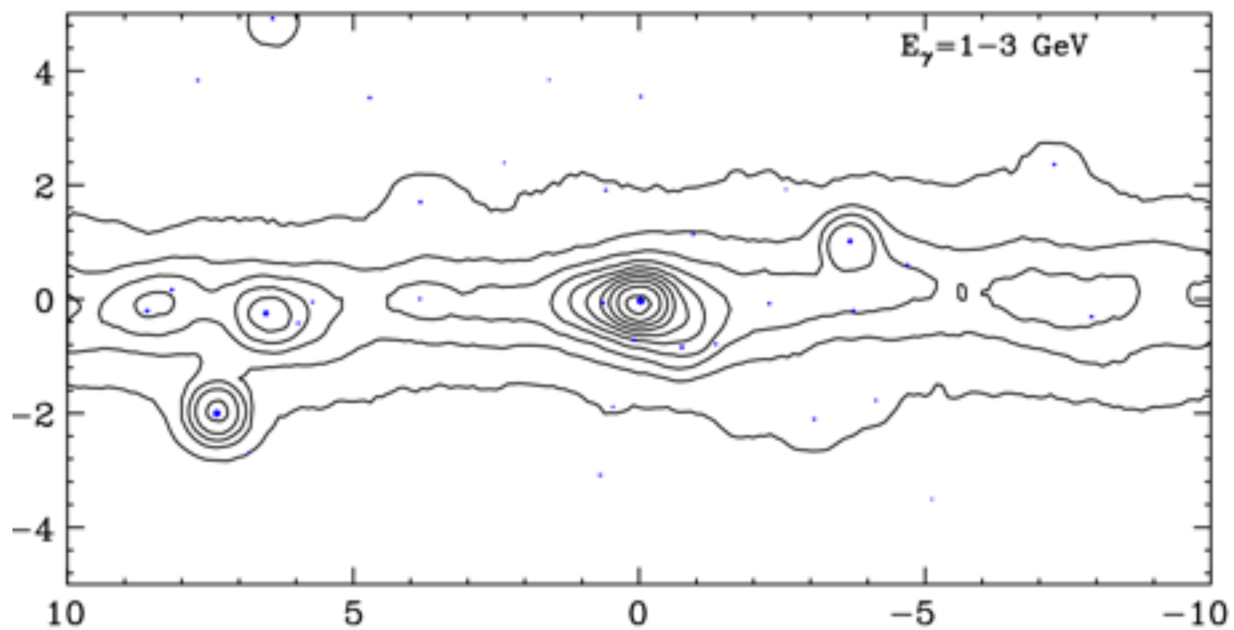
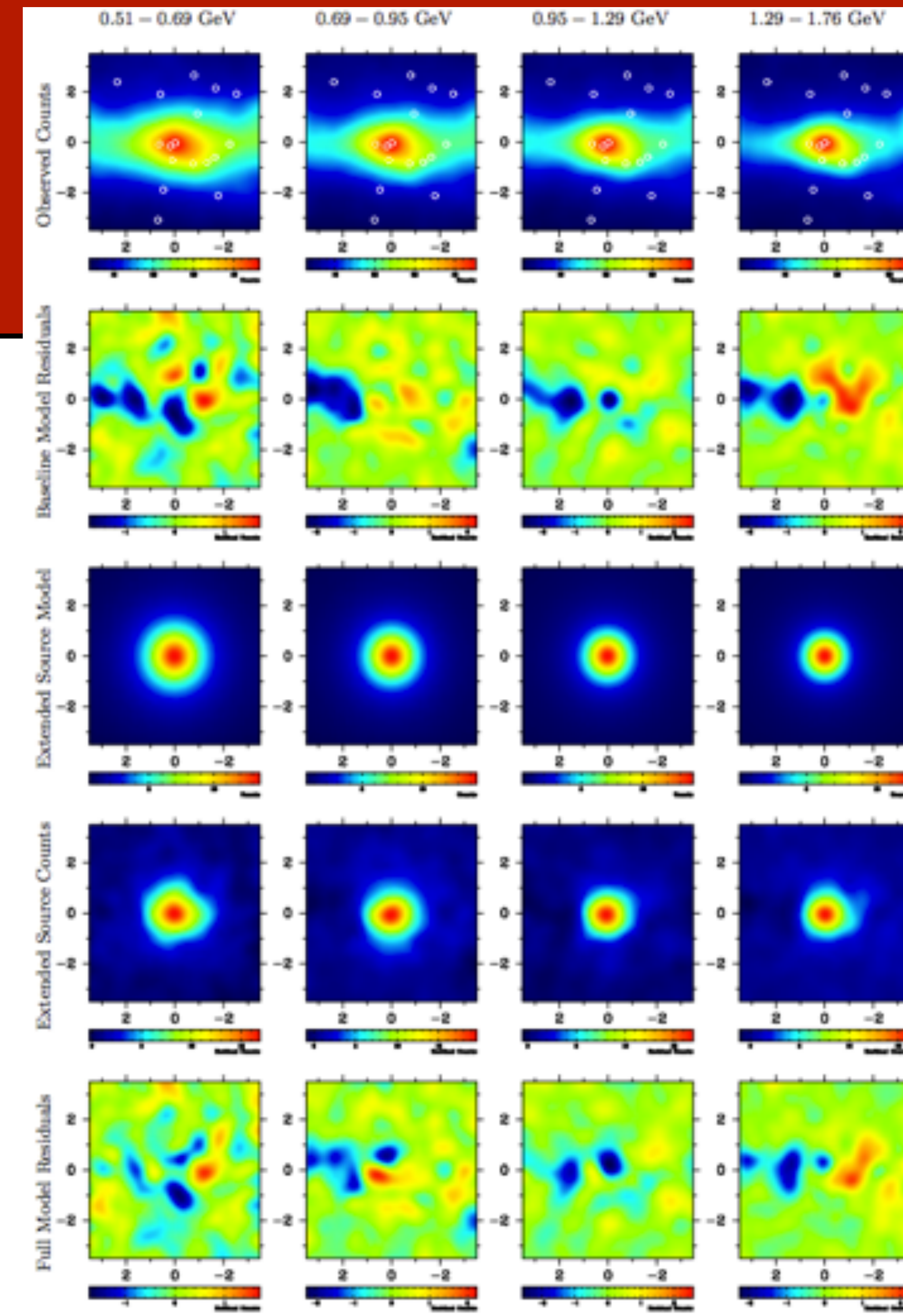
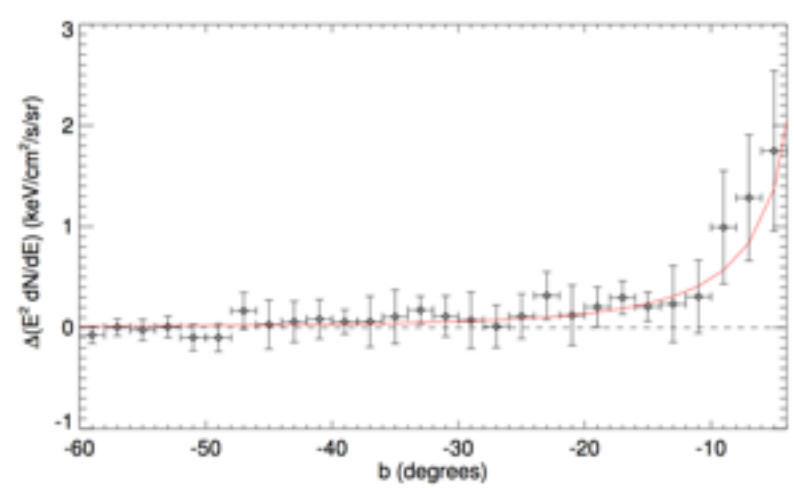
Dark Matter in the Galactic Center





Tim Linden

University of Chicago



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

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

IAU 303 - Santa Fe NM, October 4, 2013

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:

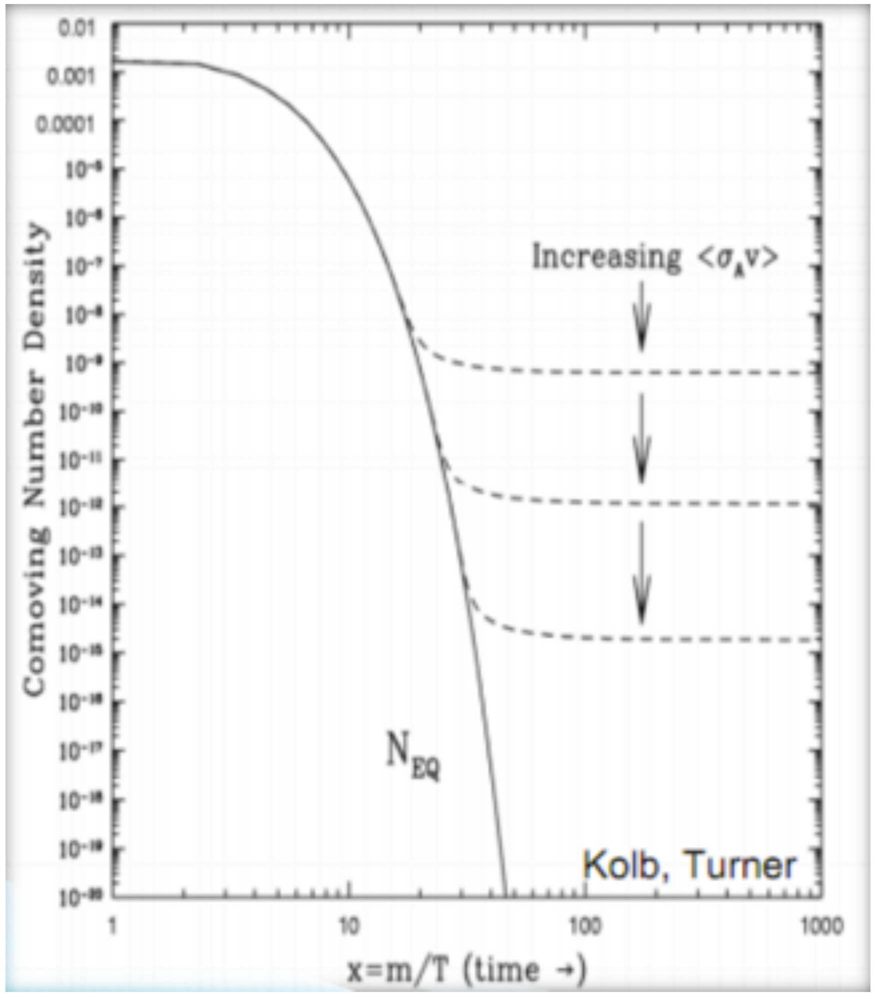
$$\rho_{NFW}(r) = \rho_c(\frac{R_c}{r})(1 + \frac{r}{R_c})^{-2}$$

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

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

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

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



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

$M_\chi \sim 100\ GeV$

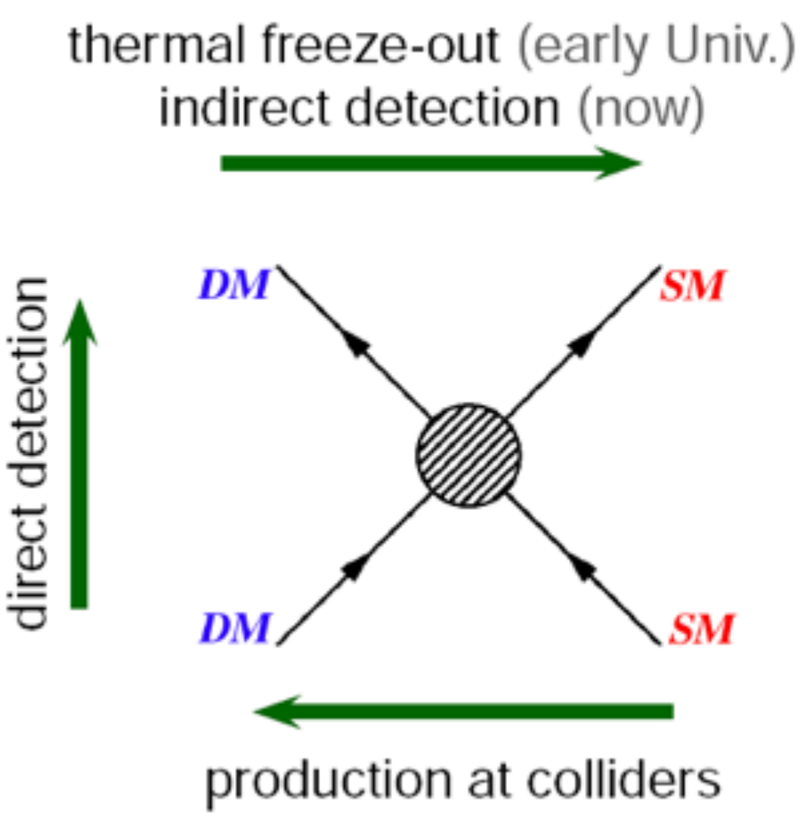
$g_\chi \sim 0.6$

Weak Force Values!

=>

$\Omega_h \sim 0.1$

Relic Density!



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 (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

