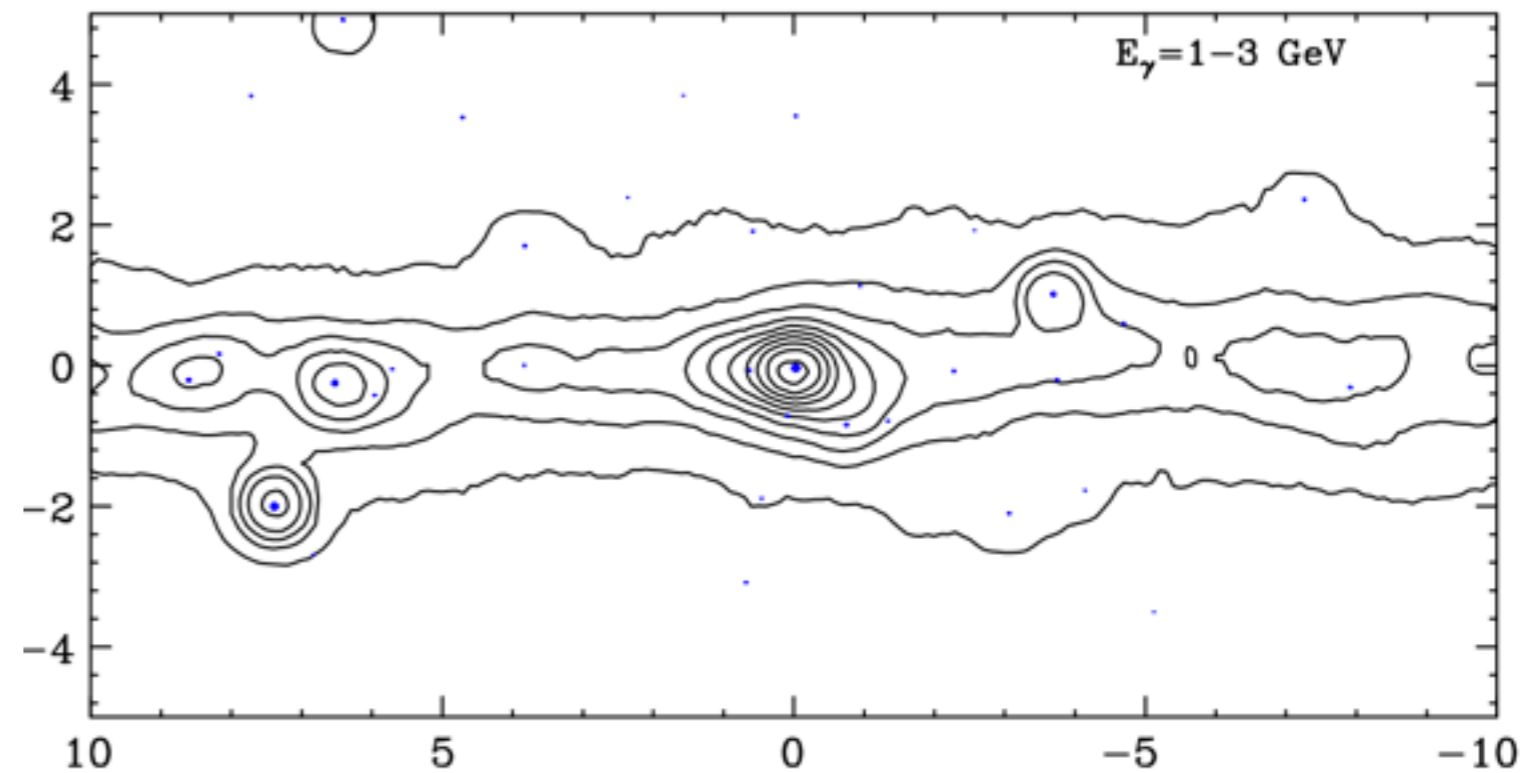
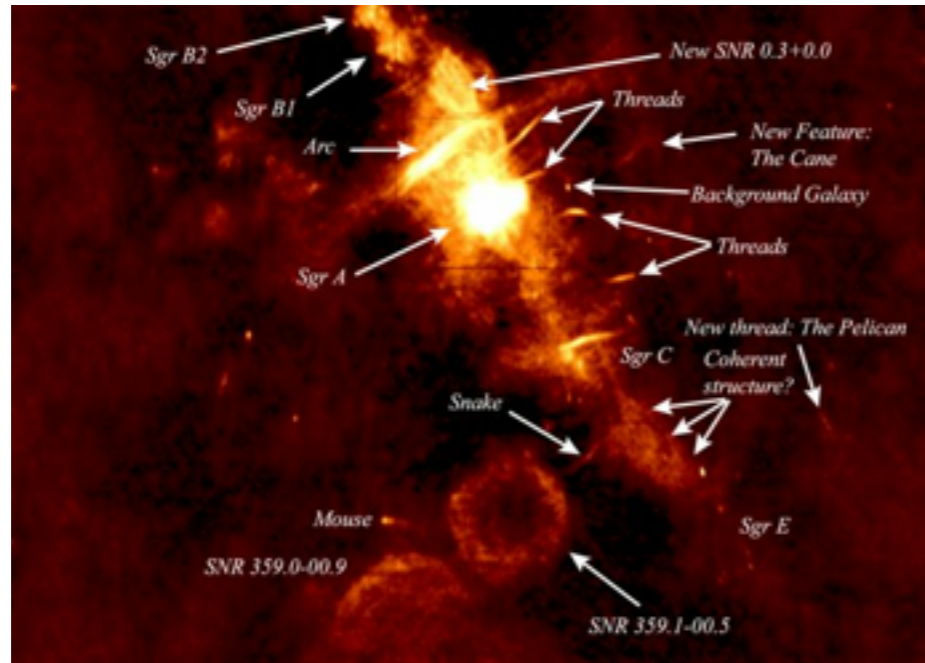
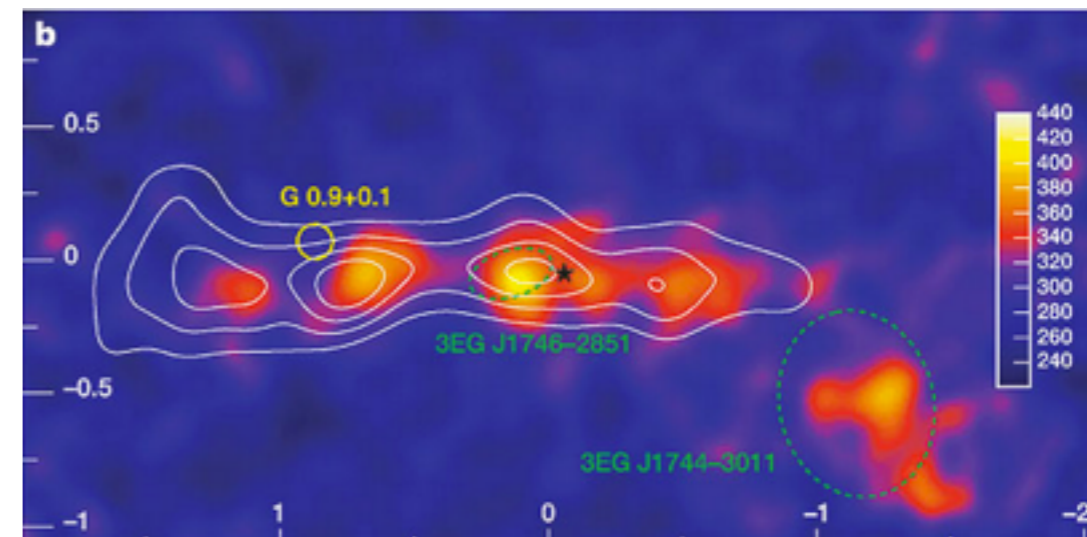


Understanding High Energy Emission from the Galactic Center: 3 Convincing Stories



Tim Linden
UC - Santa Cruz

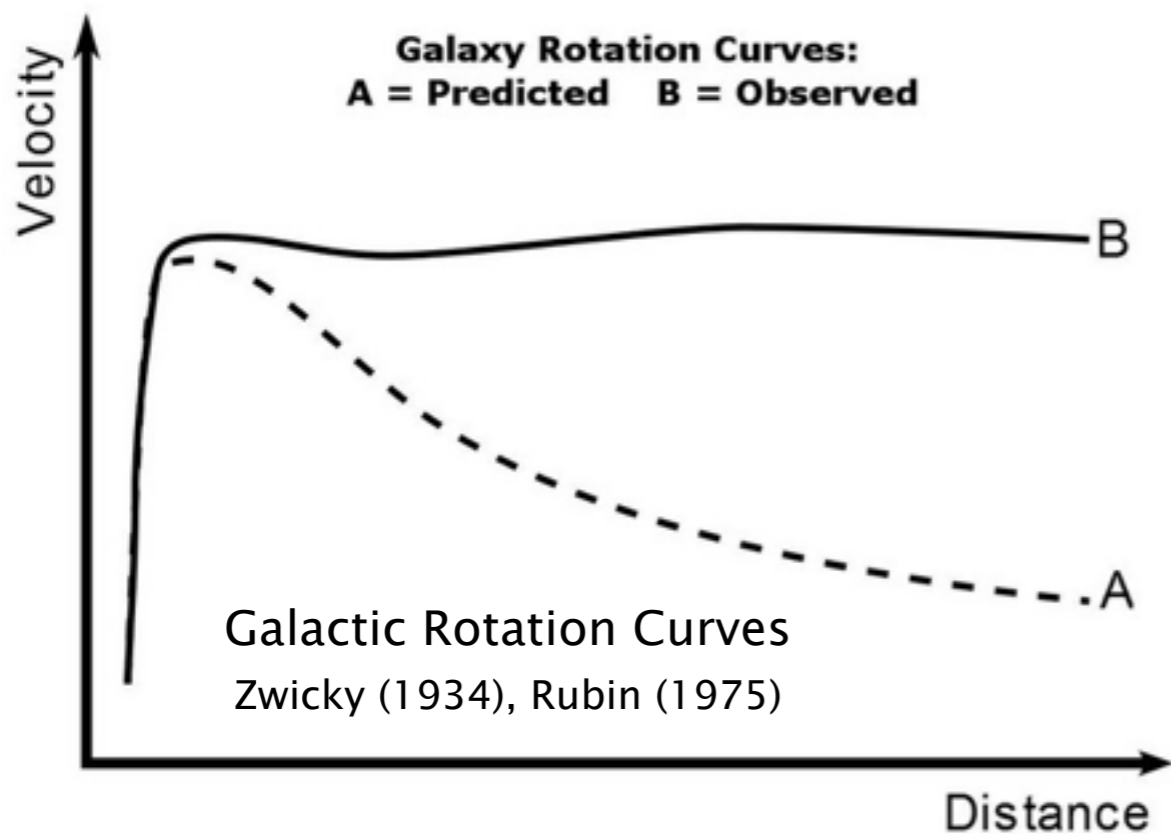
with Brandon Anderson, Dan Hooper,
Elizabeth Lovegrove, Stefano Profumo
and Farhad Yusef-Zadeh



McGill Astro Seminar

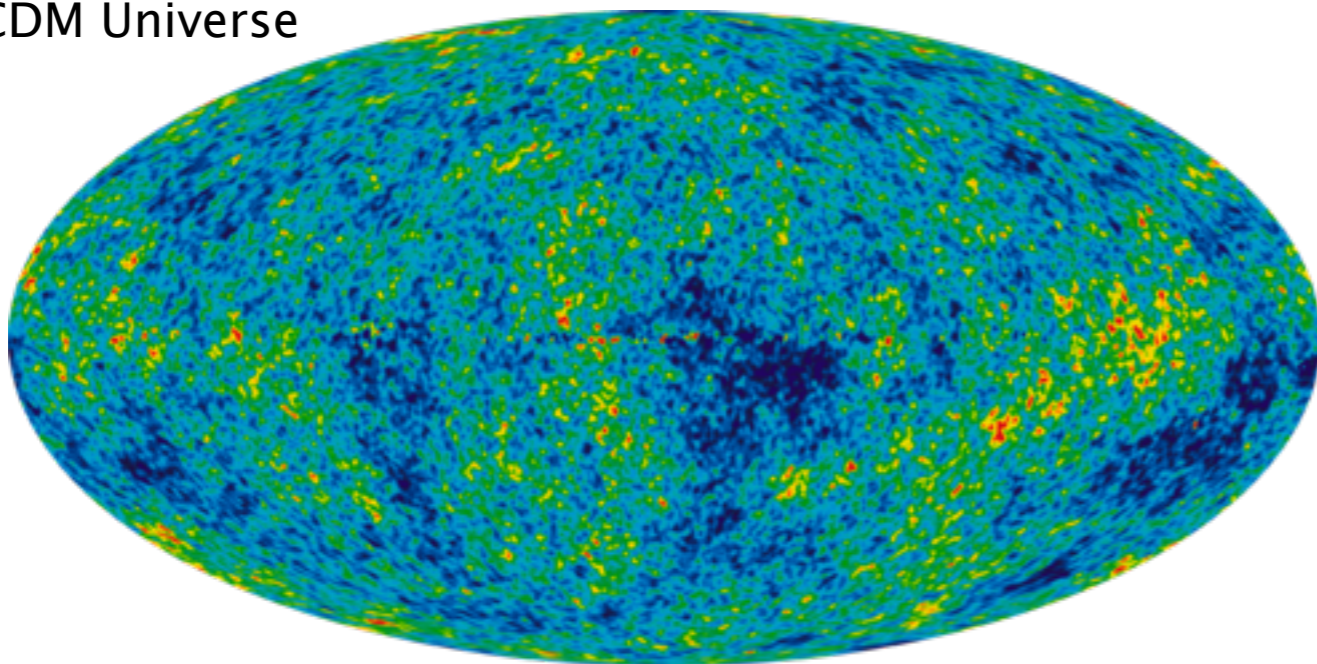
December 5, 2012

Motivating Question: Particle Dark Matter



8σ rejection of some
modified gravity theories
(2006)

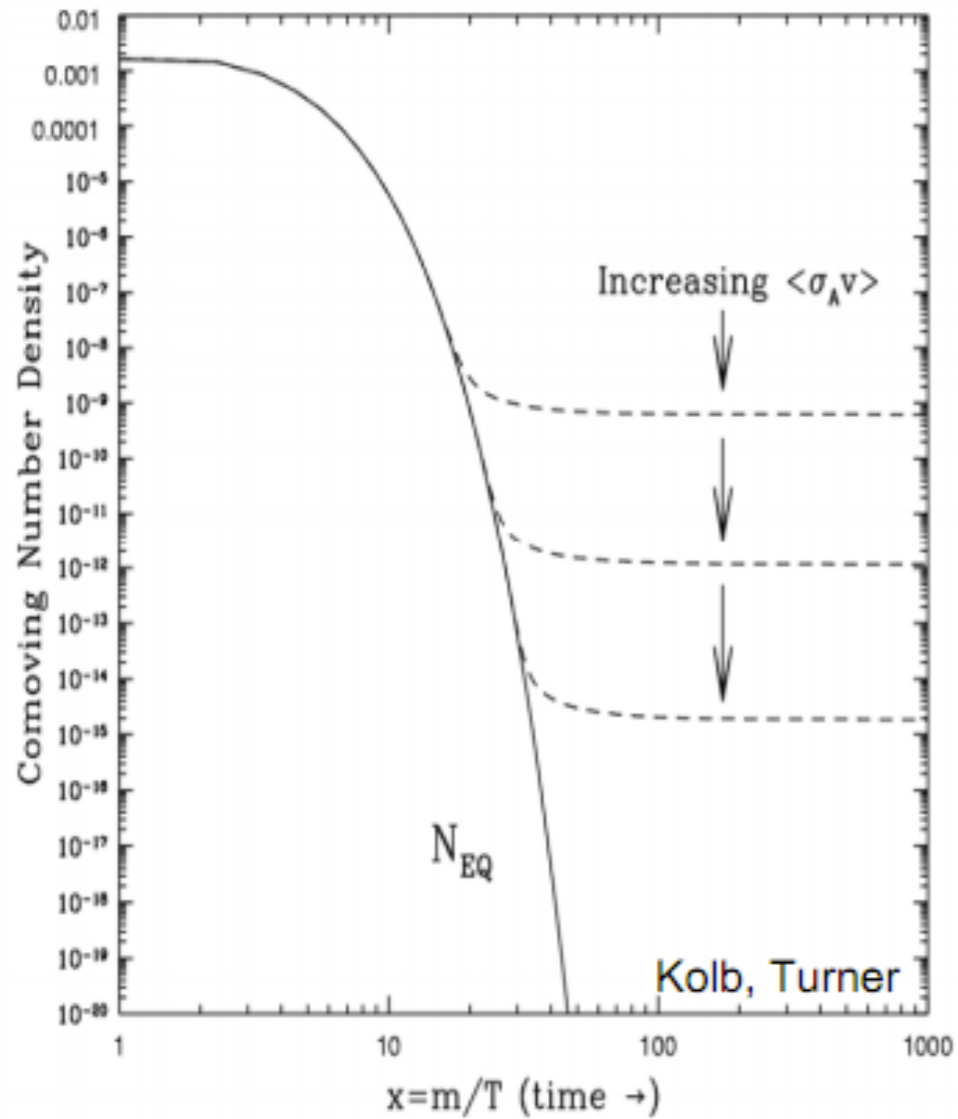
Cosmic Microwave Background is consistent
with Λ CDM Universe



Also:

Baryon Acoustic Oscillations
Gravitational Lensing
Type IA Supernova
Structure Formation
Lyman-alpha Forest

Motivating Question: WIMP Dark Matter Detection



$$\Omega_h \propto \langle \sigma v \rangle^{-1} \propto \frac{M_X^2}{g_X^4}$$

$$M_X^2 = 100 \text{ GeV}$$

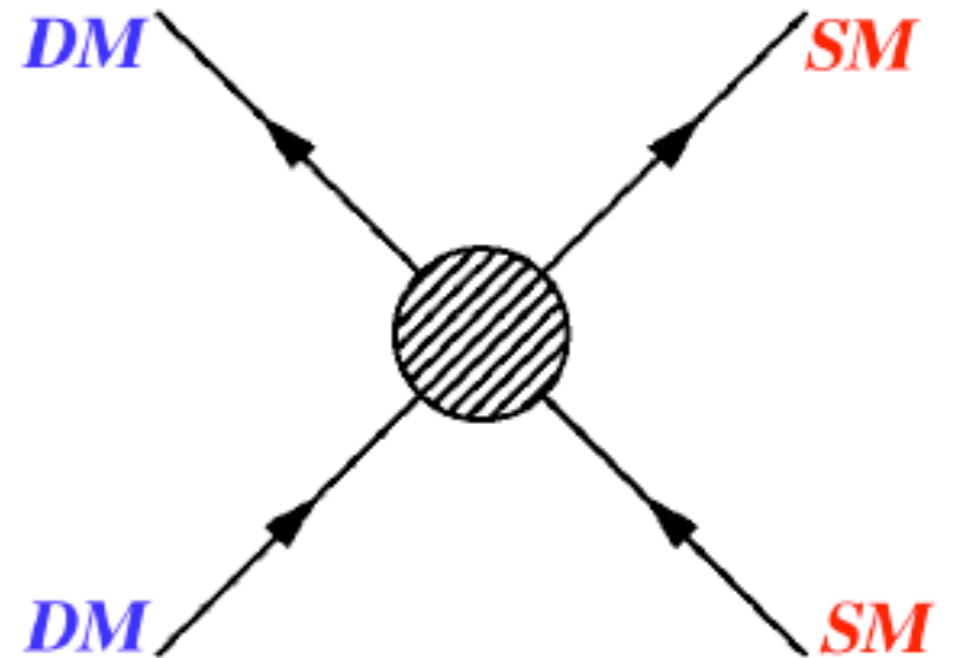
$$\Omega_h \sim 0.1$$

$$g_X^4 = 0.6$$

thermal freeze-out (early Univ.)
indirect detection (now)



direct detection

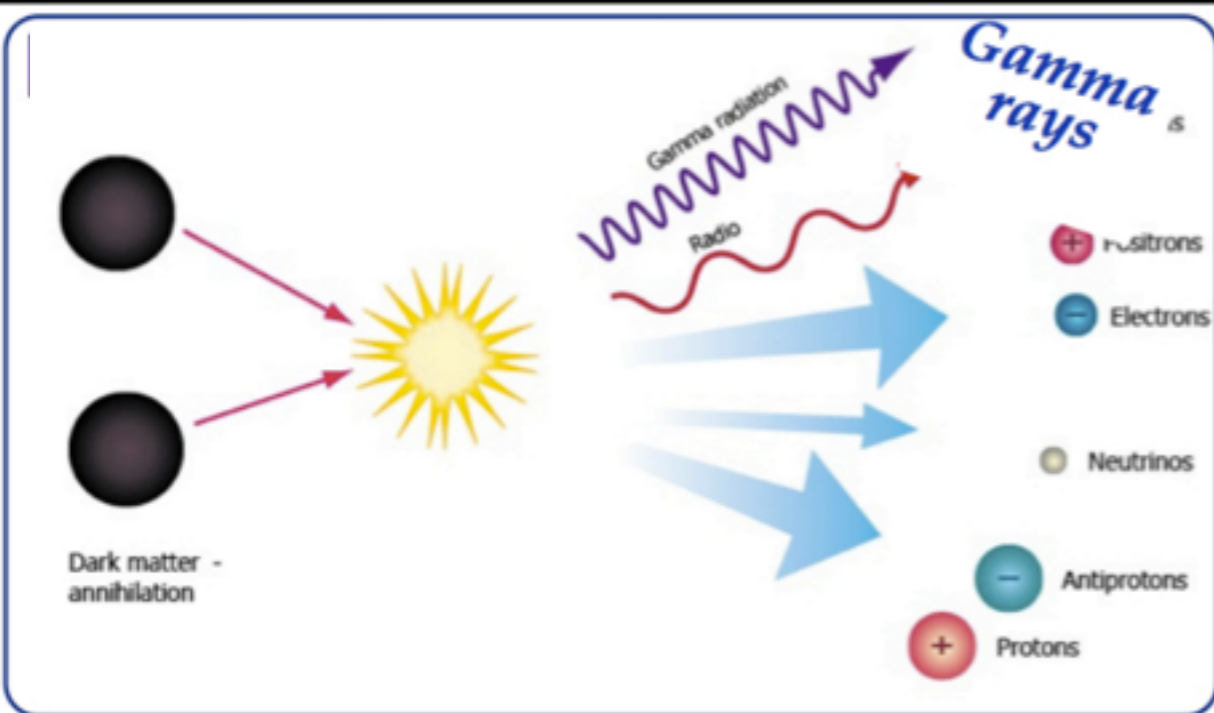


production at colliders

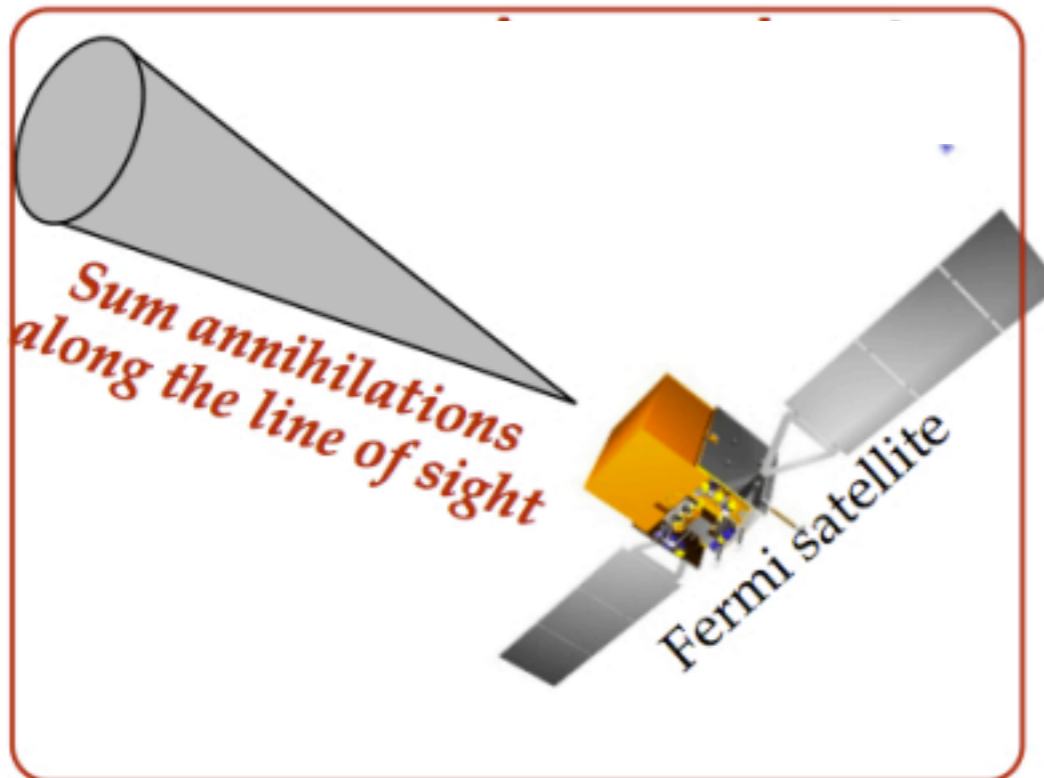


Motivating Question: Dark Matter Indirect Detection

Particle Physics

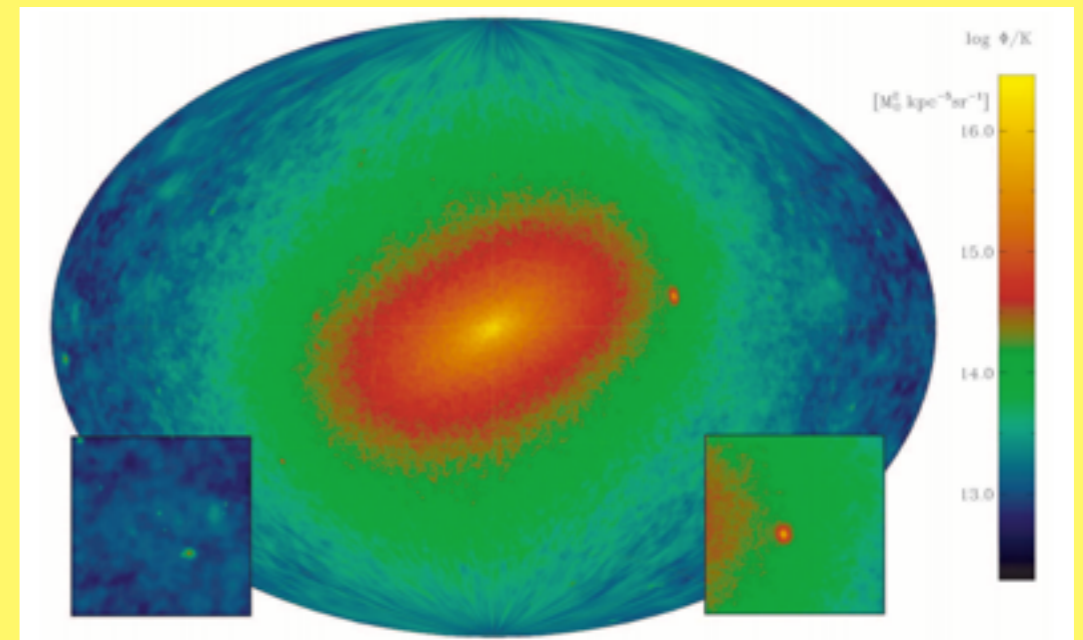


Slides Courtesy of G. Zaharijas



Instrumental Response

Astrophysics



Diemand et al. 2008

Motivating Question:

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

Slides Courtesy of G. Zaharijas

Diemand et al. 2008

The J-Factor of the Galactic Center

Ackermann et al. 2012

Dwarfs

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

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

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

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

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

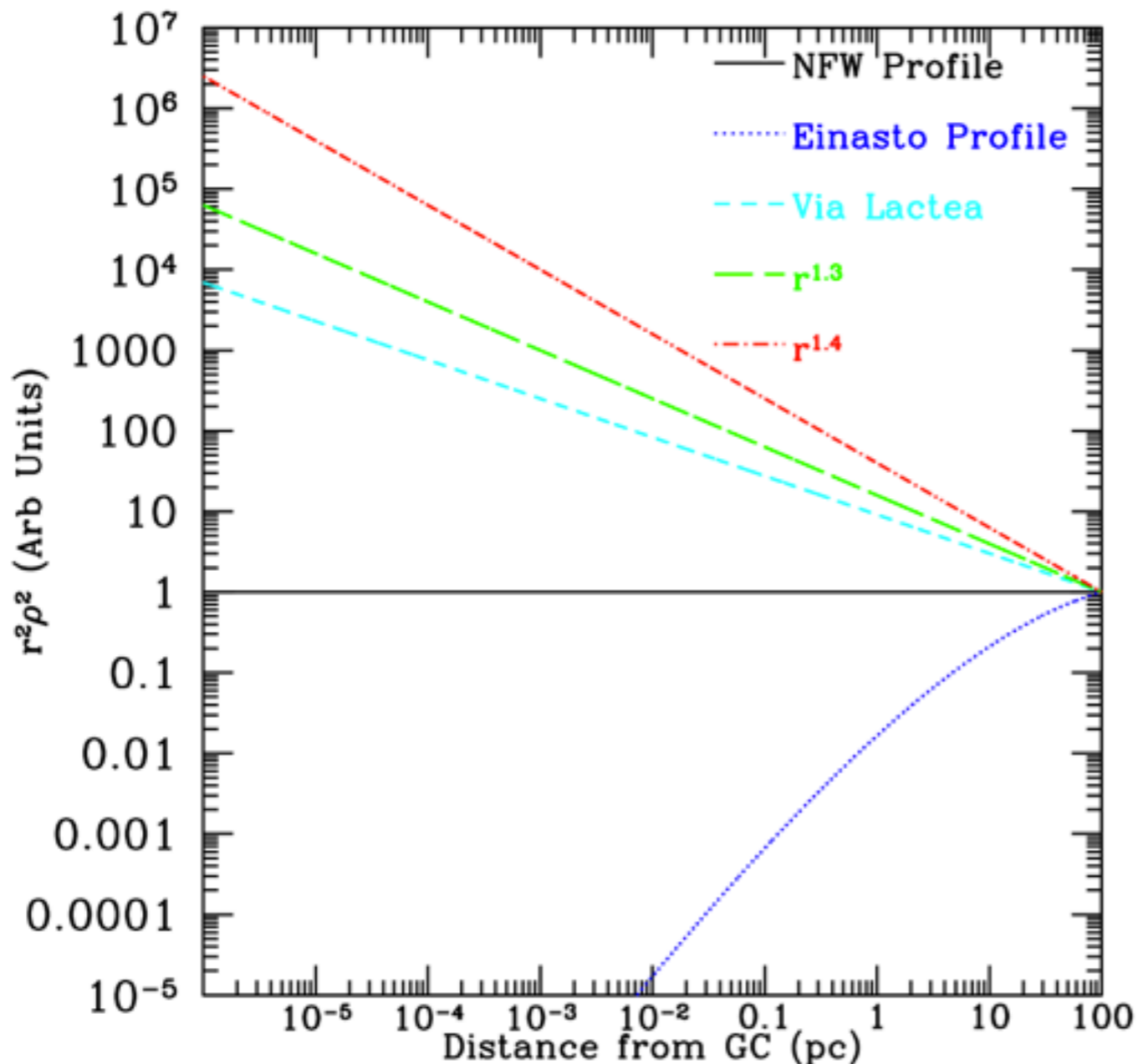
for a region within 100 pc of the Galactic center and an NFW profile

Ackermann et al. 2010

Clusters

Cluster	RA	Dec.	z	J ($10^{17} \text{GeV}^2 \text{cm}^{-5}$)
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	$1.7^{+0.1}_{-0.1}$

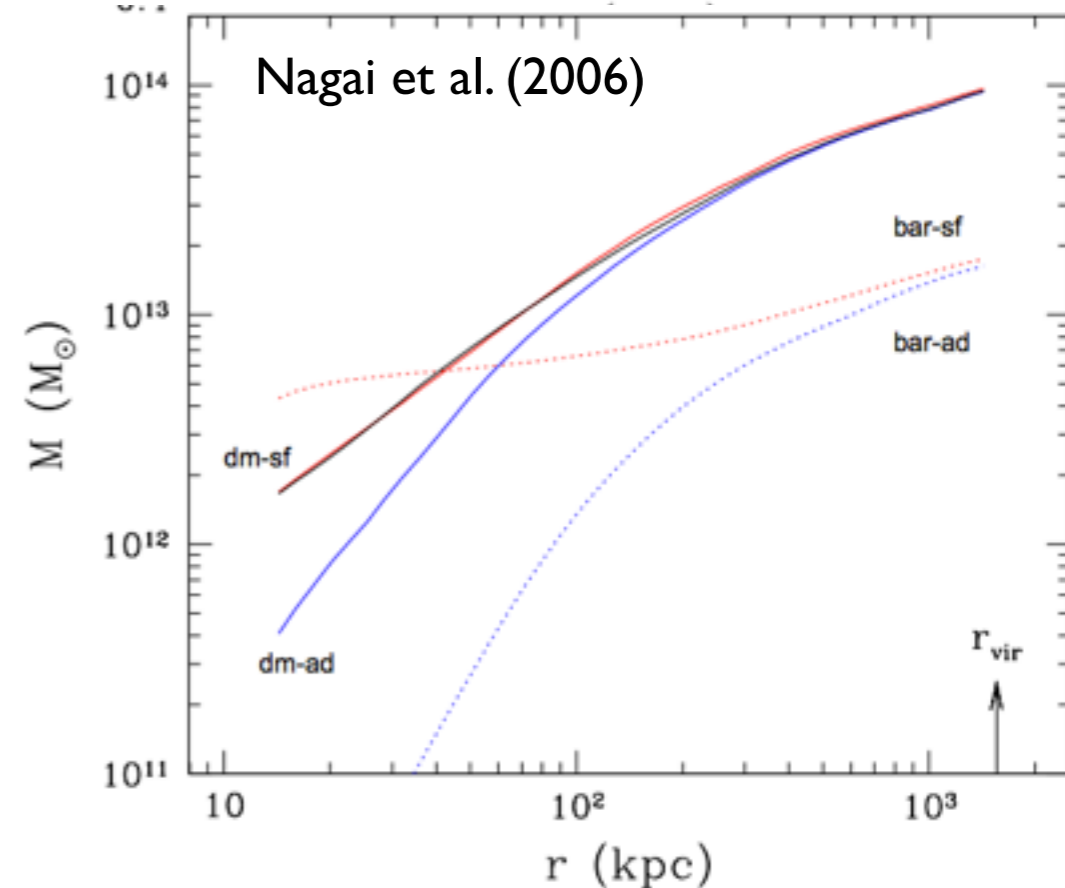
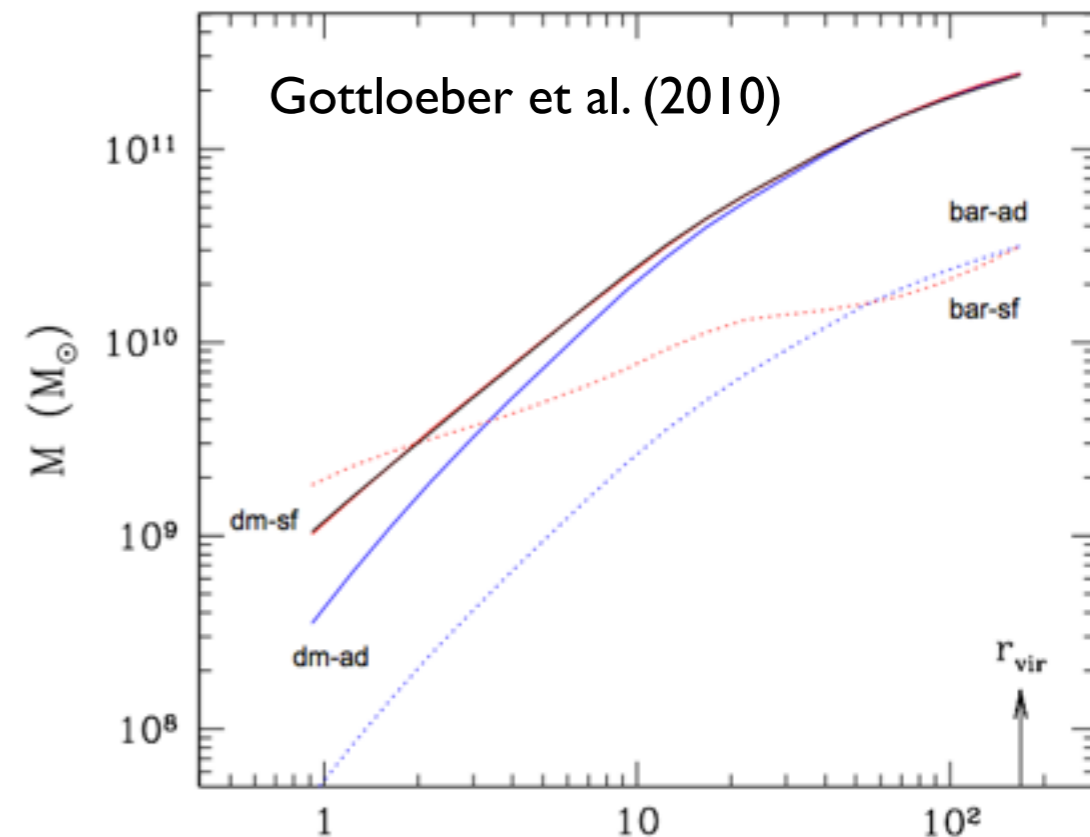
Negative: The Profile Dependence



- 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

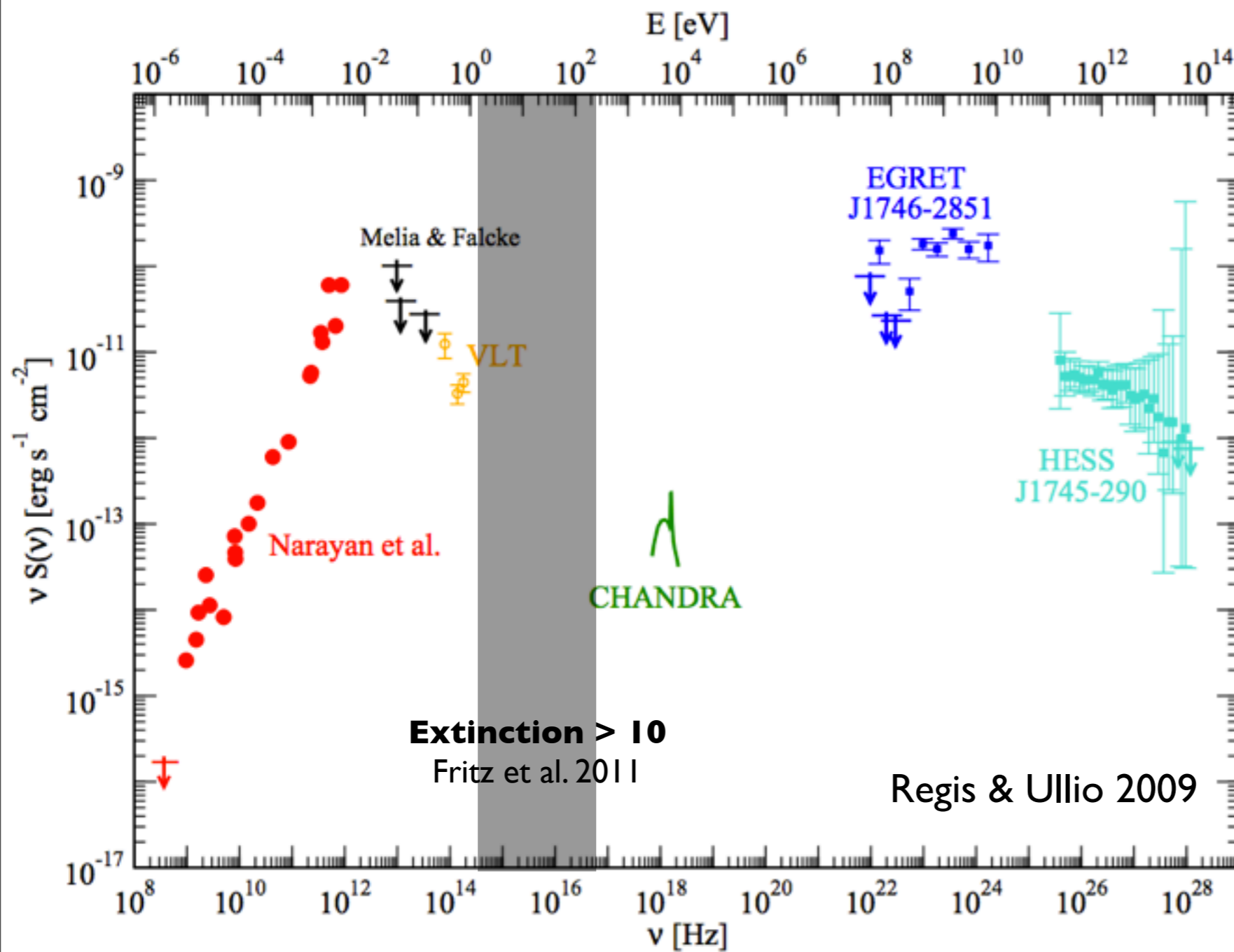
Positive! Progress in Simulations

- Simulations including the effects of baryonic contraction show a steepening of the spectral slope from $\gamma \approx 1.0$ to $\gamma \approx 1.2-1.5$
- 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

