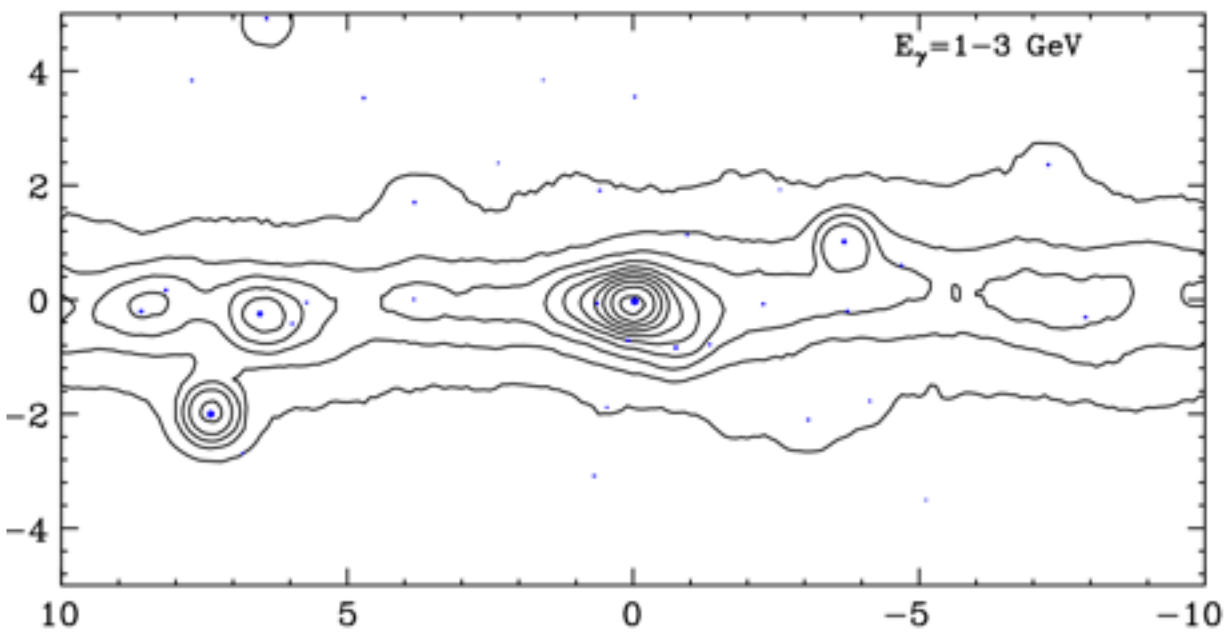
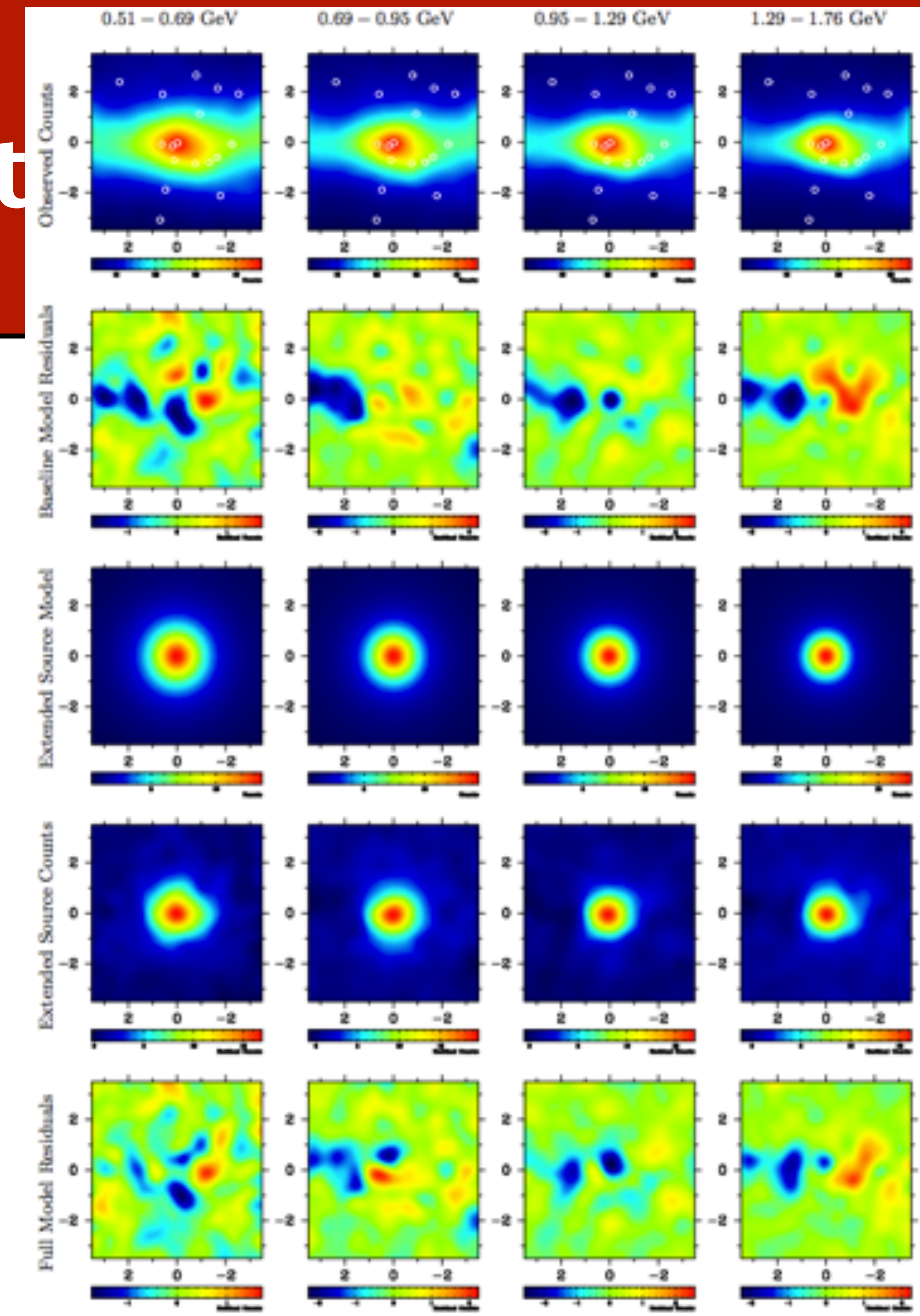
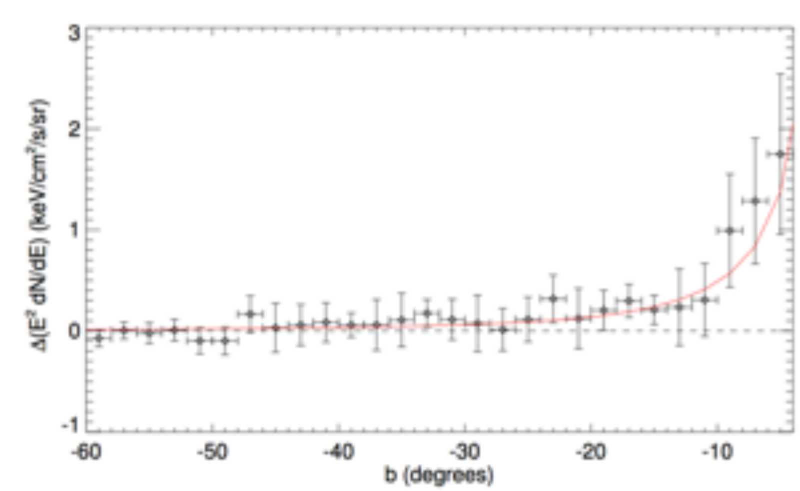
Dark Matter in the Galactic Cent





Tim Linden
University of Chicago



along with: Eric Carlson, Ilias Cholis, Dan Hooper, Manoj Kaplinghat, Stefano Profumo, Jennifer Siegal-Gaskins, Tracy Slatyer, Hai-Bo

The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus

Goal of the Talk

- Overview of Dark Matter Physics
- A Gamma-Ray Signal at the Galactic Center !?
- Supporting Lower-Energy Observations
- Necessary Future Observations

Gravitational Effects of Dark Matter in the GC

There isn't any:

Using the standard Navarro-Frenk-White Density profile for Dark Matter:

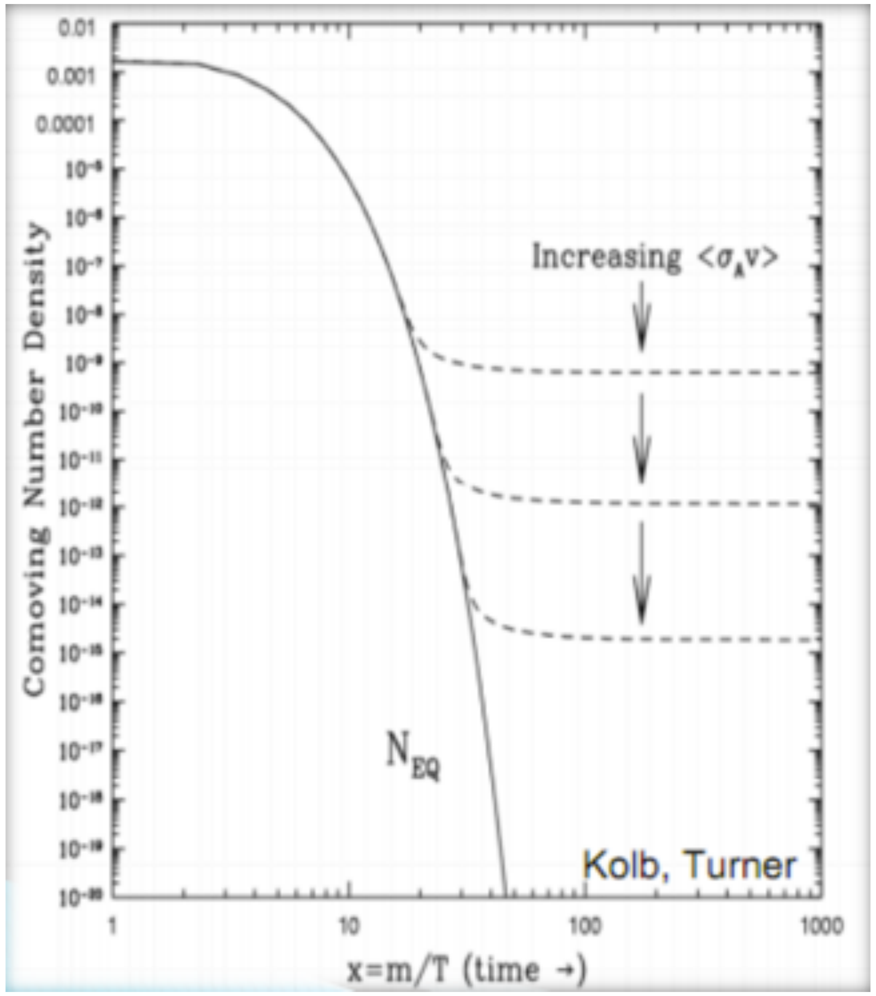
$$\rho_{NFW}(r) = \rho_c(\frac{R_c}{r})(1 + \frac{r}{R_c})^{-2}$$

We obtain a mass within 0.1 kpc of the Galactic Center which

$$\left(2.6 \times 10^7 \frac{M_\odot}{kpc^3}\right) 4\pi \int_0^{0.1kpc} r^2 \frac{22kpc}{r} \left(1 + \frac{r}{22kpc}\right)^2 dr = 3.7 \times 10^7 M_\odot$$

Any detection of dark matter at the galactic center will depend on its particle nature

Dark Matter Particle Physics (1 Slide Only, I Swear)



$$\Omega_h \propto <\sigma v>^{-1} \propto \frac{M_\chi^2}{g_\chi^4}$$

$M_\chi \sim 100\ GeV$

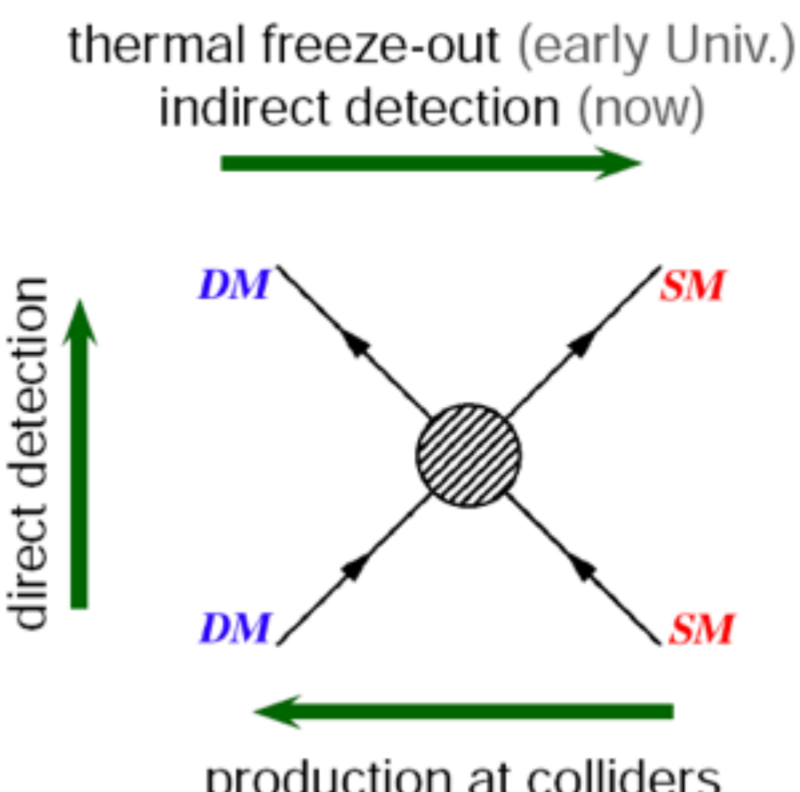
$g_\chi \sim 0.6$

<u>Weak Force Values!</u>

=>

$\Omega_h \sim 0.1$

<u>Relic Density!</u>



If this weak force interaction existed in the early universe, then it should still occur (at a suppressed rate) today.

We can look for these interactions.

