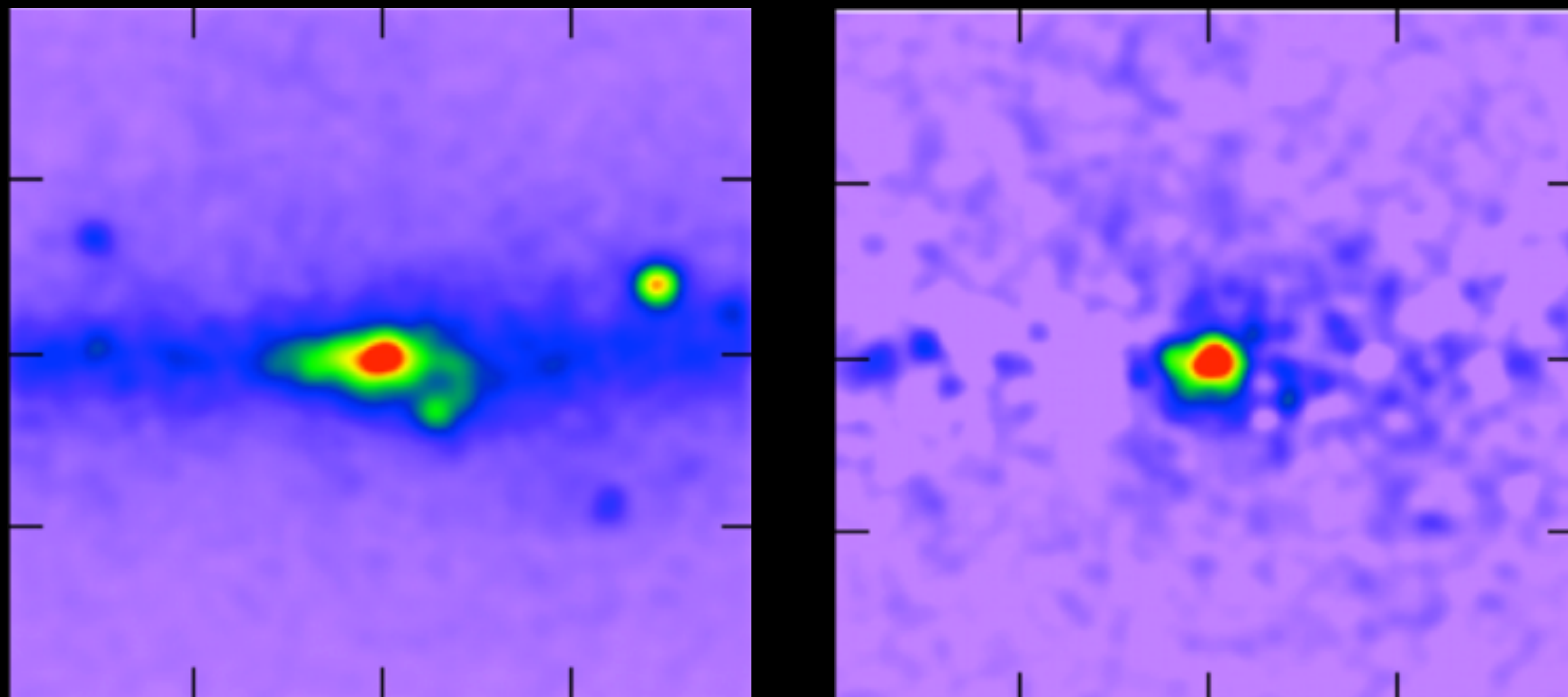
Kavli Institute
for Cosmological Physics
at The University of Chicago

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



Tim Linden

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

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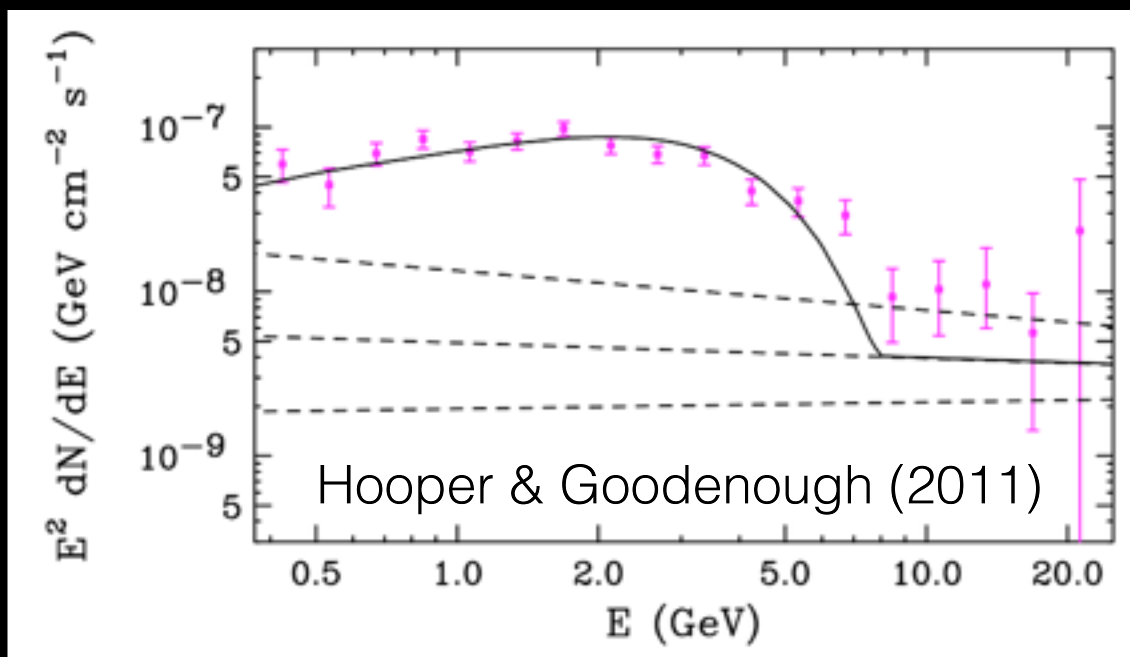
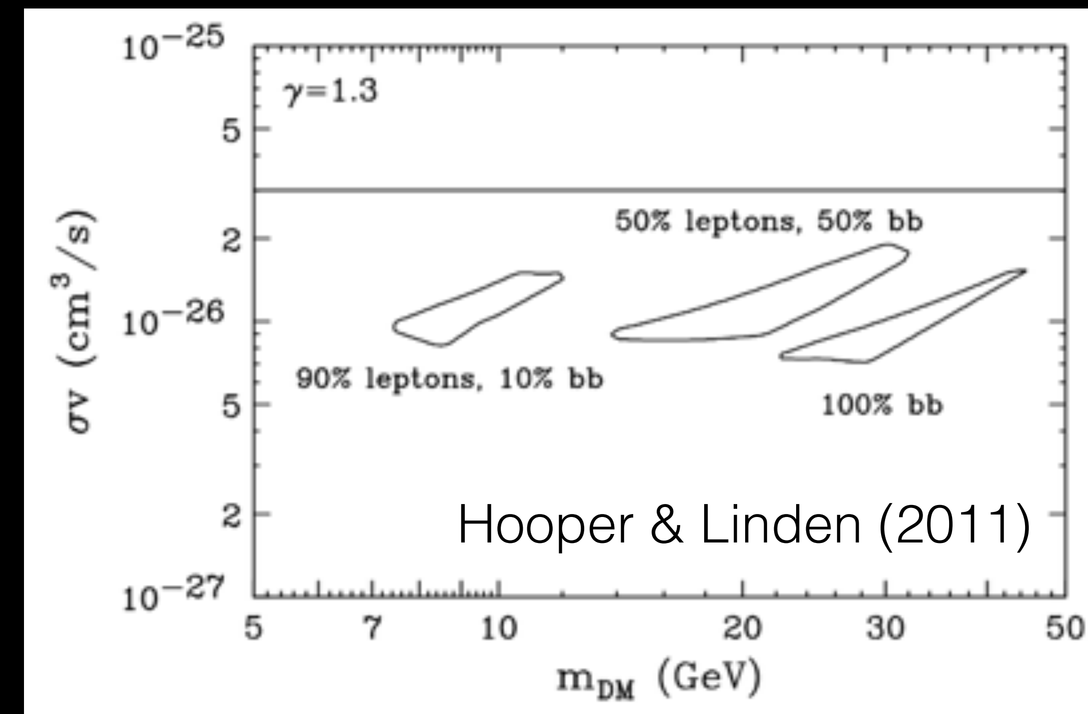
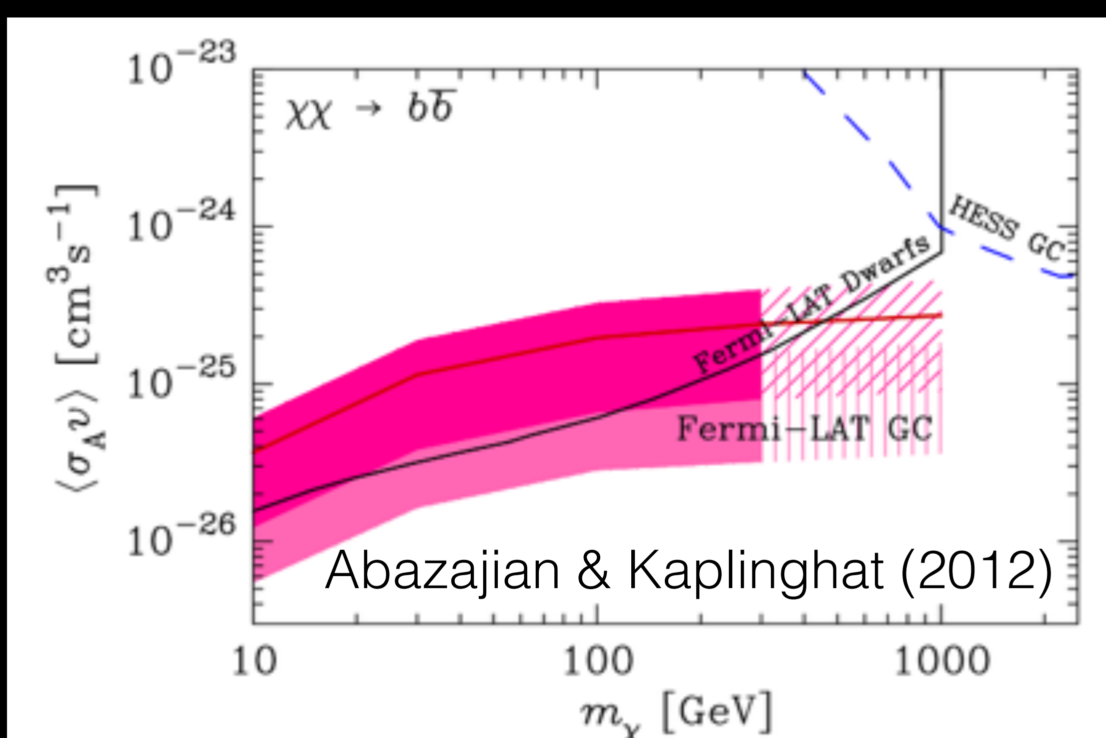
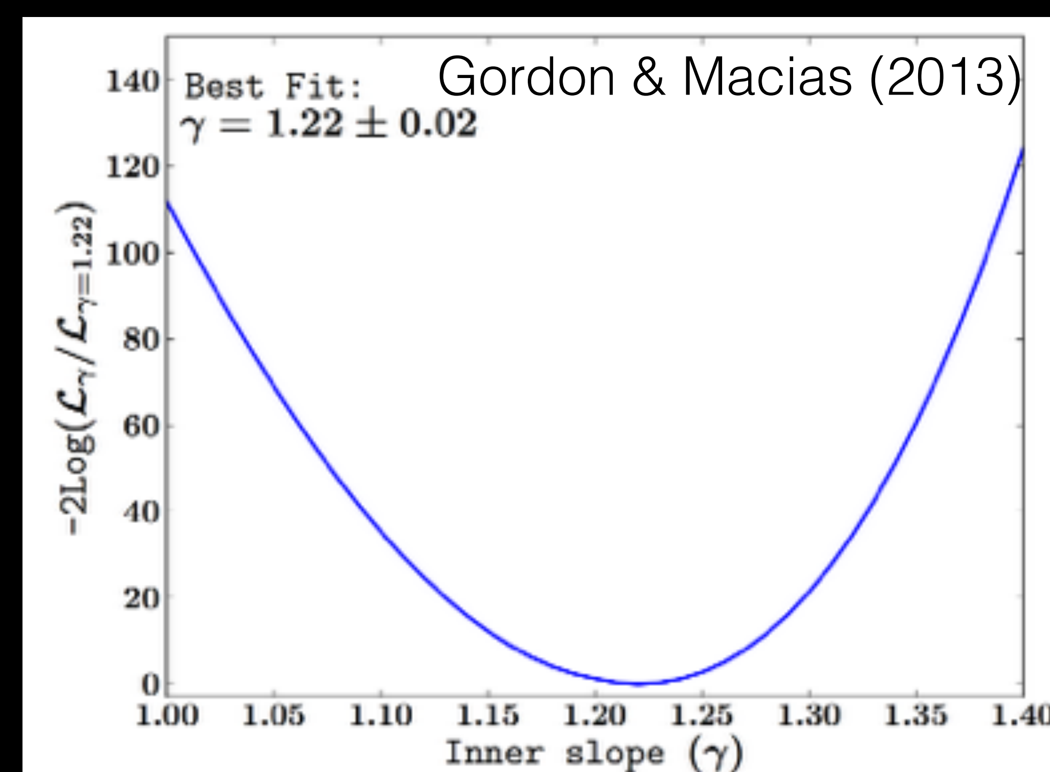
Early Observations of an Anomalous Signal at the GC

First noted as a feature in the Galactic Center region by Goodenough & Hooper (2009)



