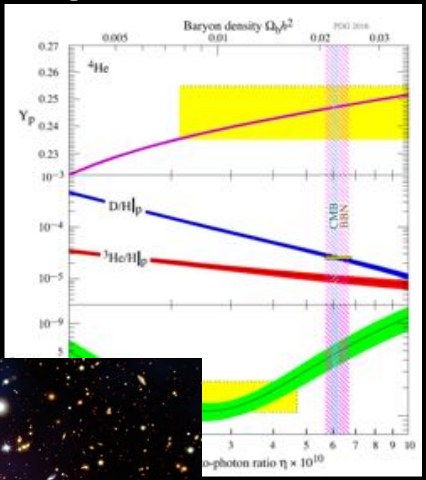
Searching for Dark Matter with X-ray lines

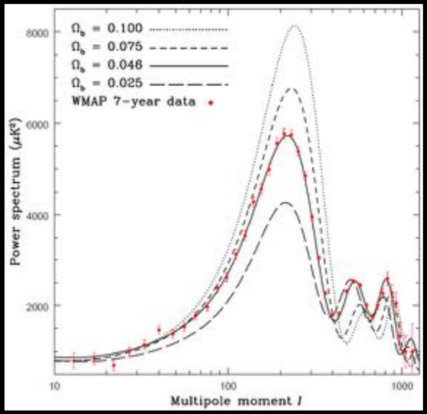
Perseus Cluster
(Chandra)

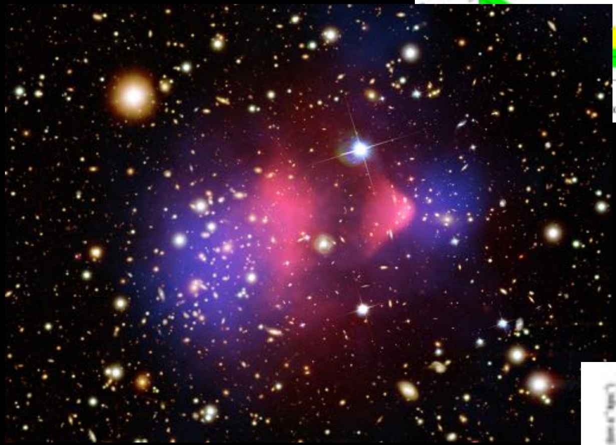
Kenny, Chun Yu Ng (吴震宇)
Marie Curie fellow
GRAPPA, University of Amsterdam

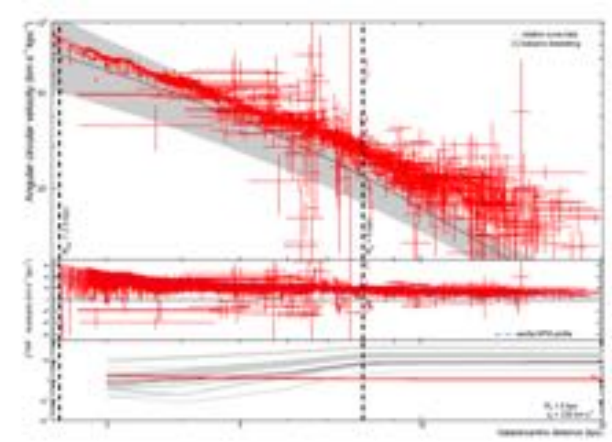
Dark Matter problem

- BBN/ CMB
- Clusters
- Galaxies/Local





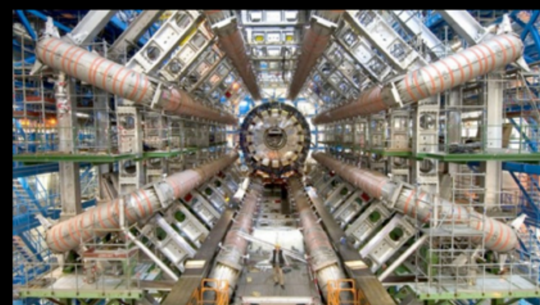


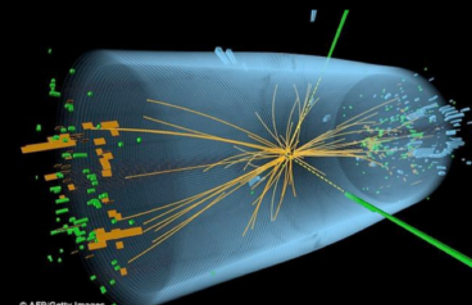


Dark Matter Detection

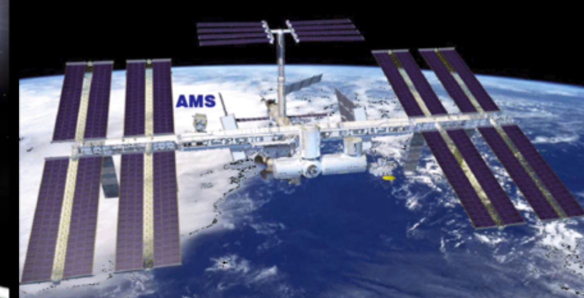
- Direct Detection

- Collider Search





- *Indirect Detection*



Dark Matter Indirect Detection

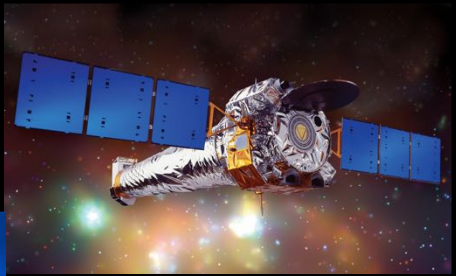
Particle Physics Astrophysics/detector

$$\frac{dF}{dE} = \frac{1}{4\pi}\frac{\Gamma}{m_\chi}\frac{dN}{dE}\int d\Omega \int d\ell \rho_\chi[r(\ell)]$$

X-ray Searches of Dark Matter

- Sensitive instruments

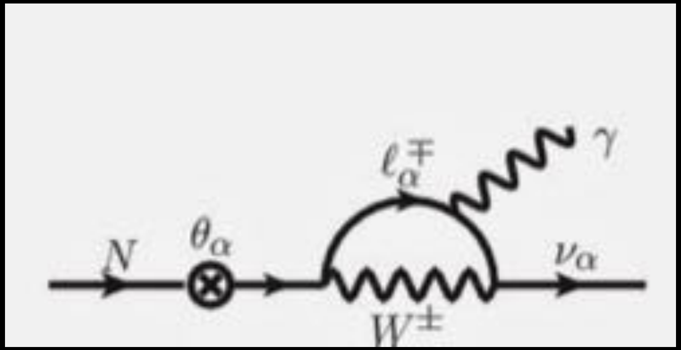
Chandra (1999 -)



XMM Newton (1999 -)

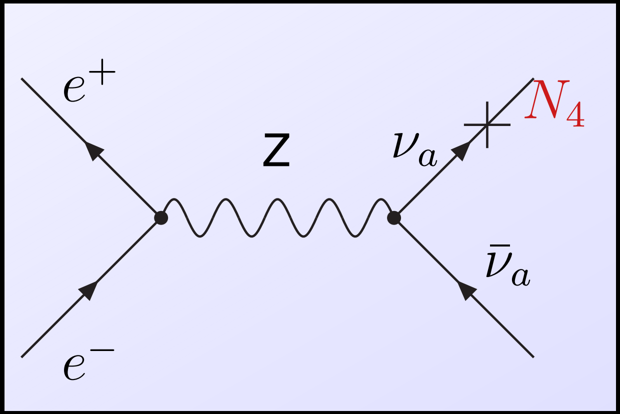
Suzaku (2005 - 2015)

- Well Motivated Candidates
  - *Sterile Neutrino (keV)*
  - Axion-like Dark Matter
  - Gravitino
  - Exciting Dark Matter
  - ++++++



Sterile Neutrino Dark Matter Production

- Non-resonant production
  - Dodelson Widrow 1994
  - Warm DM



- Resonant production
  - Shi Fuller 1999
  - Modified by primordial lepton asymmetry
  - Cool DM

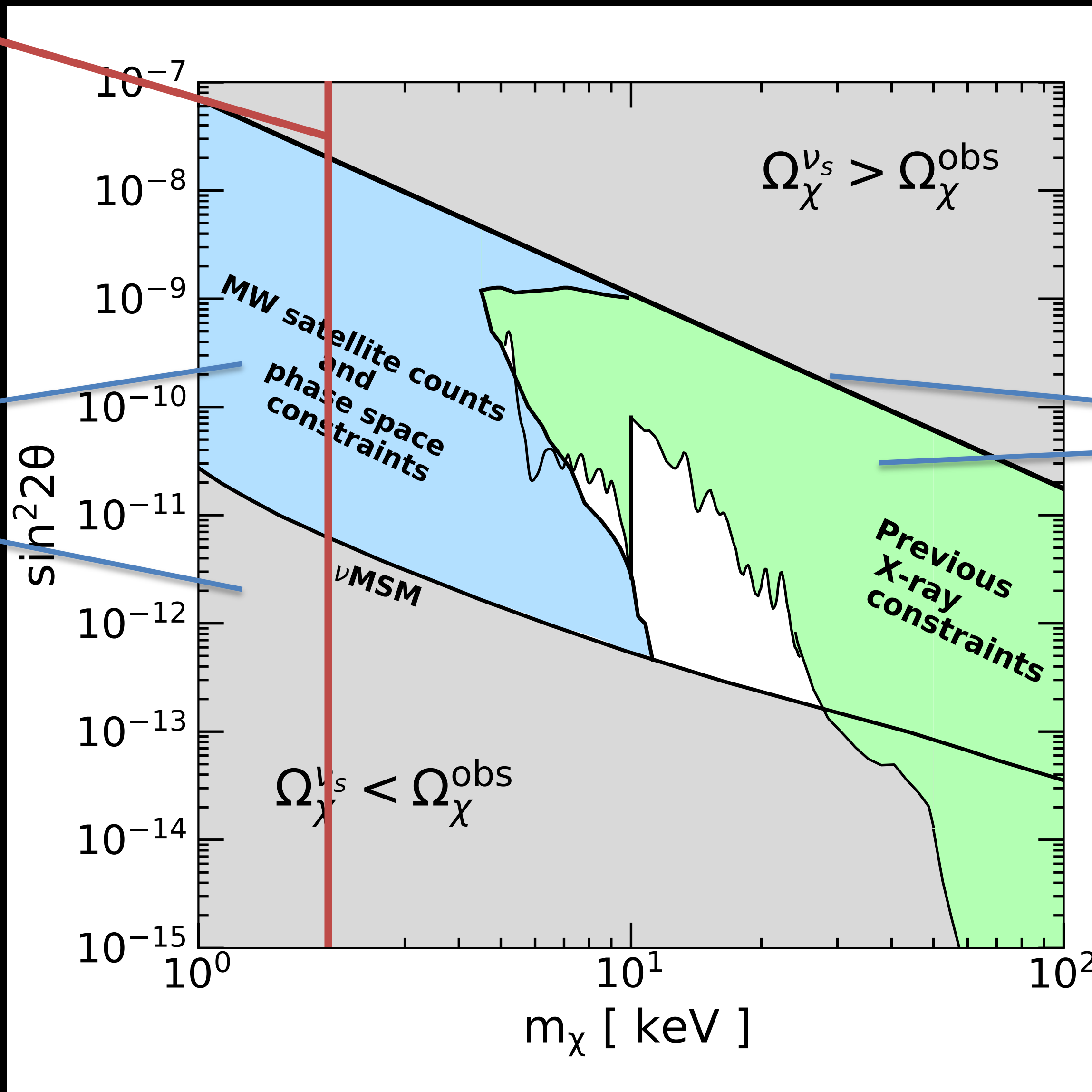
- Decay of heavy particles
  - E.g., Petraki Kusenko 2008
  - Collider signatures

Sterile Neutrino Dark Matter

Phase space constraint

Model Dependent (nuMSM)

Not applicable in, e.g.
0711.4646 Petraki, Kusenko,
1507.01977 Patwardhan et al
Etc etc

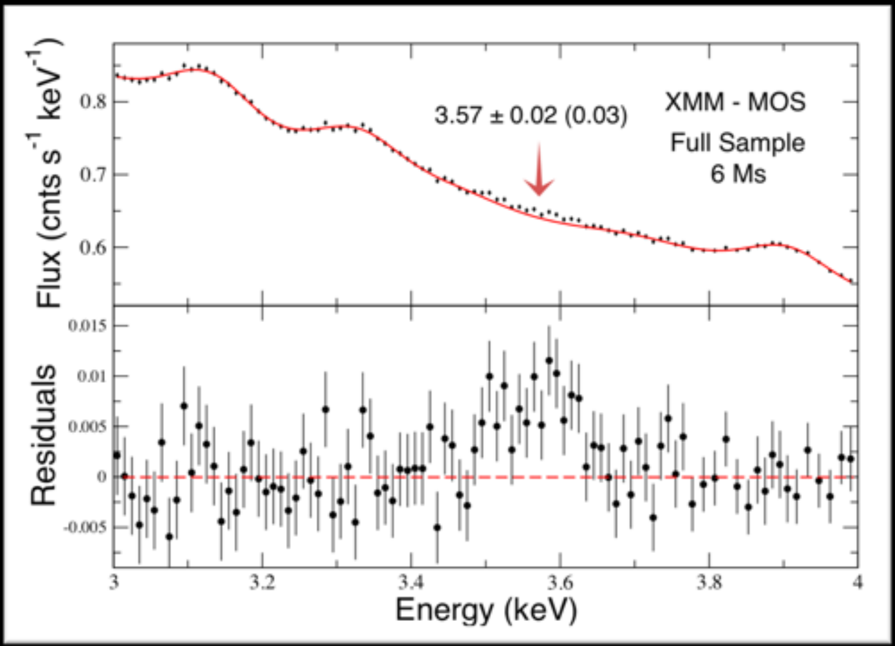


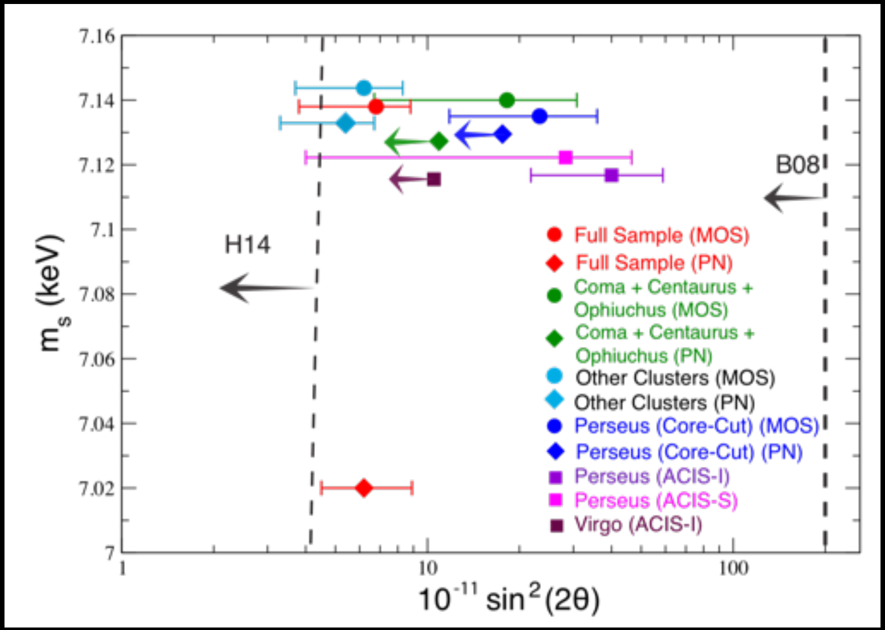
Model Independent

3.5 keV line excess!

- Bulbul et al (2014)

Sterile Neutrino DM



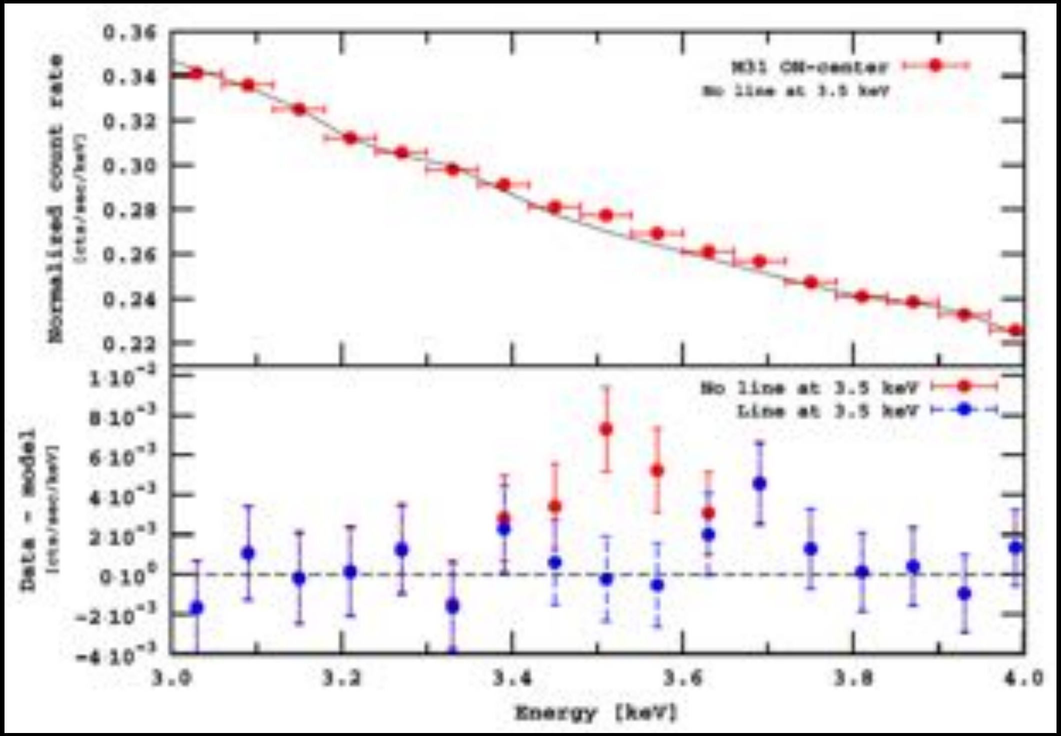


Stacked 73 clusters XMM-MOS (4-5σ)

Also
Chandra Perseus 2.5σ and 3.4σ

3.5 keV line excess!

