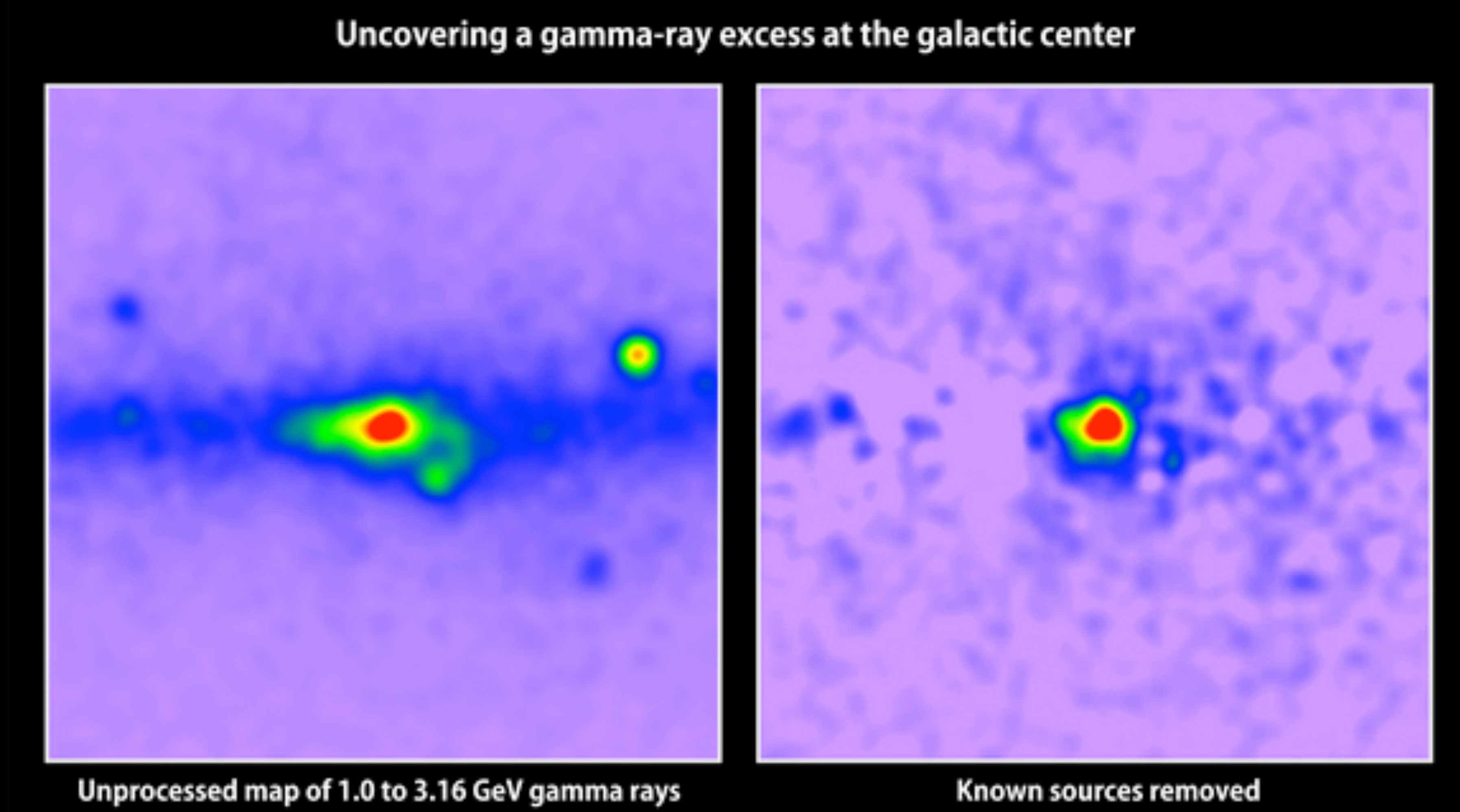
The Characterization of the Gamma-Ray Signal from the Central Milky Way:
A Compelling Case for Annihilating Dark Matter



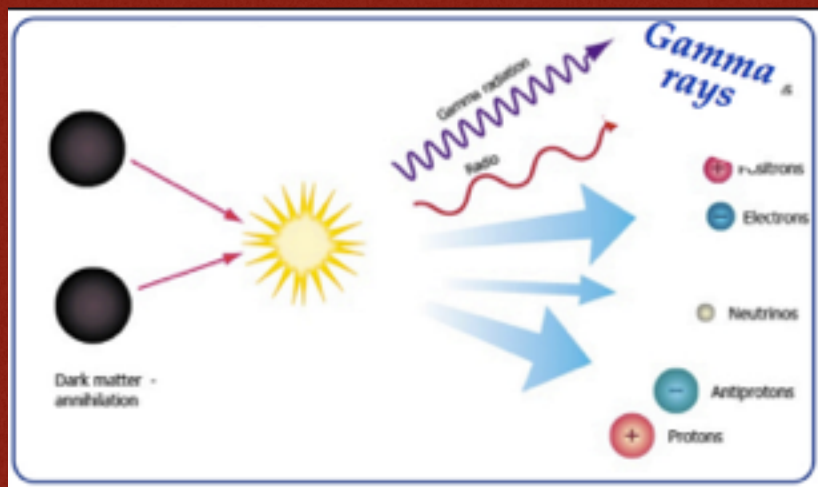
Tim Linden
Einstein/KICP Fellow
University of Chicago

arXiv: 1402.6703

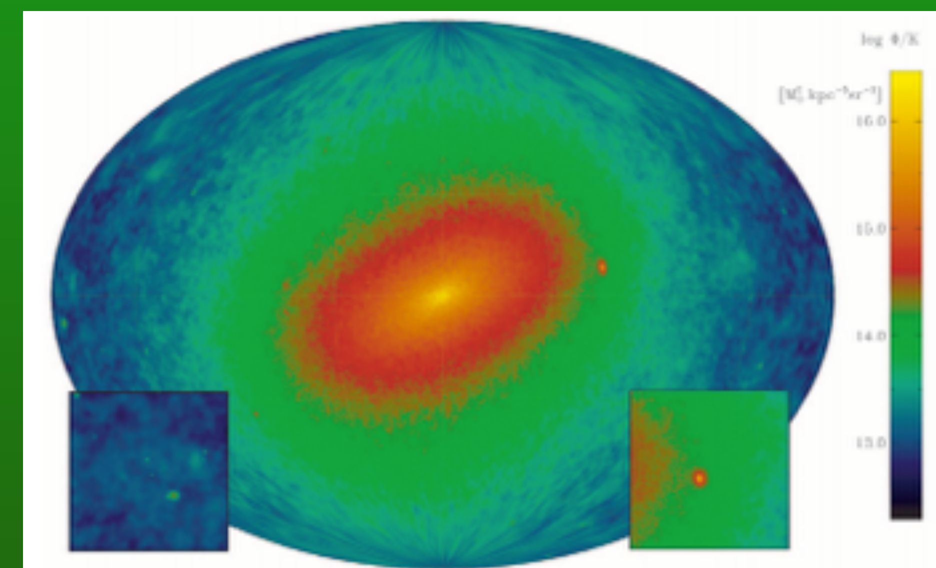
along with:
Tansu Daylan, Doug Finkbeiner, Dan Hooper, Stephen Portillo, Nick Rodd and Tracy Slatyer

Dark Matter Indirect Detection

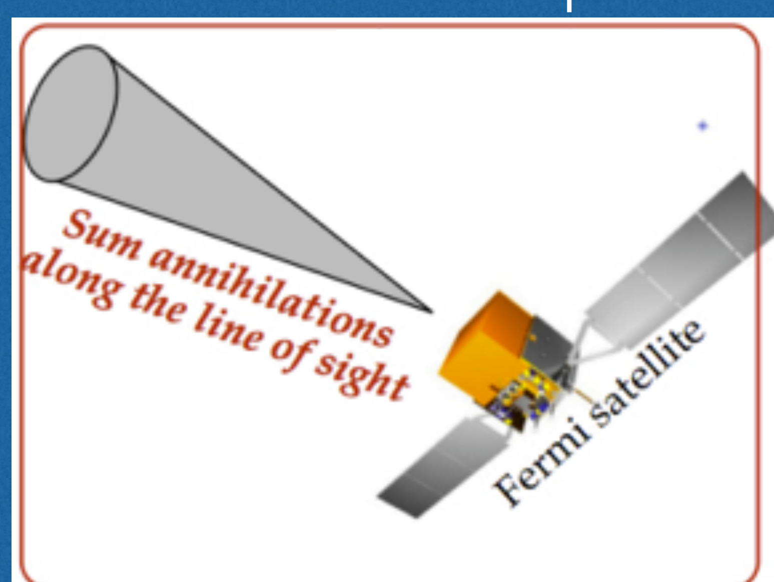
Particle Physics



Astrophysics



Instrumental Response



Slide Concept Courtesy of Gabrijela Zaharijas

The Astrophysical J-Factor

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

Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\overline{\log_{10}(J^{NFW})}^a$ ($\log_{10}[\mathrm{GeV^2\,cm^{-5}\,sr}]$)
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

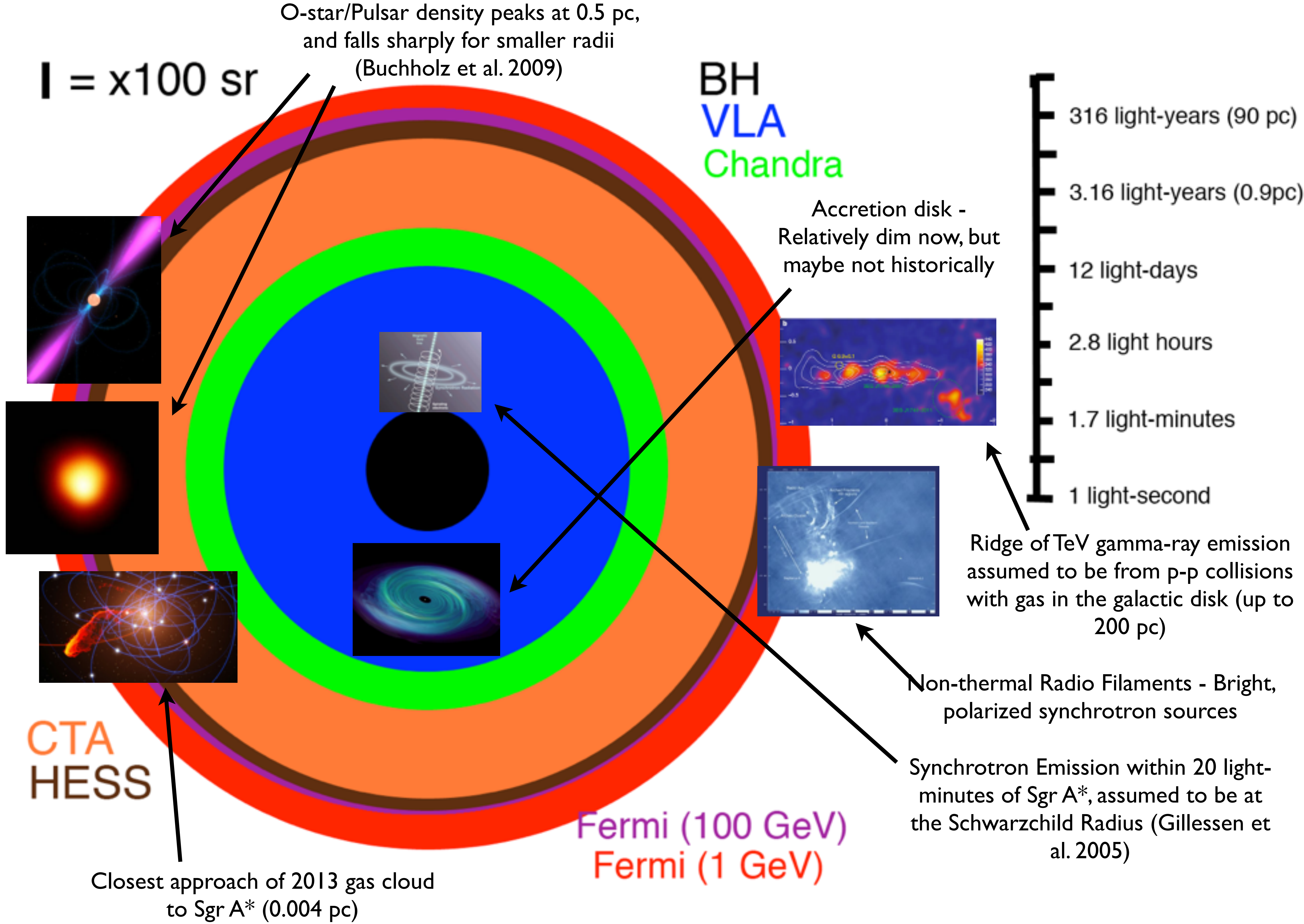
The Fermi-LAT Collaboration (2013)

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

The Galactic Center "Zoo"



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 γ, which controls the inner slope, for a canonical NFW profile $\gamma = 1$

The Galactic Center in Gamma-Rays

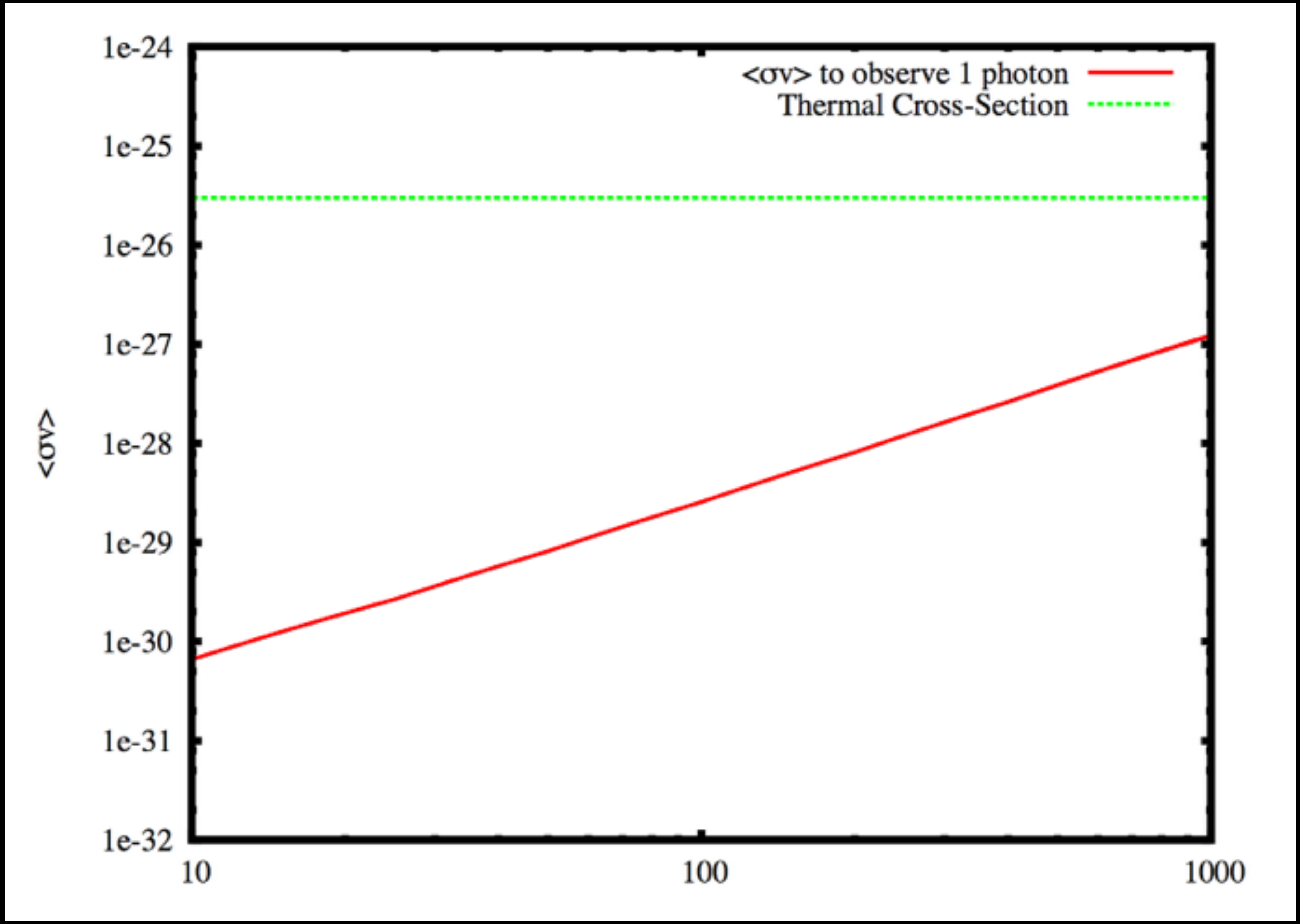
Back of the Envelope Calculation

- Total Gamma-Ray Flux from 1-3 GeV within 1° 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}

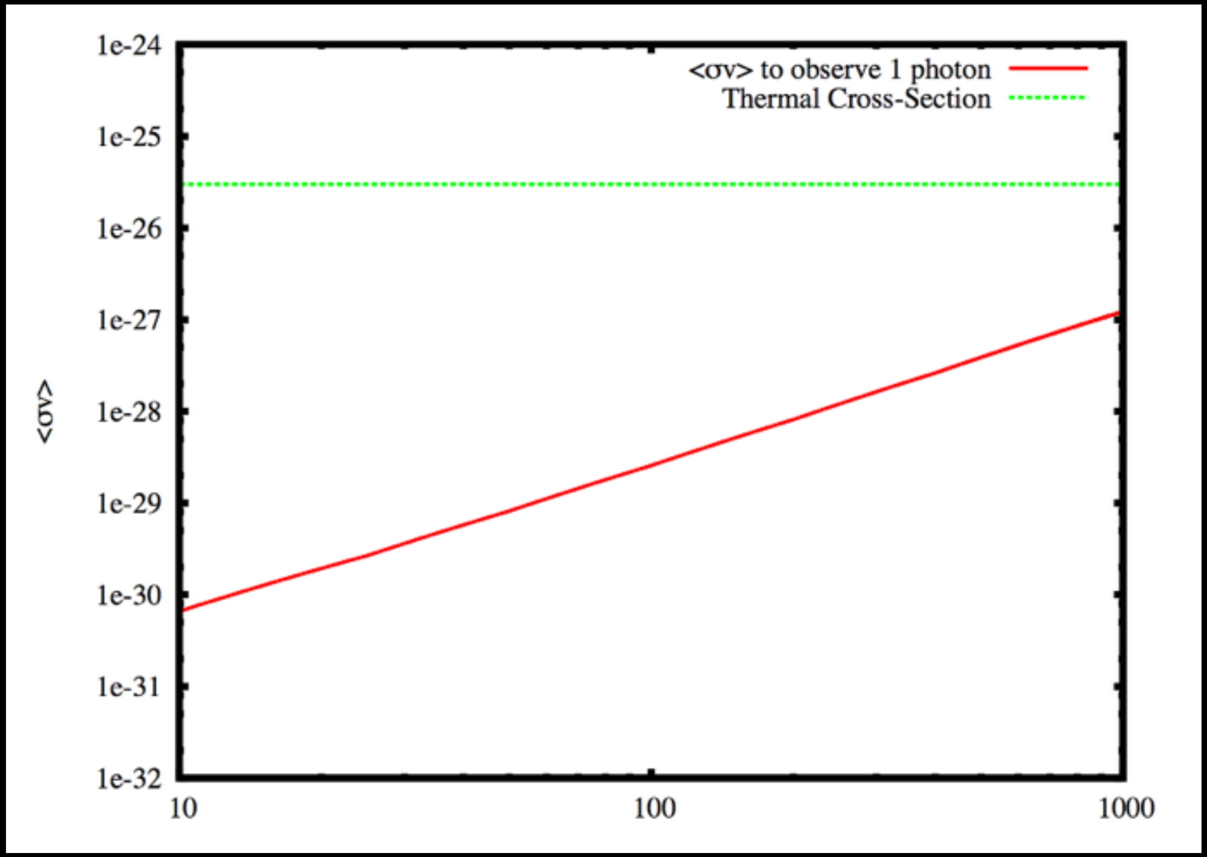
- There's no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the **most naive** prediction from dark matter simulations

The Galactic Center in Gamma-Rays



If you were able to somehow "tag" each **γ**-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 γ-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?"

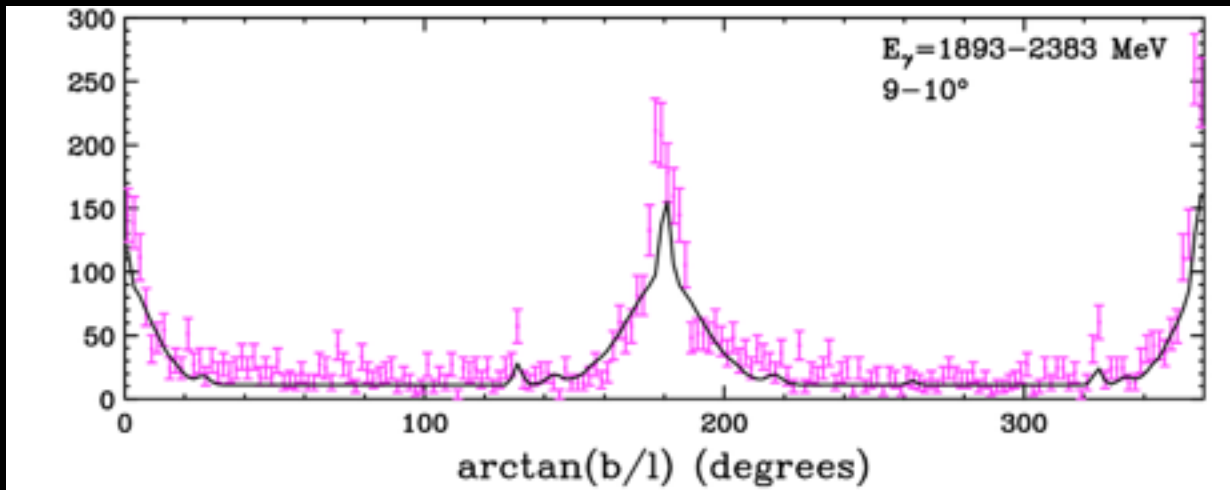
Outline of the Talk

1.) Data of the Galactic Center and Inner Galaxy Excess

2.) Models of the Galactic Center and Inner Galaxy Excess

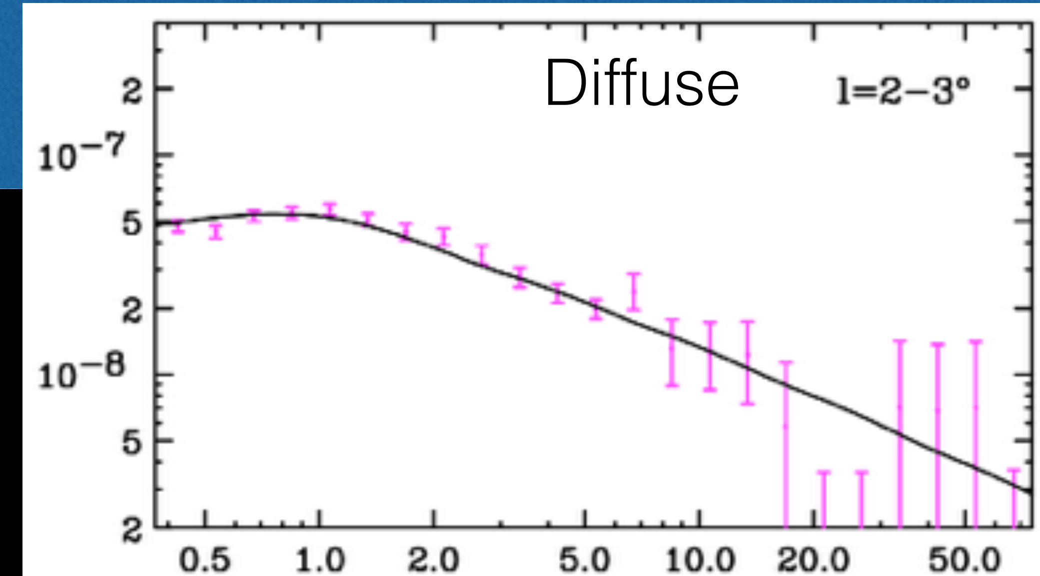
3.) Looking at the Future

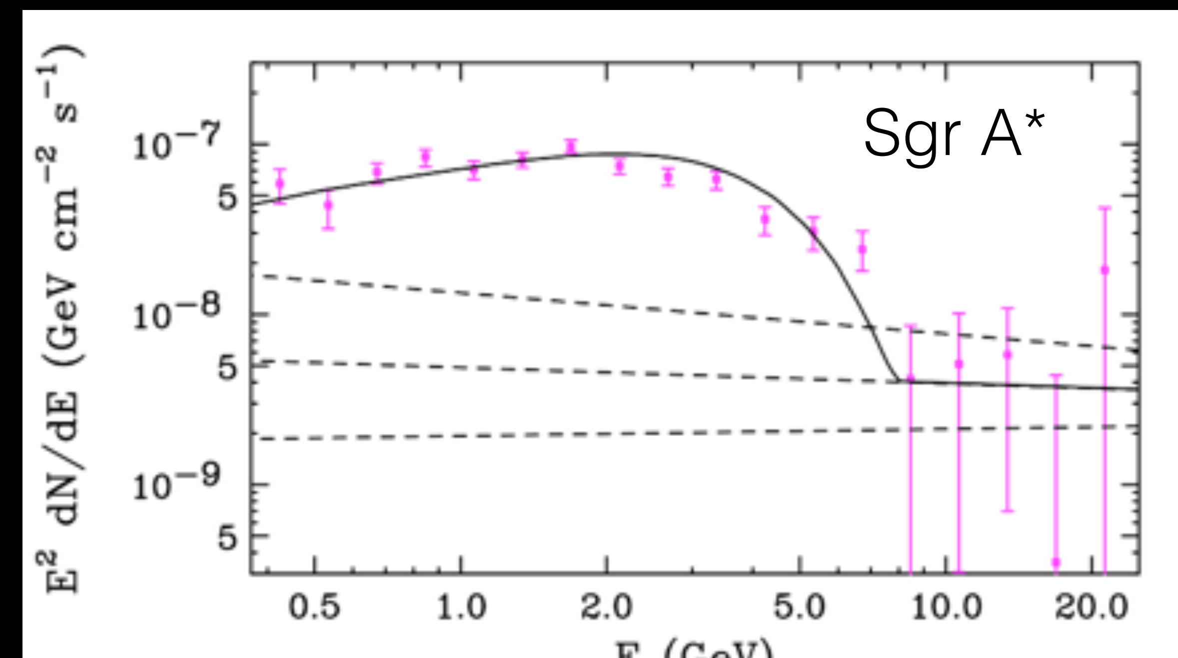
Previous Efforts

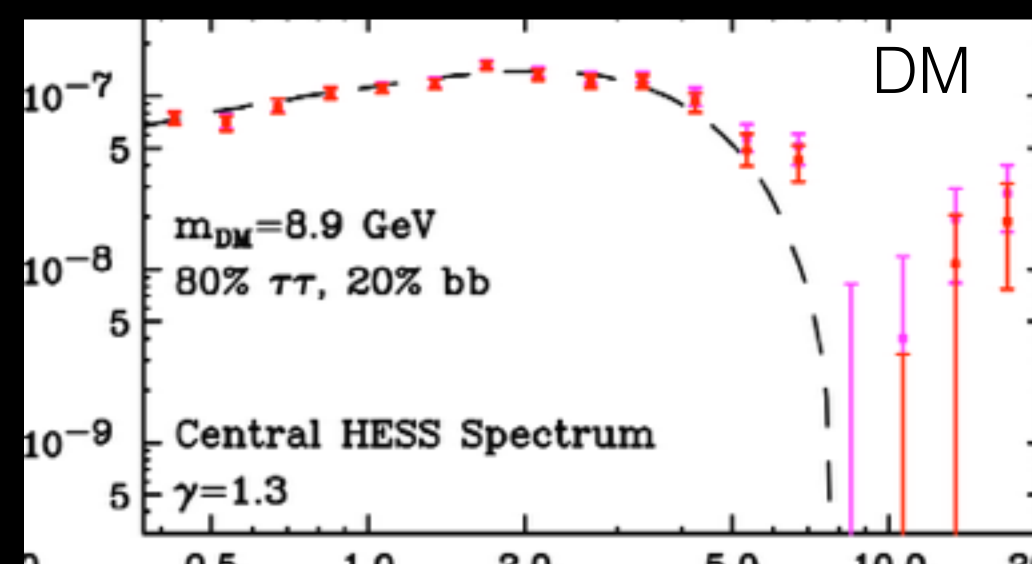


Hooper & Goodenough (2010) employed the angular distribution of observed gamma-rays to separate and model the emission from the:

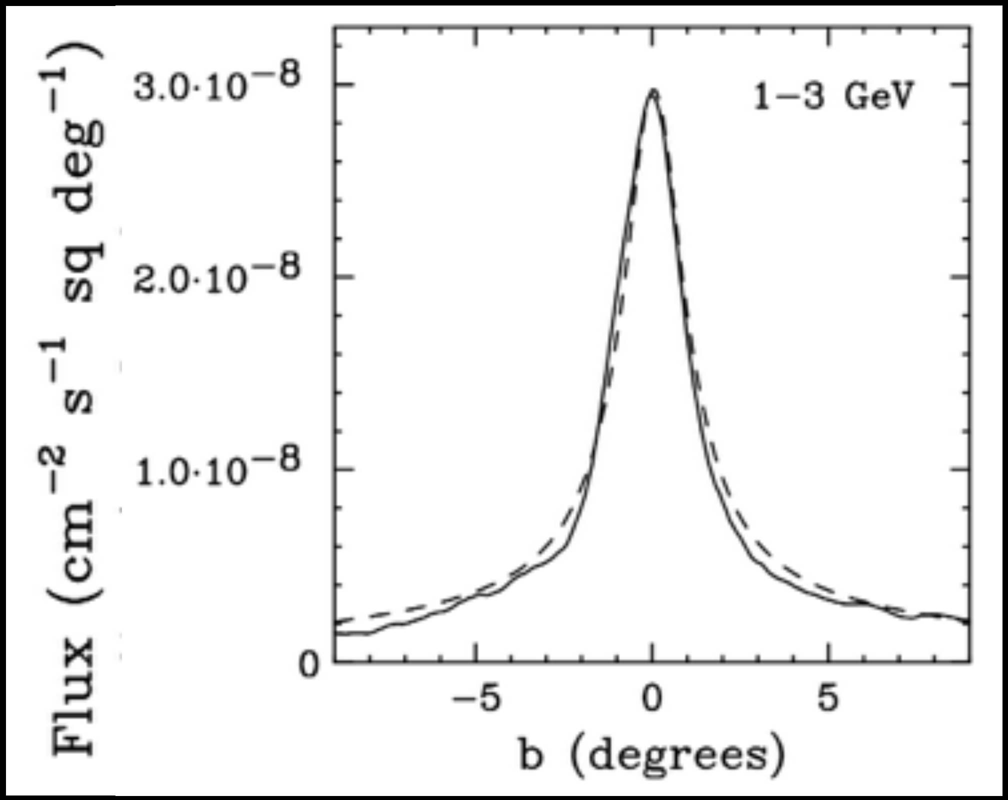
galactic disk
galactic center point source
modeled dark matter component

