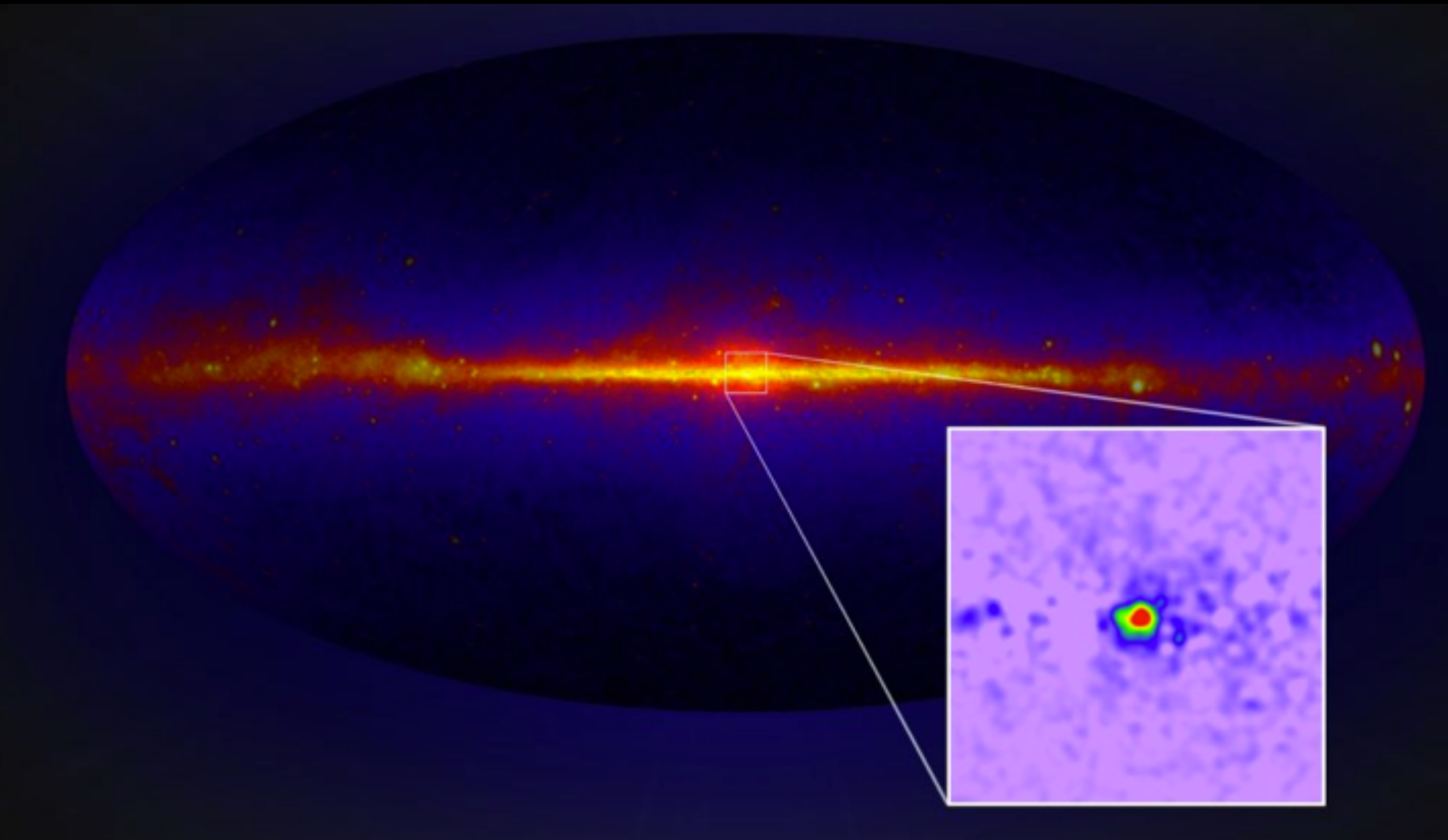


What is the Source of the Galactic Center Gamma-Ray Excess?

Tim Linden

Einstein Postdoctoral Fellow
Center for Cosmology and Astro-Particle Physics
The Ohio State University

CCAPP

The Ohio State University

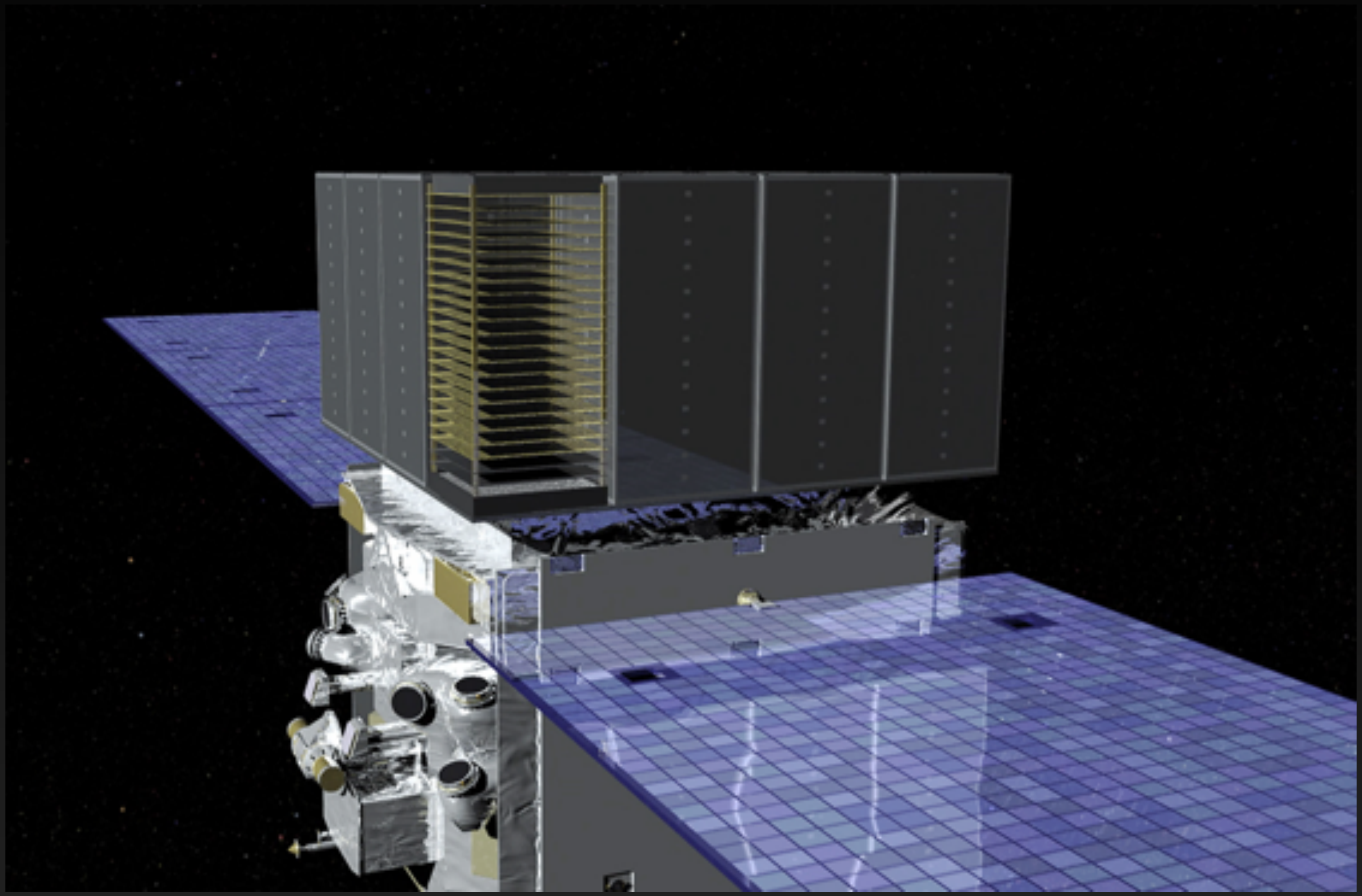
January 6, 2016

GeV Observations with the Fermi-LAT

Launched: June 2008

Observes Gamma-Rays with Energies 30 MeV - 1 TeV

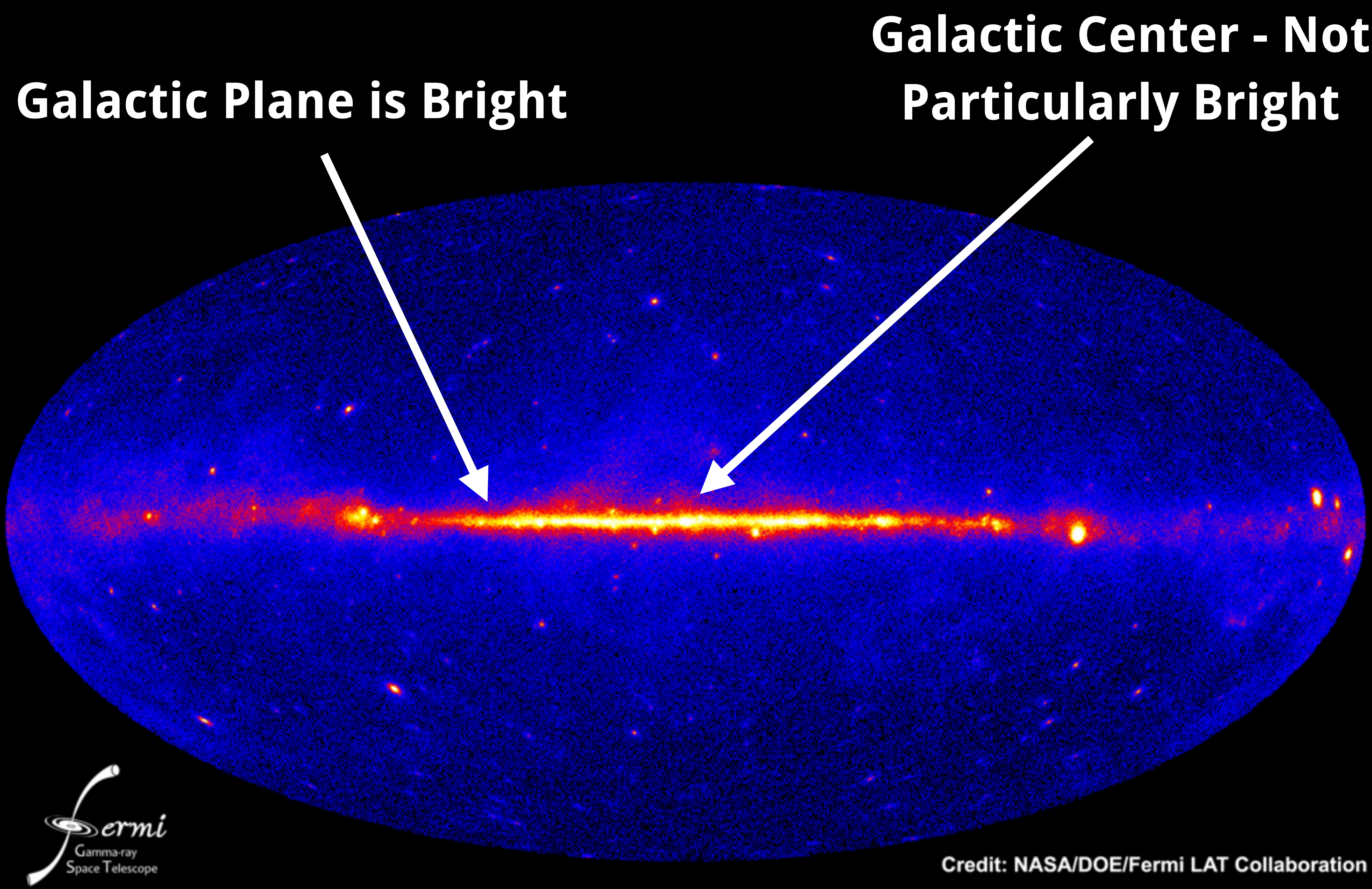
Collaboration of five countries and dozens of institutions.



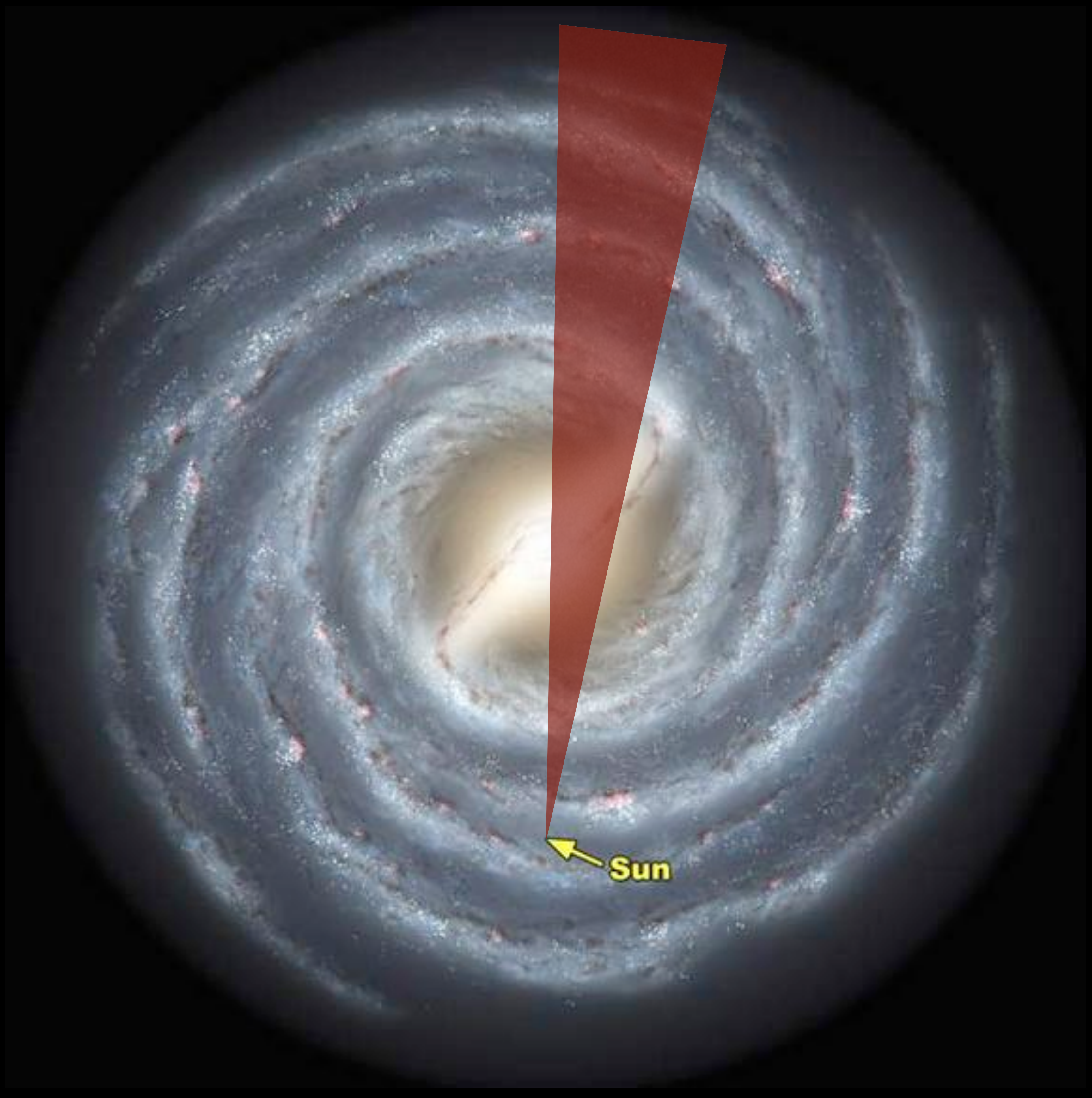
Operational Characteristics:

- Effective Area ~ 1 m^2
- Field of View ~ 2 sr
- Energy Resolution ~ 10%
- Angular Resolution ~ Energy Dependent (~1° at 1 GeV)

GeV Observations with the Fermi-LAT



Most Diffuse Gamma-Ray Emission is Local



Diffuse Gamma-Ray Emission

Supernovae source Cosmic-Ray Protons:

10^{51} erg (~10% in relativistic protons)

(~2% in relativistic electrons)

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cosmic rays propagate

$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Solved Numerically:
e.g. Galprop

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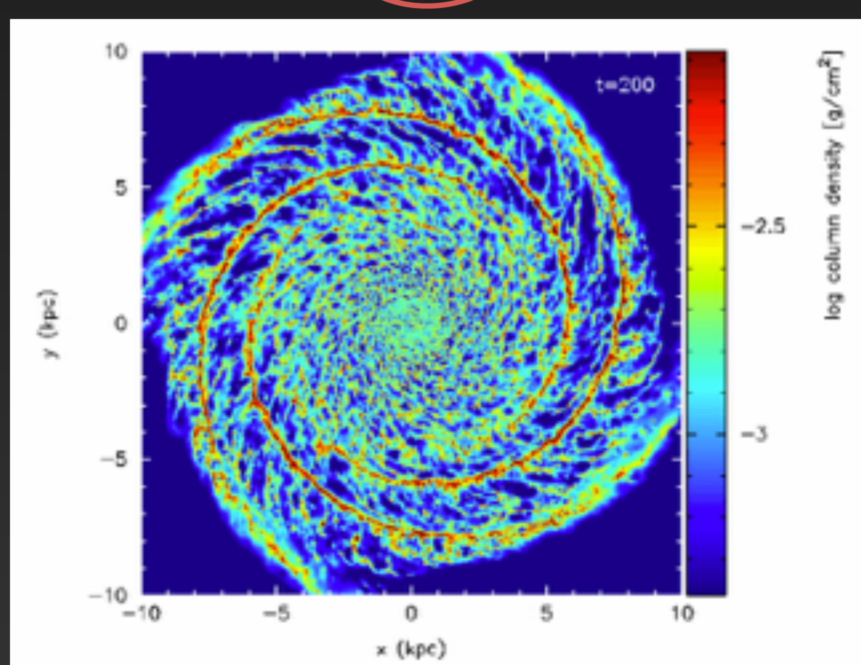
Gas/ISRF



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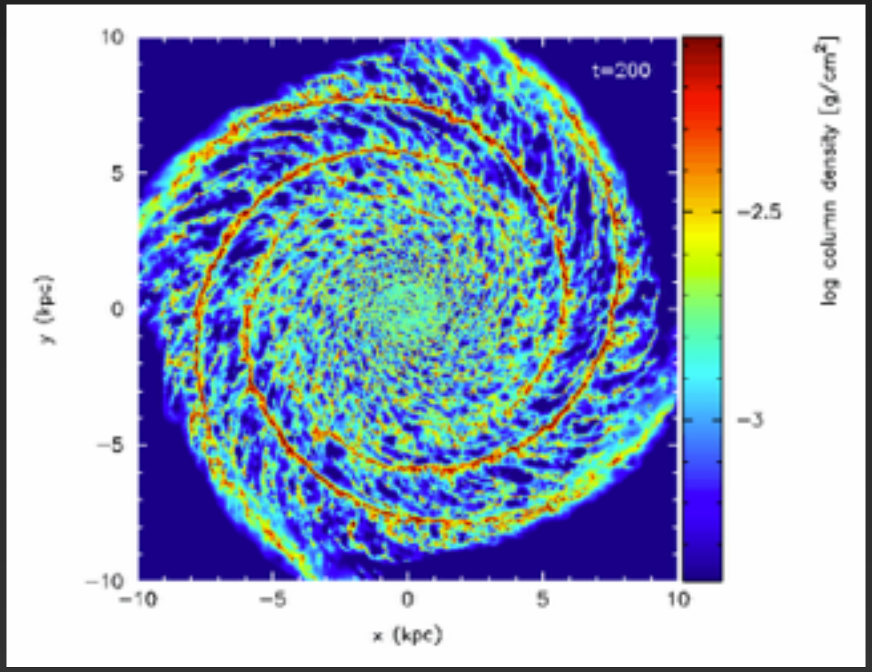
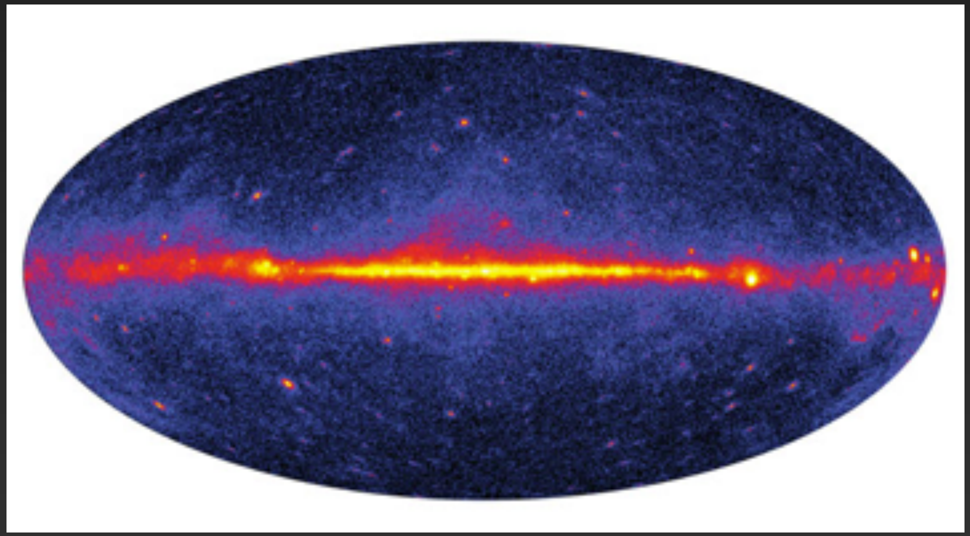




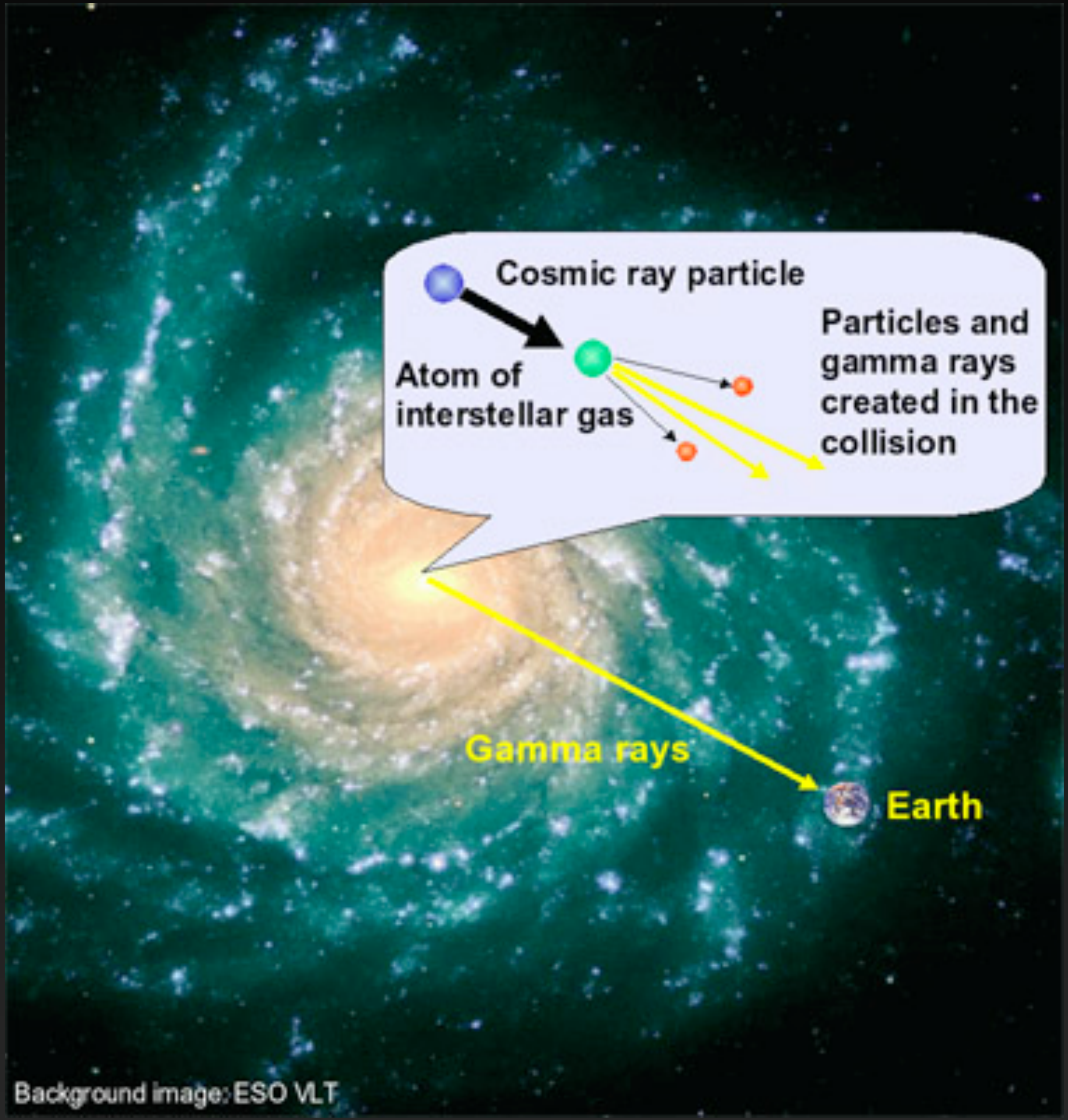
Where Do Gamma-Rays Come From?

Point Sources (SNR, pulsars, etc.)

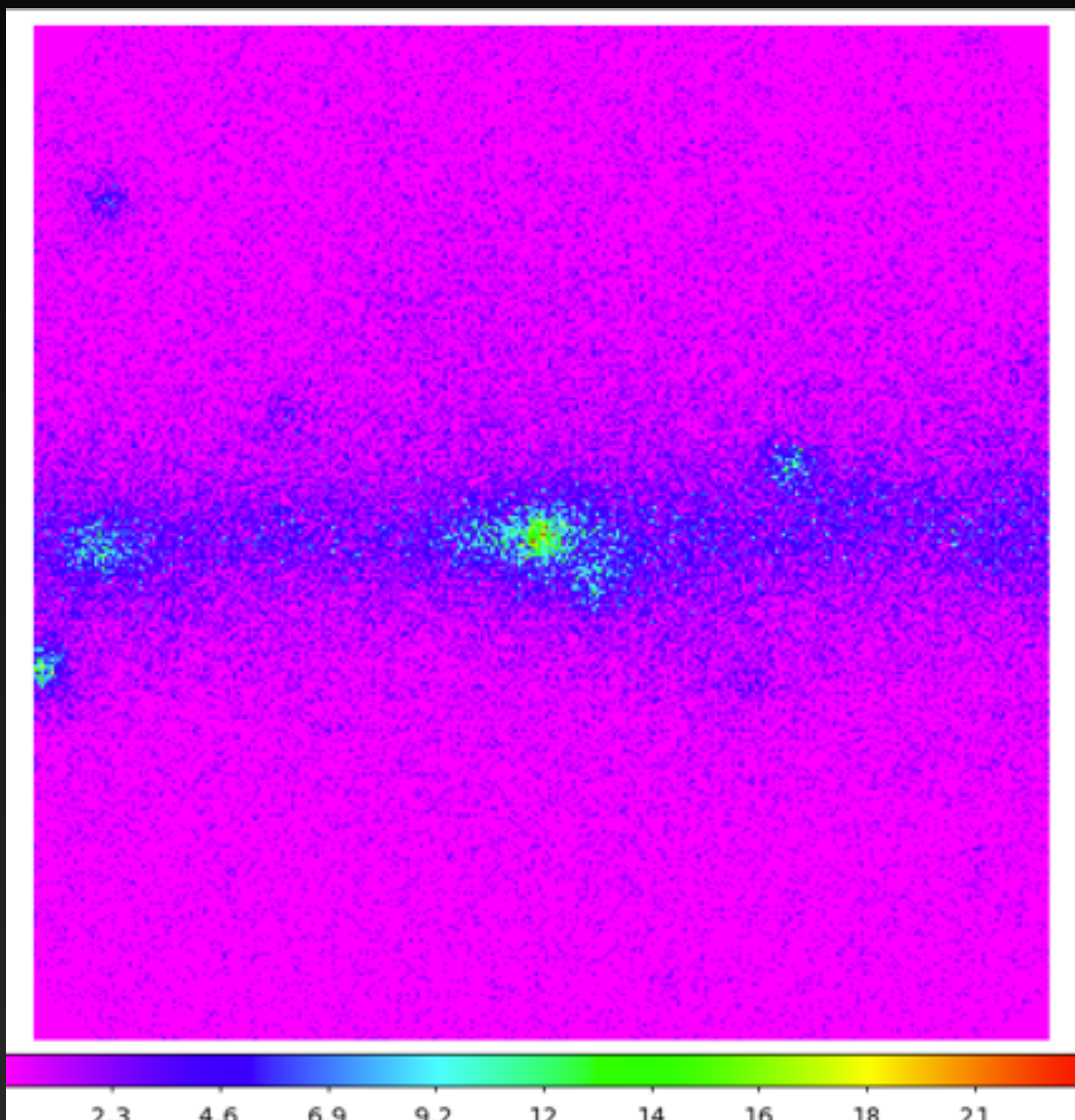
Hadronic Interactions (pp -> π^0 -> $\gamma\gamma$)

Bremsstrahlung

Inverse Compton Scattering



How Does This Analysis Work?



