X-Ray Constraints on Sterile Neutrino Dark Matter

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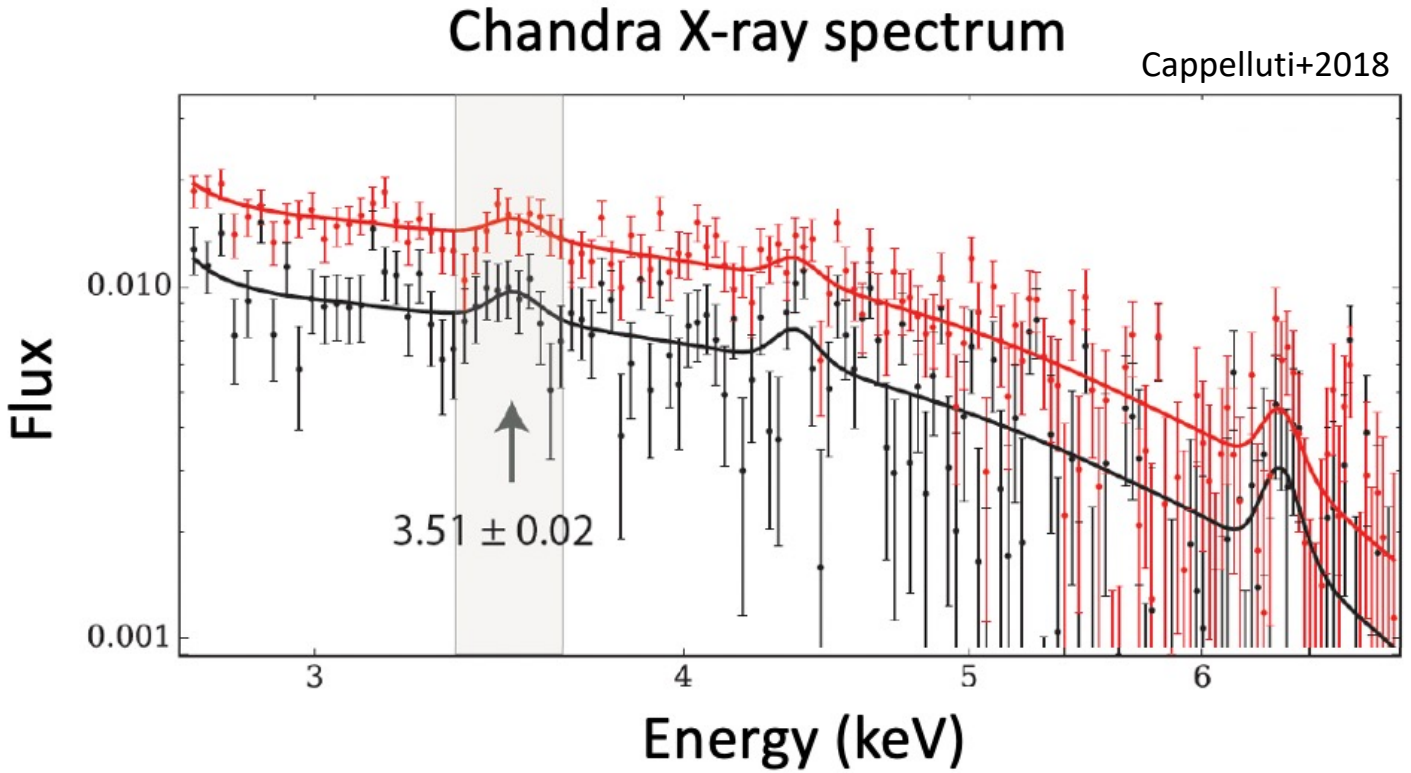
CHANDRA X-RAY OBSERVATORY

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

A Strange Feature in the X-Rays…

- ***3.5 keV***: Unidentified emission line
  - Dark matter dominated objects
  - 9 works, 4 telescopes

- Thought to be evidence of **Sterile Neutrino dark matter**



Probing The Milky Way's Dark Matter Halo for the 3.5 keV Line

- ***The Astrophysical Journal*** (December 2020)

- ~51 Ms of archival *Chandra* data
  - Peering through the Milky Way's Dark Matter Halo

- Objectives:
  - Investigate the 3.5 keV line and the sterile neutrino dark matter hypothesis
  - Constrain the parameter space

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Sterile Neutrino Dark Matter

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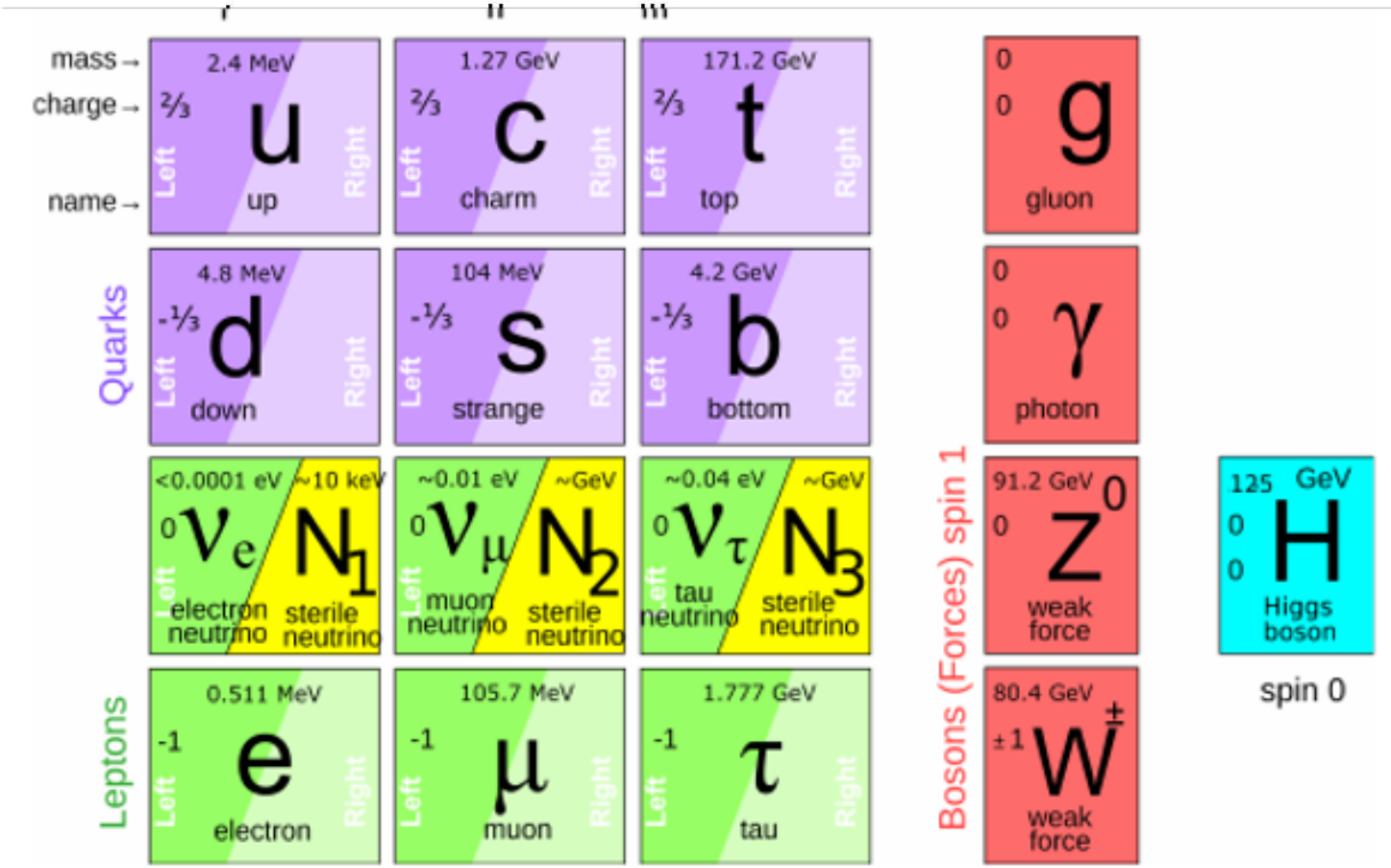
Standard Model (and beyond)

- No particle meets dark matter criteria
  - New particle must be added
- Fermions: **right-** and **left-handed** chirality
  - **Exception:** Neutrinos
- **Right-handed** neutrinos–logical addition to Standard Model
- Could help solve several mysteries
  - Neutrino mass
  - Matter-antimatter asymmetry
  - ***Dark Matter***



