Strong constraints on keV-scale sterile neutrinos with *NuSTAR*

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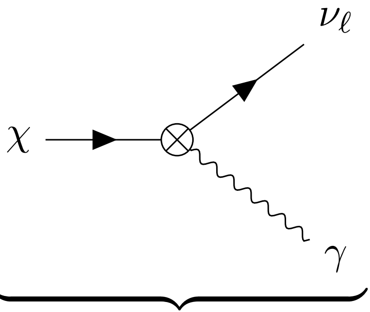
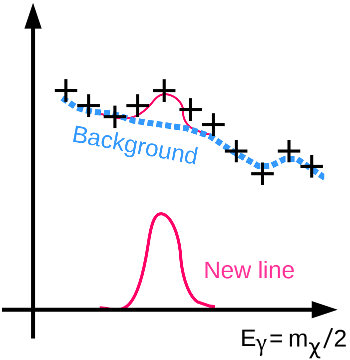
Why sterile neutrinos?

A keV-scale sterile neutrino is a very well-motivated DM candidate.

- Consequence of many models for neutrino masses and baryogenesis, including the popular neutrino-Minimal Standard Model (νMSM)
- Address tensions between cosmological observations and ΛCDM structure simulations (core-cusp, too-big-to-fail, *etc*)
- Simple final state: includes X-ray with $E_\gamma = m_\chi/2$
- K. Abazajian's review article: `arXiv:1705.01837`

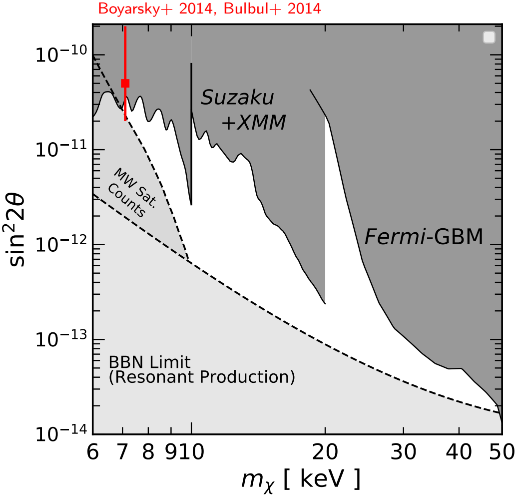


Decay rate $\propto m_\chi^5 \sin^2 2\theta$

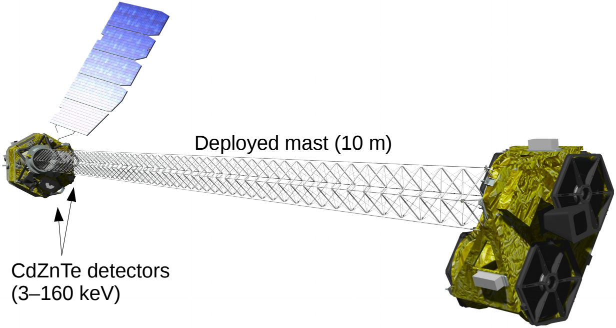


Before *NuSTAR*: large gap in νMSM parameter space.

(All limits assume sterile neutrinos constitute 100% of DM.)

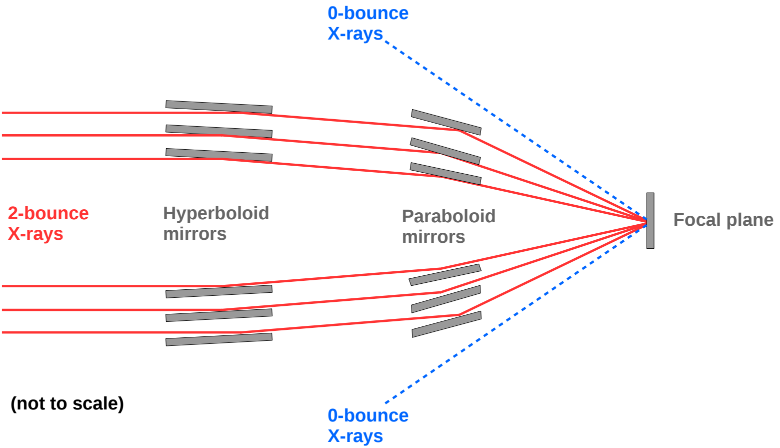


- NASA X-ray telescope launched in 2012
- Science payload: two independent, co-aligned Focal Plane Modules (FPMs, mirror + detector)
- Extends X-ray focusing past E $\sim$ 10 keV limit of previous telescopes



