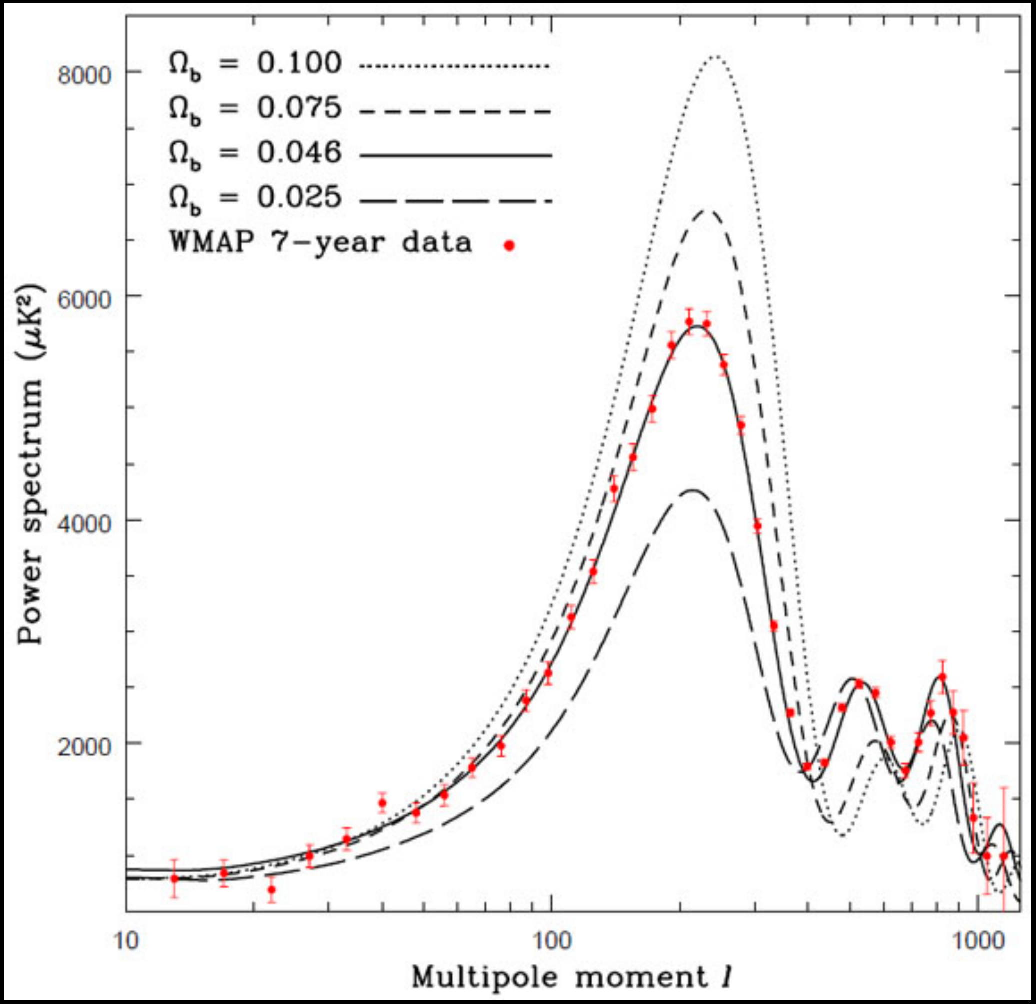
Searching for Sterile Neutrino Dark Matter with X-rays & Dark Matter Velocity Spectroscopy

Kenny, Chun Yu NG
CCAPP, The Ohio State University

Cold Dark Matter

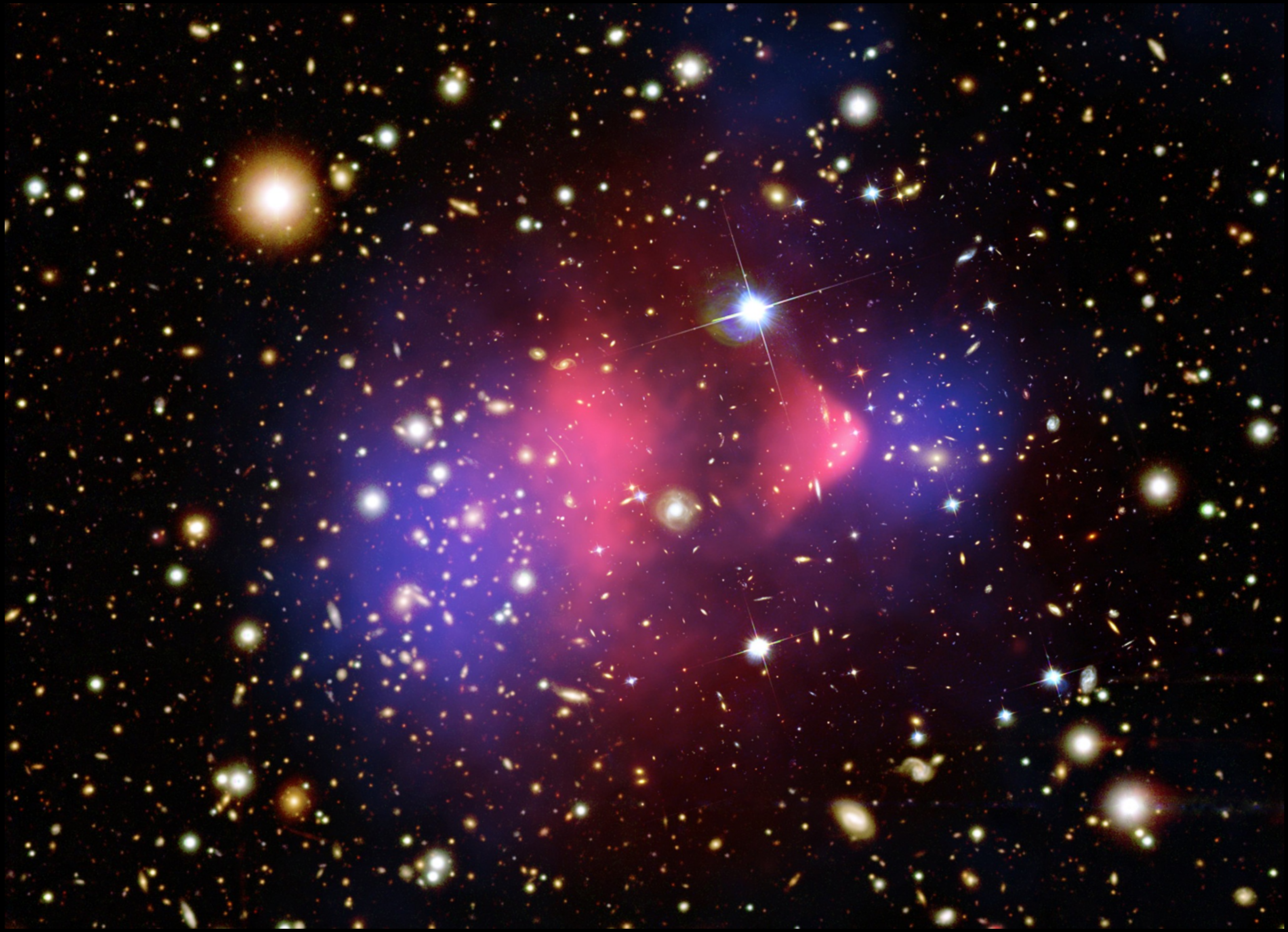
- The success of CDM models in large scales



http://ned.ipac.caltech.edu/level5/March10/Garrett/Garrett3.html

Cold Dark Matter

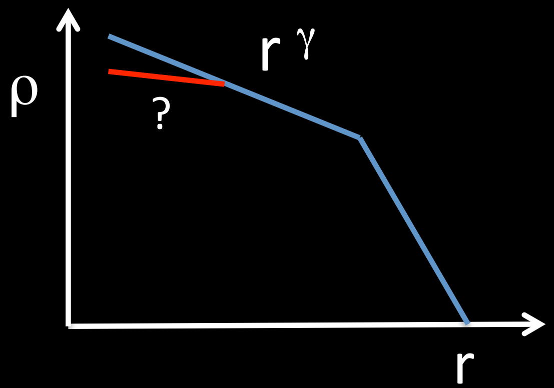
- The success of CDM models in large scales



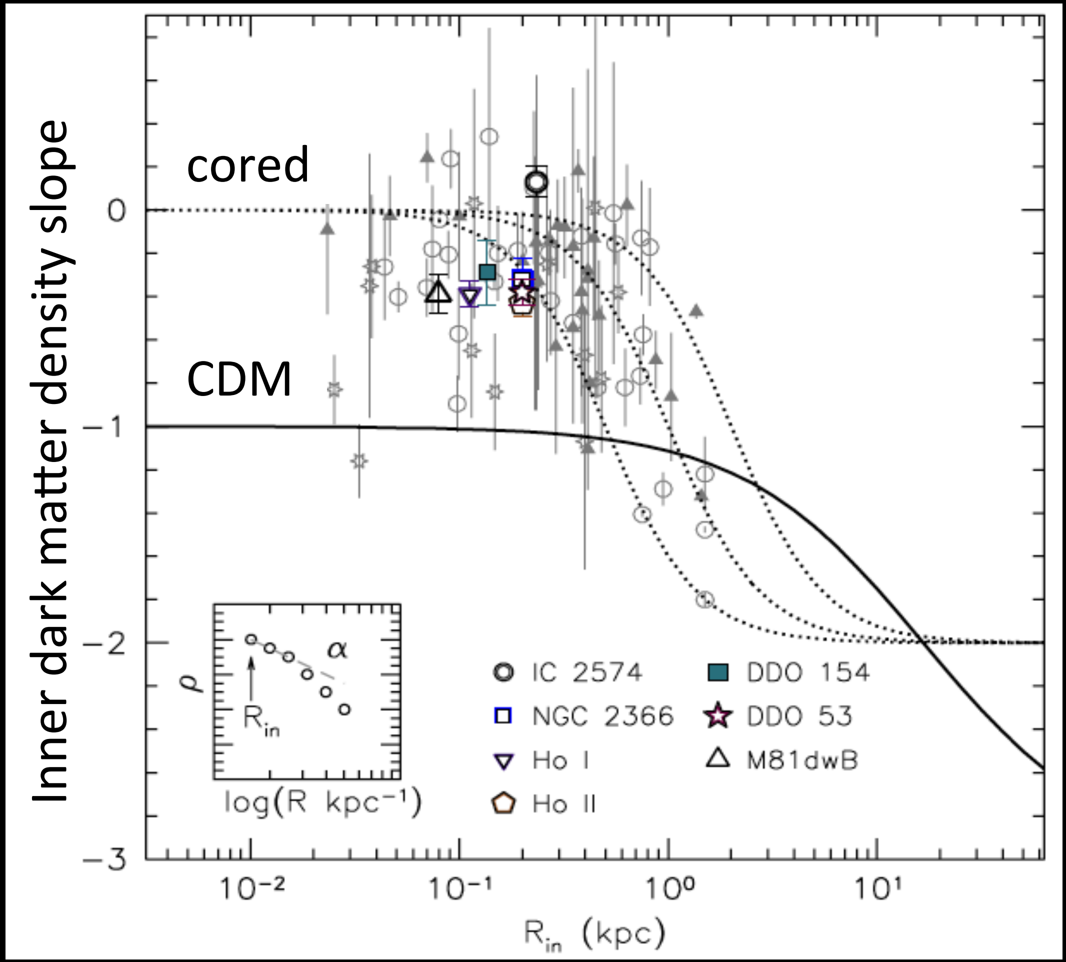
http://apod.nasa.gov/apod/ap060824.html

Cold Dark Matter

- Small Scale? (1)-- Core vs Cusp
- Cusp: <-1 index
- Core: ~0 index

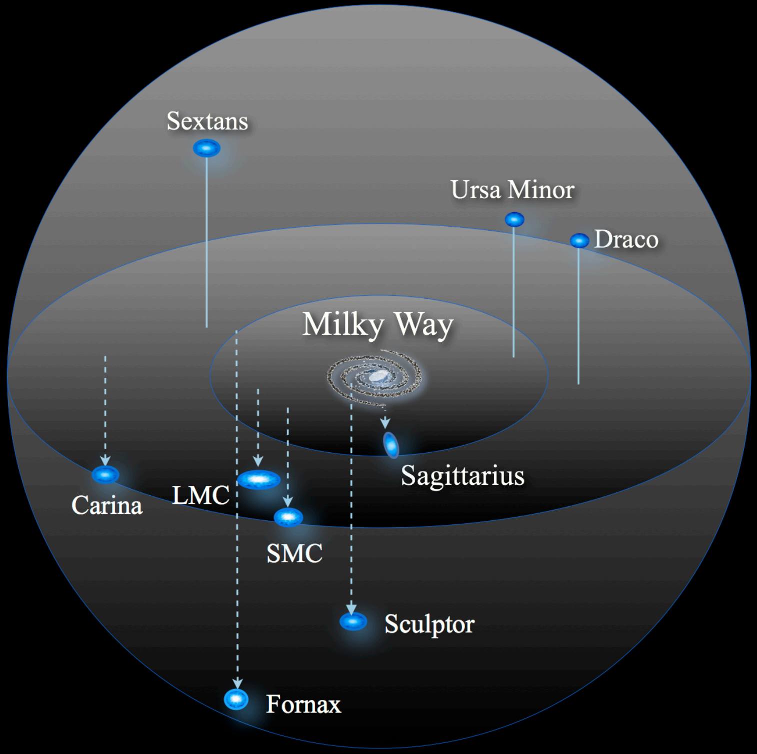


Oh et al (2011) [THINGS]