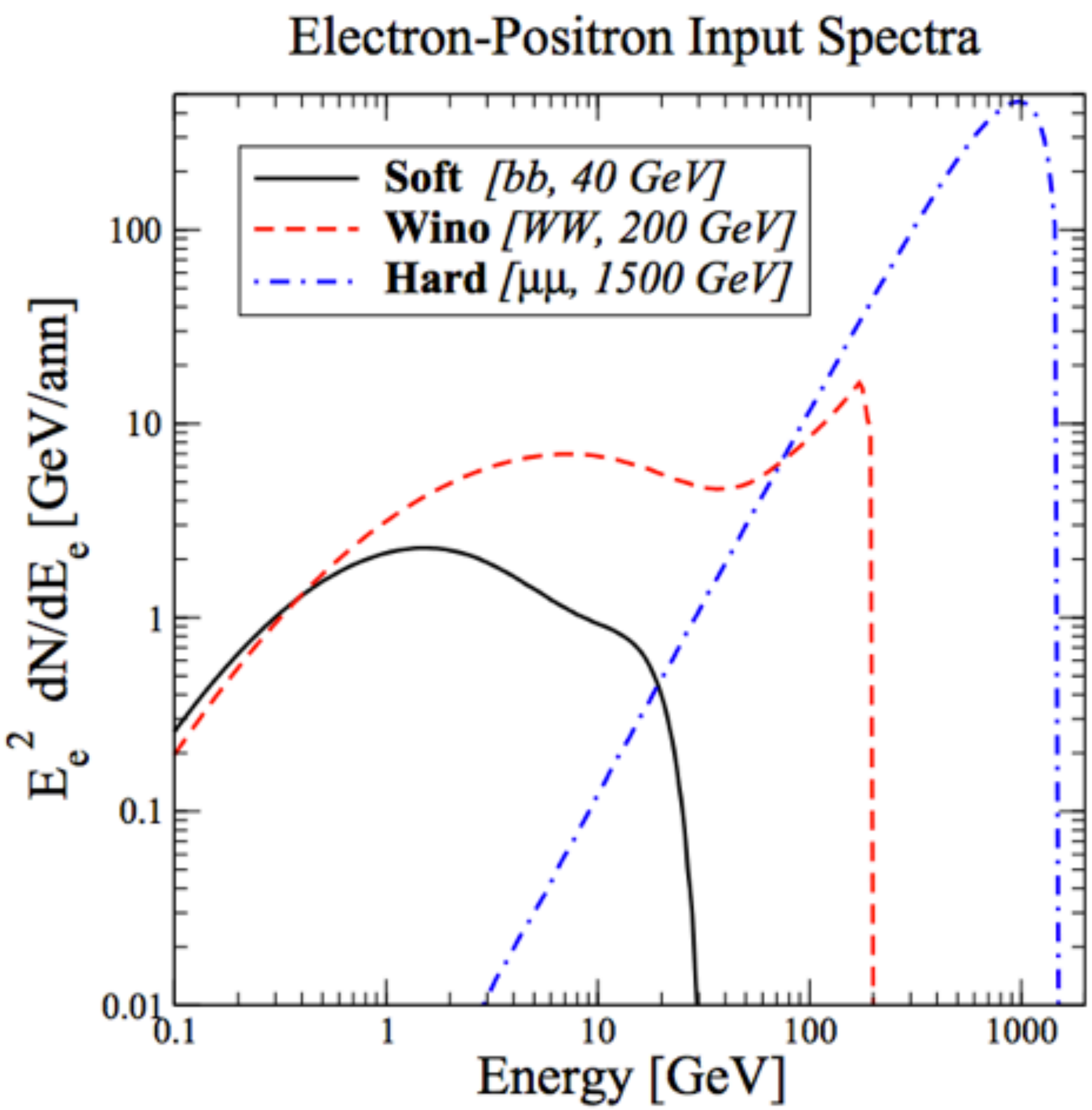
Completely Insignificant

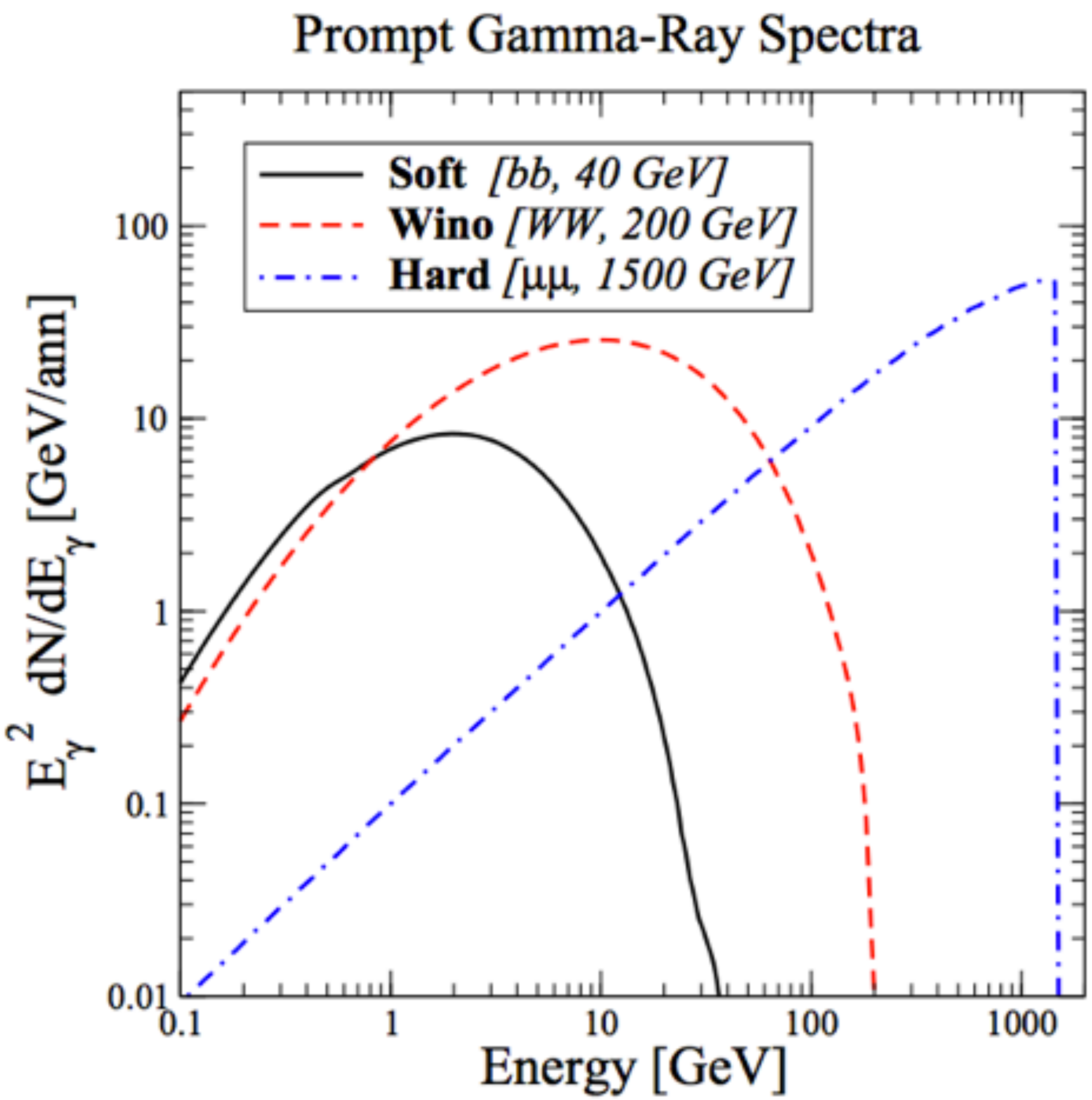
Using the NFW Profile and a standard 100 GeV dark matter particle annihilating to bb:

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

Dark Matter as a (High Energy) Source in the GC

Very Significant



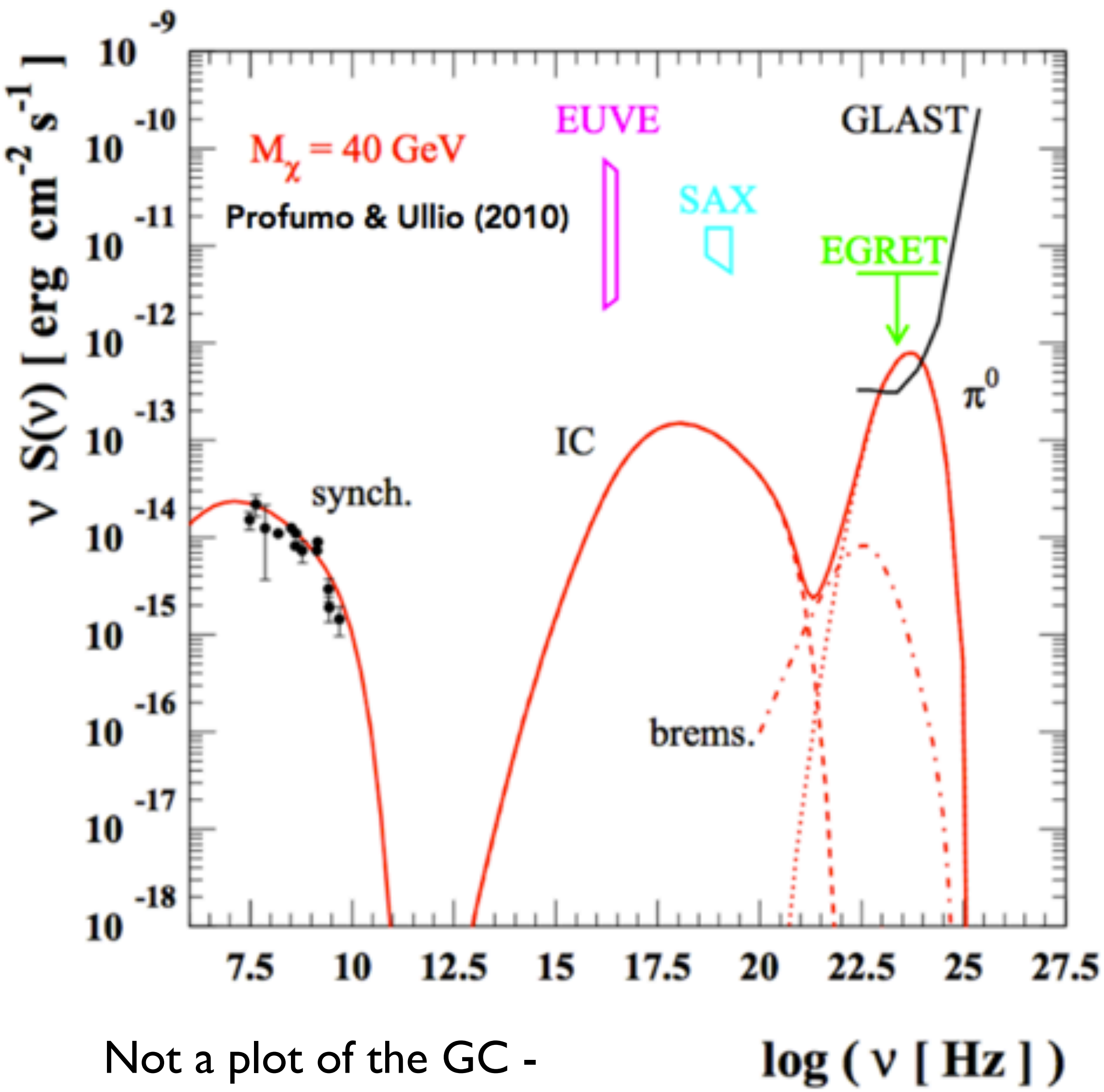


Linden et al. (2010)

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

Dark Matter as a (High Energy) Source in the GC

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

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

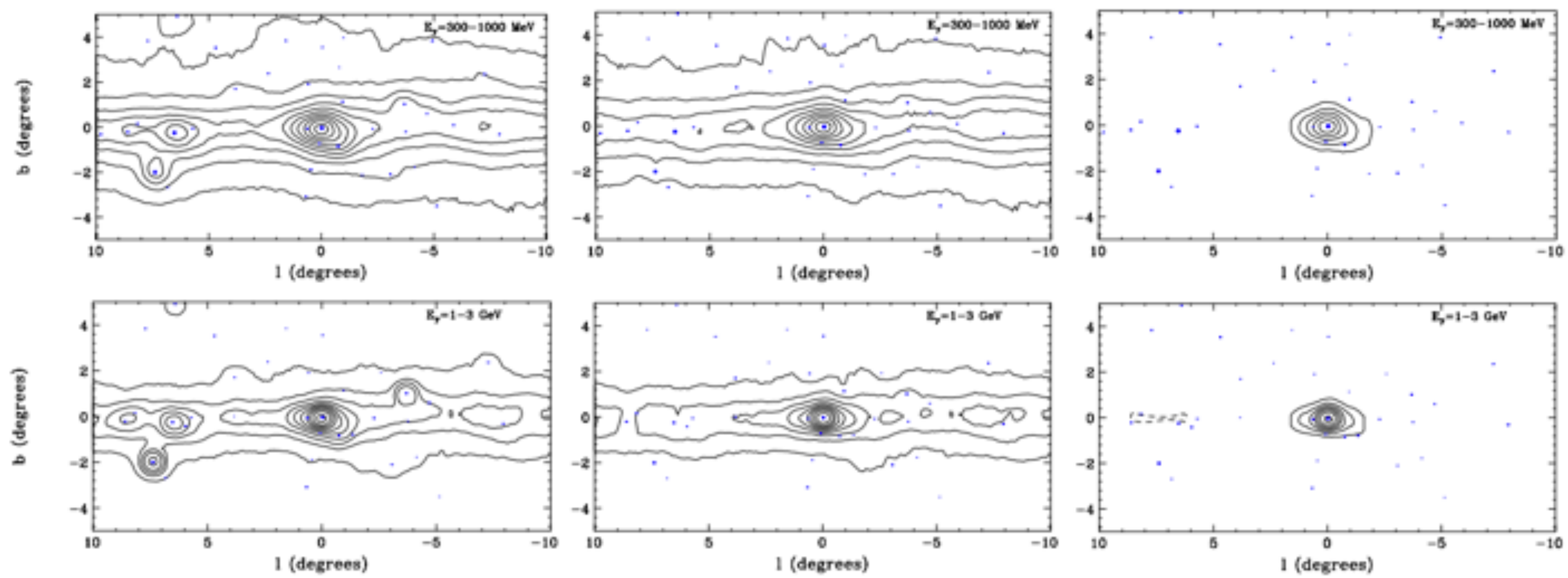
- This is equivalent to the number of photons expected in this energy bin from a "vanilla" 100 GeV dark matter candidate annihilating to bb with a cross-section **$\langle \sigma v \rangle = 1.6 \times 10^{-25}\ \mathrm{cm^3\ s^{-1}}$** (5 times our "magic" cross-section)

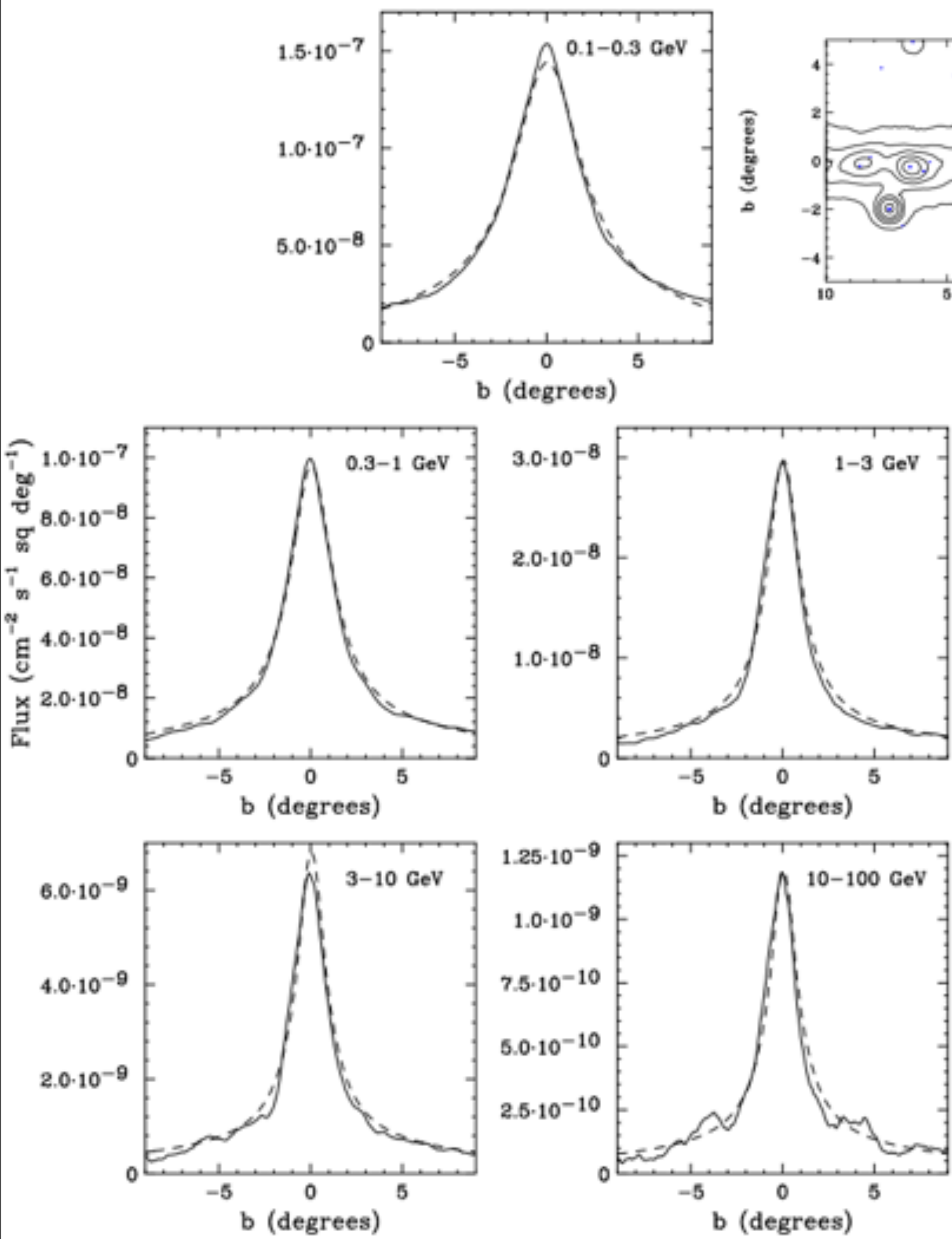
- There's no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the **most naive** prediction from dark matter simulations