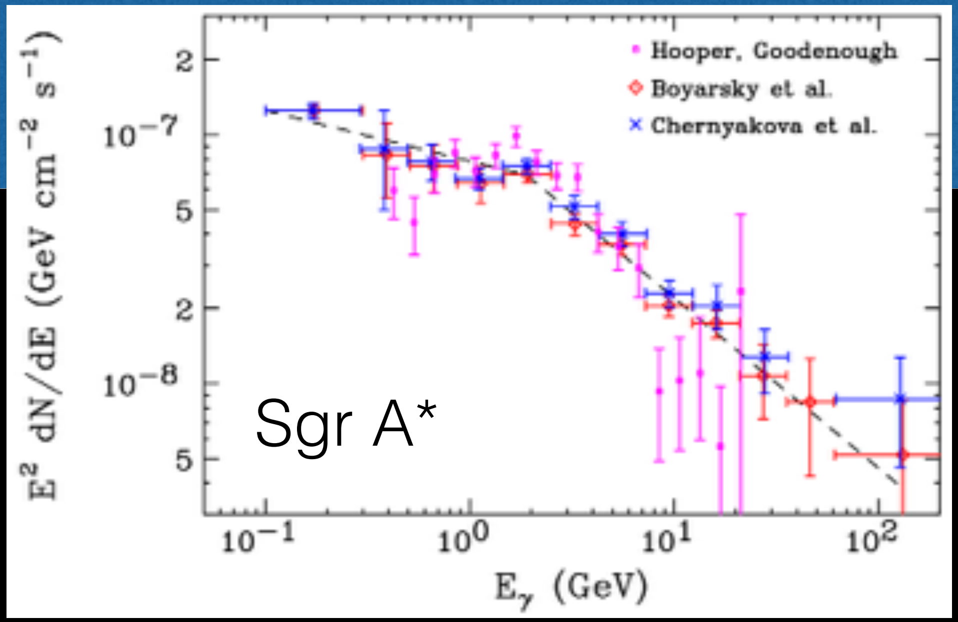


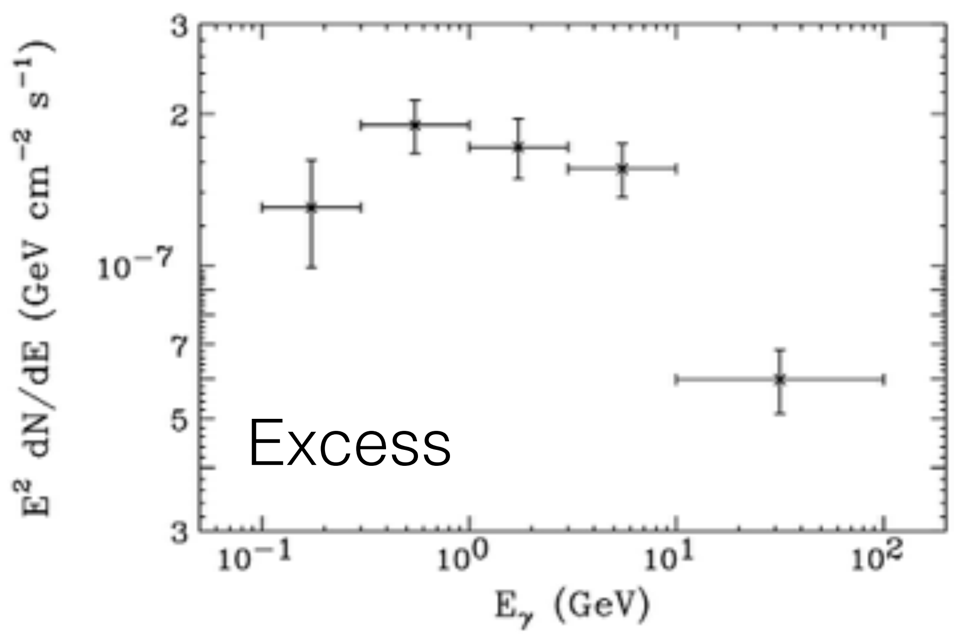




Previous Efforts





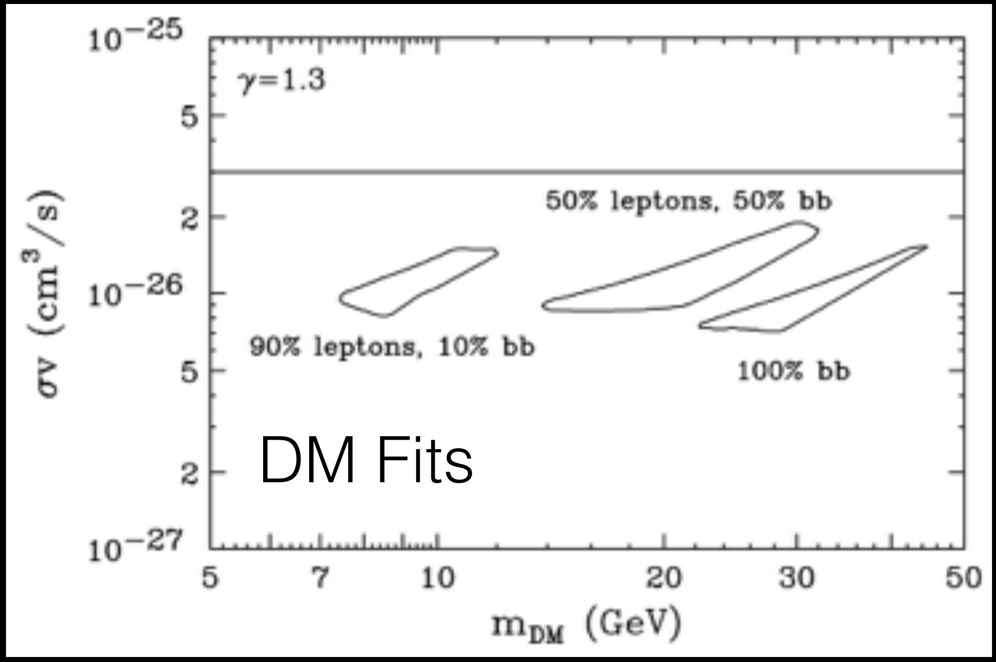


Hooper & Linden (2010) employed observationally driven models for

the distribution of gas (Kalberla & Kerp 2009)

the spectrum of nearby **γ**-ray point sources (2FGL)

the spectrum of Sgr A*

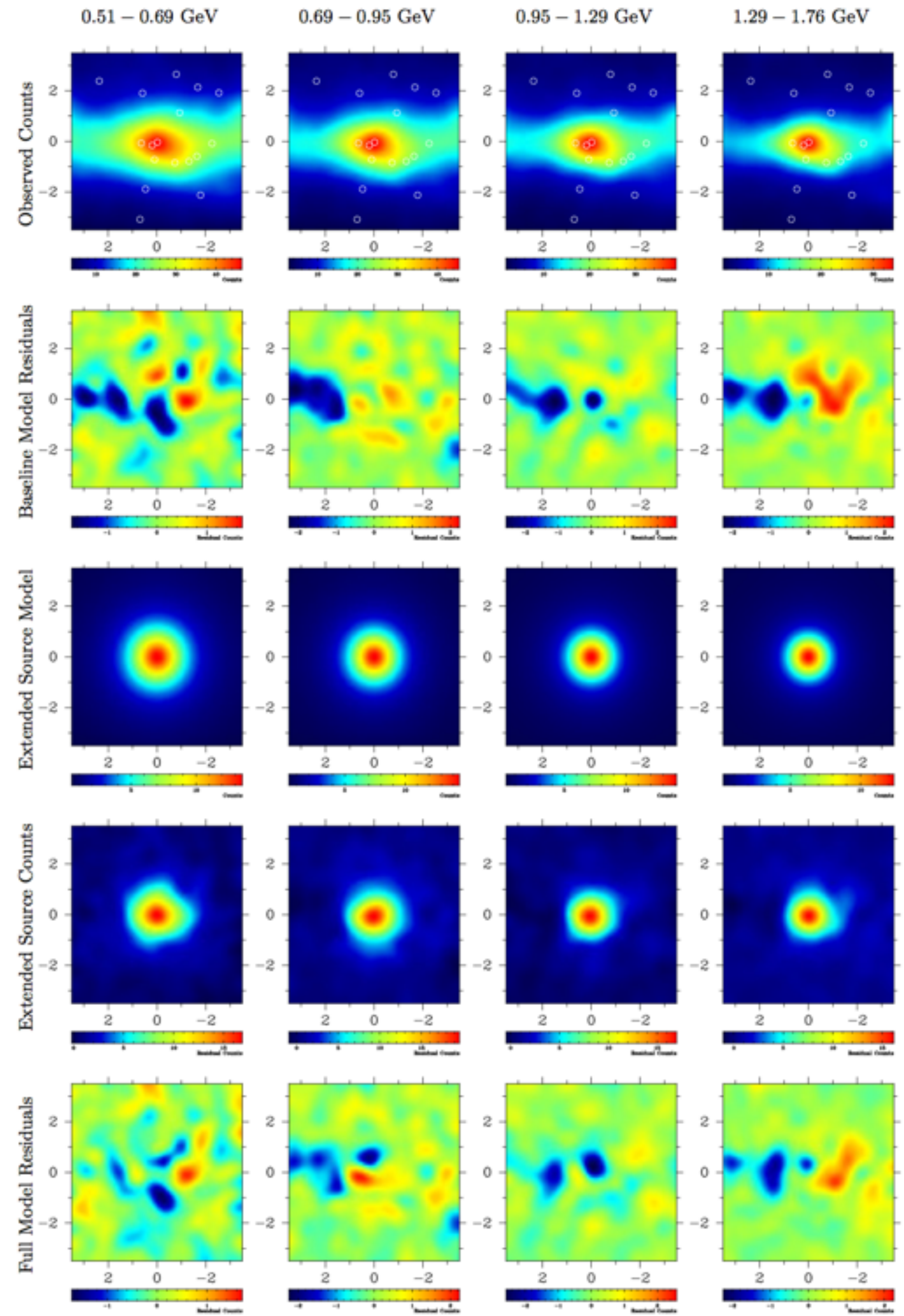


Previous Efforts

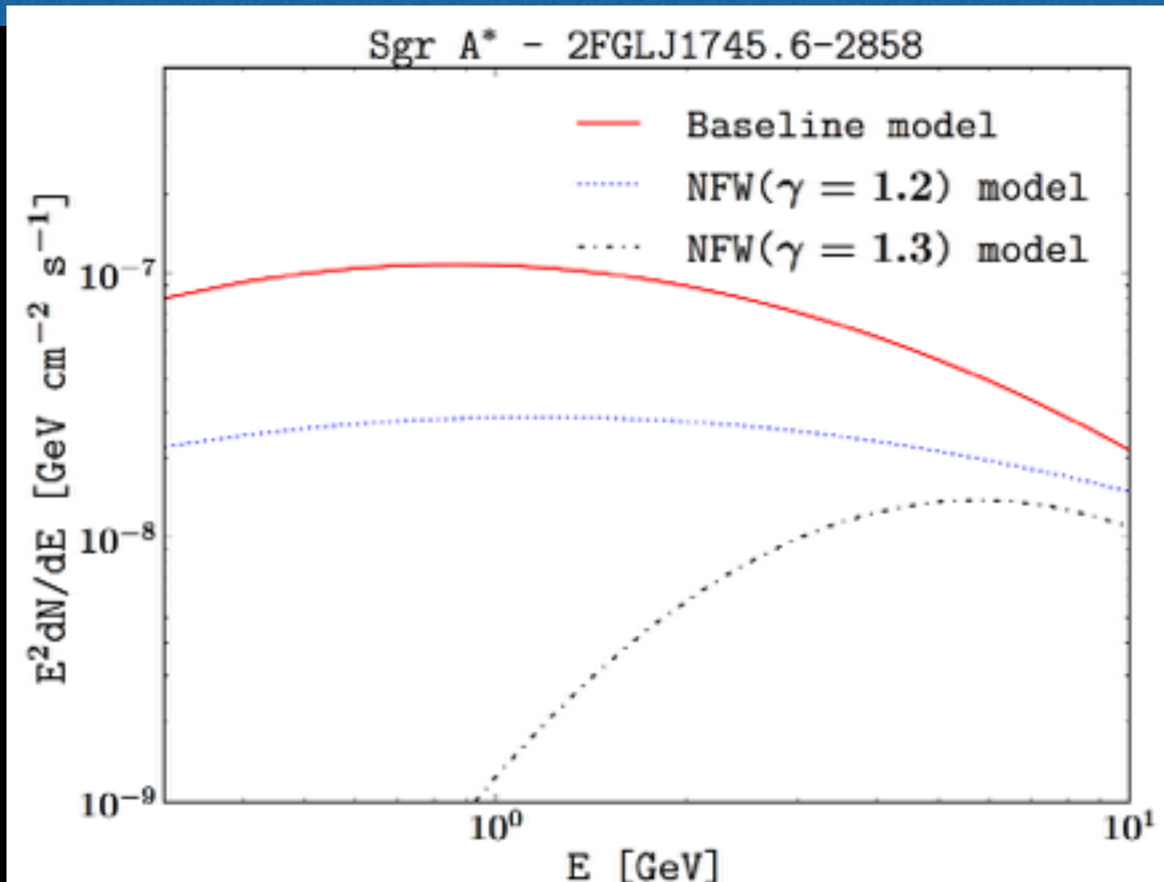
channel, m_χ	$\mathrm{TS}_\approx$	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 10 GeV	2385.7	139913.6	156.5
$b\bar{b}$, 30 GeV	3460.3	139658.3	411.8
$b\bar{b}$, 100 GeV	1303.1	139881.1	189.0
$b\bar{b}$, 300 GeV	229.4	140056.6	13.5
$b\bar{b}$, 1 TeV	25.5	140108.2	−38.0
$b\bar{b}$, 2.5 TeV	7.6	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

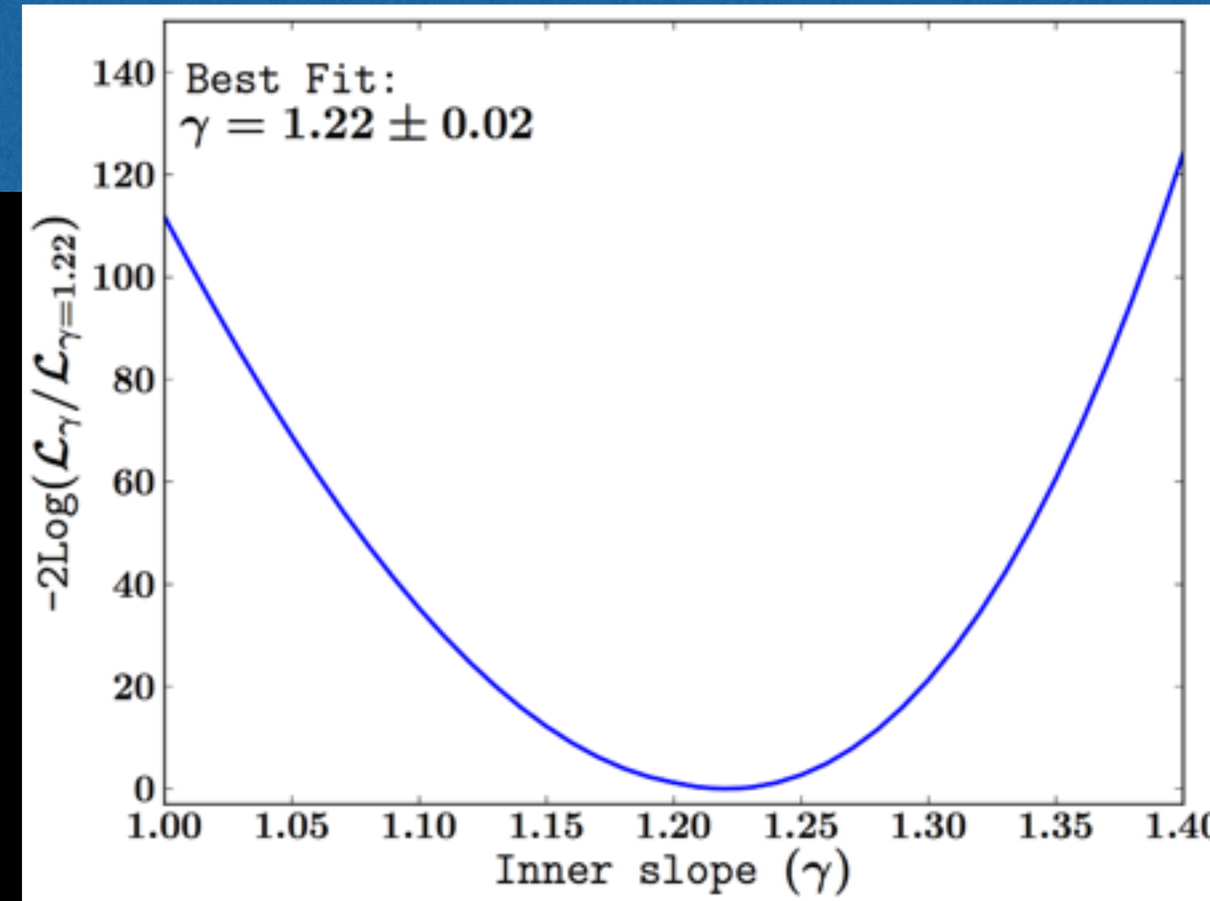
Abazajian & Kaplinghat (2012) produce a more sophisticated template fitting technique.

They quantify the **γ**-ray residual as preferable to models without a dark matter template at the level of more than 20σ

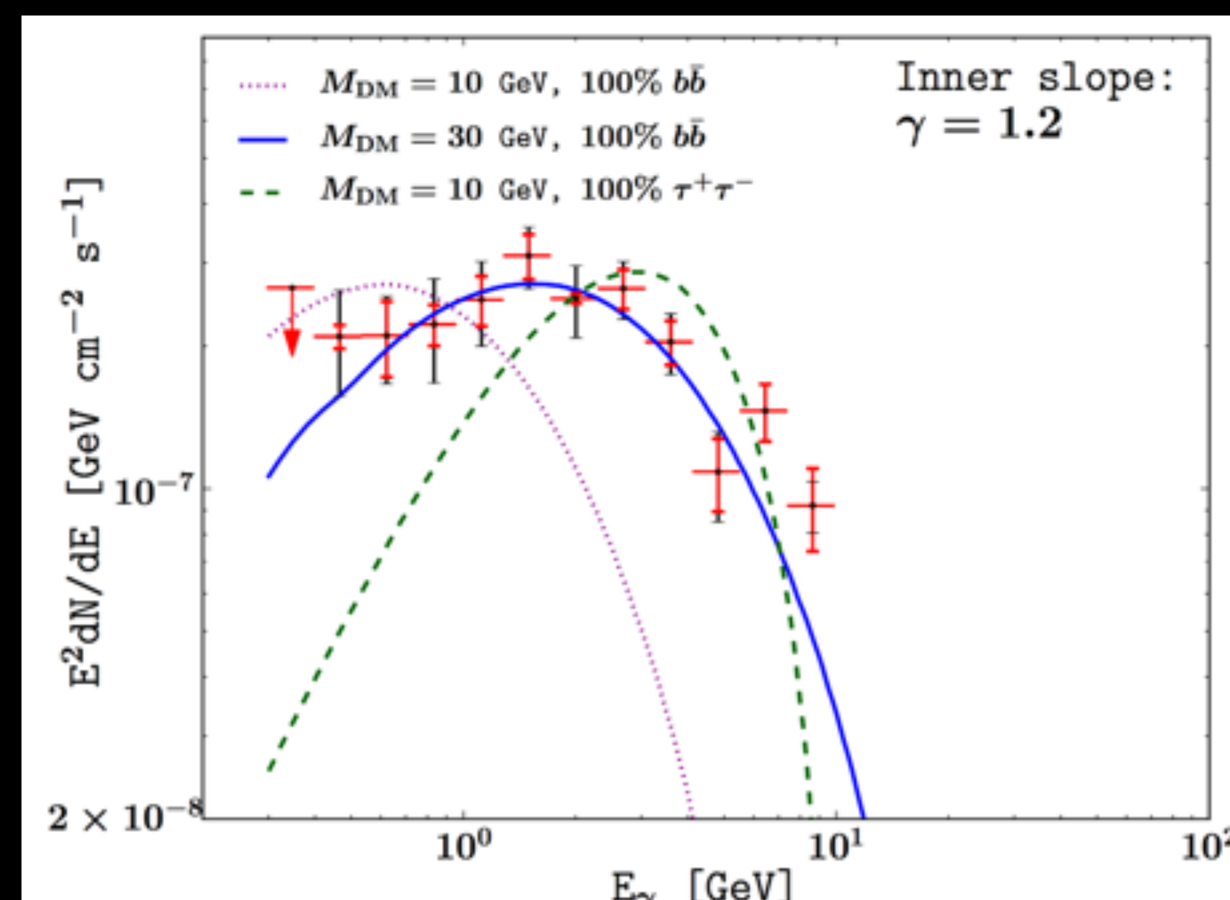


Previous Efforts

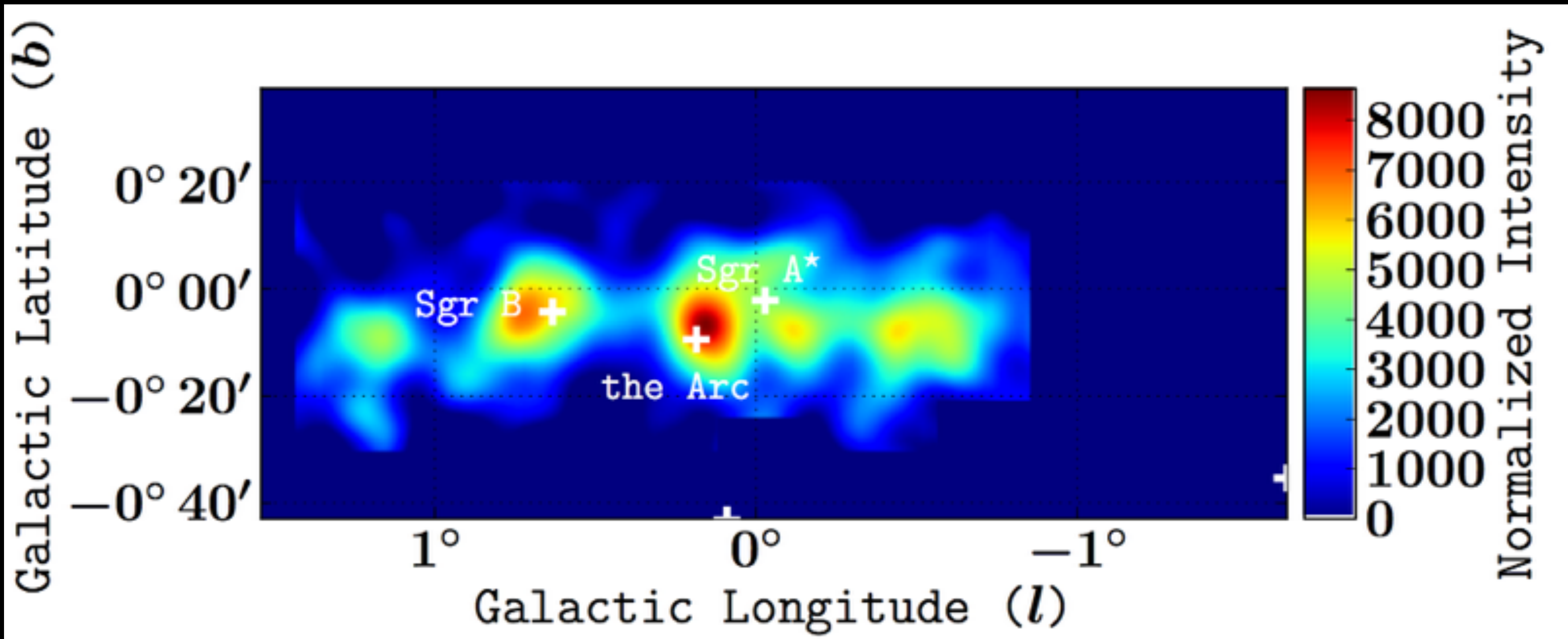




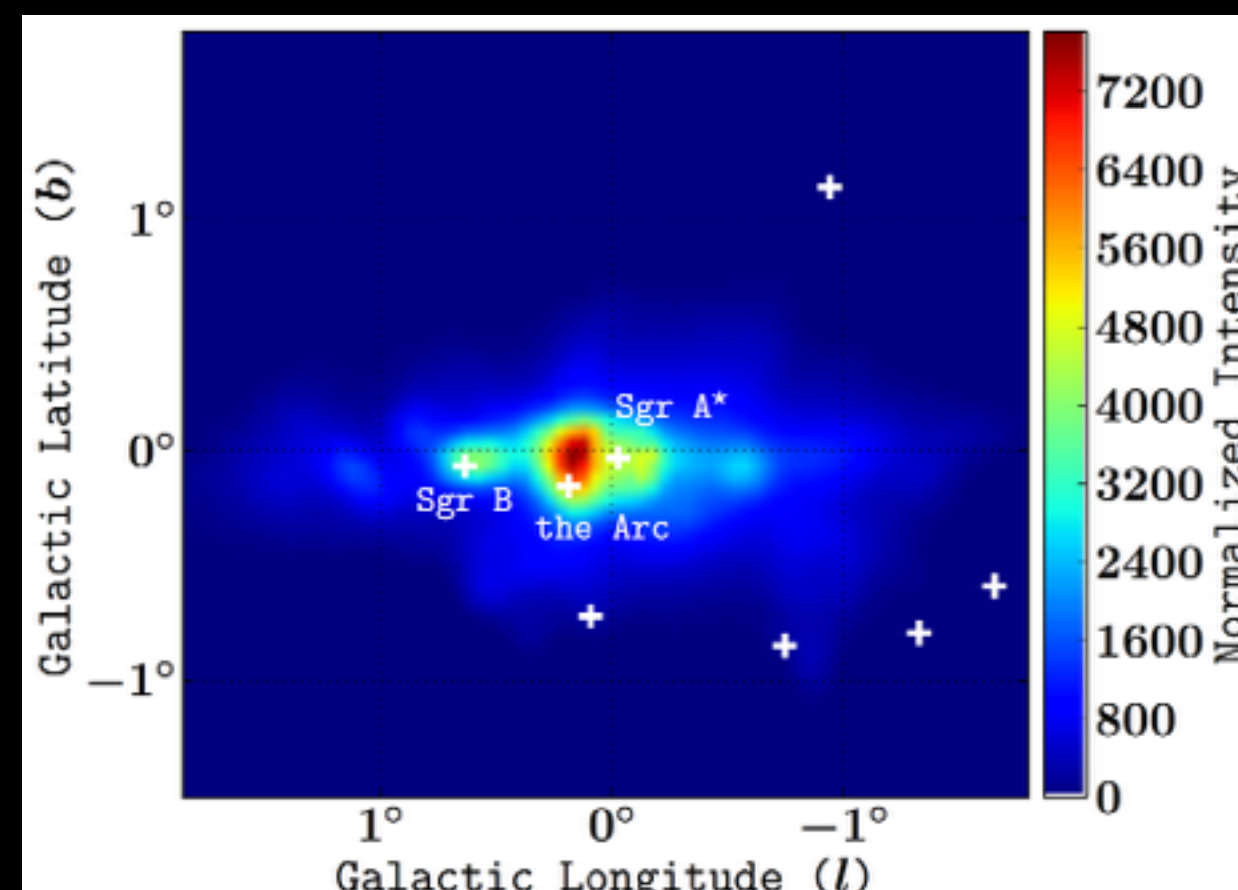
Gordon & Macias (2013) investigated variations in the spectra of the point source components, and also put strong constraints on the inner slope of the NFW profile



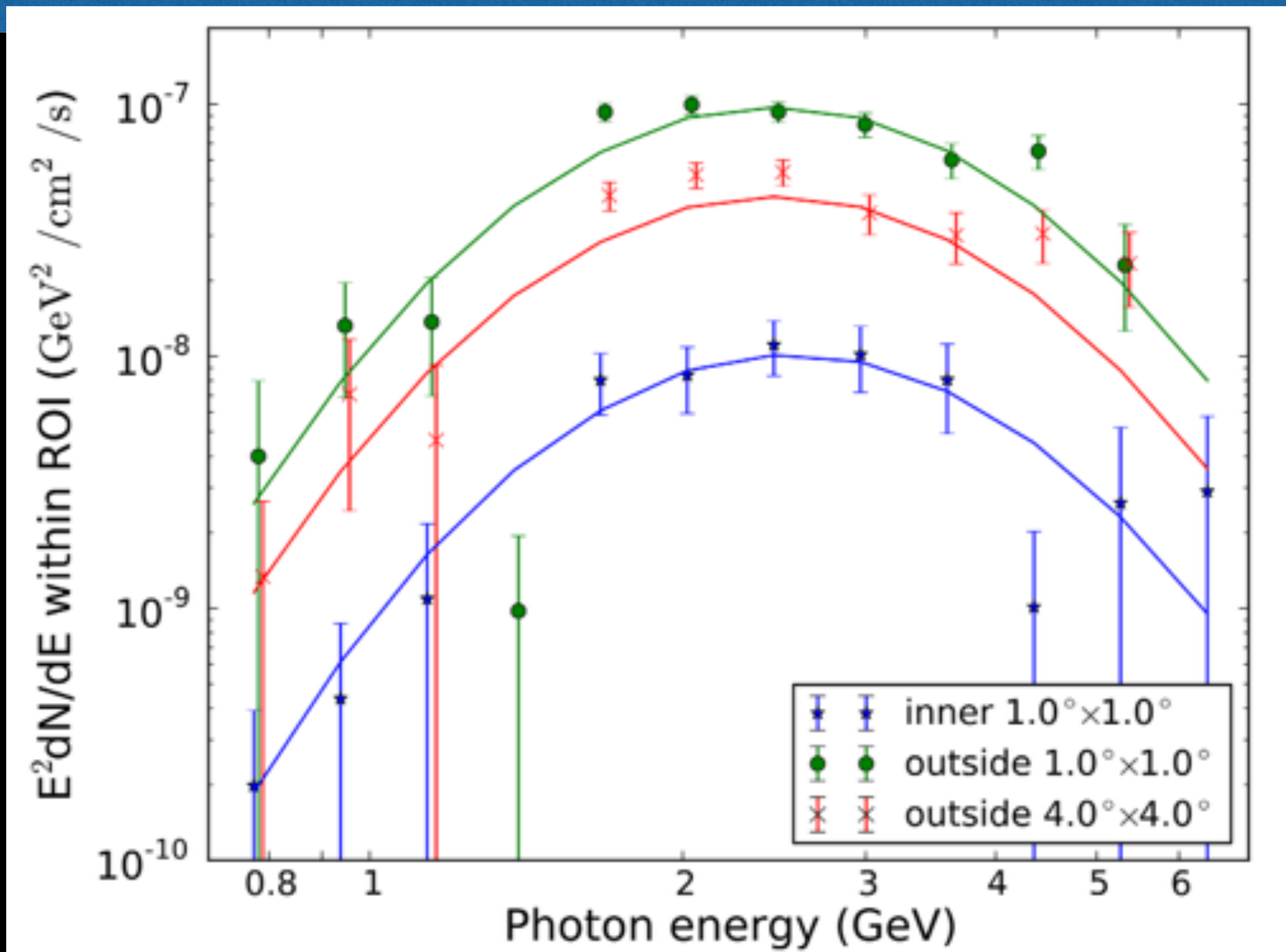
Previous Efforts

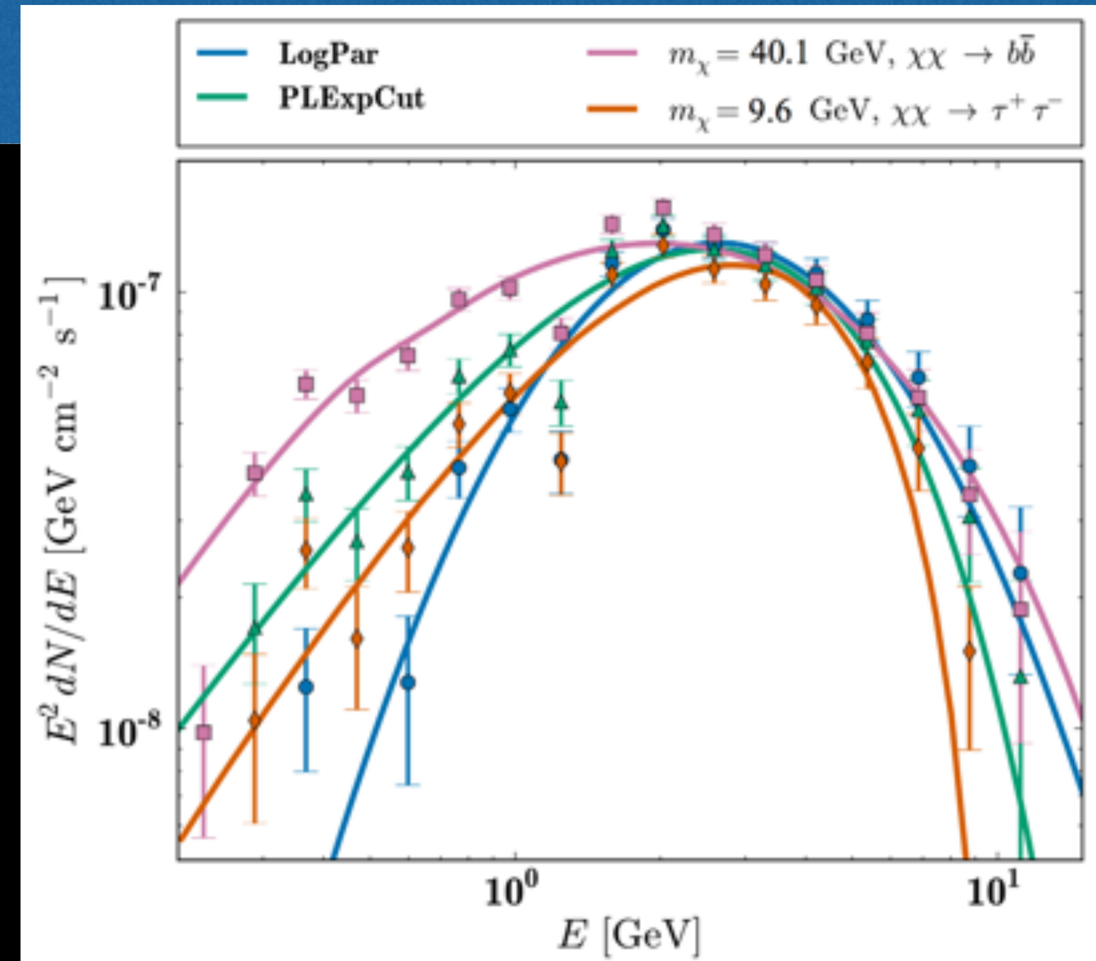


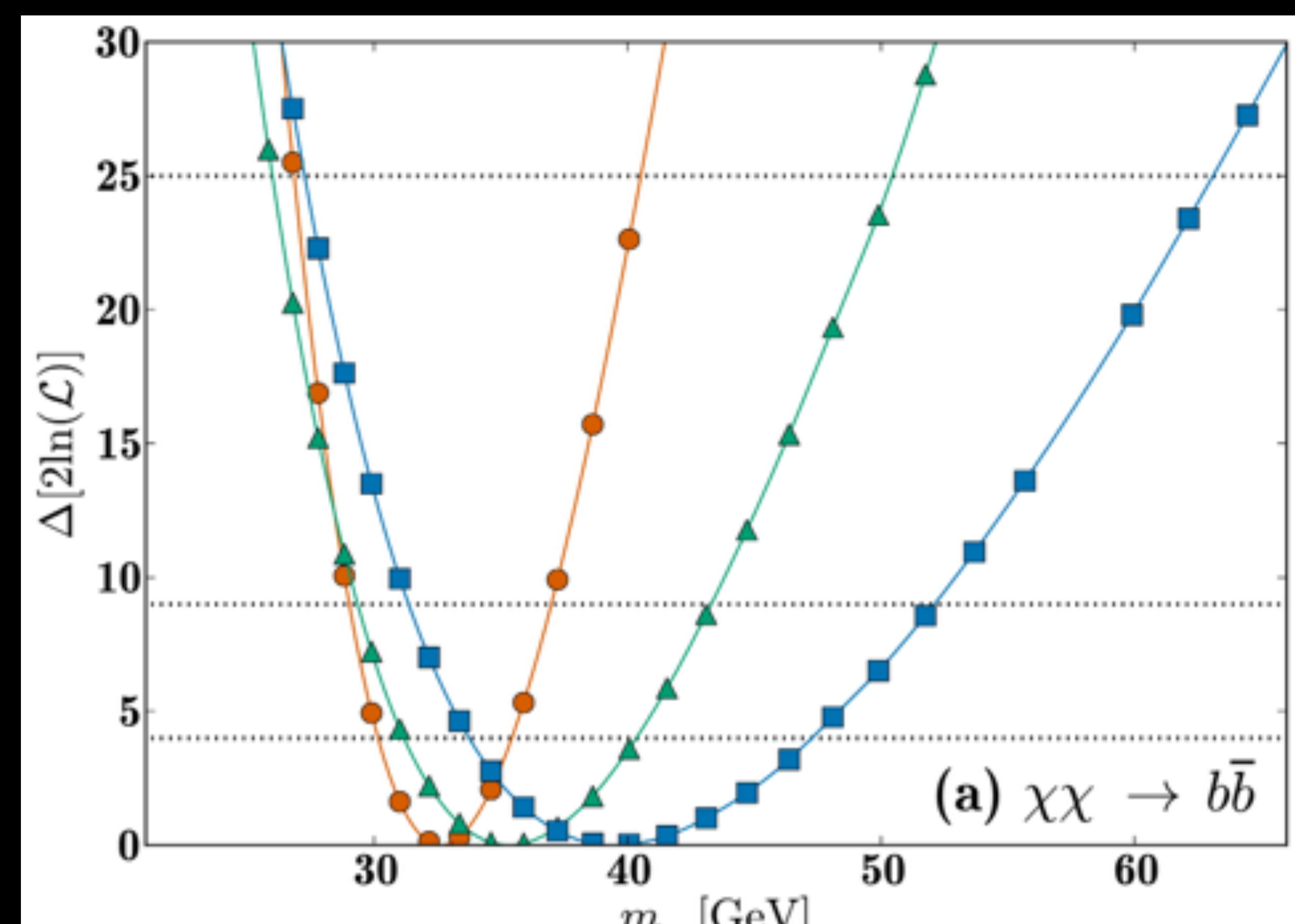
Macias & Gordon (2013) investigated possible contributions corresponding to the morphology of the HESS TeV emission and to 20 cm synchrotron emission, and found the **γ**-ray excess to be resilient to the addition of these models



