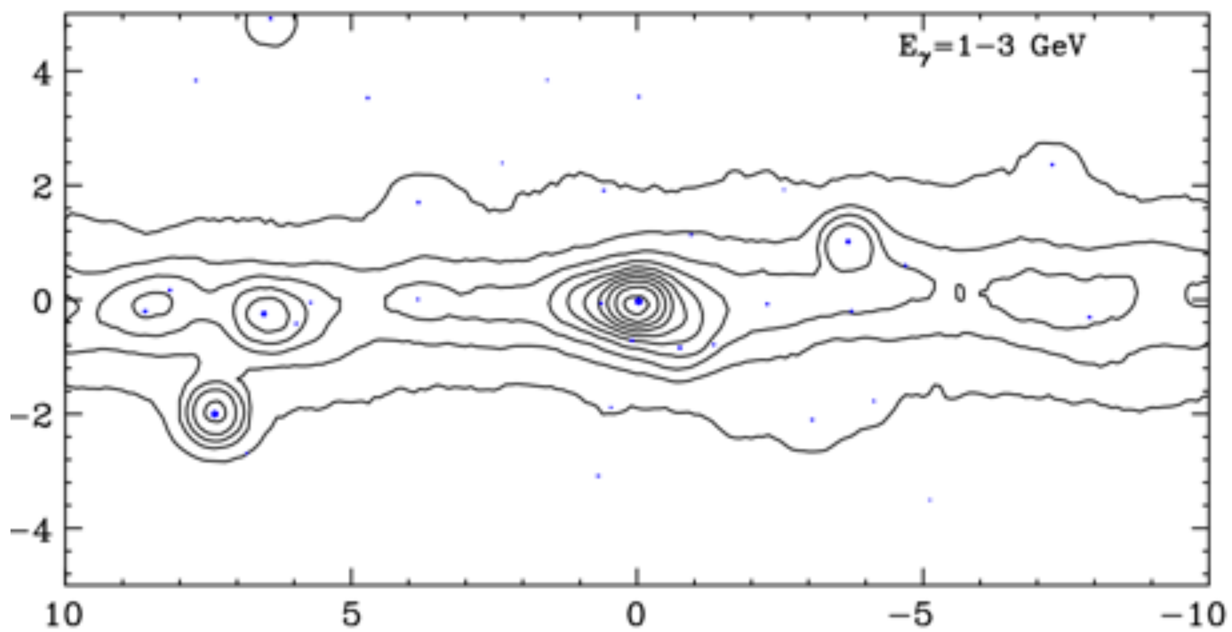
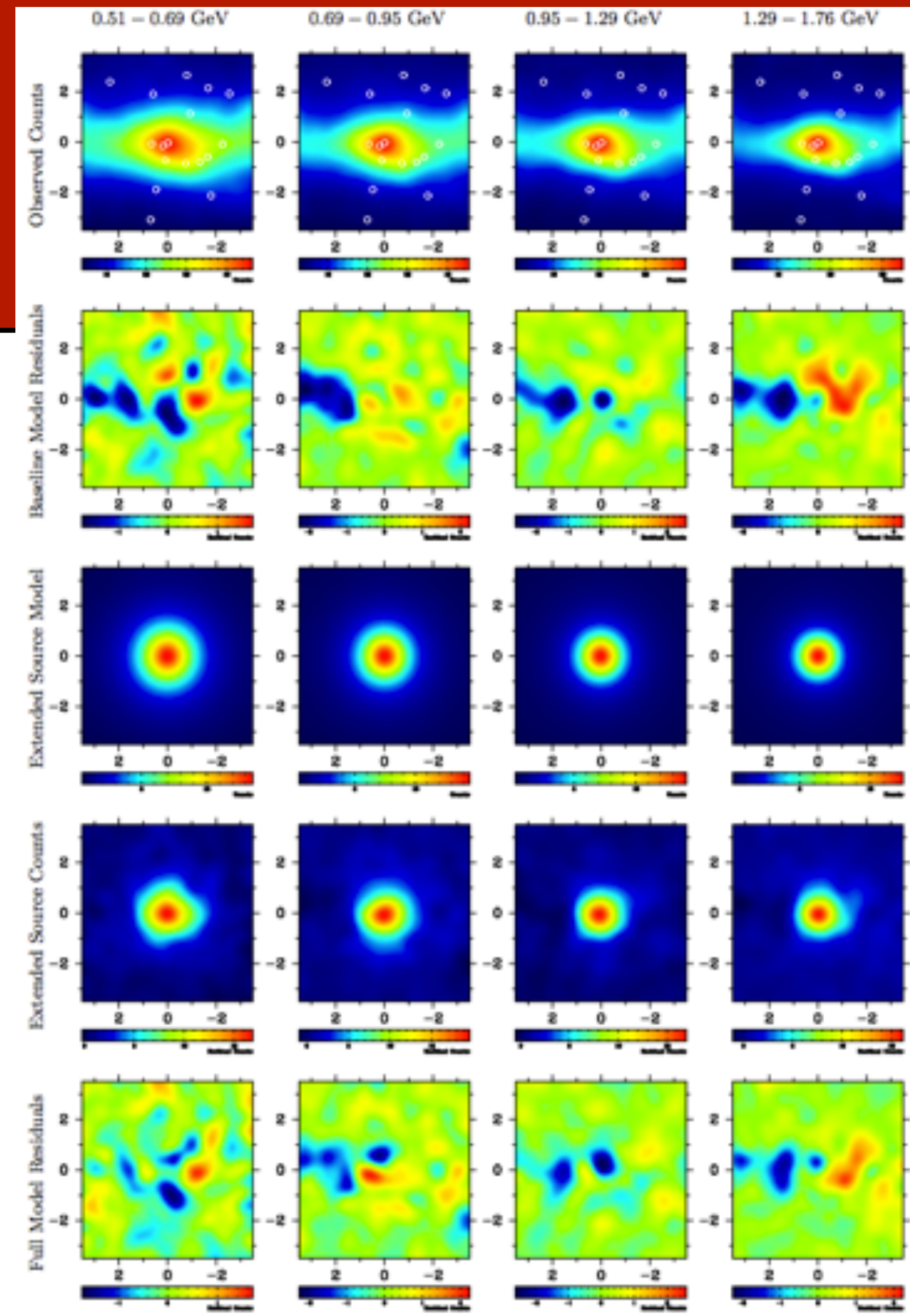
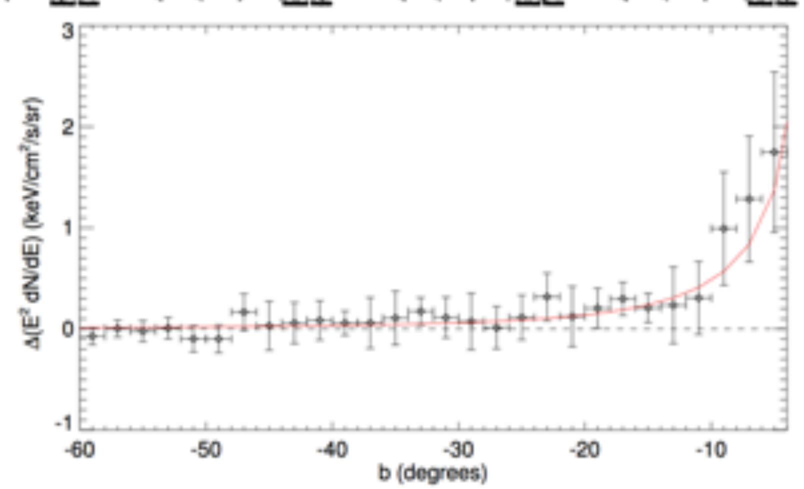
The Indirect Detection of Dark Matter at the Galactic Center







Tim Linden

UC - Santa Cruz and The University of Chicago

along with:

Dan Hooper, Elizabeth Lovegrove and Stefano Profumo

Probes of Dark Matter on Galaxy Scales

American Astronomical Society Conference -- Monterey, CA -- July 17, 2013

Goal of the Talk

- Why is the Galactic Center an important place to search for particle dark matter?

- Why are Gamma-Ray Observations setting the strongest on dark matter annihilation at the galactic center?

- A potential excess from Fermi-LAT observations !?

- Where do we go from here?

Indirect Detection of Dark Matter Starts at the GC

Ackermann et al. 2012 **Dwarfs**

Name	l deg.	b deg.	d kpc	$\overline{\log_{10}(J)}$ $\log_{10}[\mathrm{GeV}^2\mathrm{cm}^{-5}]$	σ	ref.
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]

Ackermann et al. 2010 **Clusters**

Cluster	RA	Dec.	z	J (10^{17} GeV^2 cm^{-5})
AWM 7	43.6229	41.5781	0.0172	$1.4^{+0.1}_{-0.1}$
Fornax	54.6686	-35.3103	0.0046	$6.8^{+1.0}_{-0.9}$
M49	187.4437	7.9956	0.0033	$4.4^{+0.2}_{-0.1}$
NGC 4636	190.7084	2.6880	0.0031	$4.1^{+0.3}_{-0.3}$
Centaurus (A3526)	192.1995	-41.3087	0.0114	$2.7^{+0.1}_{-0.1}$
Coma	194.9468	27.9388	0.0231	$1.7^{+0.1}_{-0.1}$

- Corresponds to the relative annihilation rate of the region compared to other astrophysical sources

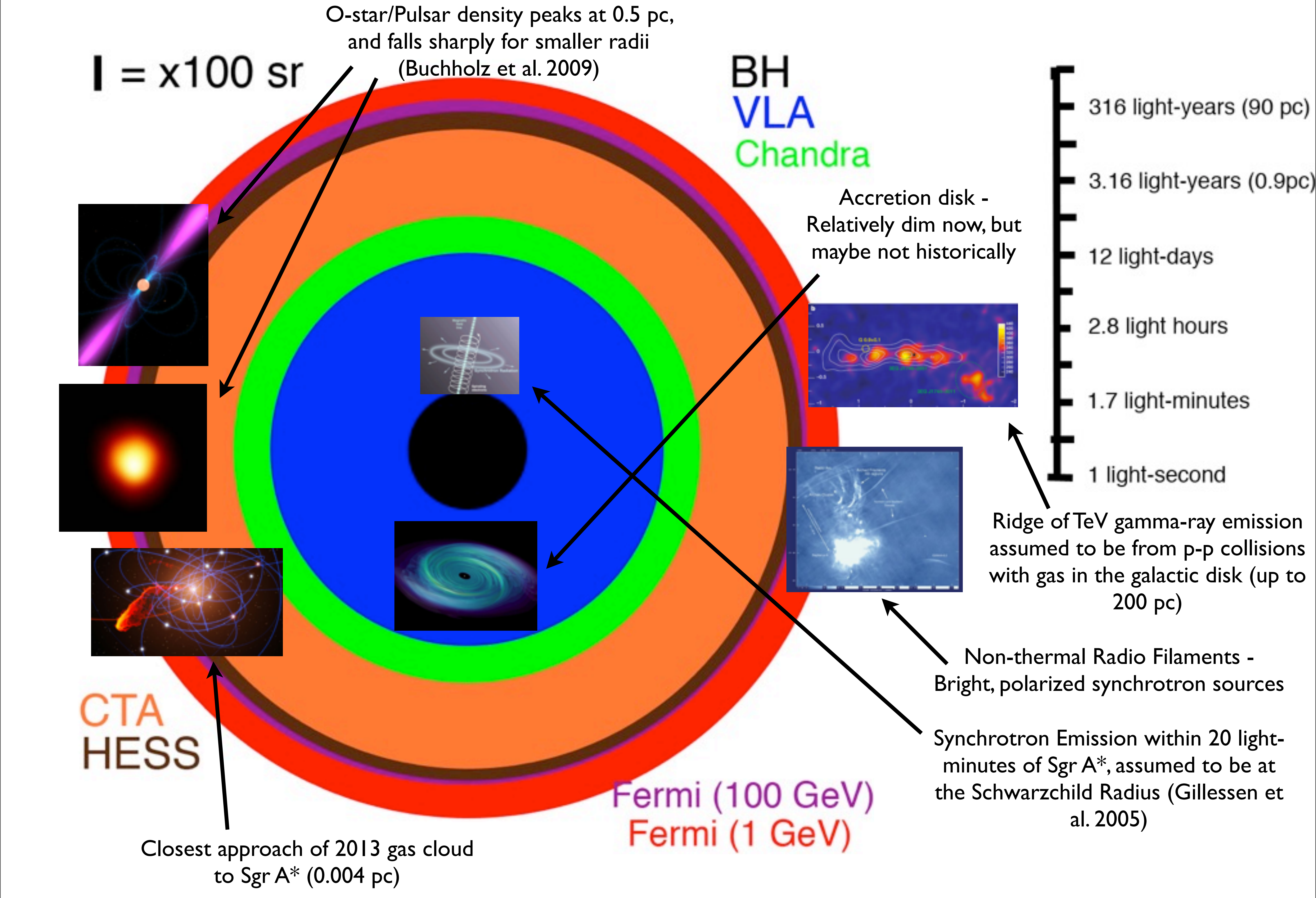
$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int d\Omega \int_{\mathrm{l.o.s.}} \rho^2(l)\,dl(\psi)$$

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

$\log_{10}(J) = 21.0$

for a region within 1° of the Galactic center and an NFW profile

What this looks like in the Galactic Center



The Flux Sensitivity (to point sources) are Lower

- **VLA - 6 x 10^{-21} erg s^{-1} cm^{-2} (10 hour exposure, 1.4 GHz, 75 MHz Band)**

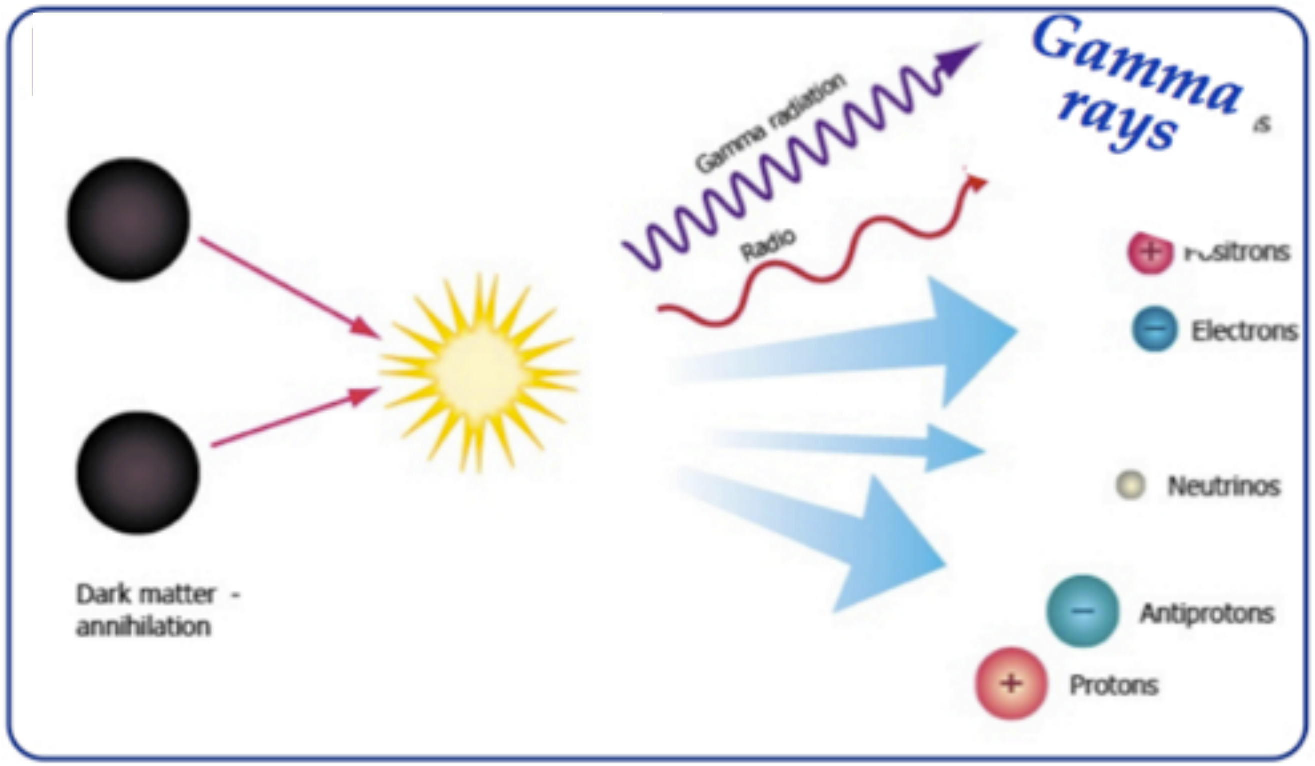
- **Chandra - 1 x 10^{-17} erg s^{-1} cm^{-2} (1 Ms exposure, 0.5-10 keV)**

- **Fermi - 8 x 10^{-13} erg s^{-1} cm^{-2} (2 year survey mode, 1 GeV)**
- **H.E.S.S. / VERITAS - 2 x 10^{-13} erg s^{-1} cm^{-2} (50 hours, 1 TeV)**
- **HAWC - 4.8 x 10^{-13} erg s^{-1} cm^{-2} (1 year, 10 TeV)**

So Maybe gamma-ray telescopes aren't the optimal instruments?

So, Why are gamma-ray telescopes setting the best limits for indirect detection?