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

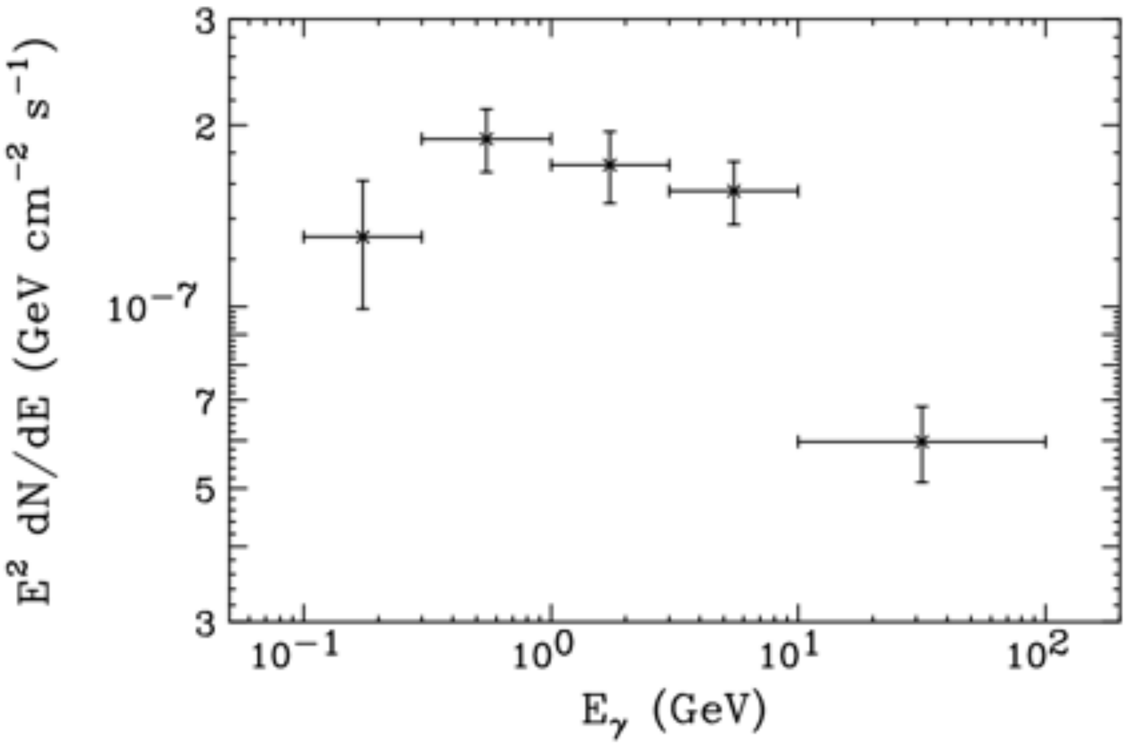




- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum
- This large residual at the center of the galaxy is a factor of 10 brighter than anything else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

Hooper & Linden (2011)

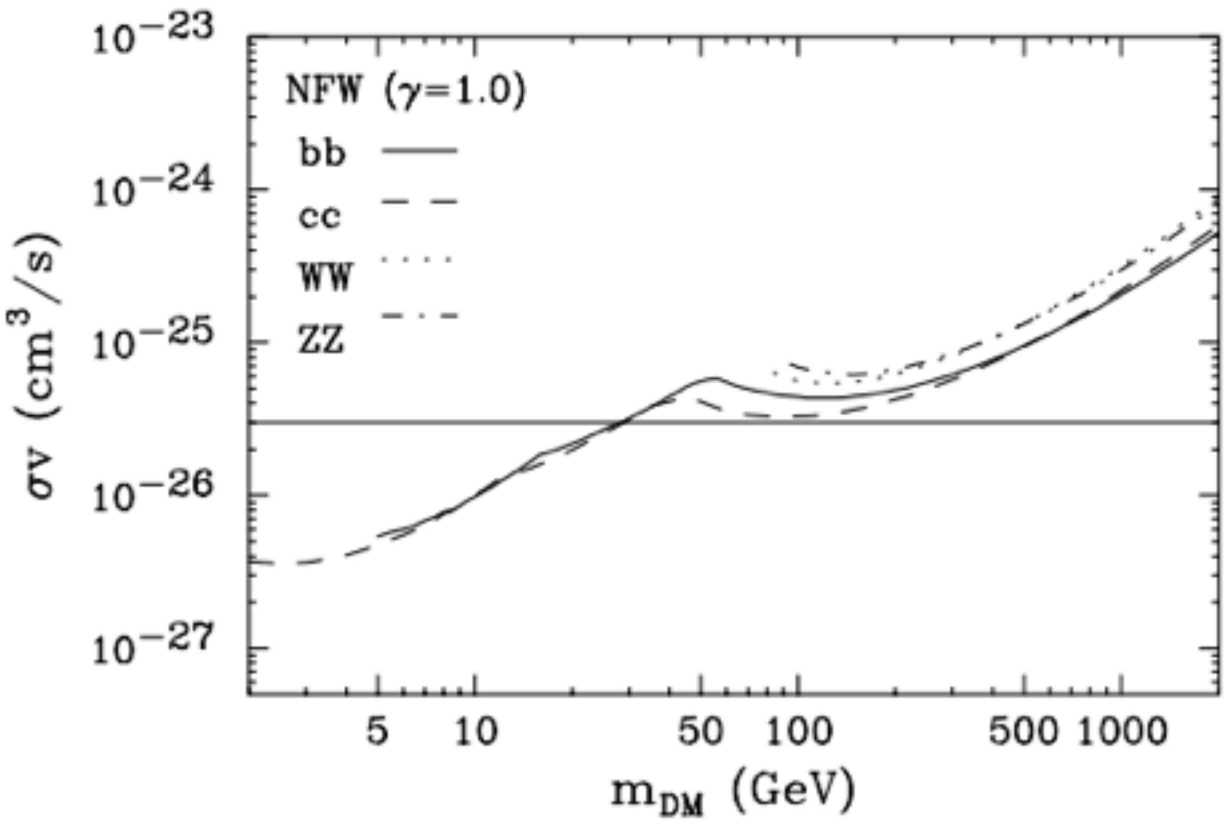
Dark Matter Limits in the Simplest Way Possible

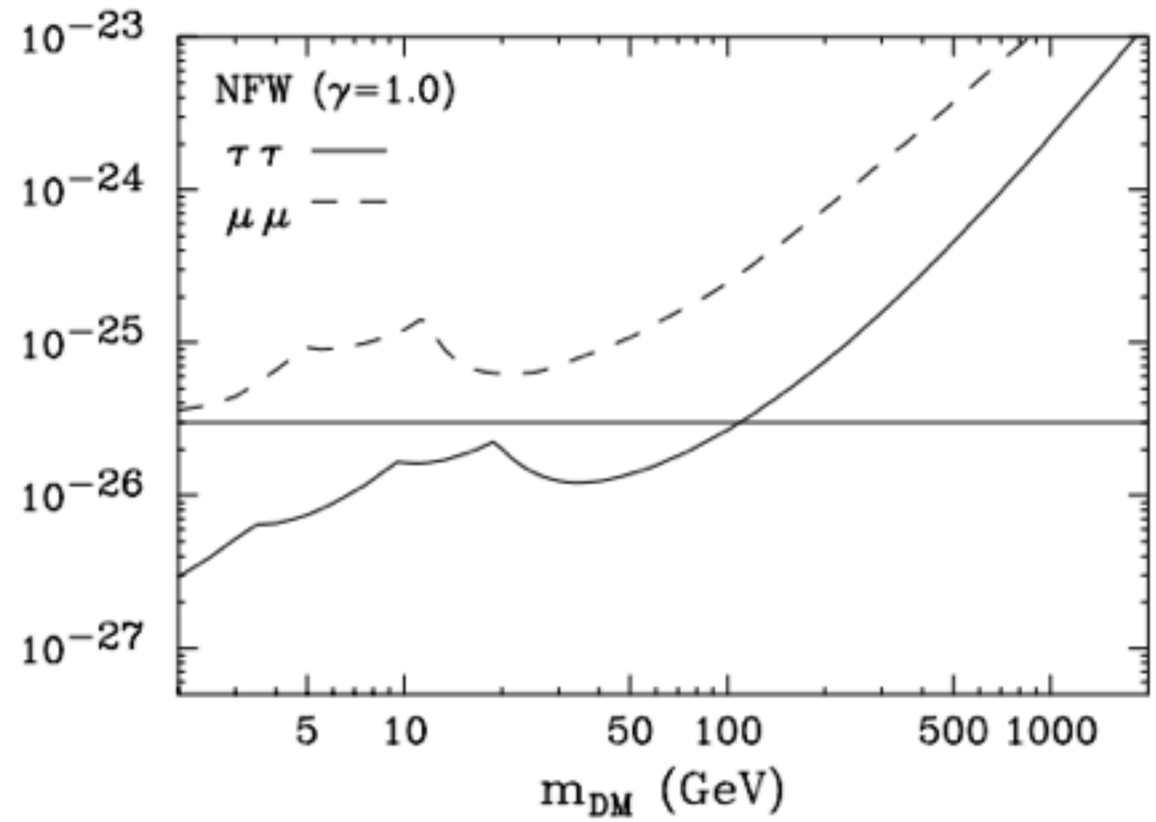


Hooper & Linden (2011)

