Dark Matter Velocity Spectroscopy

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arXiv: 1507.04744

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What is the dark matter?

- Dark matter exists and its nature is unknown
  - Characterized by bulk density and lack of interactions
- Possible clues from details of its clustering
  - Difficulties of CDM on small scales may be a clue
- But we need microphysical proof for identification
  - Decay or annihilation can produce distinctive signals

Sterile Neutrino Dark Matter

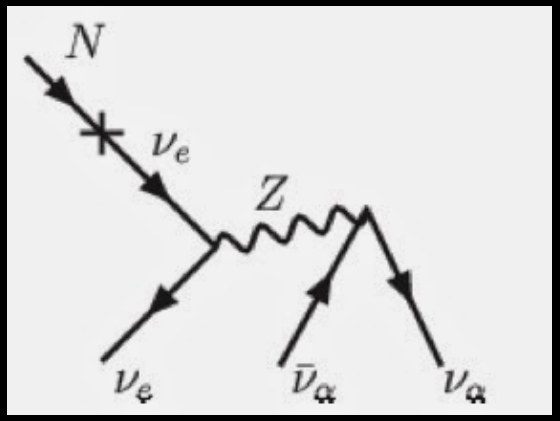
- keV-mass sterile neutrinos may be good candidates
  - Can create in the early universe
  - Can resolve small-scale clustering issues

- These actually have microphysical signals
  - Scattering, annihilation hopeless
  - But slow decay rate produces gamma rays

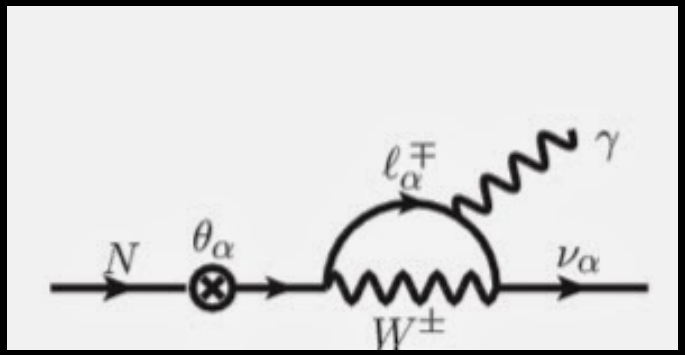
- Lots of limits on such scenarios
  - From details of production and clustering
  - From non-observation of X-rays

