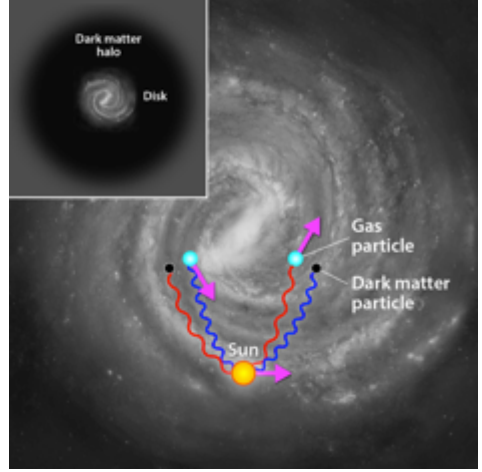

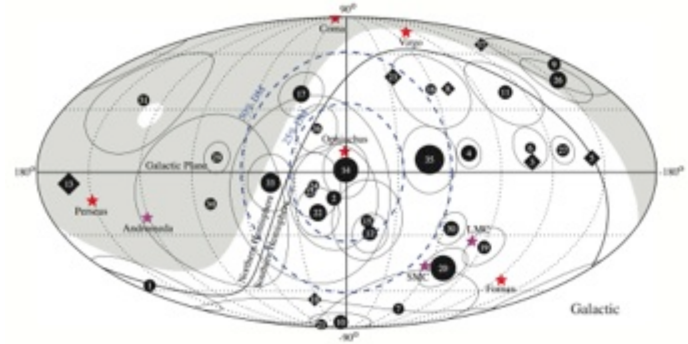

Two new avenues in dark matter indirect detection

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Kavli Institute of Particle Astrophysics and Cosmology (KIPAC)
Stanford University
SLAC National Accelerator Laboratory

Thanks to my collaborators: Tom Abel, Markus Ahlers, Shin'ichiro Ando, John F Beacom, Kohta Murase, Kenny C Y Ng, Devon Powell, Eric G Speckhard

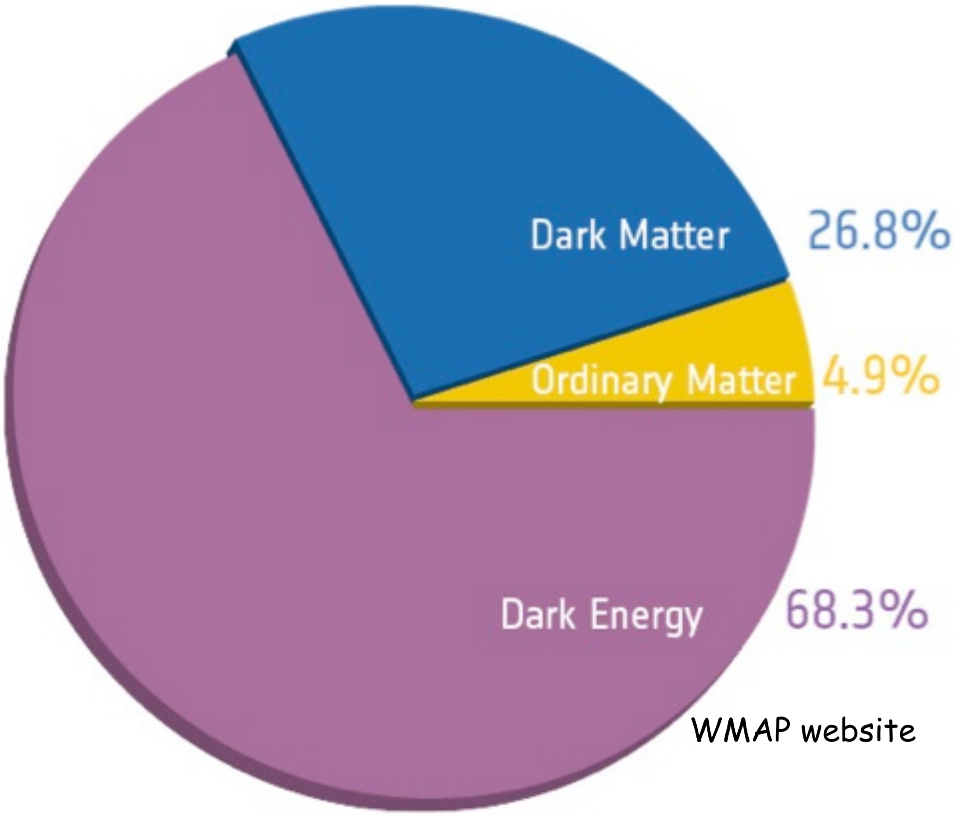
arXiv: 1507.04744 Phys. Rev. Lett. 116 (2016) 031301 arXiv: 1503.04663 Phys.Rev.Lett. 115 (2015) 071301

Contents

- ✓ Introduction to dark matter
- ✓ Dark matter velocity spectroscopy
  - General technique
  - Example: application to the 3.5 keV line
- ✓ Multi-wavelength constraints on very heavy dark matter
  - IceCube motivations
  - Dark matter interpretations and constraints

Introduction to Dark matter

The present Universe as a pie-chart

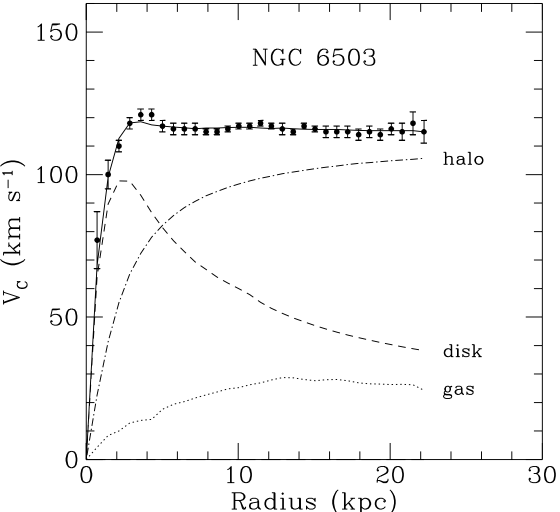


Most of the Universe is unknown

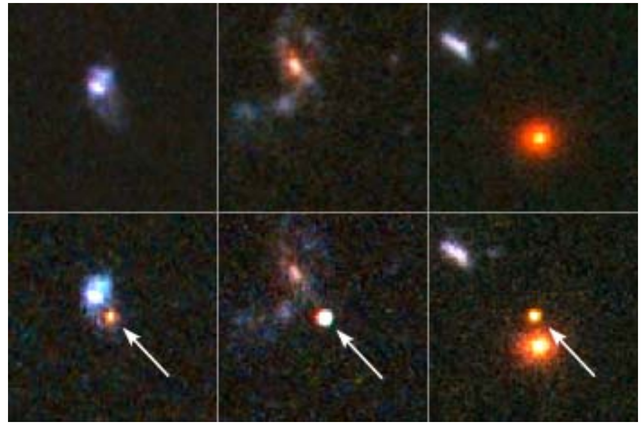
Finding this missing ~ 95% is the major goal of Physics

We concentrate on dark matter

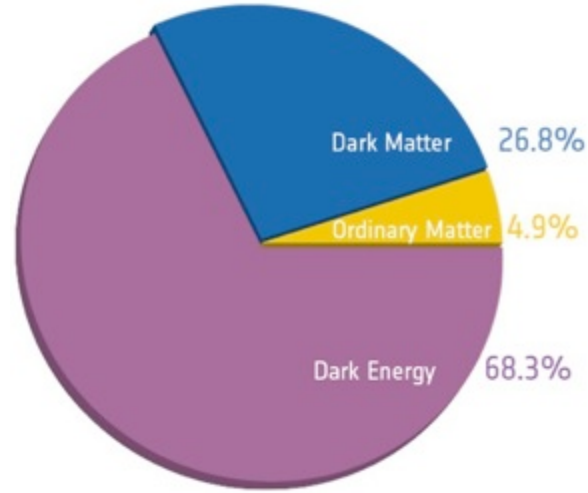
Gravitational detection of dark matter



Begeman, Broeils & Sanders MNRAS 249 (1991) 523

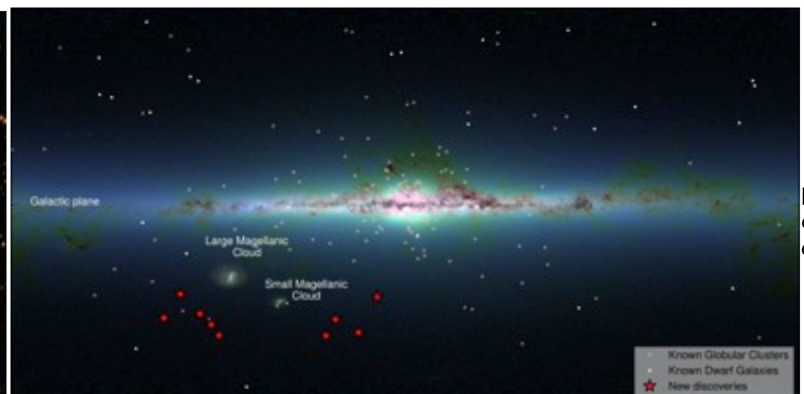


A Riess website



WMAP website

Astronomy Picture of the Day



Dwarf galaxies

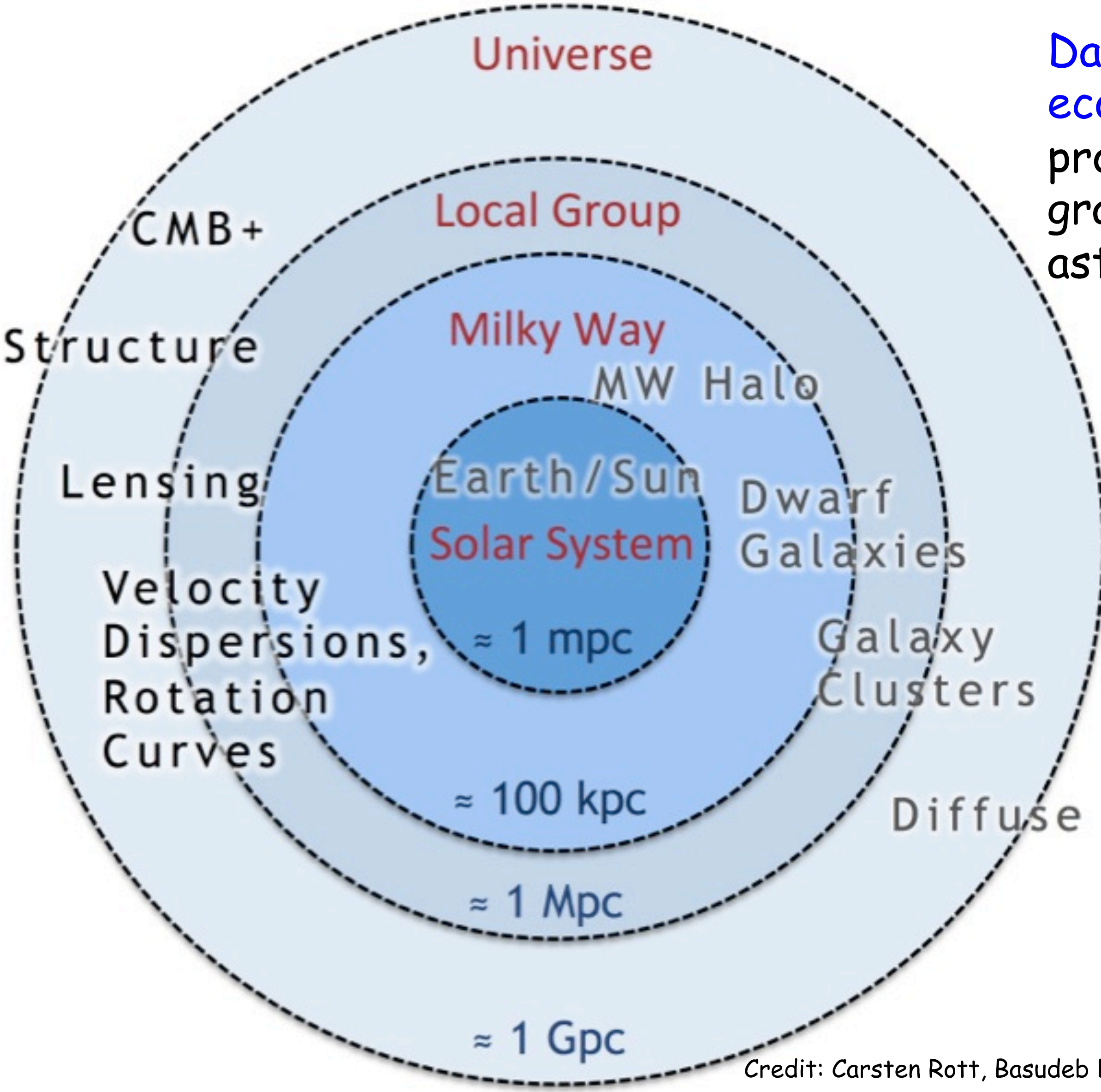
http://www.dailygalaxy.com/my_weblog/2015/08/dark-energy-observatory-discovers-eight-celestial-objects-hovering-near-the-milky-way.html

