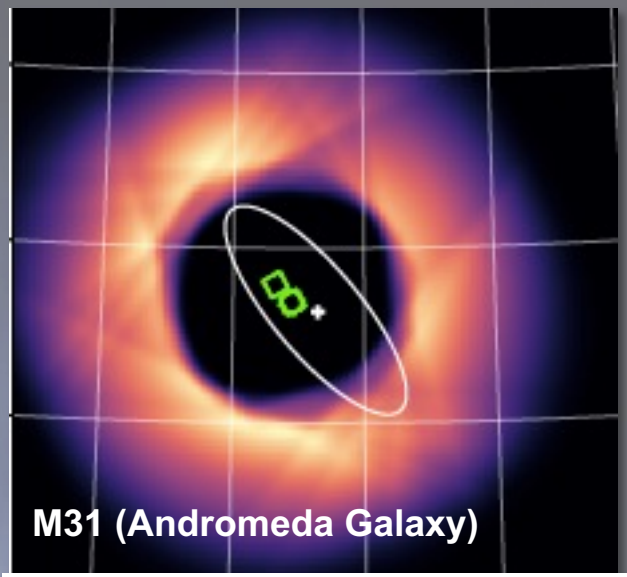


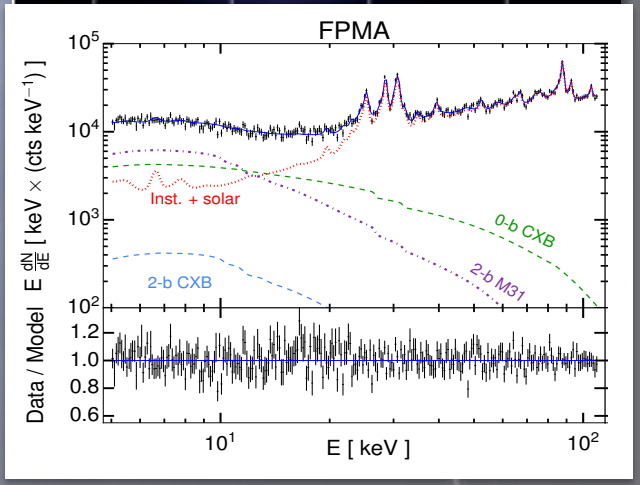
(+) Large dark matter density
(+) Large sensitivity from unfocused FOV
(–) Galactic ridge emission incl. bright Fe lines

Perez, Ng, Beacom+ (2017)



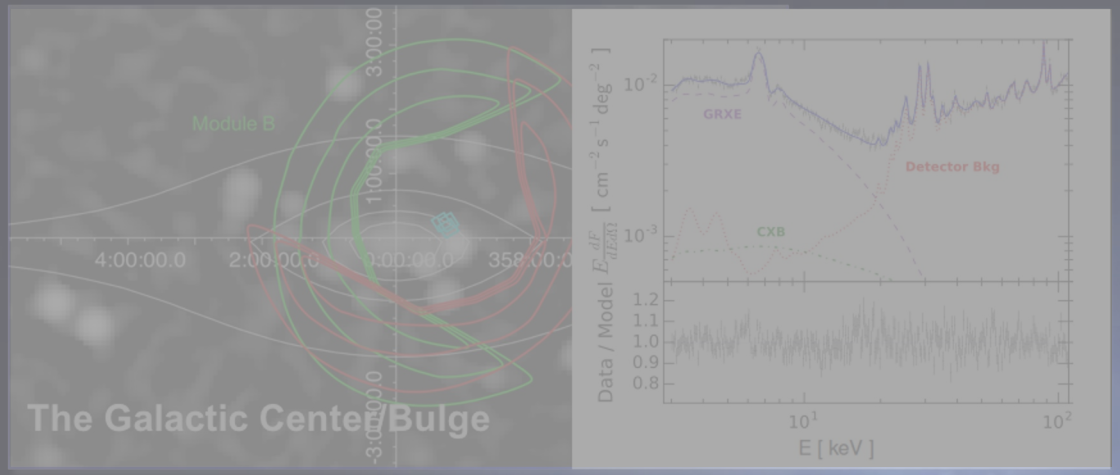
Ng, Roach+ (2019)



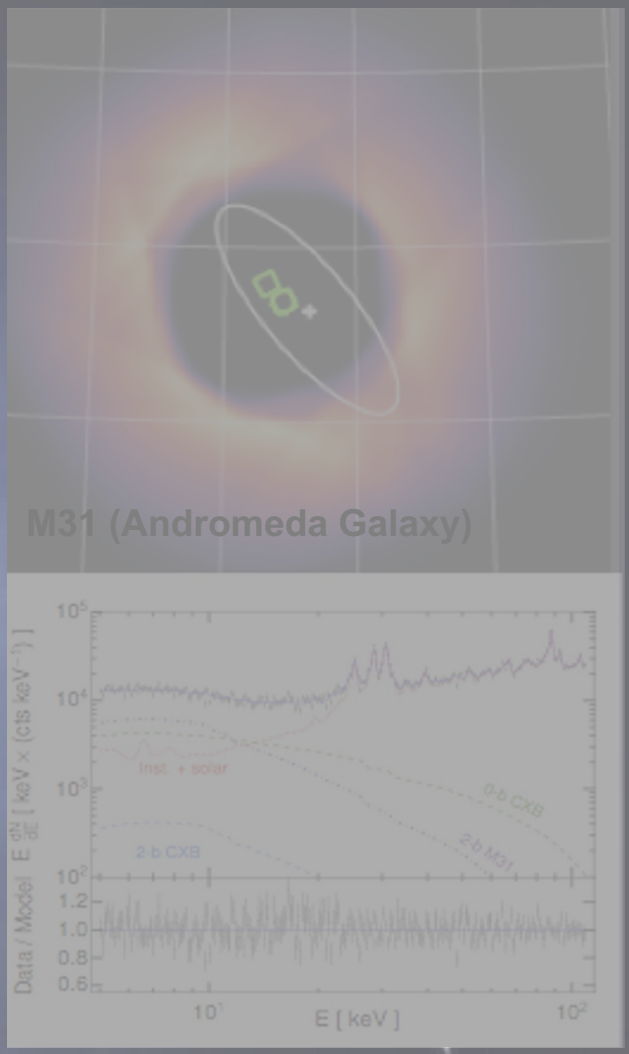


(+) No Fe emission lines
(+) surveys dark matter from both core and halo
(-) emission from M31 disk

Perez, Ng, Beacom+ (2017)

