Dark Matter: Indirect Detection

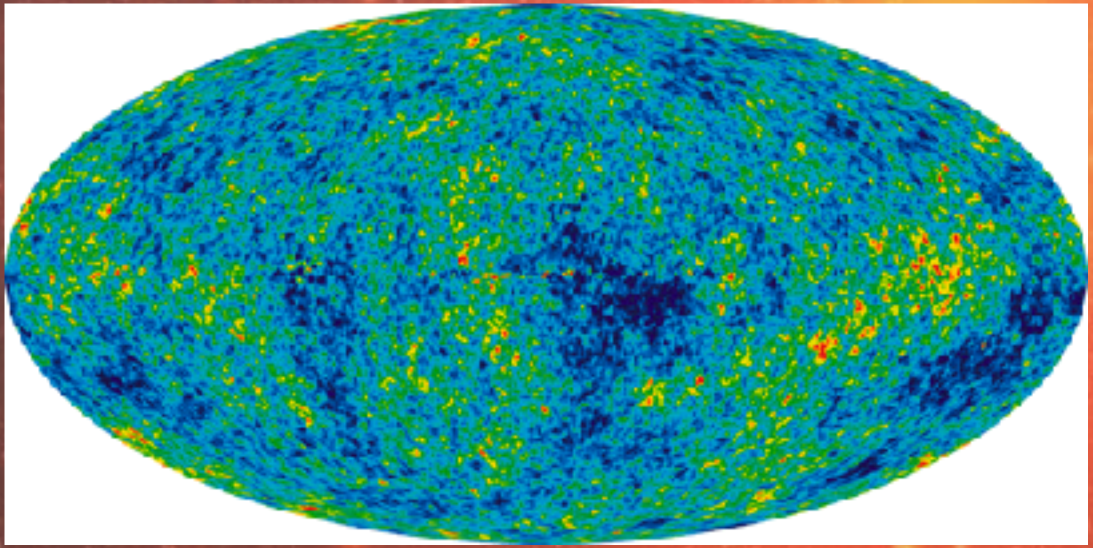
Simona Murgia

University of California, Irvine
and
Universiteit van Amsterdam
Van der Waals Visiting Professor

Topical Lectures "Dark Matter”
Nikhef
15 December 2017

Evidence for Dark Matter: A Brief Overview

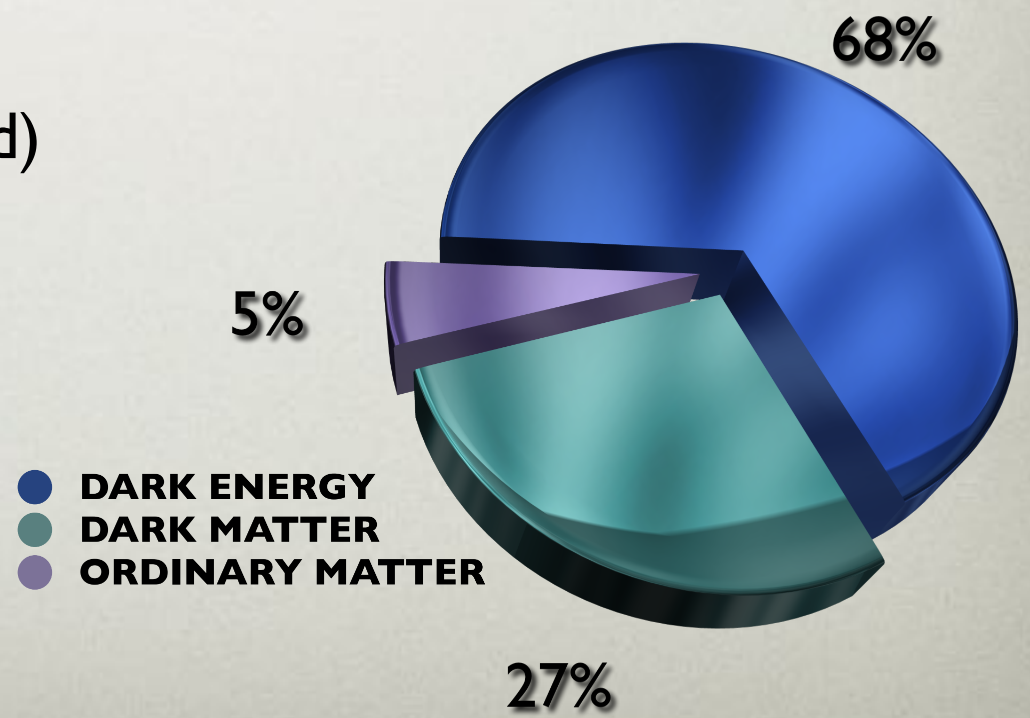
- Evidence for dark matter is found at very different scales
  - Galaxies
  - Clusters of galaxies
  - Universe



Dark Matter

- What data tell us about dark matter:
  - makes up almost all of the matter in the Universe (present day Universe mostly made out of dark energy, dark matter, and small contribution from ordinary matter)
  - interacts very weakly, and at least gravitationally, with ordinary matter
  - is cold, i.e. non-relativistic
  - is neutral
  - is stable (or it is very long-lived)

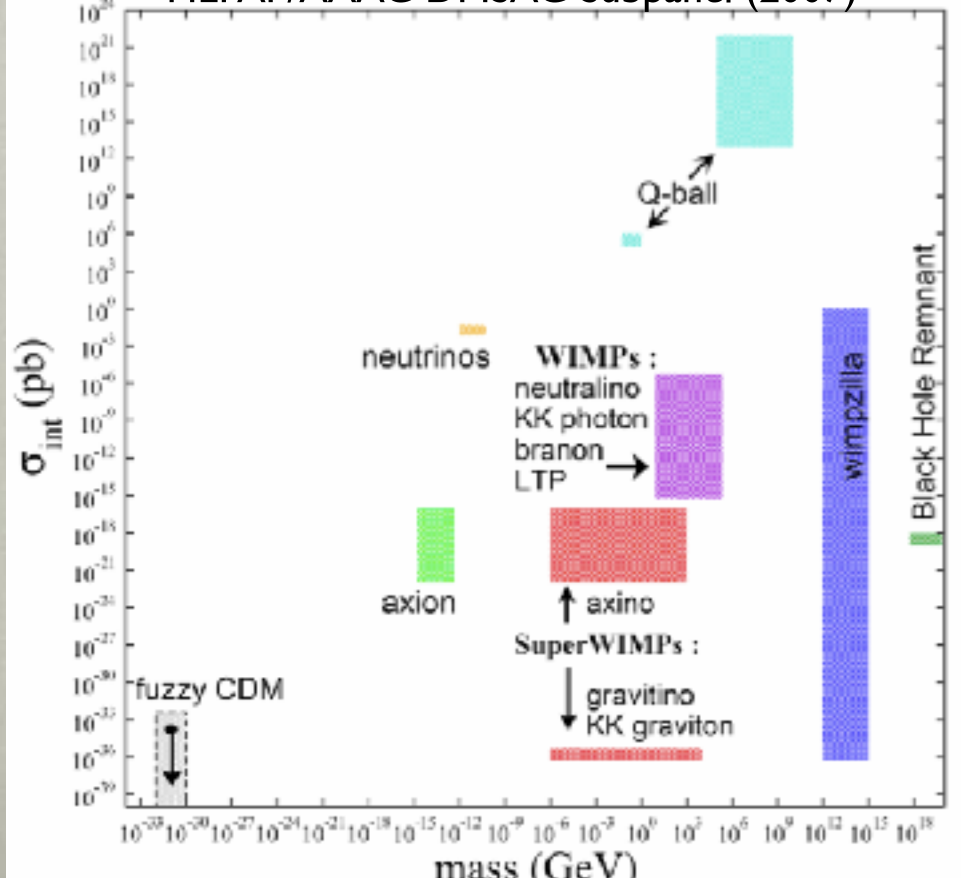
➡But not what it is...

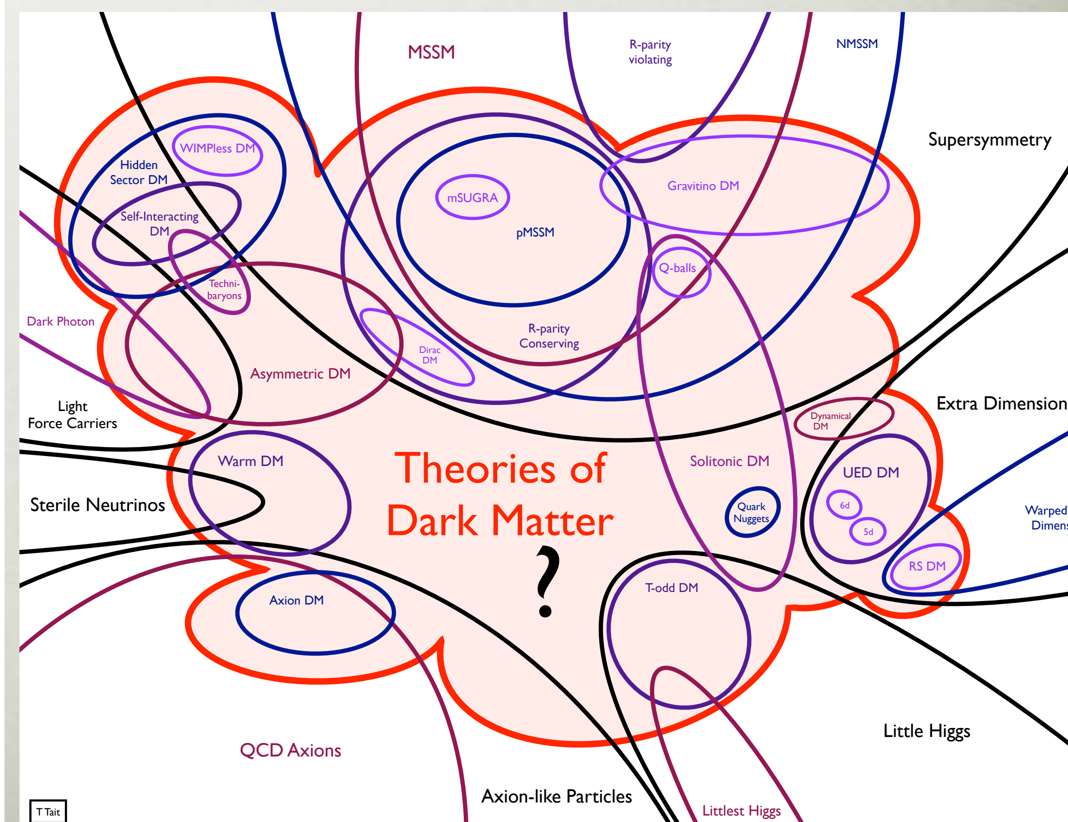


Dark Matter Candidates

- None of the known elementary particles has the right properties to be the dark matter
- Several beyond the Standard Model of particle physics scenarios have been proposed that naturally predict the existence of new particles that are excellent dark matter candidates

HEPAP/AAAC DMSAG Subpanel (2007)

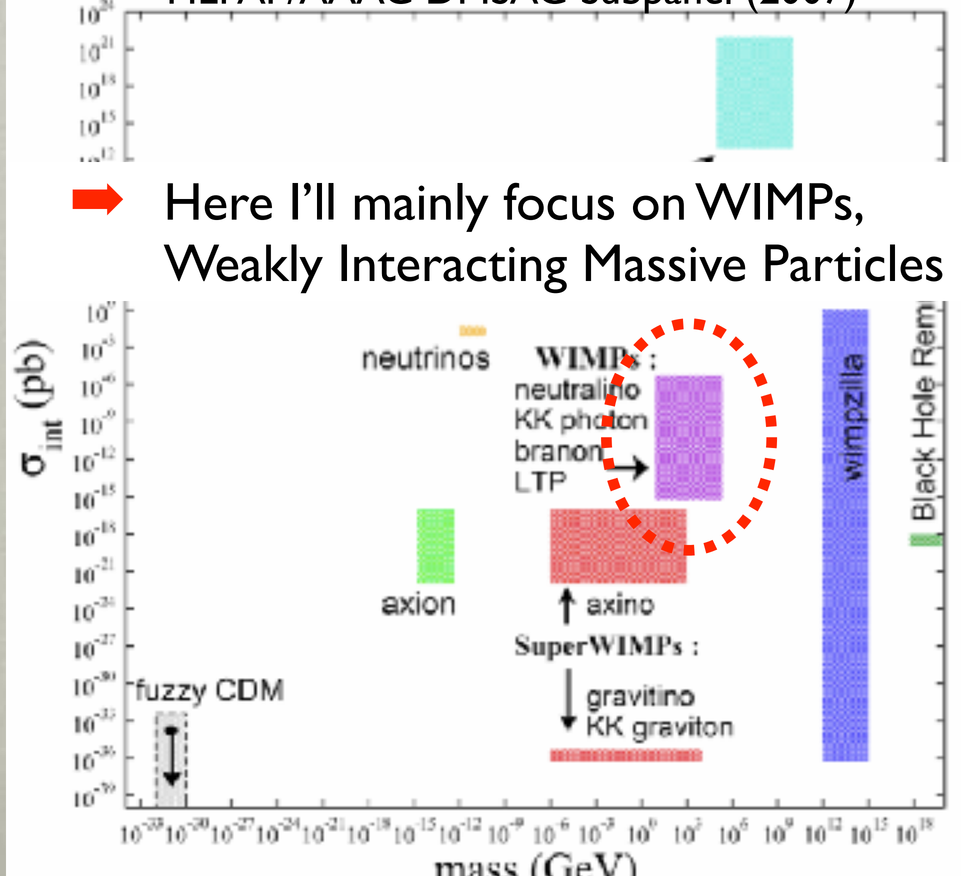




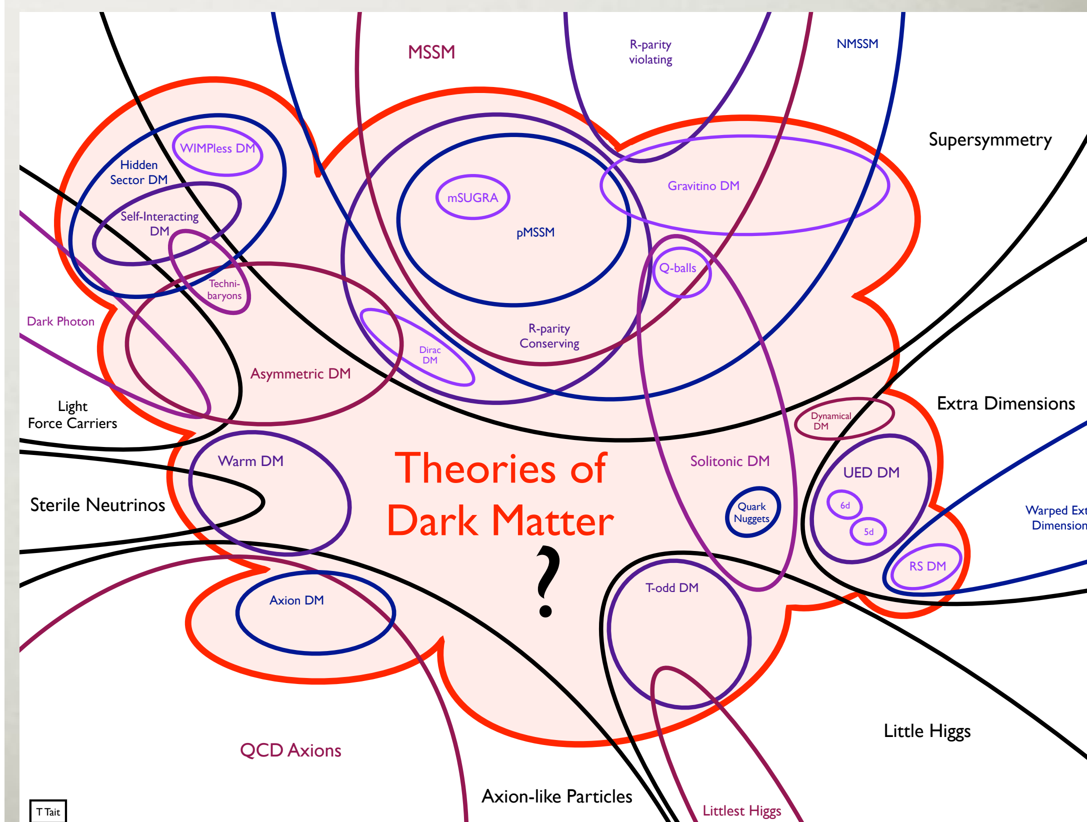
Dark Matter Candidates

- None of the known elementary particles has the right properties to be the dark matter
- Several beyond the Standard Model of particle physics scenarios have been proposed that naturally predict the existence of new particles that are excellent dark matter candidates

HEPAP/AAAC DMSAG Subpanel (2007)

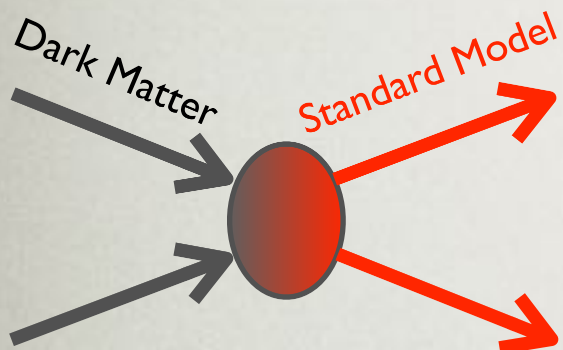


➡ Here I'll mainly focus on WIMPs, Weakly Interacting Massive Particles

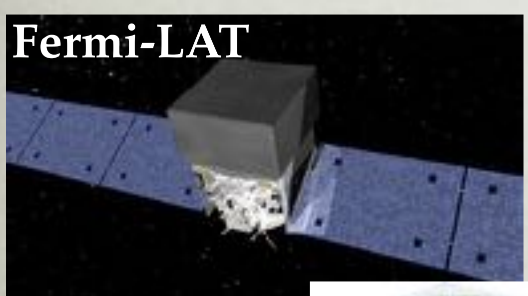


Dark Matter Searches

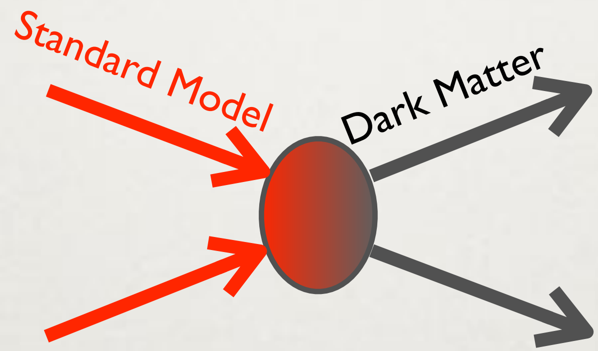
INDIRECT SEARCHES



Find its annihilation byproducts

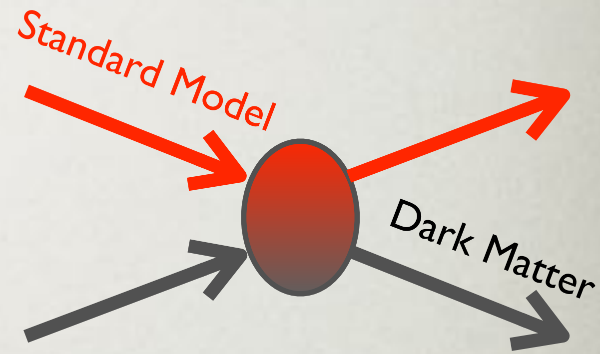


COLLIDER SEARCHES



Produce it in the lab

DIRECT SEARCHES

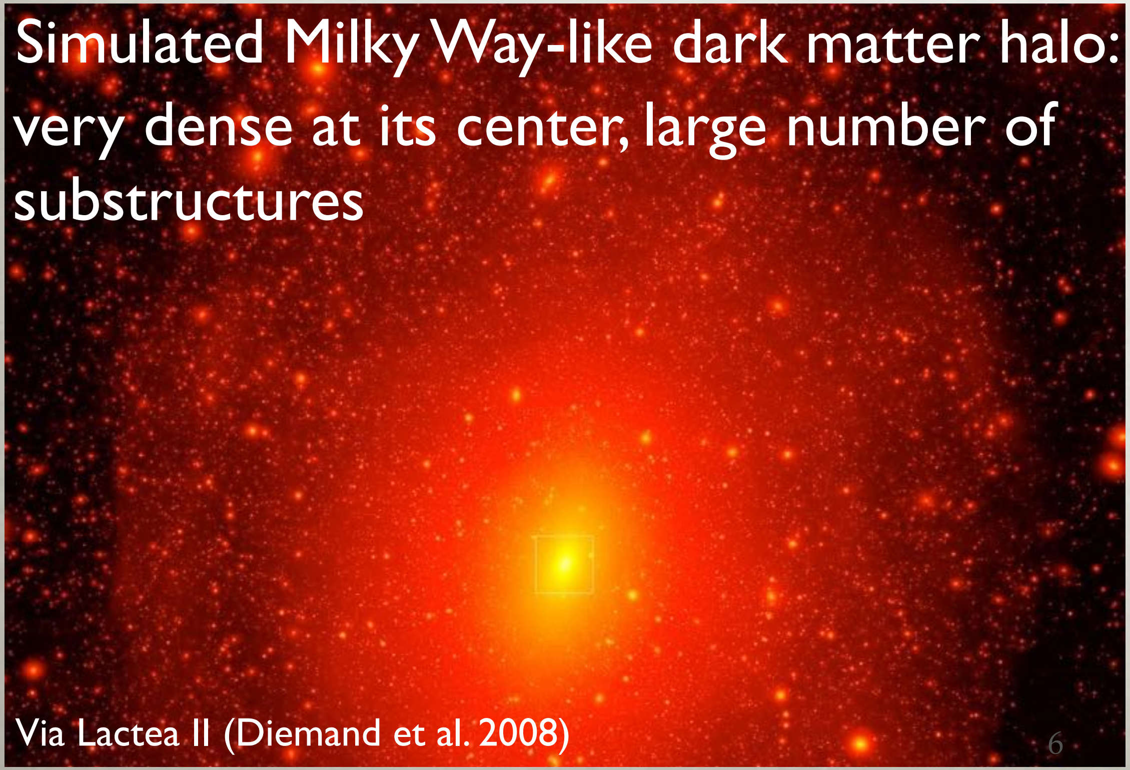


Detect energy it deposits

Indirect Dark Matter Searches

- Very rich search strategy, multi-messenger and multi-wavelength

DARK MATTER DISTRIBUTION

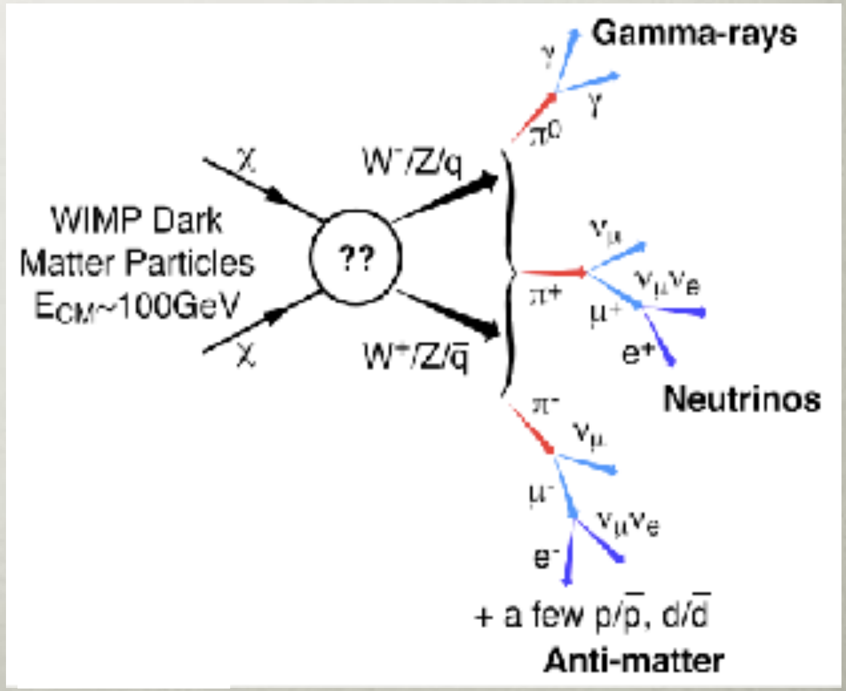


Simulated Milky Way-like dark matter halo: very dense at its center, large number of substructures

Via Lactea II (Diemand et al. 2008)

+

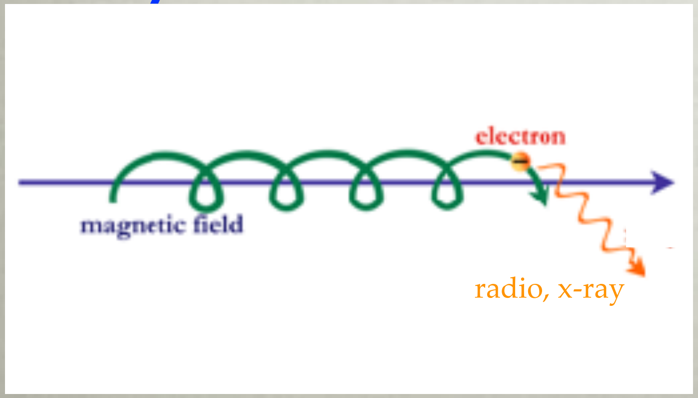
ANNIHILATION PROCESS



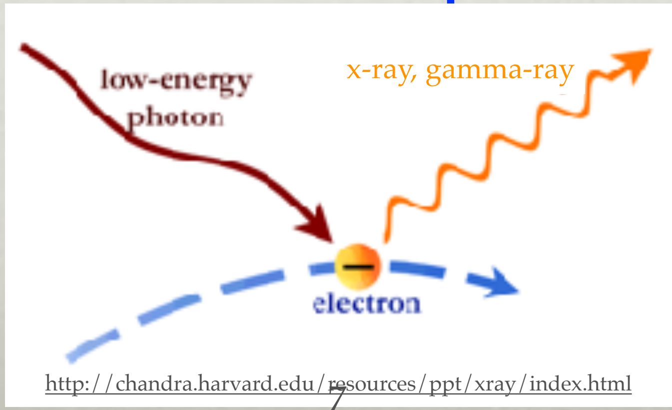
DM Messengers

- DM messengers:
  - neutral: photons, neutrinos
  - charged: electrons, antimatter (positrons, antiprotons, antideuteron, ...)
- Multi-wavelengths:
  - gamma rays from DM annihilation/decay products
  - but also emission from the interaction with the surrounding medium (interstellar gas, radiation and magnetic fields), from radio to gamma-ray (and other secondaries as well)
  - For electrons:

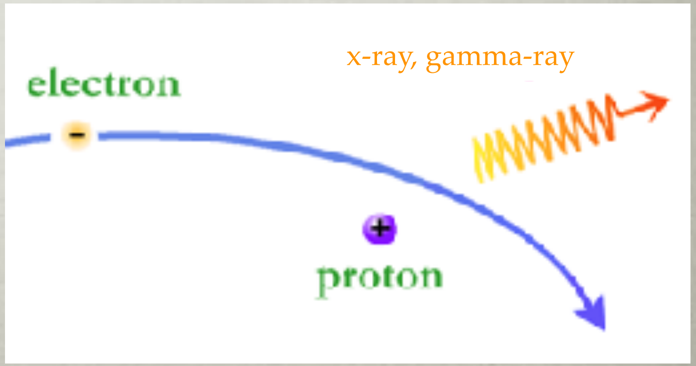
Synchrotron



Inverse Compton



Bremsstrahlung



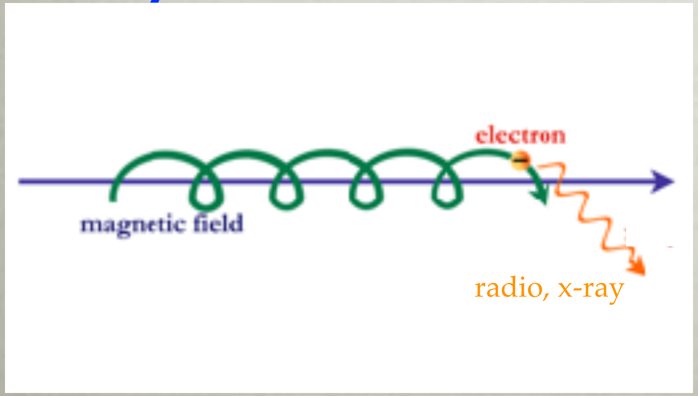
DM Messengers

- DM messengers:
  - neutral: photons, neutrinos
  - charged: electrons, antimatter (positrons, antiprotons, antideuteron, ...)

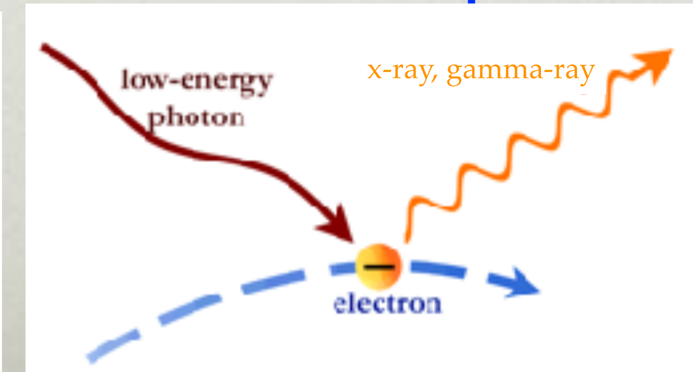
Neutral particles are more promising probes!
Among charged particles, antiparticles are favored

- Multi-wavelengths:
  - gamma rays from DM annihilation/decay products
  - but also emission from the interaction with the surrounding medium (interstellar gas, radiation and magnetic fields), from radio to gamma-ray (and other secondaries as well)
  - For electrons:

Synchrotron

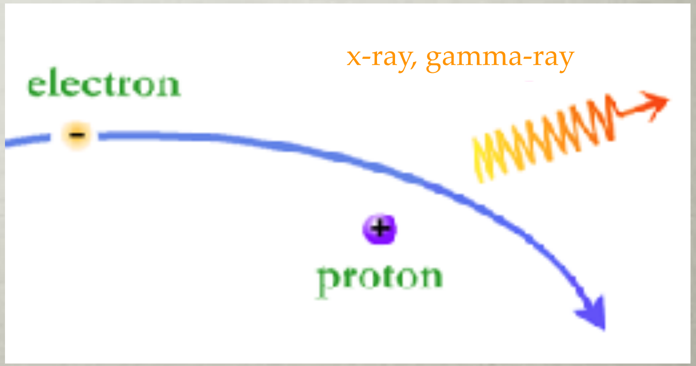


Inverse Compton



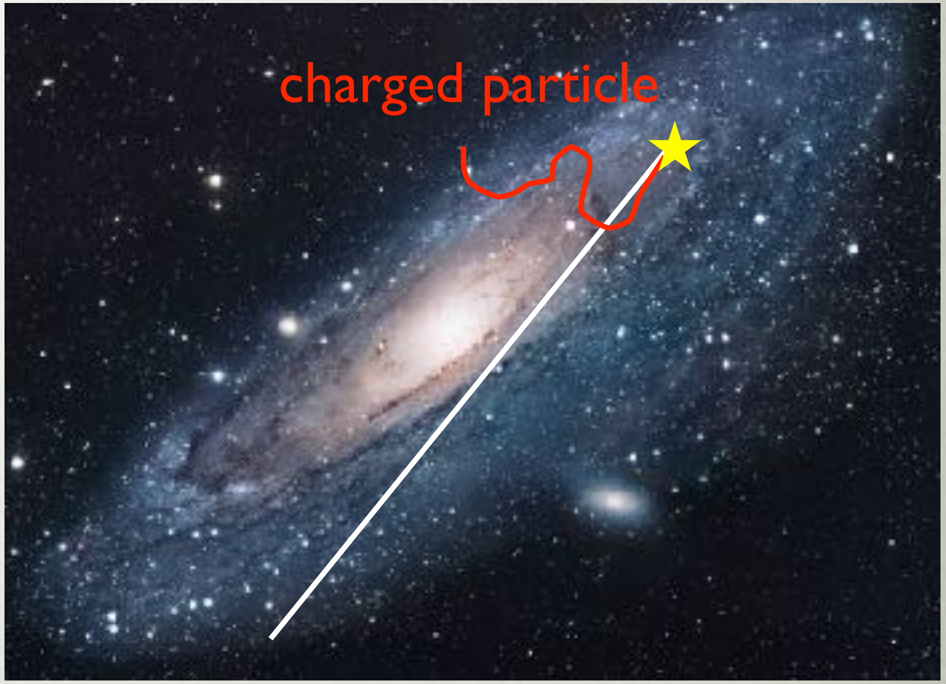
http://chandra.harvard.edu/resources/ppt/xray/index.html

Bremsstrahlung



DM Messengers

- Generally, neutral particles are more promising probes
  - No loss of energy, directionality for neutrinos, gamma-rays $\Rightarrow$ point back to source and preserve spectral information (on galactic scales)
  - Charged particles lose energy, directionality on their way to us $\Rightarrow$ important information on their origin is lost

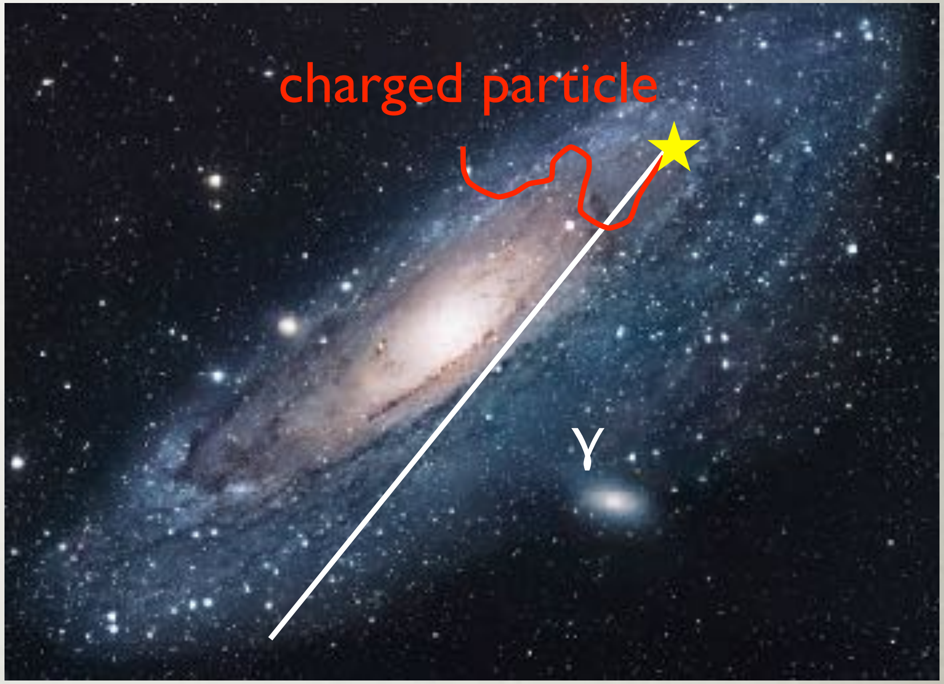


$$R \approx 10^{-6} pc \frac{1}{Z} \frac{E}{(1GeV)} \frac{(1\mu G)}{B}$$

In ~μG magnetic fields, the gyroradius for a 100 GeV electron or proton is ~ 10^{-4} pc, i.e. much shorter than the distance to a typical nearby source, which is of order of 100s pc (1 pc=3.26 light years)

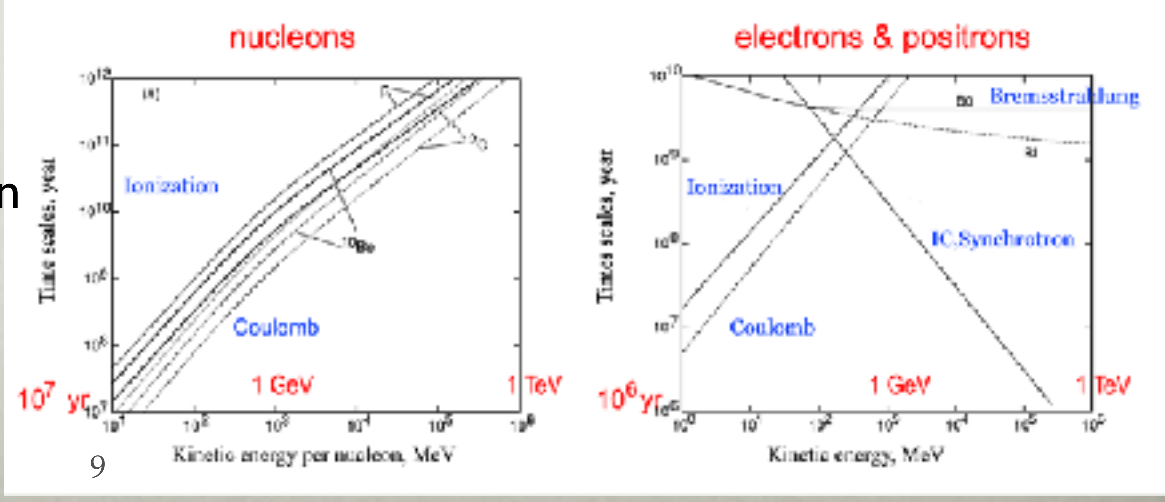
DM Messengers

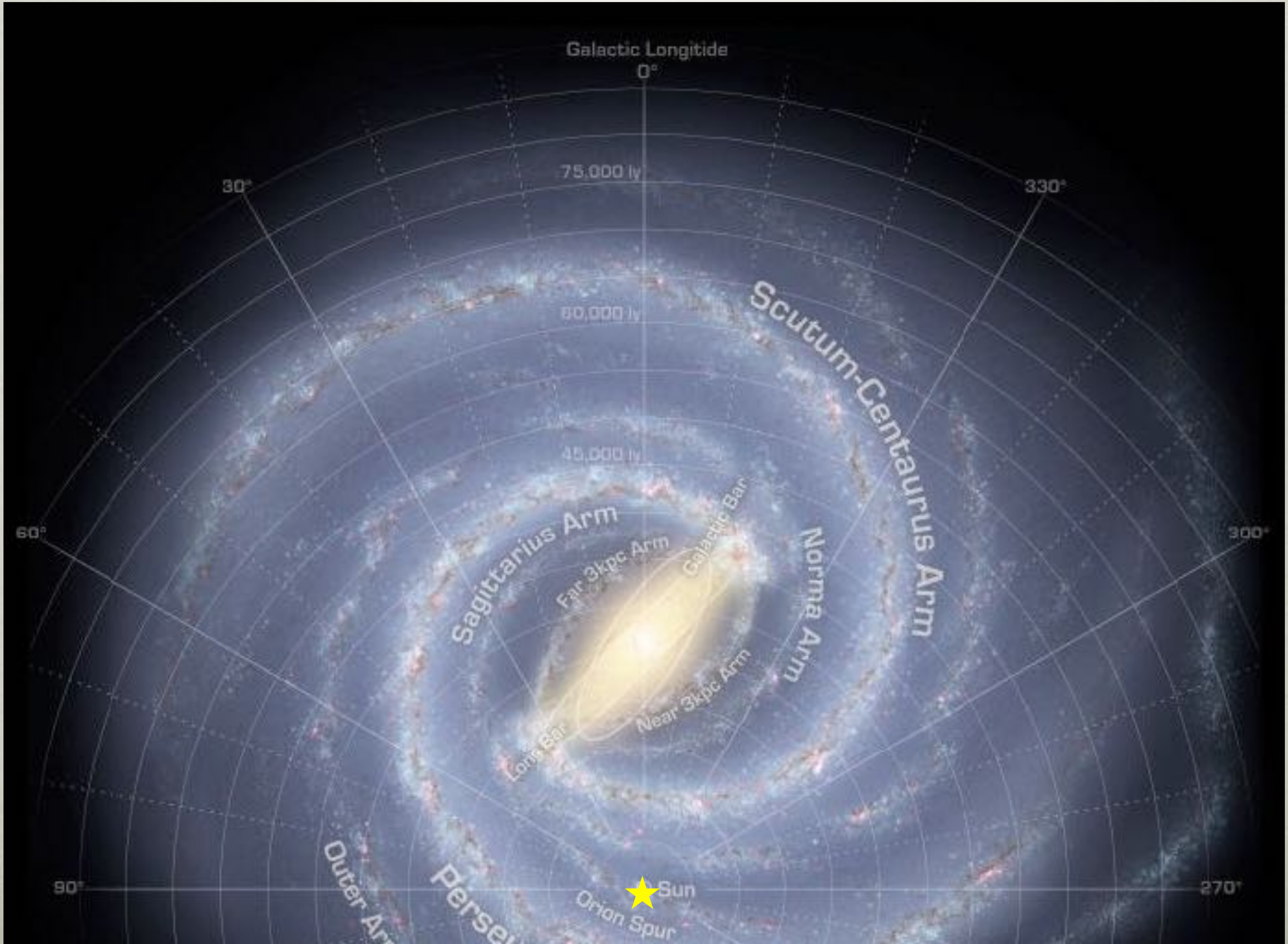
- Generally, neutral particles are more promising probes
  - No loss of energy, directionality for neutrinos, gamma-rays ⇒ point back to source and preserve spectral information (on galactic scales)
  - Charged particles lose energy, directionality on their way to us ⇒ important information on their origin is lost



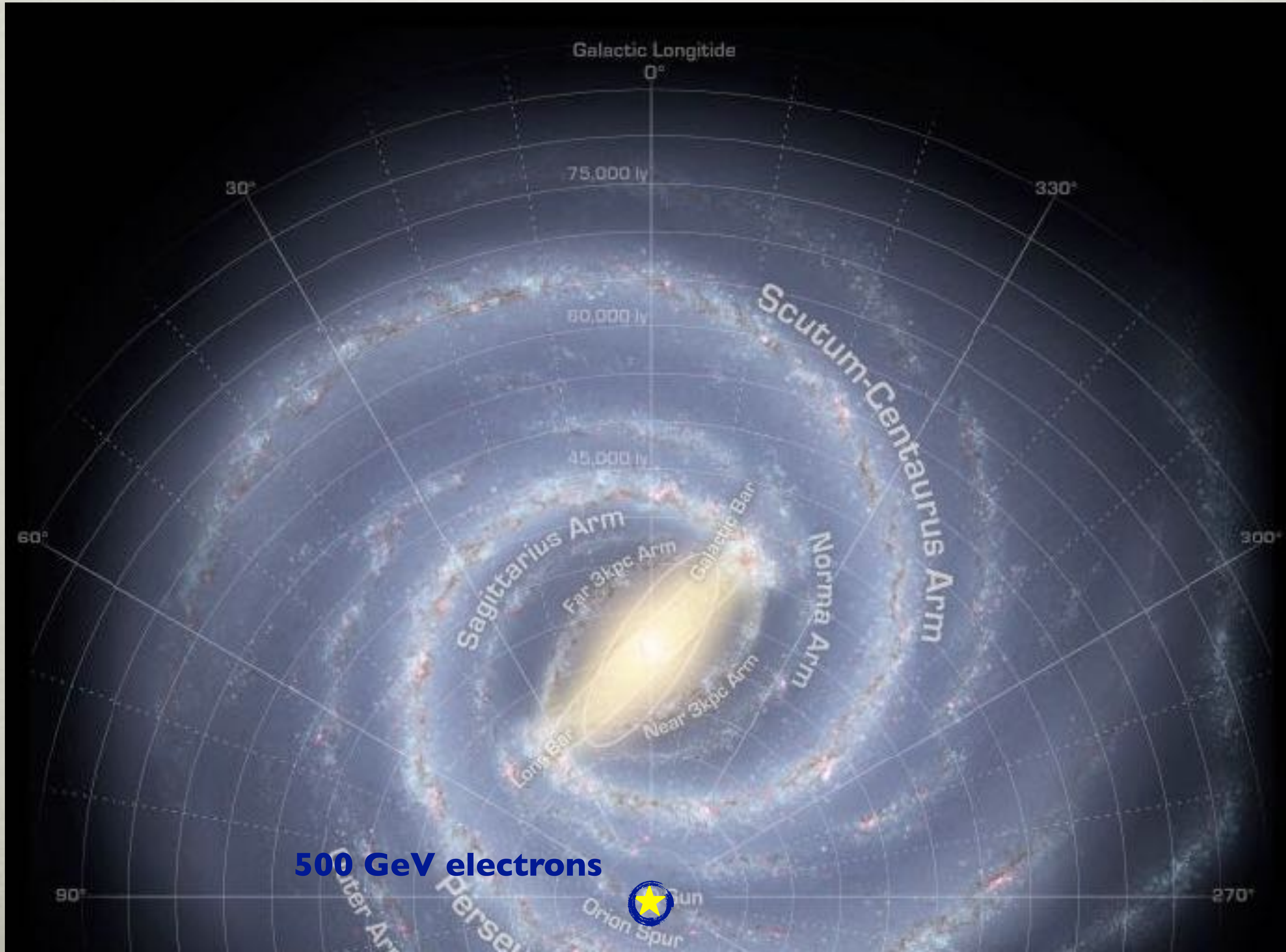
Electrons of > GeV energies primarily lose energy through synchrotron and IC emission

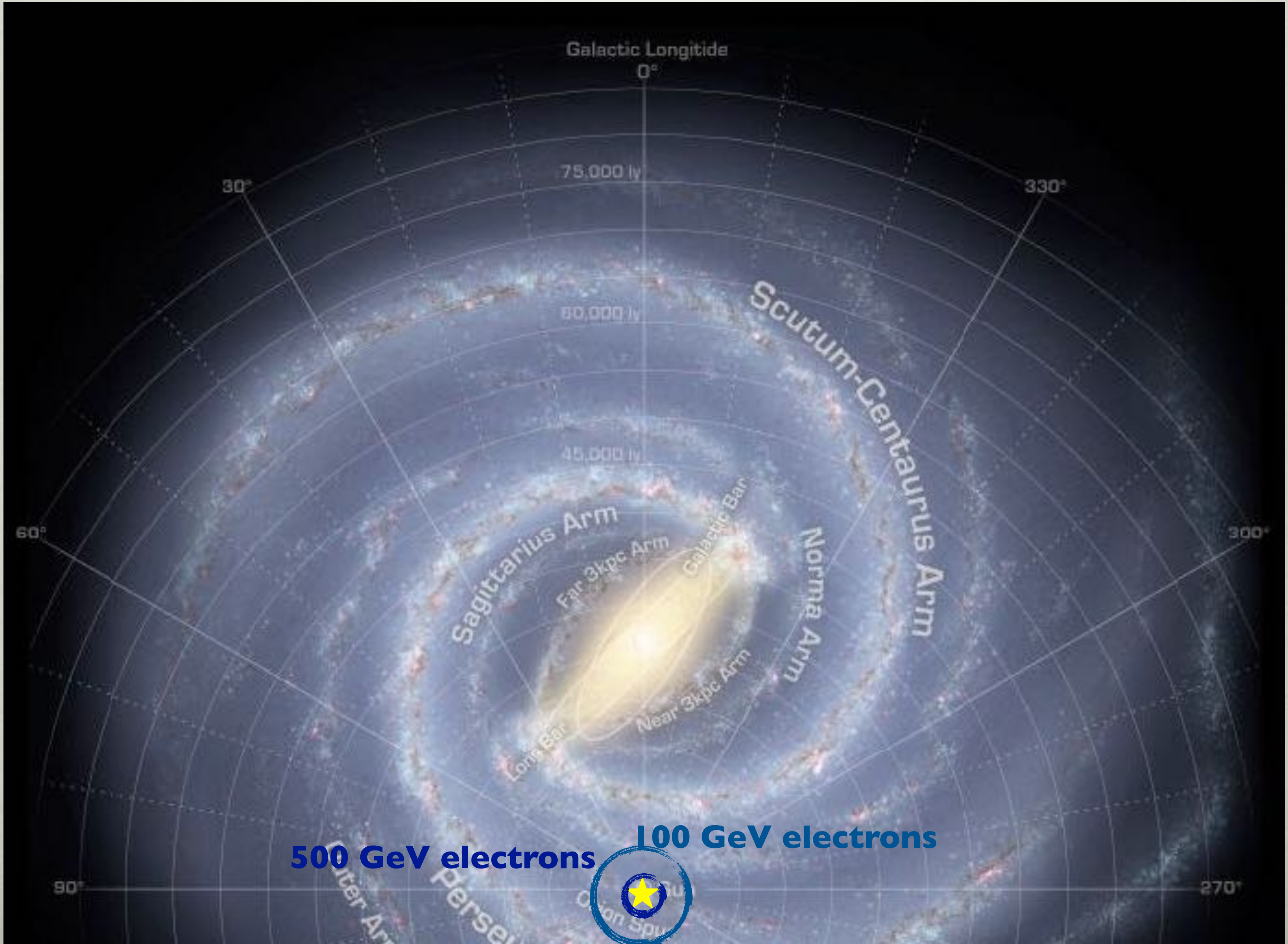
Protons primarily lose energy by scattering off of the interstellar medium (mainly hydrogen gas)

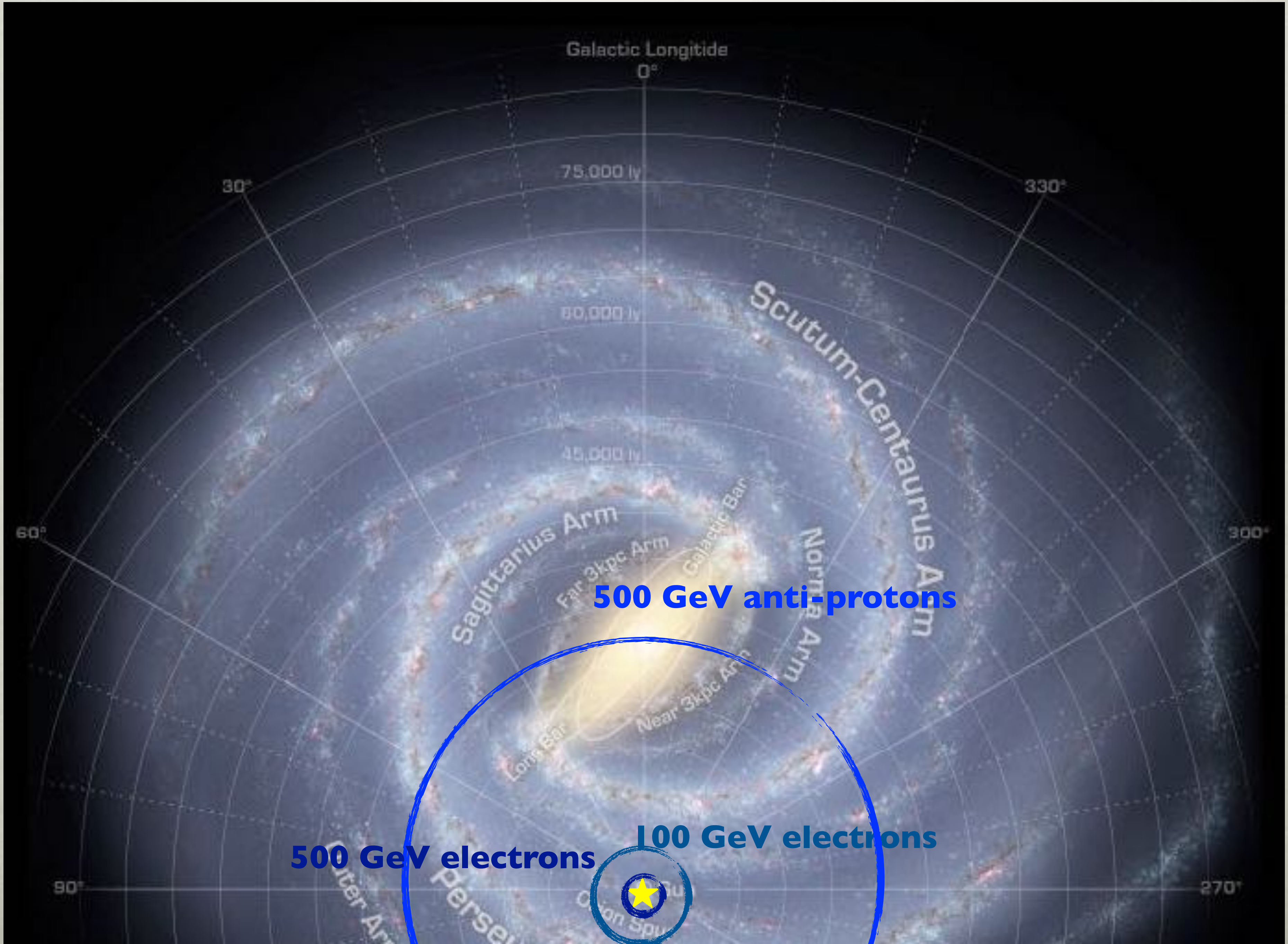


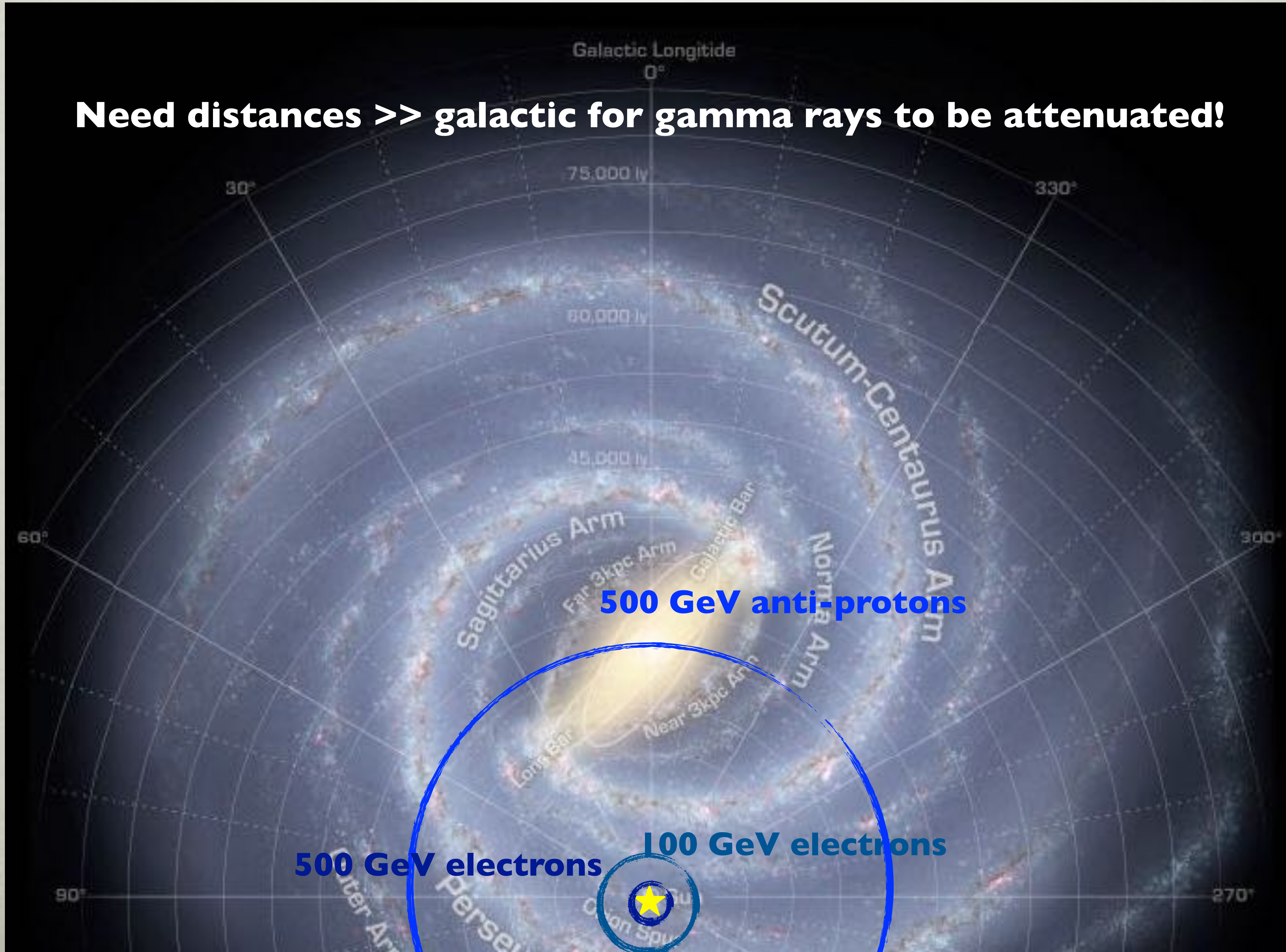


Galactic Longitide
0°
75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
270°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseu
Sun
Orion Spur

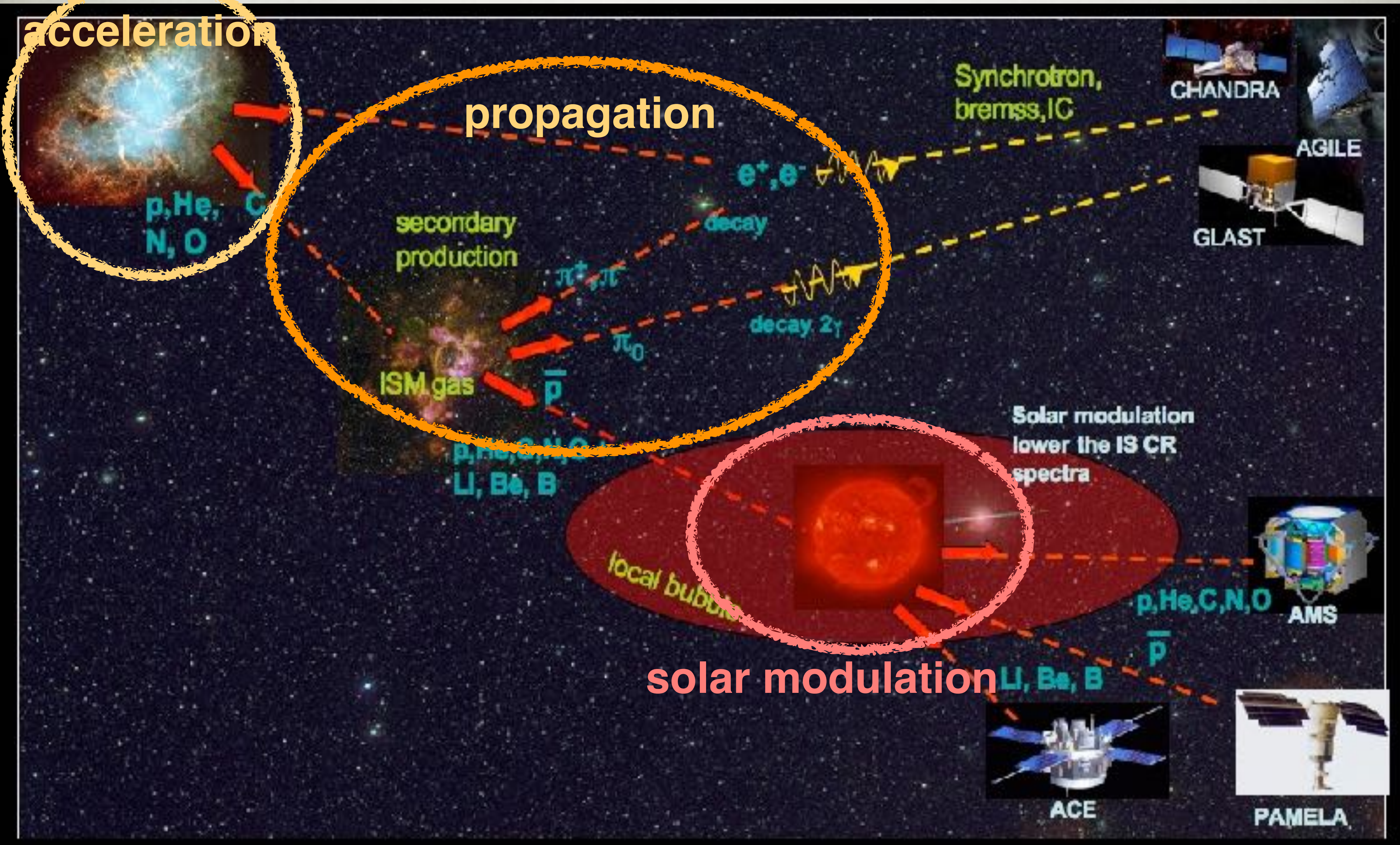

Galactic Longitide
0°
75,000 ly
30°
330°
60,000 ly
Scutum-Centaurus Arm
45,000 ly
60°
300°
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
500 GeV electrons
90°
Sun
Orion Spur
270°


Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
75,000 ly
60,000 ly
45,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Perseus
Outer Arm
Orion Spur
500 GeV electrons
100 GeV electrons


Galactic Longitide
0°
75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
270°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
500 GeV anti-protons
100 GeV electrons
500 GeV electrons


Galactic Longitude
0°
Need distances >> galactic for gamma rays to be attenuated!
75,000 ly
30°
330°
60,000 ly
Scutum-Centaurus Arm
45,000 ly
60°
300°
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
500 GeV anti-protons
Near 3kpc Arm
Long Bar
100 GeV electrons
500 GeV electrons
90°
270°

And the Background...