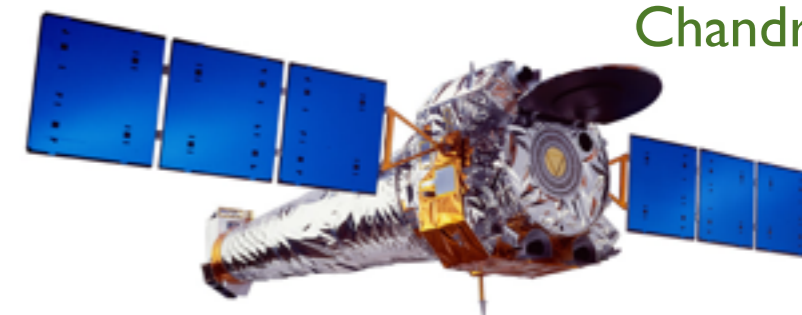
The Multi-wavelength Galactic Center



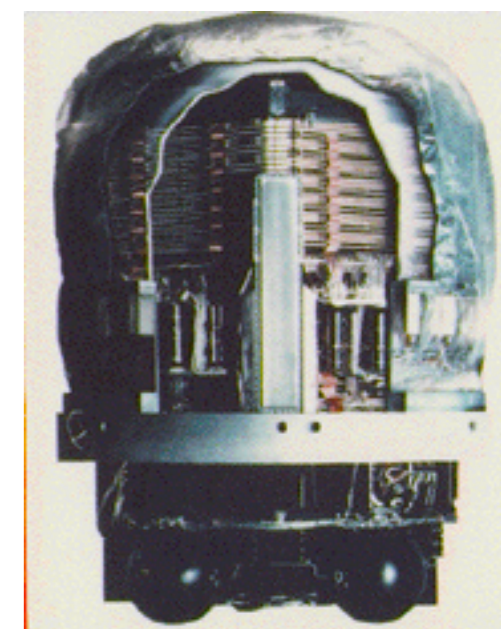
VLA



Chandra



EGRET



HESS



Fermi-LAT



Angular Scales of the Galactic Center

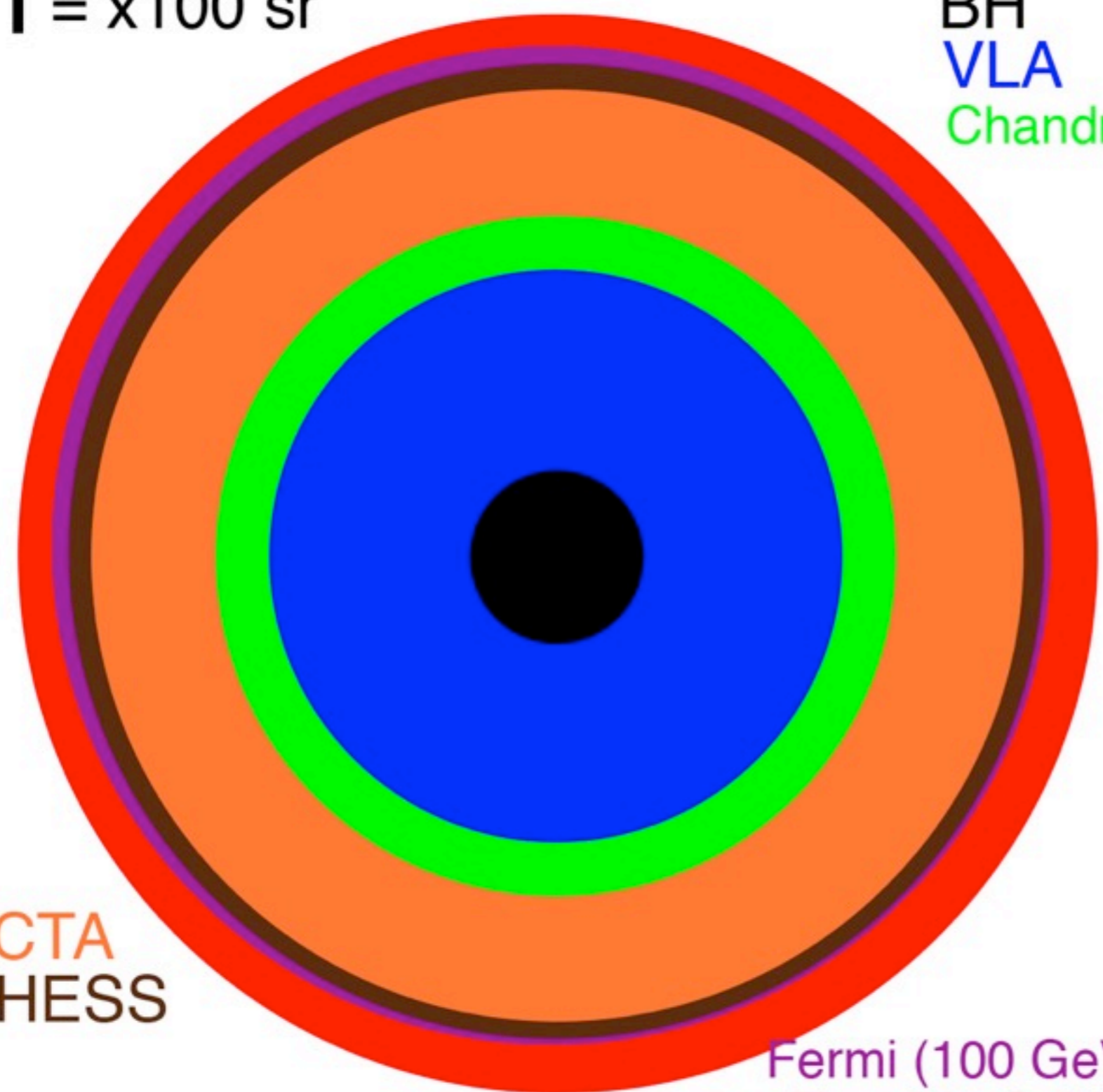
$\text{I} = \times 100 \text{ sr}$

BH
VLA
Chandra

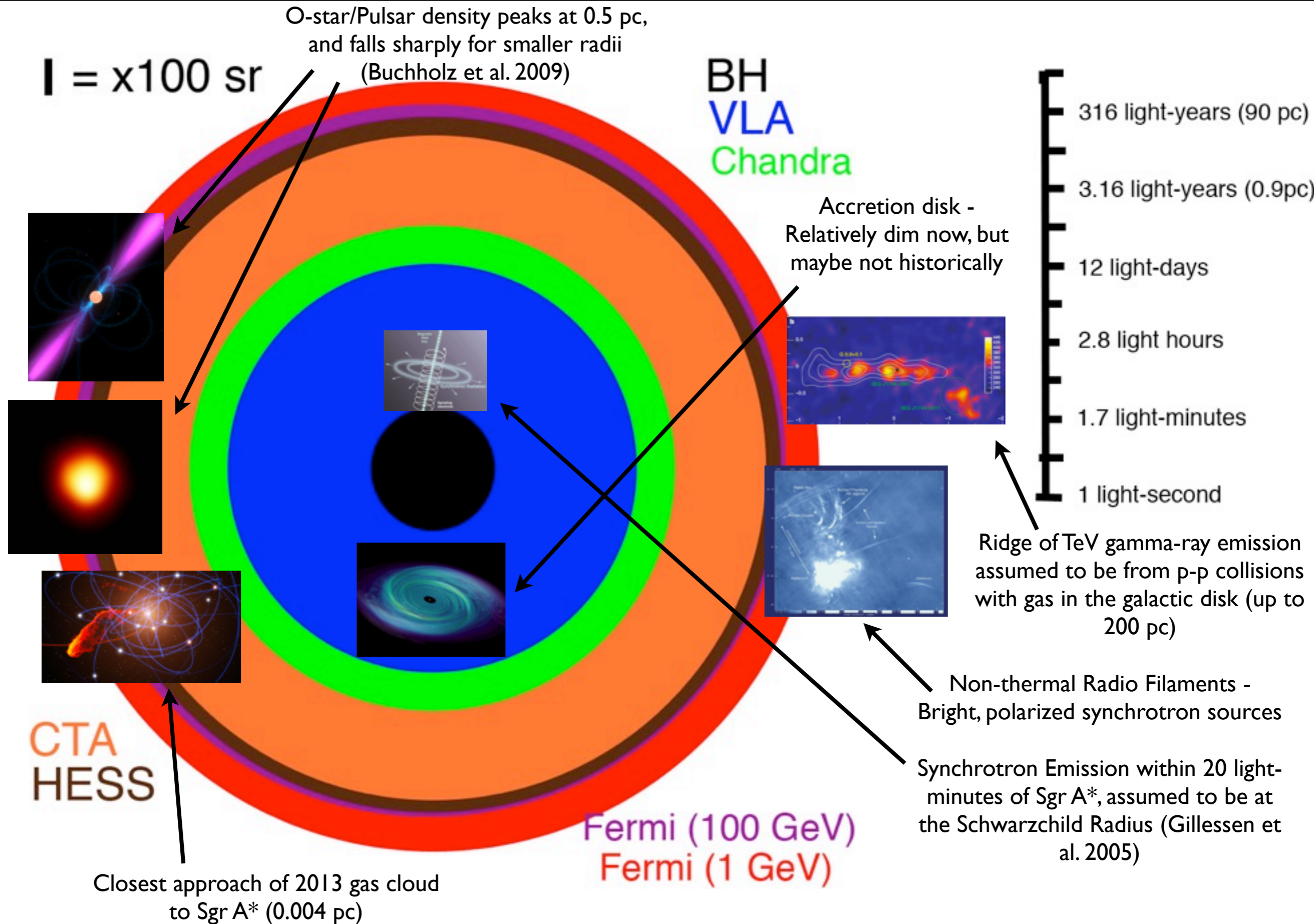


CTA
HESS

Fermi (100 GeV)
Fermi (1 GeV)



The Galactic Center "Zoo"



| = x100 sr

The “Game” of dark matter detection at the galactic center is accurate astrophysical modeling

BH
VLA
Chandra

316 light-years (90 pc)

3.1 light-years (0.9 pc)

12 light-days

2.3 light-hours

17 light-minutes

1 light-second

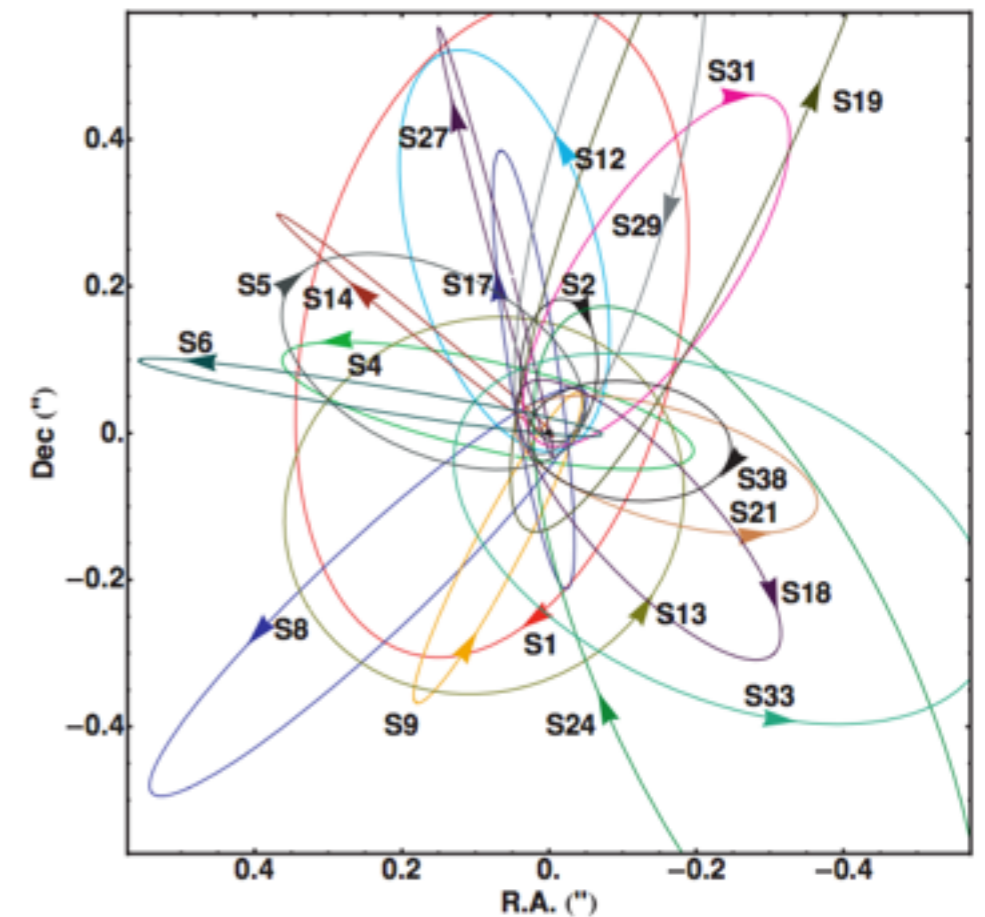
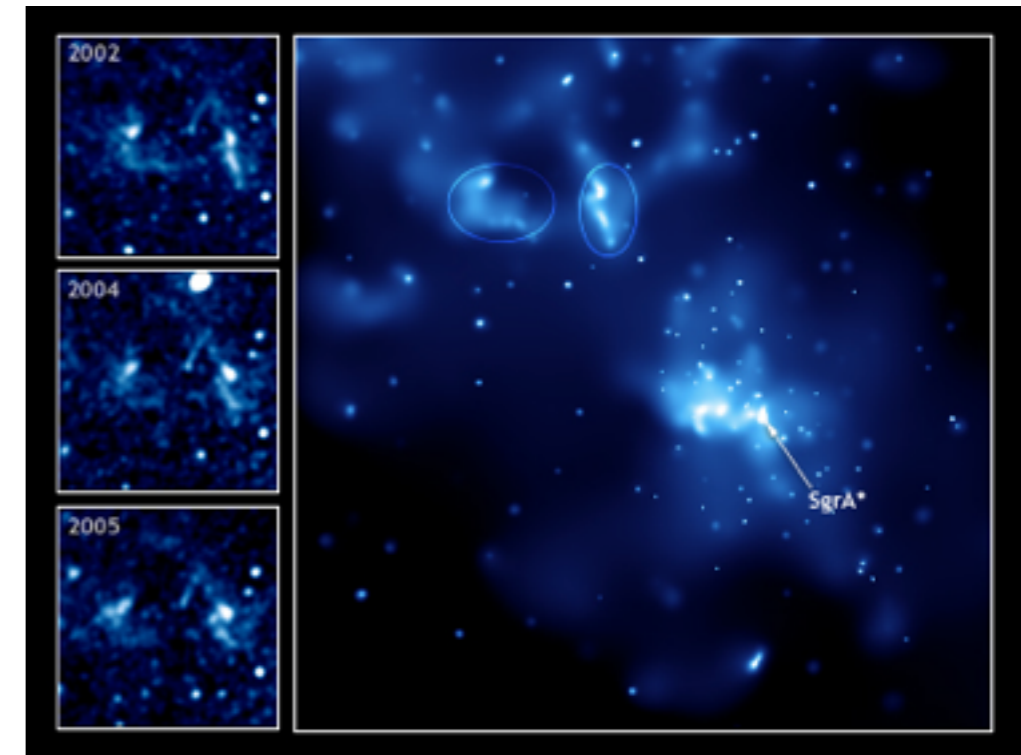
CTA
HESS

Fermi (100 GeV)
Fermi (1 GeV)

History of Galactic Center Observations (in 60 seconds)

Muno et al. 2007

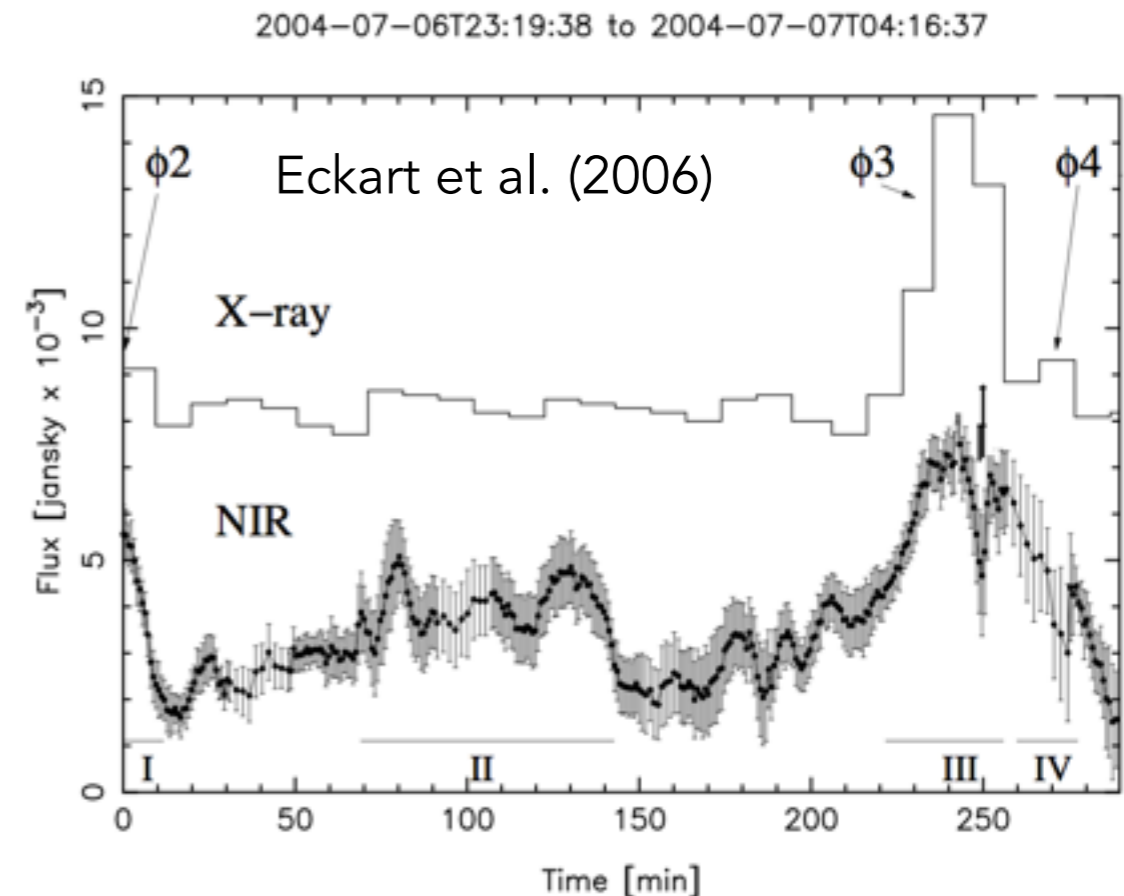
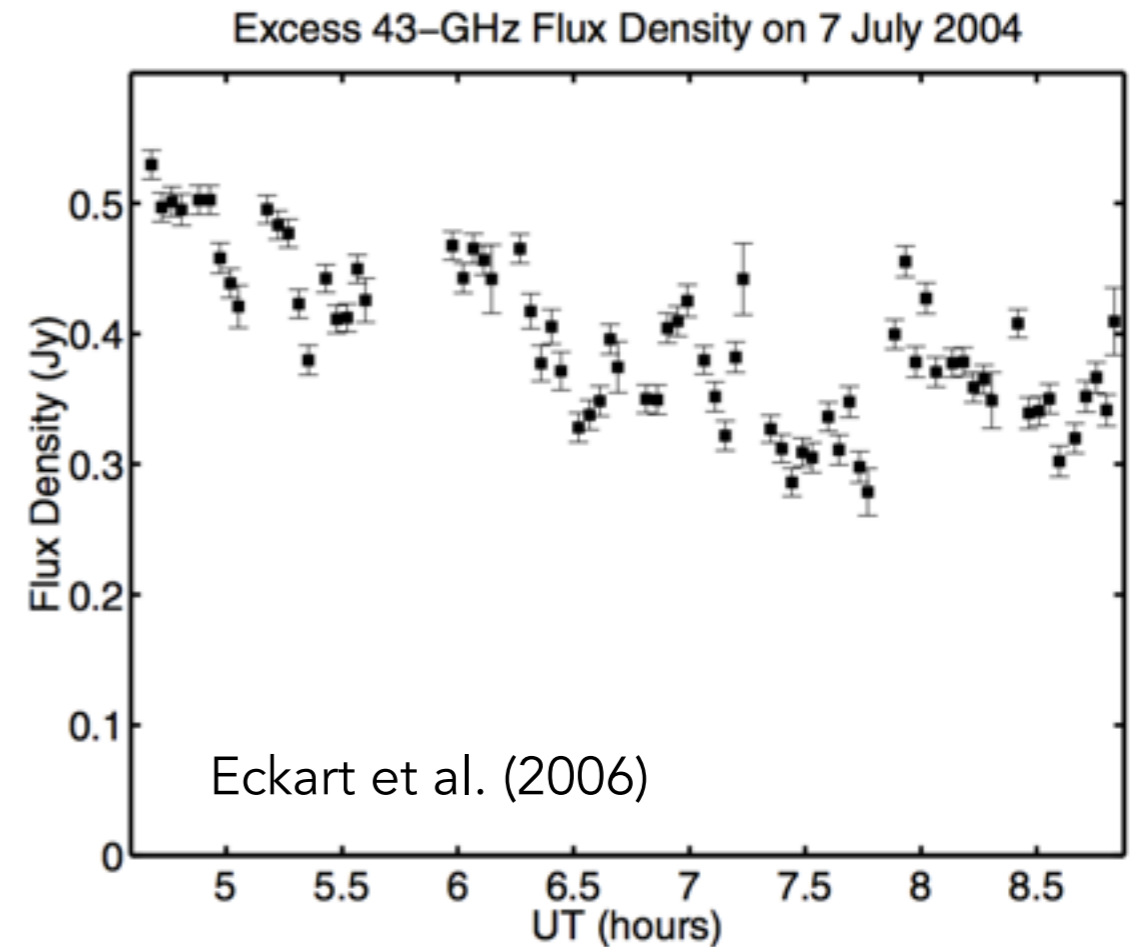
- Sgr A* Discovered via radio observations in 1974
- Measurements of stellar motion confirm the status of the central object as a black hole (Gillissen et al. 2009)
- Majority of radio emission thought to stem from accretion disk, rather than at BH event horizon (Doeleman et al. 2008)



Gillissen et al. 2009

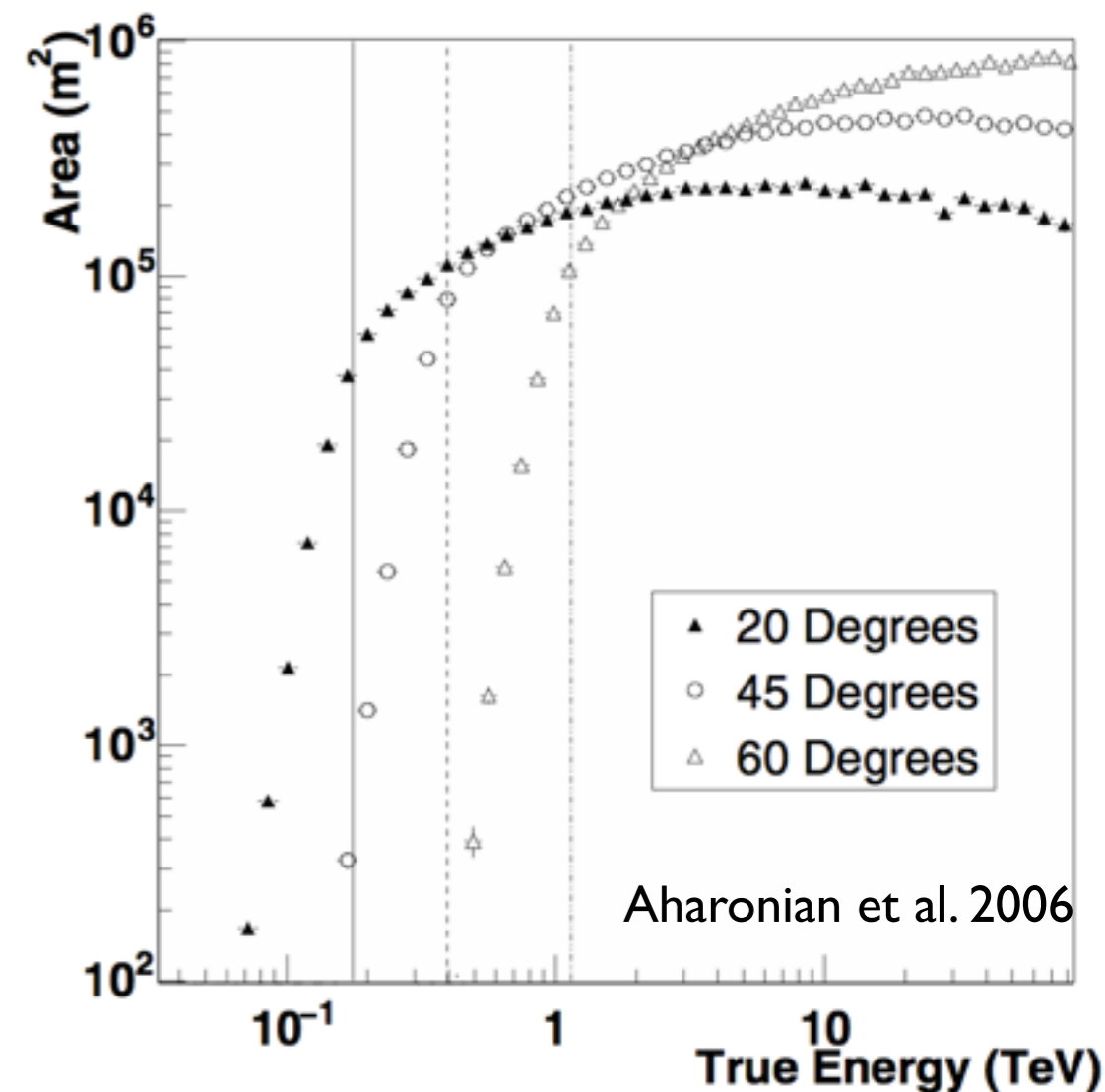
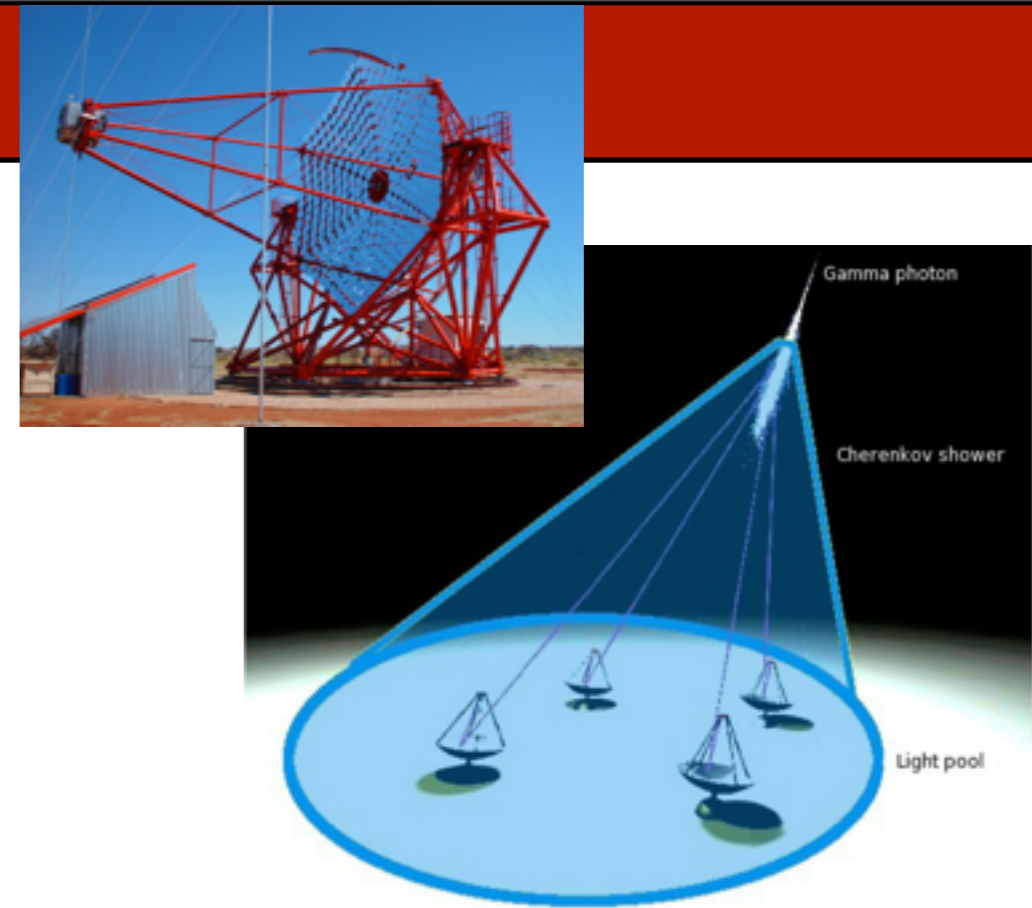
Variability at the Galactic Center

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



HESS Telescope (2004-Present)

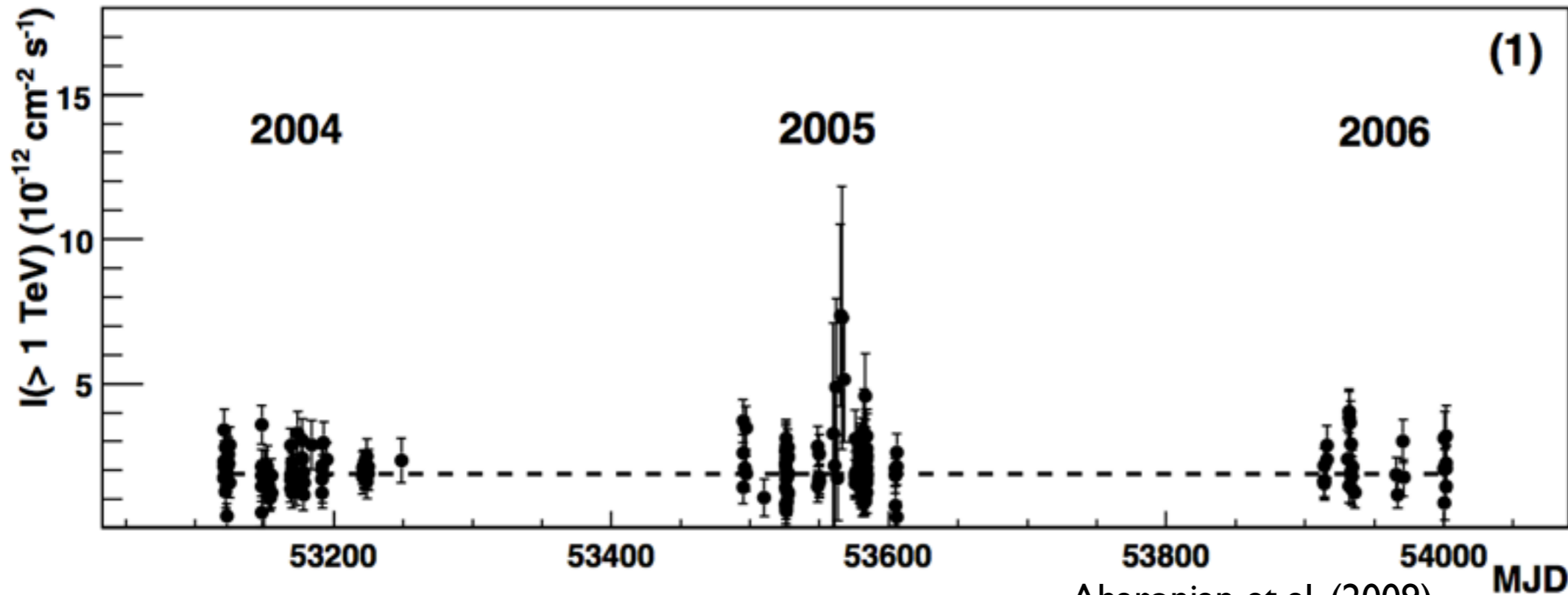
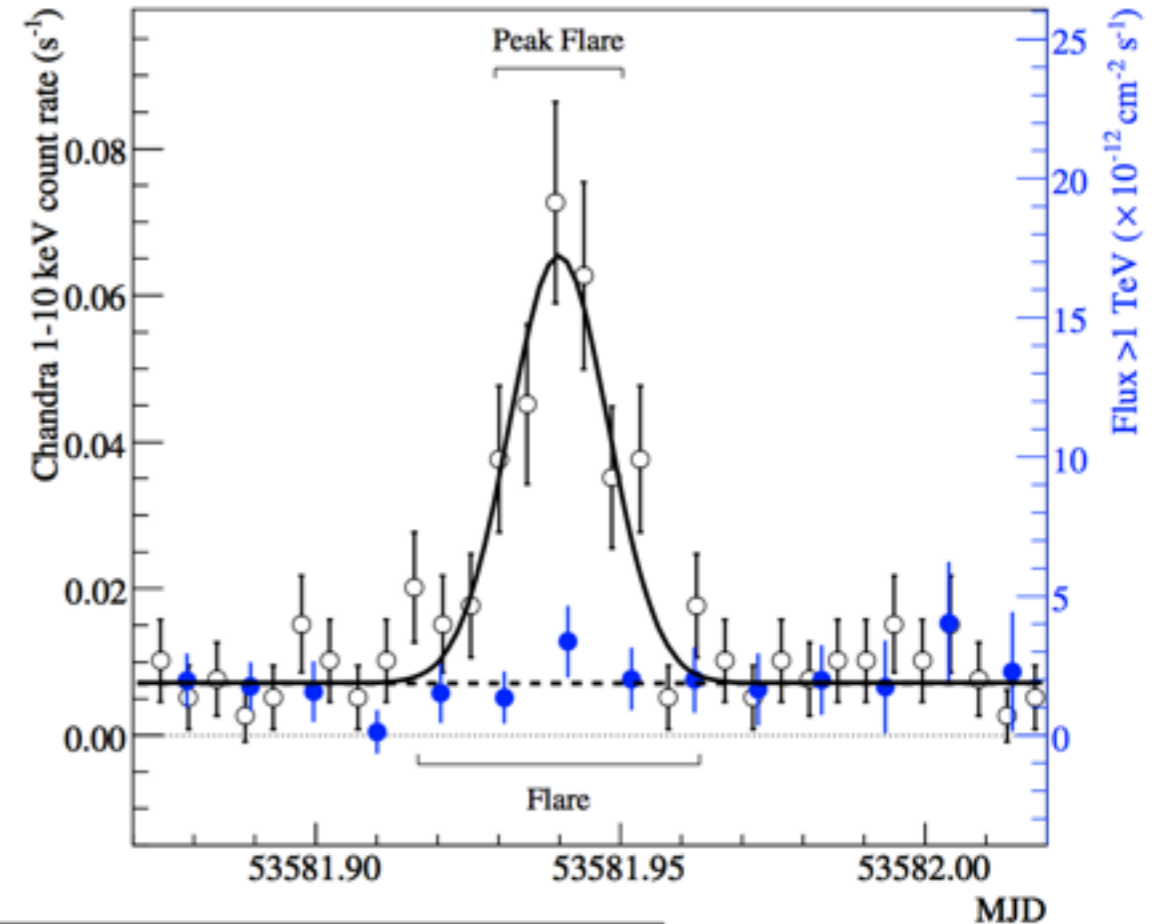
- HESS is an Atmospheric Cherenkov Telescope built in Namibia
- Effective over the energy range ~ 500 GeV - 100 TeV with an effective area on the order of 10^5 m².
- Energy Resolution $\sim 10\%$
- Angular Resolution (>1 TeV) $\sim 0.075^\circ$.
- Total Observation of the Galactic Center: 93h/112h



Understanding Astrophysical Backgrounds: HESS

- 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. (2008)



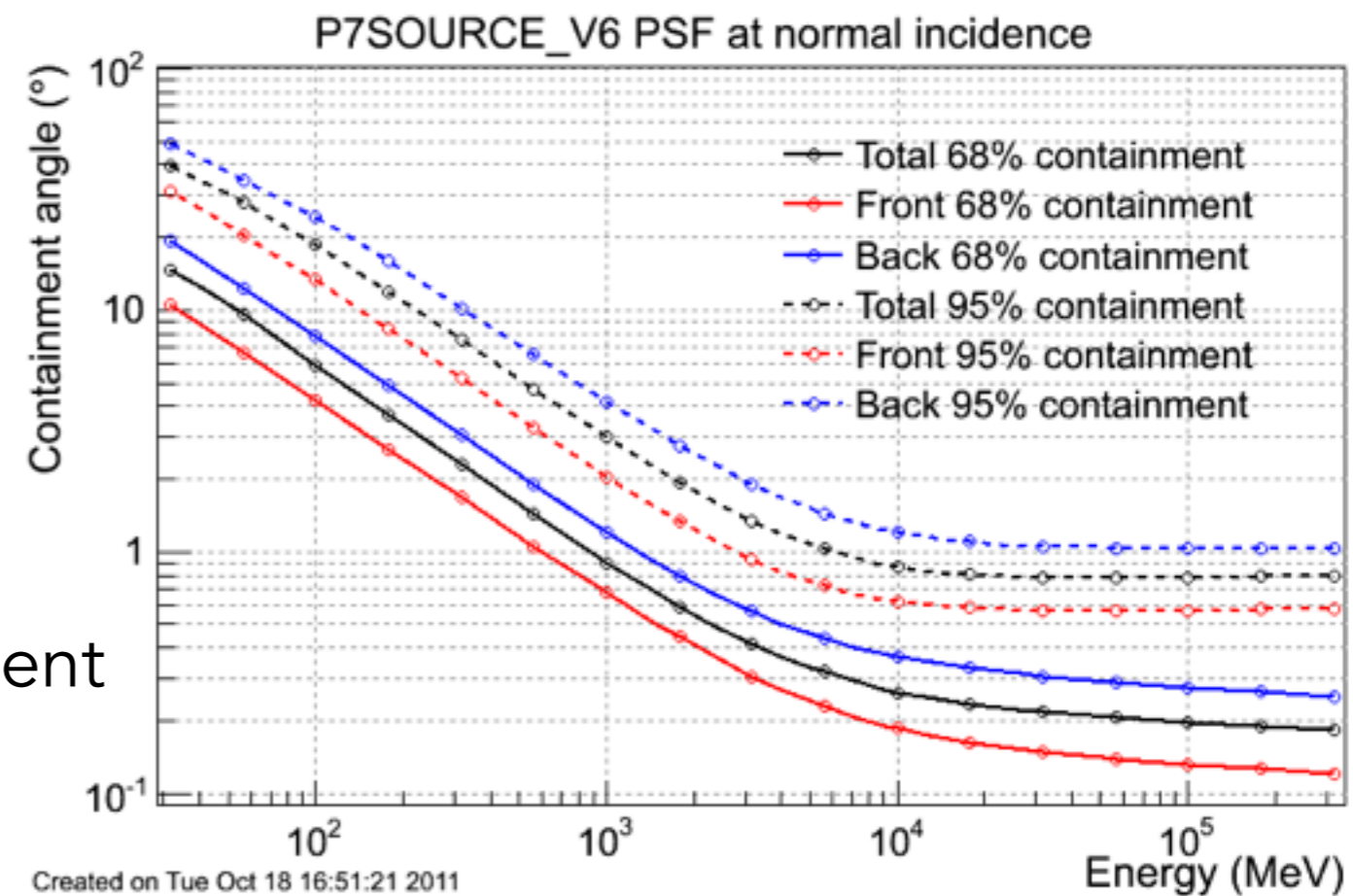
Aharonian et al. (2009)

Fermi Telescope (2008-Present)



