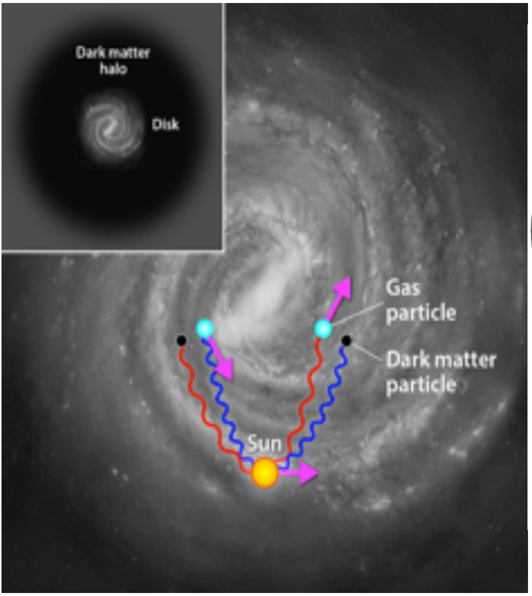

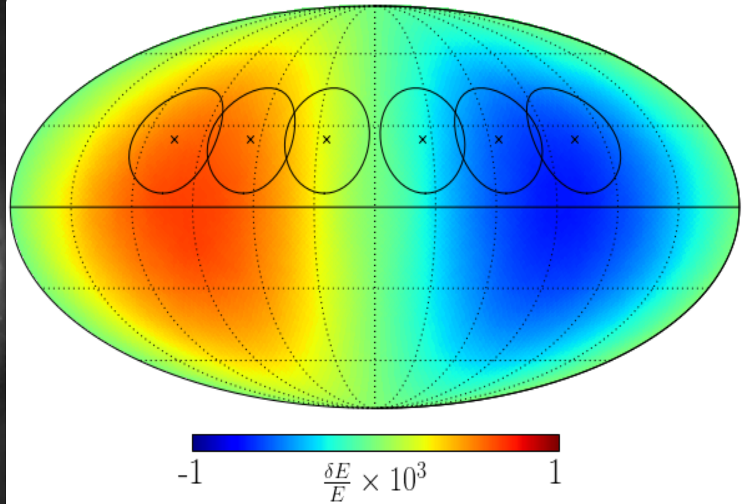

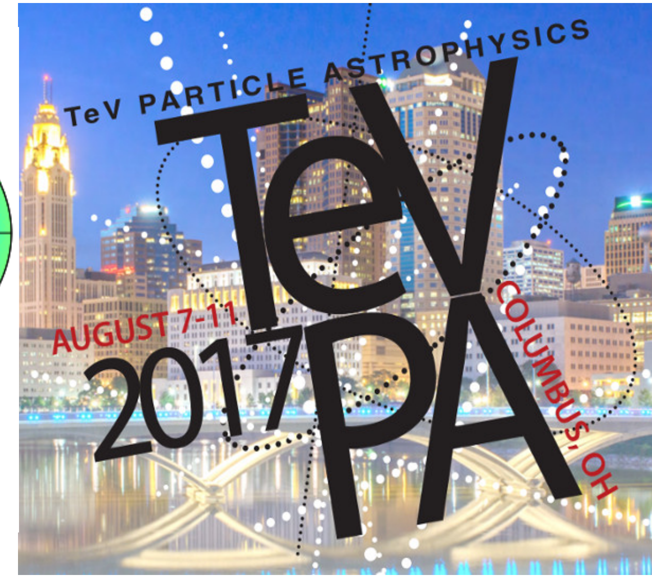

TeVPA 2017— TeV Particle Astrophysics

Dark matter velocity spectroscopy

Ranjan Laha

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Stanford University

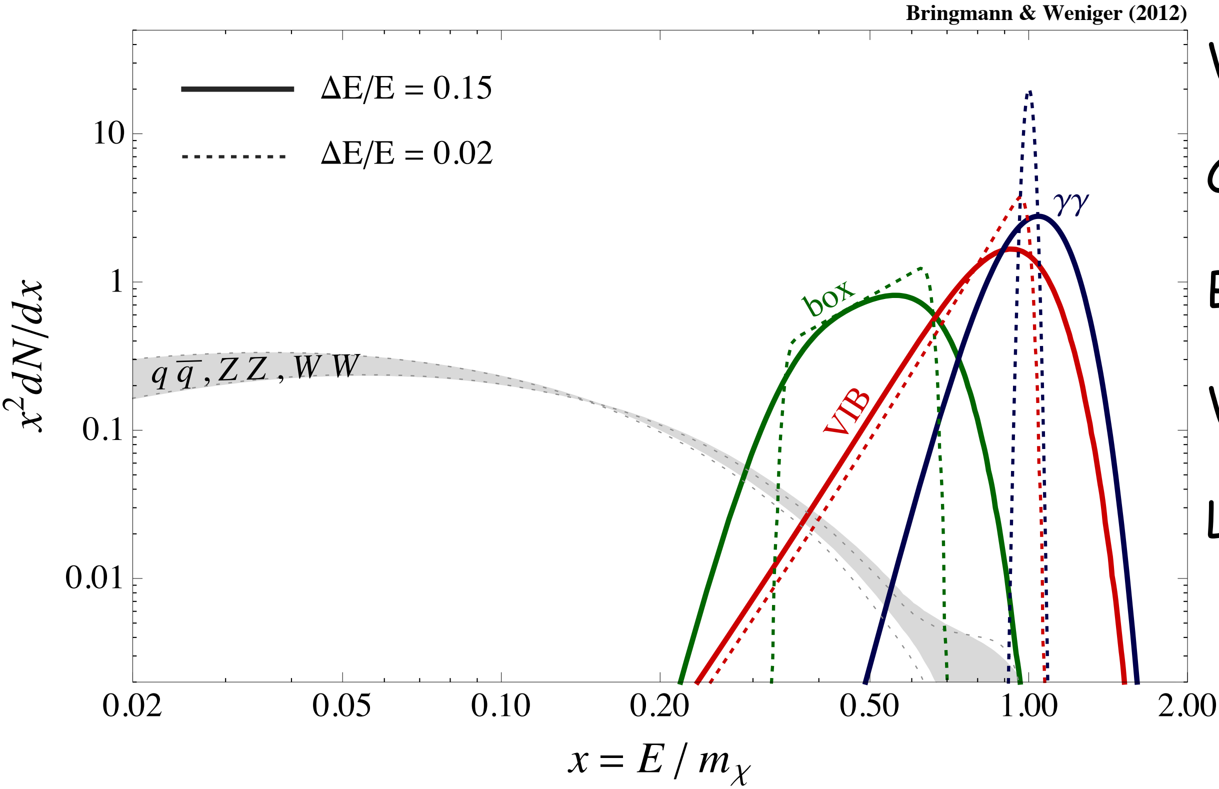
SLAC National Accelerator Laboratory

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 arXiv: 1611.02714 Phys. Rev. D95 (2017) 063012

Signal and background in indirect detection

Signals: continuum, box, lines, etc.



Various types of signal:

Continuum

Box

Virtual internal bremsstrahlung

Line

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

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

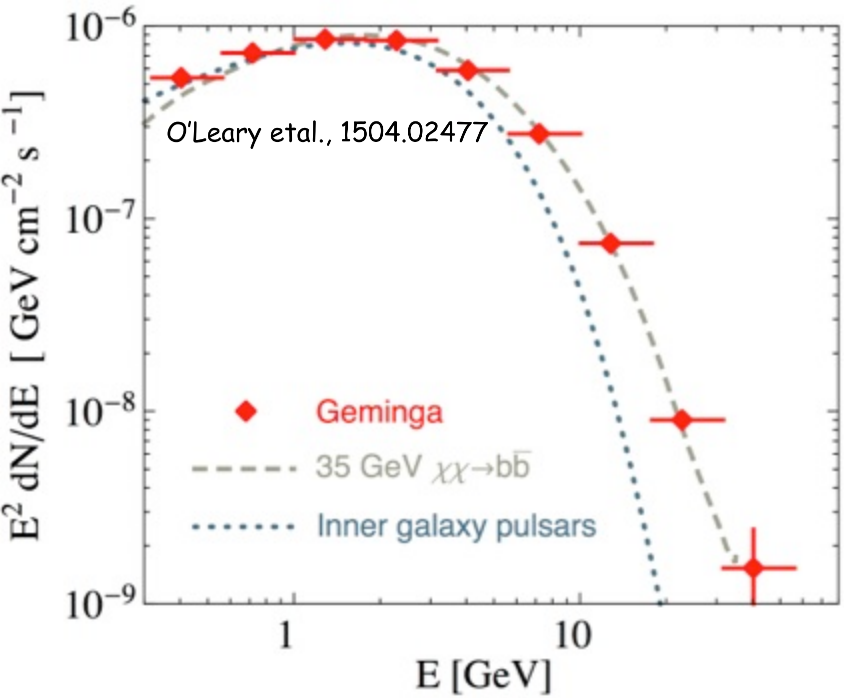
Virtual internal bremsstrahlung: $\chi\chi \rightarrow \ell^+\ell^-\gamma$