Real observation from Hubble eXtreme Deep Field Observations: left side

Mock observation from Illustris: right side

Illustris website

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

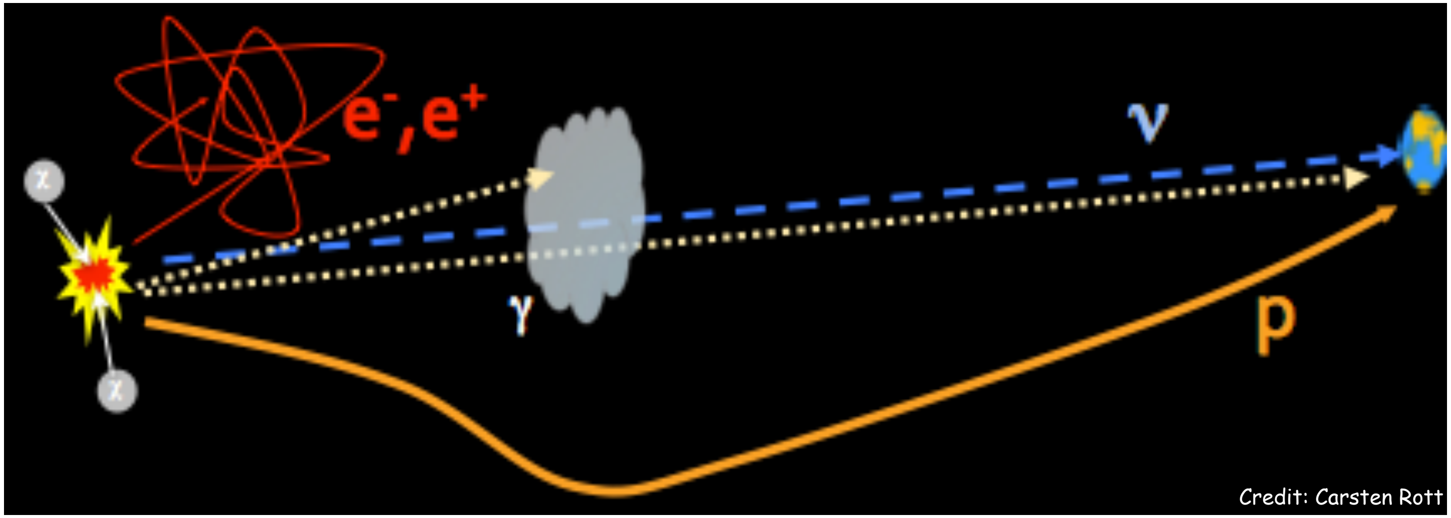
What do we know?

- Structure formation tells us that the particle must be non-relativistic
- It must have "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

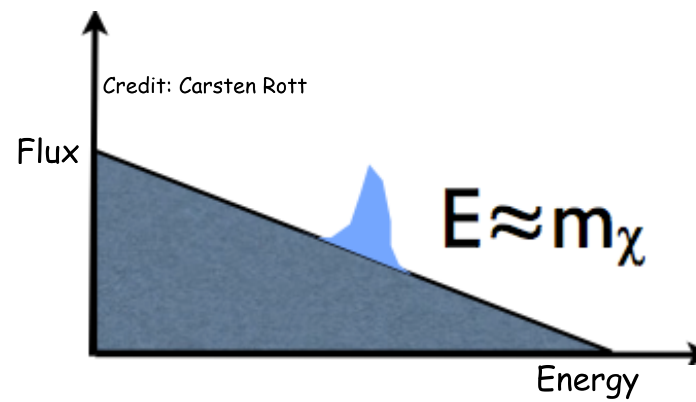
Indirect detection of dark matter



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

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

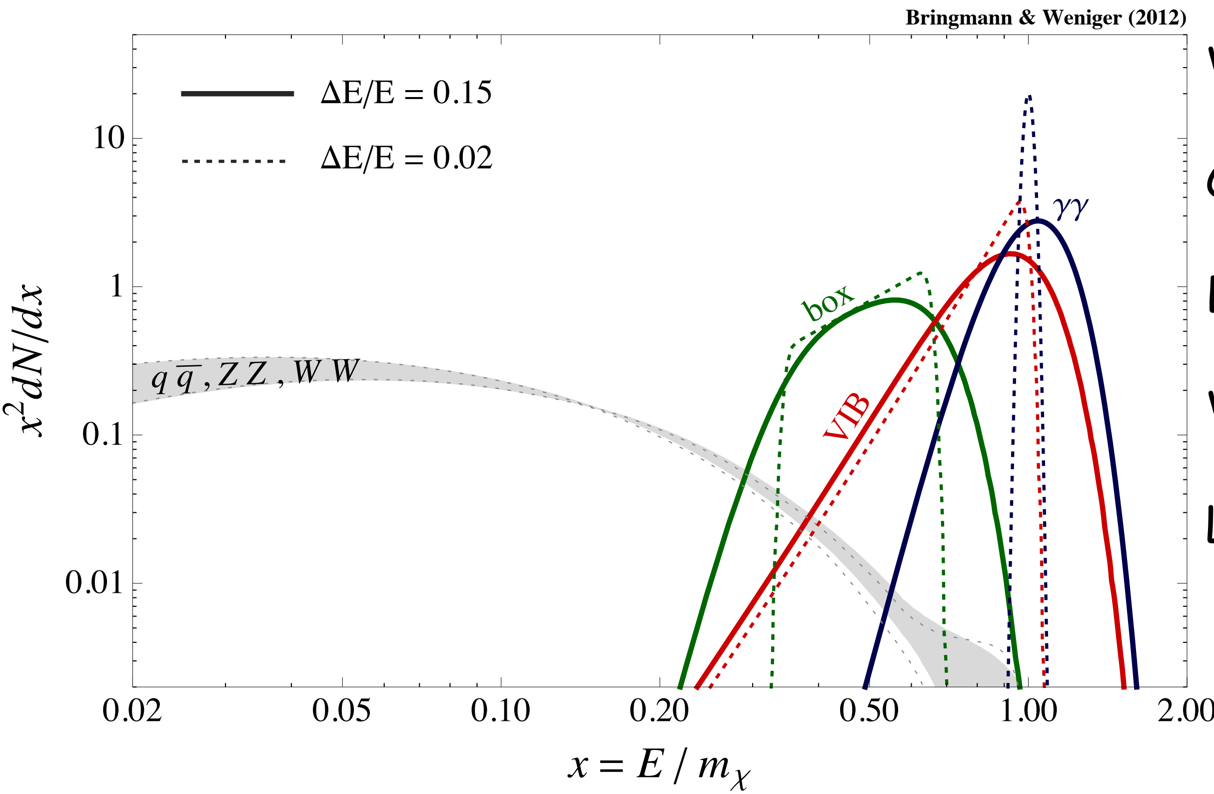
- Spectral features help --- astrophysical backgrounds are relatively smooth --- nuclear and atomic lines problematic



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

Signal and background in indirect detection

Signals: continuum, box, lines, etc.



Various types of signal:

Continuum

Box

Virtual internal bremsstrahlung

Line

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

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

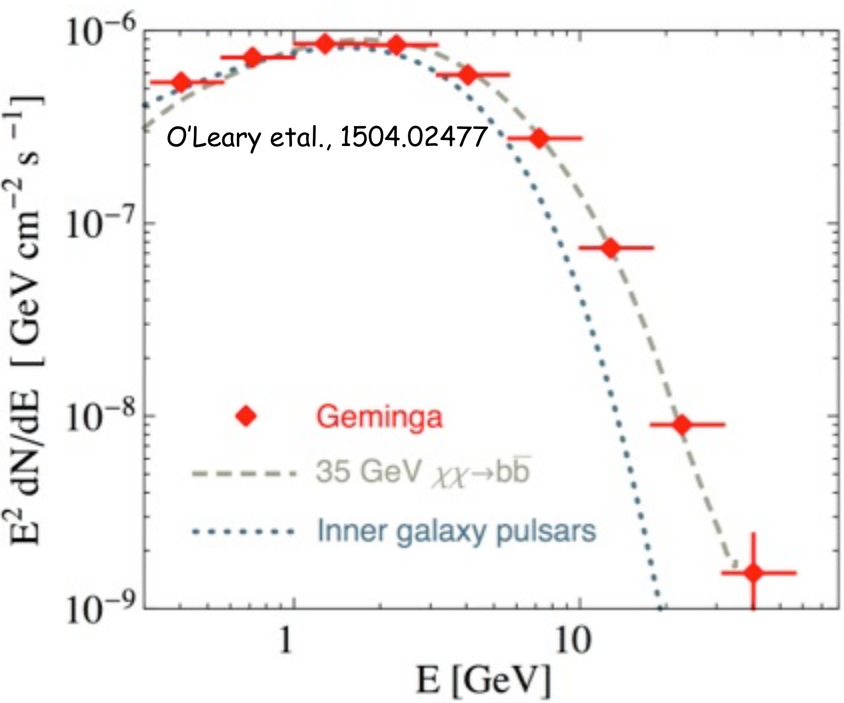
Virtual internal bremsstrahlung: $\chi\chi \to \ell^+\ell^-\gamma$

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

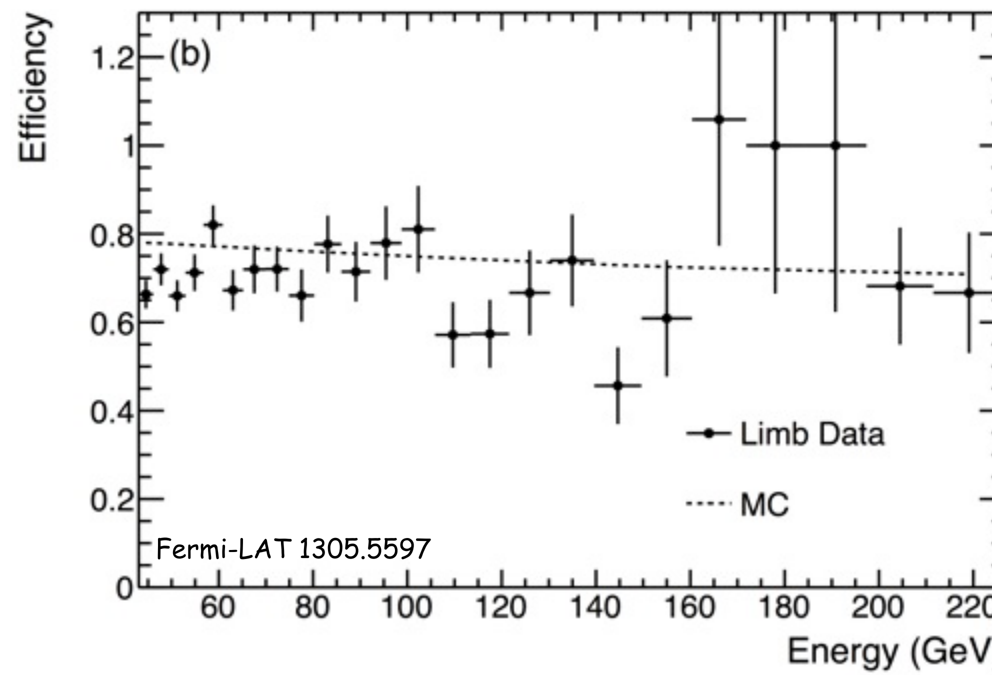
Distinct kinematic signatures important to distinguish from backgrounds