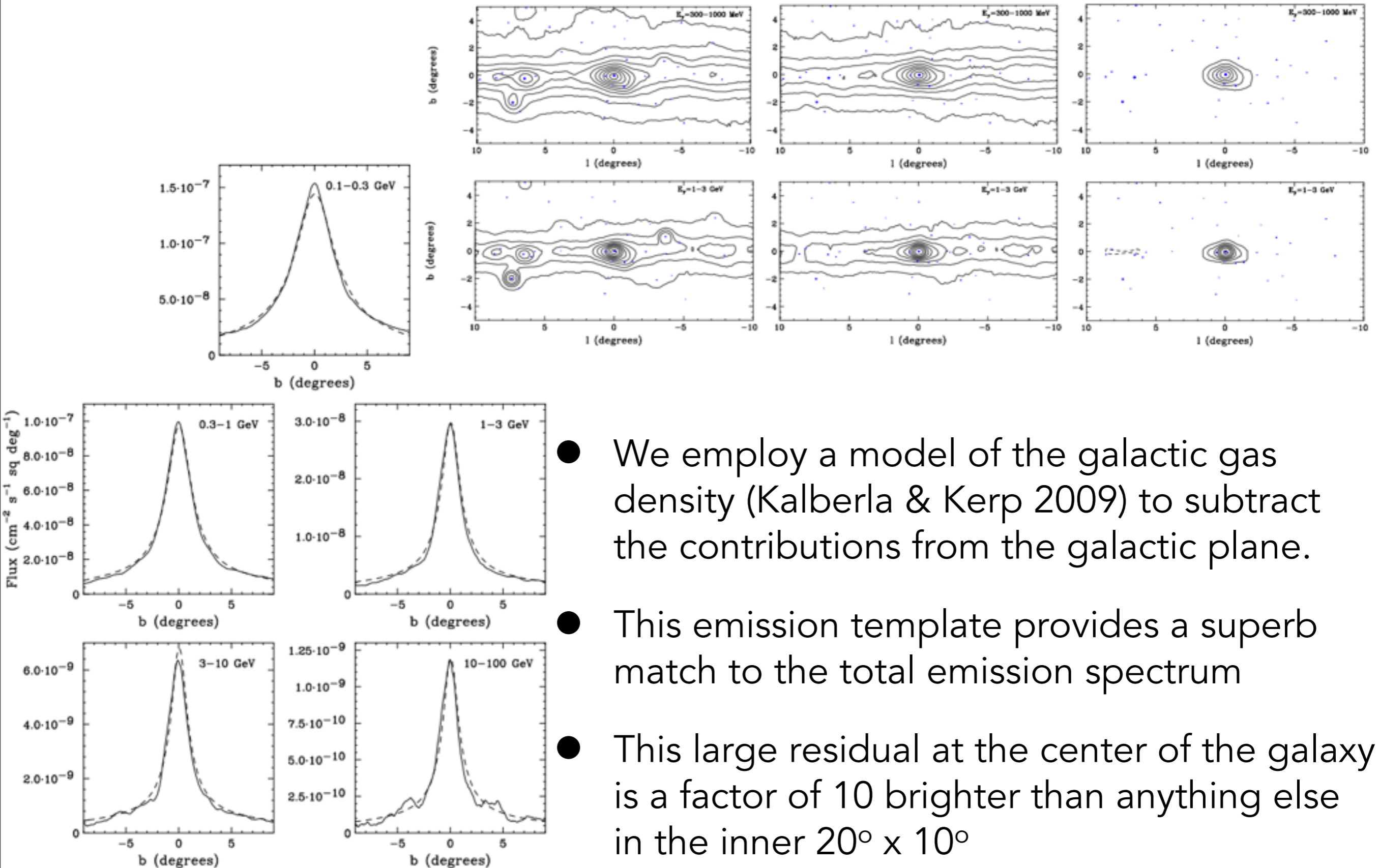
- Fermi-LAT is a space based gamma-ray detector with an effective energy range of 20 MeV-300 GeV

- Effective Area $\sim 0.8 \text{ m}^2$
- Field of View $\sim 2.4 \text{ sr}$
- Energy Resolution $\sim 10\%$
- Angular Resolution: Energy Dependent



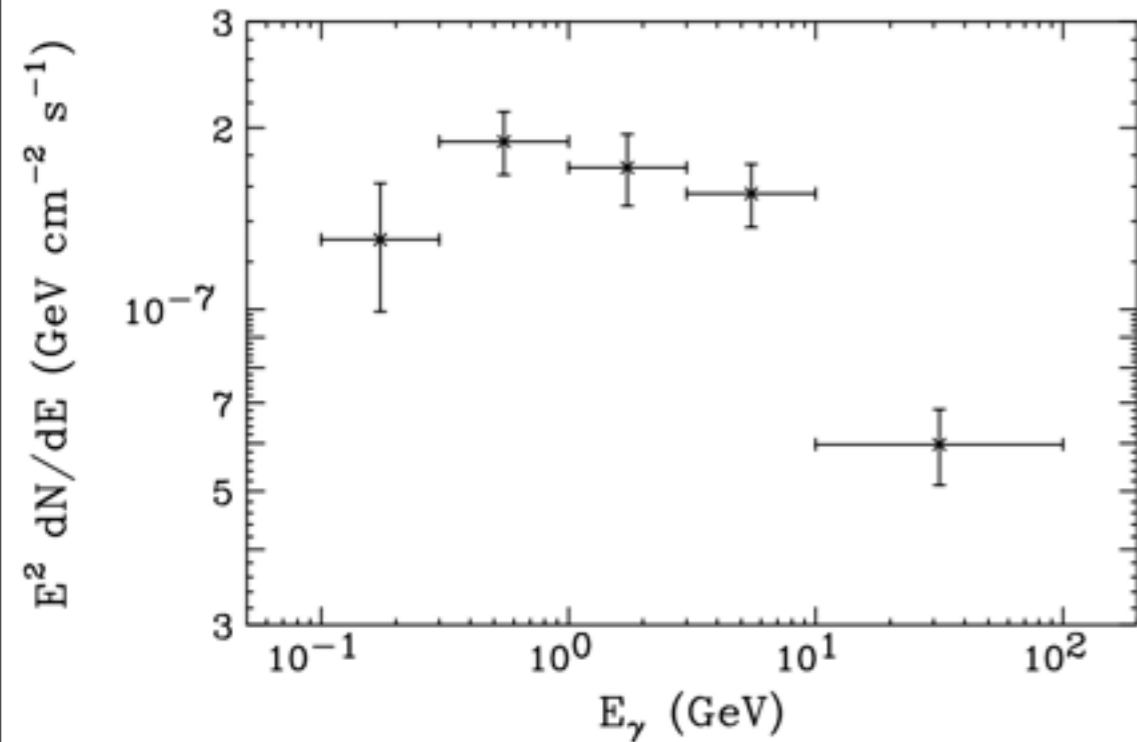
- In analyses of the Galactic Center, we will constrict ourselves to Front converting events

Subtracting the Astrophysical Background: Fermi



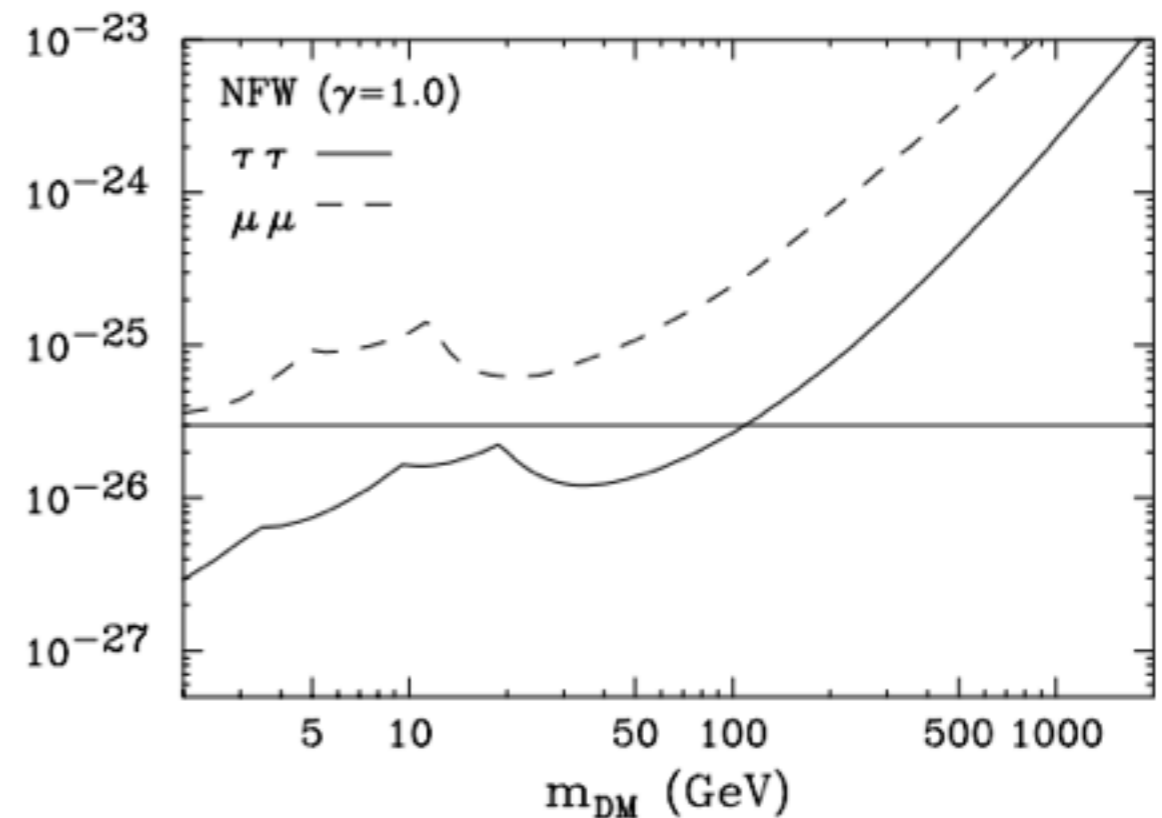
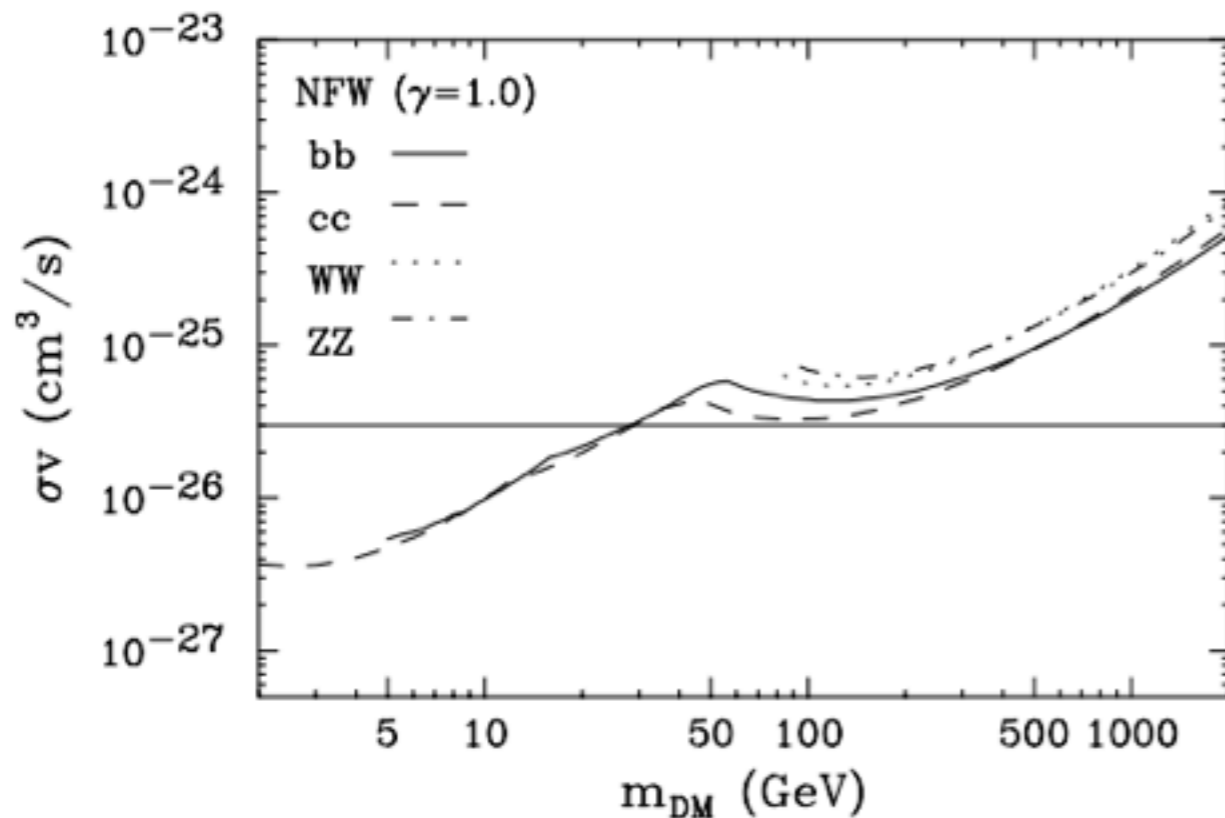
- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum
- This large residual at the center of the galaxy is a factor of 10 brighter than anything else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

Dark Matter Limits in the Simplest Way Possible

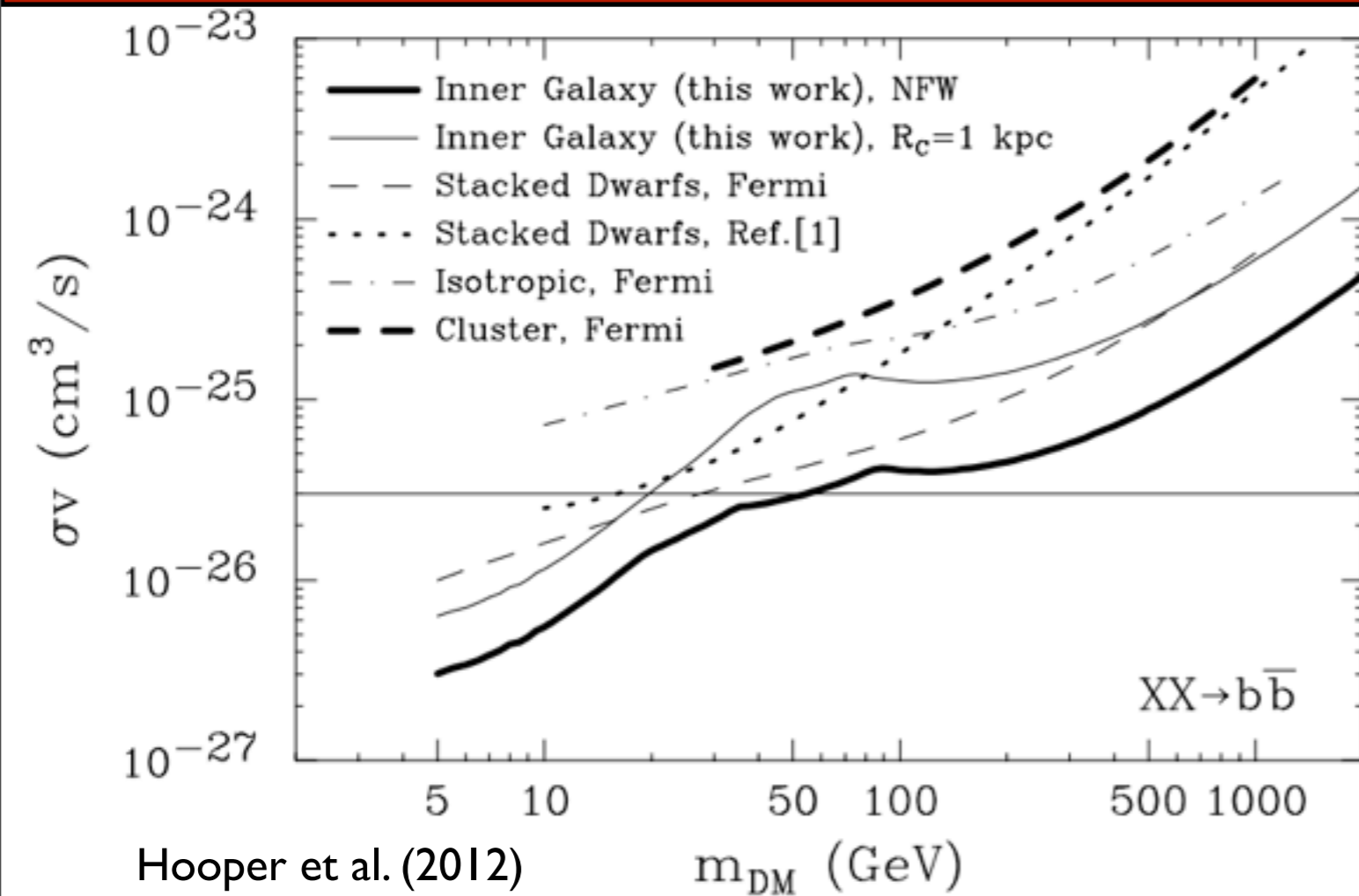


Hooper & Linden (2011)

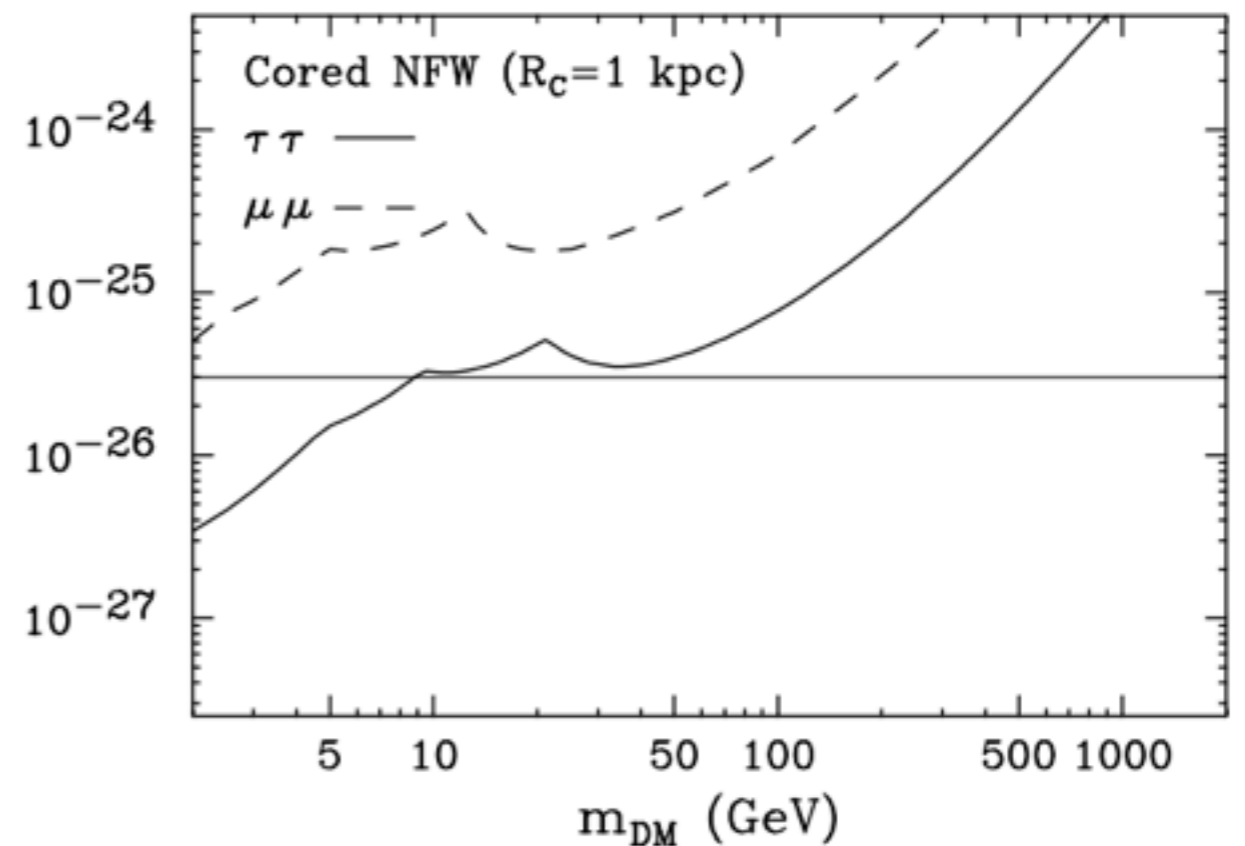
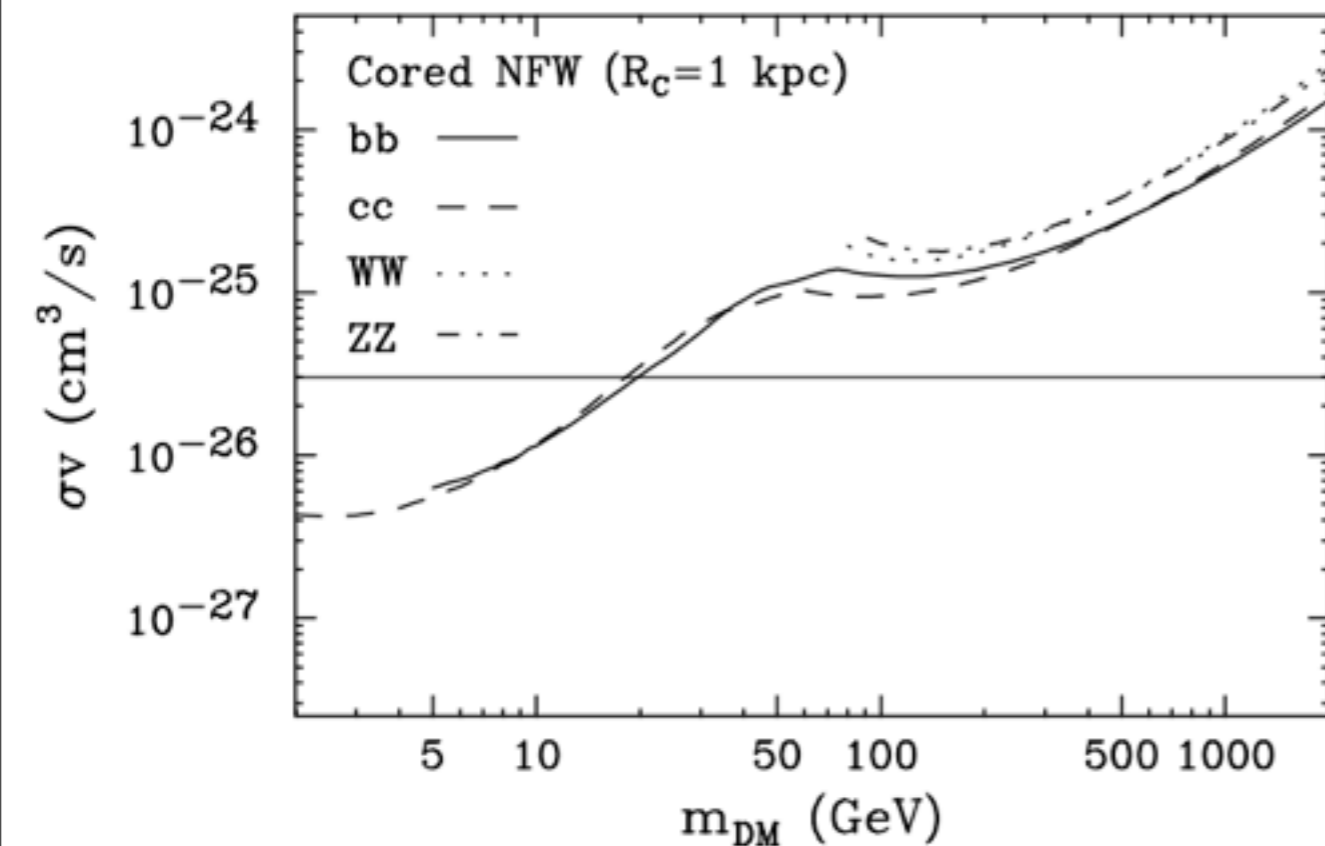
- After subtracting emission from known point sources, and an extrapolation of the line-of-sight gas density, the following "galactic center" emission is calculated
- This directly corresponds to a limit on the dark matter interaction cross-section which depends only on assumed dark matter density profile



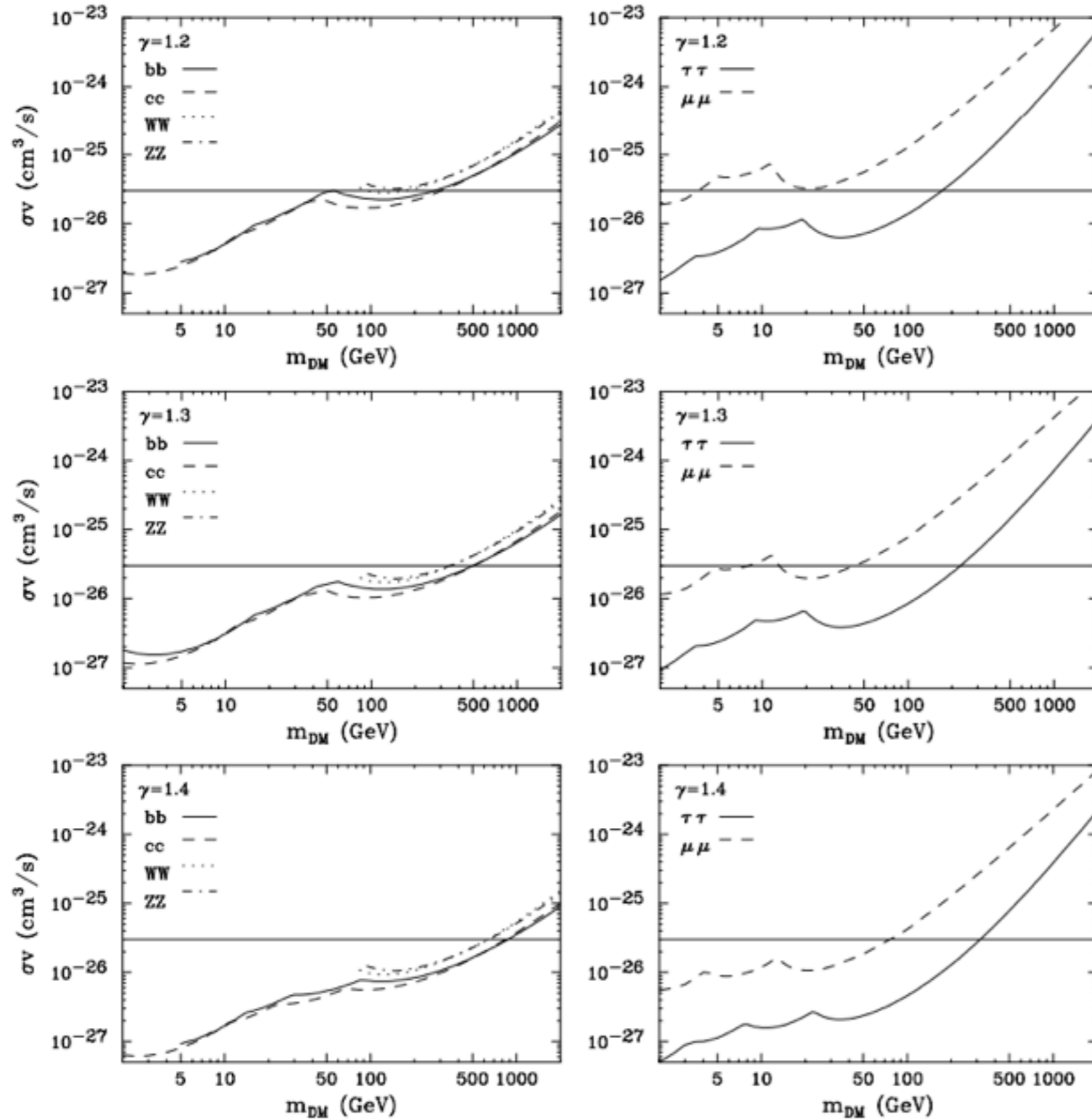
Comparison to Other Indirect Detection Regimes



- Hooper 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

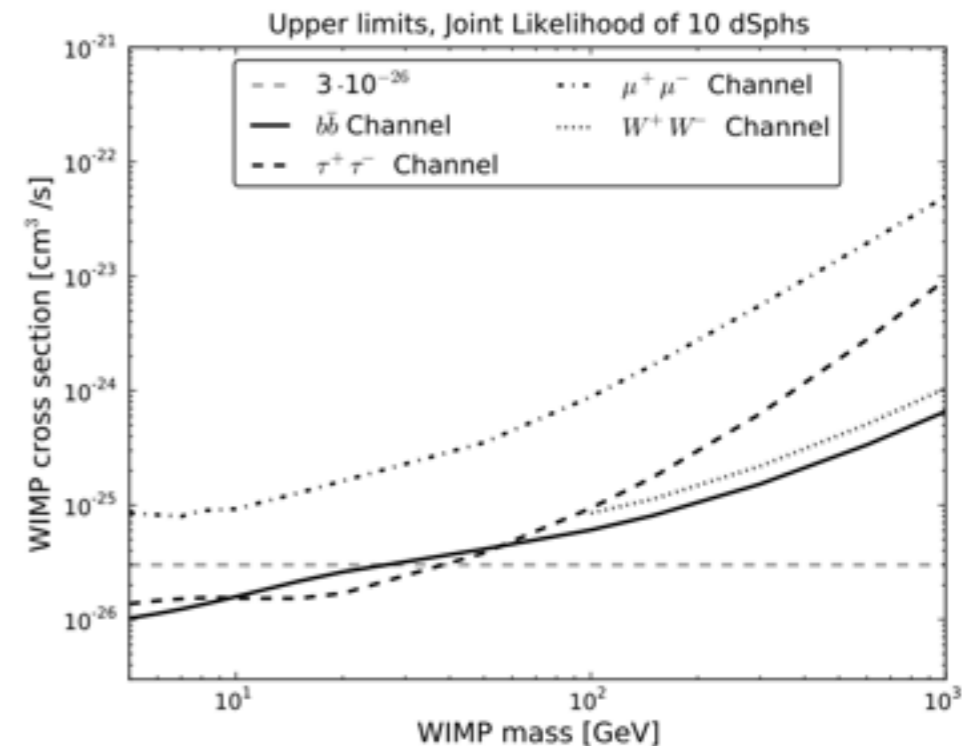


Comparison to Other Indirect Detection Regimes



Hooper & Linden (2011)

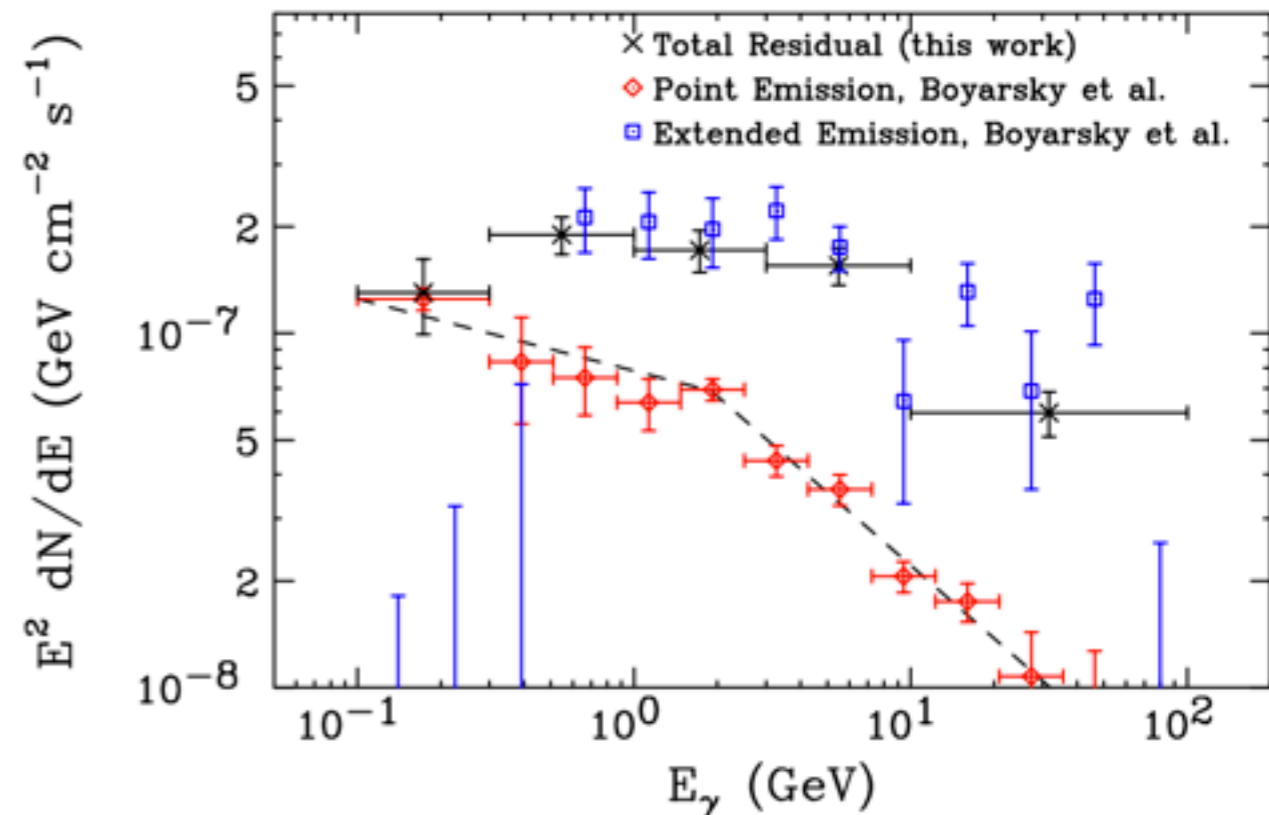
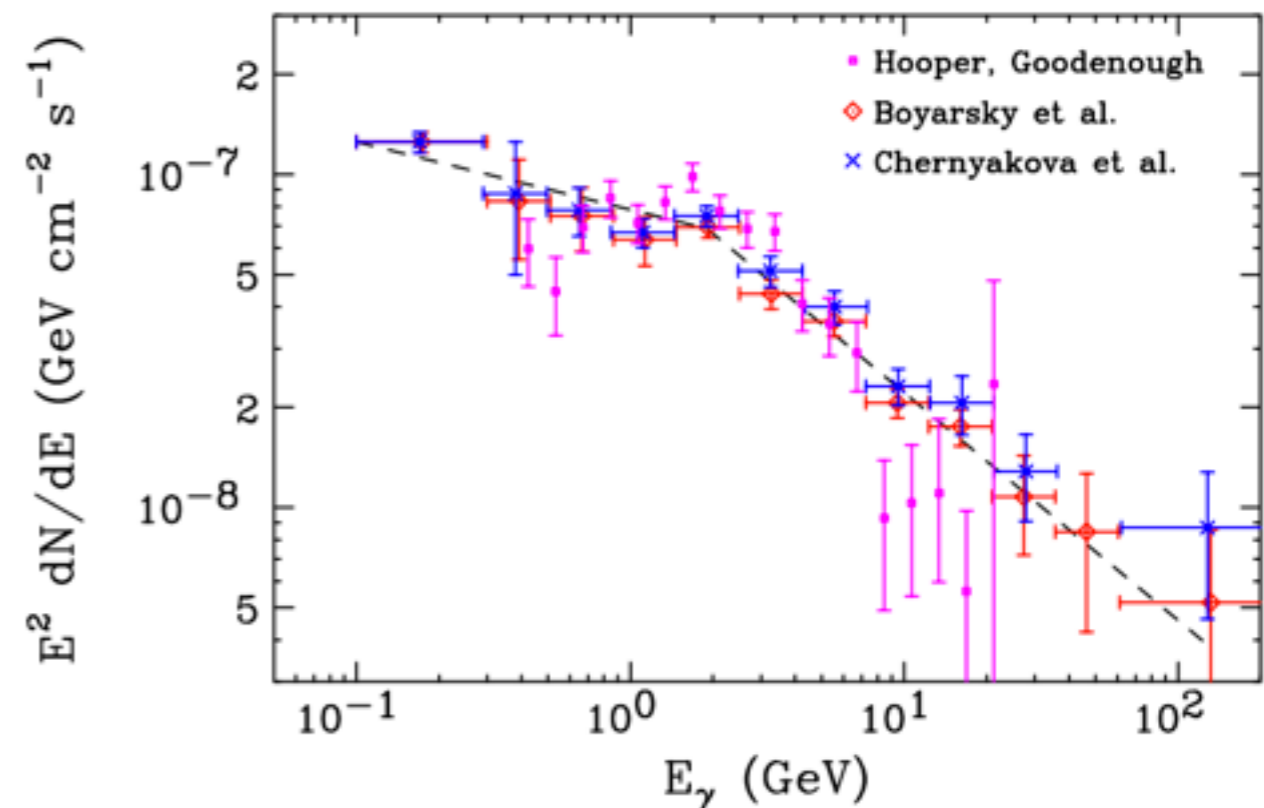
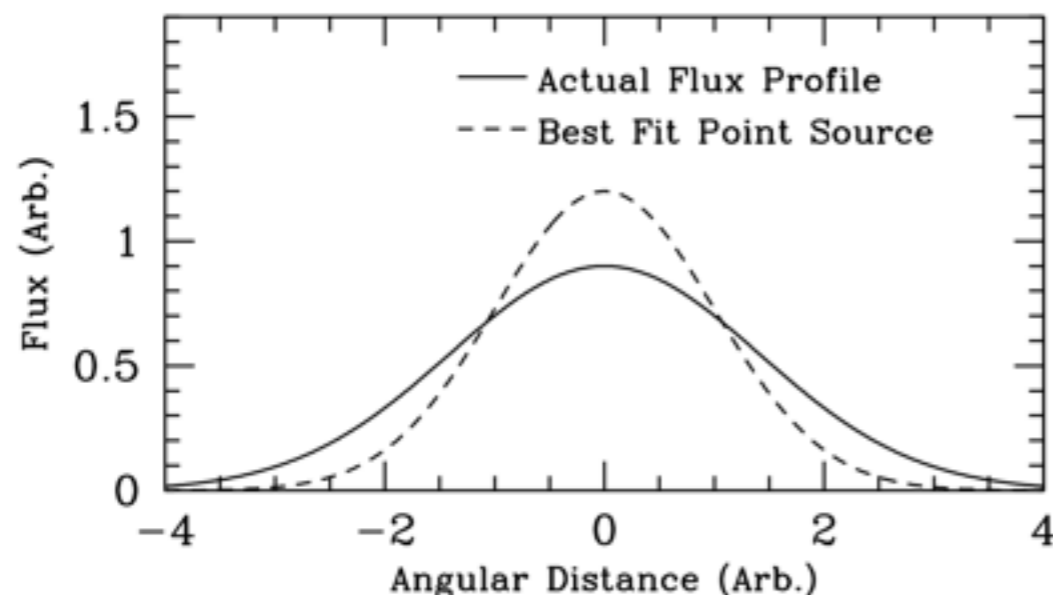
- With some adiabatic contraction of the inner dark matter profile, these limits can become substantially stronger than any other indirect detection limit



Ackermann et al. (2011)

Understanding the GC Point Source: Fermi

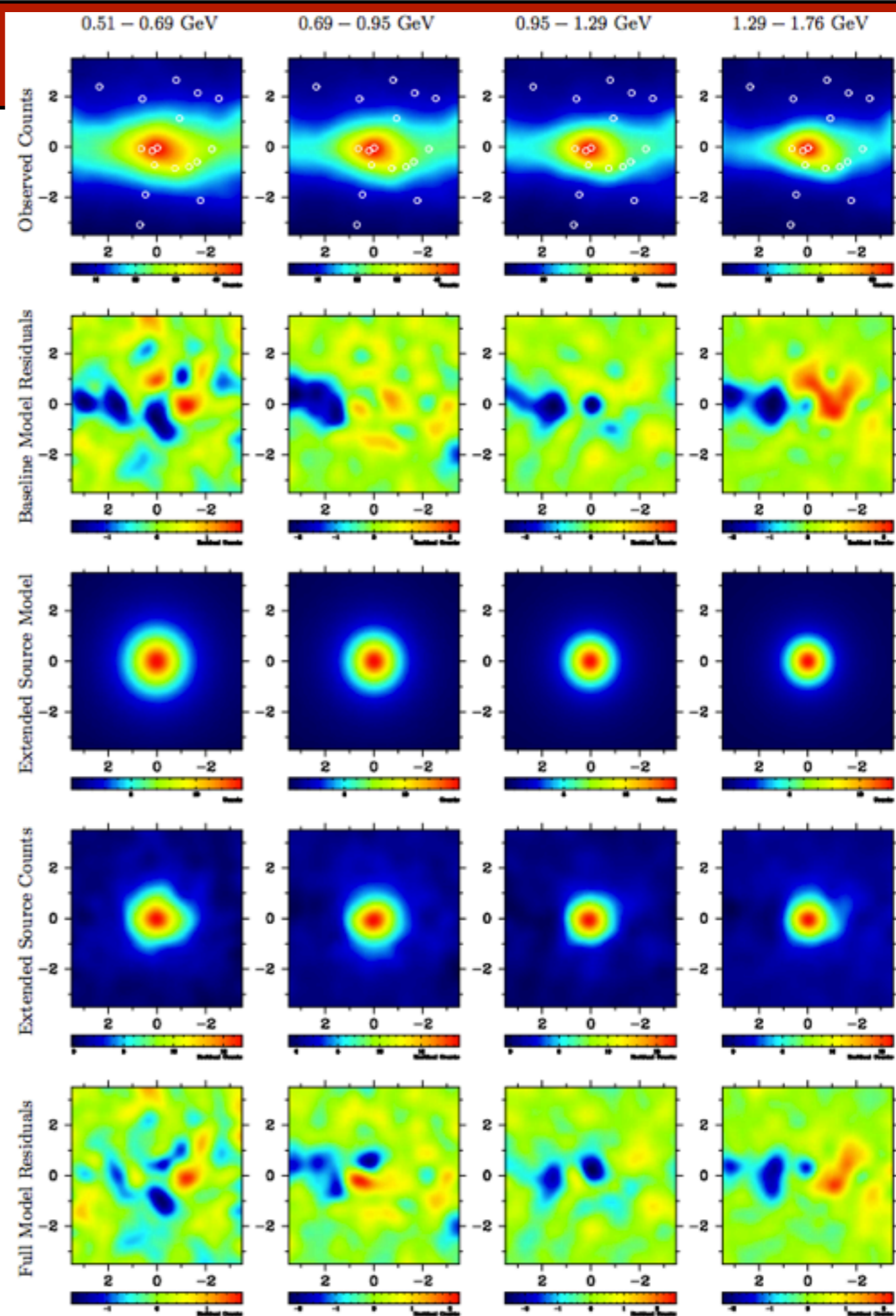
- Several efforts have been made to fit the GC point source, using both best-fitting point-source tools from the Fermi collaboration (Boyarsky et al. Chernyakova et. al), as well as independent software packages (Hooper & Goodenough)
- In all cases, the morphology of the observed emission cannot be fully 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)