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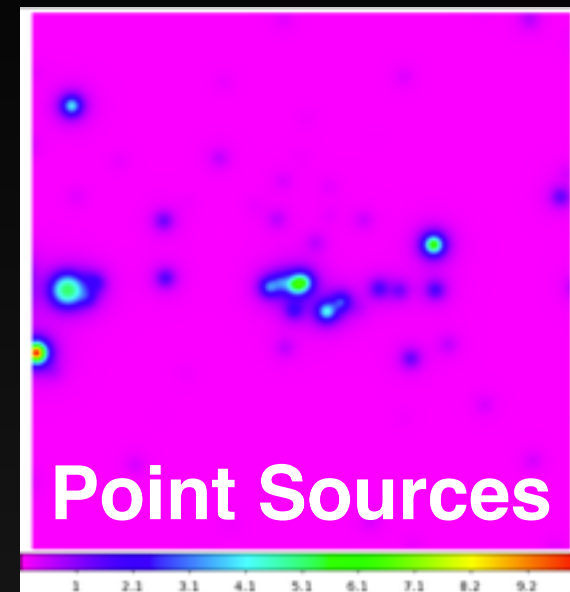

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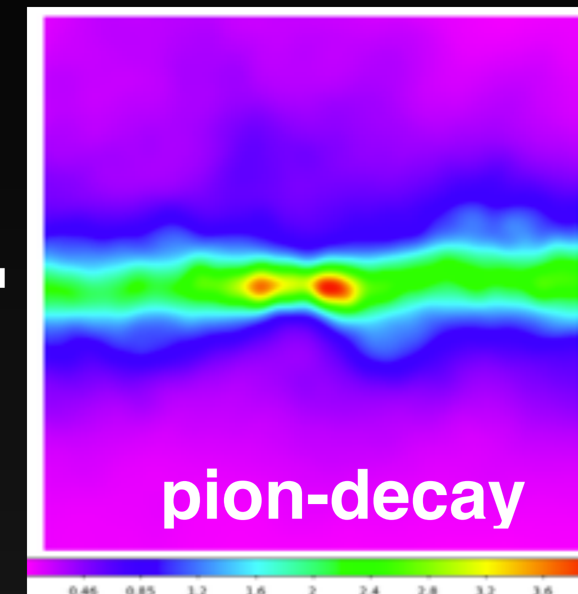

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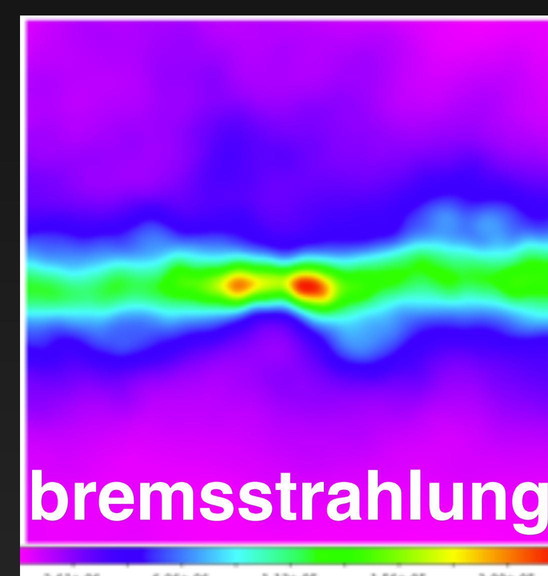

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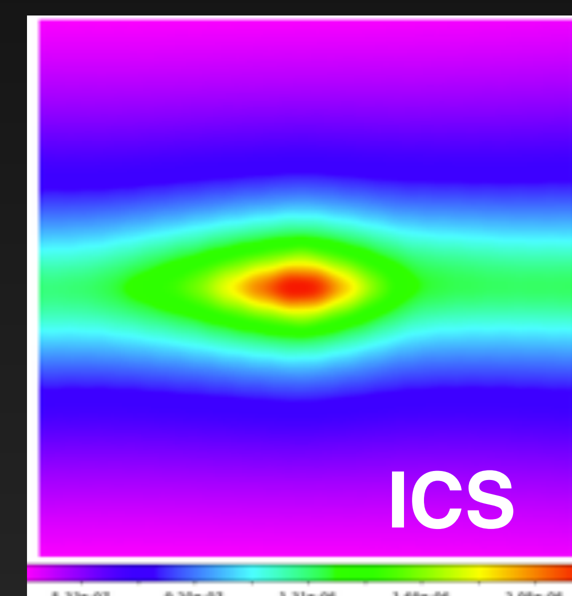

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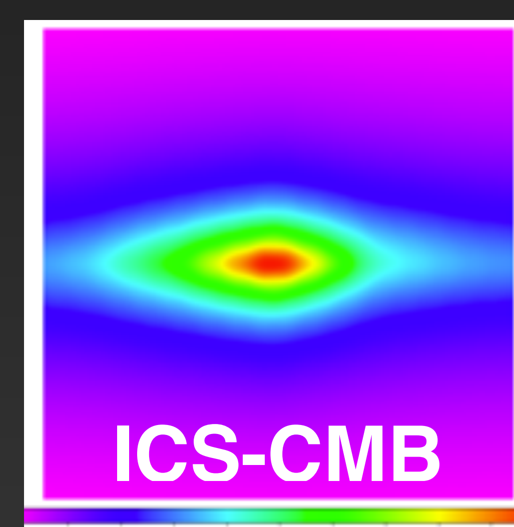


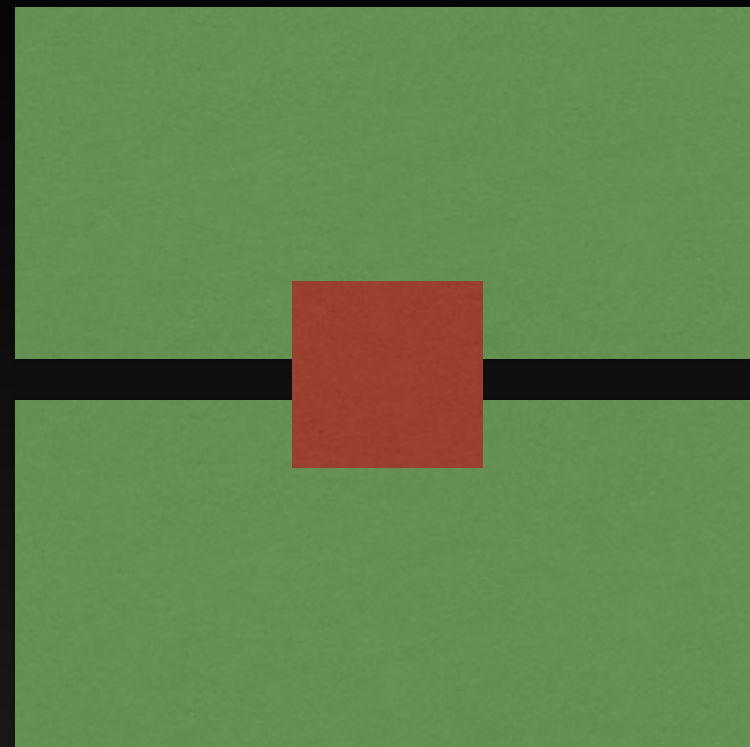
Photon Counts

750 — 950 MeV

Best Angular Resolution Cut

10º x 10º ROI

How Does This Analysis Work?



INNER GALAXY

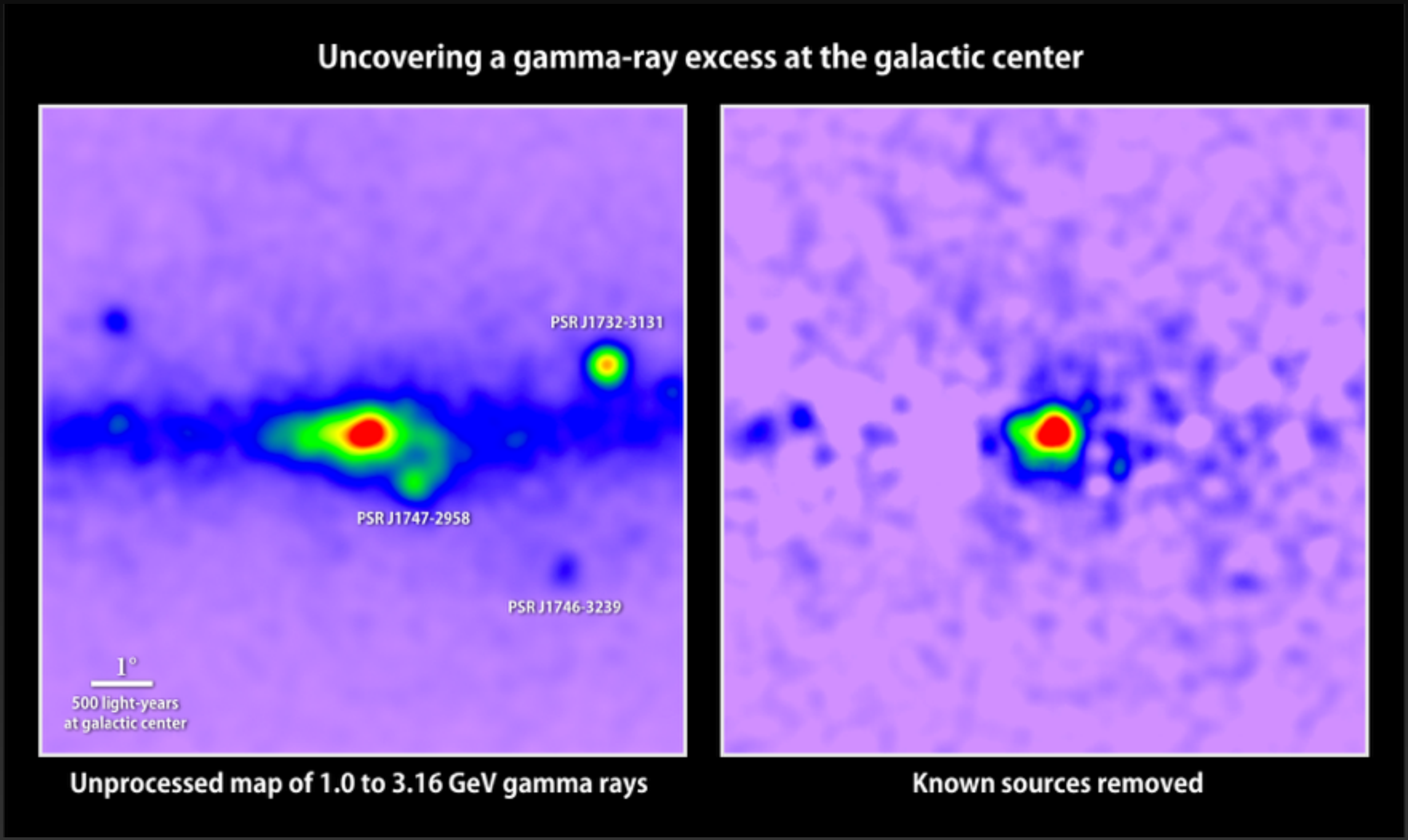
- Mask galactic plane (e.g. $|b| > 1^{\circ}$), and consider $40^{\circ} \times 40^{\circ}$ box
- Bright point sources masked at 2°
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin

GALACTIC CENTER

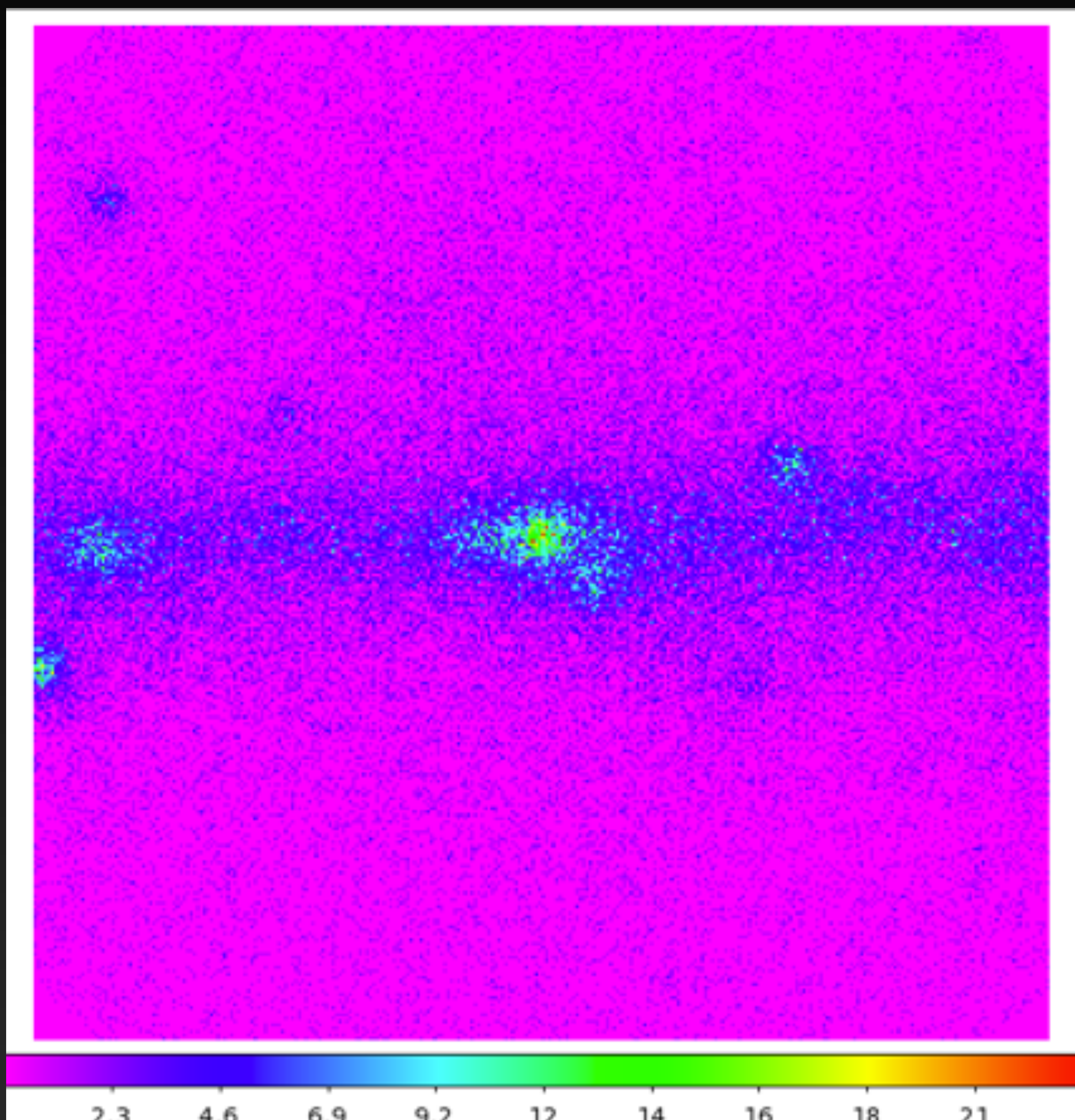
- Box around the GC ($10^{\circ} \times 10^{\circ}$)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source

Observational Results

After subtracting known sources - a bright excess remains surrounding the Galactic Center.



Observational Results



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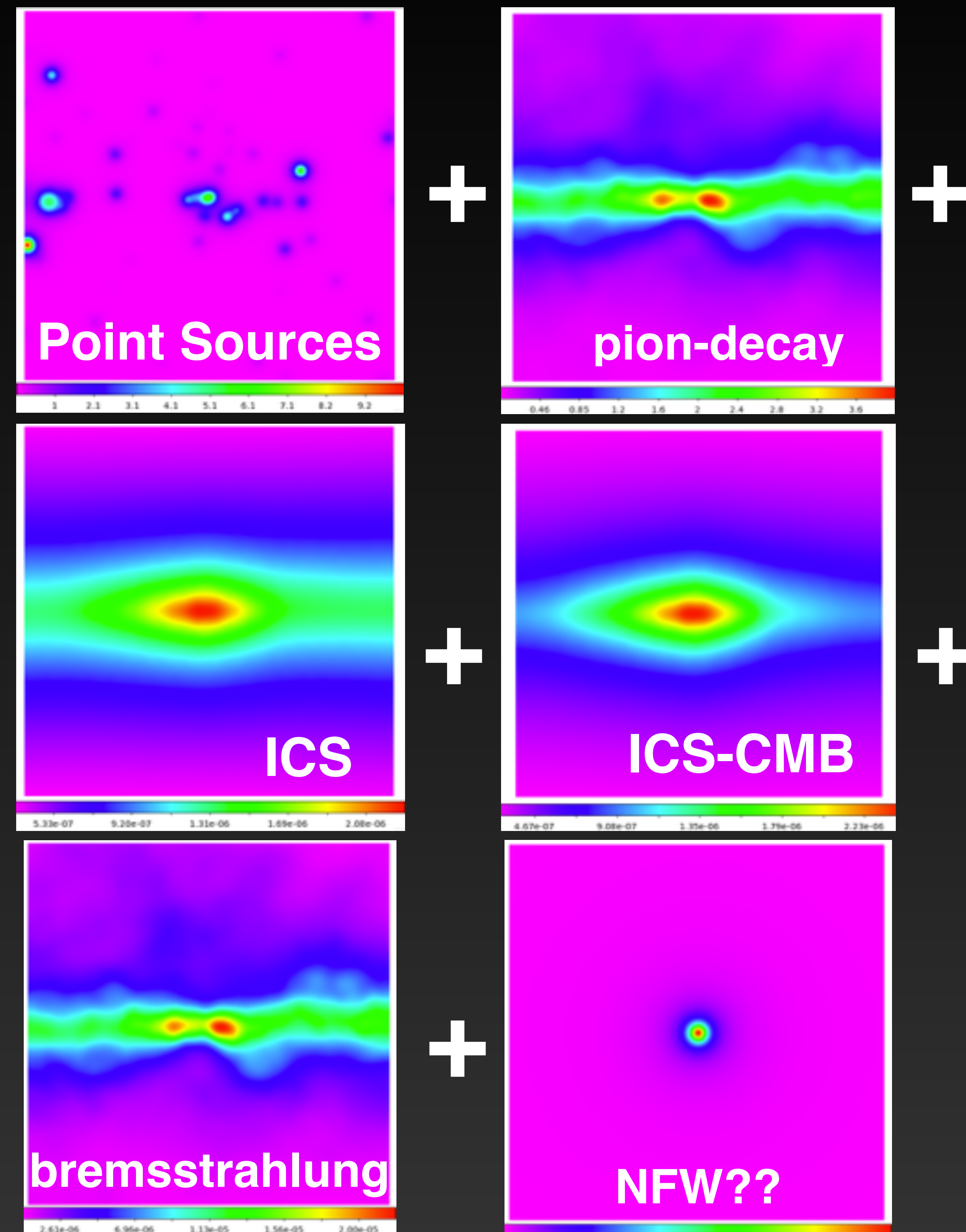

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The Navarro-Frenk White Profile

$$\rho_{\mathrm{NFW}} = \left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\frac{r}{r_s}\right)^{-3+\gamma}$$

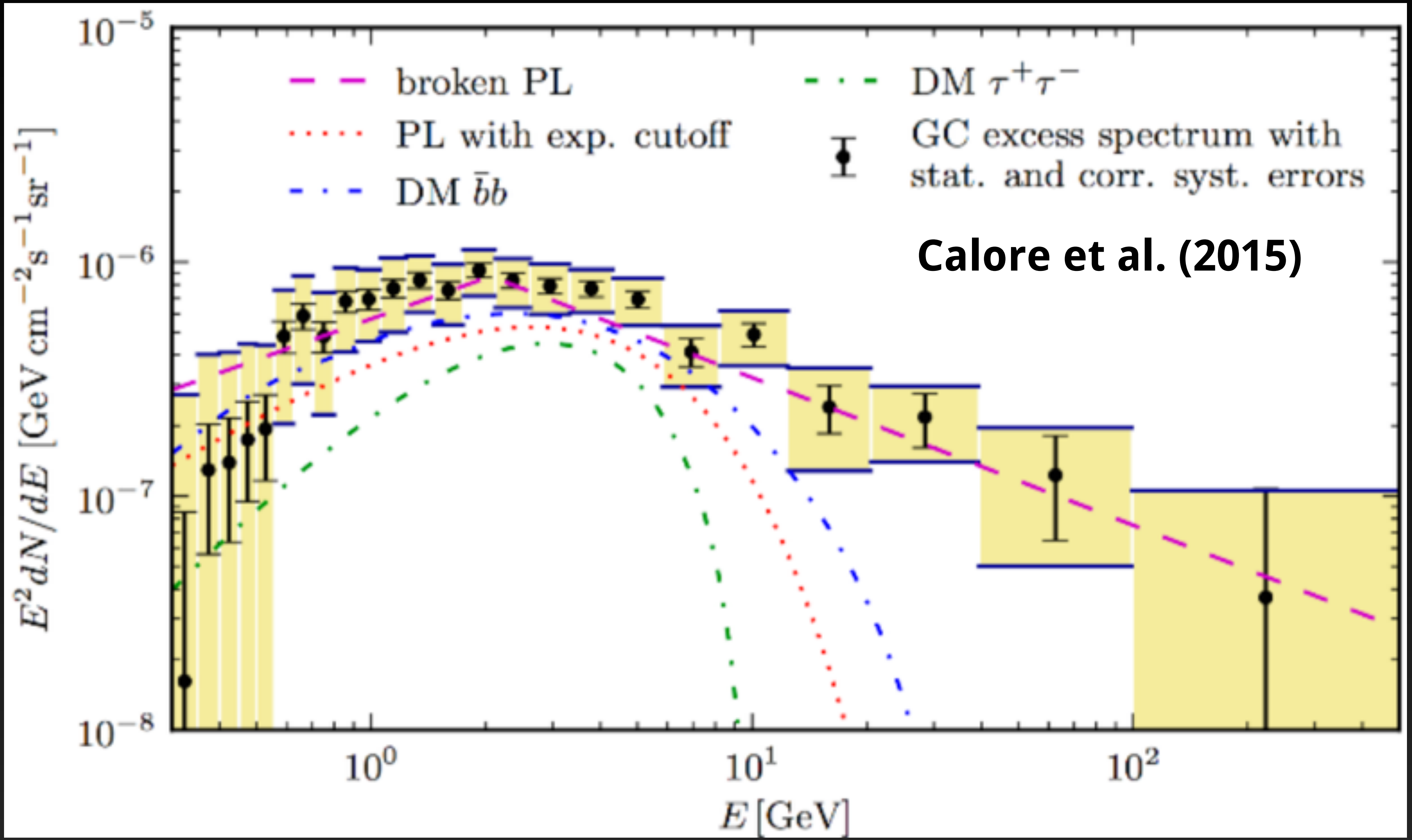
For the remainder of this talk, we employ a simple analytical model, known as the “generalized NFW Profile” which provides a reasonable fit to the observed dark matter density distribution of dark matter halos.

In the standard NFW scenario, $\gamma = 1$

Navarro, Frenk, White (1996)
Springel et al. (2008, 0809.0898)

Observational Results

IG

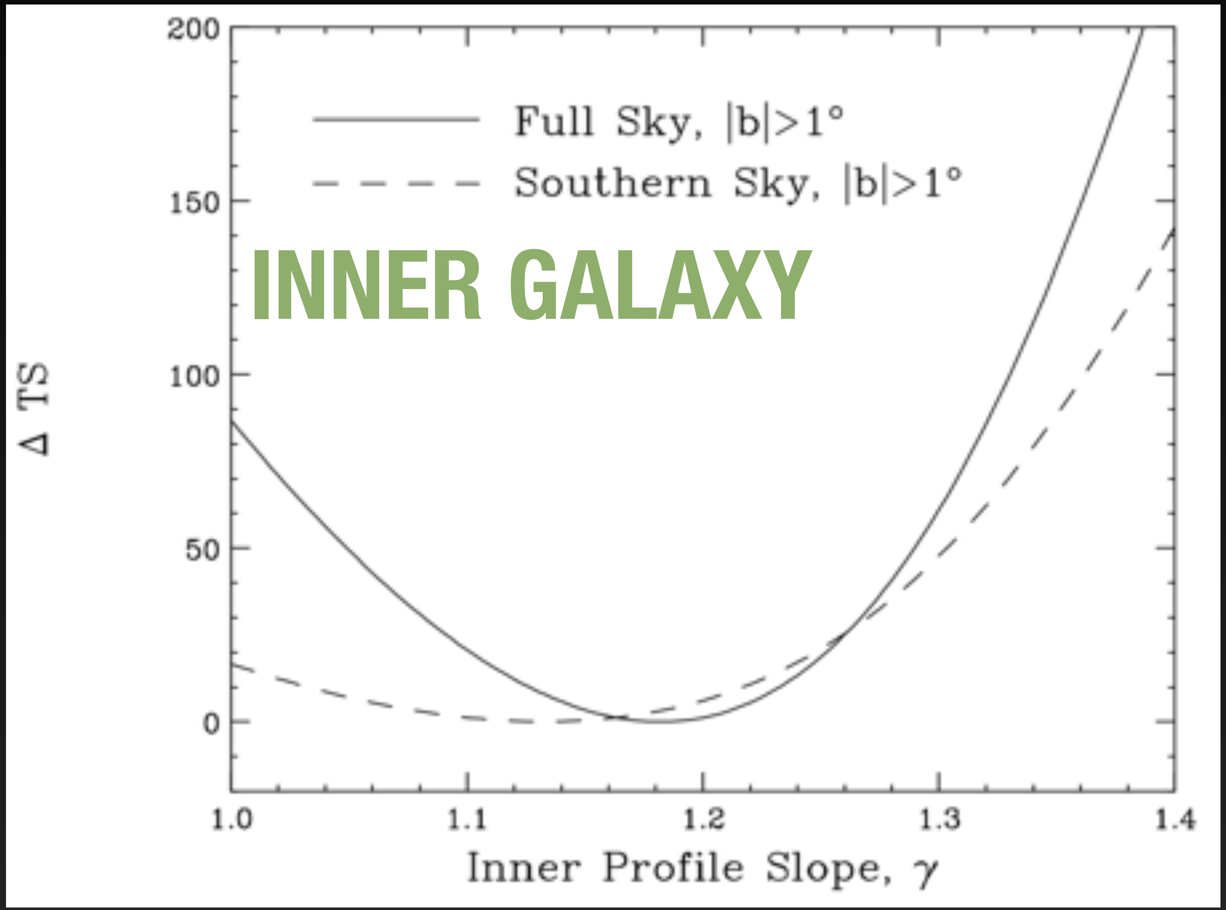


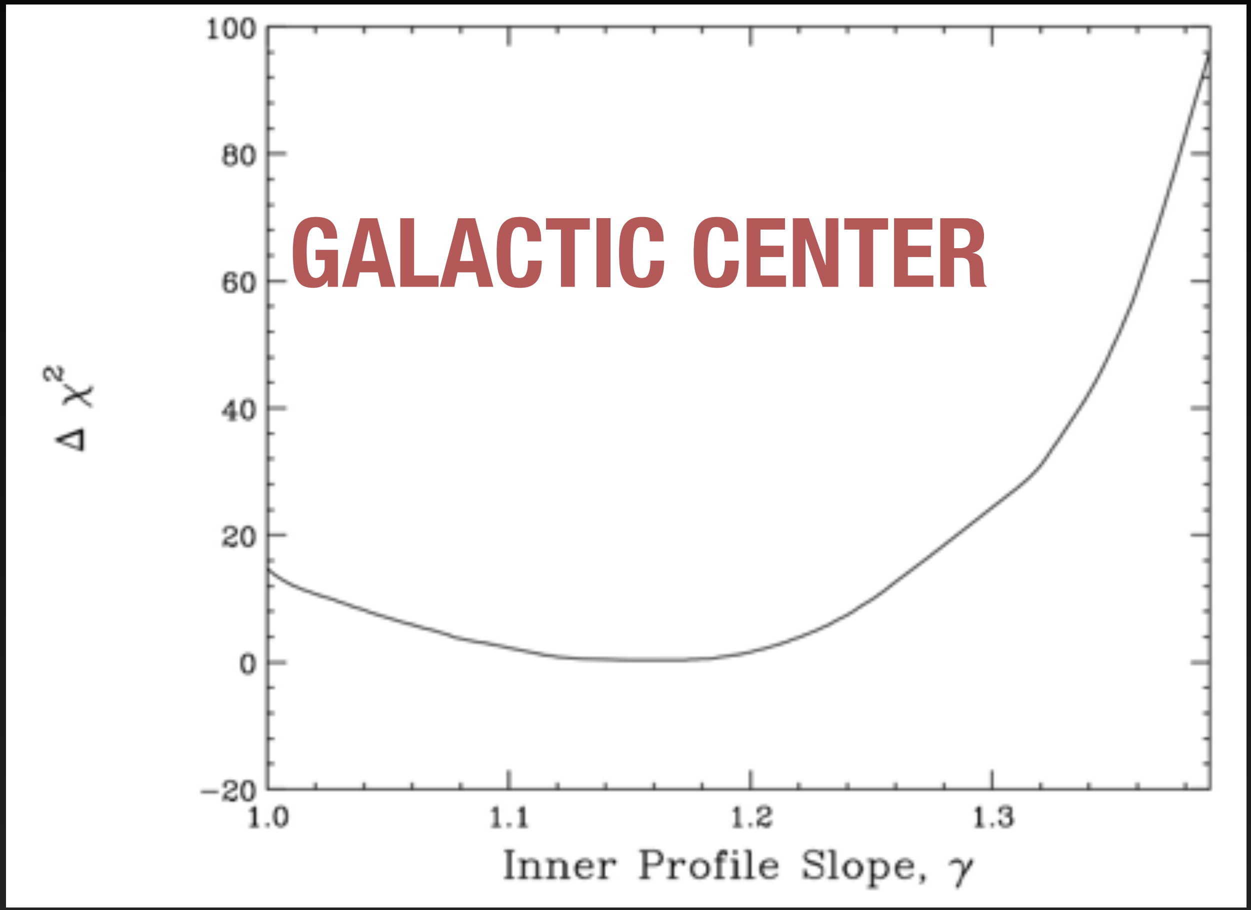
The excess has an unusual spectrum - highly peaked at an energy of ~2 GeV.

The excess is resilient to changes in diffuse background modeling.