Cold Dark Matter

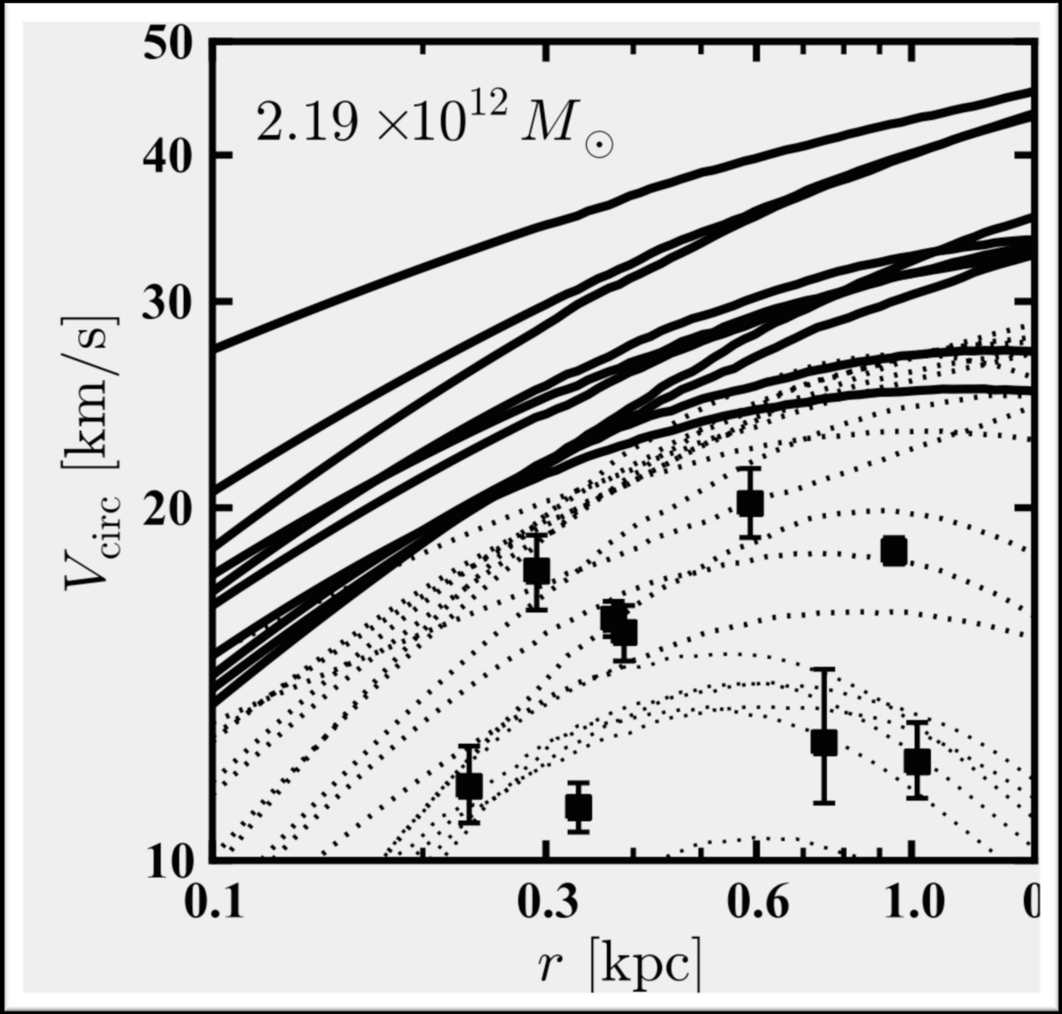
- Small Scale? (2)-- Missing satellite galaxies



Weinberg+
1306.0913

Cold Dark Matter

- Small Scale? (3)-- Too big to fail



Boylan-Kolchin+ 1111.2048

We need Dark Matter!

- Small scale problem?
  - Baryons?
  - Non-minimal Dark Matter?
    - Self-Interacting Dark Matter?
    - Warm Dark Matter?
    - +

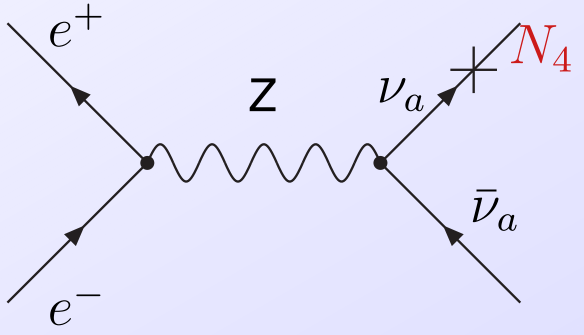
- Sterile Neutrinos Dark Matter
  - Can be a warm dark matter candidate!

Production: Non-Resonant

- Dodelson-Widrow (1994)

S. Pascoli 2009

In an interaction involving active neutrinos, a N_4 can be produced **due to loss of coherence**



The "sterile" neutrino N_4 production

- **depends on** $|V_{a4}|^2 = \sin^2\theta$
- **is controlled by** Γ_a and will stop at T_{dec}

$$\Omega_4 h^2 \simeq 0.3 \frac{\sin^2 2\theta}{10^{-8}} \left(\frac{m_4}{10\text{keV}}\right)^2$$

Production: Resonant

- Shi-Fuller(1999)
- MSW effect due to primordial lepton asymmetry

Abazajian+ 2001

$$\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + [\Delta(p)\cos 2\theta - V^D - V^T(p)]^2}. \quad (5.4)$$

$[\Delta(p)\cos 2\theta - V^D - V^T(p)]^2 \rightarrow 0$

- Can be "cool" dark matter
- Lepton asymmetry is also nice for leptogenesis.

Production: Decay of heavy particles

Petraki CosPA 2009

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N} i \partial\!\!\!/ N + \frac{1}{2}(\partial S)^2 - yH\bar{L}N - \frac{f}{2} S \bar{N}^c N - V(H,S) + h.c.$$

The Majorana masses arise after SSB

$$M = f\langle S \rangle$$

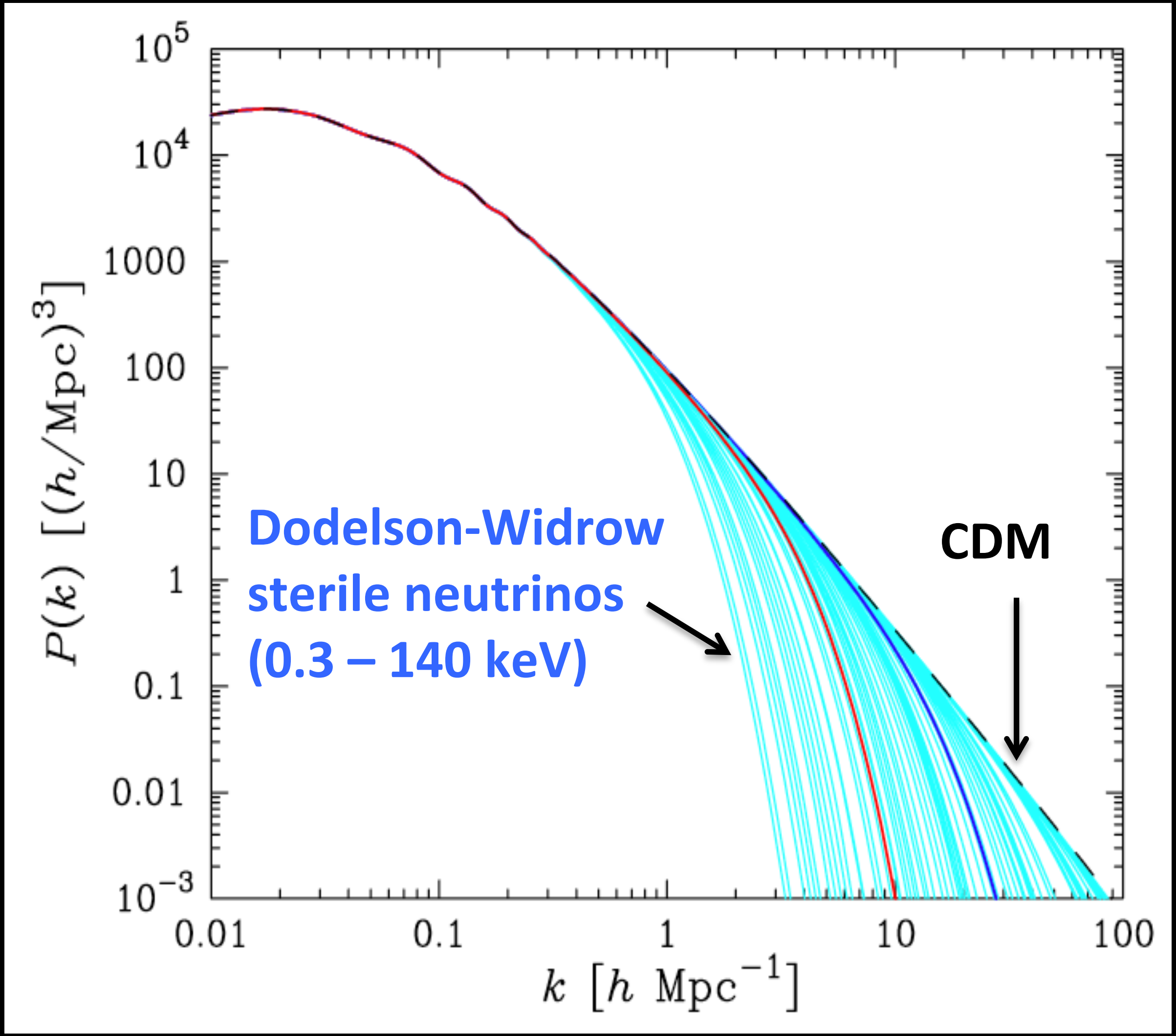
Sterile neutrinos are produced by S decays

$S \rightarrow N\,N$

- No mixing angle dependence
- New scalar -> LHC

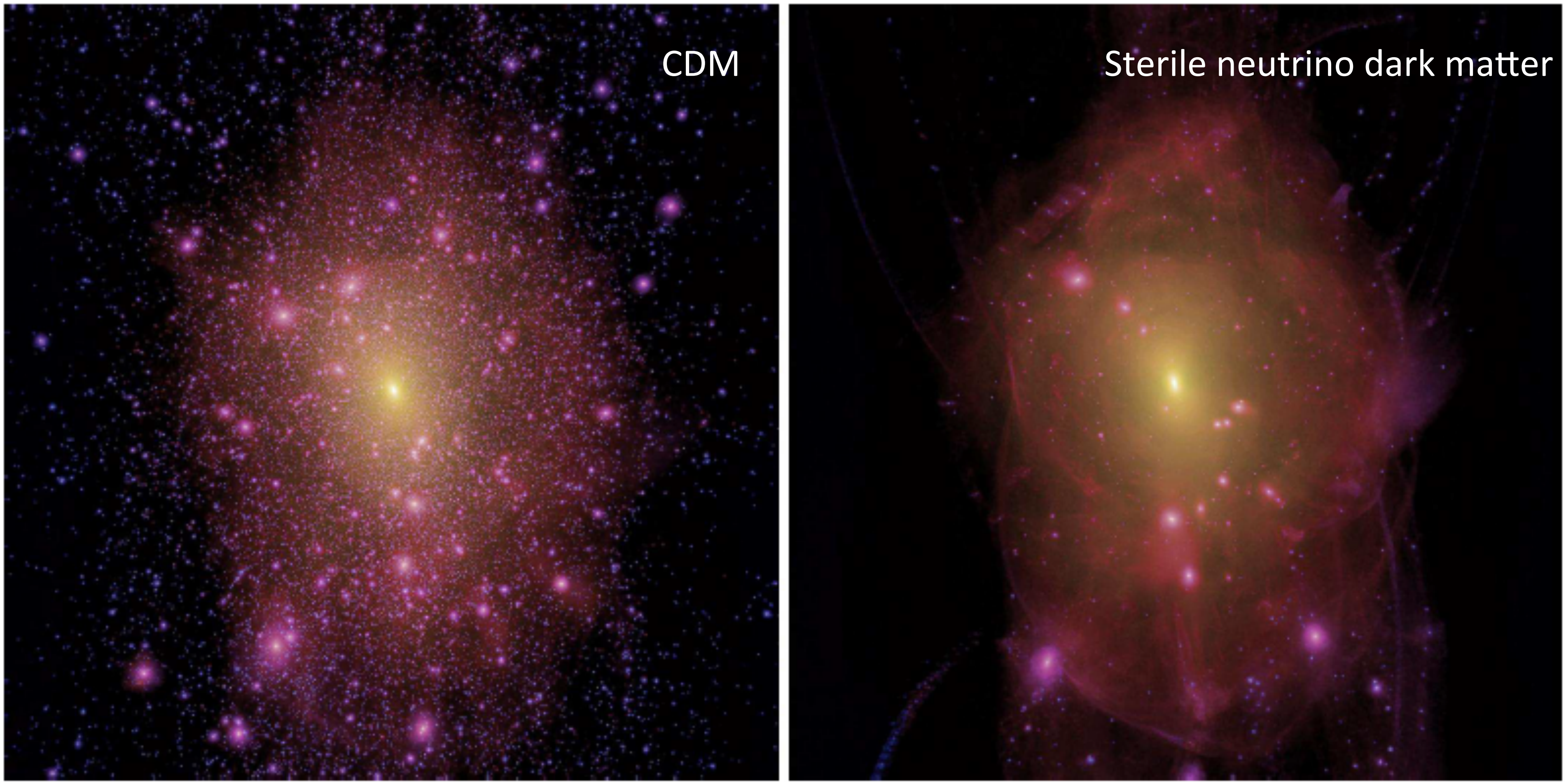
Sterile Neutrinos

Suppression of power on small scales



Abazajian, PRD (2006)