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

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

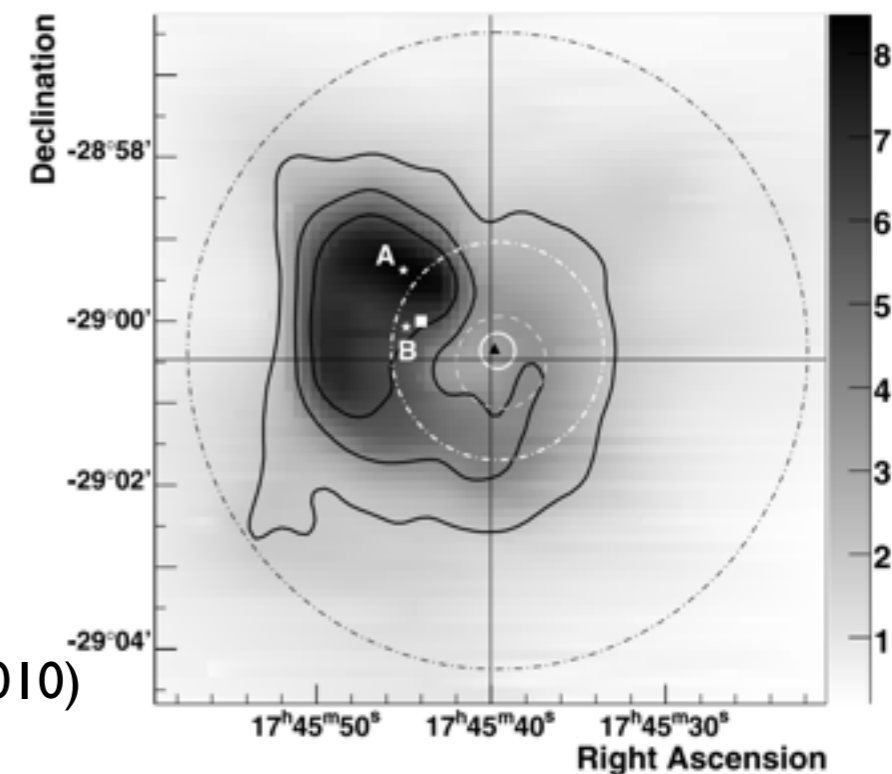
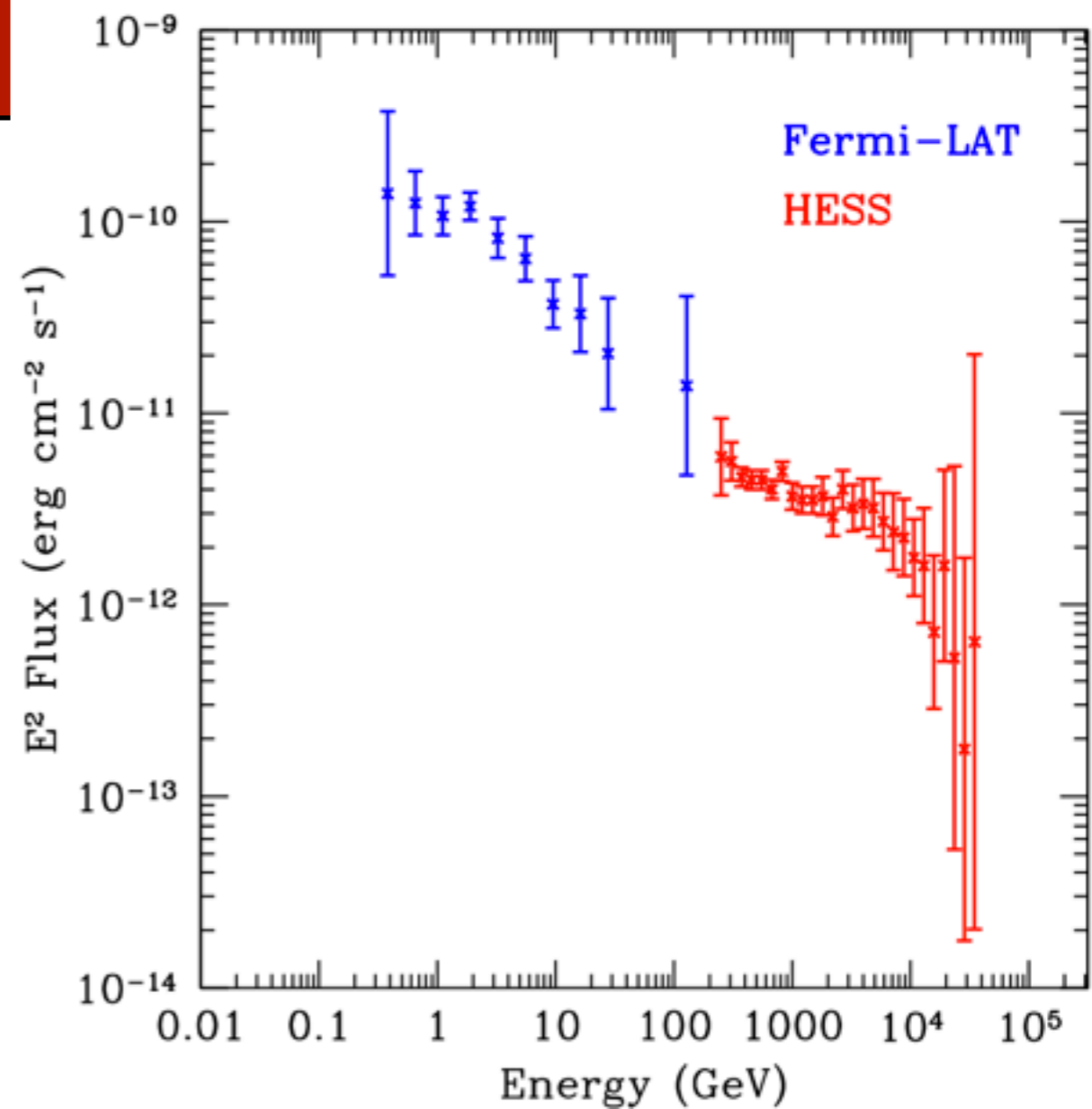
Abazajian & Kaplinghat (2012)

Independent Confirmation!

- Note: Two different, and independent methods find strong evidence for a **bright, spatially extended, spherically symmetric residual** at the position of the galactic center
- What can we learn from this?

Looking at the Point Source

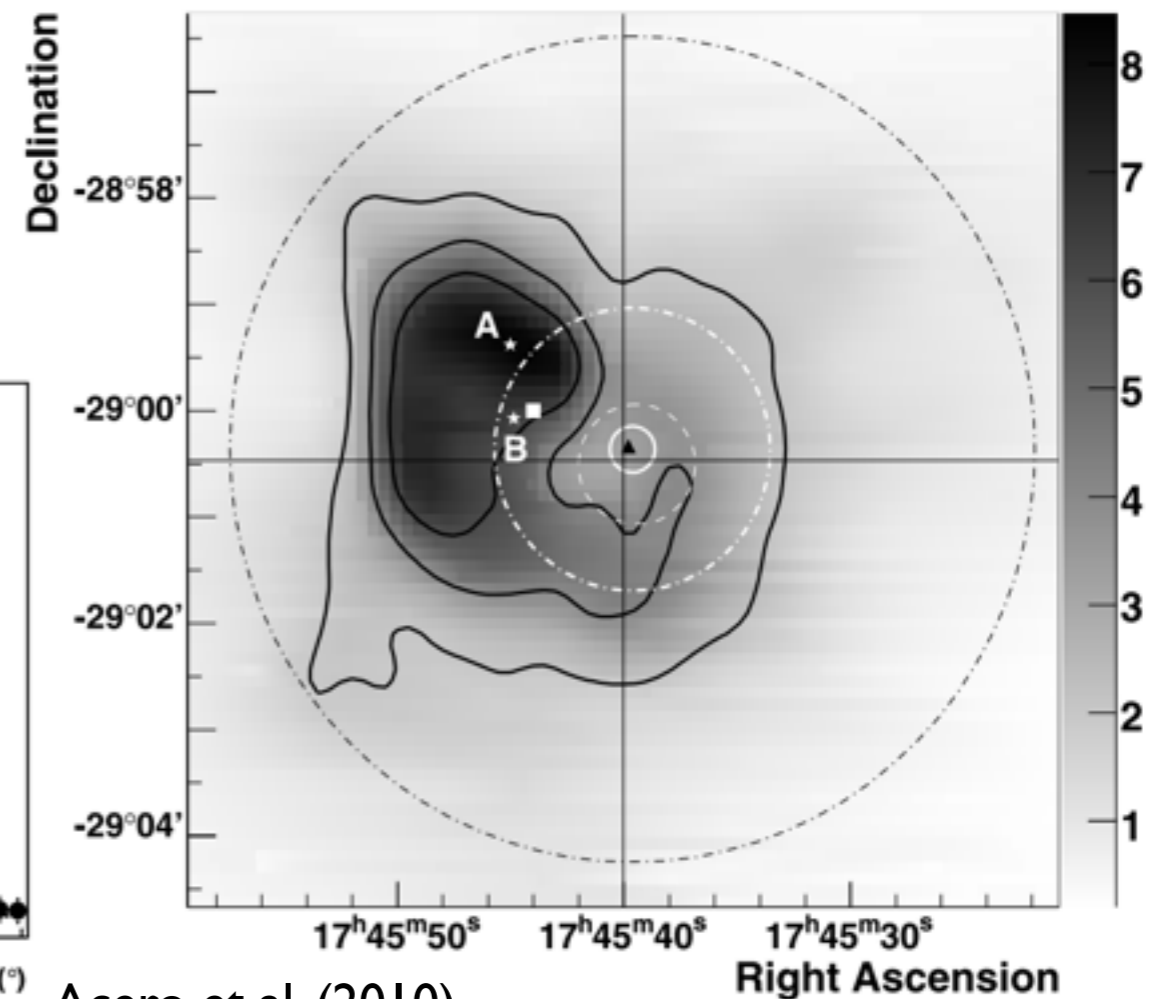
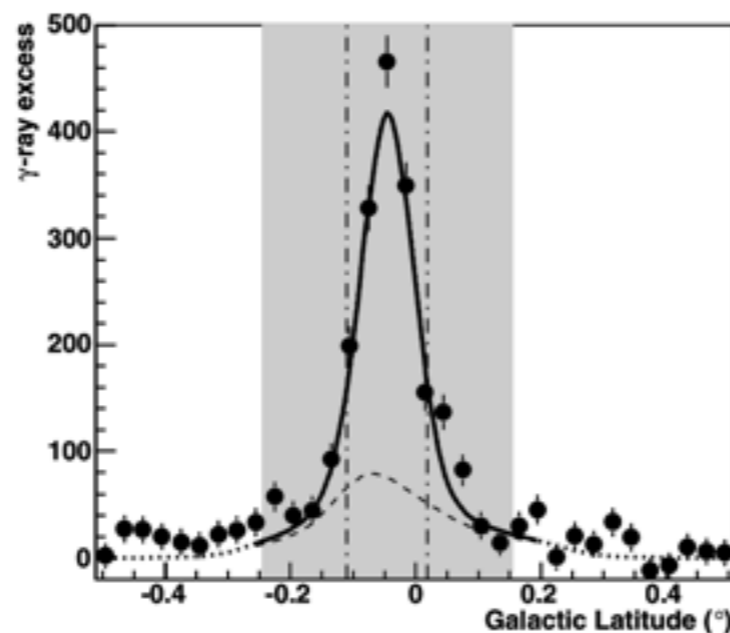
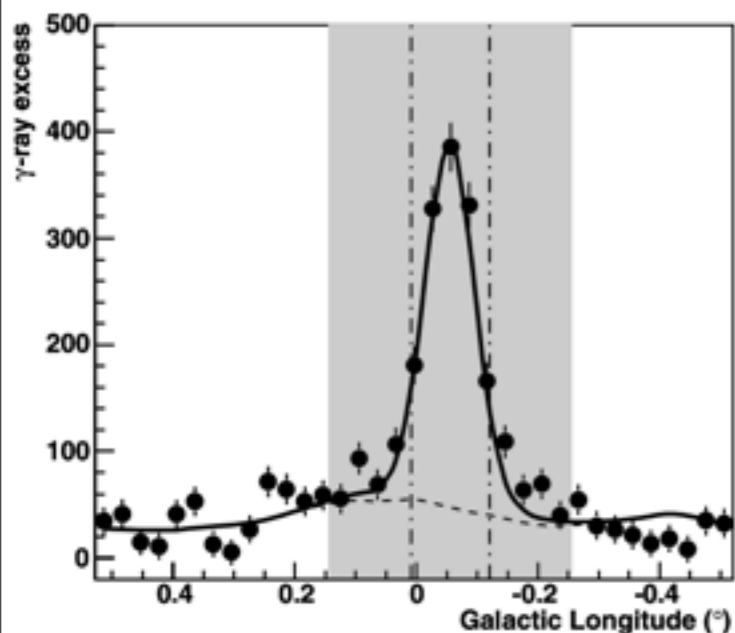
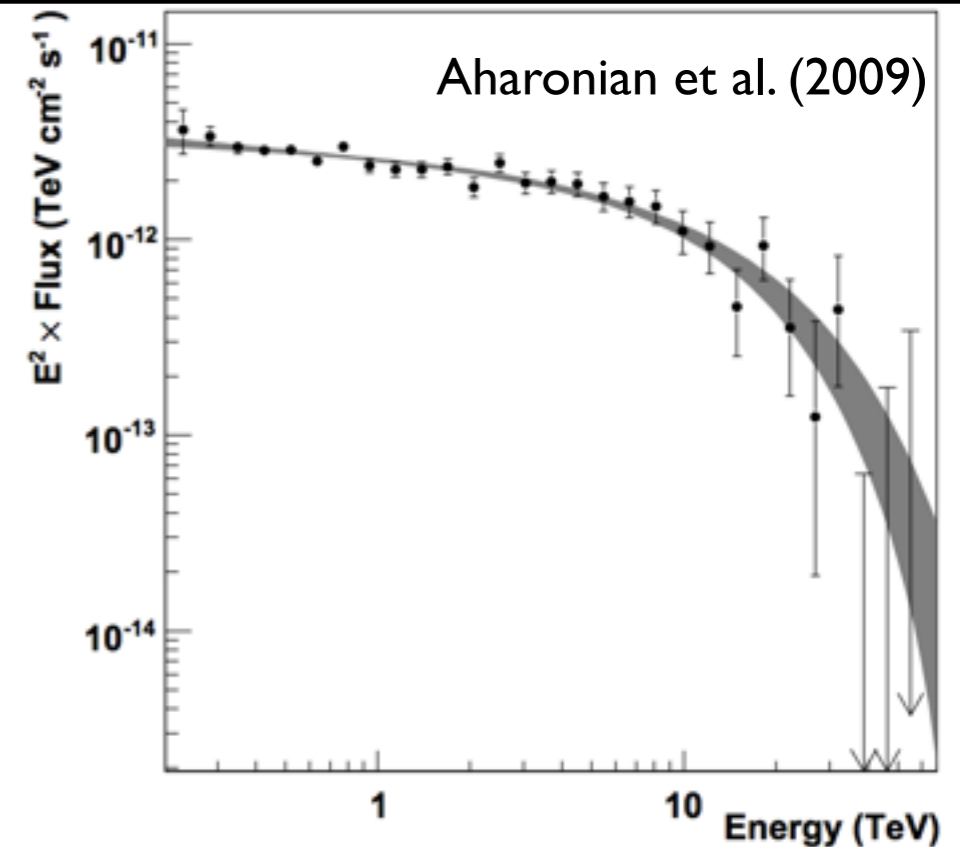
- The HESS spectrum is well fit by the Fermi acceleration of protons and their subsequent interaction with galactic gas
- Can the combined Fermi + HESS spectrum be described in the same way?
- **Problem 1:** The spectrum at GeV energies is significantly softer than at TeV energies - some modification is needed to control this transition
- **Problem 2:** The H.E.S.S. spectrum is point-like, with a better angular resolution than Fermi-LAT



Acero et al. (2010)

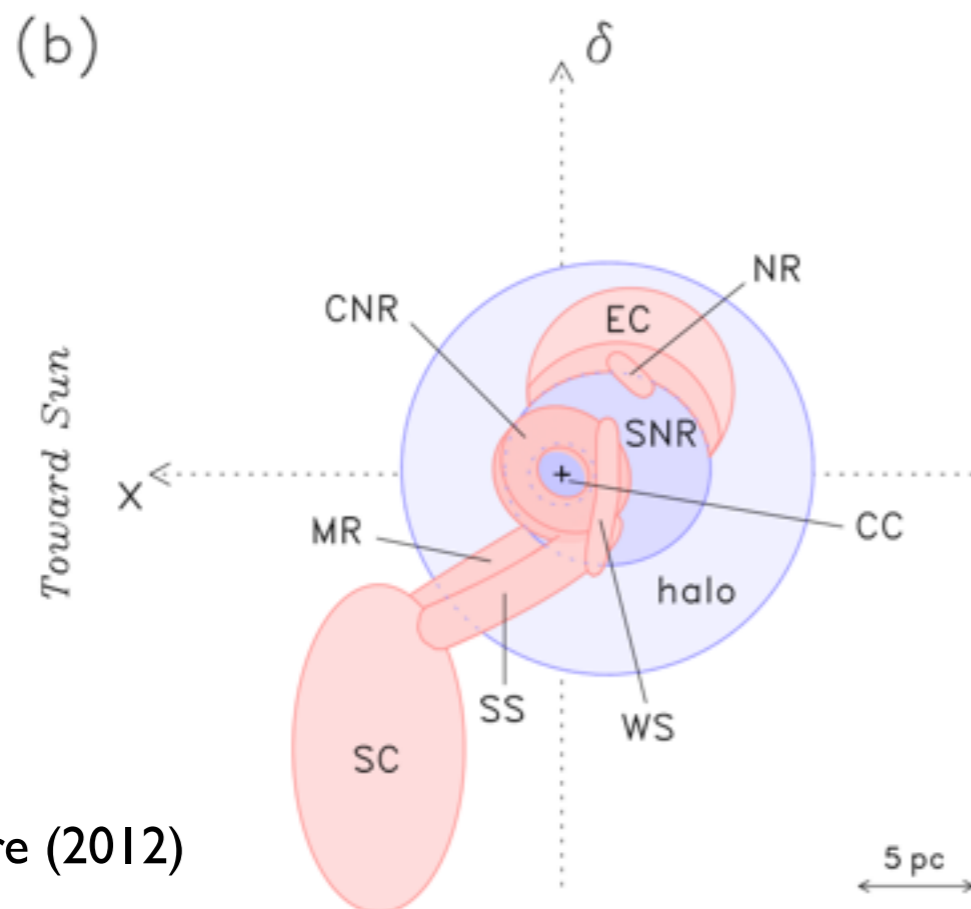
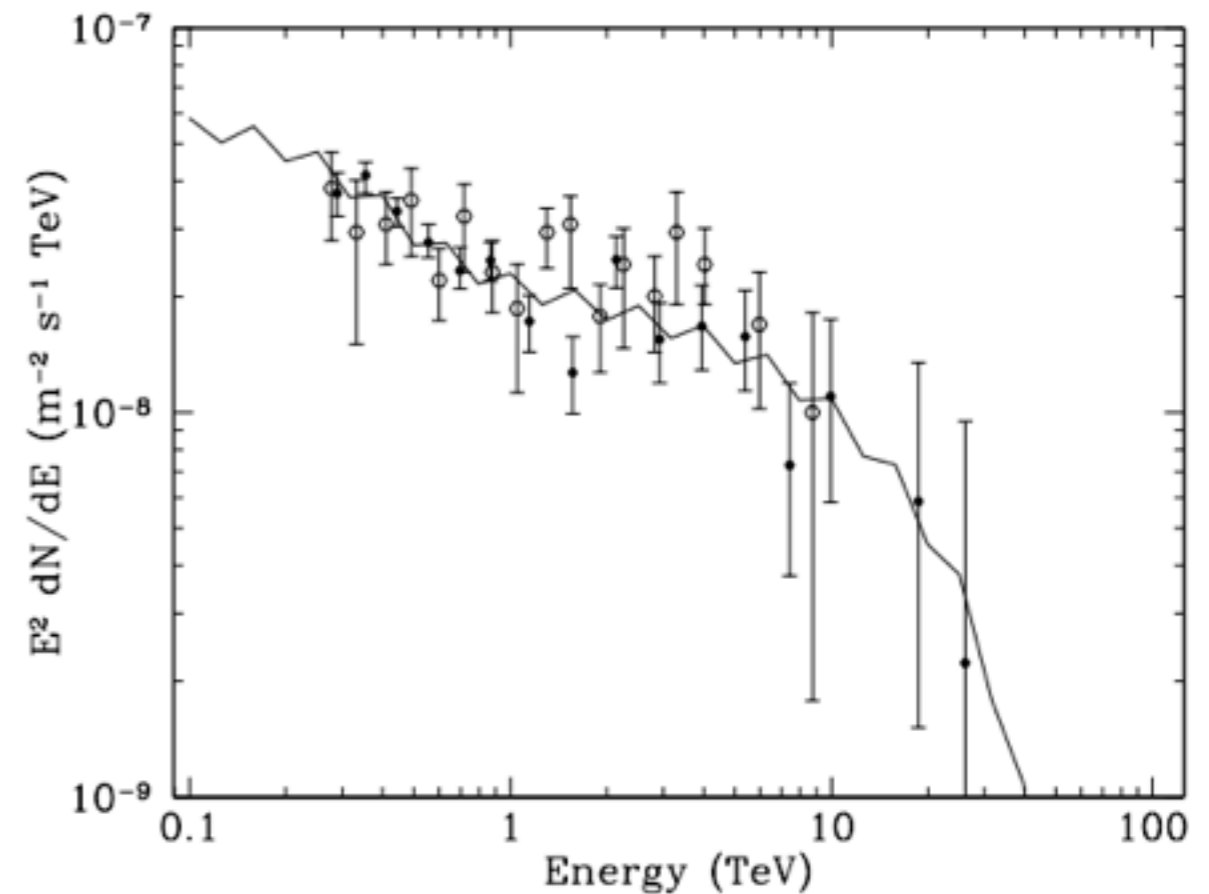
Understanding Astrophysical Backgrounds: HESS

- 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

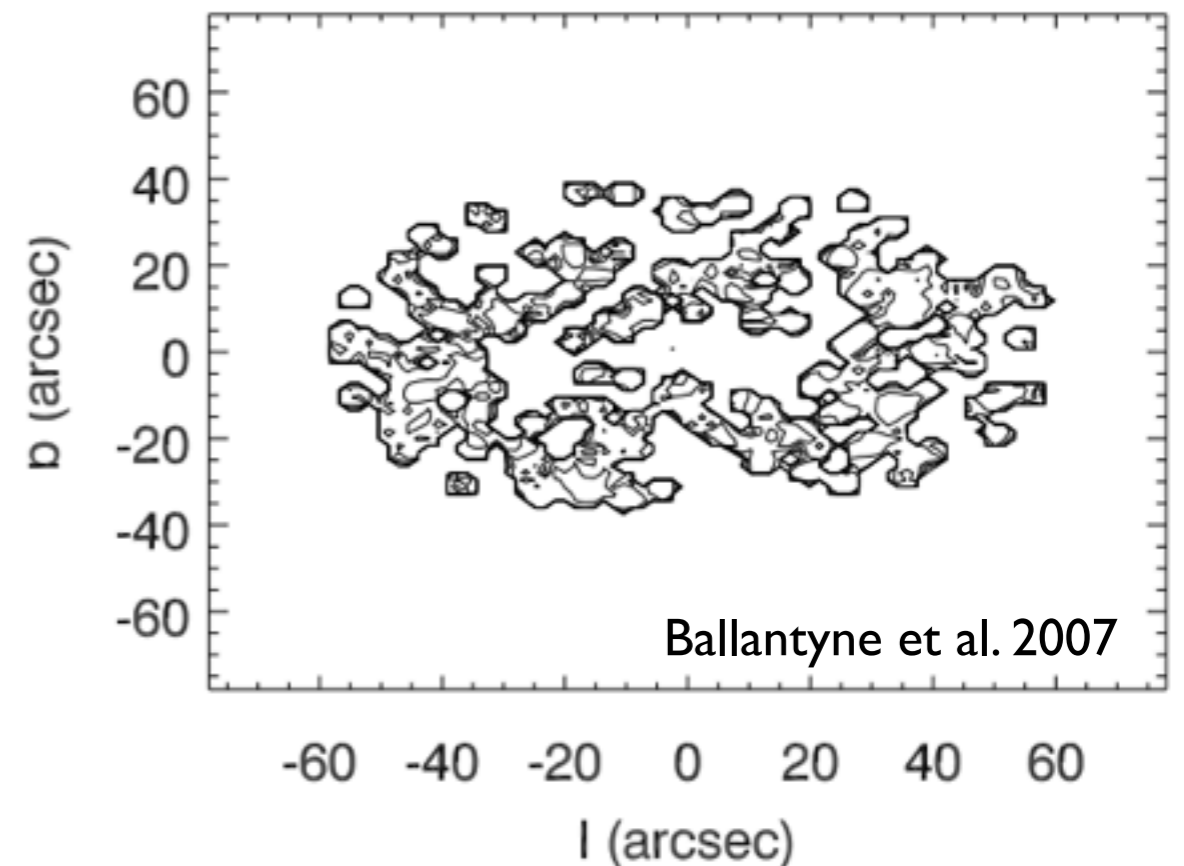


Fitting the Residual: Hadronic Processes

- 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

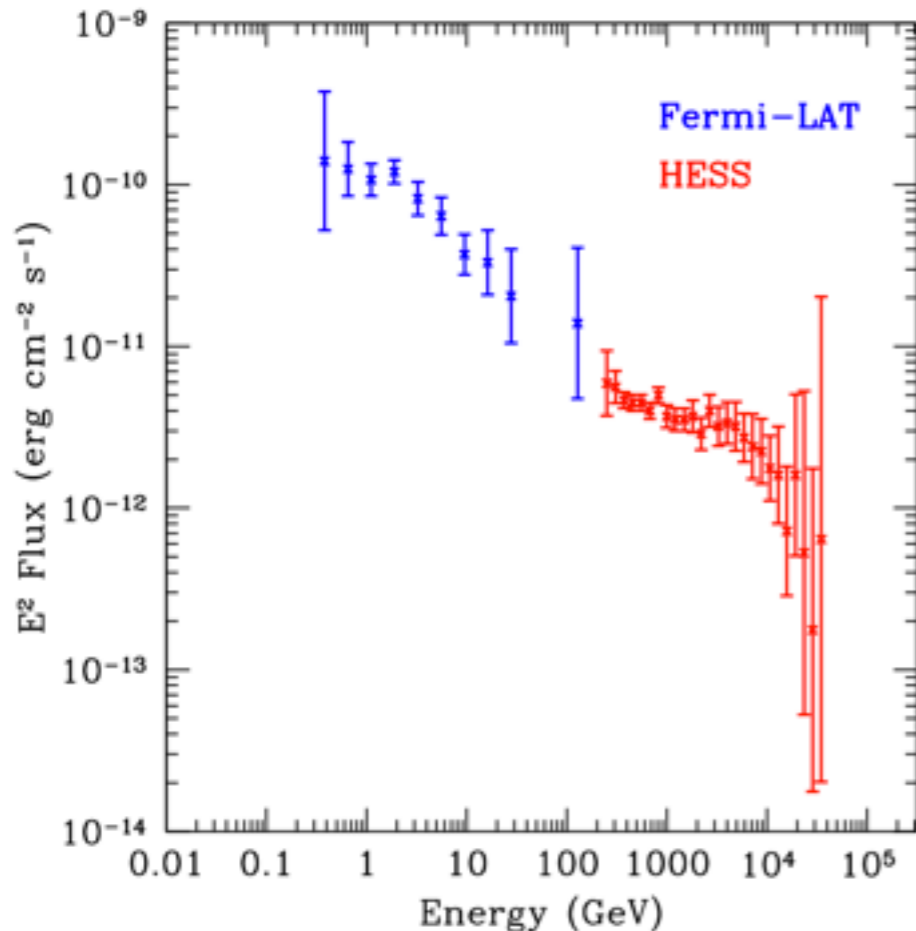
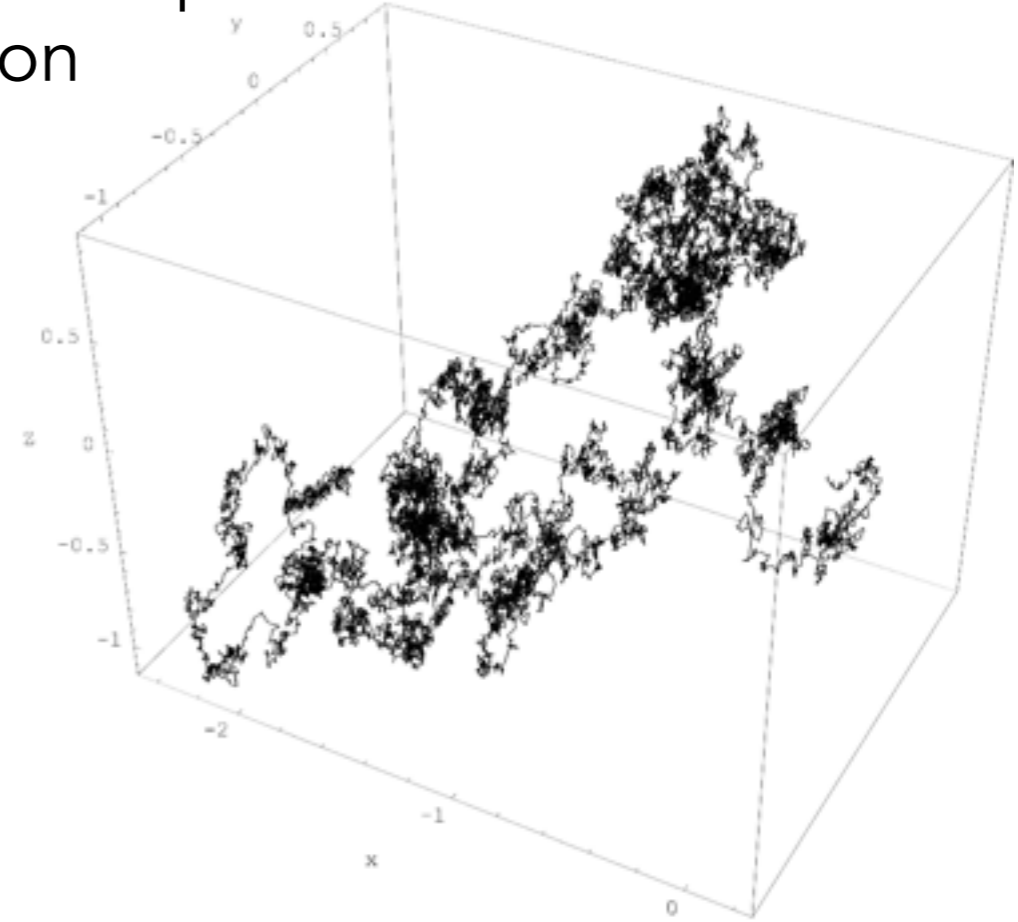


Ferriere (2012)



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



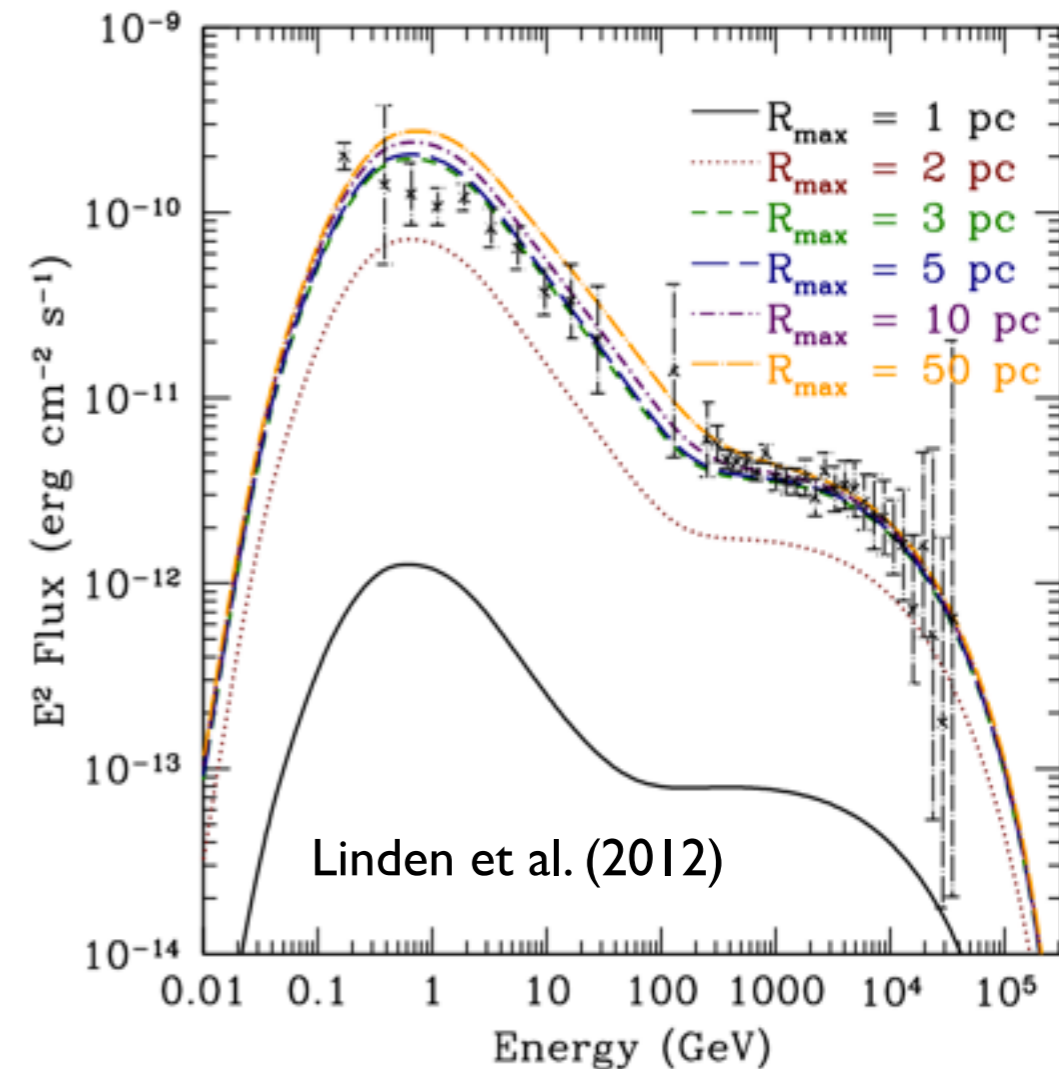
- In the regime where the diffusion step is small, then the emission intensity depends linearly on the time the particle spends within the diffusion region

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:

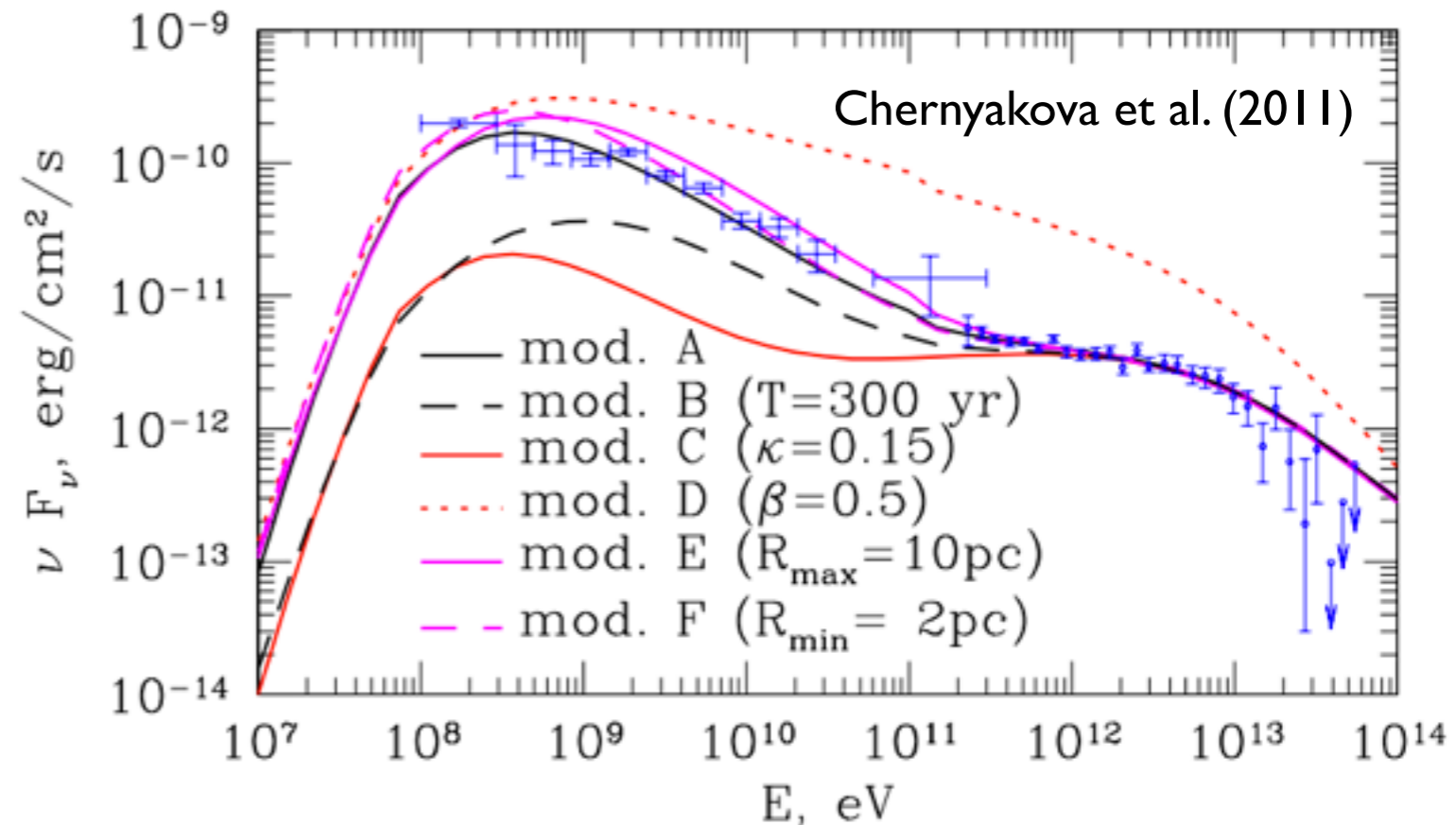
$$D_0 = 1.2 \times 10^{26} (E/1 \text{ GeV})^{0.91}$$

