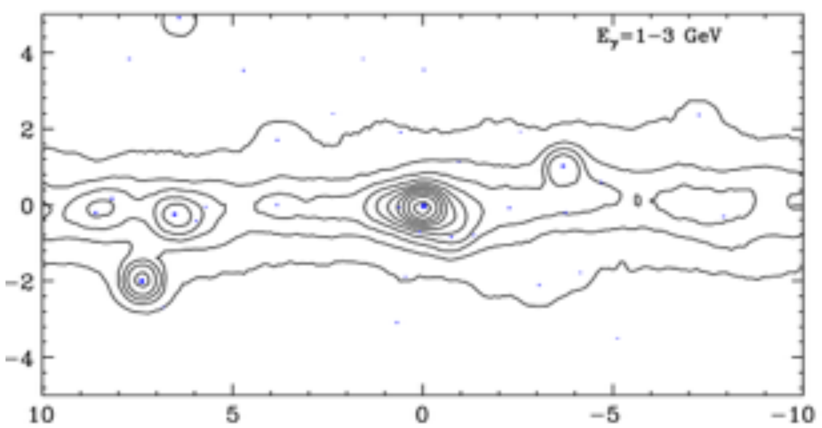
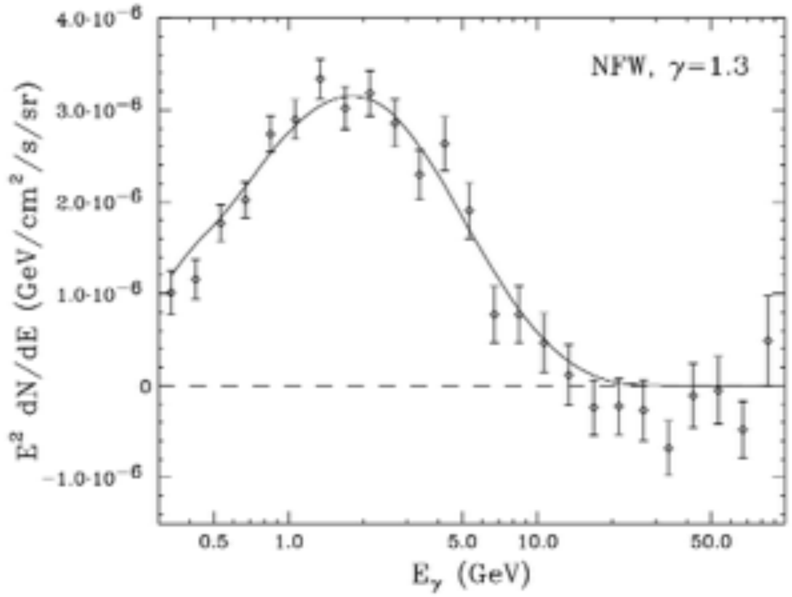
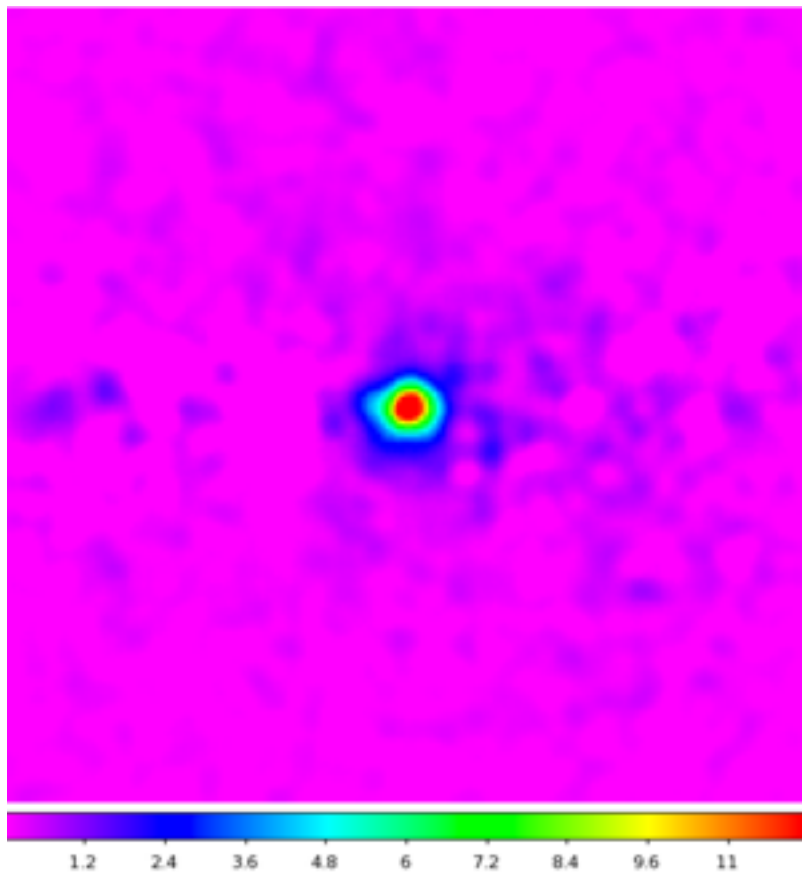
# Strong Evidence for Dark Matter Annihilation in the Galactic Center and Inner Galaxy





Tim Linden

with:

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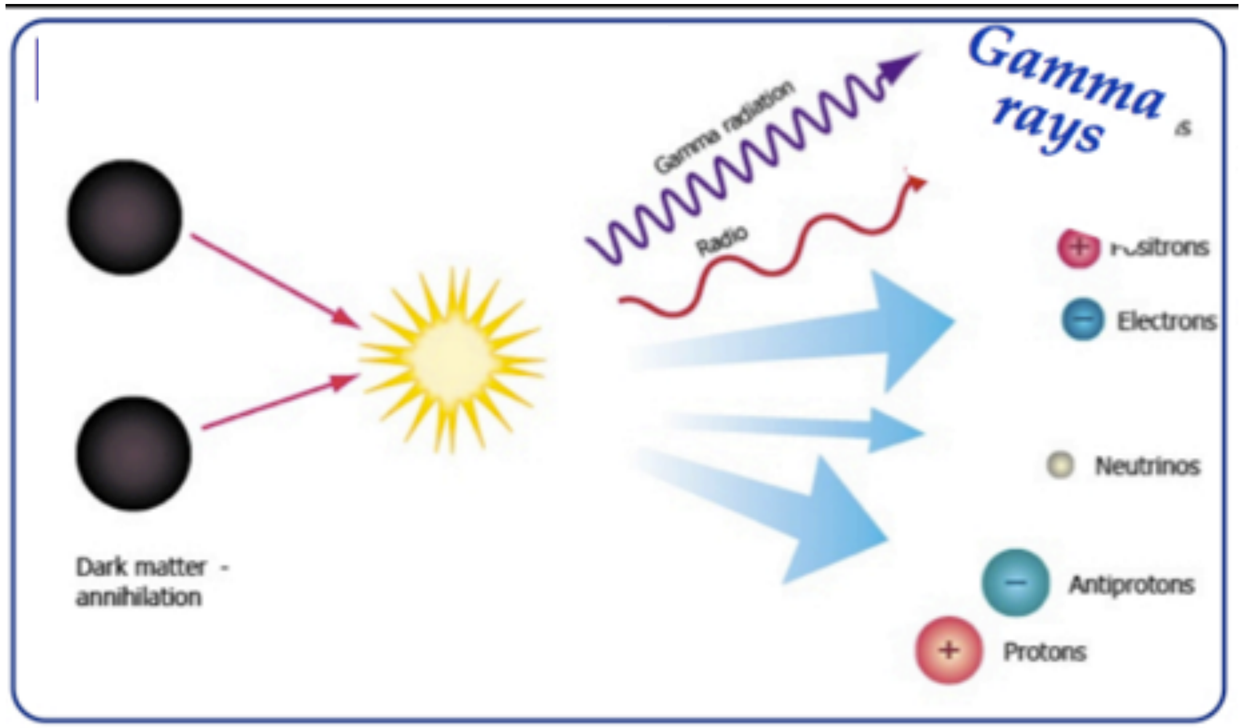
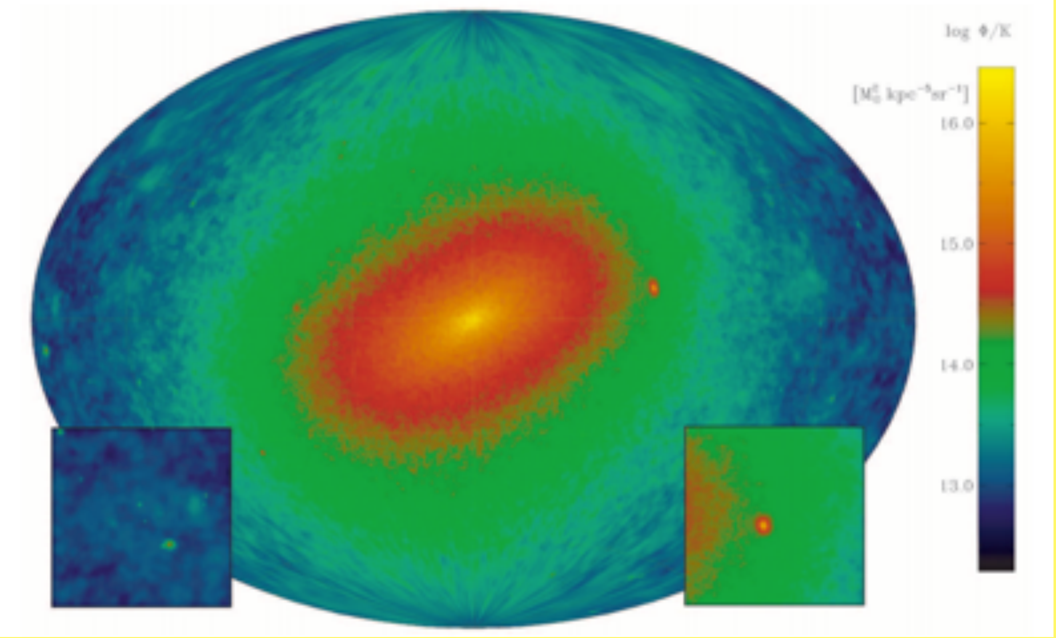
High Energy Physics Seminar, U of Wisconsin, 2-18-14

# Dark Matter Indirect Detection

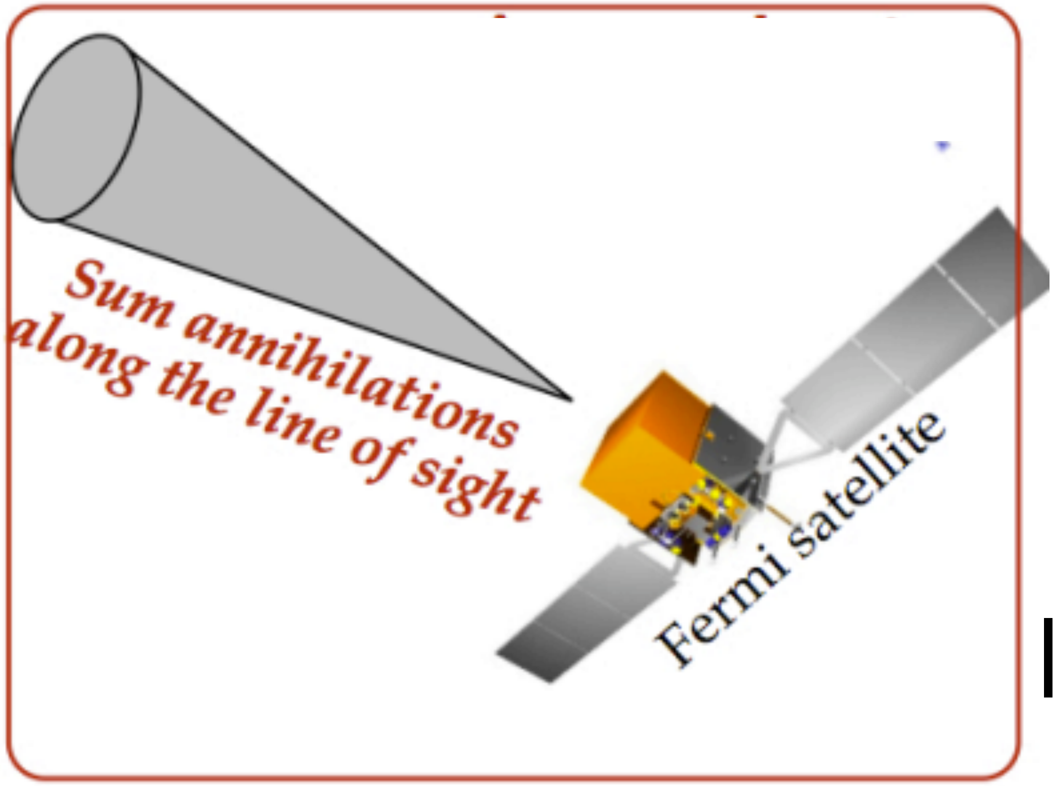
Particle Physics




Astrophysics



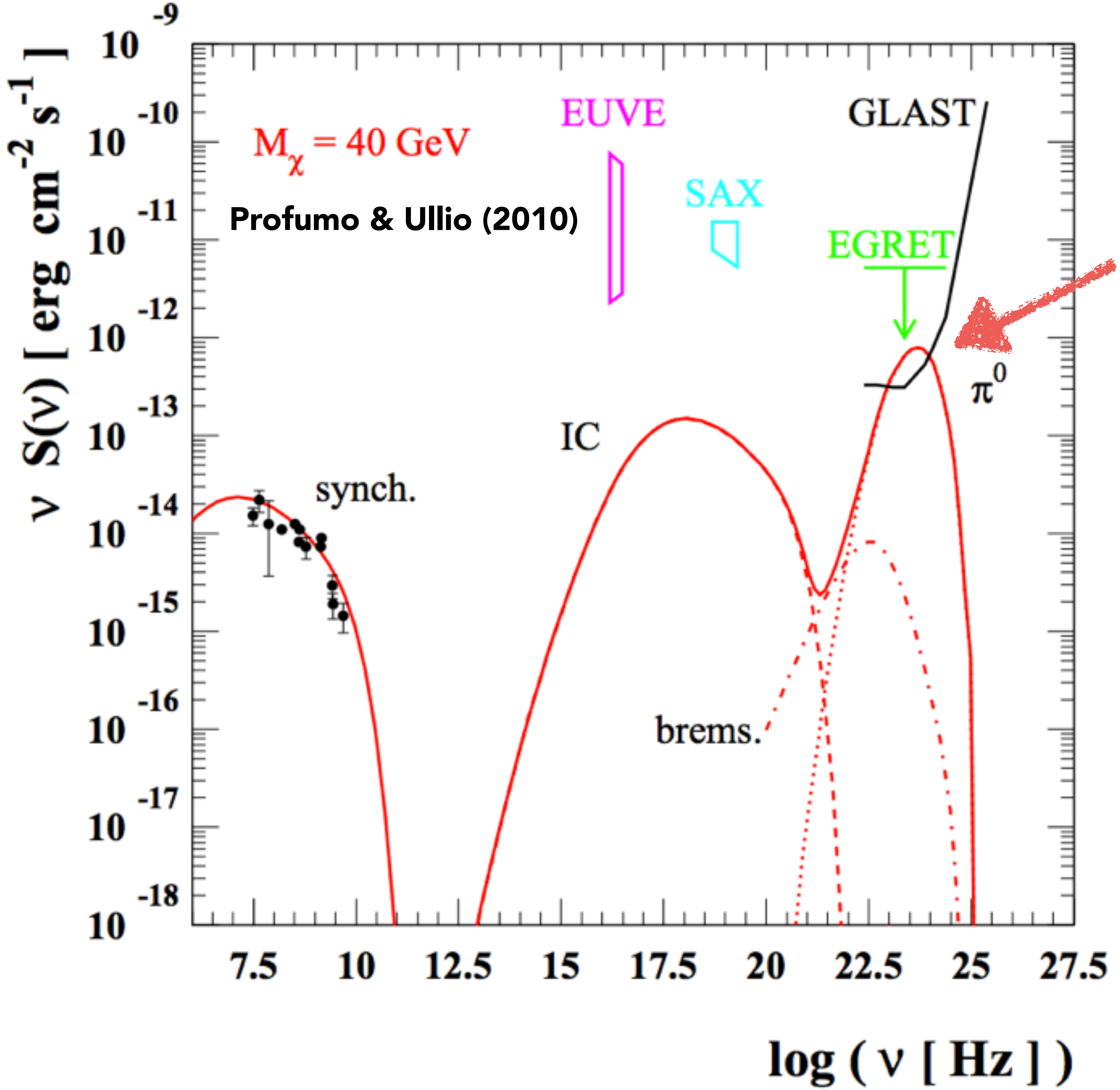
Diemand et al. 2008




Instrumental Response

Slide Concept Courtesy of Gabrijela Zaharijas

# Why Do We Search for Dark Matter in Gamma-Rays?




Dark matter annihilation dumps most of its energy into gamma-rays

**True**, but misleading

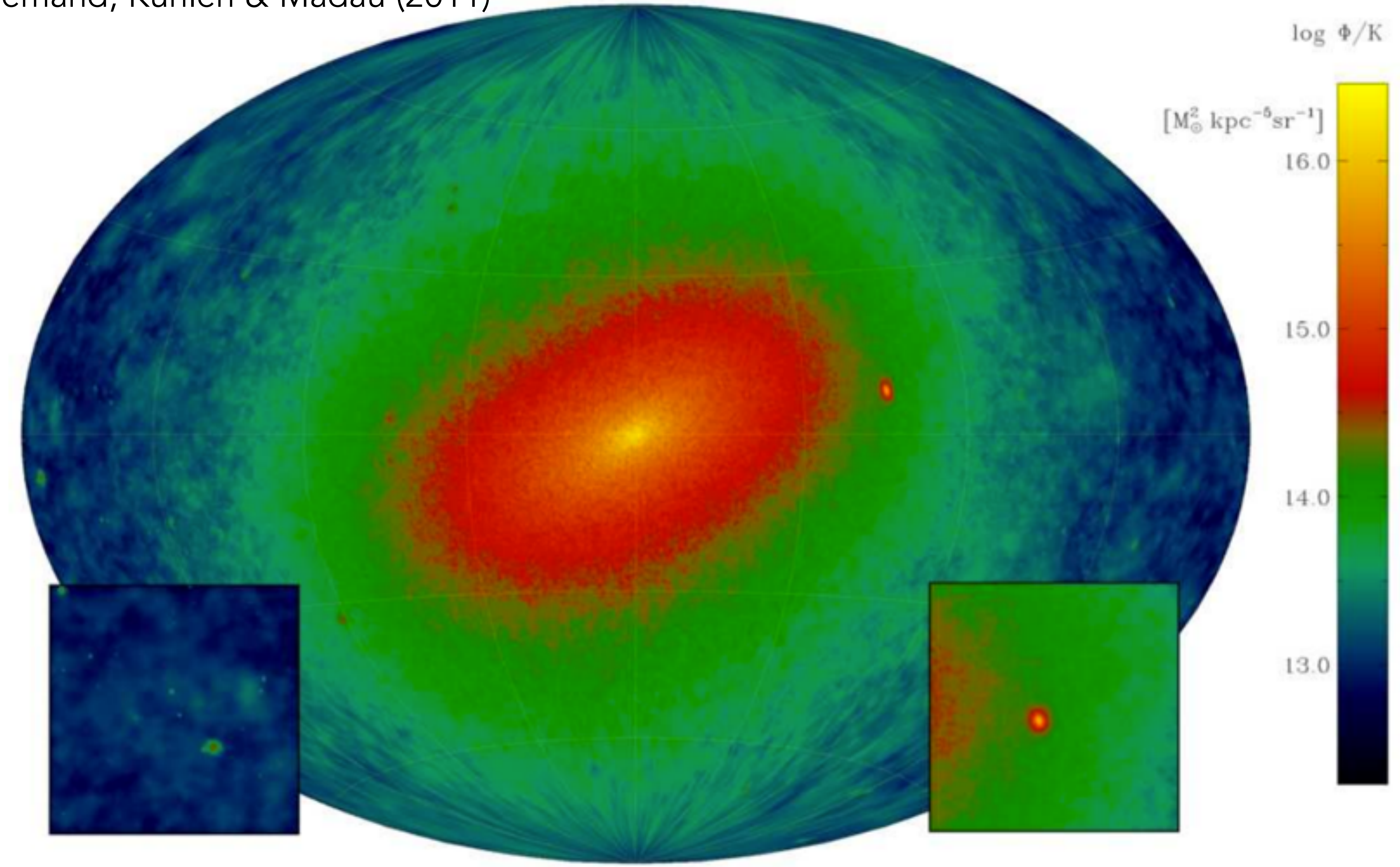
# Why Do We Search for Dark Matter in Gamma-Rays?

## 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**
- Contrast this to 5 GHz radio observations, where the astrophysical diffuse background is approximately ~4 x $10^{-10}$ erg $cm^{-2}$ $s^{-1}$ while the dark matter contribution from the same thermal relic is more than two orders of magnitude smaller than that.

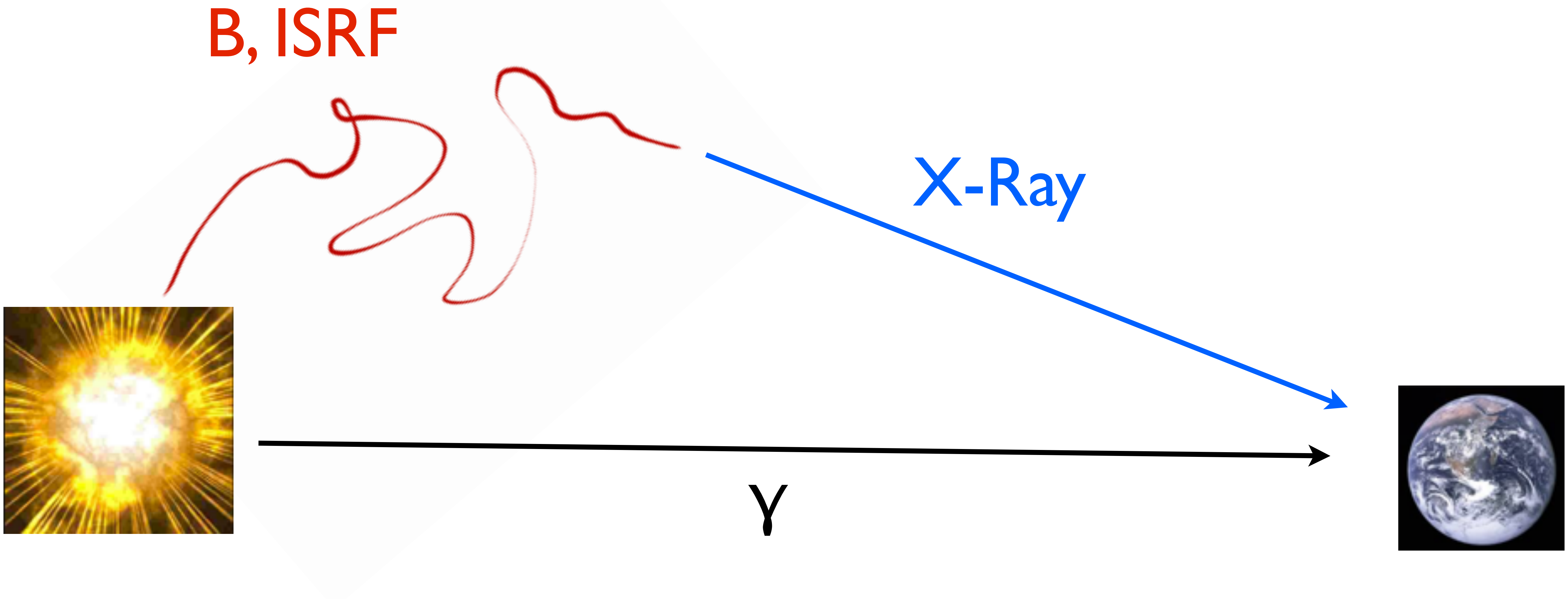
# Why Do We Search for Dark Matter in Gamma-Rays?

Diemand, Kuhlen & Madau (2011)




- The primary gamma-ray signal from dark matter annihilations is produced promptly - so the gamma-ray flux is calculable if we know the dark matter density

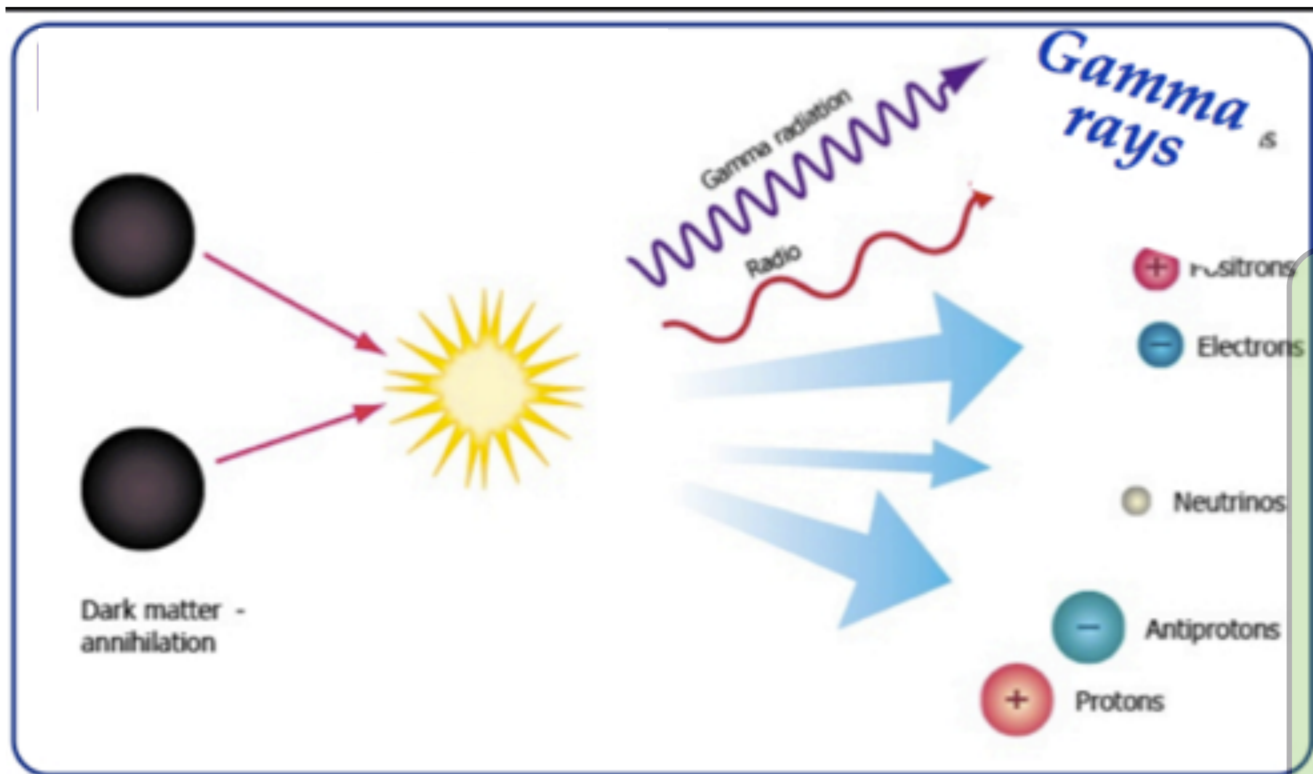
# Why Do We Search for Dark Matter in Gamma-Rays?