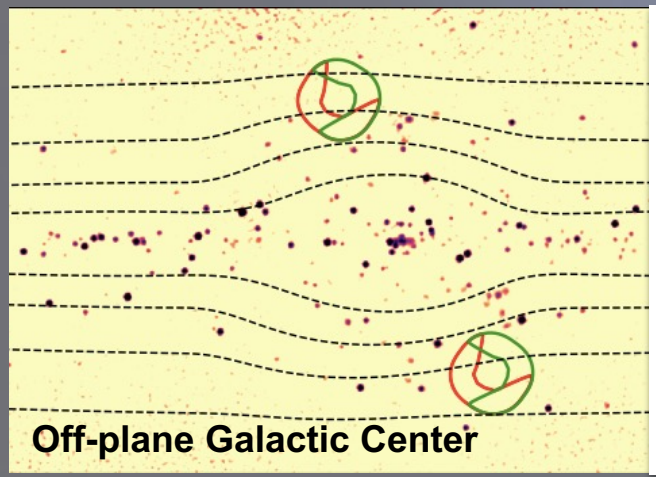


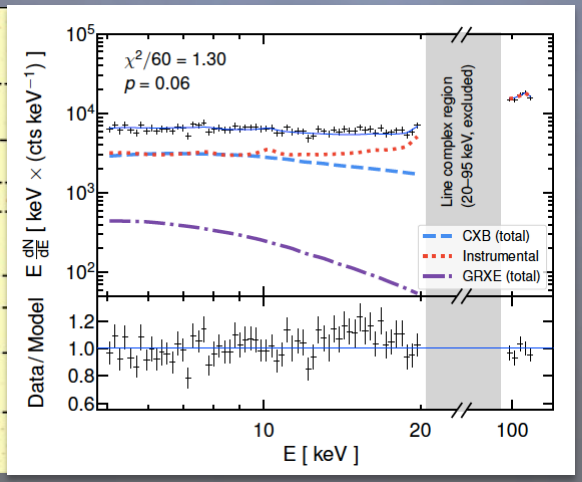
Ng, Roach, Perez+ (2019)



(+) minimal Galactic contamination
(+) near center of the dark matter halo
(-) seeing deviations from instrument background model

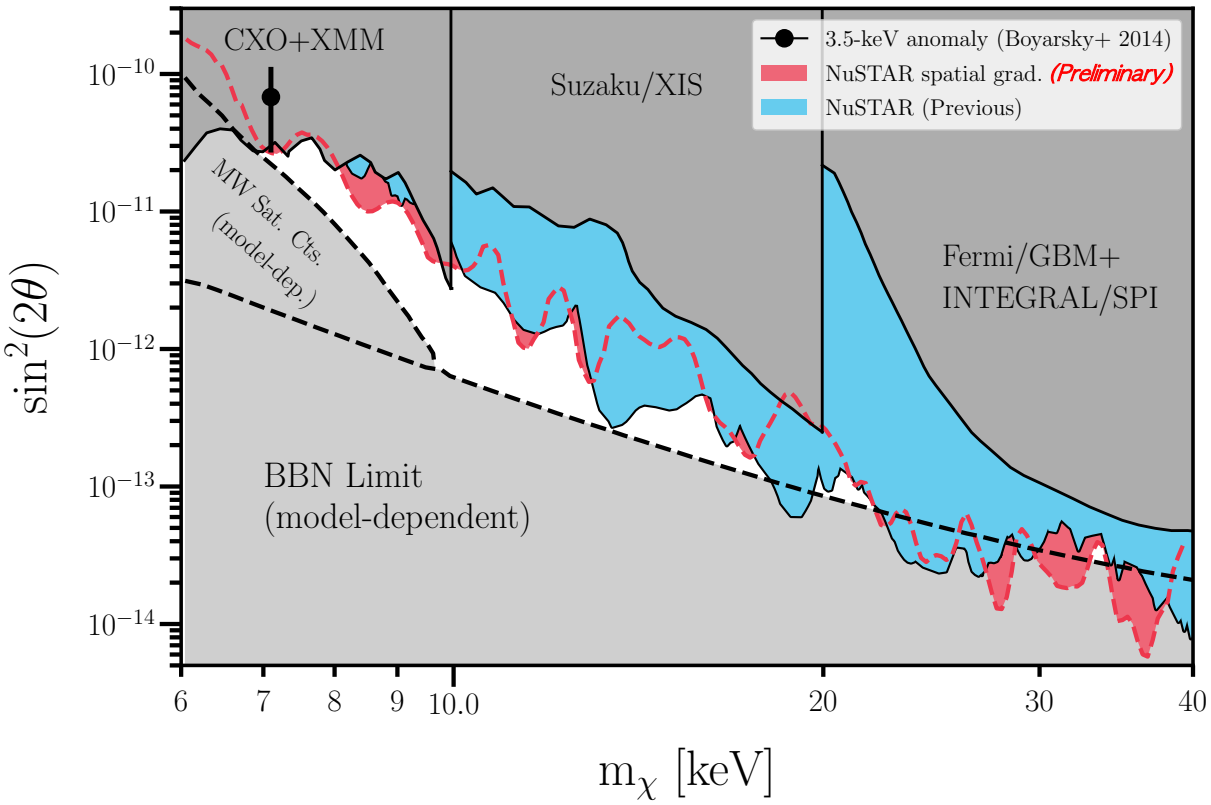
Roach, Ng+ (2020)





Towards closing the sterile neutrino dark matter window?

- Combination of Galactic center, Andromeda (M31), and Galactic bulge give leading constraints for masses 10-50 keV
- Improve on previous constraints by over an order of magnitude in some mass ranges
- ***Updated analysis uses full NuSTAR data catalog to improve low-mass sensitivity***



New! Roach et al. in prep. for PRL (2022)

Roach, Ng, Perez+ Phys. Rev. D (2020)
Ng, Roach, Perez+ Phys.Rev.D. (2019)
Perez, Ng, Beacom+ Phys.Rev.D (2017)

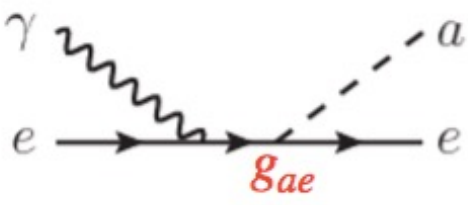
See also: Foster et al. *A deep search for decaying dark matter with XMM-Newton* (2021) 2102.02207

Stars as factories for axion-like particles (ALPs)

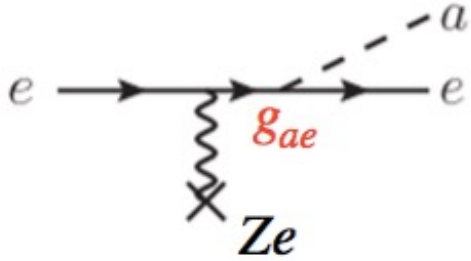
- Axions introduced to explain why the strong interactions preserve the CP symmetry (*Peccei-Quinn mechanism*)
- Axion-like particles generic feature of many BSM models (*e.g. string theory*)

$$L_a = \frac{1}{2}\left(\partial_\mu a\right)^2 - m_a^2 a^2 - i\sum g_{ai}\, a\, \bar{\psi}_i \gamma_5 \psi_i - \frac{1}{4} g_{a\gamma}\, aF\tilde{F}$$

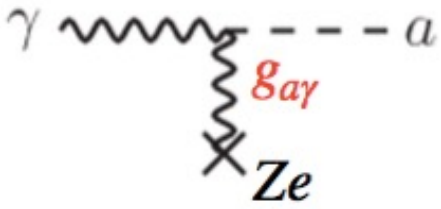
Couples to fermions — Couples to photons



Compton



Bremsstrahlung



Primakoff

Most relevant process for stars!

