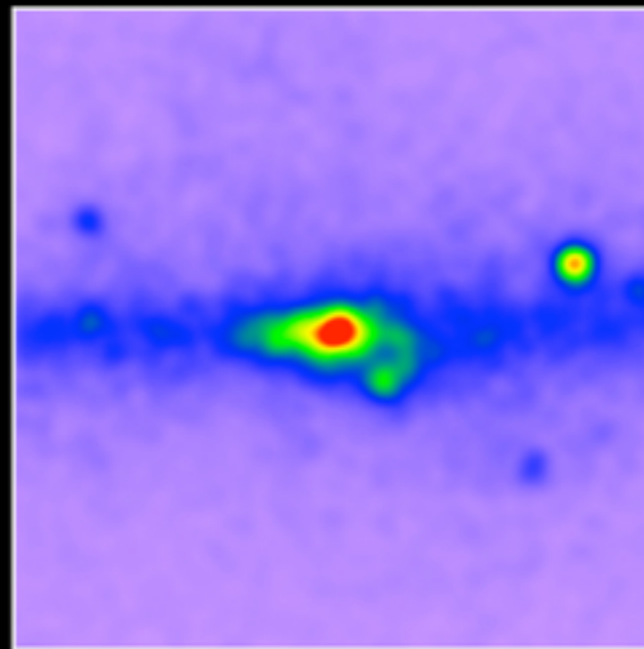
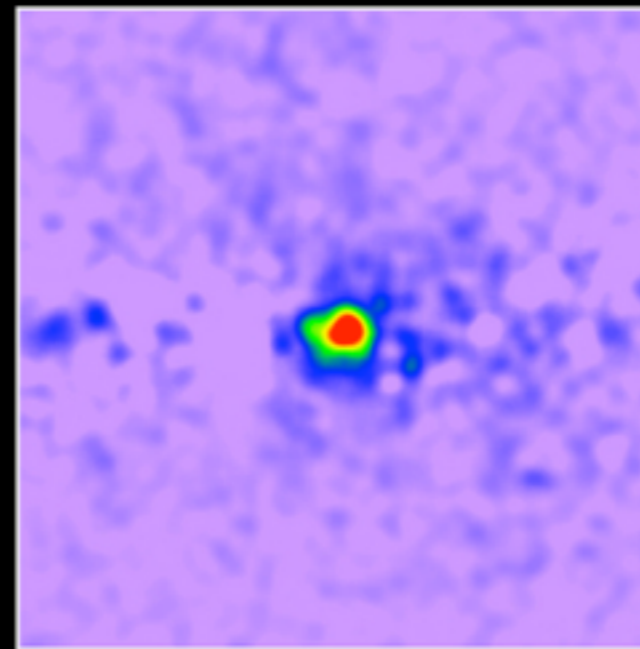


# The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Uncovering a gamma-ray excess at the galactic center



Unprocessed map of 1.0 to 3.16 GeV gamma rays



Known sources removed

**Tim Linden**

Einstein/KICP Fellow  
University of Chicago

along with:

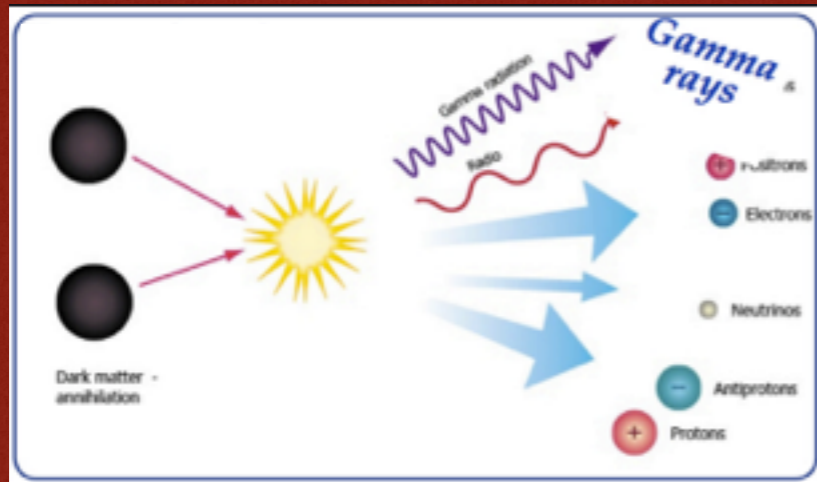
**Tansu Daylan, Doug Finkbeiner, Dan Hooper, Stephen Portillo,  
Nick Rodd and Tracy Slatyer**

arXiv: 1402.6703

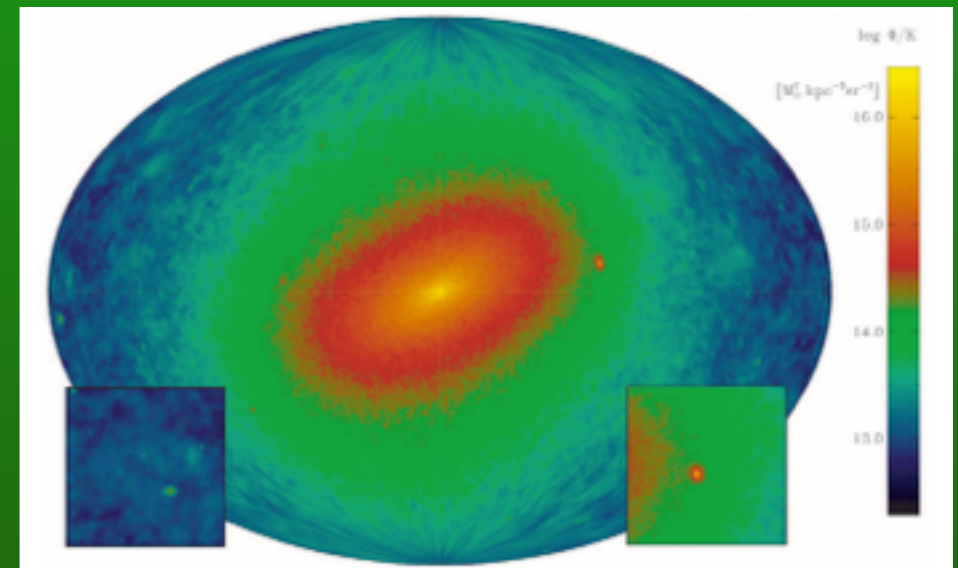
Notre Dame HEP Seminar - April 15, 2014

# Dark Matter Indirect Detection

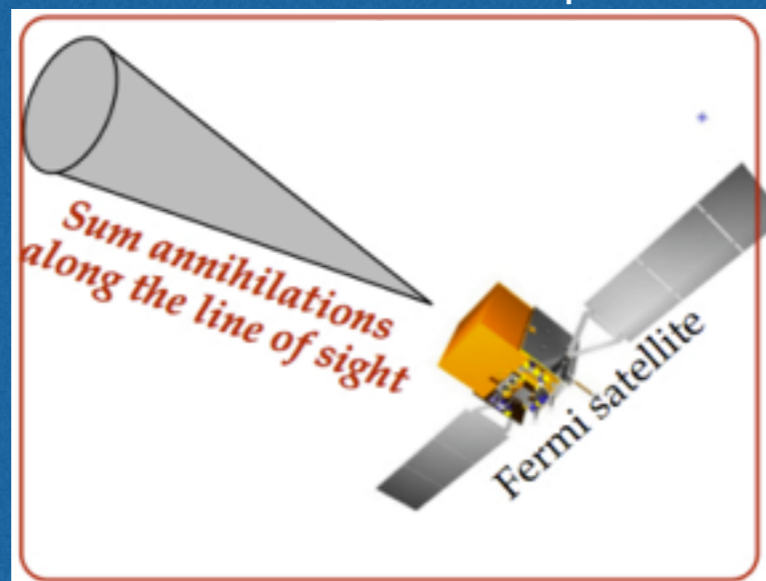
## Particle Physics



## Astrophysics



## Instrumental Response



# The Astrophysical J-Factor

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

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

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



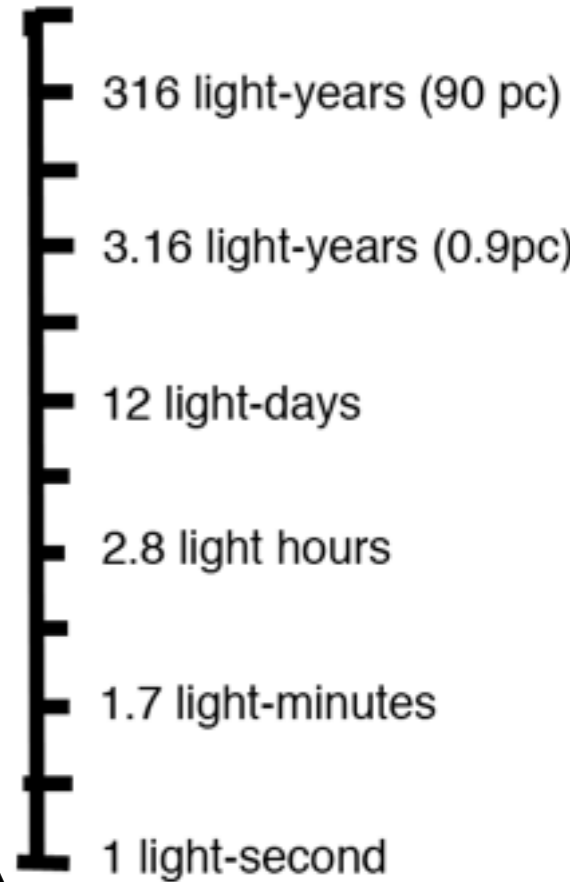
# The Galactic Center "Zoo"

O-star/Pulsar density peaks at 0.5 pc, and falls sharply for smaller radii (Buchholz et al. 2009)

$I = \times 100 \text{ sr}$

BH  
VLA  
Chandra

Accretion disk -  
Relatively dim now, but  
maybe not historically



Ridge of TeV gamma-ray emission assumed to be from p-p collisions with gas in the galactic disk (up to 200 pc)

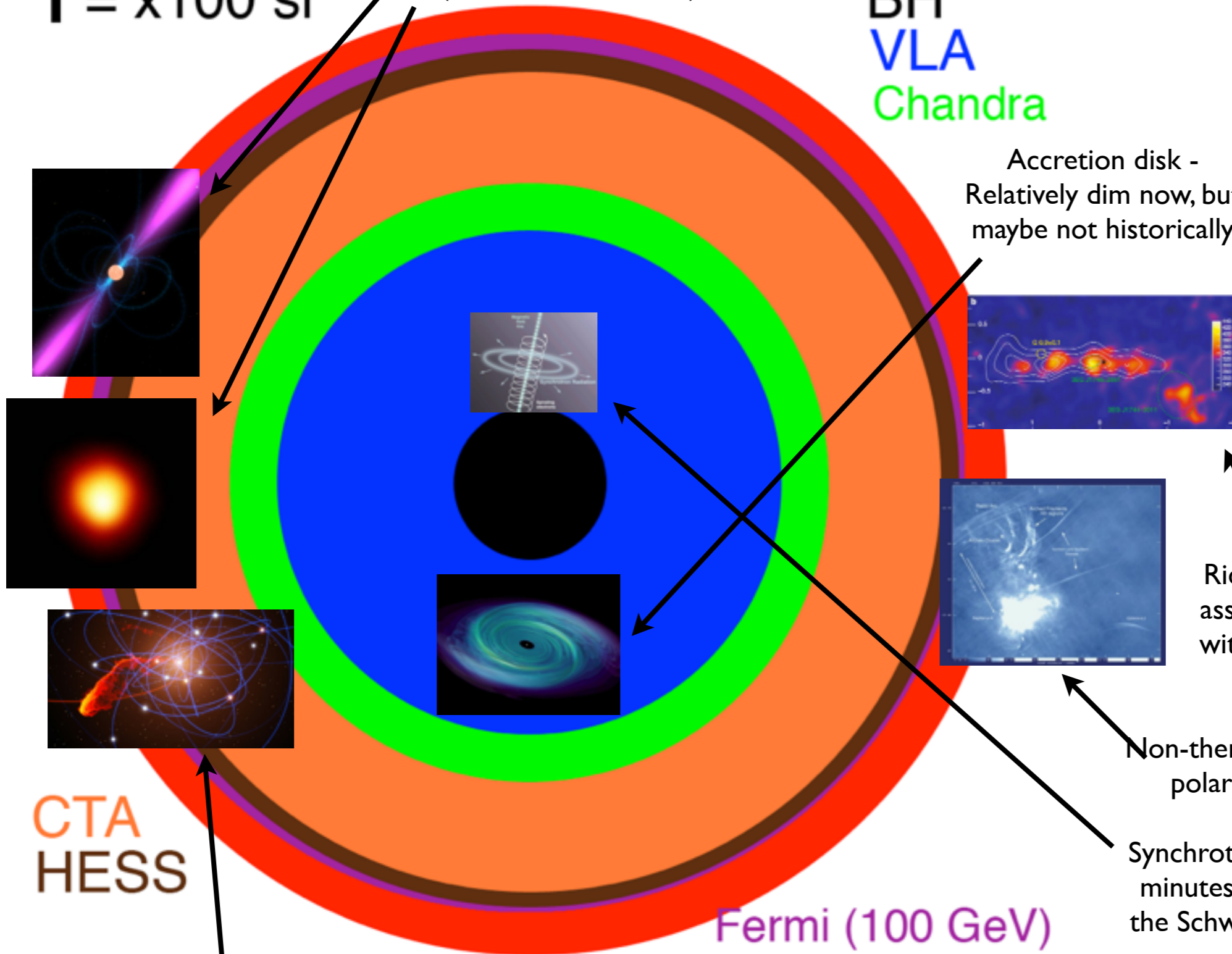
Non-thermal Radio Filaments - Bright, polarized synchrotron sources

Synchrotron Emission within 20 light-minutes of Sgr A\*, assumed to be at the Schwarzschild Radius (Gillessen et al. 2005)

Fermi (100 GeV)  
Fermi (1 GeV)

CTA  
HESS

Closest approach of 2013 gas cloud to Sgr A\* (0.004 pc)



# The Galactic Center as an Indirect Detection Target

Positive: Any indirect signal from dark matter annihilation is likely to first be detected at the center of the Milky Way Galaxy

Corollary: Any signal observed elsewhere in the Galaxy should be consistent (or also seen in) the GC

Negative: Astrophysics may make it difficult to conclusively determine that an excess in the galactic center is due to dark matter

# A Note about the NFW Profile

$$\rho_{NFW} = \rho_0 \left( \frac{r}{r_s} \right)^{-\gamma} \left( 1 + \frac{r}{r_s} \right)^{-3+\gamma}$$

For the rest of the talk, we will model the dark matter profile as a “Generalized NFW profile”, with the following functional form.

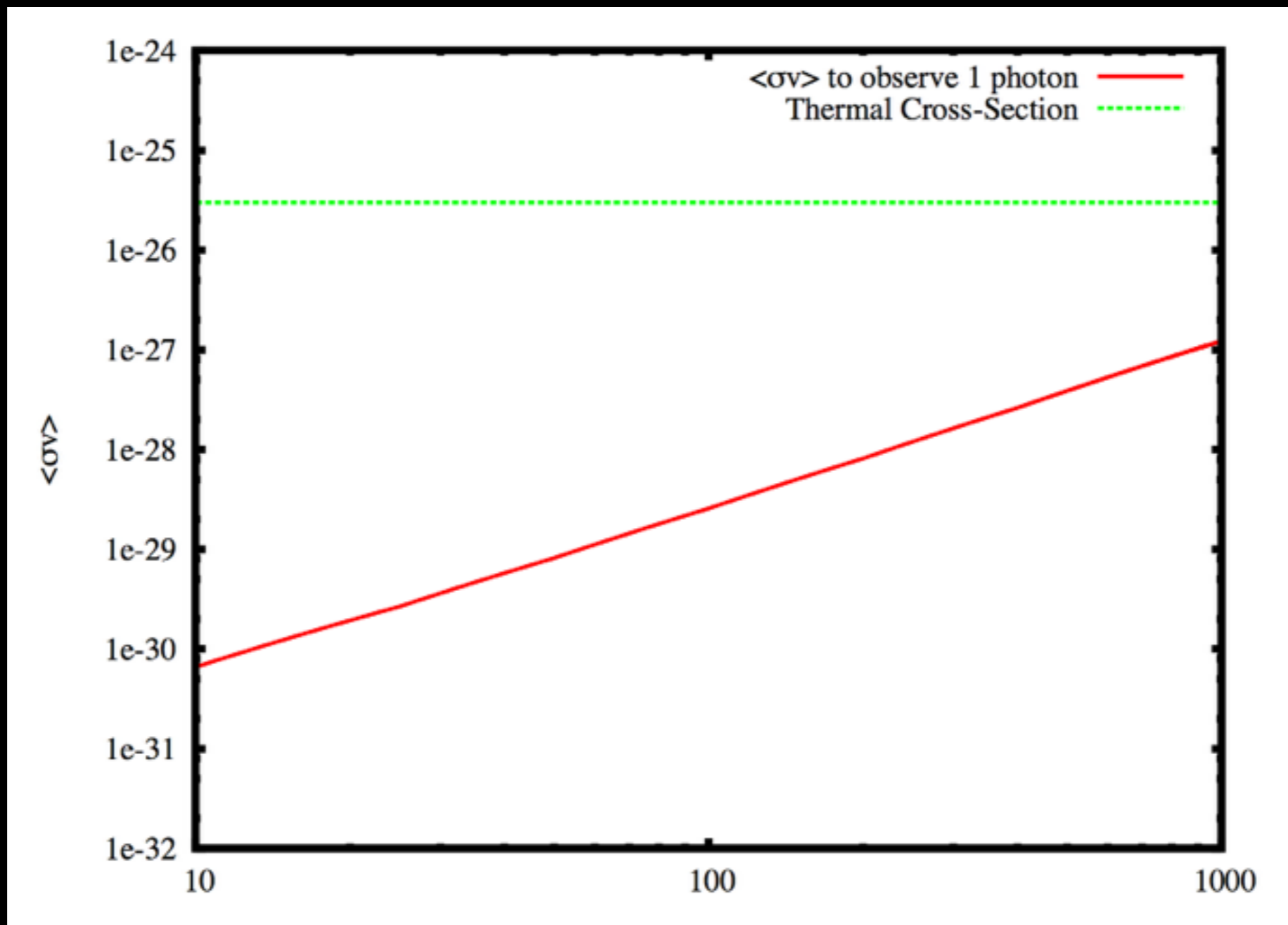
For studies of the galactic center, the most important parameter is  $\gamma$ , which controls the inner slope, for a canonical NFW profile  $\gamma = 1$

# The Galactic Center in Gamma-Rays

## Back of the Envelope Calculation

- Total Gamma-Ray Flux from 1-3 GeV within  $1^\circ$  of the GC is  $\sim 1 \times 10^{-10}$  erg cm $^{-2}$  s $^{-1}$
- The flux expected from a vanilla dark matter model (100 GeV  $\rightarrow$  bb with an NFW profile) is  $\sim 2 \times 10^{-11}$  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

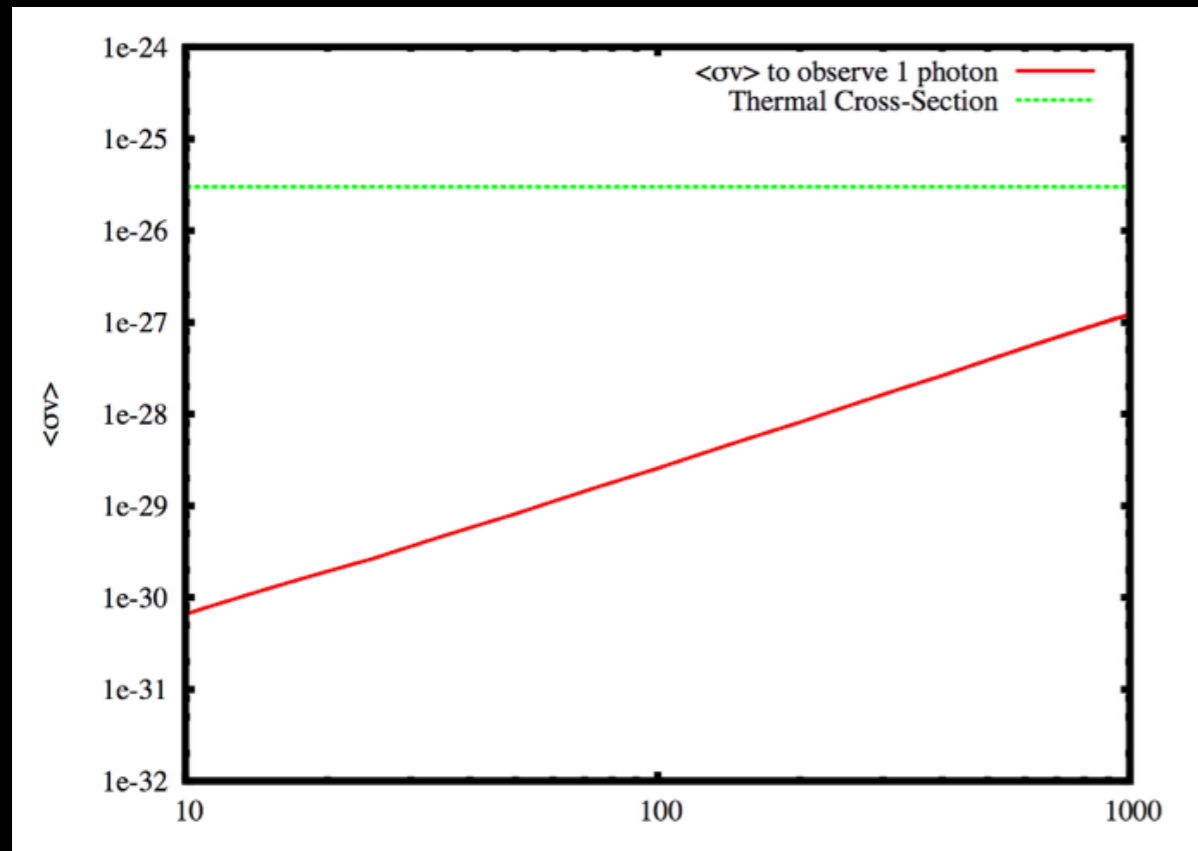
# The Galactic Center in Gamma-Rays



If you were able to somehow “tag” each  $\gamma$ -ray from the GC as “dark matter” or “astrophysics”, these are the limits you could place on dark matter annihilation



# The Galactic Center in Gamma-Rays



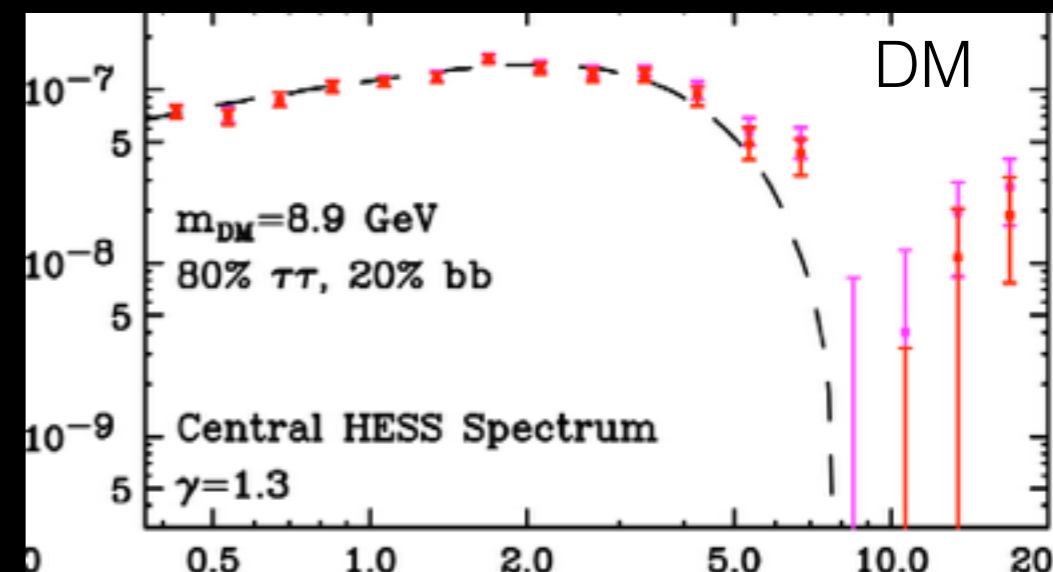
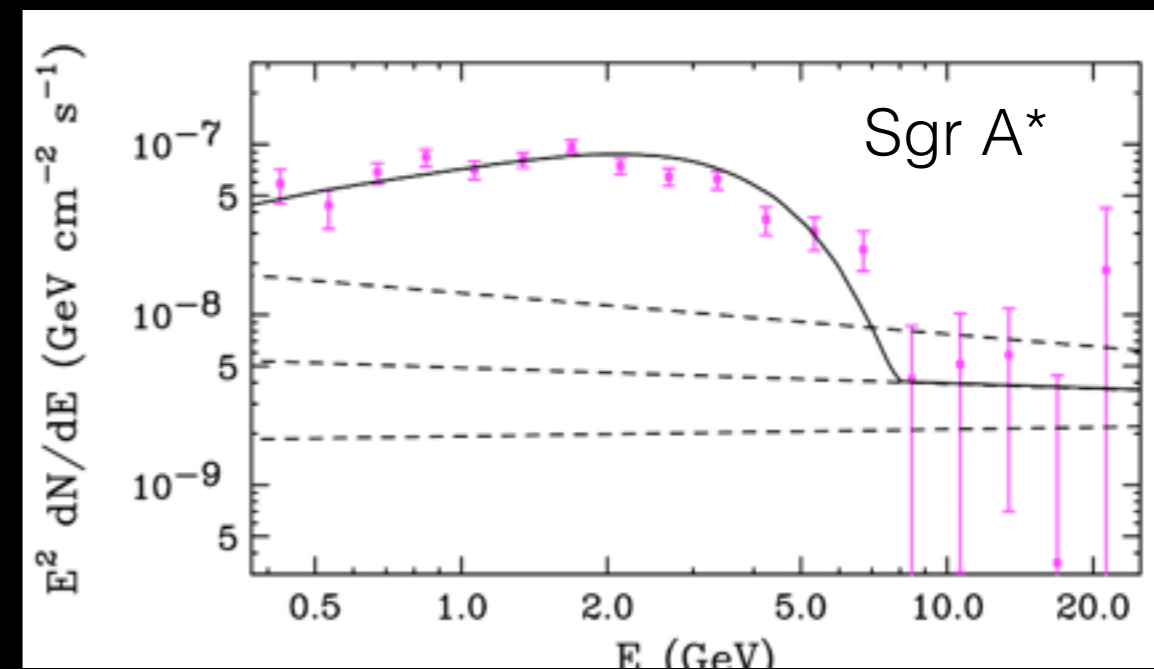
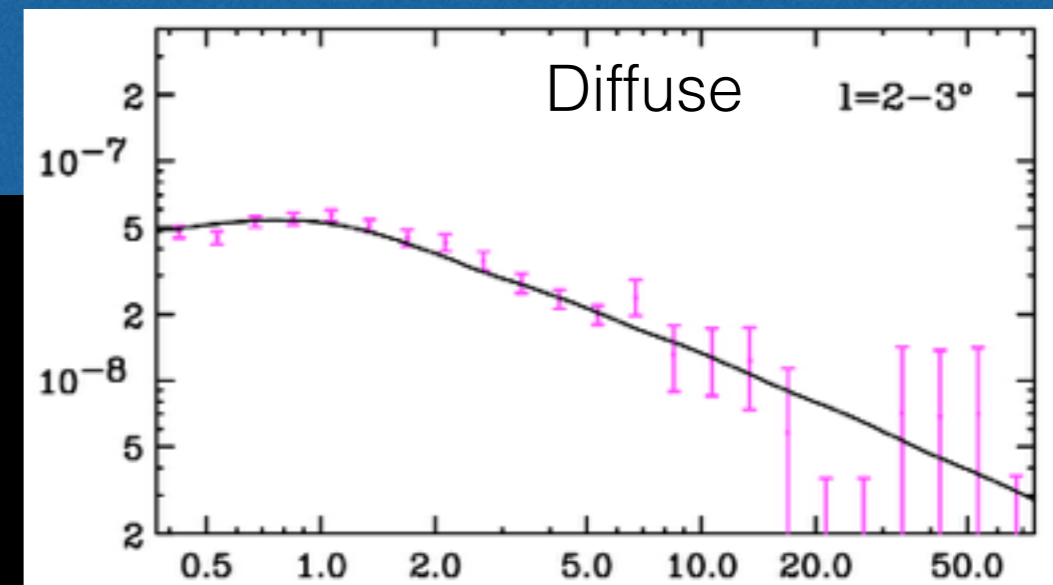
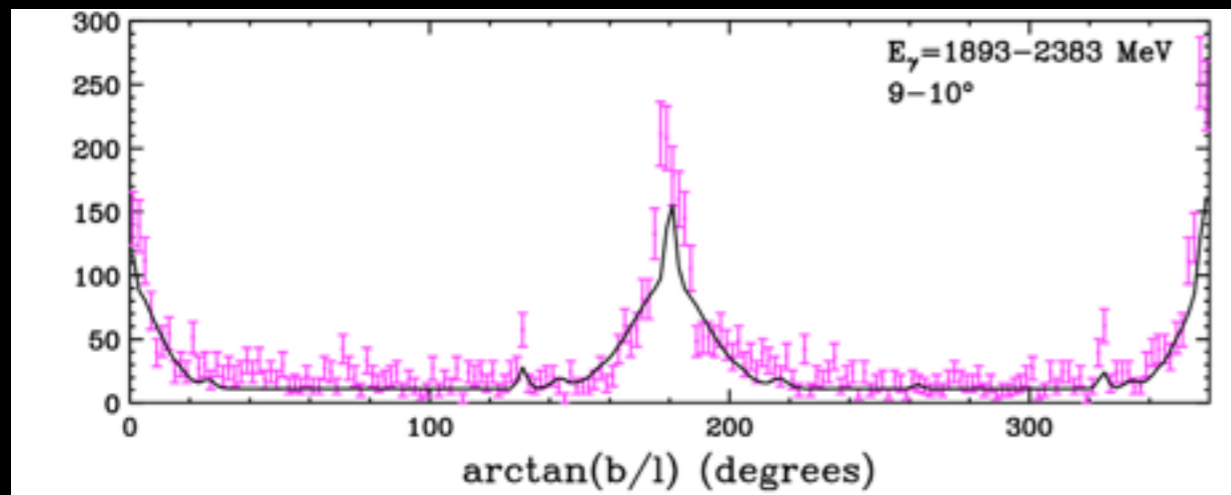
Positive - We have tons of statistics to play with, a thermal dark matter candidate should produce as many as 50,000  $\gamma$ -rays observed by the Fermi-LAT

If a signal is found, we can ask probing questions like “Does the morphology and spectrum look like dark matter annihilation?”

