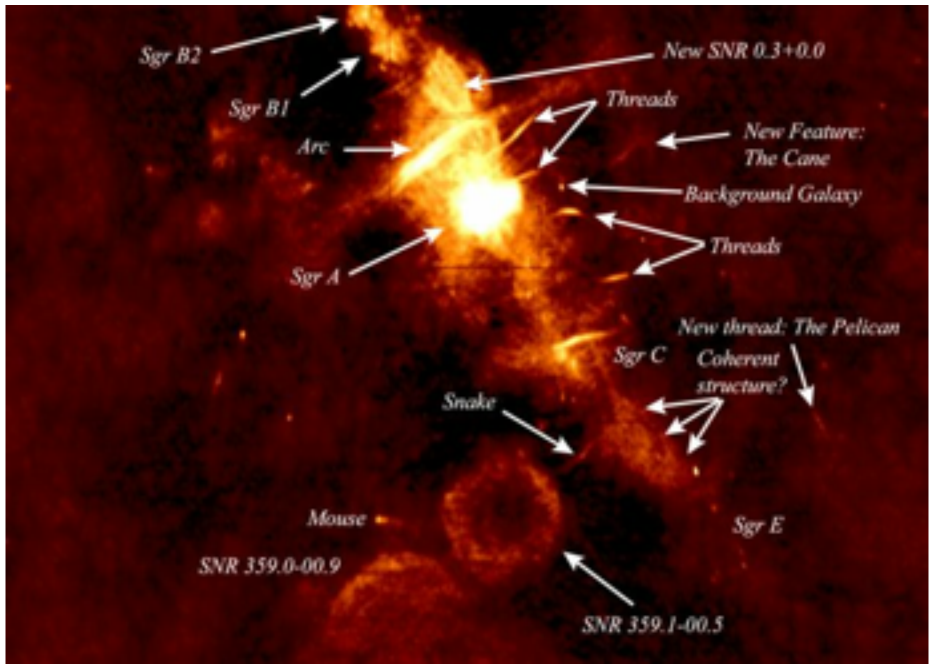
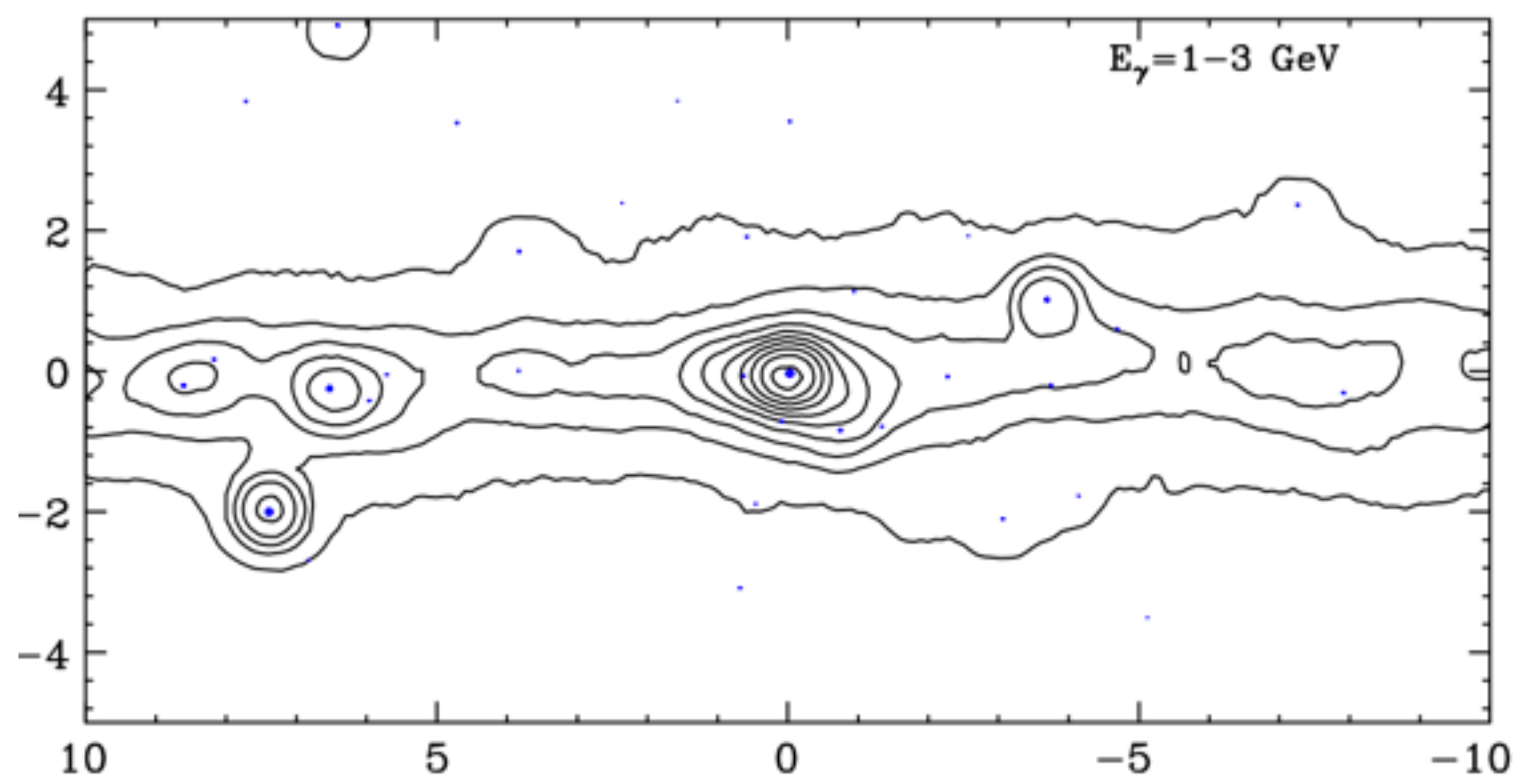
Understanding High Energy Emission from the Galactic Center:

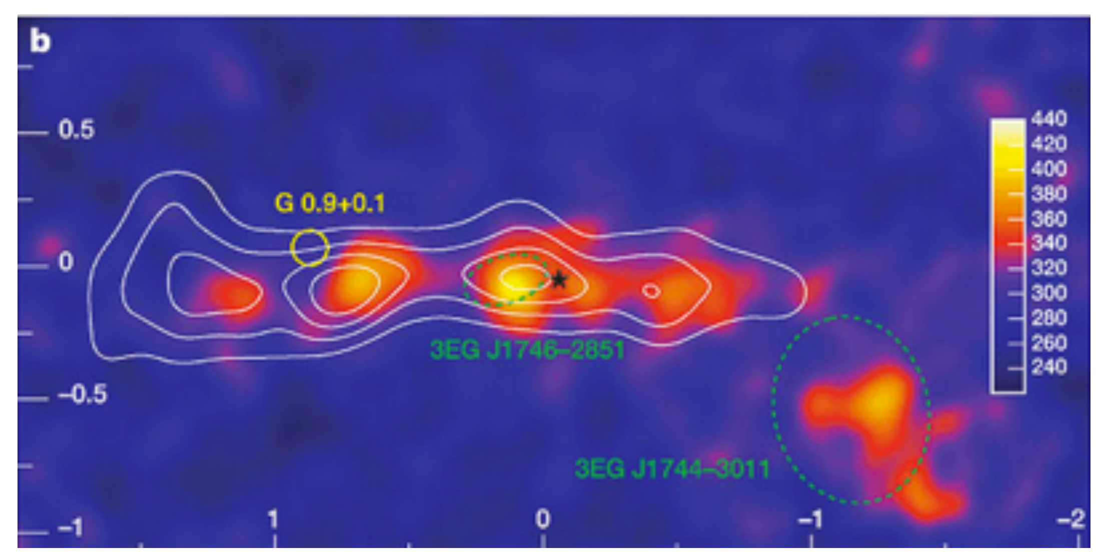
3 Convincing Stories





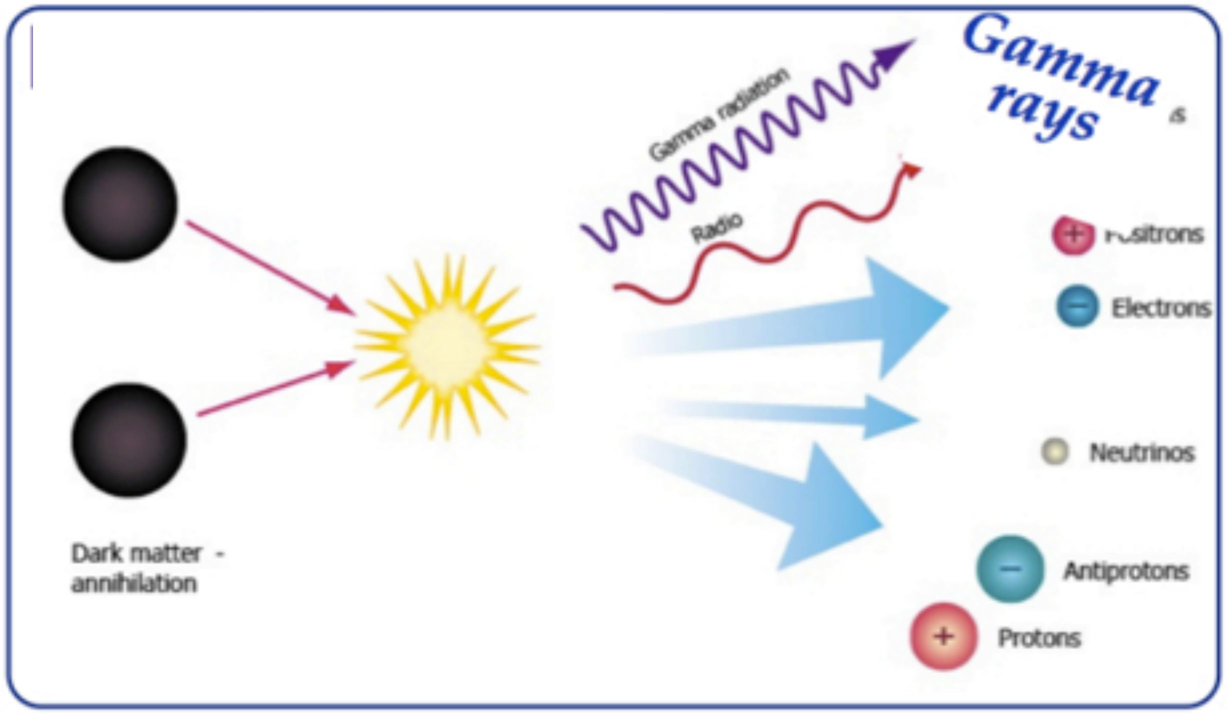
Tim Linden
UC - Santa Cruz

with Brandon Anderson, Dan Hooper, Elizabeth Lovegrove, Stefano Profumo and Farhad Yusef-Zadeh



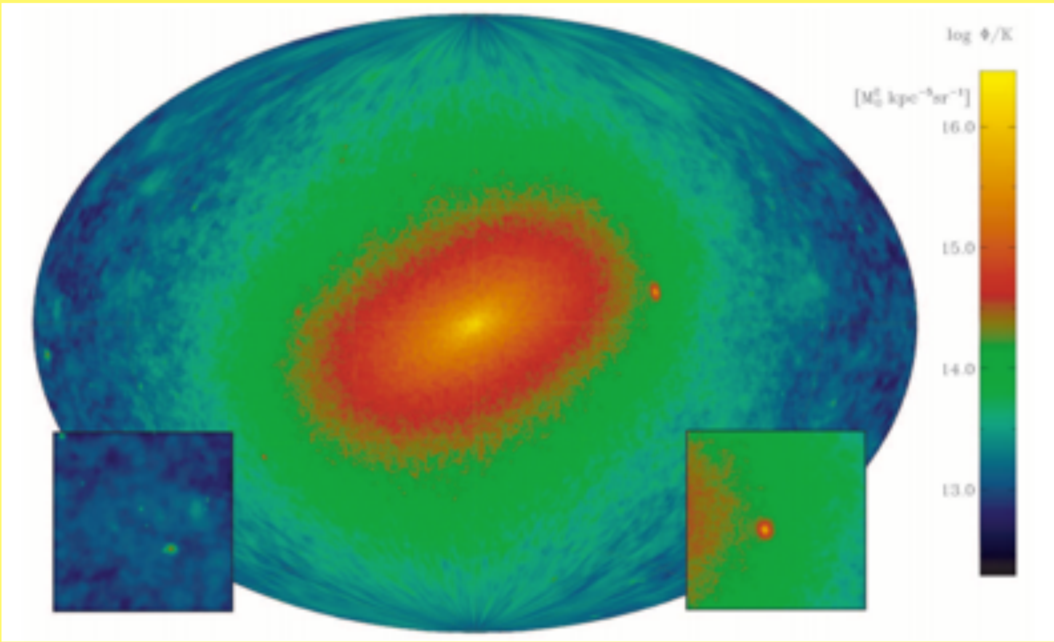
Irvine Astrophysics Seminar October 10, 2012

Dark Matter Indirect Detection



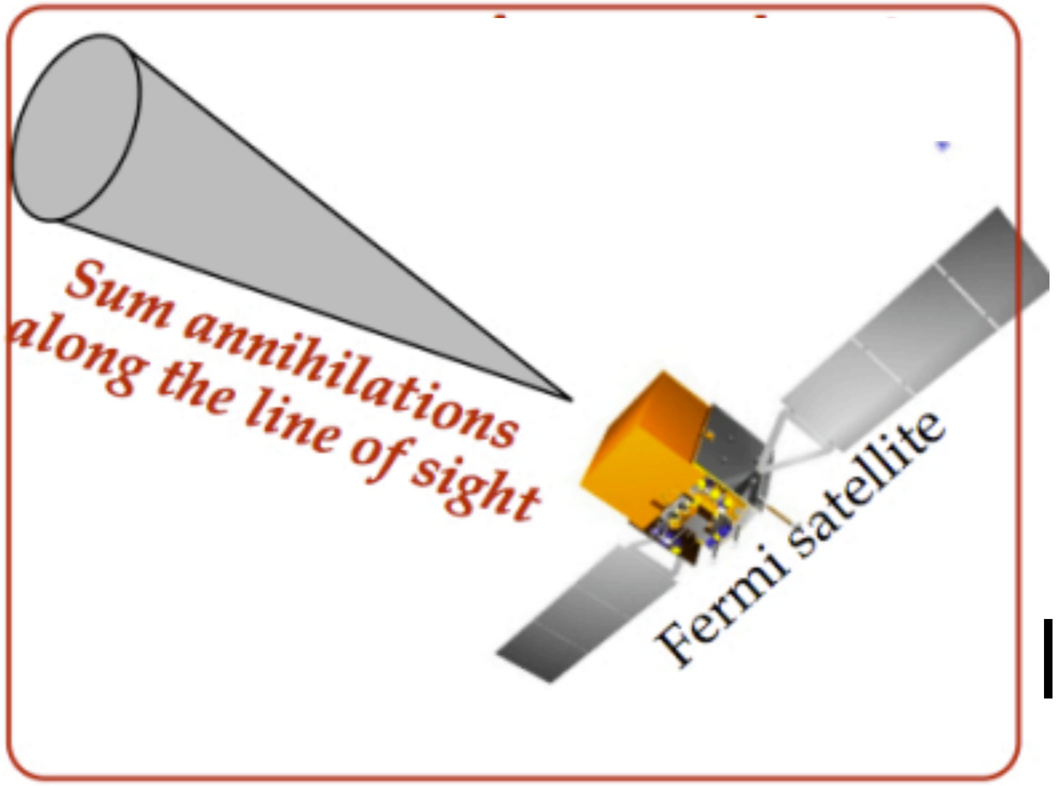
Particle Physics

Astrophysics



Diemand et al. 2008

Slides Courtesy of G. Zaharijas



Instrumental Response

Motivating Question:

Why would the galactic center be an interesting place to look for Dark Matter?

Positive! The J-Factor of 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 $(10^{17}\ \mathrm{GeV}^2\ \mathrm{cm}^{-5})$
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

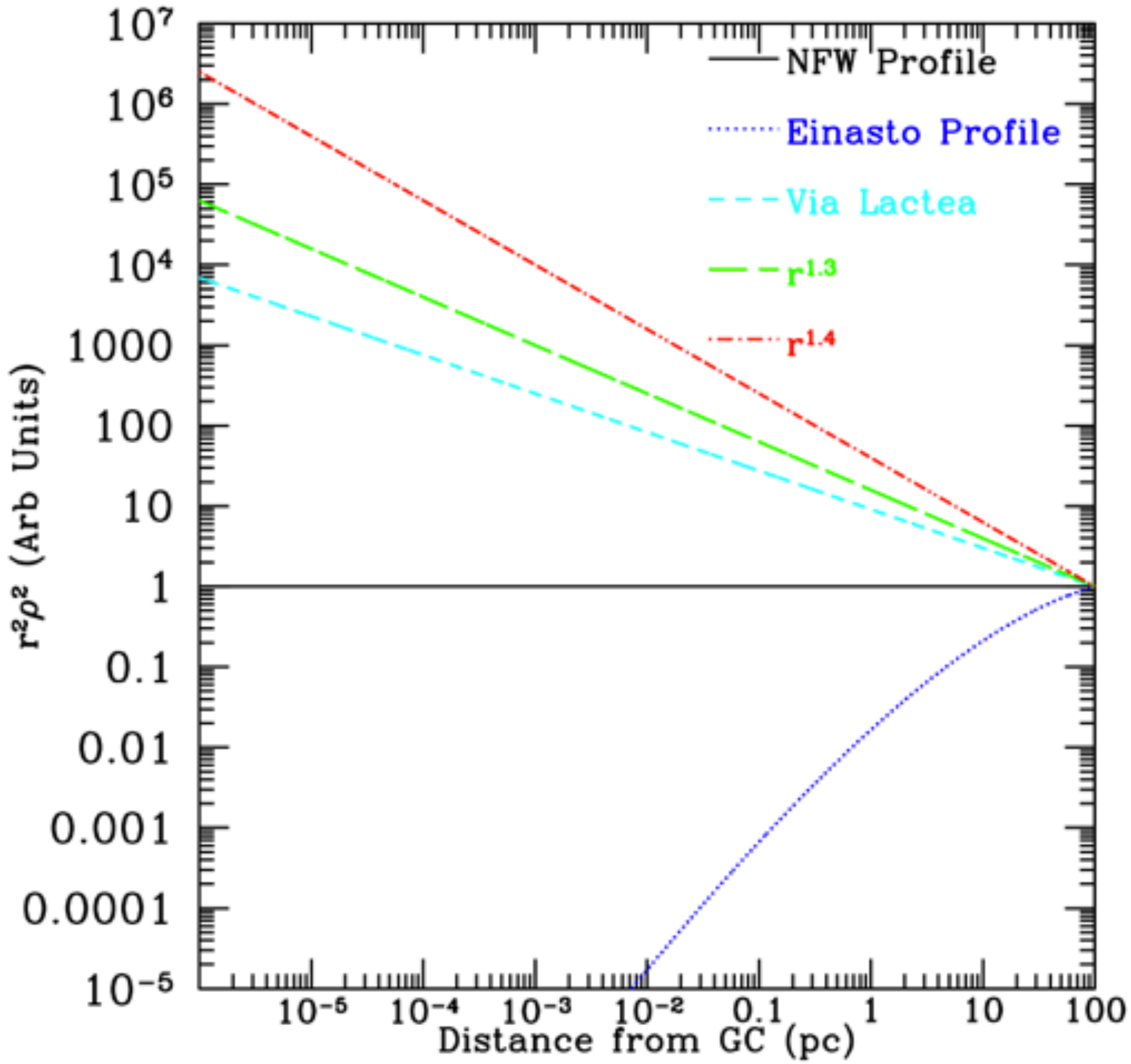
$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \rho^2(l)\mathrm{d}l(\psi)$$

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

$\log_{10}(J) = 23.91$

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

Negative: The Profile Dependence



- Assumptions for the slope of the inner dark matter profile can make **orders of magnitude** differences in the expected dark matter annihilation rate

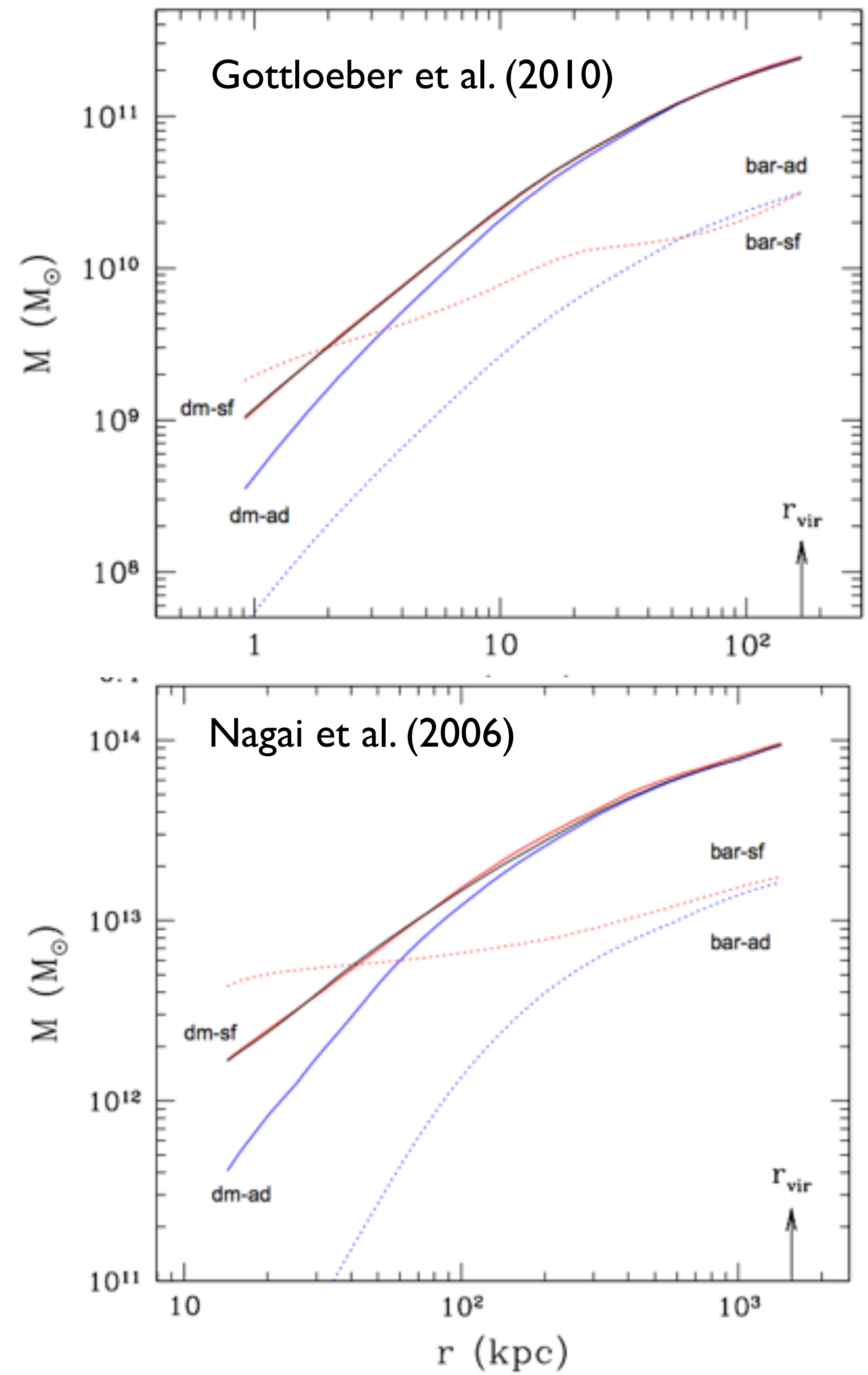
- Dark Matter is not a dominant gravitational source near the galactic center, so there are few observational handles on the dark matter density in the GC region

Positive! Progress in Simulations

- Simulations including the effects of baryonic contraction show a steepening of the spectral slope from γ≈1.0 to γ≈1.2-1.5

- Much more work is required to understand the dark matter content of the GC region

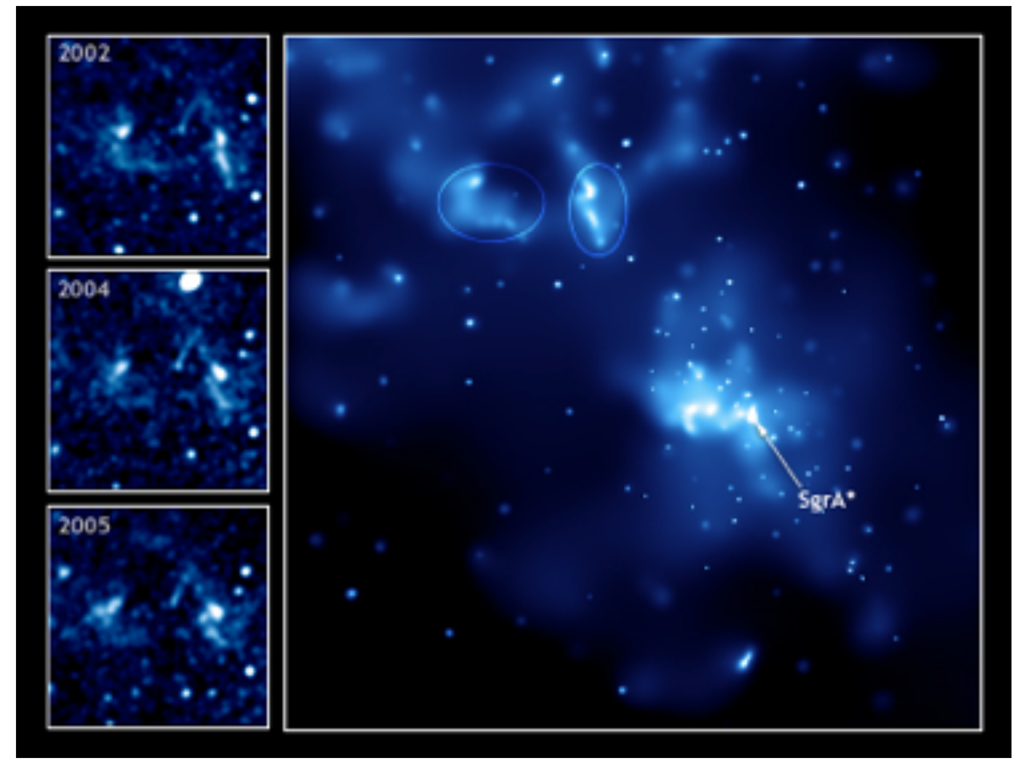
- This is imperative for understanding the signals from indirect detection

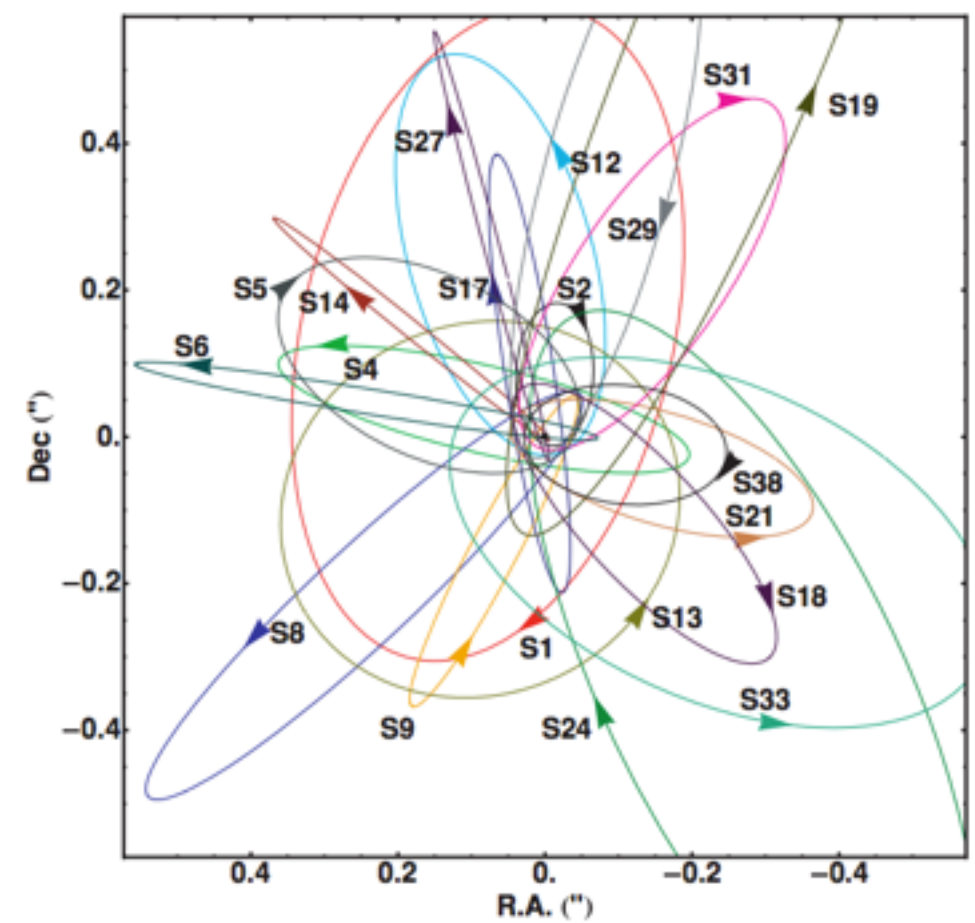


as reported in Gnedin et al. 2011

History of Galactic Center Observations (in 60 seconds)

Muno et al. 2007

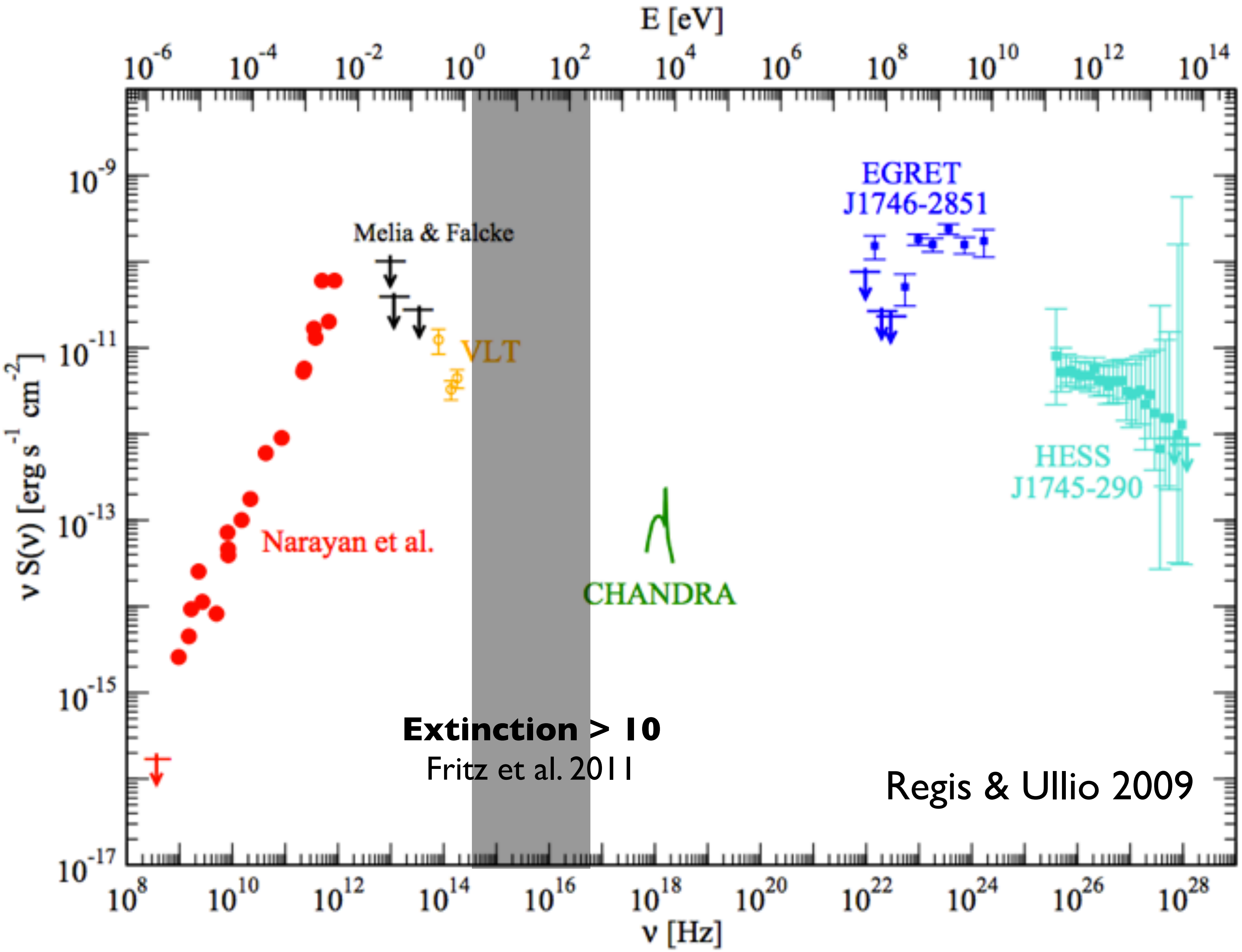




Gillissen et al. 2009

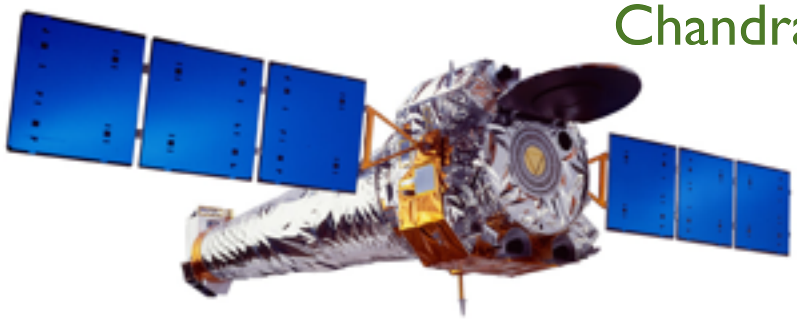
- Sgr A* Discovered via radio observations in 1974
- Measurements of stellar motion confirm the status of the central object as a black hole (Gillissen et al. 2009)
- Majority of radio emission thought to stem from accretion disk, rather than at BH event horizon (Doeleman et al. 2008)

The Multi-wavelength Galactic Center

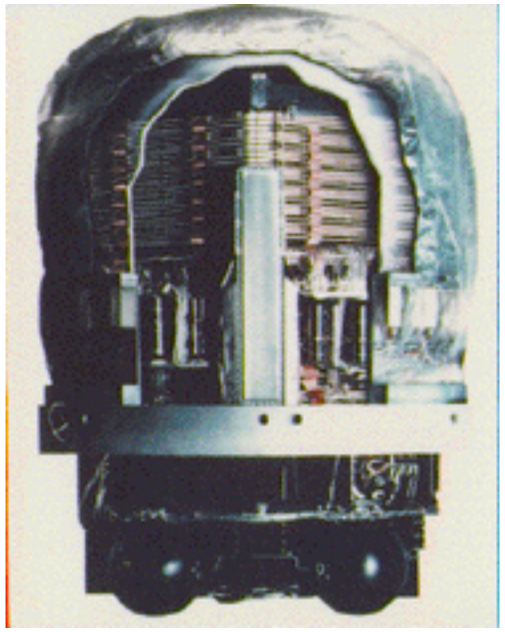


VLA

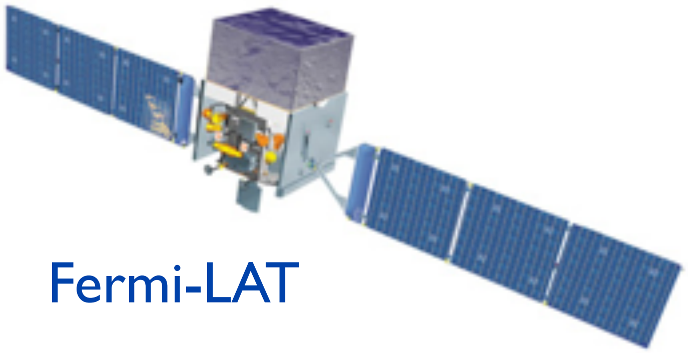
Chandra



EGRET

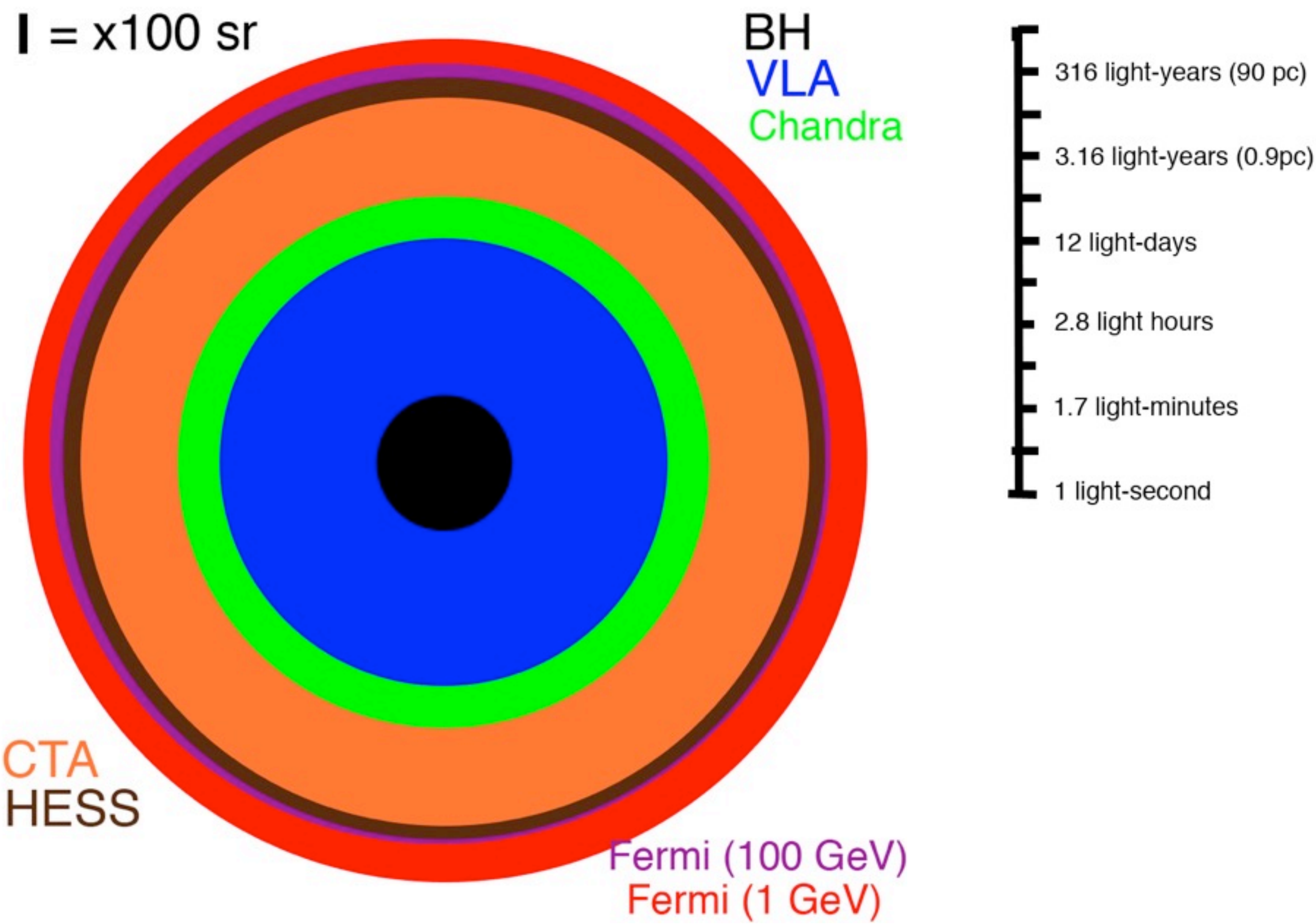


HESS

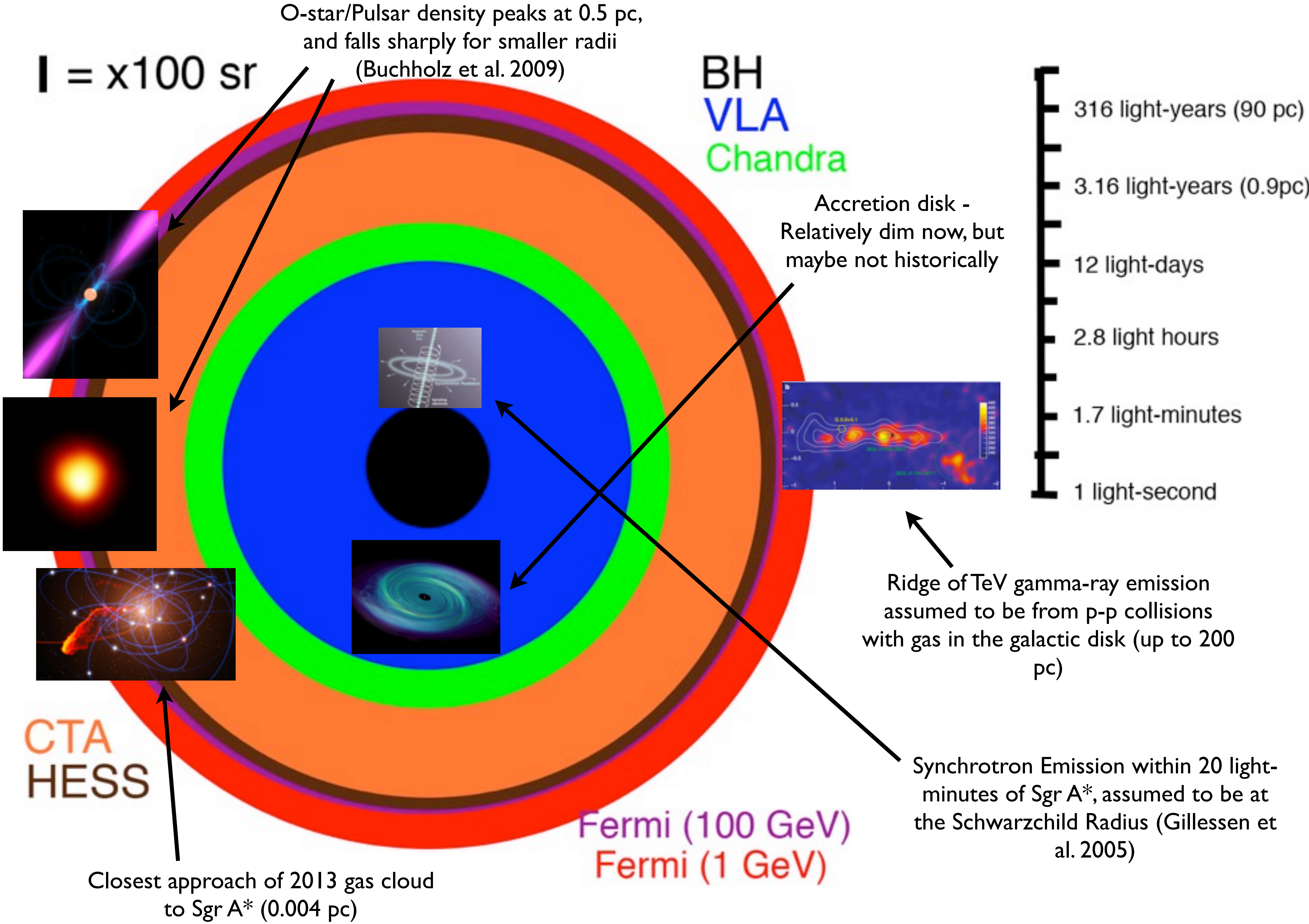


Fermi-LAT

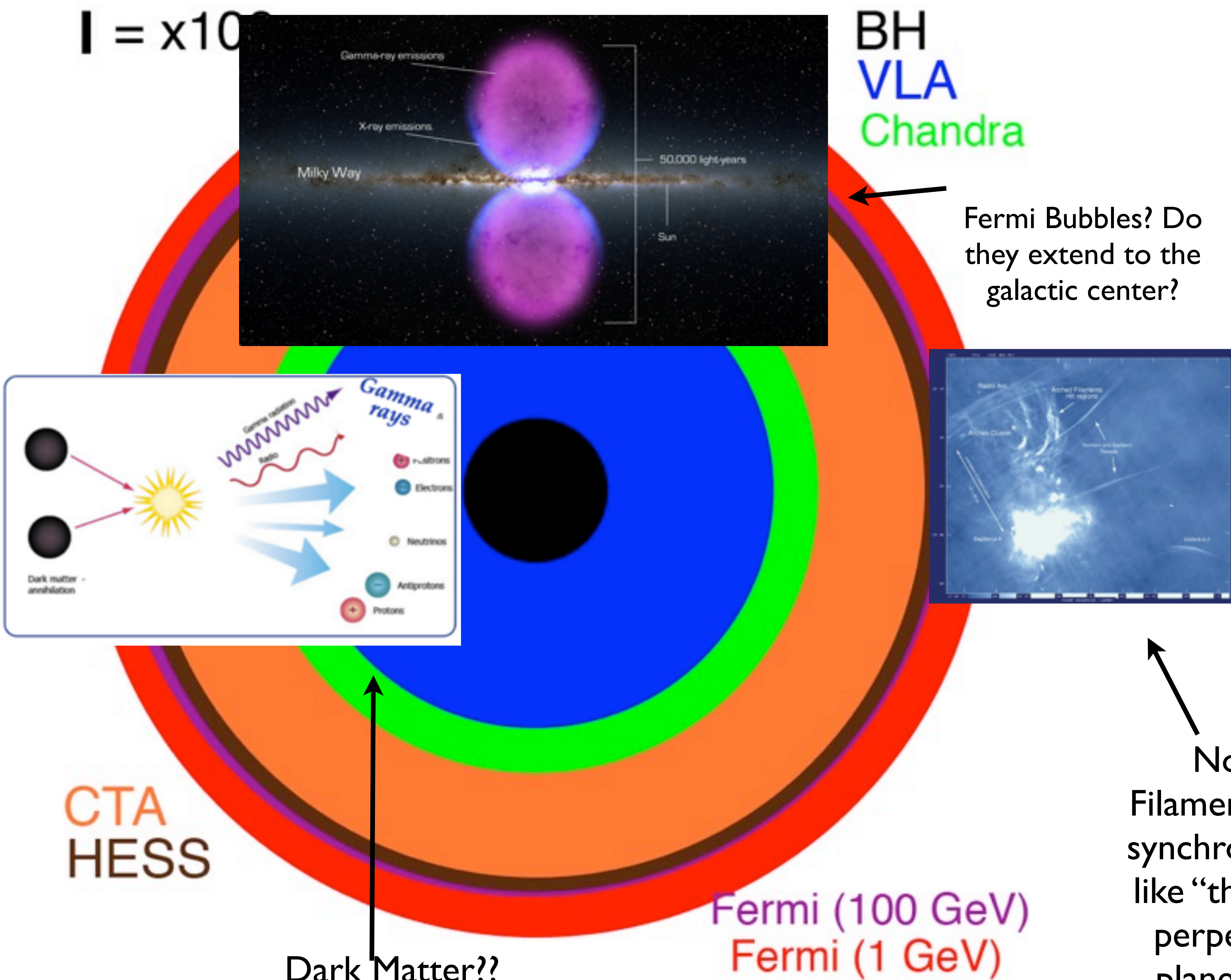
Angular Scales of the Galactic Center



The Galactic Center "Zoo"



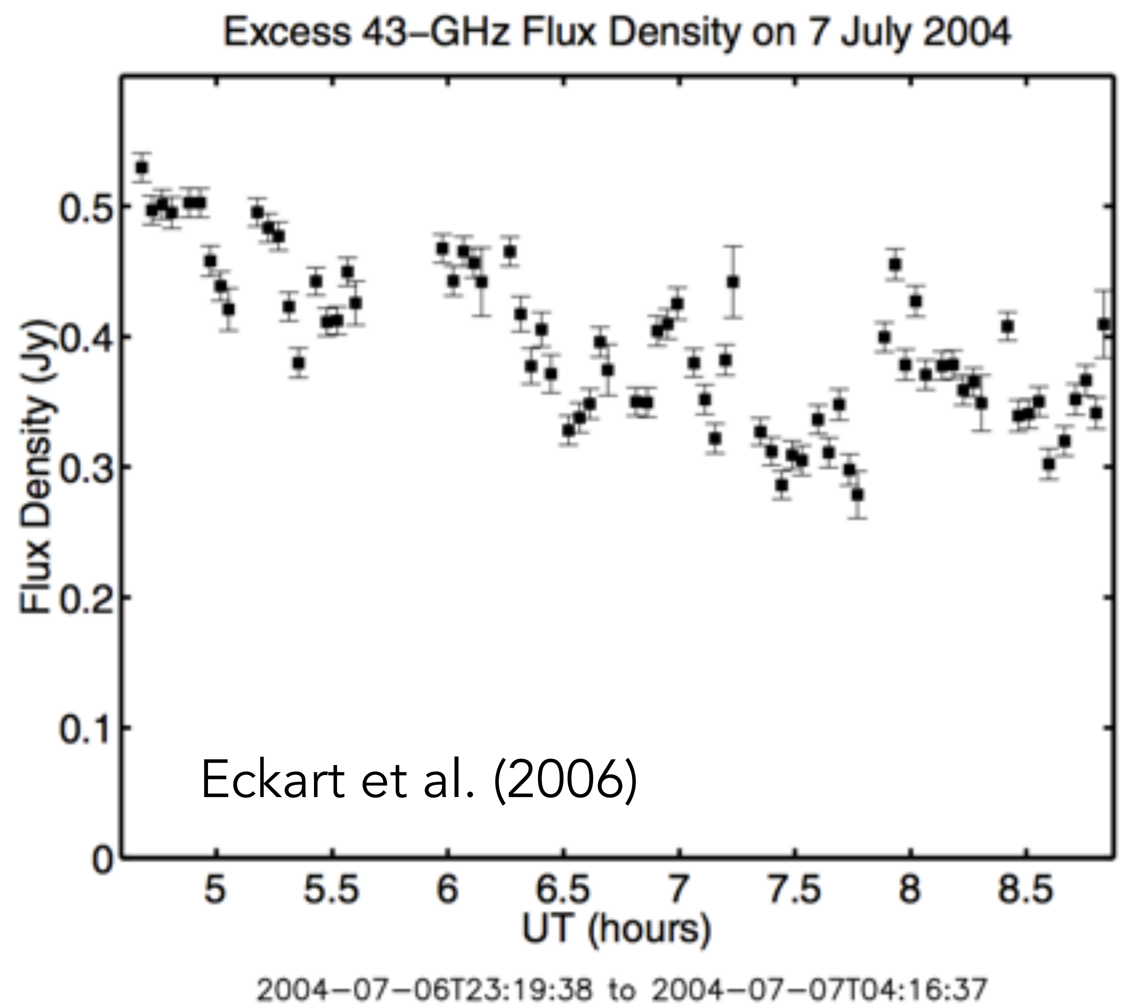
And some surprises!