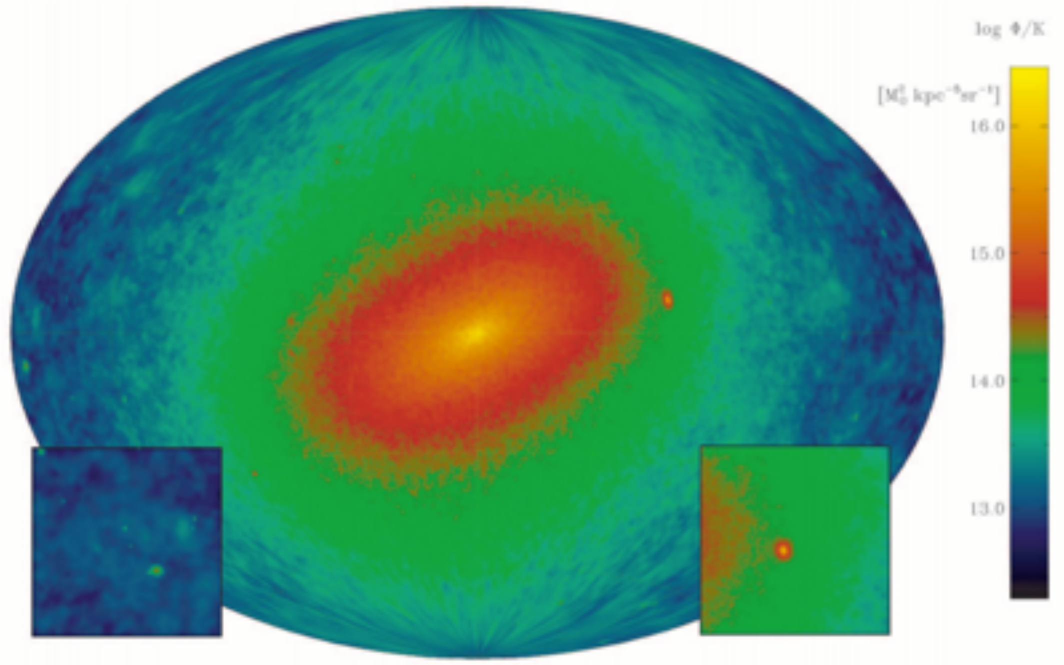
Dark Matter Indirect Detection



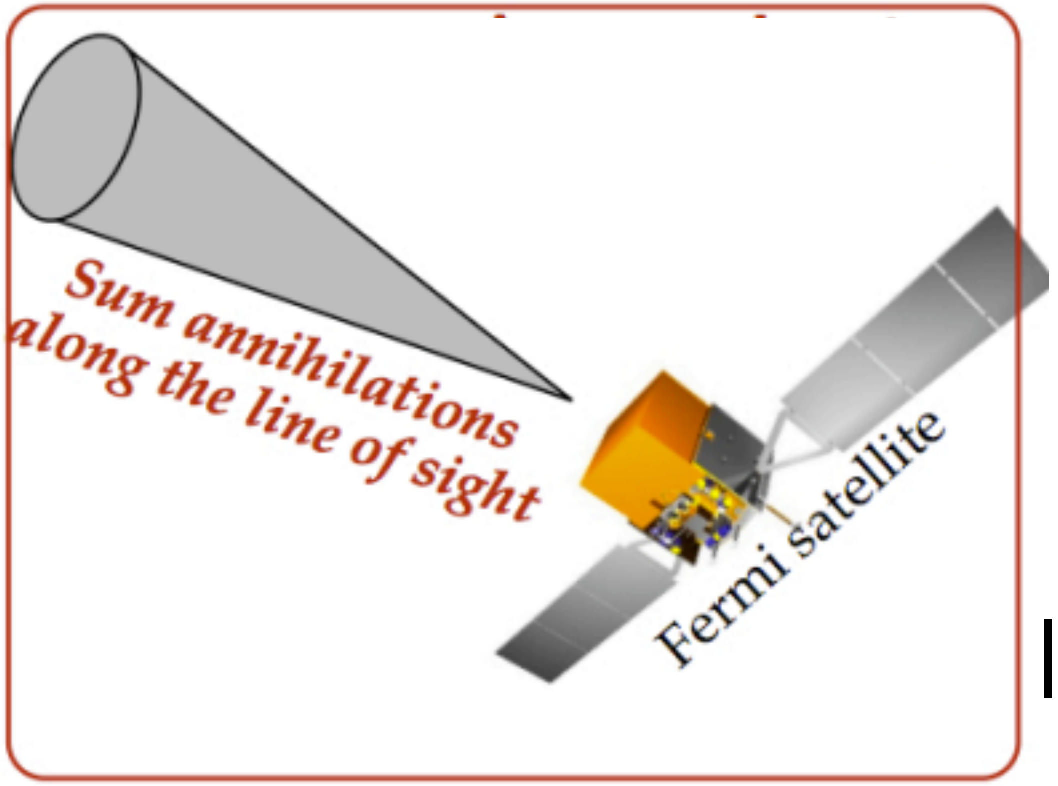
Particle Physics

Slides Courtesy of G. Zaharijas

Astrophysics



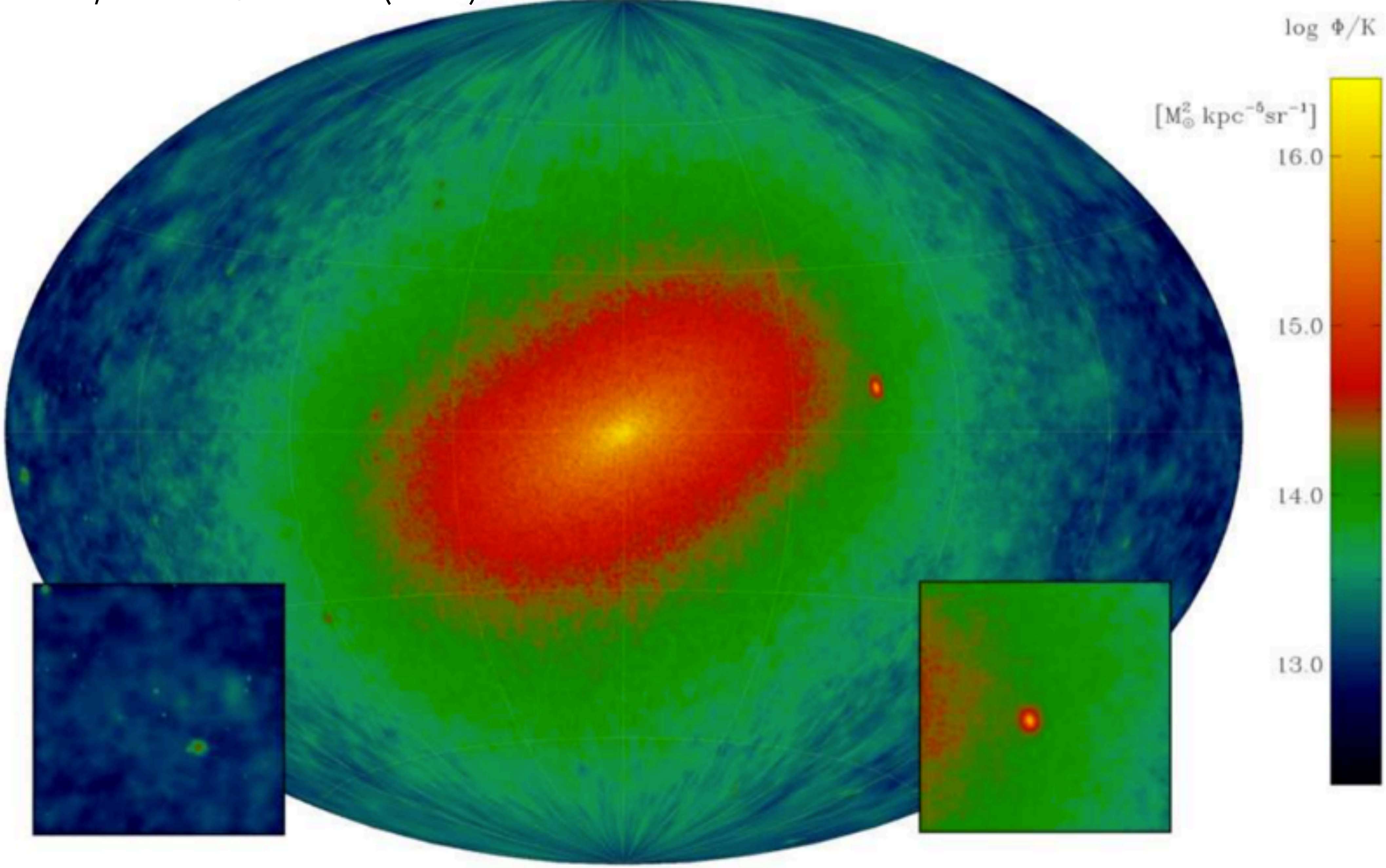
Diemand et al. 2008



Instrumental Response

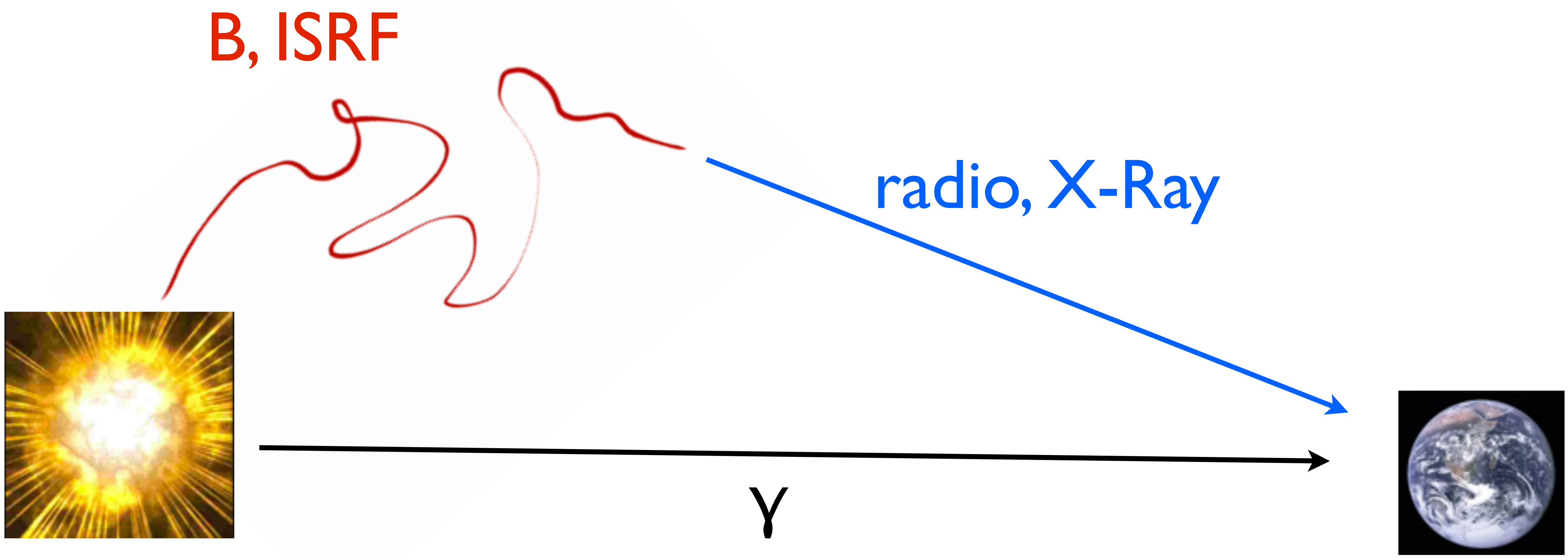
Gamma-Ray Flux Follows the Density Profile

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

Low Energy Processes and Diffusion



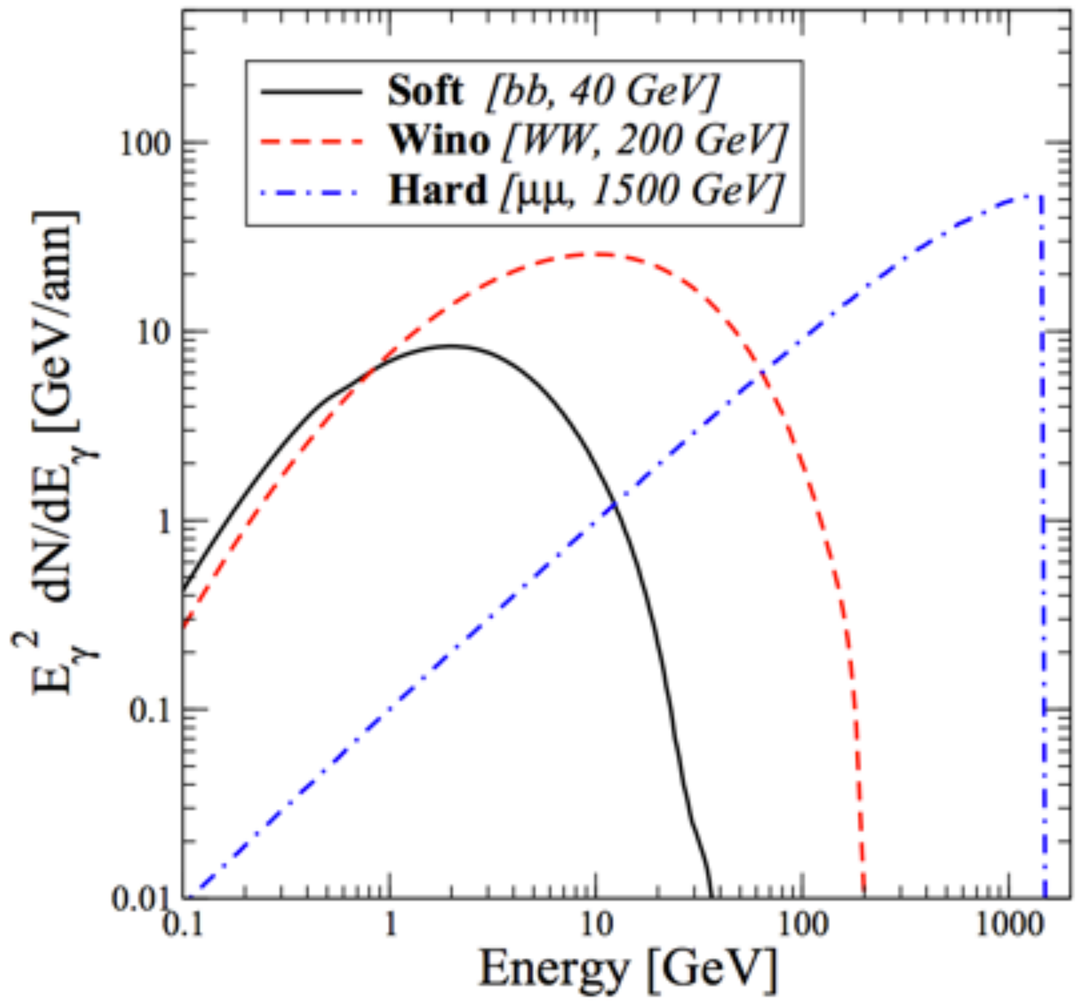
- At low energy, propagation can carry the particles which create the observed signal far from the annihilation event, before they produce anything that is seen at the Earth

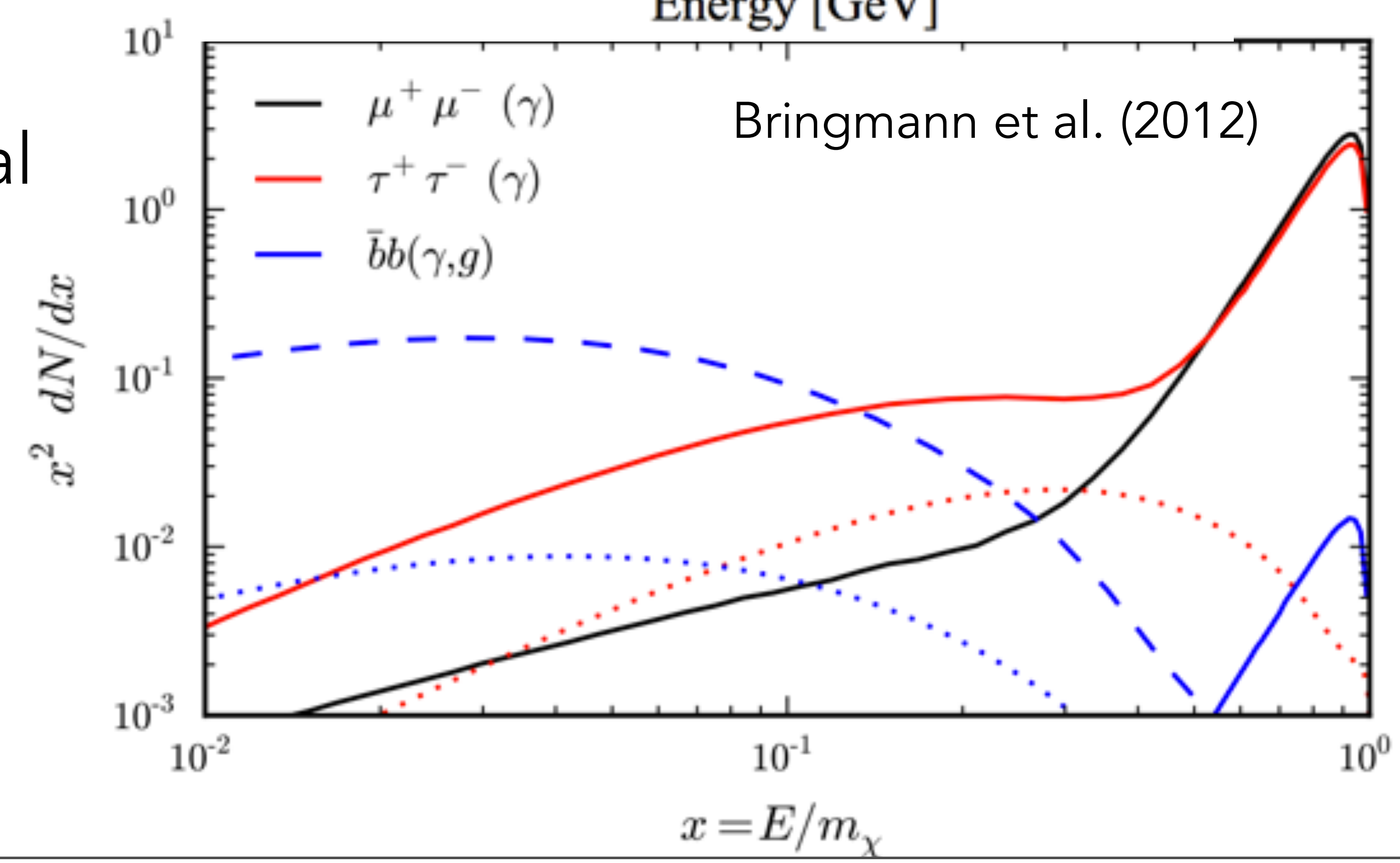
Gamma-Ray Spectrum May Have Known Features

- Once a dark matter annihilation proceeds to standard model particles, it's spectrum is calculable

- The observed spectrum tells us something about the dark matter mass and annihilation products

- We may even find unique special features -- like bumps and lines!