Drewes 2019

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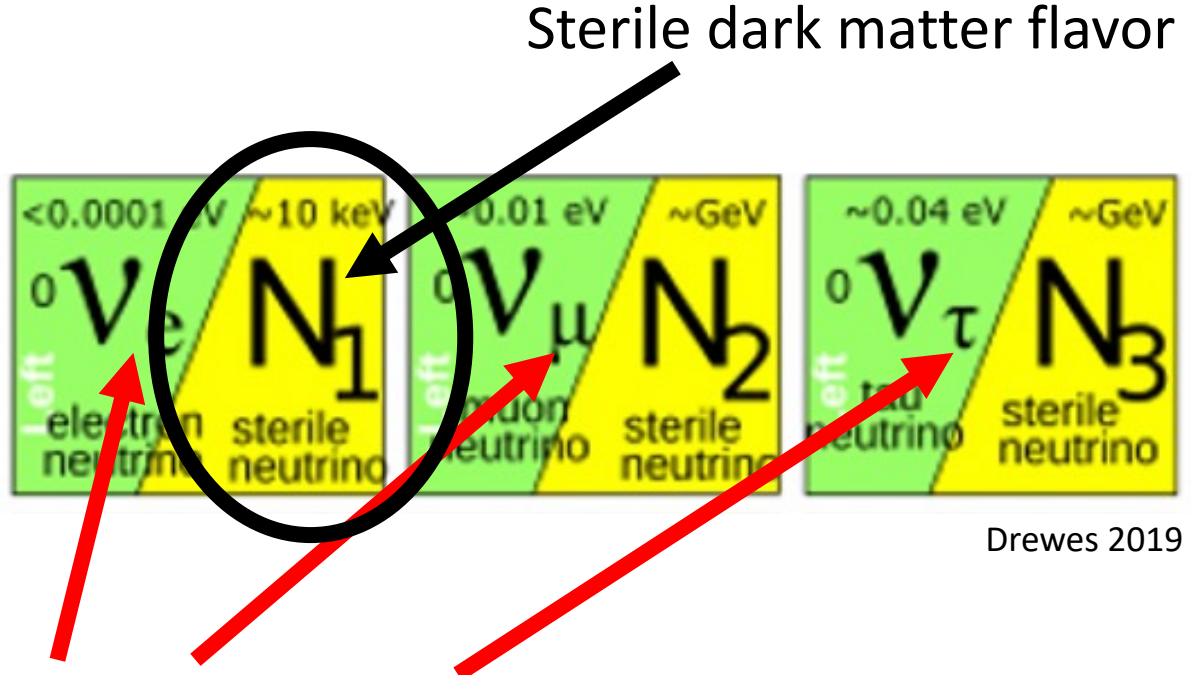
Right-Handed Neutrinos

- Do **not** couple to weak interaction
  - Dubbed "**Sterile" Neutrino**s
  - **Left**-handed: "**active"** neutrinos

- Neutrino flavor "mixing"
  - Probability: depends on **Mixing Angle** θ

- θ ~ 0.5 for Standard Model mixing
  - Common between active flavors

- θ ~ 10^{-6} for sterile dark matter flavor
  - **Little to no mixing with active neutrinos**



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Sterile Neutrino Decay ("θ–suppressed")

- Sterile neutrino decay rate:

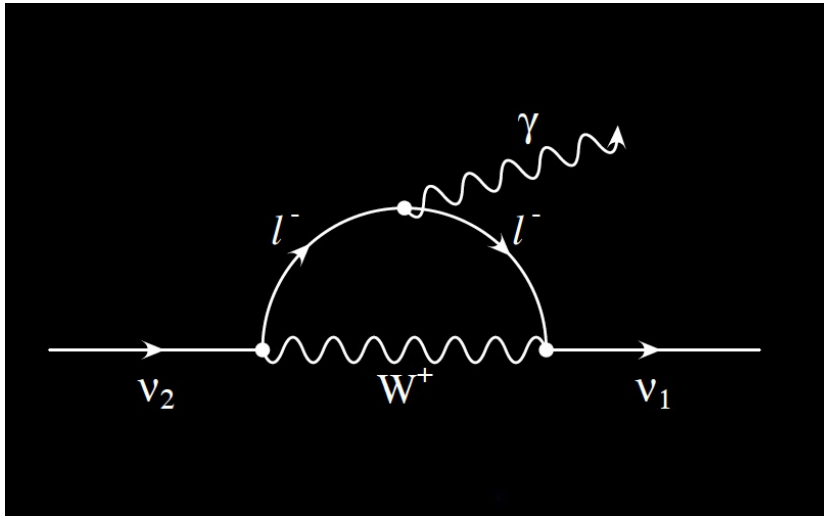
Mixing Angle term (~10^{-11})

Mass (~10 keV)

$$\Gamma_\gamma(m_s,\theta) = 1.38\times10^{-29}s^{-1}\left(\frac{sin^2(2\theta)}{10^{-7}}\right)\left(\frac{m_s}{1keV}\right)^5$$

- Products: **active neutrino** and **photon**
  - **Each** has **half** the total sterile neutrino mass-energy
  - m_s ~ 10 keV gives photon **E ~ 5 keV**

- ***Decay should be detectable by X-ray observatories***



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The 3.5 keV Line

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3.5 keV line detections

XMM-Newton:

- **73 galaxy clusters**, ~4.5σ (**Bulbul**+2014)
- **Andromeda** (M31), 3σ (**Boyarsky**+2014)
- **Galactic Center** of Milky Way, 5.7σ (Boyarsky+2015)

Chandra:

- **Perseus cluster**, ~4.5σ (**Bulbul**+2014)
- **Dark Matter Halo** of Milky Way, ~3σ (Cappelluti+2018)
- **Galactic Bulge** of Milky Way, >3σ (Hofmann+2019)

Suggests NuSTAR detections are instrumental features

Suzaku:

- **Perseus cluster**, ~5σ (Urban+2015; Franse+2016)
- **Galactic Bulge** of Milky Way, >3σ (Hofmann+2019)

NuSTAR:

- **Bullet cluster**, >3σ (Wik+2014)
- **Dark Matter Halo** of Milky Way, 11σ (Neronov+2016)
- **Earth's Dark Side**, >3σ (Perez+2017)

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Prior constraints (2014-2020)

3.5 keV ***Non-Detections****:*

- **Galaxy clusters**, *Suzaku* (Bulbul+2016)
- **Draco dwarf galaxy**, *XMM-Newton* (Ruchayskiy+2016)
- **Perseus cluster**, *Hitomi* (Hitomi+2017)
- **Galaxy clusters**, *XMM-Newton* (Bhargava+2020)
- **Dark Matter Halo** of Milky Way, *XMM-Newton* (Dessert+2020)

All show at least marginal consistency with detections

- *Science goal #1:* Investigate possible m_s ~ 7 keV sterile neutrino dark matter particle

