Kavli Institute
for Cosmological Physics
at The University of Chicago

A Compelling Case for Dark Matter Annihilation

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along with:

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arXiv: 1402.6703

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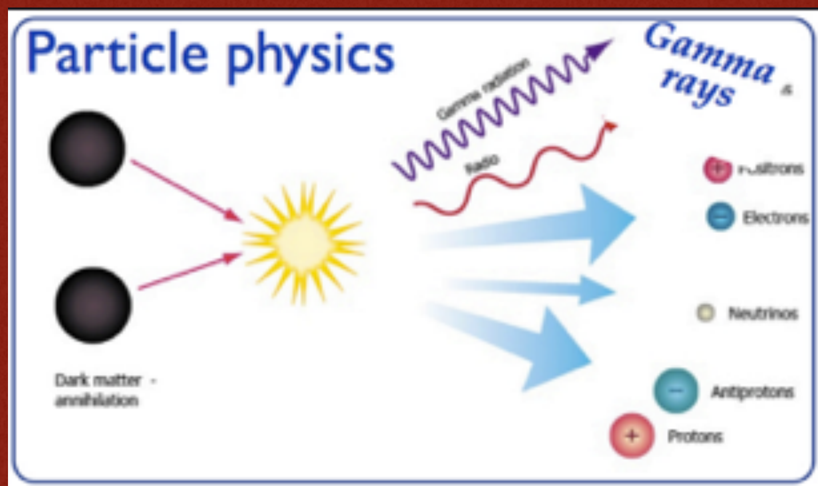
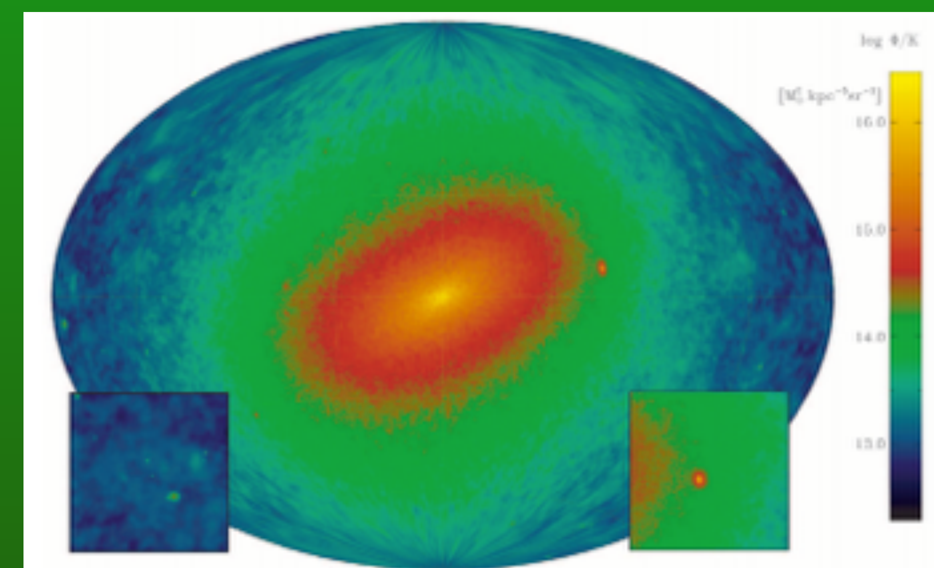
Dark Matter Indirect Detection

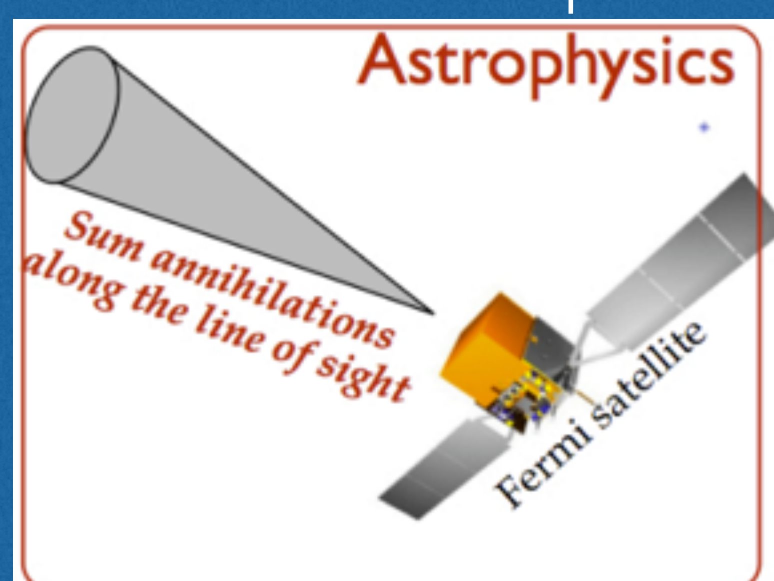
Particle Physics



Astrophysics



Instrumental Response



The Galactic Center

$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int d\Omega \int_{l.o.s} \rho^2 dl(\phi)$$

Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\overline{\log_{10}(J^{NFW})}$[a] ($\log_{10}[\mathrm{GeV}^2\,\mathrm{cm}^{-5}\,\mathrm{sr}]$)
Bootes I	358.1	69.6	66	18.8 ± 0.22
Bootes II	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Canis Major	240.0	-8.0	7	–
Carina	260.1	-22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25
Draco	86.4	34.7	76	18.8 ± 0.16
Fornax	237.1	-65.7	147	18.2 ± 0.21
Hercules	28.7	36.9	132	18.1 ± 0.25
Leo I	226.0	49.1	254	17.7 ± 0.18
Leo II	220.2	67.2	233	17.6 ± 0.18
Leo IV	265.4	56.5	154	17.9 ± 0.28
Leo V	261.9	58.5	178	–
Pisces II	79.2	-47.1	182	–
Sagittarius	5.6	-14.2	26	–
Sculptor	287.5	-83.2	86	18.6 ± 0.18
Segue 1	220.5	50.4	23	19.5 ± 0.29
Segue 2	149.4	-38.1	35	–
Sextans	243.5	42.3	86	18.4 ± 0.27
Ursa Major I	159.4	54.4	97	18.3 ± 0.24
Ursa Major II	152.5	37.4	32	19.3 ± 0.28
Ursa Minor	105.0	44.8	76	18.8 ± 0.19
Willman 1	158.6	56.8	38	19.1 ± 0.31

The Fermi-LAT Collaboration (2013)

The J-Factor of the Galactic center is:

$\log_{10}(J) = 21.02$

for a region within 100 pc of the Galactic center and an NFW profile

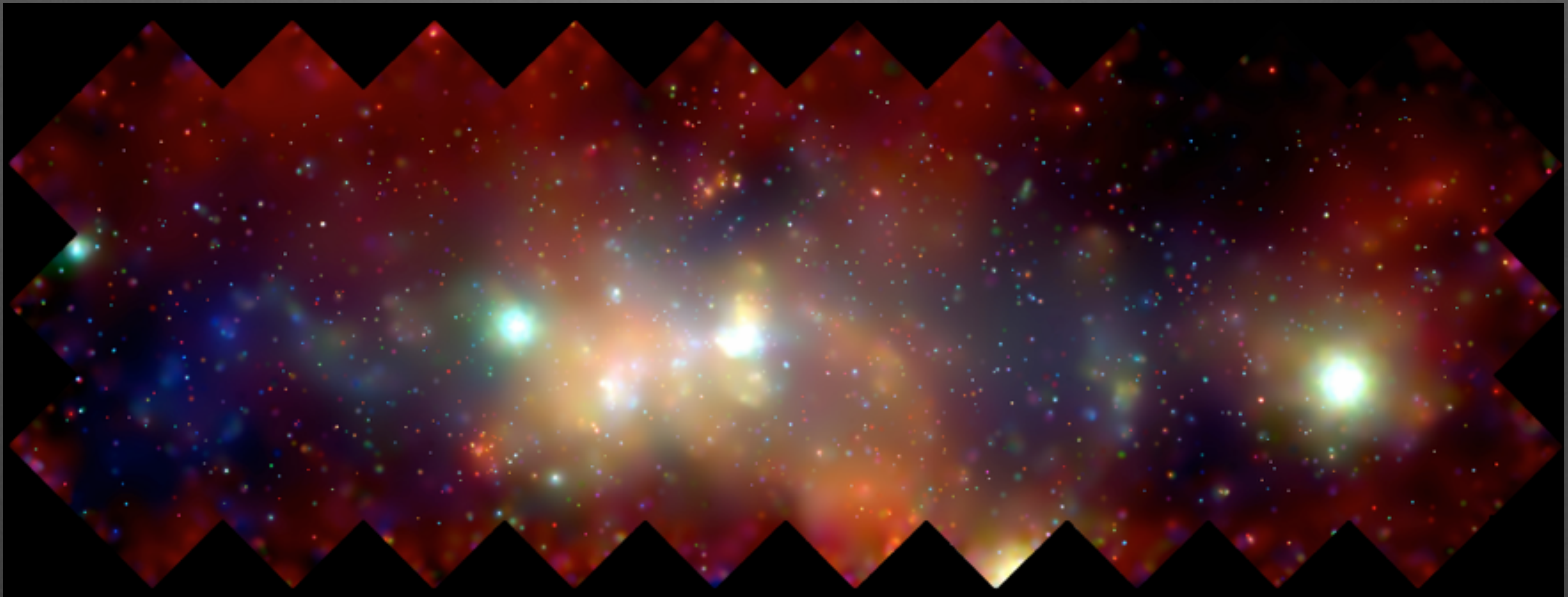
Fermi-LAT Telescope

- Space-based, pair-conversion gamma-ray detector with an energy range 30 MeV - 300 GeV
- Effective Area: ~1 m^2
- Energy Resolution: ~10%
- Angular Resolution: ~1° at 1 GeV

The Galactic Center

- Total Observed Gamma-Ray Flux from 1-3 GeV within 1° of the GC is ~1 x 10^{-10} erg cm^{-2} s^{-1}
- The flux expected from a vanilla dark matter model (100 GeV -> bb with an NFW profile) is ~2 x 10^{-11} erg cm^{-2} s^{-1}
- There's no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the most naive prediction from dark matter simulations

The Galactic Center



Goals of the Project

Study the Galactic Center Region with the Fermi-LAT telescope, derive models for the astrophysical and dark matter source templates

Set strong constraints on the dark matter annihilation cross-section, or alternatively find evidence suggesting a dark matter source

Hooper & Goodenough (2011)
Hooper & Linden (2011)
Abazajian & Kaplinghat (2012)
Hooper & Slatyer (2013)
Gordon & Macias (2013)
Macias & Gordon (2013)
Abazajian et al. (2014)
Daylan et al. (2014)