Sterile Neutrino Decays

- Primary Decay



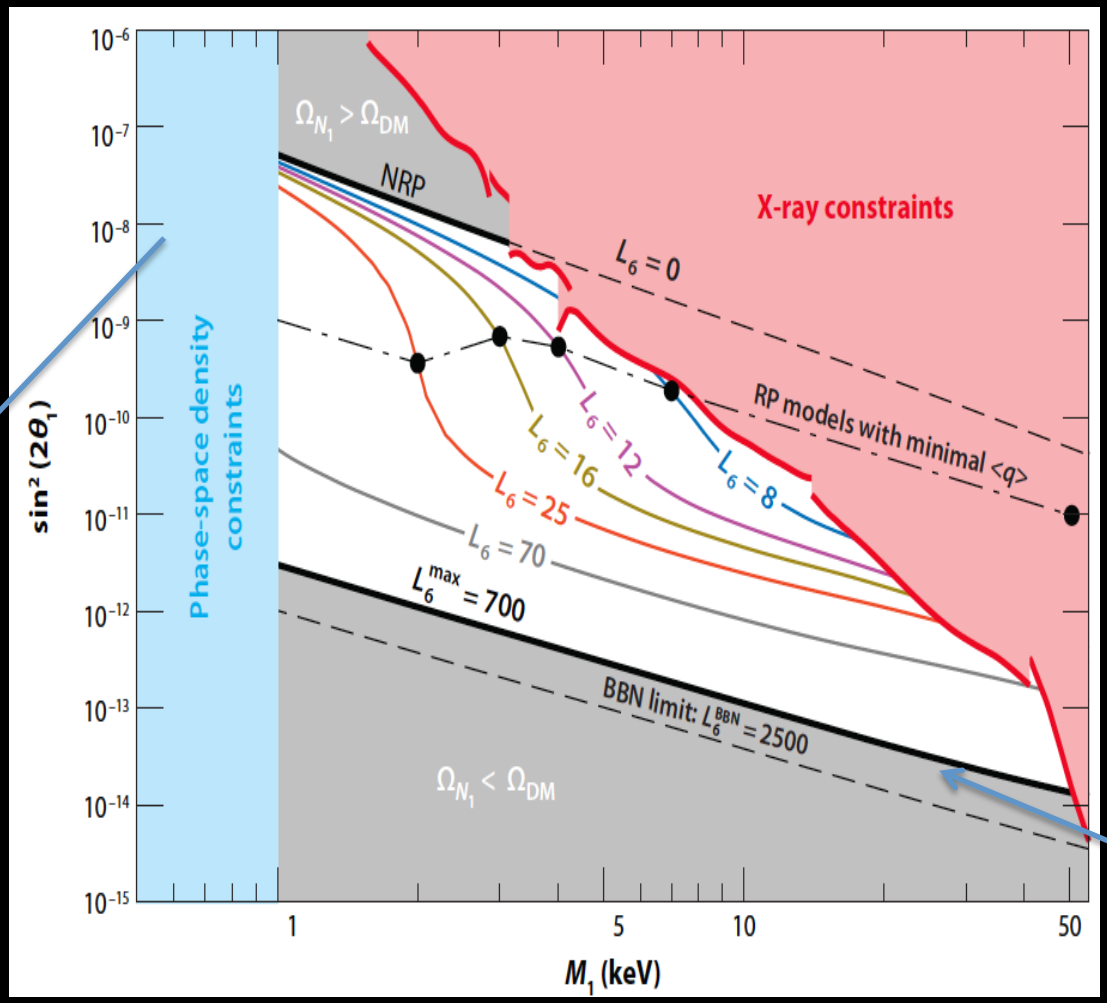
- Radiative Decay
  - Spectral line!



$$\Gamma = \frac{9\alpha G_F^2}{1024\pi^4}\sin^2 2\theta m_s^5 = 1.38\times 10^{-22}\sin^2 2\theta\left(\frac{m_s}{1\text{ keV}}\right)^5\ \text{s}^{-1} \approx \frac{1}{128}\Gamma_{3\nu},$$

Limited range of properties allowed

Galaxies/
Structures



Production
Method

- Bounded from all sides!

Search for Decay signals

- Use X-ray telescope to point at Dark Matter Clumps

X-ray Flux = $\frac{\rho_\odot R_\odot}{4\pi m_s \tau_s} \mathcal{J}(\psi) \frac{dN}{dE}$