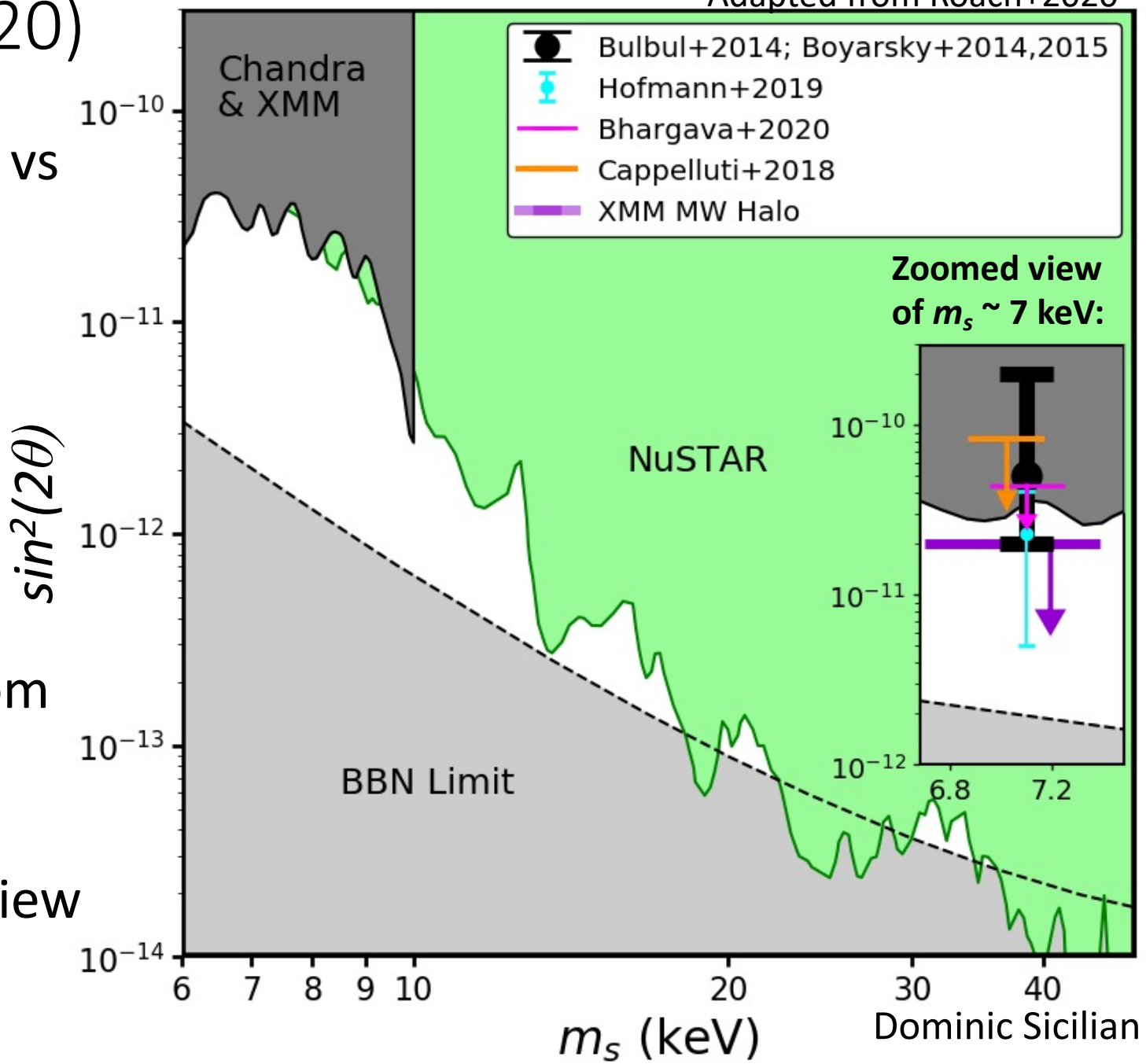
Prior constraints (2014-2020)

- *Science goal #2*: Constrain ***Mass*** vs ***Mixing Angle*** parameter space

- Use non-detections of new lines across spectrum
  - ***Mass***: twice the line Energy

- Mixing Angle term: Compute from decay rate using
  - Line Flux
  - Total dark matter in field of view

Adapted from Roach+2020



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Looking for the 3.5 keV Line in archival *Chandra* data

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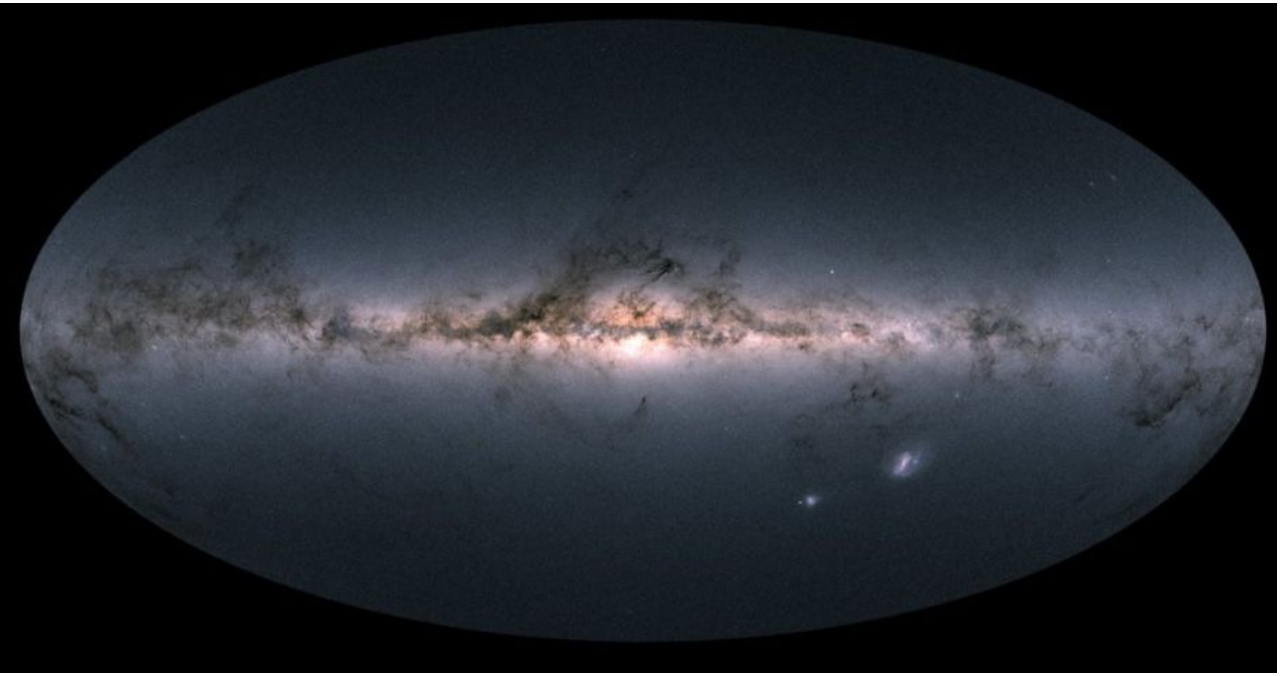
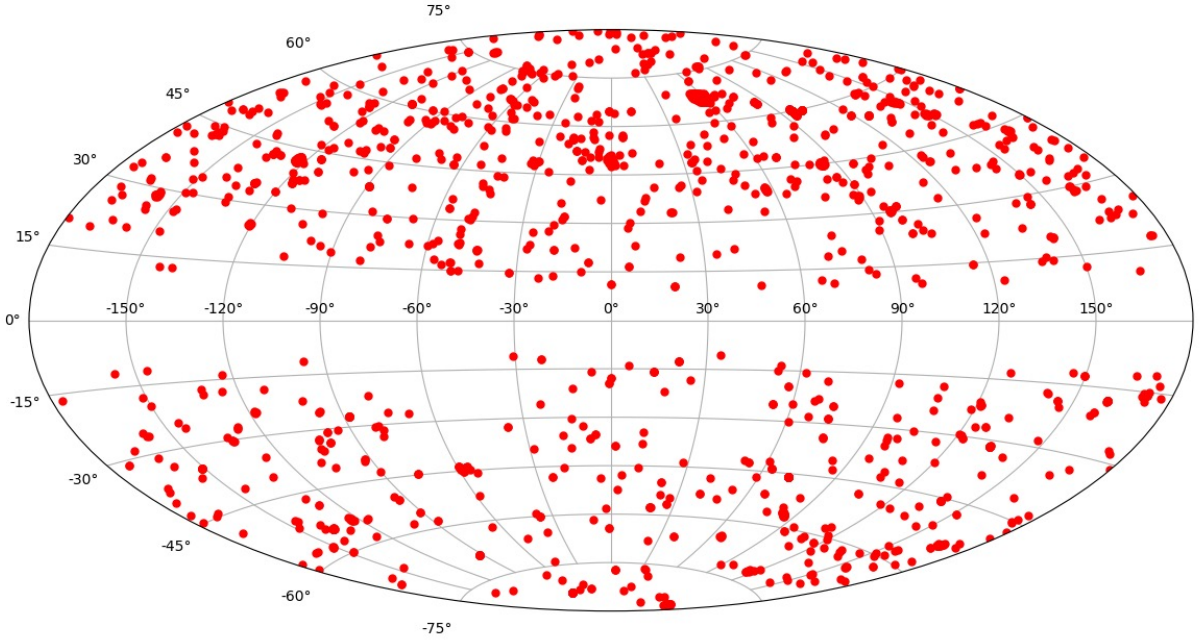
The Ultimate 3.5 keV Line Search