WIMP Signal

- Gamma rays from dark matter annihilation:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{< \sigma_{ann} v >}{2m^2_{WIMP}} \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f$$

$$\times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

WIMP Signal

- Gamma rays from dark matter annihilation:

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

$$\times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

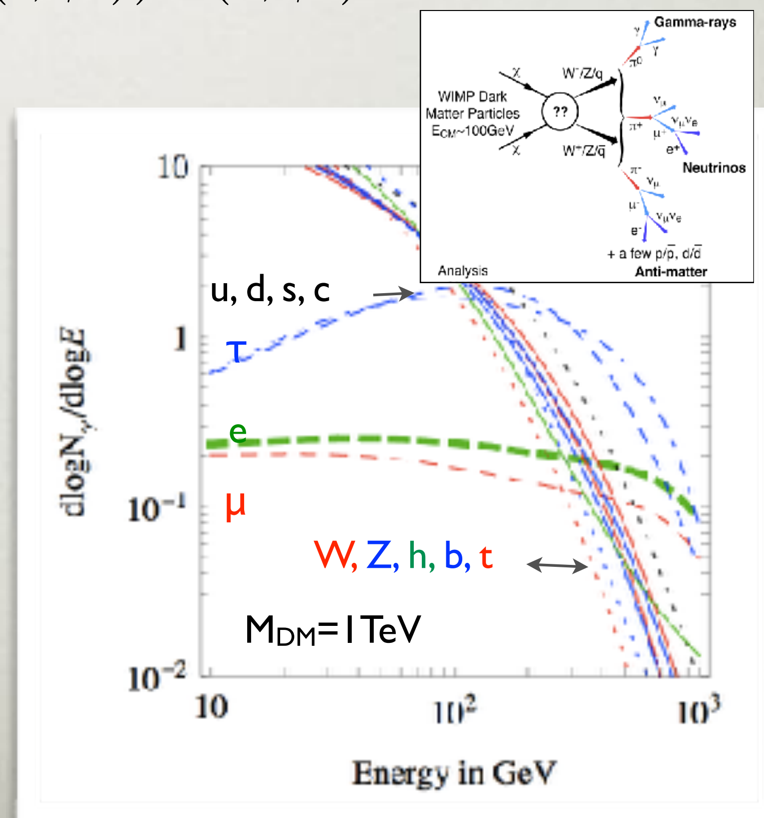
WIMP Signal

- Gamma rays from dark matter annihilation:

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann} v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

$$\times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



Cirelli et al, arXiv:0809.2409

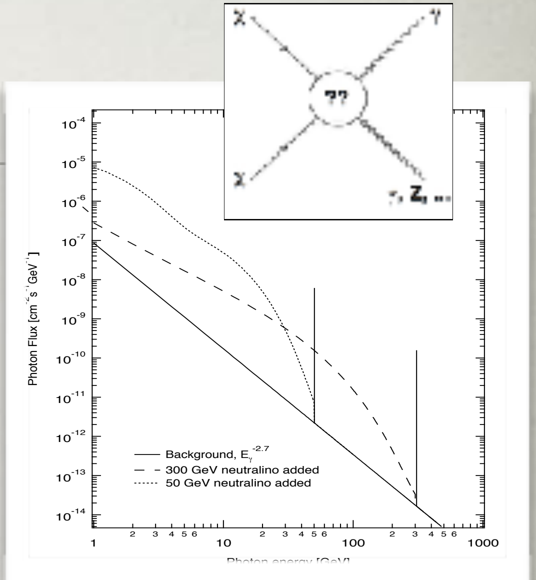
WIMP Signal

- Gamma rays from dark matter annihilation:

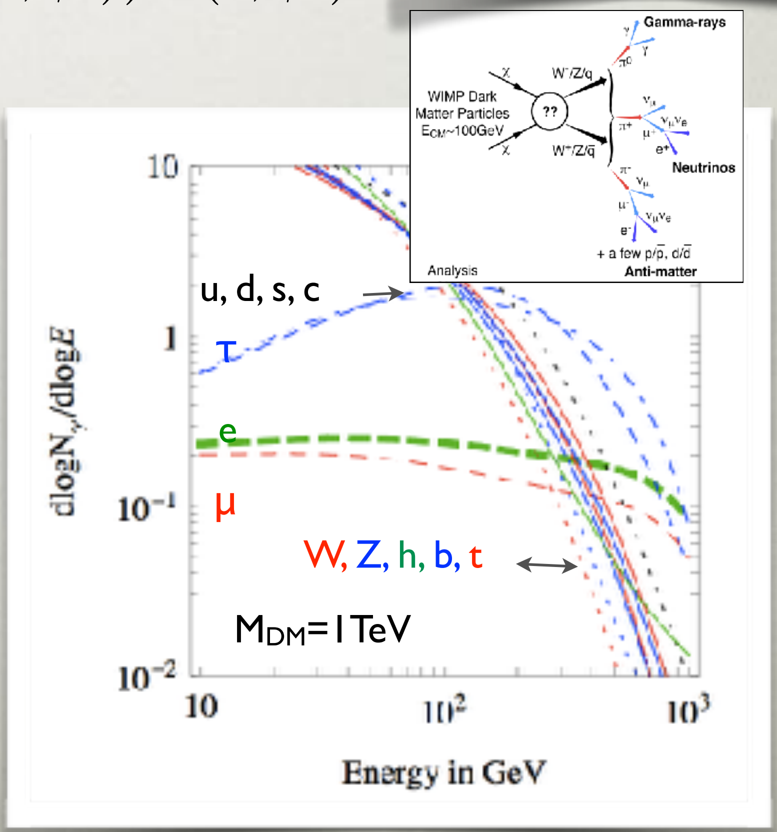
particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) \quad = \quad \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

$$\times \quad \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



Bergstrom, Ullio, Buckley



Cirelli et al, arXiv:0809.2409

WIMP Signal

- Gamma rays from dark matter annihilation:

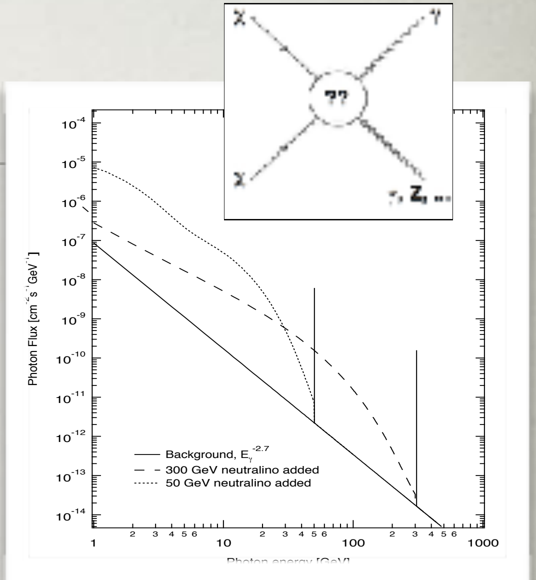
particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) \quad = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

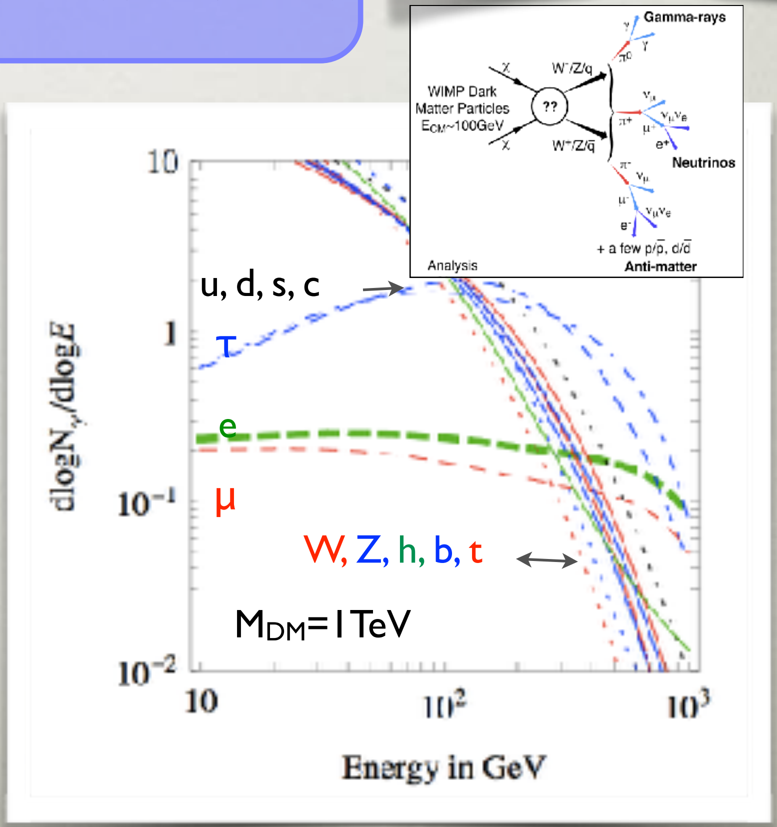
$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$

DM distribution

J - factor



Bergstrom, Ullio, Buckley



Cirelli et al, arXiv:0809.2409

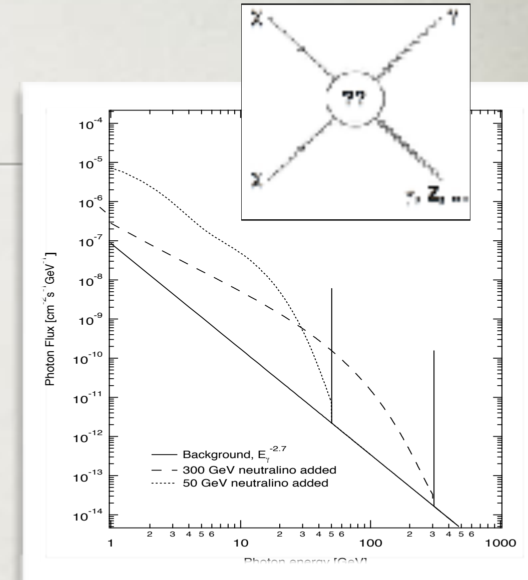
WIMP Signal

- Gamma rays from dark matter annihilation:

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

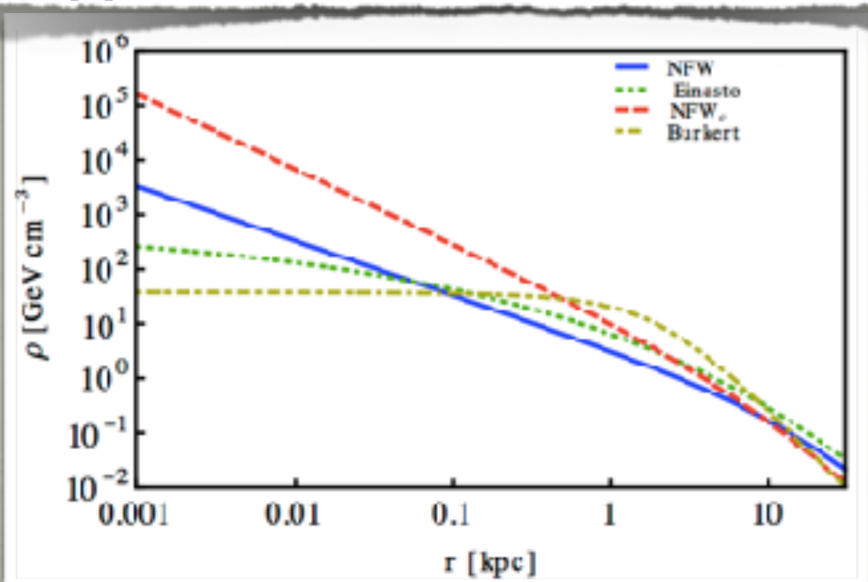
$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$



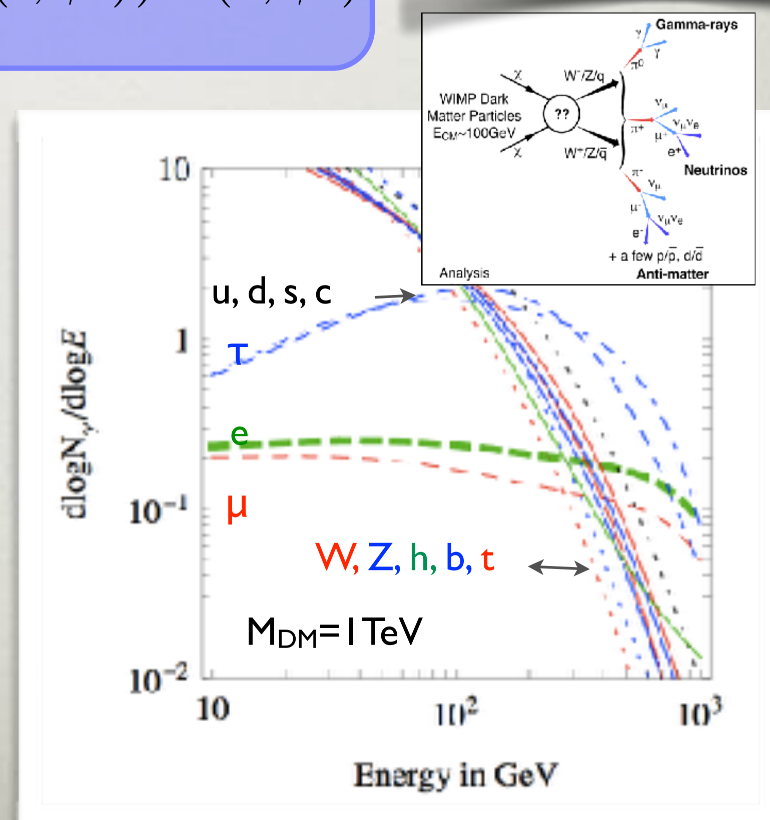
Bergstrom, Ullio, Buckley

For the central dark matter density:

$\rho(r) \sim r^{-\gamma}$ $\gamma=0$ core, $\gamma=1$ NFW/cusp



Gomez-Vargas et al, arXiv:1308.3515



Cirelli et al, arXiv:0809.2409

WIMP Signal

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) \quad = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los}\rho^2(r(l,\phi'))dl(r,\phi')}$$

DM distribution

J - factor

For DM decay:

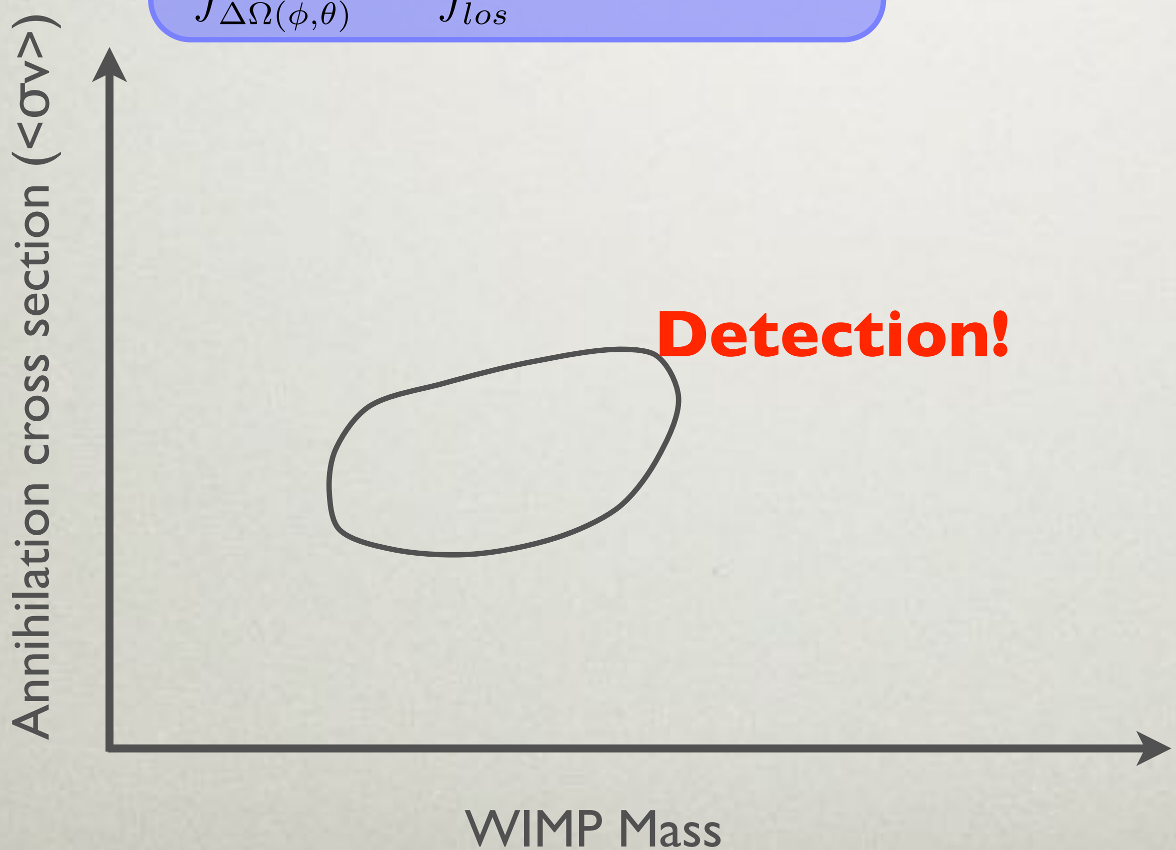
- $<\sigma_{ann}v>/2m^2_{WIMP} \rightarrow 1/\tau m_{WIMP}$
- $\rho^2 \rightarrow \rho$

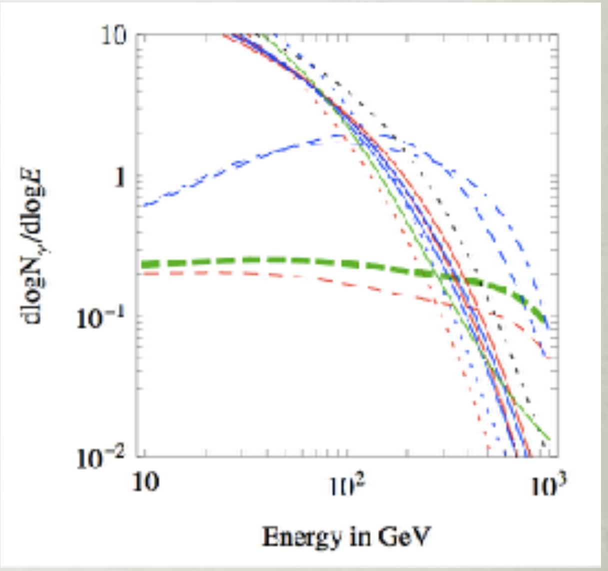
➡ Charged particles are more complicated (need to include propagation)

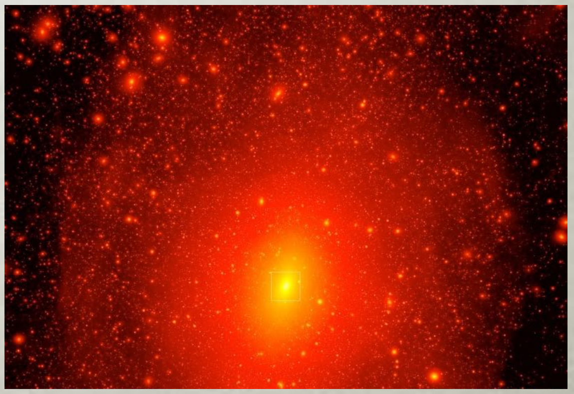
Indirect Detection Results

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$



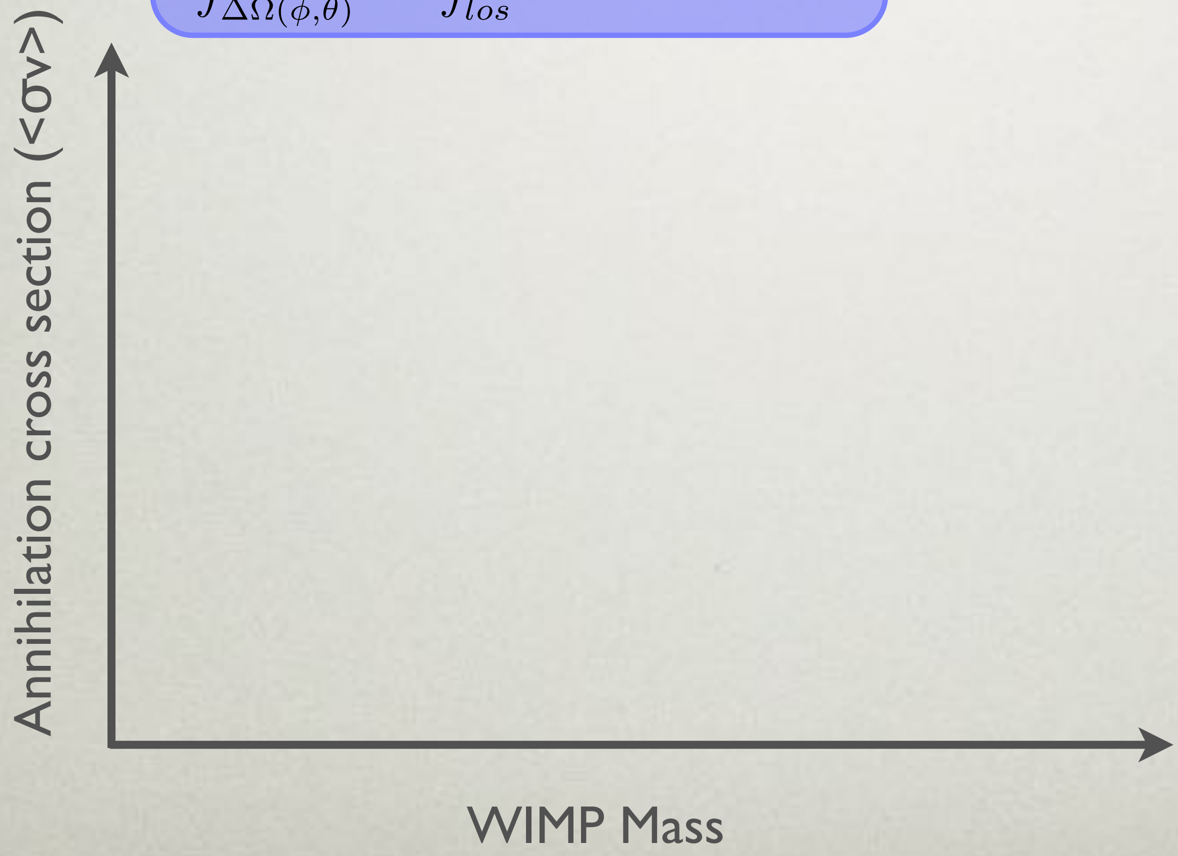




Indirect Detection Results

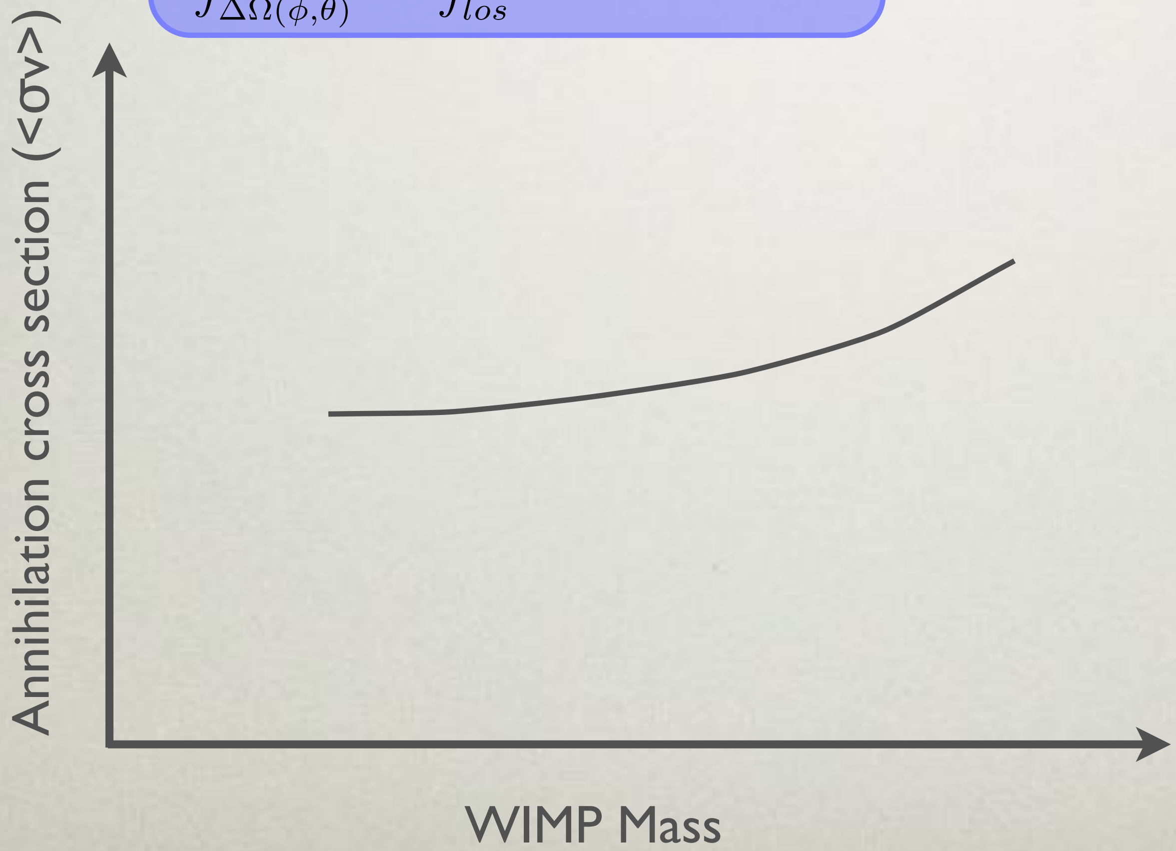
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann} v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los}\rho^2(r(l,\phi'))dl(r,\phi')}$$



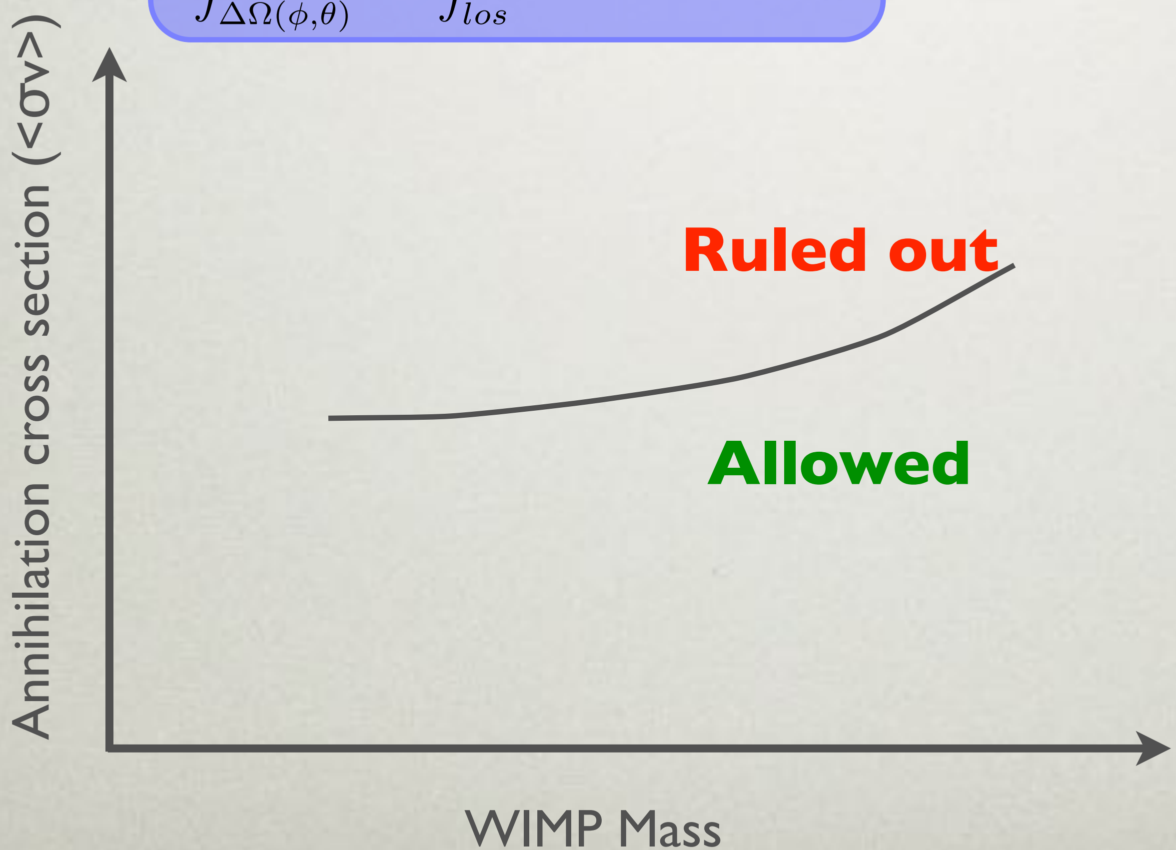
Indirect Detection Results

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$
$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$



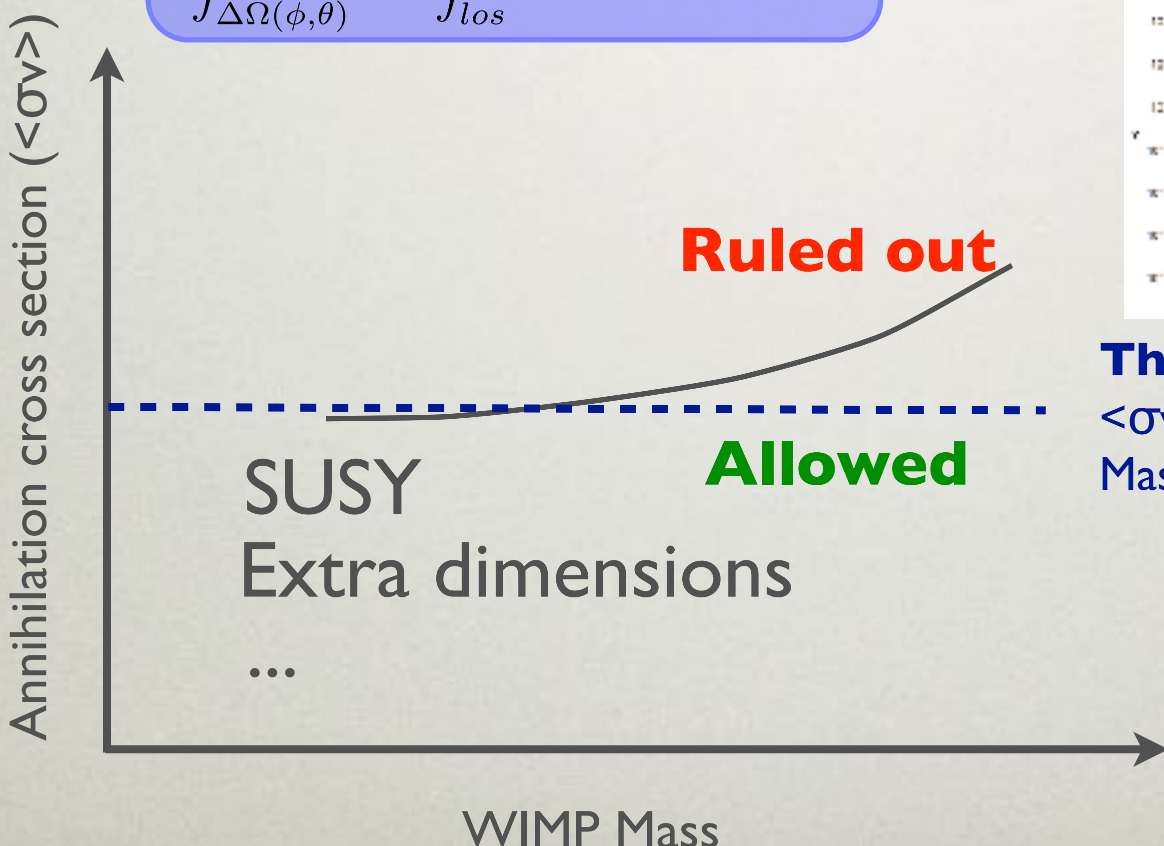
Indirect Detection Results

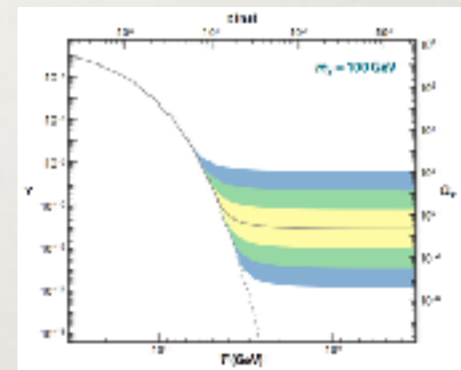
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$
$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$



Indirect Detection Results

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f} \times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$





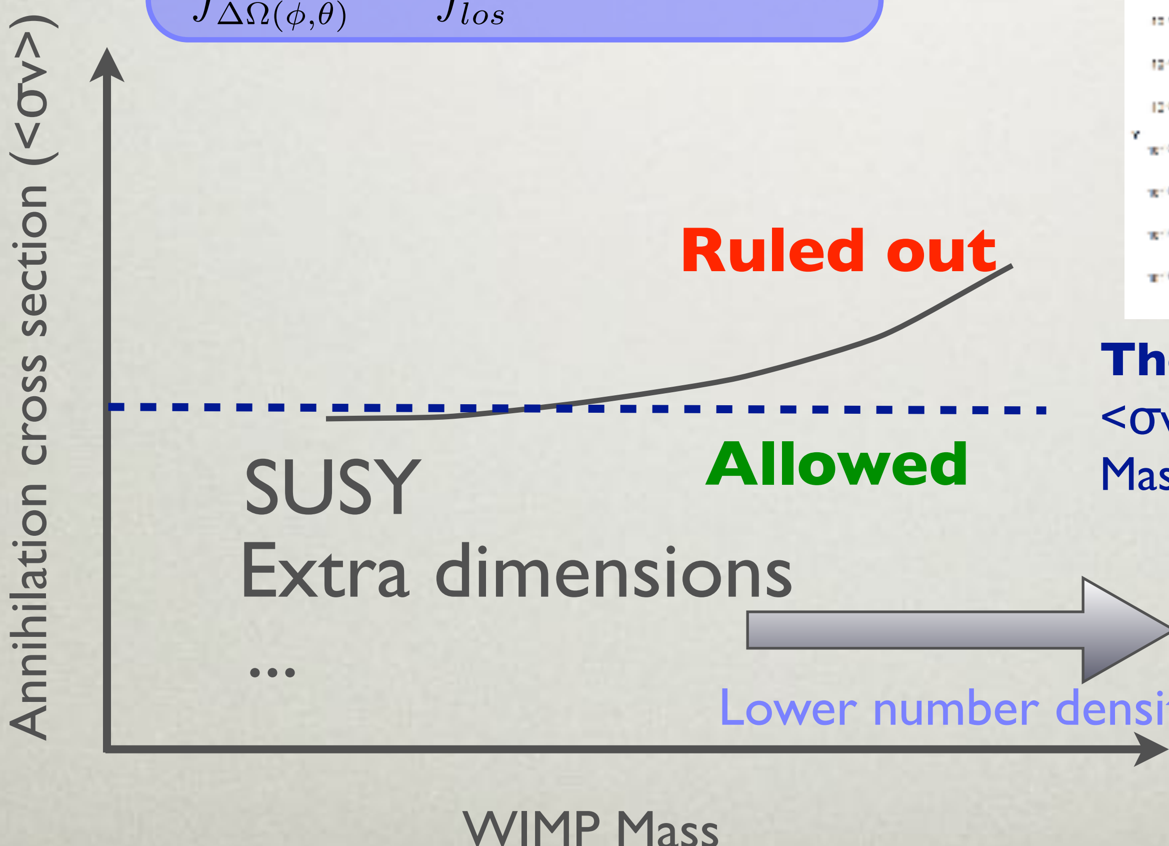
Thermal WIMP

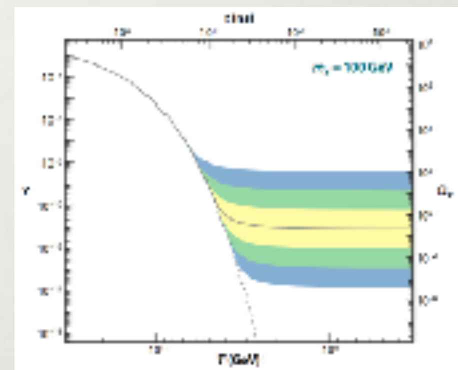
$<\sigma v>$ of order $3\text{x}10^{-26}$ cm^3/s

Mass of order100 GeV

Indirect Detection Results

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$
$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$





Thermal WIMP
<σv> of order 3×10^{-26} cm^3/s
Mass of order100 GeV

$$n = \frac{\rho}{M_{WIMP}}$$

EXPERIMENTS

Gamma rays and cosmic rays

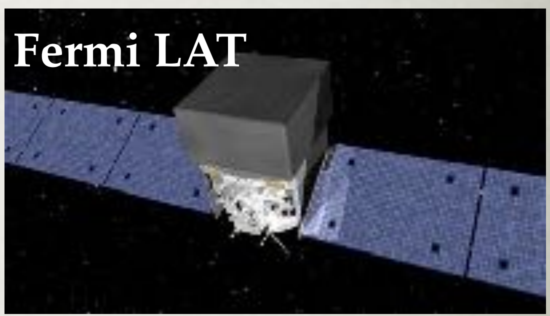
- Fermi LAT
- HESS, MAGIC, VERITAS
- PAMELA, AMS-02
- DAMPE, CALET

Neutrinos

- IceCube, ANTARES

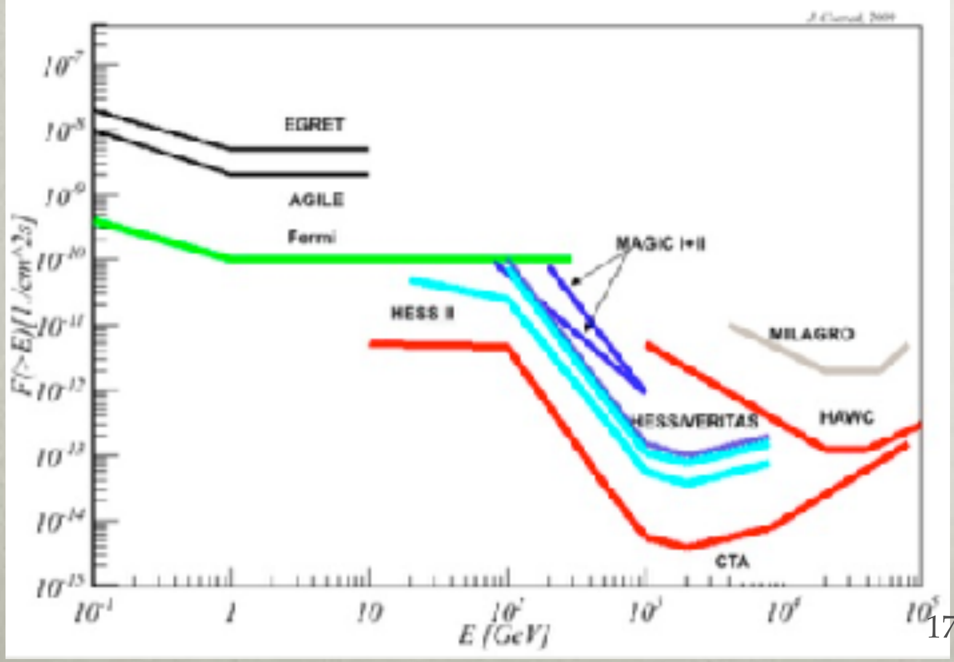
X-rays

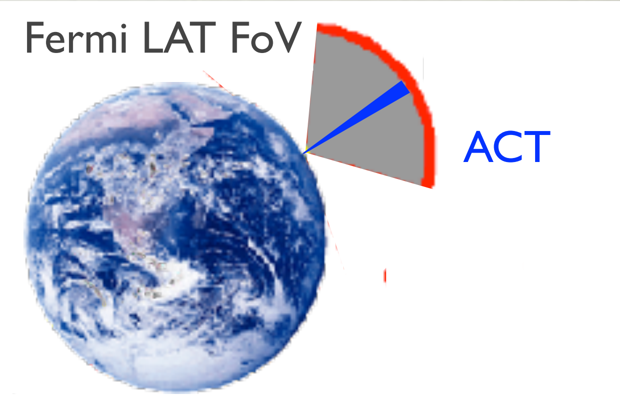
- XMM-Newton, Chandra, Hitomi



Ground vs Space Gamma ray experiments

- Lower energy thresholds accessible in space, and up to ~100 TeV energies with experiments on the ground. Overlap in the ~100 GeV region
- Larger field of view, great duty cycle, and all sky coverage in space
- Best single photon angular resolution: ~0.1° at 100 GeV, ~1° at 1 GeV (but position accuracy for bright sources is better (also depending on their spectrum)!)
- Large collecting area on the ground (high sensitivity)

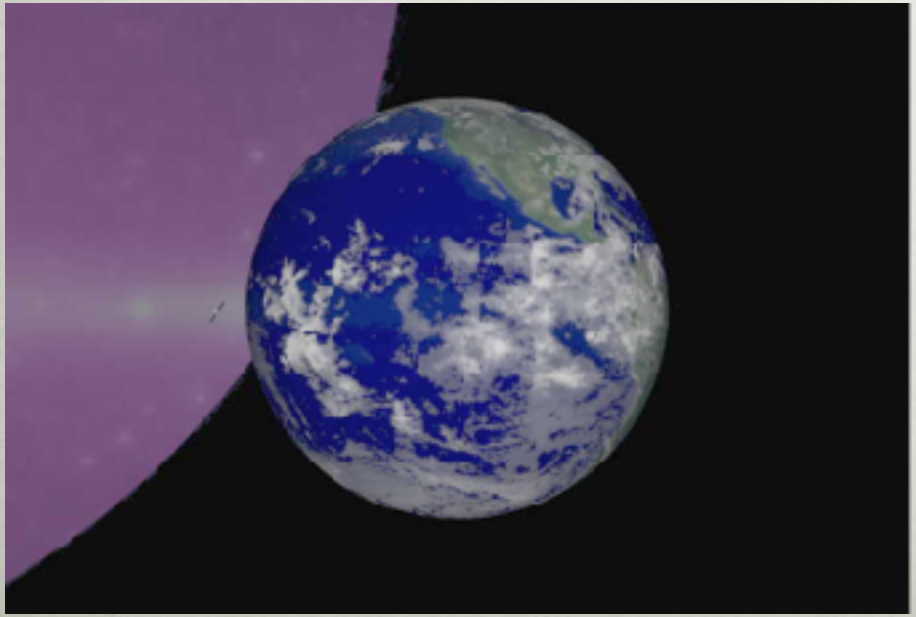


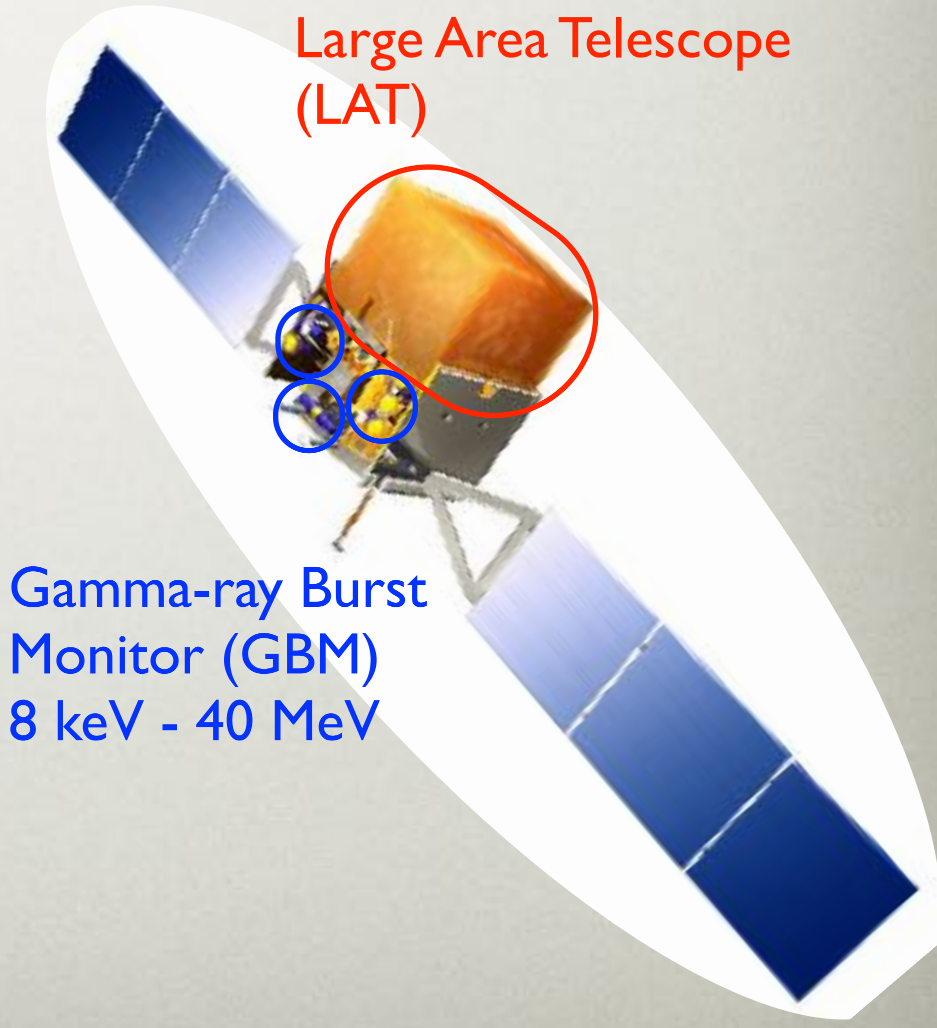


Fermi Mission
The Large Area telescope

- The Fermi Large Area Telescope observes the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity

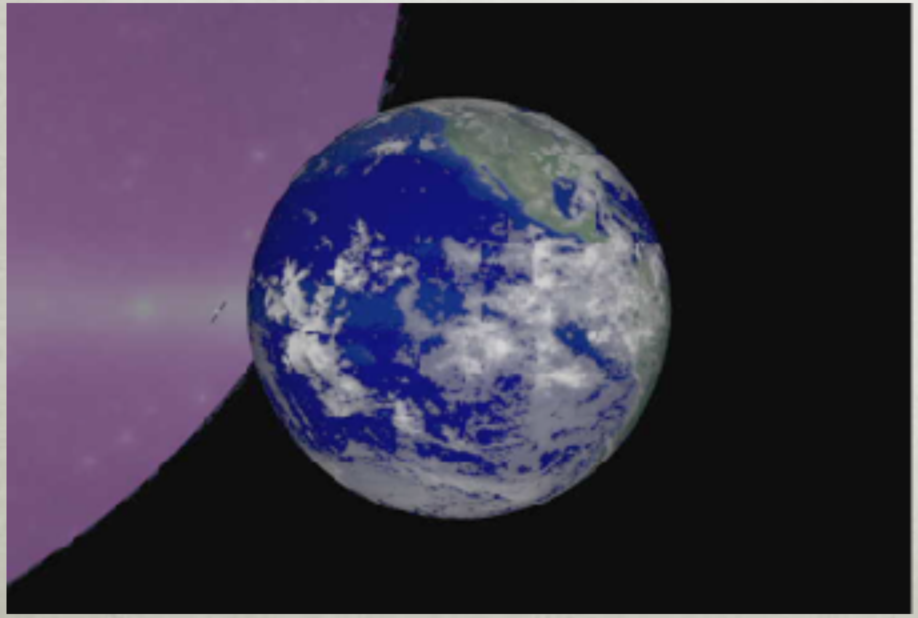
- Orbit: 565 km, 25.6° inclination, circular. The LAT observes the entire sky every ~3 hrs (2 orbits)

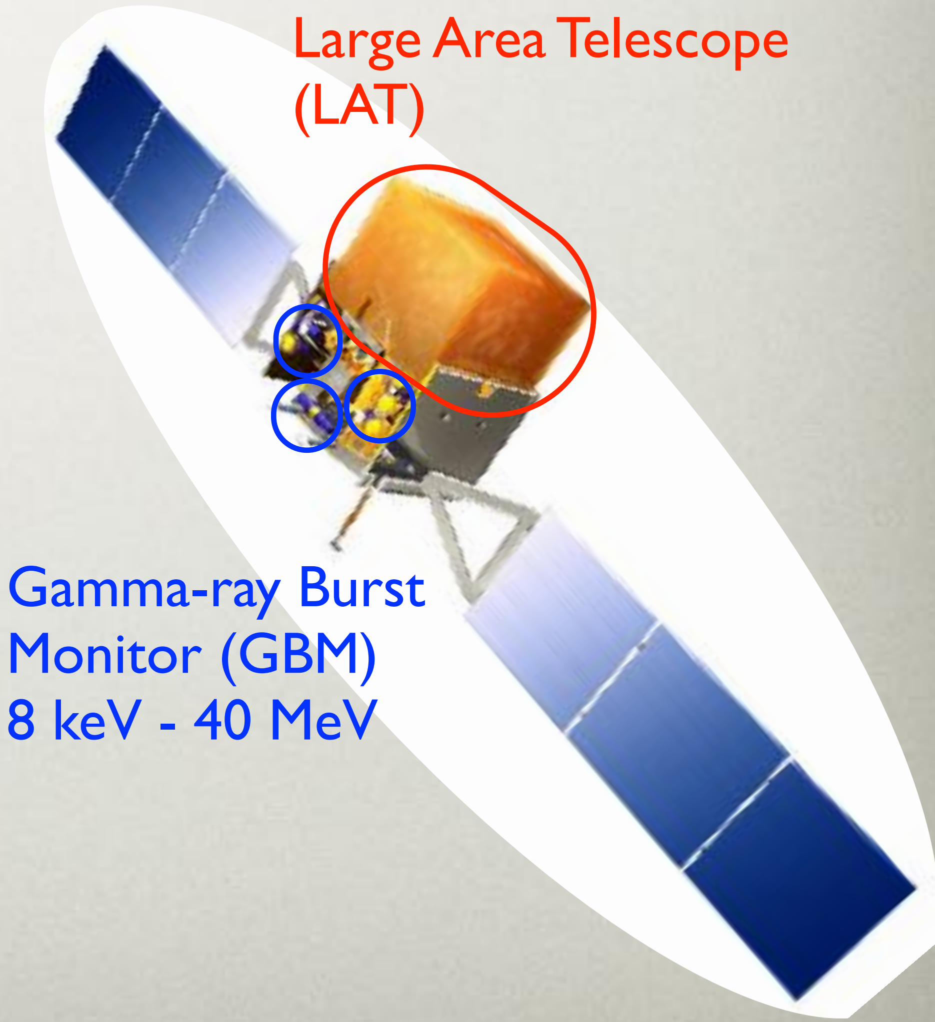




Fermi Mission
The Large Area telescope

- The Fermi Large Area Telescope observes the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity
- Orbit: 565 km, 25.6° inclination, circular. The LAT observes the entire sky every ~3 hrs (2 orbits)

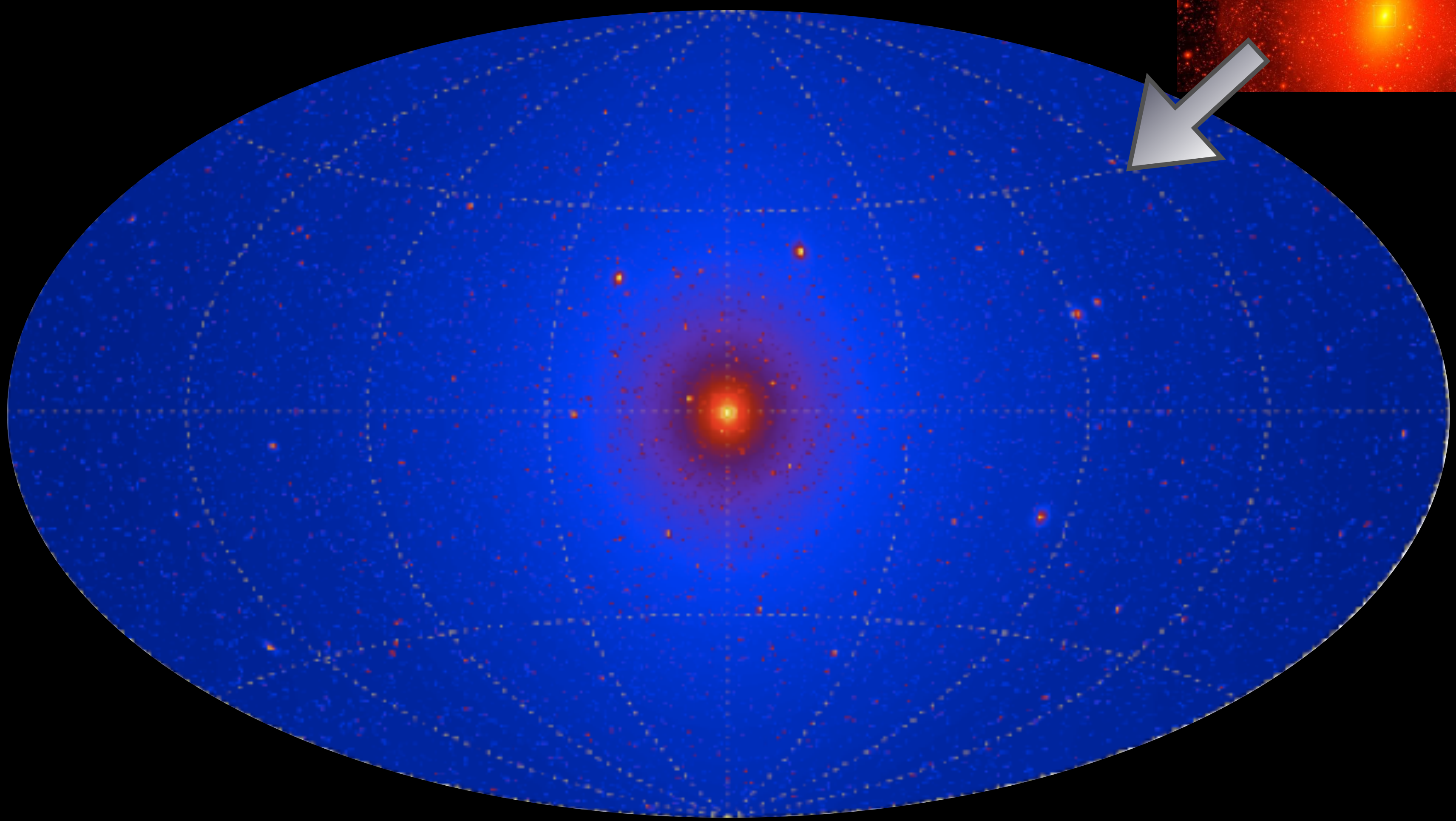


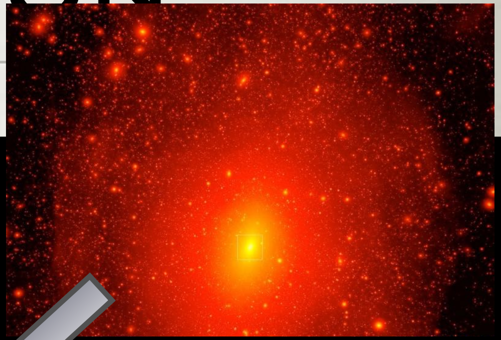


Very High Energy Γ-rays

Imaging Atmospheric Cherenkov Telescopes (IACTs)

