

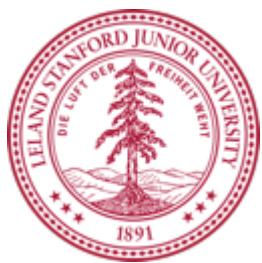
Dark matter velocity spectroscopy

Ranjan Laha

Kavli Institute of Particle Astrophysics and Cosmology (KIPAC)

Stanford University

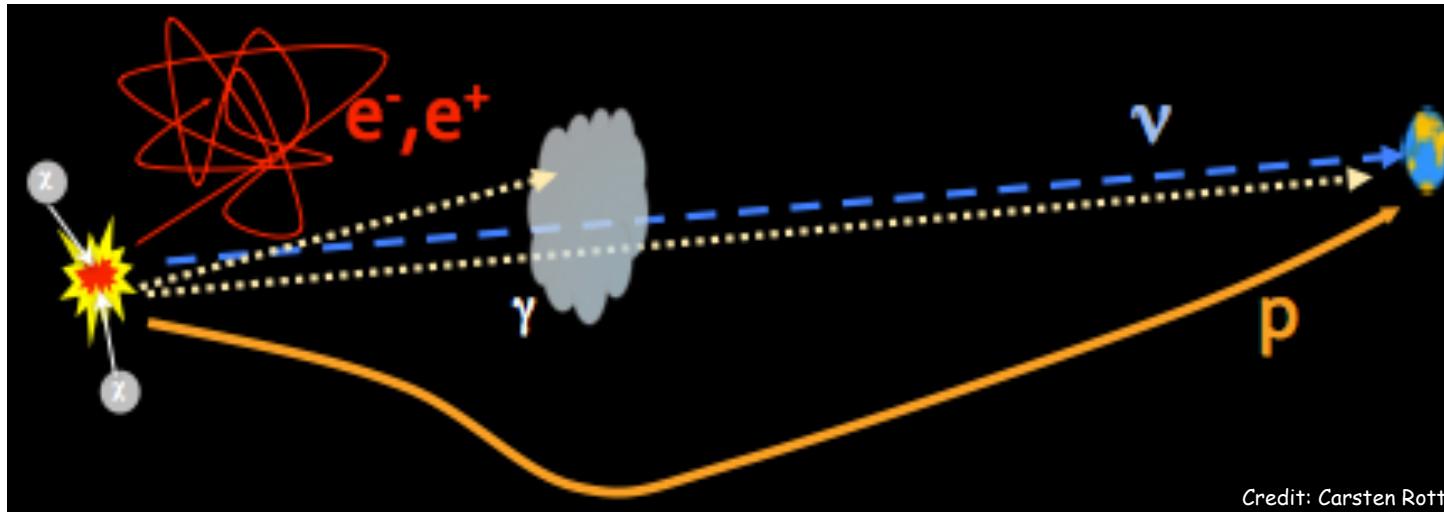
SLAC National Accelerator Laboratory



Thanks to my collaborators: Tom Abel, John F Beacom, Kenny C Y Ng, Devon Powell, Eric G Speckhard

arXiv: 1507.04744 Phys. Rev. Lett. 116 (2016) 031301 (Editors' suggestion)

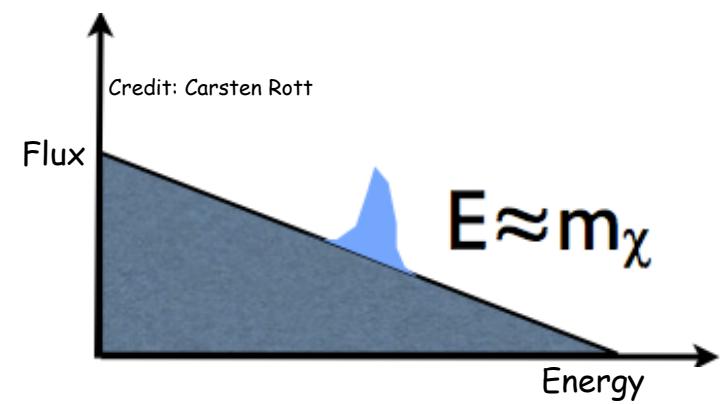
Indirect detection of dark matter



- Search for **excess** of Standard Model particles over the **expected** astrophysical background

γ ν e^+ \bar{p}

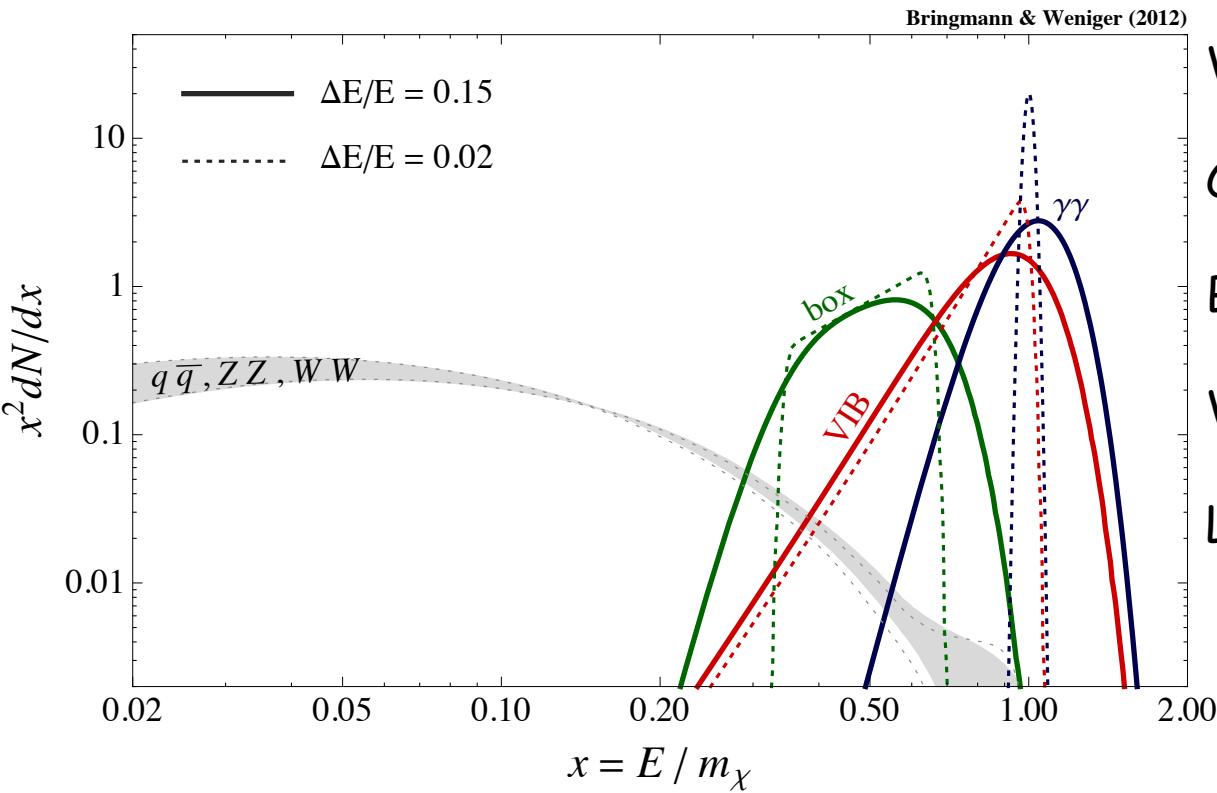
- Spectral** features help --- astrophysical backgrounds are relatively smooth --- nuclear and atomic lines problematic



- Targets:** Sun, Milky Way (Center & Halo), Dwarf galaxy, Galaxy clusters

Signal and background in indirect detection

Signals: continuum, box, lines, etc.