- At low energy, propagation can carry the particles which create the observed signal far from the annihilation event, before they produce anything that is seen at the Earth

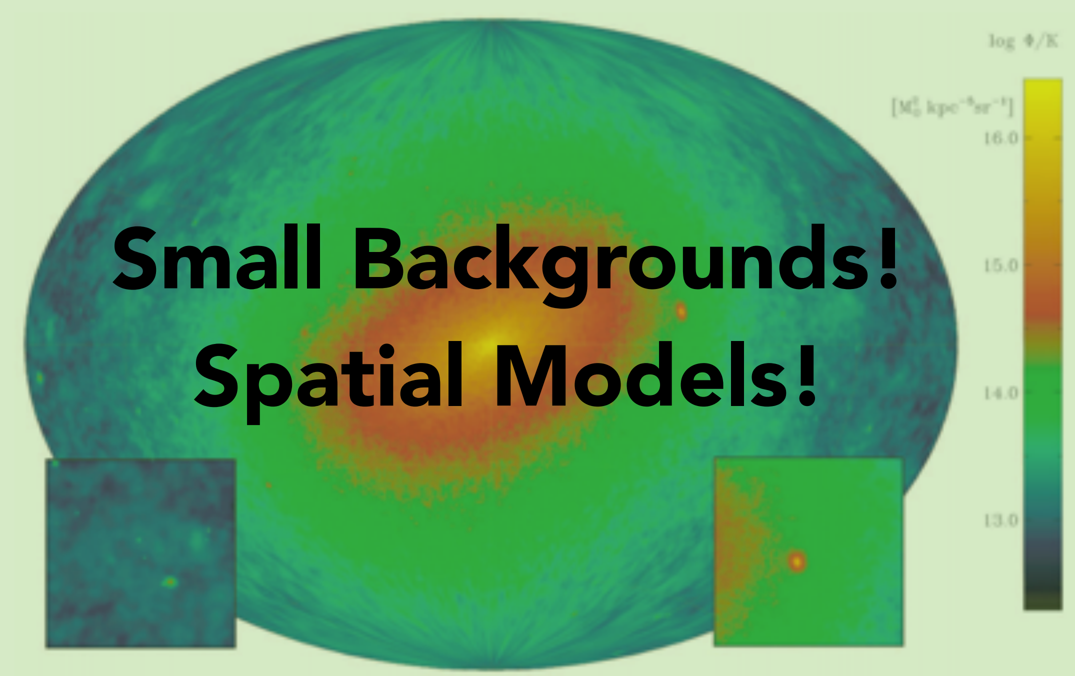
# Why Do We Search for Dark Matter in Gamma-Rays?

Particle Physics




Slides Courtesy of G. Zaharijas

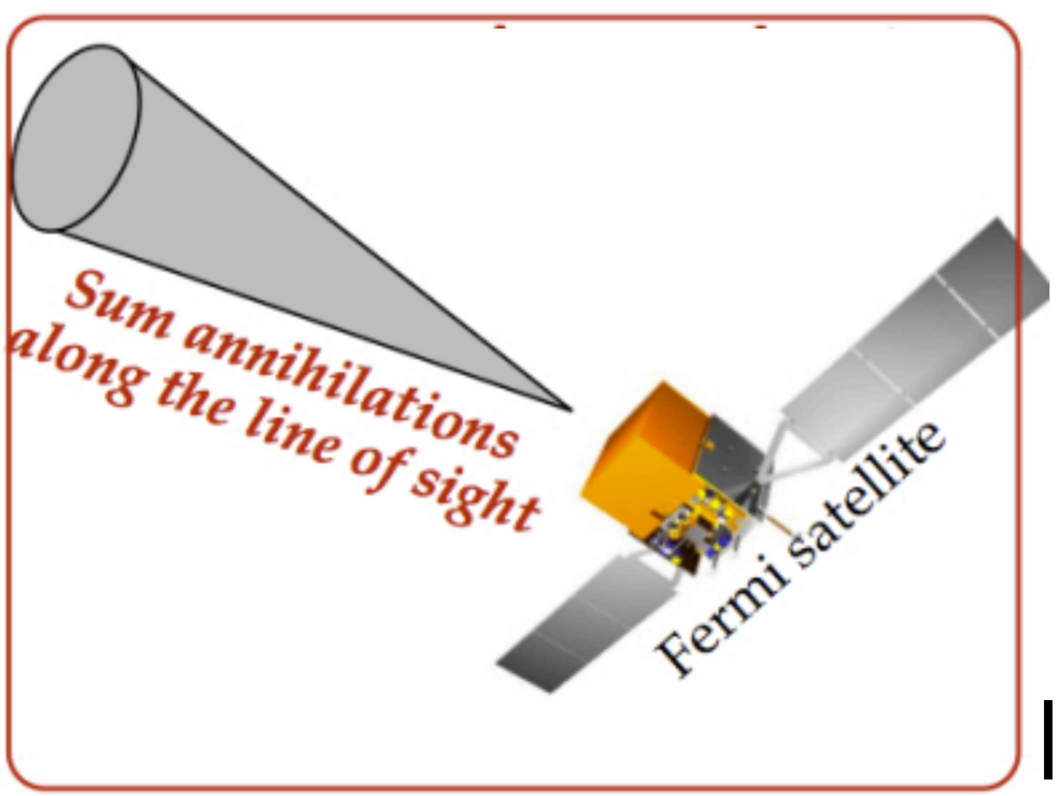
Astrophysics




**Small Backgrounds!**

**Spatial Models!**

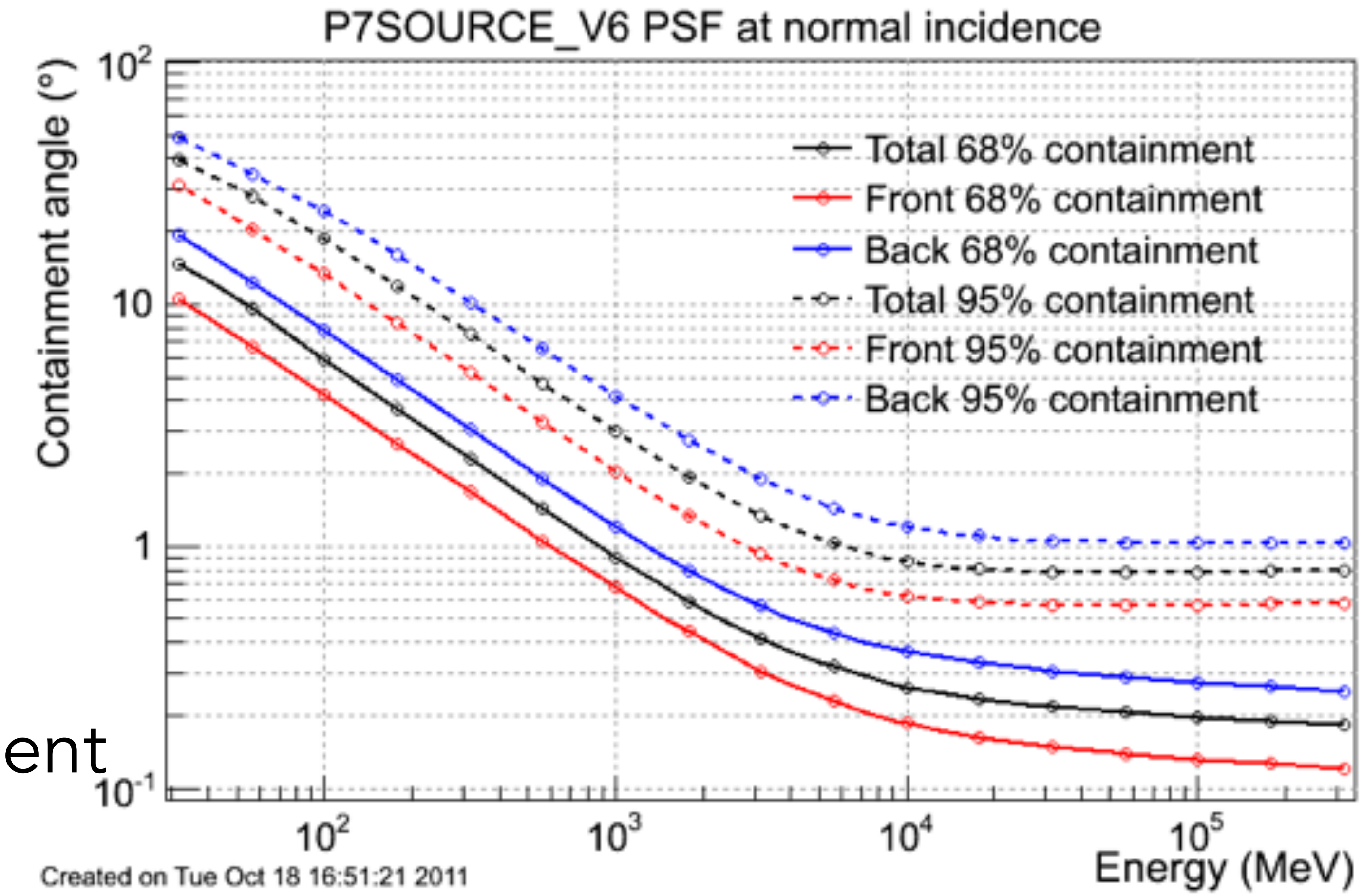
Diemand et al. 2008




Instrumental Response

# Fermi Telescope (2008-Present)

- Fermi-LAT is a space based gamma-ray detector with an effective energy range of 20 MeV-300 GeV




- Effective Area ~ 0.8 $m^2$
- Field of View ~ 2.4 sr
- Energy Resolution ~ 10%
- Angular Resolution: Energy Dependent

- In analyses of the Galactic Center, we will constrict ourselves to Front converting

# The Galactic Center is a Good Dark Matter Target

- The ``J-Factor" of a region allows us to compare the astrophysical environments for dark matter detection independent of particle physics model

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

Ackermann et al. 2012

Dwarfs

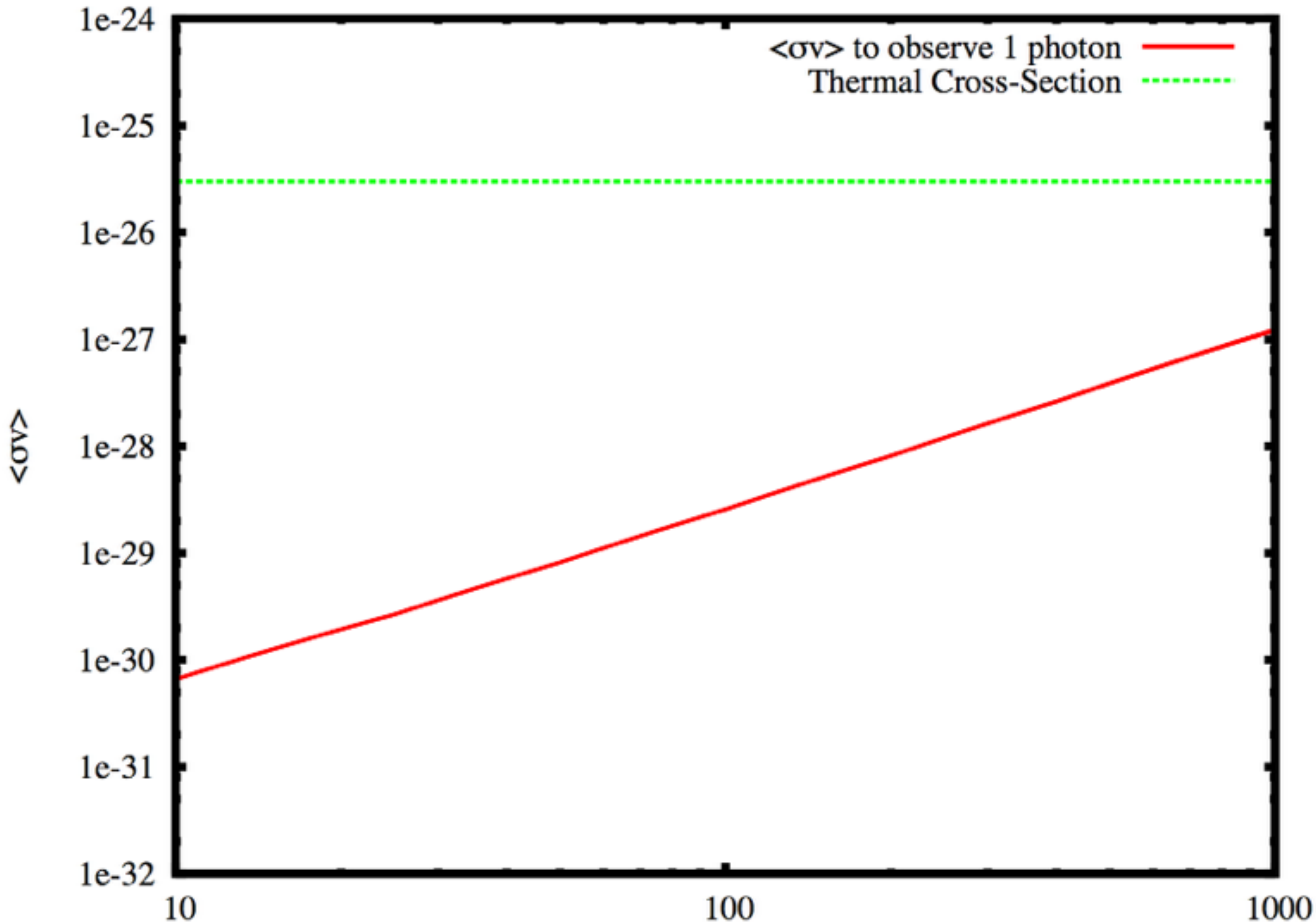
| Name | l | b | d | $\overline{\log_{10}(J)}$ | $\sigma$ | ref. |
|---|---|---|---|---|---|---|
| | deg. | deg. | kpc | $\log_{10}[\mathrm{GeV}^2\mathrm{cm}^{-5}]$ | | |
| Bootes I | 358.08 | 69.62 | 60 | 17.7 | 0.34 | [15] |
| Carina | 260.11 | −22.22 | 101 | 18.0 | 0.13 | [16] |
| Coma Berenices | 241.9 | 83.6 | 44 | 19.0 | 0.37 | [17] |
| Draco | 86.37 | 34.72 | 80 | 18.8 | 0.13 | [16] |
| Fornax | 237.1 | −65.7 | 138 | 17.7 | 0.23 | [16] |
| Sculptor | 287.15 | −83.16 | 80 | 18.4 | 0.13 | [16] |
| Segue 1 | 220.48 | 50.42 | 23 | 19.6 | 0.53 | [18] |
| Sextans | 243.4 | 42.2 | 86 | 17.8 | 0.23 | [16] |
| Ursa Major II | 152.46 | 37.44 | 32 | 19.6 | 0.40 | [17] |
| Ursa Minor | 104.95 | 44.80 | 66 | 18.5 | 0.18 | [16] |

- The J-factor of the galactic center is approximately:

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

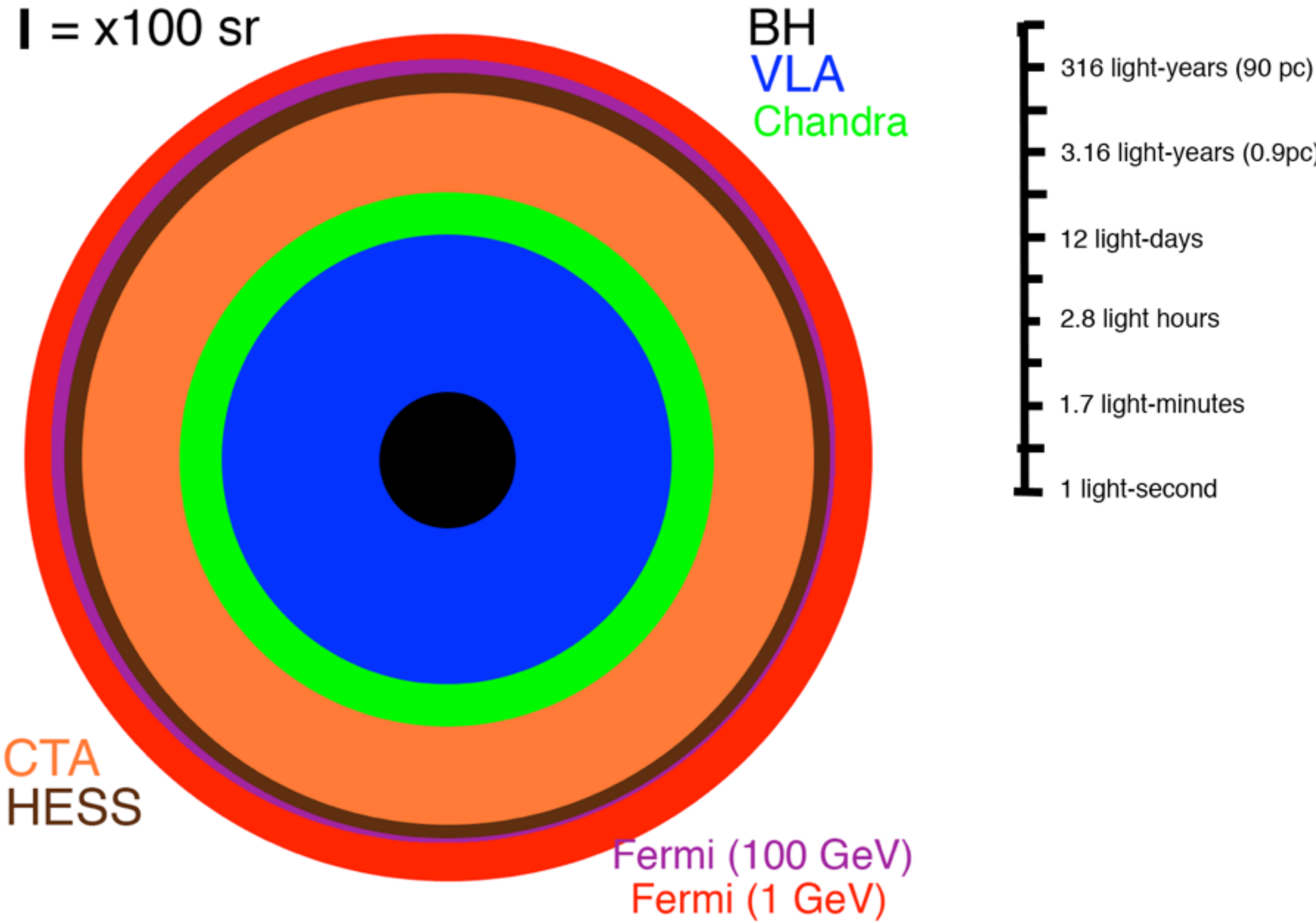
for a region within 100 pc of the Galactic center and an NFW profile

# Fermi-LAT Sensitivity to Dark Matter

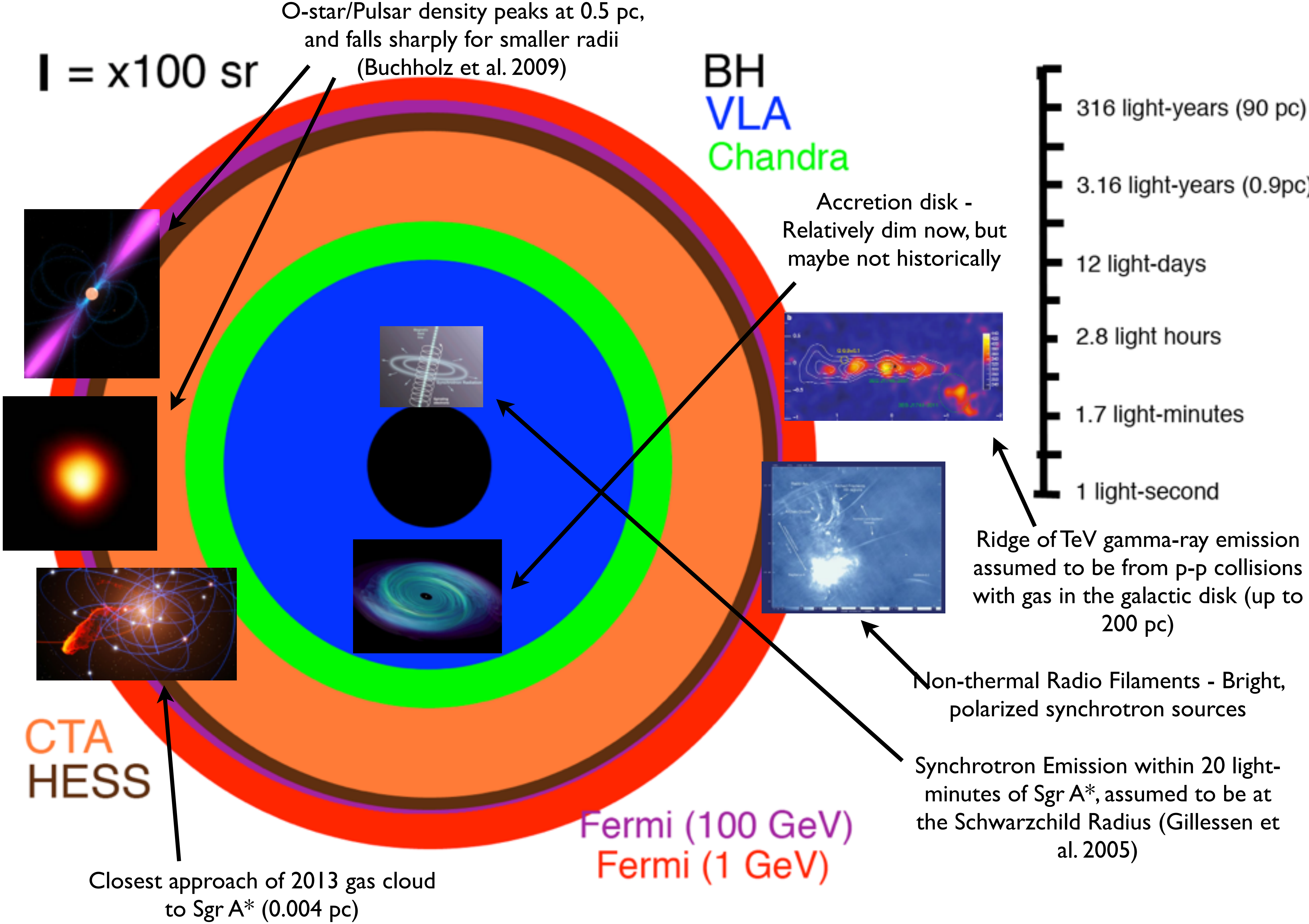



- If all dark matter photons came nicely tagged - dark matter indirect detection would be easy

