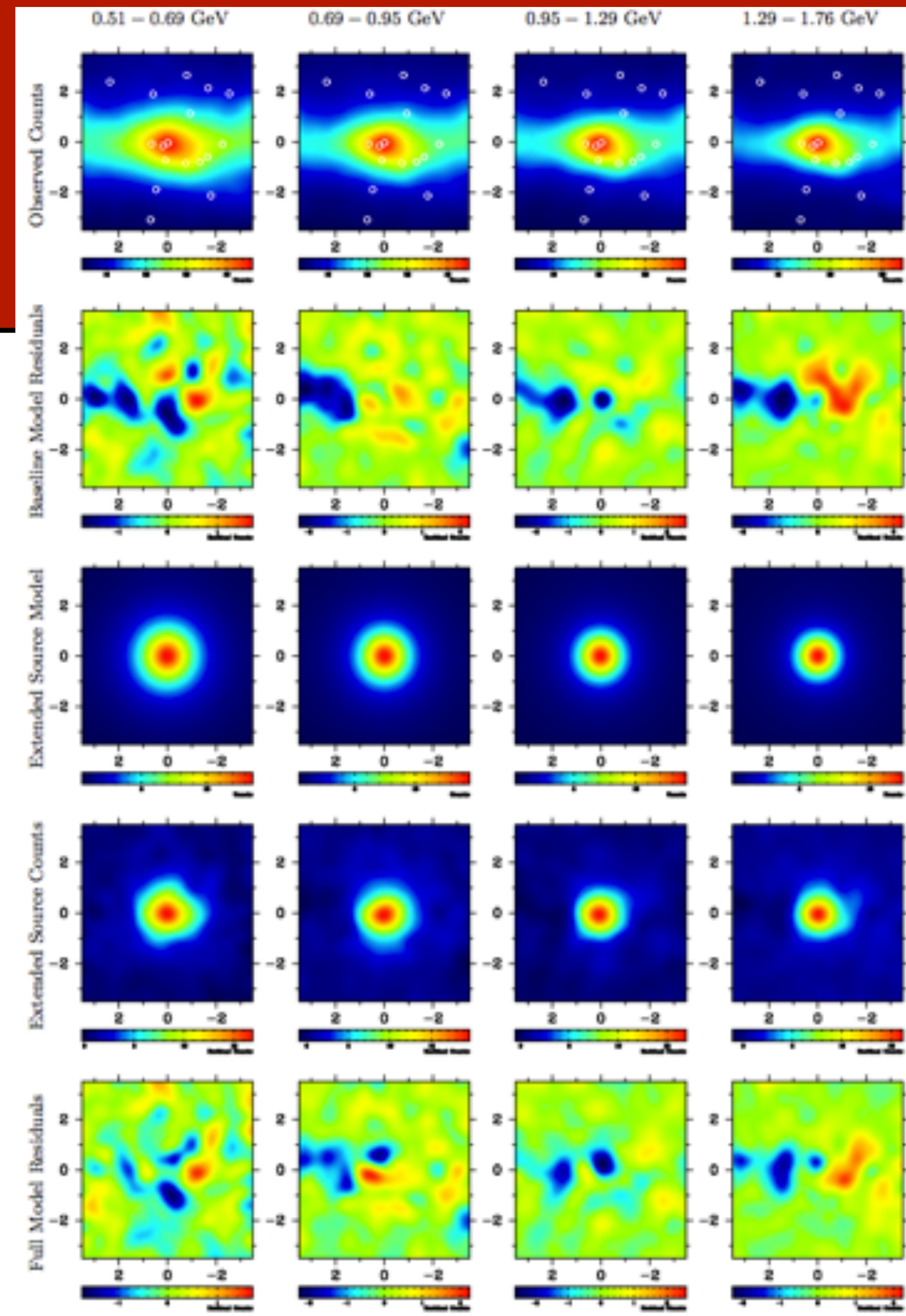
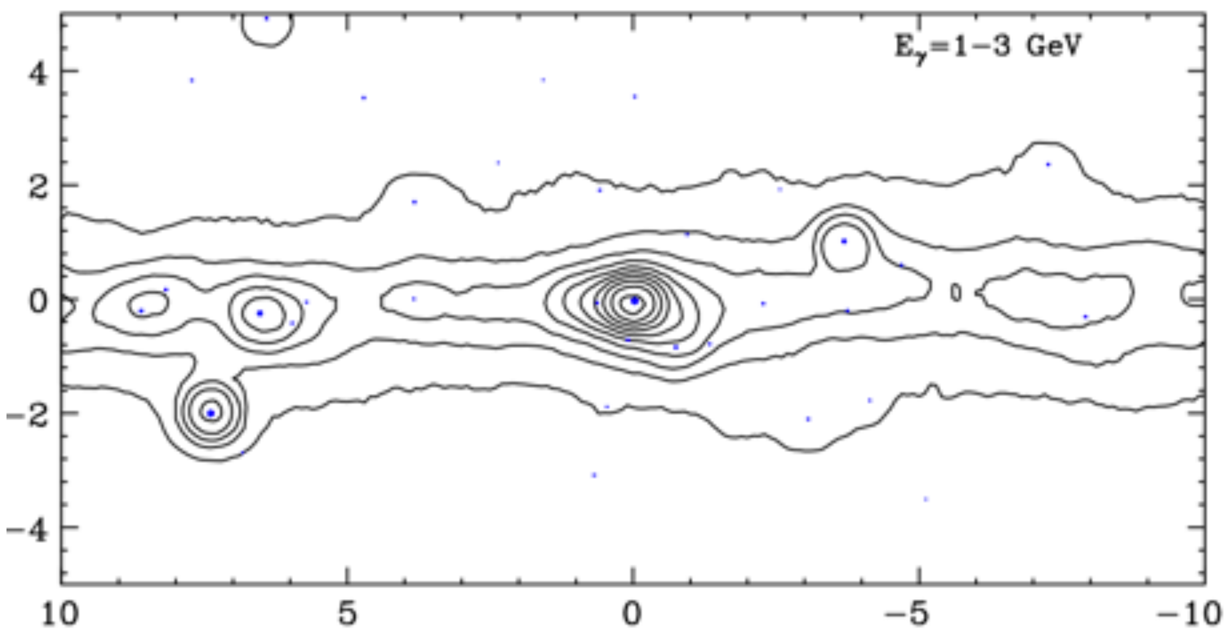
Evidence for Light Dark Matter Annihilation at the Galactic Center





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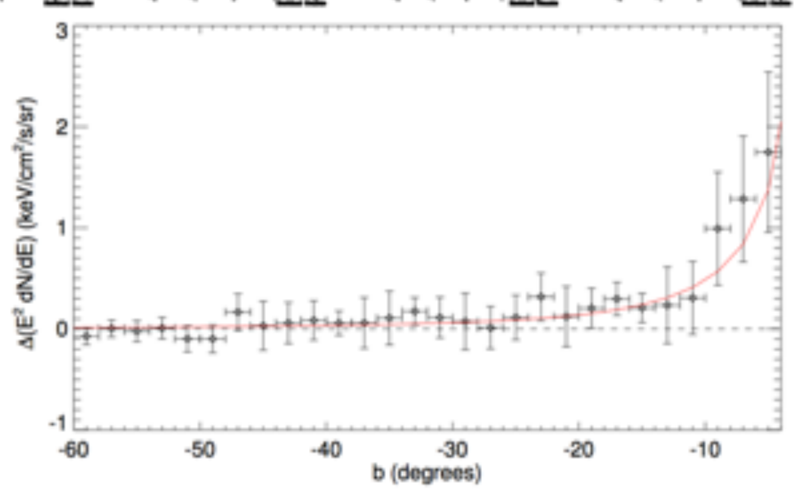
along with: Eric Carlson, Ilias Cholis, Dan Hooper, Manoj Kaplinghat, Stefano Profumo, Jennifer Siegal-Gaskins, Tracy Slatyer, Hai-Bo Yu



Identifying and Characterizing Dark Matter via Multiple Probes
Kavli Institute for Theoretical Physics -- May 14, 2013

Goal of the Talk

- What is the current status of the excess observed at the Galactic Center?
- What interpretations of this excess are best supported?
- For Discussion:
  - What arguments are currently most/least convincing?
  - Where do we go from here?

Indirect Detection of Dark Matter Starts at the GC

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 approximately:

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

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

Dark Matter May Not Be That Subdominant

Back of the Envelope Calculation

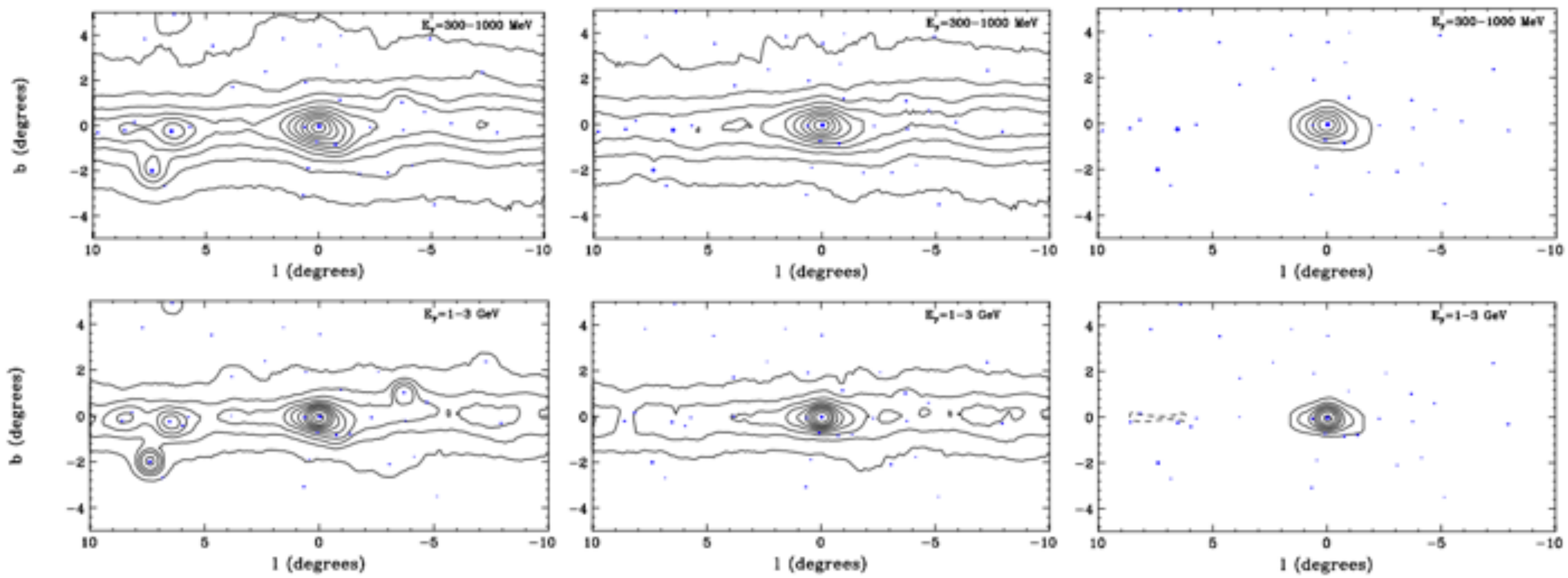
- Total Gamma-Ray Flux from 1-3 GeV within 1° of Galactic Center is

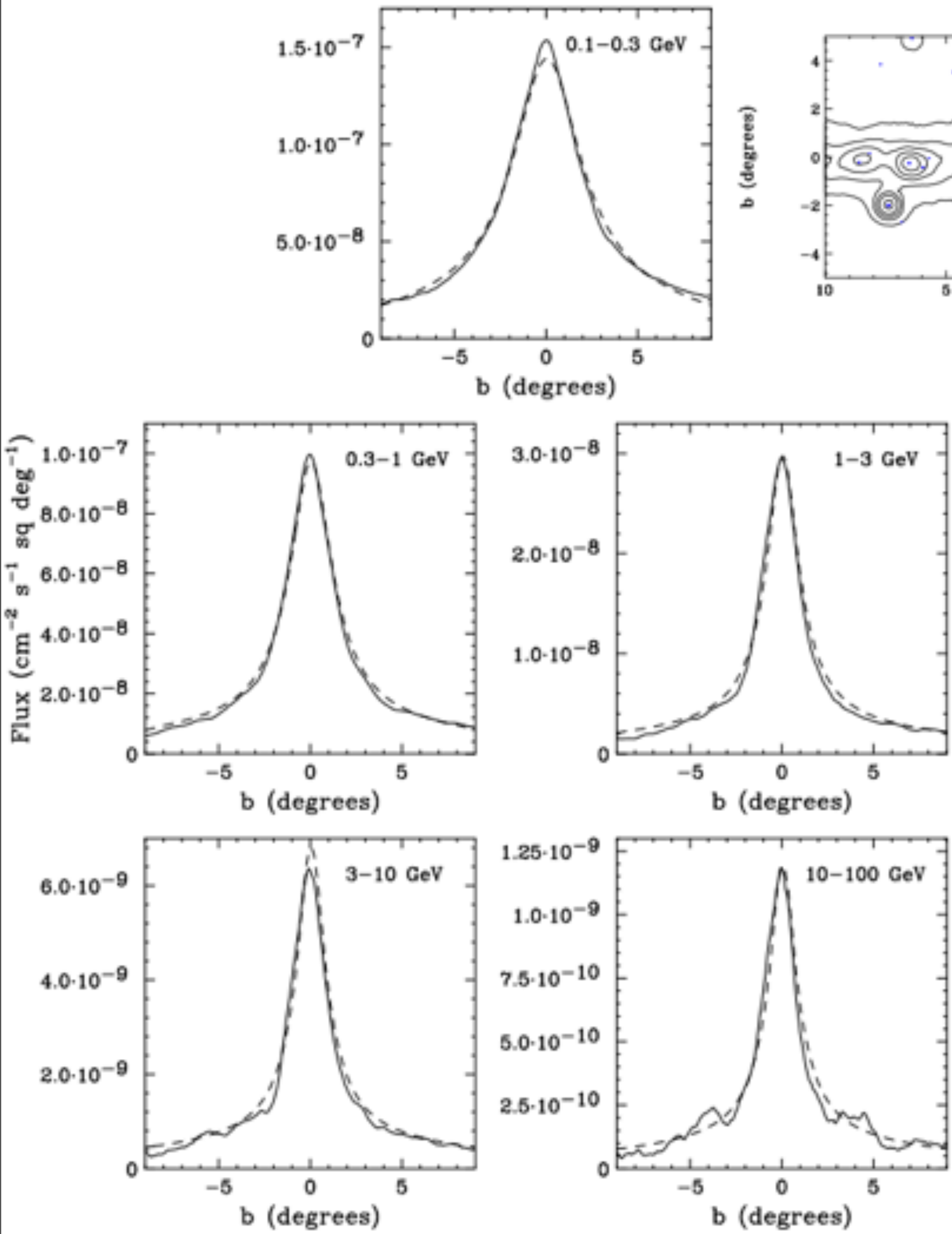
$$\sim 1 \times 10^{-7}\ cm^{-2}\ s^{-1}$$

- 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 **$\langle\sigma v\rangle = 1.6 \times 10^{-25}\ cm^3\ s^{-1}$**

- 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

Subtracting the Astrophysical Background: Fermi

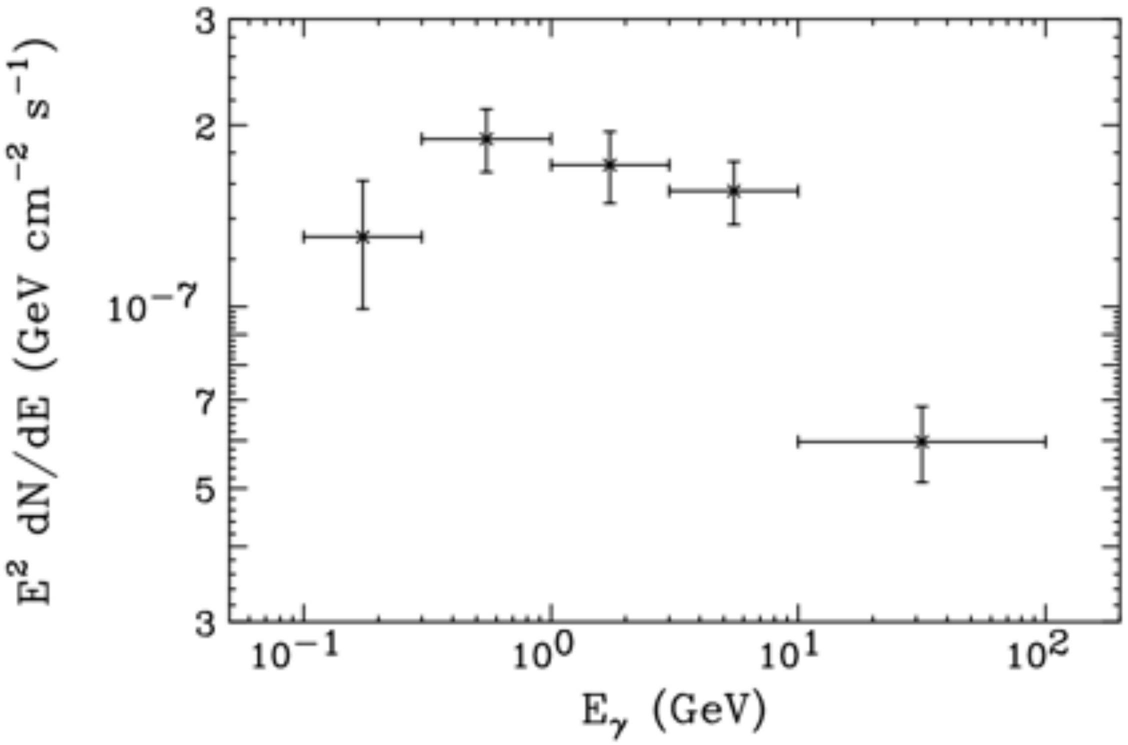




- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum
- This large residual at the center of the galaxy is a factor of 10 brighter than anything else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

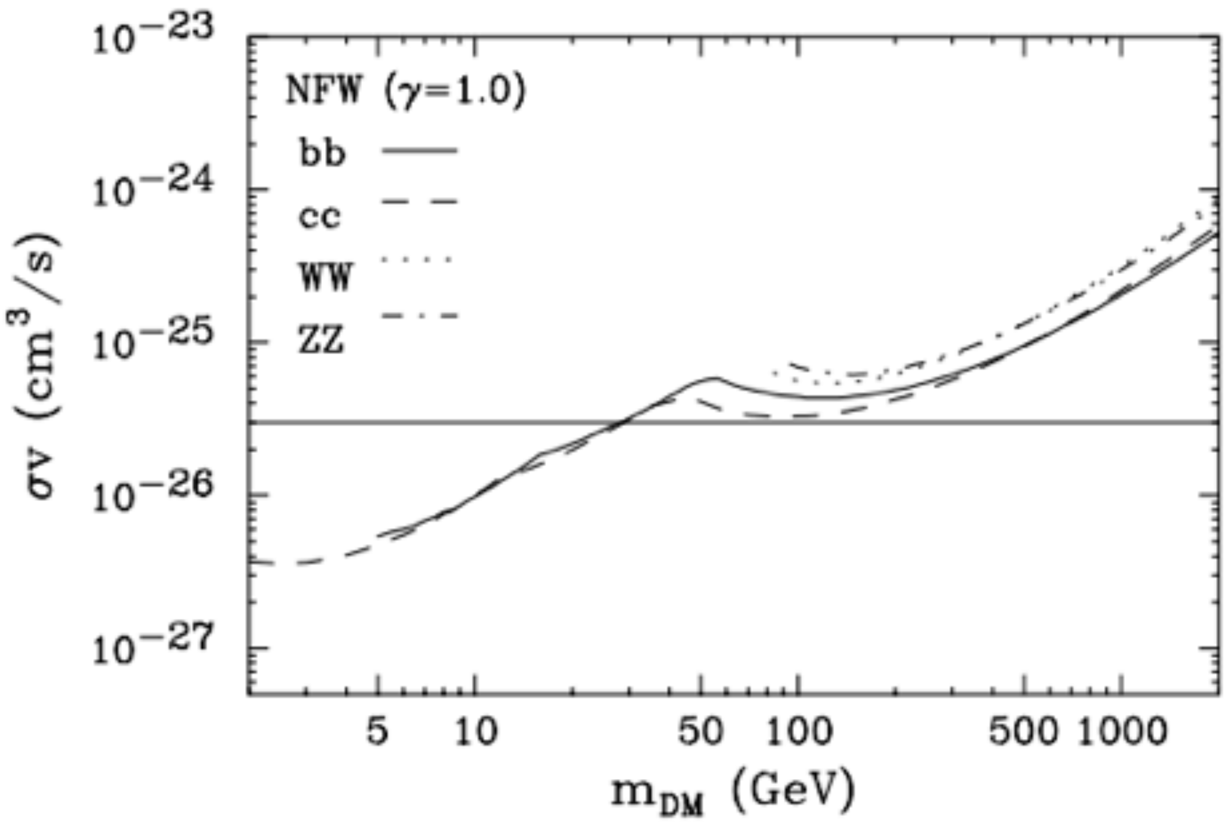
Hooper & Linden (2011)

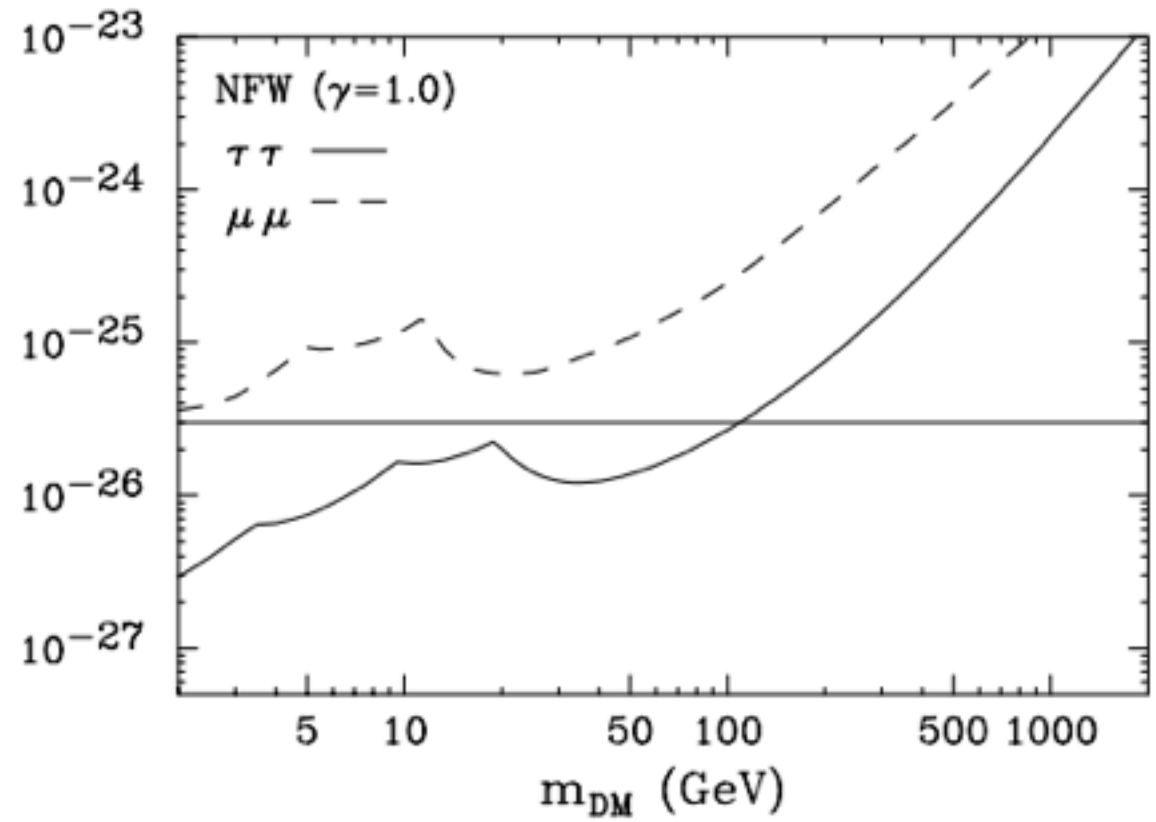
Dark Matter Limits in the Simplest Way Possible