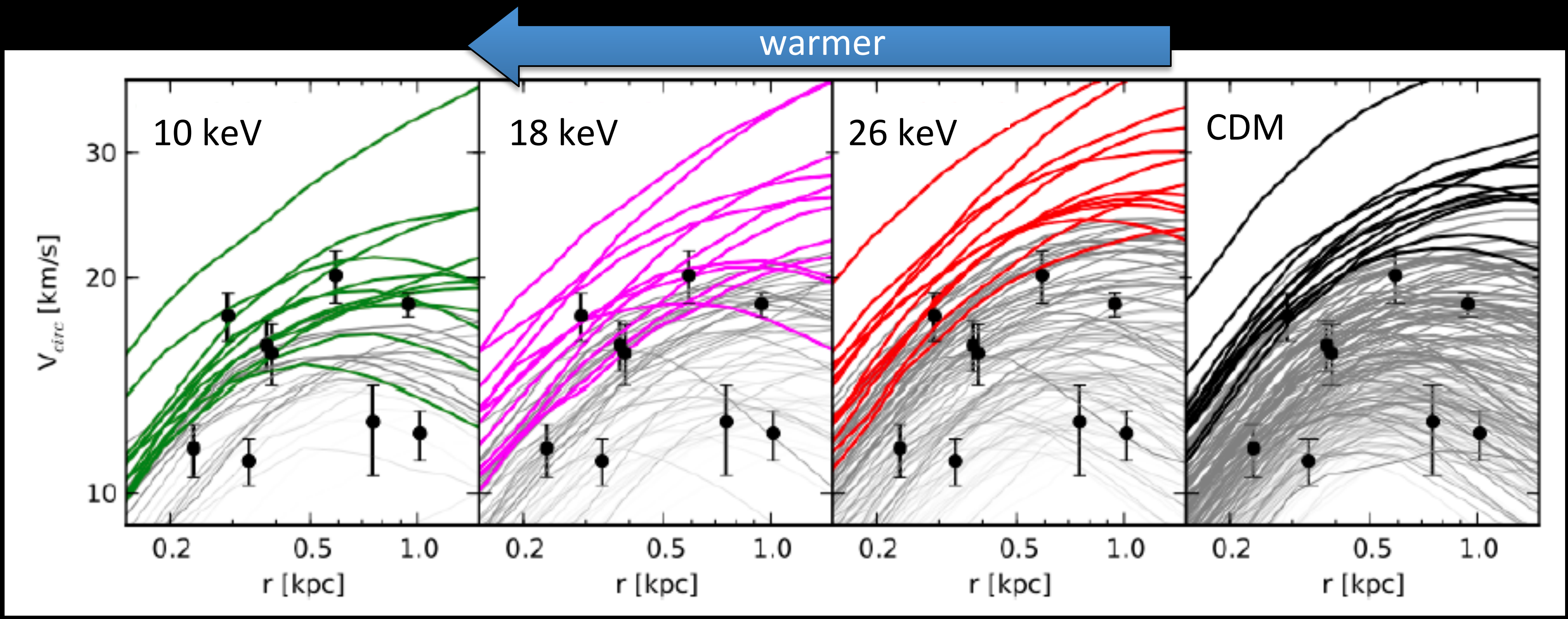
Sterile Neutrinos



Lovell et al, MNRAS (2012)

Based on a resonant sterile neutrino models in Boyarsky et al (2009)

Sterile Neutrinos



Schneider et al, MNRAS (2013)

See also:

Lovell et al, MNRAS (2012)

Anderhalden et al, MNRAS (2012)

How do we find Sterile Neutrinos?

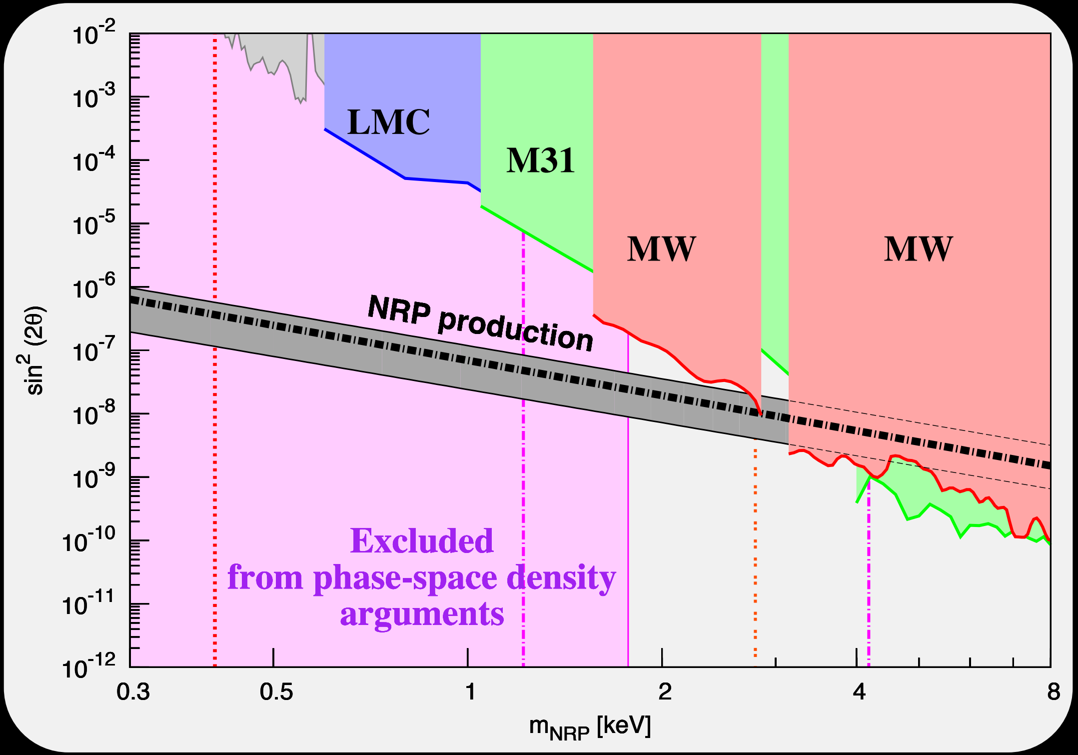
- Direct detection is hopeless

- Effect of dark matter mass or warmness
  - Galaxy dynamics
  - Structure formation

- Effect of mass and mixing
  - X-rays searches
  - pulsar kicks, etc

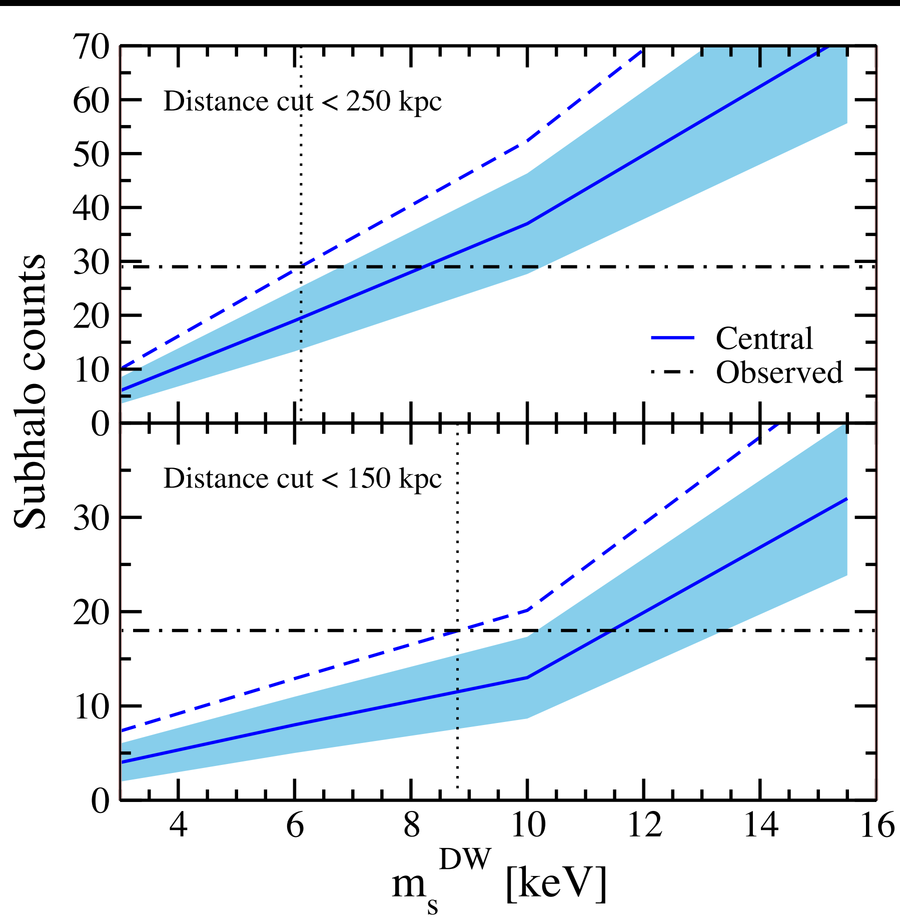
Galaxy Dynamics

- Tremaine-Gunn (1979)
- Fermionic dark matter occupy finite phase spaces
  - Pauli's exclusion principle.