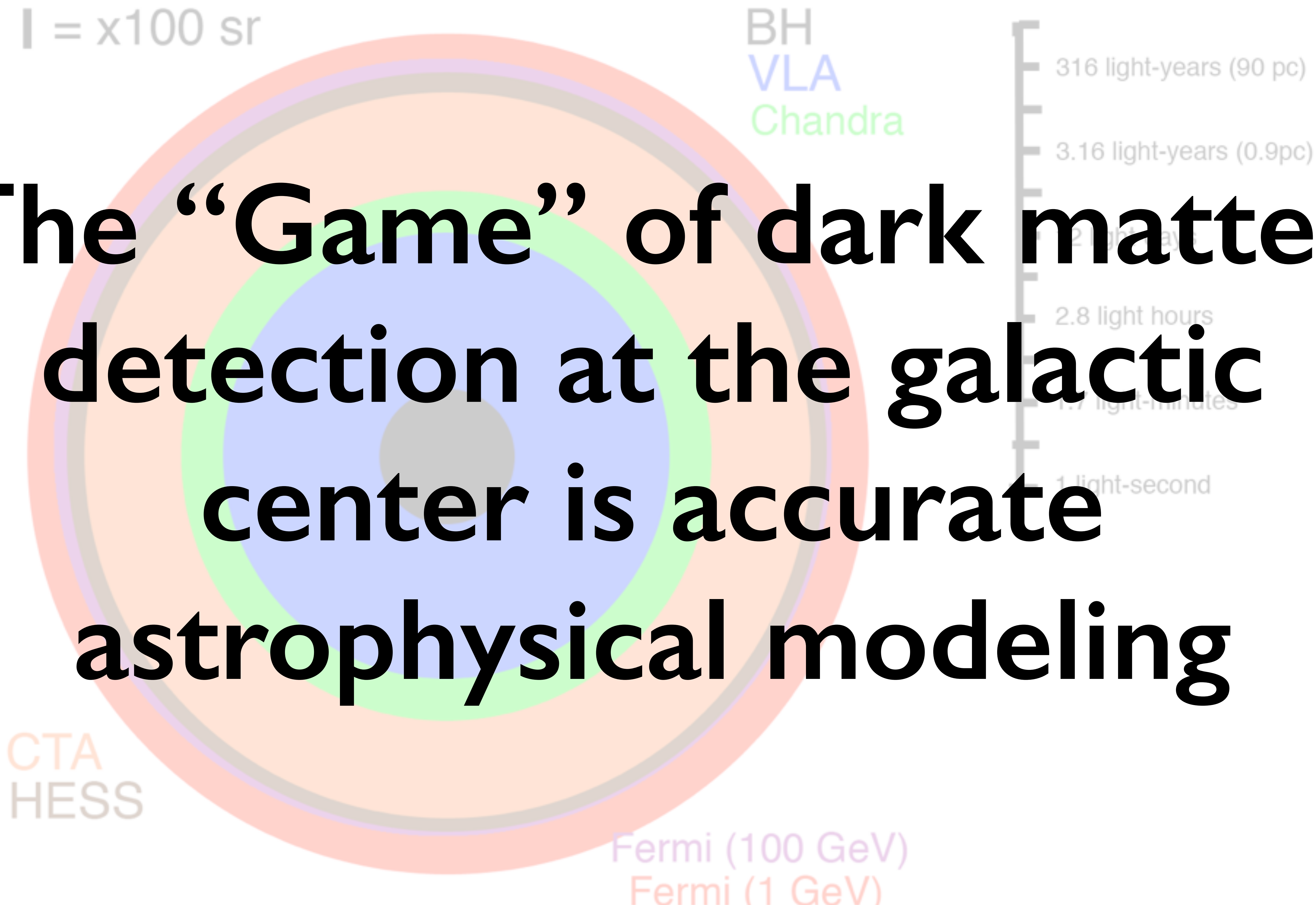
# Angular Scales of the Galactic Center



# The Galactic Center "Zoo"

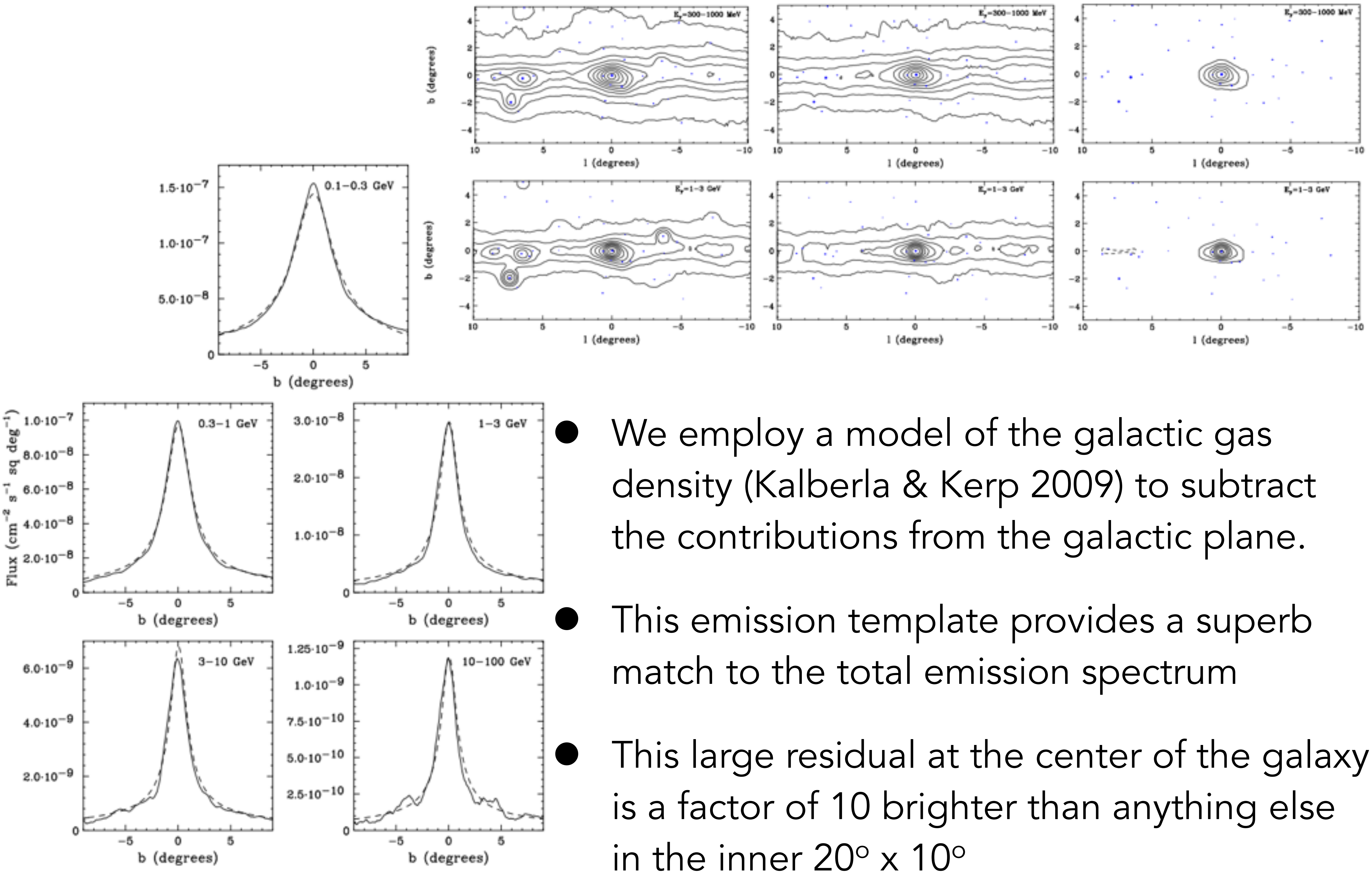


# Angular Scales of the Galactic Center




**The "Game" of dark matter detection at the galactic center is accurate astrophysical modeling**

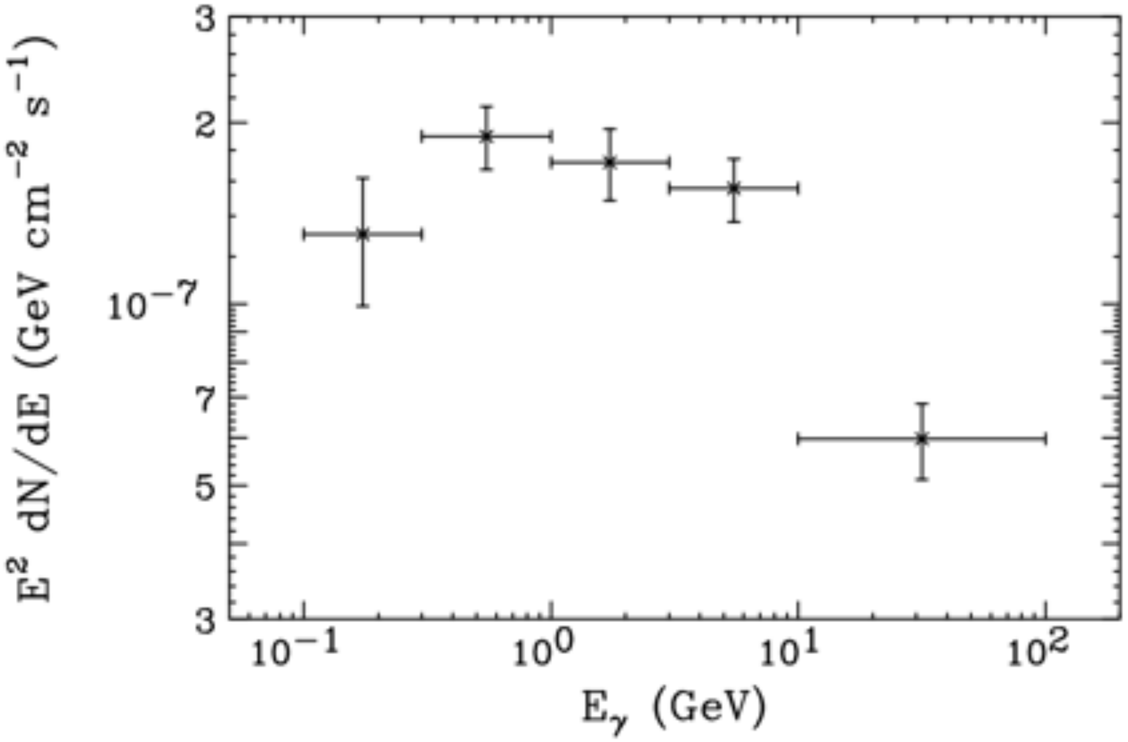
# Subtracting the Astrophysical Background: Fermi




- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum
- This large residual at the center of the galaxy is a factor of 10 brighter than anything else in the inner 20° x 10°

Hooper & Linden (2011)

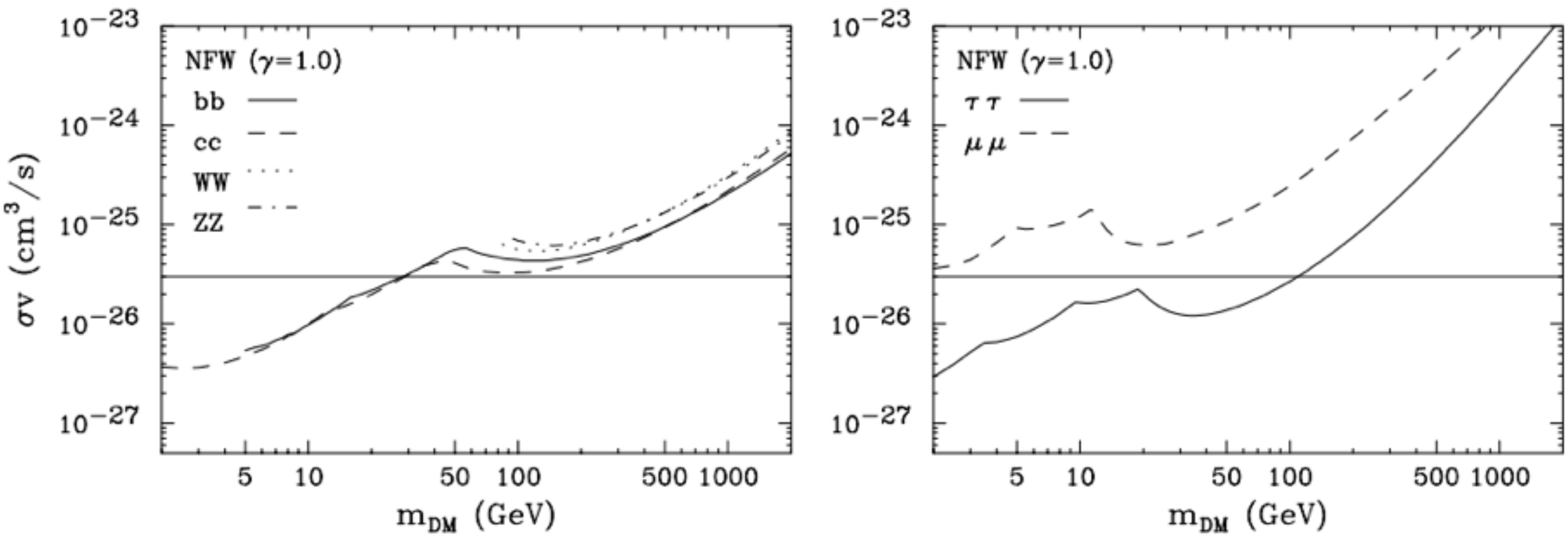
# Dark Matter Limits in the Simplest Way Possible




Hooper & Linden (2011)

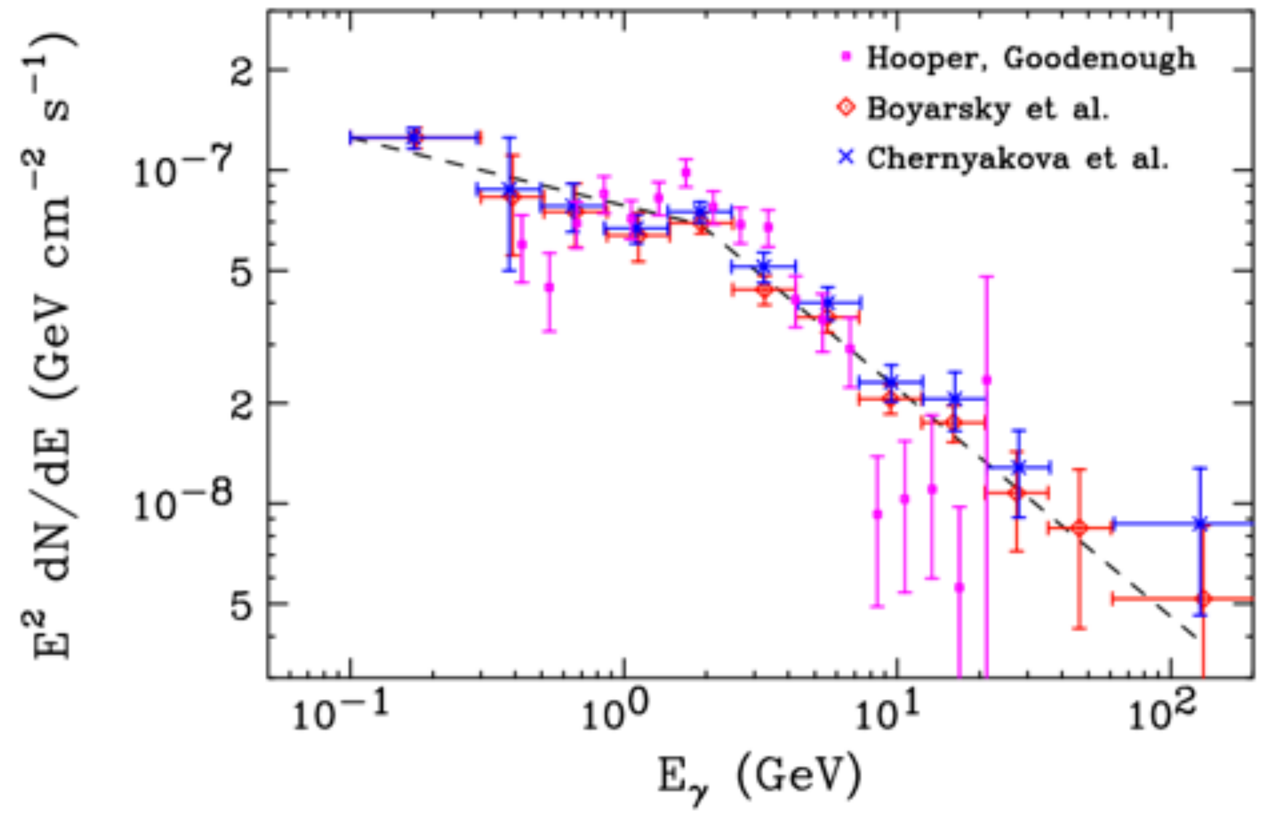
- After subtracting emission from known point sources, and an extrapolation of the line-of-sight gas density, the following "galactic center" emission is calculated

- This directly corresponds to a limit on the dark matter interaction cross-section which depends only on assumed dark

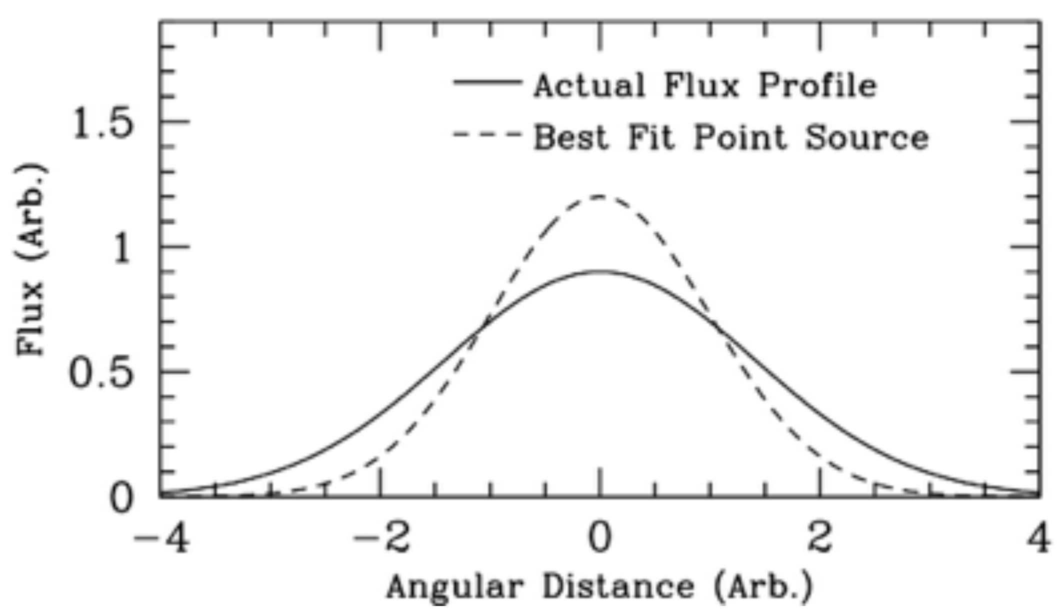


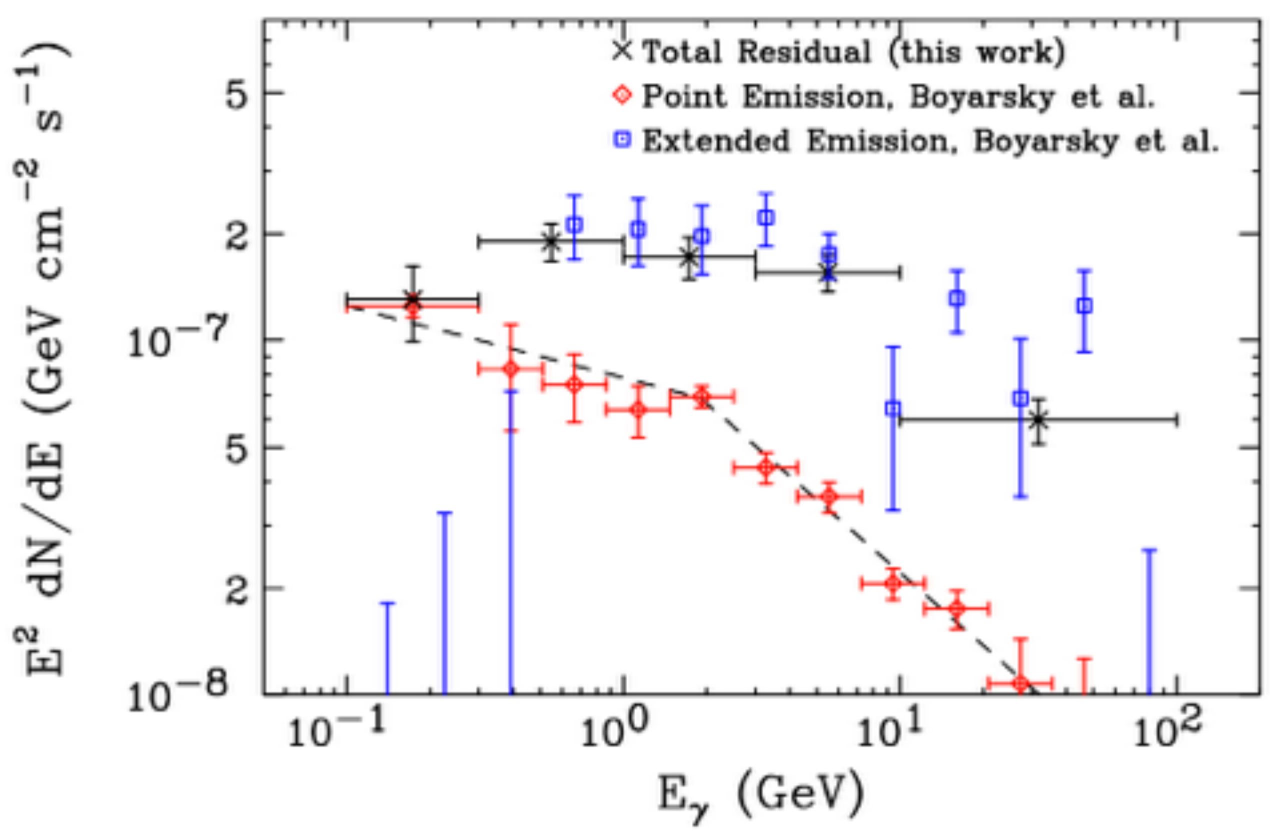
# Understanding the GC Point Source: Fermi

- Several efforts have been made to fit the GC point source, using both best-fitting point-source tools from the Fermi collaboration (Boyarsky et al. Chernyakova et. al), as well as independent software packages (Hooper & Goodenough)



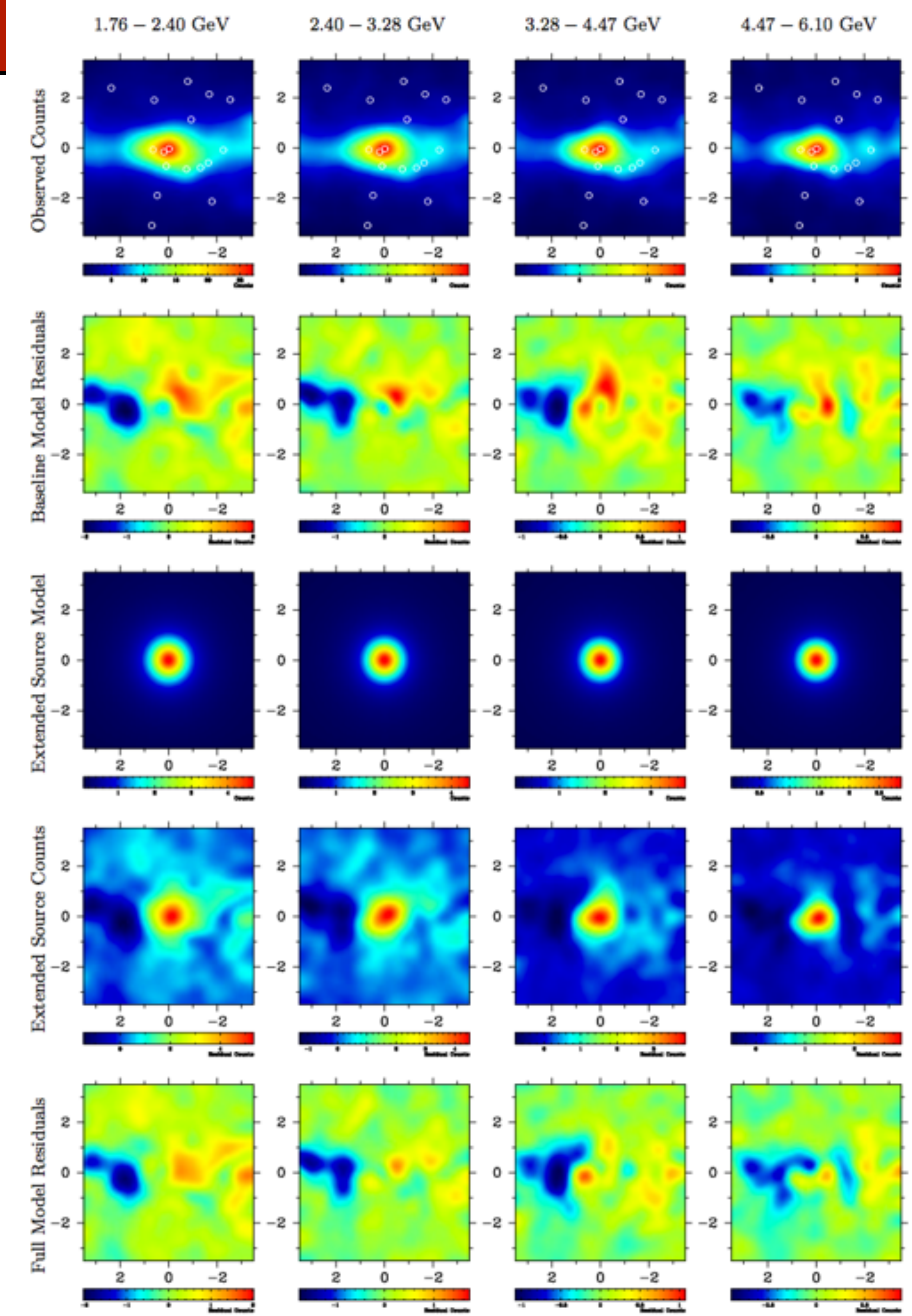

- In all cases, the morphology of the observed emission cannot be fully accounted for by a single point source smeared out by the angular




Hooper & Linden (2011)