Observational Results

GC/IG



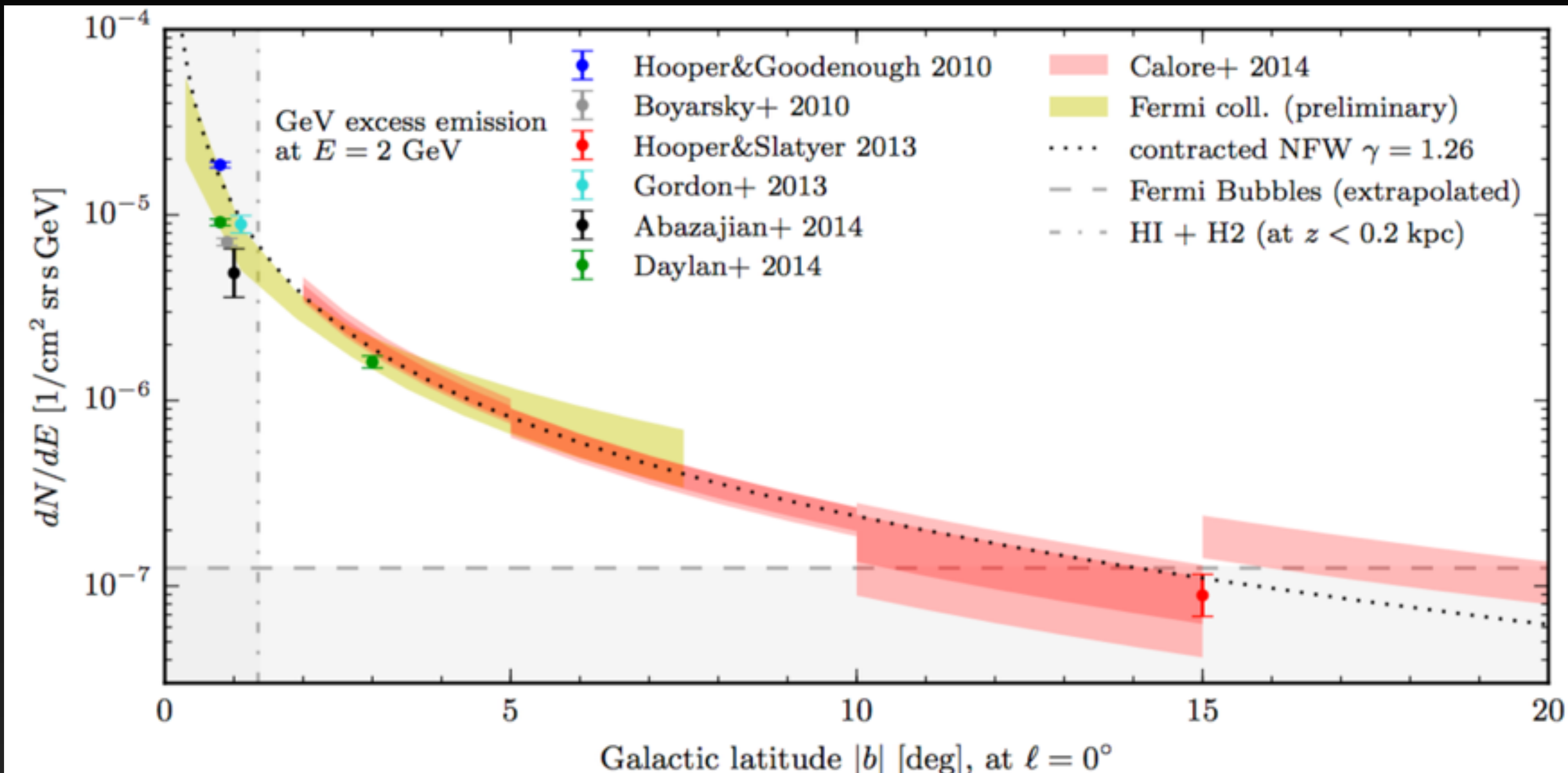


Inner galaxy prefers density profile γ = 1.18

Galactic Center prefers γ = 1.17

$$\rho_{\mathrm{NFW}} = \left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\frac{r}{r_s}\right)^{-3+\gamma}$$

Observational Results

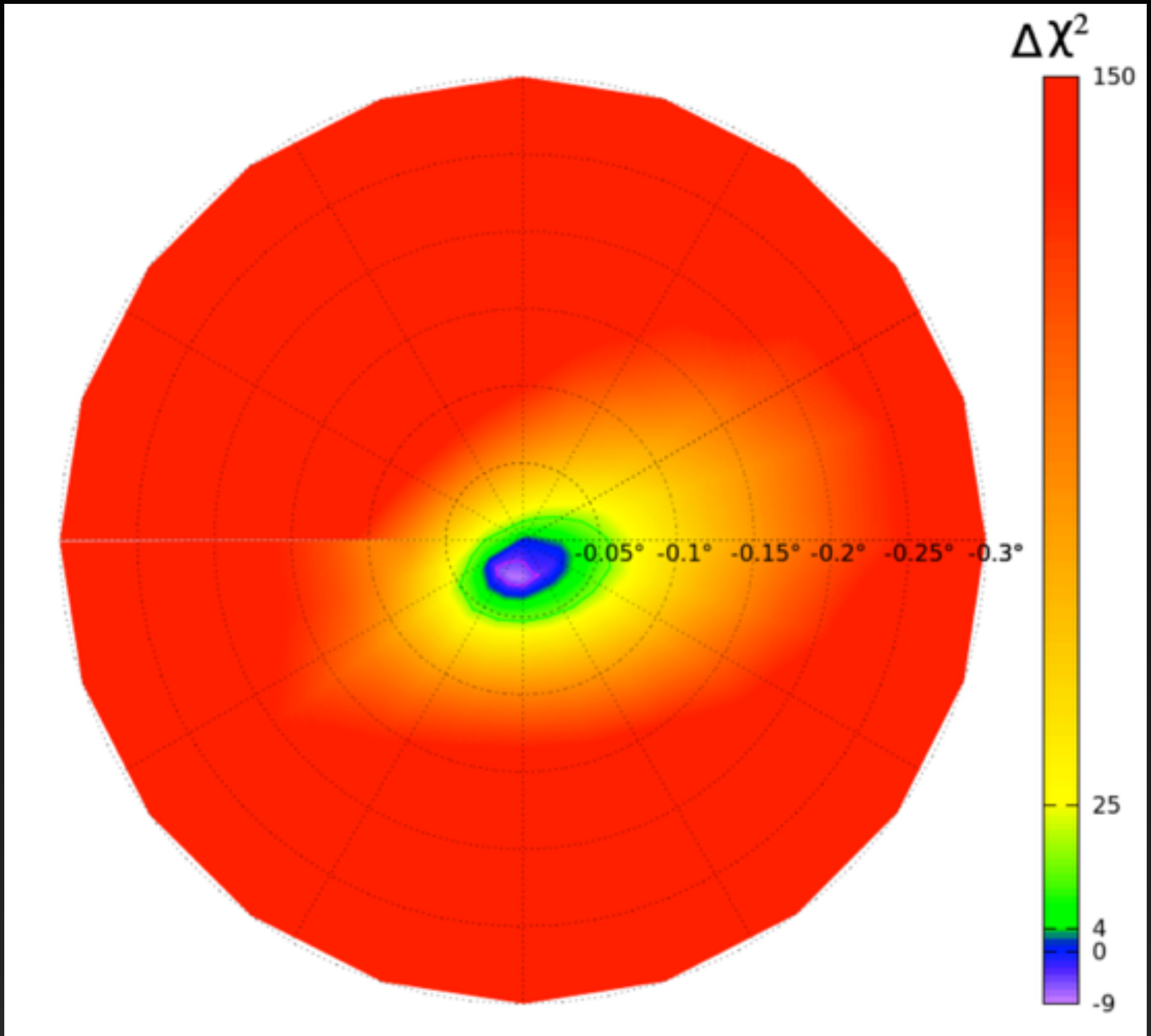


The GeV excess is statistically significant from 0.1º — 10º from the Galactic Center.

Calore et al. (2014b)

Observational Results

GC



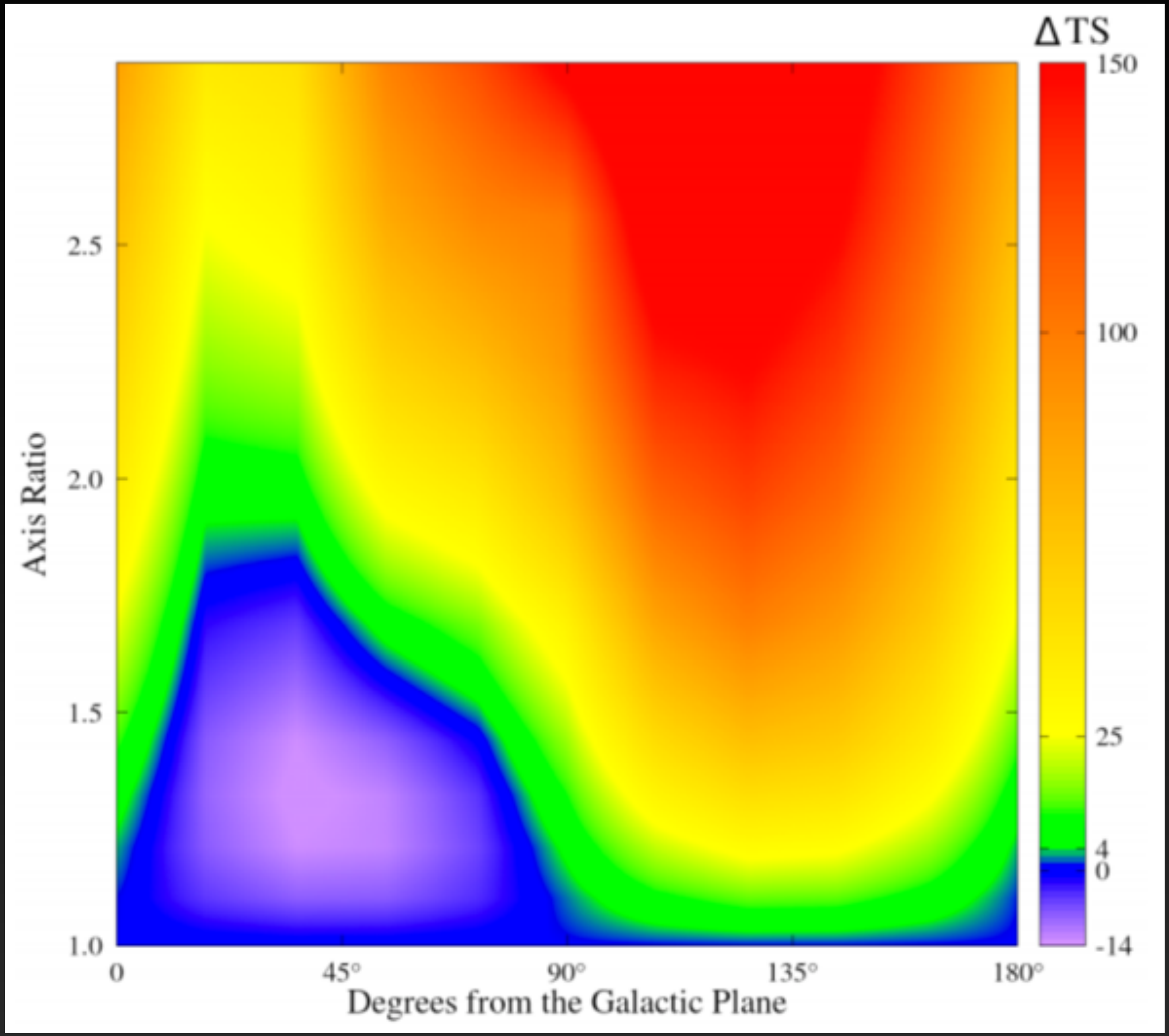
The peak of the emission source lies within 0.05° of the GC.

Strongly suggests that the feature is dynamically centered on the GC in 3D space.

Daylan et al. (2014)

Observational Results

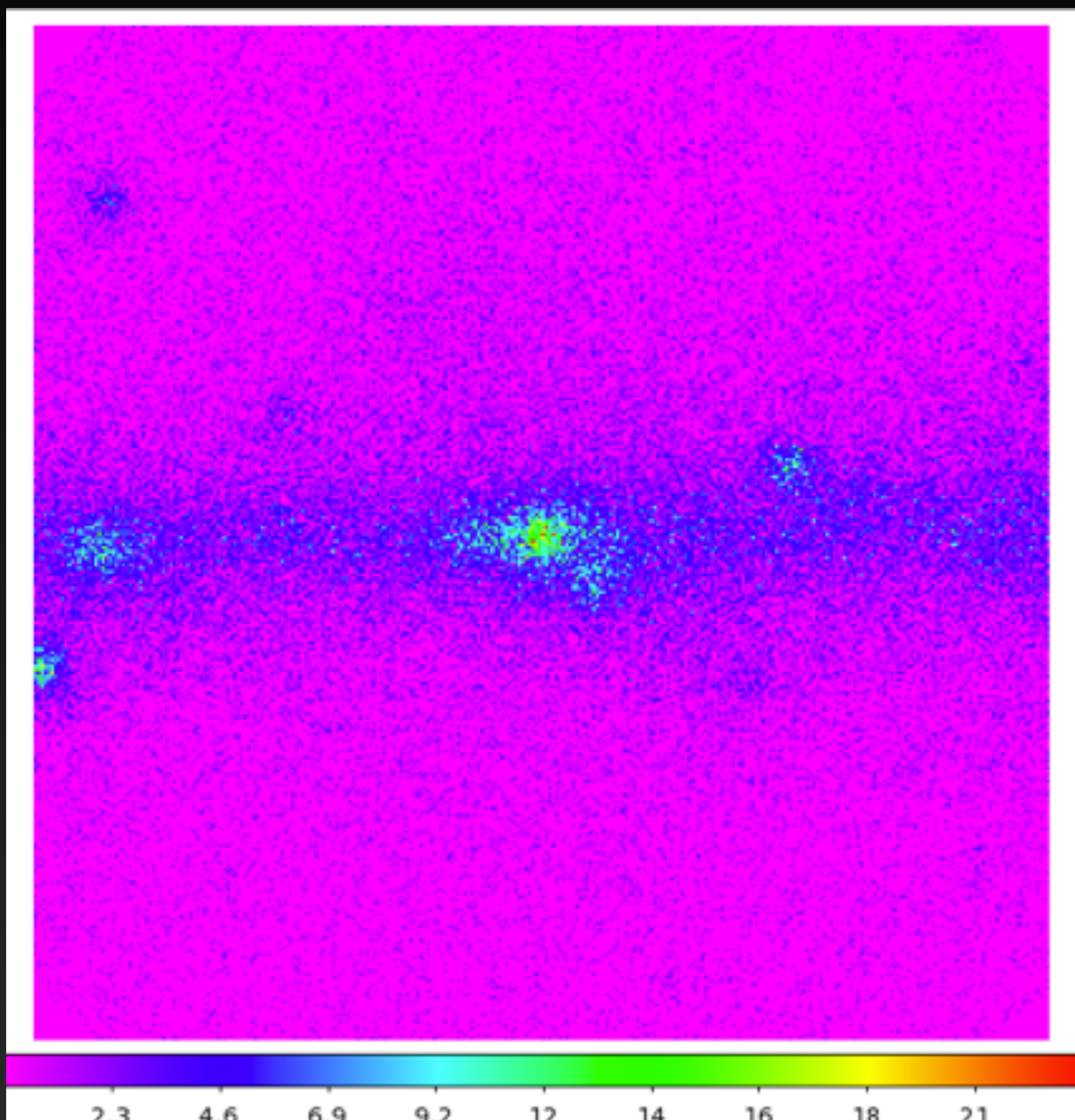
GC



The excess is approximately spherically symmetric, with an elongation parallel or perpendicular to the Galactic center of less than 20%.

Daylan et al. (2014)

Observational Results



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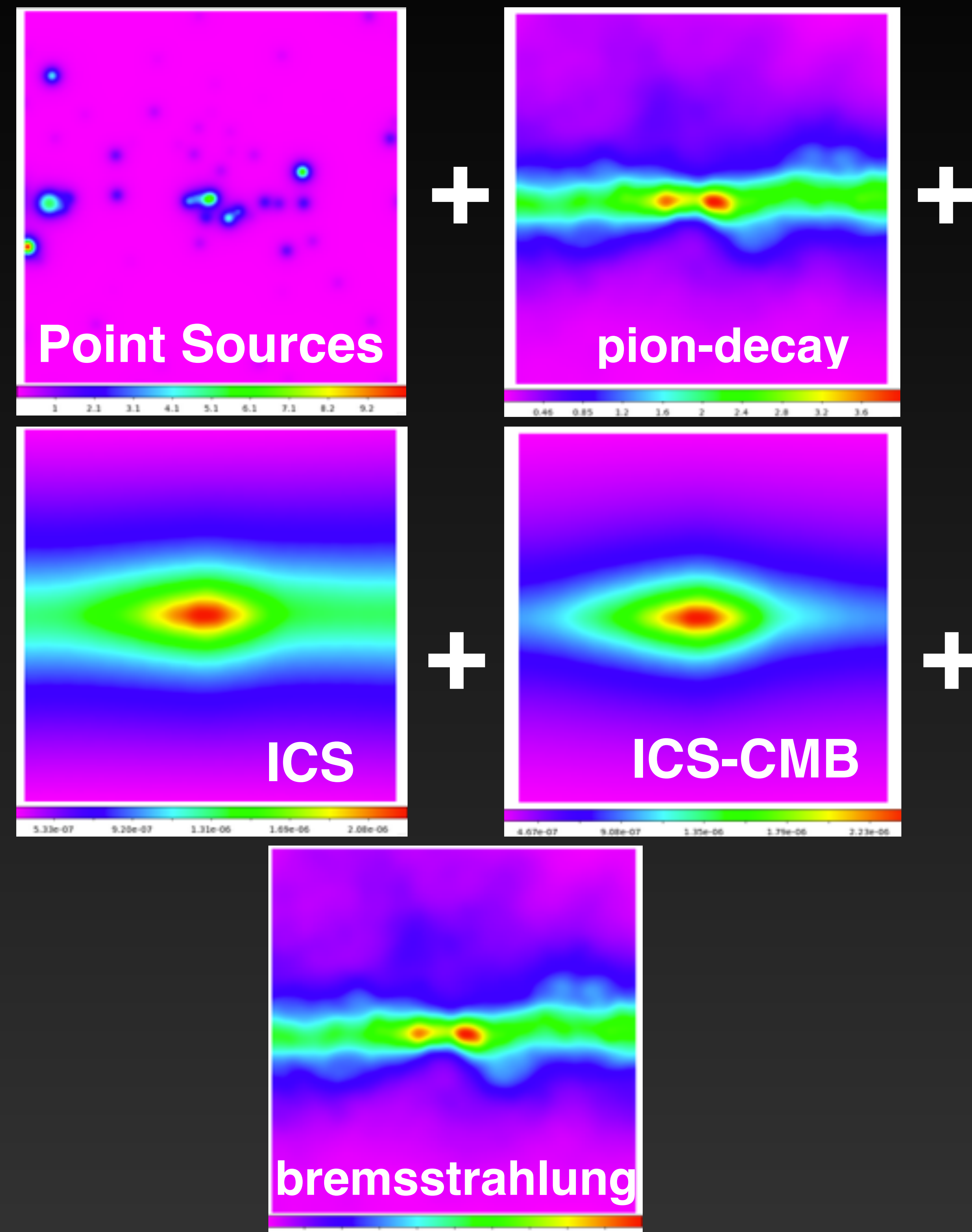
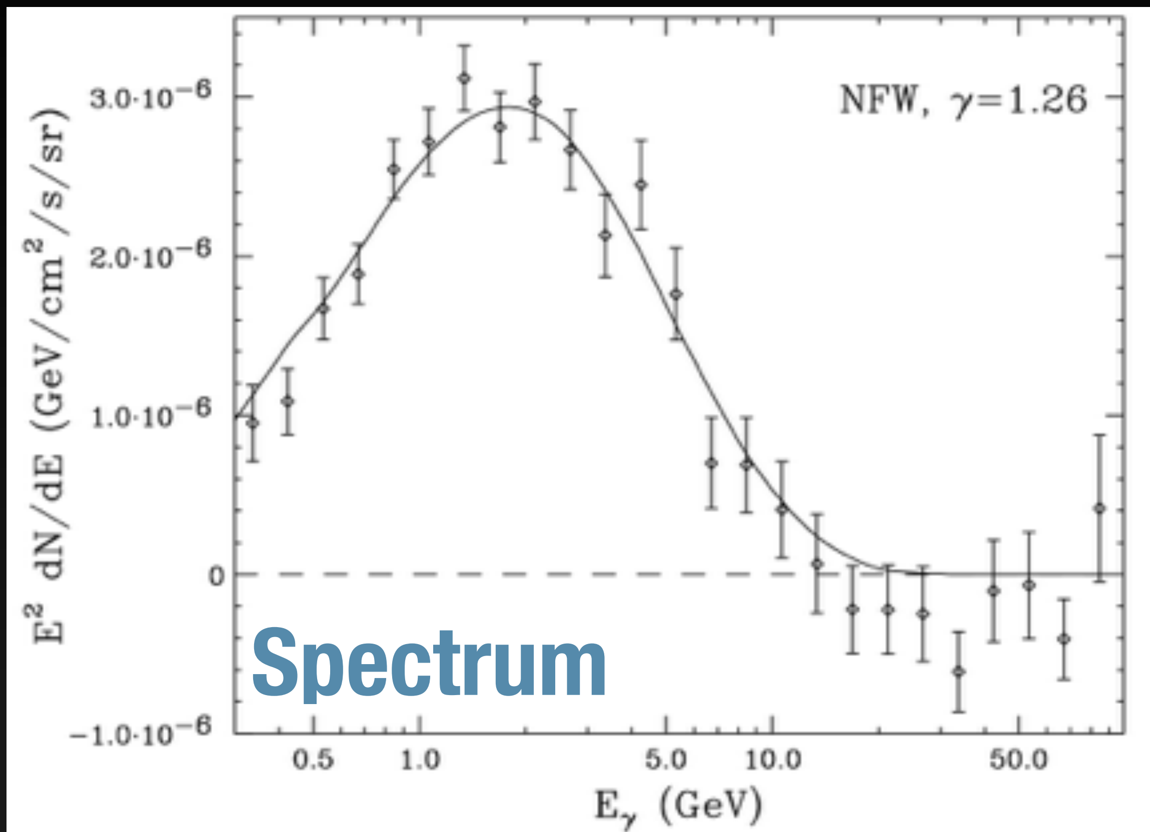
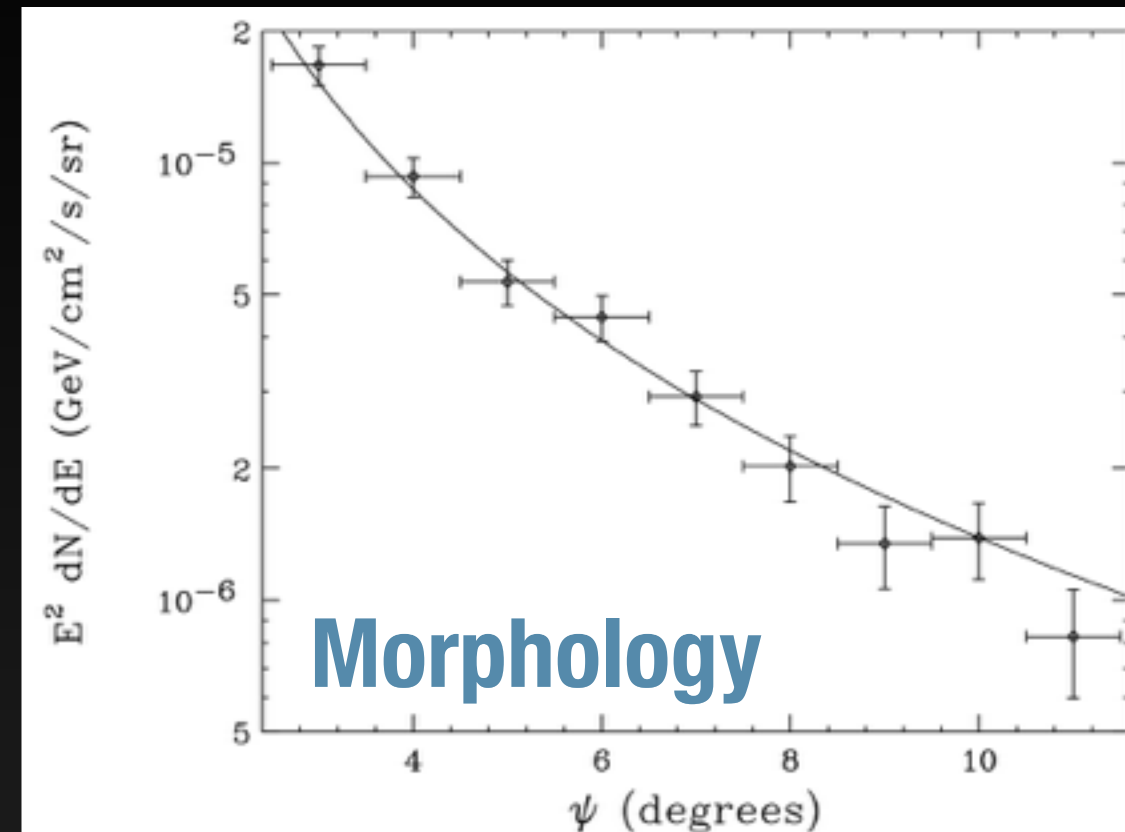


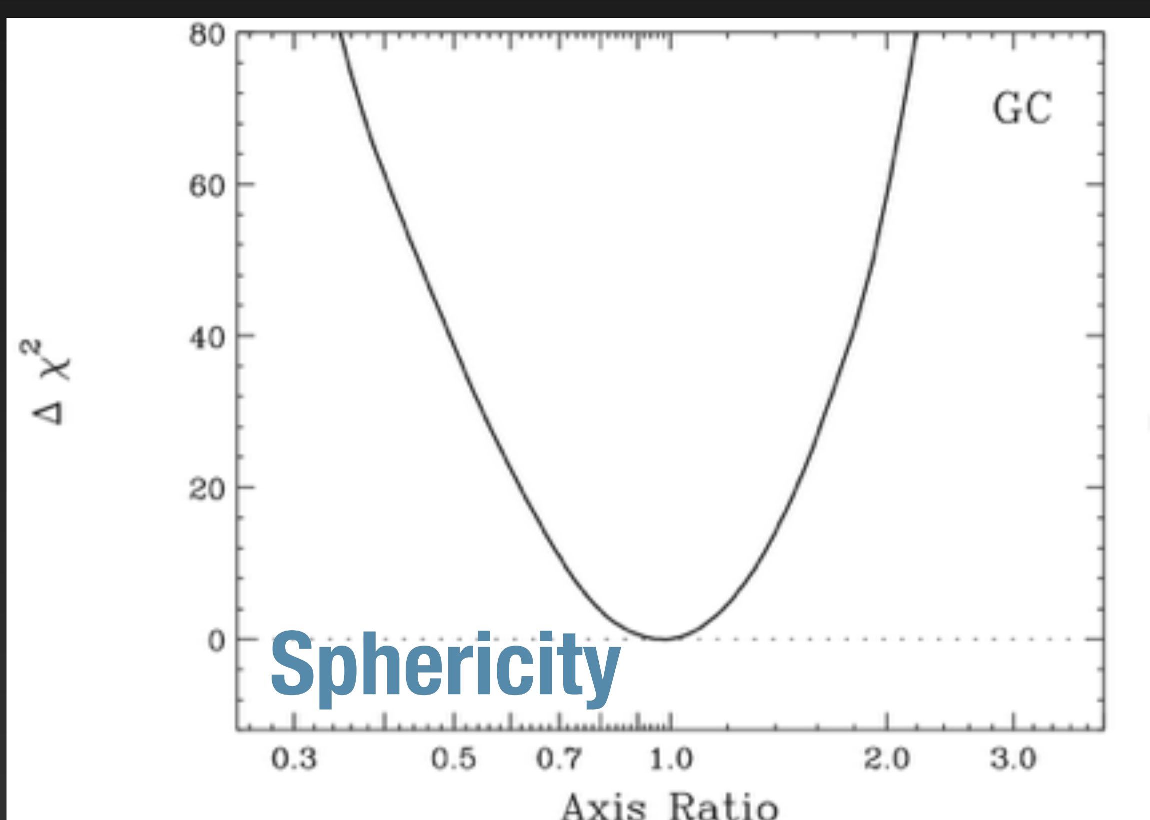
Key Results Have Been Validated

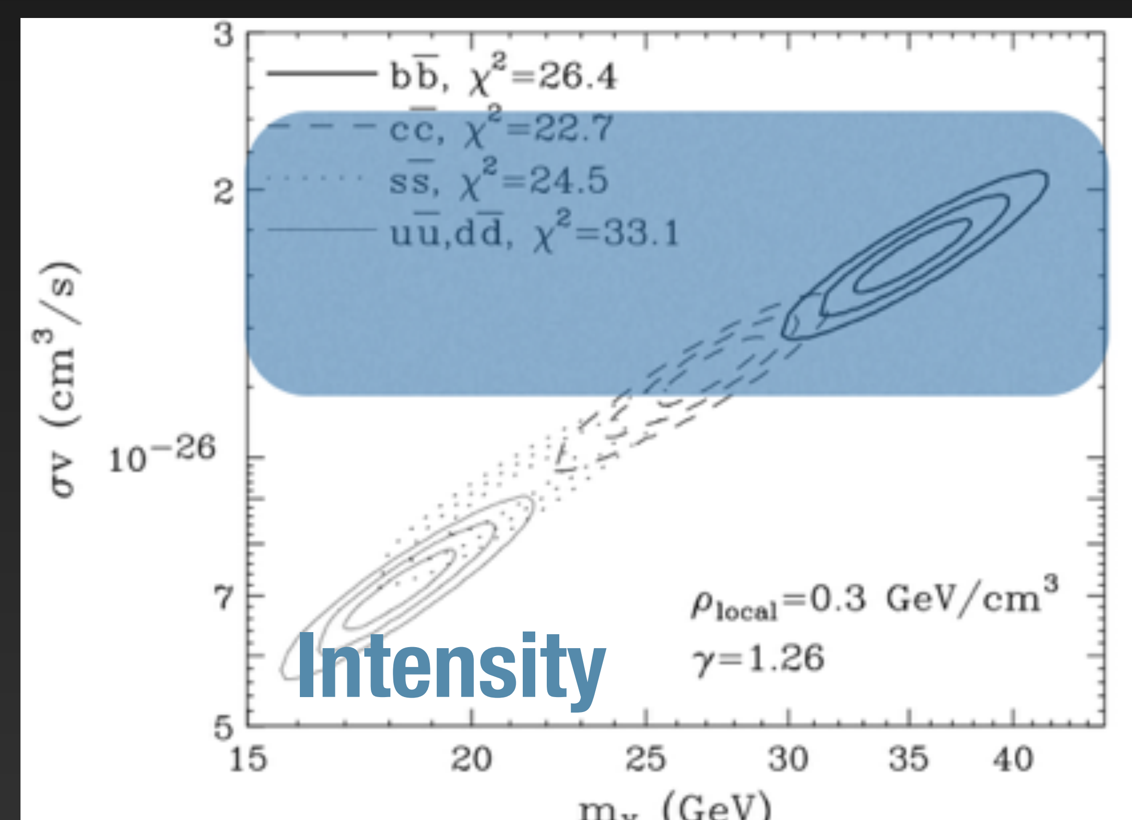
Goodenough & Hooper (2009)	0910.2998
Hooper & Goodenough (2011, PLB 697 412)	1010.2752
Hooper & TL (2011, PRD 84 12)	1110.0006
Abazajian & Kaplinghat (2012, PRD 86 8)	1207.6047
Hooper & Slatyer (2013, PDU 2 18)	1302.6589
Gordon & Macias (2013, PRD 8 8)	1306.5725
Macias & Gordon (2013, PRD 89 6)	1312.6671
Abazajian et al. (2014, PRD 90 2)	1402.4090
Daylan et al. (2014)	1402.6703
Calore et al. (2014)	1409.0042
Bartels et al. (2015)	1506.05104
Lee et al. (2015)	1506.05124
TL (2015)	1509.02928
Ajello et al. (2015)	1511.02938

A Hint of Dark Matter?