Line: $\chi\chi \rightarrow \gamma\gamma$ $\qquad \nu_s \rightarrow \nu\gamma$

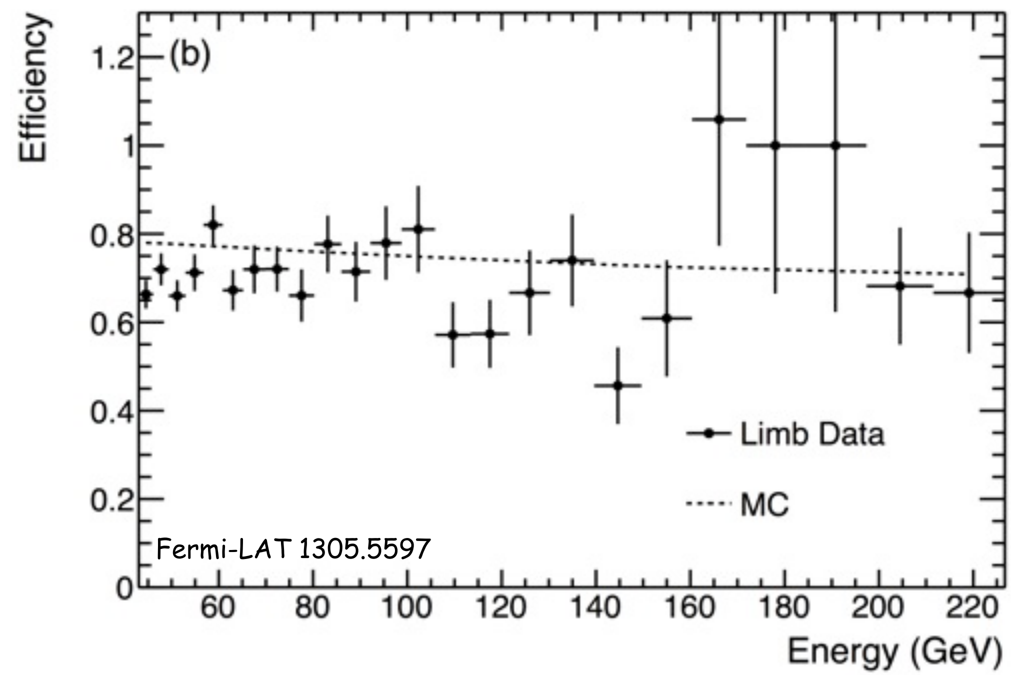
Distinct kinematic signatures important to distinguish from backgrounds

Backgrounds: astrophysical, instrumental

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



Instrumental features can mimic 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

Dark matter velocity spectroscopy

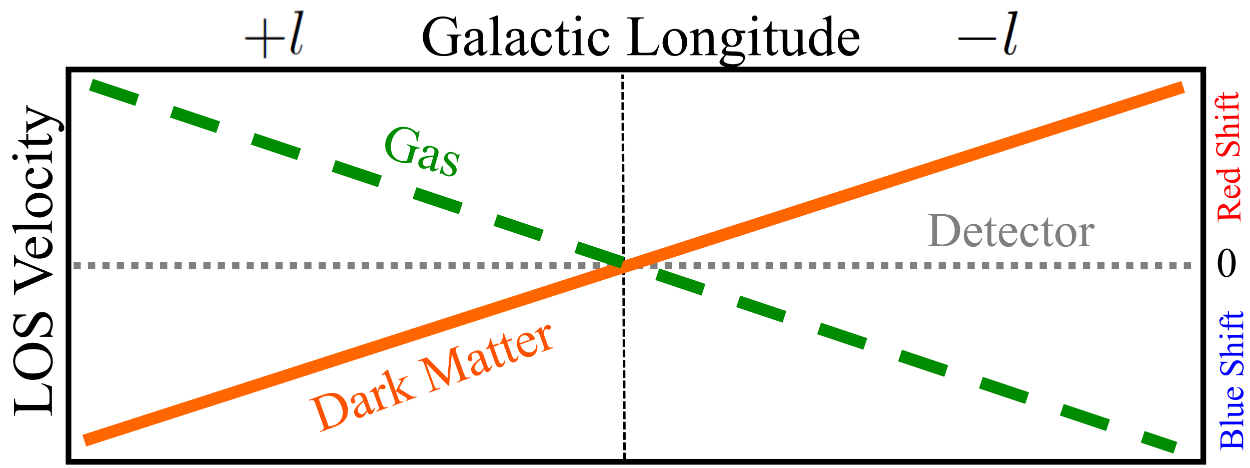
arXiv 1507.04744

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

Dark matter velocity spectroscopy

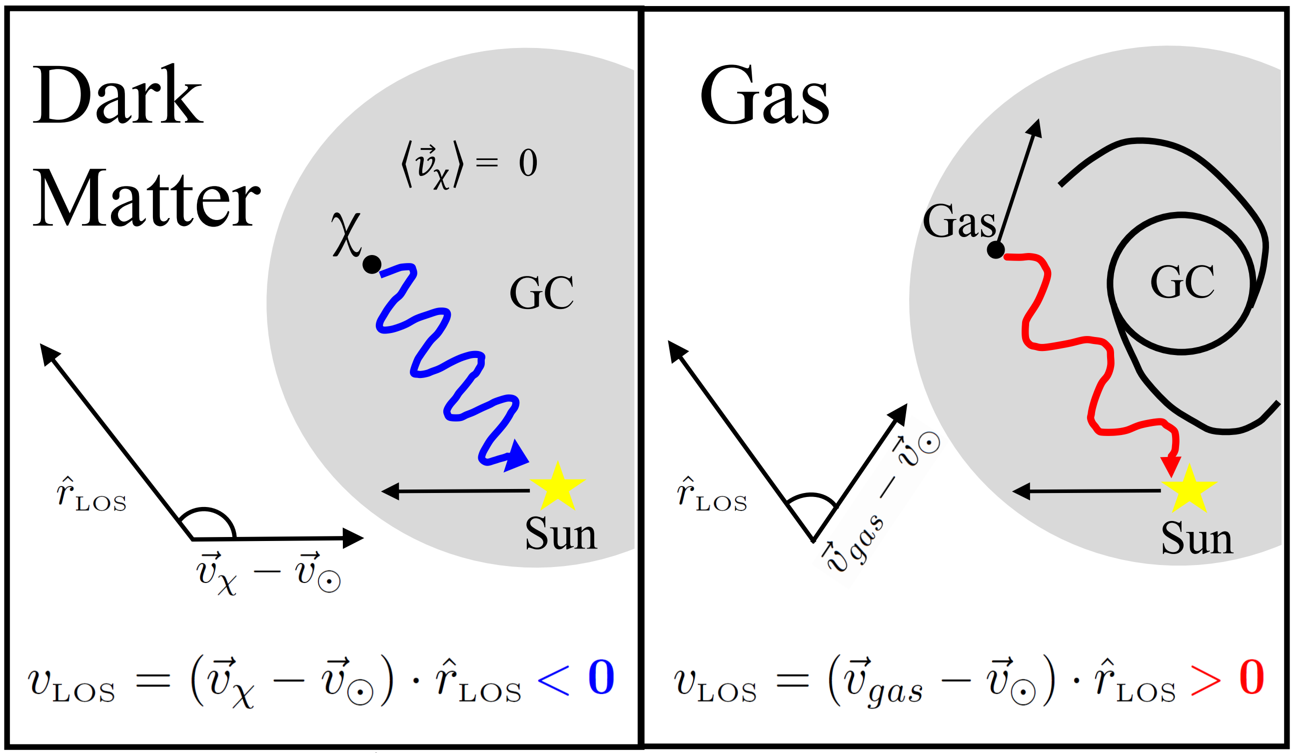
- Dark matter halo has little angular momentum

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



Speckhard etal., 1507.04744

- Sun moves at ~220 km/s



- Distinct longitudinal dependence of signal

- Doppler effect

Order of magnitude estimates

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

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

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

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

$$\boxed{\begin{array}{c} \delta E_{\rm MW}(l,b)/E = +(v_\odot/c)\,(\sin l)\,(\cos b) \\ \dfrac{\delta E_{\rm MW}}{E} \approx 10^{-3} \\ {\rm sign}(\delta E_{\rm MW}) \;\propto\; \sin l,\; {\rm for}\, l \,\epsilon\, [-\pi, \pi] \end{array}}$$

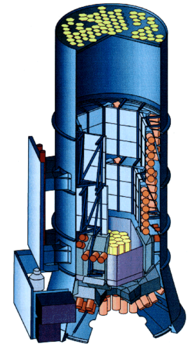
Instruments with $\sim \mathcal{O}(0.1)\%$ energy resolution