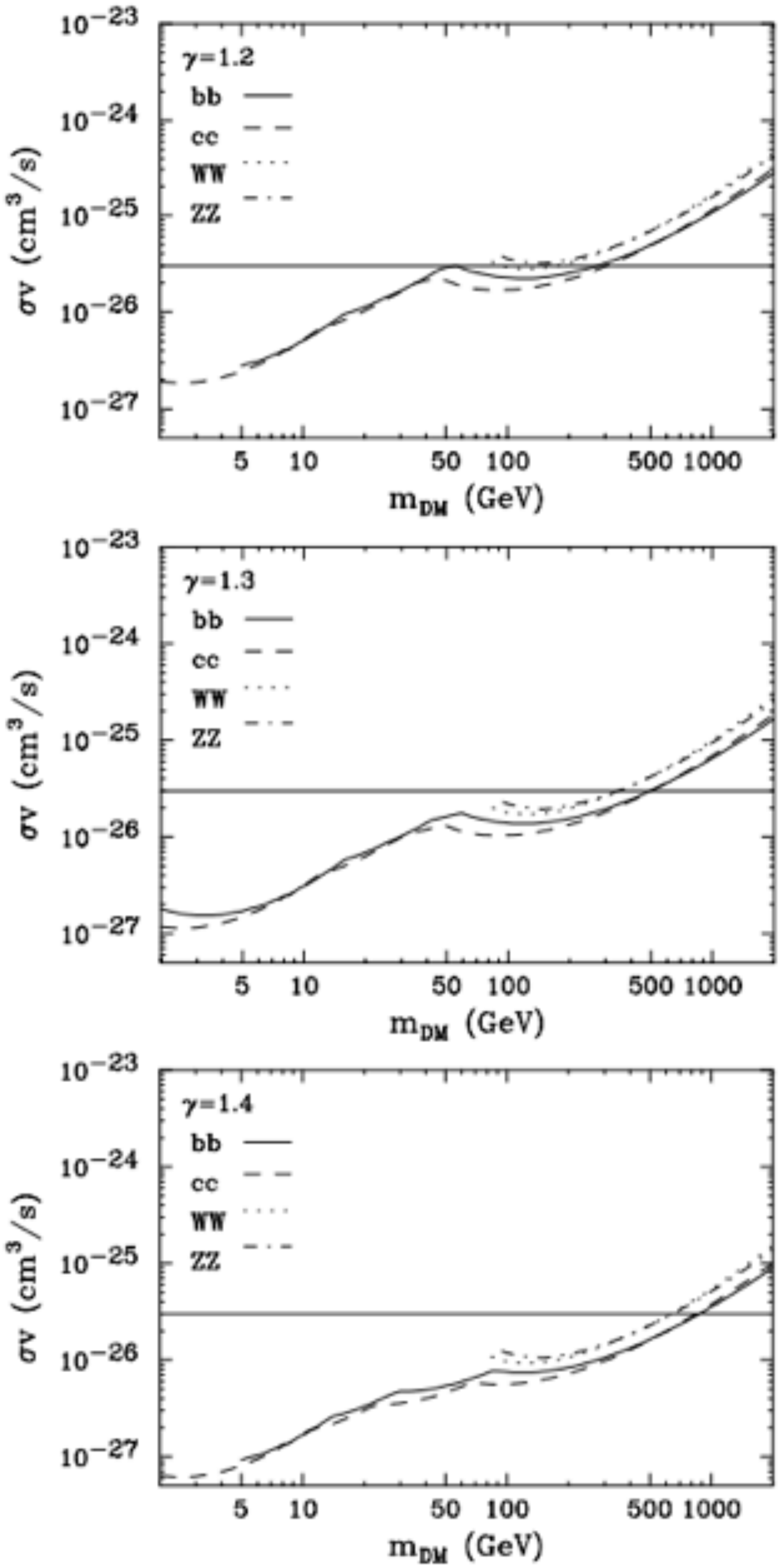
Hooper & Linden (2011)

- 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



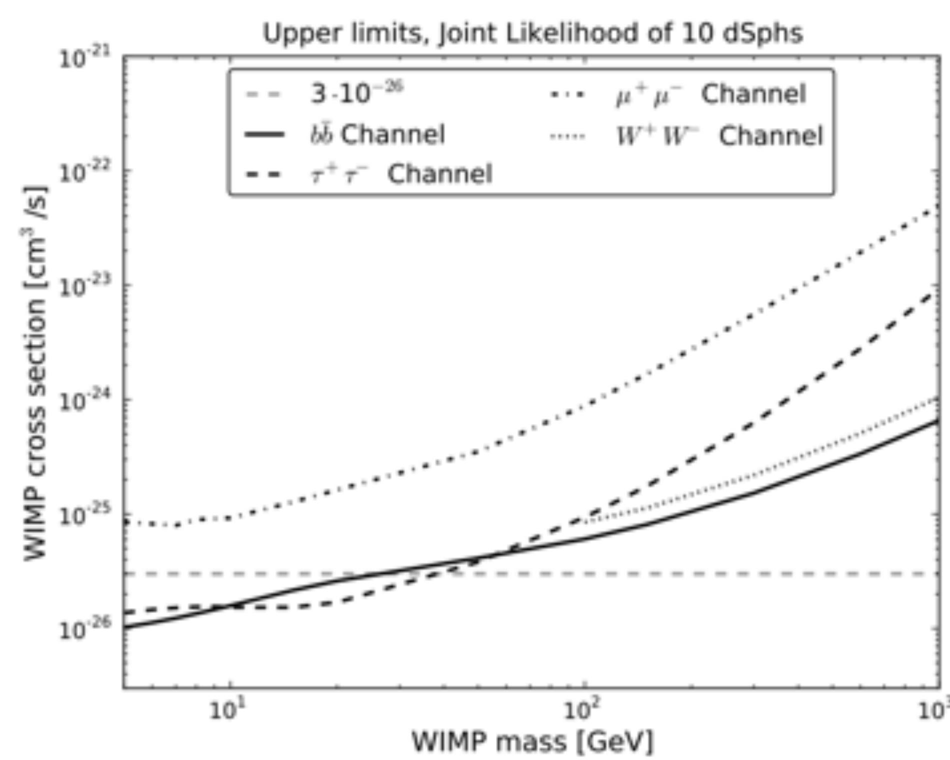


Comparison to Other Indirect Detection Regimes



Hooper & Linden (2011)

- With some adiabatic contraction of the inner dark matter profile, these limits can become substantially stronger than any other indirect detection limit

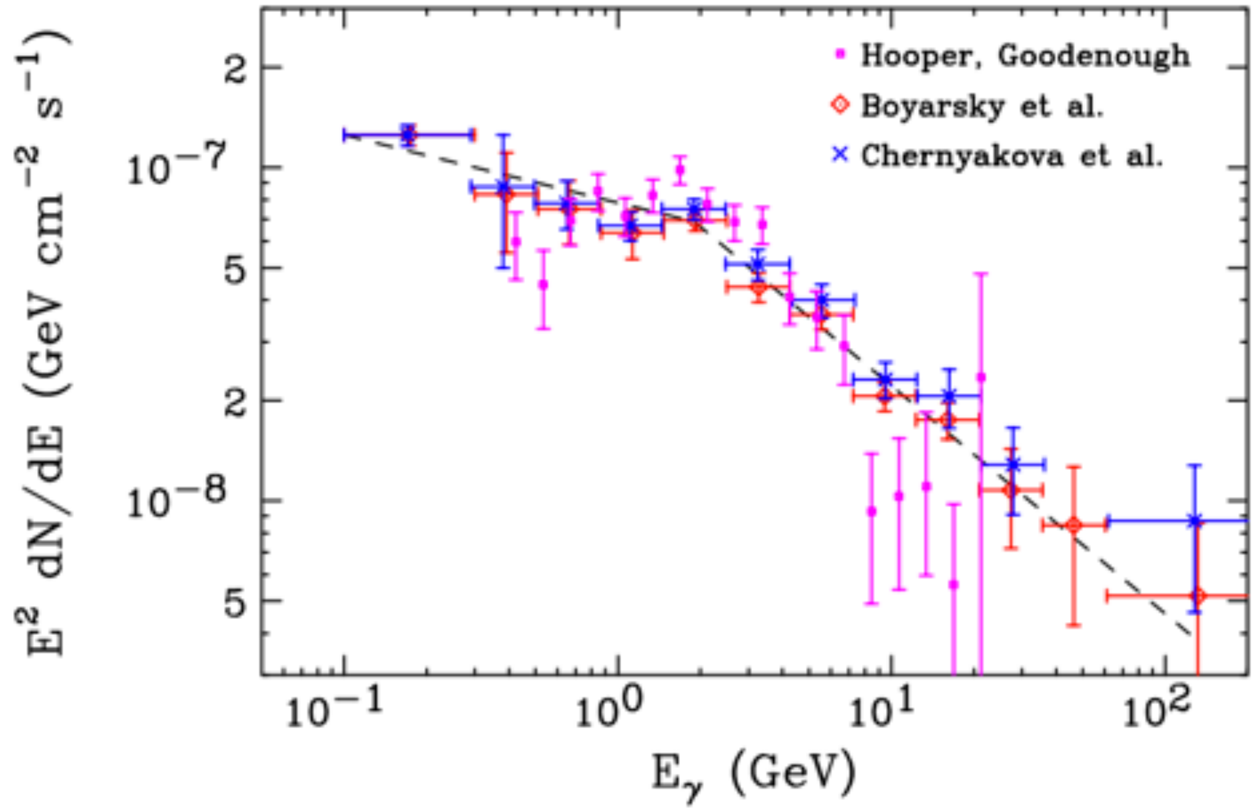


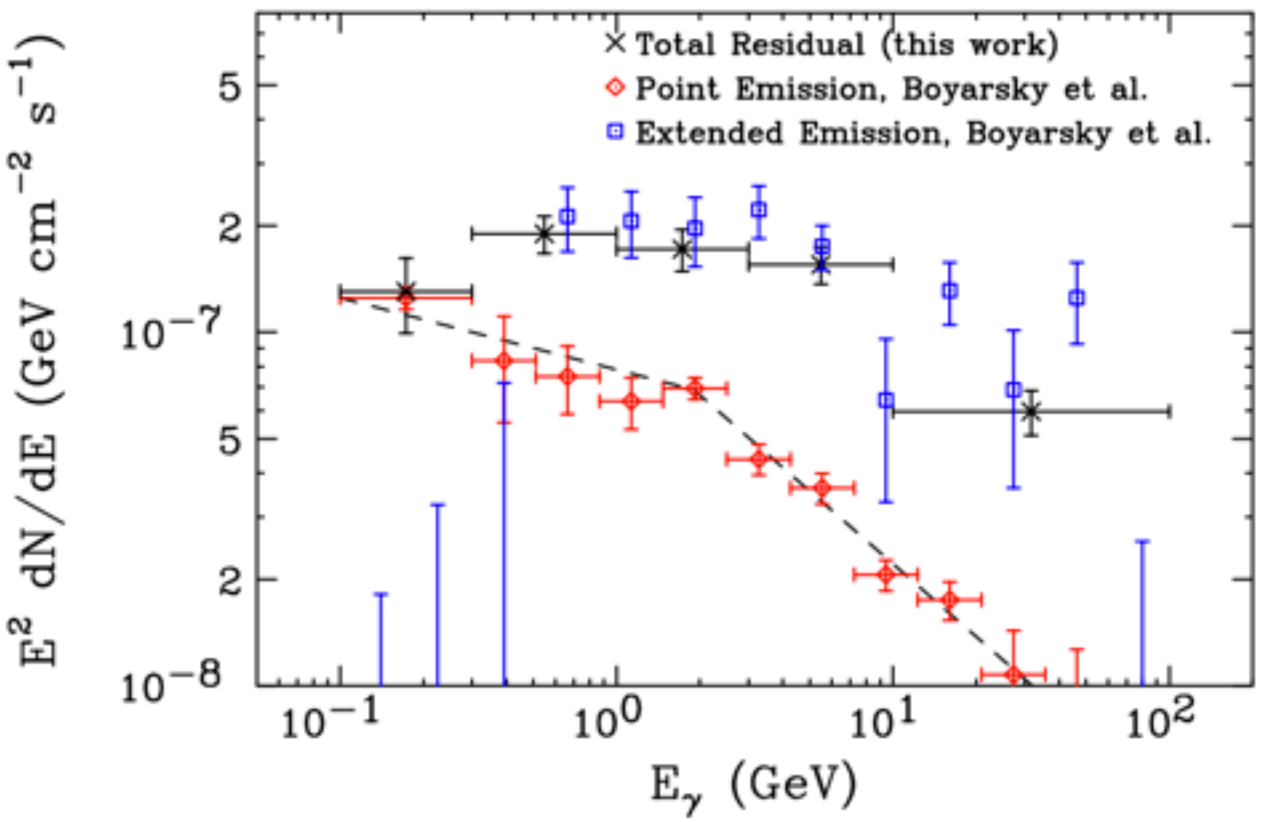
Ackermann et al. (2011)

Is It A Point Source?

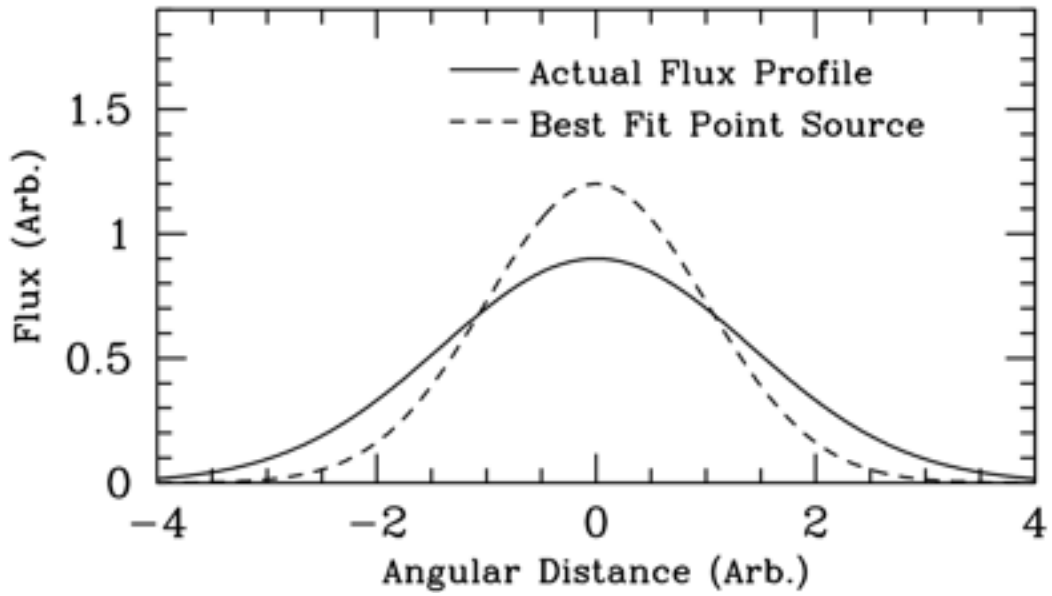
- Several efforts have been made to fit the GC point source, using both best-fitting point-source tools from the Fermi collaboration (Boyarsky et al. Chernyakova et. al), as well as independent software packages (Hooper & Goodenough)

- 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)

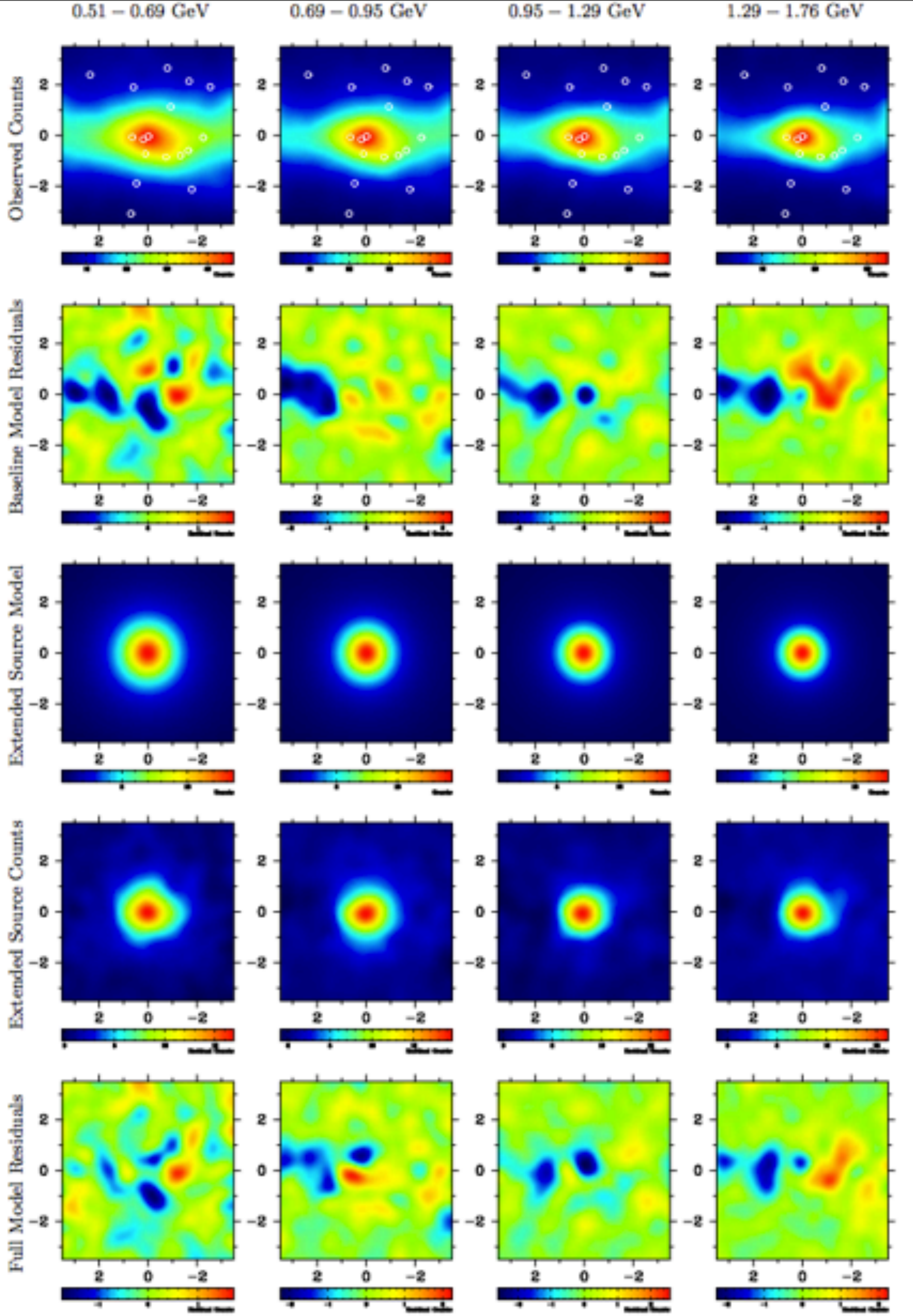


Is It A Point Source?

- 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

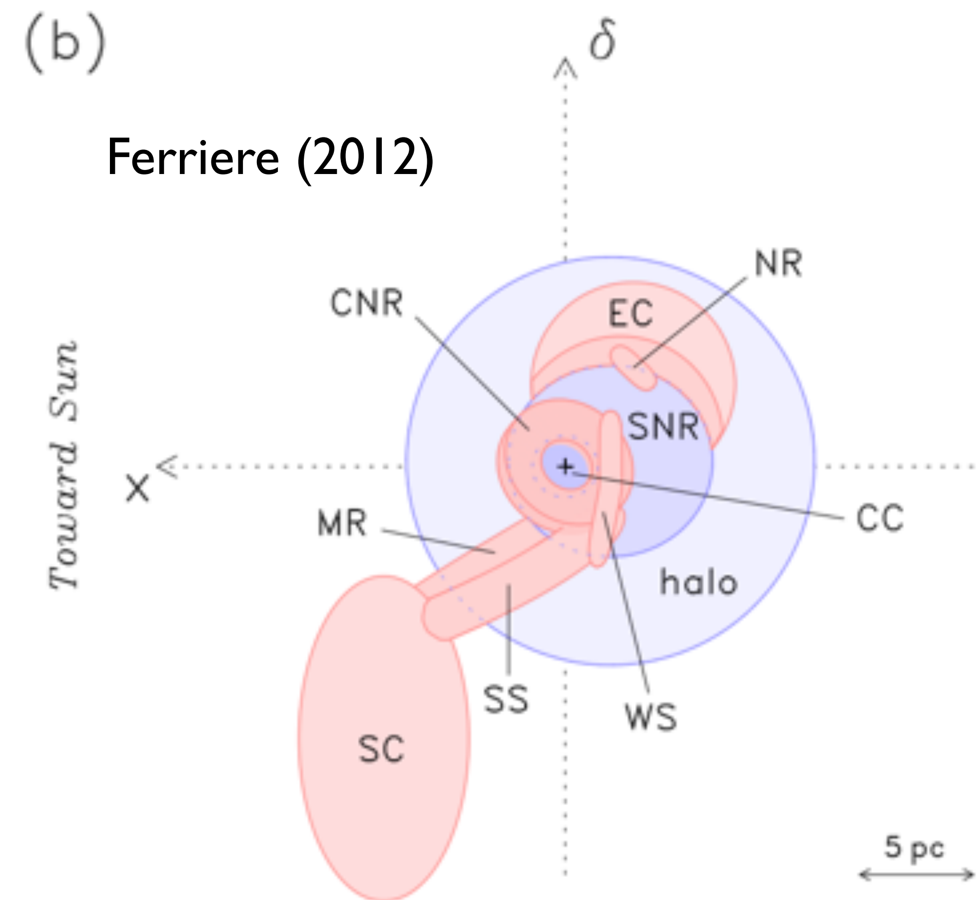
- What can we learn about physics from these observations?