Particle Physics

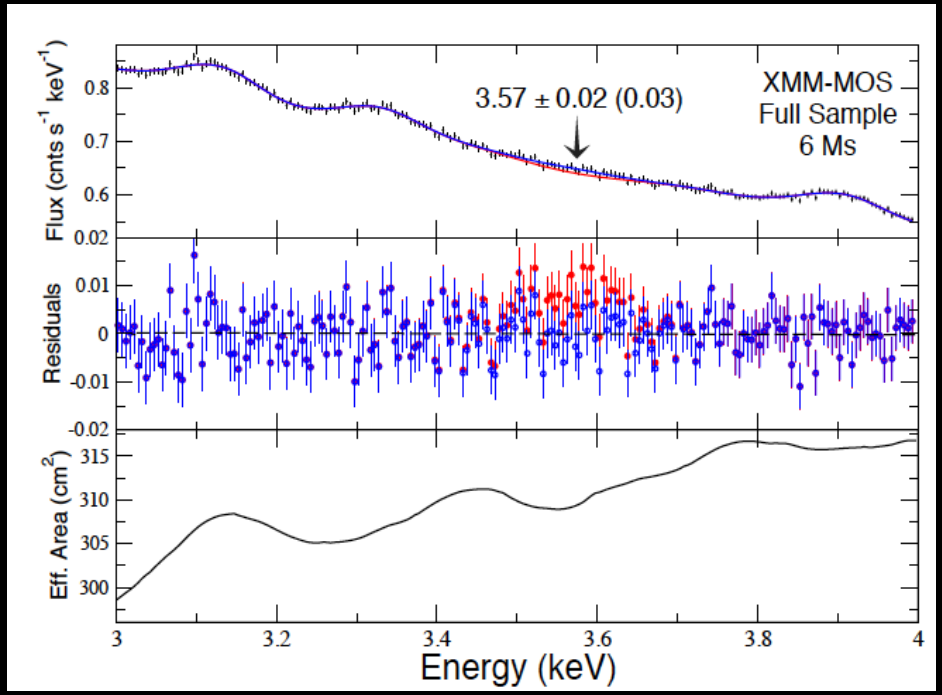
Spectral Shape

The amount of Dark Matter

$$\mathcal{J}(\psi) = \frac{1}{\rho_\odot R_\odot} \int_0^{\ell_{max}} d\ell \; \rho(\psi, \ell)$$

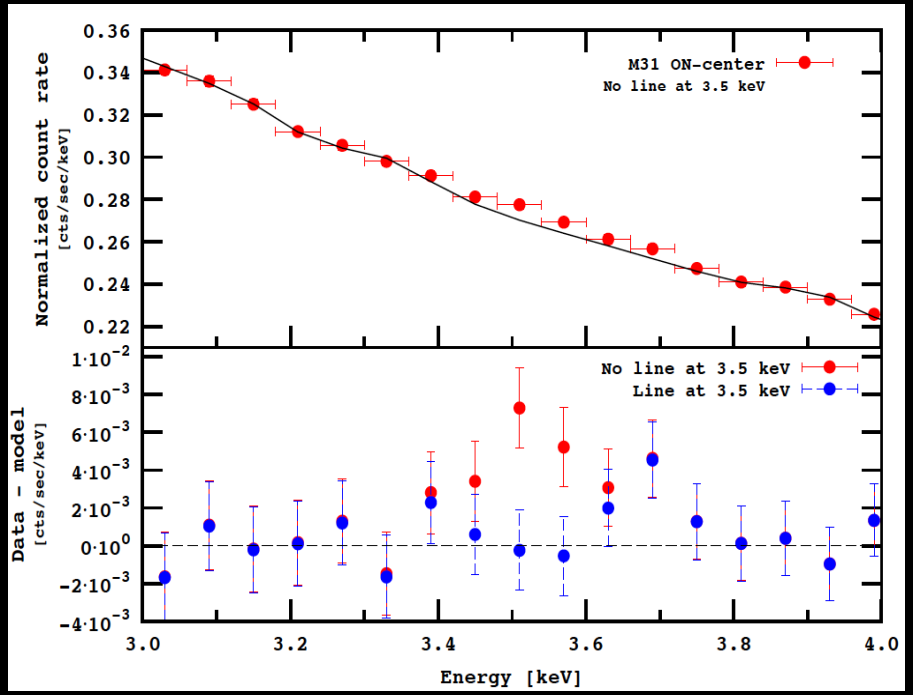
Latest claim (2014): a 3.5 keV line!

Bulbul et al (2014)



- 73 galaxy clusters stacked
- Range z = 0.01 to 0.35
- 4 to 5σ detection with XMM-Newton MOS
- Also see in XMM PN CCDs
- Also seen in Perseus with Chandra at 2.2σ

Boyarsky et al (2014)