- 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

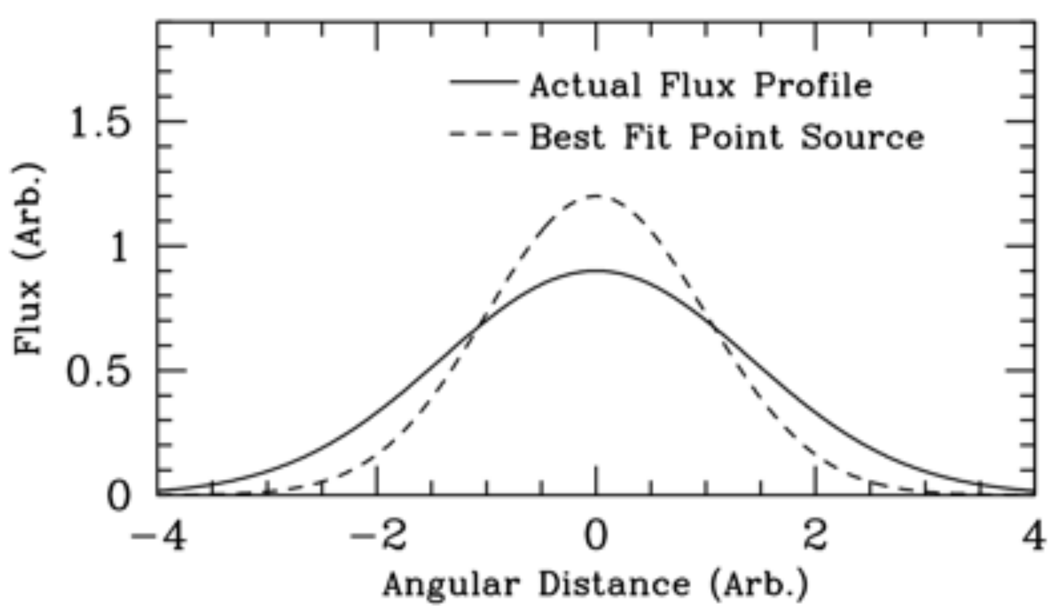


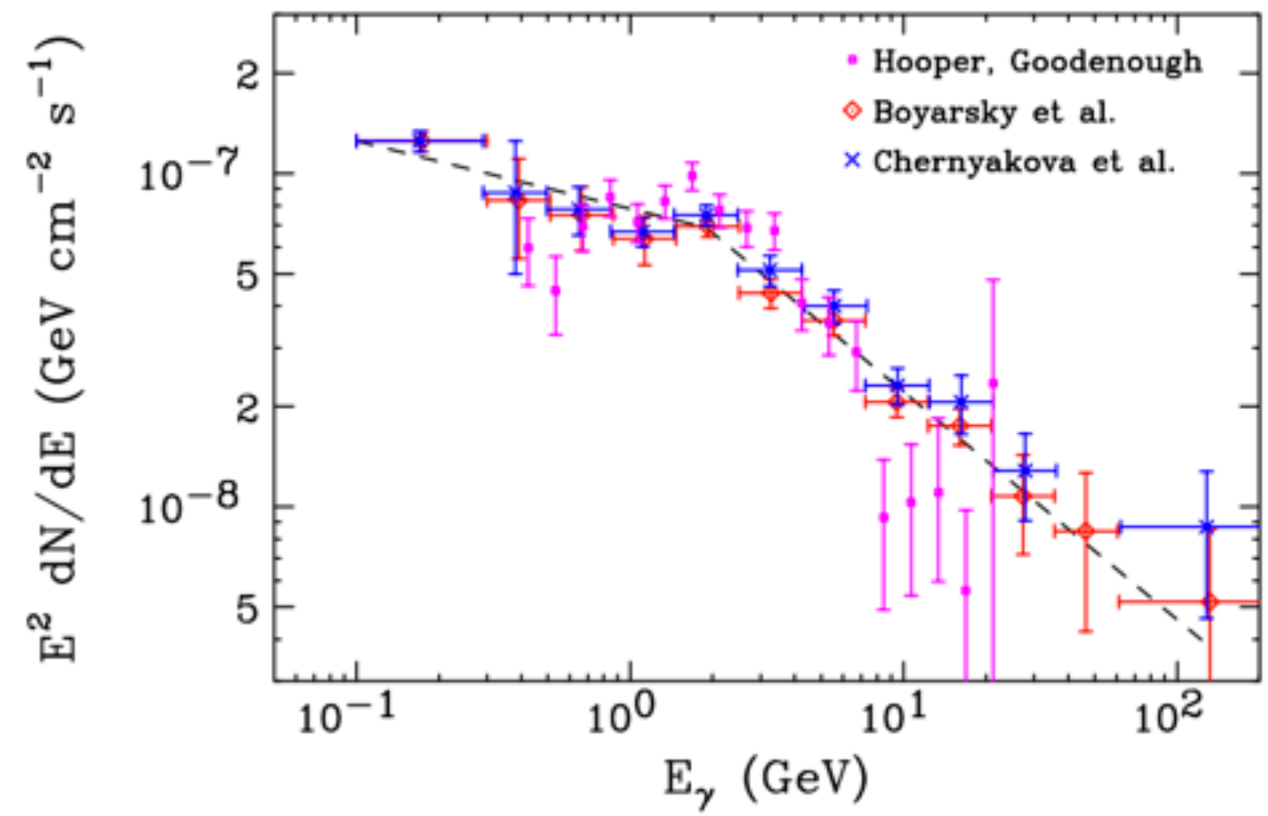


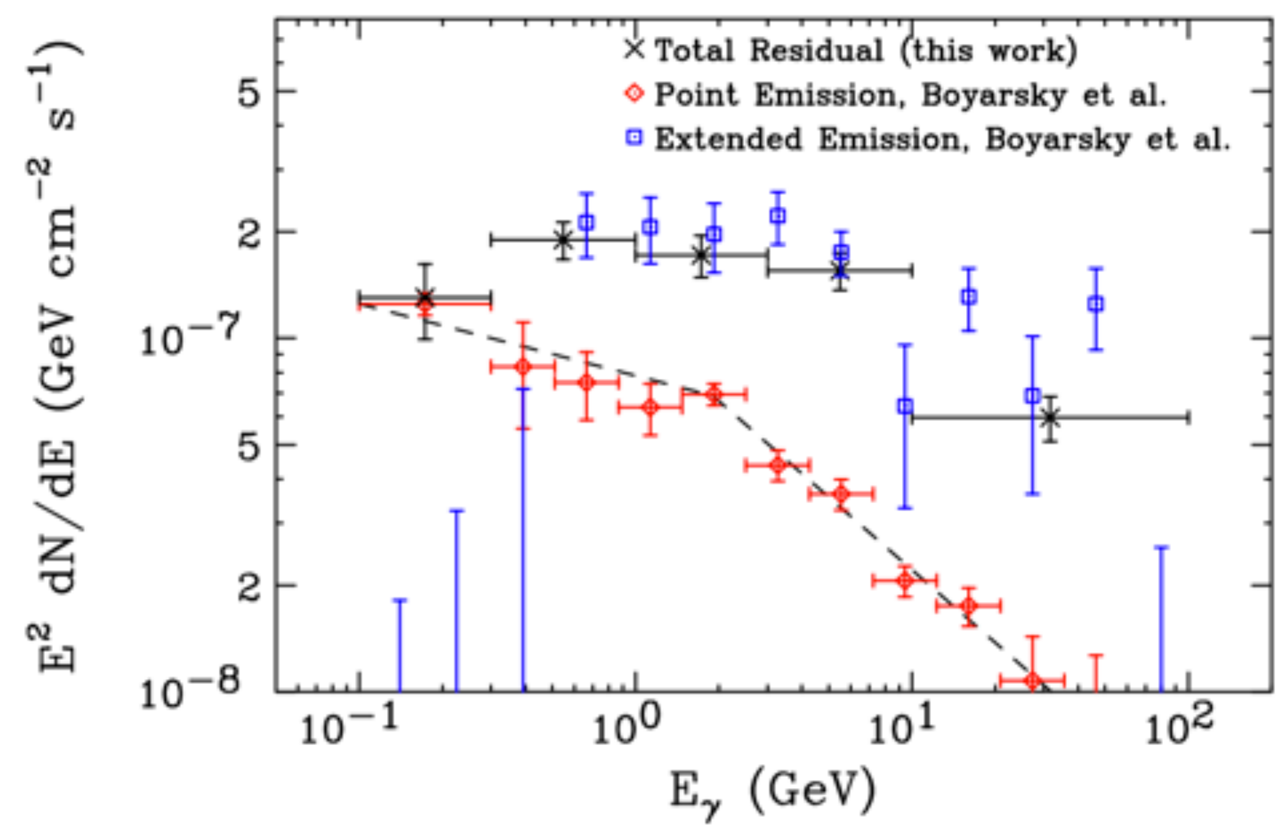
Is It A Point Source?

- 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)

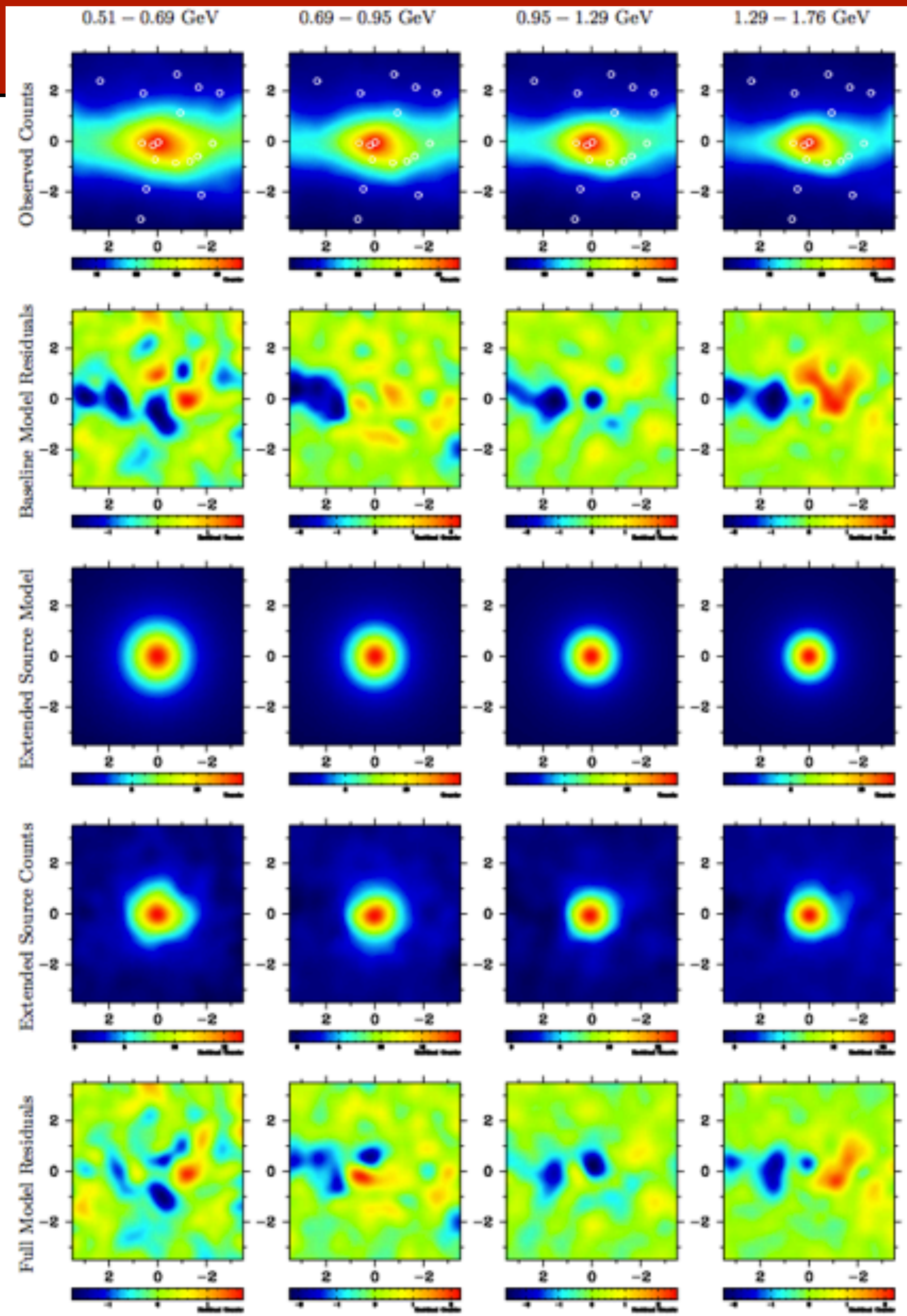
Is It A Point Source?

- 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)



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?

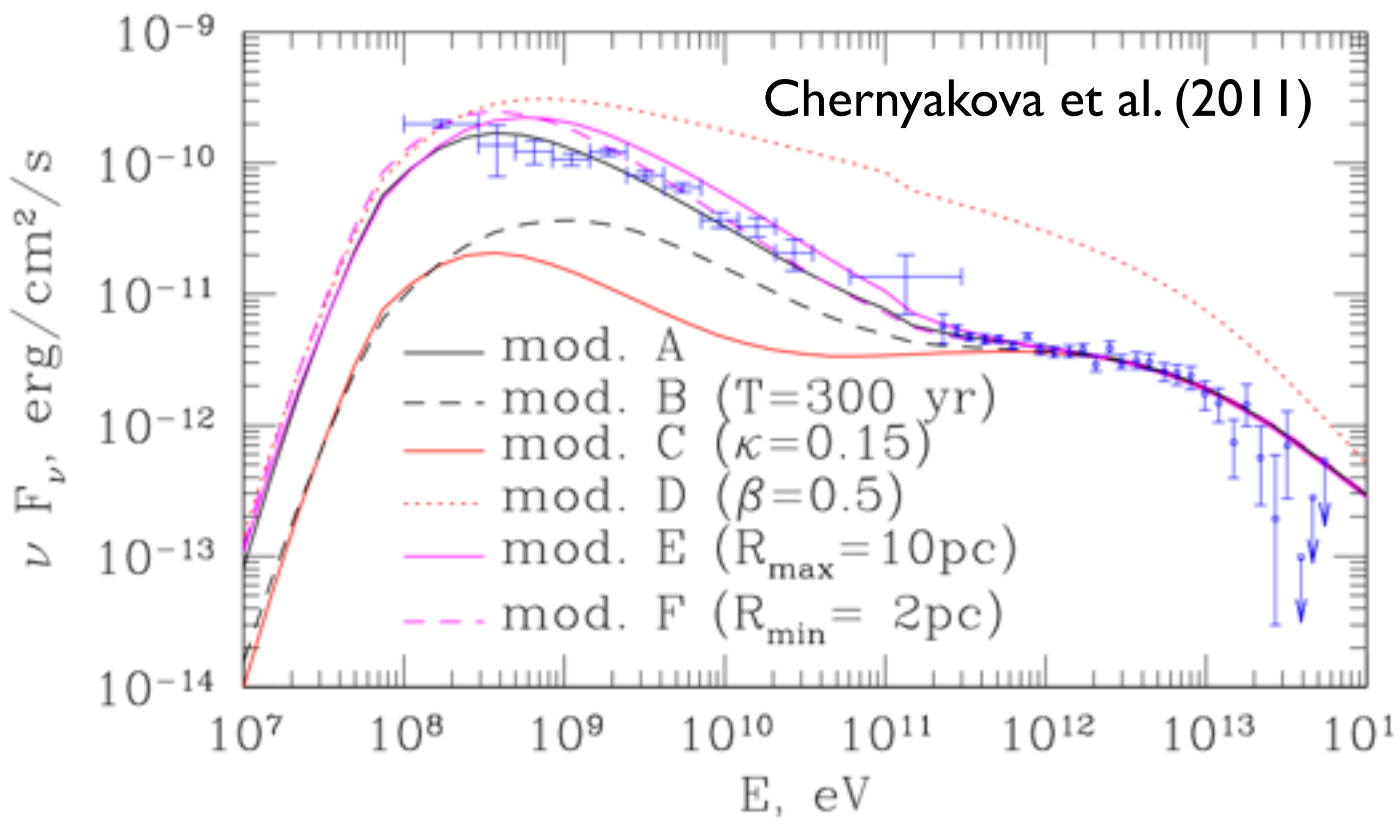
Interpretations at this Point

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

Proton Emission from Sgr A*

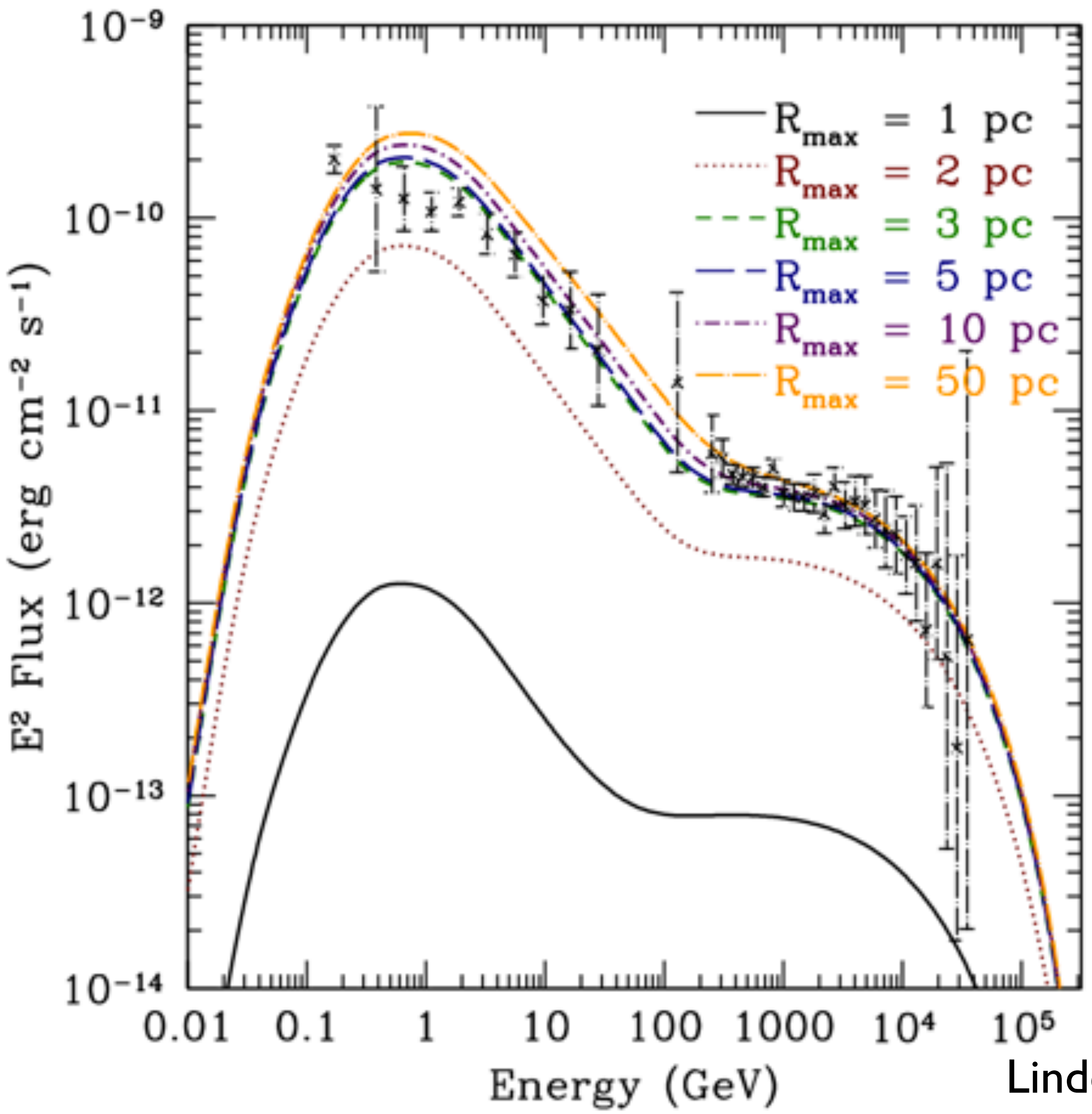
- H.E.S.S. observations of TeV gamma-rays from the GC are very well fit by a scenario where high energy protons are emitted by Sgr A* and collide with the dense gas nearby