Two Separate Analyses

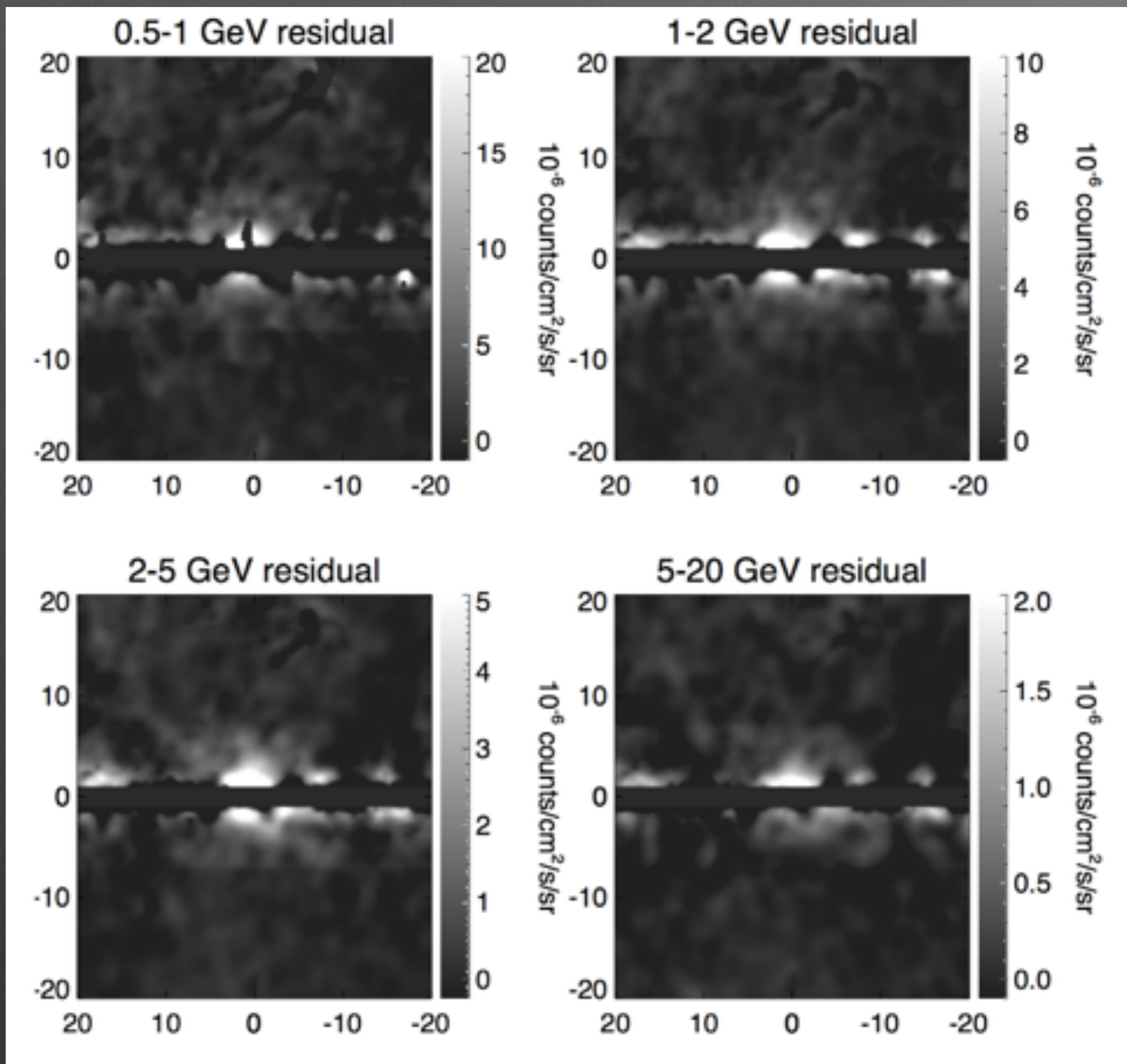
Inner Galaxy

- $|b| > 1^o$
- Bright point sources masked at 2^o
- Allow diffuse templates (galactic diffuse, isotropic, Fermi bubbles, dark matter) to float independently in each of 30 energy bins

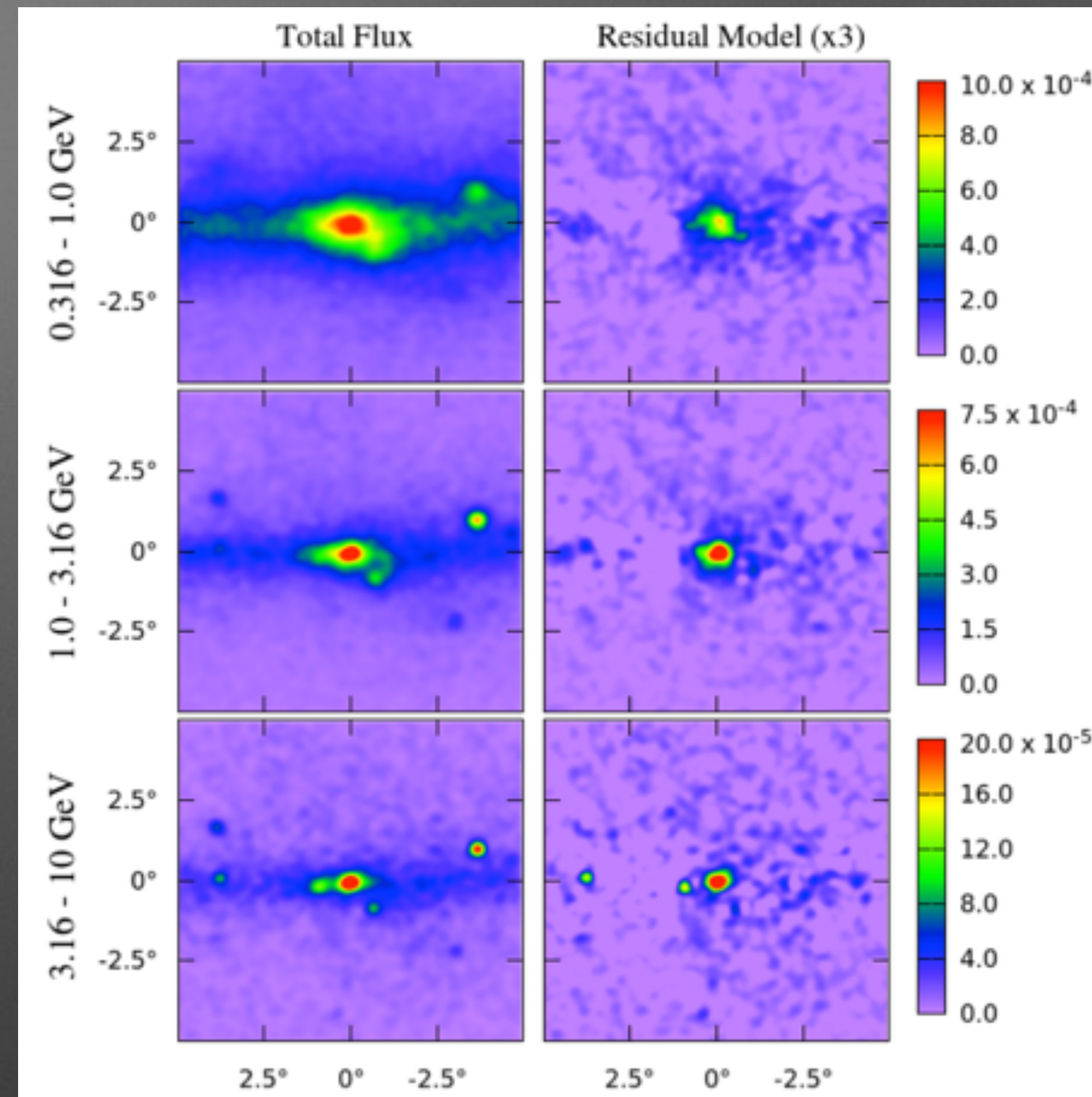
Galactic Center

- $|b| < 5^o$, $|l| < 5^o$
- Include and model all point sources (37 d.o.f.)
- Use likelihood analysis to calculate the spectrum and intensity of each source component
- Calculate log-likelihood to determine significance of component

Consistent Results!