Back of the Envelope Calculation

- Total Gamma-Ray Flux from 1-3 GeV within 1° of Galactic Center is

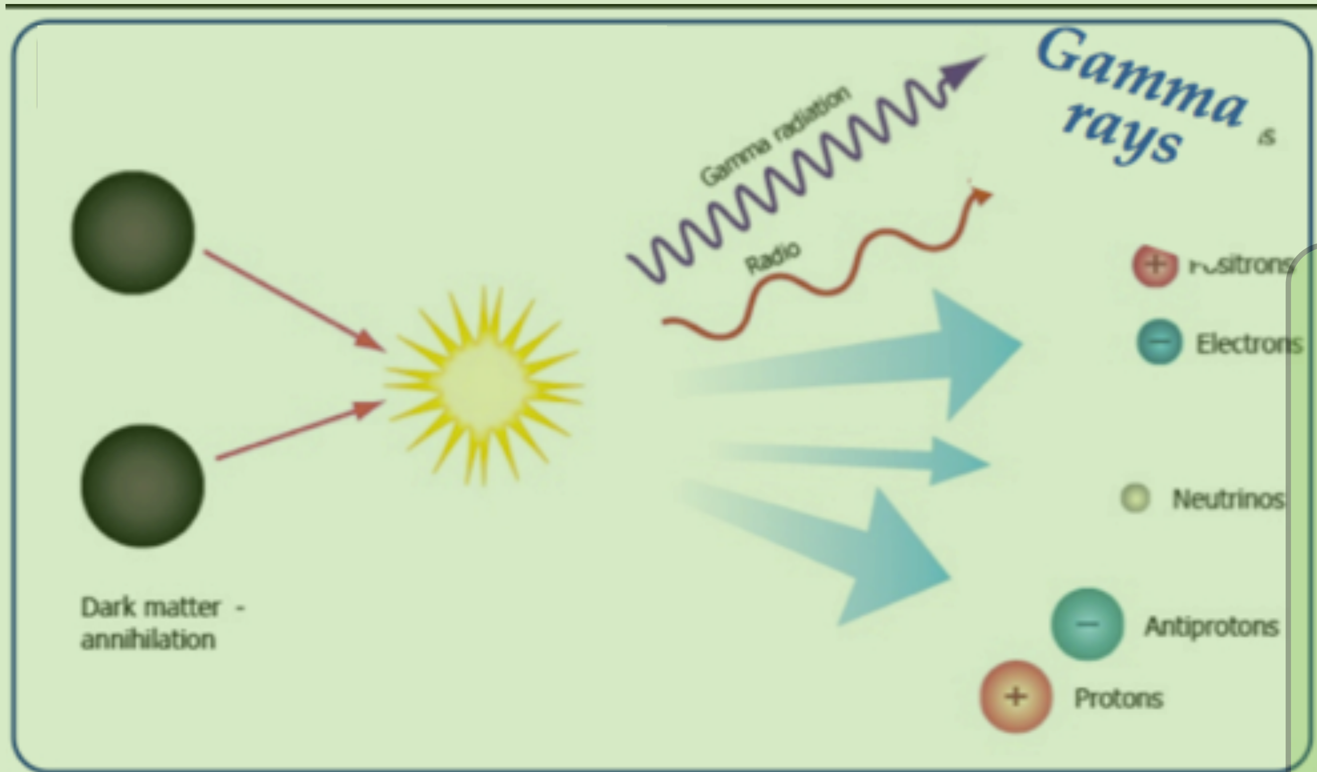
$$\sim 1 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$$

- This is equivalent to the number of photons expected in this energy bin from a "vanilla" 100 GeV dark matter candidate annihilating to bb with a cross-section **$\langle \sigma v \rangle = 1.6 \times 10^{-25}$ cm^3 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

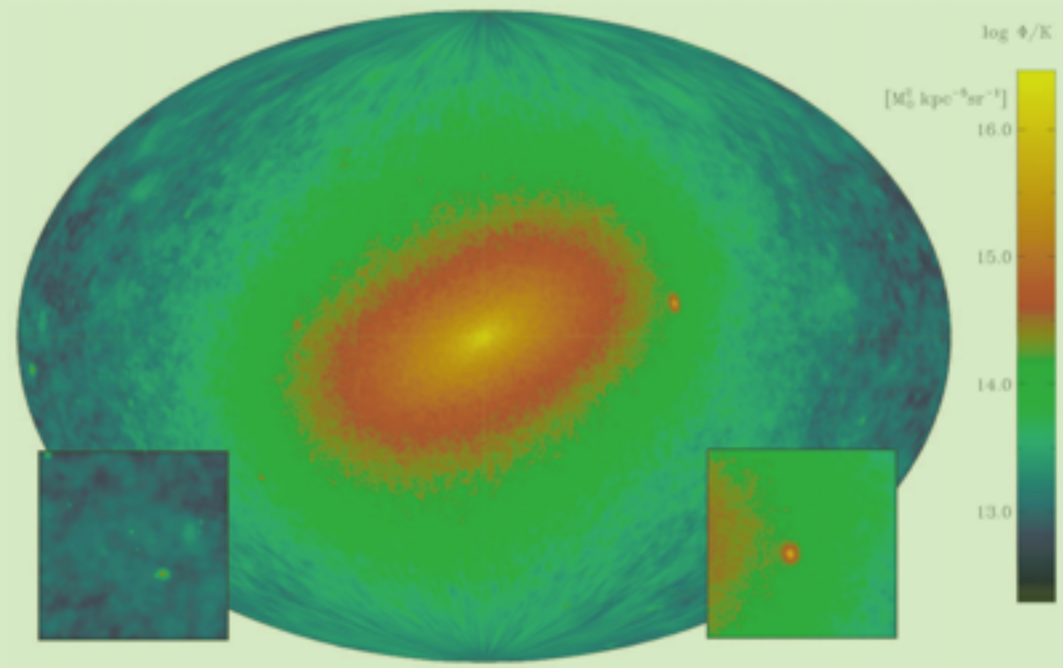
Dark Matter Indirect Detection

Particle Physics

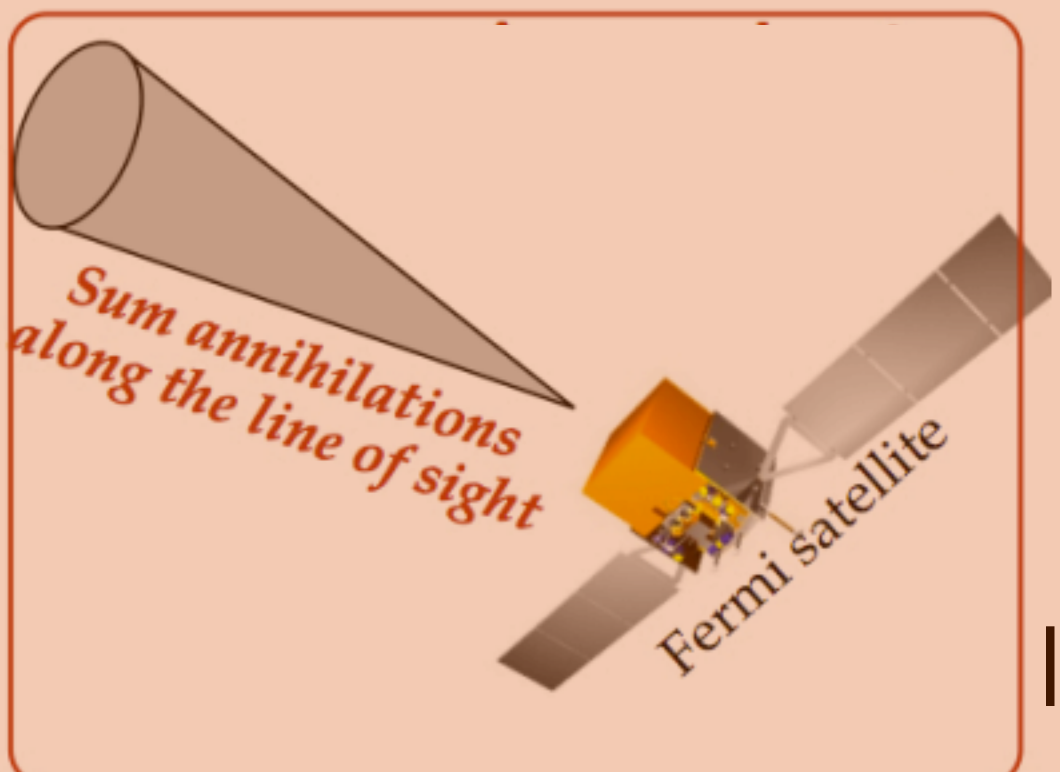


Slides Courtesy of G. Zaharijas

Astrophysics

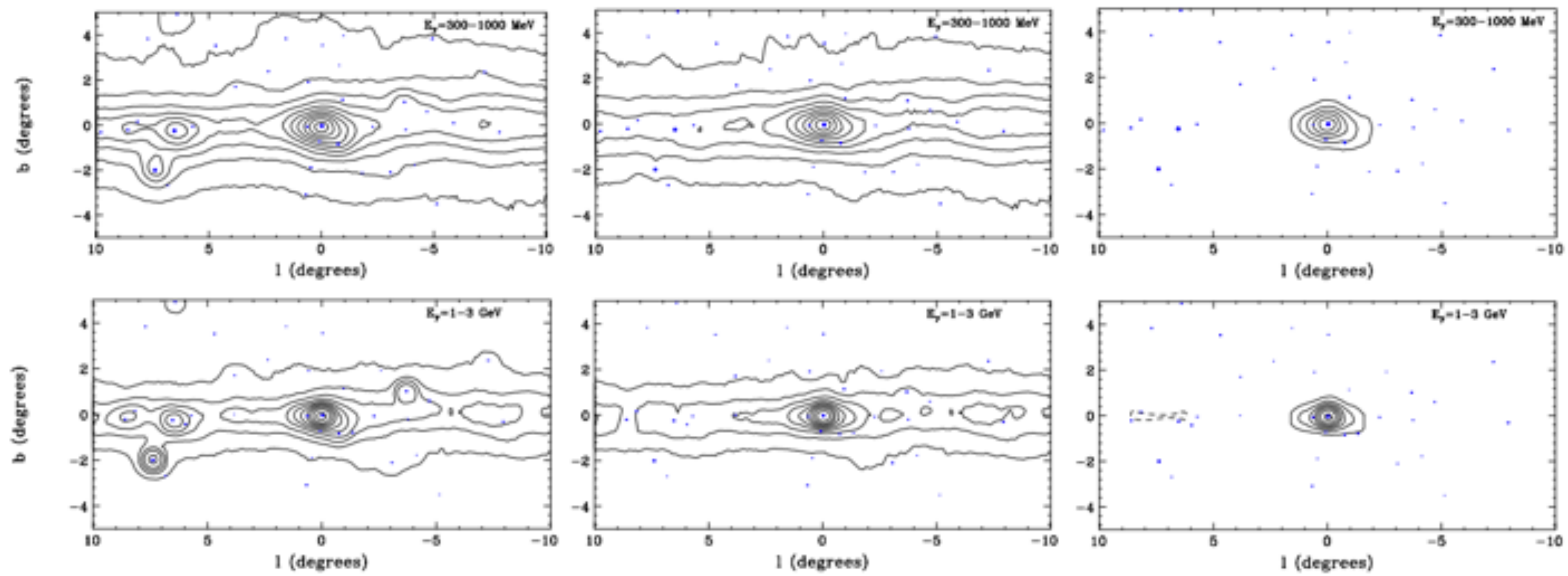


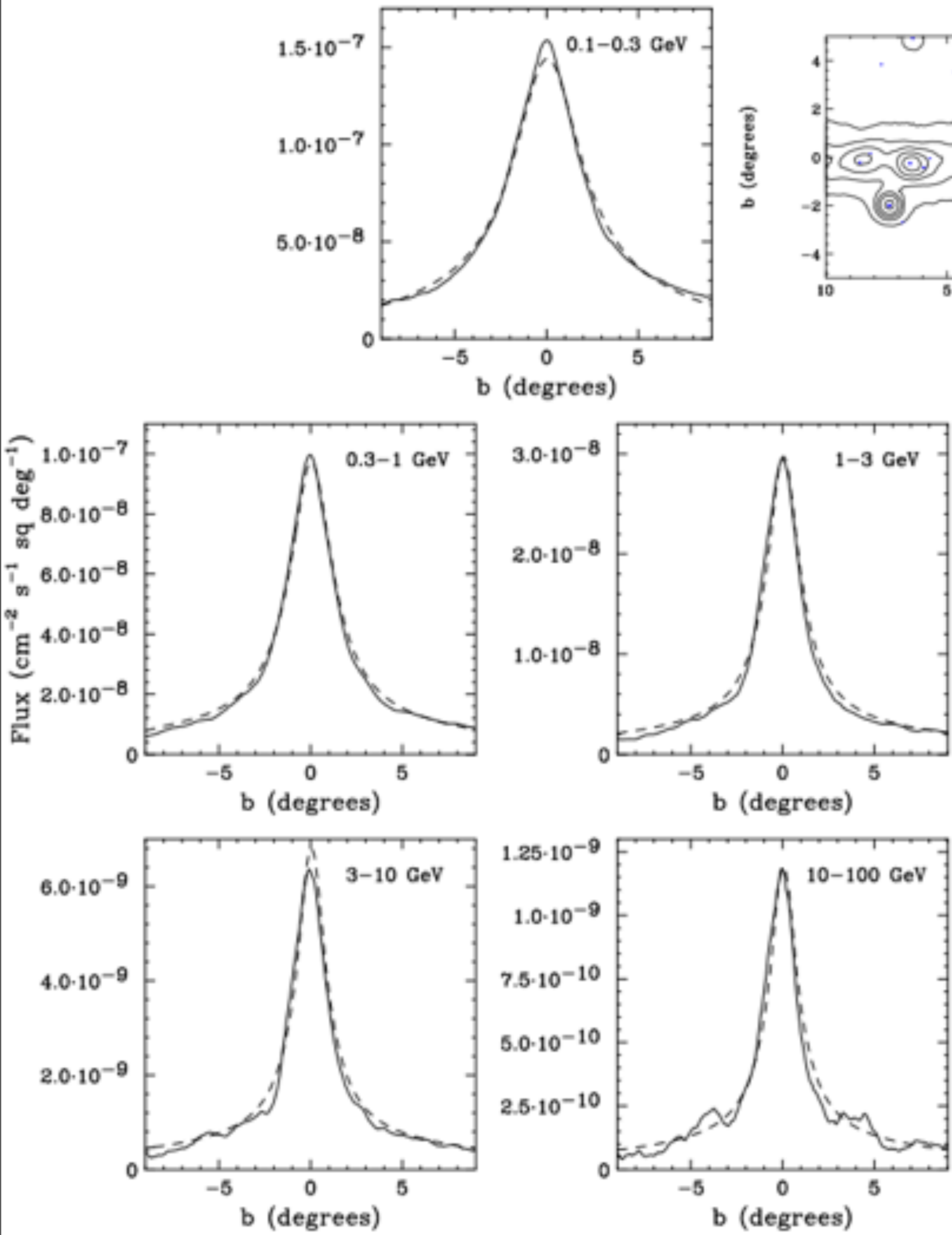
Diemand et al. 2008



Instrumental Response

Subtracting the Astrophysical Background: Fermi

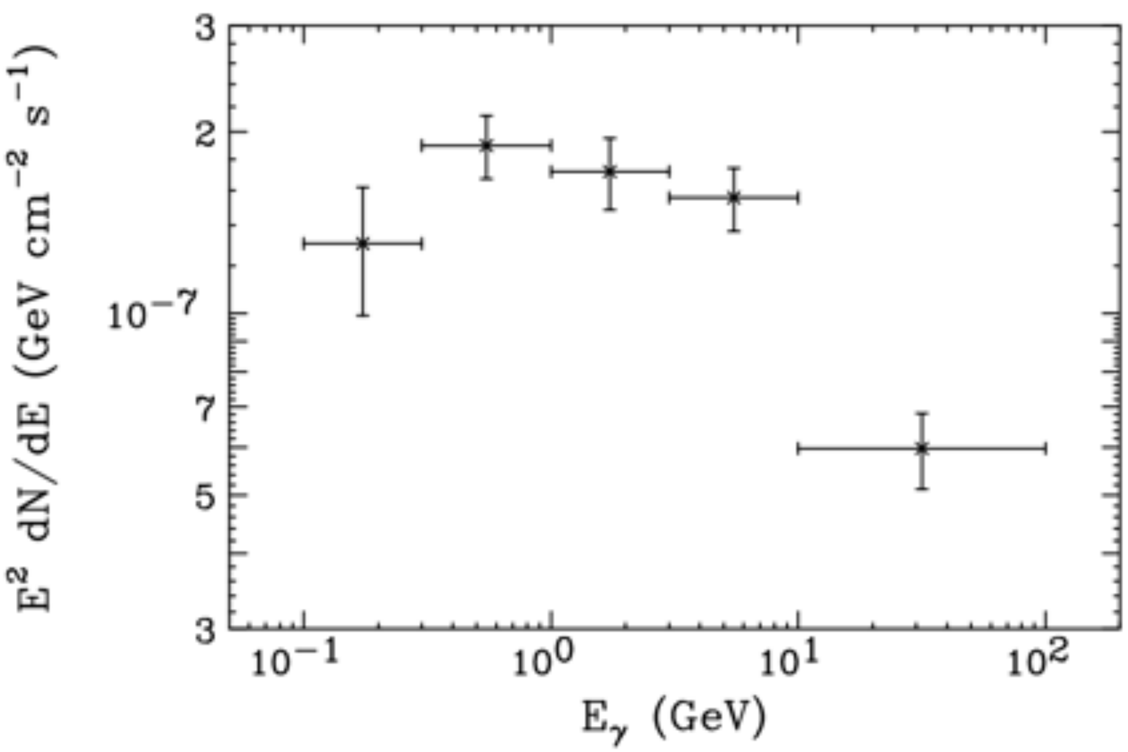




- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum
- This large residual at the center of the galaxy is a factor of 10 brighter than anything else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

Hooper & Linden (2011)

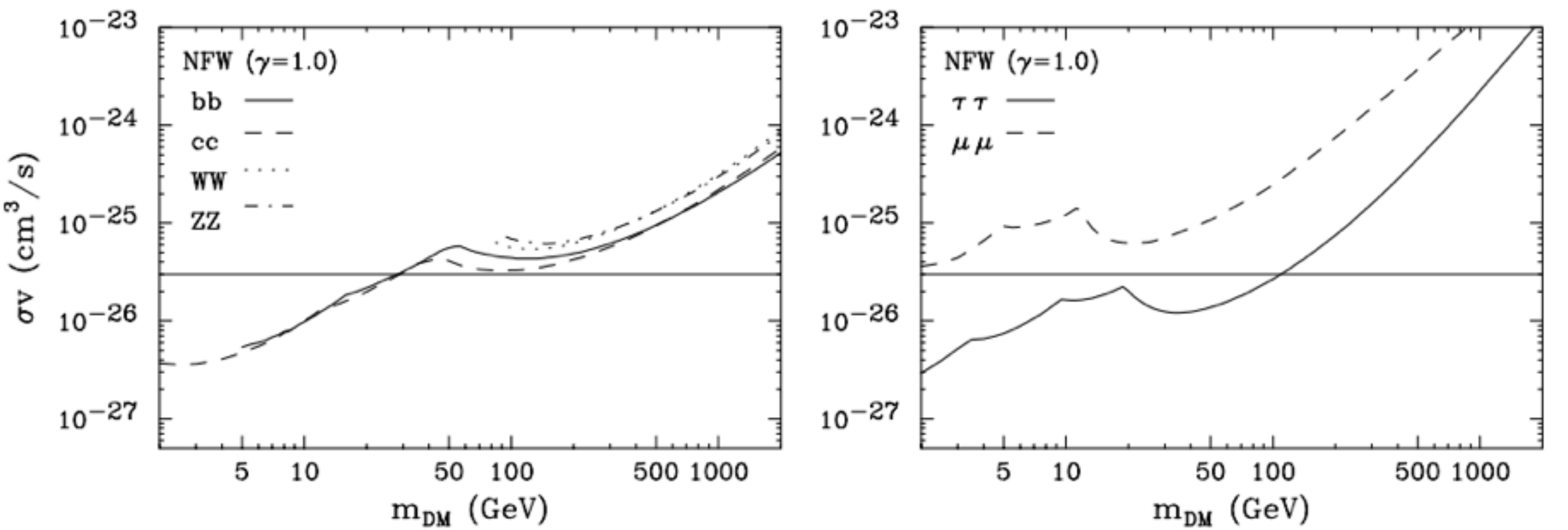
Dark Matter Limits in the Simplest Way Possible