Various types of signal:

Continuum

Box

Virtual internal bremsstrahlung

Line

Continuum: $\chi\chi \rightarrow q\bar{q}, Z\bar{Z}, W^+W^- \rightarrow$ hadronisation/decay $\rightarrow \gamma, e^+, \bar{p}, \nu$

Box: $\chi\chi \rightarrow \phi\phi; \phi \rightarrow \gamma\gamma$

Virtual internal bremsstrahlung: $\chi\chi \rightarrow \ell^+\ell^-\gamma$

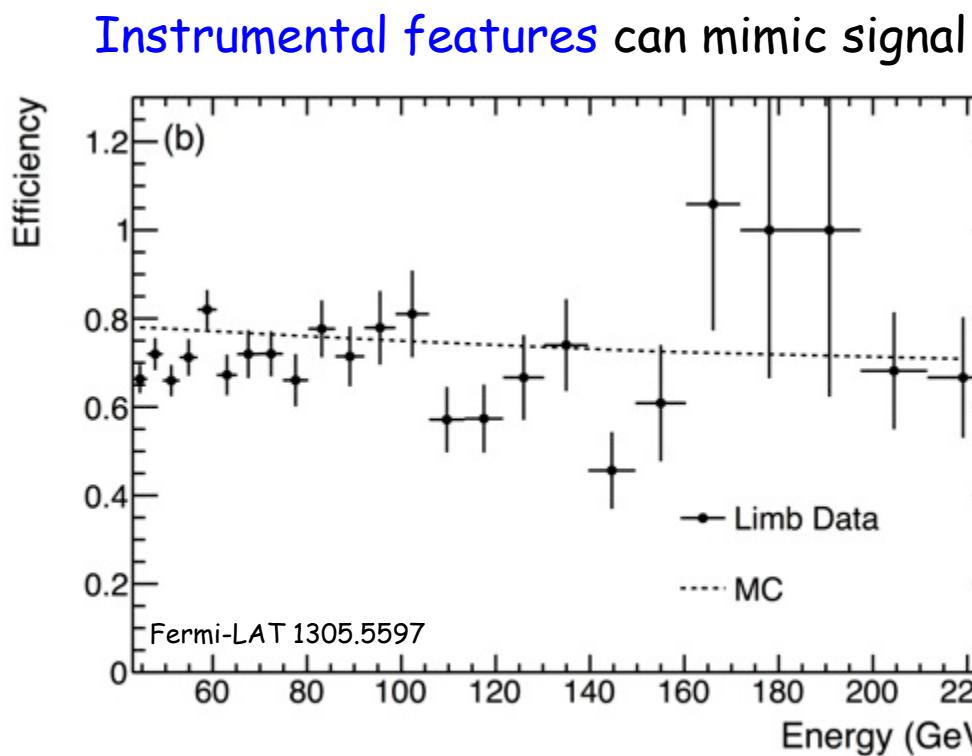
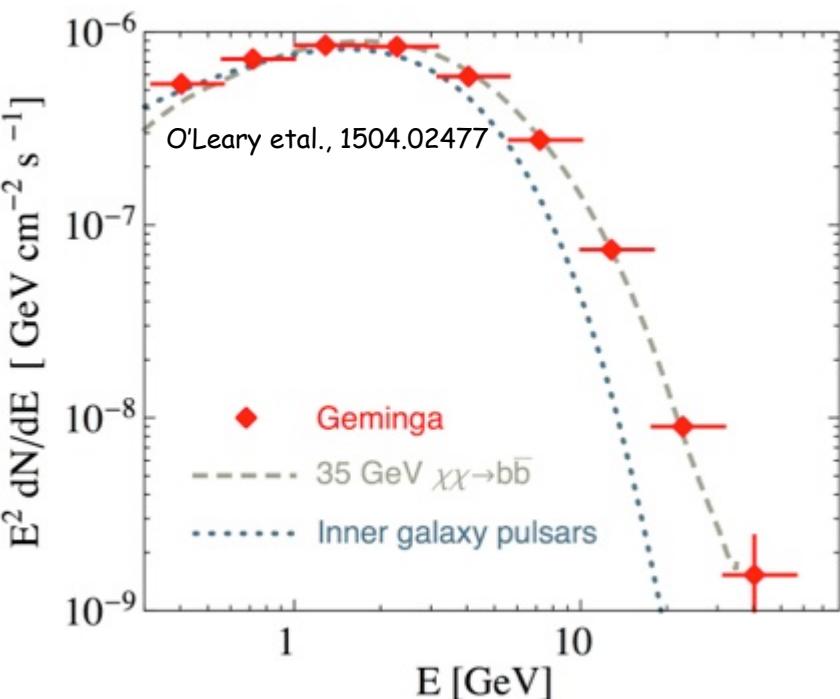
Line: $\chi\chi \rightarrow \gamma\gamma$

$\nu_s \rightarrow \nu\gamma$

Distinct kinematic signatures
important to distinguish from
backgrounds

Backgrounds: astrophysical, instrumental

Due to the faint signal strength, astrophysical backgrounds can easily mimic the dark matter signal



Ongoing controversy about the origin of the 3.5 keV line: dark matter or astrophysical

Confusion between signal and background

- Confusion between signal and background is prevalent in dark matter indirect detection
- Kinematic signatures are frequently used to distinguish between signal and background
- Is there a more distinct signature that we can identify?
- Yes, use high energy resolution instruments to see the dark matter signal in motion

Can we find a new “smoking gun”
signature of dark matter?

Dark matter velocity spectroscopy

arXiv 1507.04744

Phys. Rev. Lett. 116 (2016) 031301 (Editors' Suggestion)