- Boyarsky et al (2014)



$Sin^2(2\ theta)$ ~ $2\text{-}20 \times 10^{-11}$

Follow-up Observations (2014)

1. Rimer-Sorensen [1405.7943] Chandra GC
2. Jeltema,Profumo [1408.1699] XMM GC
3. Boyarsky + [1408.2503] XMM GC
4. Malyshev + [1408.3531] XMM dwarfs
5. Anderson + [1408.4115] Chandra+XMM Galaxies
6. Urban + [1411.0050] Suzaku Clusters
7. Tamura + [1412.1869] Suzaku Perseus

Follow-up Observations (2015-2017)

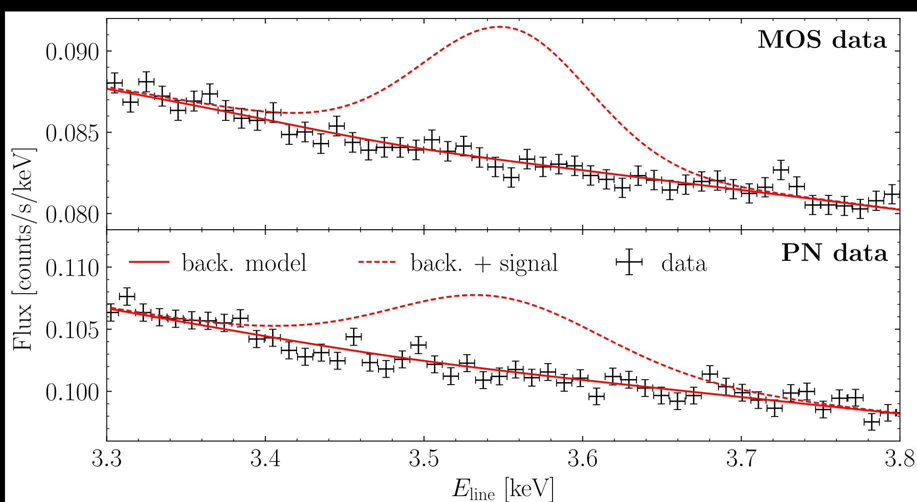
1. Sekiya+ [1504.02826] Suzaku Diffuse Background
2. *Figueroa-Feliciano+ [1506.05519] XQC MW*
3. Riemer-Sorensen+ [1507.01378] NuSTAR Bullet Clusters
4. Iakubovskyi+ [1508.05186] XMM Individual Clusters
5. Jeltema Profumo [1512.01239] XMM Draco
6. Ruchayskyiy+ [1512.07217] XMM Draco
7. Franse+ [1604.01759] Suzaku Perseus
8. Bulbul+ [1605.02034] Suzaku Stacked Clusters
9. Hofmann+ [1606.04091] Chandra Stacked Clusters

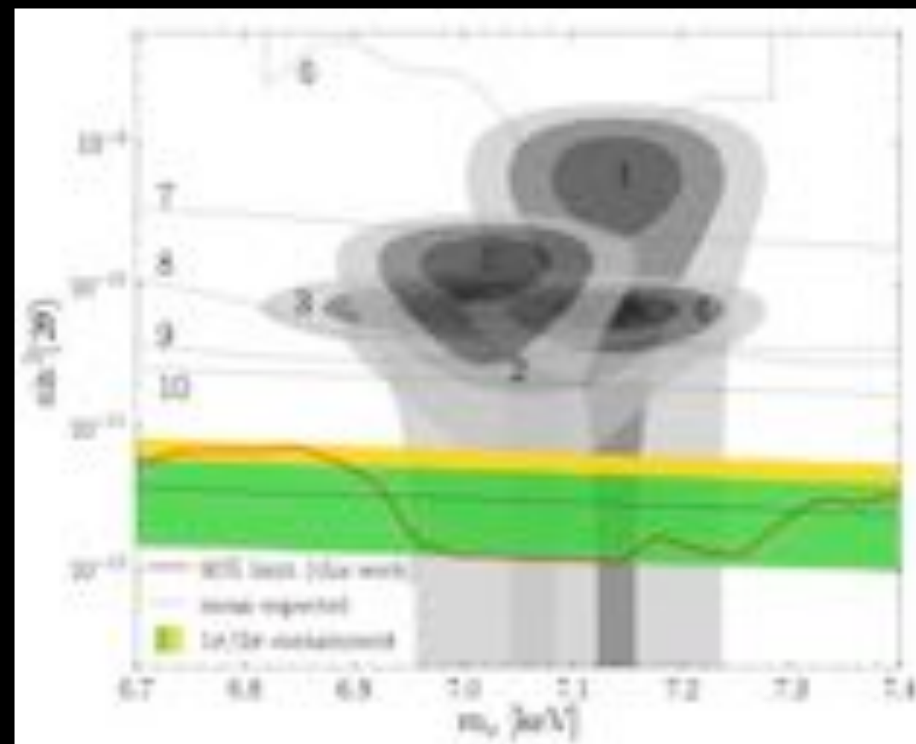
10. *Neronov+ [1607.07328] NuSTAR MW*
11. *Aharonian+ [1607.07420] Hitomi Perseus*
12. *Perez+ [1609.00667] NuSTAR GC*
13. Cappelluti [1701.07932] Chandra Deep field 10 Ms (3 sigma)

And some that I may have missed……

2018-2019

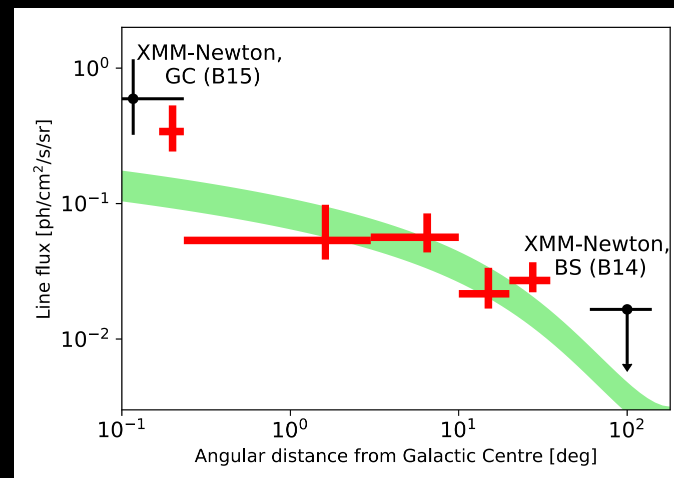
- Dessert, Rodd, Safdi 1812.06976
  - XMM Newton
  - ~30Ms
  - 5° – 45° from GC

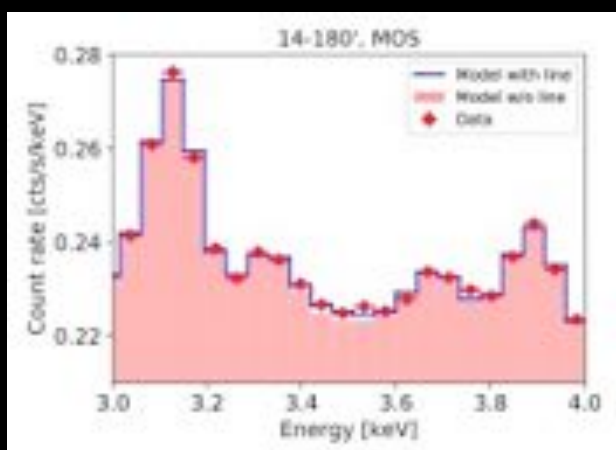


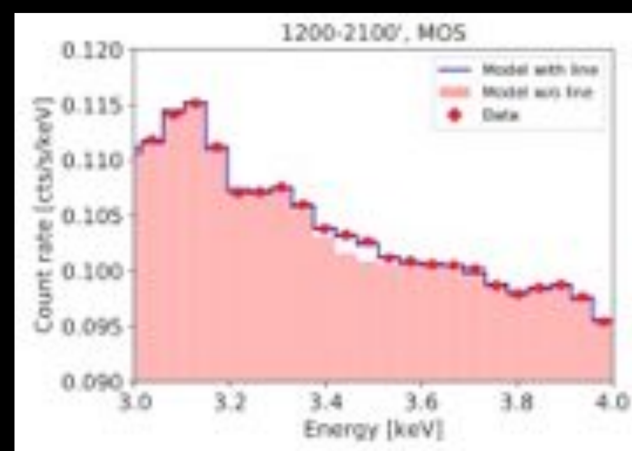


2018-2019

- Boyarsky, Iakubovskyi, Ruchayskiy, Savchenko 1812.10488
  - XMM Newton
  - $\sim 40\mathrm{Ms}$
  - $10' - 35^\circ$

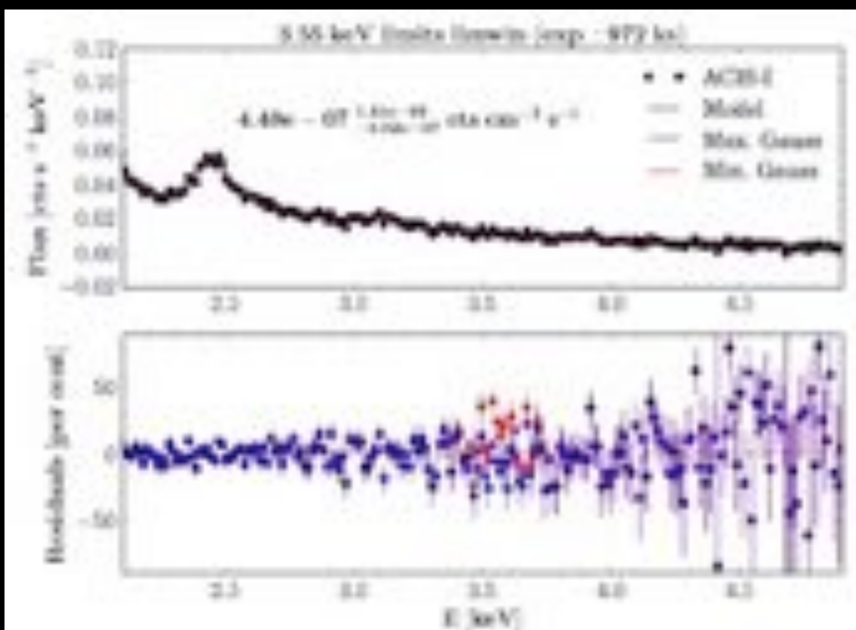


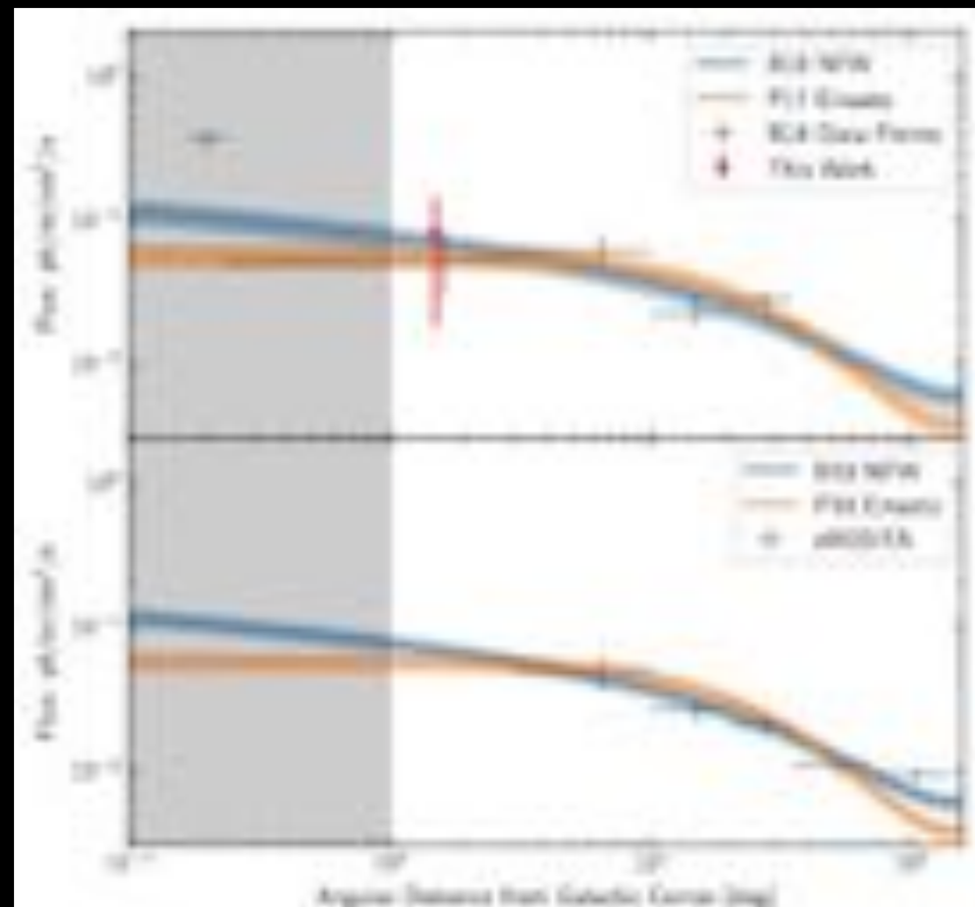




2018-2019

- Hofmann, Wegg 1905.00916
  - Chandra, ~1Ms
  - Galactic Bulge
  - 1.5 sigma detection





What is the 3.5 keV line?

- New astrophysical lines
  - Sulphur charge exchange line?

    Gu + 2015, Shah+ 2016

- Atomic abundance/ emissivity
  - Systematics? Urban + 2015 ……

- Particle Physics Models
  - ALP magnetic conversion [B-field]? Cicoli+ 2014…….
  - Exciting Dark Matter [Velocity]? Finkbeiner & Weiner 2014
  - +++++

What to do next?

- New Instruments?
  - Astro-H (Hitomi)
  - Sounding Rockets
  - NuSTAR
  - Insight/HXMT ??

other detections (Bu14a, Franse et al. 2016). Studying the origin of the 3.5 keV line with CCD resolution observations of galaxy clusters and other astronomical objects appears to have reached its limit; the problem requires higher-resolution spectroscopy such as that expected from *Hitomi* (Astro-H).

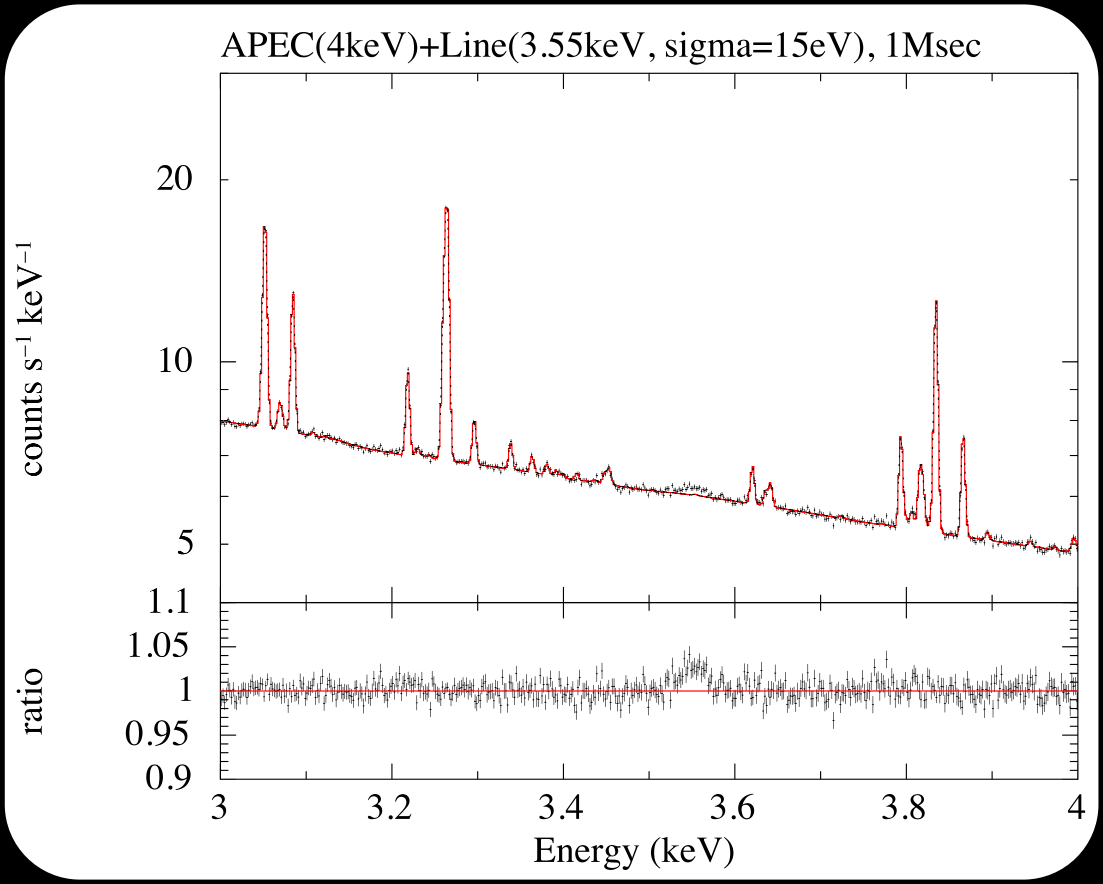
Bulbul+ 2016

- New Techniques?
  - Velocity Spectroscopy

Astro-H (Hitomi)

- Launched in Feb 17, 2016
- 10^-3 energy resolution

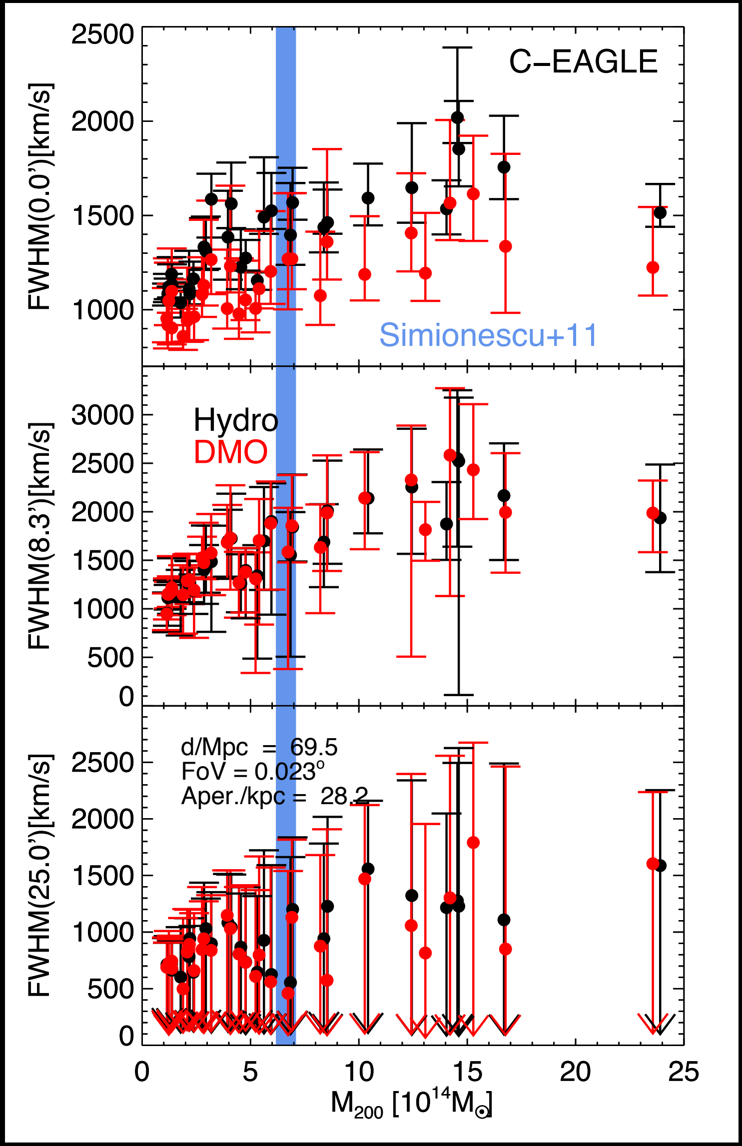
Simulation



Kitayama+
1412.1176

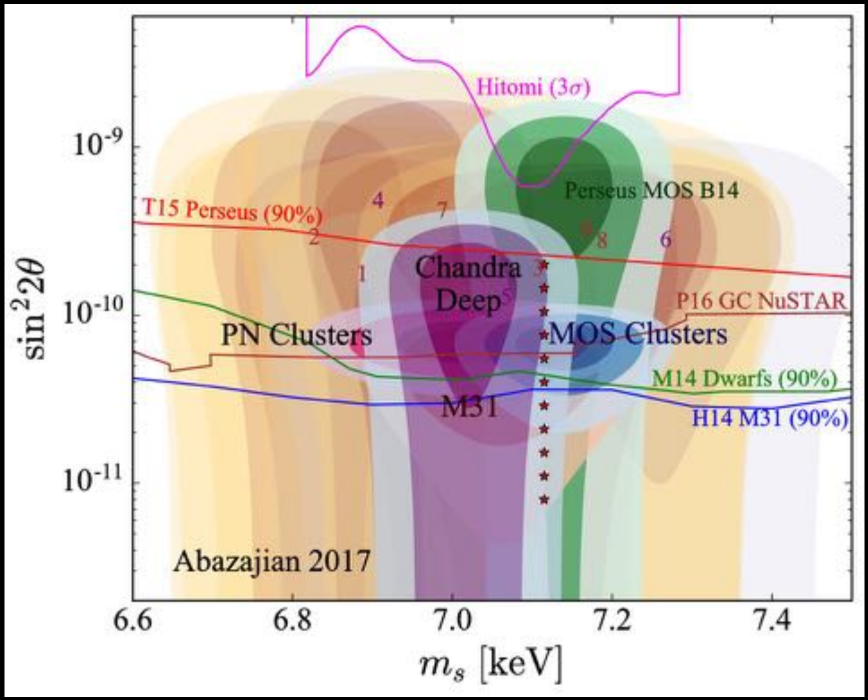
Lovell et al
1810.05168

Astro-H (Hitomi)