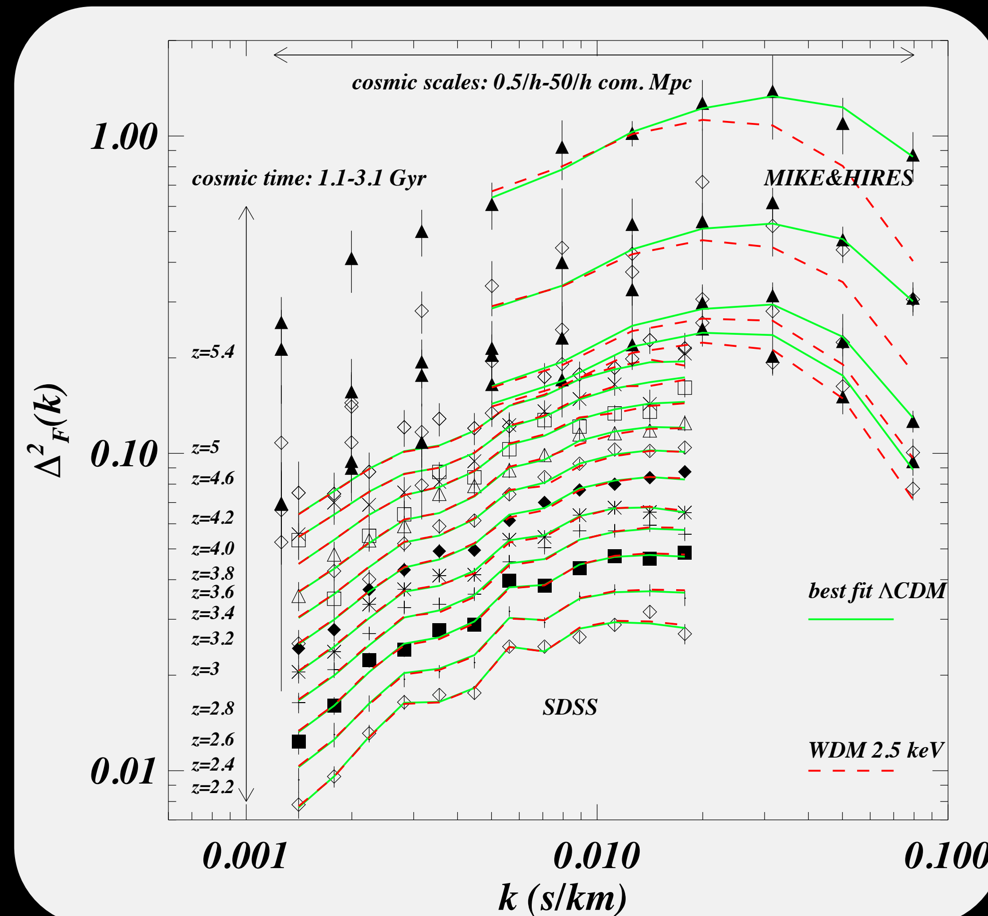


Boyarsky+
0808.3902

Structure formation



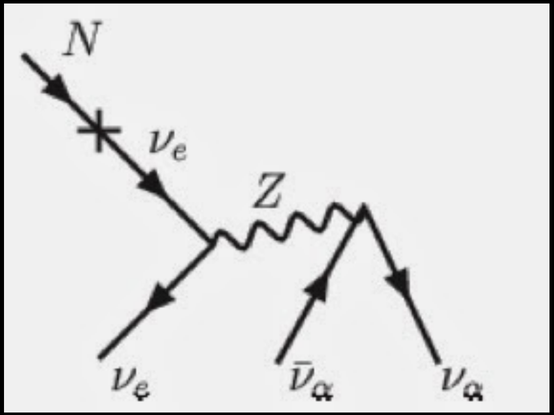
M31 subhalos, Horiuchi+ 2014



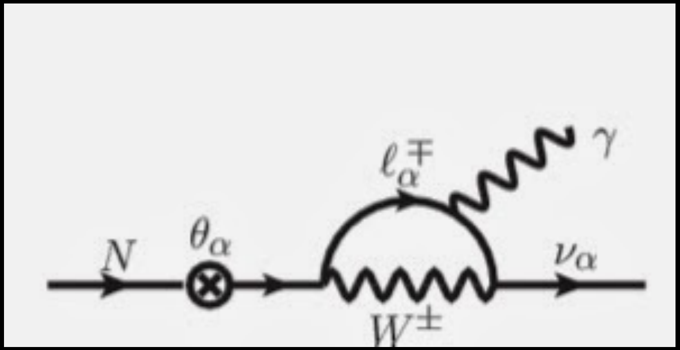
Viel+ 1306.2314

Sterile Neutrino Decays

- Primary Decay



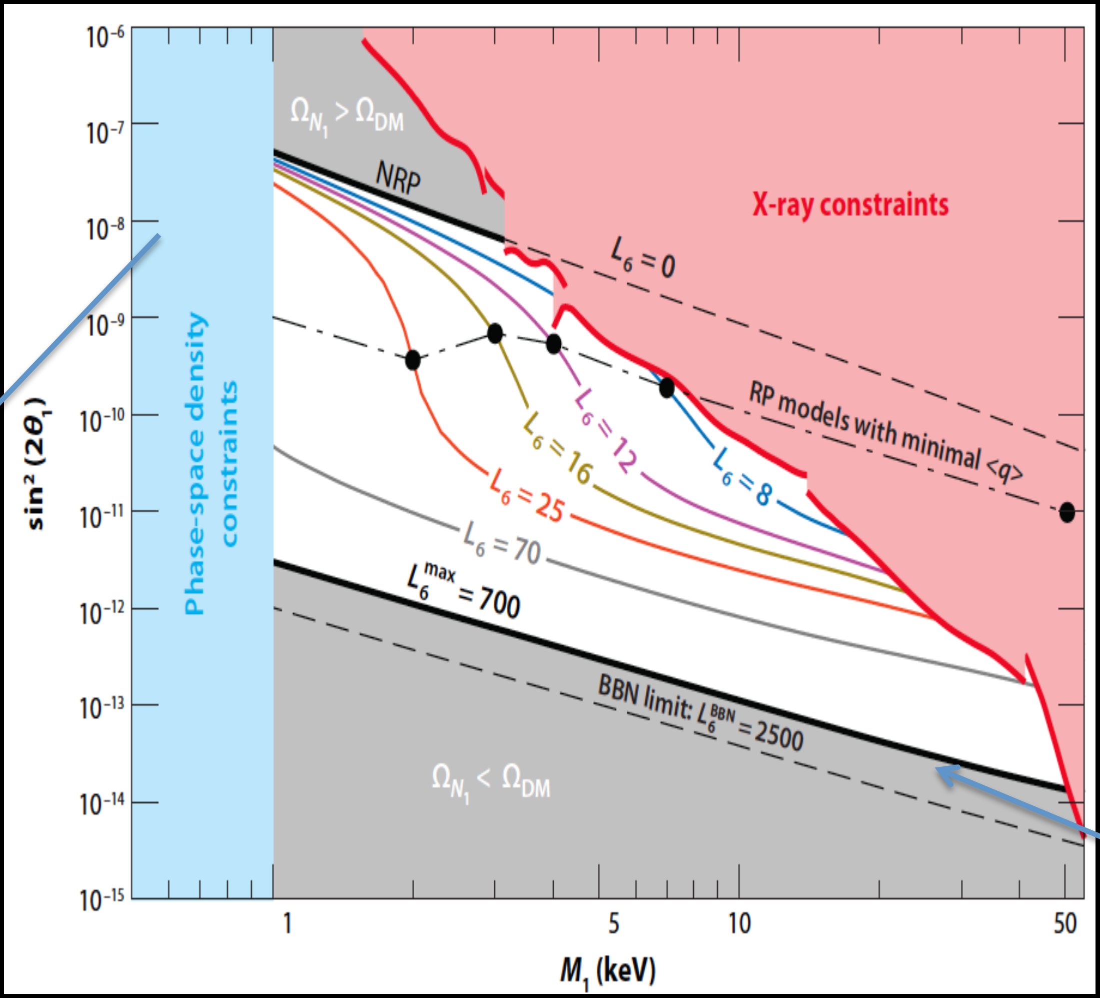
- Radiative Decay
  - Spectral line!



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

Typical Constraint Plot

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

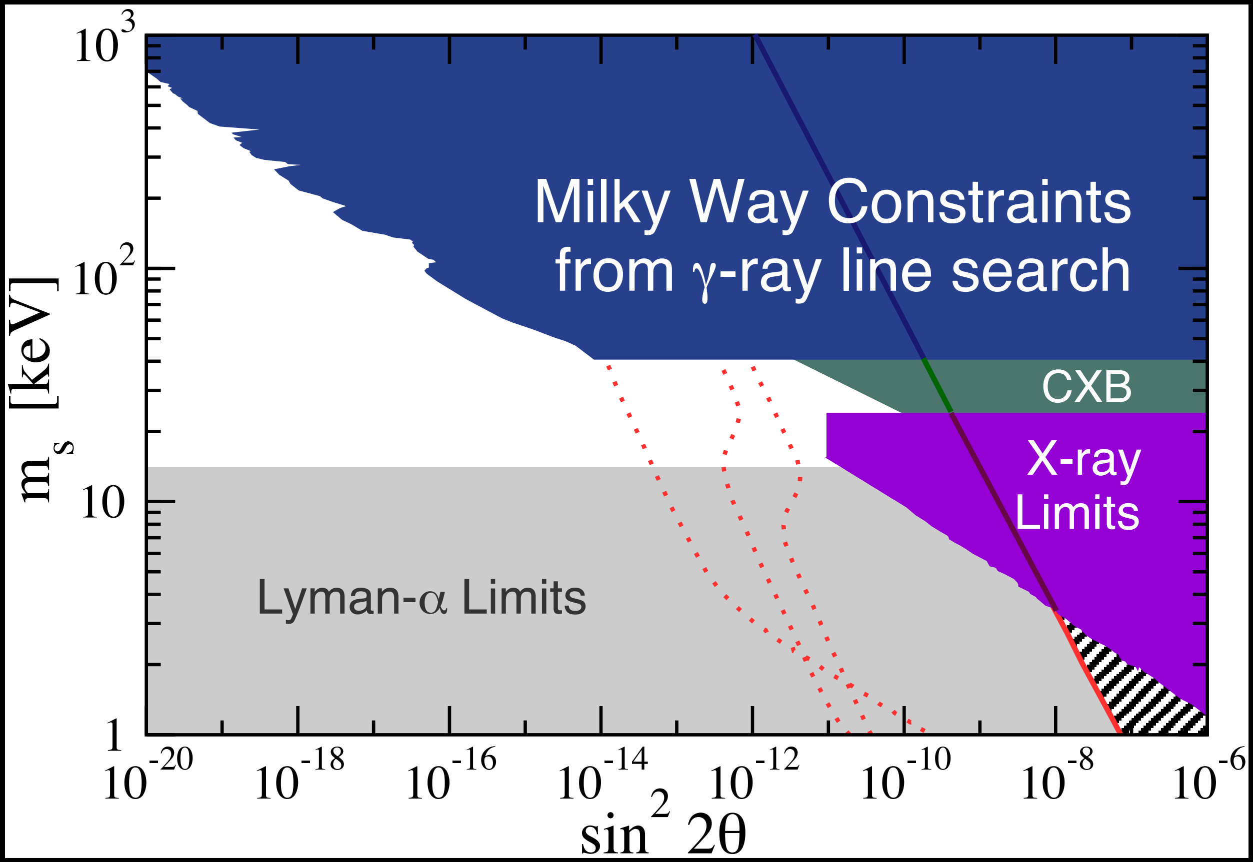
The amount of Dark Matter

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

A long History of searches

- Depending on the tools and the target

Yuksel et al. 2008



Detections were claimed

- 2.5 keV line

2010, 2012

DARK MATTER SEARCH USING *CHANDRA* OBSERVATIONS OF WILLMAN 1 AND A SPECTRAL FEATURE CONSISTENT WITH A DECAY LINE OF A 5 keV STERILE NEUTRINO

MICHAEL LOEWENSTEIN[1,2] AND ALEXANDER KUSENKO[3,4]

DARK MATTER SEARCH USING *XMM-NEWTON* OBSERVATIONS OF WILLMAN 1

MICHAEL LOEWENSTEIN[1,2] AND ALEXANDER KUSENKO[3,4]

Loewenstein+2012:We do not confirm the Chandra evidence for a 2.5 keV emission line

- 8.5 keV line

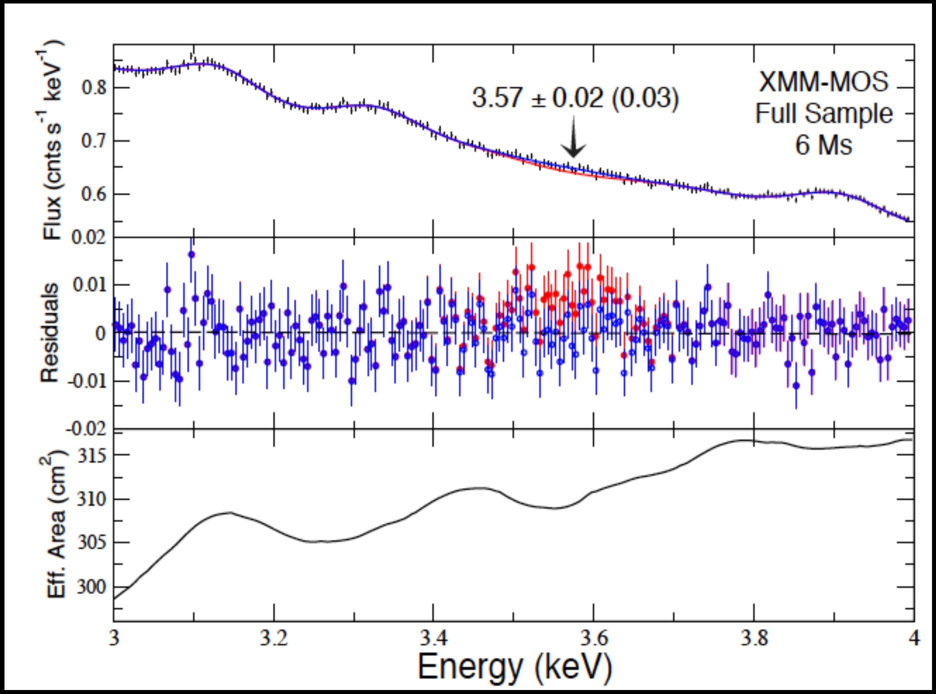
CAN THE EXCESS IN THE Fe XXVI Lyγ LINE FROM THE GALACTIC CENTER PROVIDE EVIDENCE FOR 17 keV STERILE NEUTRINOS?