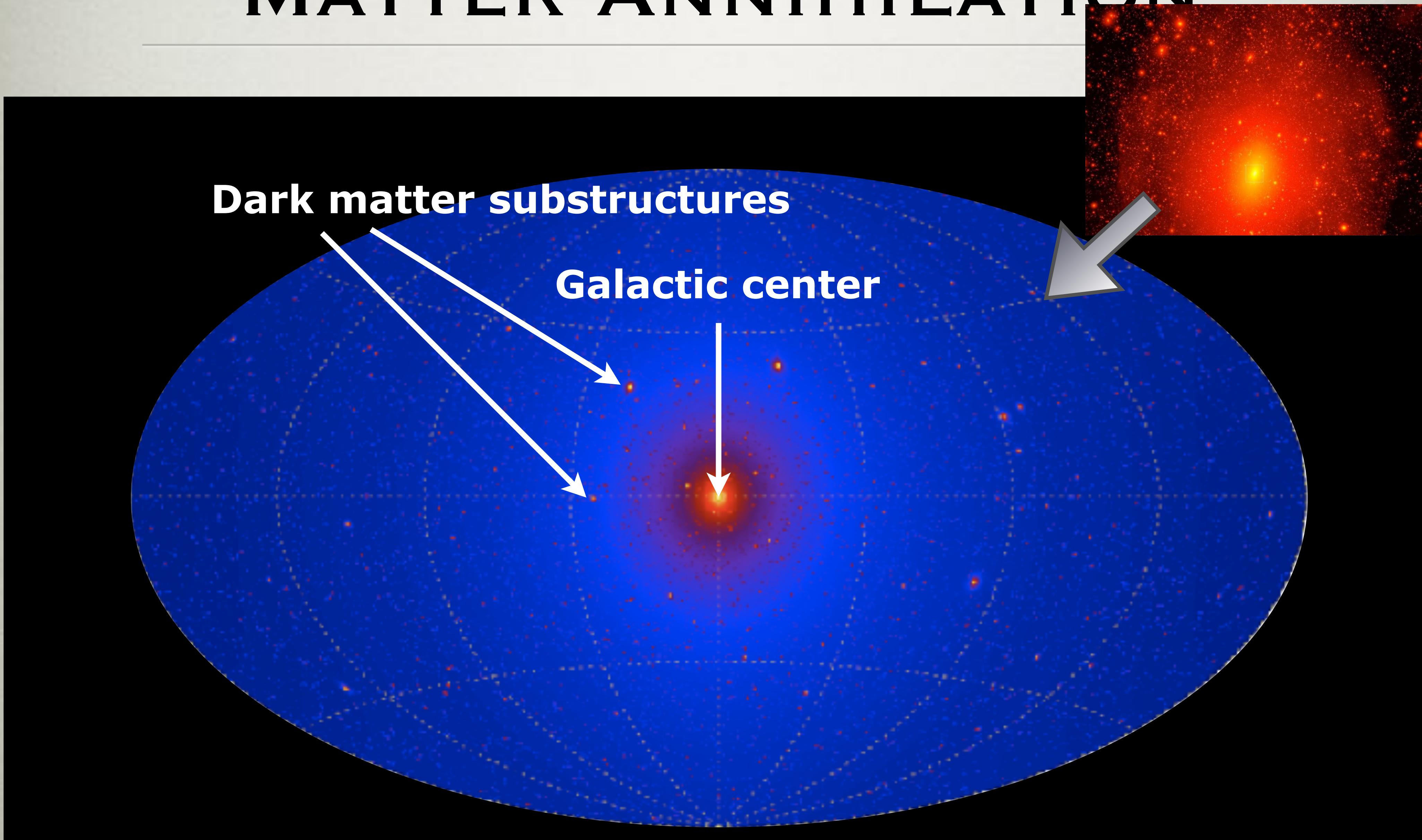
Gamma rays from Dark Matter Annihilation





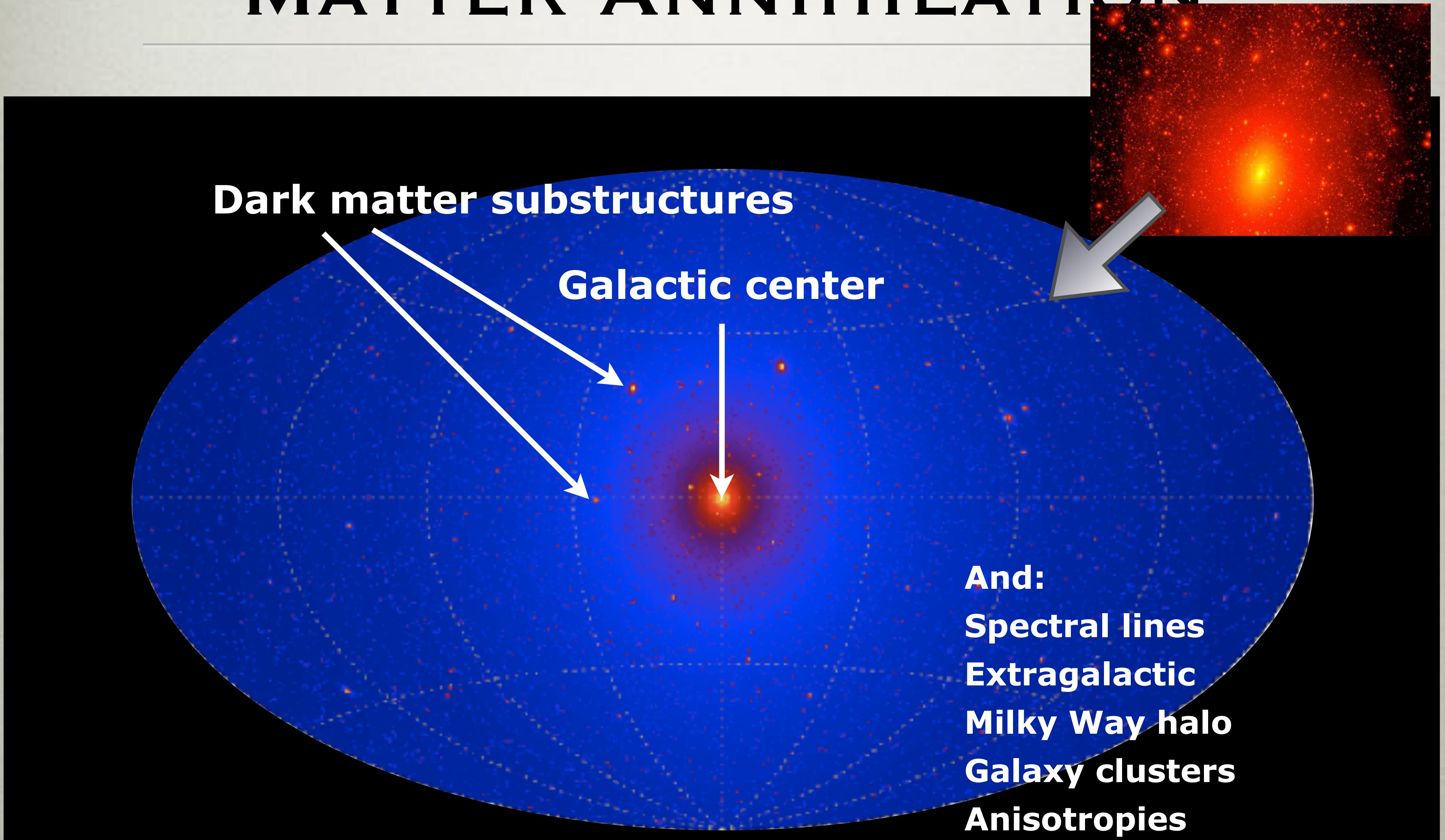
Pieri et al, arXiv:0908.0195

Gamma rays from Dark Matter Annihilation



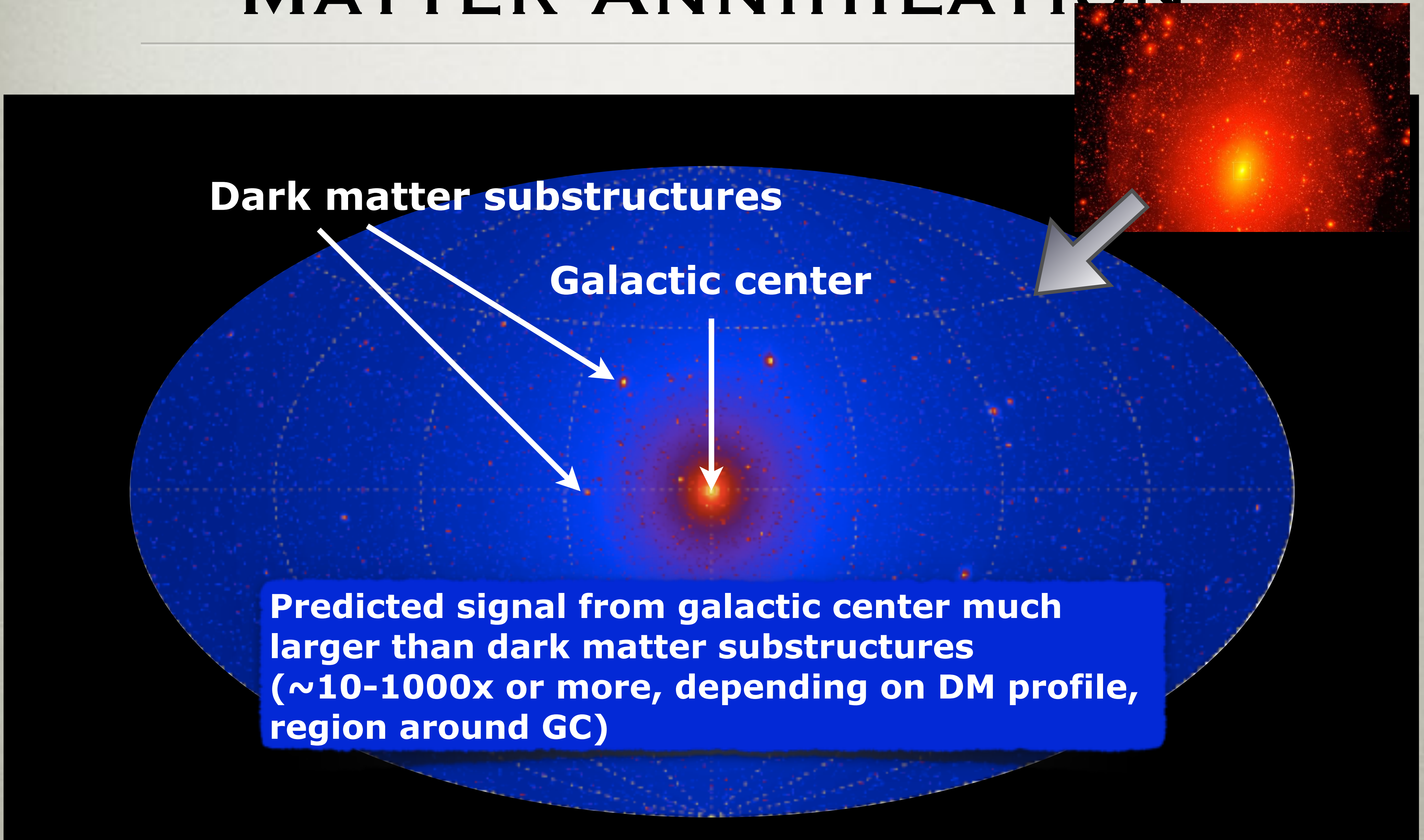
Pieri et al, arXiv:0908.0195

Gamma rays from Dark Matter Annihilation



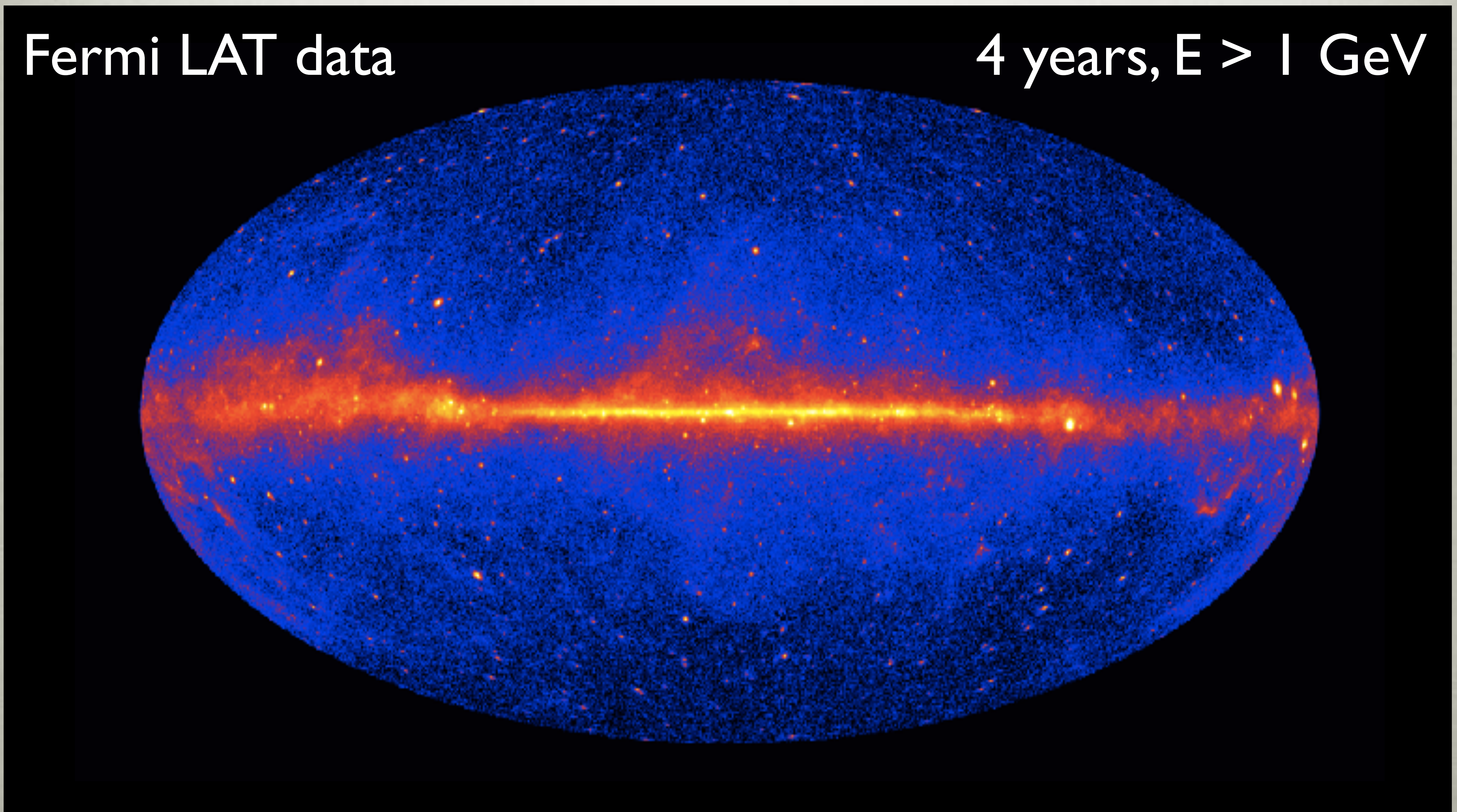
Pieri et al, arXiv:0908.0195

Gamma rays from Dark Matter Annihilation

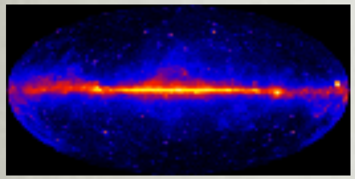


Pieri et al, arXiv:0908.0195

The Fermi Sky

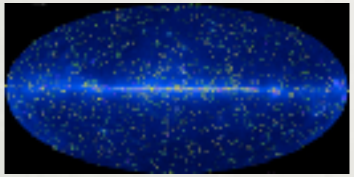


Understanding the Gamma-ray Sky



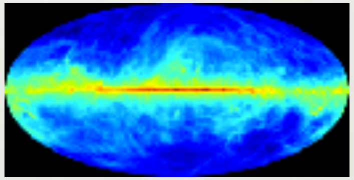
data

=



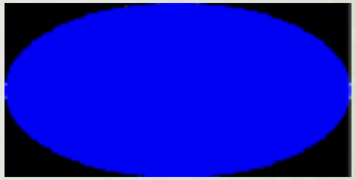
sources

+



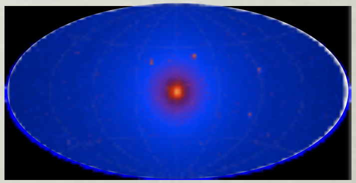
galactic interstellar emission

+



isotropic

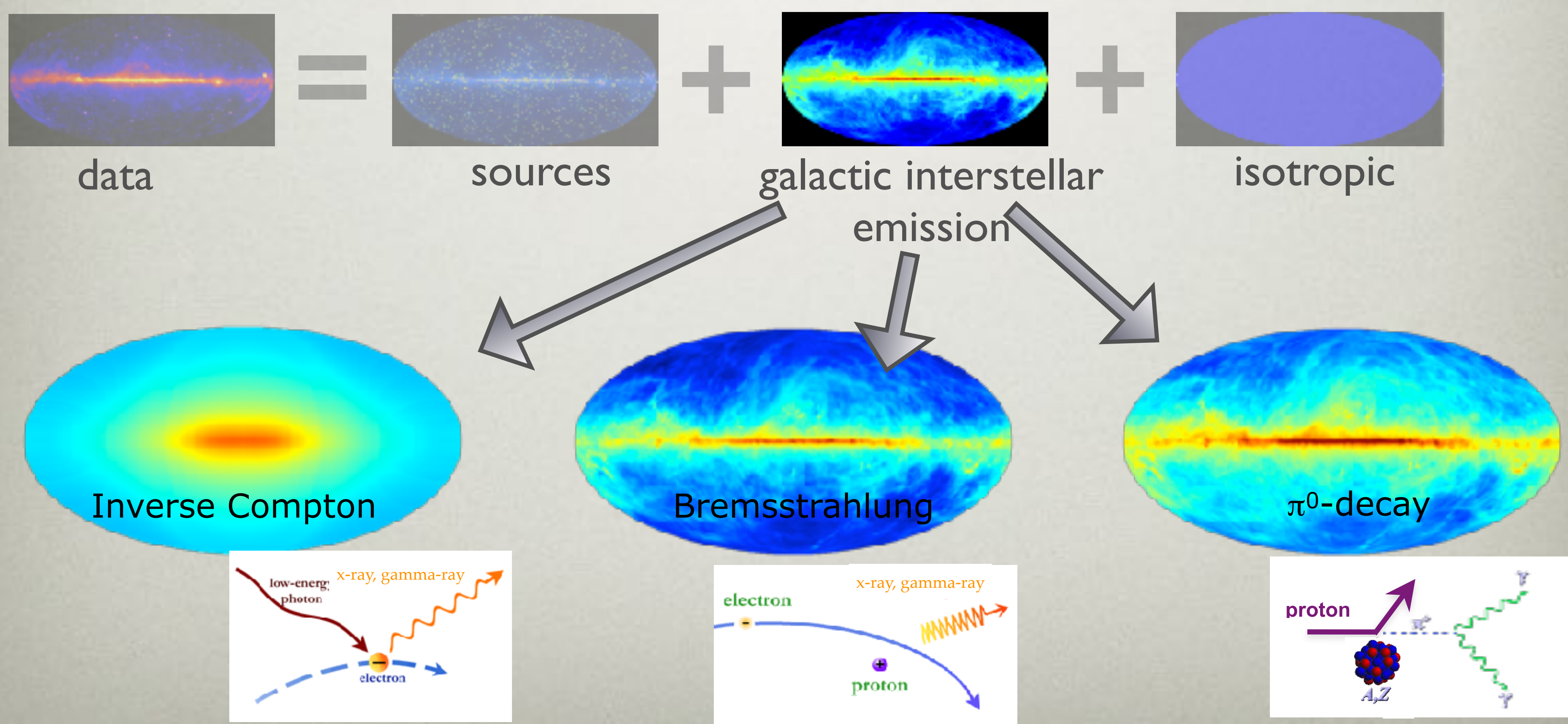
+



dark matter??

Galactic Gamma-Ray Interstellar Emission

- The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field

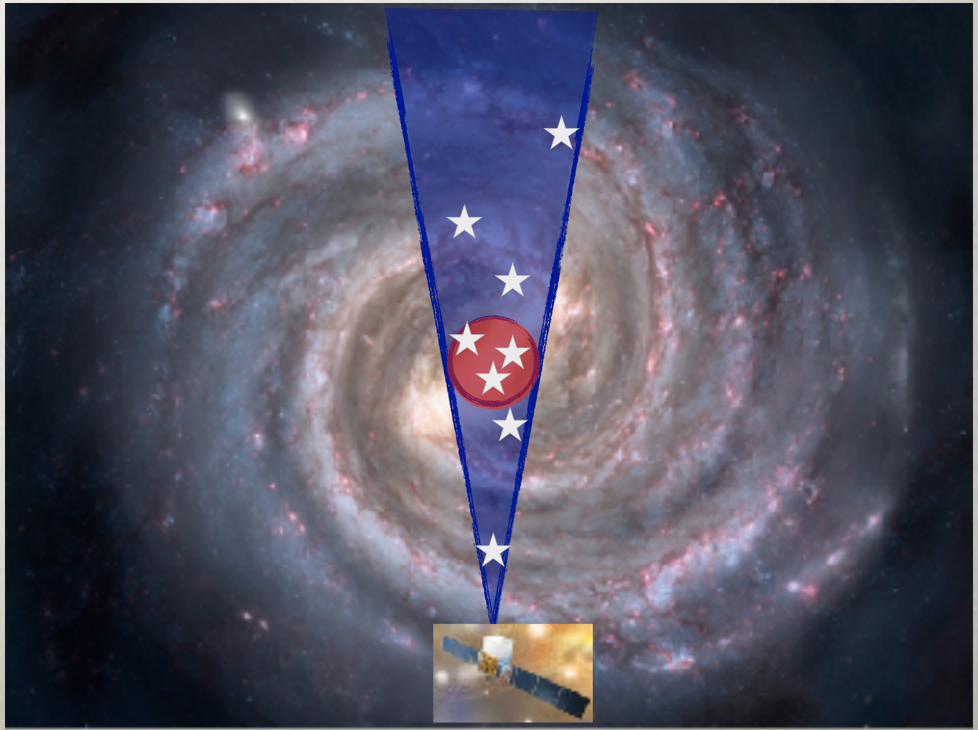


Galactic Gamma-Ray Interstellar Emission

- The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field

➡ Galactic center region: a dark matter signal is predicted to be largest here, where modeling of the interstellar emission (and sources) is problematic!

CR intensities, density of radiation fields and gas are highest and most uncertain, and significant contribution from foreground/background in the long integration path over the entire Galactic disc.



Also, large density of sources, difficult to disentangle from interstellar emission.

Galactic Center Excess

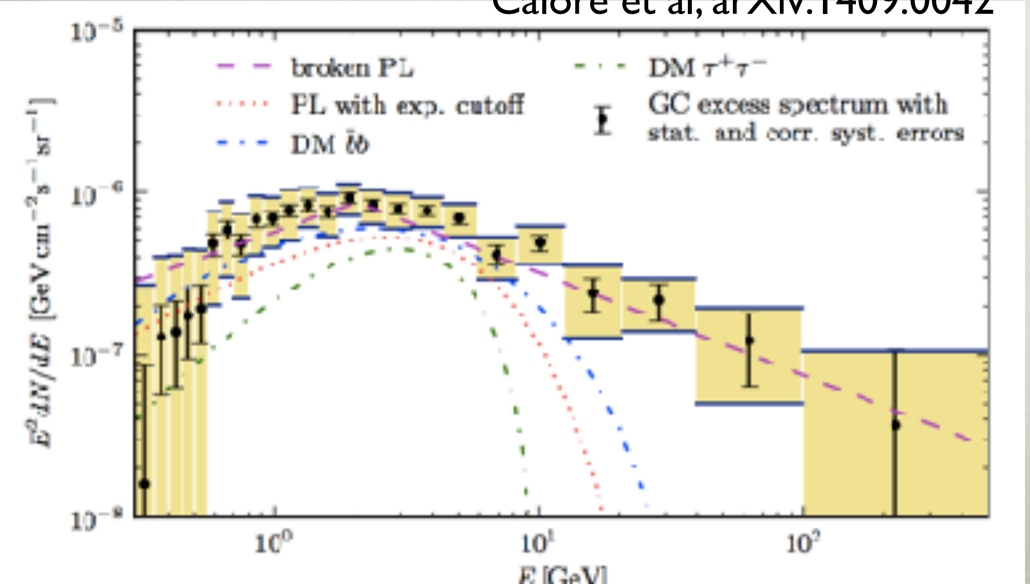
- An excess in the Fermi LAT GC data consistent with dark matter annihilation was first claimed by Goodenough and Hooper (arXiv:0910.2998.) More recent analyses also find an excess
- Different approaches in modeling the interstellar emission model (IEM): *the characterization of the signal depends on this!*

Galactic Center Excess

- An excess in the Fermi LAT GC data consistent with dark matter annihilation was first claimed by Goodenough and Hooper (arXiv:0910.2998.) More recent analyses also find an excess
- Different approaches in modeling the interstellar emission model (IEM): *the characterization of the signal depends on this!*

Interstellar emission model (IEM) based on the CR propagation code (GALPROP): physically motivated models, however do not fully capture complexity of the Galaxy

Calore et al, arXiv:1409.0042



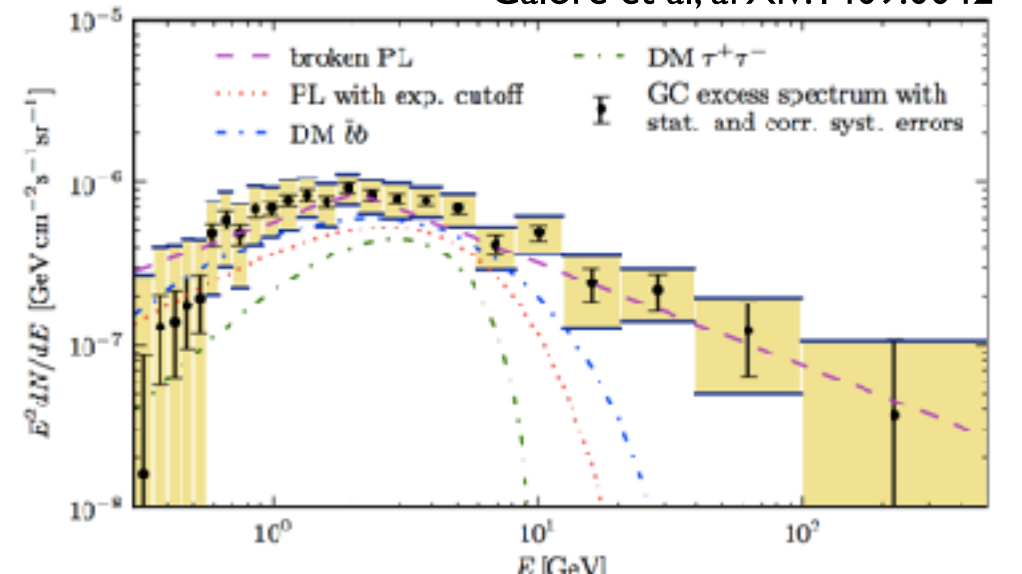
Galactic Center Excess

- An excess in the Fermi LAT GC data consistent with dark matter annihilation was first claimed by Goodenough and Hooper (arXiv:0910.2998.) More recent analyses also find an excess
- Different approaches in modeling the interstellar emission model (IEM): *the characterization of the signal depends on this!*

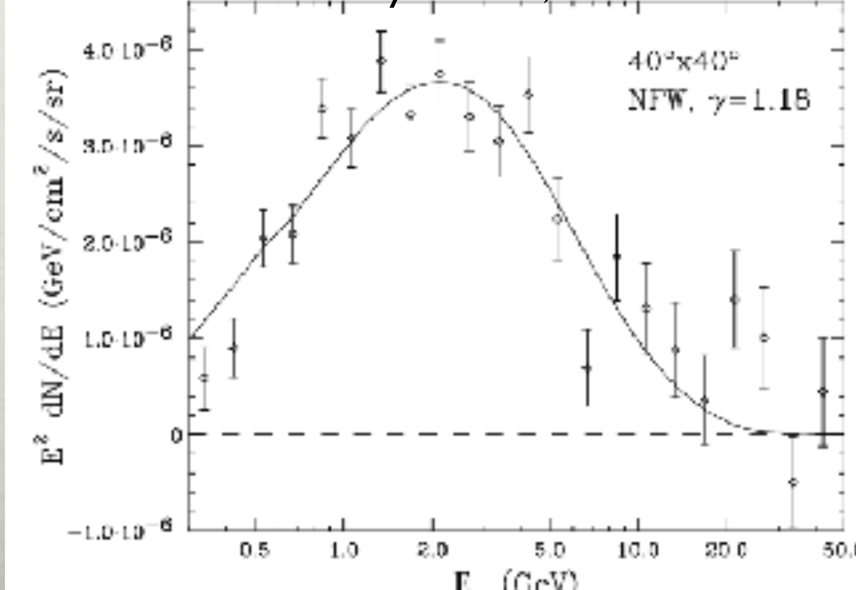
Interstellar emission model (IEM) based on the CR propagation code (GALPROP): physically motivated models, however do not fully capture complexity of the Galaxy

The IEM provided by the Fermi LAT collaboration for point source analysis most often employed: template based approach, not fully physically motivated

Calore et al, arXiv:1409.0042



Daylan et al, arXiv:1402.6703



Galactic Center Excess

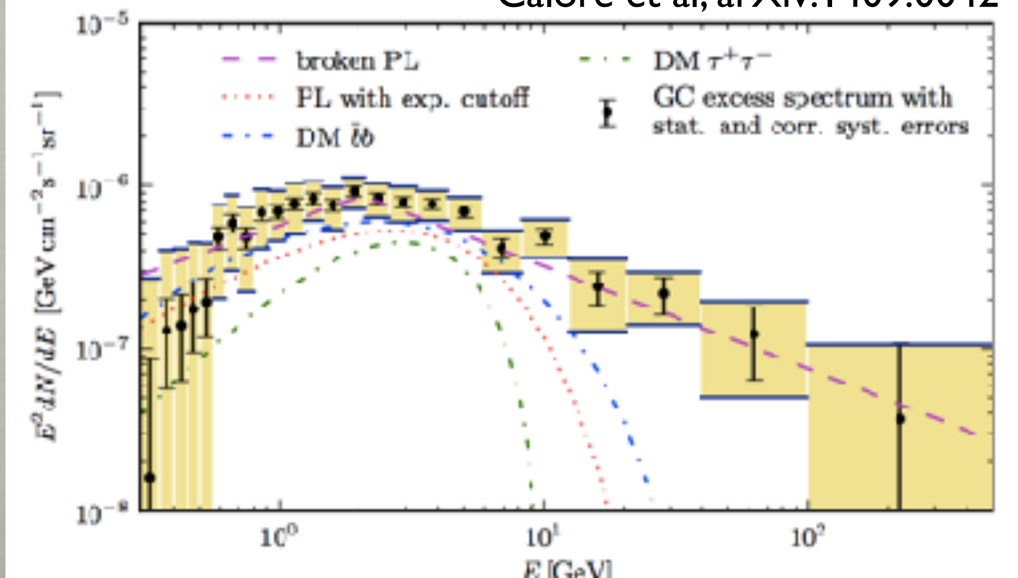
- An excess in the Fermi LAT GC data consistent with dark matter annihilation was first claimed by Goodenough and Hooper (arXiv:0910.2998.) More recent analyses also find an excess
- Different approaches in modeling the interstellar emission model (IEM): *the characterization of the signal depends on this!*

Interstellar emission model (IEM) based on the CR propagation code (GALPROP): physically motivated models, however do not fully capture complexity of the Galaxy

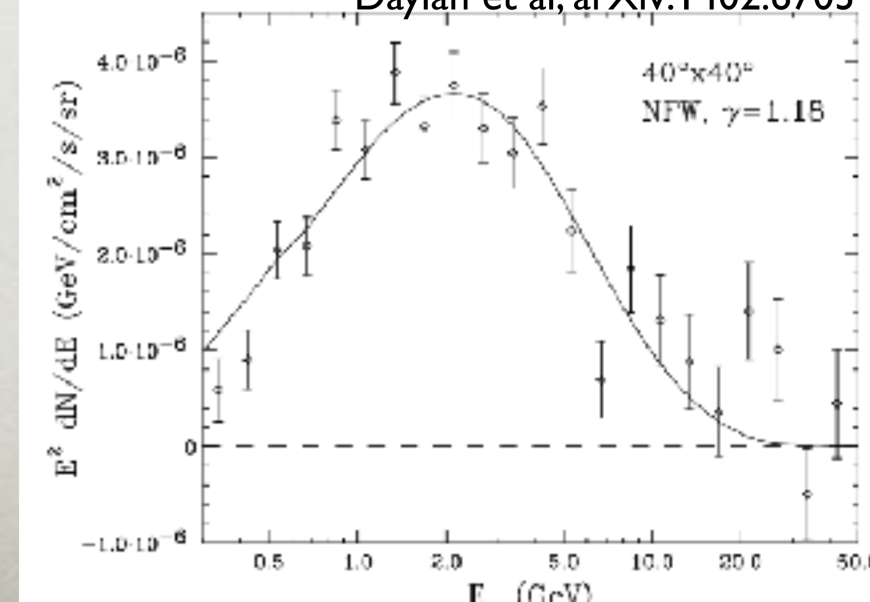
The IEM provided by the Fermi LAT collaboration for point source analysis most often employed: template based approach, not fully physically motivated

Use point sources from established gamma-ray source catalogs

Calore et al, arXiv:1409.0042



Daylan et al, arXiv:1402.6703



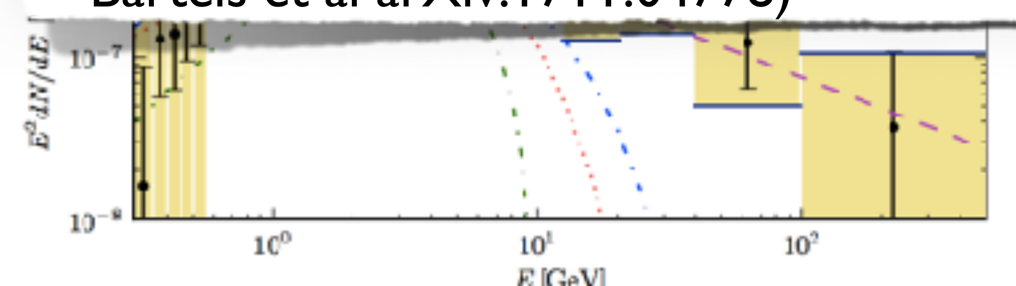
Galactic Center Excess

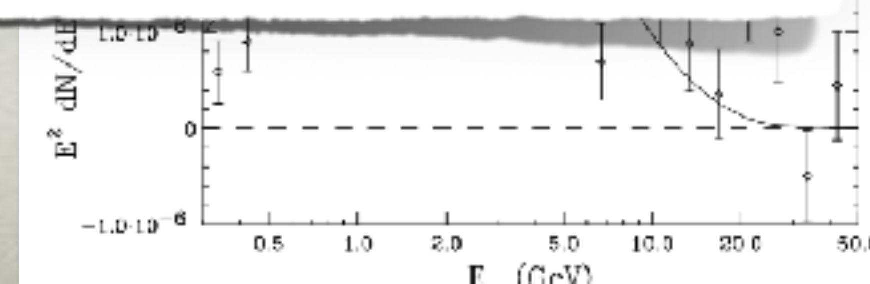
- An excess in the Fermi LAT GC data consistent with dark matter annihilation was first claimed by Goodenough and Hooper (arXiv:0910.2998.) More recent analyses also find an excess
- Different approaches in modeling the interstellar emission model (IEM): *the characterization of the signal depends on this!*

Interstellar emission model (IEM) based on the CR propagation code (GALPROP):

➡ The excess is consistent with a dark matter annihilation signal in spectrum and spatial morphology:

- ~50 GeV mass, annihilating into b-bbar with an annihilation cross-section consistent with predictions for a thermal relic, ~ few10^{-26} cm^3/s (NB: more possibilities are allowed, depending on the interstellar emission model.)
- NFW profile with slope γ=1-1.3
- Approximately spherically symmetric (but see also Macias et al arXiv:1611.06644, Bartels et al arXiv:1711.04778)

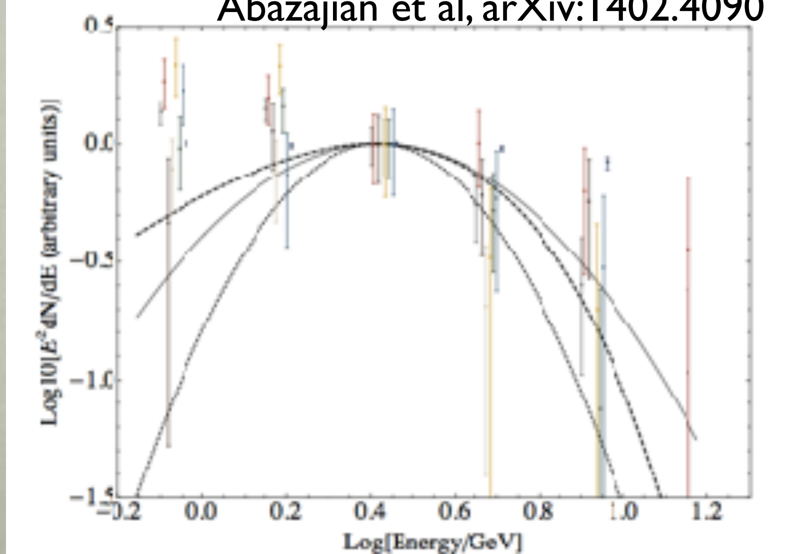




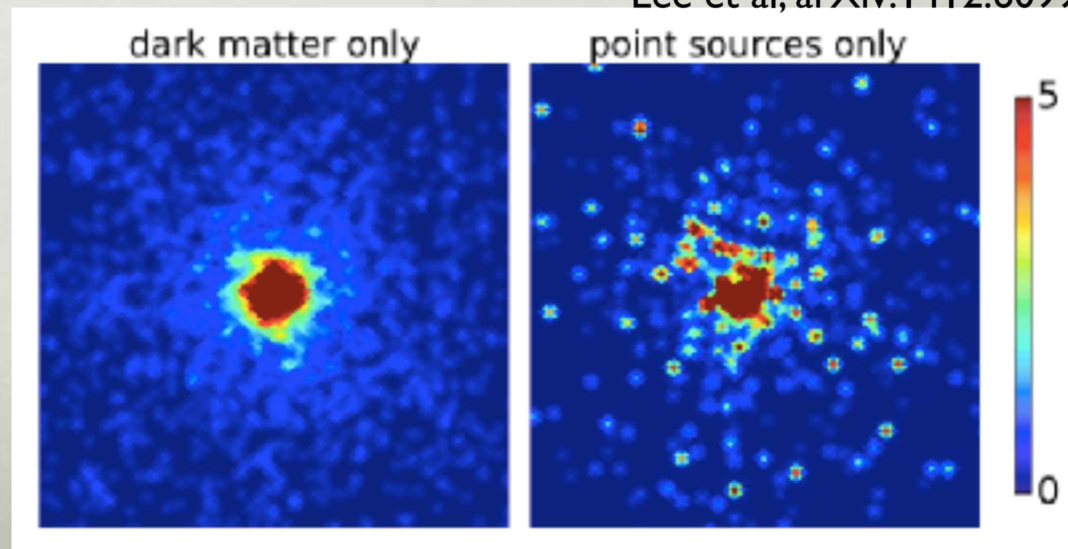
Other Interpretations

- **In addition to DM, unresolved pulsar interpretation is found plausibl**
  - Claimed excess is found consistent with O(1000) millisecond pulsars within ~1 kpc of GC (Abazajian et al arXiv:1402.4090), but see also Hooper et al arXiv:1606.09250
  - Very young pulsars might also contribute to the excess (O'Leary et al arXiv:1504.02477)
  - Spherical symmetry? Cuspy distribution? Extend out to 10°? Possibly (e.g. Abazajian et al arXiv:1402.4090, Brandt et al arXiv:1507.05616)
  - Also tested with non-poissonian photon statistics template analysis and wavelet decomposition (Lee et al arXiv:1412.6099, 1506.05124; Bartels et al arXiv:1506.05104)

Abazajian et al, arXiv:1402.4090



Lee et al, arXiv:1412.6099



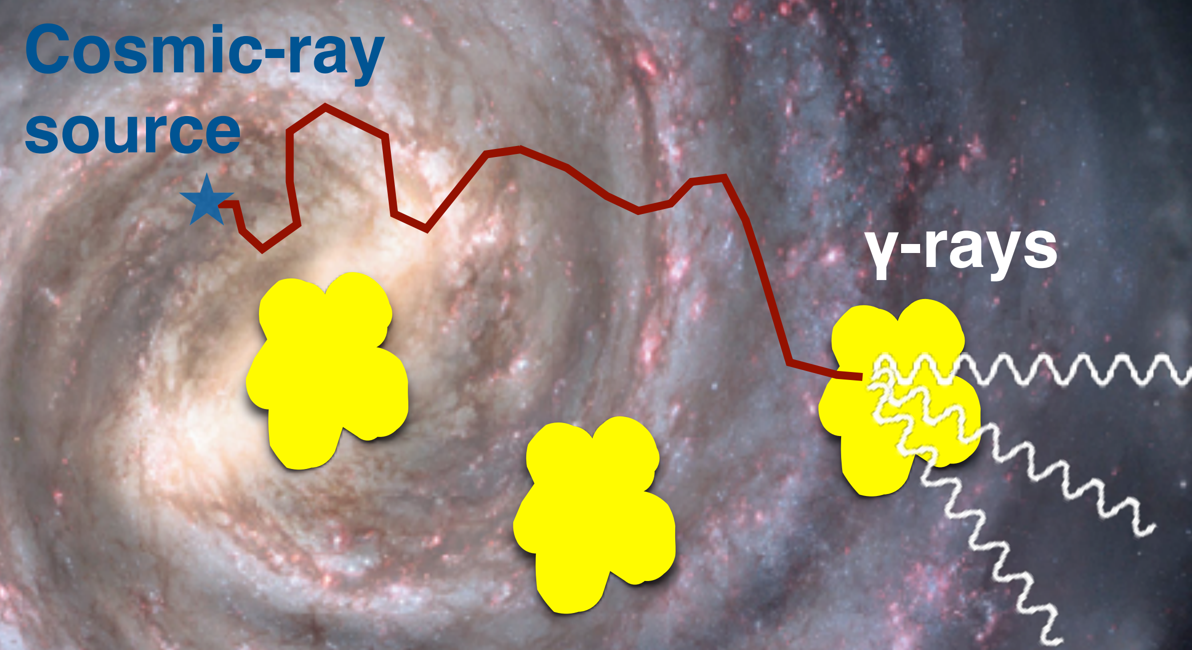
Other Interpretations

- **In addition to DM, unresolved pulsar interpretation is found plausibl**
  - Claimed excess is found consistent with O(1000) millisecond pulsars within ~1 kpc of GC (Abazajian et al arXiv:1402.4090), but see also Hooper et al arXiv:1606.09250
  - Very young pulsars might also contribute to the excess (O'Leary et al arXiv:1504.02477)
  - Spherical symmetry? Cuspy distribution? Extend out to 10^o? Possibly (e.g. Abazajian et al arXiv:1402.4090, Brandt et al arXiv:1507.05616)
  - Also tested with non-poissonian photon statistics template analysis and wavelet decomposition (Lee et al arXiv:1412.6099, 1506.05124; Bartels et al arXiv:1506.05104)

- **CR proton or electron outbursts interpretations have also been proposed** (e.g. Carlson et al arXiv:1405.7685, Petrovic et al 1405.7928, Cholis et al arX 1506.05119)

- **Additional CR sources near the GC** (e.g. Fermi LAT collaboration 2015, Gaggero et al 2015, Carlson et al 2016, Porter et al 2017)

Modeling the Interstellar Emission

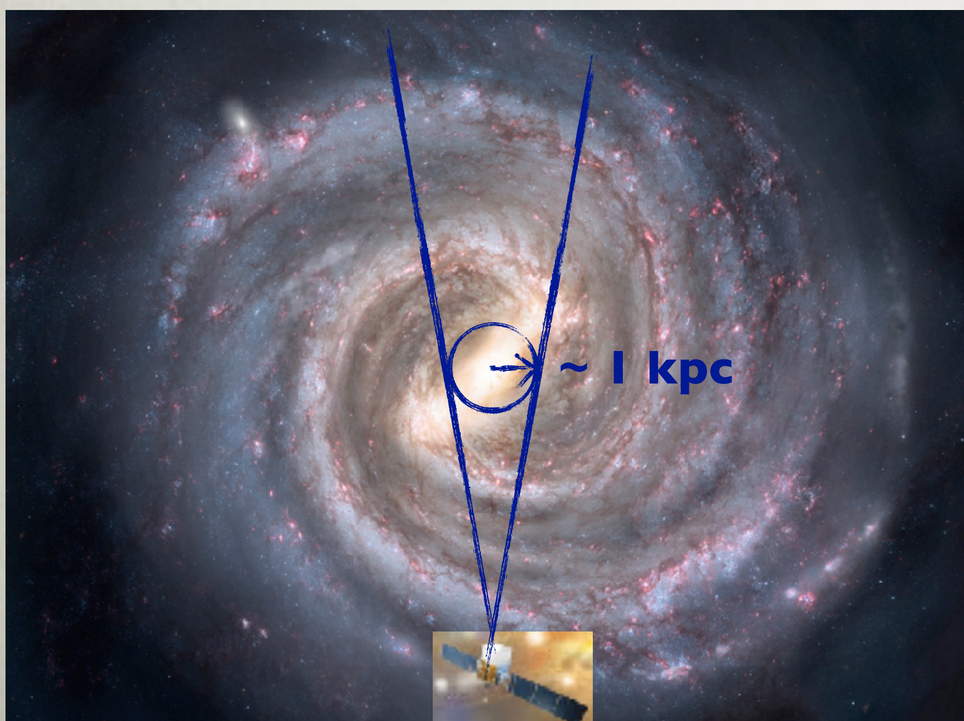


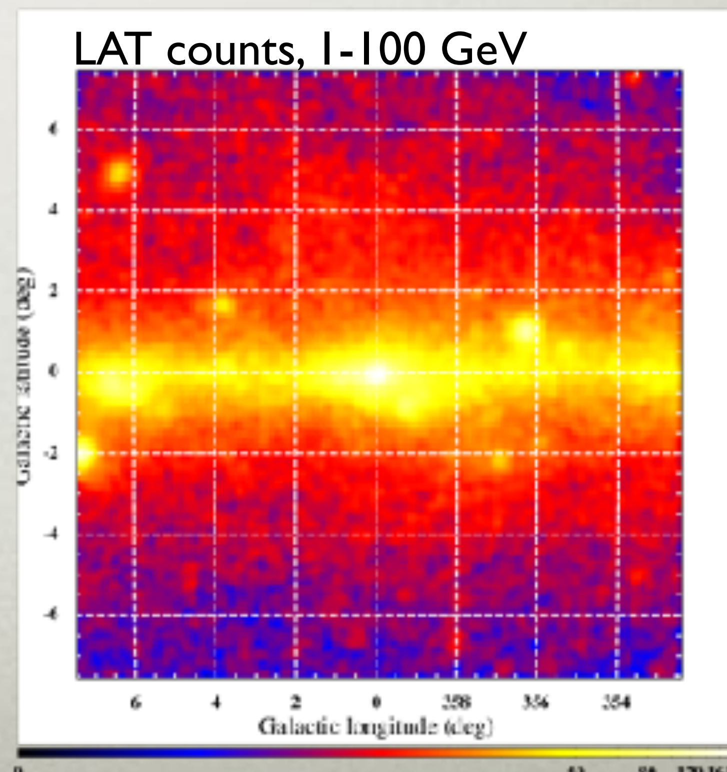
Interaction of cosmic rays and interstellar gas & radiation field = gamma-ray interstellar emission

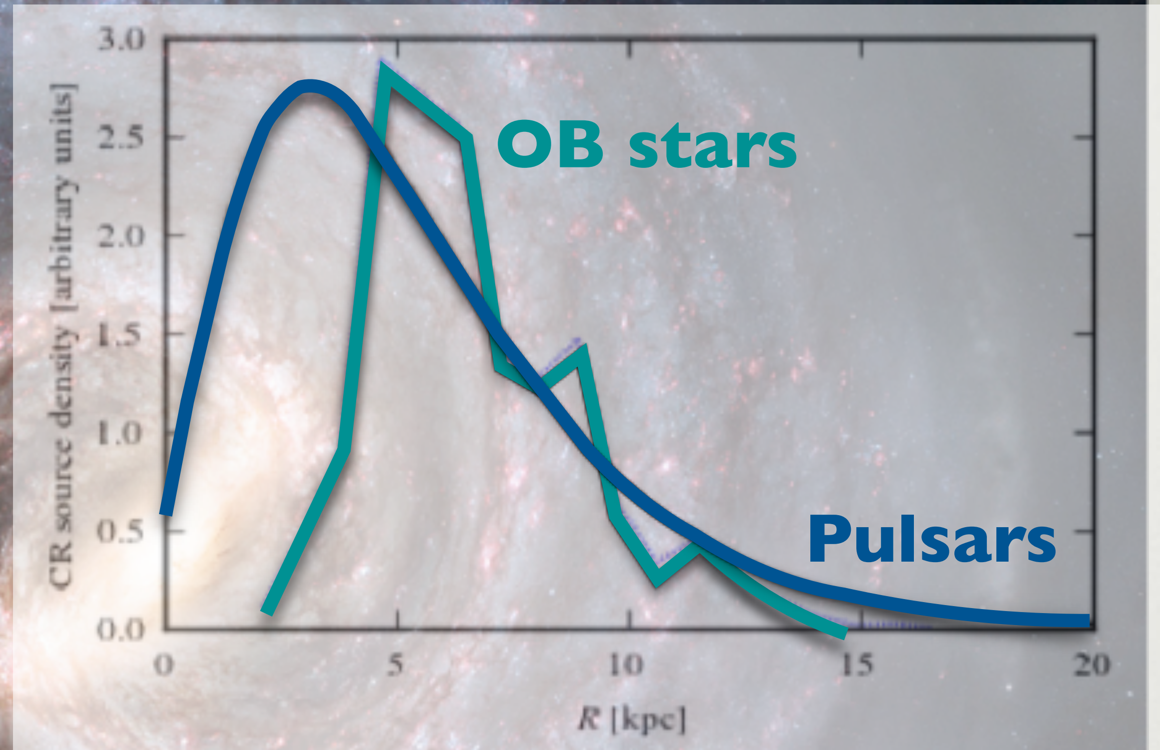
NB: Details of cosmic-ray propagation are uncertain!

Modeling the Interstellar Emission

- Approach by Fermi LAT collab. (Ajello et al 2016) is to develop a set of specialized models for the inner 15°x15° to <u>extract the emission from the innermost ~1 kpc</u>
- Determine point sources self-consistently with modeling of the interstellar emission







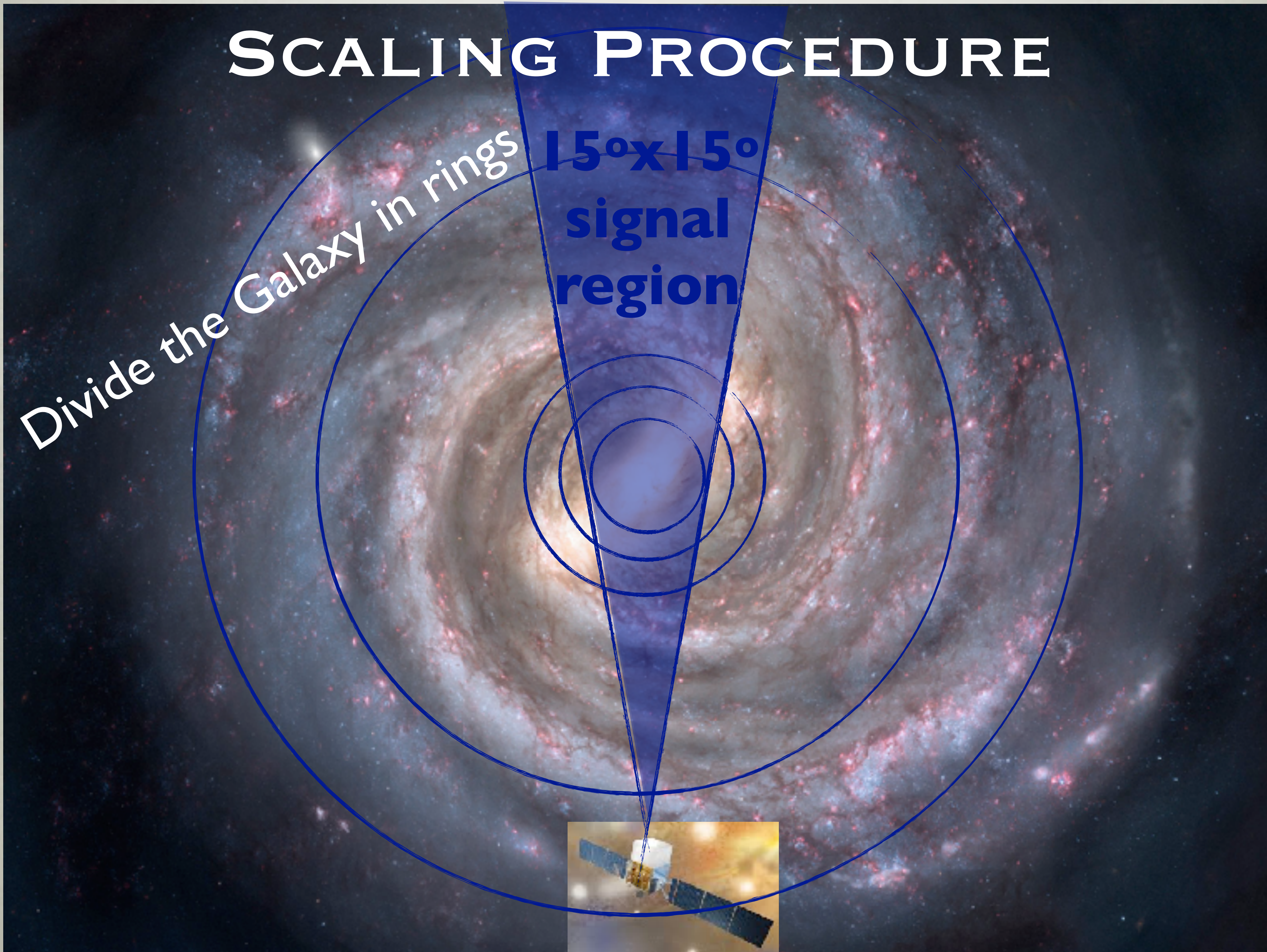
Cosmic-ray source density

- **Start with physically motivated models (GALPROP) as baseline:** select two possibilities for the CR source distribution (a major uncertainty; Pulsars, OB stars used as proxies)

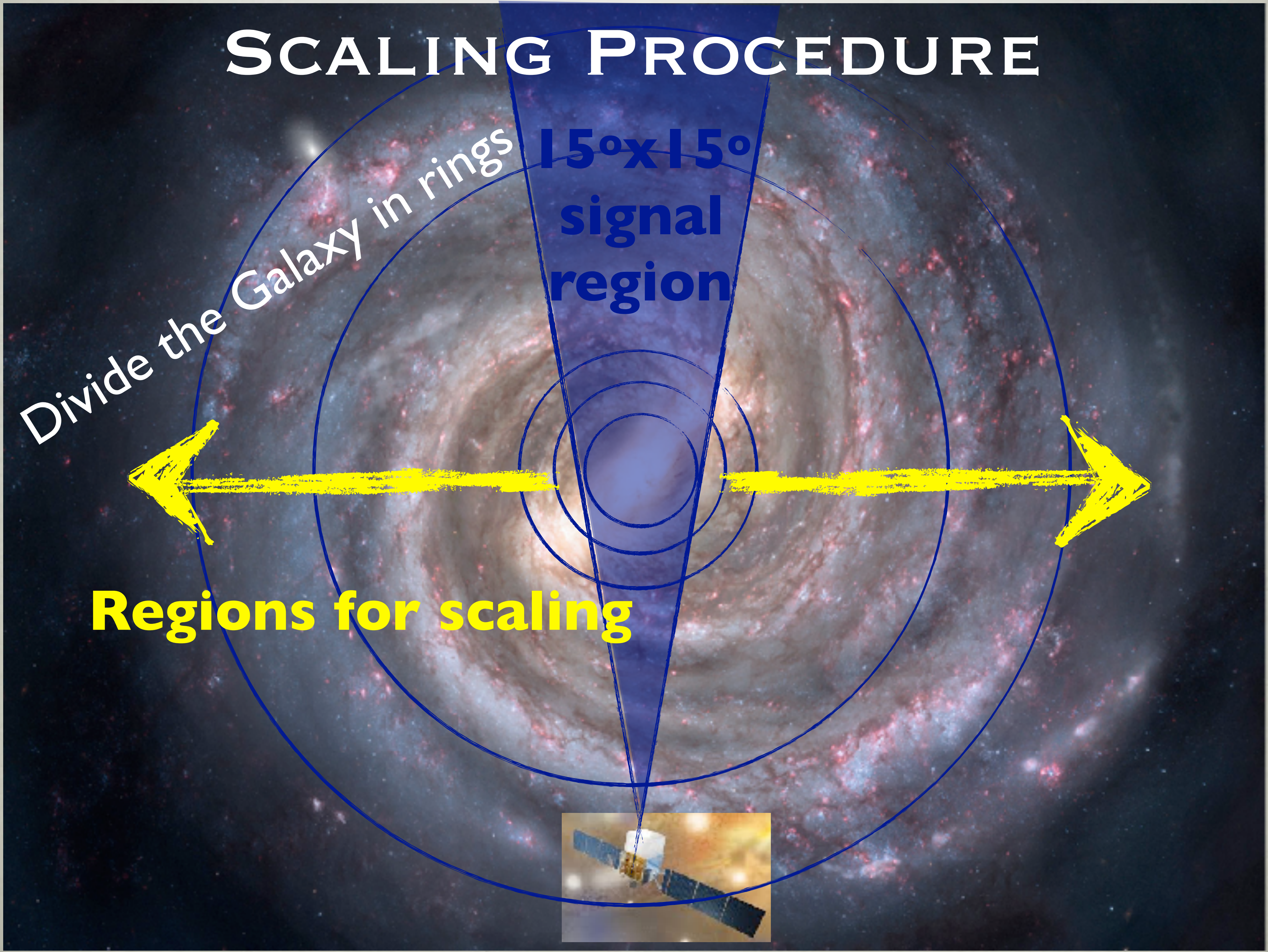
➡ Tune the γ-ray intensities (in rings) predicted by baseline models to the gamma-ray data outside of the 15°x15° region to **address some of the shortcomings of the baseline models for improved fore/background determination**