[1300,1700]km/s

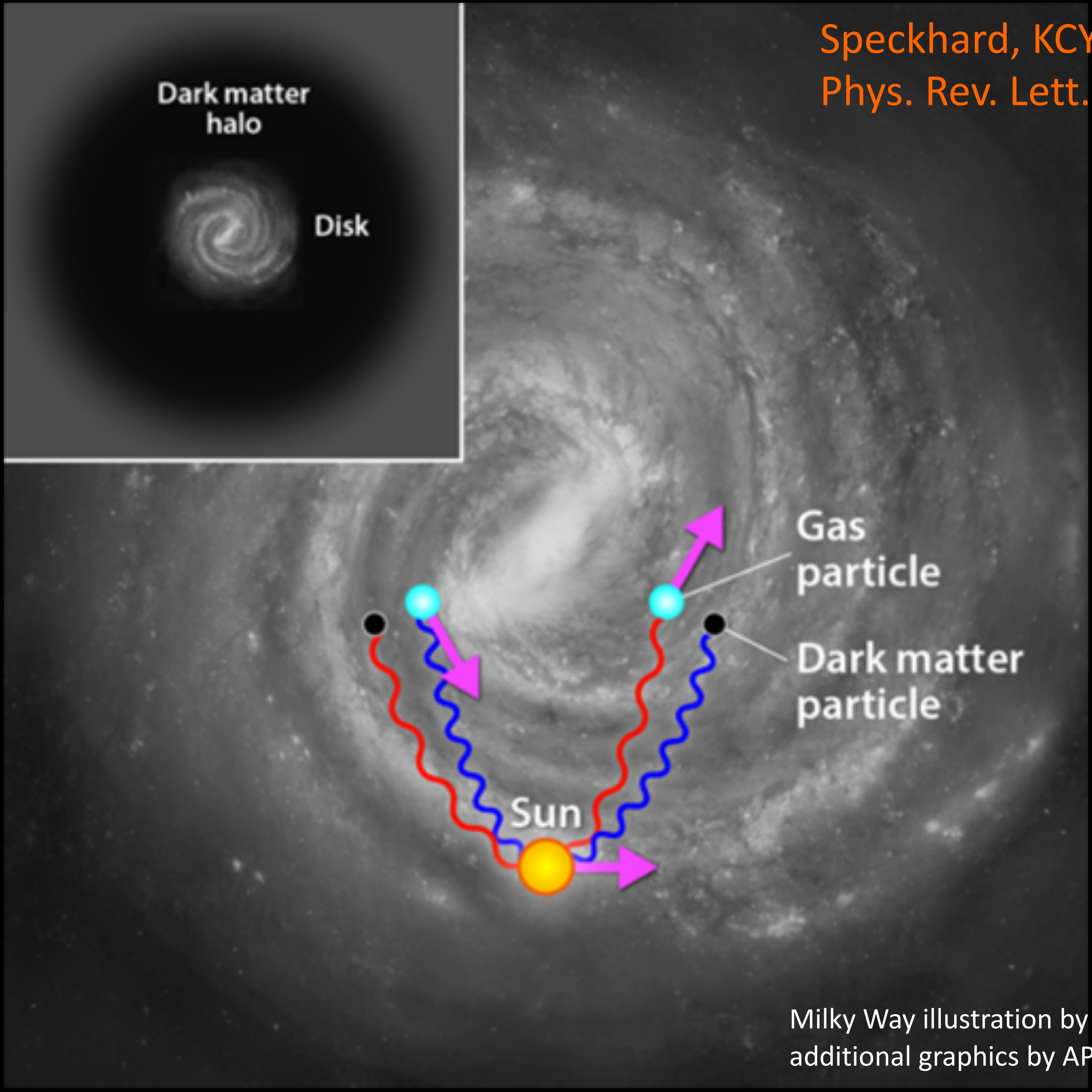
Aharonian et al
~ 200ks
1300km/s



May not rule out the dark matter interpretation using only the width

Dark Matter Velocity Spectroscopy

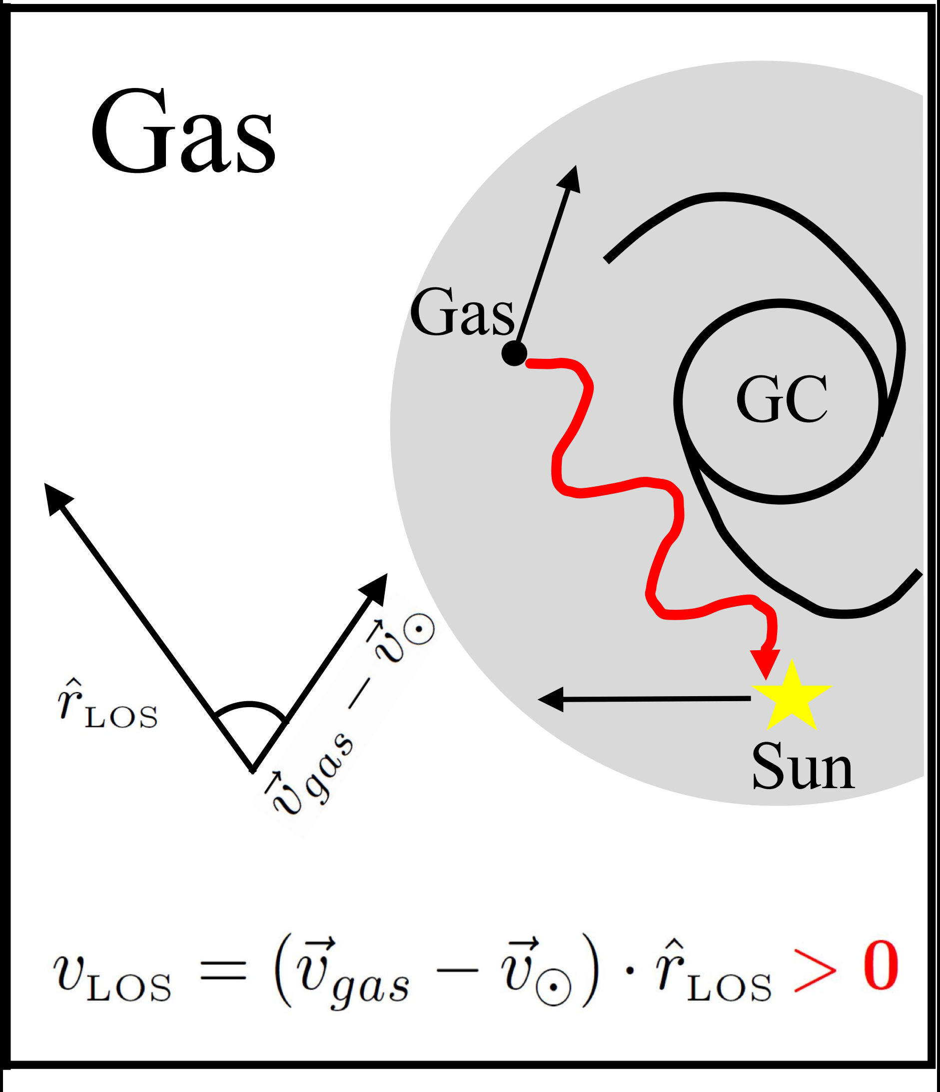
Speckhard, KCYN, Beacom, Laha
Phys. Rev. Lett. 116, 031301



Milky Way illustration by Nick Risinger (CC:BY); additional graphics by APS/Alan Stonebraker

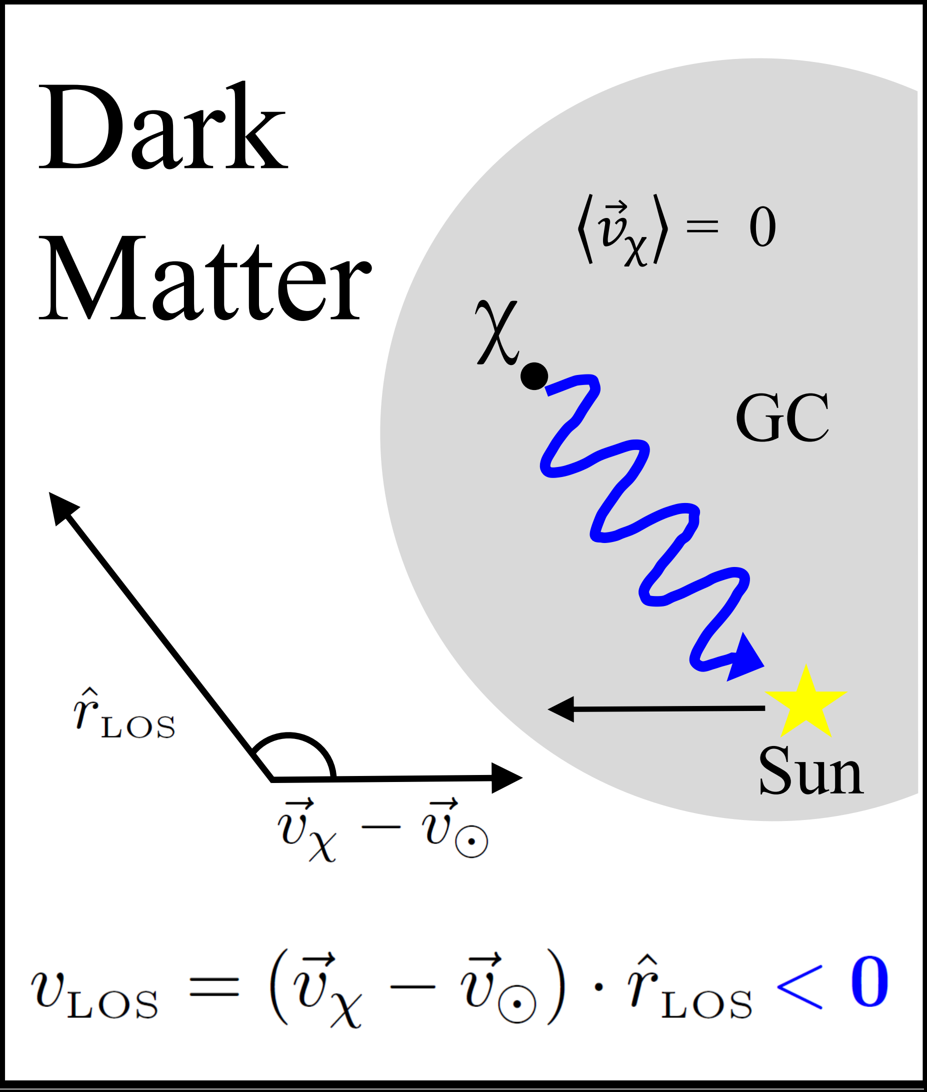
Milky Way Gas (Background)

- Gas and the Sun co-rotate in a disk
  - $V^2 \sim GM/r$
- Astro-physical line
  - Red shifted in + longitude!



Milky Way Dark Matter (signal)

- Velocity of the Sun
  - (+)220km/s, +longitude
- Mean dark matter velocity ~ 0
- DM line
  - Blue shifted for +longitude



Dark Matter Velocity Spectroscopy

- Need to model both line shifts and line widths

$$\frac{dF}{dE} = \frac{1}{4\pi}\frac{\Gamma}{m_\chi}\frac{dN}{dE}\int d\Omega \int d\ell \rho_\chi[r(\ell)]$$

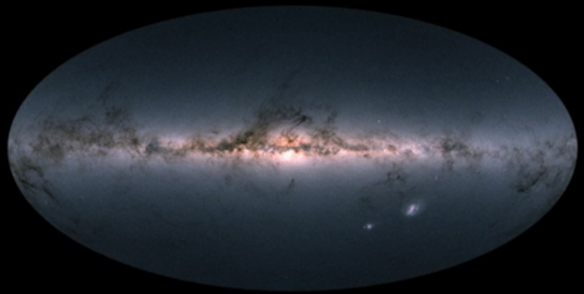
$$\frac{1}{R_\odot \rho_\odot}\int ds\, \rho_\chi(r[s,\psi])\,\frac{d\widetilde{N}(E-\delta E_{\rm MW}, r[s,\psi])}{dE}$$

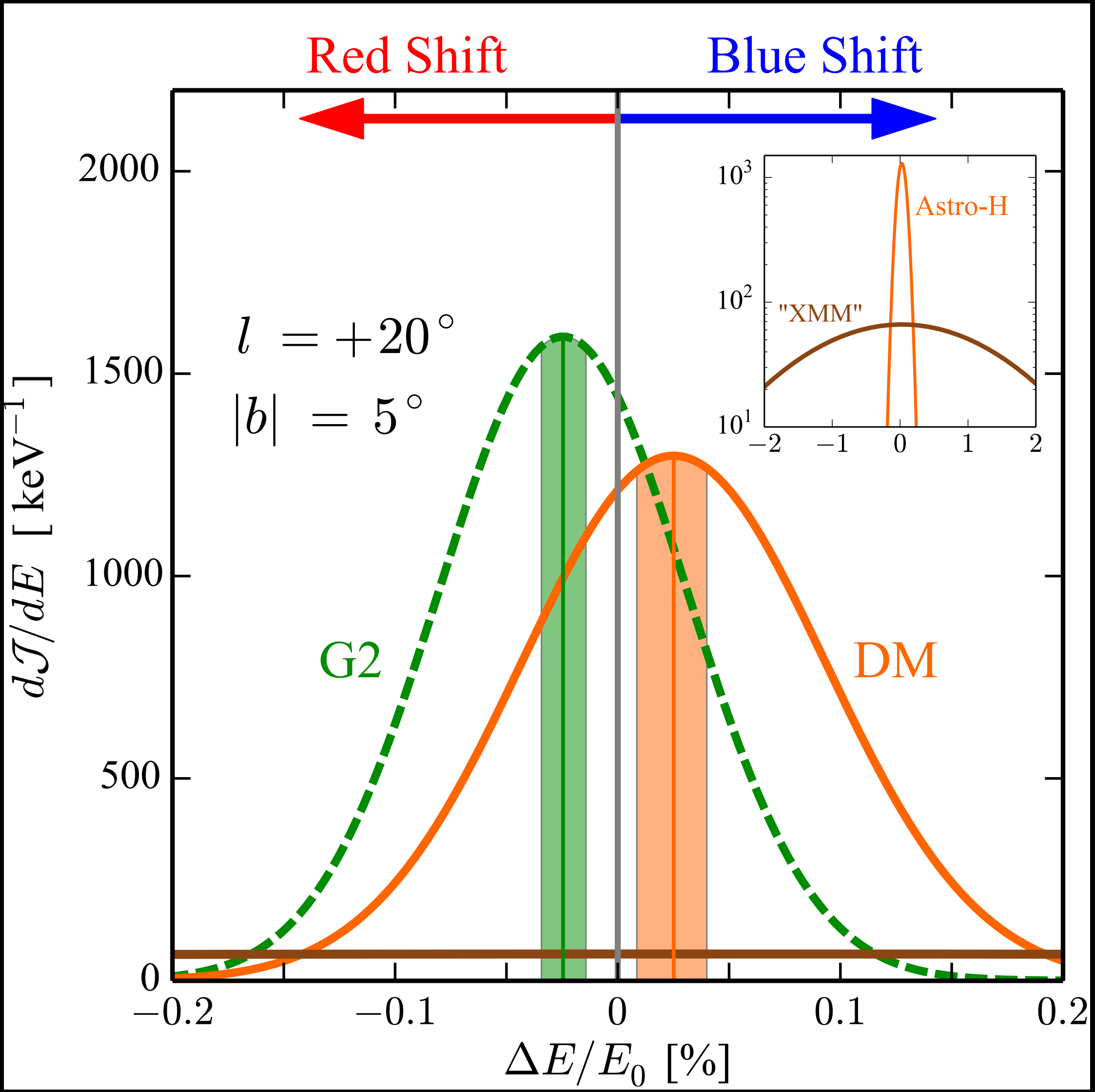
Line shift
Atomic tomography

Line dispersion
- MW Gravitational potential

Spectrum

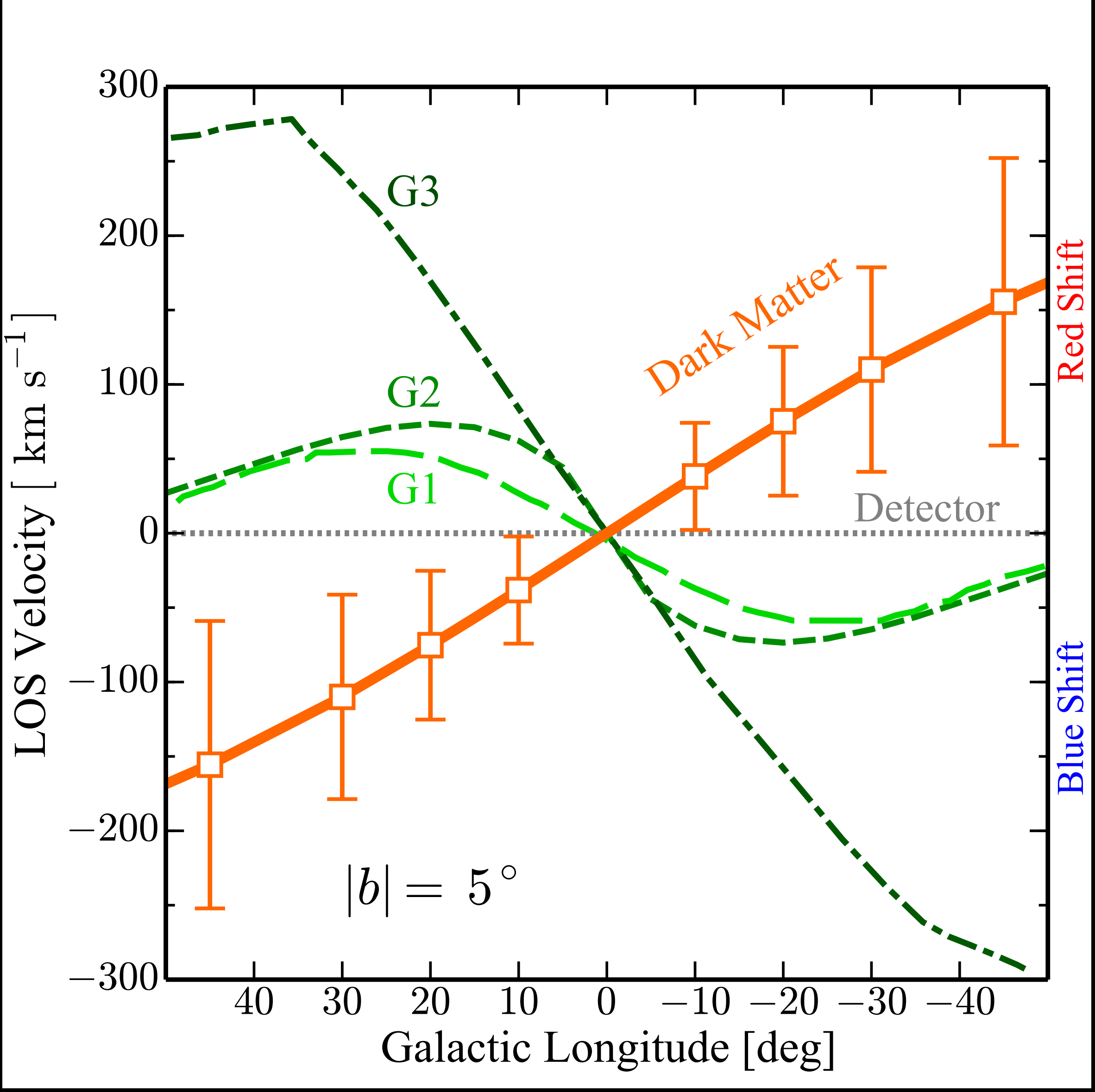
- 2Ms Astro-H observation
  - > 5 sigma detection
- Taken into account both intrinsic and detector line dispersion.