# Independent Confirmation

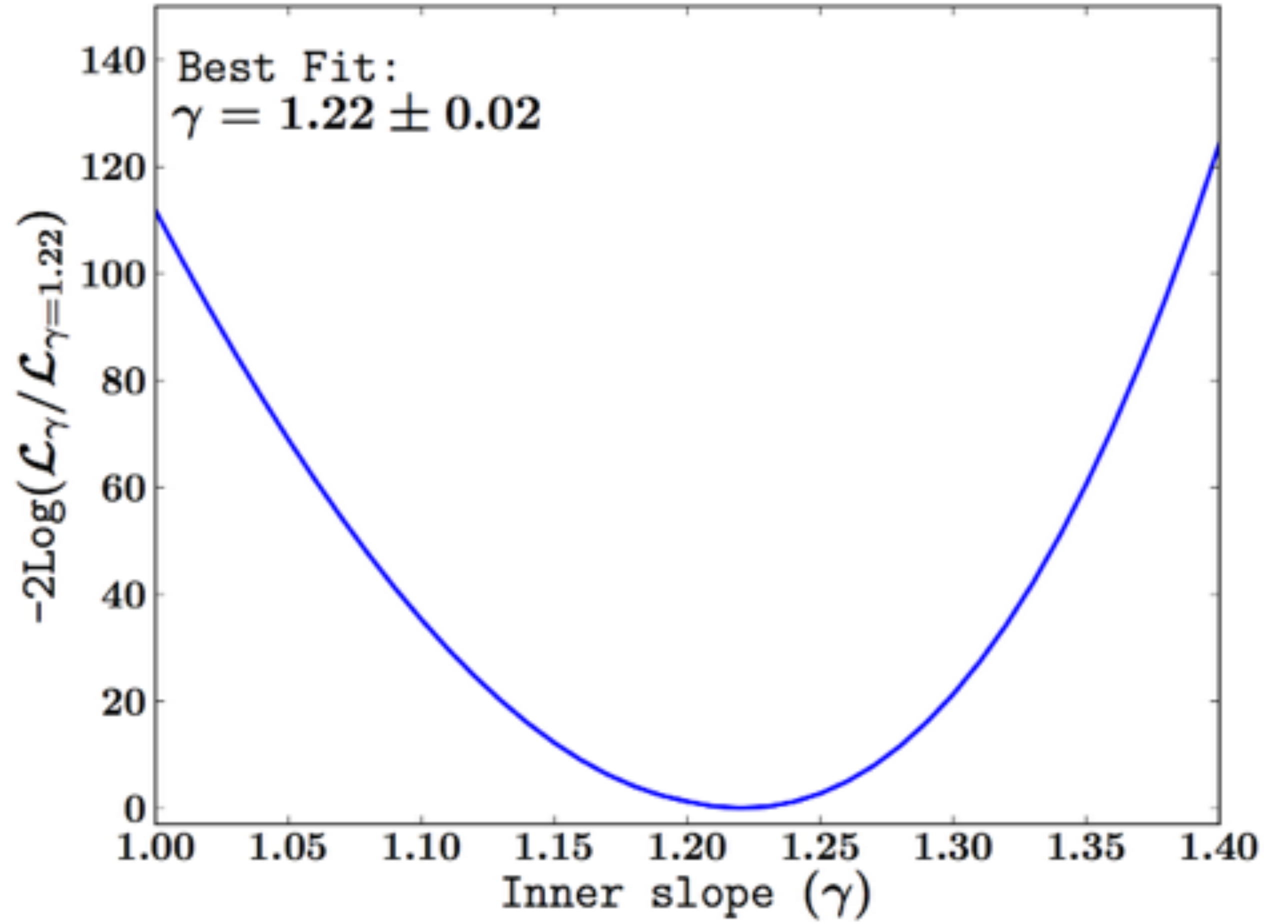


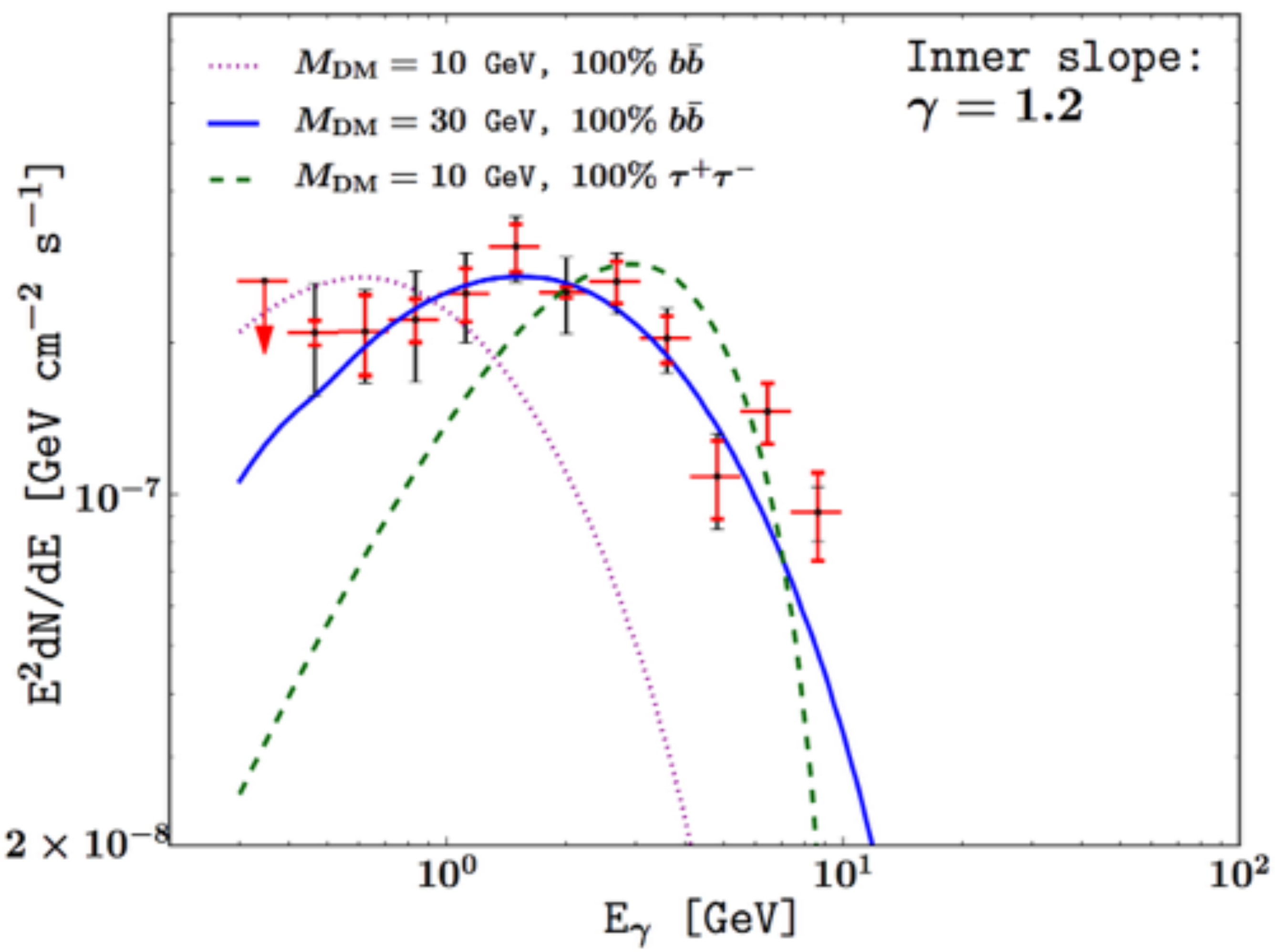

- Abazajian & Kaplinghat (2012) confirmed the existence of the source, finding strong evidence for a dark matter profile slope of approximately 1.2, and mass of approximately 30 GeV

| Spatial Model | Spectrum | $TS_{\approx}$ | $-\ln\mathcal{L}$ | $\Delta\ln\mathcal{L}$ |
|---|---|---|---|---|
| Baseline | – | - | 140070.2 | – |
| Density $\Gamma = 0.7$ | LogPar | 1725.5 | 139755.5 | 314.7 |
| Density$^2$ $\gamma = 0.9$ | LogPar | 1212.8 | 139740.0 | 330.2 |
| Density$^2$ $\gamma = 1.0$ | LogPar | 1441.8 | 139673.3 | 396.9 |
| Density$^2$ $\gamma = 1.1$ | LogPar | 2060.5 | 139651.8 | 418.3 |
| Density$^2$ $\gamma = 1.2$ | LogPar | 4044.9 | 139650.9 | 419.2 |
| Density$^2$ $\gamma = 1.3$ | LogPar | 7614.2 | 139686.8 | 383.4 |
| Density$^2$ Einasto | LogPar | 1301.3 | 139695.7 | 374.4 |
| Density$^2$ $\gamma = 1.2$ | PLCut | 3452.5 | 139663.2 | 407.0 |

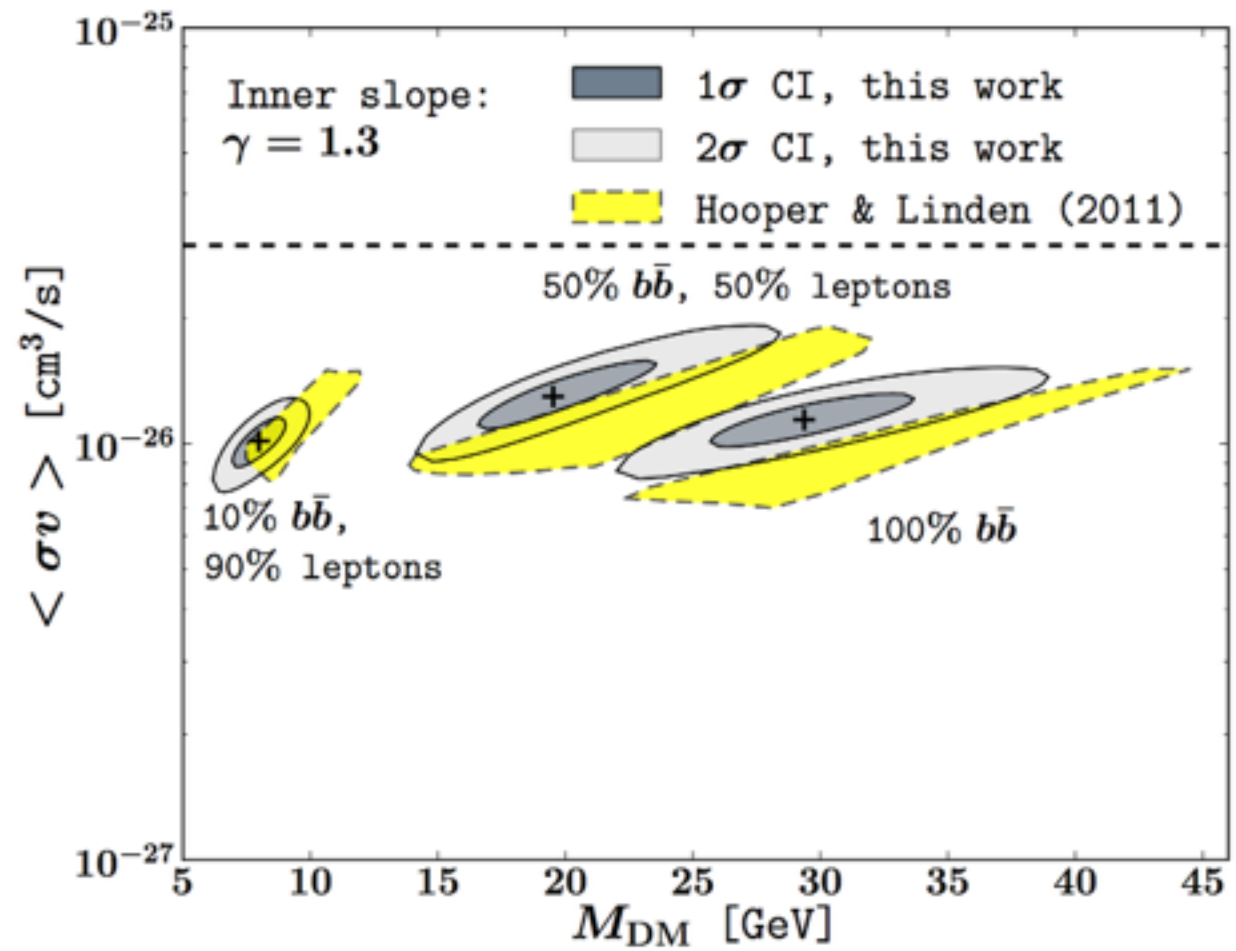
| channel, $m_\chi$ | $TS_{\approx}$ | $-\ln\mathcal{L}$ | $\Delta\ln\mathcal{L}$ |
|---|---|---|---|
| $b\bar{b}$, 10 GeV | 2385.7 | 139913.6 | 156.5 |
| $b\bar{b}$, 30 GeV | 3460.3 | 139658.3 | 411.8 |
| $b\bar{b}$, 100 GeV | 1303.1 | 139881.1 | 189.0 |
| $b\bar{b}$, 300 GeV | 229.4 | 140056.6 | 13.5 |
| $b\bar{b}$, 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 |

# Independent Confirmation

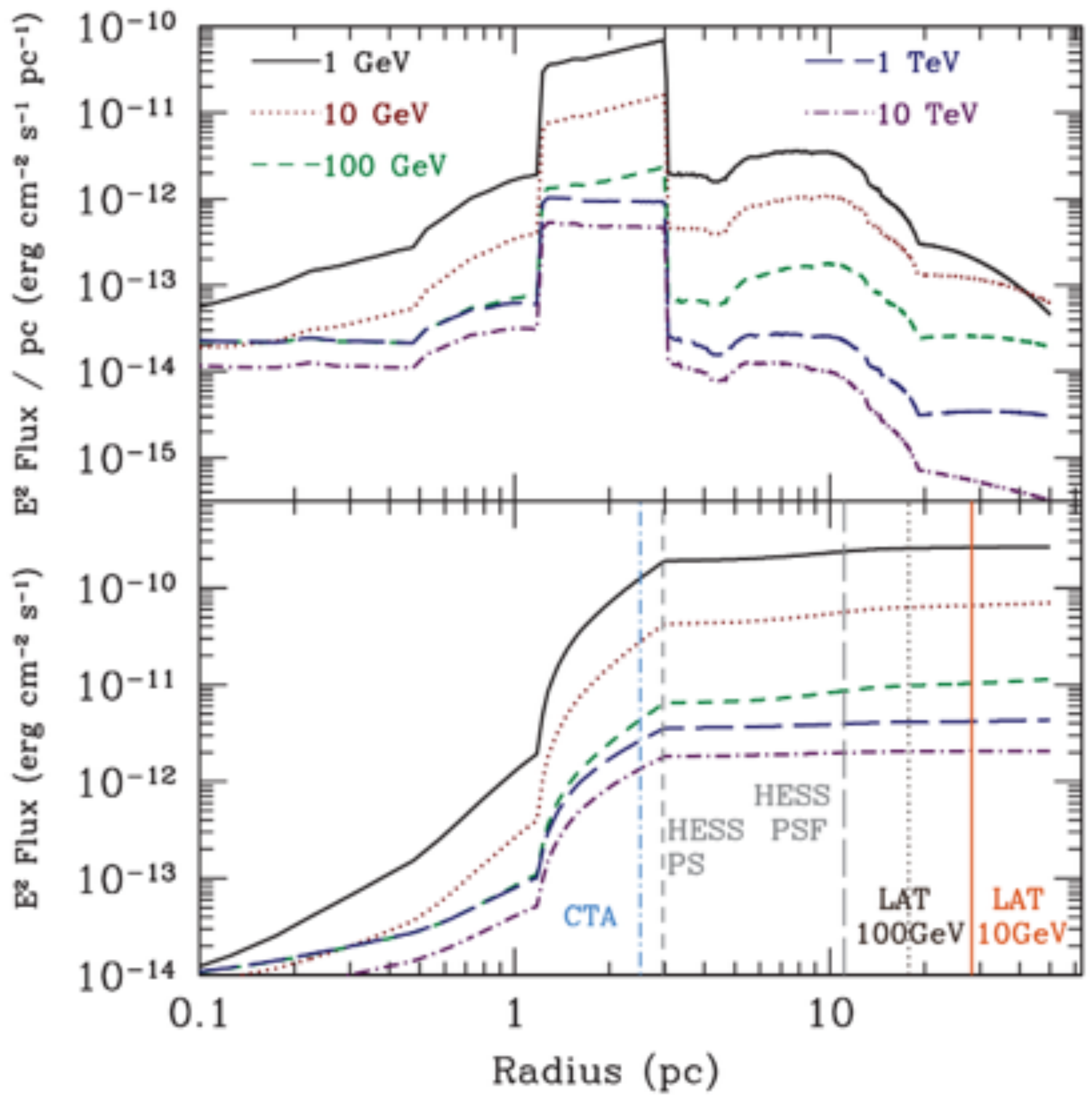


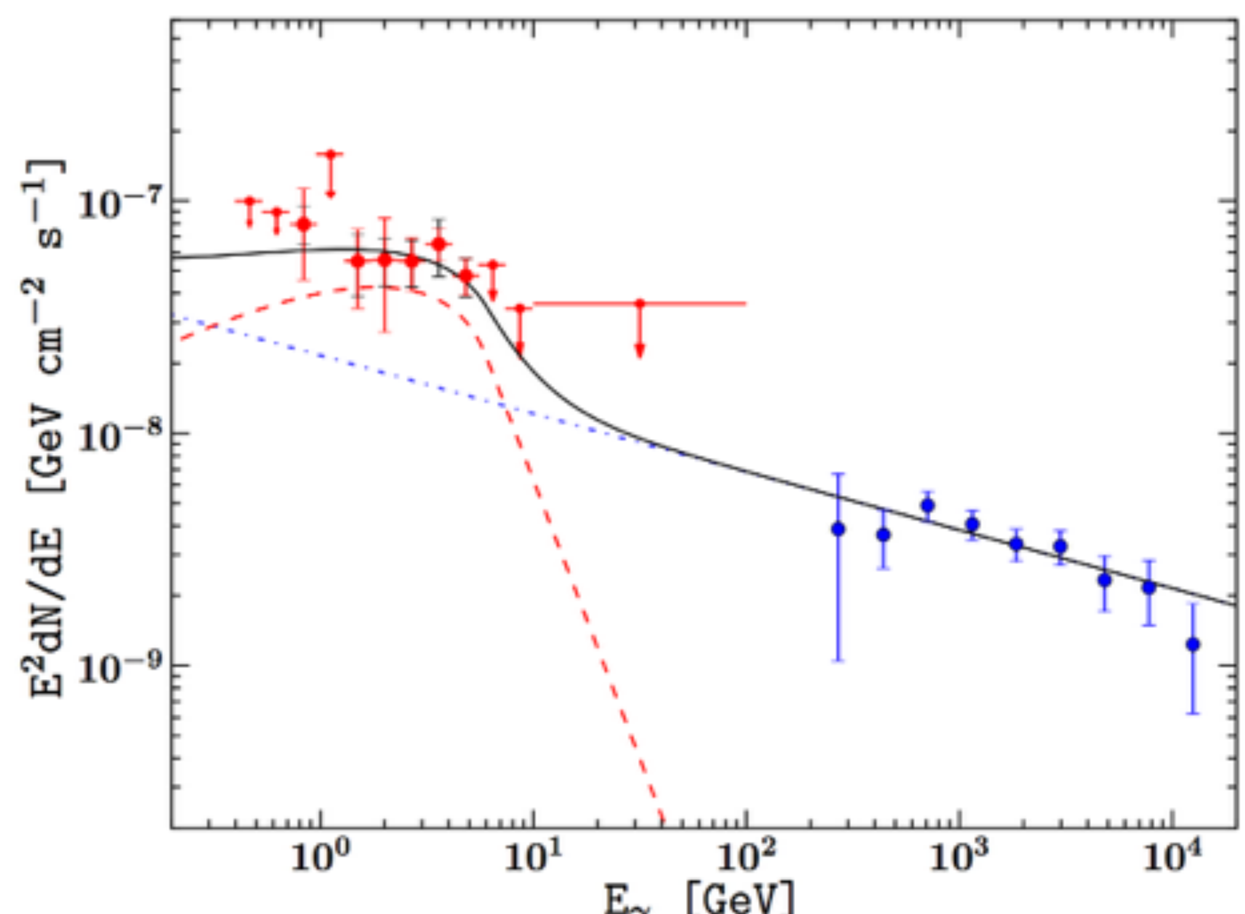

- Gordon & Macias (2013) also confirmed the residual. They placed stronger limits on the dark matter density profile, while confirming the best spectral fits.



# Independent Confirmation

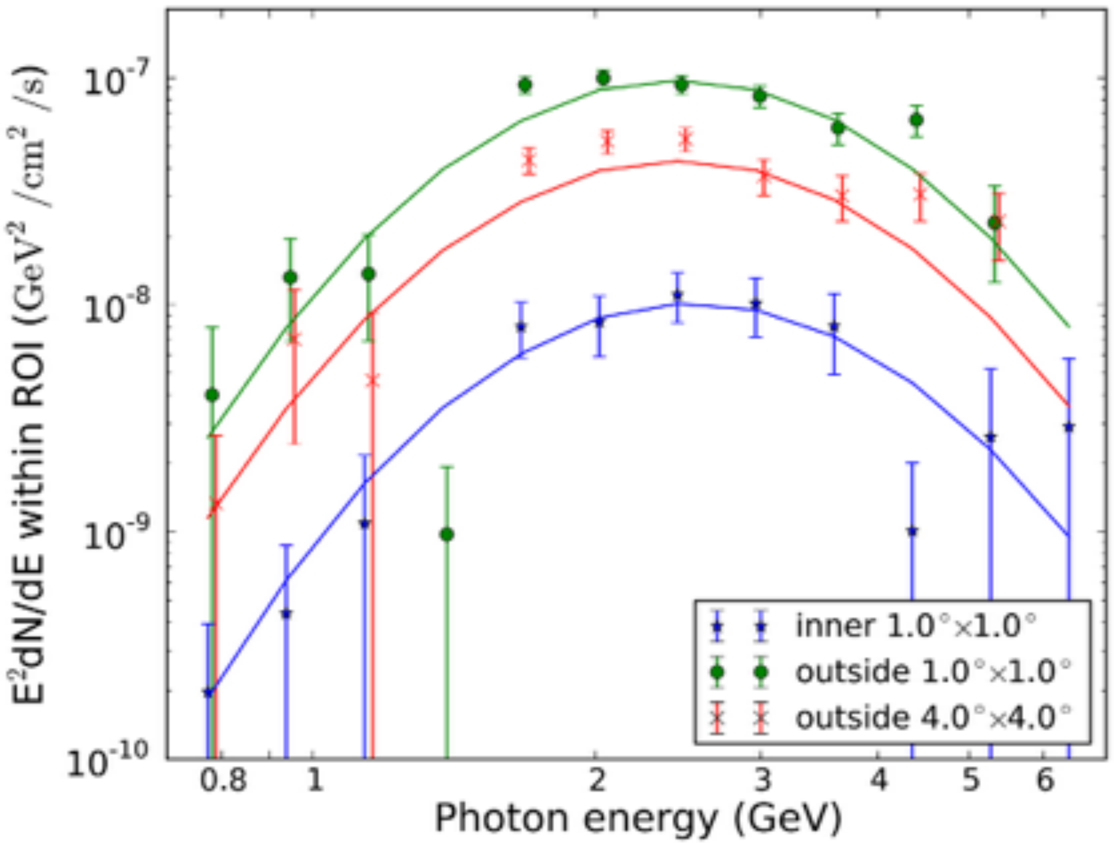



- Linden et al. (2012) showed that the morphology of the excess is not fit by hadronic emission from Sgr A* (corresponding to H.E.S.S. observations)

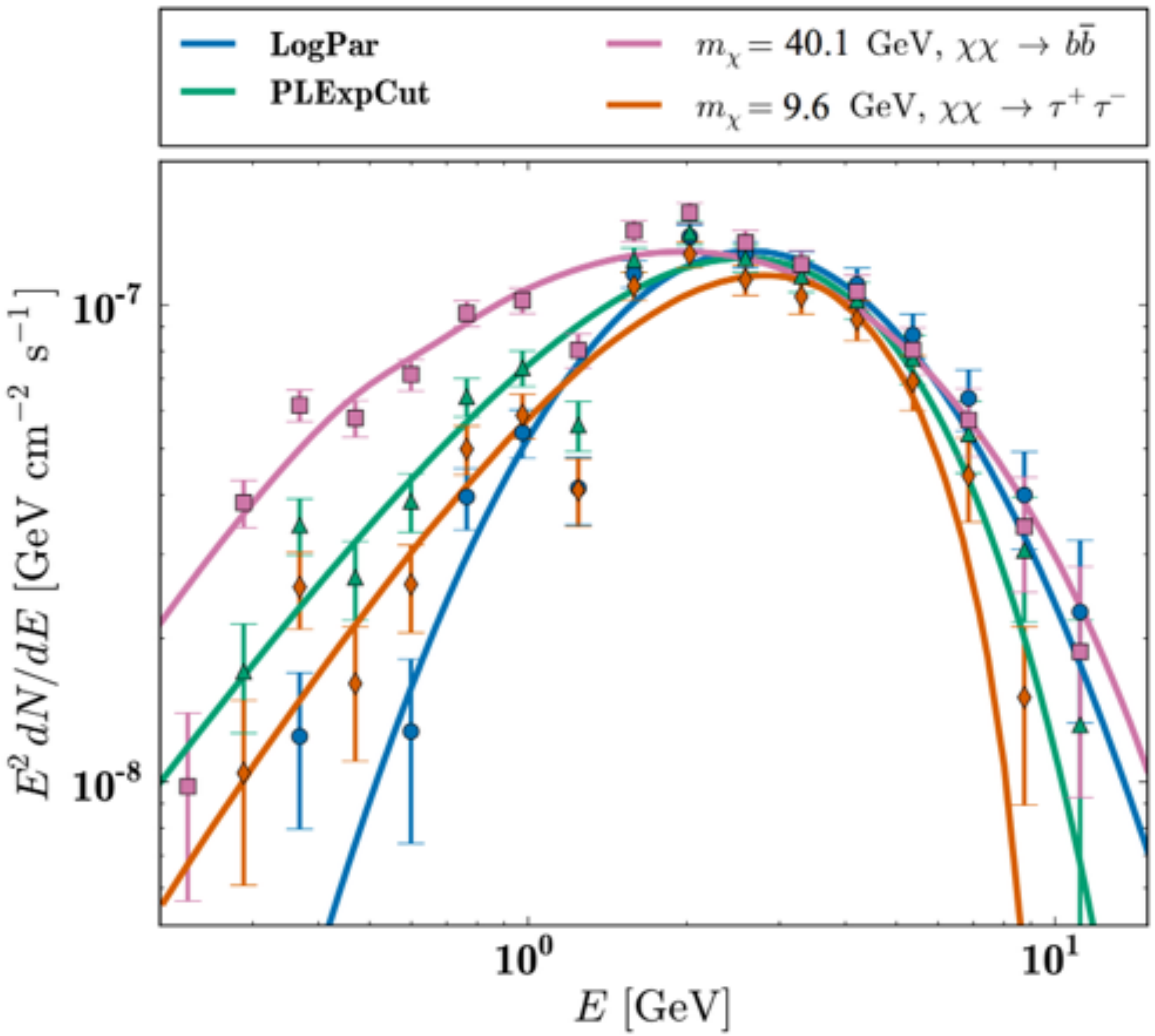



- Macias & Gordon (2013) showed that the emission does not correspond to the H.E.S.S. galactic ridge or the 20 cm map of relativistic electrons

# Independent Confirmation




- Abazajian et al. (this morning) showed that the spectrum of the GC excess is consistent inside different radial bins