Dark matter velocity spectroscopy

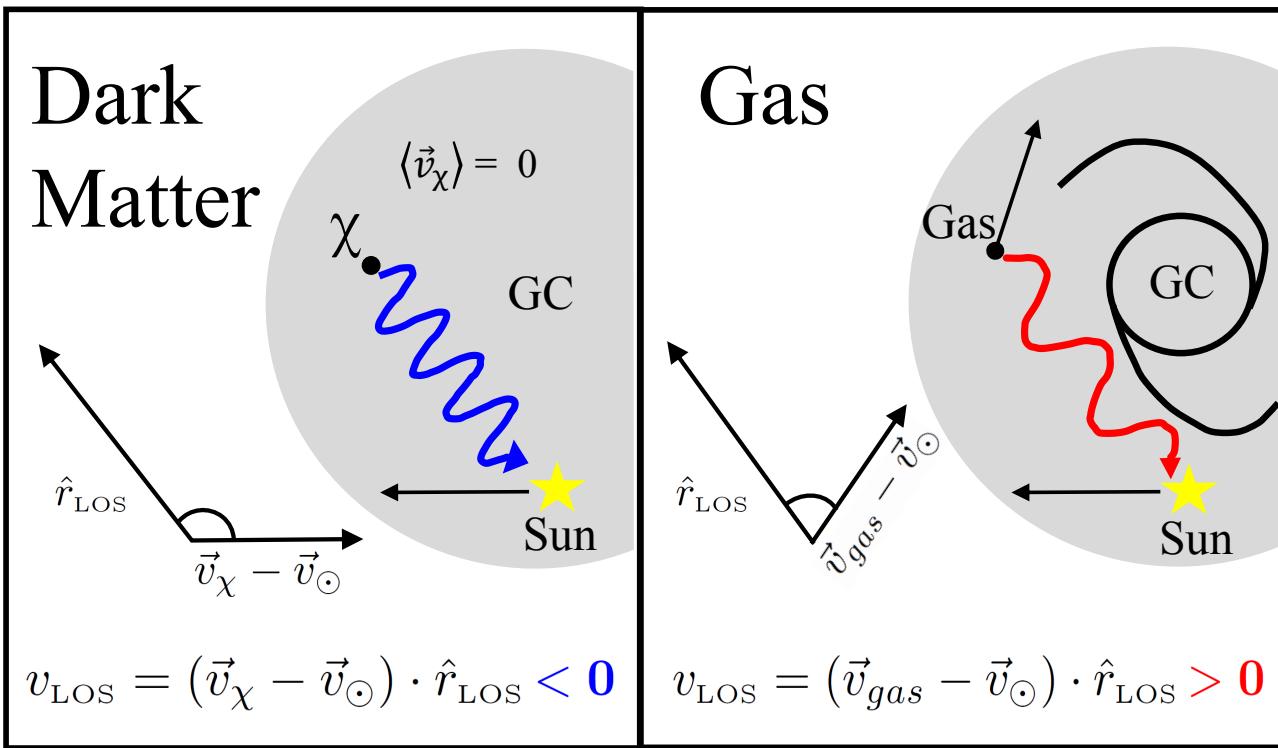
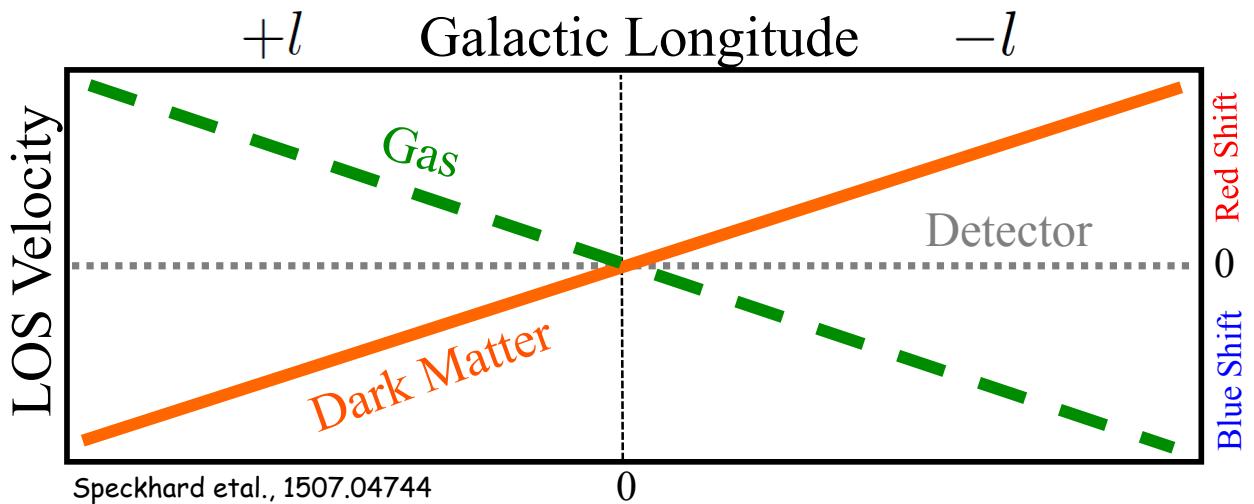
- Dark matter halo has little angular momentum

Bett, Eke, et al., "The angular momentum of cold dark matter haloes with and without baryons"; Kimm et al., "The angular momentum of baryons and dark matter revisited"

- Sun moves at ~220 km/s

- Distinct longitudinal dependence of signal

- Doppler effect



Order of magnitude estimates

$$v_{\text{LOS}} \equiv (\langle \vec{v}_\chi \rangle - \vec{v}_\odot) \cdot \hat{r}_{\text{LOS}}$$

$\langle \vec{v}_\chi \rangle$ is negligible in our approximation

$$v_\odot \approx 220 \text{ km s}^{-1}$$

For $v_{\text{LOS}} \ll c$, $\delta E_{\text{MW}}/E = -v_{\text{LOS}}/c$

$$\delta E_{\text{MW}}(l, b)/E = + (v_\odot/c) (\sin l) (\cos b)$$

$$\frac{\delta E_{\text{MW}}}{E} \approx 10^{-3}$$

$\text{sign}(\delta E_{\text{MW}}) \propto \sin l$, for $l \in [-\pi, \pi]$

Example with dark matter decay

Differential intensity $\left[\frac{dI(\psi, E)}{dE} = \frac{\Gamma}{4\pi m_\chi} \frac{dN(E)}{dE} \int ds \rho_\chi(r[s, \psi]) \right]$

Γ = Dark matter decay rate Dark matter mass Energy spectrum

Line of sight Dark matter profile

$dN(E)/dE$ is independent of dark matter profile

$$\frac{d\tilde{N}(E, r[s, \psi])}{dE} = \int dE' \frac{dN(E')}{dE'} G(E - E'; \sigma_{E'})$$

modified energy spectrum Gaussian

$\sigma_E = (E/c) \sigma_{v_{\text{LOS}}}$

width of Gaussian

total mass inside a radius r'

$$\sigma_{v,r}^2(r) = \frac{G}{\rho_\chi(r)} \int_r^{R_{\text{vir}}} dr' \rho_\chi(r') \frac{M_{\text{tot}}(r')}{r'^2}$$

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

replaces $\frac{dN(E)}{dE} \frac{1}{R_\odot \rho_\odot} \int ds \rho_\chi(r[s, \chi])$

Instruments with $\sim O(0.1)\%$ energy resolution

Past



Hitomi/ Astro-H

$$\frac{\sigma_E}{E} \approx \frac{1.7 \text{ eV}}{3.5 \text{ keV}}$$

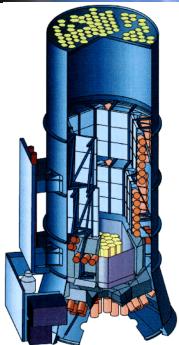


XQC Sounding Rocket experiment

23 eV FWHM at 3.3 keV

Figueroa-Feliciano et al., 2015

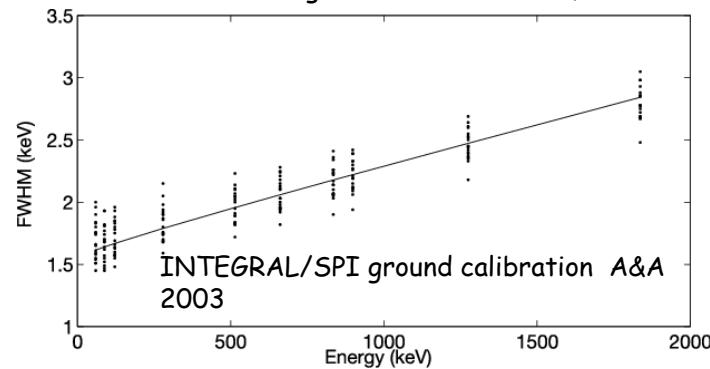
Present



INTEGRAL/ SPI

2.2 keV (FWHM) at 1.33 MeV

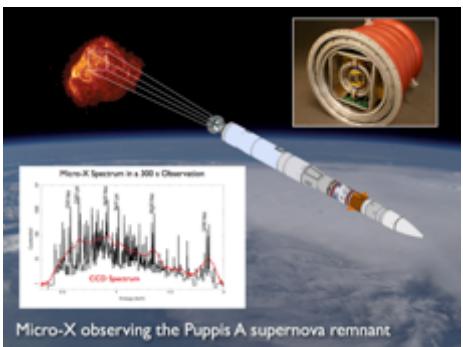
<http://www.cosmos.esa.int/web/integral/instruments-spi>