Previous Efforts



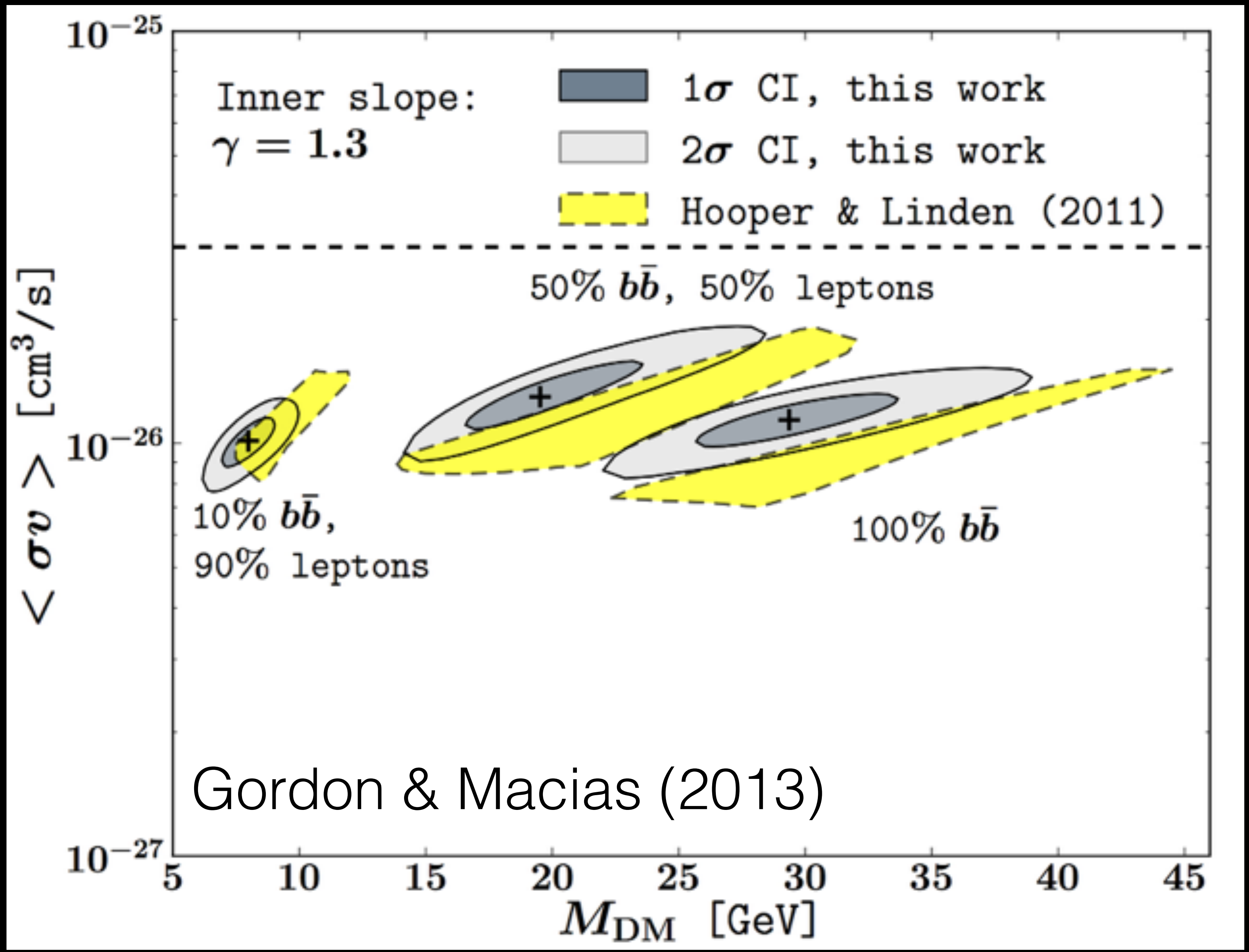




Abazajian et al. (2014) found the spectrum of the residual to be resilient to more than 4º away from the galactic center

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

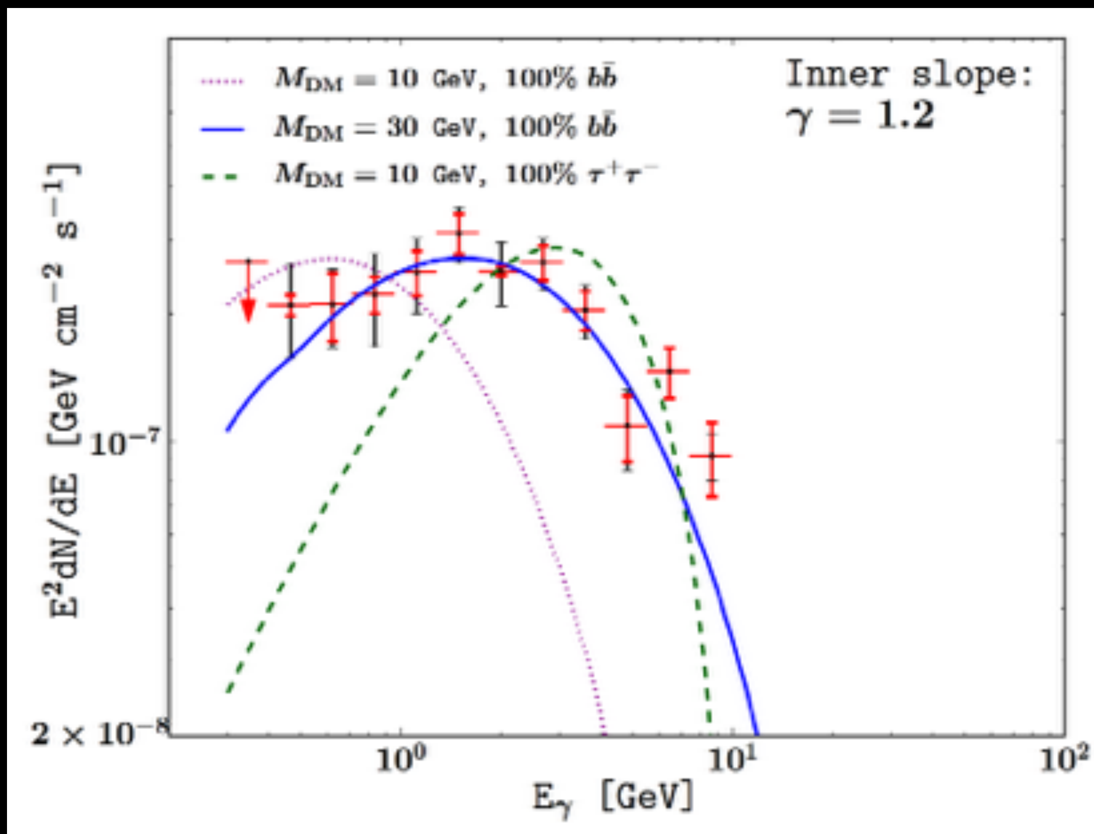
A Broad Consensus



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

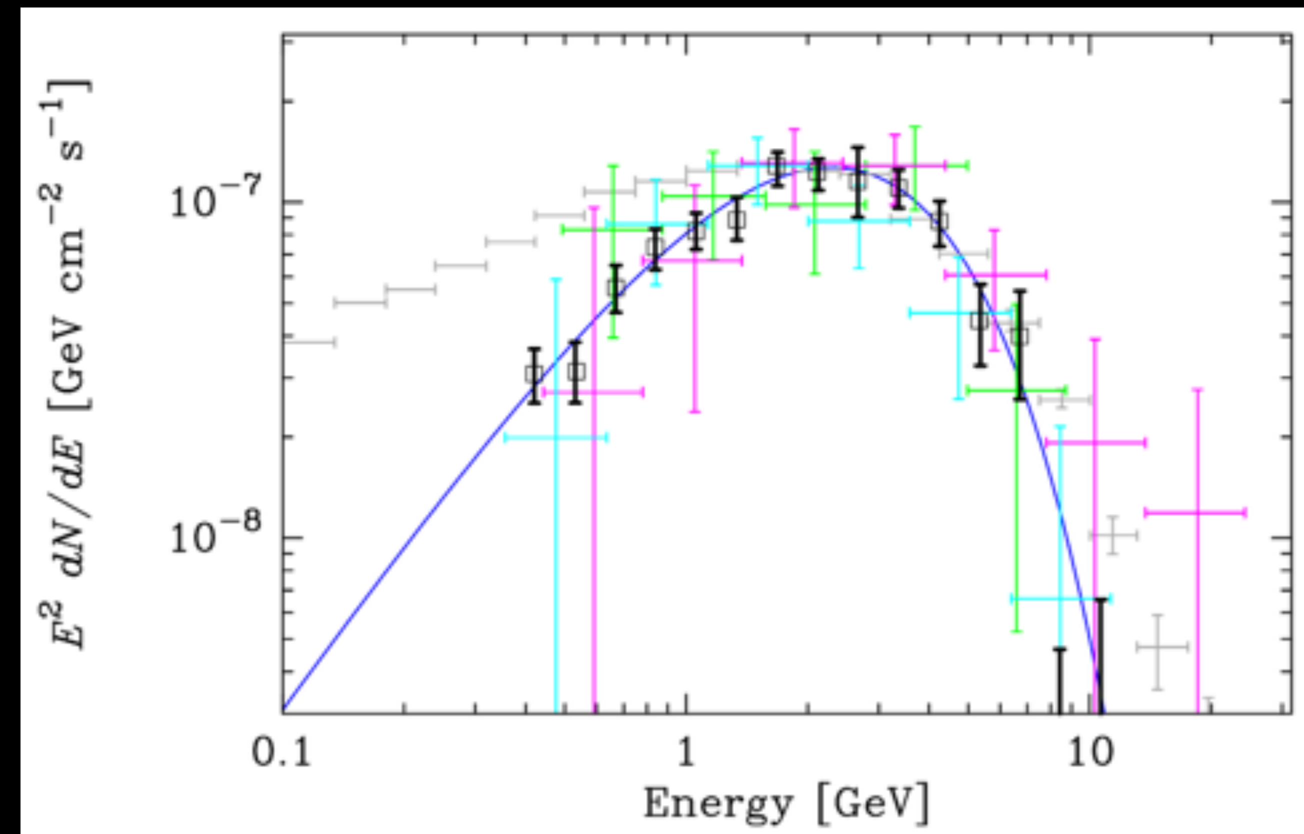
Two Interpretations of the Old Data

Dark Matter



Gordon & Macias (2013)

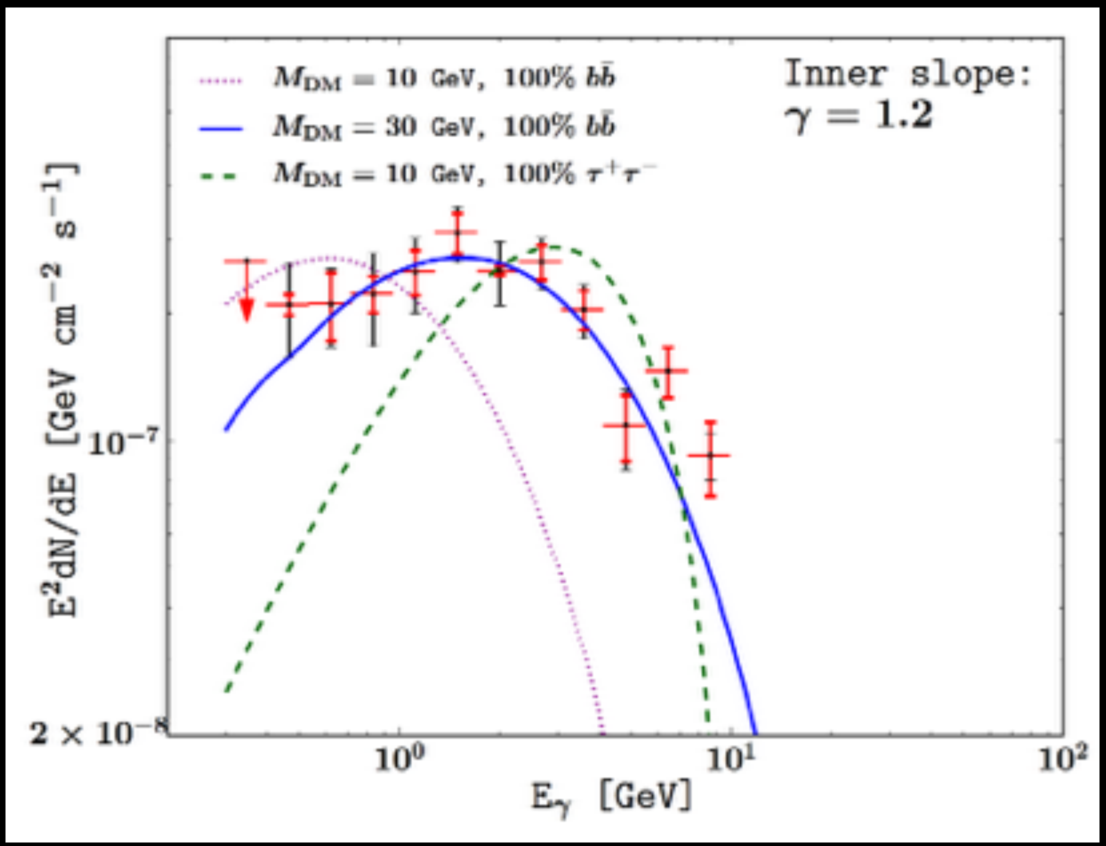
Millisecond Pulsars



Abazajian (2011)

Two Interpretations of the Old Data

Dark Matter



Gordon & Macias (2013)

Need a WIMP of mass ~25-40 GeV (if annihilating to bb)

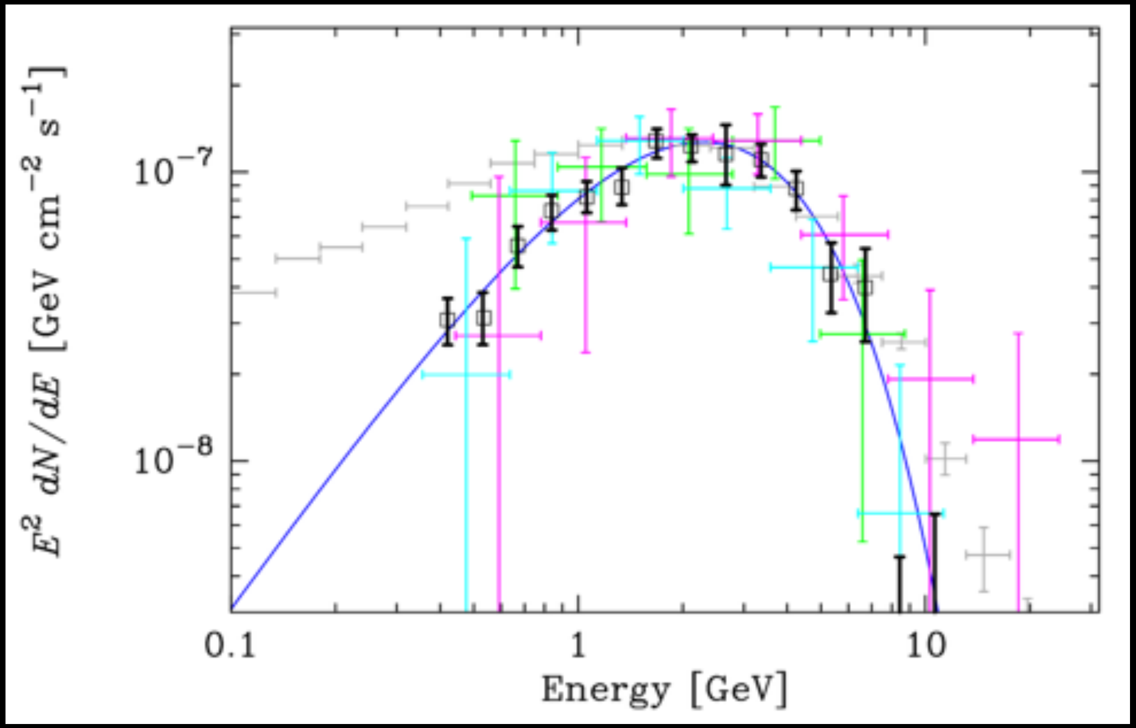
Need a slightly adiabatically contracted NFW profile $\boldsymbol{\gamma}$ ~ 1.1-1.3

Need a dark matter annihilation cross-section ~ 1.5 - 2.5 x 10^{-26}
(for a local density 0.3 GeV cm^{-3})

Two Interpretations of the Old Data

Millisecond Pulsars

Abazajian (2011)



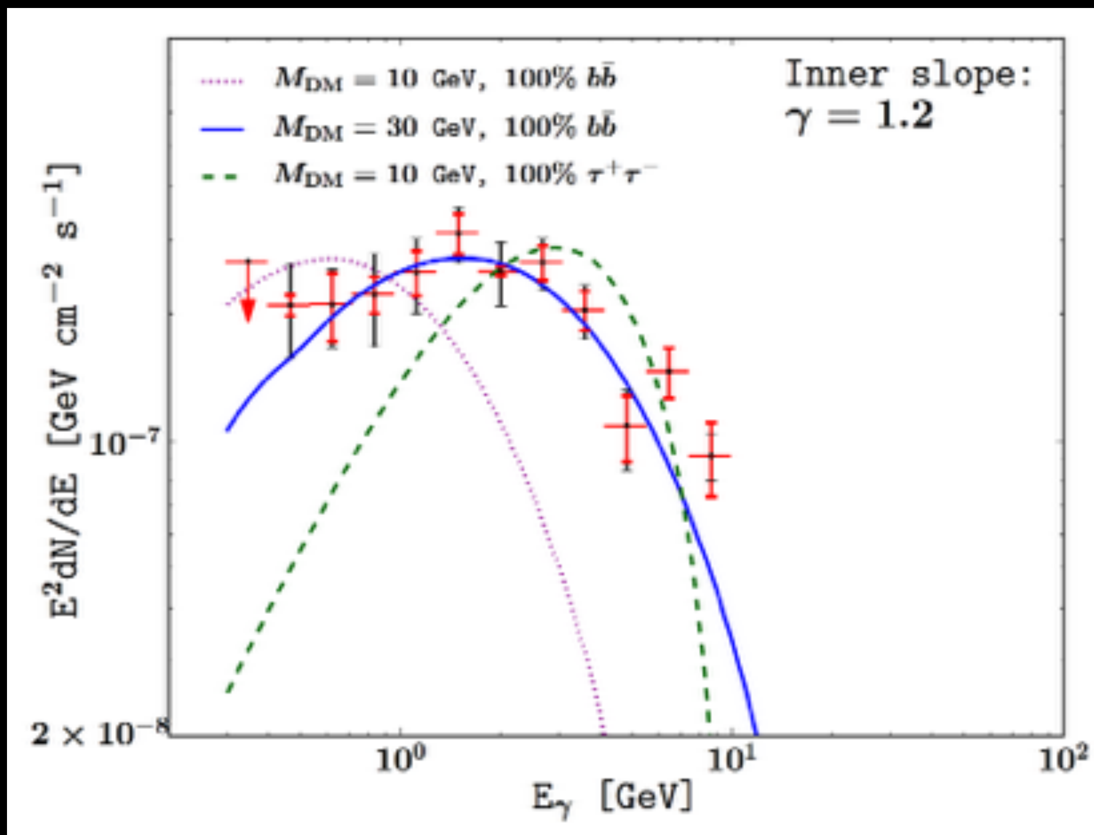
Need a population of approximately 2000 - 4000 MSPs within the inner degree around the GC

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

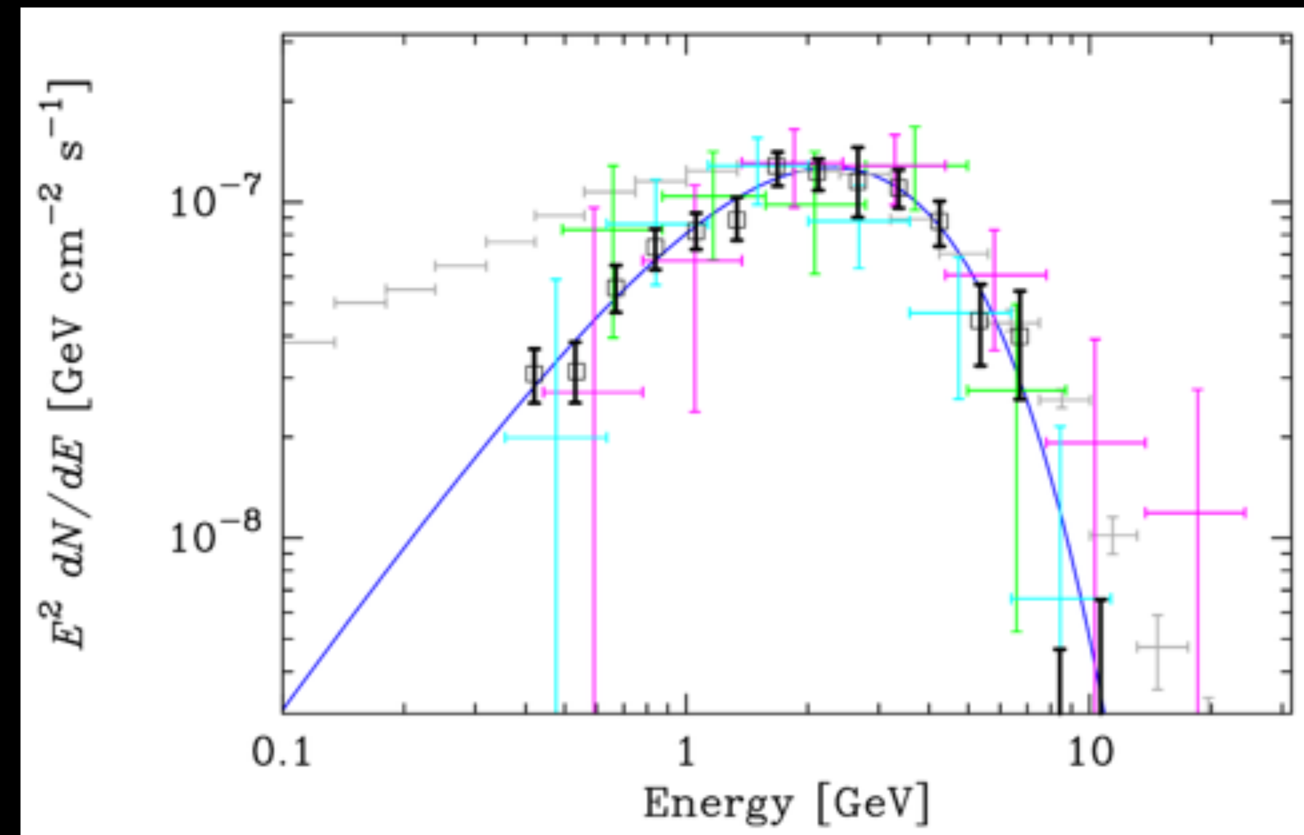
Two Interpretations of the Old Data

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

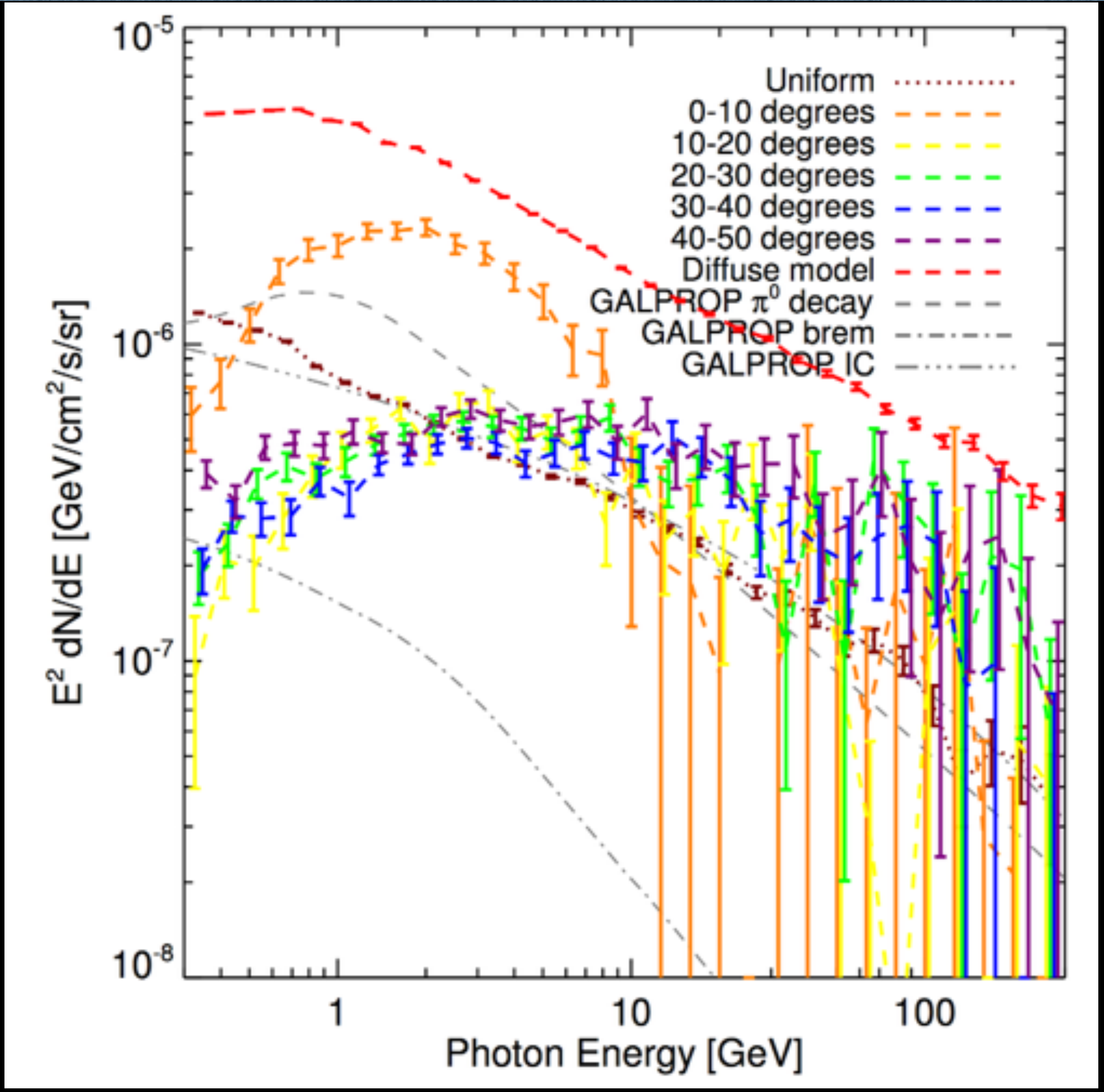
Previous Efforts

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

1.) They masked the region |b| < 1º, 2º, and 5º.