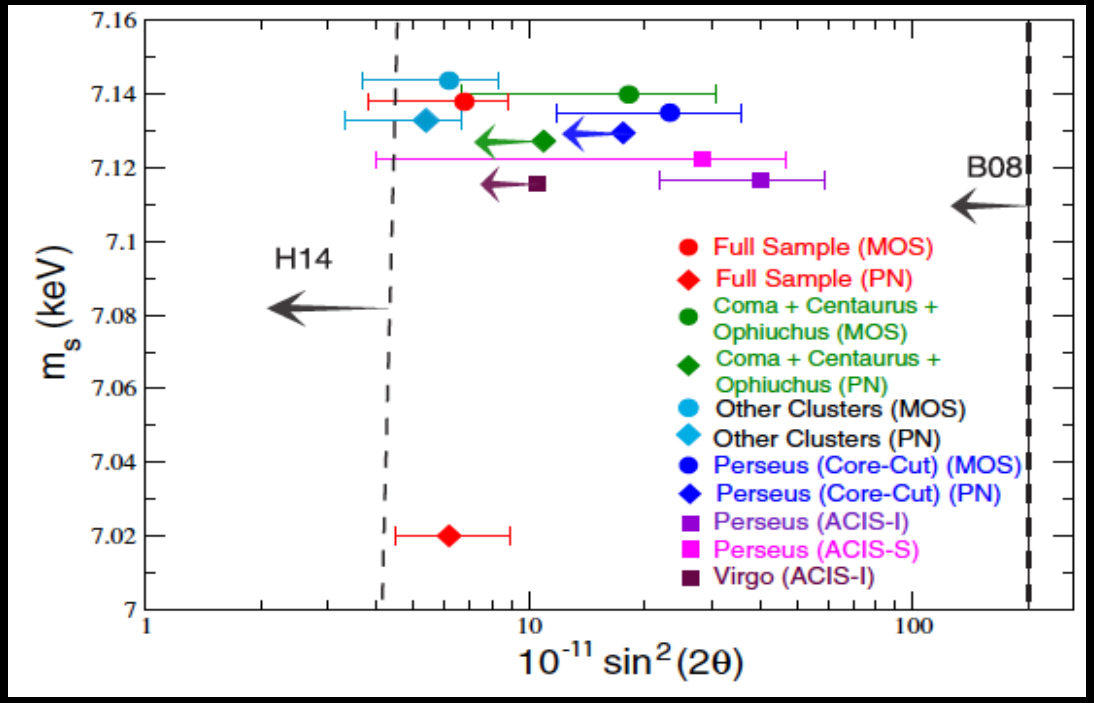


- Perseus indication at 2.3σ with XMM
- M31 indication at 3σ with XMM
- Combined detection ~4σ

Signals are consistent with each other

Slides taken from
S. Horiuchi 2014

More x-ray observations



← Bulbul et al 2014:
- ✓ 73 galaxy cluster stack [XMM]
- ✓ Perseus [XMM]
- ✓ Perseus [Chandra]
- × Coma+Cen+Ophiuchus [XMM]
- × Virgo [Chandra]

Boyarsky et al 2014:
- ✓ Perseus [XMM]
- ✓ M31 [XMM]

- × Riemer-Sorensen 2014: Milky Way [Chandra] – via modeling
- × Jeltema & Profumo 2014: Milky Way [XMM] – via modeling
- ✓ Boyarsky et al 2014b: Milky Way [XMM]
- × Anderson et al 2014: 81 galaxies [Chandra], 89 galaxies [XMM]
- × Malyshev et al 2014: 8 satellite dwarfs [XMM]
- × Tamura et al 2014: Perseus [Suzaku]
- ✓ Urban et al 2014: Perseus [Suzaku]
- × Urban et al 2014: Coma, Virgo, Ophiuchus [Suzaku]