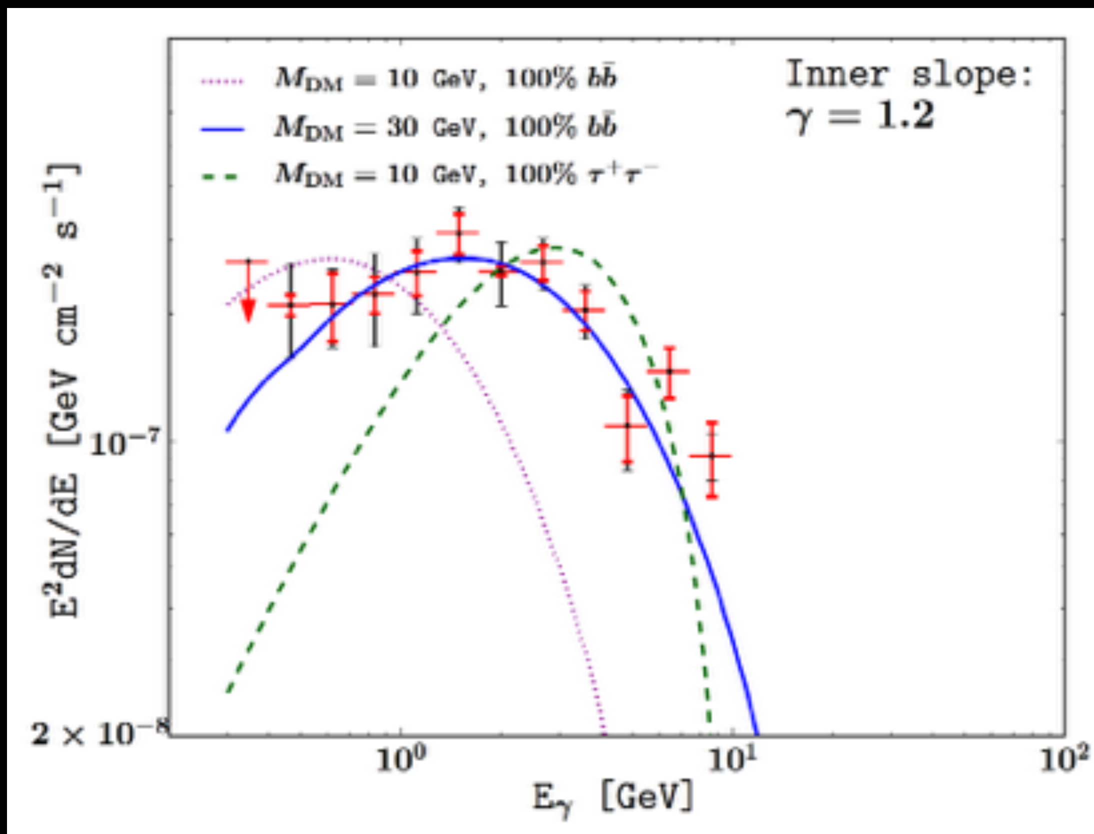






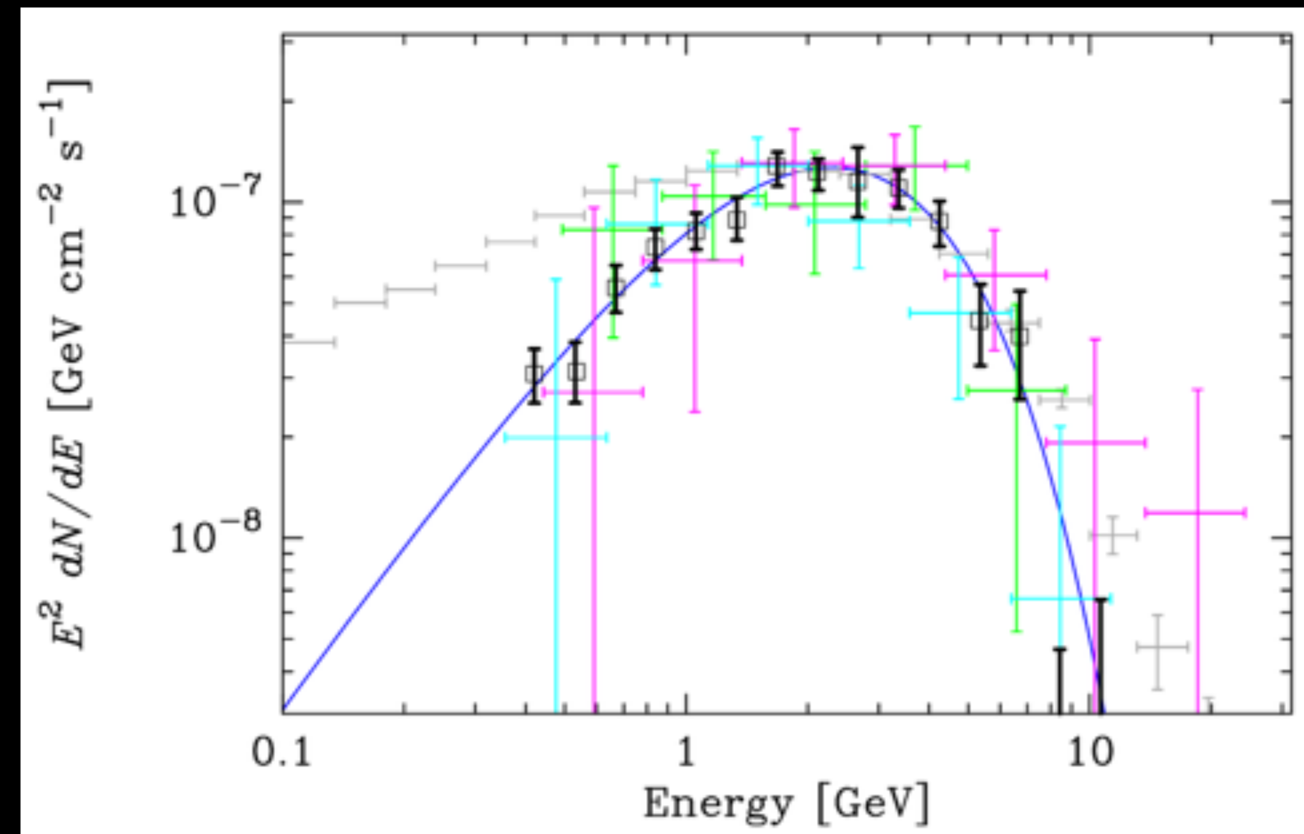
Two Interpretations of the Old Data

Dark Matter



Gordon & Macias (2013)

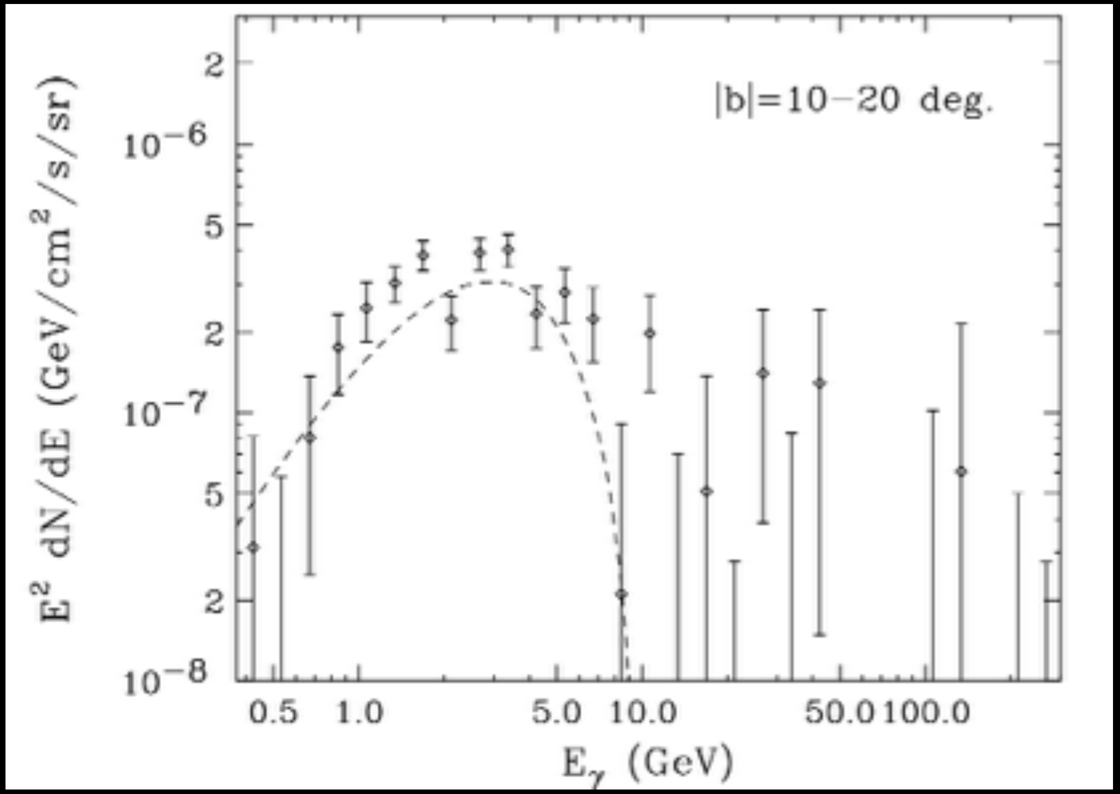
Millisecond Pulsars

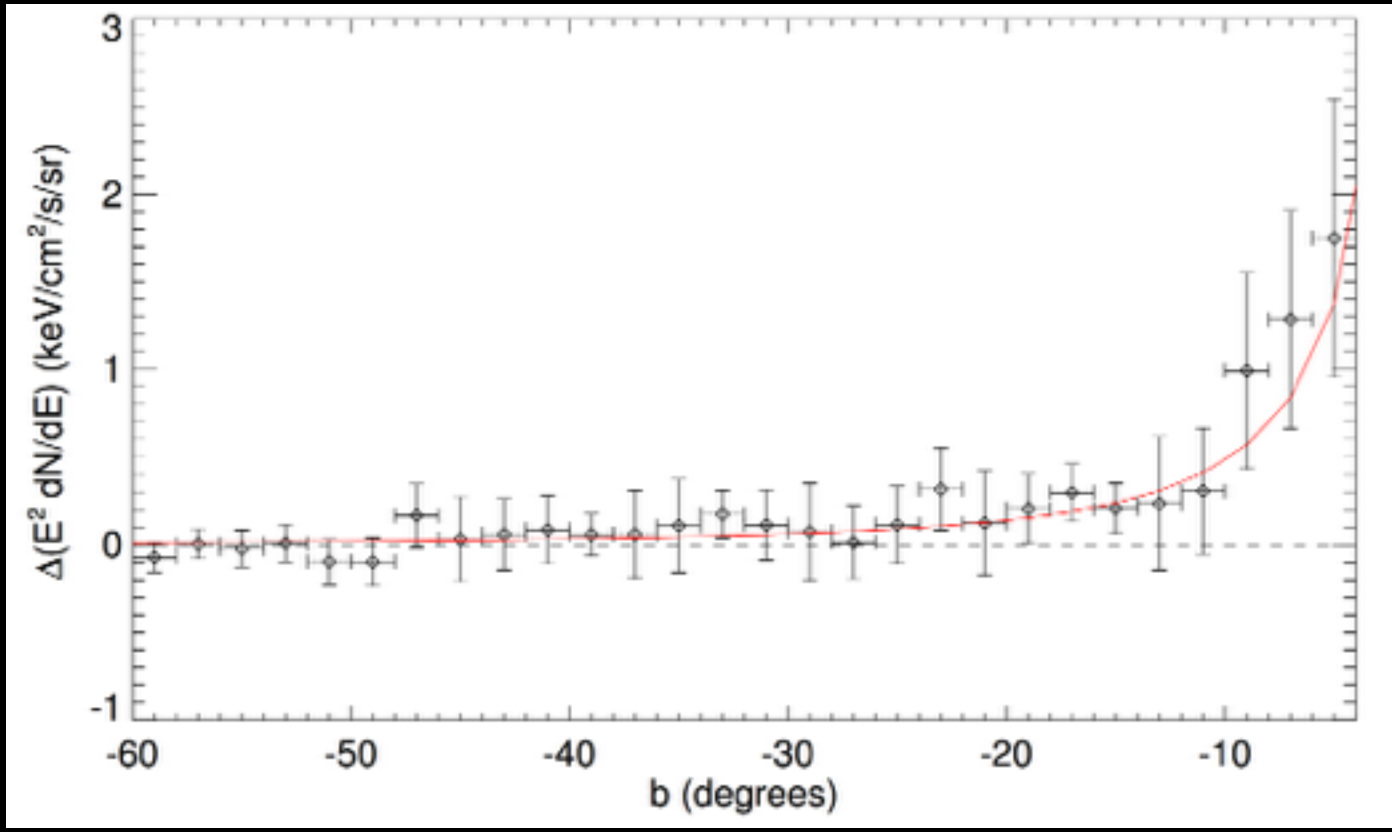


Abazajian (2011)

Early Observations of an Anomalous Signal at the GC

Work by Hooper & Slatyer found this signal in a greatly expanded range, out to at least 10 degrees from the GC





This disfavors the pulsar interpretation. A large population of MSPs 10 degrees from the GC should be observable by Fermi