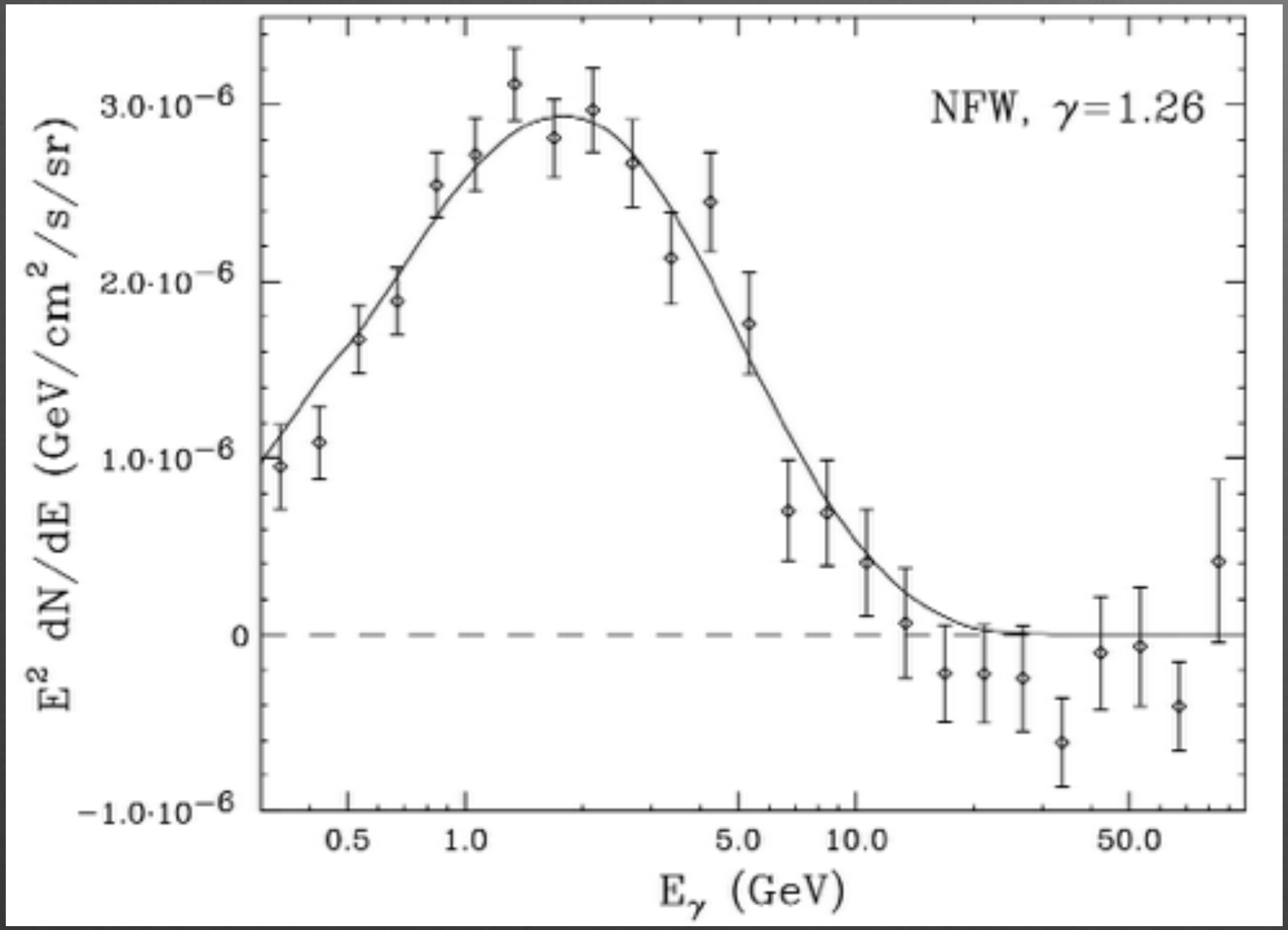


Inner Galaxy

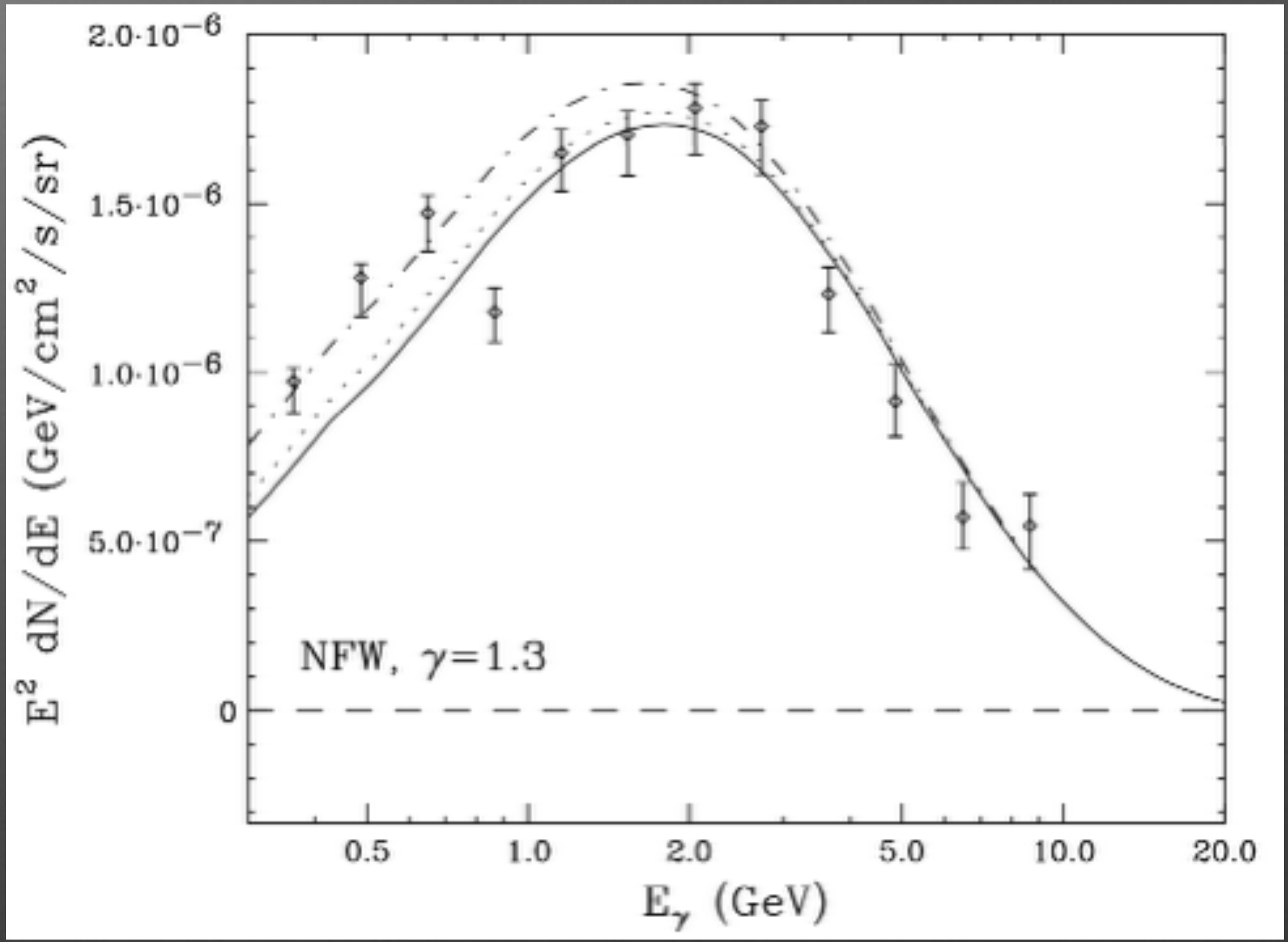


Galactic Center

Consistent Results!

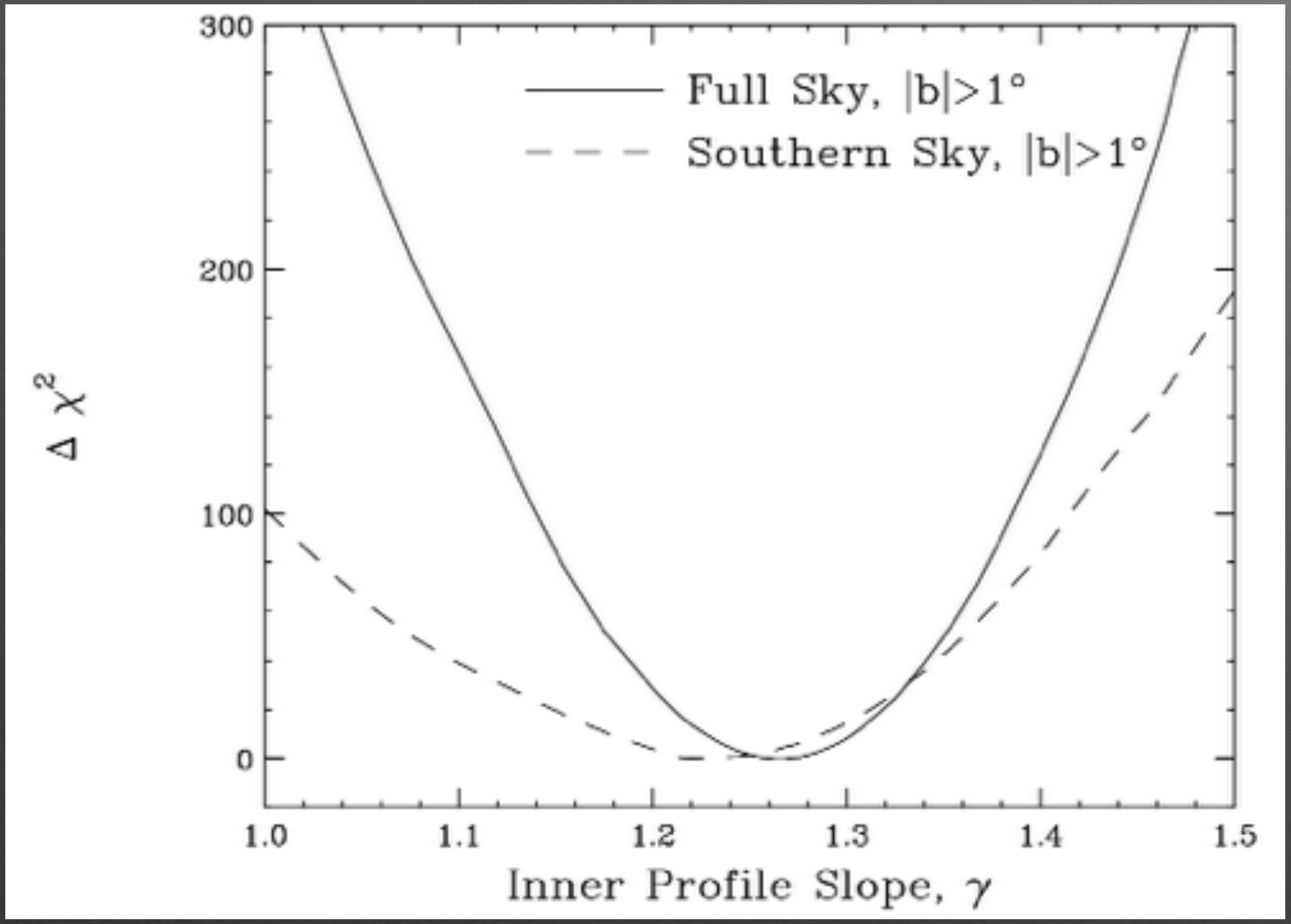


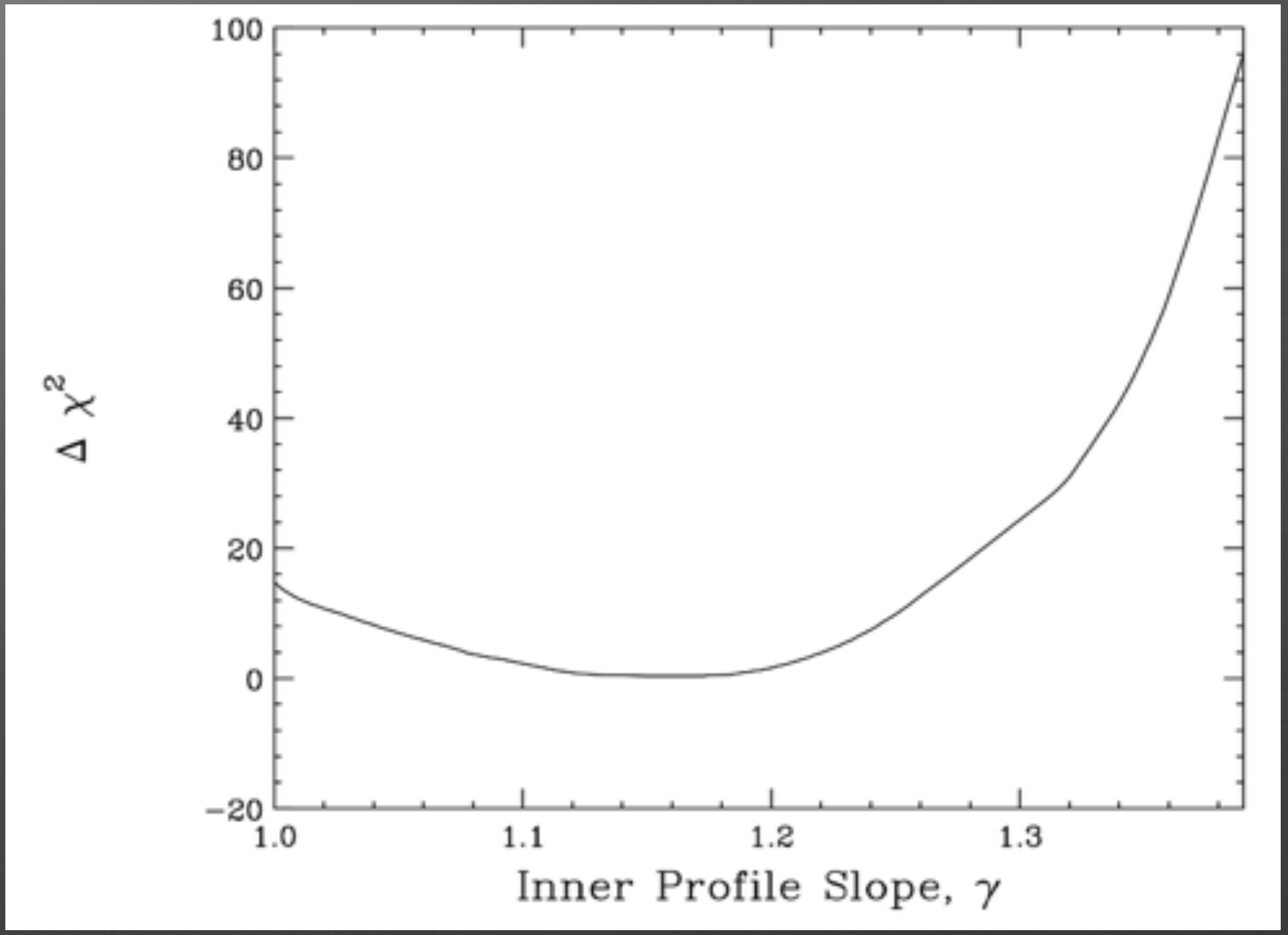
Inner Galaxy



Galactic Center

Consistent Results!