DM – Astro Separation (MW)

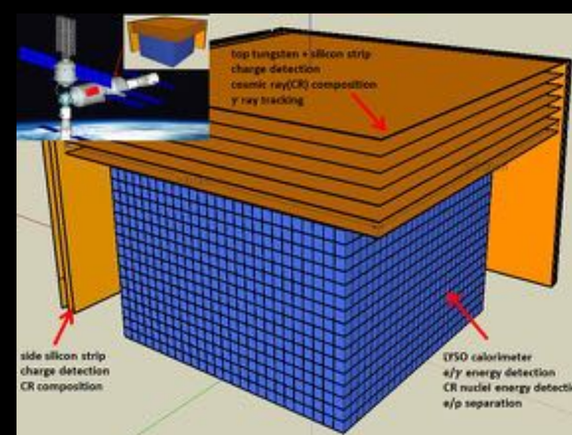
- Clean separation
  - DM
  - Astro
  - Detector effect
- Two obs. -> 3.6σ
- Minimal theoretical uncertainty



DM Velocity Spectroscopy

- Extra handle for testing line-like signal
  - The “smoking gun” sometimes is not enough

- If DM decay/annihilation produces a line.
  - HERD (GeV-TeV)
    - Photons and electrons
    - 2020?



- Dark astronomy/cosmology

A Series of Unfortunate Events……

NEWS IN FOCUS

The Japan Aerospace Exploration Agency is investigating the factors that led to Hitomi's demise.

ASTRONOMY

Software error doomed Japanese Hitomi spacecraft

Space agency declares the astronomy satellite a loss.

18 | NATURE | VOL 533 | 5 MAY 2016

A new Mission!

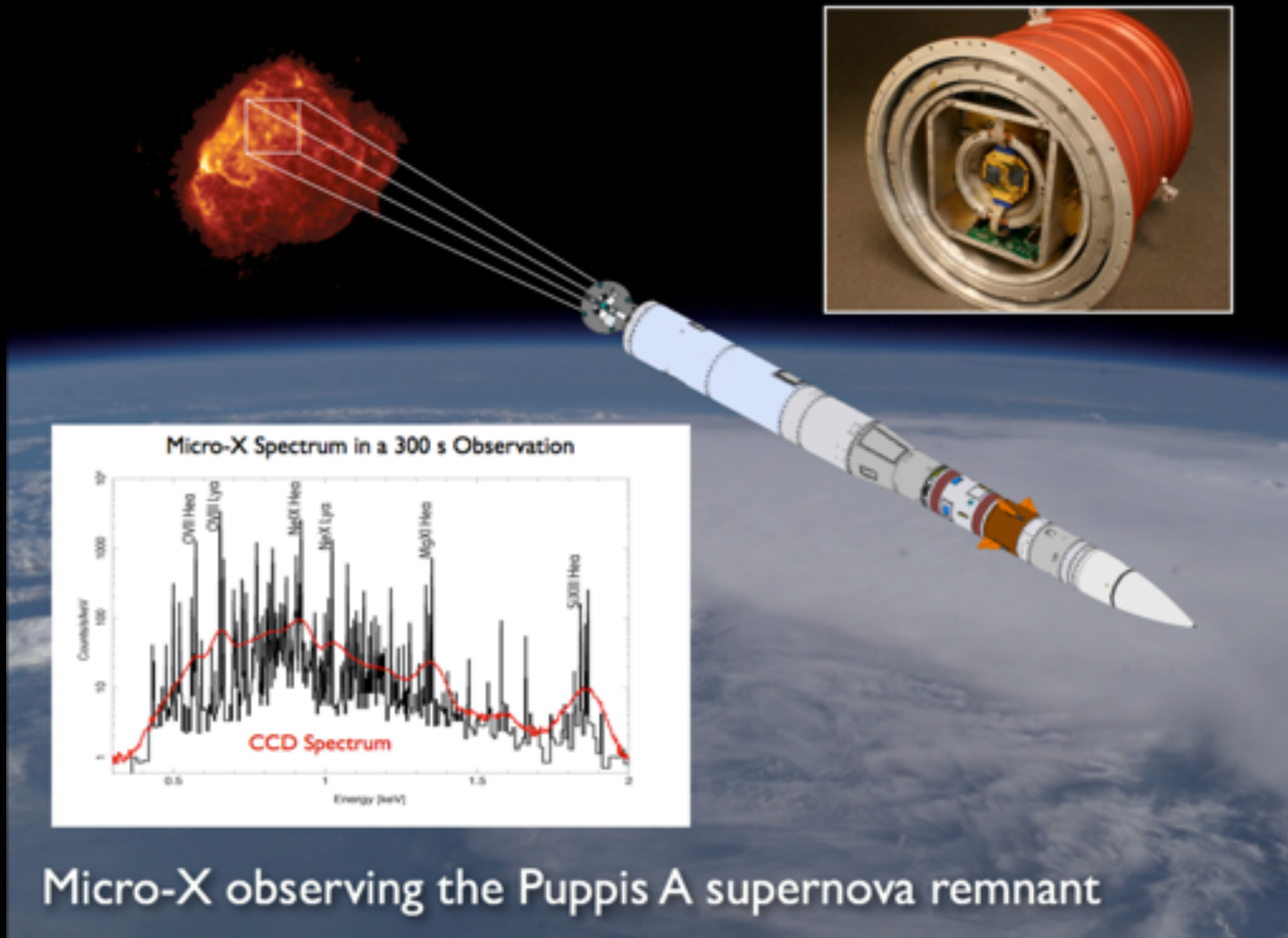
- Two detectors
- 2020-2021?

The XRISM project initiated by JAXA

JAXA has established the project team for X-Ray Imaging and Spectroscopy Mission (XRISM, p
spectroscopy capability of ASTRO-H, which had been in preparation under the name X-ray Astro
held in June, JAXA confirmed that all aspects of project implementation, including the managem
mitigation system are all satisfactory, and that the necessary countermeasures for the ASTRO-H
project team dated 2018 July 1.

XRISM is scheduled for launch during the Japanese Fiscal Year 2020 (April 2020-March 2021).

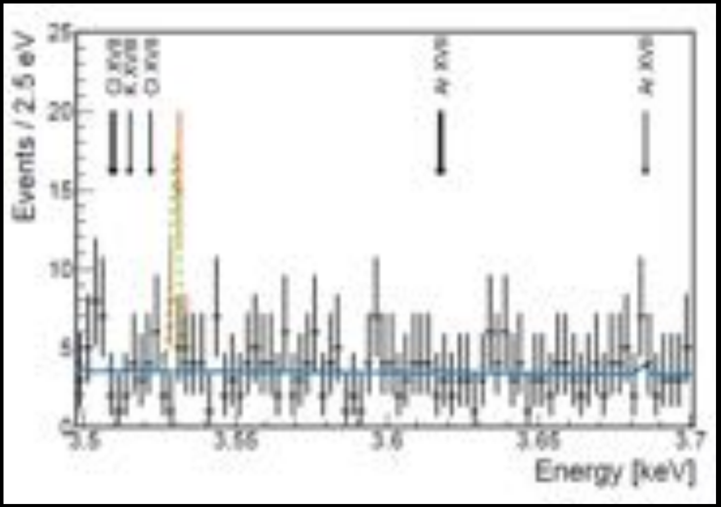
Sounding rocket (XQC, Micro-X)



http://space.mit.edu/micro-x/open-house/files/Micro-X-Pup-A-2.png

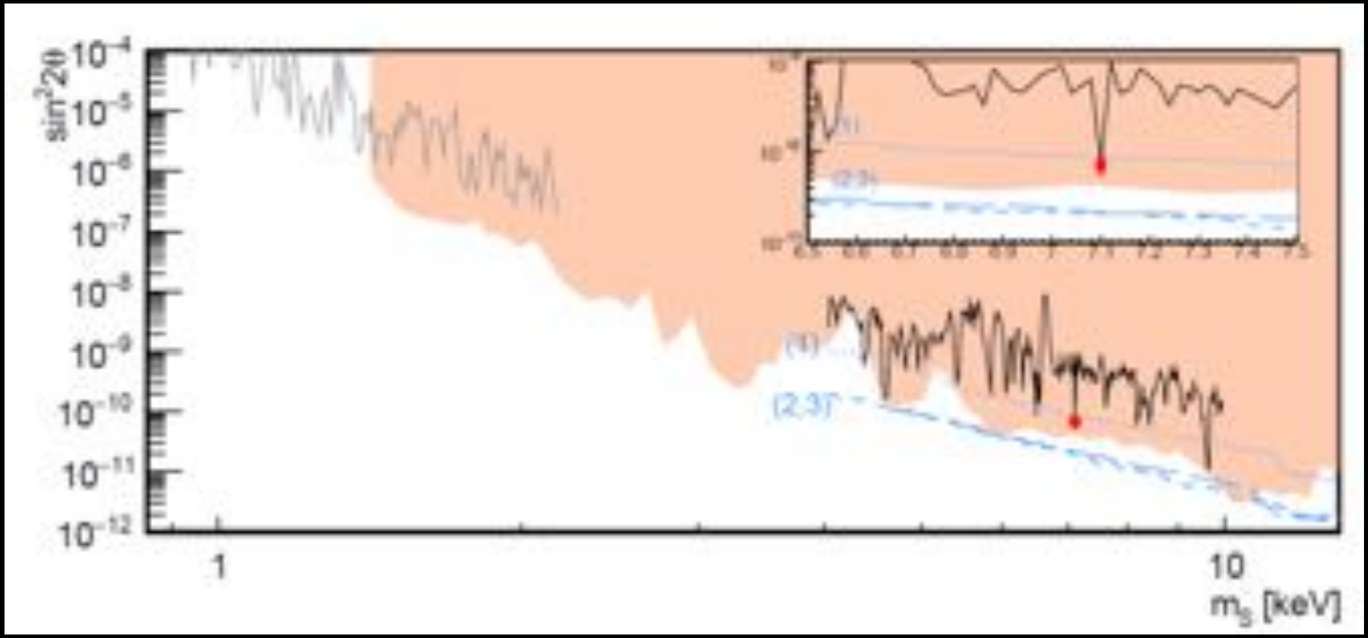
Sounding Rockets

- XQC (2011, 106s)
- Micro-X
  - Will likely detect the line!



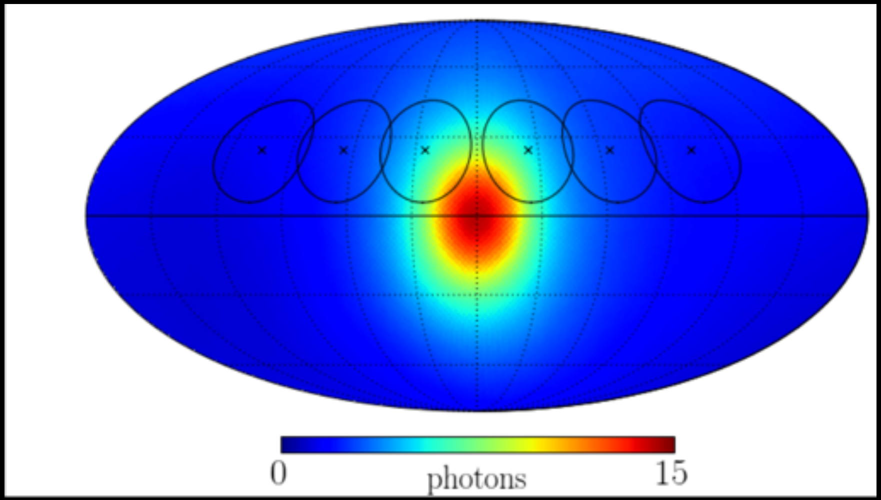
Mock Data

Figueroa-Feliciano+ [1506.05519]

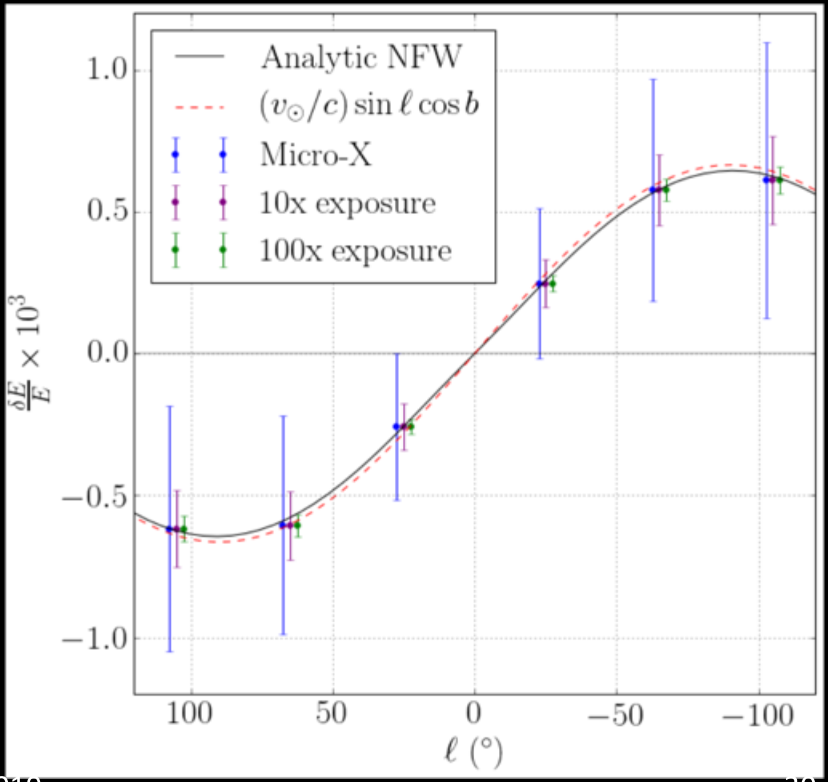


Velocity Spectroscopy with Micro-X?

- Wide FOV



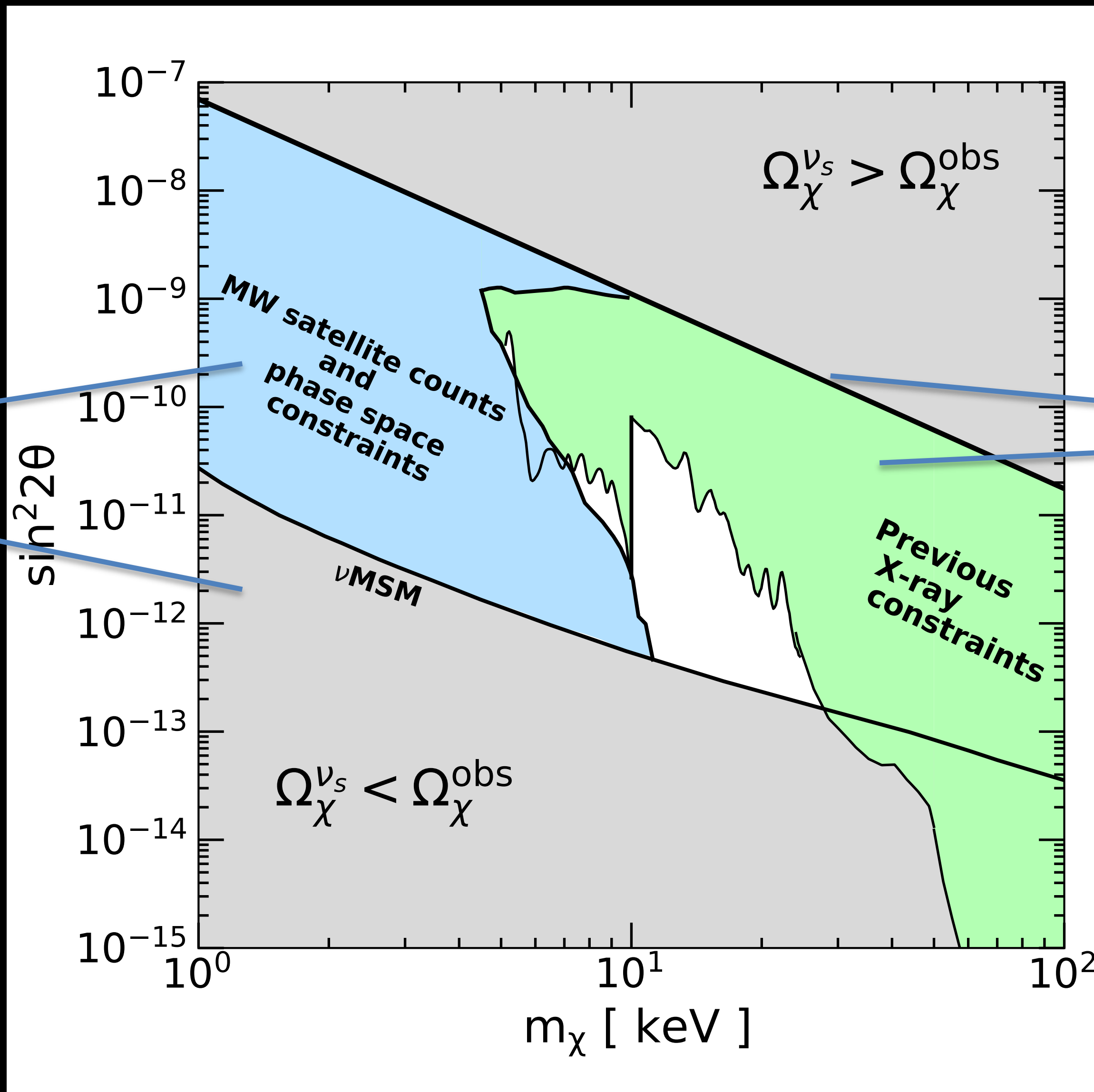
1611.02714
Powell, Laha, KCYN, Abel



- Tested with Nbody simulation
  - Micro-X
  - 6 obs, >3σ

- Looks promising!