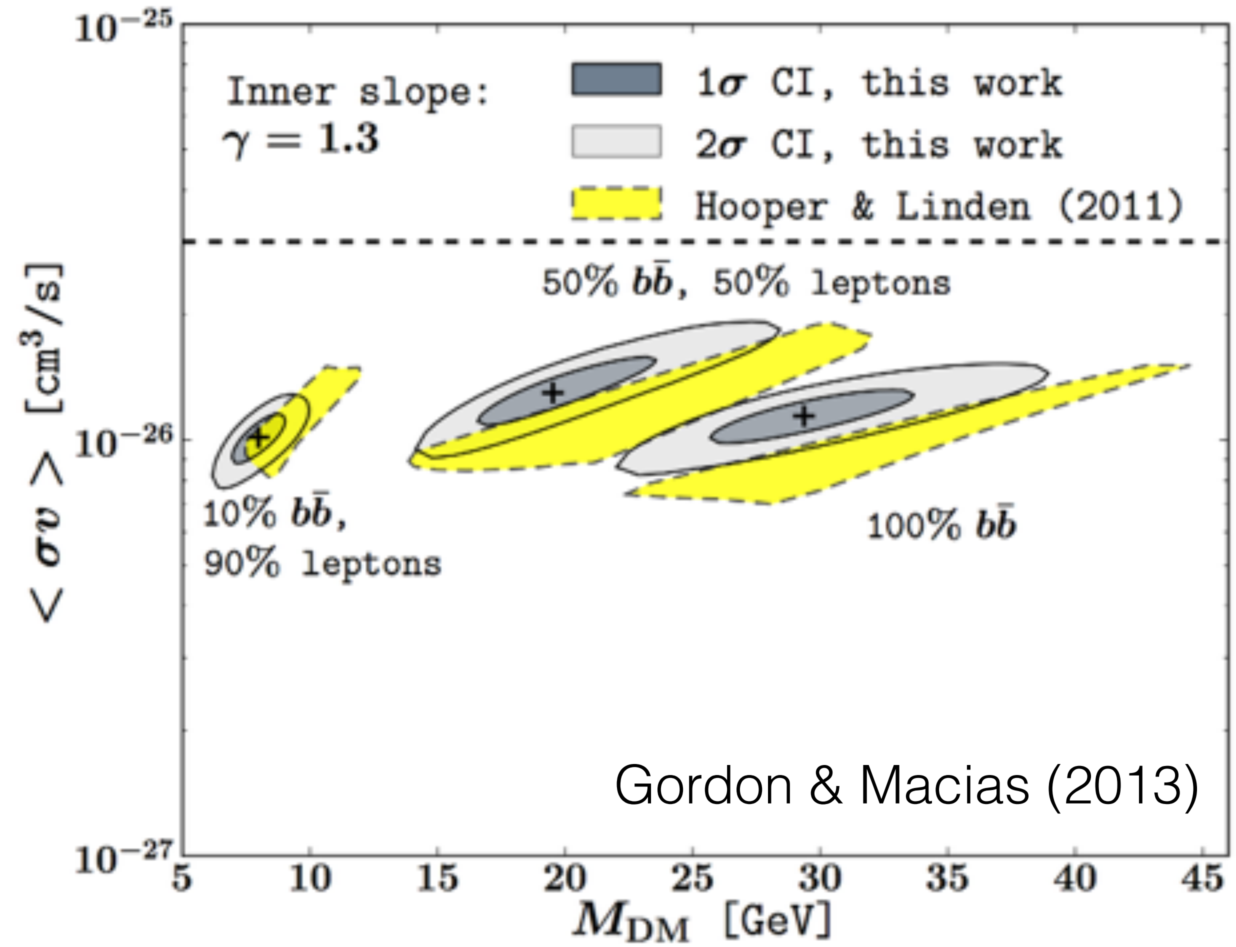

- And found that the high energy spectrum was consistent for very different models of the diffuse background, but the low energy spectrum was wildly inconsistent

# We've Found an Excess!

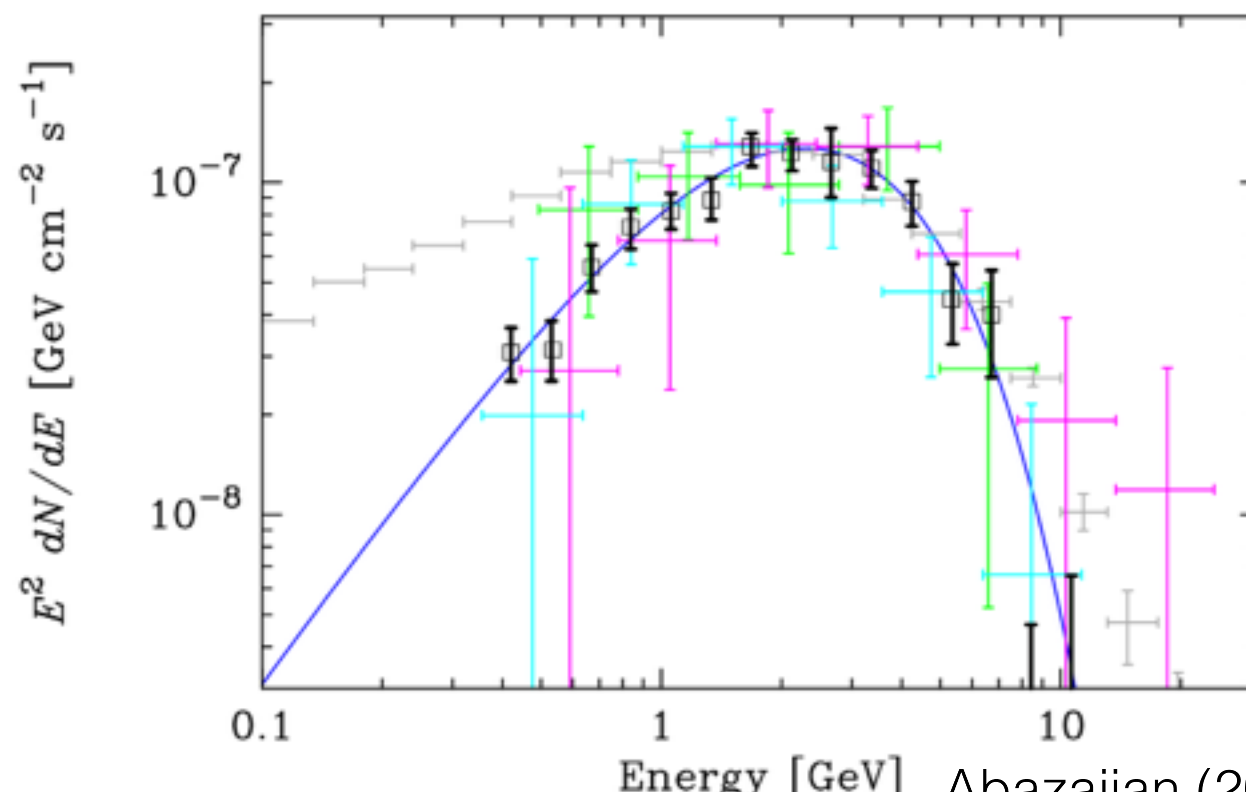
- These observations have yielded strong evidence for a **bright, extended, spherically symmetric** gamma-ray residual around the galactic center

# Interpretations of the Excess

- Two convincing interpretations of the data remain:
  - Dark Matter annihilation following a slightly adiabatically contracted inner profile
  - A large population of dim MSPs centrally concentrated around the central black hole




Gordon & Macias (2013)




Abazajian (2011)

# What is it?

- *Three Camps:*

- **a.) Dark Matter Proponent -** This looks like a dark matter signal, and we have good reason to believe a dark matter signal is here. This is very promising.
    - ``This is the strongest observational evidence yet for dark matter annihilation, and is stronger than the first observations of the accelerating expansion of the universe." - Dan Hooper (referring to results from the rest of this talk)

- **b.) Pulsar Proponent -** This looks similar to the spectrum of pulsars, and we expect a sizable pulsar population in the center of the galaxy. As good Bayesian's we should consider that model first. (K. Abazajian, M. Kaplinghat)

- **c.) Galactic Center Agnostic -** The galactic center is a very complicated region, and we don't know much about the astrophysics which occurs there. It is very difficult to believe that any posited signal is not just the result of systematic uncertainties.

Slide concept courtesy of Dan Hooper

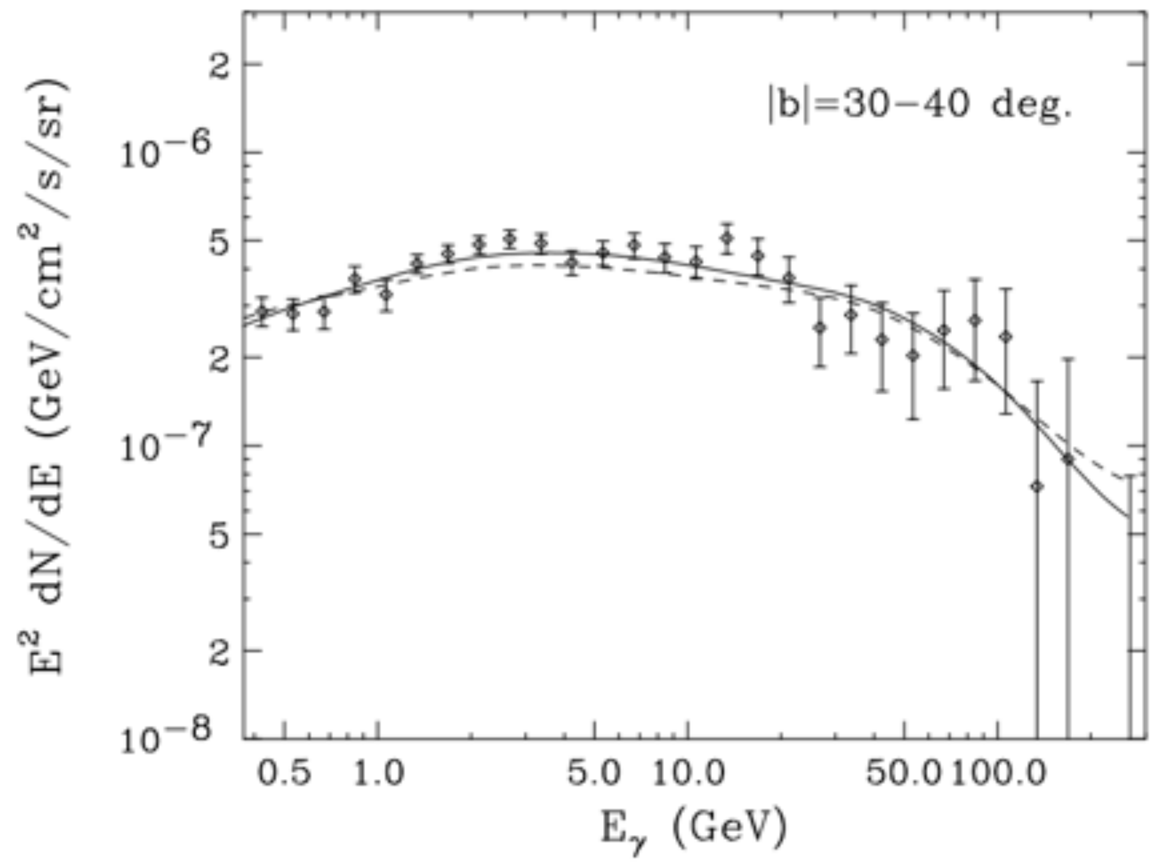
# Strong new evidence for a Dark Matter Interpretation

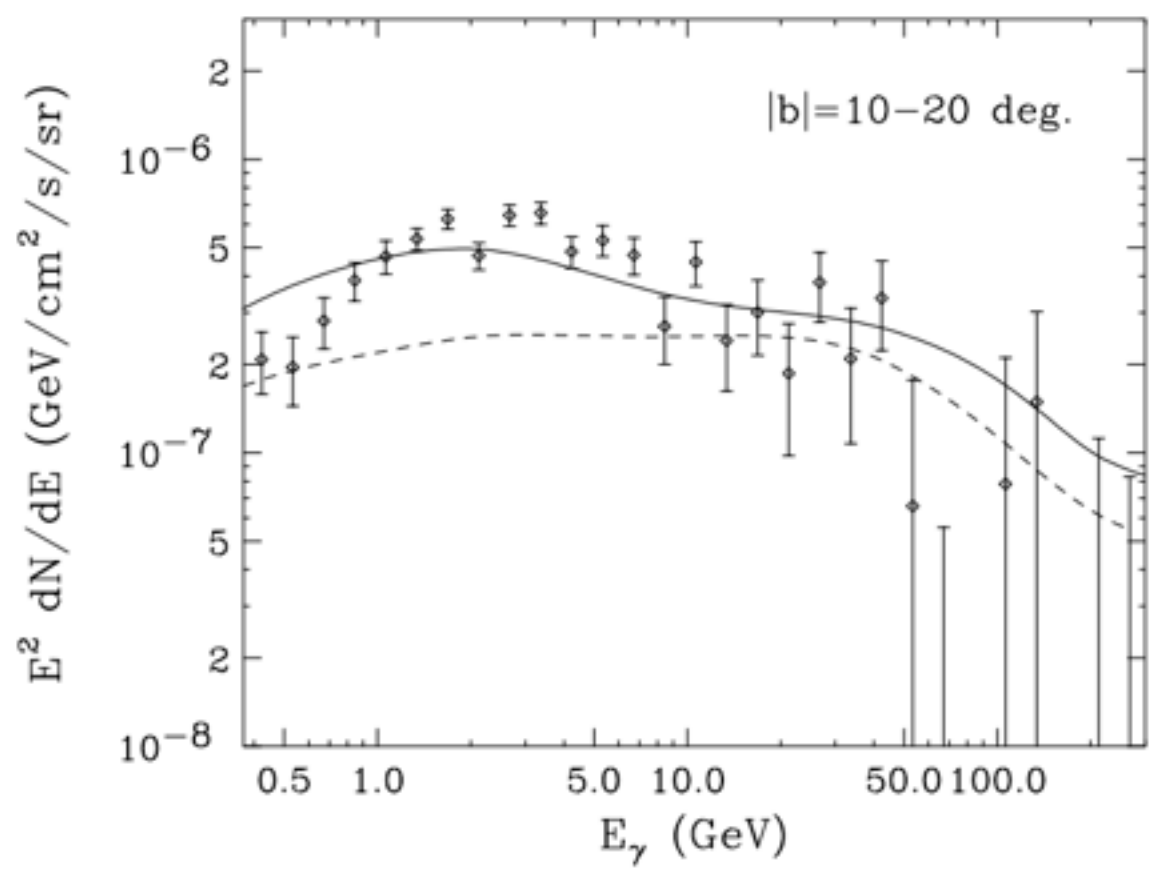
- For the rest of the talk, I will show new data indicating that the ``Dark Matter Proponent" view is not crazy.

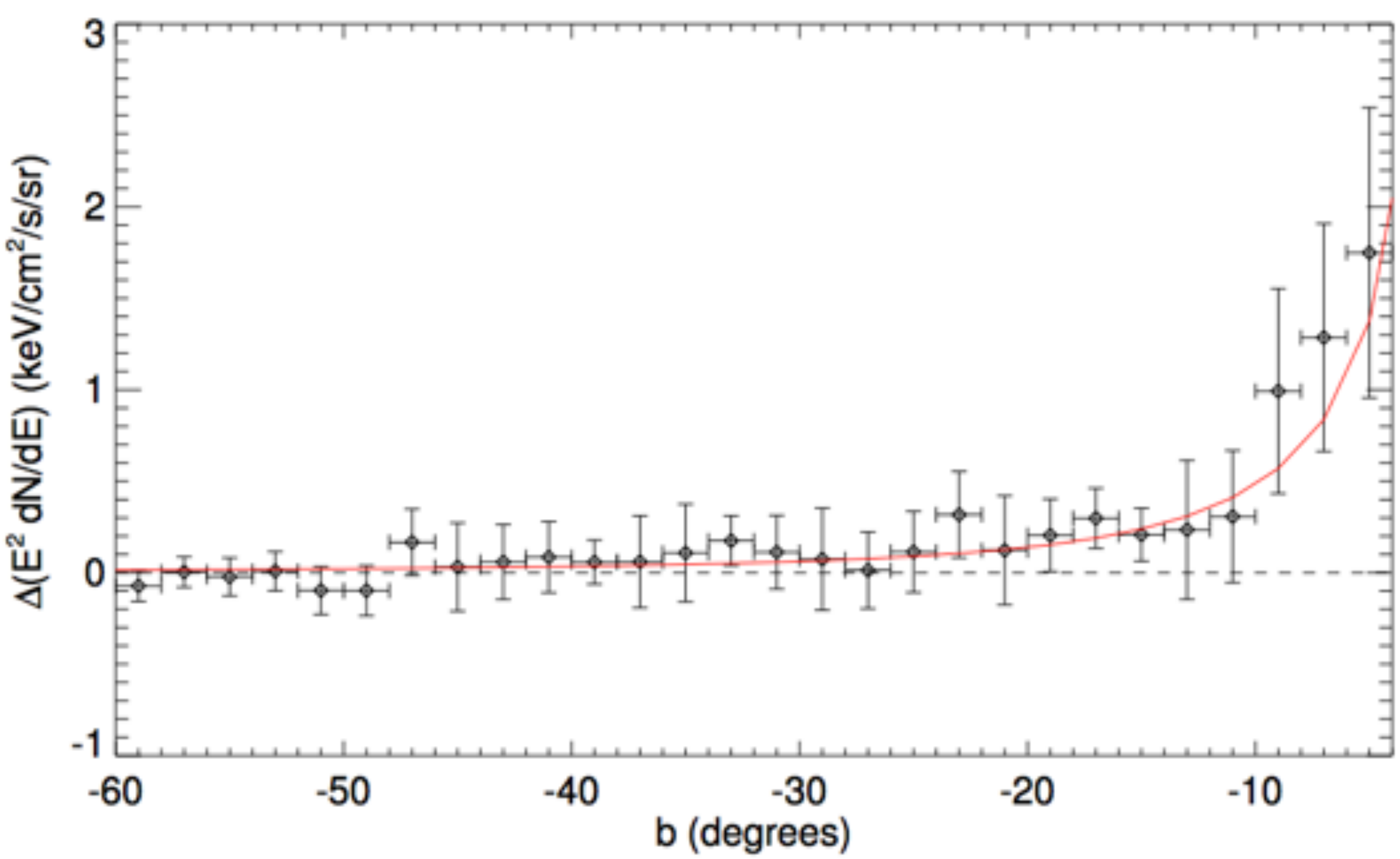
- Specifically, I hope to convince you:
  - We are able to control systematics in the galactic center region well enough to trust the excess
  - The newest data favors the dark matter interpretation over pulsar, or other astrophysical, interpretations

# An Extended Region of Interest

- Hooper & Slatyer (2013) examined the region inside of the Fermi bubbles, and found evidence for a similar spectral excess



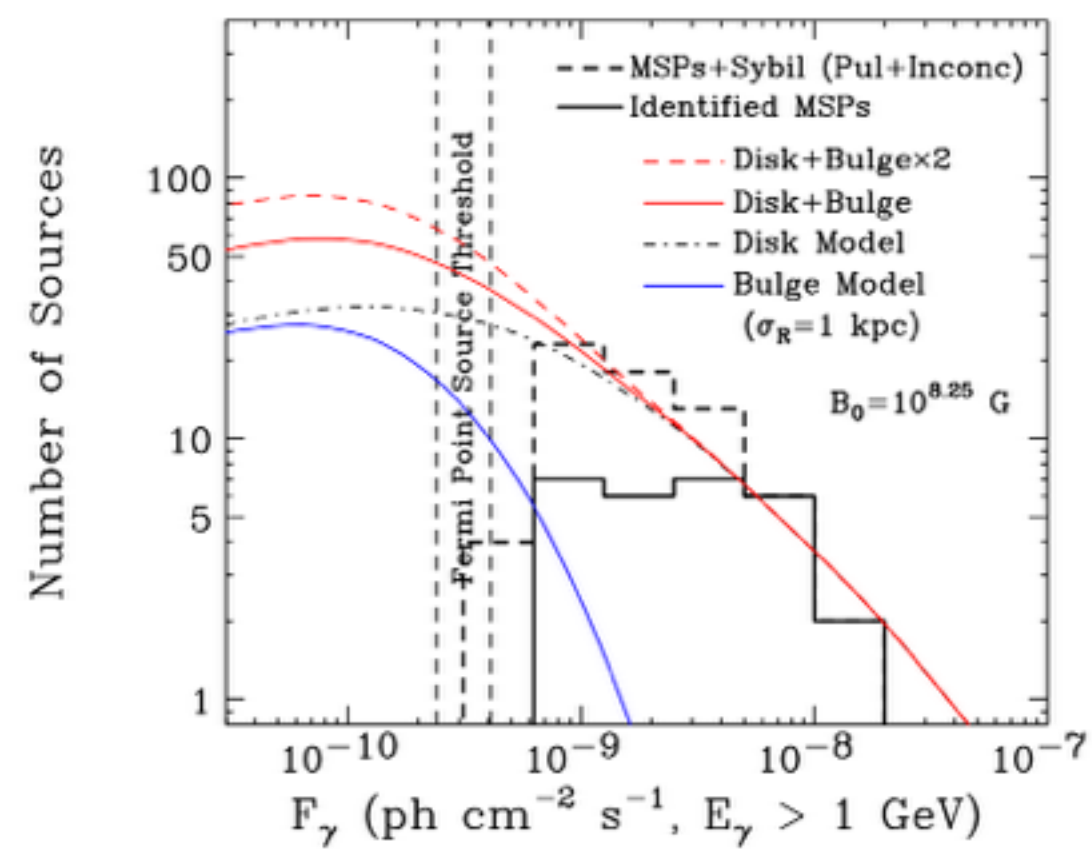



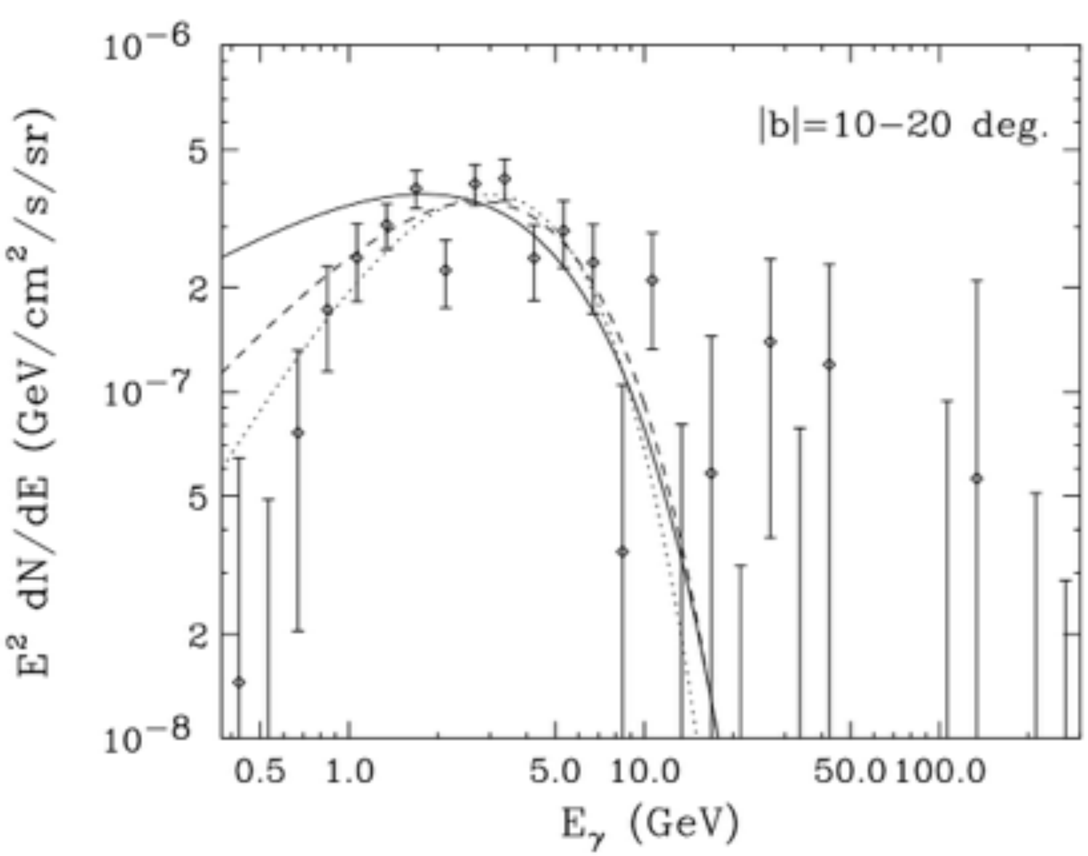



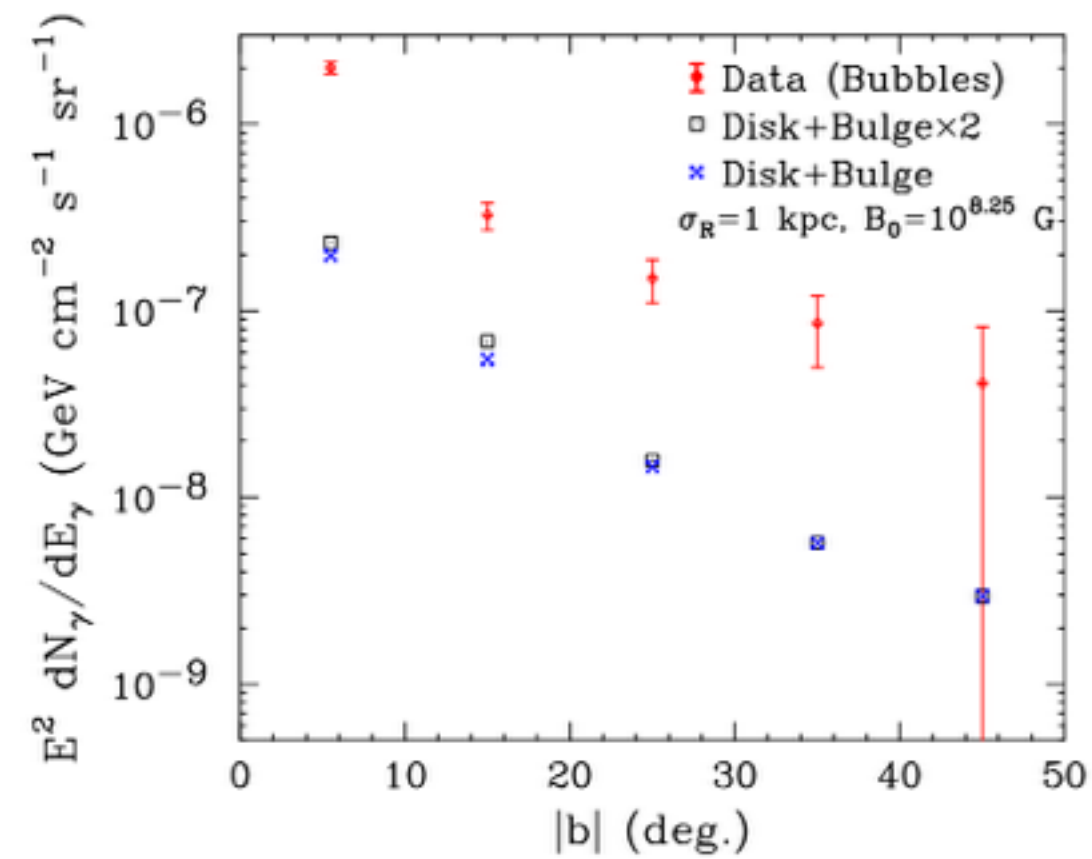
# An Extended Region of Interest

Hooper et al. (2013)

