Searching for Dark Matter with X-ray lines

Perseus Cluster
(Chandra)

Kenny, Chun Yu Ng

Weizmann Institute of Science

- Dark Matter Velocity Spectroscopy
  - Hitomi (Astro-h) type

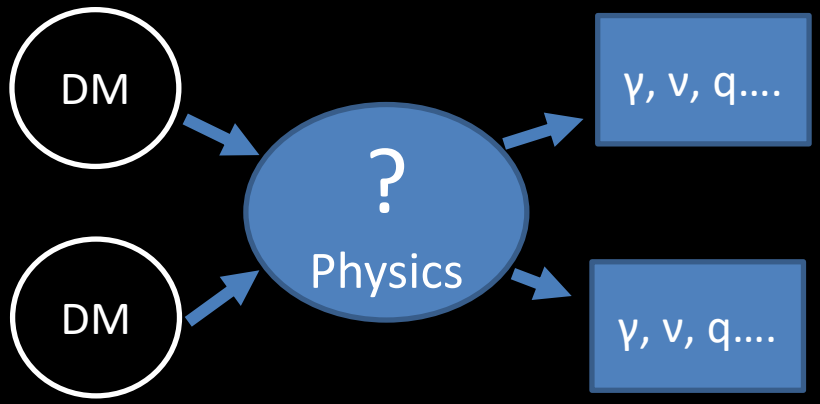
    Speckhard, *KCYN*, Beacom, Laha [1507.04744] PRL 2015
  - Sounding rocket type

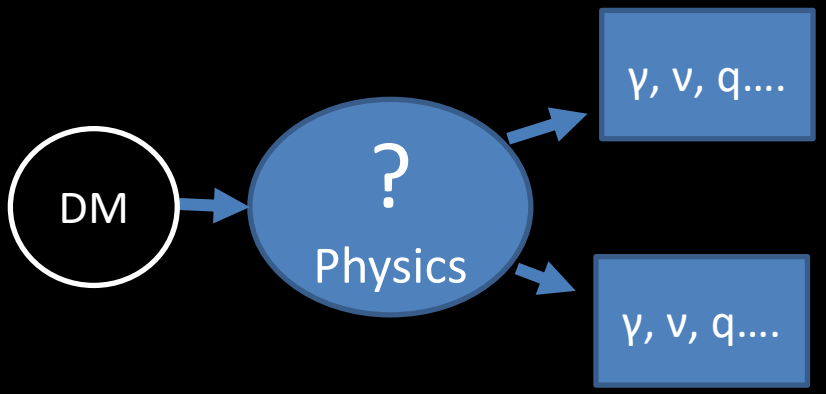
    Powell, Laha, *KCYN*, Abel [1611.02714] submitted

- Dark Matter Search with NuSTAR

  Perez, *KCYN*, Beacom, Hersh, Horiuchi, Krivonos [1609.00667] submitted

Dark Matter Indirect Detection





Particle Physics Astrophysics

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

X-ray Searches of Dark Matter

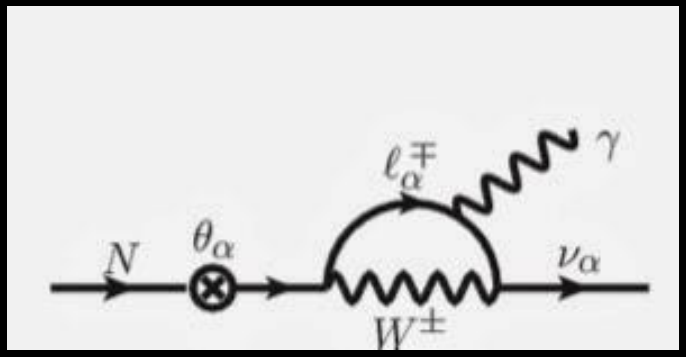
- Sensitive instruments

Chandra (1999 -)

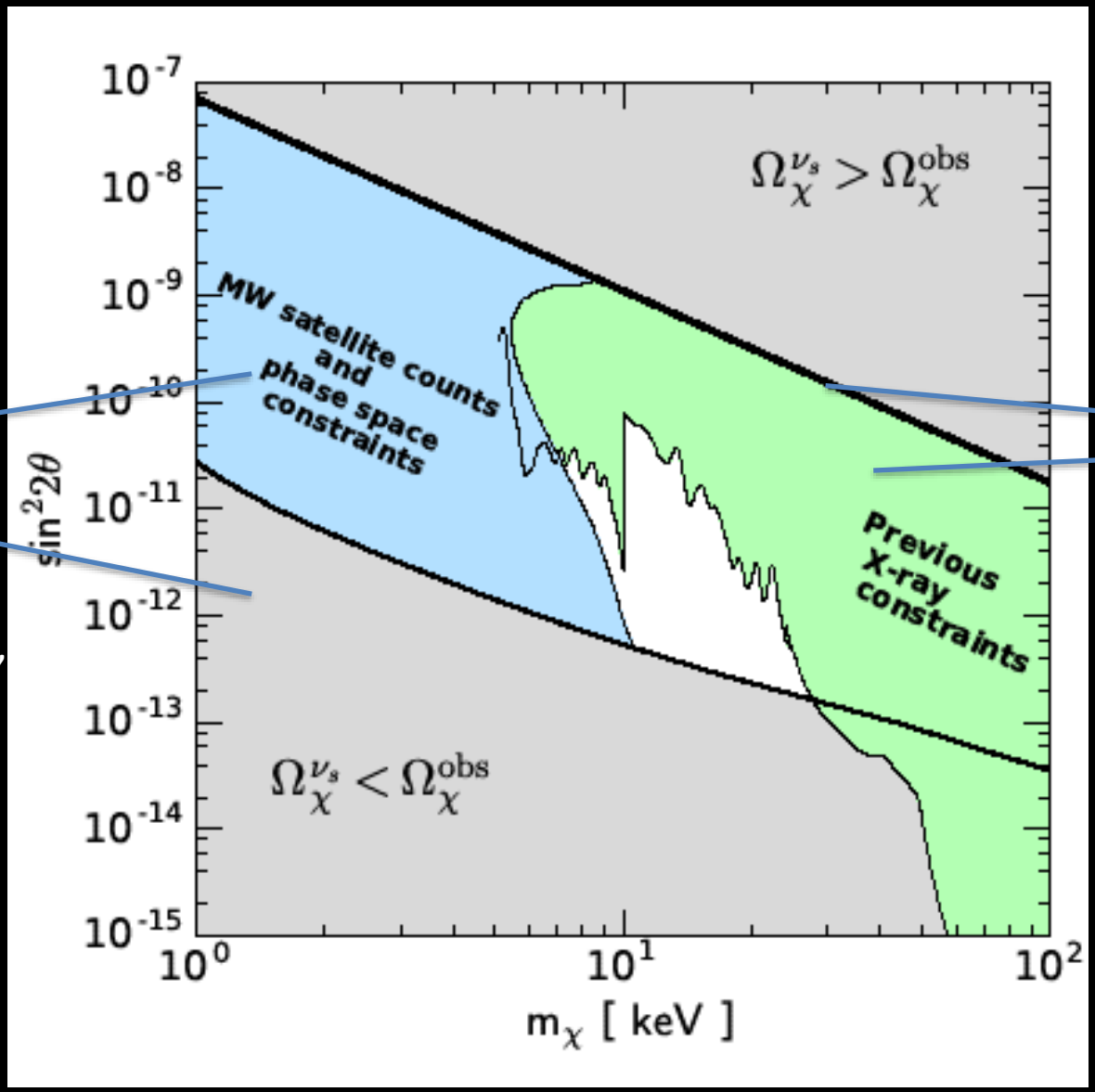
XMM Newton (1999 -)

Suzaku (2005 - 2015)

- Many Candidates
  - *Sterile Neutrino*
  - Axion-like Dark Matter
  - Gravitino
  - Exciting Dark Matter
  - ++++++



Sterile Neutrino Dark Matter



Model Dependent (nuMSM)

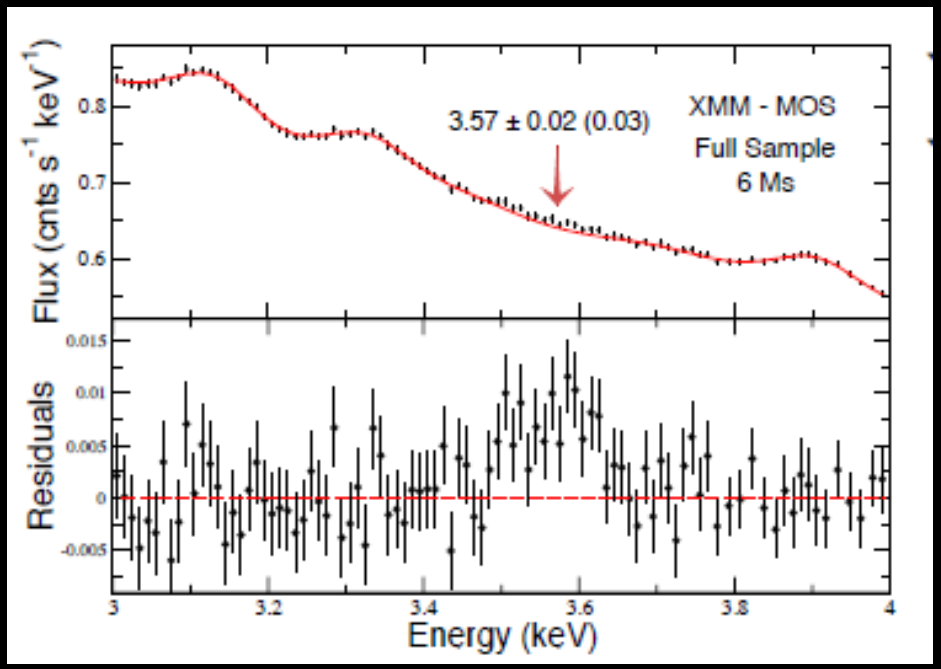
Not applicable in, e.g.
1507.01977 Patwardhan et al
+
+