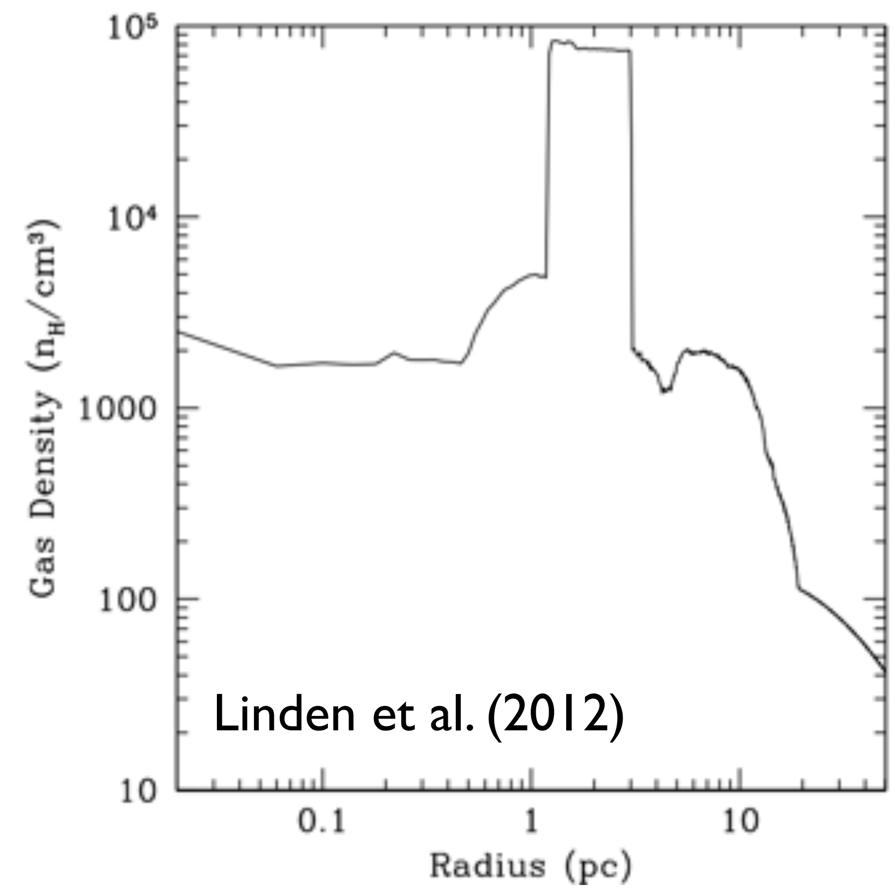
Interpretations at this Point

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

Understanding the Gas Morphology

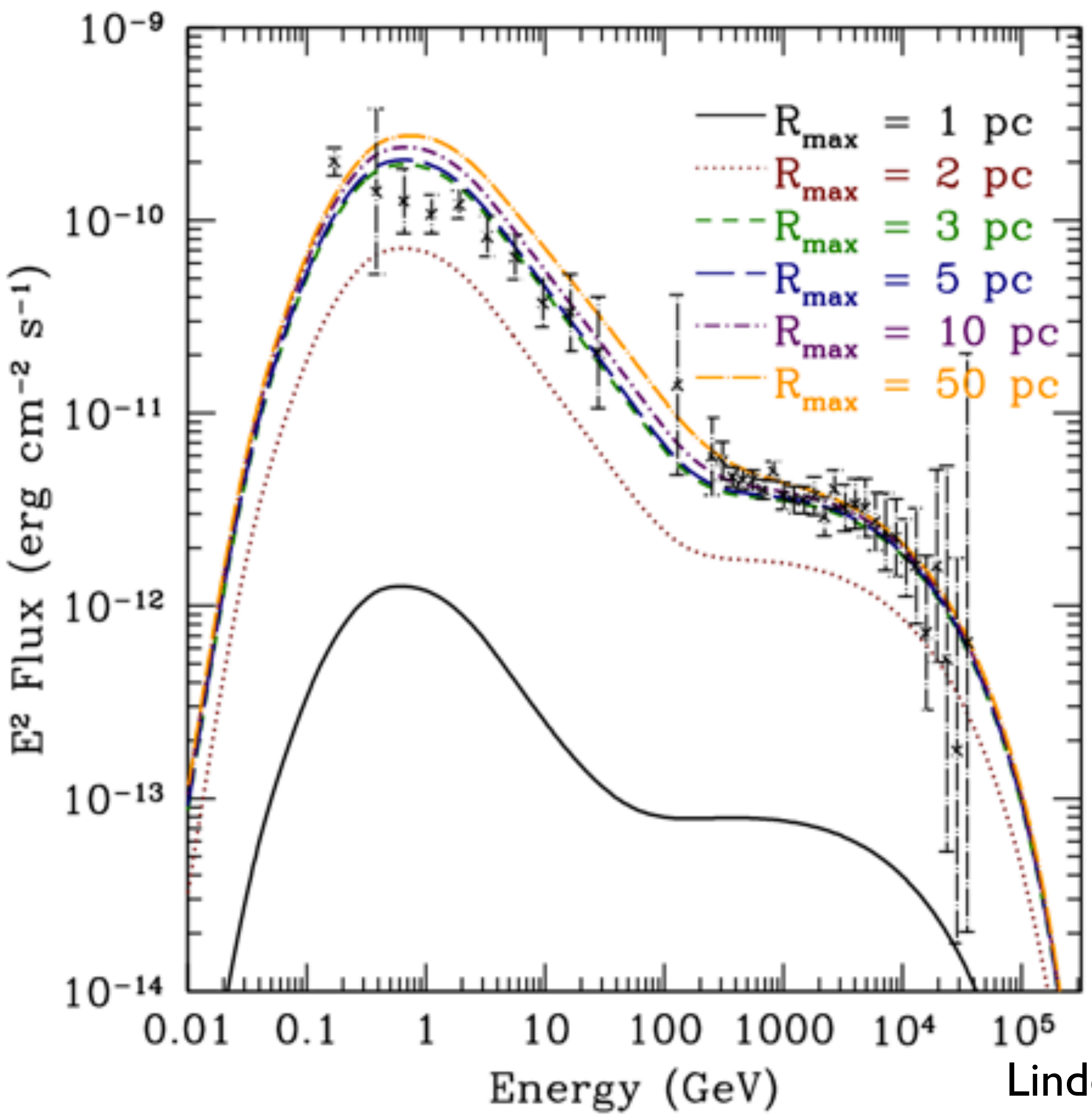
- Detailed models of the galactic gas density exist in the literature
- We employ a spherically symmetric model for galactic gas, and use this to calculate the morphology of the gamma-ray emission as a function of energy
- By far the dominant feature is the Circumnuclear ring between 1-3 pc from the GC



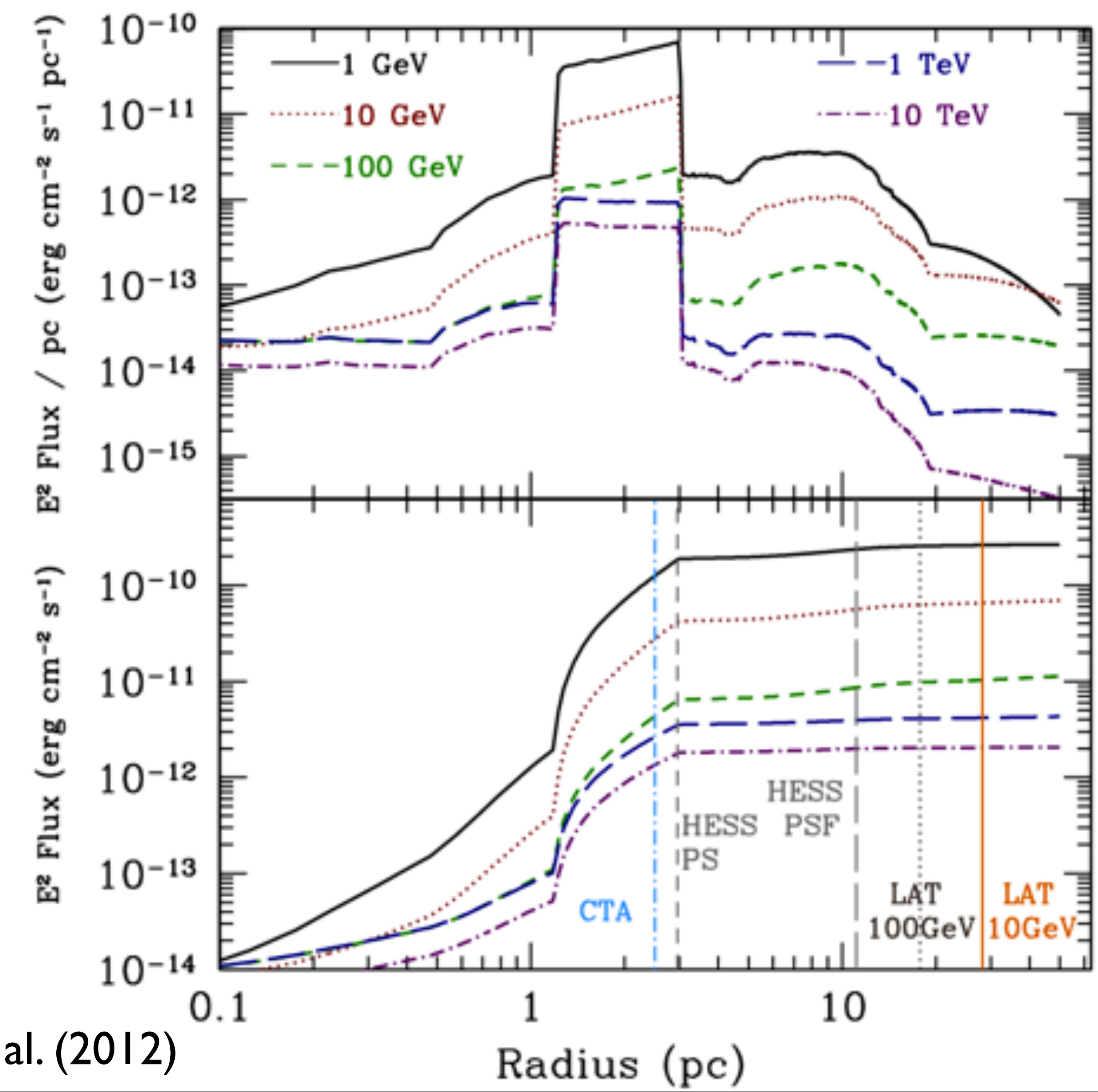


Understanding the Gas Morphology

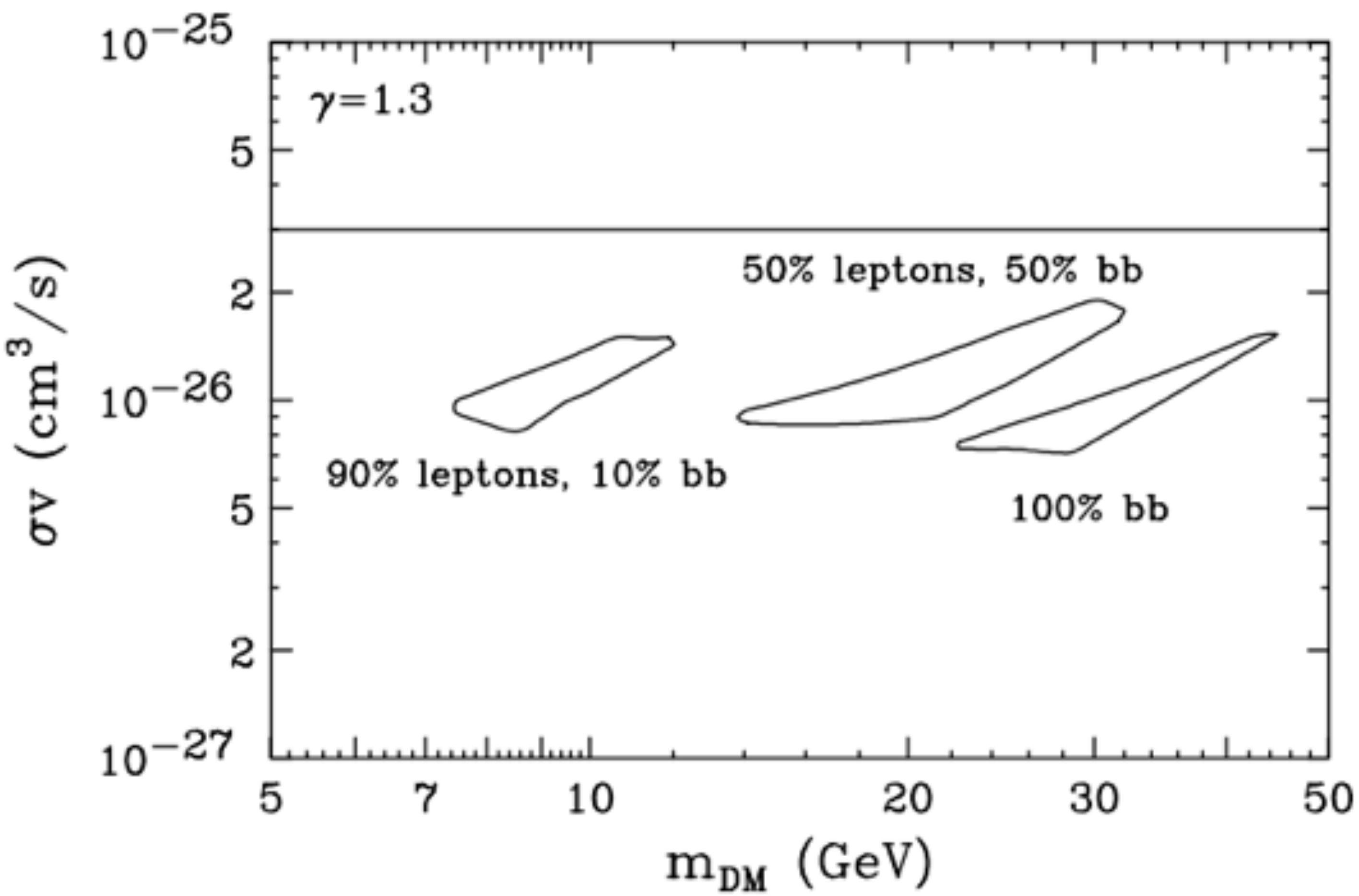
- The vast majority of emission stems from within 3 pc of the galactic center at all energies
- This lies below the PSF of all current gamma-ray instruments
- This effectively rules out hadronic interactions from Sgr A* as the source of the Fermi-LAT excess



Linden et al. (2012)



Dark Matter Fits



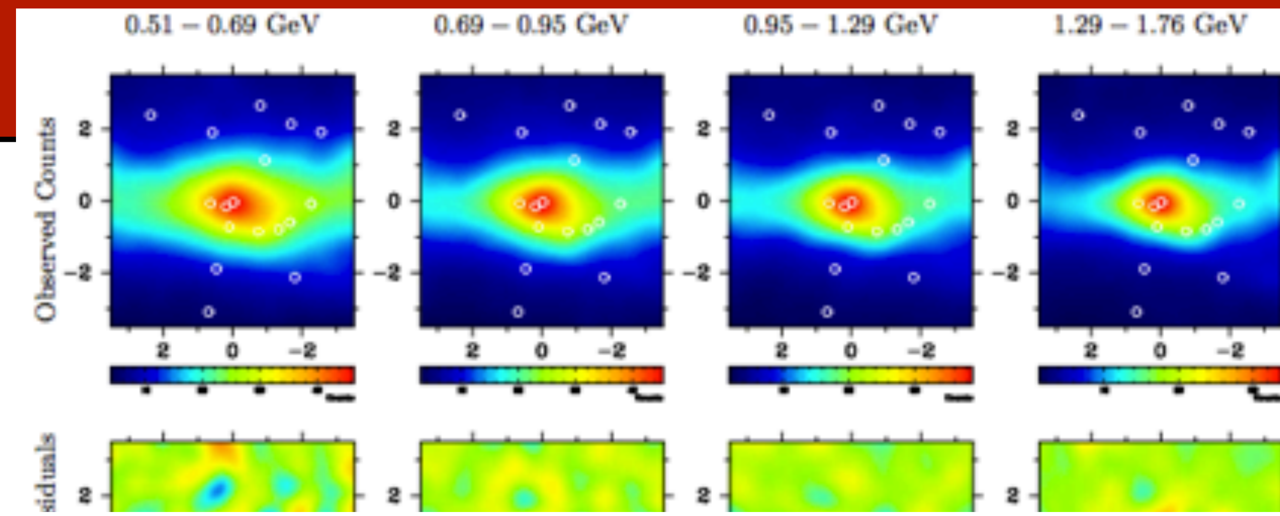
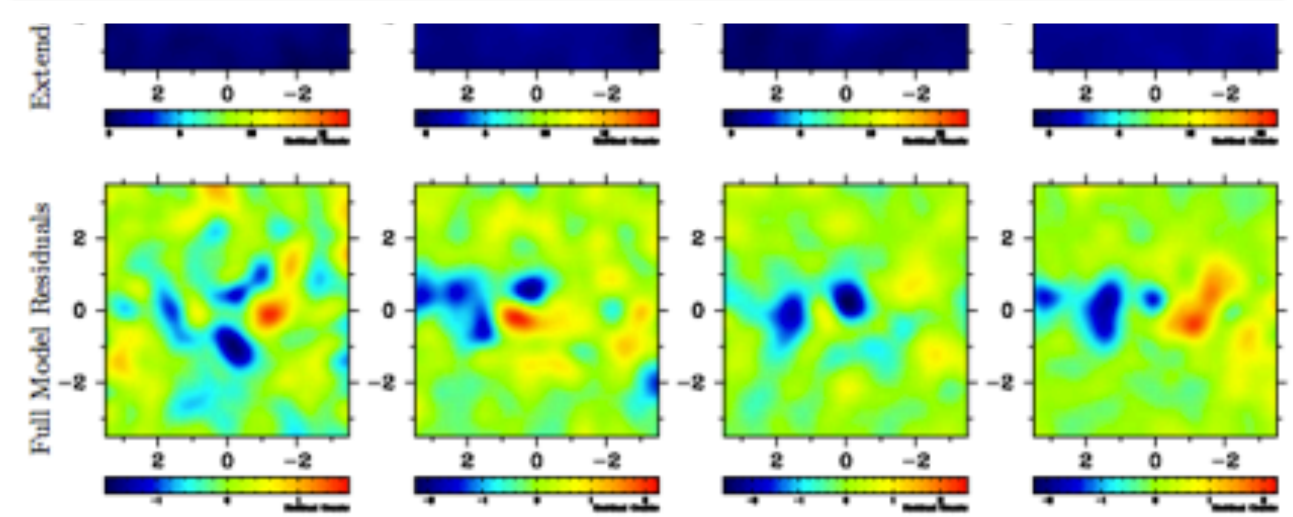


TABLE II. The best-fit TS, negative log likelihoods, and $\Delta\mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

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

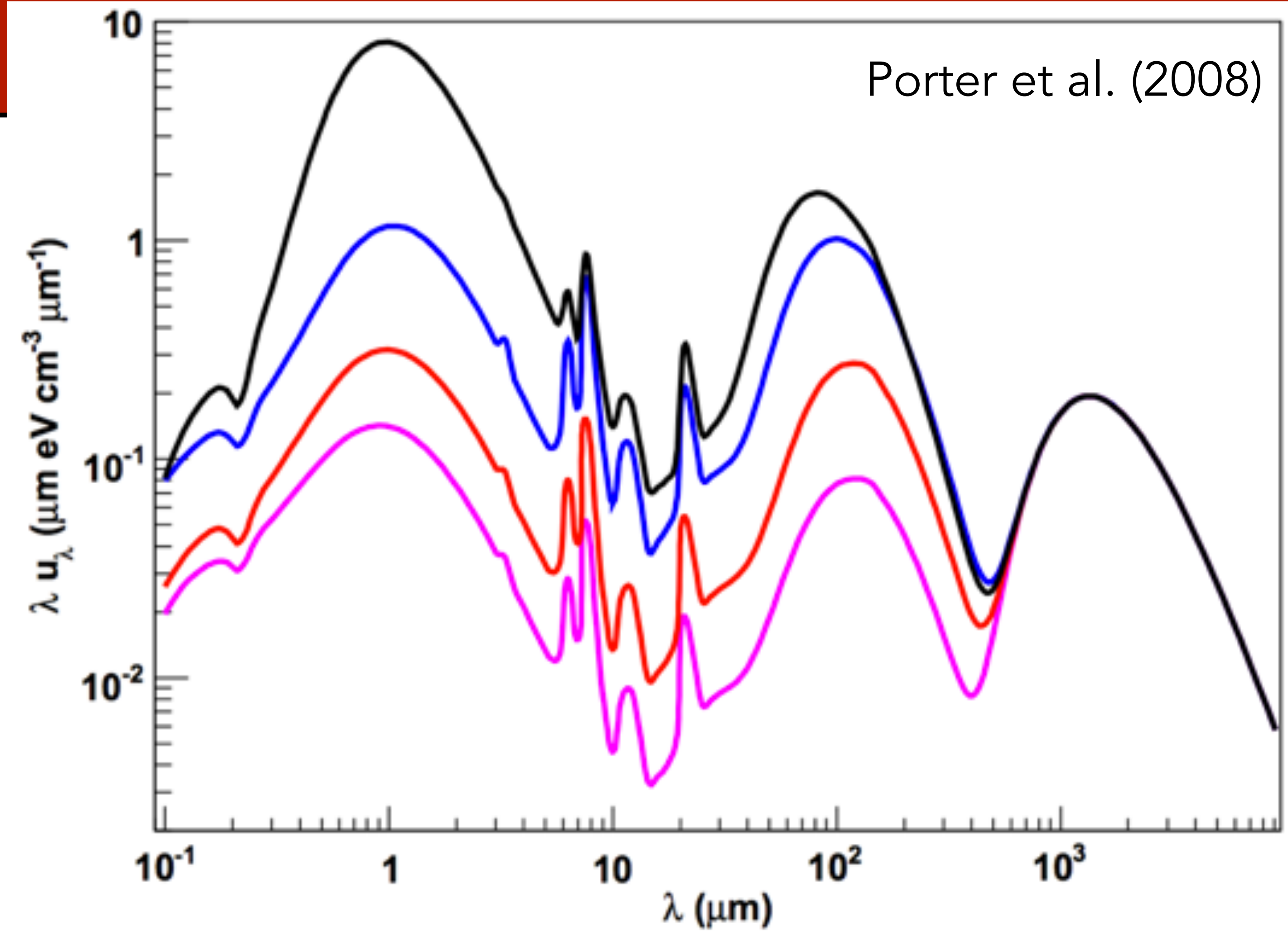
Abazajian & Kaplinghat (2012)