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

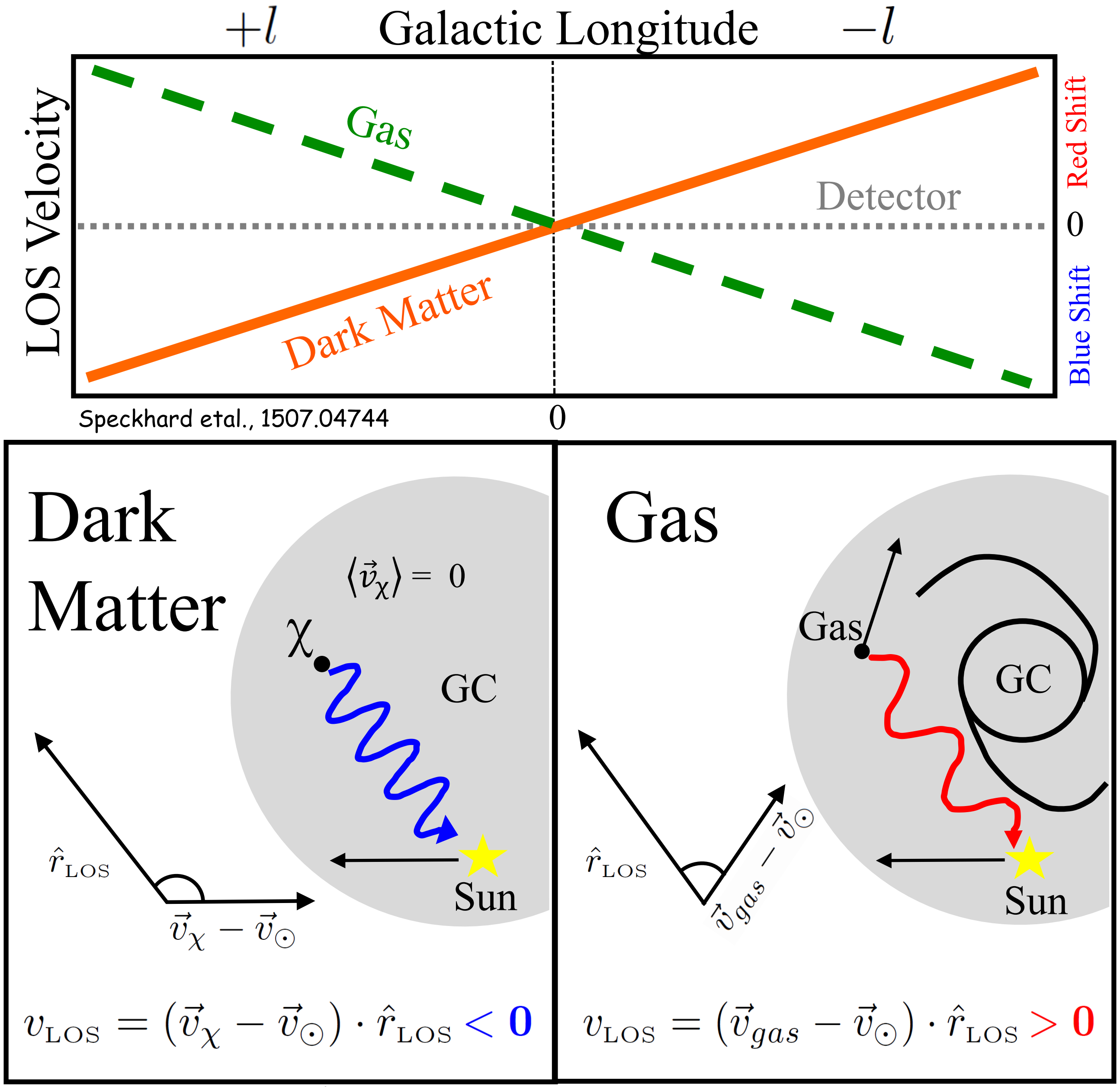
Phys. Rev. Lett. 116 (2016) 031301 (Editors' Suggestion)

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"

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

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

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

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

Example with dark matter decay

Differential intensity

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

Line of sight

Dark matter profile

Γ = Dark matter decay rate

Dark matter mass

Energy spectrum

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

modified energy spectrum

Gaussian

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

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

width of Gaussian

total mass inside a radius r'

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

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

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

Past

Hitomi/ Astro-H

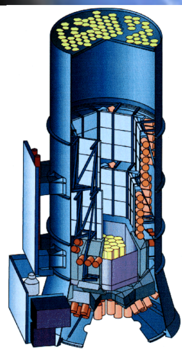
$$\frac{\sigma_E}{E} \approx \frac{1.7\,\mathrm{eV}}{3.5\,\mathrm{keV}}$$

XQC Sounding Rocket experiment

23 eV FWHM at 3.3 keV

Figueroa-Feliciano etal., 2015

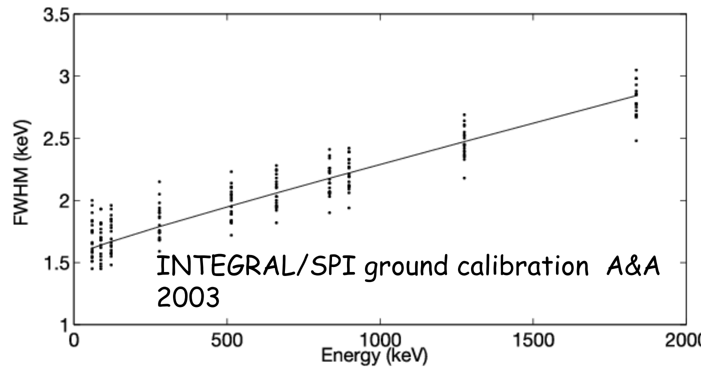
Present



INTEGRAL/ SPI

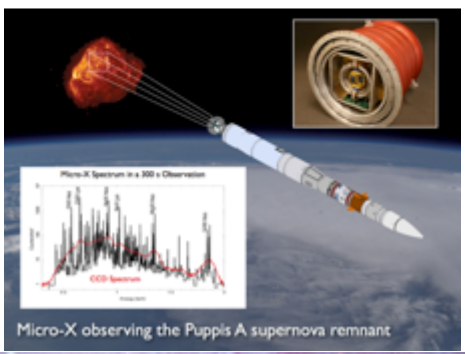
2.2 keV FWHM at 1.33 MeV

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



INTEGRAL/SPI ground calibration A&A 2003

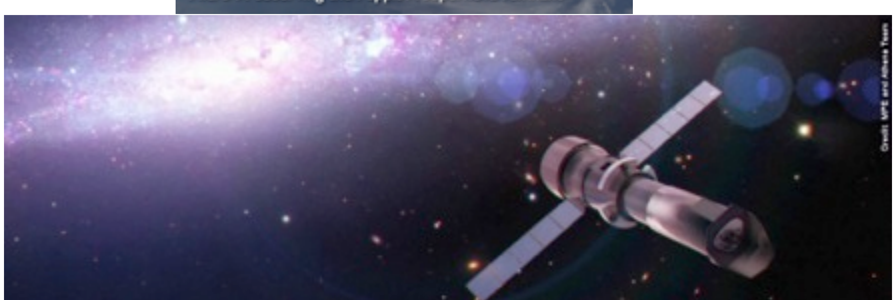
Future



Micro-X

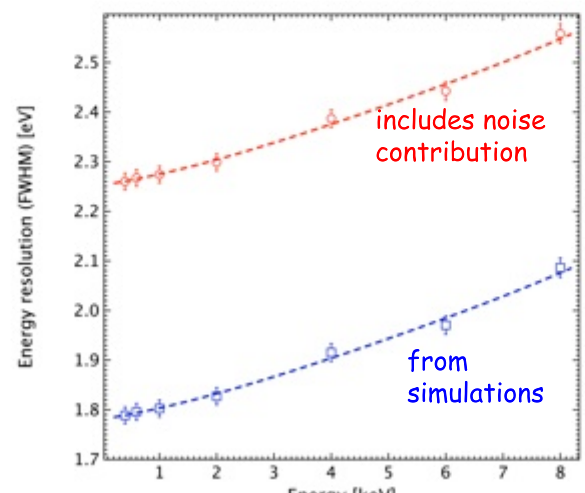
3 eV FWHM at 3.5 keV

Figueroa-Feliciano etal. 2015



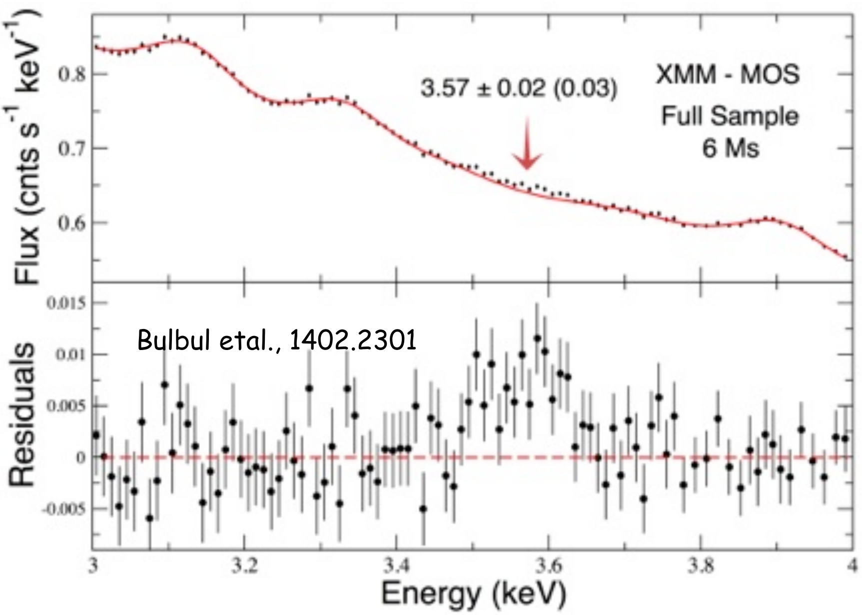
ATHENA

ATHENA X-IFU
1608.08105

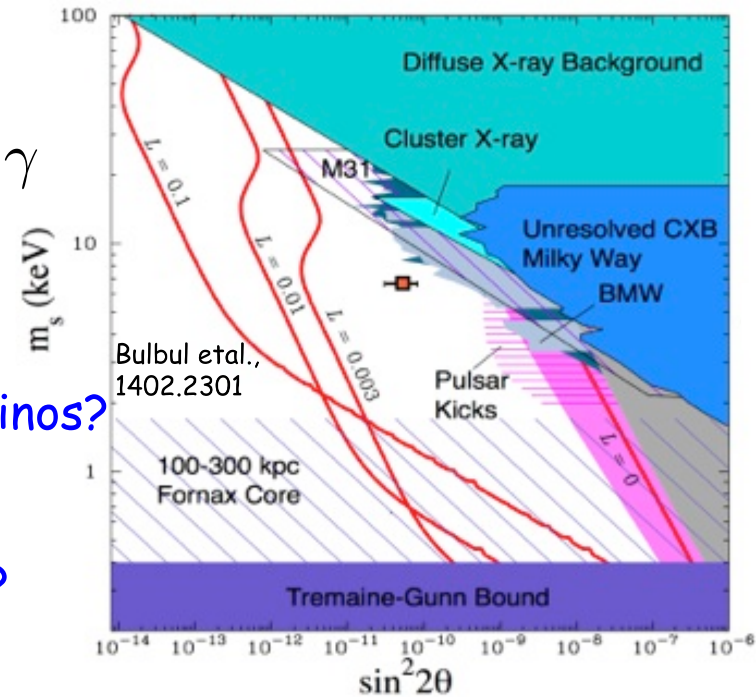


Application to 3.5 keV line

3.5 keV

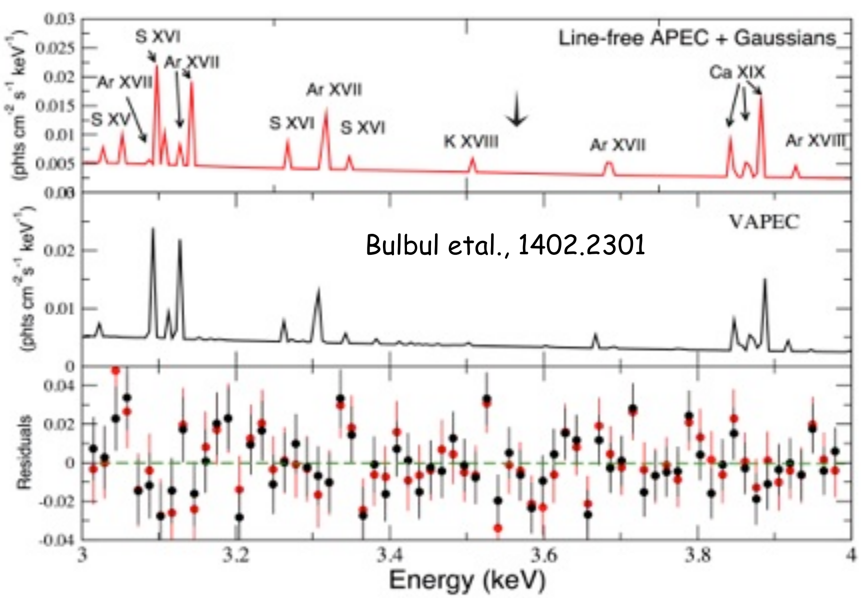


$$\nu_s \rightarrow \nu_a + \gamma$$



Sterile neutrinos?