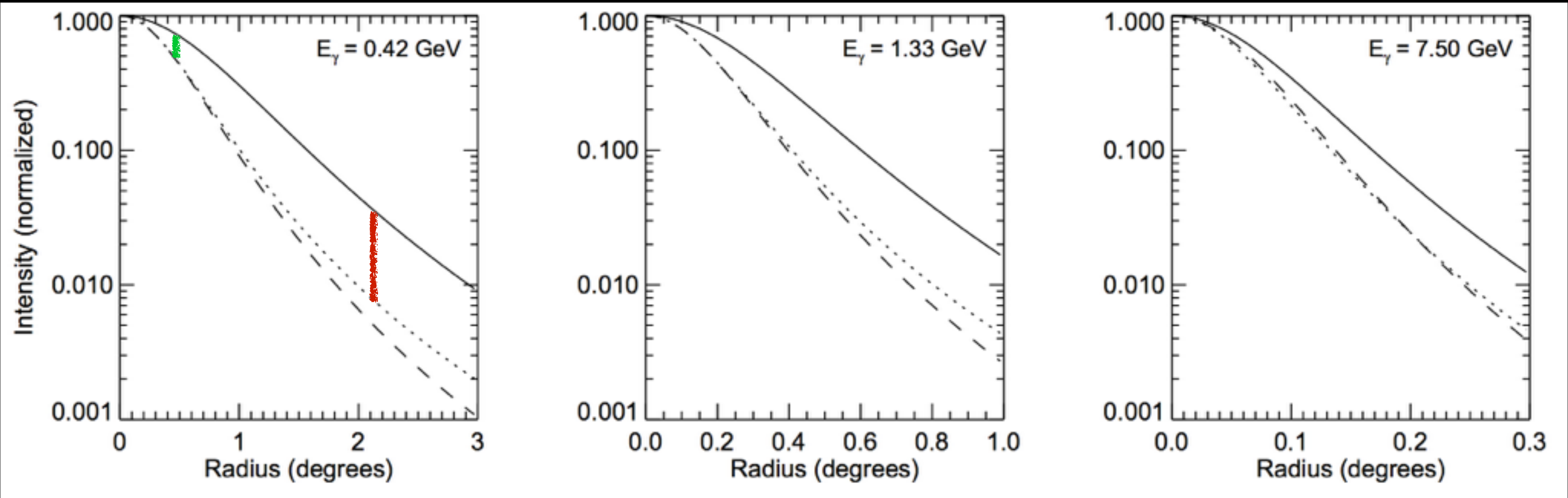
The Current Analysis - Three Objectives

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

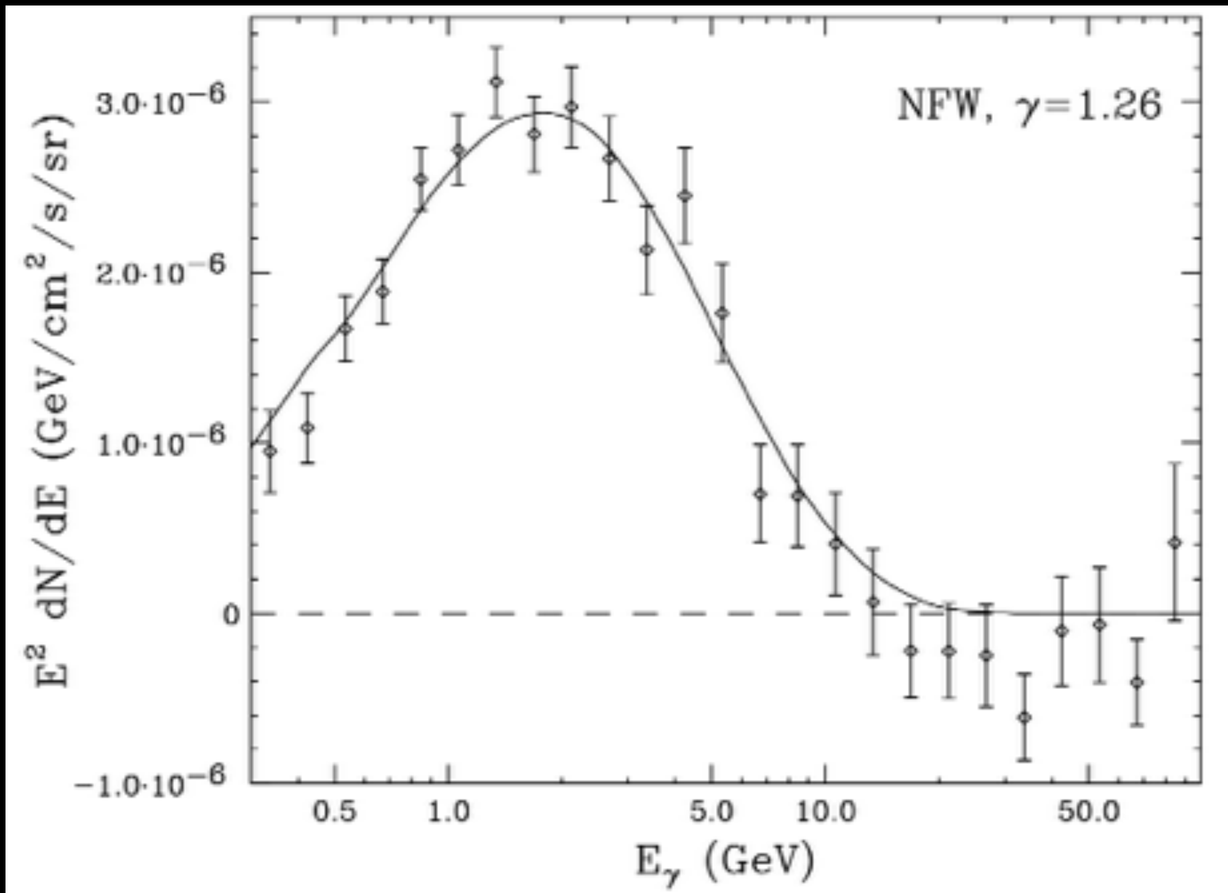
Inner Galaxy - $|b| > 1^{o}$

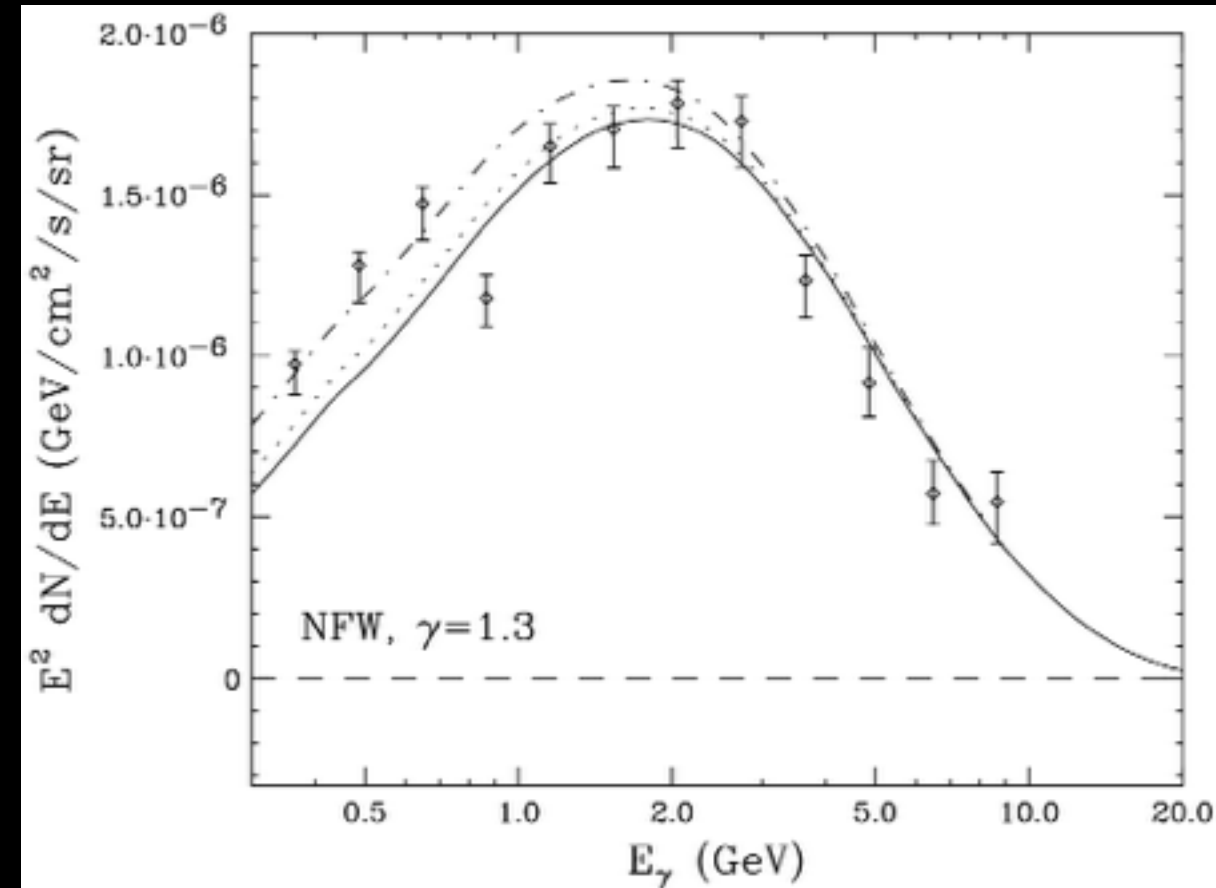
- Mask bright point sources at 2^{o}
- Let normalization of diffuse, isotropic, Fermi bubbles and dark matter float in each energy bin

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

- Allow the normalization of point sources, and spectrum of bright point sources to vary
- Fit each component to a spectral model and calculate the best fit likelihood of models with and without dark matter