Sterile Neutrino Dark Matter



Model Dependent (nuMSM)

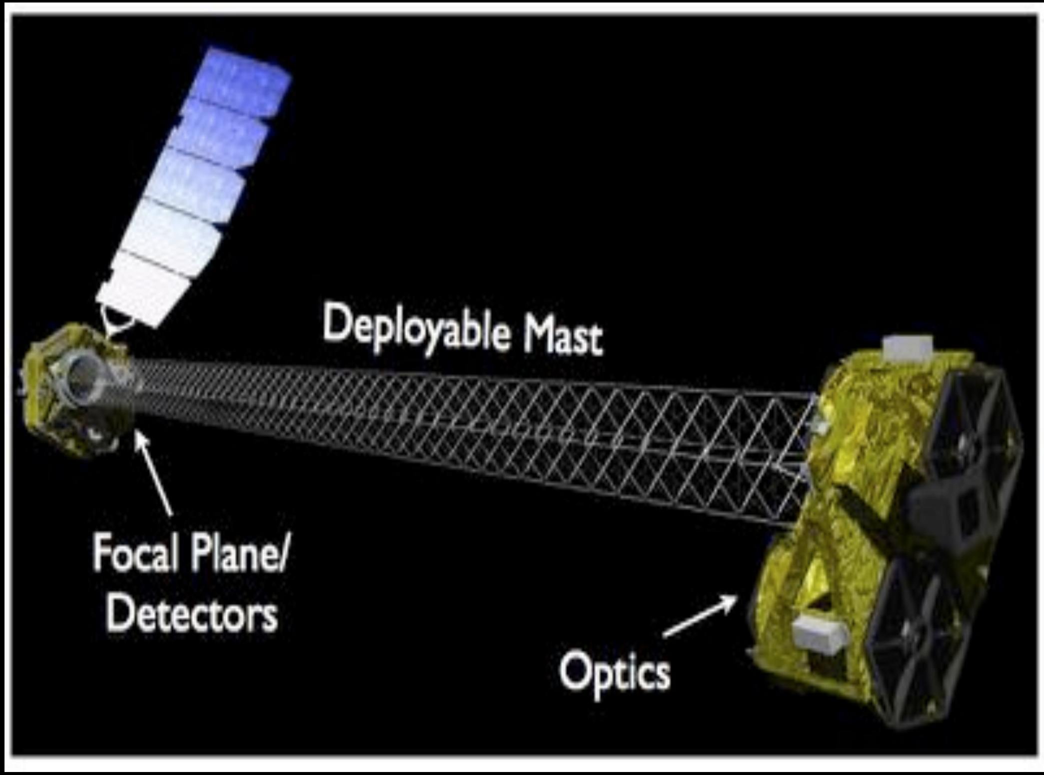
Model Independent

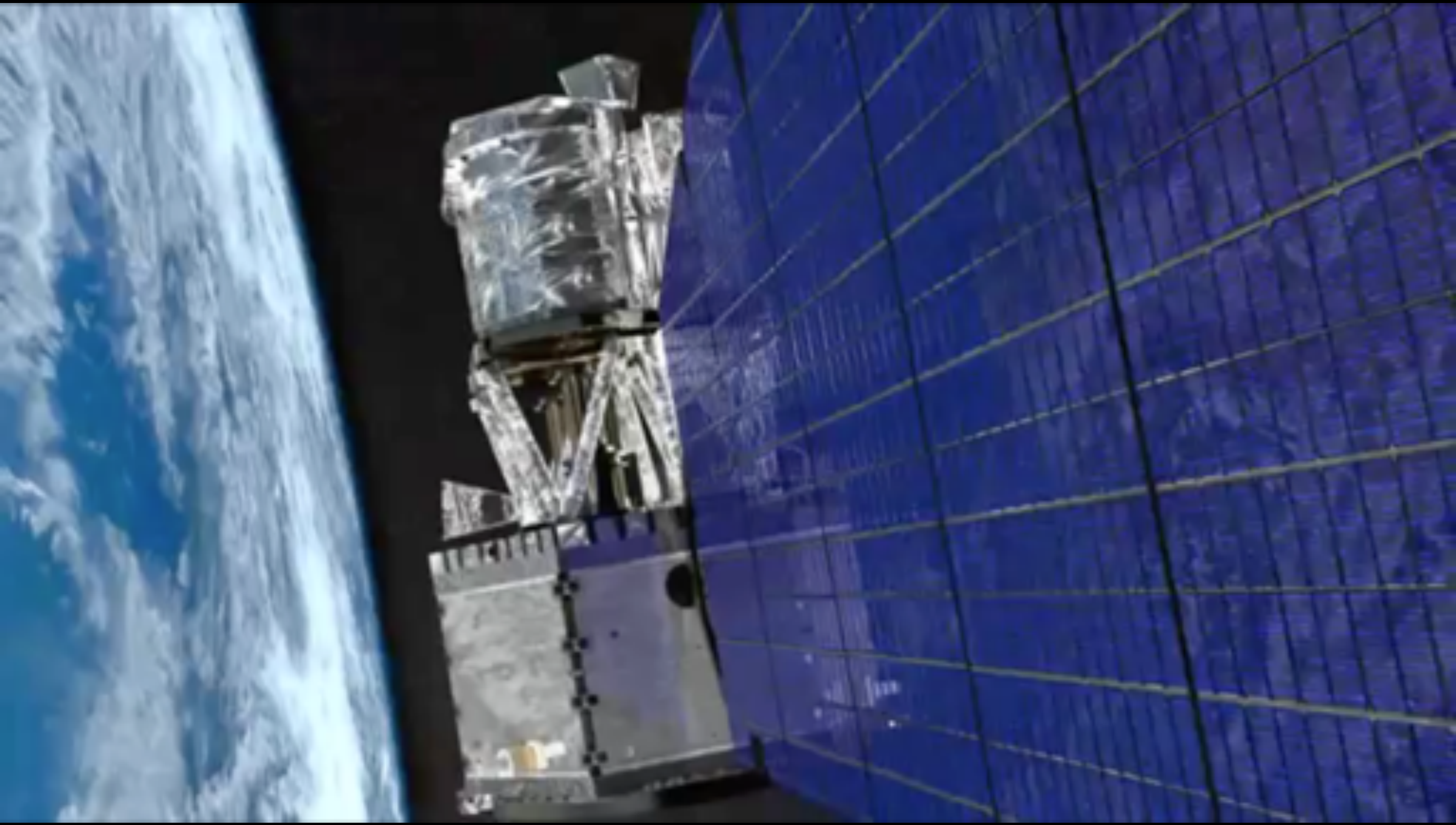
Not applicable in, e.g.
0711.4646 Petraki, Kusenko,
1507.01977 Patwardhan et al
Etc etc

NuSTAR

- **Nu**clear **S**pectroscopic **T**elescope **Ar**ray

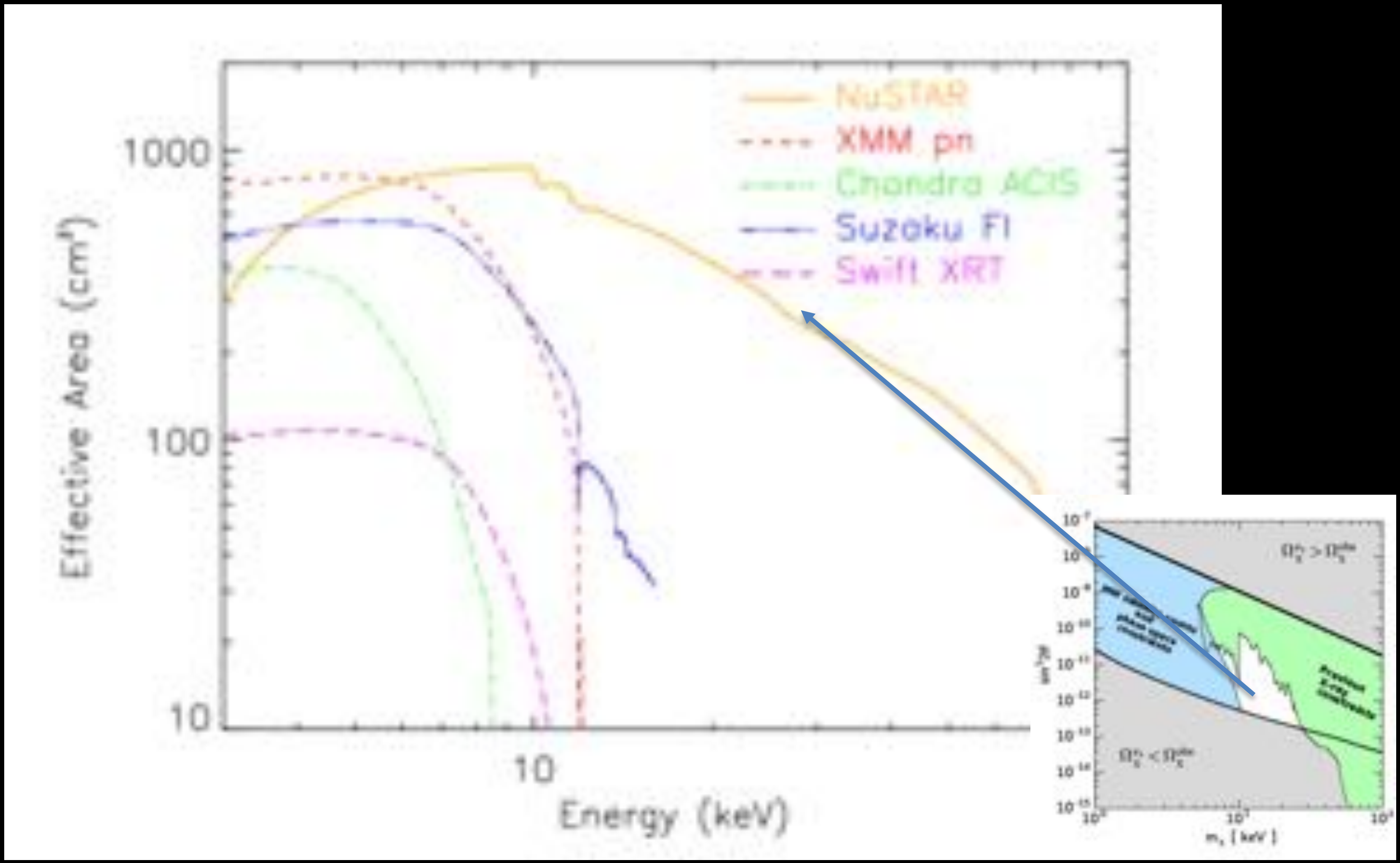
- Neronov, Malyshev, Eckert [1607.07328]
  - Diffuse sky, MW halo
- Perez, KCYN, Beacom, Hersh, Horiuchi, Krivonos [1609.00667]
  - Galactic Center





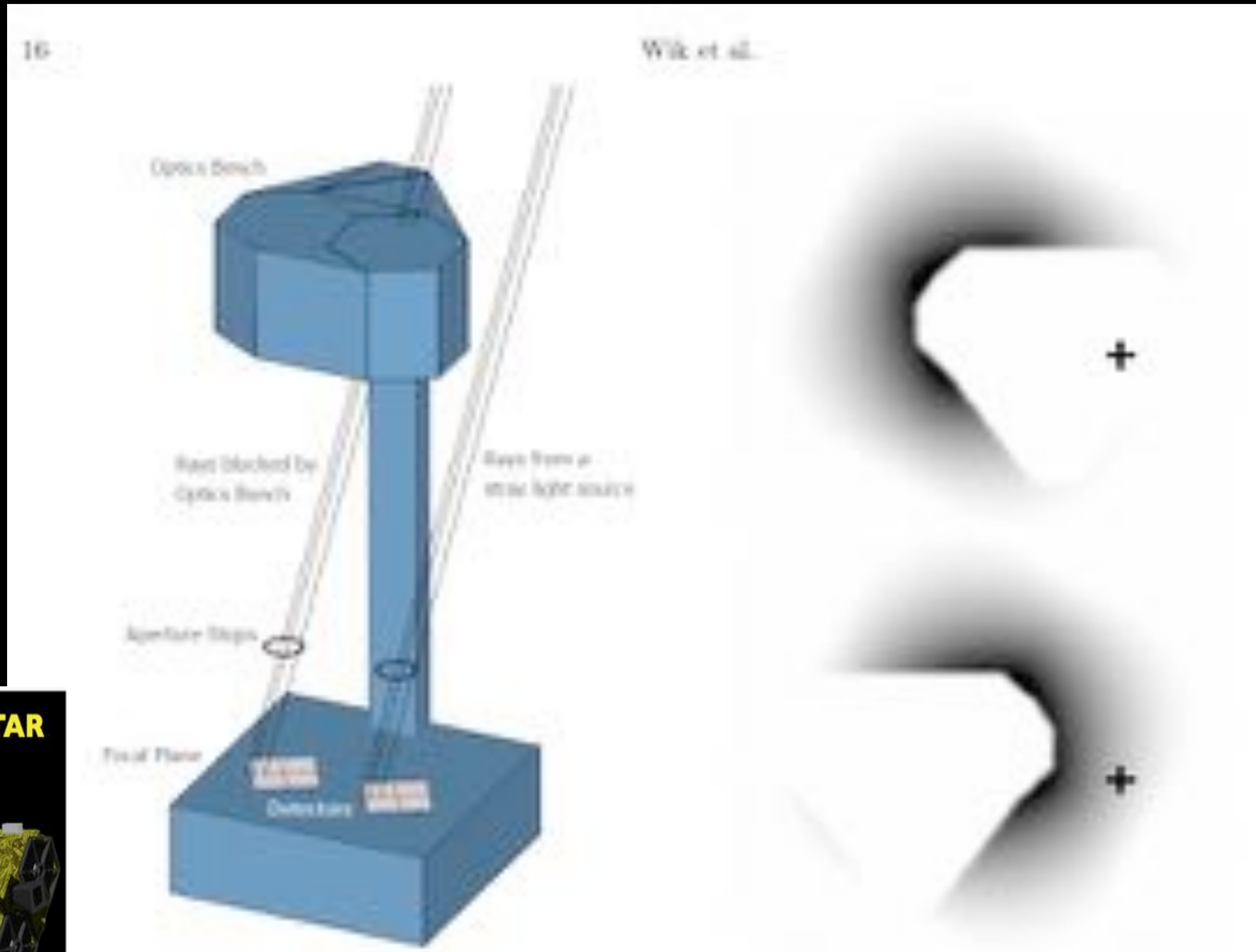
NuSTAR

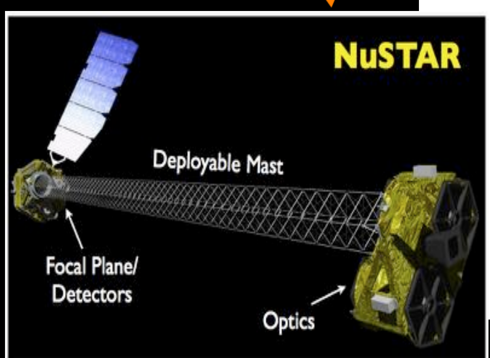
- Focusing observations



Zero Bounce Photons

- 500cm2
  -> 10cm2
- 0.1deg
  -> 2deg
- Diffuse Dark Matter ✓

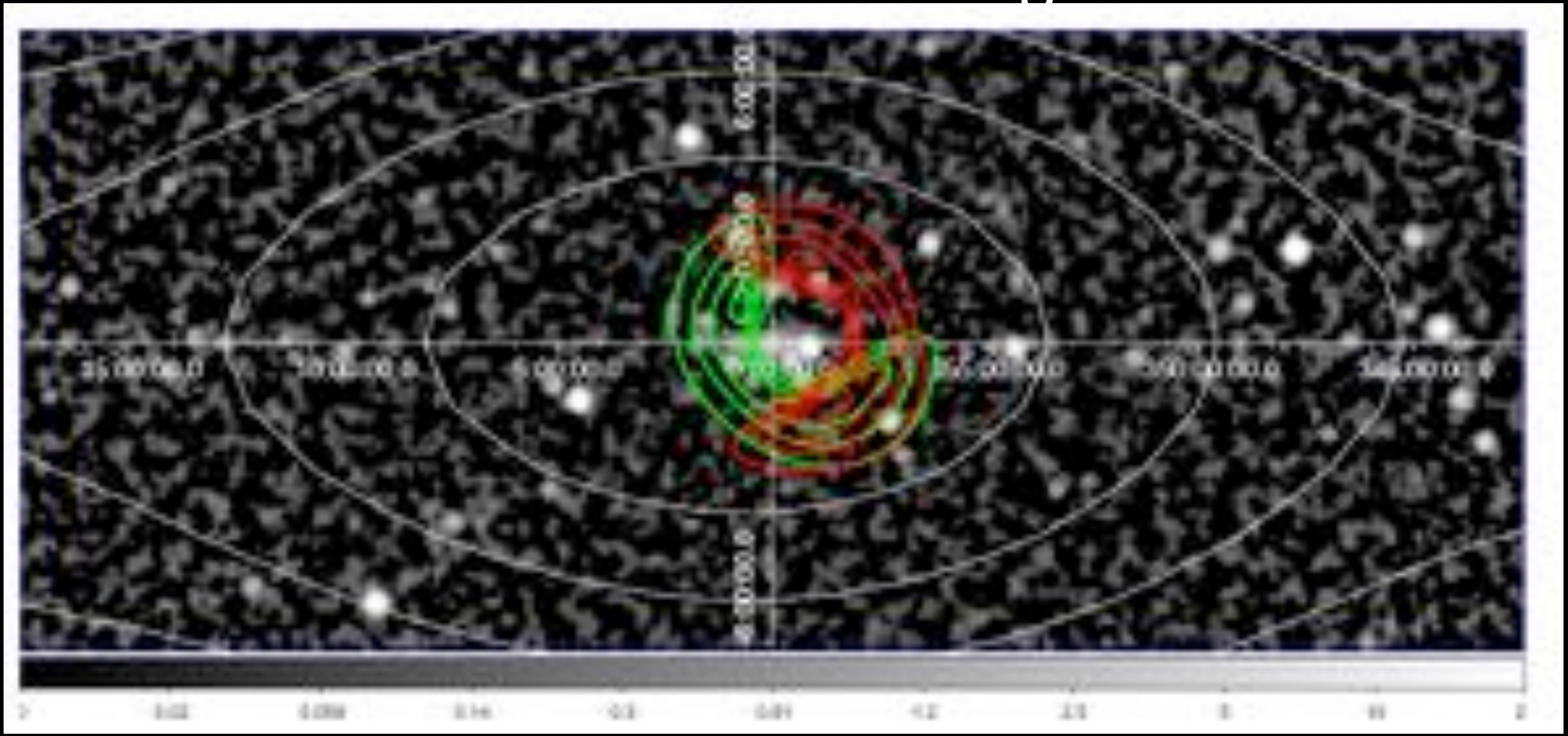




NuSTAR MW GC Observation

Perez, KCYN, Beacom, Hersh, Horiuchi, Krivonos 2016 (1609.00667)