DMITRY PROKHOROV[1] AND JOSEPH SILK[2,3]

  – Not much follow up on this

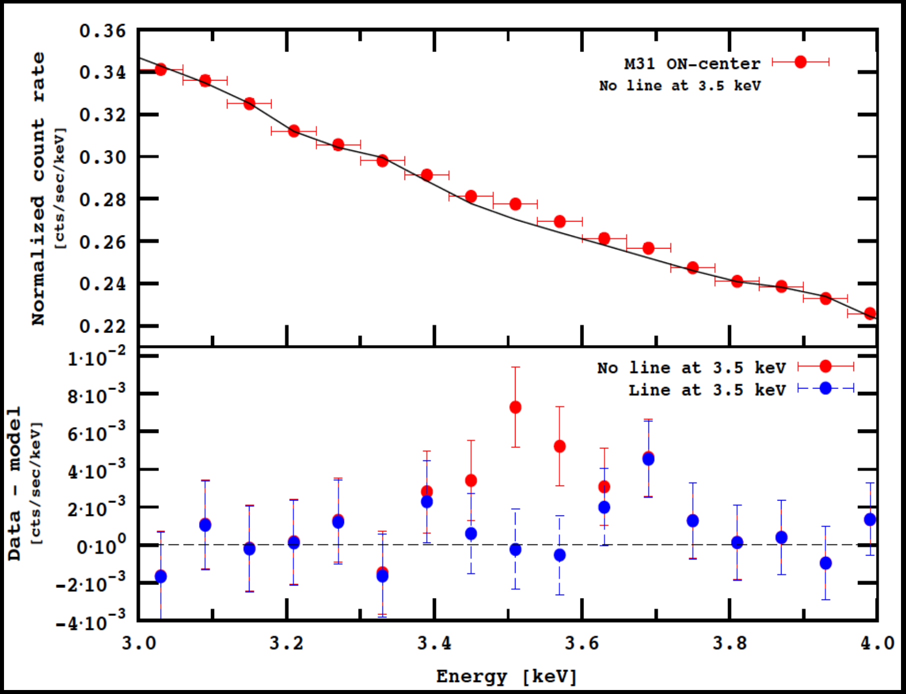
Latest claim (2014): a 3.5 keV line!

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)

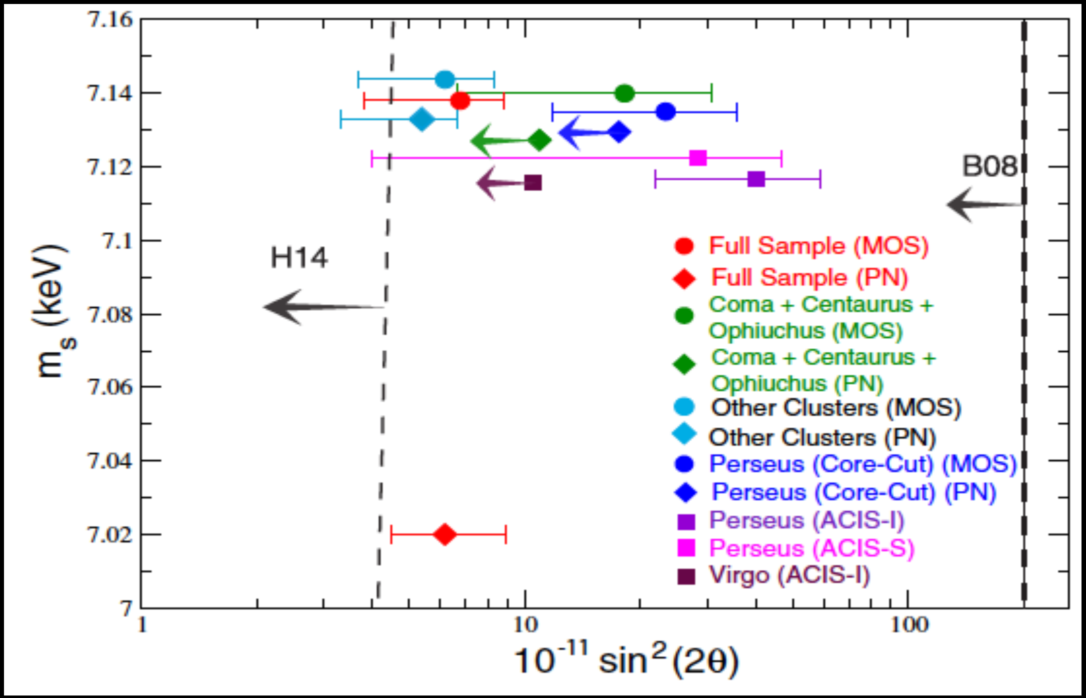


- Perseus indication at 2.3σ with XMM
- M31 indication at 3σ with XMM
- Combined detection ~4σ

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]

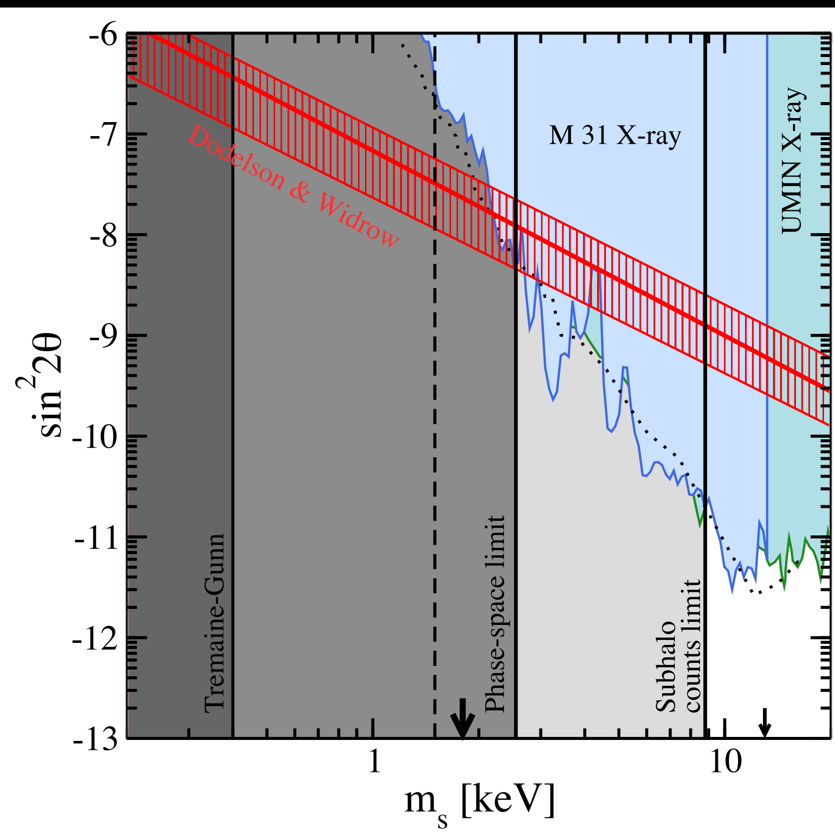
Boyarsky et al 2014:
✓ Perseus [XMM]
✓ M31 [XMM]

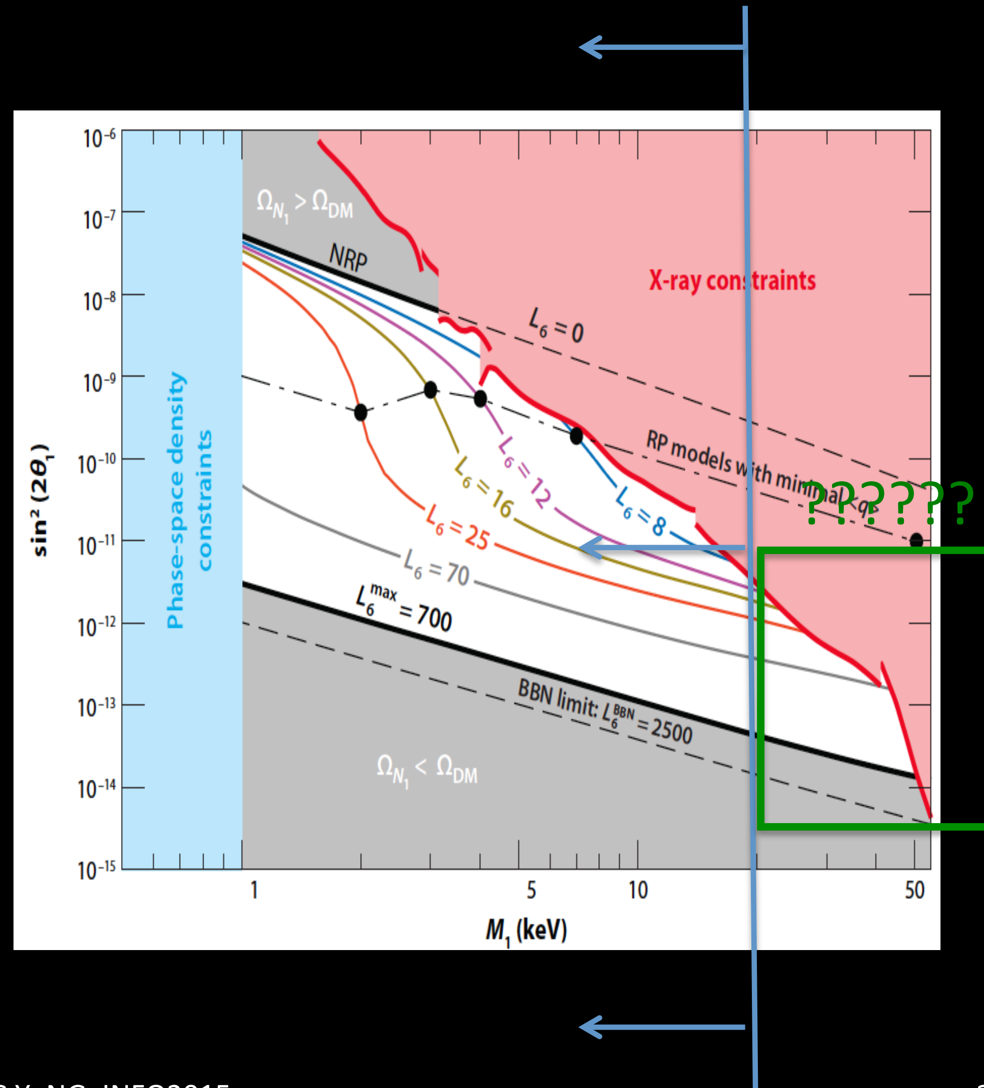
× Riemer-Sorensen 2014: Milky Way [Chandra] – via modeling
× Jeltema & Profumo 2014: Milky Way [XMM] – via modeling ← Contested in: Bulbul et al 2014b, Boyarsky et al 2014c
✓ Boyarsky et al 2014b: Milky Way [XMM]
× Anderson et al 2014: 81 galaxies [Chandra], 89 galaxies [XMM]
× Malyshev et al 2014: 8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

Slides taken from S. Horiuchi 2014

In the mean time

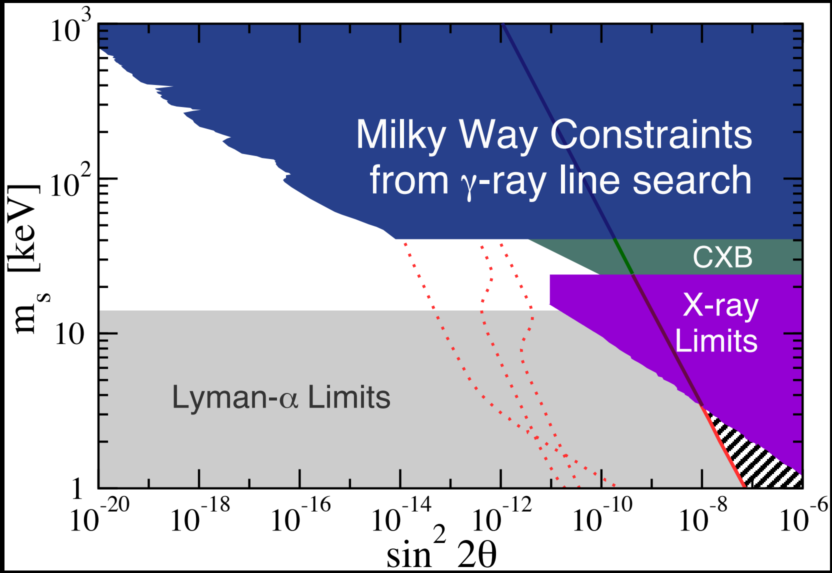
- Latest constraints





An annoying energy gap 10-20 keV

- Mass range 20 - 40 keV
- Last probed by
  - HEAO-1 (1979)