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



Hadronic Emission Models for Fermi and HESS

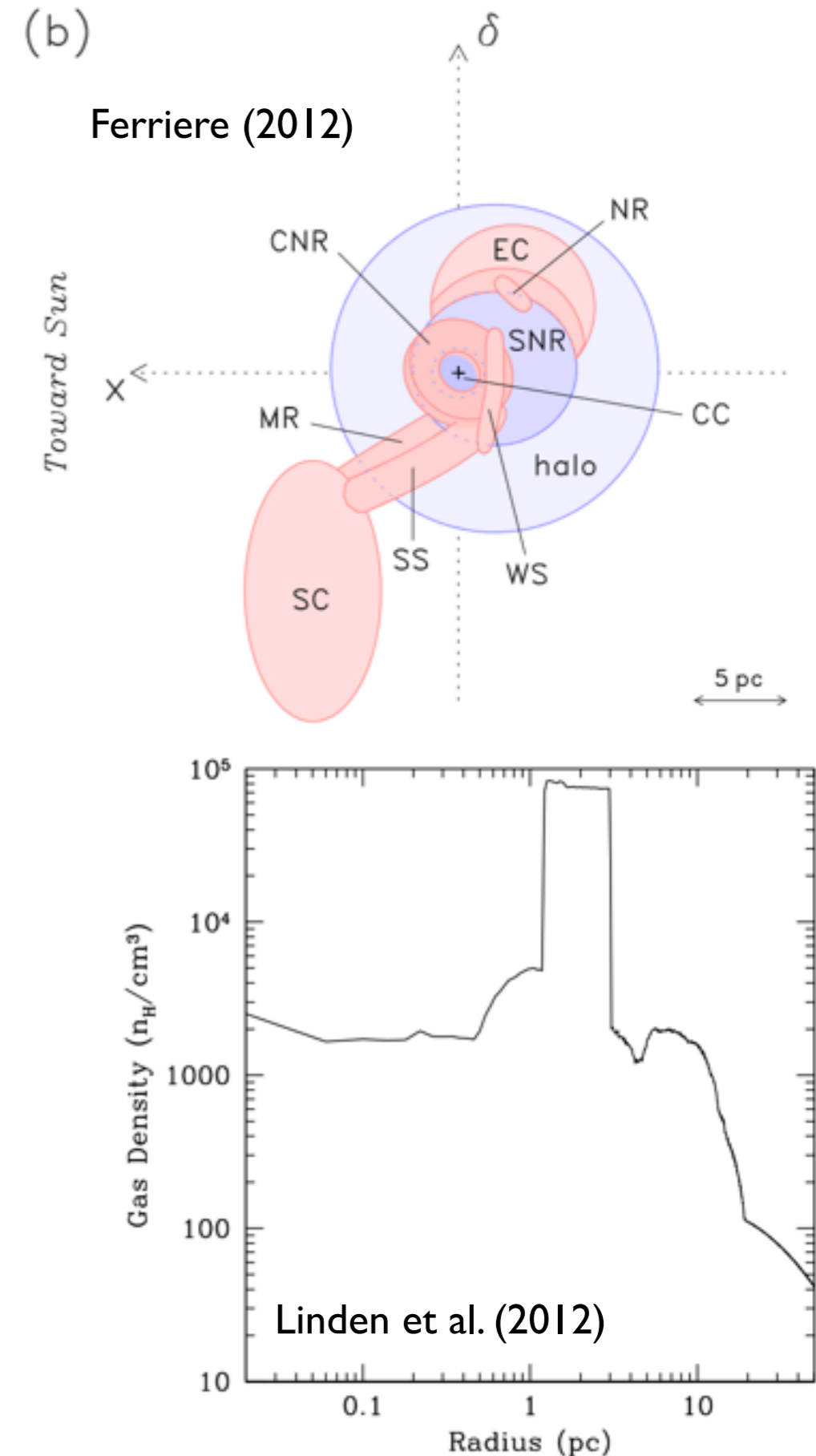
- By setting allowing the diffusion constant to float to a set of best fit values - a single hadronic emission model can fit the entirety of the Fermi/HESS data



- 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 ($1000 n_{\text{H}}/\text{cm}^{-3}$ within 3 pc of the galactic center, and $0 n_{\text{H}}/\text{cm}^{-3}$ outside)

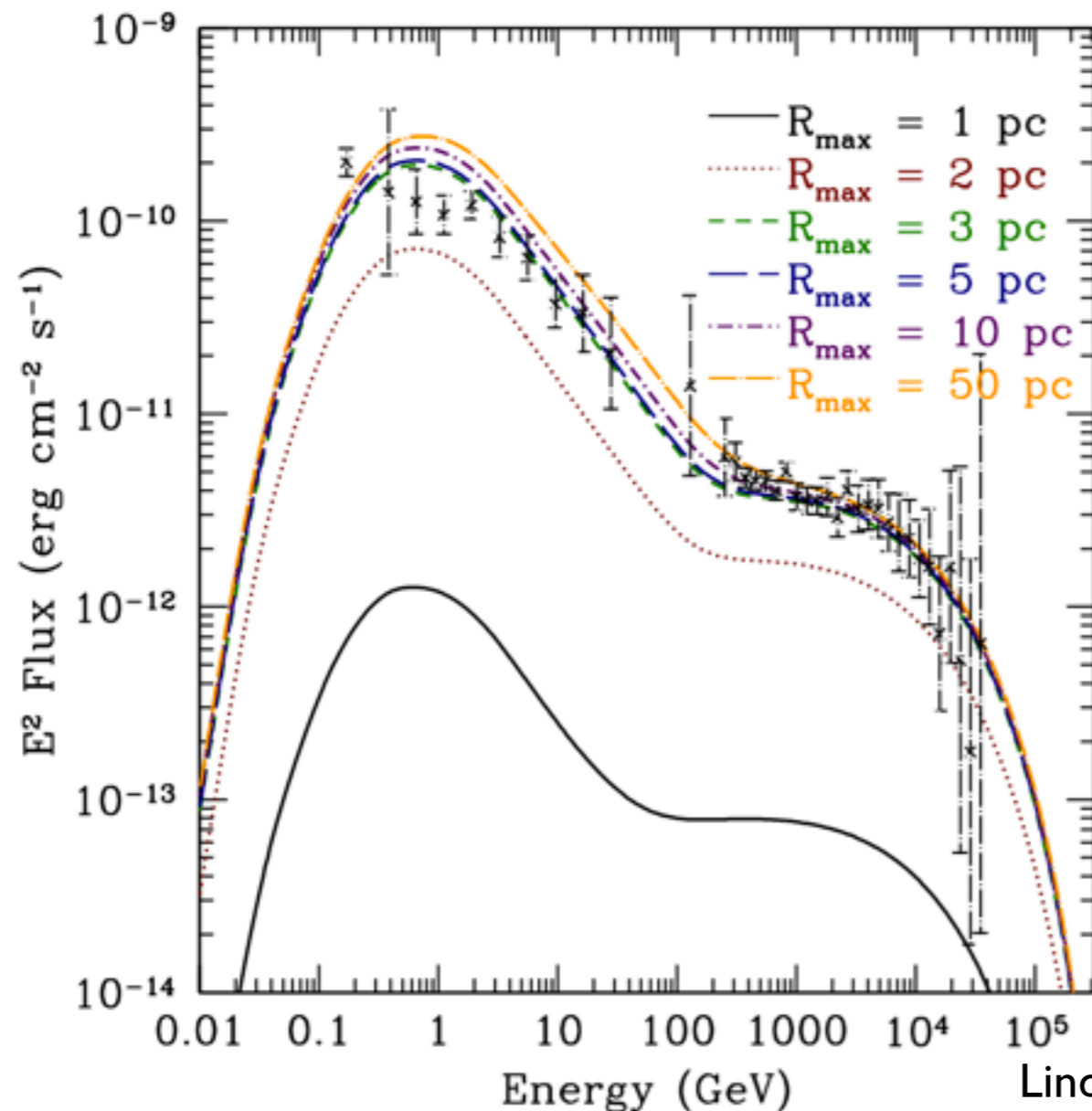
Employing a Realistic Gas Model

- 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

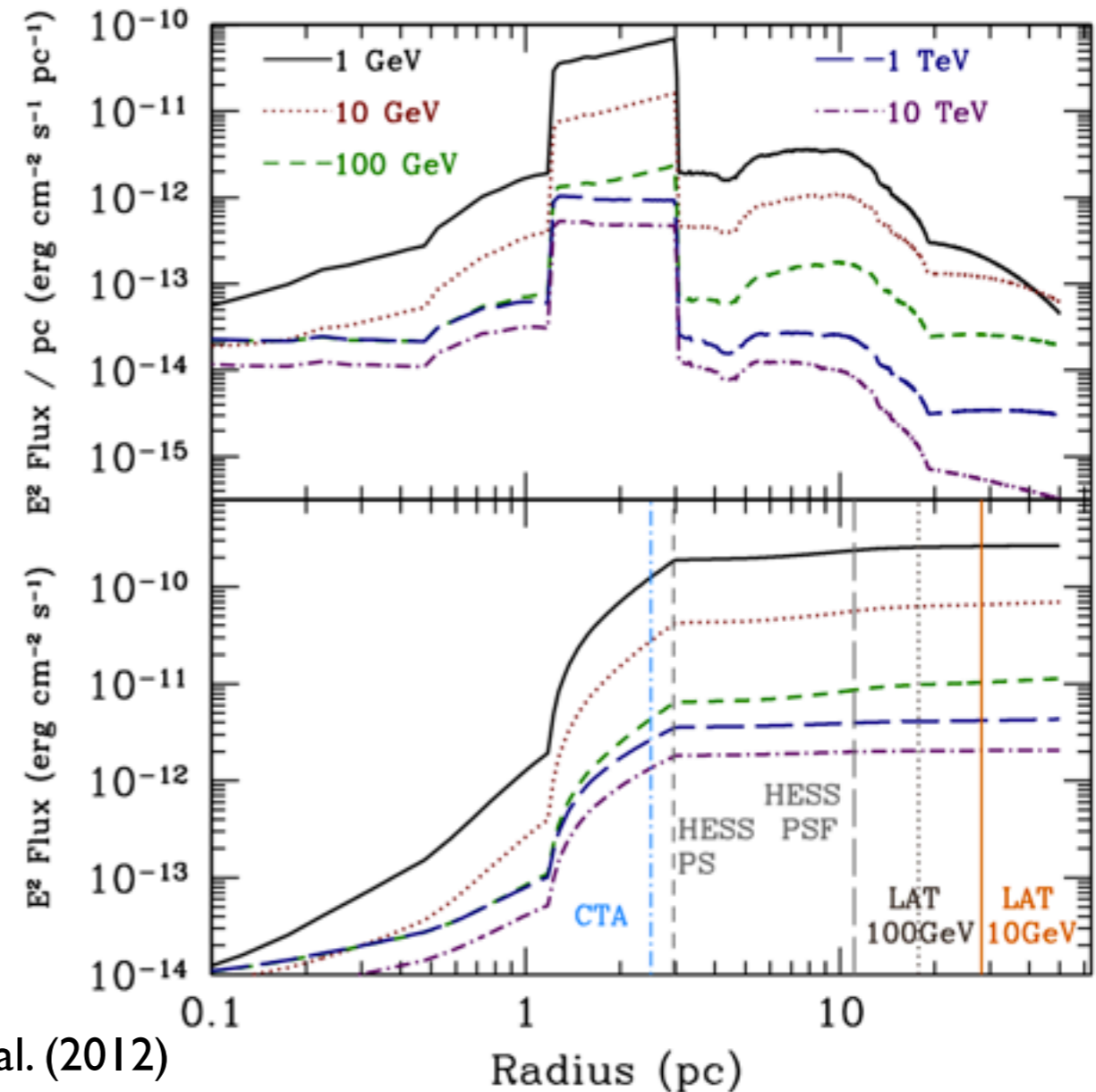


Employing a Realistic Gas Model

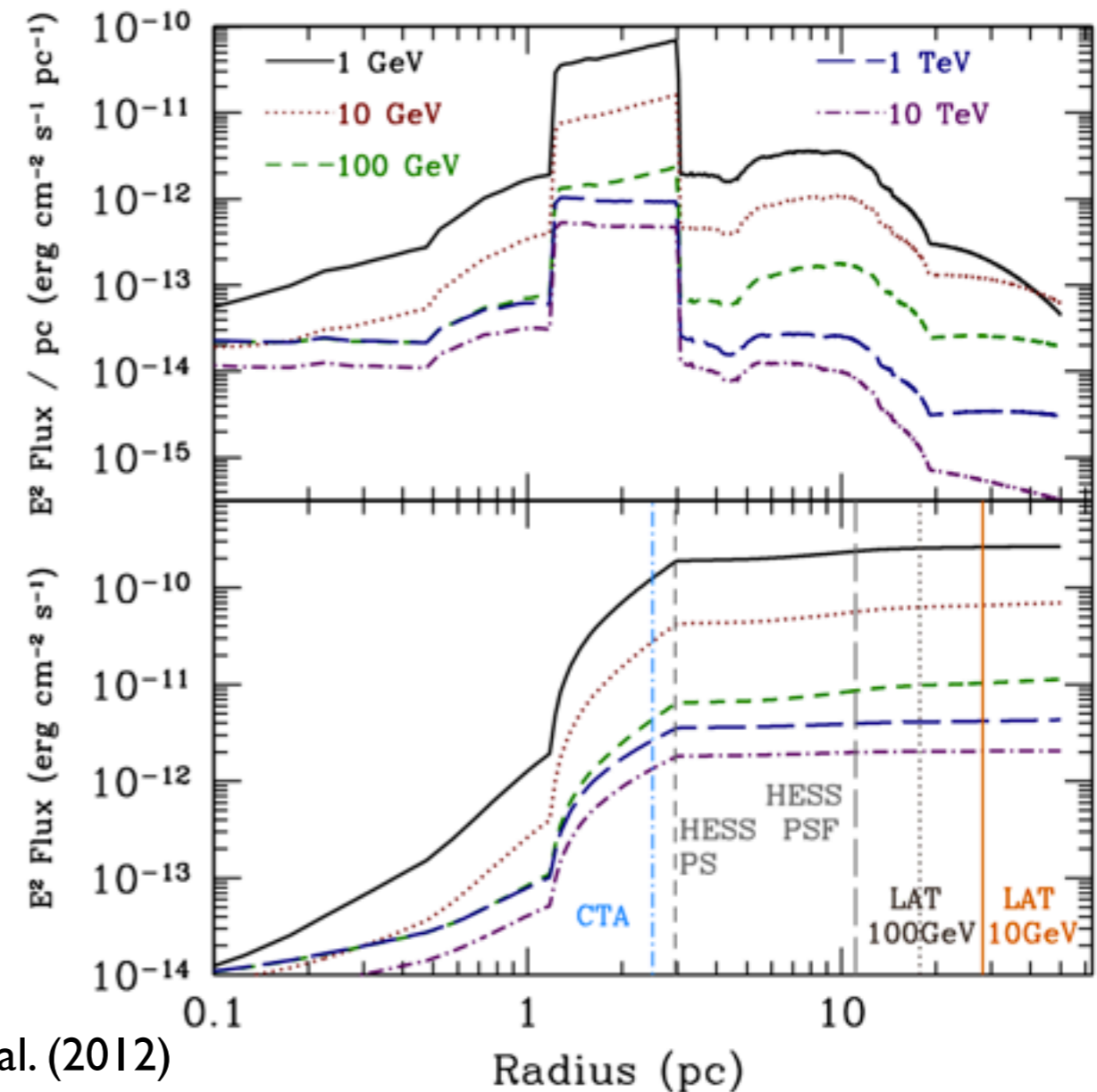
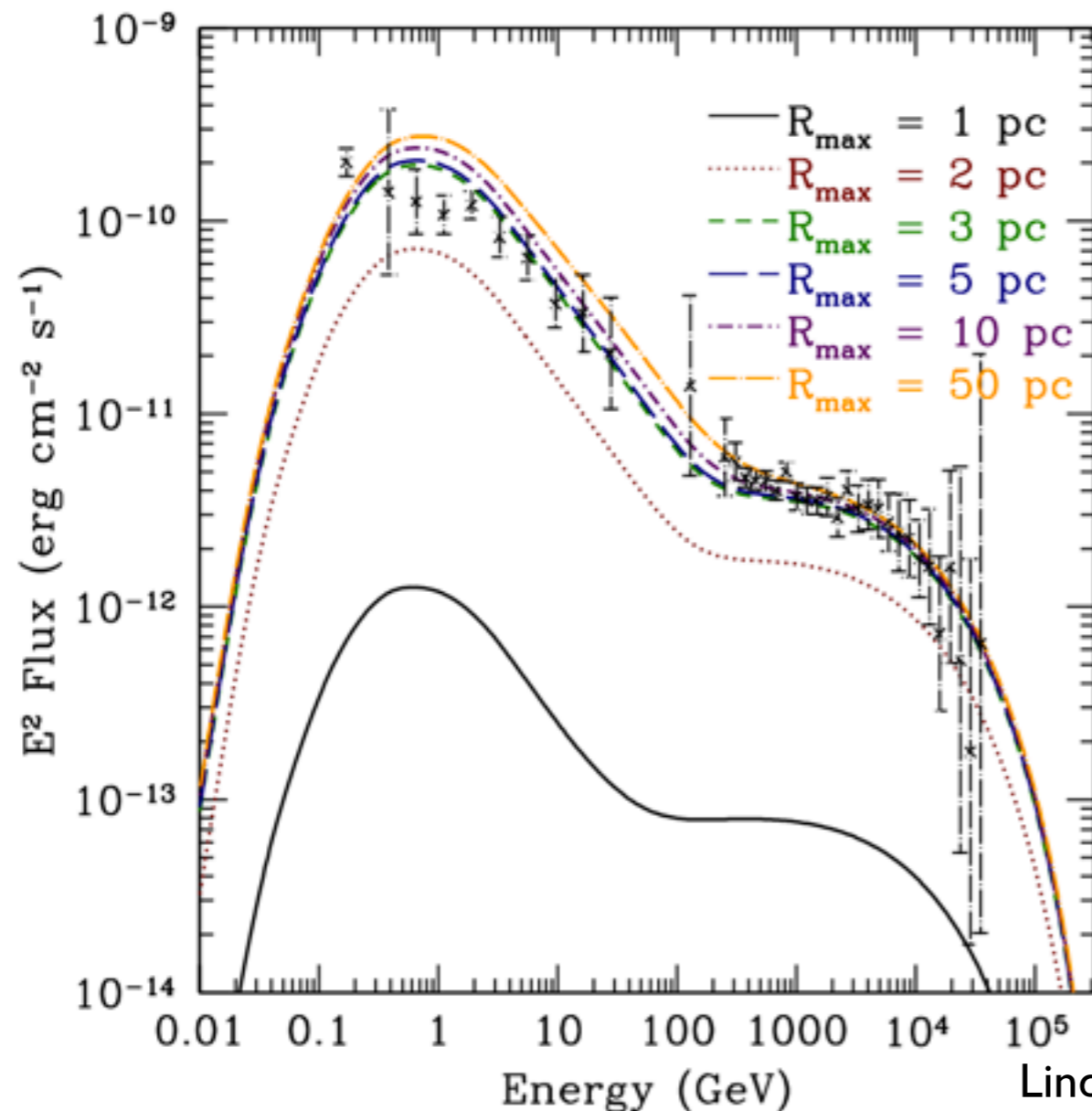
- The vast majority of emission stems from within 3 pc of the galactic center at all energies
- This lies below the PSF of all current gamma-ray instruments
- This effectively rules out hadronic interactions from Sgr A* as the source of the Fermi-LAT excess



Linden et al. (2012)

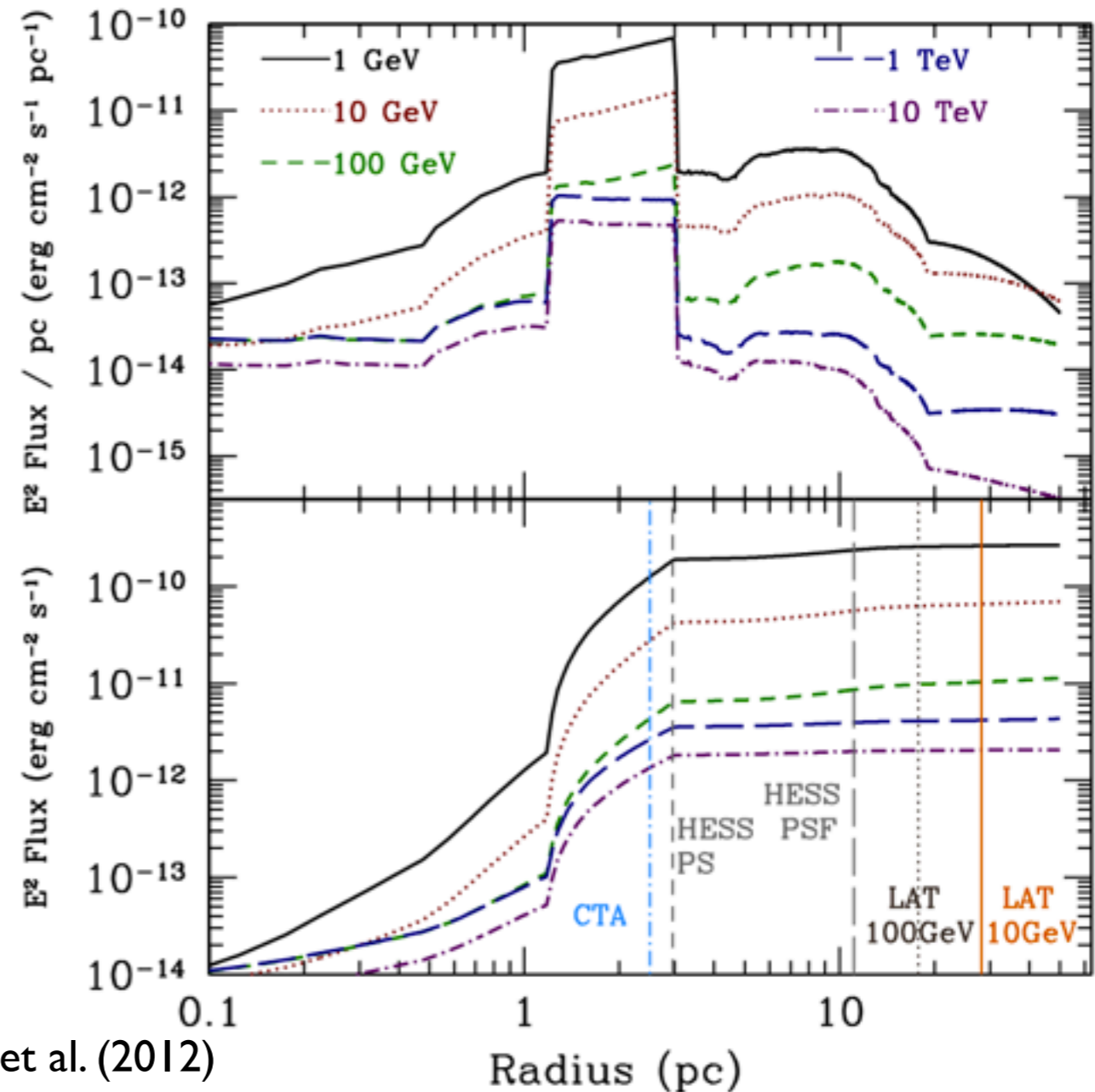
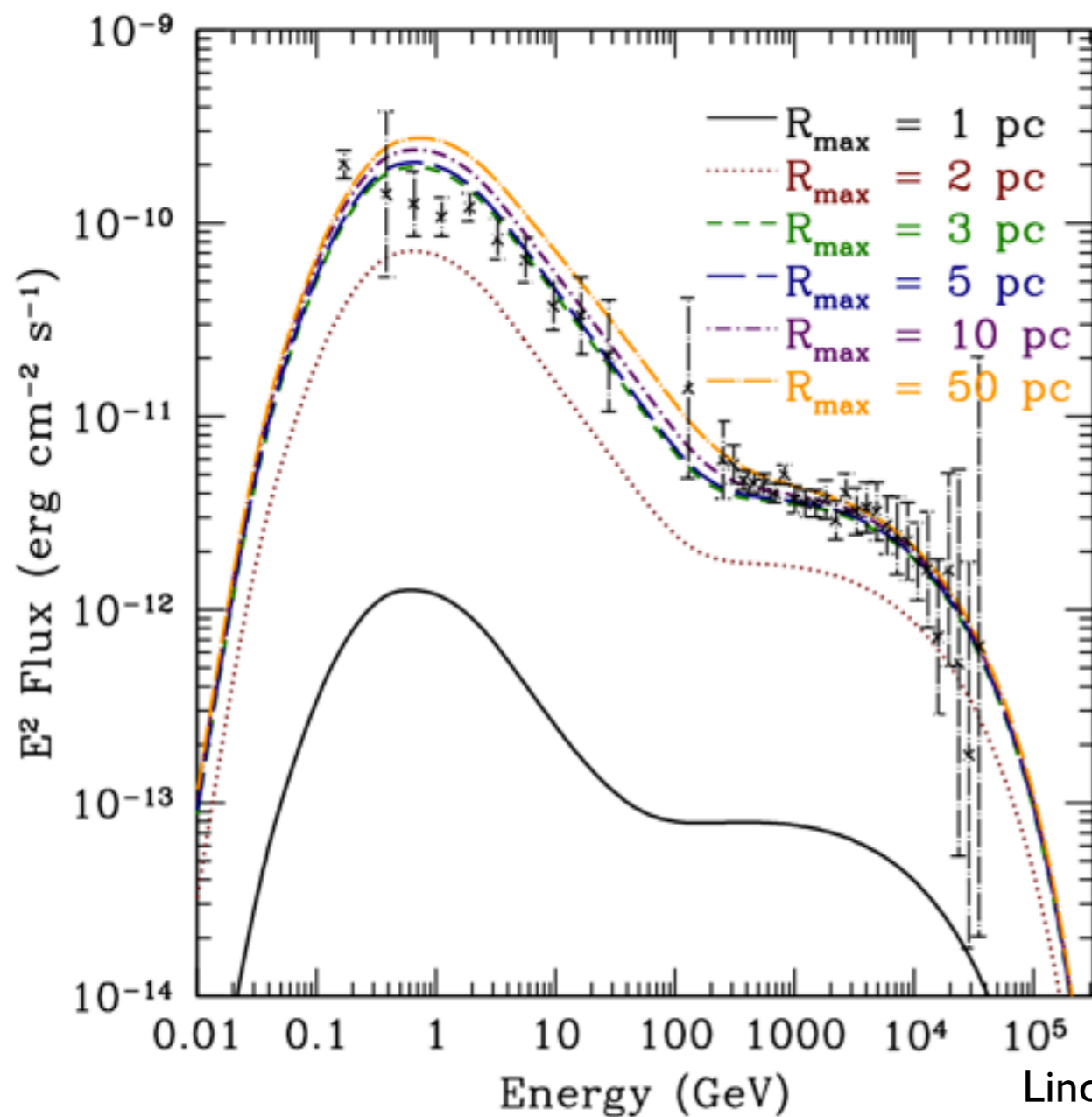


Understanding High Energy Emission from the Galactic Center: 2 Convincing Stories



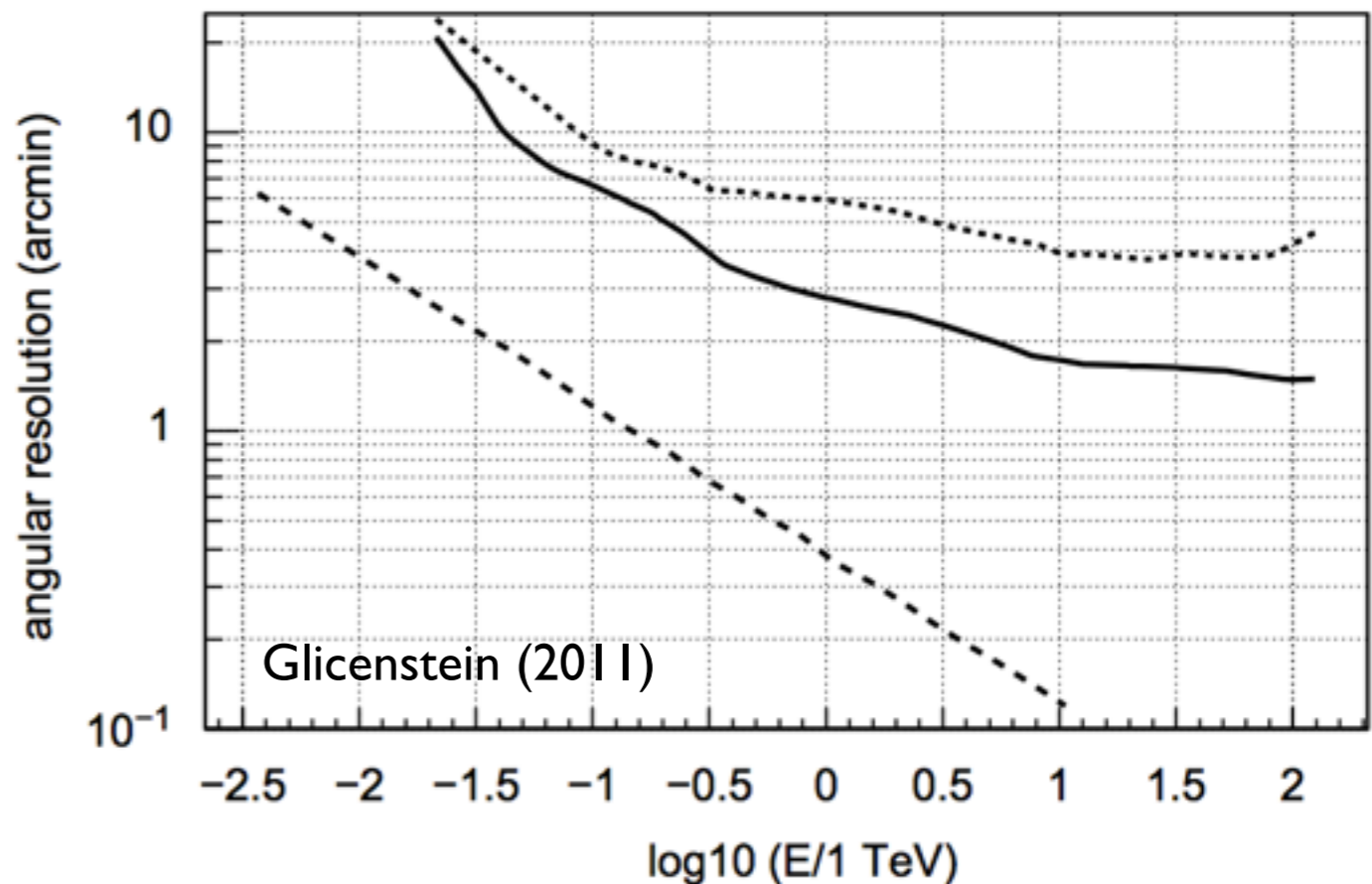
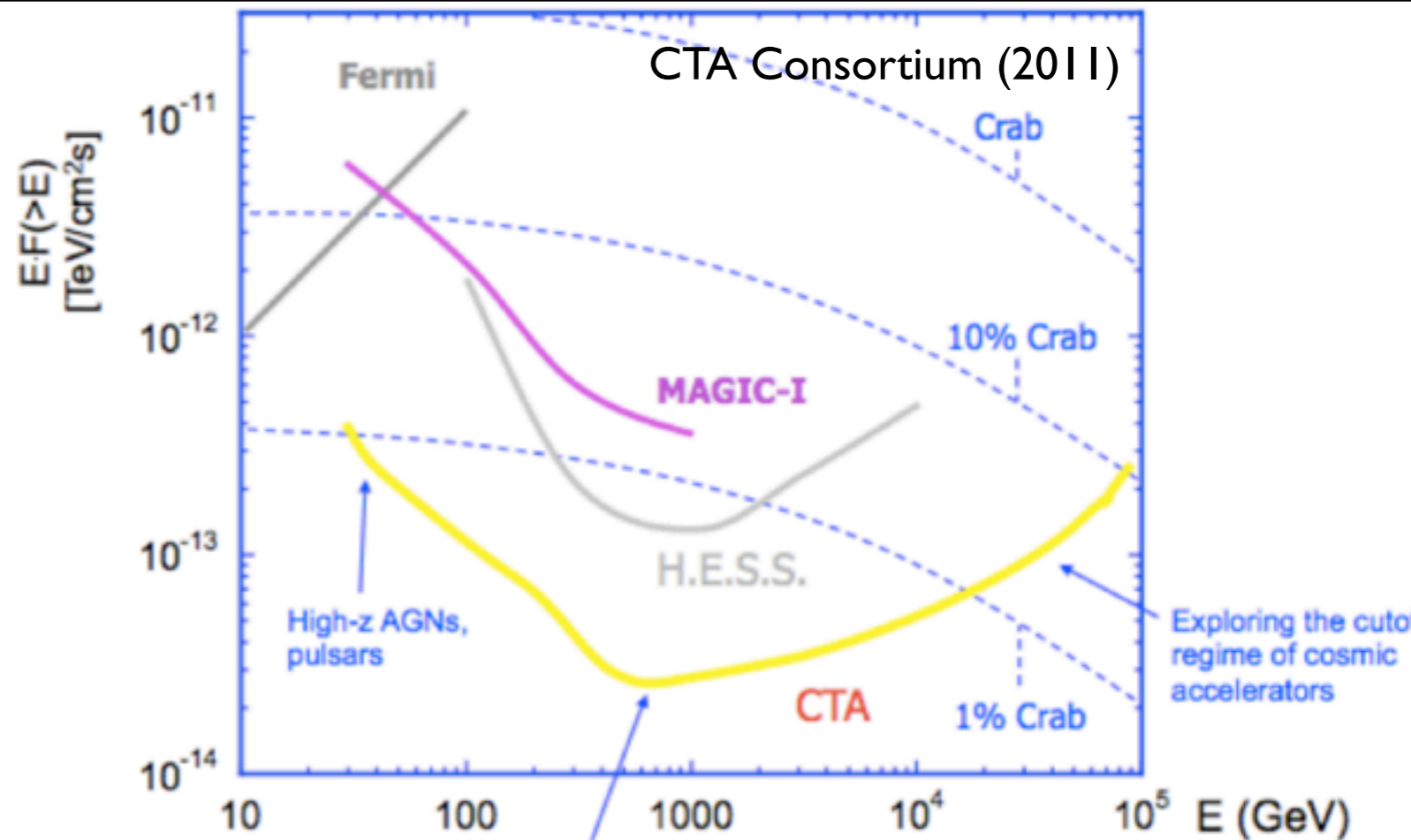
CTA and the Galactic Center

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



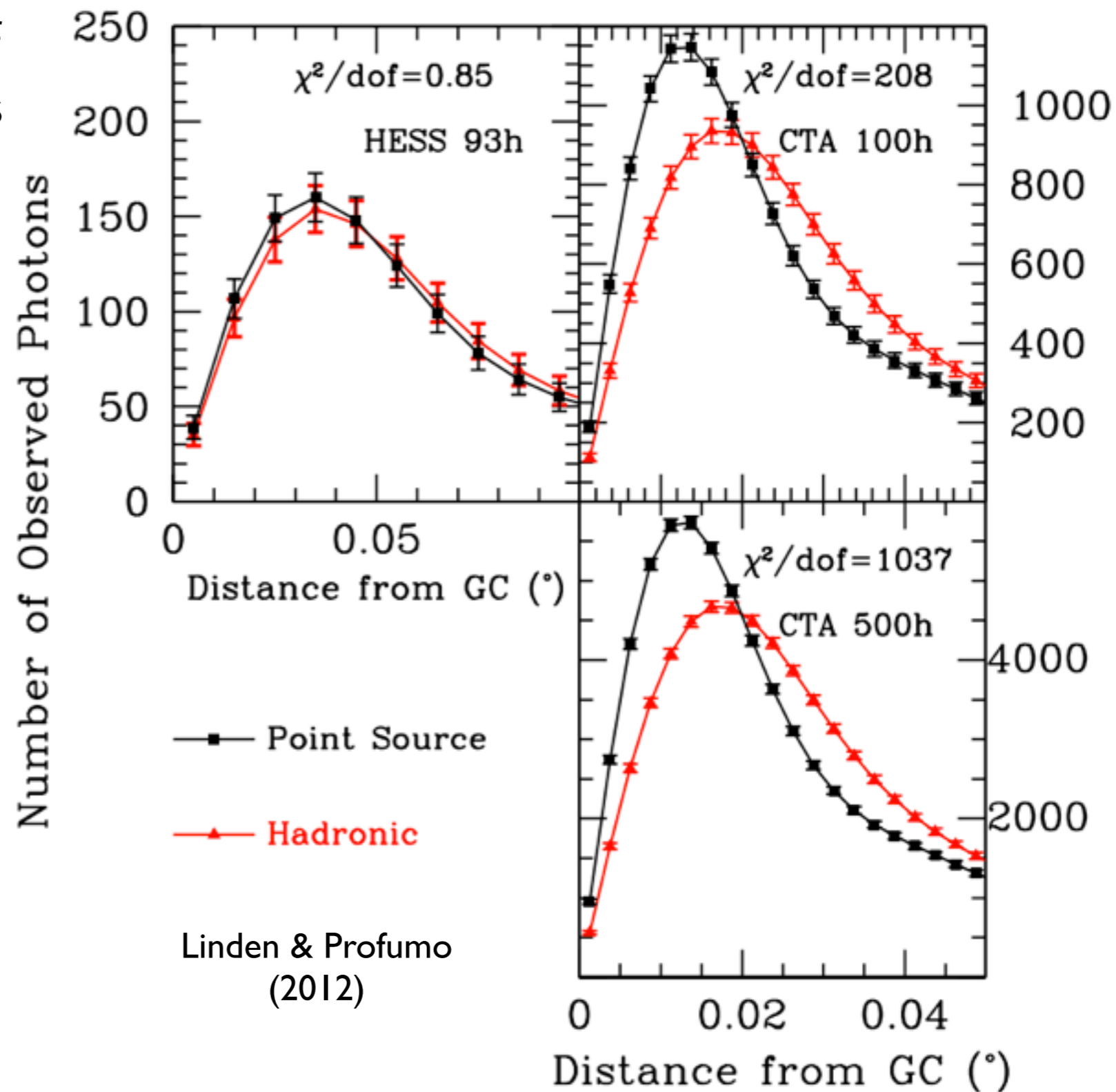
CTA and the Galactic Center

- 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°



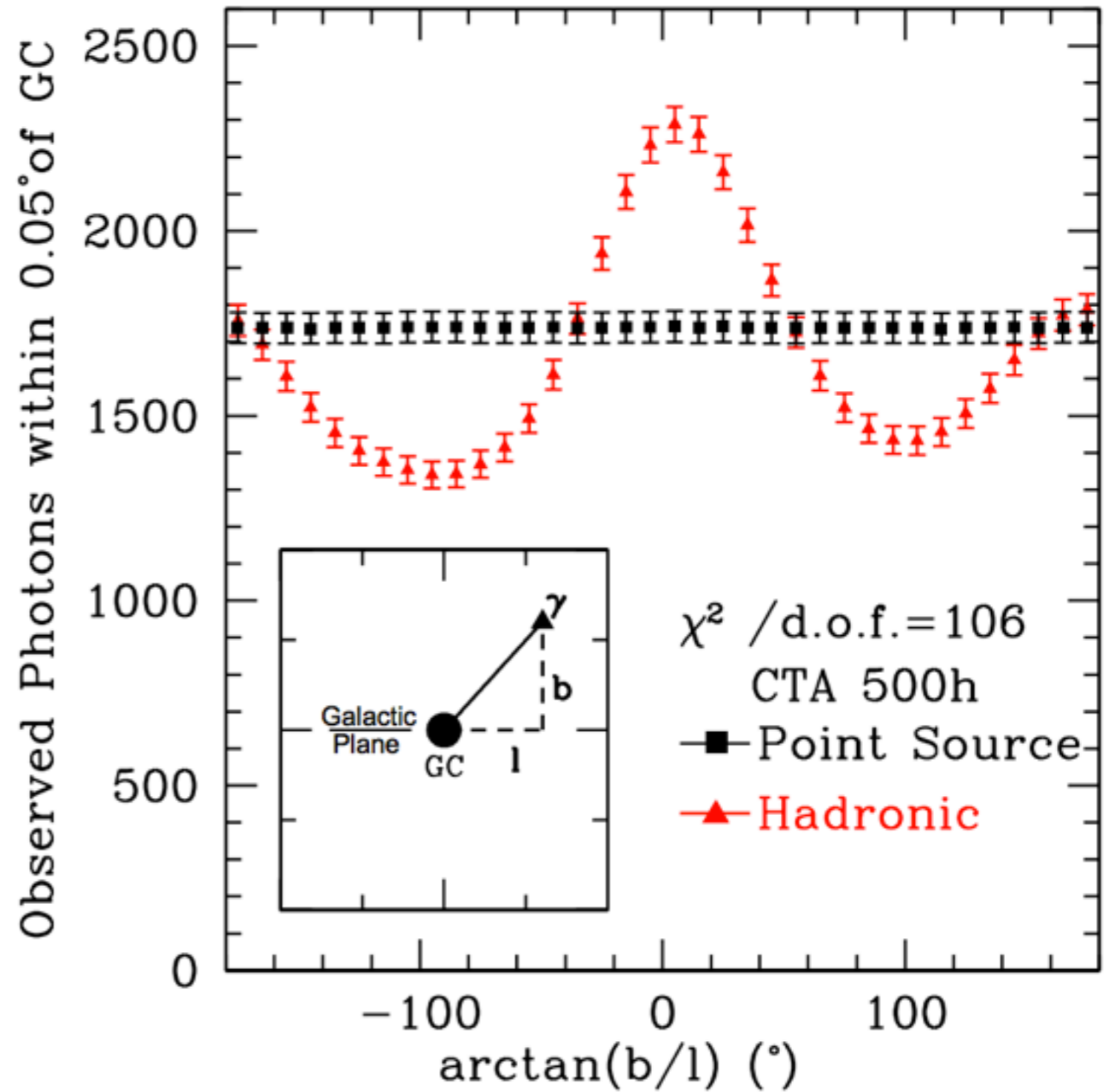
CTA and the Galactic Center

- 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 conclusively determine whether the galactic center source stems from a hadronic emission channel