# Outline of the Talk

- 1.) Data of the Galactic Center and Inner Galaxy Excess
- 2.) Models of the Galactic Center and Inner Galaxy Excess
- 3.) Looking at the Future

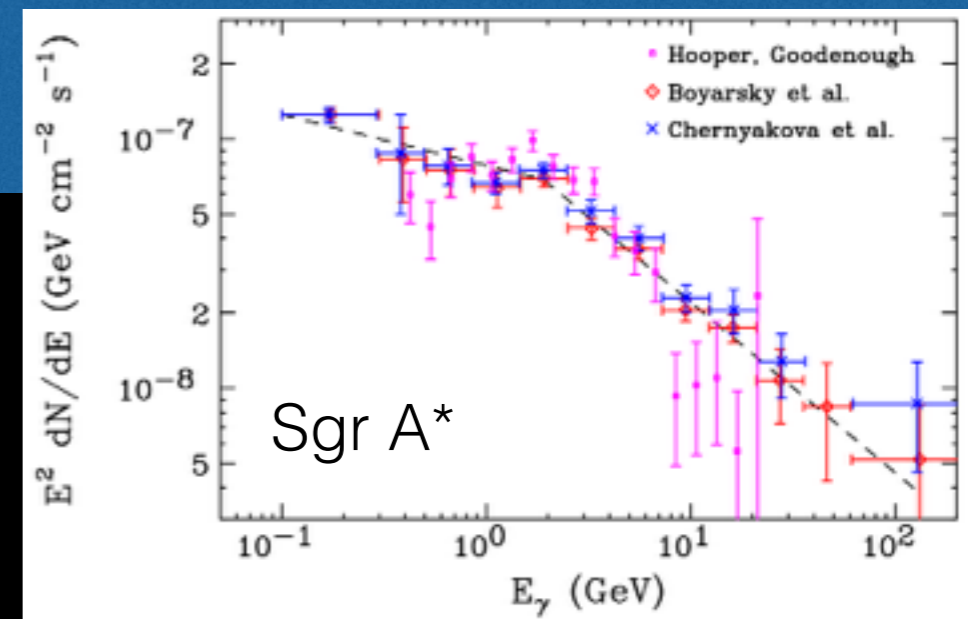
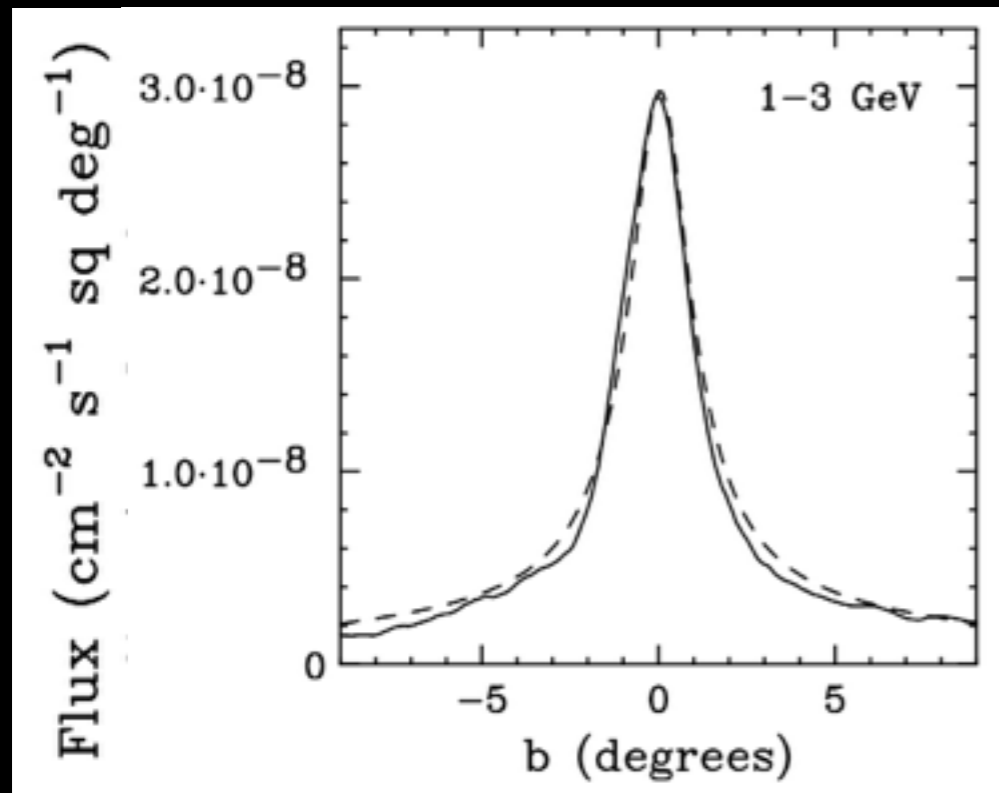
# Previous Efforts



Hooper & Goodenough (2010) employed the angular distribution of observed gamma-rays to separate and model the emission from the:

- galactic disk
- galactic center point source
- modeled dark matter component

# Previous Efforts



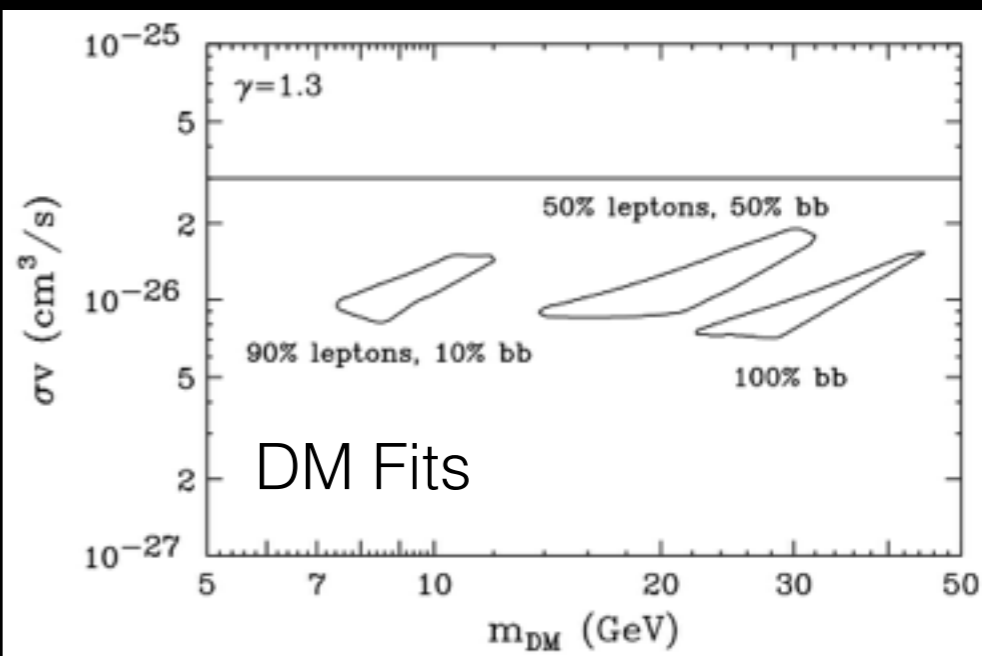
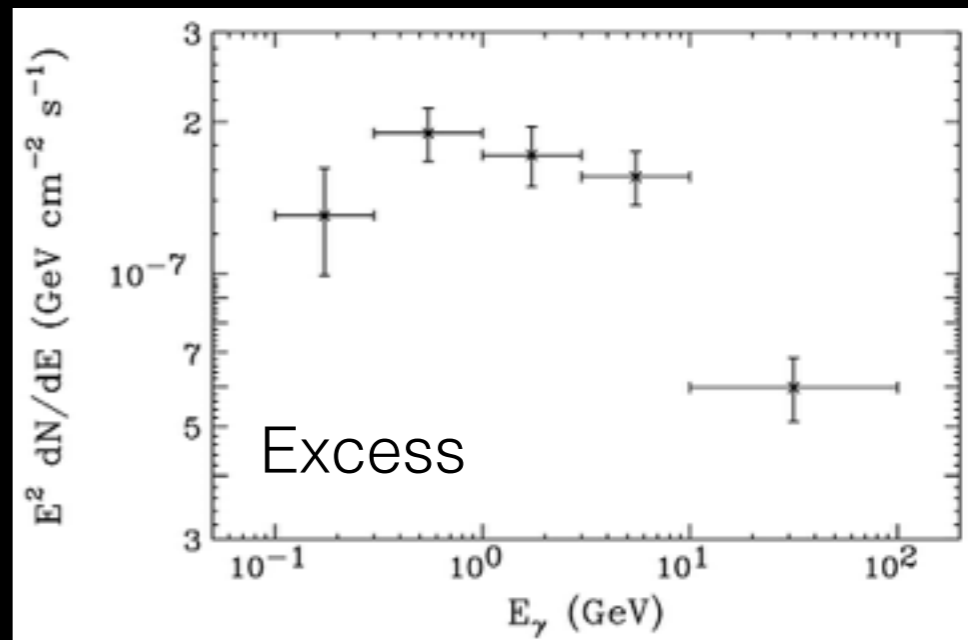
Hooper & Linden (2010) employed observationally driven models for

the distribution of gas (Kalberla & Kerp 2009)

the spectrum of nearby  $\gamma$ -ray point

sources (2FGL)

the spectrum of Sgr A\*



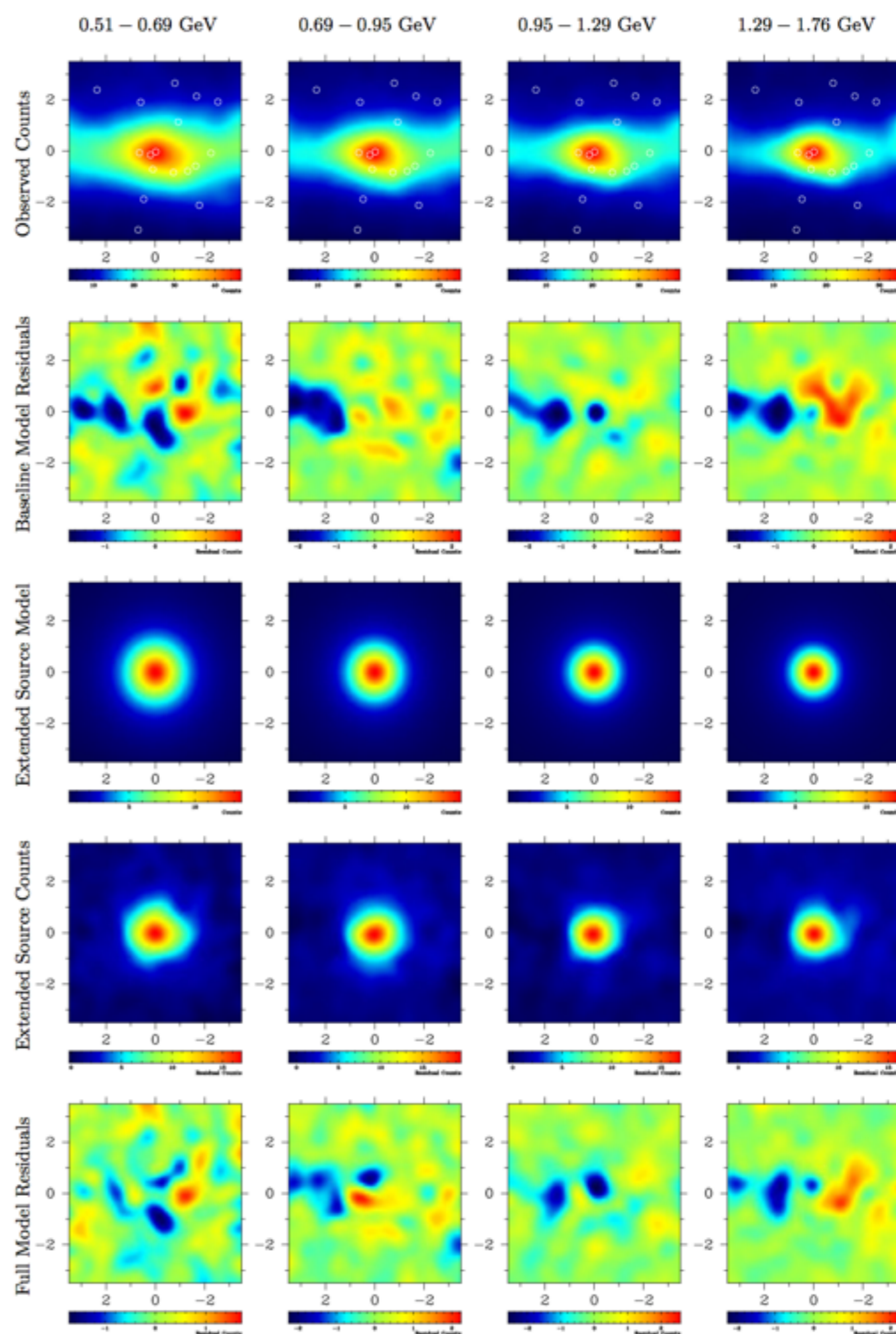


# Previous Efforts

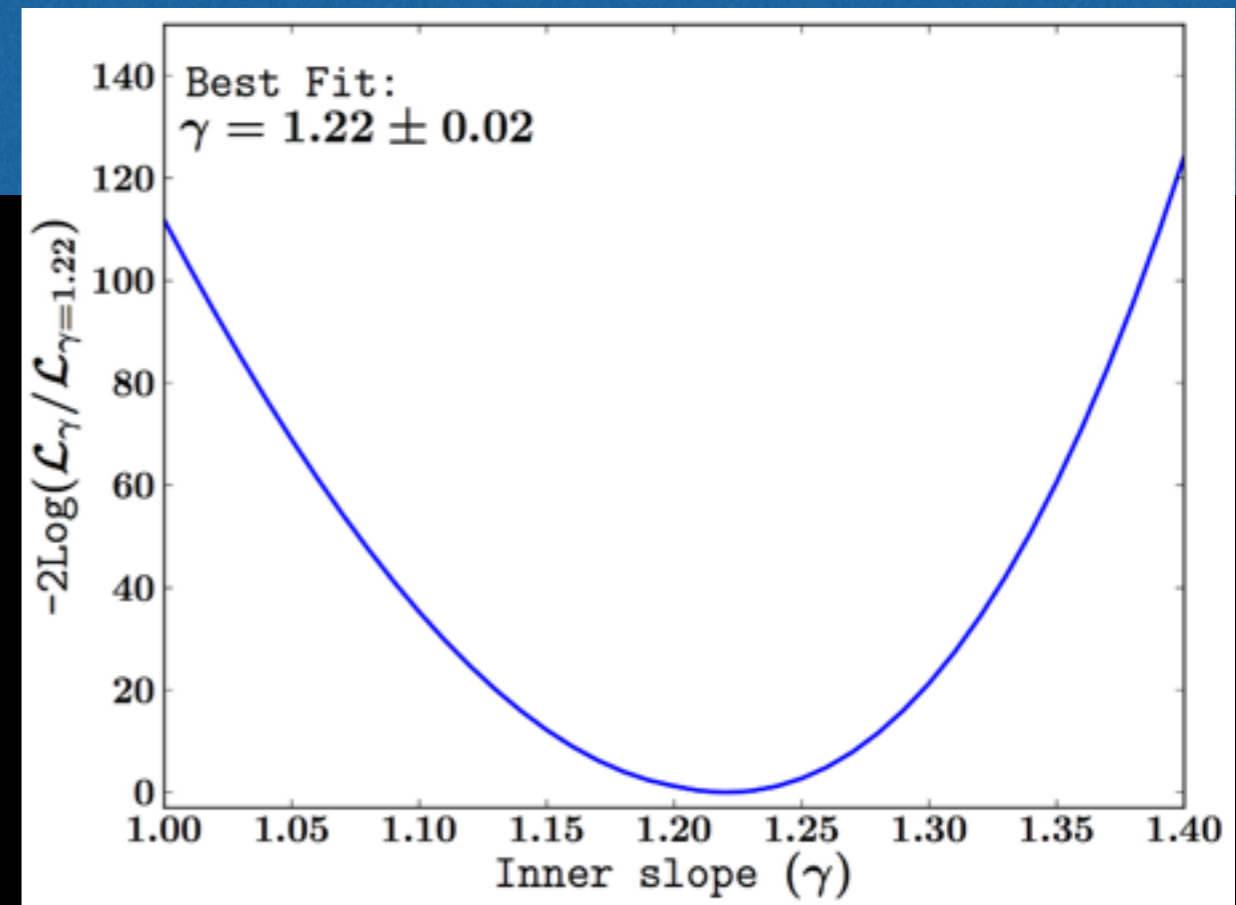
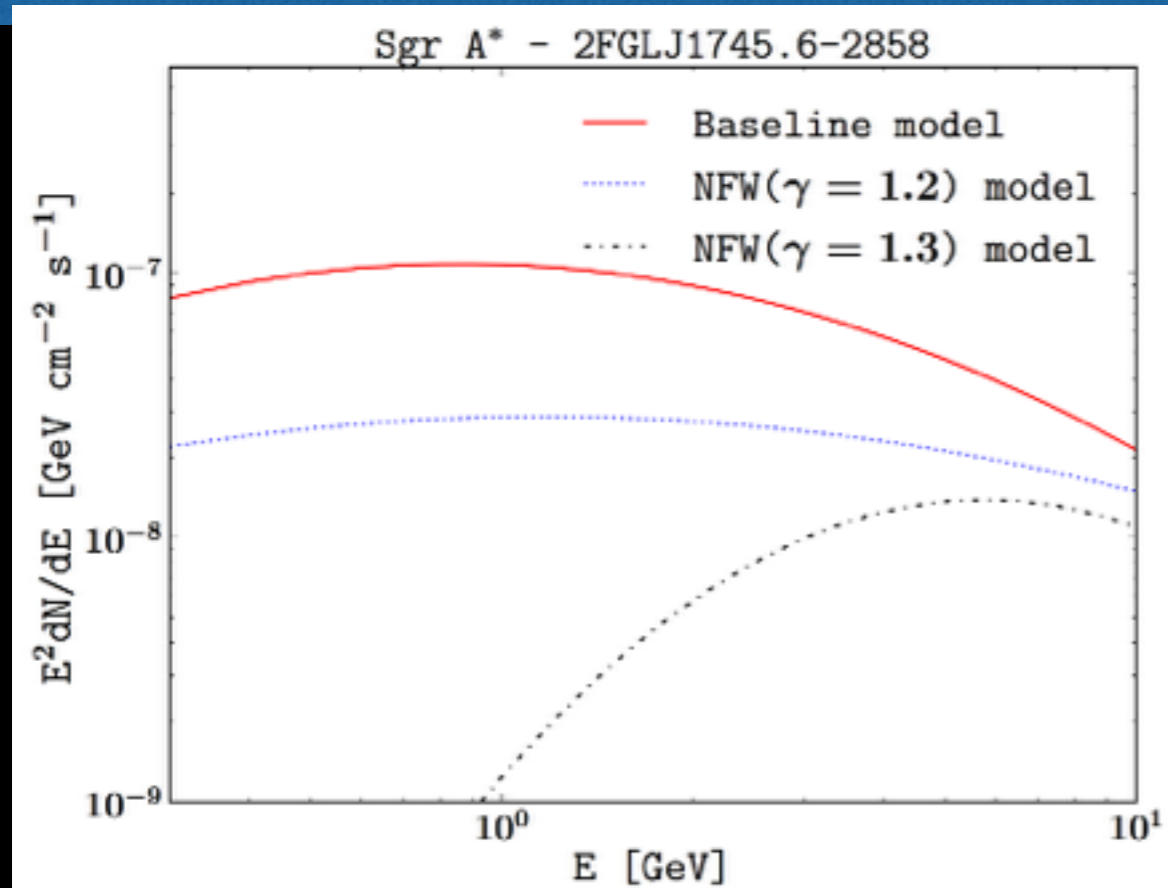
channel, $m_\chi$	$TS_{\approx}$	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
$b\bar{b}$ , 10 GeV	2385.7	139913.6	156.5
$b\bar{b}$ , 30 GeV	3460.3	139658.3	411.8
$b\bar{b}$ , 100 GeV	1303.1	139881.1	189.0
$b\bar{b}$ , 300 GeV	229.4	140056.6	13.5
$b\bar{b}$ , 1 TeV	25.5	140108.2	-38.0
$b\bar{b}$ , 2.5 TeV	7.6	140114.2	-44.0
$\tau^+\tau^-$ , 10 GeV	1628.7	139787.7	282.5
$\tau^+\tau^-$ , 30 GeV	232.7	140055.9	14.2
$\tau^+\tau^-$ , 100 GeV	4.10	140113.4	-43.3

Abazajian & Kaplinghat (2012) produce a more sophisticated template fitting technique.

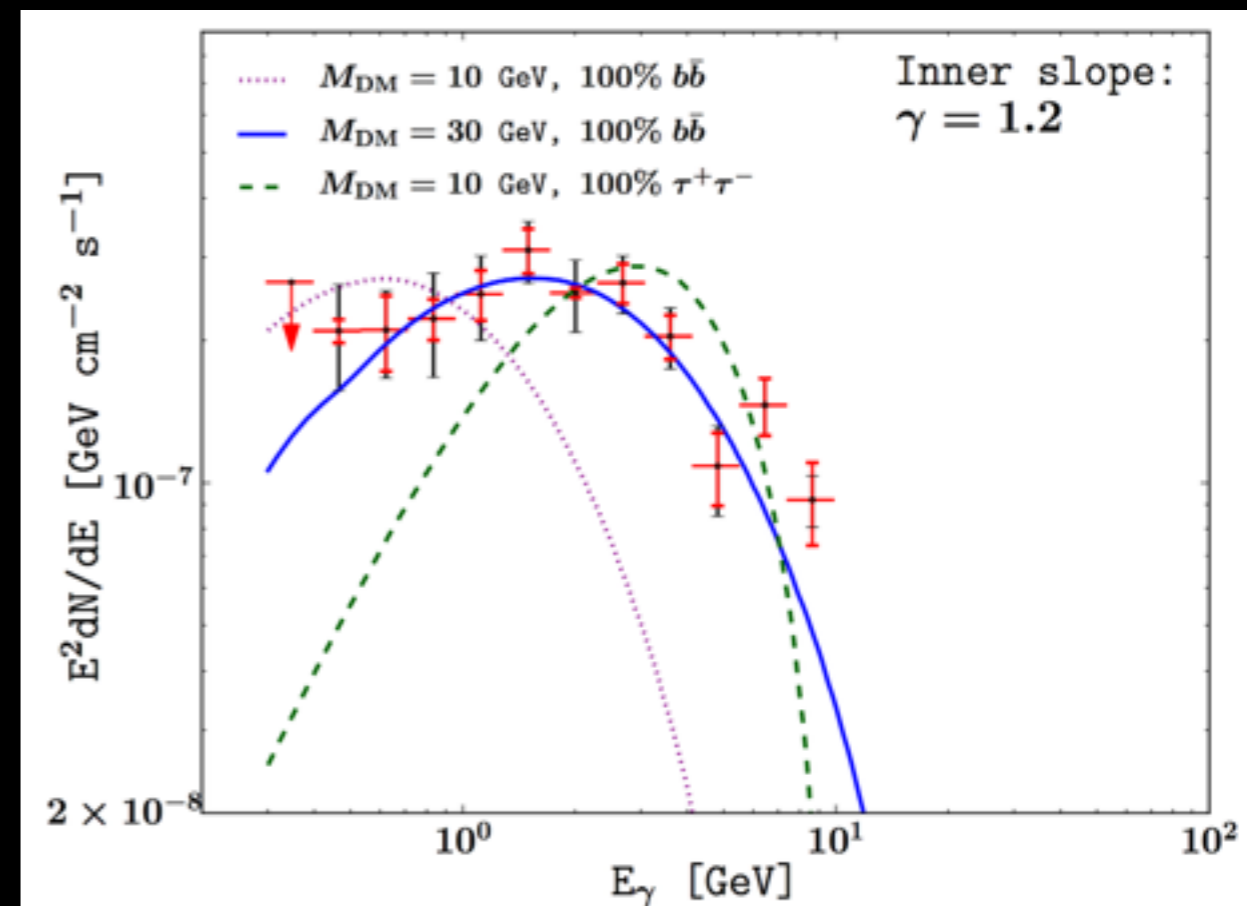
They quantify the  $\gamma$ -ray residual as preferable to models without a dark matter template at the level of more than  $20\sigma$



# Previous Efforts

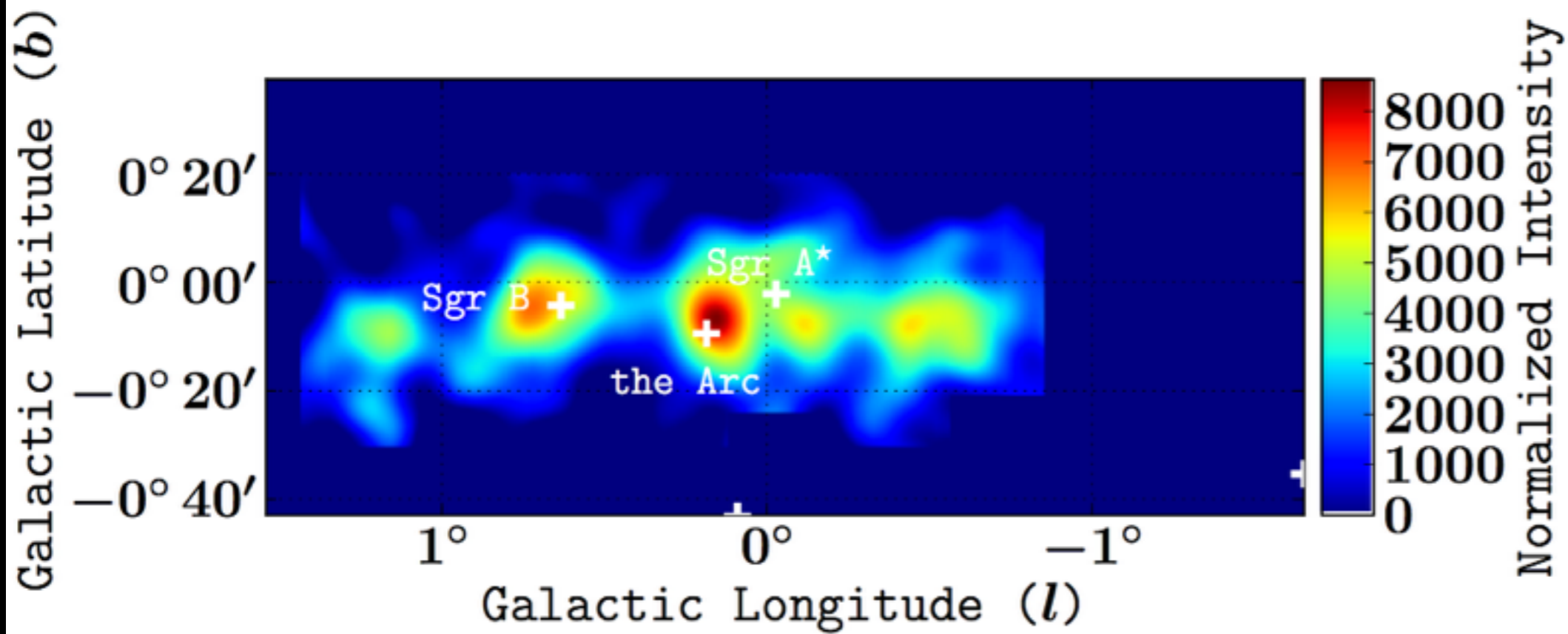


Gordon & Macias (2013) investigated variations in the spectra of the point source components, and also put strong constraints on the inner slope of the NFW profile

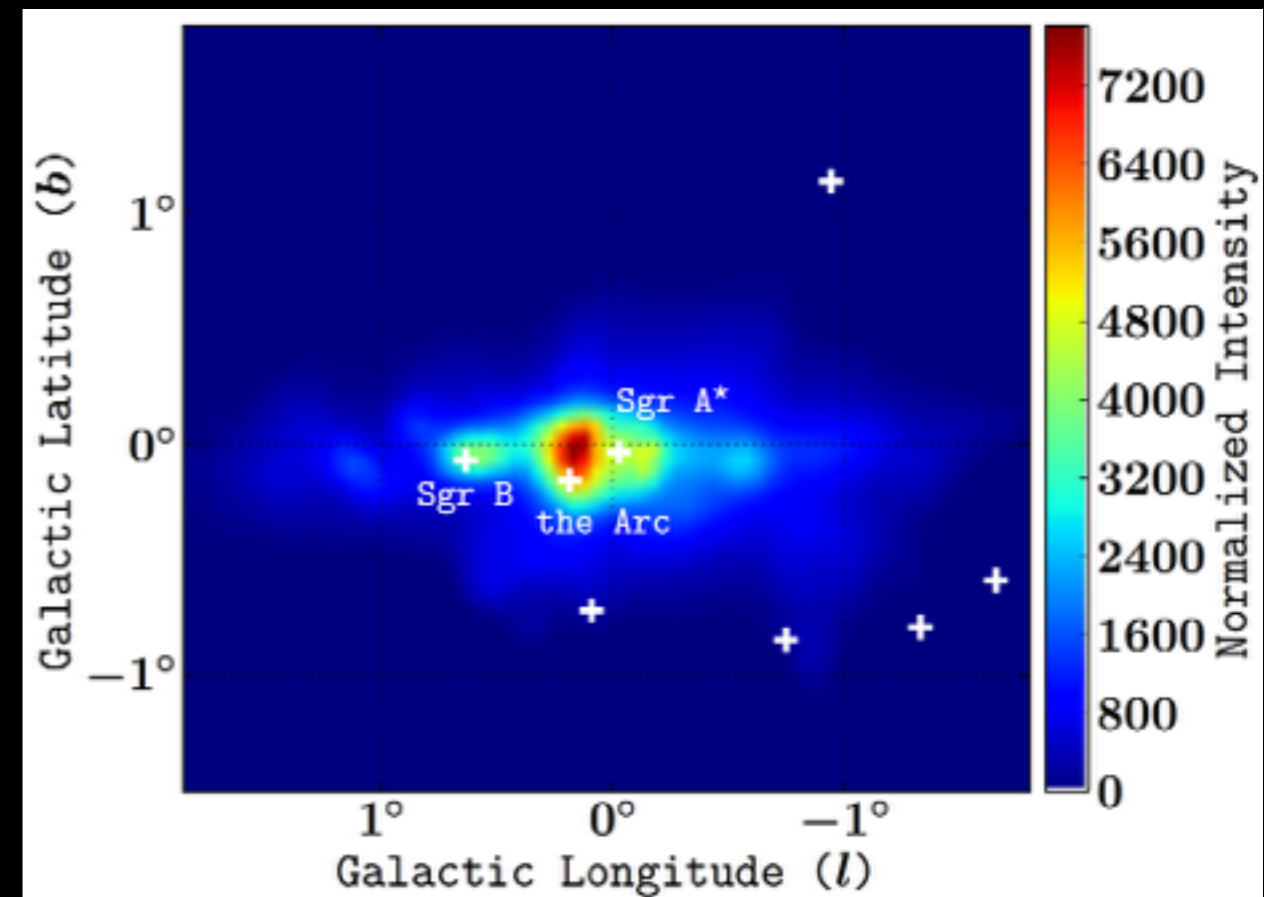




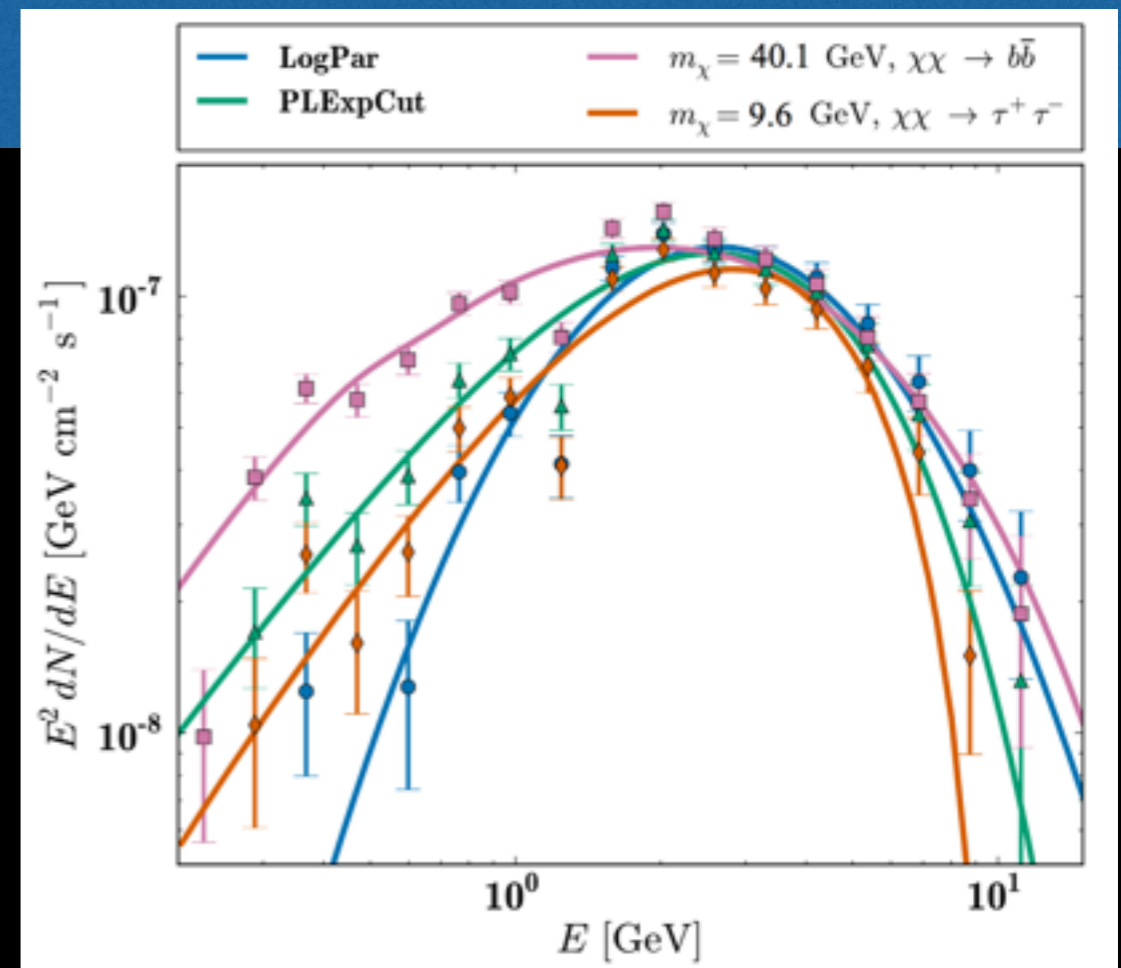
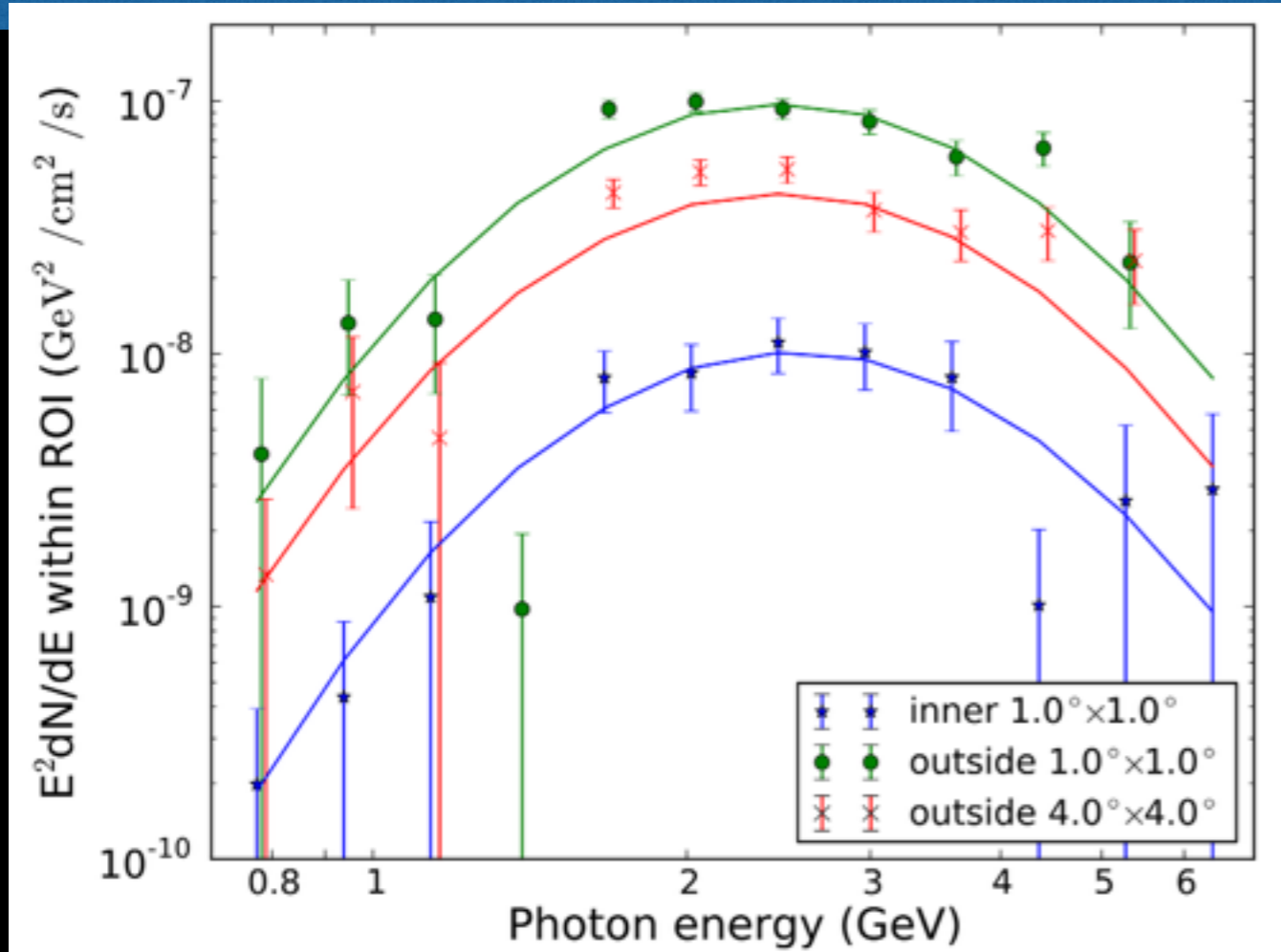
# Previous Efforts



Macias & Gordon (2013) investigated possible contributions corresponding to the morphology of the HESS TeV emission and to 20 cm synchrotron emission, and found the  $\gamma$ -ray excess to be resilient to the addition of these models