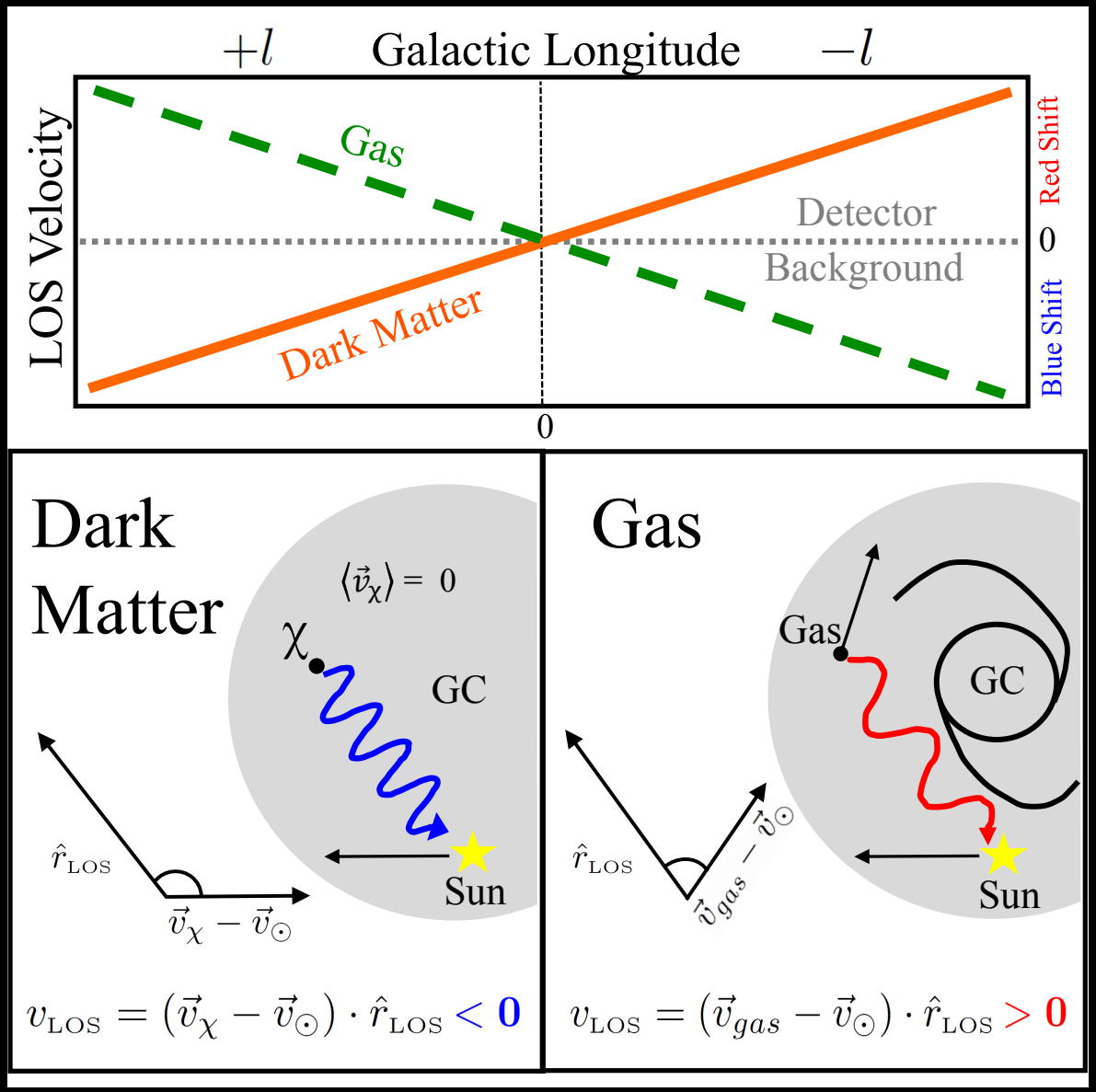
← Contested in:
Bulbul et al 2014b
Boyarsky et al 2014c

Slides taken from
S. Horiuchi 2014

How Do We Resolve This?

- Stakes are high for discovery of dark matter
- Investment is high but could not resolve
- A smoking gun is not enough

Dark Matter Velocity Spectroscopy



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What is Needed?

- Detect the line flux
- Detect the velocity shift
- Distinguish from other causes

Solutions to the 3.5 keV line?

- SXS - Astro-H
  - 10^{-3} resolution !