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

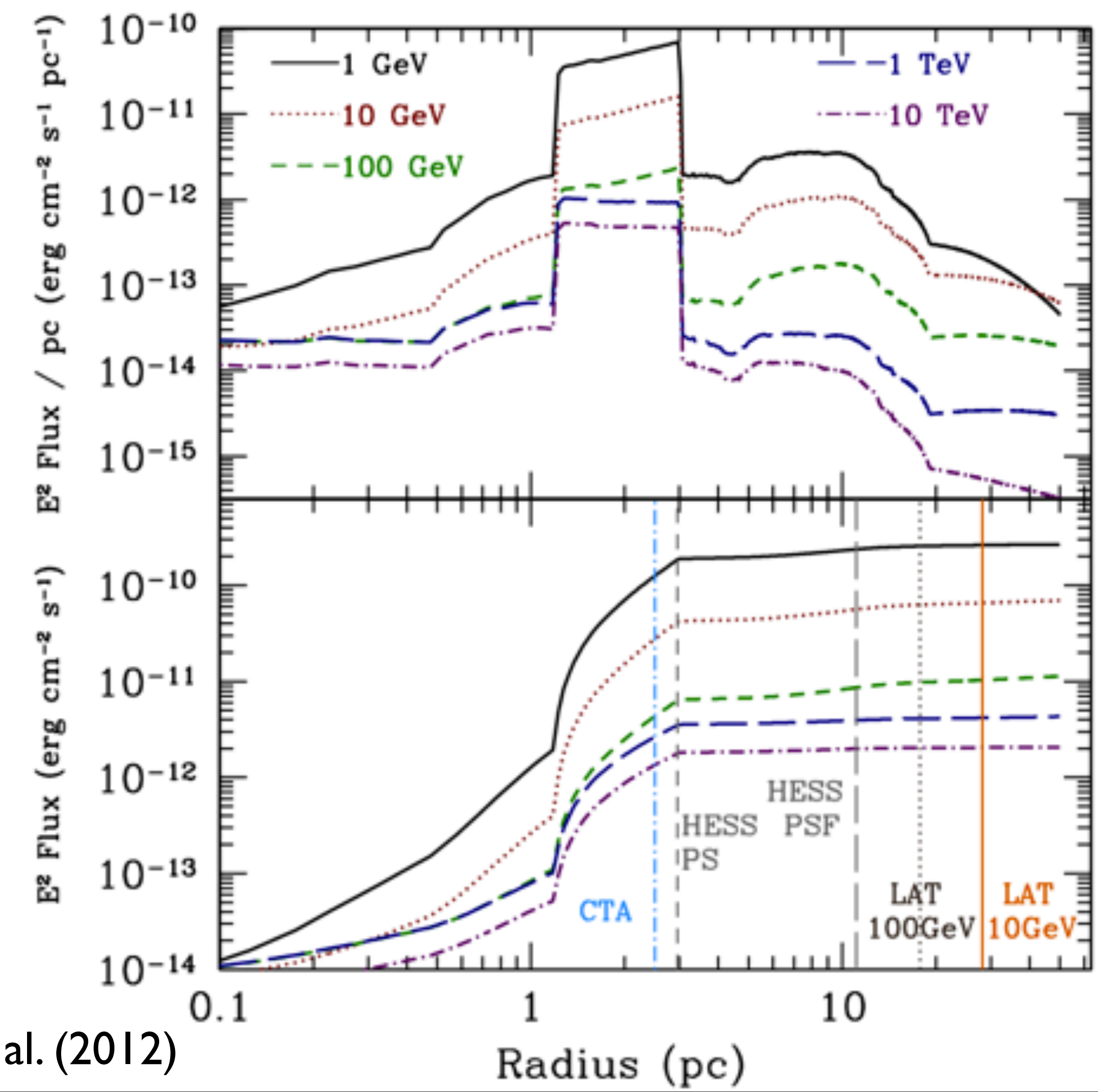


Understanding the Gas Morphology

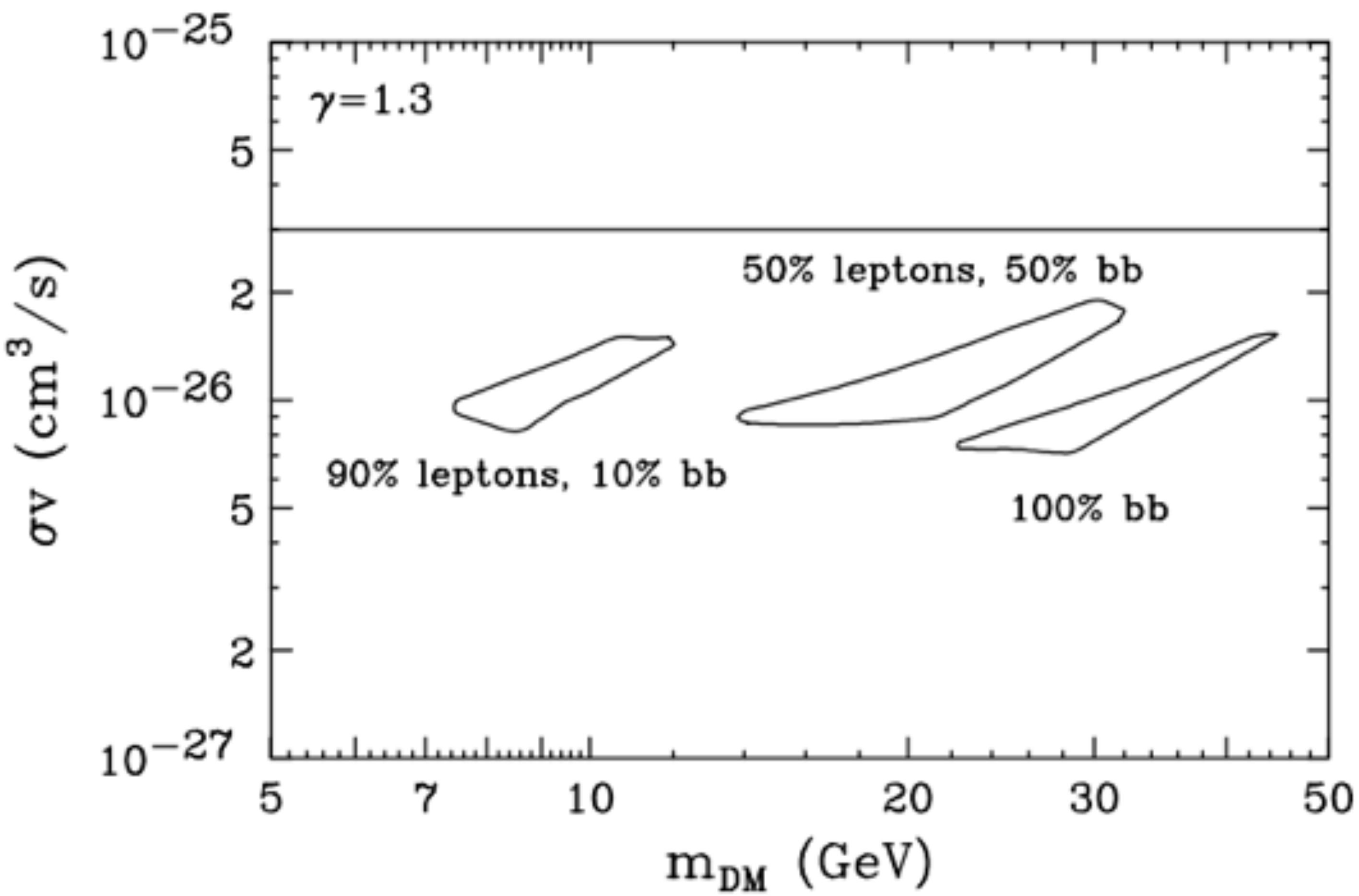
- The vast majority of emission stems from within 3 pc of the galactic center at all energies
- This lies below the PSF of all current gamma-ray instruments
- This effectively rules out hadronic interactions from Sgr A* as the source of the Fermi-LAT excess



Linden et al. (2012)



Dark Matter Fits



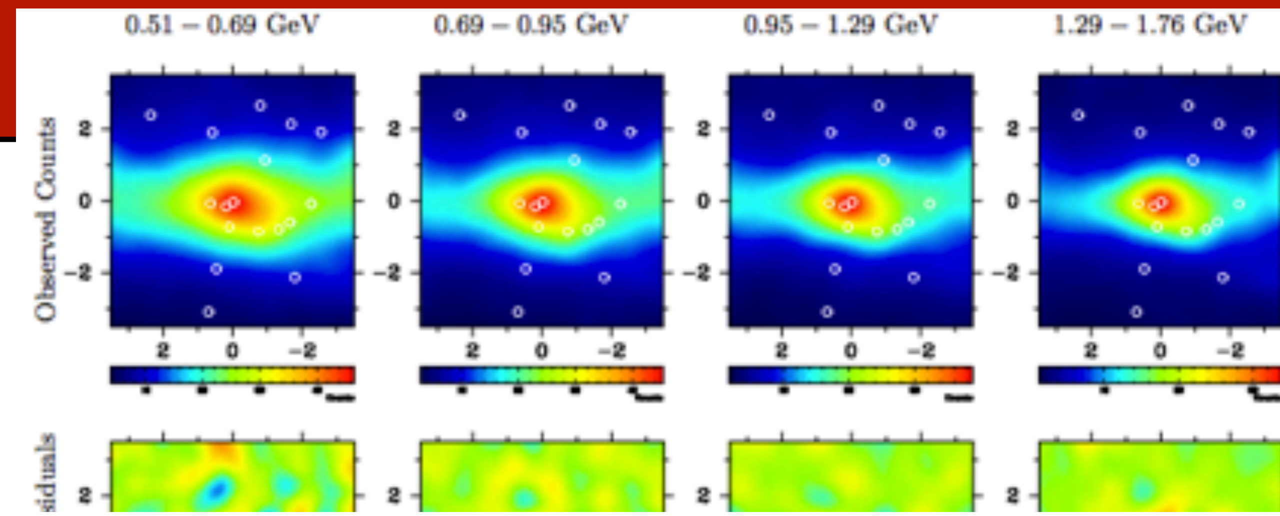


TABLE II. The best-fit TS, negative log likelihoods, and $\Delta\mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

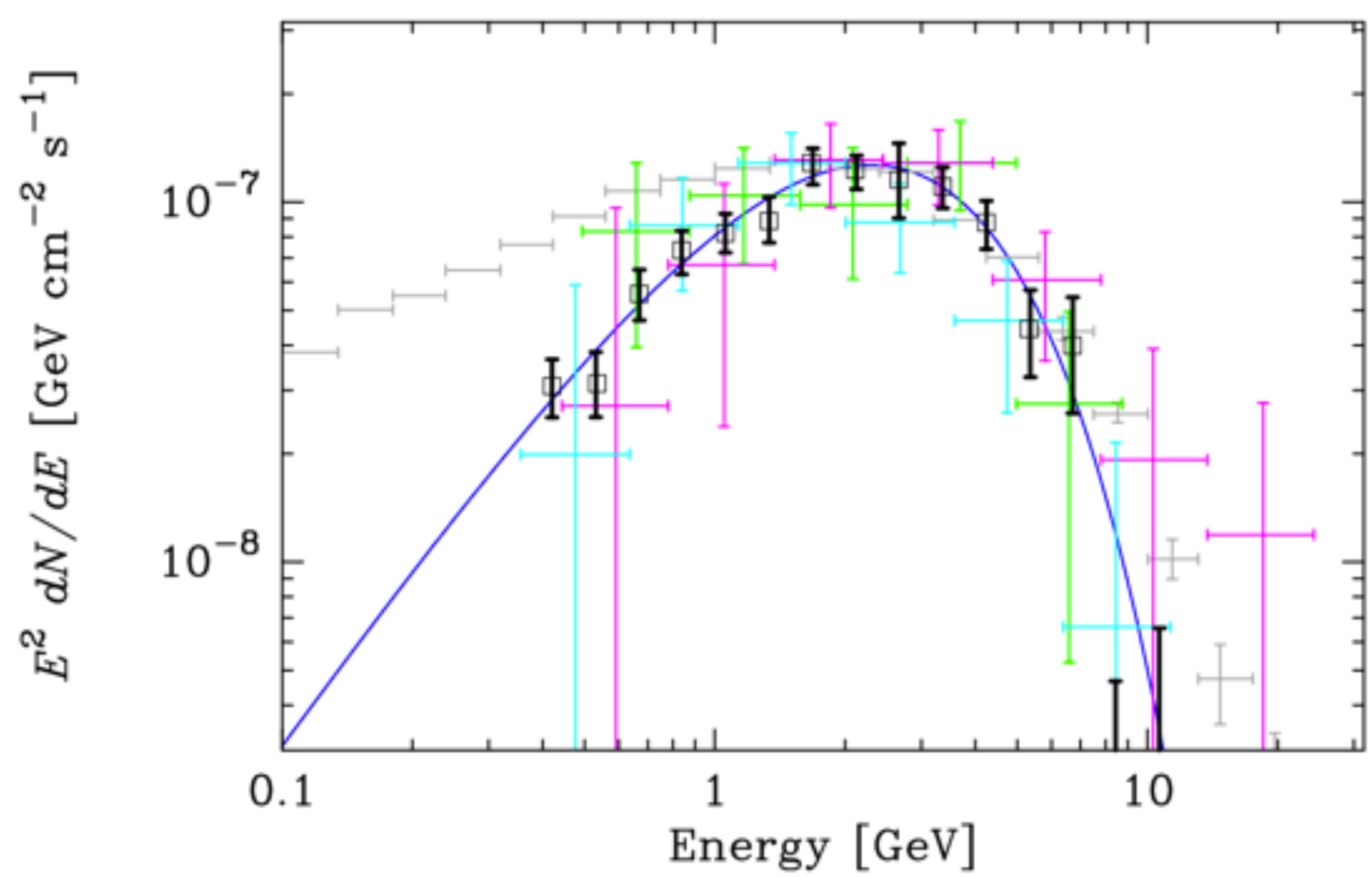
channel, m_χ	TS	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 10 GeV	2385.7	139913.6	156.5
$b\bar{b}$, 30 GeV	3460.3	139658.3	411.8
$b\bar{b}$, 100 GeV	1303.1	139881.1	189.0
$b\bar{b}$, 300 GeV	229.4	140056.6	13.5
$b\bar{b}$, 1 TeV	25.5	140108.2	−38.0
$b\bar{b}$, 2.5 TeV	7.6	140114.2	−44.0
$\tau^+\tau^-$, 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 morphology and spectrum of the residual
- Of course dark matter predictions are somewhat malleable

See Next Talk by Chris Gordon

Abazajian & Kaplinghat (2012)

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

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

See Next Talk by Chris Gordon

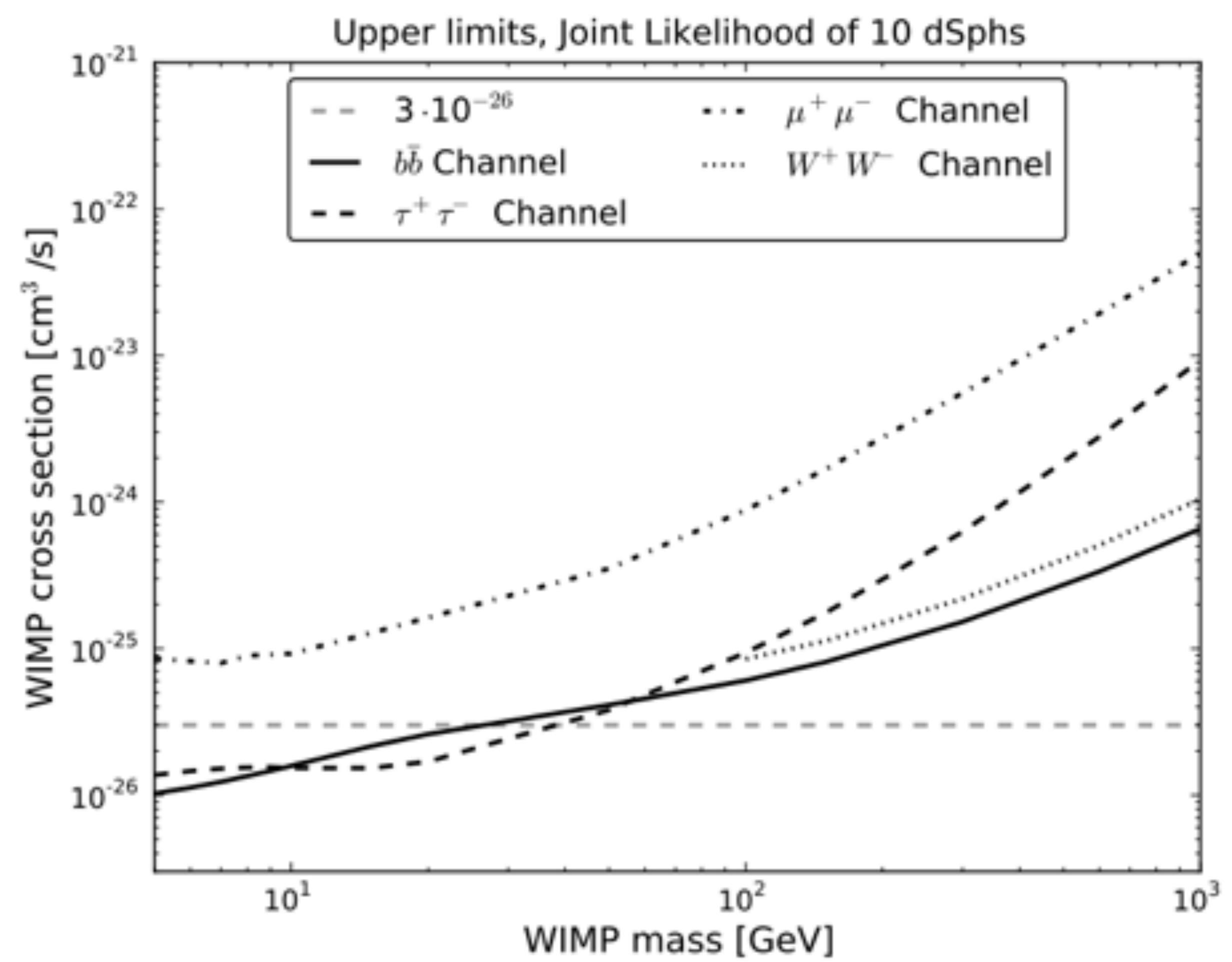
Abazajian (2011)

Where Do We Go From Here?