0-bounce and 2-bounce

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

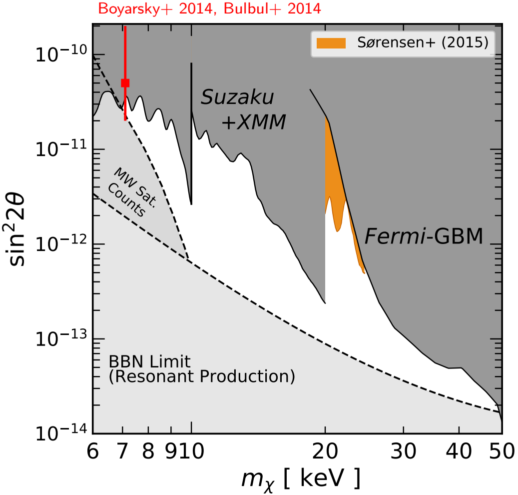


Bullet Cluster survey (Riemer-Sørensen+ 2015, `arXiv:1507.01378`):

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

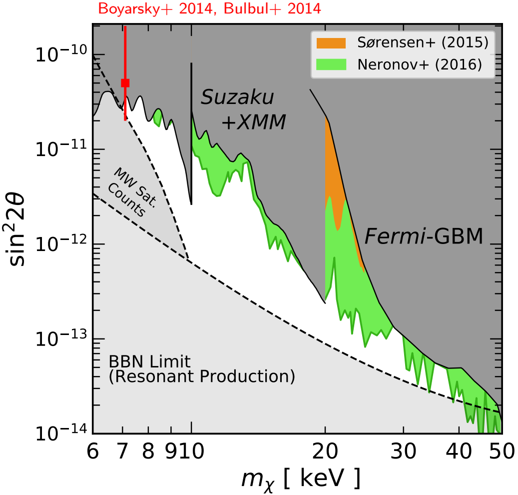


Blank-sky extragalactic survey (Neronov+ 2016, `arXiv:1607.07328`):

Total exposure: ~7.5 Ms

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

- **(−)** Low DM density

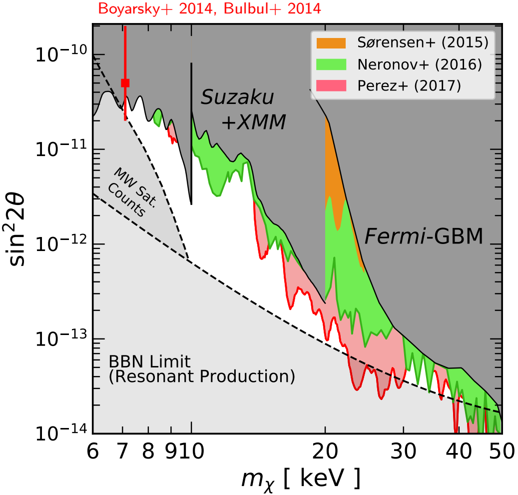


Milky Way Galactic center survey (Perez+ 2017, `arXiv:1609.00667`):

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



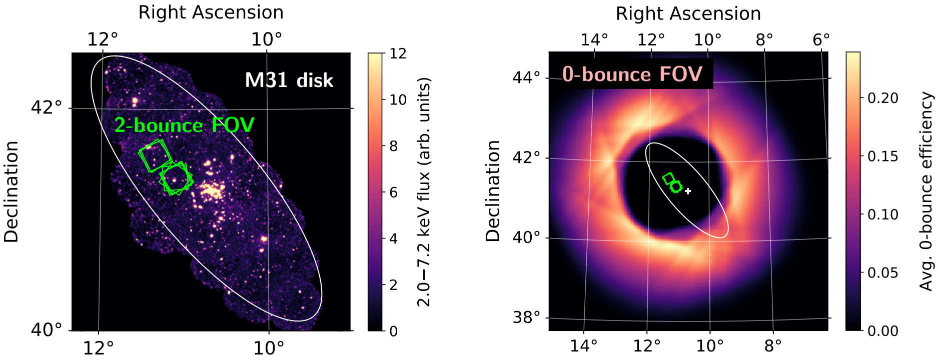
NuSTAR's large aperture for unfocused X-rays is a game-changer!

But we can go even further!

M31 survey (Ng+ 2019)

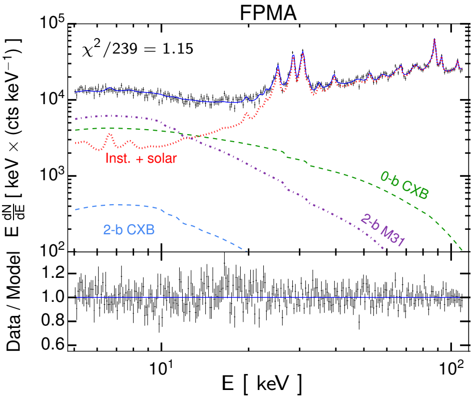
Improves upon Galactic center search from (Perez+ 2017):