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

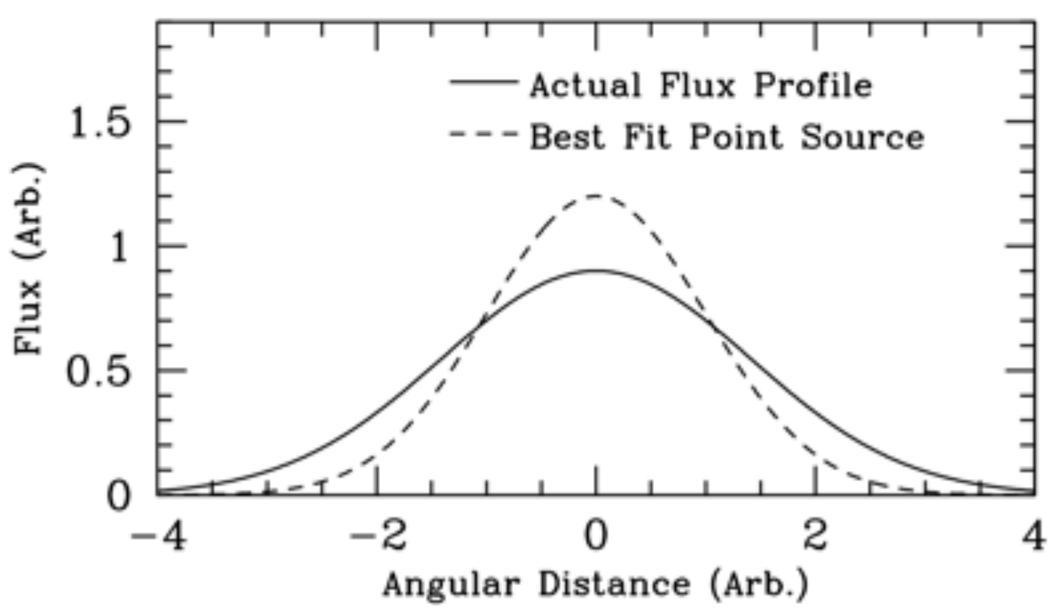
- This directly corresponds to a limit on the dark matter interaction cross-section which depends only on assumed dark matter density profile

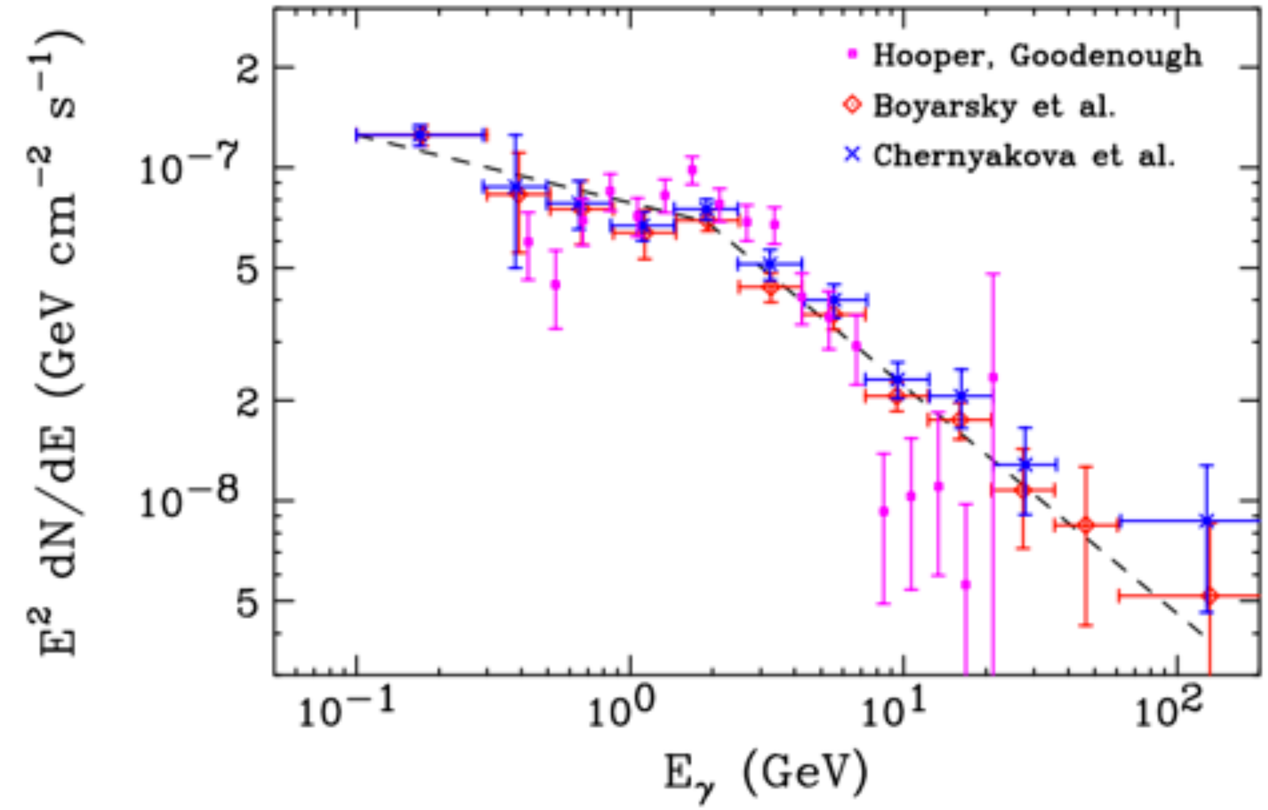


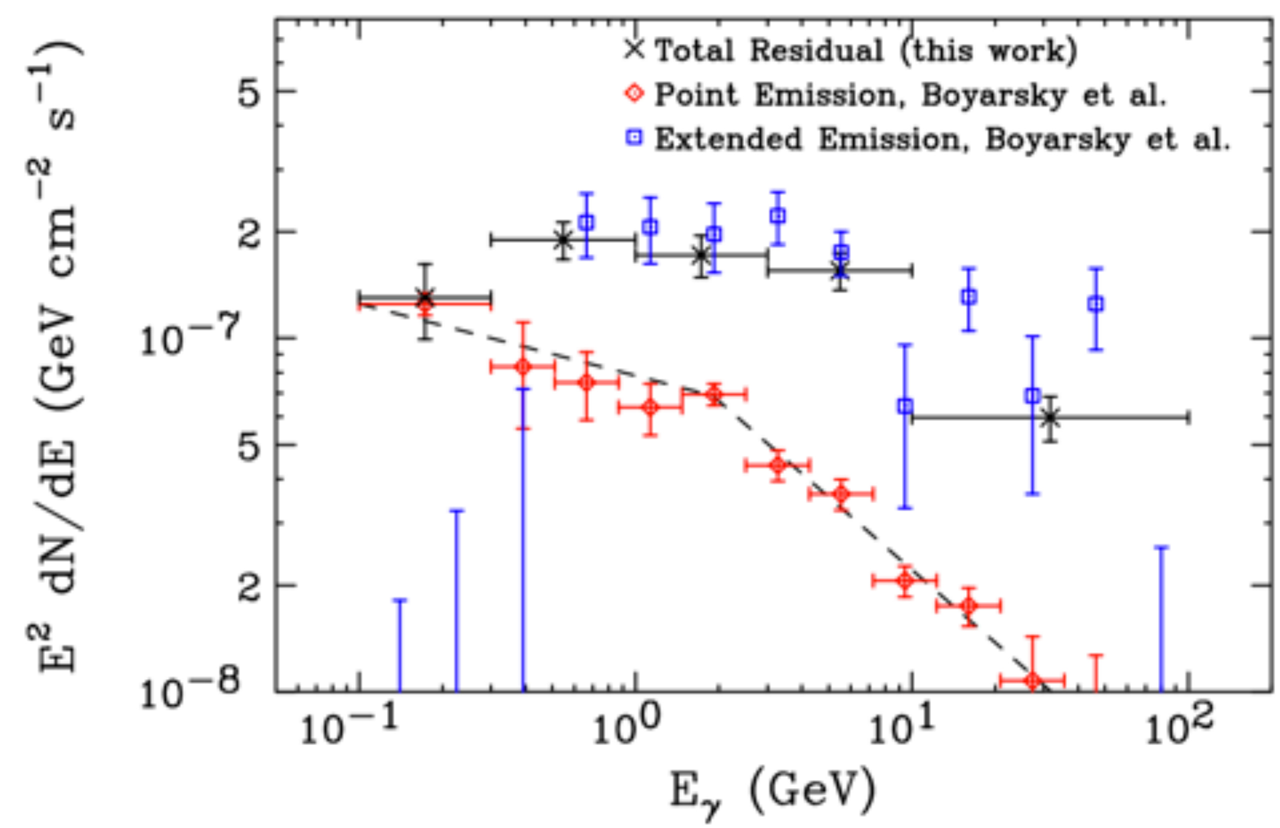
Is It A Point Source?

- 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 resolution of the Fermi-LAT







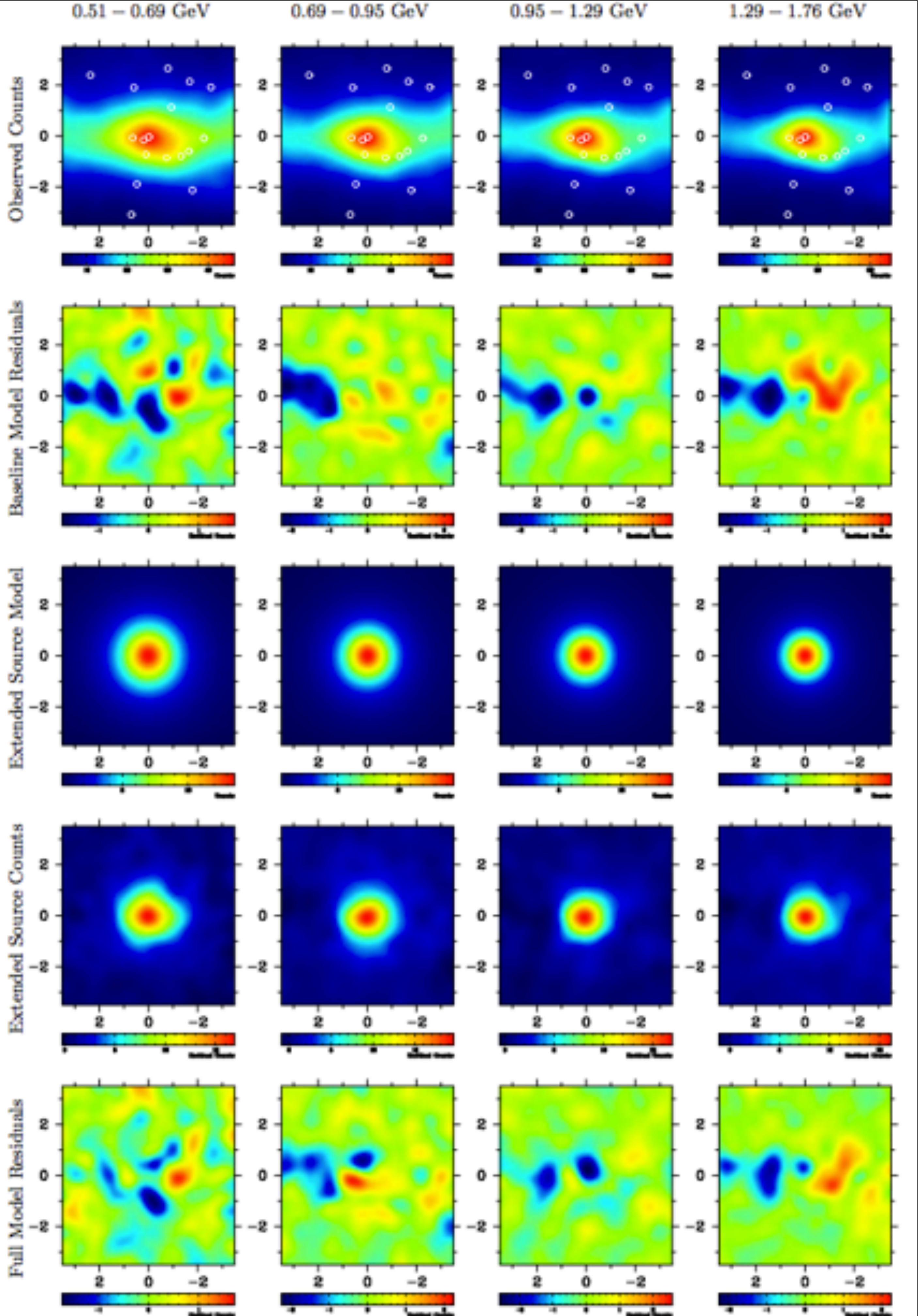
Hooper & Linden (2011)

Is It A Point Source?

- Abazajian & Kaplinghat found a 20σ preference for models including an extended, spherically symmetric excess

- Including only a point source at the galactic center significantly oversubtracts the GC

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

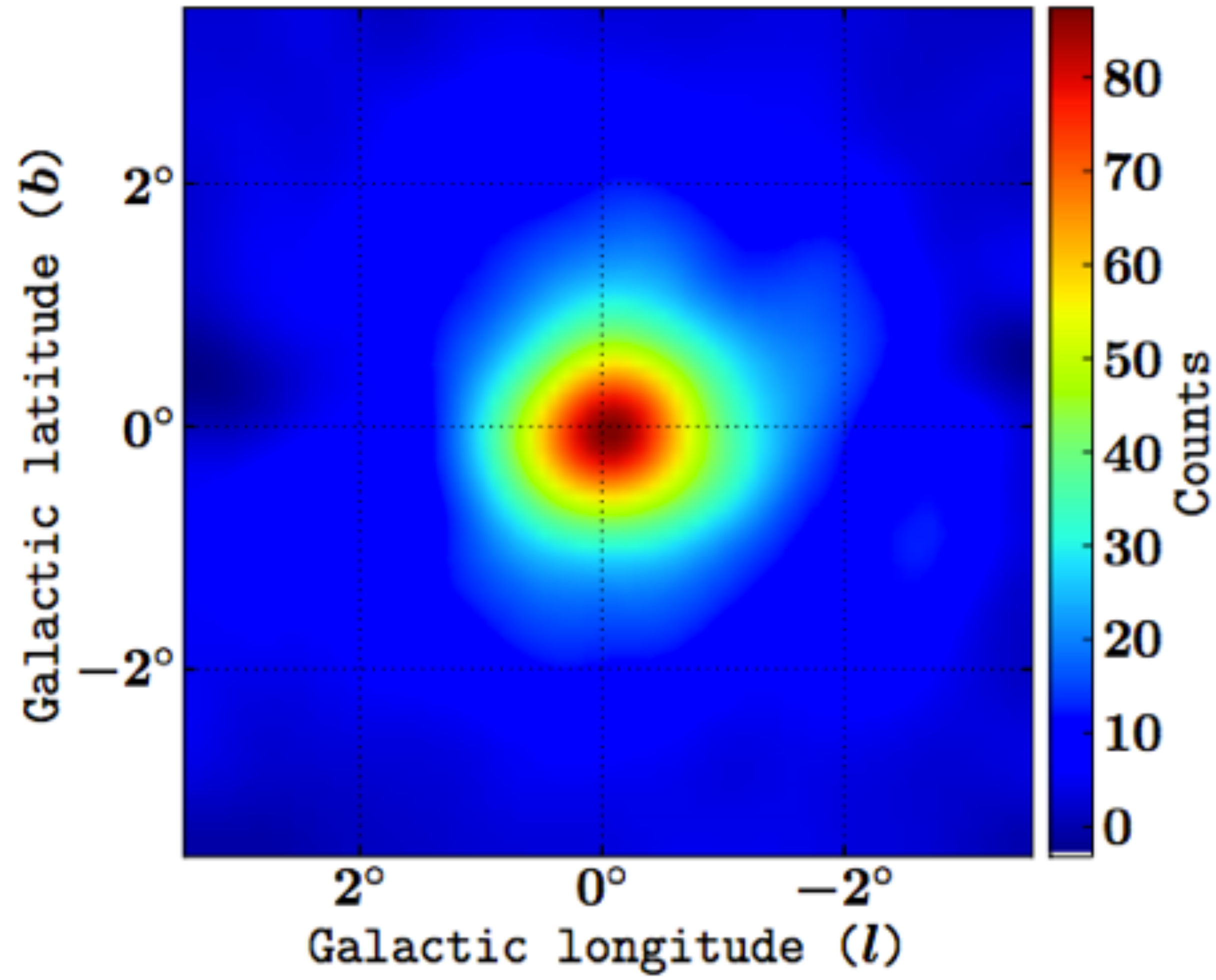


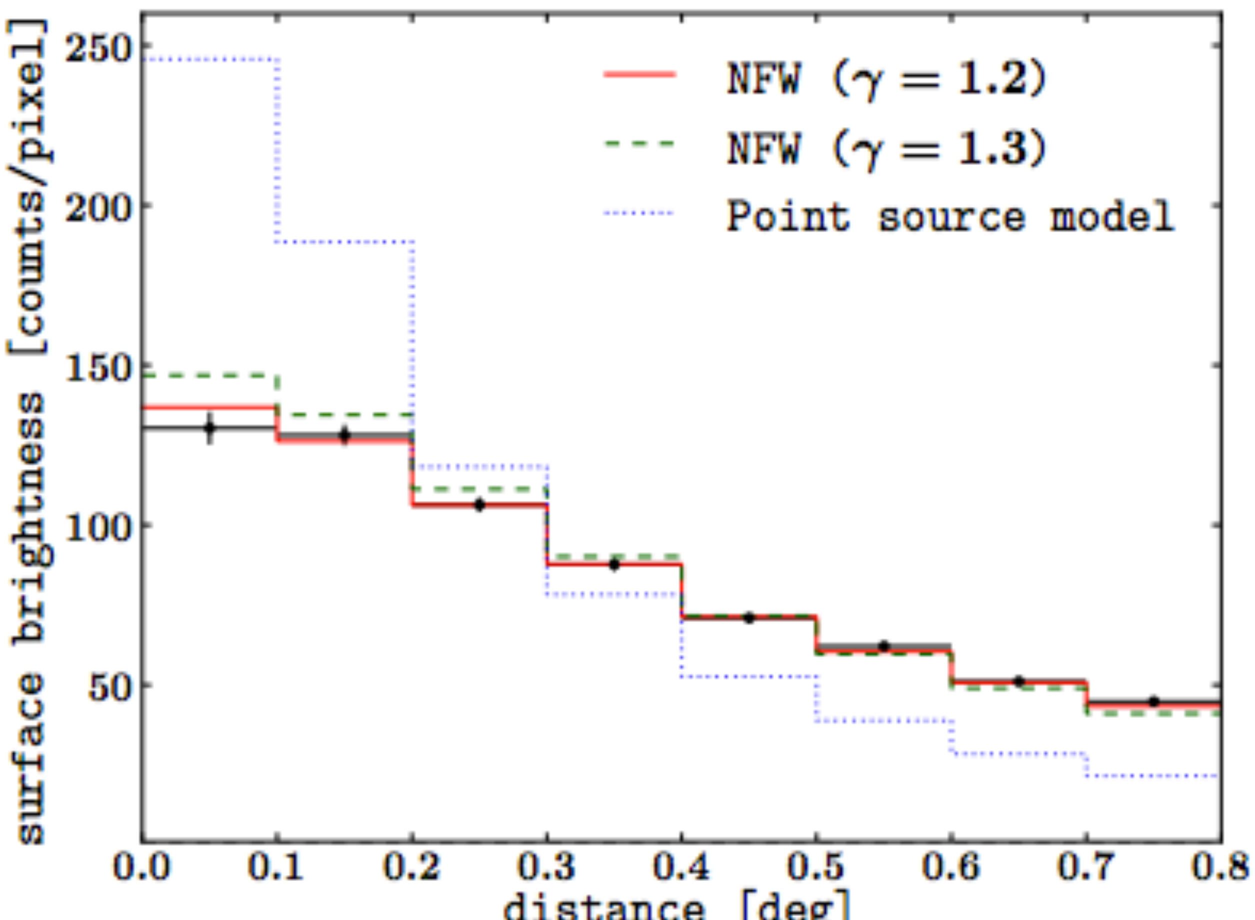
Abazajian & Kaplinghat (2012)