FWHM of 3 eV at 3.5 keV

Figueroa-Feliciano et al. 2015

Future



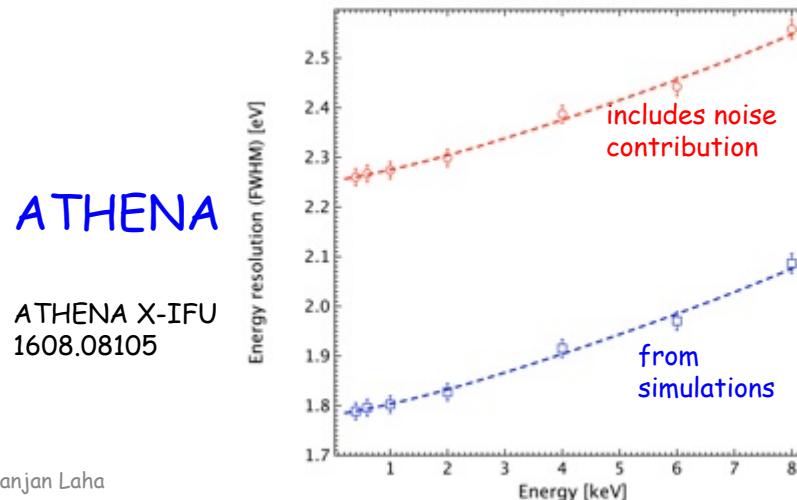
Micro-X

Micro-X observing the Puppis A supernova remnant

ATHENA

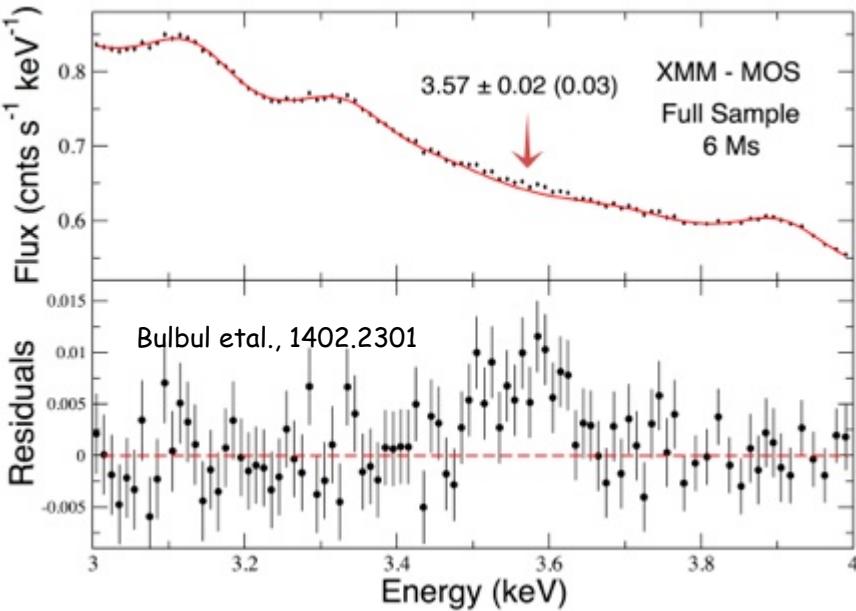
ATHENA X-IFU
1608.08105

Ranjan Laha



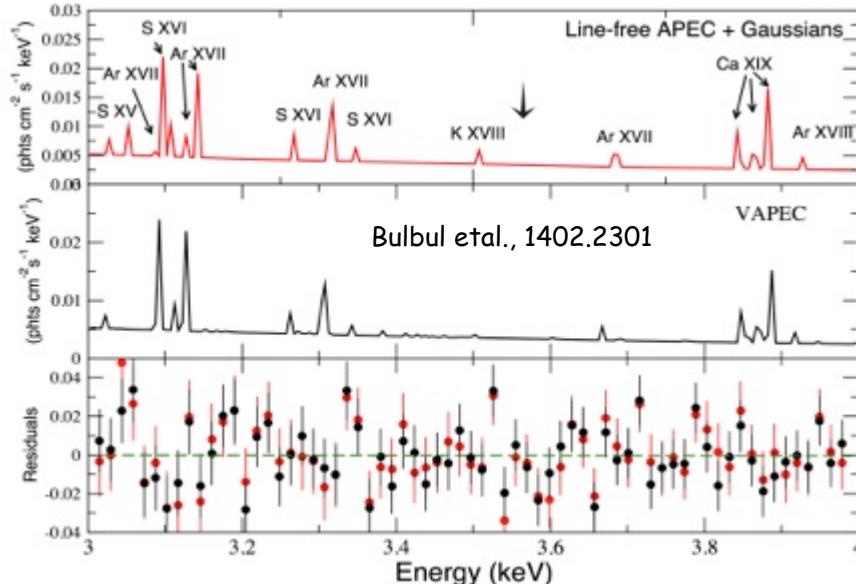
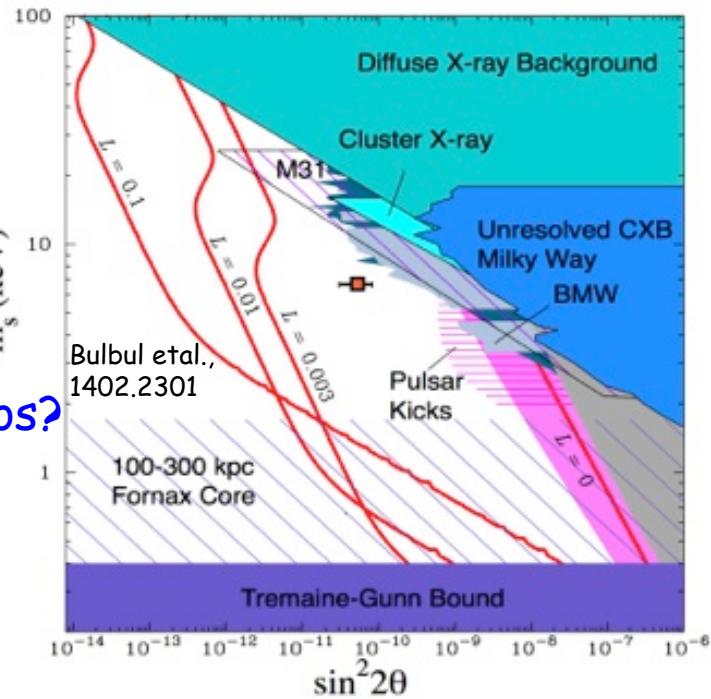
Application to 3.5 keV line

3.5 keV



$$\nu_s \rightarrow \nu_a + \gamma$$

Sterile neutrinos?
Baryonic astrophysics?



Stacking of 73 galaxy clusters
Redshift z = 0.01 to 0.35
4 to 5 σ detection with XMM-Newton and
2 σ in Perseus with Chandra

2.3 σ in Perseus with XMM-Newton
3 σ in M31 with XMM-Newton
Combined detection $\sim 4\sigma$

Conflicting results in many different studies

3.5 keV controversy

Riemer-Sorensen 2014 Milky Way via Chandra ✗

Jeltema and Profumo 2014 Milky Way via XMM-Newton ✗ (Contested by Bulbul et al., 2014 and Boyarsky et al., 2014)

Boyarsky et al. 2014 Milky Way via XMM-Newton ✓

Anderson et al., 2014 Local group galaxies via Chandra and XMM-Newton ✗

Malyshev et al., 2014 satellite dwarf galaxies via XMM-Newton ✗

Tamura et al., 2014 Perseus via Suzaku ✗

Urban et al., 2014 Perseus via Suzaku ✓

Urabs et al., 2014 Coma, Virgo, and Ophiuchus via Suzaku ✗

Carlson et al., 2014 morphological studies ✗

Philips et al., 2015 super-solar abundance ✗

Hofman et al., 2016 33 clusters ✗

Iakubovskiy et al., 2015 individual clusters ✓

HITOMI 2016 Perseus cluster ✗

Jeltema and Profumo 2015 Draco dwarf ✗

Shah et al., 2016 Laboratory ✗

Bulbul et al., 2015 Draco dwarf ✓

Conlon et al., 2016 Perseus ✓

Franse et al., 2016 Perseus cluster ✓

Bulbul et al., 2016 stacked cluster ✓

Solutions to the 3.5 keV line controversy?