Spectrum of the Residuals

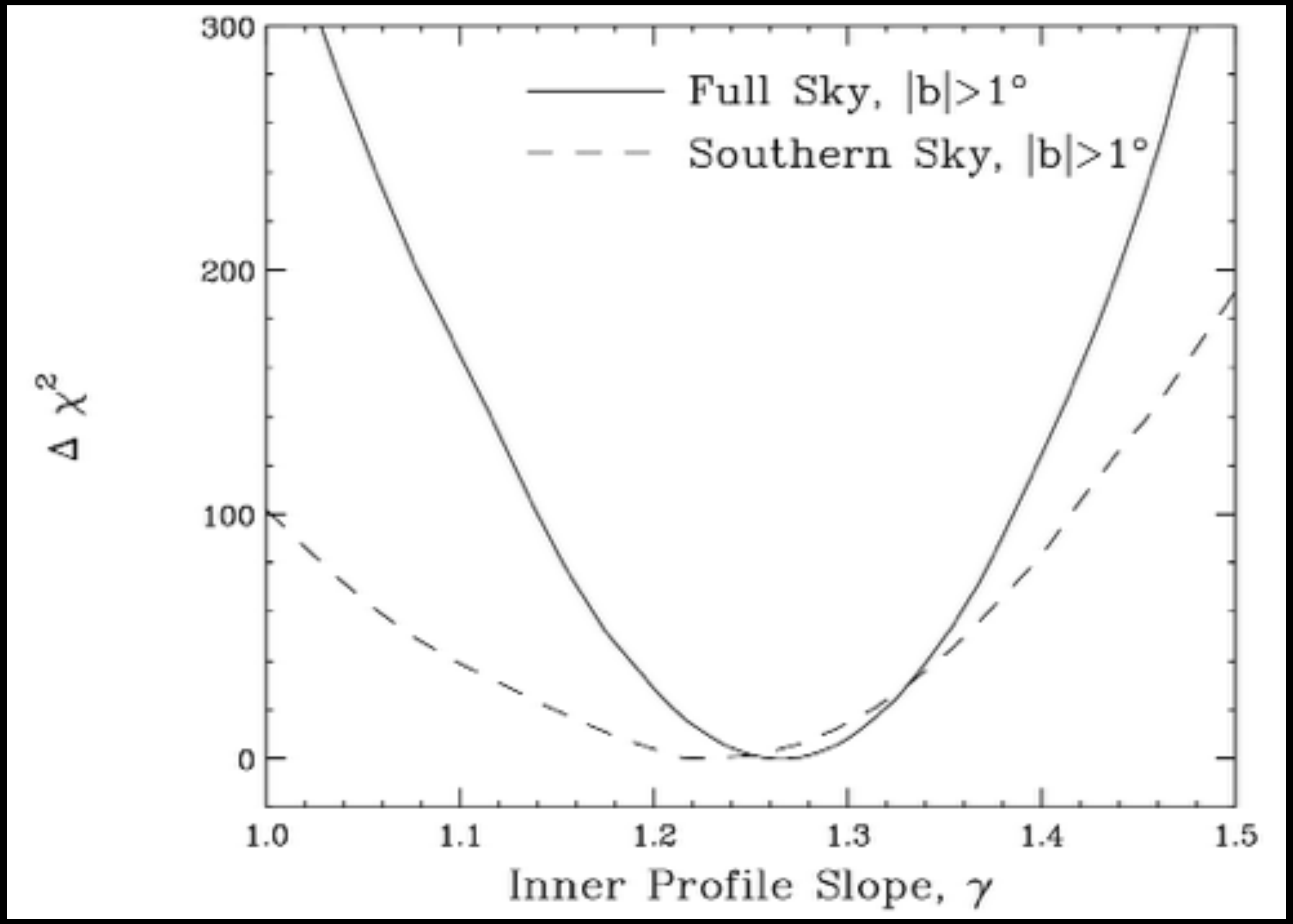


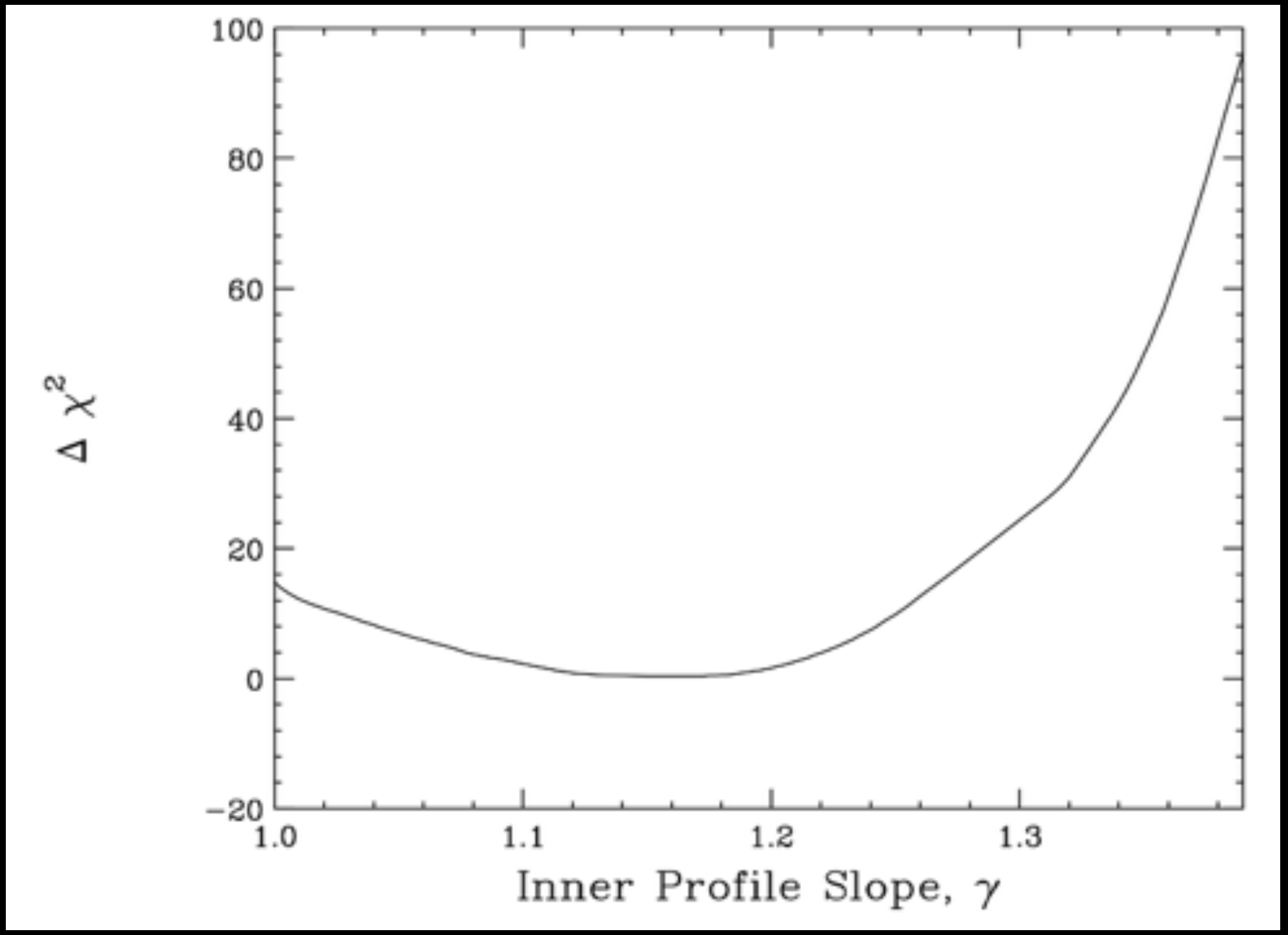


Inner Galaxy - The DM template naturally picks up the following spectral shape - the normalization of the NFW template is allowed to float independently in every energy bin

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.

The Morphology of the Gamma-Ray Excess

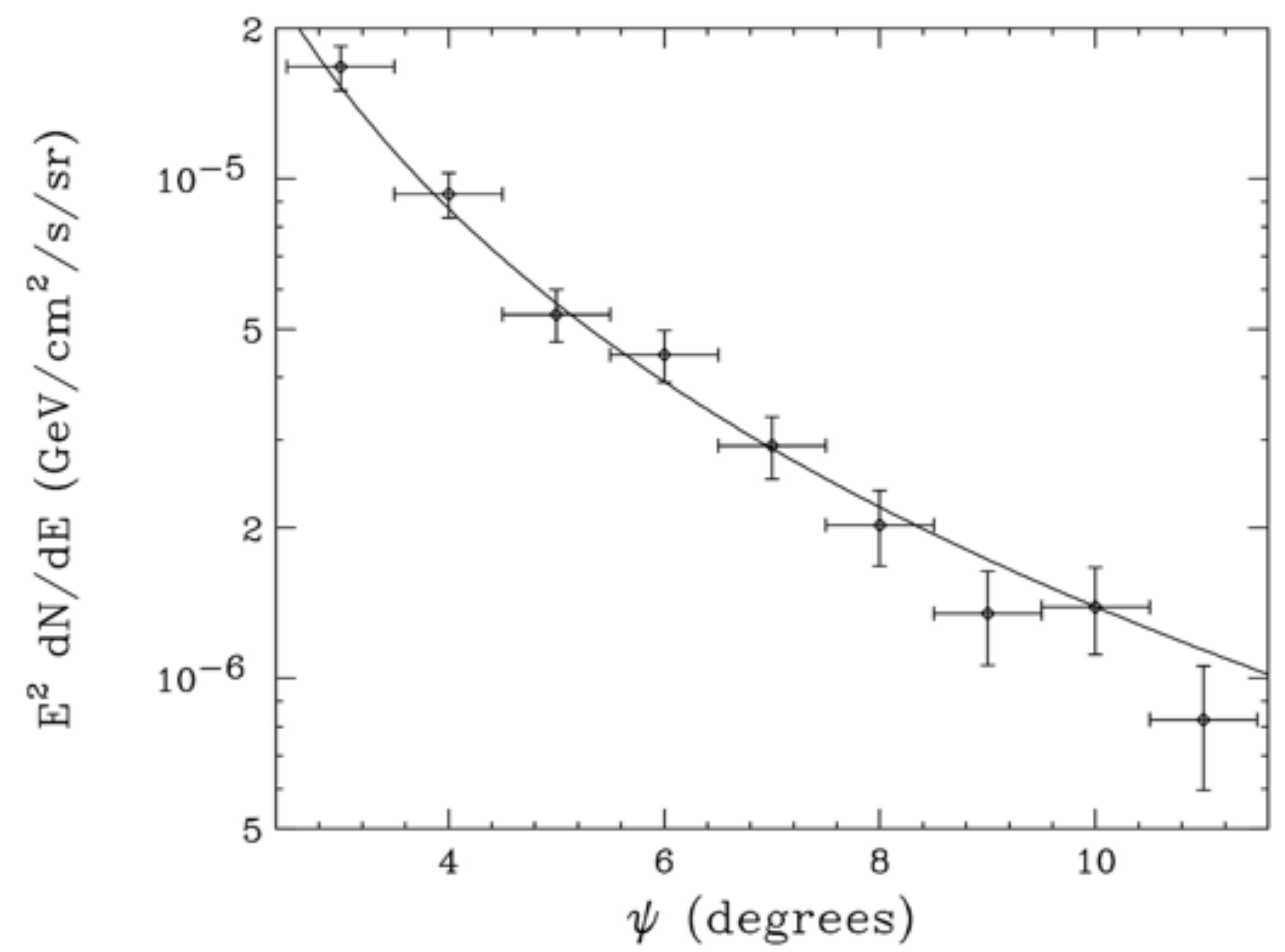




Inner Galaxy - The best fit is given by a generalized NFW profile with **γ**=1.26. The Southern sky has a consistent fit to the spectrum of the full sky.

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

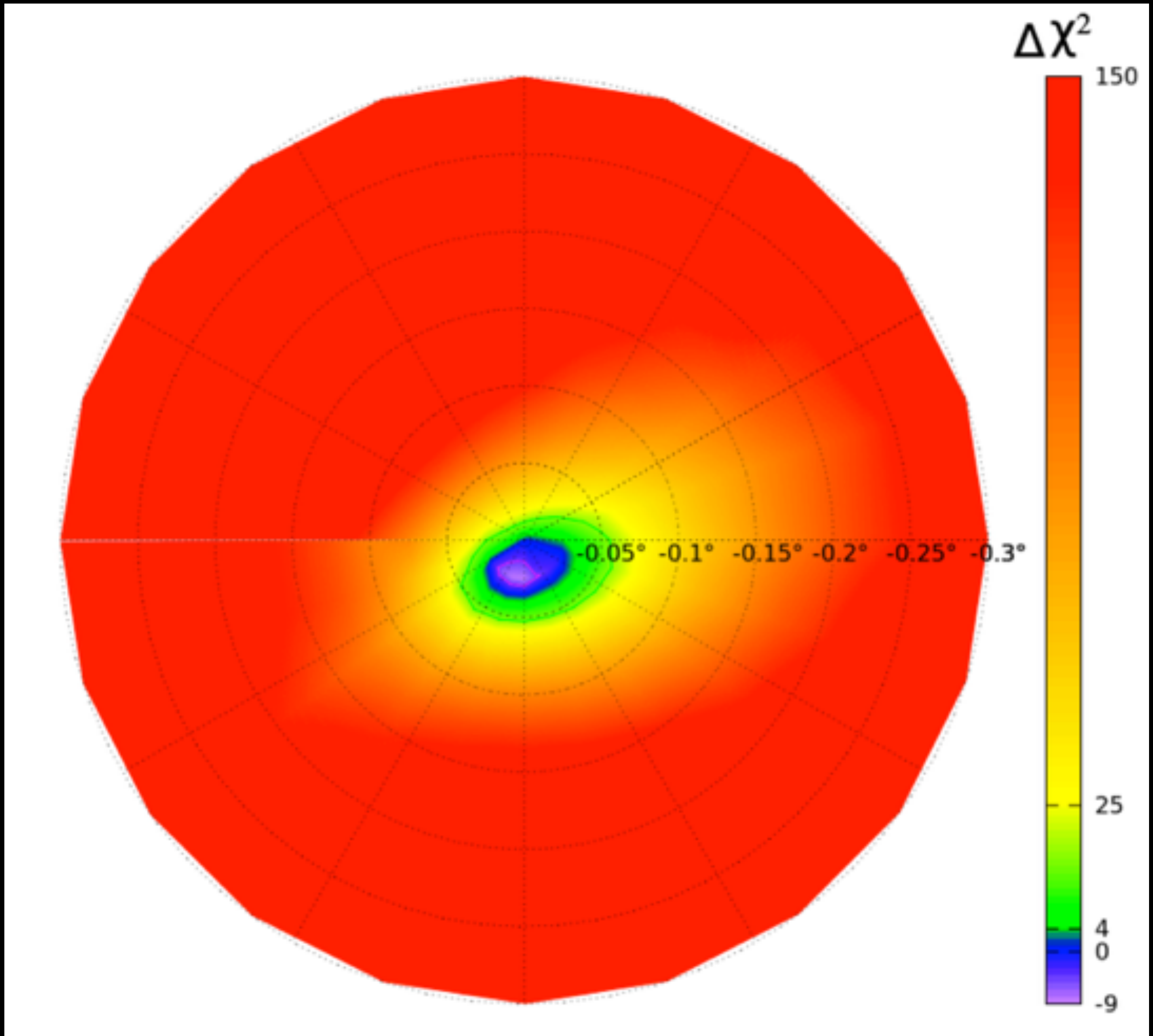
The Morphology of the Gamma-Ray Excess



Lastly, it is worth noting that our models allow the spectra of the fit to float in each energy bin, but we have thus far been forcing the model to follow the NFW morphology throughout the entire sky.

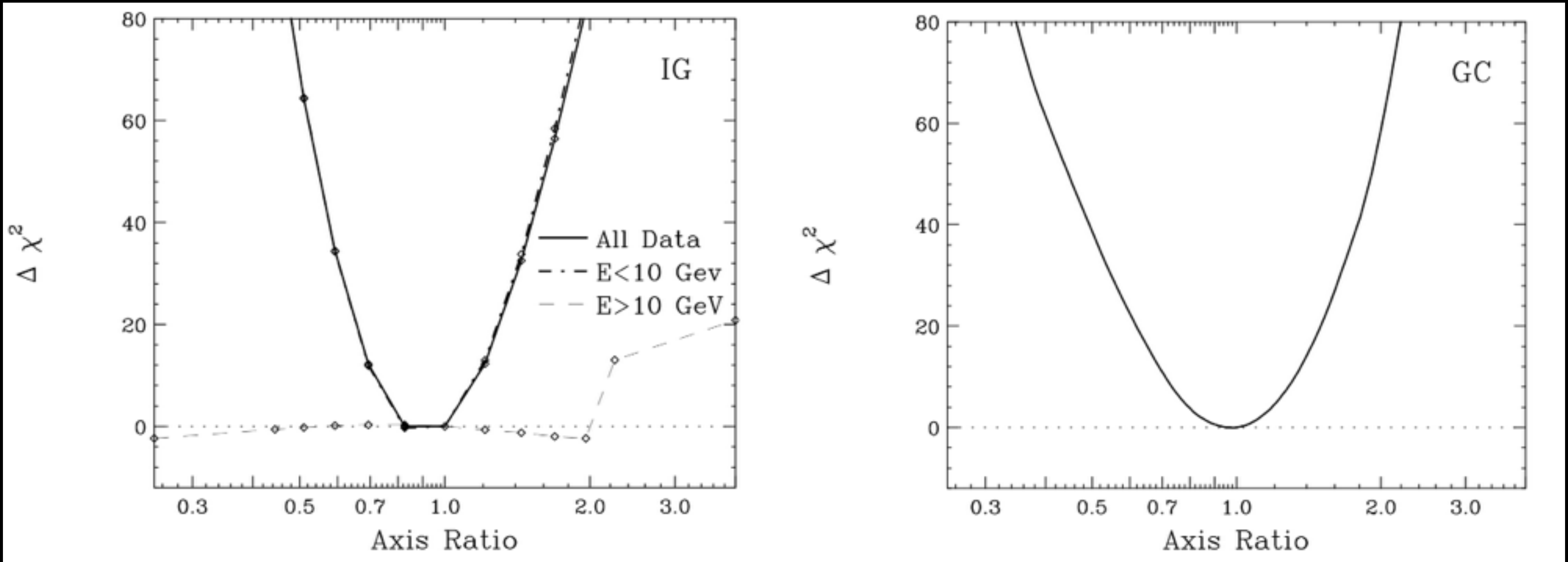
We can instead fix the spectrum of the Inner Galaxy excess, and allow the normalization to float in 1^{o} angular bins. We find the residual to be statistically significant out to 12o from the Galactic Center. Following a slightly steeper profile (at high latitudes) of $\boldsymbol{\gamma}$ = 1.4.