Scaling Procedure

Scaling Procedure

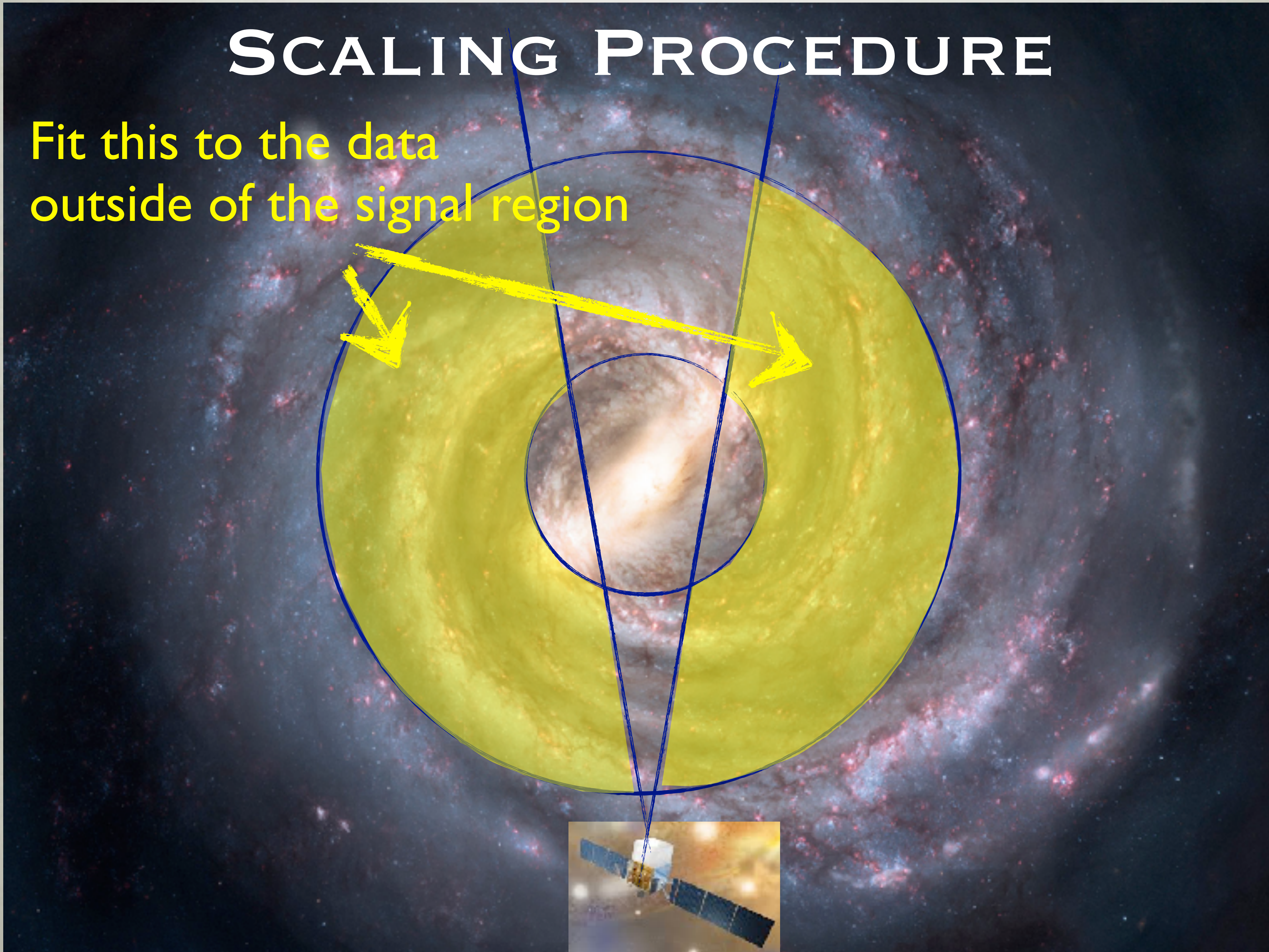


Scaling Procedure

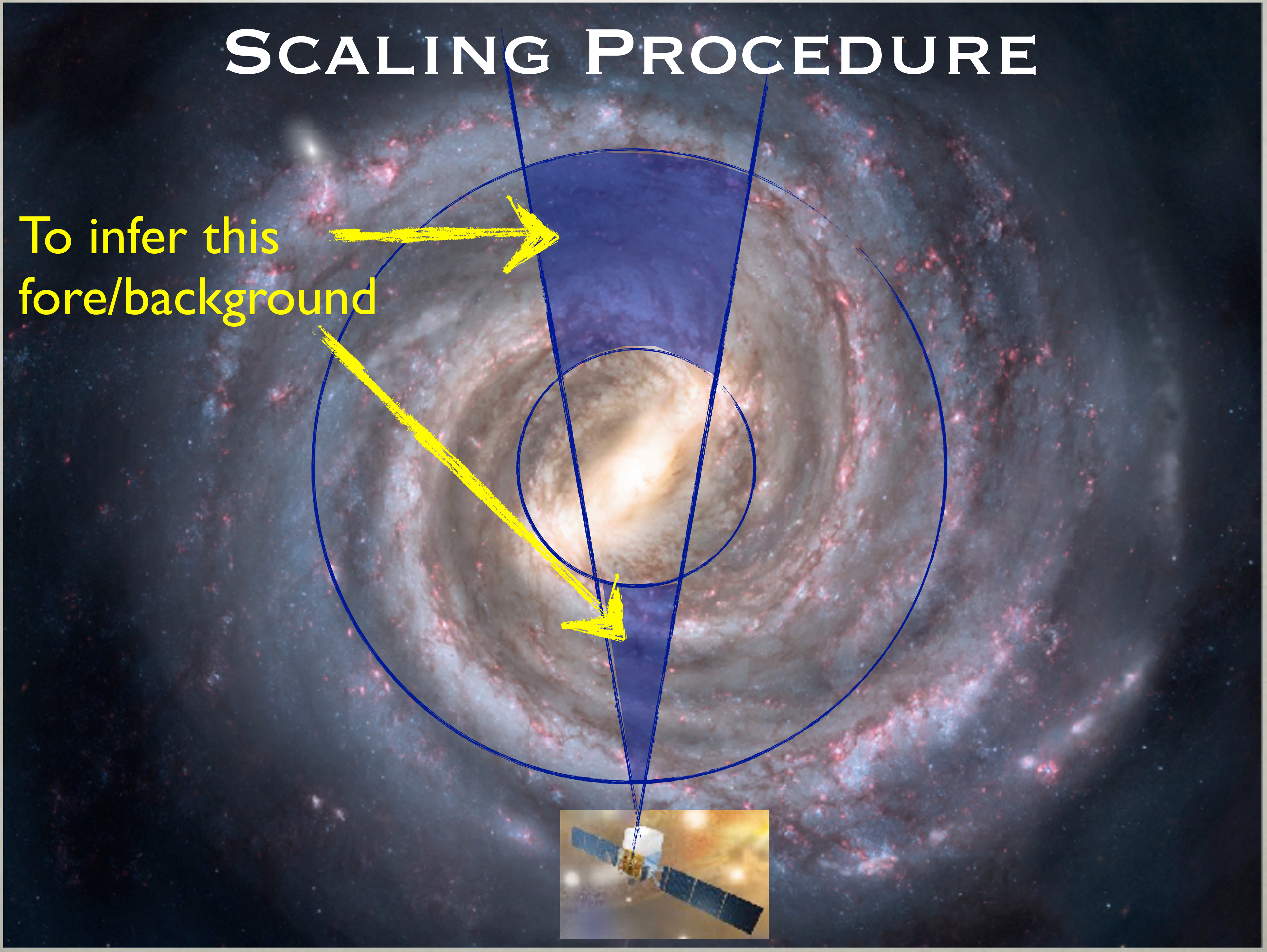


Scaling Procedure

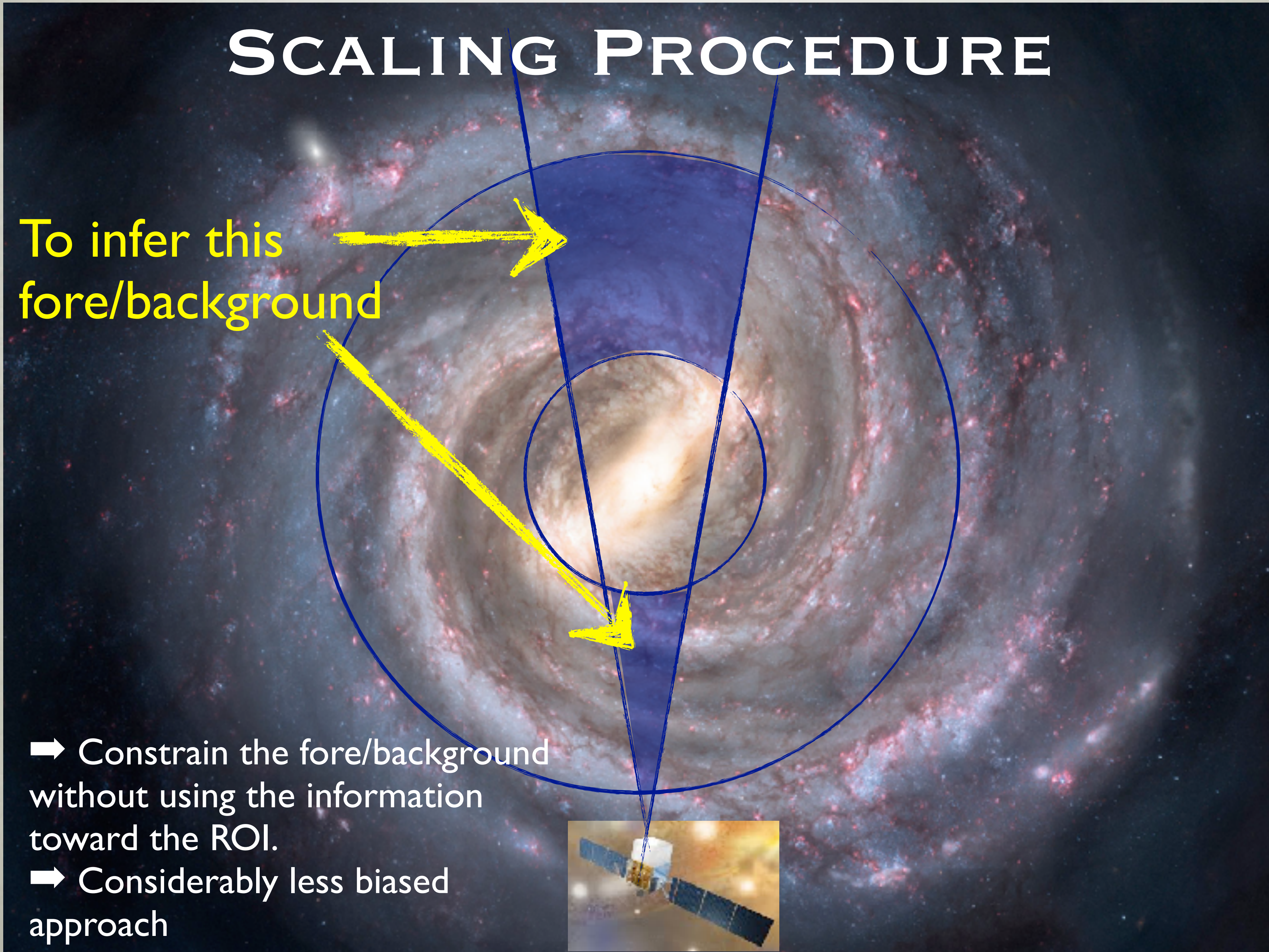
Fit this to the data
outside of the signal region



Scaling Procedure



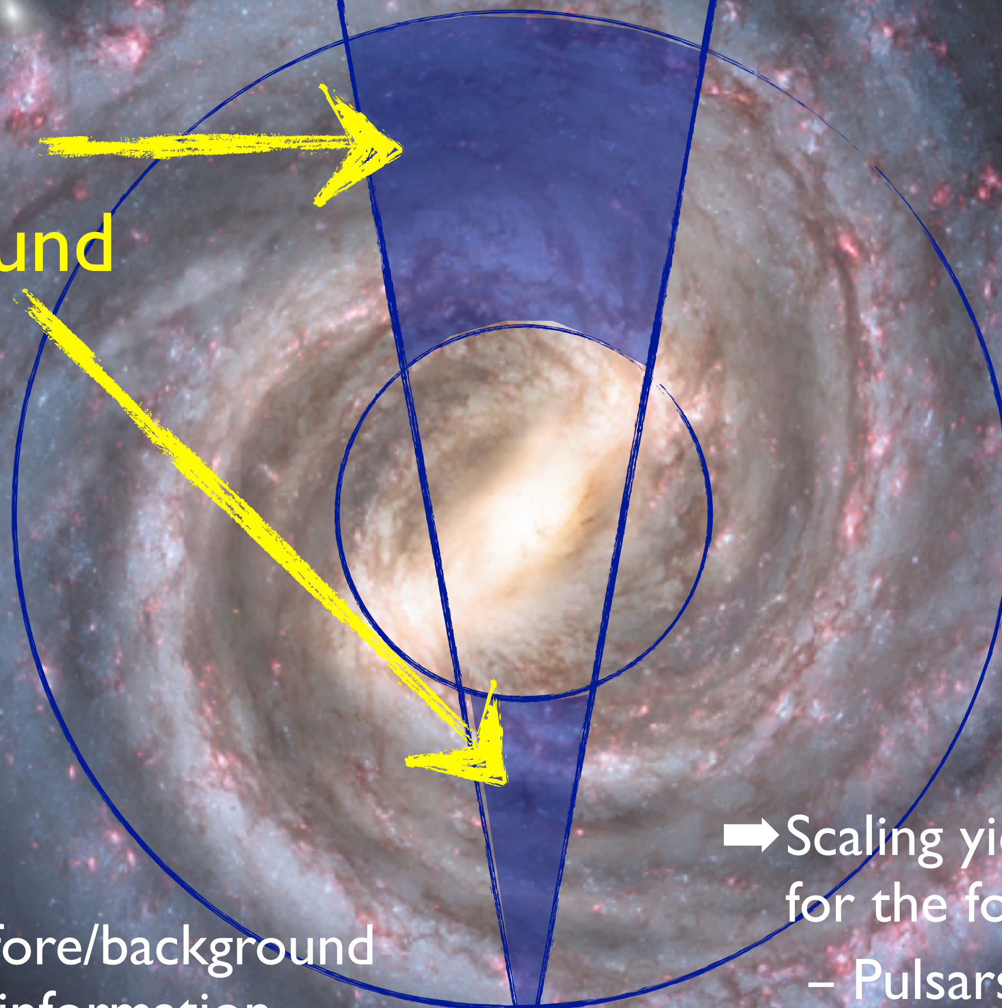
Scaling Procedure



➡ Constrain the fore/background without using the information toward the ROI.

➡ Considerably less biased approach

Scaling Procedure



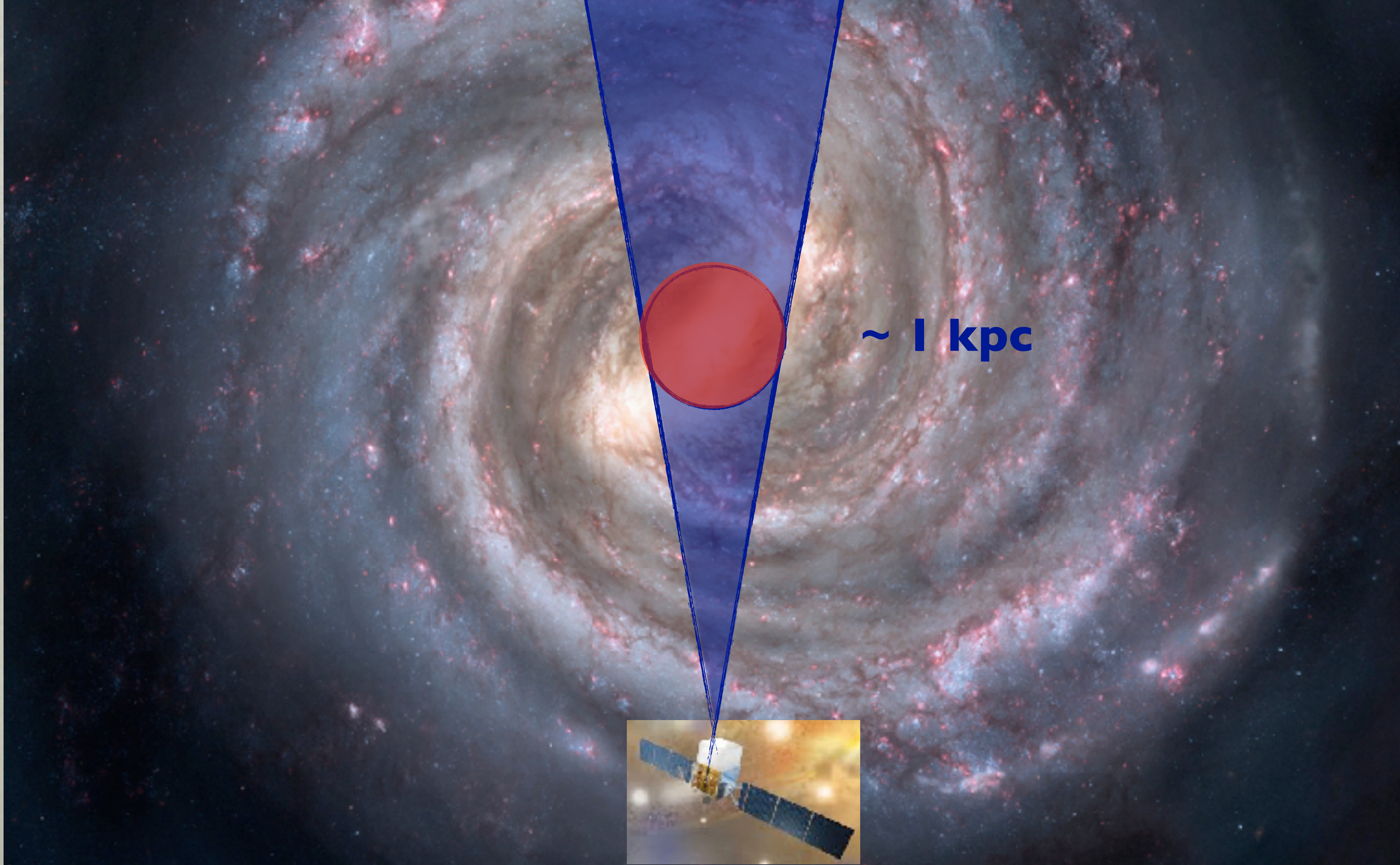
➡ Scaling yields four variants for the fore/background IEM:

– Pulsars, intensity scaled
– Pulsars, index scaled
– OB Stars, intensity scaled
– OB Stars, index scaled

➡ Constrain the fore/background without using the information toward the ROI.

➡ Considerably less biased approach

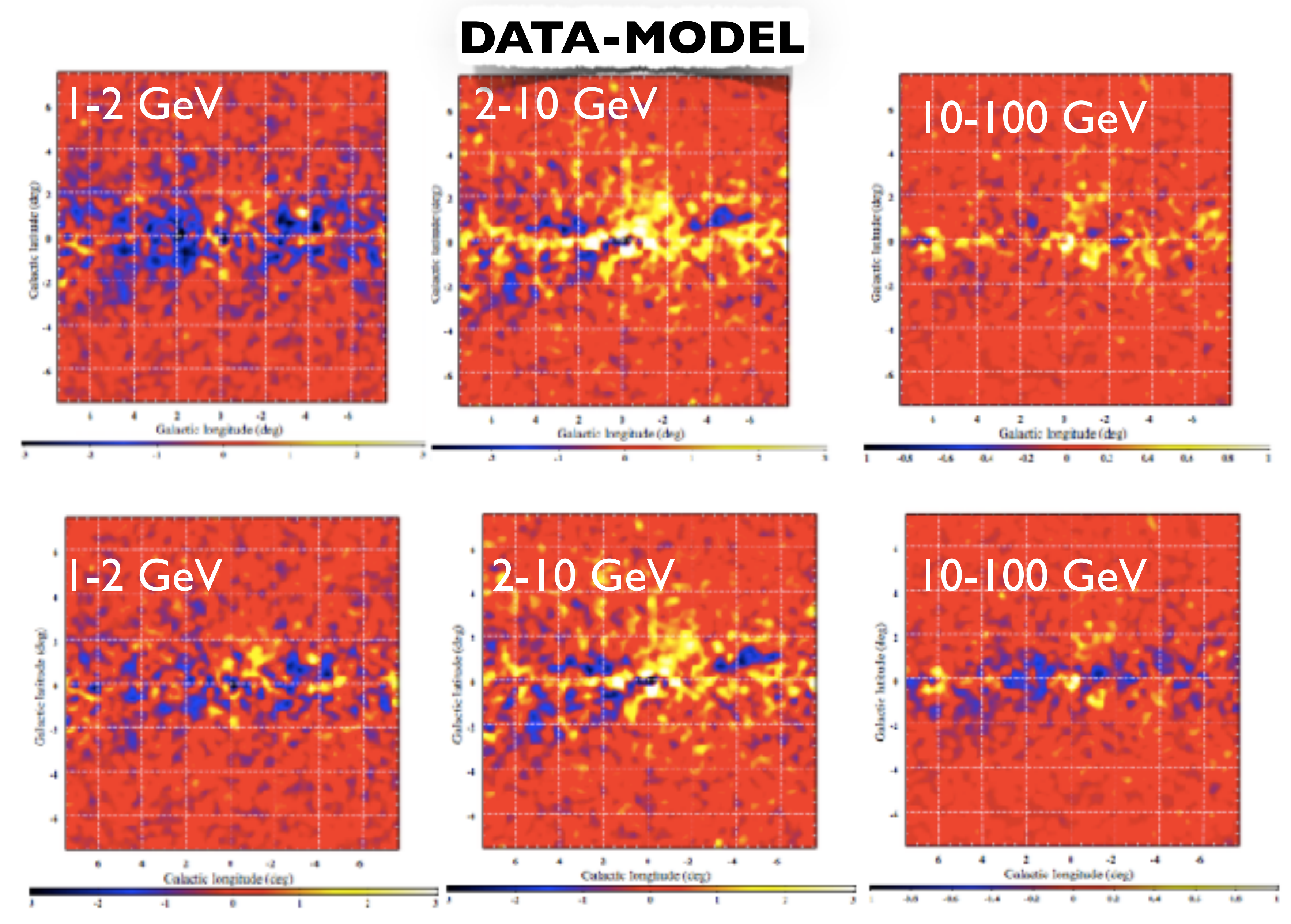
➡ Determine intensities for the **inner ~1 kpc for HI/H_2 π^0, and IC** by fitting the data in the 15°x15° region for each of the four **fore/background models** (held constant in the fit)



Residual Maps

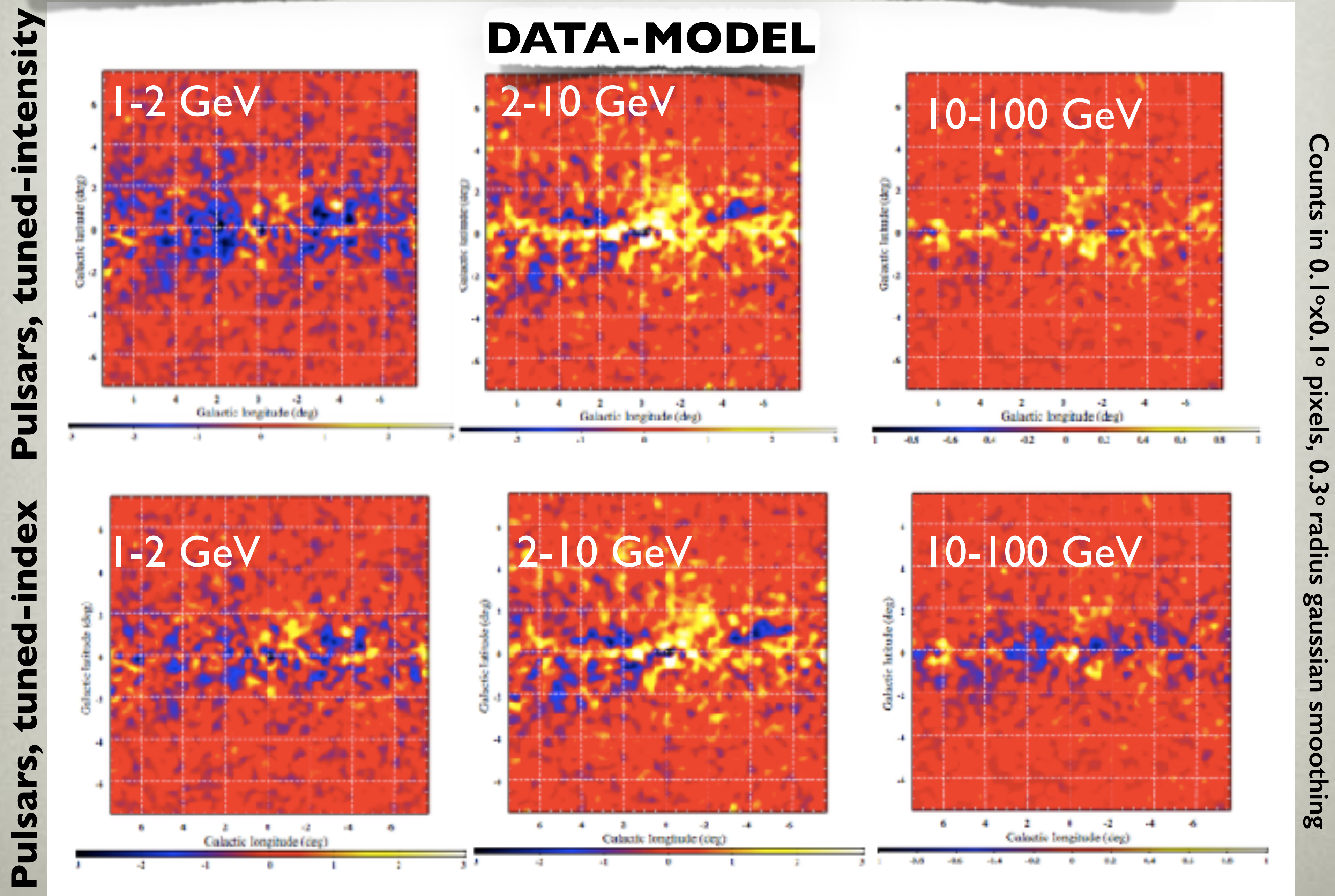
Pulsars, tuned-intensity

Pulsars, tuned-index

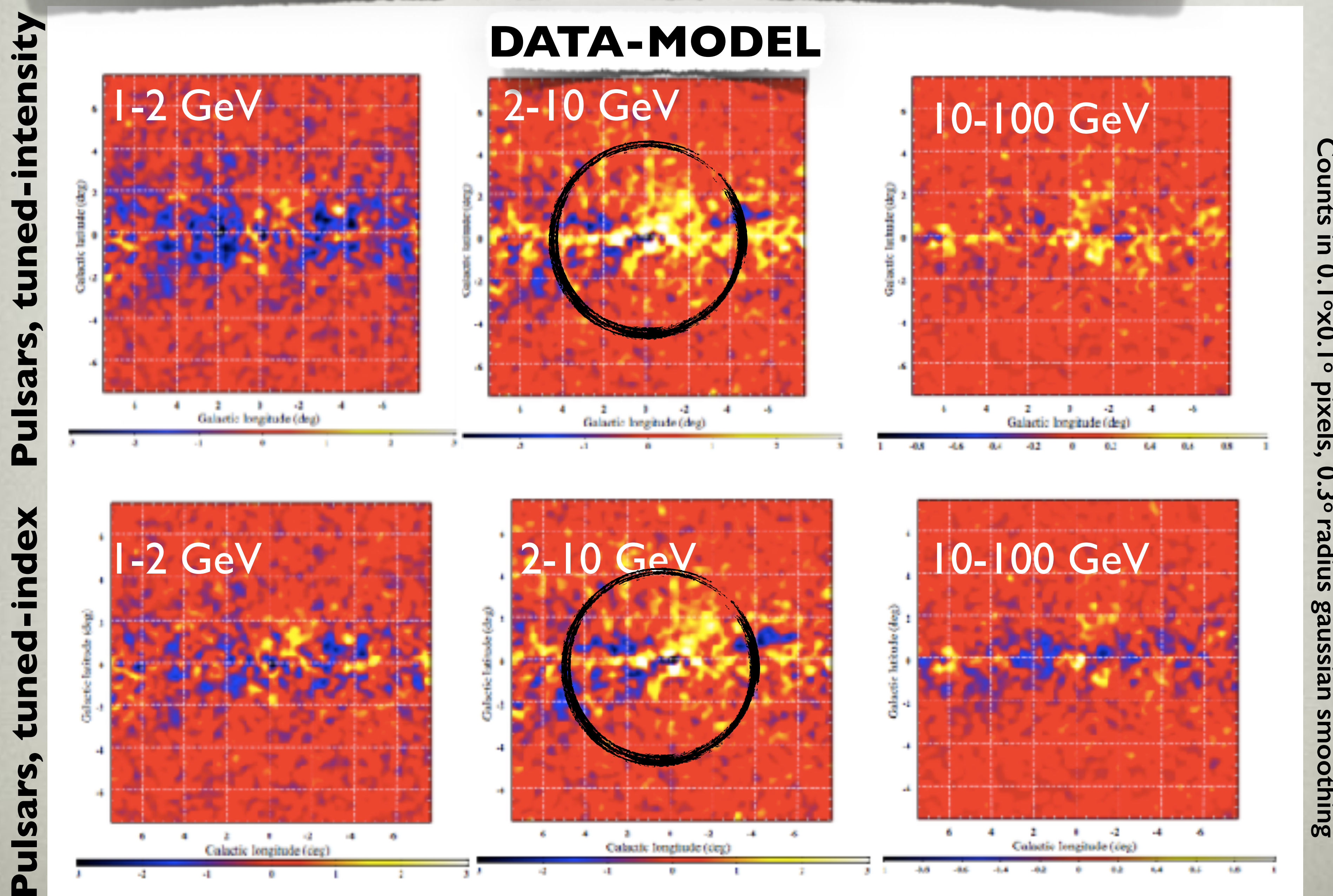


Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

Structured excesses and deficits point to imperfectly modeled components and/or un-modeled contributions



Structured excesses and deficits point to imperfectly modeled components and/or un-modeled contributions

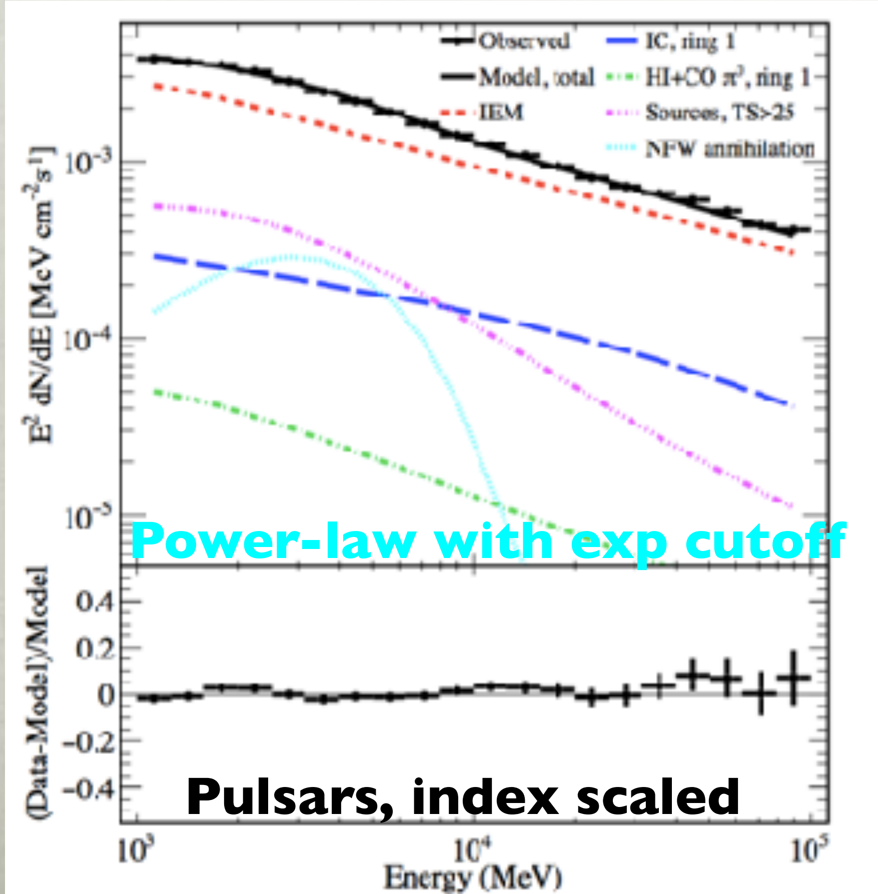


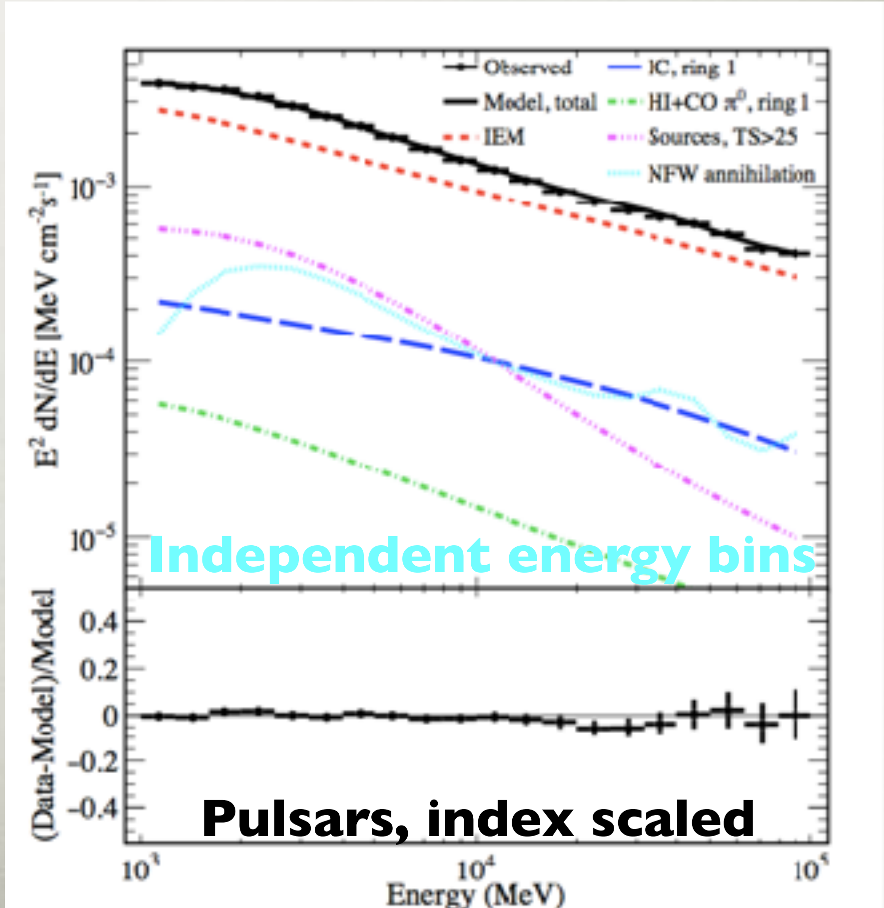
Additional Component

- Spatial morphology: 2D gaussians, dark matter annihilation/decay, or a gas-like as proxy for unresolved source. Spectrum: **exponentially cutoff power law** (motivated by some dark matter and pulsar models); fit in **independent energy bins**

➡ The dark matter annihilation morphology yields the most significant improvements in the data-model agreement for the 4 fore/background IEMs

Integrated flux in 15°x15° ROI



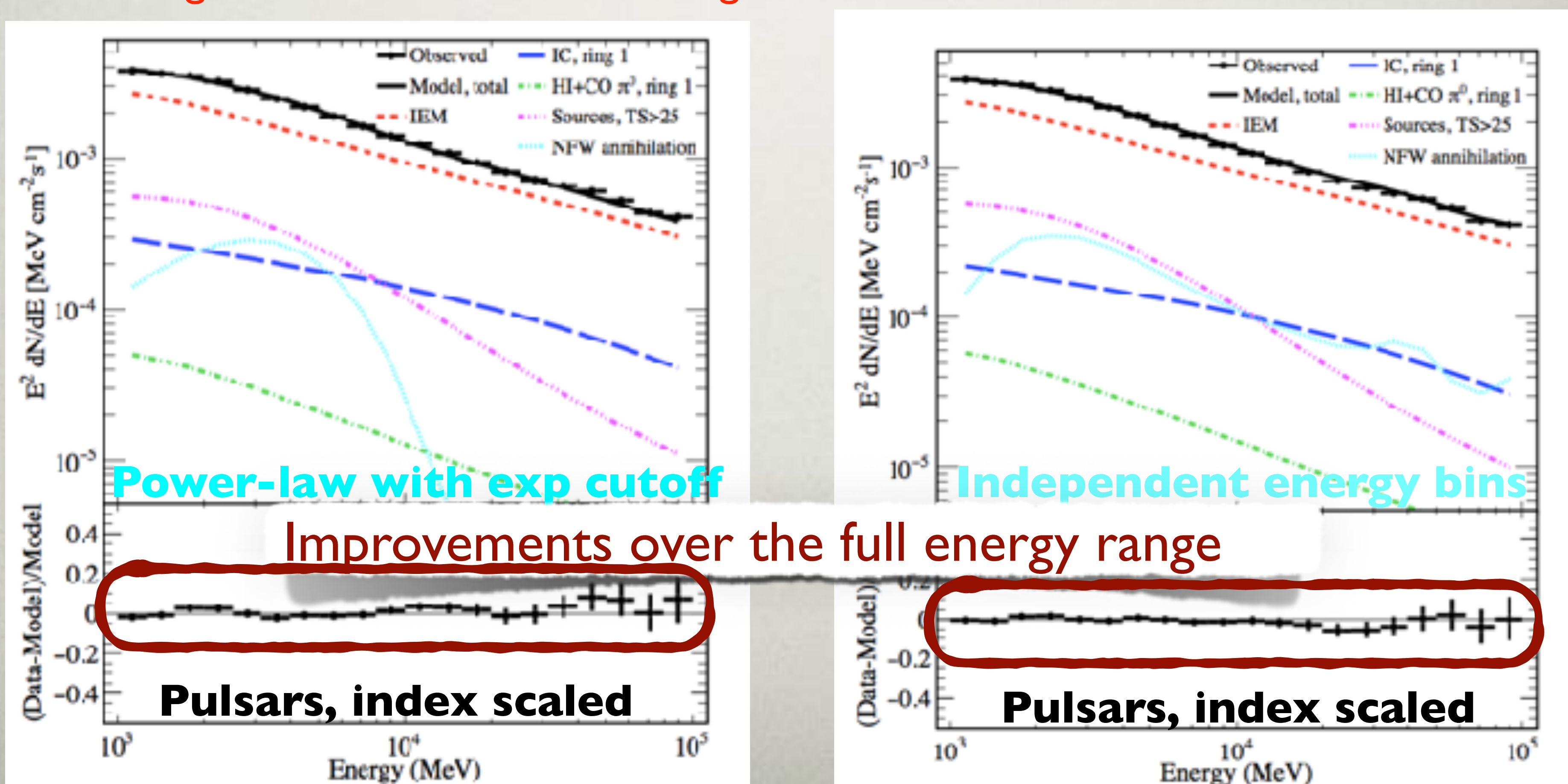


Additional Component

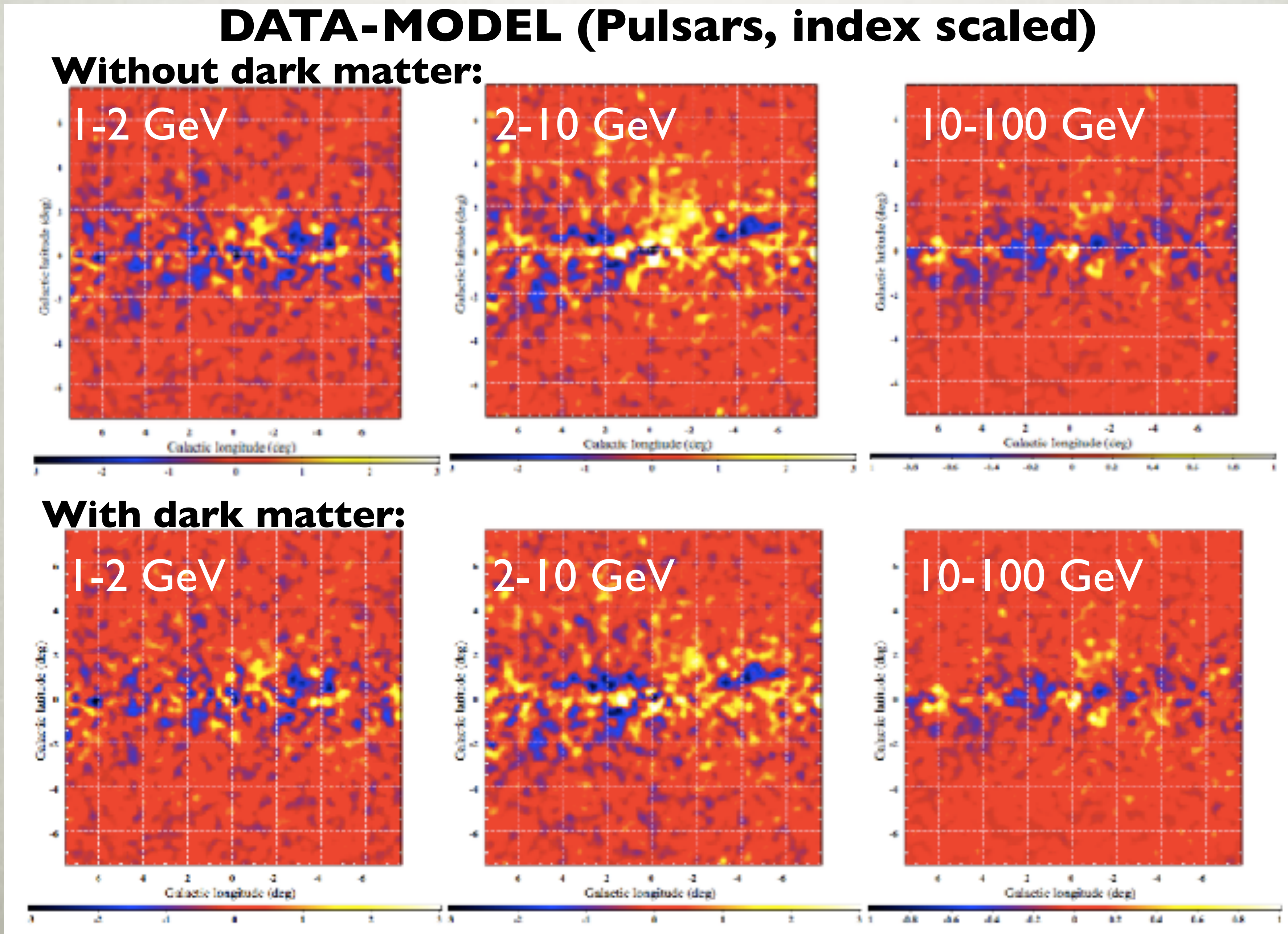
- Spatial morphology: 2D gaussians, dark matter annihilation/decay, or a gas-like as proxy for unresolved source. Spectrum: **exponentially cutoff power law** (motivated by some dark matter and pulsar models); fit in **independent energy bins**

➡ The dark matter annihilation morphology yields the most significant improvements in the data-model agreement for the 4 fore/background IEMs

Integrated flux in 15°x15° ROI



Residual Maps
Dark Matter

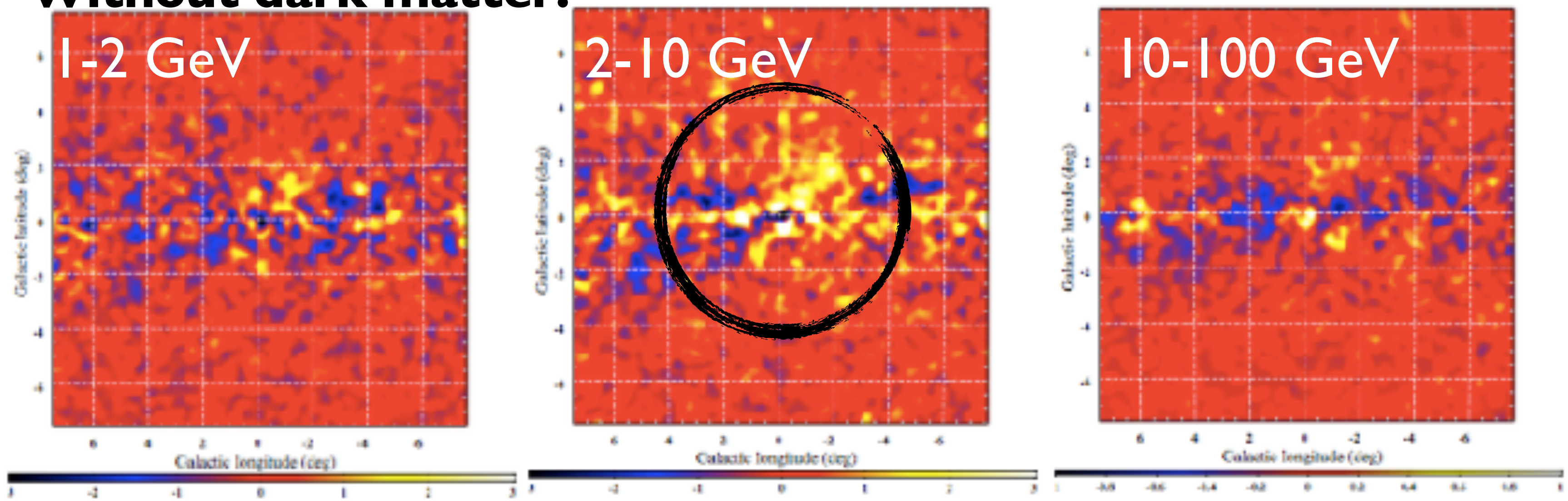


Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

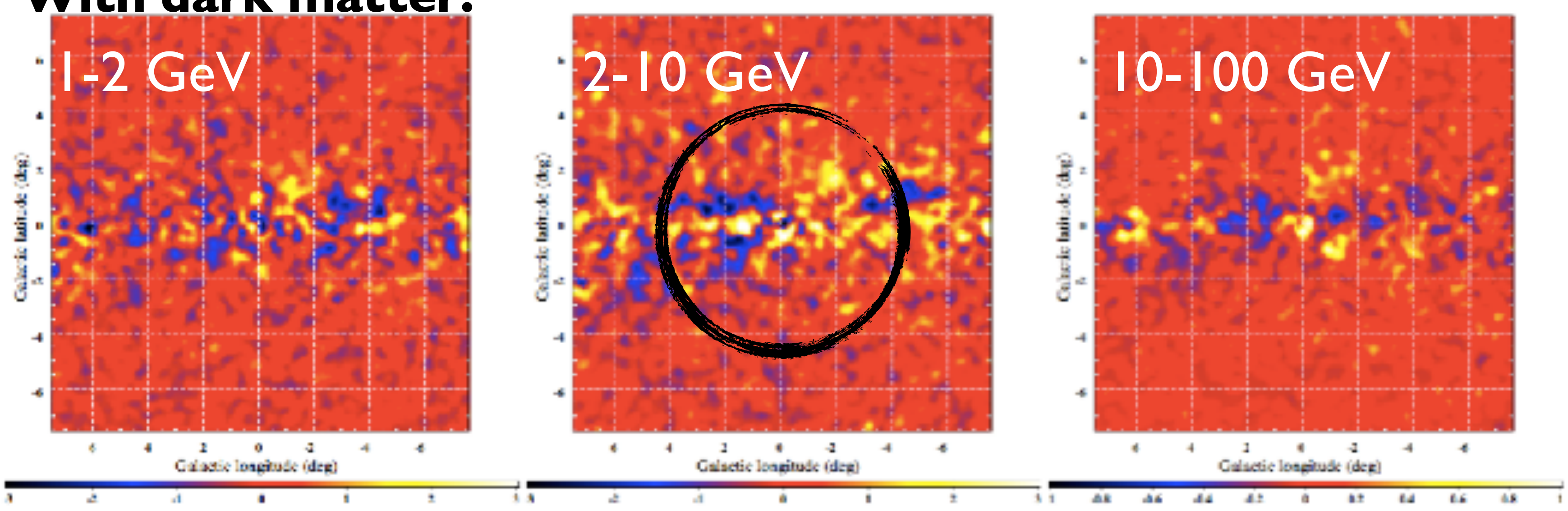
Residual Maps
Dark Matter

DATA-MODEL (Pulsars, index scaled)

Without dark matter:



With dark matter:

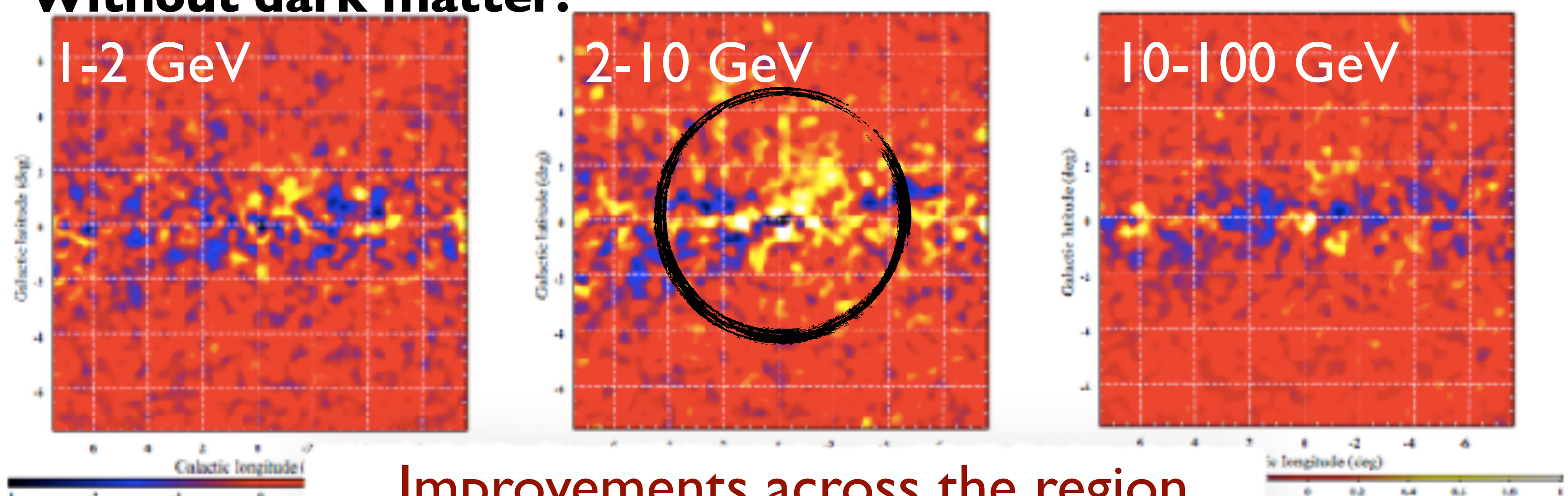


Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

Residual Maps
Dark Matter

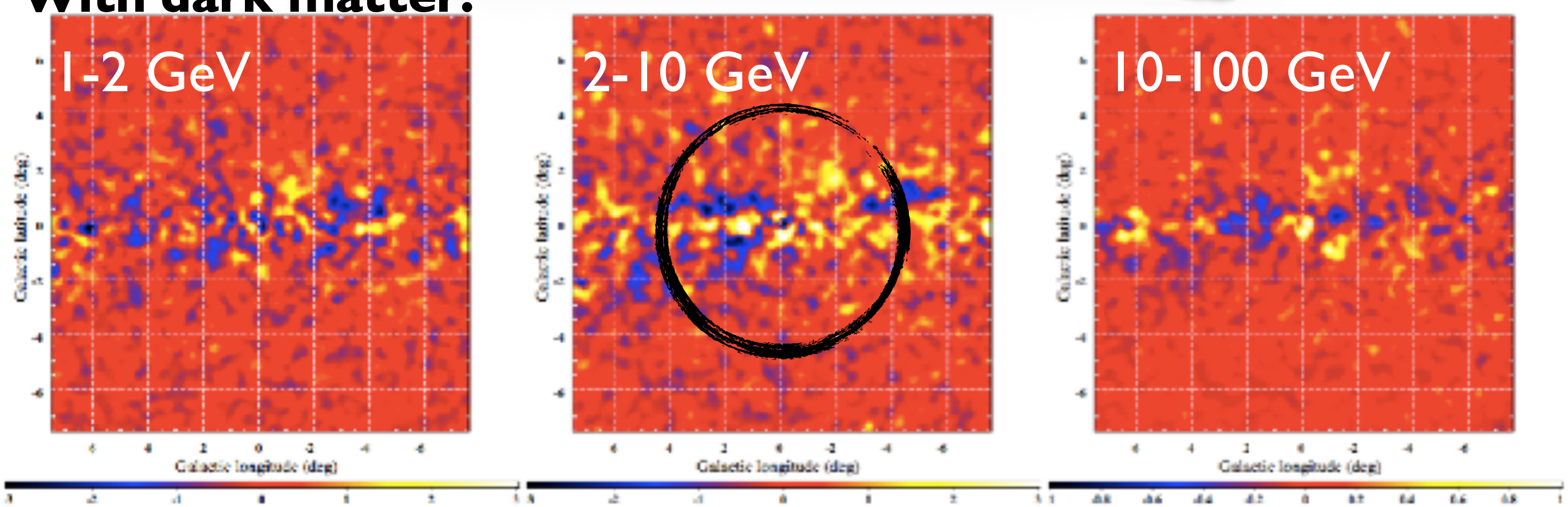
DATA-MODEL (Pulsars, index scaled)

Without dark matter:



Improvements across the region

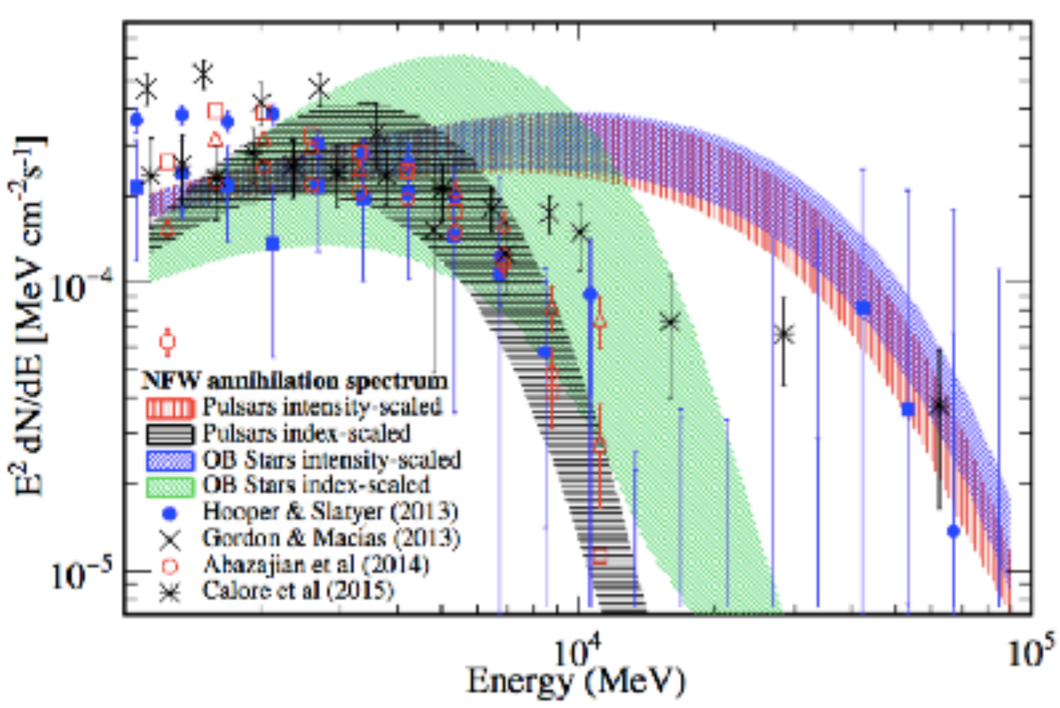
With dark matter:

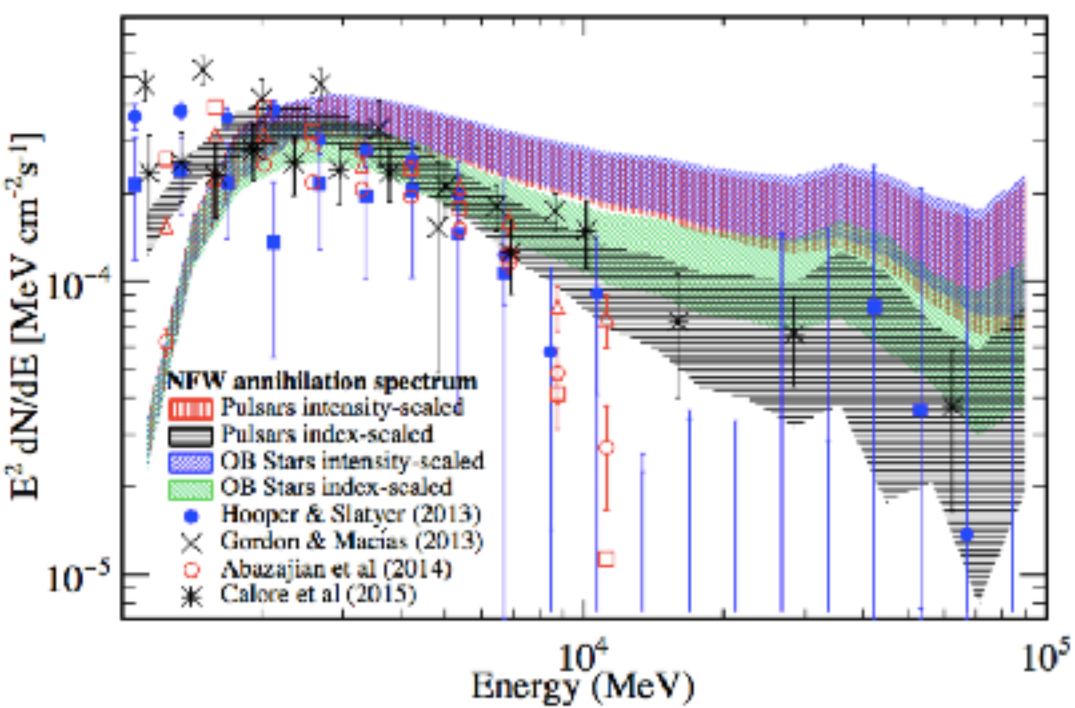


Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

Dark Matter Component Spectrum

- The dark matter component spectrum depends strongly on the fore/background models.