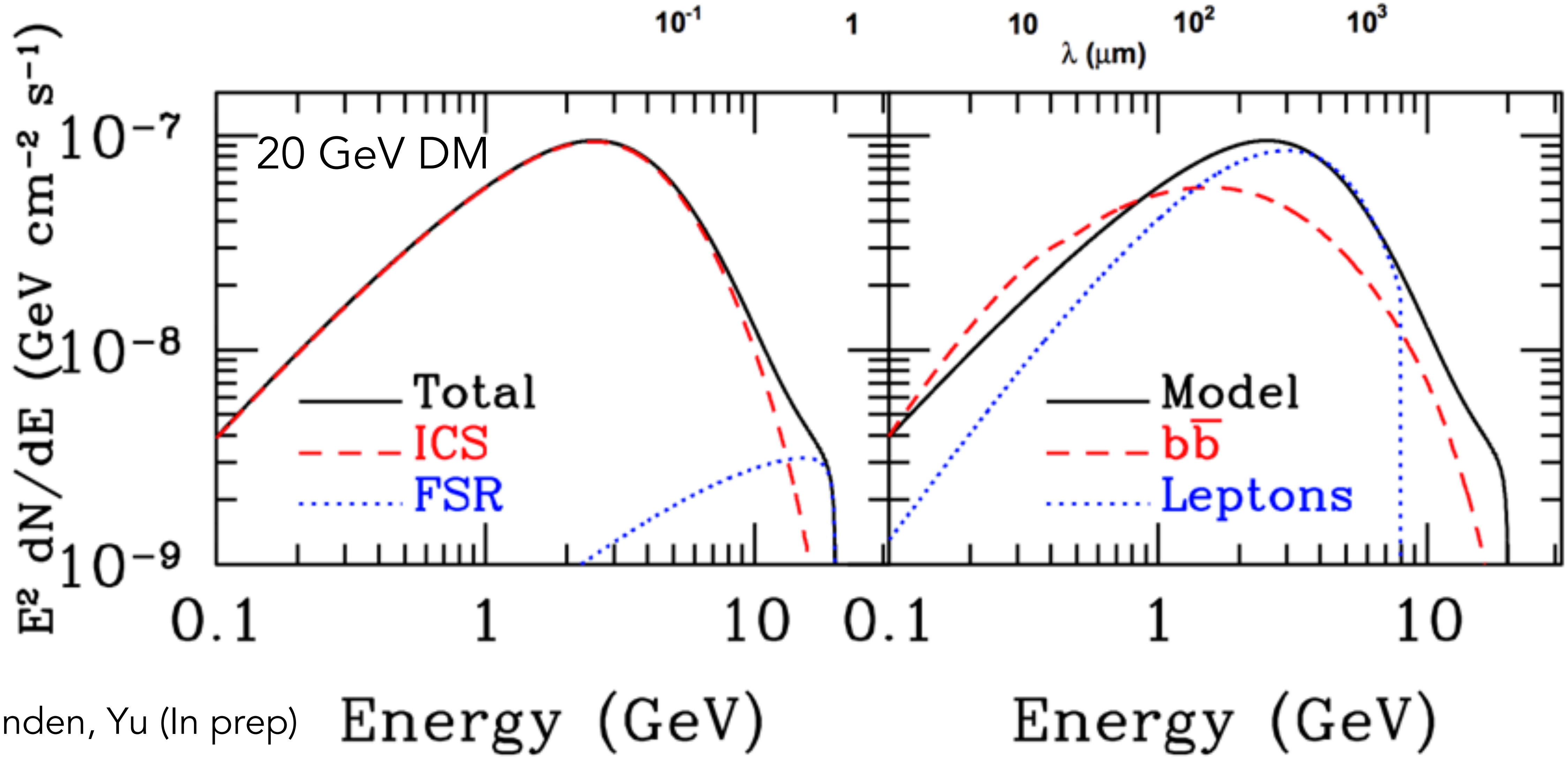
Dark Matter Fits

- More exotic models can also fit the excess

$$\chi\chi \to \Phi\Phi \to e^+e^-$$

and the subsequent ICS of the ISRF





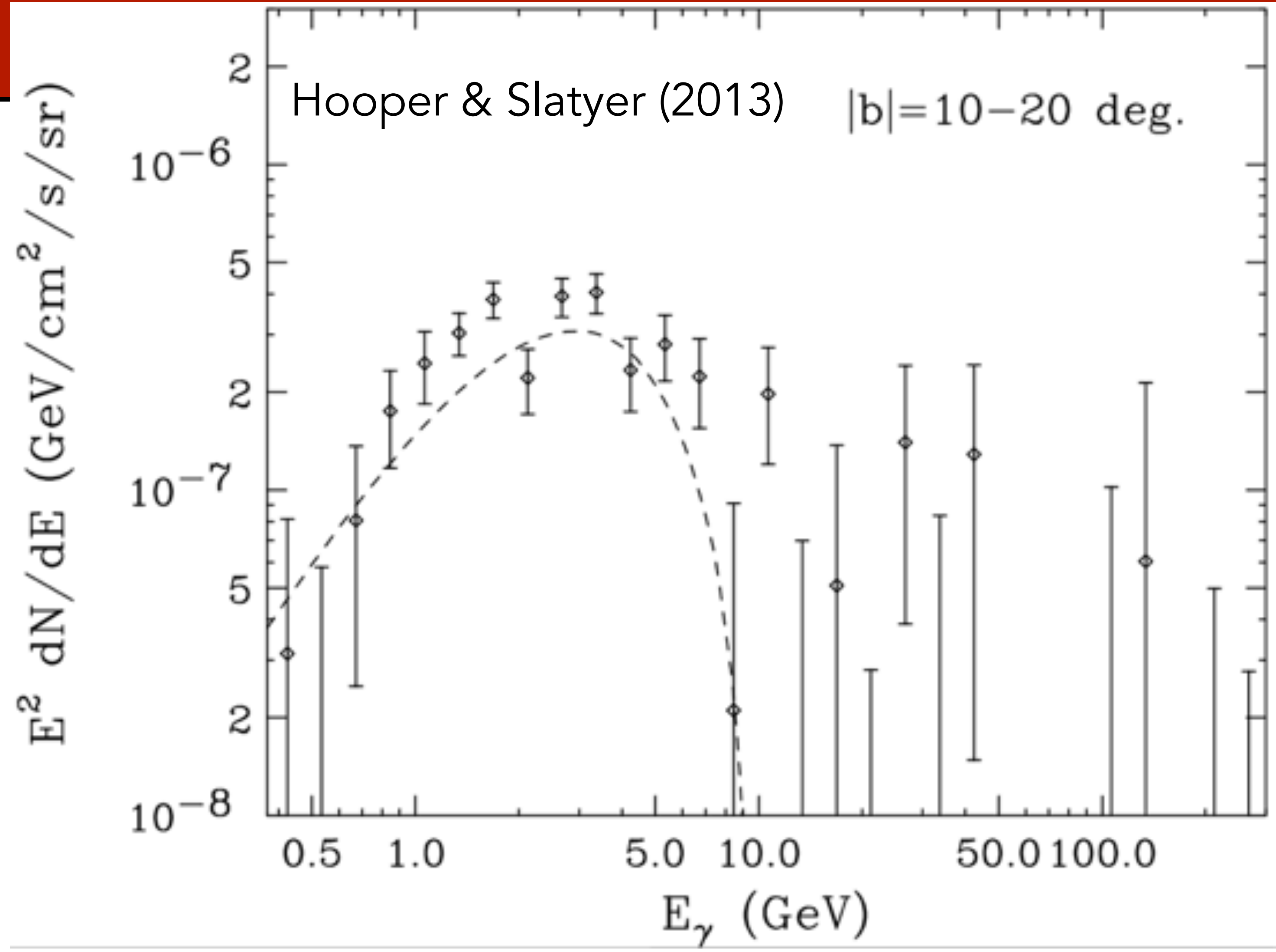
Kaplinghat, Linden, Yu (In prep)

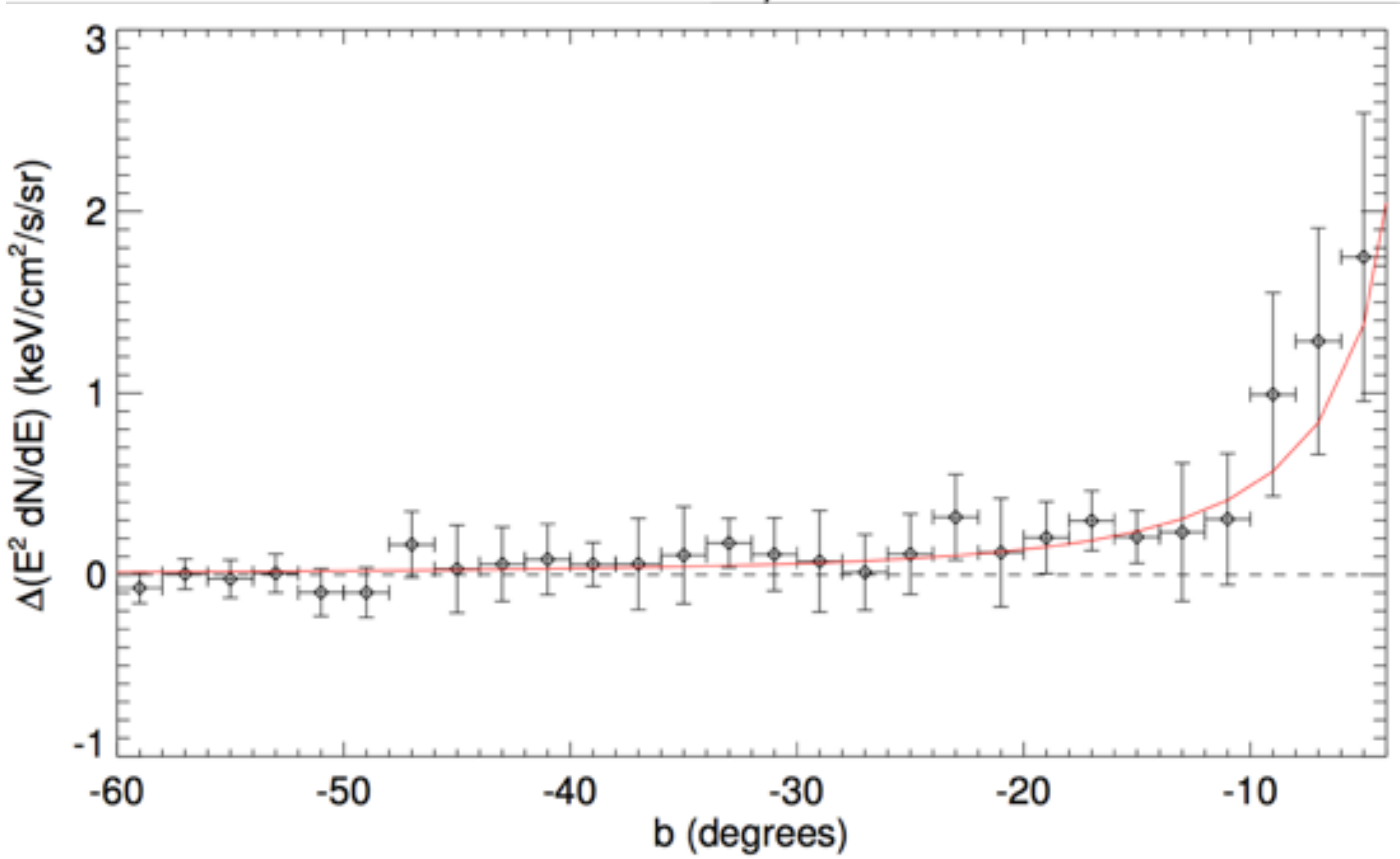
Dark Matter Fits

- 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

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

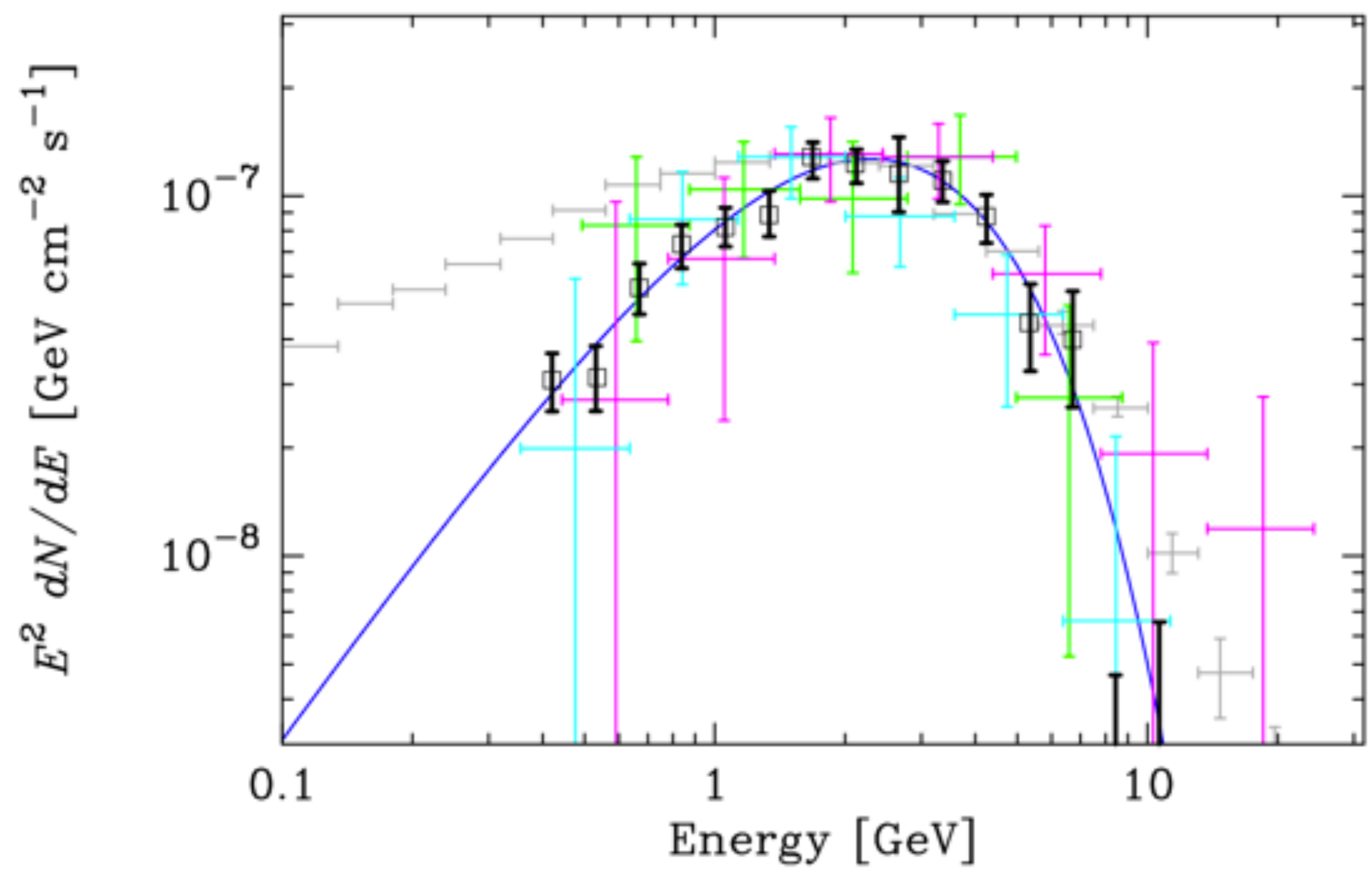
- Most Importantly: This residual is still observed far from the complicated backgrounds of the GC





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



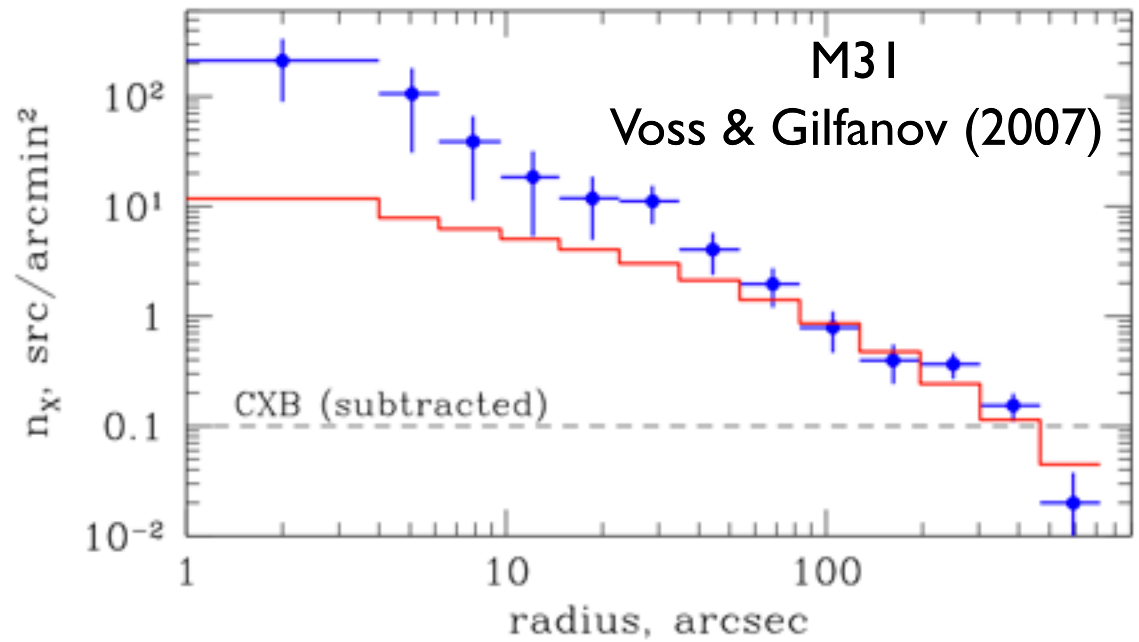
$$\text{Omega Cen:} \quad \Gamma = 0.7^{+0.7+0.4}_{-0.6-0.4}, E_c = 1.2^{+0.7+0.2}_{-0.4-0.2},$$
$$\text{NGC 6388:} \quad \Gamma = 1.1^{+0.7+0.8}_{-0.5-0.8}, E_c = 1.8^{+1.2+1.8}_{-0.7-0.6},$$
$$\text{M 28:} \quad \Gamma = 1.1^{+0.7+0.6}_{-0.5-0.7}, E_c = 1.0^{+0.6+0.4}_{-0.3-0.2},$$
$$\text{NGC 6652:}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

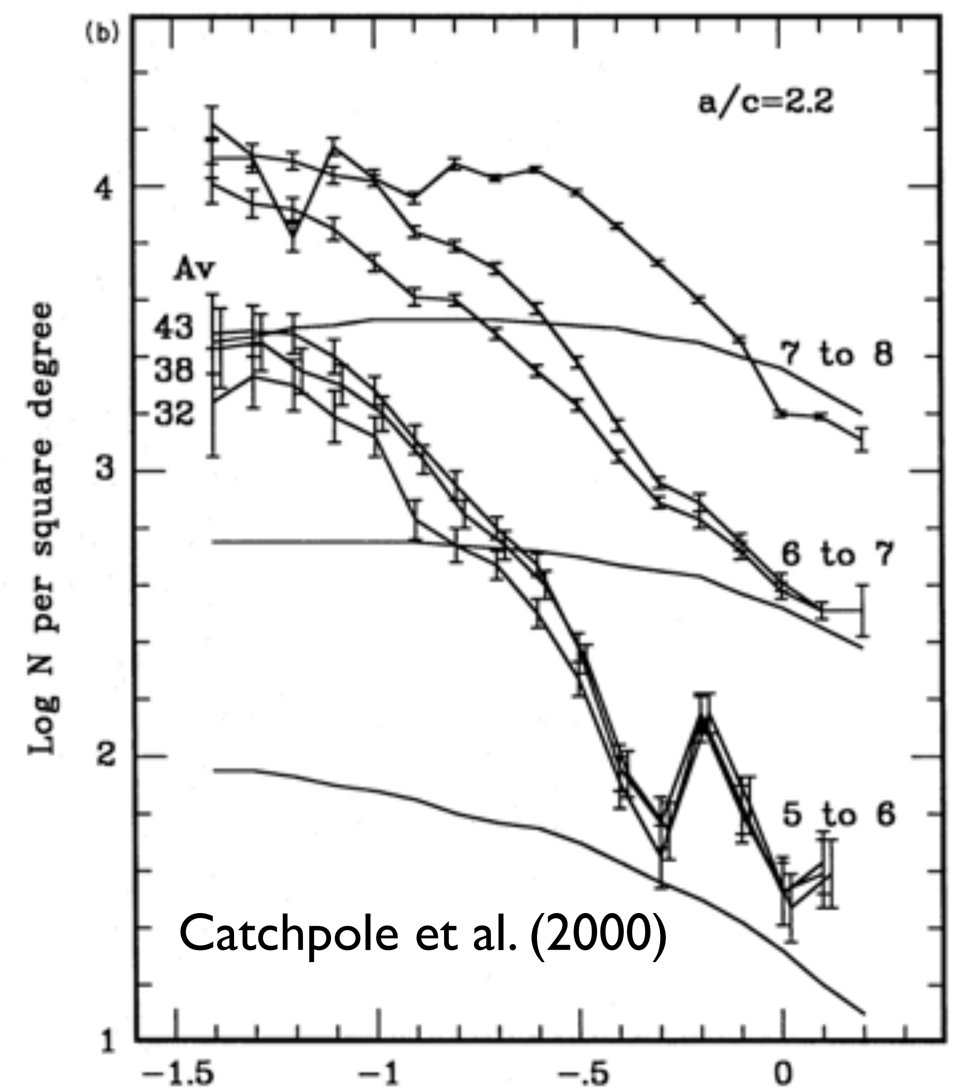
Abazajian (2011)

Millisecond Pulsar Fits

- Must explain the high density of pulsars near the Galactic Center ($\sim r^{-2.6}$)

- Single stars and X-Ray point sources are not as compact towards galaxy centers
  - Two body interactions in the densest clusters?
  - Mass segregation?