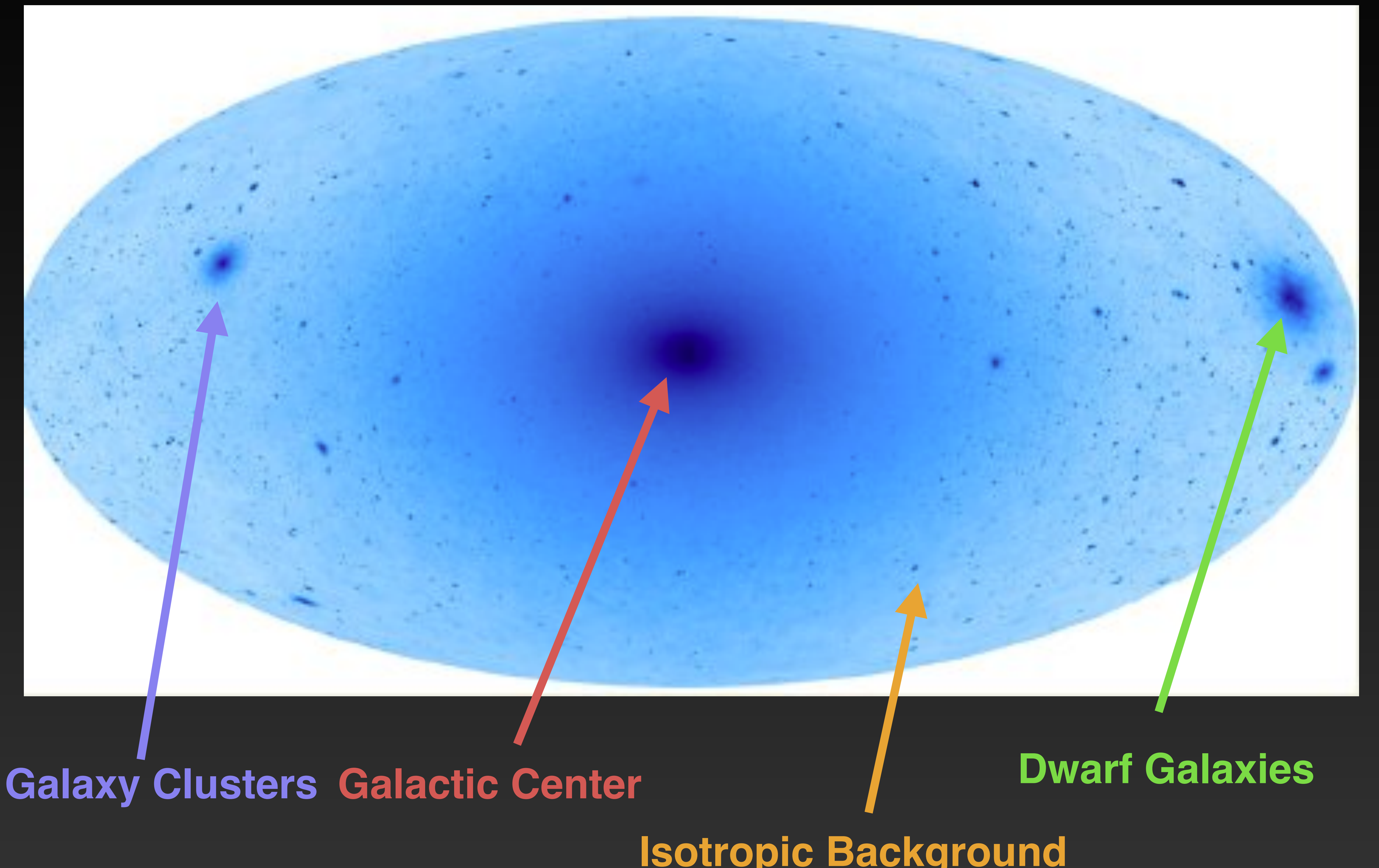








Where to Observe Dark Matter



Astrophysics Has Been (Relatively) Cooperative

The observed gamma-ray intensity from the inner 1o surrounding the Galactic center, in an energy range between 1-3 GeV is:

$$1 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$$

The prediction from a 100 GeV neutralino annihilating to bb at a thermal cross section is:

$$2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$$

There is no particular reason this needs to be true - the astrophysical gamma-ray flux could easily be a million times brighter.

Trying to Kill the Beast

Astrophysical mechanisms might also explain the excess!

1.) What if there is a new population of point sources near the galactic center?

2.) What if our best models for diffuse astrophysical emission are wrong?

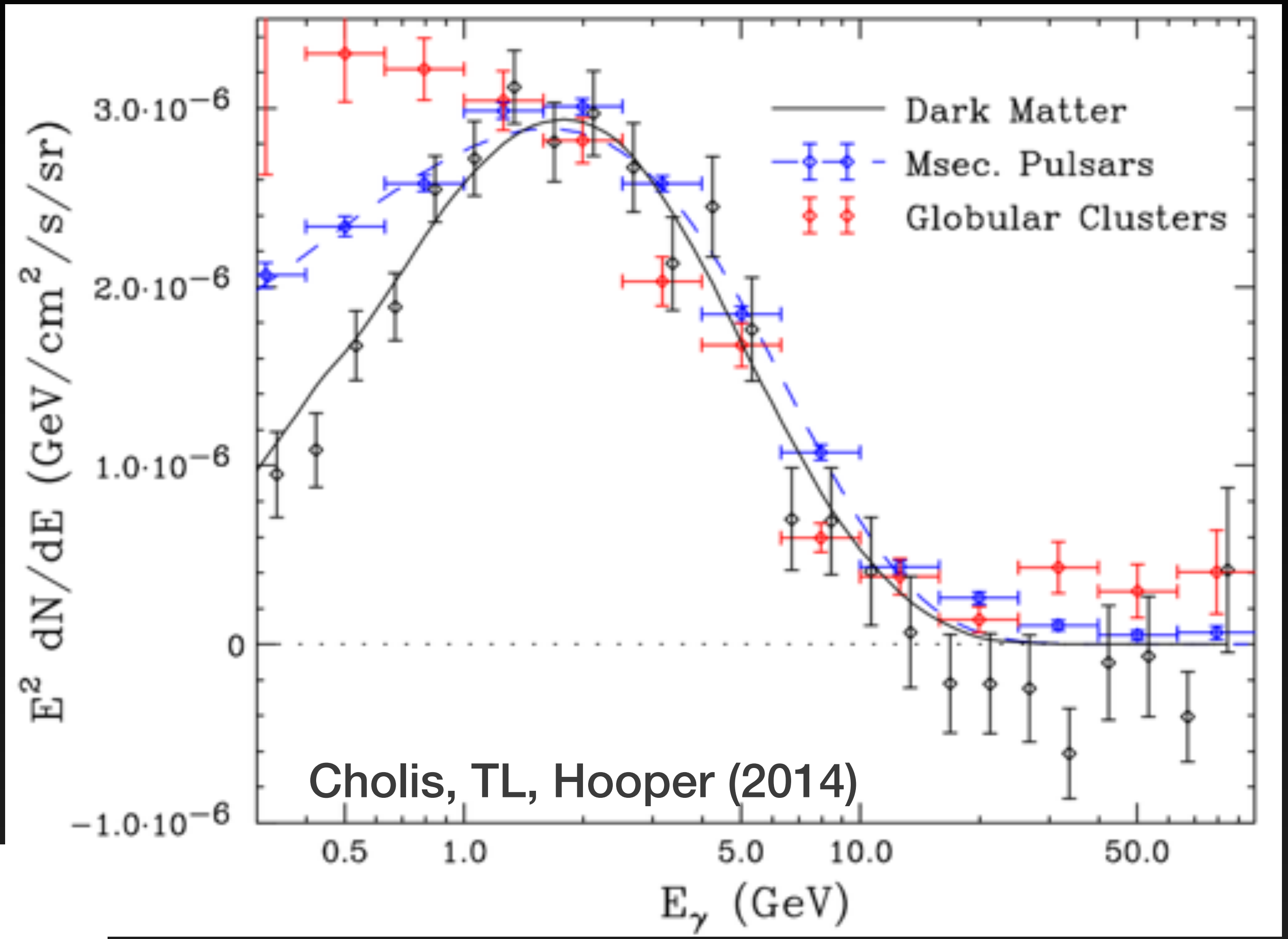
3.) What if the galactic center has a complex/active past?

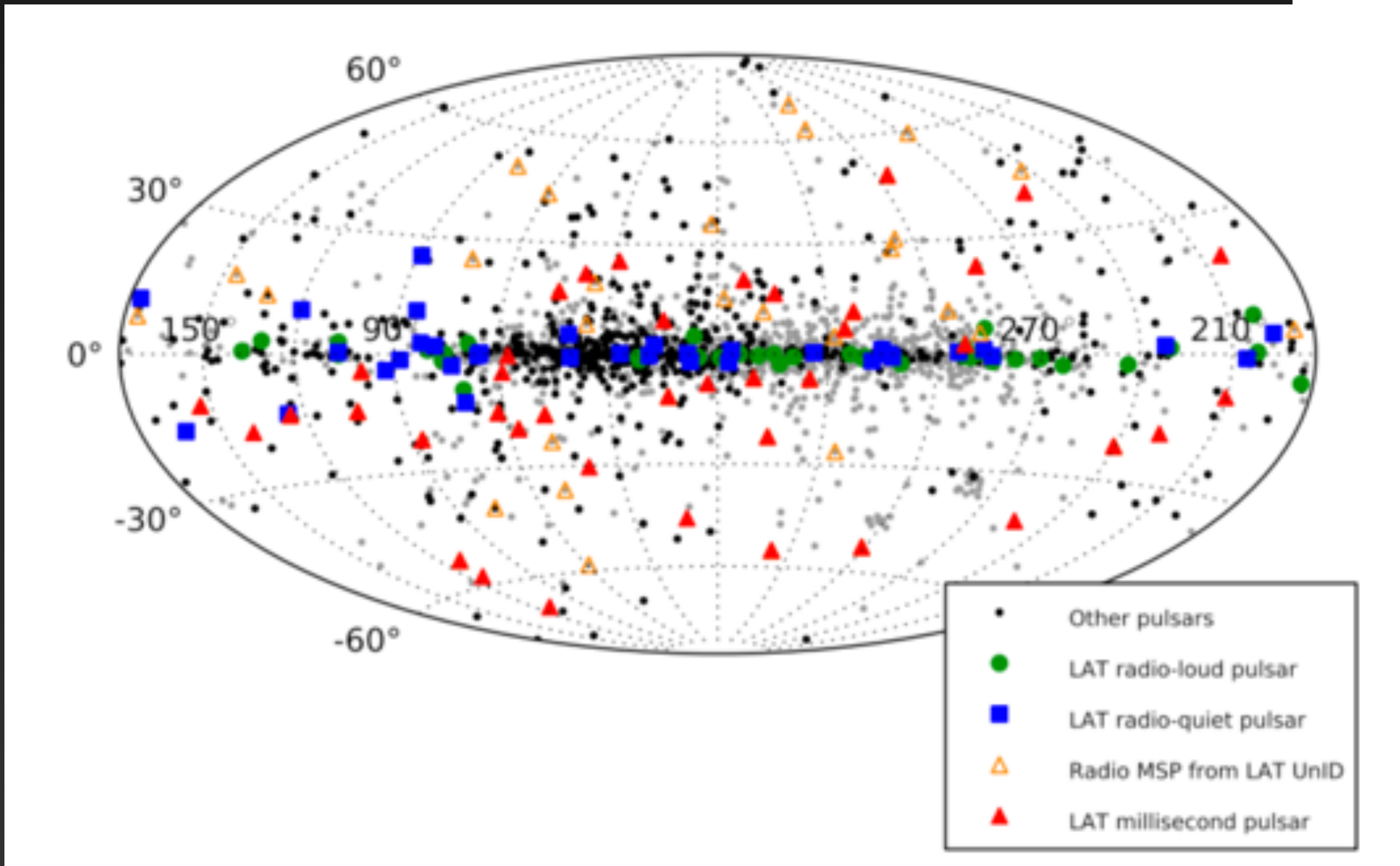
To some extent, all three of these are certainly true. So a better question is:

Can uncertainties in our astrophysical modeling plausibly explain the Galactic Center observations?

Pulsars in the Galactic Center

- The peak of the MSP energy spectrum matches the peak of the GeV excess





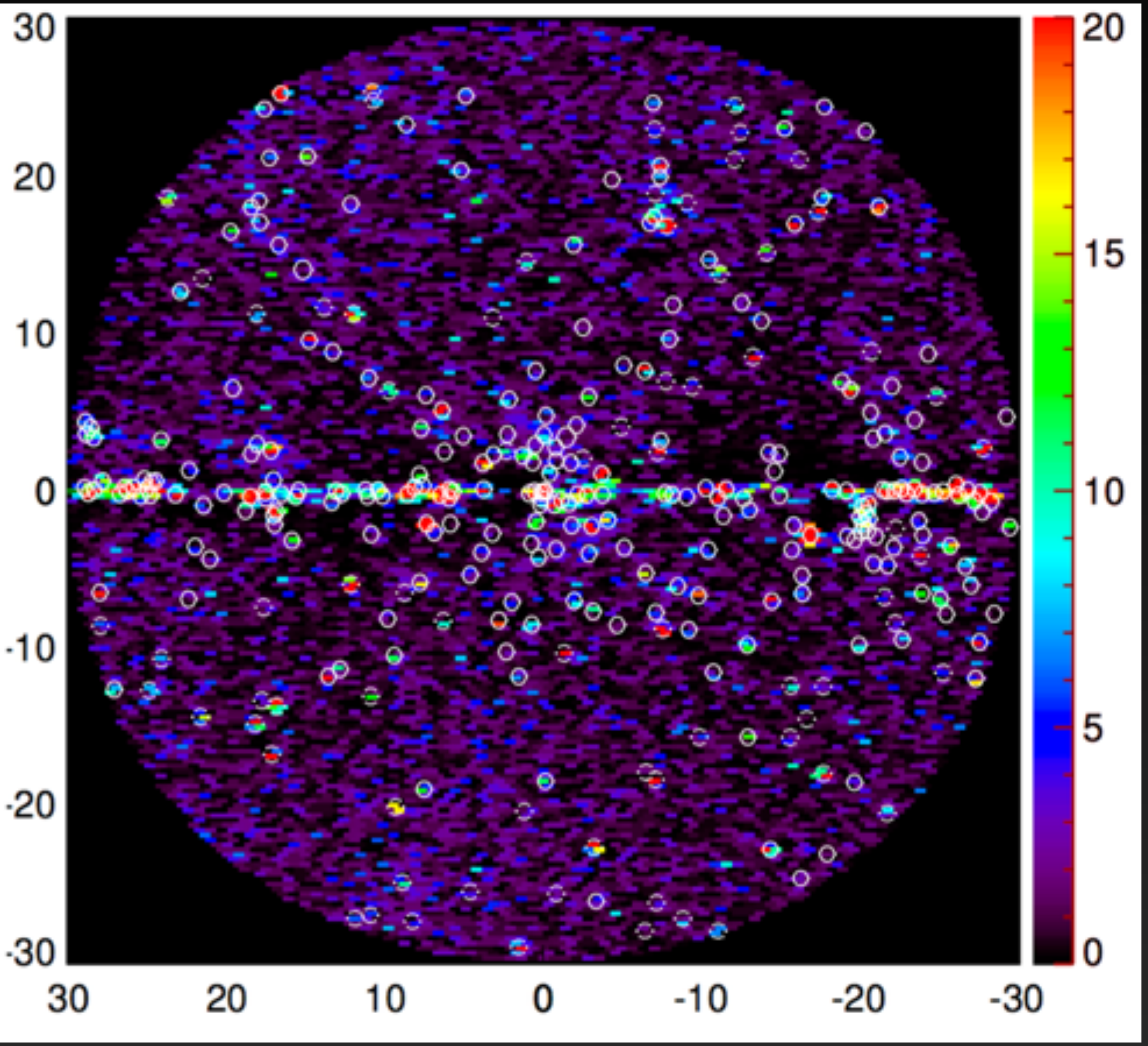
- MSPs are thought to be overabundant in dense star-forming regions like the Galactic Center

Pulsars in the Galactic Center

IG

In each pixel, you can calculate the probability that the data is explained by Poisson fluctuations around the best fit model.

Many pixels are found to have large fluctuations - a possible indication of point source contributions.



Lee et al. (2015)

Pulsars in the Galactic Center

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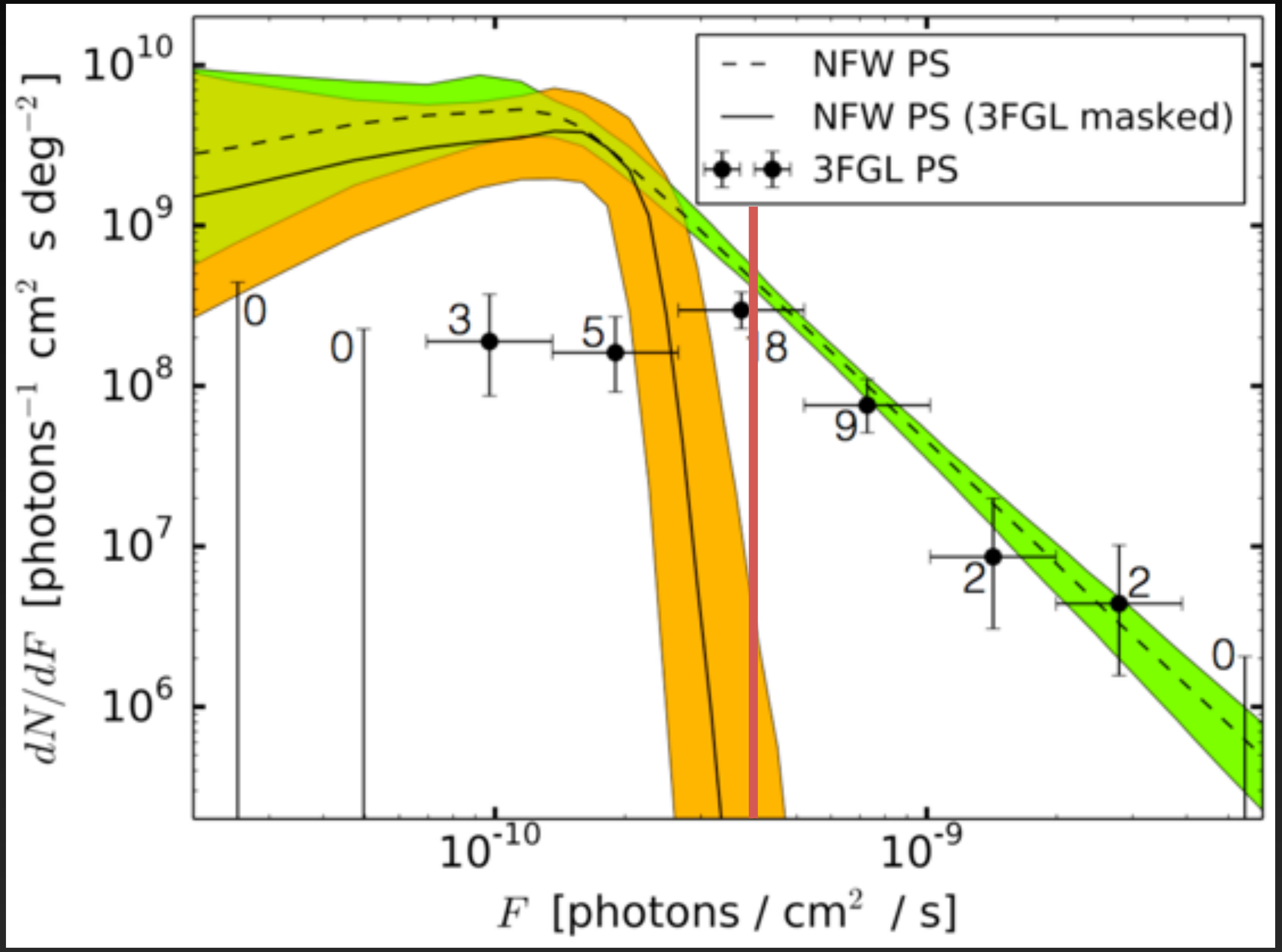
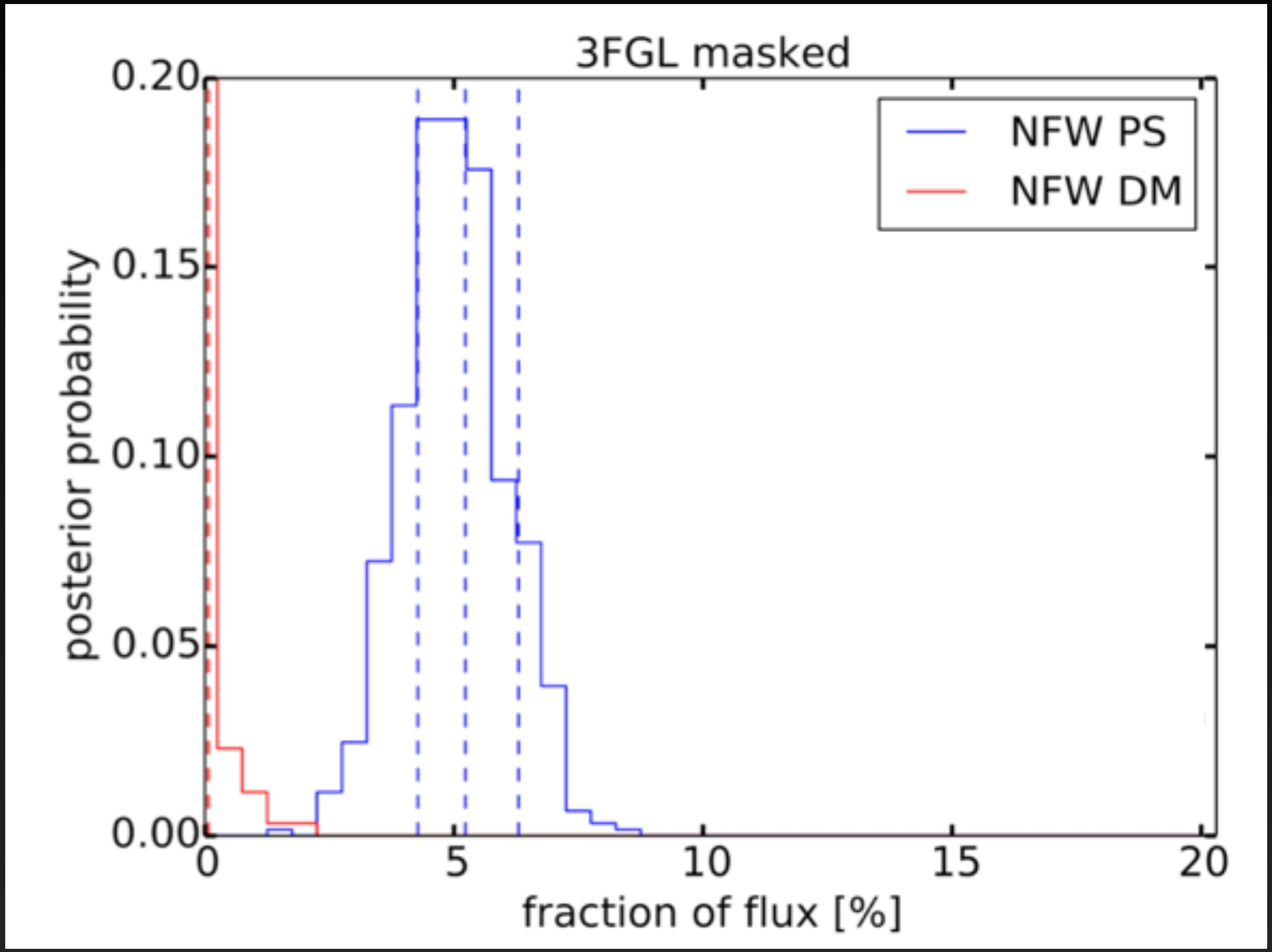


Lee et al. (2015)

Can produce skymaps and flux distributions of non-Poissonian emission, and see how this absorbs the point-to-point variations.

Pulsars in the Galactic Center

IG

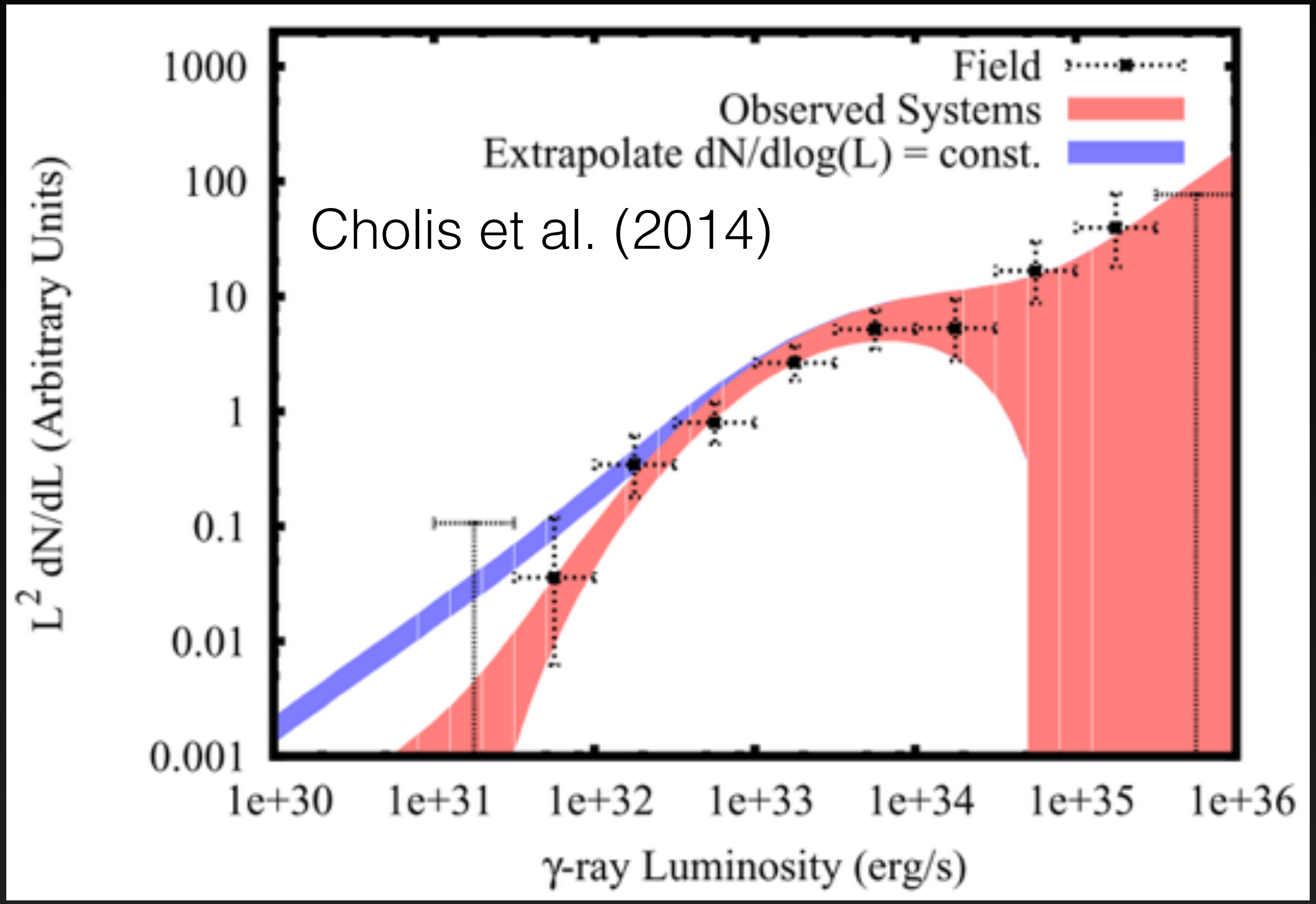


When both a traditional NFW template and the non-Poissonian NFW template are allowed to float arbitrarily, the non-Poissonian template absorbs the gamma-ray excess.