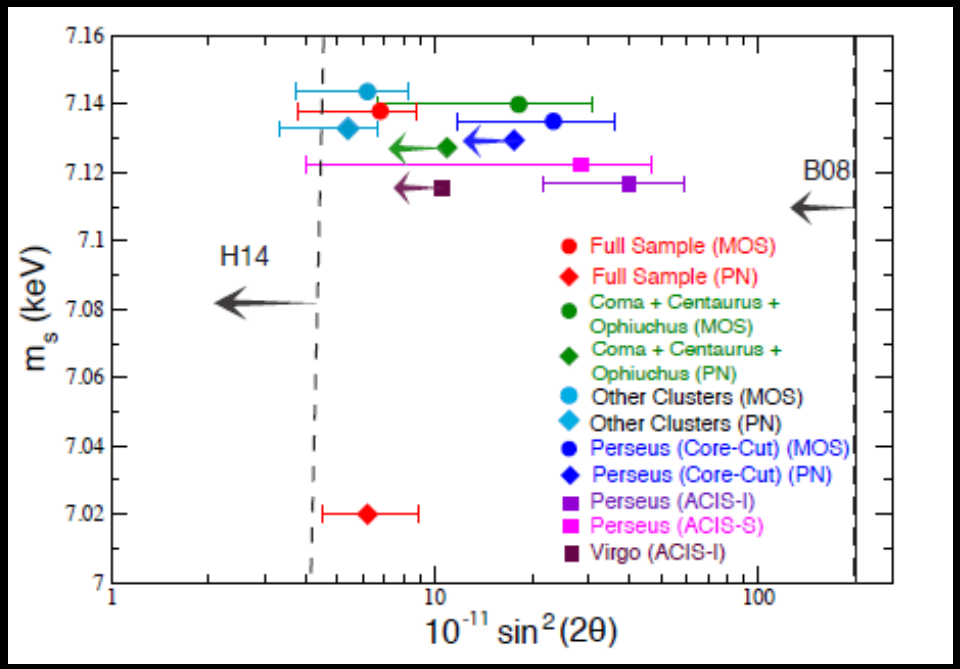
Model Independent

3.5 keV line excess!

- Bulbul et al (2014)

Sterile Neutrino DM



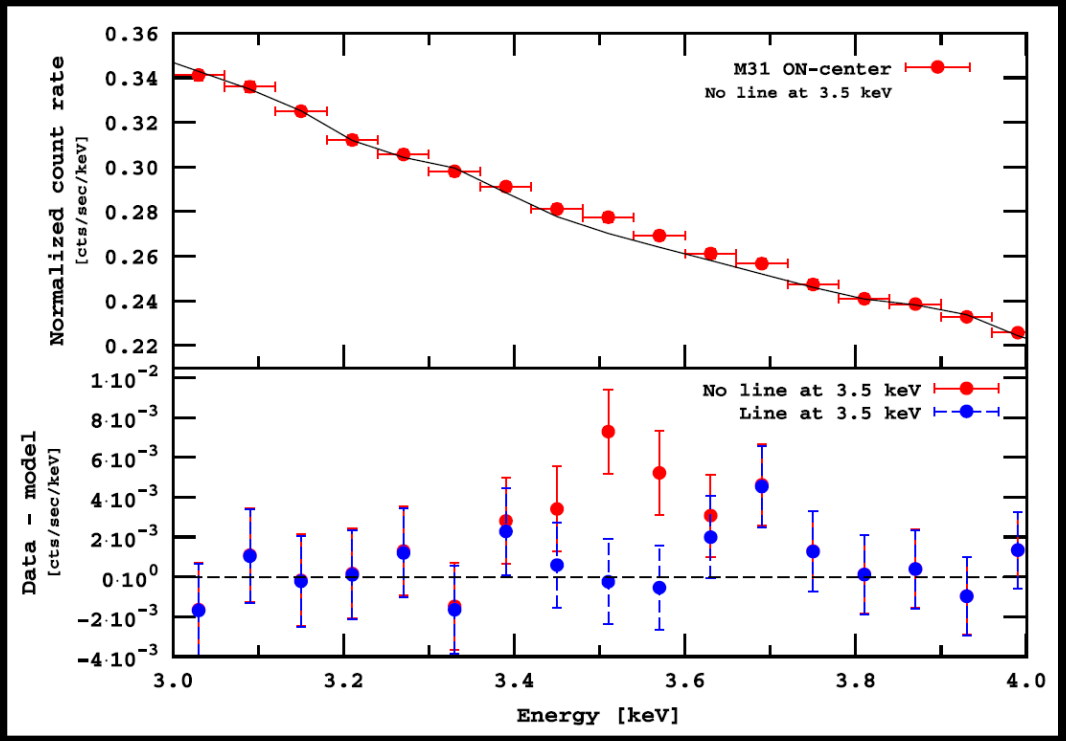


Stacked 73 clusters XMM-MOS (4-5σ)

Also
Chandra Perseus 2.5σ and 3.4σ

3.5 keV line excess!

- Boyarsky et al (2014)



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

What to do

- New Instruments
  - Astro-H (Hitomi)
  - Sounding Rockets
  - NuSTAR



sented stacked *Suzaku* and *XMM-Newton* clusters and 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).

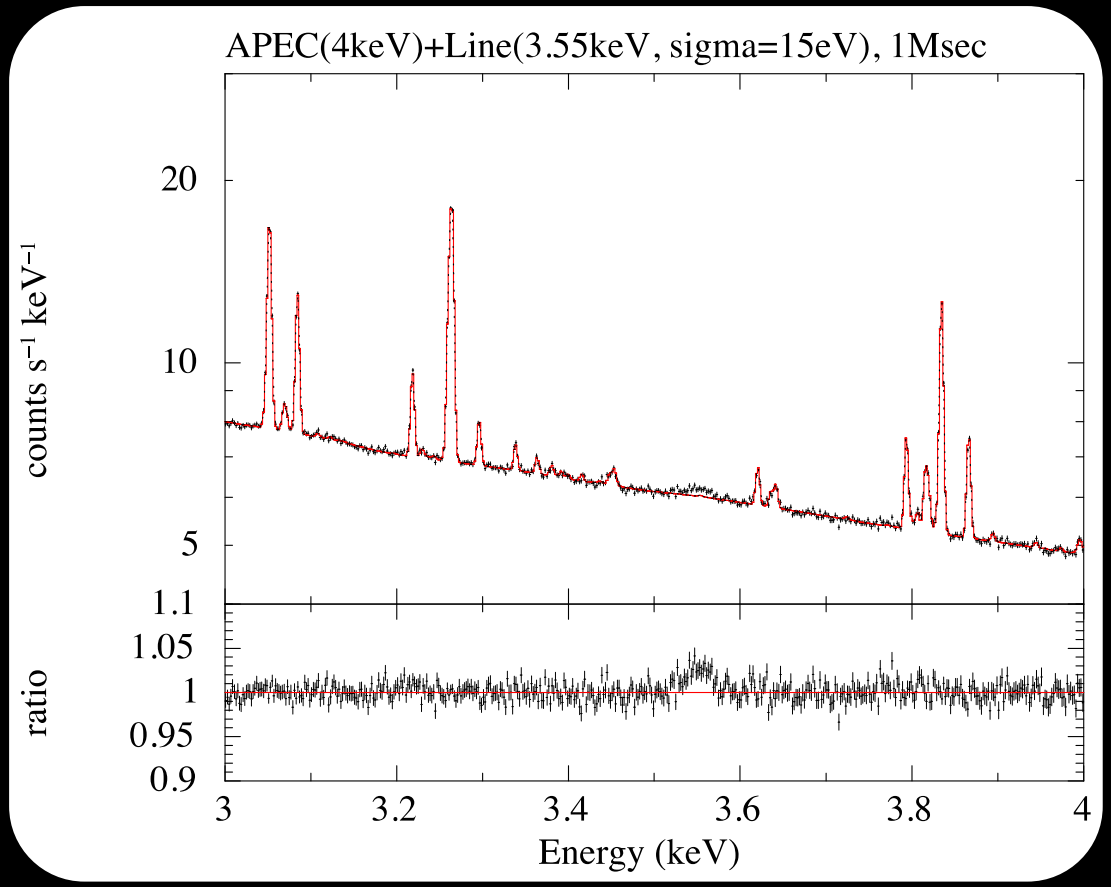
Bulbul+ 2016

- New Techniques
  - Velocity Spectroscopy

Astro-H (Hitomi)