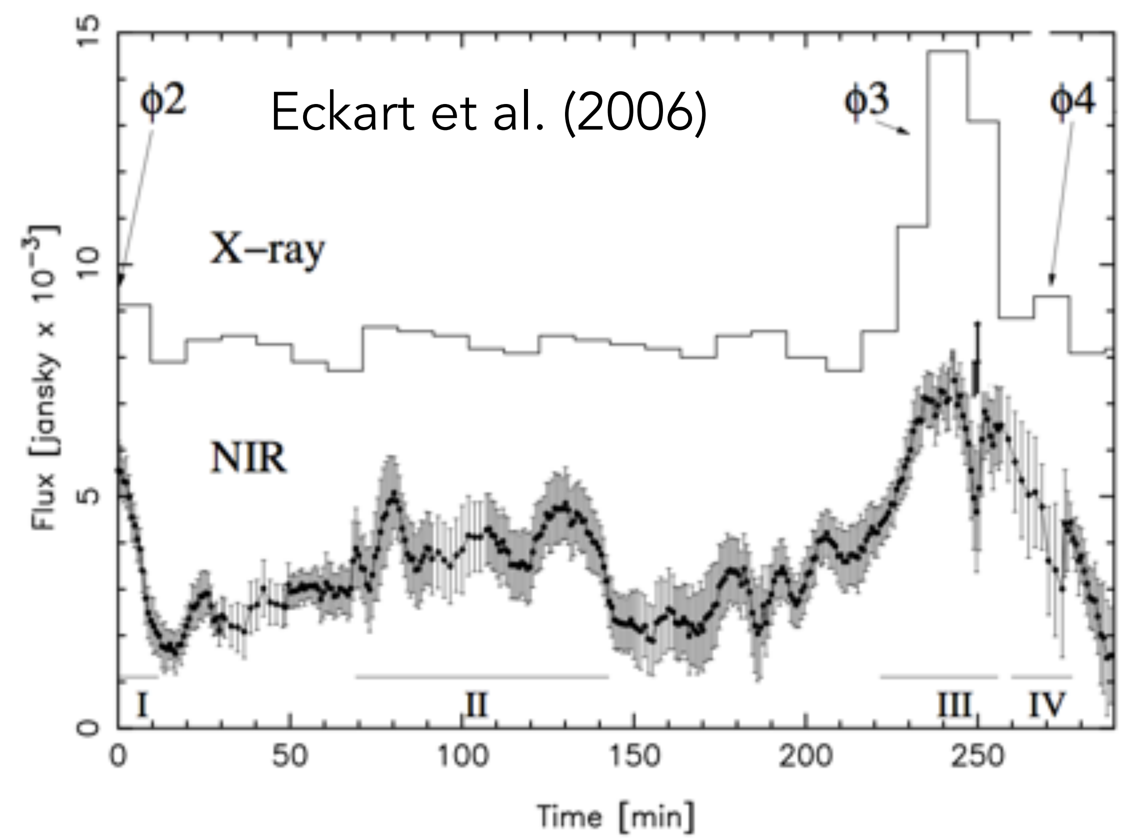


Non-thermal Radio Filaments - Bright, polarized synchrotron sources shaped like “thin threads” and lying perpendicular to galactic plane (Yusef-Zadeh et al. 1984)

Variability at the Galactic Center

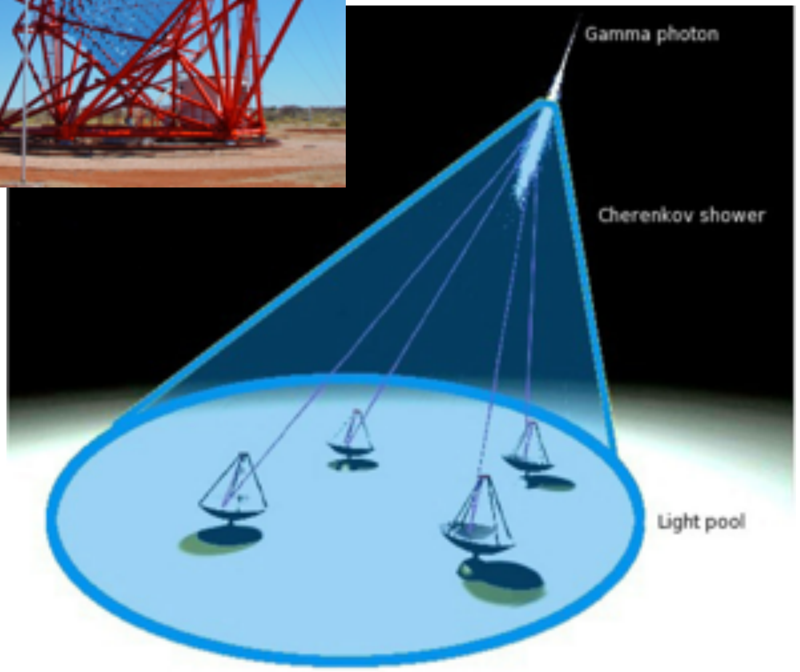
- Sgr A* is highly variable (on multiple time scales) at both radio and X-Ray energies

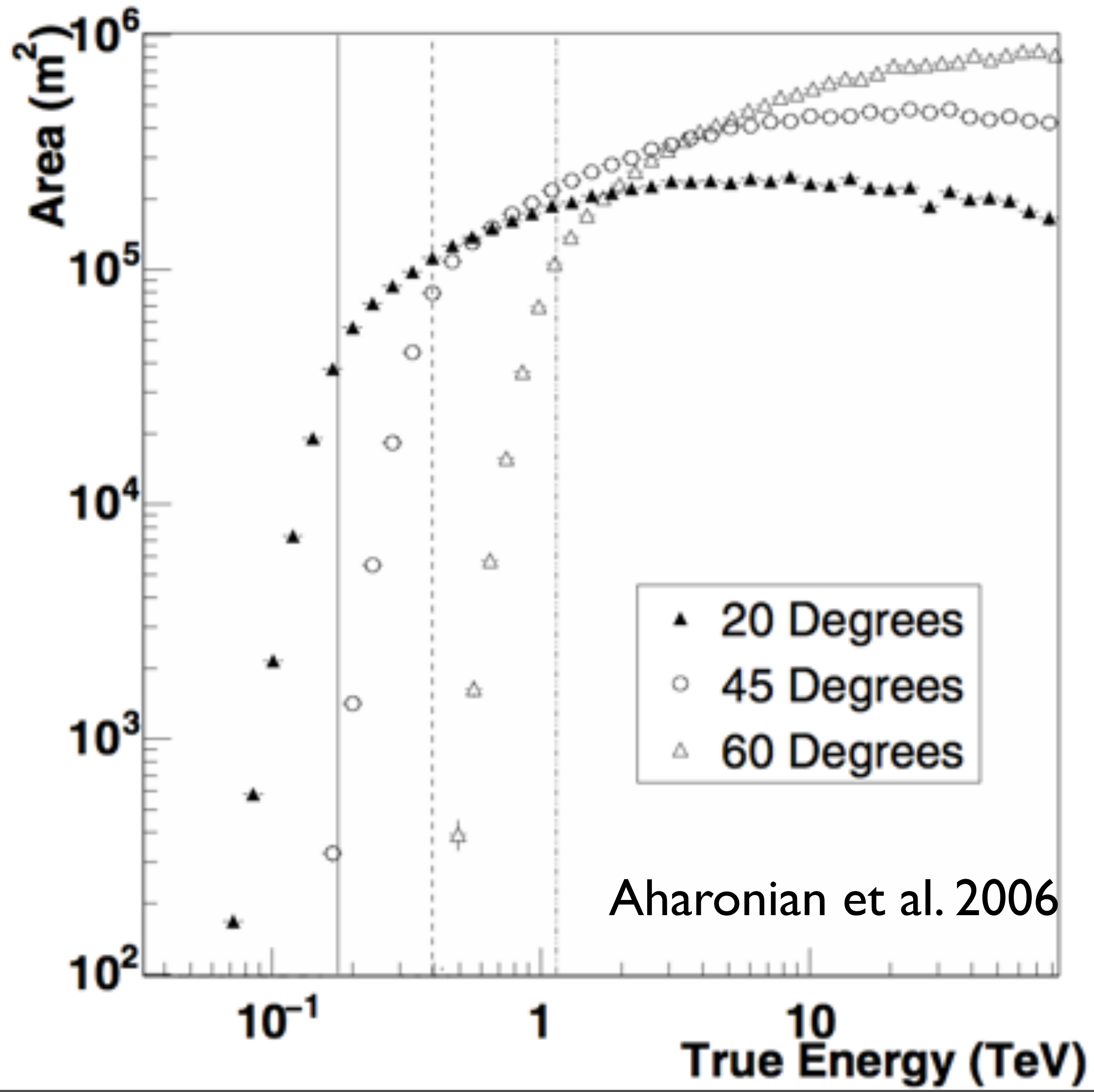




HESS Telescope (2004-Present)

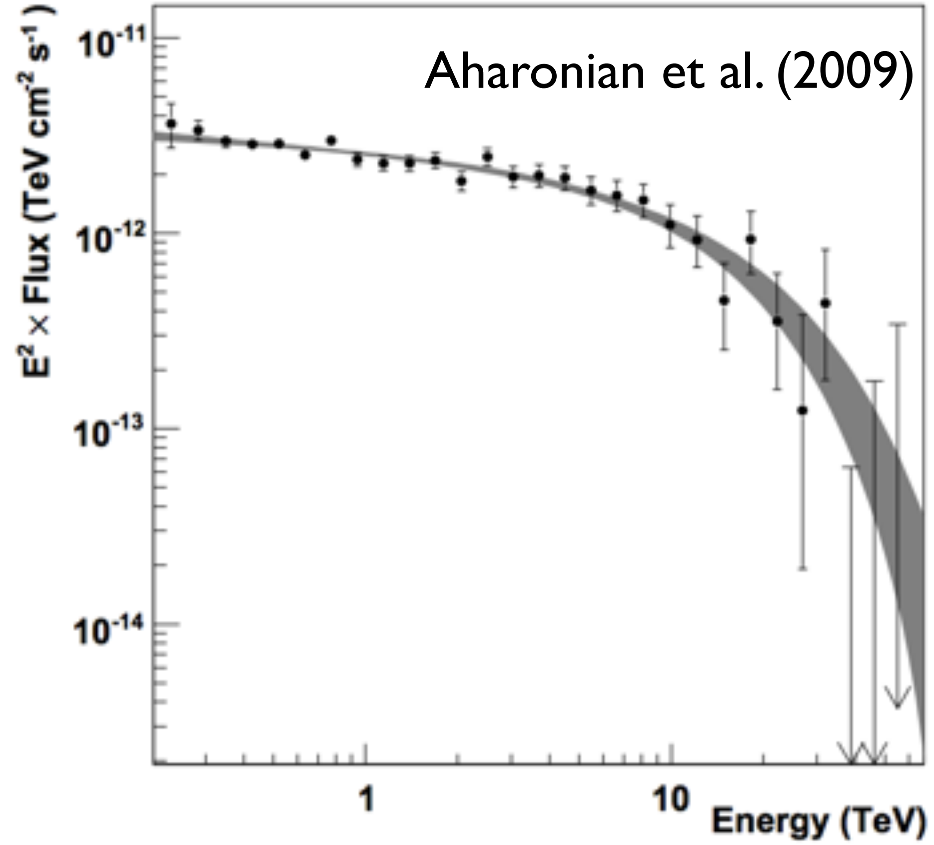
- HESS is an Atmospheric Cherenkov Telescope built in Namibia
- Effective over the energy range ~500 GeV - 100 TeV with an effective area on the order of 10^5 m^2.
- Energy Resolution ~ 10%
- Angular Resolution (>1 TeV) ~ 0.075°.
- Total Observation of the Galactic Center: 93h/112h



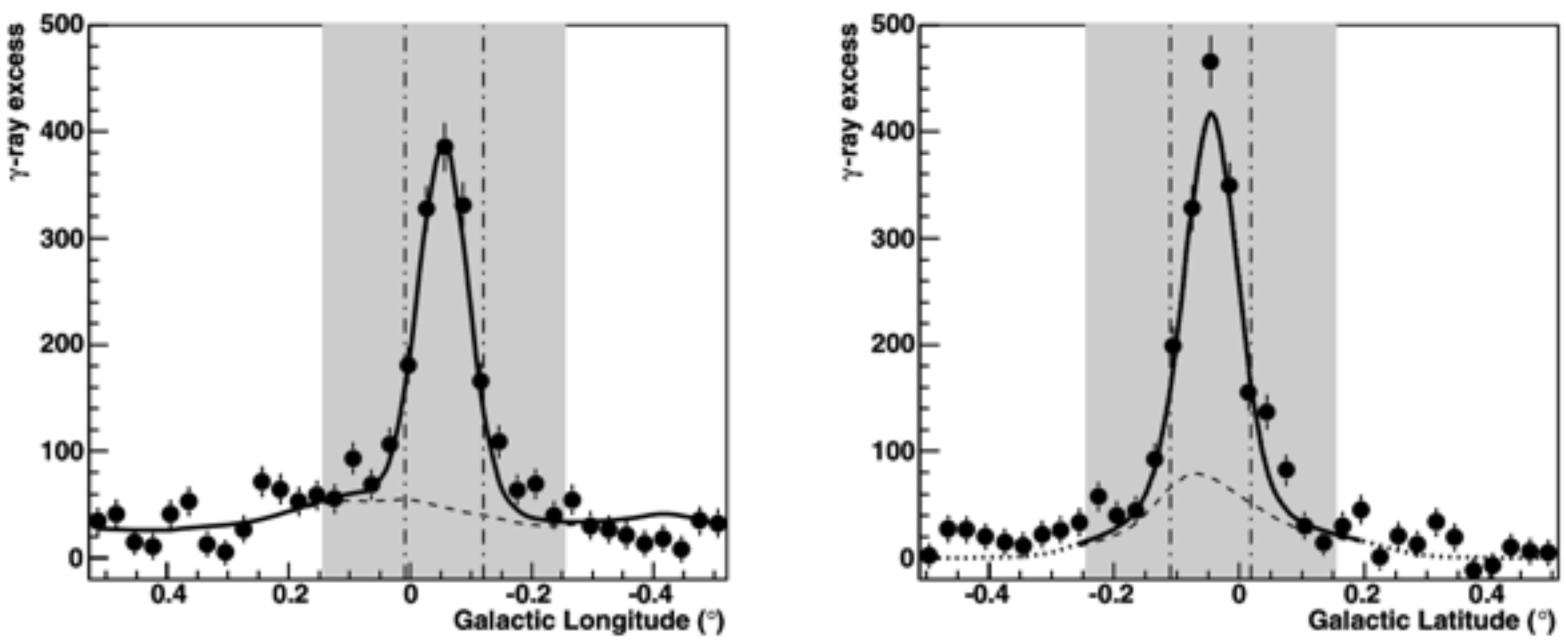


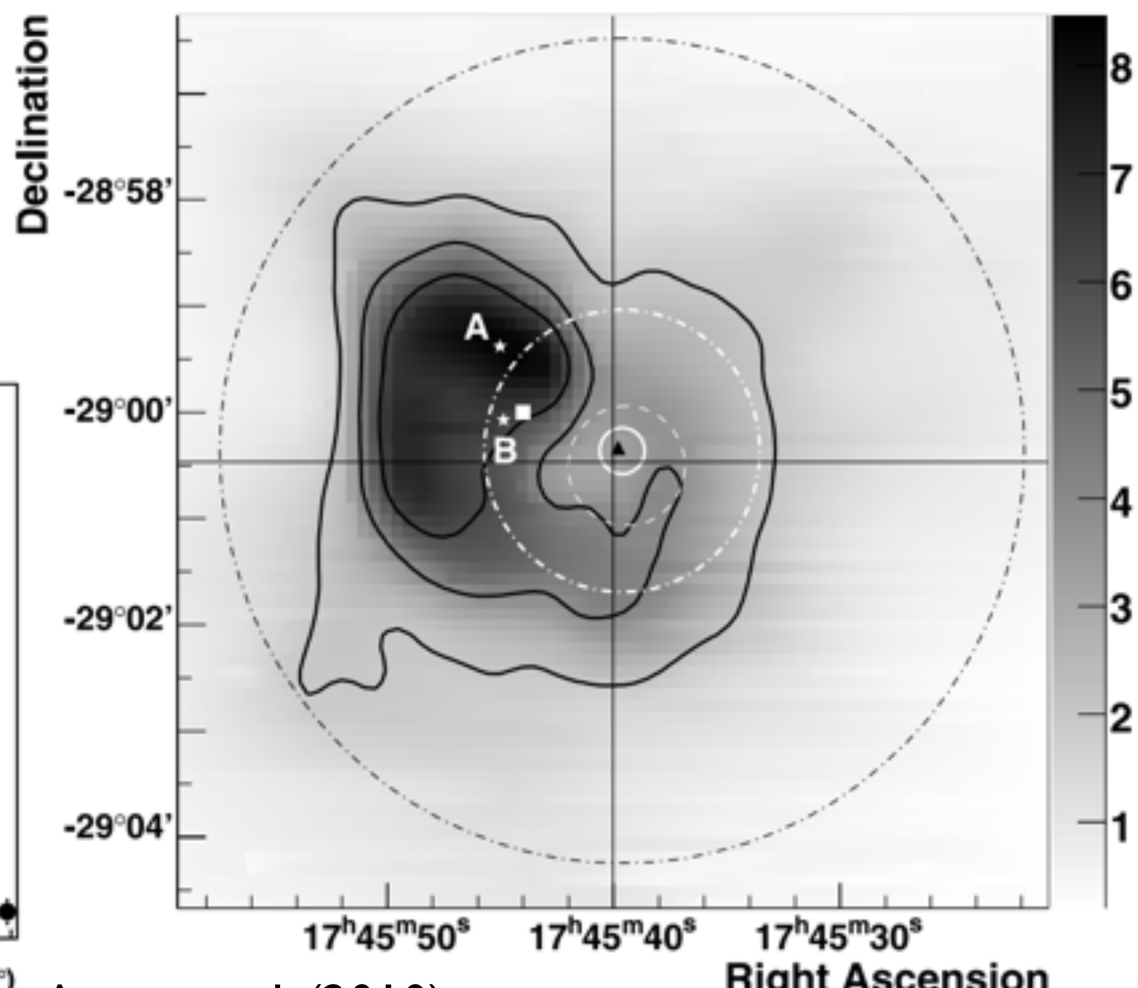
Understanding Astrophysical Backgrounds: HESS

- HESS spectrum well matched by flat E^{-2} spectrum, up to energies of ~10 TeV, where an exponential cutoff is observed



- HESS source is localized to within 13″ of Galactic center (solid white curve) - the 68% and 95% confidence levels on the source extension are at ~1 and 3 pc

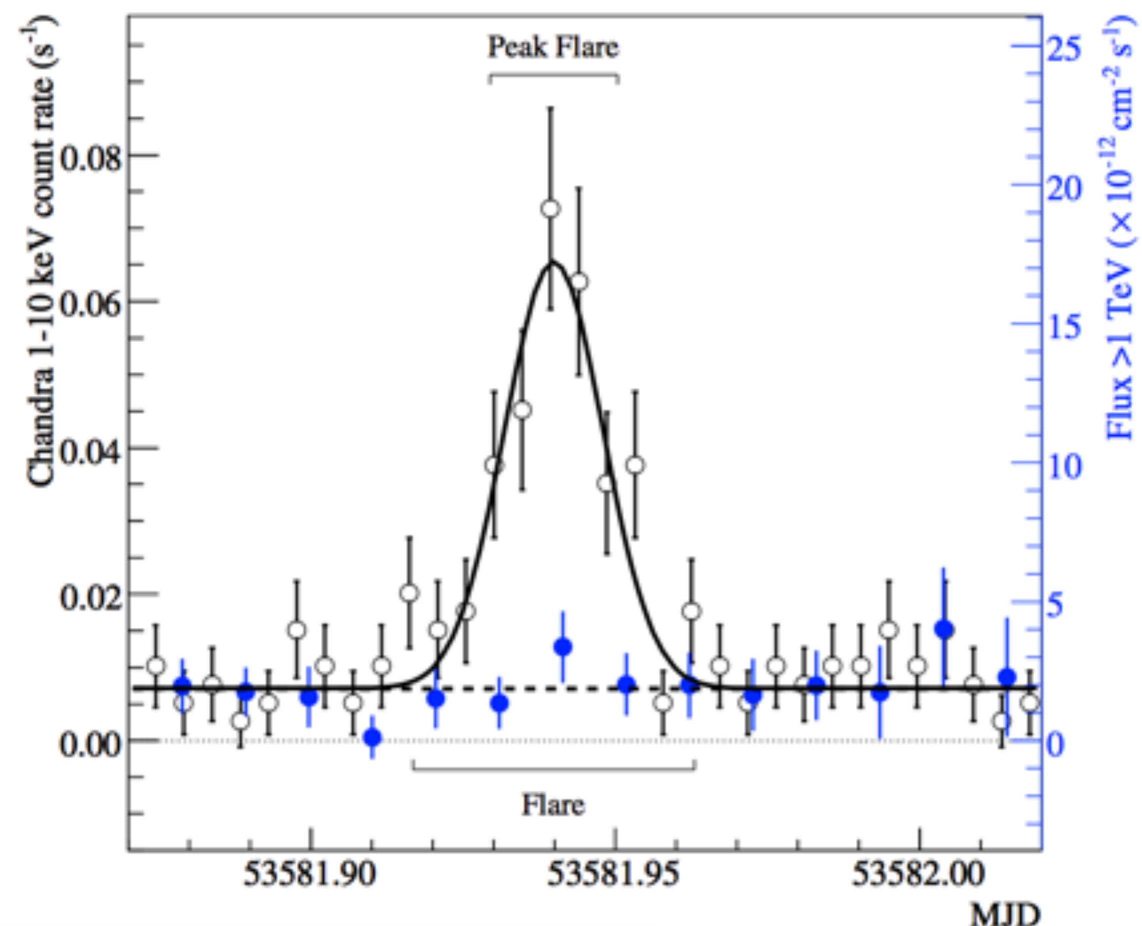




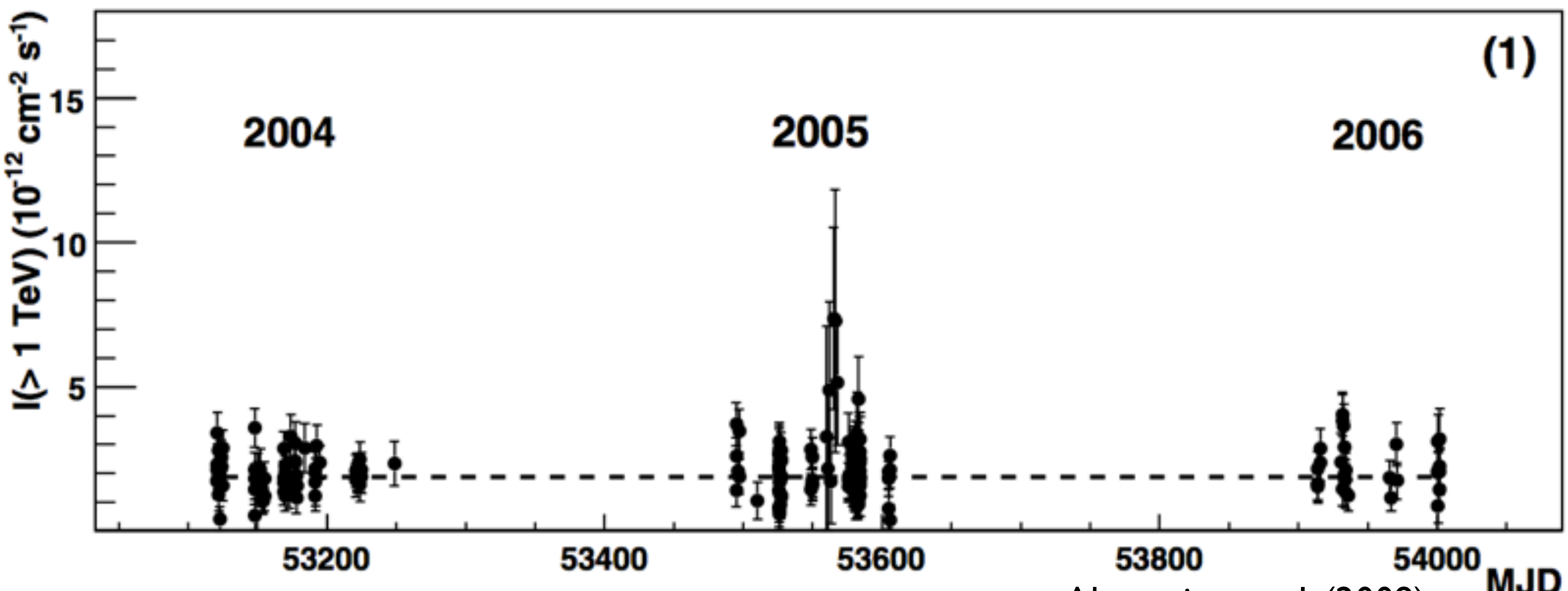
Acero et al. (2010)

Understanding Astrophysical Backgrounds: HESS

Aharonian et al. (2008)



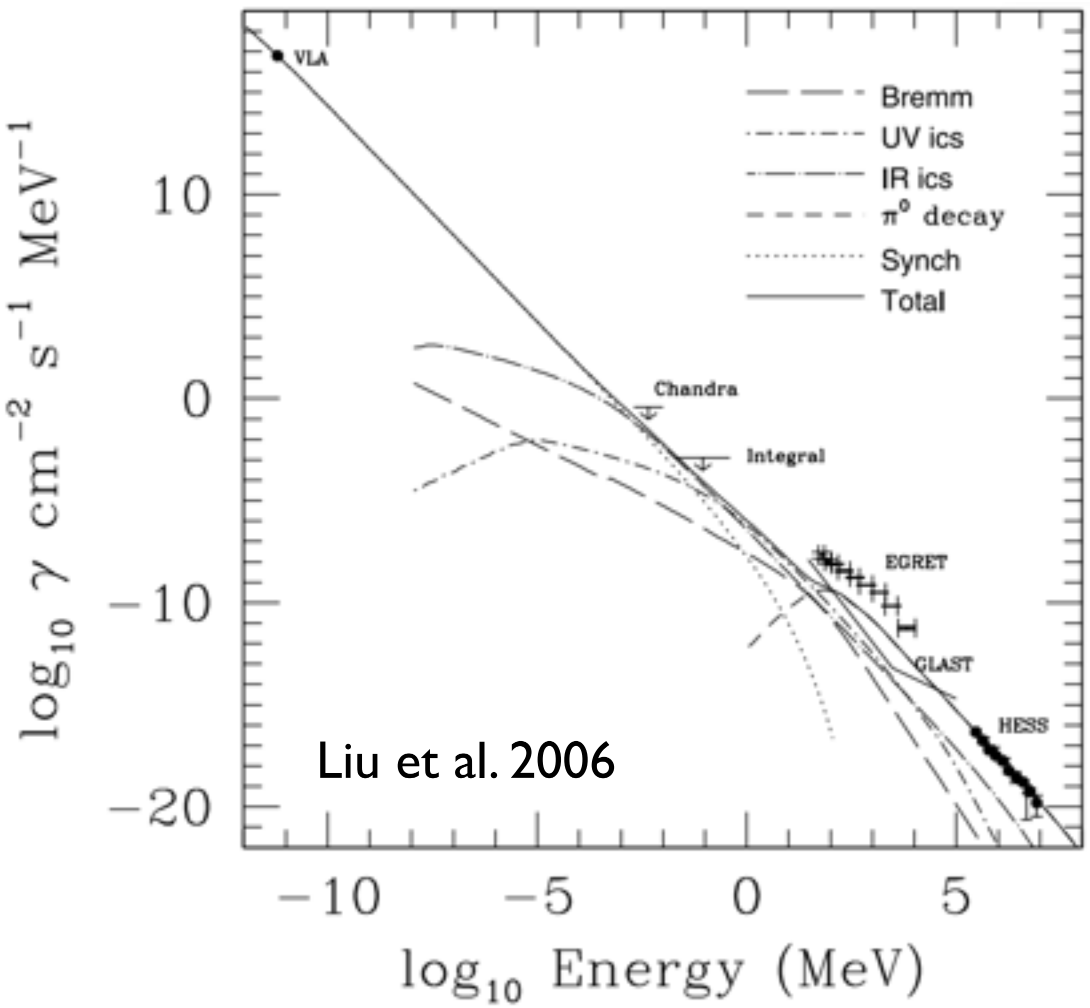
- However, HESS shows no variability, even during outbursts observed by Chandra
- This implies that the source of the emission is spatially distinct from lower energy sources

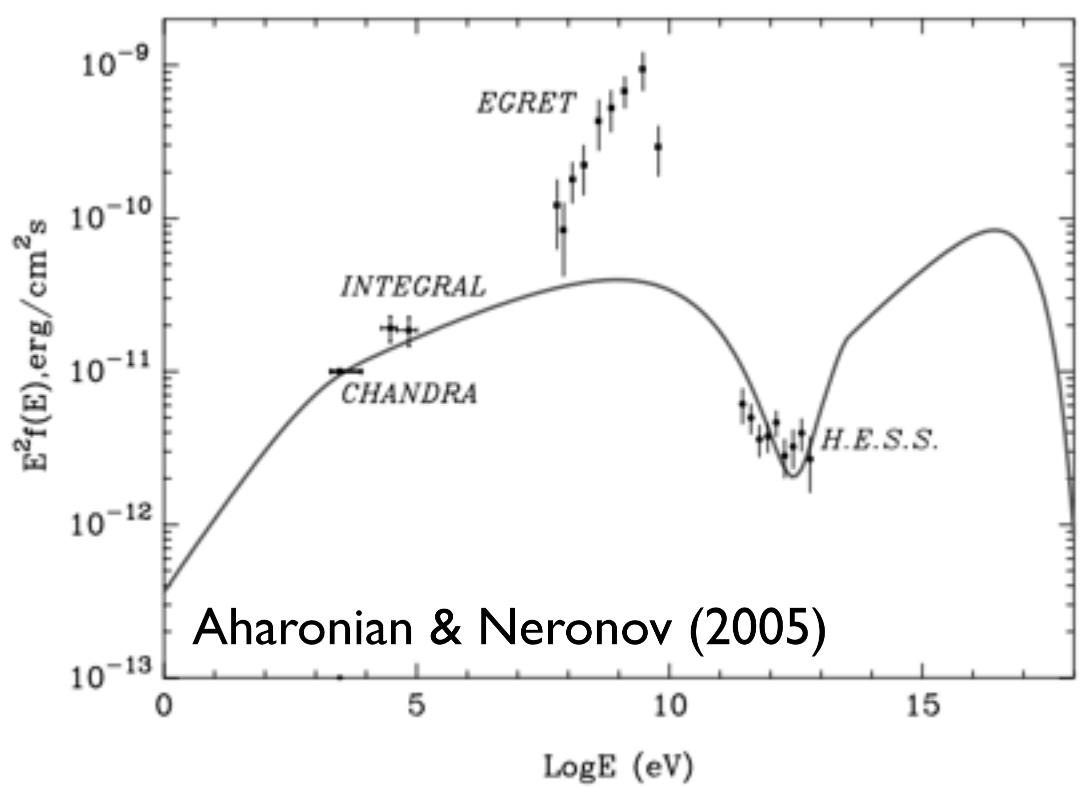


Aharonian et al. (2009)

Fitting the Residual: Hadronic Processes

- The lack of variability indicates that the emission may be stemming from a region farther away from the GC itself
- A recent model examined the possibility that protons emitted from the galactic center produce gamma-rays through their subsequent interaction with galactic gas
- This has the potential to produce the vast majority of emission from TeV scales all the way down to radio energies
- Normalization depends sensitively on diffusion **(stay tuned!)**

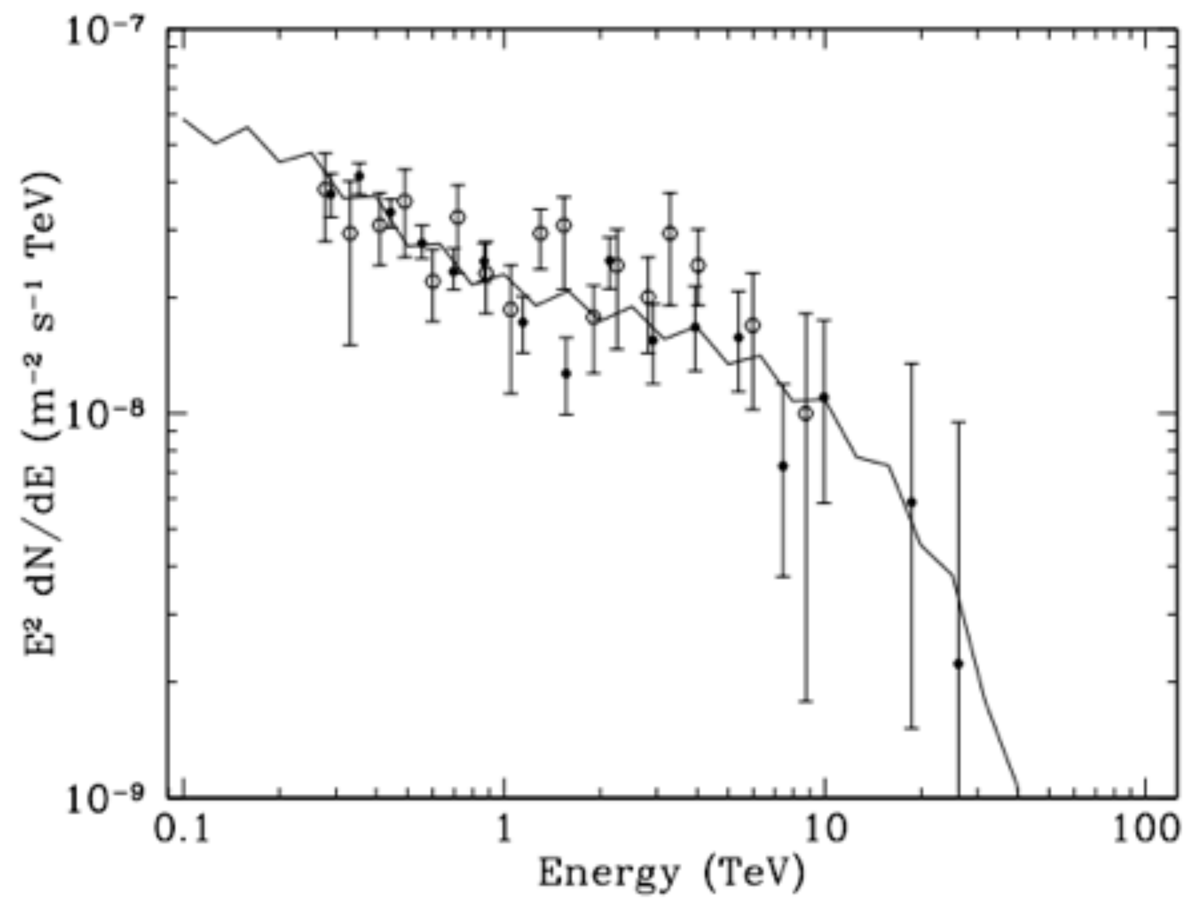


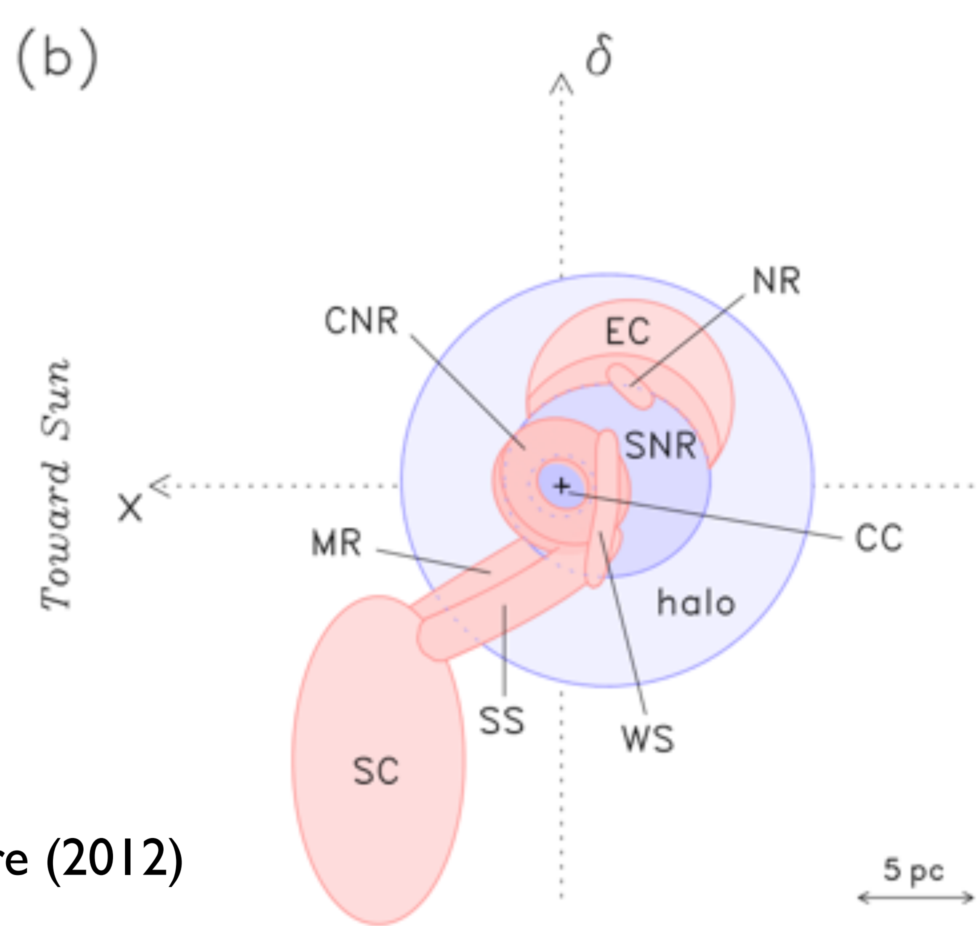


Fitting the Residual: Hadronic Processes

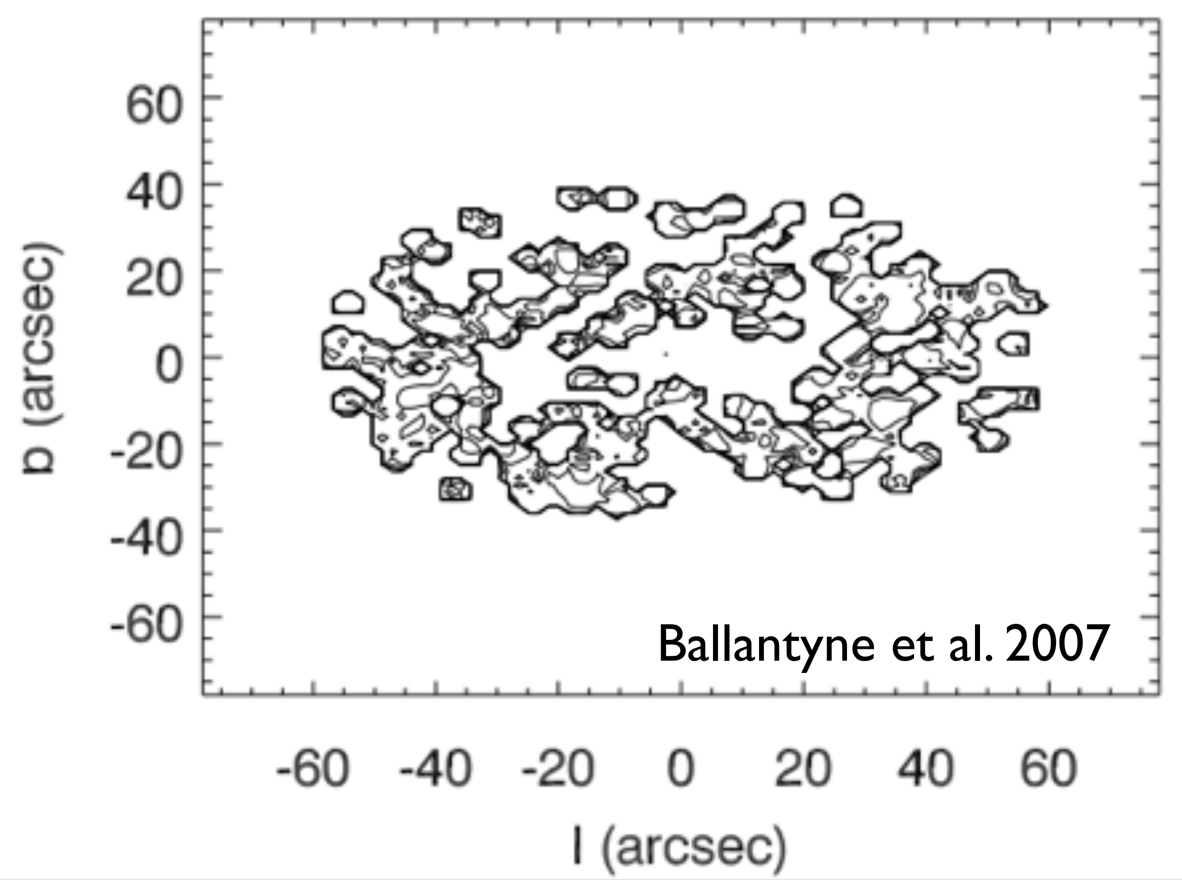
- A recent model examined the possibility that protons injected from the galactic center encountered the circumnuclear ring