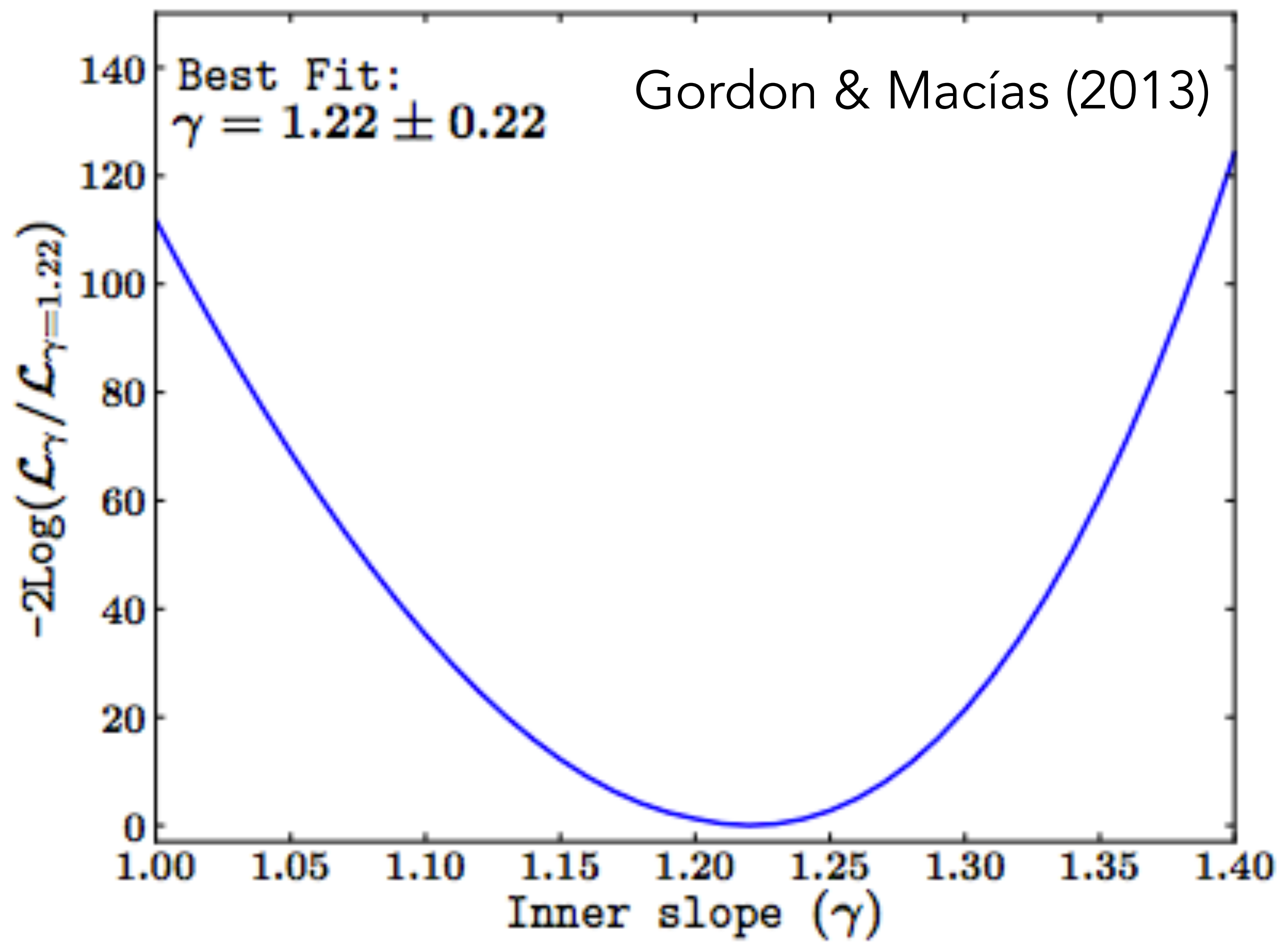
Is It A Point Source?

- Gordon & Macías attempted a similar study with the same results

- They find that the dark matter profile must be slightly adiabatically contracted at high significance







So You Think You've Found An Excess?

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

- What can we learn about physics from these observations?

Possible Interpretations

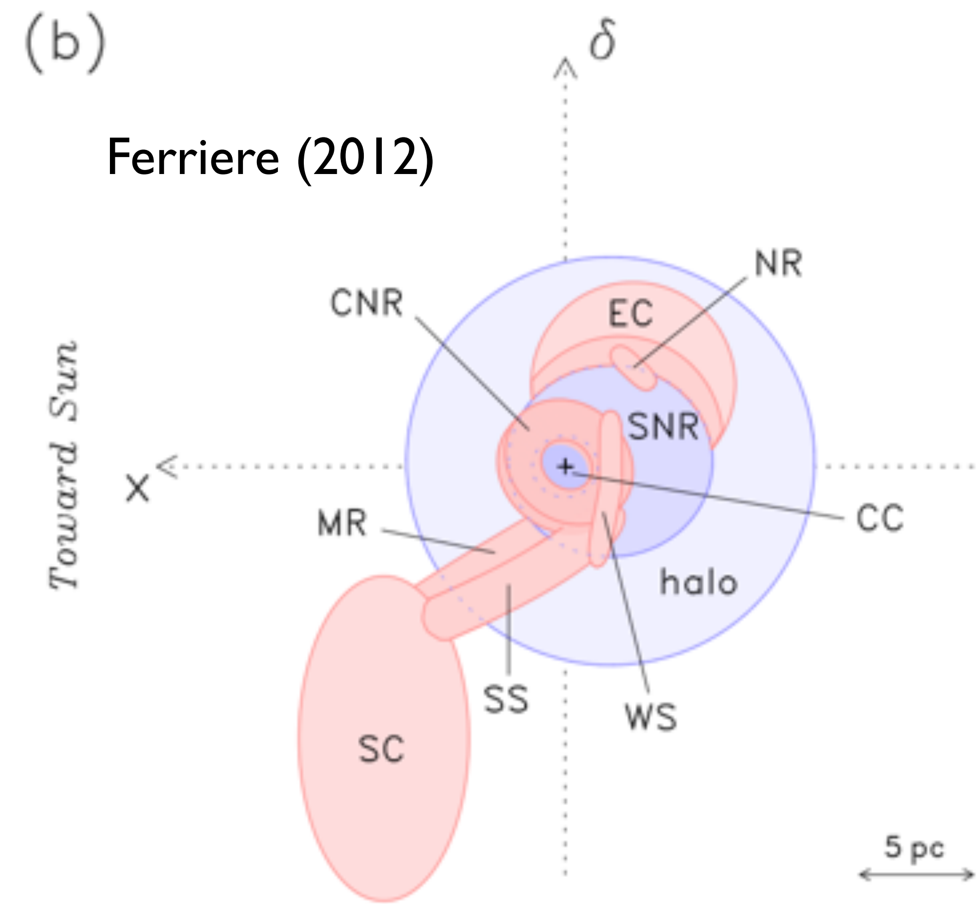
- 1.) Annihilating Dark Matter
- 2.) π^0 decay
- 3.) A new astrophysical source
  - e.g. millisecond pulsars
  - Something else?

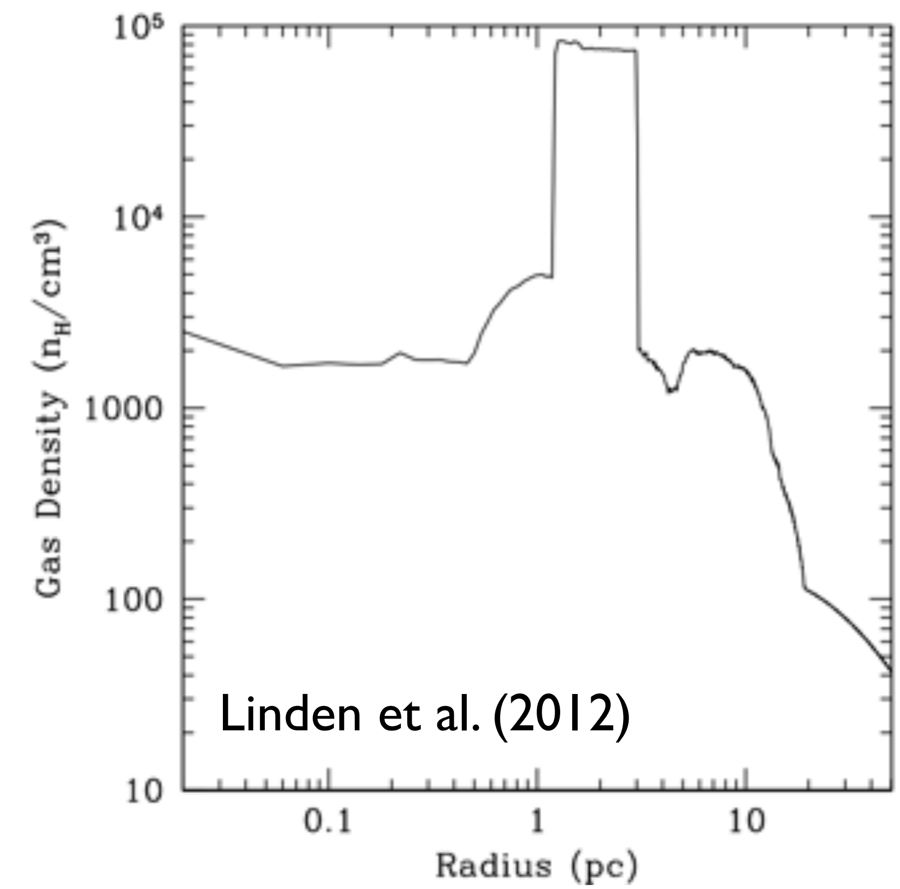
Understanding the Gas Morphology

- Detailed models of the galactic gas density exist in the literature

- We employ a spherically symmetric model for galactic gas, and use this to calculate the morphology of the gamma-ray emission as a function of energy

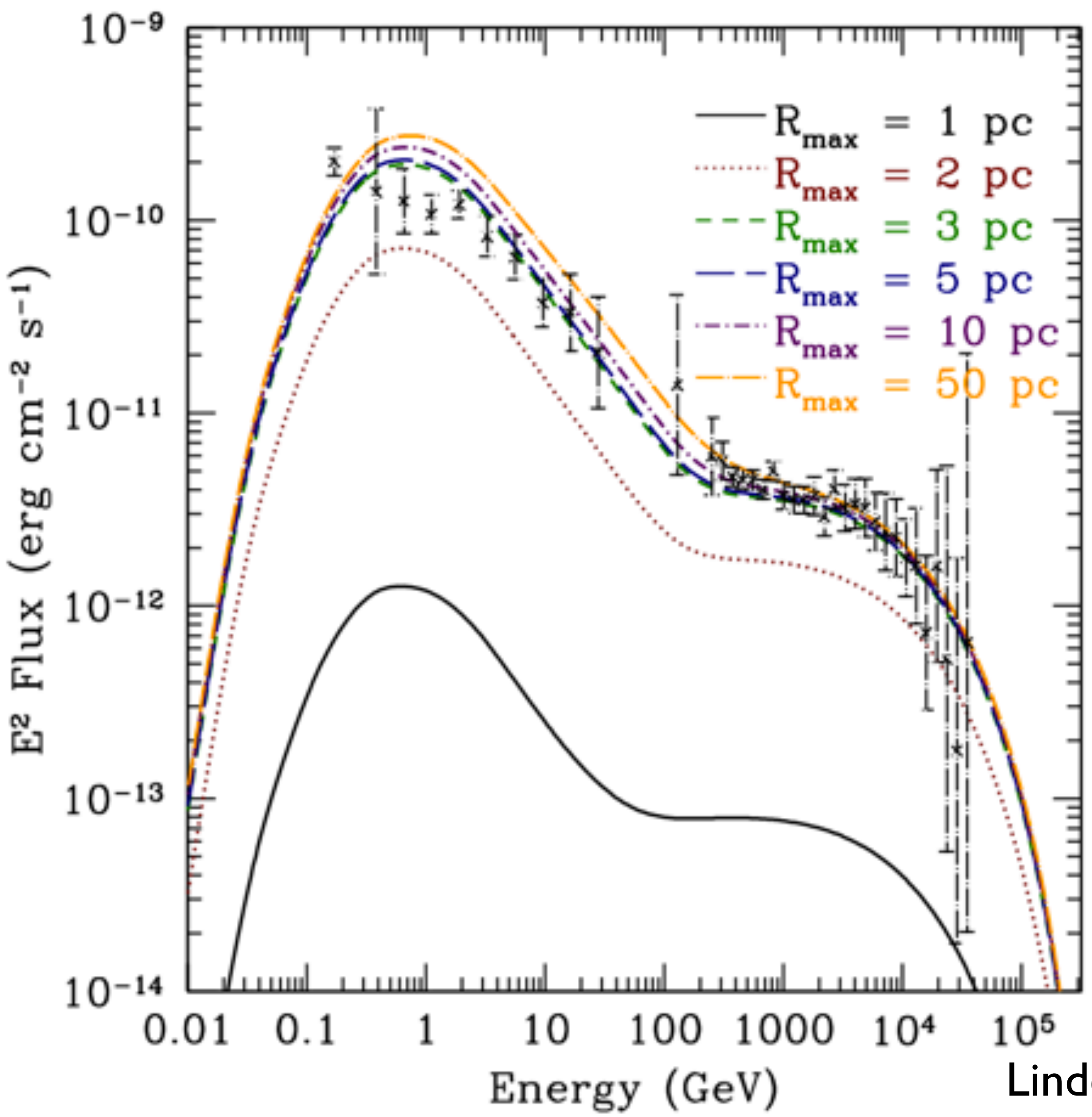
- By far the dominant feature is the Circumnuclear ring between 1-3 pc from the GC