- Launched in Feb 17, 2016

Simulation

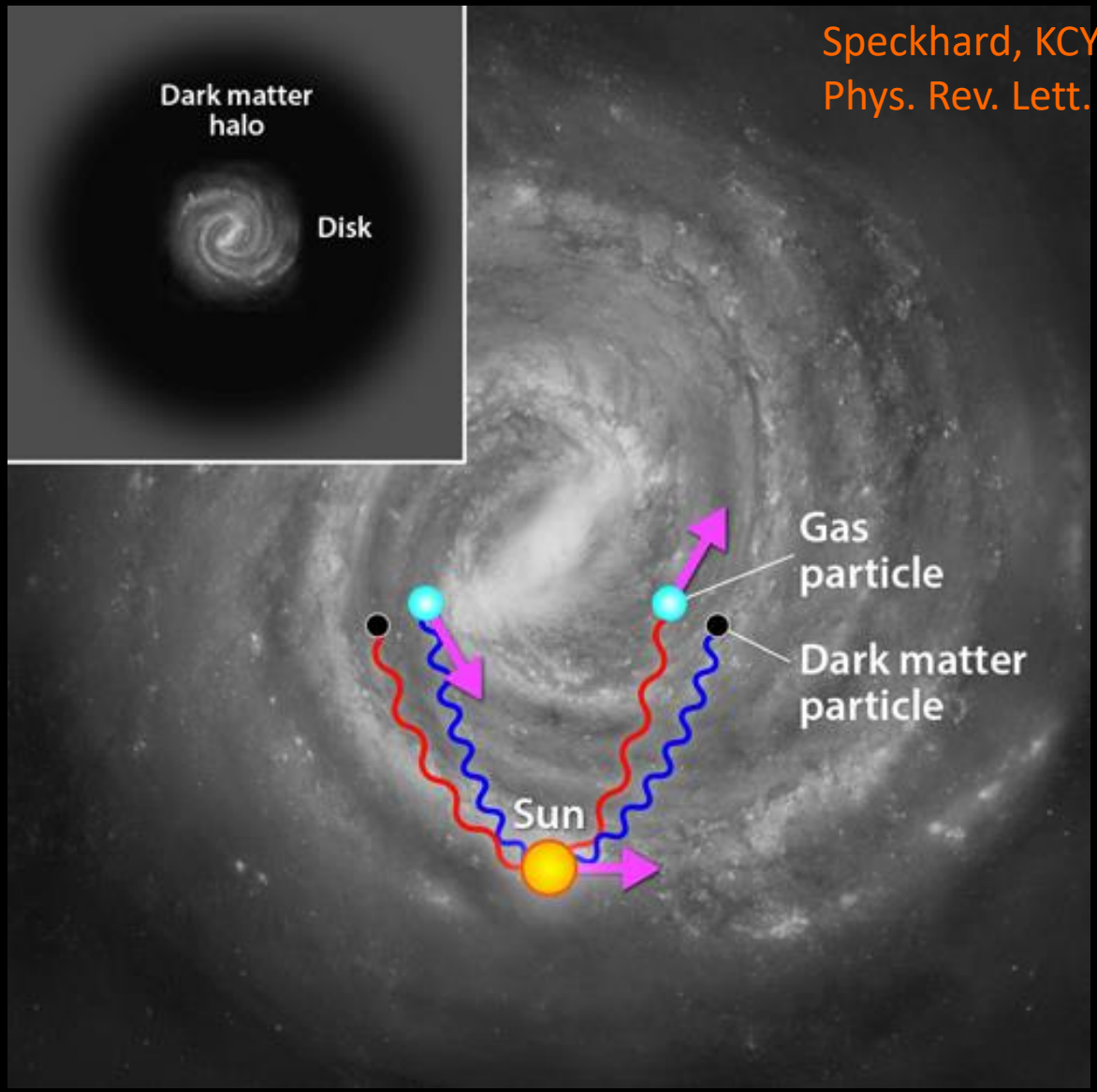


10^{-3} energy resolution !

Kitayama+
1412.1176

Dark Matter Velocity Spectroscopy

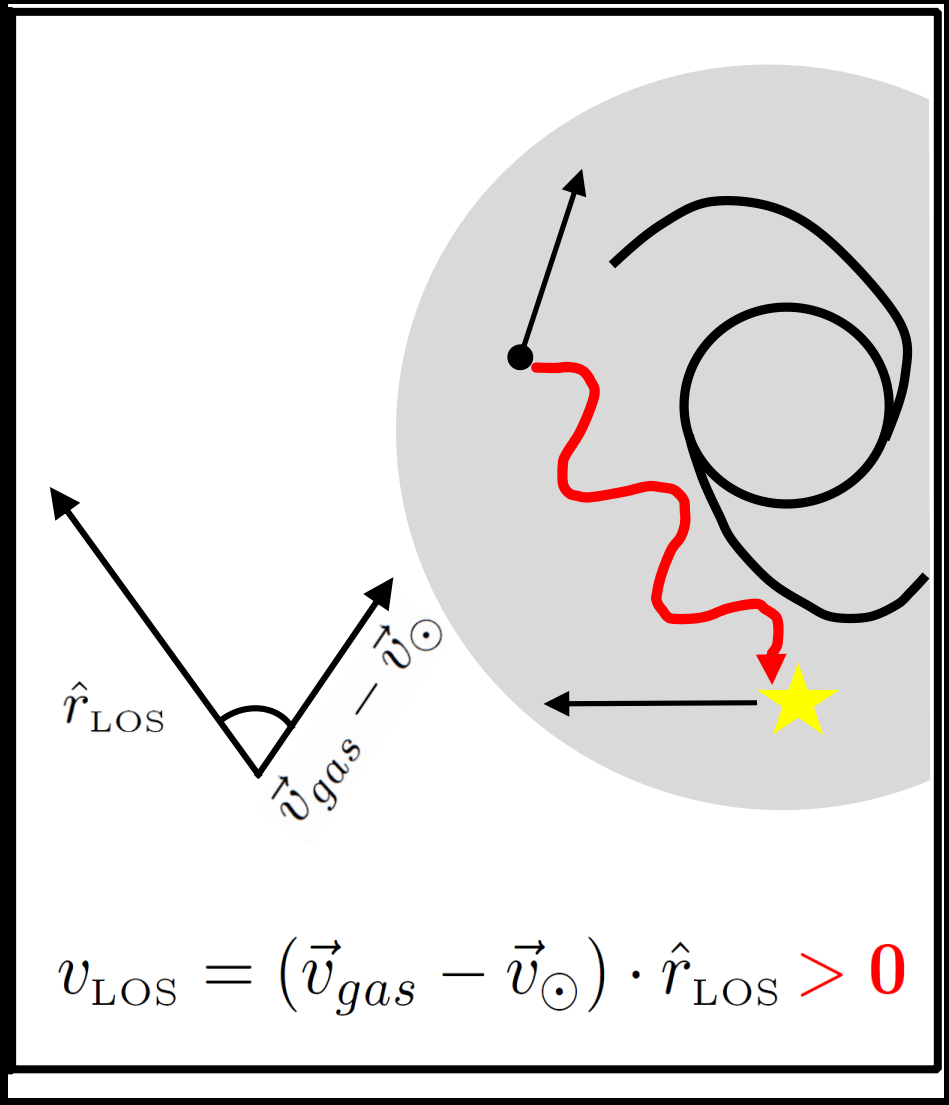
Speckhard, KCYN, Beacom, Laha
Phys. Rev. Lett. 116, 031301



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

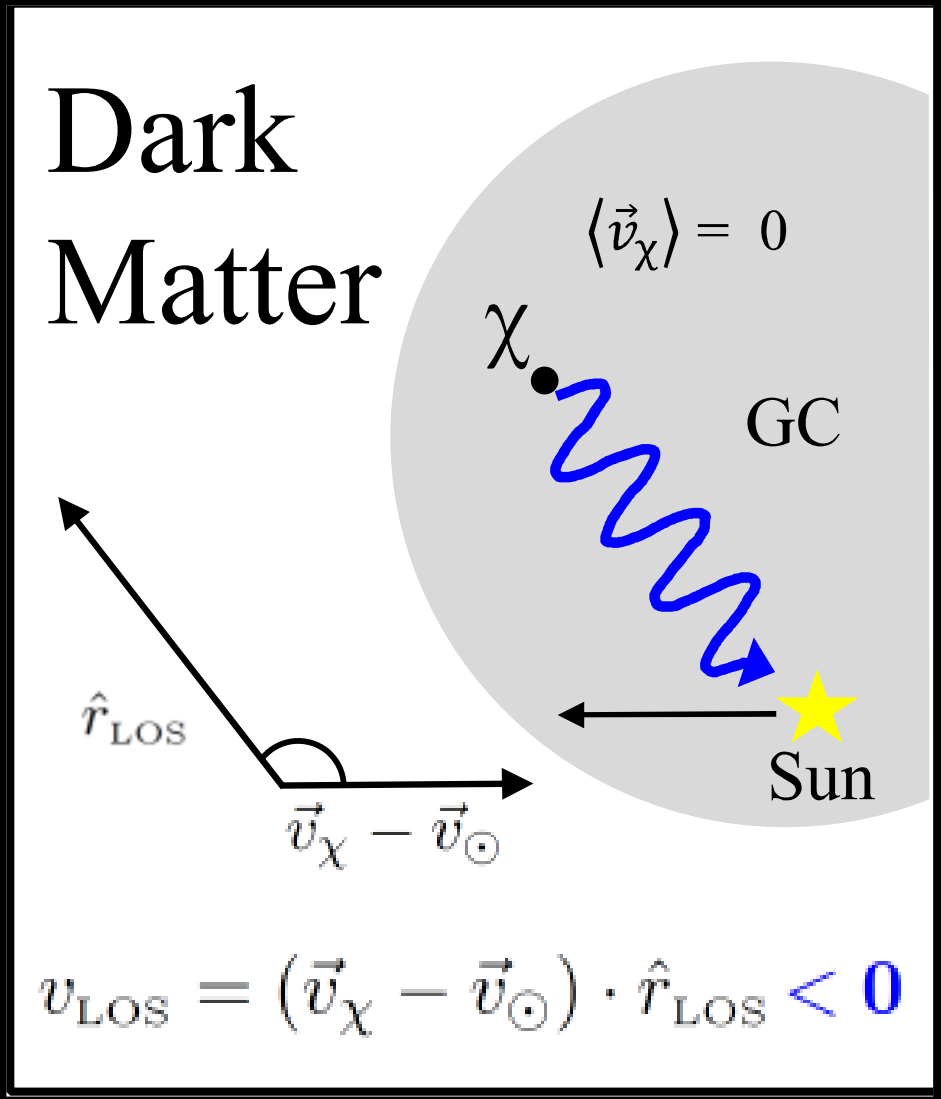
Milky Way Gas (Background)