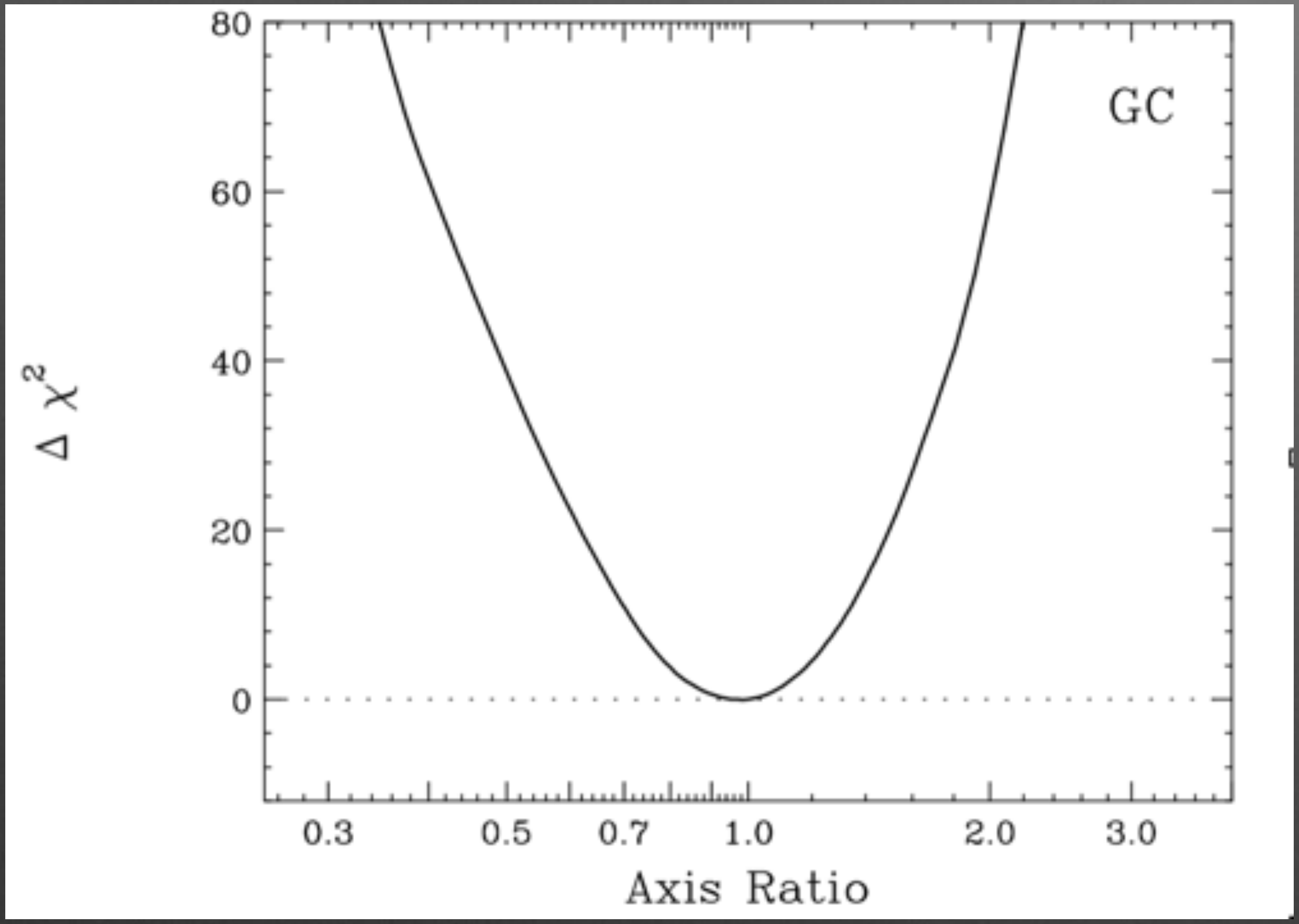


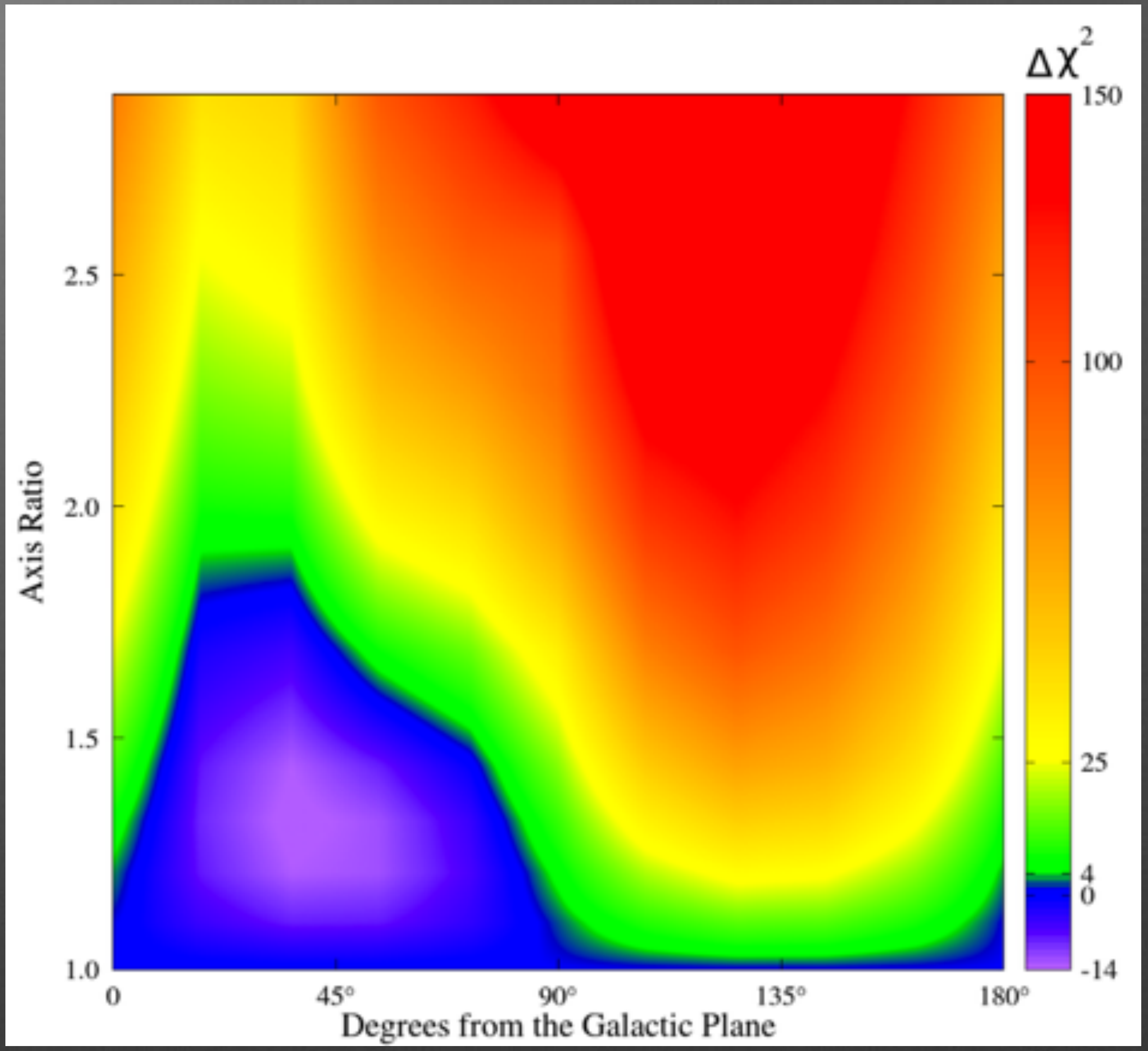


Inner Galaxy

Galactic Center

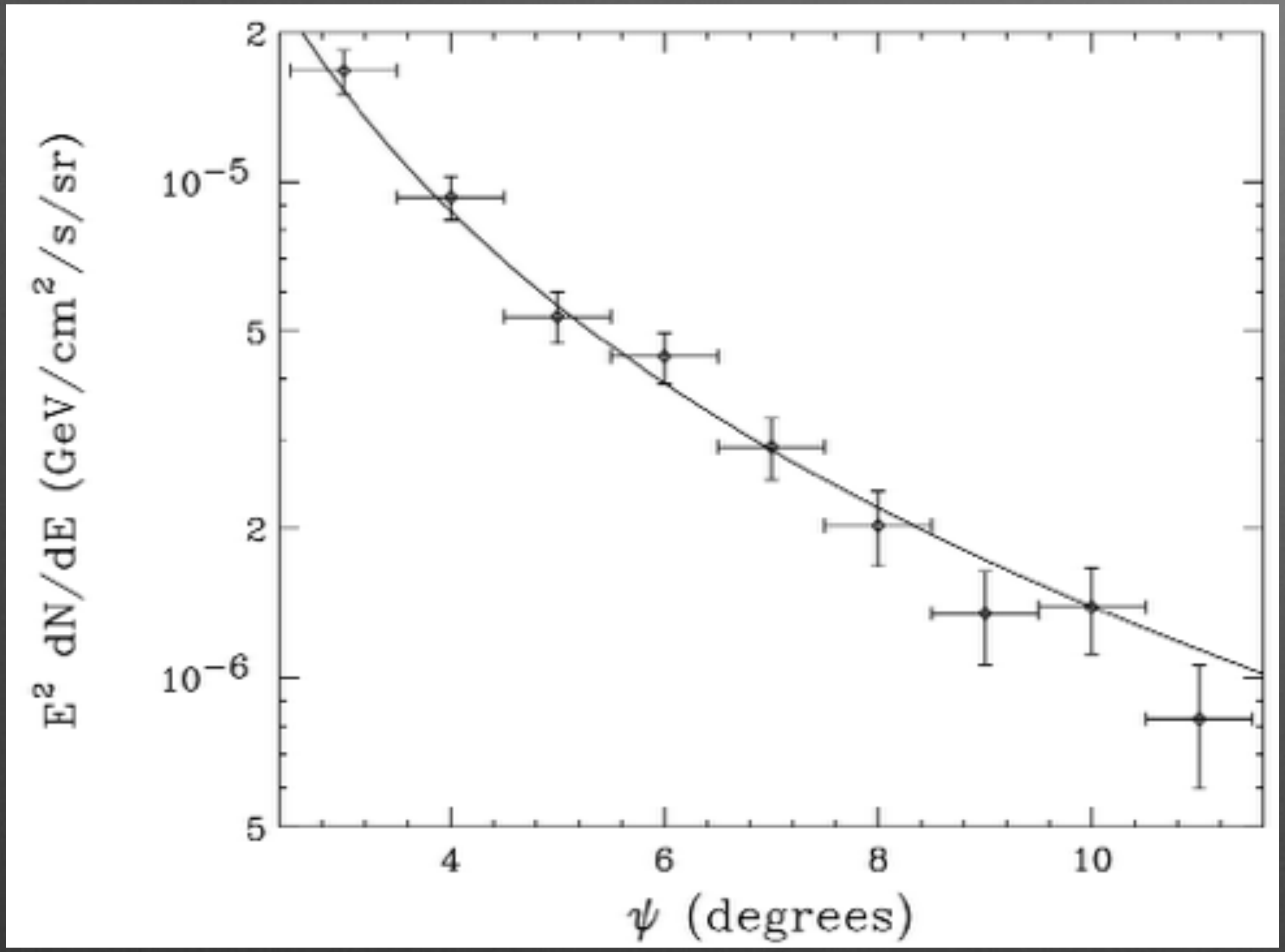
Constraining Results!