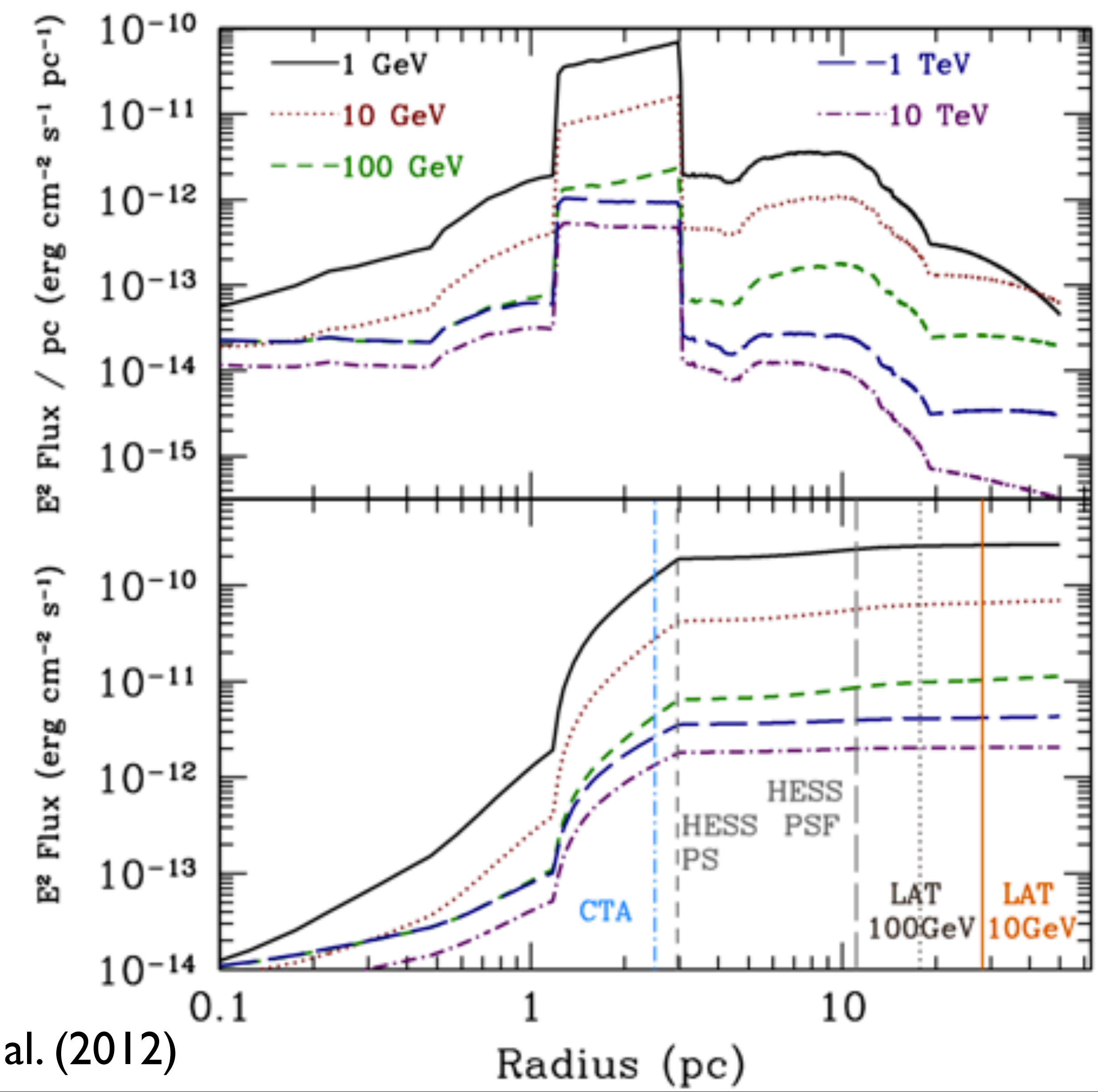


Understanding the Gas Morphology

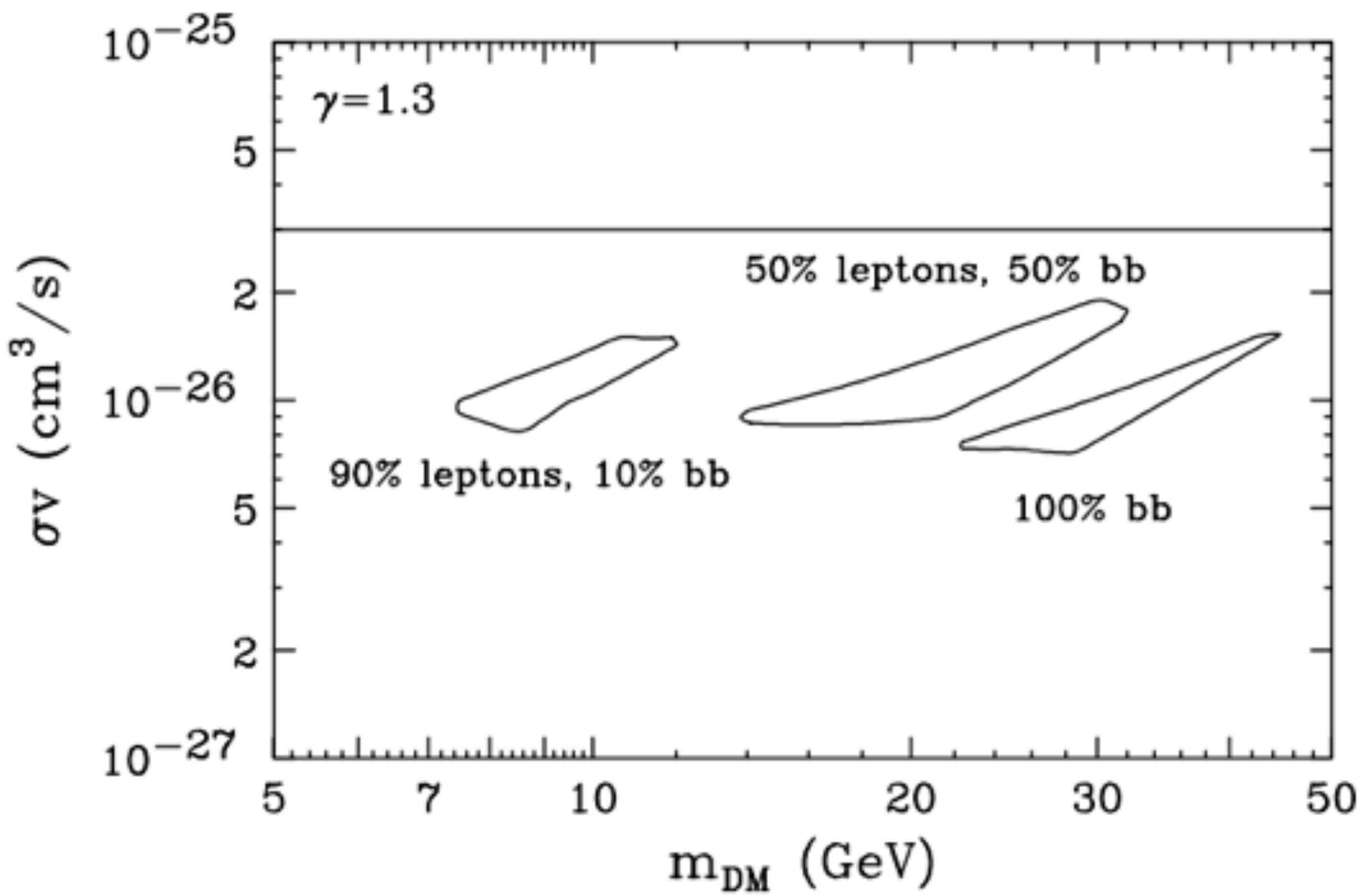
- The vast majority of emission stems from within 3 pc of the galactic center at all energies
- This lies below the PSF of all current gamma-ray instruments
- This effectively rules out hadronic interactions from Sgr A* as the source of the Fermi-LAT excess



Linden et al. (2012)



Dark Matter Fits



- Dark Matter creates an excellent statistical fit to both the morphology and the spectrum of the residual

- Of course dark matter predictions are somewhat malleable

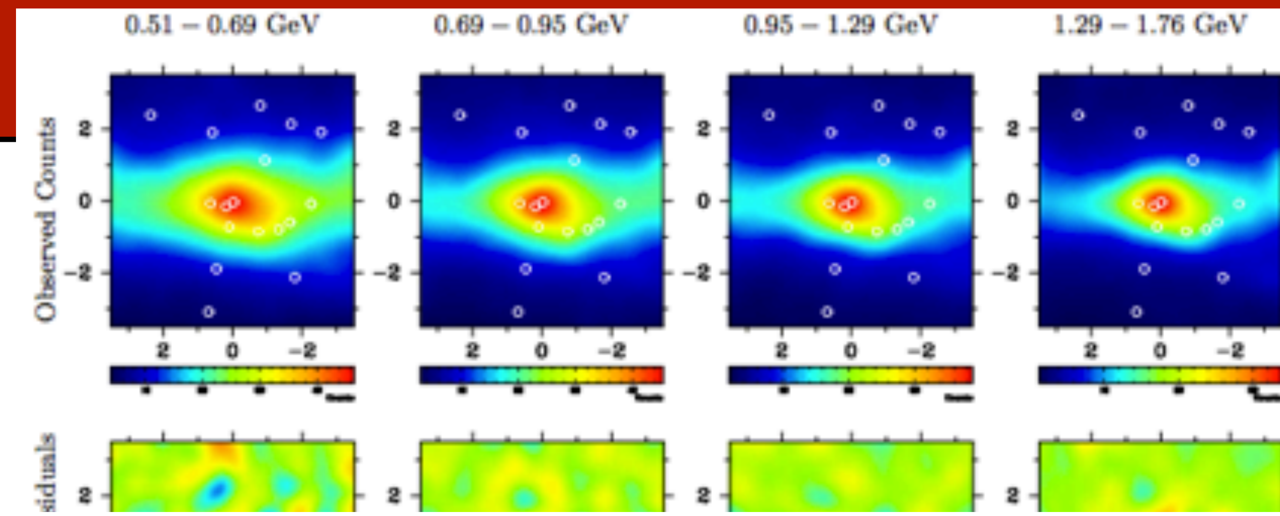
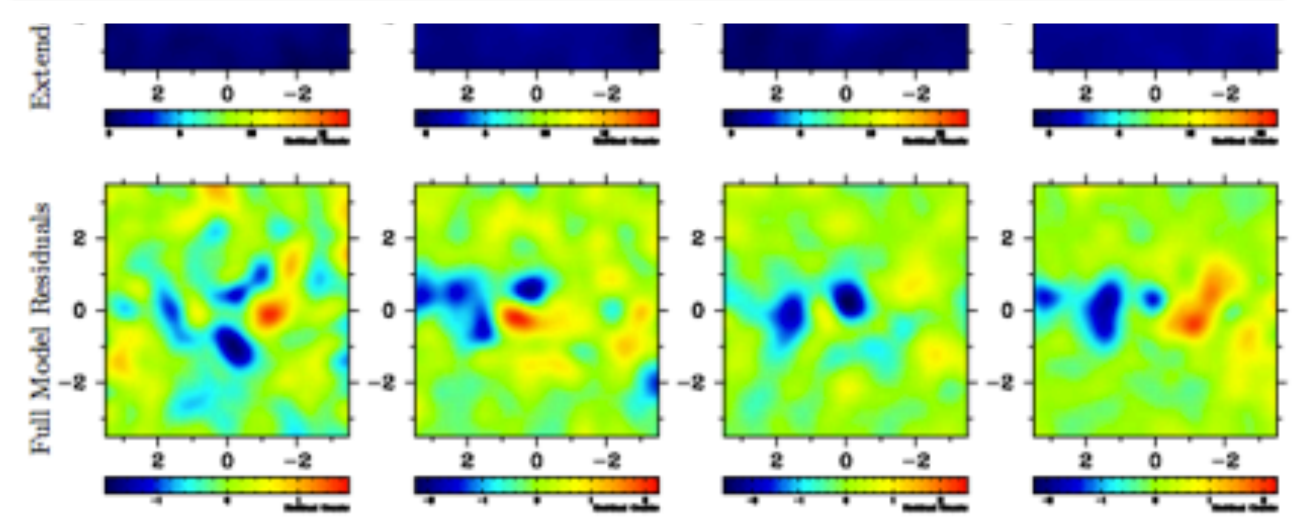


TABLE II. The best-fit TS, negative log likelihoods, and $\Delta\mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

channel, m_χ	TS	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 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)

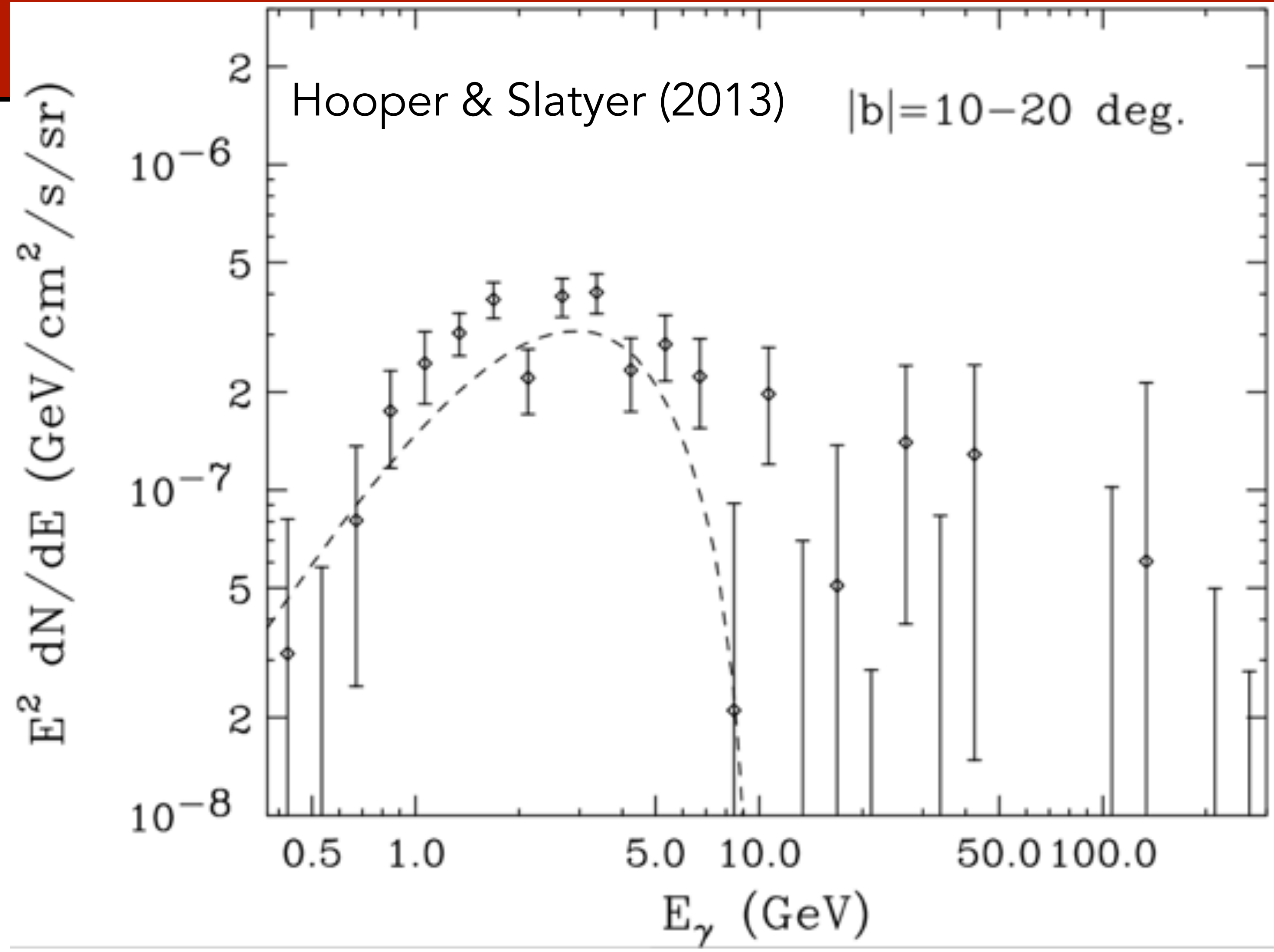
Dark Matter Fits

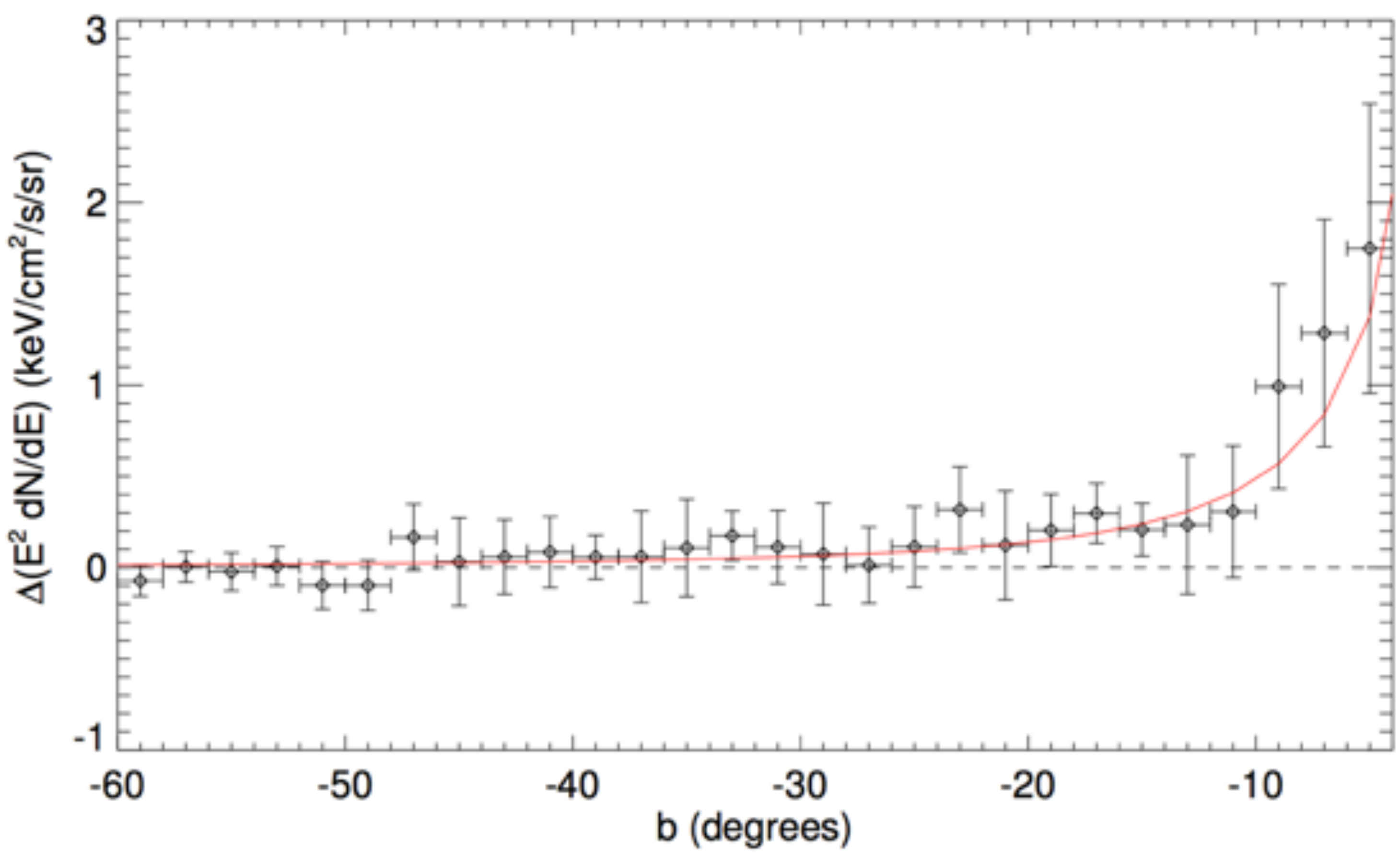
- Recently, Hooper & Slatyer found evidence for an extension of this emission far from the GC

- The morphology of this residual matches that found in the GC

  $(\rho_r \propto r^{-1.2})$

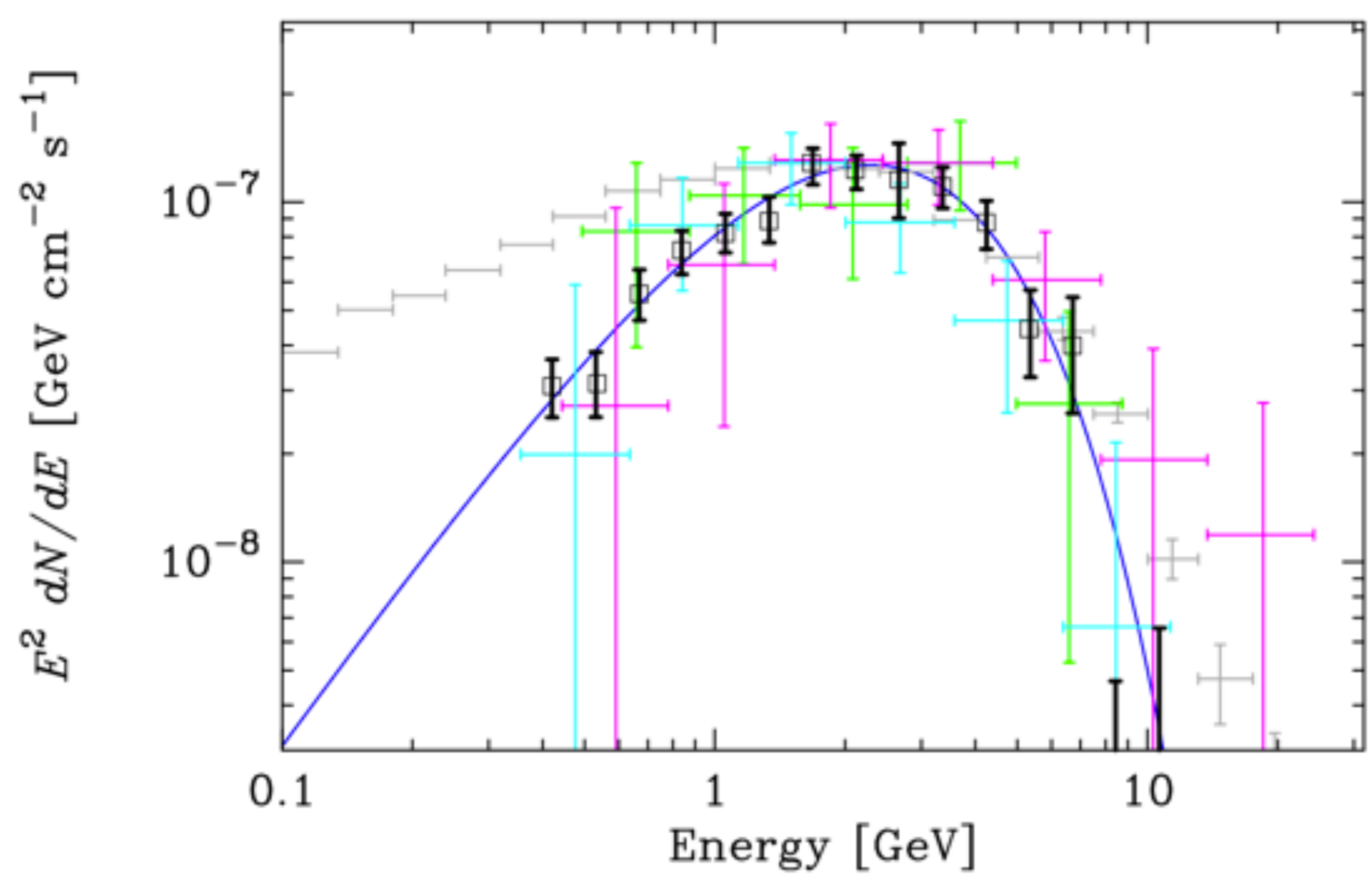
- Most Importantly: This residual is still observed far from the complicated backgrounds of the GC