Baryonic astrophysics?



Stacking of 73 galaxy clusters
Redshift z = 0.01 to 0.35
4 to 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 ✓

Queiroz & Sinha 2014

Campos & Rodejohann 2016

Hofman etal., 2016 33 clusters ✗

HITOMI 2016 Perseus cluster ✗

Shah etal., 2016 Laboratory ✗

Conlon etal., 2016 Perseus ✓

Slide idea: Shunsaku Horiuchi and Kenny C Y Ng

Solutions to the 3.5 keV line controversy?

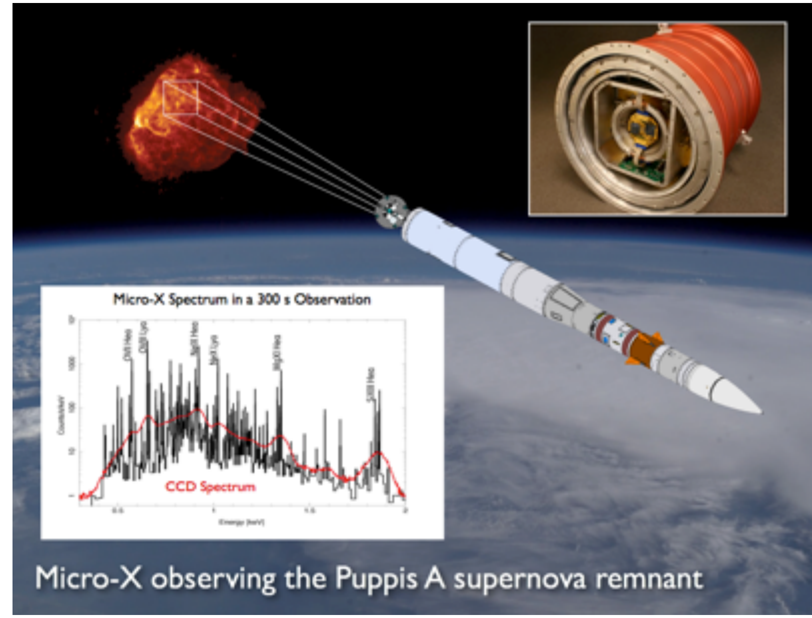
- **Micro-X**

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

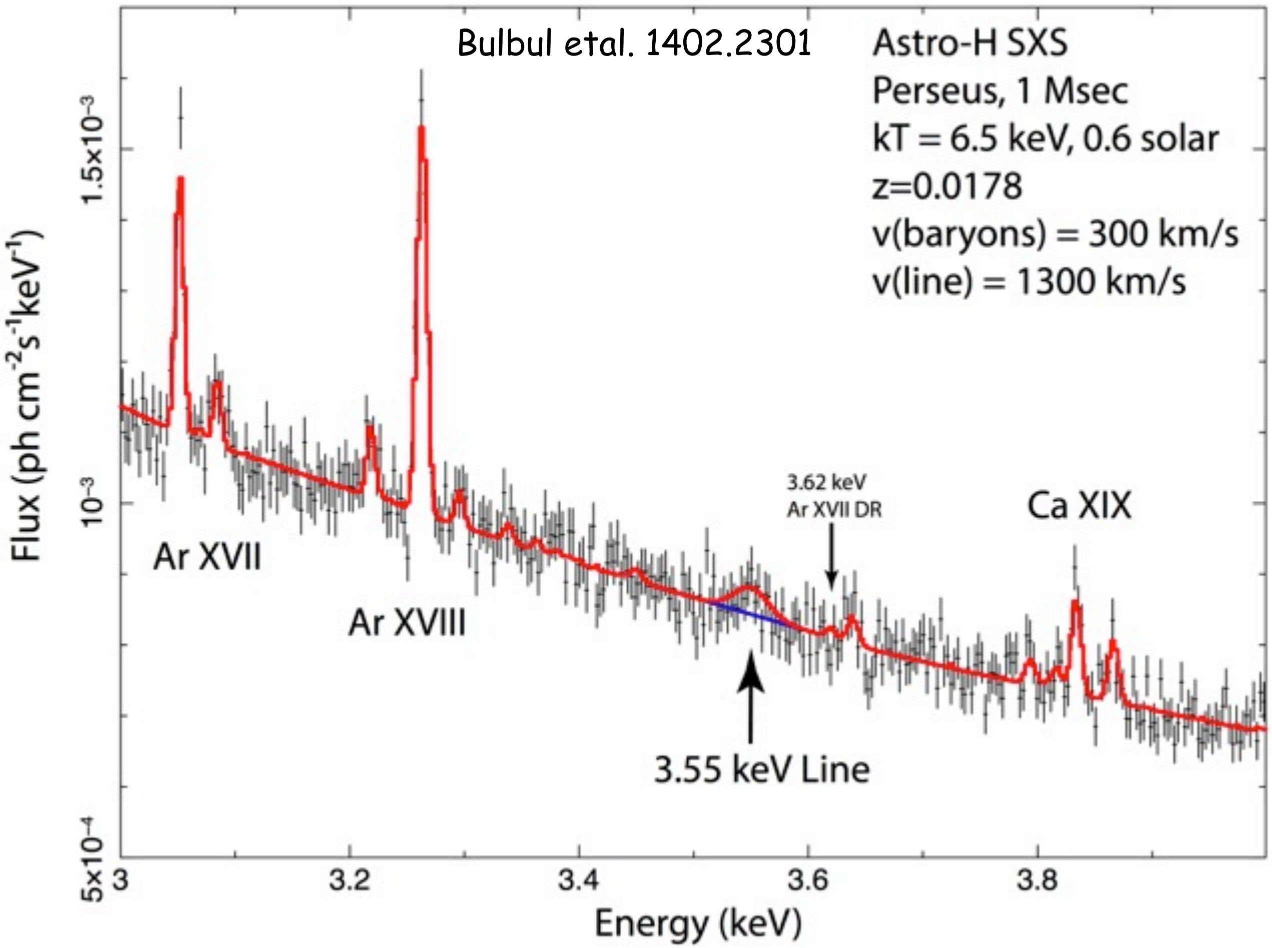
Satellite

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

Lost due to technical failure ☹

Slide idea: Kenny C Y Ng

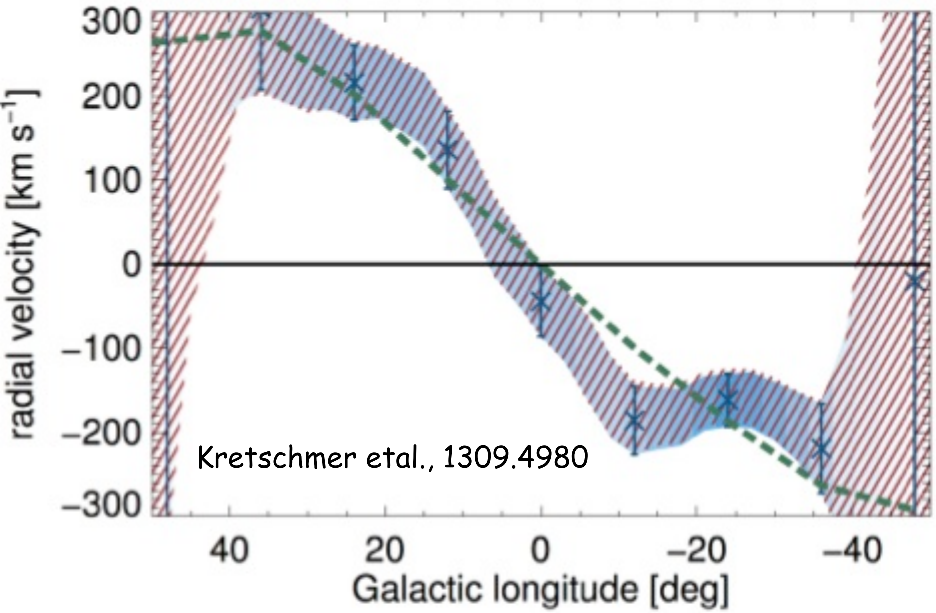
Looking at clusters



Dark matter line broader than plasma emission line

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

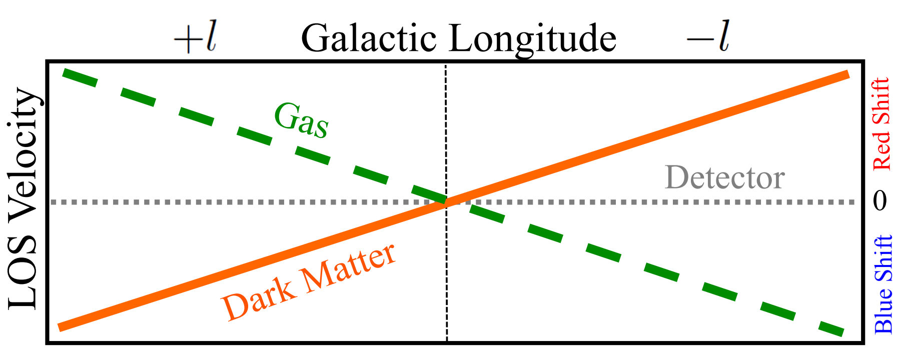
Rotation of baryonic matter



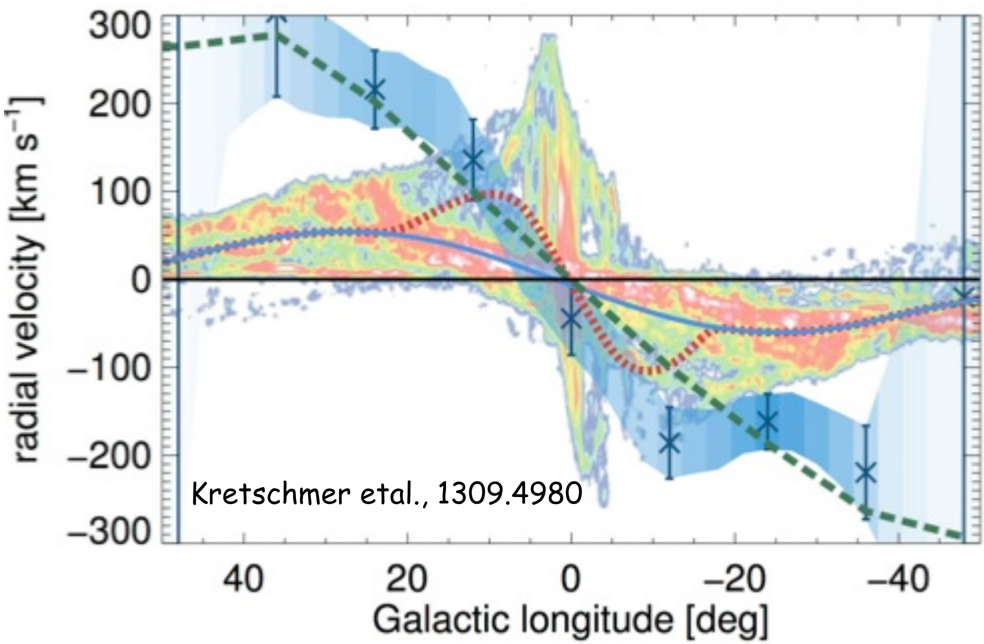
Radial velocity of gas as measured by ^{26}Al