Astrophysics of Dark Matter Annihilation

- Dark Matter Annihilation Rate is separable into astrophysical and particle physics components

$$\Phi_{DM} = \int\int \frac{dN}{dE} < \sigma v > \frac{\rho^2}{M_{DM}^2} dV dE = \left[\int \frac{dN}{dE} < \sigma v > \frac{1}{M_{DM}^2} dE\right] \left[\int \rho_r^2 dV\right]$$

Particle Physics | Astrophysics

- The particle physics properties should be independent of the position in the universe – so we can compare different dark matter detection regimes without regard for a given dark matter particle physics model

Dark Matter Annihilation at the Galactic Center

Ackermann et al. 2012

Dwarfs

Name	l	b	d	$\overline{\log_{10}(J)}$	σ	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]

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

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

- The J-factor of the galactic center is

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

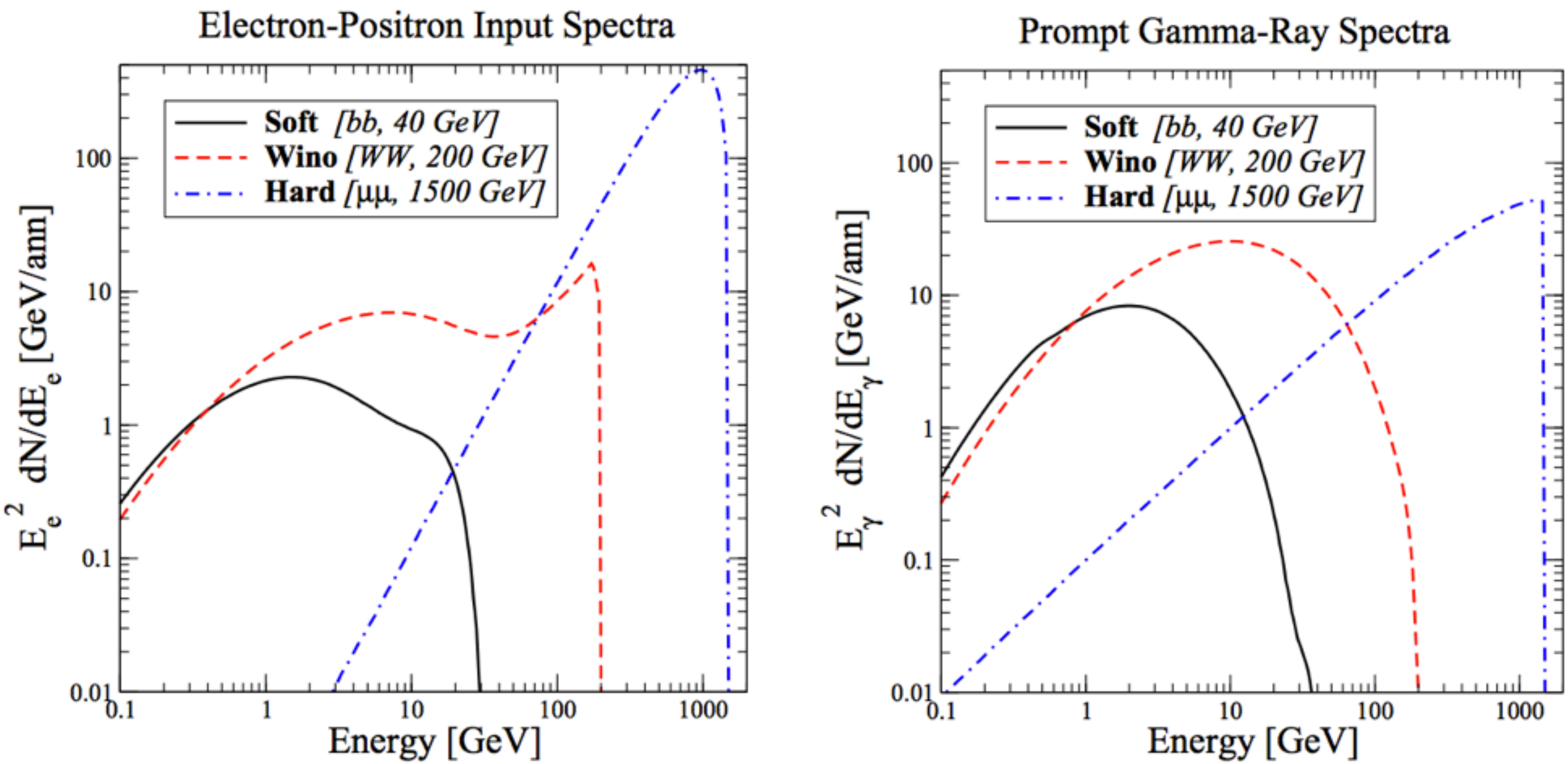
for a region within 1° of the Galactic center and an NFW profile

Completely Insignificant

Using the NFW Profile and a standard 100 GeV dark matter particle annihilating to bb:

$$2M_{DM}\frac{<\sigma v>}{2}\frac{\rho_0^2}{M_{DM}^2}4\pi\int_0^{100pc} r^2\rho_{r,NFW}^2 dr = 4.2\times 10^{35}\frac{erg}{s}$$

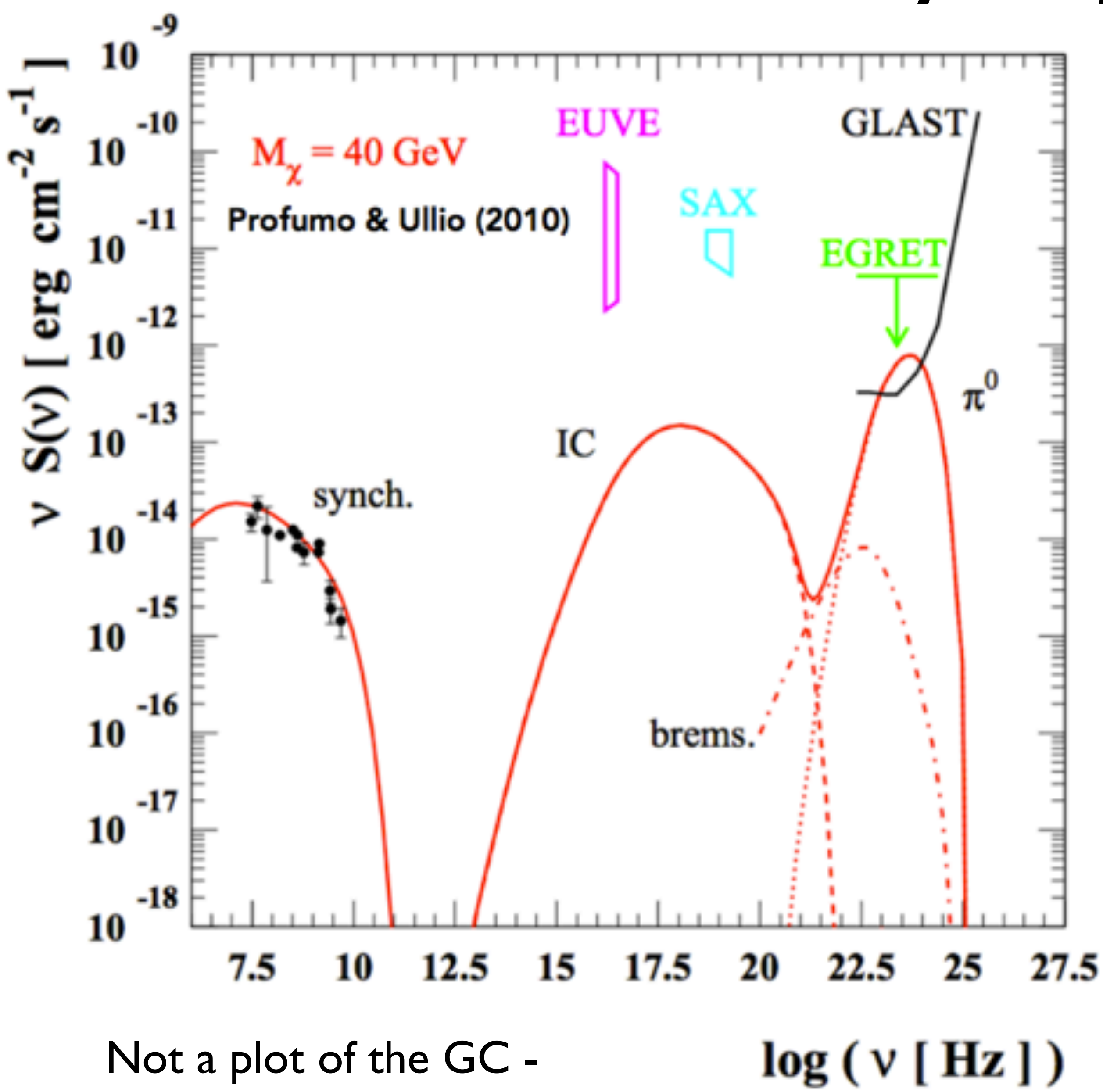
Very Significant



Linden et al. (2010)

Dark Matter annihilation injects energy primarily in the GeV energy range, can produce a significant population of high energy particles.

Very Significant



Not a plot of the GC - don't look too closely!

Dark Matter annihilation can produce non-thermal emission on many energy scales

Back of the Envelope Calculation

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

$$\sim 1 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$$

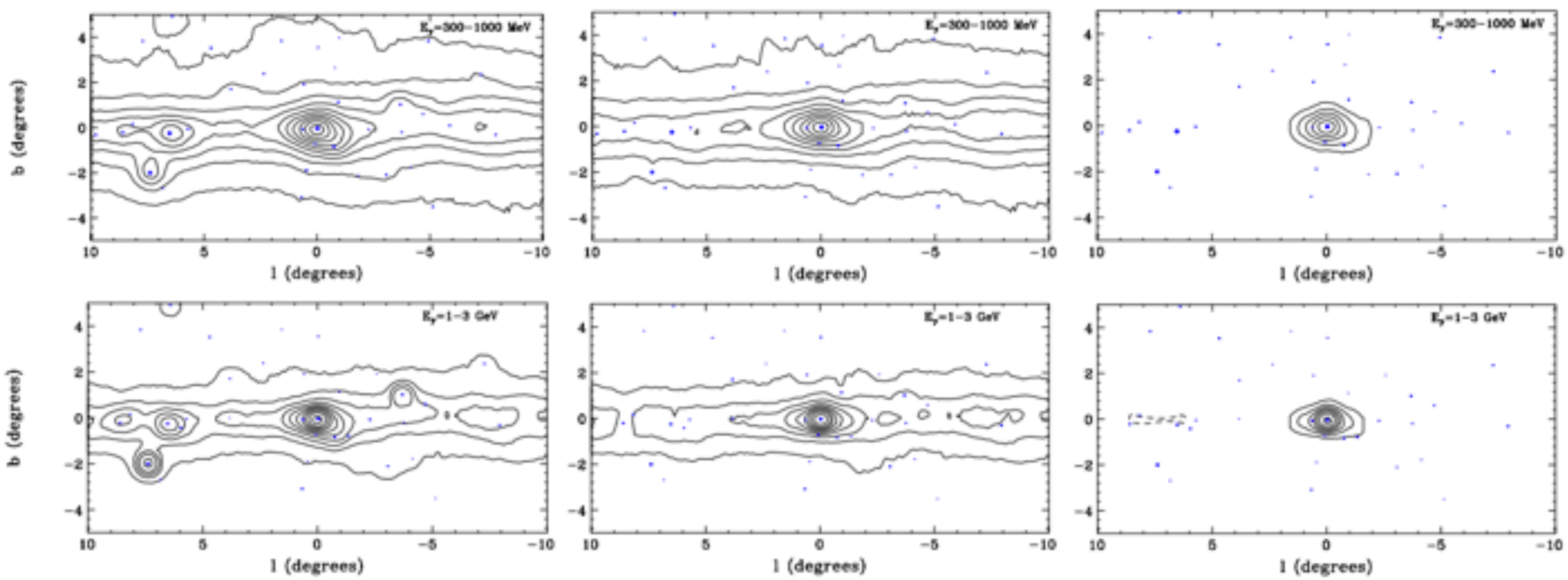
- This is equivalent to the number of photons expected in this energy bin from a "vanilla" 100 GeV dark matter candidate annihilating to bb with a cross-section **$\langle\sigma v\rangle = 1.6 \times 10^{-25}$ cm^3 s^{-1}** (5 times our "magic" cross-section)

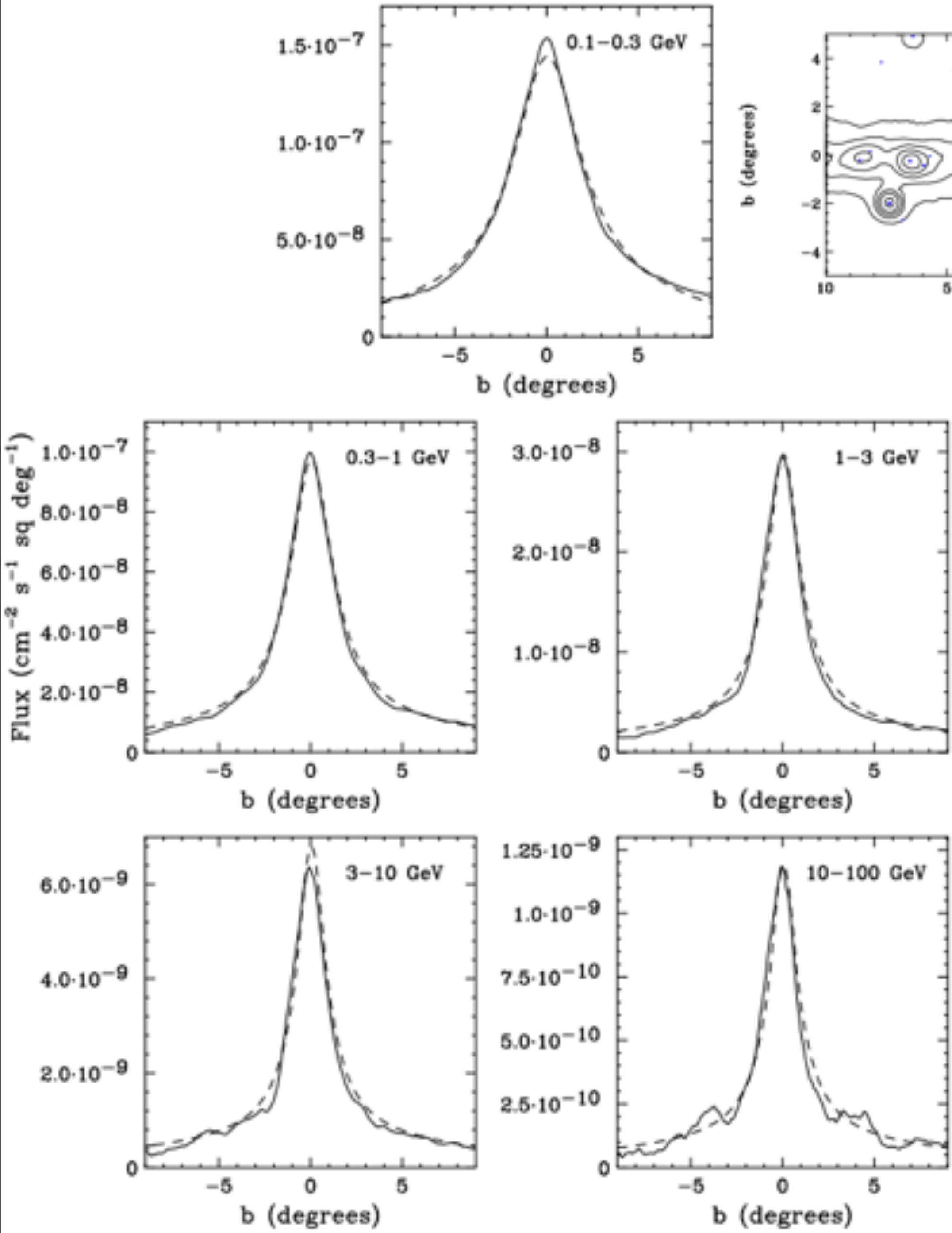
- There's no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the **most naive** prediction from dark matter

So you want to search for dark matter at the Galactic Center?

What do you do?