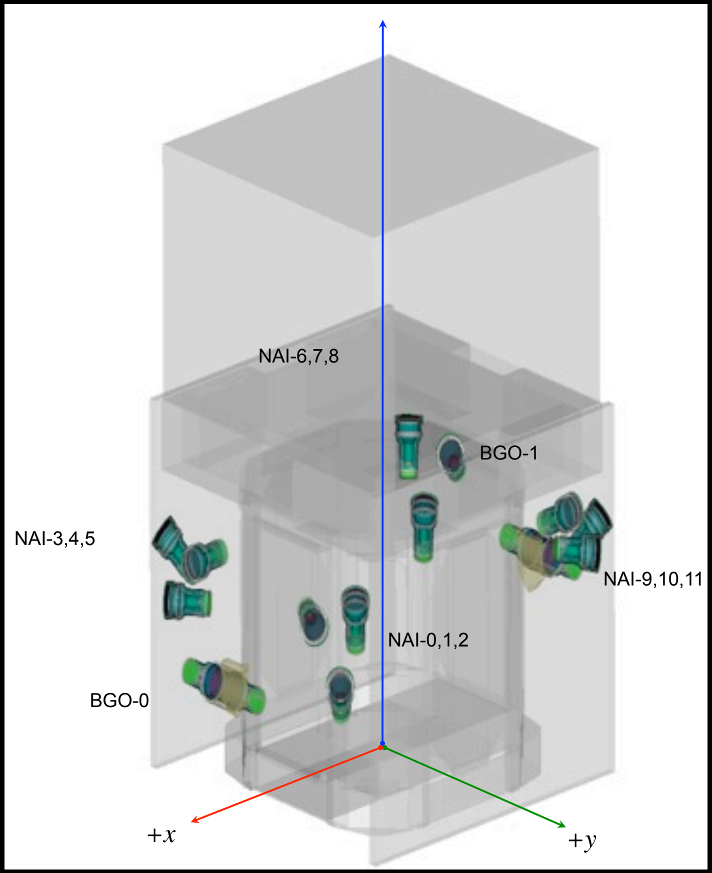


	Chandra	XMM-N	Suzaku	????	INTEGEAL
FoV	17' x 17'	30' x 30'	18' x 18'		
range [keV]	0.4–8	0.2–12	0.3–12	10 – 20 keV	20 keV +
E res (E/dE)	~50	~50	~50		
Ang res	1"	6"	90"		

A new tool?

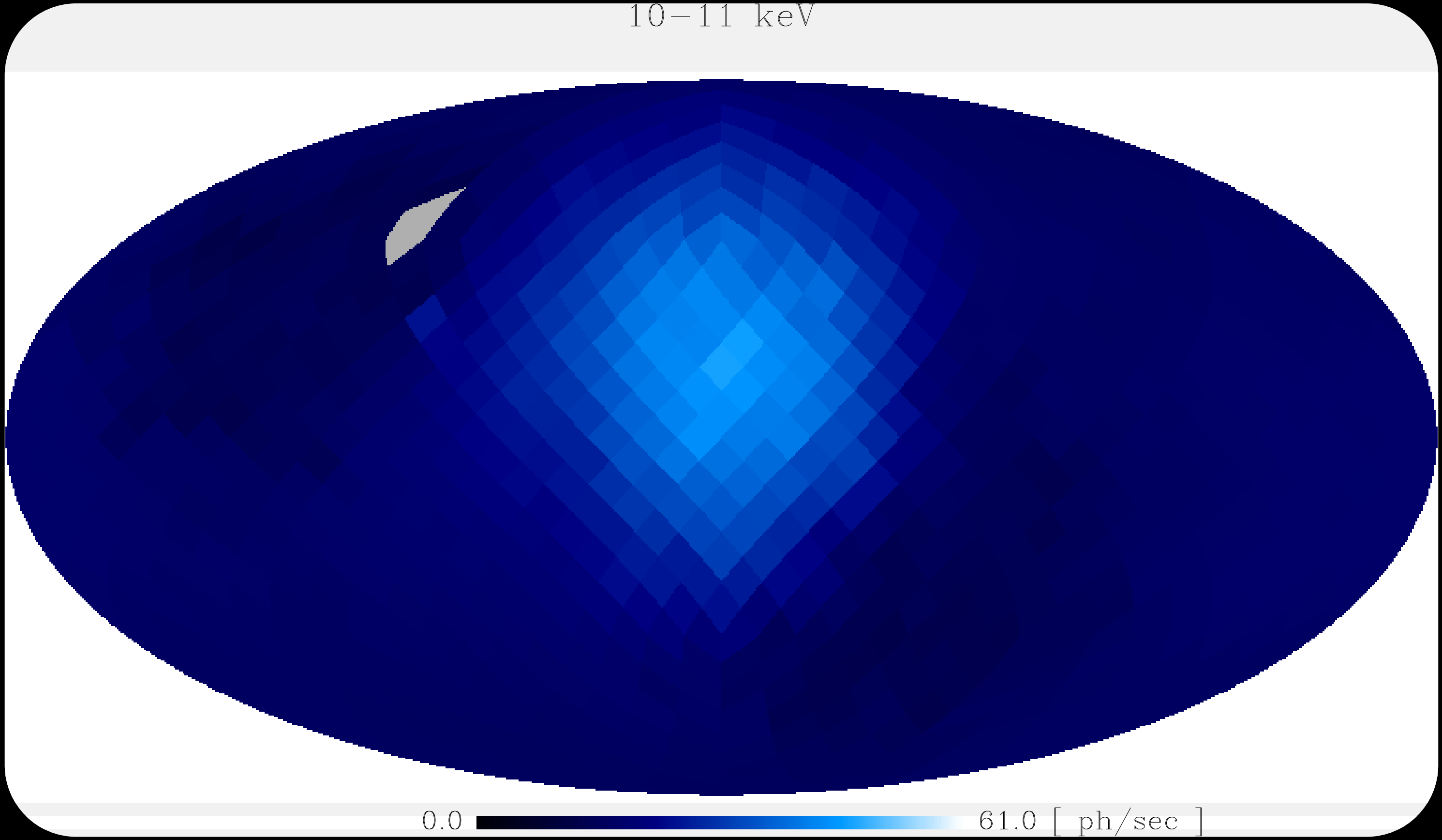
- Fermi Gamma Ray Burst Monitor (GBM)

Ng, Horiuchi, Gaskins, Smith, Preece 1504.04027



A blurry Sky map

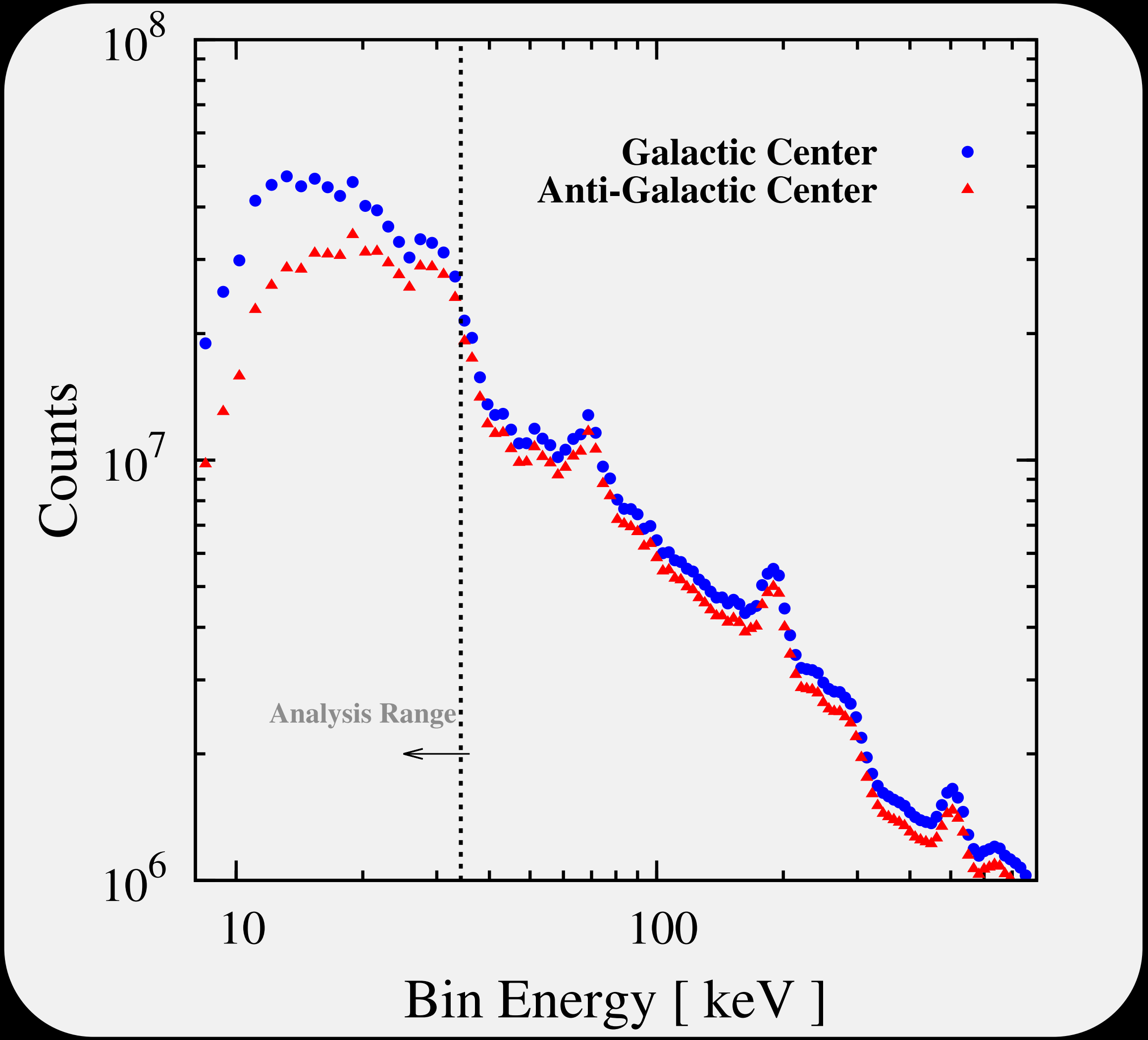
- 10 – 11 keV



- We found the galaxy!