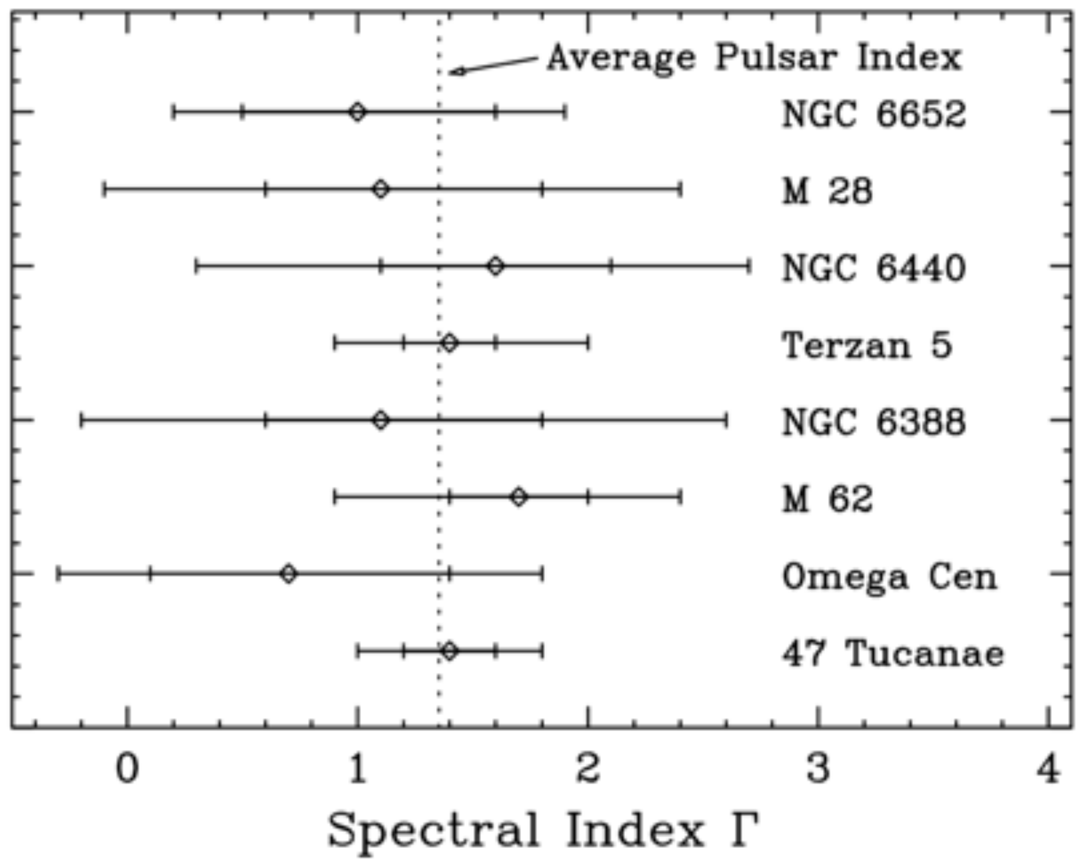


Millisecond Pulsar Fits

- However, the average globular cluster does not have the same spectral index

- Instead the globular cluster spectral index is similar to the average pulsar index, and are similar to each other

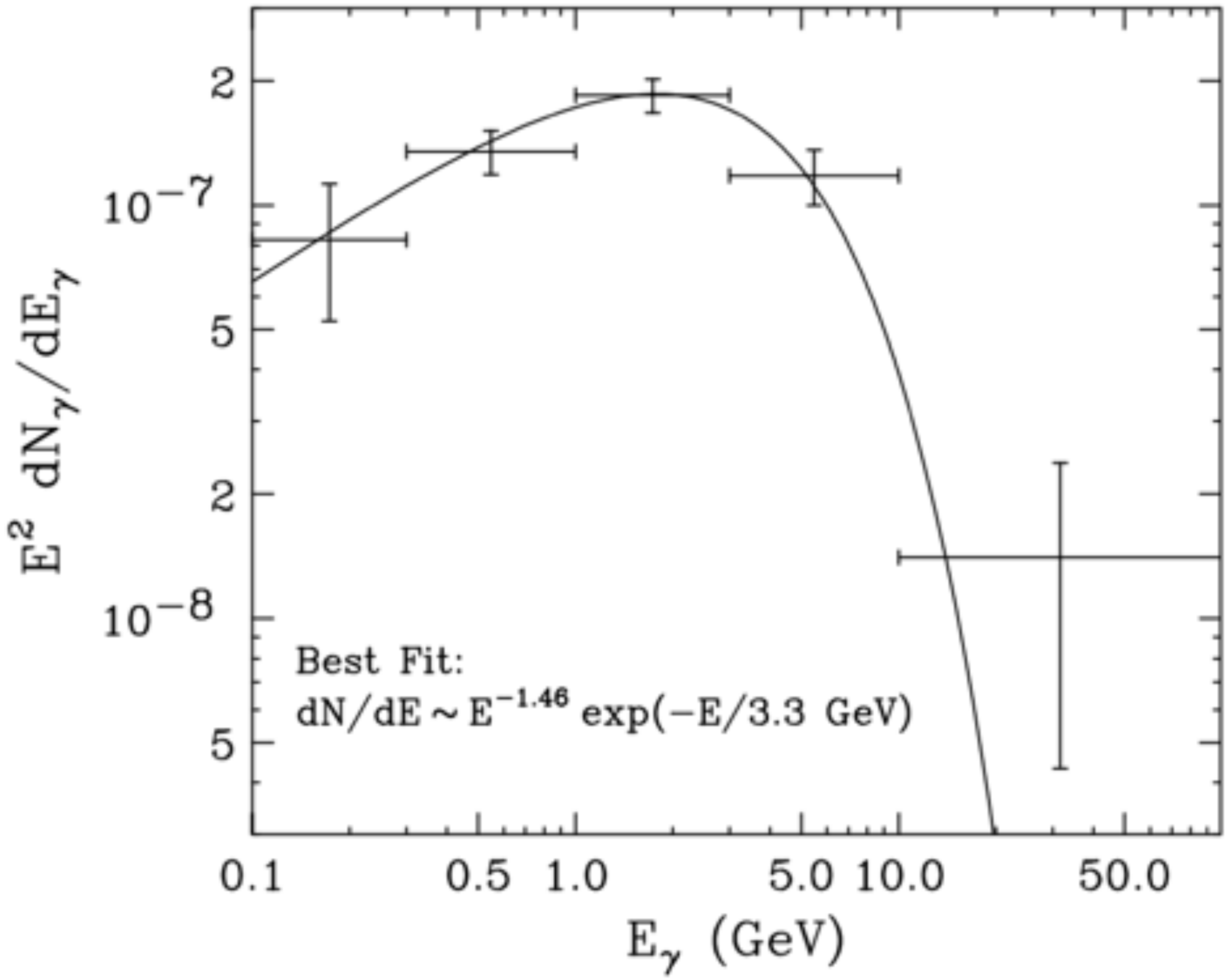
Hooper & Linden (2011)

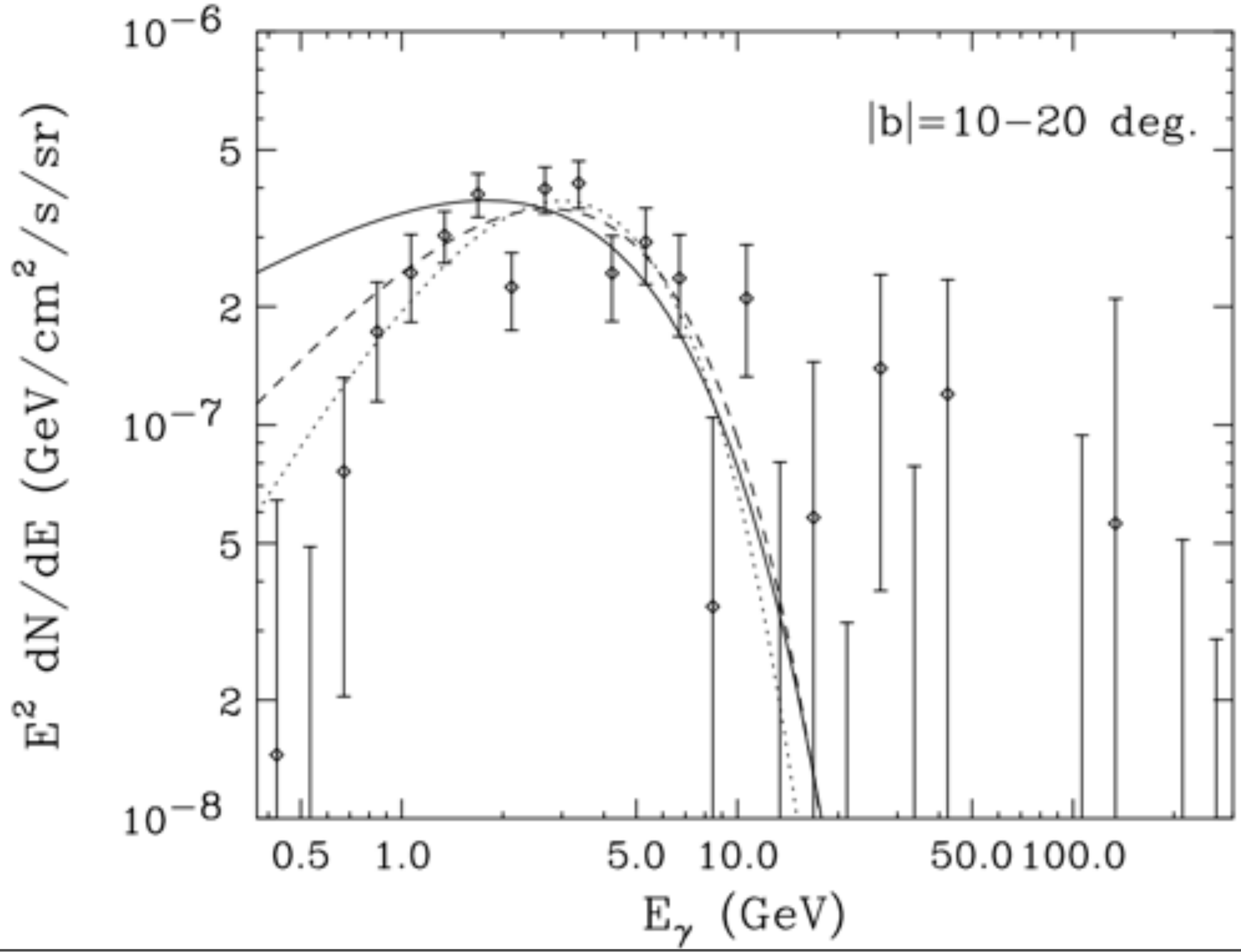


Millisecond Pulsar Fits

- 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



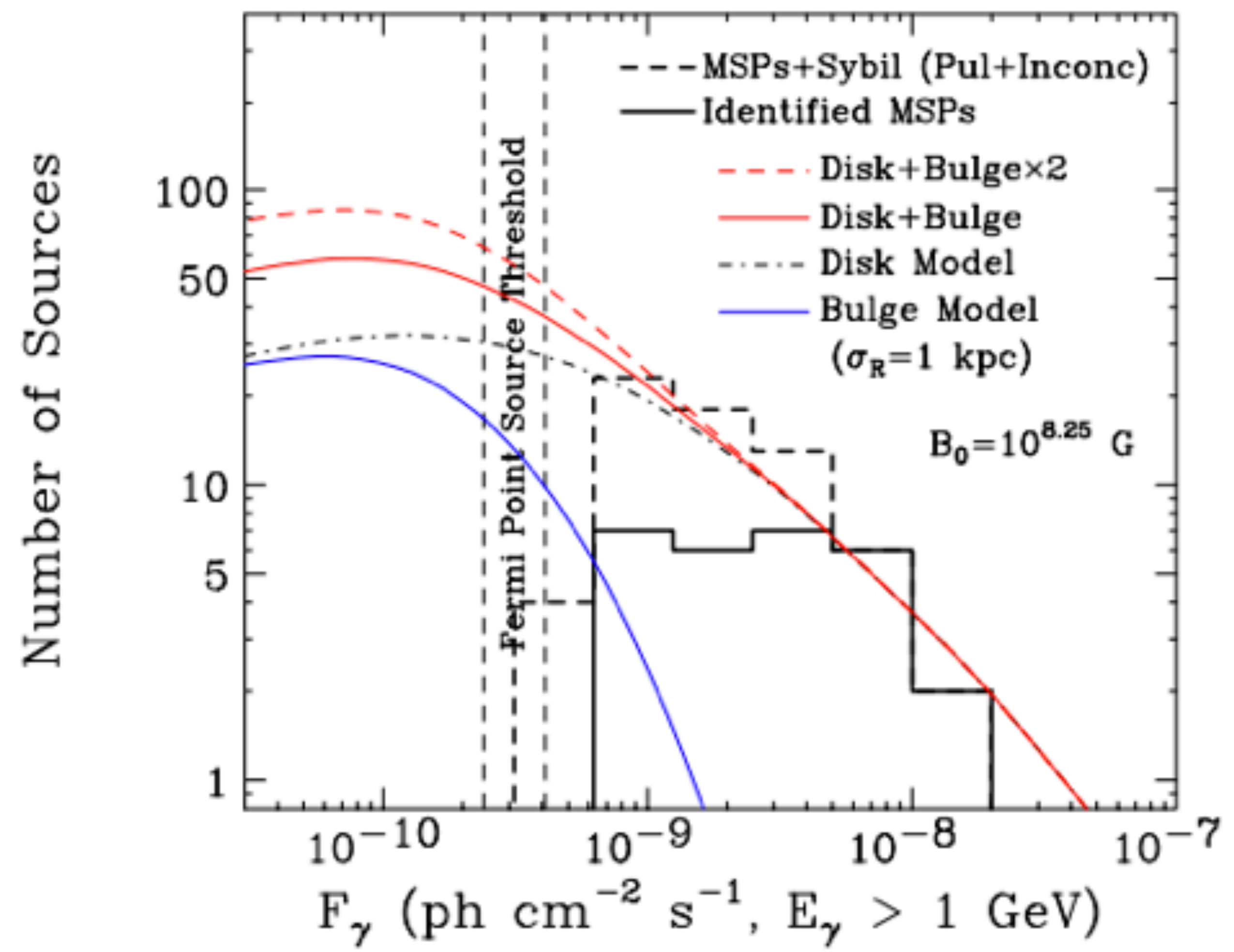


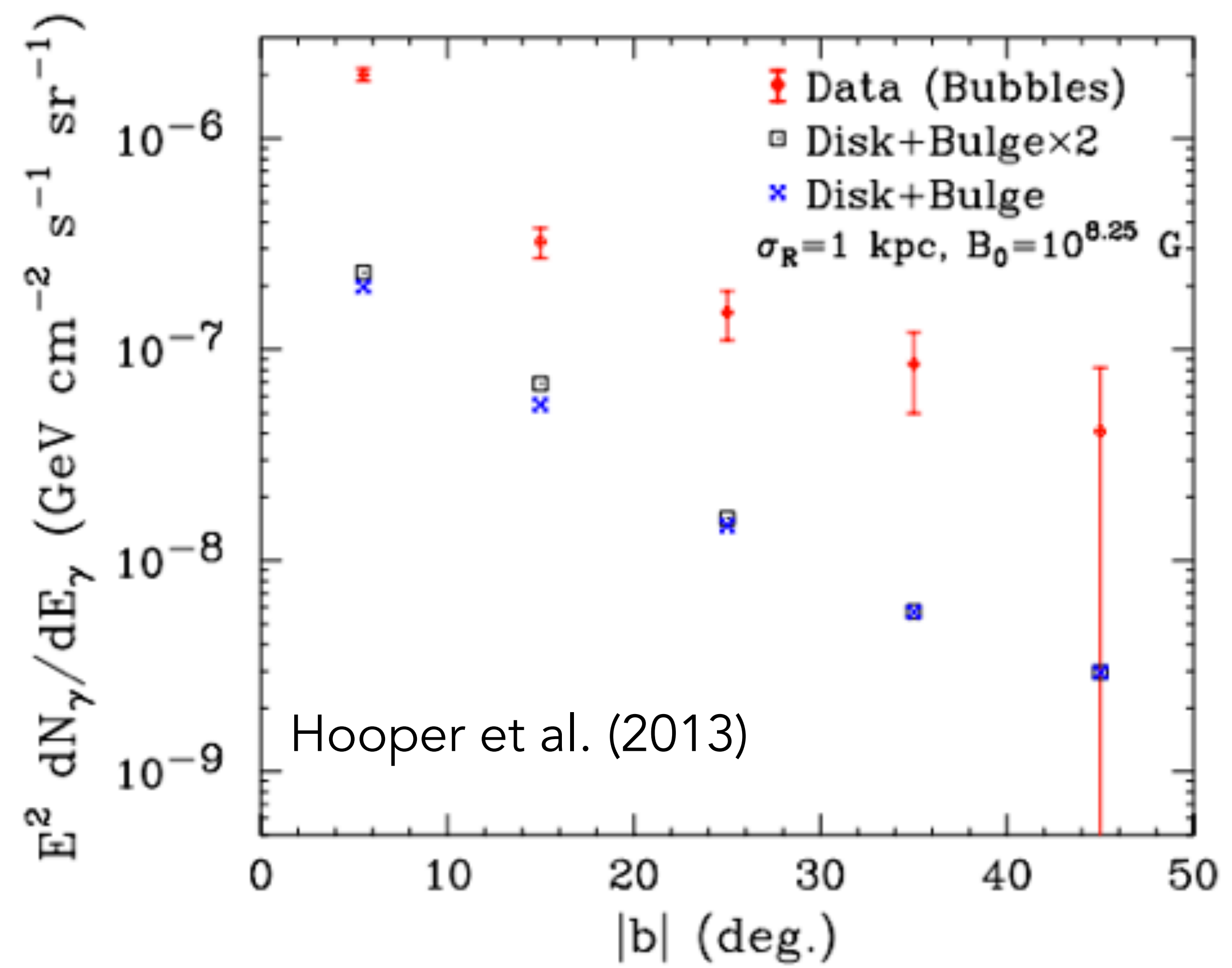
Hooper et al. (2013)

Millisecond Pulsar Fits

- Additionally, it is difficult to produce the diffuse emission from the haze region, without overproducing the number of observed point sources

- Models which saturate the number of detected point sources, underproduce the observed diffuse emission by an order of magnitude

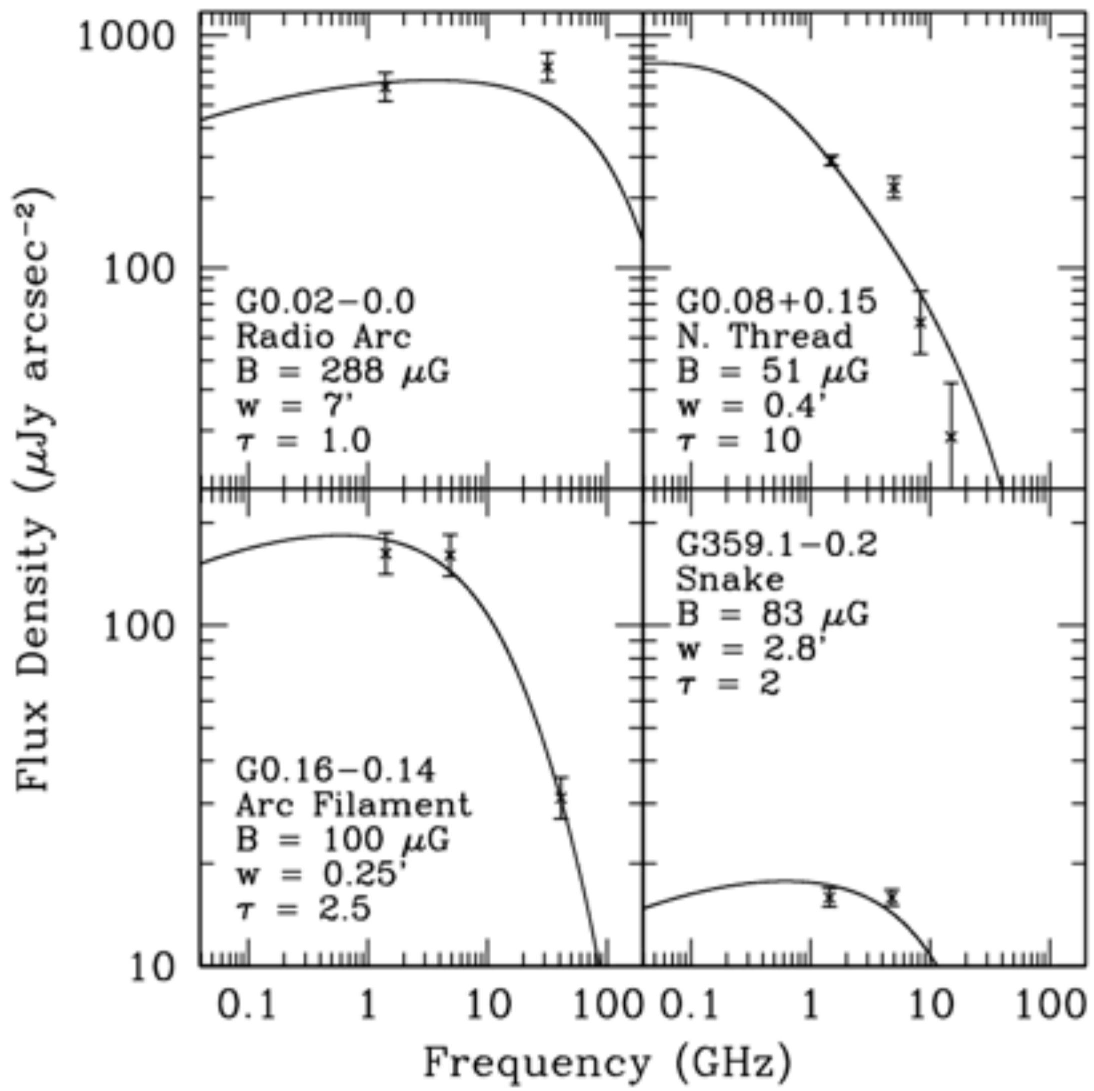




The Dark Matter Interpretation

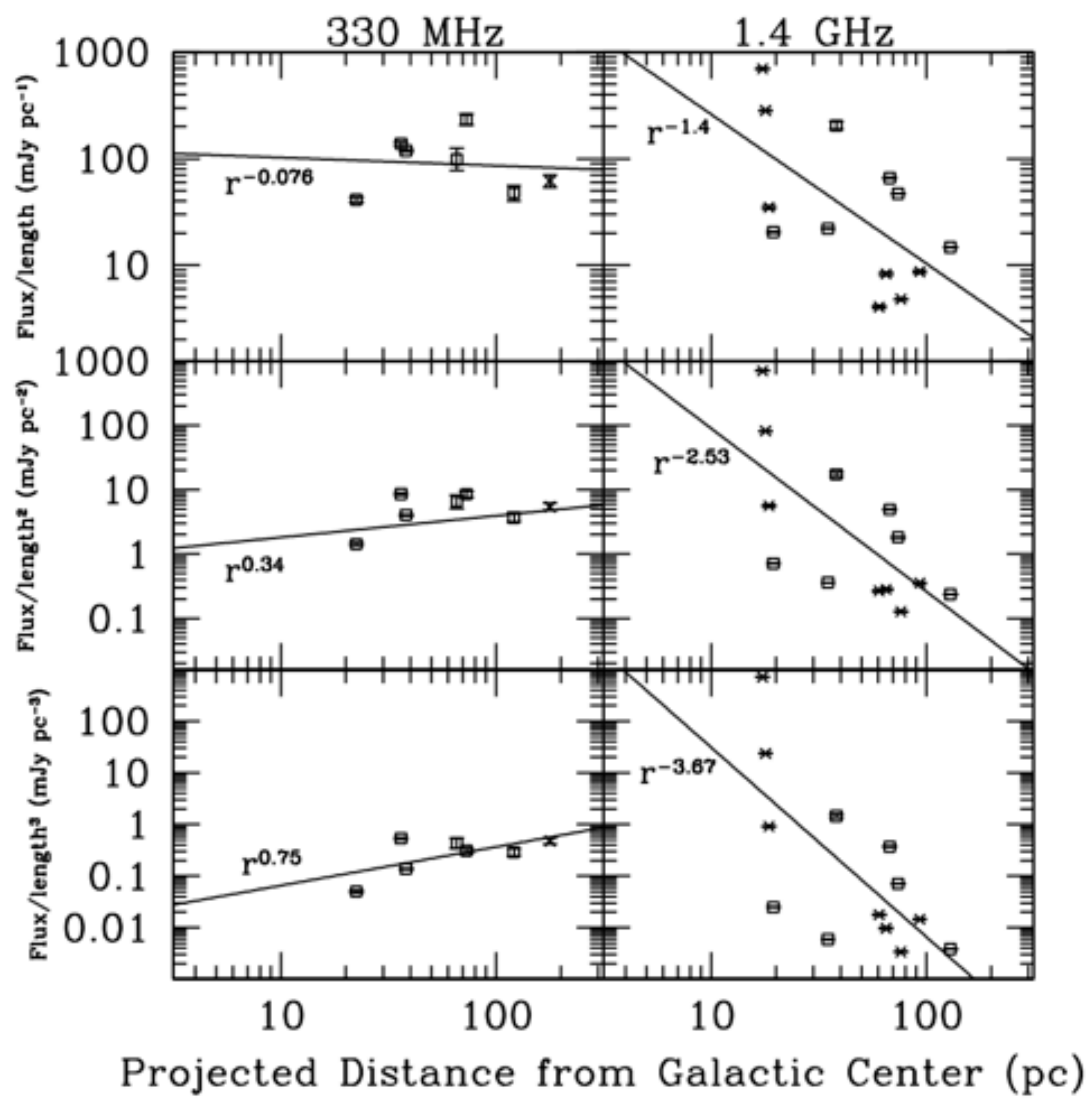
What other observations support/oppose a dark matter interpretation?