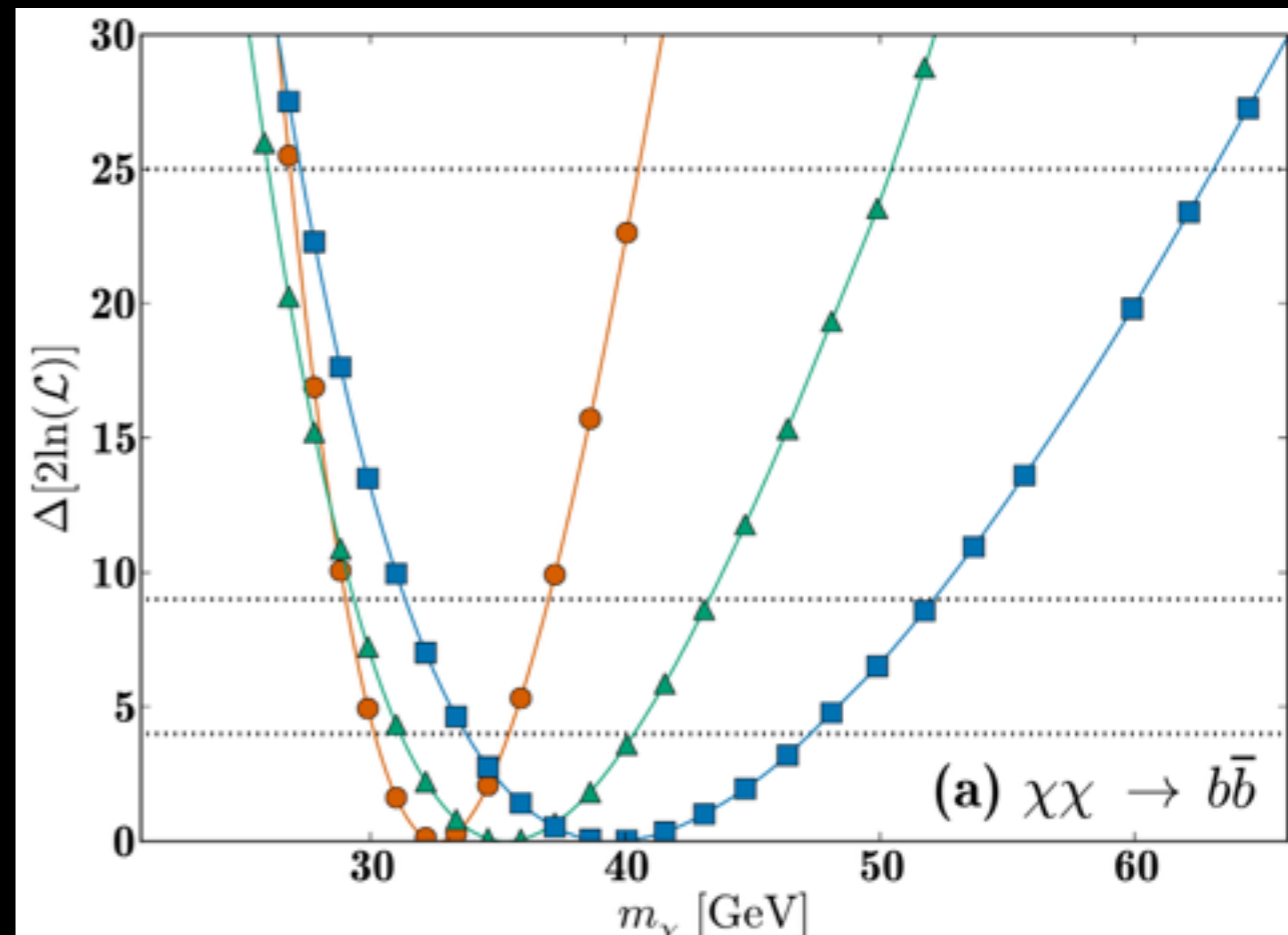


# Previous Efforts



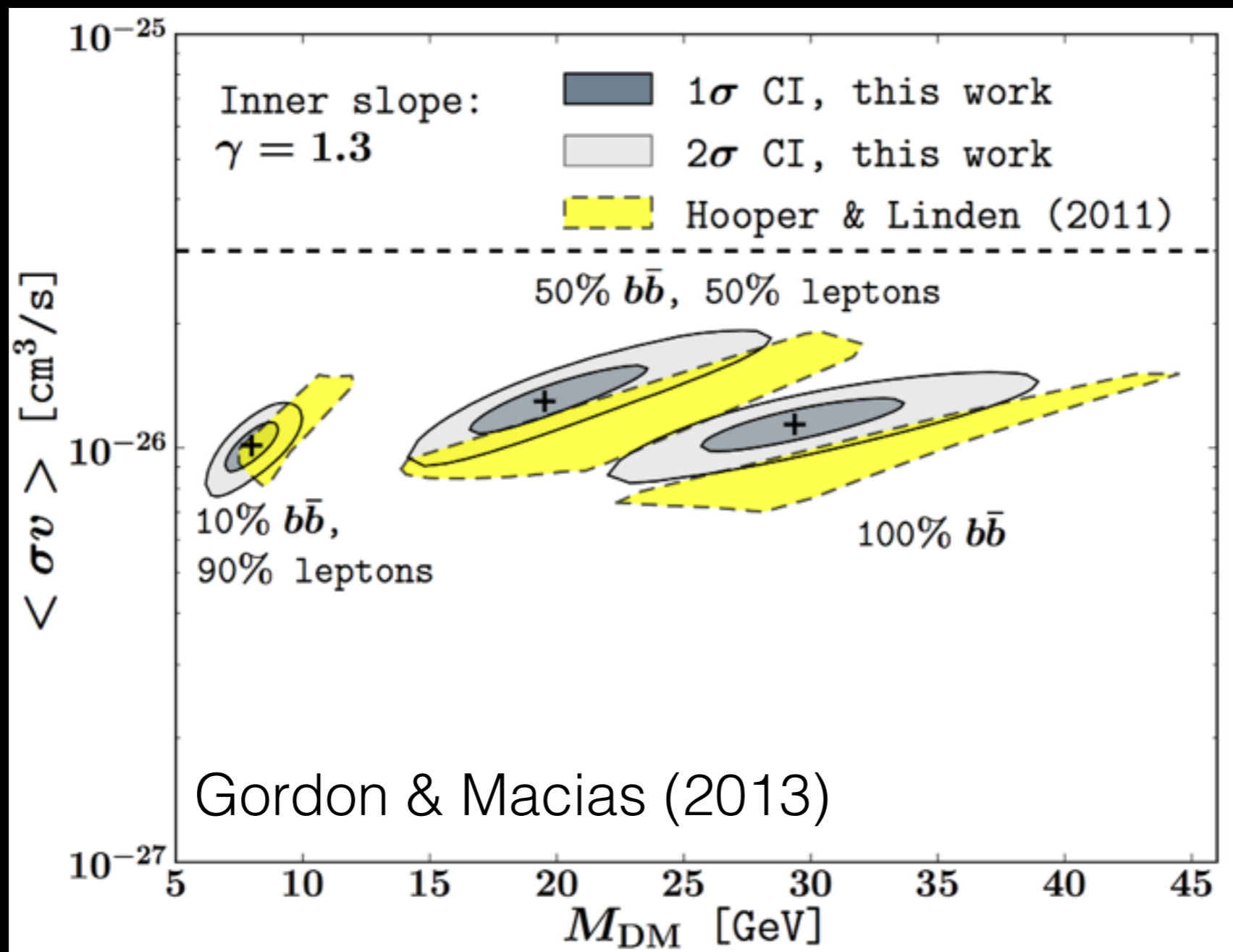
Abazajian et al. (2014) found the spectrum of the residual to be resilient to more than  $4^\circ$  away from the galactic center

They did find the low energy spectrum to be highly model dependent





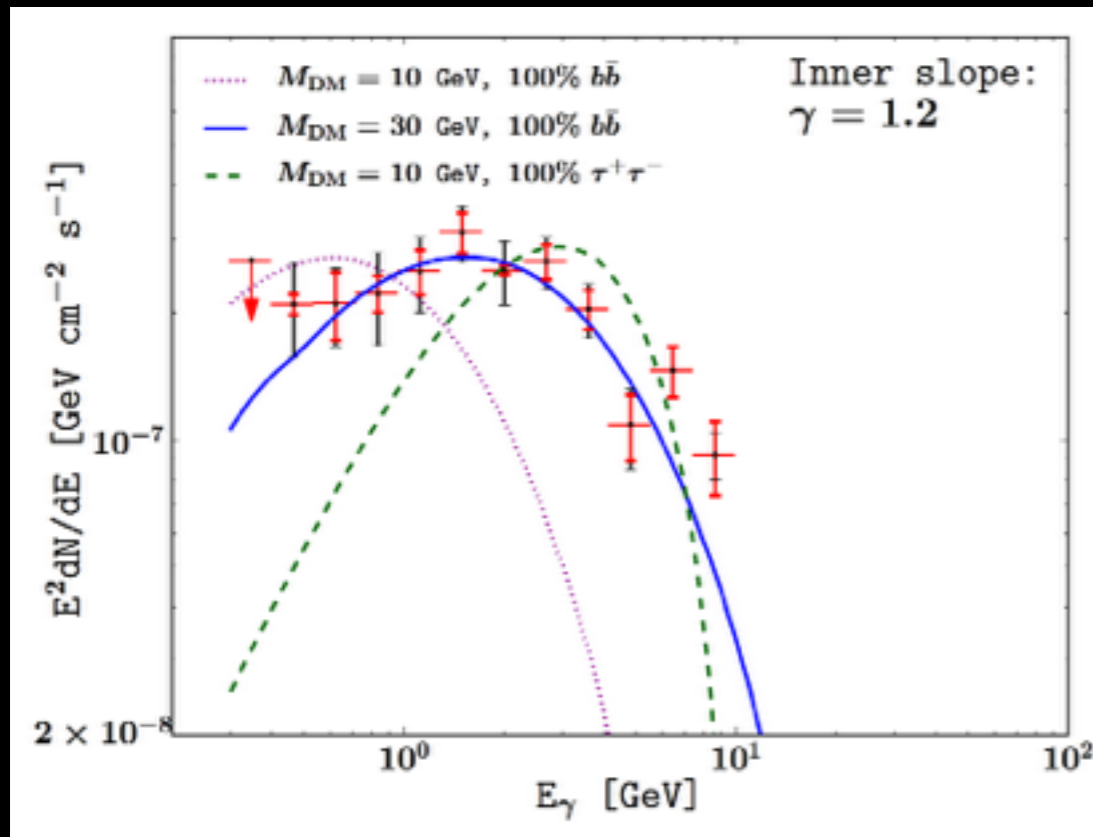
# A Broad Consensus



At this point, there are 7 studies by three independent groups, which both qualitatively and quantitatively agree on the major features of the  $\gamma$ -ray excess

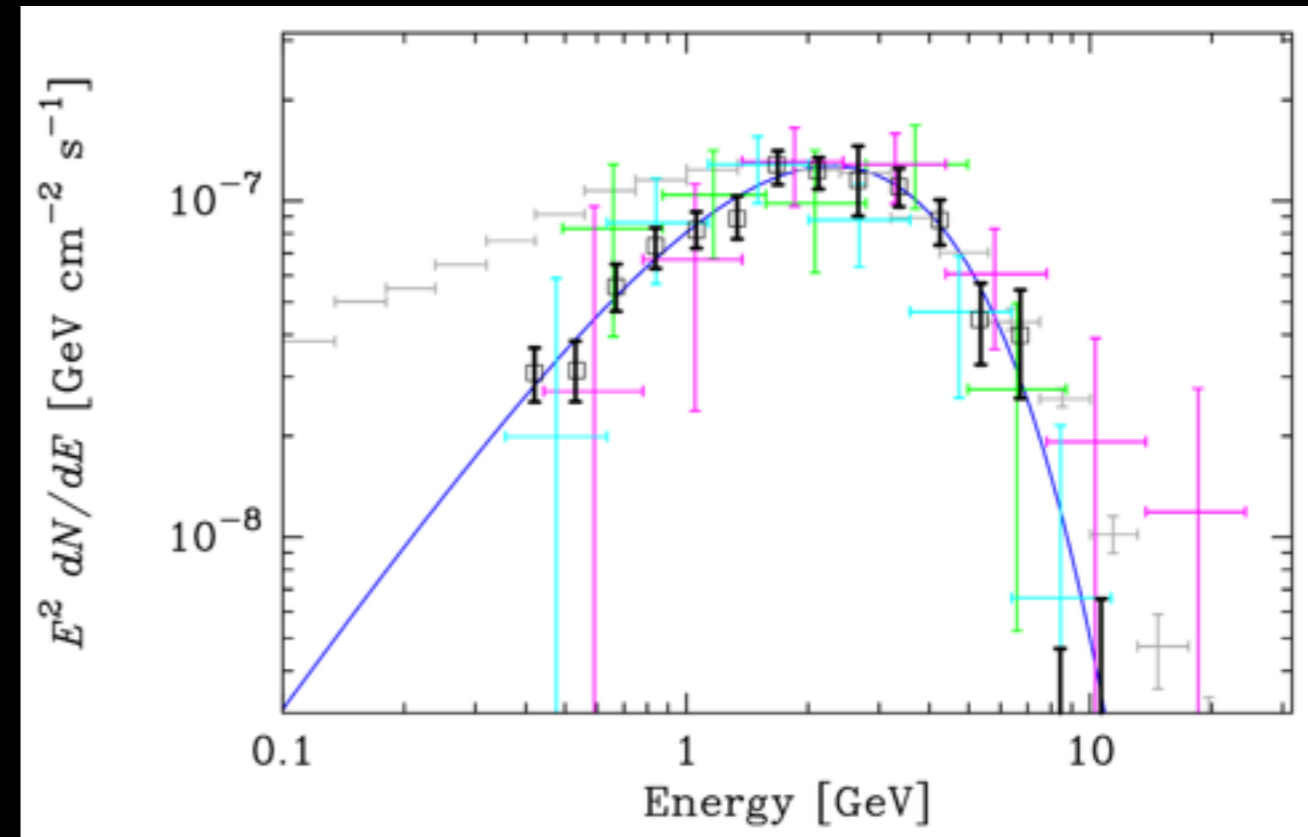
# Two Interpretations of the Old Data

## Dark Matter



Gordon & Macias (2013)

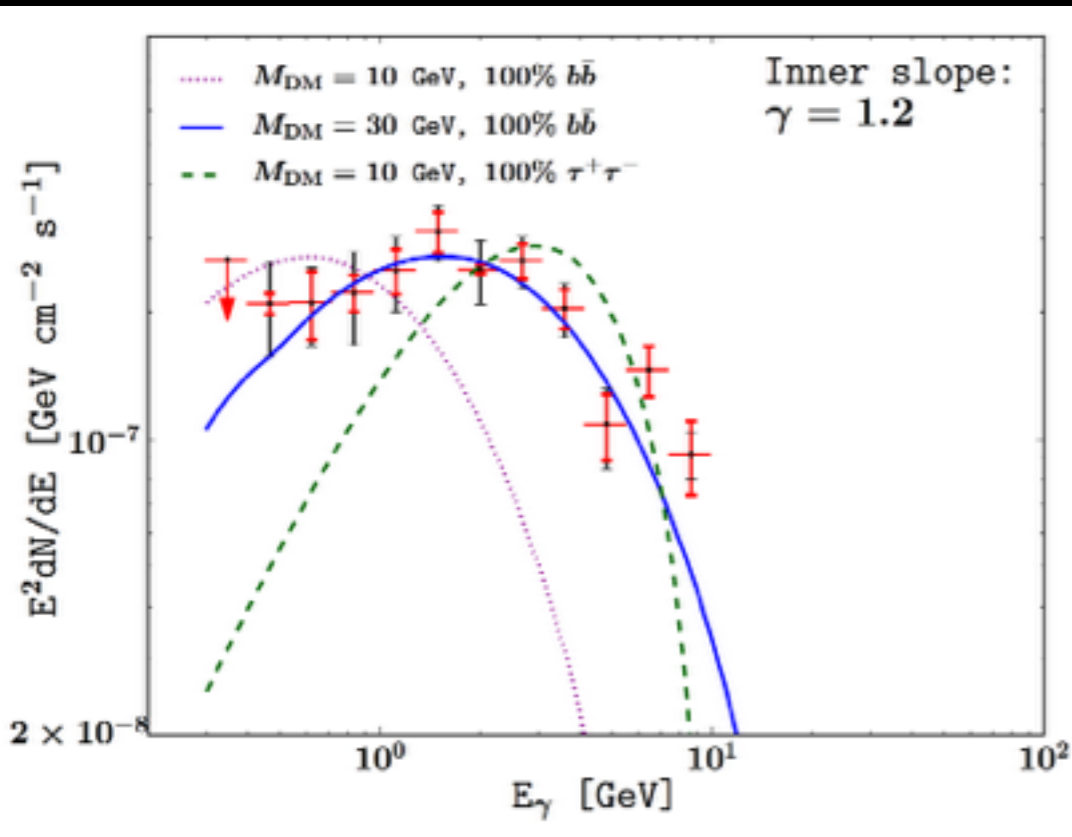
## Millisecond Pulsars



Abazajian (2011)

# Two Interpretations of the Old Data

## Dark Matter



Gordon & Macias (2013)

Need a WIMP of mass  $\sim 25\text{-}40$  GeV (if annihilating to  $b\bar{b}$ )

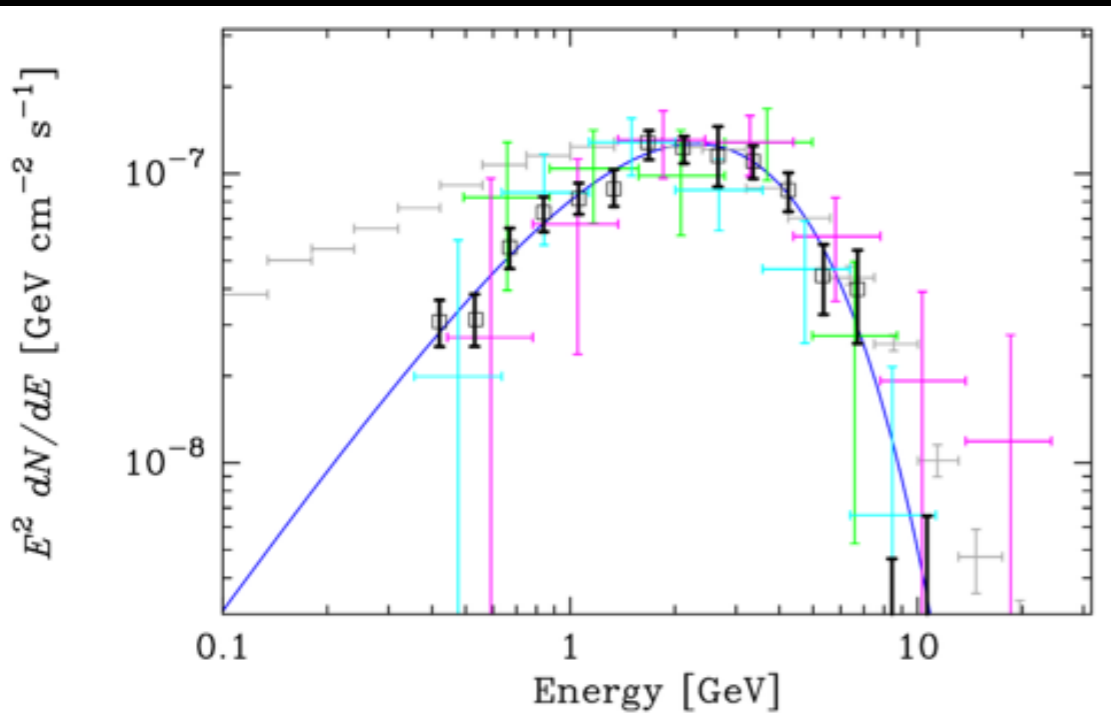
Need a slightly adiabatically contracted NFW profile  $\gamma \sim 1.1\text{-}1.3$

Need a dark matter annihilation cross-section  $\sim 1.5 - 2.5 \times 10^{-26}$  (for a local density  $0.3 \text{ GeV cm}^{-3}$ )

# Two Interpretations of the Old Data

## Millisecond Pulsars

Abazajian (2011)



Need a population of approximately 2000 - 4000 MSPs within the inner degree around the GC

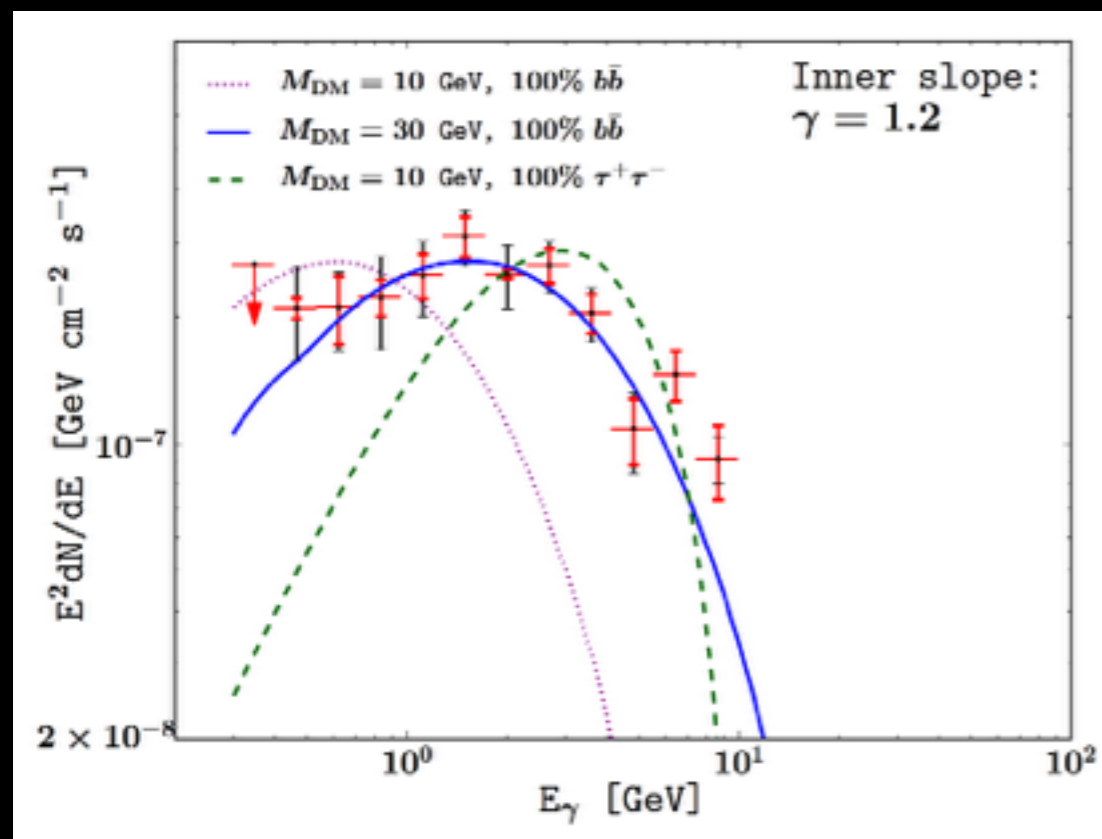
MSPs must follow the square of the spherically symmetric stellar density (dynamical interactions)

Average pulsar spectra must be slightly harder at low energies, and a significant number of pulsars must have escaped detection by radio surveys



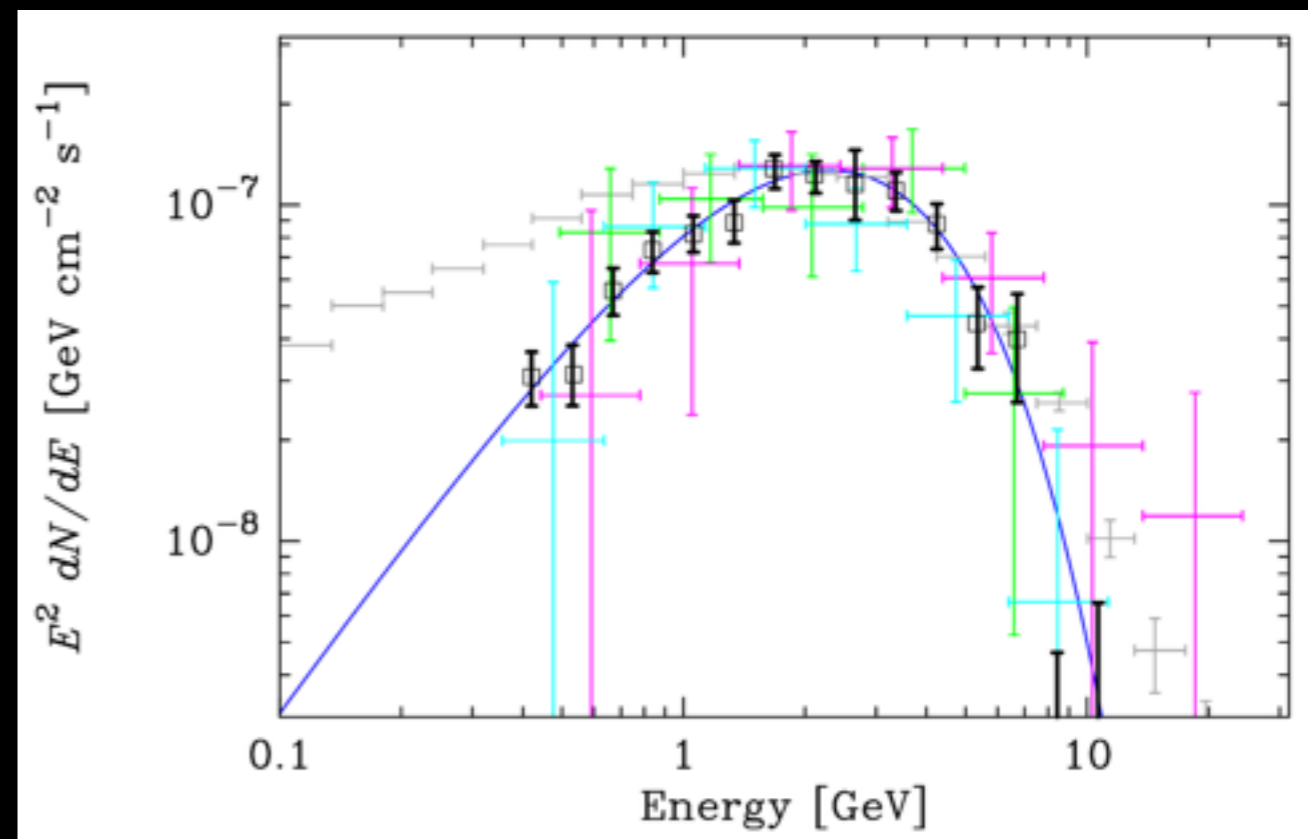
# Two Interpretations of the Old Data

## Dark Matter



Gordon & Macias (2013)

## Millisecond Pulsars



Abazajian (2011)

While it is easy to debate the relative strength of these models - it is fair to say data up until this point did not strongly favor either.

Instead, arguments normally were reduced to the relative Bayesian priors you would put on each type of model

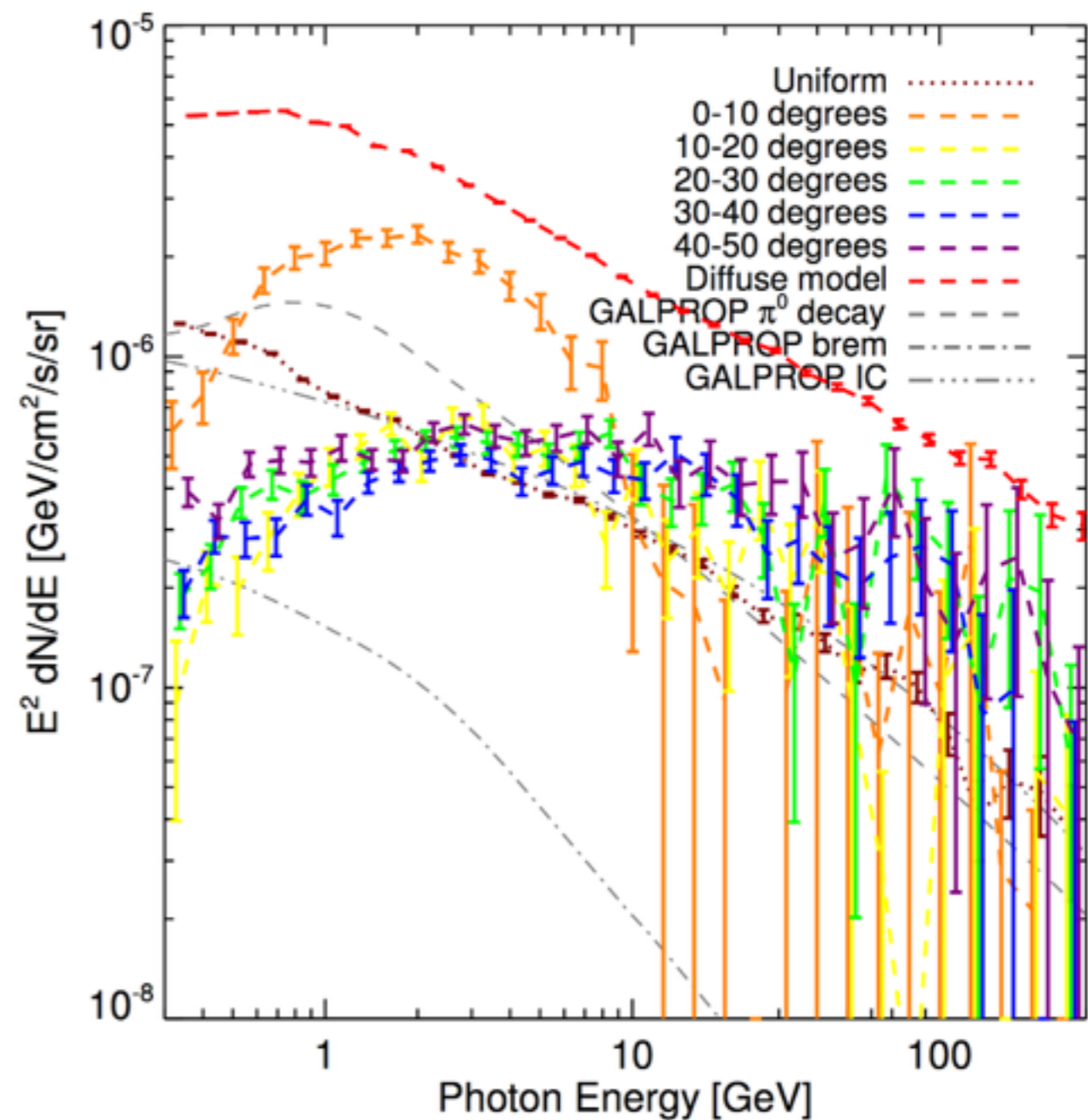
# Previous Efforts

In the meantime, Hooper & Slatyer (2013) produced a completely different analysis:

1.) They masked the region  $|b| < 1^\circ$ ,  $2^\circ$ , and  $5^\circ$ .