Ng+ 2015

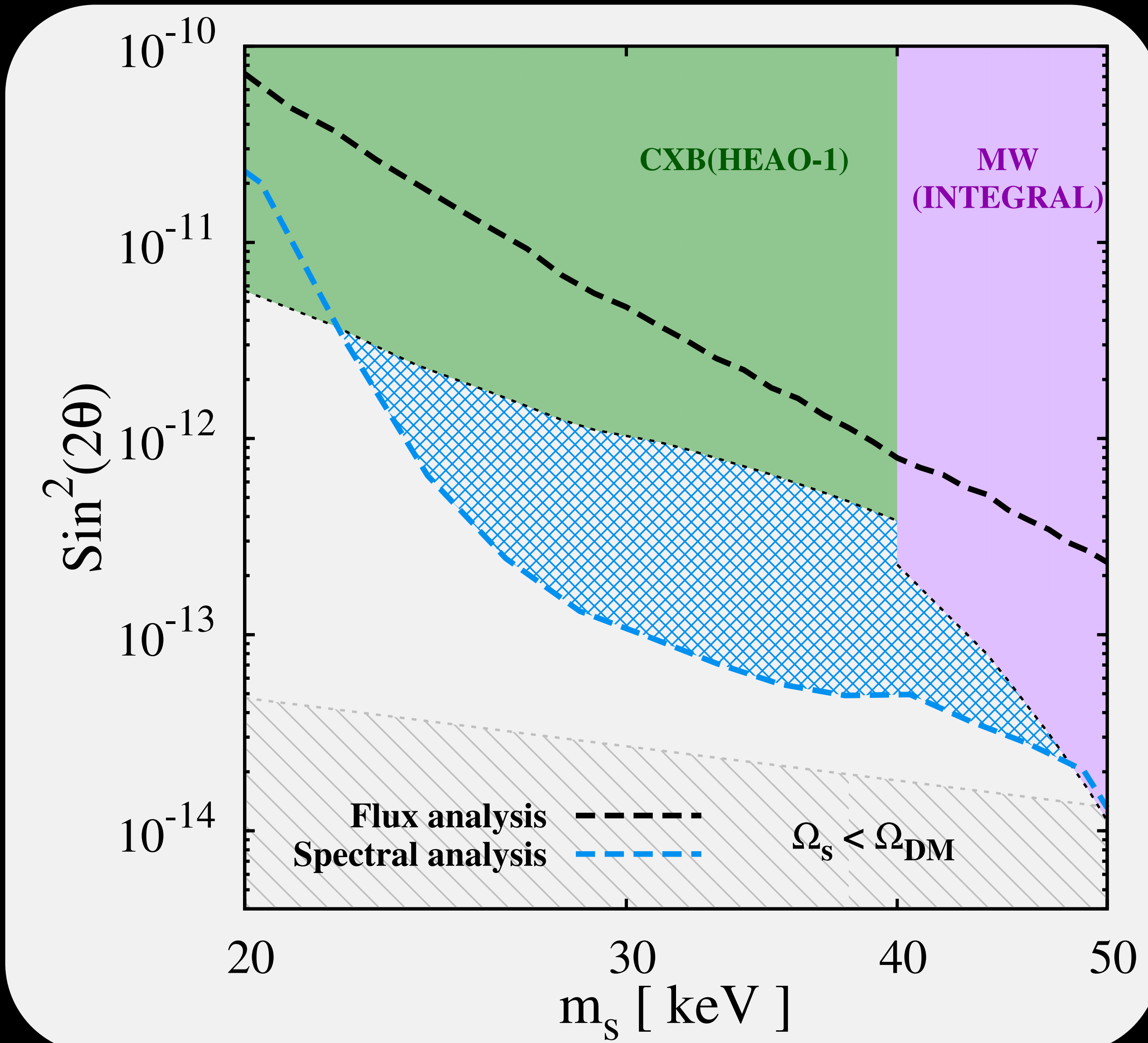
Lots of photons



- The data set is systematic dominated

Ng+ 2015

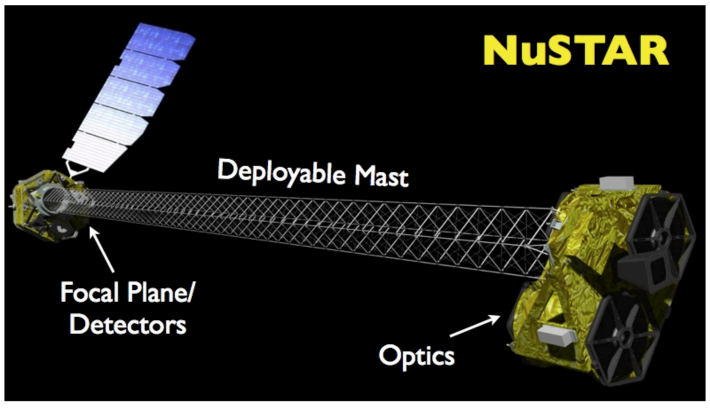
Final Constraint-Fermi GBM



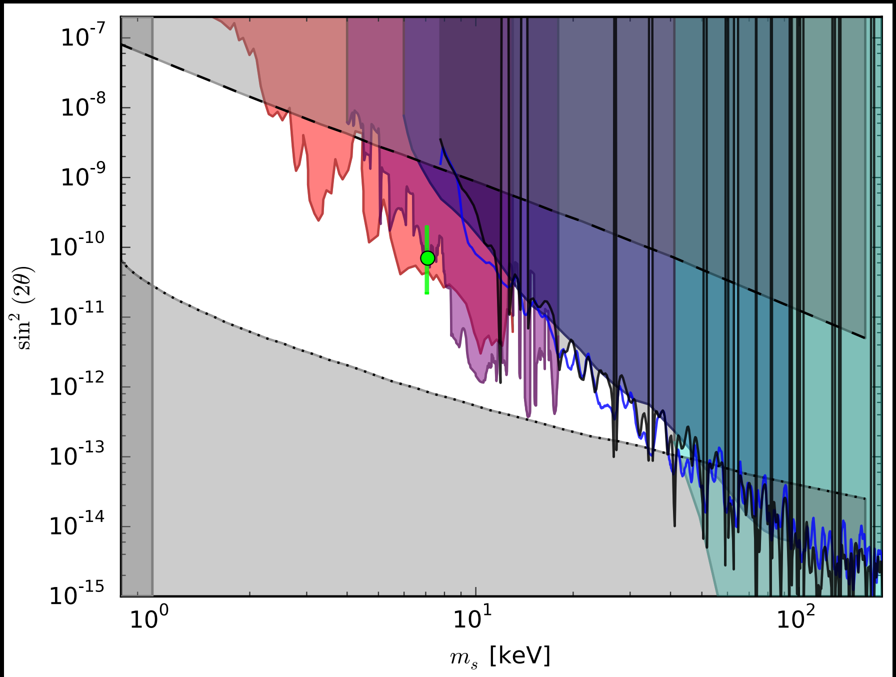
Ng+ 2015

What is next?

- Improving GBM?
  - We only use simple background removals, far from statistical limit



- NuSTAR - running
  - Launched
  - 3 – 80 keV



Bullet Clusster
Reimer-Sorensen+
1507.01378

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)	8×10^{-5}	4	several x 10^{-5}
Instrumental background (/s/keV/FoV)	$2 \times 10^{-3}/0.7 \times 10^{-3}$ (@0.5/6 keV)	0.1/0.1 (@0.5/6 keV)	$6 \times 10^{-3}/2 \times 10^{-4}$ (@10/50 keV)[1] $2 \times 10^{-3}/4 \times 10^{-5}$ (@10/50 keV)[2]

Astro-H quick reference

Dark Matter Velocity Spectroscopy

Speckhard, Ng, Beacom, Laha (submitted to arXiv)

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

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

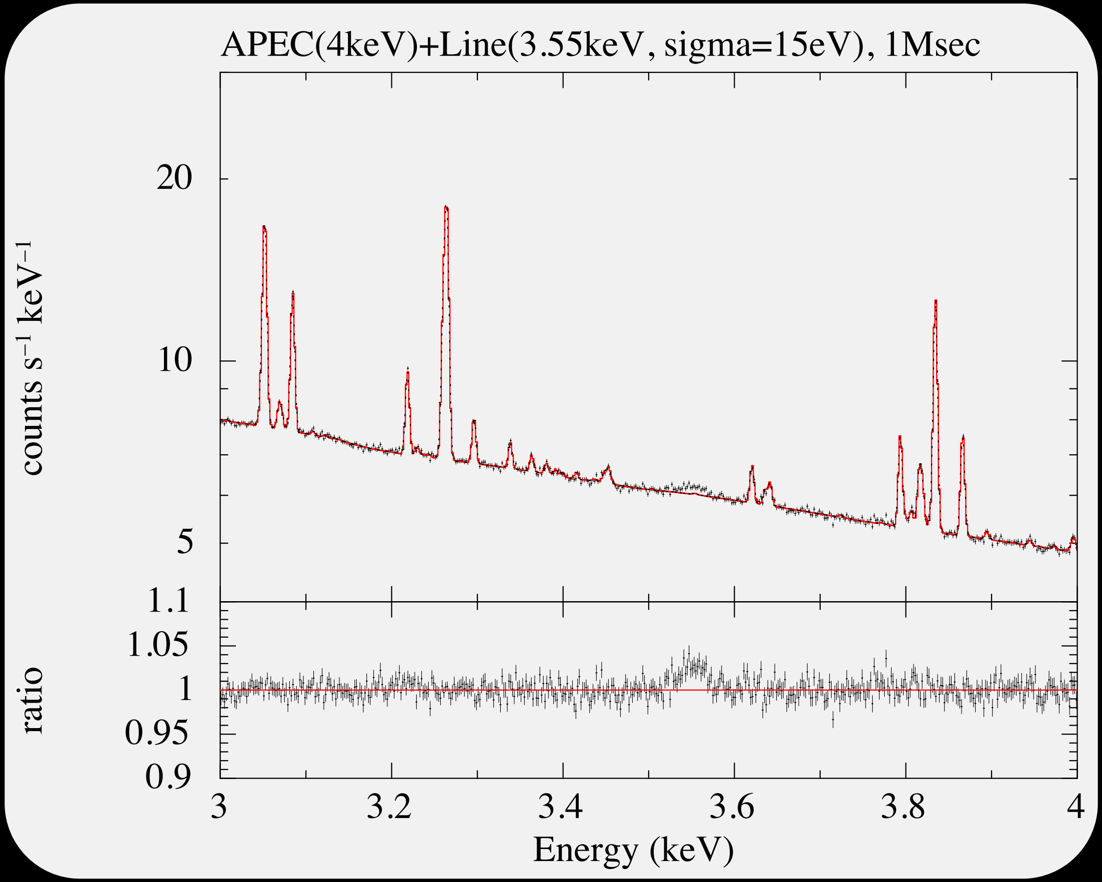
$$\frac{d\mathcal{J}}{dE} = \frac{1}{R_\odot \rho_\odot}\int ds\, \rho_\chi(r[s,\psi])\frac{d\widetilde{N}(E-\delta E_{\mathrm{MW}}, r[s,\psi])}{dE}$$

Line shift

Line dispersion

Galaxy Clusters

DM velocity ~ 1000km/s

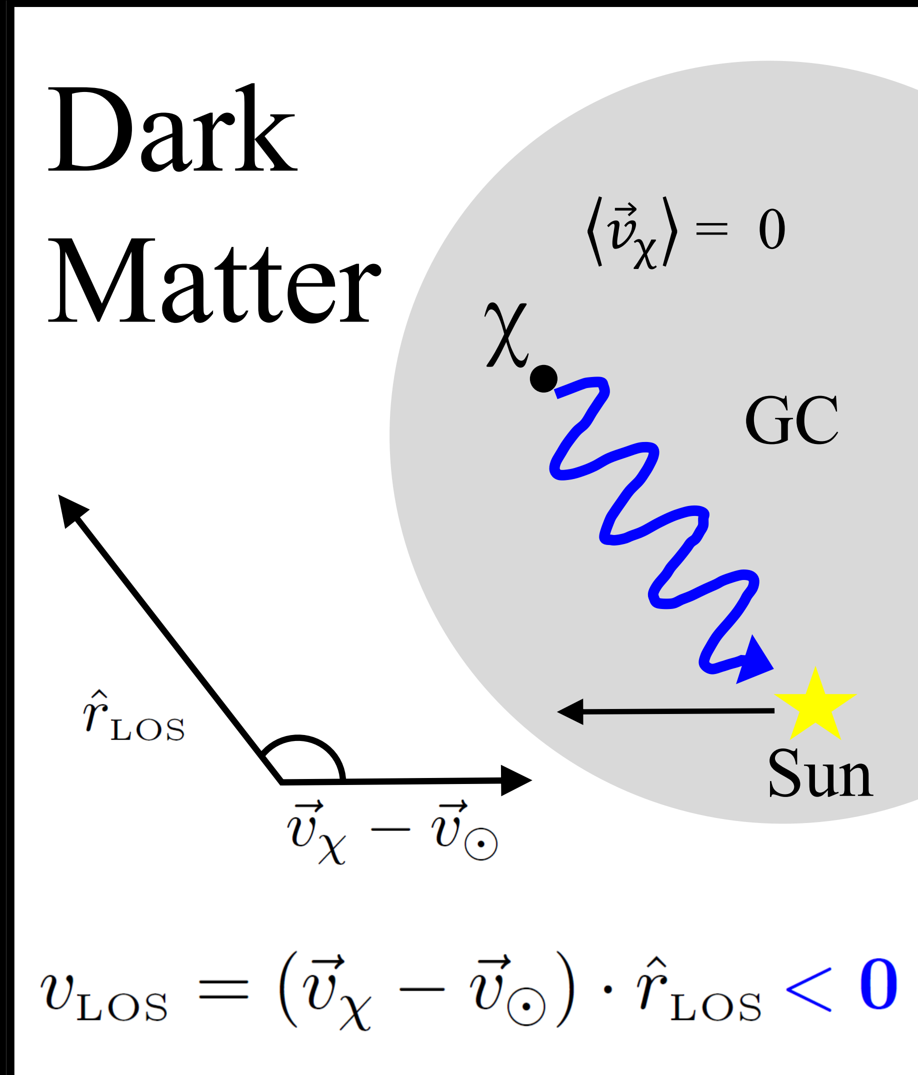


Kitayama+
1412.1176

- But bright X-ray background, turbulent velocity (?)