The Morphology of the Gamma-Ray Excess



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°

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.

Interpretations of the Excess

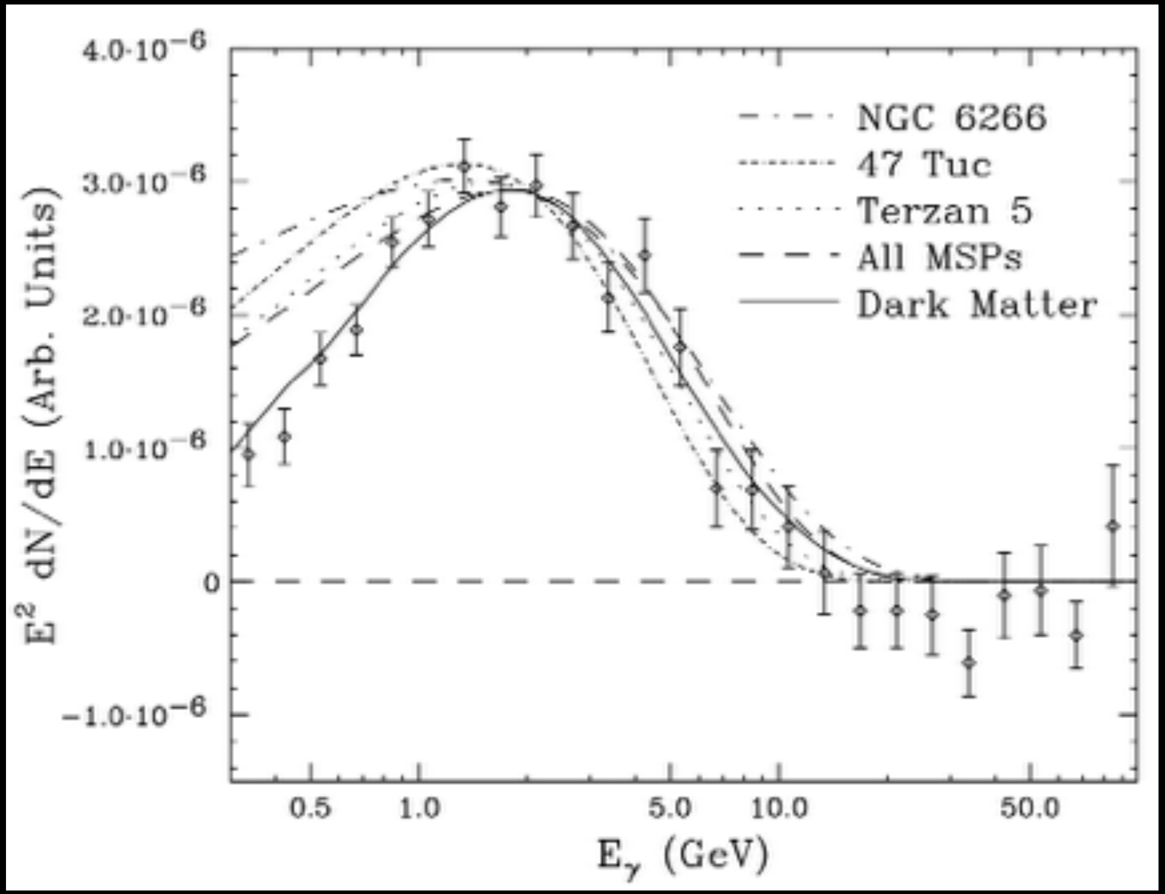
1.) Do the data prefer millisecond pulsars or dark matter annihilation?

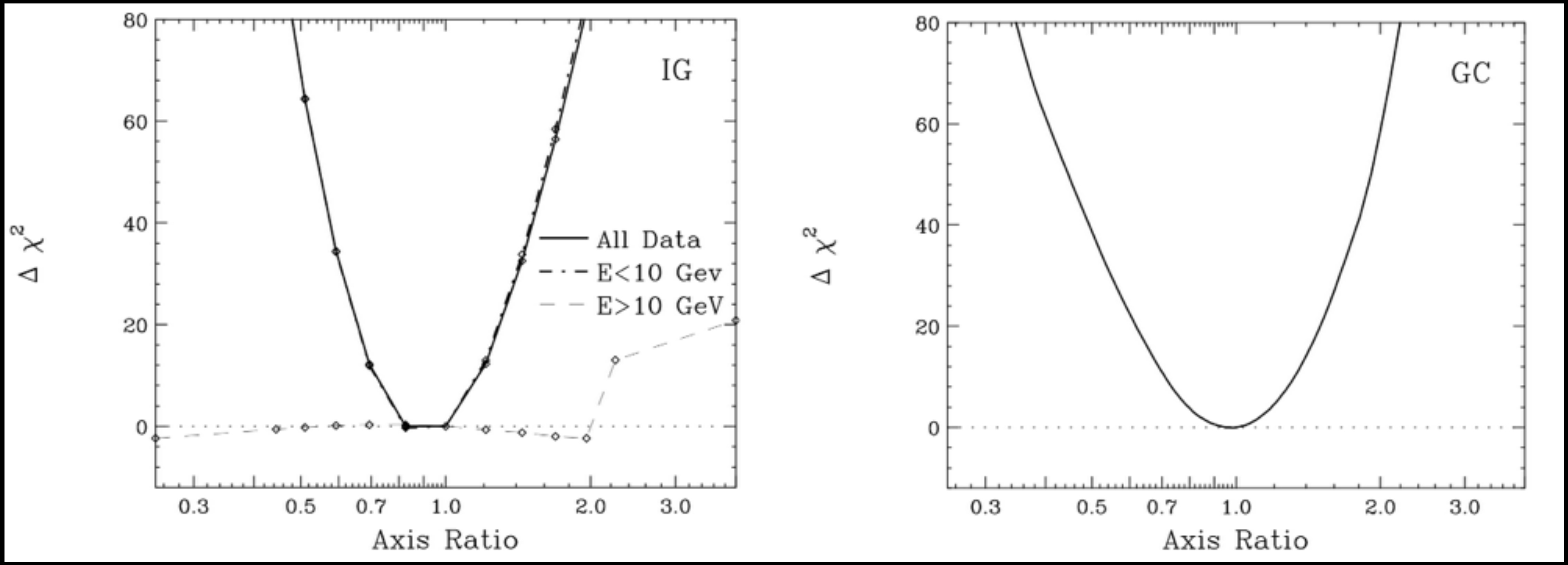
2.) How do the data compare to theoretically predicted dark matter models?

Interpretations of the Excess

The spectrum of the residual signal in the Inner Galaxy does not look like dark matter annihilation

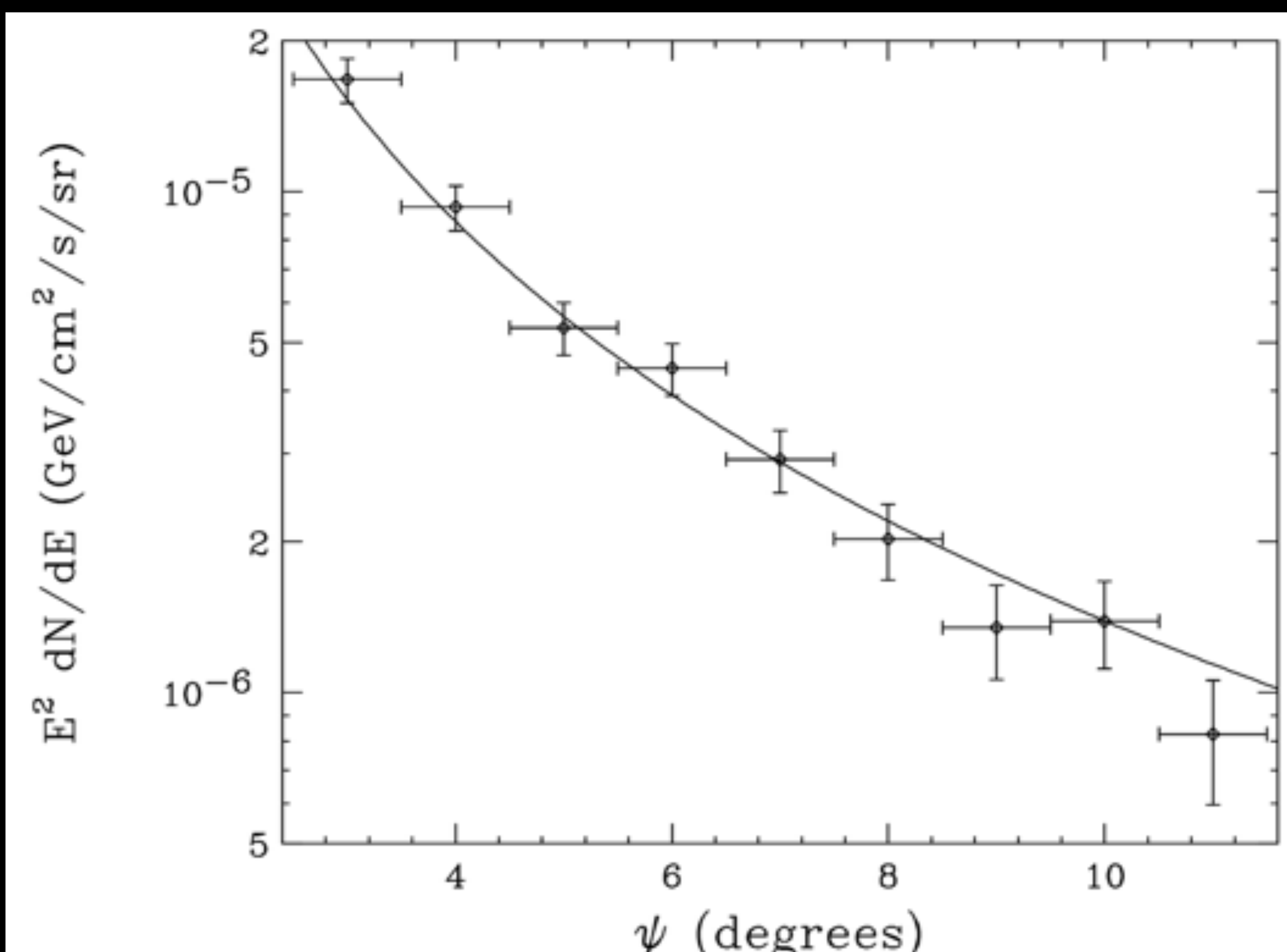
The spherical symmetry of the fit is hard to reconcile with models of MSP emission