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



Milky Way DM

- 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

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

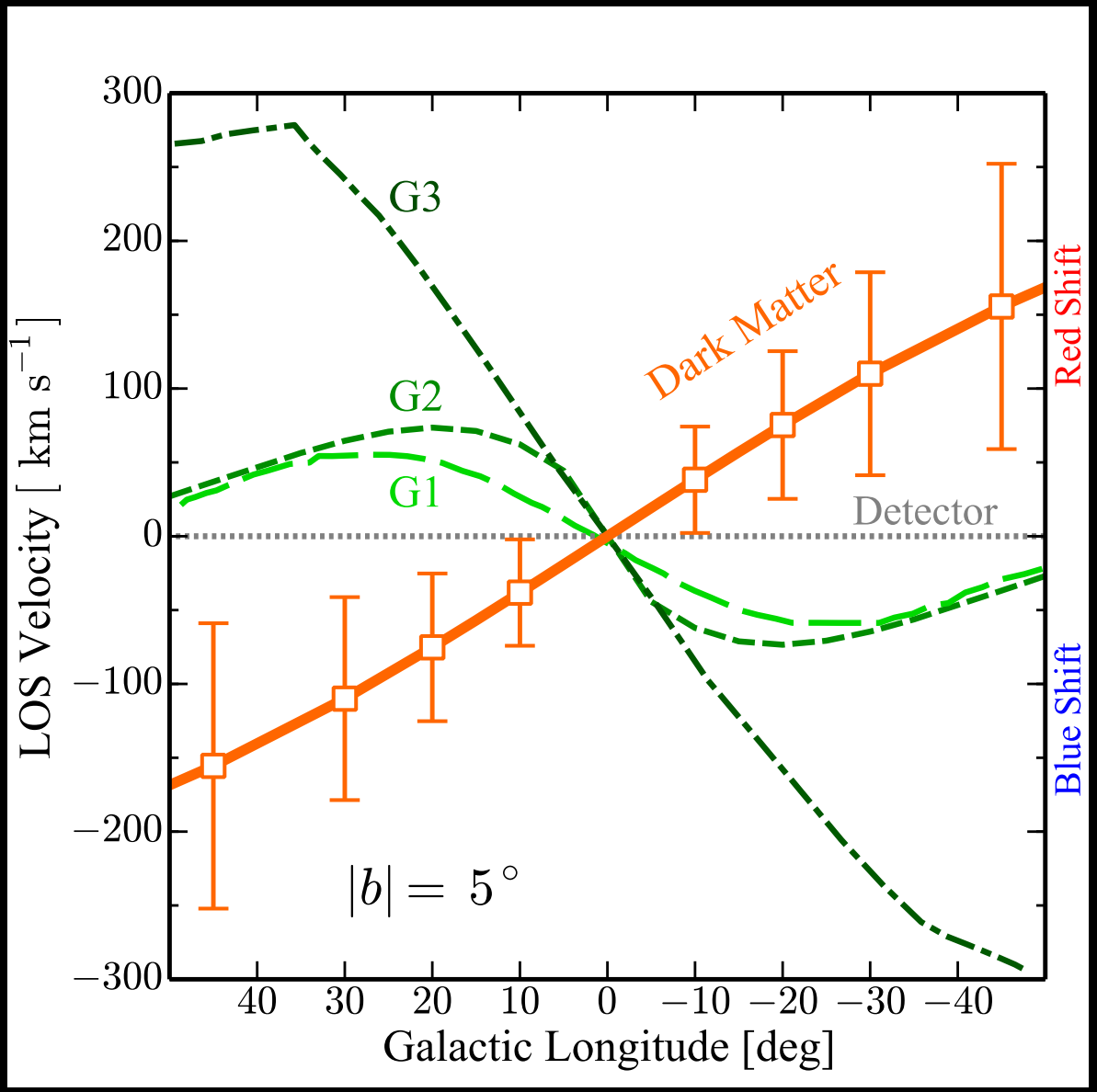
$$\frac{1}{R_\odot \rho_\odot}\int ds\, \rho_\chi(r[s,\psi])\frac{d\widetilde{N}(E-\delta E_{\rm MW}, r[s,\psi])}{dE}$$

Line shift
Atomic tomography

Line dispersion
- MW Gravitational potential

DM – Astro Separation (MW)

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



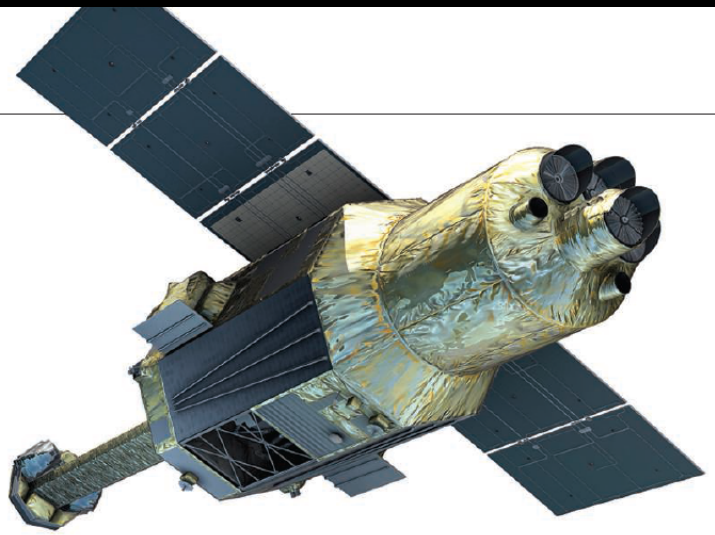
A new Hitomi!

- Simpler version 2021

SPACE SCIENCE

Japan reboots x-ray probe—and mission management

After a series of mission failures, Japan's space science agency aims to overhaul lax oversight



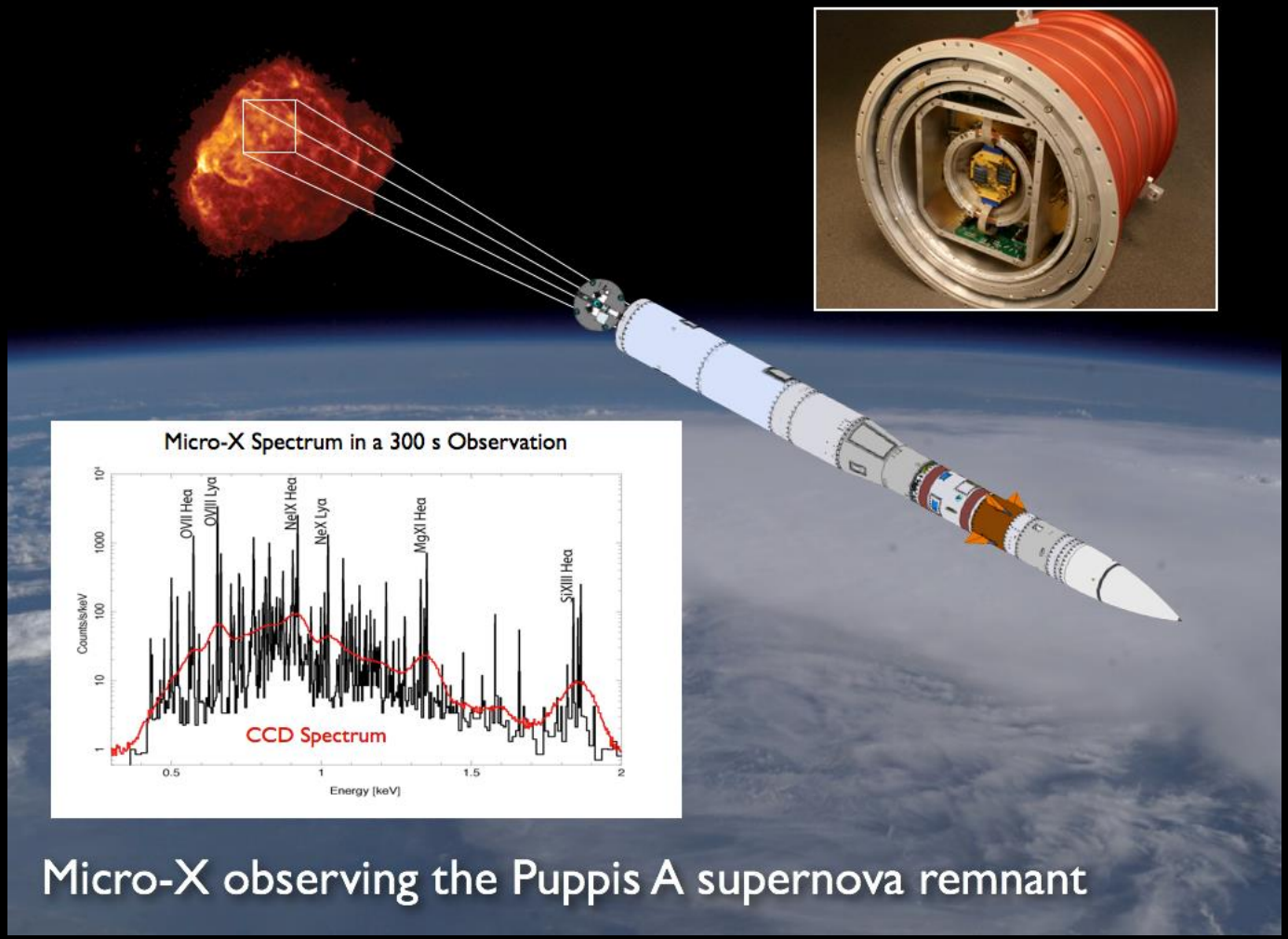
After a month in orbit, ASTRO-H broke apart. Failures in the probe's control systems were to blame.