1808.65 keV line

Measurement by INTEGRAL/ SPI



Follows the trend explained earlier



Shift and broadening of spectrum

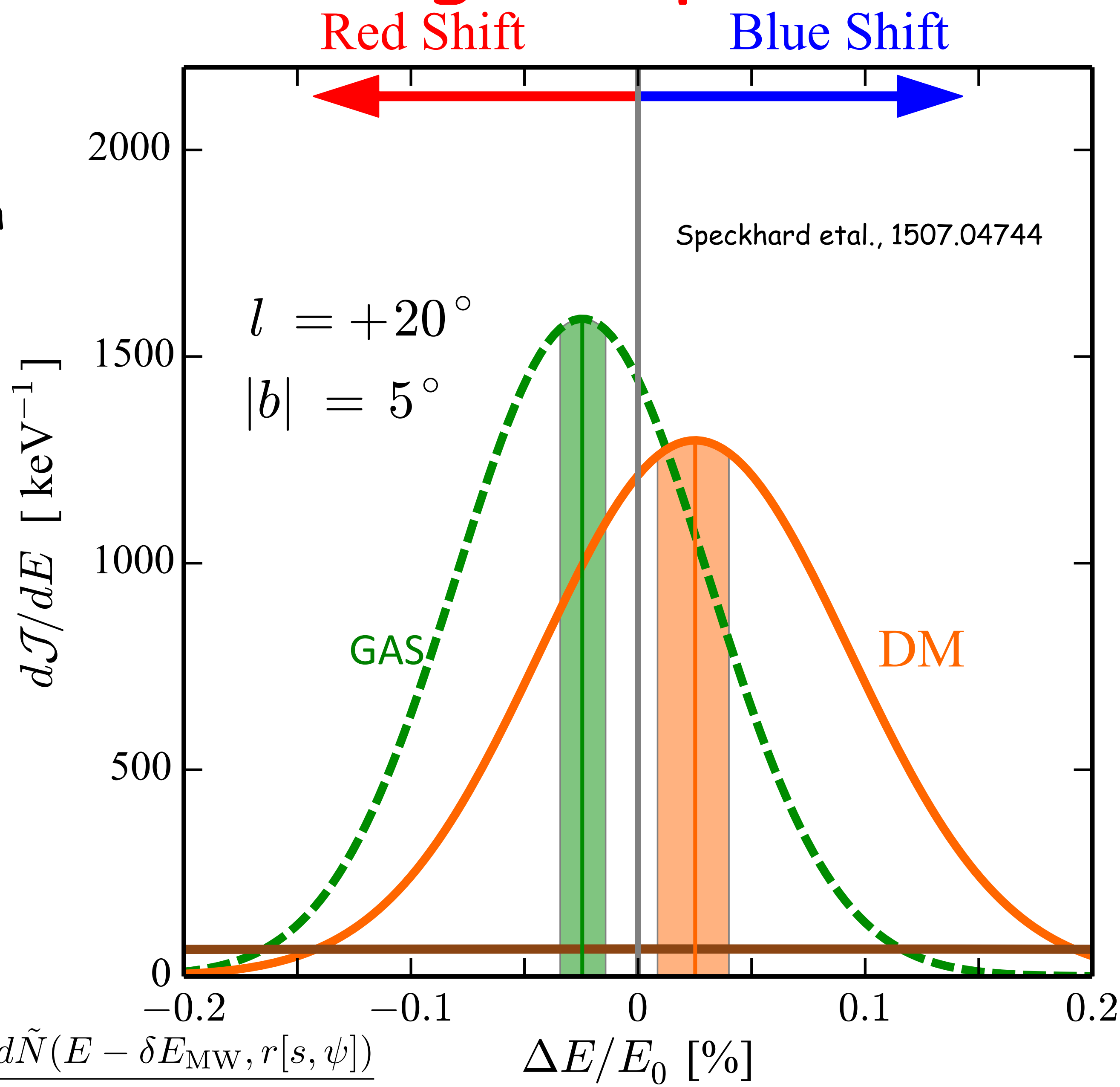
$E_0 = 3.5\,\mathrm{keV}$

2 Ms 1800 cm² arcmin² 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



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

Ranjan Laha

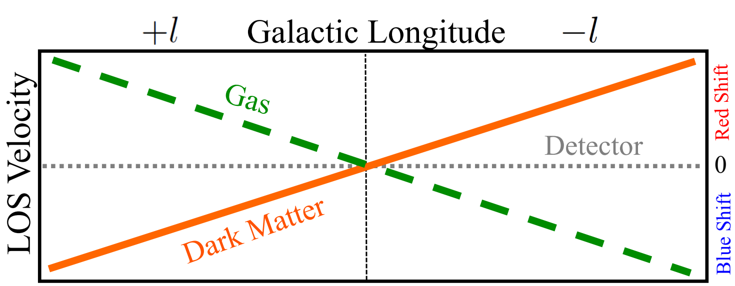
Dark matter and baryonic emission line separation

Shift in centroid of dark matter and baryonic line

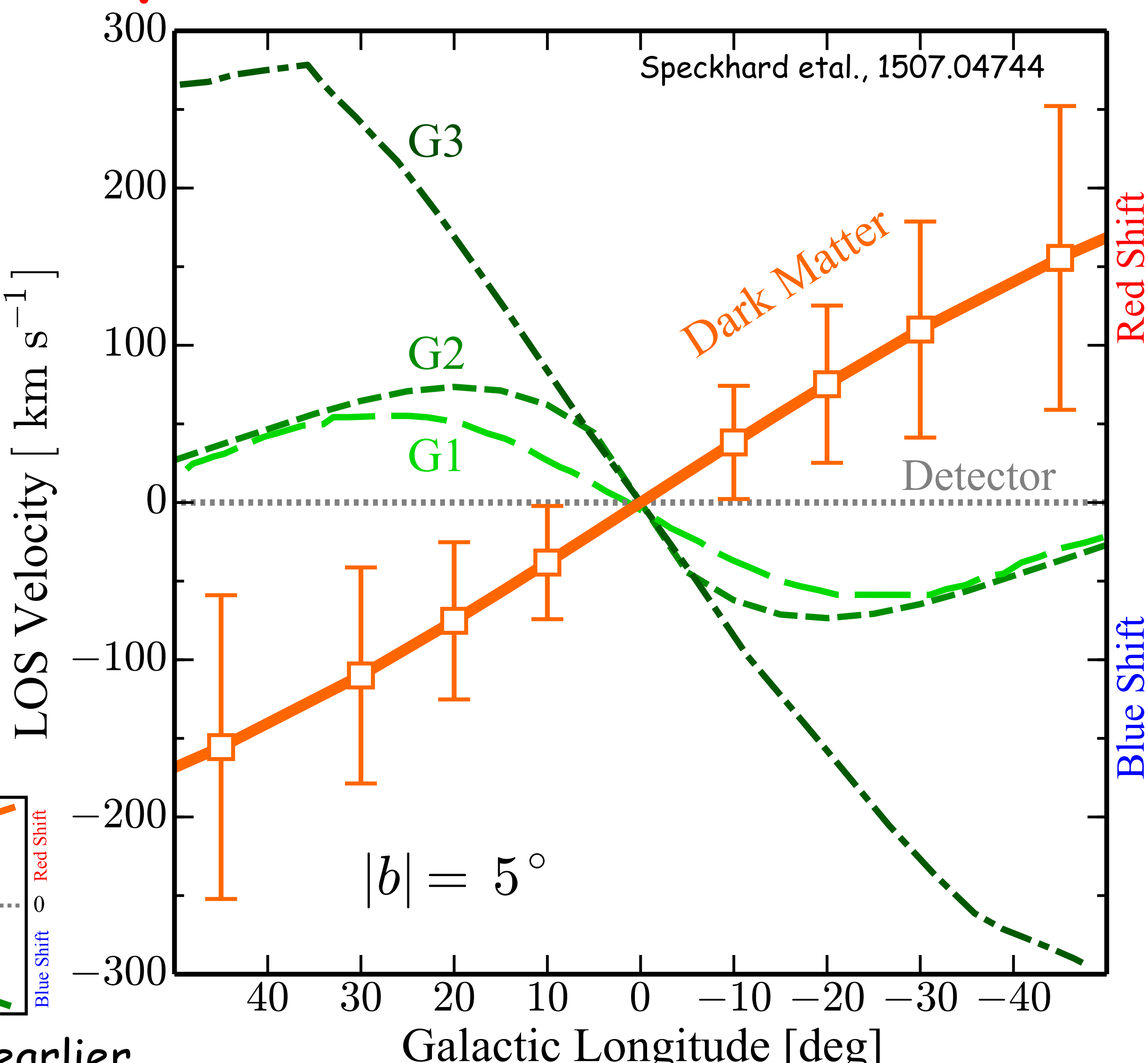
G1: distribution of free electrons

G2: hot gas distribution of MW

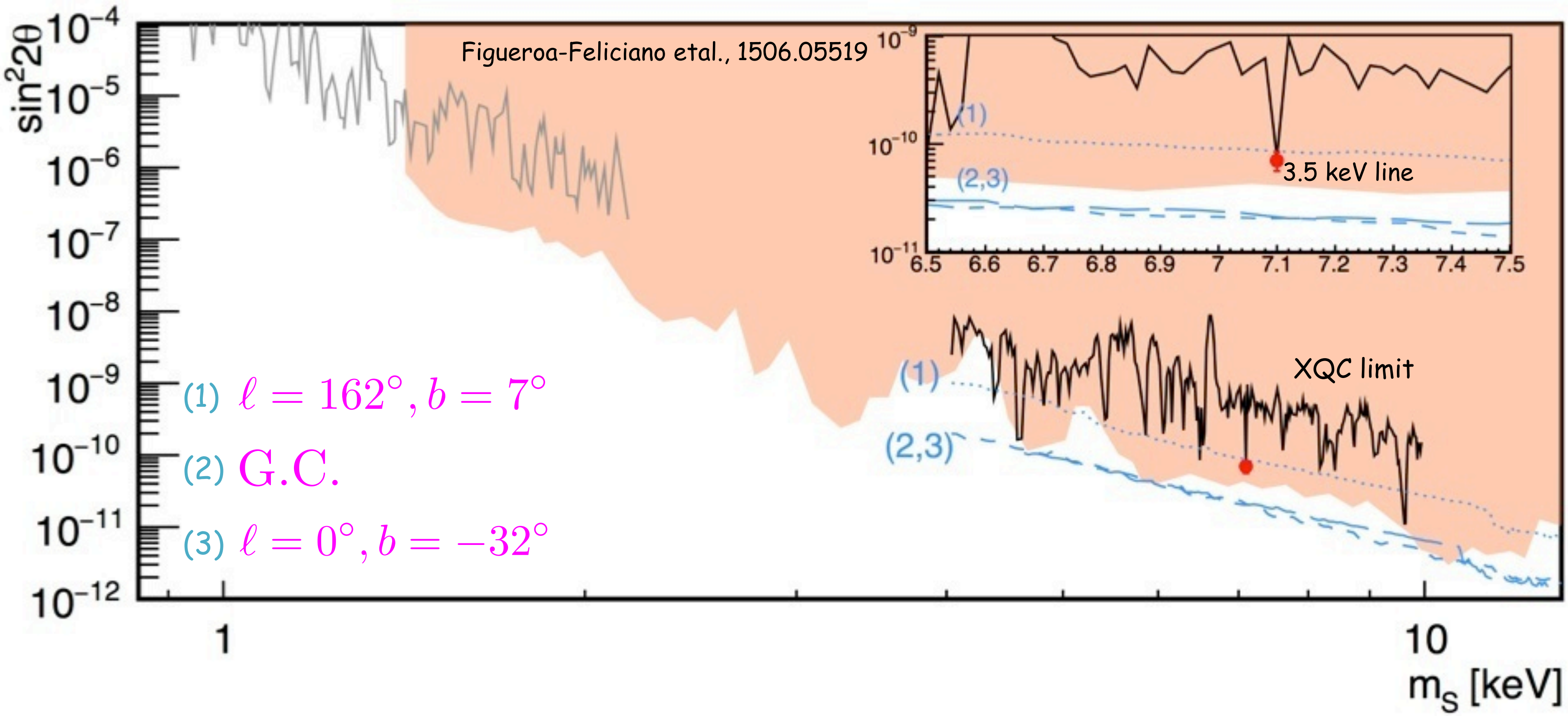
G3: observed distributions of ^{26}Al gamma-rays