Past

Hitomi/ Astro-H

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

Present

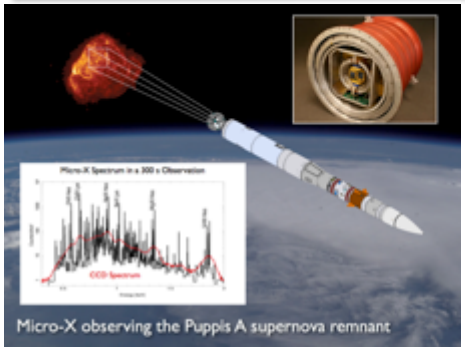


INTEGRAL/ SPI

2.2 keV (FWHM) at 1.33 MeV

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

Future



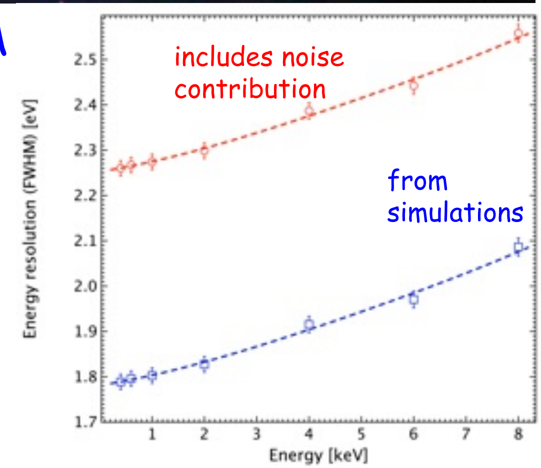
Micro-X

FWHM of 3 eV at 3.5 keV

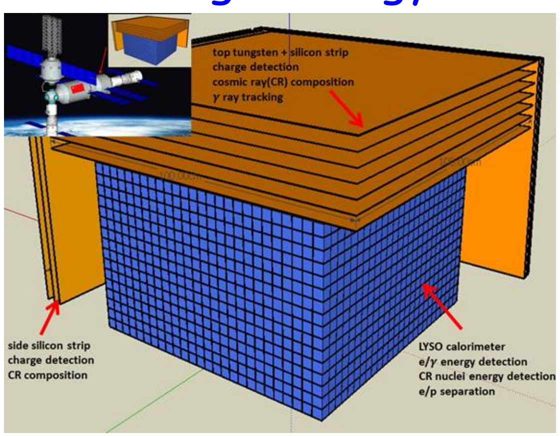
Figueroa-Feliciano etal. 2015

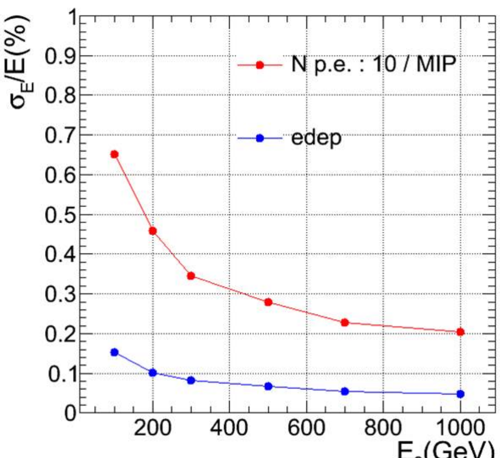
ATHENA

ATHENA X-IFU 1608.08105



HERD: High Energy Cosmic Radiation Detection





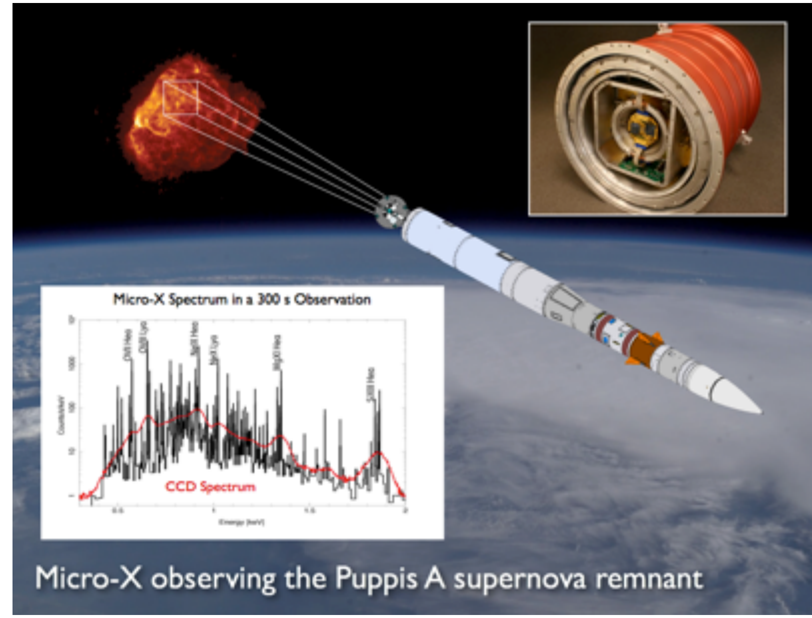
Energy resolution for electrons and gamma will be < 1% at 200 GeV

Wang & Xu Progress of the HERD detector

Application to 3.5 keV line

Solutions to the 3.5 keV line controversy?