Lee et al. (2015)

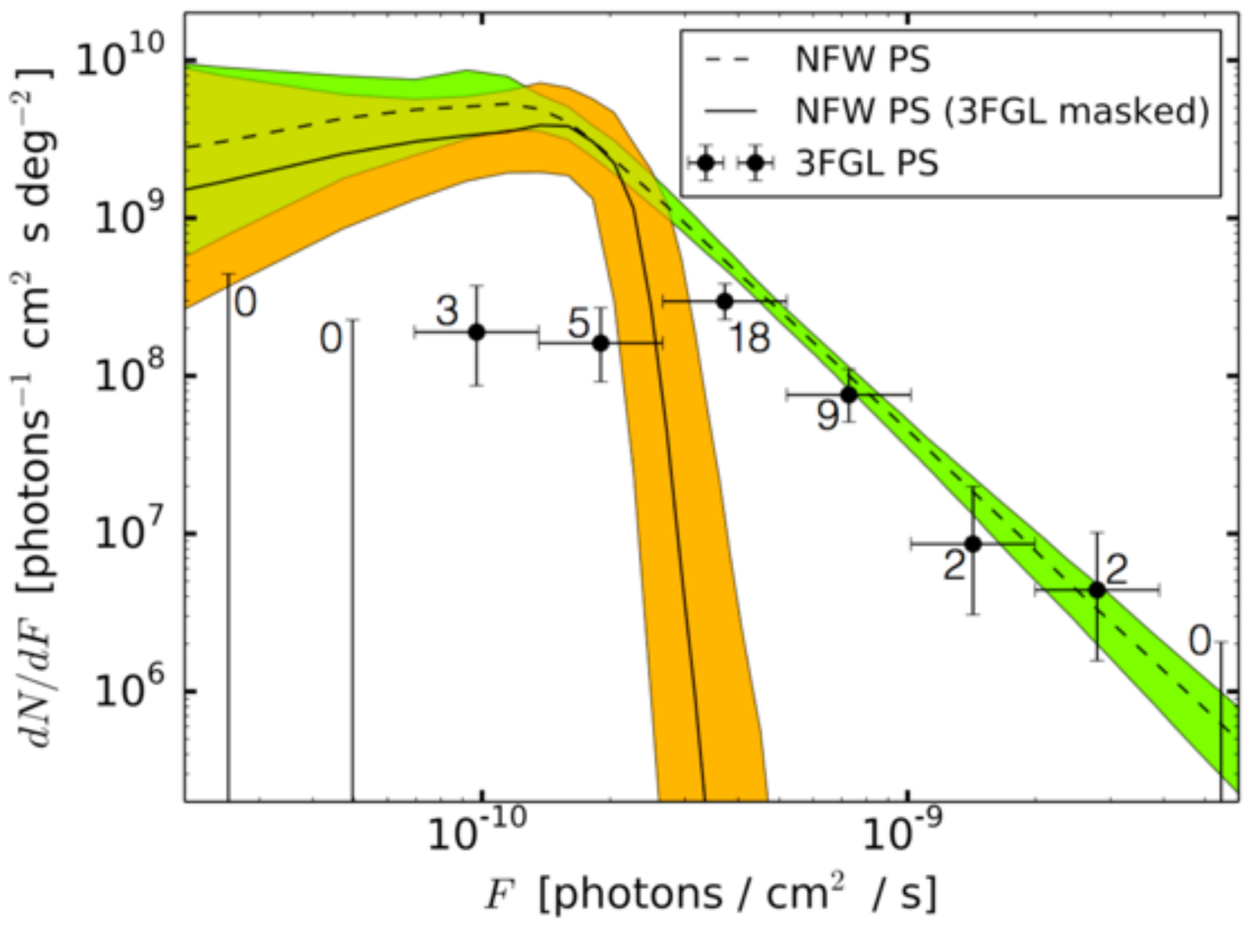
Why Haven't We Found the Pulsars?

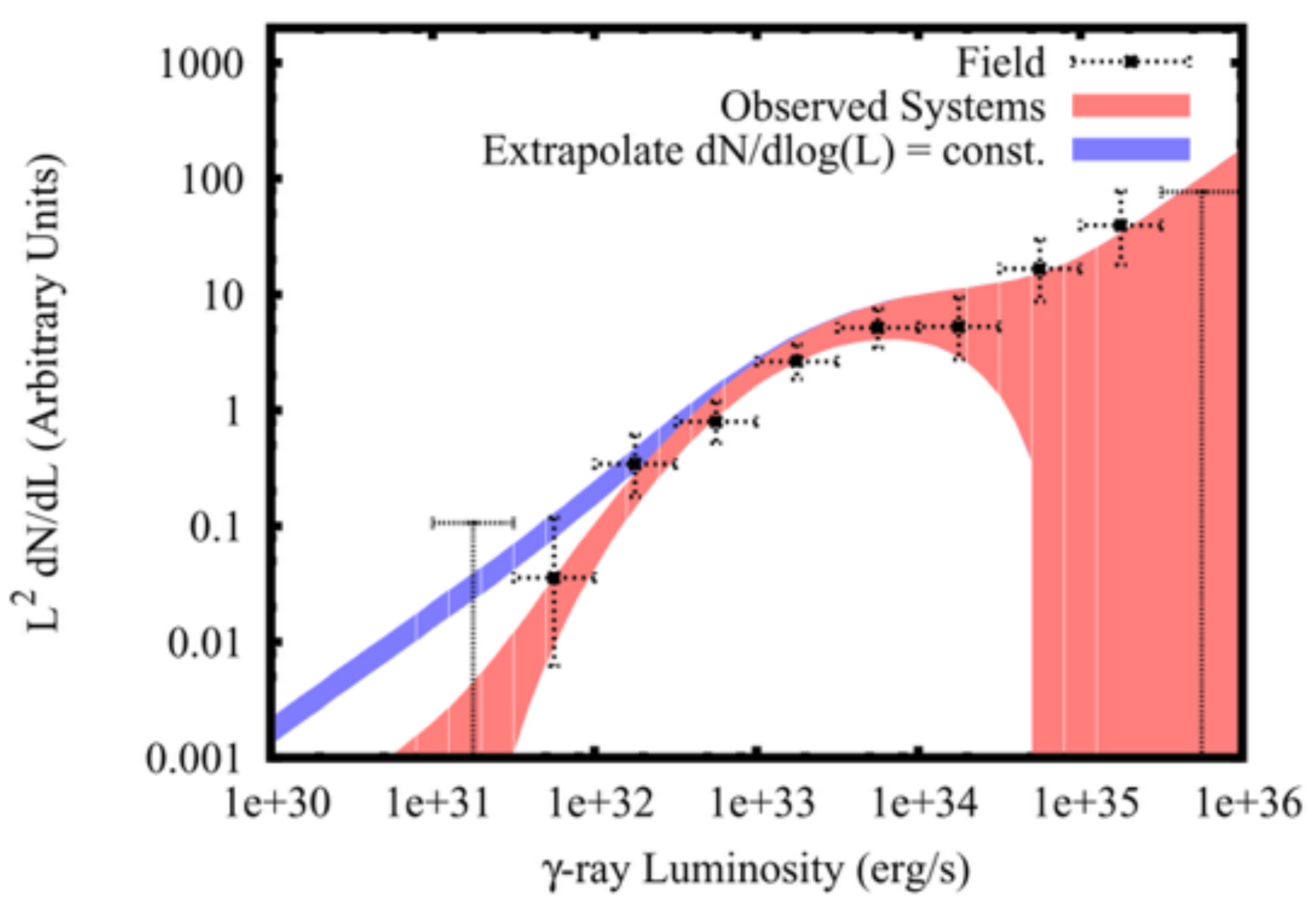
- Can measure the fluxes of known MSPs and extrapolate to a posited galactic center population.



- There would need to be 226 (+91/-67) MSPs with luminosity > 10^{34} erg s^{-1} in the circular region, and 61.9 (+60/-33.7) with luminosity > 10^{35} erg s^{-1}.

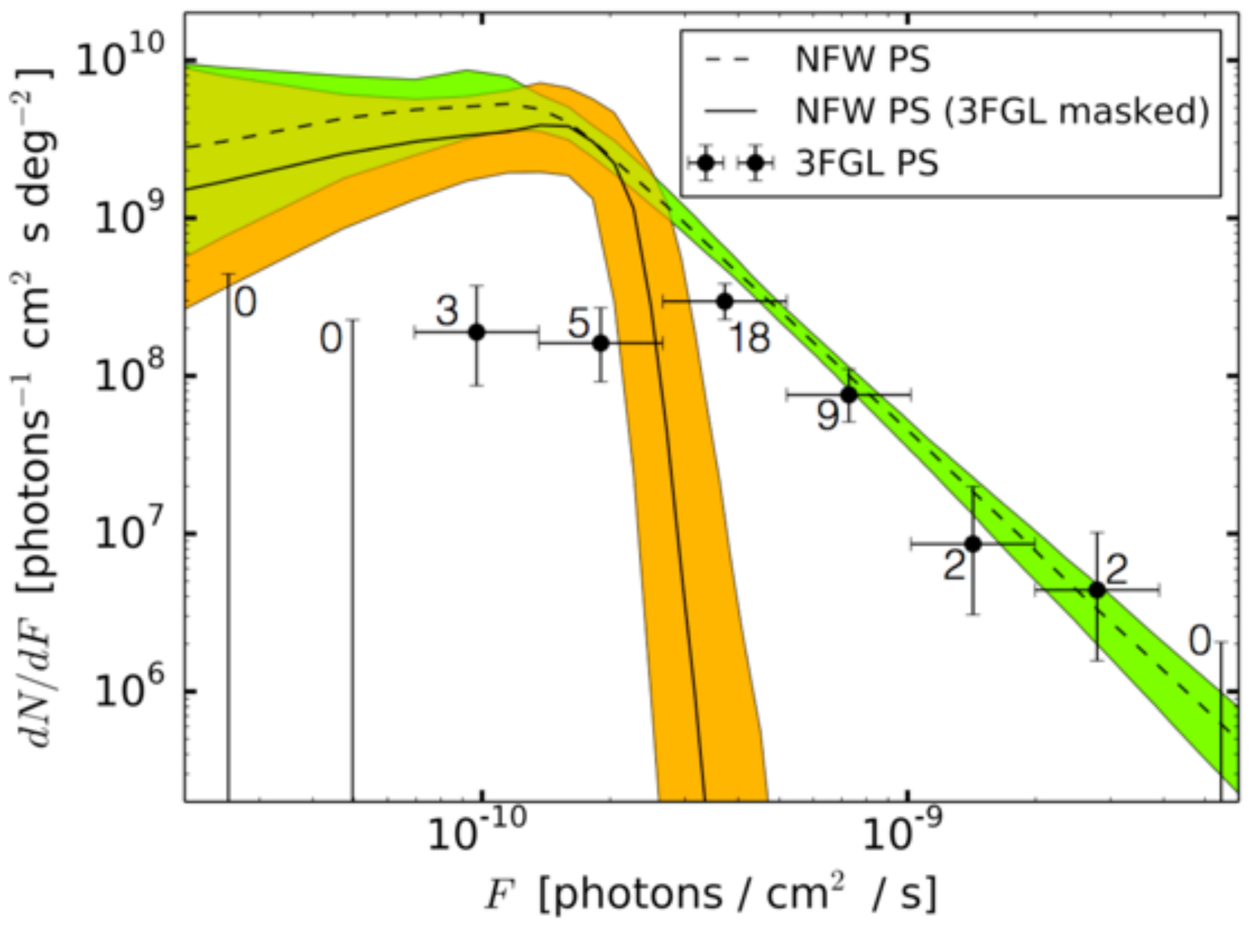
Why Haven't We Found the Pulsars?

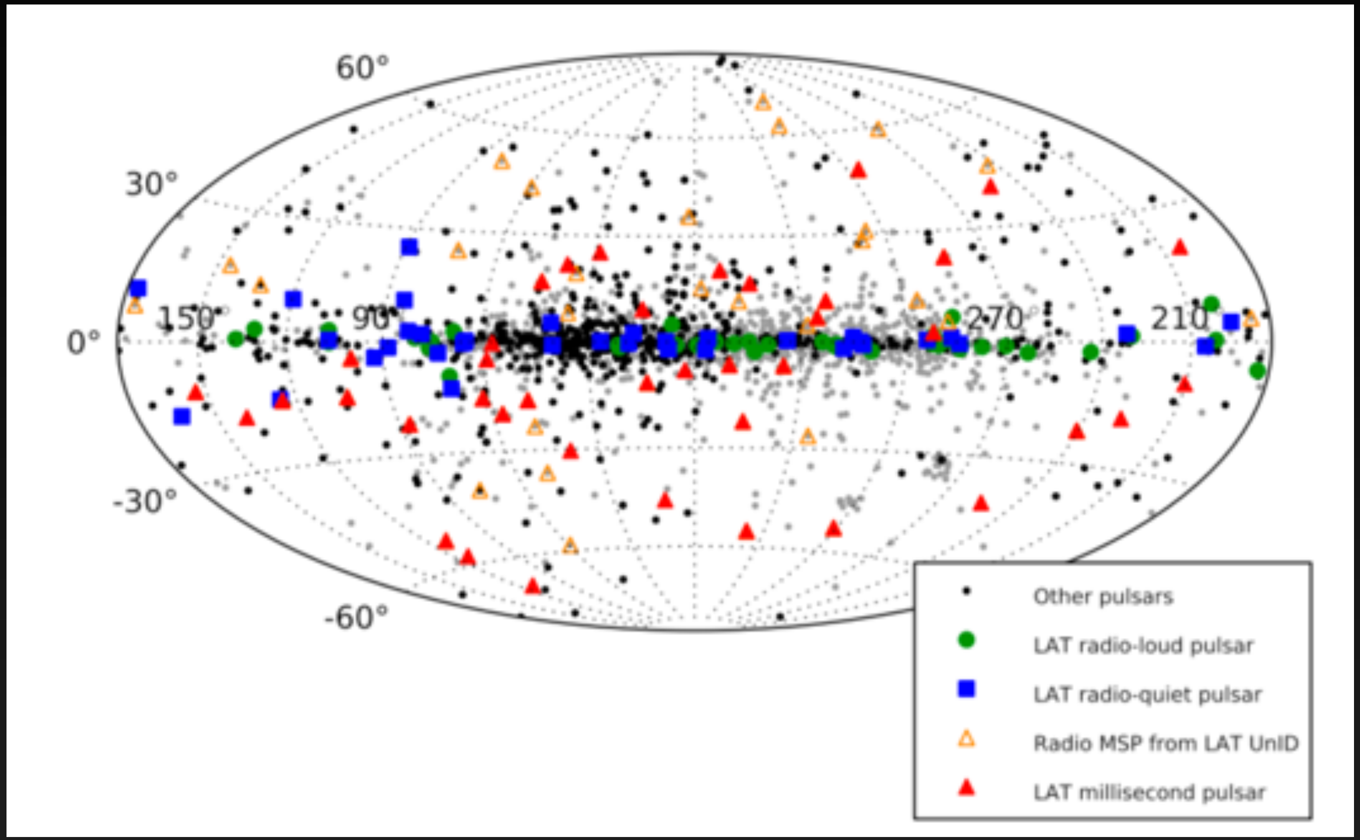




- A luminosity of 10^{35} erg s^{-1} at the galactic center is equivalent to a gamma-ray flux of 8.0×10^{-9} photons cm^{-2} s^{-1}. These systems have not been observed in the Galactic Center.

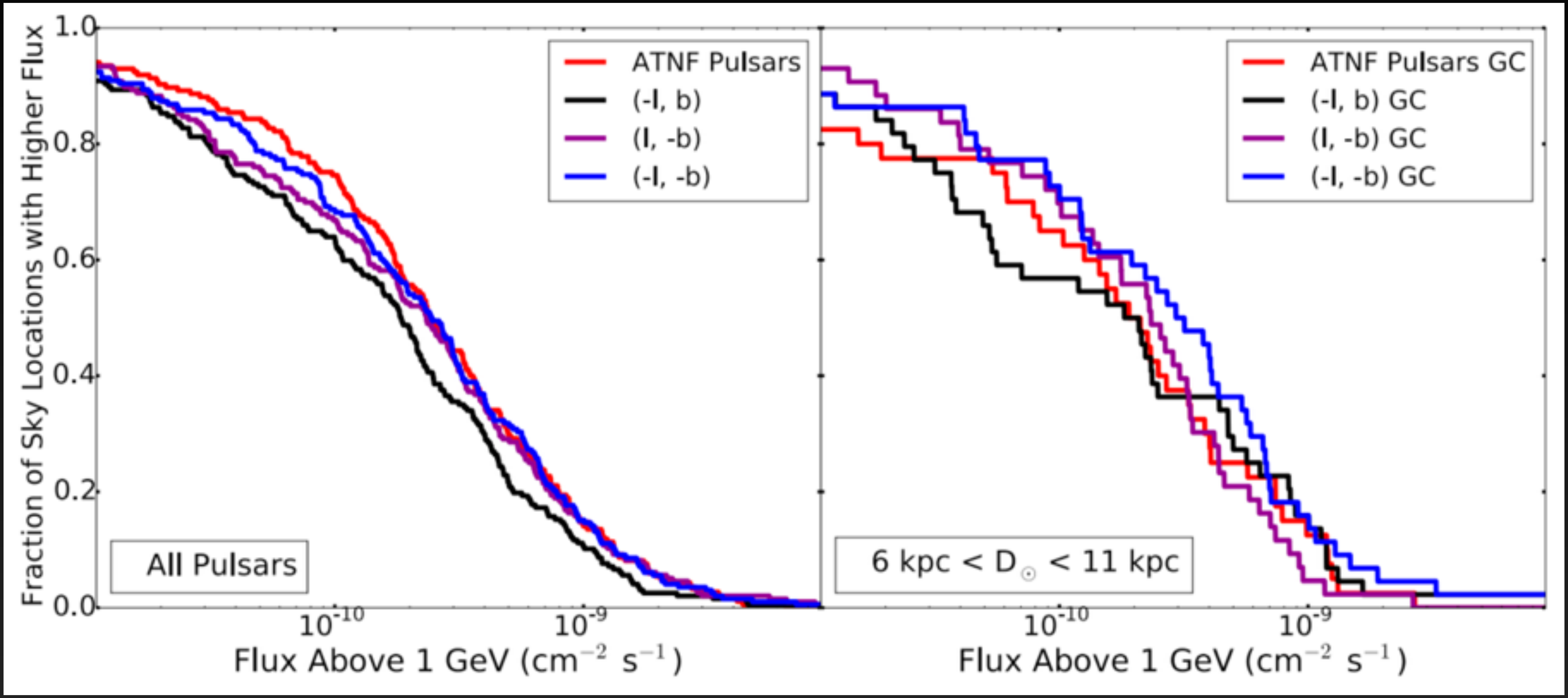
Why Haven't We Found the Pulsars?





- Even if the previous models are a little off, these should be relatively bright sources.
- We can cross-correlate these hotspots with known radio pulsars.

Why Haven't We Found the Pulsars?



TL (2015)

- **Additionally, these gamma-ray hotspots do not correlate with the location of any known radio pulsars.**

How Do We Test the Pulsar Hypothesis?

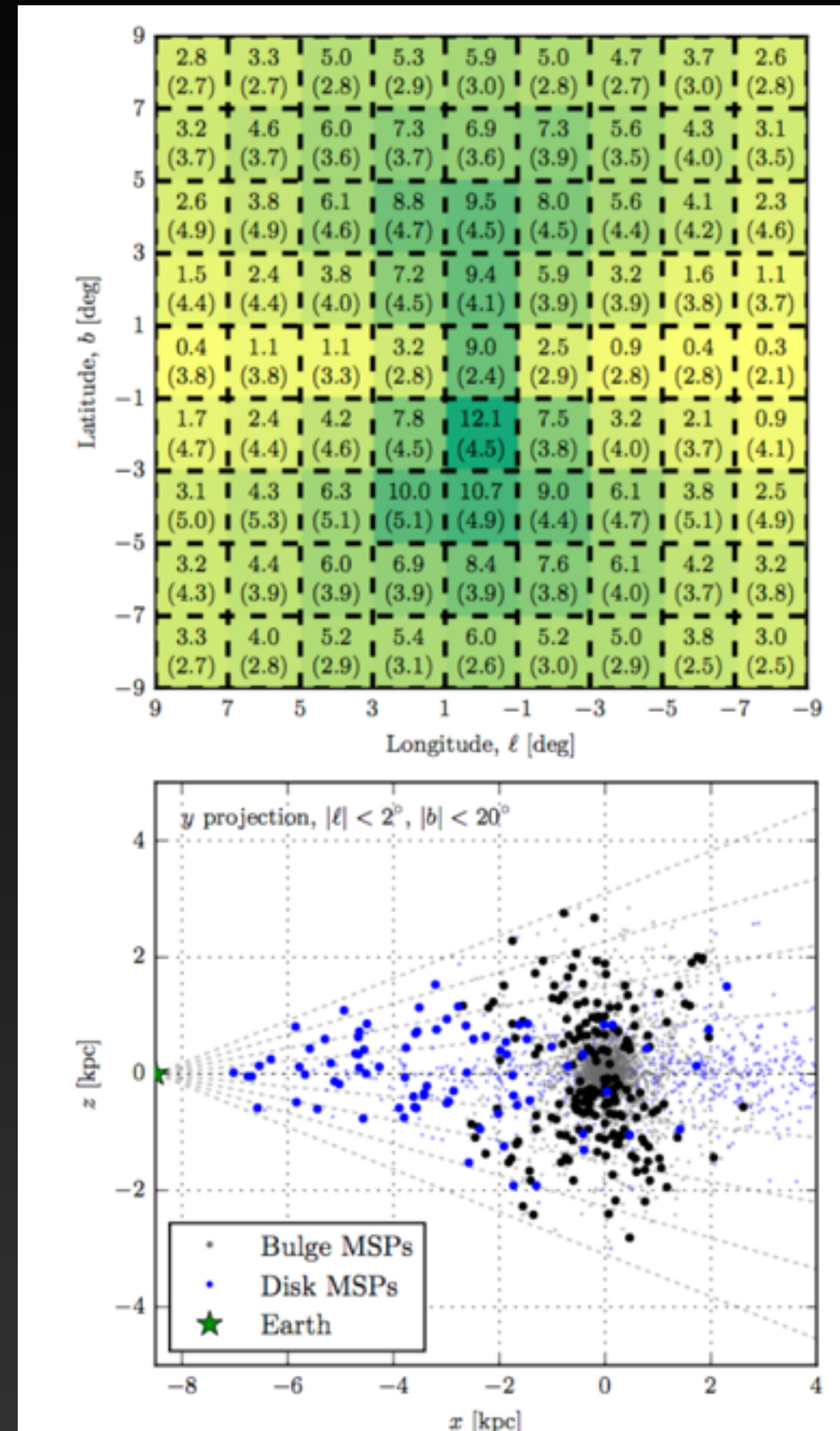
- **Future Gamma-Ray Observations by the Fermi-LAT are unlikely to resolve this degeneracy**

- **The observation of radio pulsars coincident with gamma-ray hotspots would be smoking-gun evidence for a pulsar interpretation**

How Do We Test the Pulsar Hypothesis?

- Radio Observations with GBT targeted at gamma-ray hotspots would be expected to find ~5-10 MSPs with a 200 hr commitment.

- Fortunately, SKA observations are likely to conclusively find MSPs in the GC, or rule out this scenario entirely.



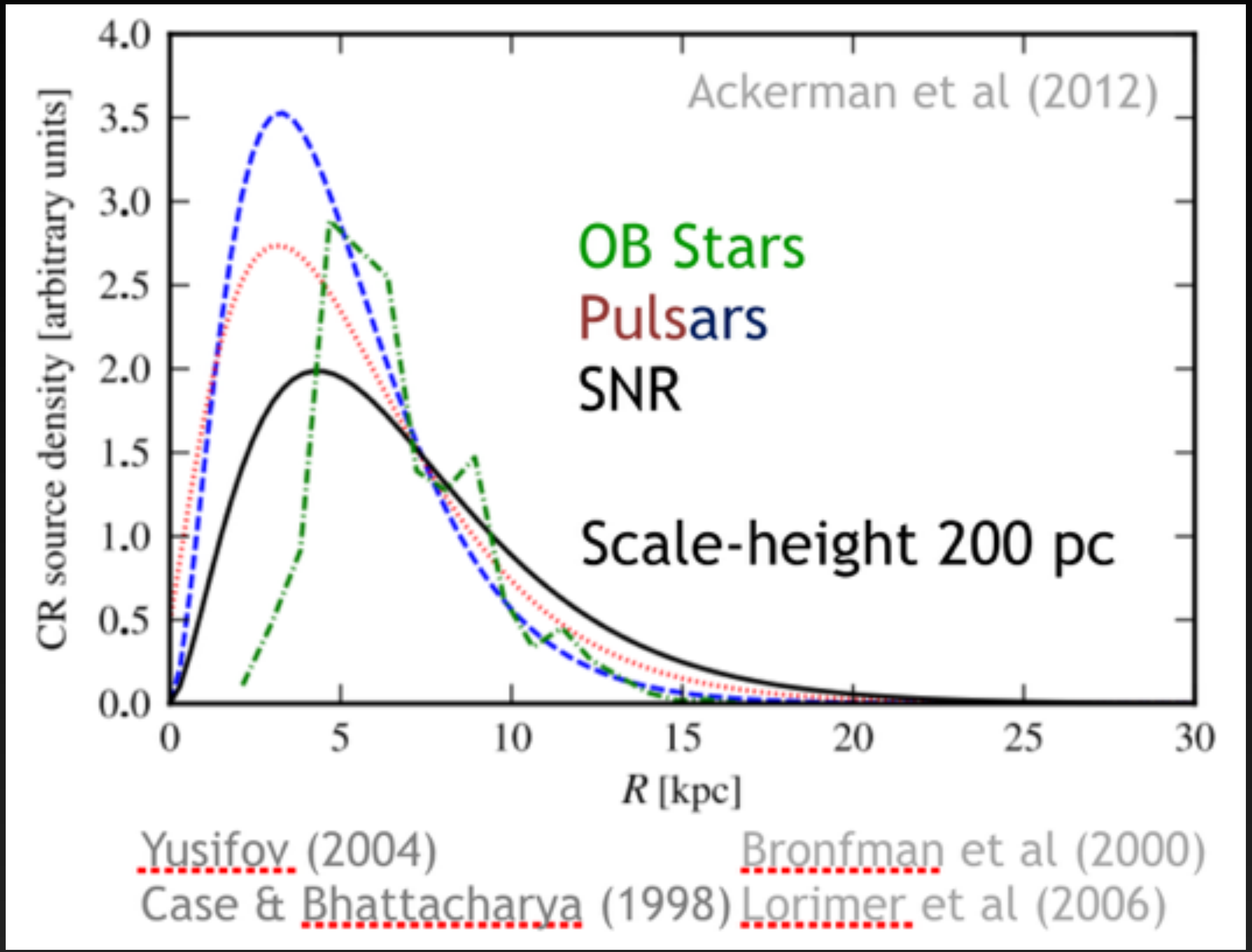
Calore et al. (2015)

New Cosmic-Ray Injection Sources

Cosmic-Ray Injection is thought to trace the historic (~10^9 yr) supernova rate.