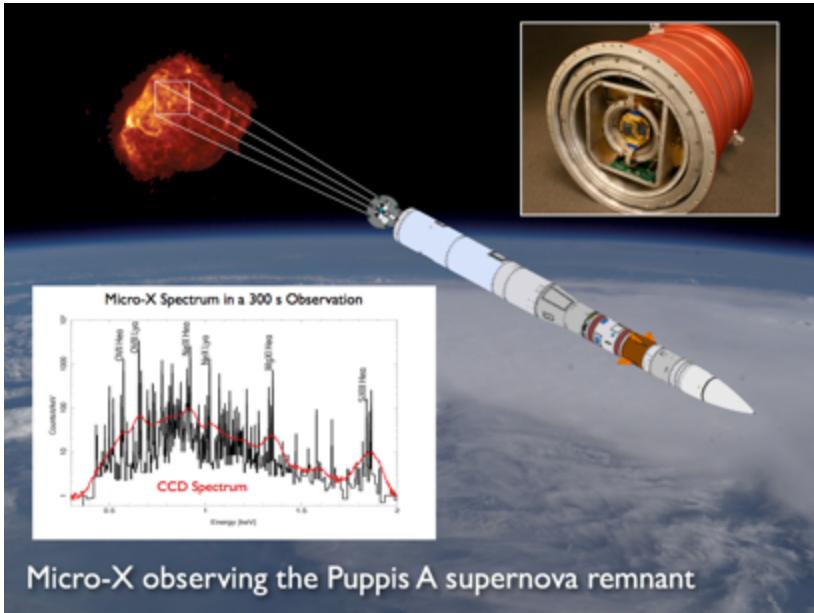
- Micro-X

Wide field of view

Rocket

$\sim 10^{-3}$ energy resolution near 3.5 keV

Figueroa-Feliciano et al. 2015



- SXS - Hitomi (Astro-H)