See talk by E Bulbul in TeVPA 2017



- **Micro-X**

Wide field of view

Rocket

~10^{-3} energy resolution near 3.5 keV

Figueroa-Feliciano etal. 2015

- **SXS – Hitomi (Astro-H)**

Narrow field of view

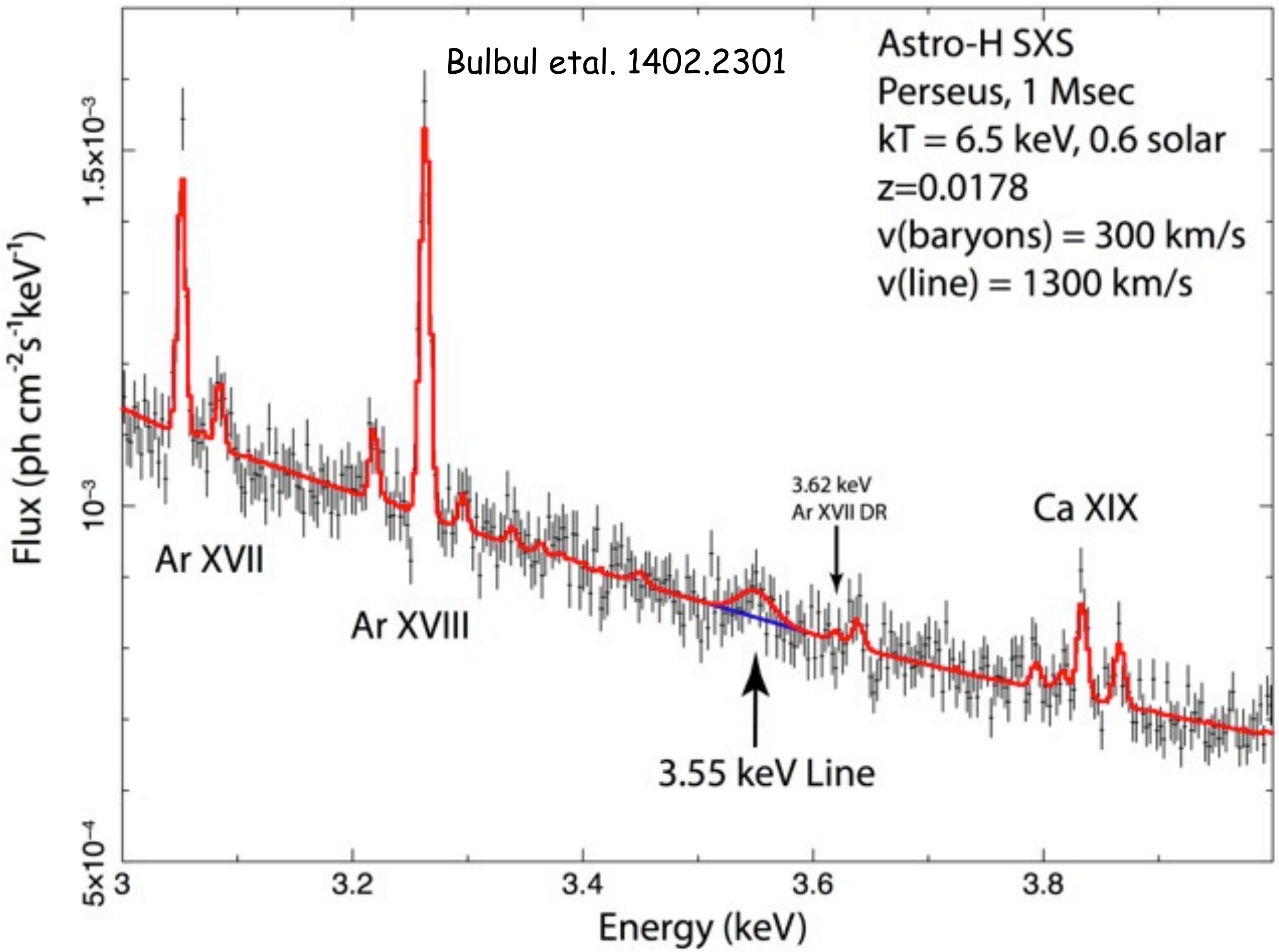
Satellite

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

Lost due to technical failure 

Slide idea: Kenny C Y Ng

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

Shift and broadening of spectrum

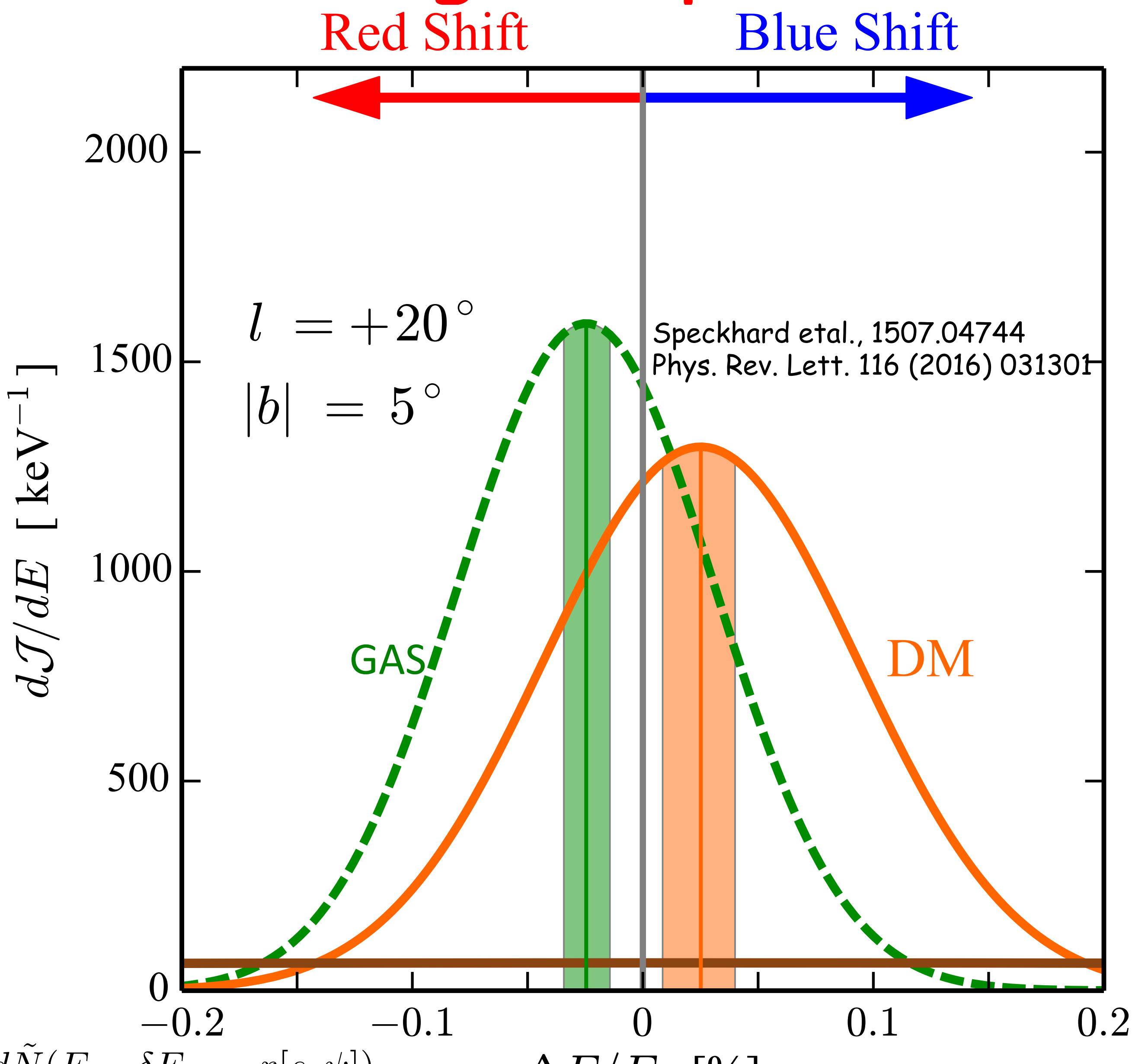
$E_0 = 3.5\,\mathrm{keV}$

2 Ms 1800 cm^2 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



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

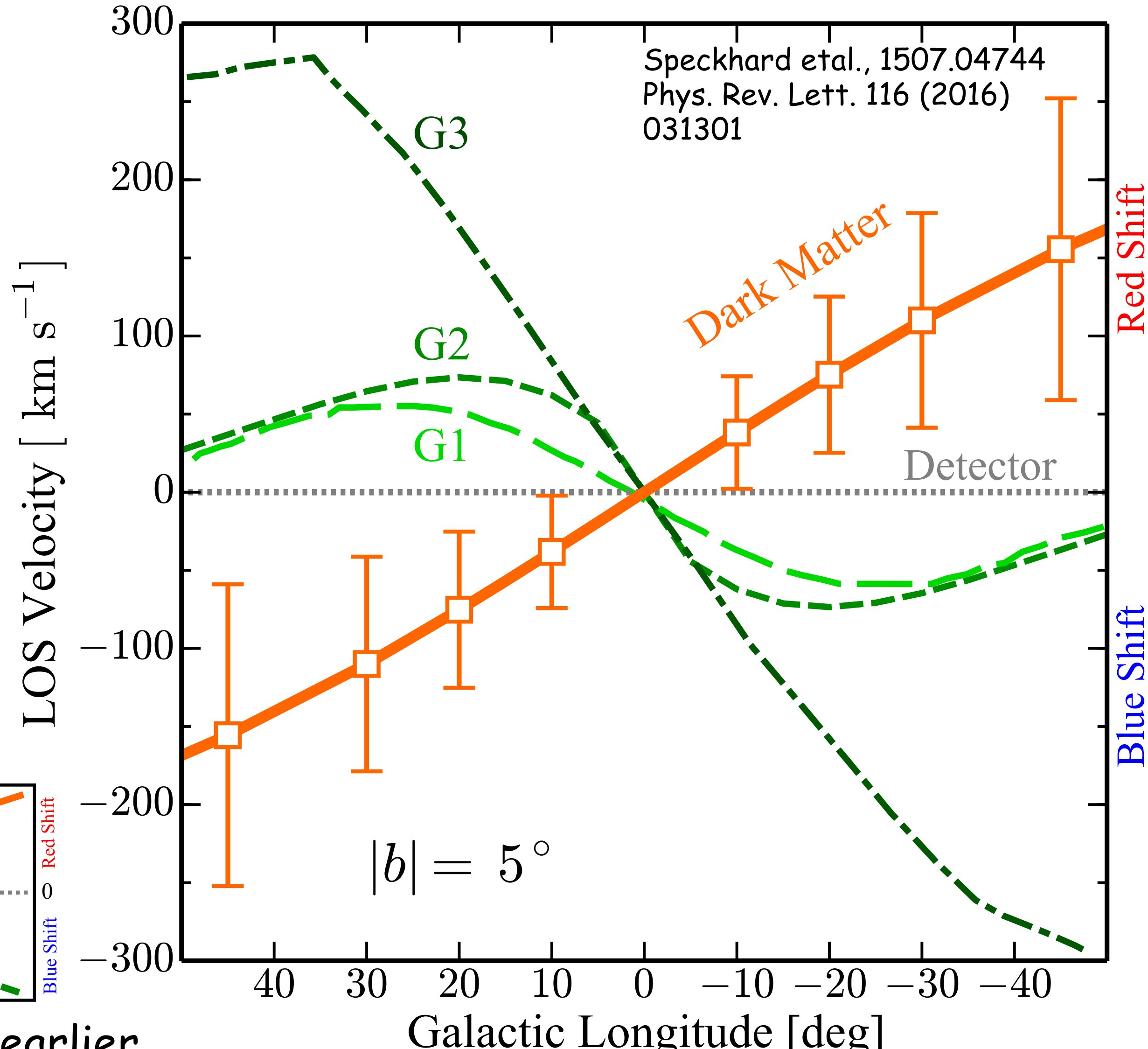
Dark matter and baryonic emission line separation

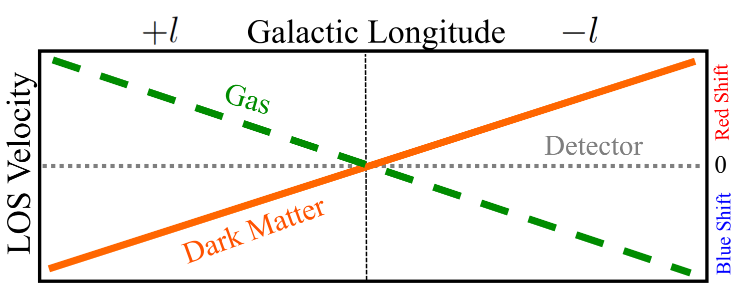
Shift in centroid of dark matter and baryonic line

G1: distribution of free electrons

G2: hot gas distribution of MW

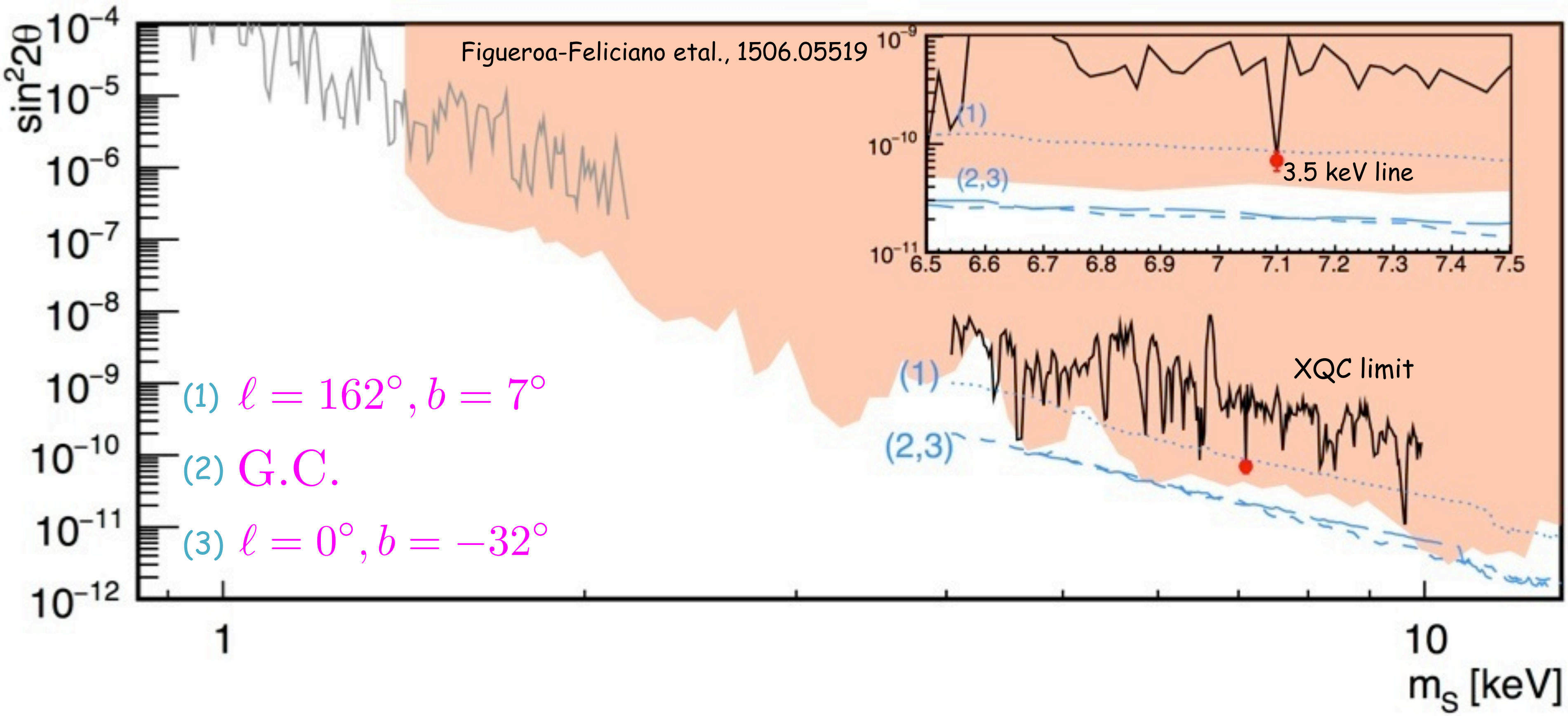
G3: observed distributions of ^{26}Al gamma-rays