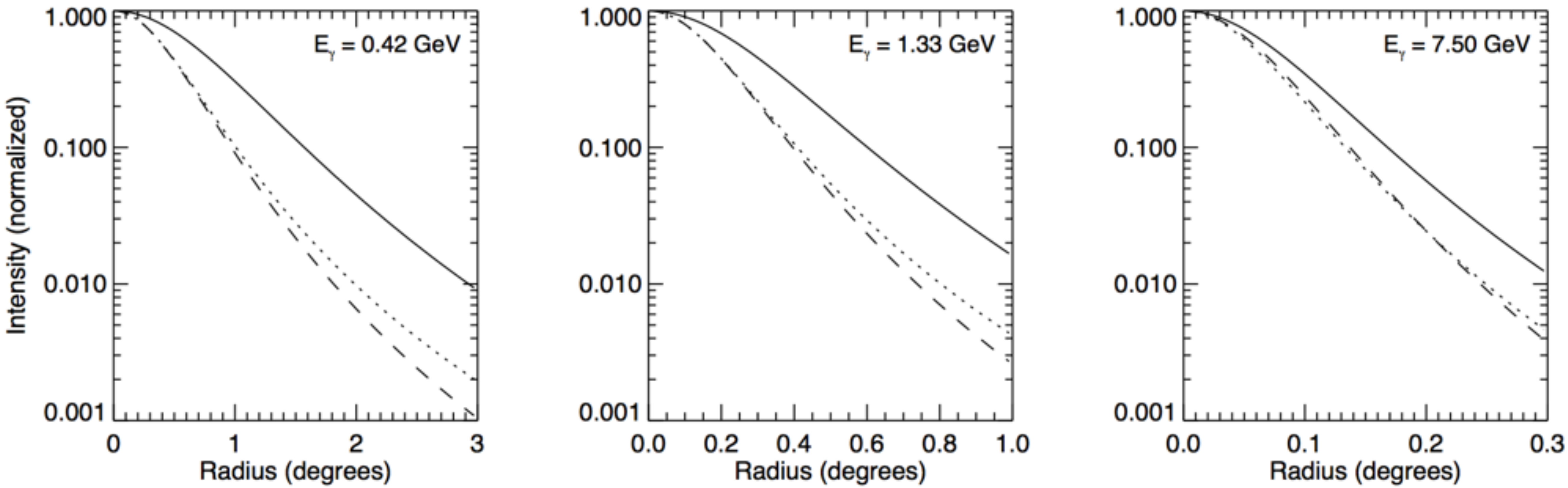
- This detection also helps to address the problem of pulsar contamination. It is difficult to explain the intensity and spectrum of the excess with pulsars, in light of Fermi constraints on observed pulsars



# An Improved Analysis Technique




- Not all photons recorded by the Fermi-LAT instrument have an equivalent accuracy in their reconstructed direction
- Fortunately, there is a marker in the analysis pipeline, called CTBCORE, which estimates how well the Fermi-LAT has reconstructed the true arrival direction
- We utilize the 50% of photons with the best CTBCORE values, and reconstruct the Instrument Response Functions against observations of bright point sources (Portillo & Finkbeiner, 2014, to be submitted)

# We’ve Found an Excess!

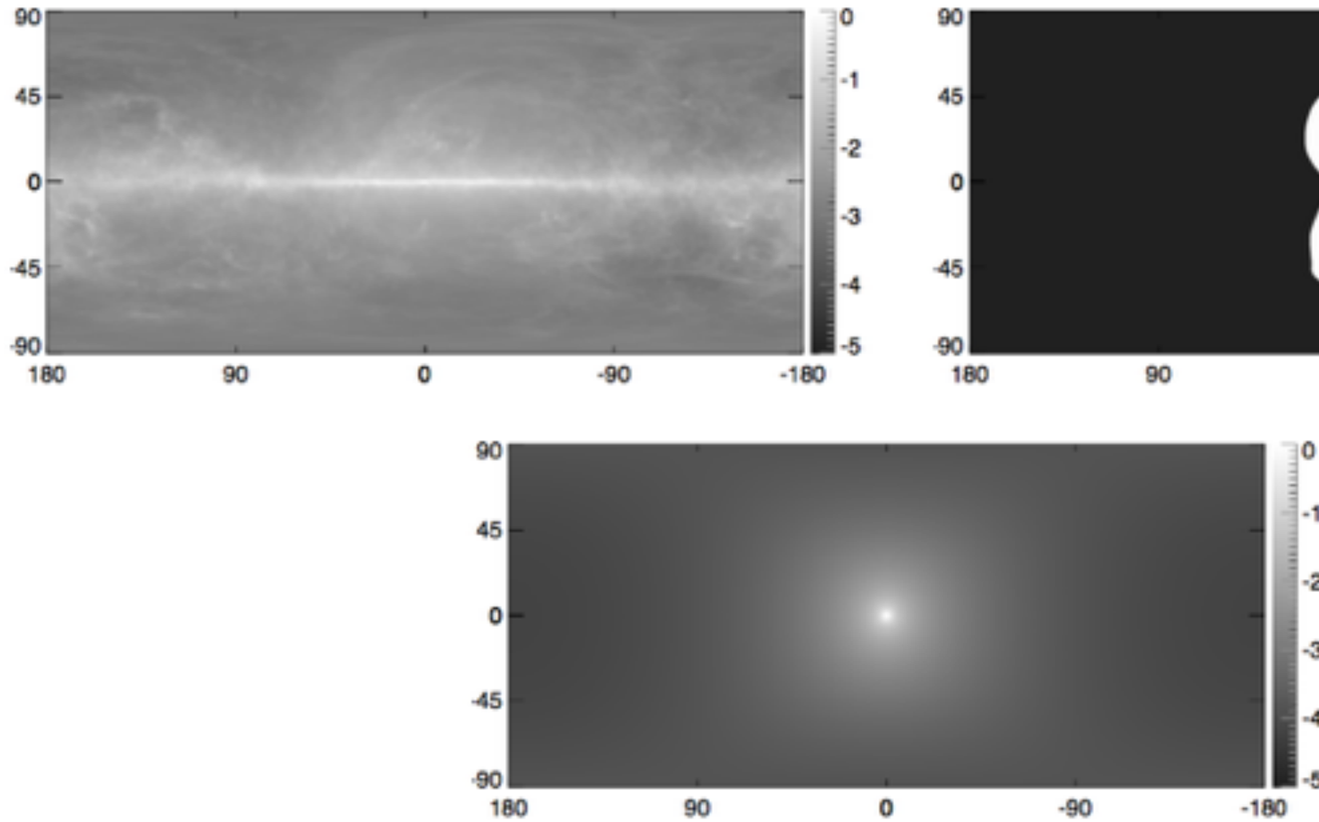
- Warning! You are now entering a zone, where the rest of this talk is preliminary. In case of a sudden change in cabin pressure, an oxygen mask will fall out of the ceiling above you. In you experience dizziness or have difficulty breathing, contact a poison control center immediately… etc. etc.

# Modeling the Galactic Center and Inner Galaxy

- For all models we employ:
  - ~5.25 years of data
  - CTBCORE Q2 cuts on UltraClean front class photons
  - Normal cuts on the instrumental performance to eliminate target observation mode photons, etc.

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer (2013, to be submitted)

# Modeling the Inner Galaxy Excess




- In order to model the dark matter excess at the inner galaxy, we mask the inner 1°, 2°, and 5° along the galactic plane, and then use models for the diffuse emission, the emission from the Fermi bubbles templates, and the spherically symmetric dark matter emission profile

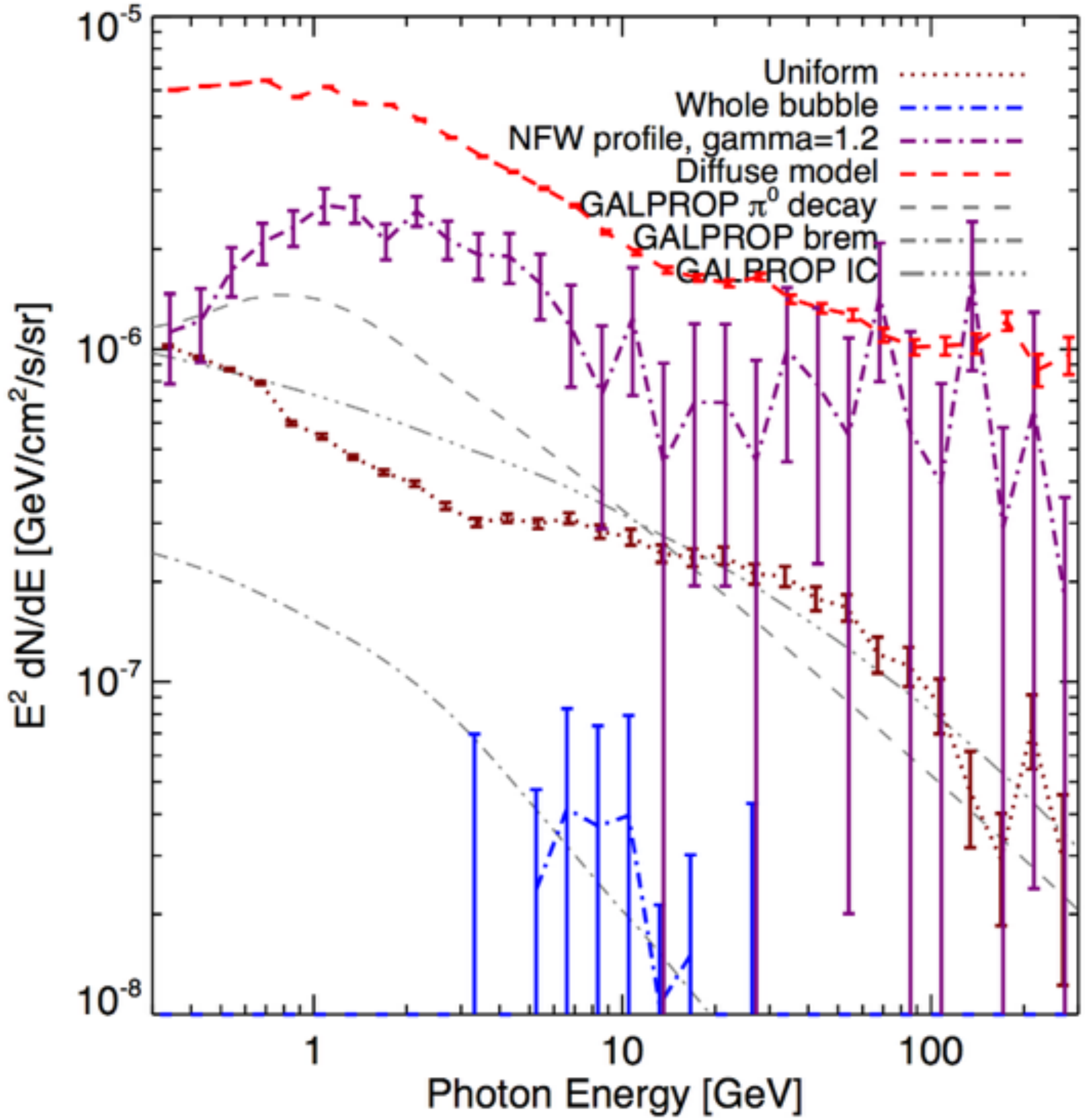
- Fermi 2FGL point sources are masked at 2°, and are not part of the fit

- We employ all photons above 10 GeV, since the PSF of the instrument is very good at these energies

# Modeling the Inner Galaxy Excess

- The relative contribution of each component is allowed to vary in 30 different energy parameters, in order to provide the best fit to the data

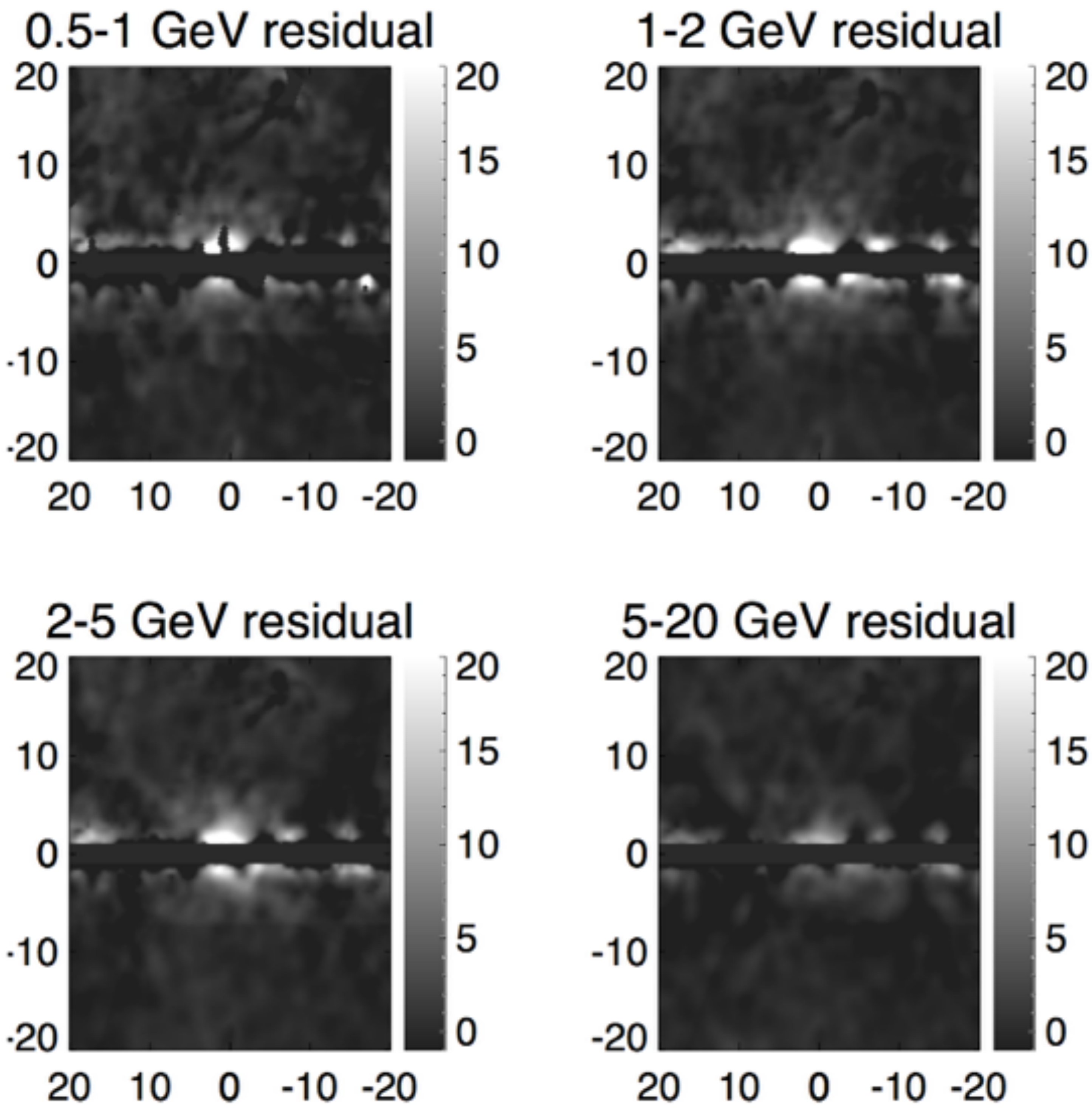
- This produces an output spectrum and morphology for each template



# The Morphology of the Inner Galaxy Excess

- The emission stemming from this dark matter template obtains this excess morphology

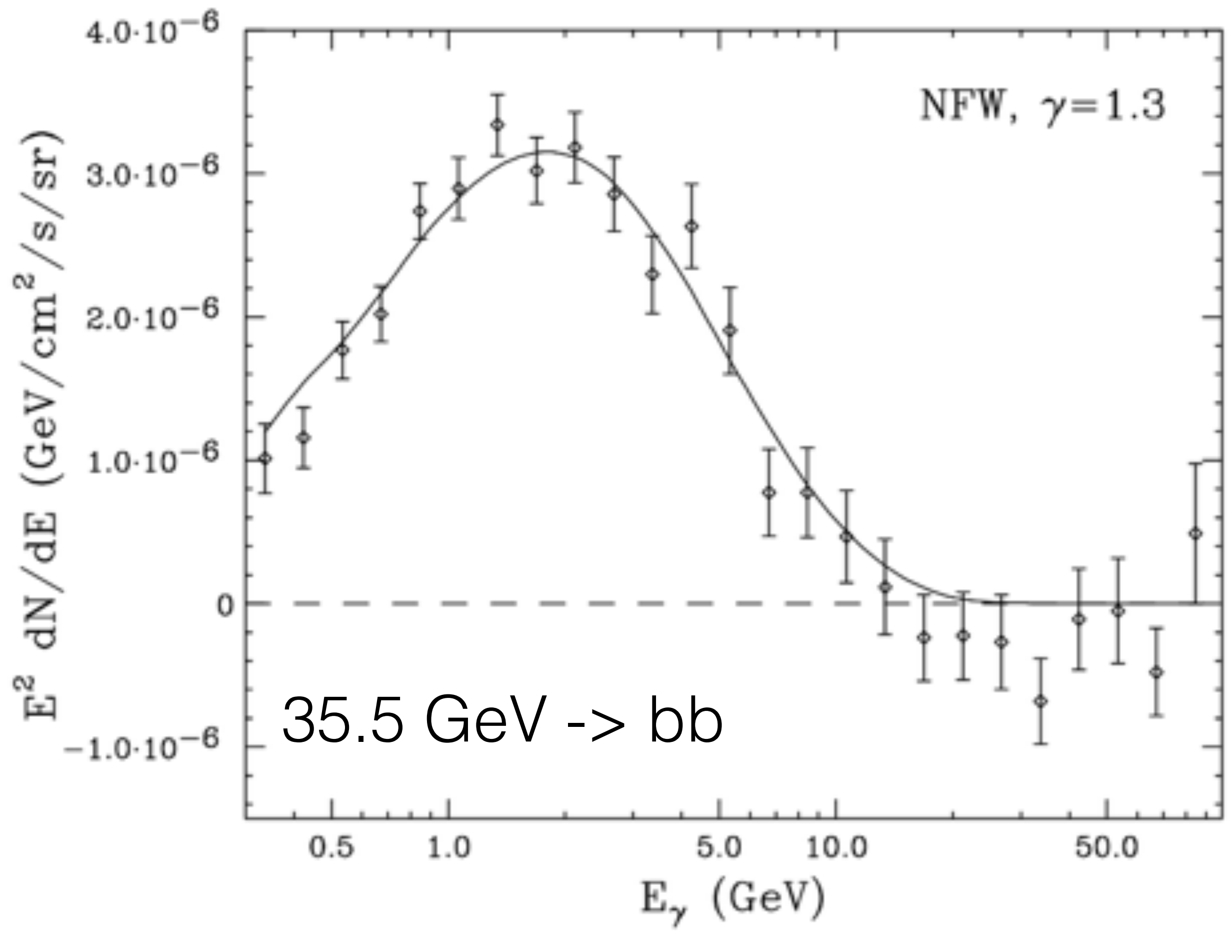
- It is peaked around the position of the galactic center, and appears to be spherically symmetric



# The Spectrum of the Inner Galaxy Excess

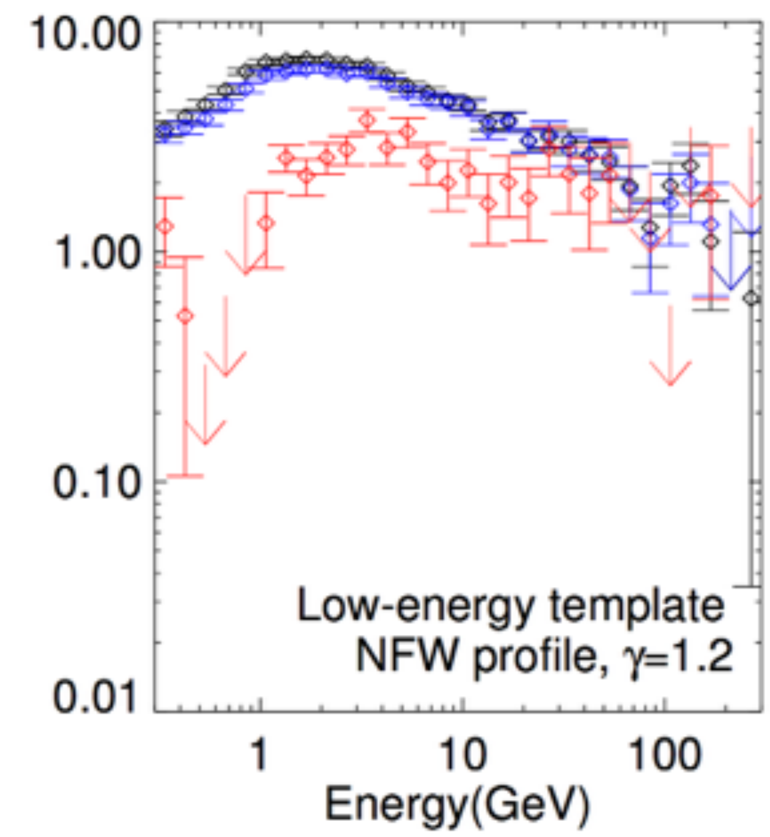
- The spectrum of this excess is extremely well fit by the annihilation of a dark mater particle with mass 35.5 GeV annihilating to bb.

- Note that the spectrum of the components were allowed to vary freely - this is not in any way forced into the model by the fitting parameters

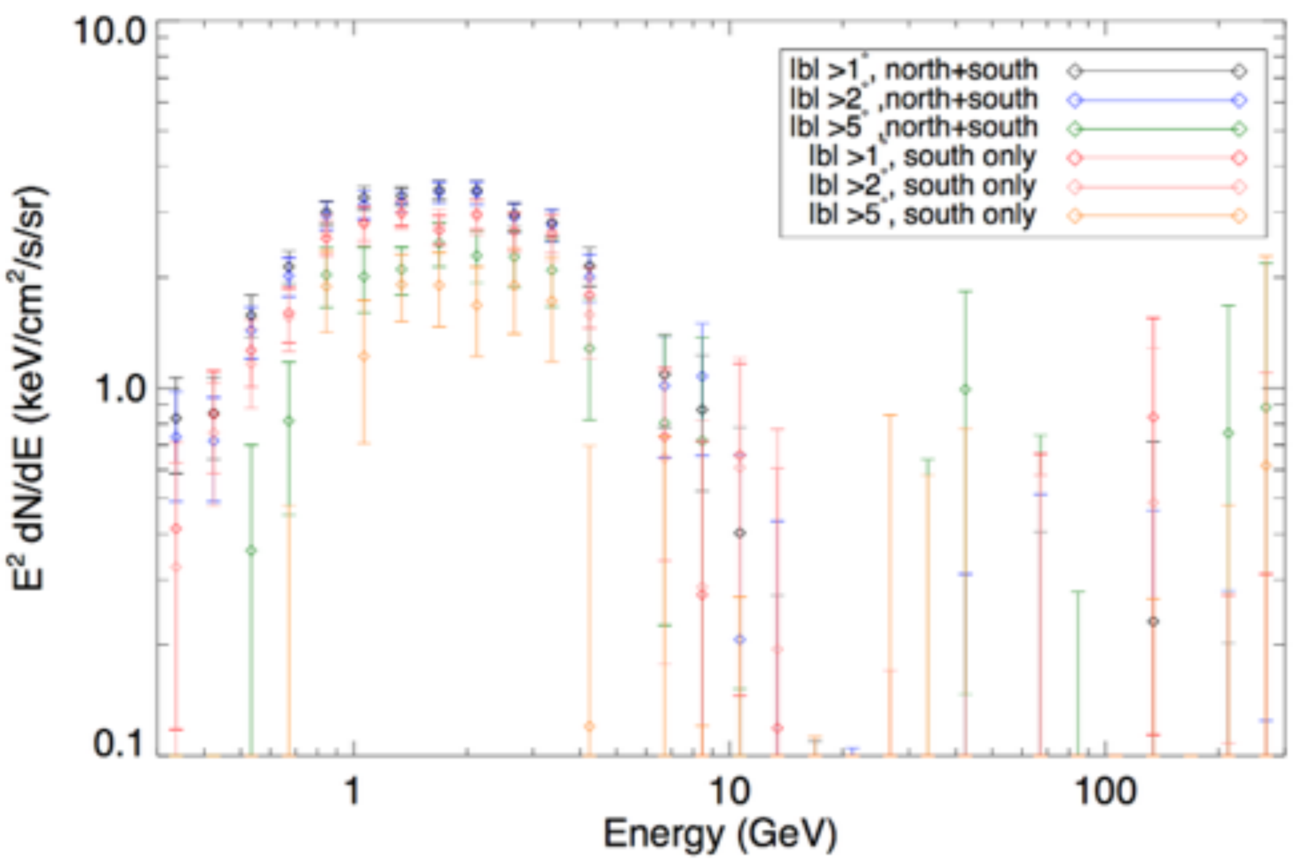


# The Spectrum of the Inner Galaxy Excess

What this plot used to look like before CTBCORE cuts



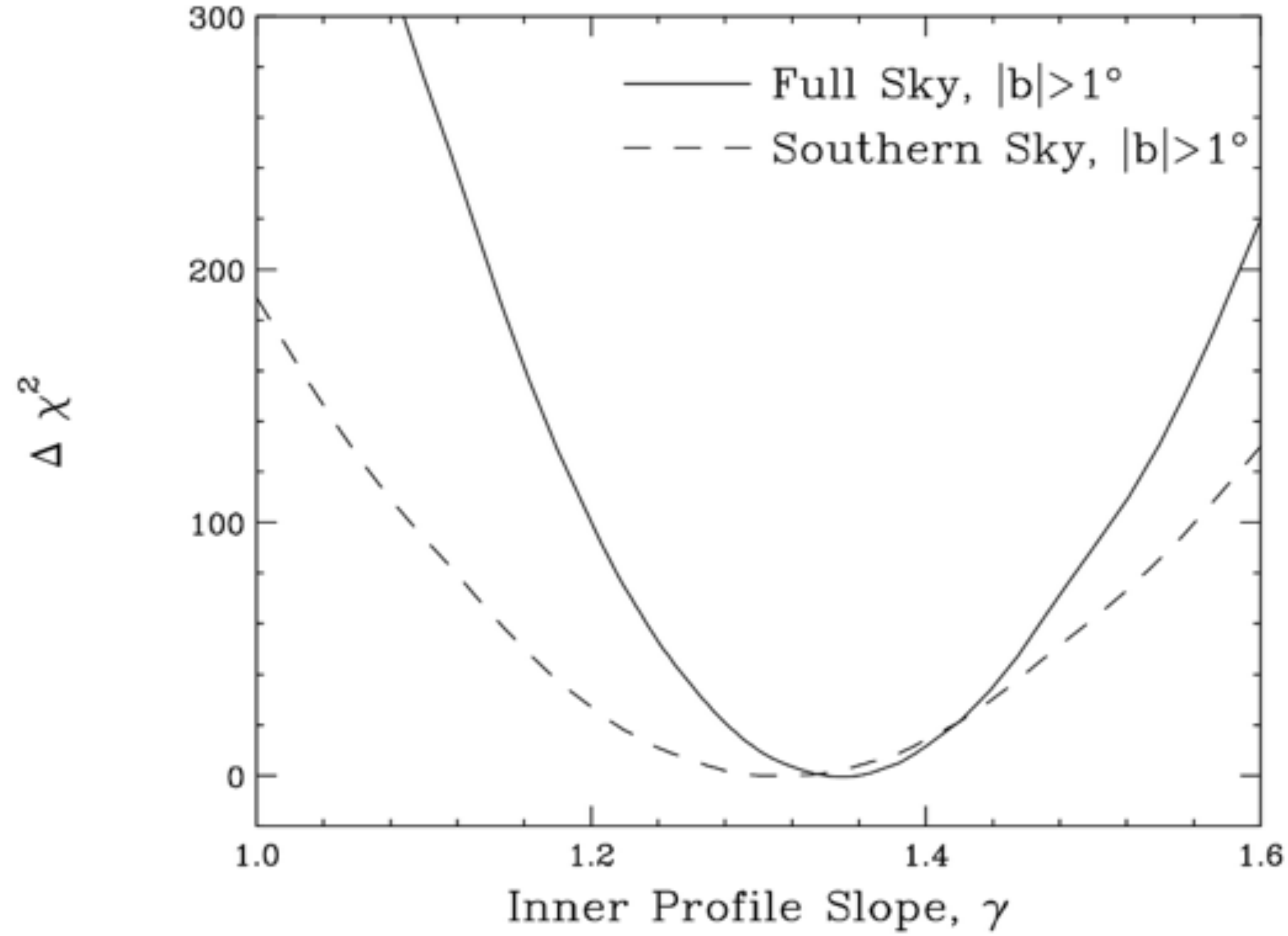

- The use of CTBCORE has greatly increased the accuracy of our models for the spectrum of the excess. They now appear to be almost independent of the choice of latitude cuts in the data