Searching for Dark Matter at the GC: Fermi–LAT

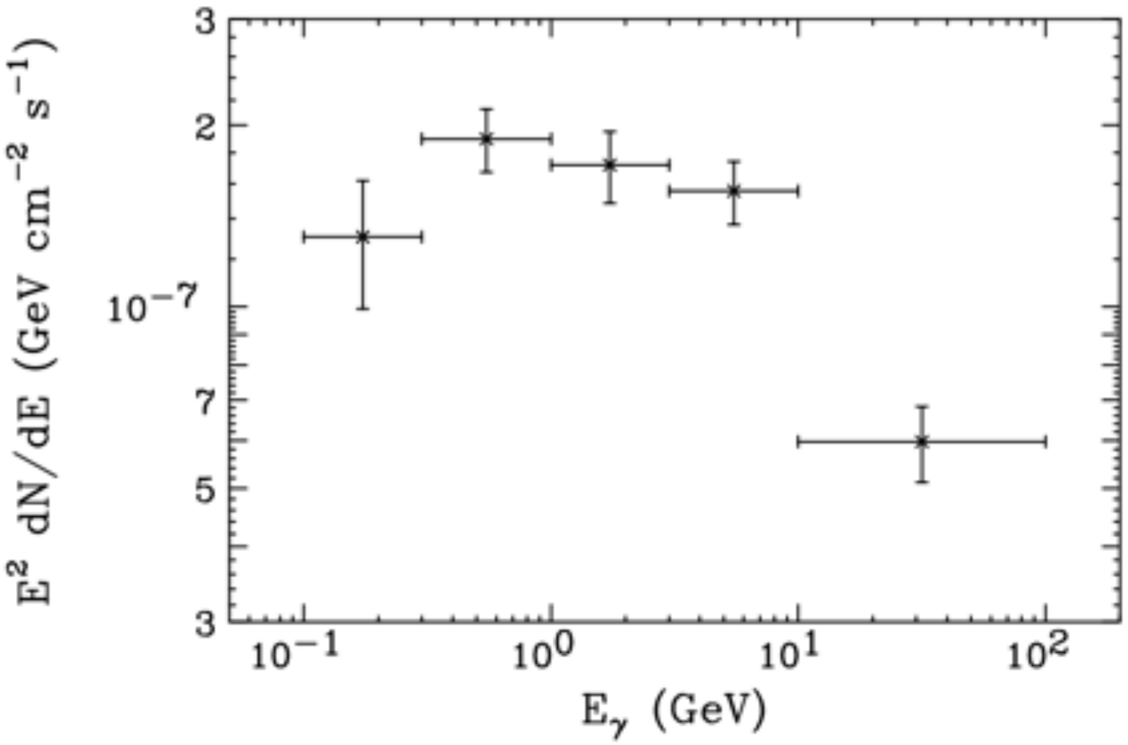




Hooper & Linden (2011)

- 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 20º x 10º

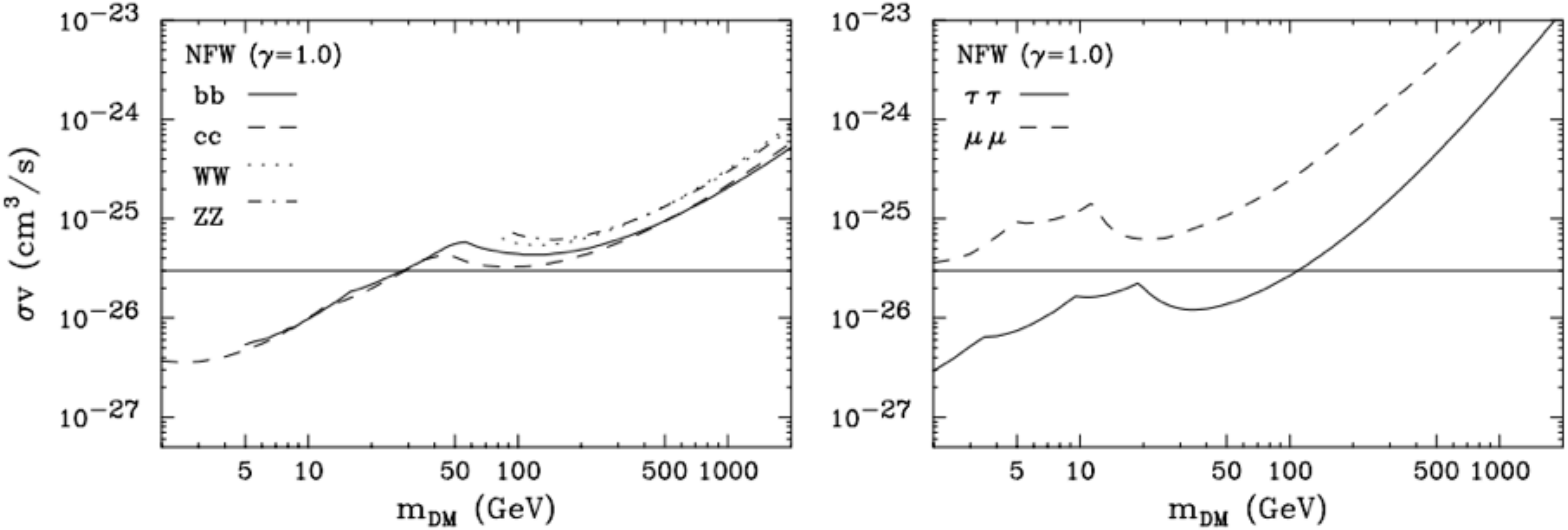
Dark Matter Limits in the Simplest Way Possible



Hooper & Linden (2011)

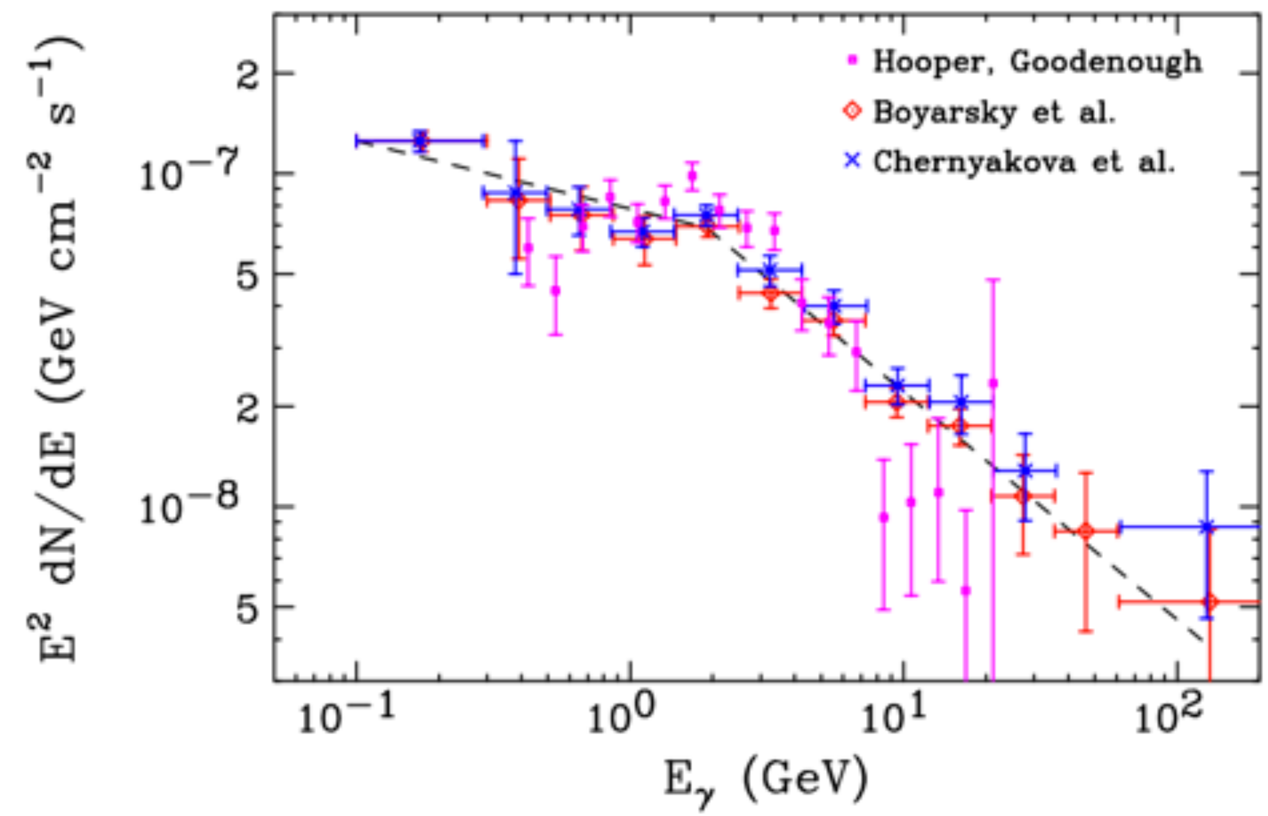
- After subtracting emission from known point sources, and an extrapolation of the line-of-sight gas density, the following "galactic center" emission is calculated

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

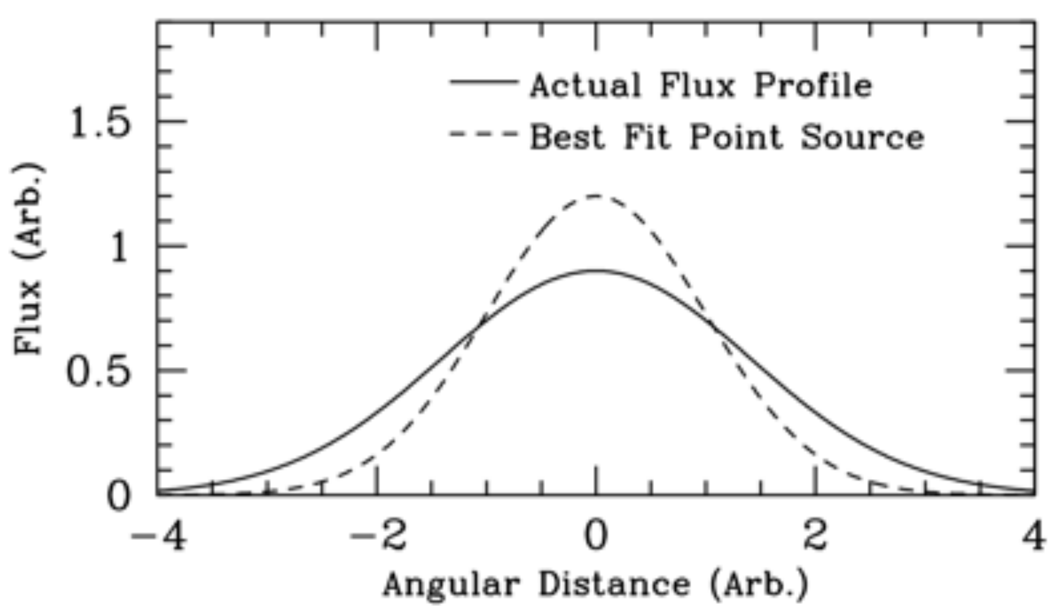


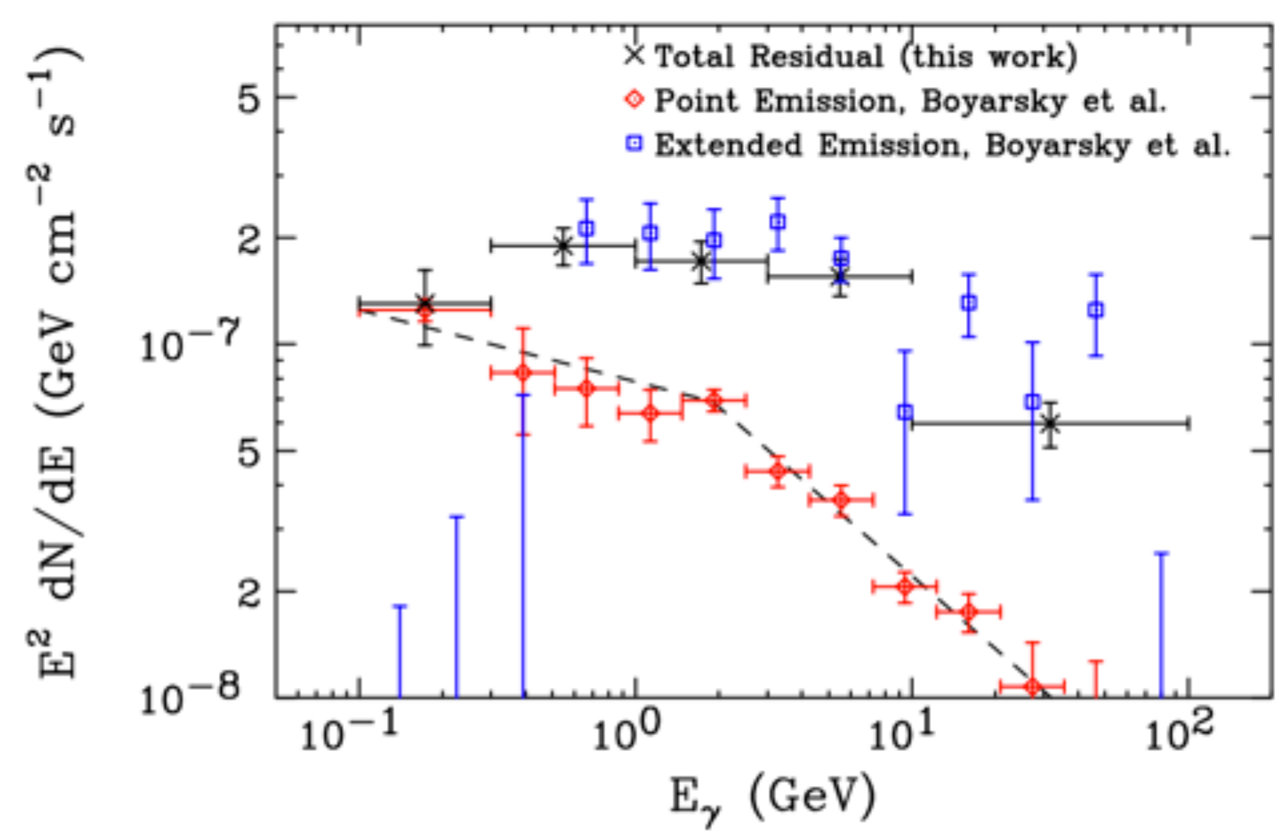
Is It A Point Source?

- 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–





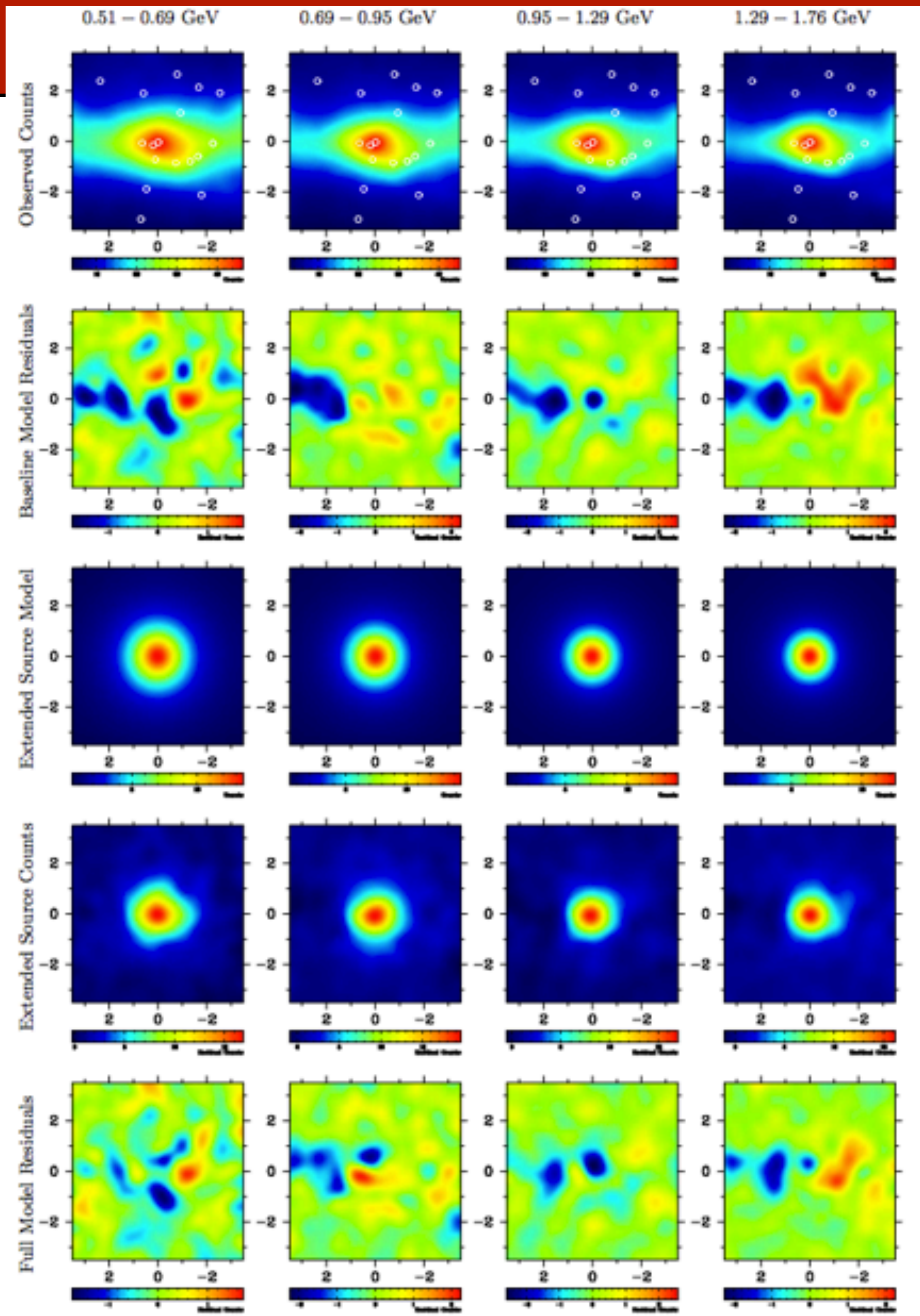
Hooper & Linden (2011)

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

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?