- 6 observations ~ 0.5Ms combining two detectors

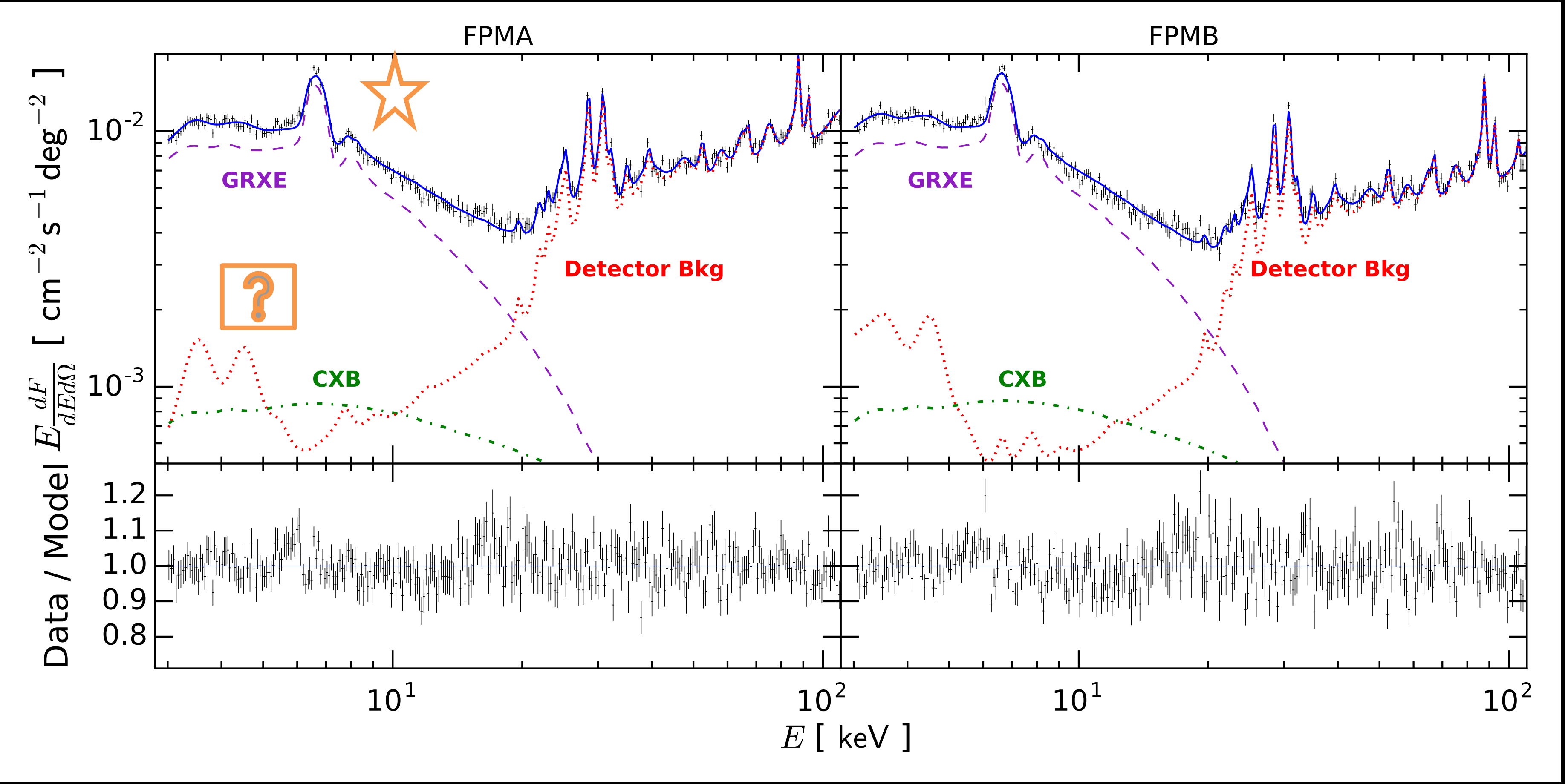


Perez+ 2016

Spectra

- A + B detector

Perez+ 2016



NuSTAR Background Model?

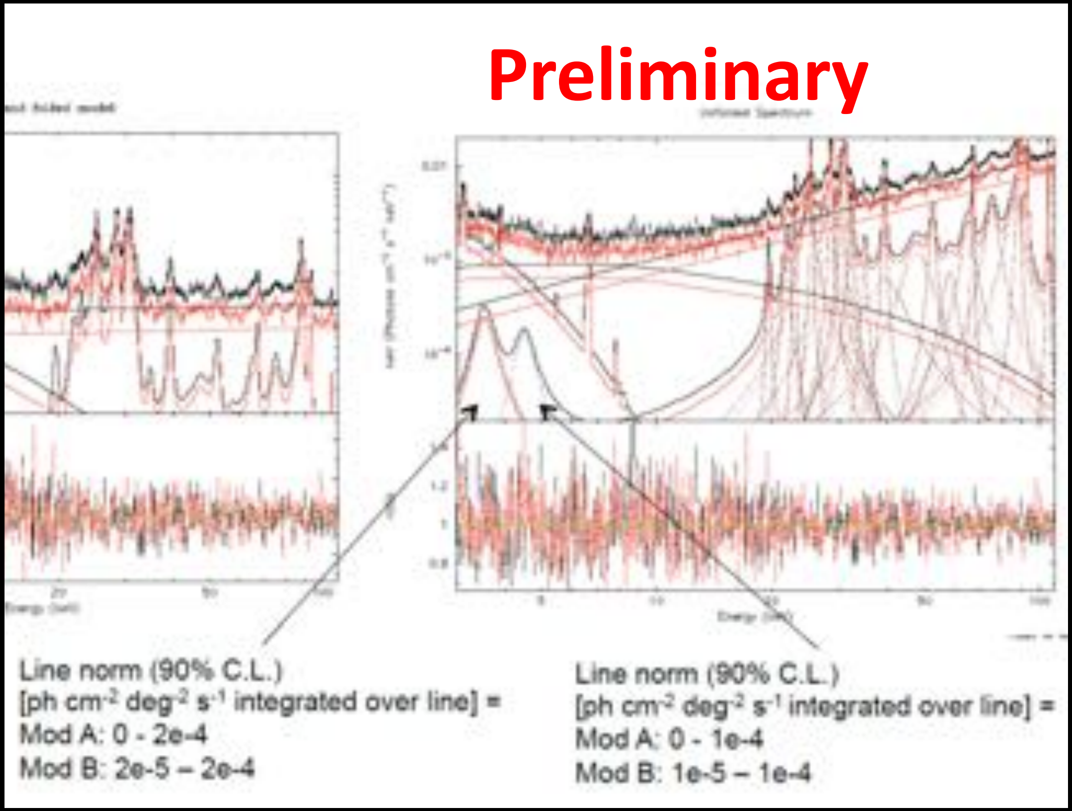
- Default background model from Wik et al 2014
- Phenomenological model

Neronov+ 2016

Line energy, keV	Significance σ	Width, keV	F, 10^{-6} cts/cm^2/s	F [illegible], 10^{-6} cts/cm^2/s	Sun?	Ghost?	Comments
$3.51^* \pm 0.02$	11.1	0.08 ± 0.05	7.7 ± 1.3	10 ± 2.5			lower edge of sensitivity band
$4.46^* \pm 0.05$	15.7	0.12 ± 0.03	5.9 ± 0.5	3.7 ± 0.5	Y		Ti $K\alpha$
$4.7^* \pm 0.1$	9.8	0.6 ± 0.1	8.9 ± 1.8	8.2 ± 1.9			
6.32 ± 0.08	6.7	0.	1.2 ± 0.2	0.66 ± 0.23	Y		Fe $K\alpha$?
7.96 ± 0.06	4.0	0.	0.5 ± 0.1	0.23 ± 0.18	Y		Cu $K\alpha$?
$10.44^* \pm 0.05$	8.9	0.2 ± 0.05	1.4 ± 0.2	1.7 ± 0.3			W L-edge residuals [50]
14.2 ± 0.1	3.3	0.	0.51 ± 0.18	0.6 ± 0.2			Sr $K\alpha$?
14.75 ± 0.05	5.9	0.	0.9 ± 0.2	1.0 ± 0.2		Y?	23 keV ghost?
15.7 ± 0.1	3.7	0.	0.57 ± 0.16	0.6 ± 0.2		Y?	24.5 keV ghost, Zr $K\alpha$?
16.7 ± 0.1	5.5	0.	0.9 ± 0.2	1.2 ± 0.2		Y?	25.3 keV ghost, Nb $K\alpha$?
$19.66^* \pm 0.06$	9.3	0.06 ± 0.14	1.3 ± 0.3	1.3 ± 0.3		Y?	28.5 keV ghost?

Checking 3.5 keV in more detail

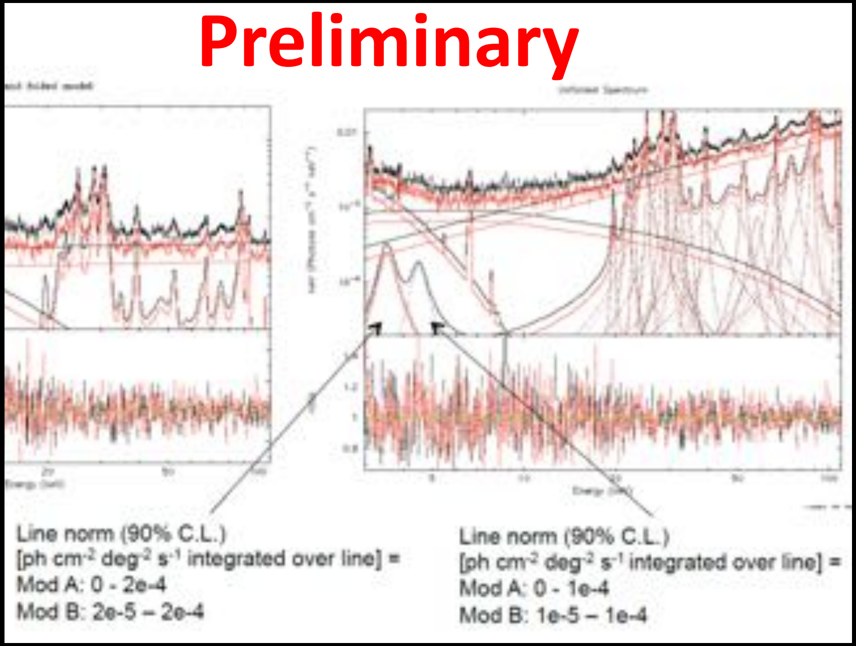
- Occulted data in GC obs (Earth blocked)



- Not as significant (less statistic)
- Flux consistent

3.5 keV in NuSTAR

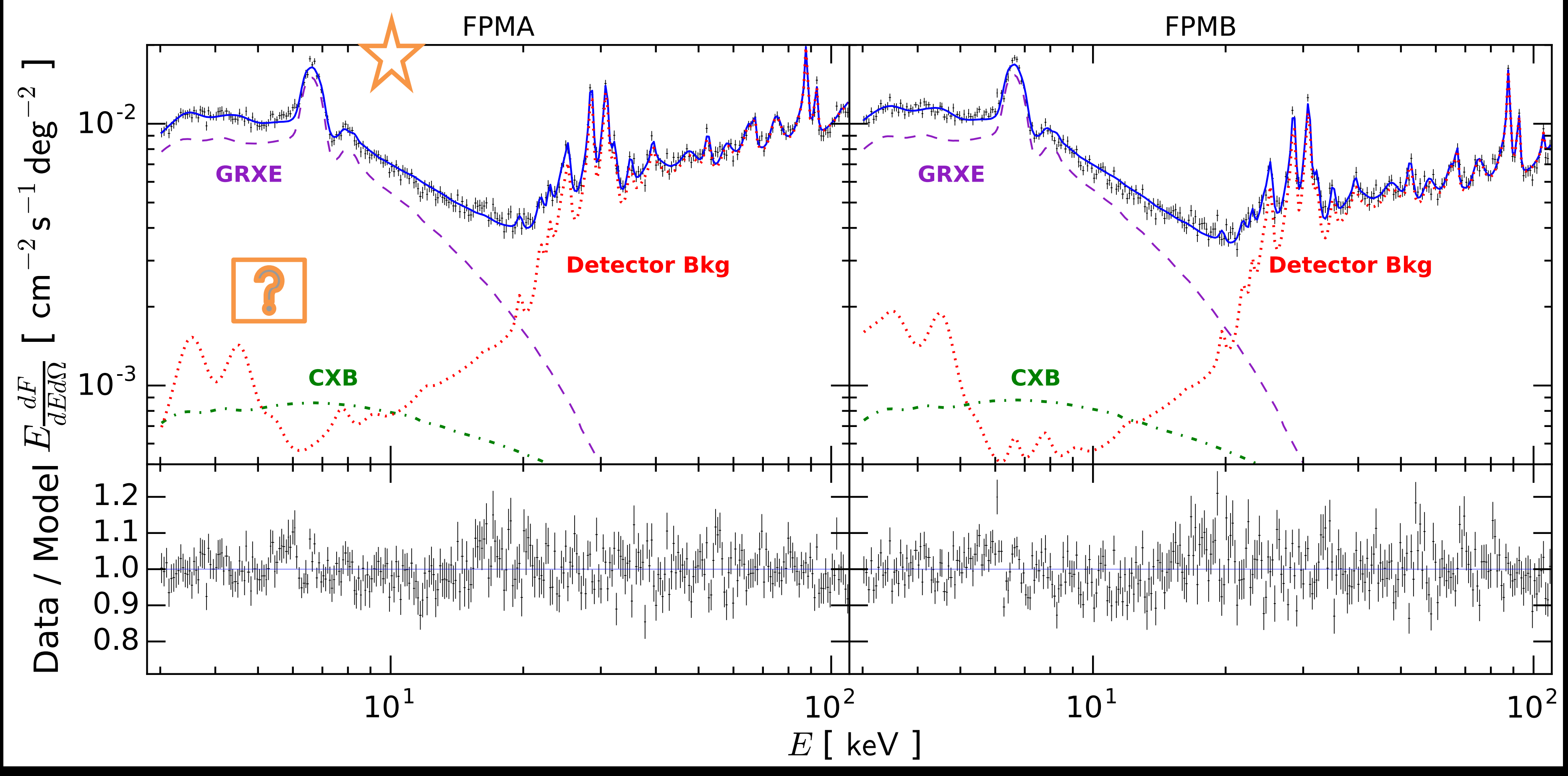
- Work in progress
- But this suggest:
  - Detector artifact
  - Detector emission
  - Maybe Solar
- Not sure about the other instruments
  - Very different detector design!