Follows the trend explained earlier

Micro-X observations



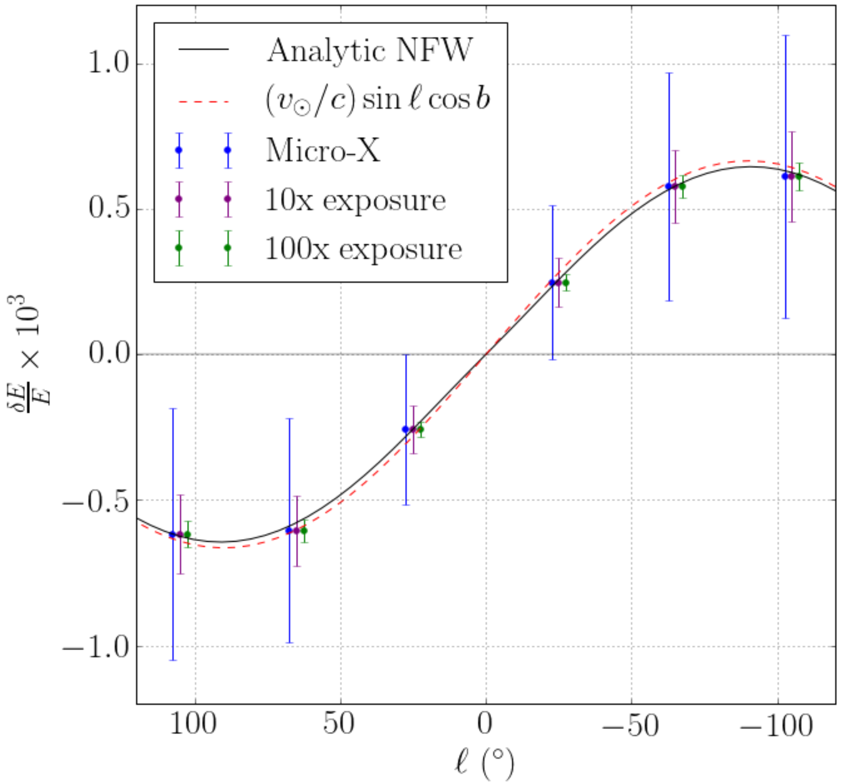
Field of view: 20° radius

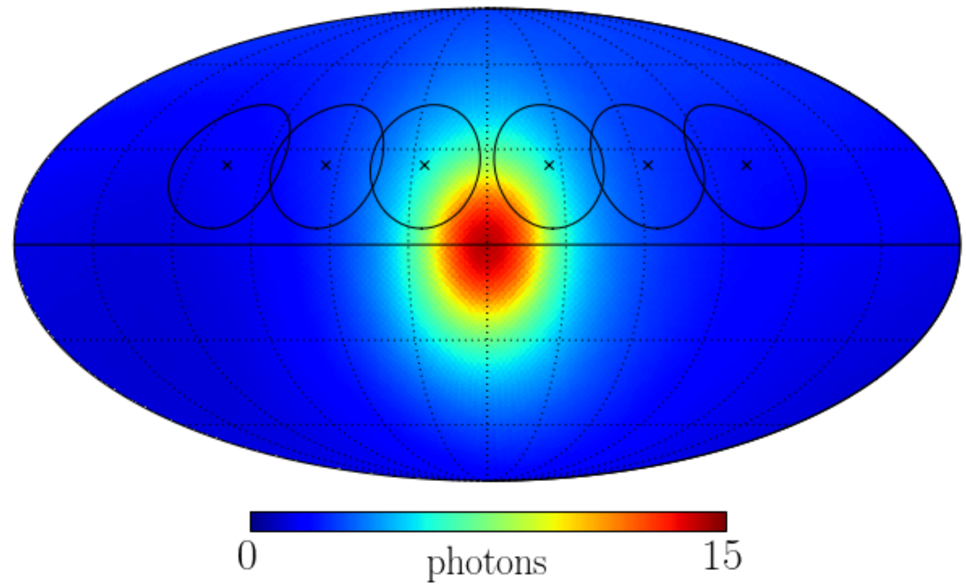
Time of observation: 300 sec

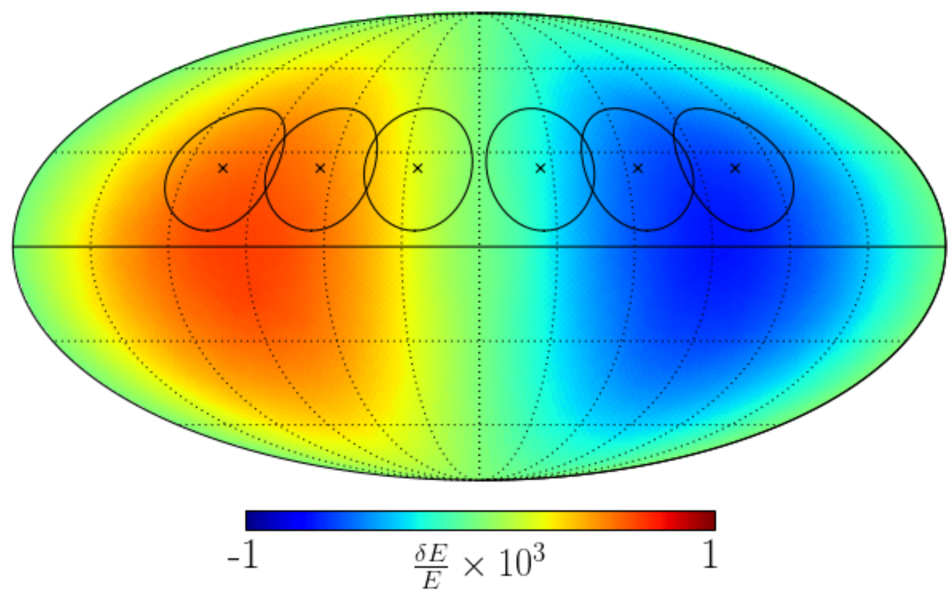
Multiple observations in multiple flights

Very promising reach

Velocity spectroscopy using Micro-X



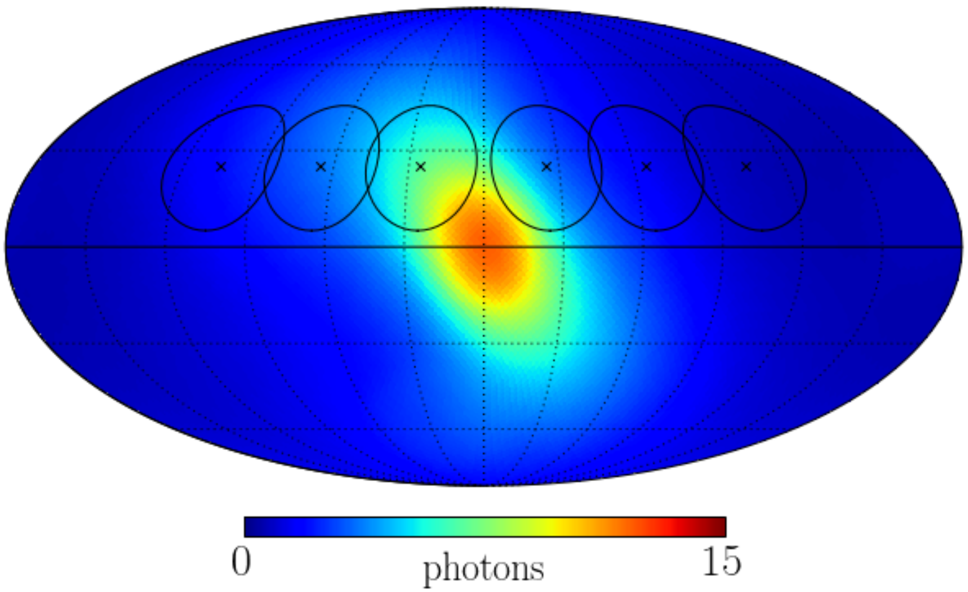


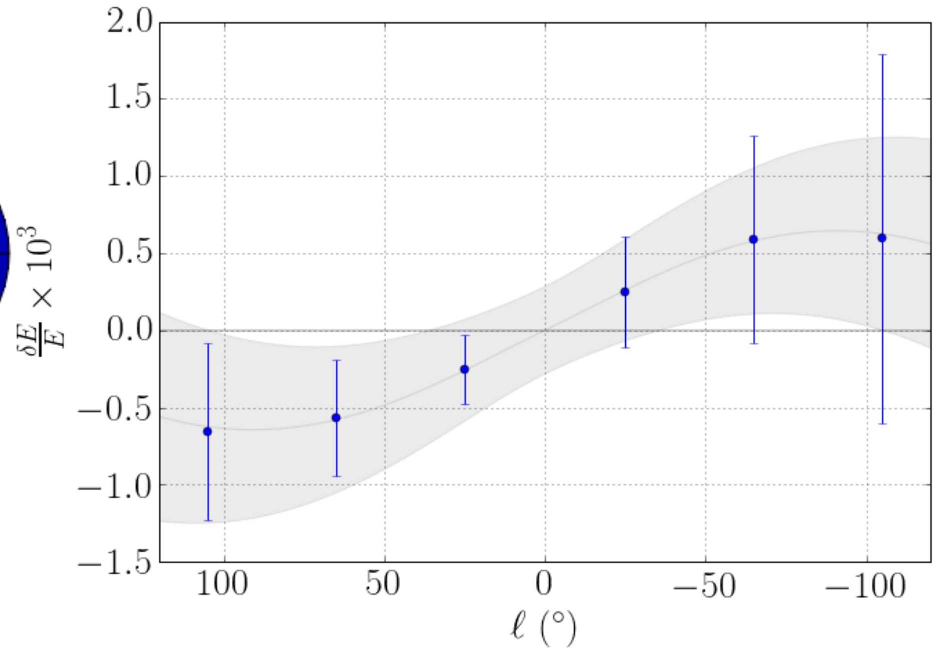


A wide field of view instrument like Micro-X can also perform dark matter velocity spectroscopy