- This region of high density molecular gas would produce bright gamma-ray emission upon the interaction with energetic protons



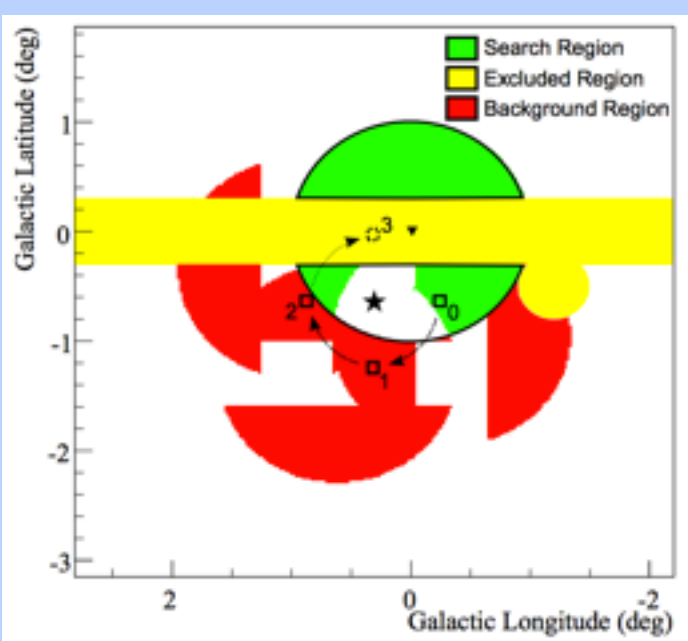


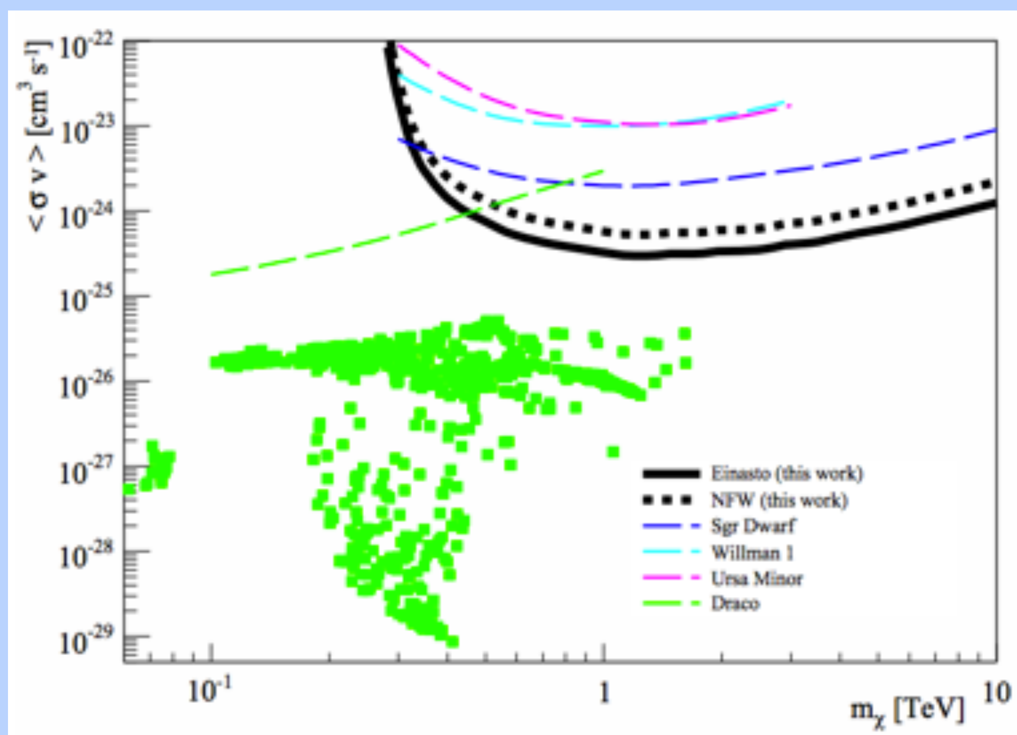
Ferriere (2012)



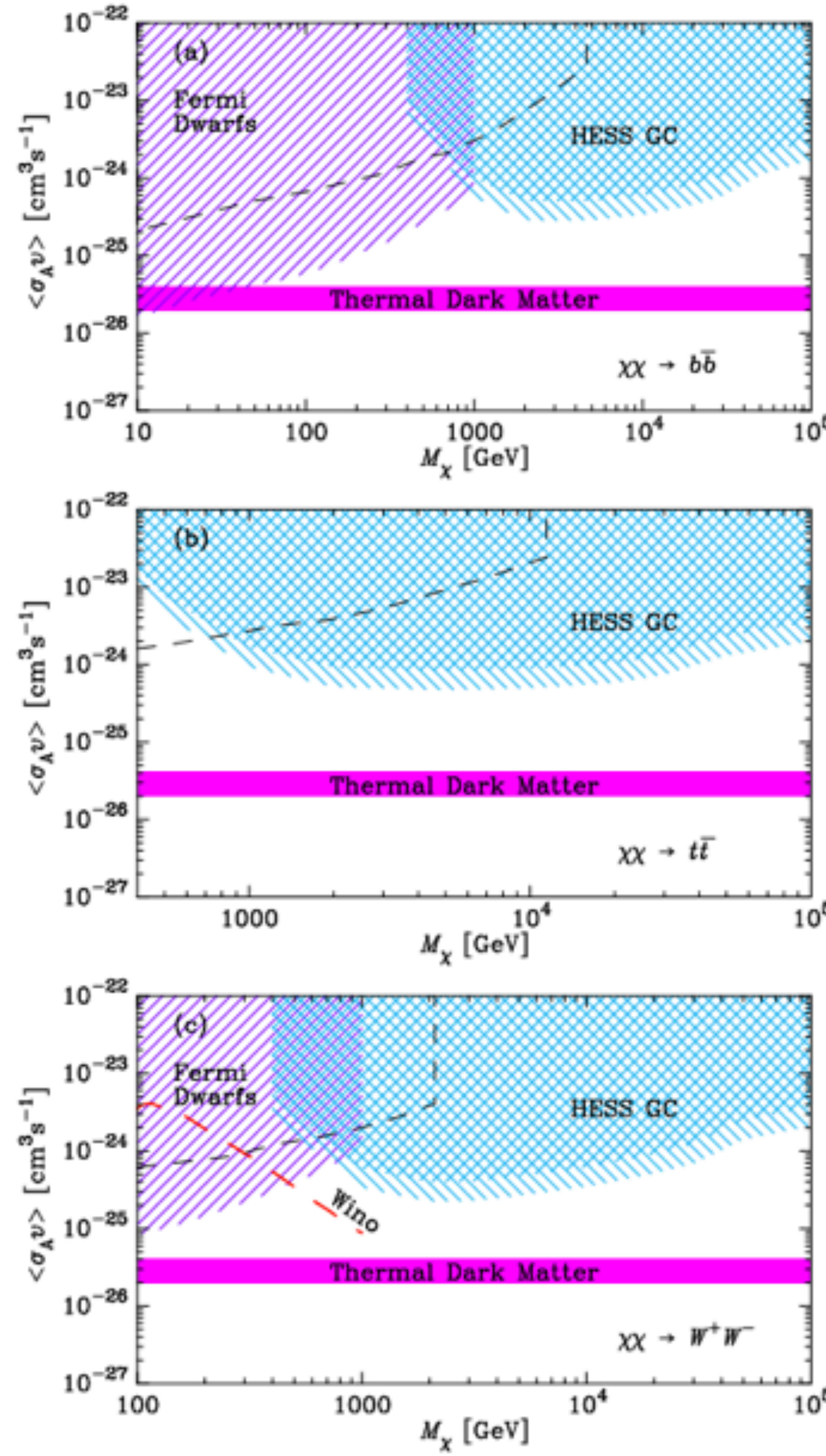
HESS Limits on TeV Dark Matter

- HESS observations of the Galactic center, and Galactic Halo provide the strongest indirect limits on TeV dark matter
- Limits are strongly profile dependent -- background subtraction weakens bounds on isothermal dark matter models as well





Abramowski et al. (2011)

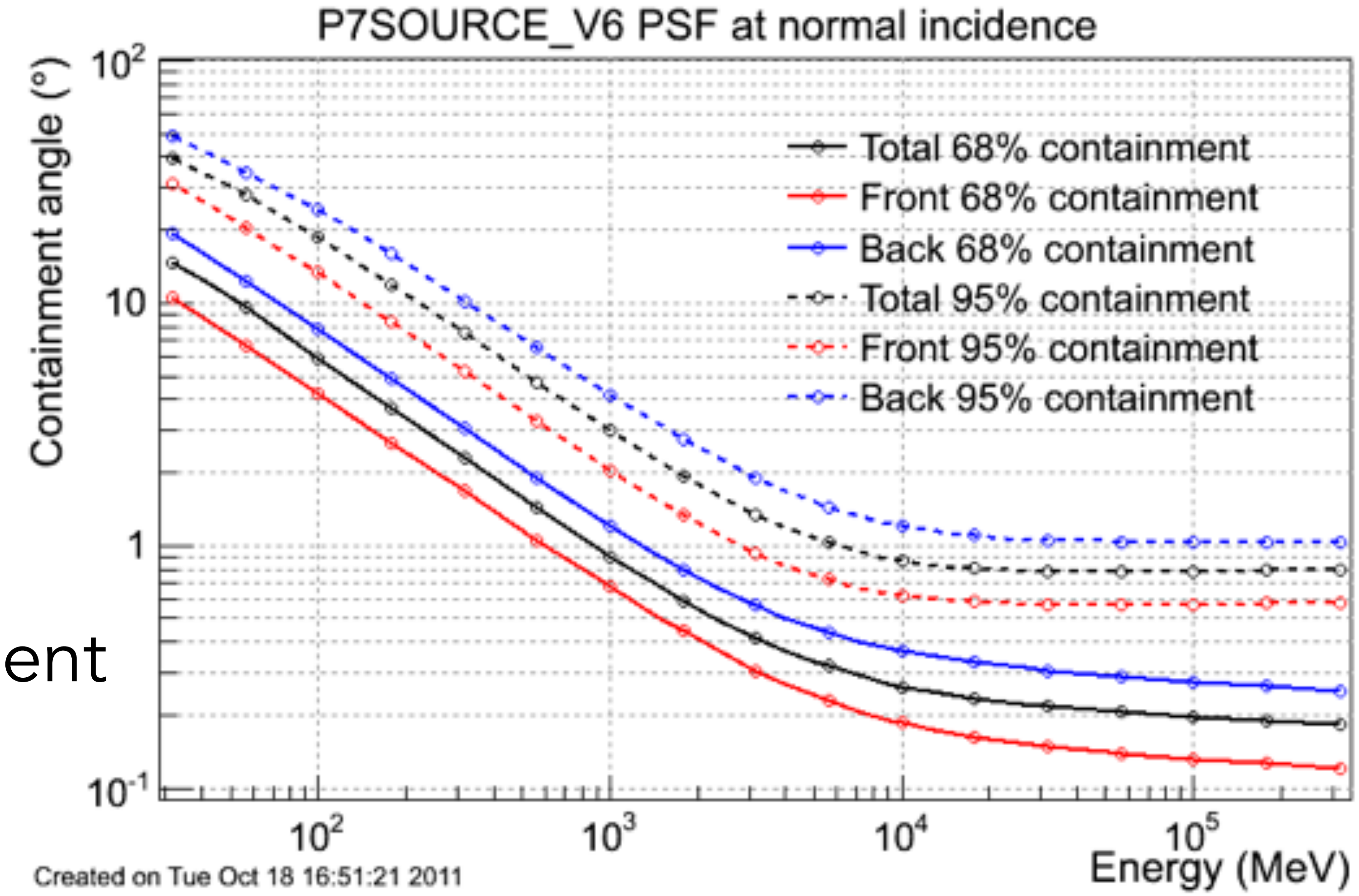


Abazajian & Harding (2011)

Fermi Telescope (2008-Present)

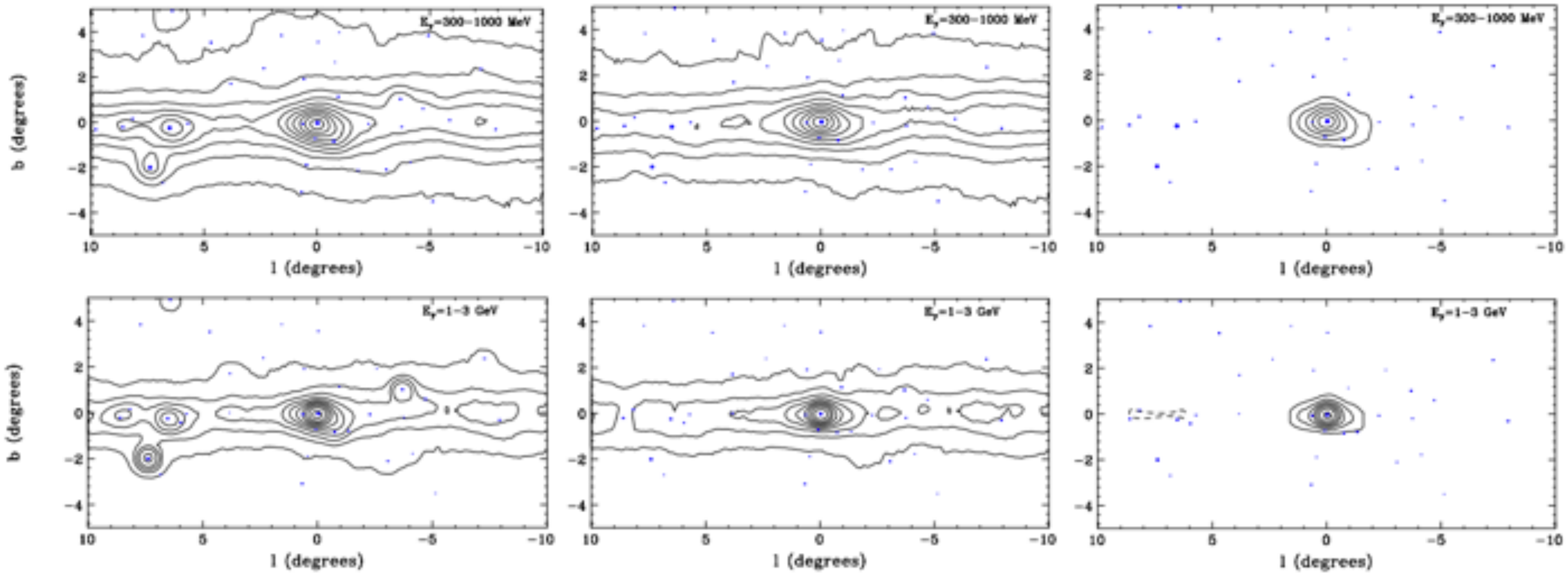
- Fermi-LAT is a space based gamma-ray detector with an effective energy range of 20 MeV-300 GeV

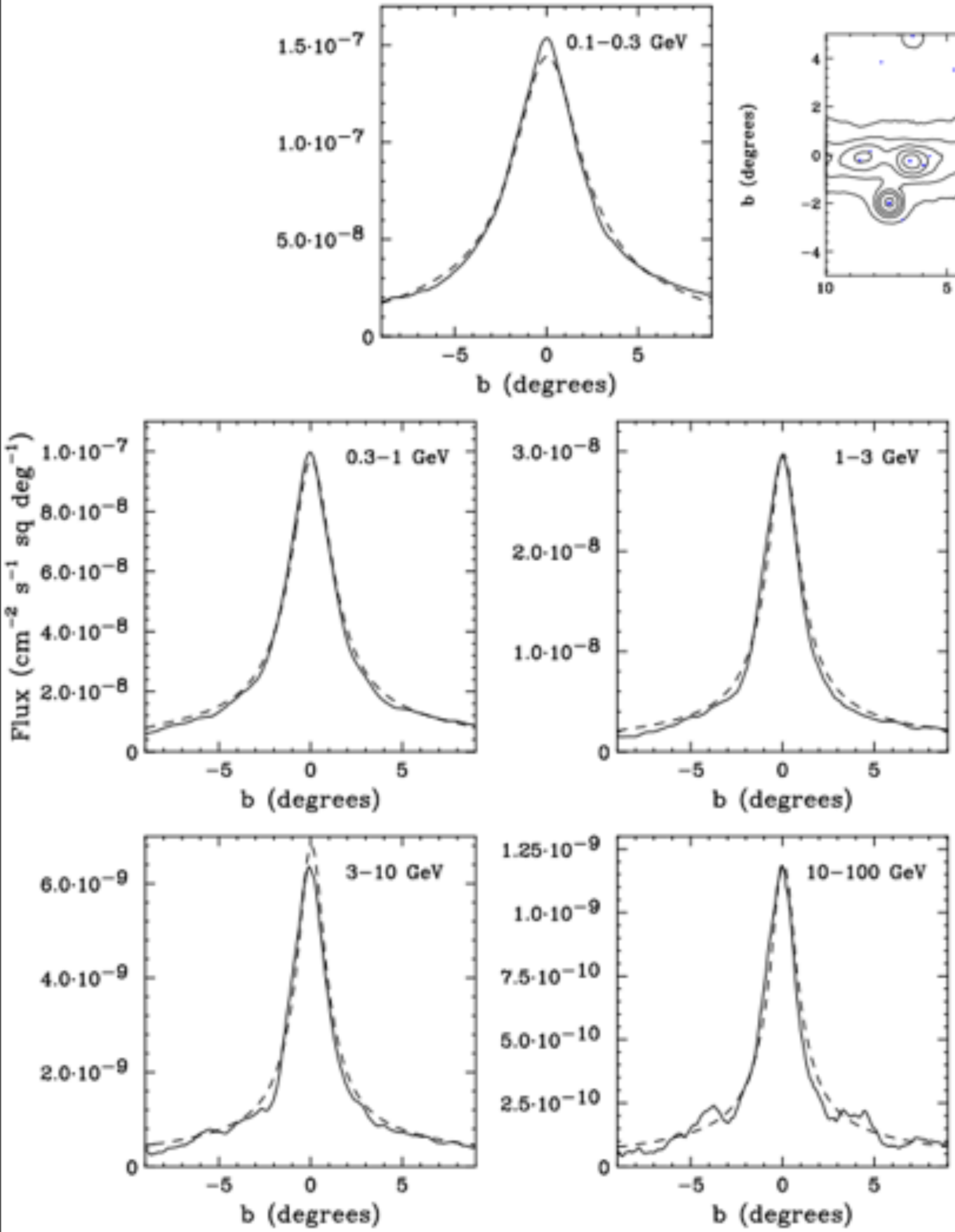
- Effective Area ~ 0.8 m^2
- Field of View ~ 2.4 sr
- Energy Resolution ~ 10%
- Angular Resolution: Energy Dependent



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

Subtracting the Astrophysical Background: Fermi

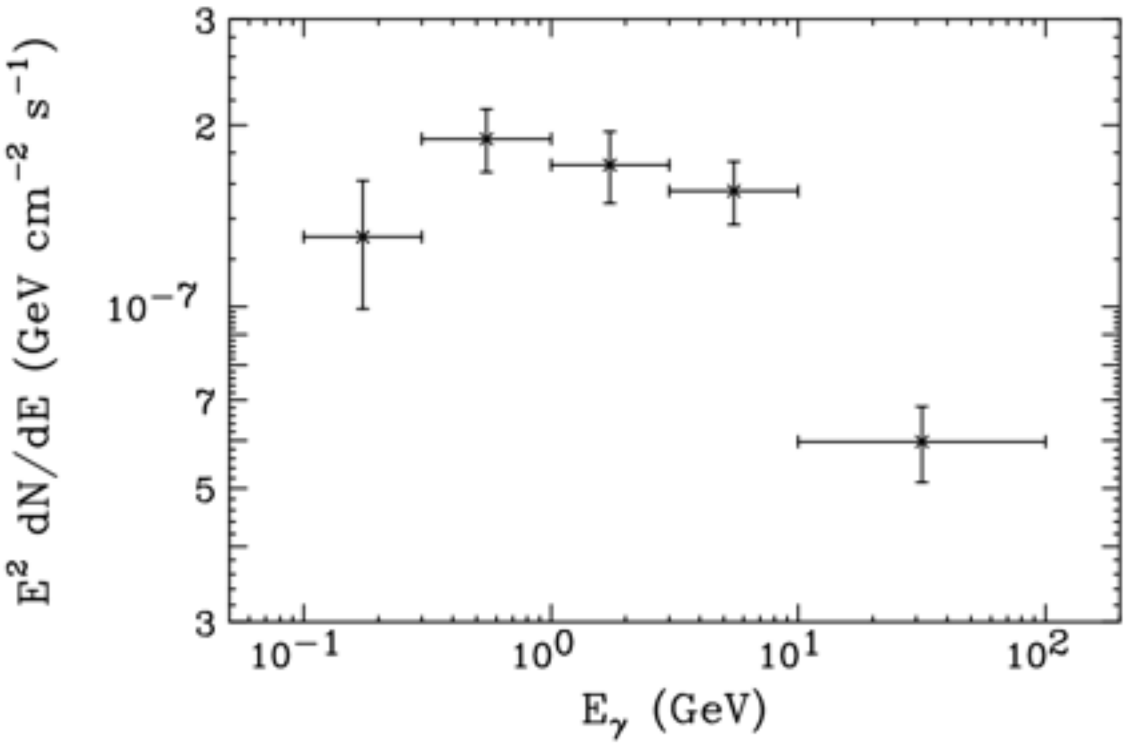




- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum in the range 7° < |l| < 10°
- This subtraction subtracts the vast majority of emission, leaving a single spherically symmetric emission around the GC

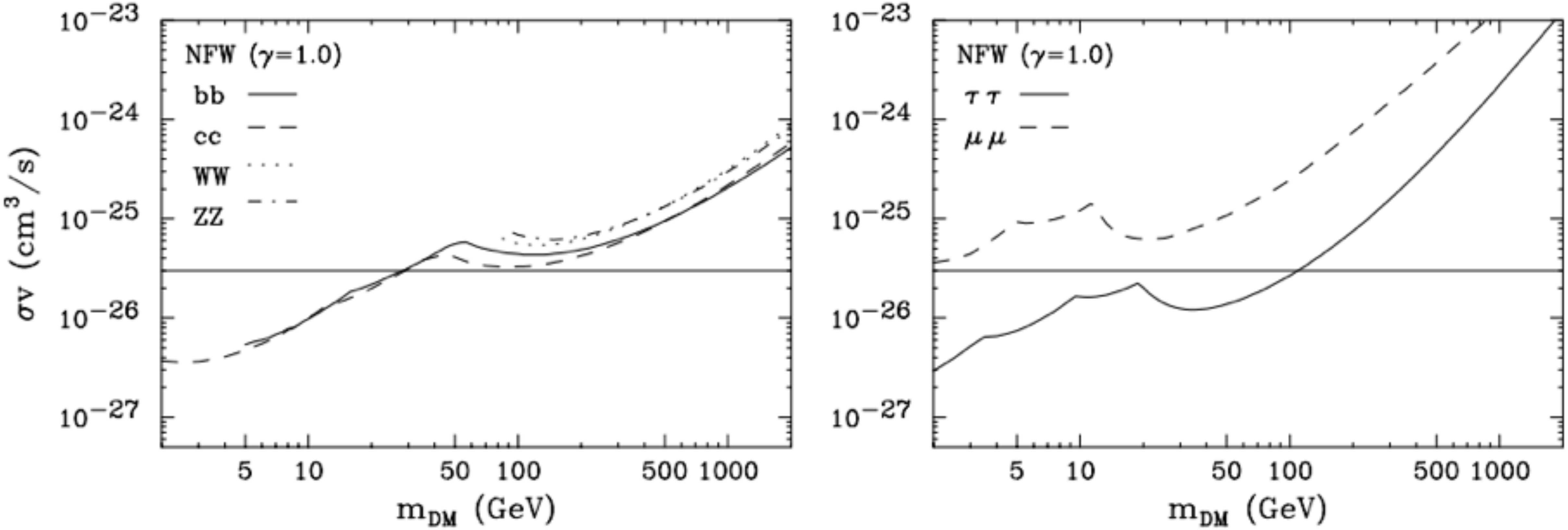
Hooper & Linden (2011)

Dark Matter Limits in the Simplest Way Possible

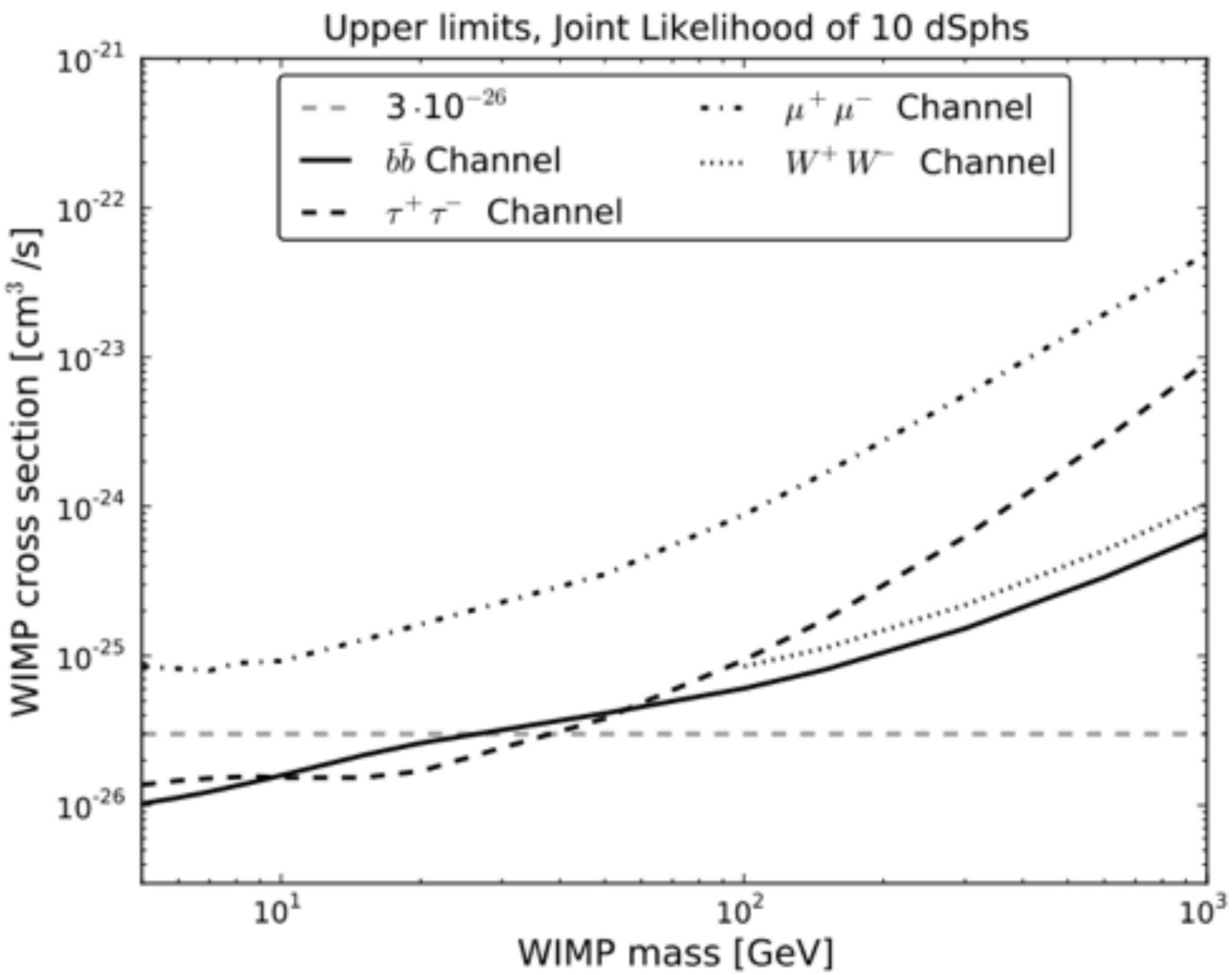


Hooper & Linden (2011)

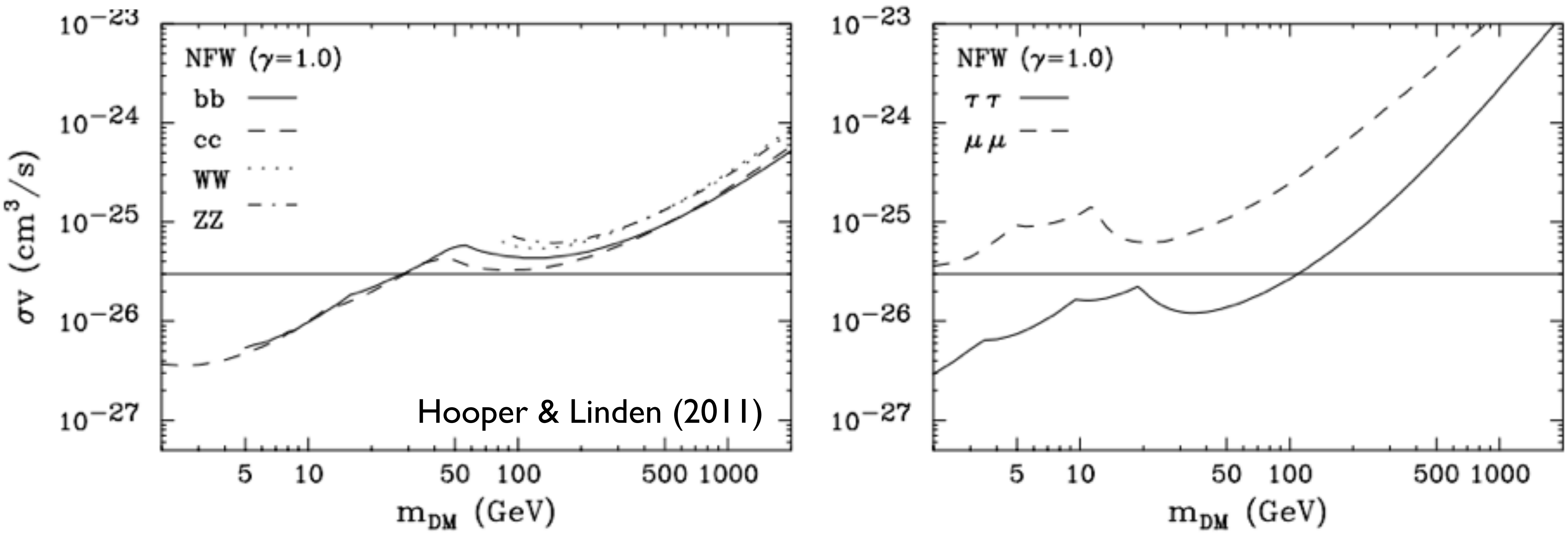
- After subtracting emission from known point sources, and an extrapolation of the line-of-sight gas density, the following "galactic center" emission is calculated
- This directly corresponds to a limit on the dark matter interaction cross-section which depends only on assumed dark matter density profile



Comparison to Other Indirect Detection Regimes



- Under the assumption of an NFW profile, the 95% confidence limits are as good or better than those from dwarf-spheroidals
- They are especially stronger for leptophilic annihilation paths



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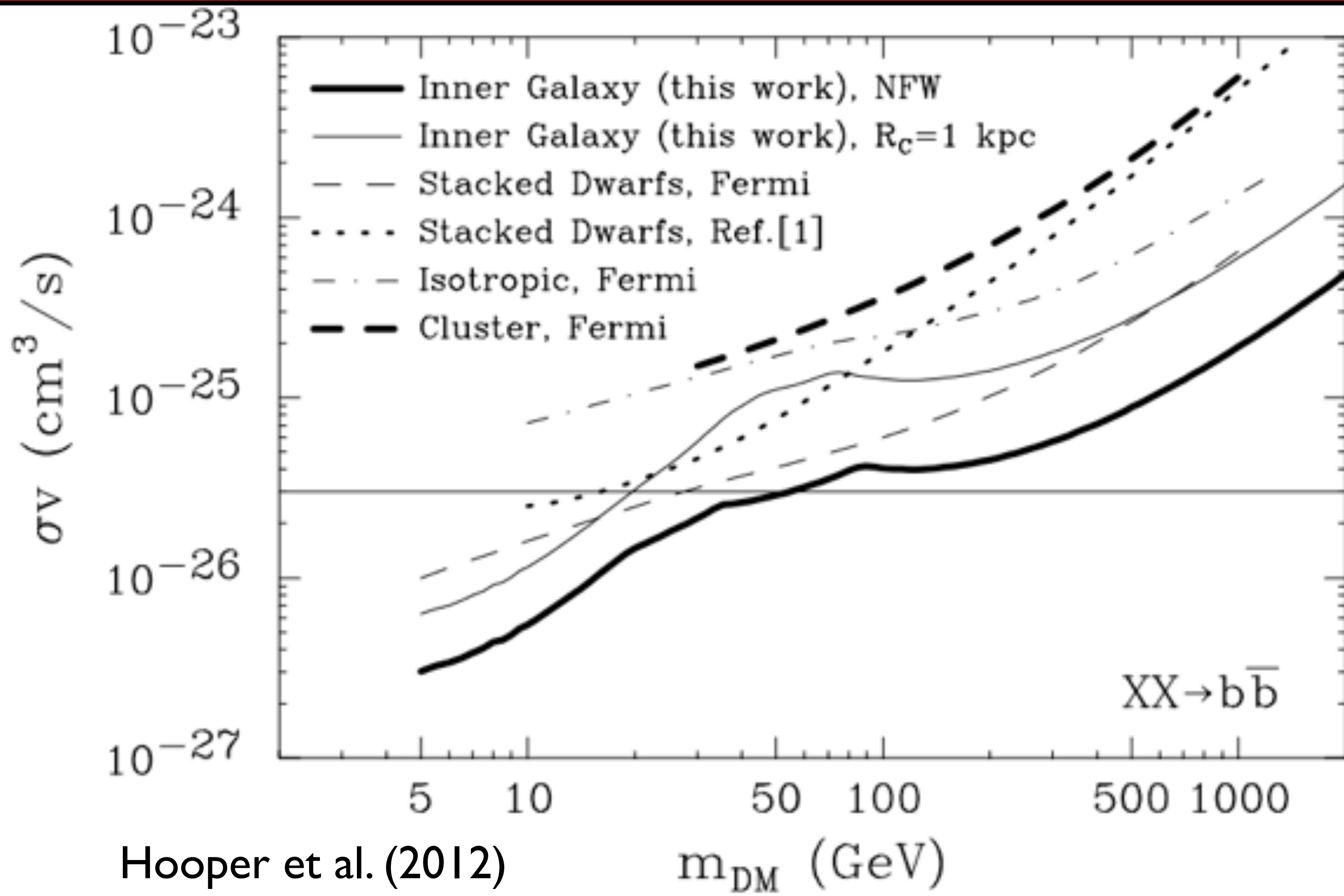
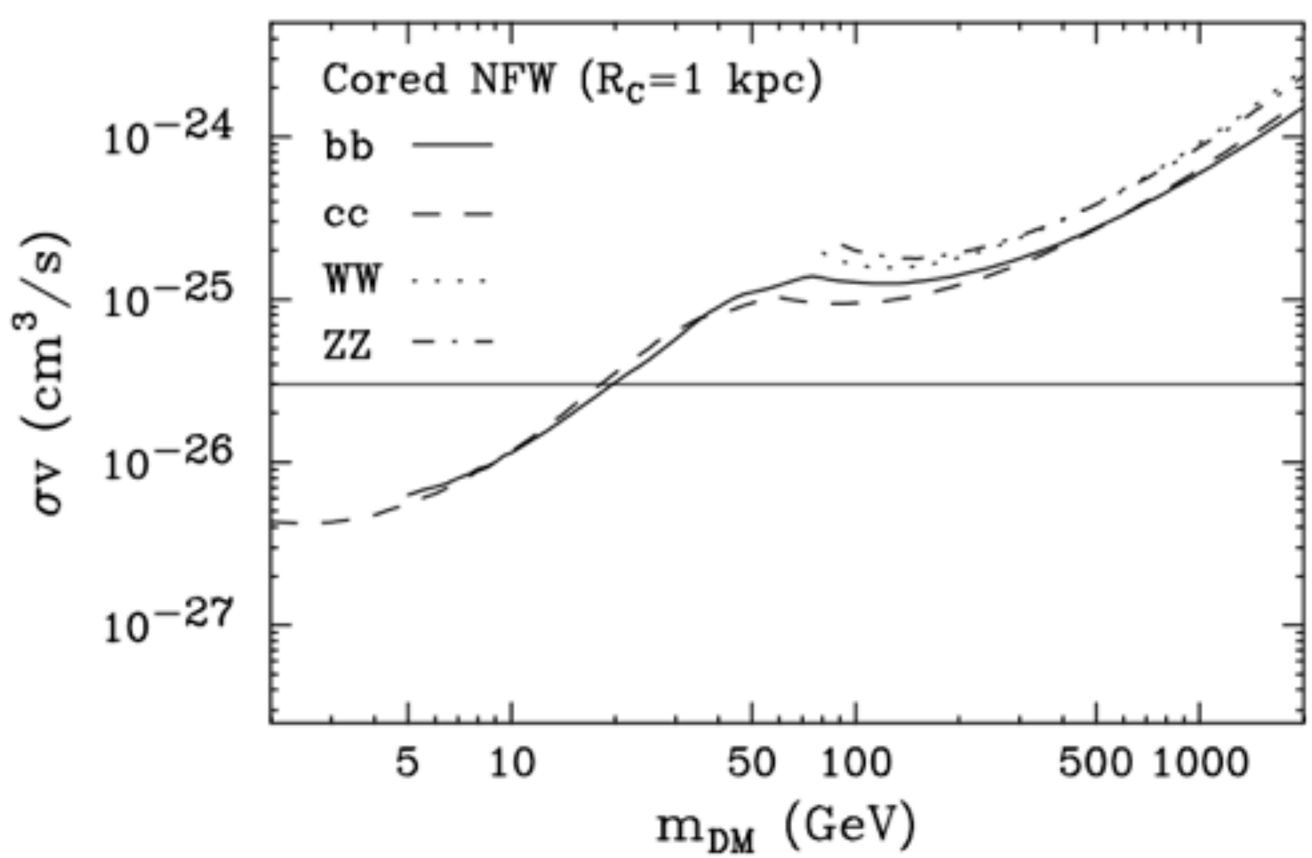
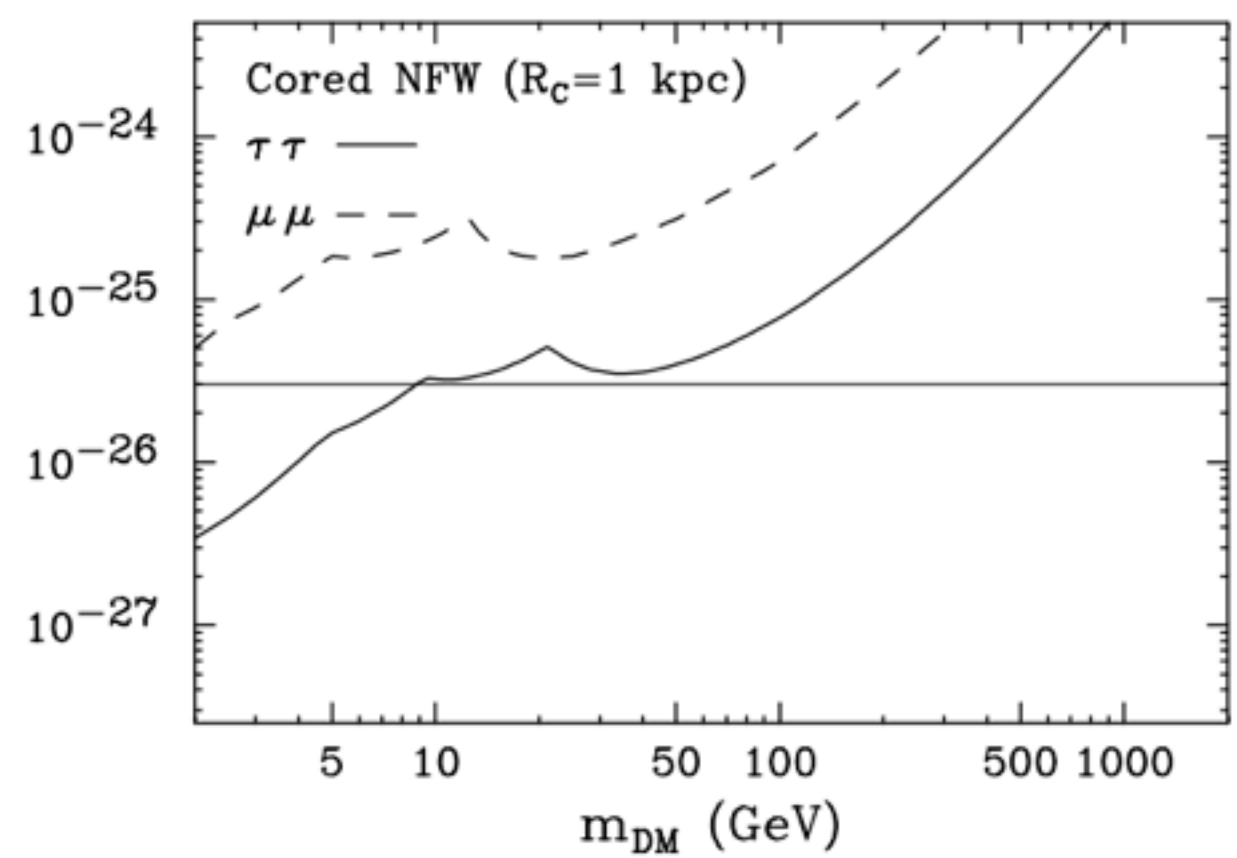