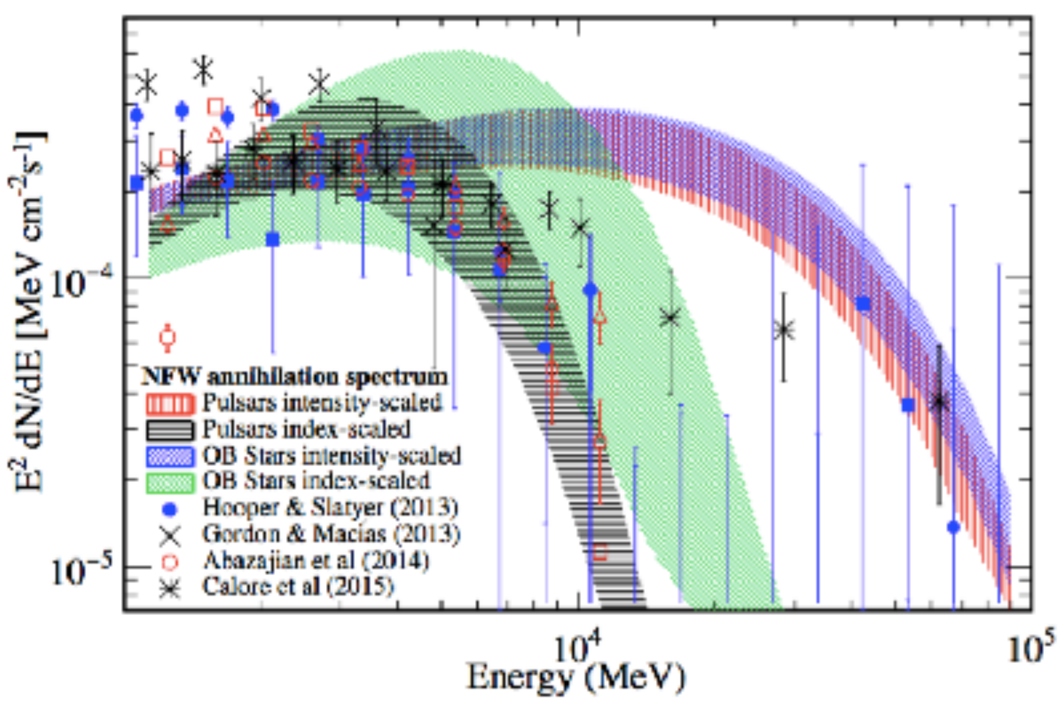


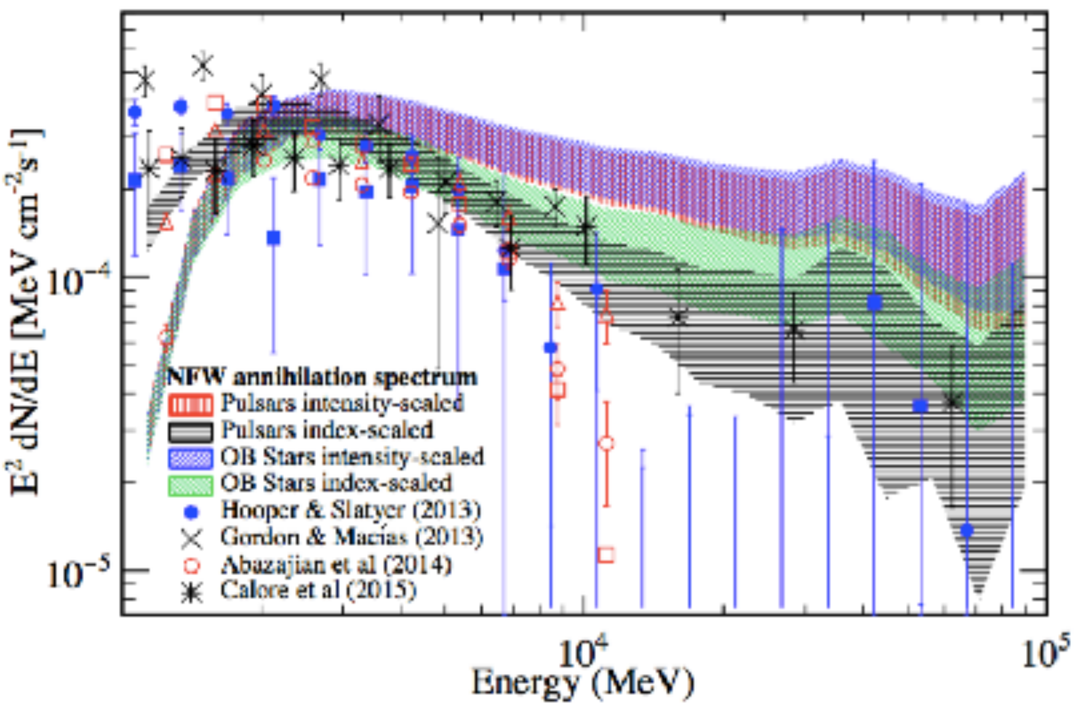


Dark Matter Component Spectrum

- The dark matter component spectrum depends strongly on the fore/background models.

➡ A broad range of interpretations is allowed





Implications for Dark Matter Models

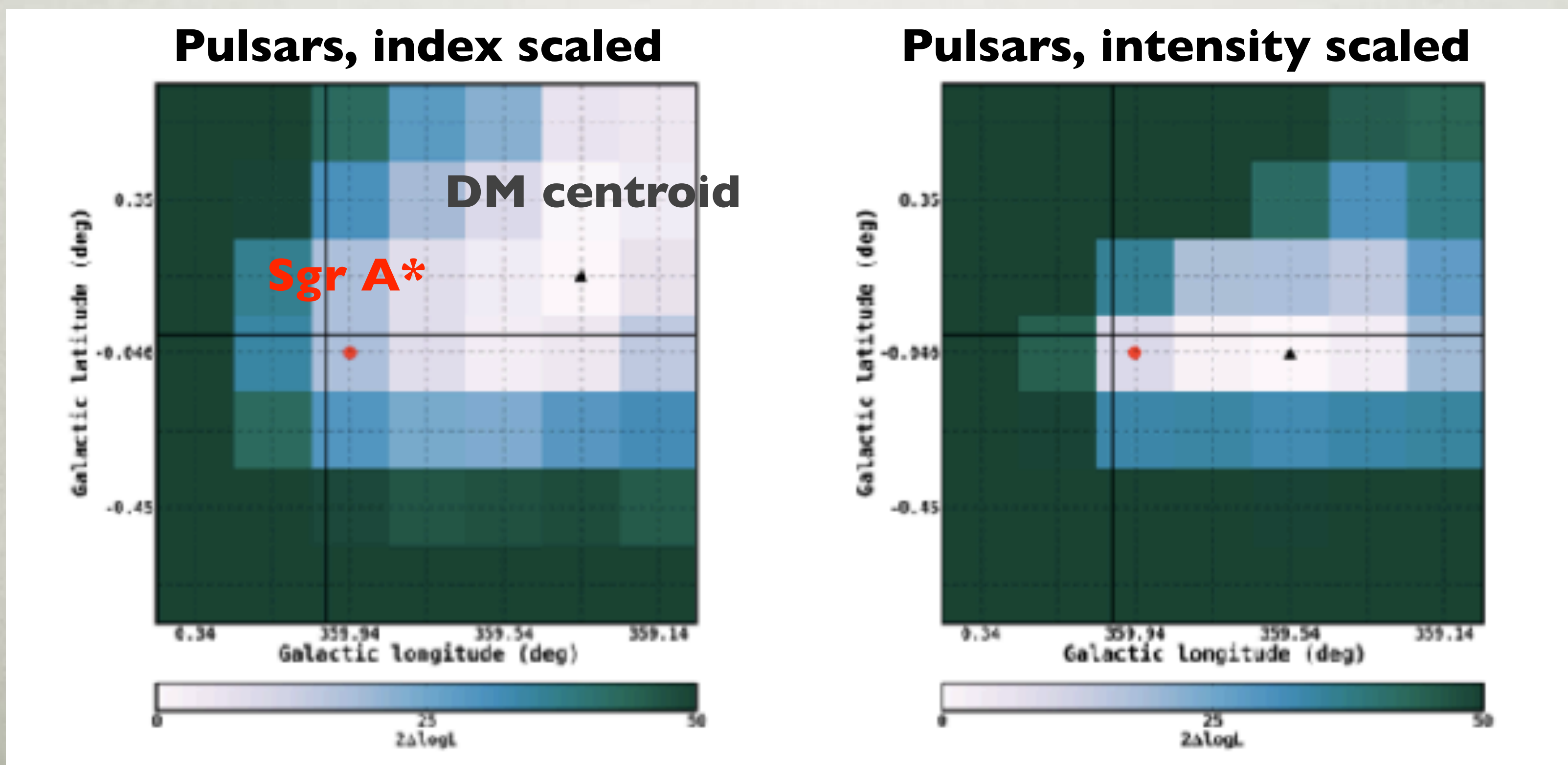
- Consider general models with DM particles annihilating into two-body (fermionic) final states where the interactions between the dark sector and standard model particles occurs via *scalar* or *vector* interactions
  - Scalar interaction proportional to the fermion mass
  - Vector interaction independent of fermion mass

  See also Alves et al arXiv:1403.5027, Liem et al arXiv:1603.05994

- Here, we fit the relative strengths of couplings to quarks and leptons to the Fermi LAT data with the IEMs+point sources developed by the Fermi LAT collaboration (Ajello et al 2016)

Dark Matter Component Morphology

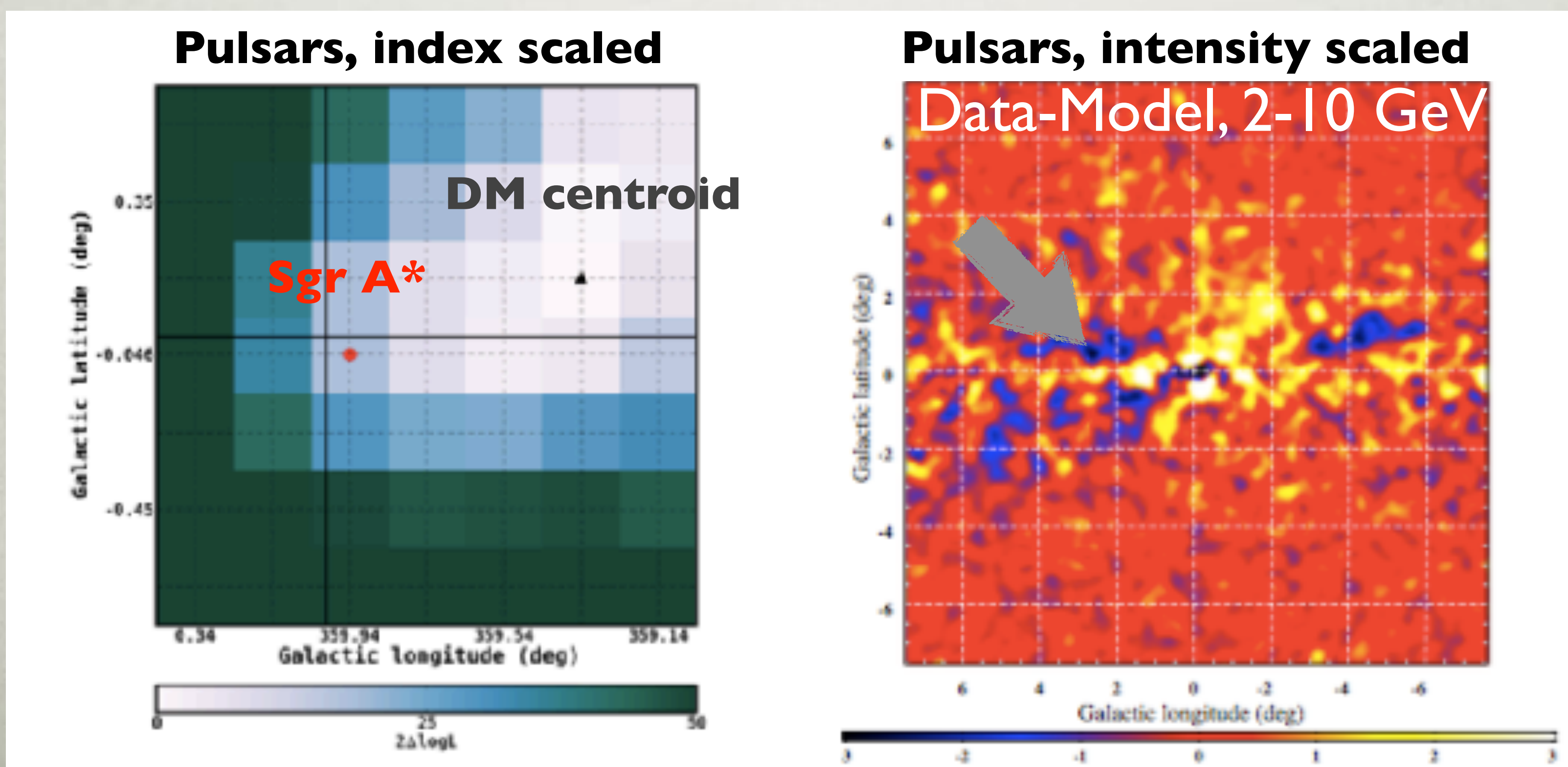
- Cuspiness of the DM profile (e.g. whether a standard, **γ=1**, or cuspier, **γ=1.2,** profile is favored) depends on IEM modeling
- Centroid is offset compared to Sgr A*, disfavored at ~90% C.L., but there is some dependence on IEM (offset ~0.5°-1°) and cannot rule out offset is due to shortcomings in modeling of IEM (see also Calore et al arXiv:1409.0042, Linden et al arXiv:1604.01026)



C. Karwin et al, arXiv:1612.05687

Dark Matter Component Morphology

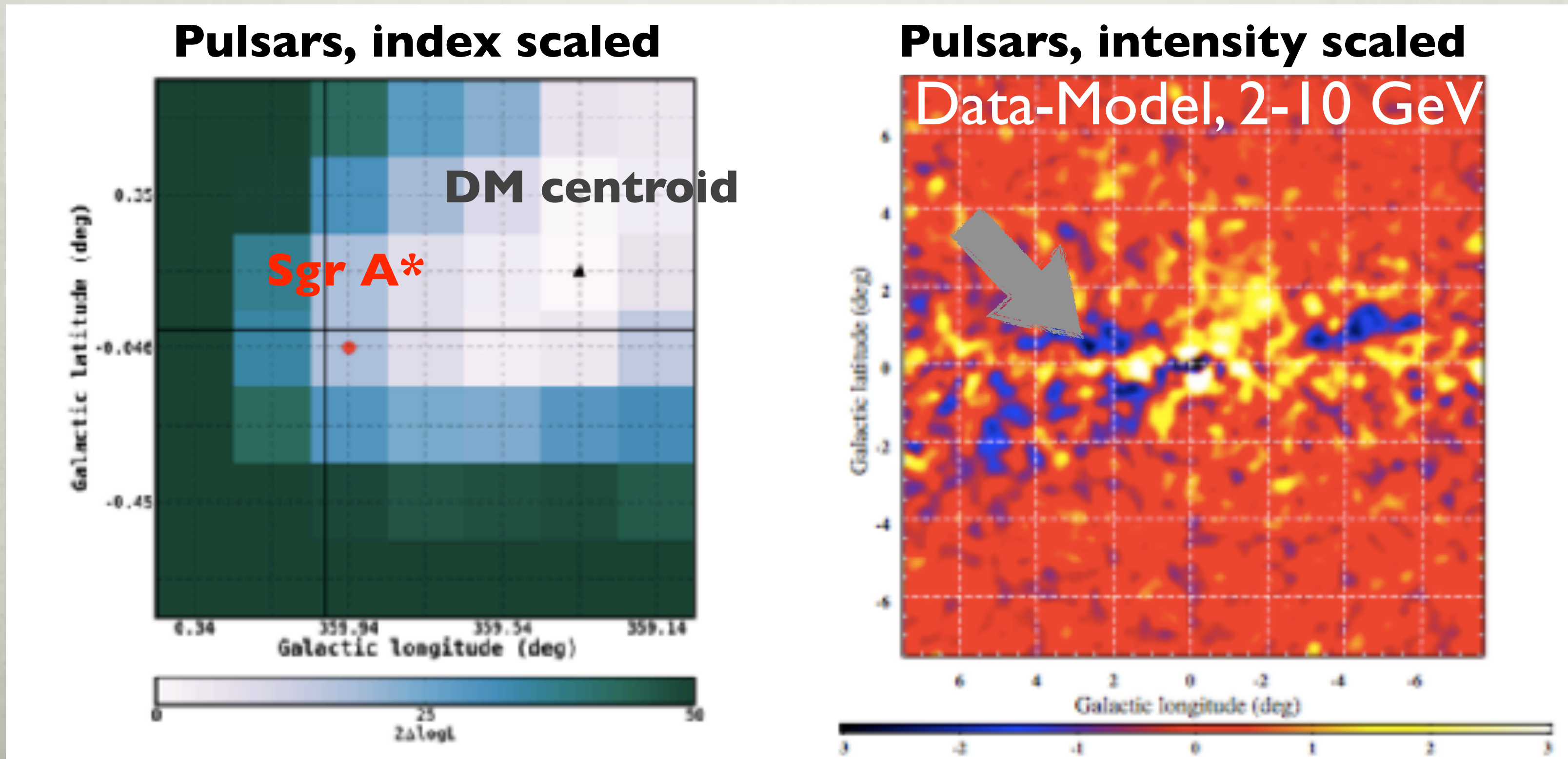
- Cuspiness of the DM profile (e.g. whether a standard, **γ=1**, or cuspier, **γ=1.2,** profile is favored) depends on IEM modeling
- Centroid is offset compared to Sgr A*, disfavored at ~90% C.L., but there is some dependence on IEM (offset ~0.5°-1°) and cannot rule out offset is due to shortcomings in modeling of IEM (see also Calore et al arXiv:1409.0042, Linden et al arXiv:1604.01026)



C. Karwin et al, arXiv:1612.05687

Dark Matter Component Morphology

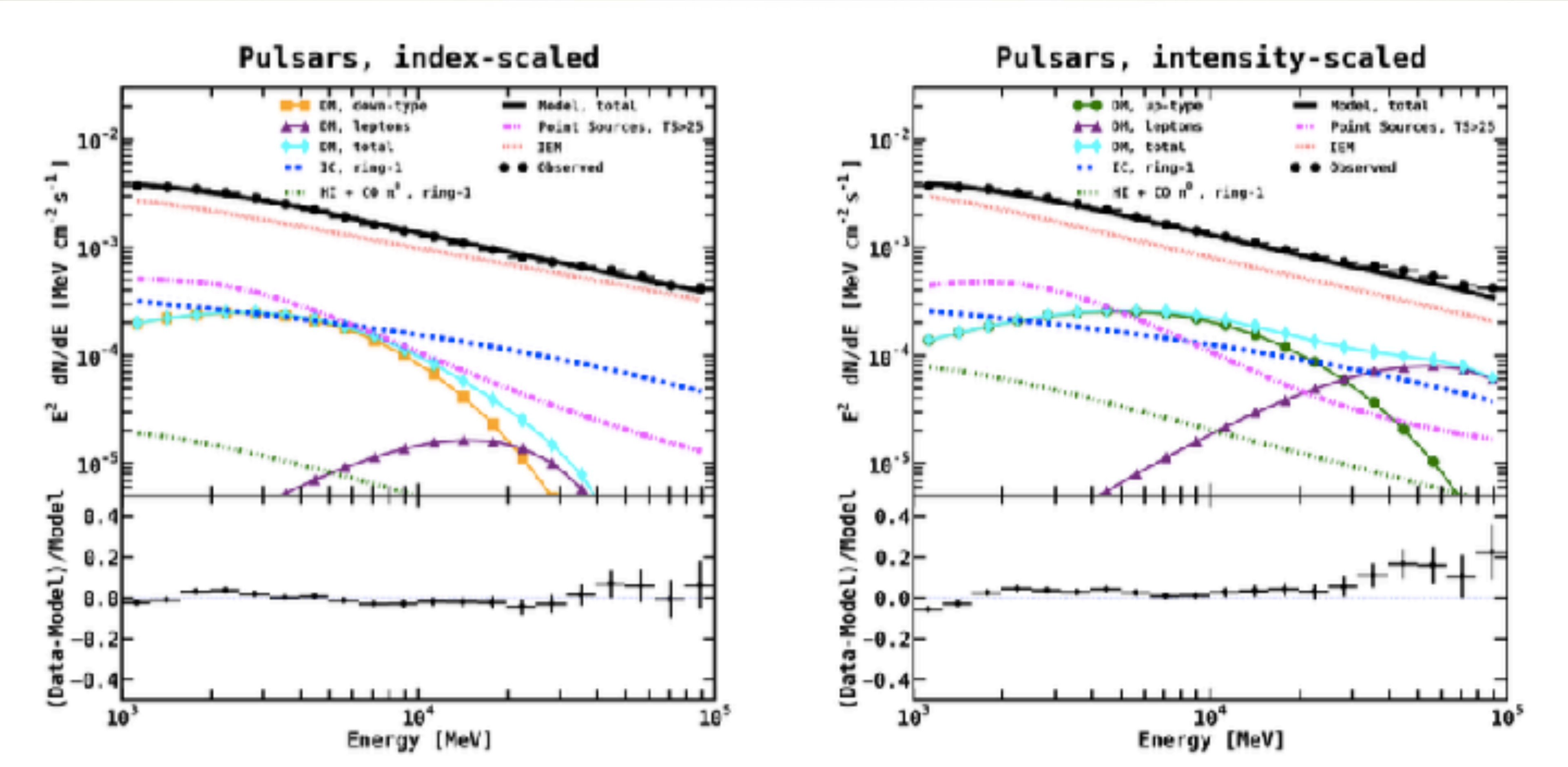
- Cuspiness of the DM profile (e.g. whether a standard, **γ=1**, or cuspier, **γ=1.2,** profile is favored) depends on IEM modeling
- Centroid is offset compared to Sgr A*, disfavored at ~90% C.L., but there is some dependence on IEM (offset ~0.5°-1°) and cannot rule out offset is due to shortcomings in modeling of IEM (see also Calore et al arXiv:1409.0042, Linden et al arXiv:1604.01026)
- No significant evidence that the high energy tail of the excess has a different spatial morphology than the few GeV bump (but see also Horiuchi et al arXiv:1604.01402)



C. Karwin et al, arXiv:1612.05687

Implications for Dark Matter Models

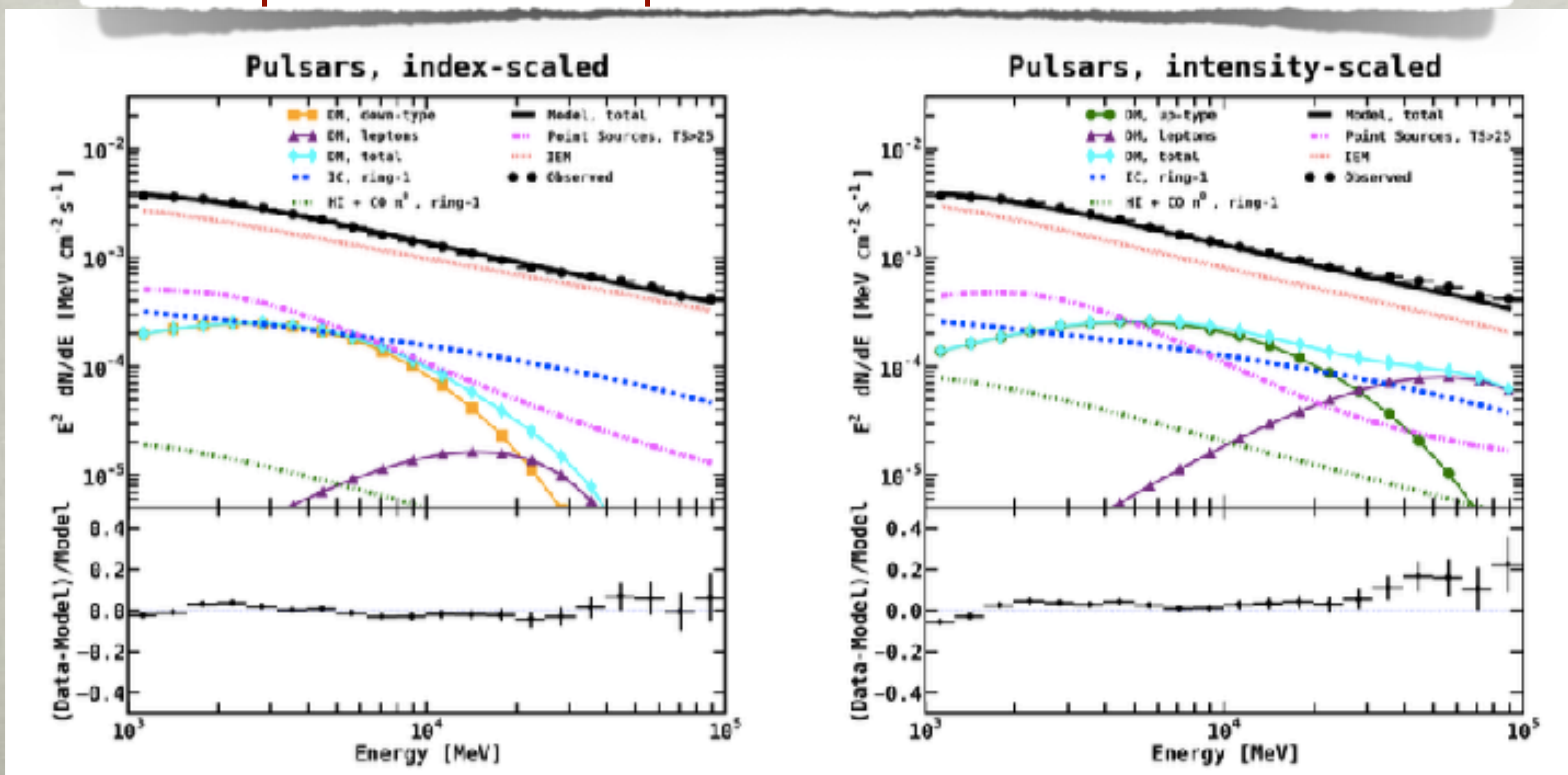
Integrated flux in 15°x15° ROI



C. Karwin et al, arXiv:1612.05687

Implications for Dark Matter Models

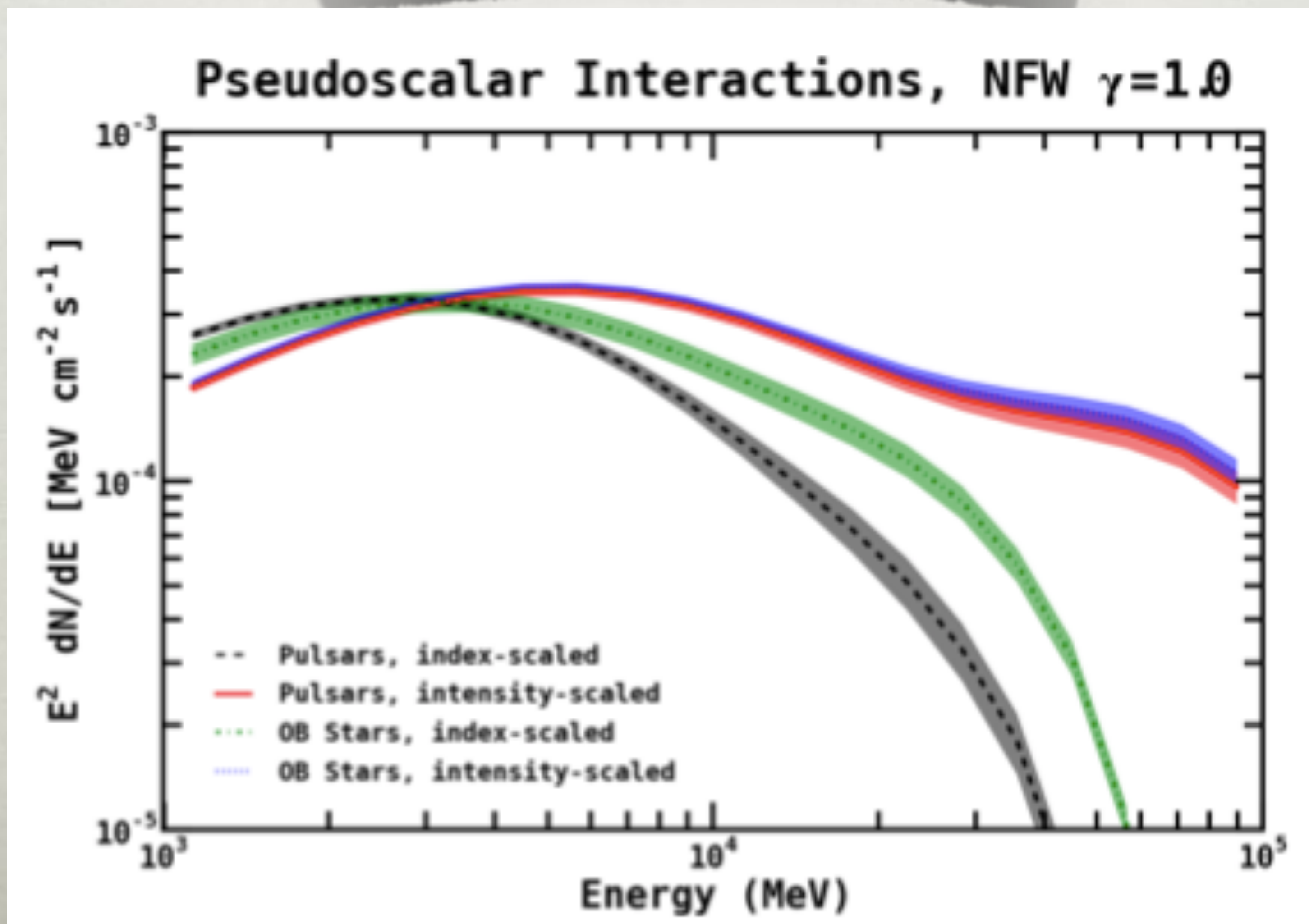
Fractional residuals based on these DM scenarios including up-type, down-type, and lepton final states generally improve (for the same number of free parameters) over the results from Fermi LAT analysis (Ajello et al 2016) based on a power law with exponential cutoff spectrum



C. Karwin et al, arXiv:1612.05687

Implications for Dark Matter Models

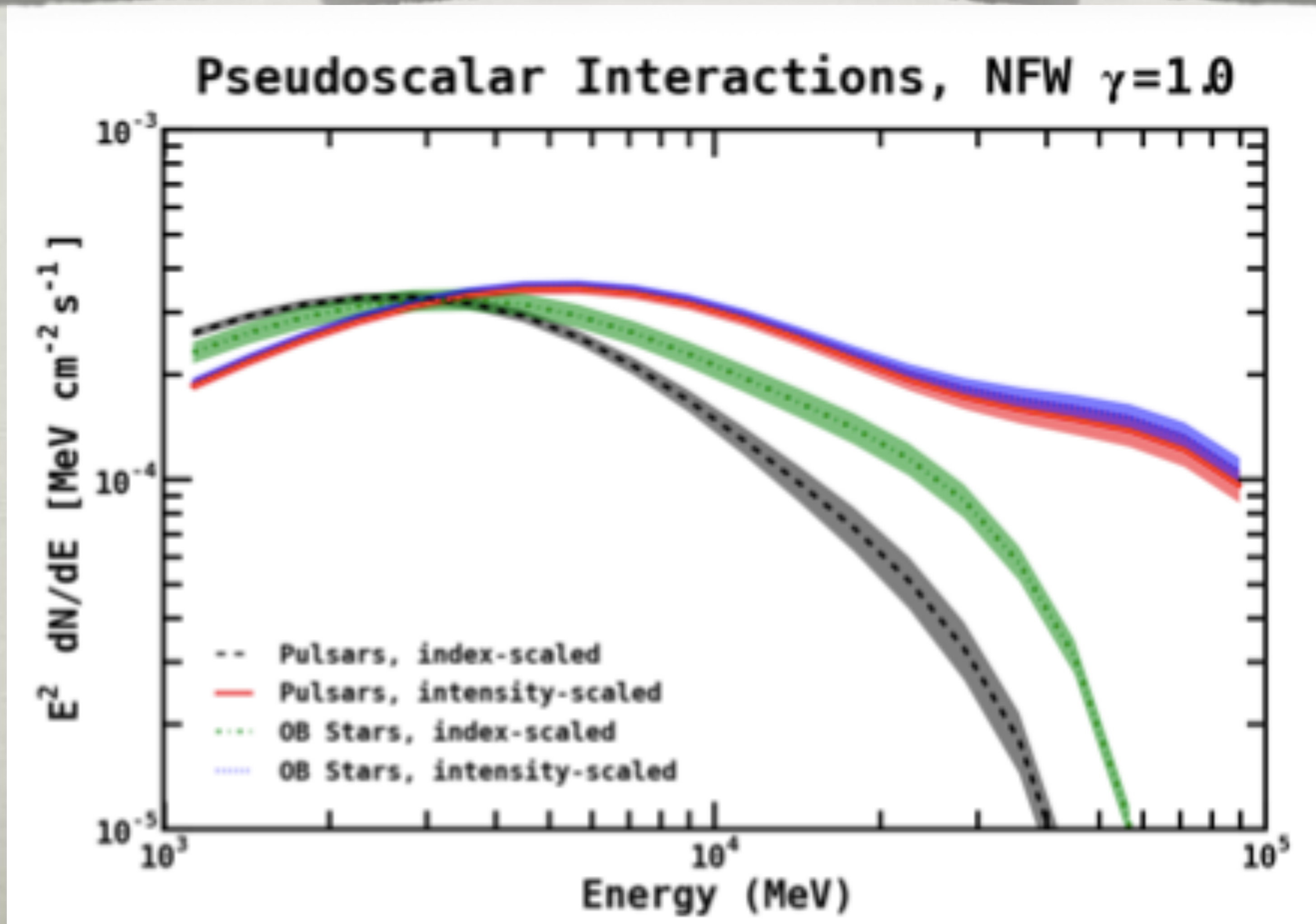
Integrated flux in 15°x15° ROI



C. Karwin et al, arXiv:1612.05687

Implications for Dark

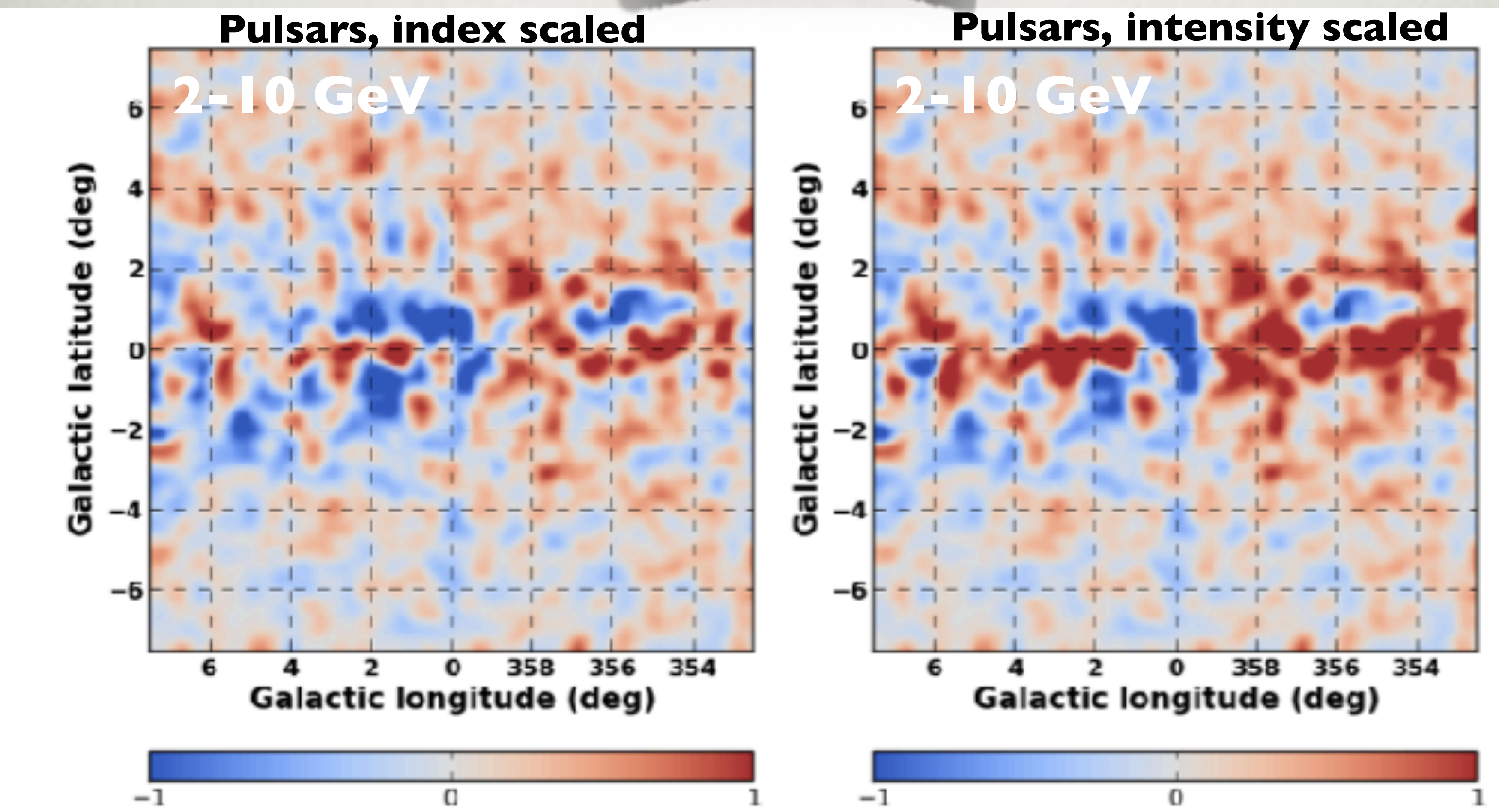
For the index-scaled IEMs, the spectrum peaks at a few GeV, while for the intensity-scaled IEMs the peak shifts to higher energies (consistent with spectrum from annihilations into leptons cutting off at the same energy (DM mass) as annihilations into quarks)



C. Karwin et al, arXiv:1612.05687

Implications for Dark Matter Models

DATA-MODEL

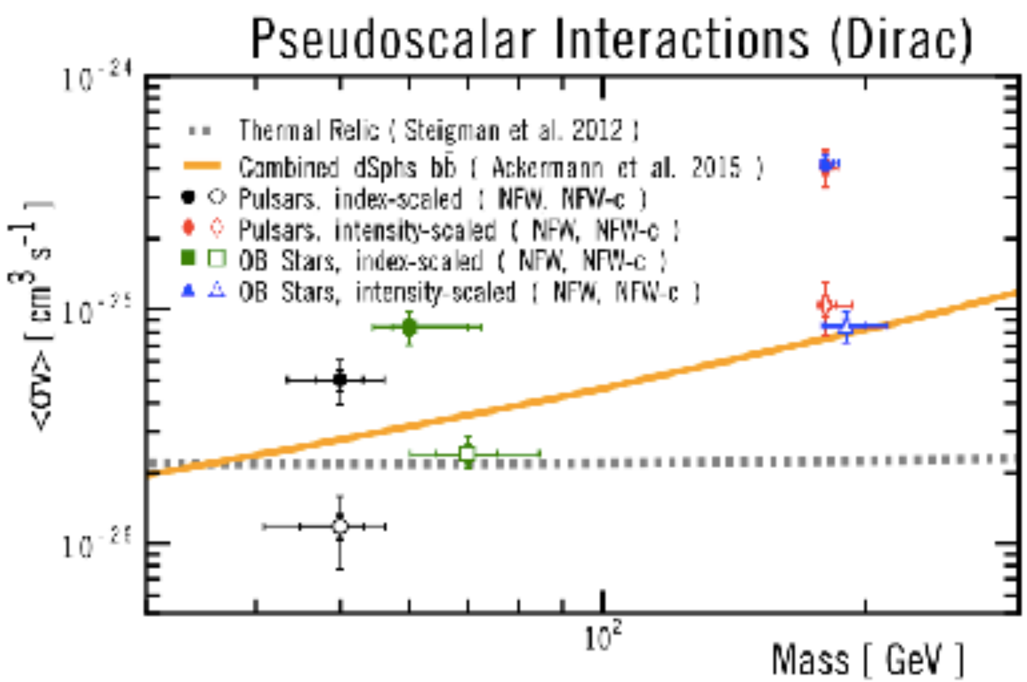


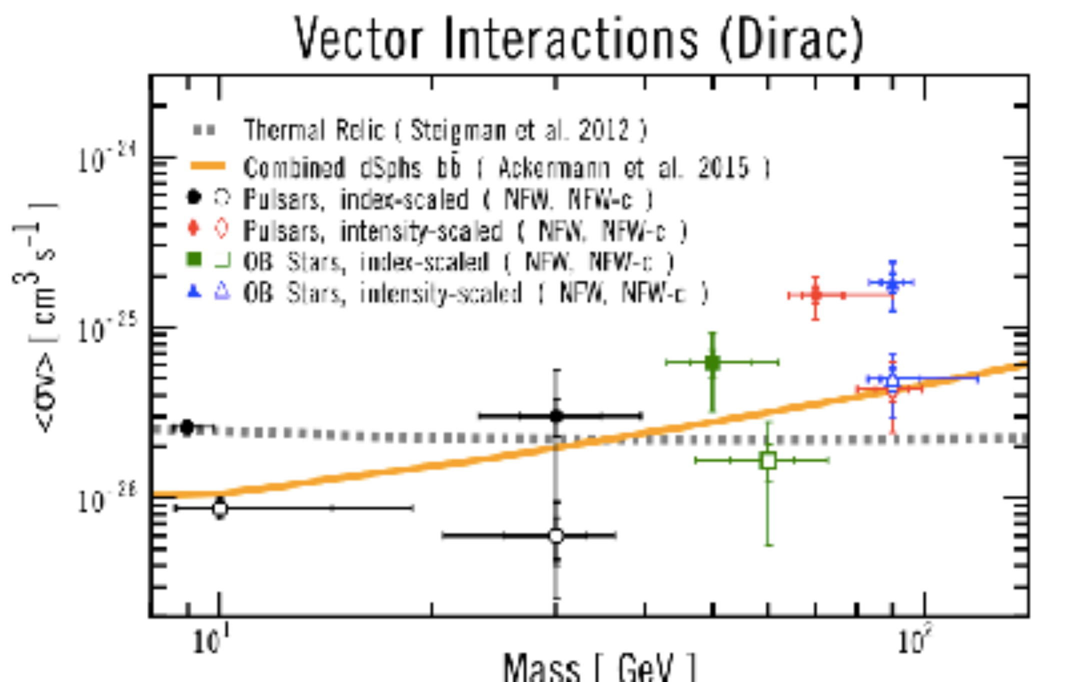
C. Karwin et al, arXiv:1612.05687

Implications for Dark Matter Models

- We translate the DM template flux for each IEMs into the inclusive annihilation cross section. We find:
  - The best-fit DM mass for the index-scaled IEMs is ~50 GeV and annihilation predominantly into bottom quarks, compatible with other analyses
  - The intensity-scaled IEMs favor higher DM masses, ~200 GeV and primarily favor annihilation into top quarks

C. Karwin et al, arXiv:1612.05687

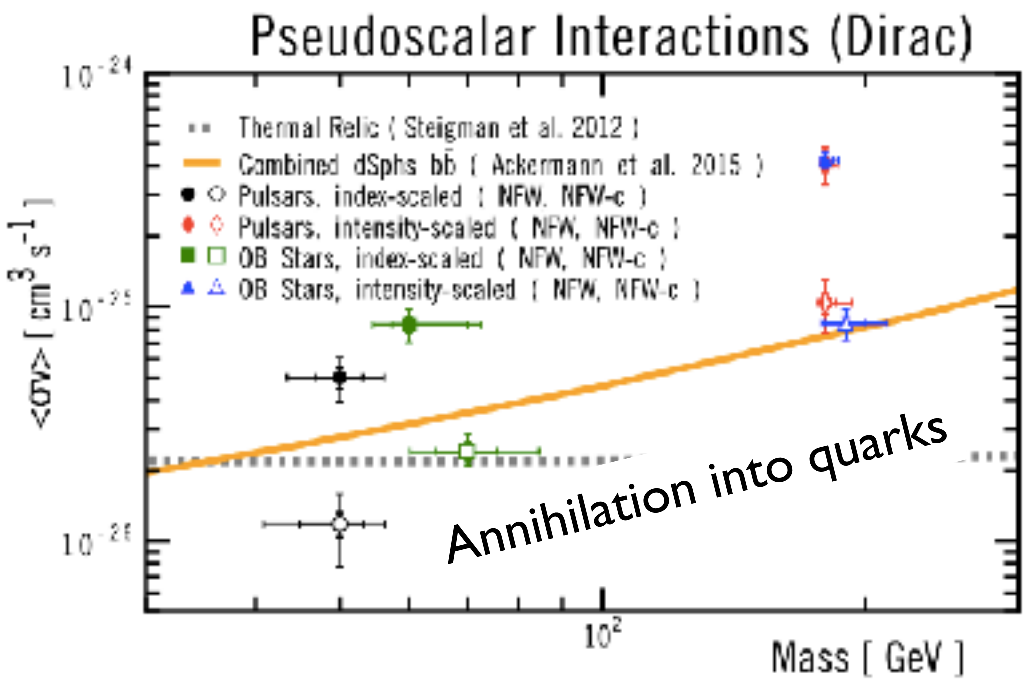


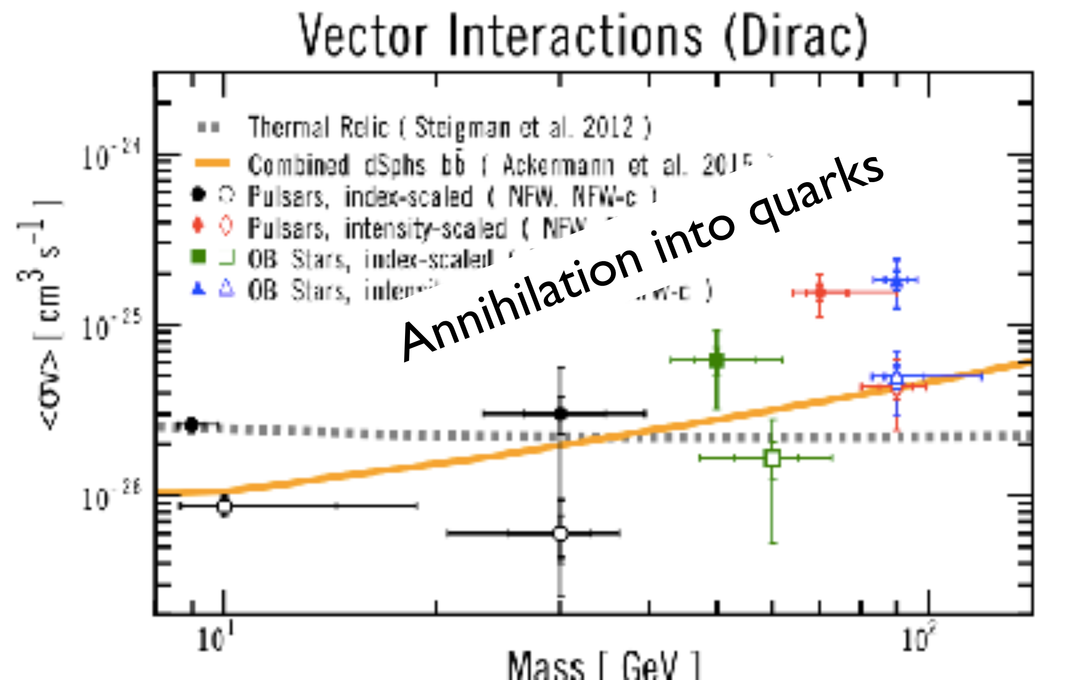


Implications for Dark Matter Models

- We translate the DM template flux for each IEMs into the inclusive annihilation cross section. We find:
  - The best-fit DM mass for the index-scaled IEMs is ~50 GeV and annihilation predominantly into bottom quarks, compatible with other analyses
  - The intensity-scaled IEMs favor higher DM masses, ~200 GeV and primarily favor annihilation into top quarks

C. Karwin et al, arXiv:1612.05687

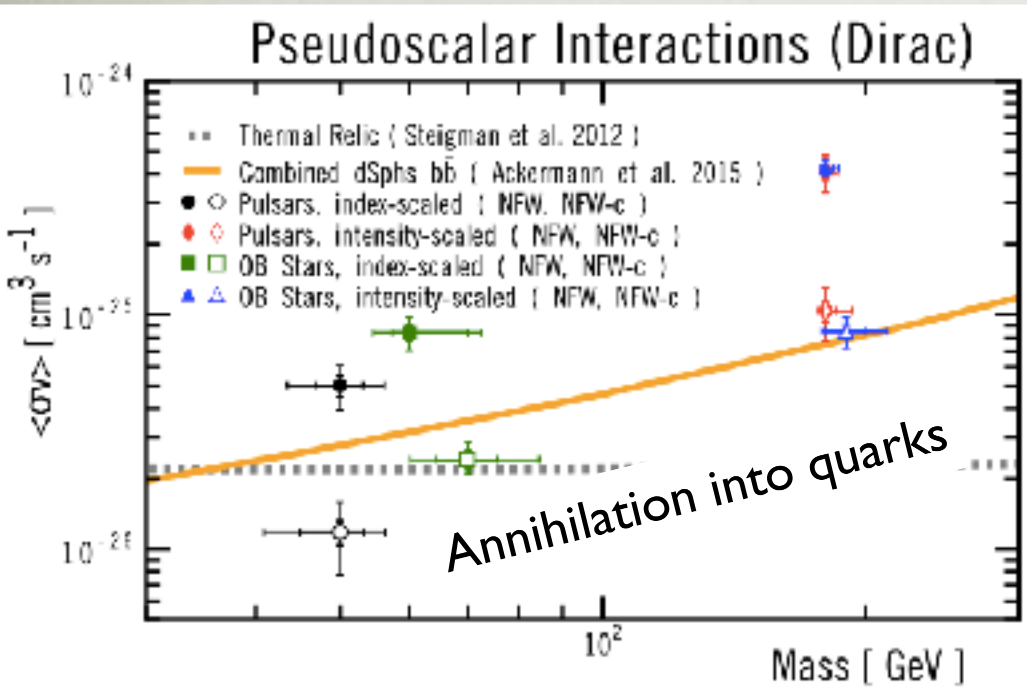


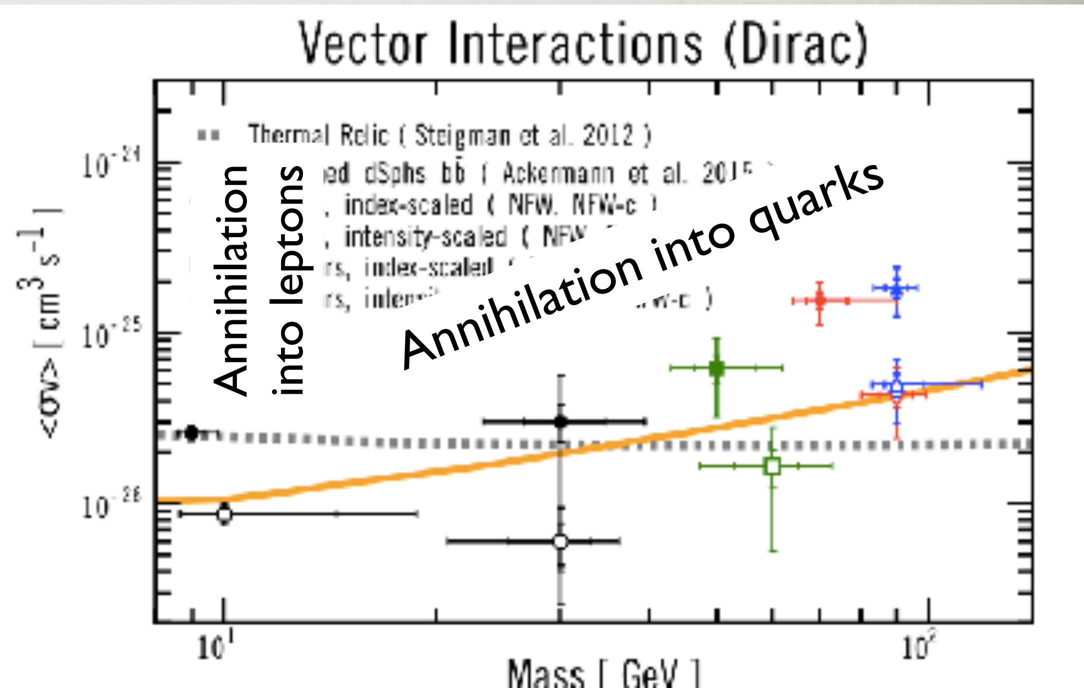


Implications for Dark Matter Models

- We translate the DM template flux for each IEMs into the inclusive annihilation cross section. We find:
  - The best-fit DM mass for the index-scaled IEMs is ~50 GeV and annihilation predominantly into bottom quarks, compatible with other analyses
  - The intensity-scaled IEMs favor higher DM masses, ~200 GeV and primarily favor annihilation into top quarks

C. Karwin et al, arXiv:1612.05687



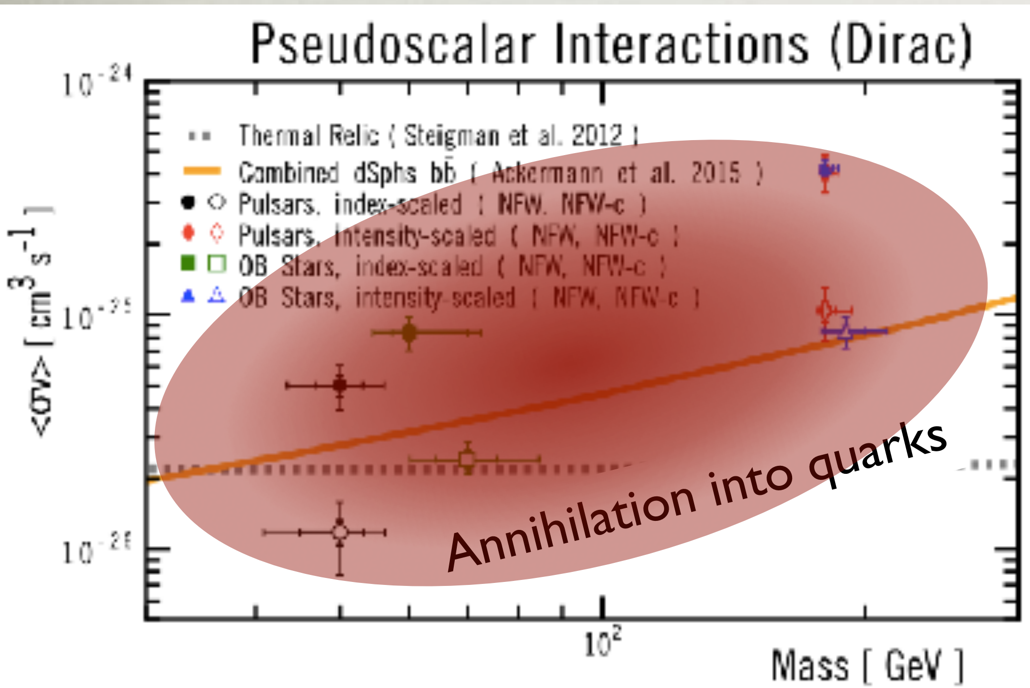


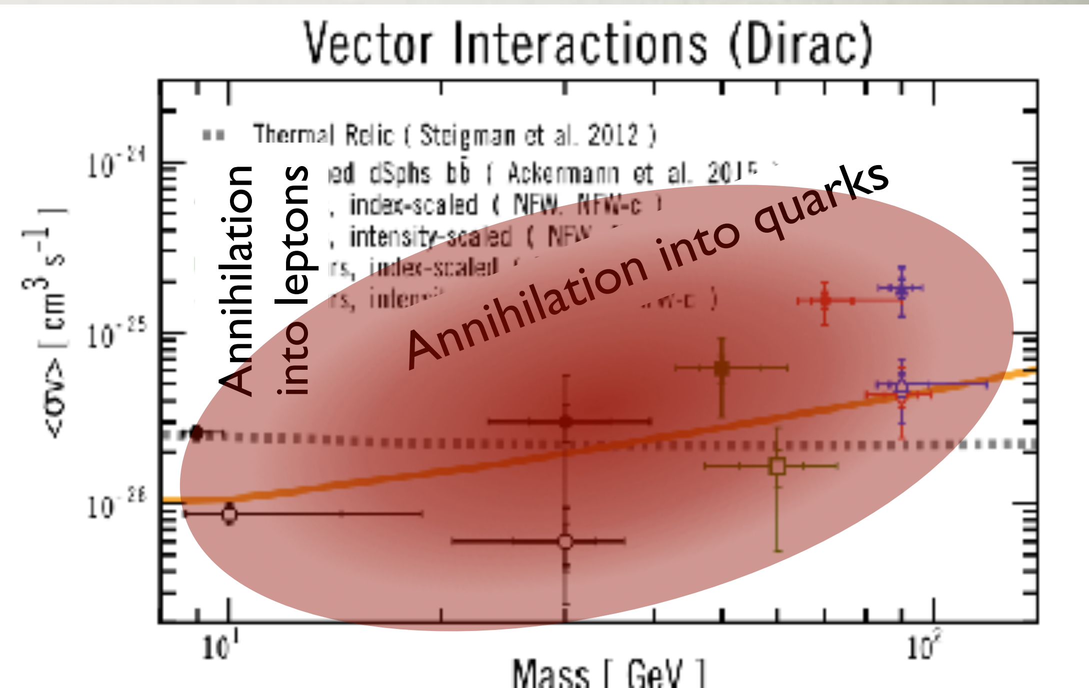
Implications for Dark Matter Models

- We translate the DM template flux for each IEMs into the inclusive annihilation cross section. We find:
  - The best-fit DM mass for the index-scaled IEMs is ~50 GeV and annihilation predominantly into bottom quarks, compatible with other analyses
  - The intensity-scaled IEMs favor higher DM masses, ~200 GeV and primarily favor annihilation into top quarks

Broad range of possibilities is allowed!