Powell, Laha, Ng, and Abel 1611.02714
(Phys. Rev. D95 (2017) 063012)

Effect of triaxiality





Triaxiality can make the line shift asymmetric

The significance decreases in the presence of triaxiality, but the main effect is still present

The technique can be used to probe triaxiality

Powell, Laha, Ng, and Abel 1611.02714
(Phys. Rev. D95 (2017) 063012)

Conclusion

- Dark matter velocity spectroscopy is a promising tool to distinguish signal and background in dark matter indirect detection

- We see smoking gun in motion

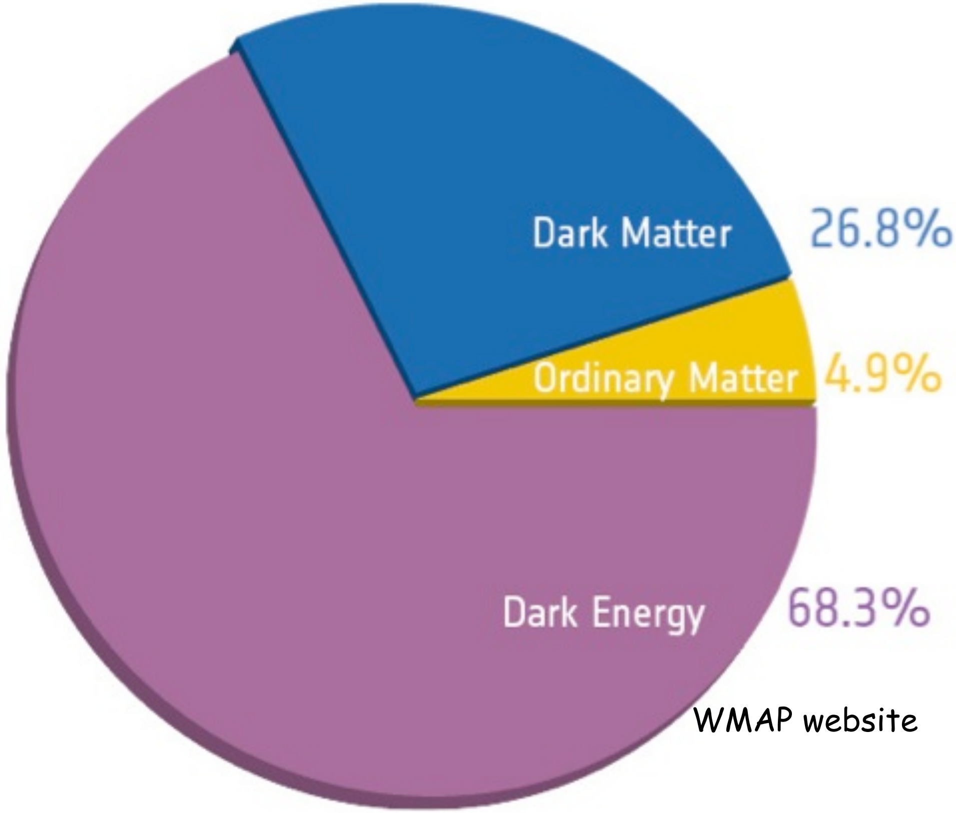
- Immediate application to the 3.5 keV line

- Future improvements in the energy resolution of telescopes at various energies will result in this technique being widely adopted

Questions and comments: rlaha@stanford.edu

Introduction to Dark matter

The present Universe as a pie-chart

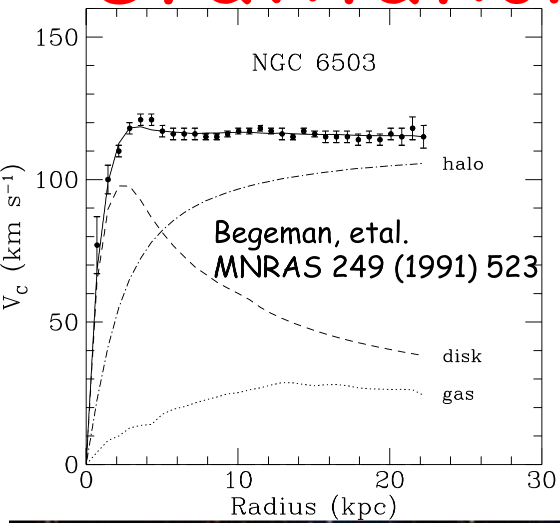


Most of the Universe is unknown

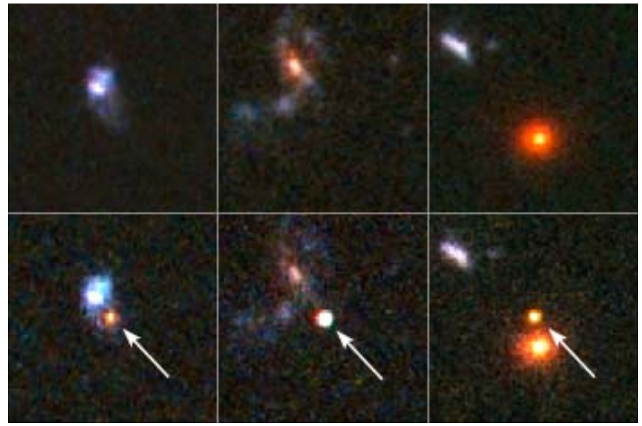
Finding this missing ~ 95% is the major goal of Physics

We concentrate on dark matter

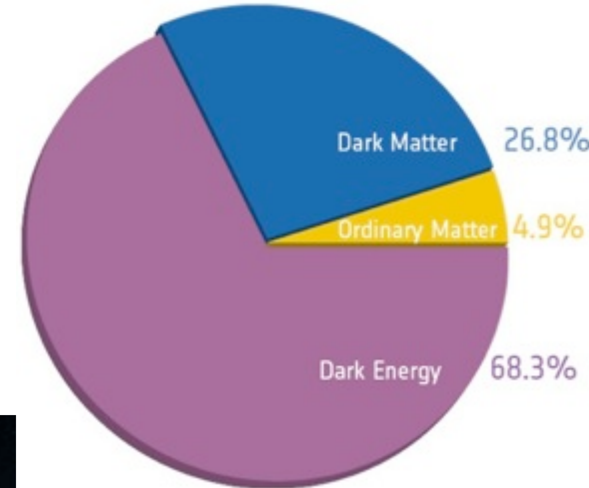
Gravitational detection of dark matter



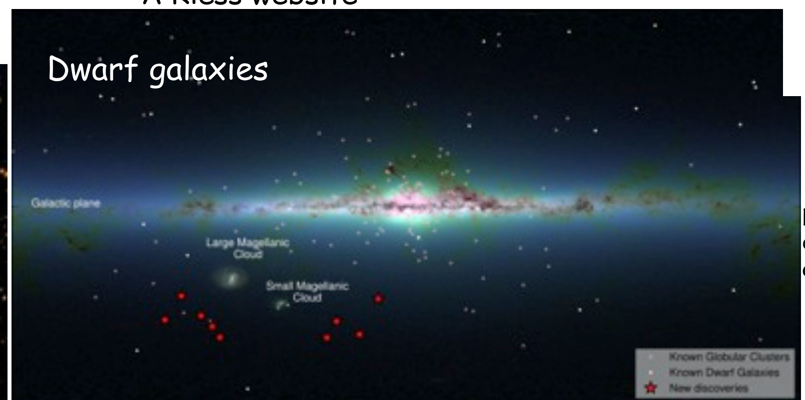
Begeman, etal.
MNRAS 249 (1991) 523



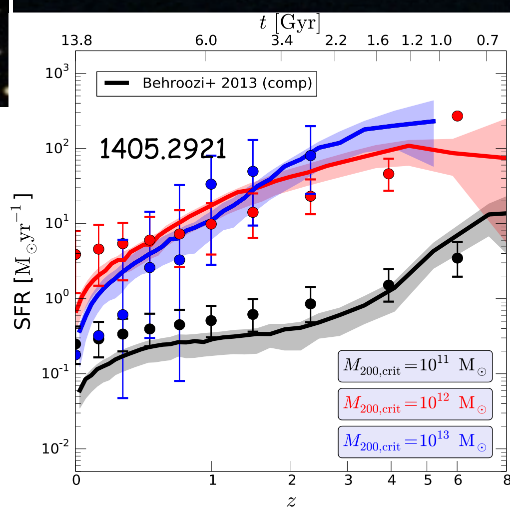
A Riess website



WMAP website

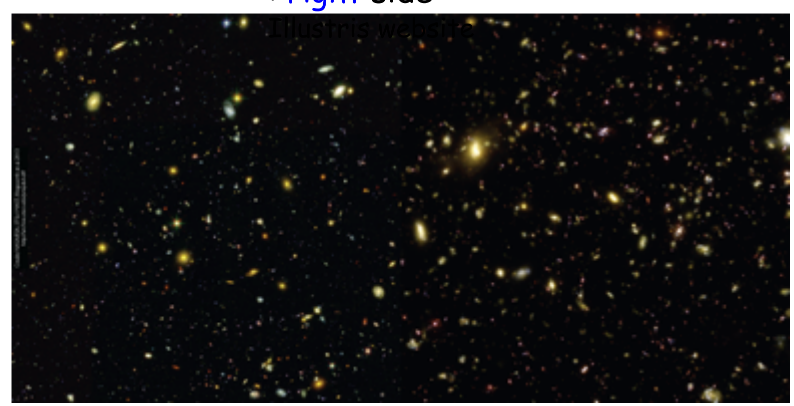


http://www.dailygalaxy.com/my_weblog/2015/08/dark-energy-observatory-discovers-eight-celestial-objects-hovering-near-the-milky-way.html