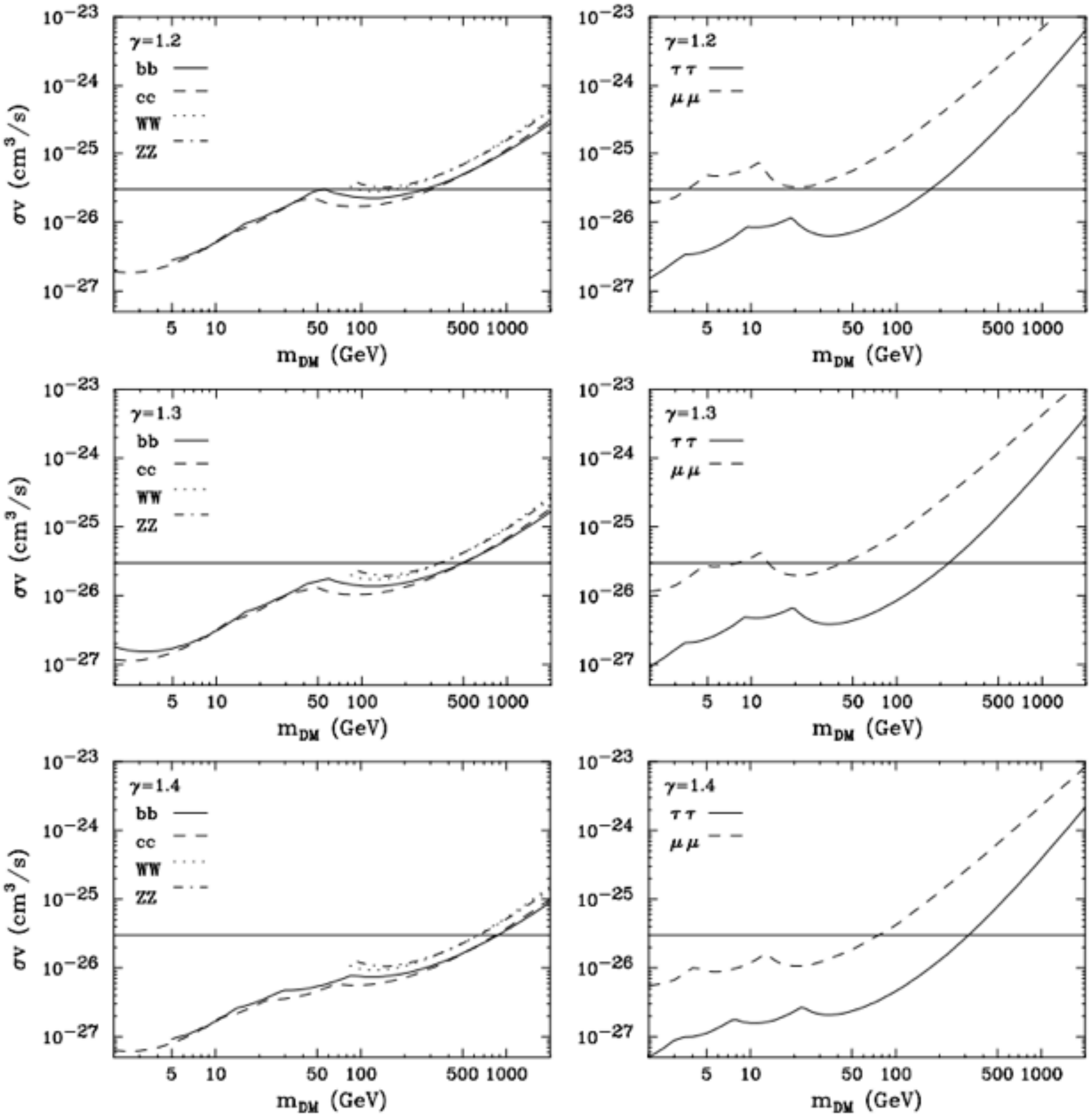
Hooper et al. (2012)

- Hooper et al. (2012) further tweaked the methods used to derive these limits, deriving rigorous constraints under a wide variety of assumptions
- These are the strongest gamma-ray limits on the cross-section for dark matter annihilation



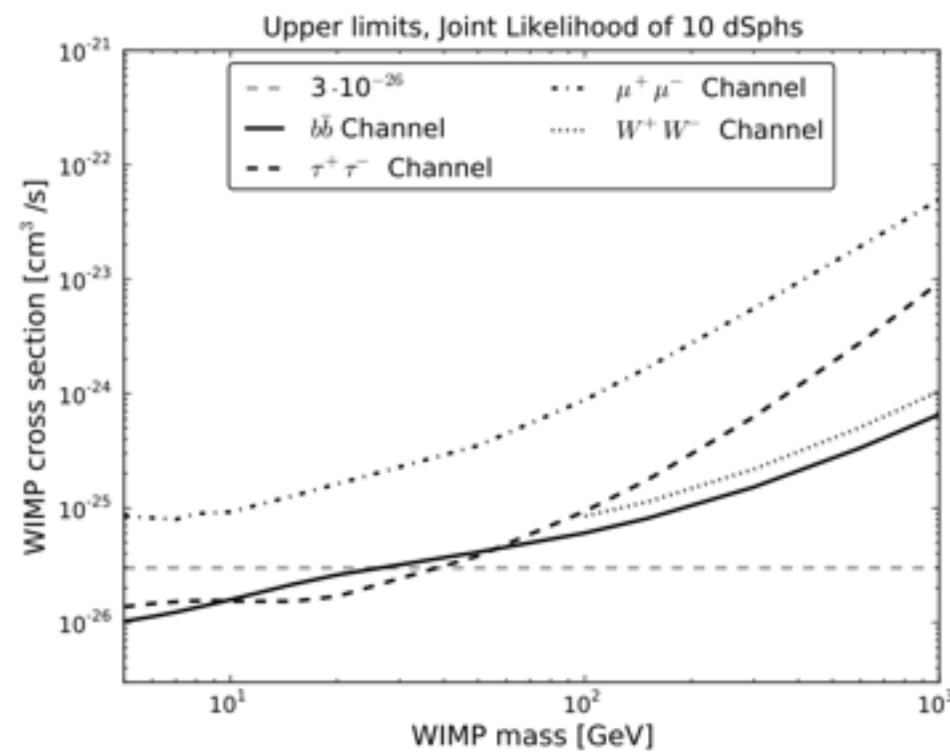


Comparison to Other Indirect Detection Regimes



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

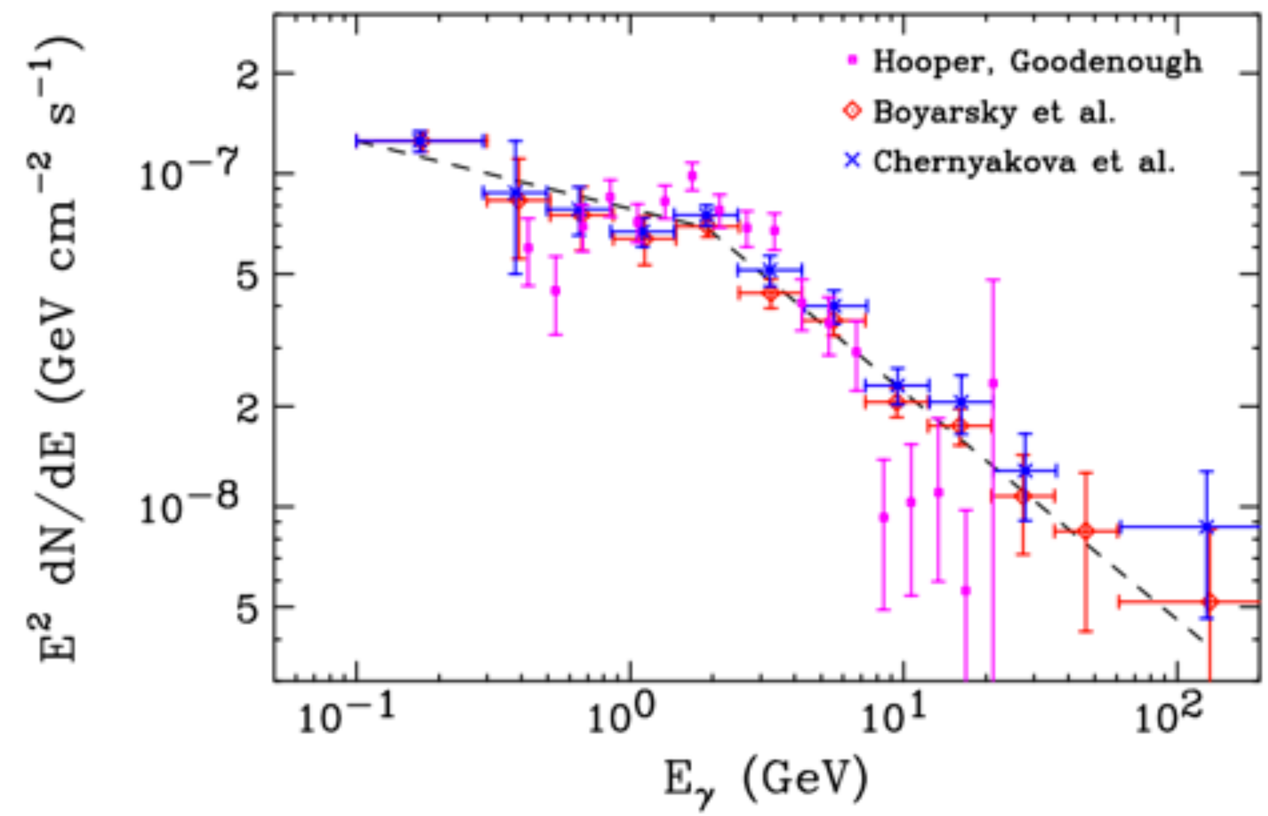


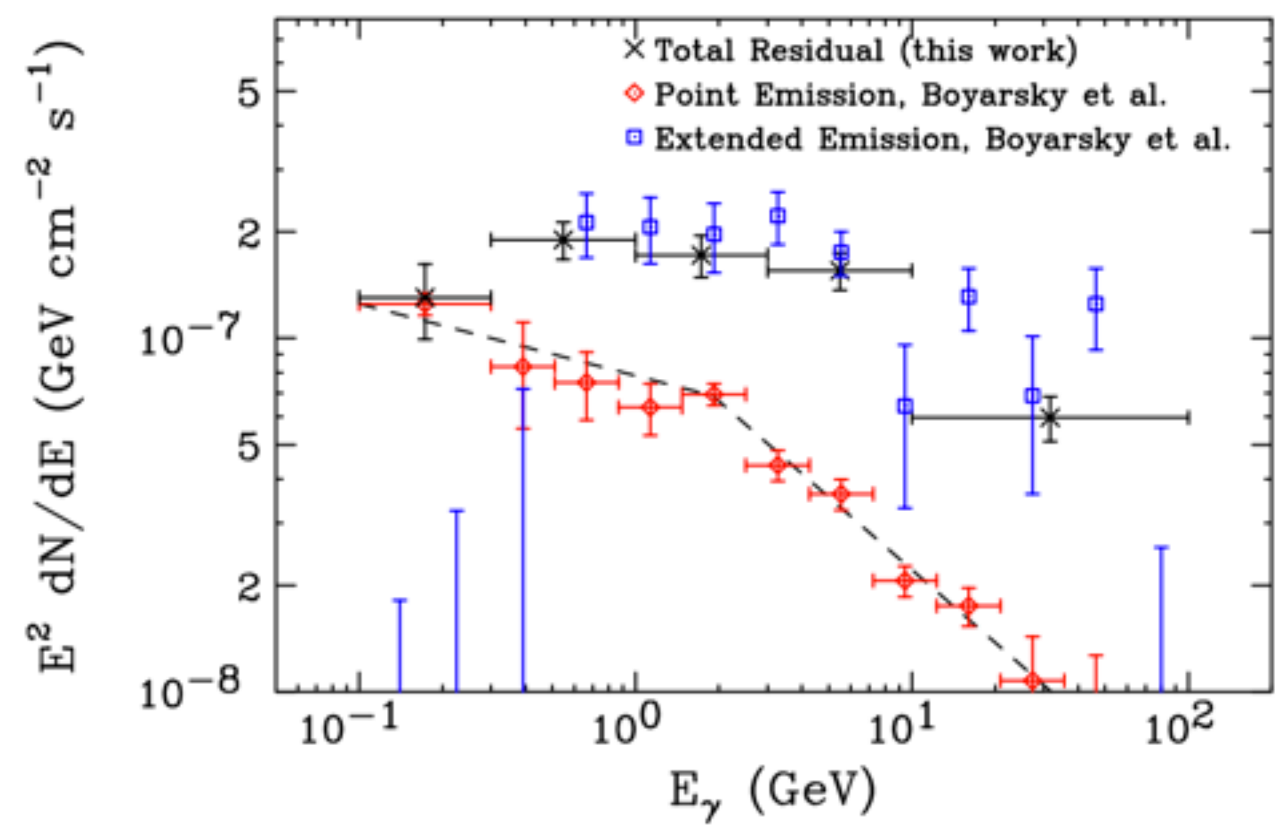
Ackermann et al. (2011)

Understanding the GC Point Source: Fermi

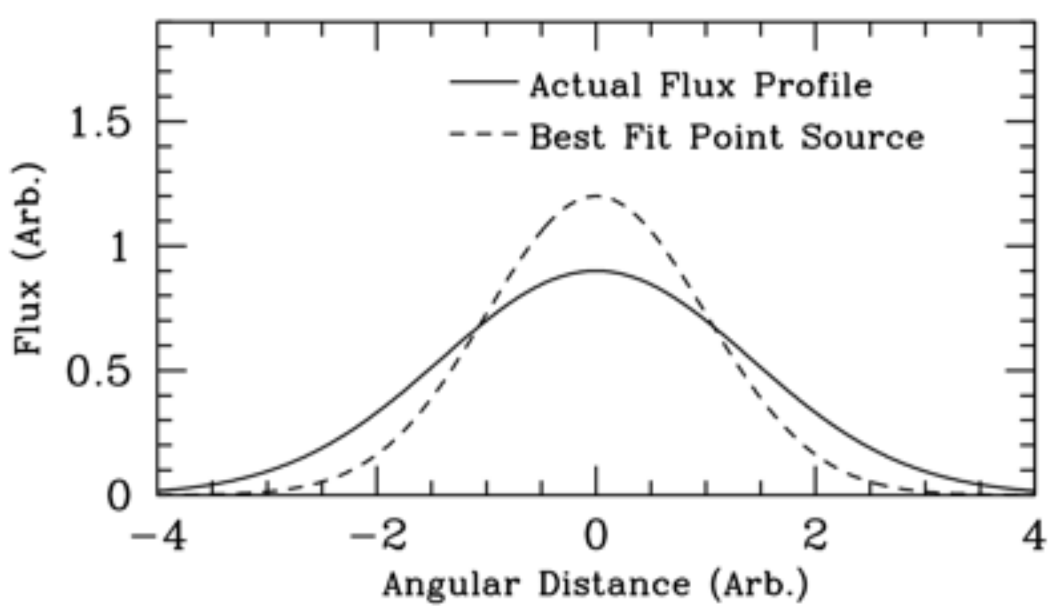
- Several efforts have been made to fit the GC point source, using both best-fitting point-source tools from the Fermi collaboration (Boyarsky et al. Chernyakova et. al), as well as independent software packages (Hooper & Goodenough)

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





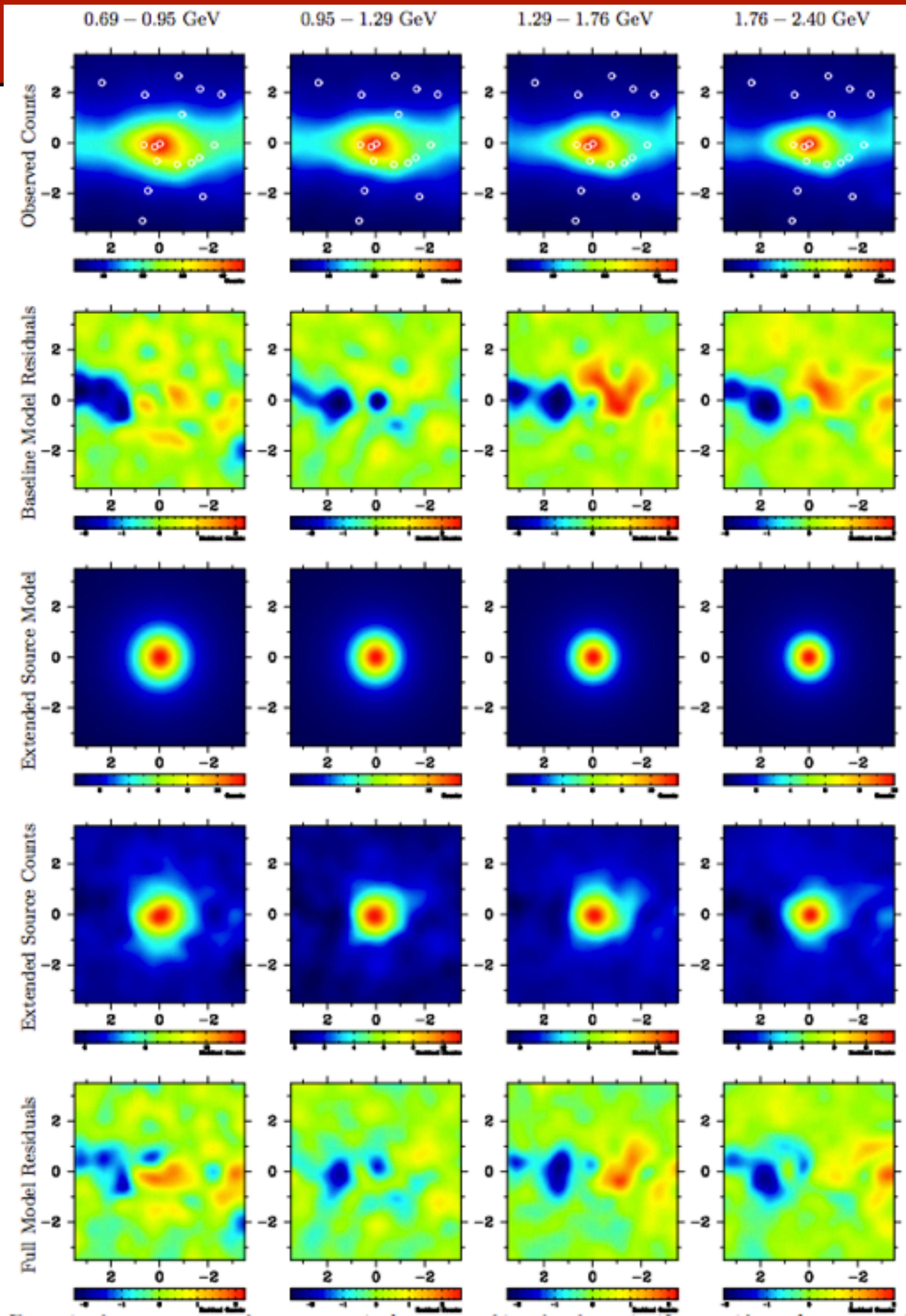
Hooper & Linden (2011)



Independent Confirmation!

- Abazajian & Kaplinghat employed a more sophisticated template-based regression analysis

- This also found an extremely significant improvement in the overall fit with the addition of a spherical profile with similar characteristics to that of Hooper & Goodenough and Hooper & Linden



Abazajian & Kaplinghat (2012)

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Spatial Model	Spectrum	TS	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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

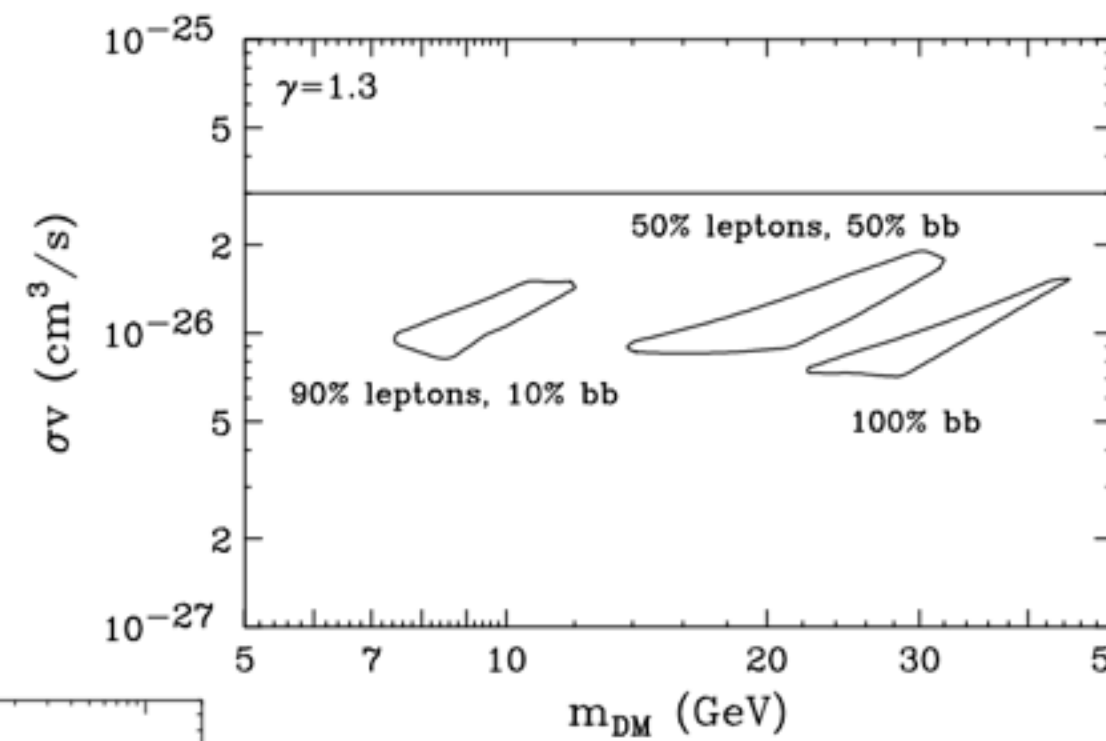
TABLE II. The best-fit TS, negative log likelihoods, and $\Delta\mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

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

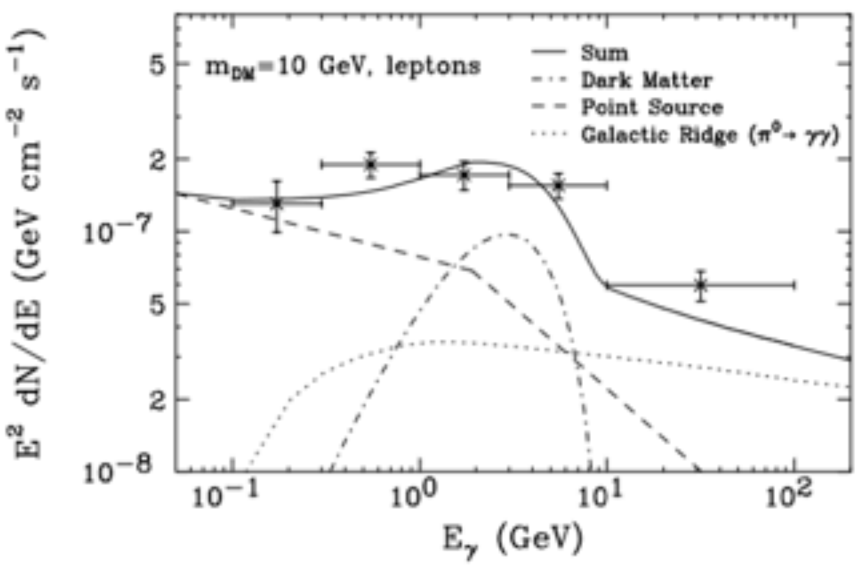
Abazajian & Kaplinghat (2012)

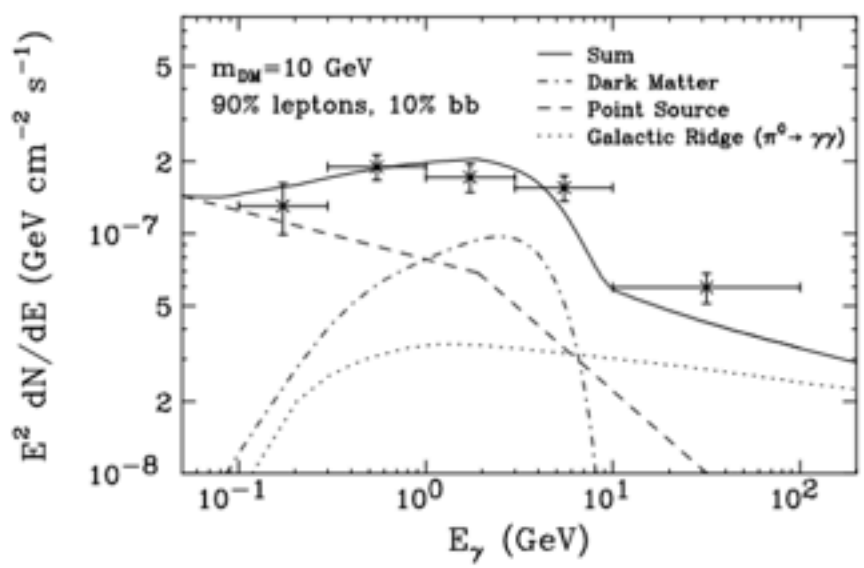
Best fitting Models for Low-Mass Dark Matter

- For a best fitting profile γ = 1.3, we find an available parameter space for dark matter models which match the observed GC excess

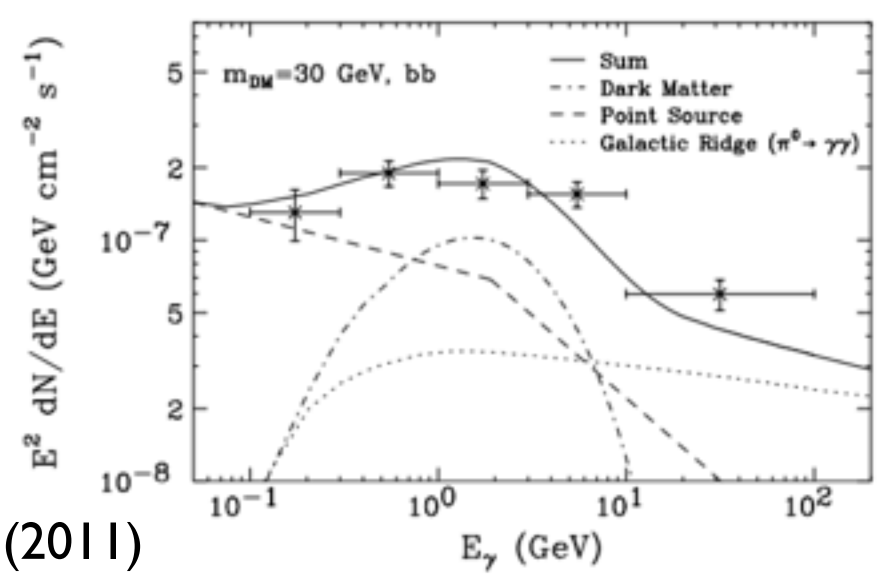


- These models are compatible with estimates for the relic density of dark matter





- The models combine with best fitting astrophysical backgrounds such as the GC point source and the galactic ridge, to fit the total GC excess



Hooper & Linden (2011)

Best fitting Models for Low-Mass Dark Matter

- Abazajian & Kaplinghat find a wider range of dark matter masses which provide improved fits to the data

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
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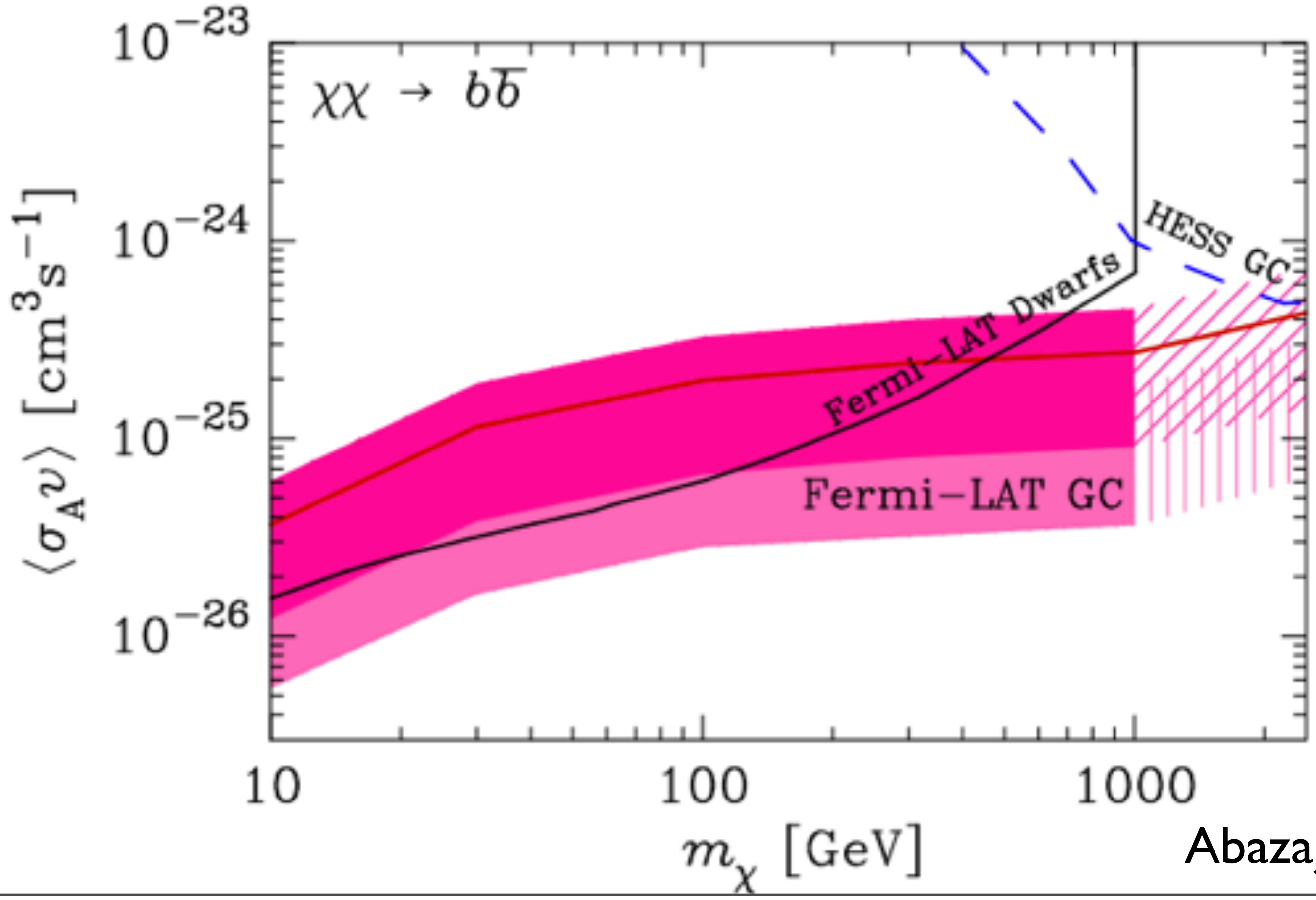
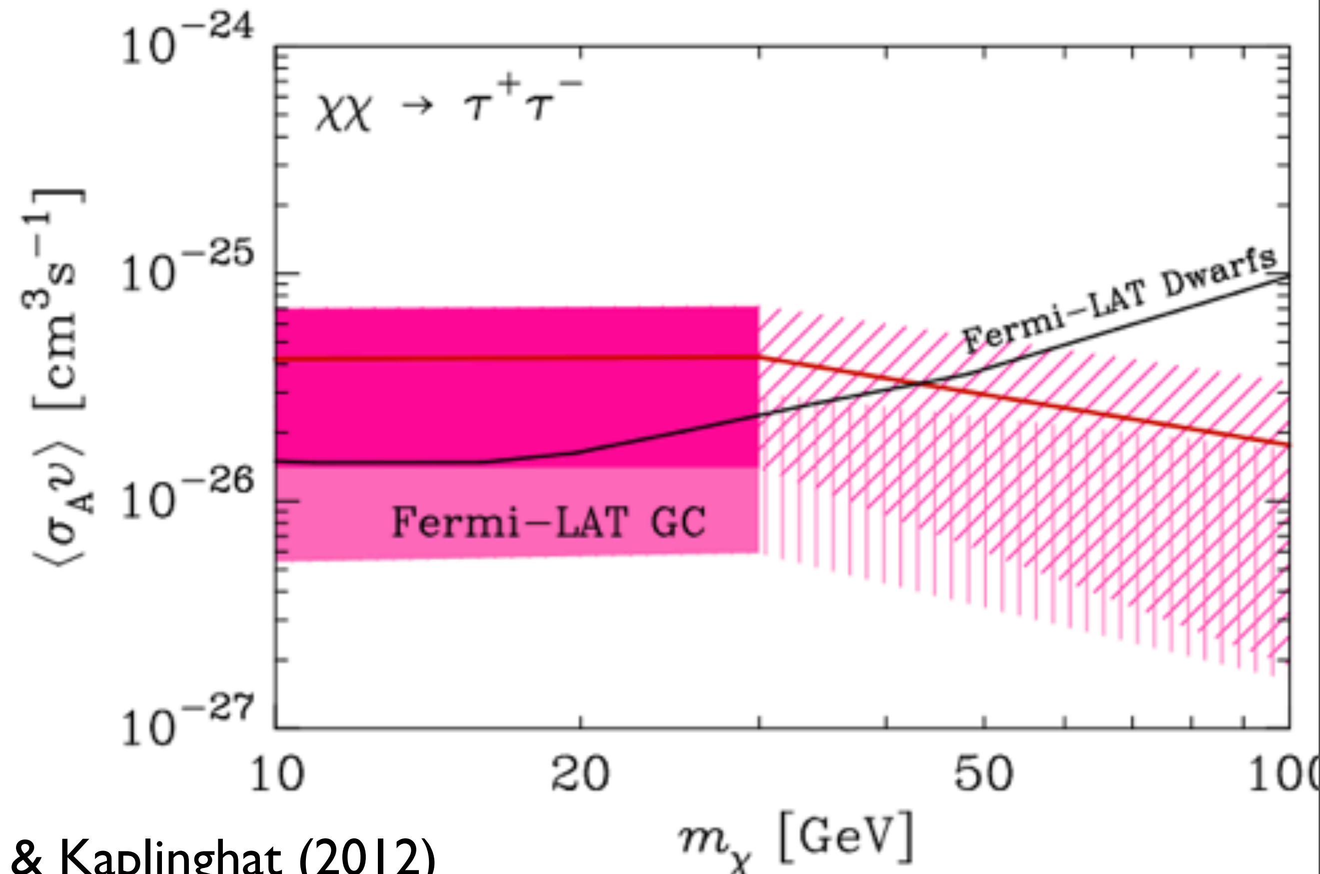
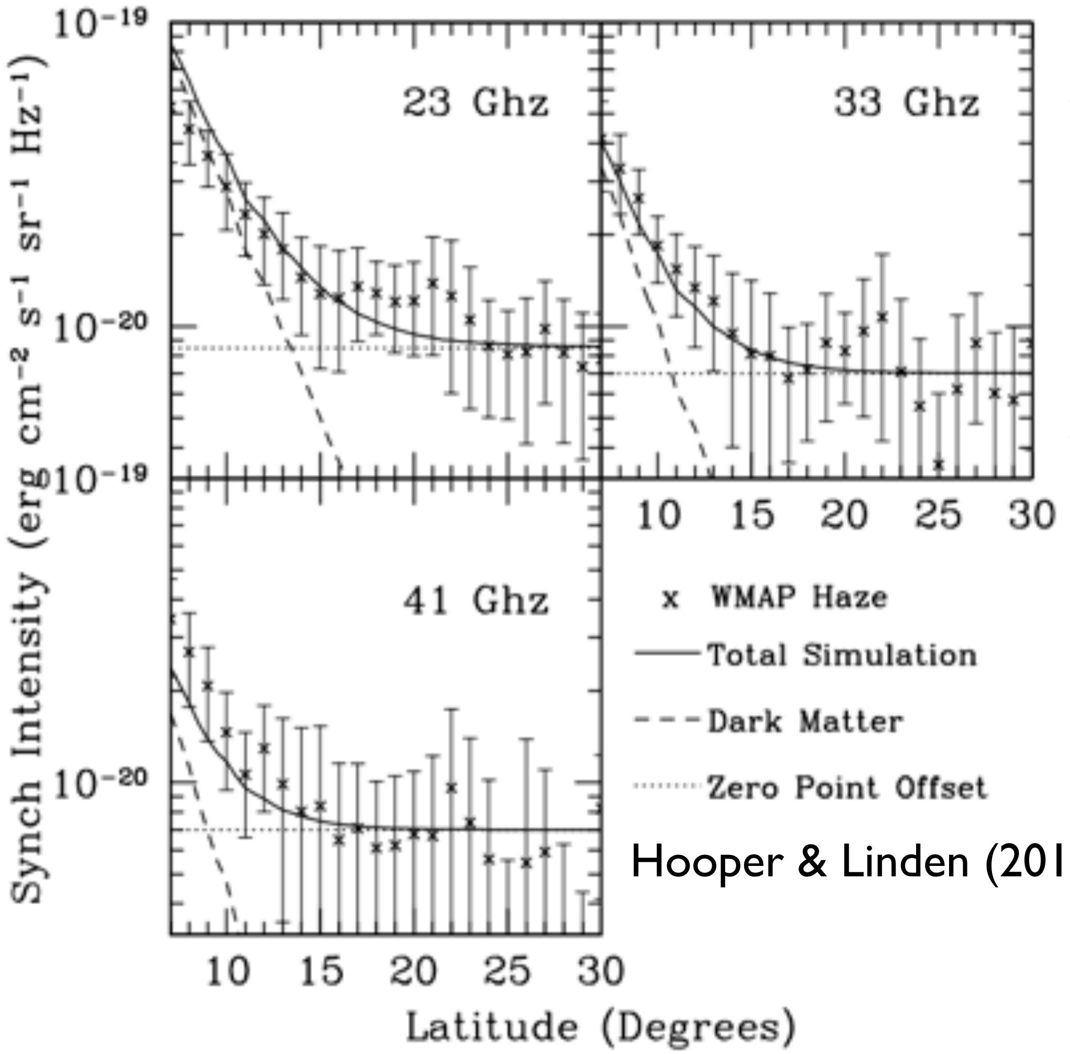




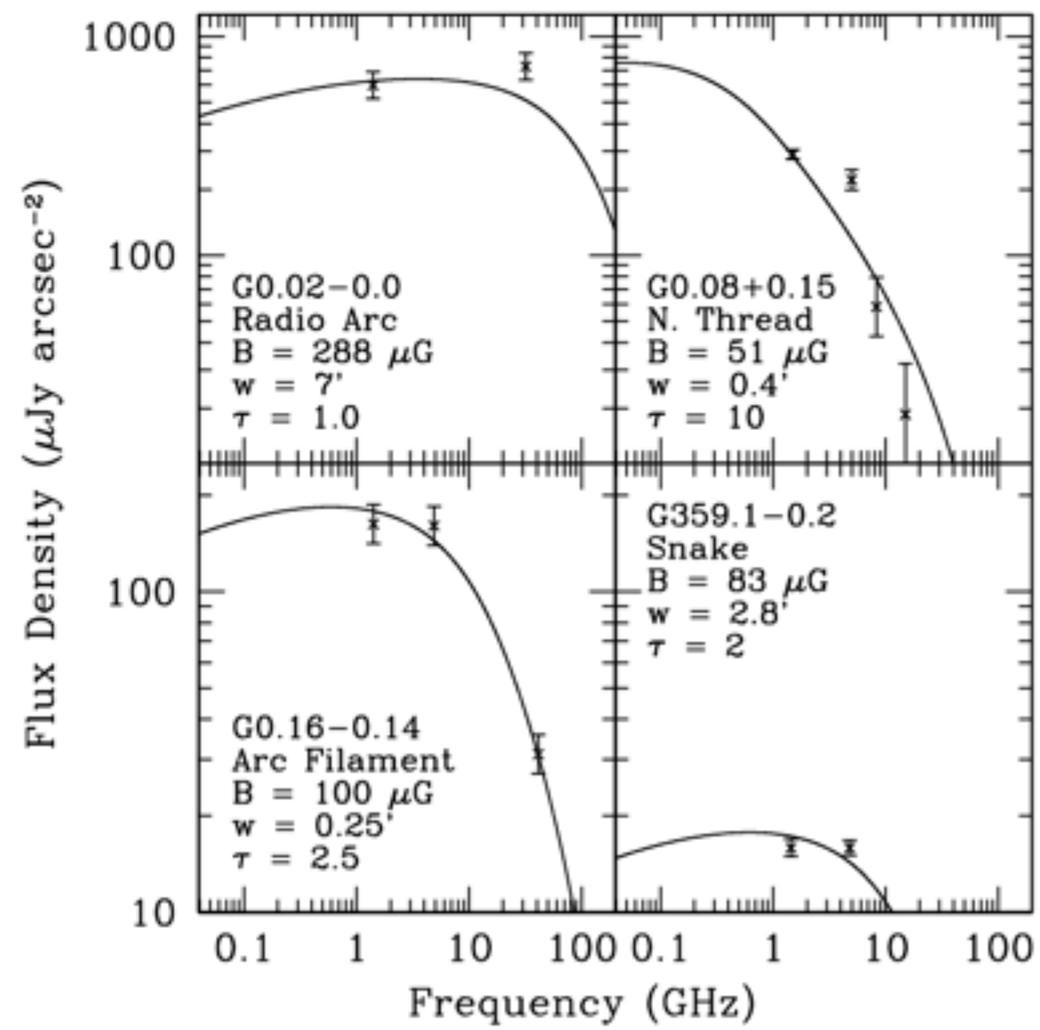
Abazajian & Kaplinghat (2012)

Other Observations Fitting Light DM: Indirect



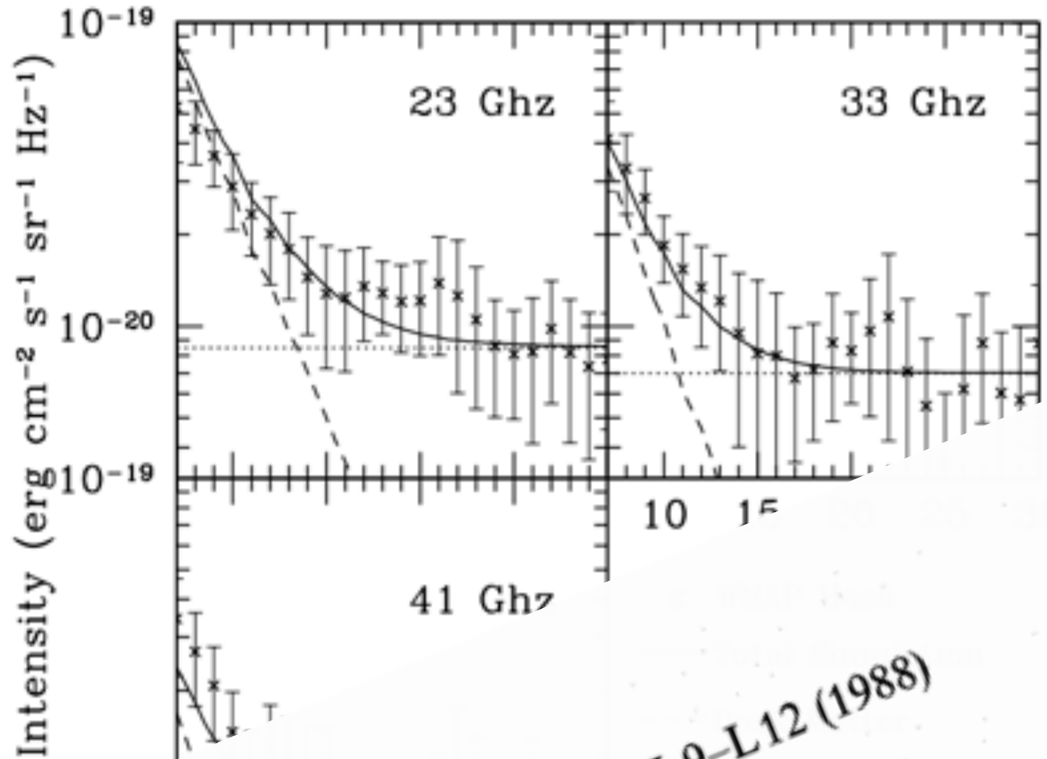
Hooper & Linden (2011)

- The same dark matter model provides a reasonable explanation to the intensity and morphology of the WMAP haze
- The magnetic field must be slightly stronger above the galactic plane than usually assumed
- The same dark matter model also provides a fit to the spectrum and intensity of the filamentary arcs
- Light DM annihilation naturally provides the near delta-function electron spectrum necessary to explain the synchrotron spectrum of the filaments



Linden et al. (2011)

Other Observations Fitting Light DM: Indirect



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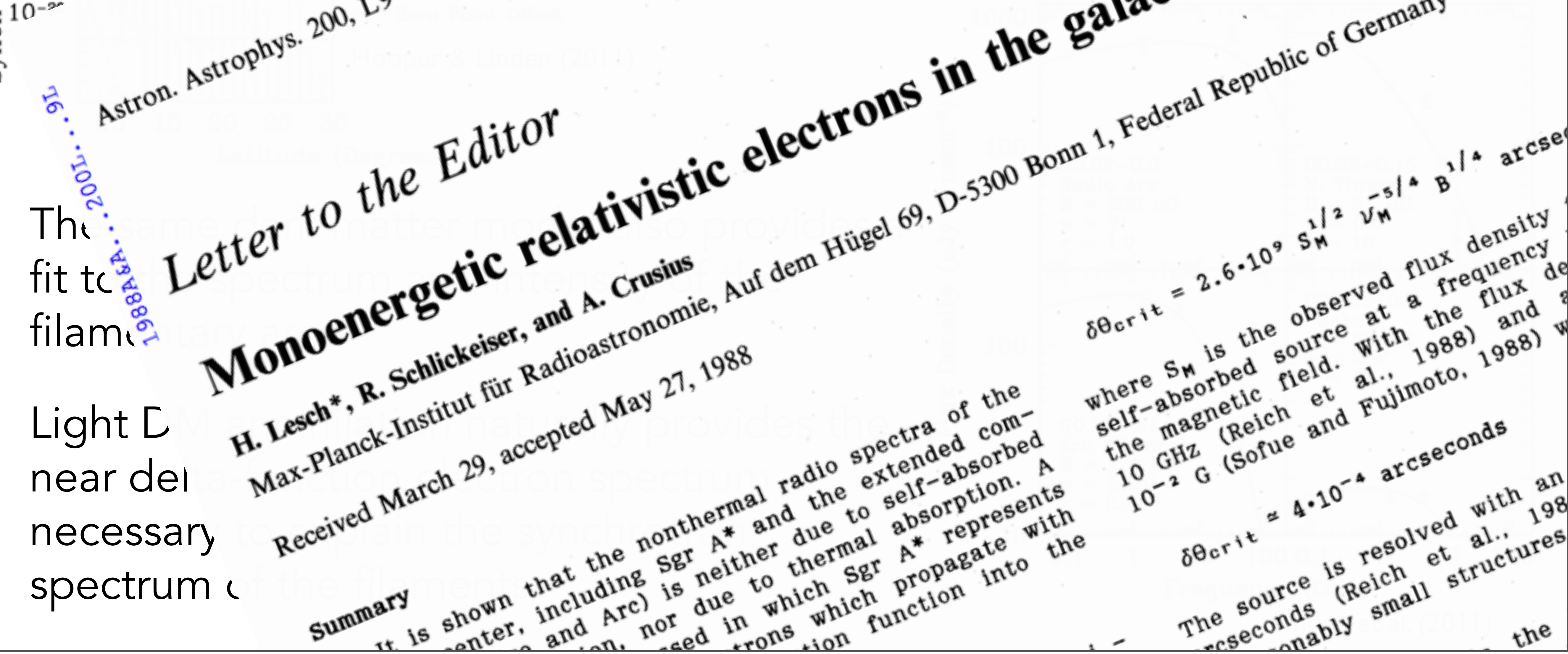

ASTRONOMY AND ASTROPHYSICS

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

Astron. Astrophys. 200, L9–L12 (1988)

Letter to the Editor

Monoenergetic relativistic electrons in the galactic center

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

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Received March 29, accepted May 27, 1988

Summary

It is shown that the nonthermal radio spectra of the ... center, including Sgr A* and the extended com- ... and Arc) is neither due to self-absorbed ... on, nor due to thermal absorption. A ... sed in which Sgr A* represents ... trons which propagate with ... tion function into the

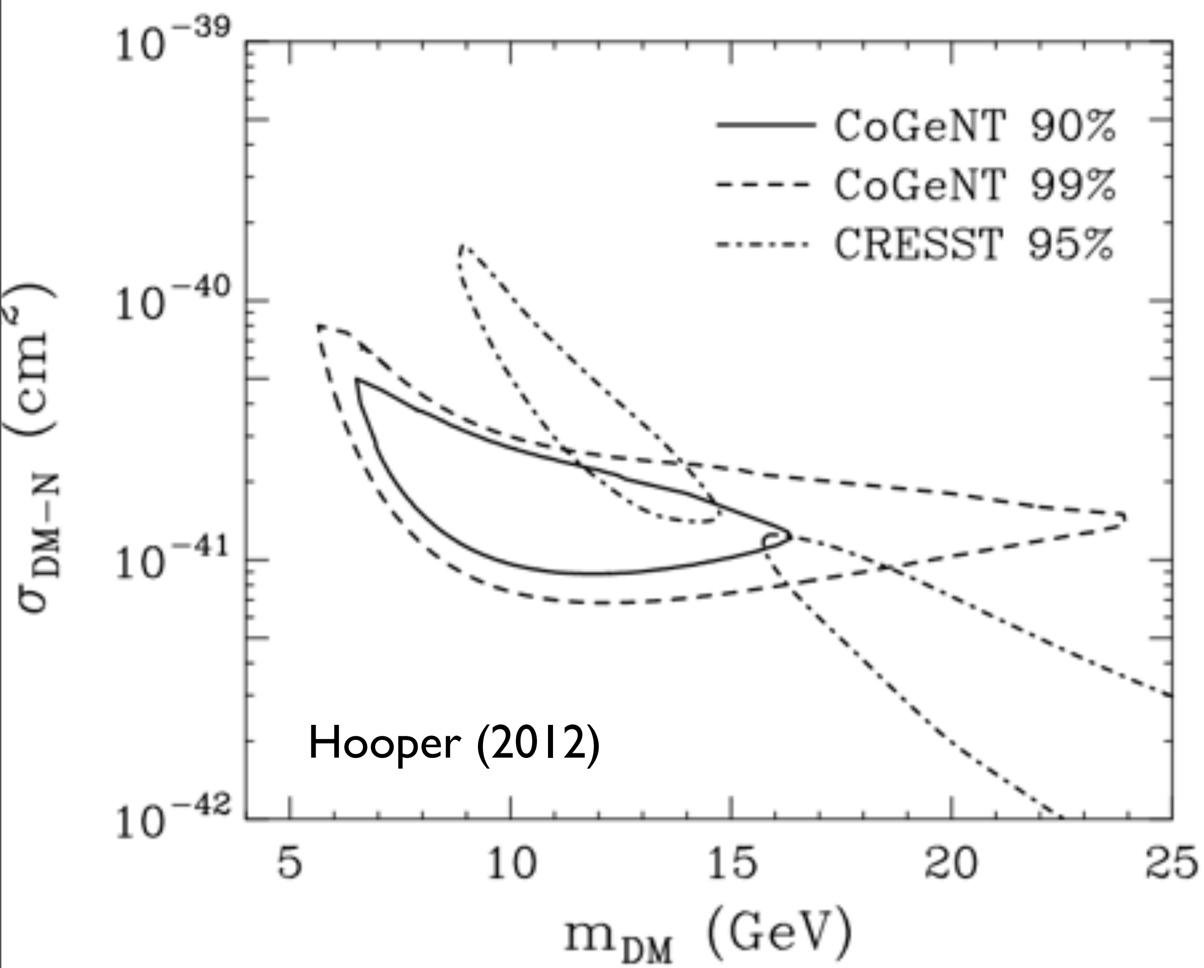
$\delta\theta_{crit} = 2.6 \cdot 10^9\, S_M^{1/2}\, \nu_M^{-5/4}\, B^{1/4}$ arcse...