- Isolate possible dark matter signal
  - Eliminate all baryonic X-ray sources

51 Ms of archival *Chandra* Source Catalog data; ~1900 observations from 2000-2014

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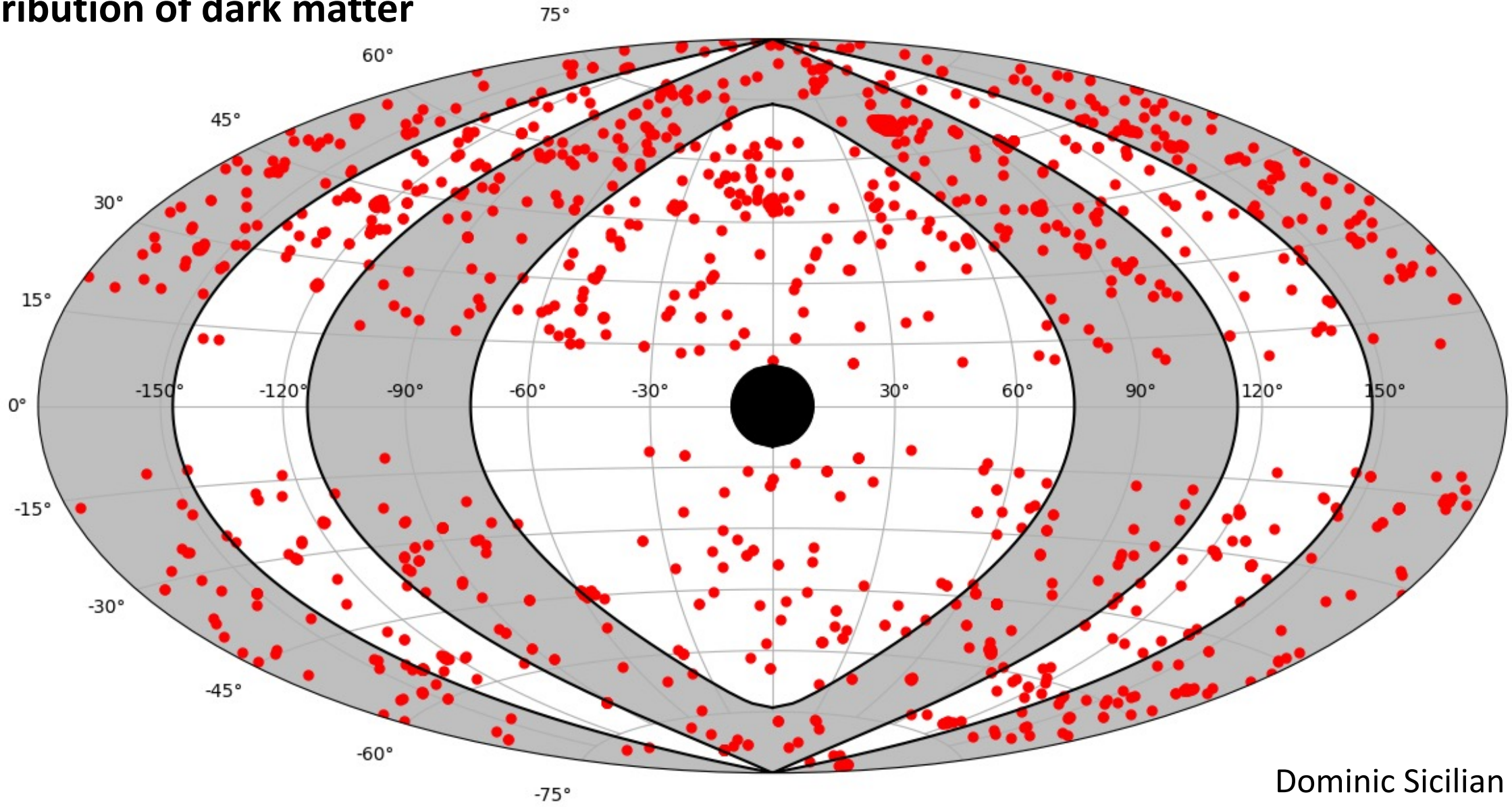
- Wide spatial distribution
  - Compare **line flux/upper-limits** with **Navarro-Frenk-White (NFW) distribution of dark matter**



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Results

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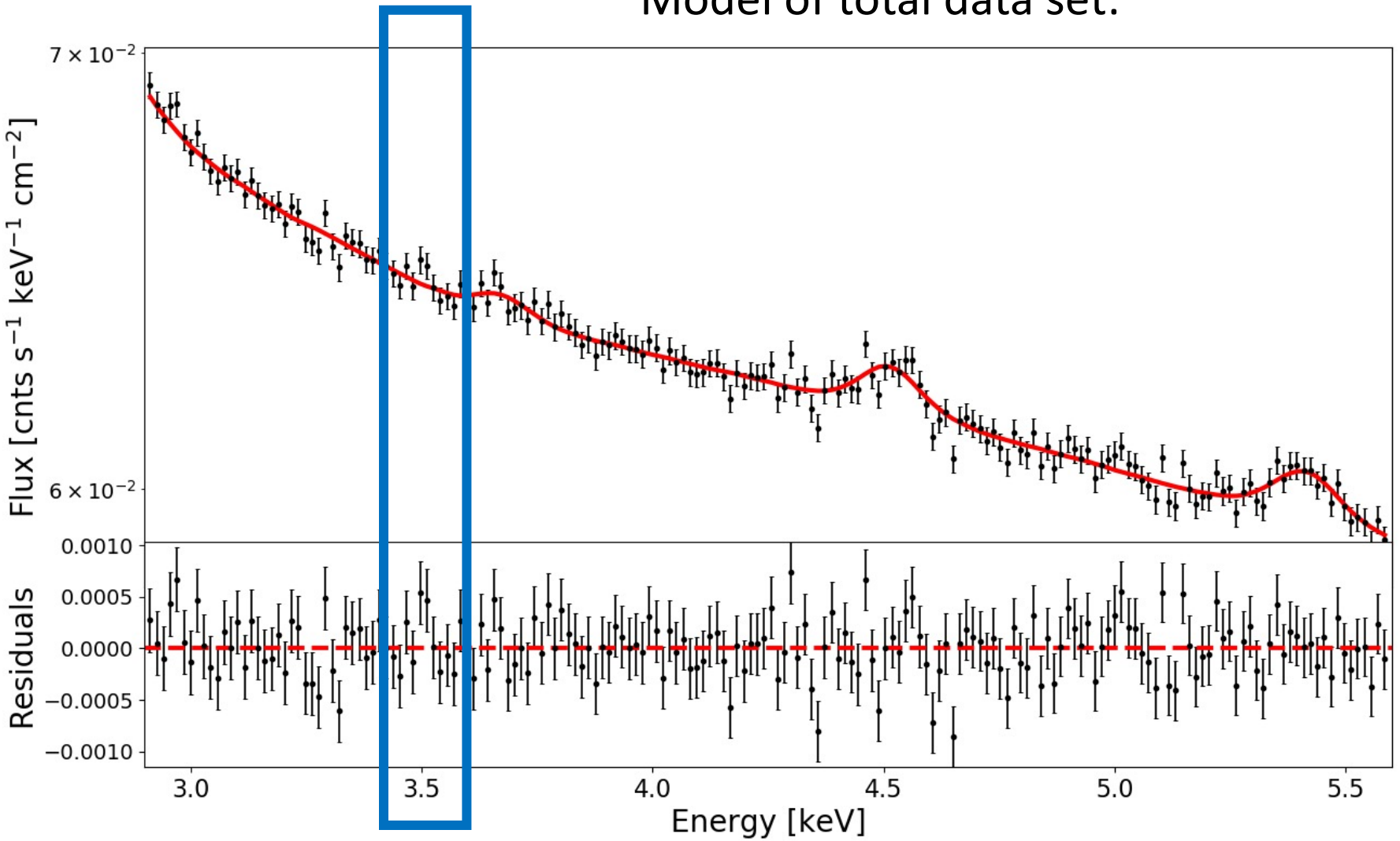
Modeling 51 Ms of *Chandra* Data

- **CXB**: absorbed powerlaw
- **Particle background**: powerlaw plus emission features
- All fitting: Markov Chain Monte Carlo (MCMC)

Model of total data set:



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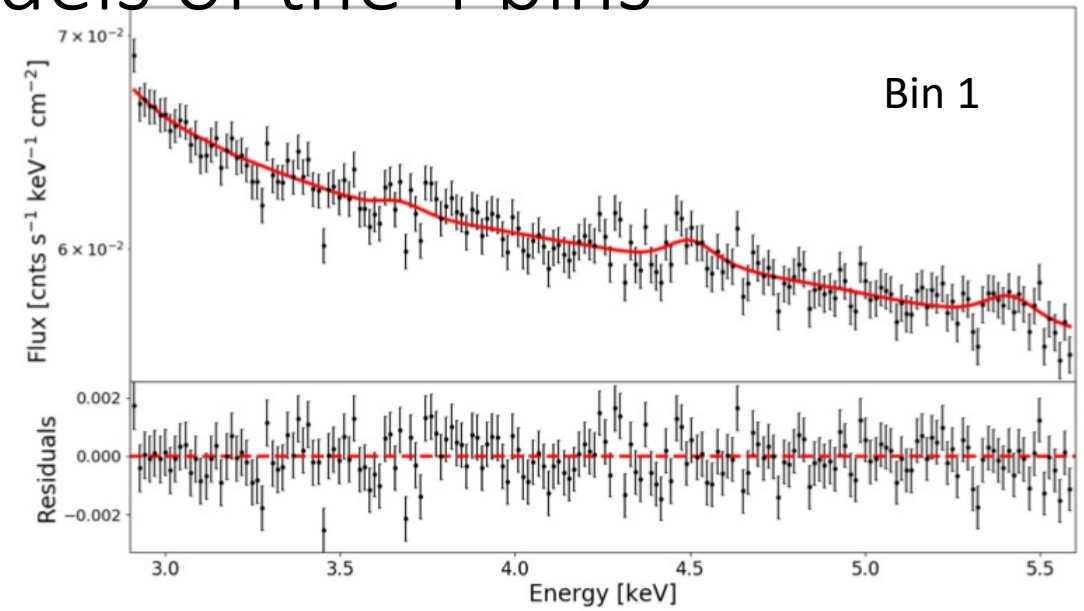
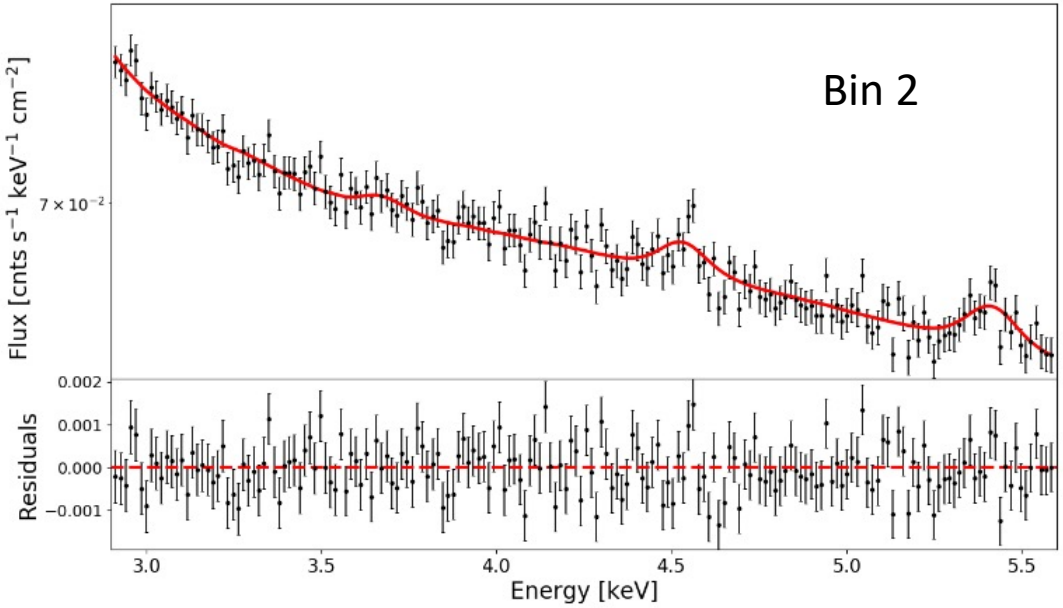
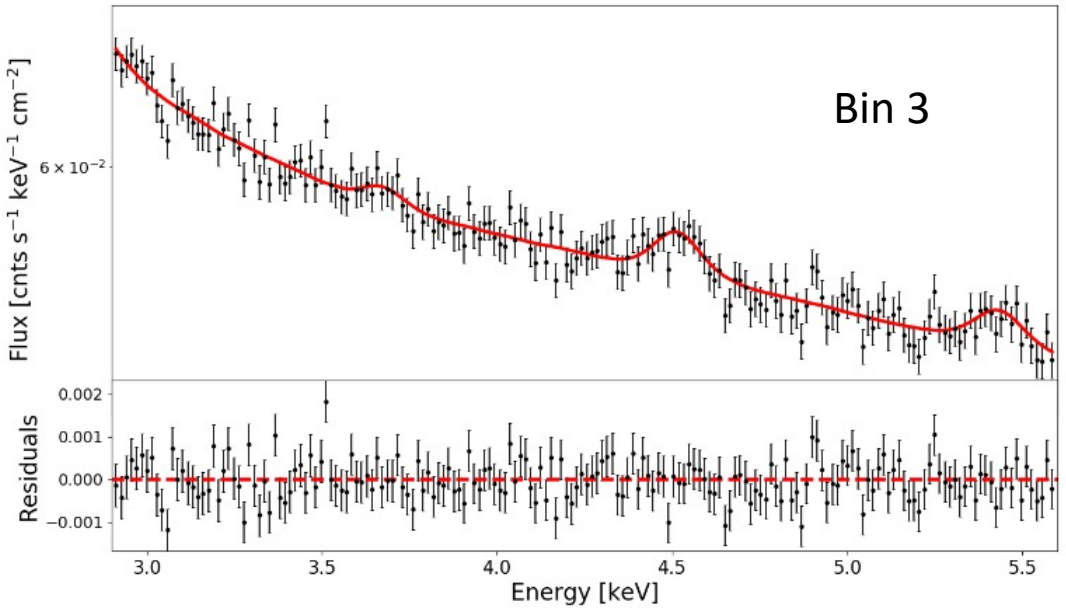
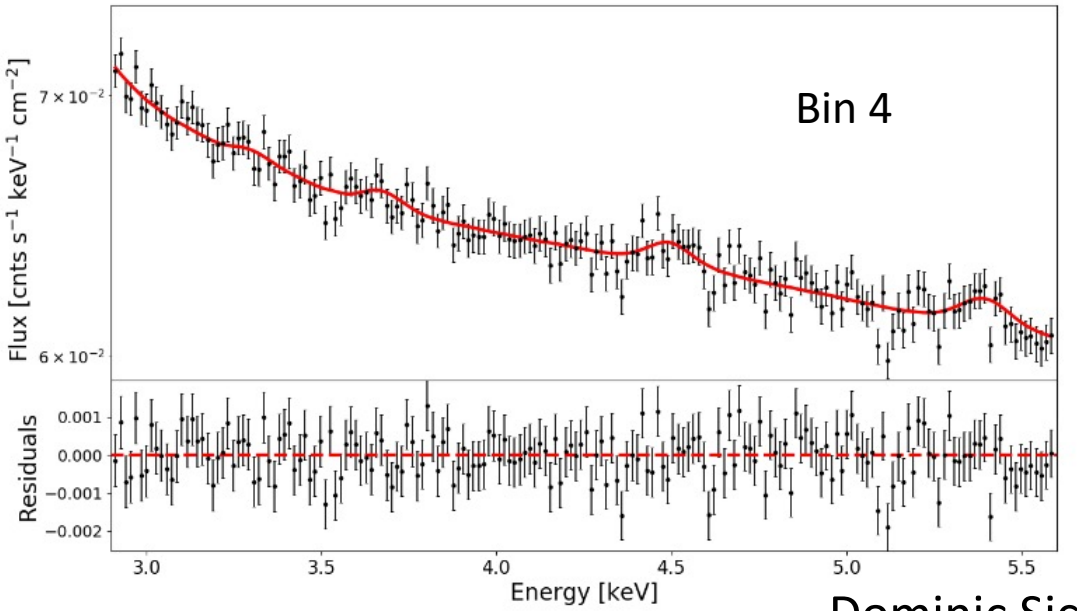
Models of the 4 bins









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3.5 keV Line Upper Limits

- Added a ~3.5 keV emission component on top of model
- Tested significance with two methods
  - χ^2
  - Bayesian Information Criterion (BIC)
- Both confirm **non-detection**

Bin	$I_{3.51}$ **Upper-Limit** $[10^{-7}$ ph cm^{-2} s$^{-1}]$
1	4.45
2	4.67
3	4.54
4	3.42
ALL	2.34

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Data without Source Removal

- Point-source removal process reduces statistics

Data	Total Counts	Particle Background Counts	Signal-to-Noise
Full fields	151177565	139226685	971.98
Source-removed	126560247	118028924	758.35

Bin	θ_{GC} [deg]	t_{exp} [Ms]	ObsIDs	Counts (w/sources)	Counts (w/out)	A_i [deg^2]	A_f [deg^2]
1	10–74	8.00	306	1569344	1224559	19.18	13.44
2	74–114	14.07	715	3540528	2666281	57.96	43.98
3	114–147	17.58	473	4374038	2785435	36.24	19.57
4	>147	11.00	413	2466970	1855048	27.63	19.05
	TOTAL	50.65	1907	11950880	8531323	141.01	96.04