2.) Instead of modeling the point sources, they masked the region around bright point sources

3.) They then use template fitting models to allow the normalization of the diffuse emission, isotropic emission, Fermi bubbles template, and dark matter template to float



without a DM template

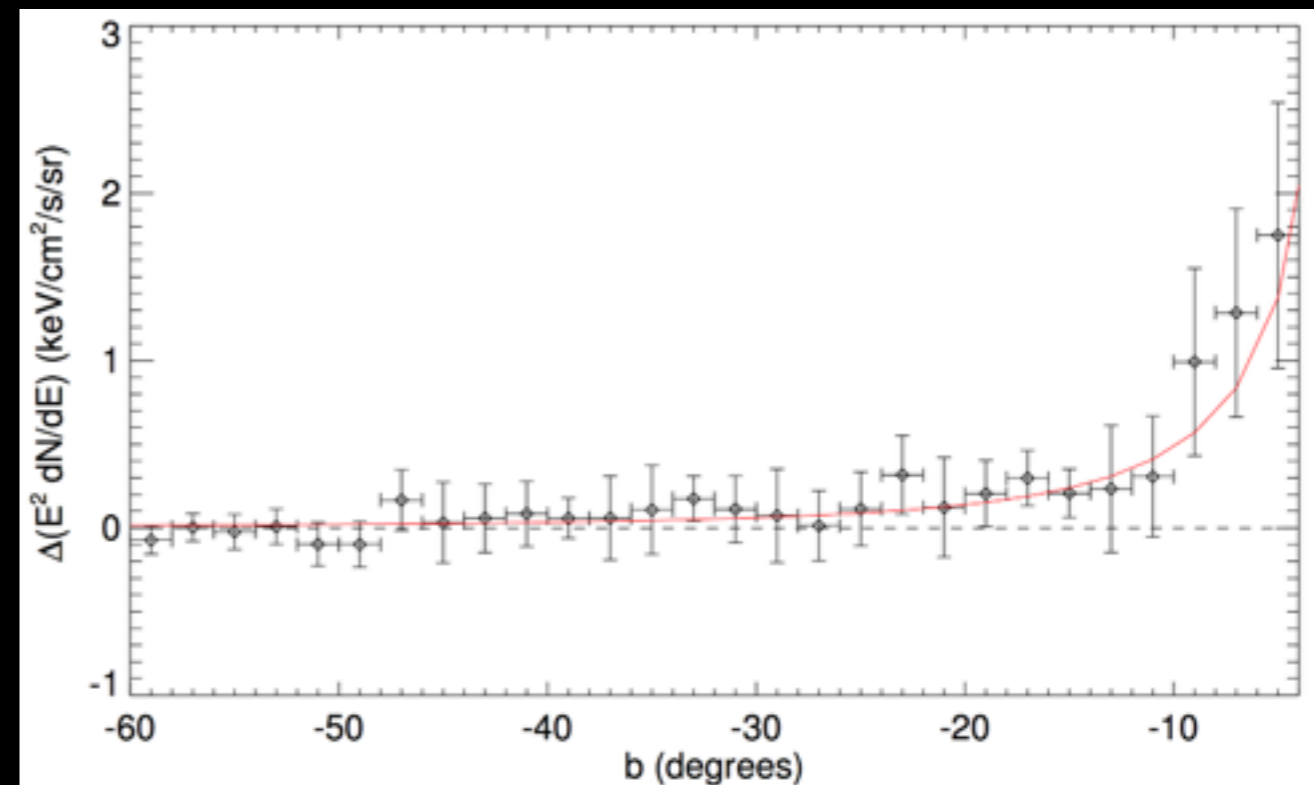
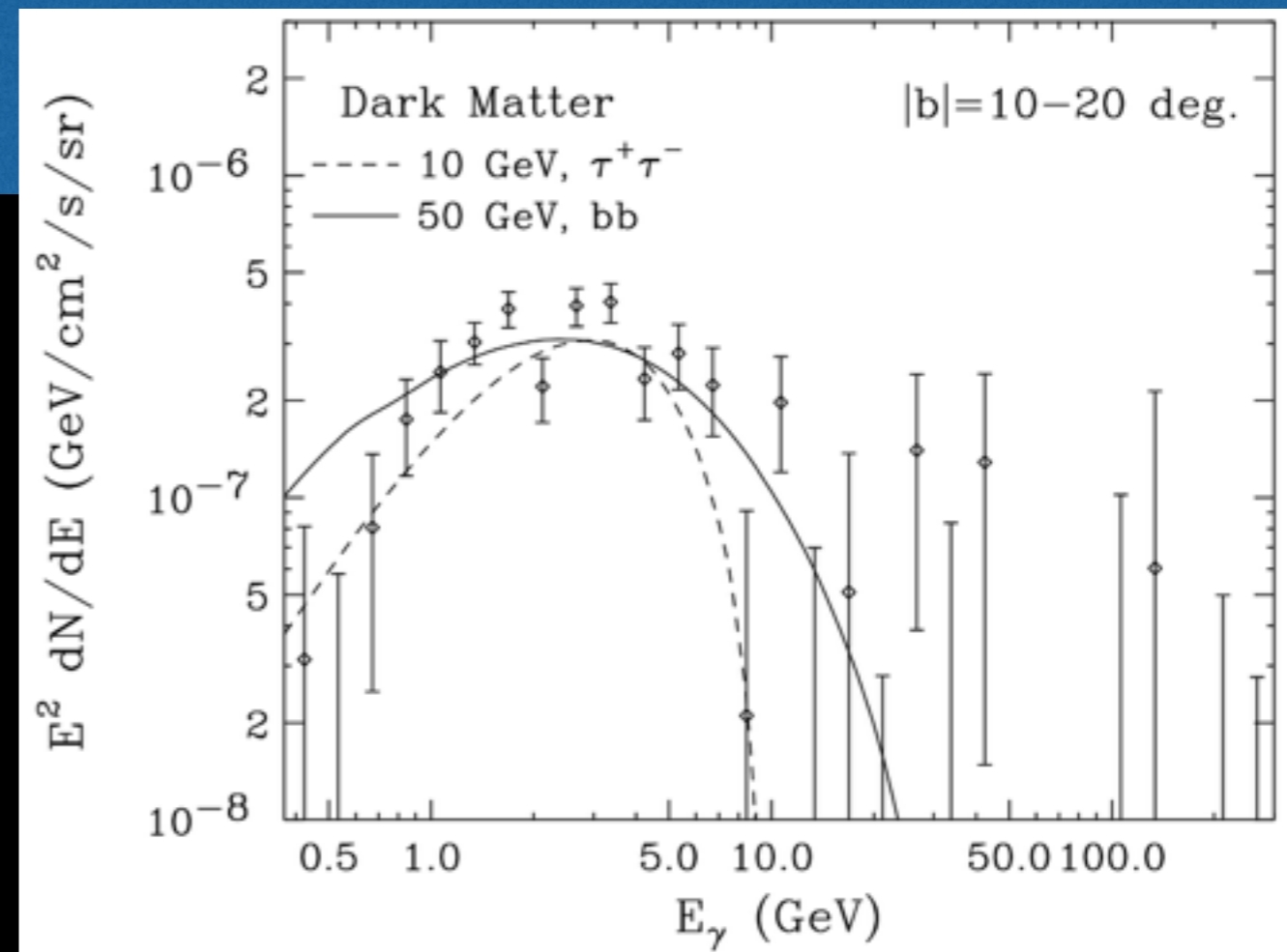
# Previous Efforts

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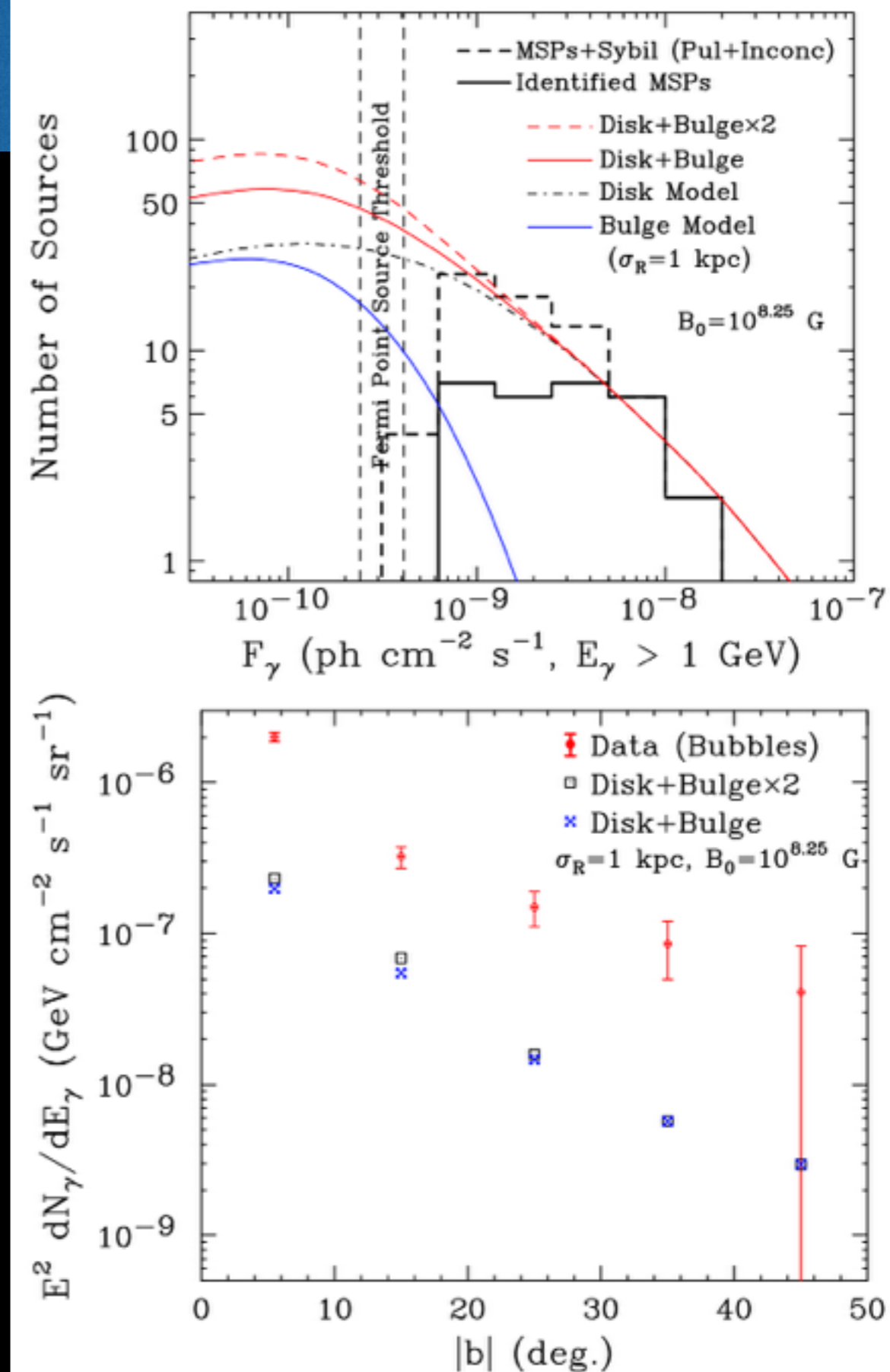
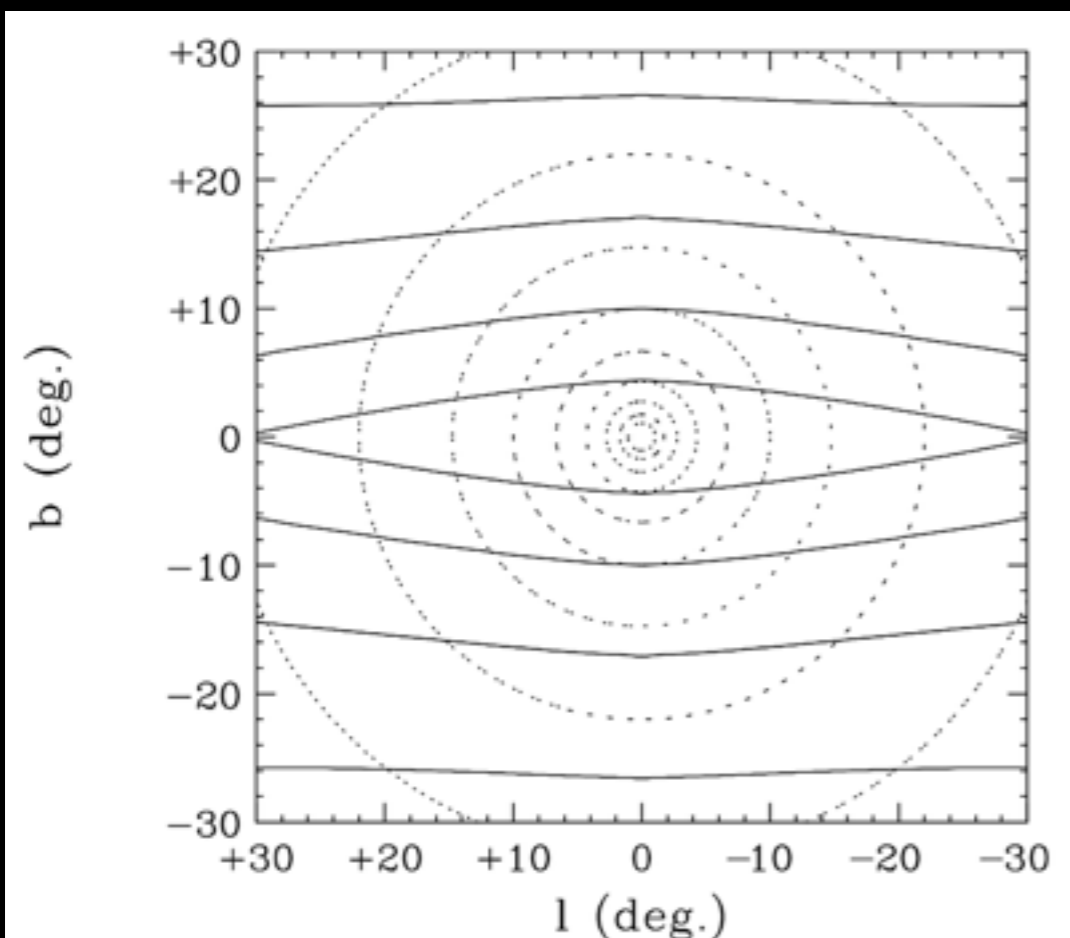


# The Inner Galaxy Analysis

This disfavored pulsar interpretations for two reasons

Pulsars are not expected to be distantly located off the plane

The brightest pulsars from this population should be observed as point sources by the Fermi-LAT

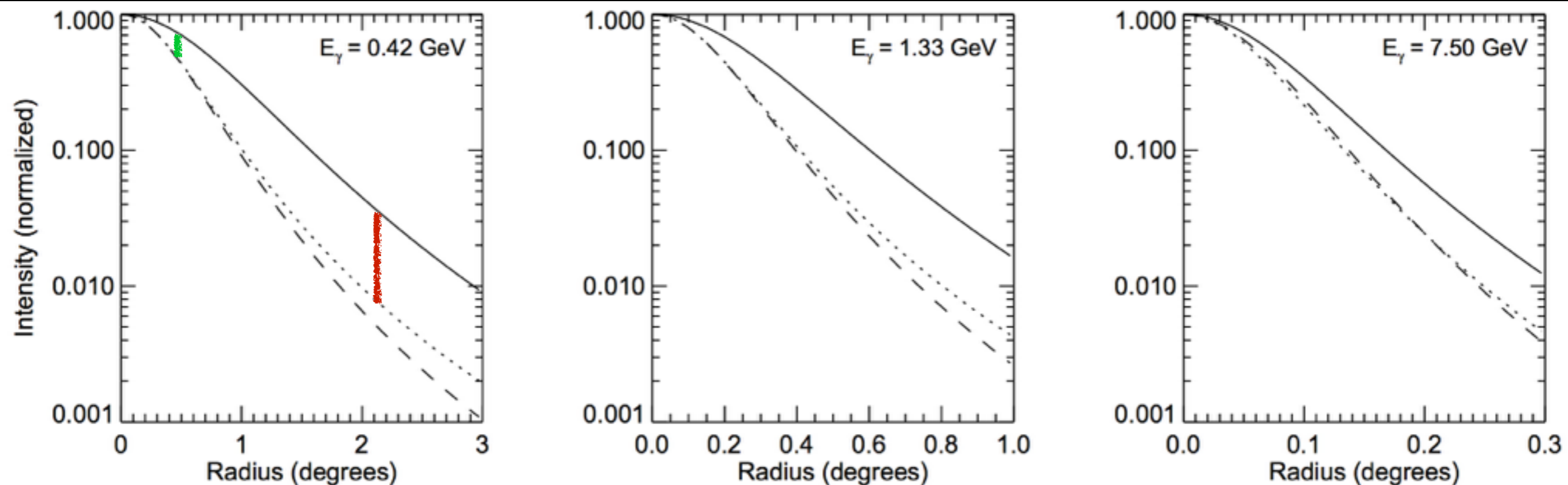




# The Current Paper - Three Objectives

- 1.) Produce a significantly enhanced version of the Fermi dataset, using only photons with the best directional reconstruction
- 2.) Test the compatibility of the excess in the Galactic Center and Inner Galaxy
- 3.) Produce multiple tests of the dark matter interpretation of the data - concentrating on tests which can differentiate a dark matter or pulsar signal

# CTBCORE QUALITY CUTS



- 1.) Each photon observed by the Fermi-LAT has a different uncertainty in the directional reconstruction
- 2.) The Pass 7 analysis includes a parameter, CTBCORE, which indicates how well each individual photon was measured
- 3.) We select only the 50% of photons with the best CTBCORE values, this not only improves the overall PSF, but greatly diminishes the non-Gaussian tails

# Data Selection

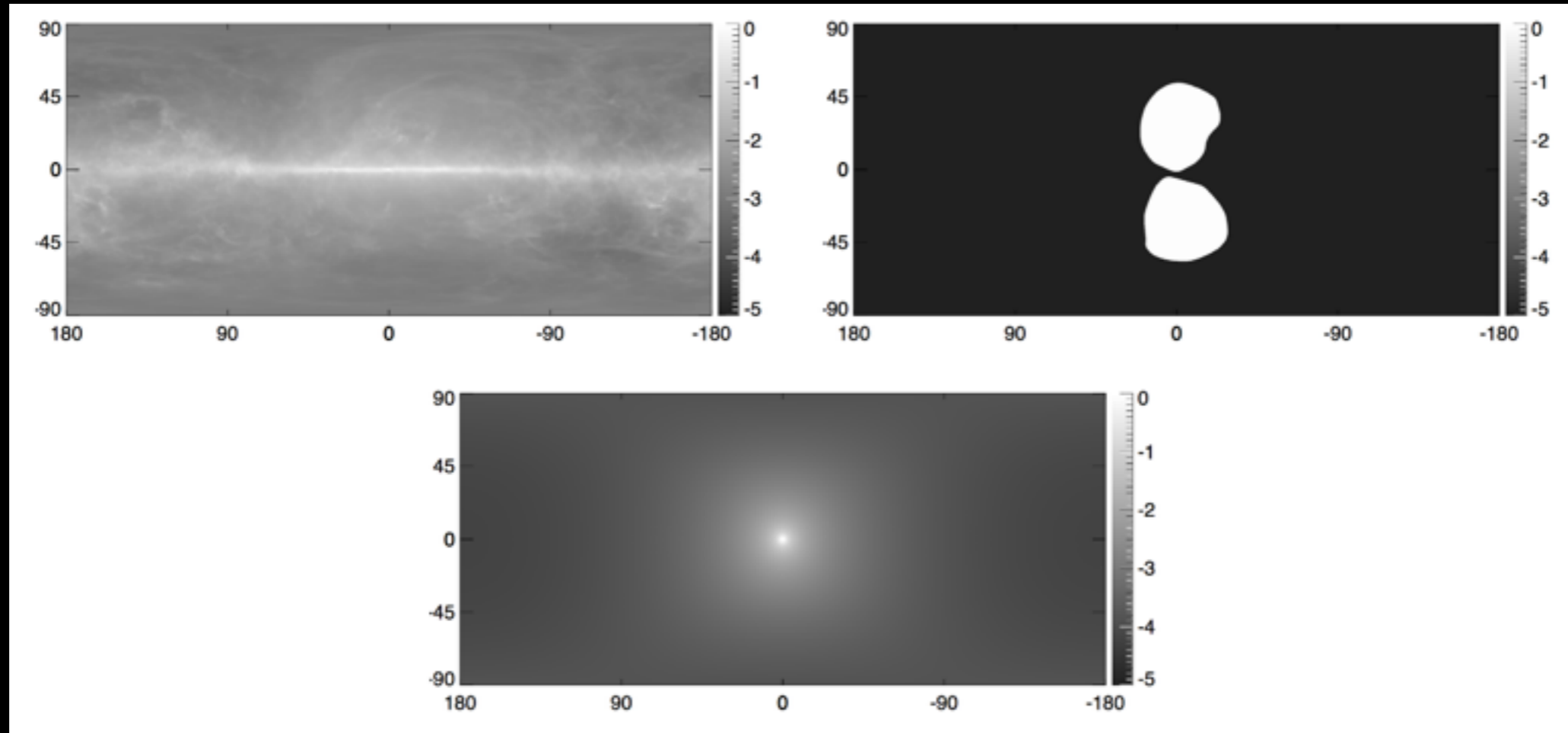
The new CTBCORE cut is applied to two different selections of the Fermi-LAT data

Inner Galaxy -  $|b| > 1^\circ$

Galactic Center -  $|| < 5^\circ |b| < 5^\circ$

The inner galaxy excess is also done at  $|b| > 5^\circ$  to remove any dependence between the different analyses

# The Inner Galaxy Excess



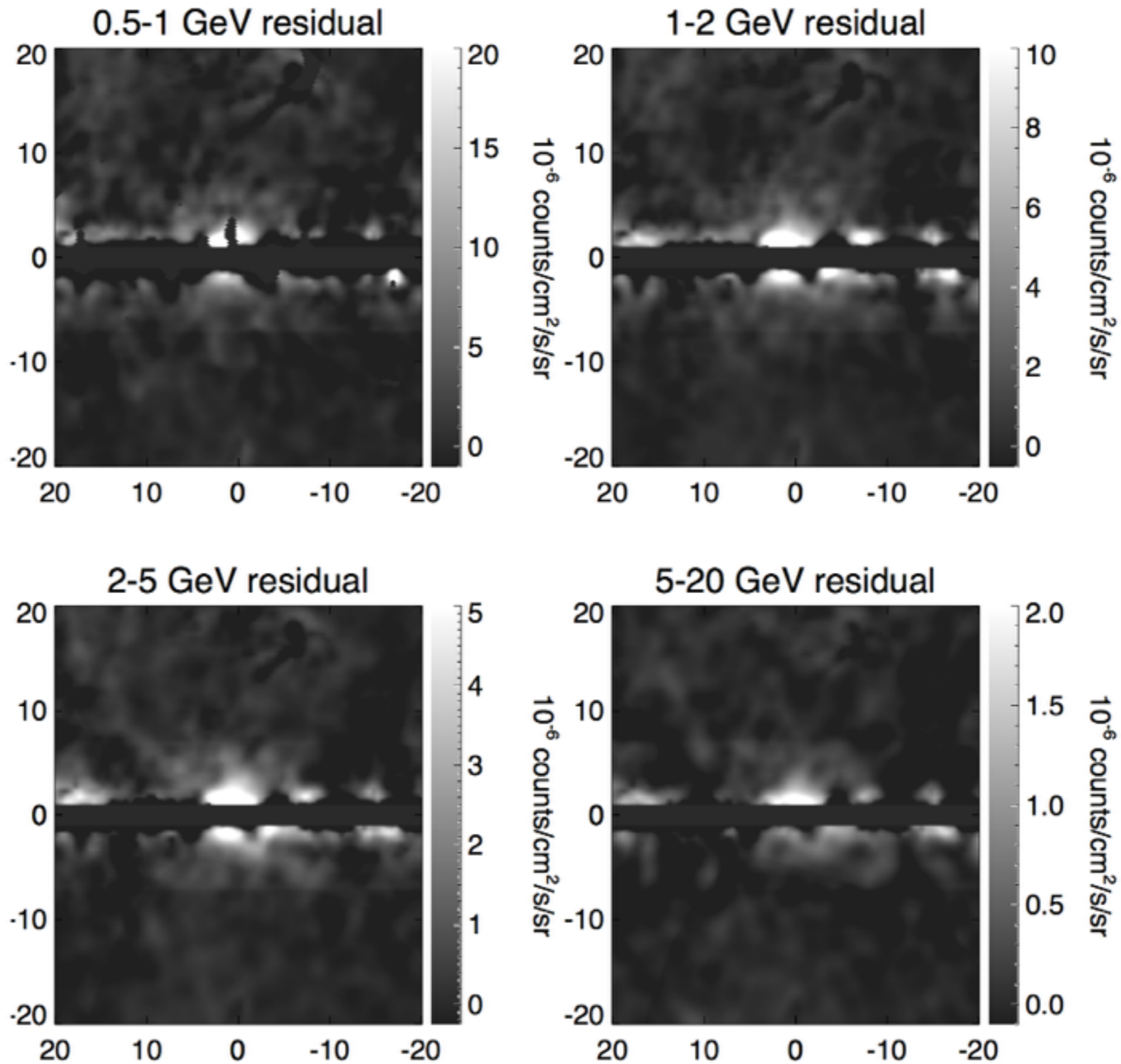
- 1.) Mask  $|b| < 1^\circ$ , and a  $2^\circ$  radius around all 1FGL sources
- 2.) Employ models for the diffuse emission, isotropic emission, Fermi bubbles, and a dark matter component
- 3.) Allow the normalization of each component to float in 25 different energy bins, from 300 MeV - 100 GeV



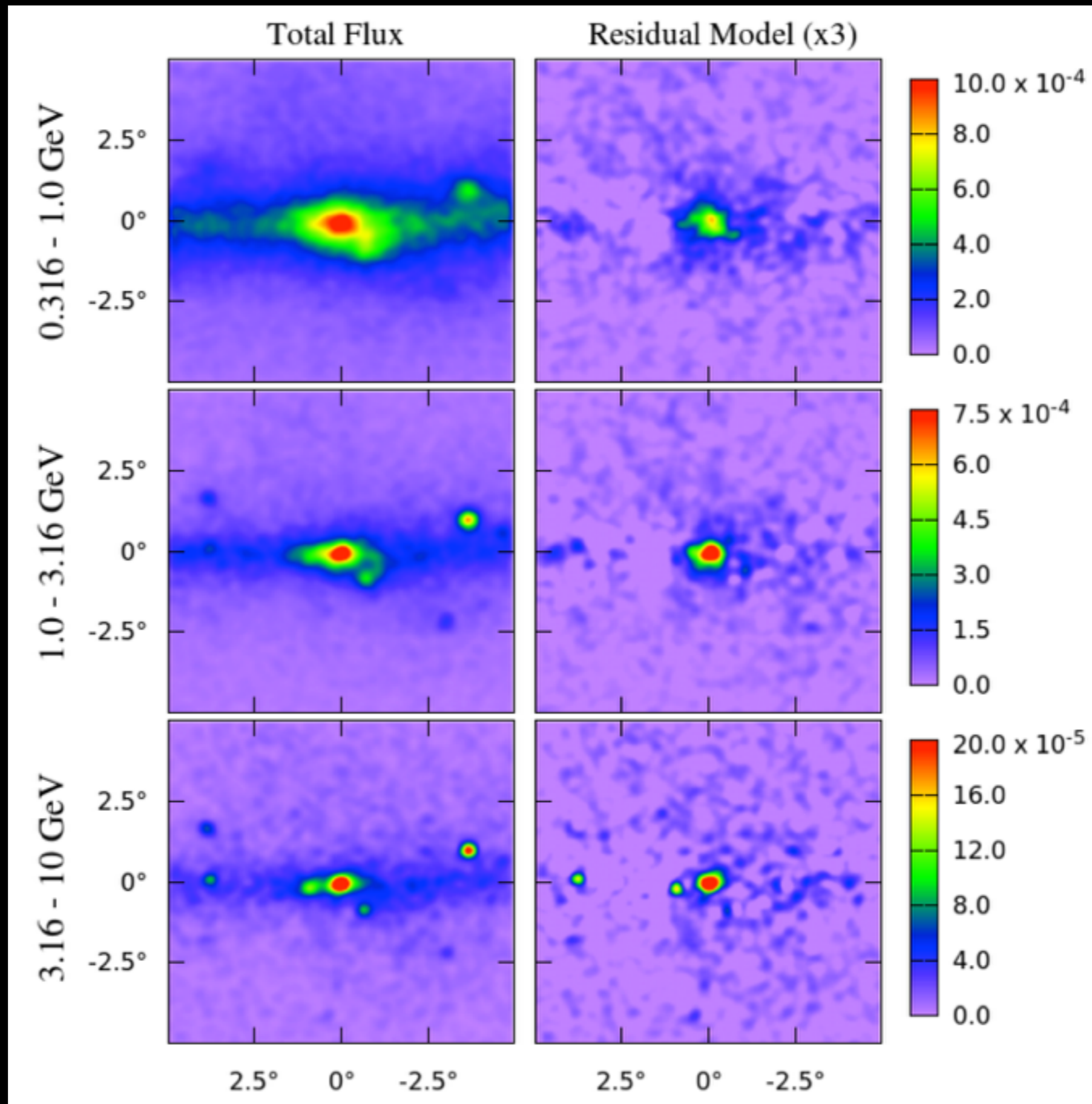
# Galactic Center Modeling

- 1.) Instead model the inner  $|| < 5^\circ$ ,  $|b| < 5^\circ$
- 2.) Must include all point sources in the model - along with models for the diffuse emission, isotropic emission, 20cm map
- 3.) In order to obtain the best fitting model, we allow the normalizations and spectra of multiple sources to vary, using the Fermi tool *gtlike* (and the MINUIT algorithm) to determine the best model for each component (same as previous works)

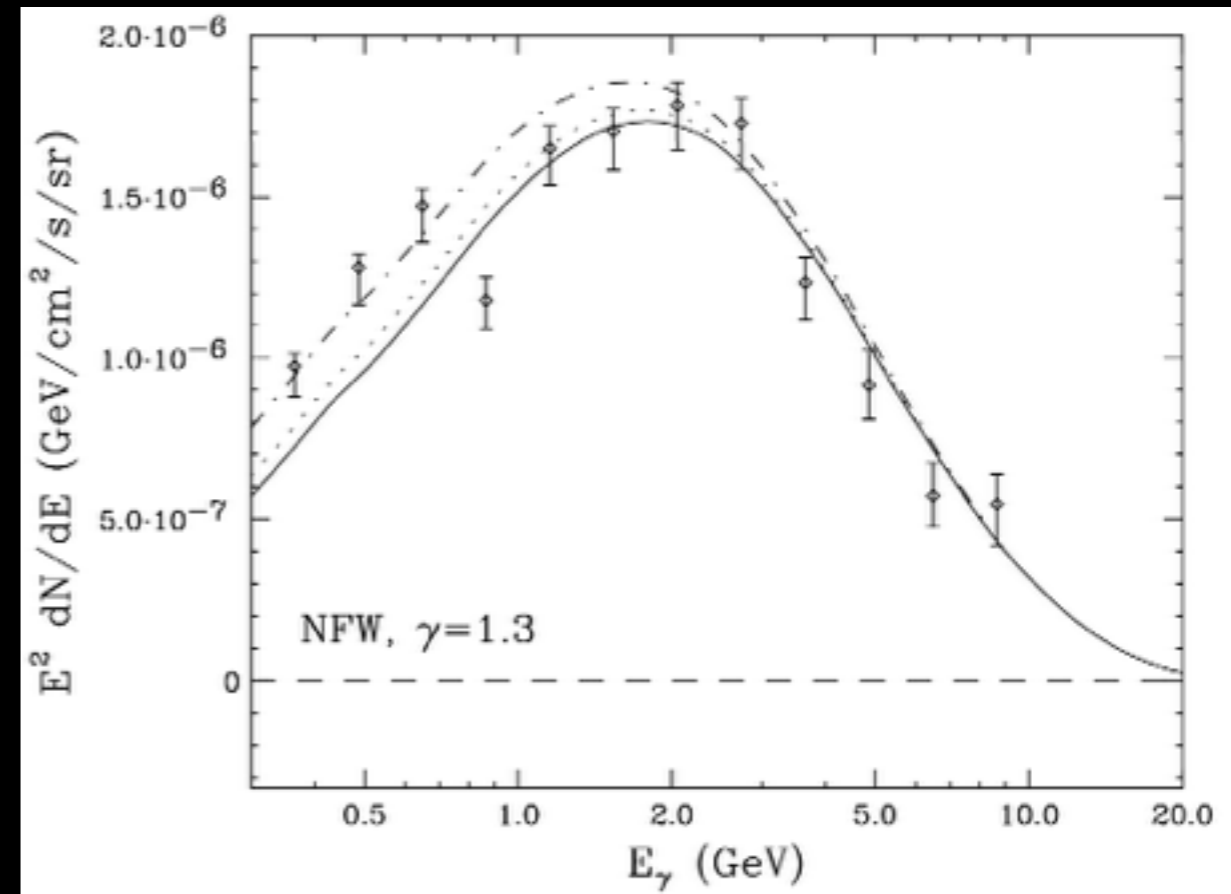
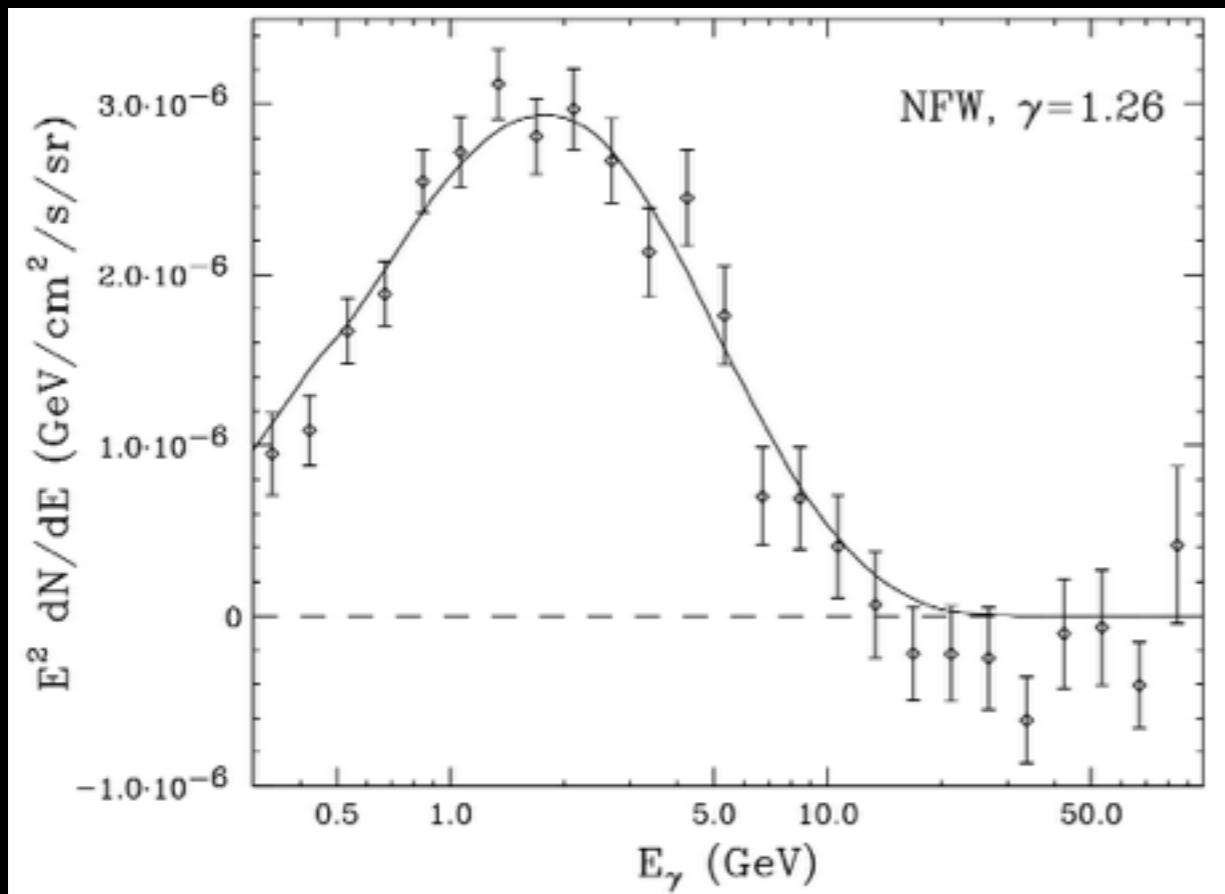
# Skymaps of the Residuals



# Skymaps of the Residuals



# Spectrum of the Residuals



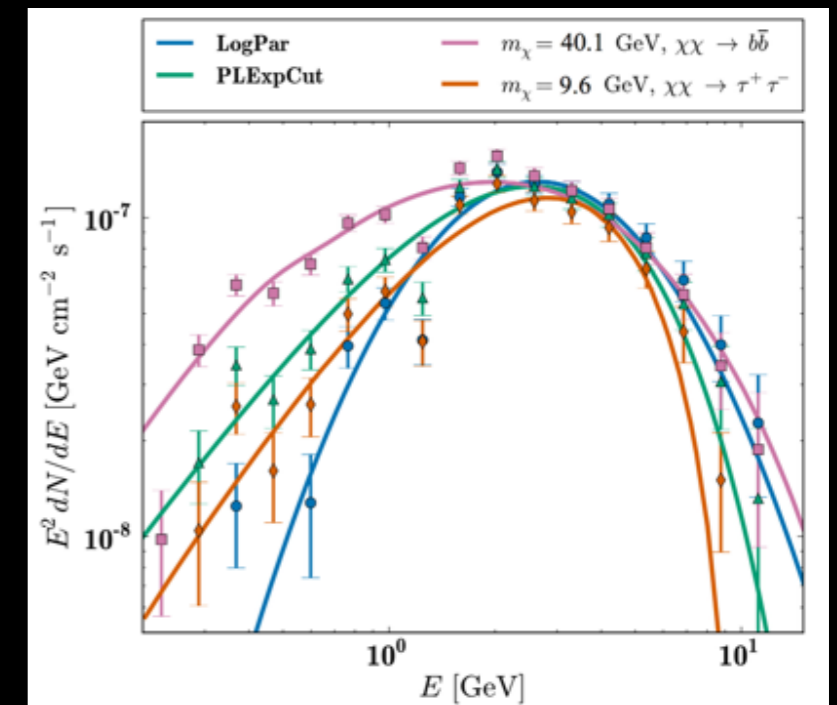
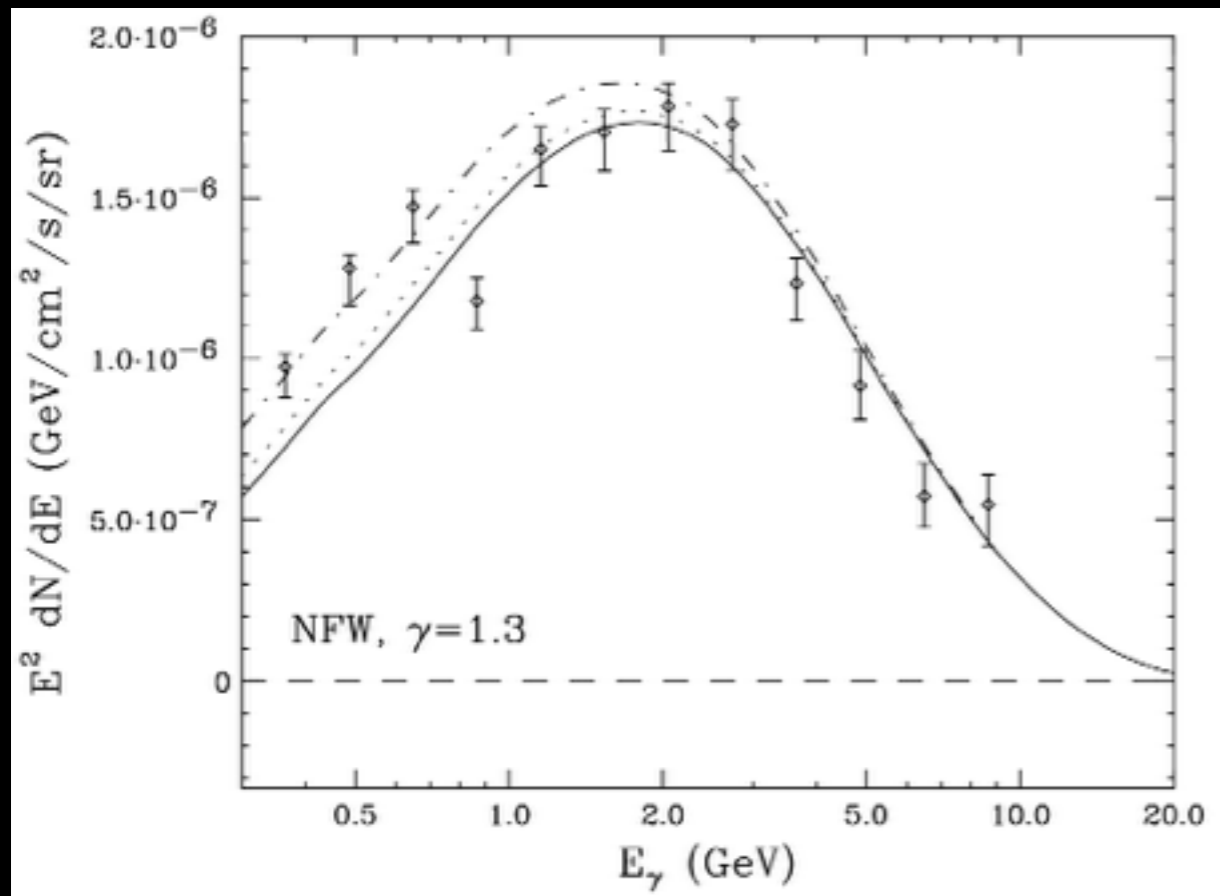
**Inner Galaxy** - The DM template naturally picks up the following spectral shape - the normalization of the NFW template is allowed to float independently in every energy bin

**Galactic Center** - Various initial seeds for the dark matter spectrum, the best fit spectrum is then calculated and fed back into the fitting algorithm, the process is repeated iteratively until a best fit solution is reached. We find the final spectrum to be independent of the initial seed.