Millisecond Pulsar Fits

- A population of undiscovered MSPs in the Galactic Center could fit the observed excess
- The spectrum of the MSP population is a reasonable fit
- I know there should be some MSPs in the GC

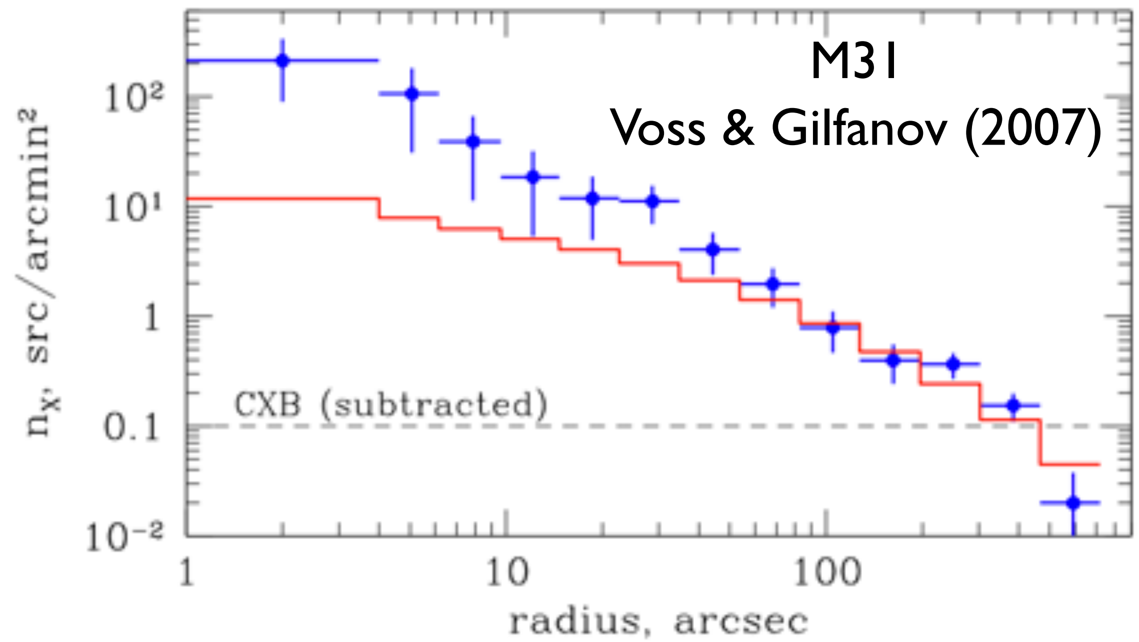


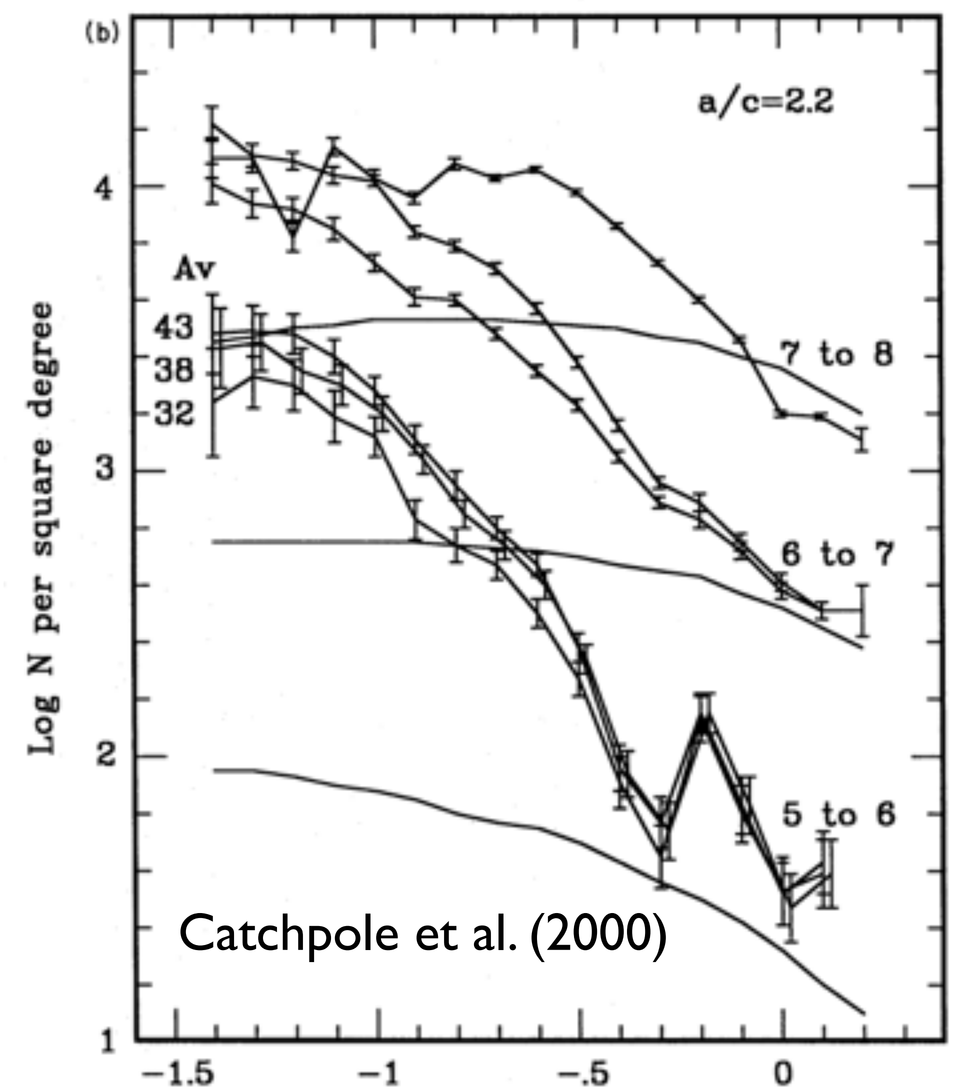
$$
\begin{aligned}
\text{Omega Cen:} \quad & \Gamma = 0.7^{+0.7+0.4}_{-0.6-0.4}, E_c = 1.2^{+0.7+0.2}_{-0.4-0.2}, \\
\text{NGC 6388:} \quad & \Gamma = 1.1^{+0.7+0.8}_{-0.5-0.8}, E_c = 1.8^{+1.2+1.8}_{-0.7-0.6}, \\
\text{M 28:} \quad & \Gamma = 1.1^{+0.7+0.6}_{-0.5-0.7}, E_c = 1.0^{+0.6+0.4}_{-0.3-0.2}, \\
\text{NGC 6652:} \quad & \Gamma = 1.0^{+0.6+0.3}_{-0.5-0.3}, E_c = 1.8^{+1.2+0.4}_{-0.6-0.3}.
\end{aligned}
$$

Abazajian (2011)

Millisecond Pulsar Fits

- Must explain the high density of pulsars near the Galactic Center (~$r^{-2.6}$)
- Single stars and X-Ray point sources are not as compact towards galaxy centers
  - Two body interactions in the densest clusters?
  - Mass segregation?





The Dark Matter Interpretation

What other observations support/oppose a dark matter interpretation?

Other Evidence

- WMAP Haze
  - Excess has harder spectrum than known astrophysical components
  - Seems to correlate to Fermi bubbles, not seen in nearby galaxies
- ARCADE-2 Excess
  - Difficult to model with any astrophysical signal, requires hard lepton spectrum
  - May be too homogenous to be produced by dark matter
- Direct Detection
  - Multiple signals observed by CRESST, CoGeNT, DAMA/LIBRA, CDMS etc.
  - Contradicting limits by Xenon 100, CDMS, many signals are inconsistent.
- Filamentary Arcs
- Galaxy Clusters

Where Do We Go From Here?

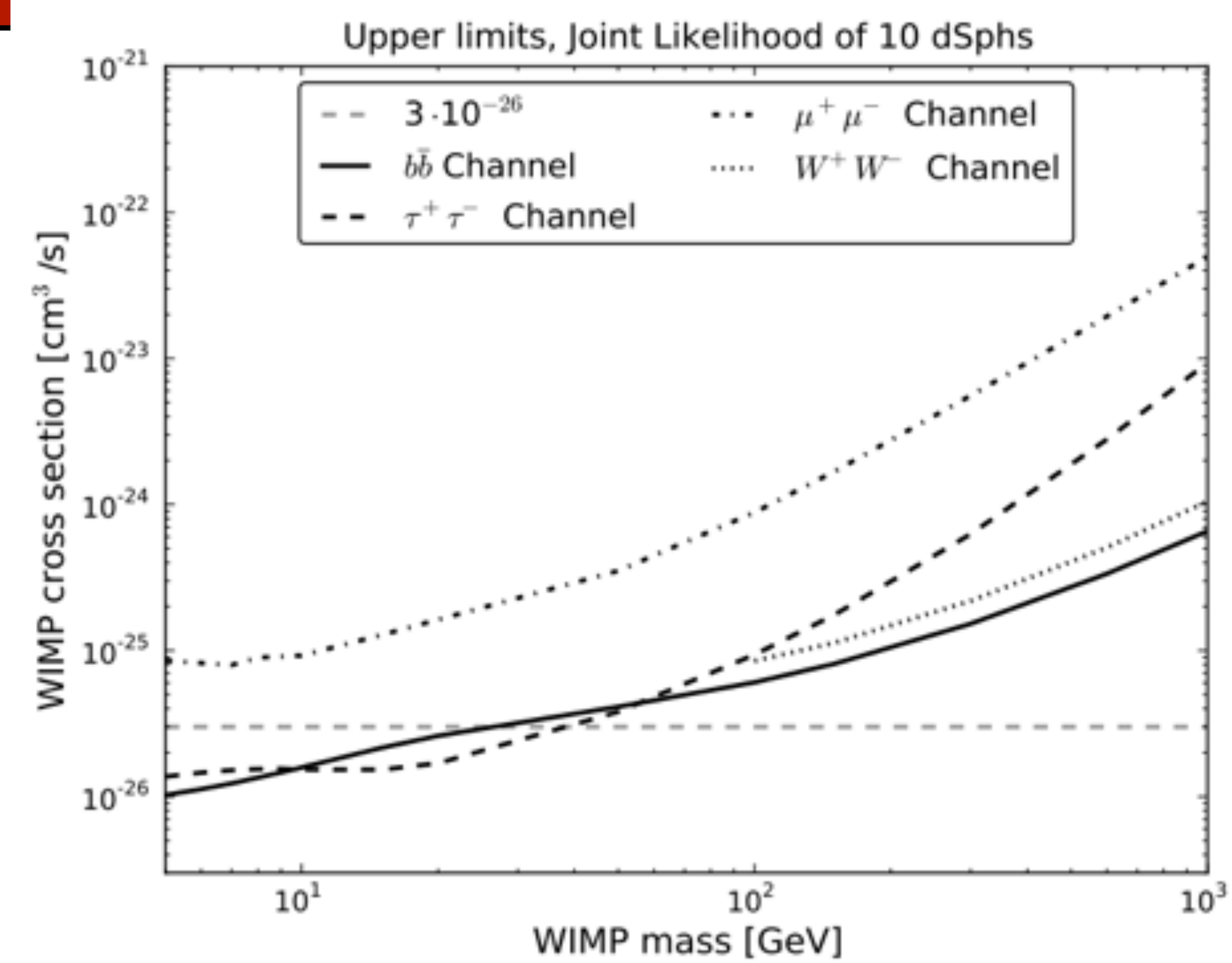
- Personal Opinion: It's not clear that new data from the GC will greatly improve our measurements of the GC excess - at least not in any way which can distinguish dark matter and MSPs

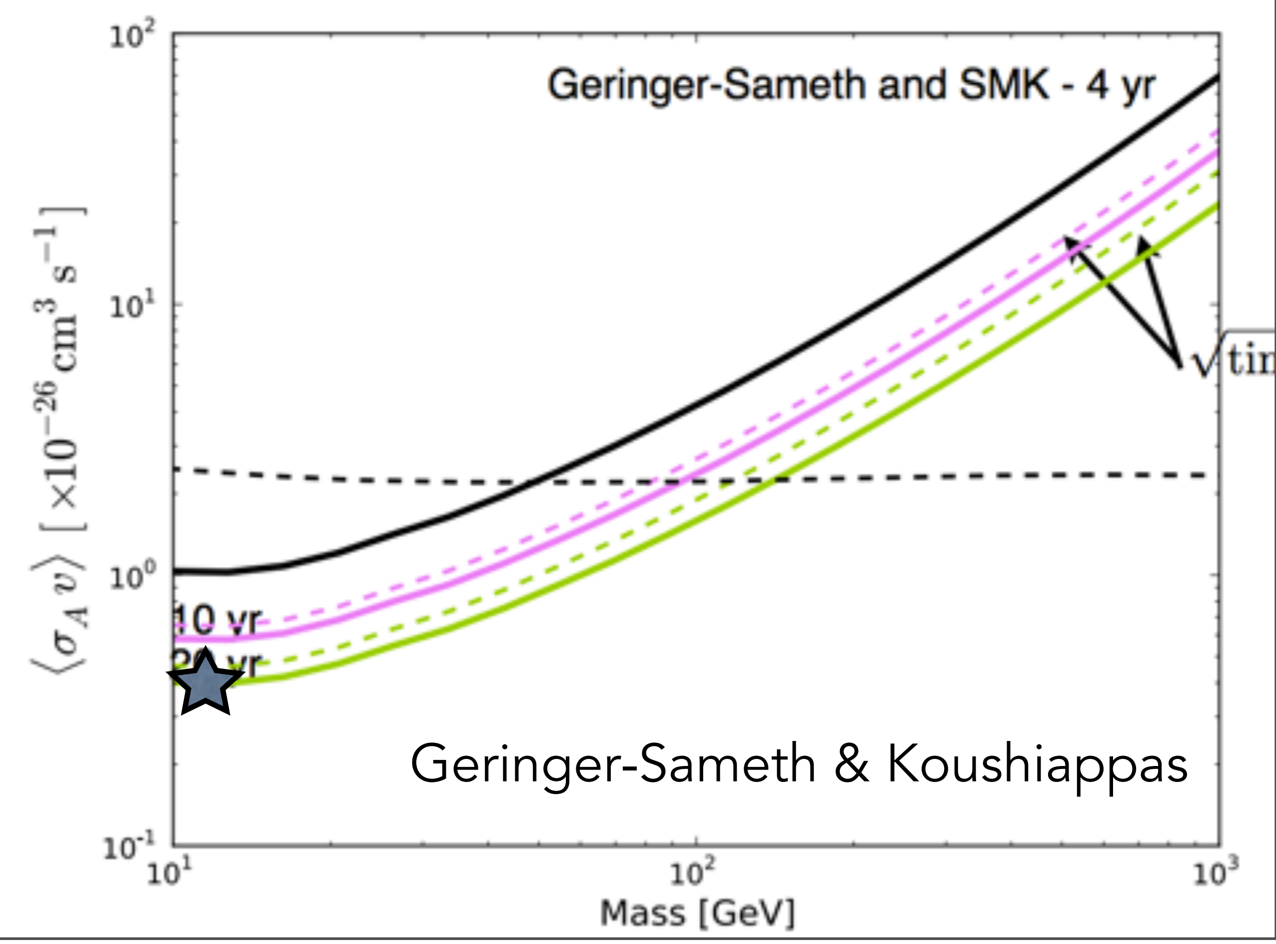
- We can measure some properties of the excess (such as its spherical symmetry) which could point towards, or away from a DM origin

Where Do We Go From Here?