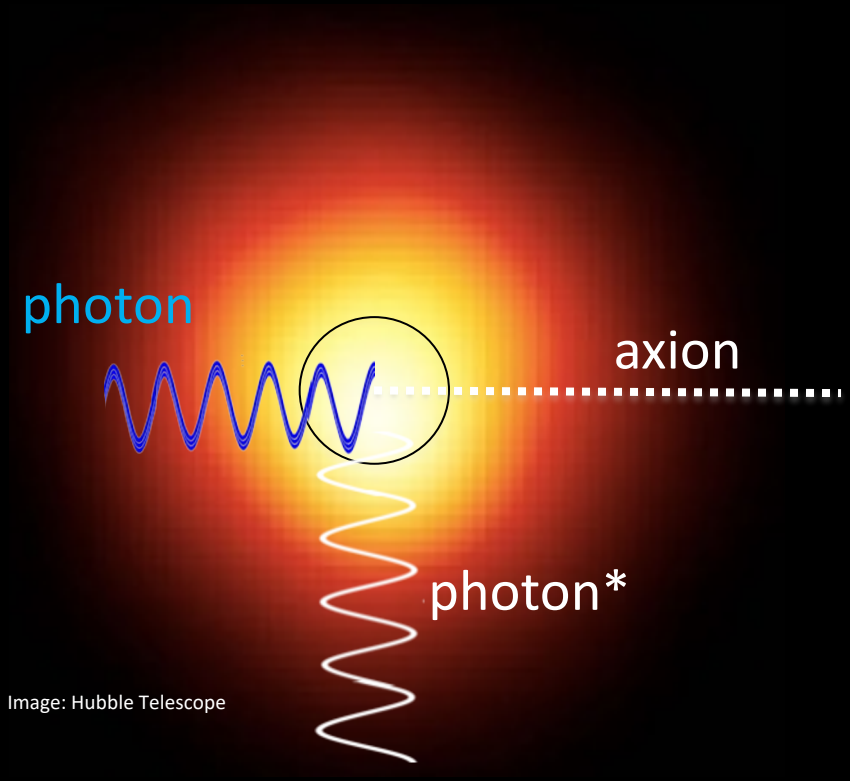
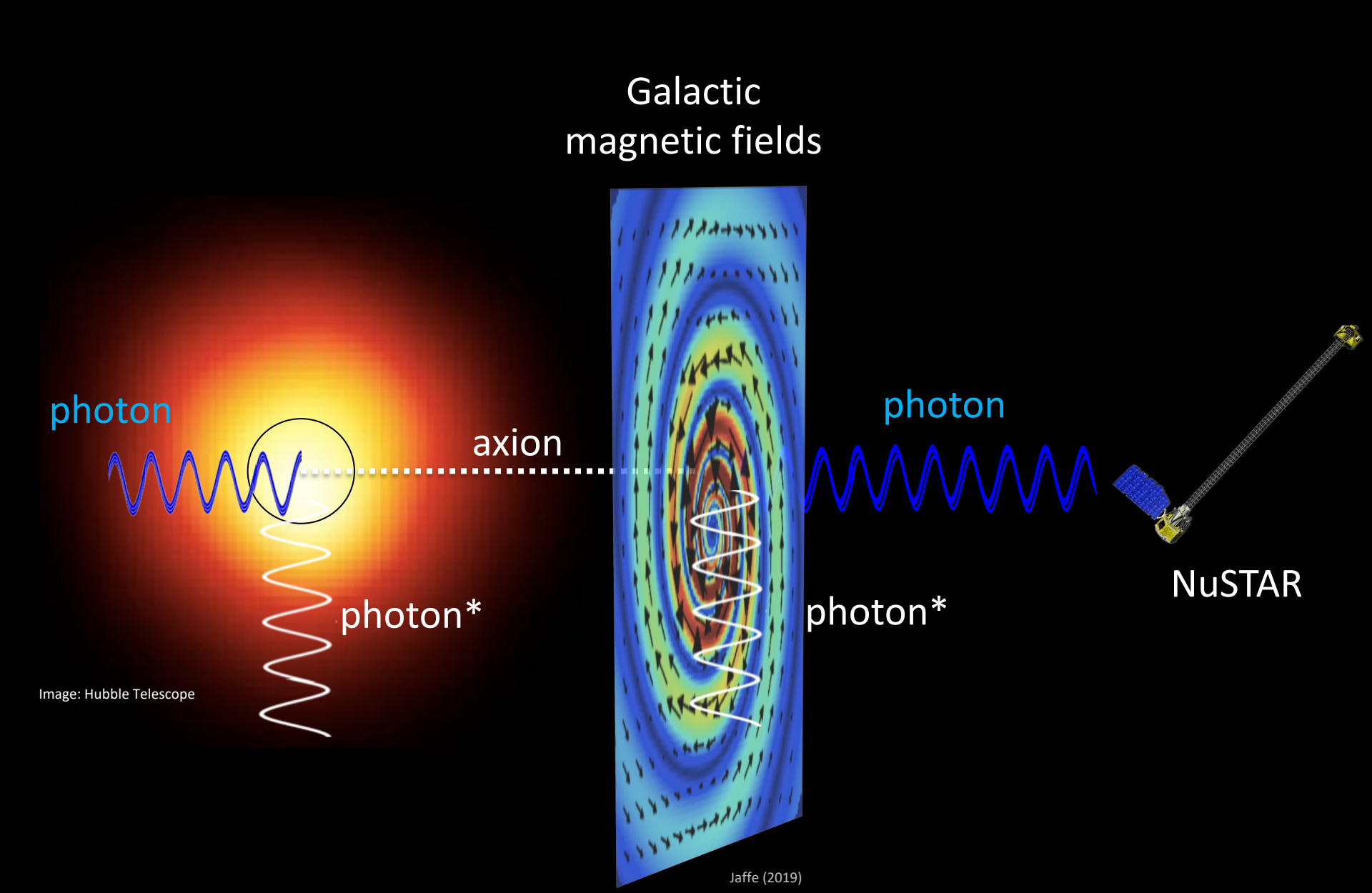