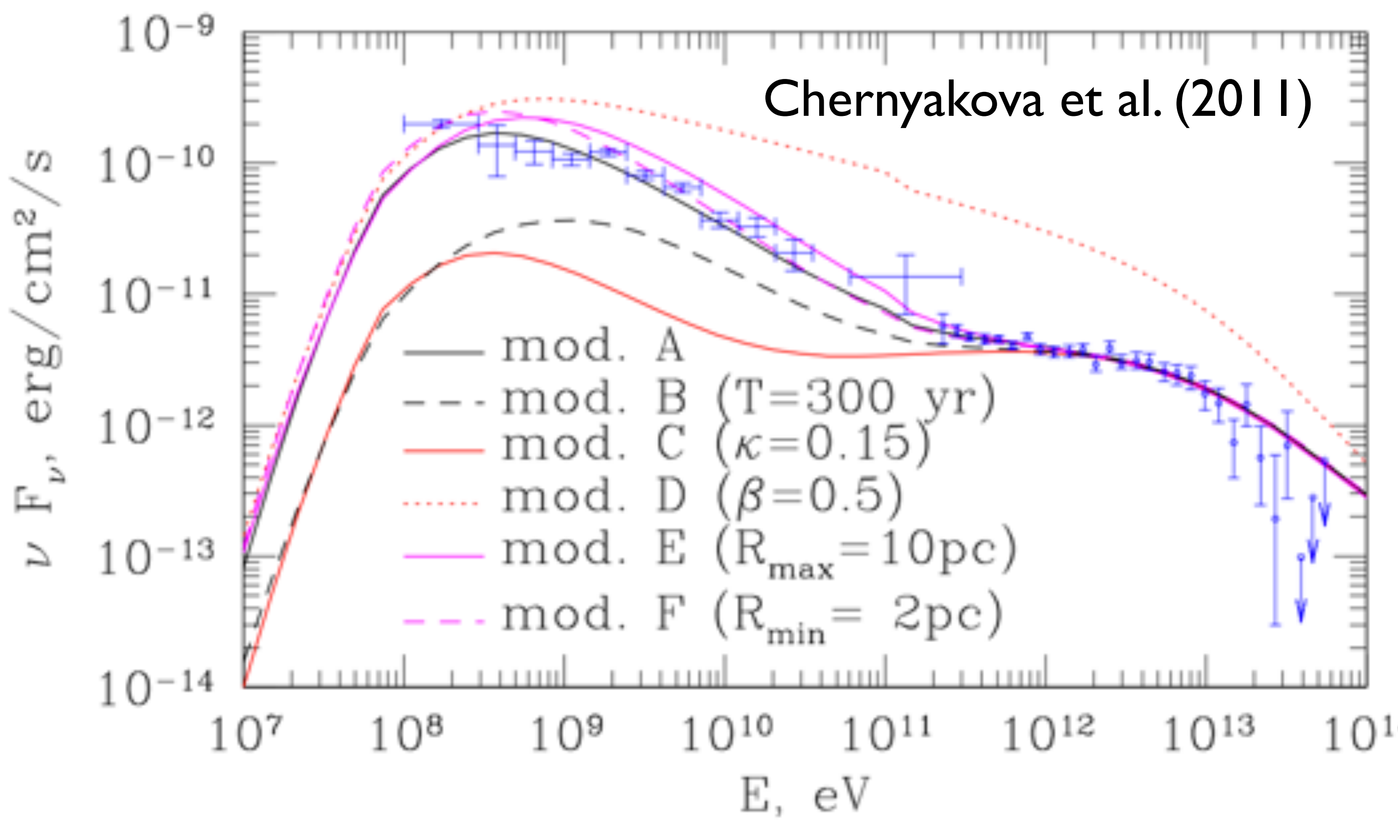
Interpretations at this Point

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

Proton Emission from Sgr A*

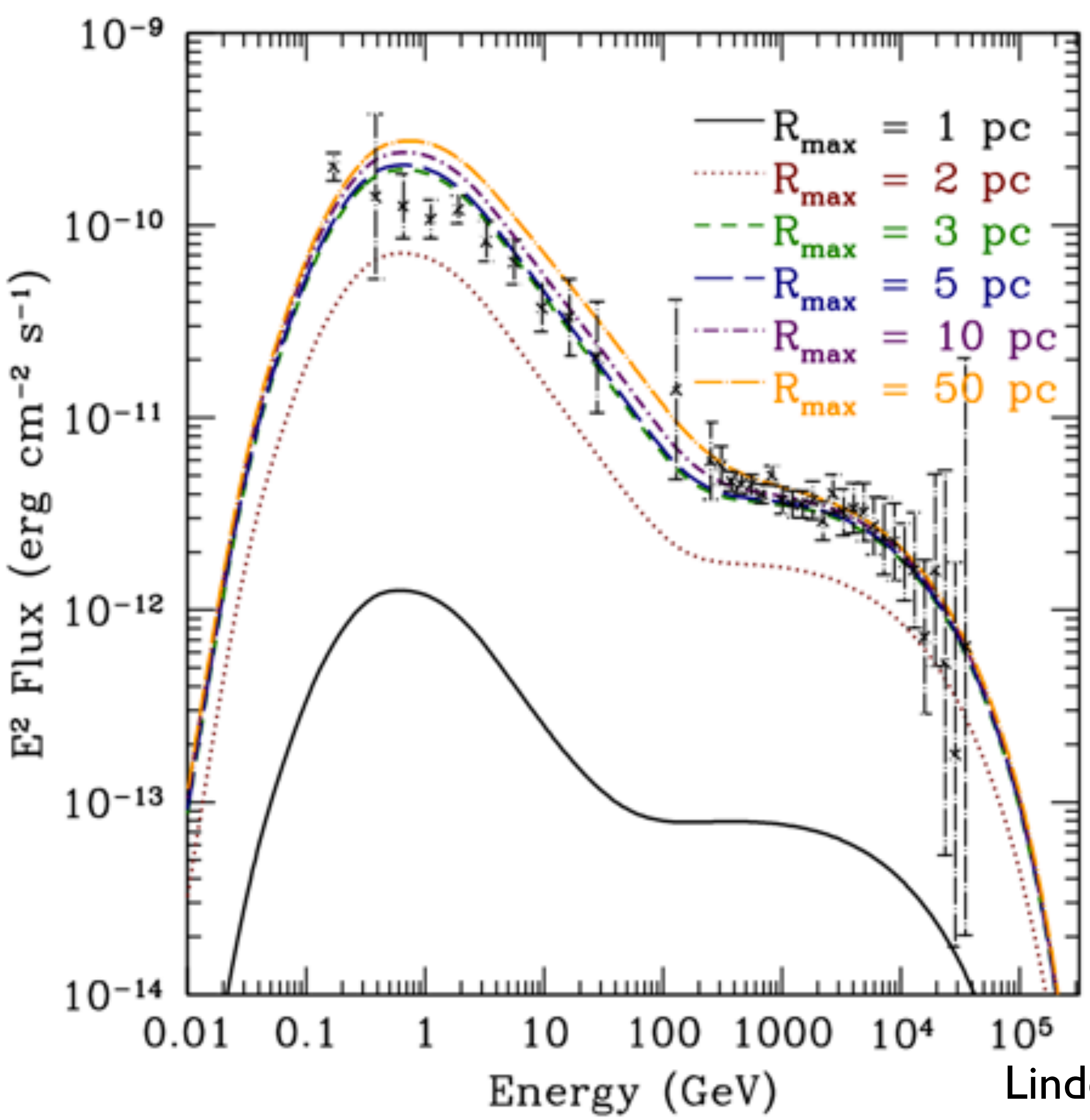
- H.E.S.S. observations of TeV gamma-rays from the GC are very well fit by a scenario where high energy protons are emitted by Sgr A* and collide with the dense gas nearby

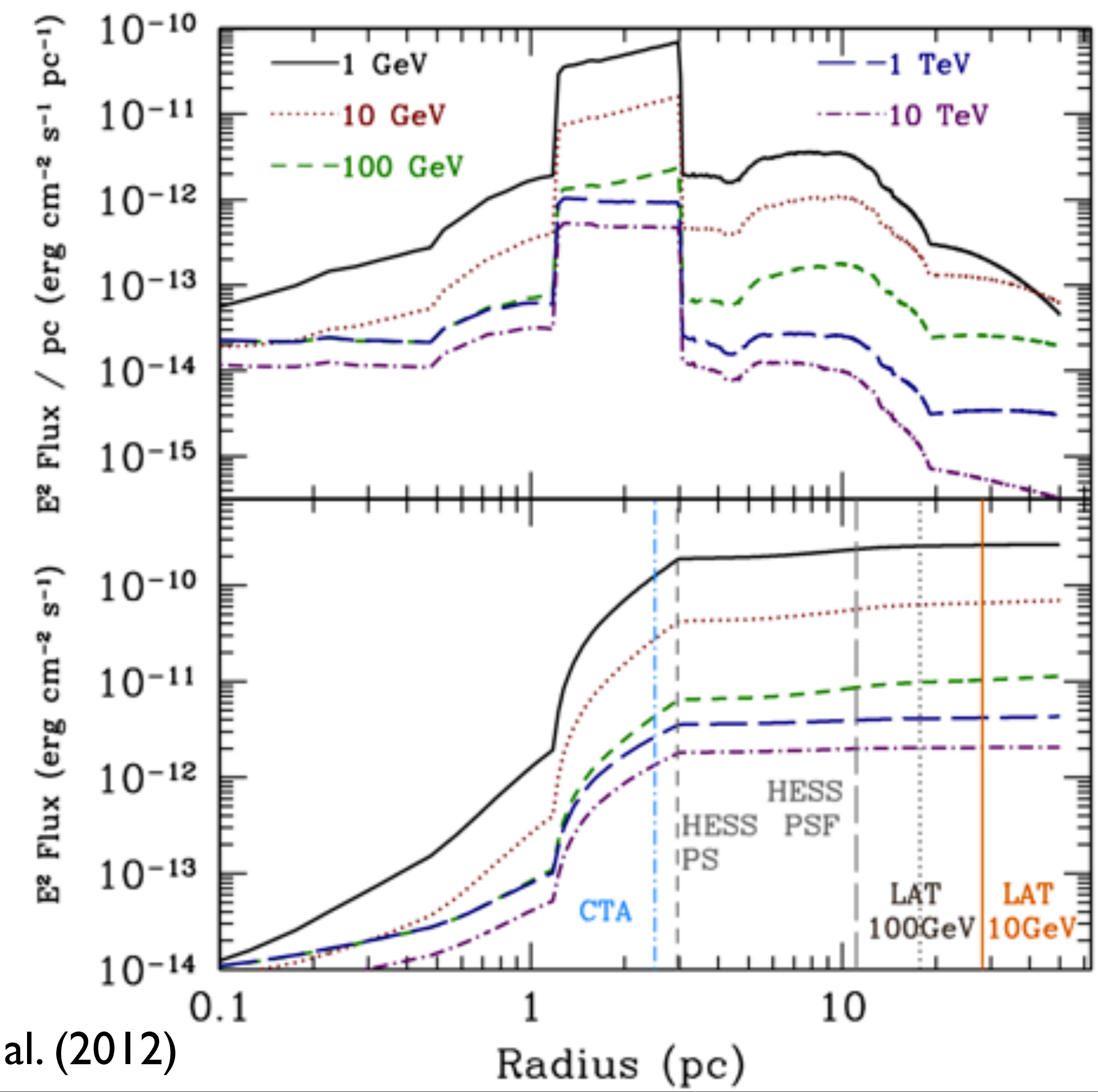
- Tuning the diffusion parameter can explain the different gamma-ray spectra observed at GeV and TeV energies



Understanding the Gas Morphology

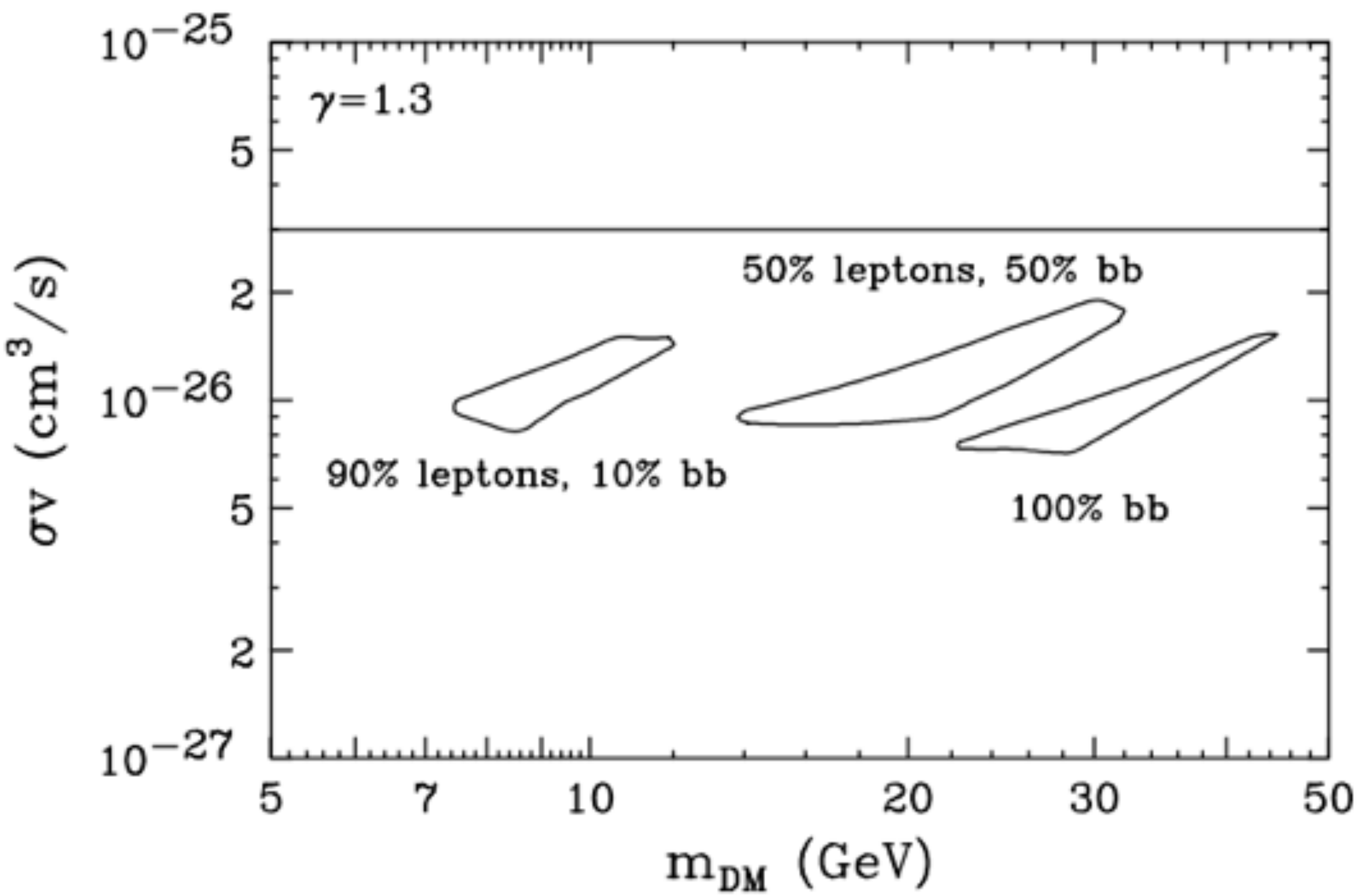
- The vast majority of emission stems from within 3 pc of the galactic center at all energies
- This lies below the PSF of all current gamma-ray instruments
- This effectively rules out hadronic interactions from Sgr A* as the source of the Fermi-LAT excess