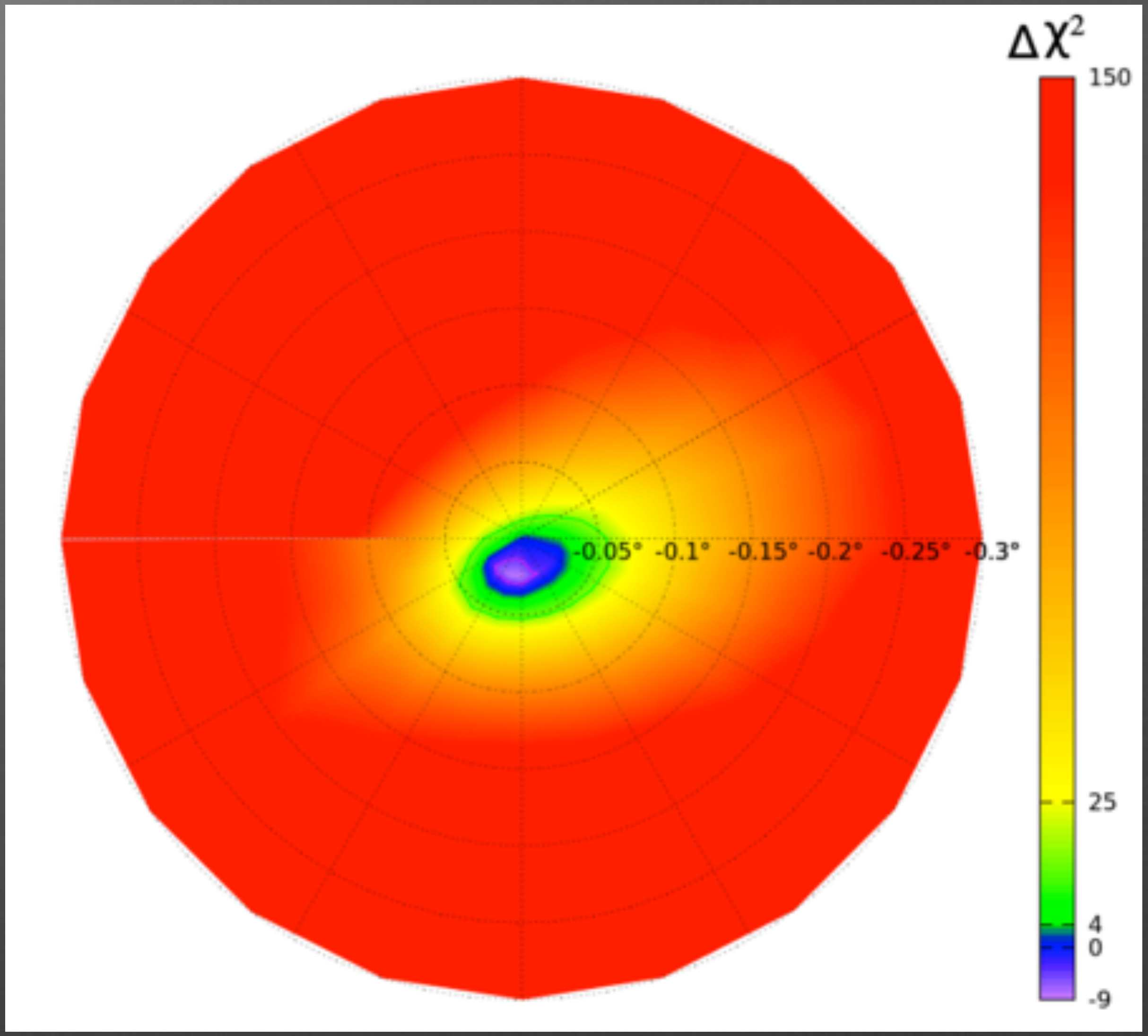


Galactic Center

Constraining Results!



Inner Galaxy



Galactic Center

Small Bug

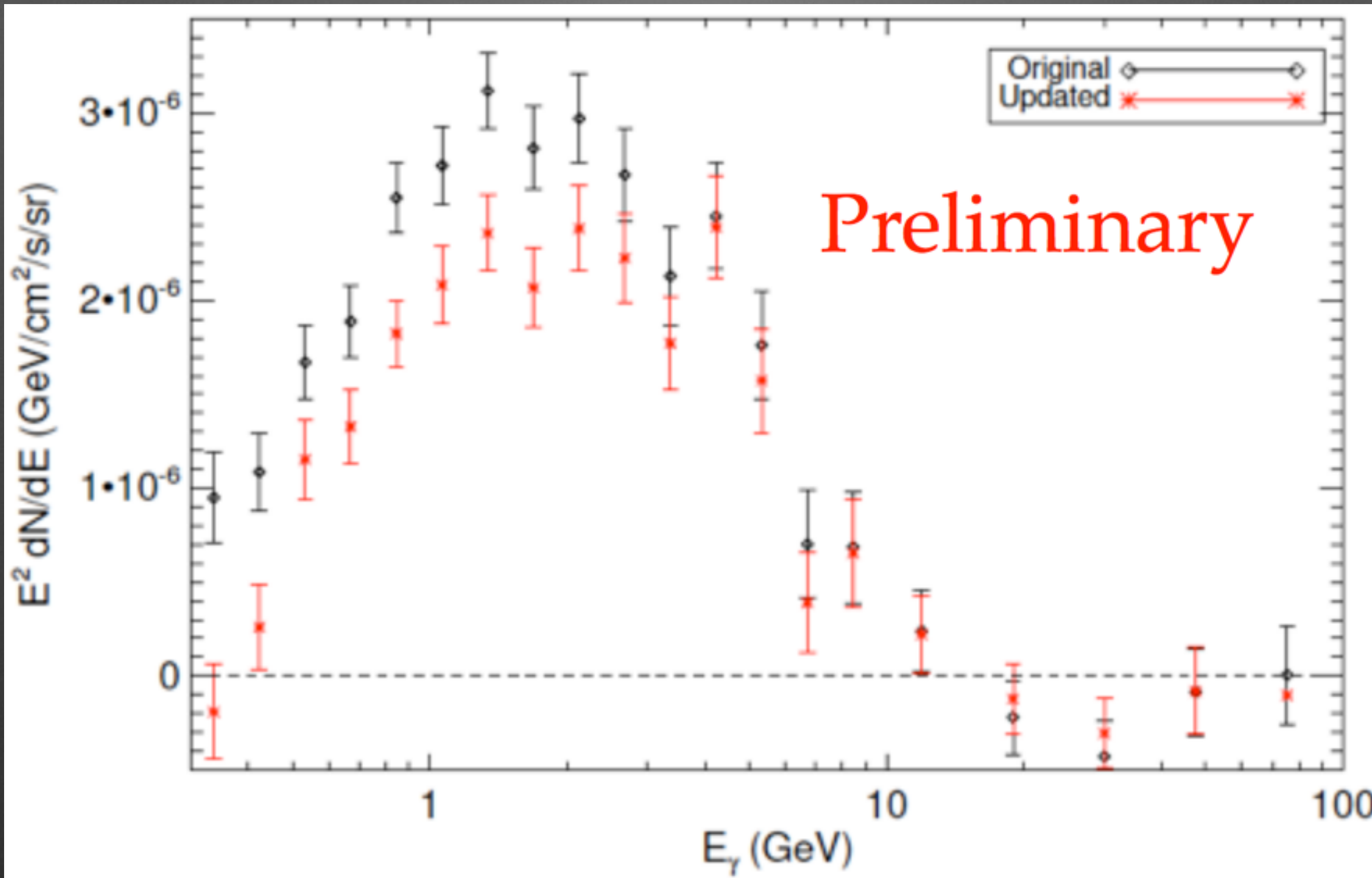
After the work was posted on arXiv a small bug was found in the code for the Inner Galaxy analysis, which affects the smoothing of the diffuse background model

Work is currently ongoing to update the results based on the new model. Early results show that the best fit dark matter cross-sections change by approximately 20%.