Image: Hubble Telescope

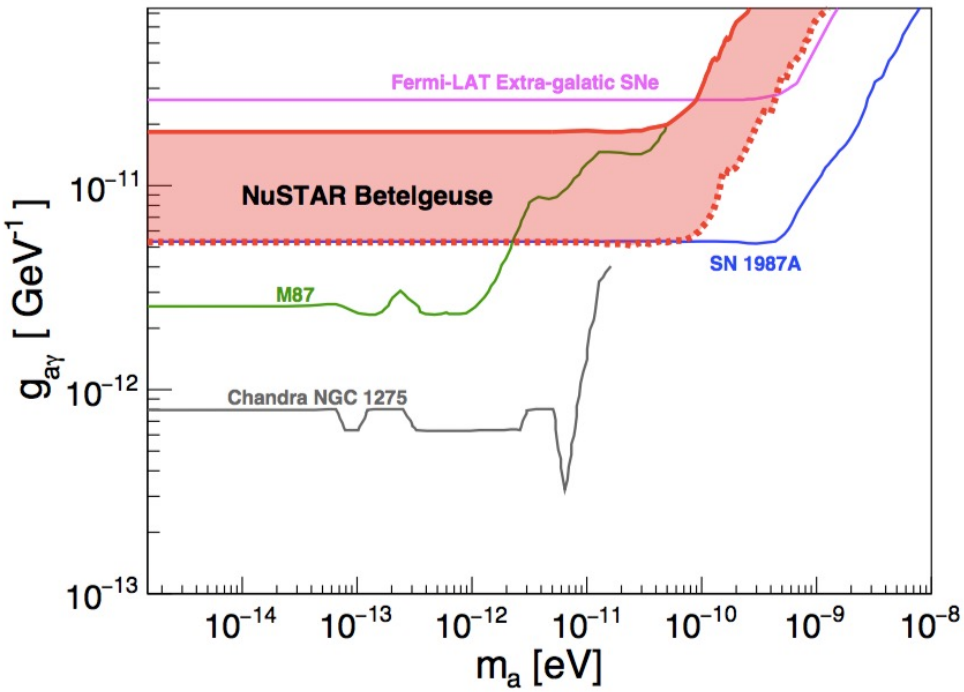

Galactic
magnetic fields
photon
axion
photon
photon*
photon*
NuSTAR
Image: Hubble Telescope
Jaffe (2019)

Constraints on ultra-light axion-like particles

- Astrophysical limits from these searches give **low-mass axion limits** at least ~3x deeper than CAST
- **Comparable to next-generation axion experiments** ALPS-II and Baby-IAXO

  See also: Dessert+ (2020), Payez+ (2015), Meyer+ (2020), Marsh+ (2017), Reynolds+ (2019),

Xiao et al. PRL (2021)



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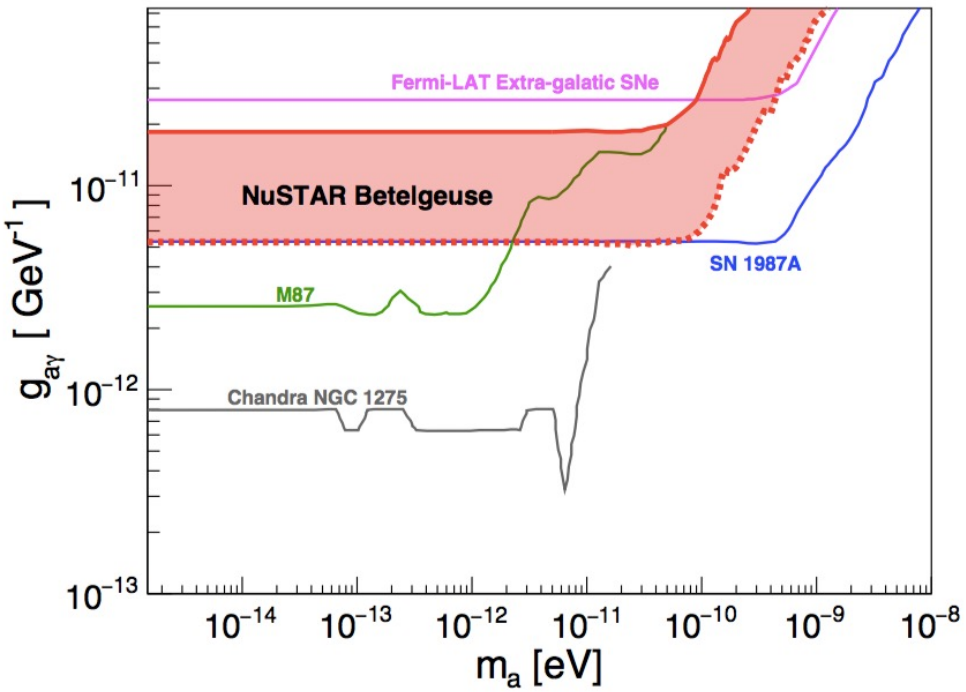
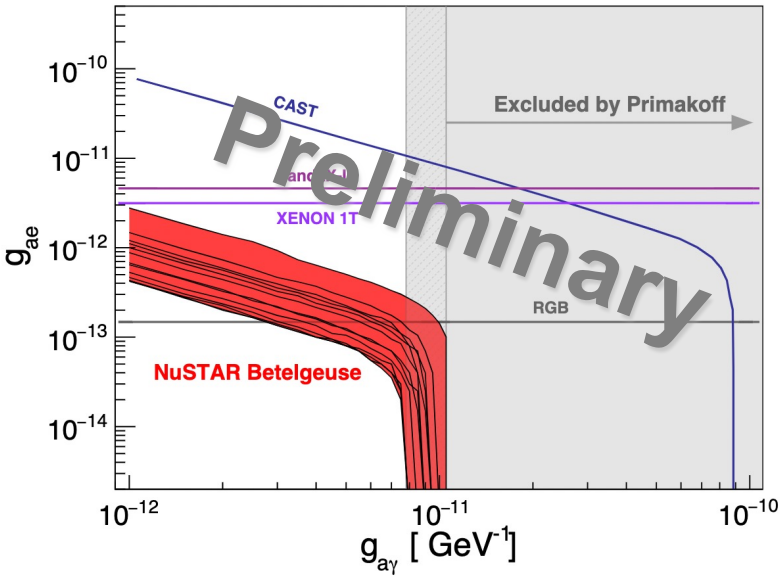