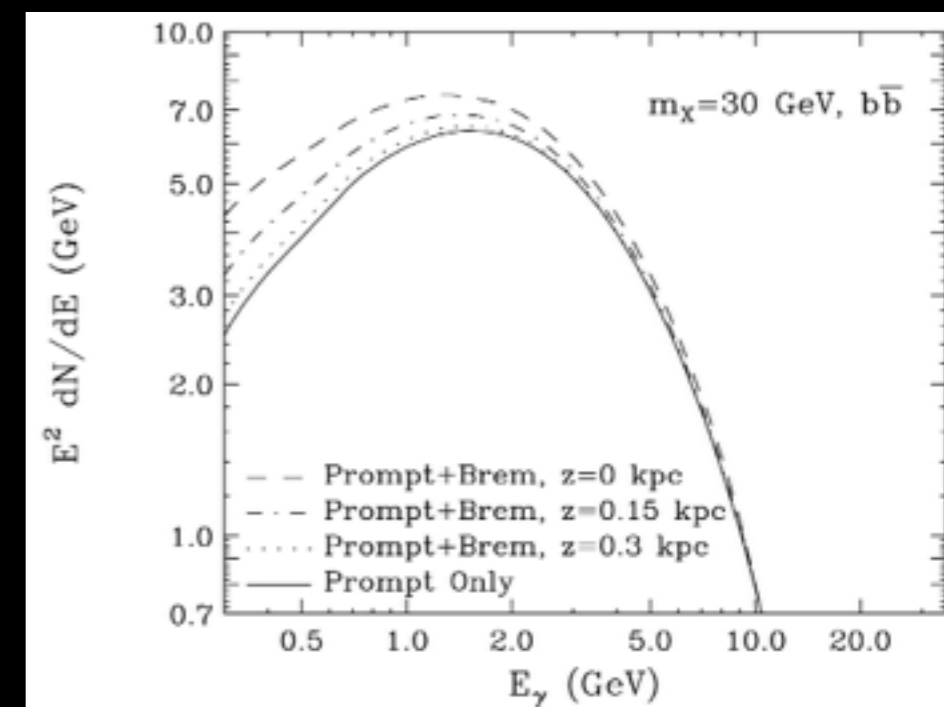
# Spectrum of the Residuals

The residual spectra are almost identical, except for some variation below 1 GeV. This could be explained by either measurement or theory:

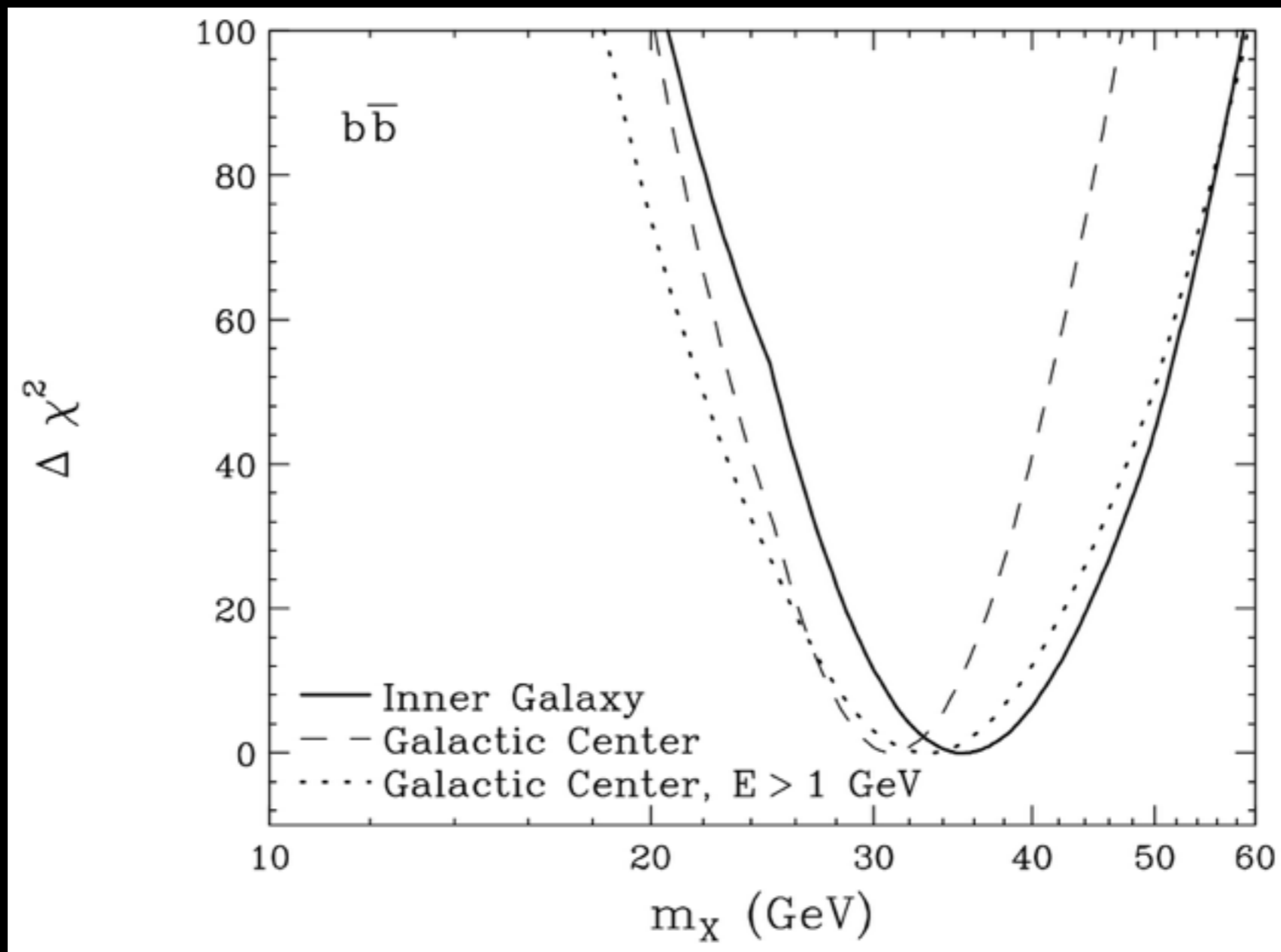


Measurement - The poor PSF of the Fermi-LAT (even with CTBCORE cuts) makes it difficult to distinguish between emission from the many point sources and diffuse emission templates in the GC.

Theory - Any dark matter annihilation (or generally any process which produces  $\gamma$ -rays) will also produce  $e^+e^-$  pairs which produce bremsstrahlung emission close to the galactic center

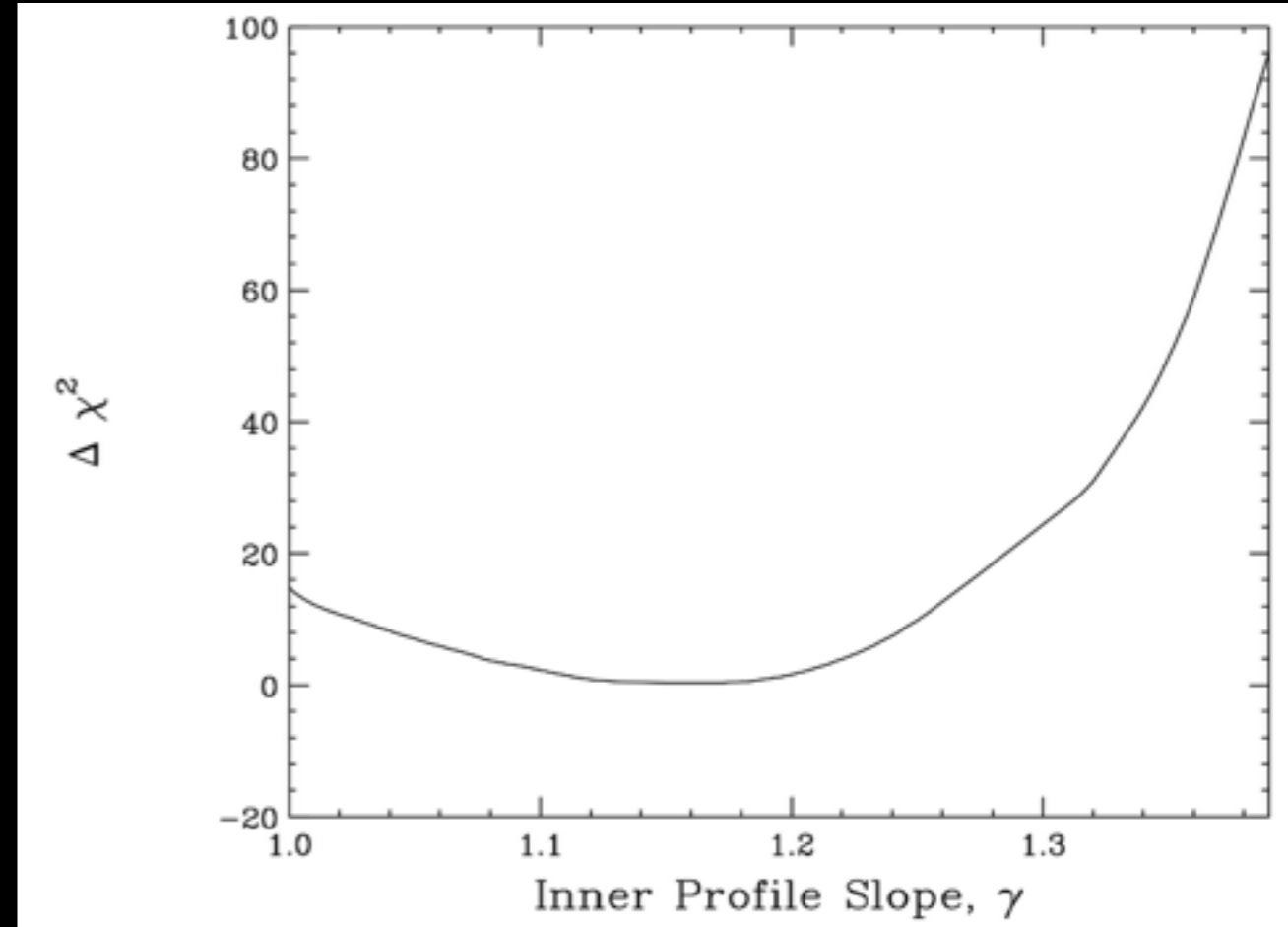
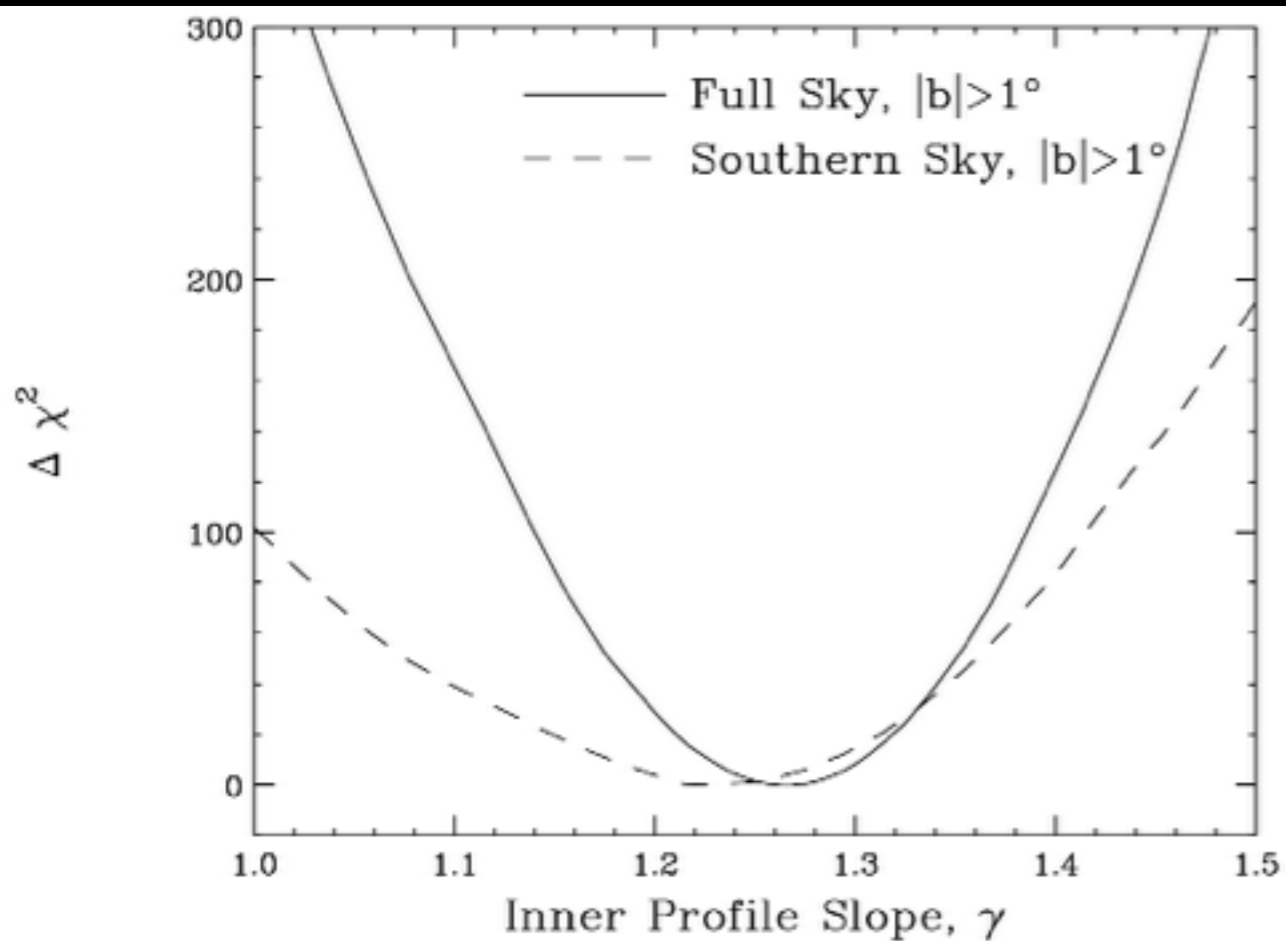


# Spectrum of the Residuals



Still, these changes are very minor. The best fit dark matter model for the Galactic Center and Inner Galaxy Excesses are nearly identical

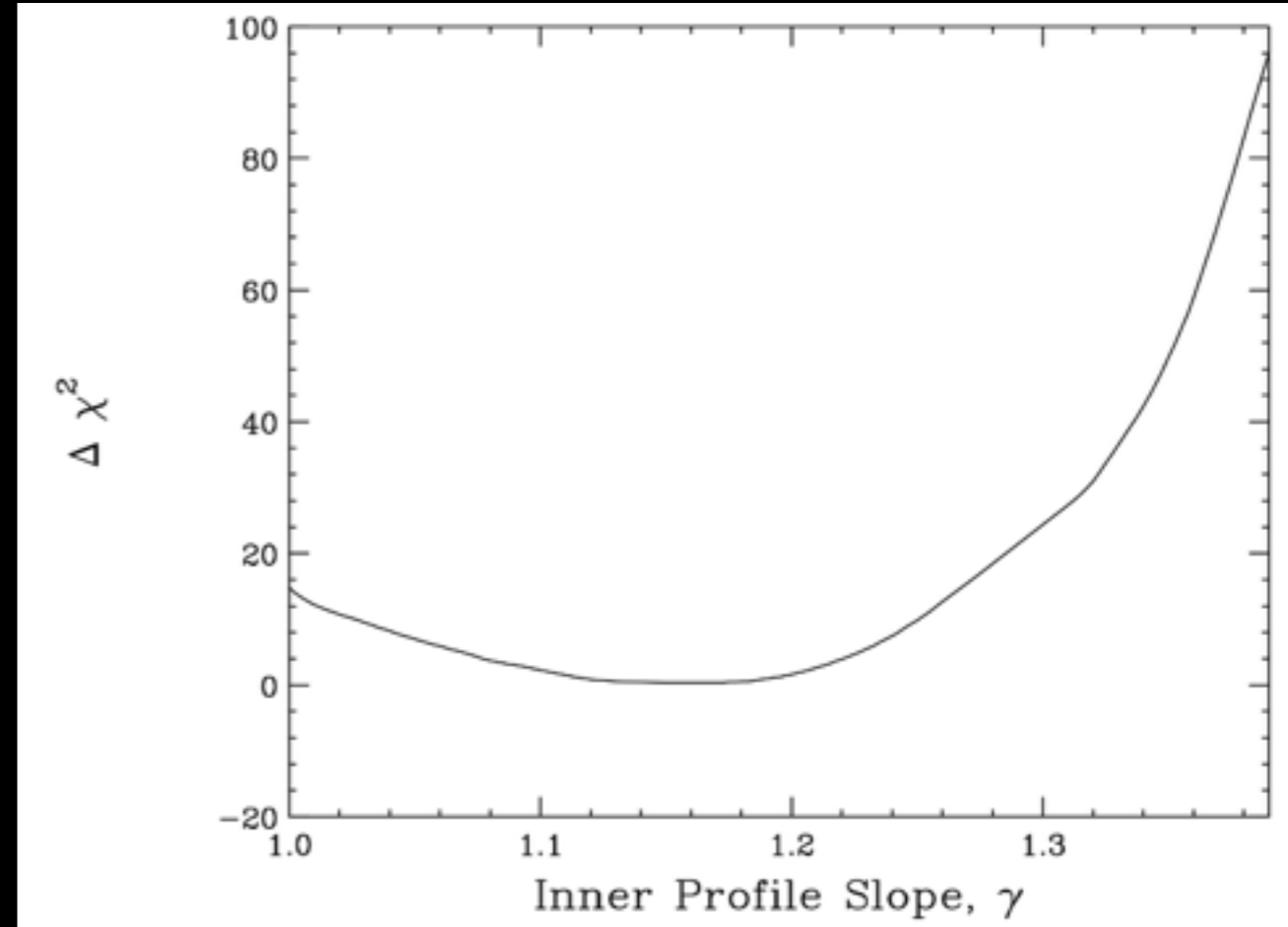
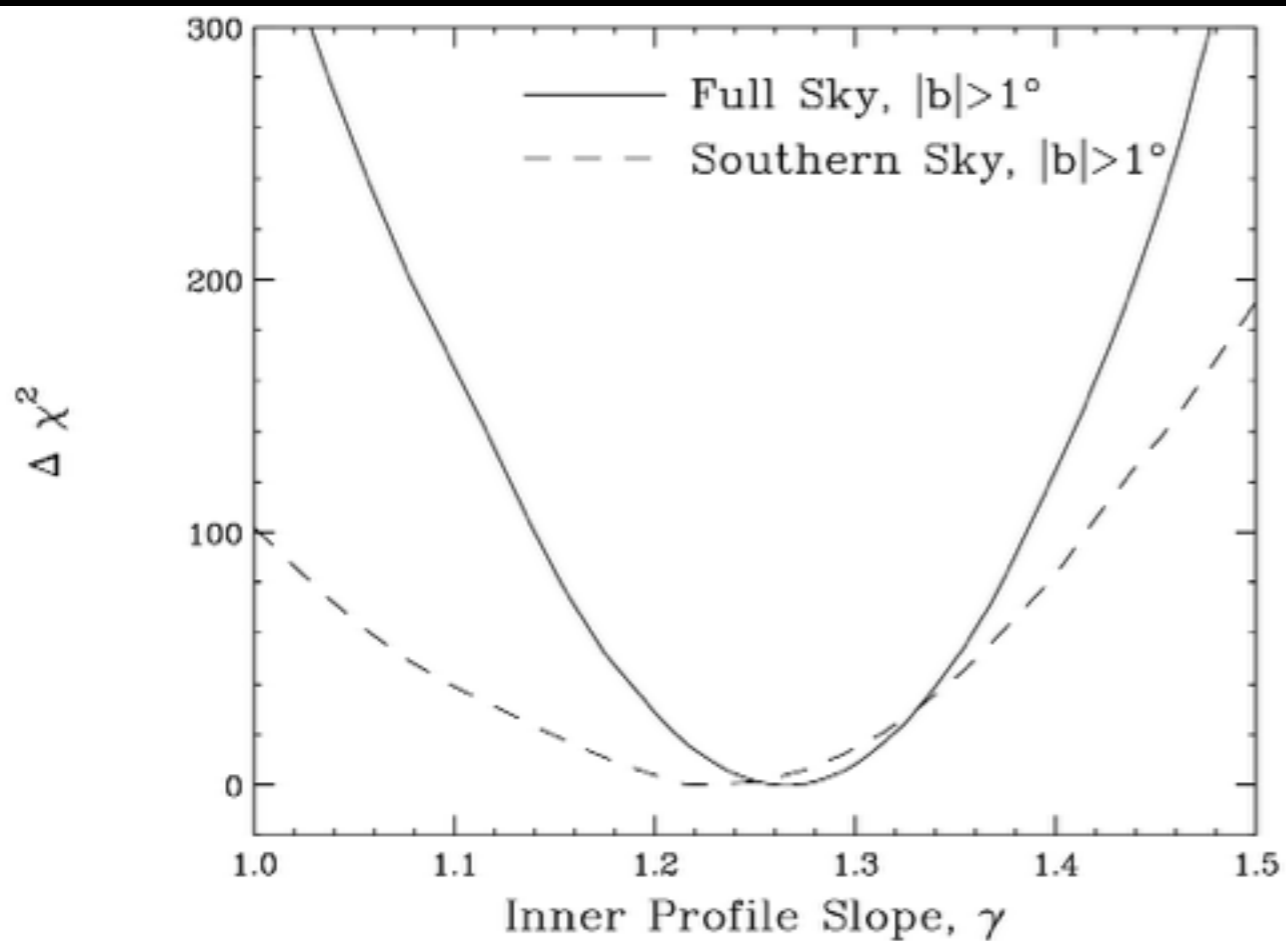
# The Morphology of the Gamma-Ray Excess



Inner Galaxy - The best fit is given by a generalized NFW profile with  $\gamma=1.26$ . The Southern sky has a consistent fit to the spectrum of the full sky.

Galactic Center - The best fit is given by  $\gamma=1.17$ .

# The Morphology of the Gamma-Ray Excess

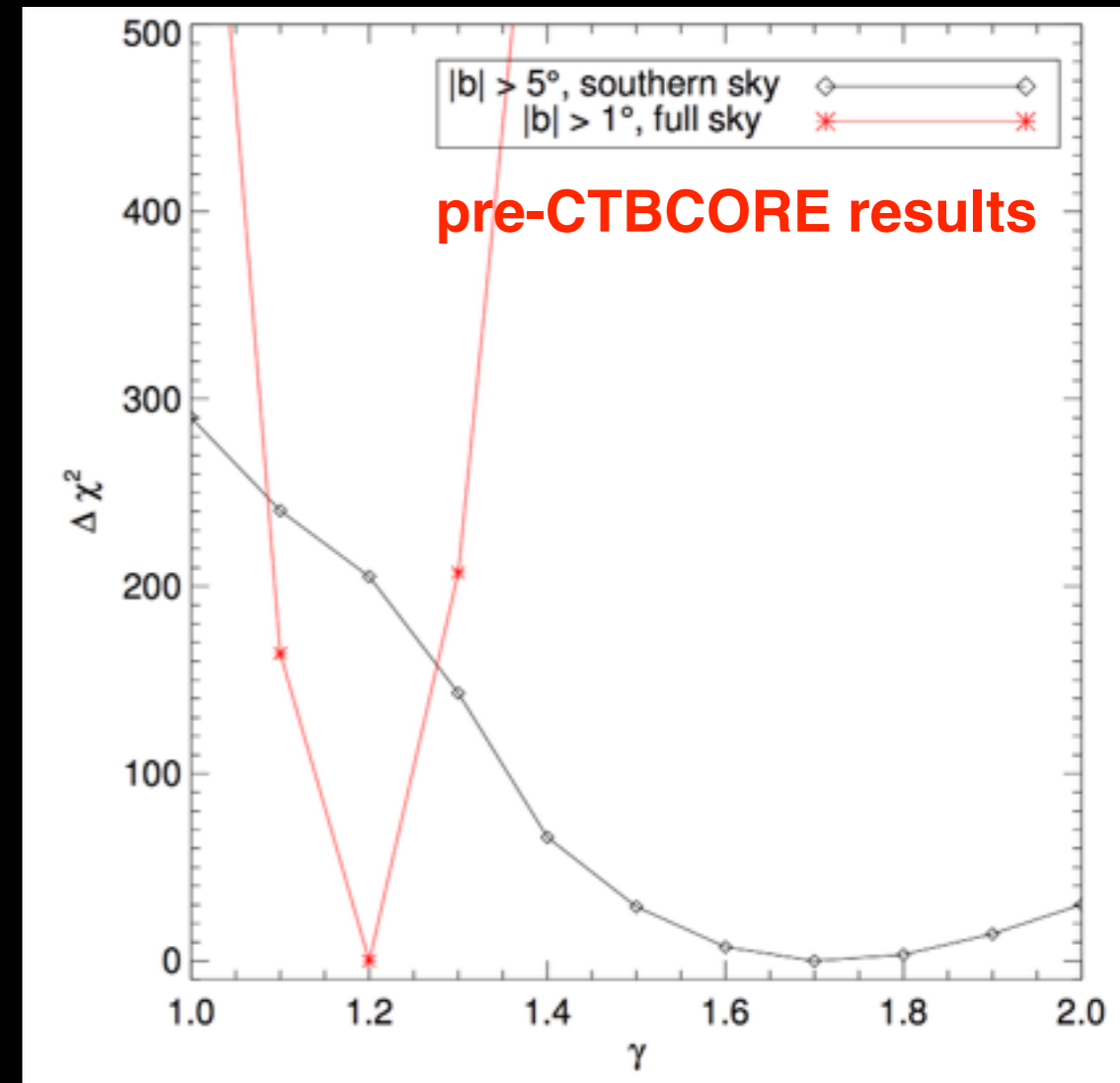
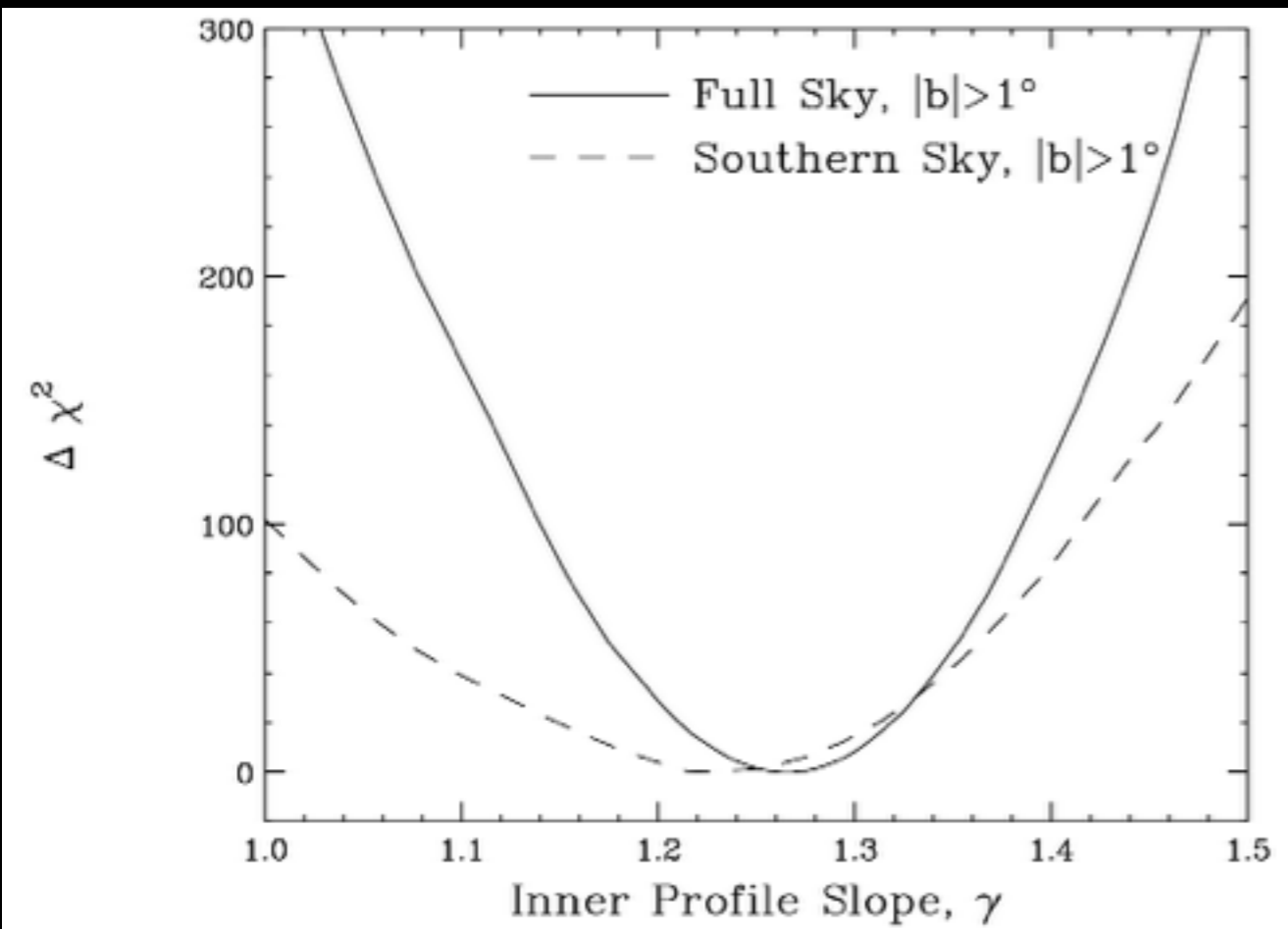


First, it is worth noting that the fit of  $\gamma=1.26$  is not strongly rejected by the Galactic center data.