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

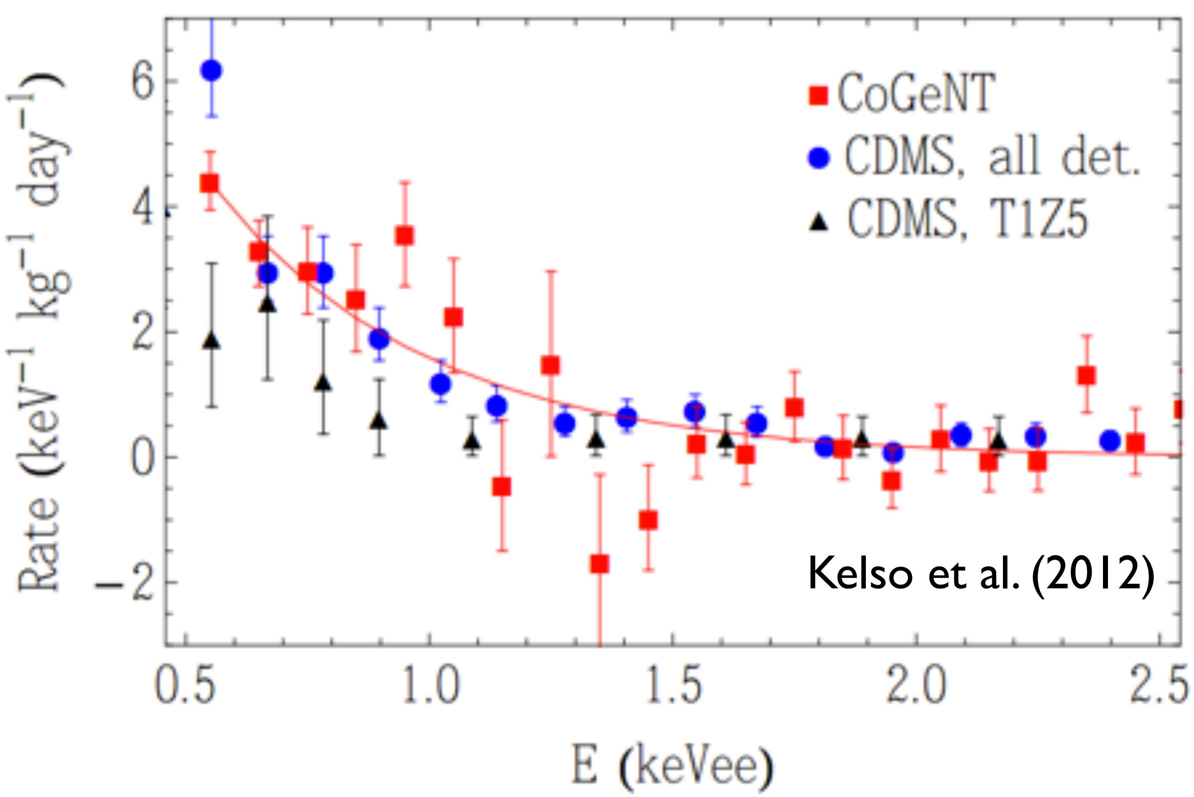
$\delta\theta_{crit} \simeq 4 \cdot 10^{-4}$ arcseconds

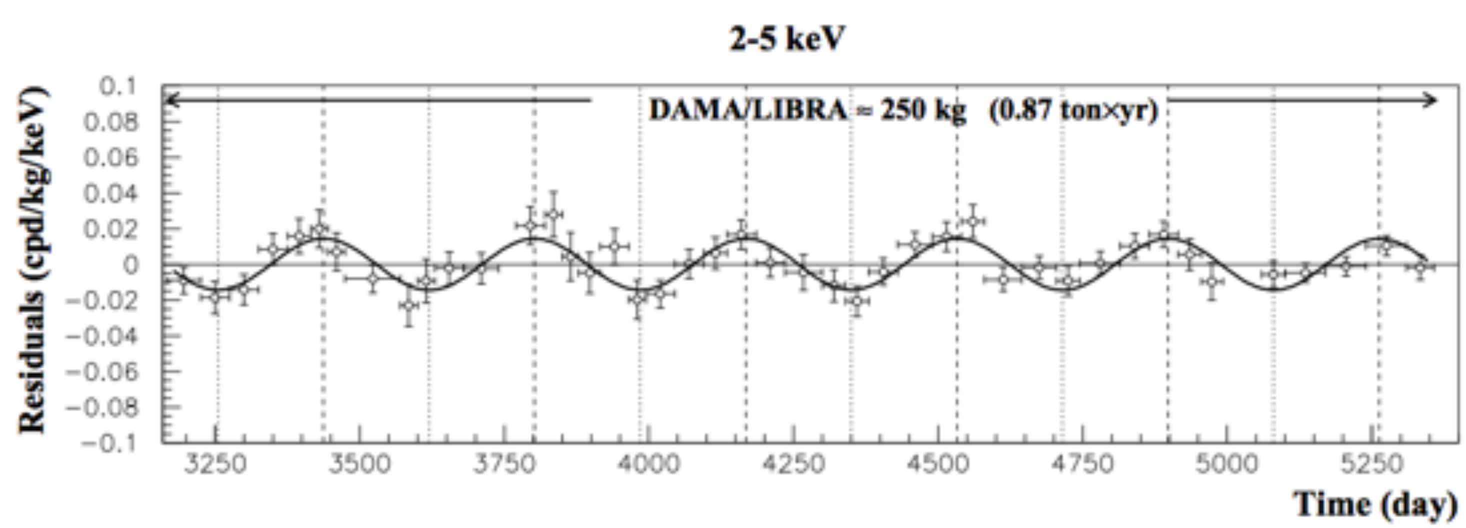
The source is resolved with an ... arcseconds (Reich et al., 198... ...onably small structures ... the

Other Observations Fitting Light DM: Direct



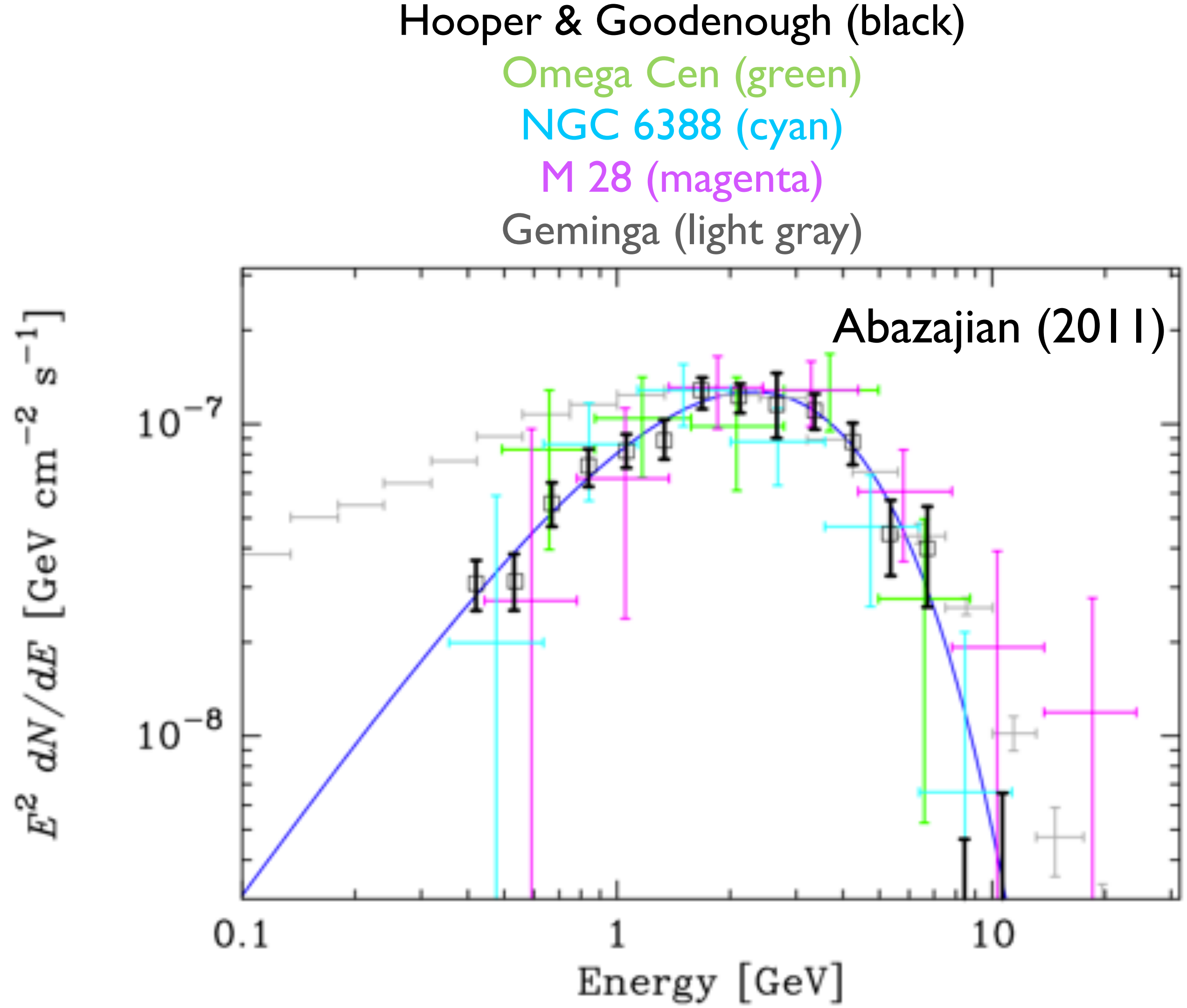
- Light Dark Matter (~10 GeV) provides a compelling fit to the excesses currently observed by DAMA, CoGeNT and CRESST
- Light Dark Matter may also be compatible with observed signal/limits at CDMS
- However, a recent error found in CoGeNT analysis may affect some early dark matter interpretations

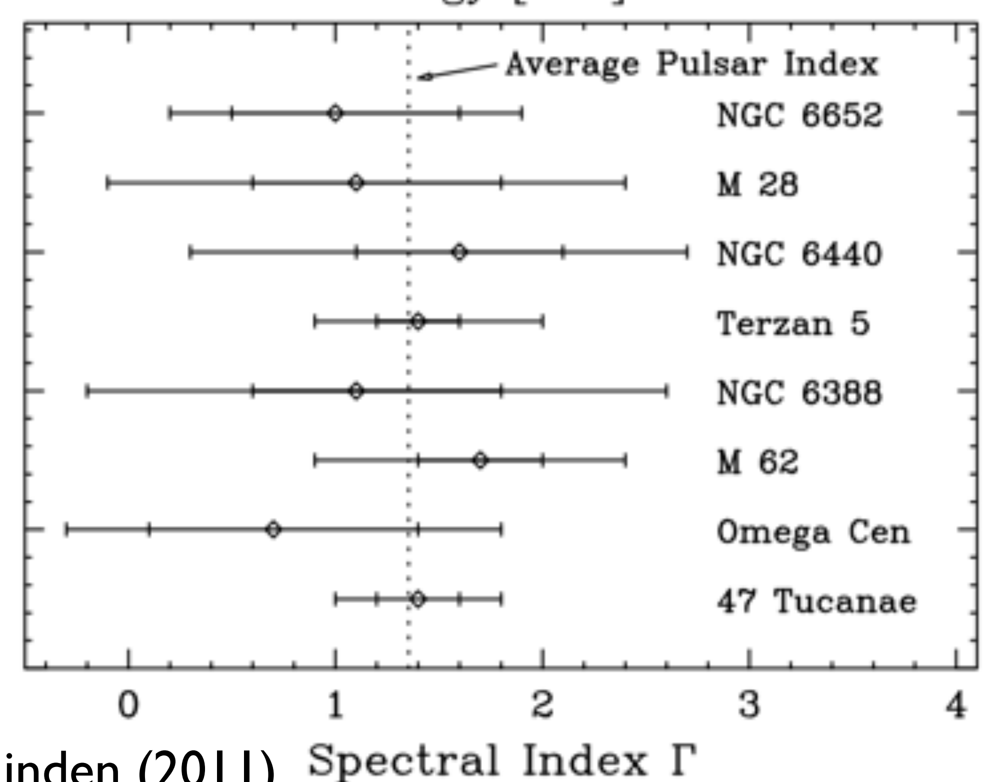




An Alternative Explanation: Milli-second Pulsars

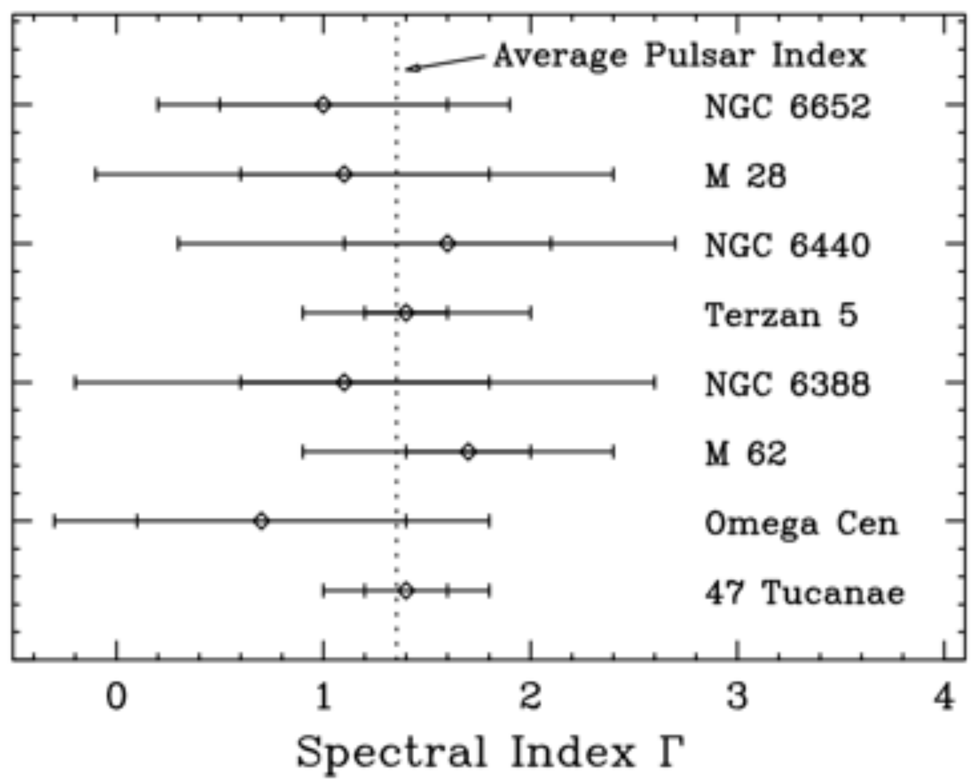
- Populations of Millisecond pulsars have been observed in multiple globular clusters (Terzan 5, Omega Cen, NGC 6388, M 28)
- Hooper & Goodenough source is ~200 brighter than Omega Cen - which correlates nicely with the 1000x larger mass of the GC region
- Spectrum of MSP population is very similar to the observed gamma-ray excess

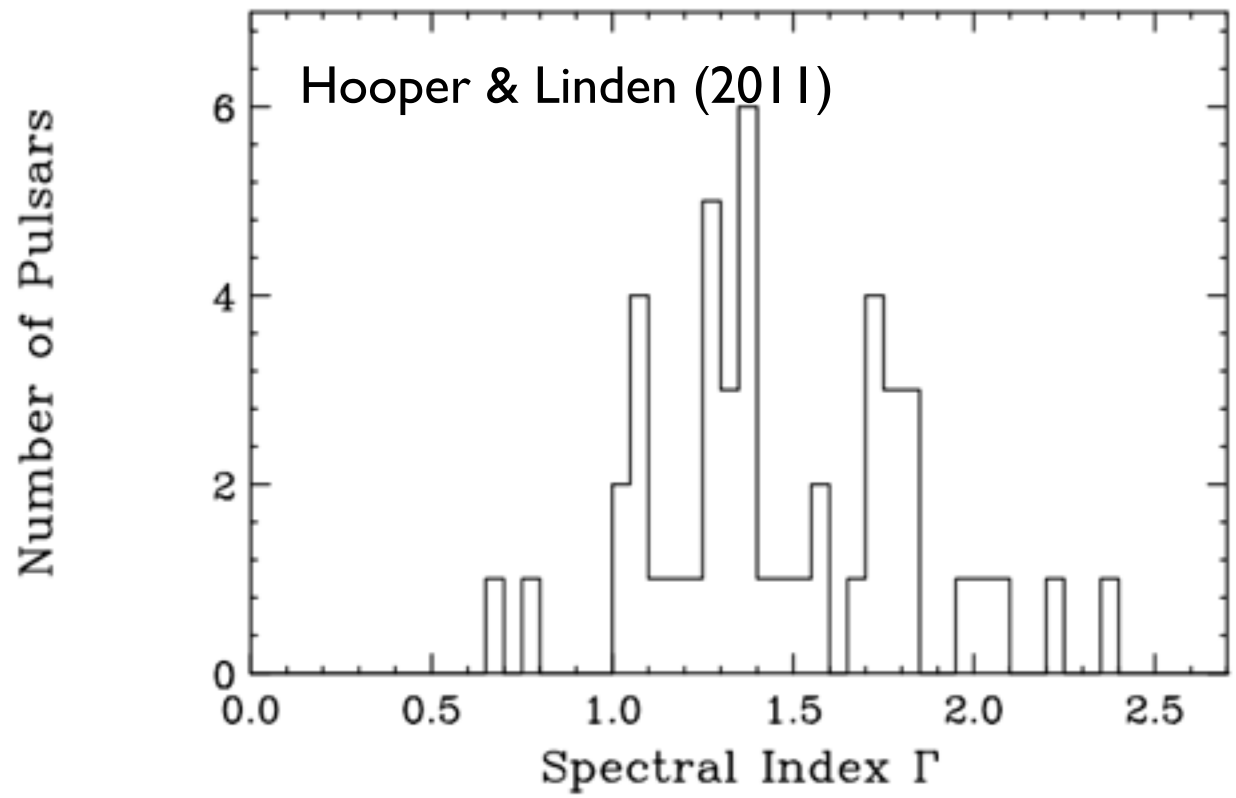




Hooper & Linden (2011)

An Alternative Explanation: Milli-second Pulsars



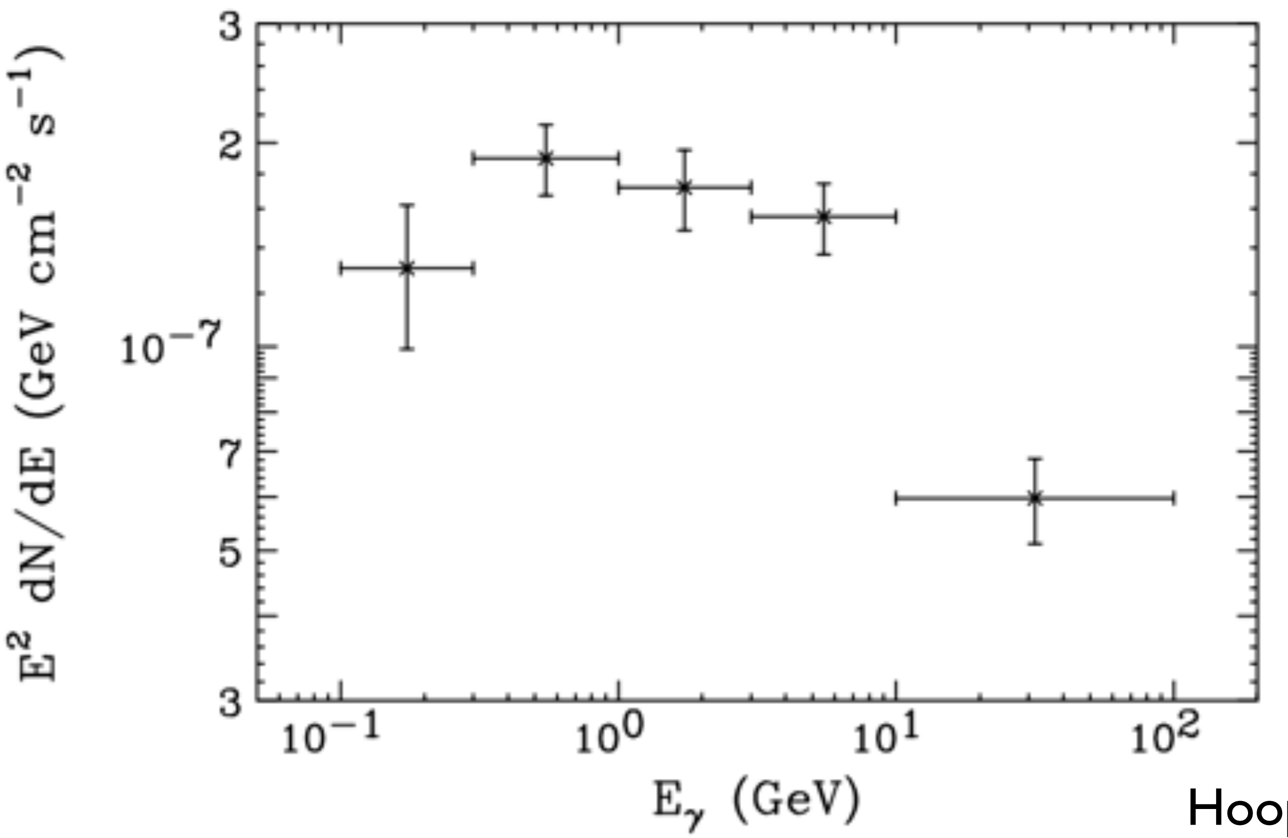


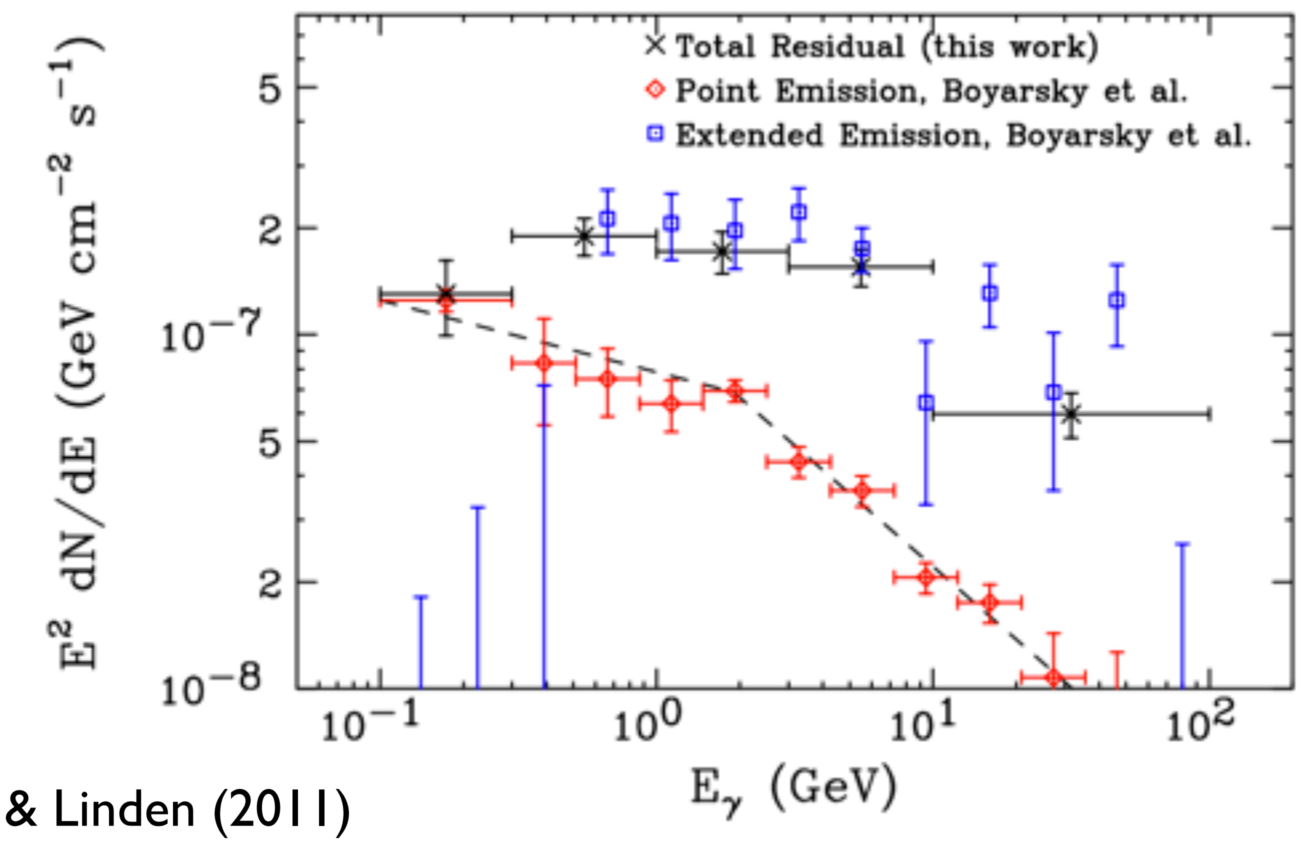
- However the hardness of the Galactic Center spectrum ($\Gamma <\approx 1.0$) is difficult to explain with the spectra of the class of observed Fermi-LAT pulsars

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

Note: Models of light dark matter and millisecond pulsars seek only to explain the bump in the Fermi GeV spectrum.

In both cases, another mechanism (such as proton emission from the galactic center) must be responsible for the TeV emission





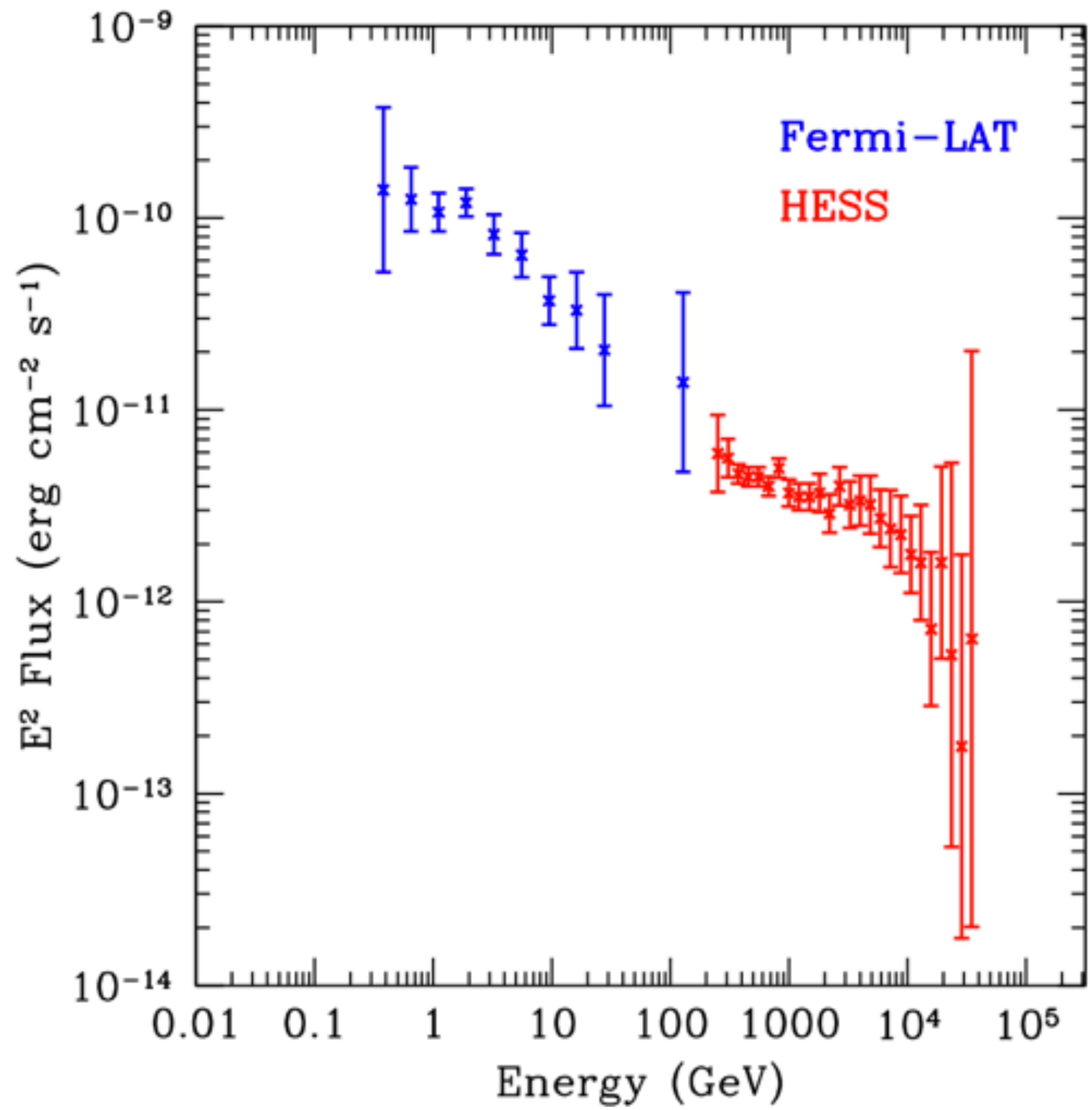
Hooper & Linden (2011)

A Combined Hadronic Scenario

- The HESS spectrum is well fit by the Fermi acceleration of protons and their subsequent interaction with galactic gas

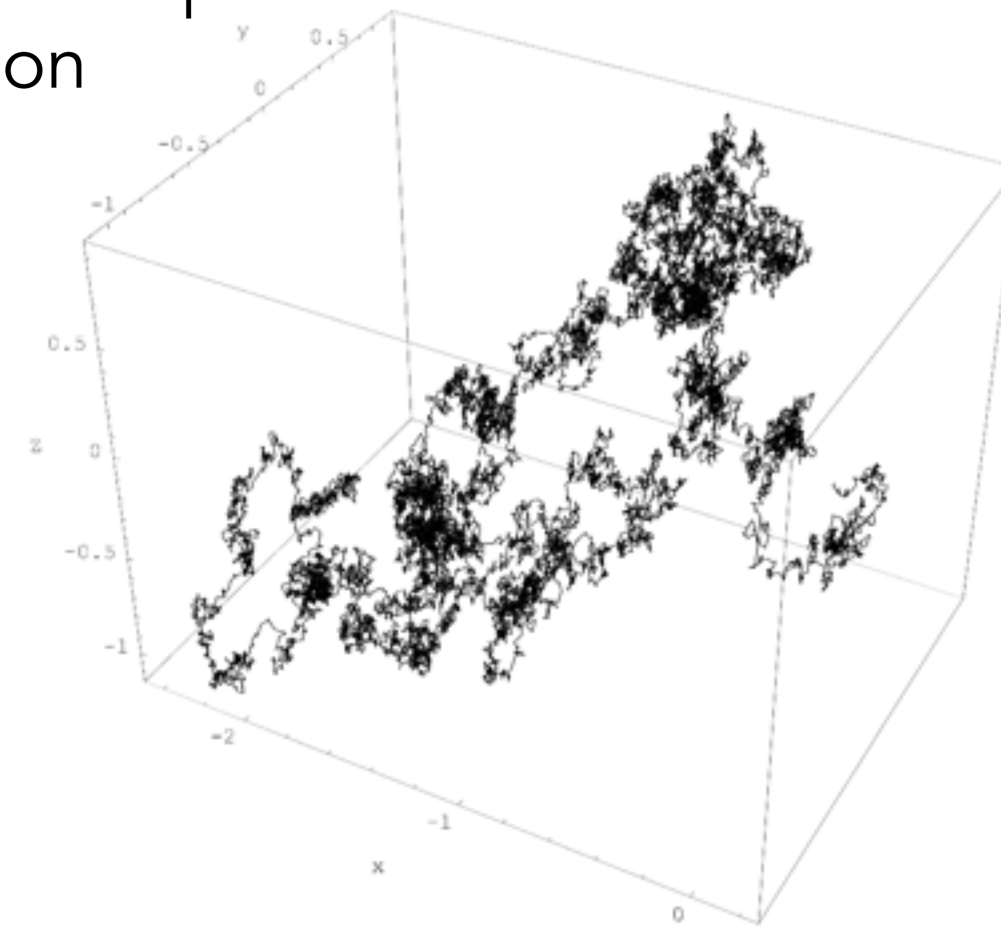
- Can the combined Fermi + HESS spectrum be described in the same way?

- **Problem:** The spectrum at GeV energies is significantly softer than at TeV energies - some modification is needed to control this transition

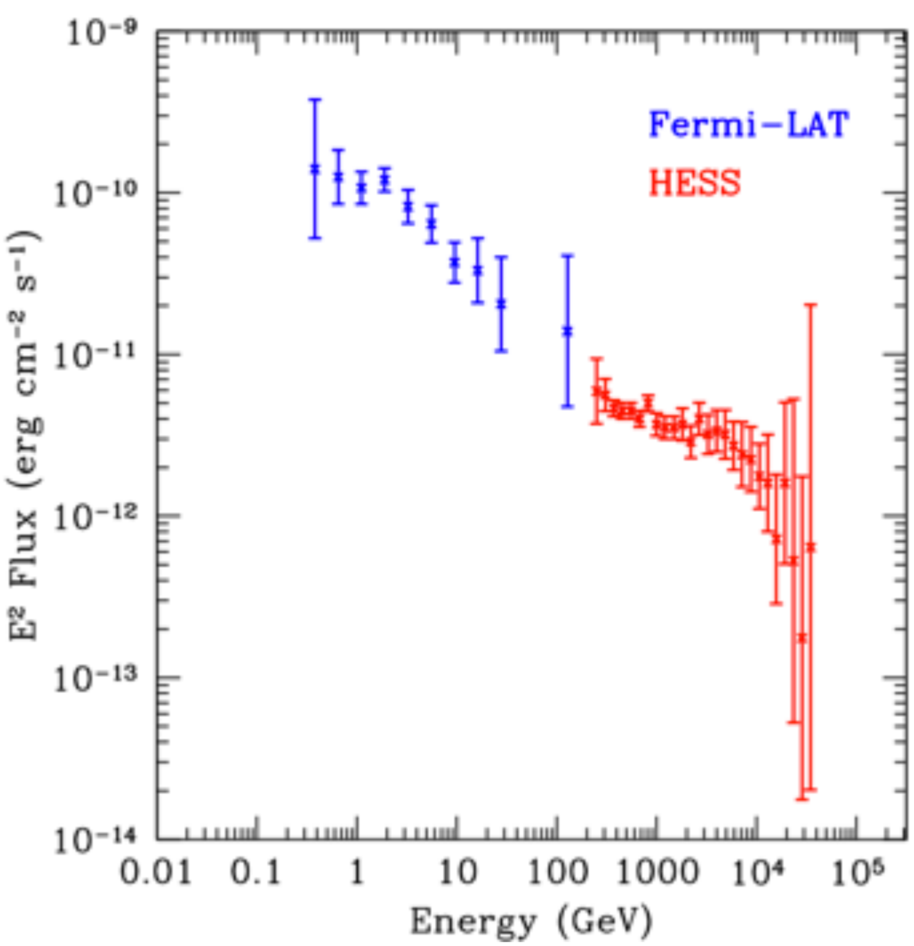


Controlling the Emission Spectrum with Diffusion

- We can imagine two scenarios for cosmic-ray transport from the central black hole: rectilinear or diffusive transportation



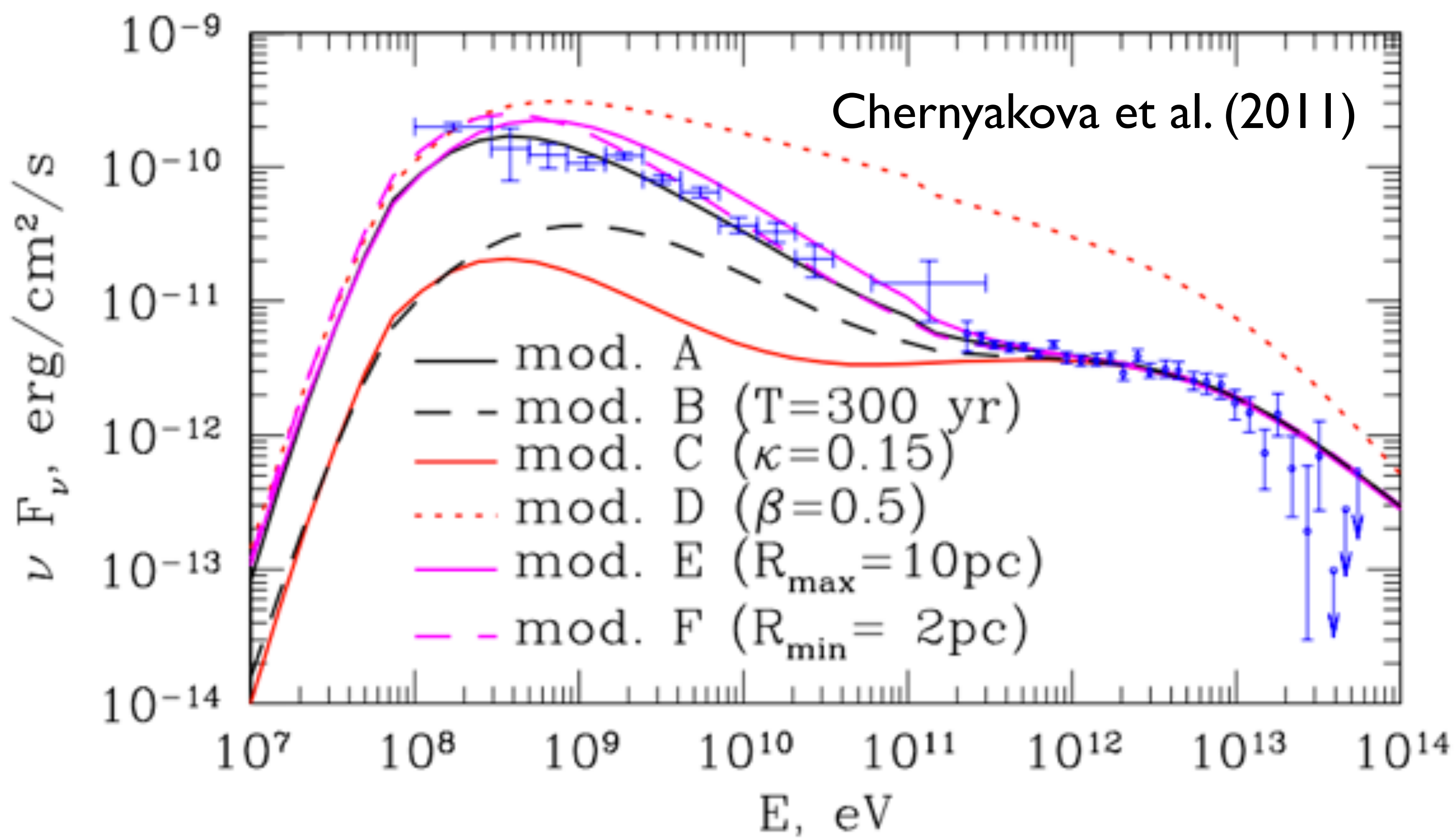
- In the regime where the diffusion stepsize exceeds the diffusion region, the emission intensity is energy independent, and an E^{-2} proton injection spectrum corresponds directly to an E^{-2} gamma-ray spectrum



- In the regime where the diffusion step is small, then the emission intensity depends linearly on the time the particle spends within the diffusion region

Hadronic Emission Models for Fermi and HESS

- By setting allowing the diffusion constant to float to a set of best fit values - a single hadronic emission model can fit the entirety of the Fermi/ HESS data



- Several model parameters can also be adjusted, such as the duration of particle injection, the occurrence of recent flares, the maximum radius for diffusion etc.