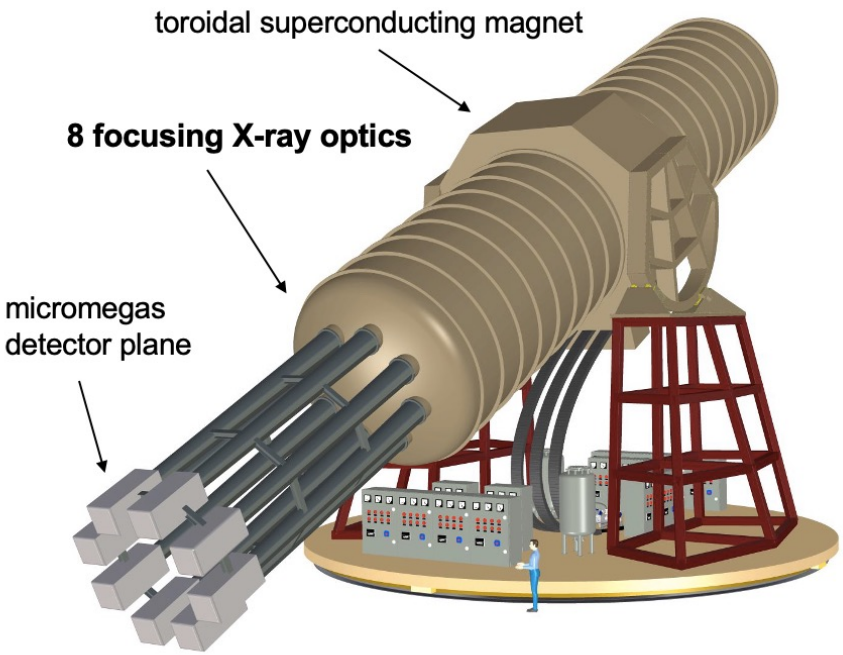
Xiao et al. in prep. for PRL (2022)



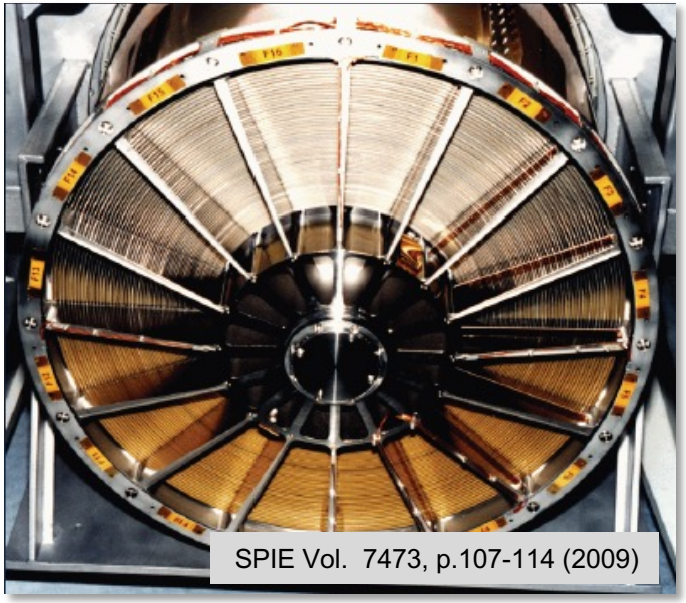
- Can also probe g_{ae} through Bremsstrahlung and Compton ALP processes

See also:
Dessert+ (2021) 2104.1277; Dessert+ (2021) 1903.05088; Dessert+ (2022) 2104.12772

Adapting X-ray Optics for the International Axion Observatory

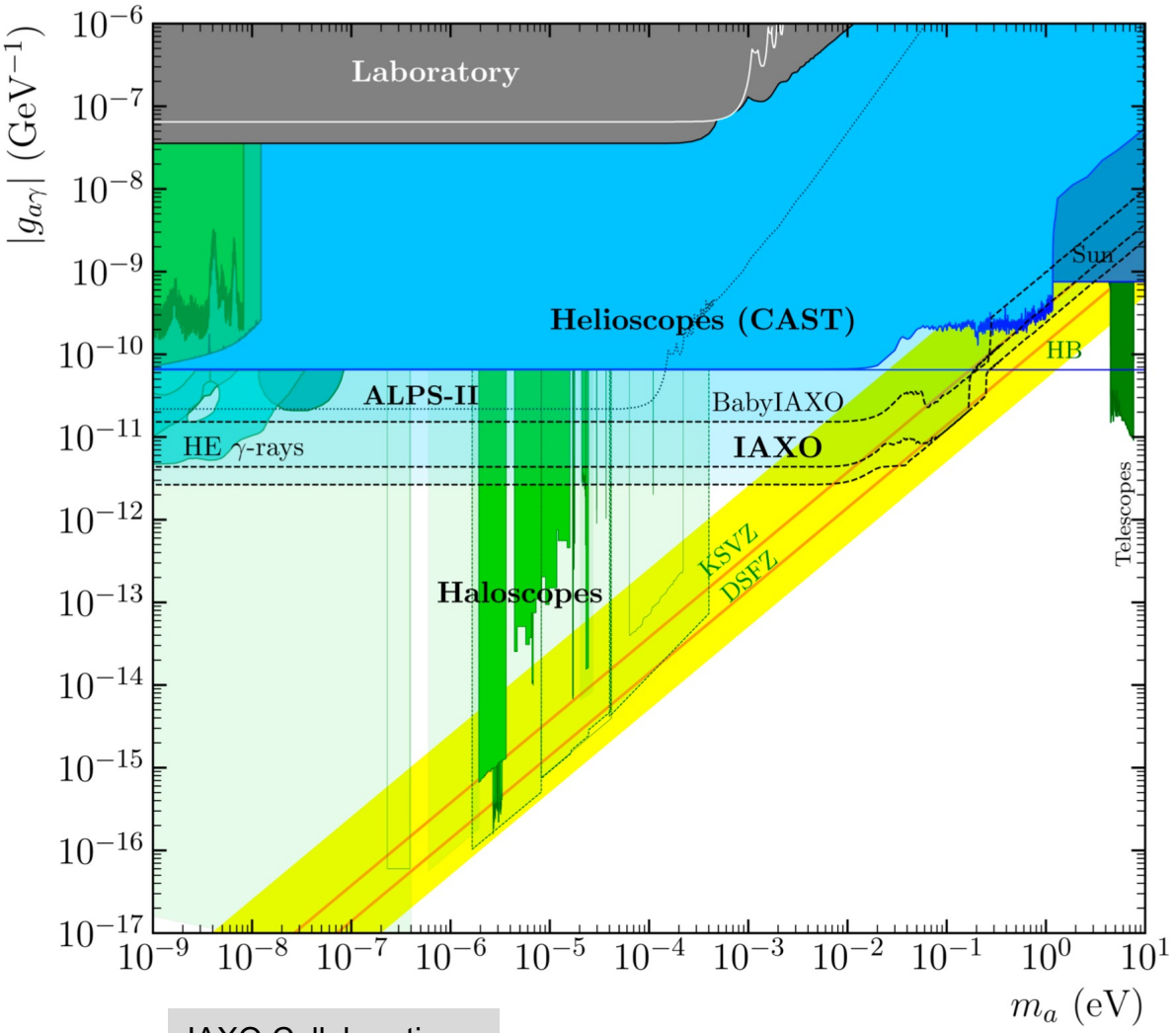


- Each magnet bore will be instrumented with a large-diameter X-ray focusing optic
- Inner optics utilize the same segmented glass technology as the NuSTAR satellite telescope



- **IAXO** will use a strong magnetic field to convert solar axions into X-ray photons that are focused onto low-background detectors
- **BabyIAXO** will be risk mitigation/improvement for all systems + *novel axion sensitivity!*