Secondly, the value of  $\gamma$  depends sensitively on the interaction between the dark matter profile and the dominant gravitational potential (due to baryons). It is completely reasonable that the value of  $\gamma$  may shift slightly as a function of galactocentric radius



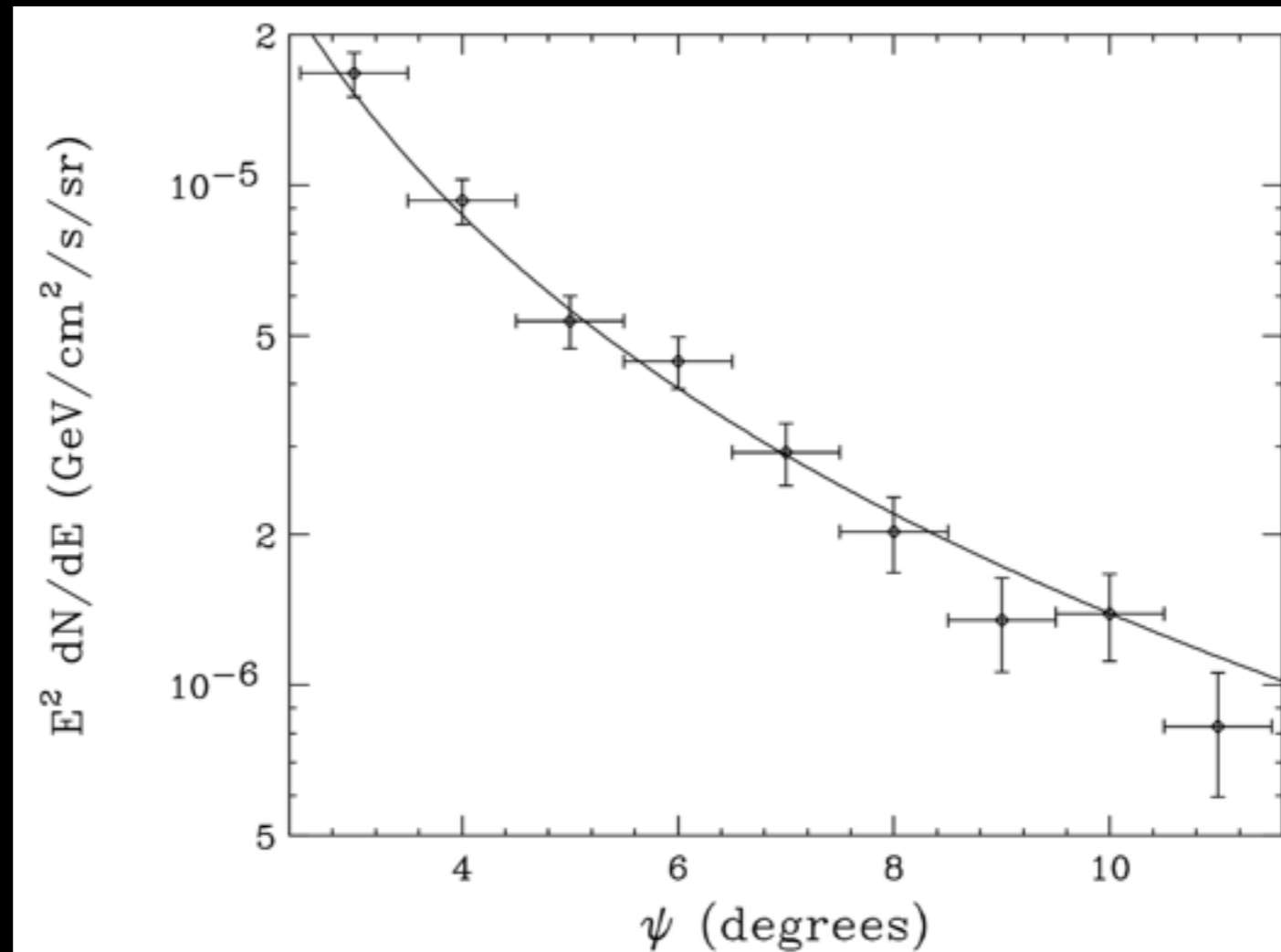
# The Morphology of the Gamma-Ray Excess



Hooper & Slatyer (2013)

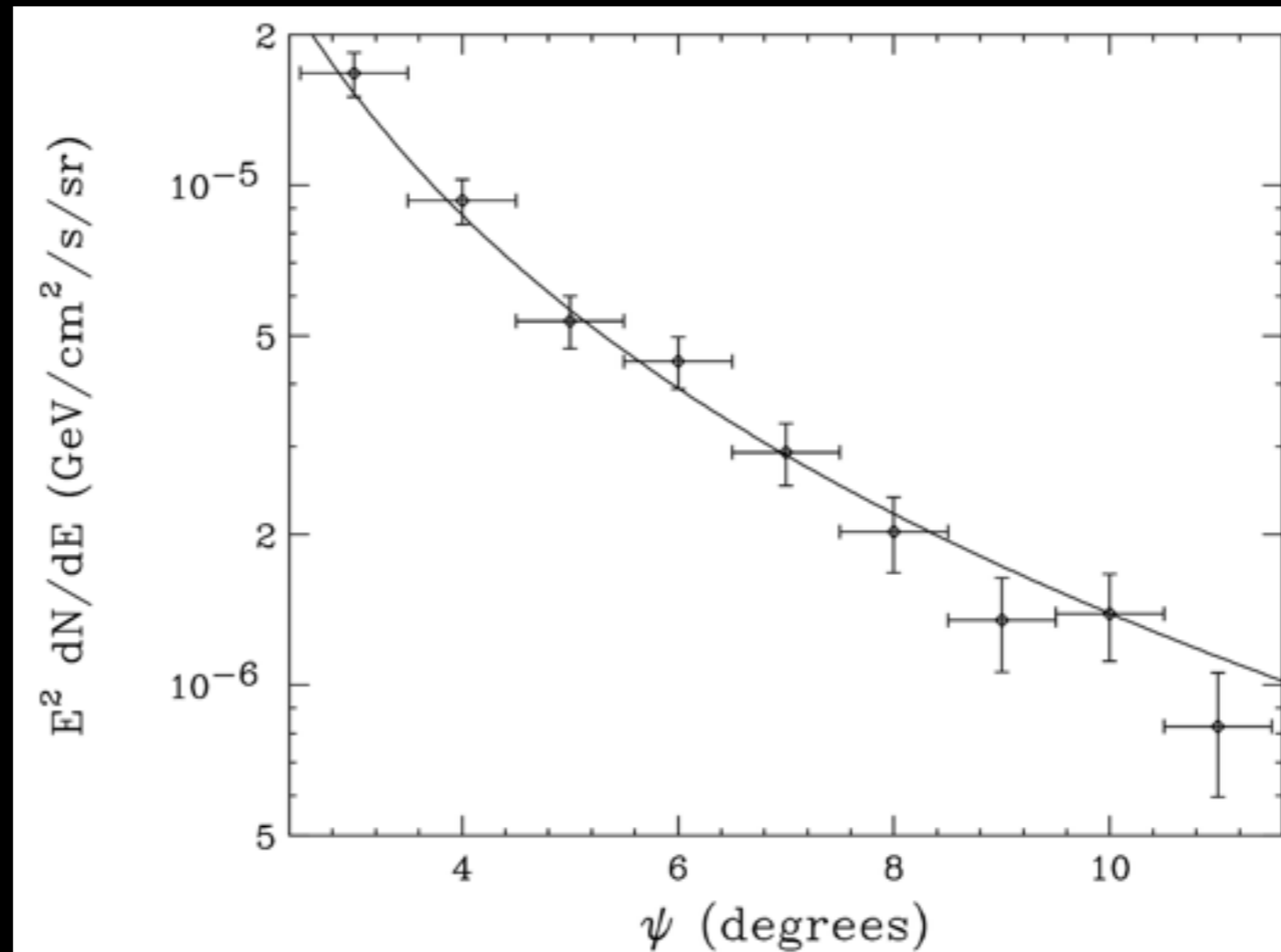
Third, it's worth noting how much the usage of CTBCORE improves our models of the data. Previous to our CTBCORE fits, the value of  $\gamma$  was highly sensitive to our choice of ROI

# The Morphology of the Gamma-Ray Excess



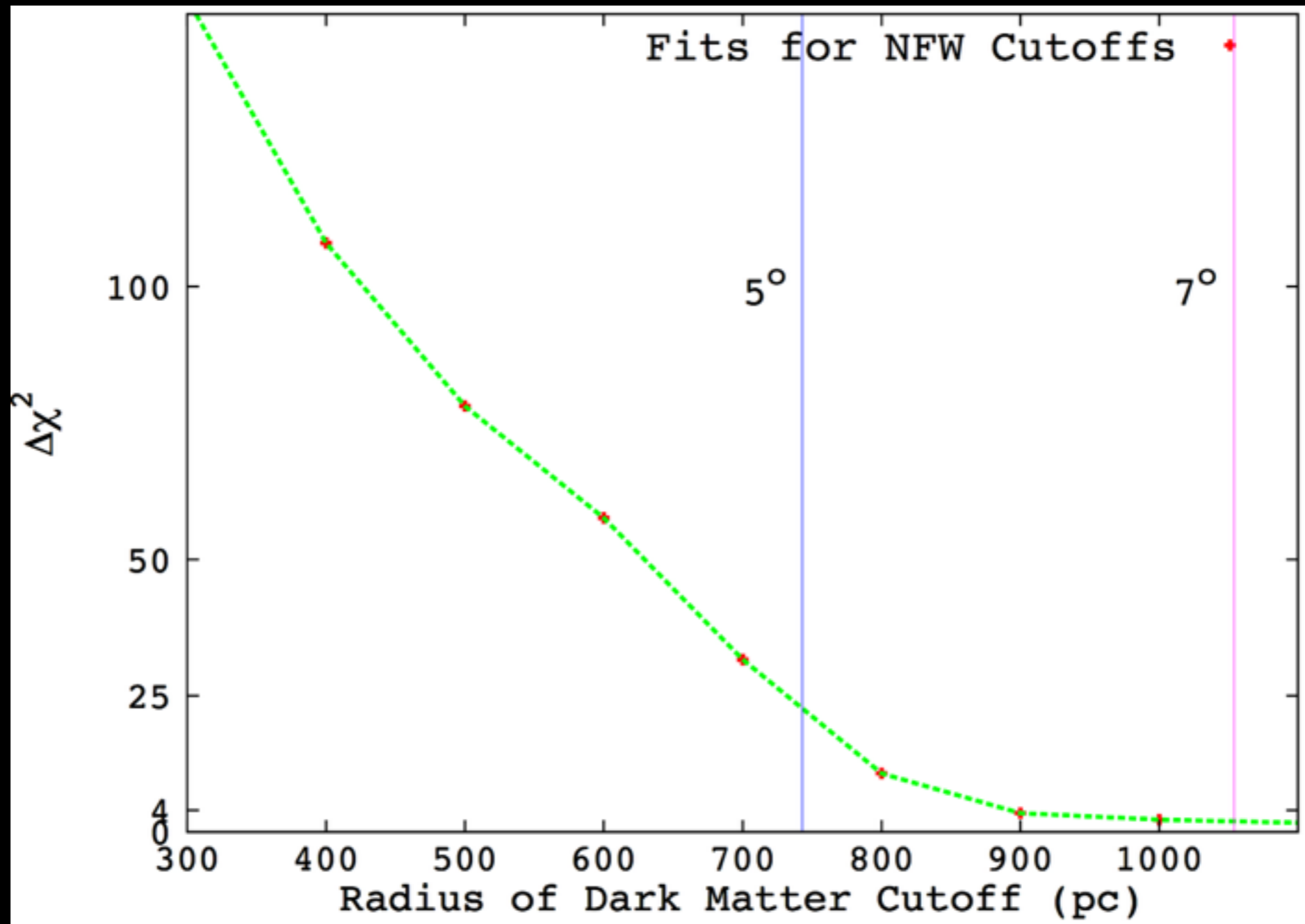
We can instead fix the spectrum of the Inner Galaxy excess, and allow the normalization to float in  $1^\circ$  angular bins. We find the residual to be statistically significant out to  $12^\circ$  from the Galactic Center. Following a slightly steeper profile (at high latitudes) of  $\gamma = 1.4$ .

# The Morphology of the Gamma-Ray Excess



This may again be due to the interaction of the dark matter density profile with baryons, or may be due to measurement effects — since large scale features far from the Galactic Center may be partially absorbed into the data-driven galactic diffuse model

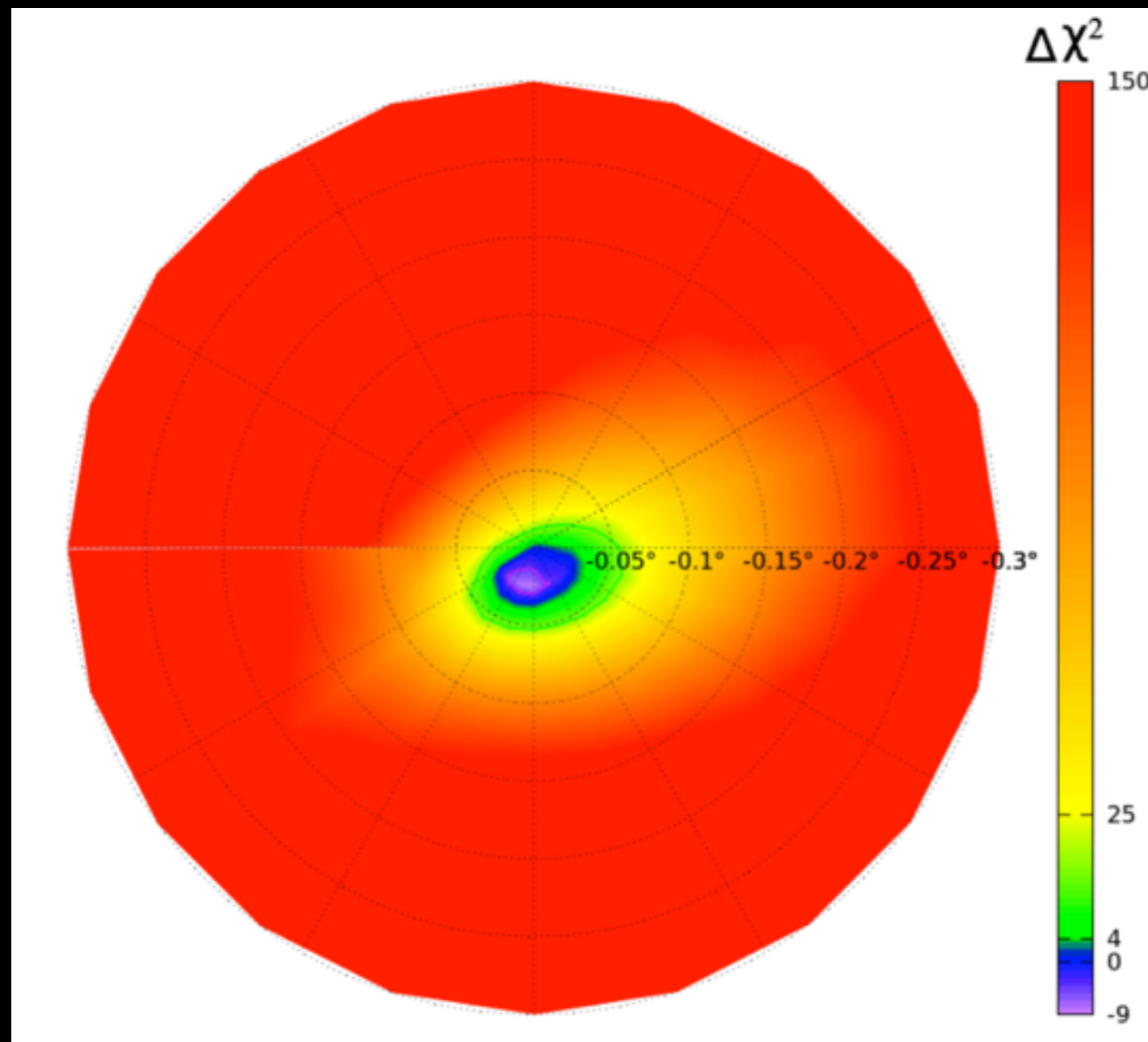
# The Morphology of the Gamma-Ray Excess



**Galactic Center Model:** We can ask a similar question, by investigating if the data prefers a NFW profile that is cut off at various radii from the position of the Galactic Center. The data prefer that the NFW profile persists throughout the simulation region.

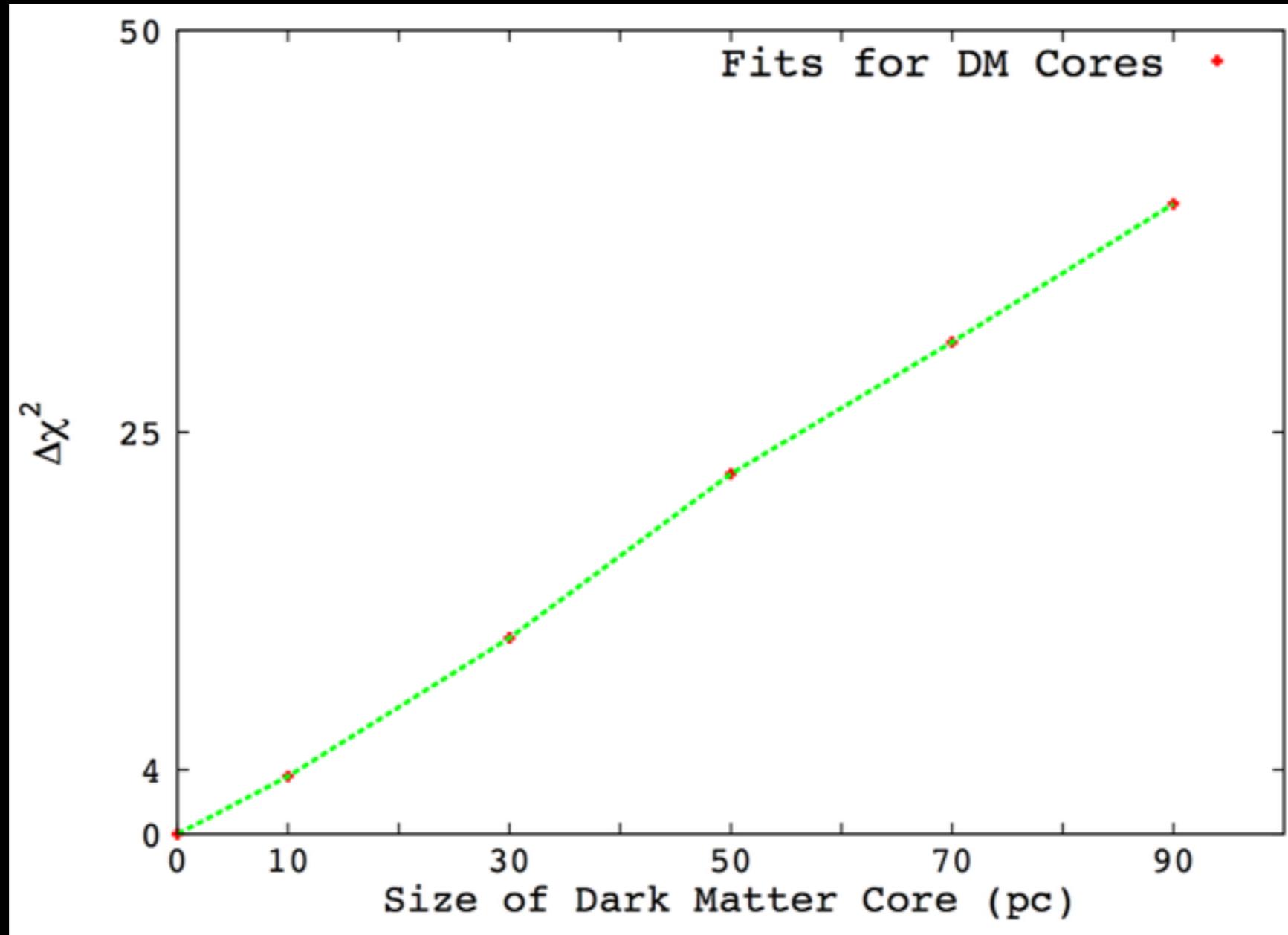


# The Morphology of the Gamma-Ray Excess



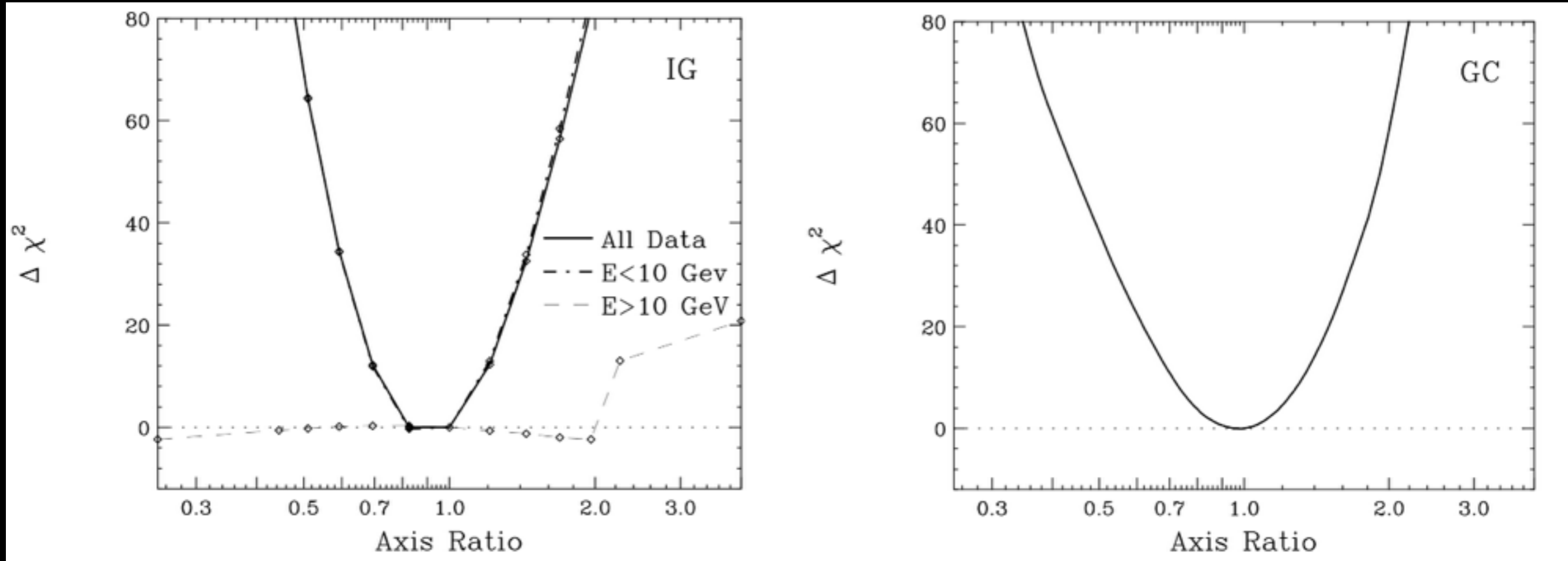
**Galactic Center Model:** We can test models where the DM profile is spatially offset from the true position of the Galactic Center. We find the data to prefer a NFW profile centered on the position of Sgr A\* to within  $0.05^\circ$

# The Morphology of the Gamma-Ray Excess



**Galactic Center Model:** We can ask whether the data prefers a core in the dark matter density profile (as advocated in certain models). By testing dark matter profiles with various core sizes, we can reject any core larger than 15 pc at more than  $2\sigma$

# The Morphology of the Gamma-Ray Excess



**Ellipticity:** We can also ask if the data prefer a spherically symmetric profile.

Axis ratios of greater than 20% either along or perpendicular to the galactic plane.

# The Current Paper - Three Objectives

- 1.) Produce a significantly enhanced version of the Fermi dataset, using only photons with the best directional reconstruction
- 2.) Test the compatibility of the excess in the Galactic Center and Inner Galaxy
- 3.) Produce multiple tests of the dark matter interpretation of the data - concentrating on tests which can differentiate a dark matter or pulsar signal



# Interpretations of the Excess

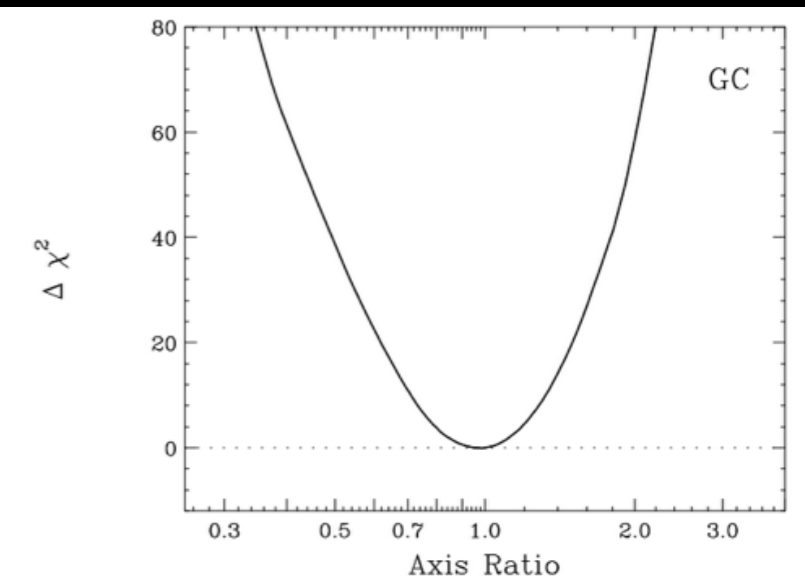
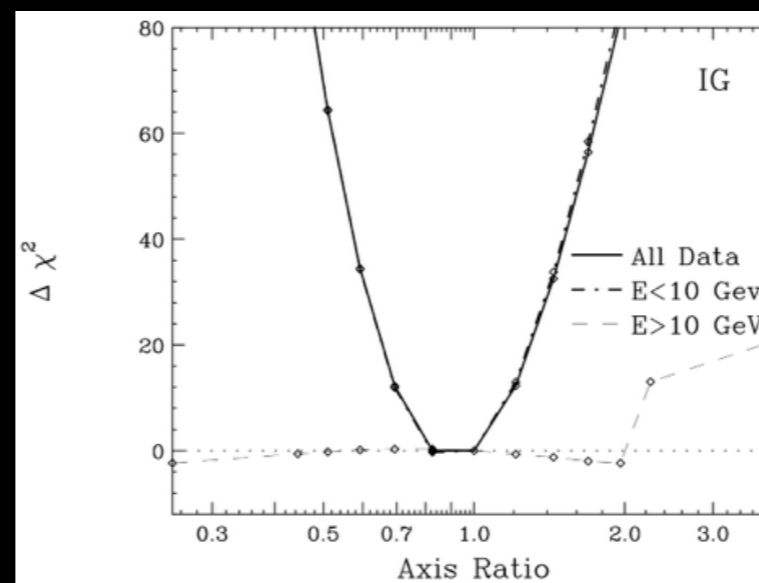
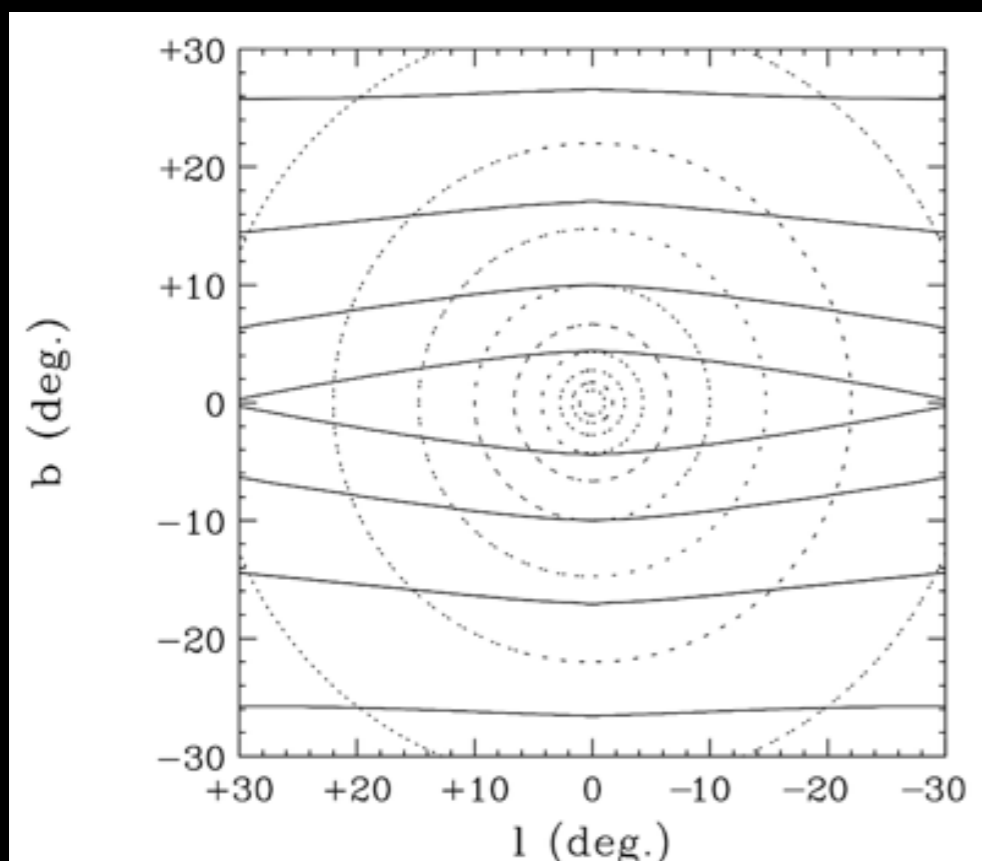
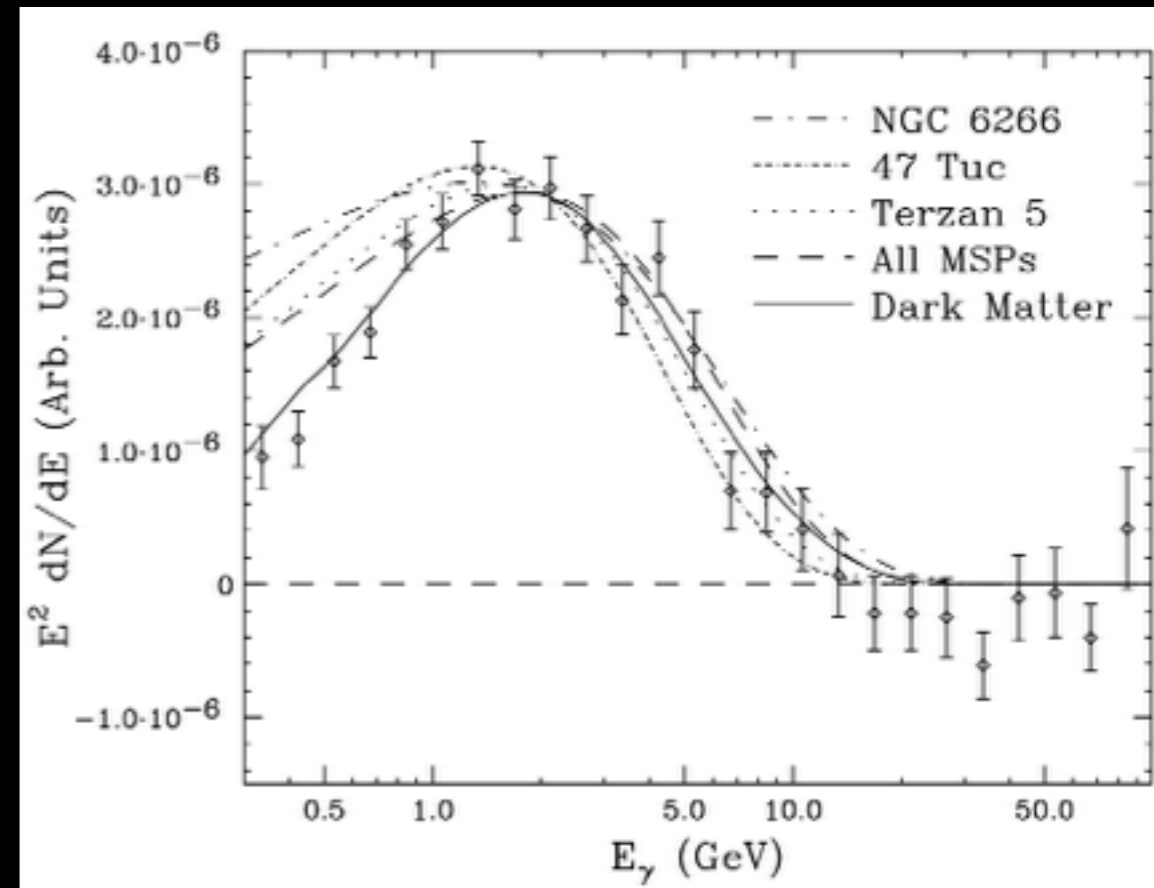
1.) Do the data prefer millisecond pulsars or dark matter annihilation?

2.) How do the data compare to theoretically predicted dark matter models?