Narrow field of view

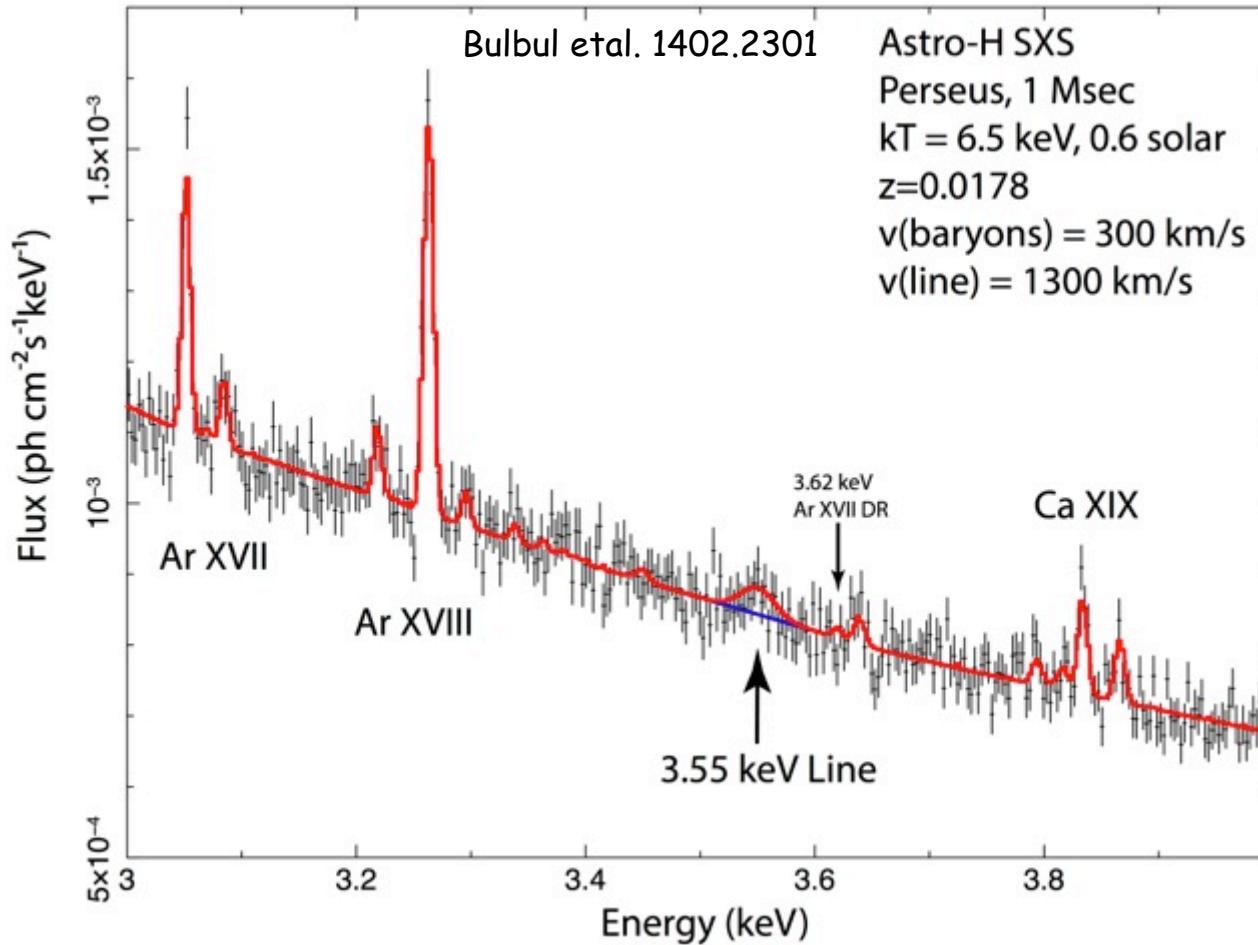
Satellite

$\sim 10^{-3}$ energy resolution at ~ 3.5 keV

Lost due to technical failure



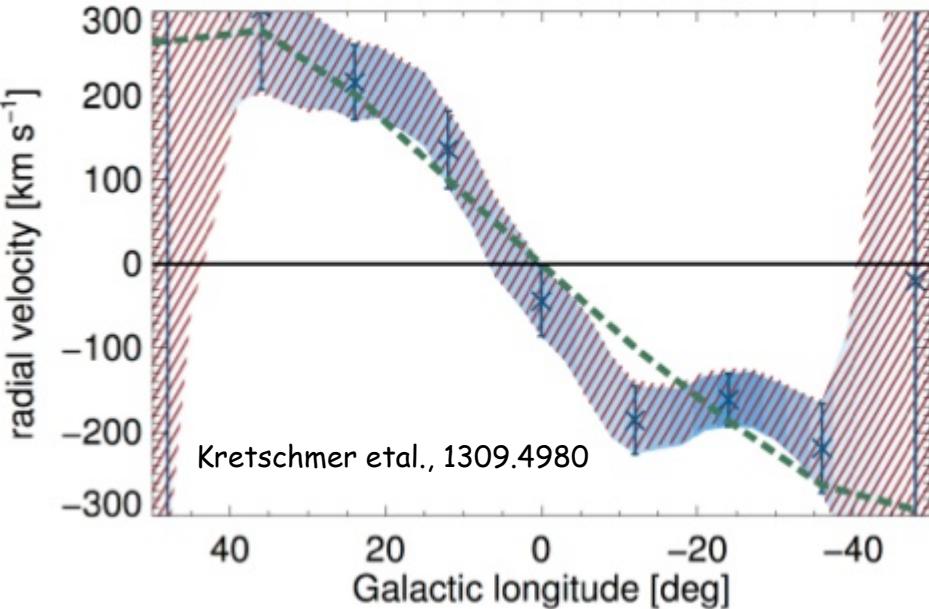
Looking at clusters



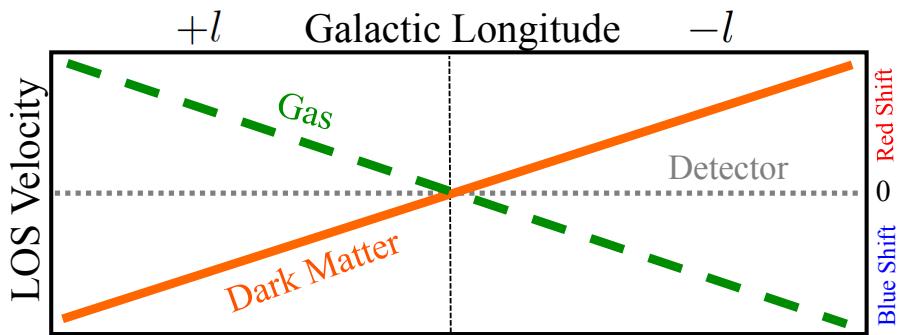
Dark matter line **broader** than plasma emission line

Plasma emission lines are broadened by the turbulence in the X-ray emitting gas

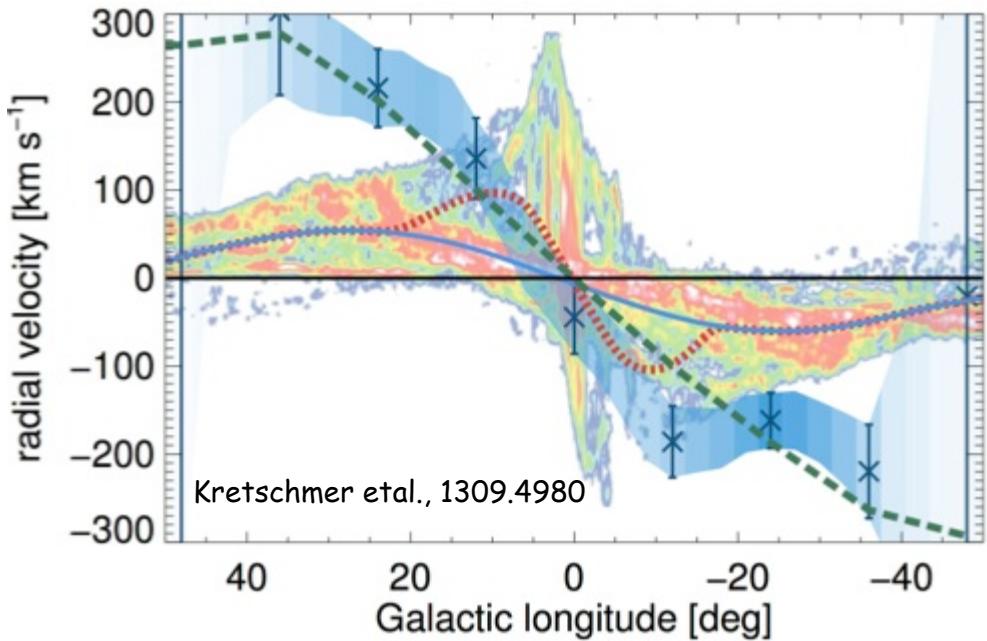
Rotation of baryonic matter



Radial velocity of gas as measured by ^{26}Al
1808.65 keV line
Measurement by INTEGRAL/ SPI



Follows the trend explained earlier



Shift and broadening of spectrum

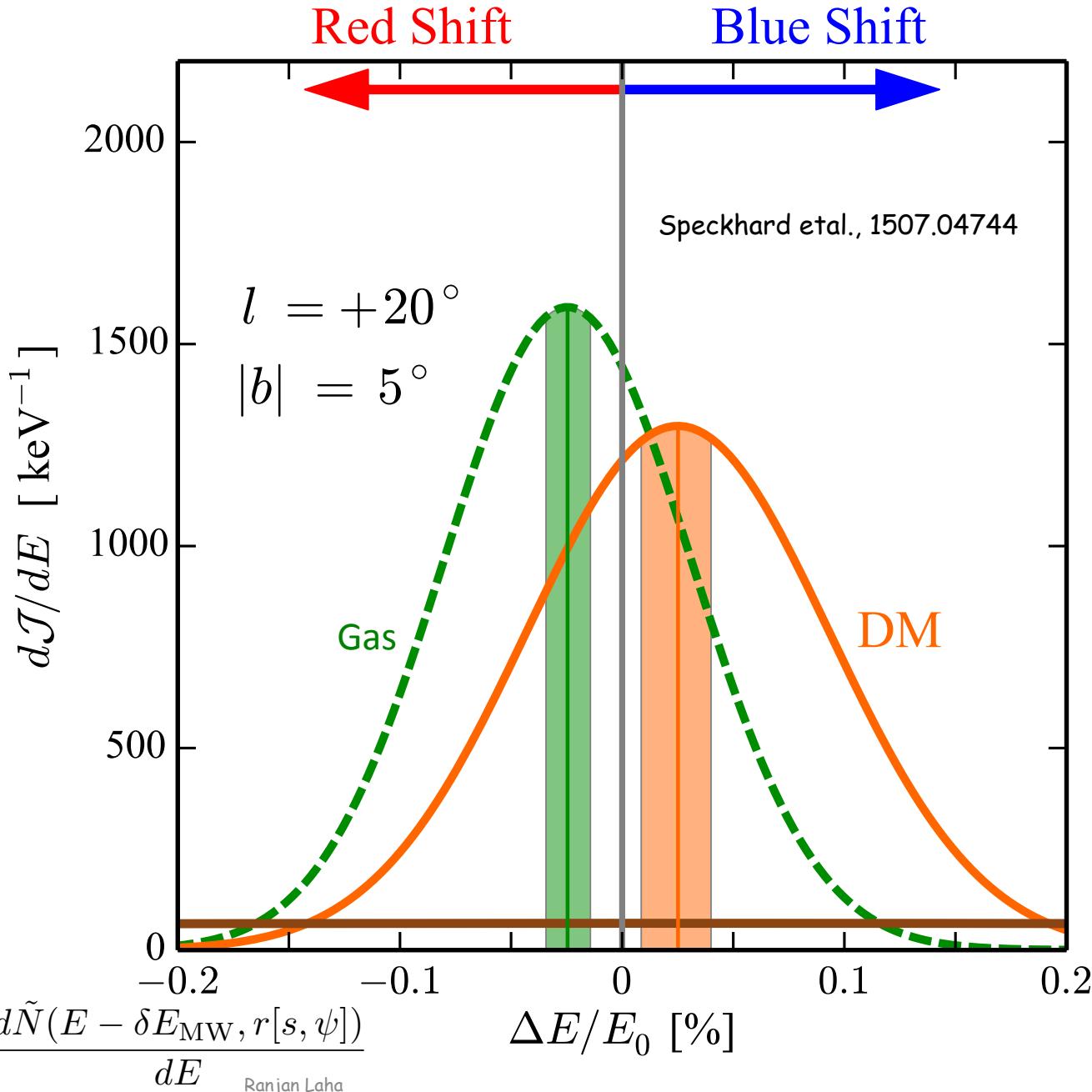
$E_0 = 3.5 \text{ keV}$

2 Ms $1800 \text{ cm}^2 \text{ arcmin}^2$
observation 5σ
detection

Broadening of line due to
finite velocity dispersion

Shift of the centroid of
line due to Doppler
effect

Shift of the center of
dark matter line is
opposite to that of the
shift of the center of
baryonic line