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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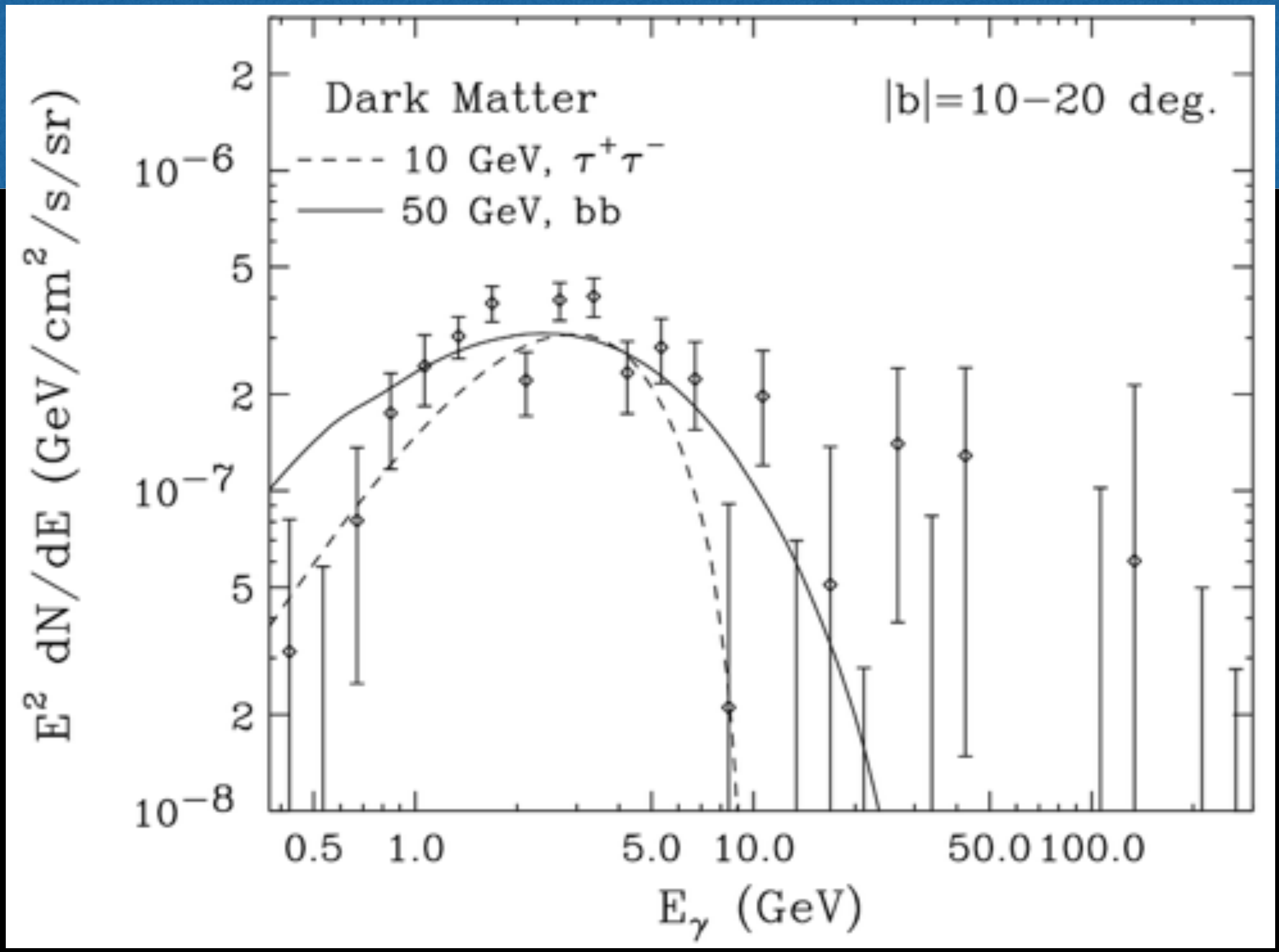
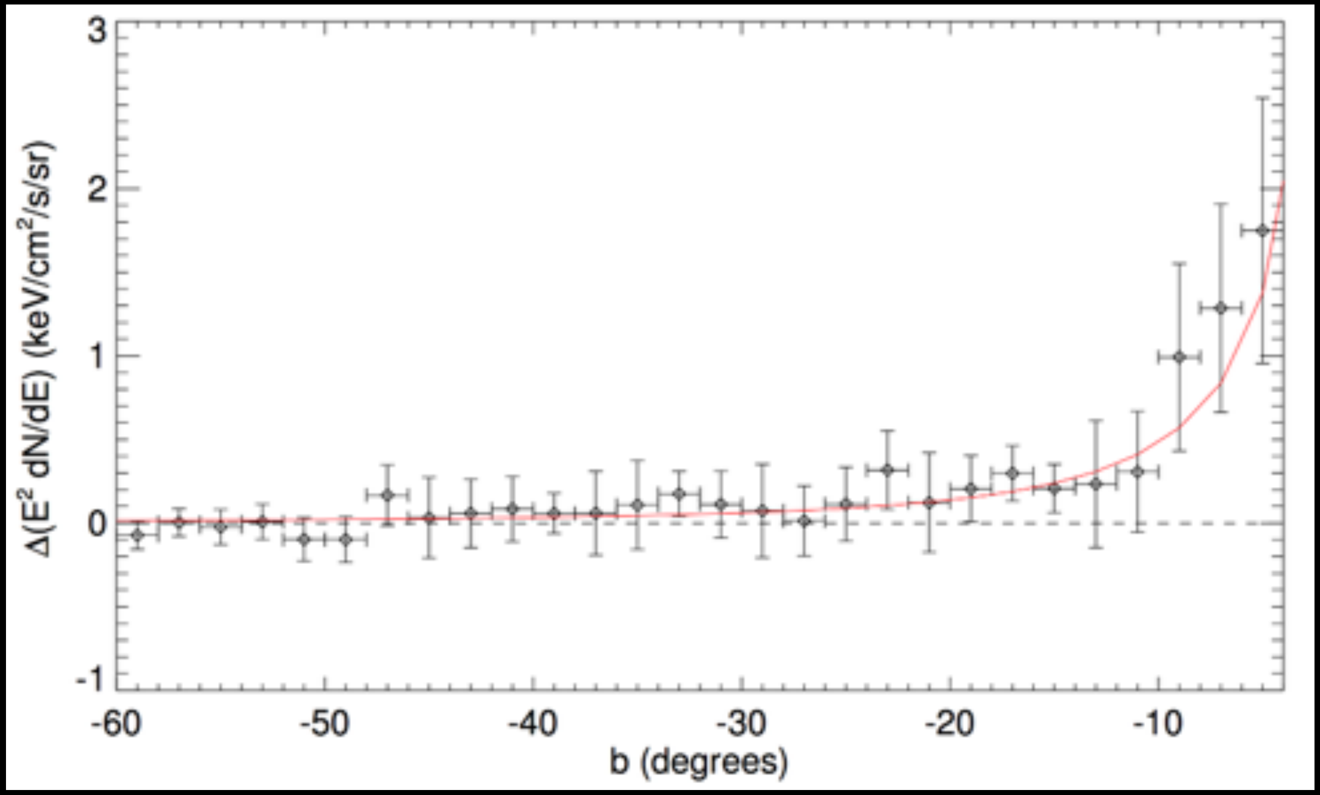


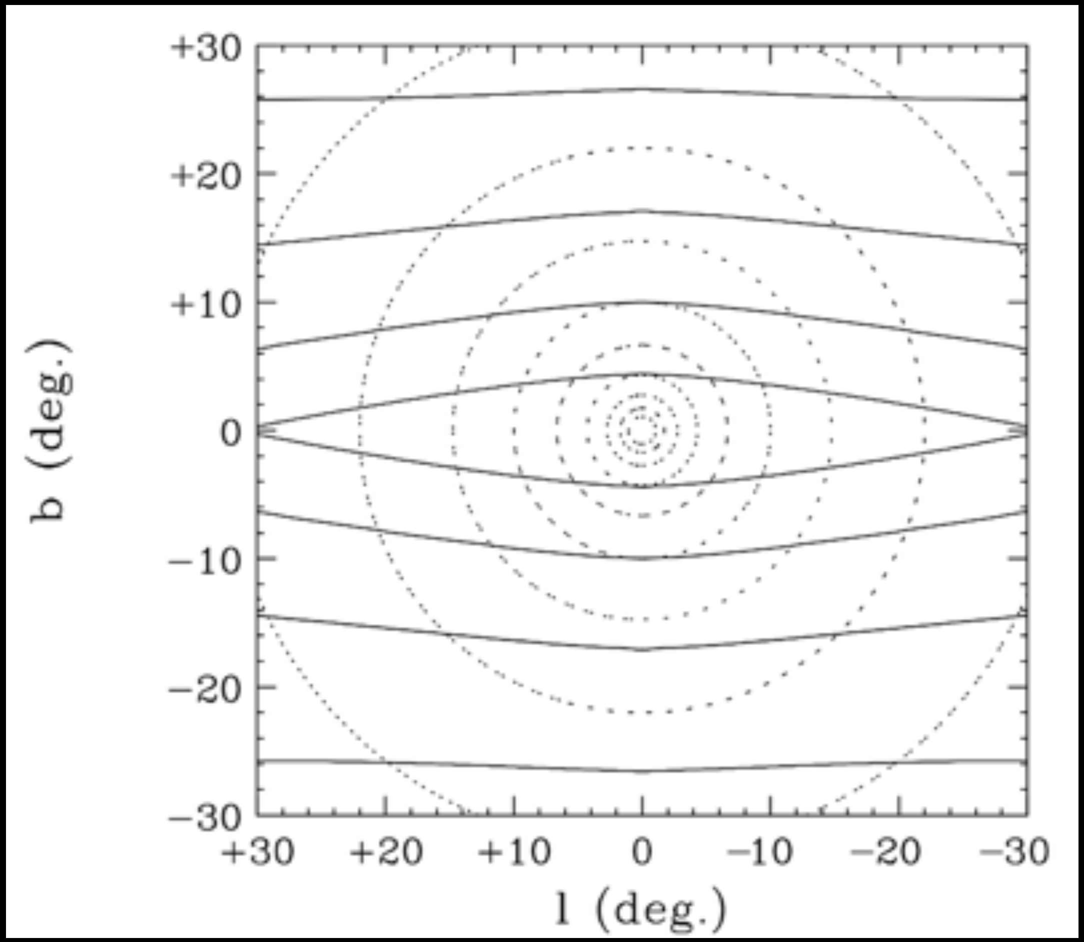


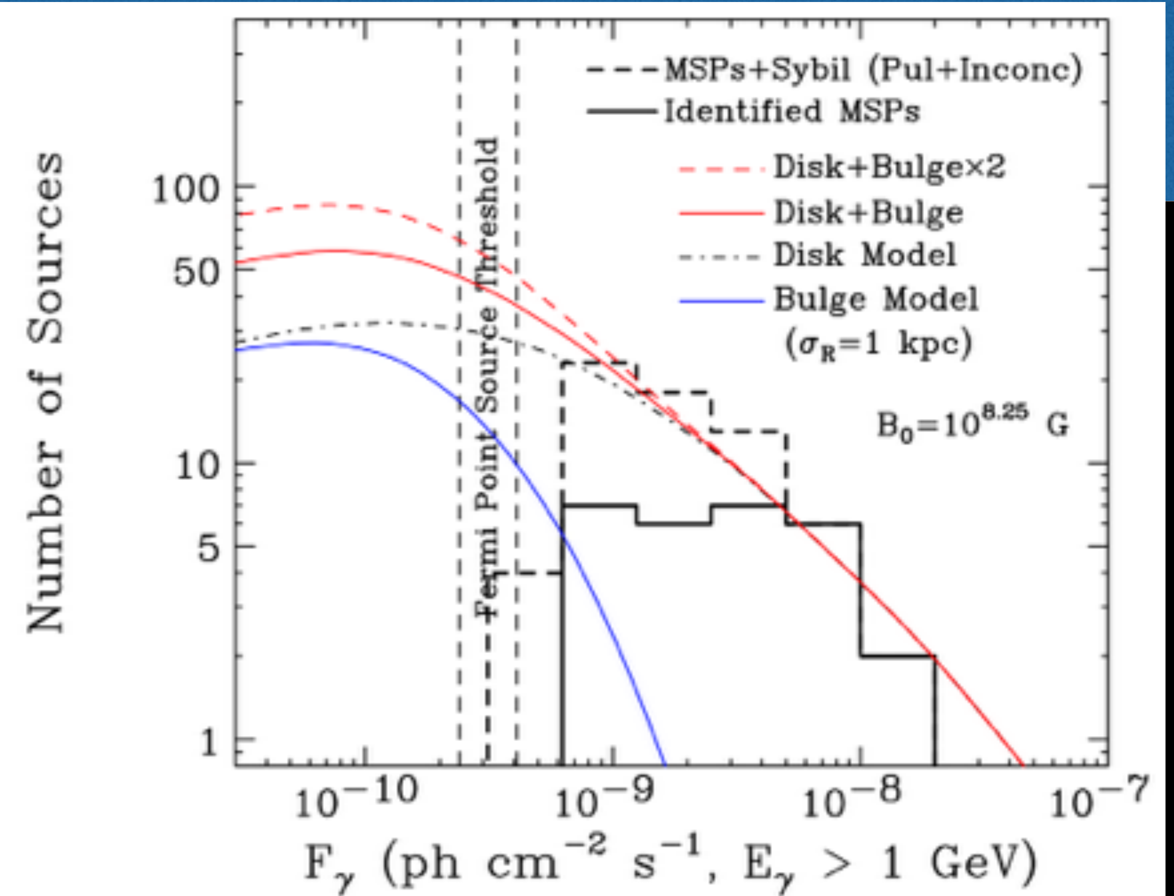
The Inner Galaxy Analysis

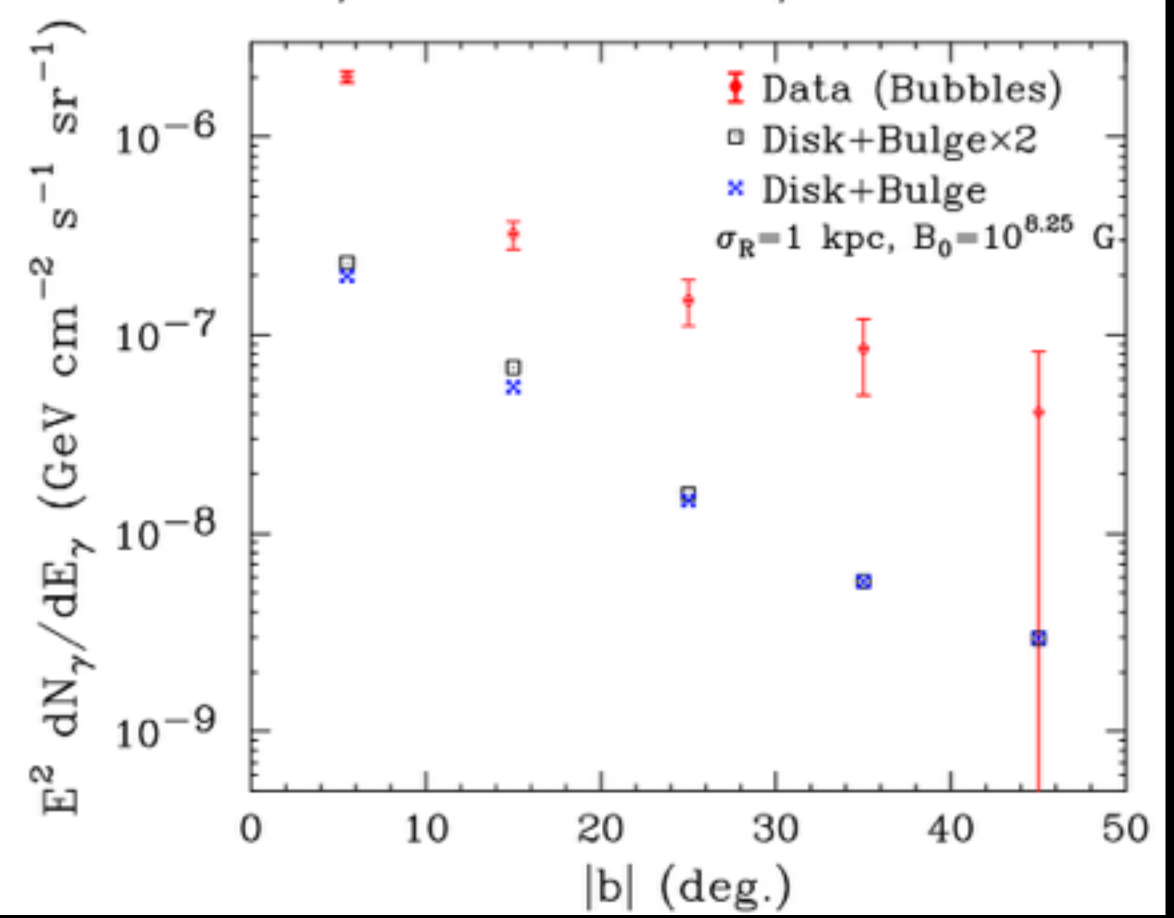
This disfavored pulsar interpretations for two reasons

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







Hooper et al. (2013)

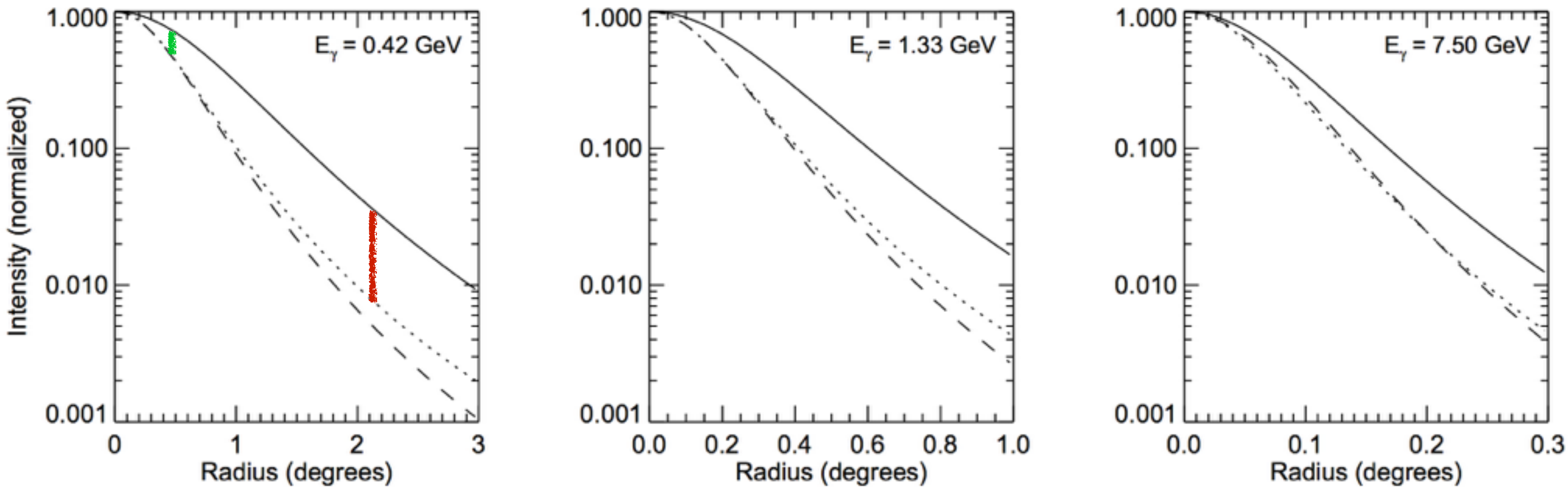
The Current Paper - Three Objectives

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

Portillo & Finkbeiner (2014, TBS)

Data Selection

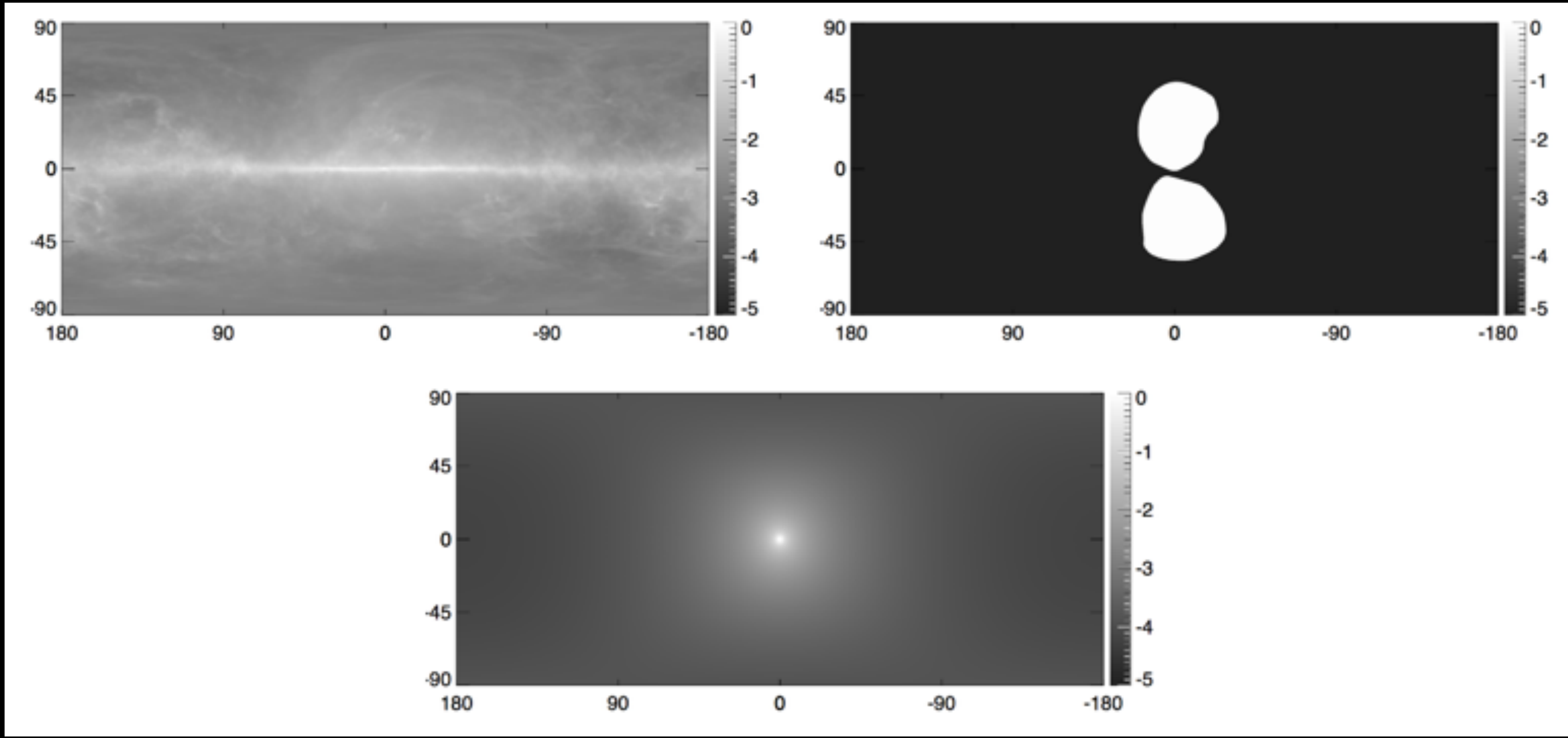
The new CTBCORE cut is applied to two different selections of the Fermi-LAT data

Inner Galaxy - $|b| > 1^o$

Galactic Center - $| l | < 5^o$ $|b| < 5^o$

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

The Inner Galaxy Excess



1.) Mask |b| < 1°, and a 2° 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

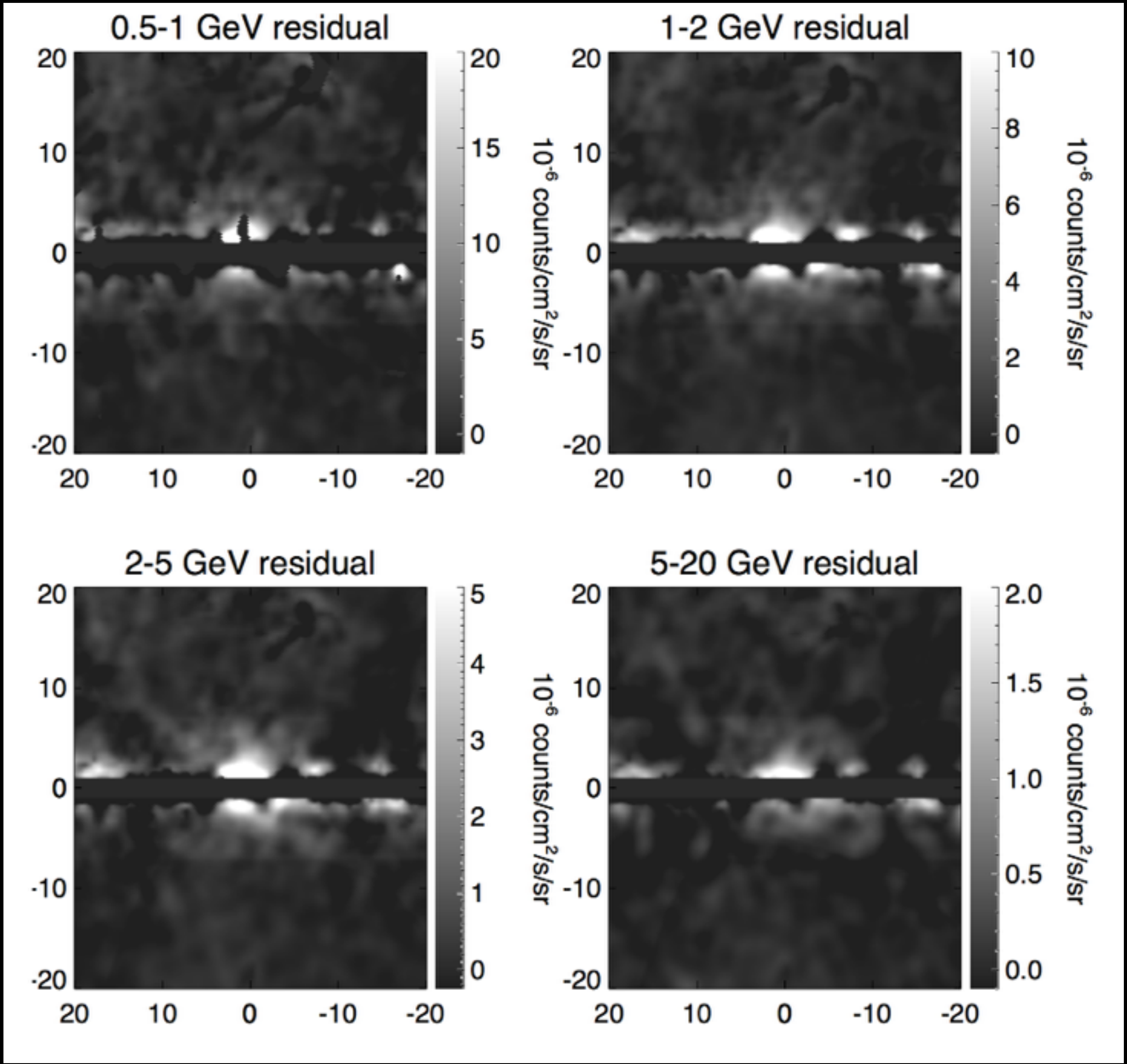
Galactic Center Modeling

1.) Instead model the inner $|l| < 5^o$, $|b| < 5^o$

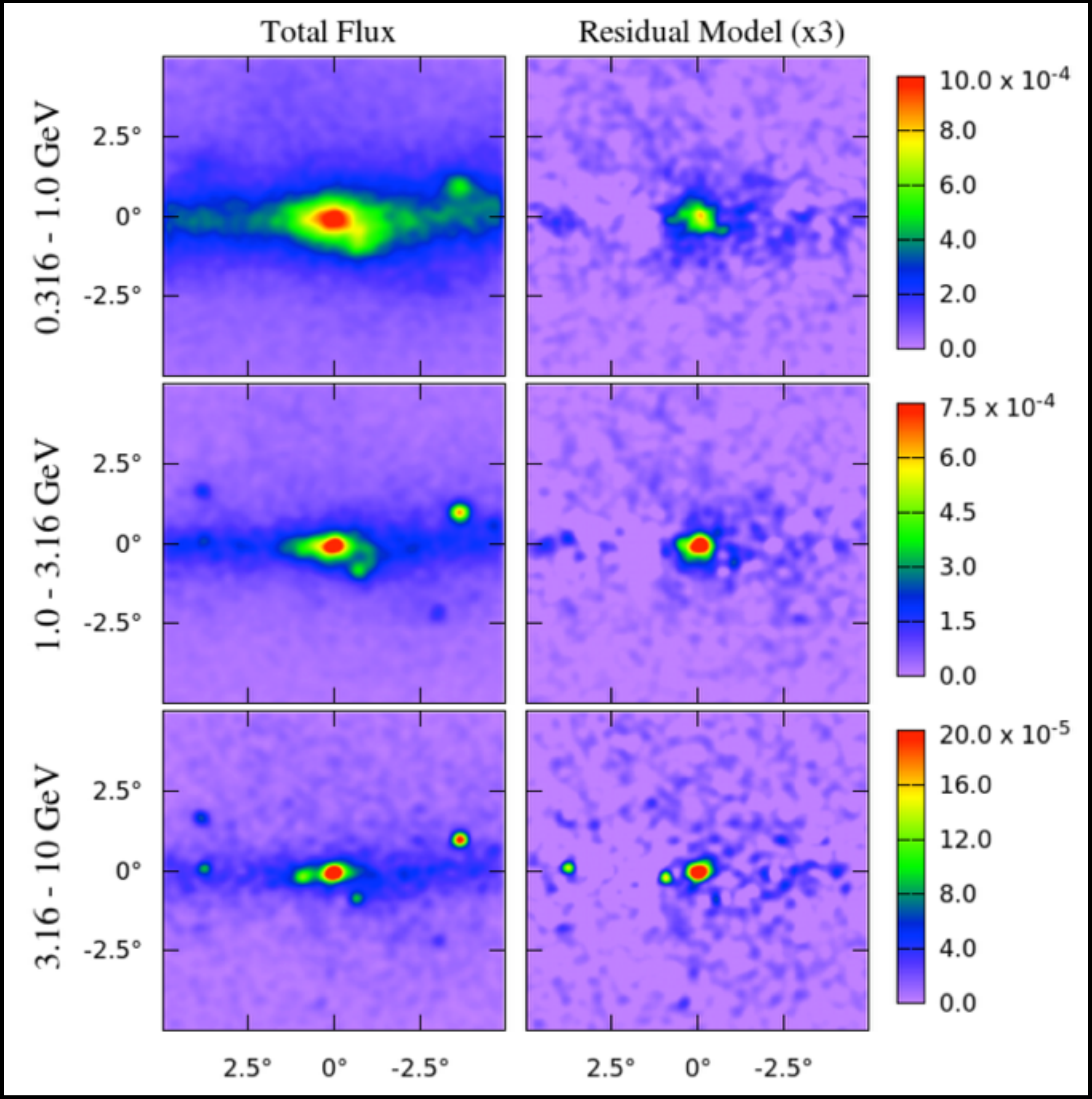
2.) Must include all point sources in the model - along with models for the diffuse emission, isotropic emission, 20cm map

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)