# Interpretations of the Excess

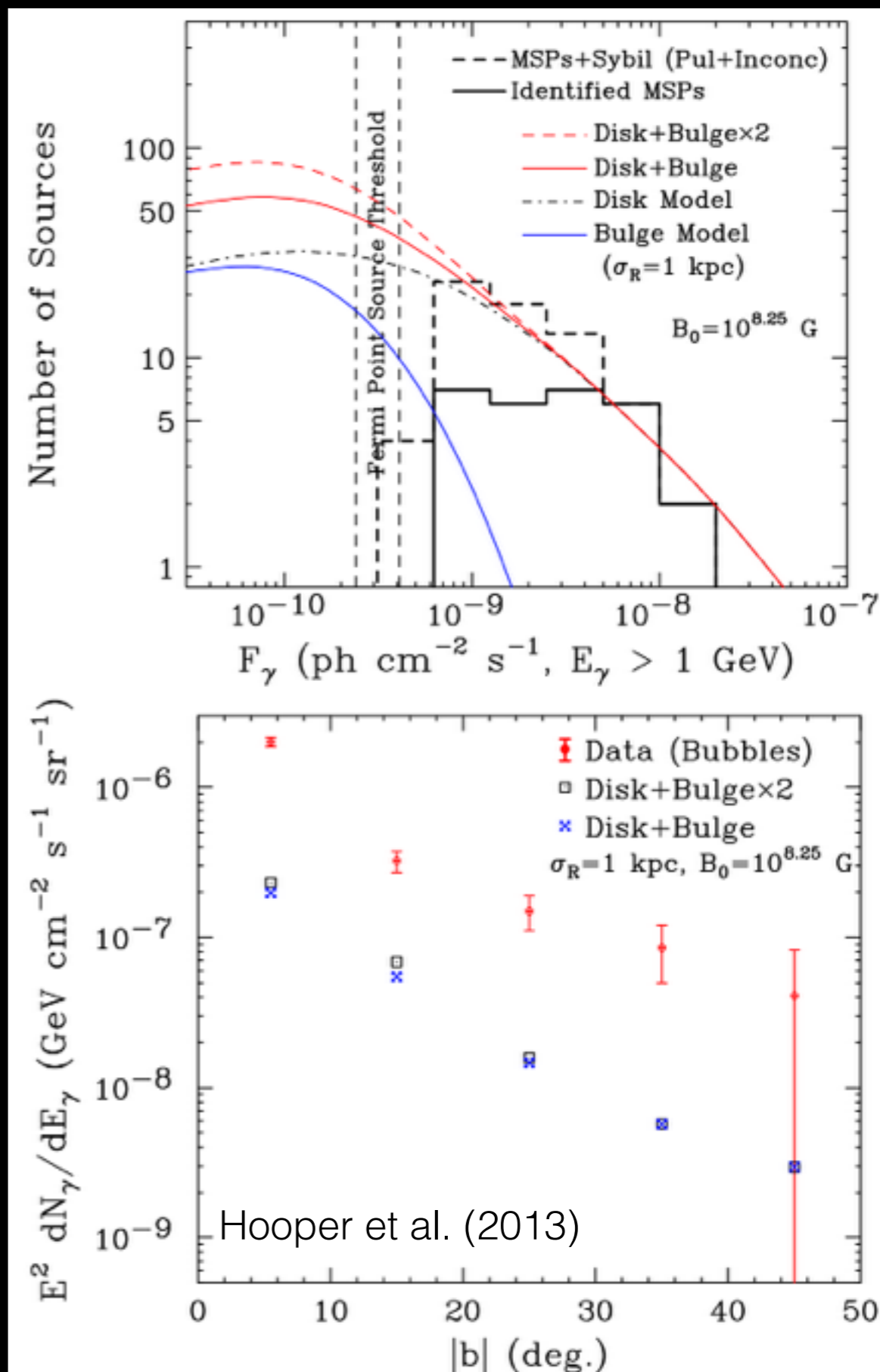
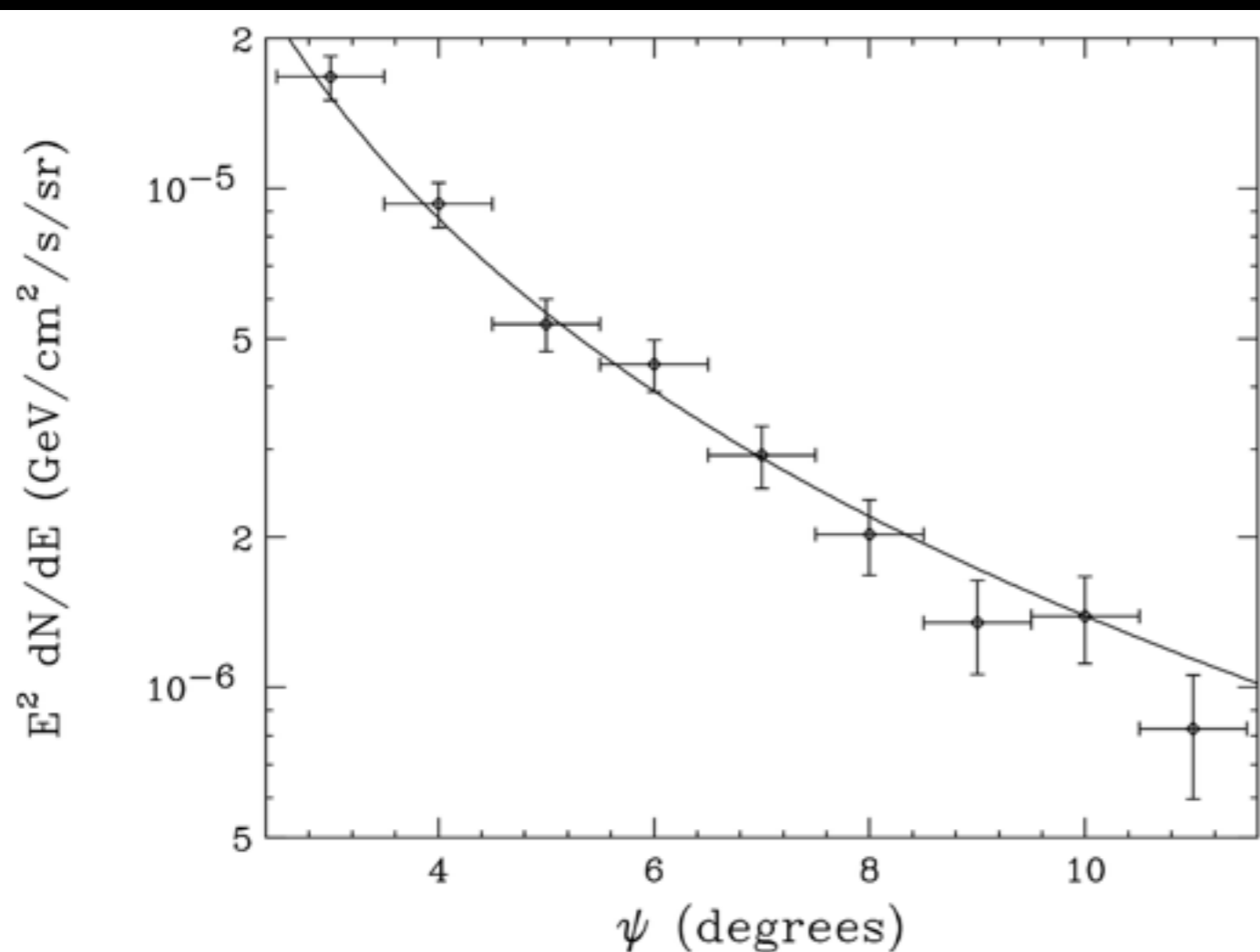
The spectrum of the residual signal in the Inner Galaxy does not look like millisecond pulsars

The spherical symmetry of the fit is hard to reconcile with models of MSP emission

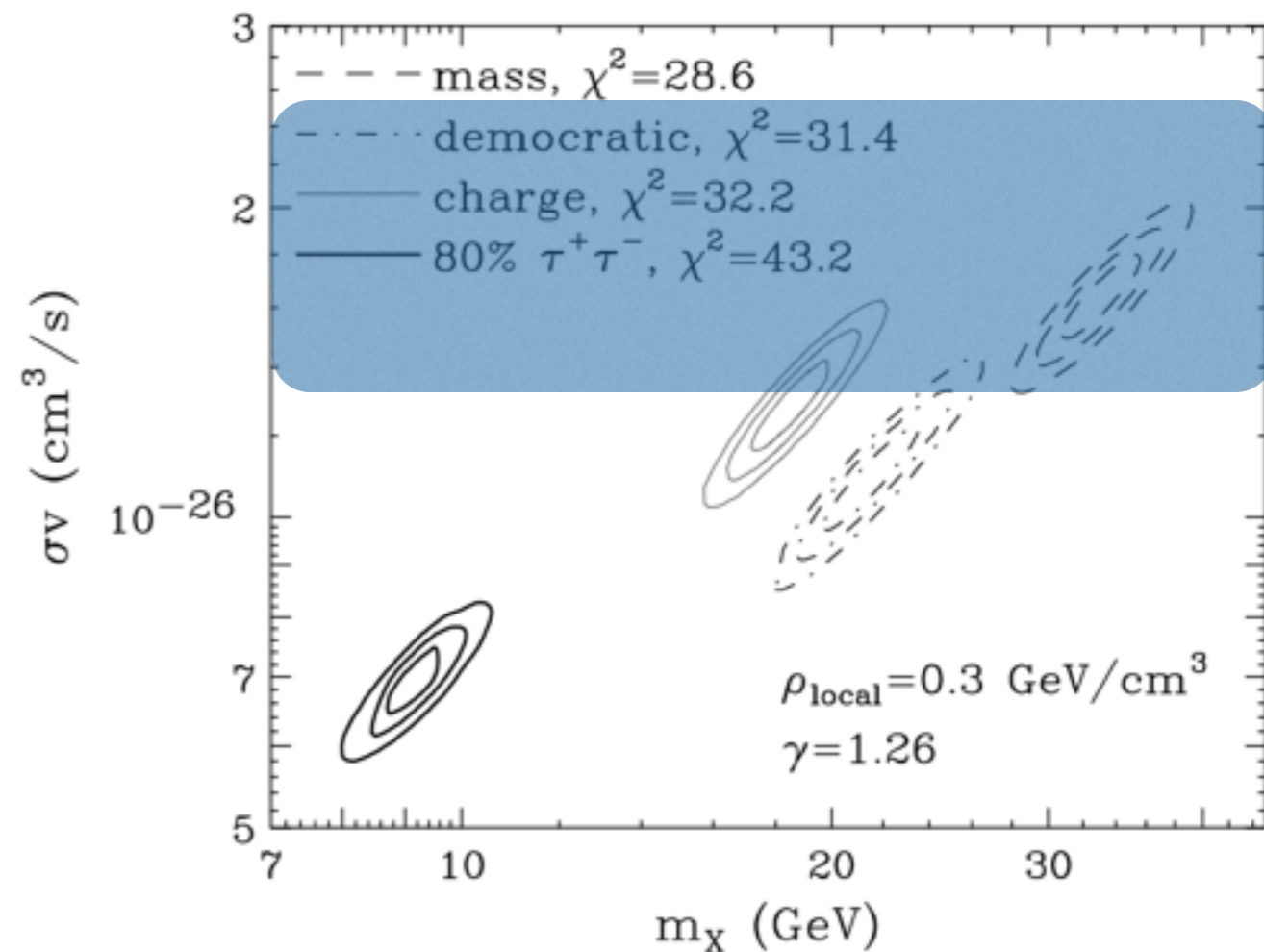
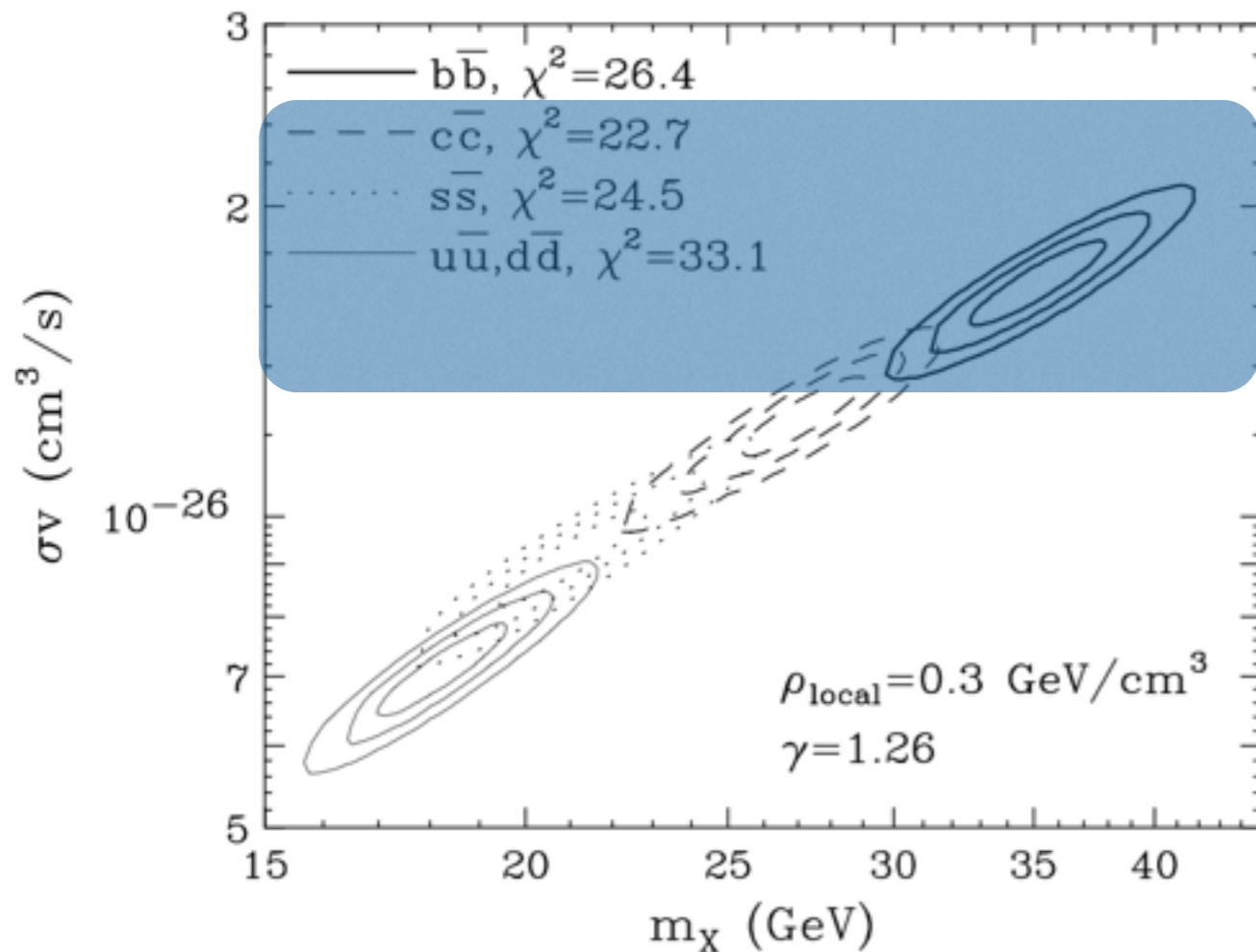


# Interpretations of the Excess

The clear extension of the source out to  $11^\circ$  from the galactic center, with a consistent morphology, makes it difficult to produce the intensity of the emission with pulsars



# Dark Matter Fits to the Data



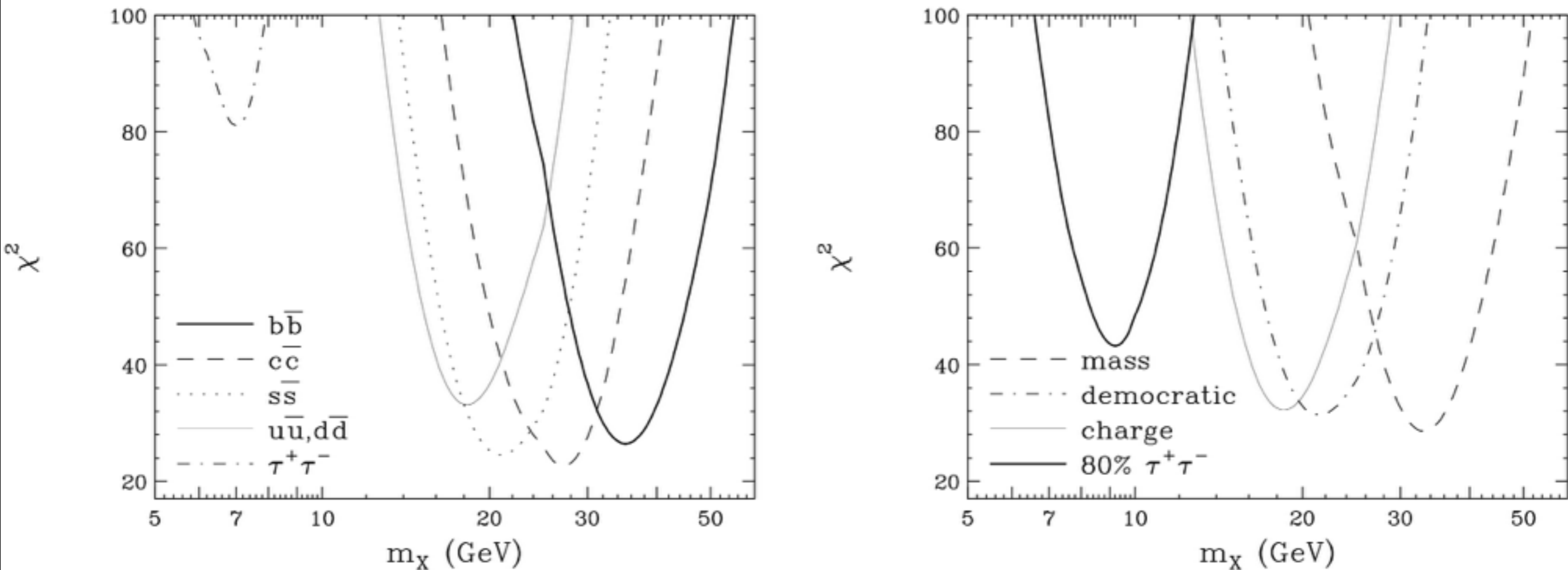
The gamma-ray excess is very well fit by simple, theoretically motivated dark matter models.

We tune only:

- 1.) The dark matter mass and annihilation pathway
- 2.) The dark matter profile slope
- 3.) The dark matter annihilation cross-section



# Dark Matter Fits to the Data



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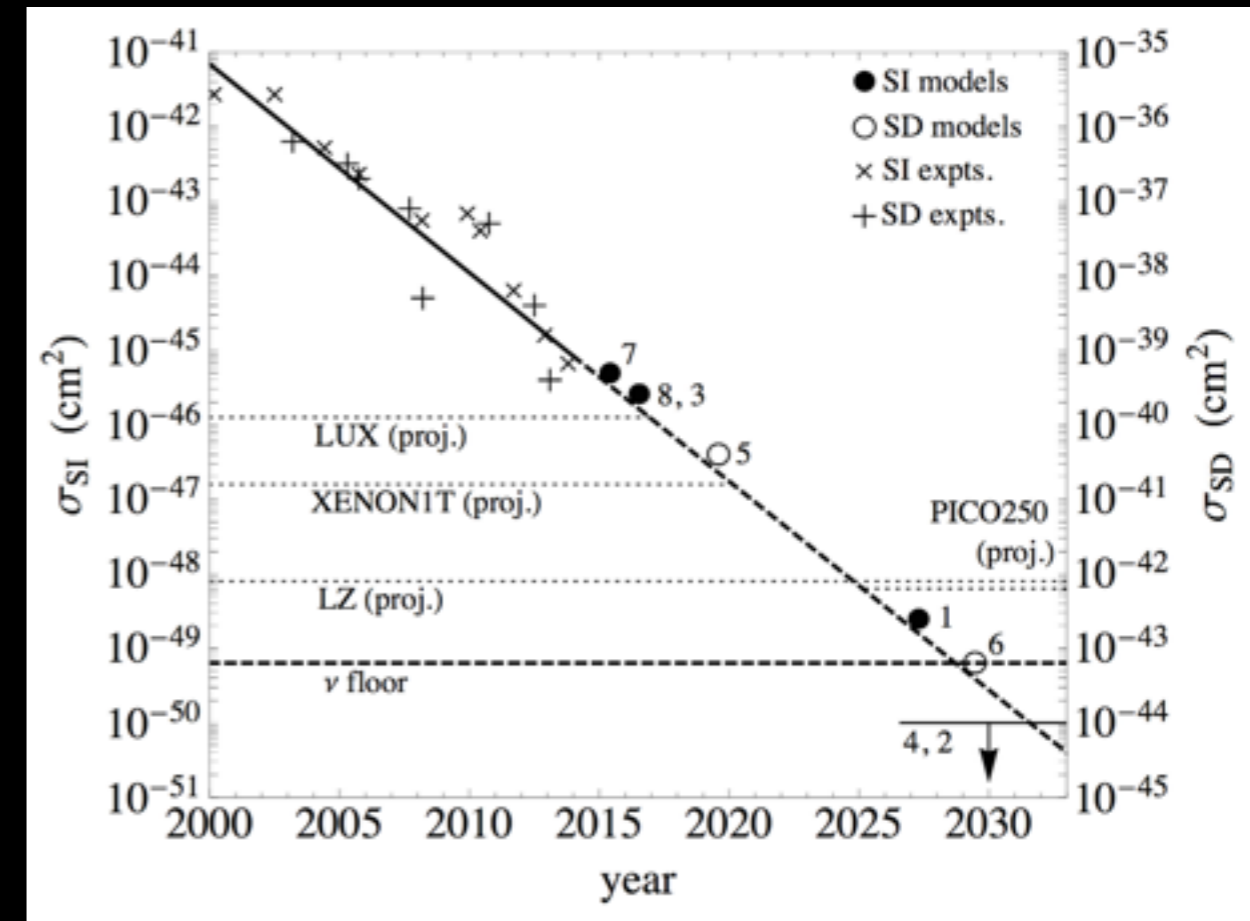
# Dark Matter Fits to the Data

This is in stark contrast to nearly every other excess which has claimed to fit a dark matter signal:

- 1.) **PAMELA/AMS** — Need leptophilic dark matter, with a Sommerfeld enhanced cross-section (100 - 1000x thermal). Need a cored profile to avoid Fermi-LAT constraints
- 2.) **DAMA/LIBRA** - Require a fine-tuned inelastic dark matter model, with finely tuned splitting between final states to avoid other direct detection experiments
- 3.) **130 GeV Line** - Need to highly enhance ( $\sim x100$ ) the direct annihilation to  $\gamma \gamma$  compared to expectations from a loop level process.

# Dark Matter Fits to the Data

Approximately half of the dark matter models which explain the gamma-ray excess are currently compatible with constraints from colliders and direct detection searches



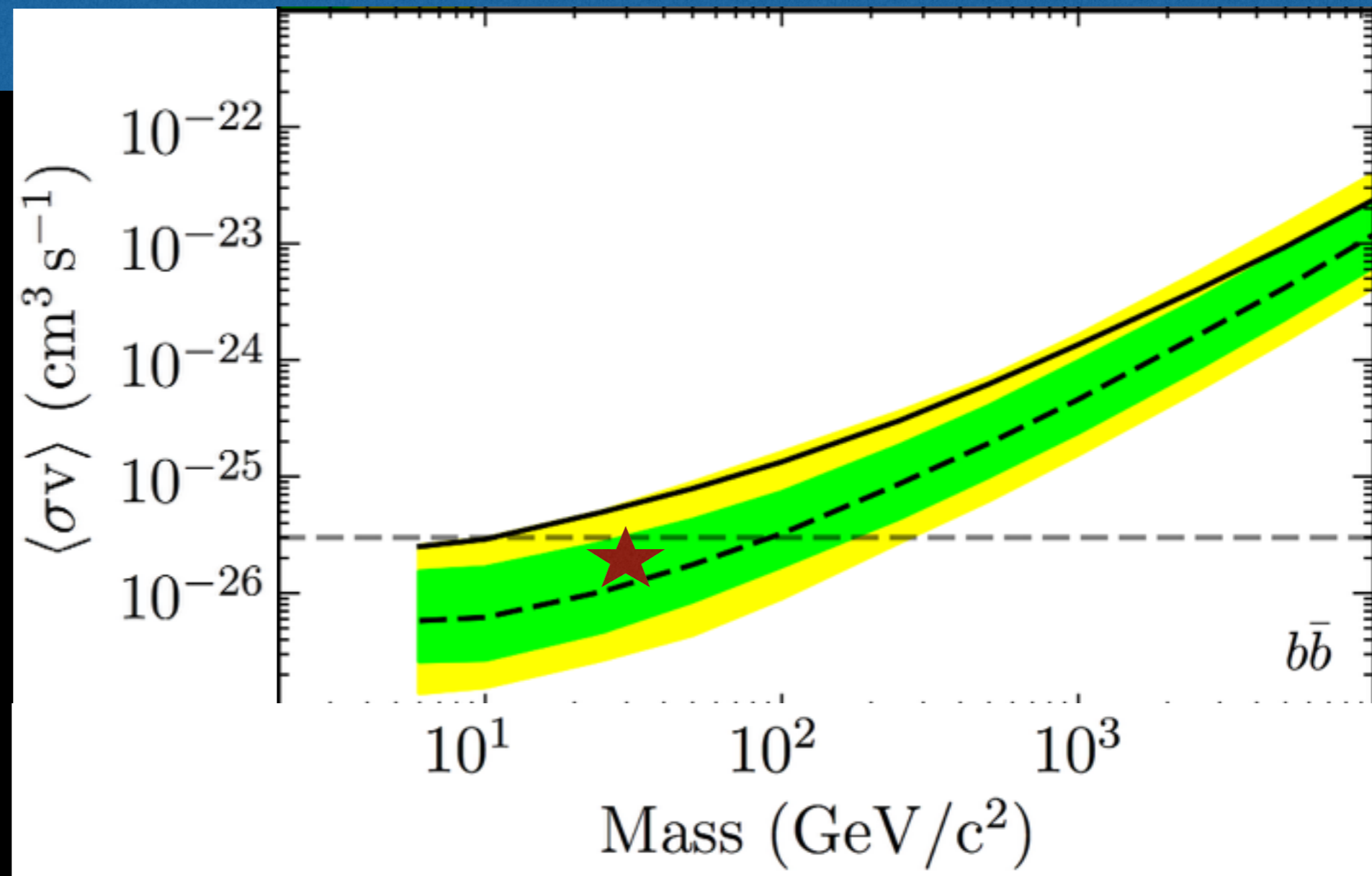
In general, s-channel annihilations are much more likely to be compatible with other constraints than t-channel annihilations

$\langle S \rangle_{DM}$	Type	Interaction	Elastic Scattering	Kinematic Suppression
1/2	Dirac	$\bar{\chi}\gamma^5\chi\bar{q}q$	SI (scalar)	$(q/2m_\chi)^2$
1/2	Majorana	$\bar{\chi}\gamma^5\chi\bar{q}q$	SI (scalar)	$(q/2m_\chi)^2$
1/2	Dirac	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	SD	$(q^2/4m_n m_\chi)^2$
1/2	Majorana	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	SD	$(q^2/4m_n m_\chi)^2$
1/2	Dirac	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	SI (vector)	1
1/2	Dirac	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	SD	$(q/2m_n)^2$ or $(q/2m_\chi)^2$
1/2	Dirac	$\chi\gamma^\mu\gamma^5\chi q\gamma_\mu\gamma^5q$	SD	1
1/2	Majorana	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	SD	1
0	Complex	$\phi^\dagger\phi\bar{q}q$	SI (scalar)	1
0	Real	$\phi^2\bar{q}q$	SI (scalar)	1
0	Complex	$\phi^\dagger\phi\bar{q}\gamma^5q$	SD (scalar)	$(q/2m_n)^2$
0	Real	$\phi^2\bar{q}\gamma^5q$	SD (scalar)	$(q/2m_n)^2$
1	Complex	$B_\mu^\dagger B^\mu\bar{q}q$	SI (scalar)	1
1	Real	$B_\mu B^\mu\bar{q}q$	SI (scalar)	1
1	Complex	$B_\mu^\dagger B^\mu\bar{q}\gamma^5q$	SD	$(q/2m_n)^2$
1	Real	$B_\mu B^\mu\bar{q}\gamma^5q$	SD	$(q/2m_n)^2$

# The Current State of the Excess

- 1.) The excess is hugely statistically robust ( $40\sigma$  for the Inner Galaxy,  $17\sigma$  for the Galactic Center). This gives us  $\sim 30,000$  photons in the dark matter signal, which we can use to scan the morphology and spectrum of the excess.
- 2.) The excess is extremely well fit by very standard dark matter models. No strange theoretical tricks are necessary.
- 3.) There is no other reasonable model which has been put forward to explain the excess.

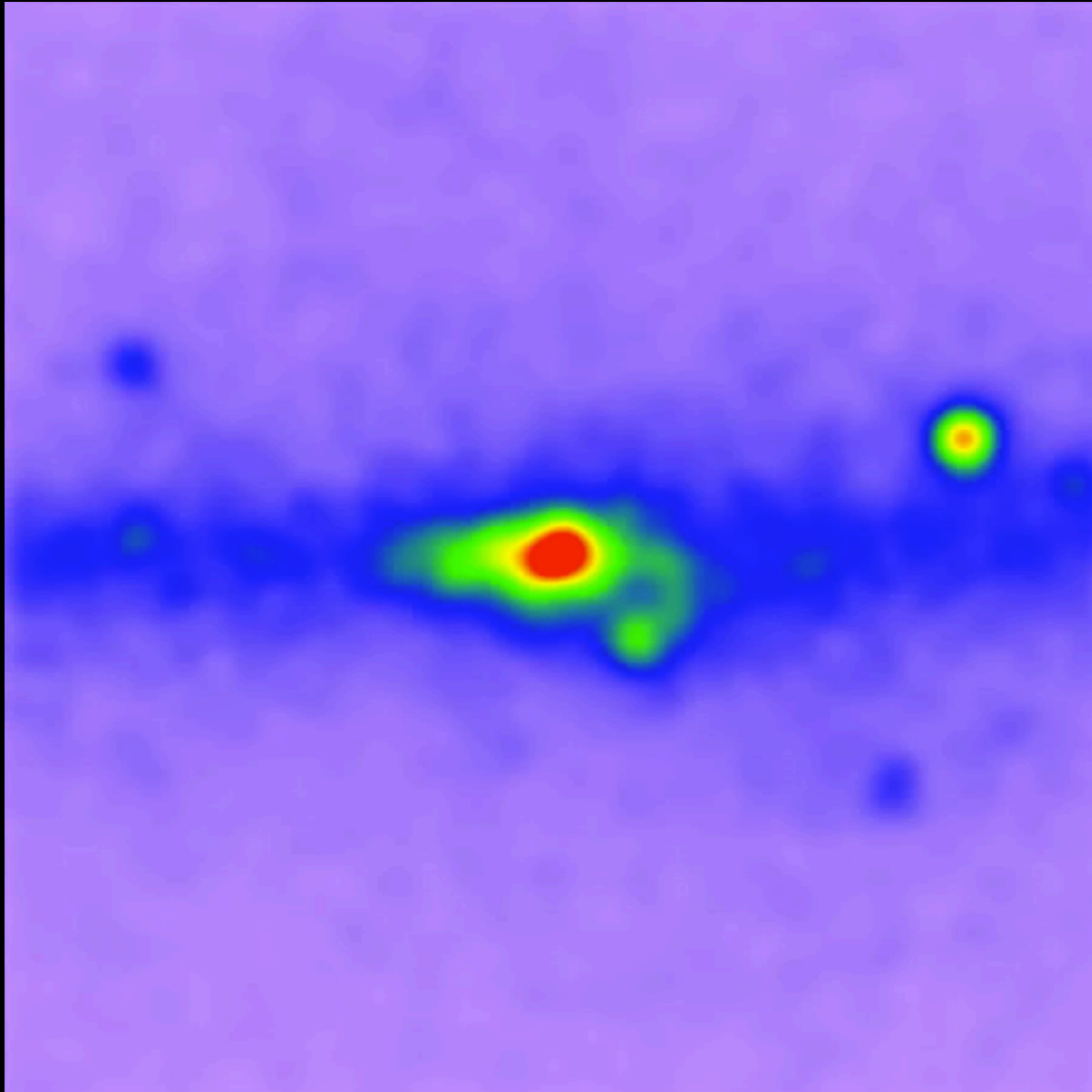
# Future Tests



**How would we test this excess?** - Dwarf galaxies are another natural target for dark matter indirect detection. Interestingly, the Fermi-LAT finds an excess with a local significance of  $2.7\sigma$  at the mass most favored by our dark matter model.

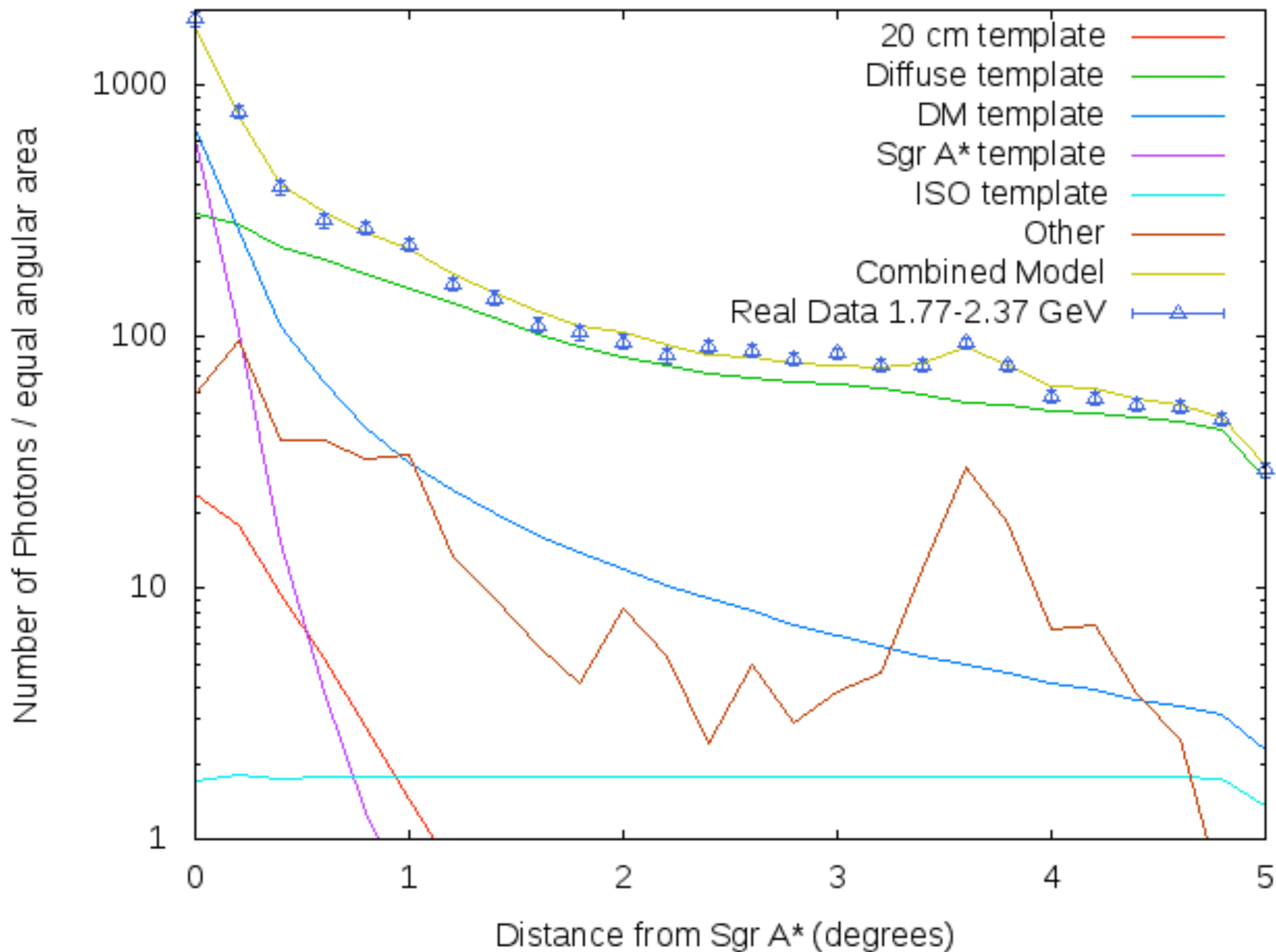


# Conclusion

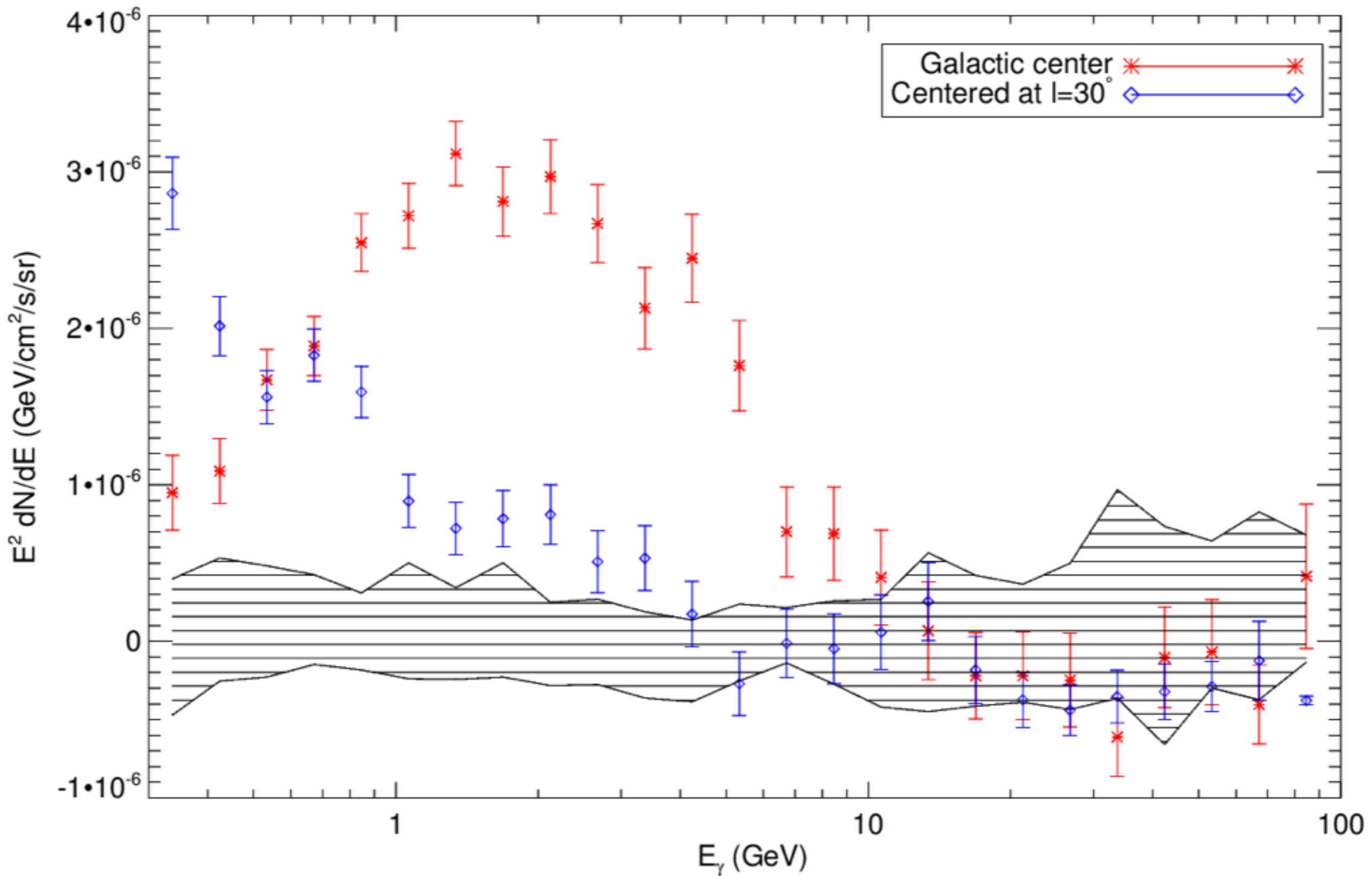


# Extra Slides

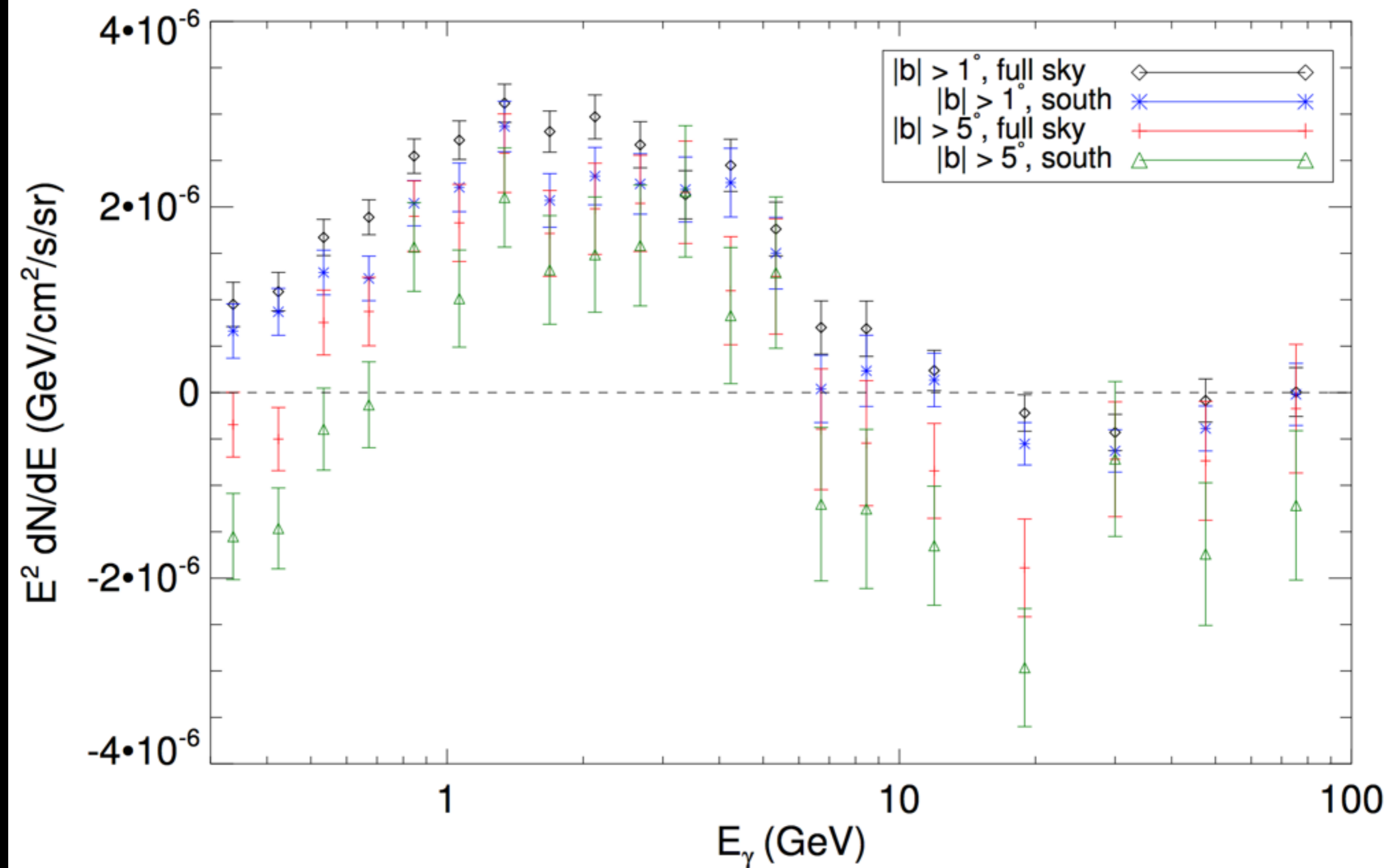
# How Big Is This Excess?