By **Dennis Normile**, *in Sagamihara, Japan*

When Japan launched the ASTRO-H x-ray satellite on 17 February, the astrophysics community held its collective breath. Two previous Japanese-U.S. x-ray missions had failed, and scientists hungered for next month. And NASA, which provided Hitomi's key instrument—the Soft X-Ray Spectrometer (SXS)—is discussing with JAXA the possibility of building a replacement, says NASA astrophysics spokesperson Felicia Chou in Washington, D.C. Tsuneta says the mission, slated for launch in 2021, will be simpler and cheaper, carrying two instru- supernova remnants. It got off to a promising start. After a smooth launch, operators spent a month testing and tuning its instruments. The SXS "was performing exceptionally well," says ASTRO-H science working

8, 2016

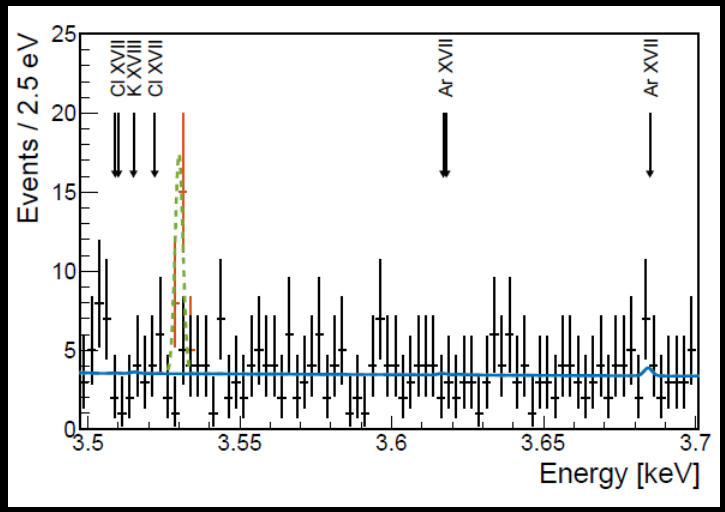
Sounding rocket (XQC, Micro-X)



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

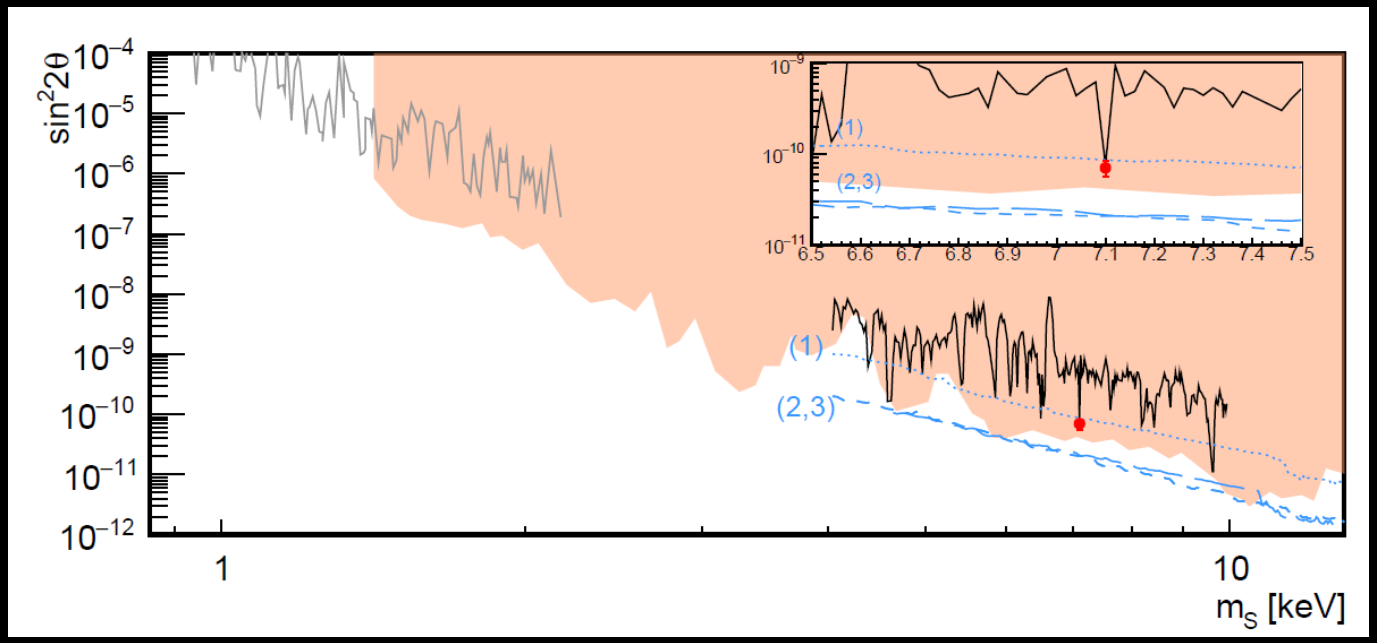
Sounding Rockets

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



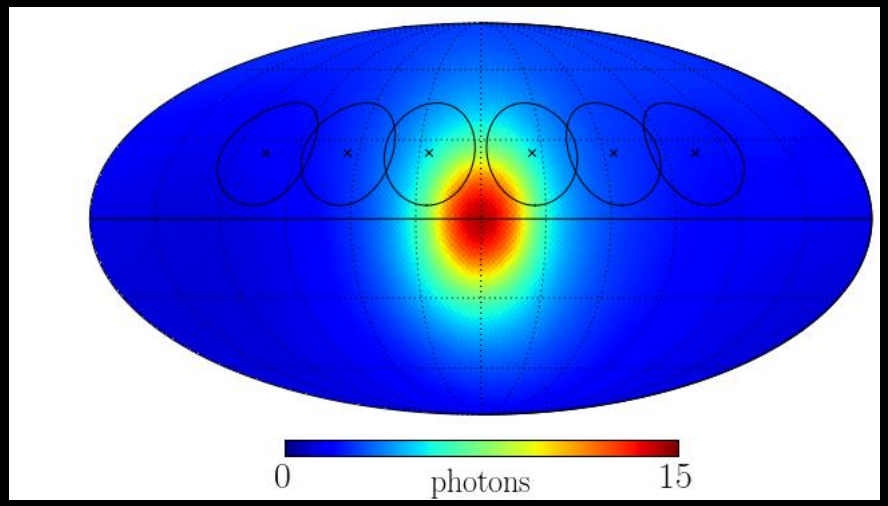
Mock Data

Figueroa-Feliciano+ [1506.05519]



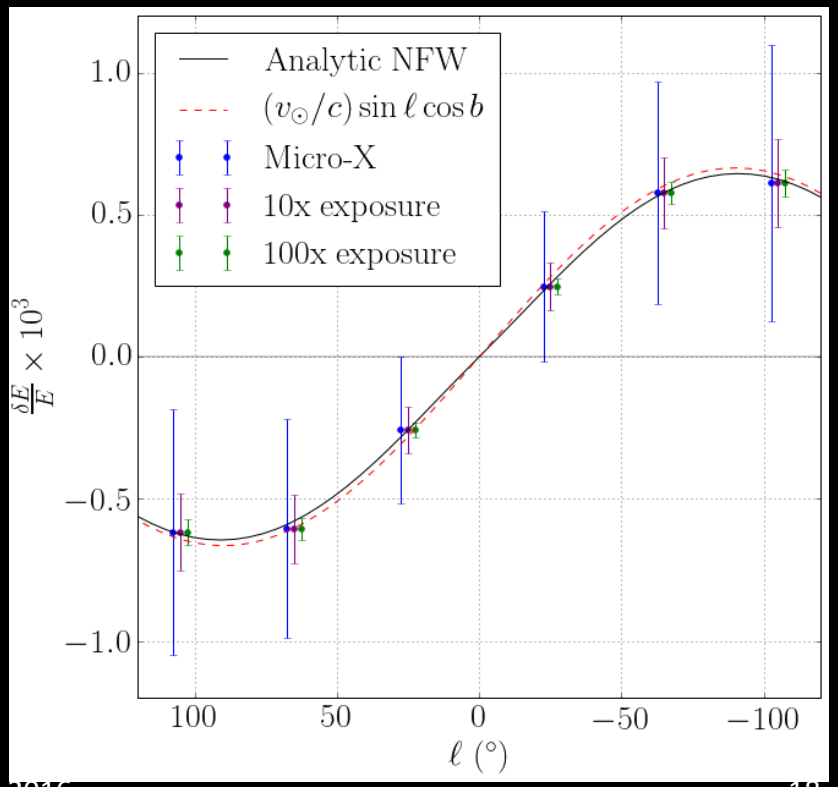
Velocity Spectroscopy with Micro-X?

- Wide FOV



1611.02714
Powell, Laha, KCYN, Abel

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

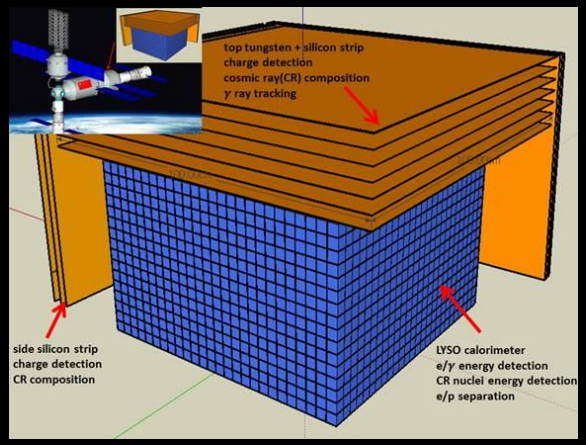


- Looks promising!