Follows the trend explained earlier



Micro-X observations



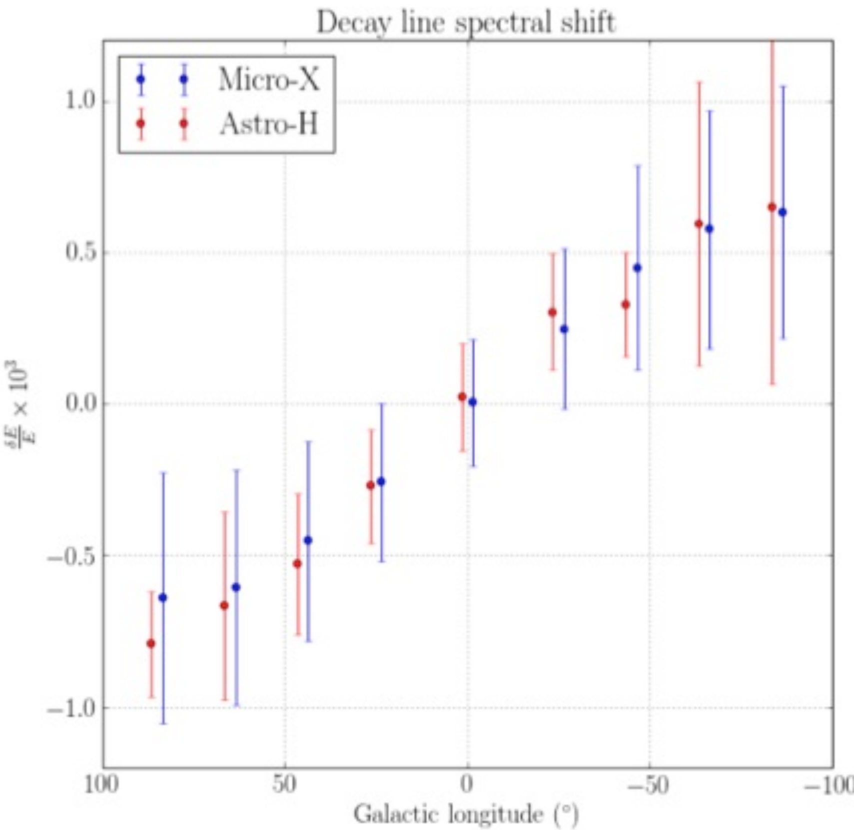
Field of view: 20° radius

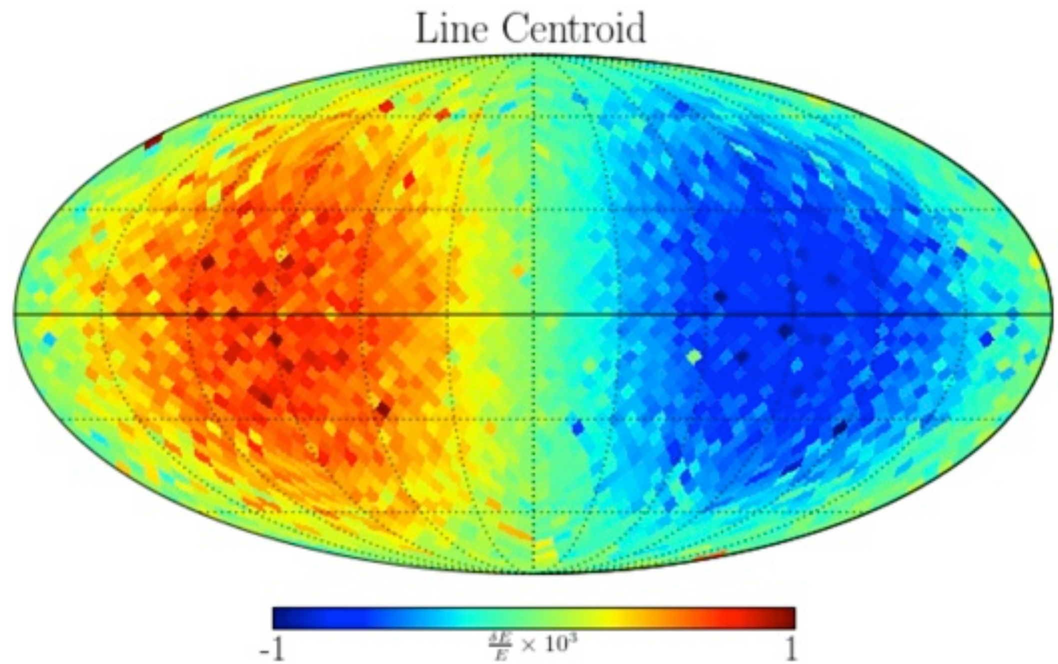
Time of observation: 300 sec

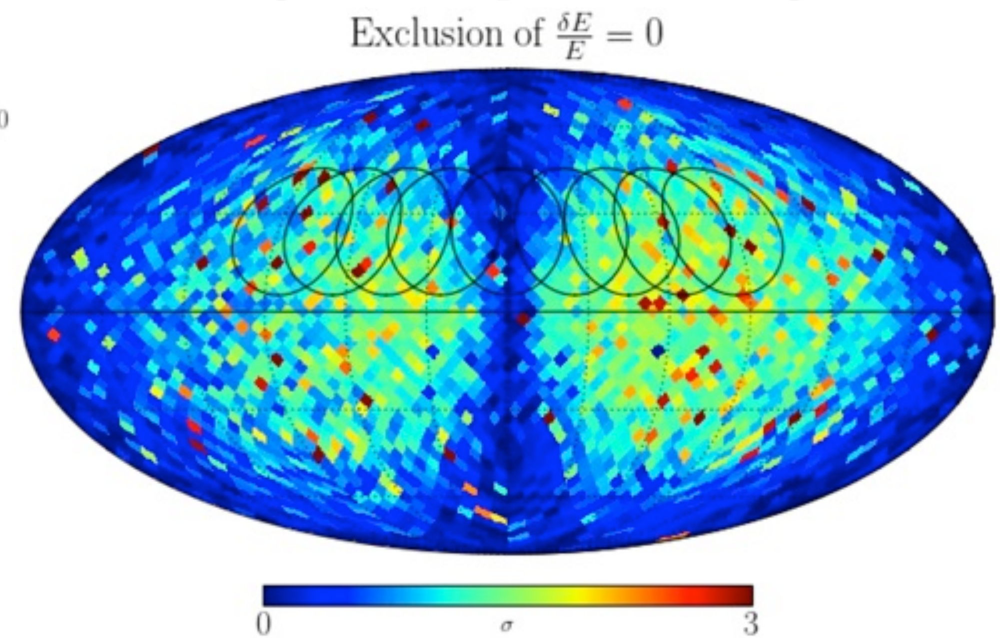
Multiple observations in multiple flights

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, etal., in prep.

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

Multi-wavelength constraints on very heavy dark matter

arXiv 1503.04663

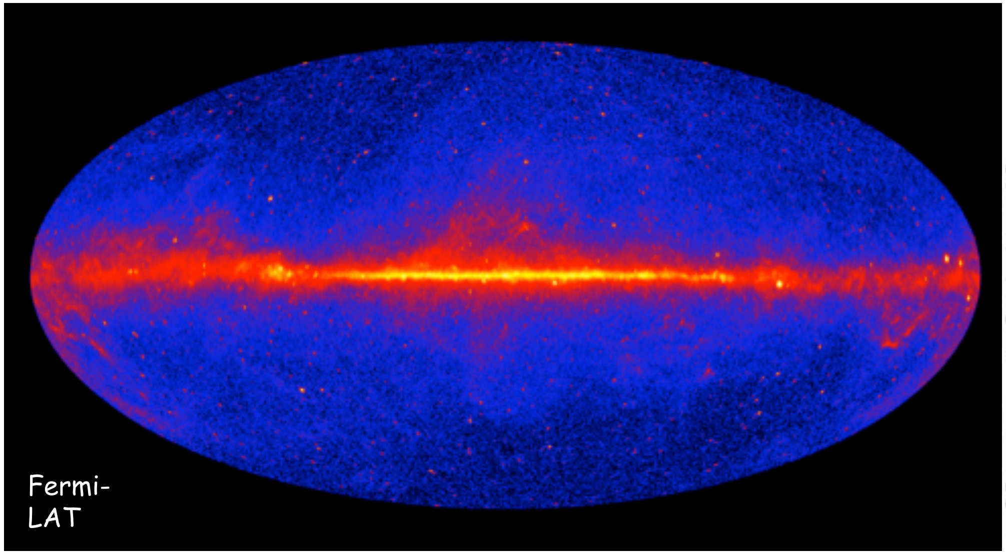
Phys. Rev. Lett. 115 (2015) 071301 (Editors' Suggestion)

Motivation for very heavy dark matter

- Very heavy dark matter => masses $\gtrsim$ 100 TeV
- Difficult to test in colliders: beyond the kinematical reach of present and future colliders
- Difficult to test in direct detection experiments: low flux in Earth
- Is there a way to constrain or cross check any signal for these masses for viable models ?
- IceCube is considered to be the only instrument capable of searching for very heavy dark matter. I will show that very high energy photon searches are equally constraining

Motivation for IceCube

Puzzling questions about the high energy astrophysical universe



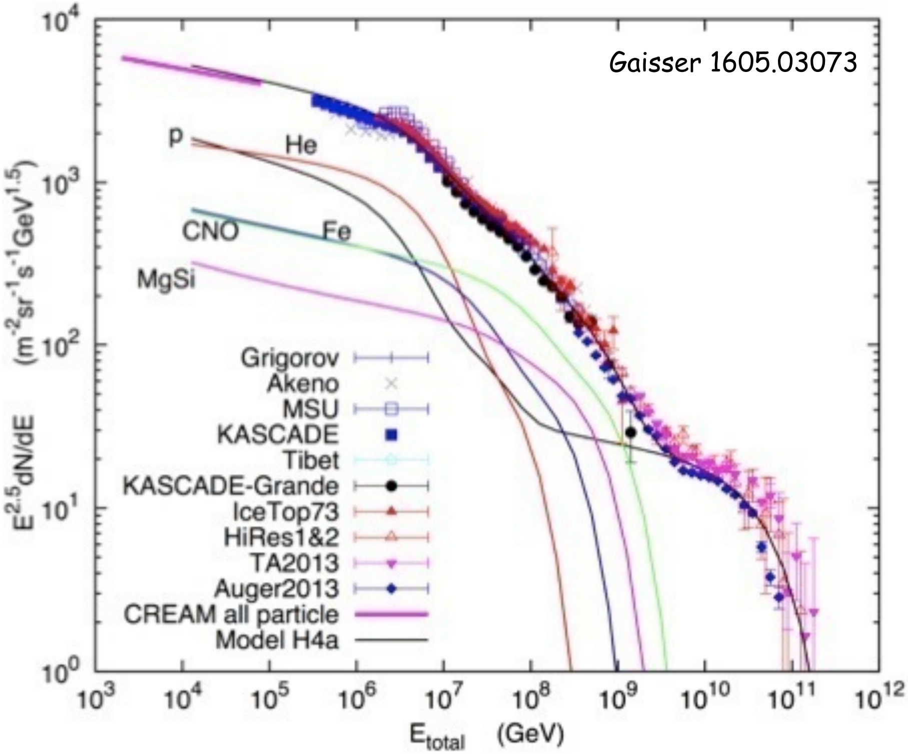
Gamma-ray sky: what process produces them?

Leptonic: $e^- + \gamma \rightarrow e^- + \gamma$

Hadronic: $p + p \rightarrow \pi^0 \rightarrow \gamma + \gamma$

$p + p \rightarrow \pi/K + \ldots \rightarrow \nu/\bar{\nu}$

The key difference are the neutrinos



Cosmic rays observed over a huge energy range

Neutrinos are inevitably produced in cosmic ray interactions

Neutrinos as cosmic messengers

\+ No deflection from source

\+ Can escape from very dense sources

\+ No interaction on the way from source to detector

\+ Complementary to gamma-rays

.....

\- Large detectors required

\- Very long time required to collect signal

.....