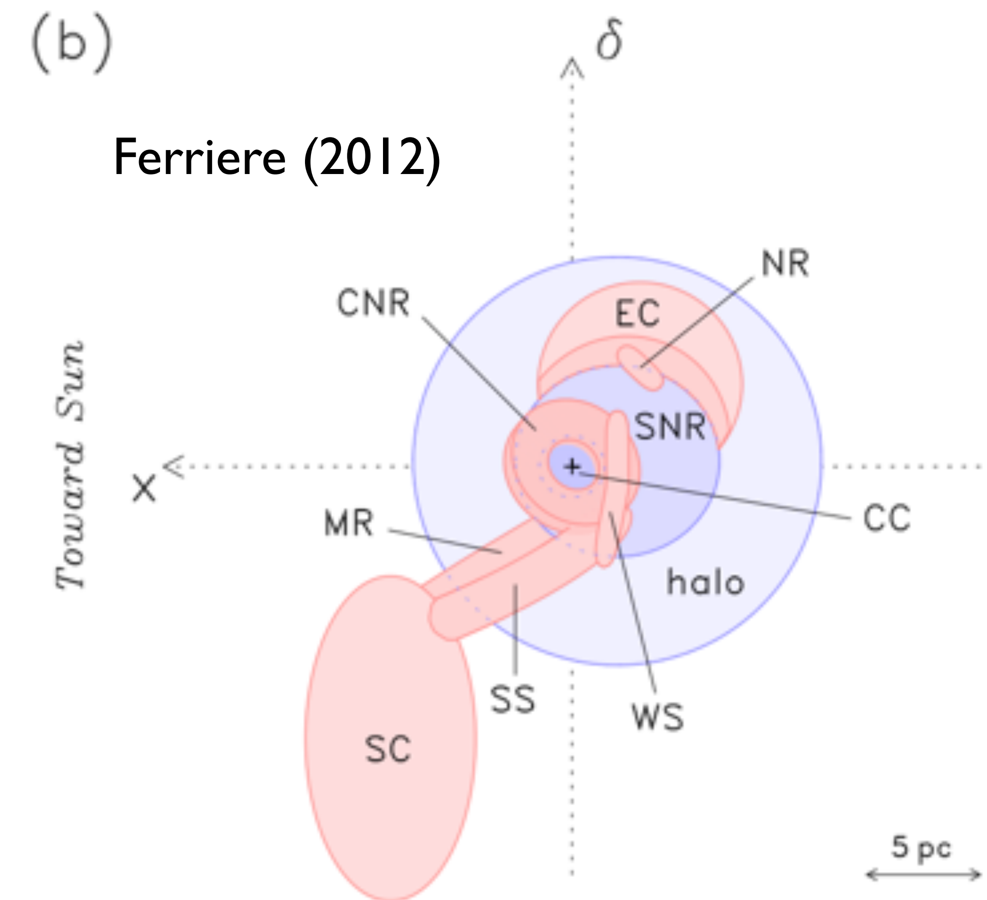
- Models are formed with a step-function gas density profile (1000 n_H/cm^{-3} within 3 pc of the galactic center, and 0 n_H/cm^{-3} outside)

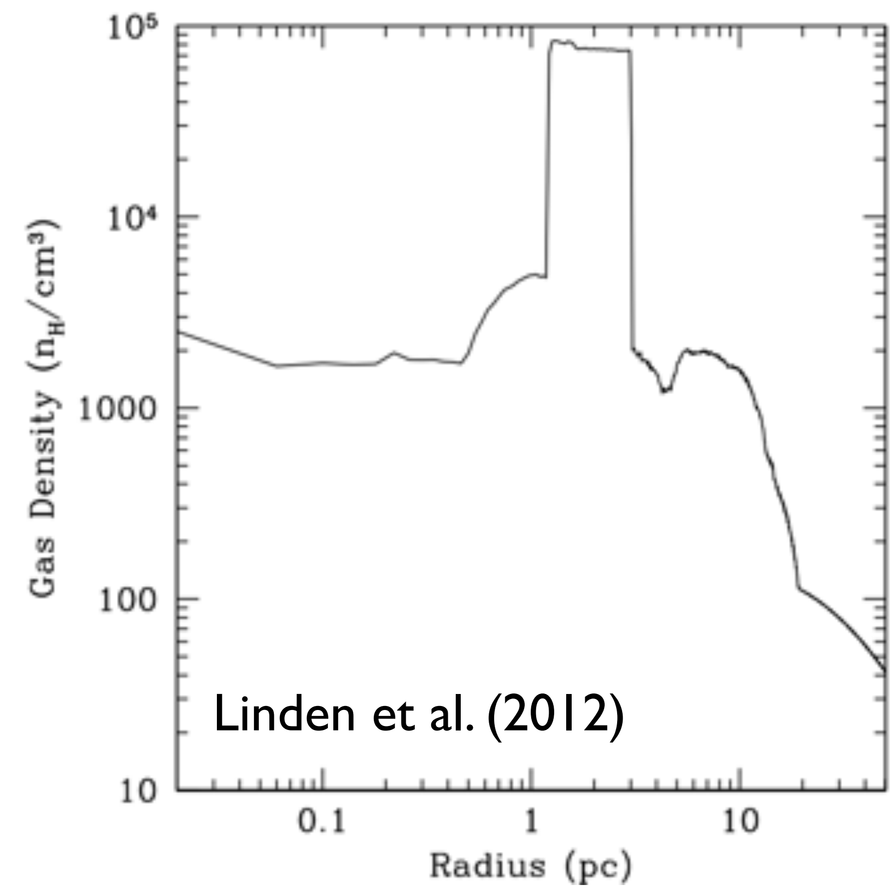
Employing a Realistic Gas Model

- 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

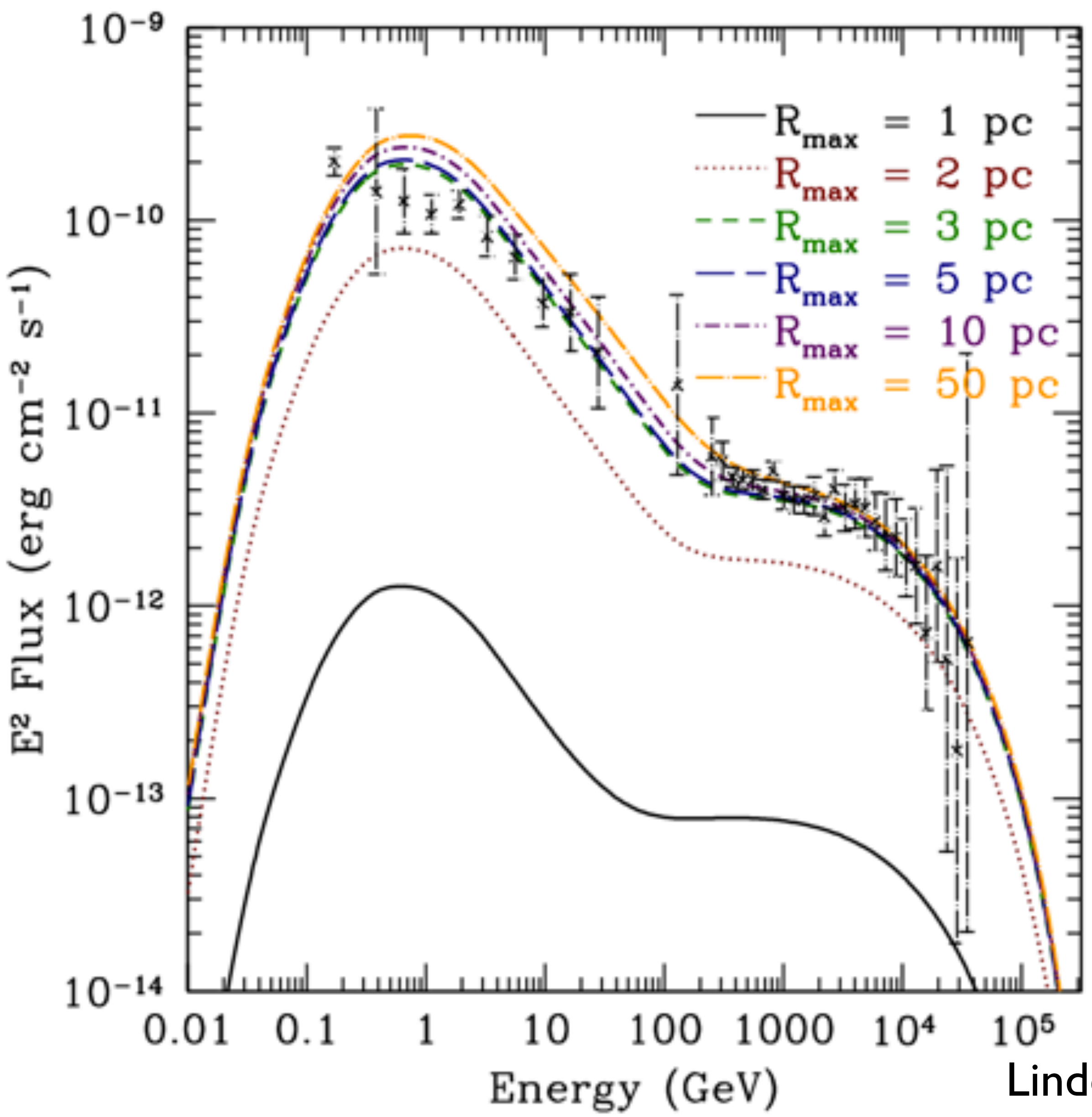
- By far the dominant feature is the Circumnuclear ring between 1-3 pc from the GC

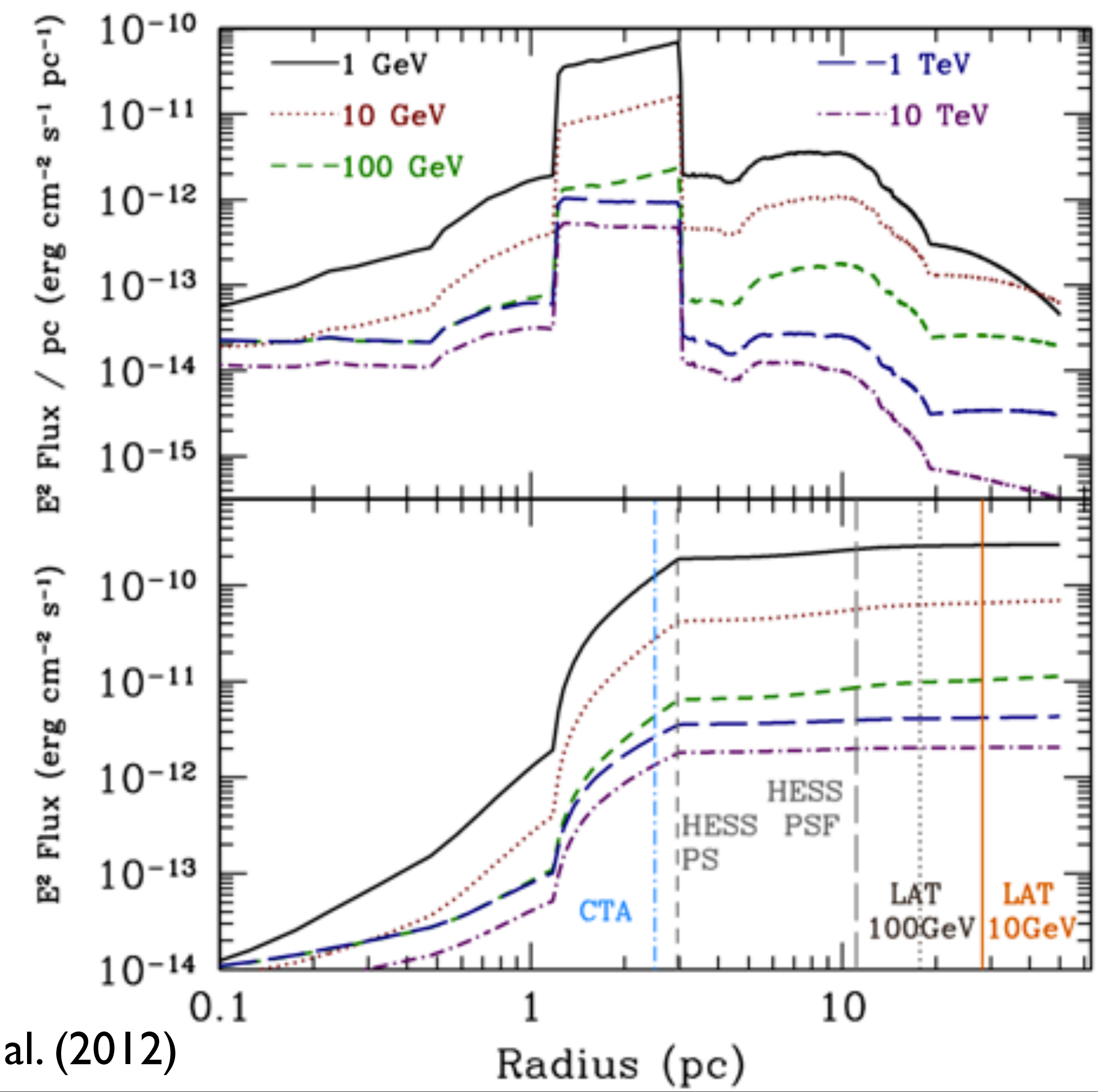




Employing a Realistic Gas Model

- 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

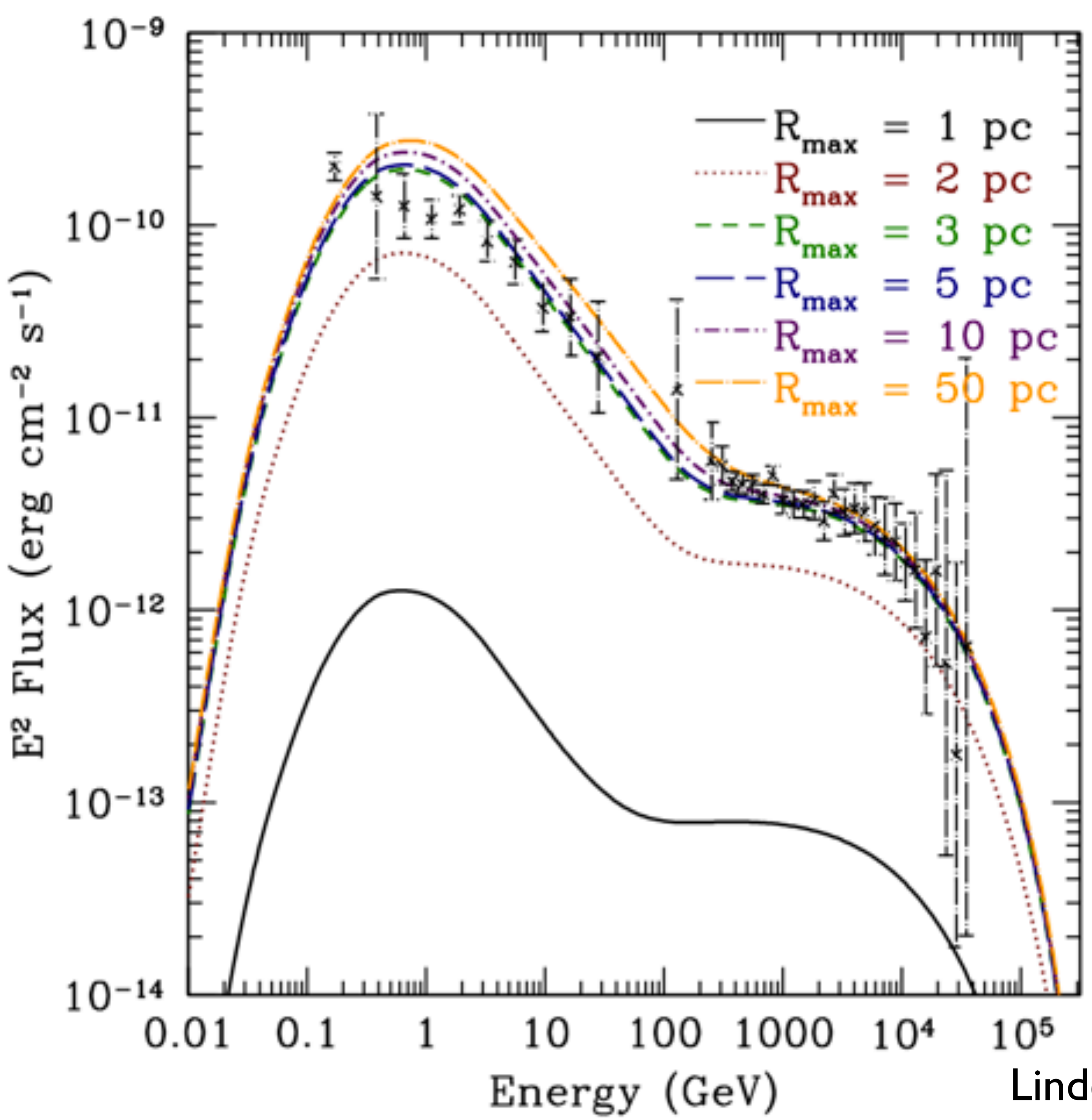




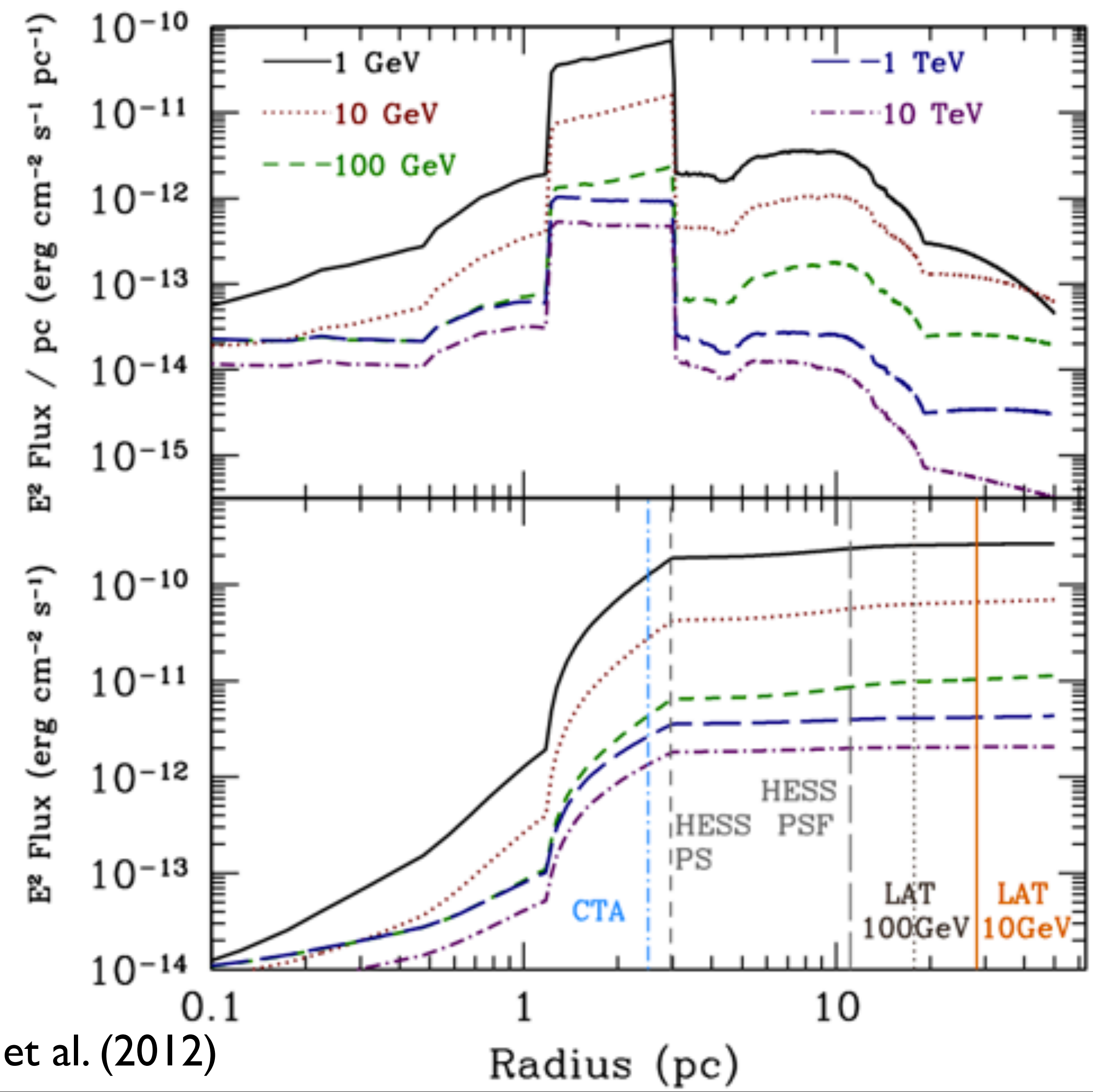
Linden et al. (2012)

Employing a Realistic Gas Model

But CTA may be able to probe this emission profile directly!



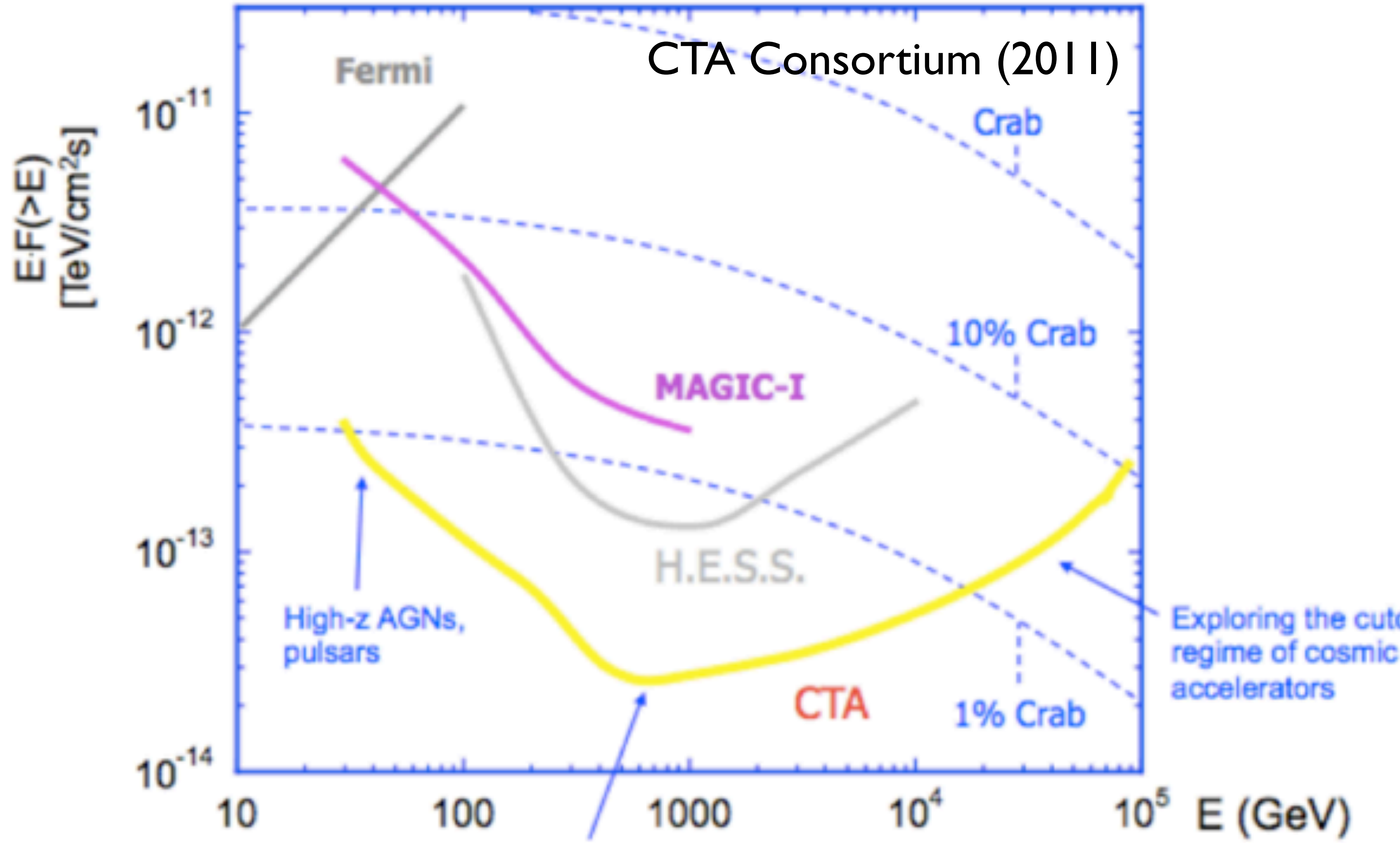
Linden et al. (2012)

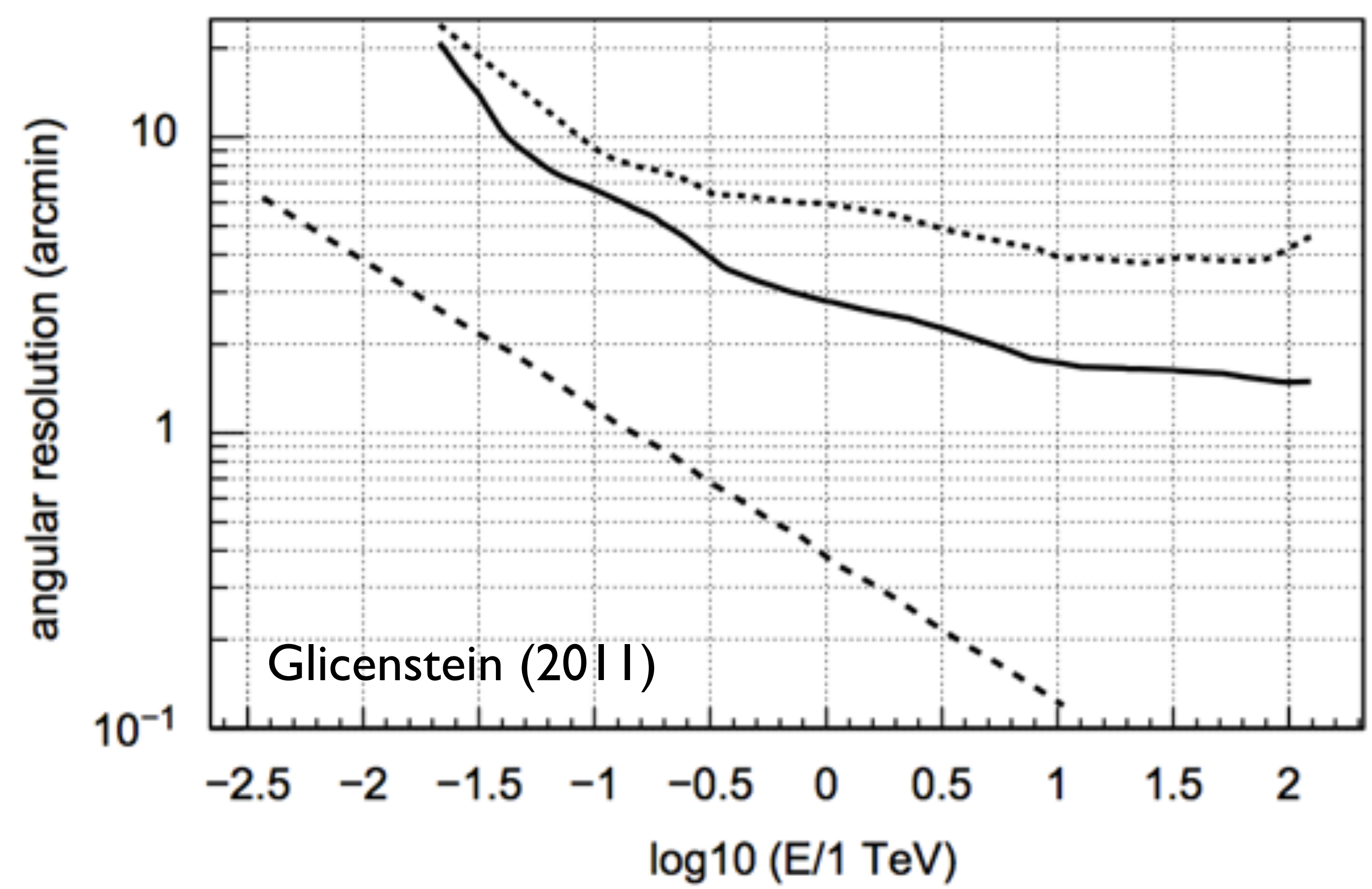


CTA and the Galactic Center

- However, CTA may be able to distinguish between these models:

- The instrument specifications for CTA are not yet entirely known, so we employ the following:
  - An order of magnitude improvement in the effective area over HESS
  - A reduction in the PSF from 1-10 TeV from 0.075° to 0.03°

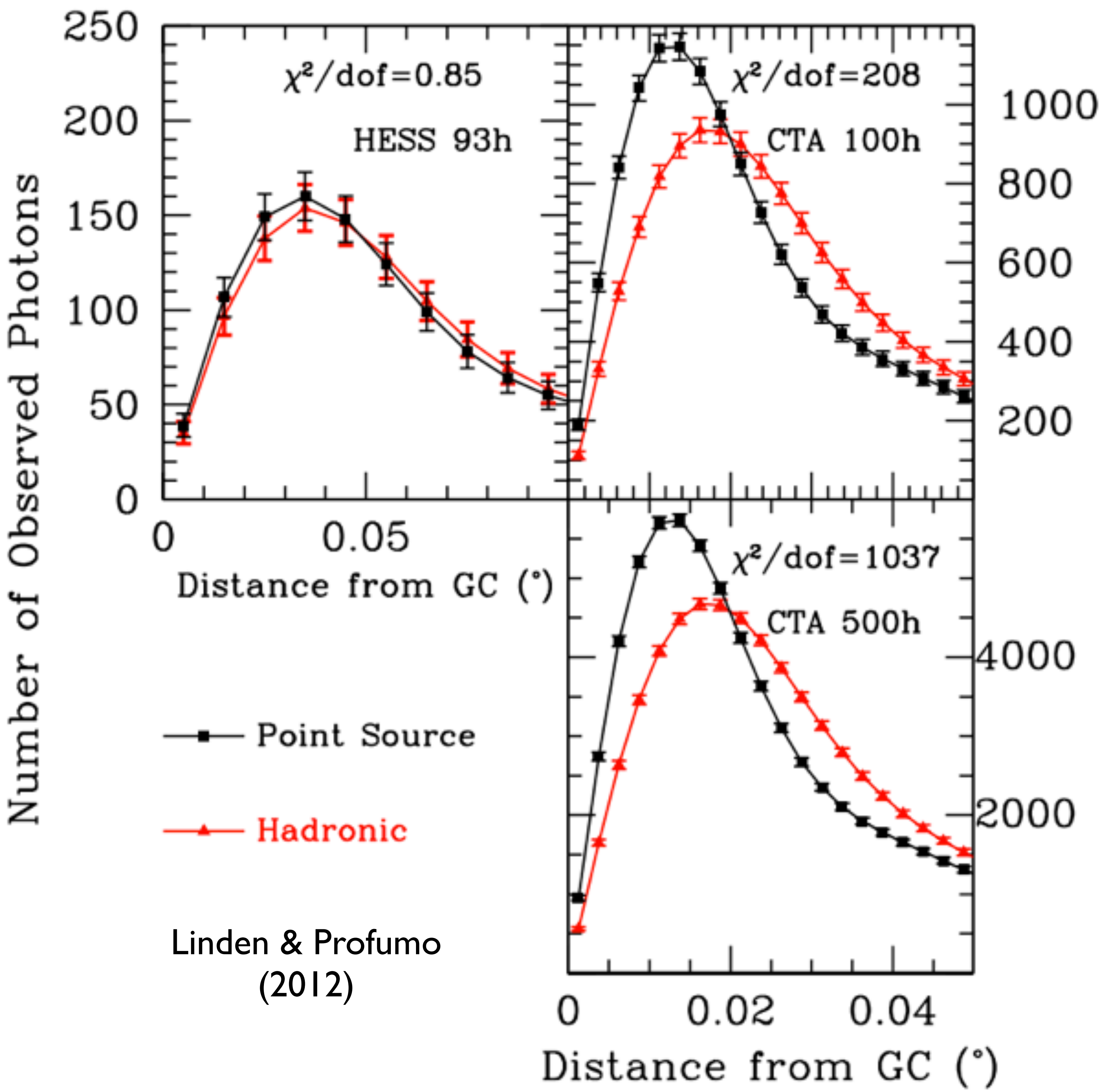




CTA and the Galactic Center

- By convolving our models of the gas and proton densities in the galactic center region with the PSF and effective area of each instrument, we can determine whether CTA can distinguish between these scenarios

- CTA will <u>conclusively</u> determine whether the galactic center source stems from a hadronic emission channel



Linden & Profumo (2012)

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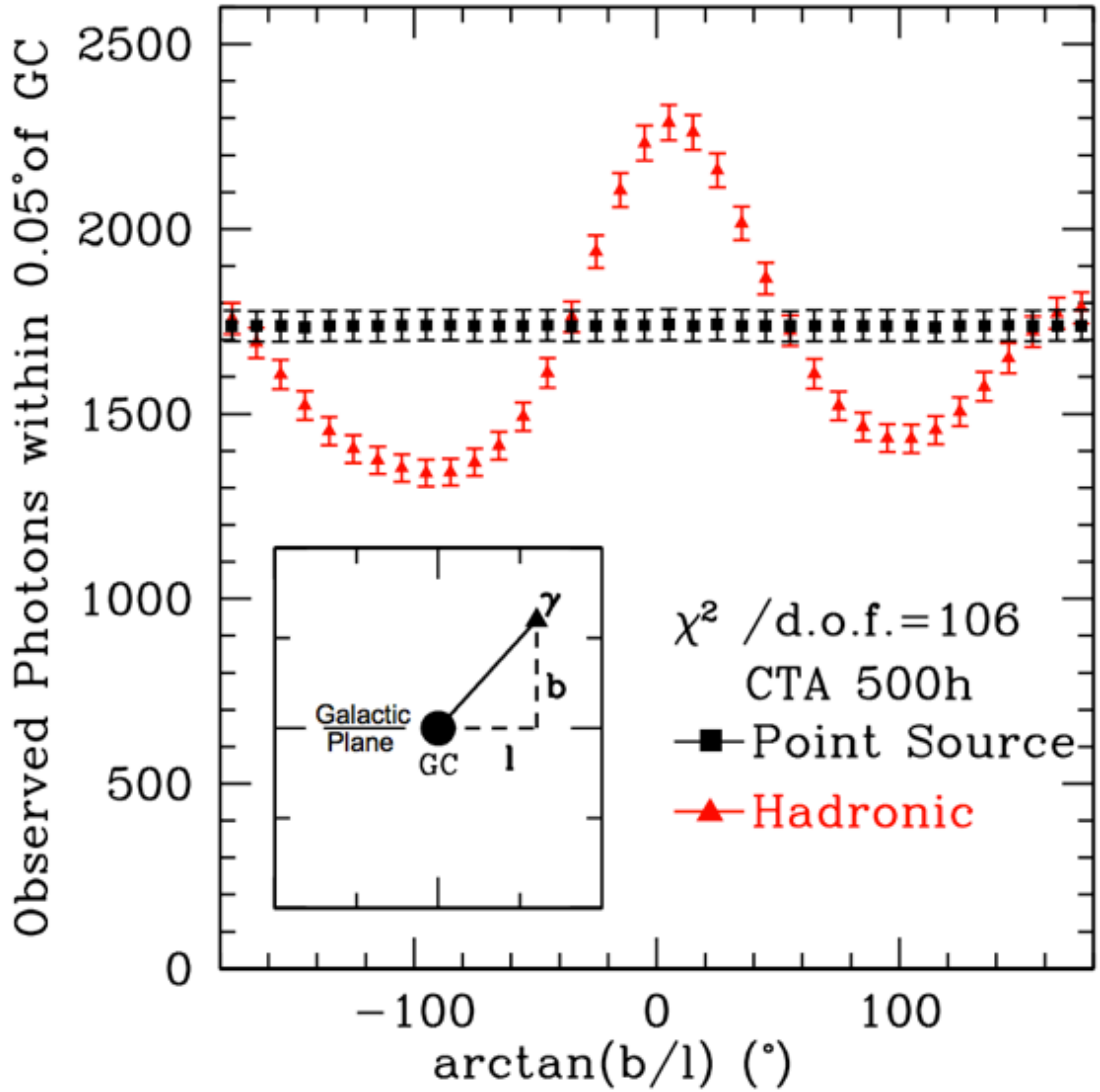


Linden & Profumo (2012)

Conclusions - GeV Excess

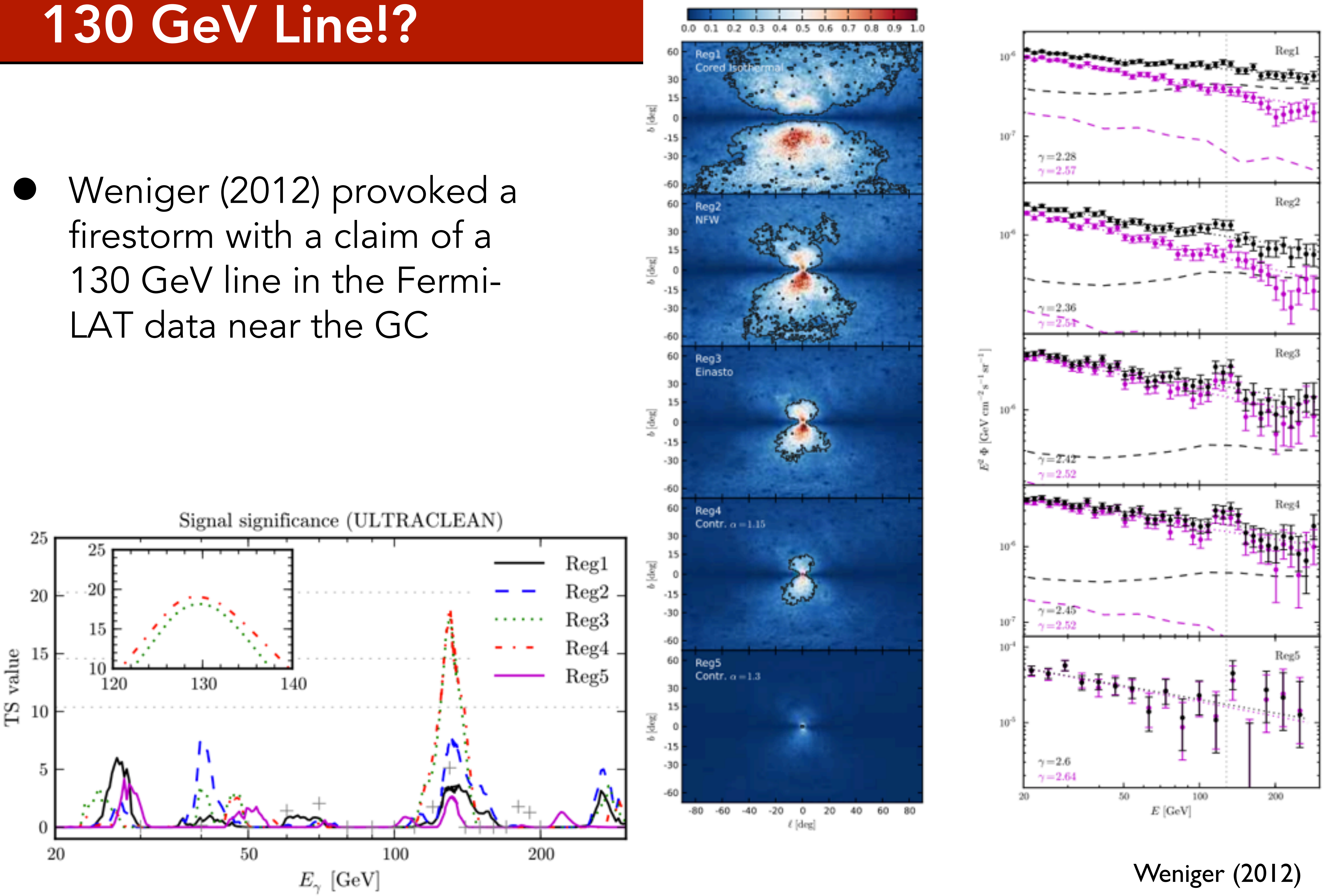
- The spectral properties - and the lack of variability - observed in the Fermi and HESS GC source imply a distinct emission mechanism which is distinct from lower-energy emission

- Dark Matter Models, Pulsar Models, and proton emission from the galactic center all form convincing explanations to current observations

- New observations and techniques will be critical to understanding the nature of the galactic center high energy emission

130 GeV Line!?

- Weniger (2012) provoked a firestorm with a claim of a 130 GeV line in the Fermi-LAT data near the GC

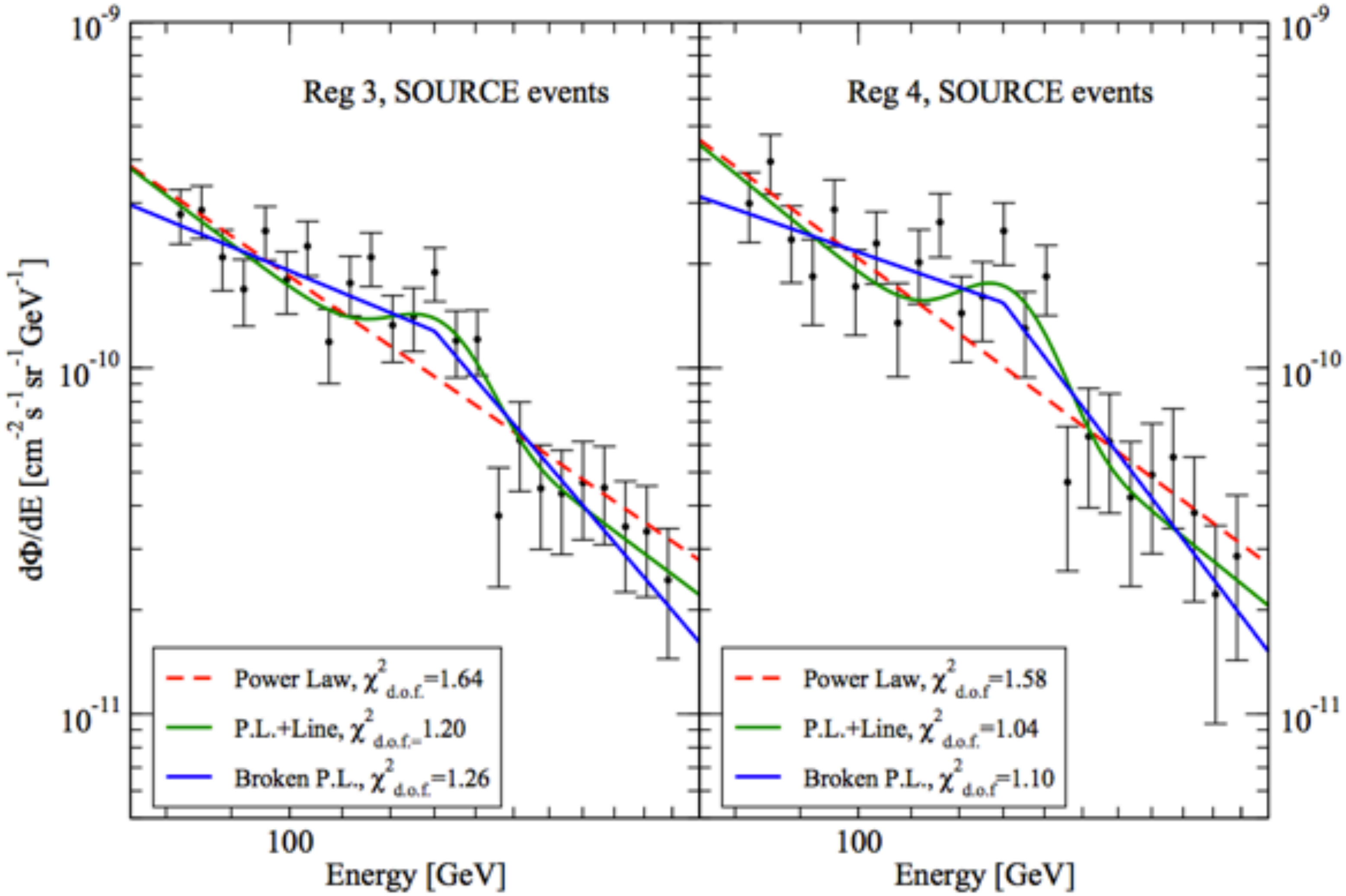


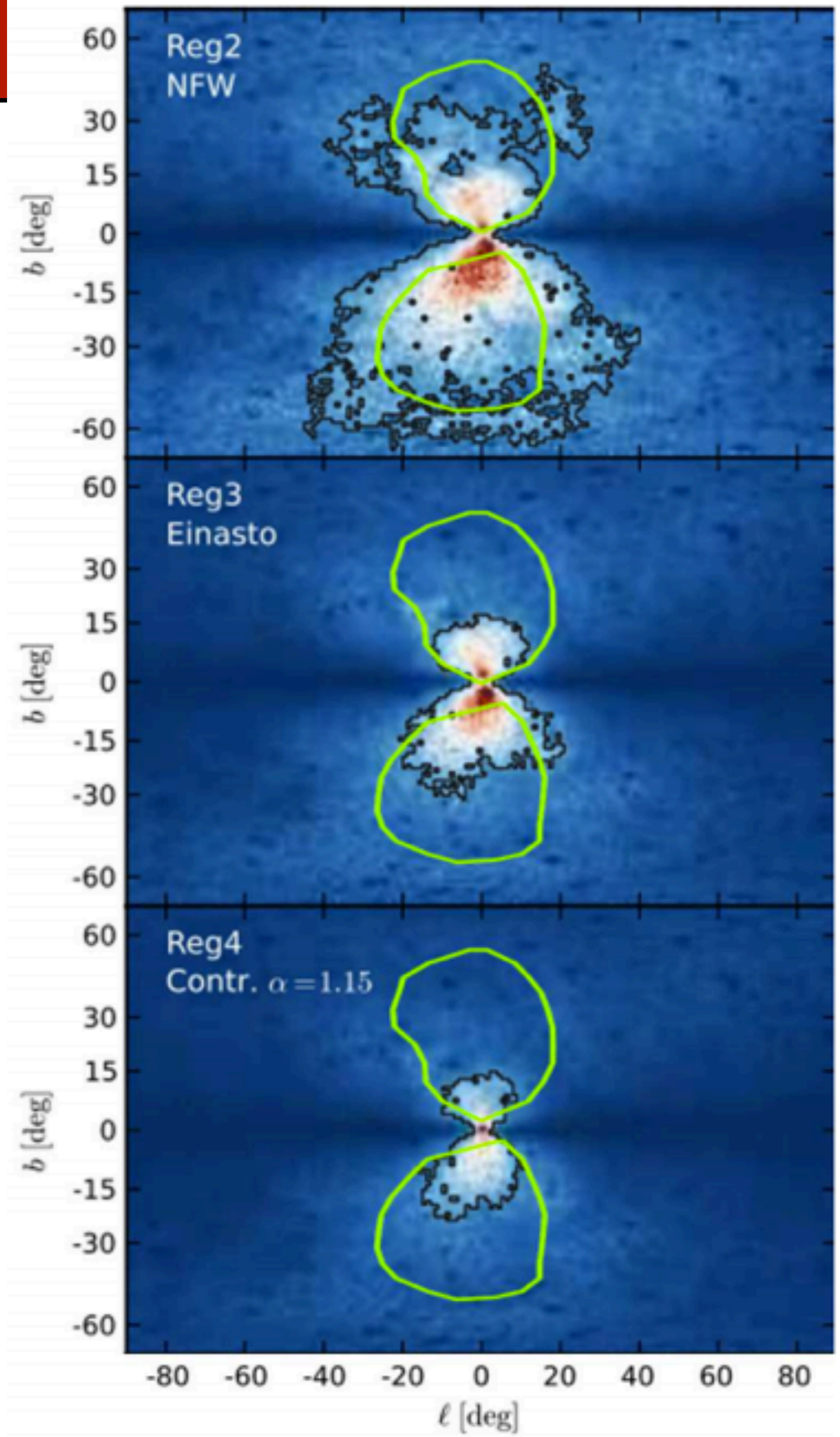
Weniger (2012)