Linden et al. (2012)

Dark Matter Fits



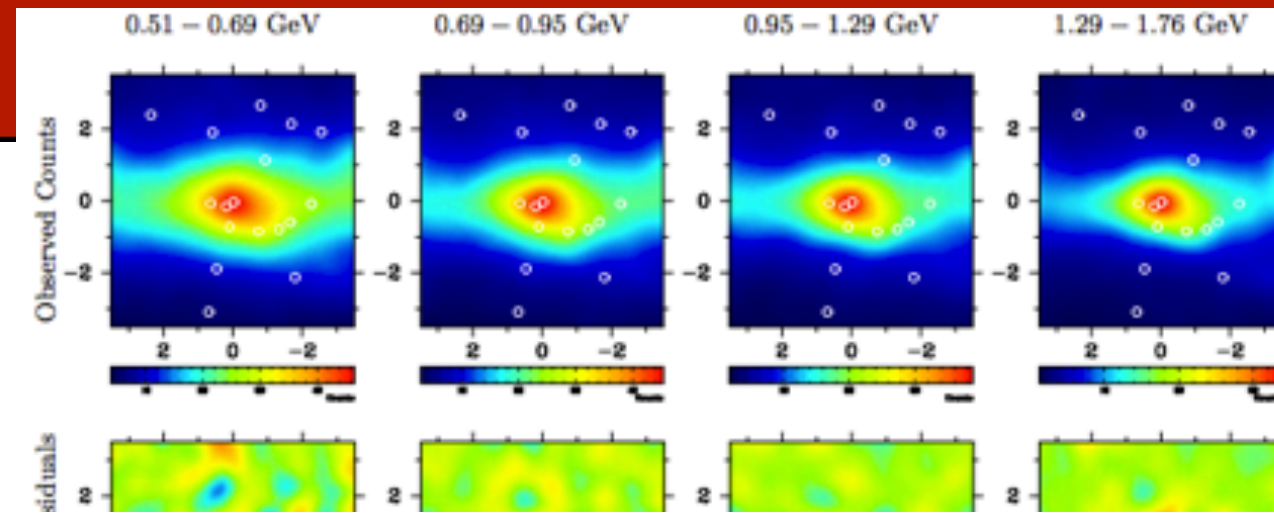
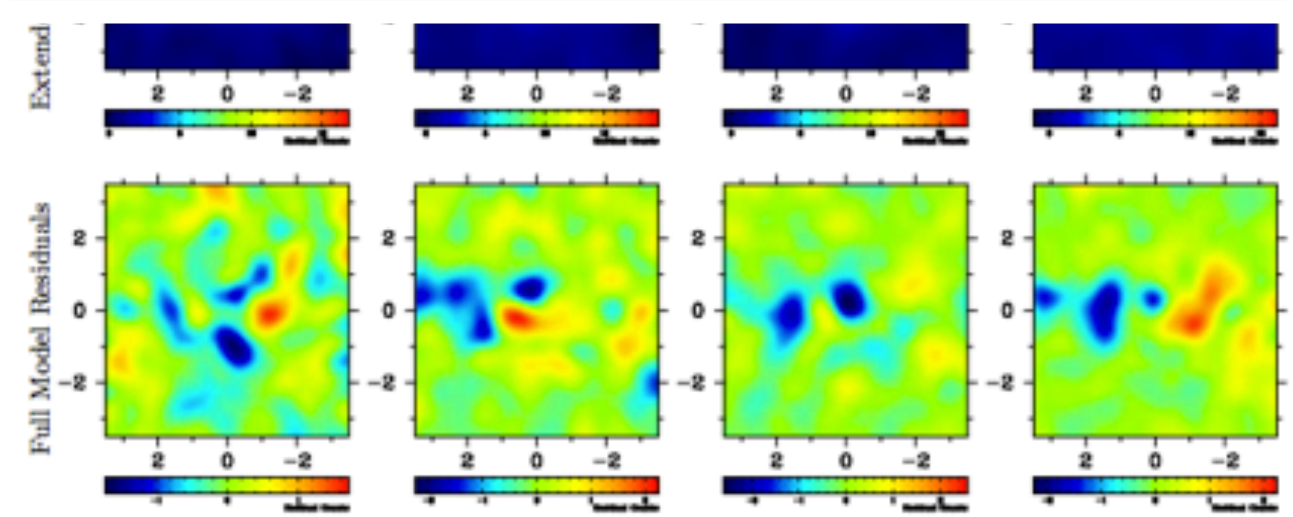


TABLE II. The best-fit TS, negative log likelihoods, and $\Delta\mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

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



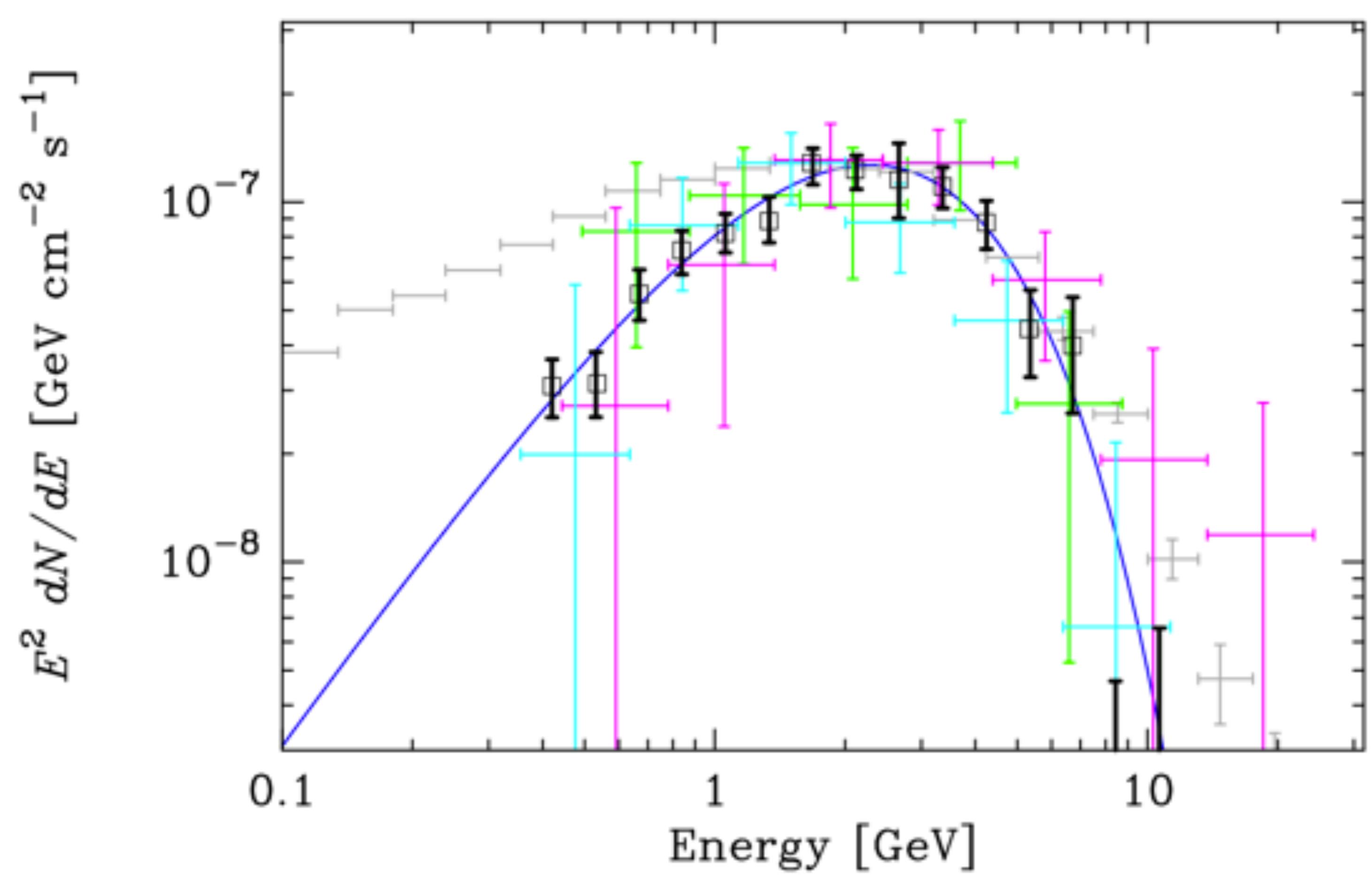
- Dark Matter creates an excellent statistical fit to both the morpholog and spectrum of the residual

- Of course dark matter predictions are somewhat malleable

See Next Talk by Chris Gordon

Abazajian & Kaplinghat

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

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

See Next Talk by Chris Gordon

Abazajian (2011)

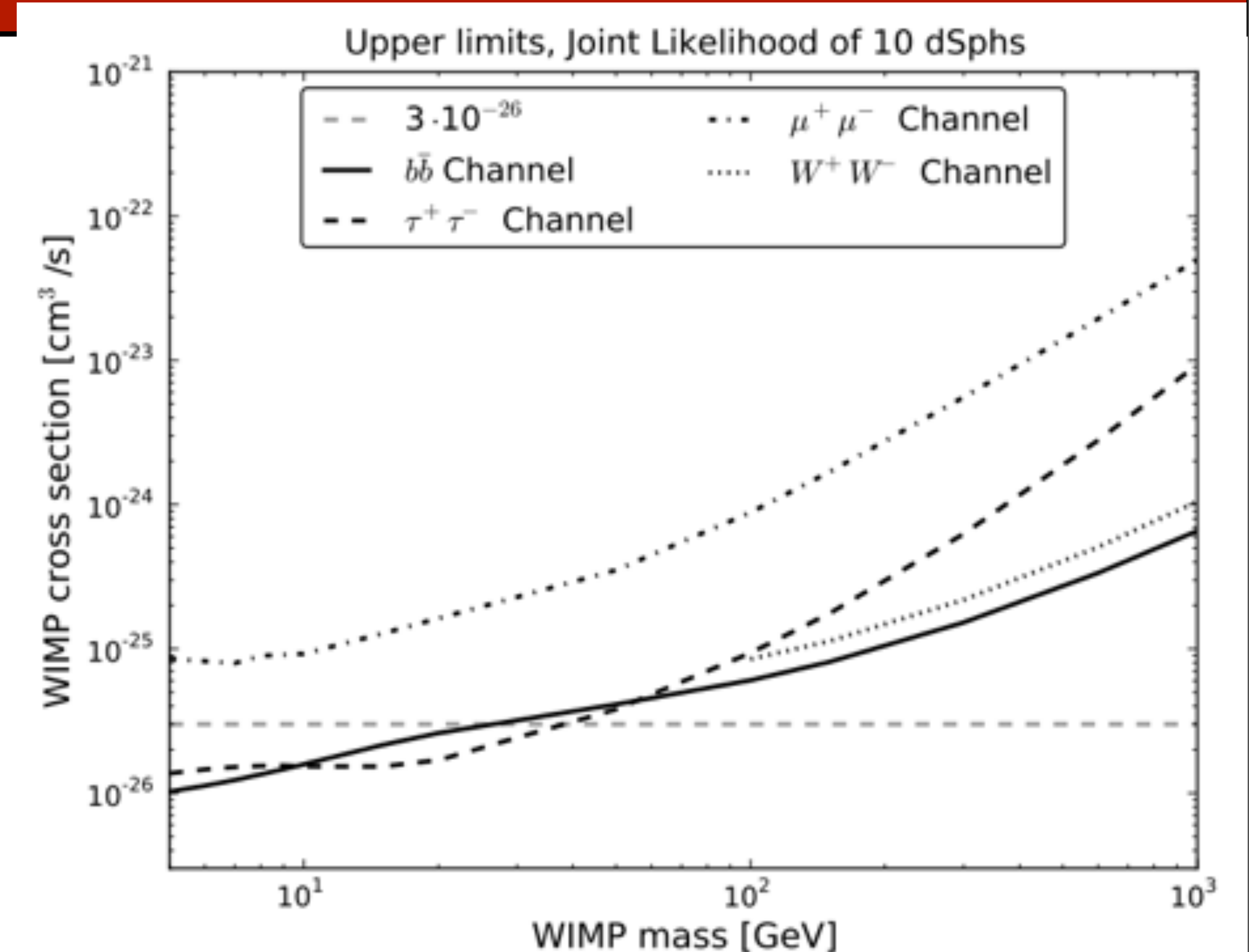
Where Do We Go From Here?