Properties	SXS	SXI	HXI
Effective area (cm^2)	50/225 (@0.5/6 keV)	214/360 (@0.5/6 keV)	300 (@30 keV)
Energy range (keV)	0.3-12.0	0.4-12.0	5-80
Angular resolution in HPD (arcmin)	1.3	1.3	1.7
Field of view ($arcmin^2$)	3.05x3.05	38x38	9x9
Energy resolution in FWHM (eV)	5	150 (@6 keV)	< 2000 (@60 keV)
Timing resolution (s)	$8x10^{-5}$	4	several x 10^{-5}
Instrumental background (/s/keV/FoV)	$2x10^{-3}/0.7x10^{-3}$ (@0.5/6 keV)	0.1/0.1 (@0.5/6 keV)	$6x10^{-3}/2x10^{-4}$ (@10/50 keV)[1] $2x10^{-3}/4x10^{-5}$ (@10/50 keV)[2]

Astro-H quick reference

Modified Signal Calculations

- 10^{-3} resolution <=> Typical galactic velocity
  - Velocity effects become important!

$$\frac{\rho_\odot R_\odot}{4\pi m_s \tau_s} \mathcal{J}(\psi) \frac{dN}{dE}$$

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

Line shift

Line dispersion

Line flux detection

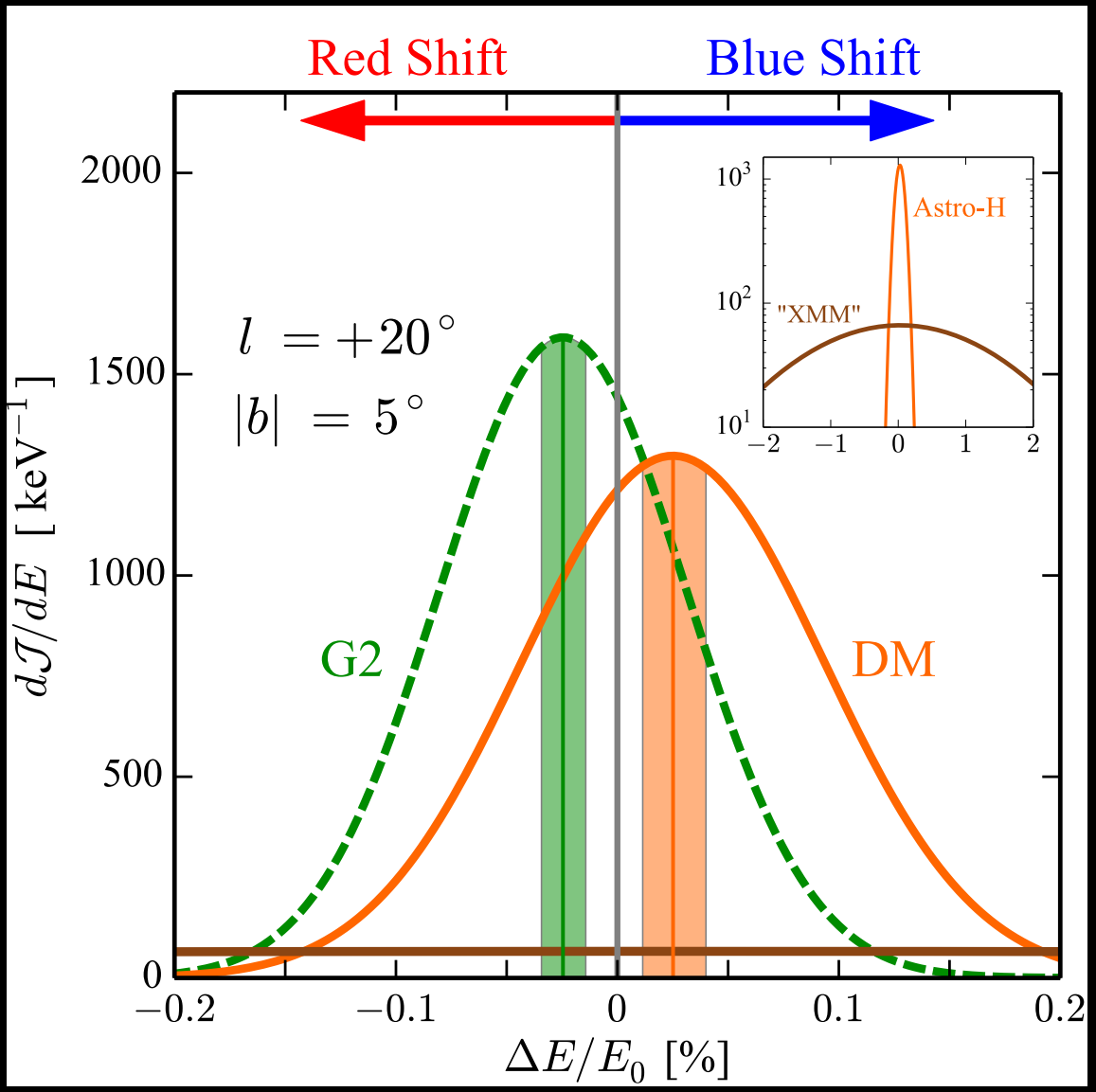
At longitude = 20 degrees, latitude = 5 degrees
2 Ms exposure