Note:

1.) The qualitative conclusions of the paper remain unchanged.
2.) The bug does not affect either the galactic center analysis or the rings fit (on the last slide)

Small Bug



Original
Updated
Preliminary
$3 \cdot 10^{-6}$
$2 \cdot 10^{-6}$
$1 \cdot 10^{-6}$
0
1
10
100
E_γ (GeV)
E^2 dN/dE (GeV/cm^2/s/sr)

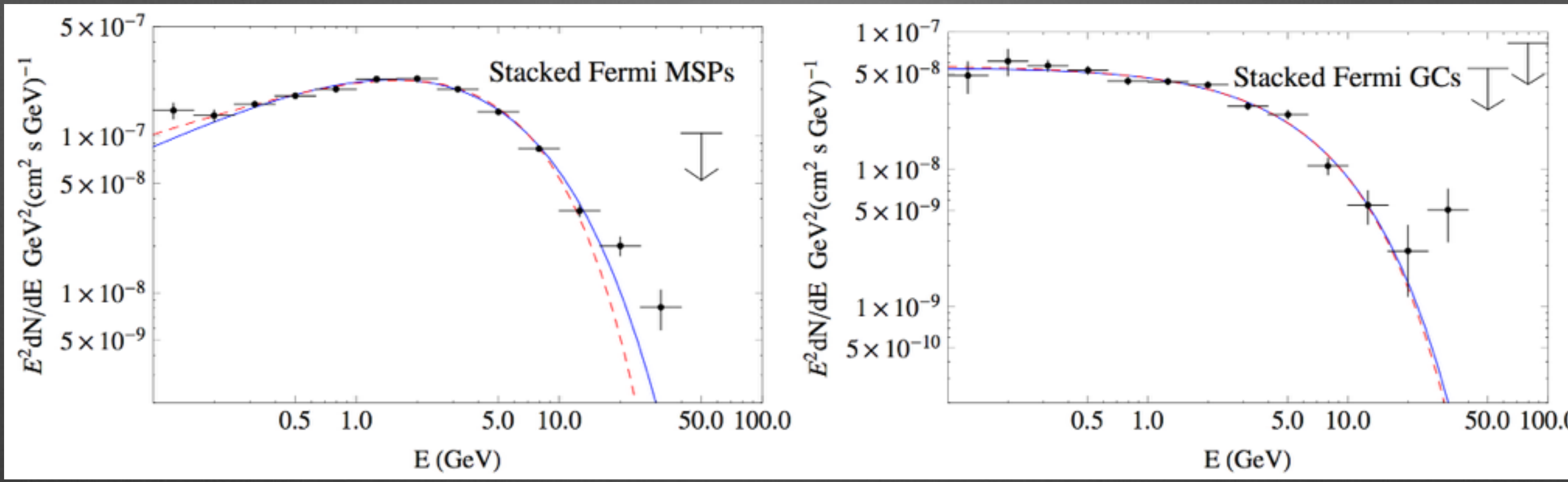
Data Analysis Review

- Two Relatively Non-Controversial Assertions:
  - The residual emission is real, compared to the Fermi-LAT diffuse models
  - The residual emission is not a previously known addition to the Fermi diffuse model (e.g. it does not trace missing gas)

Data Analysis Review

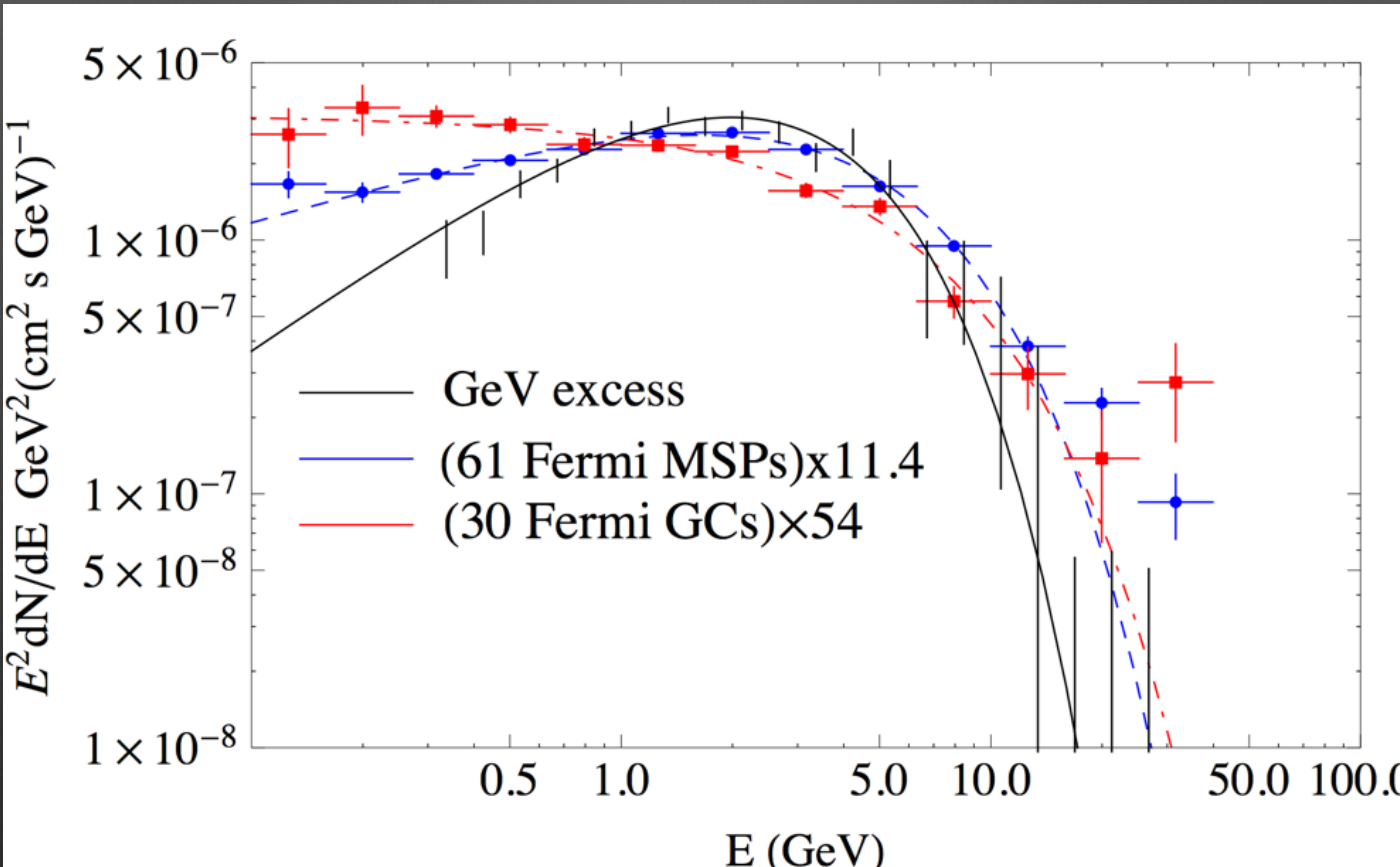
- Several Models have been proposed to explain the excess
  - An undetected population of MSPs (Abazajian et al. 2011)
  - A recent outburst from the galactic center
    - Hadrons (Carlson & Profumo 2014)
    - Leptons (Petrovic et al. 2014)
- Dark Matter (numerous papers)

Millisecond Pulsars



Fermi observations allow us to study the spectrum of the millisecond pulsar population

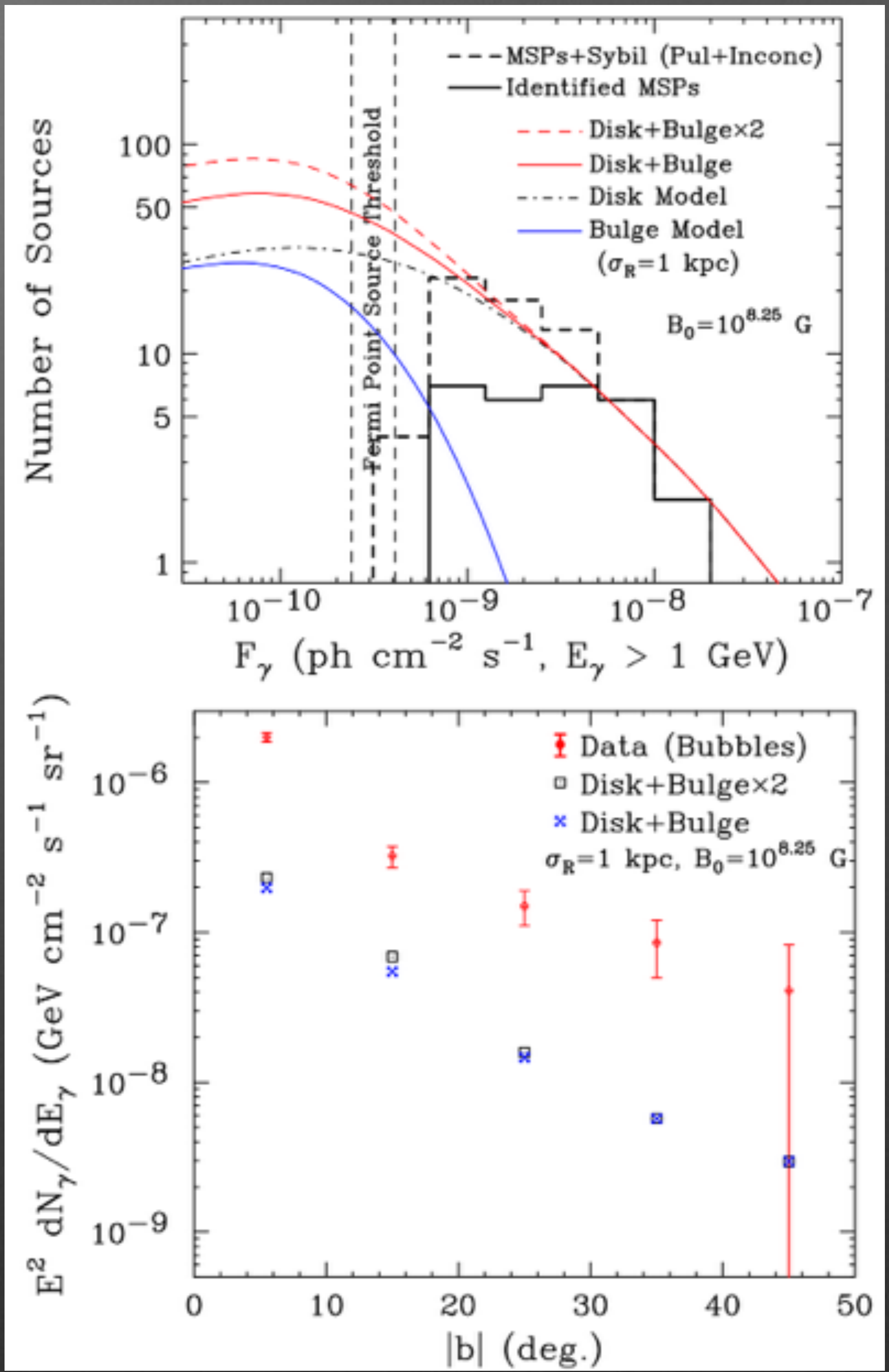
Millisecond Pulsars



Millisecond Pulsars

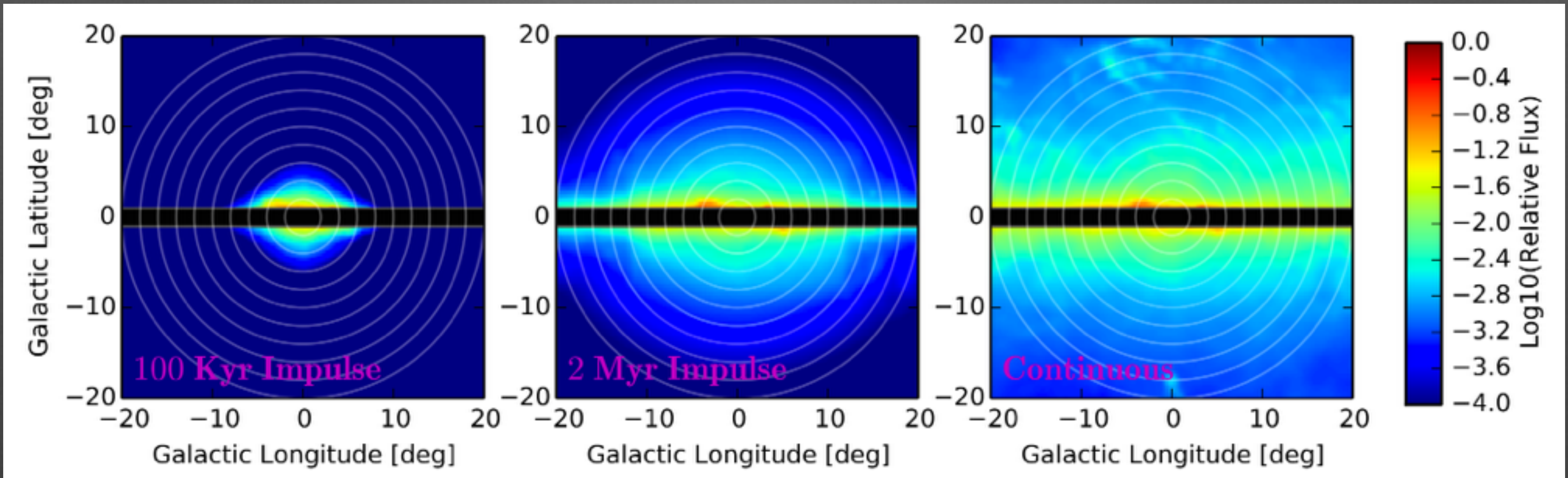
- Hooper et al. (2013) showed that MSPs could not produce the total diffuse intensity of the excess, without overproducing the number of bright point sources that should be detected by Fermi-LAT