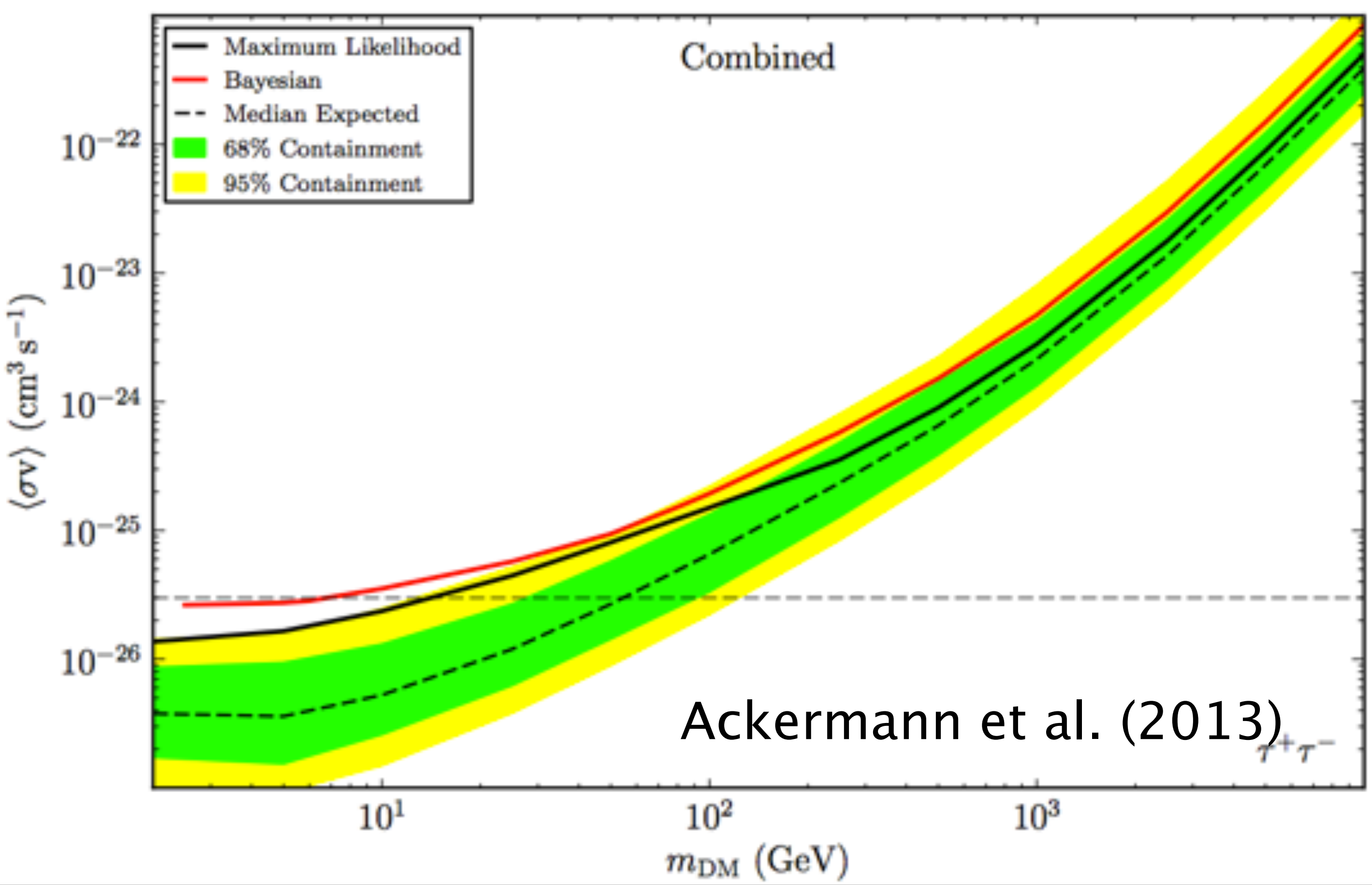
- Personal Opinion: It's not clear that new data from the GC will greatly improve our measurements of the GC excess – at least not in any way which can distinguish dark matter and MSPs

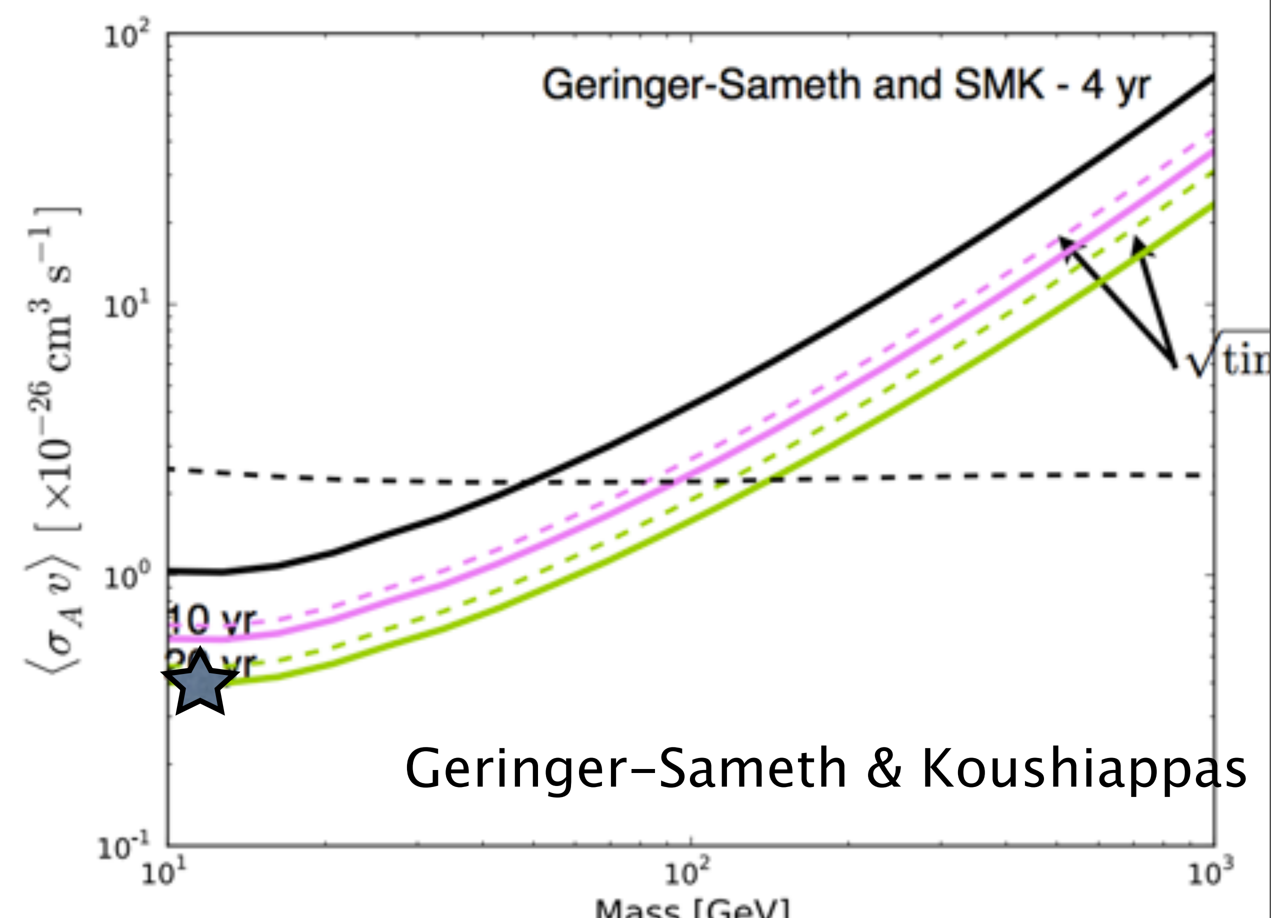
Where Do We Go From Here?

- 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



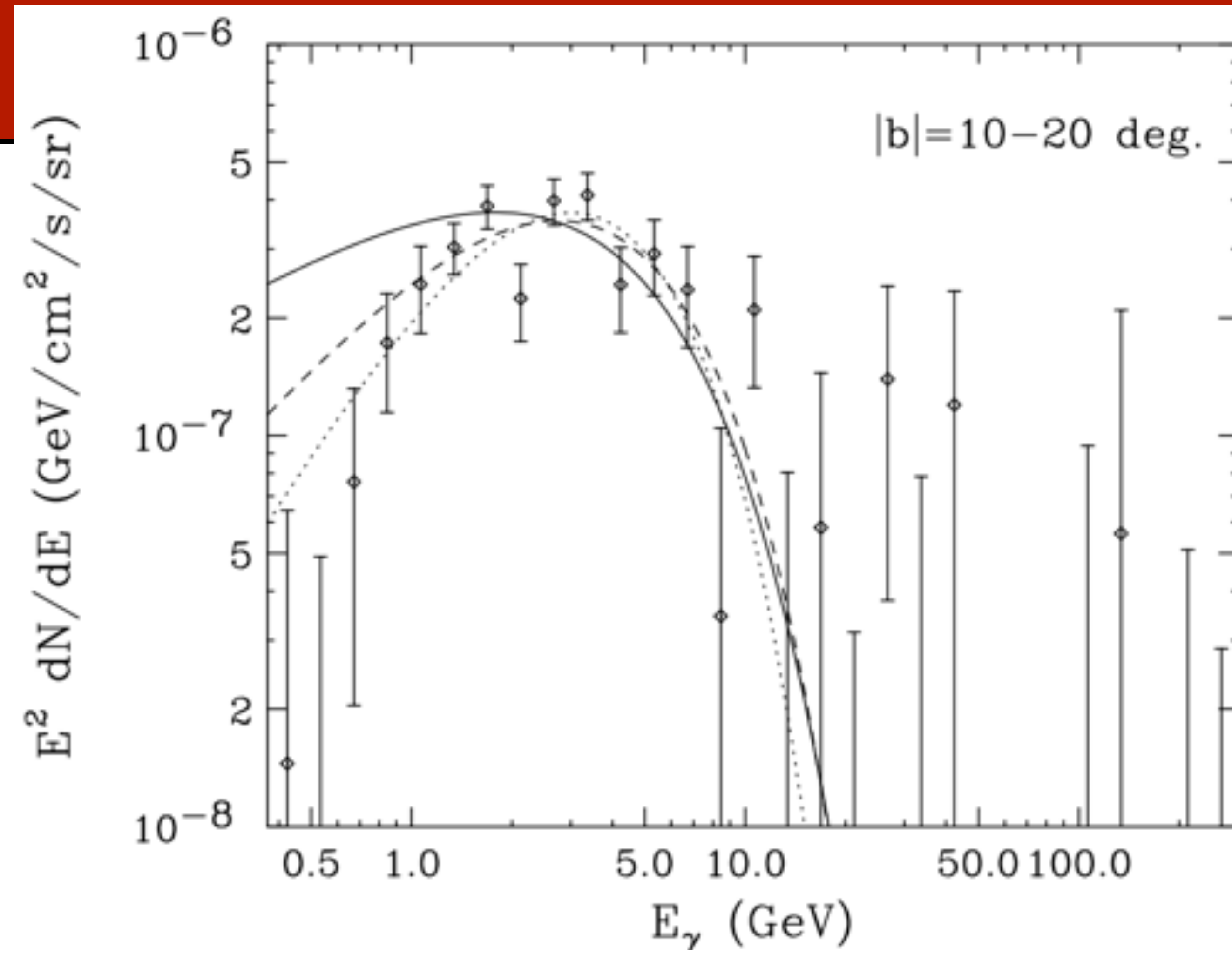


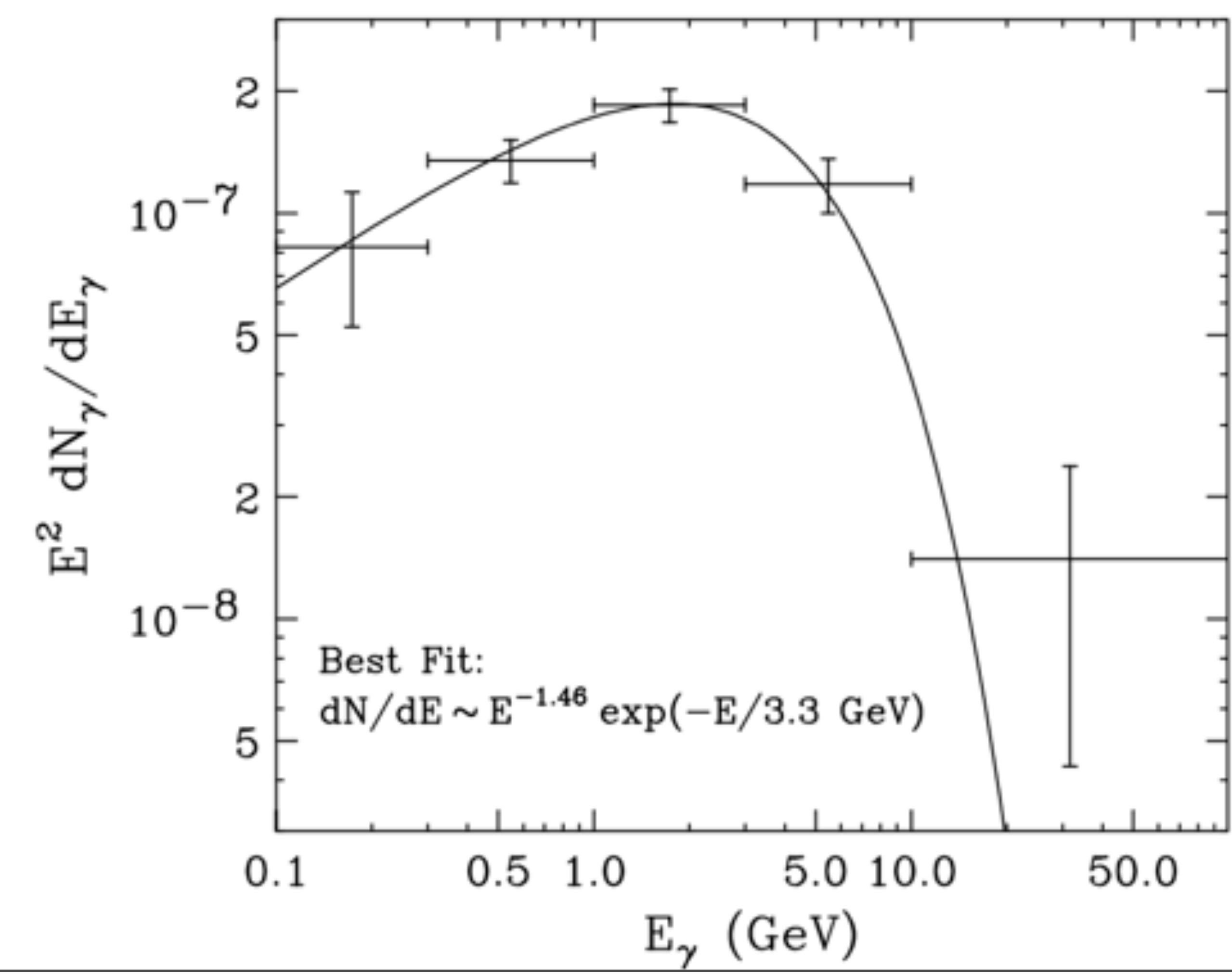


Fermi Bubbles?

- The spectrum of millisecond pulsars does not fit the observed ϒ-ray spectrum of the Fermi bubbles

- Smaller background contamination = Small possibility that mis-subtraction of point sources can solve this





Hooper et al.