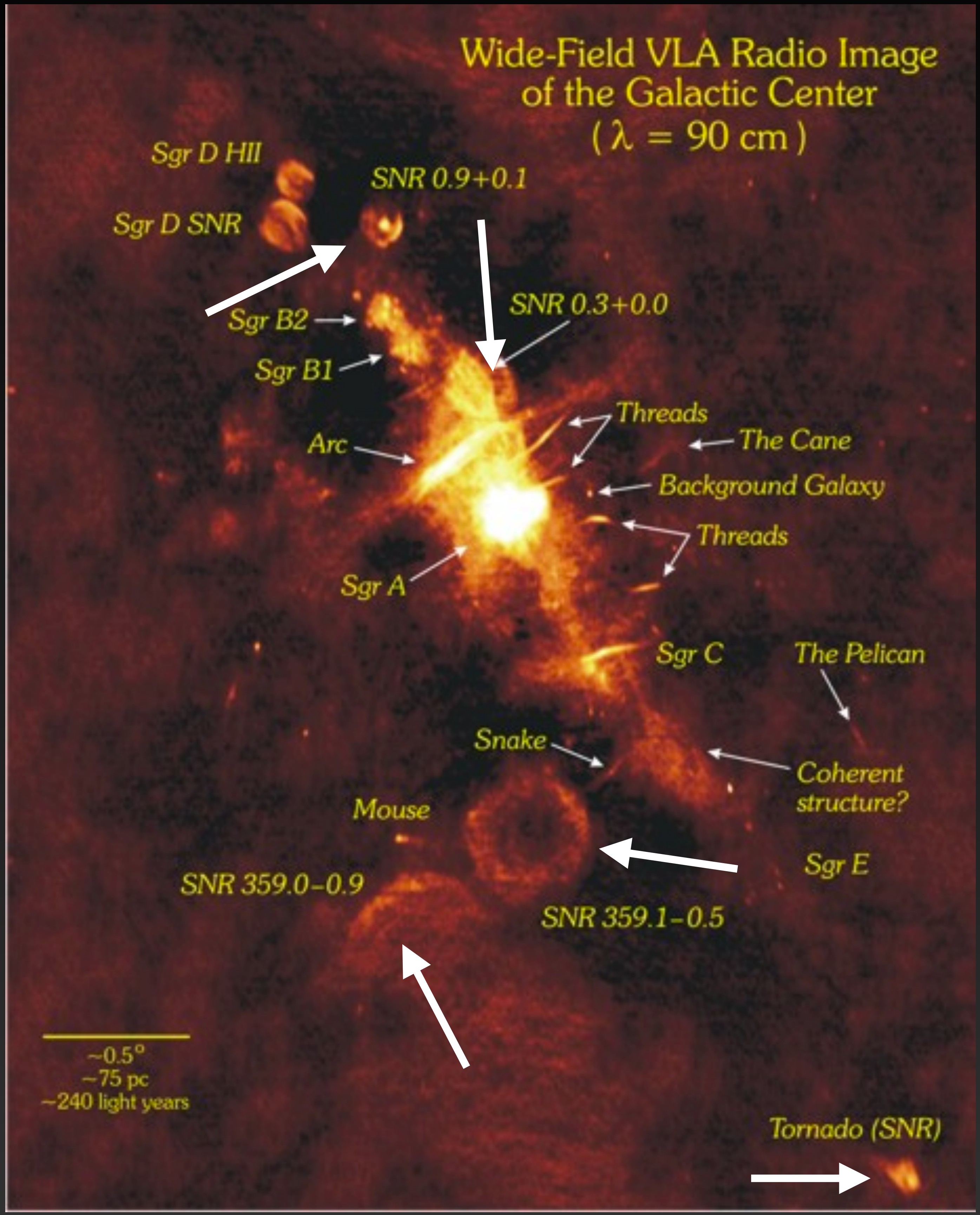
Need tracers of current and past supernovae rate:

- Observed SNR
- Pulsars
- OB Stars



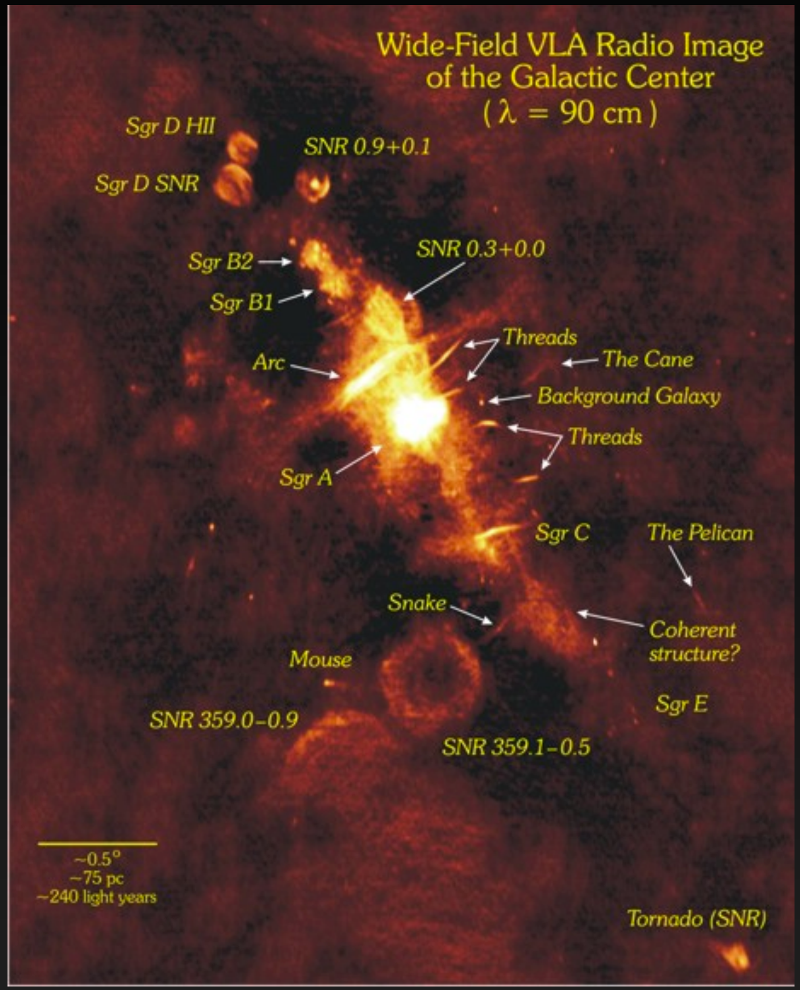
Interestingly the models used for these analyses have extremely small injection rates near the GC (in several cases identically 0).

New Cosmic-Ray Injection Sources



New Cosmic-Ray Injection Sources

Observations indicate that a substantial fraction of the total galactic star formation rate is contained in the central molecular zone:



- **3% (free-free emission,** Longmore et al. 2013**)**
- **10% (young stellar objects,** Yusef-Zadeh et al. 2009**)**
- **20% (Wolf-Rayet stars,** Rosslowe & Crowther 2015**)**

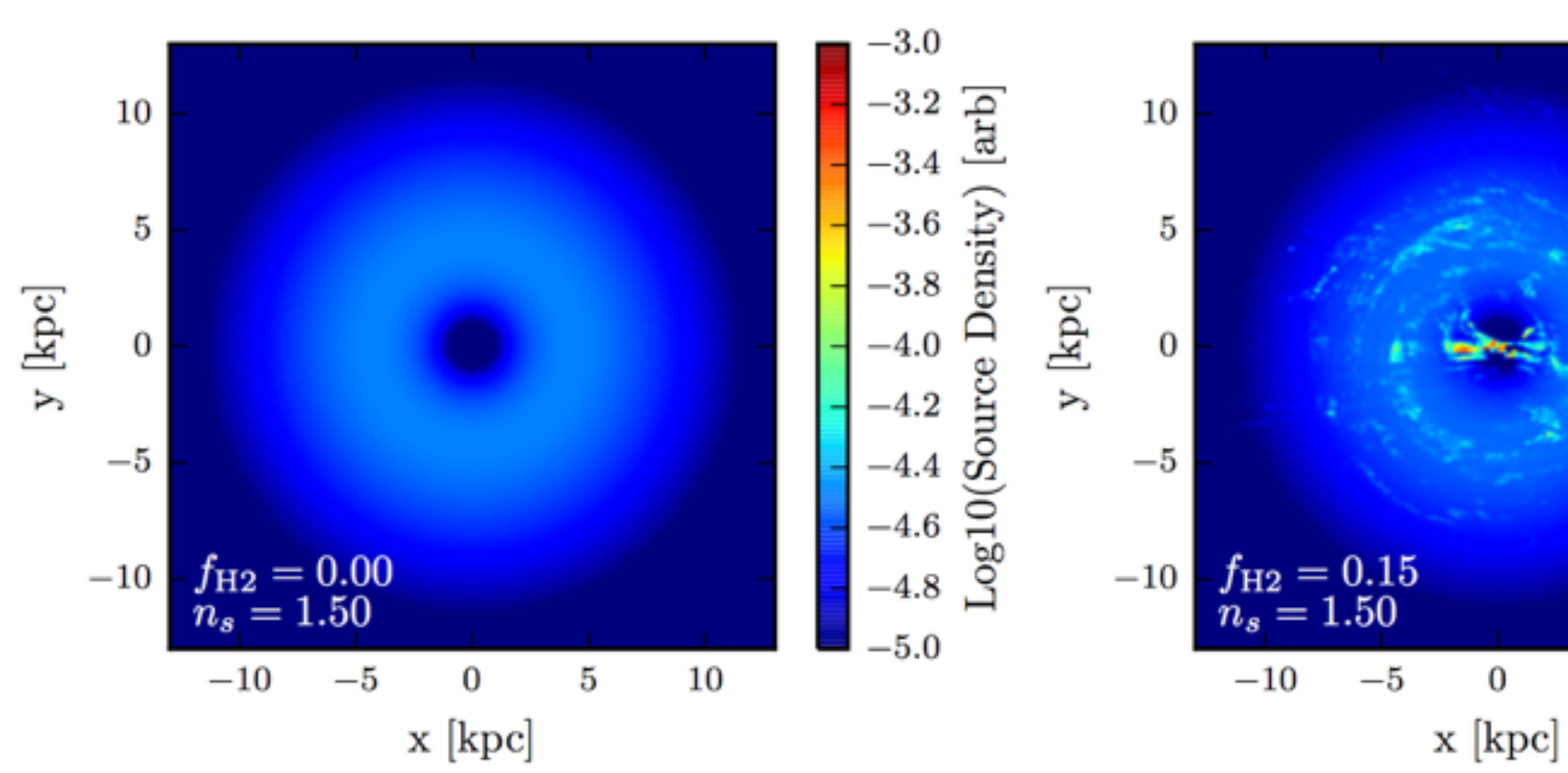
Is the Galactic Center gamma-ray flux actually underluminous?

Cosmic-Ray Injection Sources

Solution: Add a new cosmic-ray injection component tracing the molecular gas density.

Observational Resilient: Several molecular gas tracers are sensitive to gas overdensities near the Galactic center.

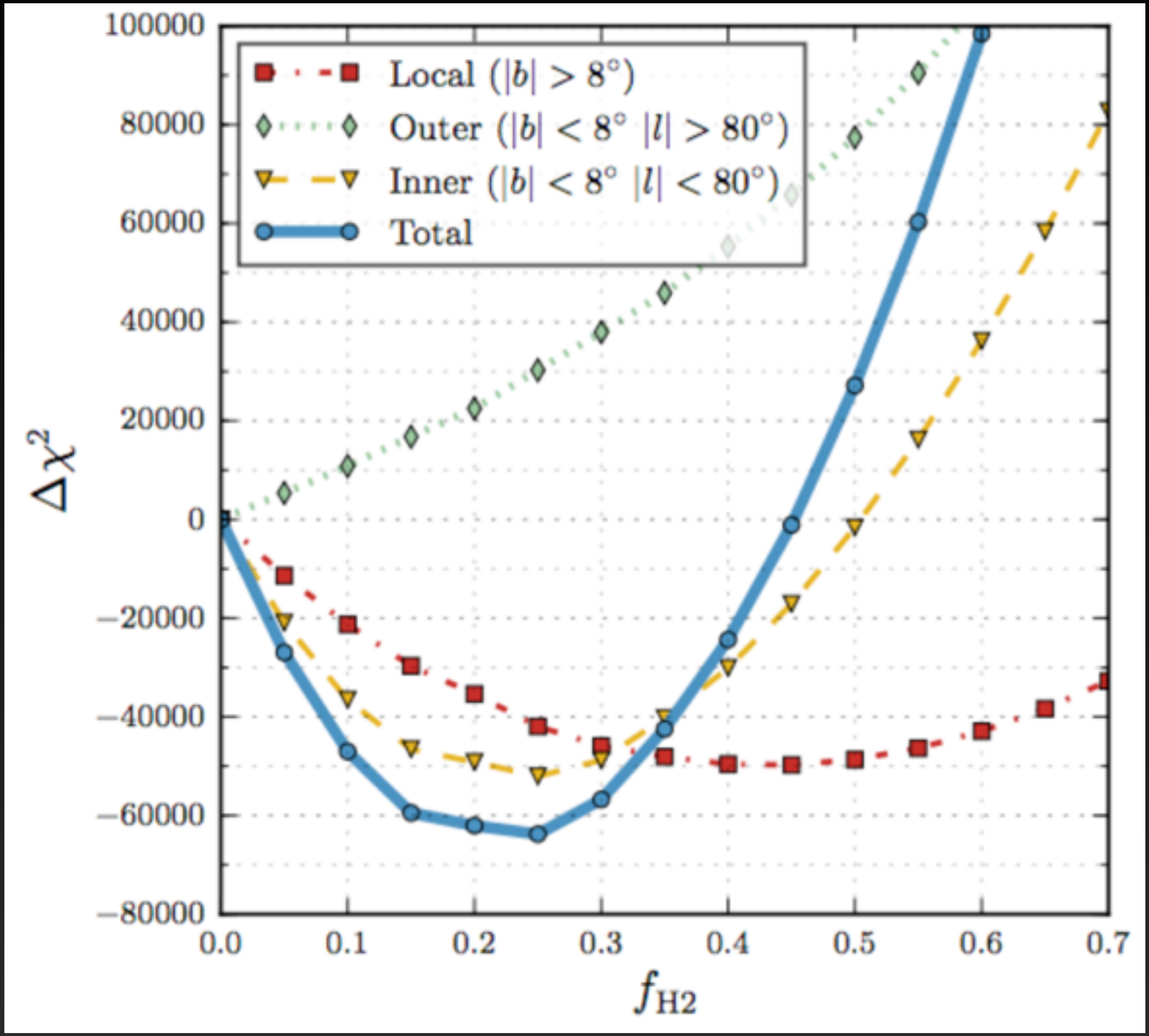
Theoretically Motivated: Molecular Gas overdensities seed star formation, a correlation given by the Kennicutt-Schmidt relation.



Carlson et al. (2015)

Adding a Molecular Gas Component

This new tracer improves the fit to the gamma-ray data in regions away from the Galactic center.



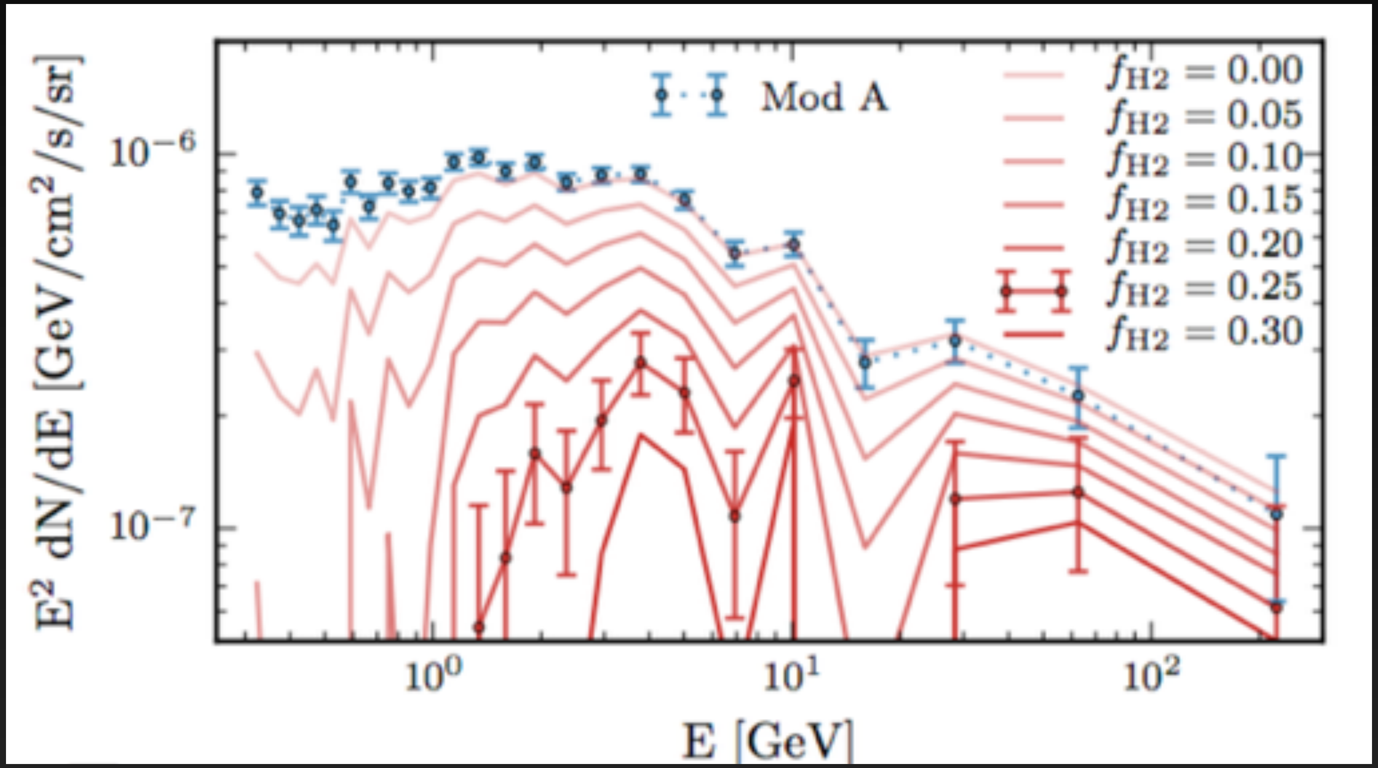
**** This is, by itself, an important result — and should be incorporated in the next generation of gamma-ray diffuse models.**

Carlson et al. (2015)

Degeneracy with the Excess

IG

Imposing the best fit global model on the Inner Galaxy decreases the intensity of the excess.

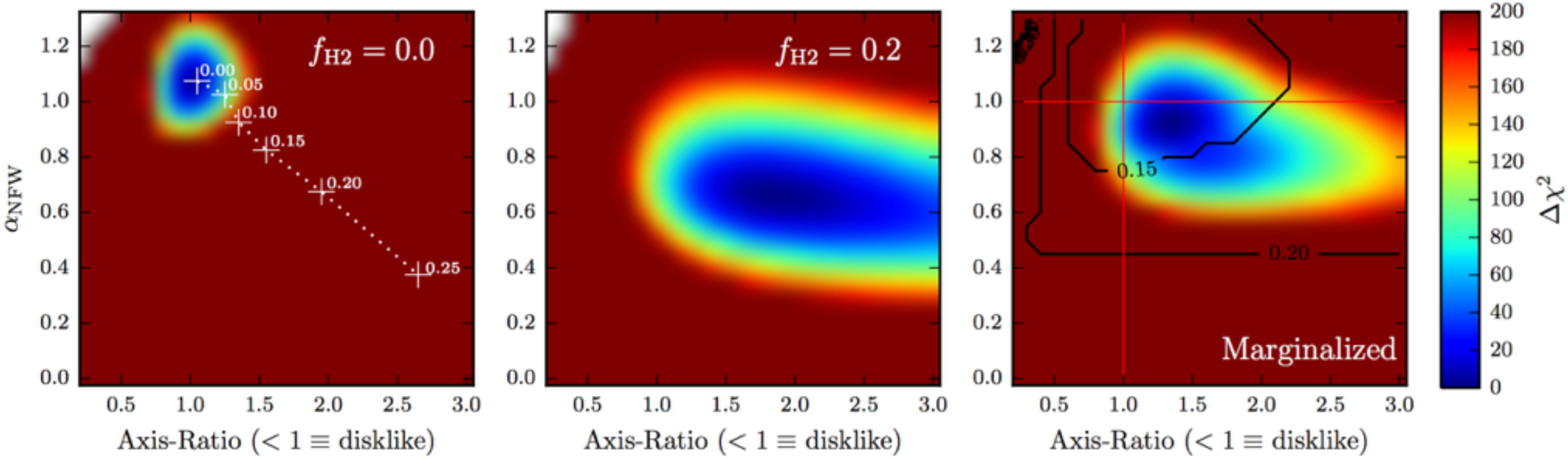


Additionally, the spectrum of the excess becomes significantly harder for high values of f_{H2}.

Carlson et al. (2015)

Degeneracy with the Excess

IG



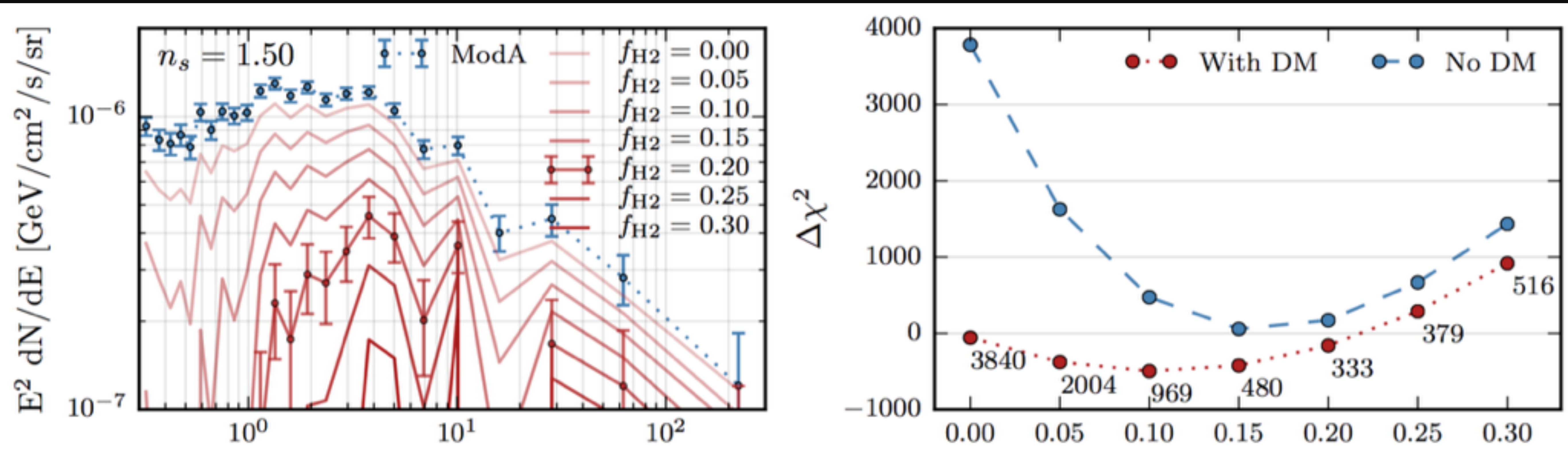
Interestingly, the intensity of the gamma-ray excess increases if it is flattened and stretched perpendicular to the Galactic plane.

In this case it becomes degenerate with the Fermi bubbles.

Carlson et al. (2016, in prep)

Less Degeneracy in the IG

IG



However, when f_{H2} is allowed to float independently in the IG, the best fit value is f_{H2} = 0.10, and the excess remains relatively bright.

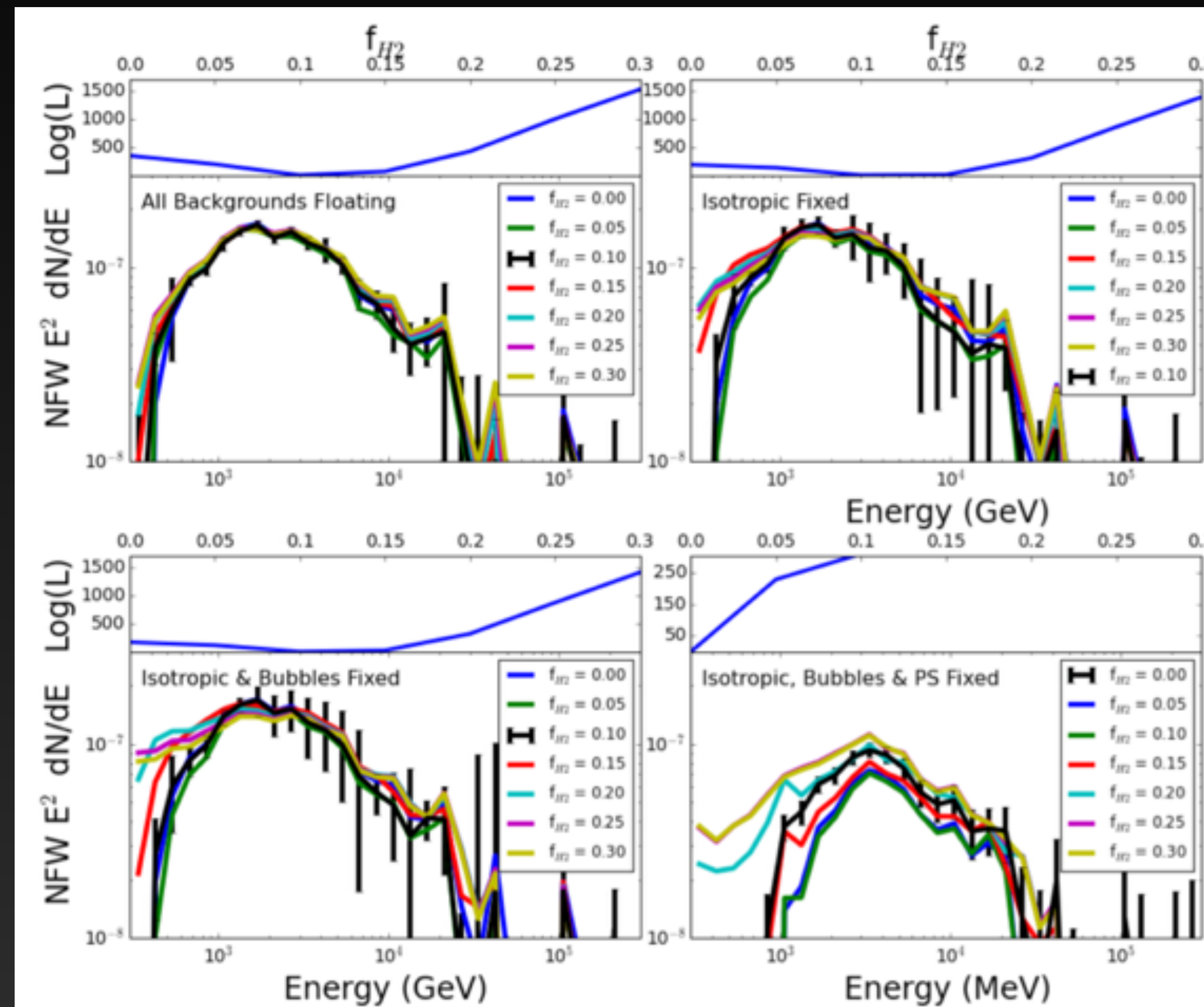
Carlson et al. (2016, in prep)

No Degeneracy in the GC

GC

In the GC, this degeneracy disappears. The intensity, spectrum, and morphology of the excess is a resilient feature.

The statistical significance of the excess is dominated by the inner ~2º.



Carlson et al. (2016, in prep)

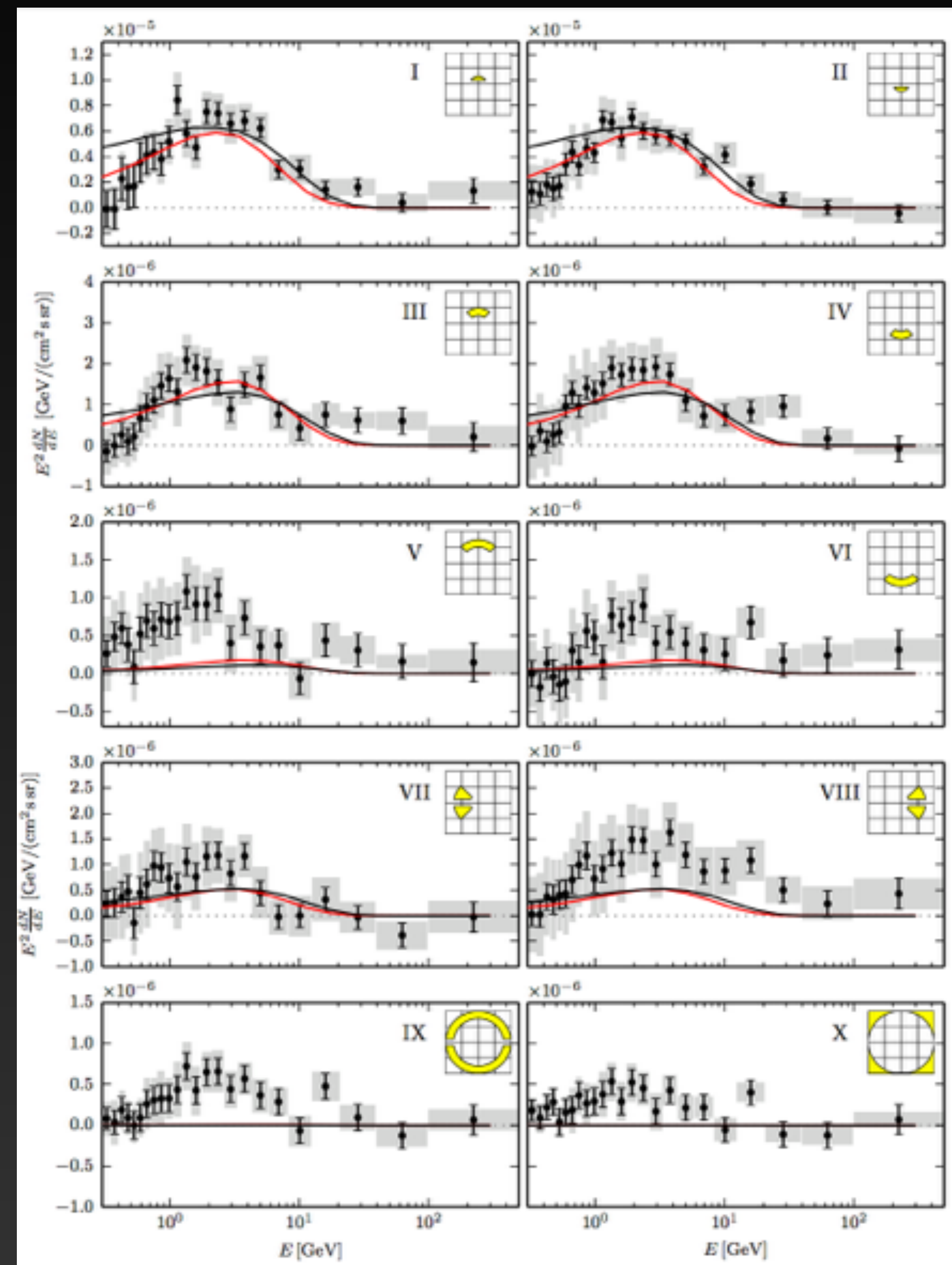
Leptonic Outbursts

IG

Emission could be concentrated in the GC if it is produced by a recent outburst.