Unique sensitivity to ALPs, high-mass axions



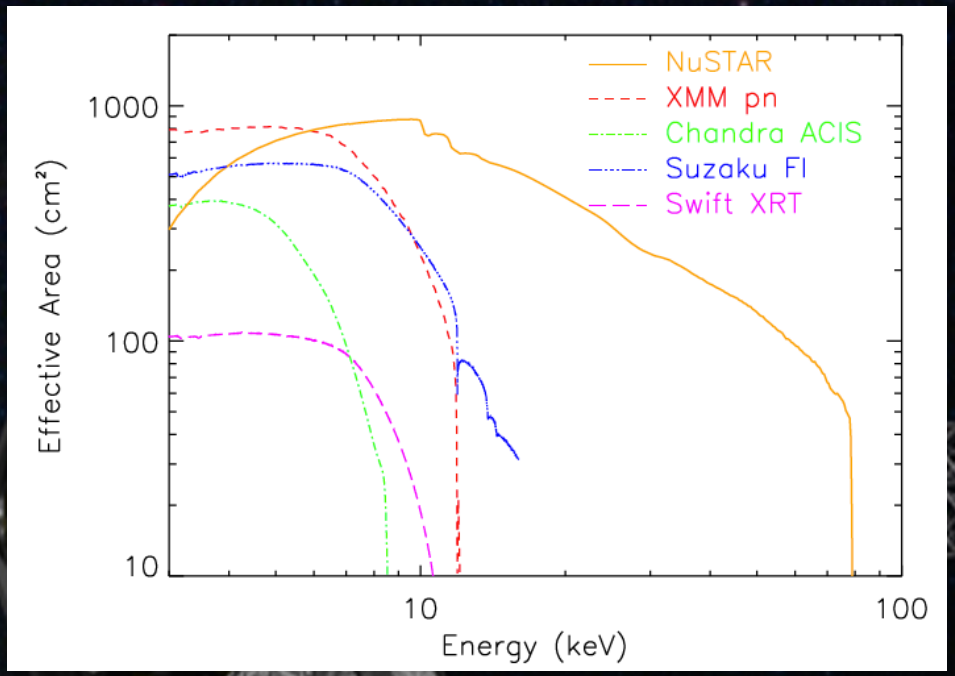
IAXO Collaboration, JHEP 05 (2021) 137

- Improve sensitivity over one order of magnitude across broad mass range
- **Unique sensitivity to QCD axions with m > 10^{-3} eV**
- *Sensitivity is independent of assumption that axion is dark matter*
- Axions in the mass range could be cold dark matter candidates, depending on tuning of vacuum realignment mechanism, axion string or domain walls decay to axion post-inflation

- NuSTAR has delivered leading sensitivity to light dark matter and stellar backgrounds to new physics
- *Much of this sensitivity not foreseen before launch!*
- NuSTAR technology being adapted for dedicated solar axion searches with IAXO
- Looking forward to other new windows opening on our sky

Backup

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



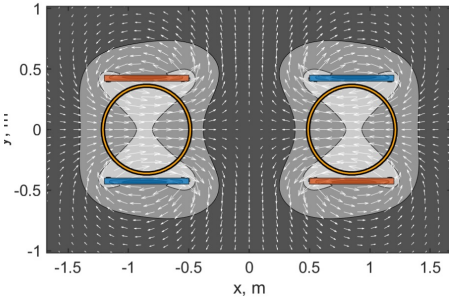
Harrison+ (2013)
arxiv:1301.7307

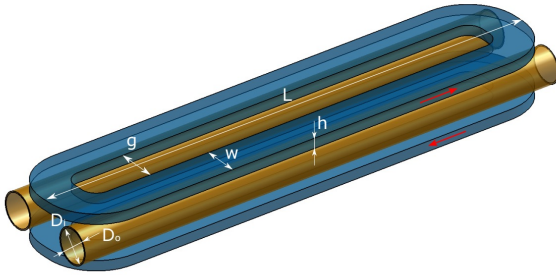
- **Energy Band:** 3–79 keV
- **Angular Resolution:**
  58" (HPD), 18" (PSF)
- **Field-of-view:** 12' x 12'
- **Energy resolution (FWHM):**
  0.4 keV at 6 keV,
  0.9 keV at 60 keV
- **Temporal resolution**: 0.1 ms
- **Maximum Flux Rate:** 10k ct/s
- **ToO response:** <24 hours

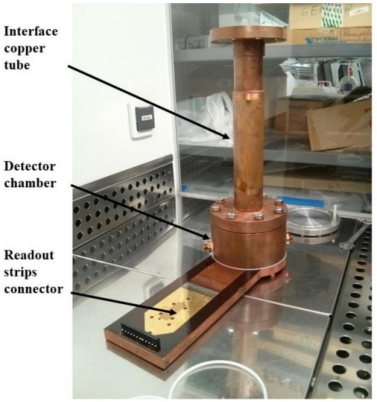
Progress on all BabyIAXO systems

Site at DESY:
HERA South Hall, former ZEUS detector hall

Common-coil "racetrack" magnet:
Uses existing infrastructure and expertise at CERN, winding layout very close to that of IAXO toroidal design