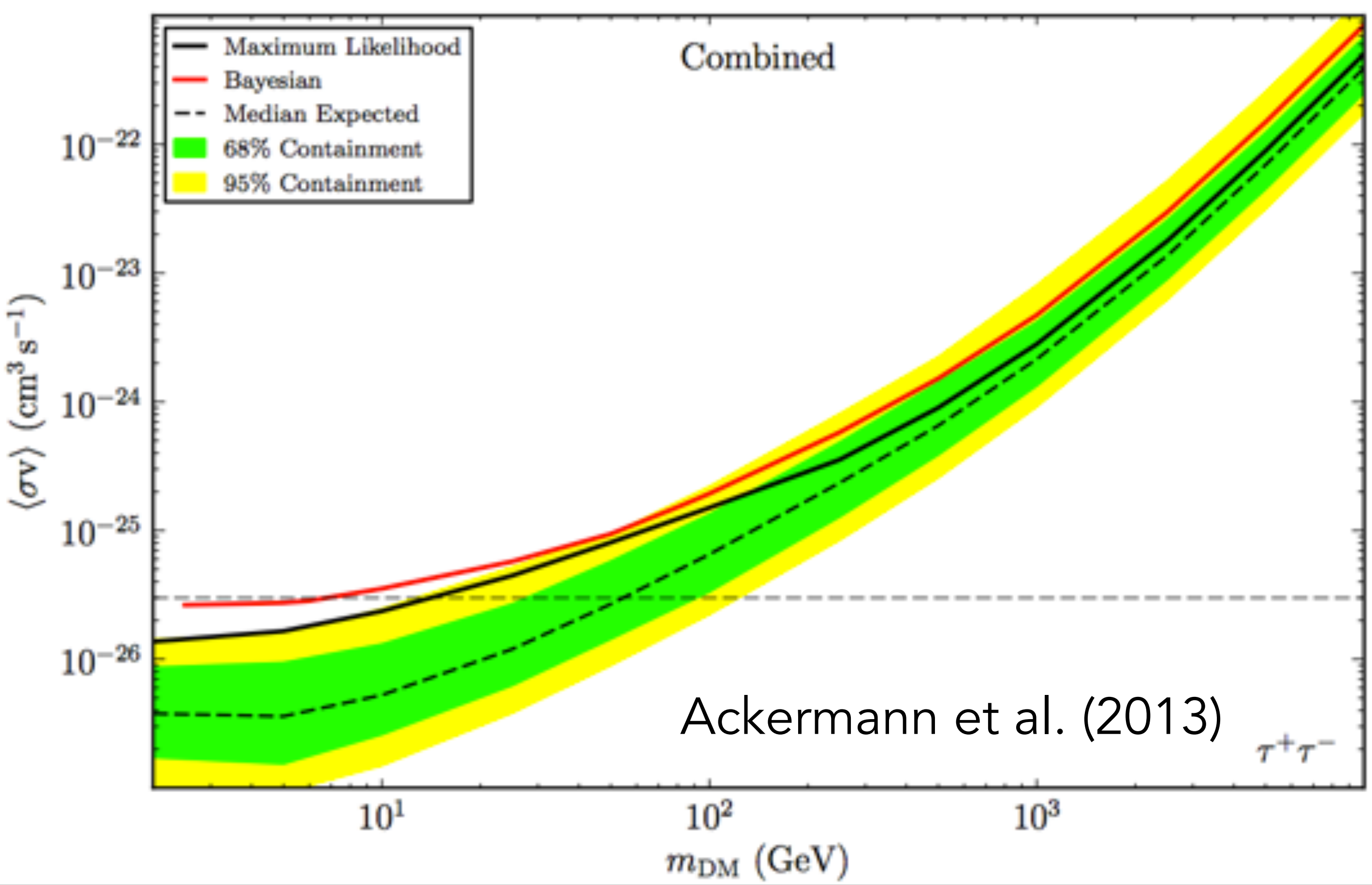
- Personal Opinion: It's not clear that new data from the GC will greatly improve our measurements of the GC excess - at least not in any way which can distinguish dark matter and MSPs

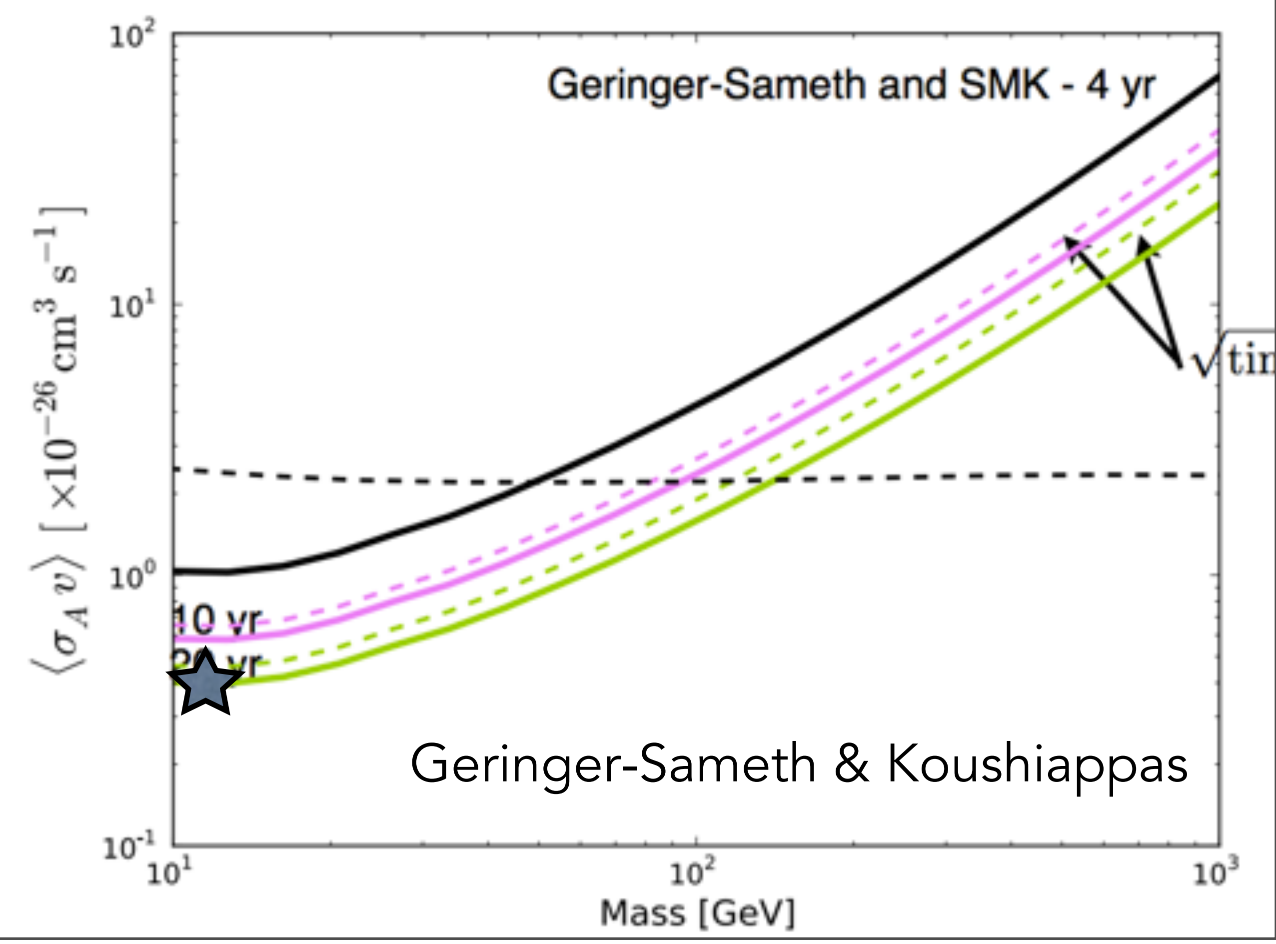
Where Do We Go From Here?

- 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

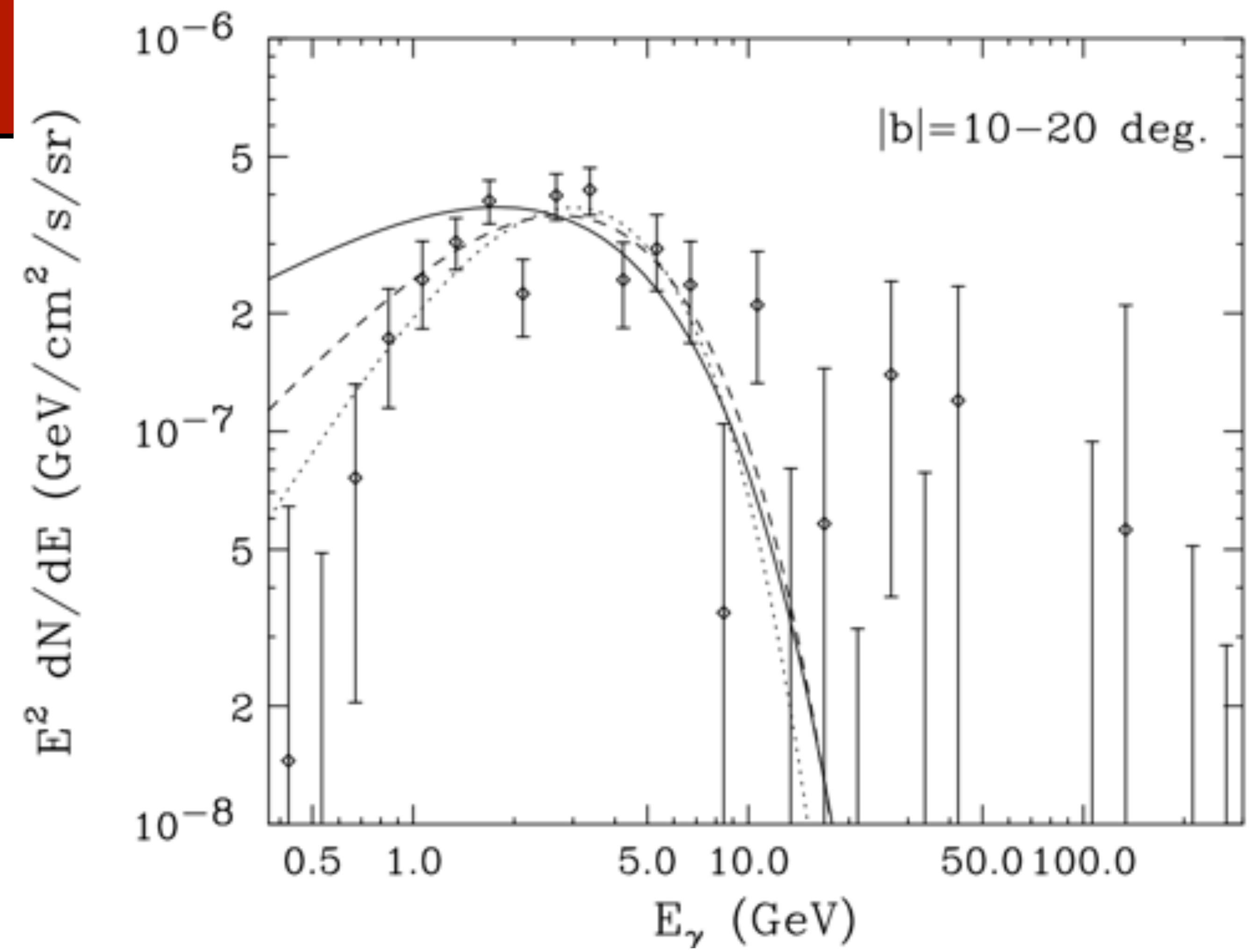


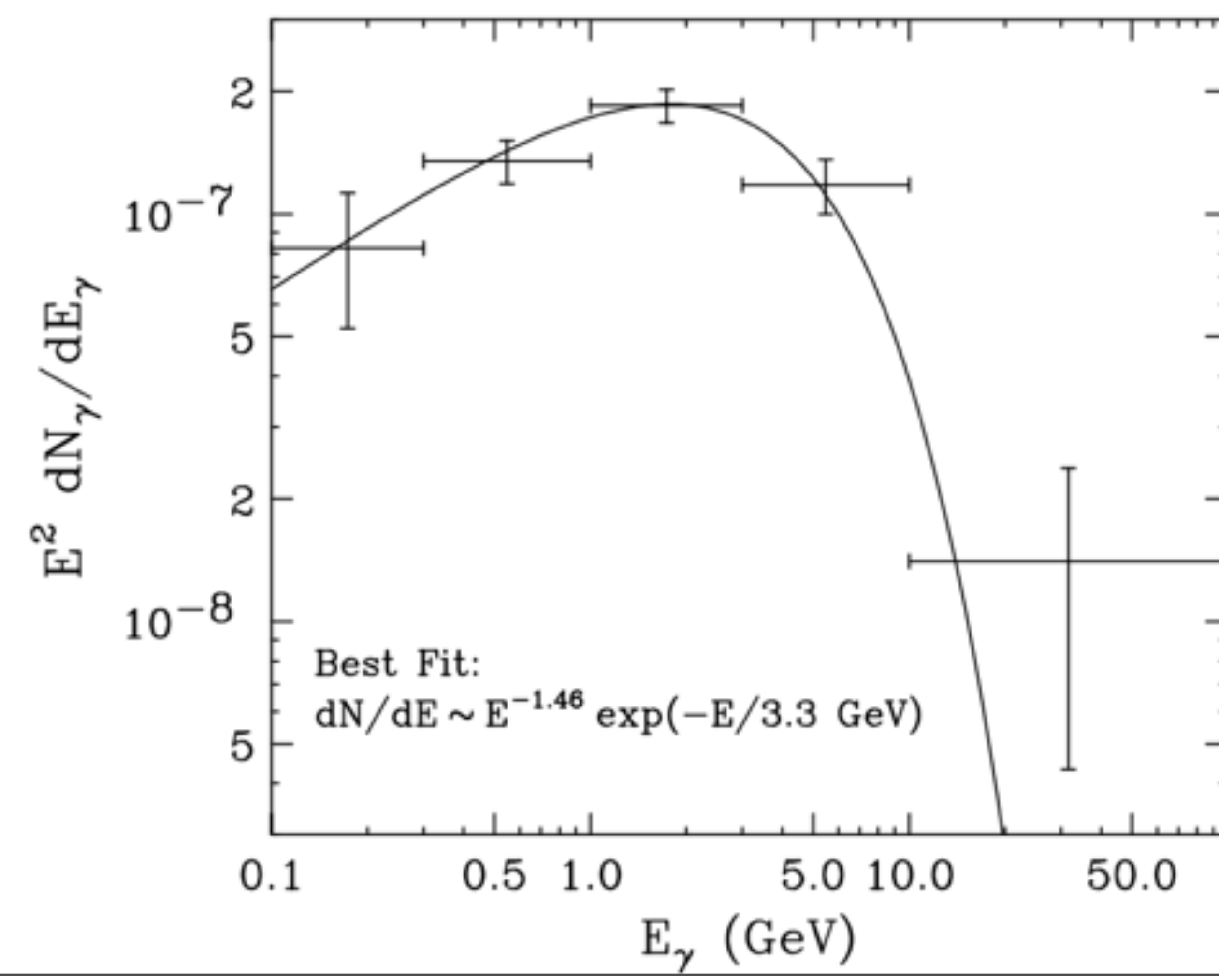


Fermi Bubbles?