# The Morphology of the Inner Galaxy Excess

- The morphology of the inner galaxy excess is fit by an NFW profile, which prefers a slope of approximately **$\gamma$**=1.3

- This is consistent for both the full sky, as well as observations of just the southern sky (which is cleaner)

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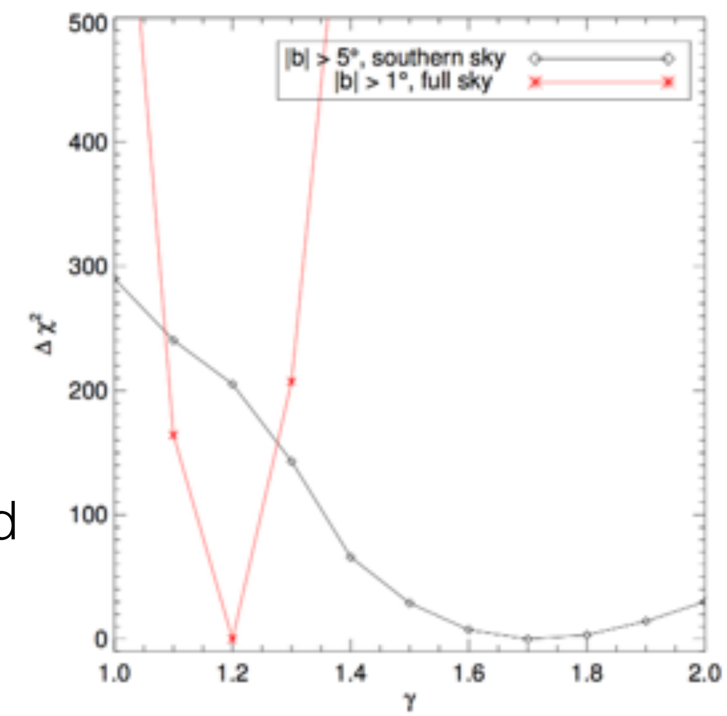


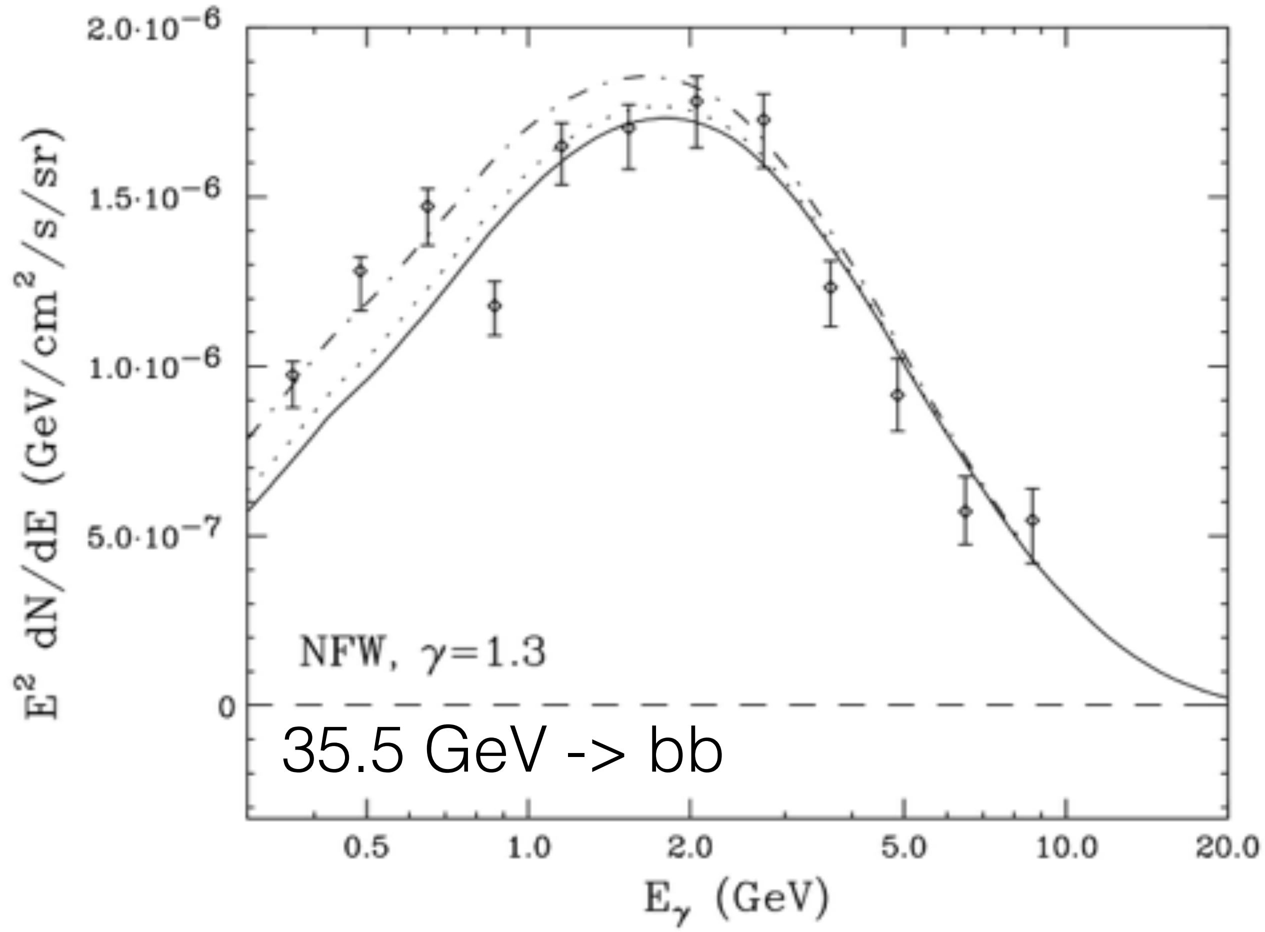
# Modeling the Galactic Center Excess

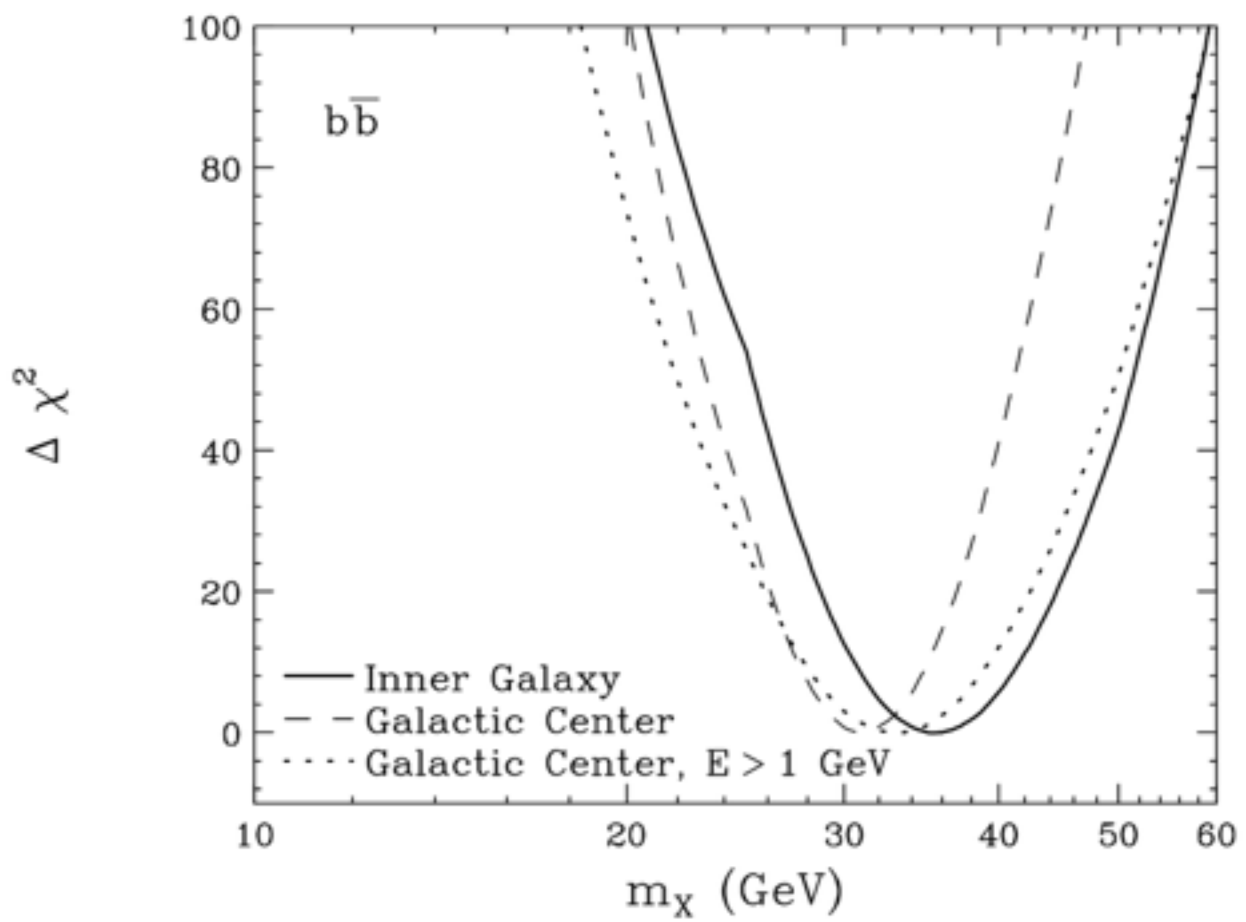
- Unlike the inner galaxy, we do not have the option of masking point sources (we would have no ROI left), so we must model them
- We include models for all point sources found in the 2FGL catalog. Bright point sources are allowed to vary in both normalization and spectrum from the best fit 2FGL values. Dim point sources are allowed to vary only in normalization
- The Fermi tool gtlike employs the MINUIT fitting algorithm in order to determine the best fitting spectrum and flux of each source
- We generate a "model independent" spectrum by using the following algorithm:
    - Find the flux of the dark matter component by seeding the fit with a given spectrum (sometimes dark matter, sometimes a simple broken-power law)
    - Find the best fit to the data, then allow the dark matter component to float independently in each energy bin
    - Interpolate that fit to a continuous spectrum, and reseed the fit to the data
    - Repeat until any input spectrum converges to the same output

# The Spectrum of the Galactic Center Excess

- The spectrum of the GC is nearly identical to the spectrum of the inner galaxy excess.

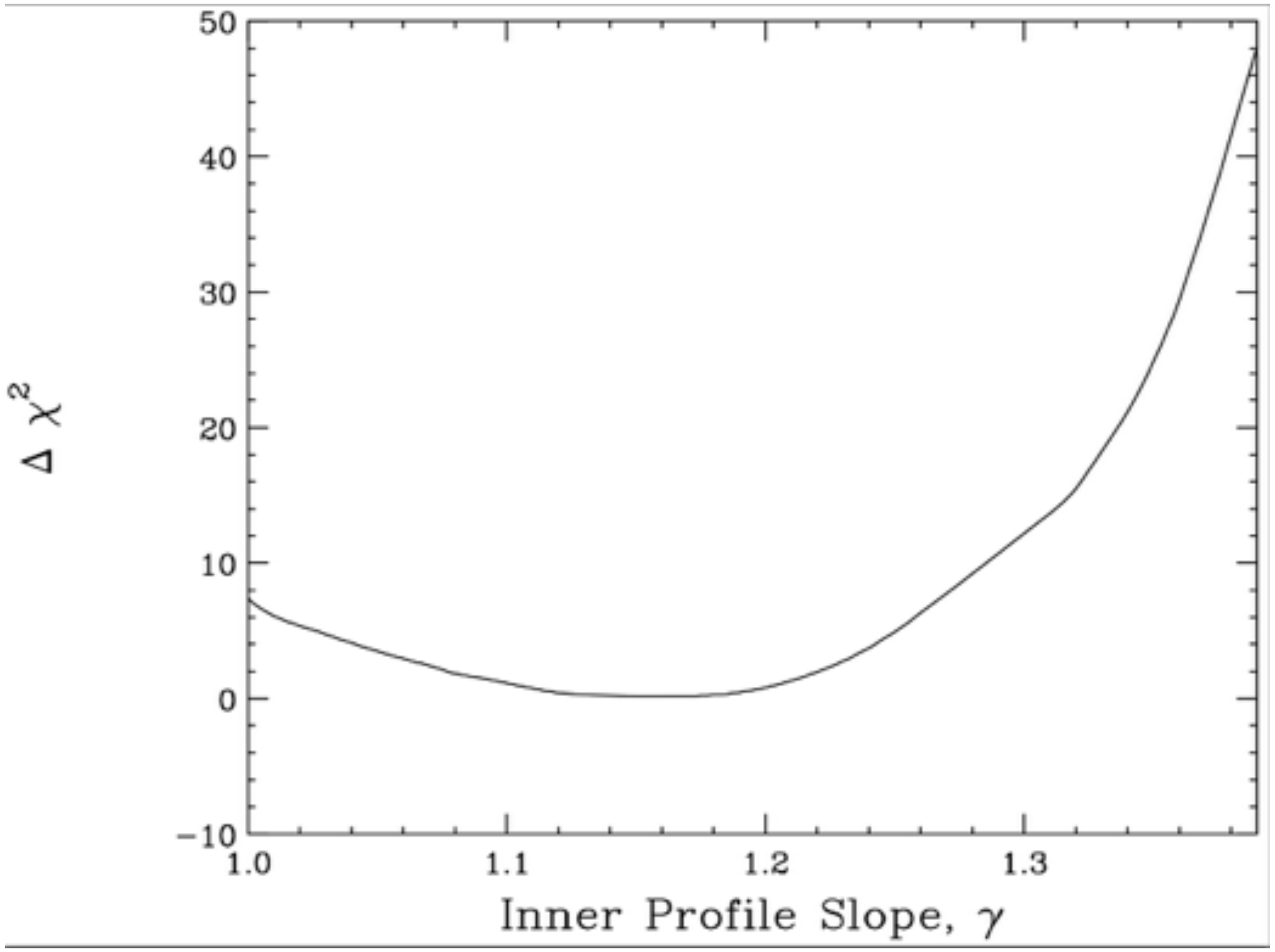
- There are some uncertainties in the measurements below 1 GeV. This is to be expected as the PSF of the instrument begins to exceed 1° in this region, making it difficult to disentangle the many source populations.



# The Morphology of the Galactic Center Excess

- The galactic center excess prefers a slightly flatter slope, approximately $\gamma$=1.15-1.2. The degeneracy with the point sources at the galactic center allow the profile to become significantly flatter with only a small change in chi-squared




- The difference between the slopes in the inner 5° and in the broader inner galaxy range are perfectly consistent with models of dark matter profiles in the presence of baryons

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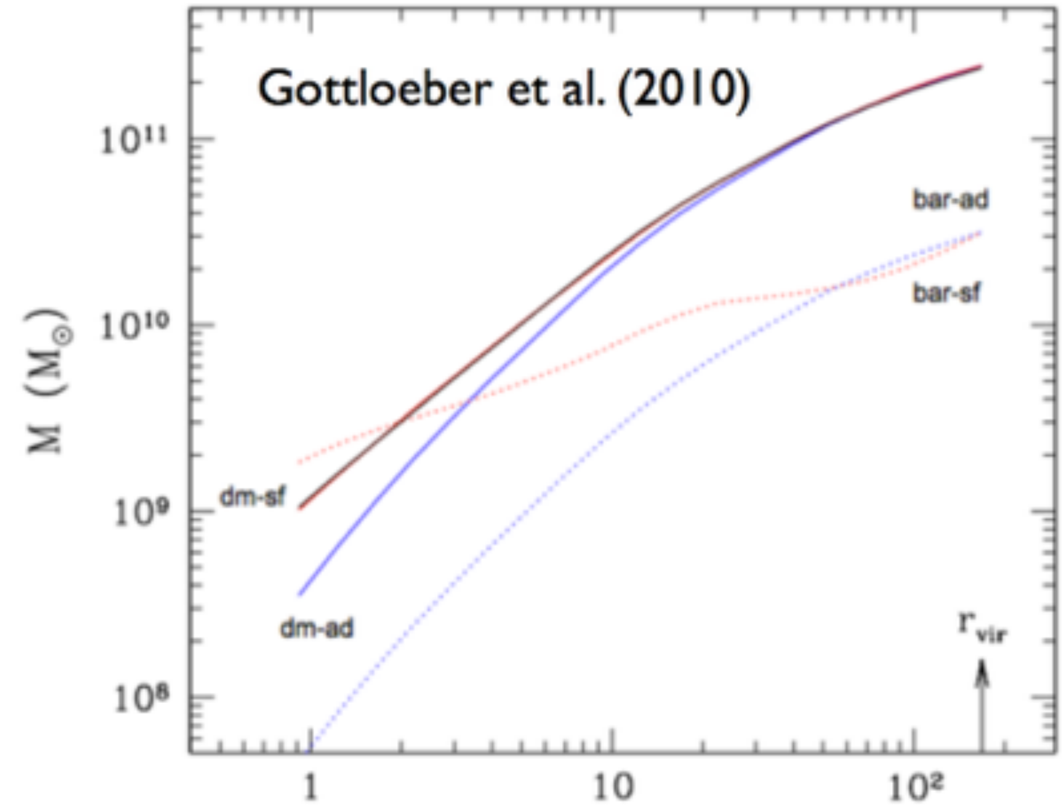
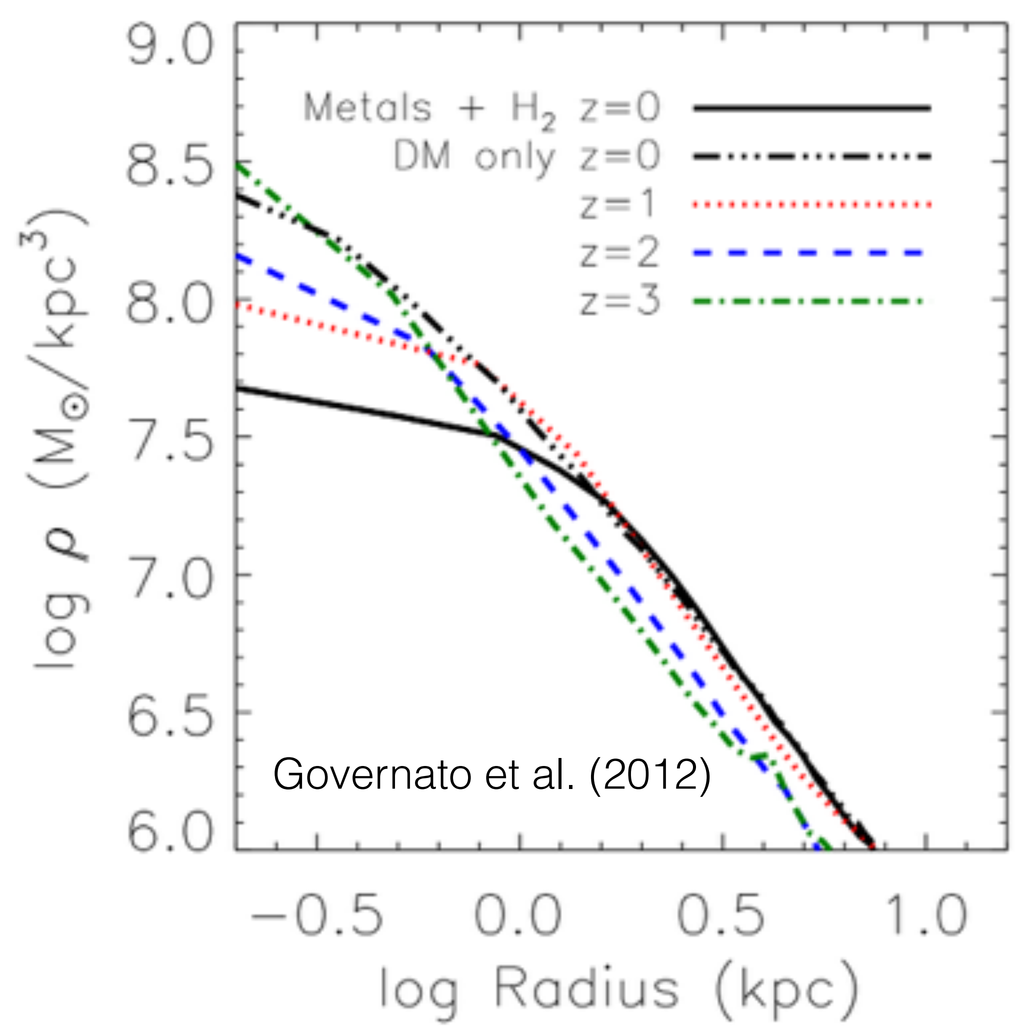


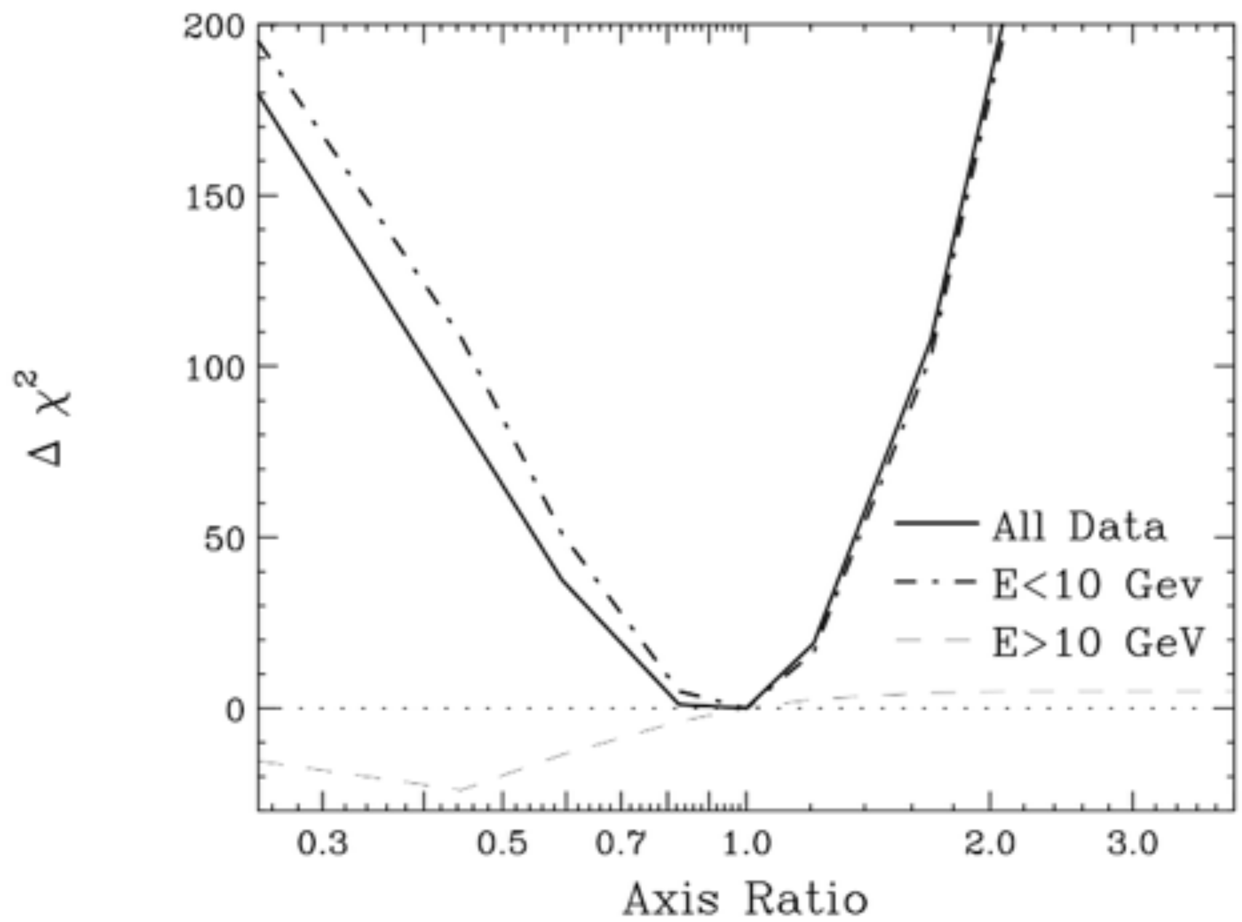



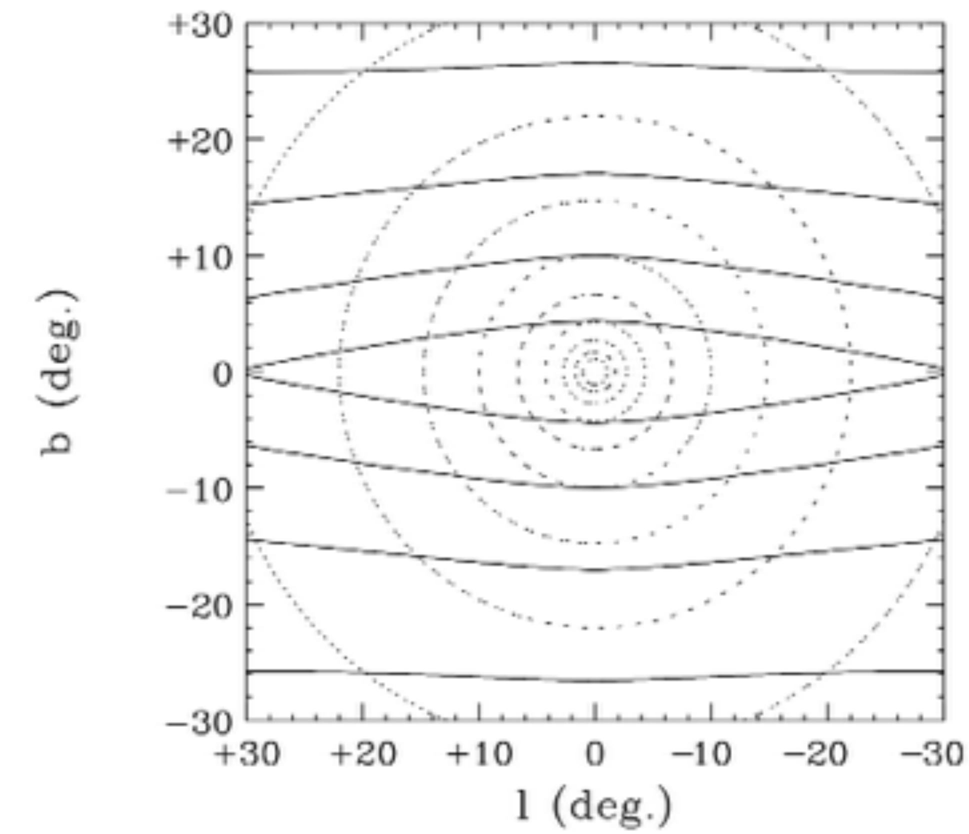
# We've Found an Excess!