C. Karwin et al, arXiv:1612.05687



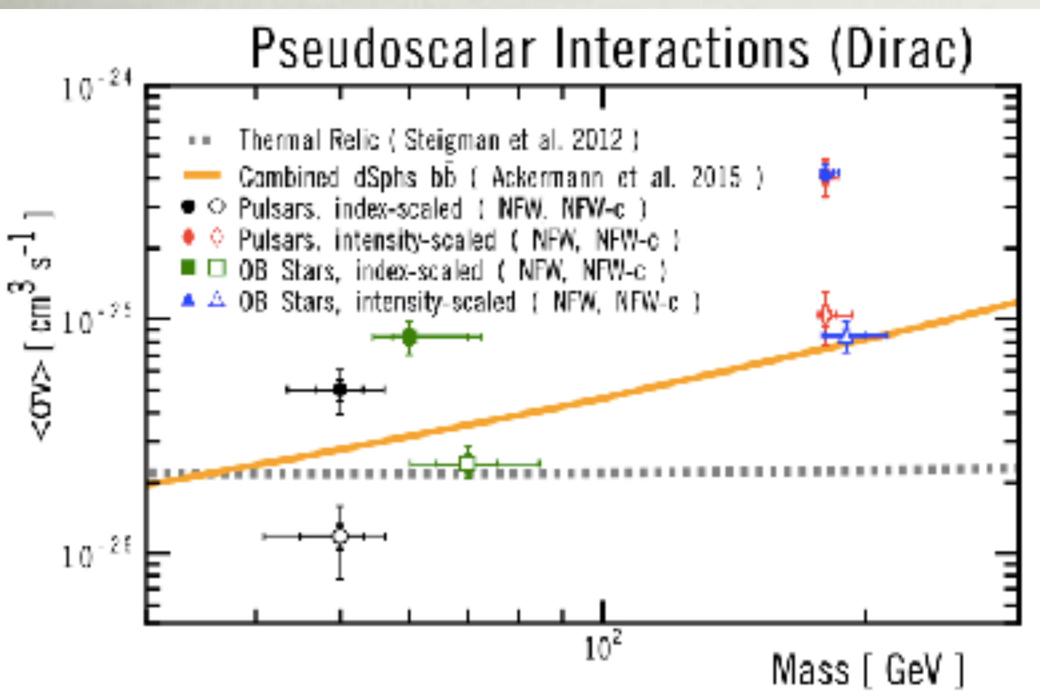


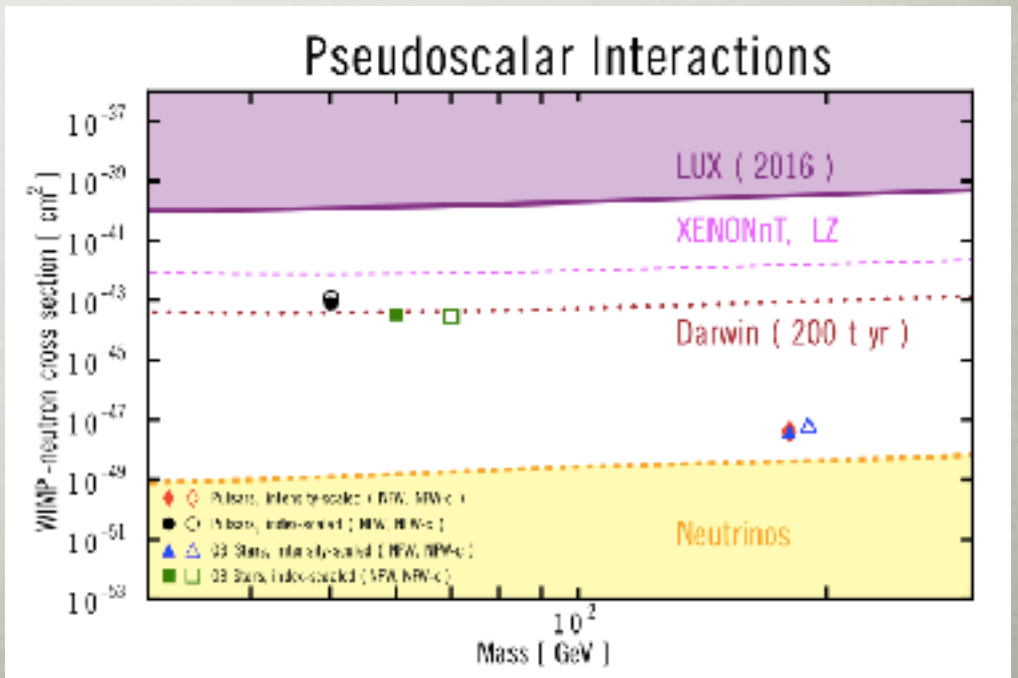
Implications for Dark Matter Models

- We map these intervals into the WIMP-neutron scattering cross sections
- The allowed range is well below current and projected direct detection constraints for pseudo-scalar interactions, but is typically ruled out for vector interactions

➡ Uncertainties in modeling the interstellar emission significantly affect the interpretation

C. Karwin et al, arXiv:1612.05687



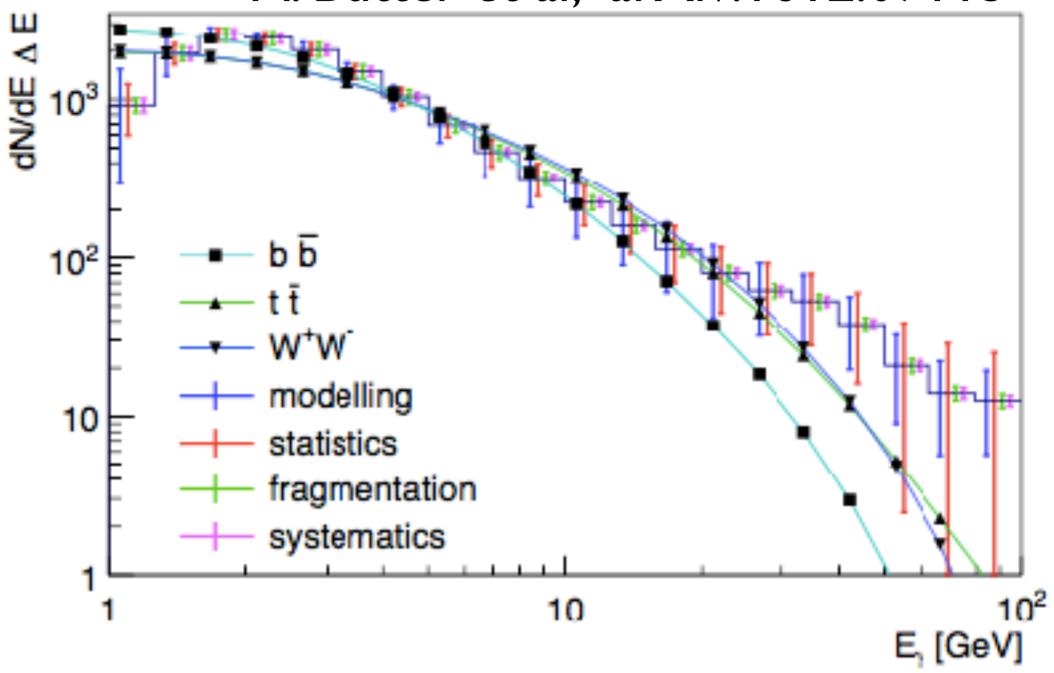


Implications for Dark Matter Models

- *In the framework of the minimal supersymmetric extension of the Standard Model (MSSM), we find that a neutralino DM annihilating into a pair of top quarks with DM masses above 250 GeV is favored (A. Butter et al arXiv:1612.07115)*
- Direct detection rules out much of the lower mass range
- See also Achterberg et al arXiv:1502.05703, Bertone et al arXiv:1507.07008
- (We assume the DM candidate comprises all of the DM and the same annihilation cross section which explains the GC excess also determines the thermal relic abundance)

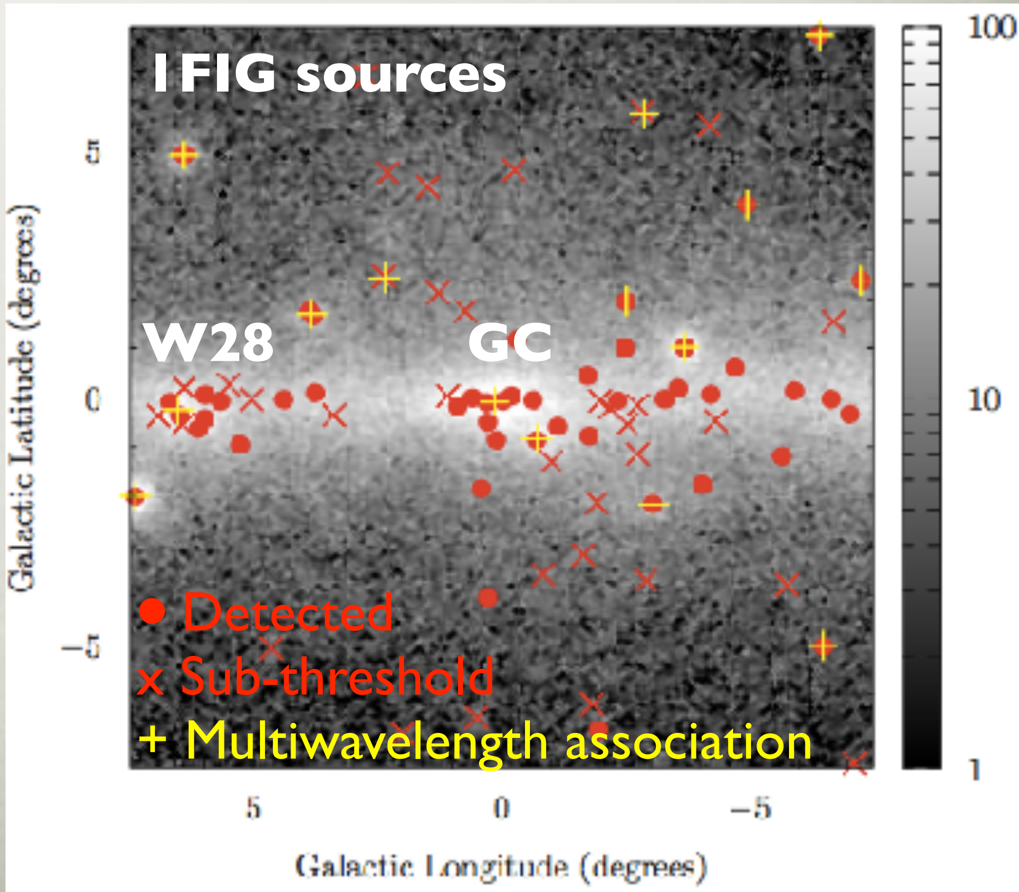
➡ Uncertainties in modeling the interstellar emission significantly affect the interpretation (e.g. presence of high energy tail in the GC excess spectrum)

A. Butter et al, arXiv:1612.07115



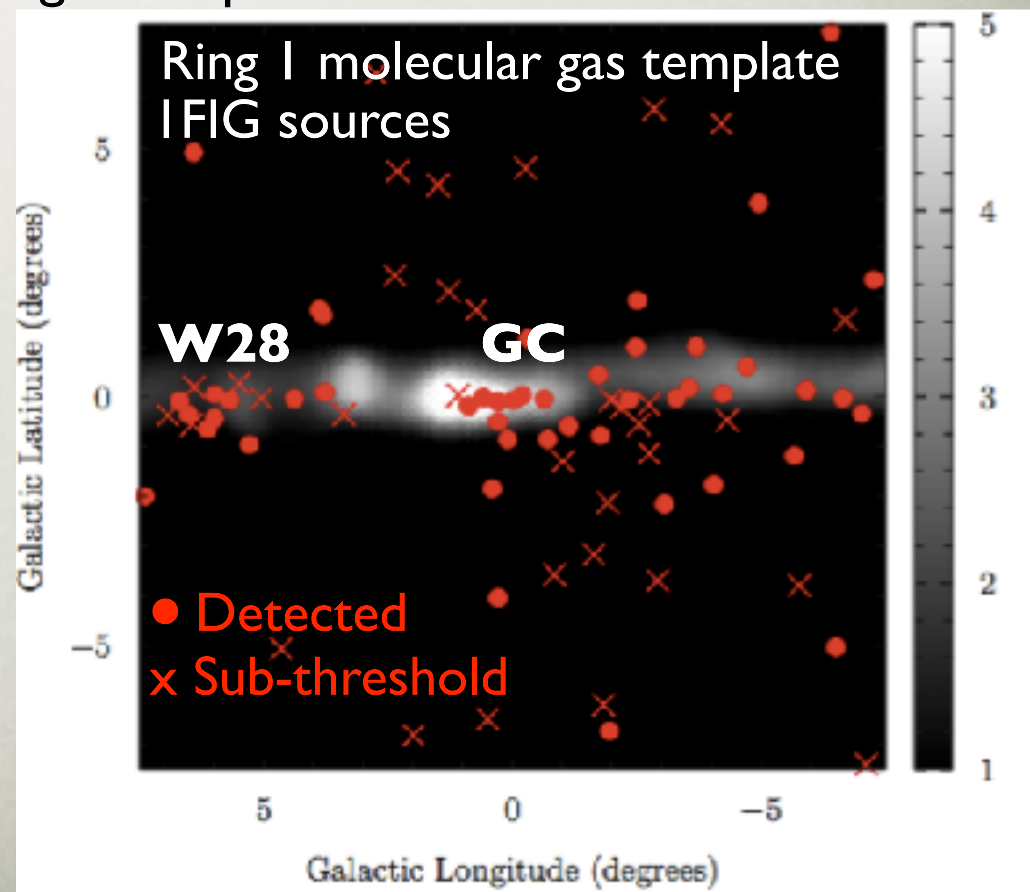
First Fermi–LAT Inner Galaxy Point Source Catalog (1FIG)

- 48 point sources significantly (>4σ) detected in the 15°x15° region
- More than two thirds of the 1FIG sources do not have associations with sources in known classes of gamma-ray emitters
  - tend to be close to the Galactic plane



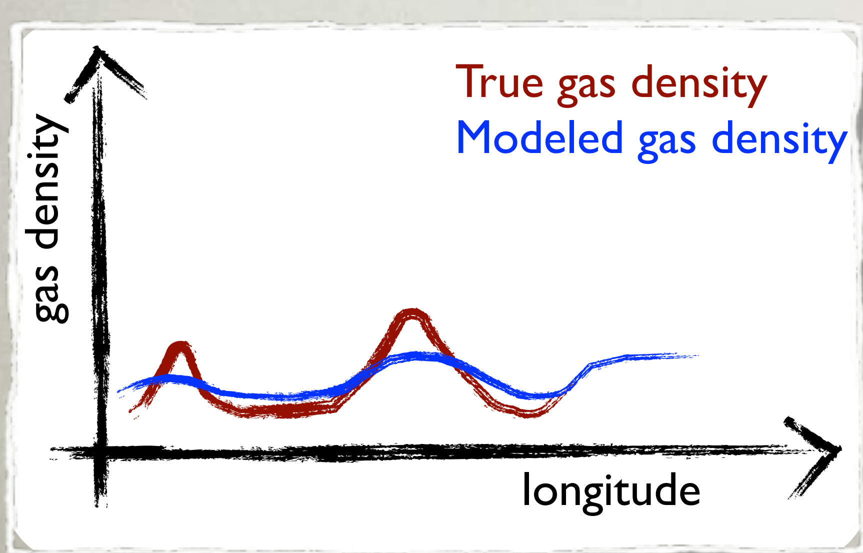
First Fermi–LAT Inner Galaxy Point Source Catalog (1FIG)

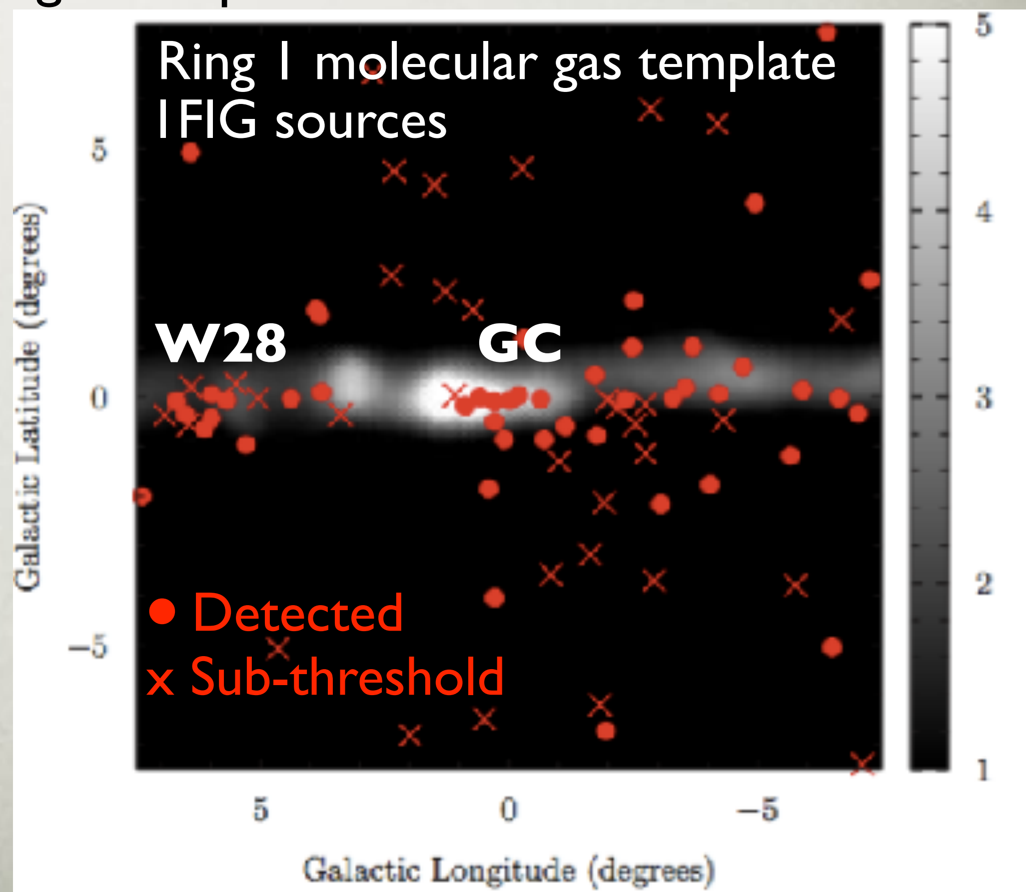
- 48 point sources significantly (>4σ) detected in the 15°x15° region
- More than two thirds of the 1FIG sources do not have associations with sources in known classes of gamma-ray emitters
  - tend to be close to the Galactic plane
  - many appear to trace features in the ring 1 gas templates



First Fermi–LAT Inner Galaxy Point Source Catalog (1FIG)

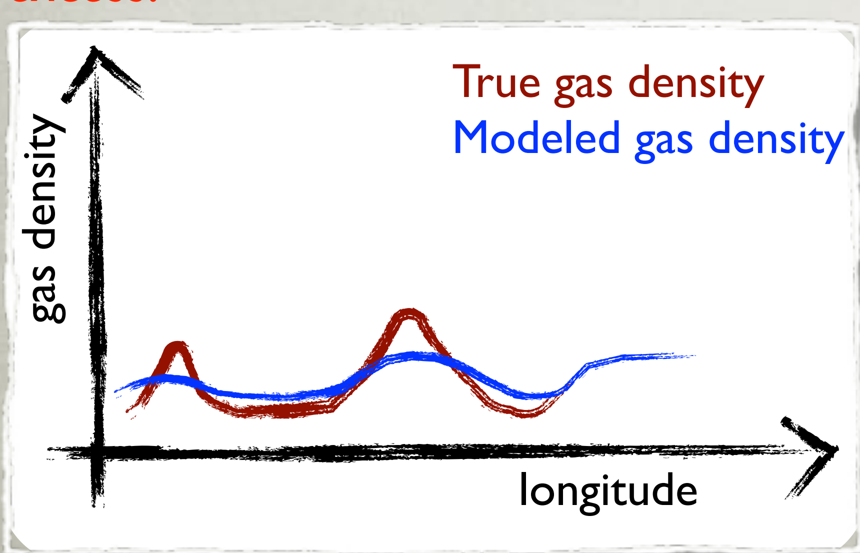
- 48 point sources significantly (>4σ) detected in the 15°x15° region
- More than two thirds of the 1FIG sources do not have associations with sources in known classes of gamma-ray emitters
  - tend to be close to the Galactic plane
  - many appear to trace features in the ring 1 gas templates
  - *might be mis-identified interstellar emission*

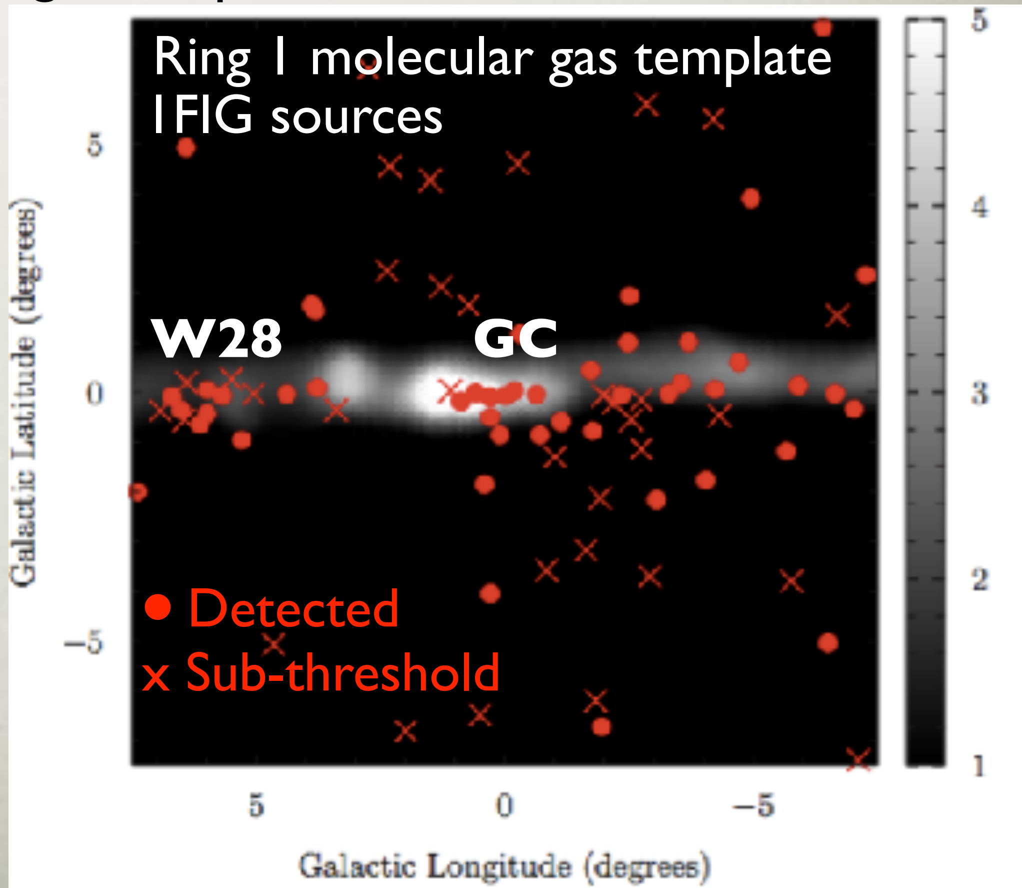




First Fermi–LAT Inner Galaxy Point Source Catalog (1FIG)

- 48 point sources significantly (>4σ) detected in the 15°x15° region
- More than two thirds of the 1FIG sources do not have associations with sources in known classes of gamma-ray emitters
  - tend to be close to the Galactic plane
  - many appear to trace features in the ring 1 gas templates
  - *might be mis-identified interstellar emission*
  - ➡ *this issue might be important for point source interpretation of the galactic center excess!*

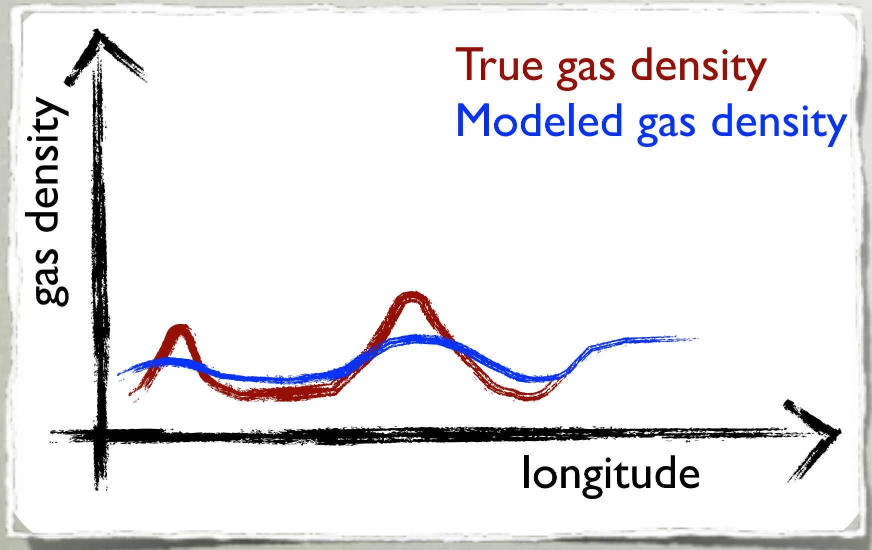


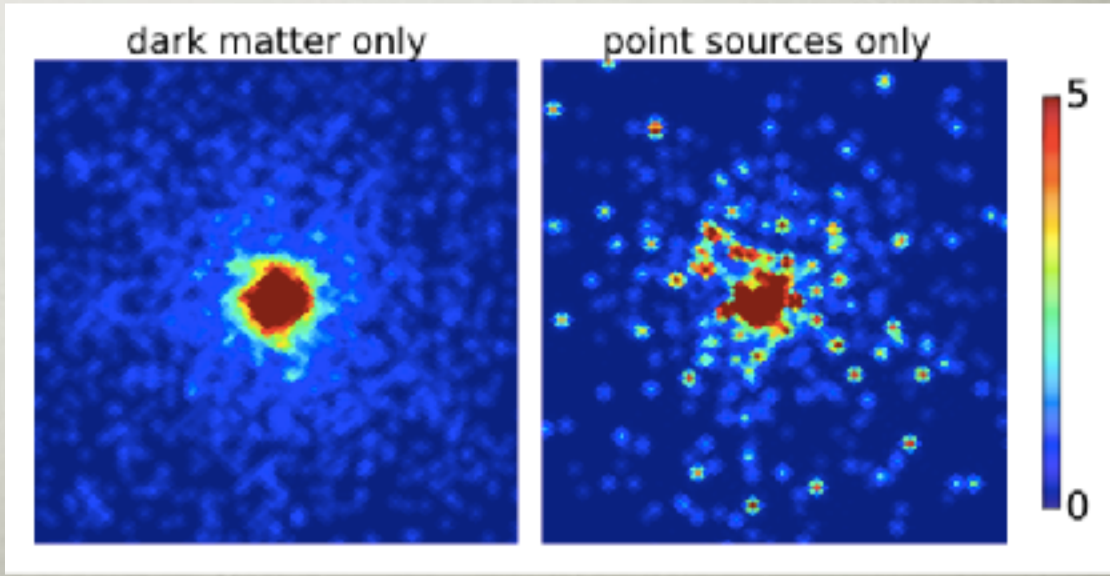


Unresolved Sources
Some Caveats

- It is likely that some sources below (and above) the detection threshold are mis-identified interstellar emission from gas
- In addition, the (millisecond) pulsars spatial morphology (and luminosity function) are not well constrained and these parameters could therefore be adjusted to match unrelated contributions, such as the GC excess

Lee et al, arXiv:1412.6099



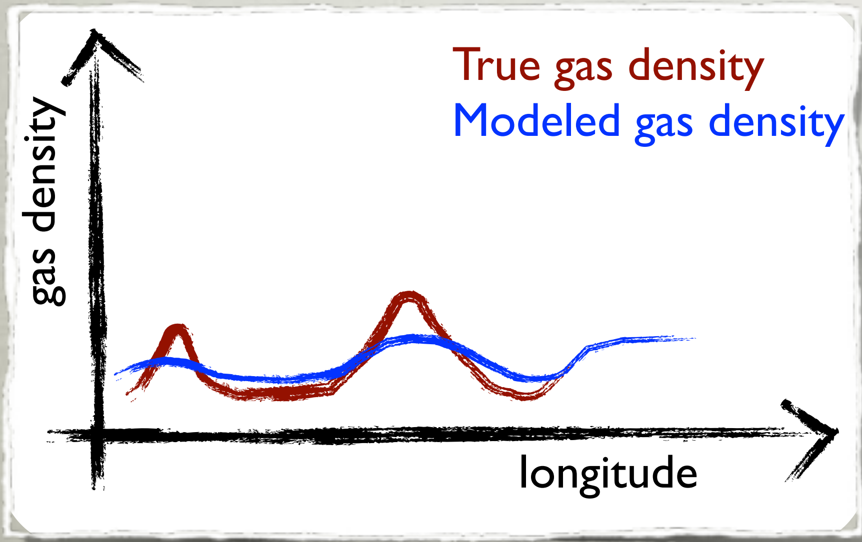


Unresolved Sources

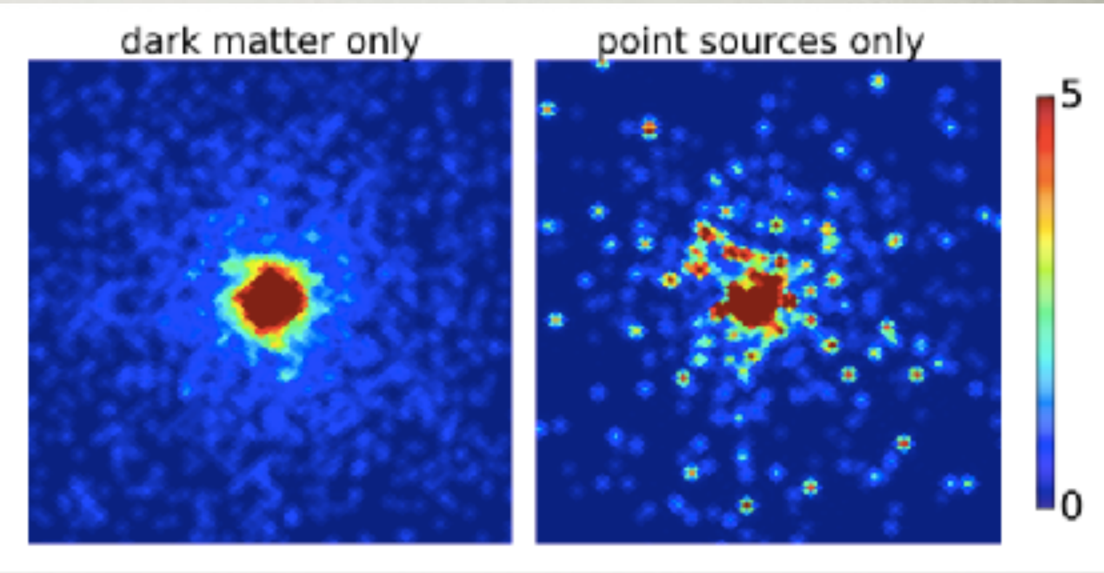
Some Caveats

- These sources must be detected to confirm that the GC excess is generated by a collection of unresolved millisecond pulsars
- More γ-ray data will help, but even more crucial is the potential of radio surveys (MeerKAT, SKA) to uncover a large number of millisecond pulsars in the Galactic bulge that contribute to the GC excess (e.g. Calore et al arXiv:1512.06825)

(A recent claim by the Fermi LAT collaboration on the detection of the point sources generating the Galactic center excess has been retracted, see Fermi LAT Collaboration arXiv:1705.00009 and Bartels et al arXiv:1710.10266)



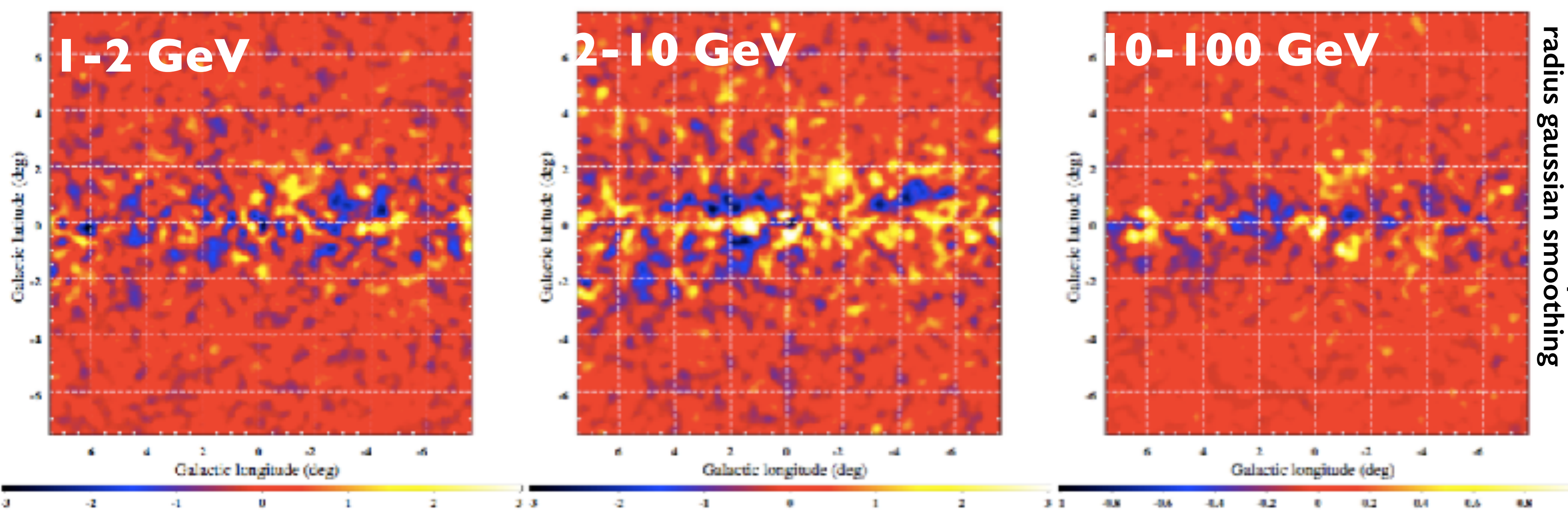
Lee et al, arXiv:1412.6099



Residual Maps
Dark Matter

Improvements across the region, but some discrepancies between data and model remain

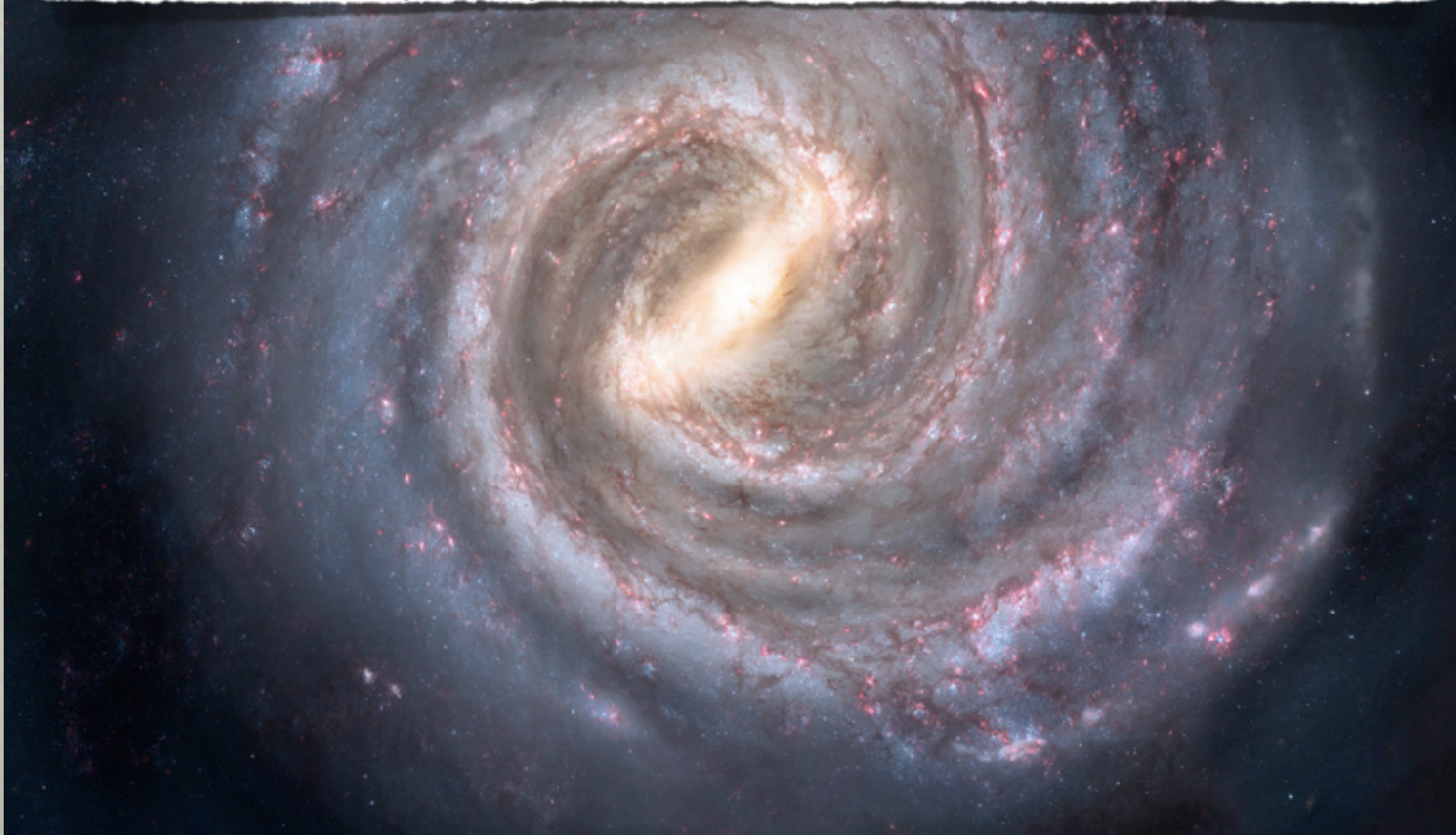
DATA-MODEL (Pulsars, index scaled - with dark matter)



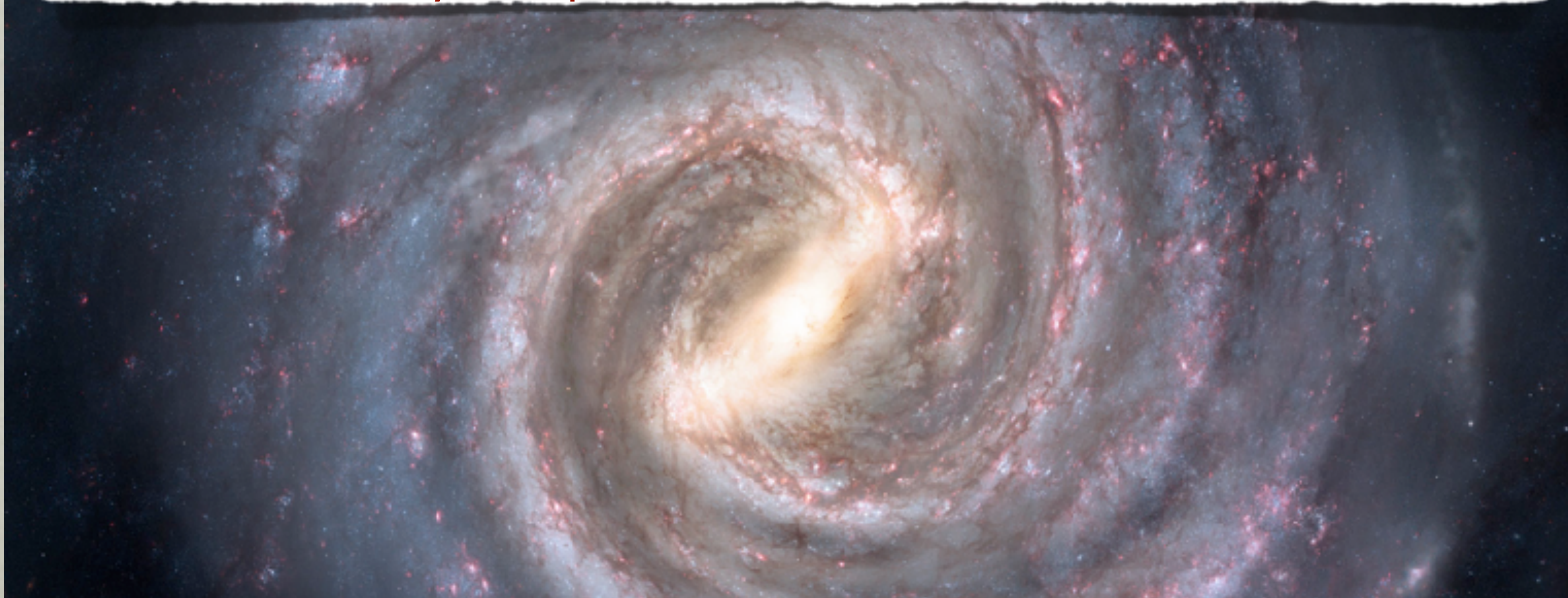
Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

- ✦ There are limitations in all interstellar emission models employed so far (e.g., cylindrical symmetry, the gas distribution, as well as interplay between the interstellar emission and point sources)

➡ Work is underway to improve these models



- ✦ There are limitations in all interstellar emission models employed so far (e.g., cylindrical symmetry, the gas distribution, as well as interplay between the interstellar emission and point sources)
- ➡ Work is underway to improve these models



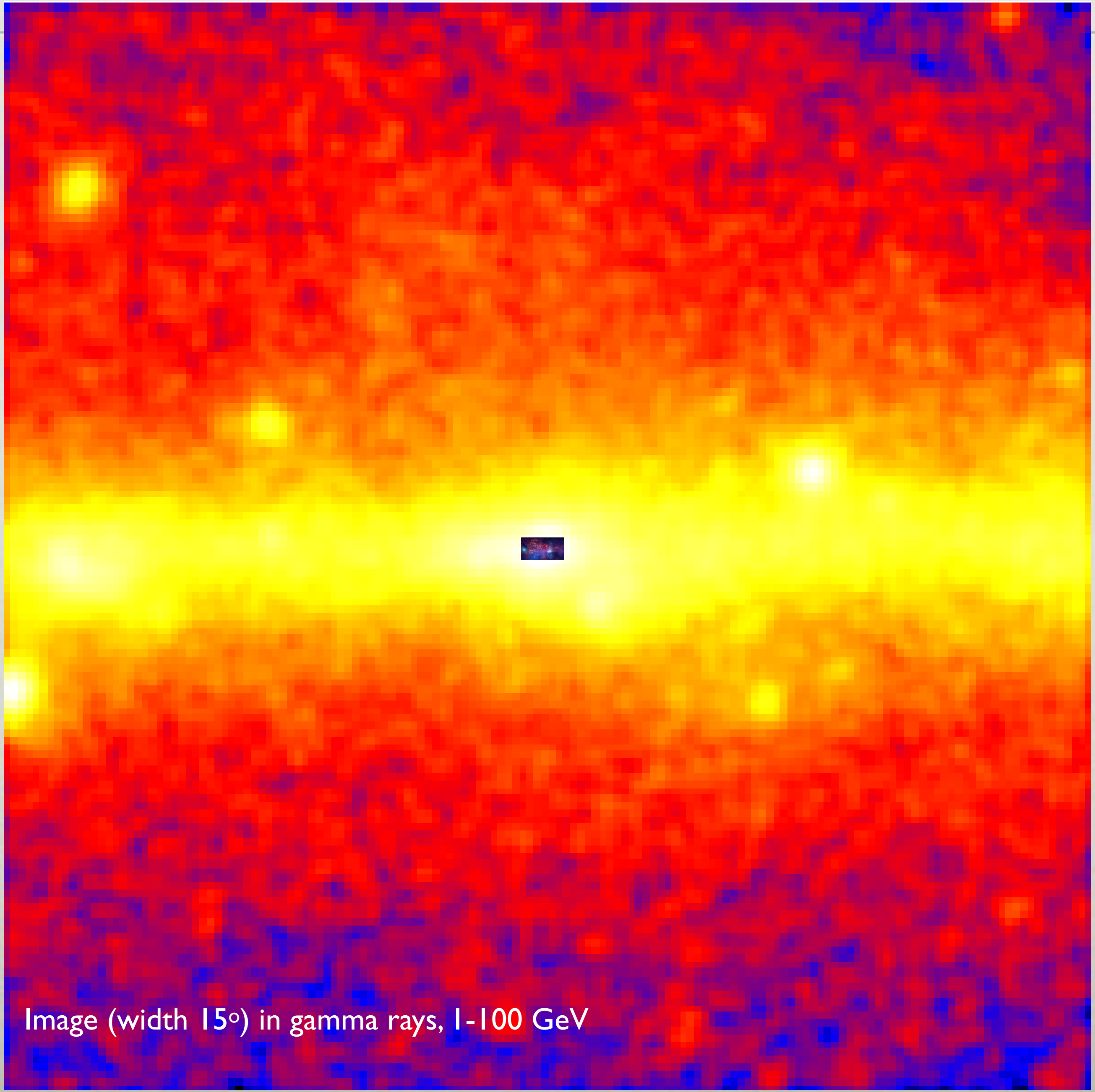
- ✦ **The GC excess is a small fraction of the total observed emission (e.g. ~5-10% in a 15°x15° region)**
- ➡ **Improvements in modeling the interstellar emission are crucial to confirm the properties of the excess!**

Central Region of the Milky Way

Image (width~0.5°) combines a near-infrared view from the Hubble Space Telescope (yellow), an infrared view from the Spitzer Space Telescope (red) and an X-ray view from the Chandra X-ray Observatory blue and violet) into one multi-wavelength picture.

Central Region of the Milky Way

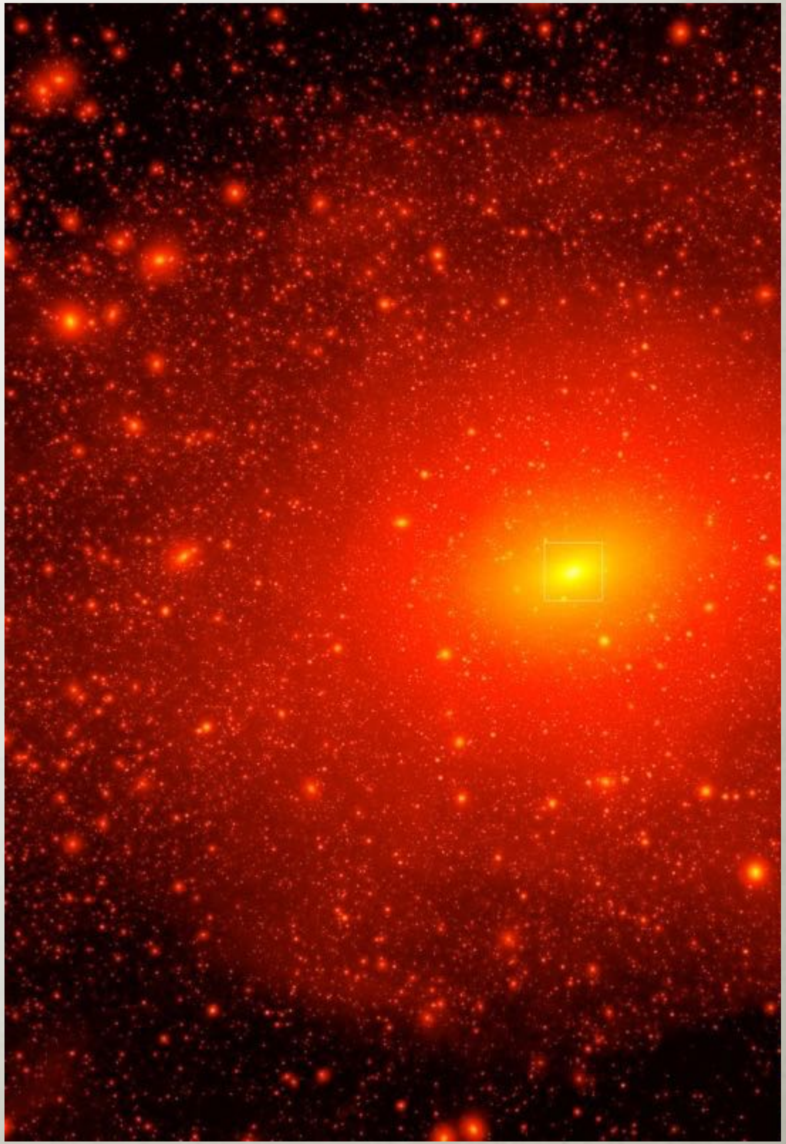
Central Region of the Milky Way



Dwarf Spheroidal Galaxies

- Optically observed dwarf spheroidal galaxies: largest clumps predicted by N-body simulations

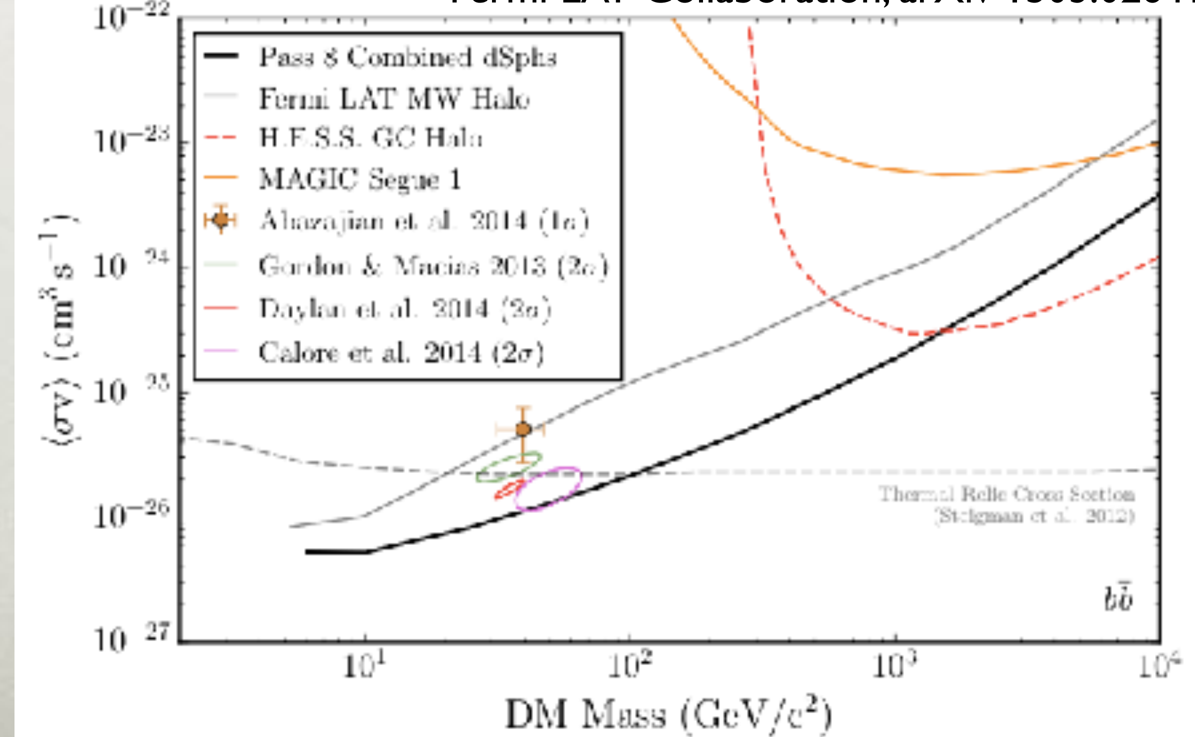
- Excellent targets for gamma-ray DM searches
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - DM density inferred from the stellar data!
  - Expected to be free from other gamma ray sources and have low dust/gas content, very few stars



Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found

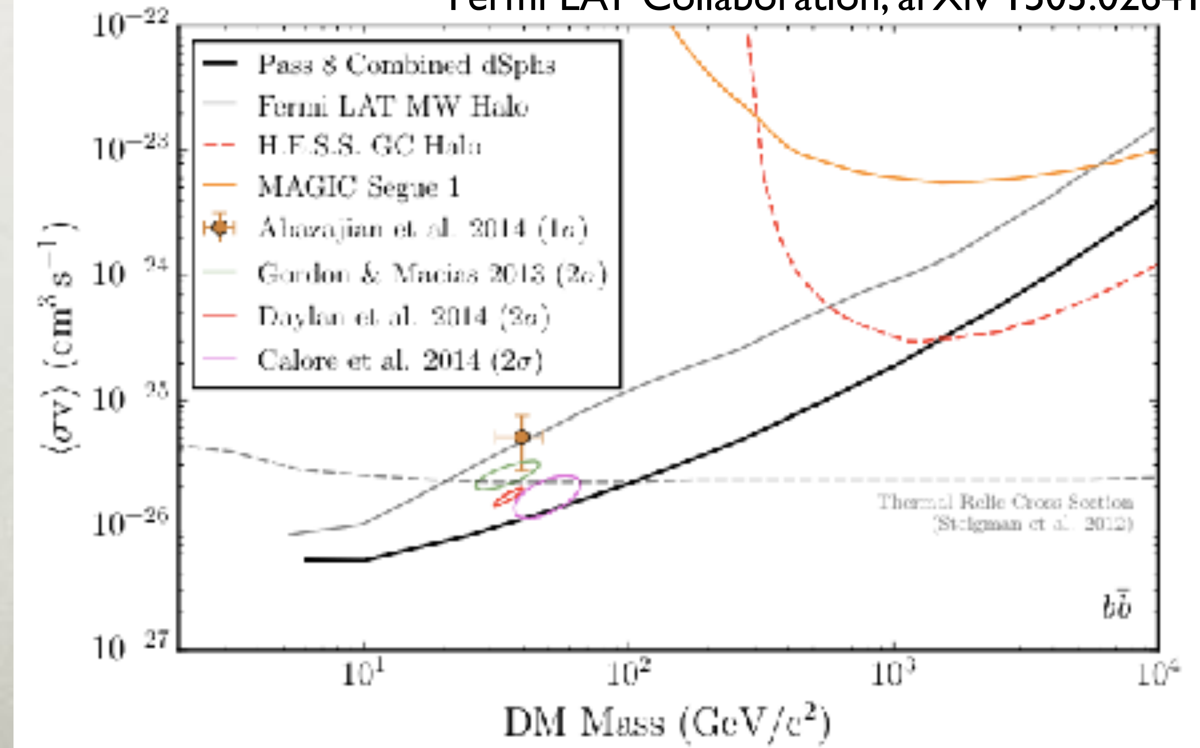
Fermi LAT Collaboration, arXiv 1503.02641



Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

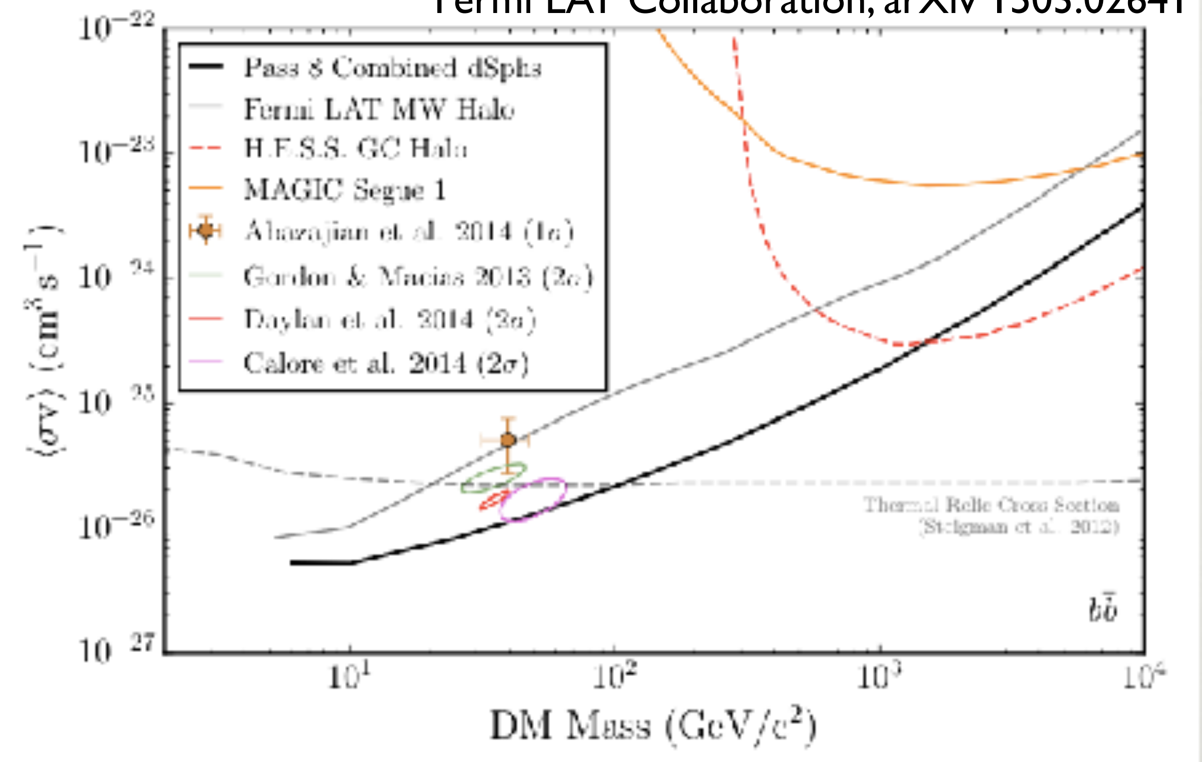
Fermi LAT Collaboration, arXiv 1503.02641



Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

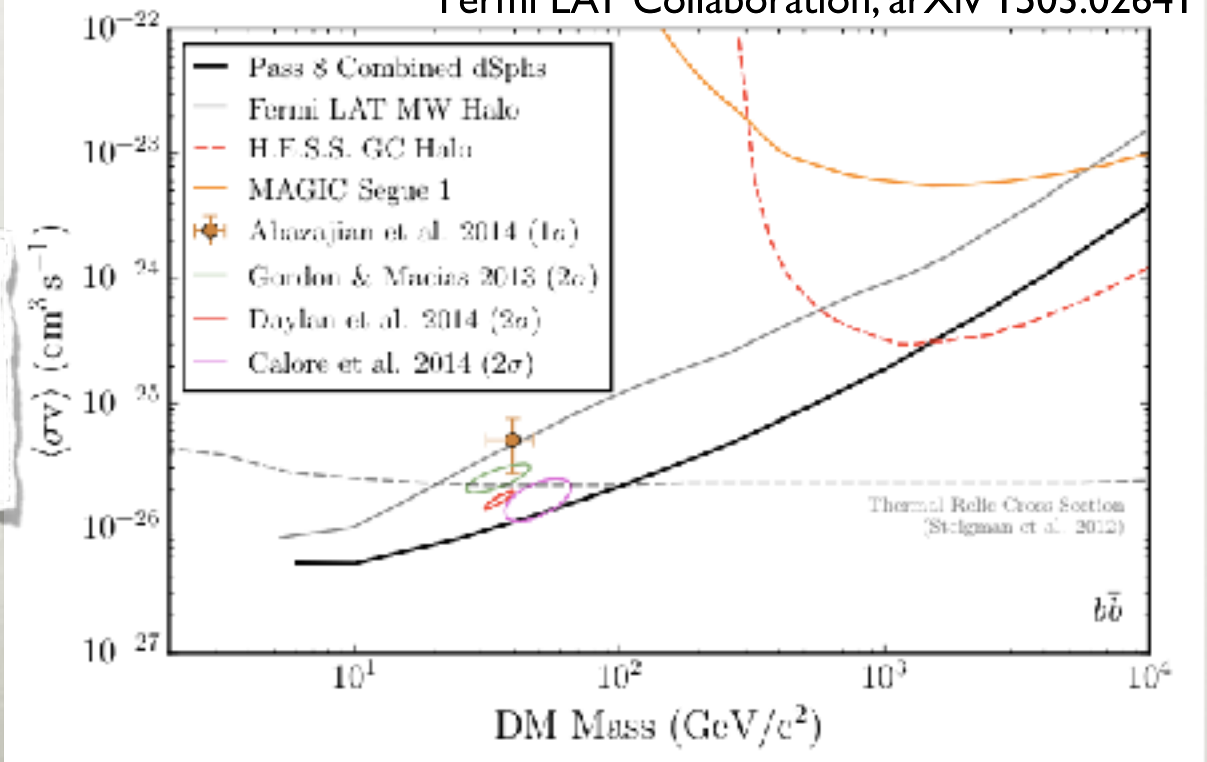
Fermi LAT Collaboration, arXiv 1503.02641



Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
    - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

Fermi LAT Collaboration, arXiv 1503.02641

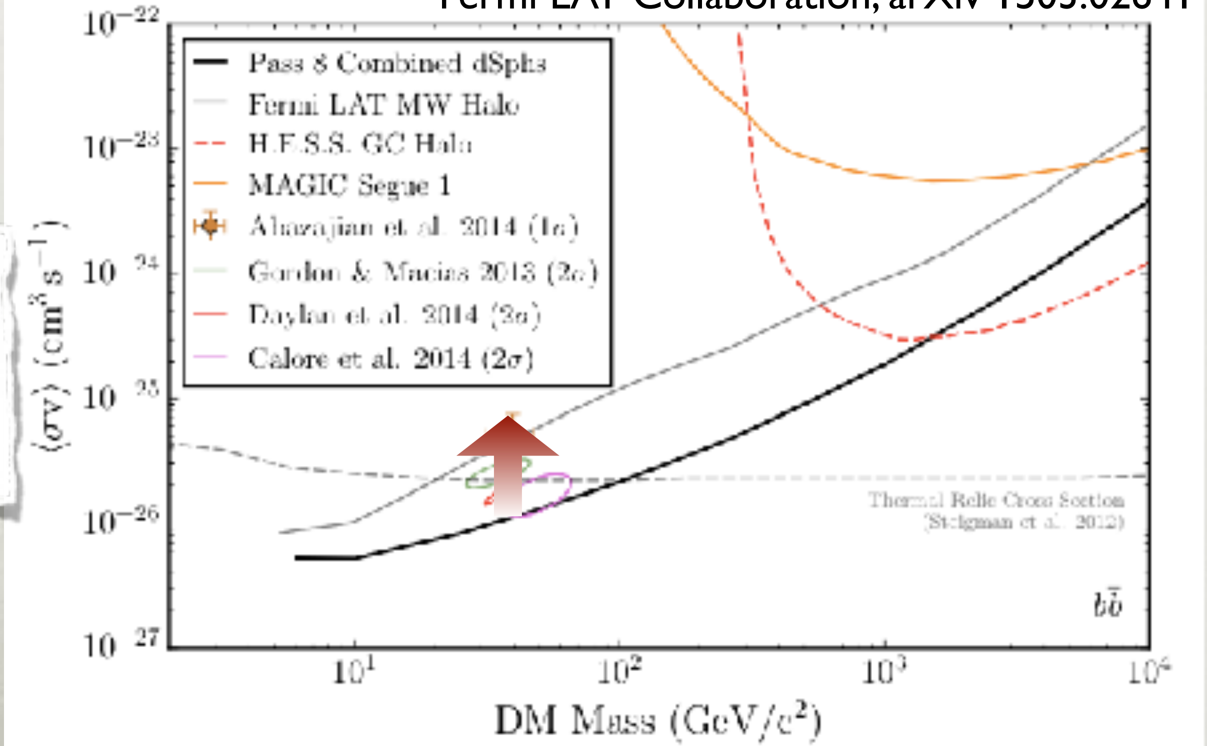


N.B.:
Non-spherical DM halos weaken dSph limits by ~2x (see e.g. Hayashi et al, arXiv: 1603.08046, Klop et al, arXiv:1609.03509).

Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
    - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

Fermi LAT Collaboration, arXiv 1503.02641

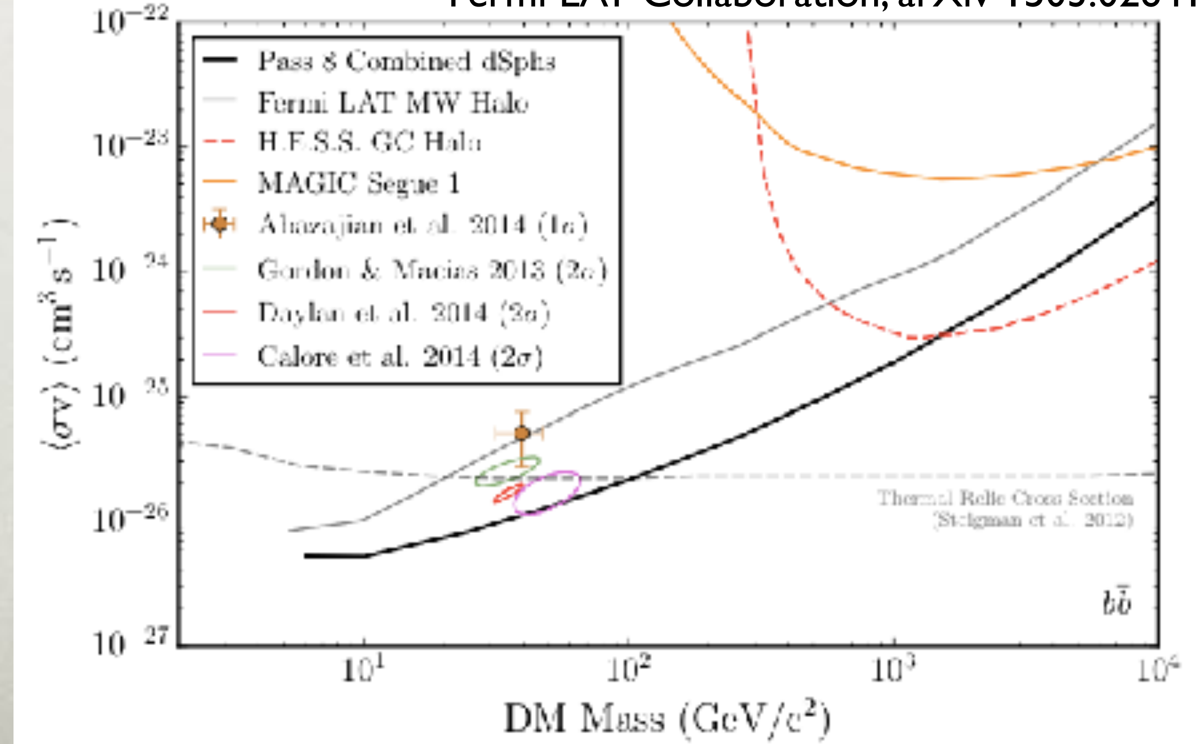


N.B.:
Non-spherical DM halos weaken dSph limits by ~2x (see e.g. Hayashi et al, arXiv: 1603.08046, Klop et al, arXiv:1609.03509).

Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

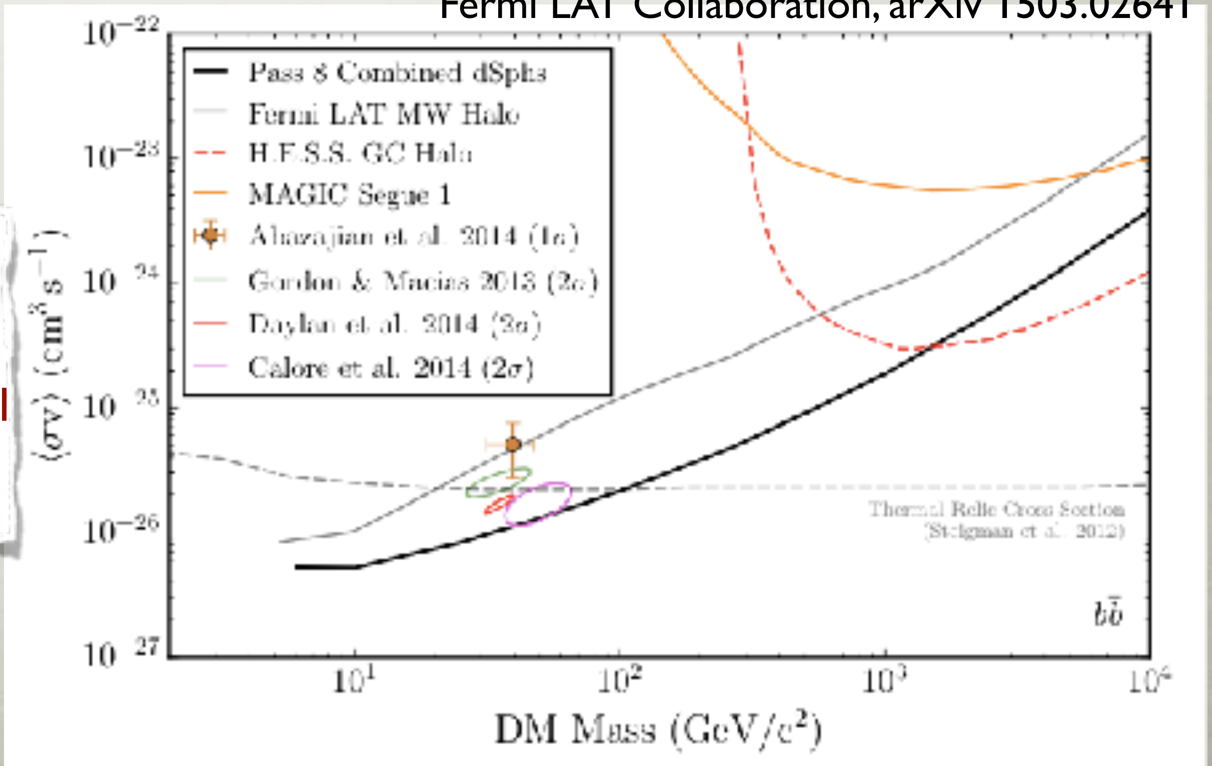
Fermi LAT Collaboration, arXiv 1503.02641



Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

Fermi LAT Collaboration, arXiv 1503.02641

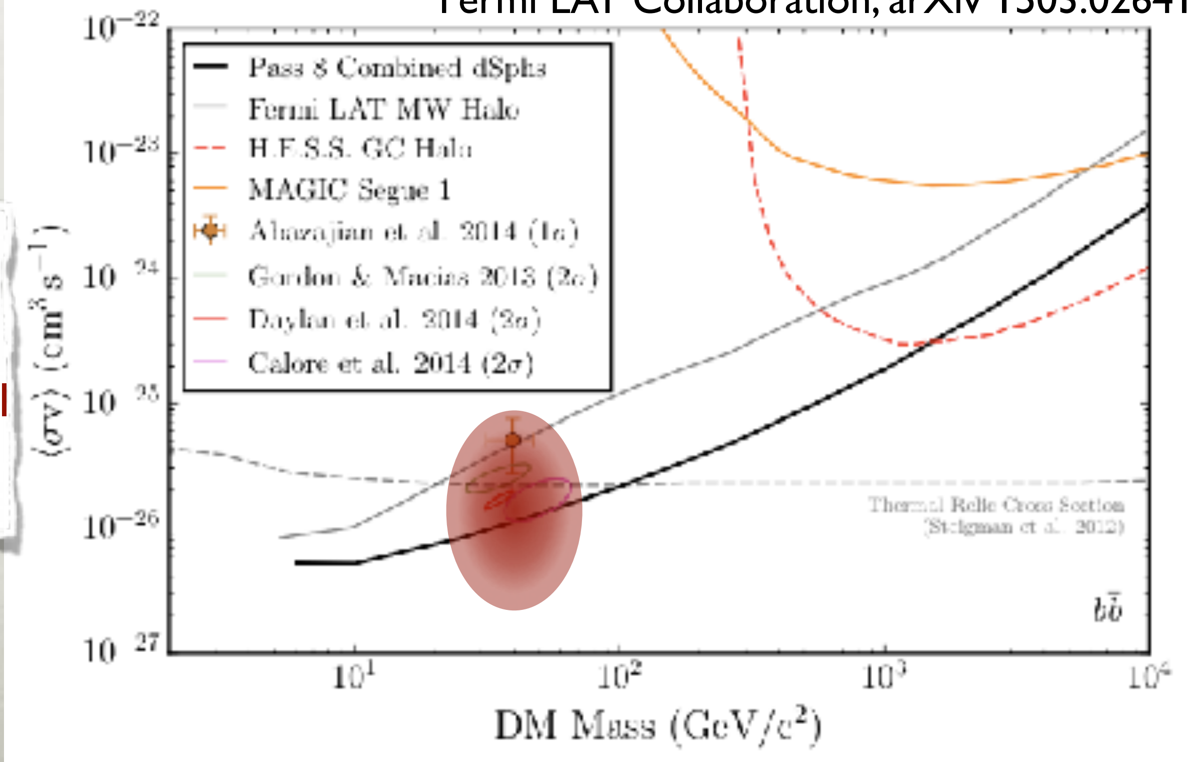


N.B.:
GC excess contours do not fully reflect uncertainties in the DM profile (see Abazajian et al arXiv:1510.06424, Benito et al arXiv:1612.02010)

Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
    - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

Fermi LAT Collaboration, arXiv 1503.02641

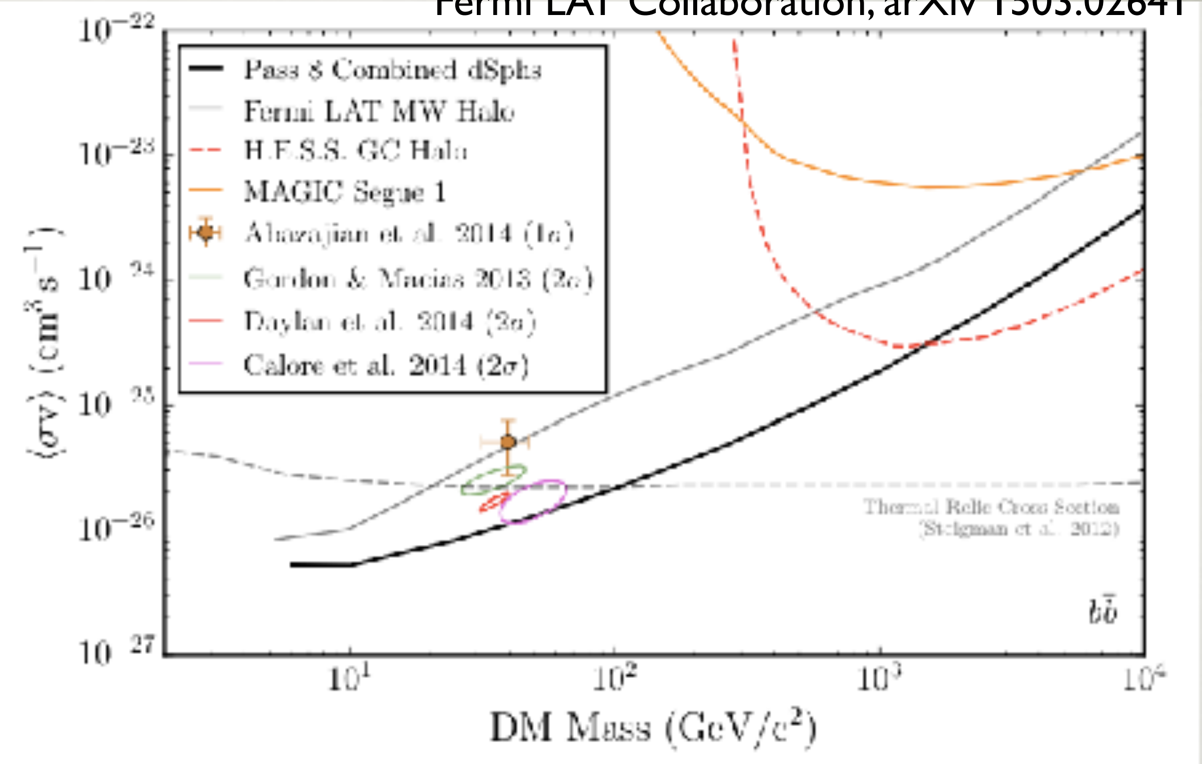


N.B.:
GC excess contours do not fully reflect uncertainties in the DM profile (see Abazajian et al arXiv:1510.06424, Benito et al arXiv:1612.02010)

Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

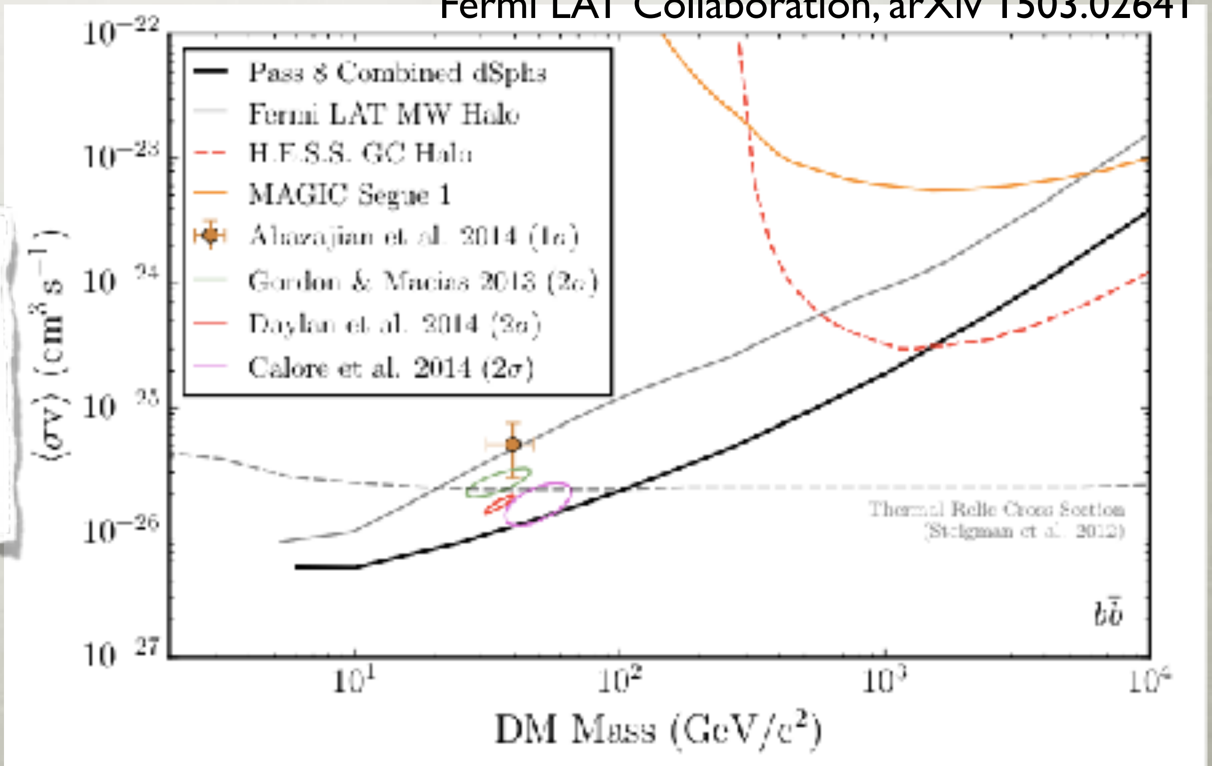
Fermi LAT Collaboration, arXiv 1503.02641



Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

Fermi LAT Collaboration, arXiv 1503.02641

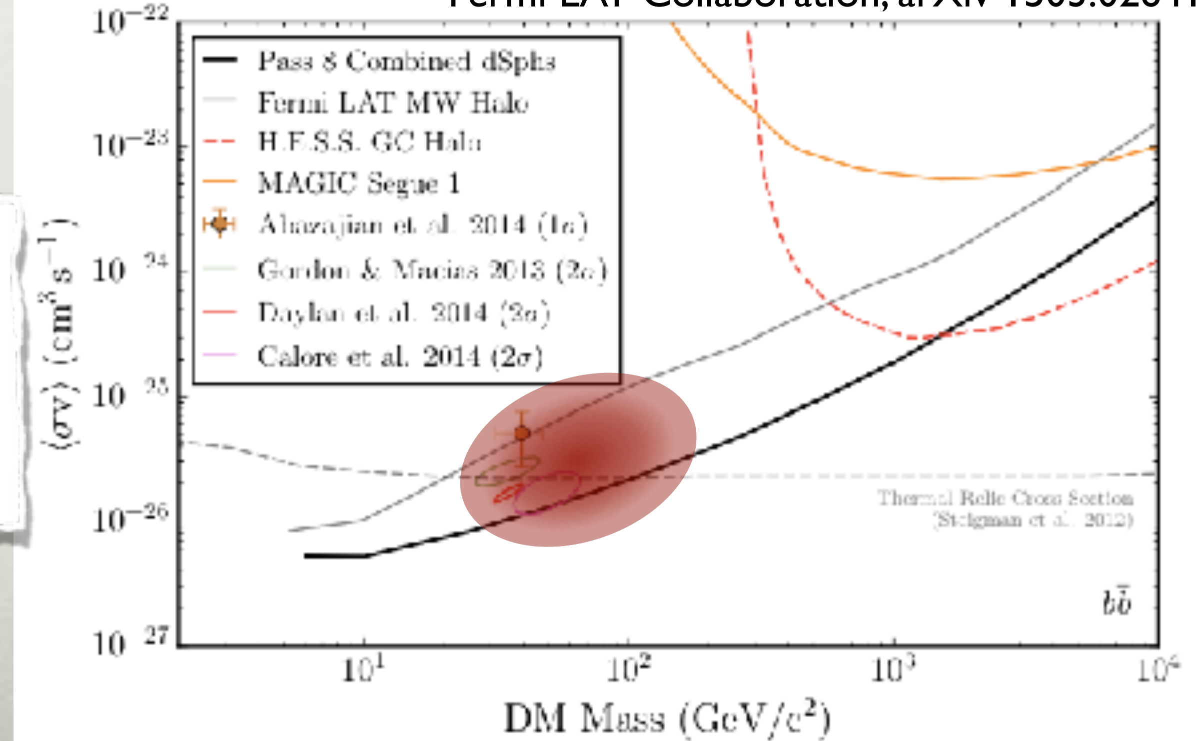


N.B.:
Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv: 1411.2592, Karwin et al arXiv:1612.05687)

Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

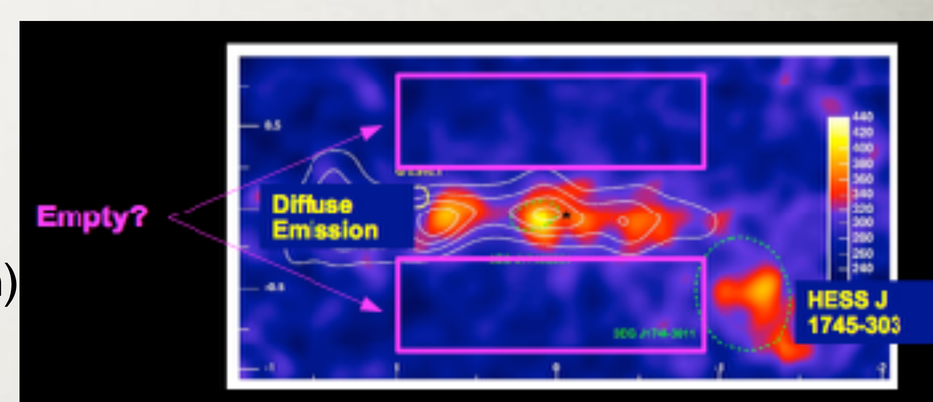
Fermi LAT Collaboration, arXiv 1503.02641

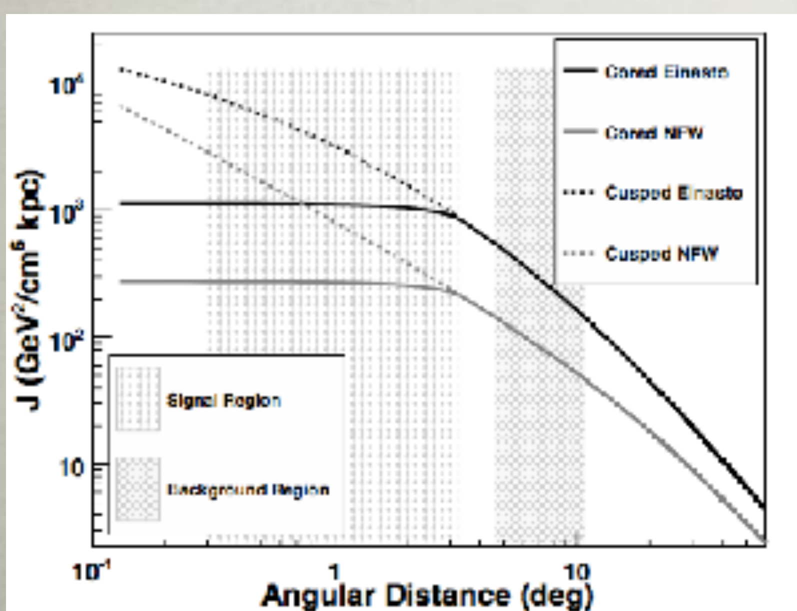


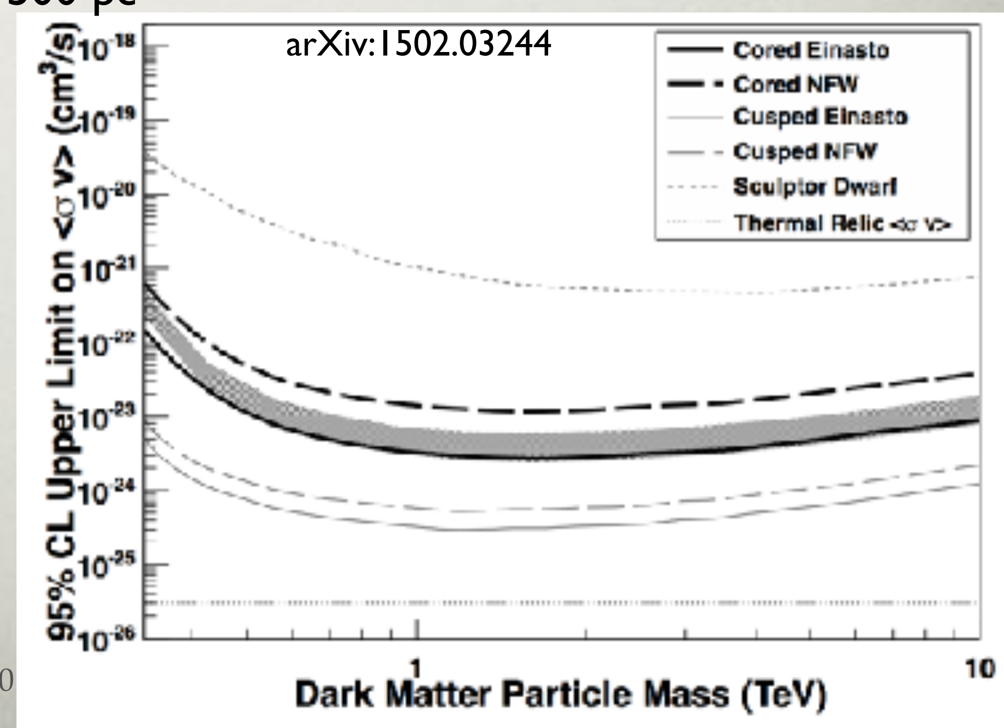
N.B.:
Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv: 1411.2592, Karwin et al arXiv:1612.05687)

H.E.S.S.: Galactic Center Region

- GC is complicated by astrophysics, look away from it!
- Signal region: relatively close to GC but "free" from astrophysical background
- Select a region where the contribution from DM is smaller for background subtraction (background region)
- Small dependence on DM profile
- Limits are also derived for cored (constant within 500 pc from the GC) DM profiles



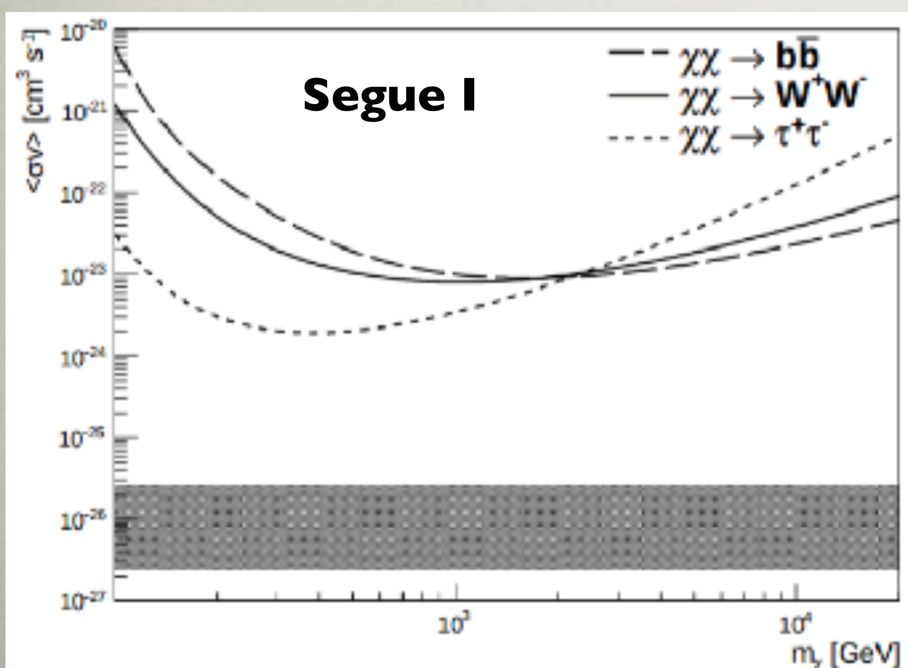




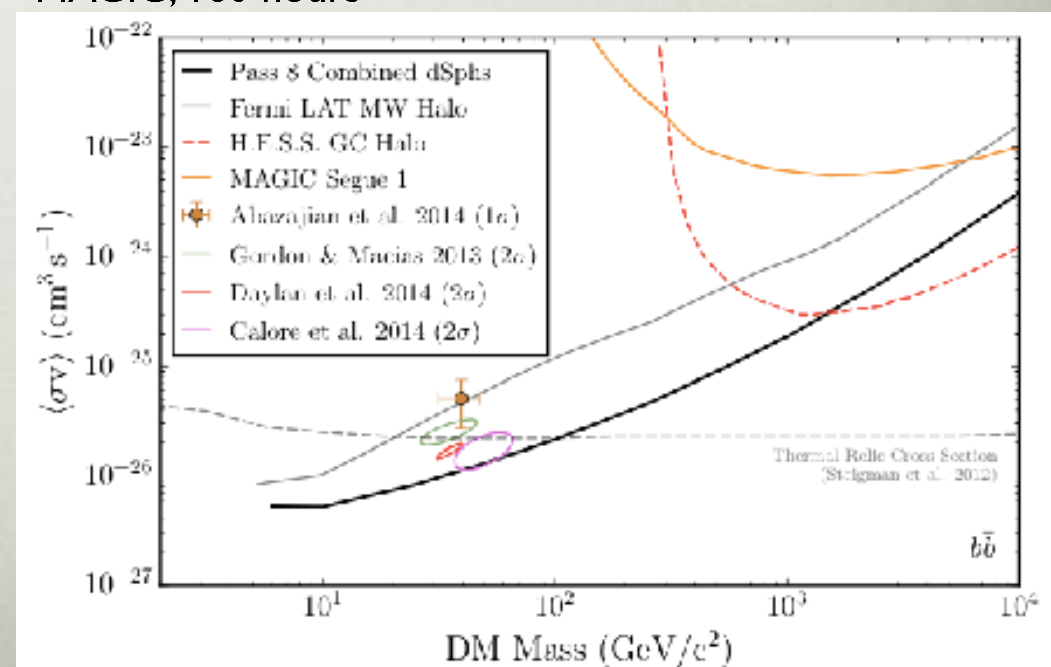
Dwarf Spheroidal Galaxies
IACTs

- Observations of dSphs with IACTs competitive with Fermi above DM masses ~3 TeV
- MAGIC latest results corresponding to 160 hrs of observation of Segue I are the strongest

VERITAS, 48 hours

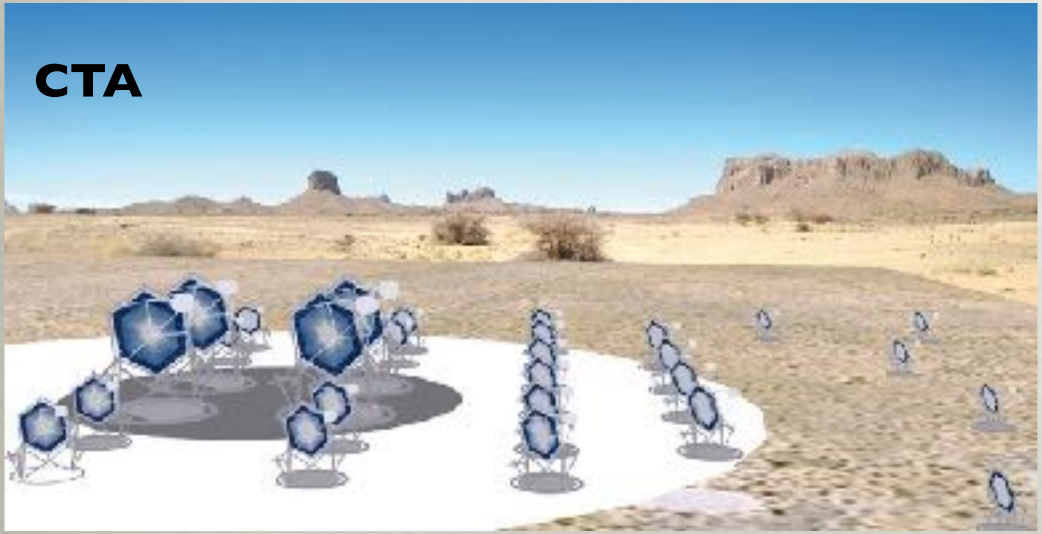


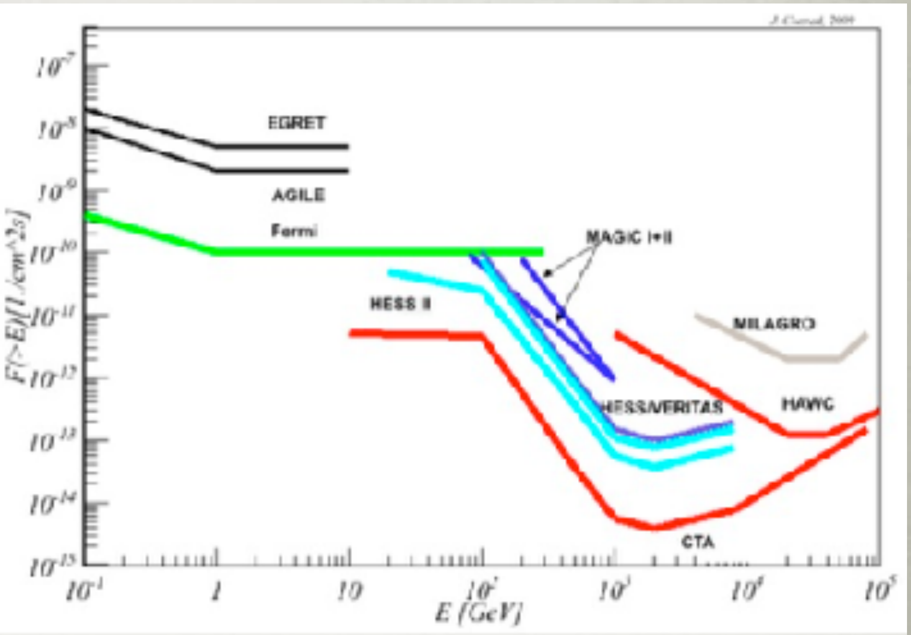
MAGIC, 160 hours



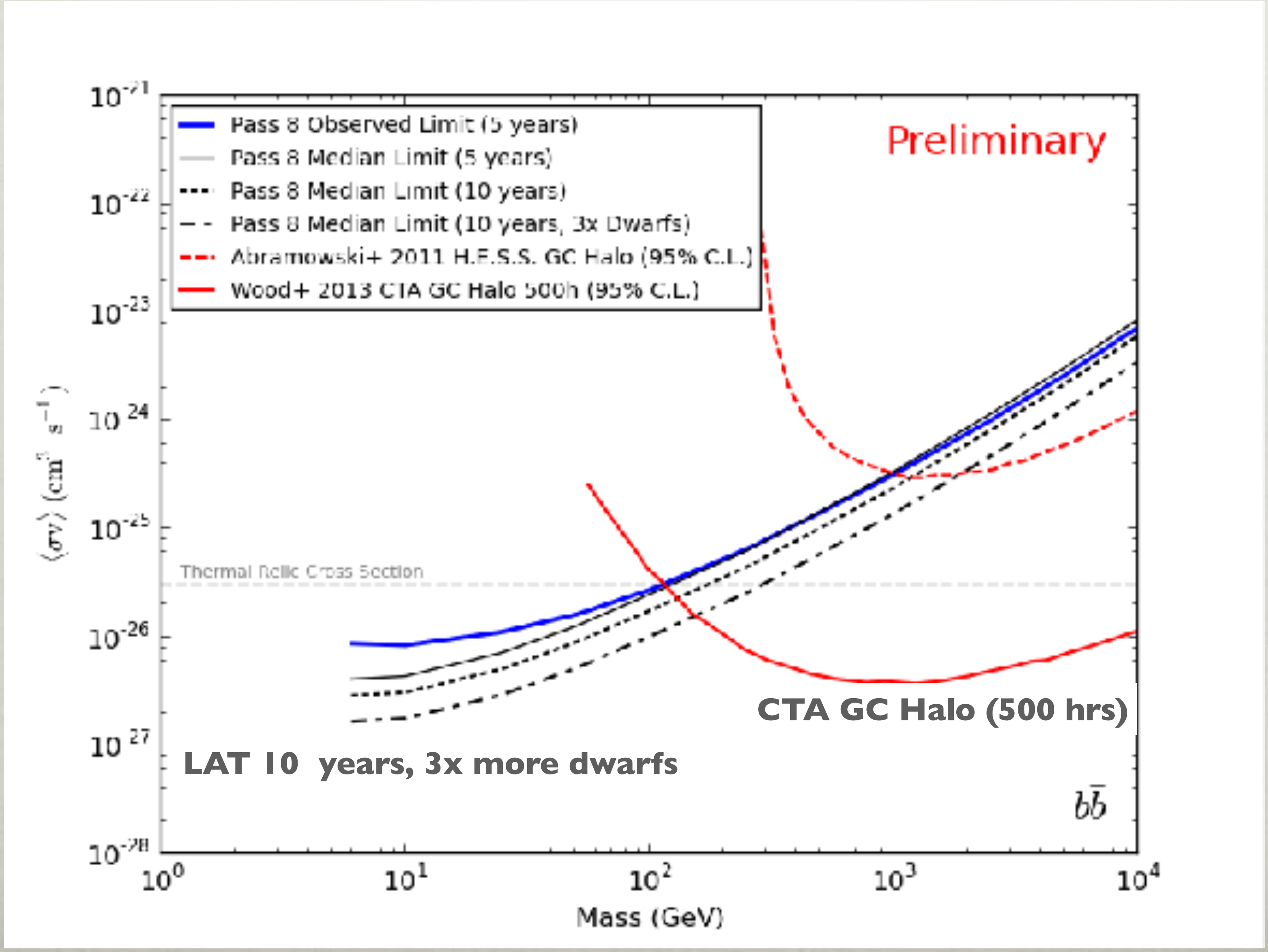
CTA

- Next generation gamma ray observatory
- Basic design: small core of large telescopes, surrounded by mid size telescopes and an outer ring of small telescopes
- Improve sensitivity of current ATCs (~10x), extend to lower and higher energies (~ 10s GeV to >100 TeV).

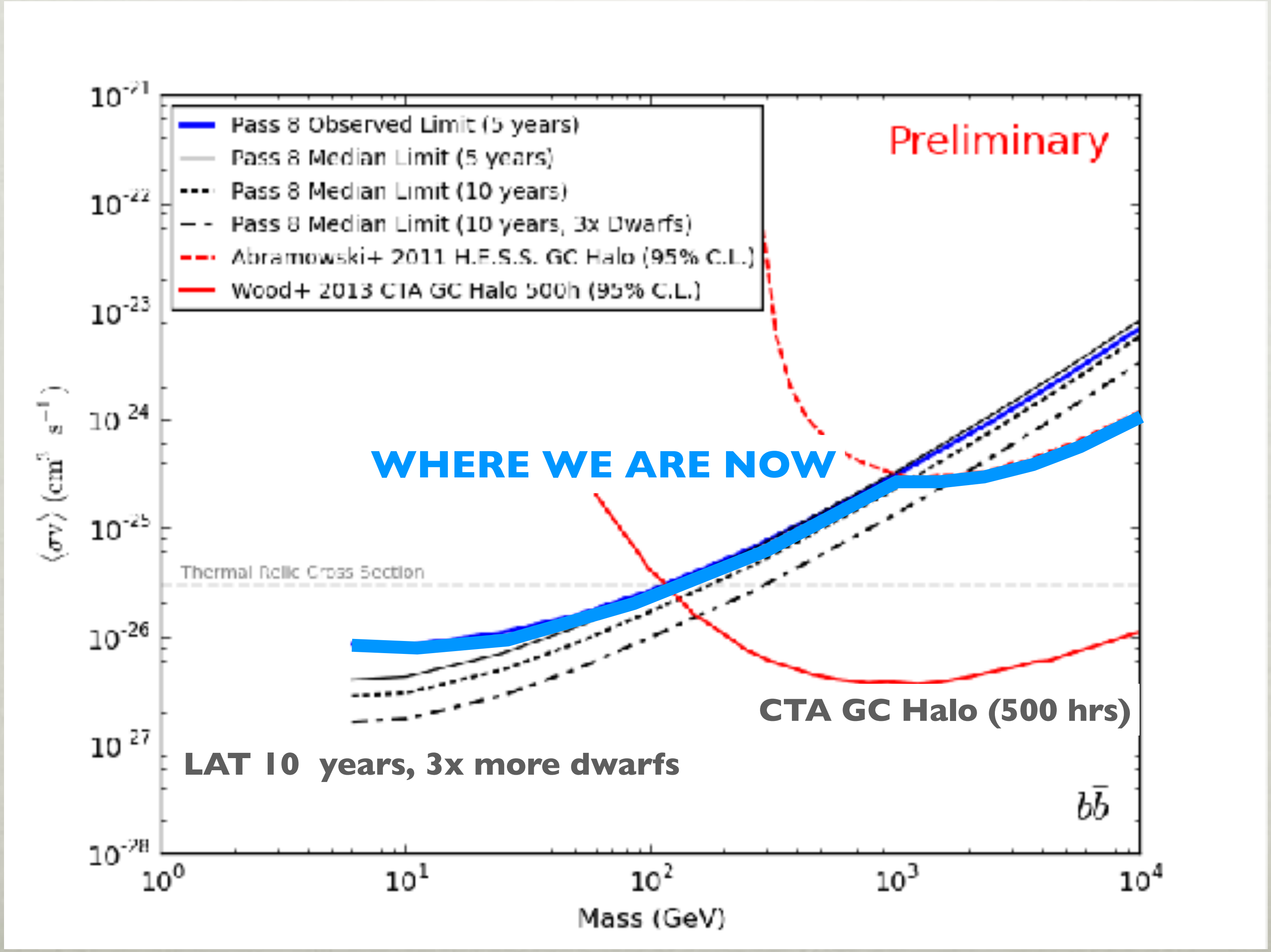




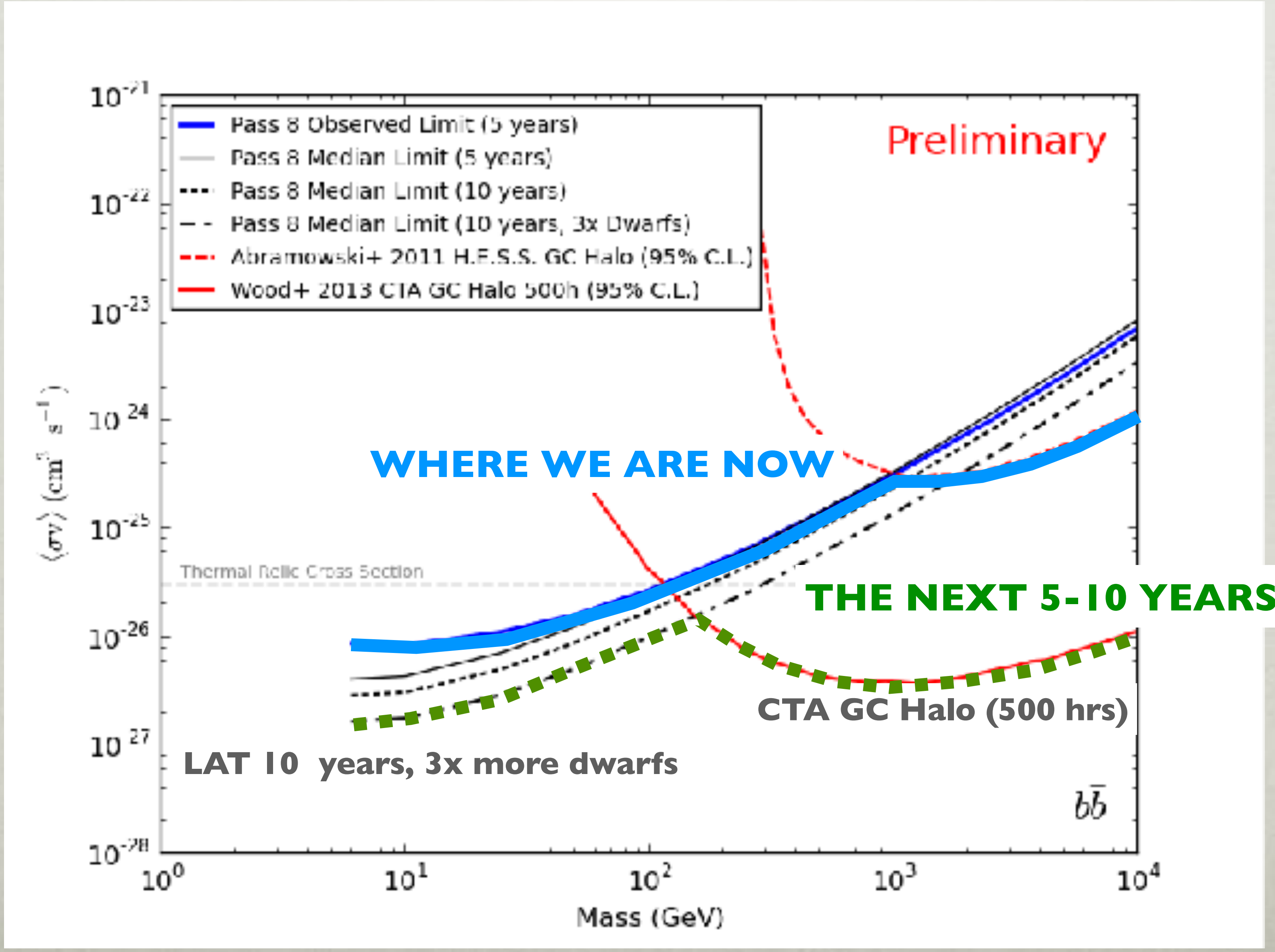
Putting it all Together



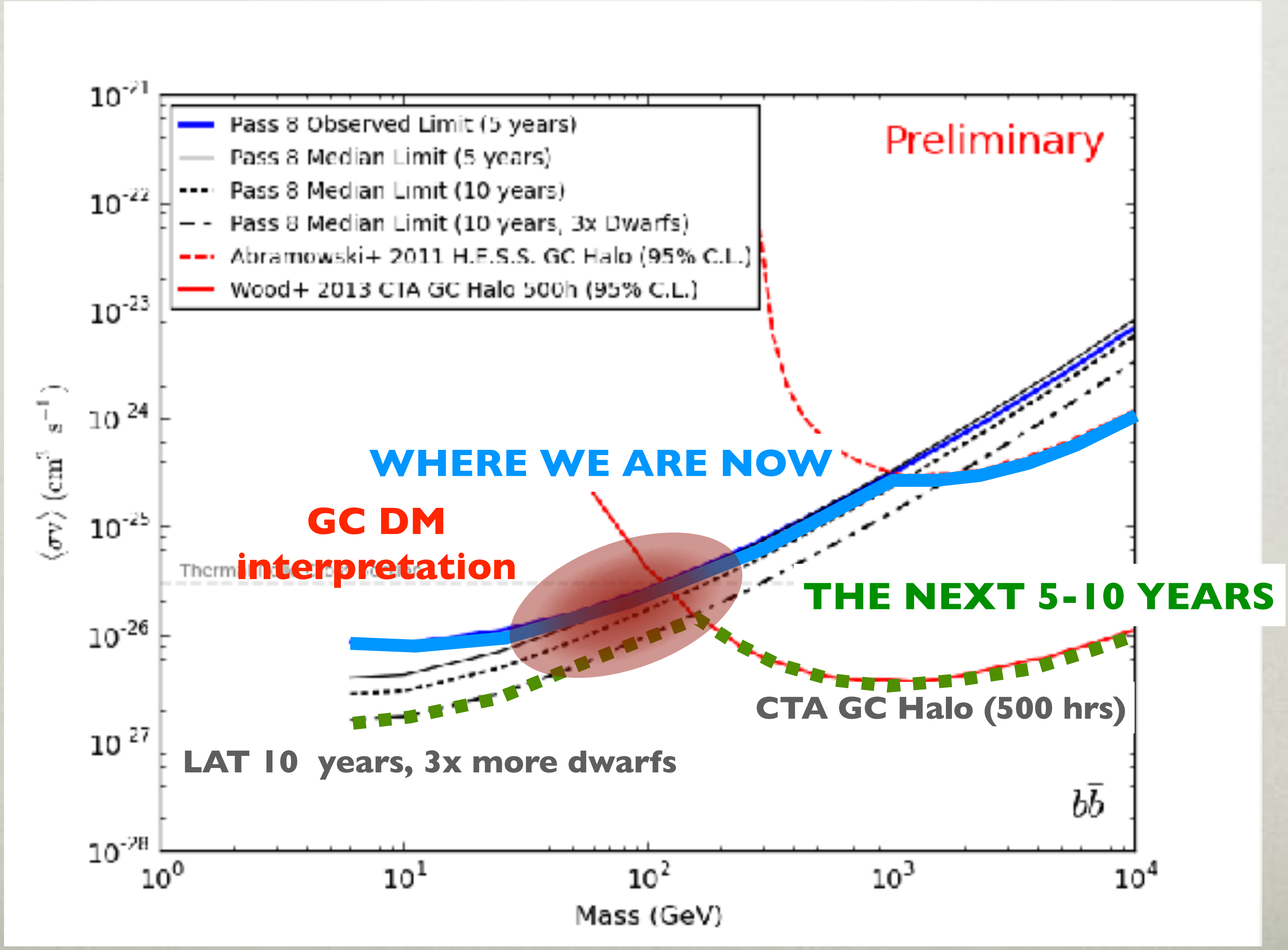
Putting it all Together



Putting it all Together



Putting it all Together

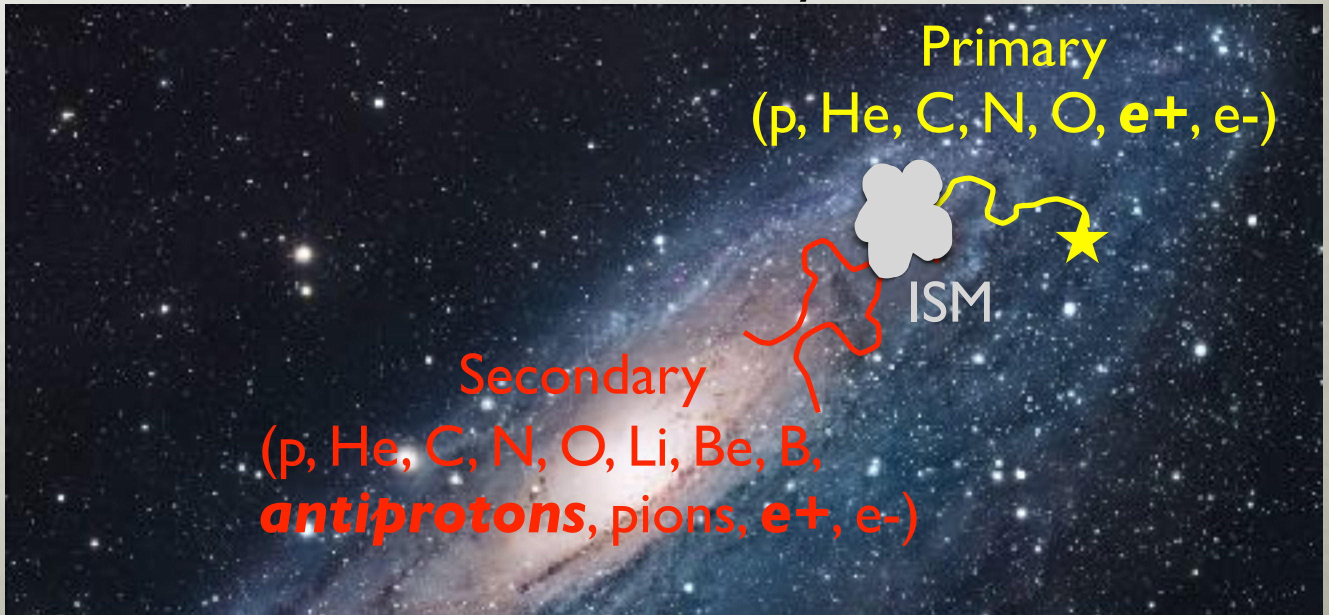


Cosmic rays

- **Antiparticles** are the better candidates for DM searches with charged CRs (far fewer are produced from conventional astrophysical processes)
- It is generally assumed they are produced as **secondaries** by interactions of primary CRs (accelerated at some source, e.g. supernova remnant) with the interstellar medium

➡ Anomalies/excesses in recent years are quoted with respect to this assumption!

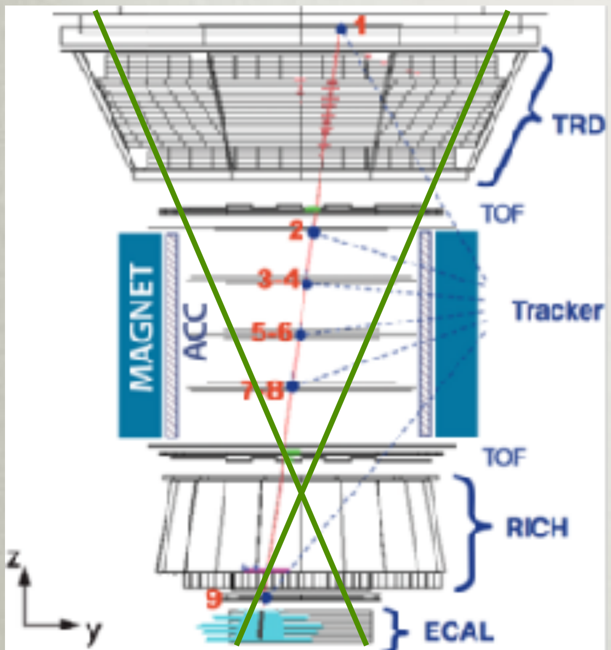
- Other production processes have been proposed to explain recent data, e.g. production and acceleration of secondaries at source, nearby source, in addition to dark matter



Cosmic rays

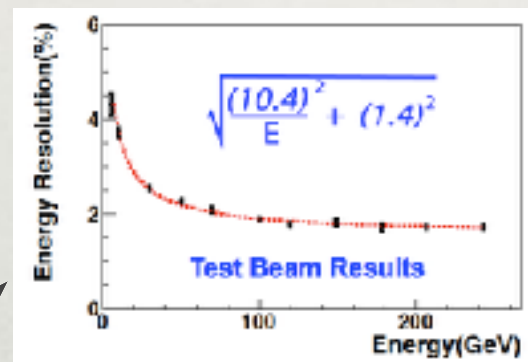
Magnetic spectrometers+

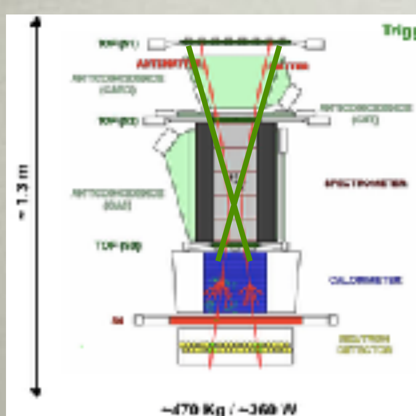
Charge discrimination, but smaller field of view and heavy



~3m

AMS-02



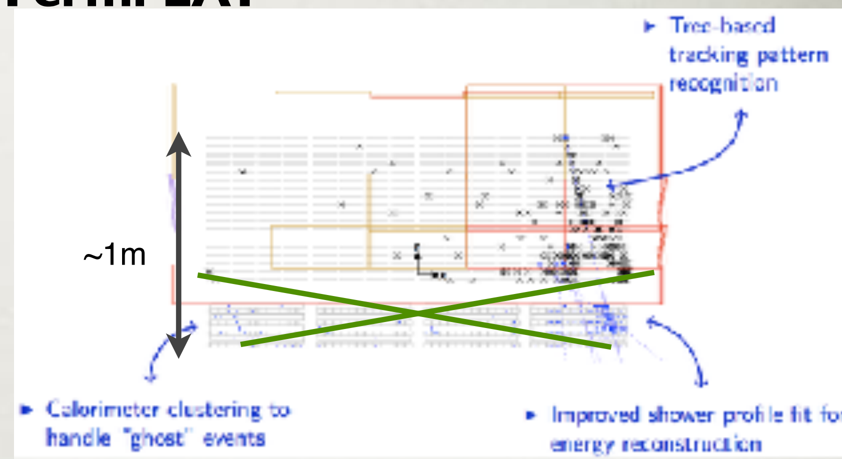


PAMELA

Energy resolution for e,γ: 5-15%

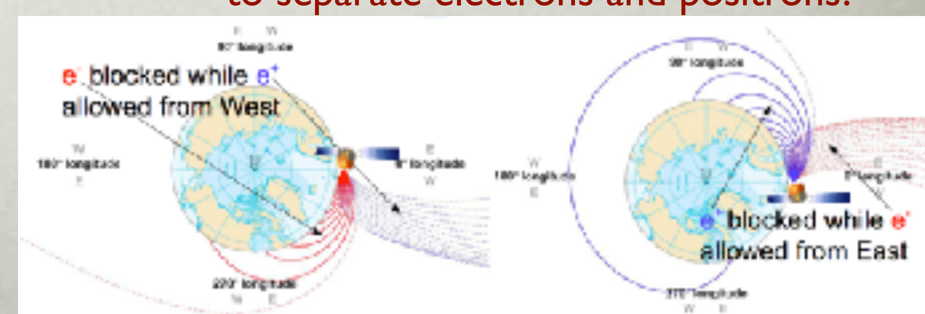
Calorimeters+

Fermi LAT



~1m

But can use the Earth magnetic field to separate electrons and positrons!