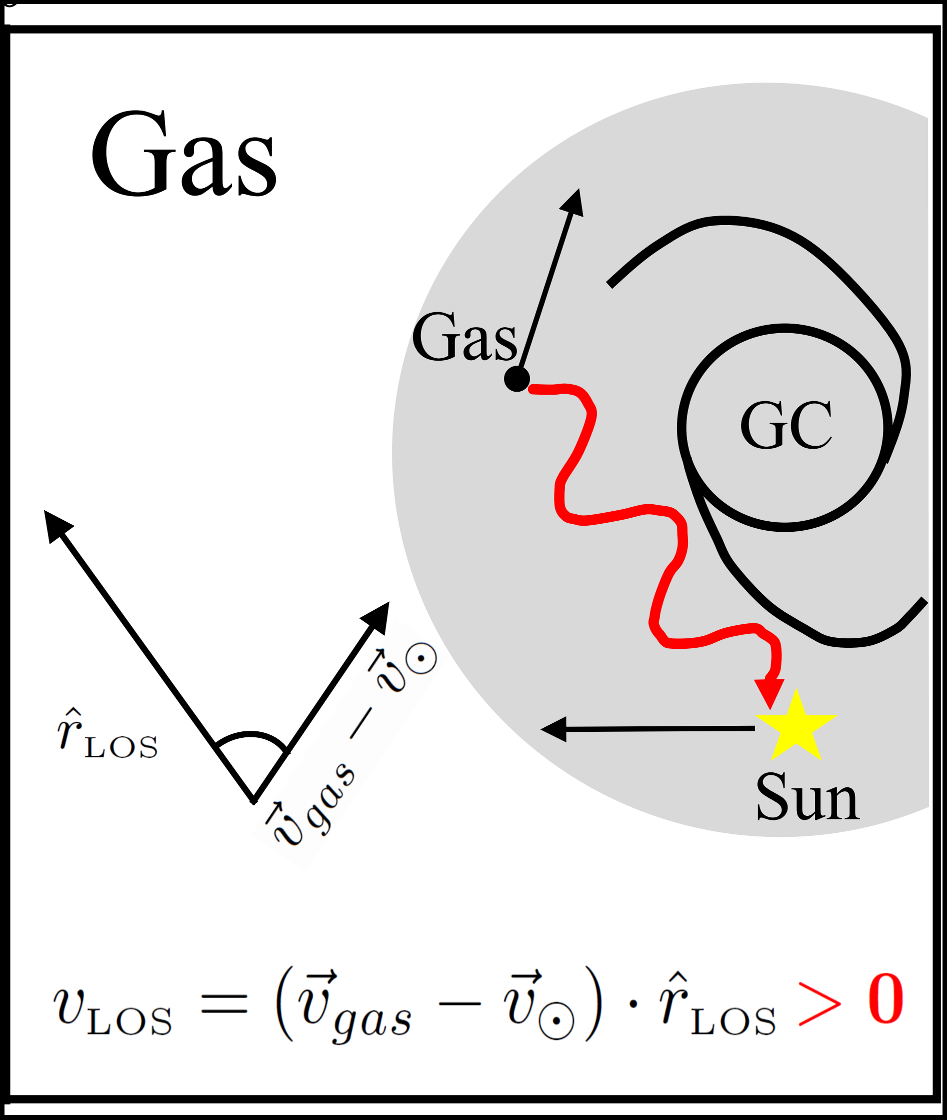
Milky Way DM

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



Milky Way Gas (Background)

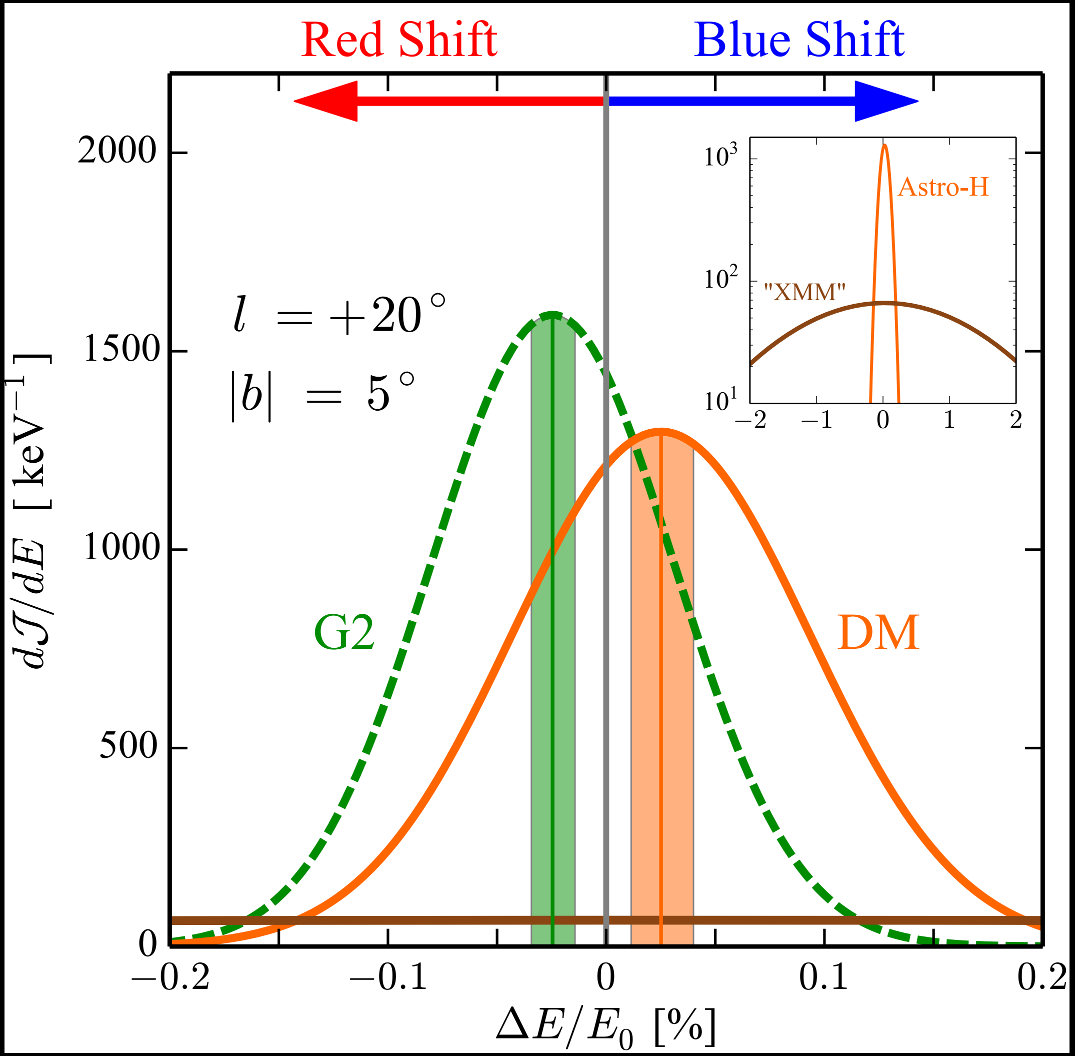
- Gas and the Sun co-rotate in a disk
  - $V^2 \sim GM/r$
- Astro-physical line
  - Red shifted in + long.!



Spectrum

- 2Ms Astro-H observation
  - > 5 sigma detection

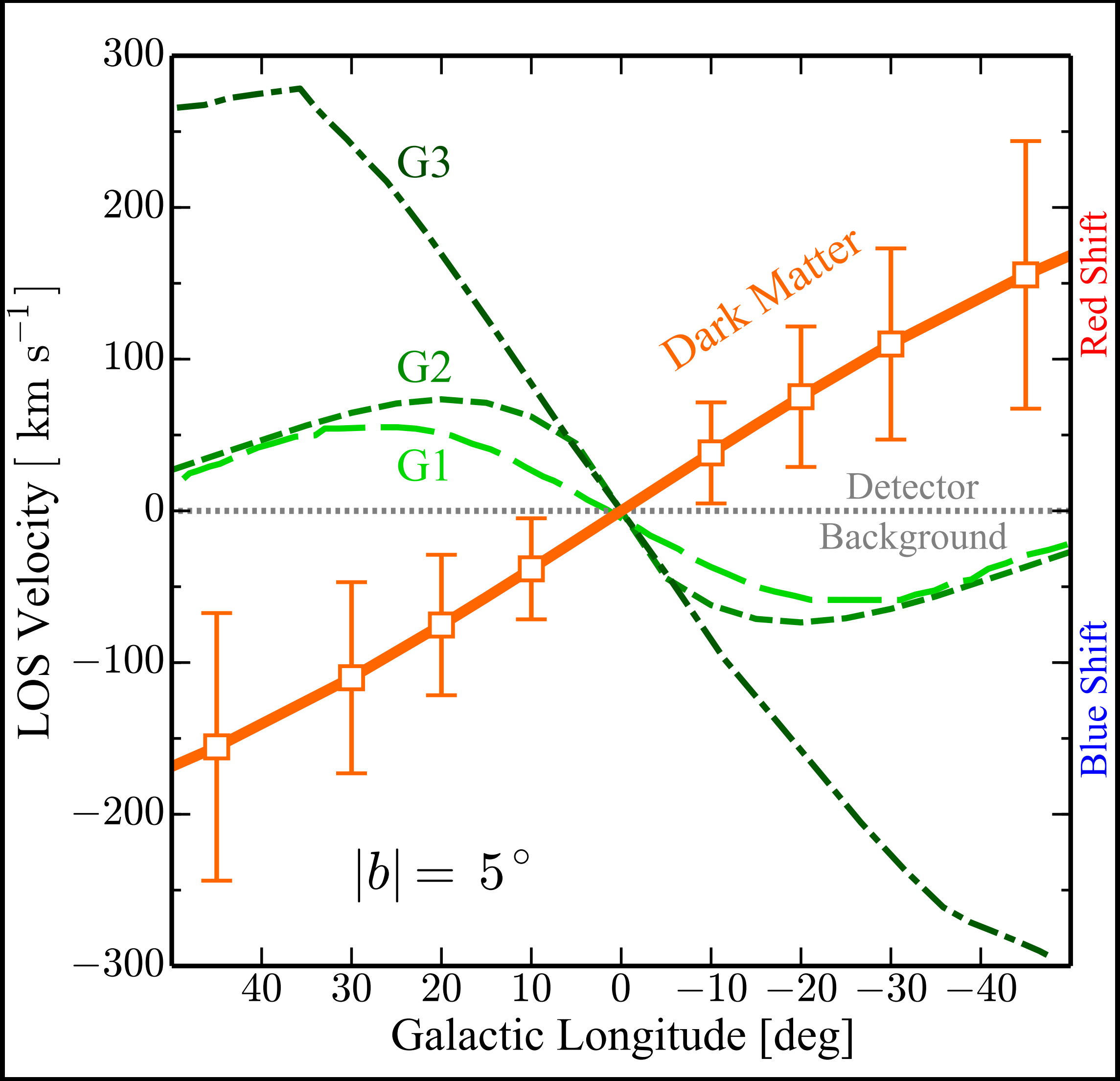
- Taken into account both intrinsic and detector line dispersion.



DM – Astro Separation

- Clean separation
  - DM
  - Astro
  - Detector effect

- Minimal theoretical uncertainty



DM Velocity Spectroscopy

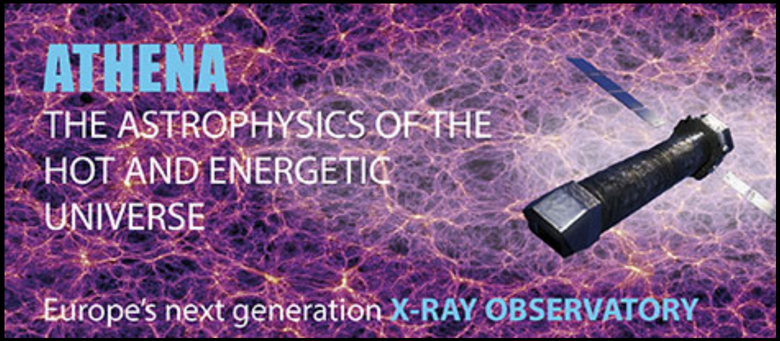
- Extra handle for testing line-like signal
  - The "smoking gun" sometimes is not enough

- If DM decay/annihilation produces a line.
- Allow us to do Dark Astronomy
  - Currently no velocity information on DM!

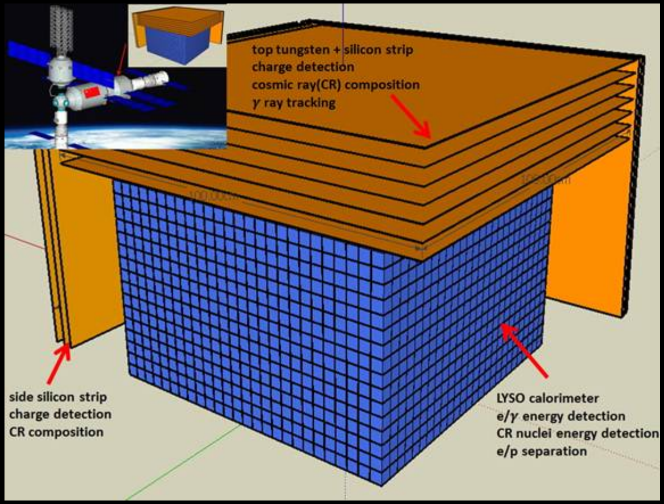
- Dark Cosmology?

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?



arXiv soon

Dark Matter Velocity Spectroscopy

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(Dated: July 16, 2015)

Dark matter decays or annihilations that produce line-like spectra may be smoking-gun signals. However, even such distinctive signatures can be mimicked by astrophysical or instrumental causes. We show that velocity spectroscopy—the measurement of energy shifts induced by relative motion of source and observer—can separate these three causes with minimal theoretical uncertainties. The principal obstacle has been energy resolution, but upcoming and proposed experiments will make significant improvements. As an example, we show that the imminent Astro-H mission can use Milky Way observations to separate possible causes of the 3.5-keV line. We discuss other applications.

Conclusion

- X-ray observations are powerful probes of Sterile neutrino Dark Matter
- NuSTAR, Fermi-GBM test > 20 keV mass
- Astro-H can test the origin the 3.5 keV line
- The window can be closed soon
  - => New production methods.