DM Velocity Spectroscopy

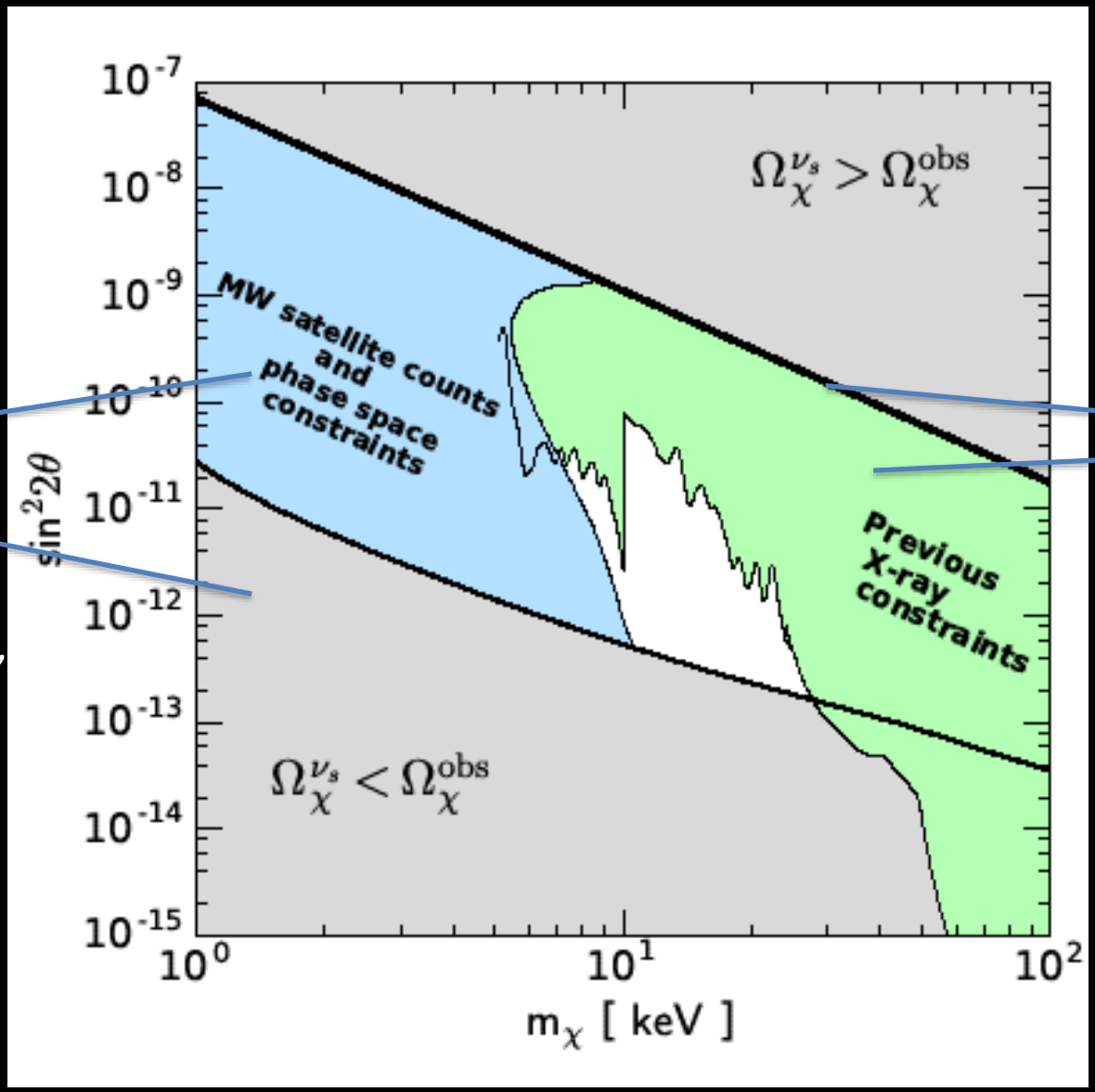
- Extra handle for testing line-like signal
  - The “smoking gun” sometimes is not enough

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



- Dark Astronomy

Sterile Neutrino Dark Matter



Model Dependent (nuMSM)

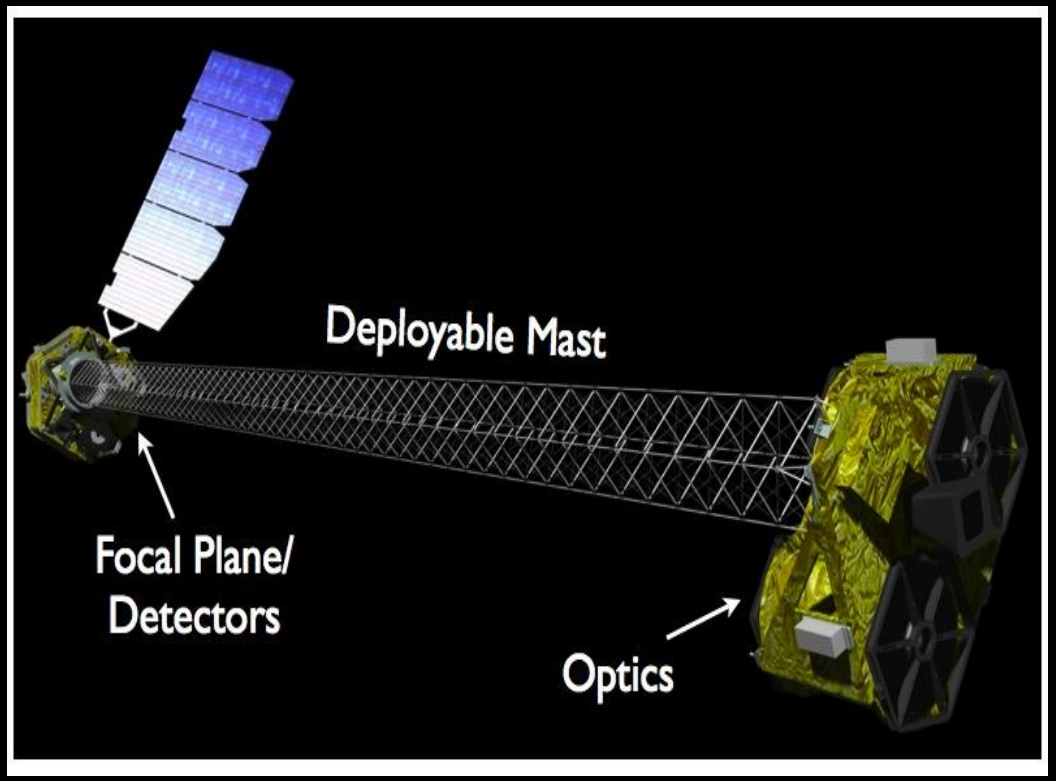
Not applicable in, e.g.
1507.01977 Patwardhan et al
+
+

Model Independent

NuSTAR (2012 -)

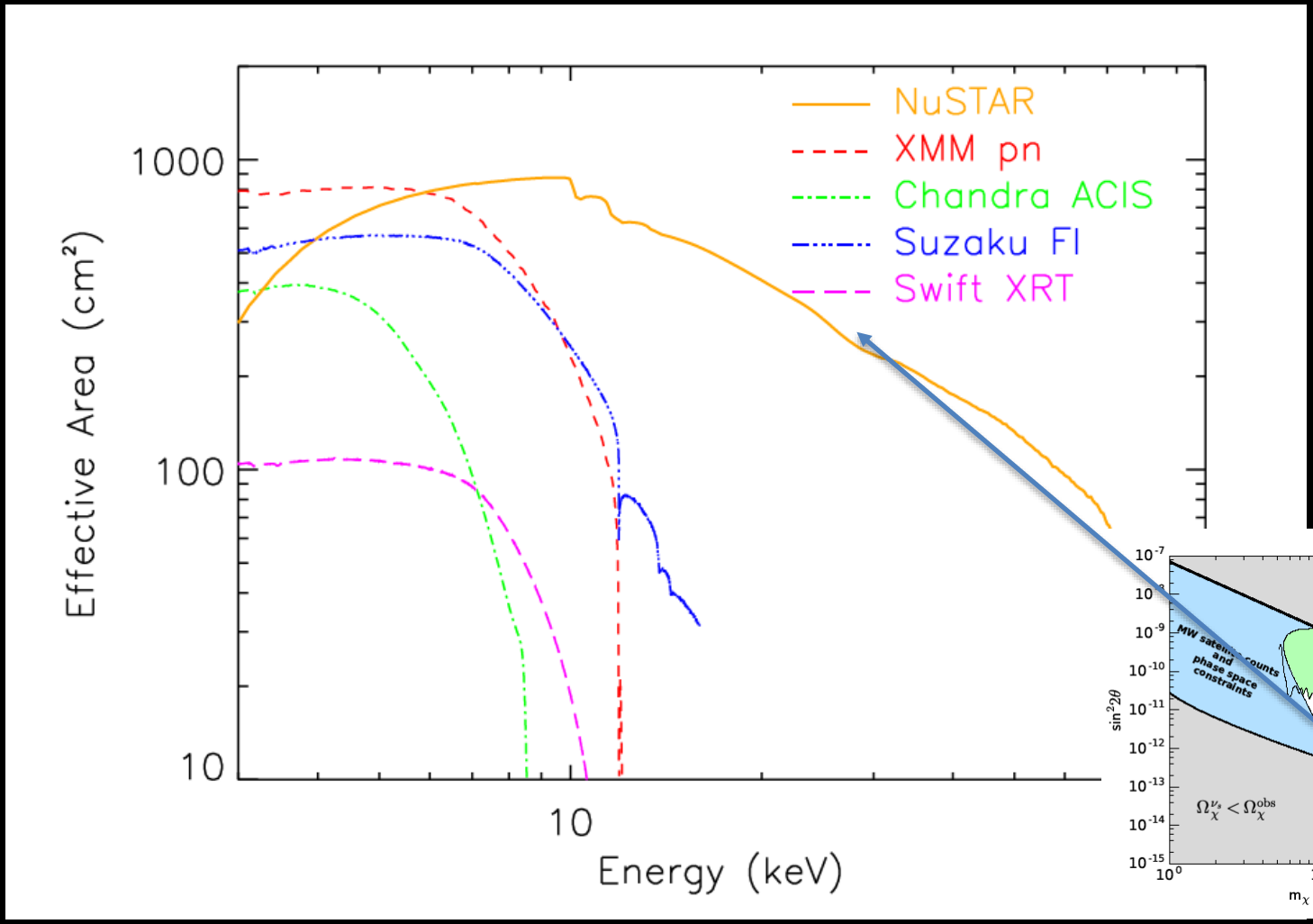
- **Nu**clear **S**pectroscopic **T**elescope **Ar**ray