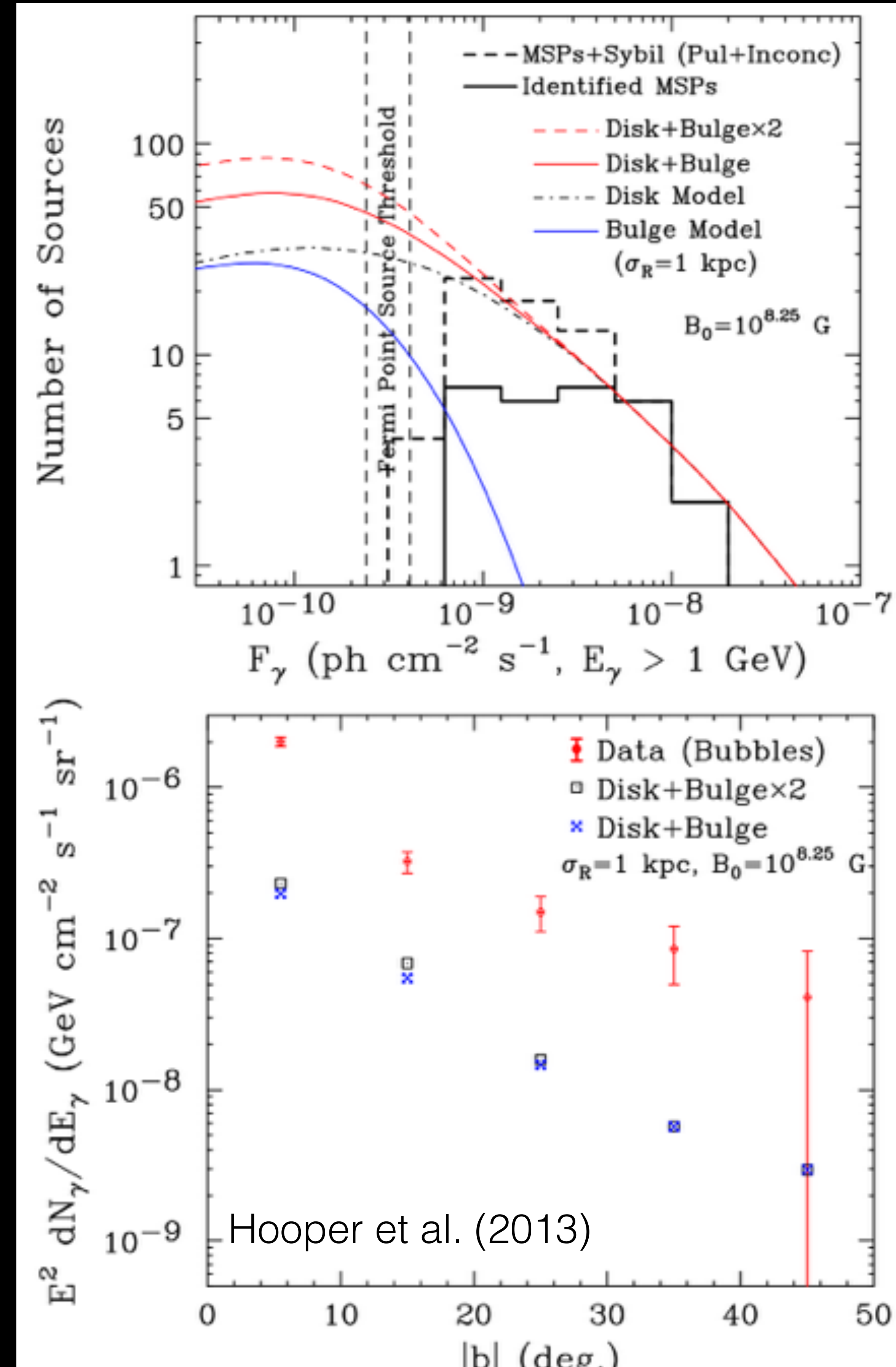




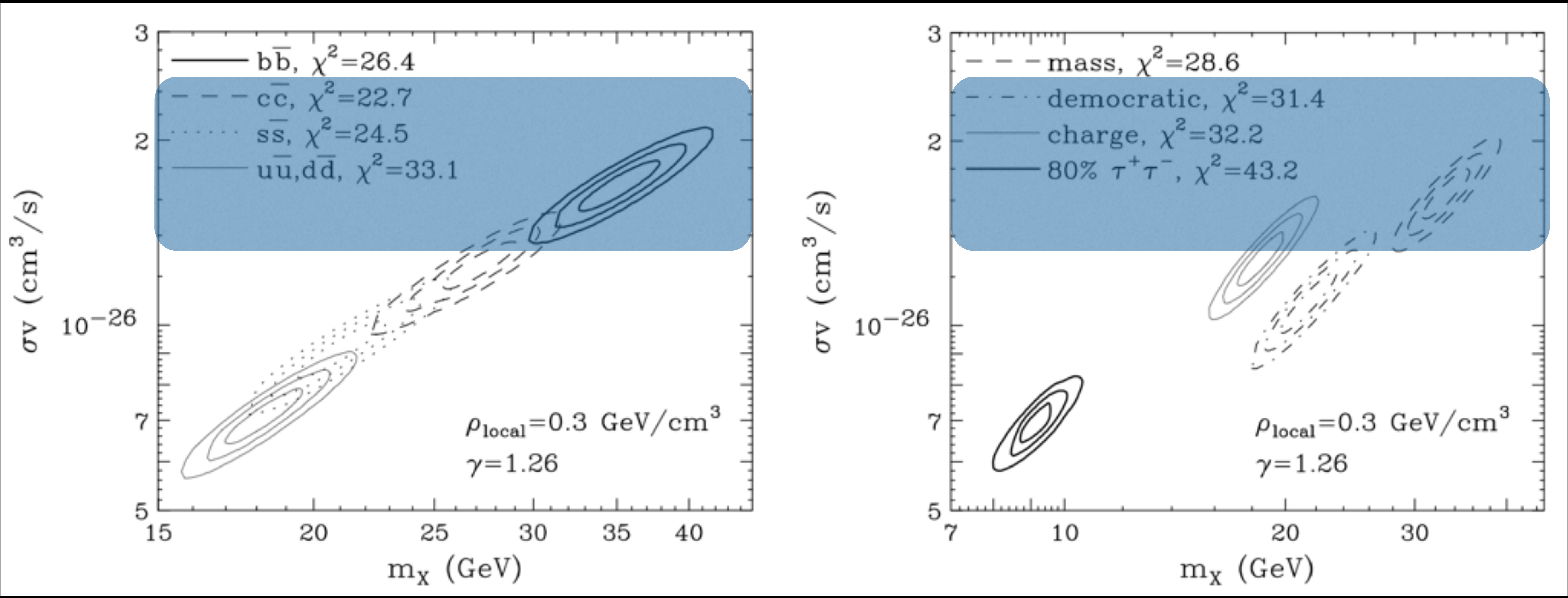
Interpretations of the Excess

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

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 Summerfeld 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.

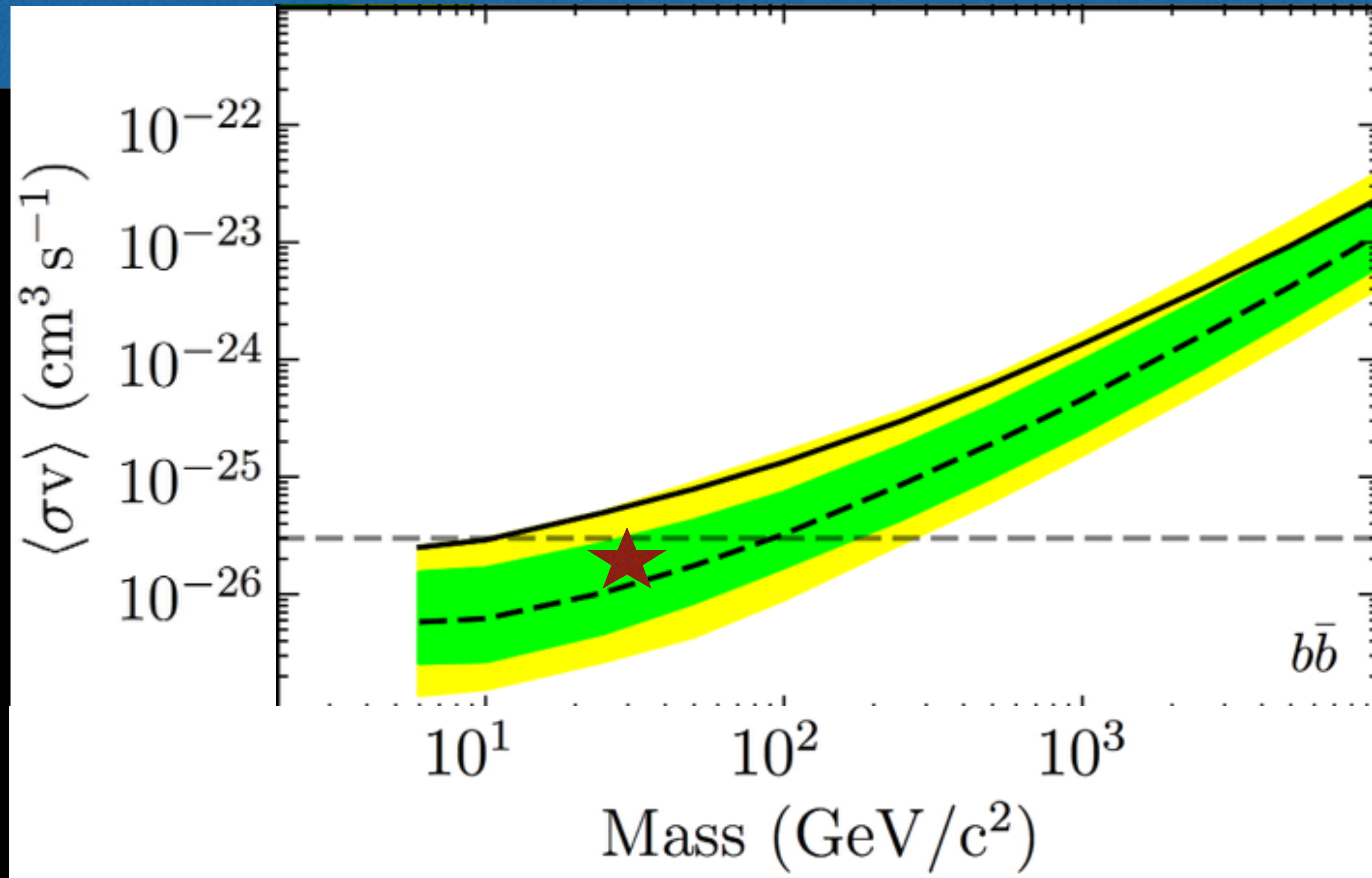
The Current State of the Excess

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.

Is this how the story should unfold?

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

Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\log_{10}(J^{NFW})^a$ ($\log_{10}$[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)

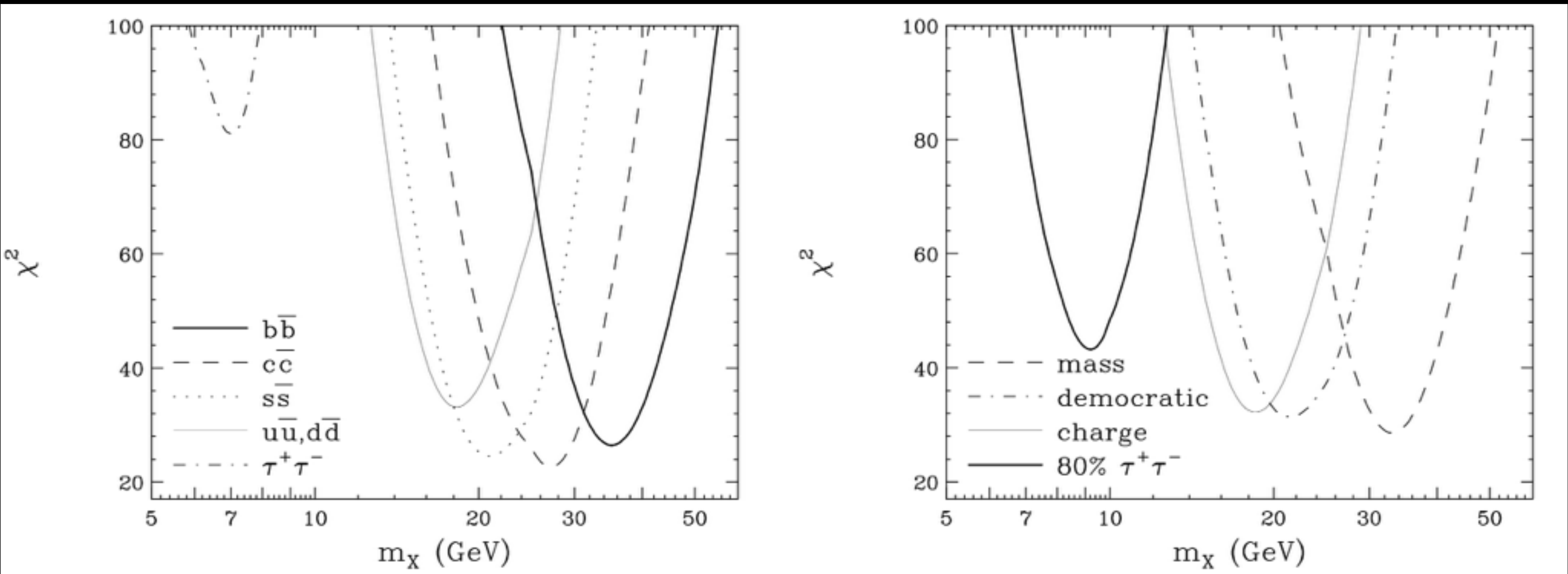
The J-Factor of the Galactic center is:

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

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

Extra Slides

Dark Matter Fits to the Data



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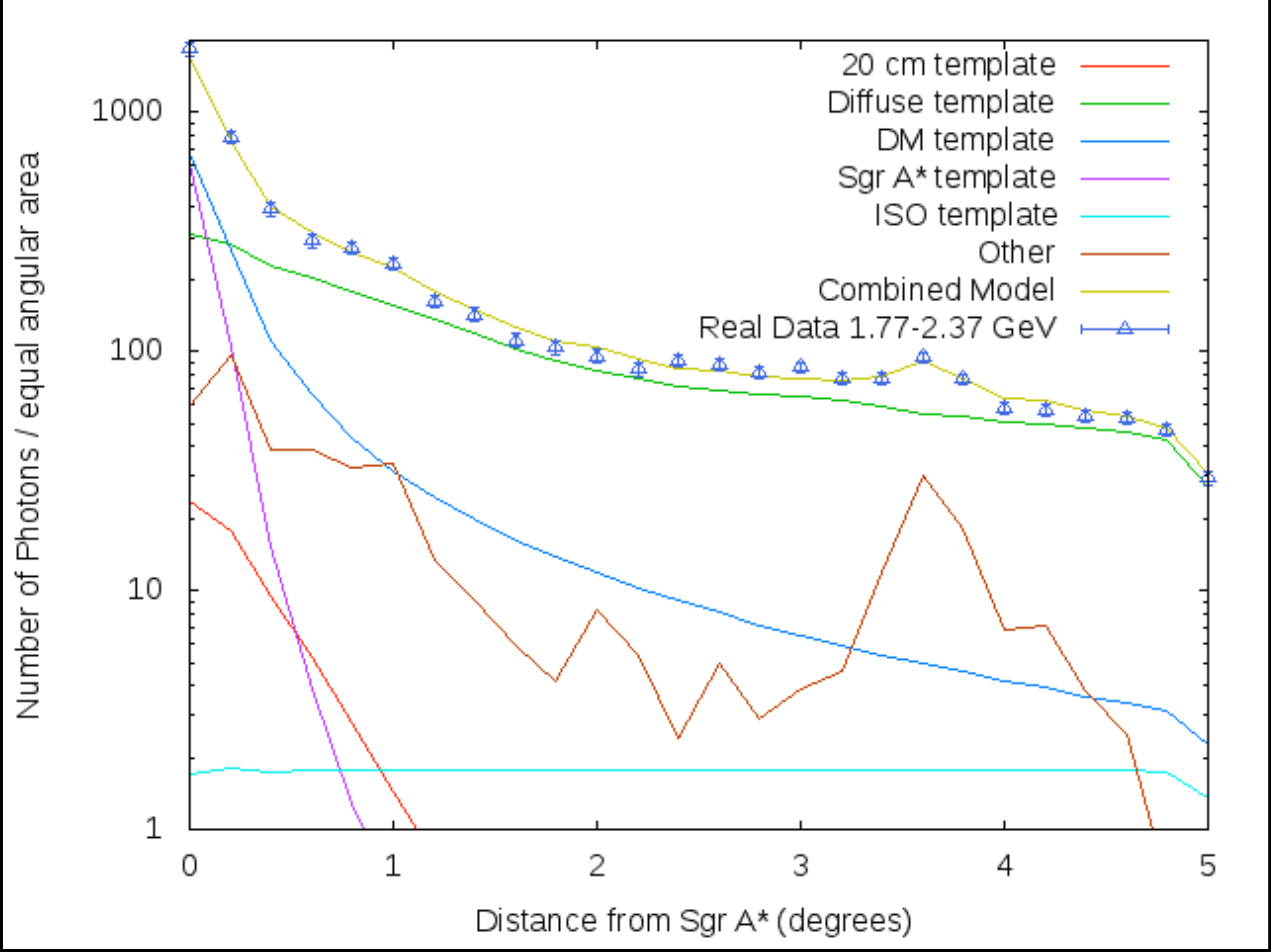
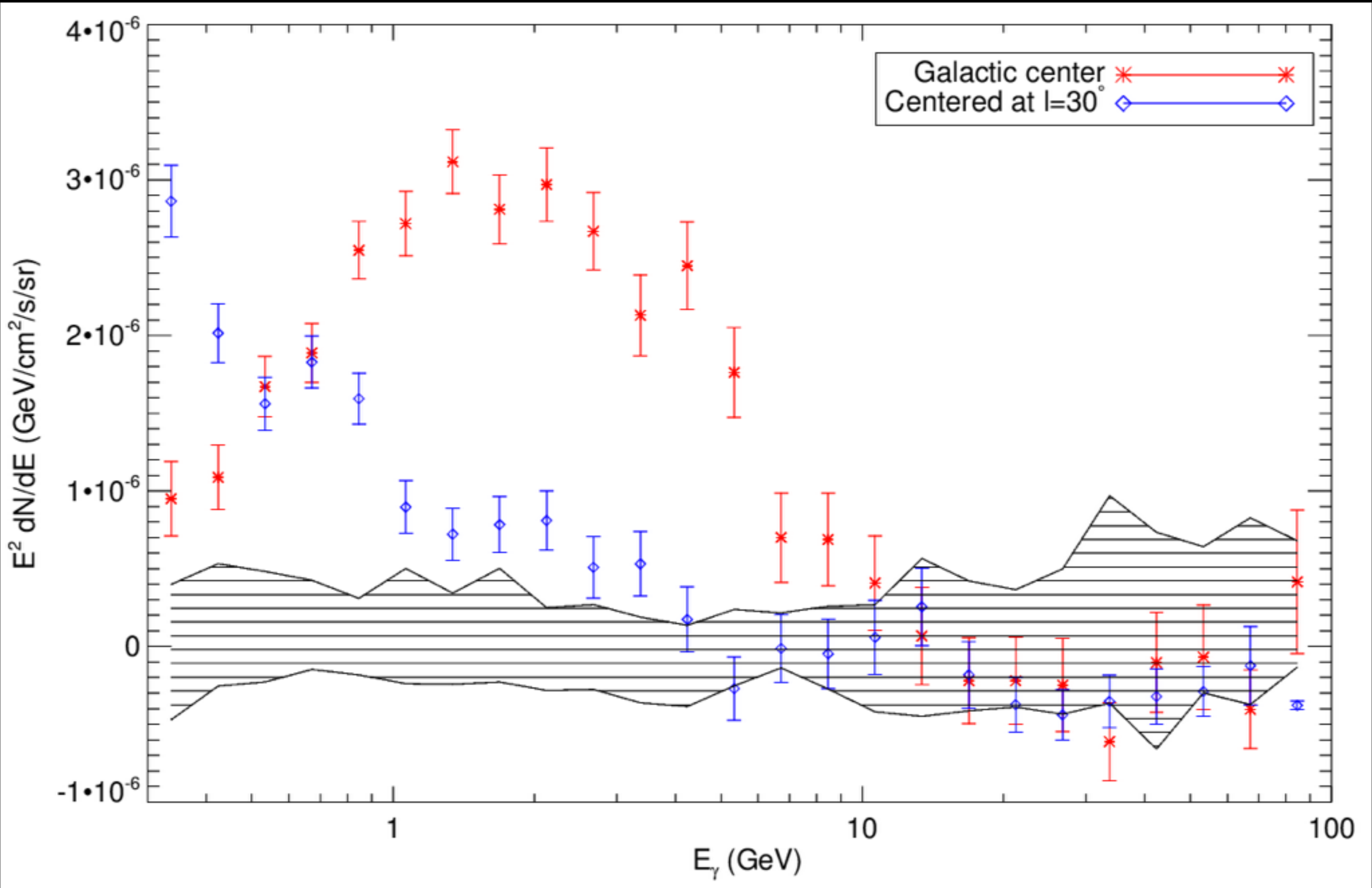
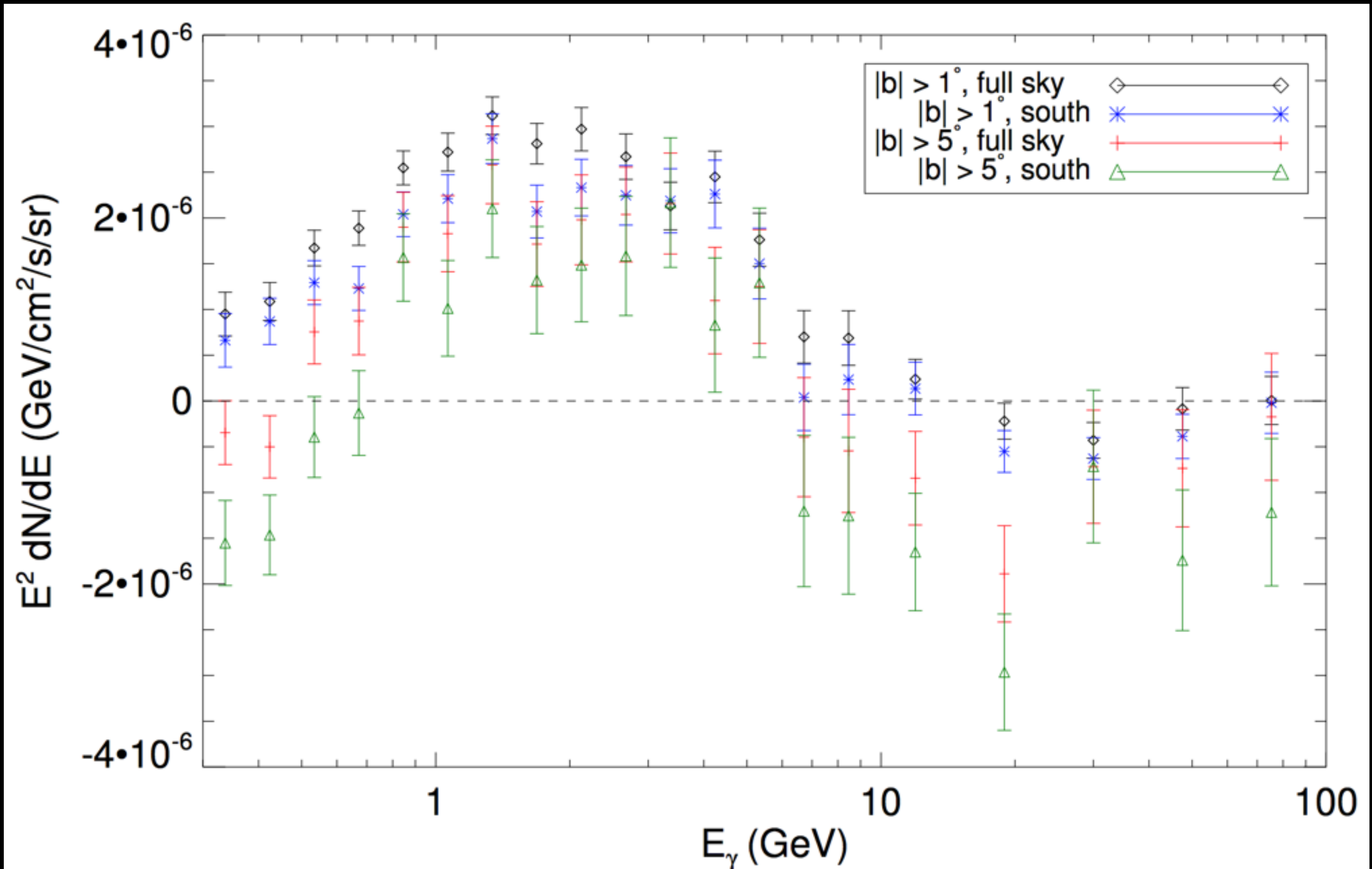
How Big Is This Excess?



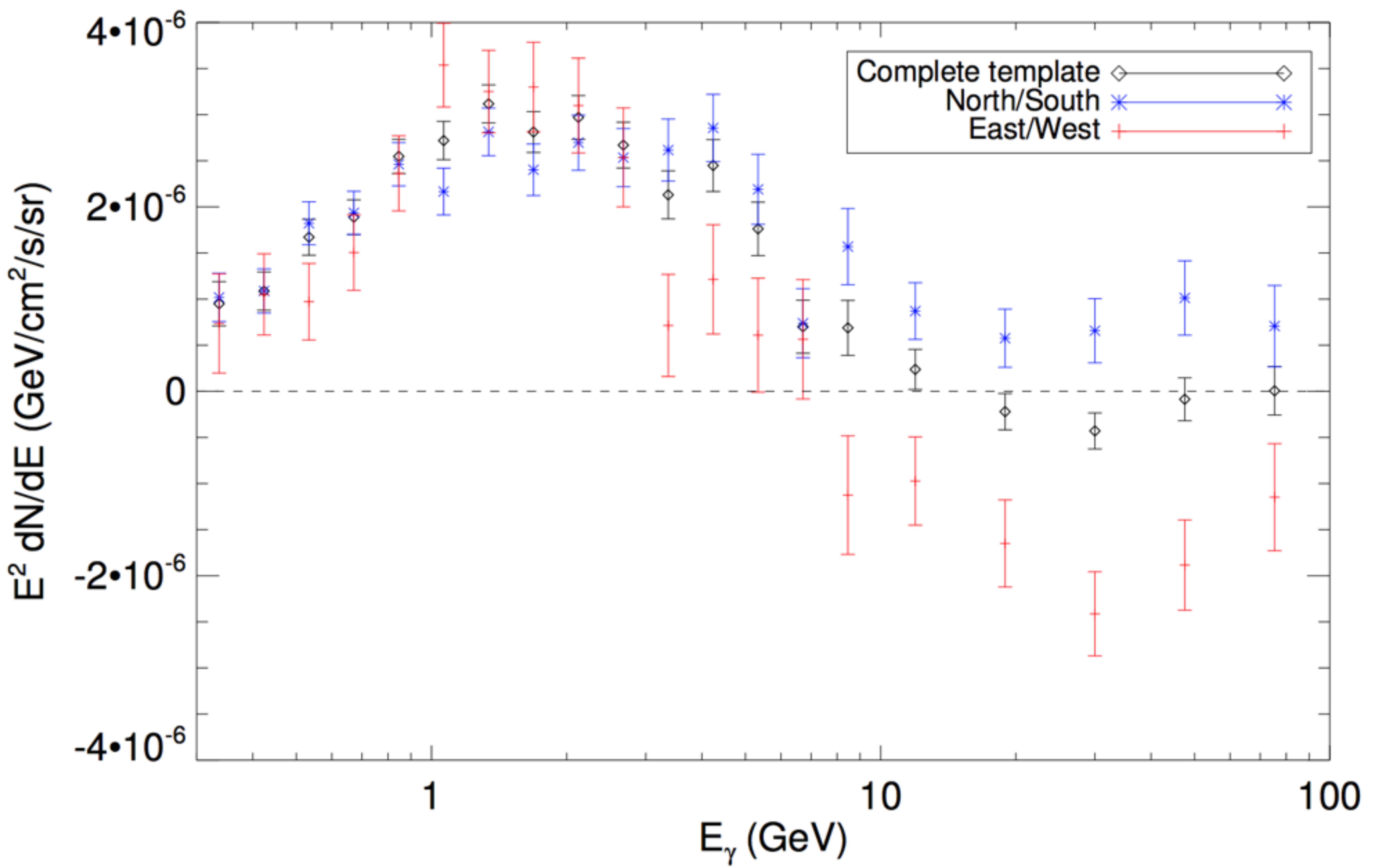
Do Other Residuals Have the Same Spectrum?