IceCube neutrino telescope

IceCube neutrino telescope

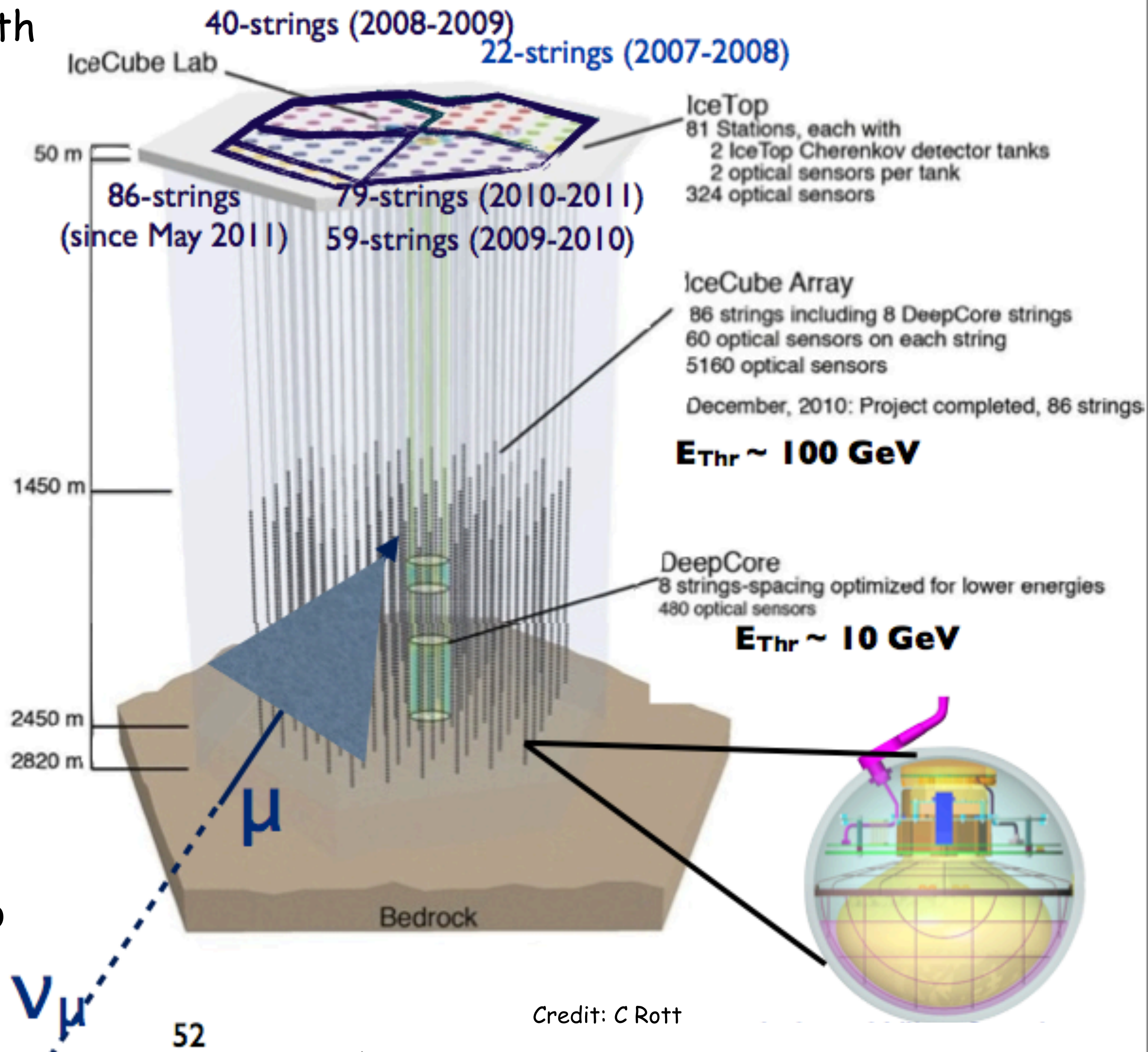
Gigaton effective volume neutrino detector at South Pole

5160 Digital Optical Modules distributed over 86 strings

Completed in Dec 2010; data in full configuration from May 2011

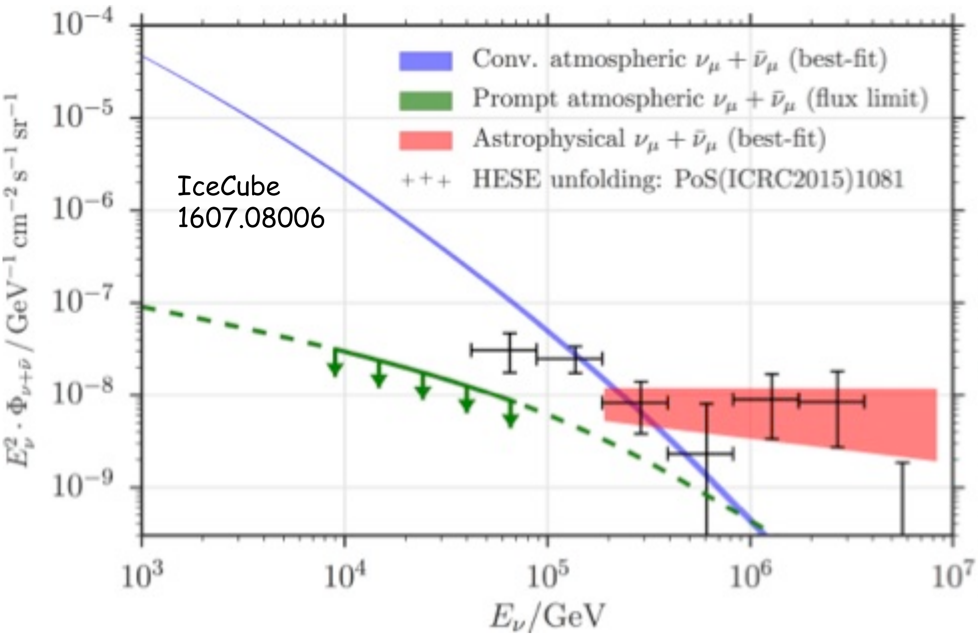
Data acquired during construction phase is analyzed

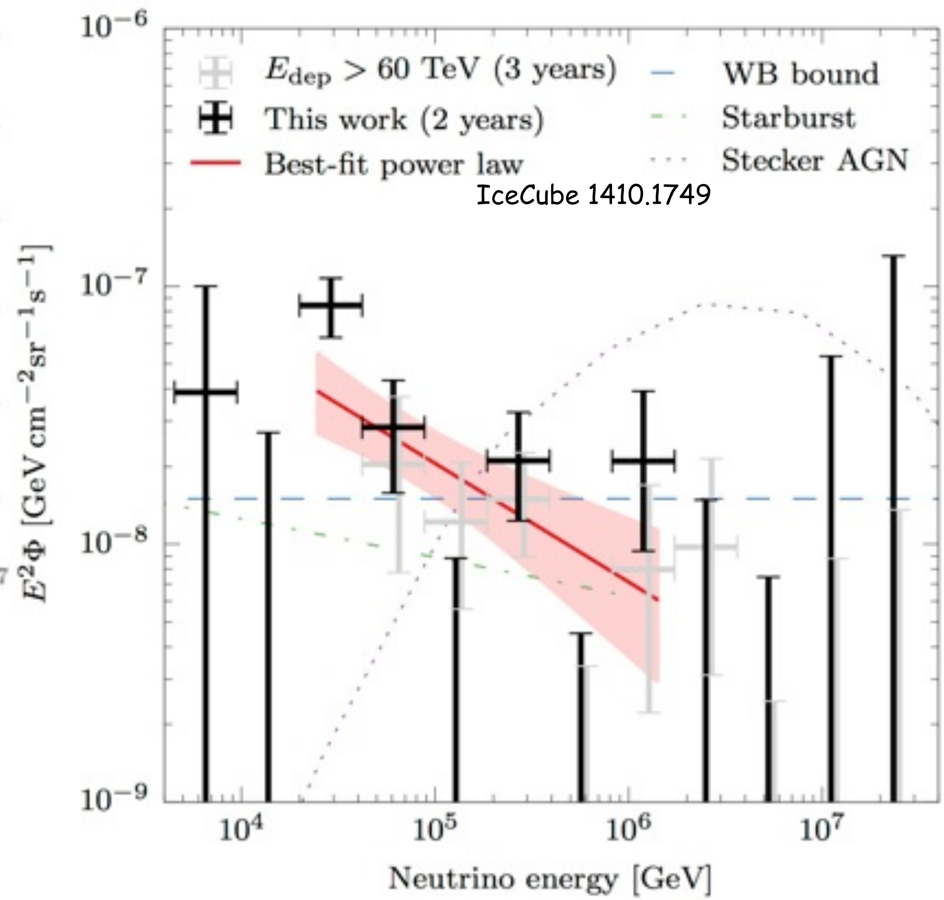
Neutrino detected through Cherenkov light emission from charged particles produced due to neutrino CC/NC interactions



Credit: C Rott

"IceCube excess neutrinos"





Diffuse spectrum of neutrinos

Time-independent

Clear evidence of the astrophysical nature of these neutrinos

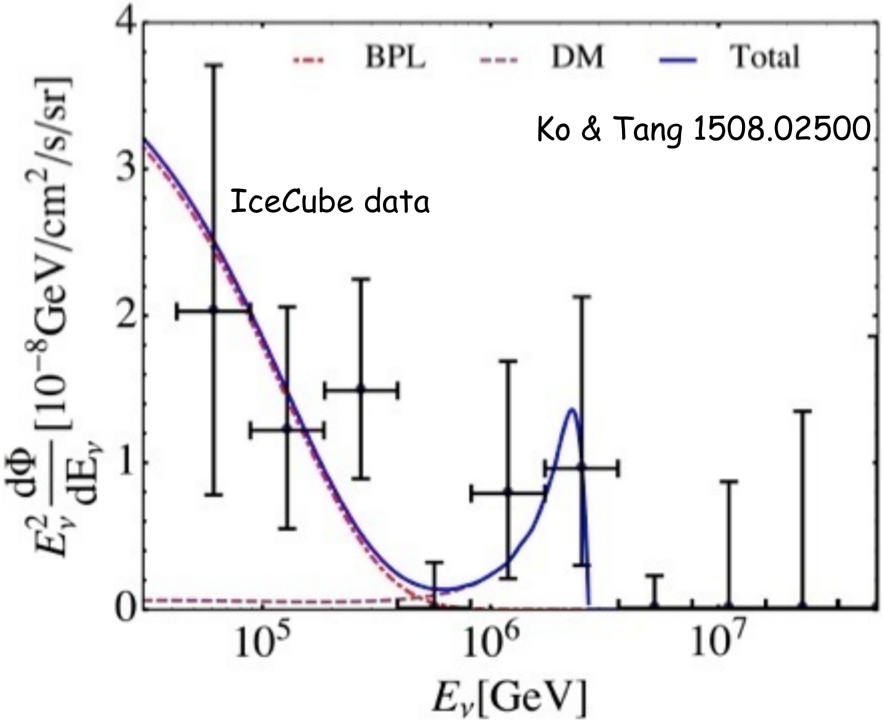
None of them point to a specific source

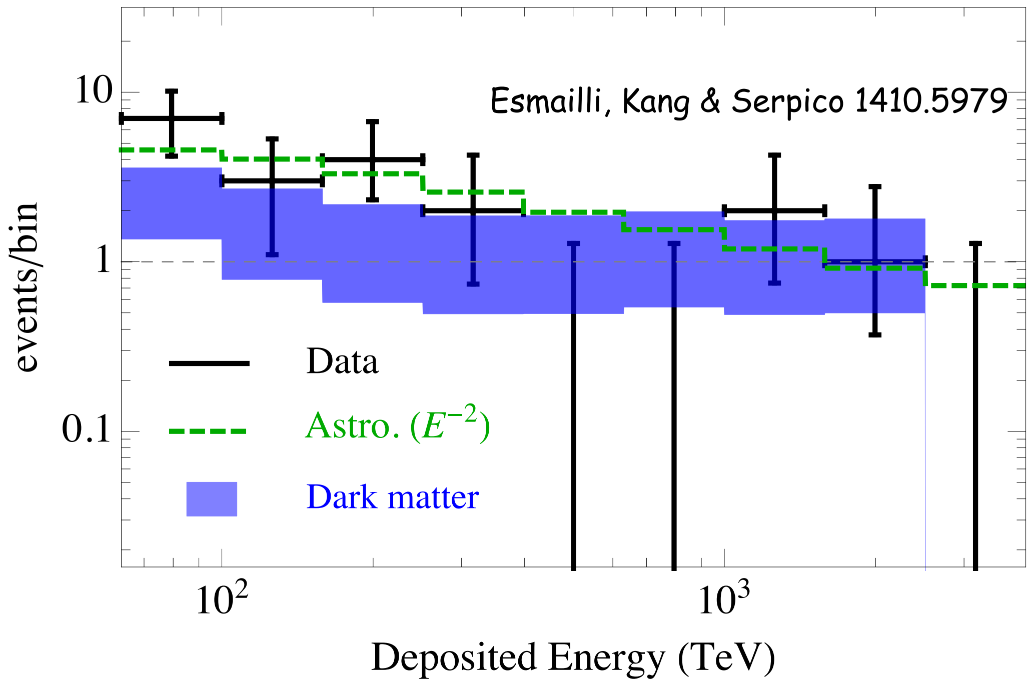
Dark matter interpretation and constraints