Spectra

- A + B detector

Perez+ 2016

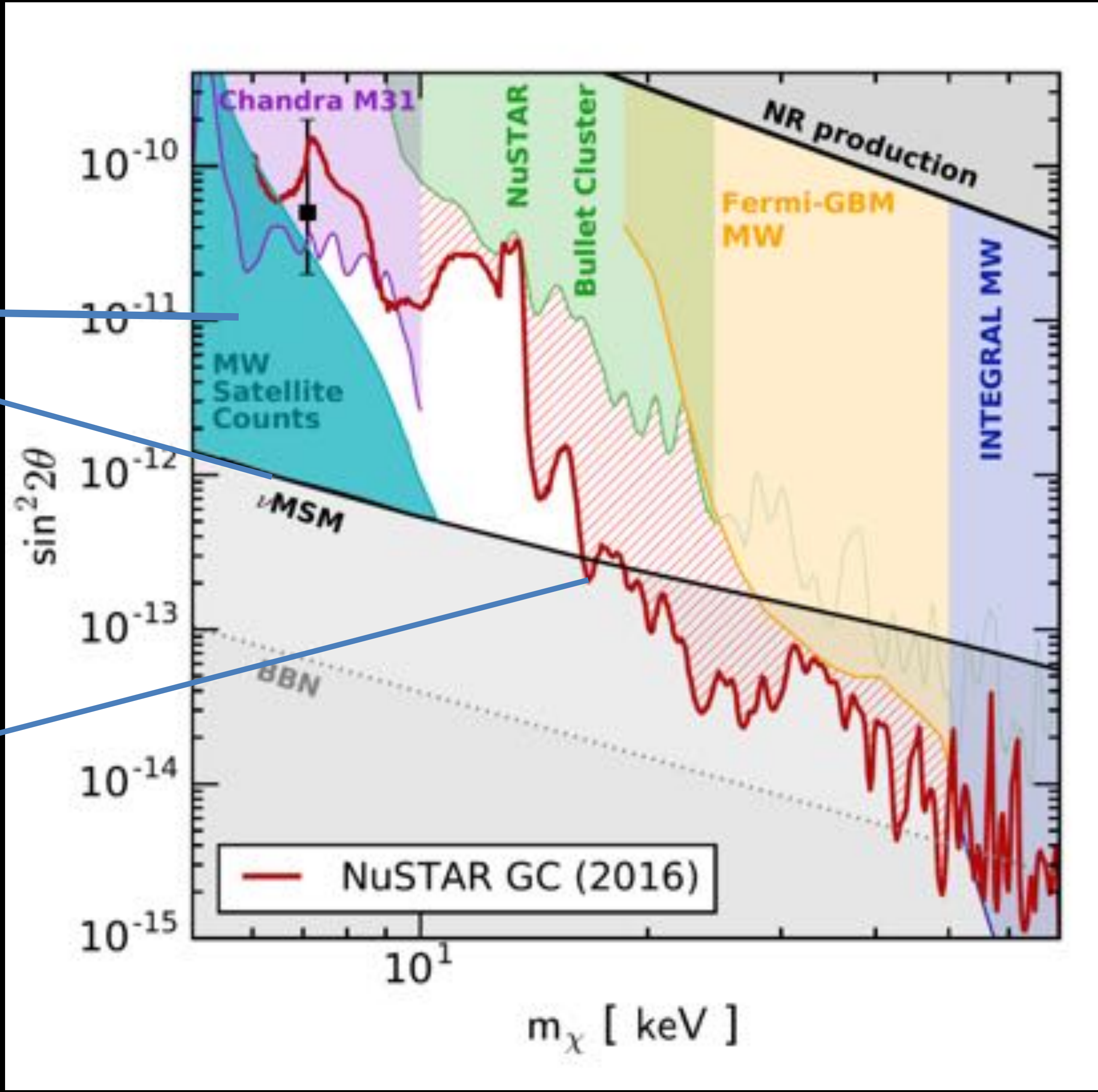


Dark Matter Limit

Perez+ 2016

Resonantly produced Sterile Neutrino Dark Matter in nuMSM

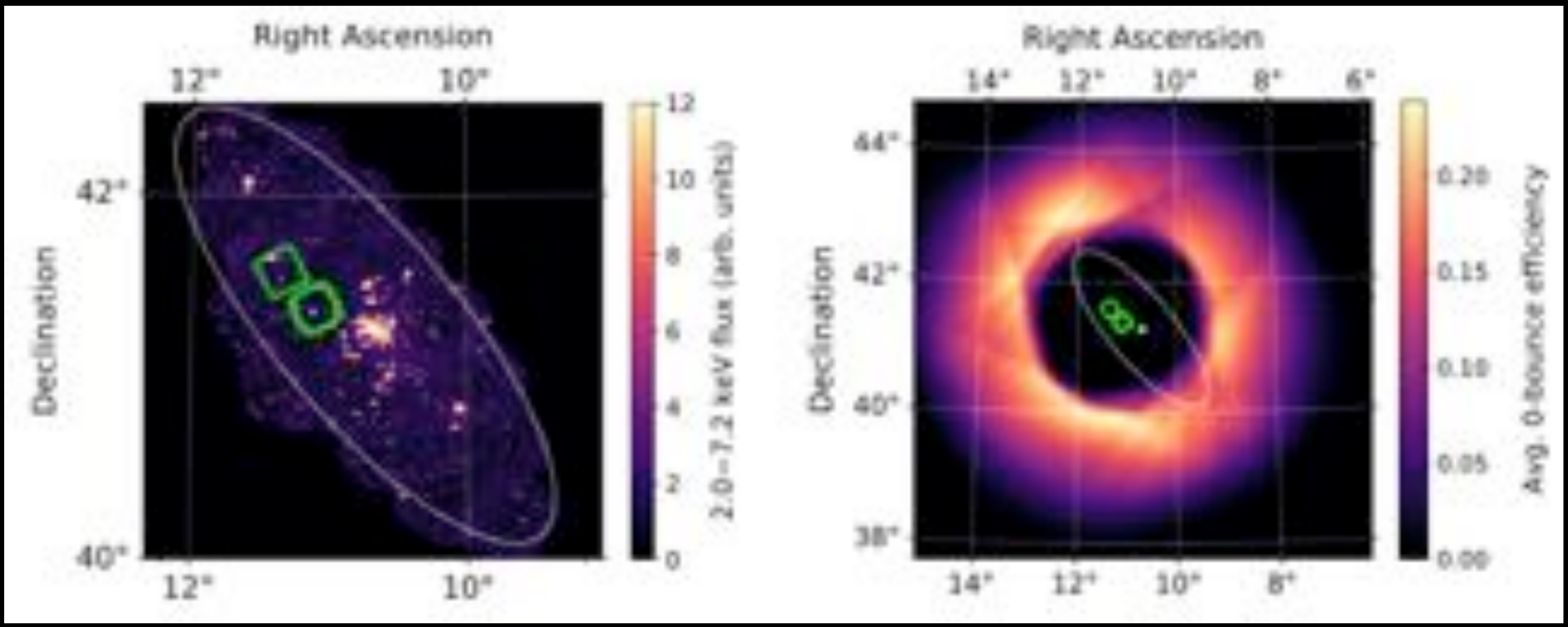
Strong limits above ~10keV



NuSTAR Andromeda

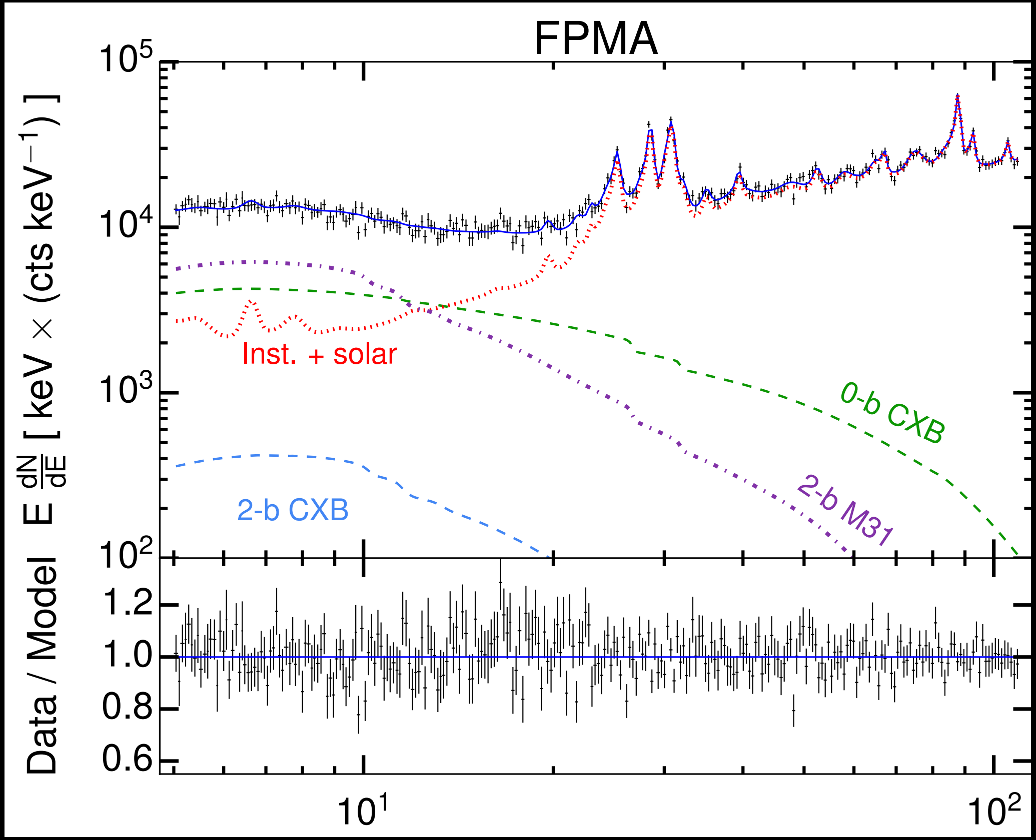
- 8 observations
- 1.2 Ms (A + B module)

KCYN, Roach, Perez, Beacom, Horiuchi, Krivonos, Wik
1901.01262



NuSTAR M31 Spectrum

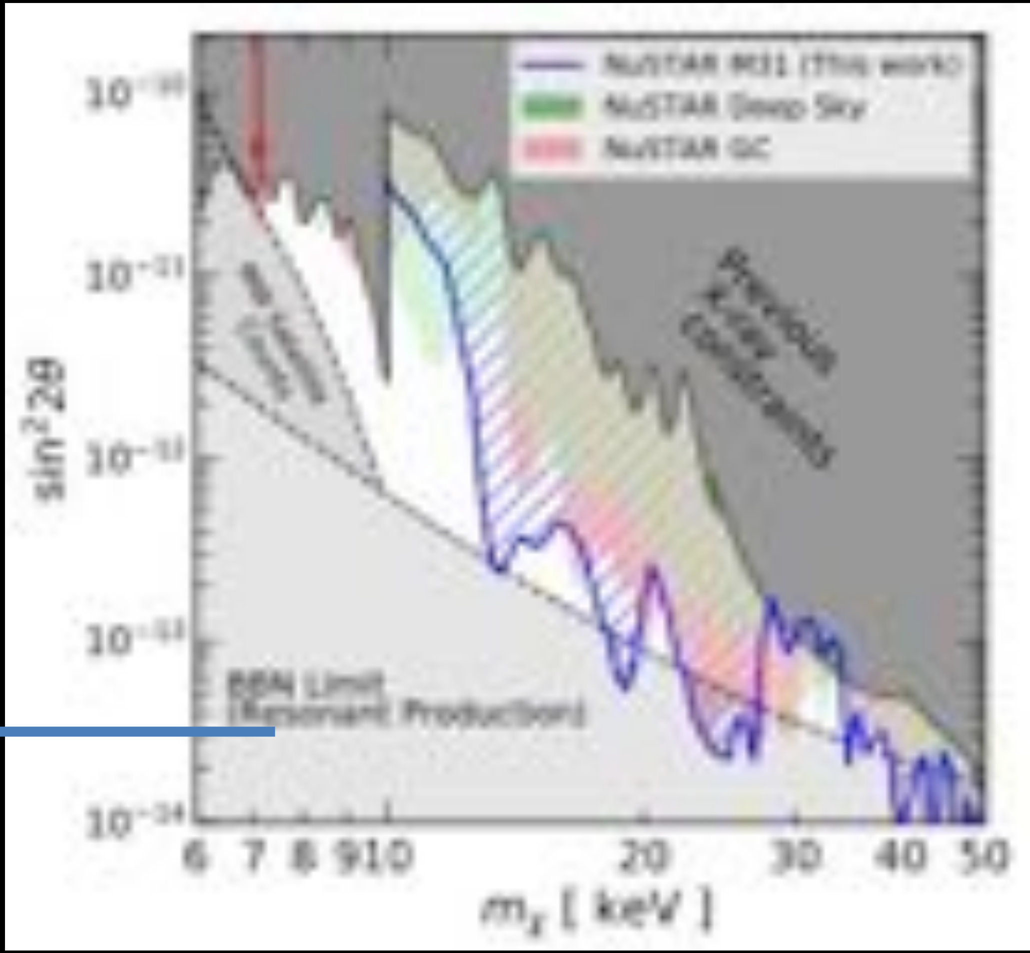
- 0-bounce + 2 bounce!
  - 1.5x (decay) – 2.5x (ann.) signal boost
- > 5keV
  - Understanding the low energy background (in prep.)
- Lower astrophysical background
- Statistically combined (not stacked)



NuSTAR M31 Constraints

- Closing in the nuMSM window
  - ~ 13keV
  - New production method for SnuDM

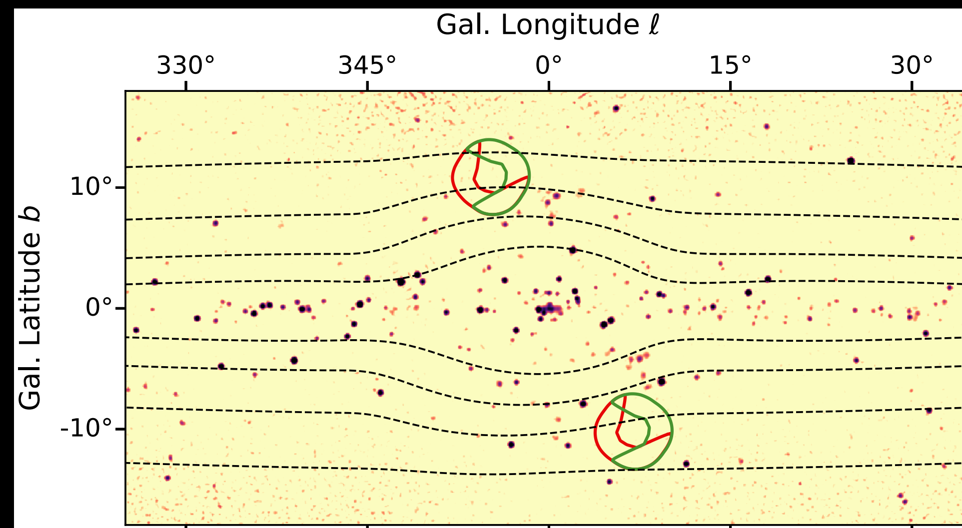
- Updated production computation
  - Venumadhav et al. 2016

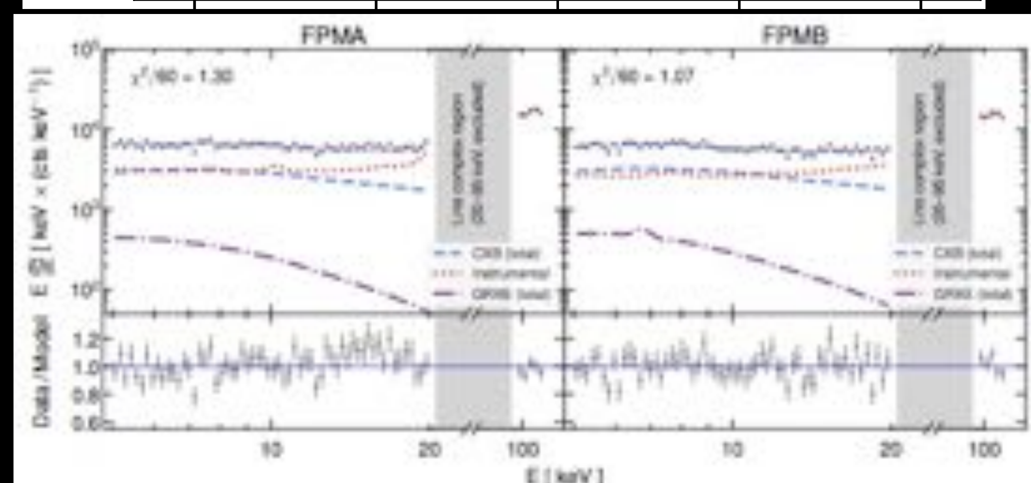


NuSTAR Galactic Bulge analysis

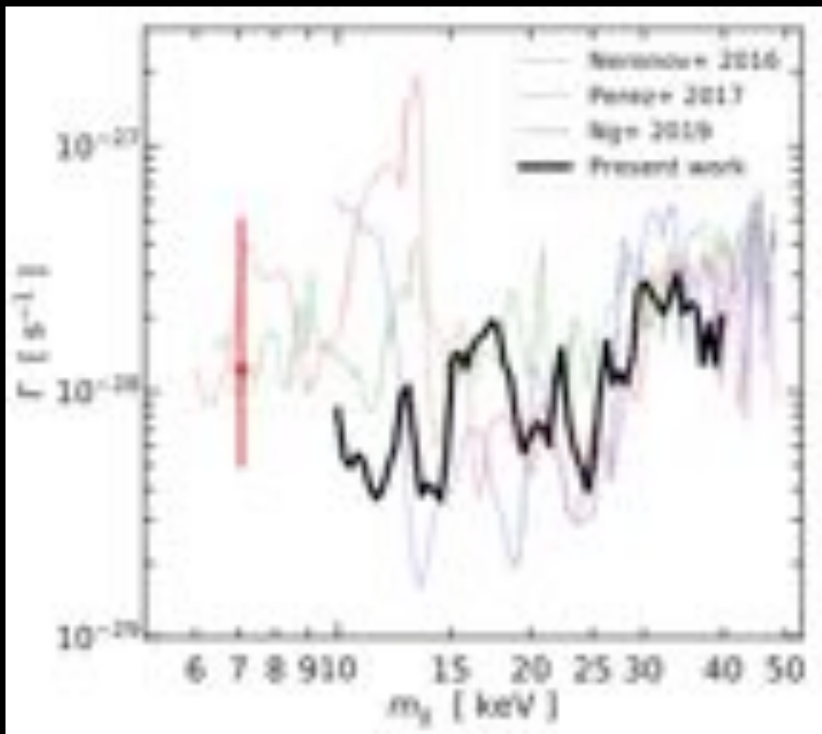
Galactic Center: Perez, KCYN, Beacom, Hersh, Horiuchi, Krivonos (1609.00667)
M31: KCYN, Roach, Perez, Beacom, Horiuchi, Krivonos, Wik (1901.01262)
Galactic bulge: Roach, KCYN, Perez, Beacom, Horiuchi, Krivonos, Wik (1908.09037)

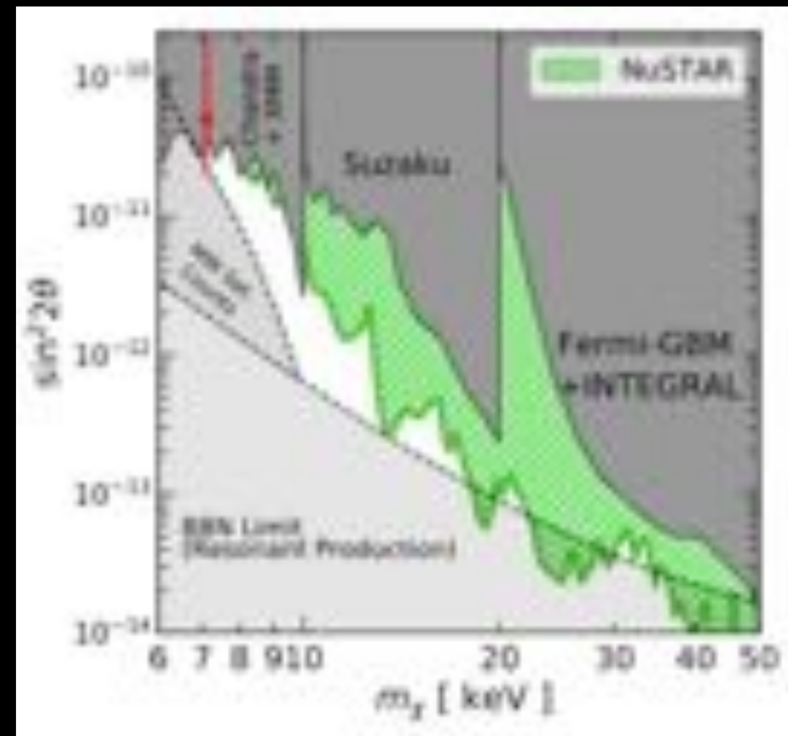
- Two dedicated observations
  - ~200ks
- Large J-factor
- Small Background
- ***>5 keV***
  - ***10 keV DM mass***





Closing the window with NuSTAR





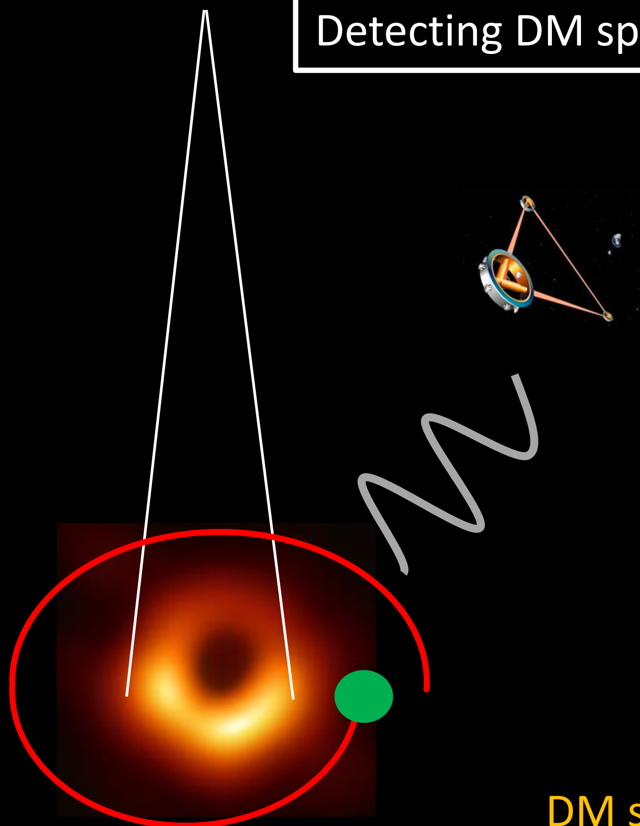
Roach+ 1908.09037

- More observations
- Include 3--5 keV data?
  - Testing the 3.5 keV line

A new window to the Universe: Gravitational Waves!