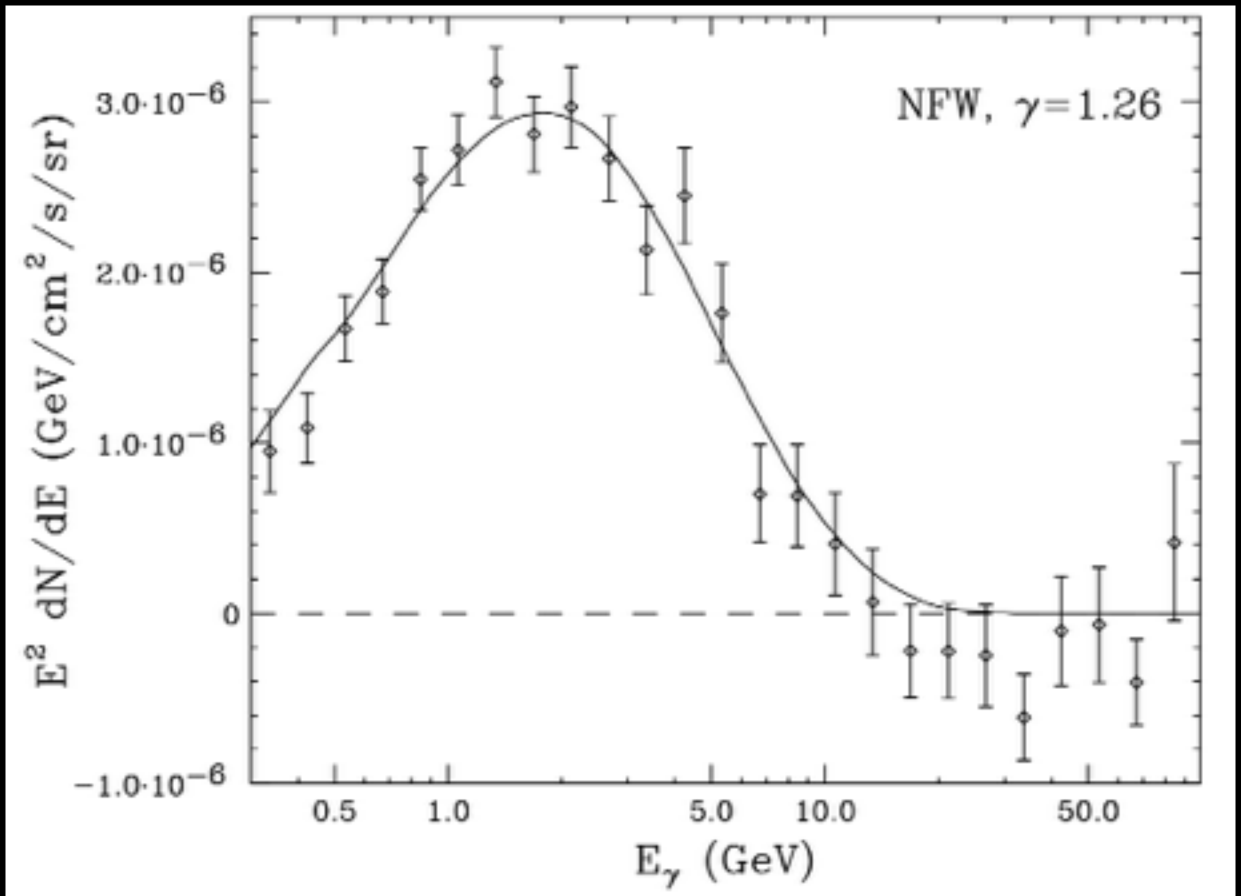
Skymaps of the Residuals

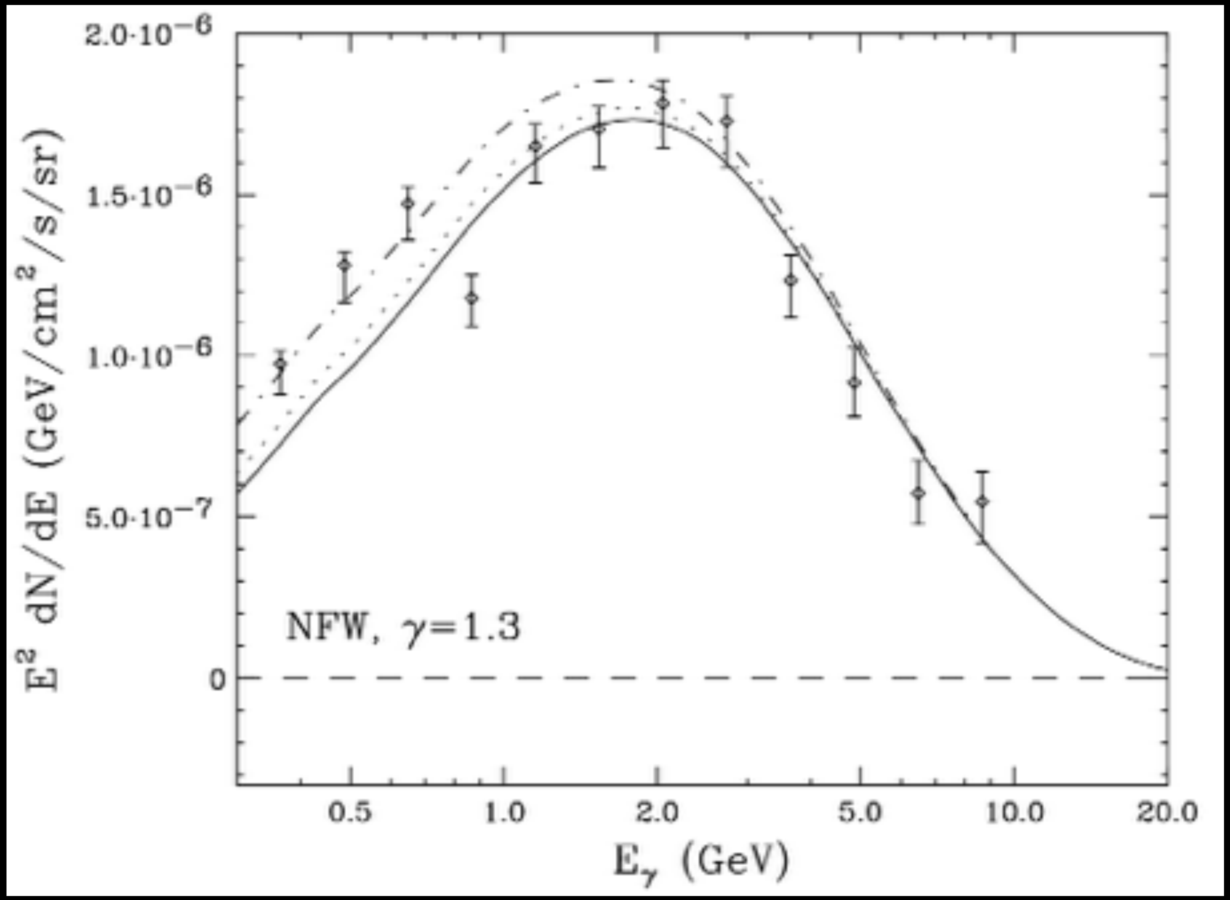


Skymaps of the Residuals



Spectrum of the Residuals

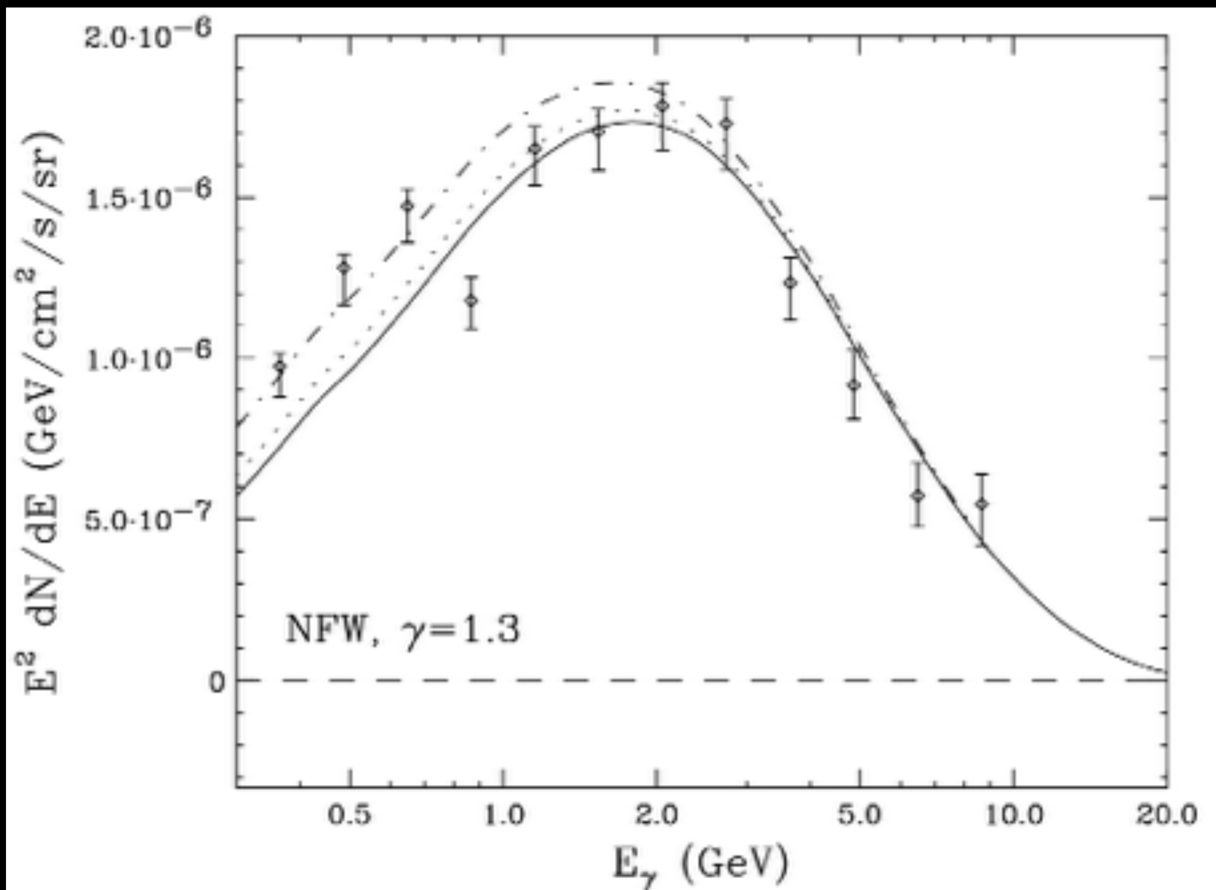




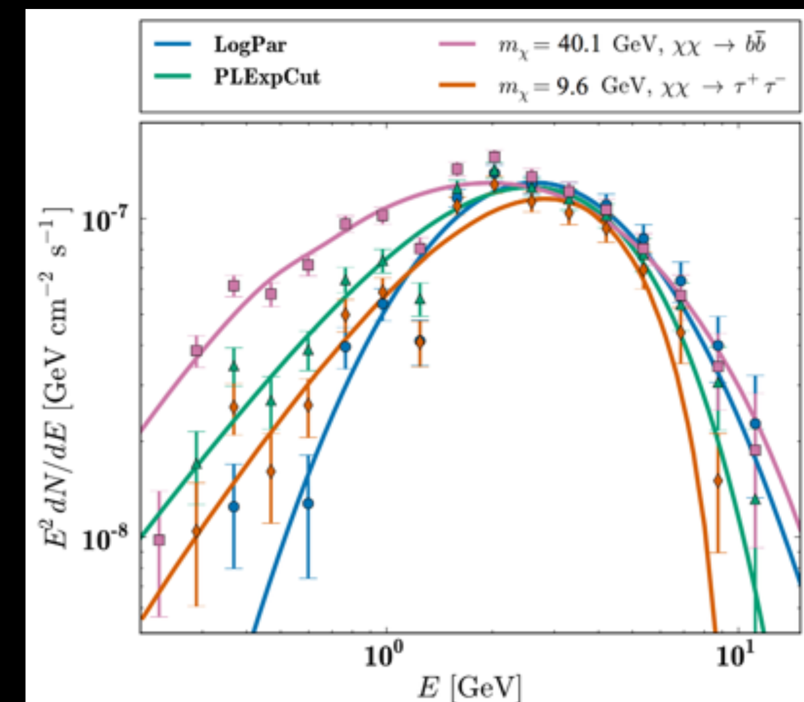
Inner Galaxy - The DM template naturally picks up the following spectral shape - the normalization of the NFW template is allowed to float independently in every energy bin

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

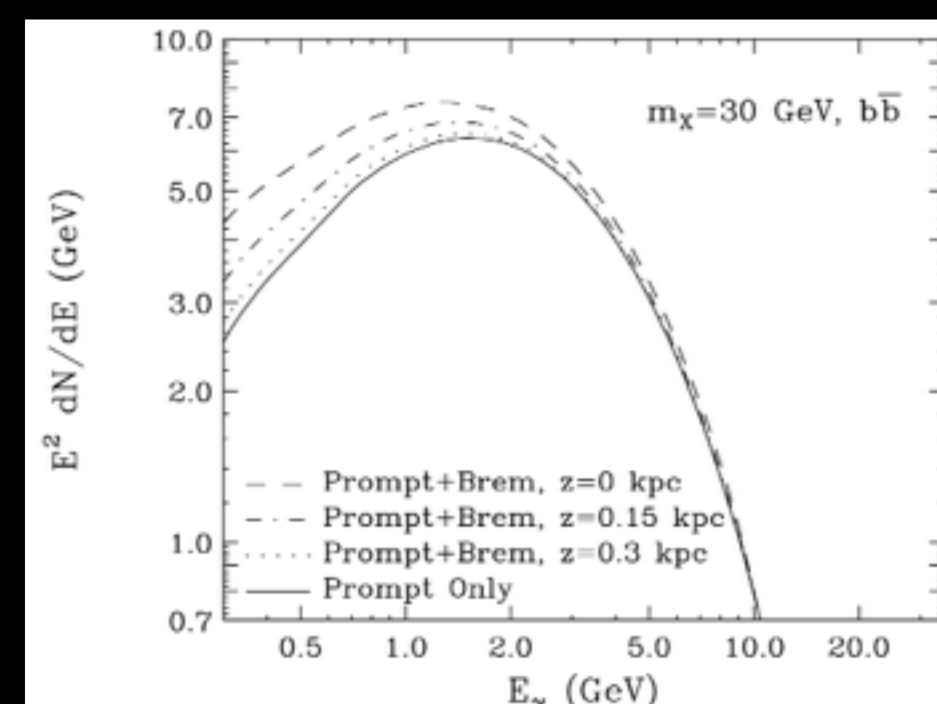


The residual spectra are almost identical, except for some variation below 1 GeV. This could be explained by either measurement or theory:

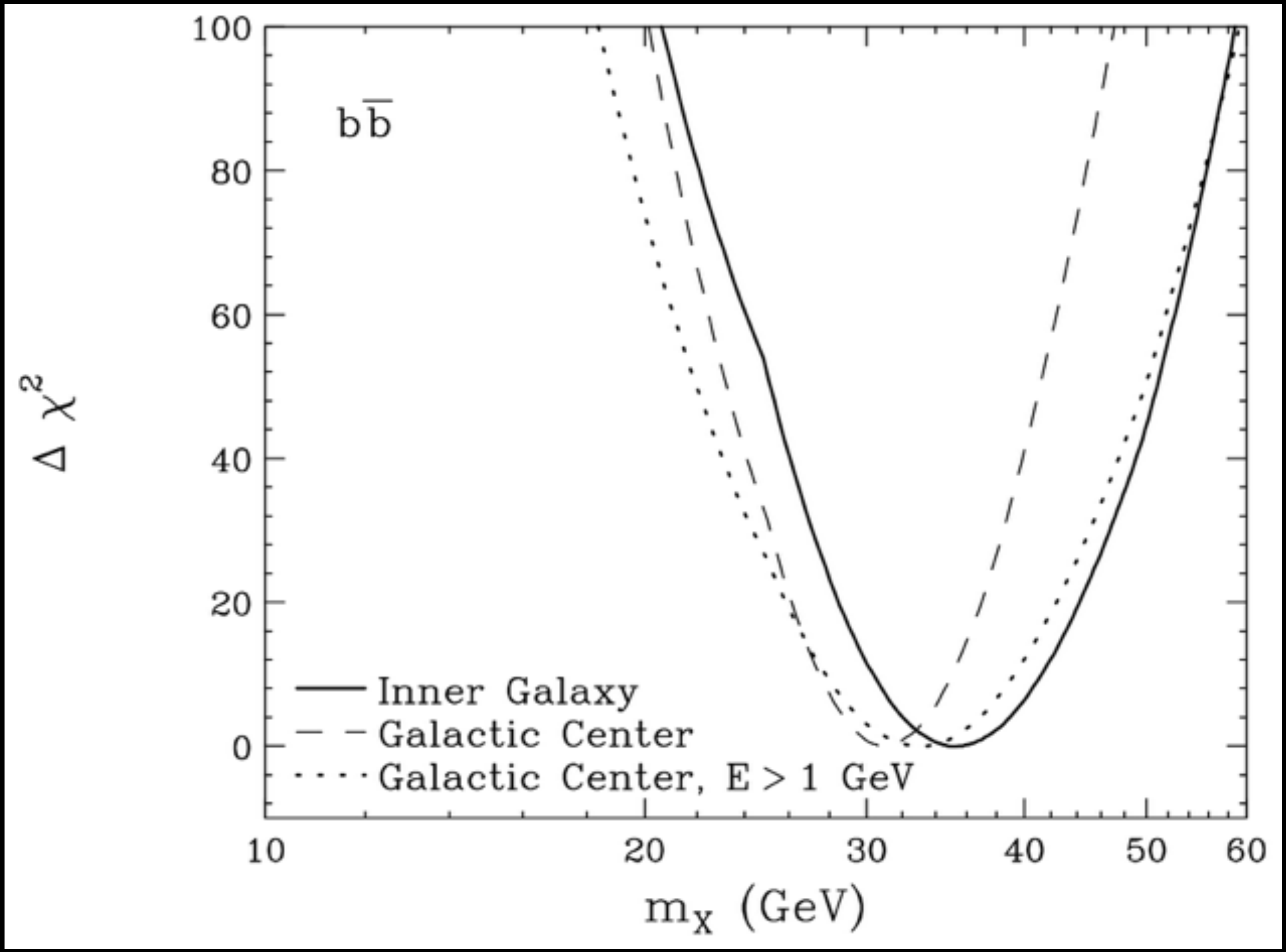


Measurement - The poor PSF of the Fermi-LAT (even with CTBCORE cuts) makes it difficult to distinguish between emission from the many point sources and diffuse emission templates in the GC.

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

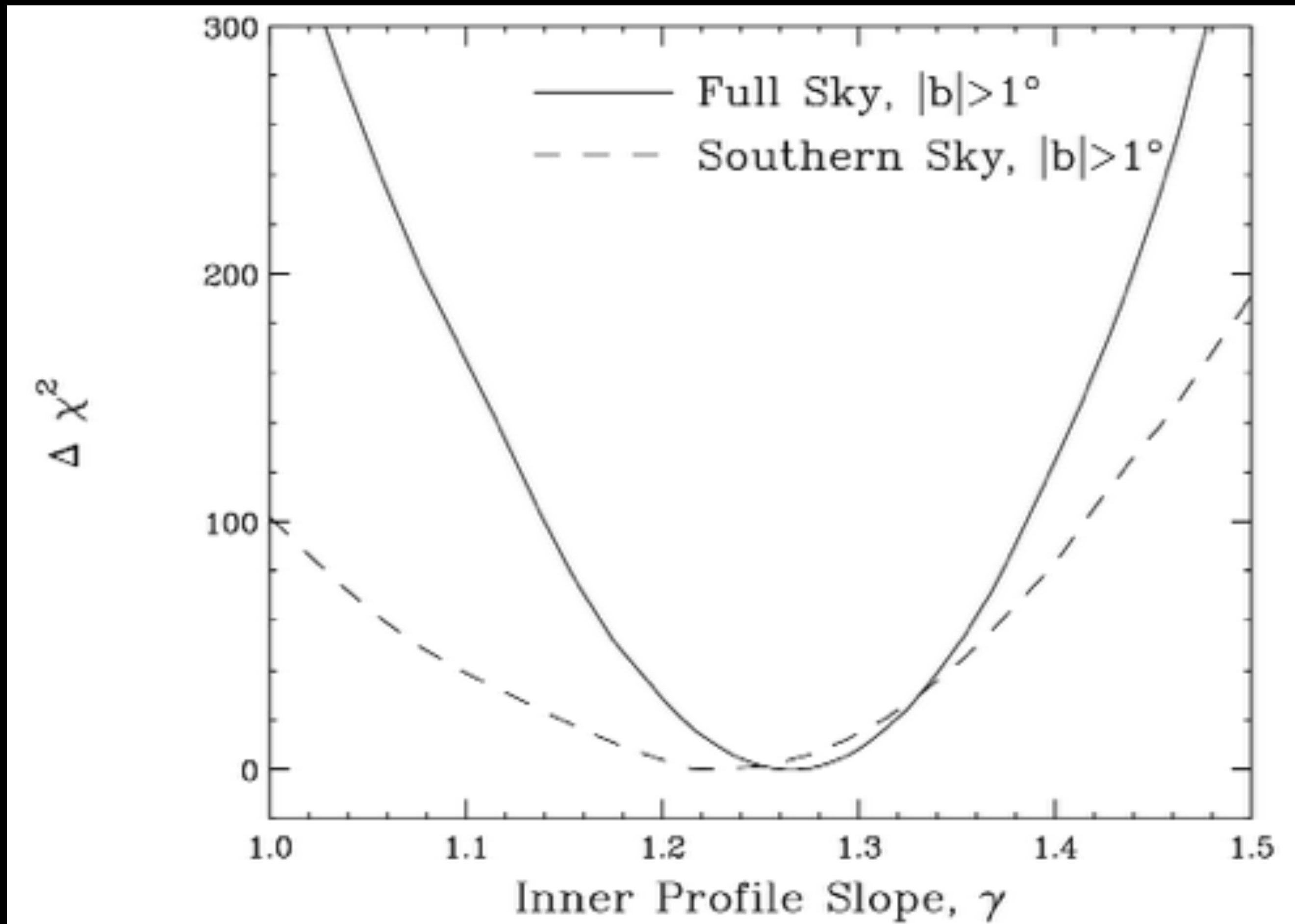


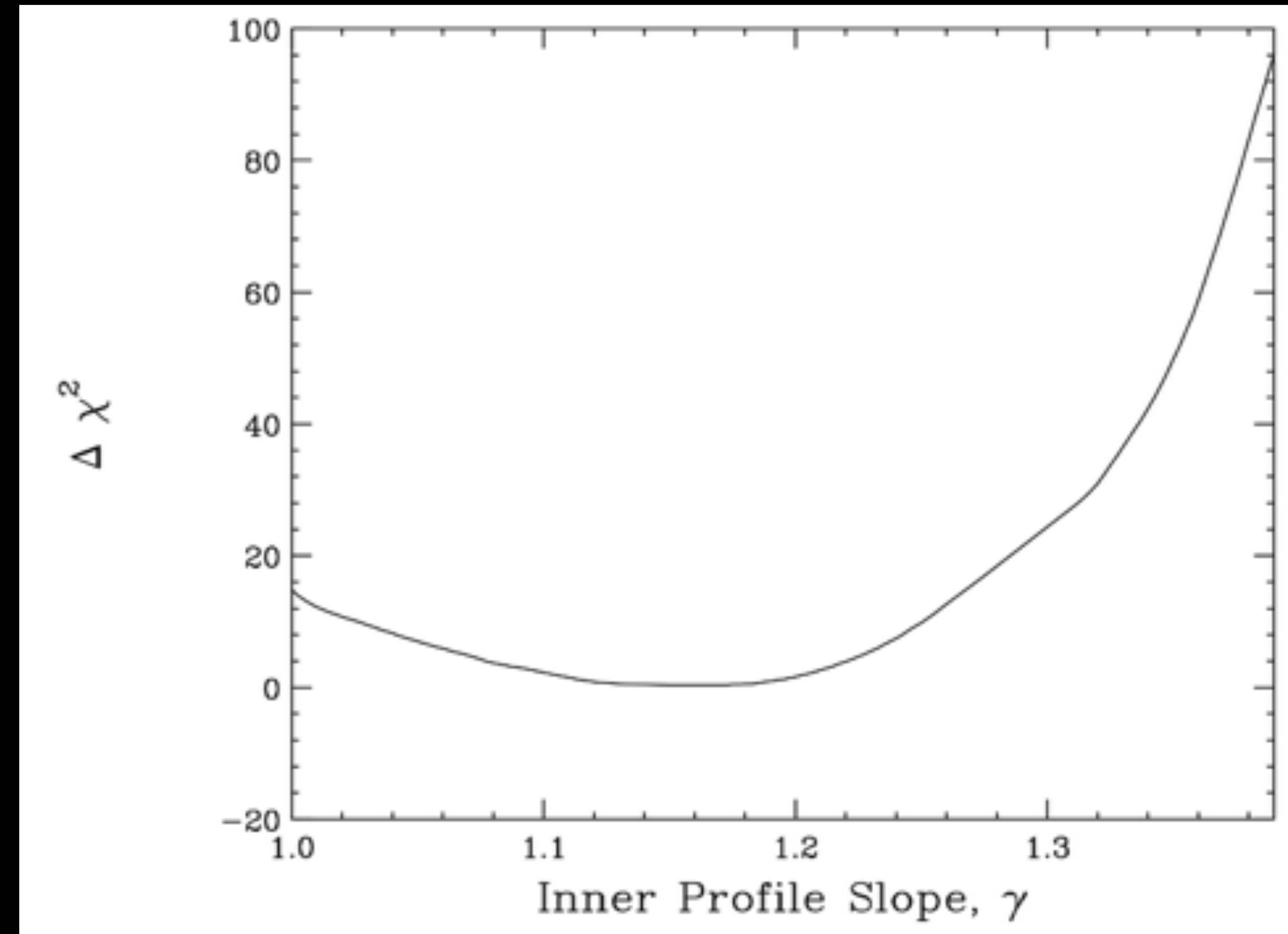
Spectrum of the Residuals



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

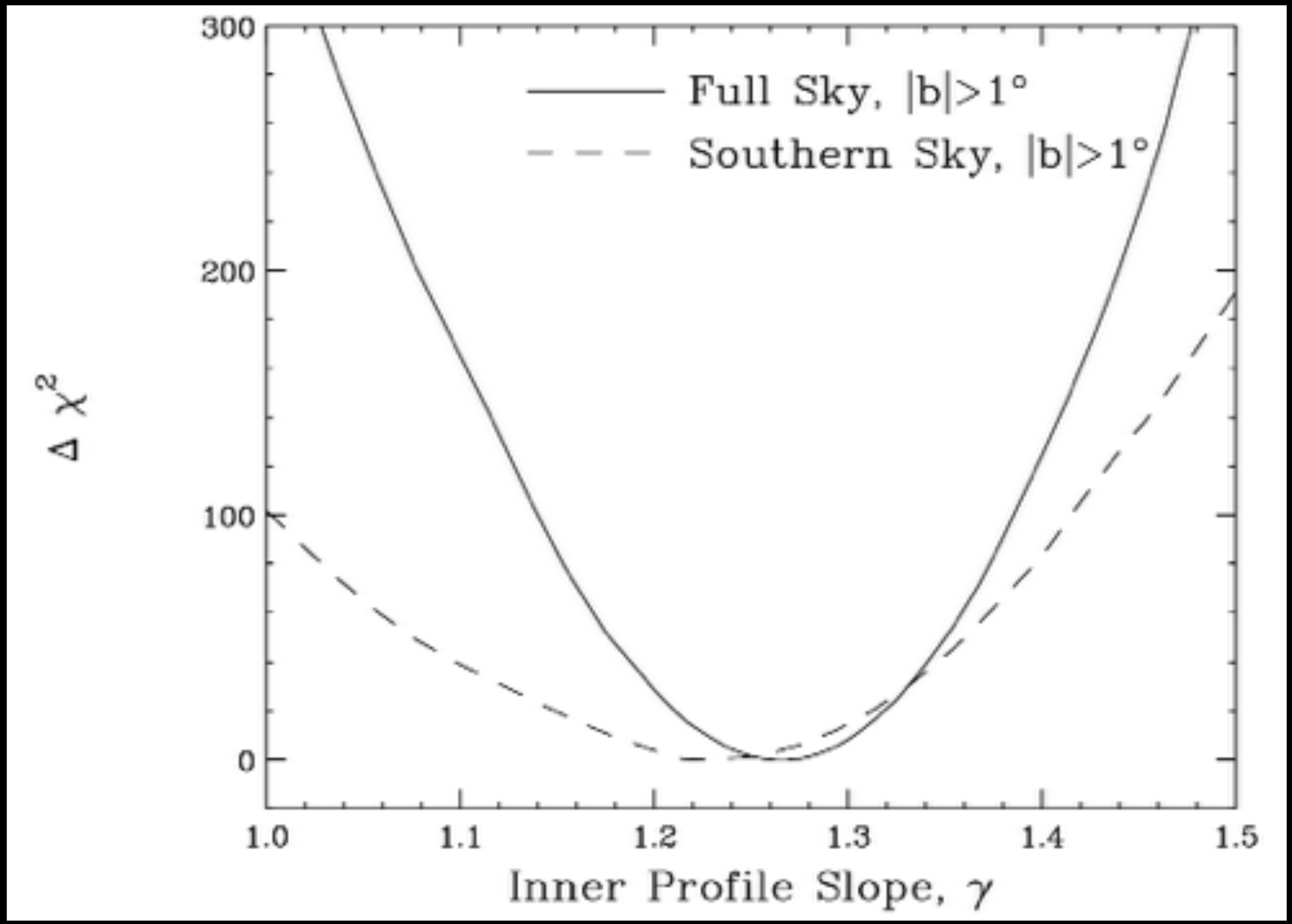


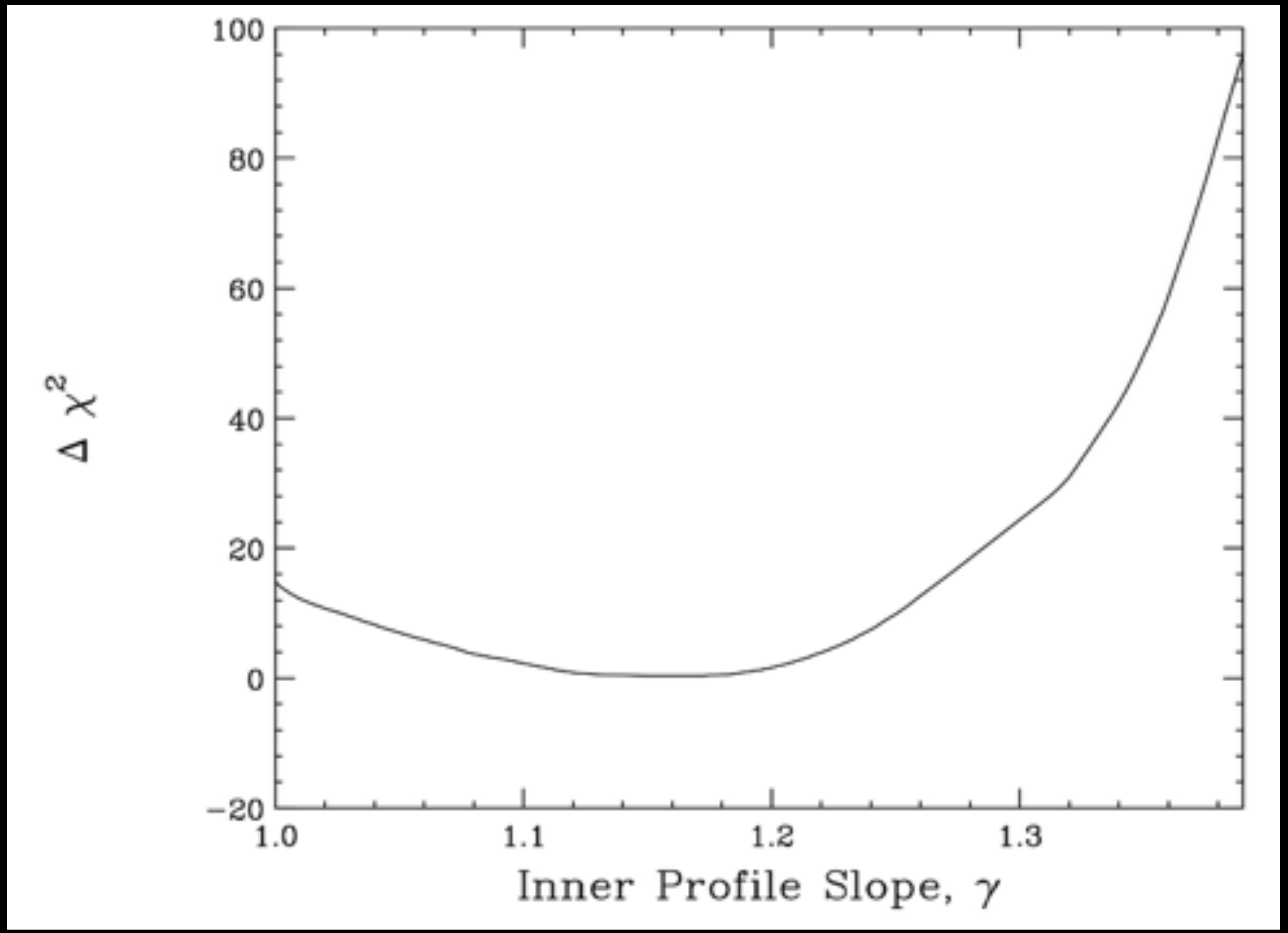


Inner Galaxy - The best fit is given by a generalized NFW profile with γ=1.26. The Southern sky has a consistent fit to the spectrum of the full sky.

Galactic Center - The best fit is given by γ=1.17.