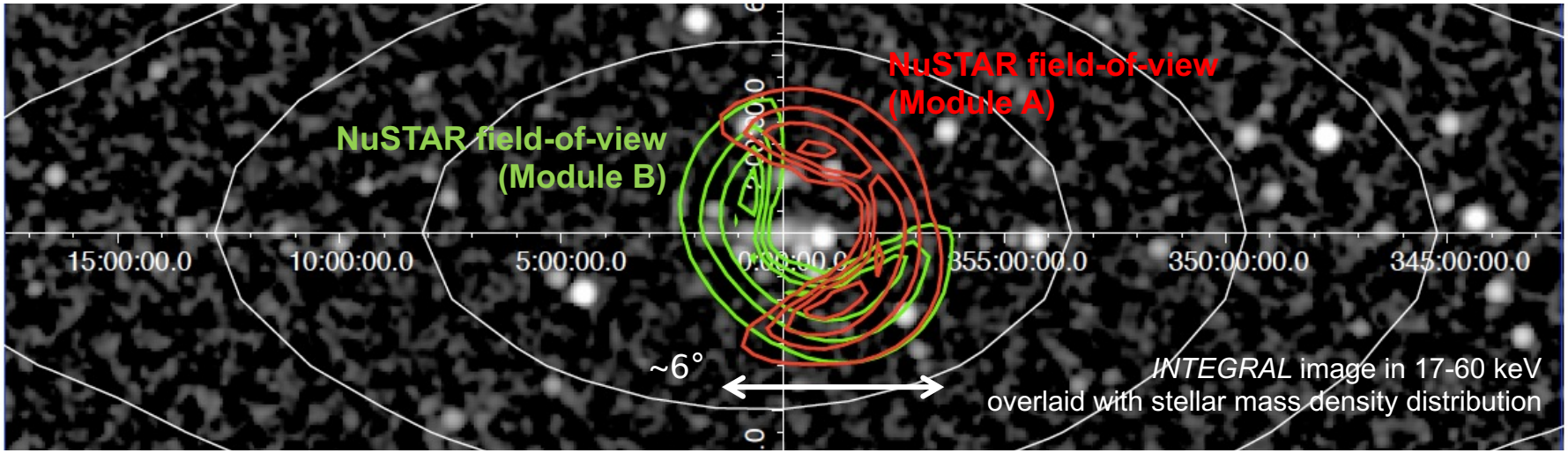


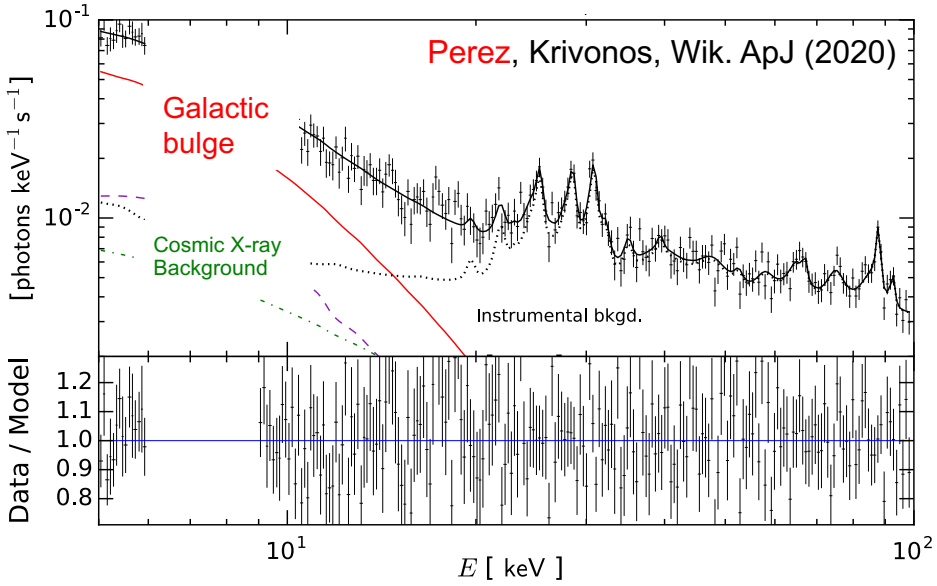


Micromegas detectors:
Surface tests improved shielding, 4pi muon veto
Underground tests underway

Support and drive:
Re-use CTA MST prototype

Population changes in the Galactic bulge





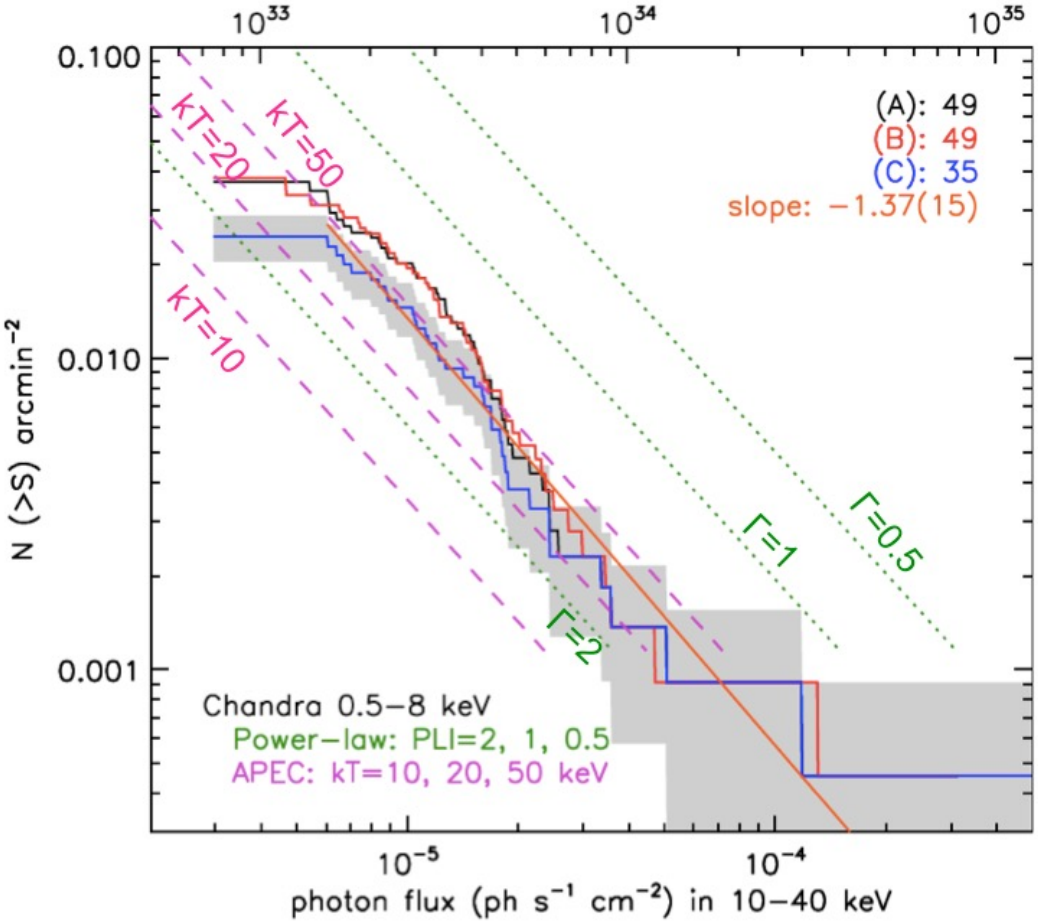
- First broad-band X-ray observations of the Galactic bulge confirm spectrum dominated by *non-magnetic white dwarf binaries*
- No hard X-ray emission >20 keV
- *Supports conclusions from Fe emission line measurements*

Xu et al. 2016; Yamauchi et al. 2016; Koyama 2018; Nobukawa et al. 2016

NuSTAR point sources indicate heavy mCVs

- The NuSTAR (10–40 keV) and Chandra (0.5–8 keV) distributions match if the average spectra are **Γ~1.5–2 or kT ~ 20–50 keV**
- High percentage with Fe lines (60%) and hard spectra **support dominant mCV population**
- High plasma temperature translates to $\mathbf{M_{WD} > 0.8M_{\odot}}$
- Consistent with average white dwarf mass measured by SDSS