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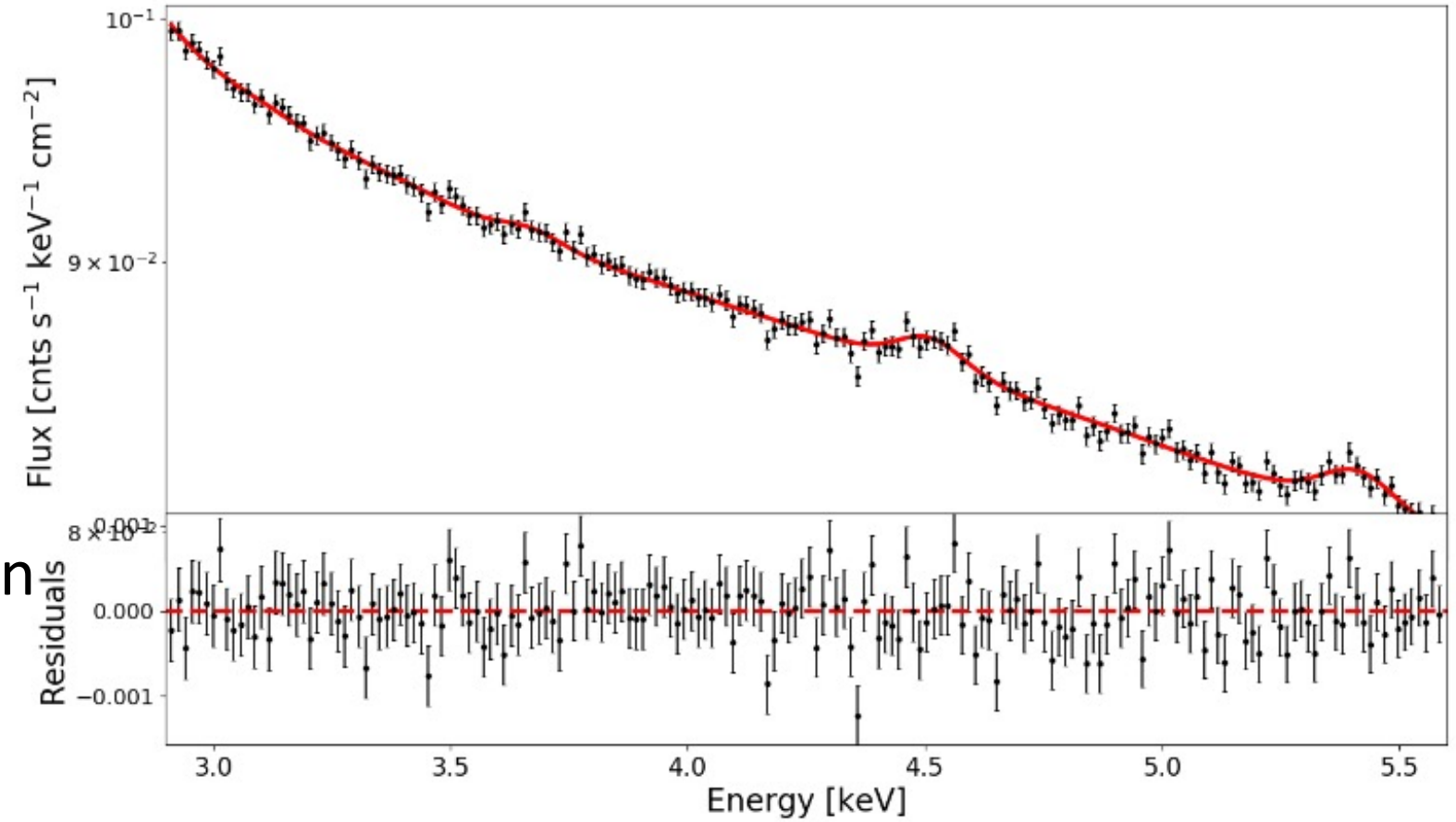
Source-intact models

- Same methodology as main data set
- Contains more dark matter **and** more baryons
- Yields stronger non-detection than main data set



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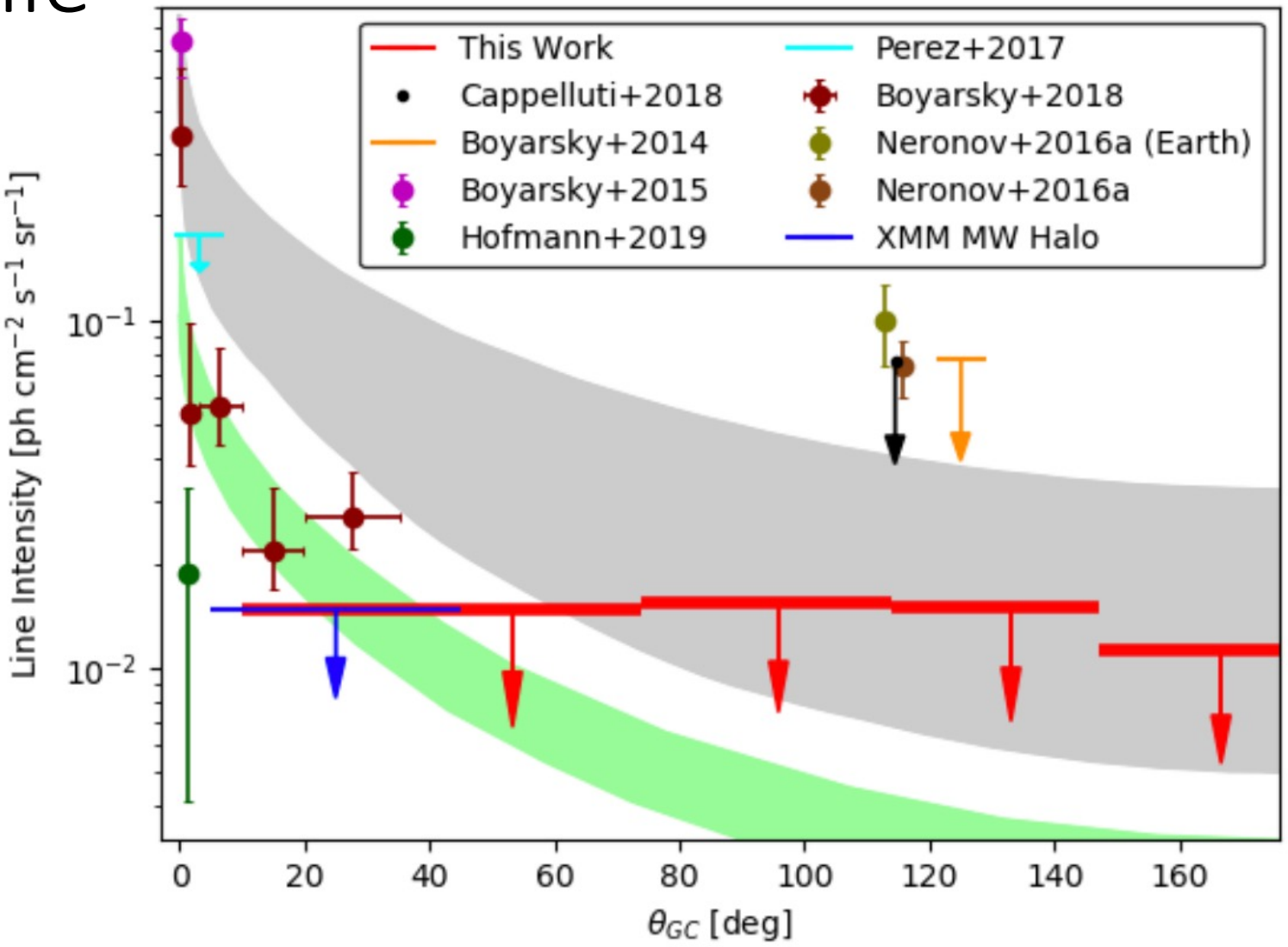
3.5 keV Line Profile

- Shown: Upper-limits compared to two NFW profiles
- Exact match with XMM Halo constraints
- *NuSTAR* detections excluded
- Correspondence to NFW profile ***not*** fully excluded