CTA and the Galactic Center

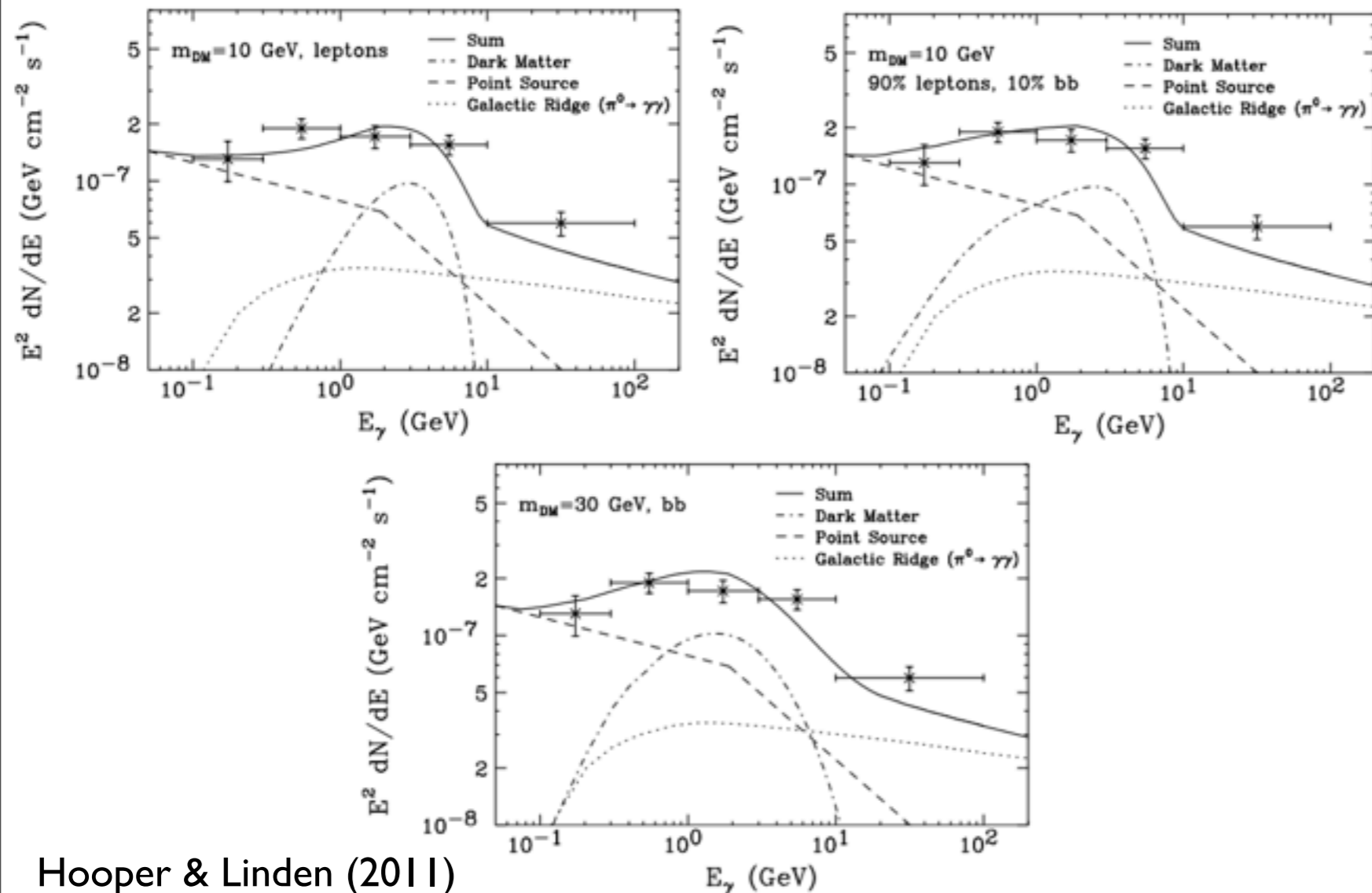
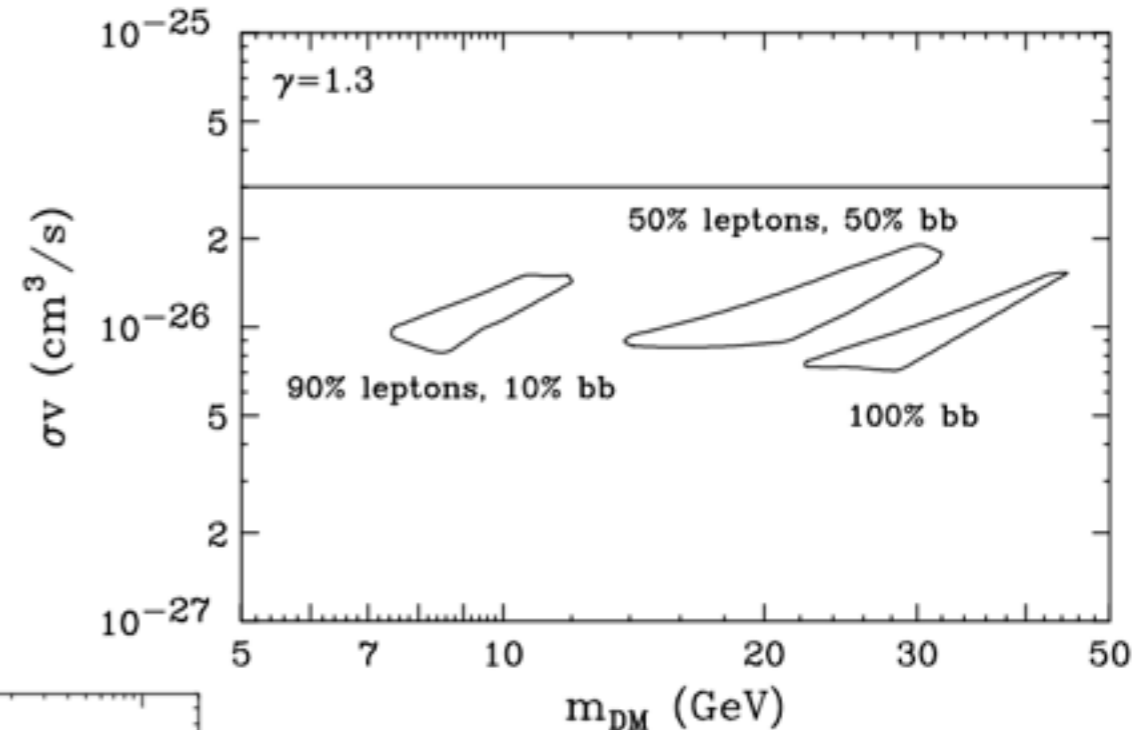
- By convolving our models of the gas and proton densities in the galactic center region with the PSF and effective area of each instrument, we can determine whether CTA can distinguish between these scenarios
- CTA will conclusively determine whether the galactic center source stems from a hadronic emission channel



Linden & Profumo
(2012)

Story 2: Low-Mass Dark Matter

- For a best fitting profile $\gamma = 1.3$, 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

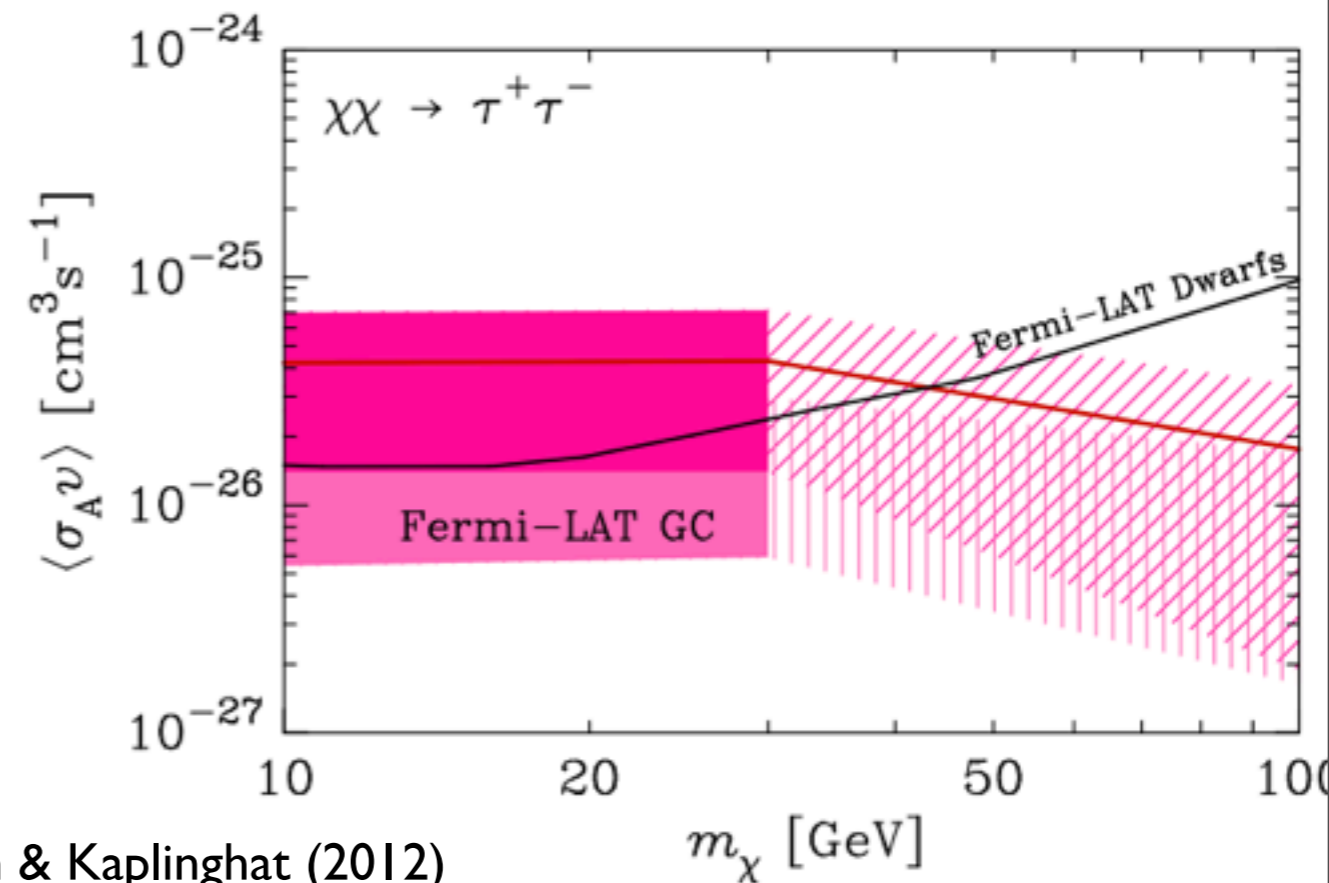
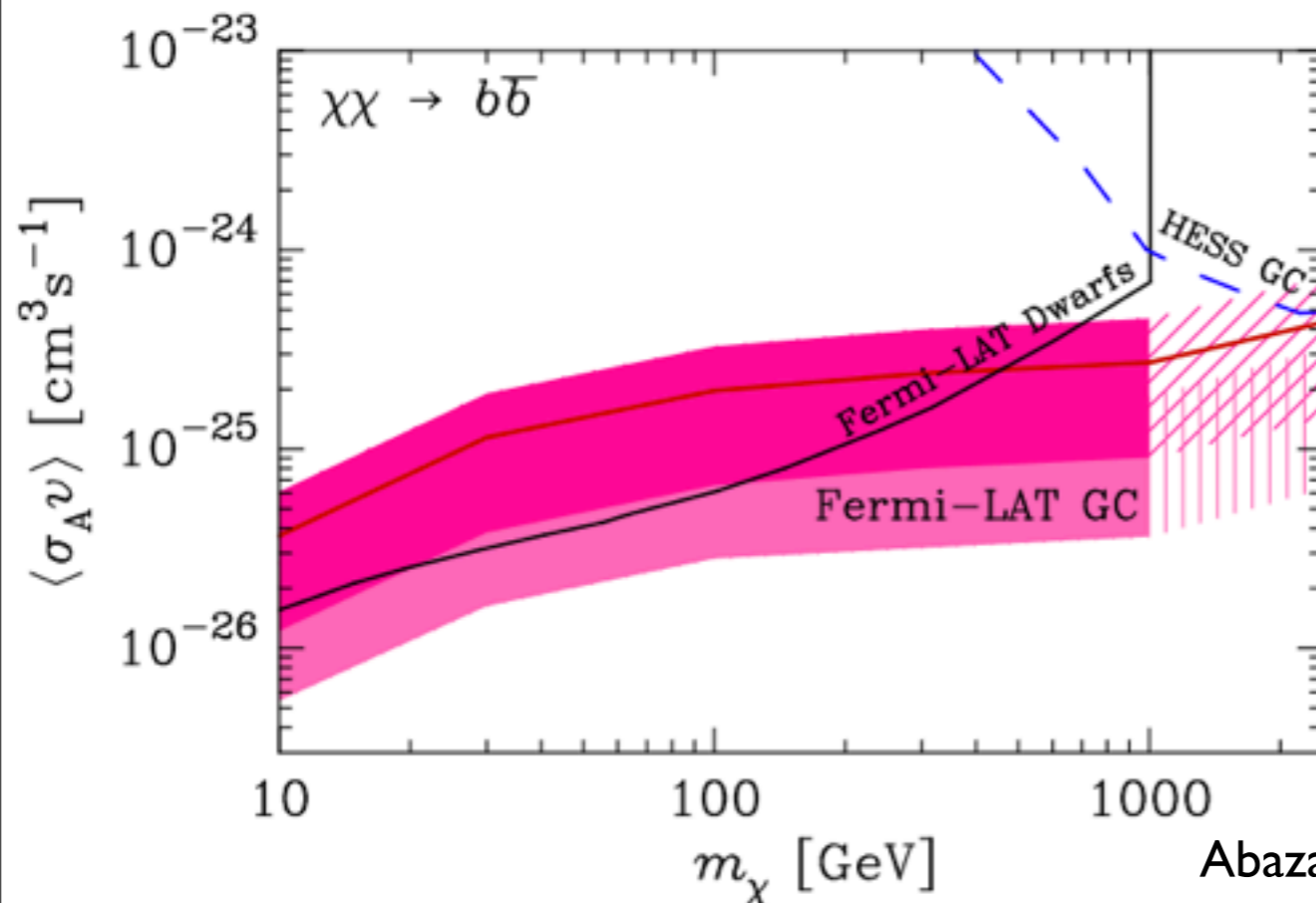
Hooper & Linden (2011)

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
- However, fits with low dark matter mass are much, much better

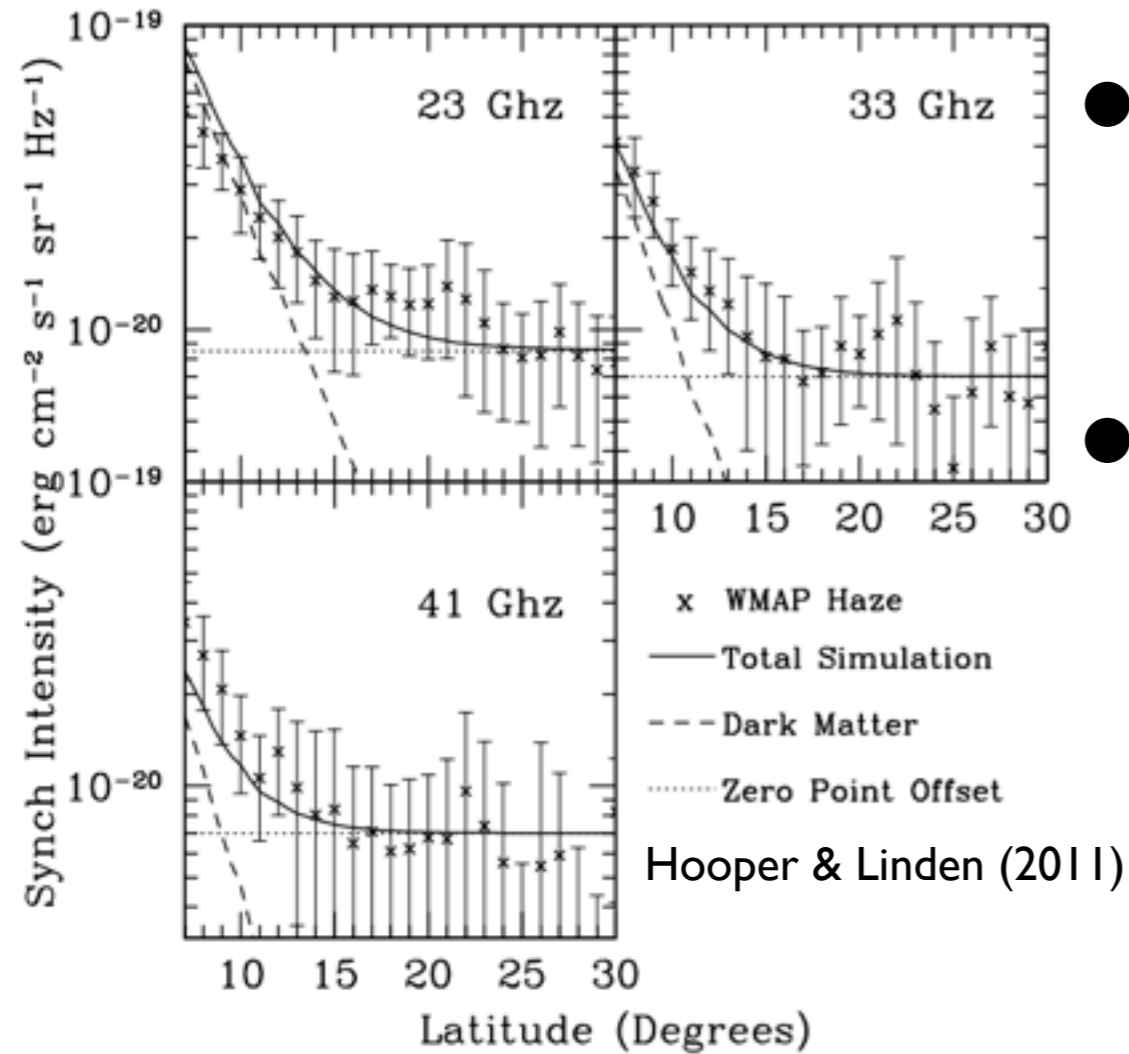
TABLE II. The best-fit TS, negative log likelihoods, and $\Delta\mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

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



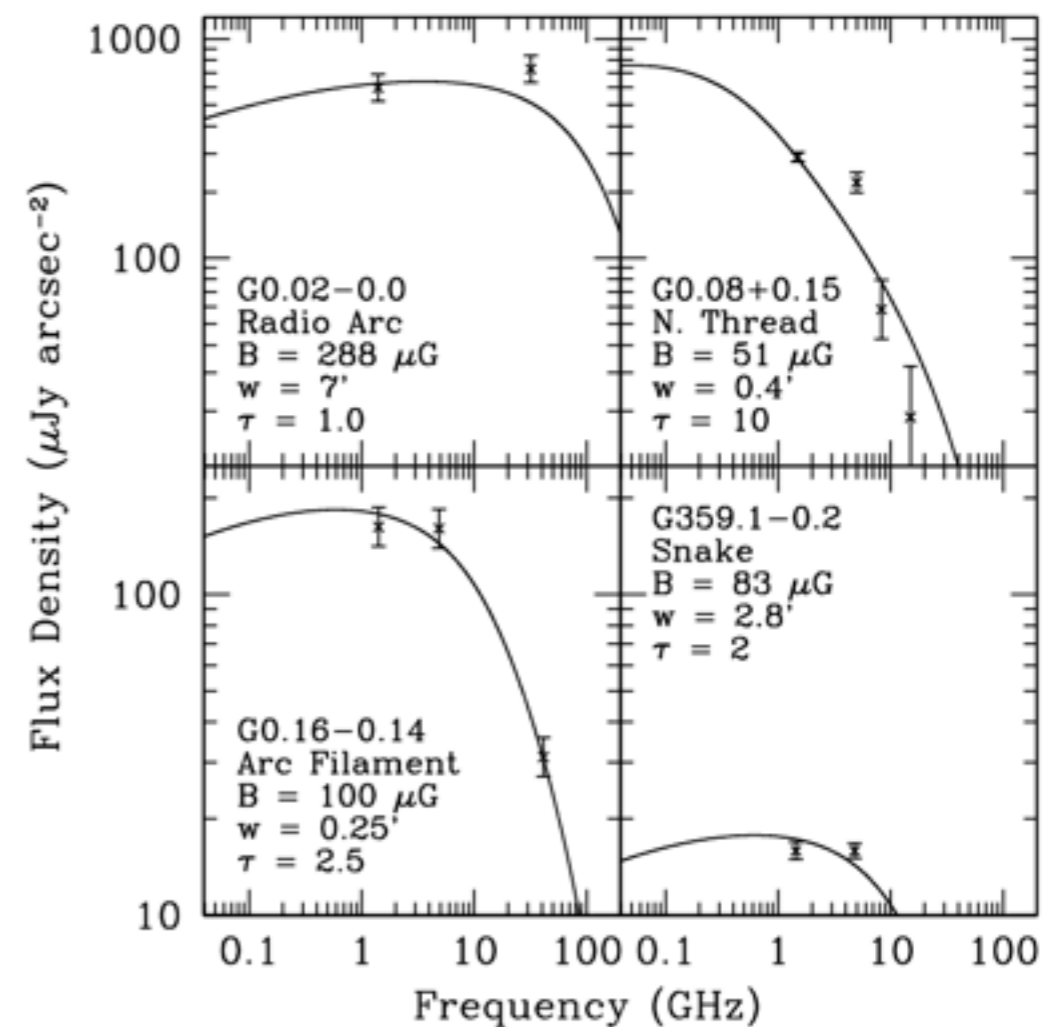
Abazajian & Kaplinghat (2012)

Other Observations Fitting Light DM: Indirect



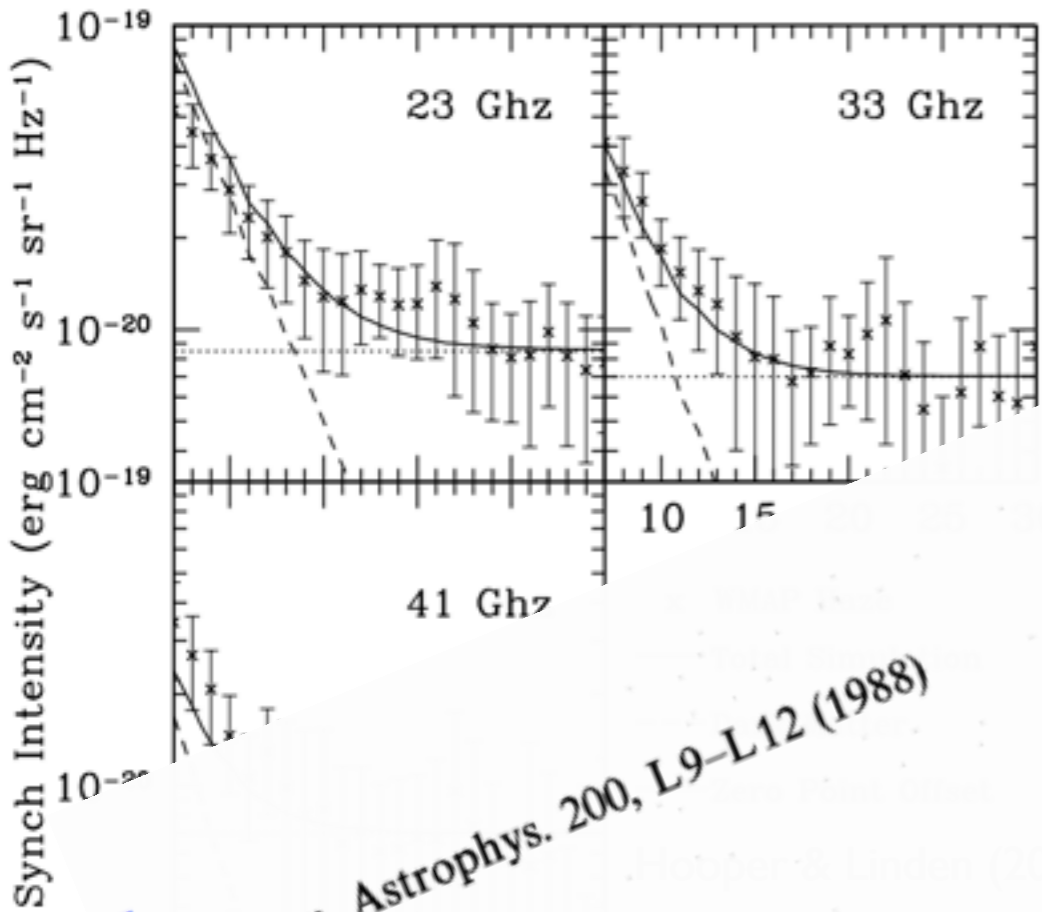
- The same dark matter model provides a reasonable explanation to the intensity and morphology of the WMAP haze
- The magnetic field must be slightly stronger above the galactic plane than usually assumed

- 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



- The same dark matter distribution is reasonable and fits the data.

ASTRONOMY
AND
ASTROPHYSICS

The magnetic field must be slightly stronger above the galactic plane than usually assumed.

Letter to the Editor

Monoenergetic relativistic electrons in the galactic center

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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

It is shown that the nonthermal radio spectra of the galactic center, including Sgr A* and the extended component (the Arc) is neither due to self-absorbed emission, nor due to thermal absorption. A power-law distribution of monoenergetic relativistic electrons which propagate with a diffusion function into the

where S_M is the observed flux density of the self-absorbed source at a frequency ν , B is the magnetic field. With the flux density S_{10} at 10 GHz (Reich et al., 1988) and B_{10} at 10^{-2} G (Sofue and Fujimoto, 1988) we find

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

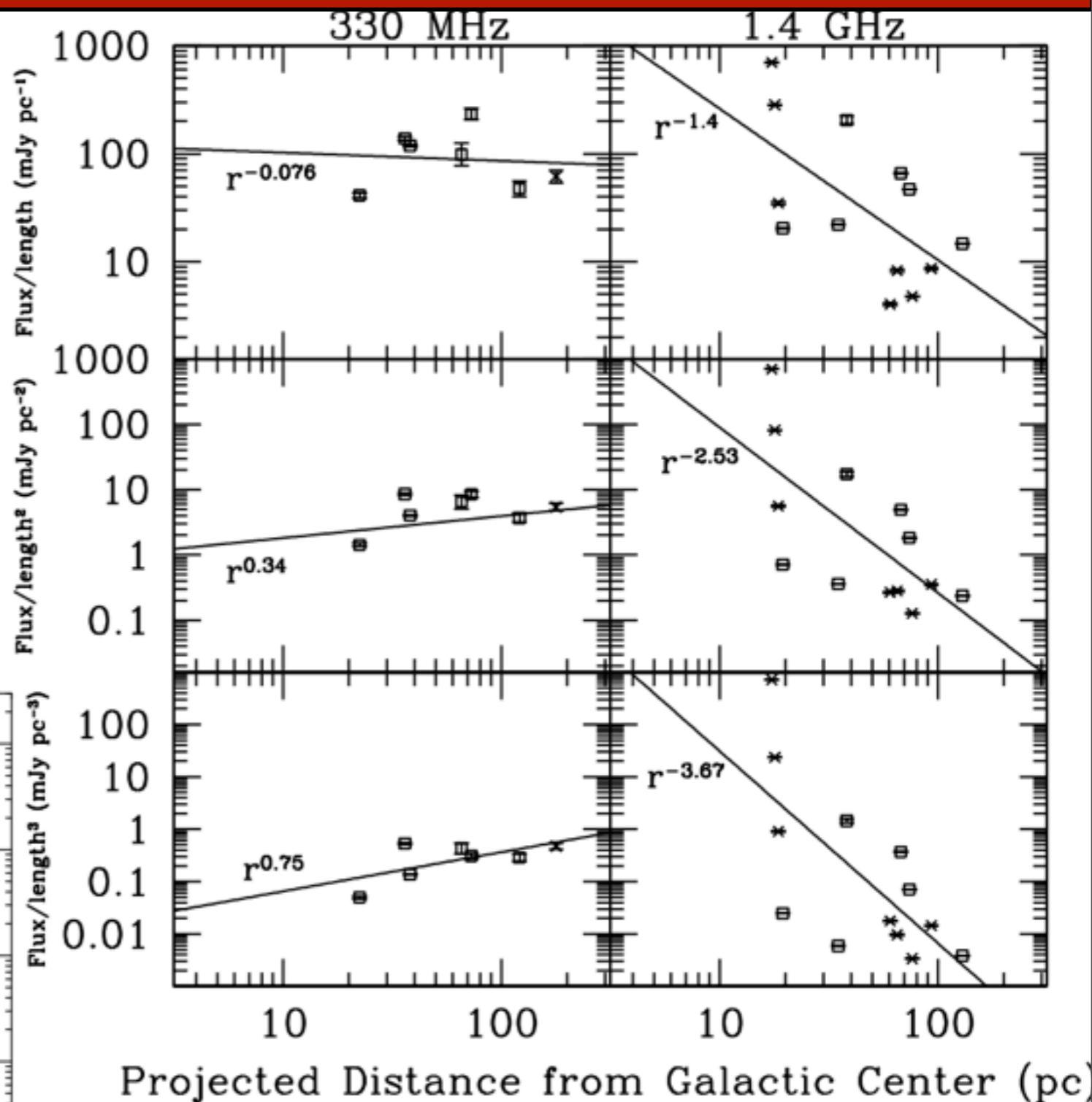
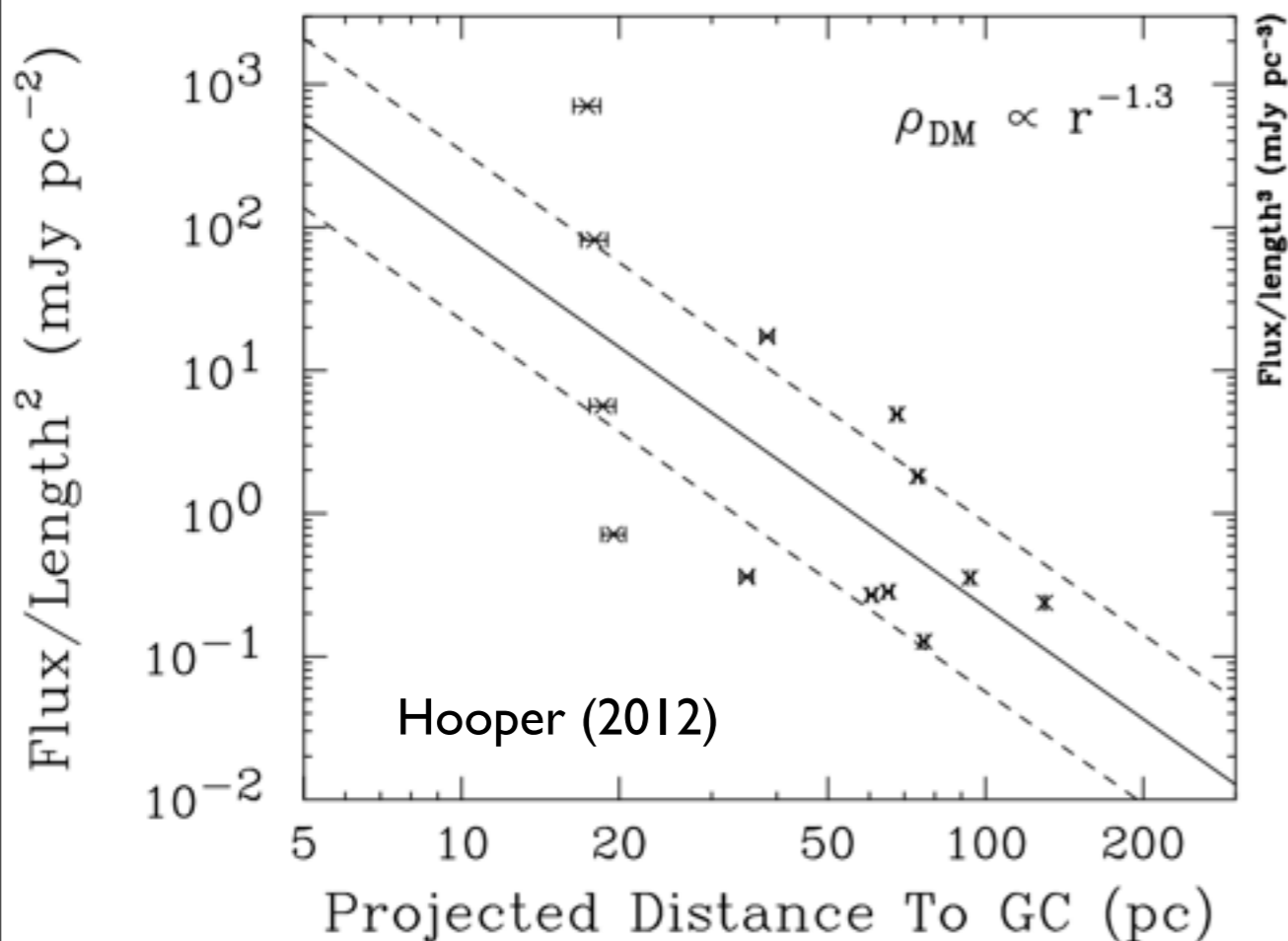
The source is resolved with an angular size of $\delta\theta_{\text{crit}} \approx 4 \cdot 10^{-4}$ arcseconds (Reich et al., 1988). This implies that the source consists of reasonably small structures.

16...1001...2002...19988691

- The fit to the data is a power-law distribution of monoenergetic relativistic electrons in the galactic center.
- Light DM is necessary to fit the spectrum.

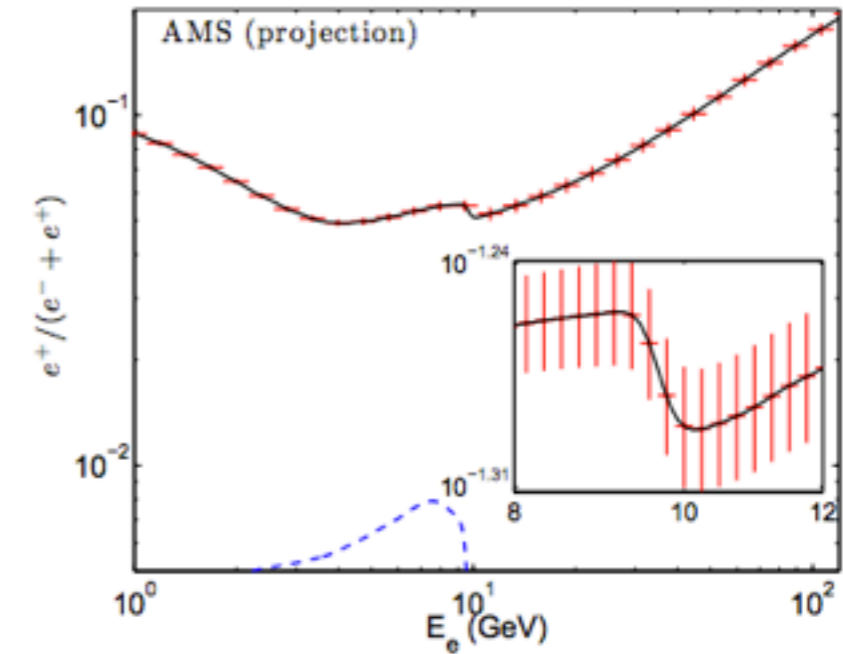
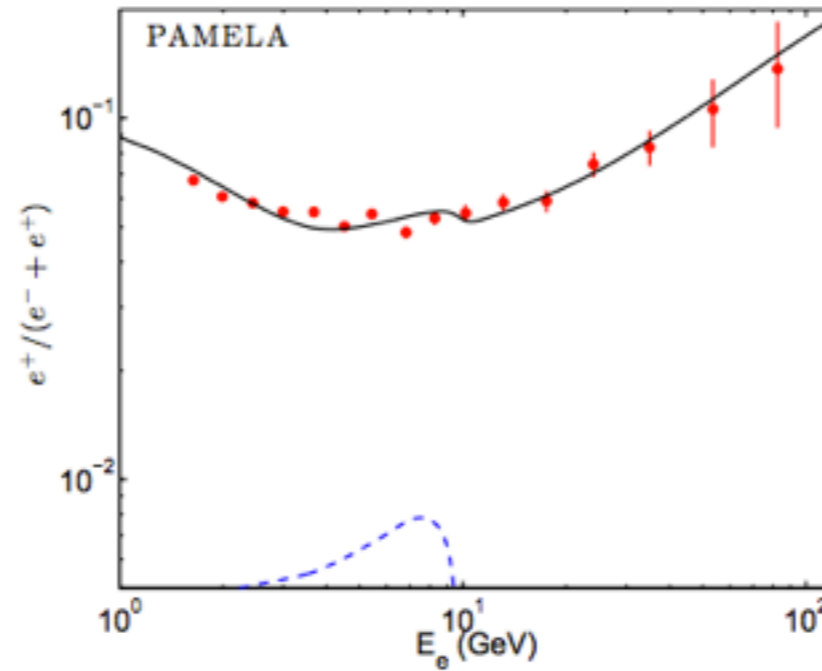
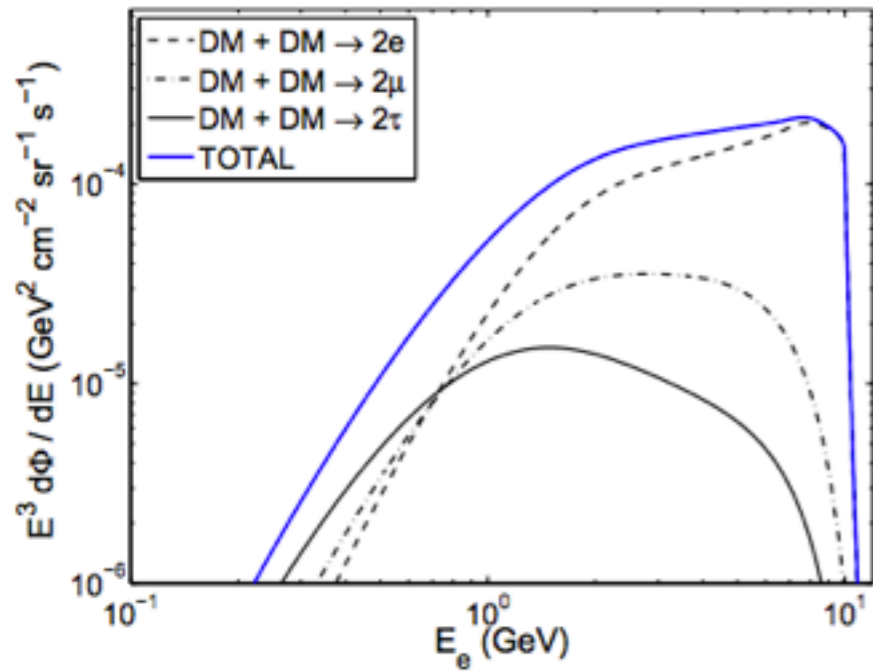
The Radial Dependence of the Filamentary Arcs

- 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)