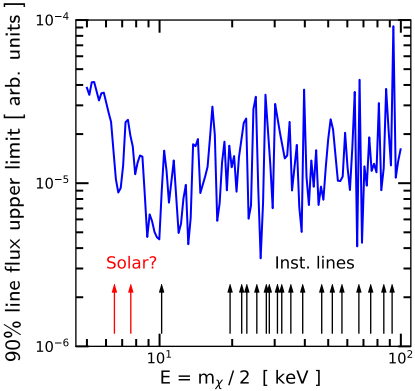
- Large statistics (1.2 Ms *vs* 0.4 Ms, resp.)
- No bright emission lines from M31
- 0-bounce FOV covers M31 halo; boost from 2-bounce FOV



Ng+ 2019, arXiv:1901.01262

Good fit quality ⇒ robust DM constraints.





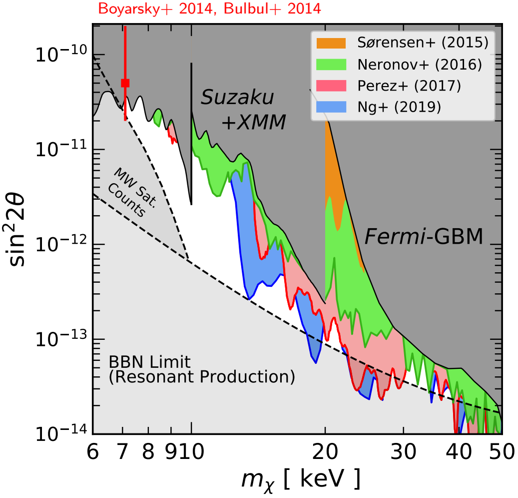
Ng+ 2019, arXiv:1901.01262

The νMSM (with *NuSTAR*)

M31 survey (Ng+ 2019, `arXiv:1901.01262`)

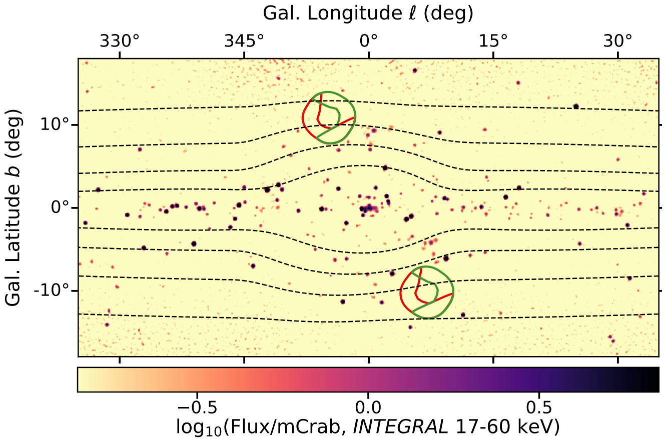
Total exposure: $\sim$1.2 Ms

Fills sensitivity gap betw. 12–20 keV (caused by Fe line emission) in the Galactic Center survey (Perez+ 2017)



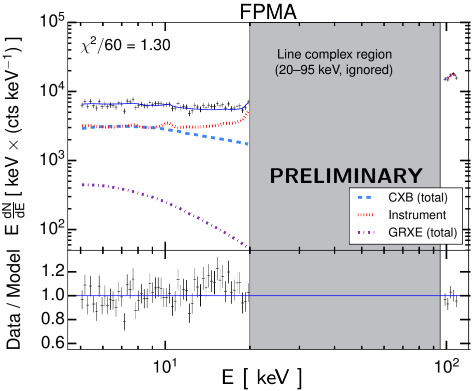
Gal. bulge survey (Roach+ 2019)

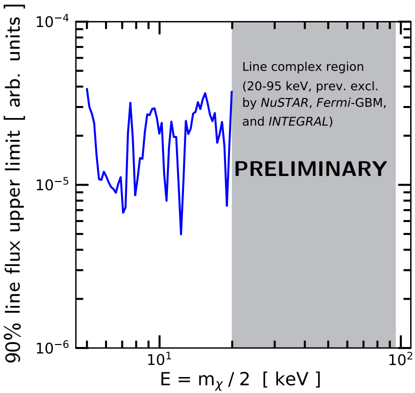
Two new observations: minimal point-source and Galactic ridge emission, while remaining near the center of the DM halo.