- Current updated measurements show that MSPs can account for <5-10% of the total intensity of the excess



Hooper et al. (2013)

Hadronic Emission



Carlson & Profumo (2014)

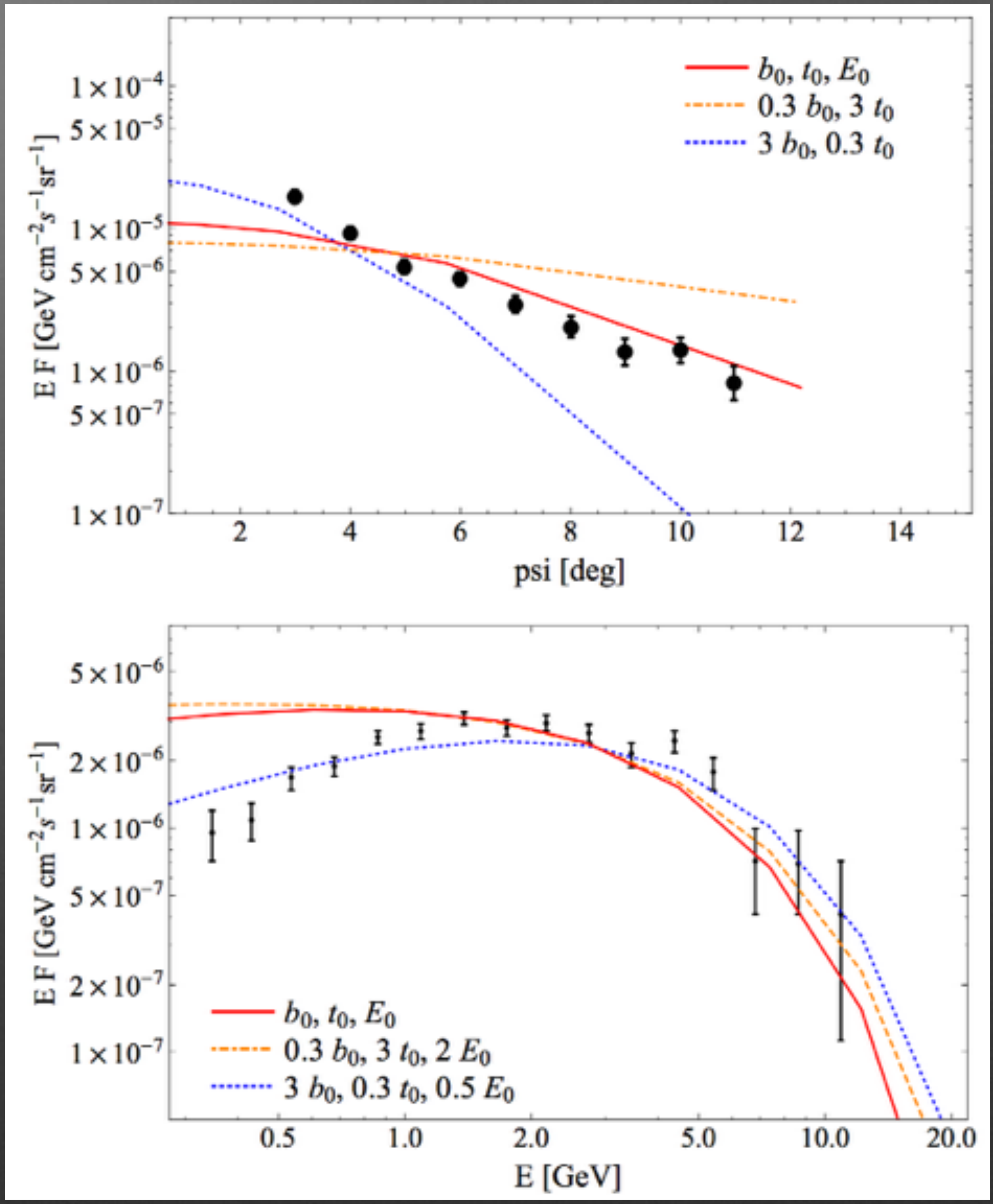
Carlson & Profumo (2014) proposed that an outburst of protons from the galactic center could explain the spherical symmetry and spectrum of the excess

Hadronic Emission

- Thanks to Eric Carlson and Stefano Profumo for providing us with the galprop output files.
- We have run these models through our code (similar to what we do with the dark matter fits). The models pick up the following TS values:
    - 19 kyr: **TS = 14.5** (with arbitrary spectrum: **TS = 26.6**)
    - 100 kyr: **TS = 0.0** (with arbitrary spectrum: **TS = 0.28**)
    - 2 Myr: **TS = 0.0**, (with arbitrary spectrum: **TS = 0.0**)
    - 7.5 Myr Continuous: **TS = 0.0** (with arbitrary spectrum: **TS = 0.0**)
    - Dark Matter Template (Daylan et al. 2014): **TS = 288**

Leptonic Emission

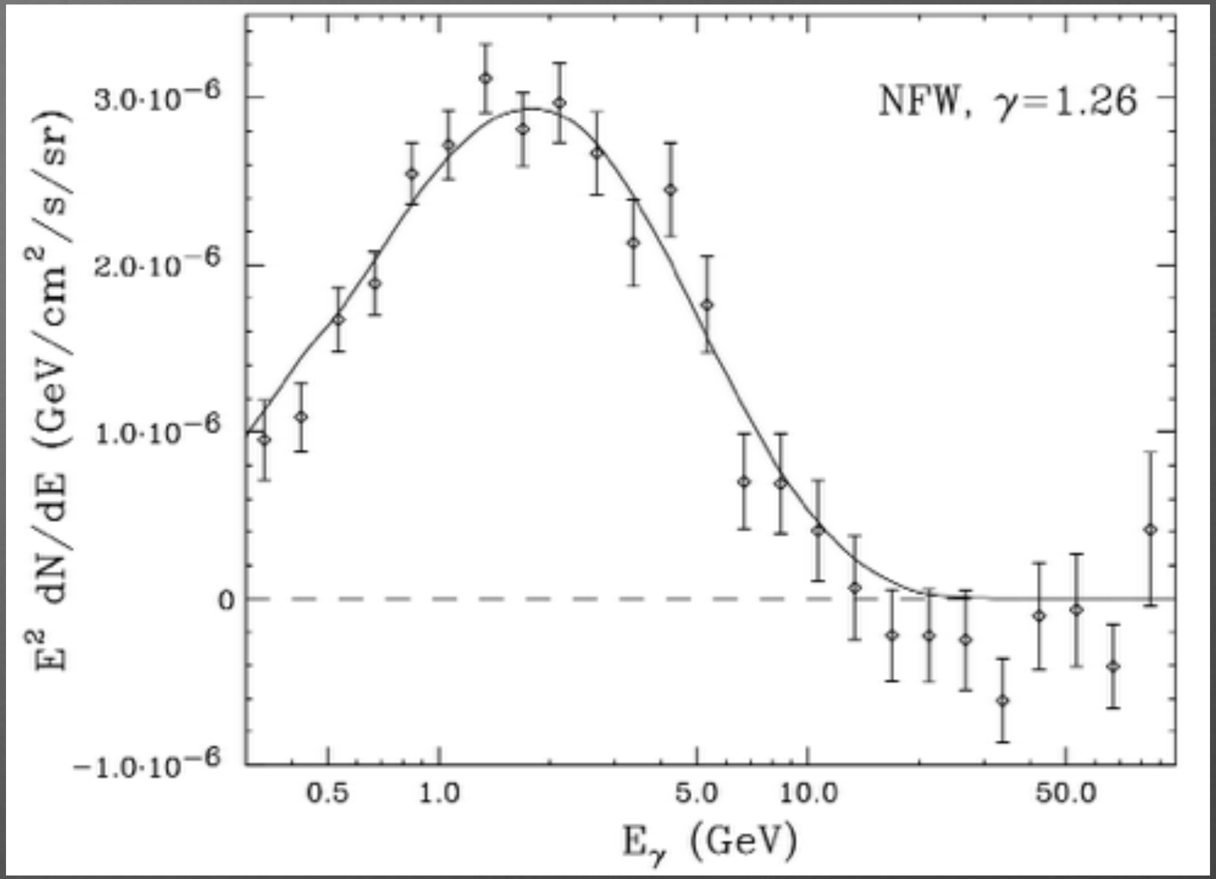
- A peaked spectrum of cosmic-ray leptons can also produce hard emission from bremsstrahlung or inverse Compton scattering
- However, electrons cool rapidly, it is difficult to produce the same hard spectrum over several degrees in the sky