Leptonic outbursts are most reasonable because the target ISRF is relatively spherically symmetric.

However, electrons cool too rapidly to produce a similar gamma-ray spectrum from 0.1º — 10º from the GC.



Cholis et al. (2015)

Leptonic Outbursts

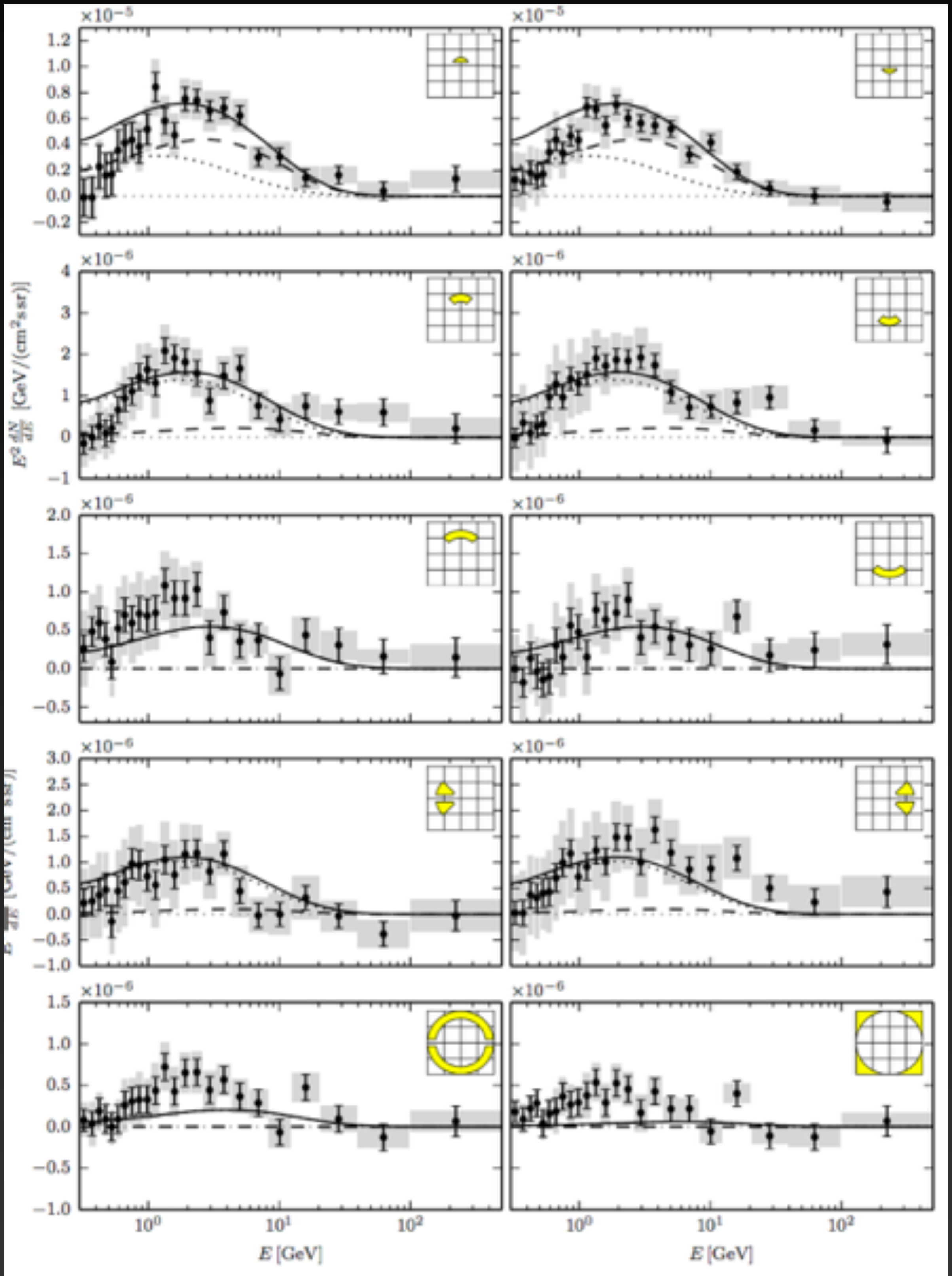
However, two outbursts can produce the emission, but only if:

1.) Each outburst has a very hard injection spectrum $E^{-1.2}$ — $E^{-1.5}$

2.) The outbursts are well timed (1 Myr + 100 kyr). The old outburst is 10x brighter than the new outburst.

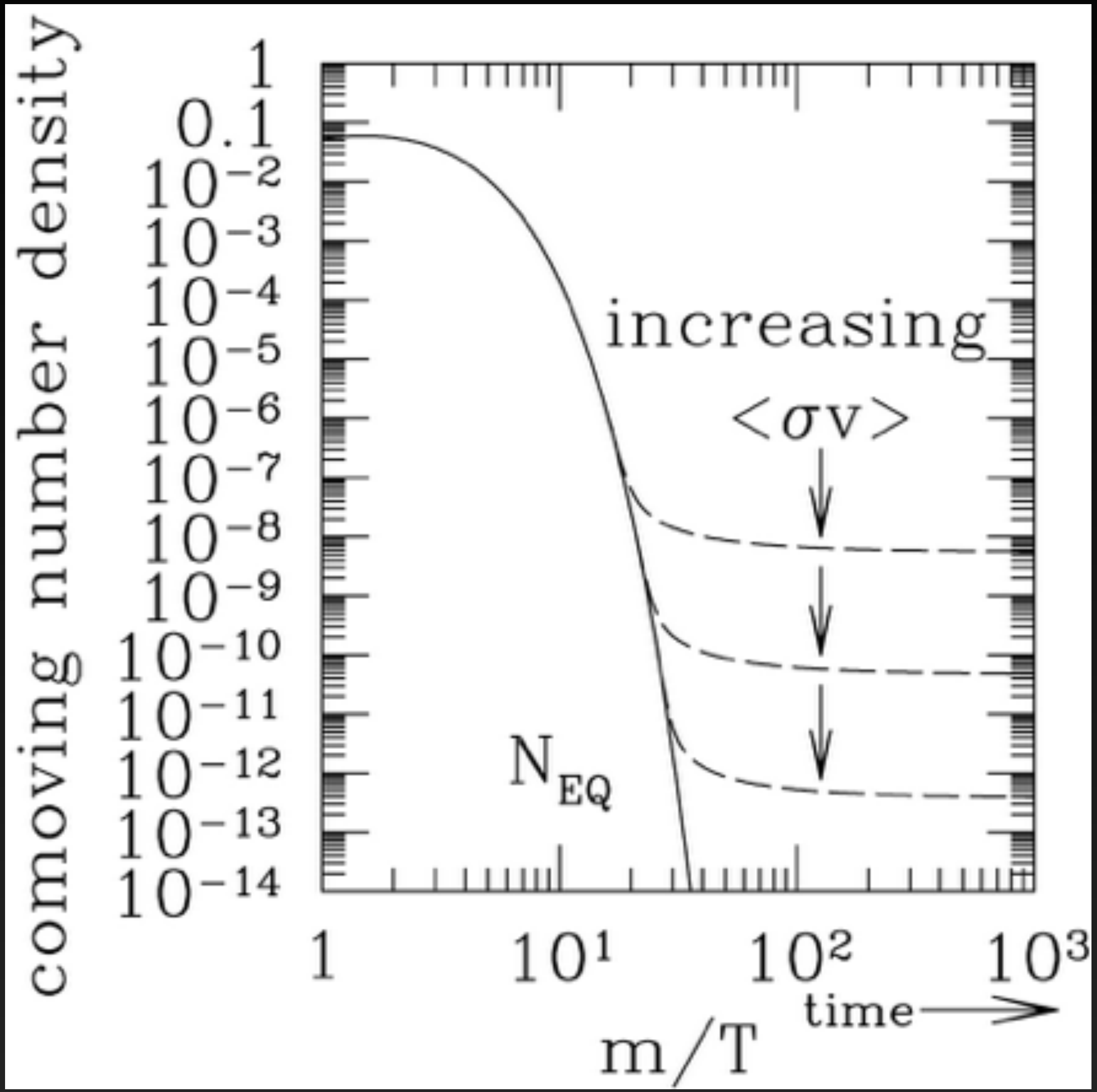
3.) A third outburst or bright collection of point sources is responsible for the inner $\sim 1^{o}$.

Cholis et al. (2015)



Do not dismiss novel physics so readily….

Dark Matter in Thermal Equilibrium



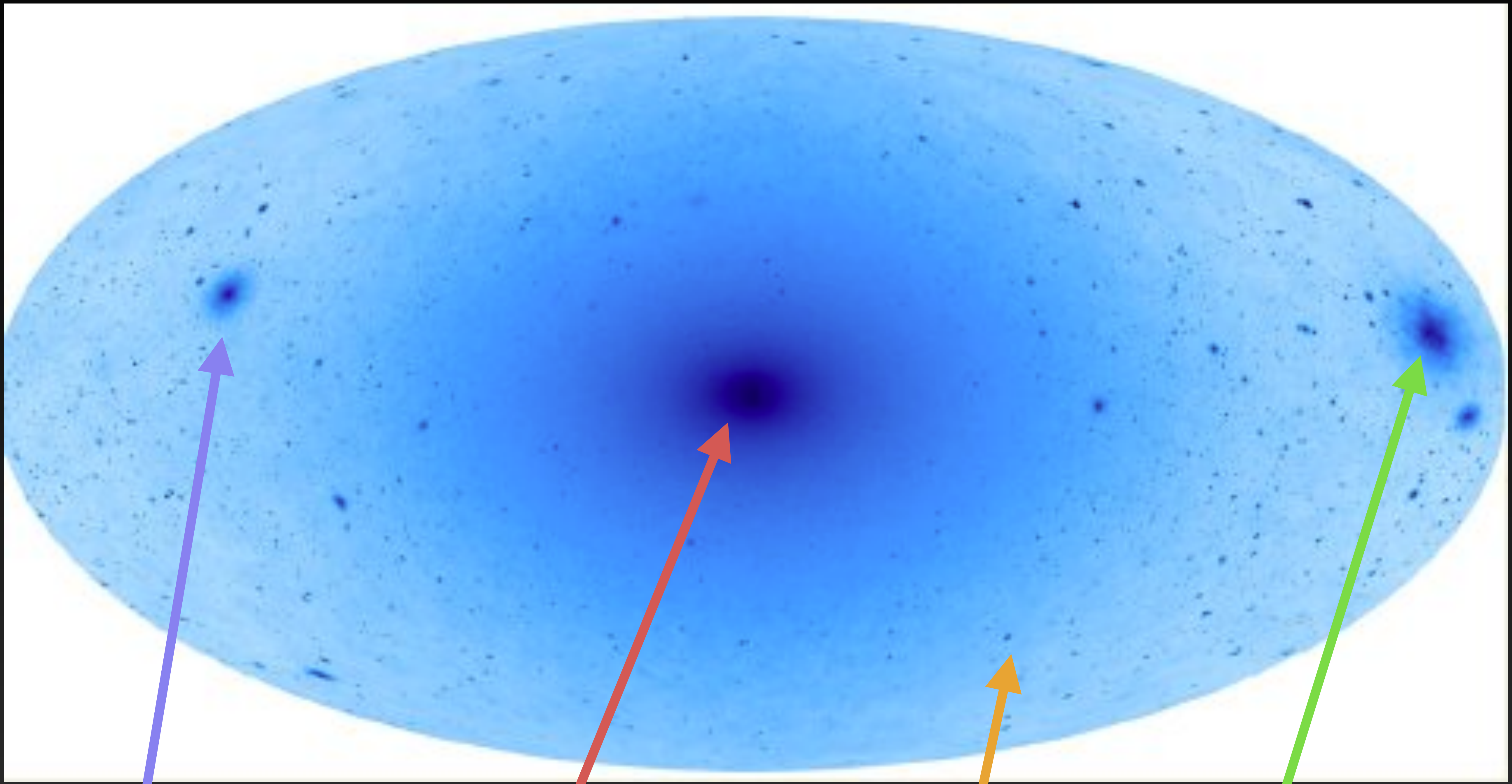
A particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the Early Universe.

$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\mathrm{f.o.}}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

$$\langle\sigma v\rangle \sim 10^{-8}\ \mathrm{GeV}^{-2}\left(3\times 10^{-28}\ \mathrm{GeV}^2\ \mathrm{cm}^2\right)\ 10^{10}\ \frac{\mathrm{cm}}{\mathrm{s}} = 3\times 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

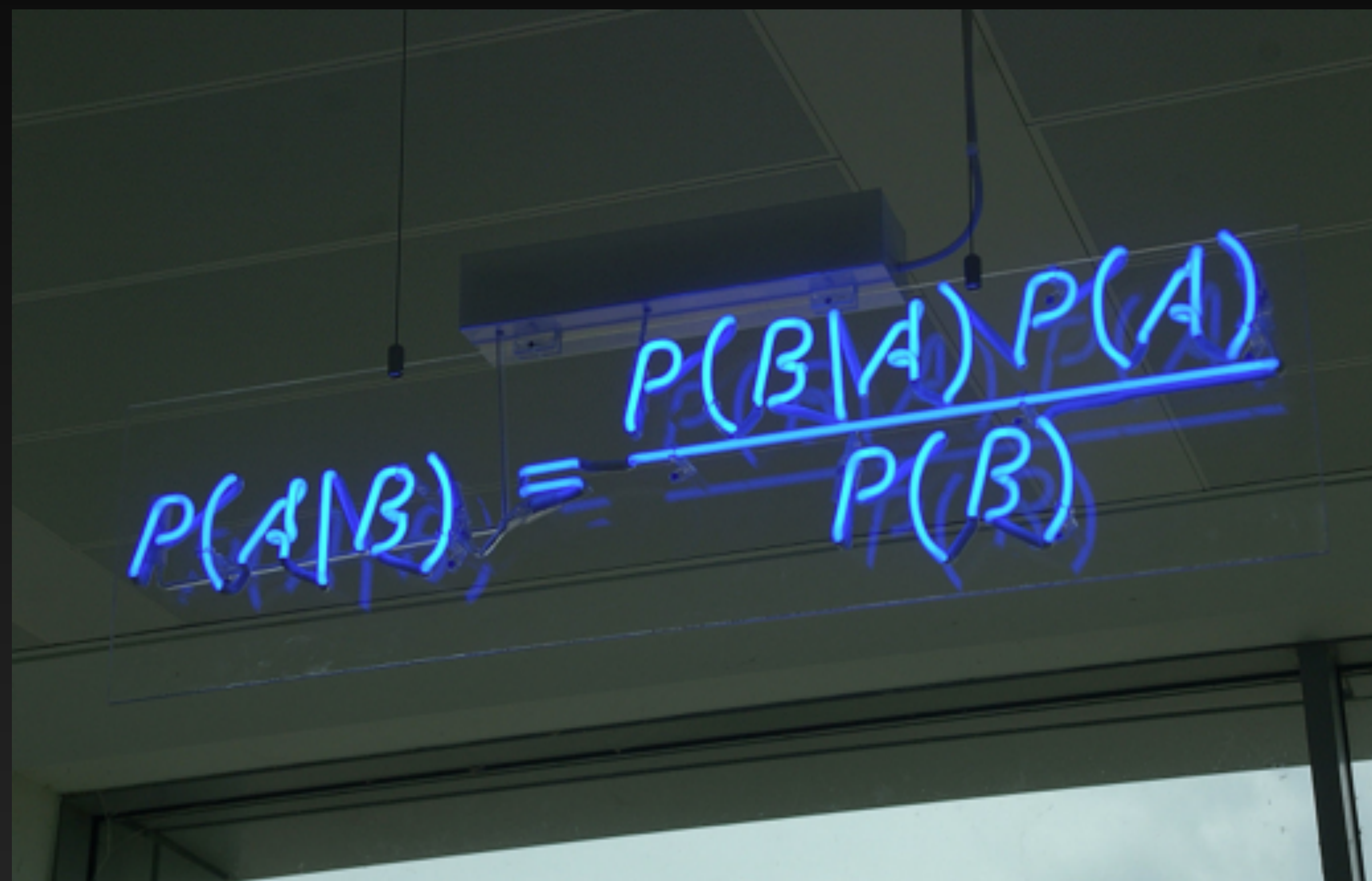
see talk by Matt Buckley tomorrow

Where to Observe Dark Matter



Observing a Dark Matter Particle

Myriad Evidence Suggests Dark Matter exists, and should have non-gravitational interactions:



We shouldn’t think of dark matter searches as a “needle in a haystack”. Our theoretical priors should lead us to bet that particle dark matter can be feasibly observed.

The Status of the Galactic Center Excess

1.) Over the last two years - the existence of a significant gamma-ray excess (compared to current astrophysical models) has been confirmed.

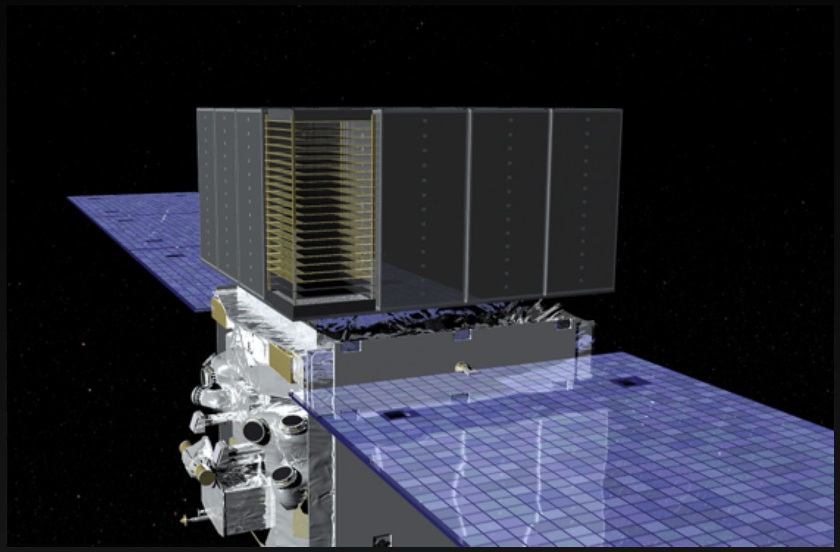
2.) The gamma-ray excess has features compatible with a dark matter signal — a dark matter motivated NFW profile remains the best fitting template to the gamma-ray data.

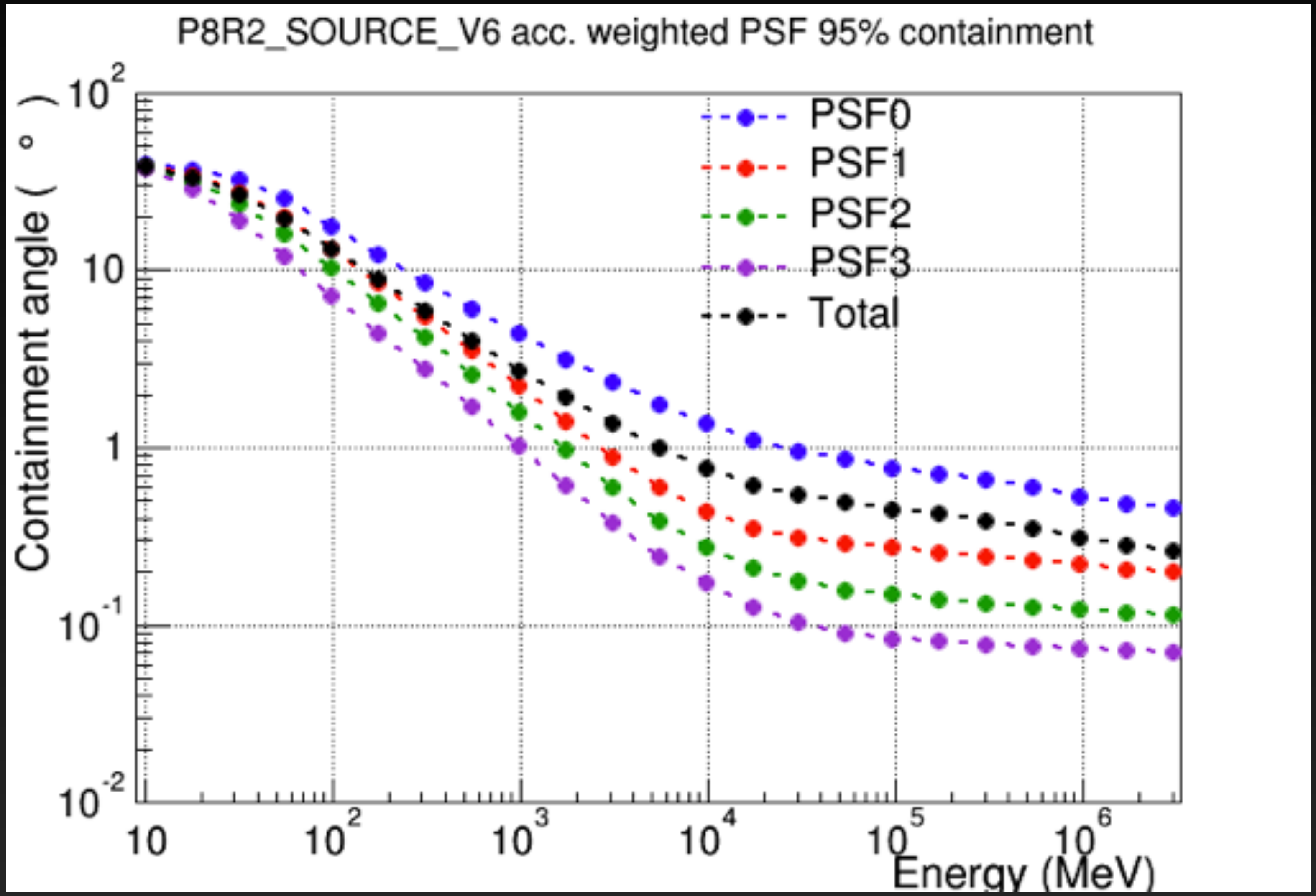
3.) Several well motivated astrophysical models have been produced, and new techniques are being developed to differentiate between these models.

4.) New multi wavelength models and studies are needed.

EXTRA SLIDES

Angular Resolution





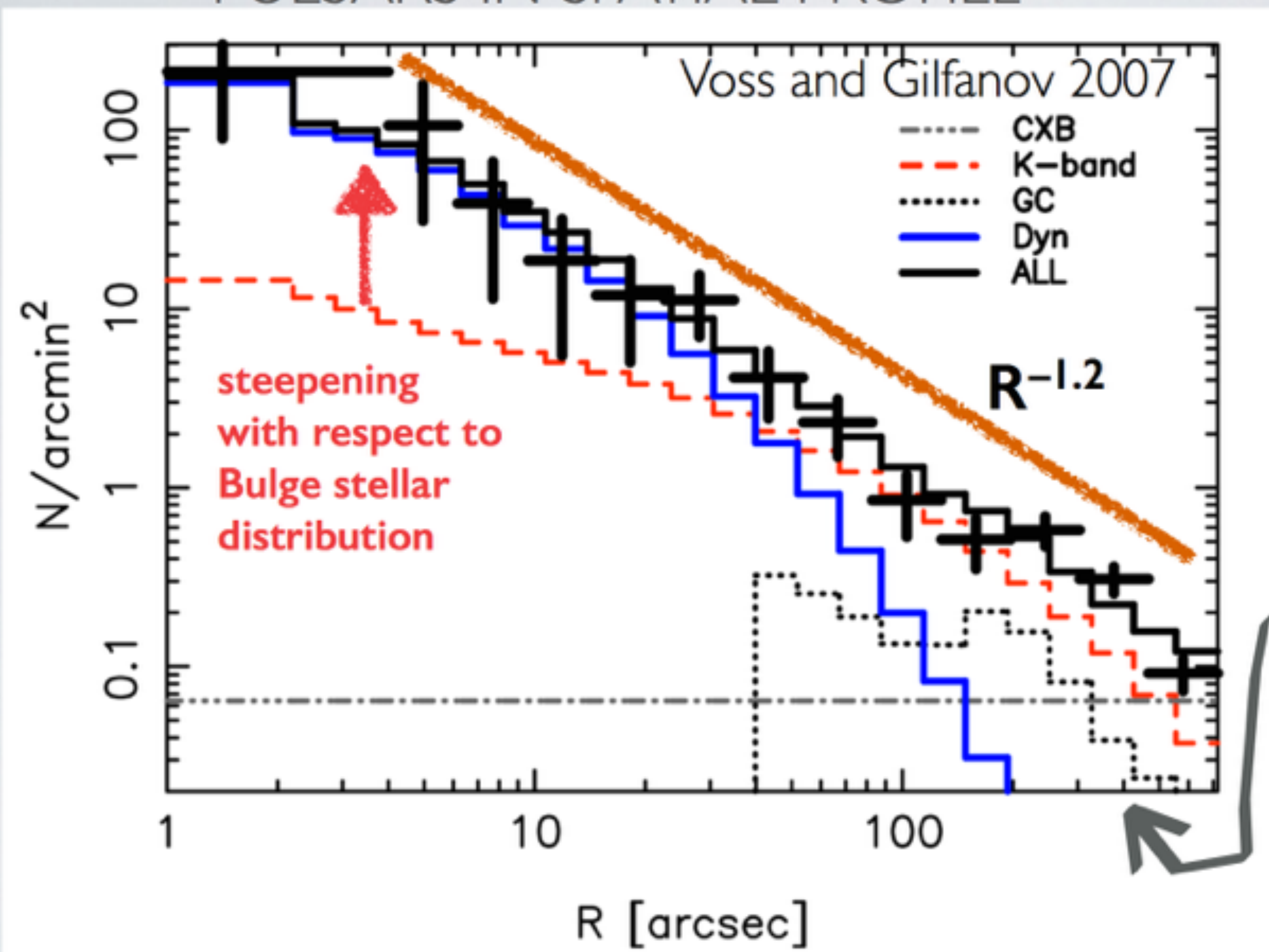
The relatively poor angular resolution of the Fermi-LAT smears these signals into each other.