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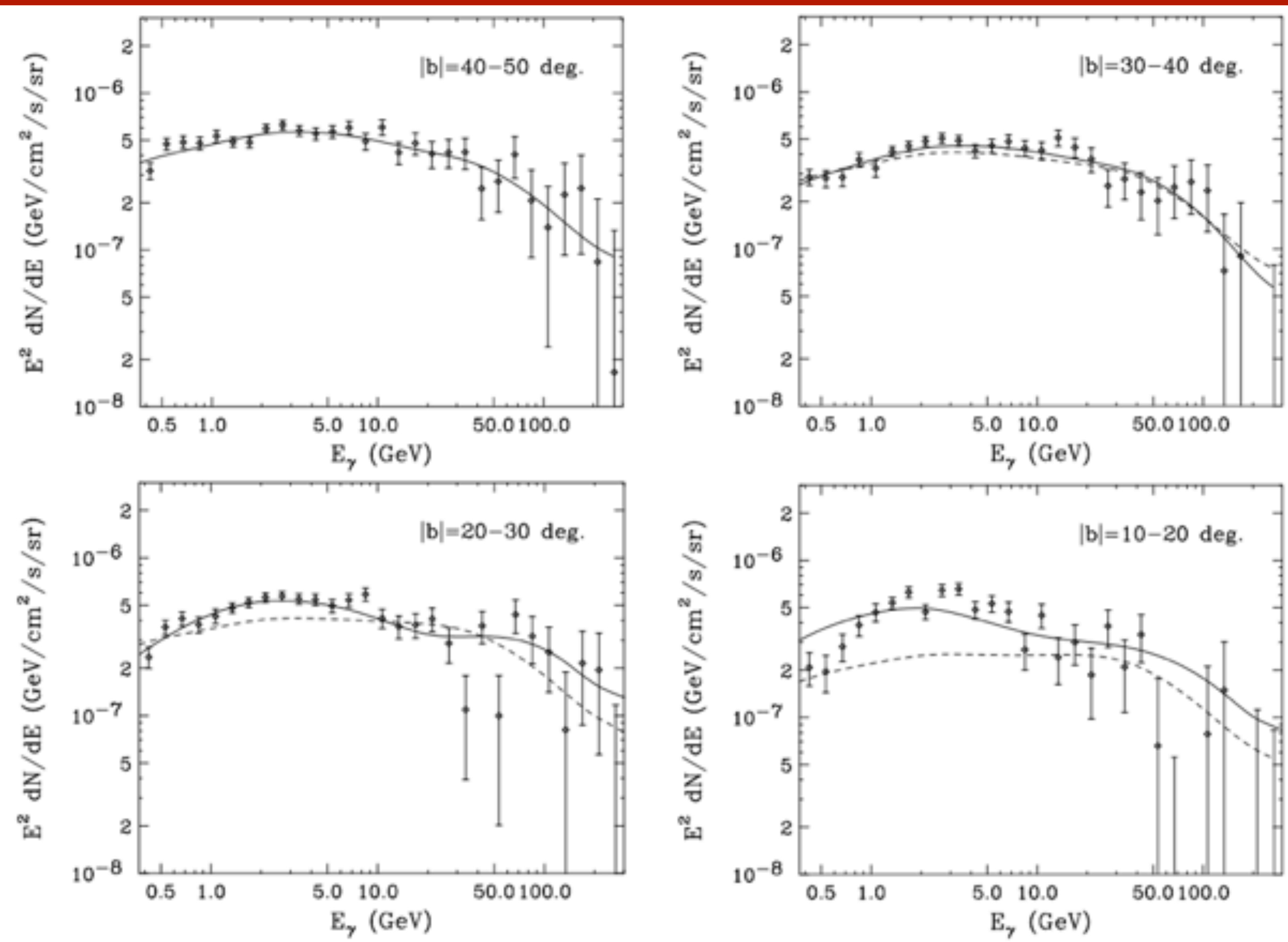
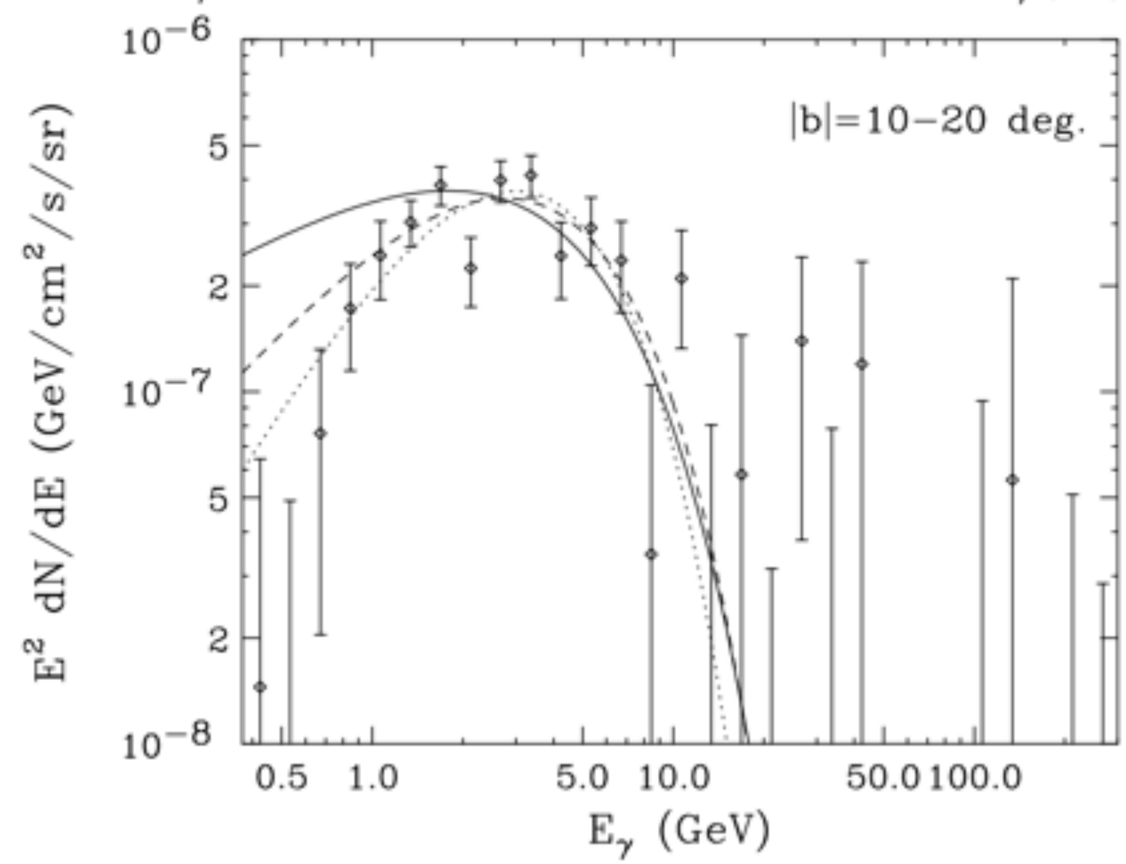


Hooper & Slatyer



Hooper et al.

Radio Observations of the Galactic Center

Name	Alternative Name	$\alpha^{1.4GHz}_{0.33GHz}$	$\alpha^{4.8GHz}_{1.4GHz}$	$\alpha^{>}_{4.8GHz}$	References
G0.08+0.15	Northern Thread	-0.5	-0.5	-2.0	Lang et al. (1999b); LaRosa et al. (2000)
G358.85+0.47	The Pelican	-0.6	-0.8 ± 0.2	-1.5 ± 0.3	Kassim et al. (1999); Lang et al. (1999a)
G359.1-0.02	The Snake	-1.1	~0.0	*	Nicholls & Gray (1993); Gray et al. (1995)
G359.32-0.16	——	-0.1	-1.0	——	LaRosa et al. (2004)
G359.79+0.17	RF-N8	-0.6 ± 0.1	-0.9 to -1.3	——	Law et al. (2008a)
G359.85+0.39	RF-N10	0.15 to -1.1*⋆	-0.6 to -1.5*⋆	——	LaRosa et al. (2001); Law et al. (2008a)
G359.96+0.09	Southern Thread	-0.5	——	——	LaRosa et al. (2000)
G359.45-0.040	Sgr C Filament	-0.5	——	-0.46 ± 0.32	Liszt & Spiker (1995); Law et al. (2008a)
G359.54+0.18	Ripple	——	-0.5 to -0.8	——	Law et al. (2008a)
G359.36+0.10	RF-C12	——	-0.5 to -1.8	——	Law et al. (2008a)
G0.15+0.23	RF-N1 (in Radio Arc)	——	+0.2 to -0.5	——	Law et al. (2008a)
G0.09-0.09	——	——	——	0.15	Reich (2003)

*Two very different values exist in the literature for the high frequency spectrum of the Snake. Gray et al. (1995) cites a value of -0.2 ± 0.2, while a more recent analysis by Law et al. (2008b) yields $\alpha^{8.33}_{4.8GHz}$ = -1.86 ± 0.64

*Spectrum is highly position dependent, but shows a clear trend towards steeper spectral slopes at high frequencies for any given position

Linden et al. (2011)

Radio Observations of the Galactic Center

Name	Alternative Name	$\alpha_{0.33GHz}^{1.4GHz}$	$\alpha_{1.4GHz}^{4.8GHz}$
G0.08+0.15	Northern Thread	-0.5	
G358.85+0.47	The Pelican		
G359.1-0.02	The Sna...		
G359.32-0.16			
G359.79+0...			

*Tw...

± 0.2, w...

*Spectru...

Astron. Astrophys. 200, L9–L12 (1988)

1988A&A...200L...9L

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Monoenergetic relativistic electrons in the galactic center

H. Lesch*, R. Schlickeiser, and A. Crusius

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Federal Republic of Germany

Received March 29, accepted May 27, 1988

Summary

... shown that the nonthermal radio spectra of the ... including Sgr A* and the extended com... Arc) is neither due to self-absorbed ... due to thermal absorption. A ... in which Sgr A* represents ... which propagate with ... function into the

$\delta\theta_{crit} = 2.6\cdot10^{9}\, S_M^{1/2}\, \nu_M^{-5/4}\, B^{1/4}$ arcseconds

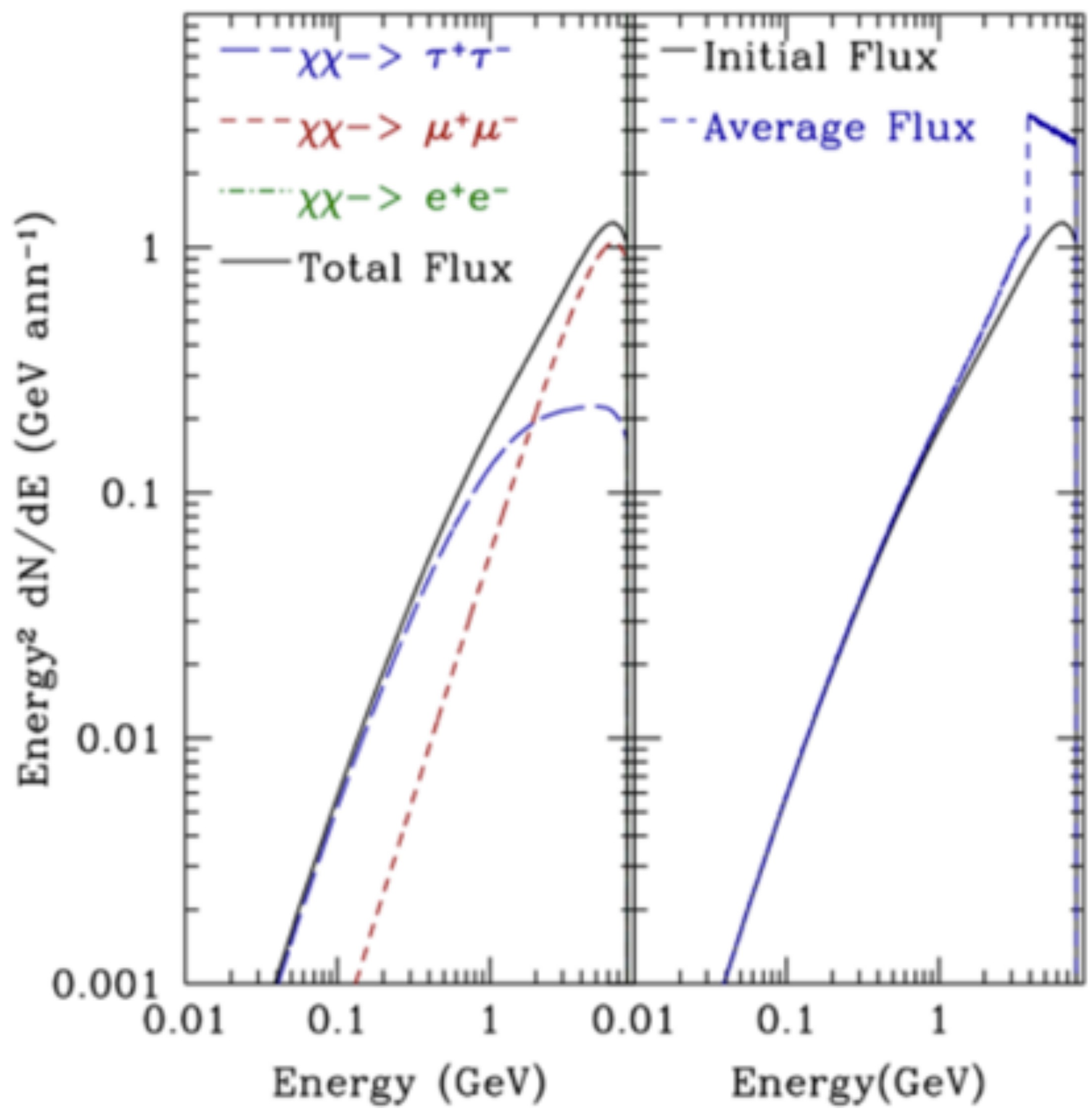
where S_M is the observed flux density for an self-absorbed source at a frequency ν_M an the magnetic field. With the flux density the 10 GHz (Reich et al., 1988) and a mag 10^{-2} G (Sofue and Fujimoto, 1988) we get

$\delta\theta_{crit} \simeq 4\cdot10^{-4}$ arcseconds

The source is resolved with an angu... ...conds (Reich et al., 1988). S... ...bly small structures to o... ...bridge...

Linden et al. (2011)

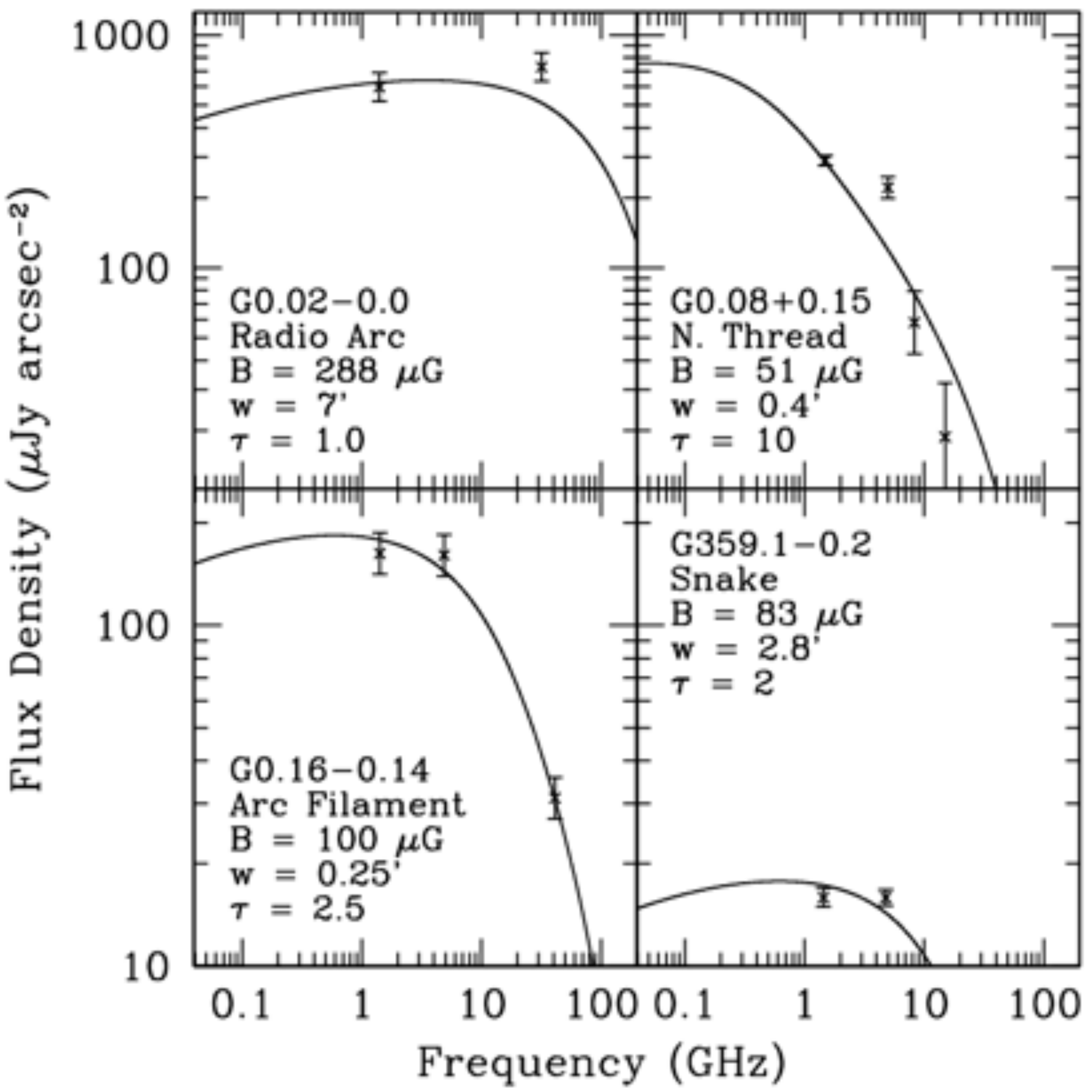
Radio Observations of the Galactic Center



Linden et al. (2011)

- Dark Matter can easily produce such a spectrum!