- We are in the midst of performing many cross-checks of the data, some of which are still ongoing (and thus some plots are not for the most recent versions of the analysis)

# Ellipticity of the Inner Galaxy Excess

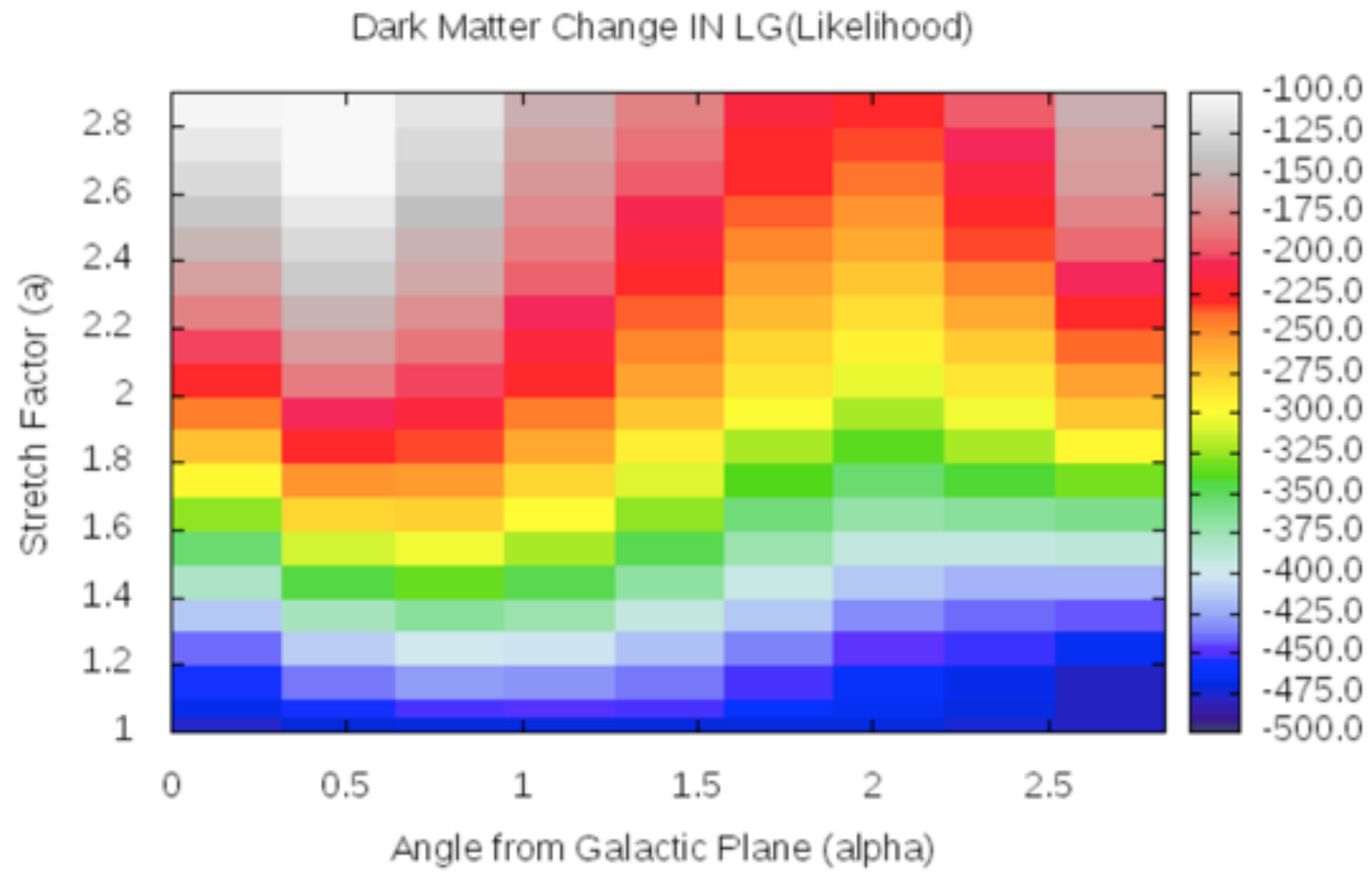
- The inner galaxy excess is strongly spherically symmetric.
- This contrasts strongly with the templates for most astrophysical emission sources (such as pulsars, which favor axis ratios of approximately 5).



# Ellipticity of the Galactic Center Excess

- The excess also appears to be approximately spherically symmetric. Adding an axis ratio ($a^2$) decreases the best fitting log likelihood.

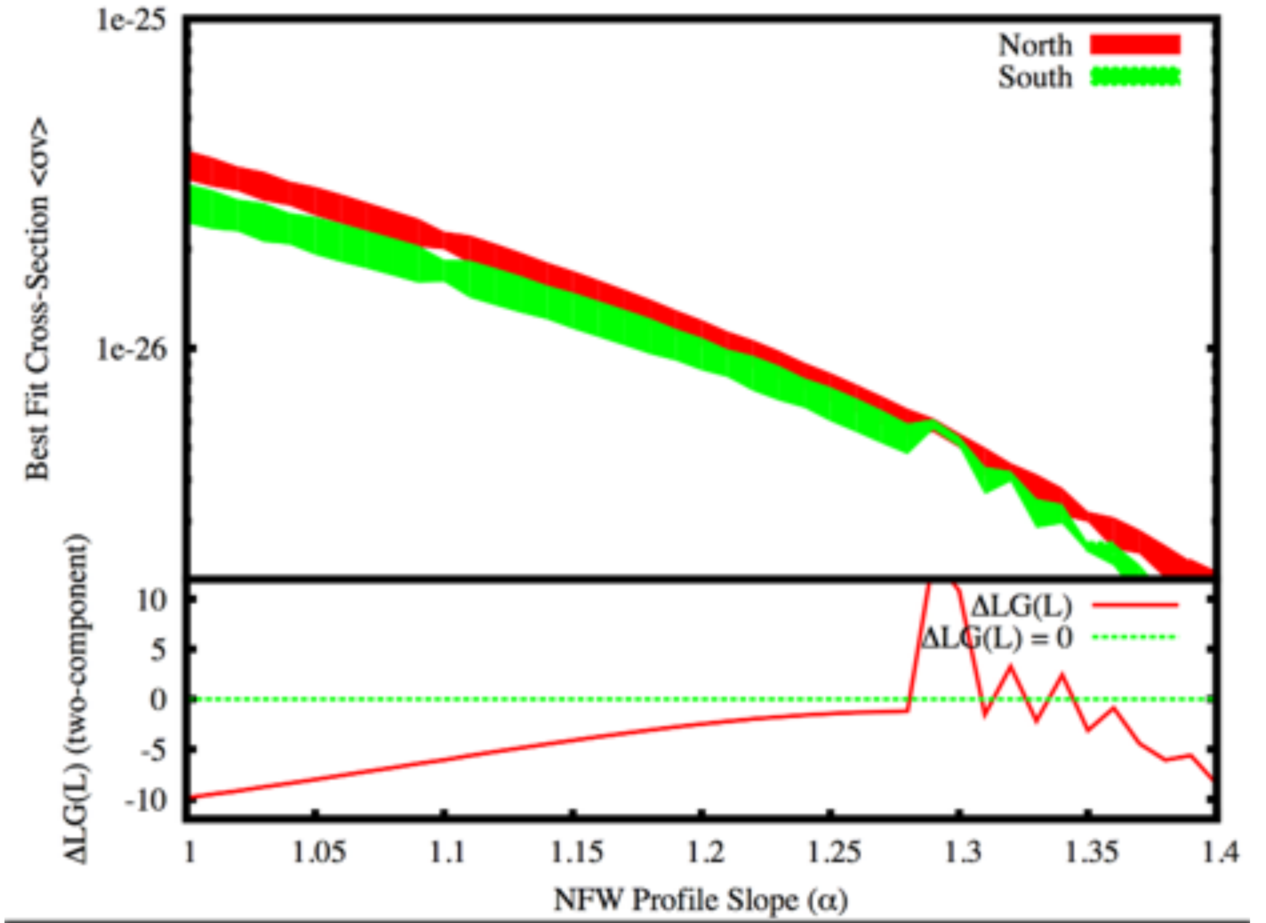


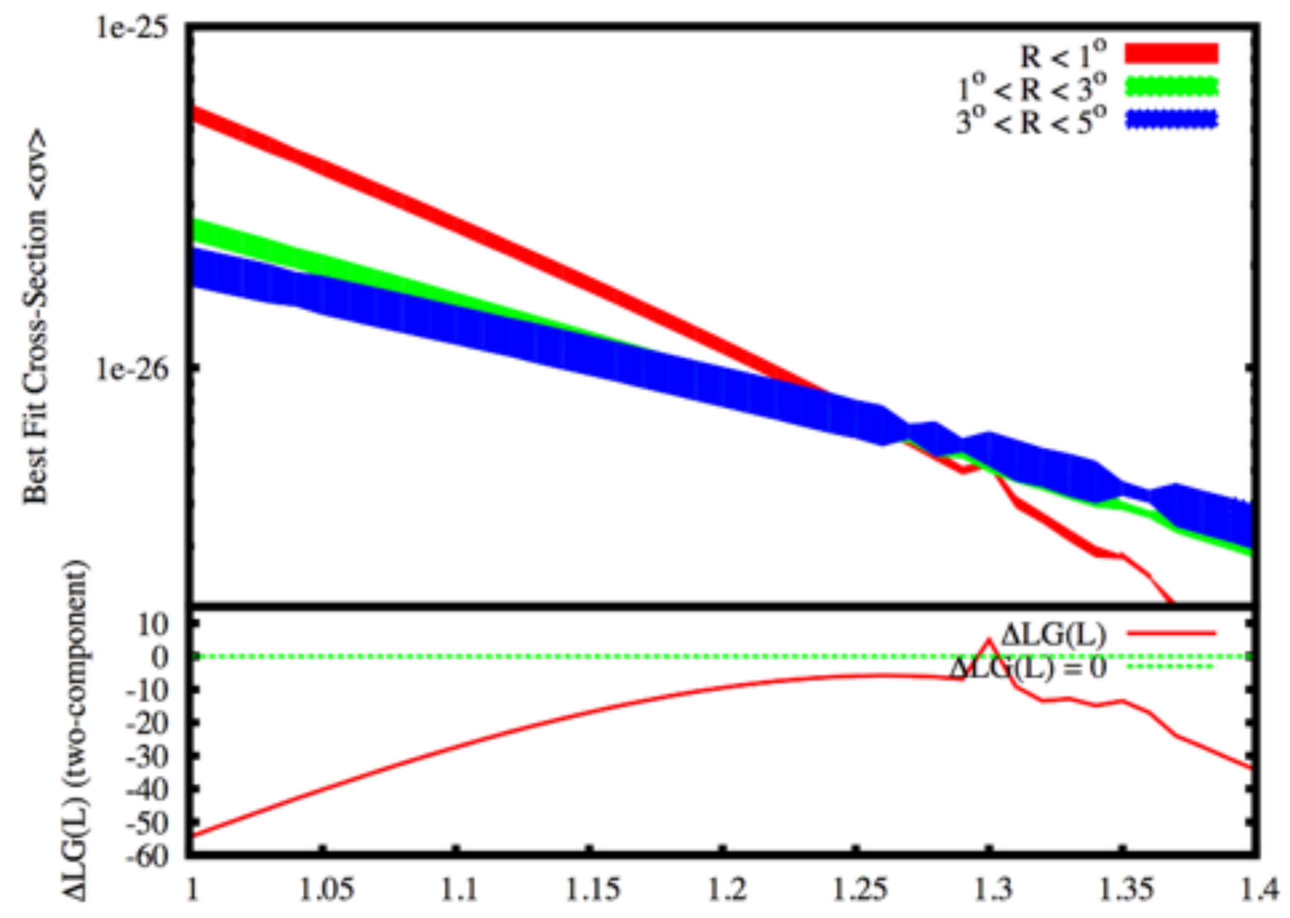

OLD PLOTS! - Uses a 30 GeV -> bbar seed, does not include centra point sources or 20cm map

# North/South Asymmetry of the Galactic Center Excess

- We find no evidence for a North/South asymmetry in the galactic center excess.

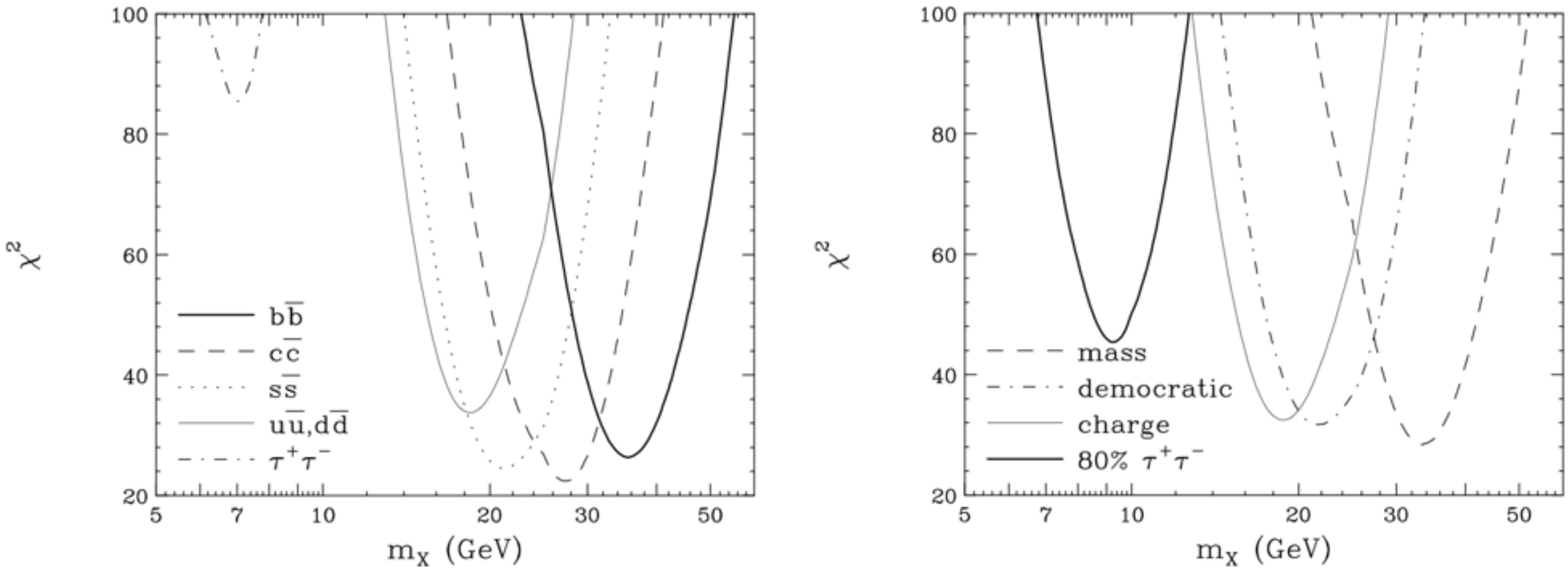
- We also find no evidence for any change in the dark matter profile as a function of the distance away from the galactic center



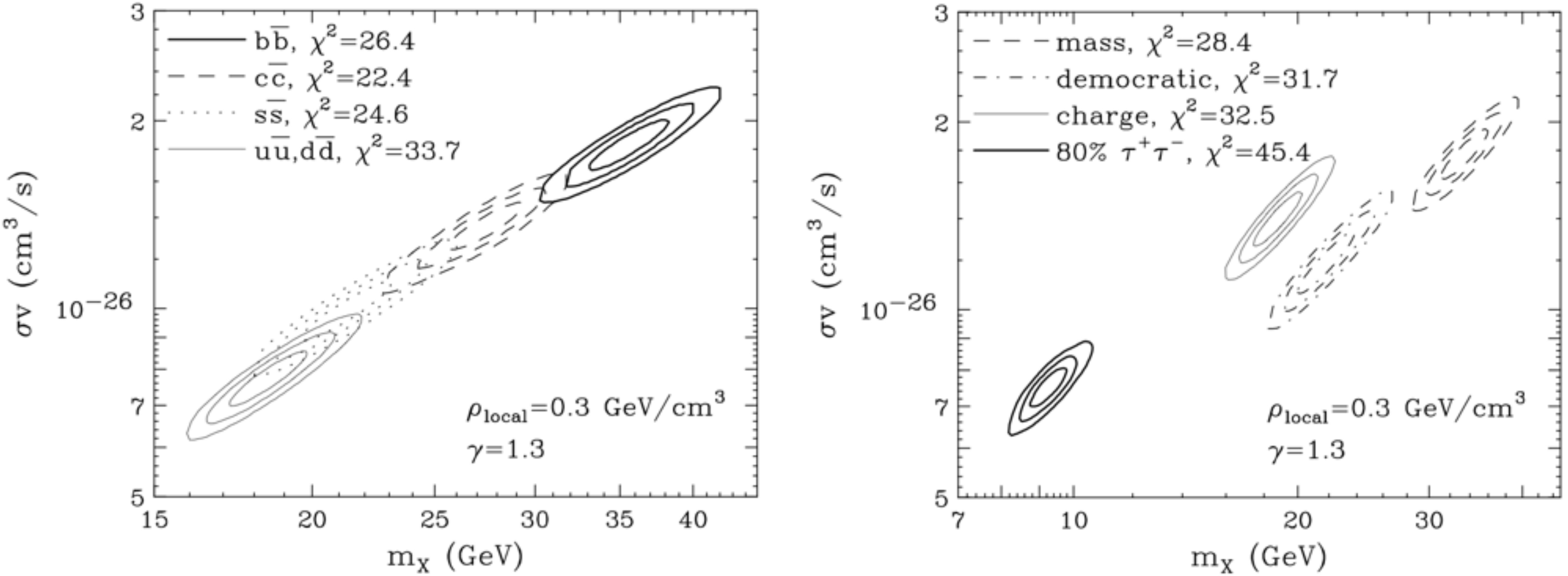

OLD PLOTS! - Uses a 30 GeV -> bbar seed, does not include central point sources or 20cm map

# Some Particle Physics Interpretations




- This excess is well fit by a variety of well-motivated dark matter models.
- Coupling to mass produces a particularly good fit, and allows the dark matter mass to be approximately half the Z-boson mass.

# Some Particle Physics Interpretations

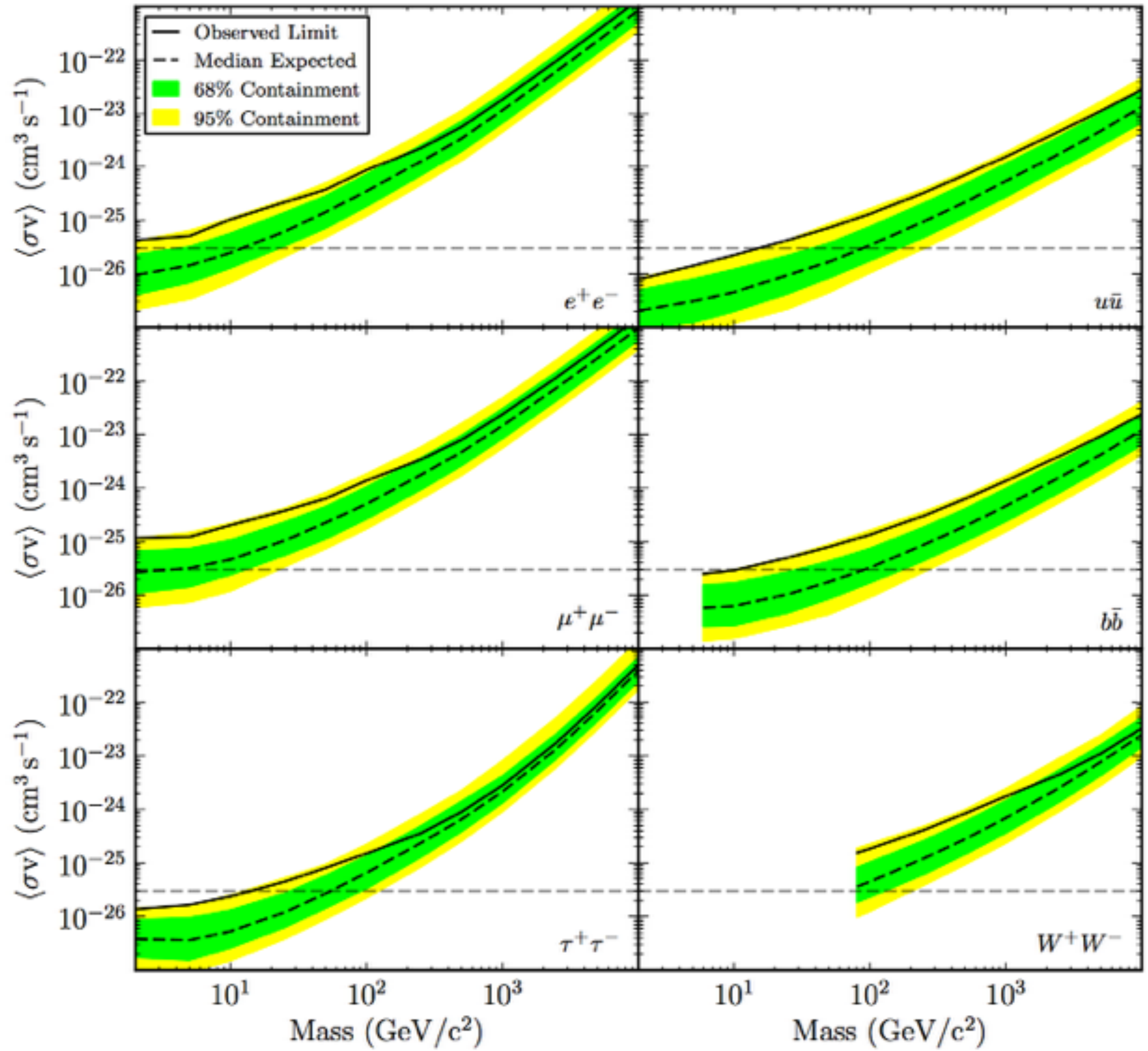



- The cross-sections are consistent with that of a thermally produced dark matter relic

# A Hint of An Excess in Dwarf Spheroidals?

- The most recent observations of dwarfs by the Fermi-LAT collaboration also find that their limits on the dark matter annihilation cross-section are weaker than would be expected by simulations

- Interestingly, they are about 2-sigma above their expected limits for the same 30 GeV particle annihilating to bb




Fermi-LAT Collaboration (2013)

# Conclusions

- We have found a consistent, spherically symmetric signal in both the galactic center and the inner galaxy, extending to almost 20o away from the GC
- The spectrum of this excess is consistent in all regions
- This excess is highly spherically symmetric in all regions
- This excess falls as a approximately $\rho^{-2.0}$ - $\rho^{-2.6}$ through all regions

**These are all <u>exactly</u> the properties you expect from a dark matter signal**

**These are <u>not</u> the properties you expect from <u>any</u> astrophysical signal**

# Conclusions

- The prior against a dark matter interpretation is large (those finding dark matter are currently batting .000)

- However, this excess deserves to be taken seriously as possible evidence for the annihilation of a dark matter particle