130 GeV Line!?

- The emission could also be compatible with a broken power-law

- ~~That broken power-law could be driven by the Fermi bubbles~~

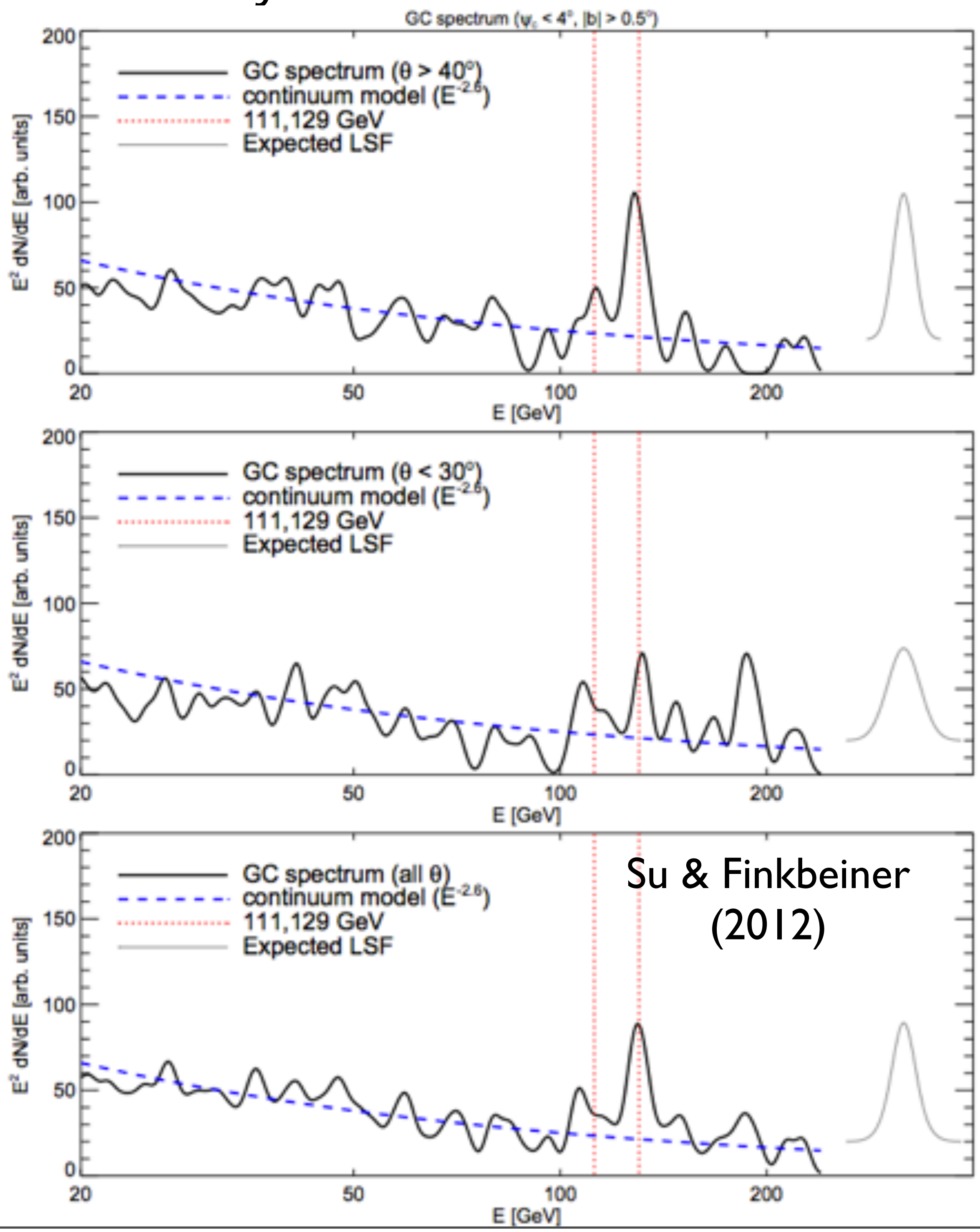


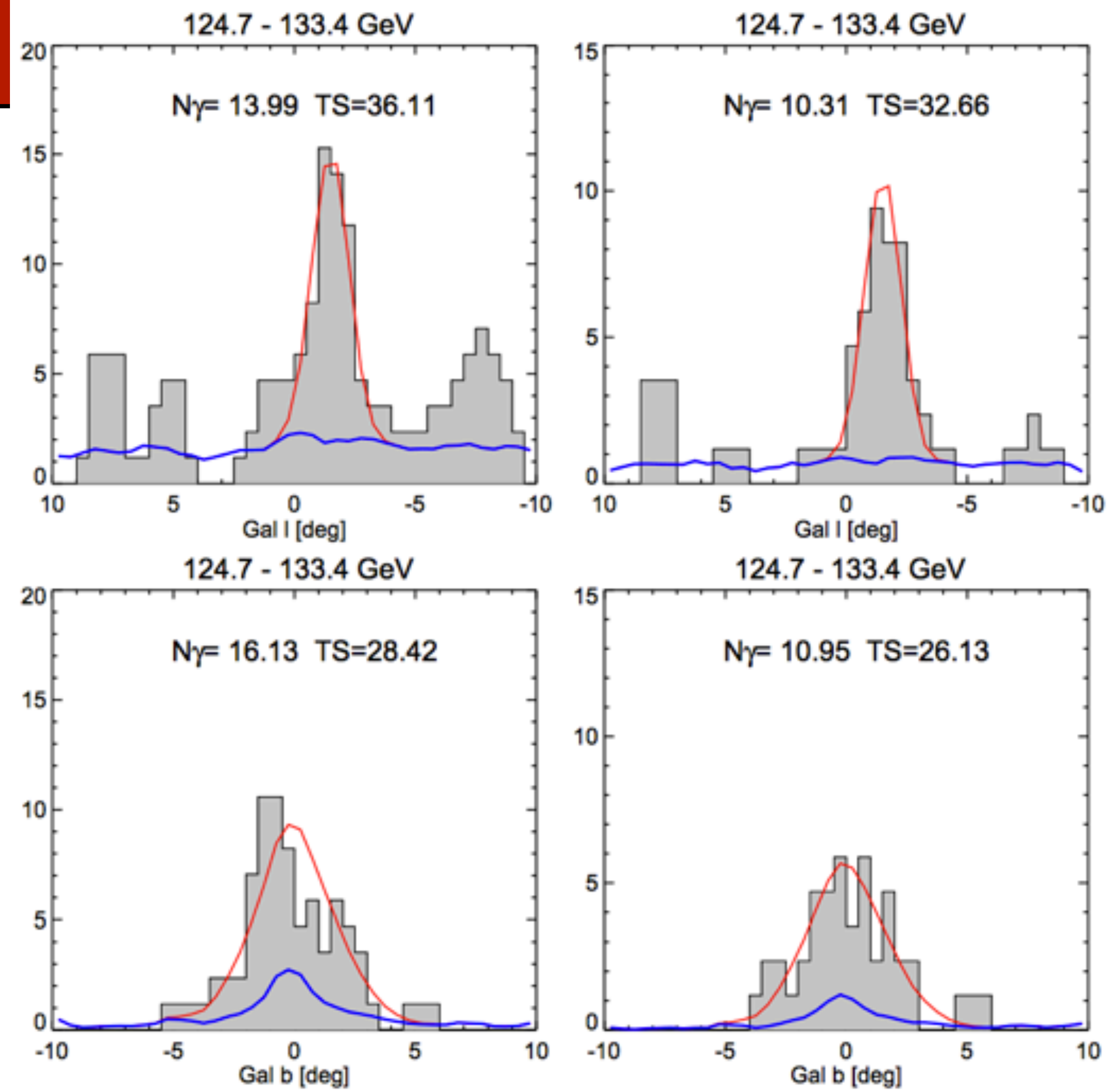


Profumo & Linden (2012)

130 GeV Line!?

- Su & Finkbeiner confirmed the result of Weniger (2012) using a template based analysis



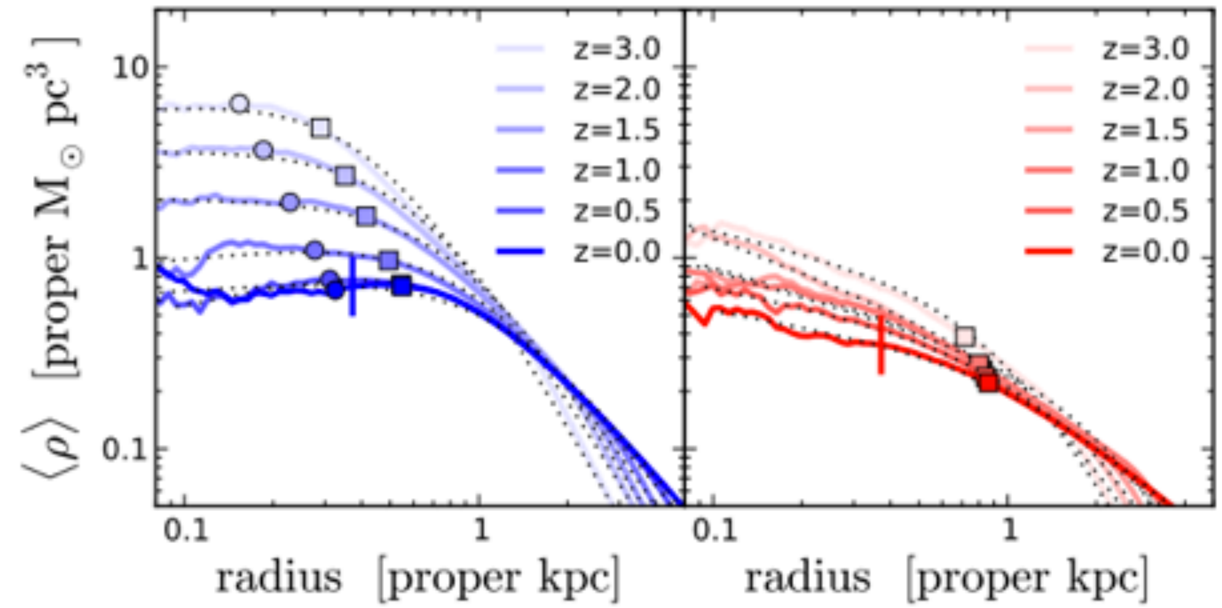


- They found the line signal to be highly concentrated near the GC

- They also found tentative evidence for a second gamma-ray line at ~110 GeV

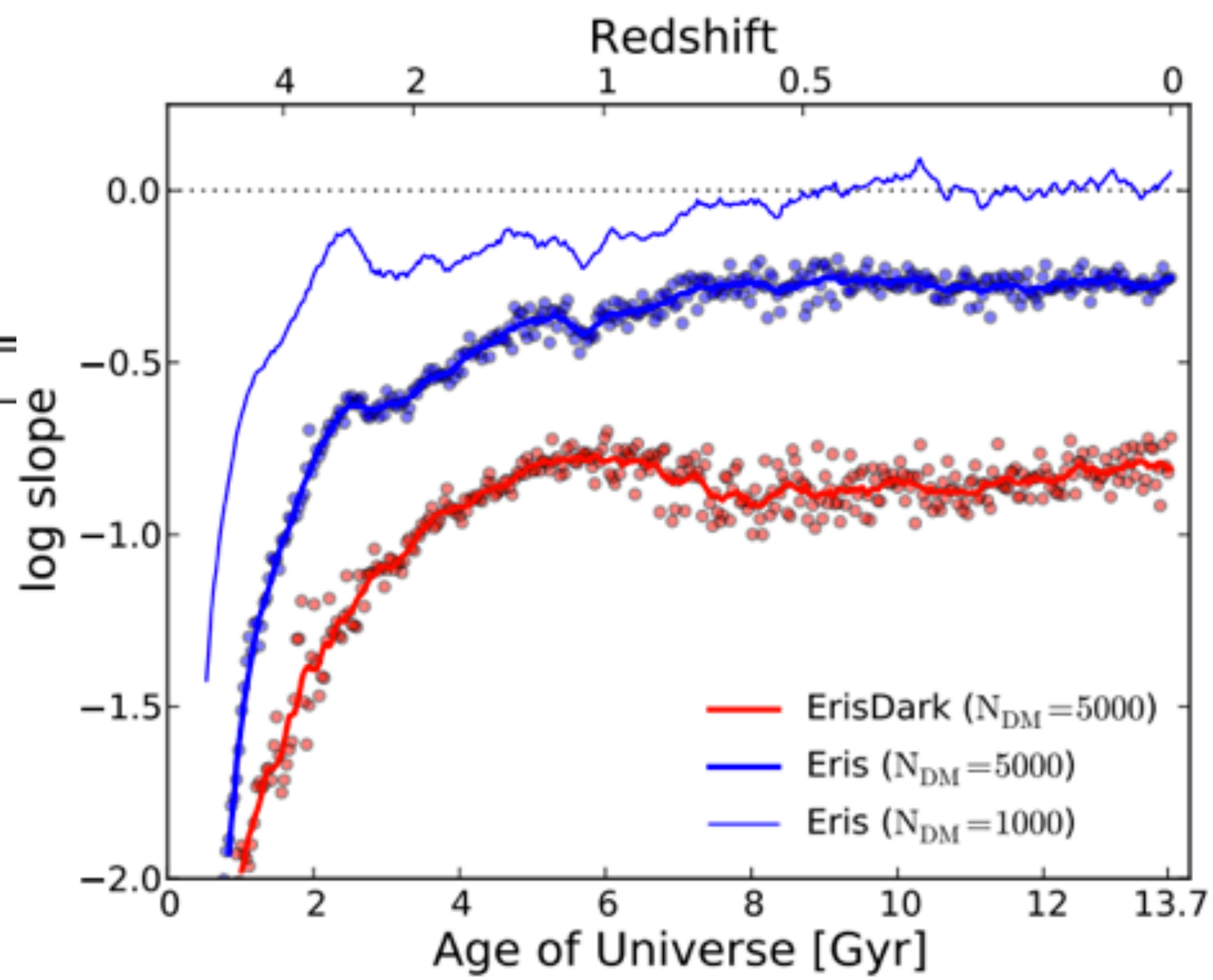
130 GeV Line!?

- Kuhlen et al. showed that the peak of the central dark matter density could peak ~100 pc away from the dynamical center of the galaxy



- However, this occurs in highly cored profiles, while the distribution of 130 line photons is more similar to an Einasto profile

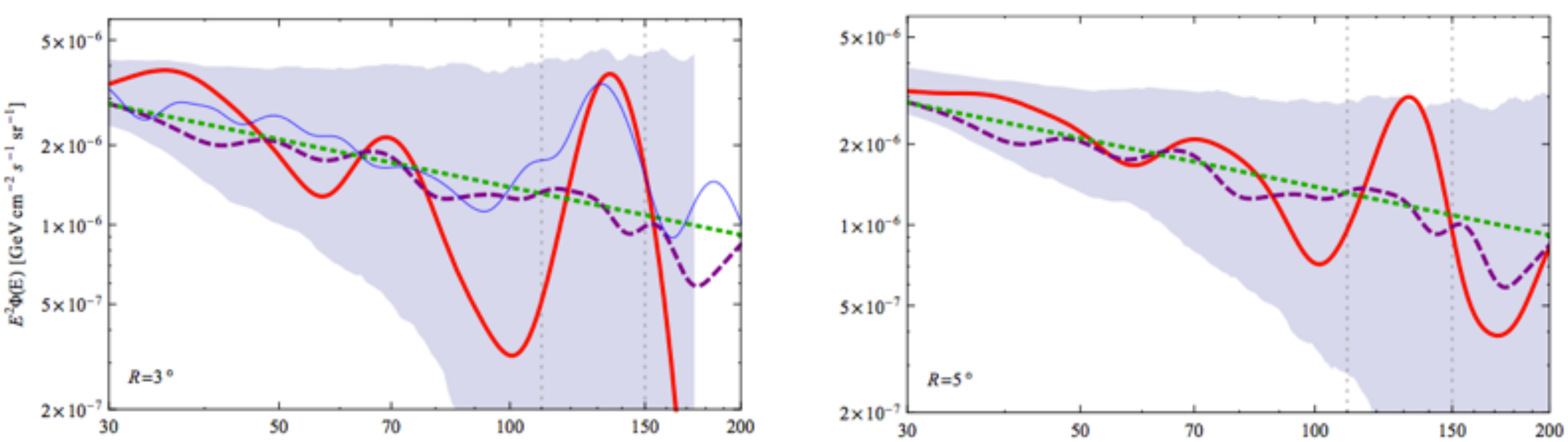
Models	Before trials	After trials (one line)
Gaussian (centered)	5.0σ	3.7σ
Gaussian (off center, $\theta > 40°$)	5.5σ	3.7σ
unbinned ℓ	5.2σ	3.2σ
unbinned ℓ ($\theta > 40°$)	4.9σ	2.8σ
unbinned b	4.8σ	3.5σ
unbinned b ($\theta > 40°$)	4.6σ	3.2σ
NFW $\alpha = 1.0$ (off center)	6.1σ	4.5σ
NFW $\alpha = 1.2$ (off center)	6.5σ	5.0σ
NFW $\alpha = 1.3$ (off center)	6.0σ	4.4σ
NFW $\alpha = 1.4$ (off center)	5.6σ	3.8σ
NFW $\alpha = 1.5$ (off center)	5.2σ	3.2σ
Einasto (off center)	**6.6σ**	**5.1σ**



Kuhlen et al. (2012)

Is the Line Anywhere Else?

- Hektor, Raidal, & Tempel examined the population of Galaxy Clusters and found some evidence of a line signal
- However, the projected cross-section and radial distribution do not match a dark matter candidate, and are **not** consistent with the GC

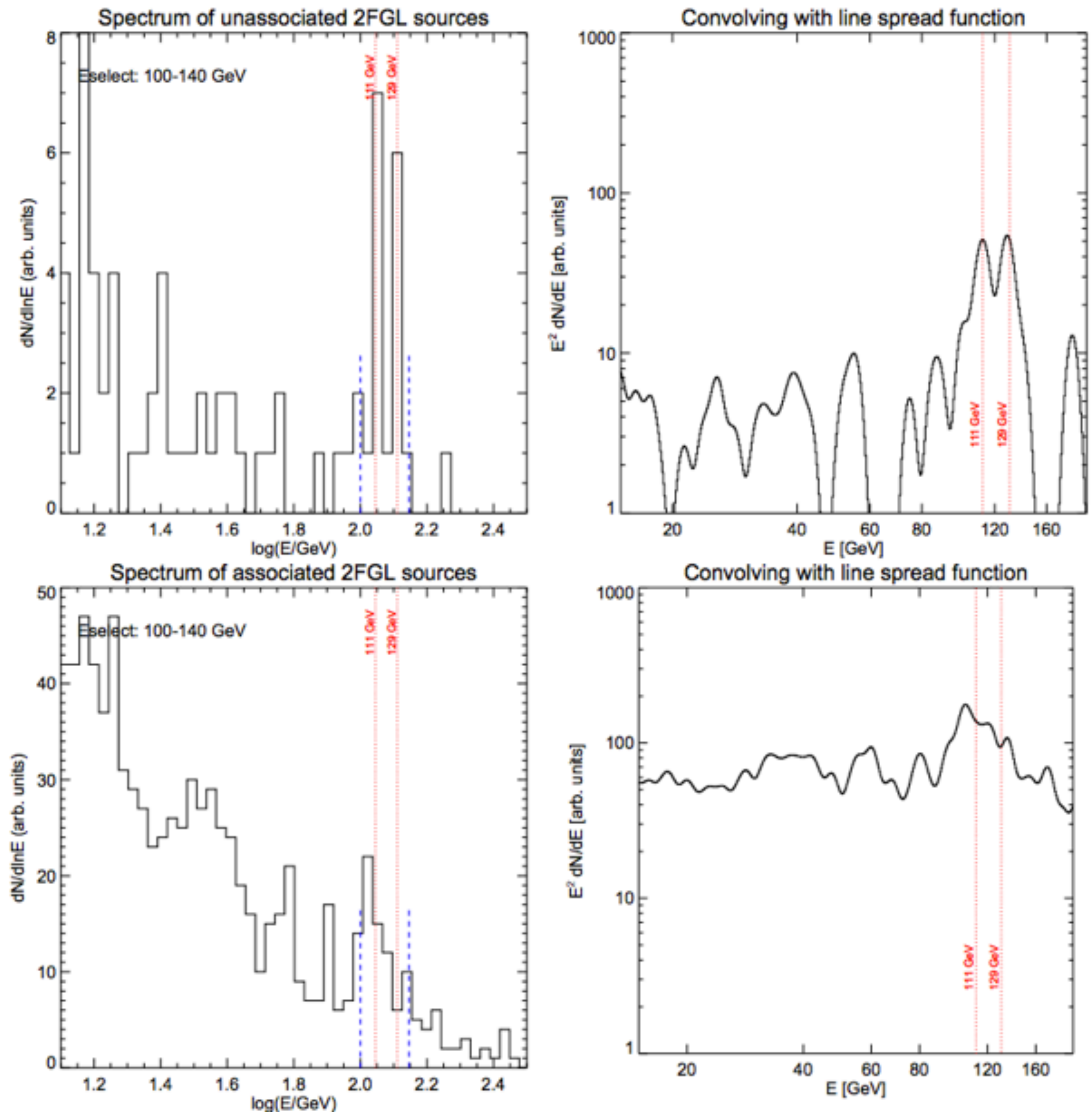


Radius R (deg)	1	2	3	4	5	6	7	8	9	10	15
N (110...150 GeV)	2	4	6	10	16	24	30	35	40	48	101
N (20...300 GeV)	15	55	114	219	336	504	666	875	1105	1370	3044
N_{signal} (110...150 GeV)	1.6	2.2	2.0	3.2	4.5	5.6	7.2	9.5	8.8	7.4	4.6
Significance (σ)	2.0	2.7	2.7	3.2	3.2	3.1	3.1	3.0	3.0	3.0	2.9

Hektor et al. (2012)

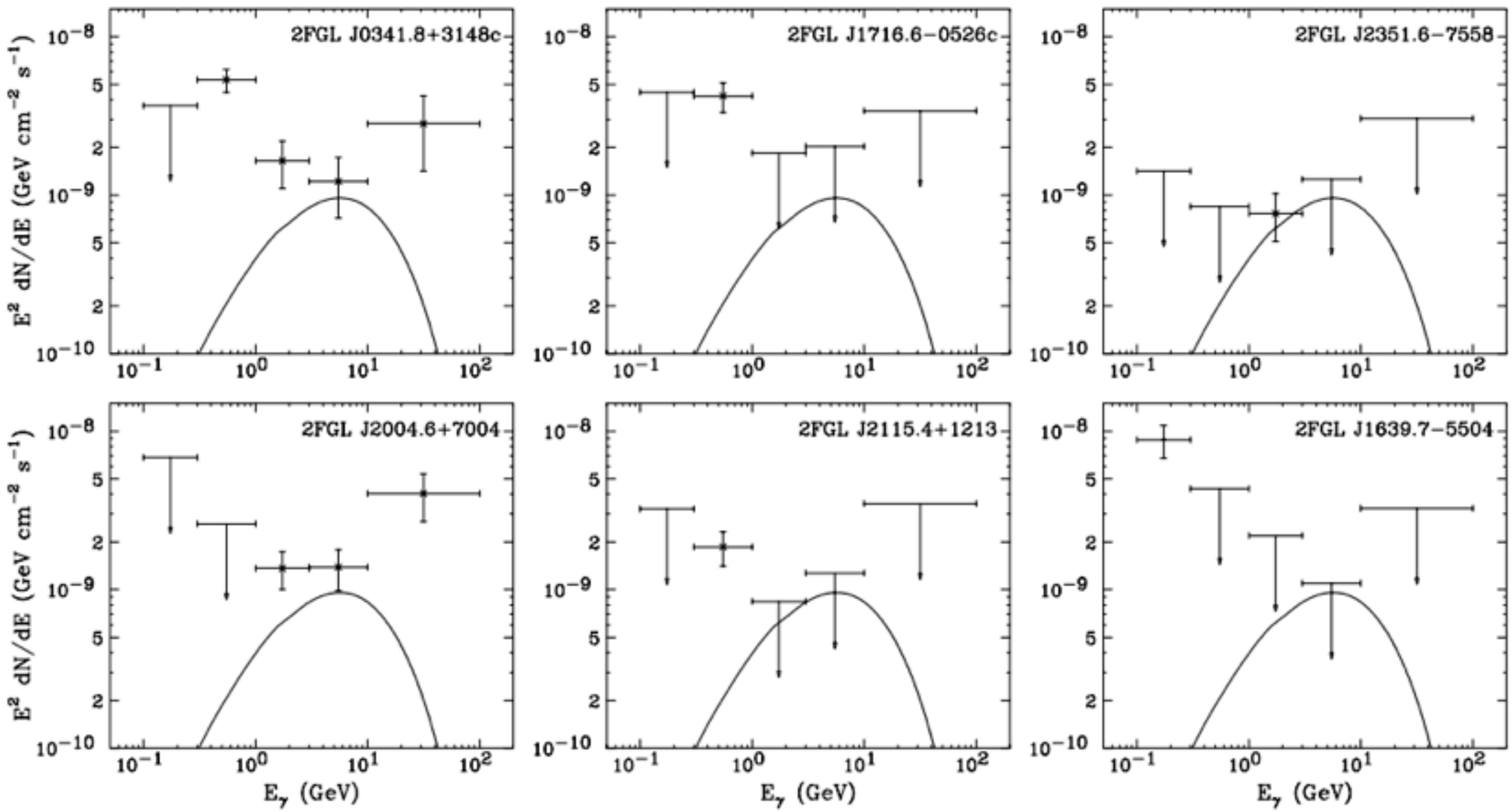
Is the Line Anywhere Else?

- A second Su & Finkbeiner paper examined the population of unassociated point sources, and found evidence for a gamma-ray line at the same energies
- This could be evidence that several of the unassociated point sources host dark matter subhalos
- The associated point sources can be used as a control sample for this hypothesis, and show no evidence of a line



Su & Finkbeiner (2012b)

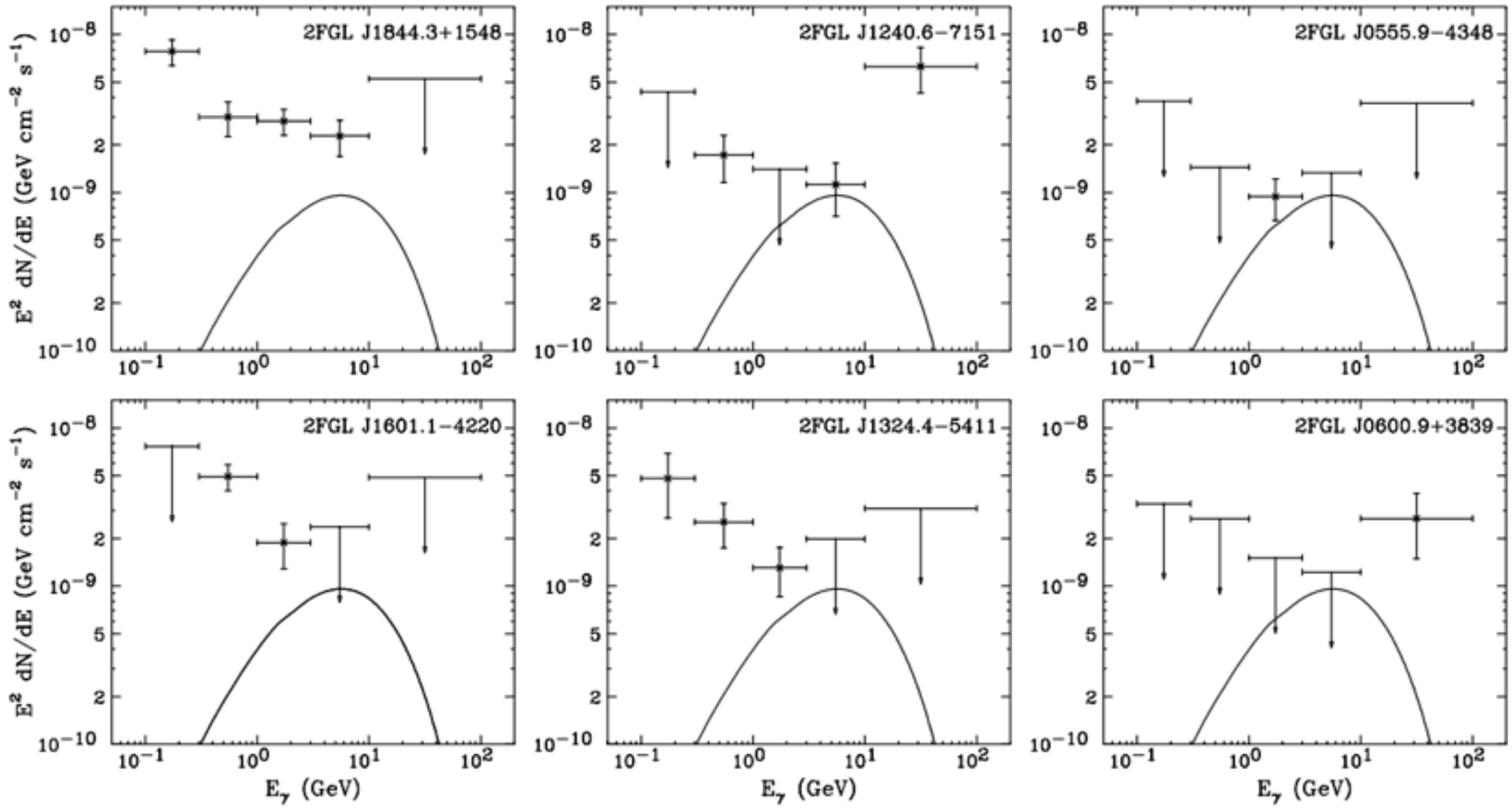
Is the Line Anywhere Else?



Hooper & Linden (2012)

- However, the continuum emission for each source (which is what placed them into the 2FGL source catalog in the first place) is not compatible with any normal model for dark matter annihilation

Is the Line Anywhere Else?

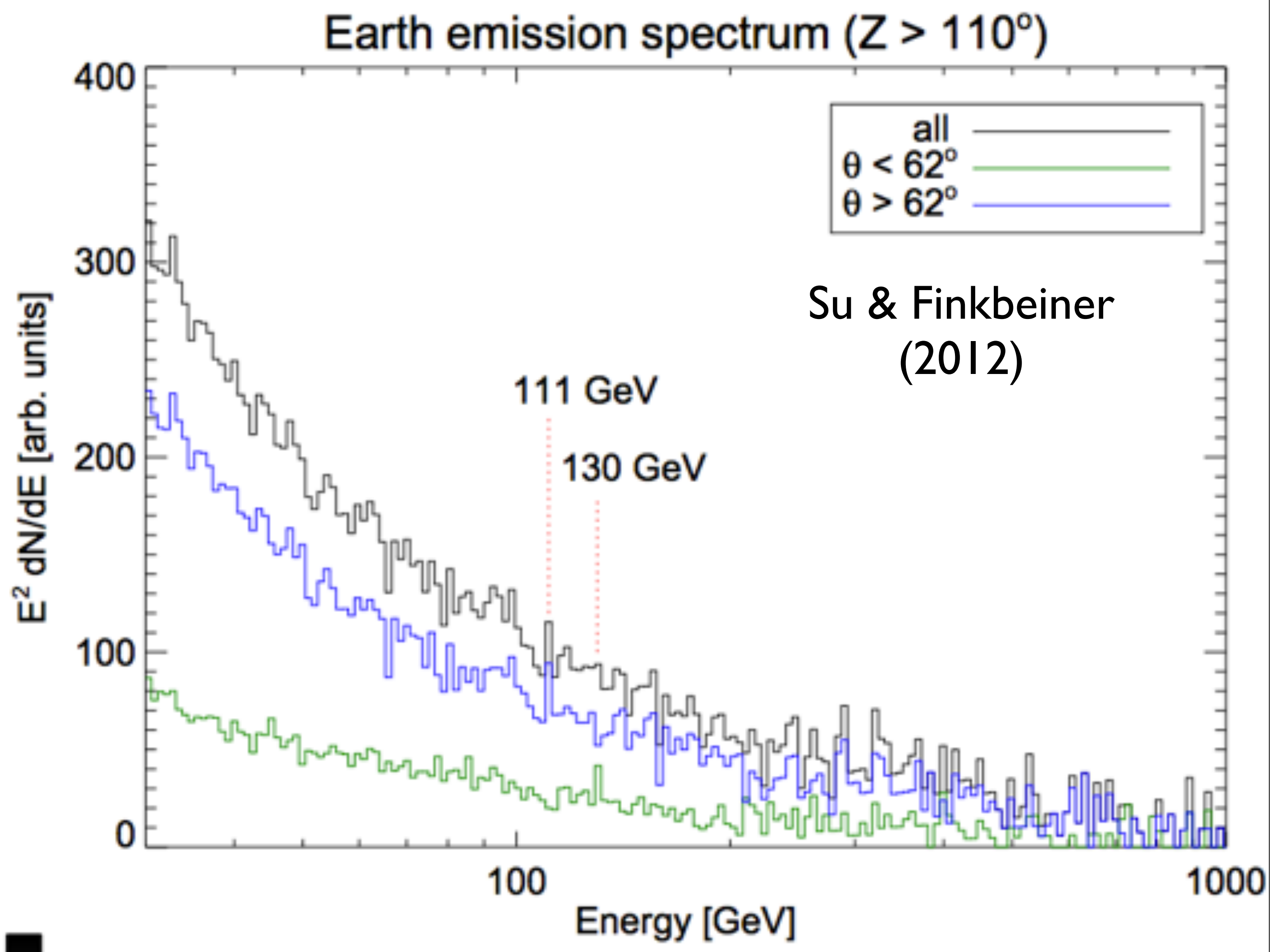


Hooper & Linden (2012)

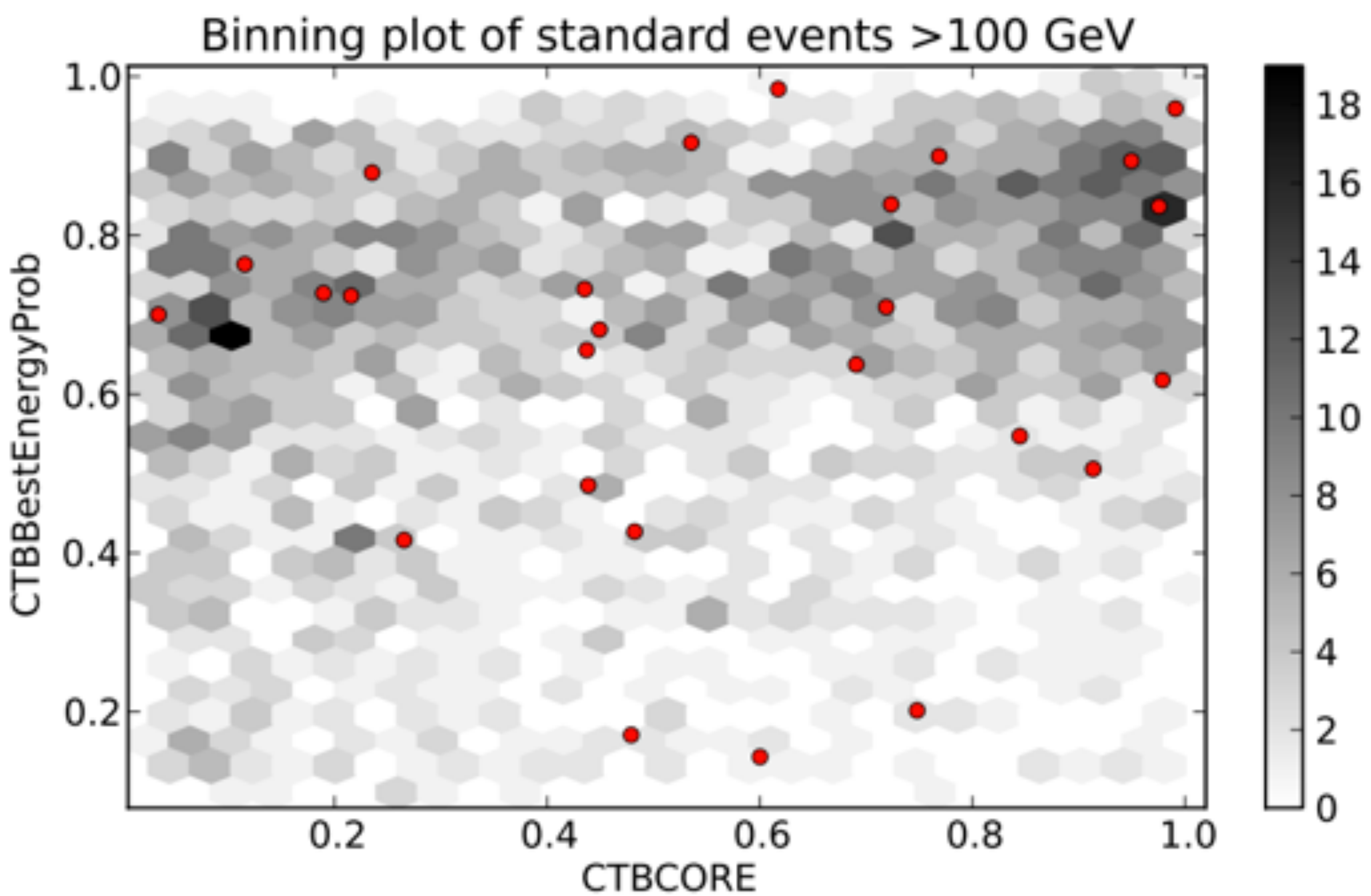
- However, the continuum emission for each source (which is what placed them into the 2FGL source catalog in the first place) is not compatible with any normal model for dark matter annihilation

Is the Line Instrumental?

- Some hint of a gamma-ray line in photons from the Earth albedo - which would be a clear indication of systematic errors in energy reconstruction



- However, a systematic problem should also be seen in the galactic plane

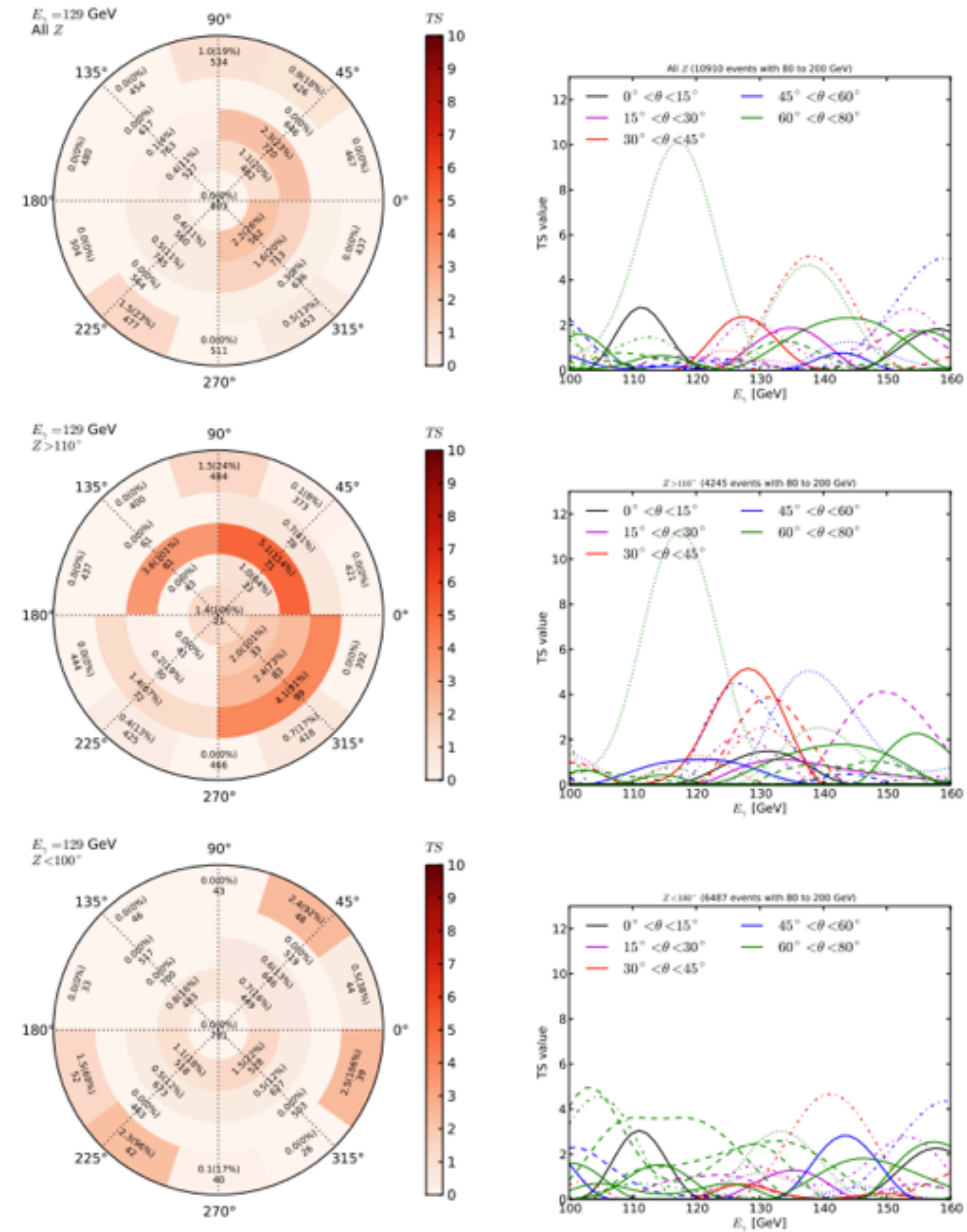


Is the Line Instrumental?