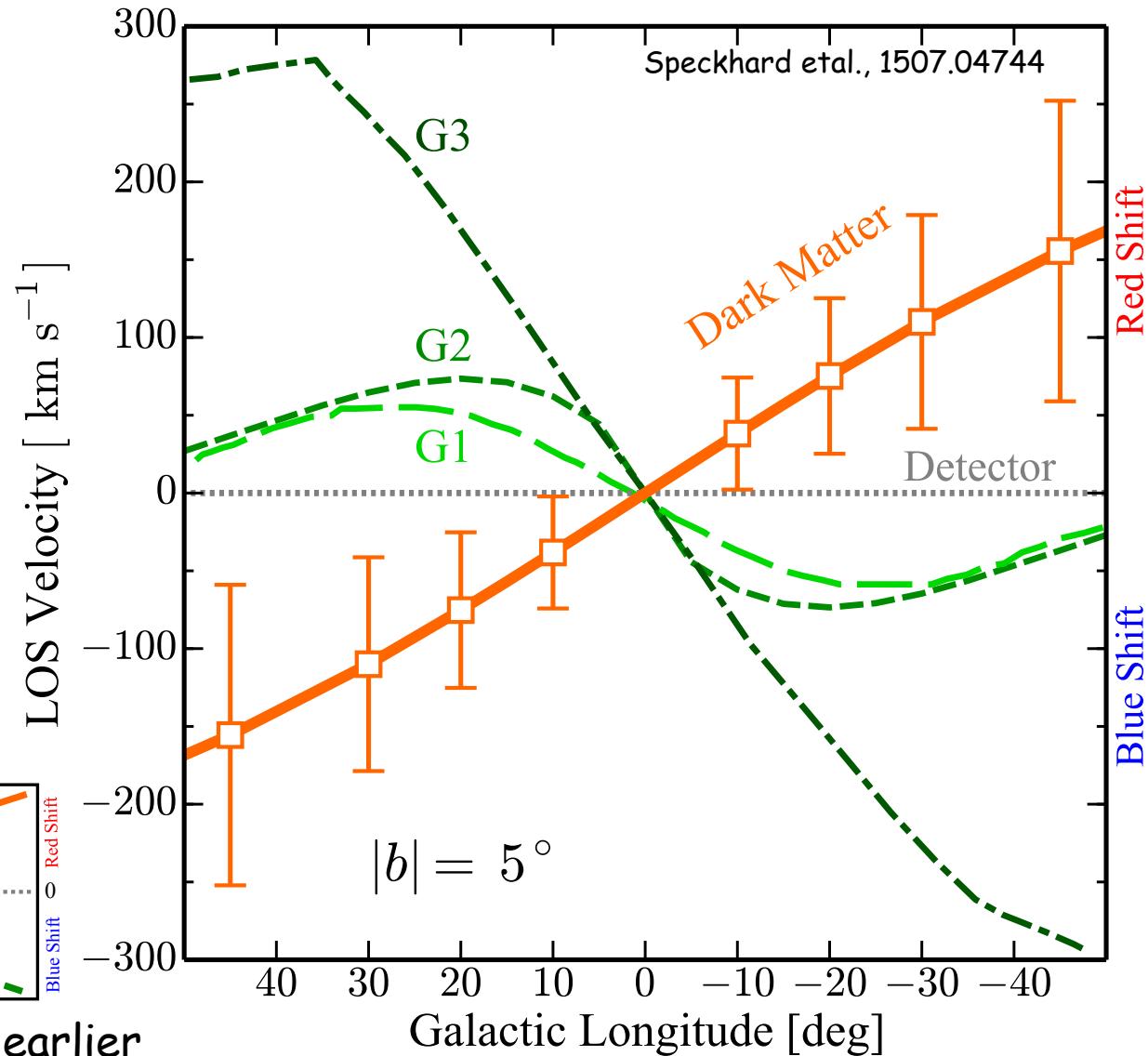
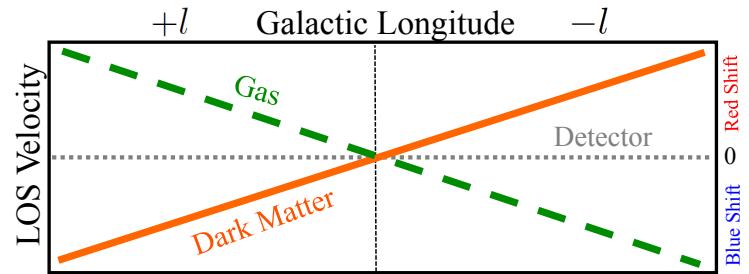
Dark matter and baryonic emission line separation