The Morphology of the Gamma-Ray Excess

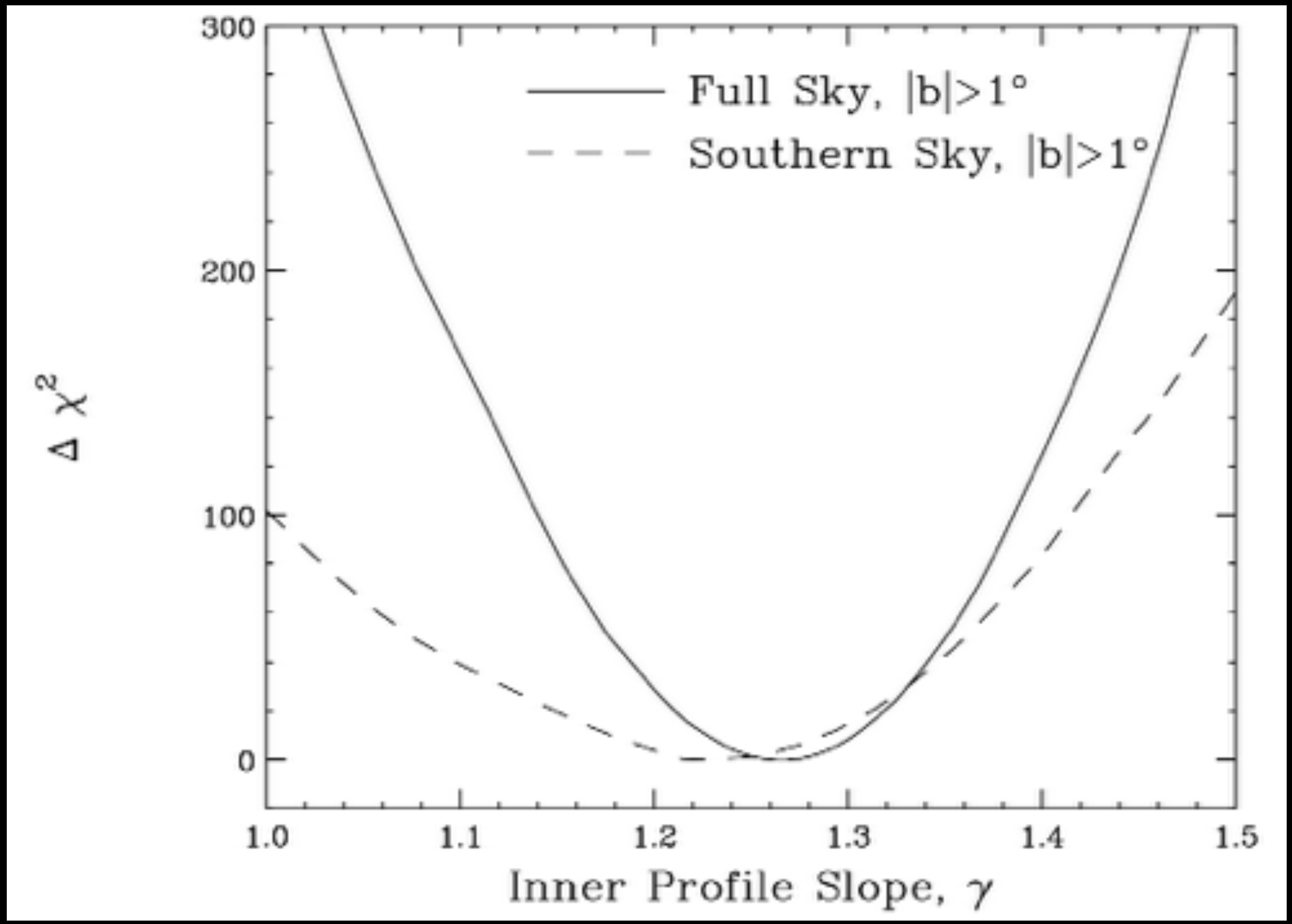


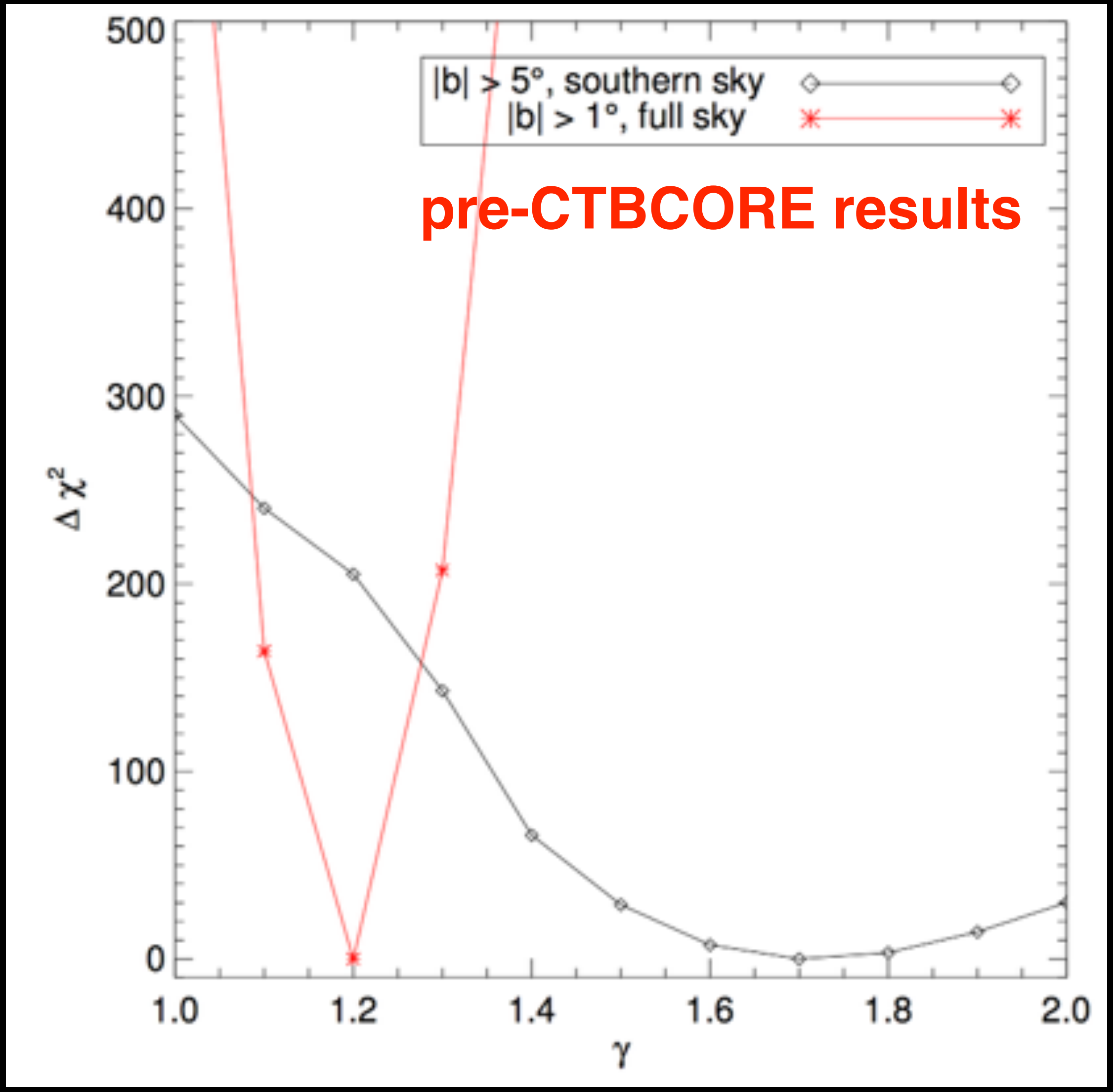


First, it is worth noting that the fit of γ=1.26 is not strongly rejected by the Galactic center data.

Secondly, the value of γ 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 γ may shift slightly as a function of galactocentric radius

The Morphology of the Gamma-Ray Excess

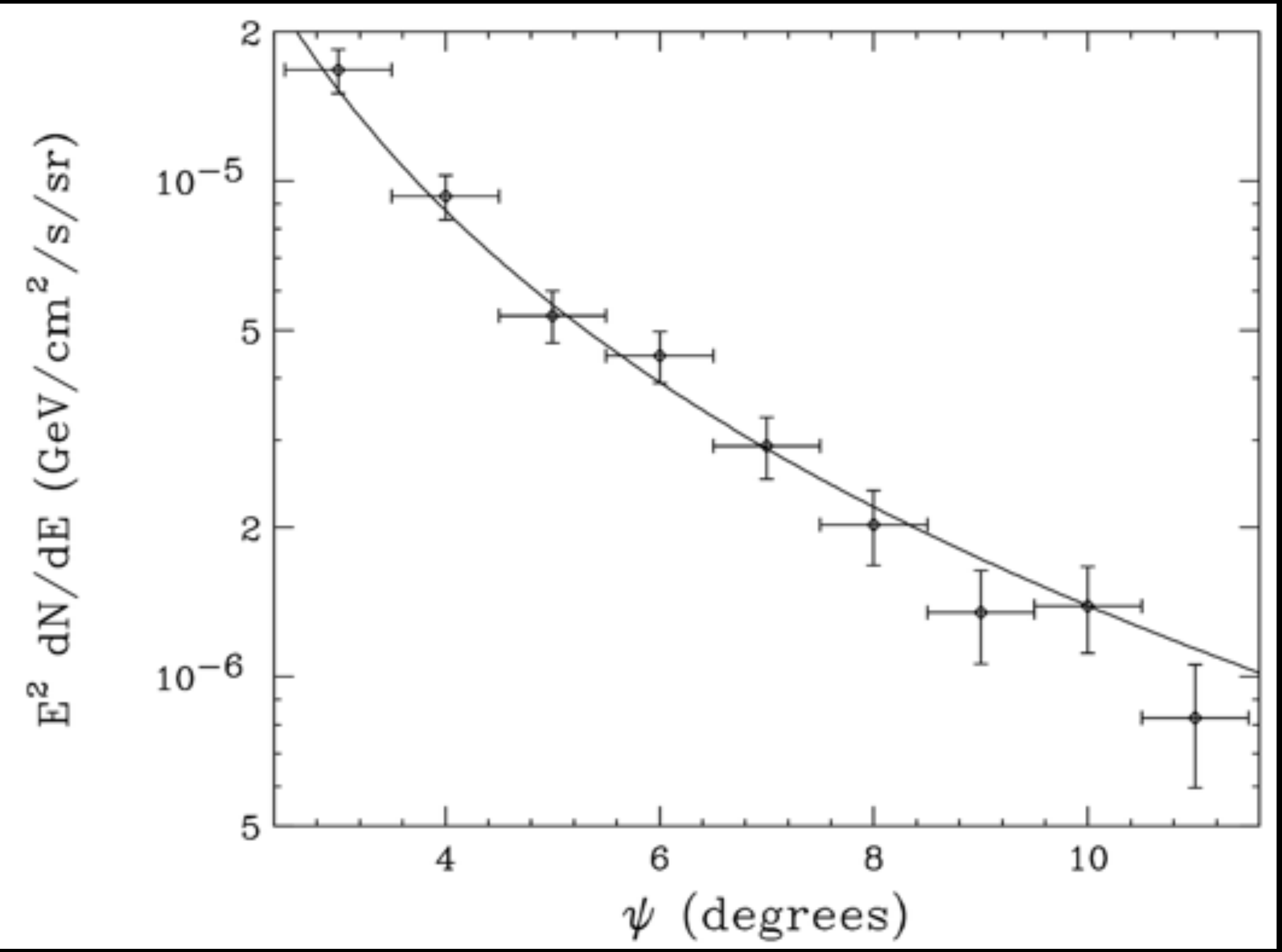




Hooper & Slatyer (2013)

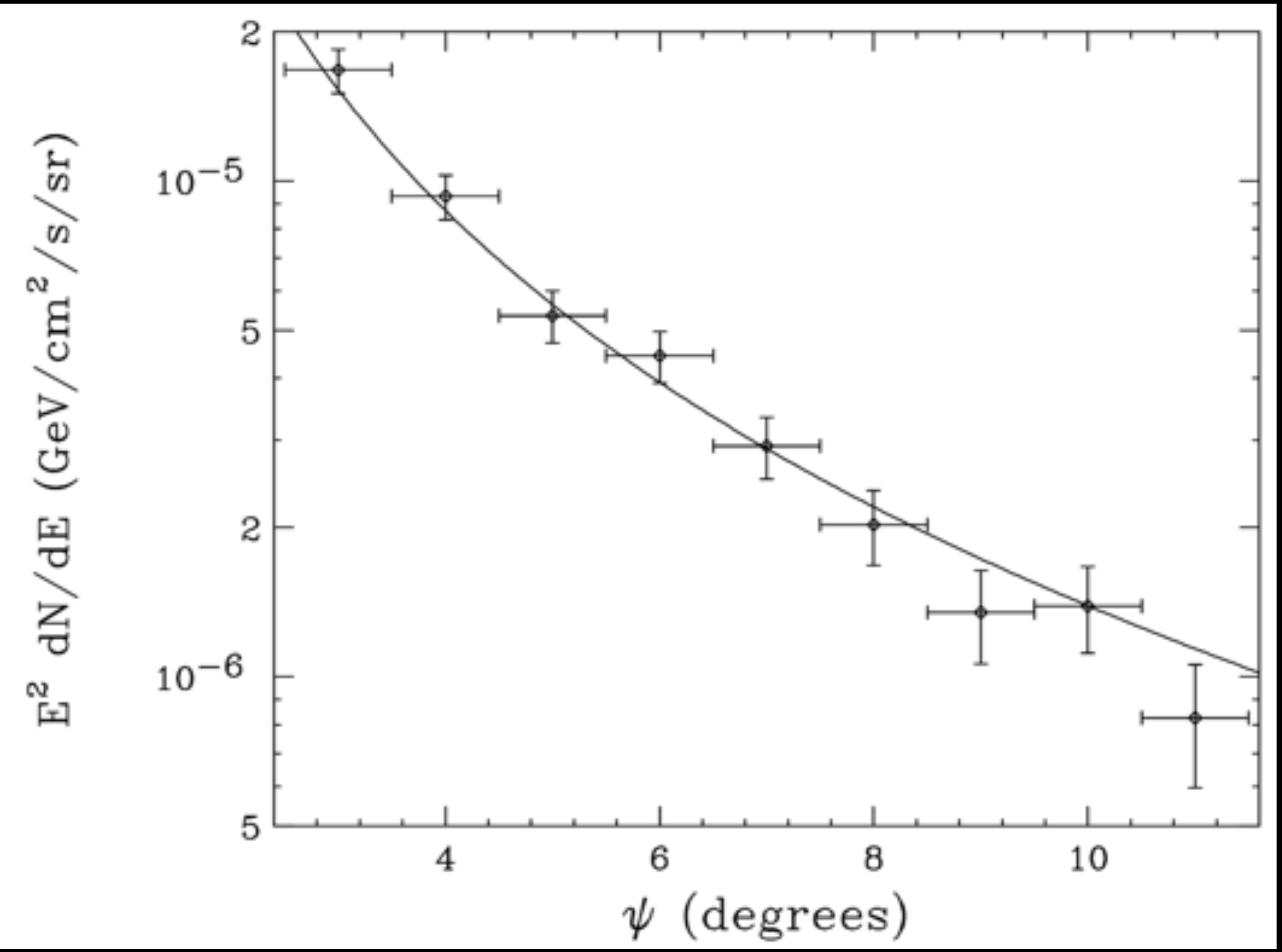
Third, it's worth noting how much the usage of CTBCORE improves our models of the data. Previous to our CTBCORE fits, the value of γ was highly sensitive to our choice of ROI

The Morphology of the Gamma-Ray Excess



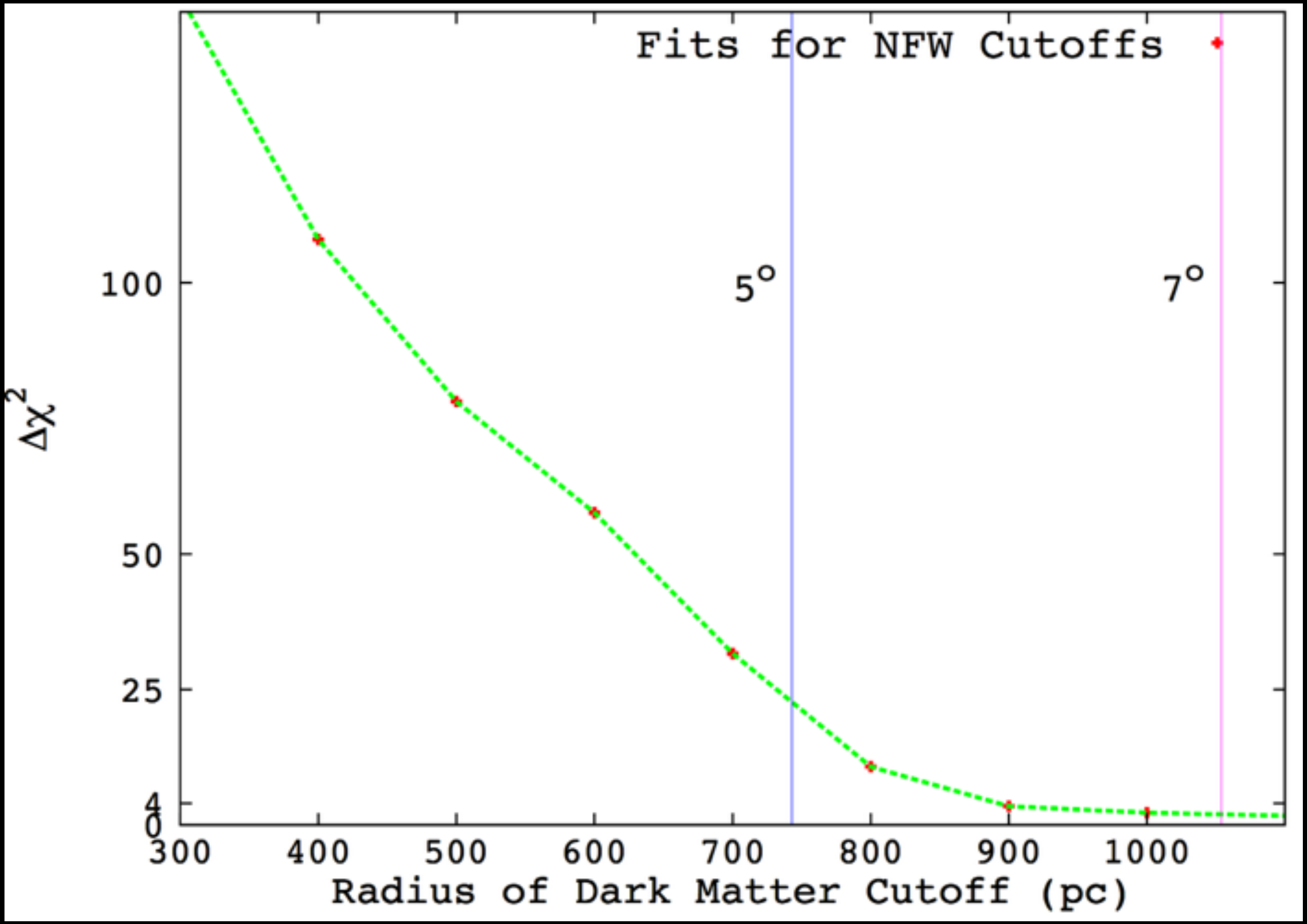
We can instead fix the spectrum of the Inner Galaxy excess, and allow the normalization to float in 1^{o} angular bins. We find the residual to be statistically significant out to 12o from the Galactic Center. Following a slightly steeper profile (at high latitudes) of $\boldsymbol{\gamma}$ = 1.4.

The Morphology of the Gamma-Ray Excess



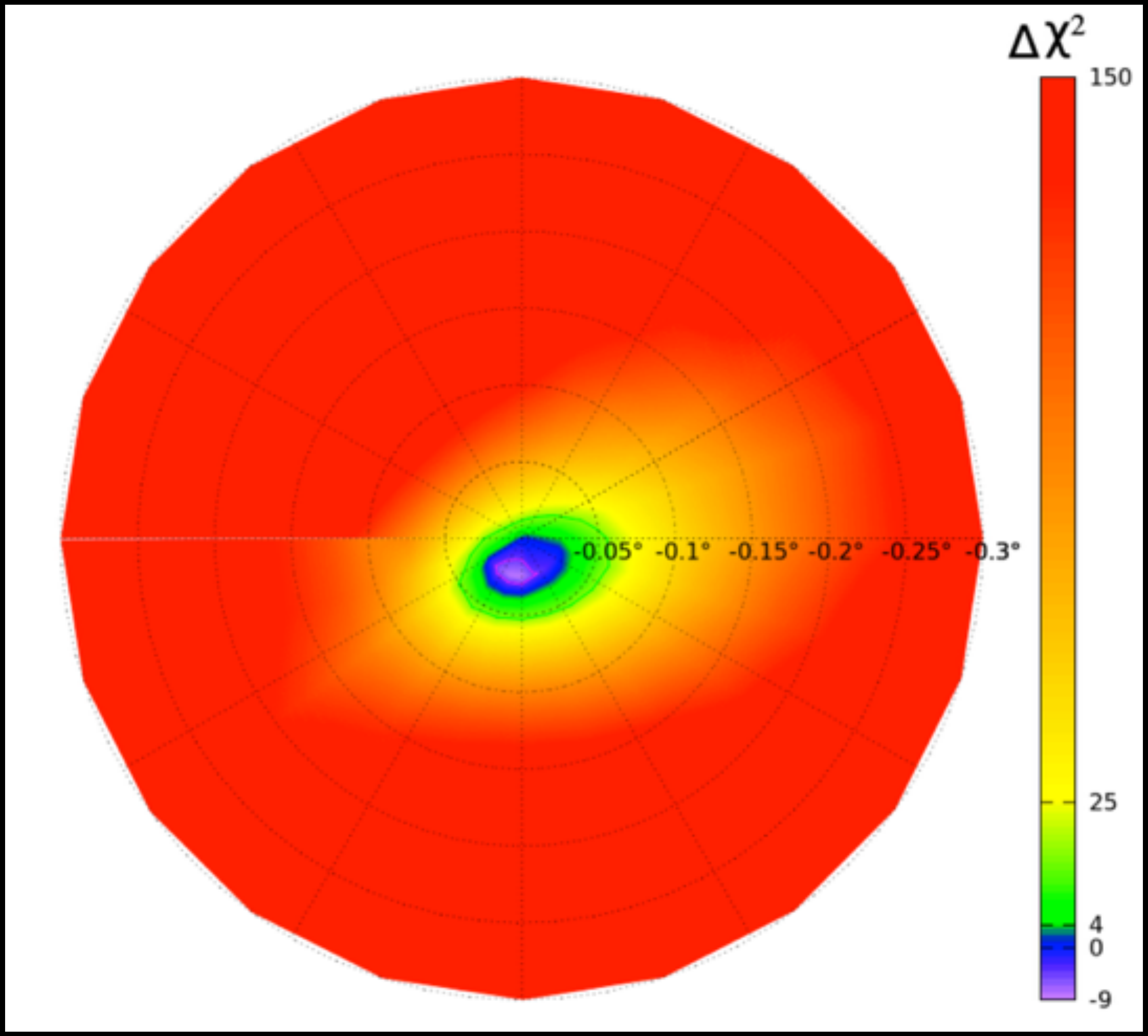
This may again be due to the interaction of the dark matter density profile with baryons, or may be due to measurement effects — since large scale features far from the Galactic Center may be partially absorbed into the data-driven galactic diffuse model

The Morphology of the Gamma-Ray Excess



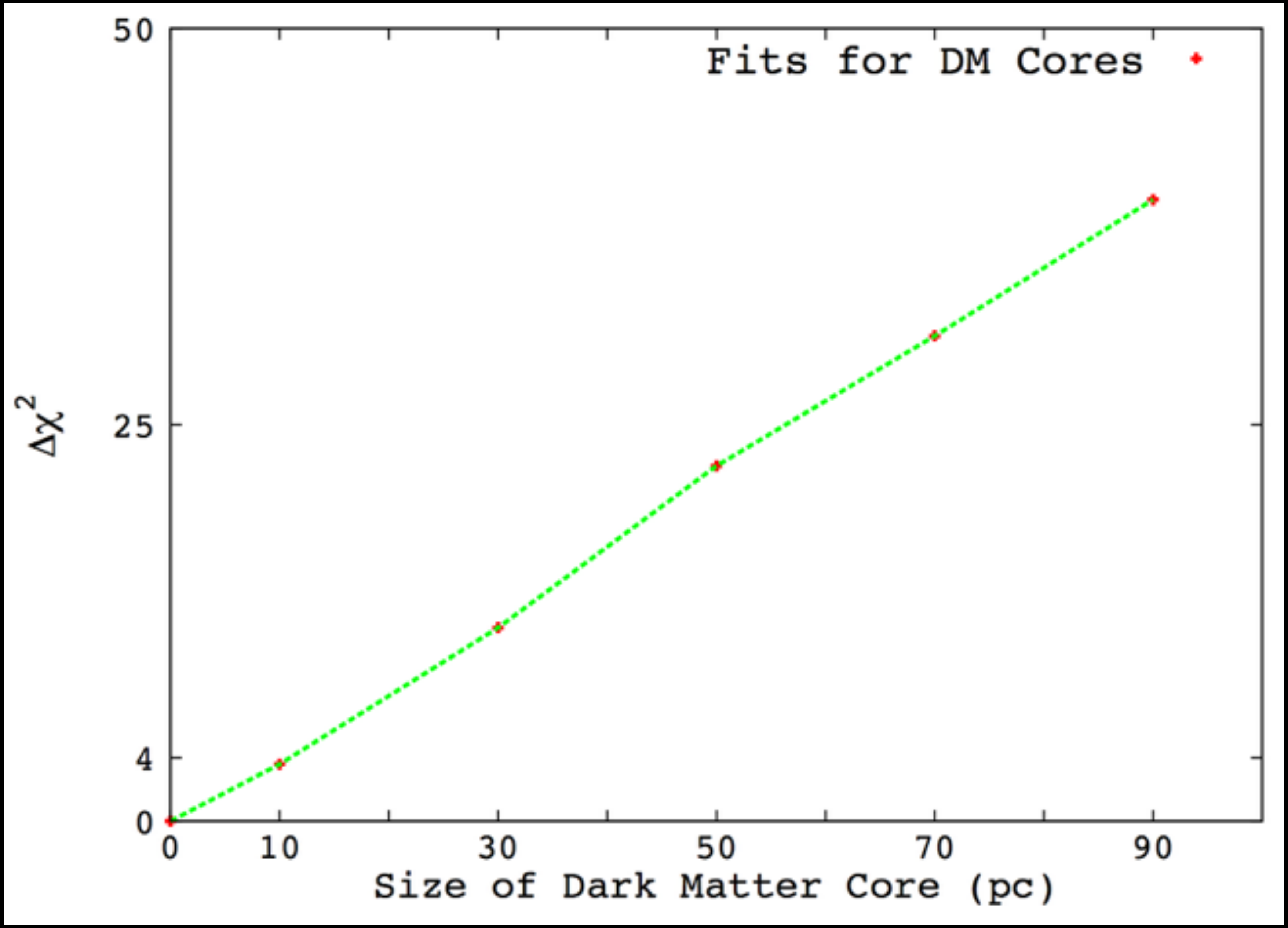
Galactic Center Model: We can ask a similar question, by investigating if the data prefers a NFW profile that is cut off at various radii from the position of the Galactic Center. The data prefer that the NFW profile persists throughout the simulation region.

The Morphology of the Gamma-Ray Excess



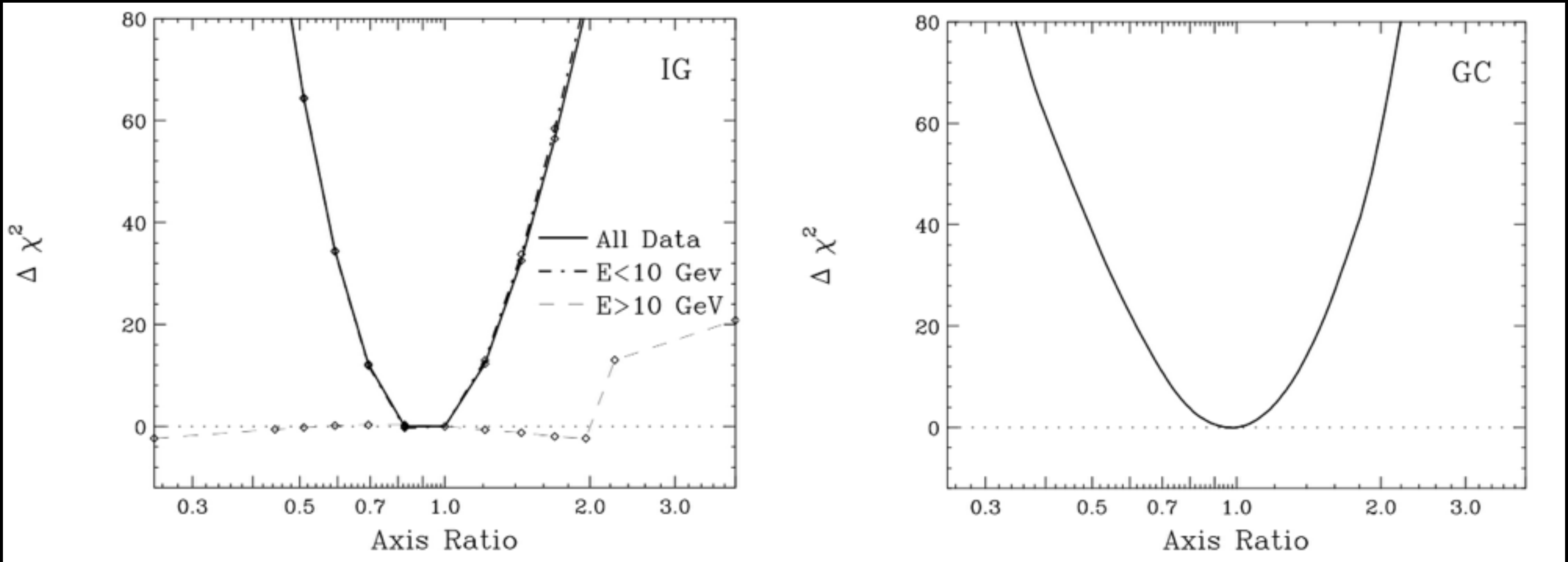
Galactic Center Model: We can test models where the DM profile is spatially offset from the true position of the Galactic Center. We find the data to prefer a NFW profile centered on the position of Sgr A* to within 0.05^{o}

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 2σ

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

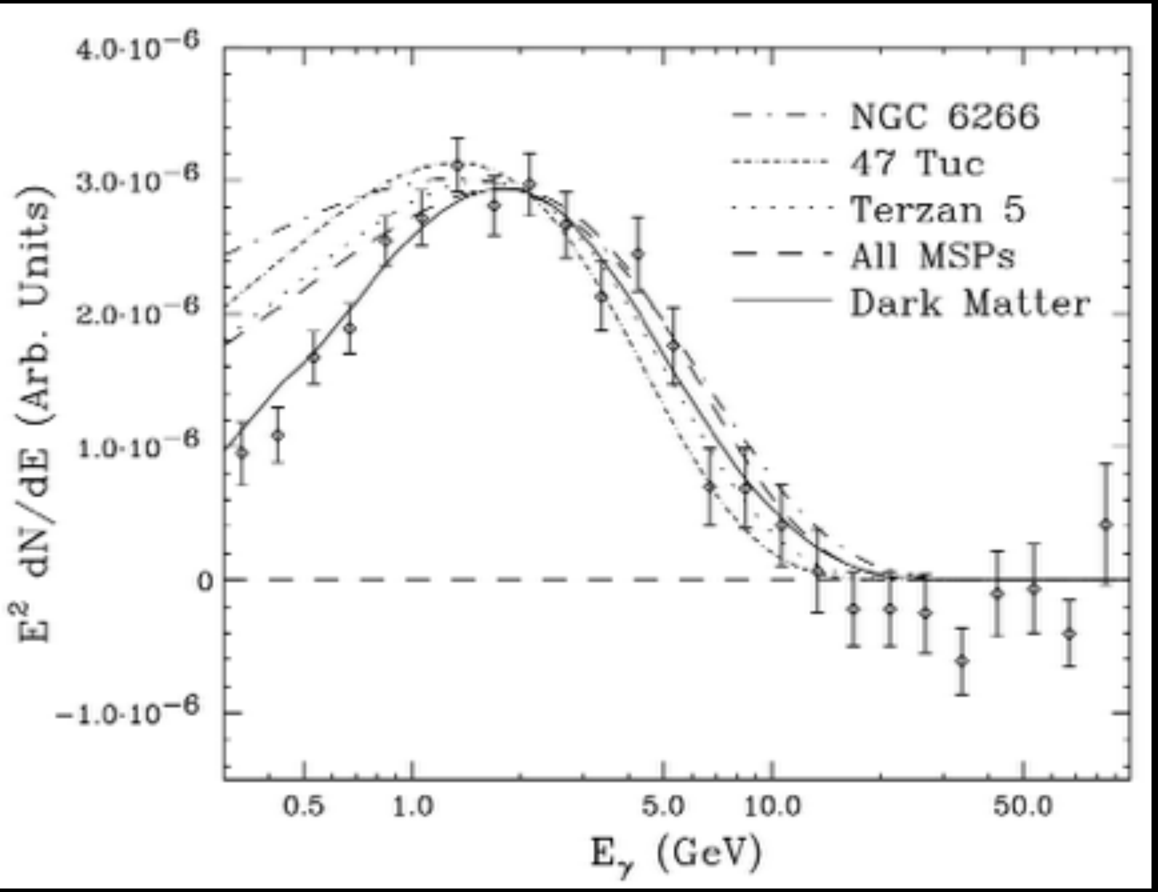
1.) Do the data prefer millisecond pulsars or dark matter annihilation?