- While dwarfs would provide a background free environment for the possible detection of a dark matter signal, it's not clear that the limits will ever hit the cross-sections indicated by GC observations

- Maybe DES will provide more "good" dwarfs



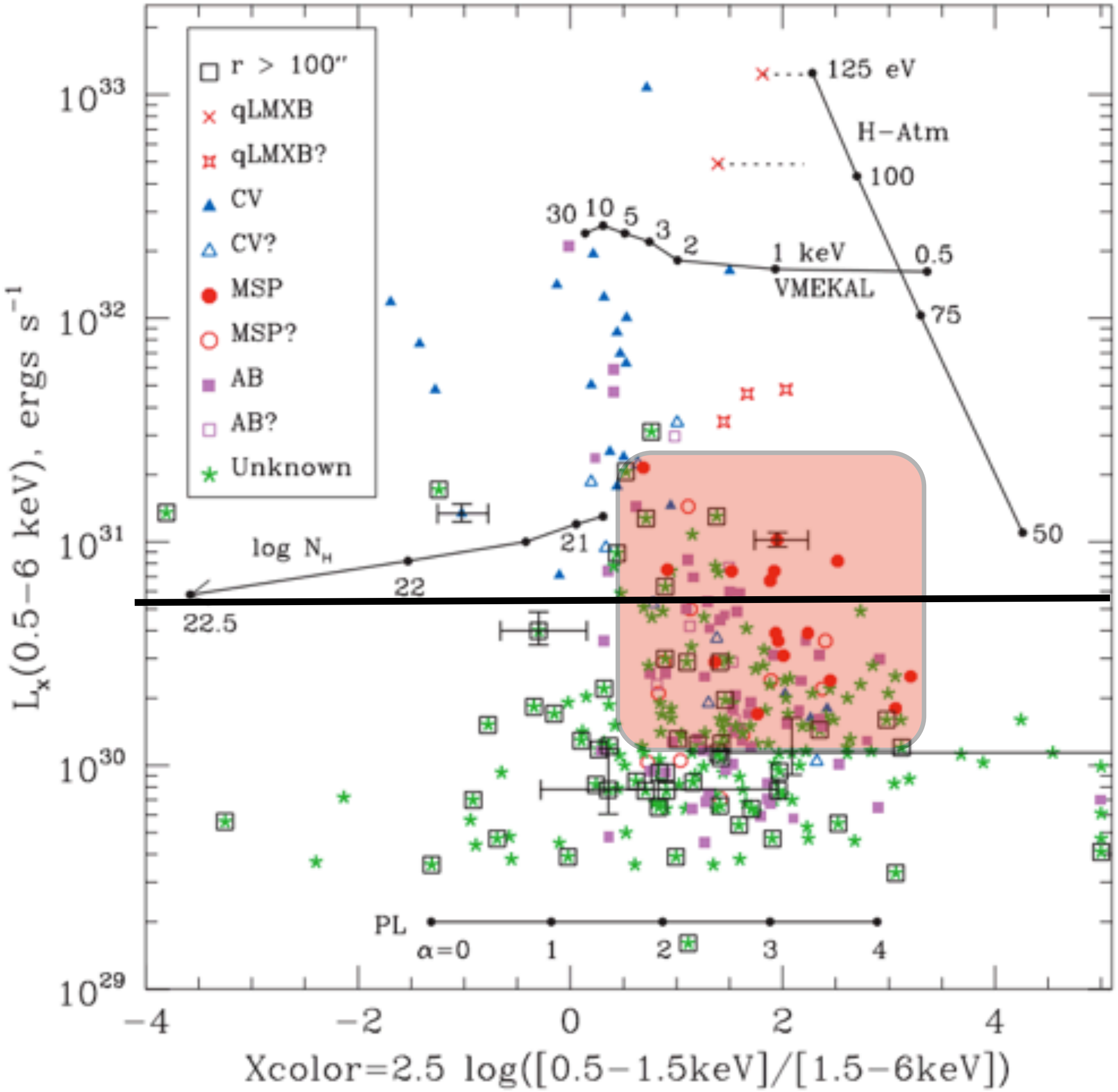


Where Do We Go From Here?

- X-Ray observations find a total of 2347 point sources within 40 pc of the GC - this could include a large population of MSPs

- MSPs exist in a particular location on the luminosity-color diagram in 47 Tuc

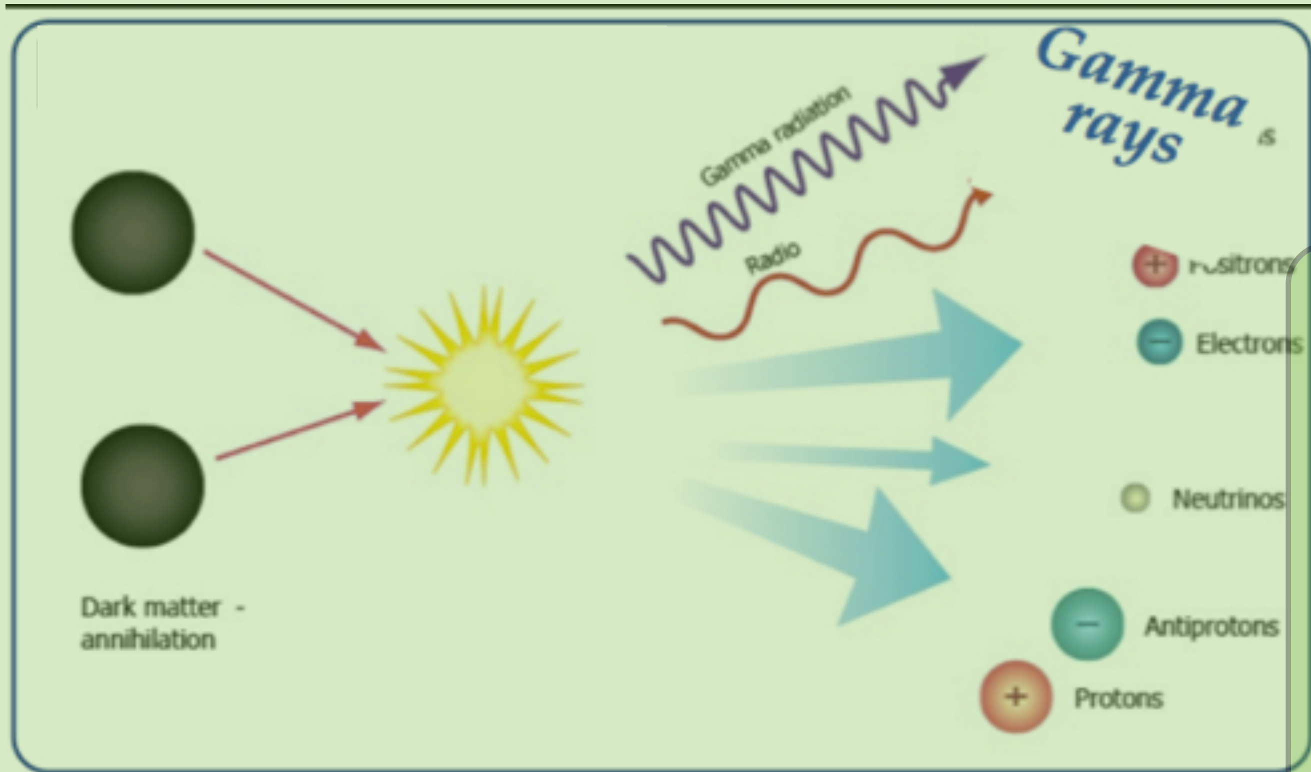
- Can this information be used to determine the statistical distribution of MSPs?



Heinke et al. (2006)

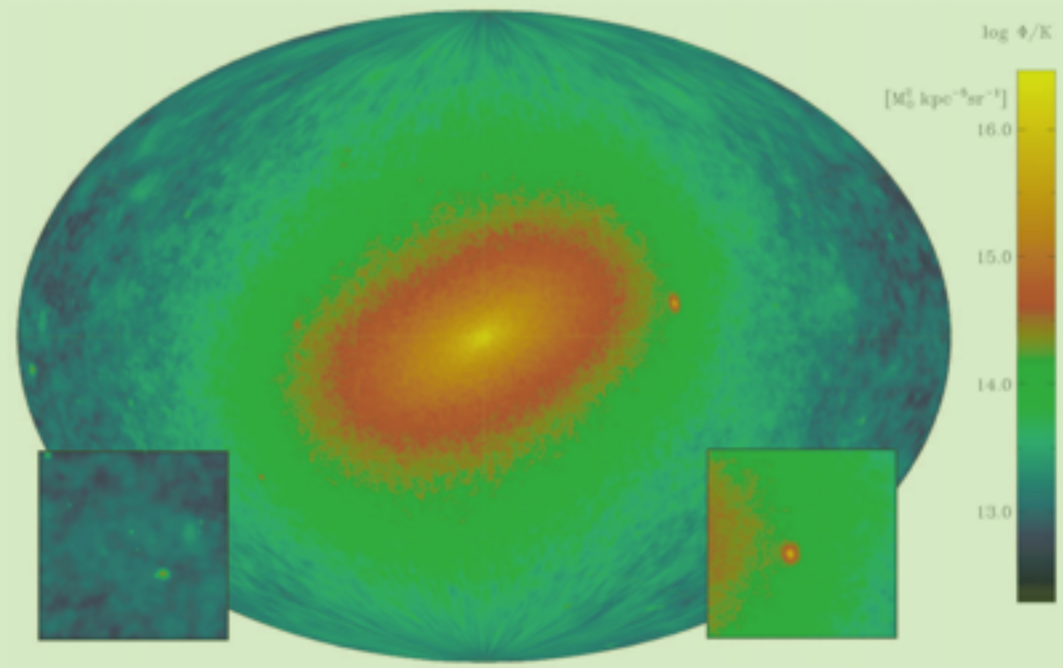
We Can Turn this Picture Around

Particle Physics

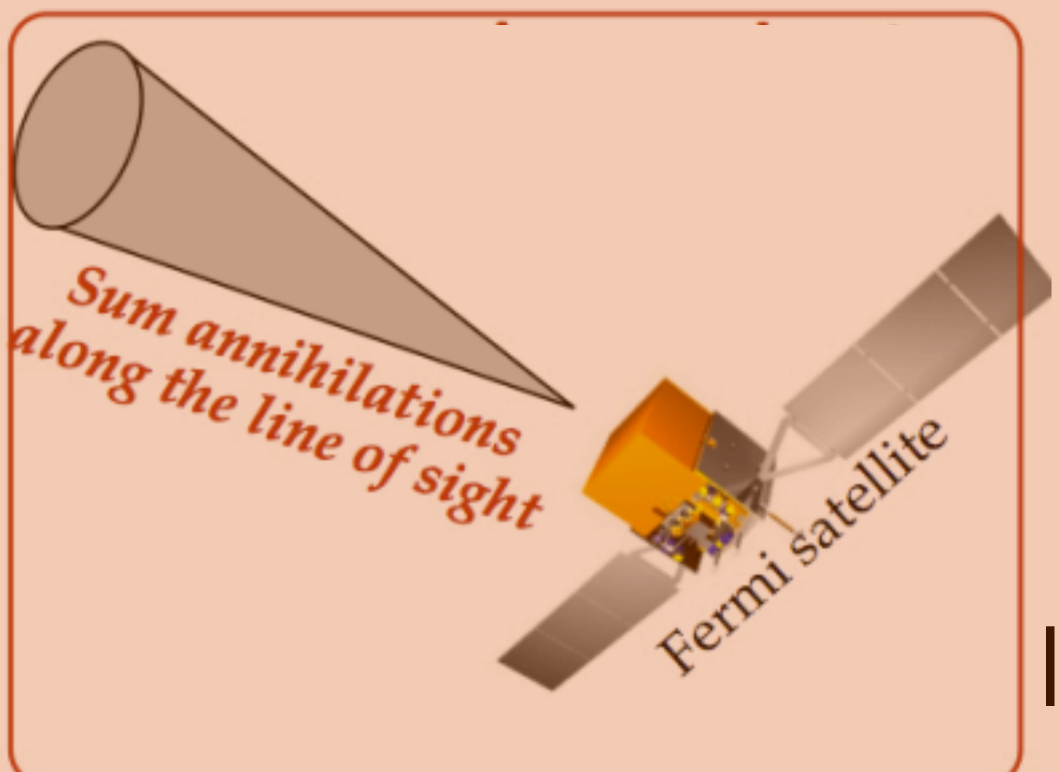


Slides Courtesy of G. Zaharijas

Astrophysics



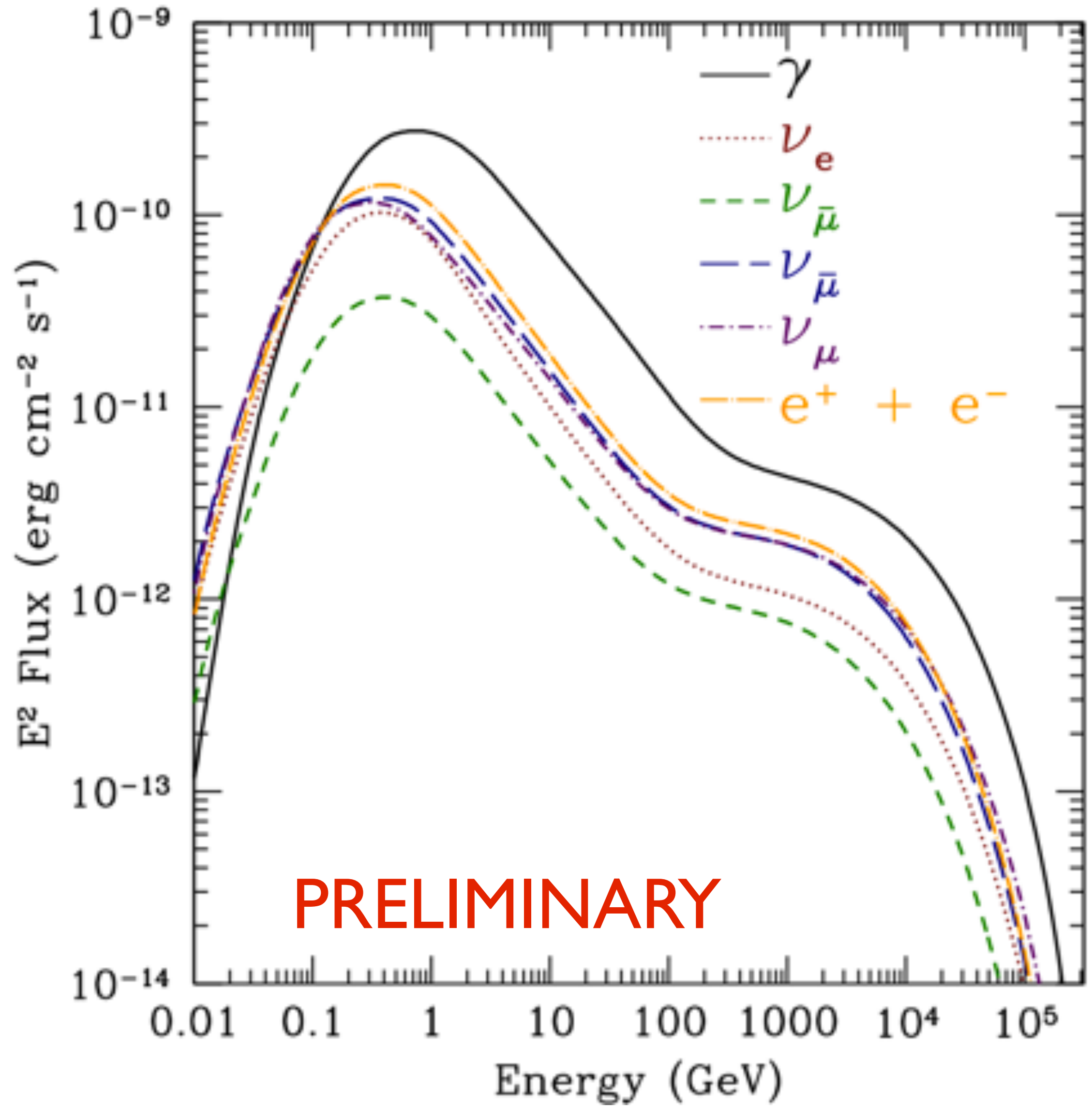
Diemand et al. 2008

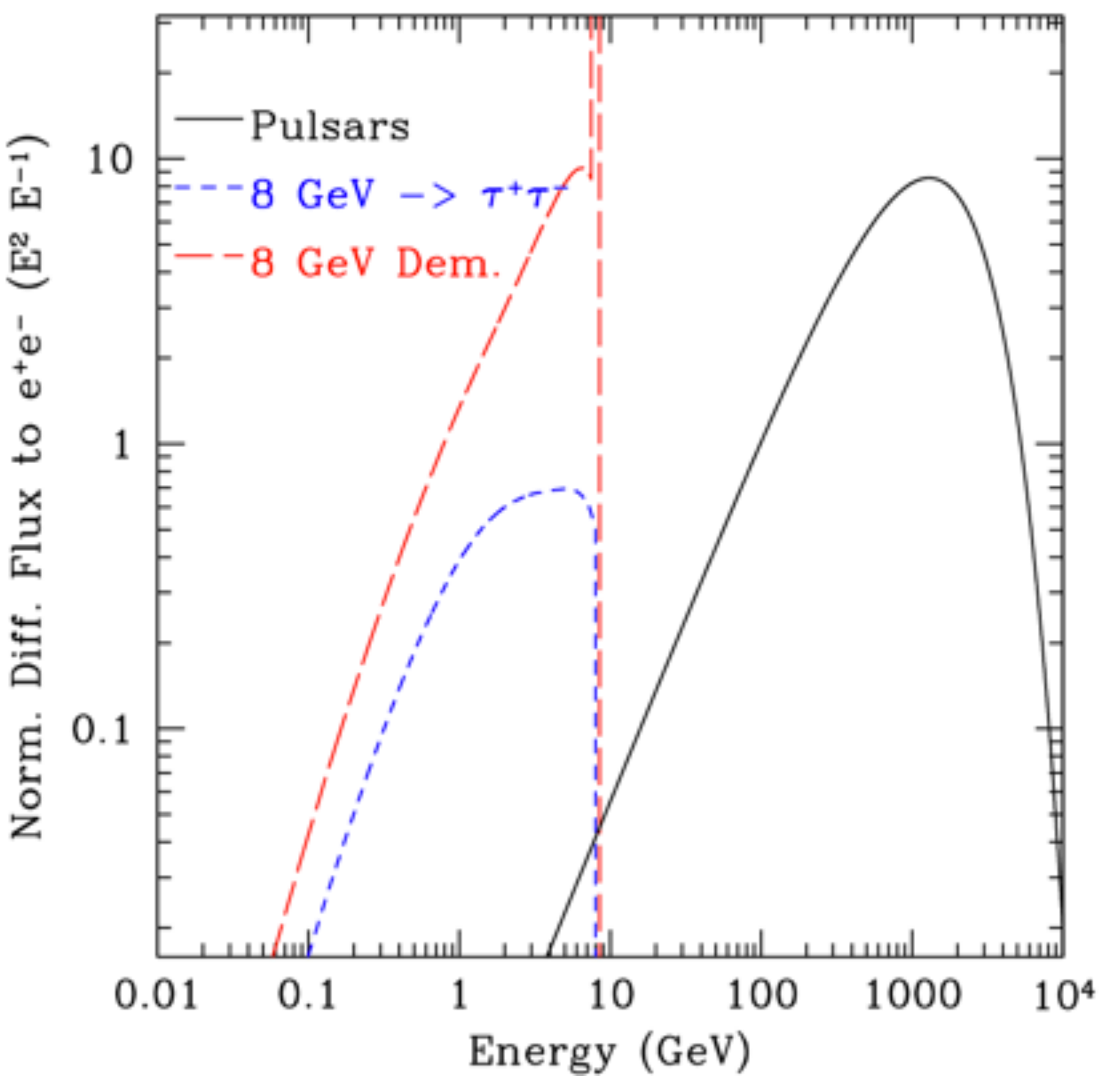


Instrumental Response

Where Do We Go From Here?

- Another method for distinguishing between gamma-ray emission models is to investigate the production of electron and positron pairs
- These charged leptons will lose considerable energy to synchrotron radiation, producing a bright radio signal in the galactic center





Positive: The angular resolution of radio telescopes is significantly greater than gamma-ray observatories

Negative: The diffusion and energy loss time of charged electrons adds additional uncertainties to the model

Where Do We Go From Here?

- What future measurements are most likely to constrain, or provide convincing evidence for a dark matter signal?

- What new missions, pointing strategies, analyses are most likely to elucidate current dark matter models?

- Comments?
- Opinions?
- Criticism?