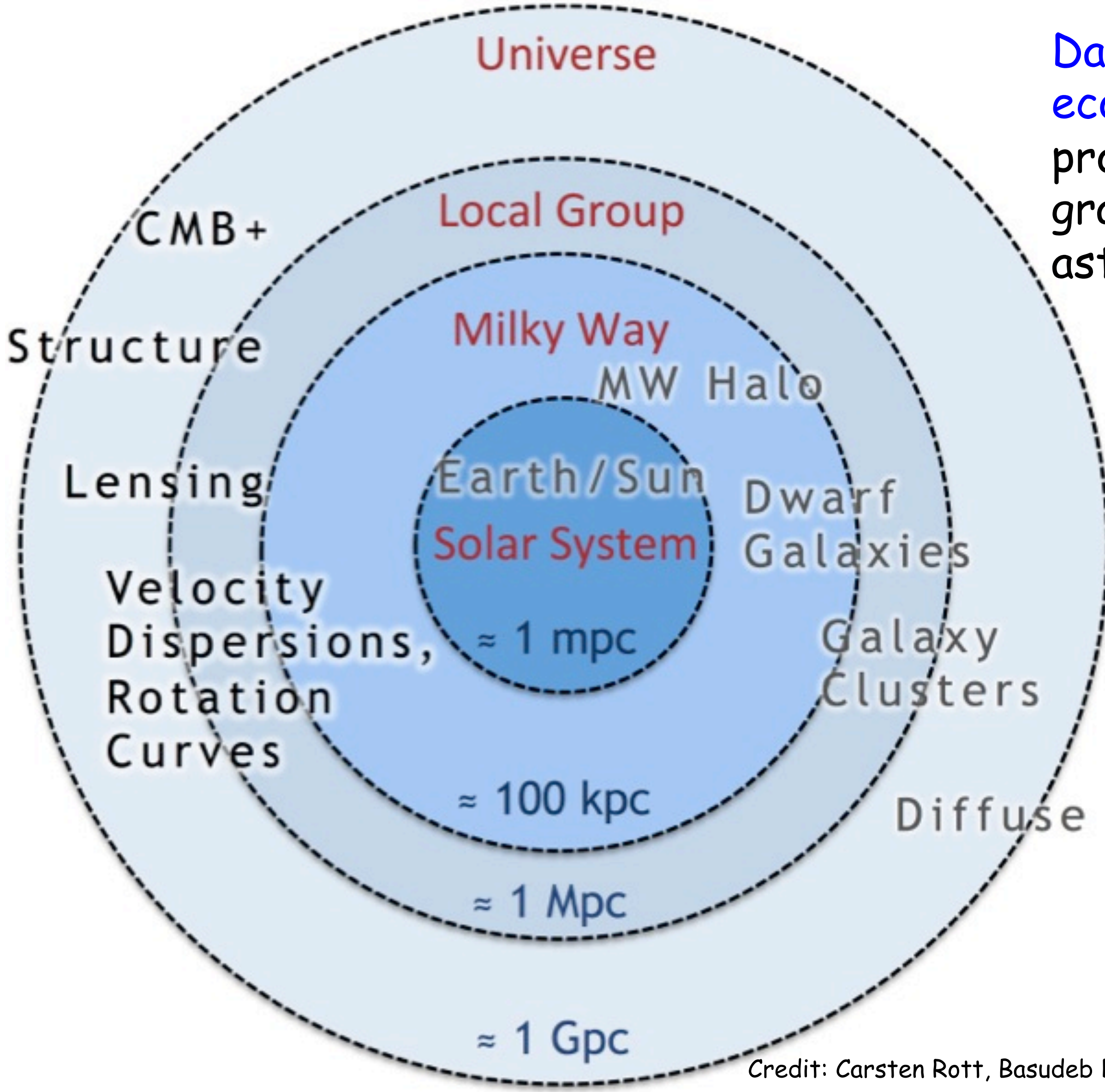


Real observation from Hubble eXtreme Deep Field Observations : left side

Mock observation from Illustris : right side



Gravitational evidence of dark matter at all scales



Dark matter is the most economical solution to the problem of the need of extra gravitational potential at all astrophysical scales

Many different experiments probing vastly different scales of the Universe confirm the presence of dark matter

Modifications of gravity at both non-relativistic and relativistic scales are required to solve this missing gravitational potential problem --- very hard --- no single unified theory exists

Credit: Carsten Rott, Basudeb Dasgupta

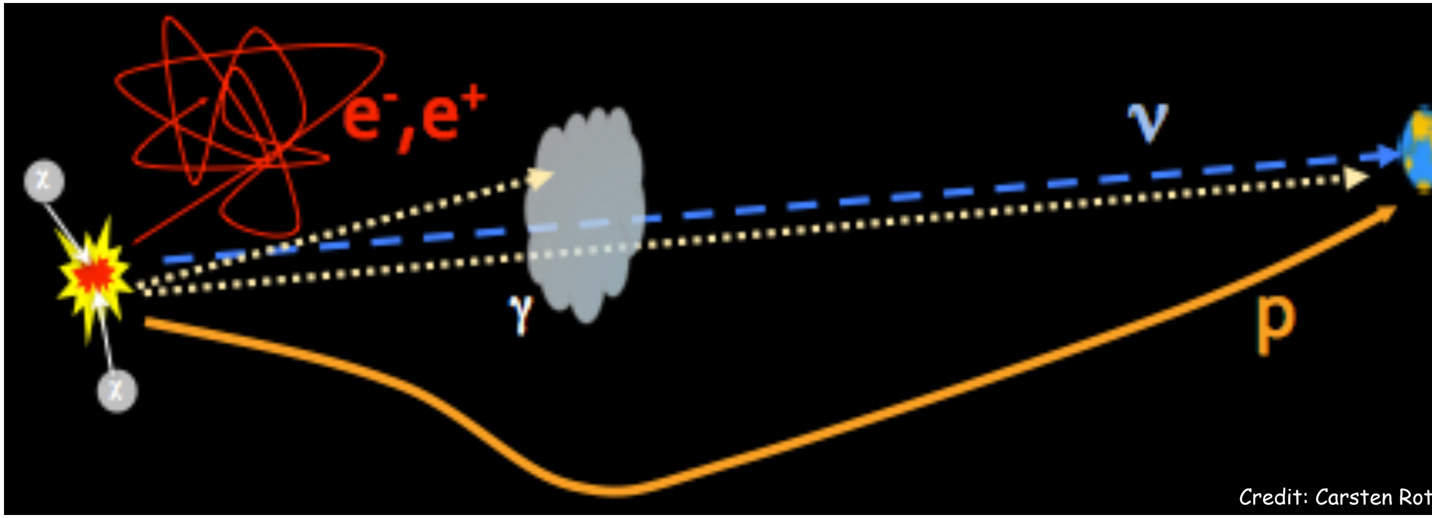
What do we know?

- Structure formation tells us that the particle must be non-relativistic
- Experiences "weak" interactions with other Standard Model particles
- The lifetime of the particle must be longer than the age of the Universe

What do we want to know?

- Mass of the particle
- Lifetime of the particle
- Interaction strength of the particle with itself and other Standard Model particles

Indirect detection of dark matter

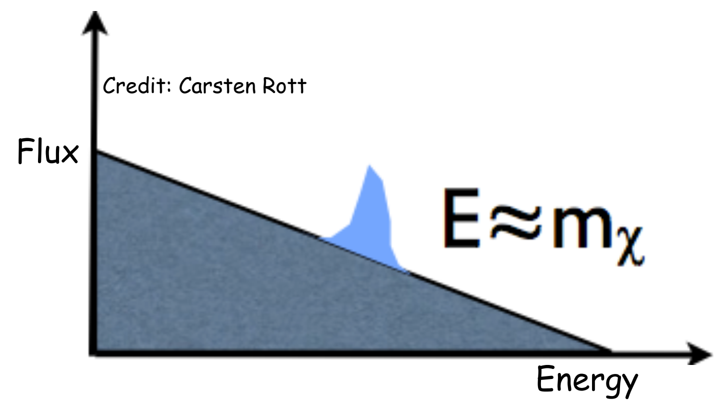


See talk by Slatyer

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

$$\gamma \qquad \nu \qquad e^+ \qquad \overline{p}$$

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



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

Example with dark matter decay

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

Line of sight

Dark matter profile

Γ = Dark matter decay rate

Dark matter mass

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

modified energy spectrum

Gaussian

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

total mass inside a radius r'

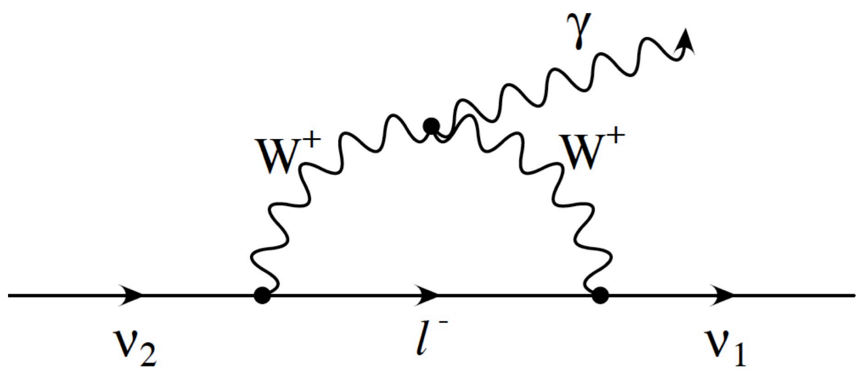
$$\sigma_E = (E/c)\, \sigma_{v_{\rm LOS}}$$

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

width of Gaussian

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

Sterile neutrino



$$\nu_s \to \nu_a + \gamma$$

$$E_\gamma = \frac{m_s}{2}$$

$$\Gamma_\gamma \approx 7 \times 10^{-33}\,\mathrm{s}^{-1}\,\frac{\sin^2 2\theta}{10^{-10}}\,\left(\frac{m_s}{\mathrm{keV}}\right)^5$$