Signal events = 44

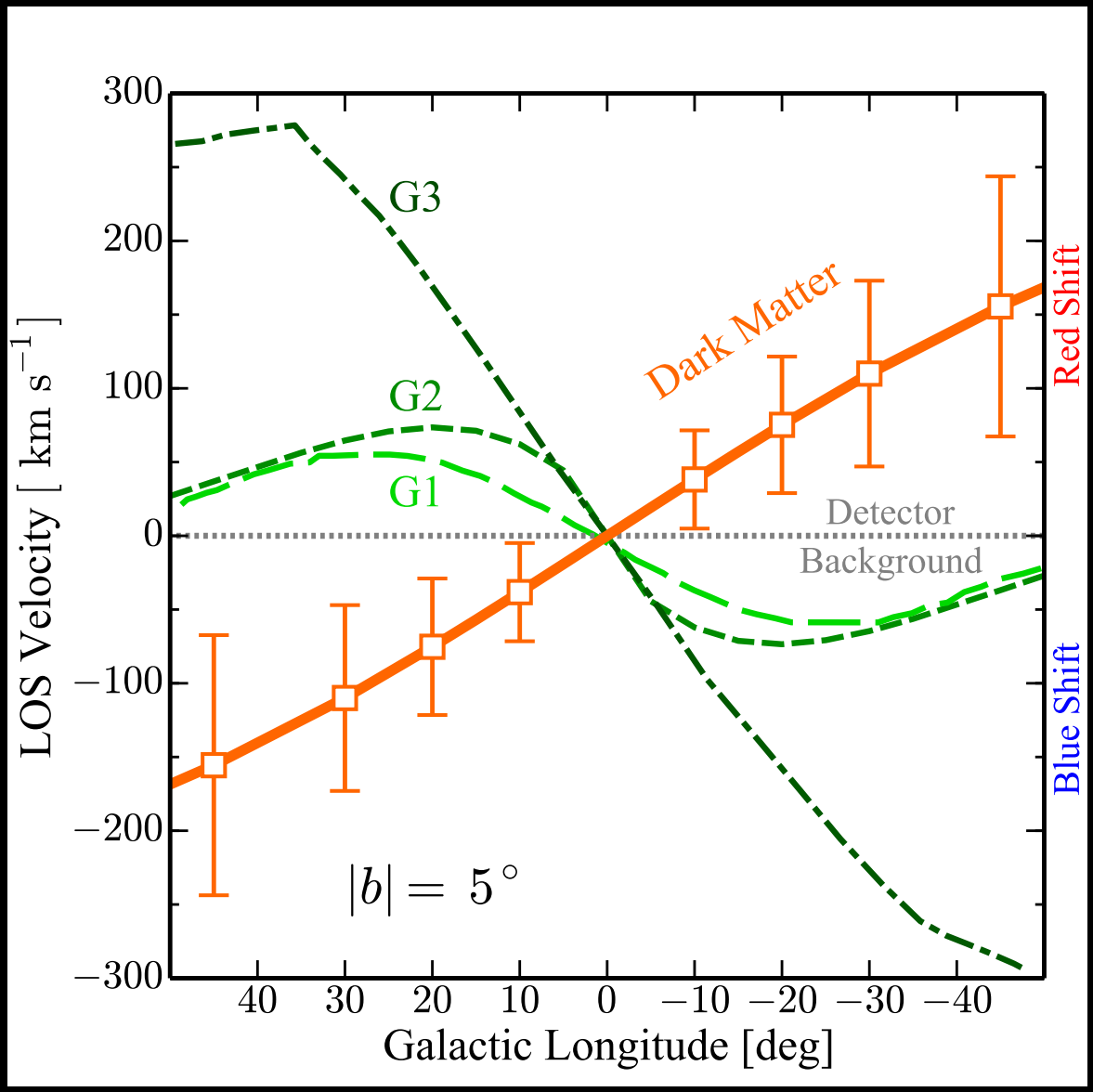
Background events = 5 + 5 + 5 = 15
(due to cosmic, Galactic, and detector backgrounds)