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



NuSTAR

- Focusing observations



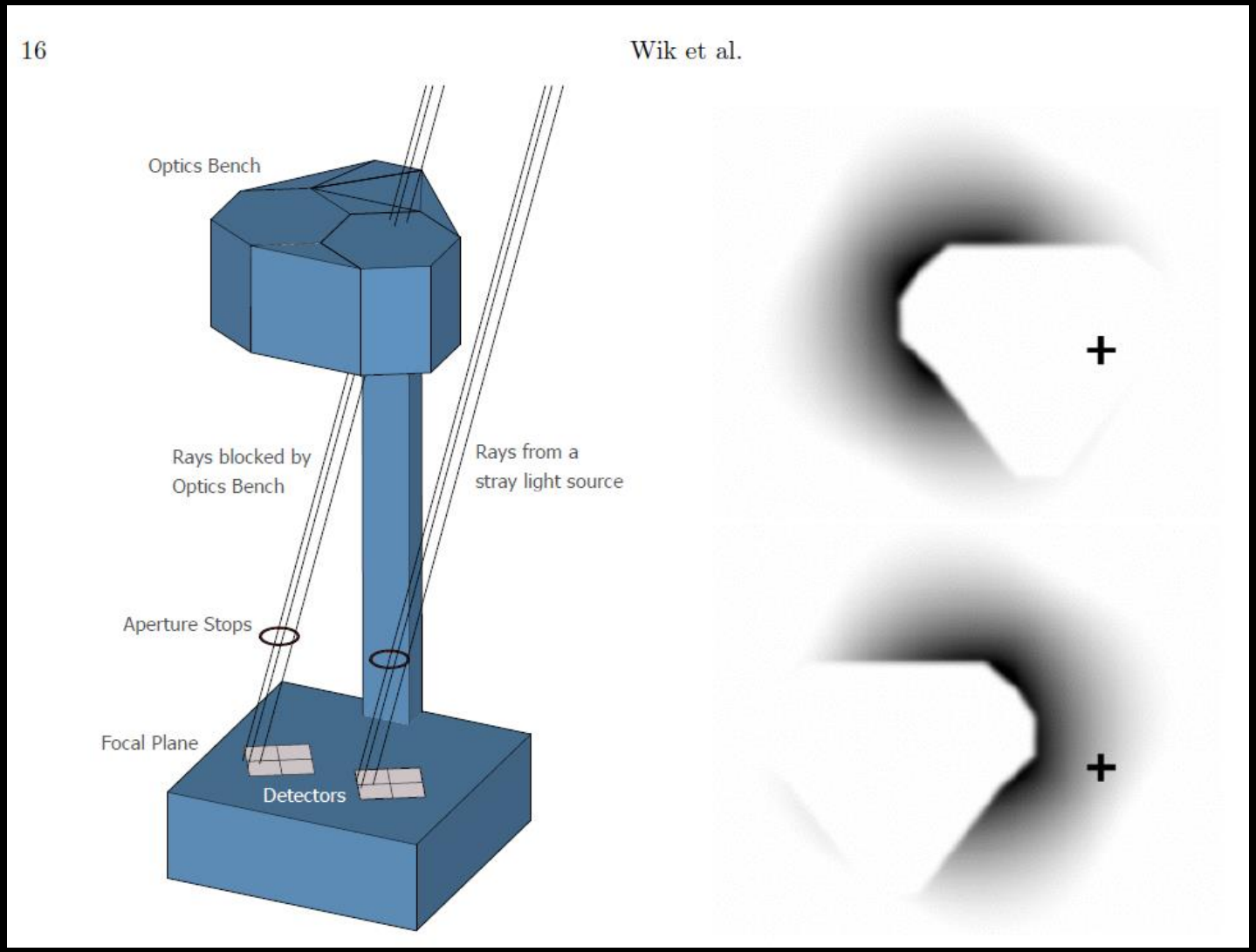
NuSTAR

- 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	$1.5''(1\sigma)$
Temporal resolution	2 μs
Target of opportunity response	< 24 hr
Slew rate	0.06° s^{-1}
Settling time	200 s (typ)