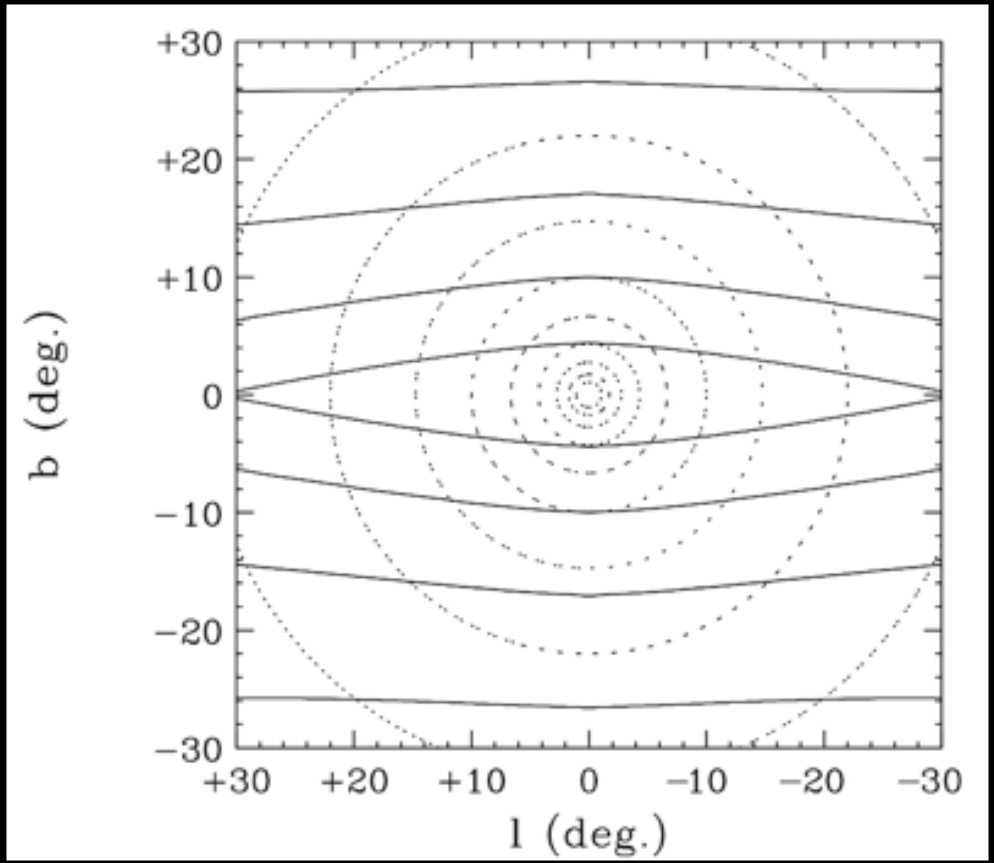
2.) How do the data compare to theoretically predicted dark matter models?

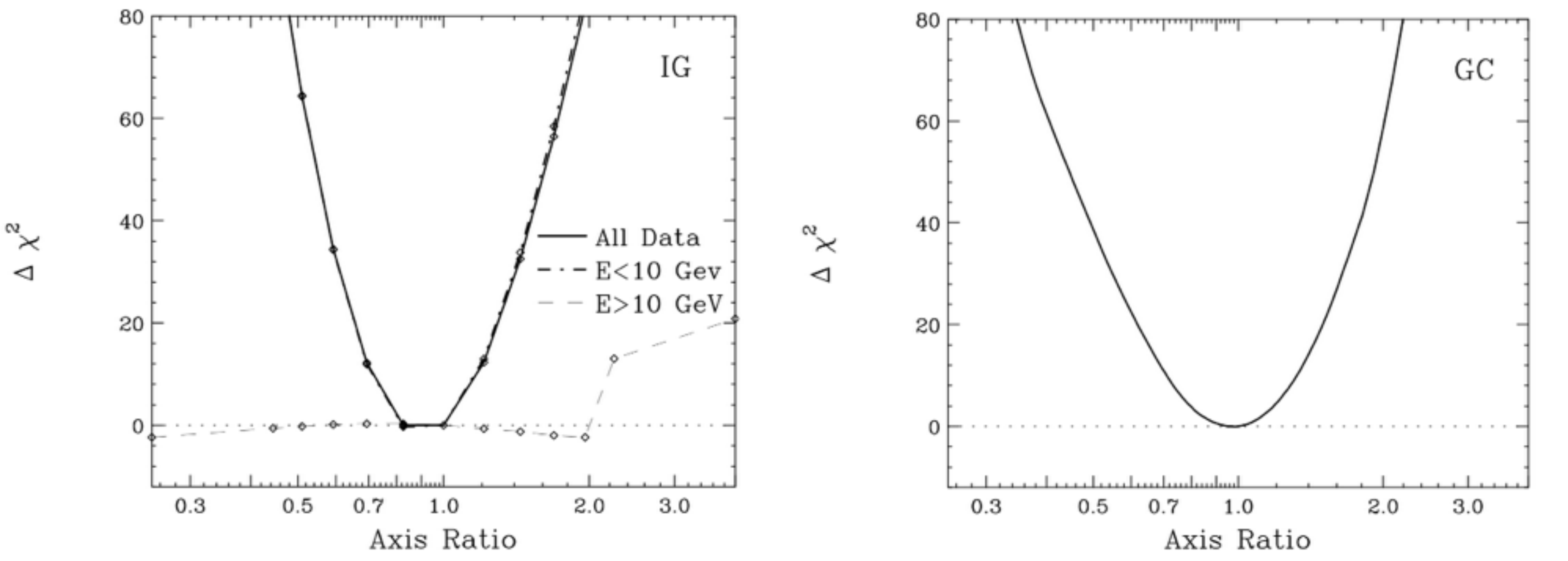
Interpretations of the Excess

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

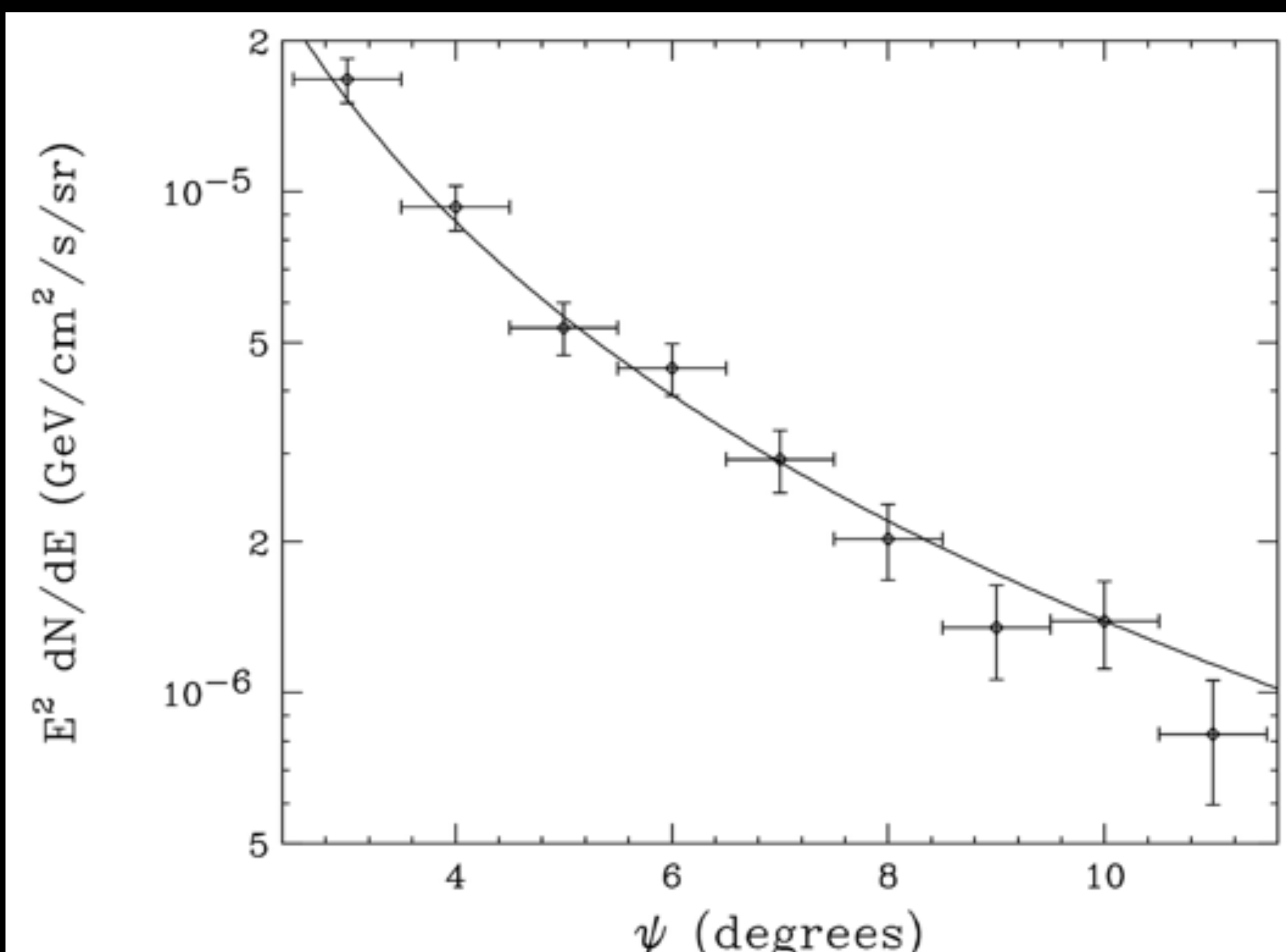


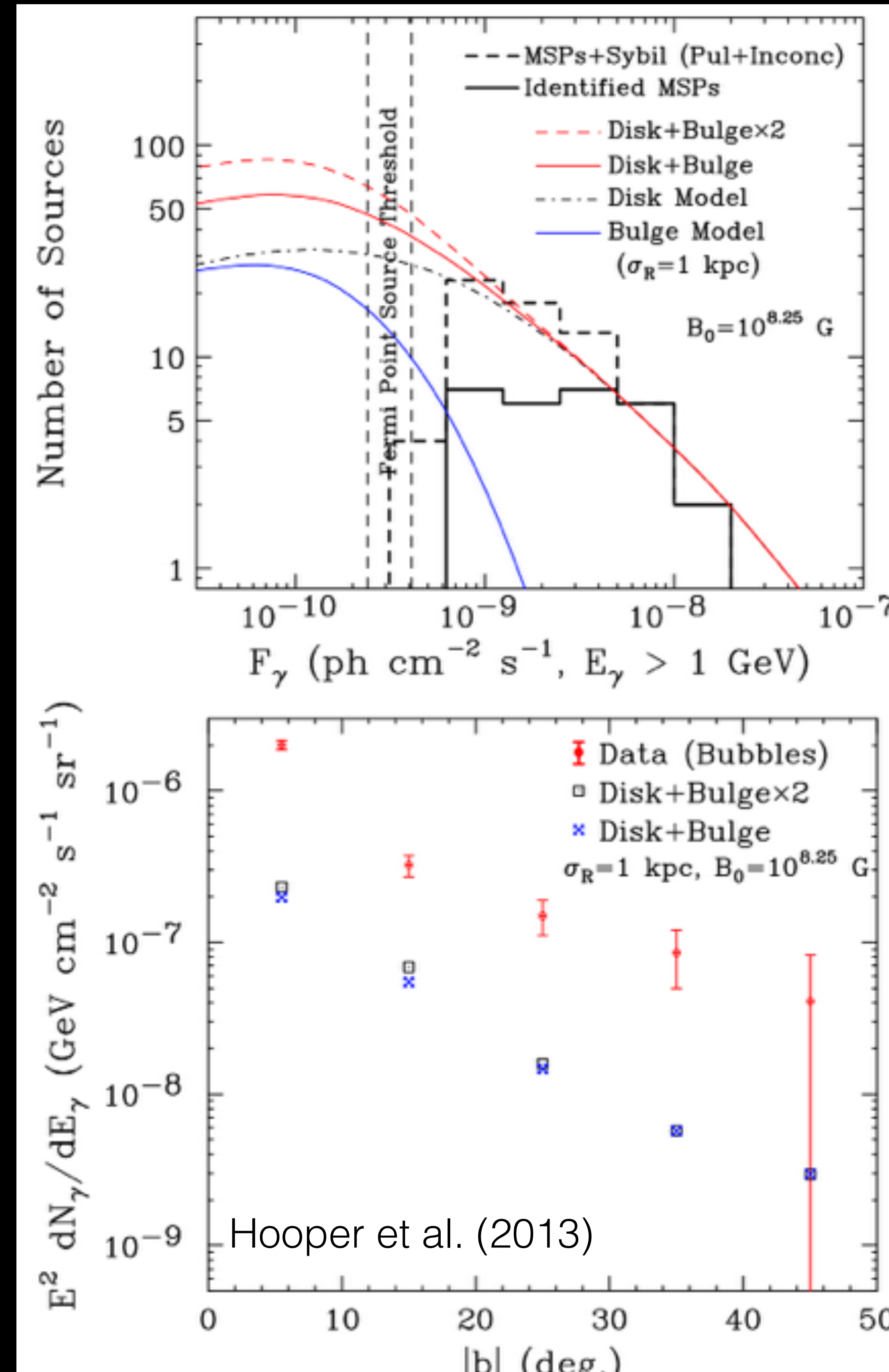




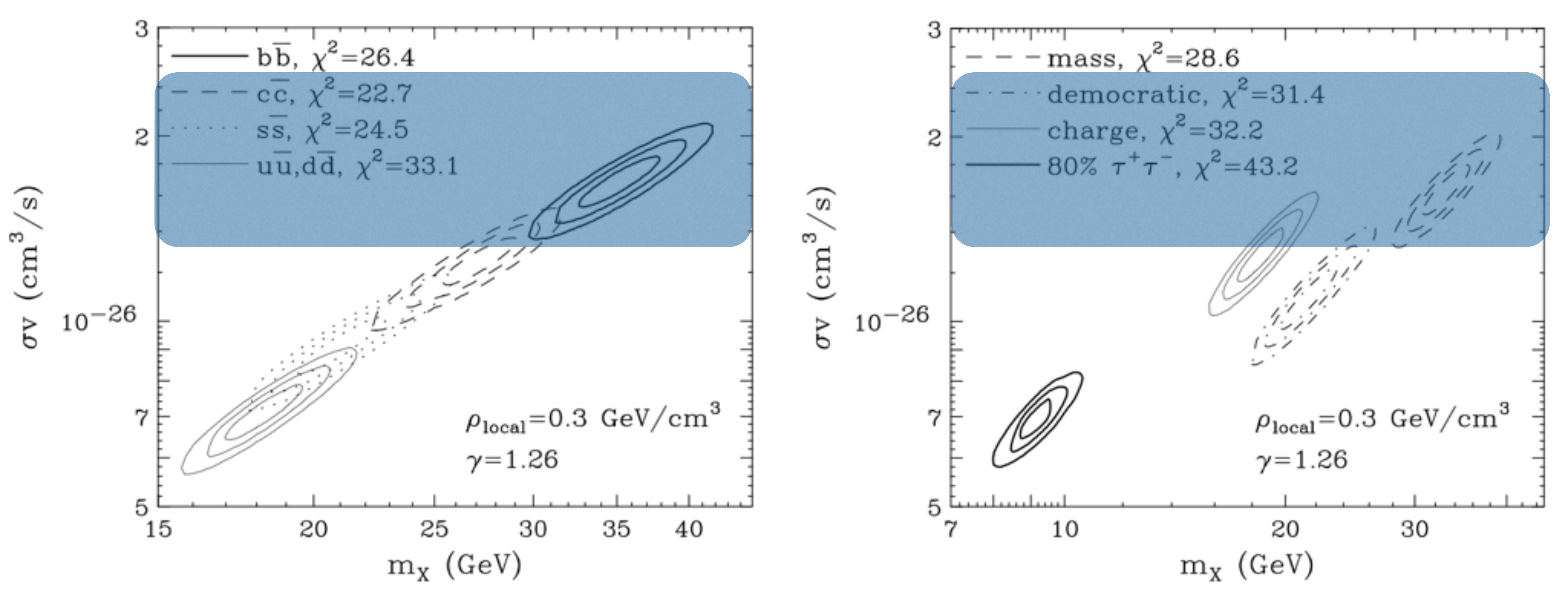
Interpretations of the Excess

The clear extension of the source out to 11° 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

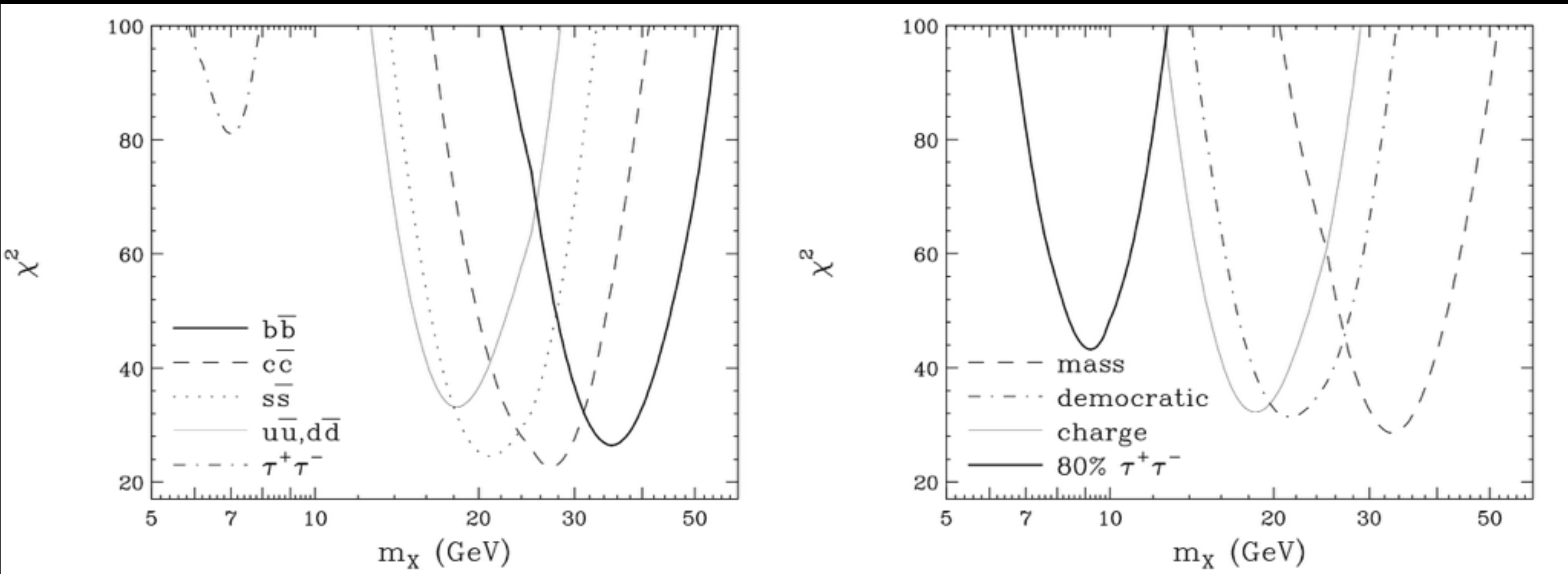


The gamma-ray excess is very well fit by simple, theoretically motivated dark matter models.

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



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

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

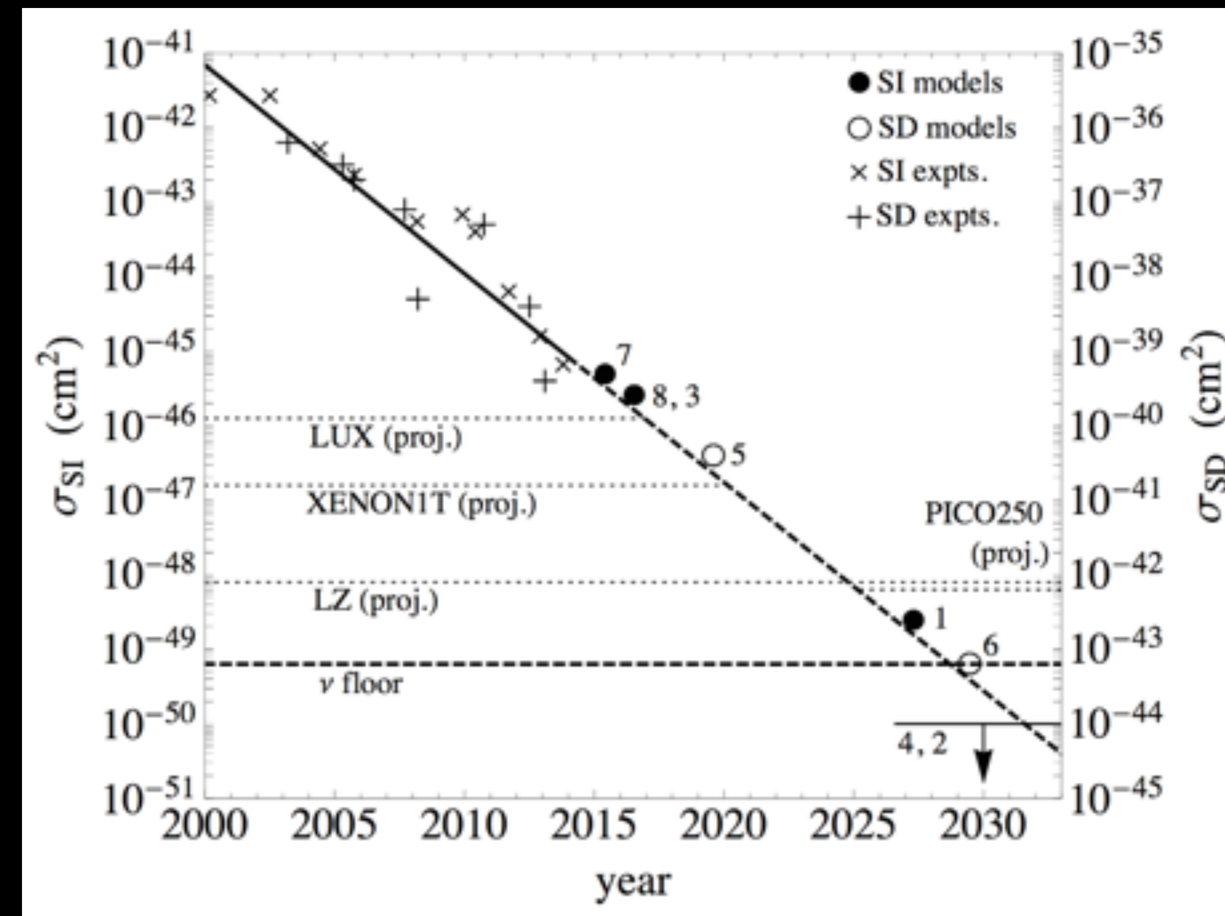
1.) **PAMELA/AMS —** Need leptophilic dark matter, with a Sommerfeld enhanced cross-section (100 - 1000x thermal). Need a cored profile to avoid Fermi-LAT constraints

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 (~ 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	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	SD	$(q^2/4m_n m_\chi)^2$
1/2	Majorana	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	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	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	SD	$(q/2m_n)^2$ or $(q/2m_\chi)^2$
1/2	Dirac	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	SD	1
1/2	Majorana	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	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	$\phi^\dagger\phi\bar{q}\gamma^5 q$	SD (scalar)	$(q/2m_n)^2$
0	Real	$\phi^2\bar{q}\gamma^5 q$	SD (scalar)	$(q/2m_n)^2$
1	Complex	$B^\dagger_\mu B^\mu\bar{q}q$	SI (scalar)	1
1	Real	$B_\mu B^\mu\bar{q}q$	SI (scalar)	1
1	Complex	$B^\dagger_\mu B^\mu\bar{q}\gamma^5 q$	SD	$(q/2m_n)^2$
1	Real	$B_\mu B^\mu\bar{q}\gamma^5 q$	SD	$(q/2m_n)^2$

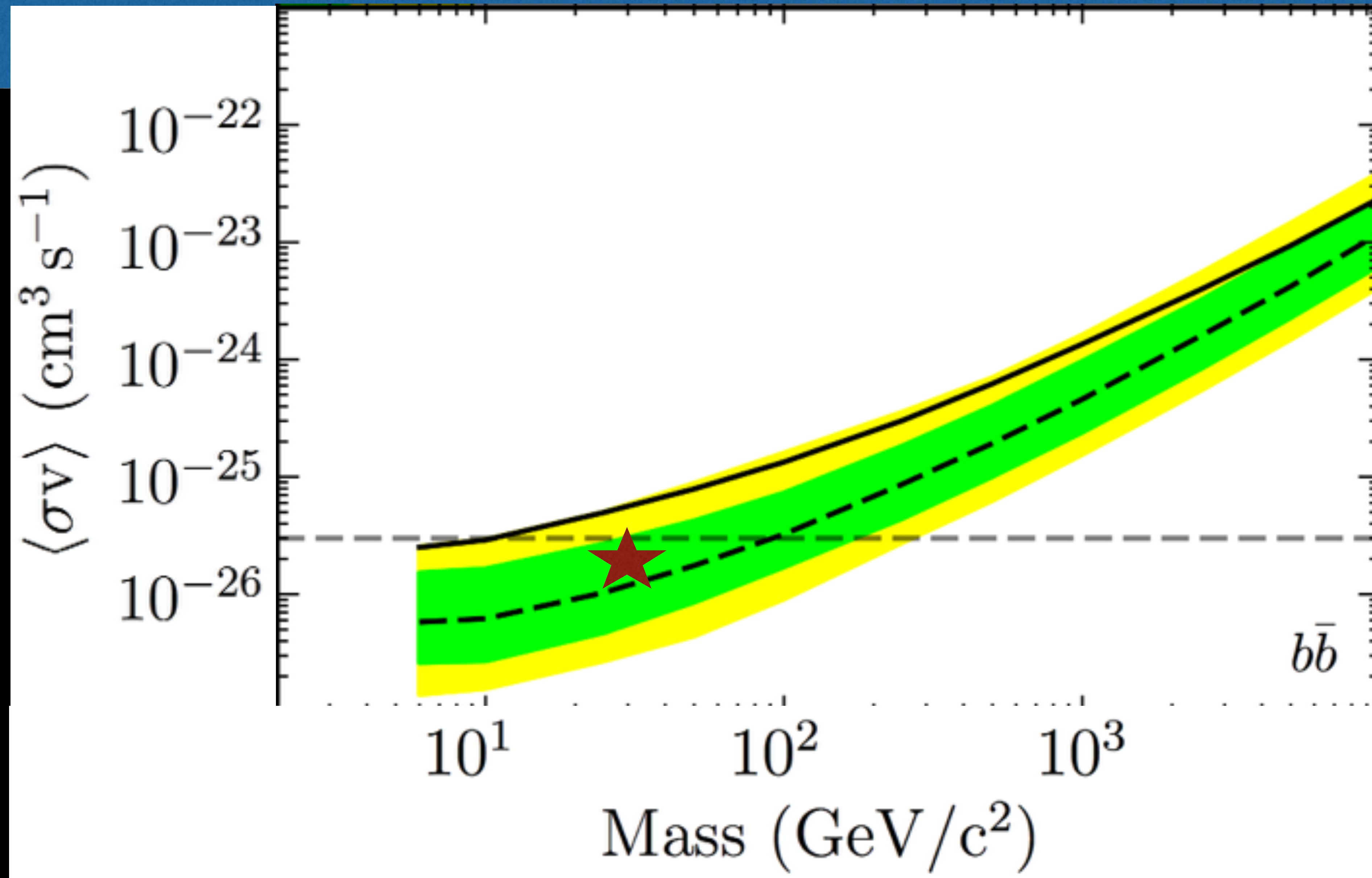
The Current State of the Excess

1.) The excess is hugely statistically robust (40σ for the Inner Galaxy, 17σ for the Galactic Center). This gives us ~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.

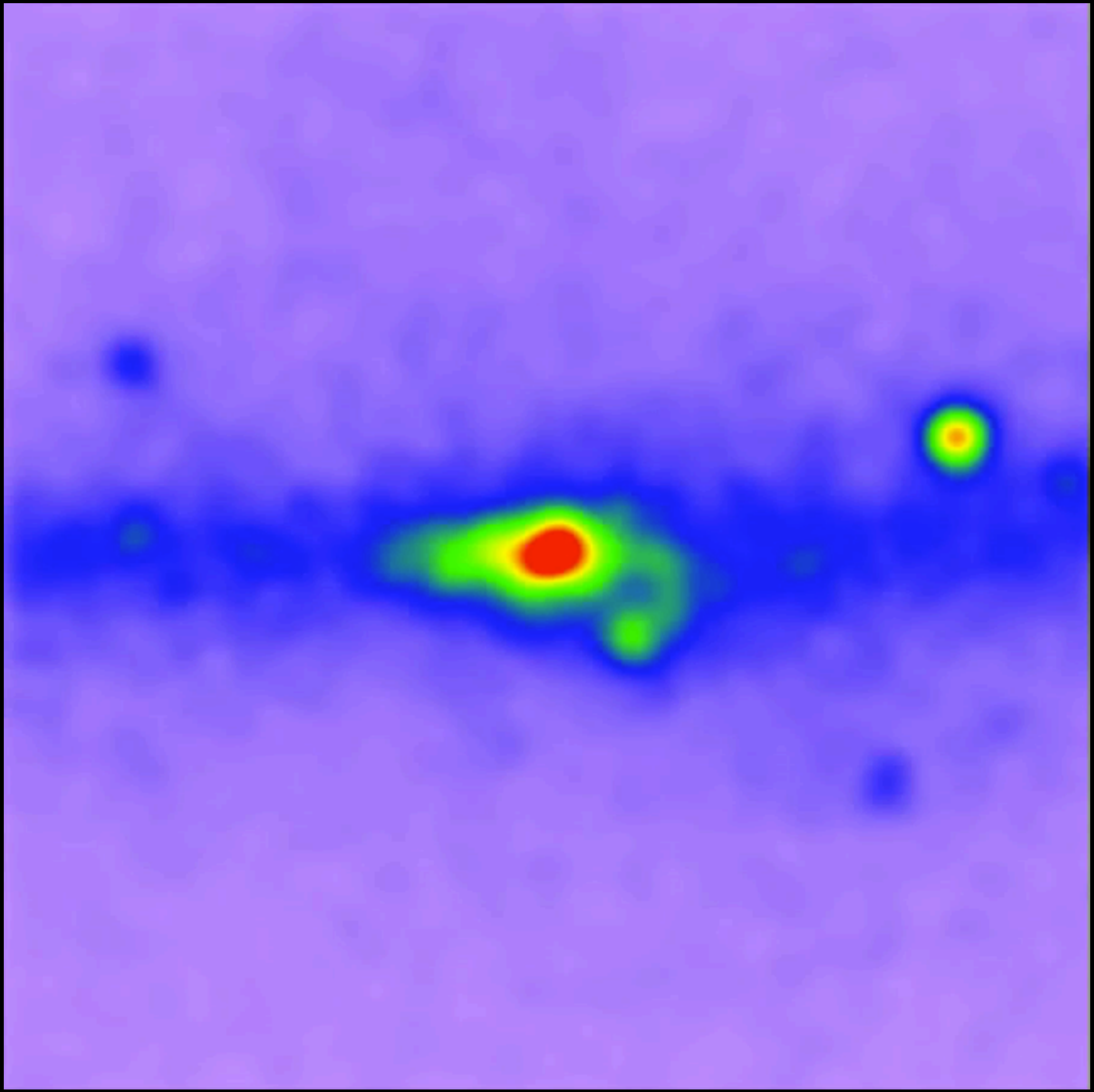
3.) There is no other reasonable model which has been put forward to explain the excess.