More than 9 sigma

Line Shift Detection



Line Shift Separation



DM Velocity Spectroscopy

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

- Ideas generalize

  keV to MeV to GeV

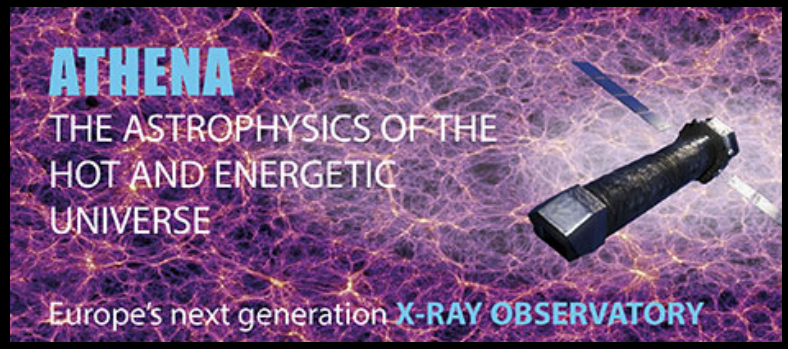
  MW to M31 and cosmology

  Decay and annihilation

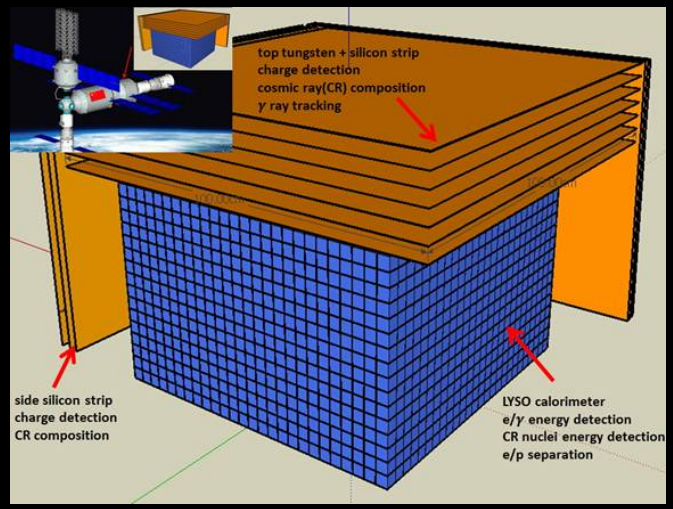
- New way to probe velocity distribution of DM

Future mission with ~10^{-3} resolution

- Athena (keV range)
  - E-resolution 2x better than SXS on Astro-H
  - ~5x photon collecting area
  - 2020-2030?



- HERD (GeV-TeV)
  - Photons and electrons
  - 2020?



Conclusions

- X-ray observations are powerful probes of Sterile neutrino Dark Matter
- Astro-H: increased sensitivity.
- Astro-H can test the origin the 3.5 keV line
  - With DM Vel. Spectroscopy
- Technique is much more general