Dark matter motivation of the "IceCube excess neutrinos"

- Typical astrophysical neutrino spectrum are smooth
- "IceCube excess neutrinos" have a cutoff at around a few PeV
- Dark matter signature in indirect detection is a cutoff due to kinematic considerations
- Dark matter annihilation does not work due to unitarity constraints (see however Zavala 1404.2932)
- Dark matter decay is a simple process which can give the requisite signature

Dark matter fits to IceCube data





- Various different decaying dark matter fits to the data

$$m_\chi \approx 3\,\mathrm{PeV}$$

$$\tau_\chi \approx 10^{27.5}\,\mathrm{s}$$

✓ Feldstein, etal.
✓ Esmaili & Serpico
✓ Rott, Kohri & Park
✓ Dev etal.
✓ Queiroz, Yaguna & Weniger

The constraint on the dark matter lifetime depends on the amount of data being explained by dark matter

Mass too high for colliders

Resultant dark matter flux is too low for direct detection experiments

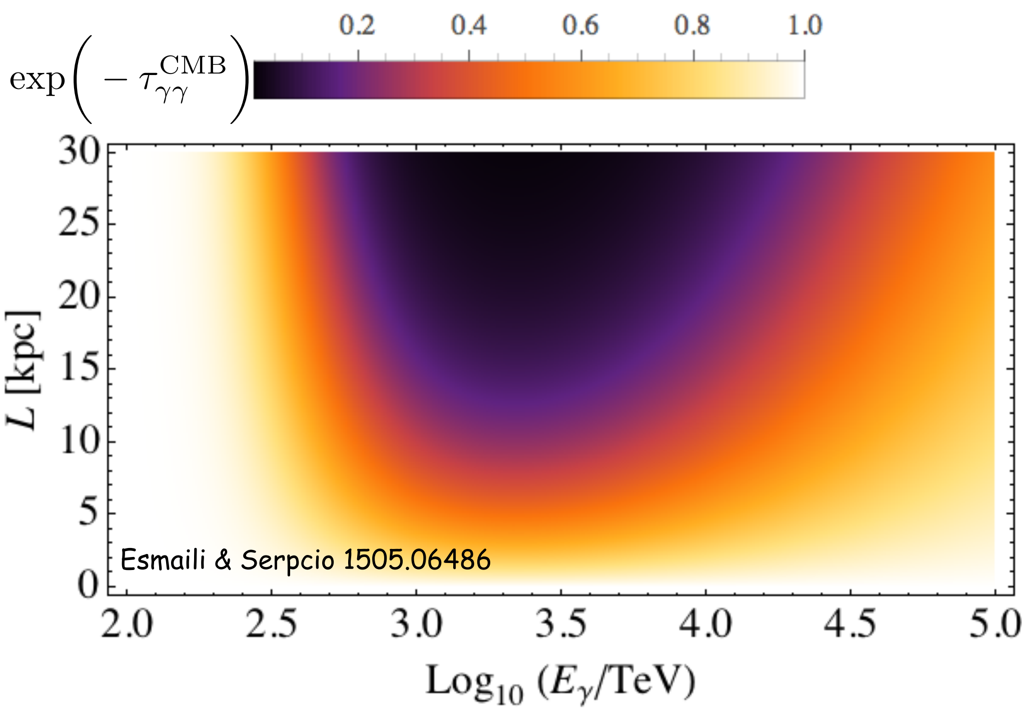
Some example channels:

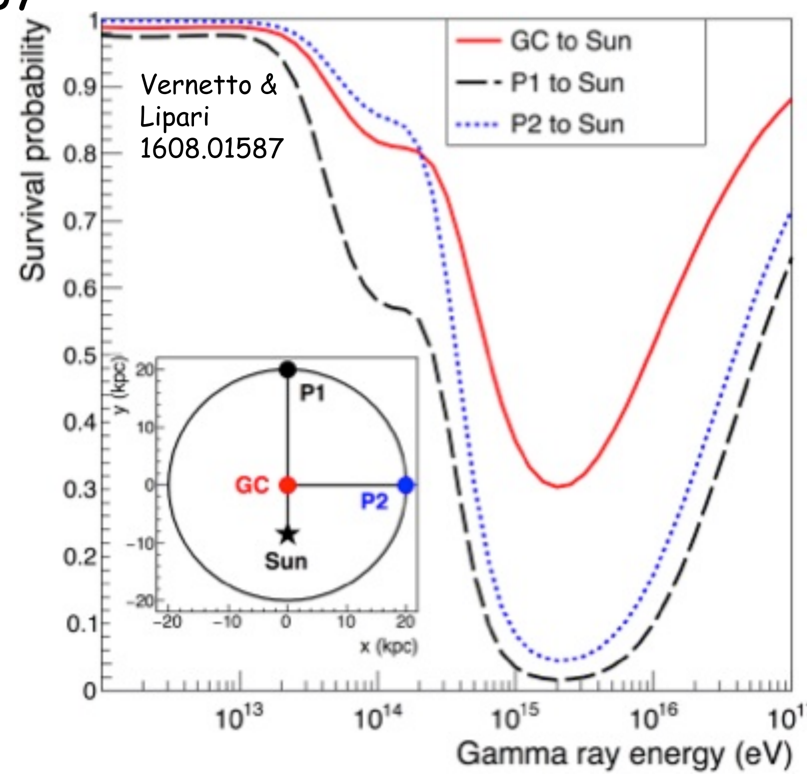
$$\chi \to \nu_e \bar{\nu}_e : \chi \to q\bar{q} \approx 0.12 : 0.88$$

$$\chi \to \ell^\pm W^\mp : \chi \to \nu Z : \chi \to \nu h \approx 2 : 1 : 1$$

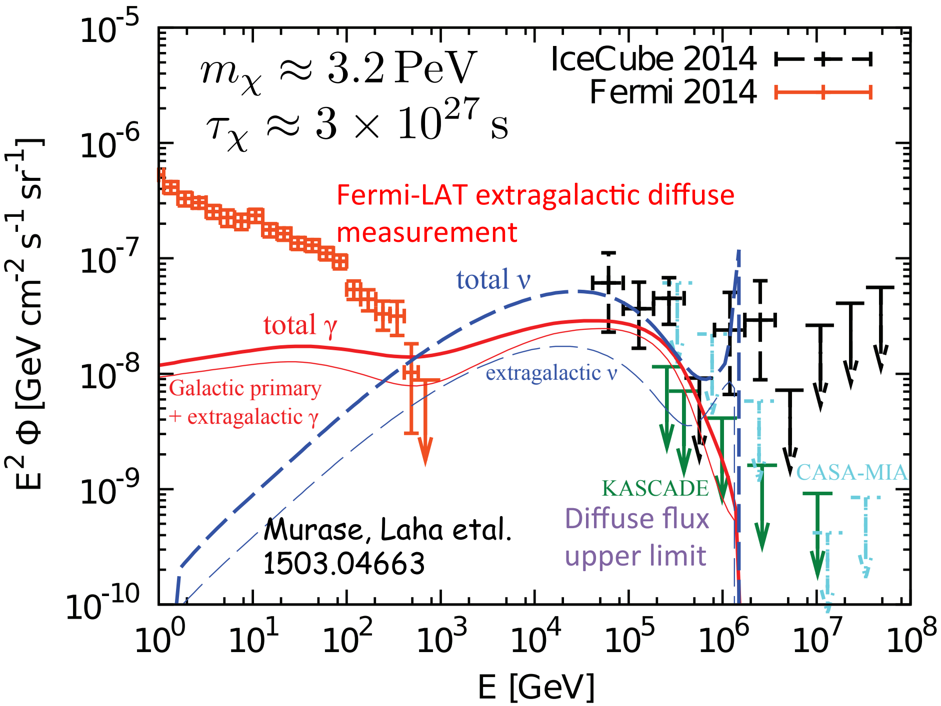
Very high-energy gamma-rays

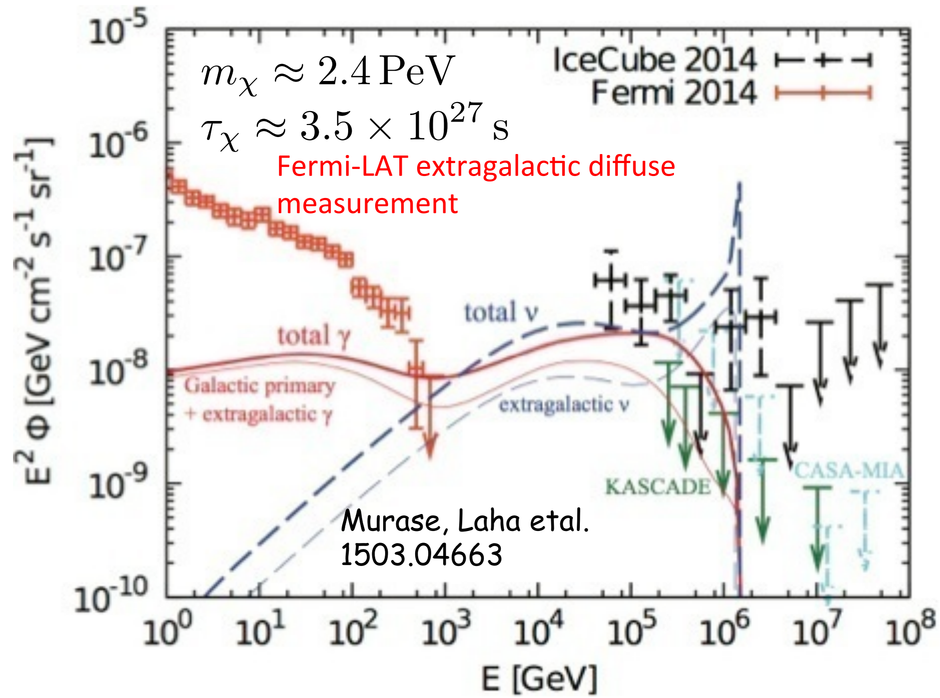
- Search for very high energy (VHE) gamma-rays (> 100 TeV) are useful in this context: CASA-MIA, KASCADE
- Attenuation of VHE gamma-rays important $\gamma_{\rm VHE}\,\gamma_{\rm CMB/EBL} \to e^+ e^-$
- Inverse Compton of the background photons by the electron – positron pair produce gamma-rays with energy in the Fermi-LAT band





Multi-wavelength constraints





Constraints on prompt photons by CASA-MIA, KASCADE

Constraints on cascaded photons by Fermi-LAT

Future constraints by HAWC (~ 100 GeV – 100 TeV), Tibet AS+MD (~ 1 TeV – 10^4 TeV) and IceCube (~ 1 PeV – 10 PeV) VHE gamma-ray searches

Heavy dark matter models have started taking these constraints into account

Take-away for multi-wavelength constraints on very heavy dark matter

- IceCube has started the new field of neutrino astronomy
- IceCube can probe very heavy dark matter, which is difficult to probe otherwise
- Many dark matter models have been proposed to explain a part or the full data of "IceCube excess neutrinos"
- Searches for very high energy photons can be used to constrain many of these models
- Future complementary limits (HAWC, Tibet AS+MD, and IceCube) from very high energy neutrinos and gamma-rays can further probe these models

Conclusion

- It is important to devise new strategies by which we can distinguish signal from background in dark matter experiments

- Dark matter velocity spectroscopy is a new technique to distinguish signal and background in dark matter indirect detection --- we see dark matter in motion

- Multi-wavelength constraints can be used to constrain very heavy dark matter which is difficult to constrain otherwise

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