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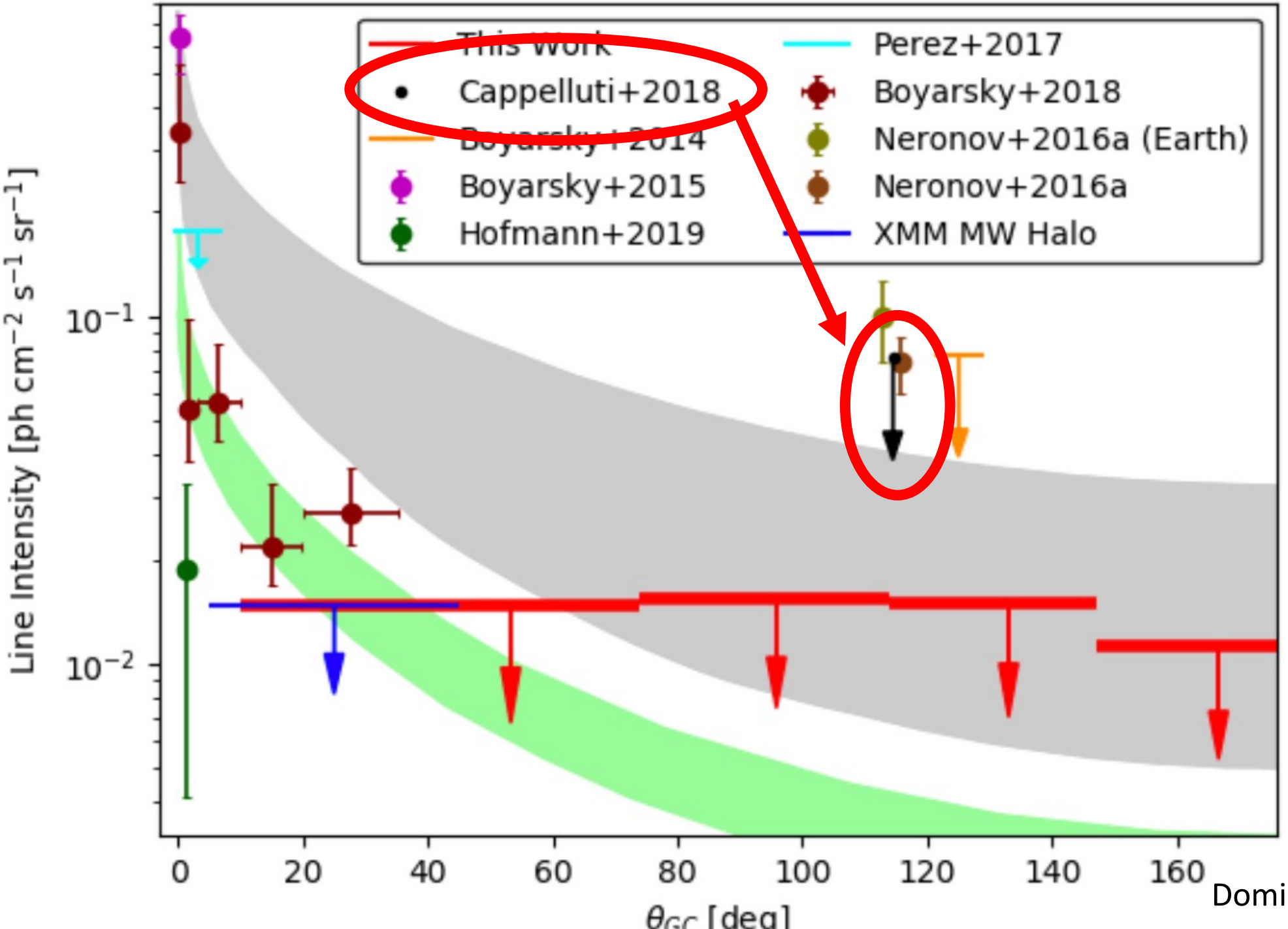

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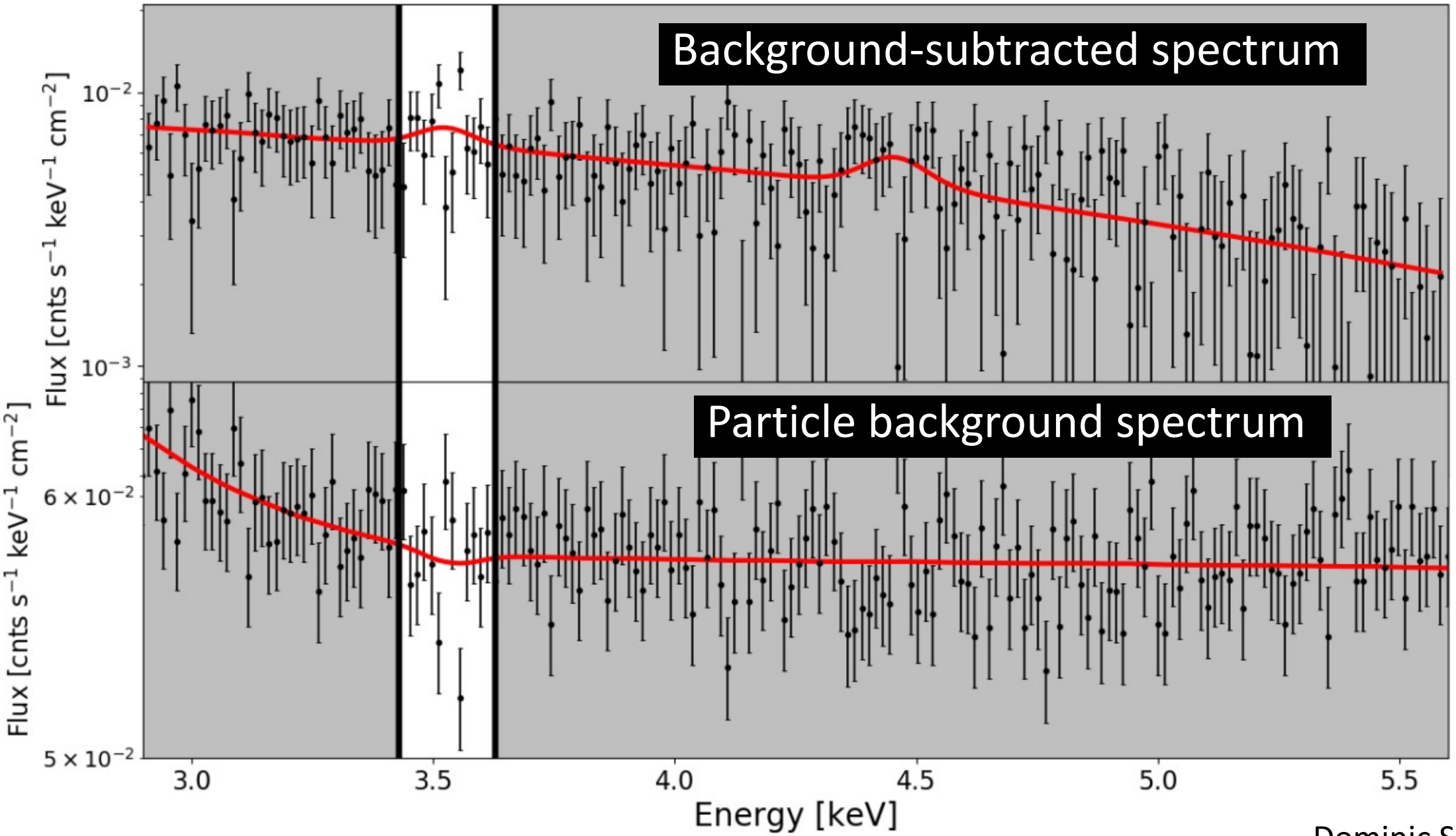