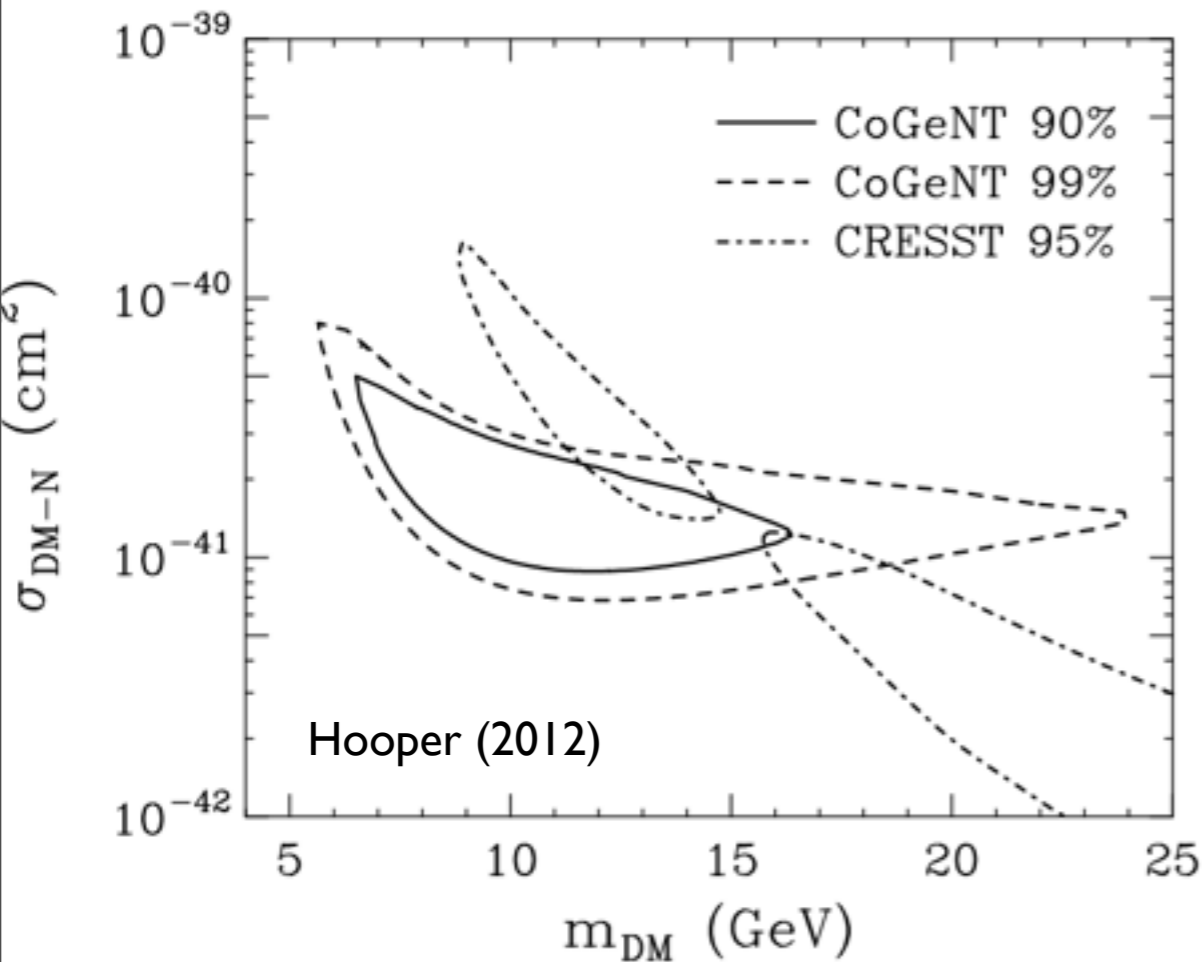
Other Observations Fitting Light DM: Indirect



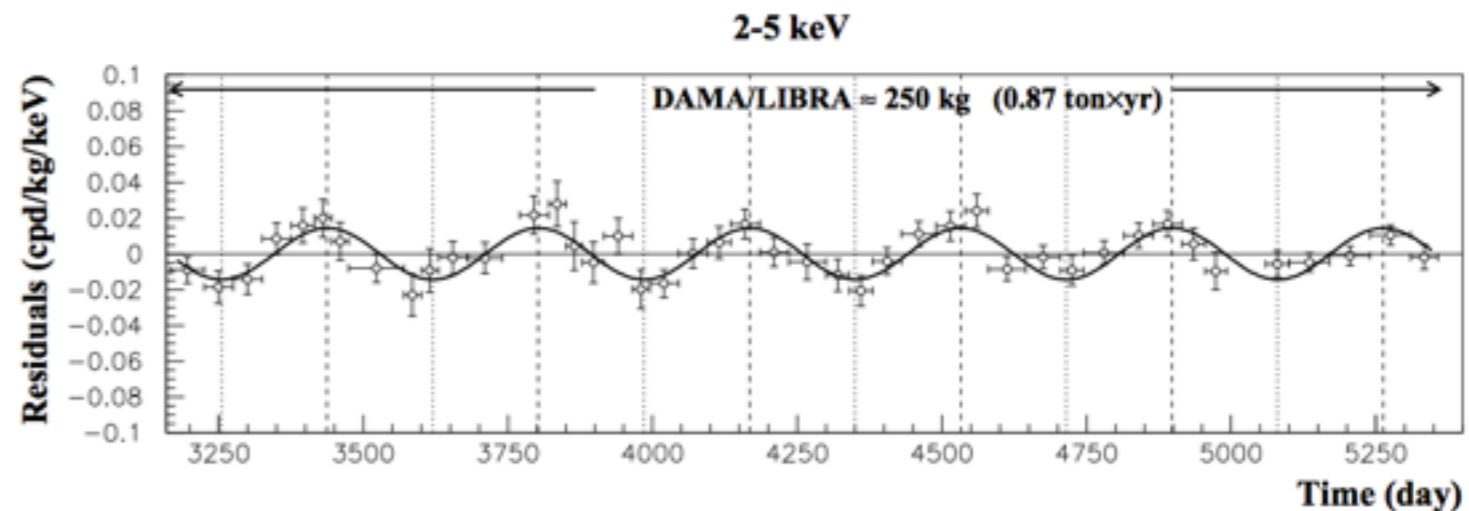
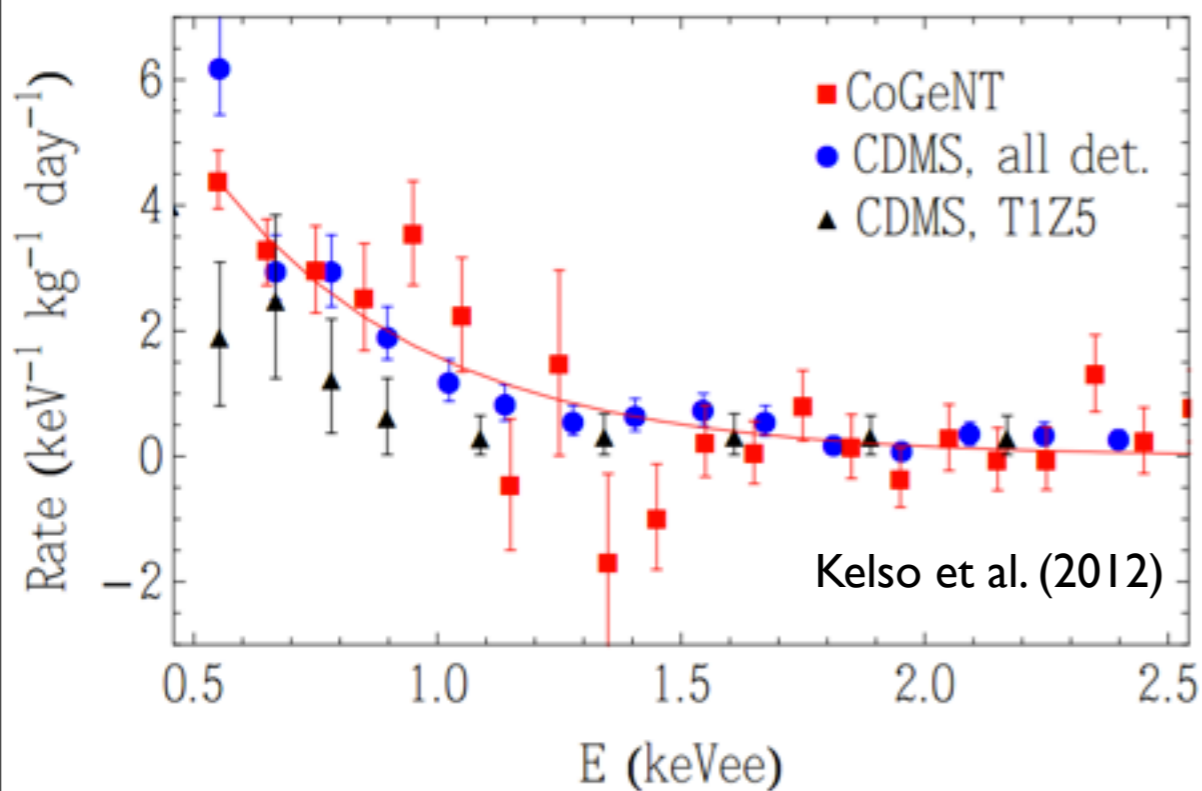
Hooper & Xue (2012)

- Light, leptophilic Dark Matter models will be observable by AMS.
- Solar Modulation must be taken into account (marginally) at these energy levels

Other Observations Fitting Light DM: Direct

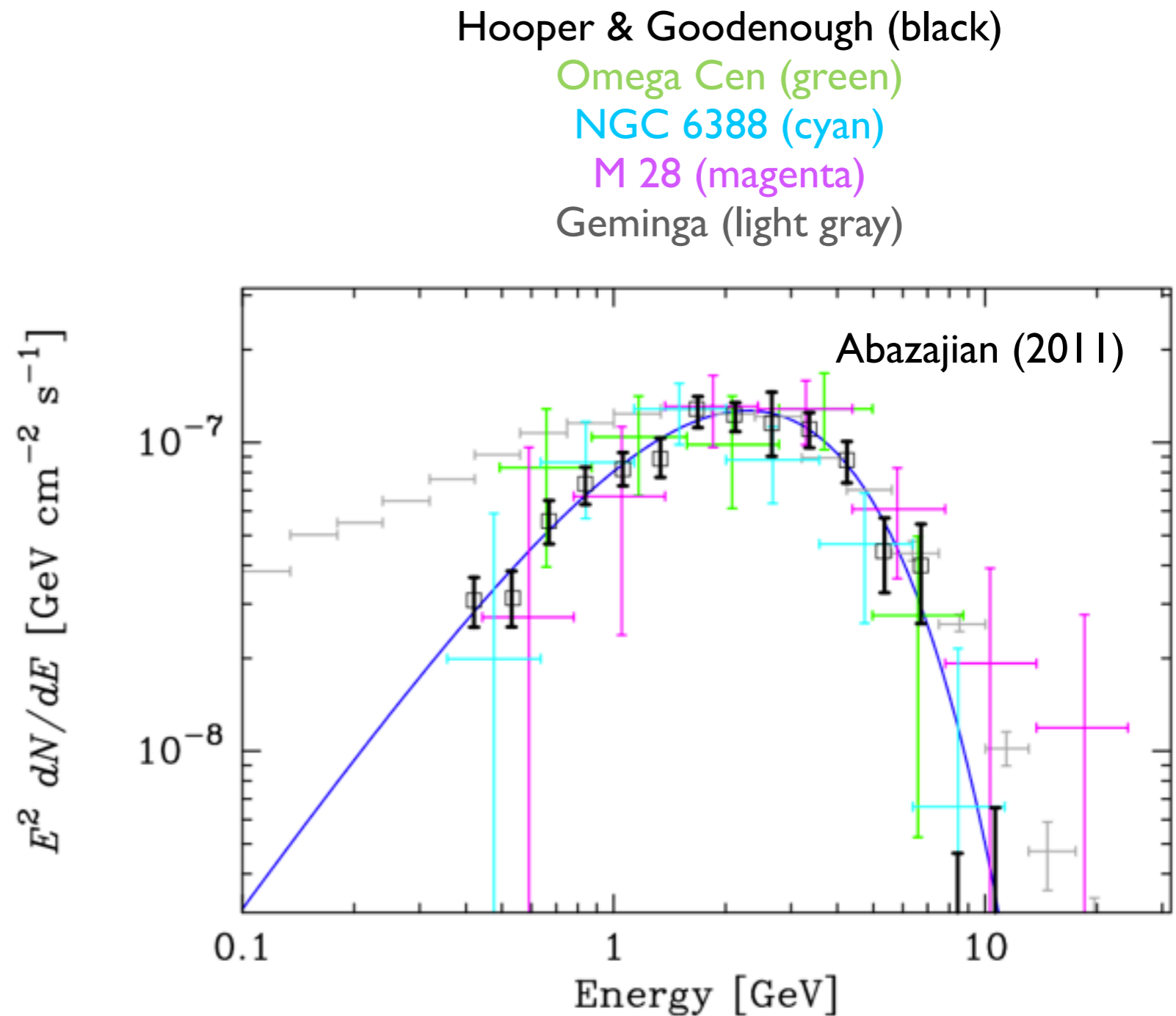


- Light Dark Matter (~10 GeV) provides a compelling fit to the excesses currently observed by DAMA, CoGeNT and CRESST
- Light Dark Matter may also be compatible with observed signal/limits at CDMS
- This issue will be resolved on the experimental side, with current and upcoming data



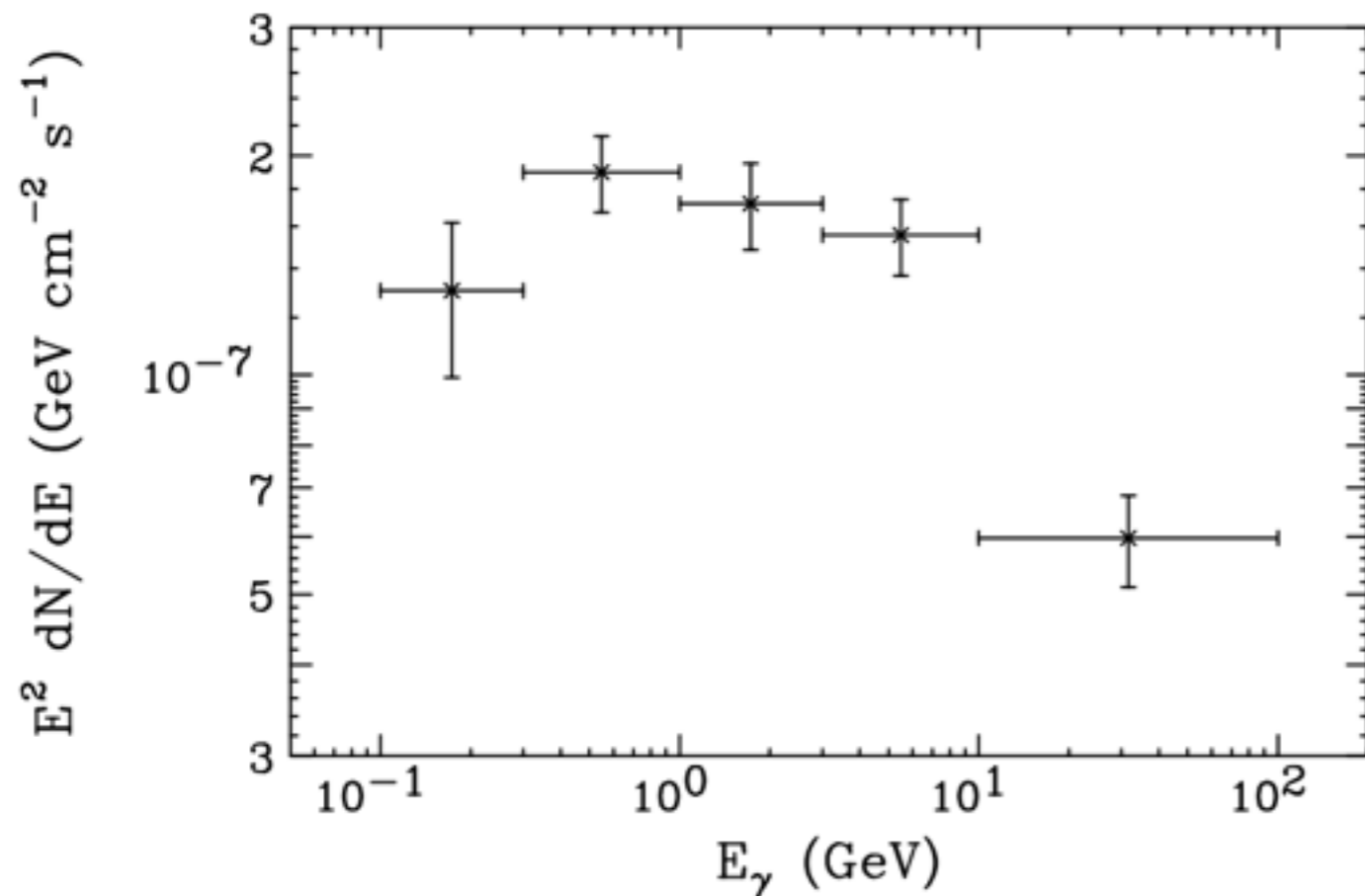
Story 3: Milli-second Pulsars

- Populations of Millisecond pulsars have been observed in multiple globular clusters (Terzan 5, Omega Cen, NGC 6388, M 28)
- GC source is ~ 200 brighter than Omega Cen - which correlates nicely with the 1000x larger mass of the GC region

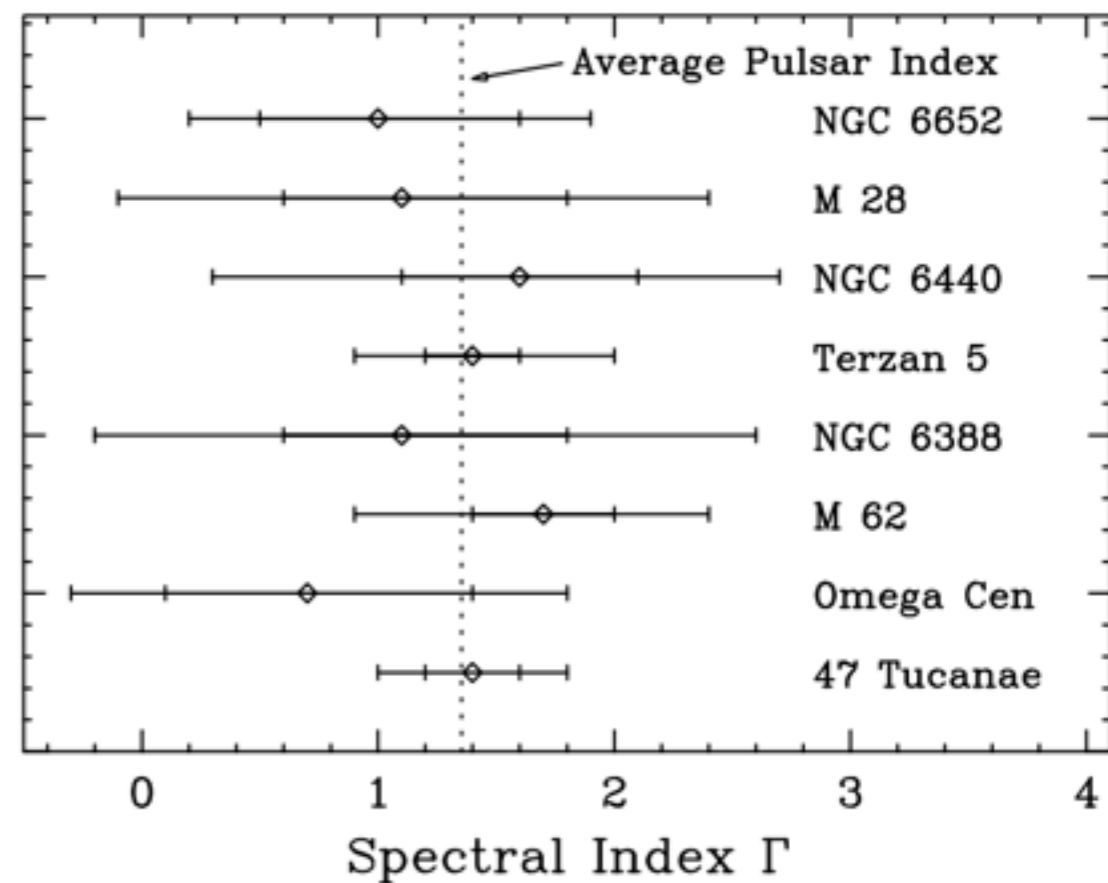
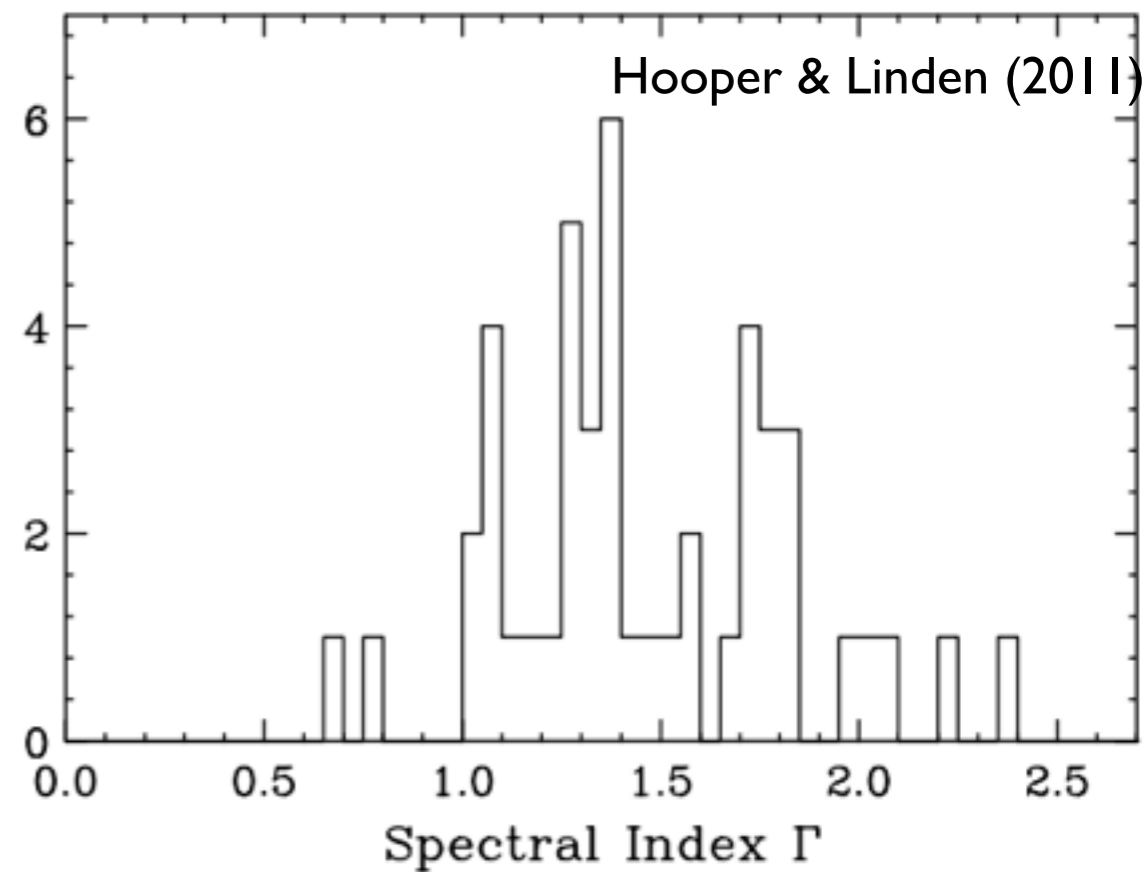


Millisecond Pulsar Spectrum

- But is the spectrum of the observed residual ($\Gamma < \approx 1.0$) too hard below 1 GeV?

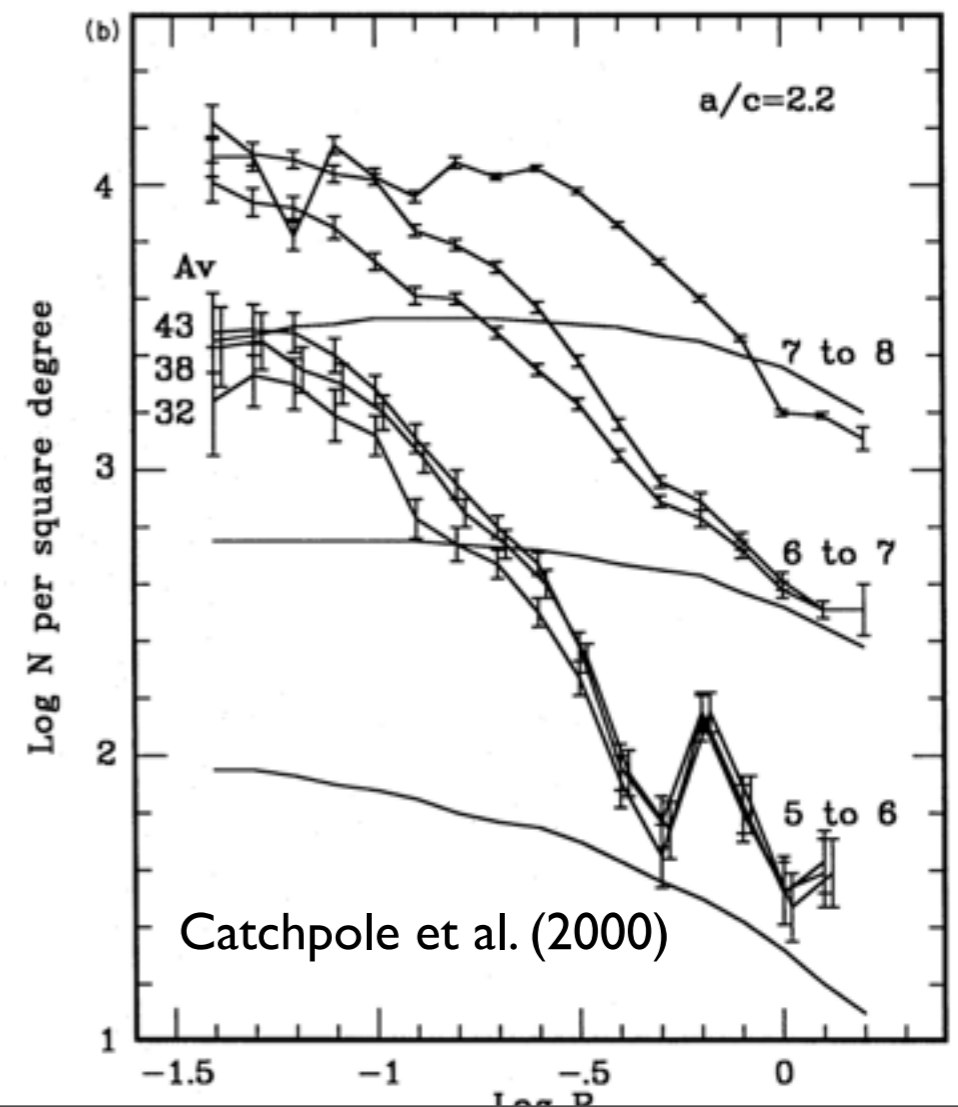
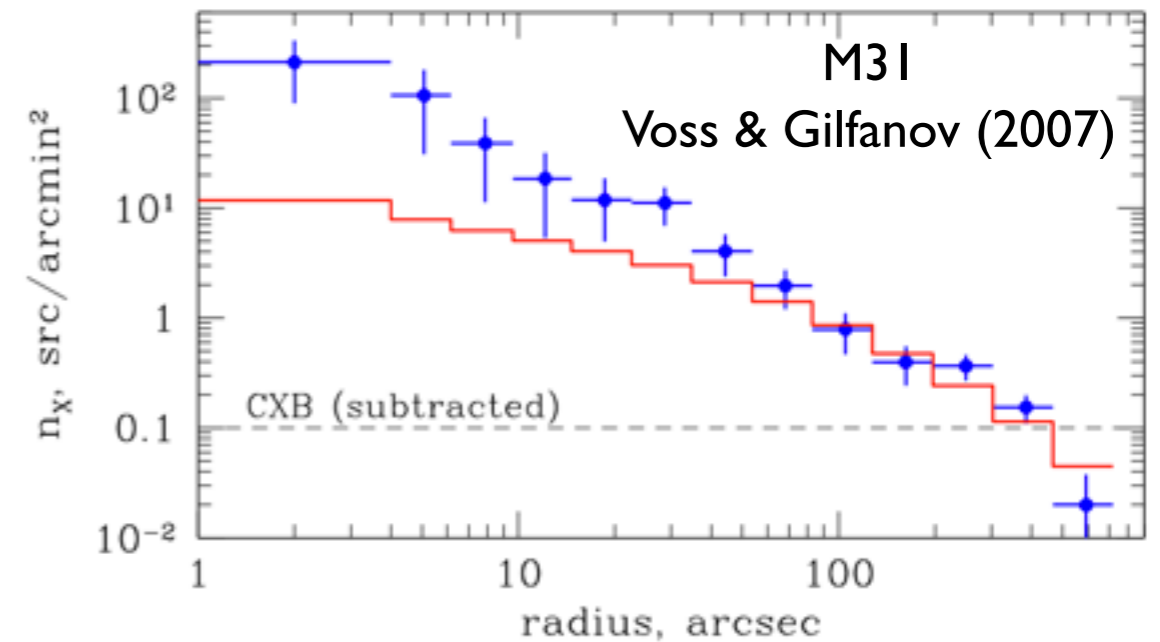


Number of Pulsars



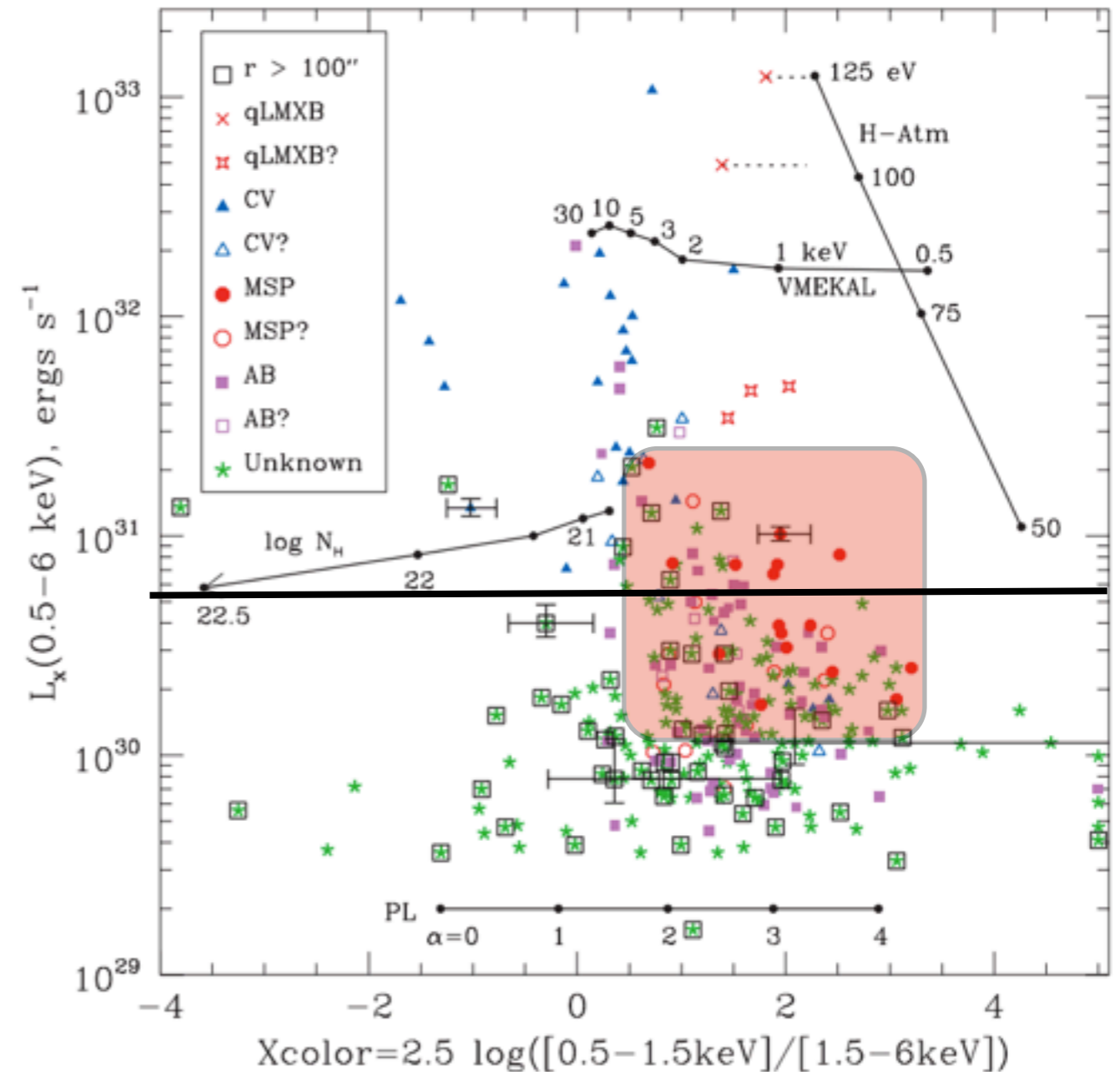
Millisecond Pulsar Density

- 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?



Can the Distribution of GC MSPs be Determined?

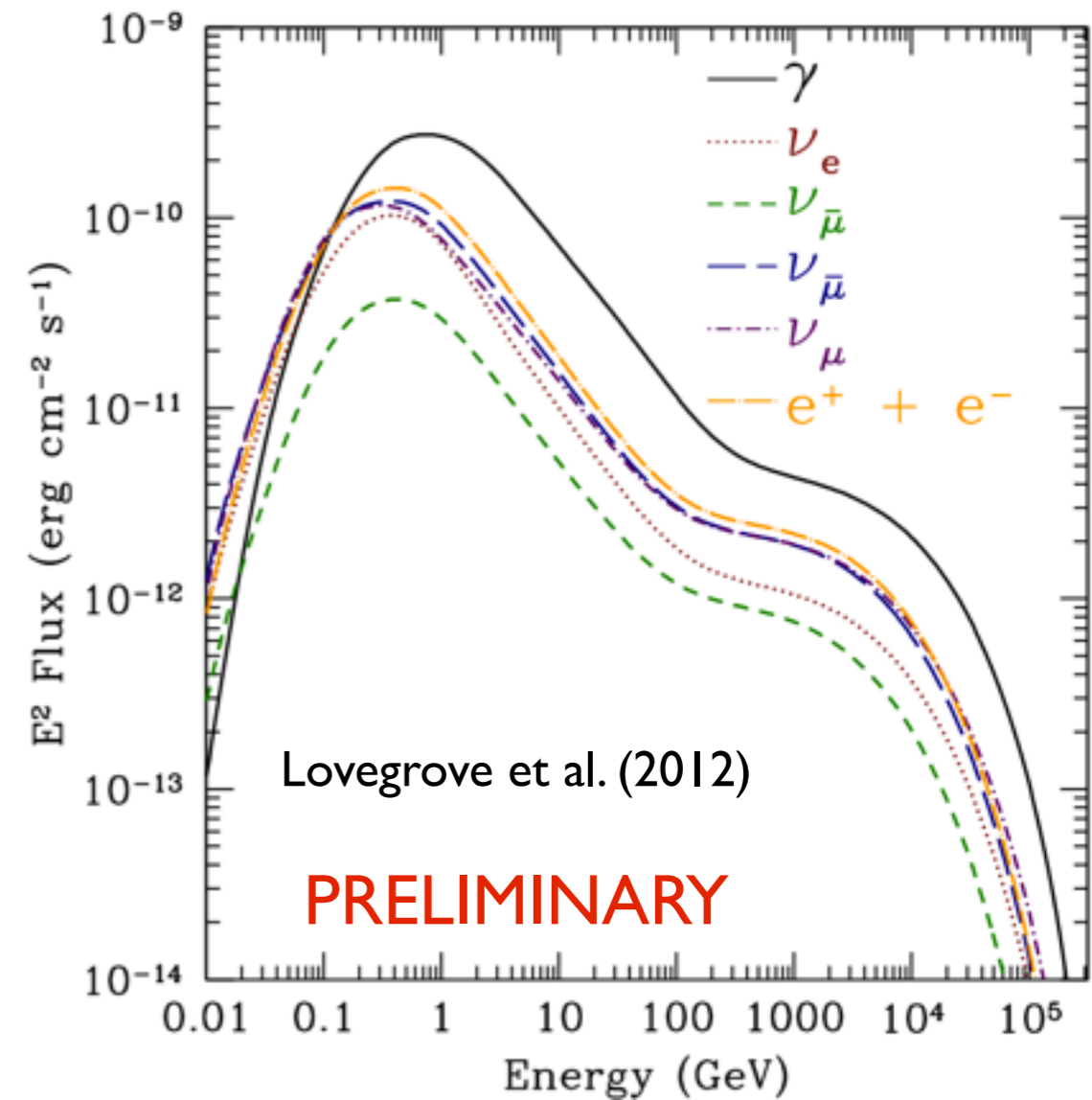
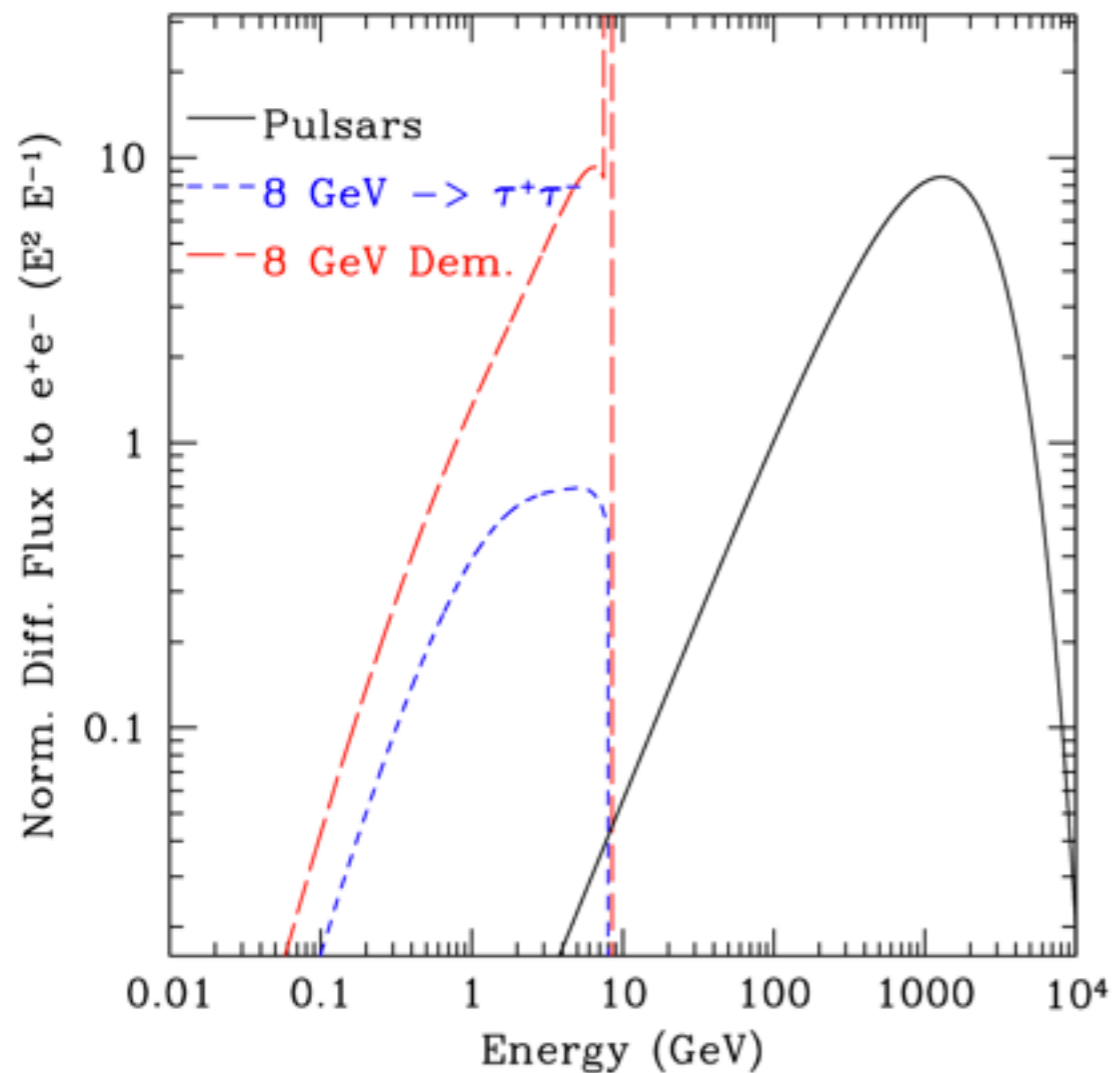
- X-Ray observations find a total of 2347 point sources within 40 pc of the GC - this could include a large population of MSPs
- MSPs exist in a particular location on the luminosity-color diagram in 47 Tuc



Heinke et al. (2006)