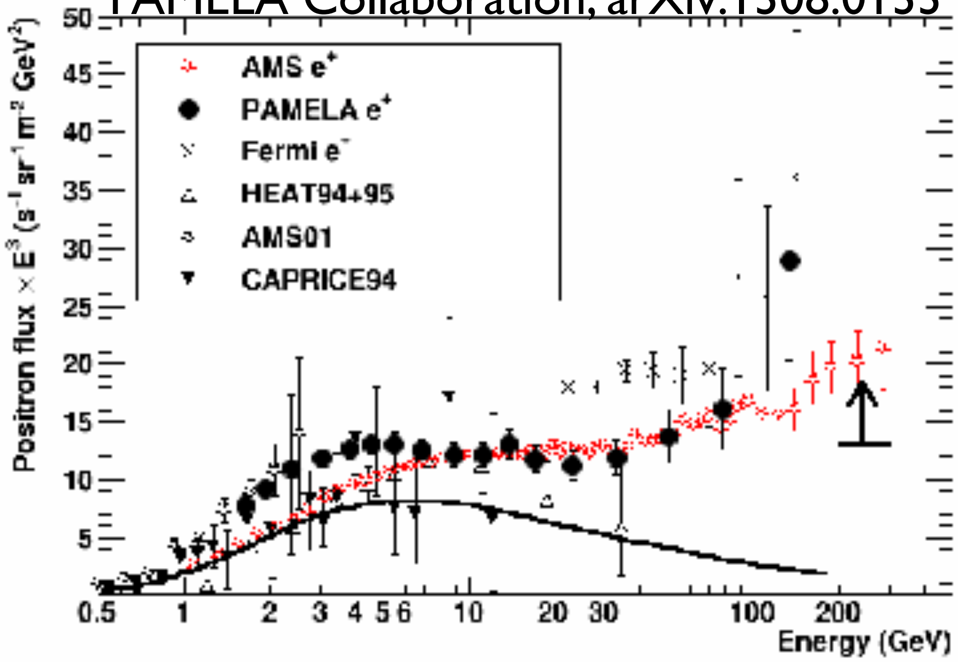


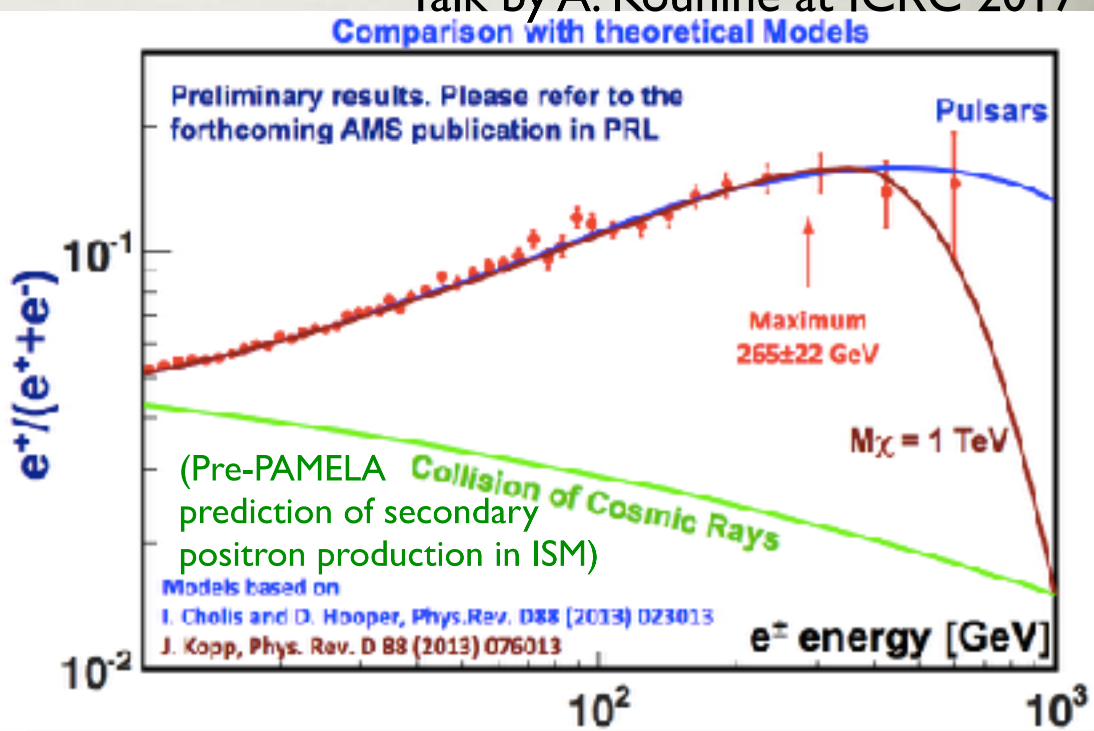
Positrons

- Positron fraction measured up to several hundred GeV (AMS-02). Rises at high energy, up to ~250 GeV

Talk by A. Kounine at ICRC 2017

PAMELA Collaboration, arXiv:1308.0133

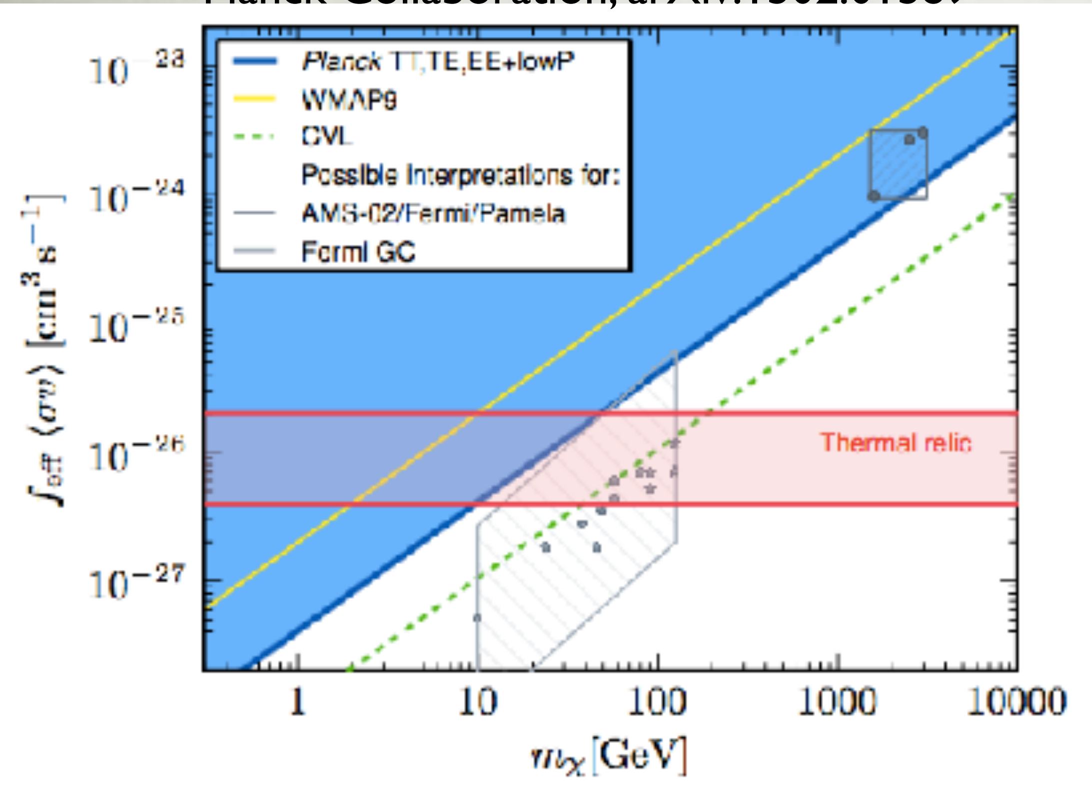




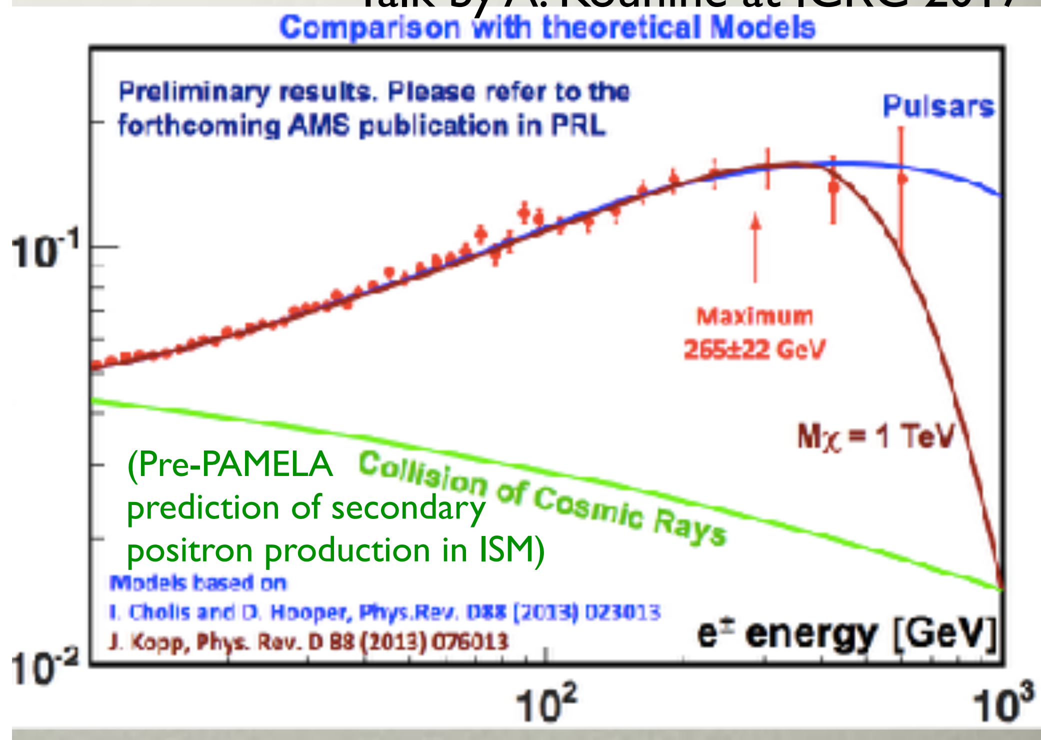
Positrons

- Positron fraction measured up to several hundred GeV (AMS-02). Rises at high energy, up to ~250 GeV
- Dark matter can reproduce the rise, but it is disfavored by other searches (gamma rays, CMB, …)

Planck Collaboration, arXiv:1502.01589



Talk by A. Kounine at ICRC 2017

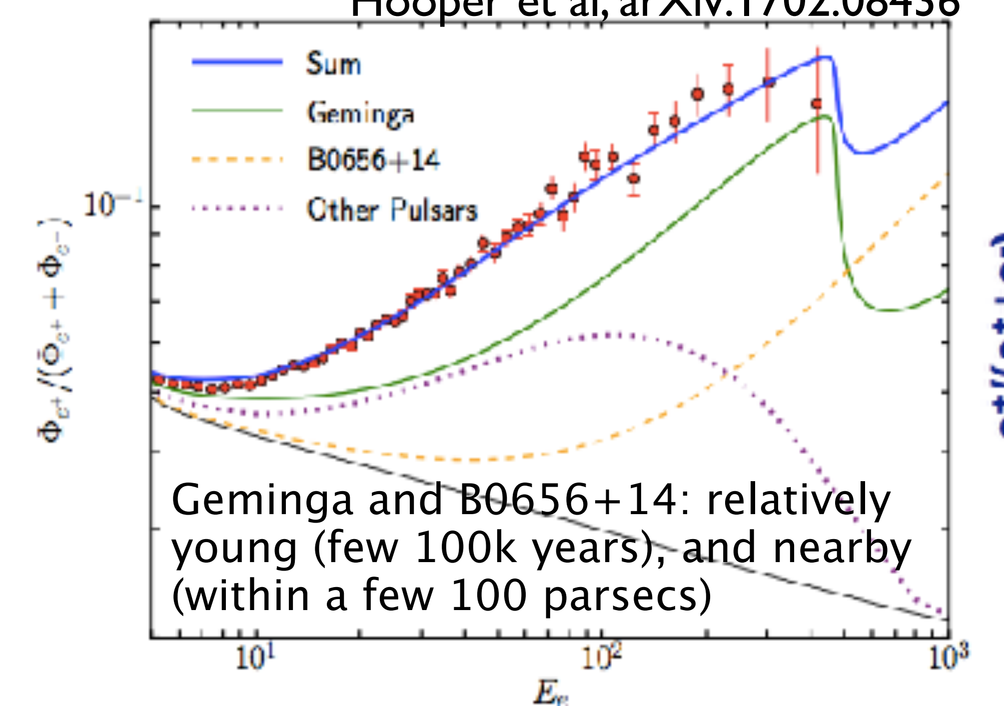


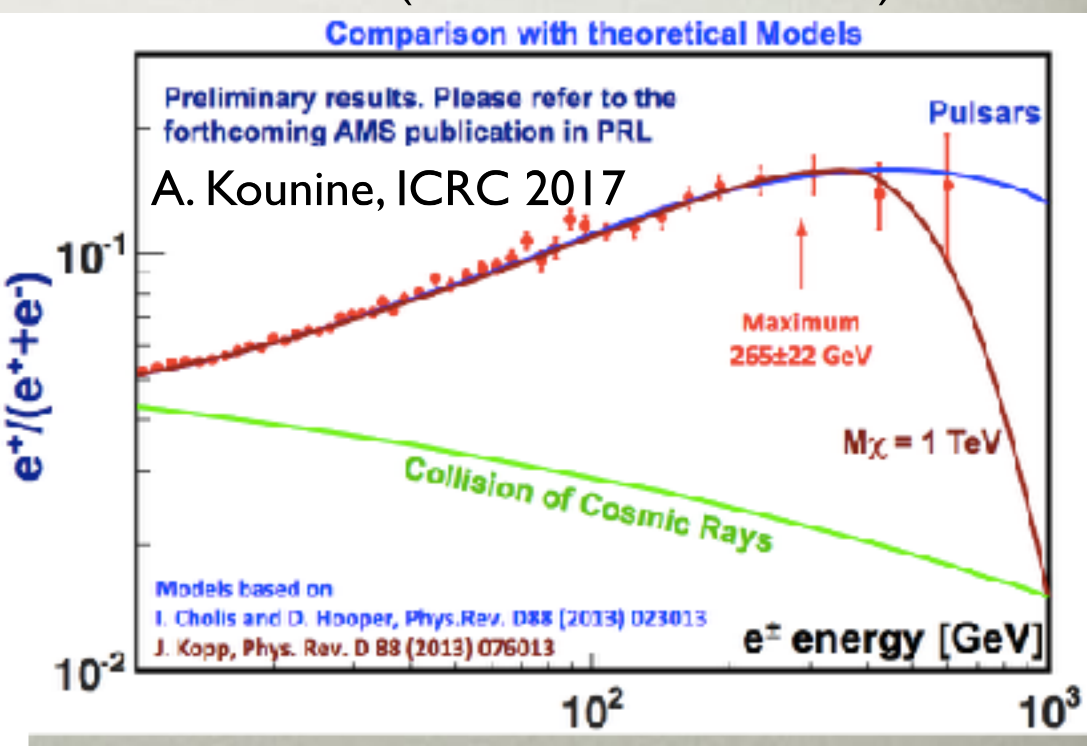
Positrons

- Other plausible interpretations (**nearby single source**, population of sources, production of secondaries at source, …)
- E.g., observations of very high energy gamma rays (HAWC and Milagro) from nearby pulsars predict a significant contribution from these sources to the high energy positron flux, which could explain the AMS-02 and PAMELA data, but see also Abeysekara et al arXiv:1711.06223

➡ Anisotropy in the e+e- data could confirm the nearby source hypothesis. Predicted anisotropy is consistent with current bounds (Fermi LAT, AMS-02)

Hooper et al, arXiv:1702.08436

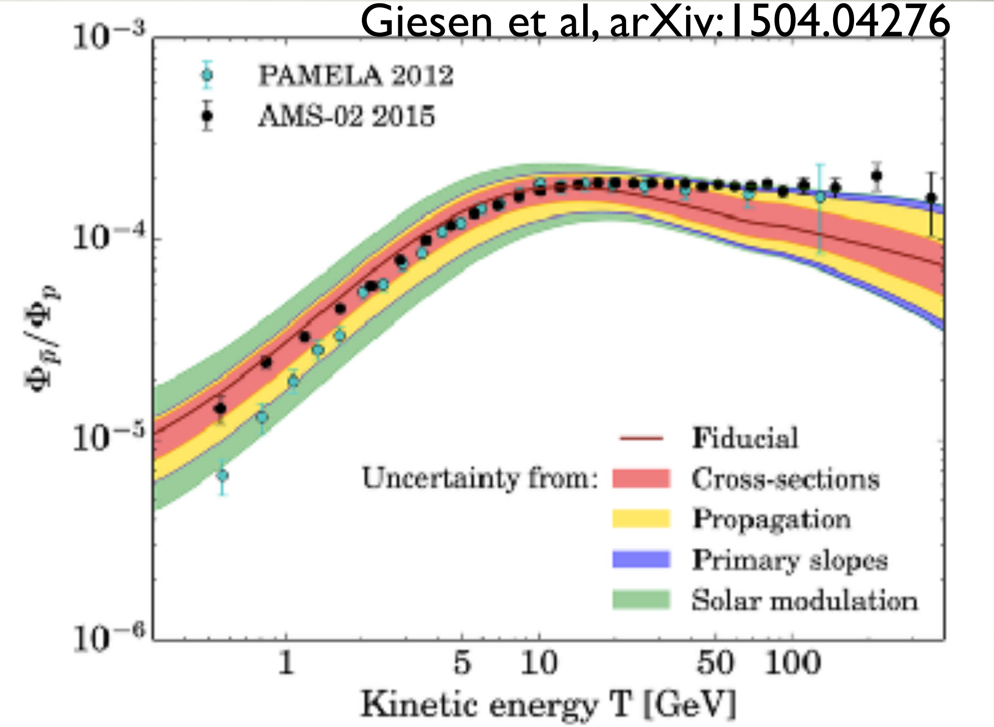




Antiprotons

- Generally in agreement with secondary production predictions (based on B/C measurements and antiprotons produced by CR interactions in the interstellar medium) also consistent with primary source to explain positron fraction

Giesen et al, arXiv:1504.04276

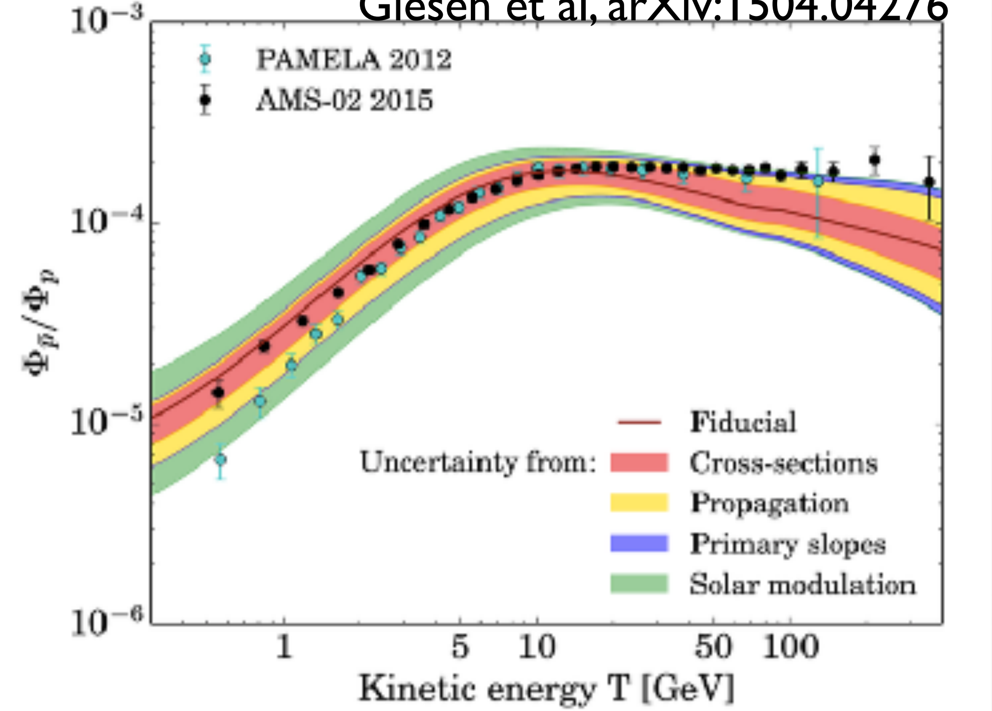


Antiprotons

- Generally in agreement with secondary production predictions (based on B/C measurements and antiprotons produced by CR interactions in the interstellar medium) also consistent with primary source to explain positron fraction

➡ LHCb measurement of the antiproton production cross section in p-He collisions crucial in reducing uncertainties in predictions for CR antiprotons

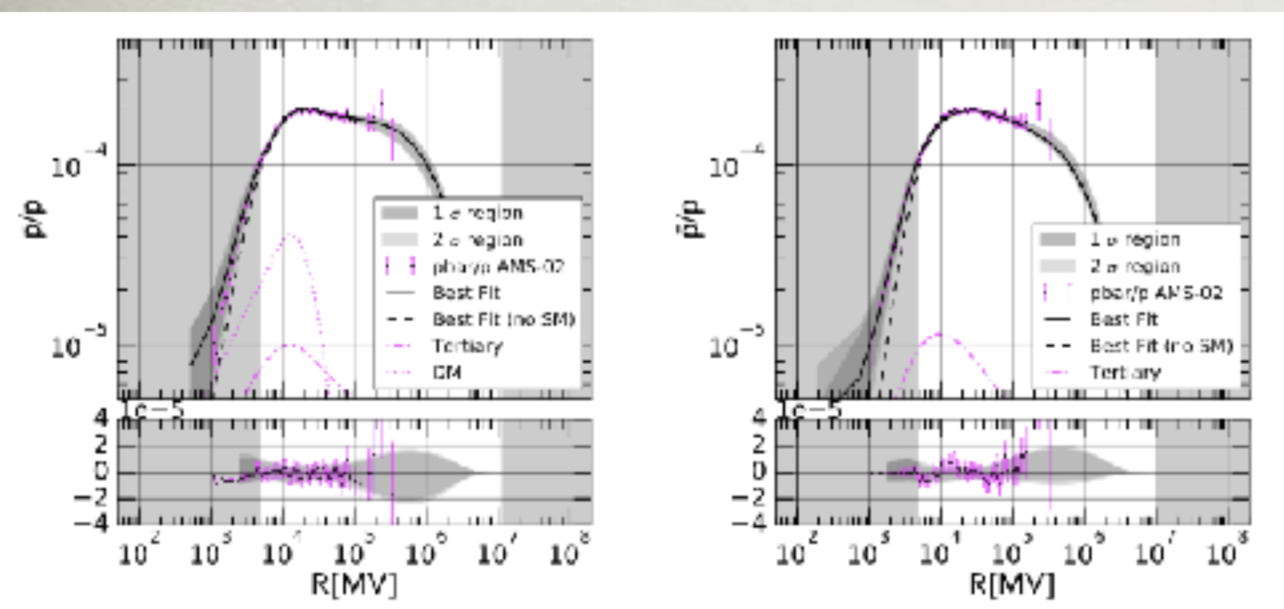
Giesen et al, arXiv:1504.04276

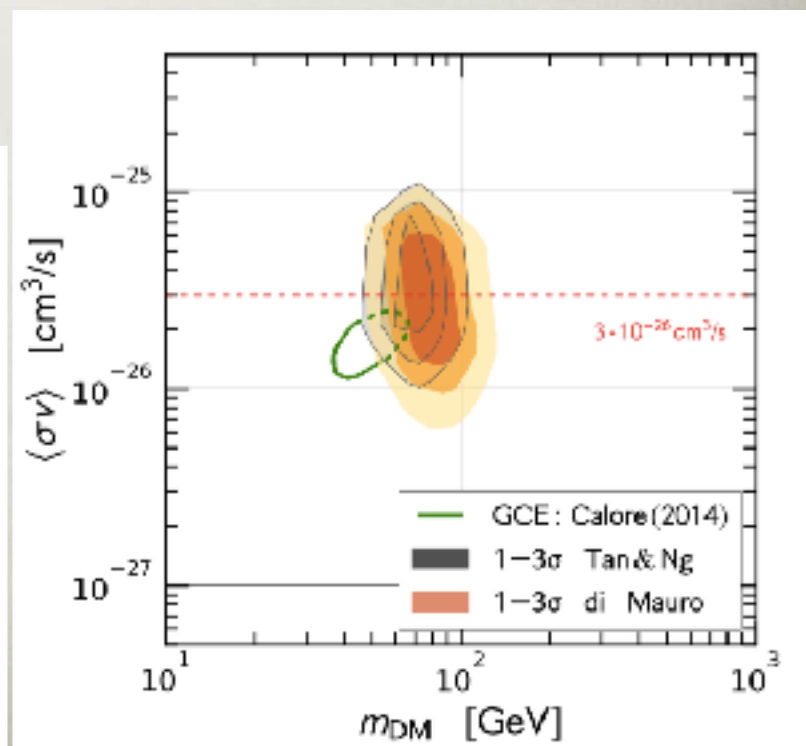


Antiprotons

- However, if a dark matter signal is fitted concurrently with CR propagation parameters, a signal is observed which is consistent with GC excess (assuming B/C is not representative of propagation for light nuclei, Johannesson et al, arXiv:1602.02243)

Cuoco et al, arXiv:1610.03071

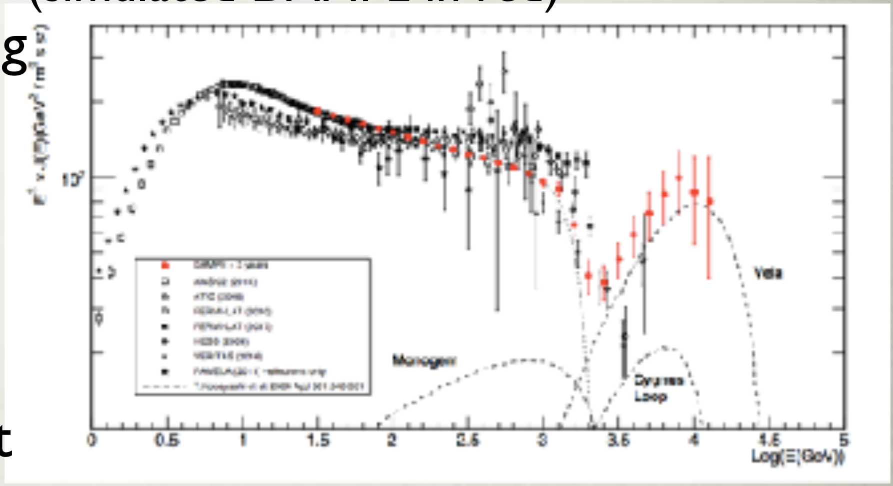


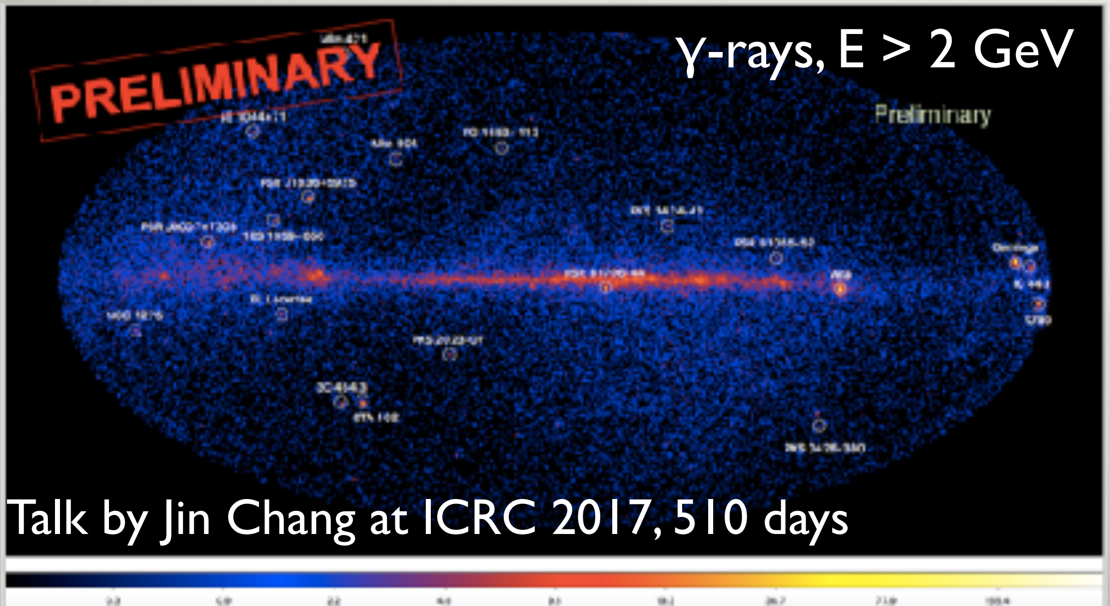


DAMPE

- Launched in Dec 2015. 1GeV - 10 TeV e/γ, 100 GeV - 100 TeV cosmic rays. Tracker+thick imaging calorimeter, excellent energy resolution (~1% @100 GeV, compare to ~10% for Fermi-LAT)
- Search for γ-ray lines, features in electron and positron spectra
- Recently claimed detection of a spectral break at E~0.9 TeV in the electron+positron spectrum

Electron and positron spectrum (simulated DAMPE in red)



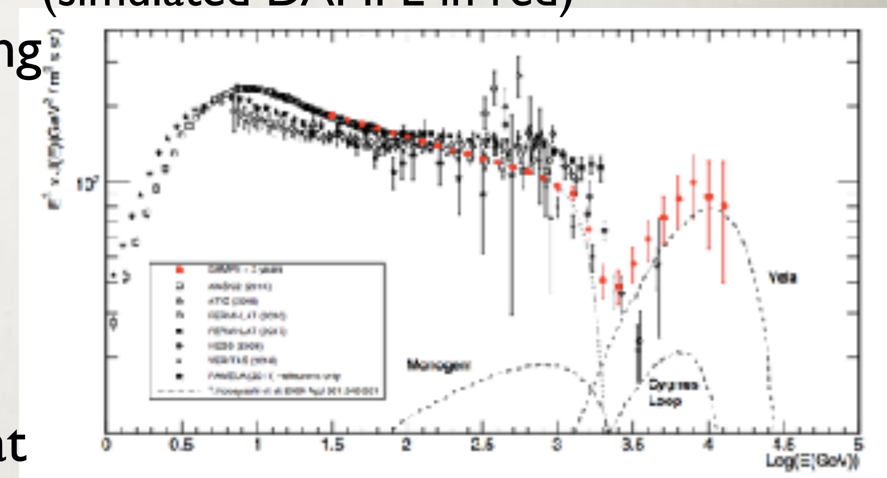


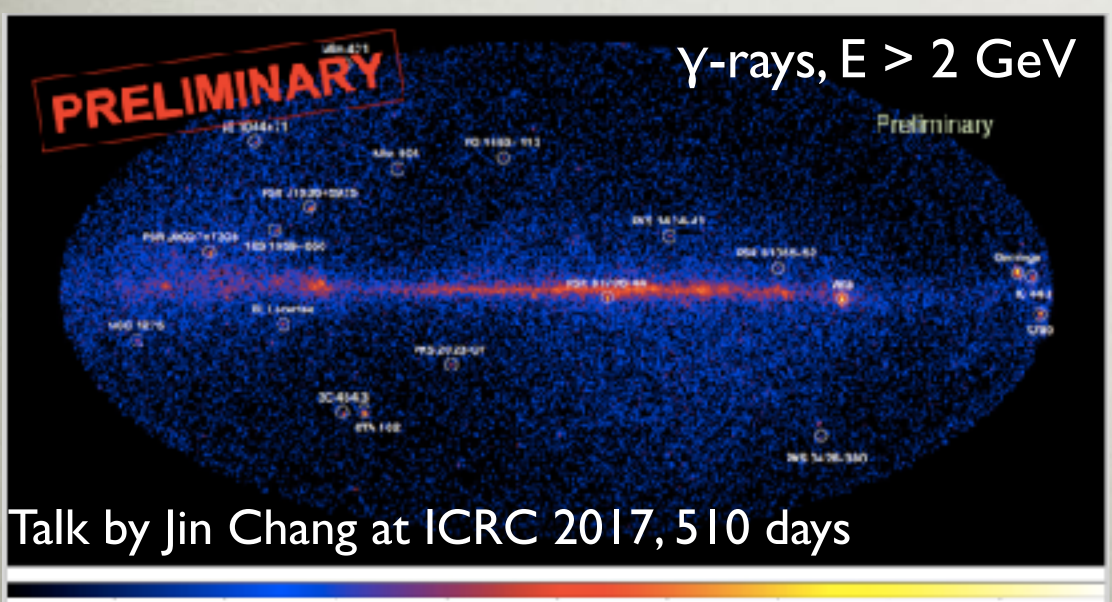
Talk by Jin Chang at ICRC 2017, 510 days

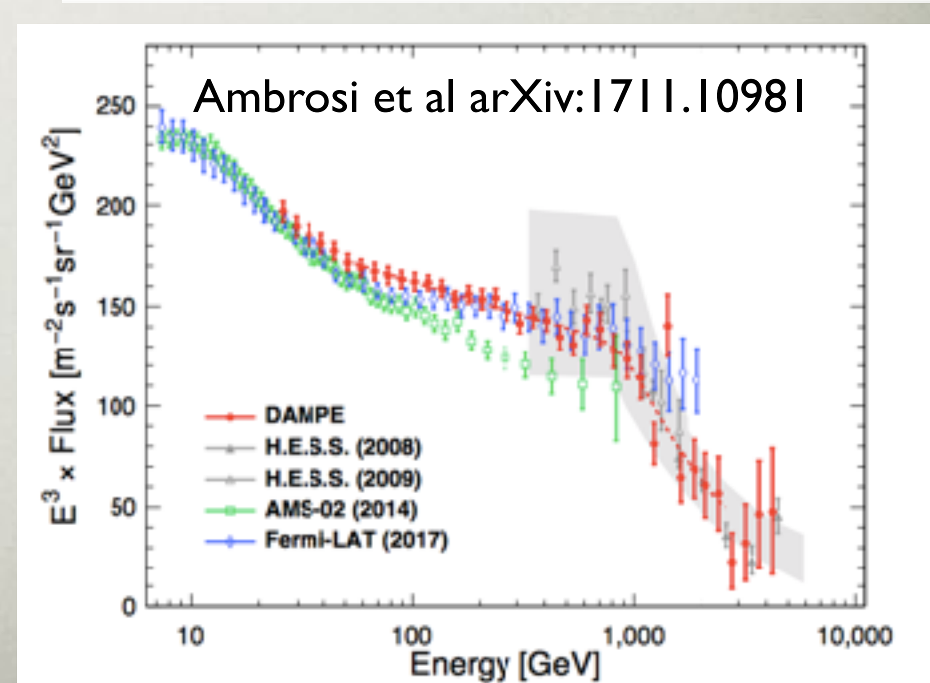
DAMPE

- Launched in Dec 2015. 1GeV - 10 TeV e/γ, 100 GeV - 100 TeV cosmic rays. Tracker+thick imaging calorimeter, excellent energy resolution (~1% @100 GeV, compare to ~10% for Fermi-LAT)
- Search for γ-ray lines, features in electron and positron spectra
- Recently claimed detection of a spectral break at E~0.9 TeV in the electron+positron spectrum

Electron and positron spectrum (simulated DAMPE in red)



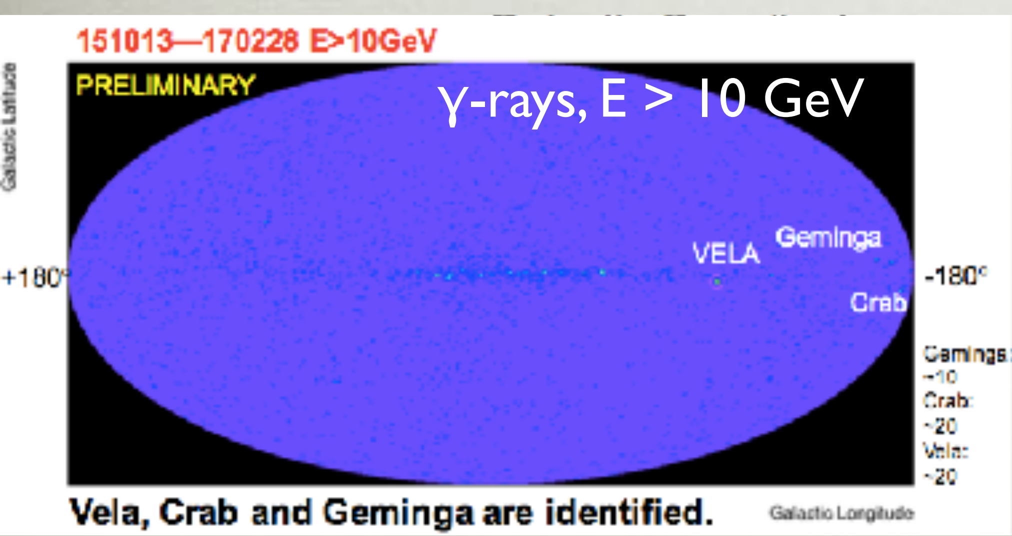


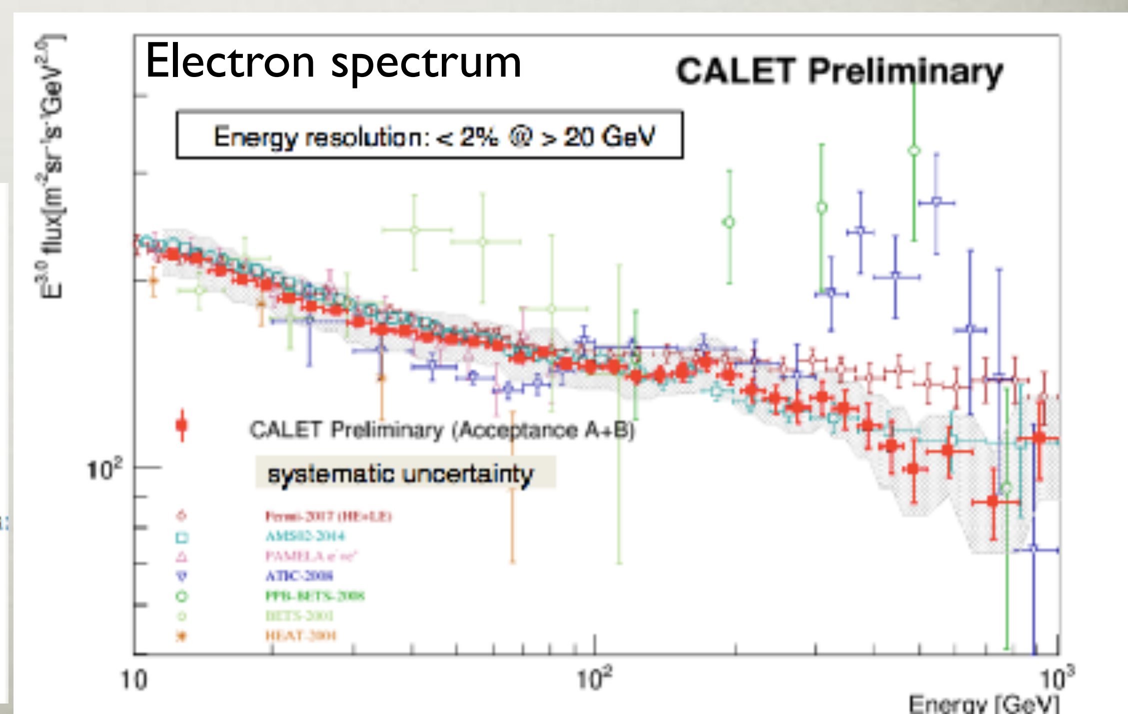


CALET

- On ISS since Aug 2015. 10 (1) GeV - 10 (20) TeV γ (e), 10's GeV - 1000 TeV nuclei. Thick calorimeter, excellent energy resolution.
- Test dark matter scenarios and interpretation via spectral features in e+e- and γ spectra, e.g. lines, LKP. Detection of nearby astrophysical sources of electrons
- High precision measurement of the electron spectrum at high energy with excellent energy resolution might reveal evidence of a nearby source (e.g. SNR)

Talk by Shoji Torii at ICRC 2017

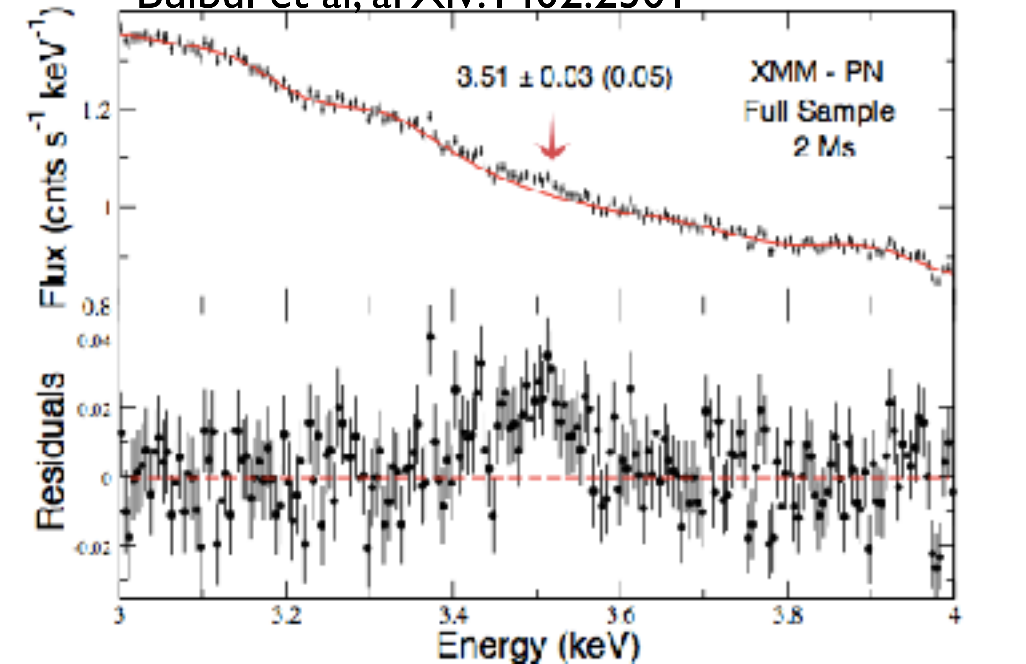




X-rays

- X-ray line at 3.5 keV observed by XMM-Newton and Chandra in the (stacked) data from clusters of galaxies, Perseus cluster, Andromeda galaxy, Galactic center (Bulbul et al, arXiv:1402.2301, Boyarsky et al, arXiv:1402.4119). Stacked clusters cover 0.01 < z < 0.35. *Line at same energy in the blue-shifted frame.*
- Possible interpretations: emission line of heavy ions (e.g. K, Ar) in the thermal plasma, DM in the form of a 7 keV **sterile neutrino**

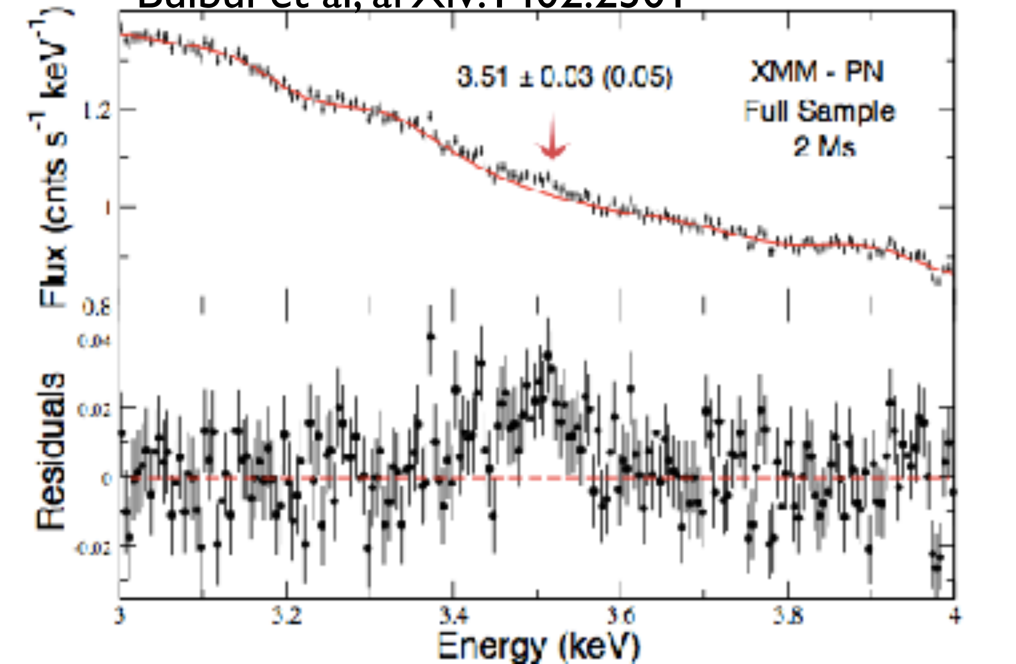
Bulbul et al, arXiv:1402.2301



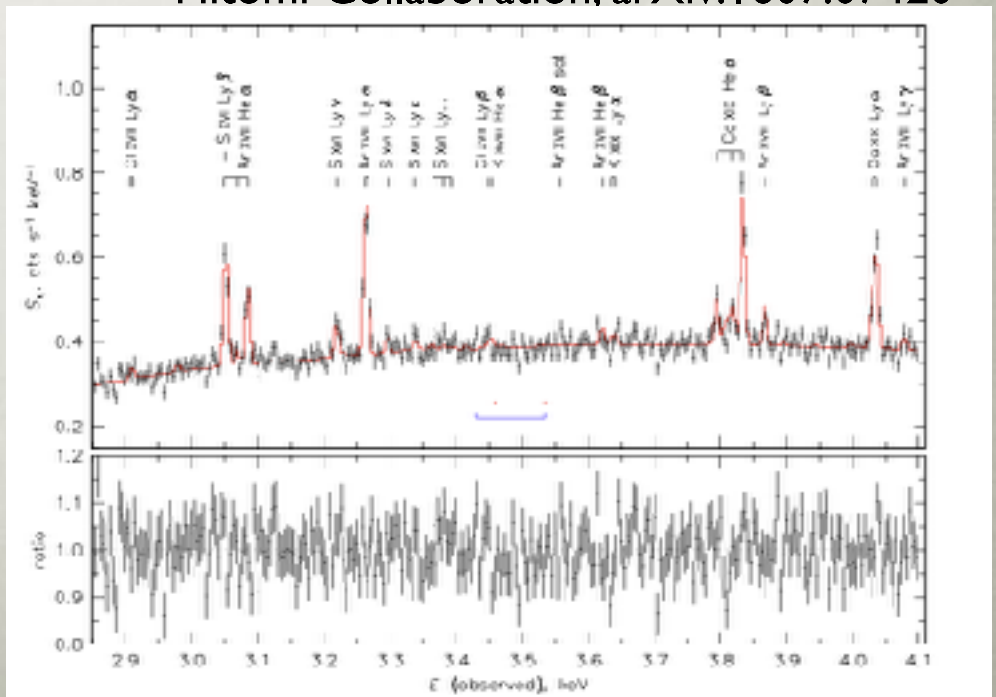
X-rays

- X-ray line at 3.5 keV observed by XMM-Newton and Chandra in the (stacked) data from clusters of galaxies, Perseus cluster, Andromeda galaxy, Galactic center (Bulbul et al, arXiv:1402.2301, Boyarsky et al, arXiv:1402.4119). Stacked clusters cover 0.01 < z < 0.35. *Line at same energy in the blue-shifted frame.*
- Possible interpretations: emission line of heavy ions (e.g. K, Ar) in the thermal plasma, DM in the form of a 7 keV **sterile neutrino**
- Hitomi (better spectral resolution), in its short life, does not confirm a significant line in the Perseus cluster, or the enhancement in some emission lines needed for the astrophysical interpretation

Bulbul et al, arXiv:1402.2301



Hitomi Collaboration, arXiv:1607.07420



X-rays

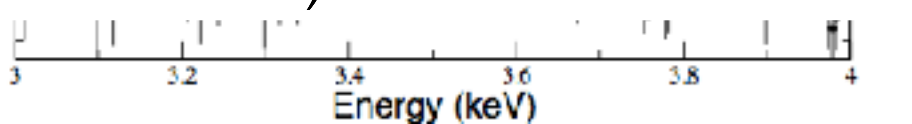
- X-ray line at 3.5 keV observed by XMM-Newton and Chandra in the (stacked) data from clusters of galaxies, Perseus cluster, Andromeda galaxy, Galactic center (Bulbul et al, arXiv: 1402.2301, Boyarsky et al, arXiv:1402.4119). Stacked clusters cover 0.01 < z < 0.35. *Line at same energy in the blue-shifted frame.*
- Possible interpretations: emission line of heavy ions (e.g. K, Ar) in the thermal plasma, DM in the form of a 7 keV **sterile neutrino**
- Hitomi (better spectral resolution), in its short life, does not confirm a significant line in the Perseus cluster, or the enhancement in some emission lines needed for the astrophysical interpretation

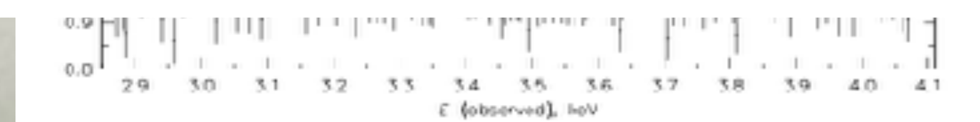
Hitomi Collaboration, arXiv:1607.07420

Bulbul et al, arXiv:1402.2301

➡ Future experiments will shed more light on this (e.g. Hitomi's replacement XARM in early 2020, Athena in late 2020)

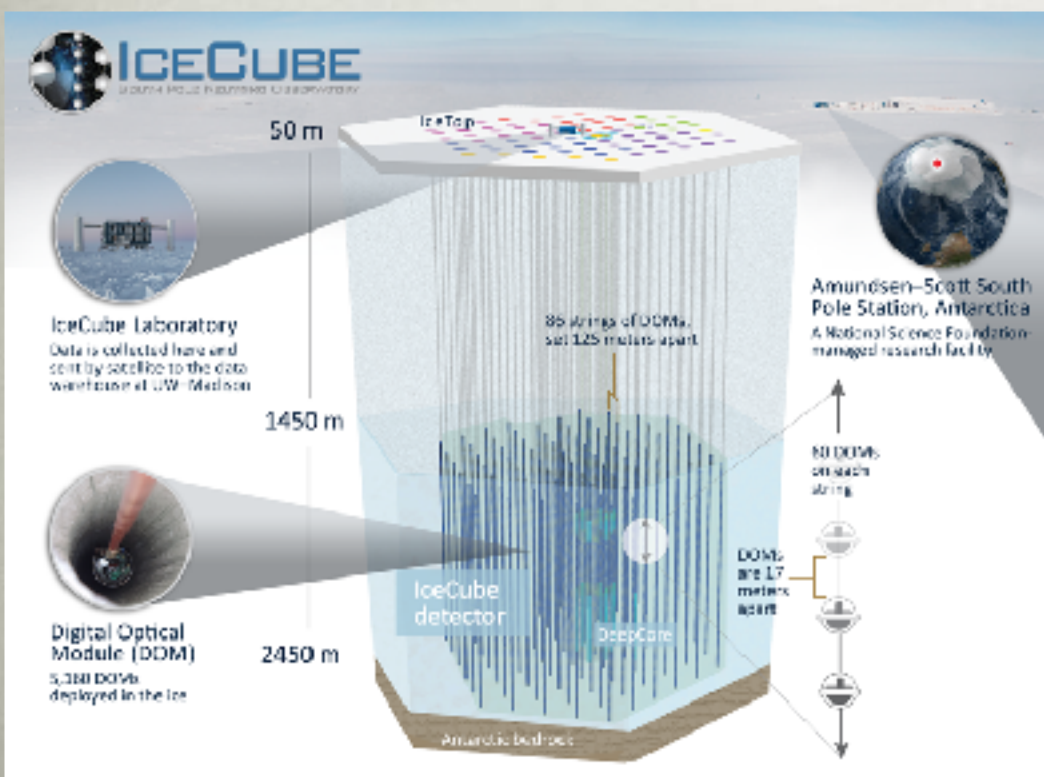
➡ Dark matter velocity spectroscopy might be able to distinguish between DM, astrophysical, or instrumental origin of line emission (Speckhard et al, arXiv: 1507.04744)





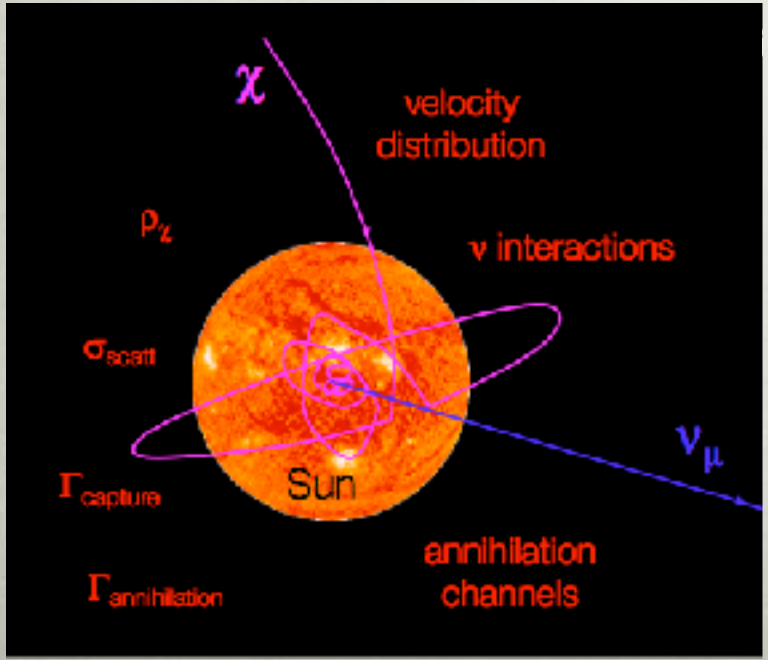
Neutrinos

- Neutrinos are generated by accelerated protons and nuclei interacting with surrounding medium
- Neutrinos can travel unimpeded from the source where they were generated thus carrying unique information on the origin of CRs
- The IceCube (South Pole) and ANTARES (Mediterranean Sea) neutrino telescopes search for these events



IceCube: Sun

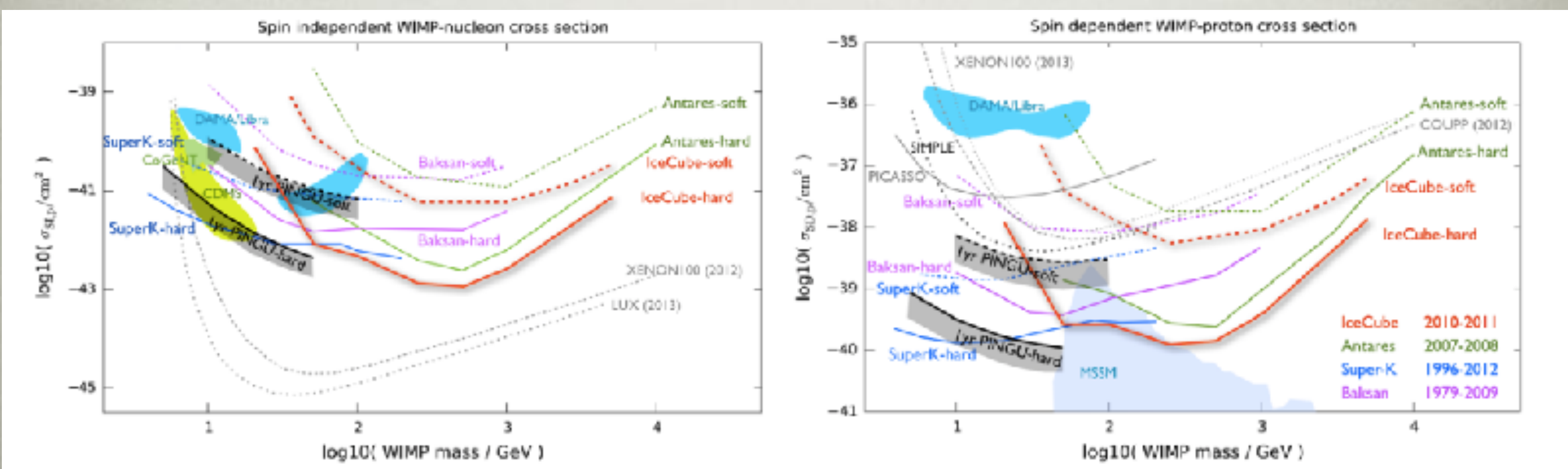
- Dark matter captured in the Sun
- Model uncertainties (velocity distribution, density, capture rate, scattering cross-section, annihilation cross-section, annihilation channel, and propagation/interaction/oscillation of neutrinos)



IceCube: Sun

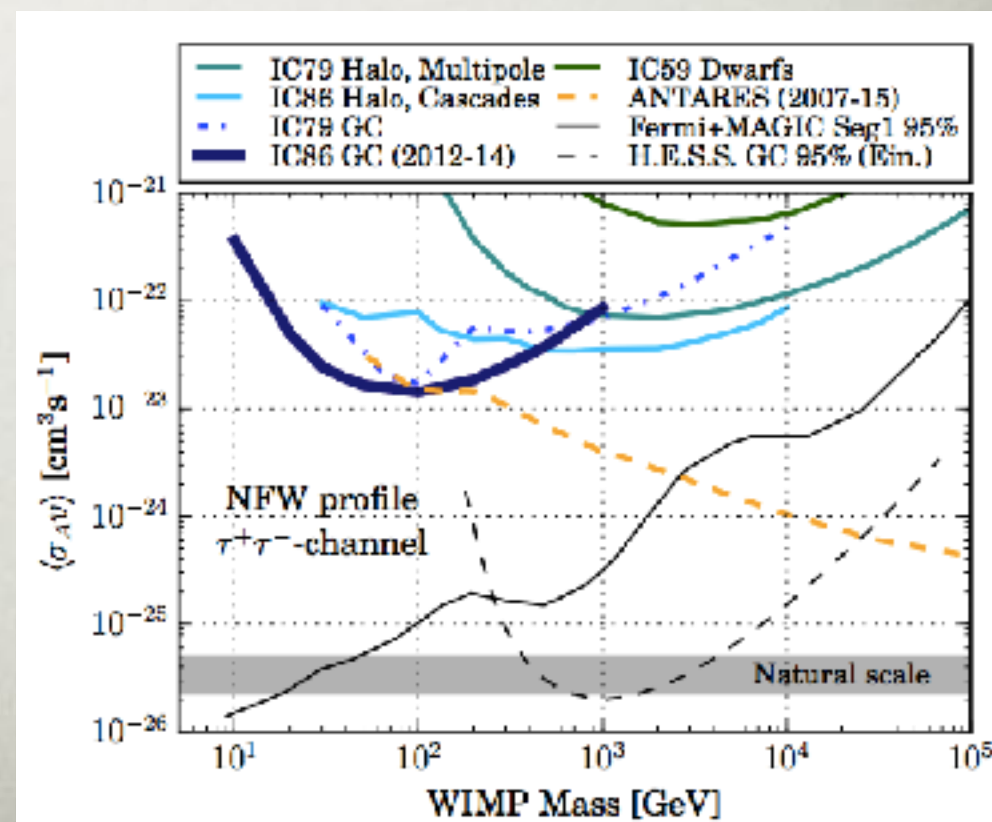
- Dark matter captured in the Sun
- Model uncertainties (velocity distribution, density, capture rate, scattering cross-section, annihilation cross-section, annihilation channel, and propagation/interaction/oscillation of neutrinos)
- Competitive limits compared to direct detection for spin-dependent interactions for heavy DM

$$\text{Soft} \rightarrow b\bar{b}$$
$$\text{Hard} \rightarrow W^+W^- \ (\tau \text{ below } W \text{ mass})$$



Galactic Center and Halo

- Search for a signal from the galactic center or halo
- Cleaner analysis than for solar DM
- Limits complementary to gamma-rays searches for heavy dark matter



Conclusions

- Intriguing hints of potential signals has been claimed, e.g. in gamma rays from the Galactic center. However the conventional astrophysics background is currently a limitation!

  Complementarity will also help, e.g. a consistent signal from other DM targets/searches (e.g. dSph, direct and collider DM searches) would provide most compelling confirmation of the DM interpretation for the GC gamma-ray excess
- The anomaly in the CR positron fraction remains, but many viable interpretations other than DM exist
- In the meanwhile, indirect dark matter searches continue to set strong constraints on the nature of DM
- Improvements in current experiments as well as upcoming experiments promise more interesting results to come
- Complementarity with direct detection and collider searches is crucial

Conclusions

- Intriguing hints of potential signals has been claimed, e.g. in gamma rays from the Galactic center. However the conventional astrophysics background is currently a limitation!

  Complementarity will also help, e.g. a consistent signal from other DM targets/searches (e.g. dSph, direct and collider DM searches) would provide most compelling confirmation of the DM interpretation for the GC gamma-ray excess
- The anomaly in the CR positron fraction remains, but many viable interpretations other than DM exist
- In the meanwhile, indirect dark matter searches continue to set strong constraints on the nature of DM
- Improvements in current experiments as well as upcoming experiments promise more interesting results to come
- Complementarity with direct detection and collider searches is crucial

Thank you!