- 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. (2013)

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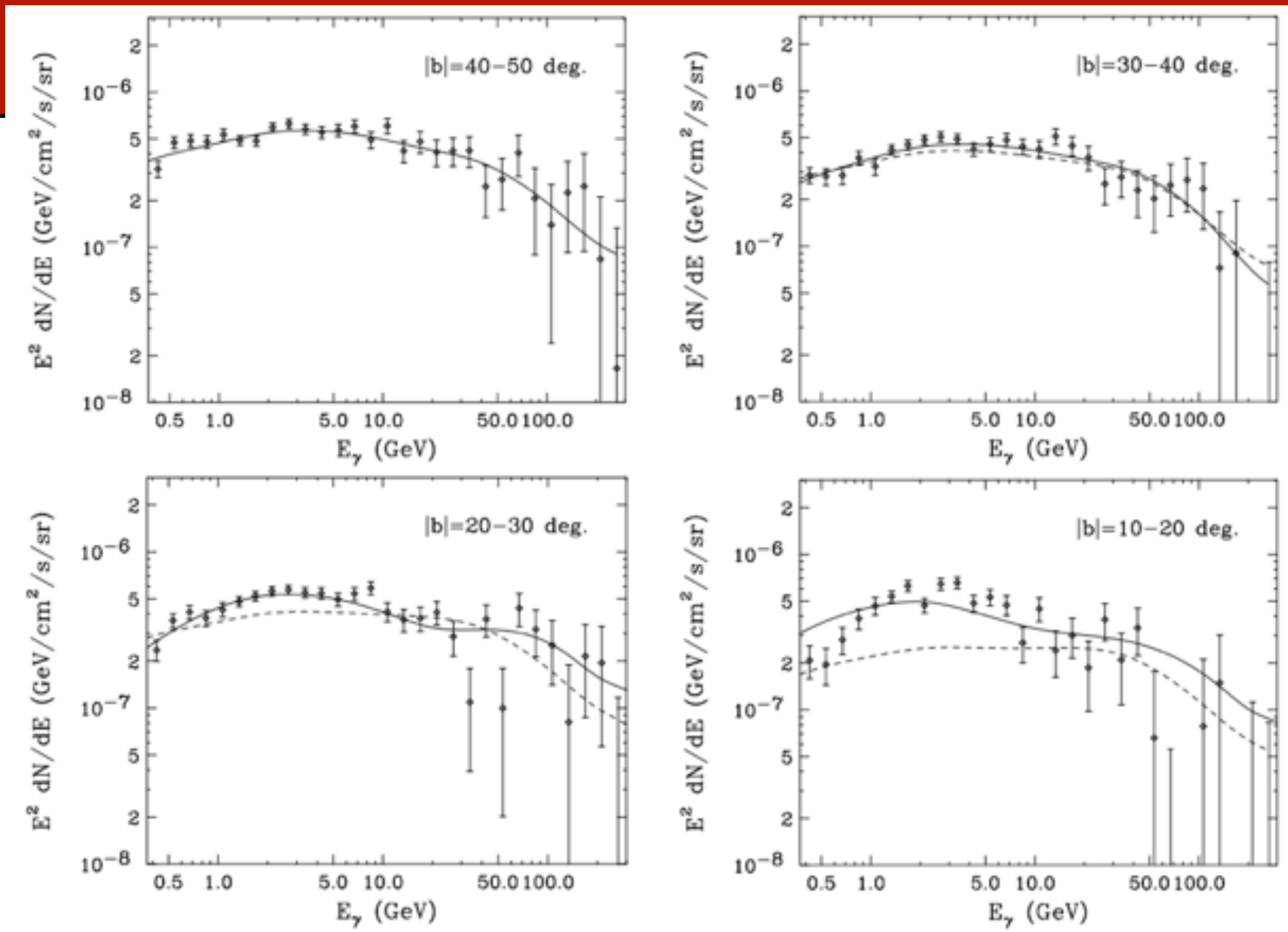
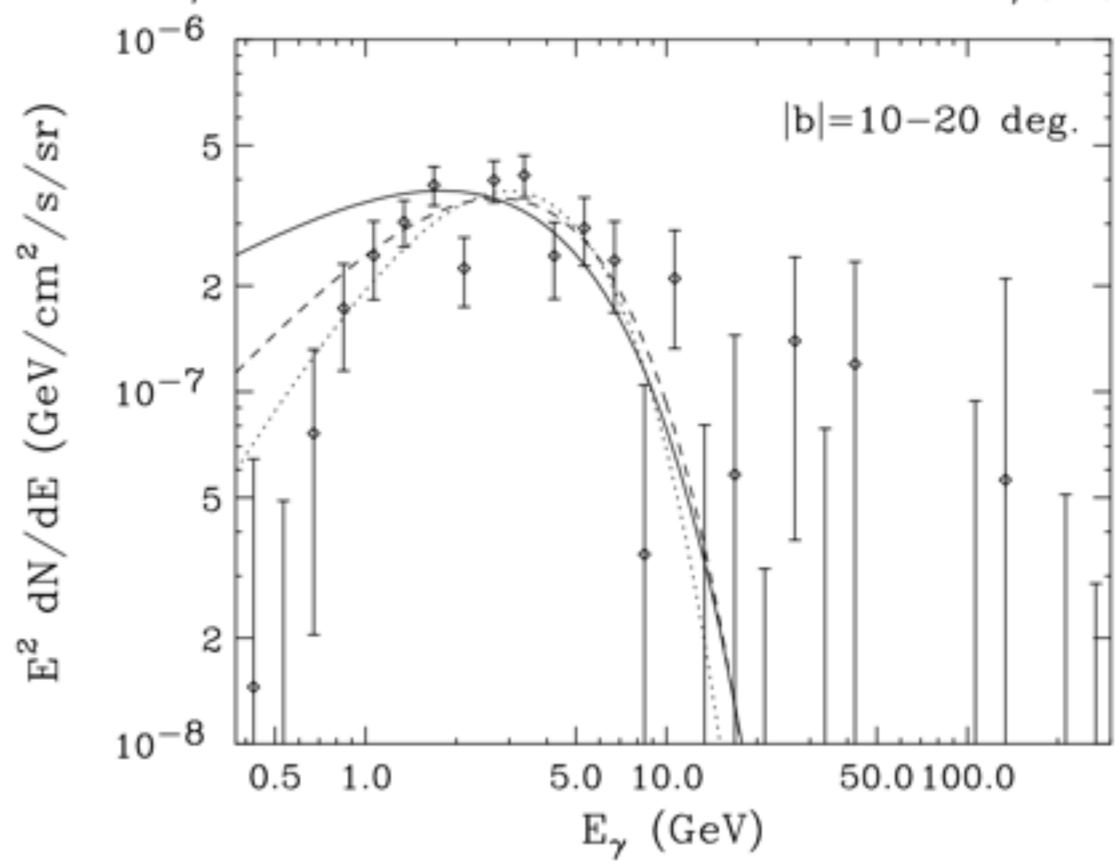


Hooper & Slatyer (2013)



Hooper et al. (2013)

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	$\alpha^{1.4GHz}_{0.33GHz}$	$\alpha^{4.8GHz}_{1.4G...}$
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...			
G...			

*Tw...	[illegible]
± 0.2, w...	[illegible]
*Spectru...	[illegible]

Linden et al. (2011)

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

Astron. Astrophys. 200, L9–L12 (1988)

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 ...er, including Sgr A* and the extended com- ...nd Arc) is neither due to self-absorbed ...nor 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

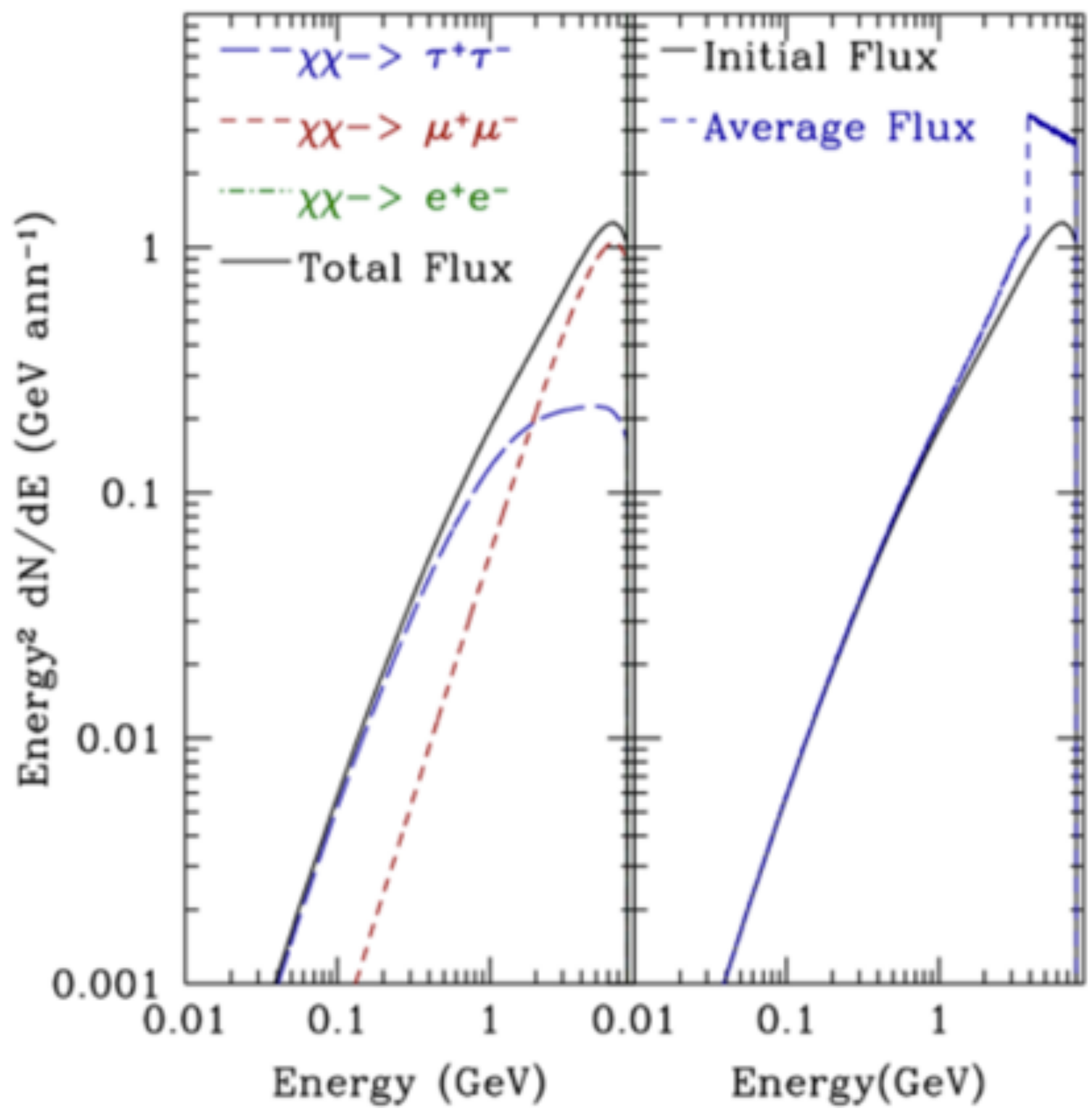
where S_M is the observed flux density for an self-absorbed source at a frequency ν_M an the magnetic field. With the flux density the (Reich et al., 1988) and a mag 10 GHz (Sofue and Fujimoto, 1988) we get 10^{-2} G

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

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

Friday, October 4, 2013

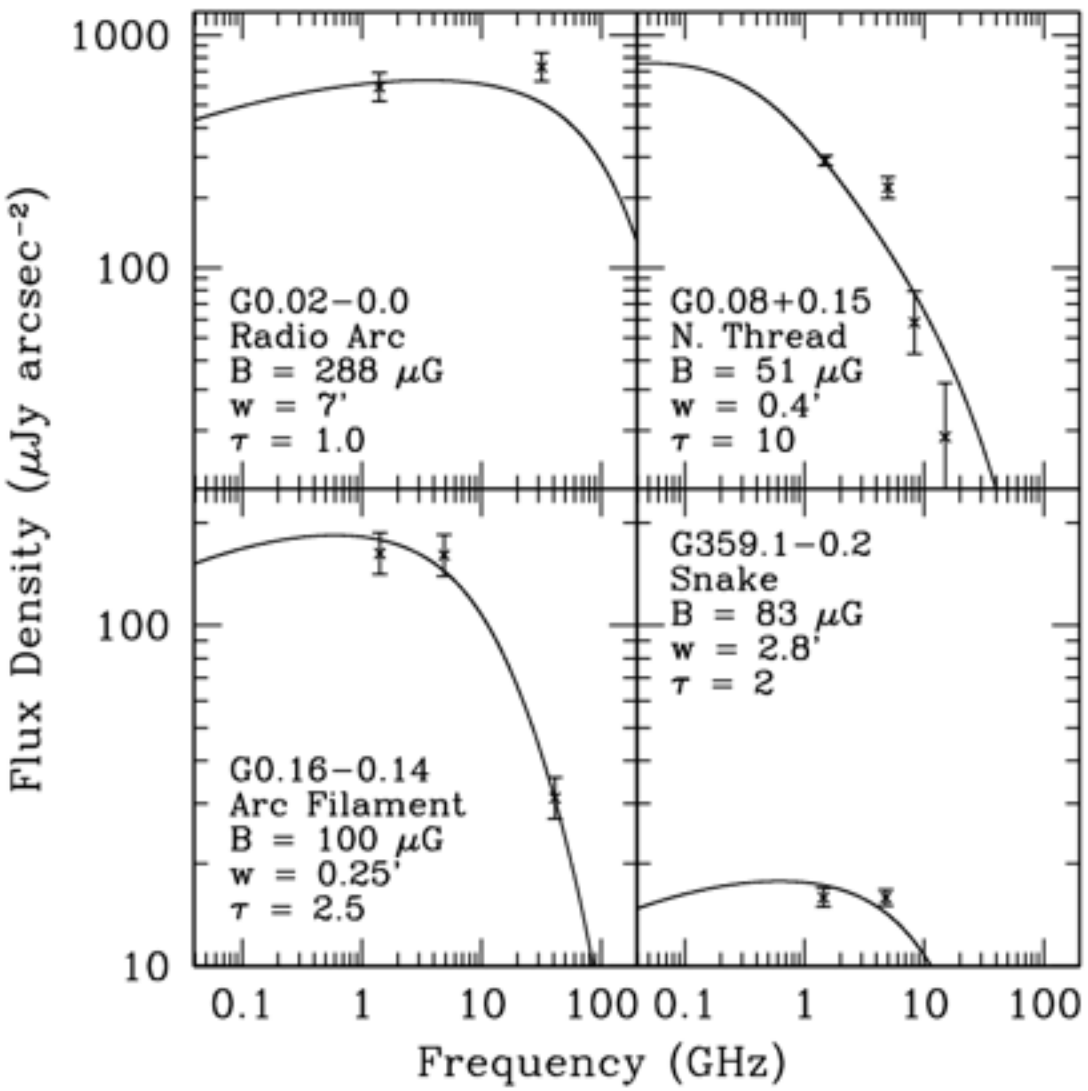
Radio Observations of the Galactic Center