Evidence for A Dark Matter Interpretation



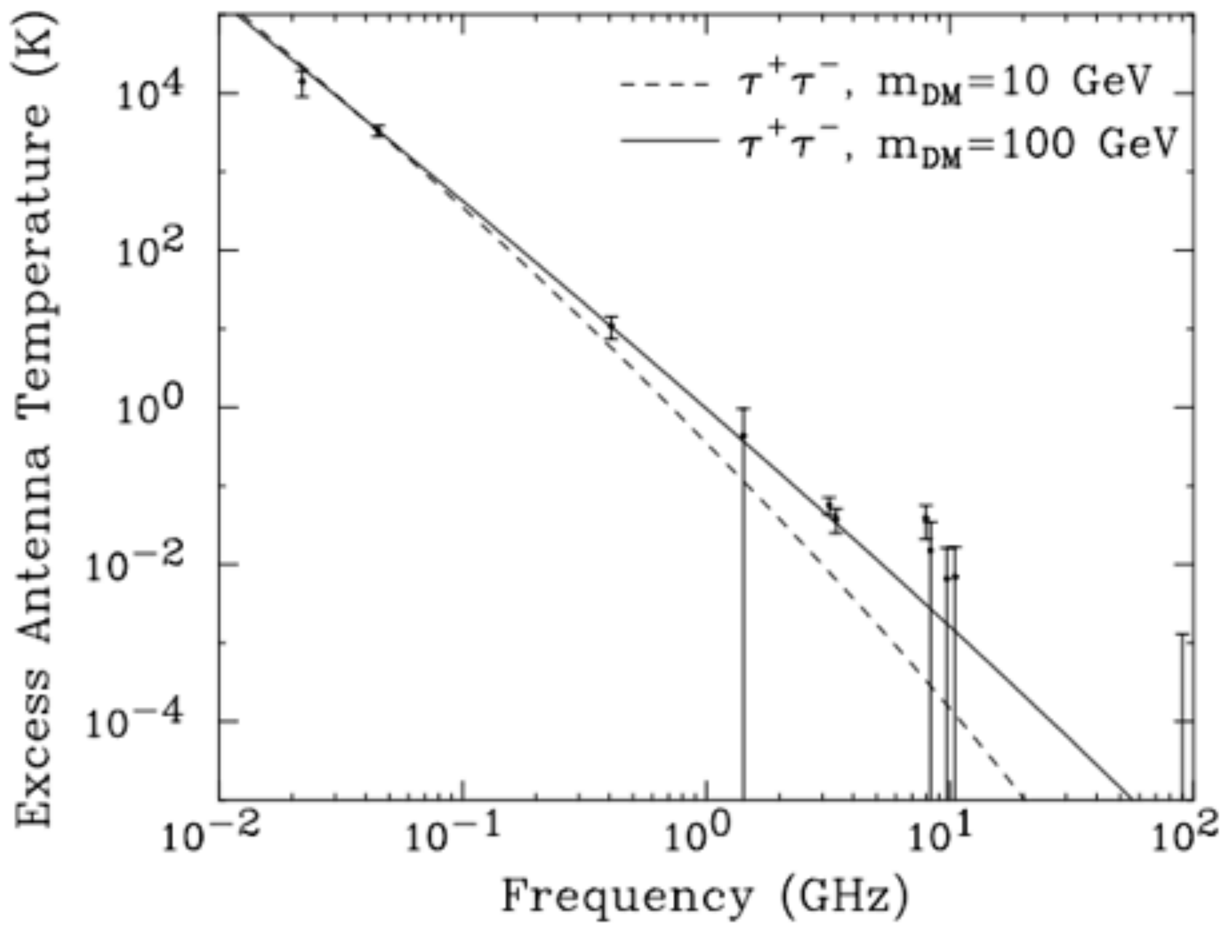
Linden et al. (2011)

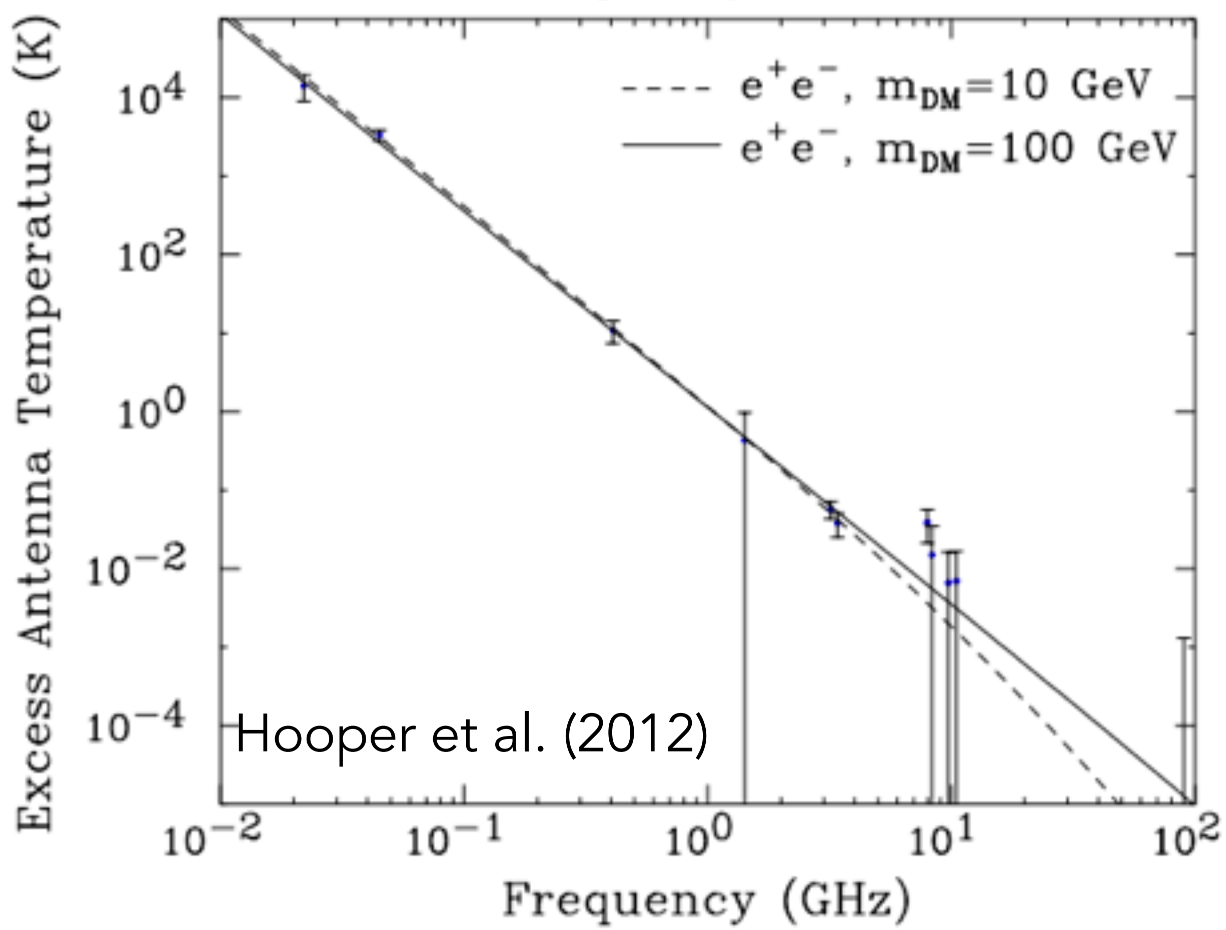
- Hard spectrum, non-thermal radio filaments can be fit with dark matter annihilation



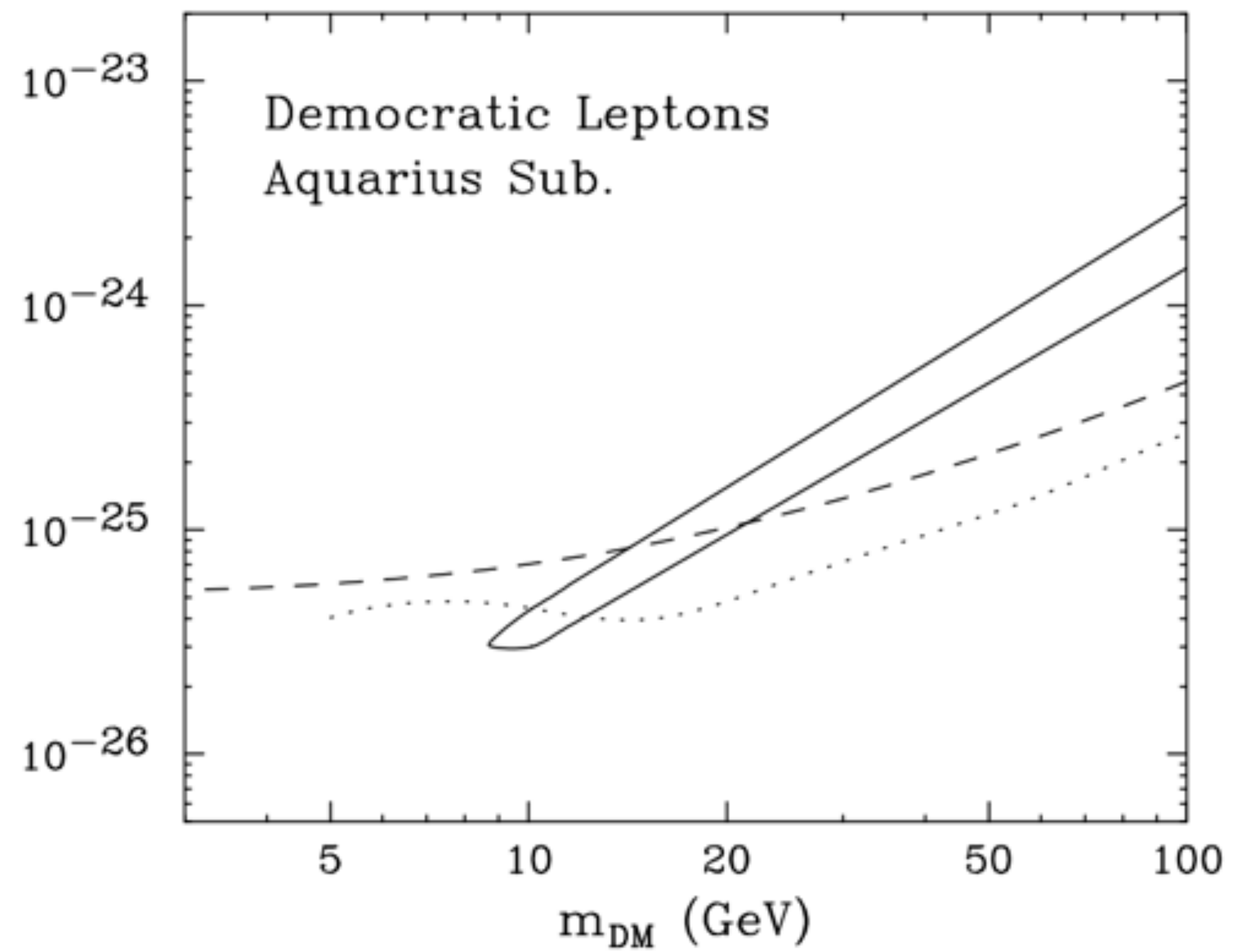
- The radial profile of radio filaments may suggest a dark matter injection morphology

Evidence for A Dark Matter Interpretation

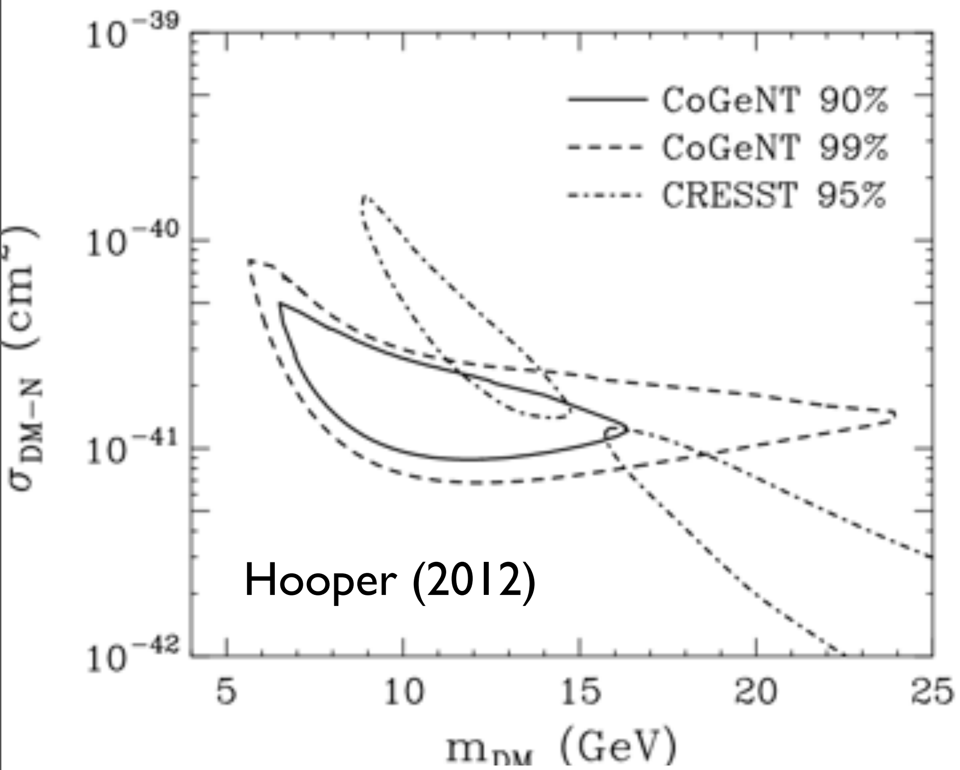


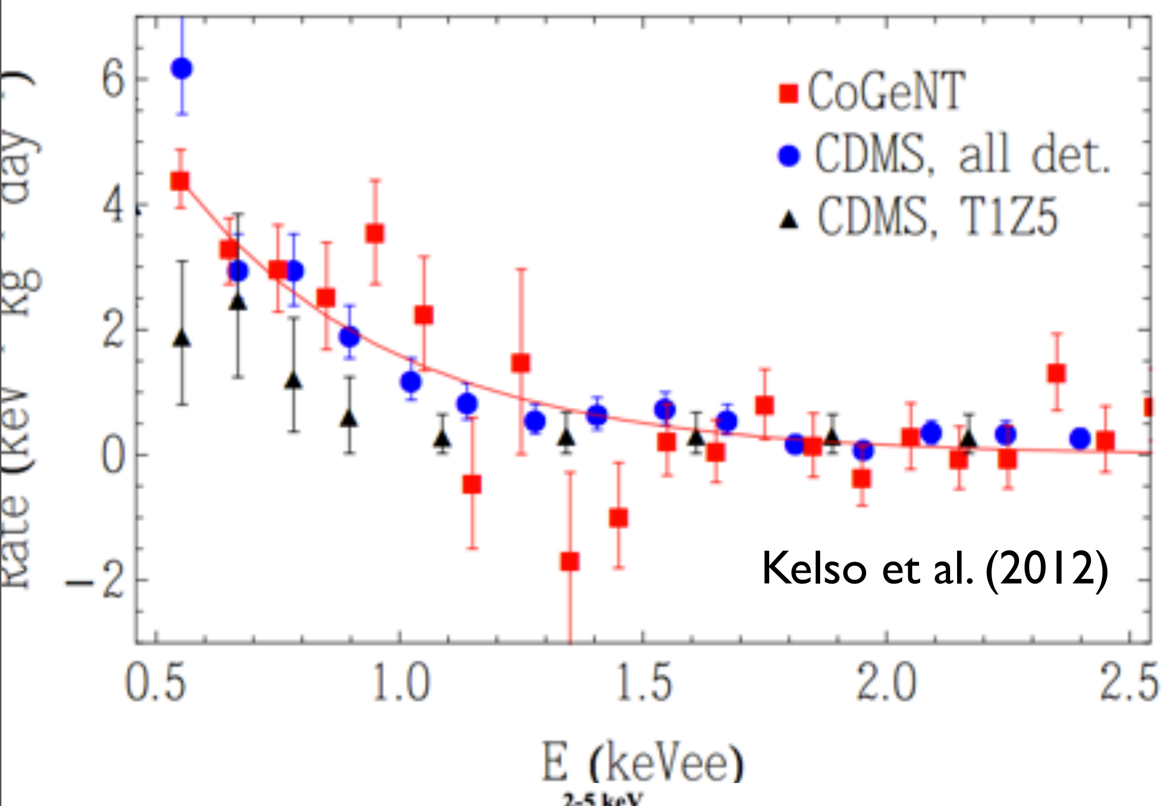


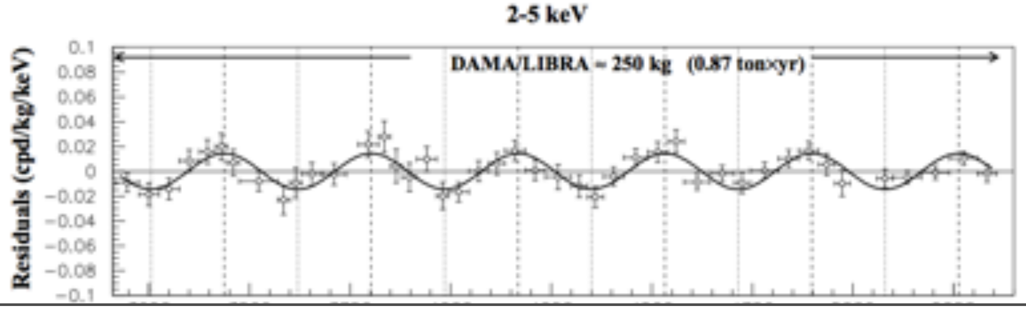
- ARCADE-2 observed an isotropic, hard spectrum synchrotron background, which cannot be fit by galactic emission
- Light, leptophilic dark matter models produce a reasonable match to this excess



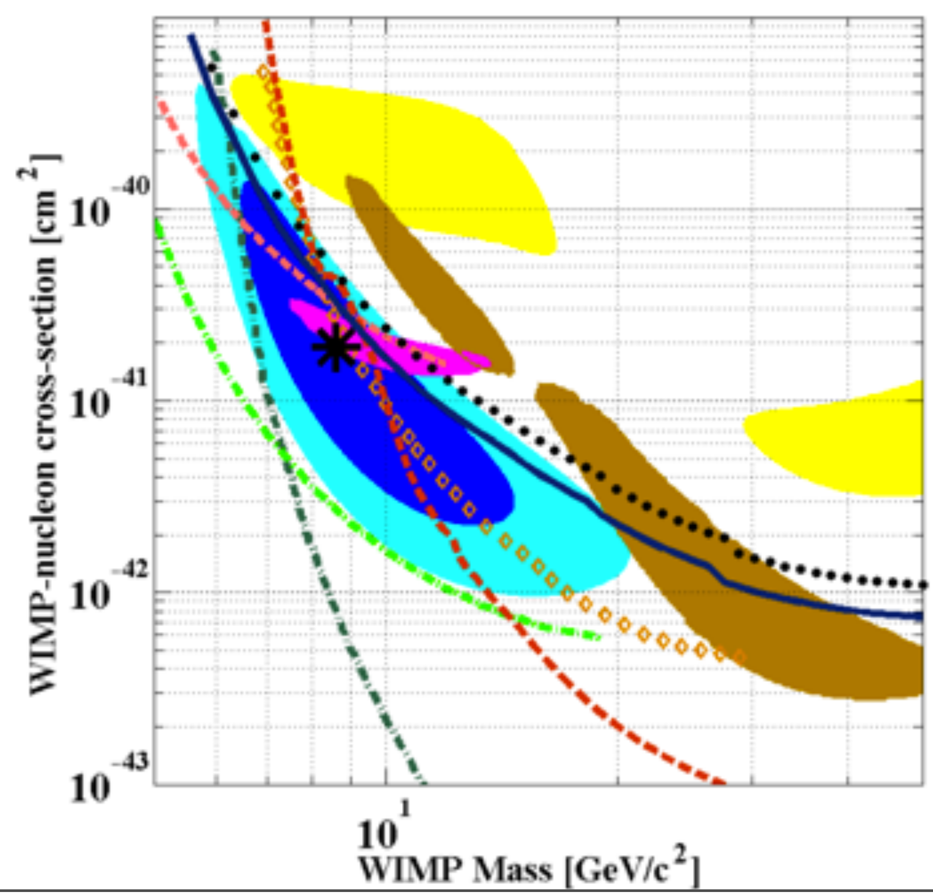
Evidence for A Dark Matter Interpretation