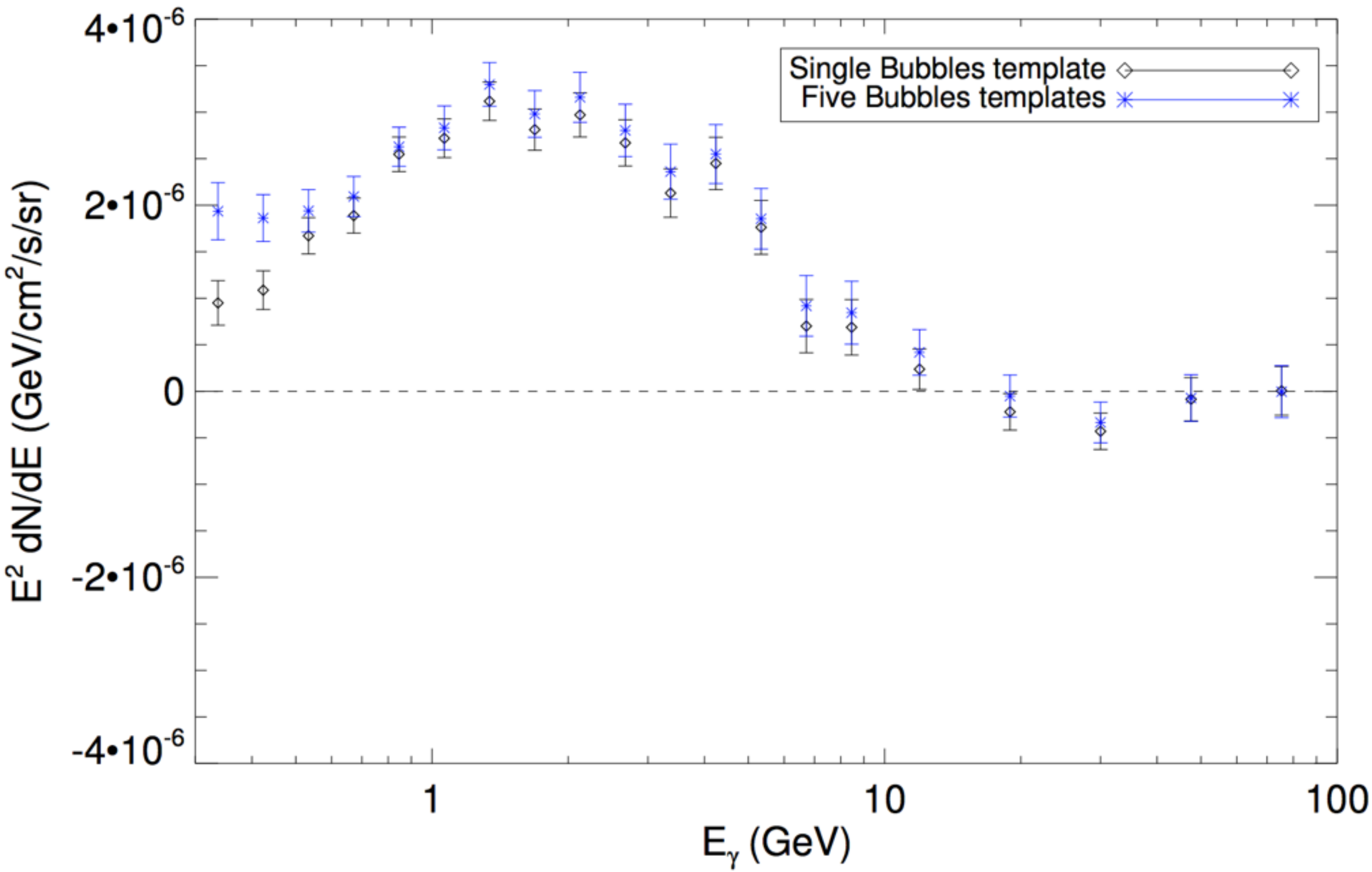
Wait, Some of the Same Photons are in Each Sample?



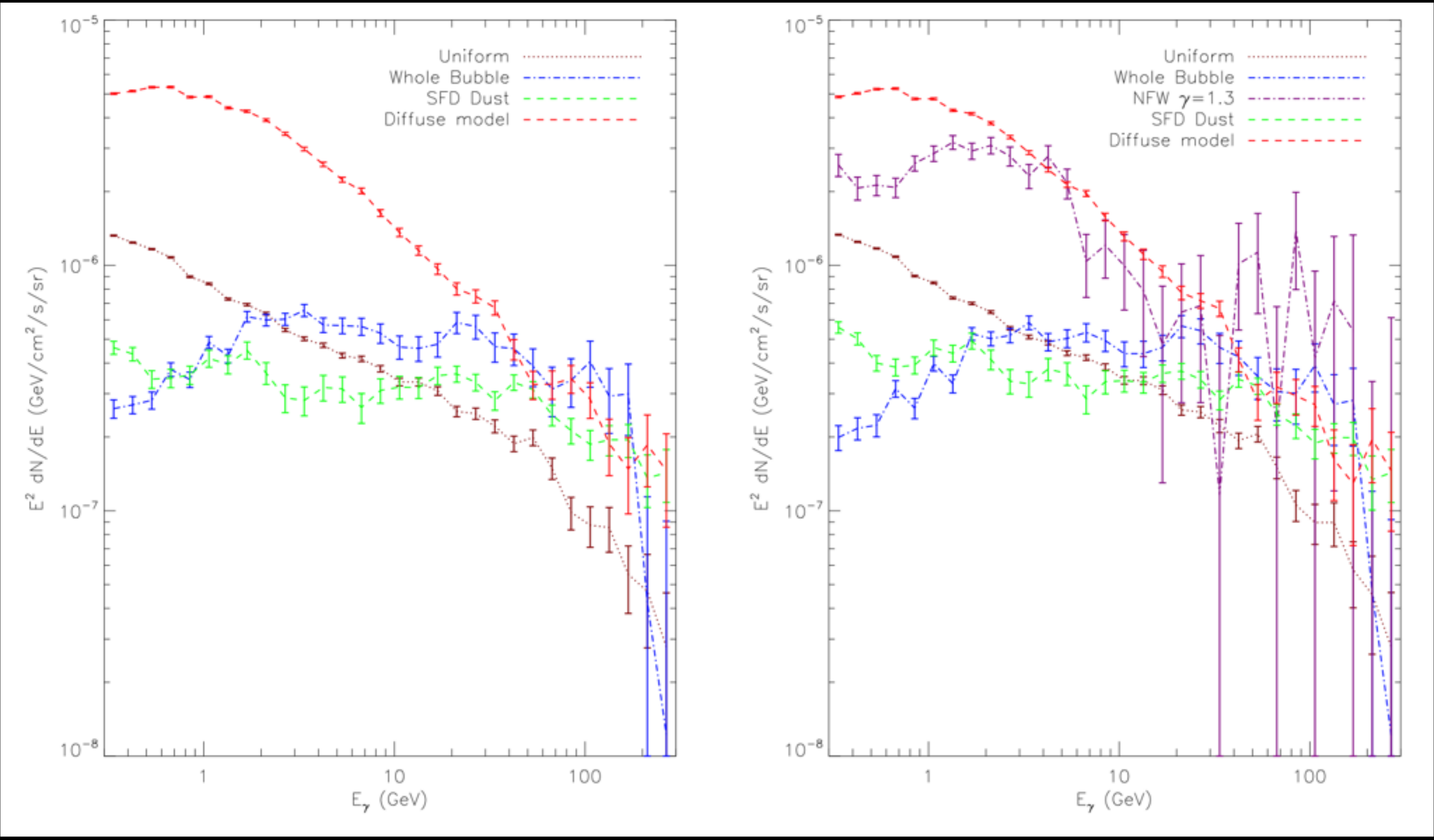
Maybe it's just part of the Bubbles?



Maybe the Bubbles Have A Spectral Variation?



Does it Correlate with Gas?



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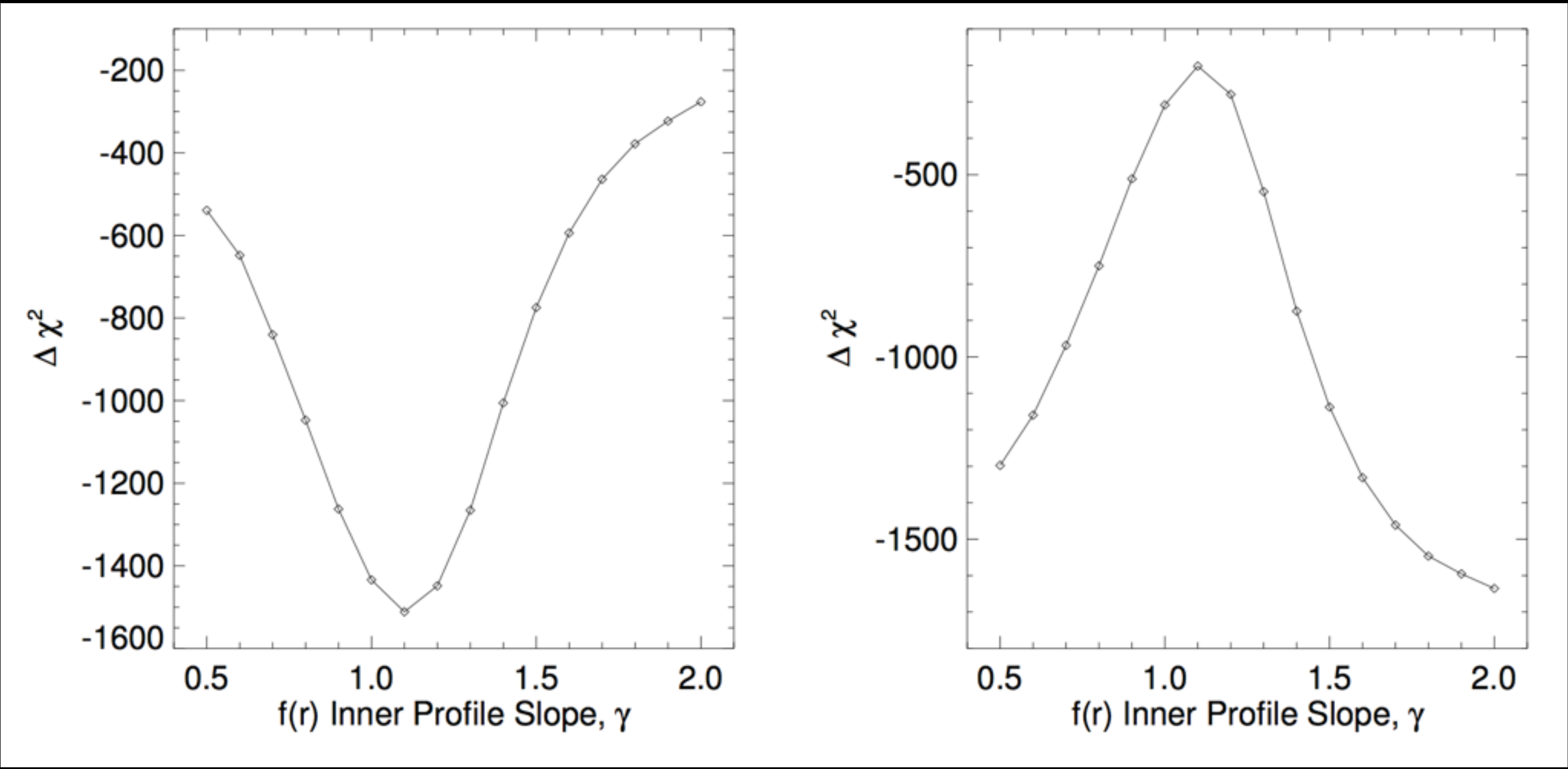
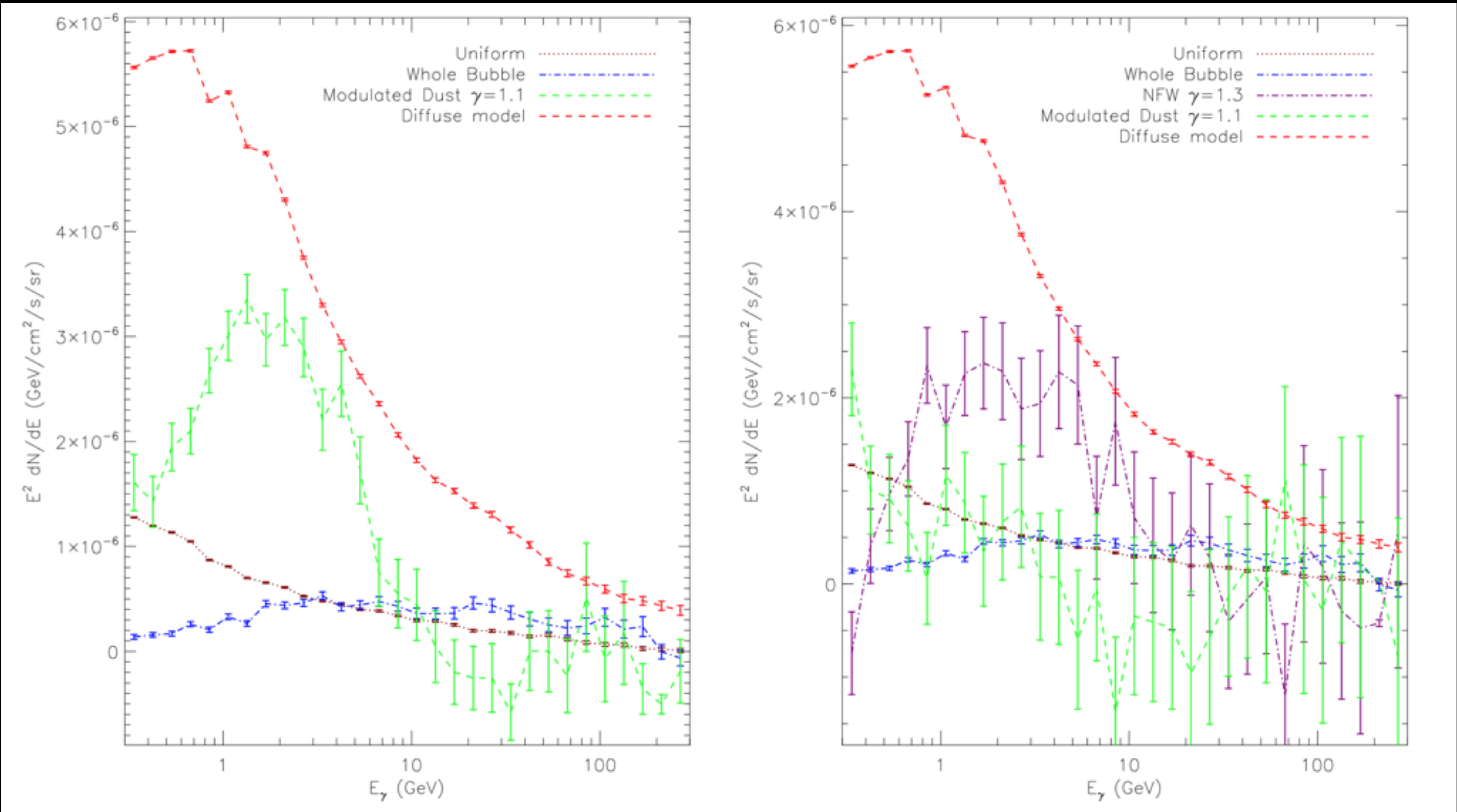


Even more generically, you can add an f(r) α r^(-gamma) profile for the SFD template, this is highly preferred in the model with no dark matter (left), but the dark matter template is still highly preferred even when gamma can float freely (right)

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