- Some hint of a gamma-ray line in photons from the Earth albedo - which would be a clear indication of systematic errors

- However, a systematic problem should also be seen in the galactic plane

- The significance of the line signal appears to populate the full plane of instrumental phase space



Finkbeiner et al. (2012)

Conclusions - 130 GeV Line

- The line signal observed at the galactic center is statistically significant
- There is currently no convincing evidence for line signals anywhere else in the gamma-ray sky
- All current explanations for the gamma-ray line are unconvincing
- **Help!?** (HESS-II? New Observation Strategies? Smart models?)

Conclusions - Galactic Center

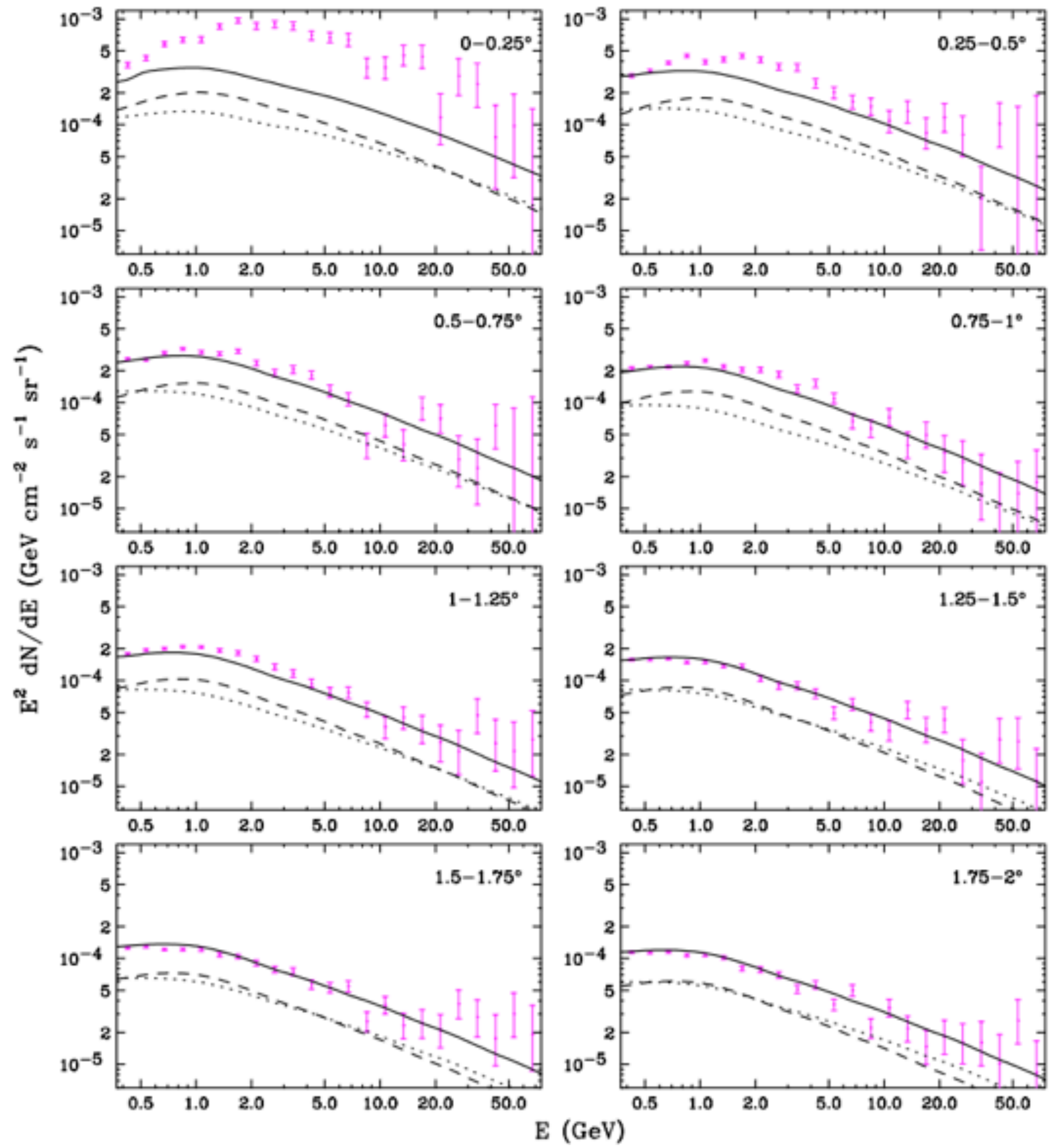
- The galactic center is one of the most exciting places to search for a dark matter signal
- Present observatories are capable of both making exciting discoveries, and setting stringent limits on the properties of WIMP dark matter
- Upcoming instruments are likely to make exciting discoveries of both the astrophysical and dark matter properties of the galactic center region

Extra Slides

What is the WMAP Haze?

- To determine the best - fit dark matter annihilation profile, Hooper & Goodenough bin the residuals as a function of radius
- Then the residual as a function of radius can be compared with the dark matter injection profile convolved with the PSF of the Fermi-LAT

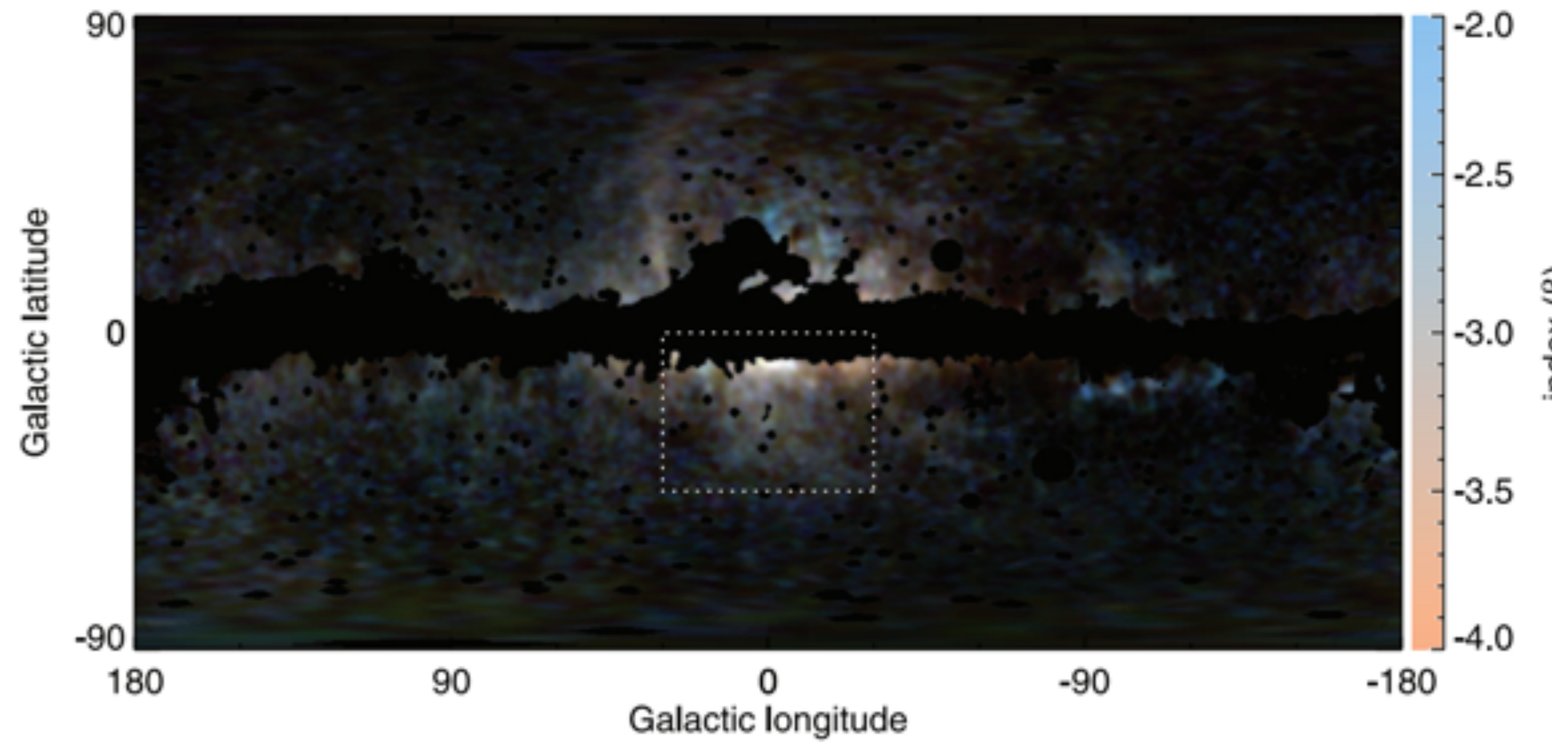
Hooper & Goodenough (2011)

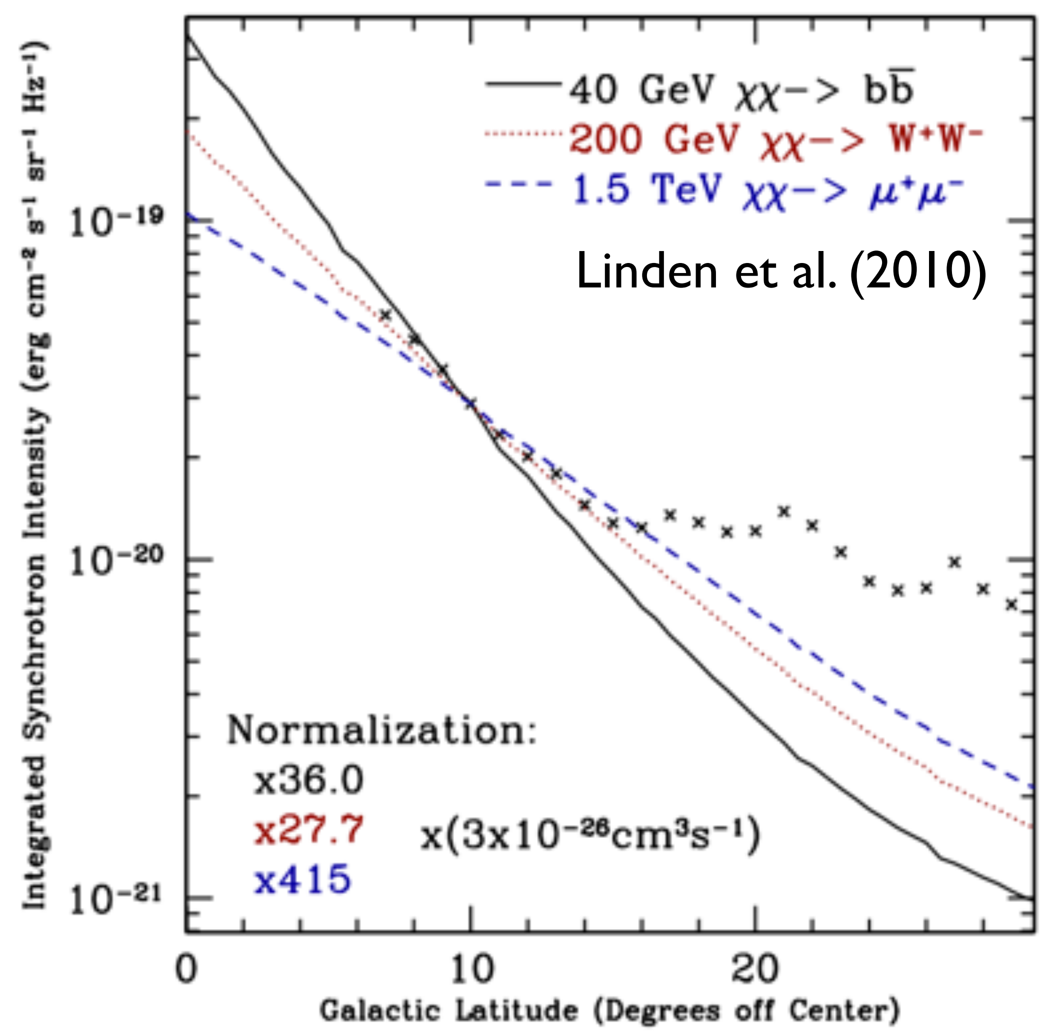


What is the WMAP Haze?

- Discovered by Doug Finkbeiner in 2004
- Synchrotron origin determined by subsequent observations
- Hard spectrum difficult to fit with lepton injection spectra typical of astrophysical phenomena
- Well fit by dark matter models with typical annihilation cross-sections and spectra
- However, modifications are needed to magnetic fields in galactic halo

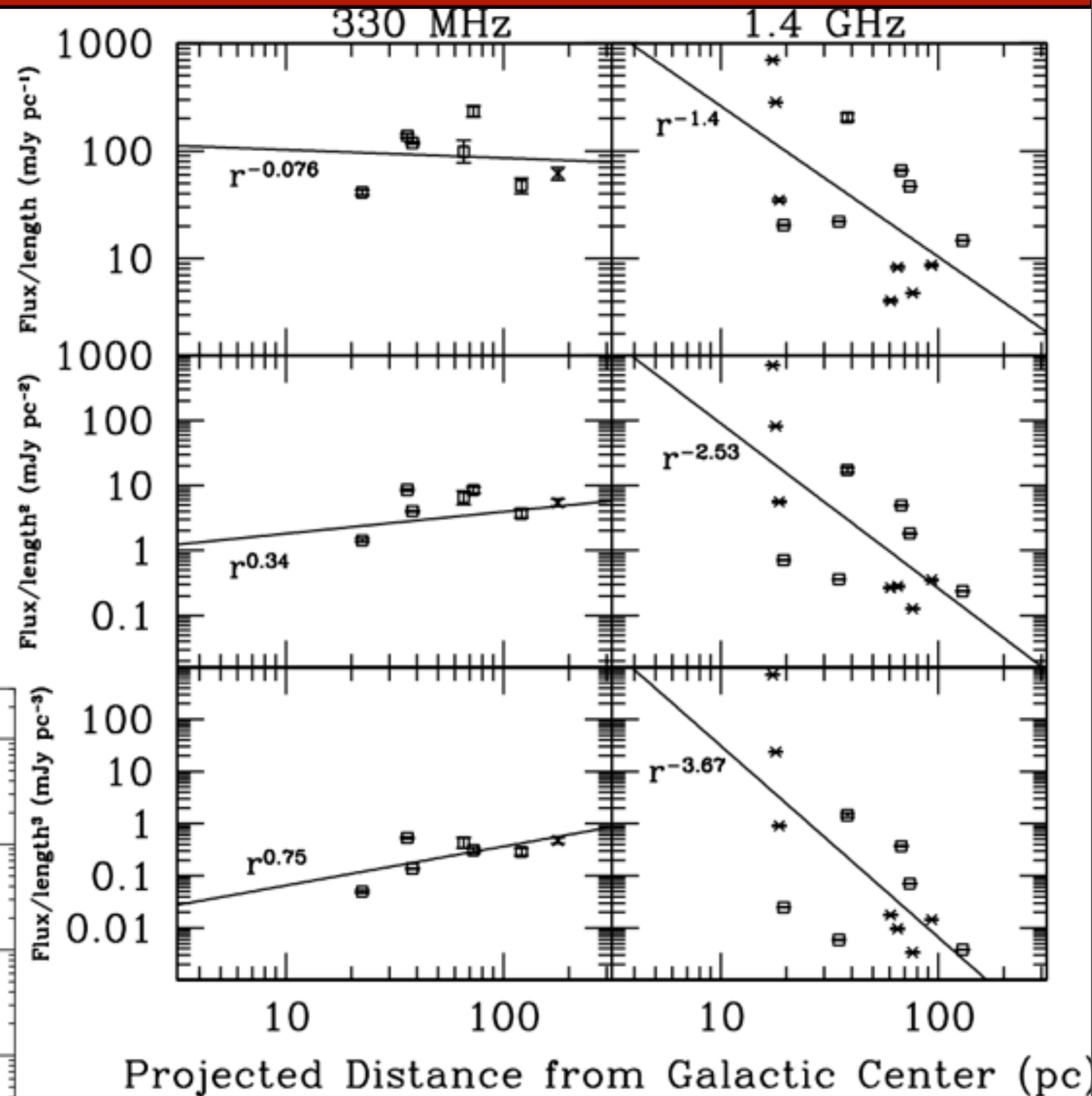
Dobler et al. (2008)



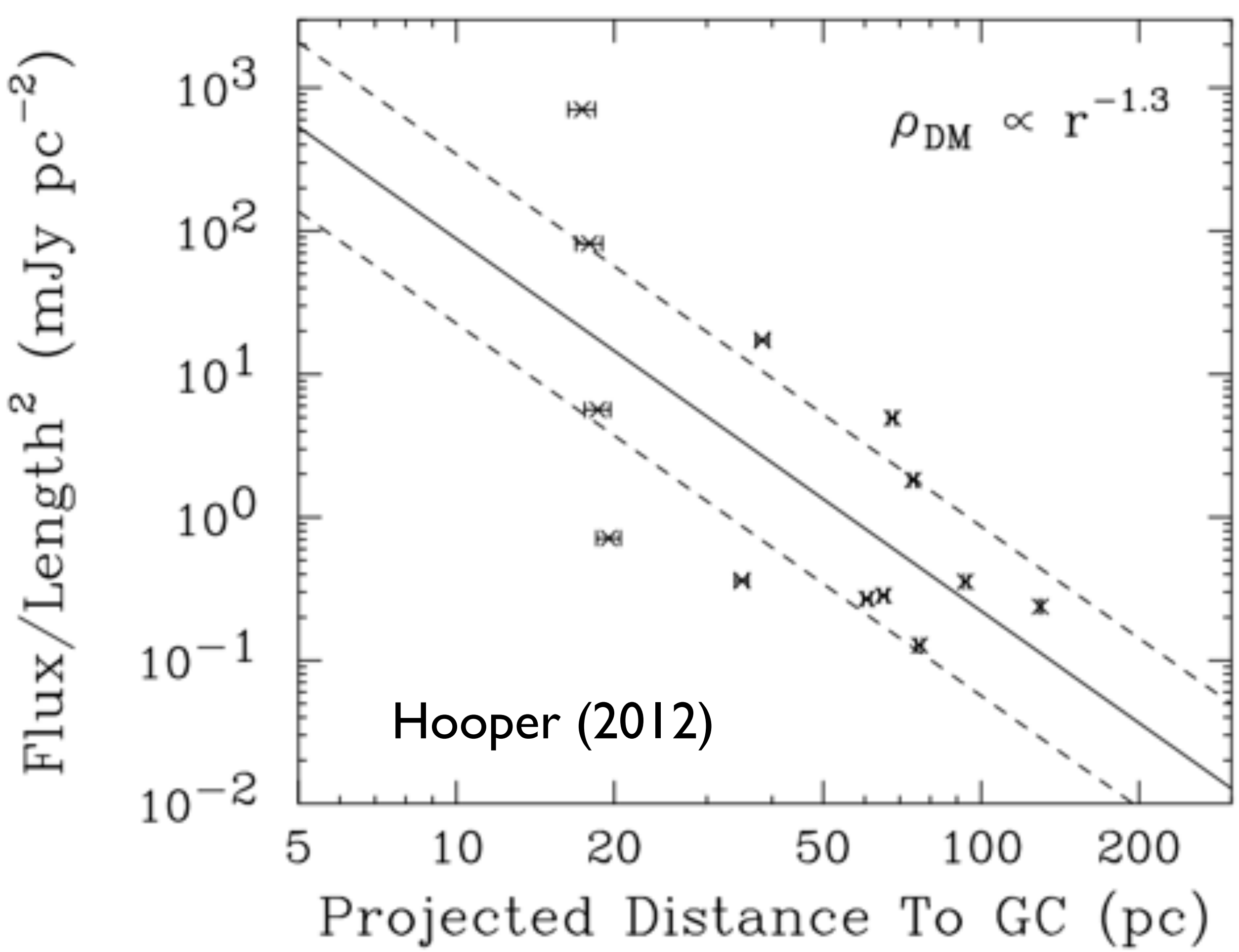


The Radial Dependence of the Filamentary Arcs

- The intensity of multiple filamentary arcs show a strong dependence on their distance from the galactic center
- This is expected in dark matter models, but not in most astrophysical interpretations of the filaments

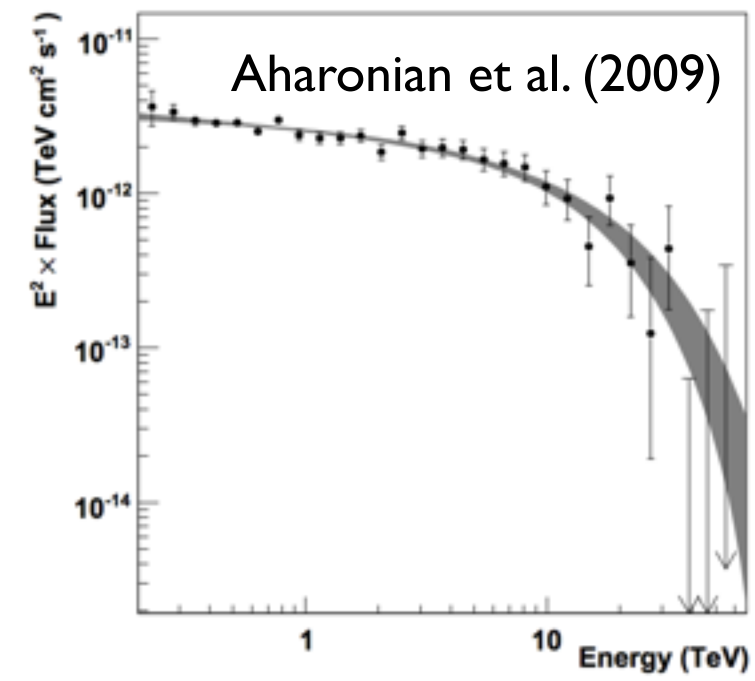


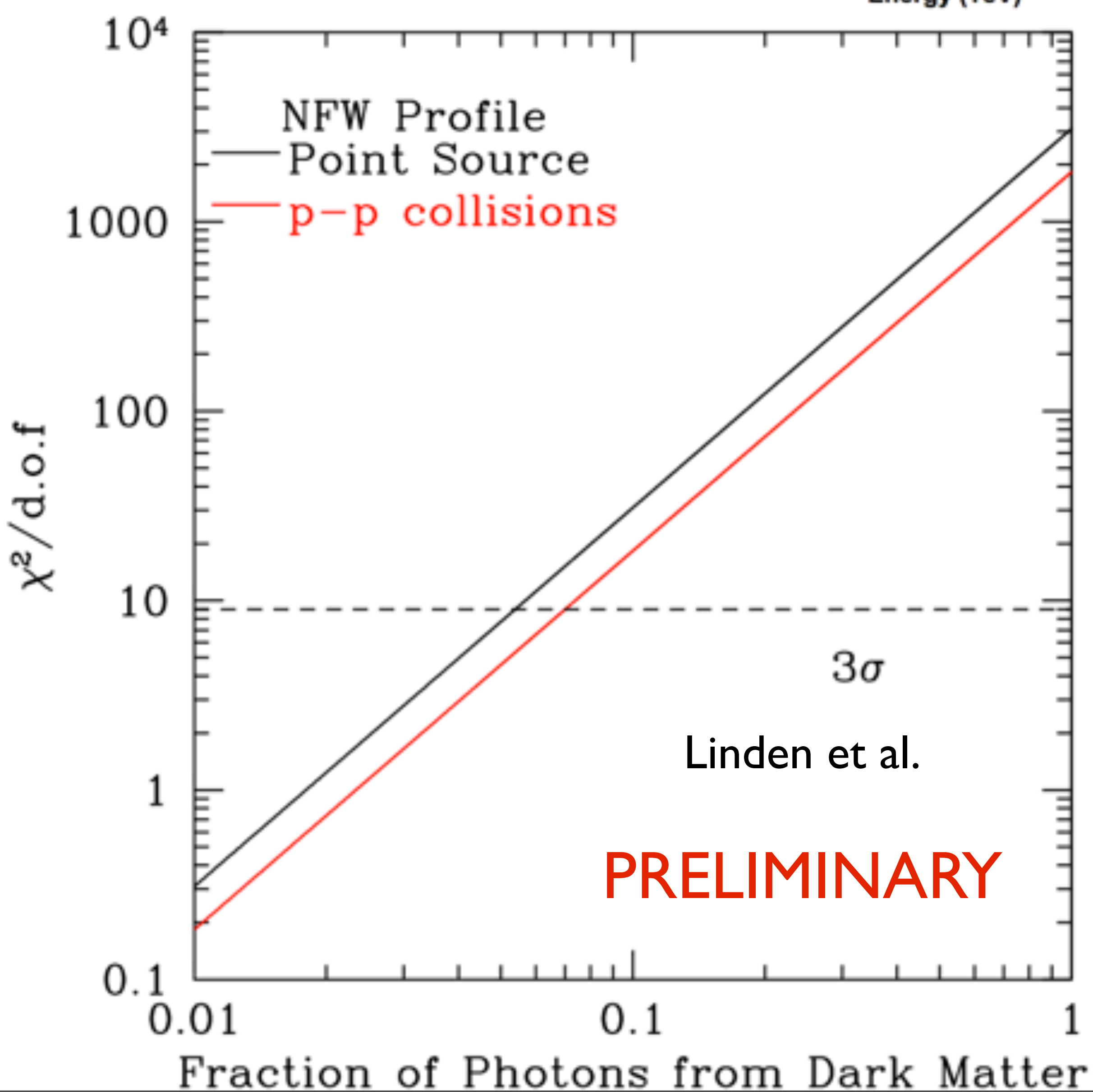
Linden et al. (2011)



Dark Matter at the Galactic Center

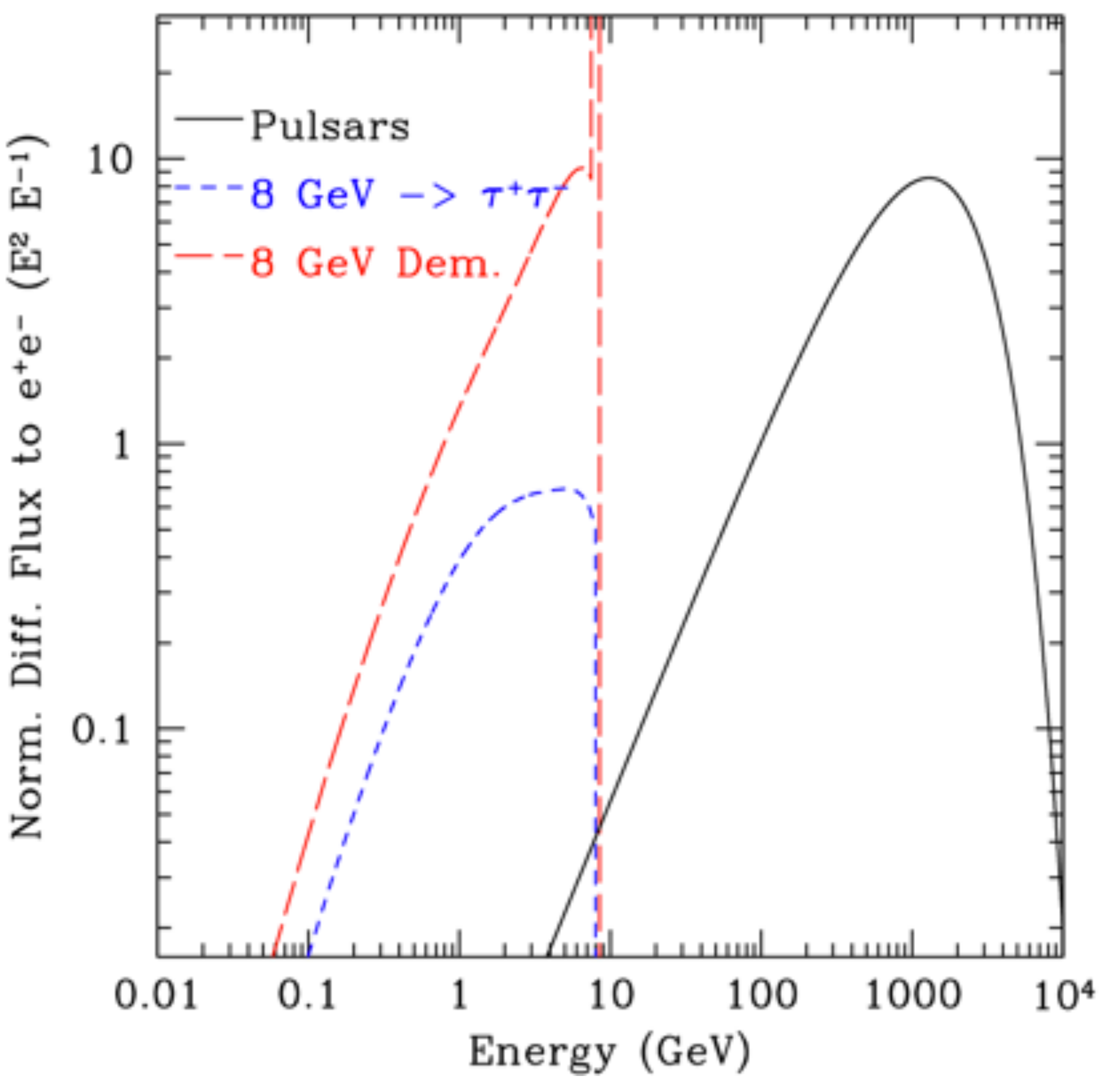
- Can use a Kolmogorov-Smirnov test after finding the CDF for the radial profile of dark matter annihilation
- Since the CDFs for dark matter and the background point-source can be compared linearly, strong limits can quickly be set on dark matter annihilation
- Limits on photon counts can then be translated to a limit on annihilation cross-section
- Of course, large uncertainties exist, stemming from models in the gas density, and in the ratio of background emission stemming from point-source vs. gas

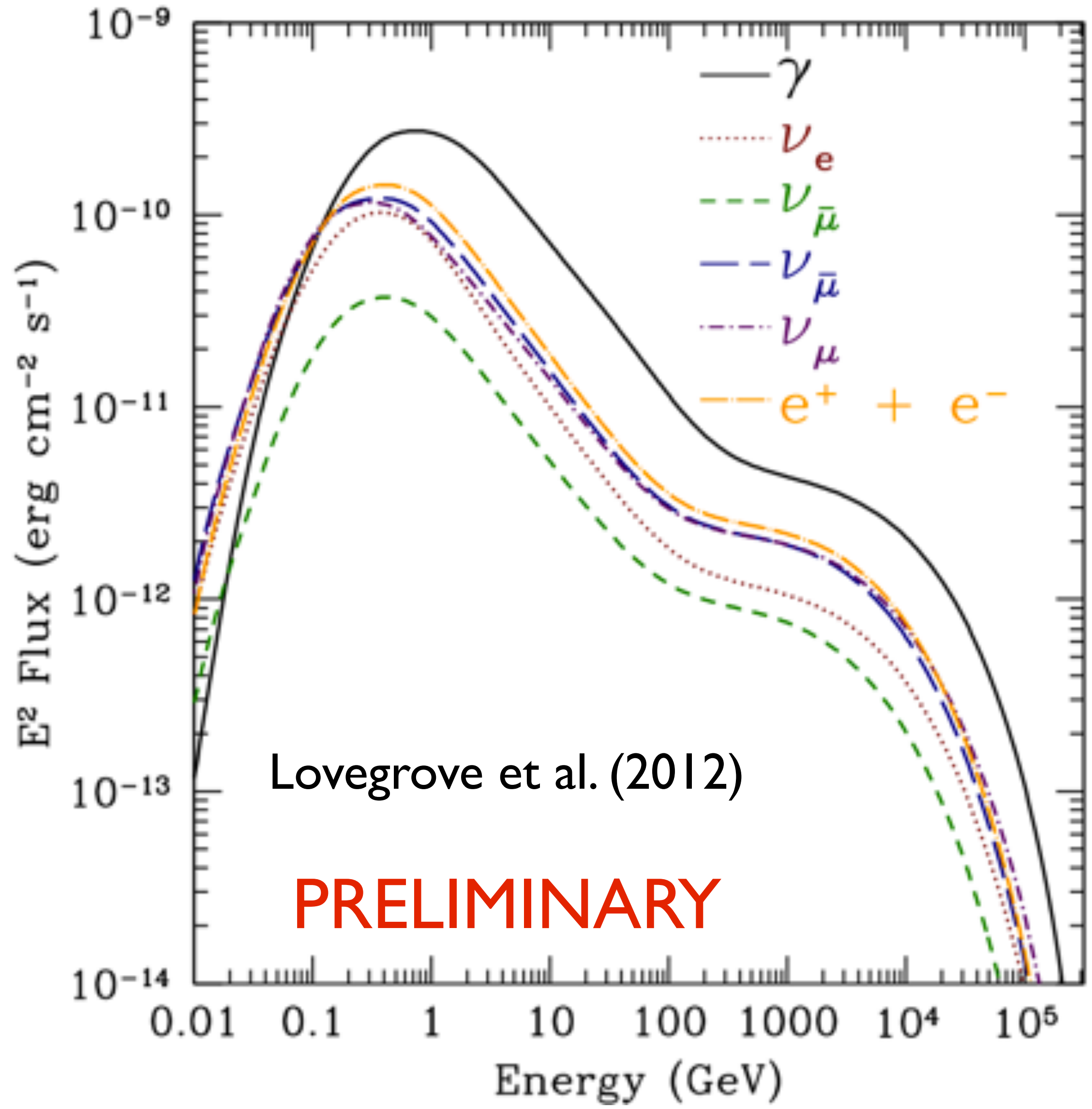




Understanding the Secondary Emission

- 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

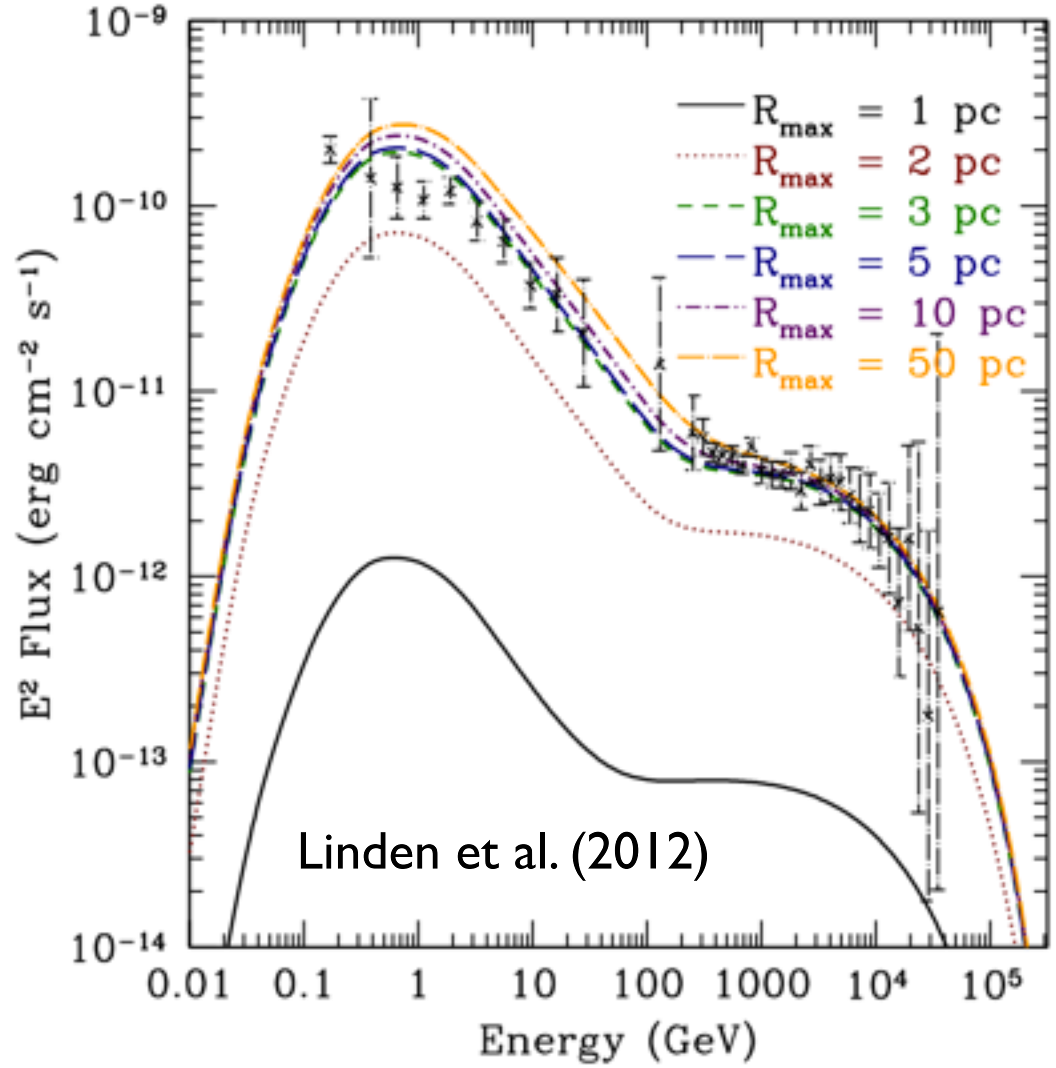
Negative: The diffusion and energy loss time of charged electrons adds additional uncertainties to the model

Modeling Benefits of the Hadronic Scenario!

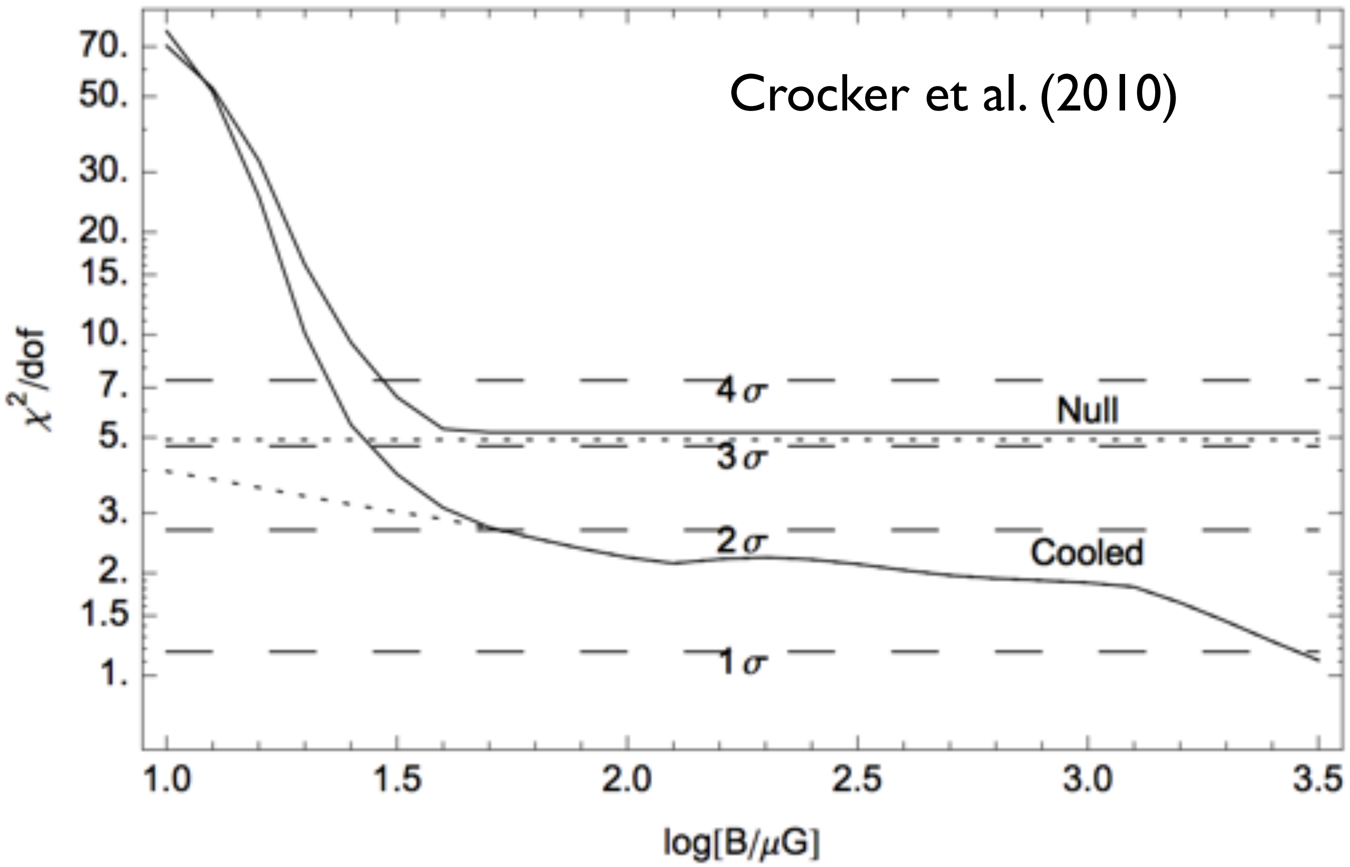
- Under the assumption that the proton source has a power-law spectrum and is in steady-state, then the slope of gamma-ray emission strongly constrains the diffusion constant in the galactic center region:

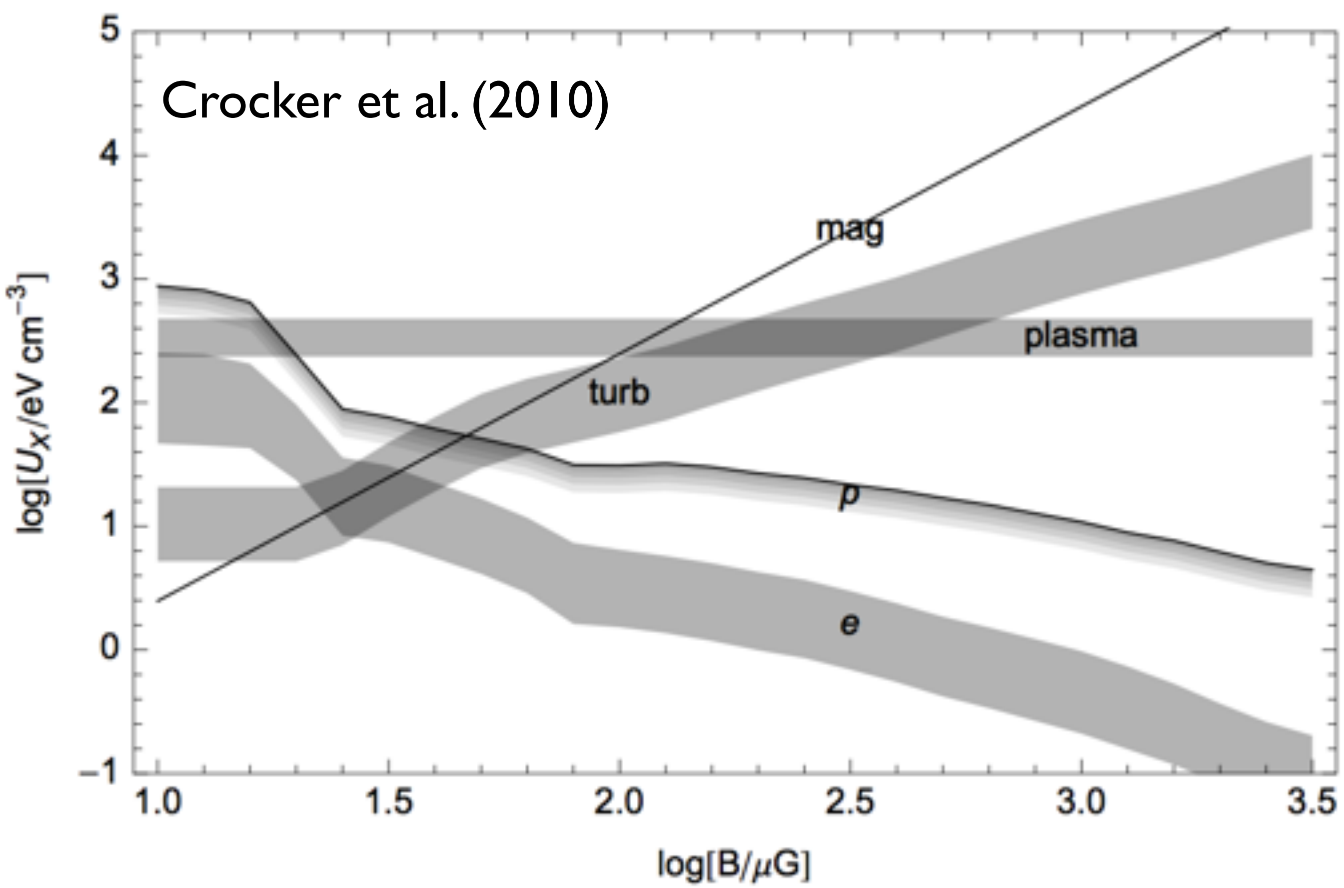
$$D_0 = 1.2 \times 10^{26}\ (E/1\ \mathrm{GeV})^{0.91}$$

- This adds additional constraints to the an understanding of lepton diffusion and propagation in the galactic center region



Models of the Galactic Center Magnetic Field





- This is particularly interesting in light of recent models which have set a minimum strength of 50 μG on the magnetic fields in the galactic center (best fit range 100-300 μG)
- This almost ensures that synchrotron is the dominant energy loss mechanism for high energy electrons
- In the hadronic scenario, the diffusion parameters are set by the fit to the gamma-ray data