INTEGRAL map from Krivonos+ 2017, arXiv:1704.03364

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



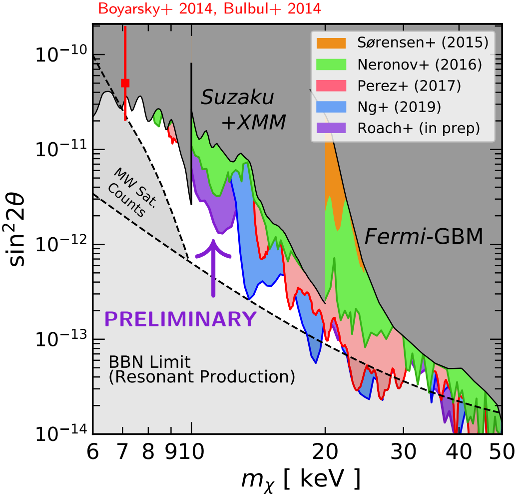


Milky Way Galactic bulge survey (Roach+ 2019, in prep):

Total exposure: $\sim$0.2 Ms

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

Competitive with—and even surpasses—limits from blank-sky survey (Neronov+ 2016) using $\lesssim$ 3% of the exposure time.



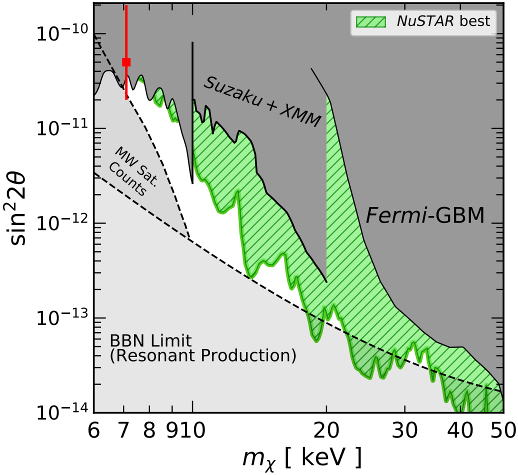
NuSTAR systematics

To limit systematic effects of stacking spectra from different observation fields, we model each spectrum separately. However, there are still systematic issues:

- **3–5 keV**: origin of the instrument background (esp. the 3.5- and 4.5-keV lines) is unclear, so we consider only E $\geq$ 5 keV data.
- **5–20 keV**: faint-sky Galactic bulge data show significant deviations from the default *NuSTAR* background model, particularly E $\sim$ 15 keV.

$\Rightarrow$ An improved background model is under development!

- keV sterile neutrinos remain one of the best-motivated DM candidates.
- *NuSTAR* has almost closed the νMSM parameter space for $m_\chi \in$ 20–50 keV.
- New *NuSTAR* background model is in development, with the goal of studying the 3.5-keV line.
- ***Stay tuned!***



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Additional references

- 3.5-keV line (i): Boyarsky+ 2014, arXiv:1402.4119
- 3.5-keV line (ii): Bulbul+ 2014, arXiv:1402.2301
- *Fermi*-GBM limits: Horiuchi+ 2015, arXiv:1502.03399
- *Suzaku* Perseus limits: Tamura+ 2014, arXiv:1412.1869
- *XMM-Newton* dSphs limits: Malyshev+ 2014, arXiv:1408.3531
- MW satellite counts: Horiuchi+ 2013, arXiv:1311.0282
- *NuSTAR* mission description: Harrison+ 2013, arXiv:1301.7307
- *NuSTAR* background model: Wik+ 2014, arXiv:1403.2722
- Galactic stellar mass model: Launhardt+ 2002, arXiv:0201294
- GRXE emissivity: Revnivtsev+ 2005, arXiv:0510050
- BBN limit code sterile-dm: Venumadhav+ 2015, arXiv:1507.06655

For full list, see our M31 paper: Ng+ 2019, arXiv:1901.01262

Backup slides

Expected *NuSTAR* event rate from sterile neutrino decay:

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} \propto m_\chi^4 \sin^2 2\theta \left(A_{0b}\Delta\Omega_{0b}\mathcal{J}_{0b} + A_{2b}\Delta\Omega_{2b}\mathcal{J}_{2b}\right)$$

where

$$\mathcal{J} = \frac{1}{\Delta\Omega}\int \xi(\text{pixel efficiency})\,\mathrm{d}\Omega \int_{\text{l.o.s.}} \rho_\chi \,\mathrm{d}\ell$$

Different ρ_χ profiles (NFW, Ein, *etc*) have $\lesssim$10% effect on derived limits in the $m_\chi - \sin^2 2\theta$ plane.

(Applies to Ng+ 2019 and Roach+ 2019 analyses.)

- Scan the m_χ range with a narrow line.
- Fit each spectrum individually, allowing the background parameters (especially instrument line strengths) to vary during the scan.
- Calculate $\Delta\chi^2 = \chi^2(\mathrm{m}_\chi; \sin^2 2\theta) - \chi^2(m_\chi; \text{no DM})$
- Combine $\Delta\chi^2$ from all spectra, and determine line detections or exclusion limits.