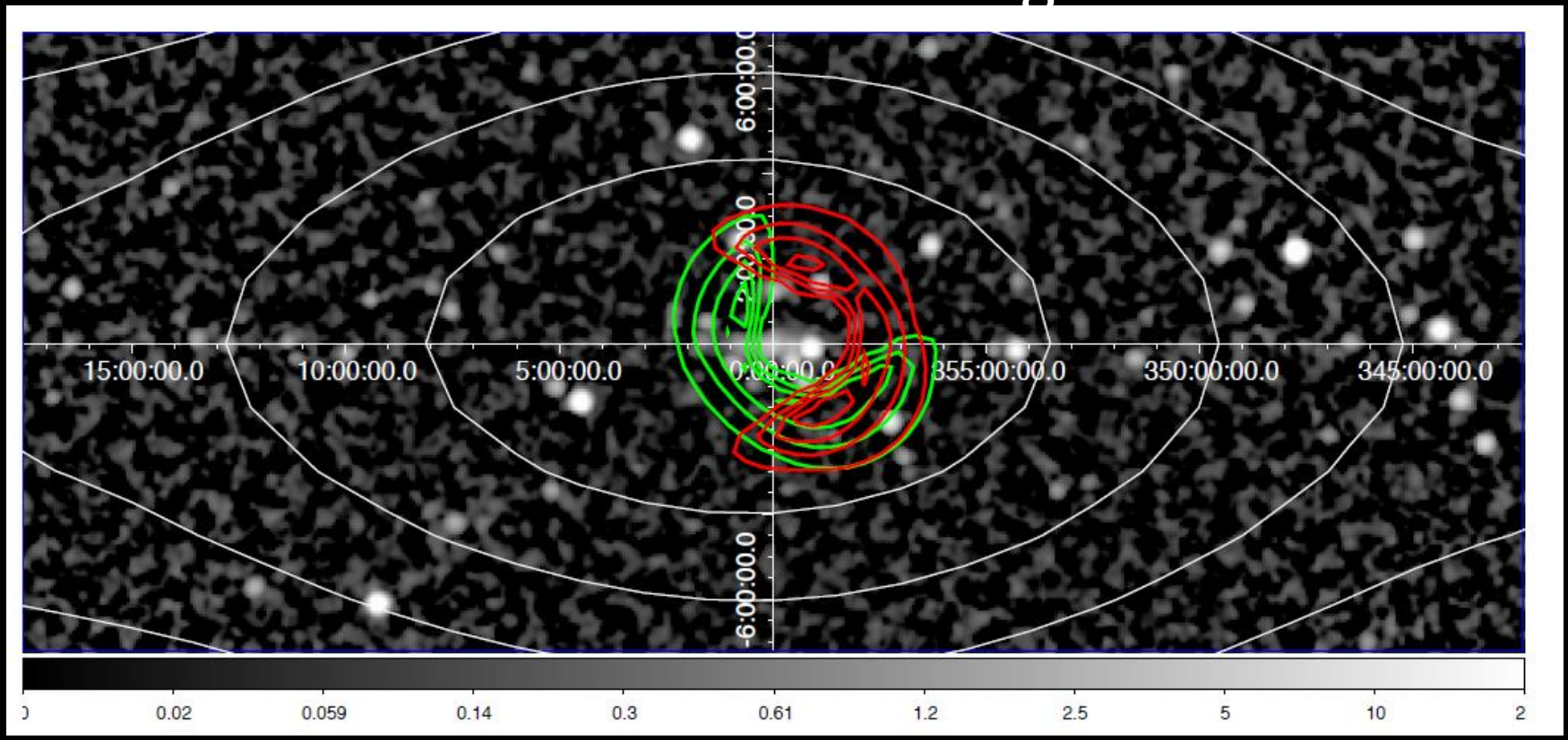
Zero Bounce Photons



NuSTAR MW GC Observation

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

- 6 observations ~ 0.5Ms combining two detectors

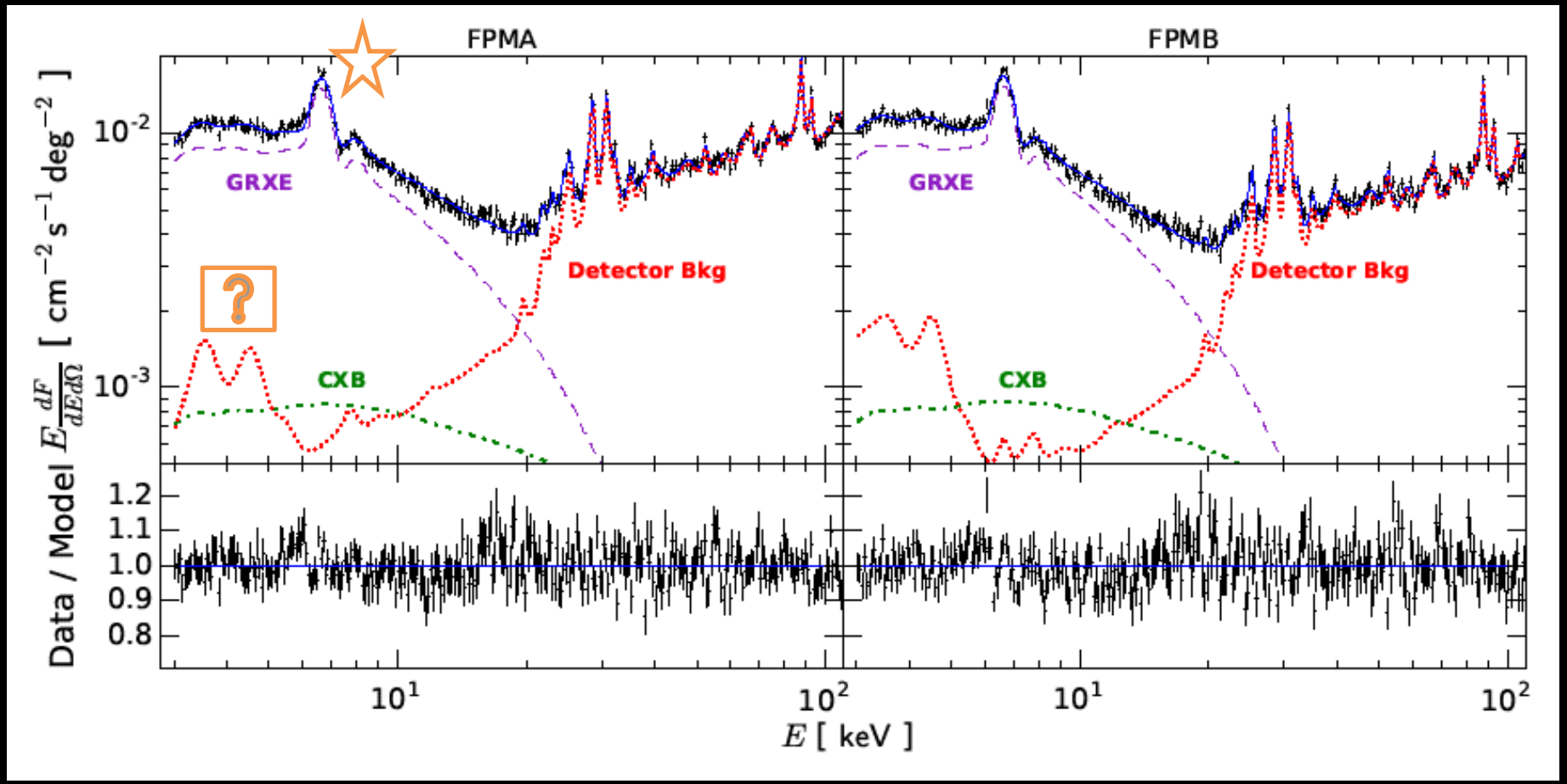


Perez+ 2016

Spectra

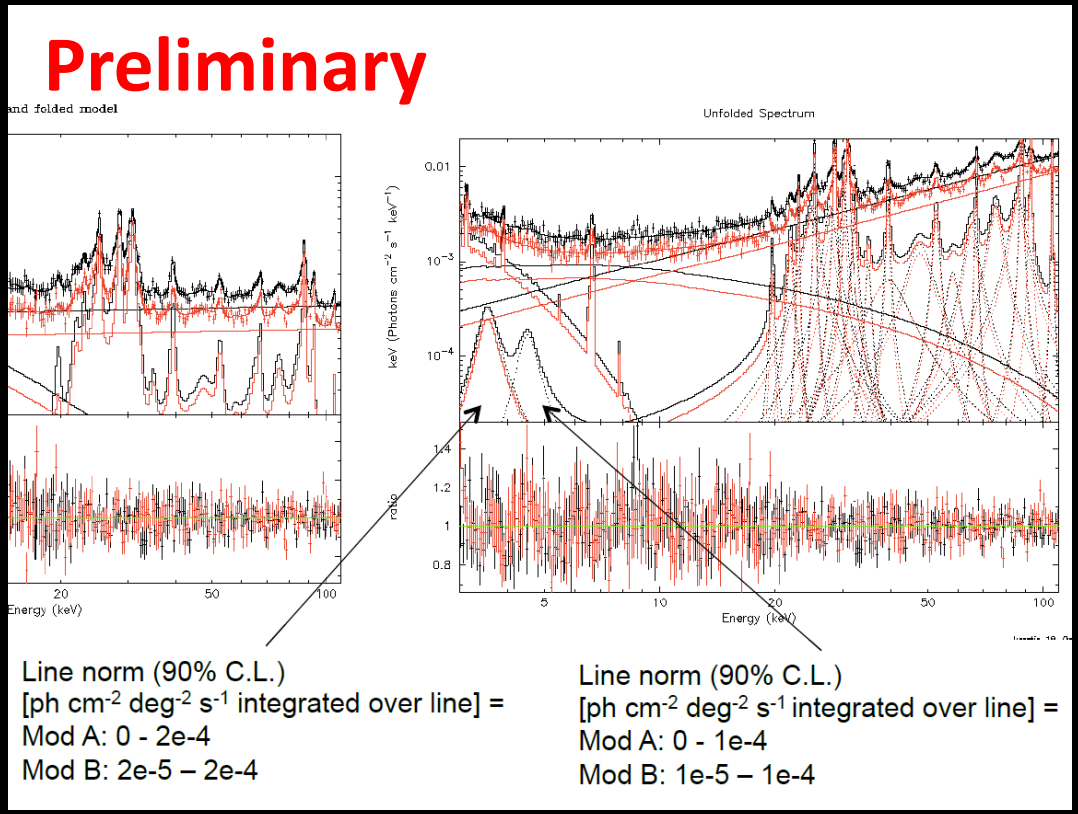
- A + B detector

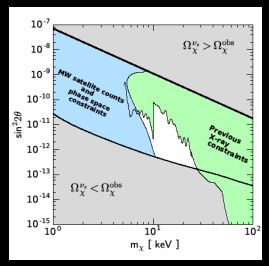
Perez+ 2016



3.5 keV in NuSTAR

- Occulted data set
  - (Earth blocked)
- Not as significant (less statistic)
- Flux consistent
- Not sure about the other instruments



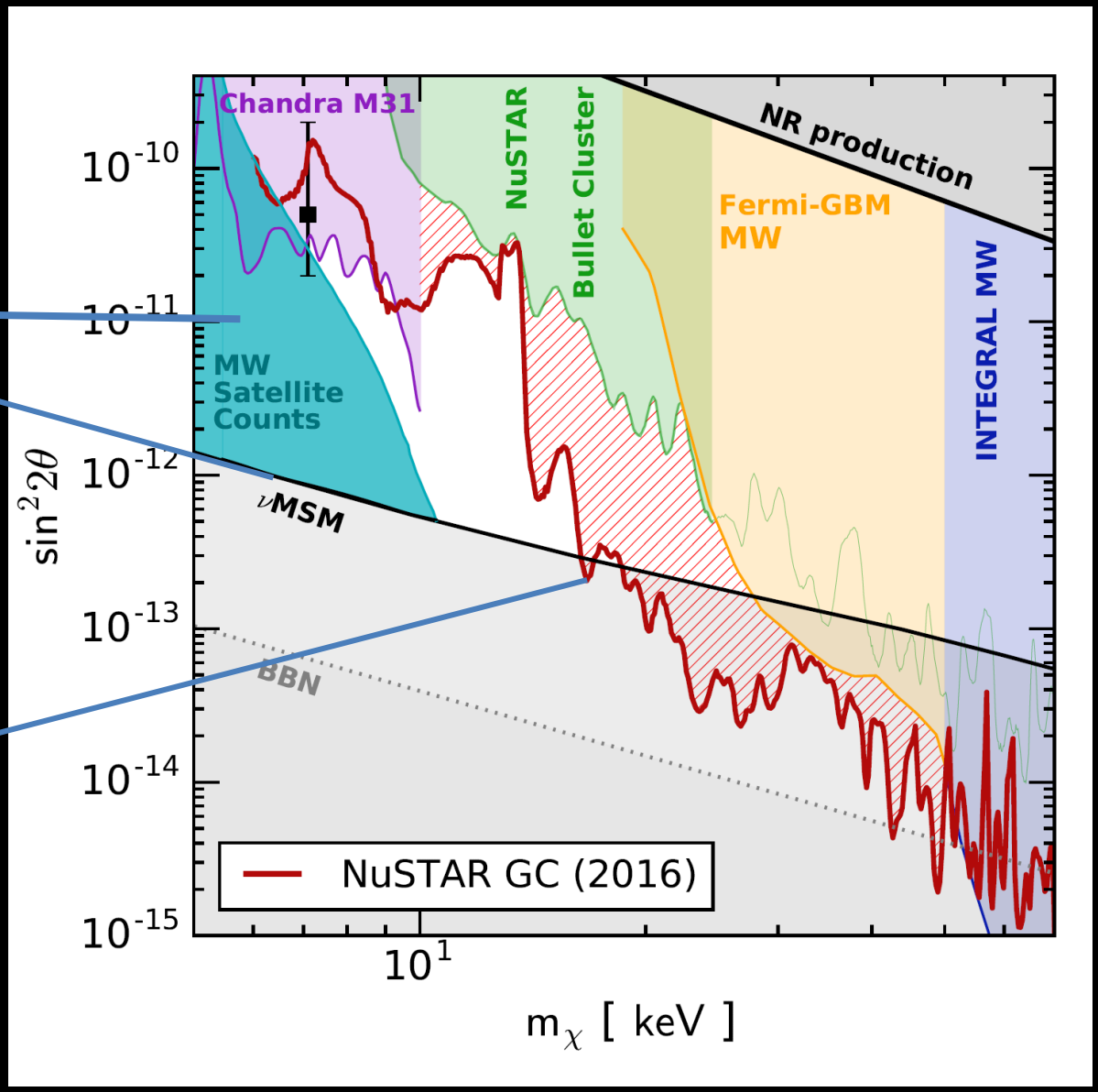


Dark Matter Limit

Perez+ 2016

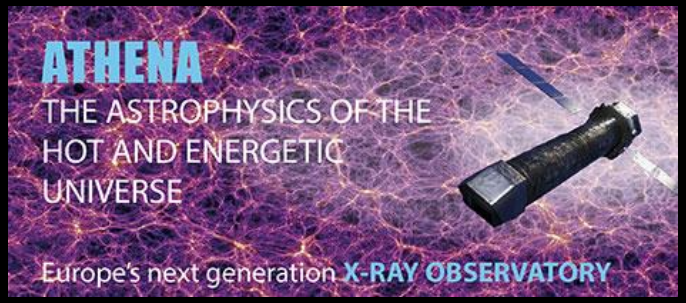
Resonantly produced Sterile Neutrino Dark Matter in nuMSM

Strongest limits above ~10keV



Summary

- Jury is still out for the 3.5 keV line.
  - New Hitomi (maybe 2021)
  - Micro-X
  - NuSTAR may be surprisingly powerful at 3.5keV
    - Or maybe not
- nuMSM under siege
- Athena (~ 2029) ……



Thanks you!