Shift in centroid of dark matter and baryonic line

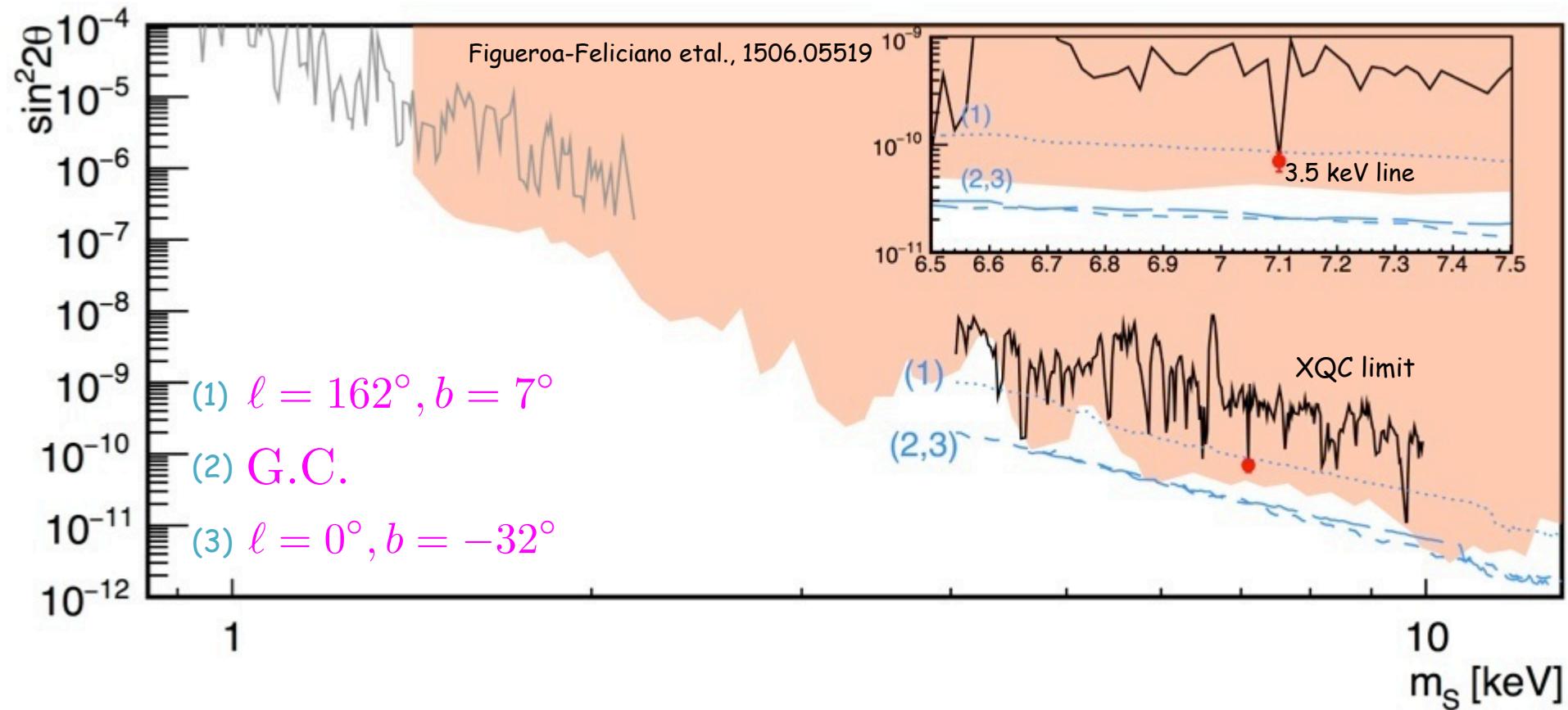
G1: distribution of free electrons

G2: hot gas distribution of MW

G3: observed distributions of ^{26}Al gamma-rays



Micro-X observations



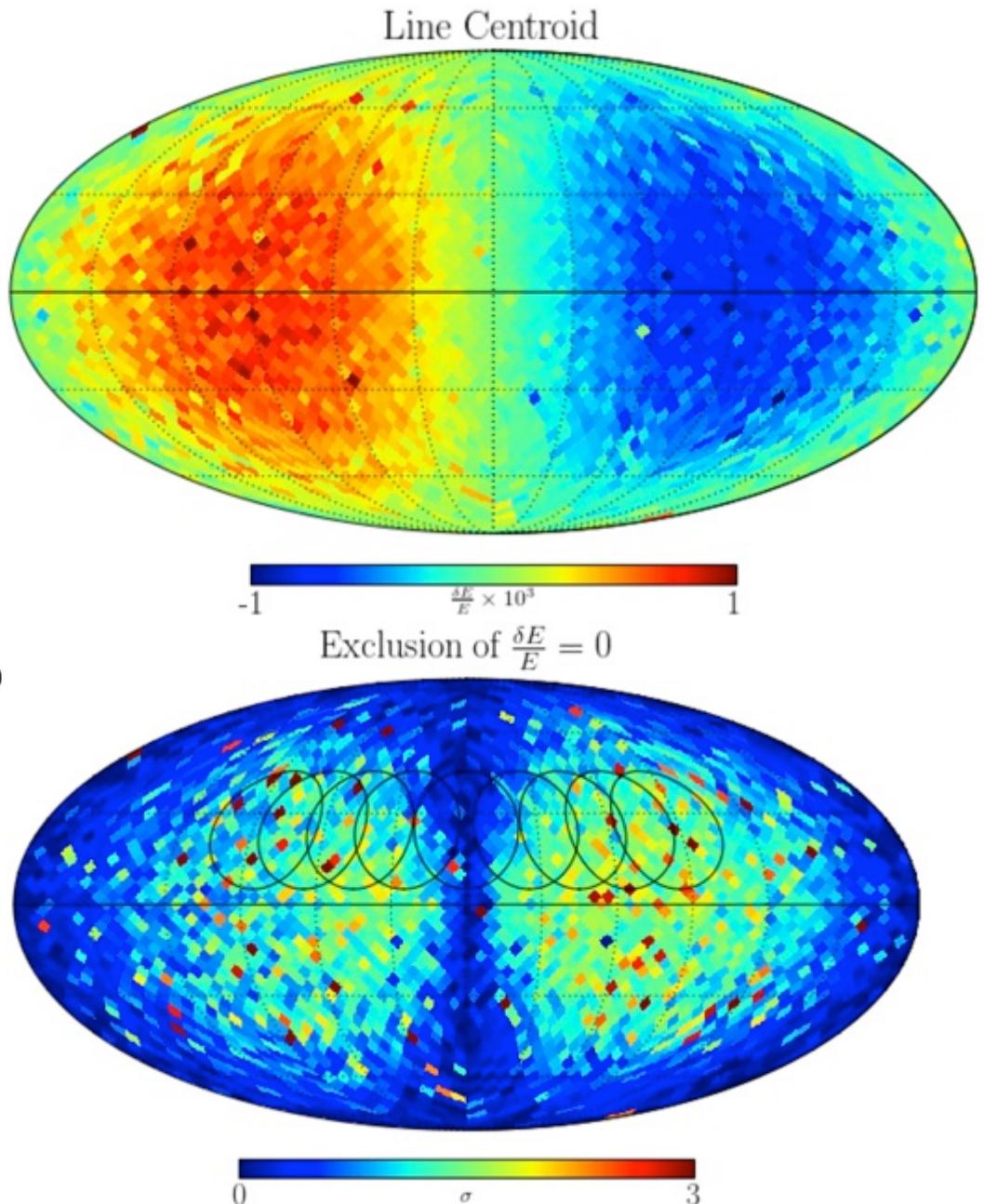
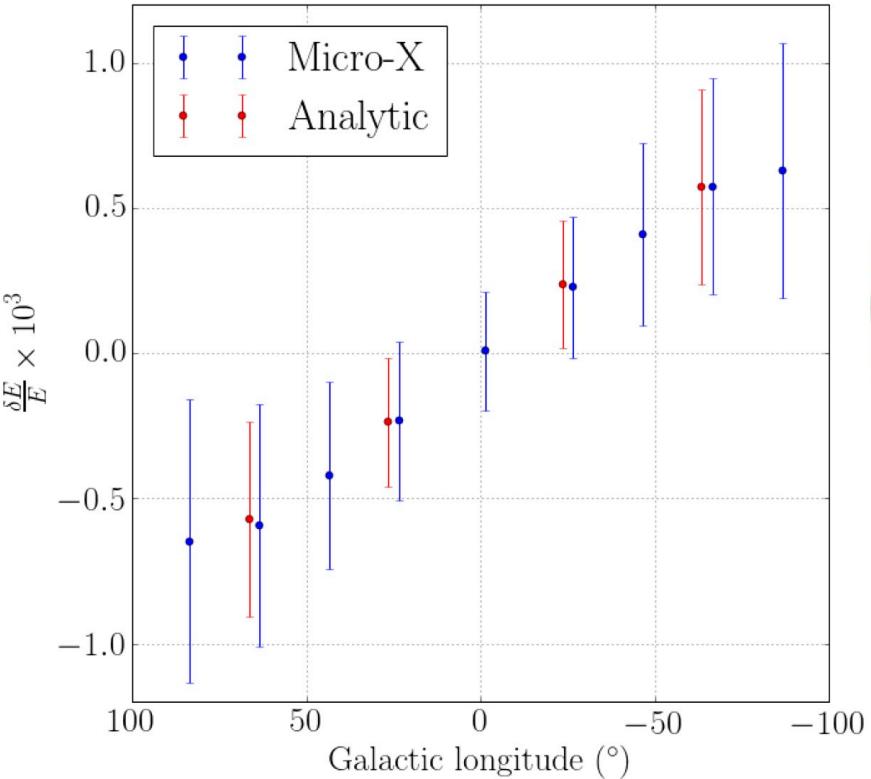
Field of view: 20° radius

Very promising reach

Time of observation: 300 sec

Multiple observations in multiple flights

Velocity spectroscopy using Micro-X



A wide field of view instrument like Micro-X can also perform dark matter velocity spectroscopy

Take-away for dark matter velocity spectroscopy

- Dark matter velocity spectroscopy is a promising tool to distinguish signal and background in dark matter indirect detection
- We see dark matter in motion
- Immediate application to the 3.5 keV line
- Future improvements in the energy resolution of telescopes at various energies will result in this technique being widely adopted