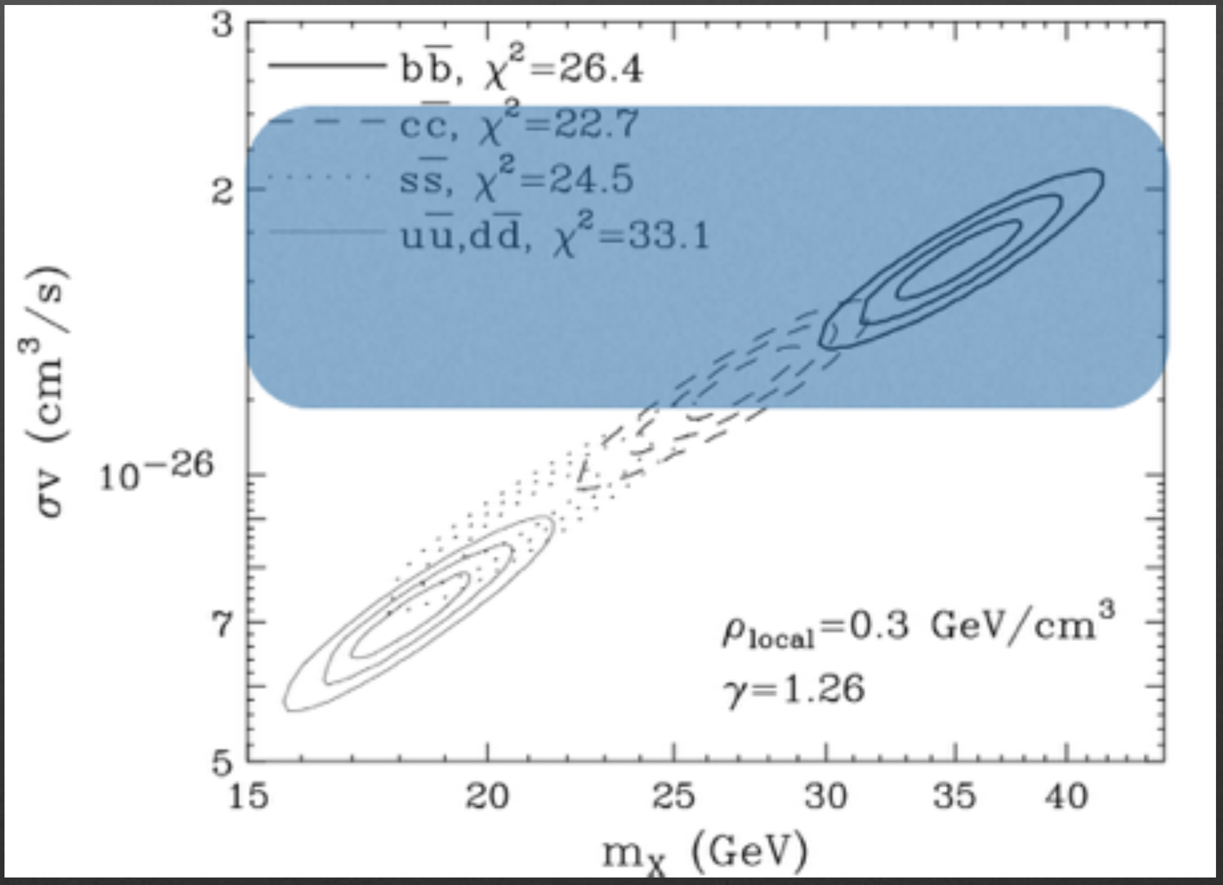


Petrovic et al. (2014)

Dark Matter Models

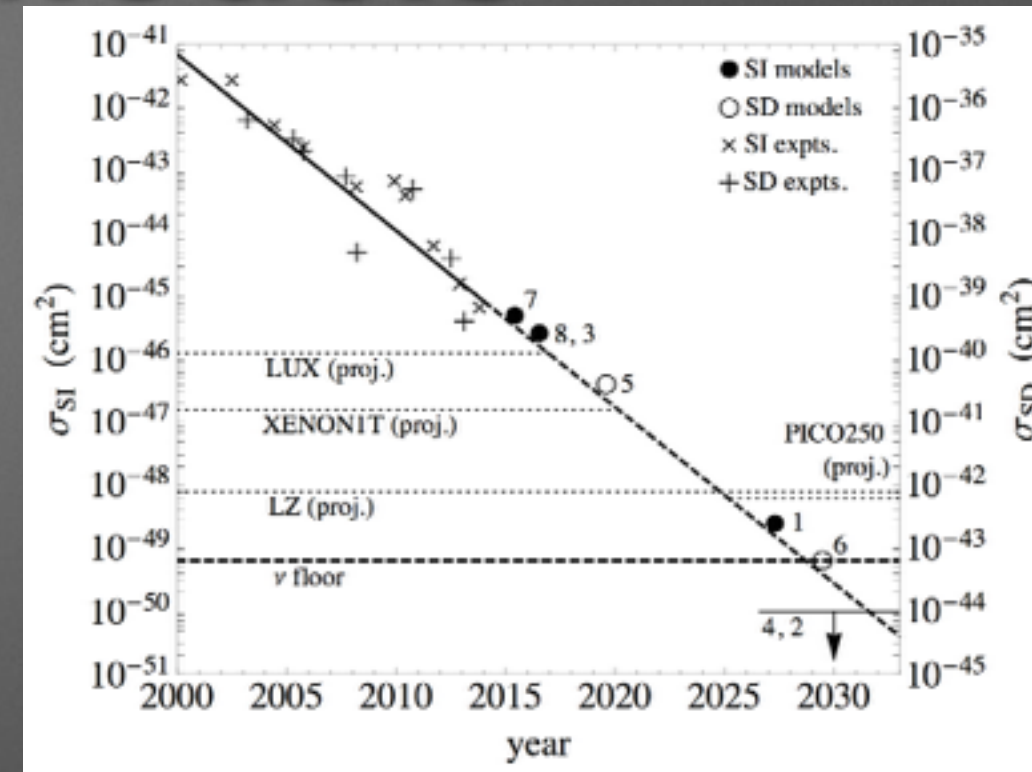
- Dark Matter Models provide a great fit to the spectrum and morphology
- These dark matter models are ‘natural’. The cross-section is compatible with a thermal relic, no theoretical tricks are necessary

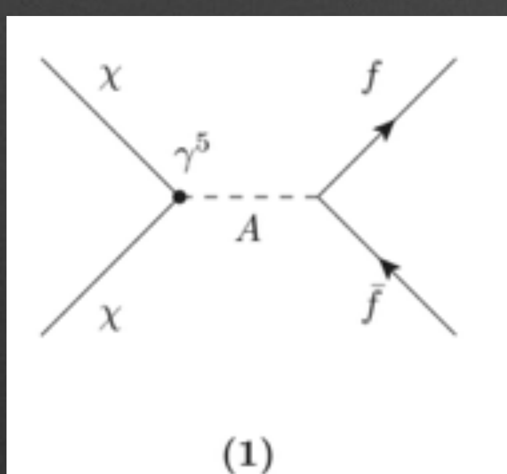


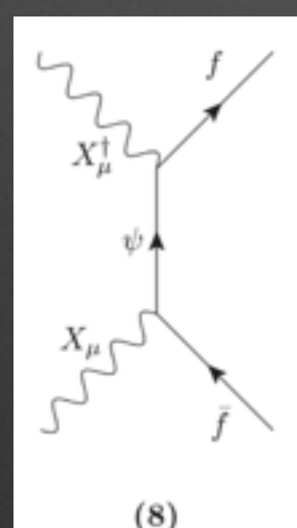


Dark Matter Models

- Many models are safe from current direct detection and collider constraints



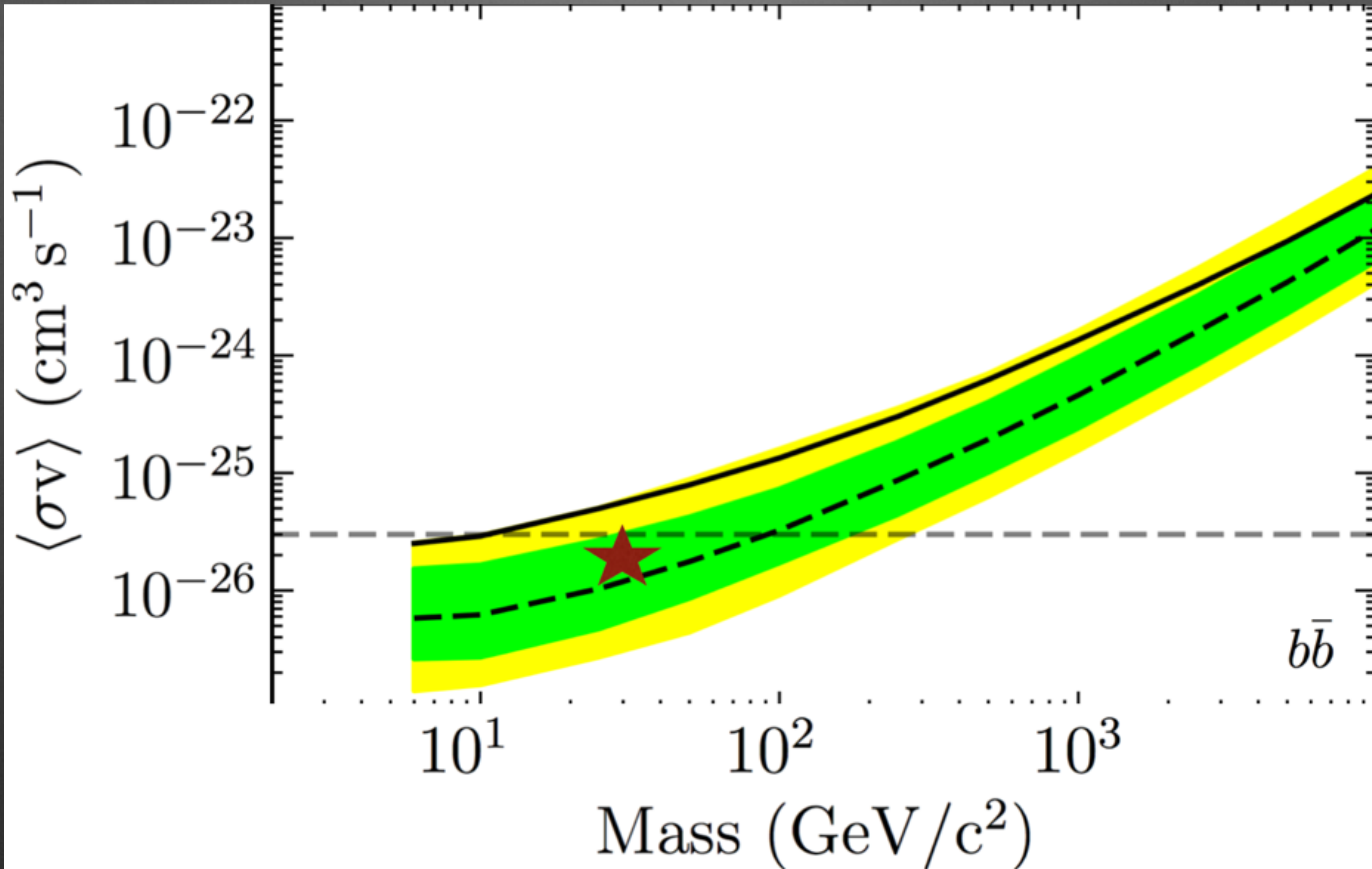




Model Number	DM	Mediator	Interactions	Elastic Scattering	Near Future Reach? Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$ or $\sigma_{SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{SI} \sim$ loop (vector)	Yes	Yes

Berlin, Hooper, McDermott (2014)

Future Indirect Tests - Dwarf Galaxies



The Fermi-LAT Collaboration (2013)

Conclusions

- The excess in emission at the galactic center (compared to diffuse models) is well established, and extremely bright
- There is no clear astrophysical interpretation of the data. In particular the hard spectrum and spherical morphology of the excess are hard to model with astrophysical templates
- Dark Matter provides a natural fit to all aspects of the data. The dark matter templates are "natural" and consistent with all astrophysical constraints
- These three above points do not establish a "bulletproof detection" of dark matter - and multiple astrophysical models should (and are) being attempted.
- Stay Tuned!