- Extreme Mass Ratio Inspirals (EMRI)

Dark Matter "Spike" Gondolo Silk PRL 1999
Detecting DM spike with GW: Eda+ 2013, 2014



EHT

$$V_{\rm fermi} \leq V_{\rm escape}$$

$$\left(\frac{6\,\pi^2 \hbar^3 \rho}{m^4 g}\right)^{1/3} \leq \sqrt{\frac{2\,G\,(M_{BH}+M_\chi)}{R}}$$

$$m_\chi \geq 30\ \text{keV} \left(\frac{\rho}{10^{20}\ \text{GeV/cm}^3}\right)^{1/4} \times (R/20M_{BH})$$

Hannuksela, ***KCYN***, Li
1906.11845

DM spikes are not compatible with keV fermionic DM

Conclusion

- Jury is still out for the 3.5 keV line.

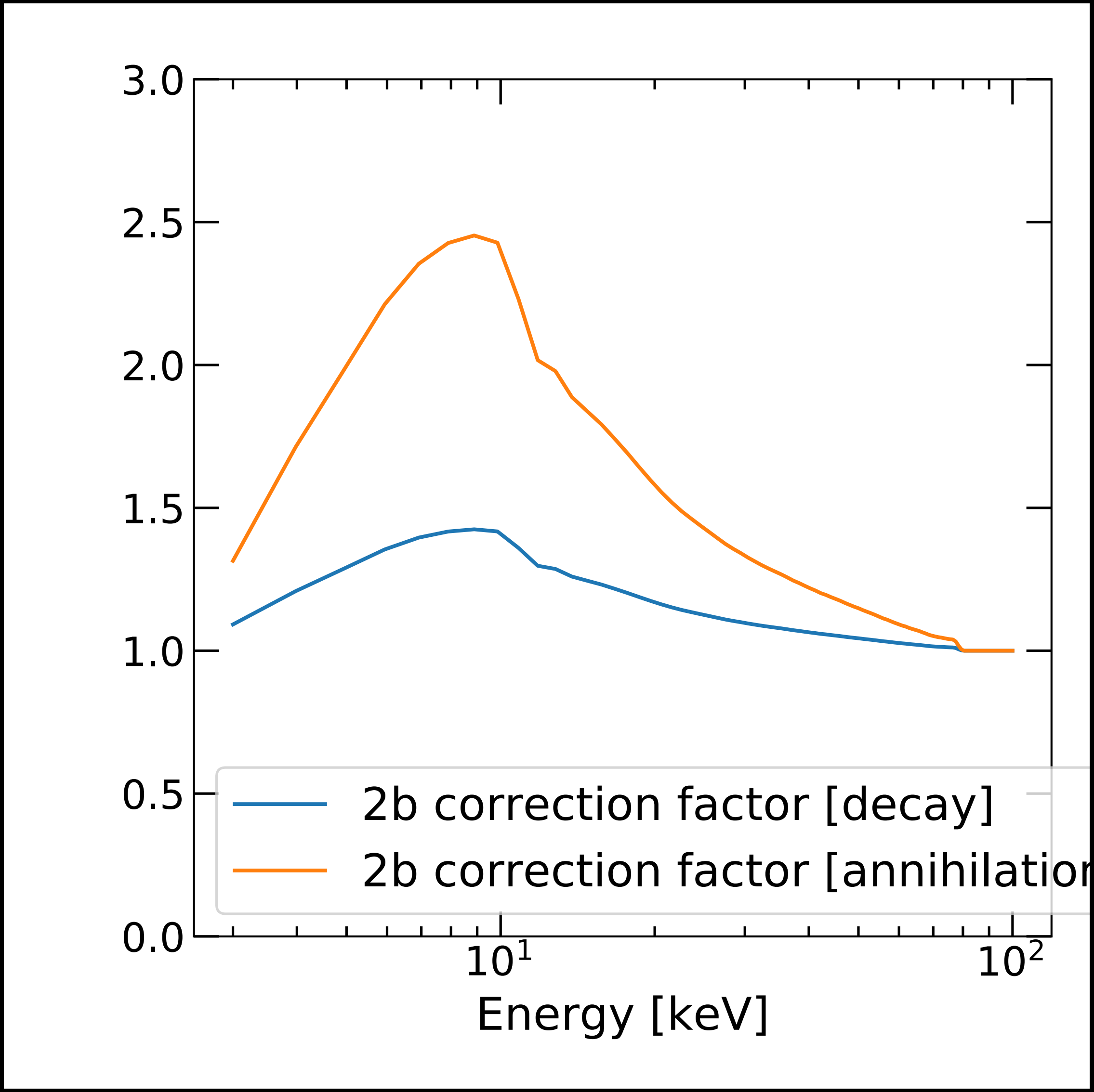
- New Hitomi (maybe 2021)
  - Apply Velocity Spectroscopy
- Micro-X (1 flight launched Jul 2018)
- NuSTAR may be surprisingly powerful at 3.5keV
  - Or maybe not
- NuMSM under siege

- Athena (~ 2029) ……

Thanks you!

Back ups

Correction factor



NuSTAR

- Focusing observations

TABLE 2
KEY OBSERVATORY PERFORMANCE PARAMETERS.

Parameter	Value
Energy range	3 – 78.4 keV
Angular resolution (HPD)	58″
Angular resolution (FWHM)	18″
FoV (50% resp.) at 10 keV	10′
FoV (50% resp.) at 68 keV	6′
Sensitivity (6 – 10 keV) [10^6 s, 3σ, $\Delta E/E = 0.5$]	2×10^{-15} erg cm^{-2} s^{-1}
Sensitivity (10 – 30 keV) [10^6 s, 3σ, $\Delta E/E = 0.5$]	1×10^{-14} erg cm^{-2} s^{-1}
Background in HPD (10 – 30 keV)	1.1×10^{-3} cts s^{-1}
Background in HPD (30 – 60 keV)	8.4×10^{-4} cts s^{-1}
Spectral resolution (FWHM)	400 eV at 10 keV, 900 eV at 68 keV
Strong source ($> 10\sigma$) positioning	1.5″(1σ)
Temporal resolution	2 μs
Target of opportunity response	< 24 hr
Slew rate	0.06° s^{-1}
Settling time	200 s (typ)

?????????

Zero Bounce Photons

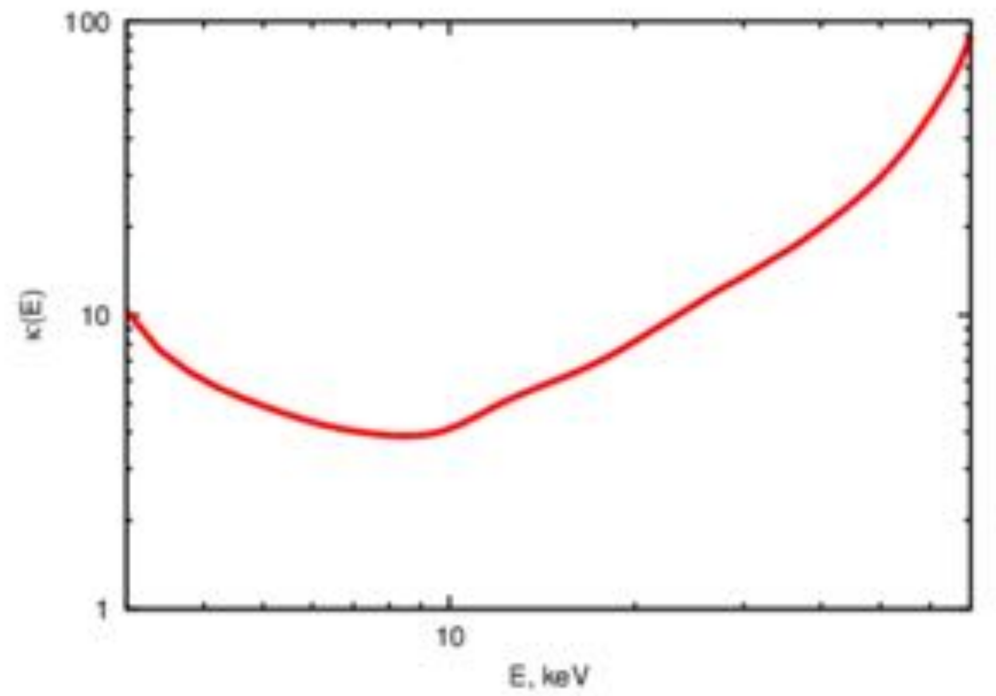
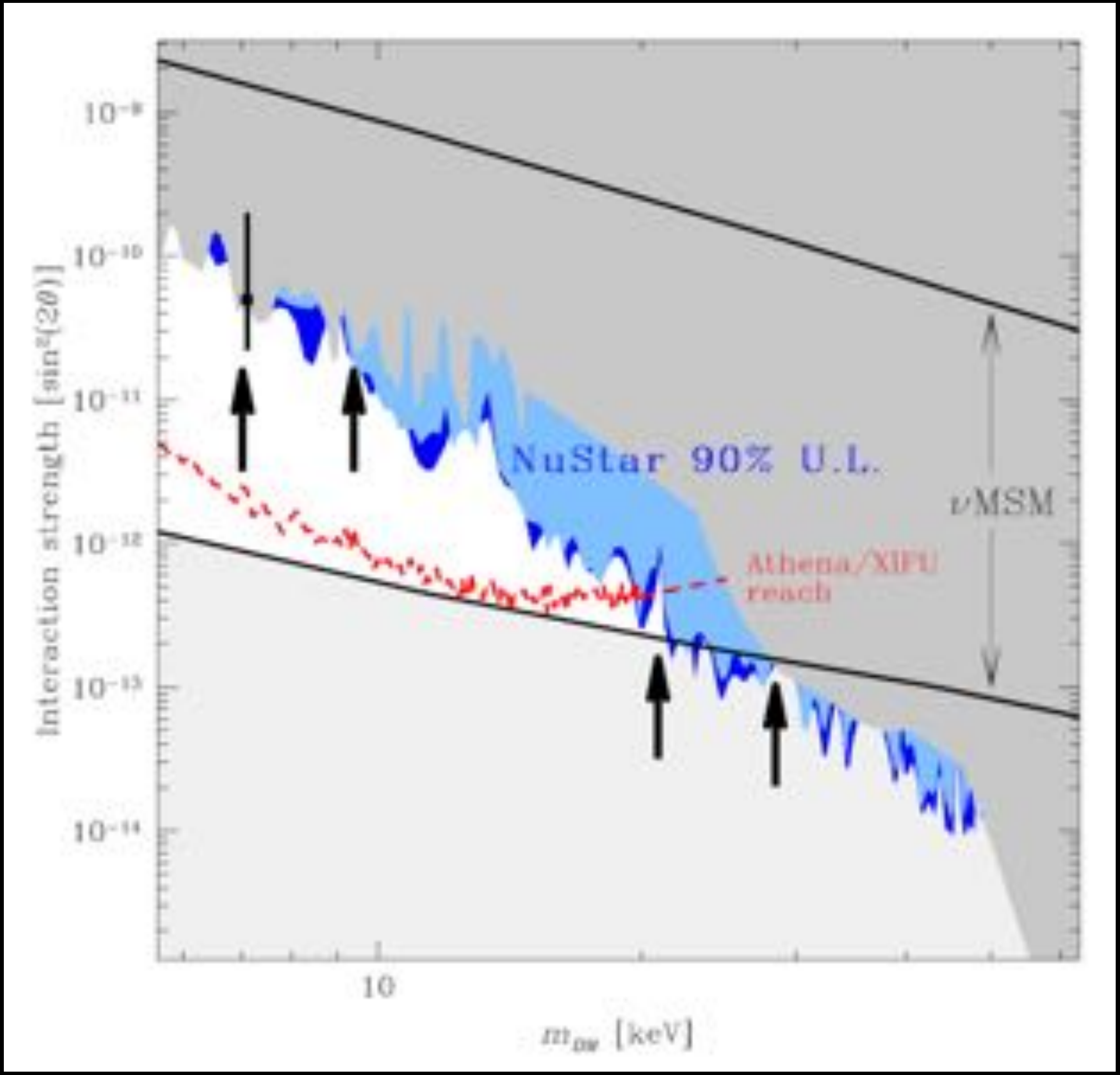


FIG. 2: The ratio of the aperture and the focused parts of the dark matter signal as a function of energy.

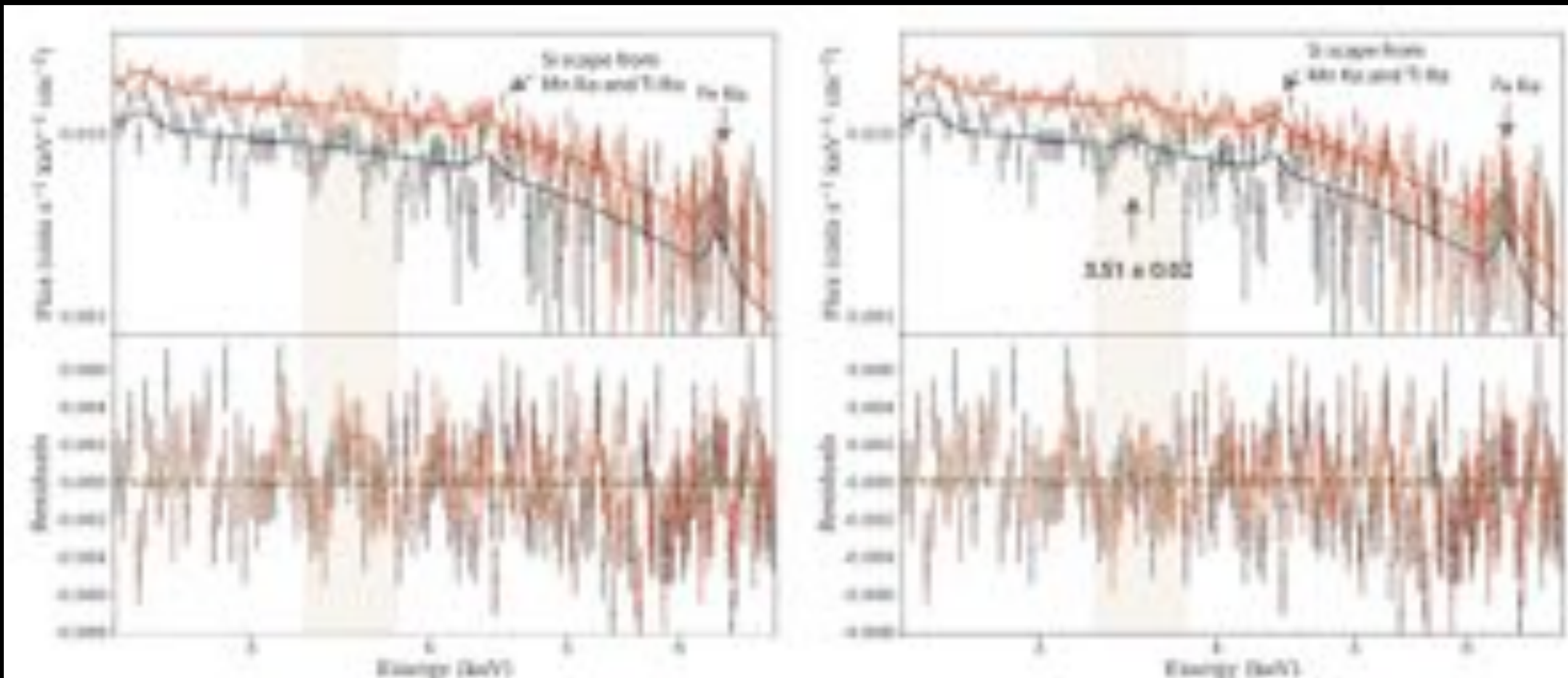
Neronov+ 2016

NuSTAR diffuse MW



Neronov+ 2016

[Latest] Chandra Deep Sky 1701.07932

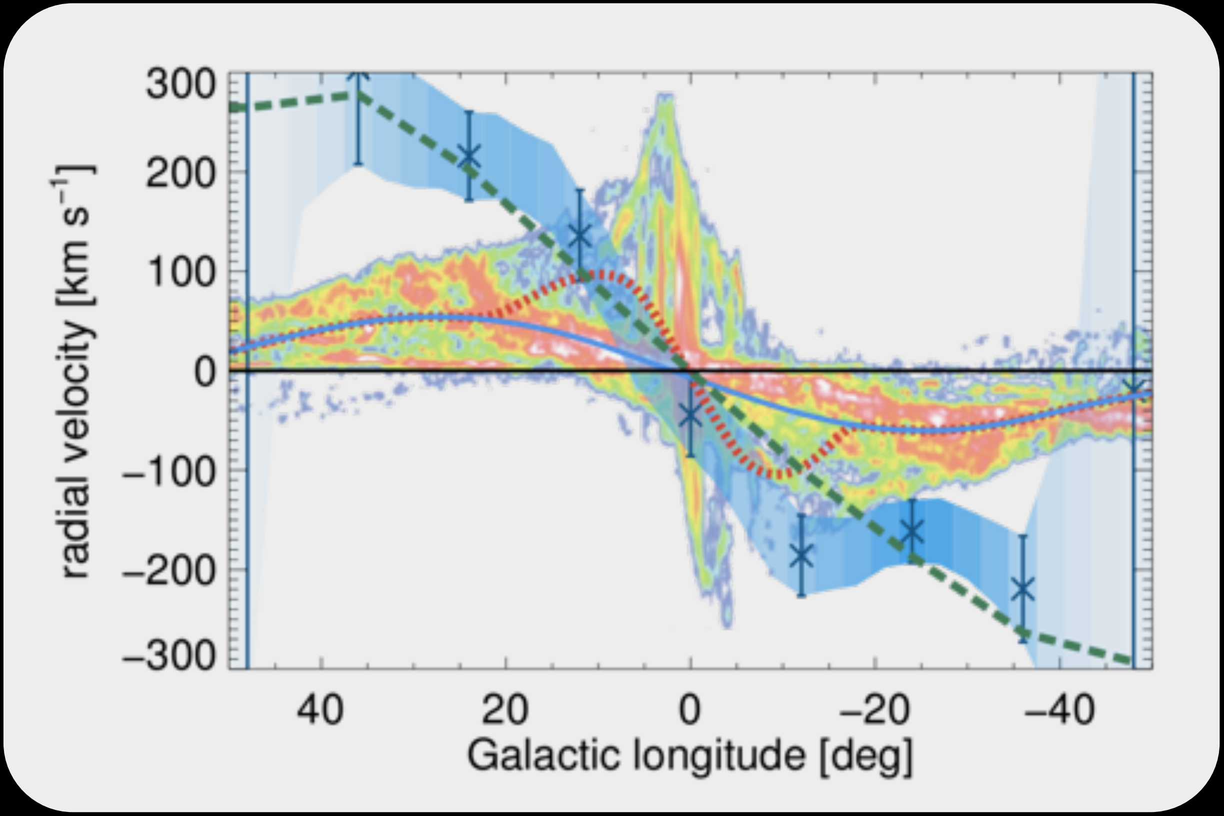


- ~3 sigma detection

Velocity Spectroscopy

- 10^{-3} E resolution <-> Typical MW velocity (~100km/s)
  - Velocity effects become important!

- CO, AL26



[Latest] Chandra Deep Sky 1701.07932

- Morphology consistent with NFW
- Consistent rates