# Do Other Residuals Have the Same Spectrum?

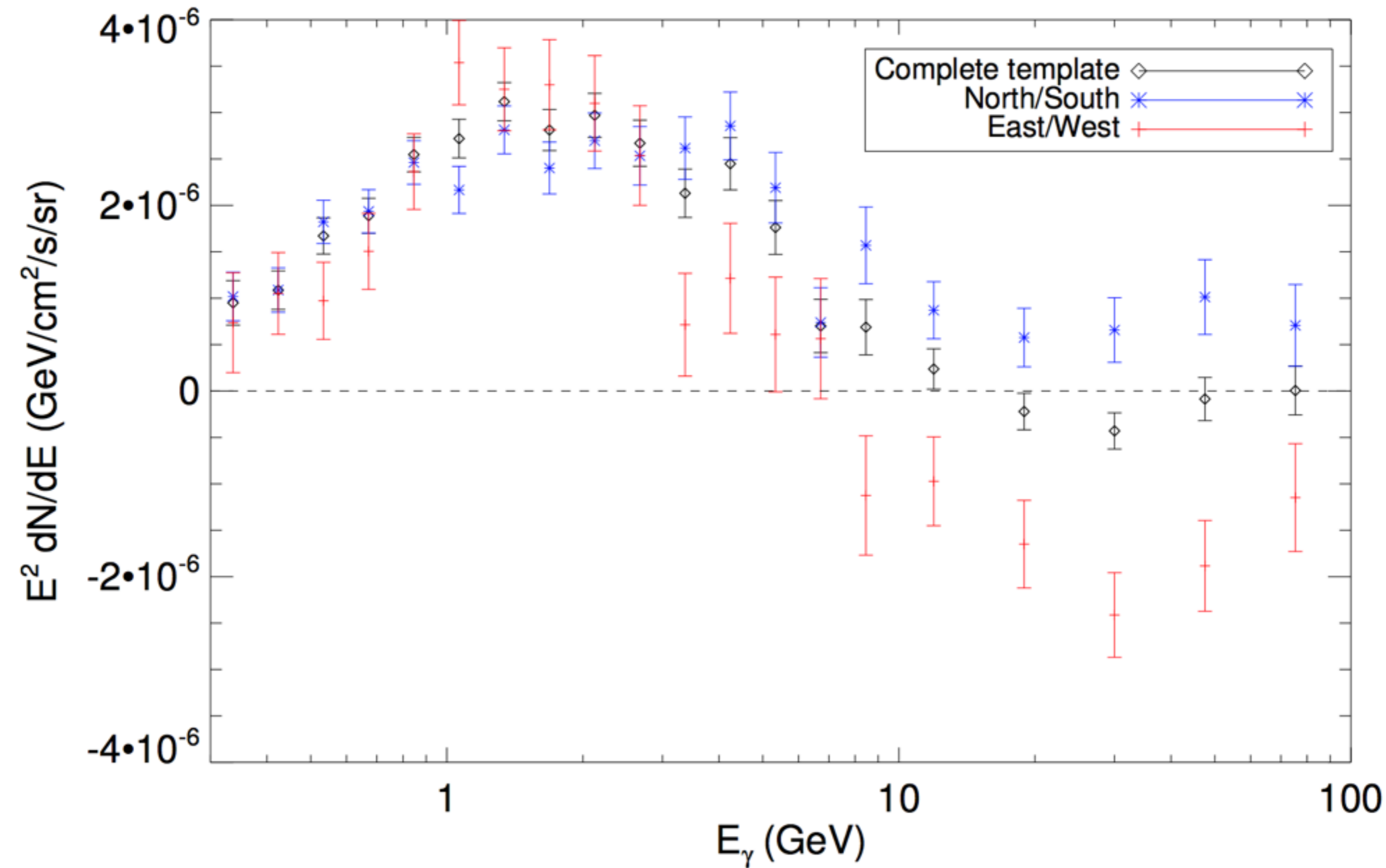


# Wait, Some of the Same Photons are in Each Sample?

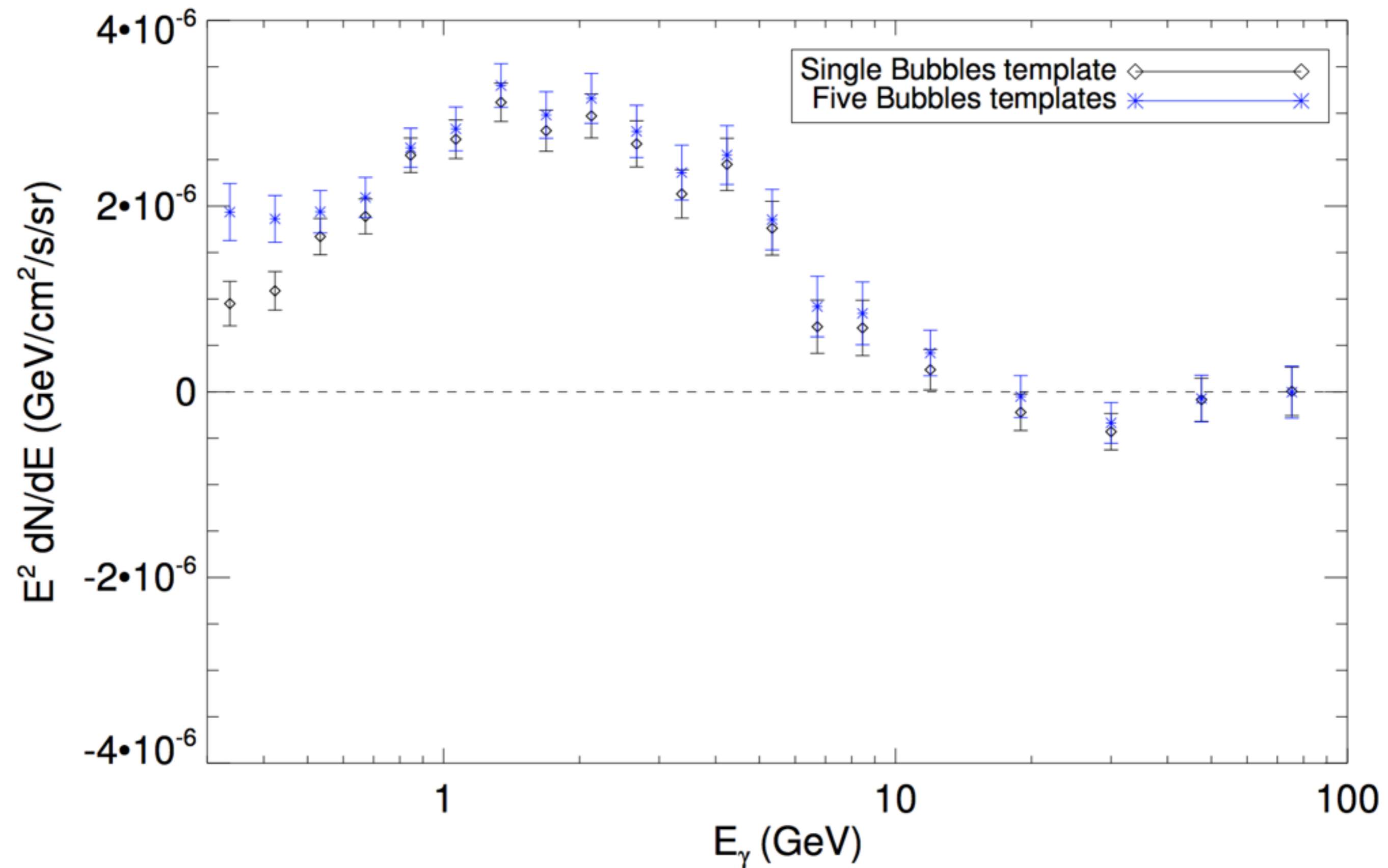




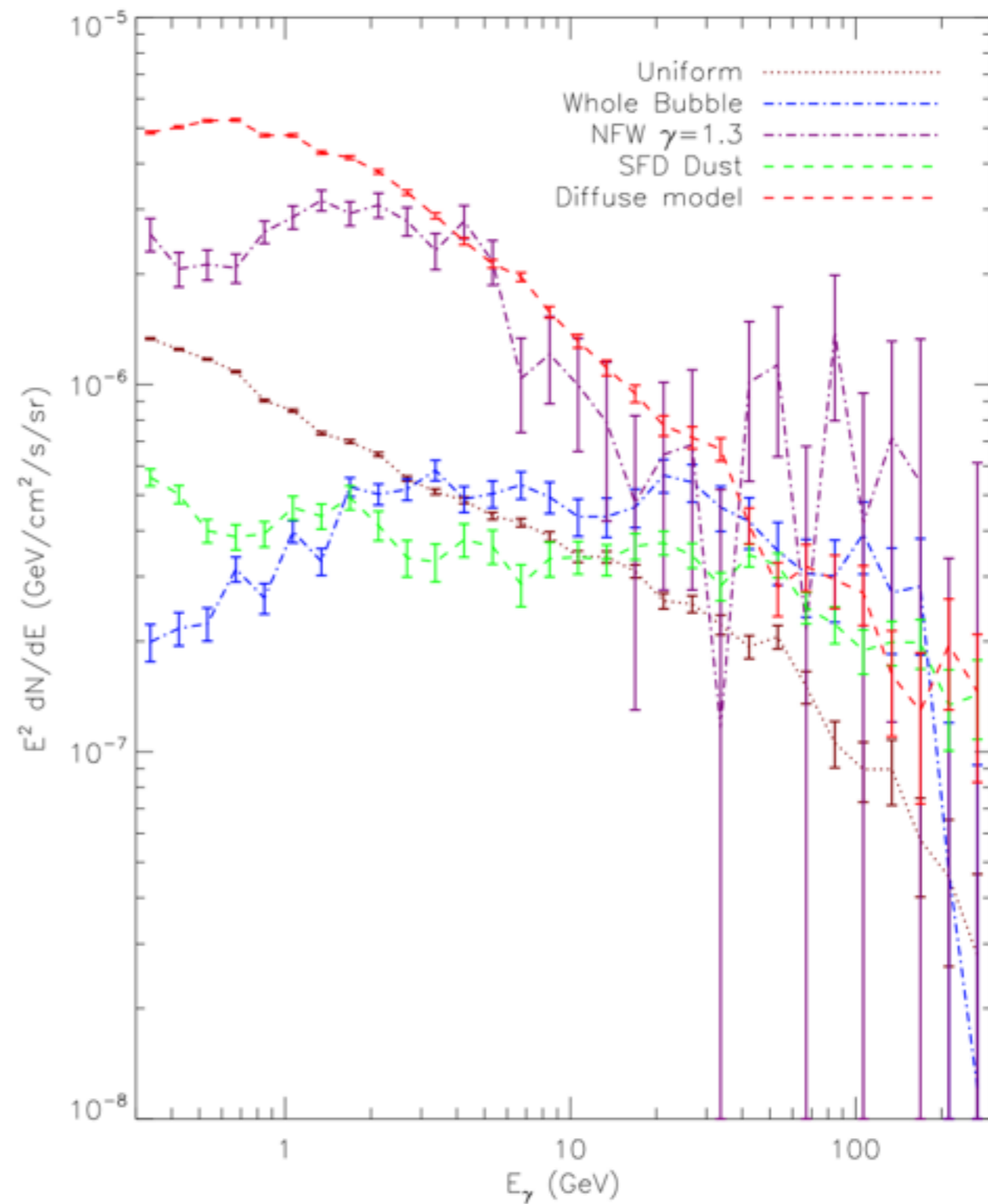
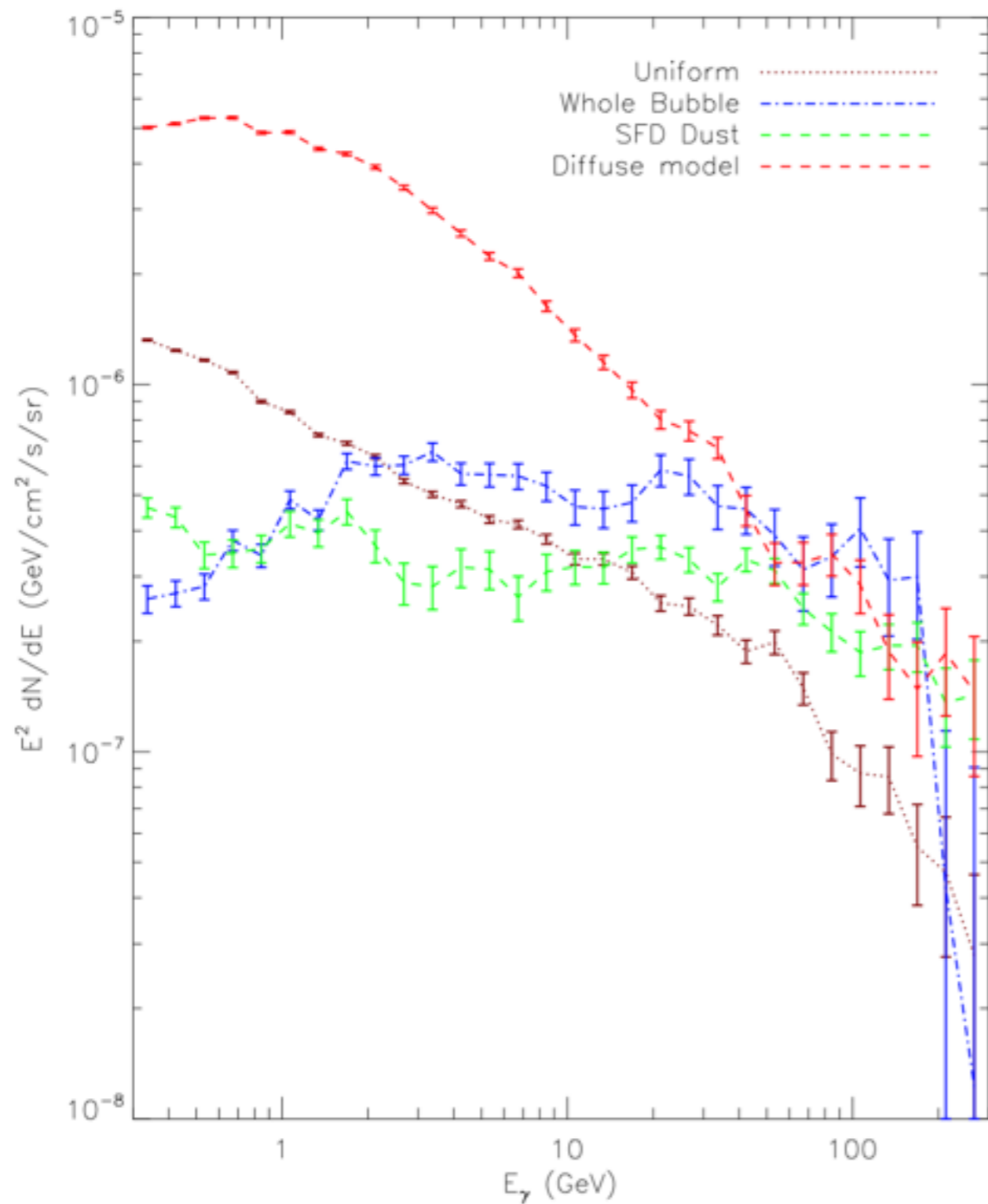
# Maybe it's just part of the Bubbles?



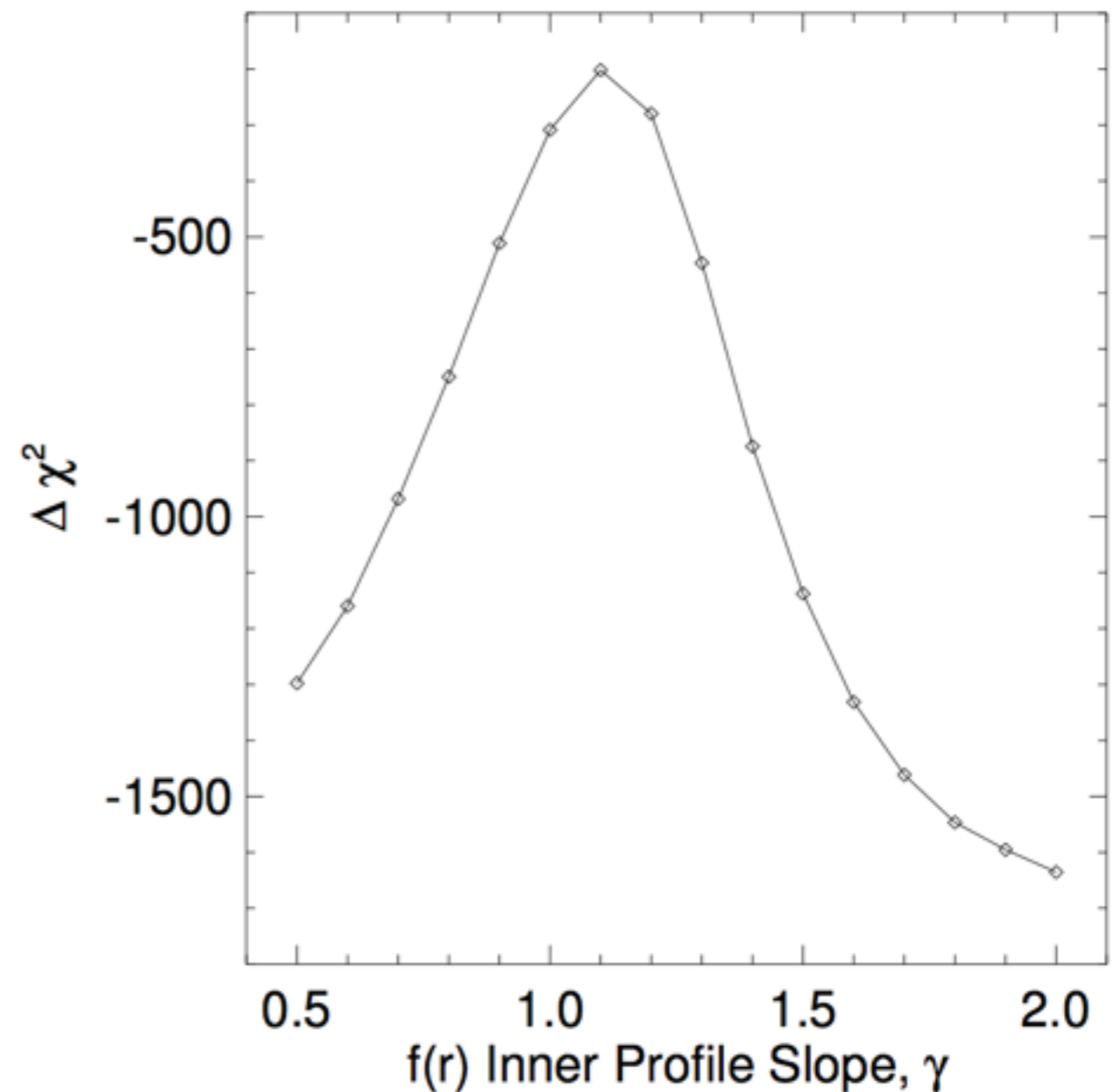
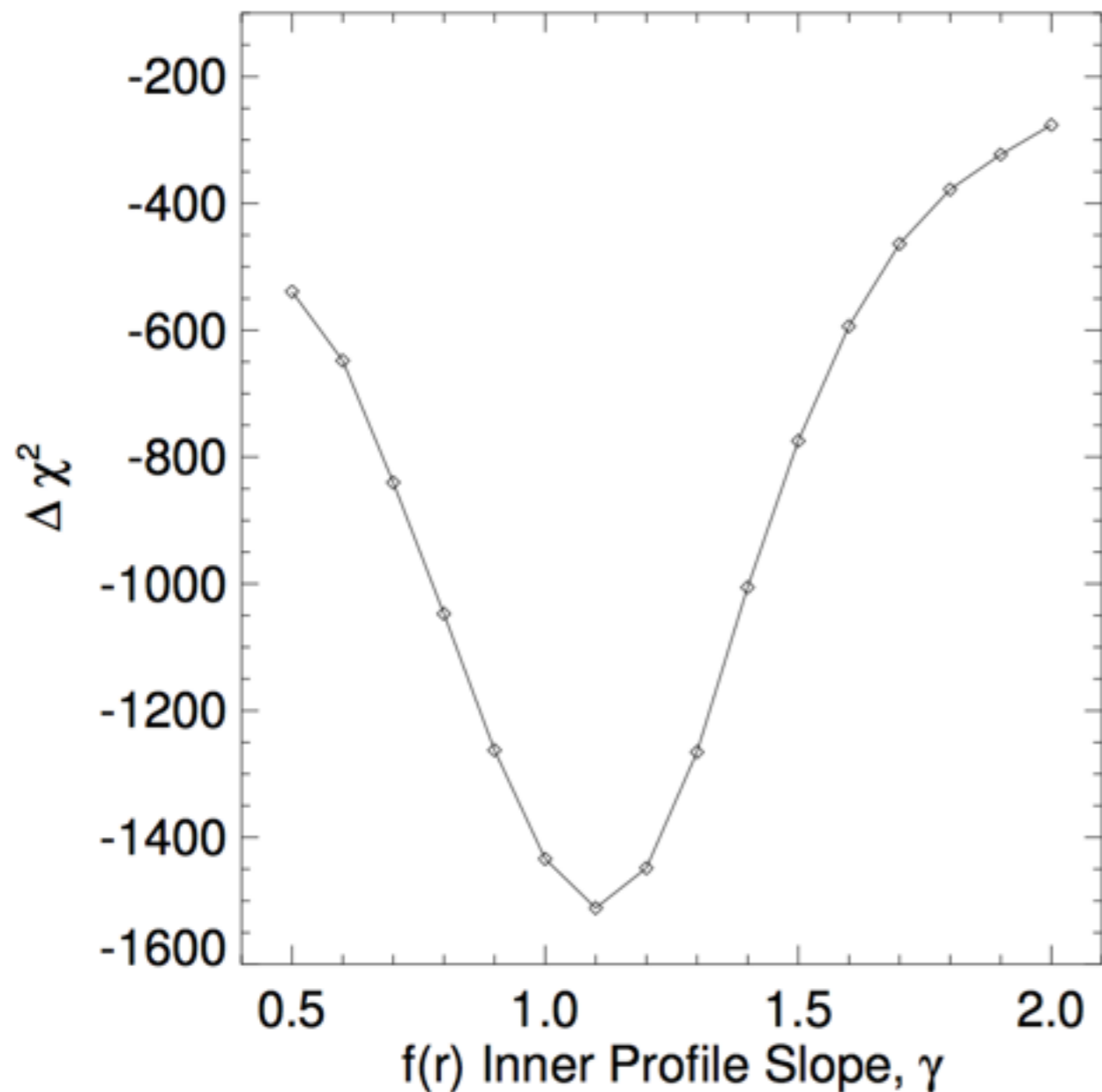
# Maybe the Bubbles Have A Spectral Variation?



# Does it Correlate with Gas?

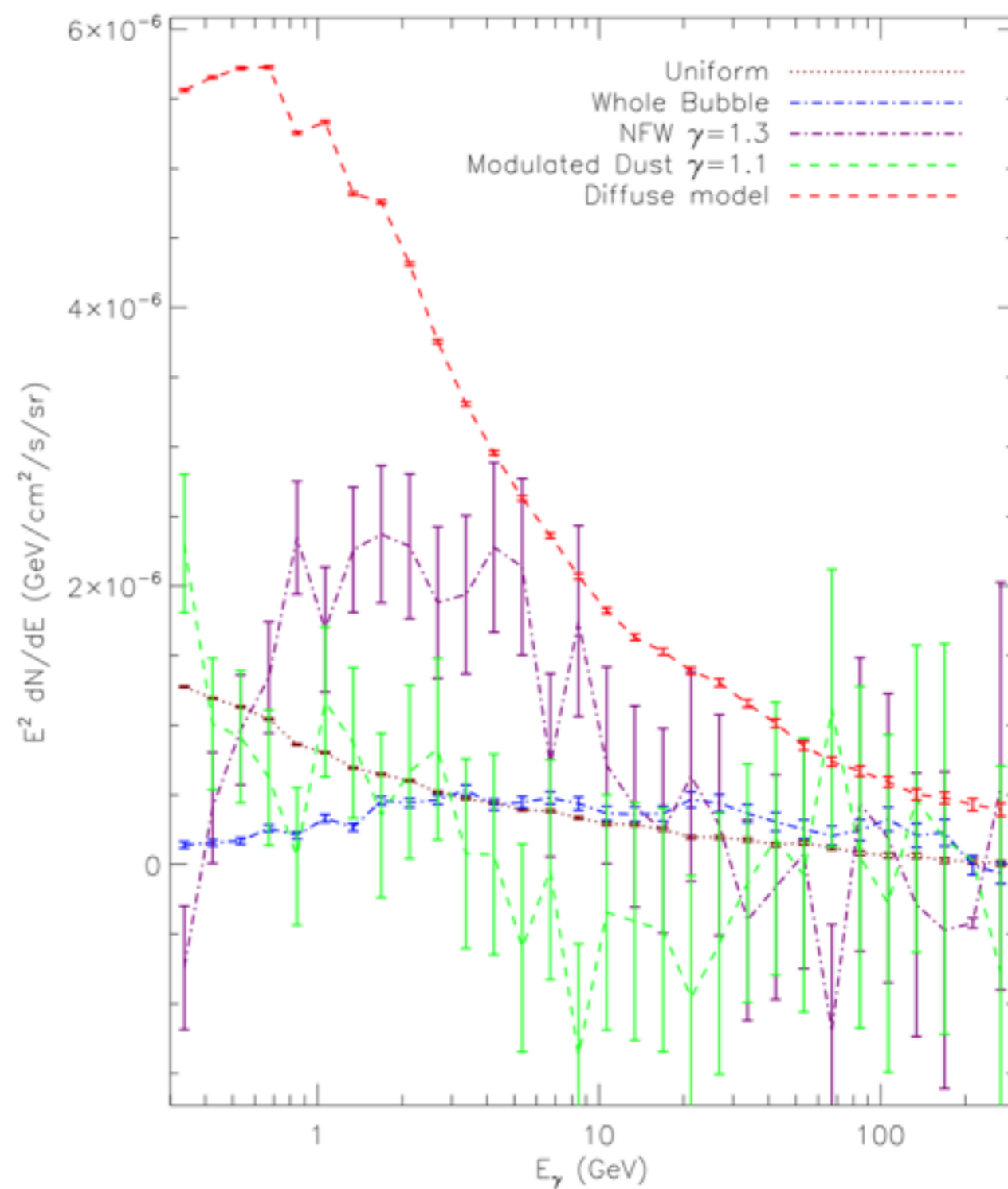
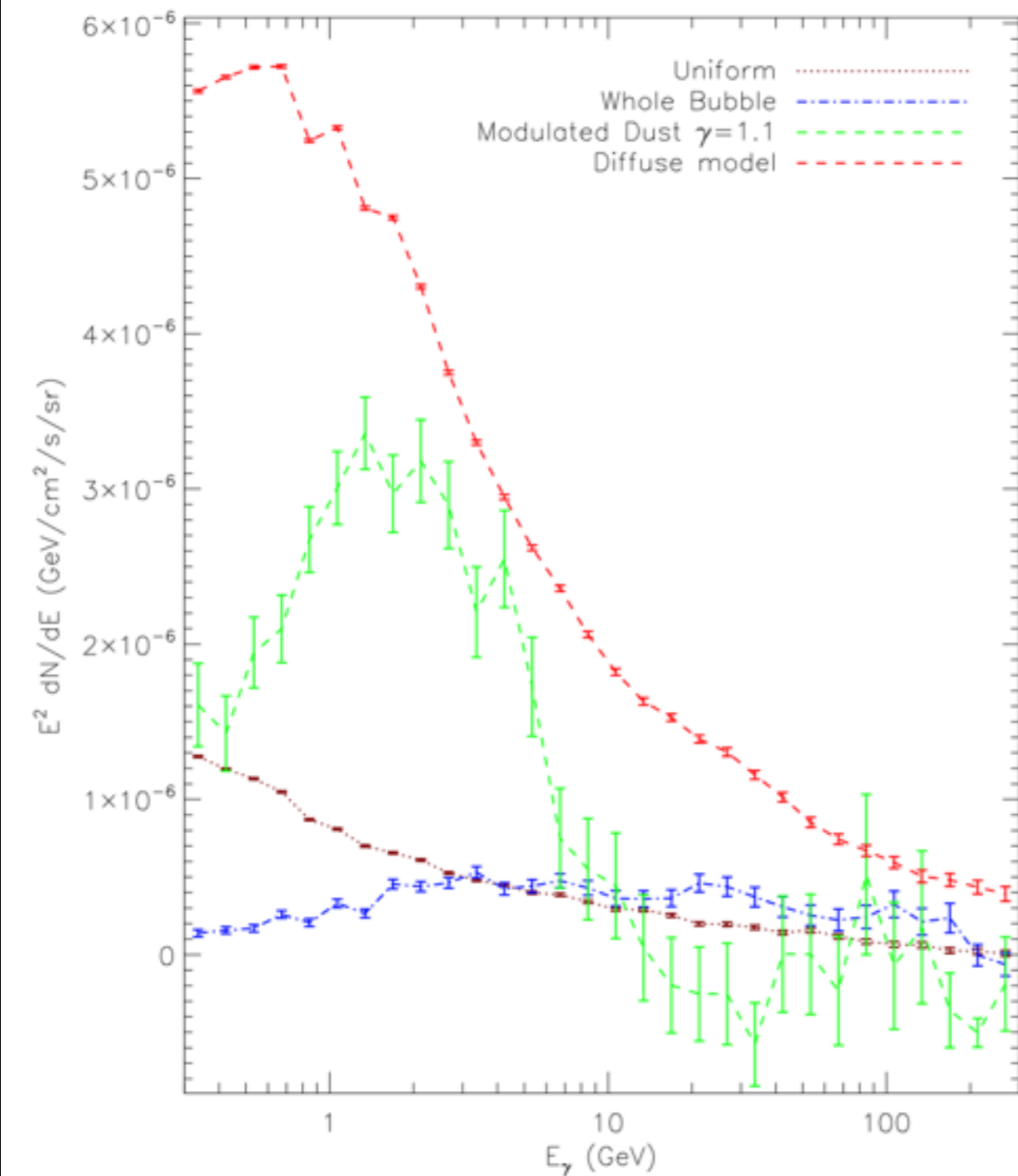


# Does it Correlate with Gas?



Even more generically, you can add an  $f(r) \propto r^{-\gamma}$  profile for the SFD template, this is highly preferred in the model with no dark matter (left), but the dark matter template is still highly preferred even when  $\gamma$  can float freely (right)

# Does it Correlate with Gas?



With the best fit modulated SFD map, the dark matter fit is still highly preferred



# Maybe the Models of the Diffuse Emission in the GC are Wrong