J. Hong+ (2016) arxiv:1605.03882



The sterile neutrino landscape

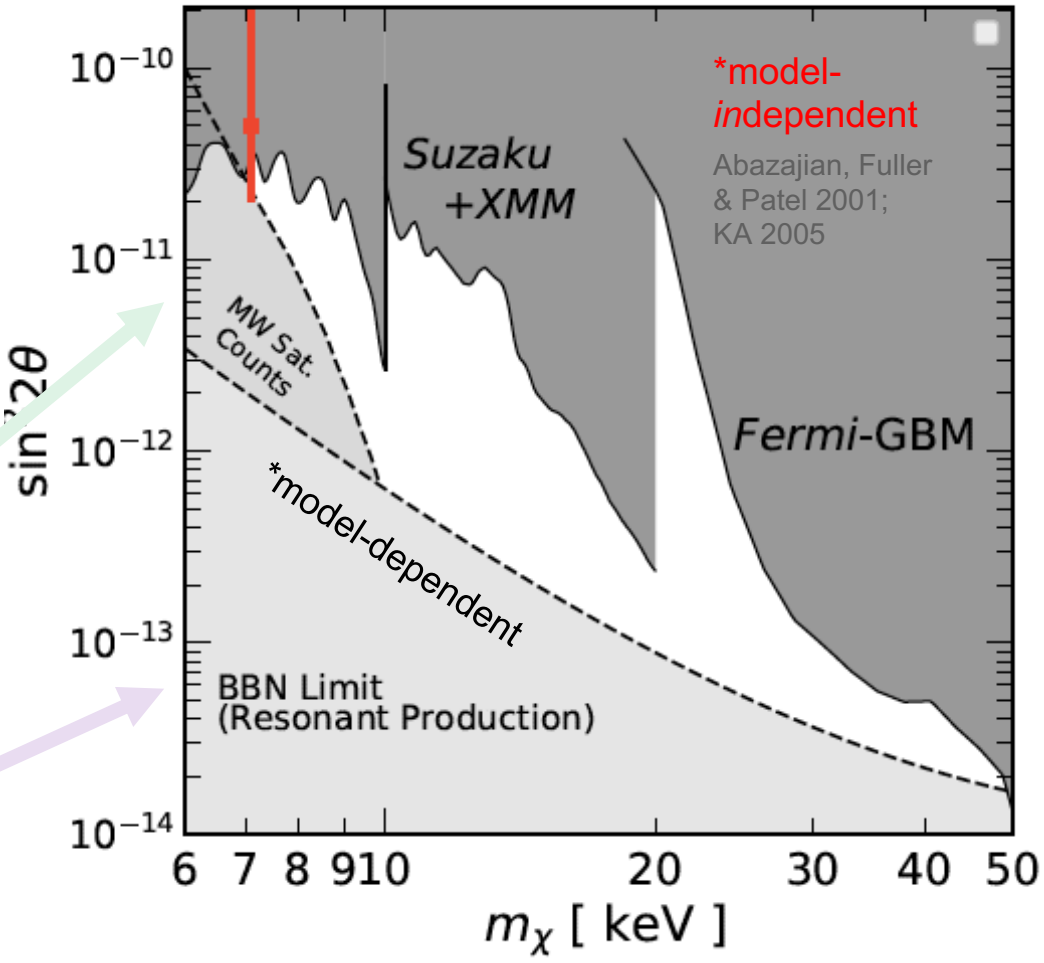
Only a narrow window remains in which sterile neutrinos (in the simplest models) can constitute all of dark matter

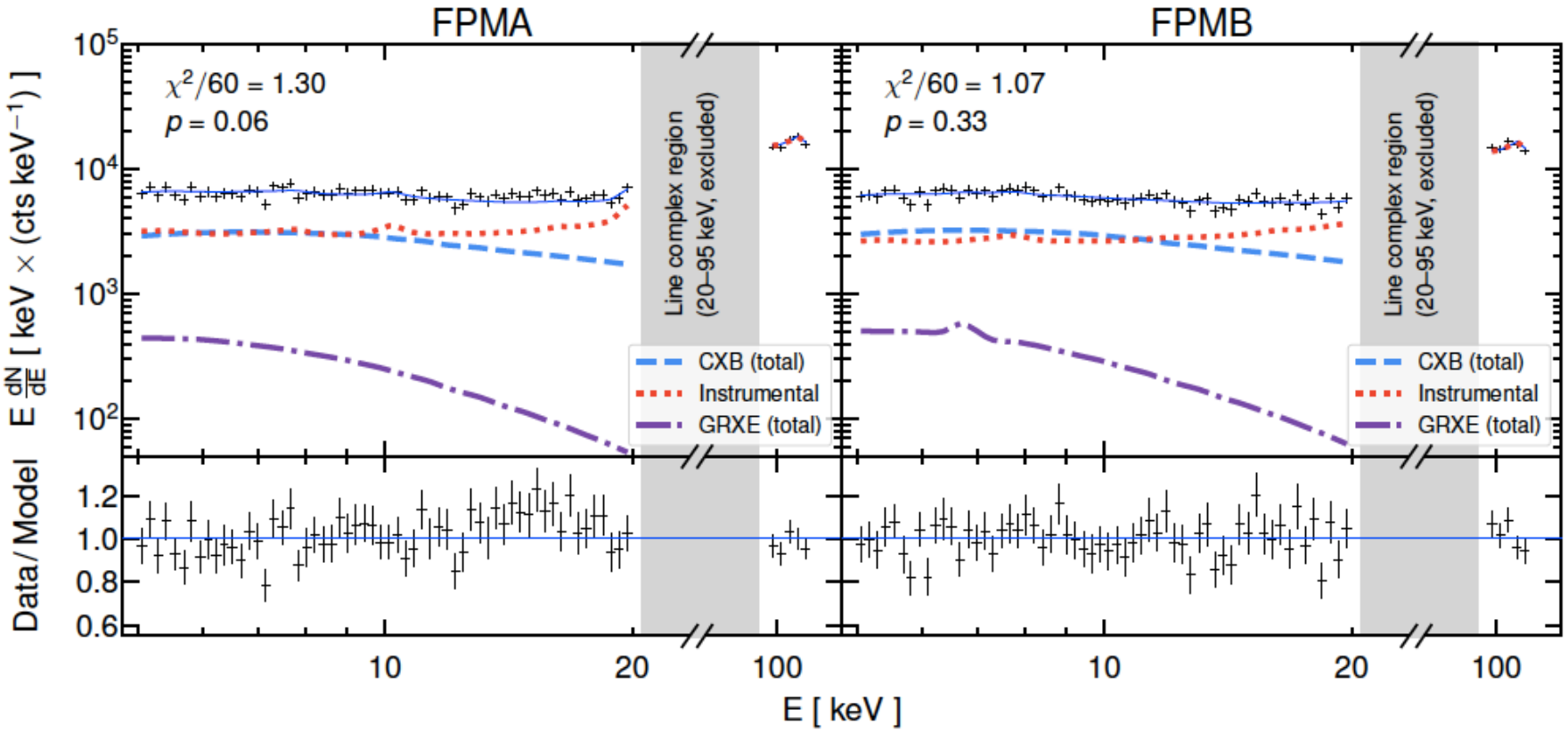
Sterile neutrinos are *fermions*, limits phase space distribution in a galaxy

$m_{DM} > \sim 1$ keV

Require momentum distribution not *underproduce* small-scale structure

Require correct dark matter abundance be produced in the early universe



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.