Linden et al. (2011)

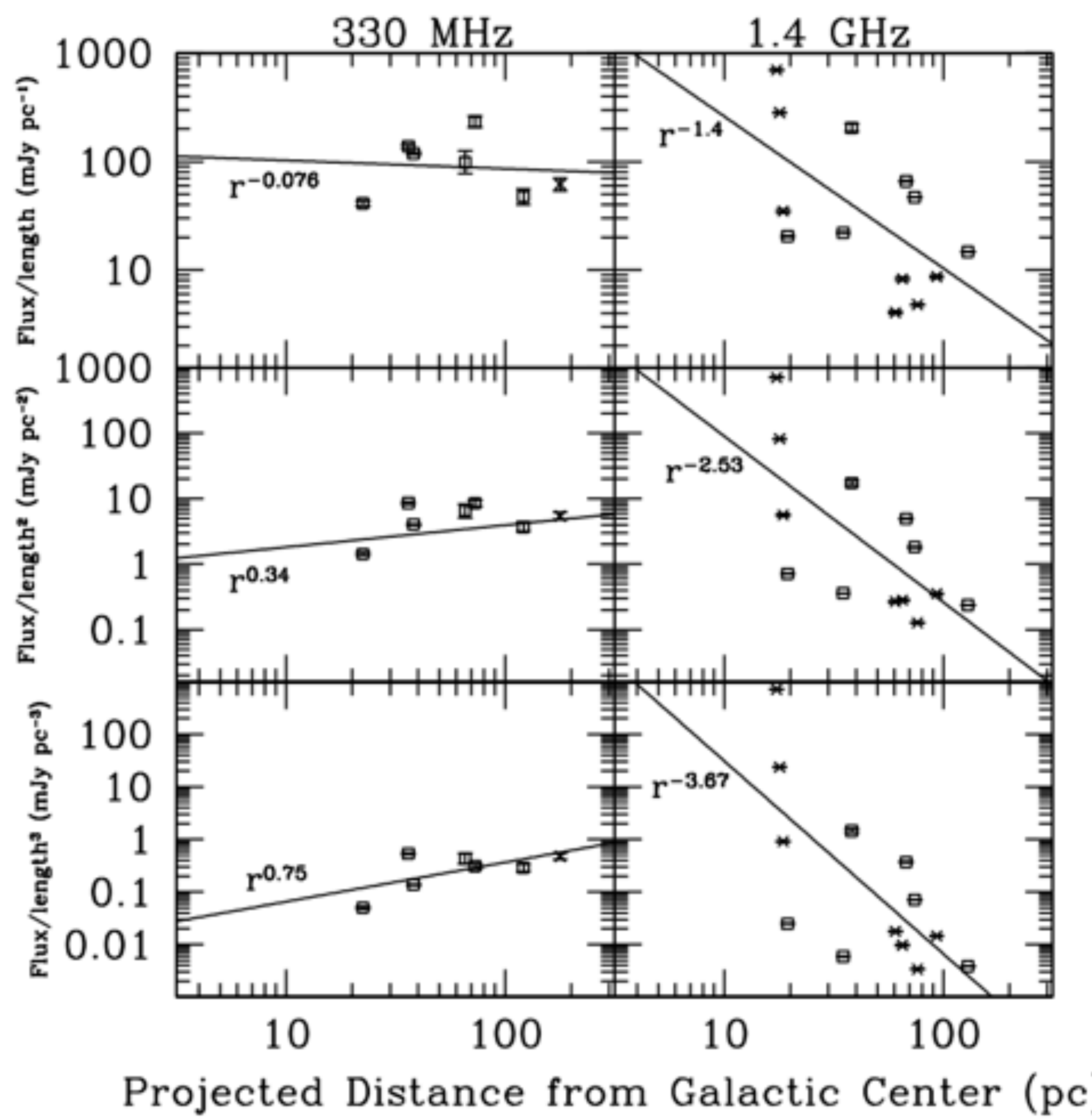
- Dark Matter can easily produce such a spectrum!

Radio Observations of the Galactic Center



Linden et al. (2011)

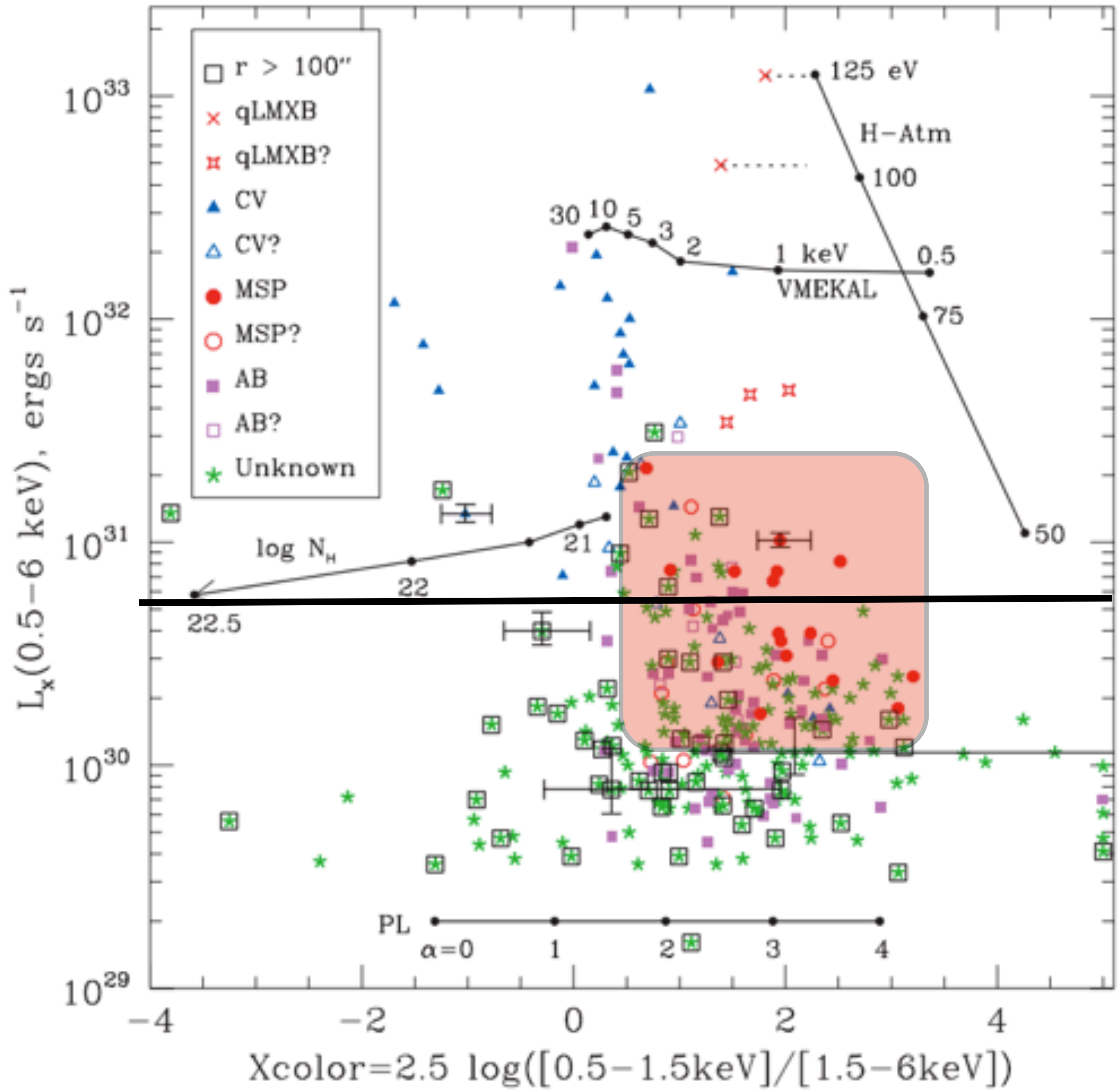
- Hard spectrum, non-thermal radio filaments can be fit with dark matter annihilation



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

Where Do We Go From Here?

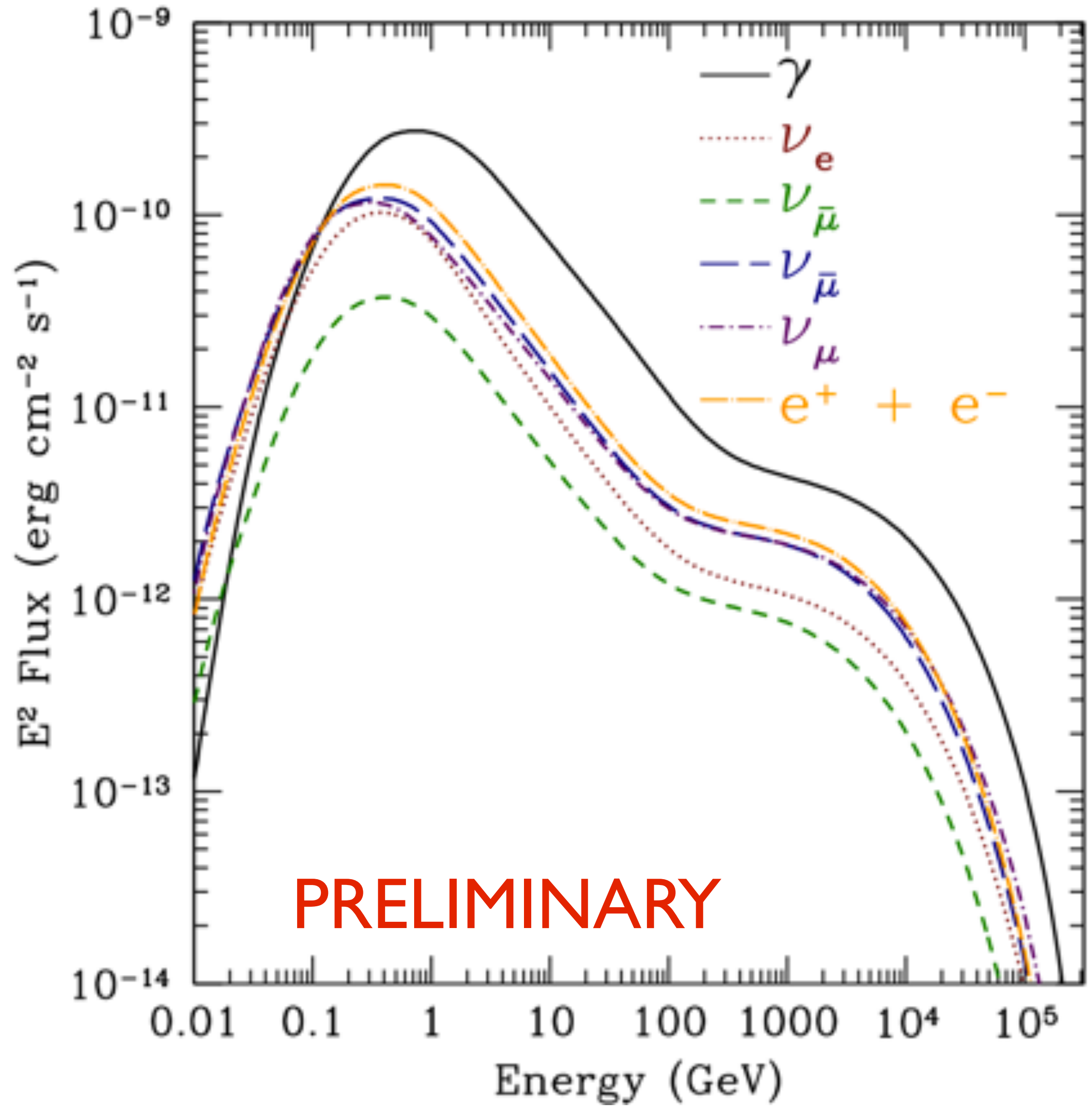
- X-Ray observations find a total of 2347 point sources within 40 pc of the GC - this could include a large population of MSPs
- MSPs exist in a particular location on the luminosity-color diagram in 47 Tuc
- Can this information be used to determine the statistical distribution of MSPs?

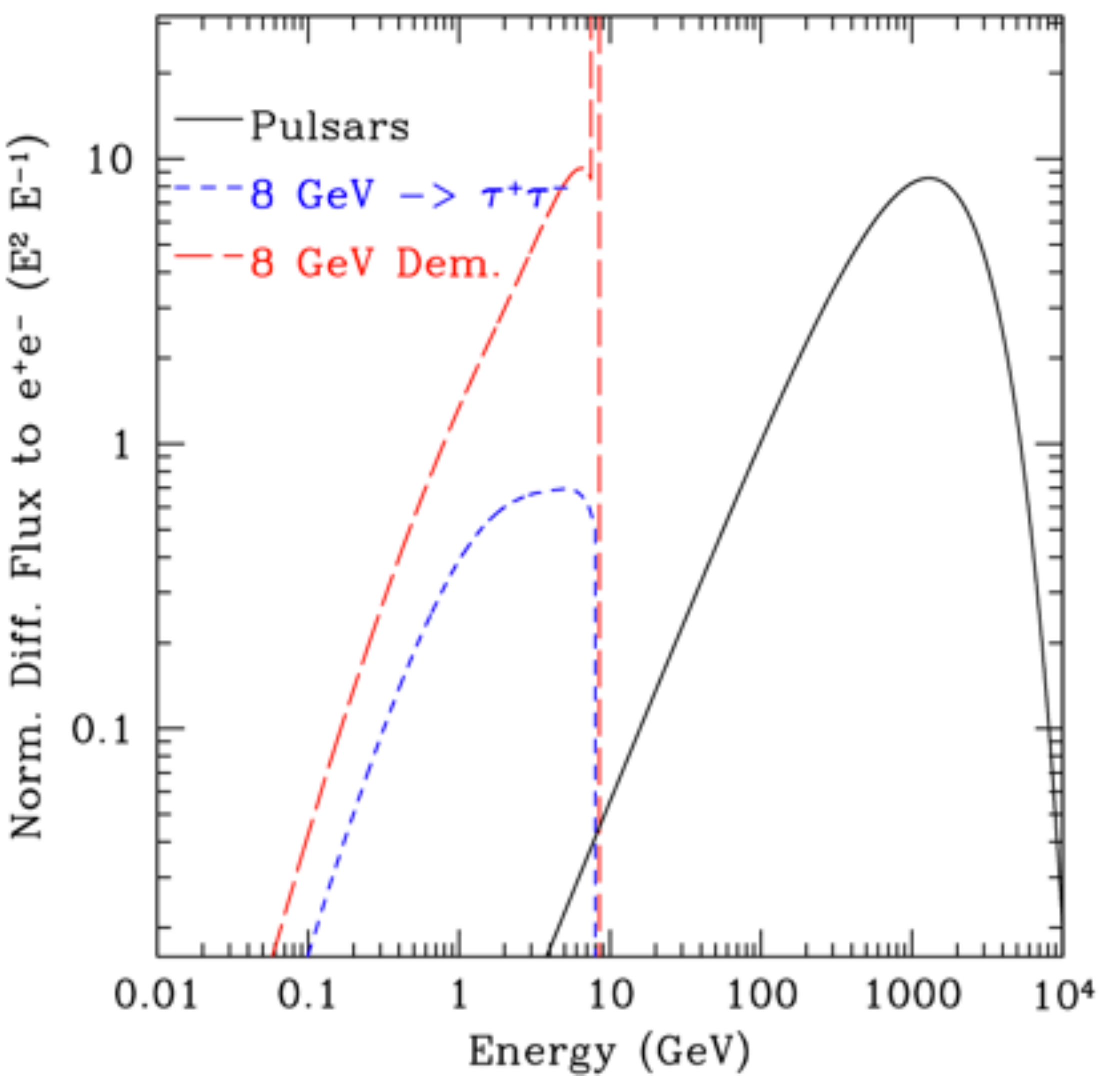


Heinke et al. (2006)

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?