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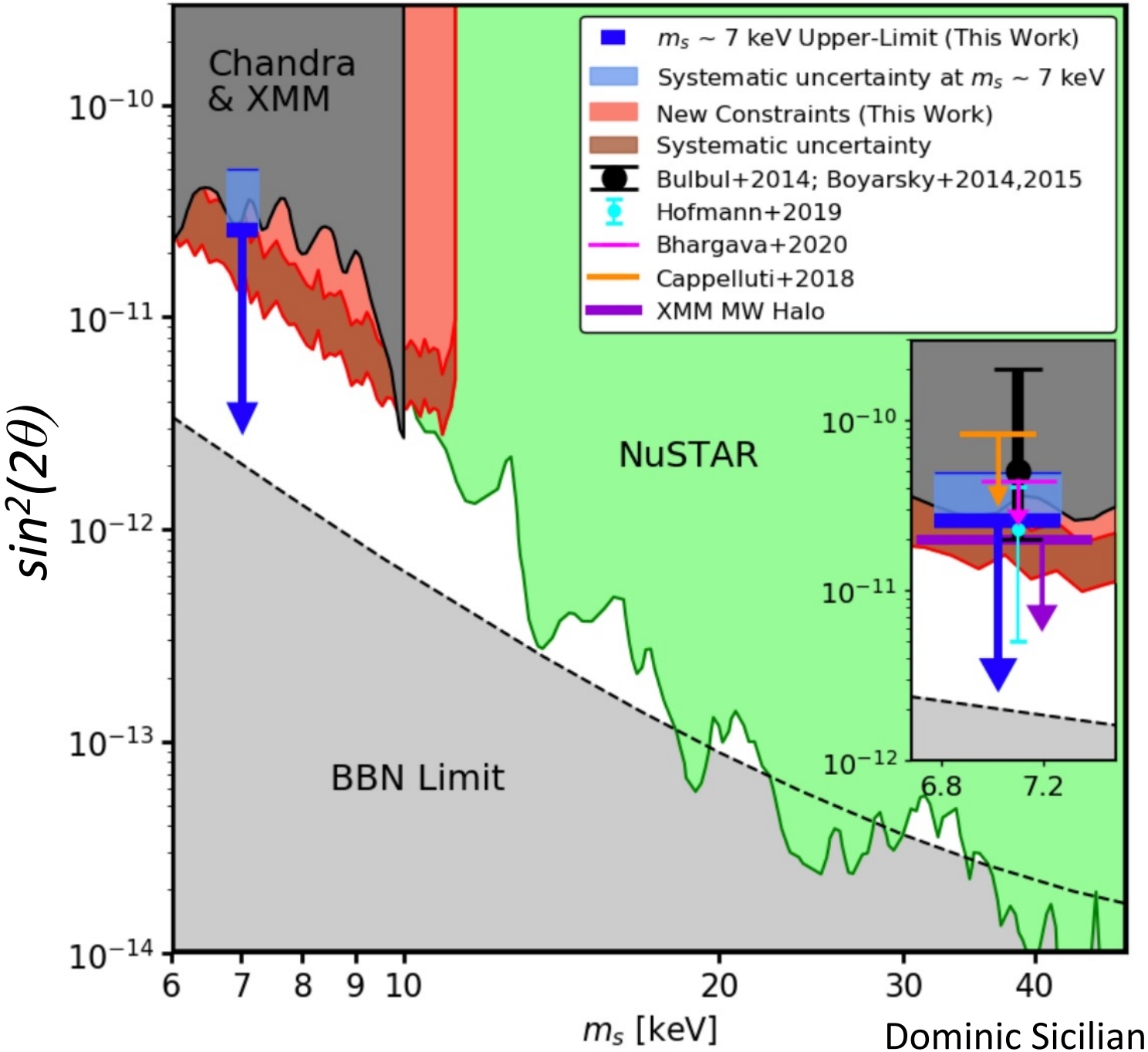
Parameter space

- **Blue:** ~7 keV sterile neutrino constraint
- **Red:** New continuum constraints
- Systematic uncertainty reflects two extreme NFW profiles



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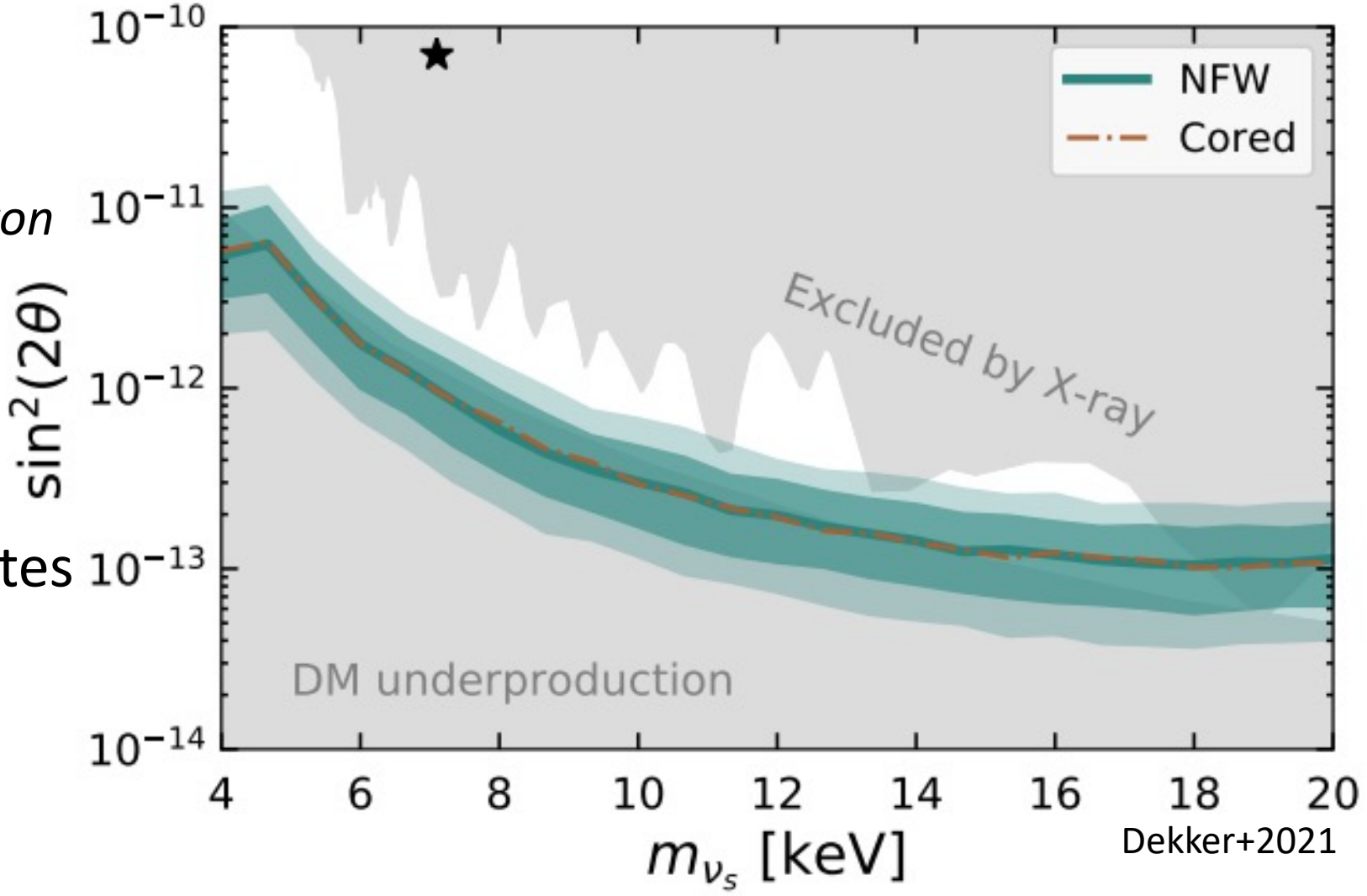
Recent Works

- New constraints: Foster+2021
  - 547 Ms (!!!) of *XMM-Newton* data
  - See Abazajian 2021

- Dekker+2021 *eROSITA* simulations on MW satellites can constrain $m_s < 20$ keV space
  - Only 2.5 ks exposure

eROSITA: simulated sensitivity



Dekker+2021

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Conclusions

- 3.5 keV line's decaying dark matter interpretation has been heavily constrained; not wholly ruled out
- Sterile neutrino dark matter parameter space has been strongly constrained
- Other insights from current/future missions
  - *XRISM*'s spectral resolution will allow us to resolve & disentangle 3.5 keV emission from nearby features
  - *eROSITA*'s all-sky coverage will improve understanding of 3.5 keV line's radial profile
  - *eROSITA* may also rule out the rest of the $m_s < 20$ parameter space

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Thank you!

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References

Abazajian+2001 · Abazajian 2020 · Abazajian 2021 · Barger+1995 · Bulbul+2014 · Bulbul+2016 · Boyarsky+2014 · Boyarsky+2015 · Boyarsky+2018 · Boyarsky+2020 · Cappelluti+2018 · Dekker+2021 · Dessert+2020 · Drewes+2013 · Drewes 2019 · Franse+2016 · Hitomi Collaboration+2017 · Hofmann+2019 · Navarro+1997 · Neronov+2016 · Pal & Wolfenstein 1982 · Perez+2017 · Philips & Sarkar 1995 · Roach+2020 · Ruchayskiy+2016 · Shrock 1974 · Sicilian+2020 · Urban+2015 · Wik+2014 · Zwicky 1933