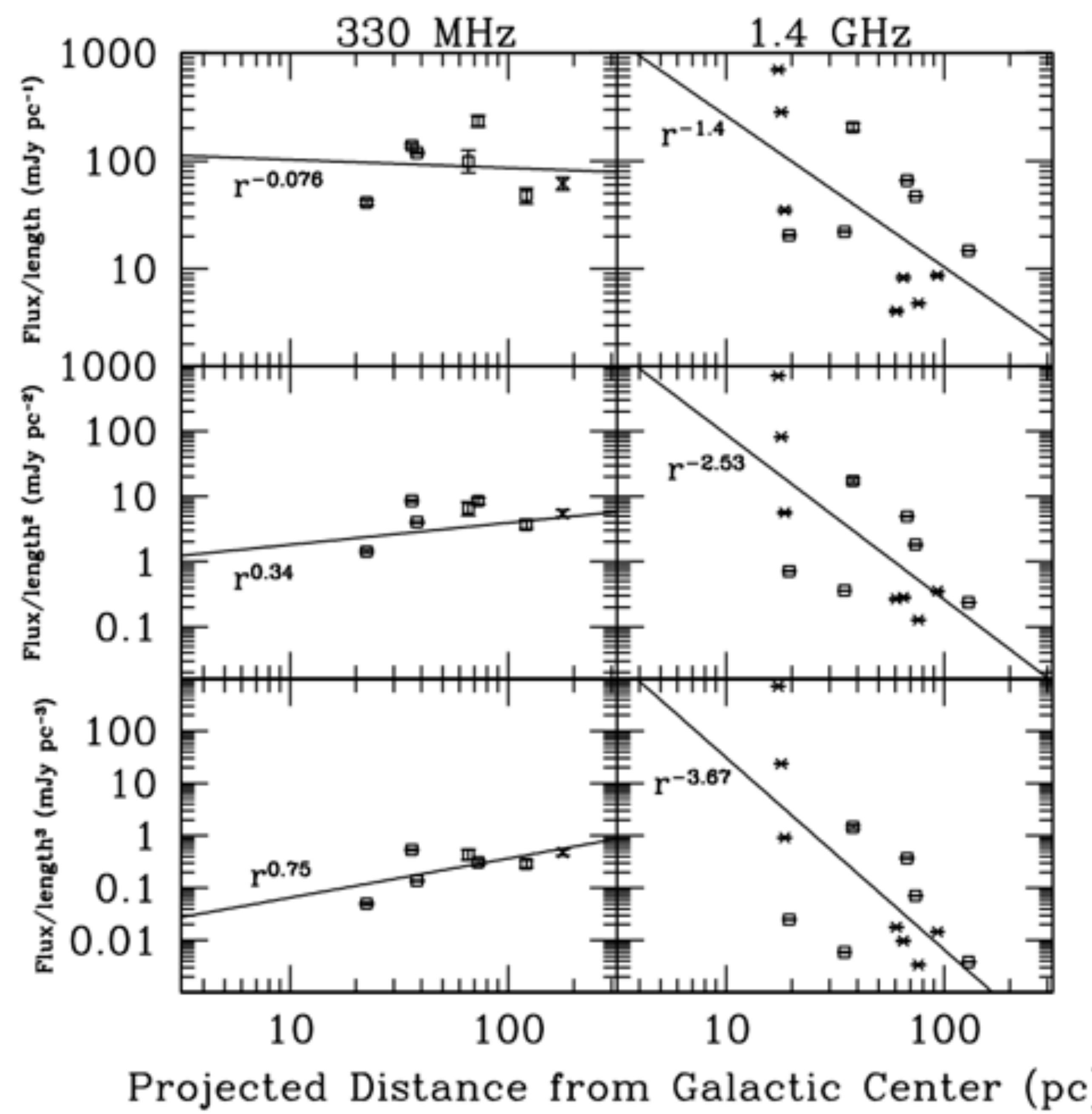
Radio Observations of the Galactic Center



Linden et al. (2011)

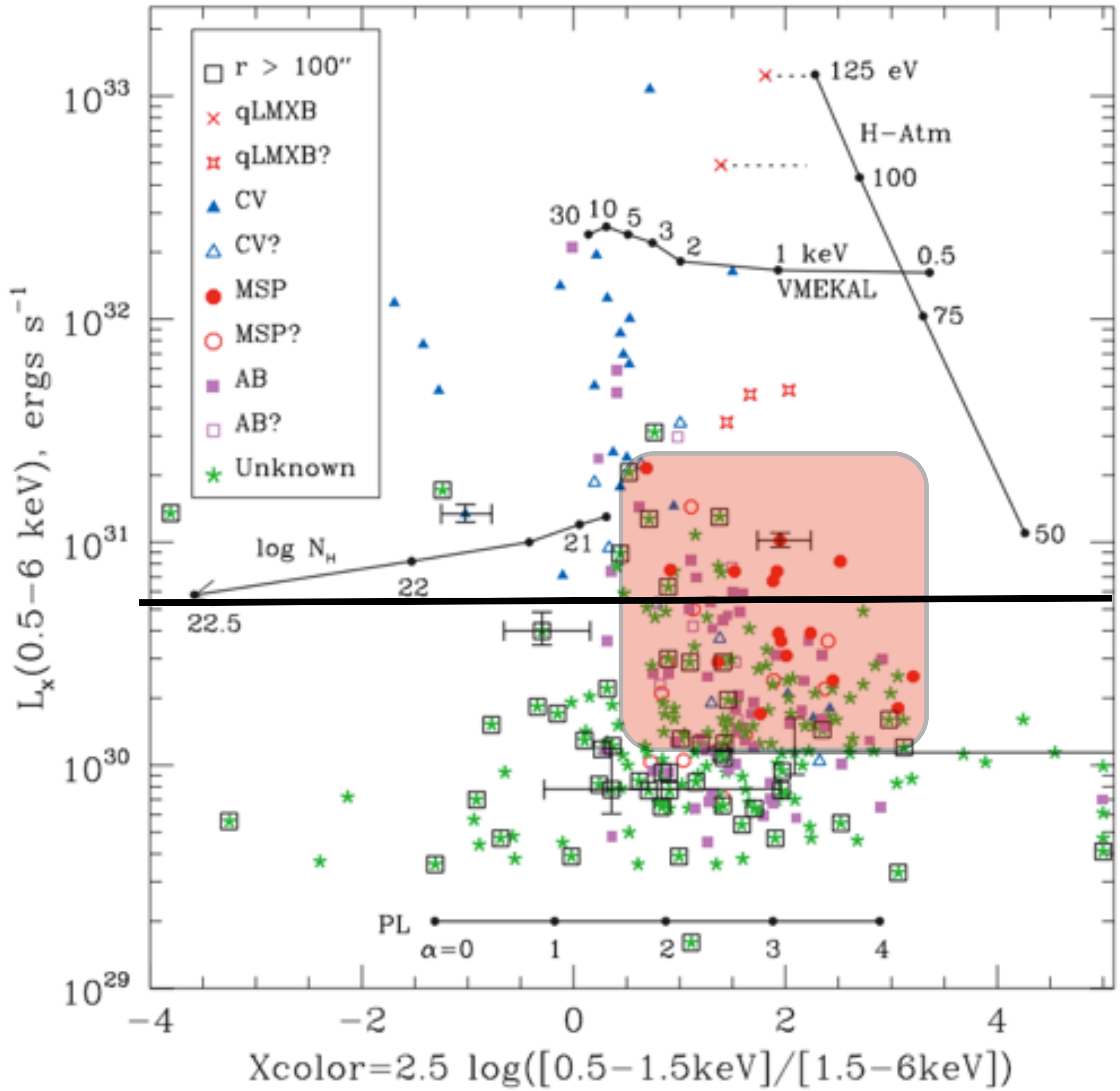
- The radial profile of radio filaments may suggest a dark matter injection morphology

- Hard spectrum, non-thermal radio filaments can be fit with dark matter annihilation



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?

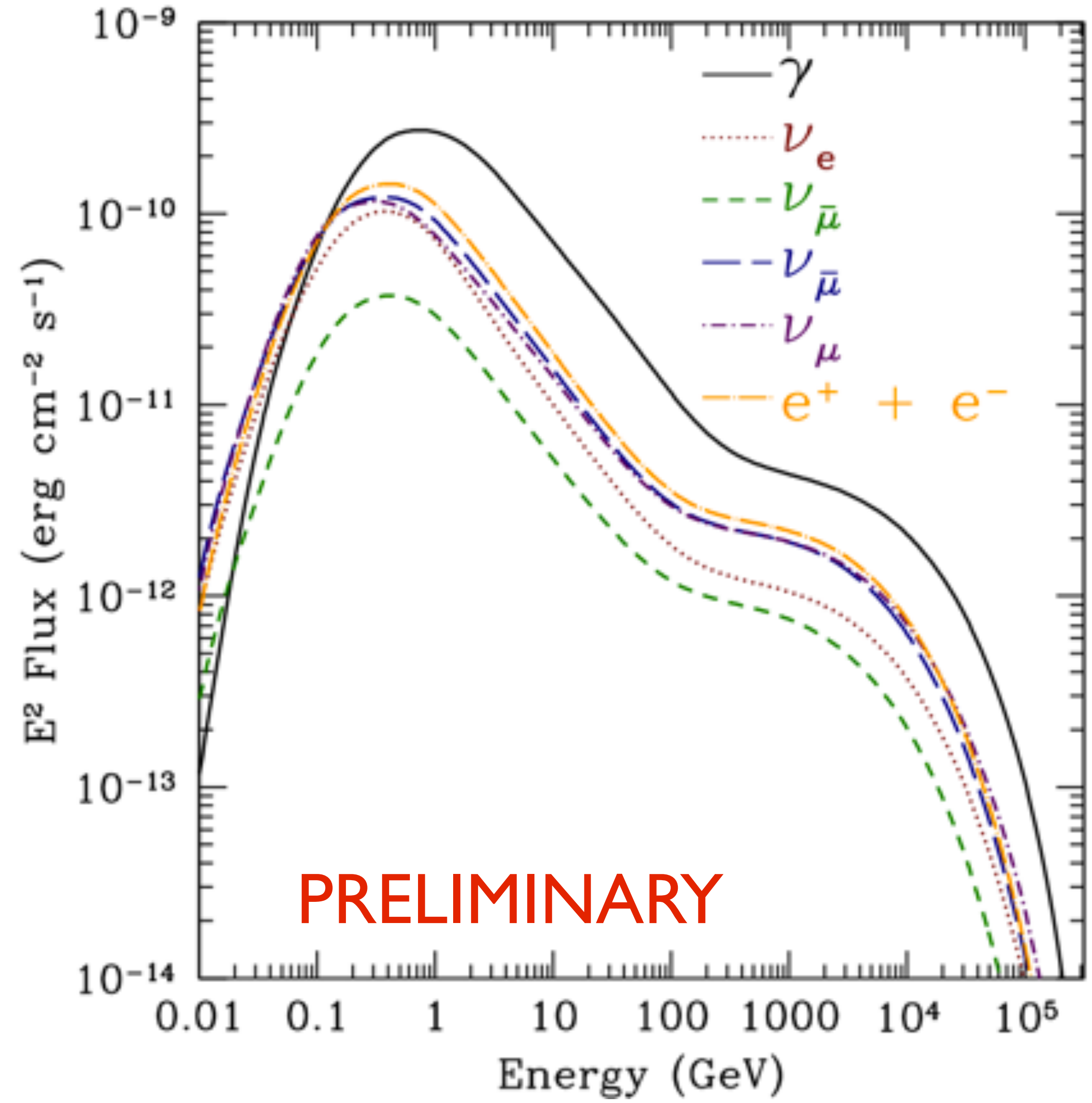


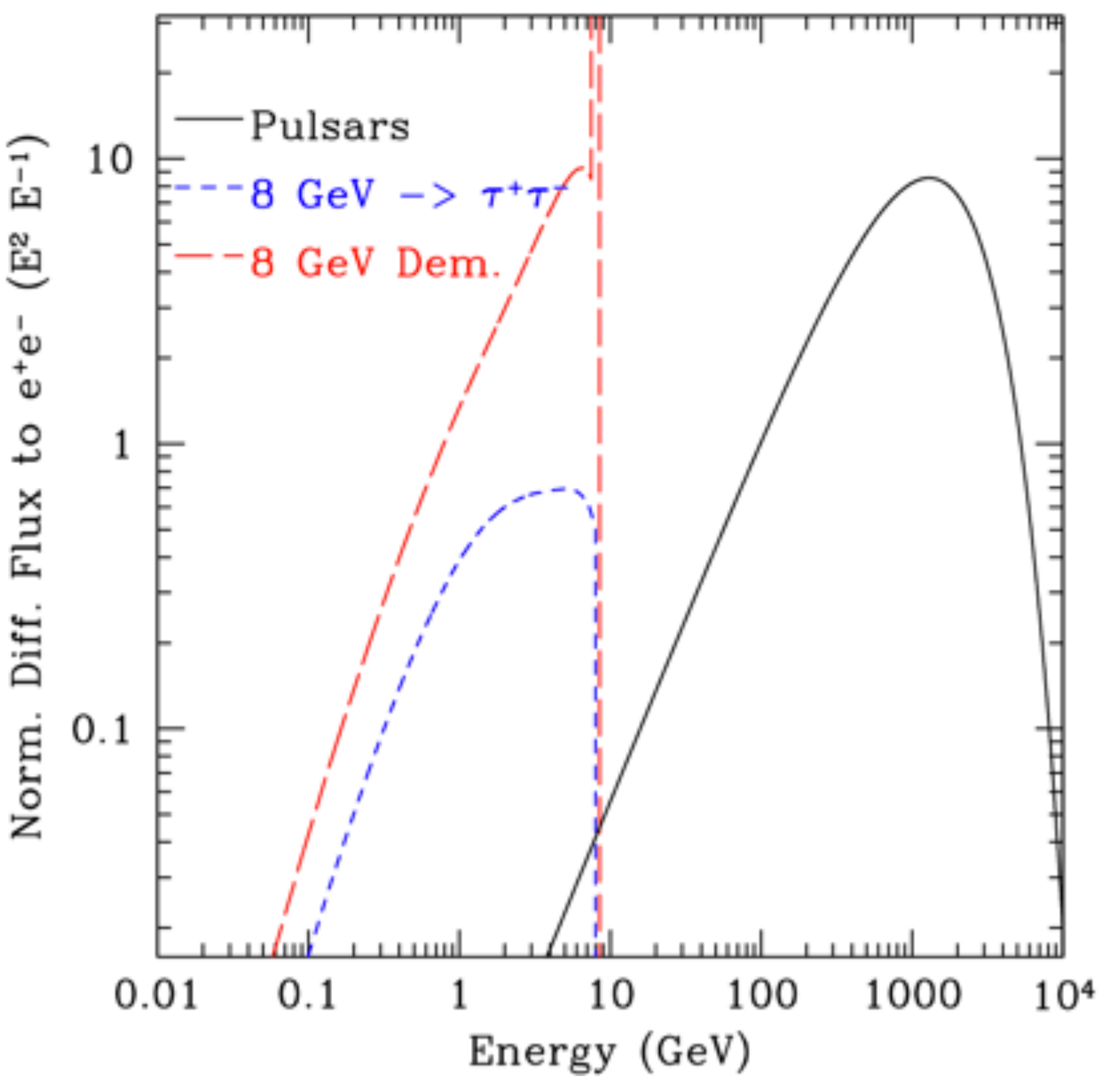
Heinke et al. (2006)

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?