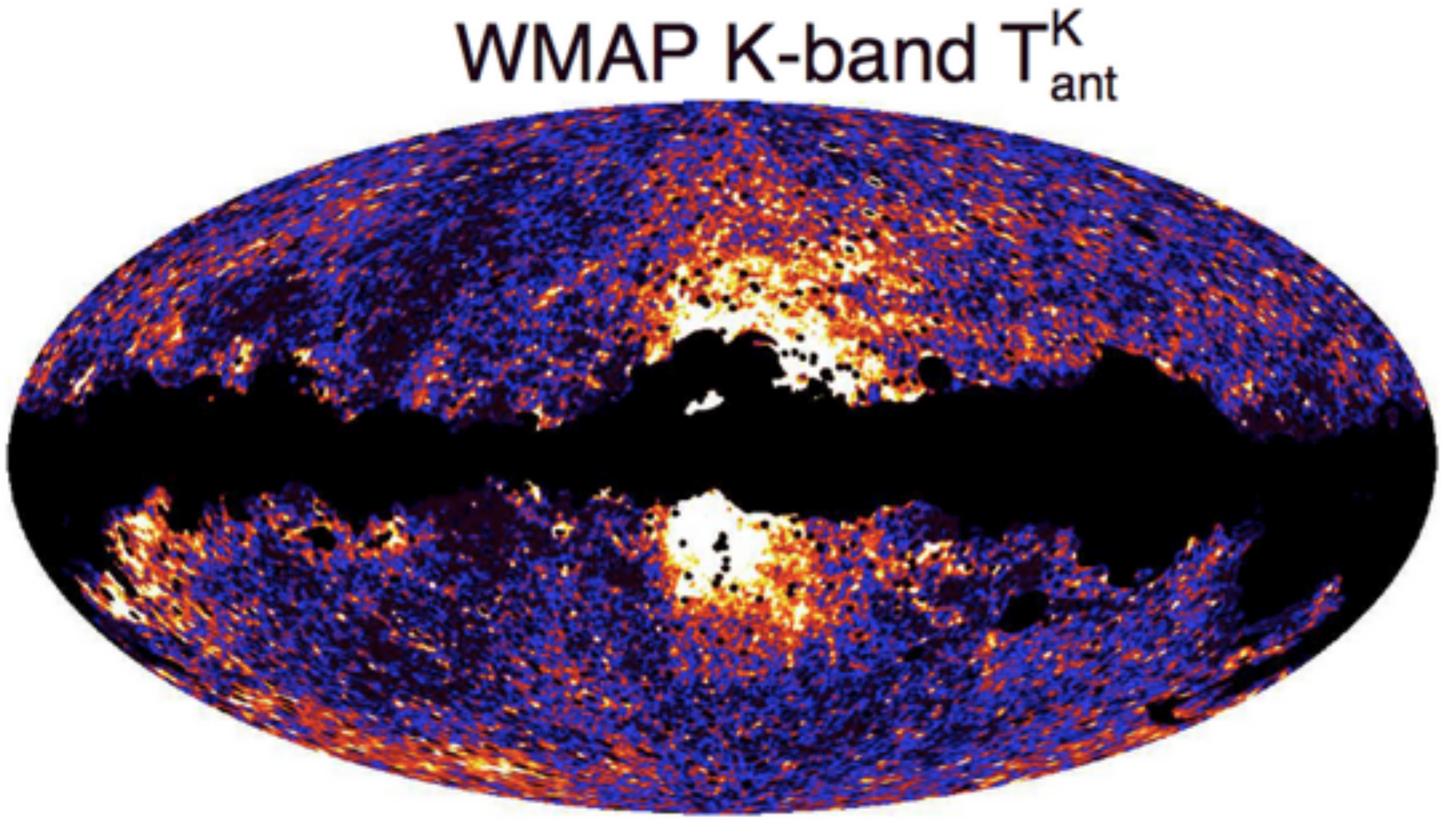


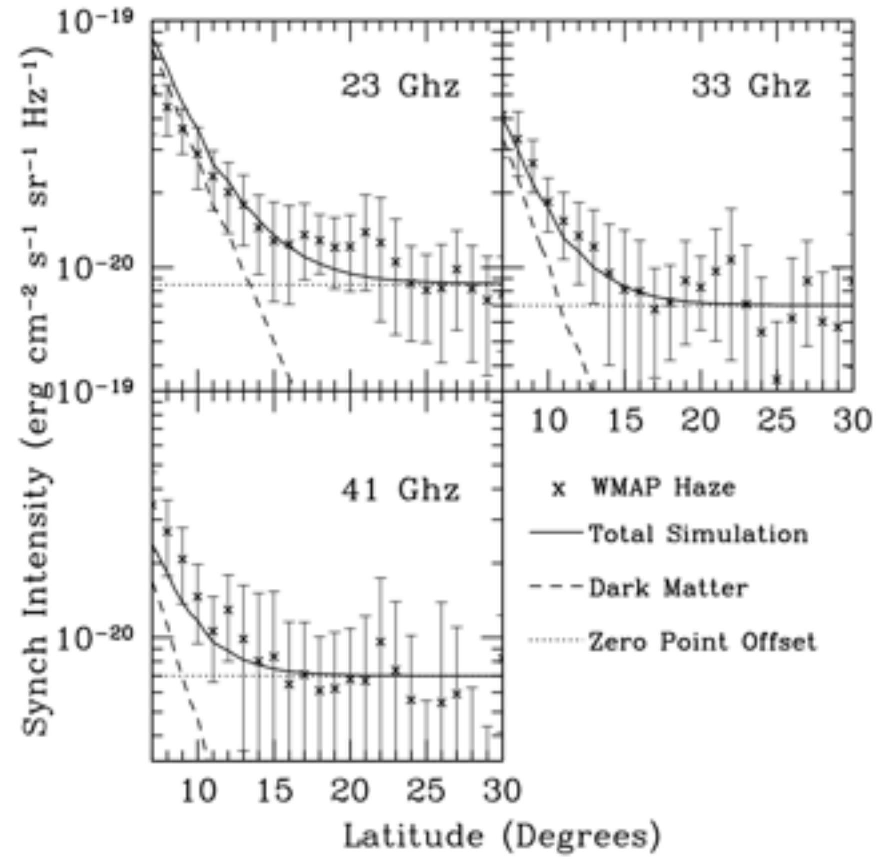


- Light Dark Matter (~10 GeV) provides a compelling fit to the excesses currently observed by DAMA, CoGeNT and CRESST
- Light Dark Matter may also be compatible with observed signal/limits at CDMS
- However, a recent error found in CoGeNT analysis may affect some early dark matter interpretations



Evidence Against A Dark Matter Interpretation

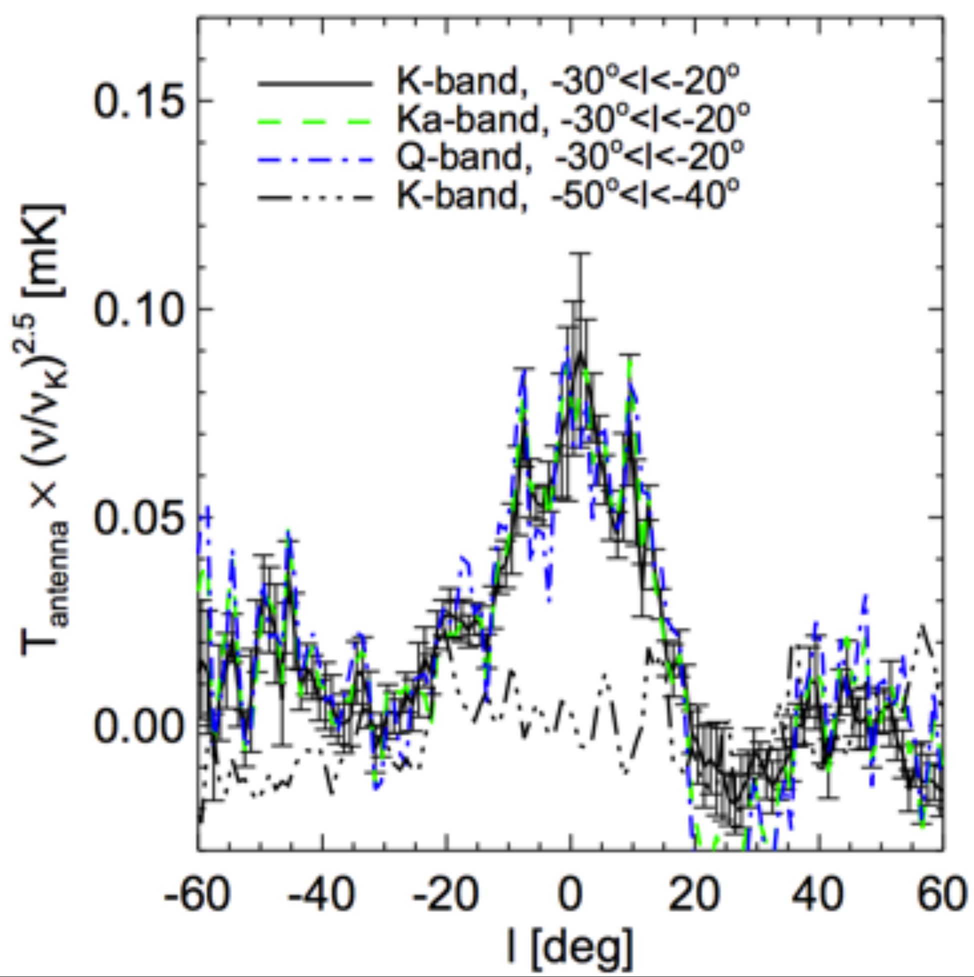




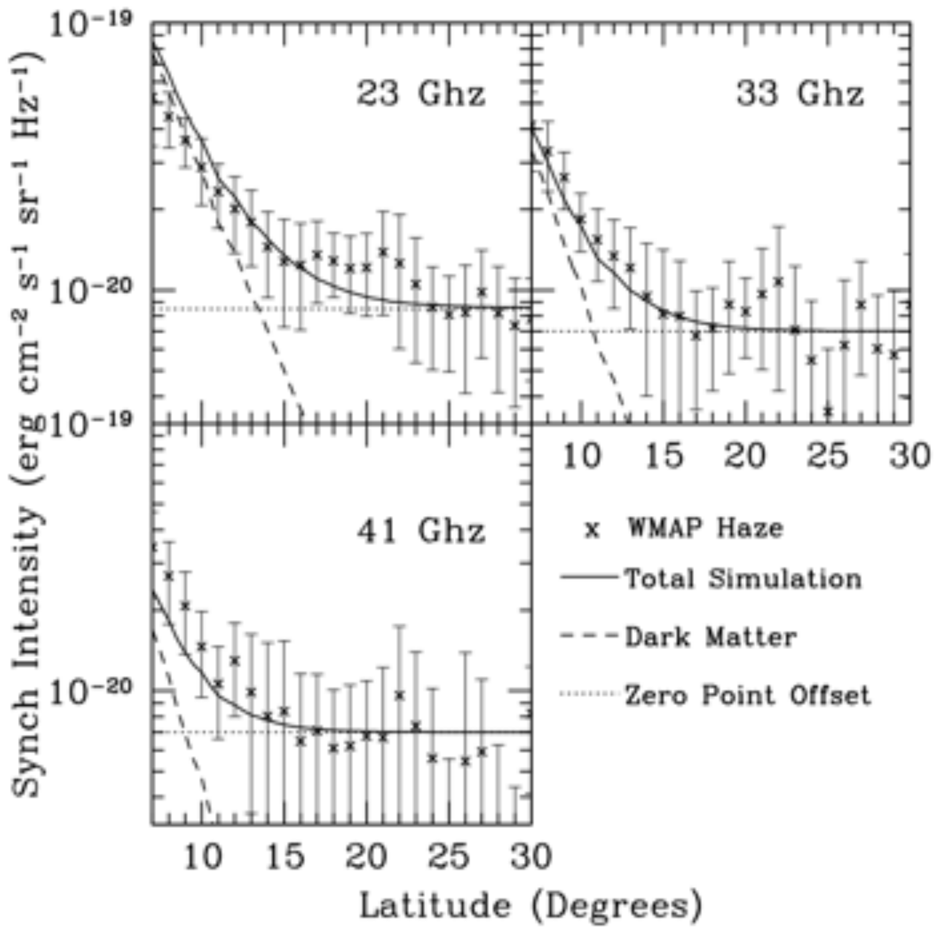
- WMAP Haze used to be dark matter signature

- However, correlation with the Fermi bubbles is problematic for a dark matter origin

- But dark matter must make some synchrotron signal

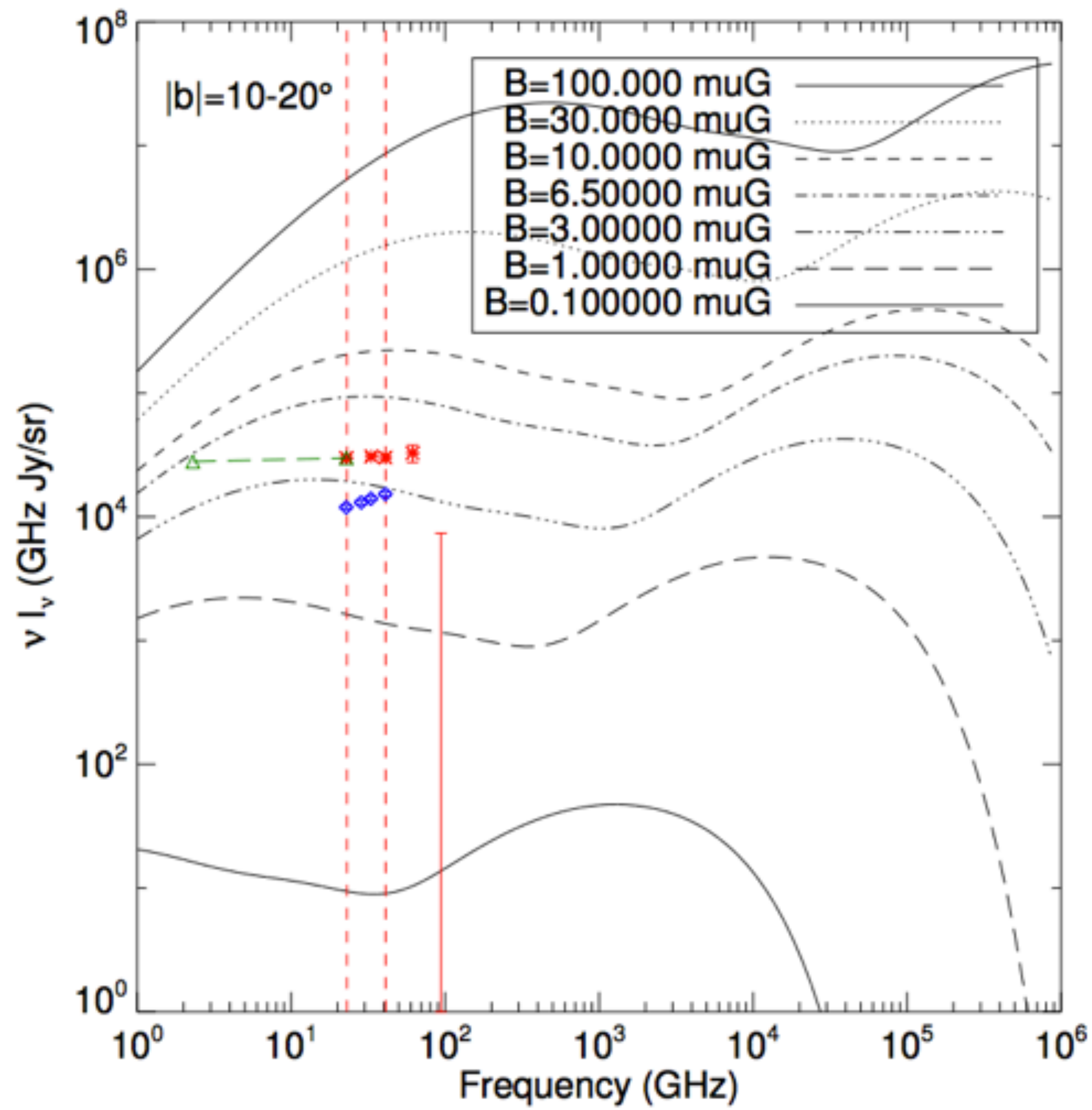


But Wait!



$$\sigma v = 1.3 \text{ x } 10^{-26} \text{ cm}^3\text{s}^{-1}$$

$$B(r,z) = 9.43\,\mu G \;\; e^{-(r-1\,\text{kpc})/5.0\,\text{kpc}} \;\; e^{-(|z|-2\,\text{kpc})/1.8\,\text{kpc}}$$



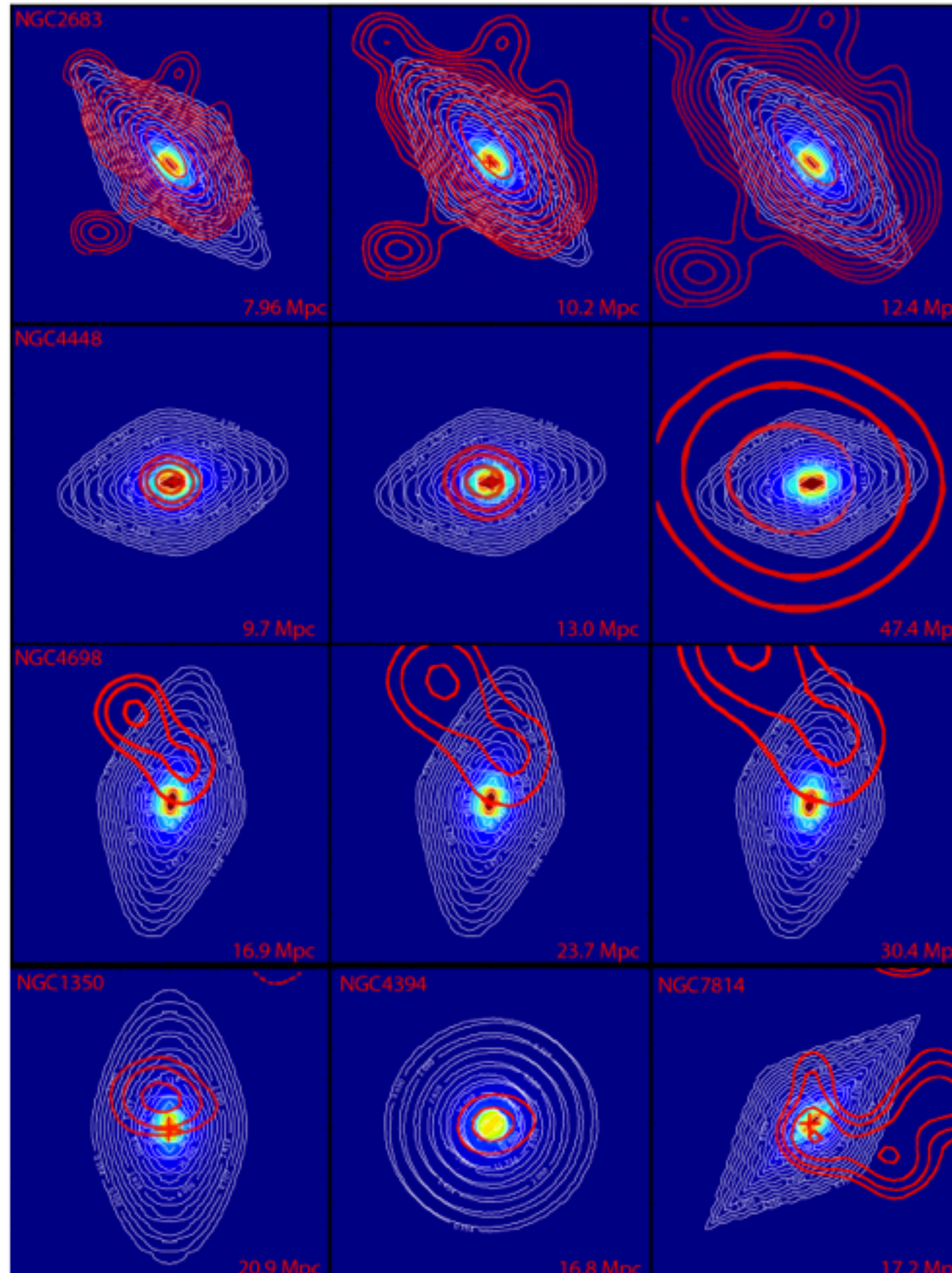
- Light dark matter fits typically used larger cross-section and magnetic field
- With the best-fit magnetic field for the synchrotron/ICS signal, dark matter would be subdominant

Evidence Against A Dark Matter Interpretation

- However many galaxies (which should look like the Milky Way) are highly underluminous in synchrotron

- This is odd for dark matter interpretations, since the particle flux should be nearly constant in each galaxy

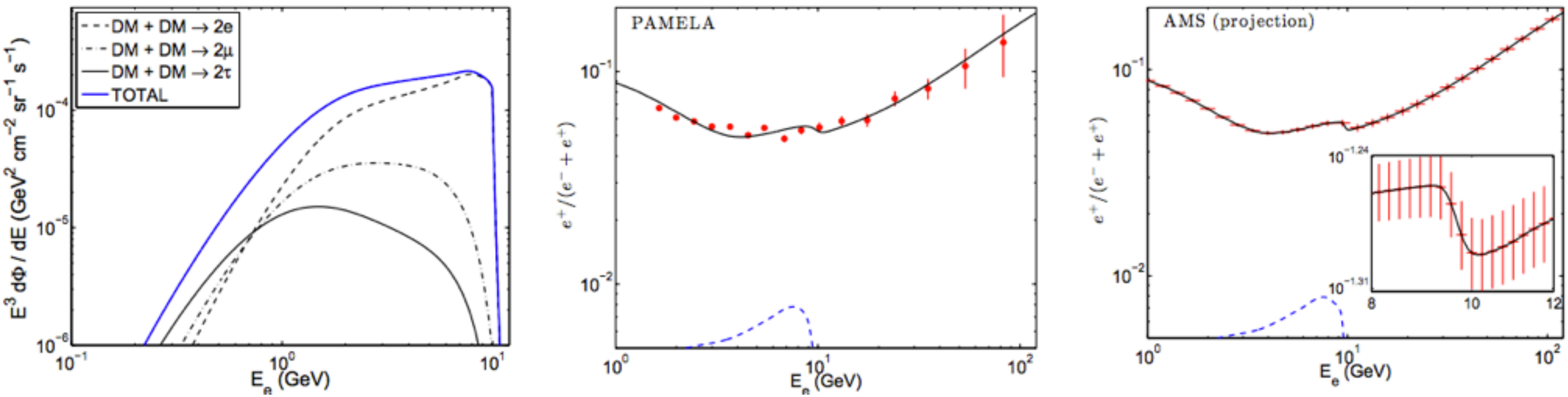
Name	Distance [Mpc]	R_{peak}	R_z	R_r
M31	0.70	.125	.0085	.0043
NGC1350	20.9	.006	.155	.0054
NGC2683	10.2 (7.96, 12.4)	.063	8.04 (2.36, ∞)	.610 (.202, 2.05)
NGC4394	16.8	.004	.0148	.030
NGC4448	13.0 (9.70, 47.4)	.004	.043 (.0172, ∞)	.0173 (.0121, ∞)
NGC4698	23.7 (16.9, 30.4)	.004	.0265 (.0162, .107)	.0034 (.0033, .0034)
NGC7814	17.2	.008	.708	.027



Carlson et al. (2013)