Future Tests



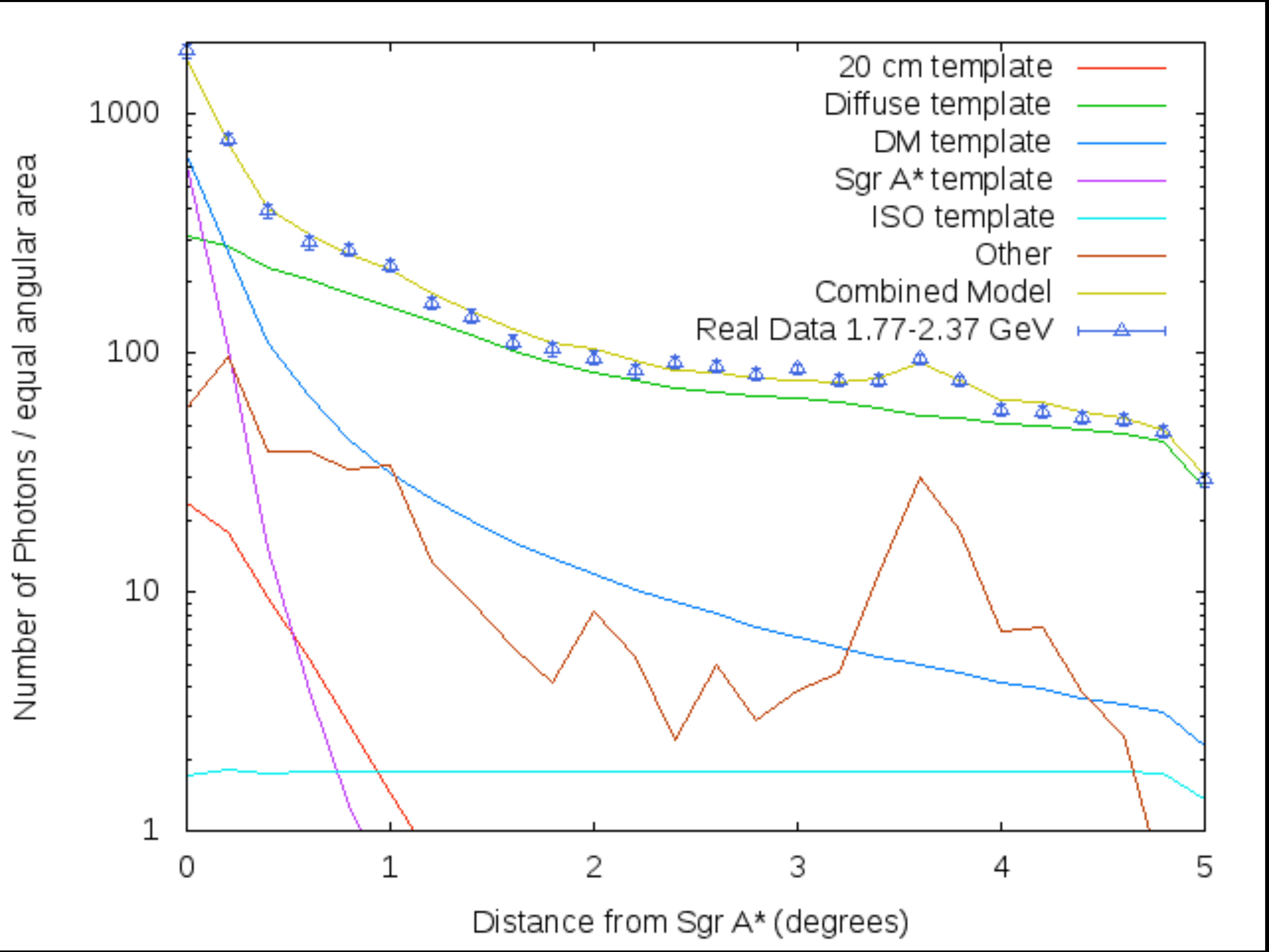
How would we test this excess? - Dwarf galaxies are another natural target for dark matter indirect detection. Interestingly, the Fermi-LAT finds an excess with a local significance of 2.7σ at the mass most favored by our dark matter model.

Conclusion

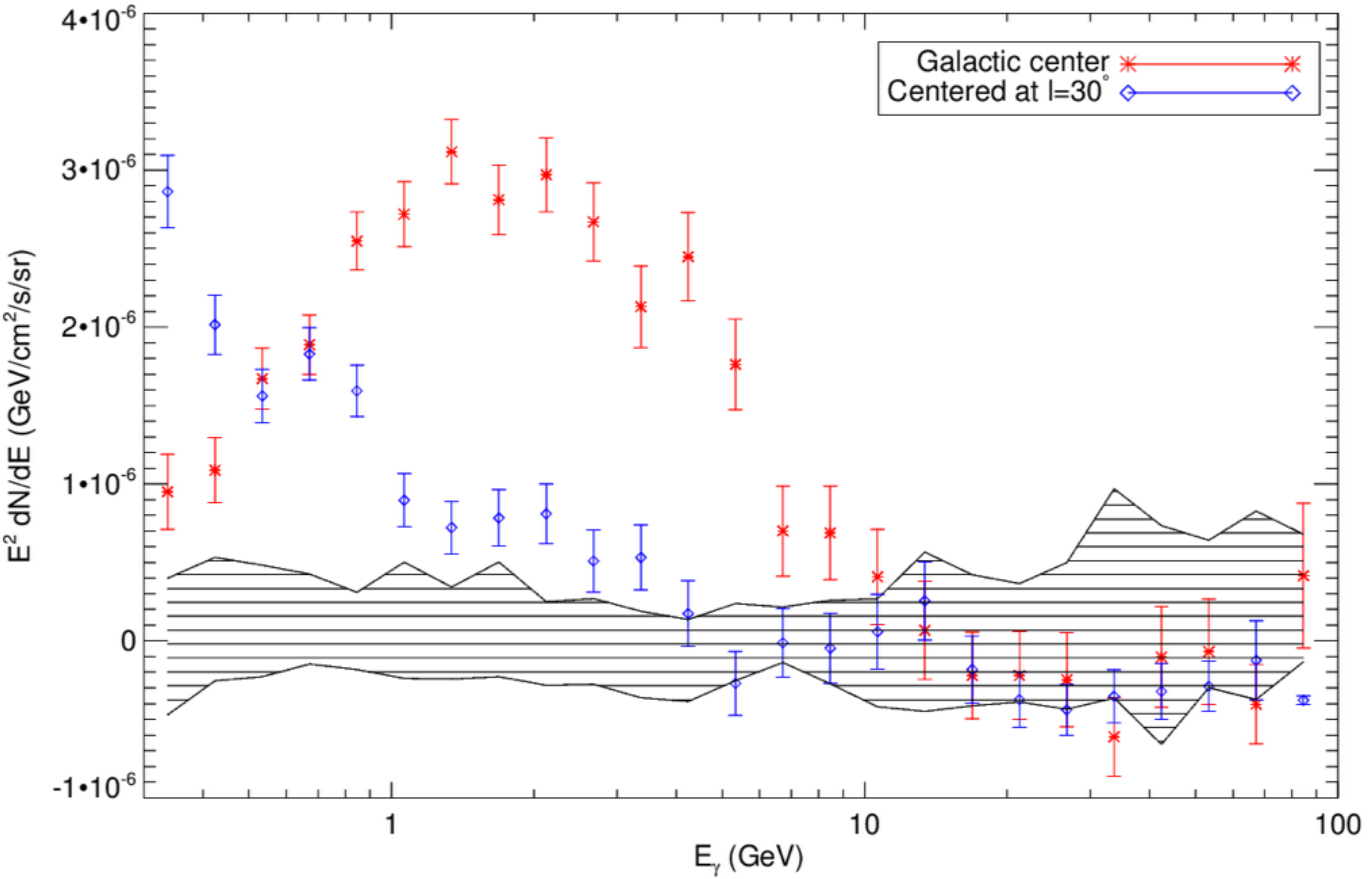


Extra Slides

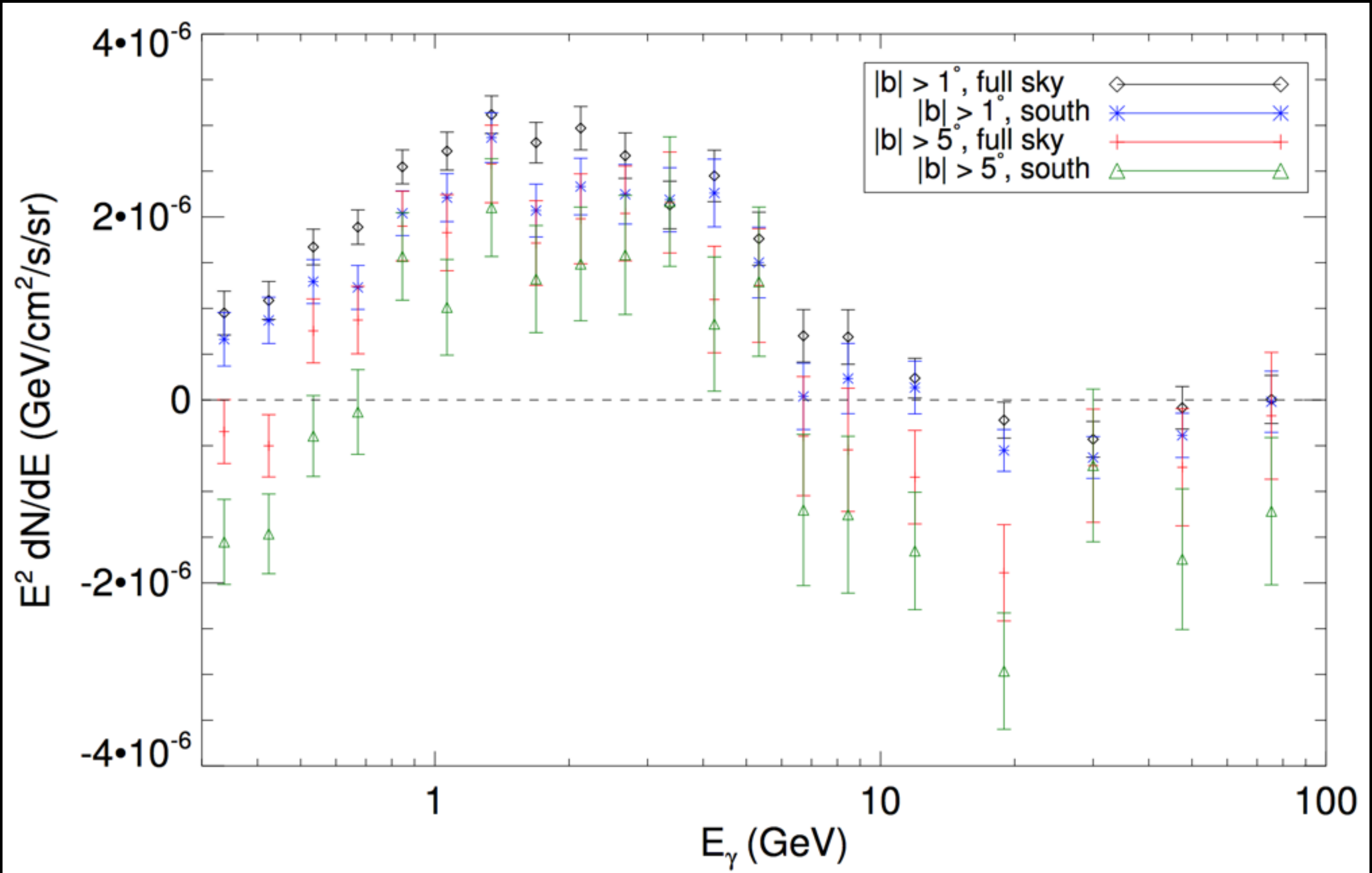
How Big Is This Excess?



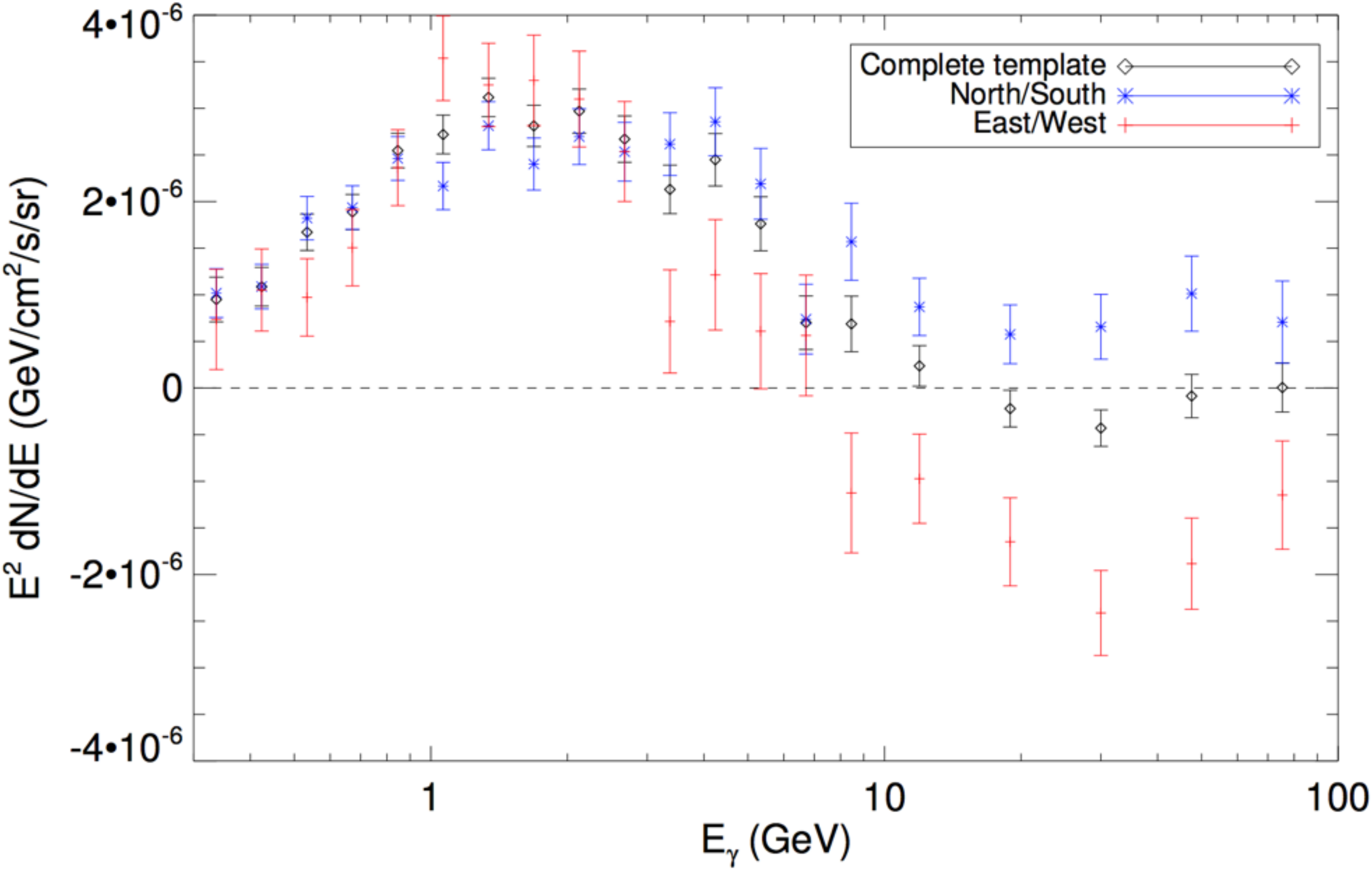
Do Other Residuals Have the Same Spectrum?



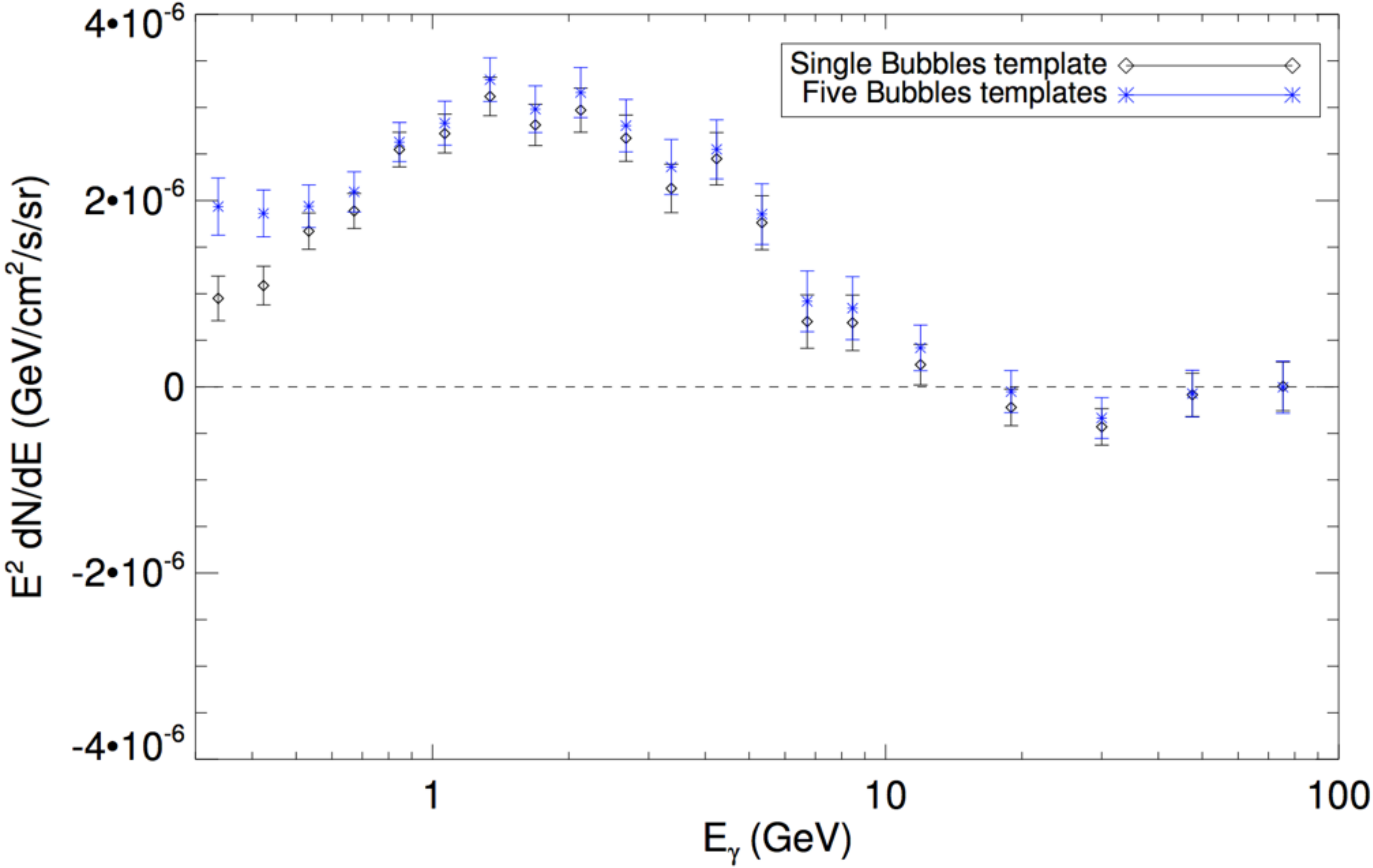
Wait, Some of the Same Photons are in Each Sample?



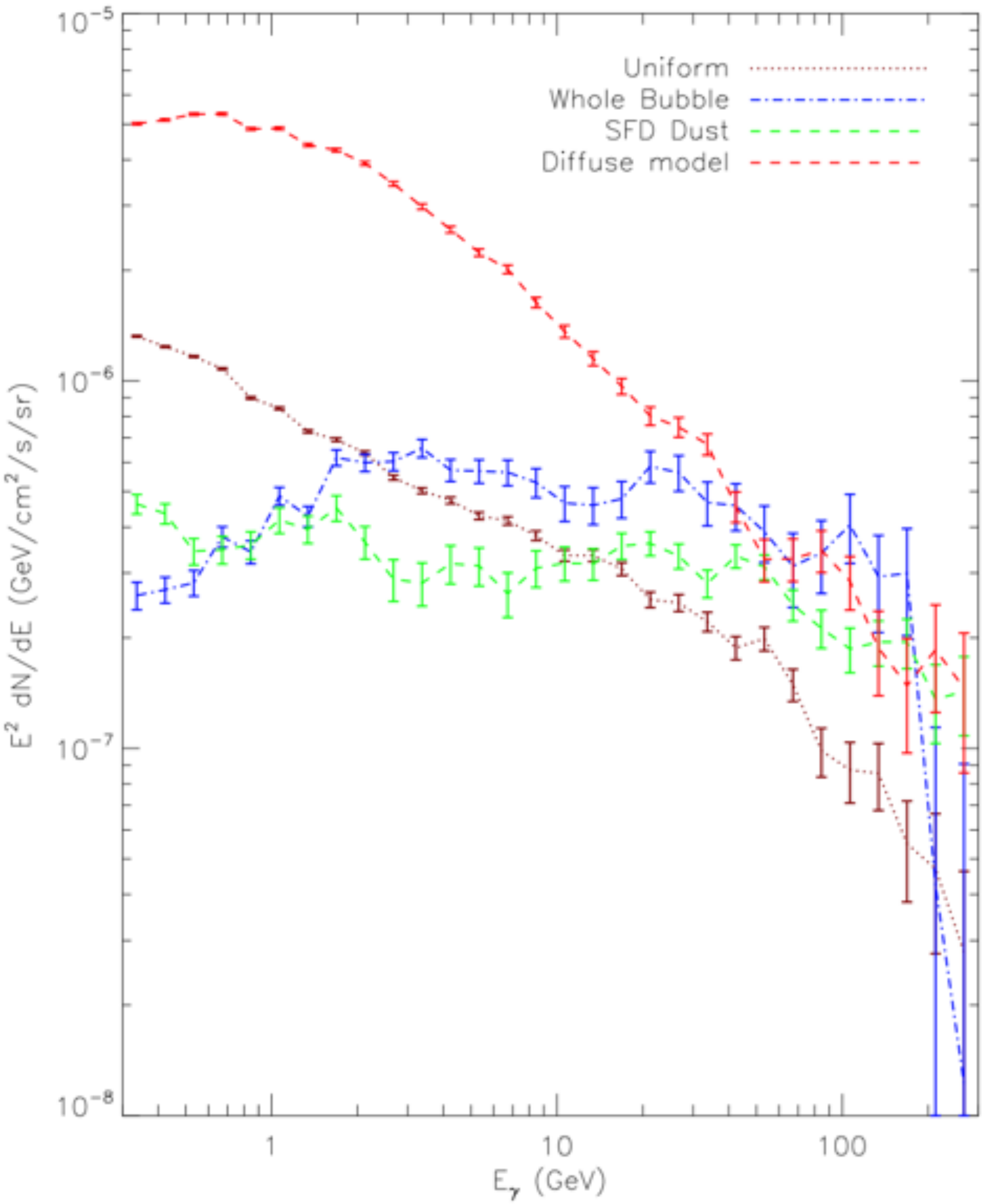
Maybe it's just part of the Bubbles?

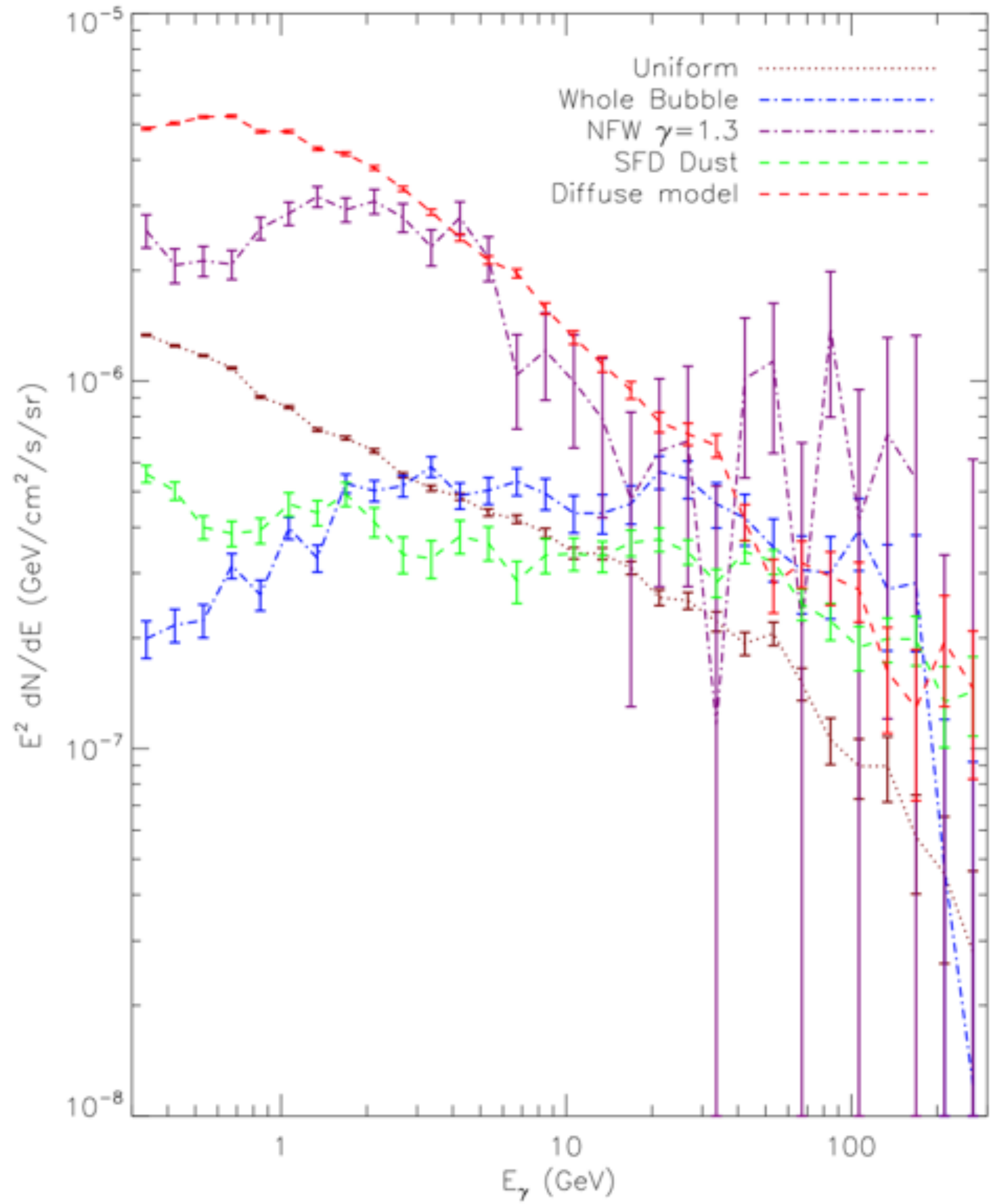


Maybe the Bubbles Have A Spectral Variation?



Does it Correlate with Gas?





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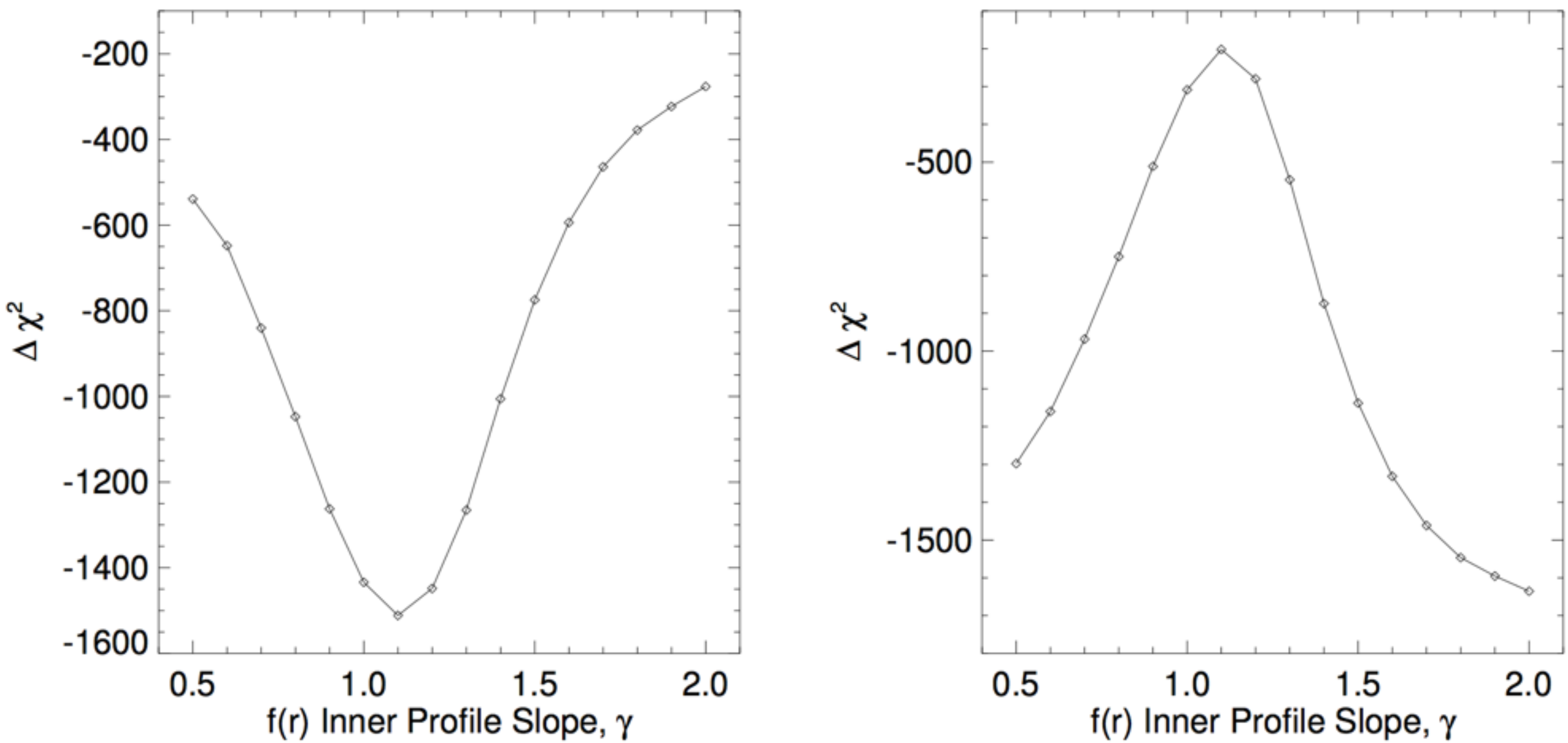
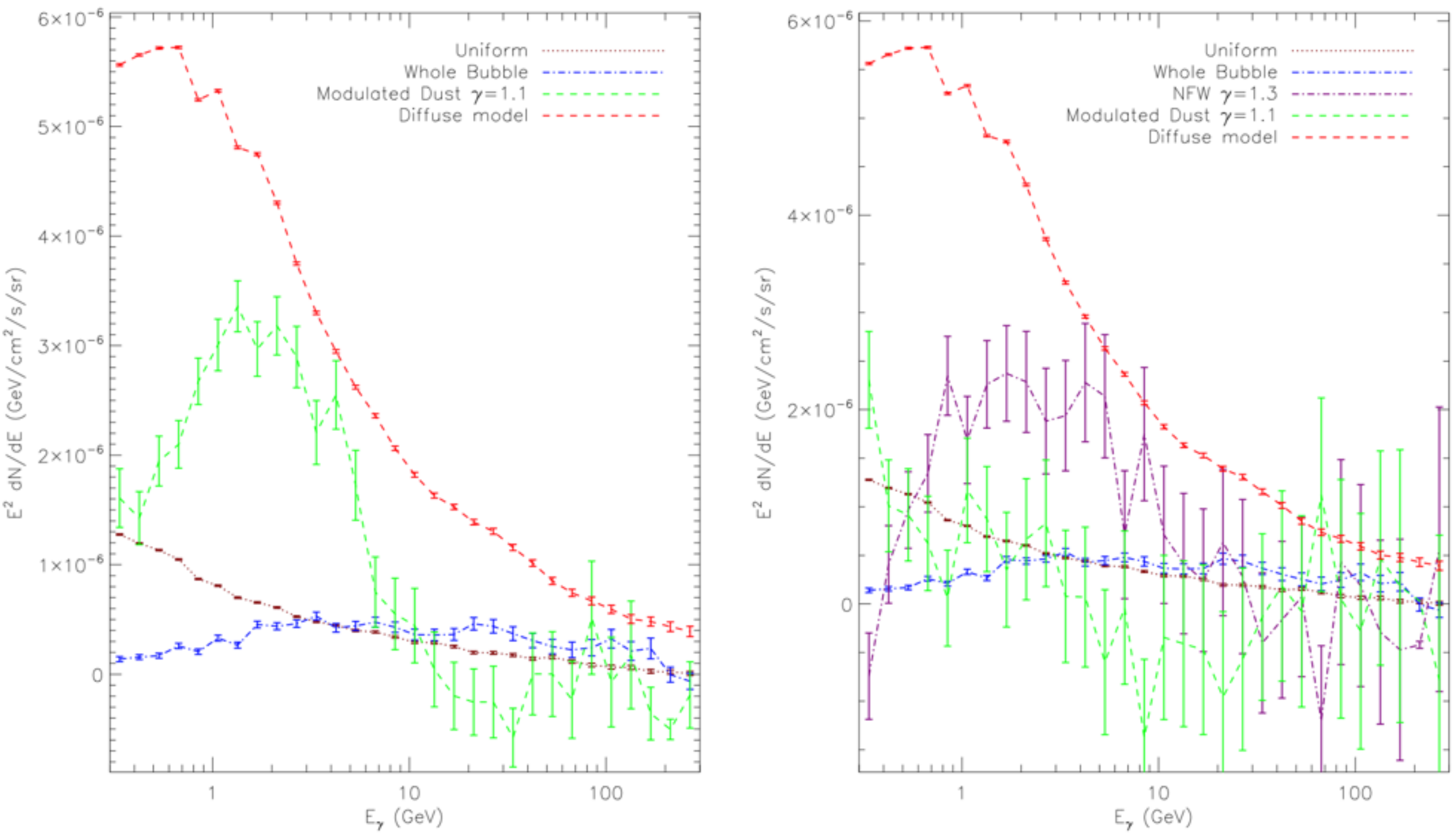


Even more generically, you can add an f(r) α r^(-gamma) profile for the SFD template, this is highly preferred in the model with no dark matter (left), but the dark matter template is still highly preferred even when gamma can float freely (right)

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