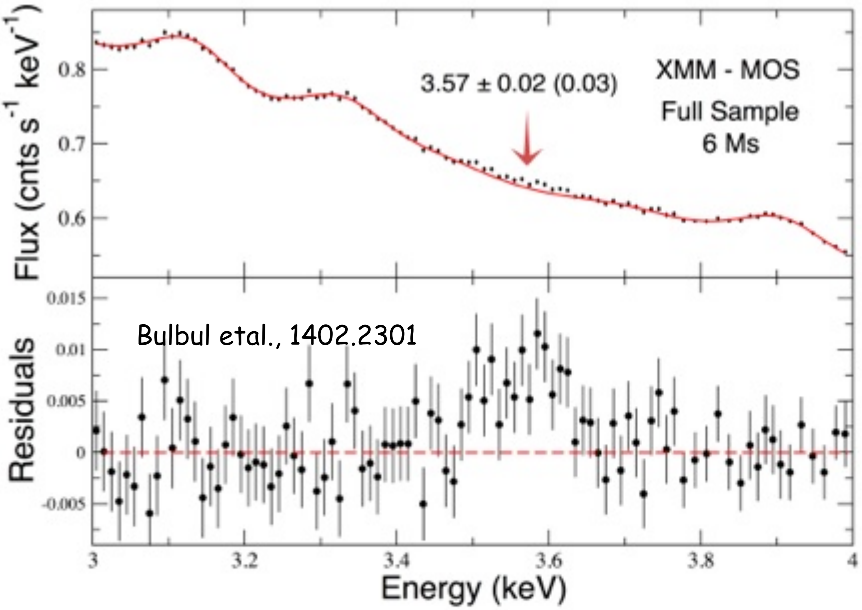
An excellent dark matter candidate --- right handed component of the active neutrino

Production scenarios:

Dodelson - Widrow mechanism (similar to vacuum oscillations of neutrinos)

Shi – Fuller mechanism (similar to MSW transitions of neutrinos)

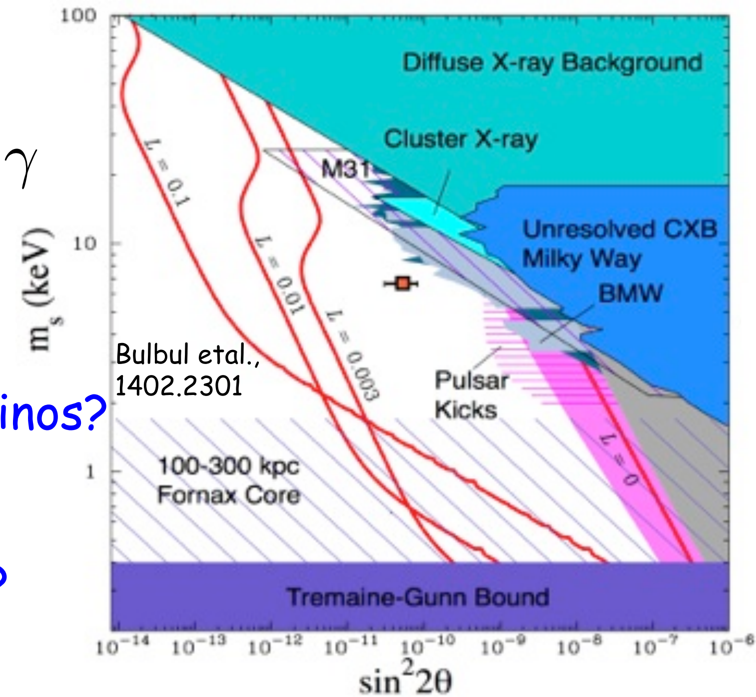
3.5 keV



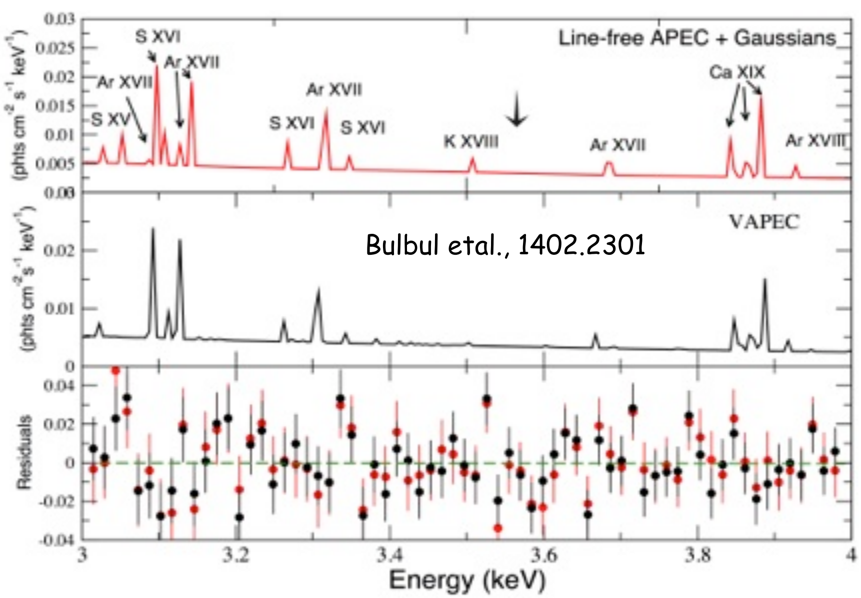
$$\nu_s \to \nu_a + \gamma$$

Sterile neutrinos?

Baryonic astrophysics?



See talk by Bulbul



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

2.3σ in Perseus with XMM-Newton
3σ in M31 with XMM-Newton
Combined detection ~ 4σ

Conflicting results in many different studies

Slide idea: Shunsaku Horiuchi

3.5 keV controversy

Riemer-Sorensen 2014 Milky Way via Chandra ✗

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

Boyarsky etal. 2014 Milky Way via XMM-Newton ✓

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

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

Tamura etal., 2014 Perseus via Suzaku ✗

Urban etal., 2014 Perseus via Suzaku ✓

Urabn etal., 2014 Coma, Virgo, and Ophiuchus via Suzaku ✗

Carlson etal., 2014 morphological studies ✗

Philips etal., 2015 super-solar abundance ✗

Iakubovskyi etal., 2015 individual clusters ✓

Jeltema and Profumo 2015 Draco dwarf ✗

Bulbul etal., 2015 Draco dwarf ✓

Franse etal., 2016 Perseus cluster ✓

Bulbul etal., 2016 stacked cluster ✓

Hofman etal., 2016 33 clusters ✗

HITOMI 2016 Perseus cluster ✗

Shah etal., 2016 Laboratory ✗

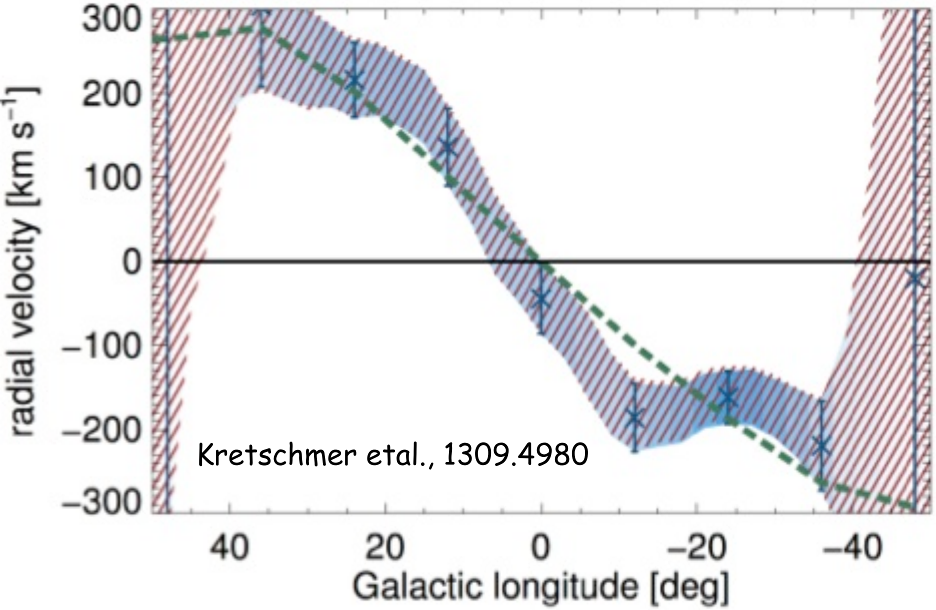
Conlon etal., 2016 Perseus ✓

Gewering-Peine etal., 2016 Diffuse ✗

Cappelluti etal., 2017 Diffuse ✓

Slide idea: Shunsaku Horiuchi and Kenny C Y Ng

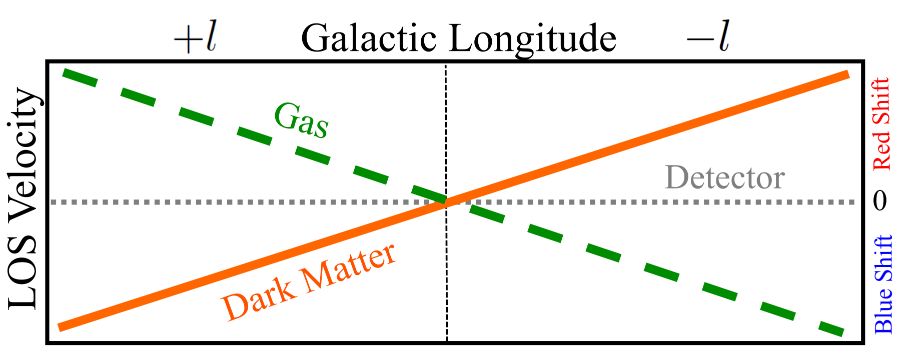
Rotation of baryonic matter



Radial velocity of gas as measured by ^{26}Al

1808.65 keV line

Measurement by INTEGRAL/ SPI



Follows the trend explained earlier