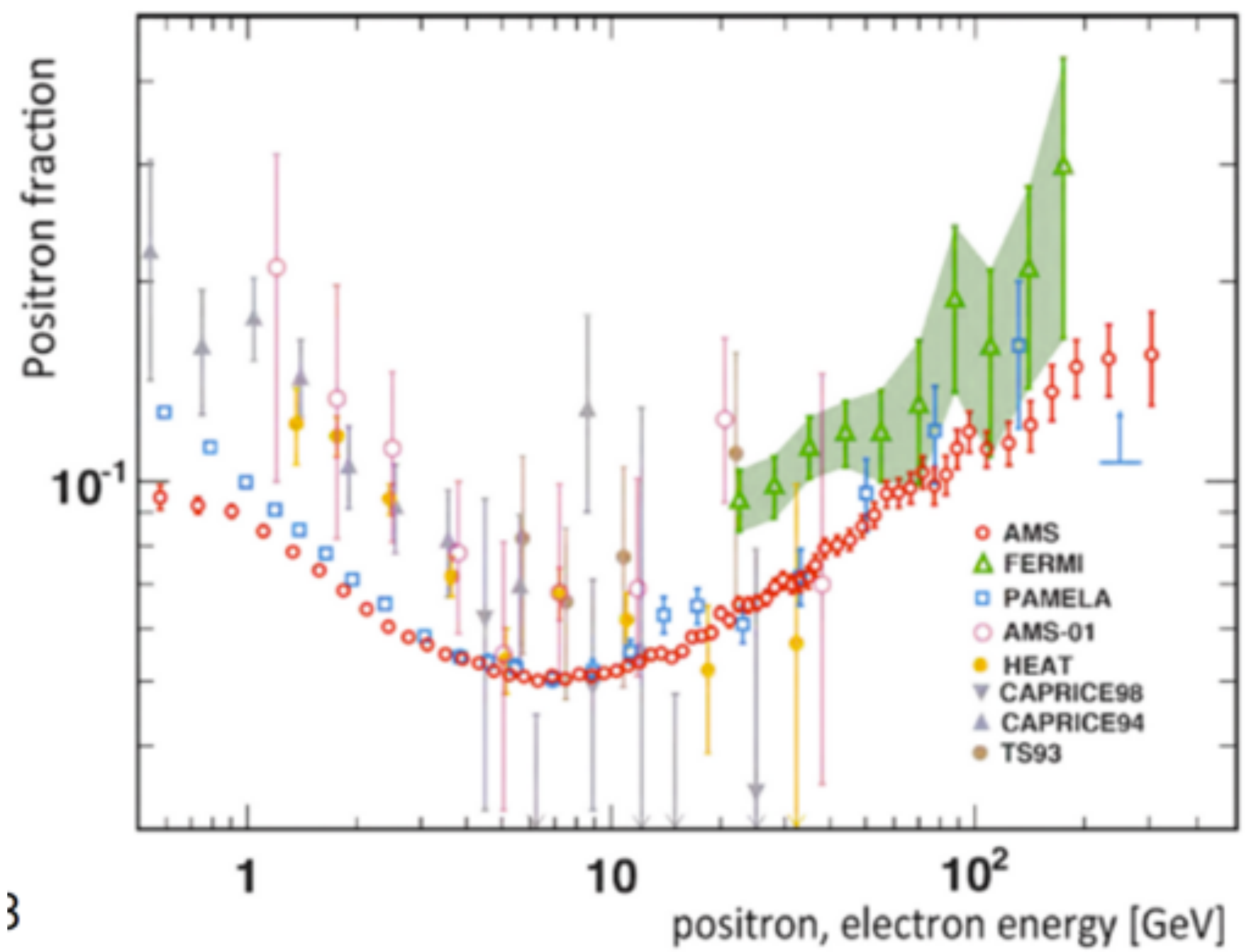
Evidence Against A Dark Matter Interpretation

Hooper & Xue (2012)



- Light Dark Matter Annihilation could have been detected with AMS-02 Data

- However, there is currently no evidence for a low-energy bump in the electron/positron fraction



Where Do We Go From Here?

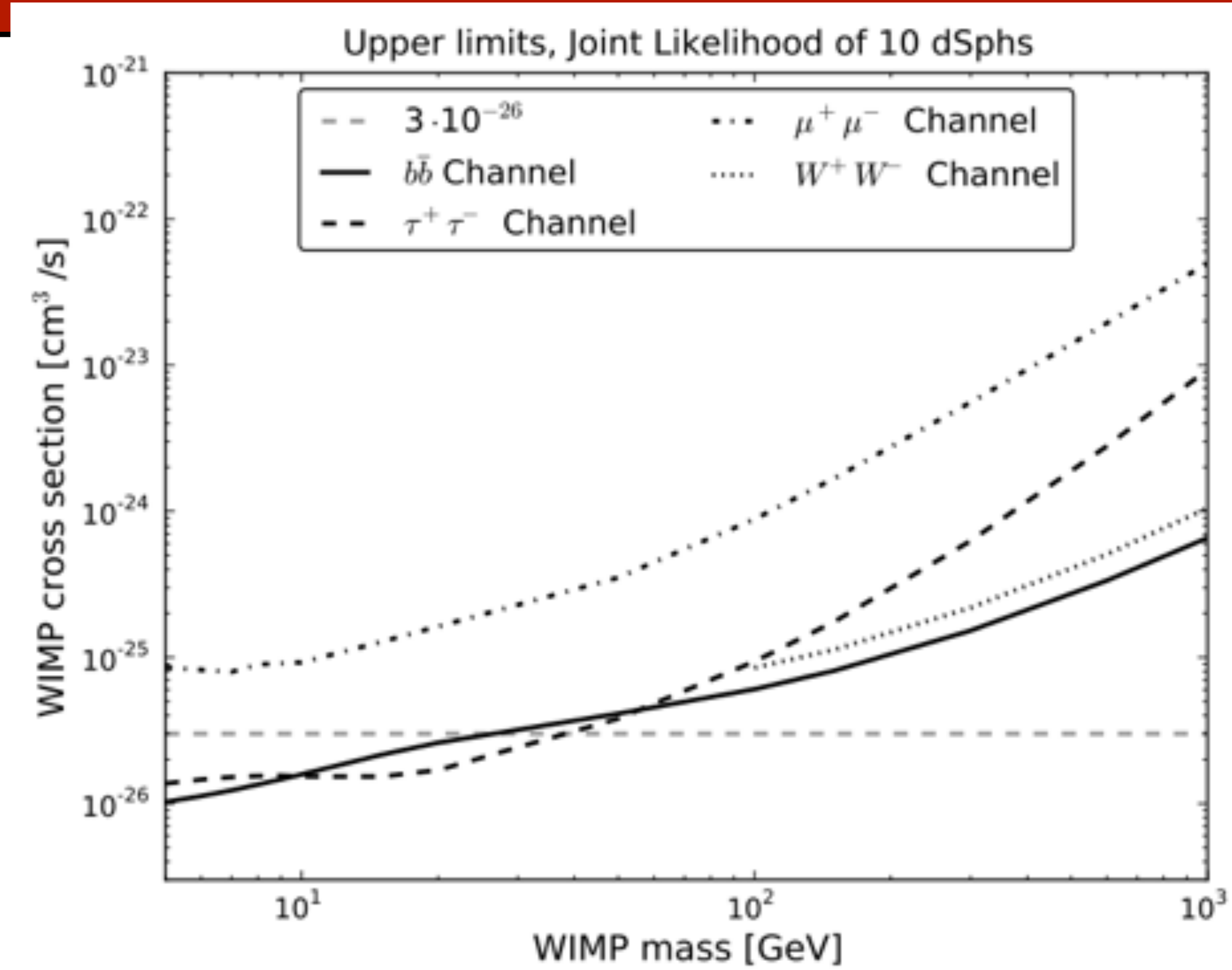
- Personal Opinion: It's not clear that new data from the GC will greatly improve our measurements of the GC excess - at least not in any way which can distinguish dark matter and MSPs

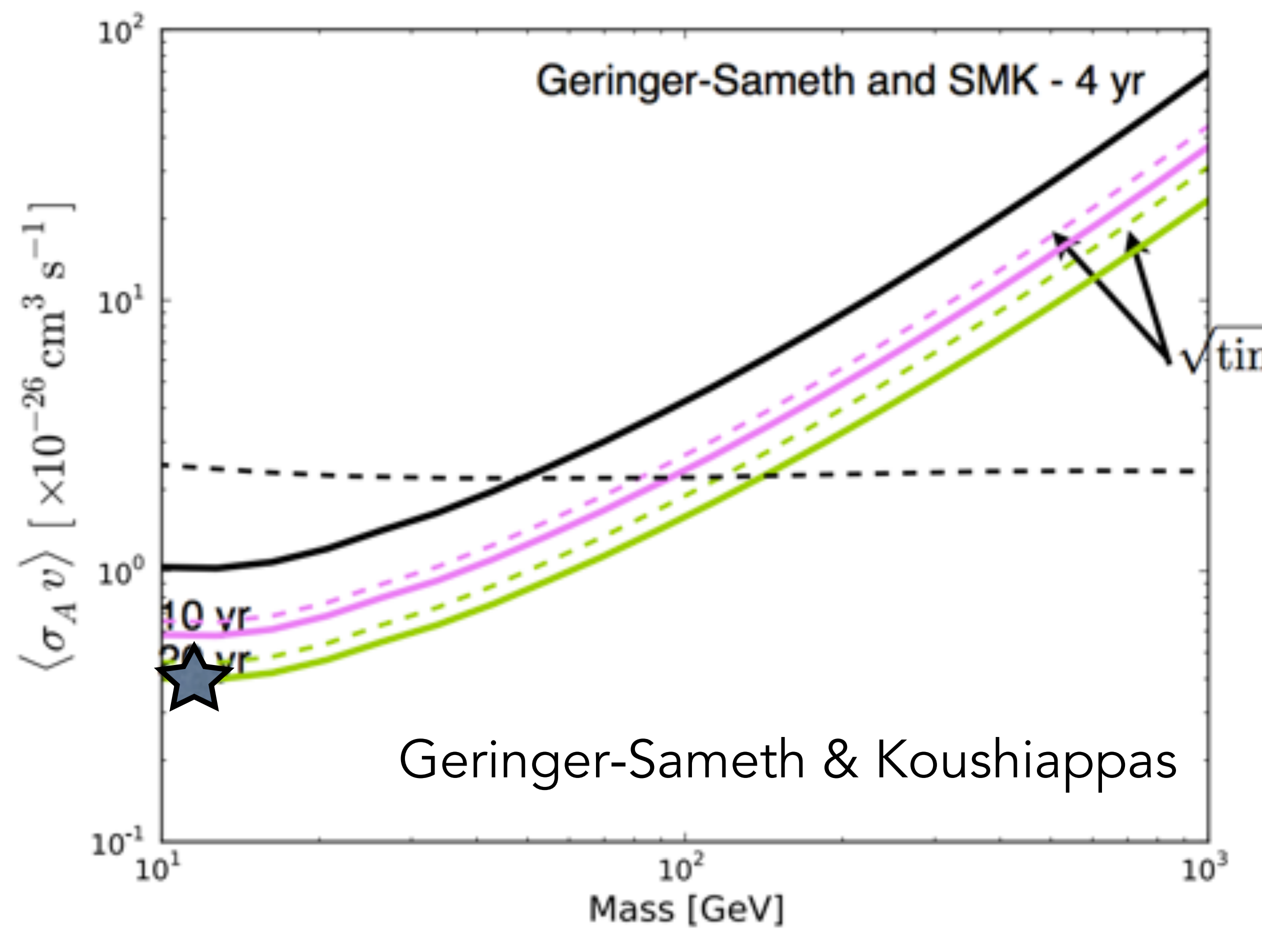
- We can measure some properties of the excess (such as its spherical symmetry) which could point towards, or away from a DM origin

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



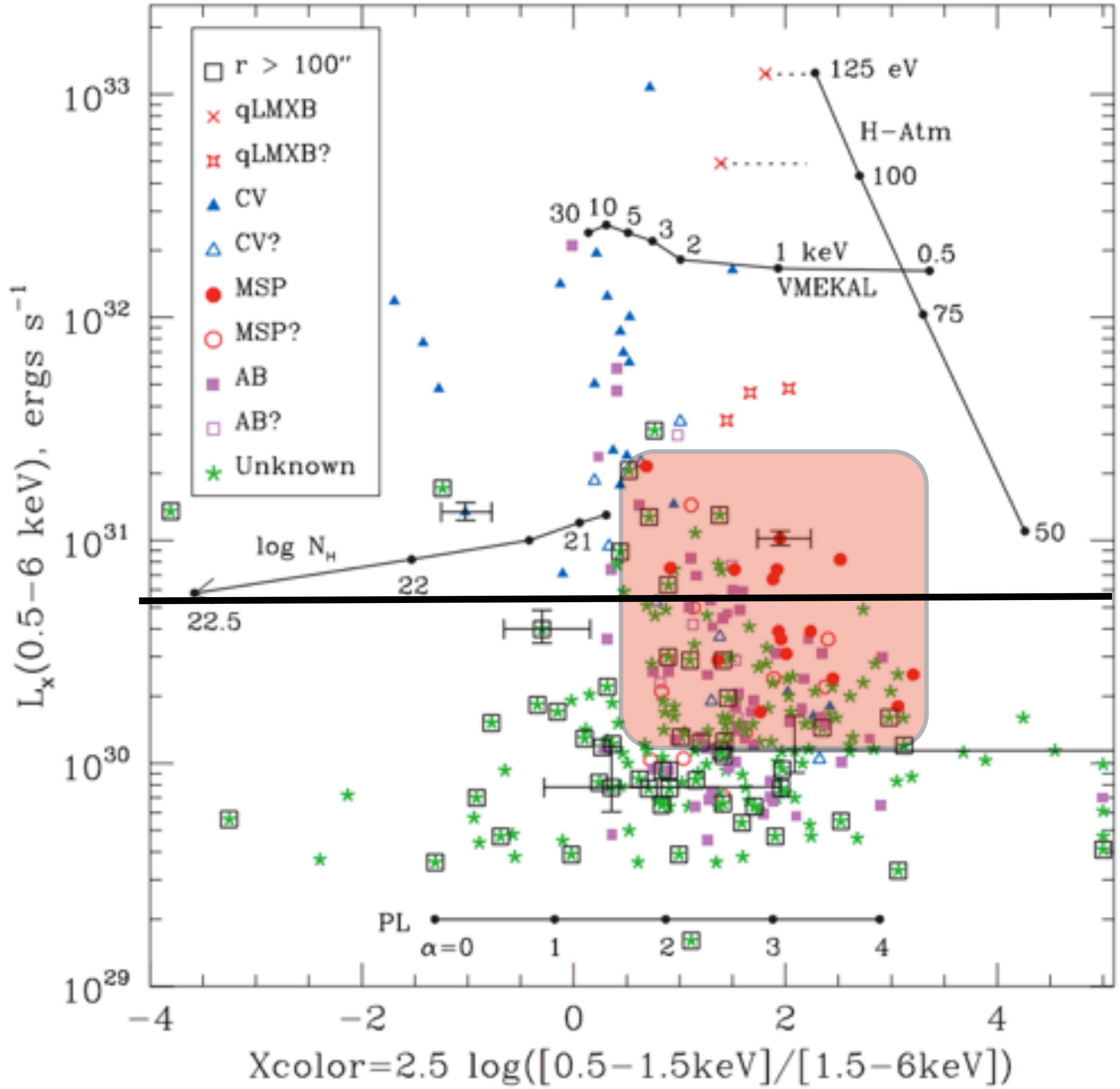


Where Do We Go From Here?

- 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

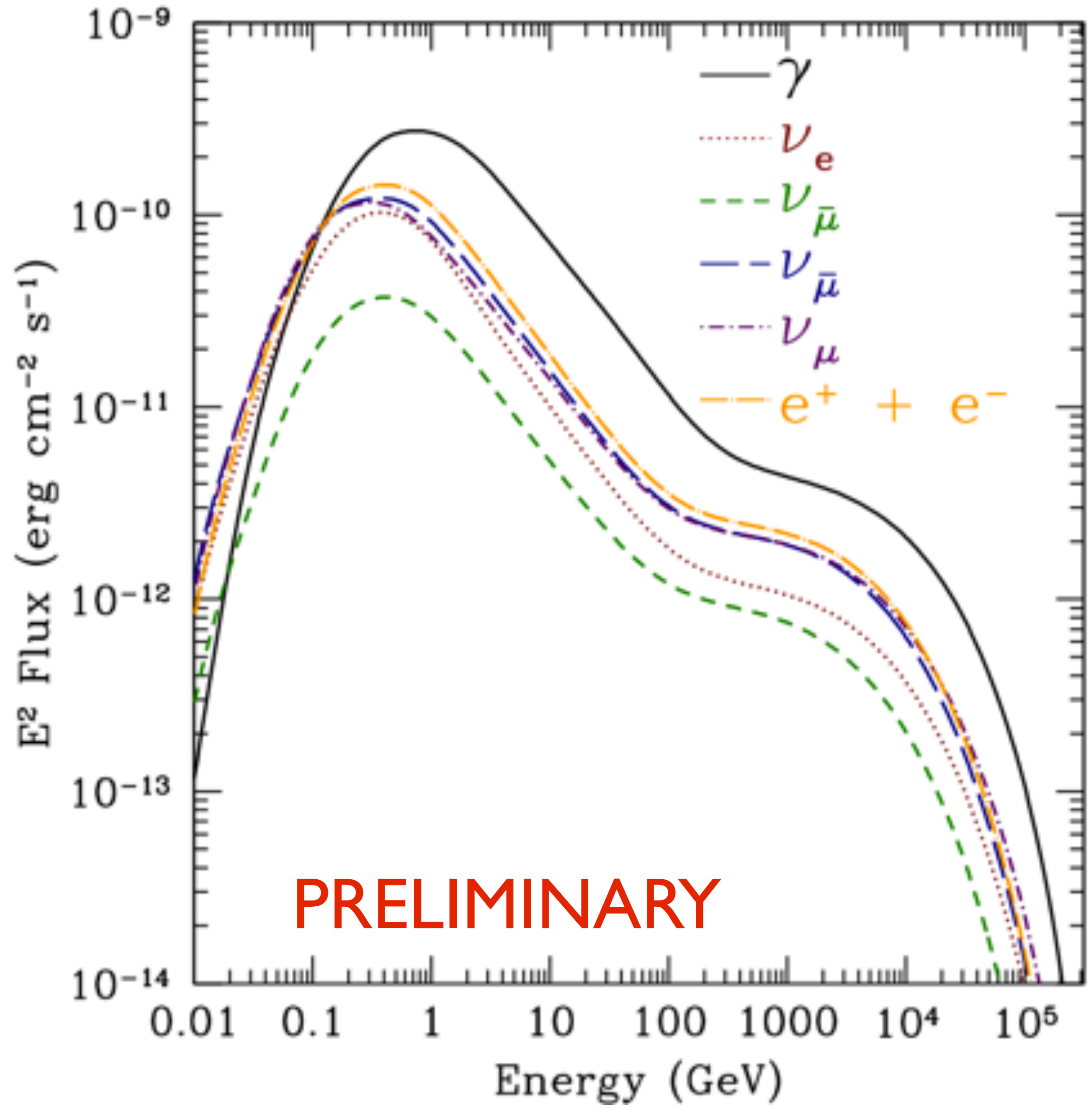
- Can this information be used to determine the statistical distribution of MSPs?

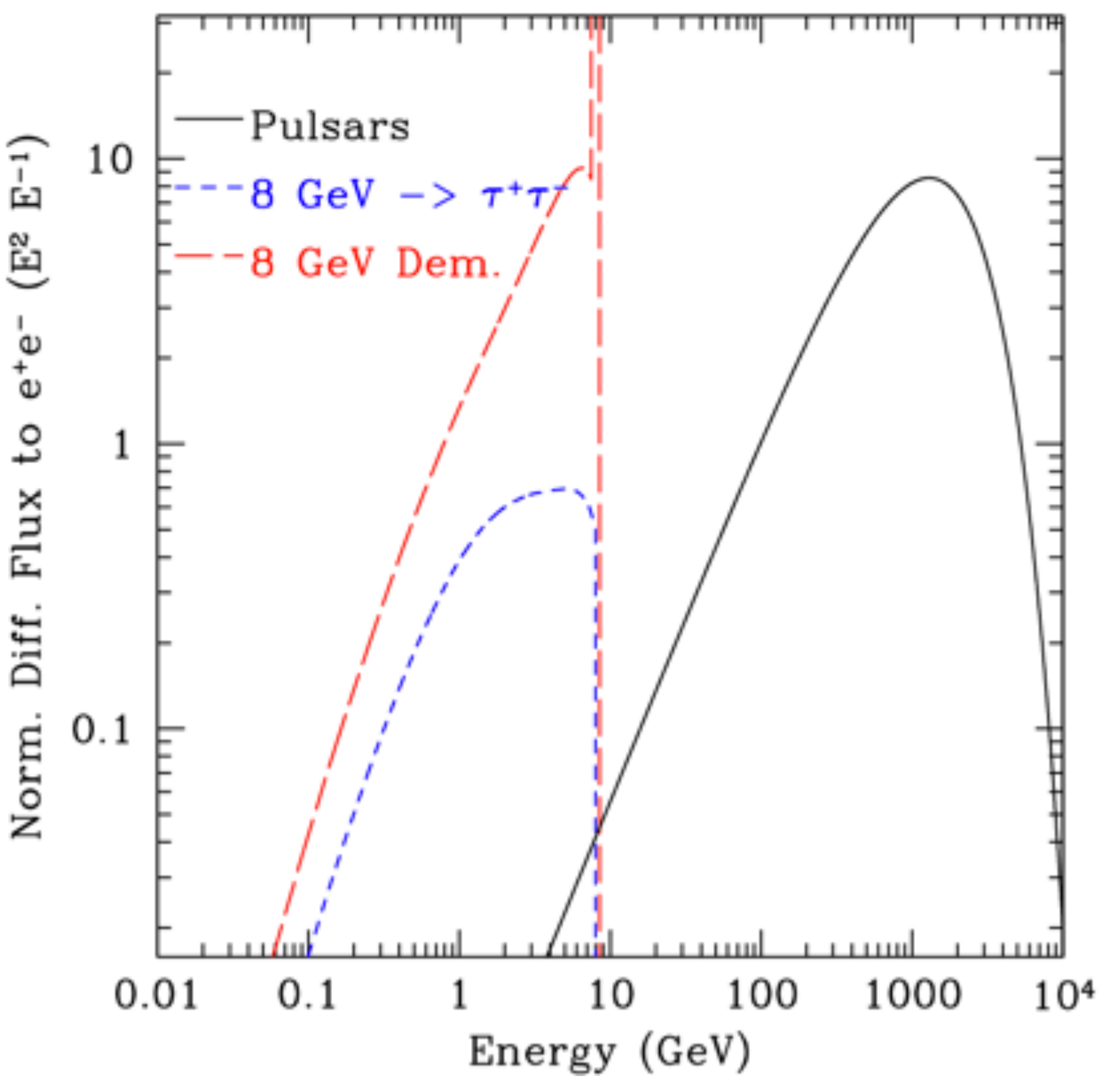


Heinke et al. (2006)

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?