Comparison to Dark Matter Models

Freese et al. (1509.05076)
Bhattacharya et al. (1509.03665)
Algeri et al. (1509.01010)
Fox & Tucker-Smith (1509.00499)
Dutta et al. (1509.05989)
Liu et al. (1508.05716)
Berlin et al. (1508.05390)
Fan et al. (1507.06993)
Hektor et al. (1507.05096)
Achterbeg et al. (1507.04644)
Biswas et al. (1507.04543)
Butter et al. (1507.02288)
Mondal et al. (1507.01793)
Cao et al. (1506.06471)
Banik et al. (1506.05665)
Ipek (1505.07826)
Buchmueller et al. (1505.07826)
Balazs et al. (1505.06758)
Medina (1505.05565)
Kim et al. (1505.04620)
Ko et al. (1504.06944)
Ko & Tang (1504.03908)
Ghorbani & Ghorbani (1504.03610)
Fortes et al. (1503.08220)
Cline et al. (1503.08213)
Rajaraman et al. (1503.05919)
Bi et al. (1503.03749)
Kopp et al. (1503.02669)
Elor et al. (1503.01773)
Gherghetta et al. (1502.07173)
Berlin et al. (1502.06000)
Achterberg et al. (1502.05703)
Modak et al. (1502.05682)
Guo et al. (1502.00508)
Chen & Nomura (1501.07413)
Kozaczuk & Martin (1501.07275)
Berlin et al. (1501.03496)
Kaplinghat et al. (1501.03507)
Alves et al. (1501.03490)
Biswas et al. (1501.02666)
Ghorbani & Ghorbani (1501.00206)
Cerdeno et al. (1501.01296)
Liu et al. (1412.1485)
Hooper (1411.4079)
Arcadi et al. (1411.2985)
Cheung et al. (1411.2619)
Agrawal et al. (1411.2592)
Kile et al. (1411.1407)
Buckley et al. (1410.6497)
Heikinheimo & Spethmann (1410.4842)
Freytsis et al. (1410.3818)
Yu et al. (1410.3347)
Cao et al. (1410.3239)
Guo et al. (1409.7864)
Yu (1409.3227)
Cahill-Rowley et al. (1409.1573)
Banik & Majumdar (1408.5795)
Bell et al. (1408.5142)
Ghorbani (1408.4929)
Okada & Seto (1408.2583)
Frank & Mondal (1408.2223)
Baek et al. (1407.6588)
Tang (1407.5492)
Balazs & Li (1407.0174)
Huang et al. (1407.0038)
McDermott (1406.6408)
Cheung et al. (1406.6372)
Arina et al. (1406.5542)
Chang & Ng (1406.4601)
Wang & Han (1406.3598)
Cline et al. (1405.7691)
Berlin et al. (1405.5204)
Mondal & Basak (1405.4877)
Martin et al. (1405.0272)
Ghosh et al. (1405.0206)
Abdullah et al. (1404.5503)
Park & Tang (1404.5257)
Cerdeno et al. (1404.2572)
Izaguirre et al. (1404.2018)
Agrawal et al. (1404.1373)
Berlin et al. (1404.0022)
Alves et al. (1403.5027)
Finkbeiner & Weiner (1402.6671)

Pulsars in the Galactic Center

DEGENERACY WITH MILLI-SECOND PULSARS IN SPATIAL PROFILE



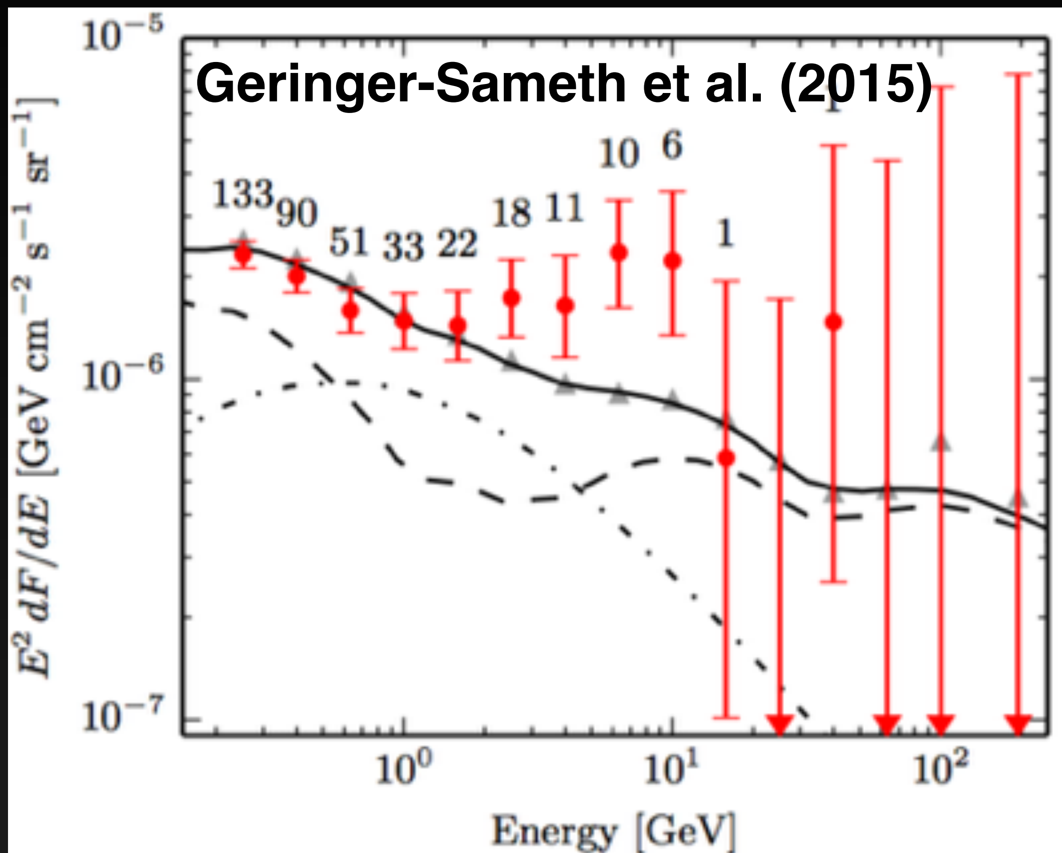
We make the reasonable assumption that Low-Mass X-ray Binaries have the same spatial distribution as MSPs

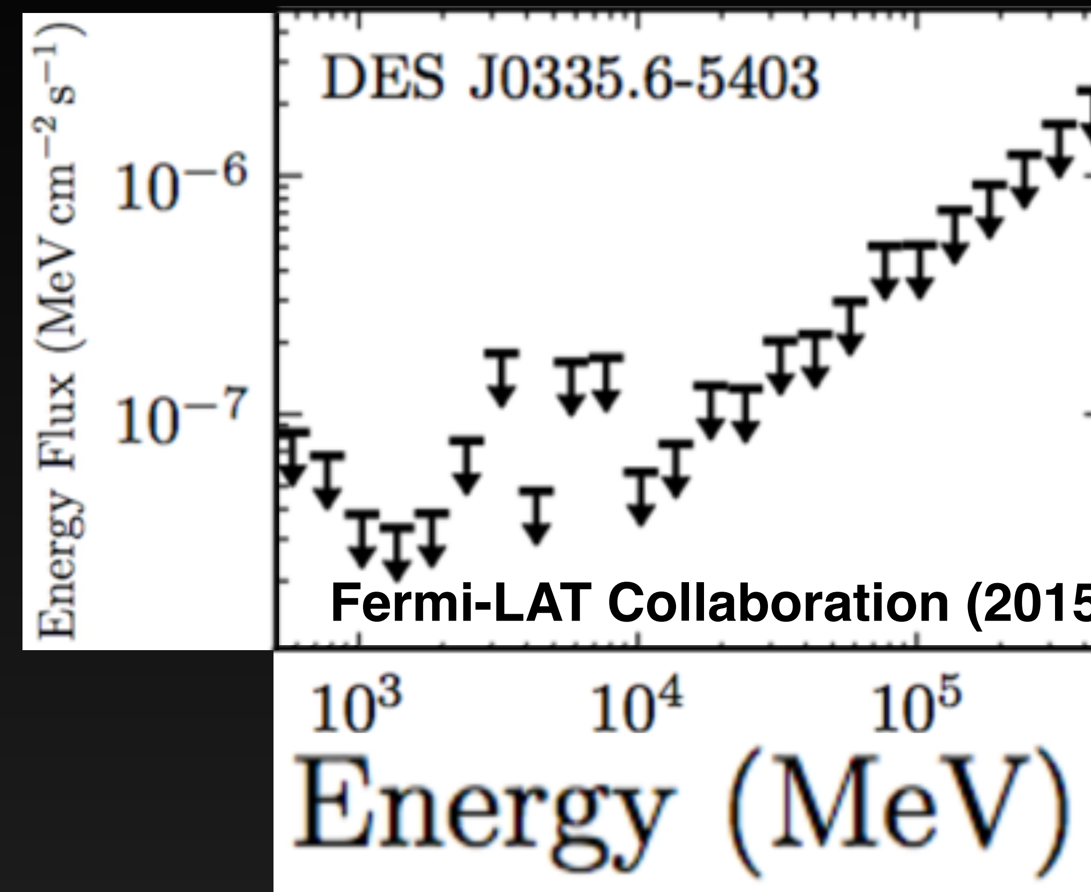
400" towards M31 center = 1.5 kpc distance from center = 10 degrees towards MW center

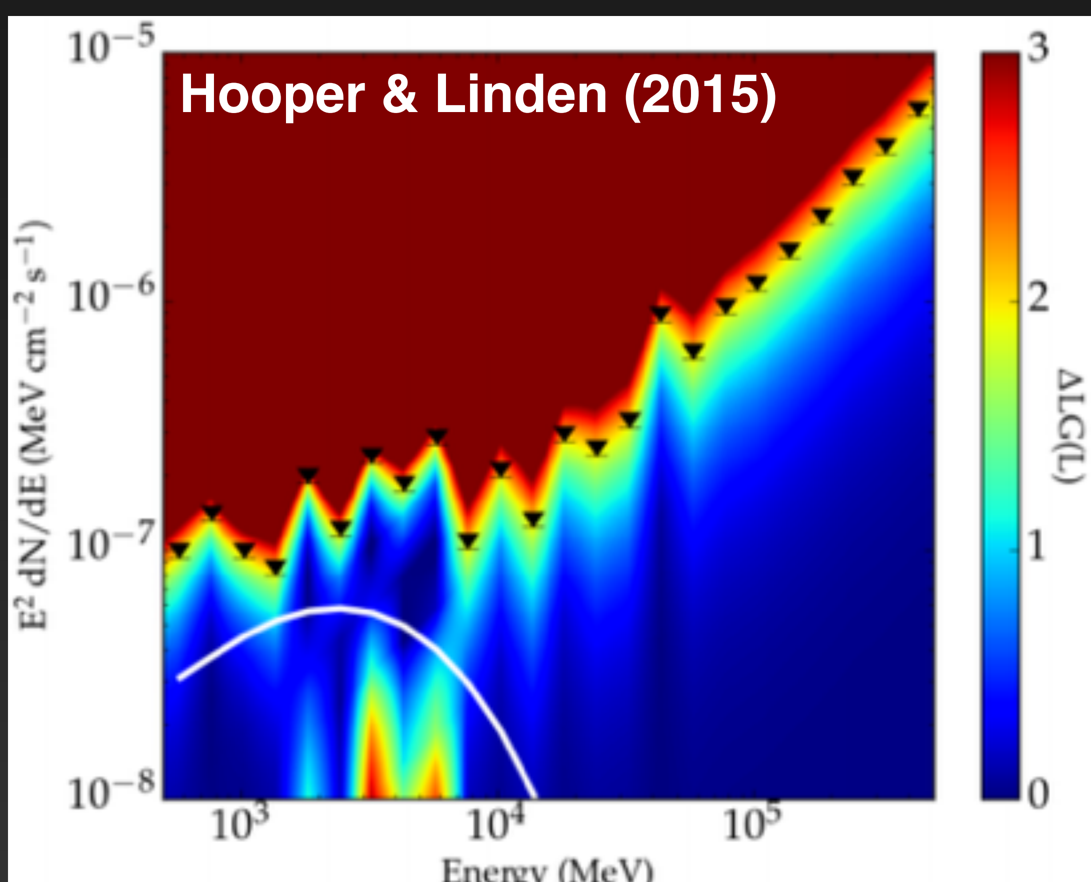
Orange line is same as best-fit excess template ($R^{-1.2}$ in projection implies $r^{-2.2}$ de-projected)!

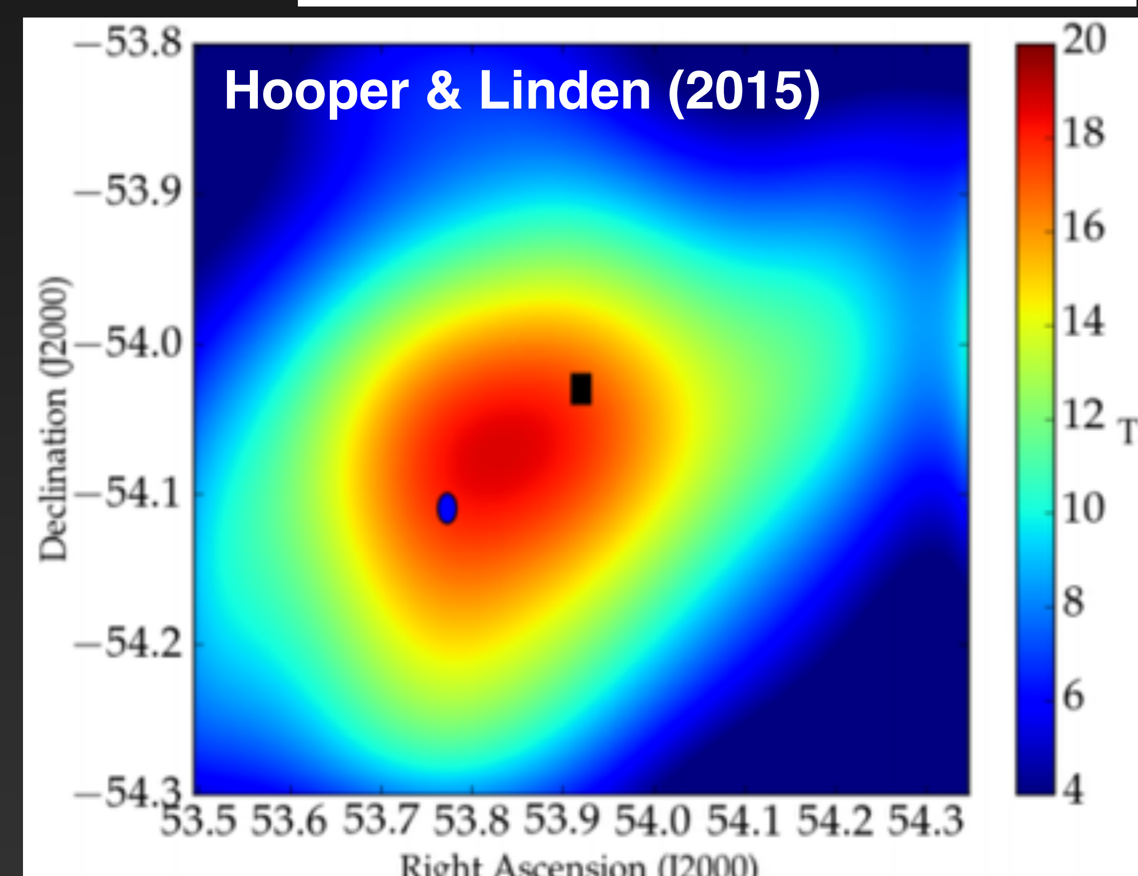
Slide from Manoj Kaplinghat

Reticulum 2 has an excess!

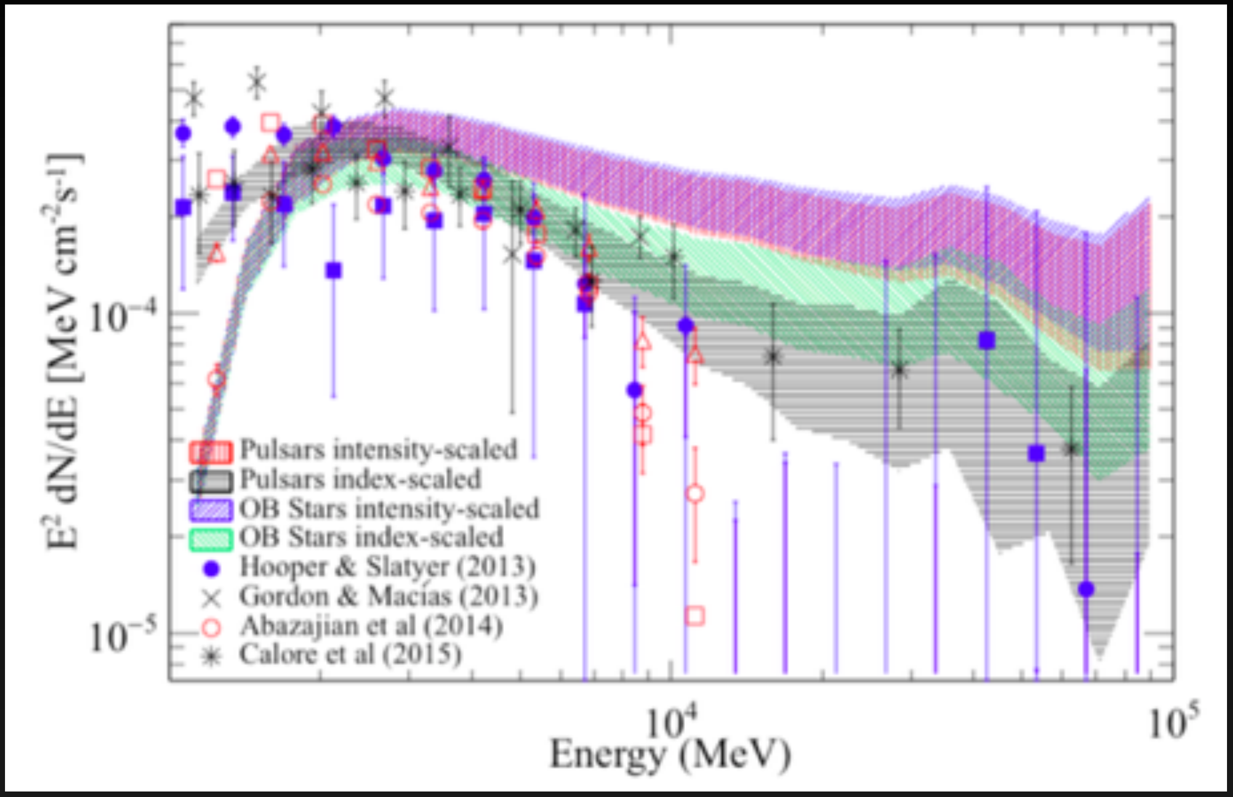




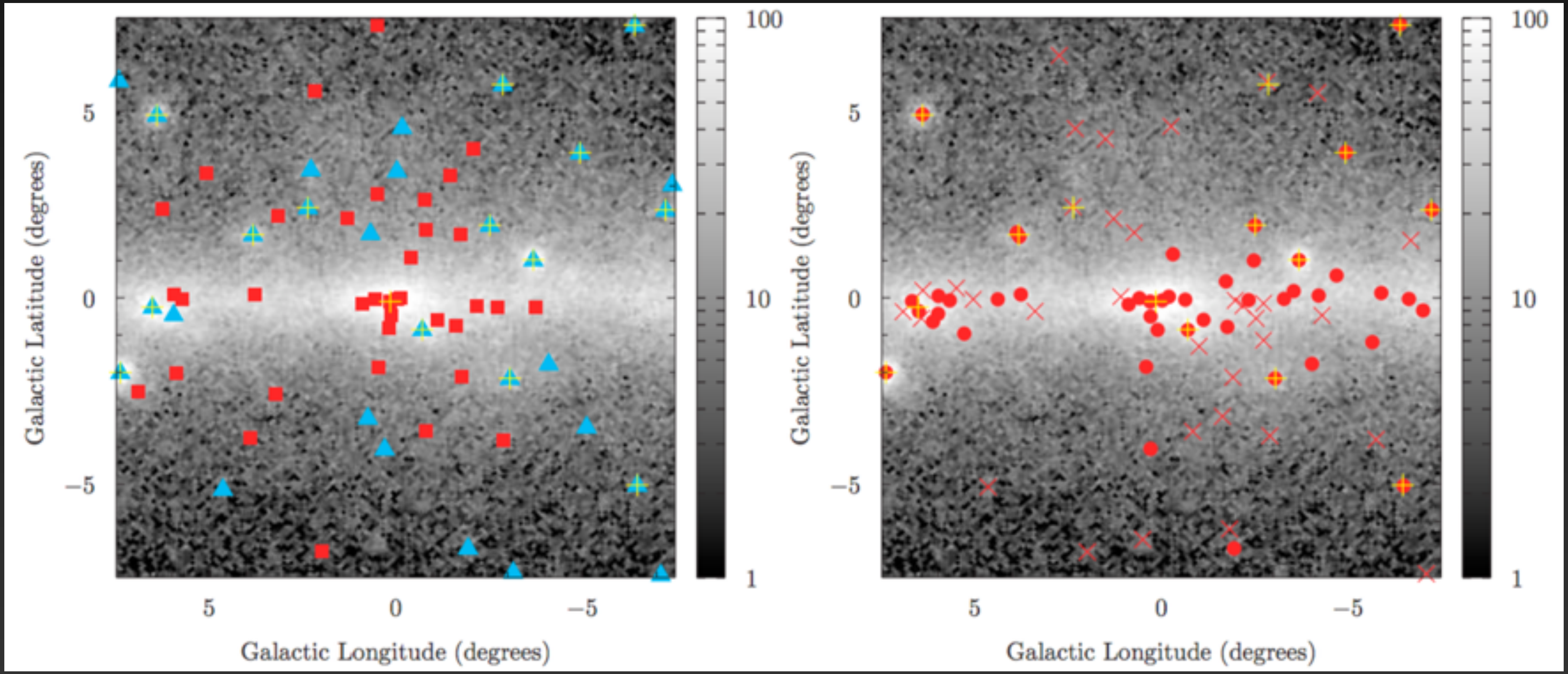




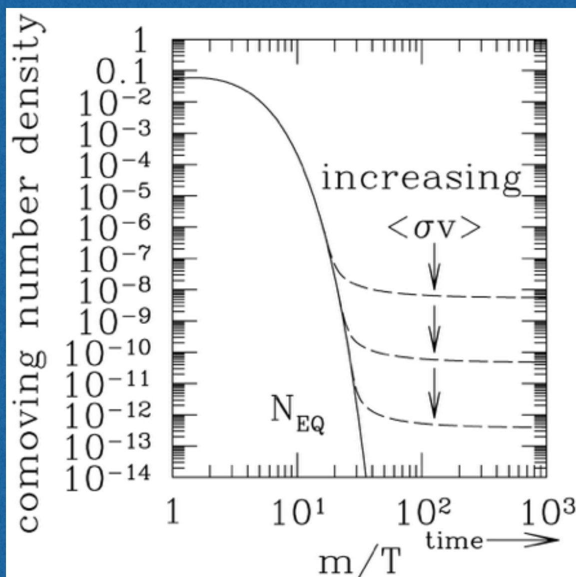
Observational Results

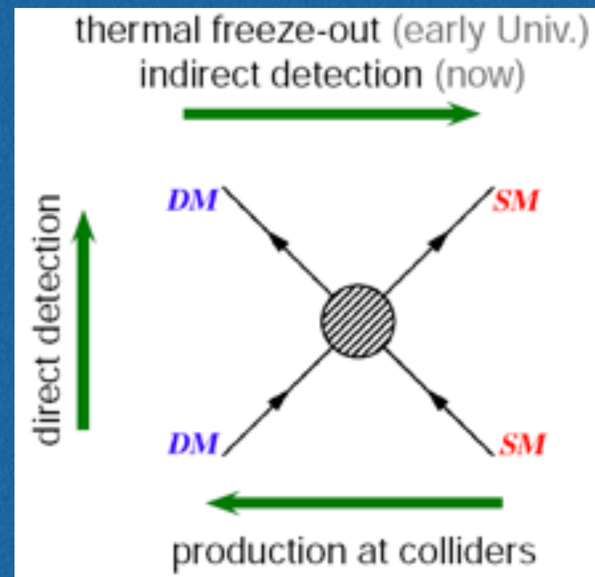


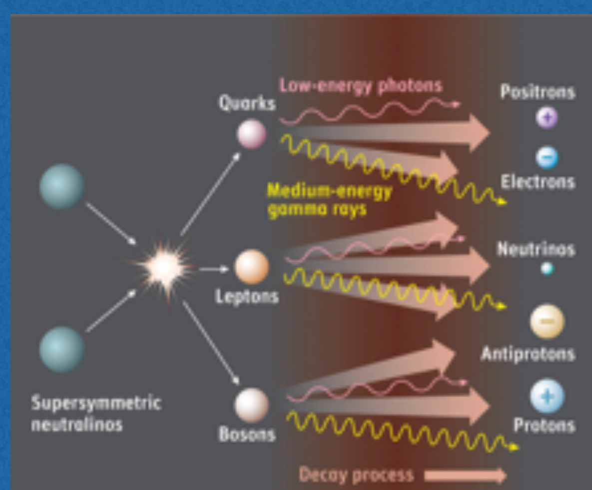
The Fermi-LAT Collaboration now officially agrees with these findings.

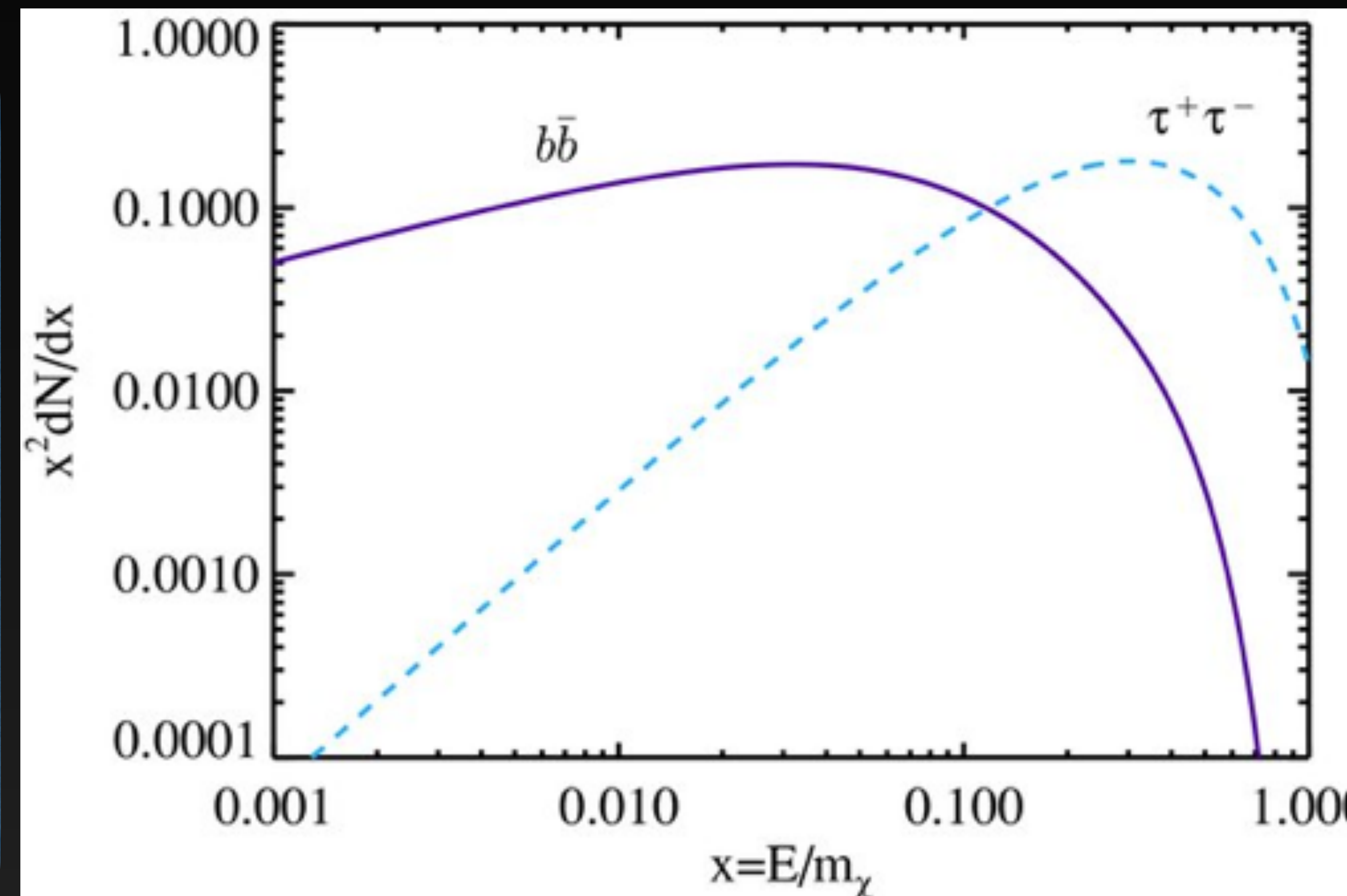


What: Gamma-Rays





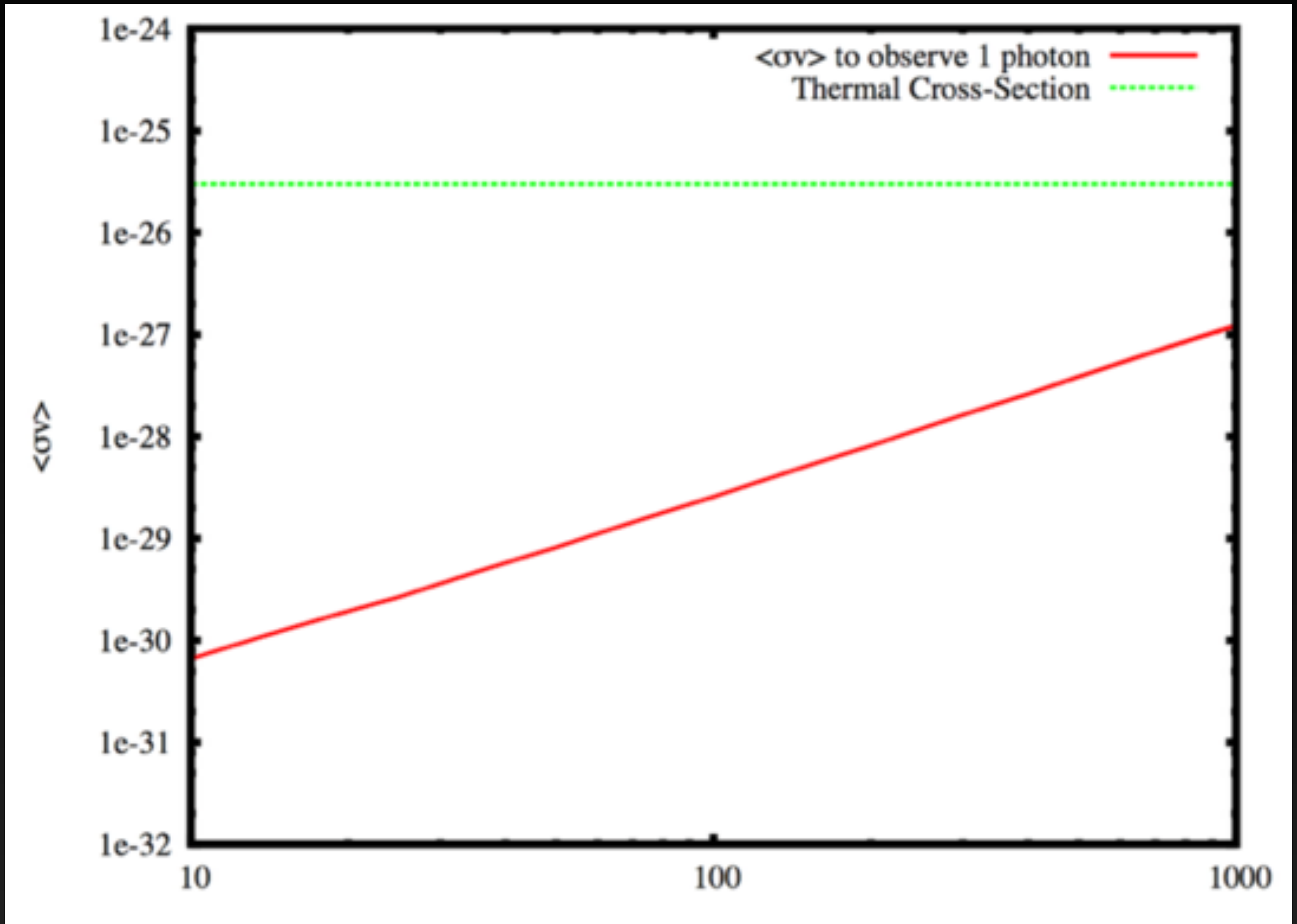




WIMP models are well motivated.

For standard WIMP scenarios, the majority of the annihilation energy is deposited at gamma-ray energies.

Why: Do We Care?



If we were in a background free experiment, or could separate dark matter gamma-rays from other signals, then we would set limits far below the thermal annihilation cross-section.

Alternatively, if dark matter annihilates at the thermal cross-section, it produces many gamma-rays observed by the Fermi-LAT.