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

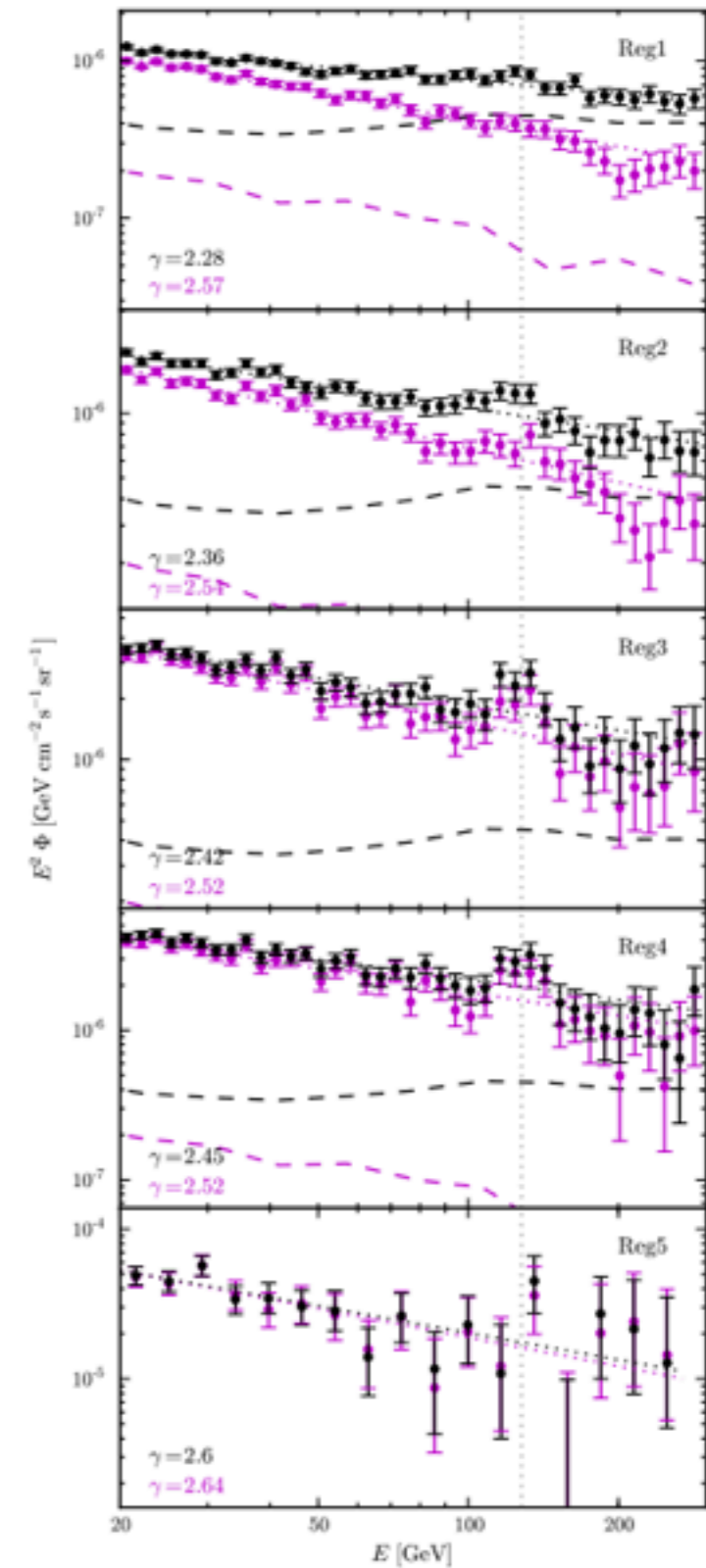
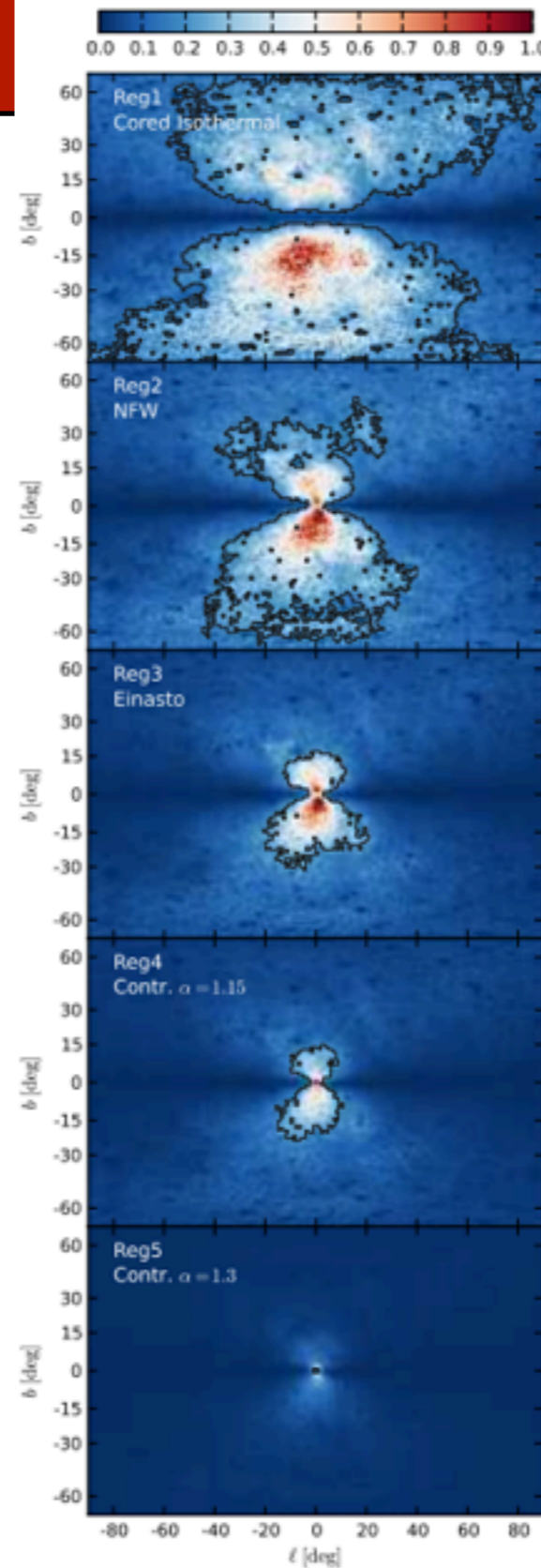
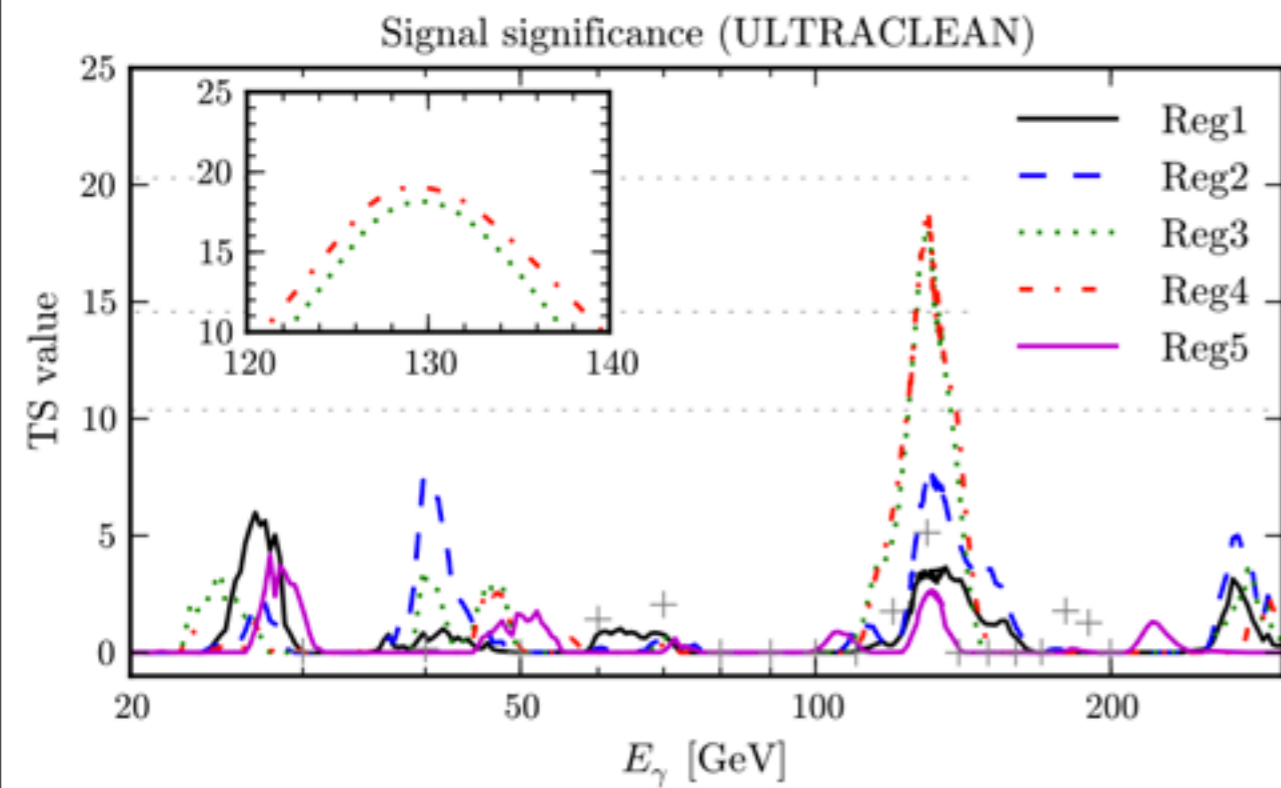
Negative: The diffusion and energy loss time of charged electrons adds additional uncertainties to the model

Conclusions

- There is **strong** evidence for an extended, spherically symmetric, excess in ~ 1 GeV gamma-ray emission surrounding the galactic center
- This excess is not easily accounted for by any known astrophysical model - and the background subtraction models used indicate that it is not correlated with galactic gas
- Dark Matter Annihilation and Pulsars both provide plausible models for this excess - the best statistical fit stems from dark matter annihilation, but the plausibility of the MSP model forces us to take it seriously
- New observations, and also novel models, are needed to separate these components

130 GeV Line!?

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

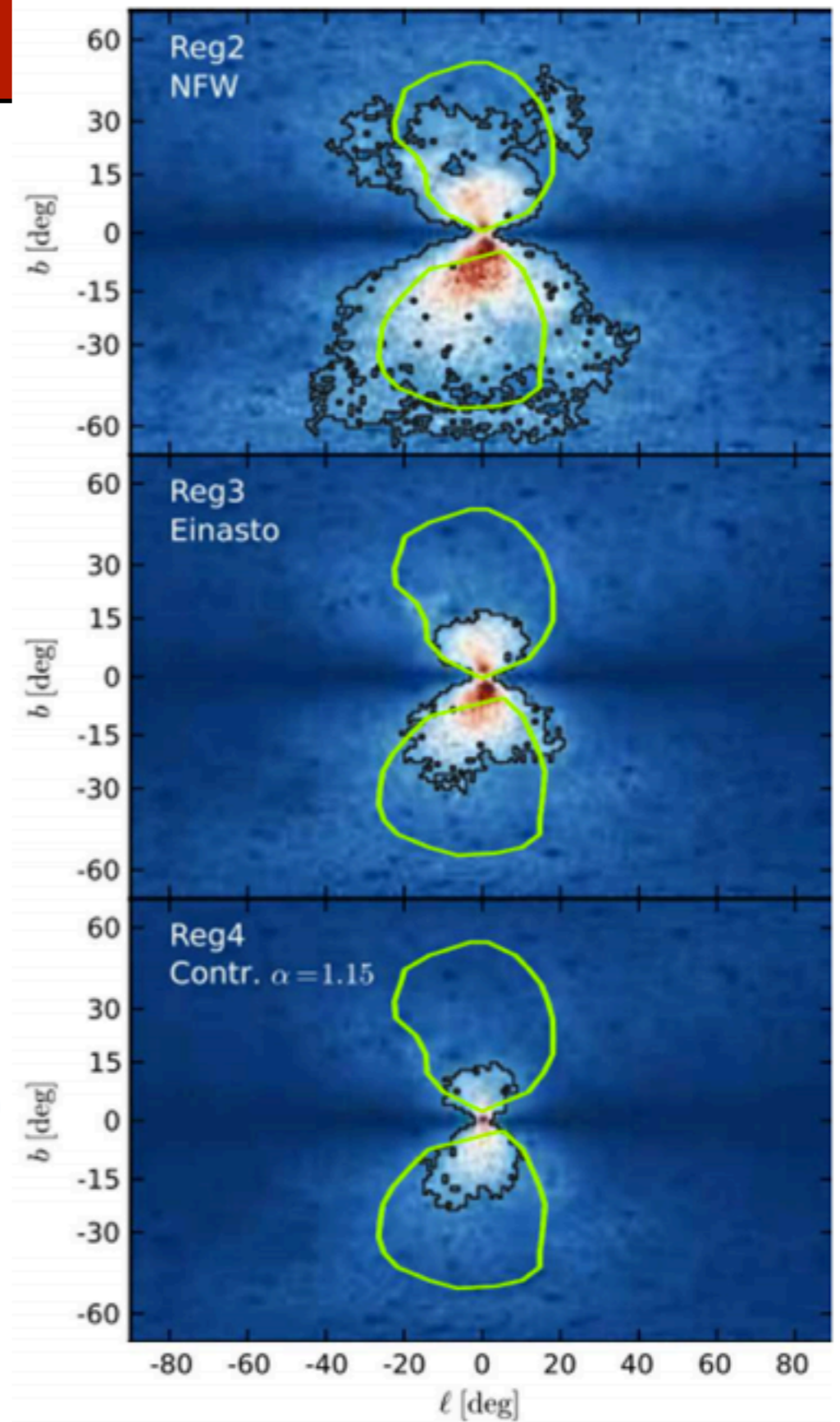
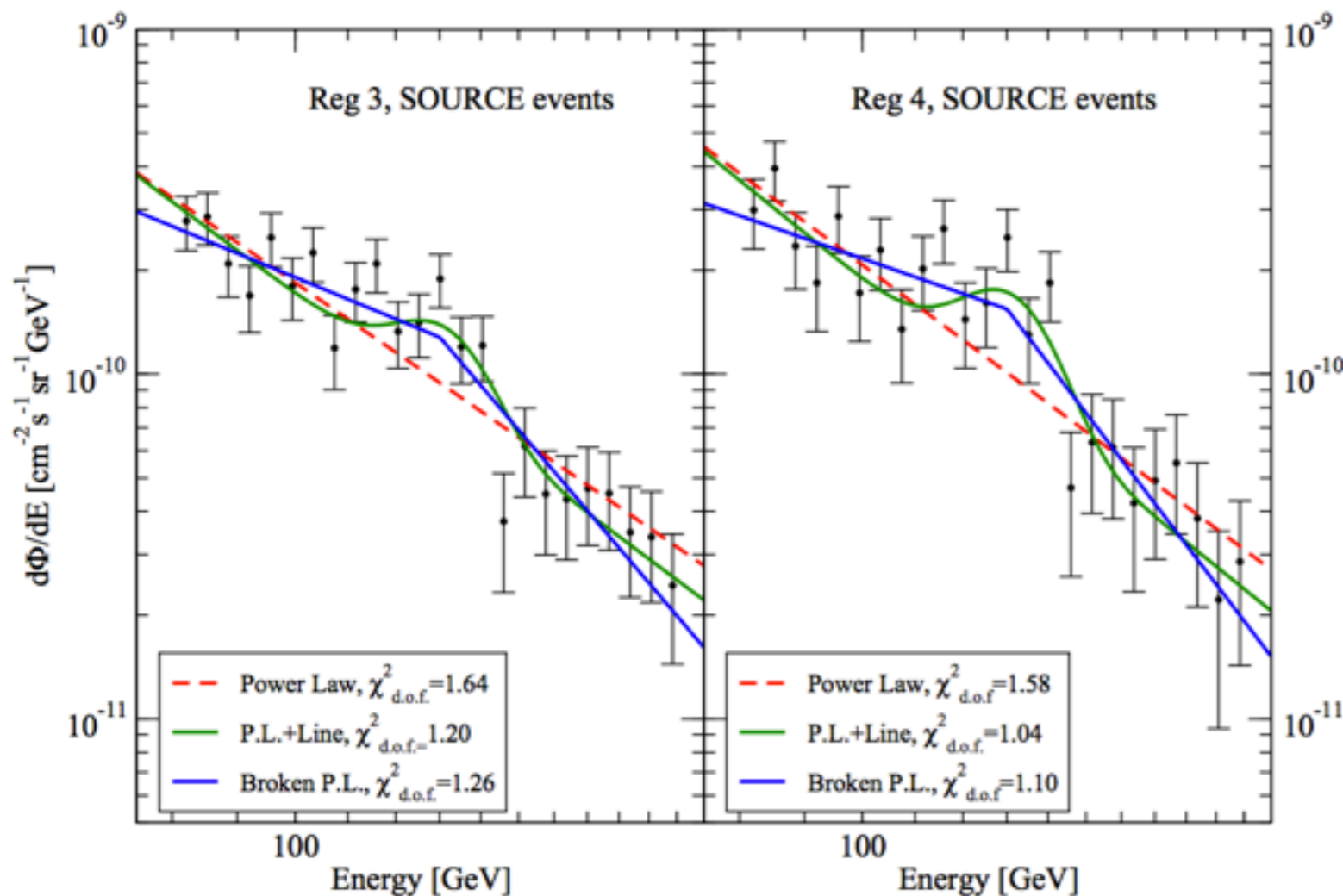


Weniger (2012)

130 GeV Line!?

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

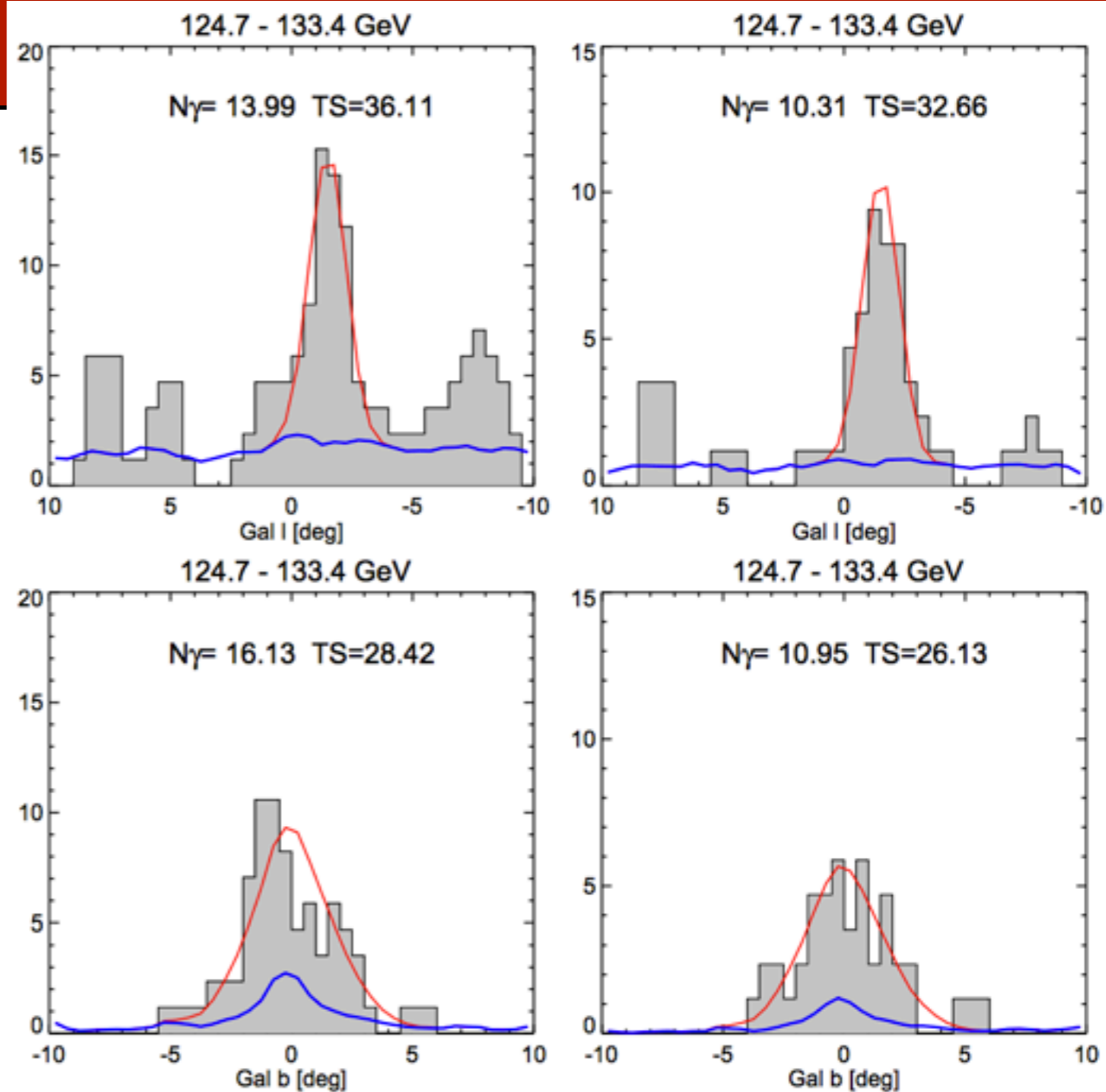
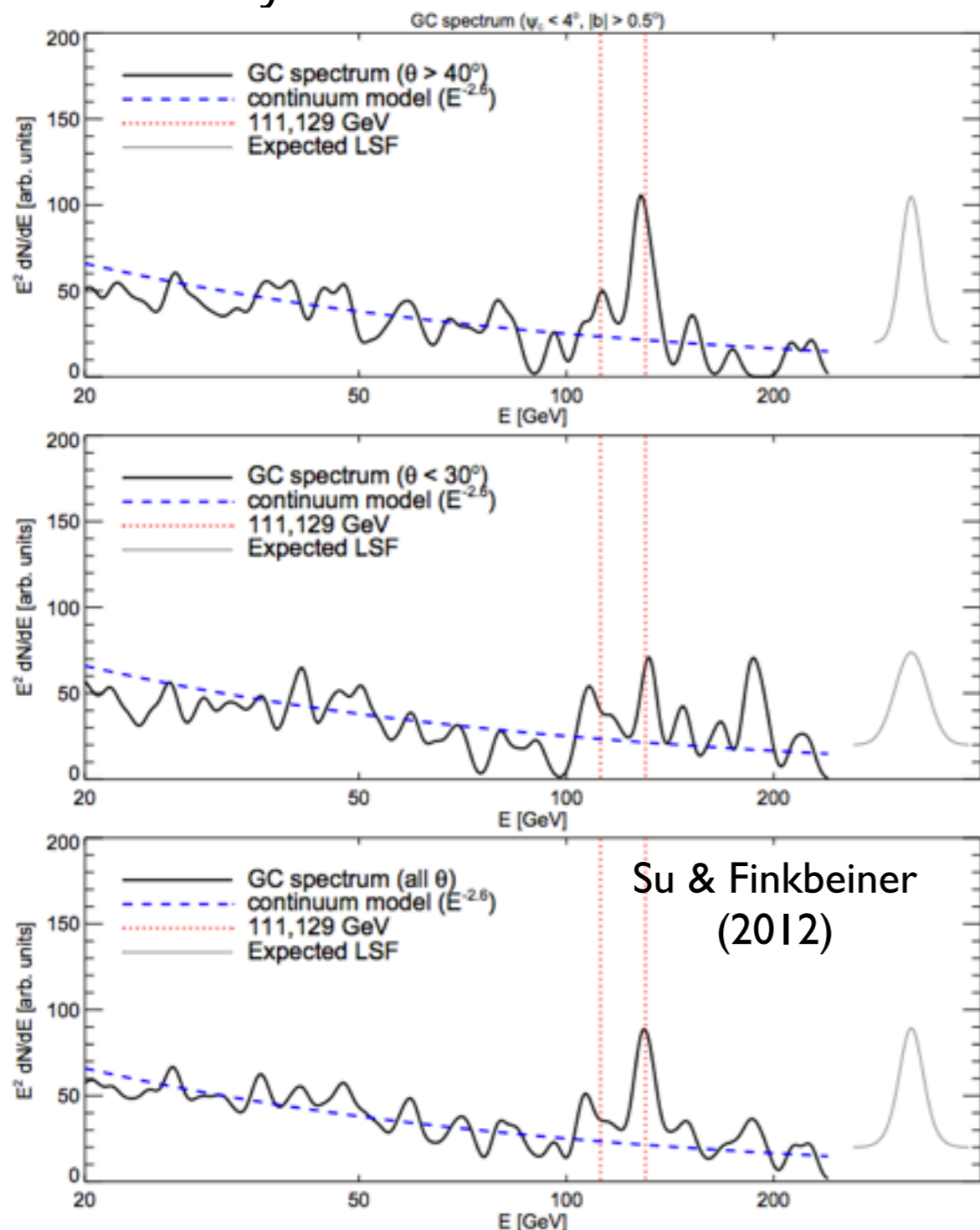
- That broken power-law could be driven by the Fermi bubbles



Profumo & Linden
(2012)

130 GeV Line!?

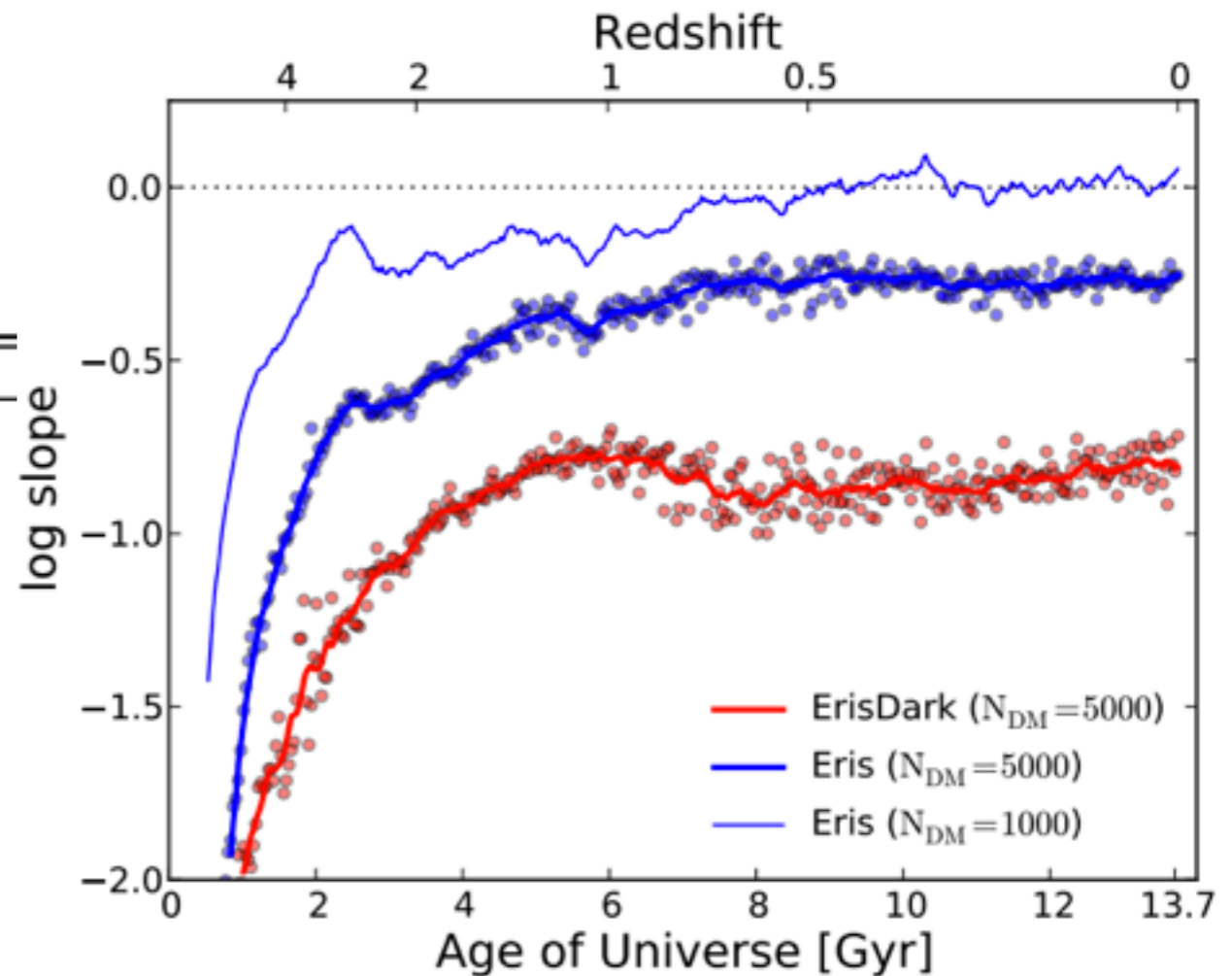
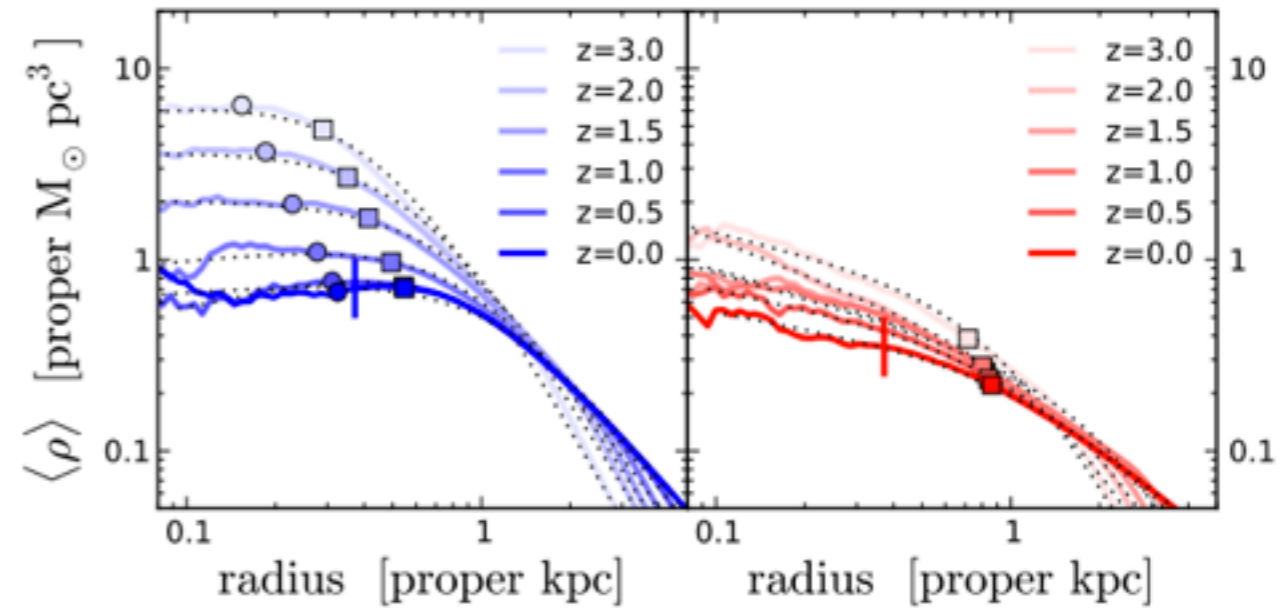
- Su & Finkbeiner confirmed the result of Weniger (2012) using a template based analysis



- 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

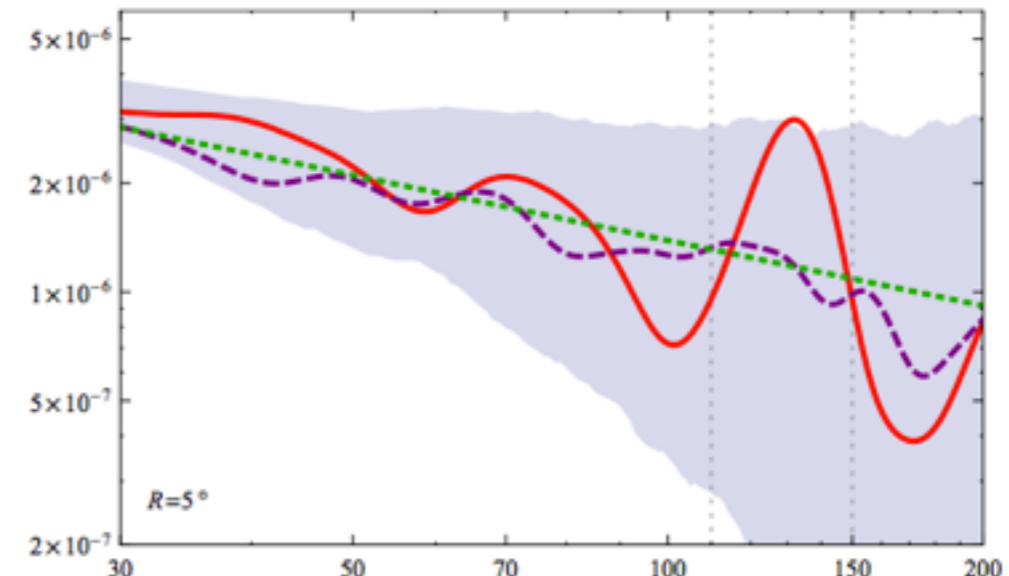
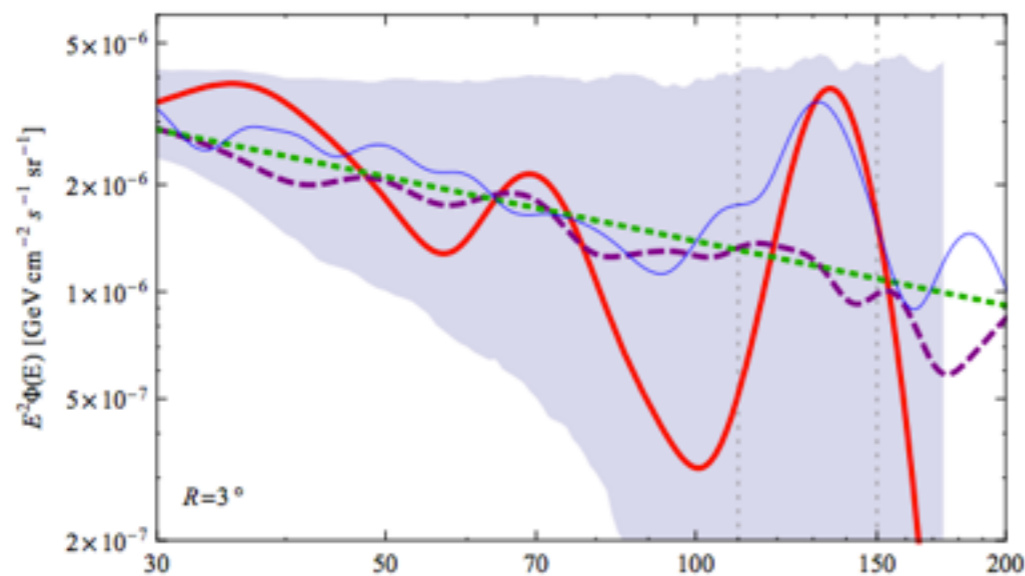


Models	Before trials	After trials (one line)
Gaussian (centered)	5.0σ	3.7σ
Gaussian (off center, $\theta > 40^\circ$)	5.5σ	3.7σ
unbinned ℓ	5.2σ	3.2σ
unbinned ℓ ($\theta > 40^\circ$)	4.9σ	2.8σ
unbinned b	4.8σ	3.5σ
unbinned b ($\theta > 40^\circ$)	4.6σ	3.2σ
NFW $\alpha = 1.0$ (off center)	6.1σ	4.5σ
NFW $\alpha = 1.2$ (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

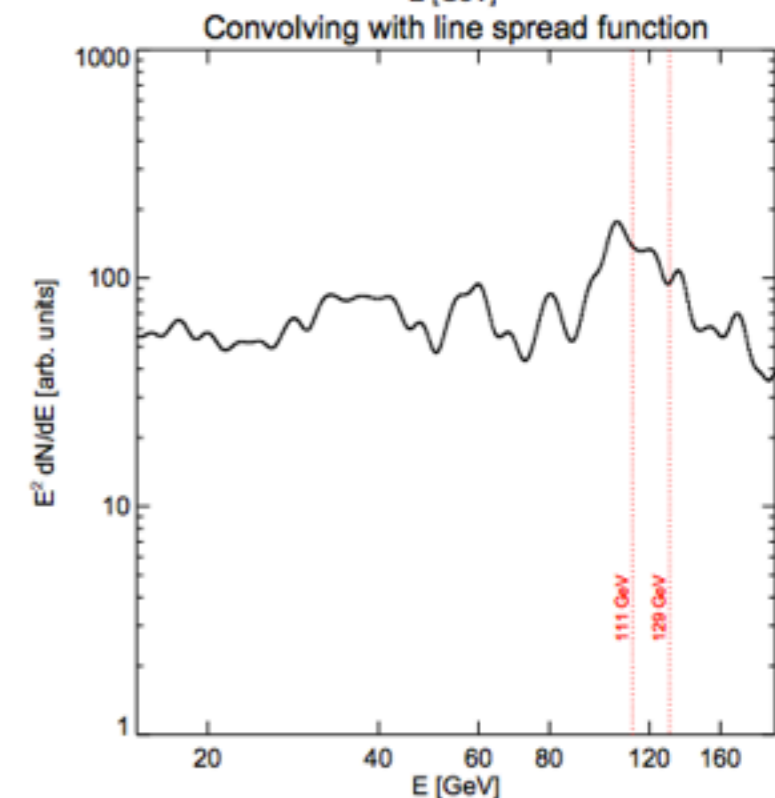
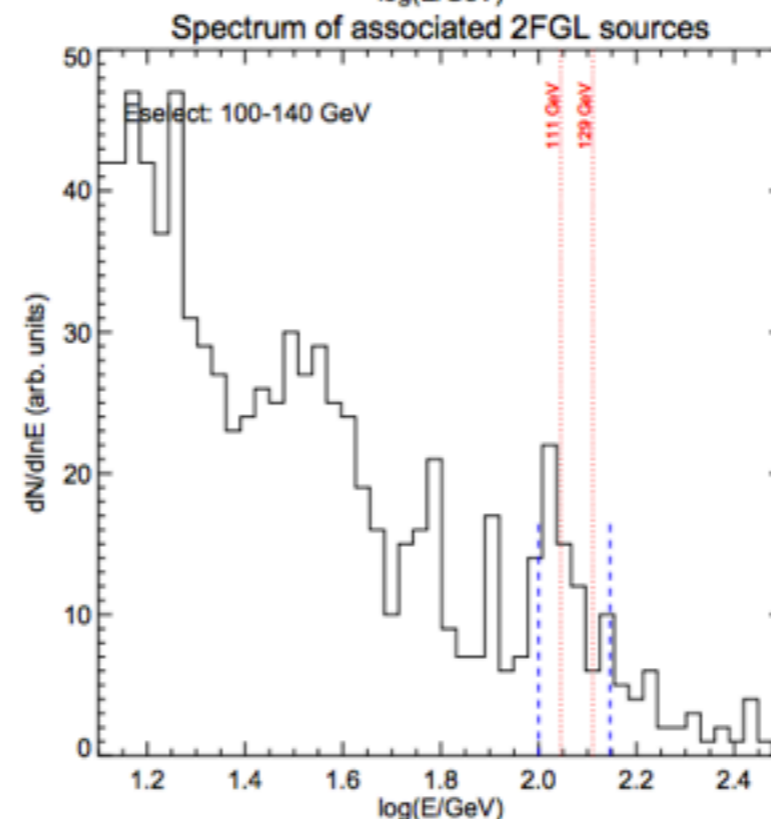
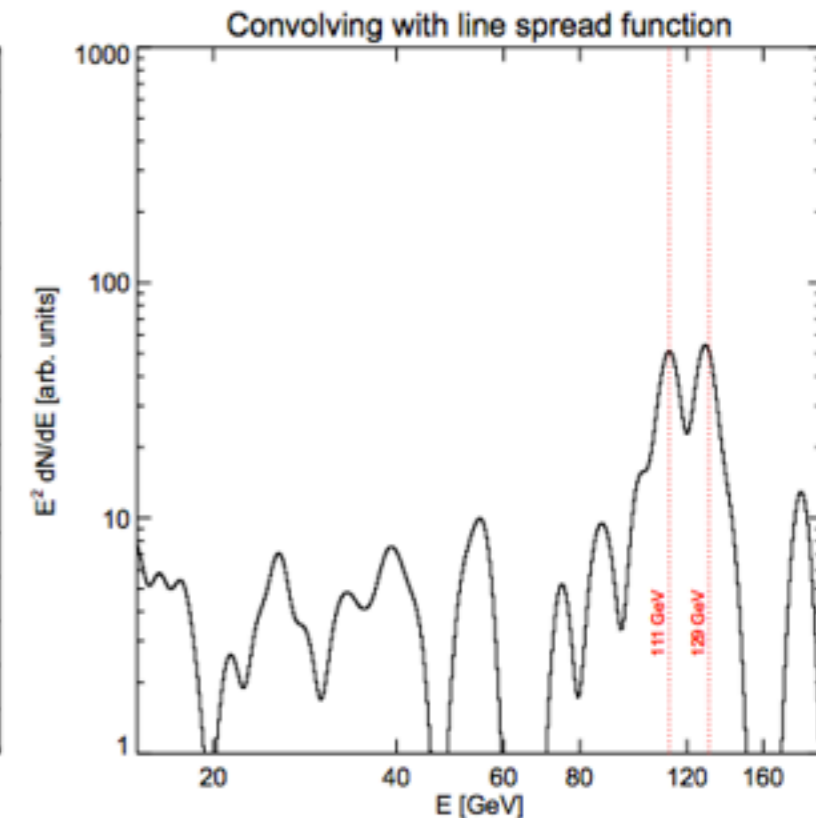
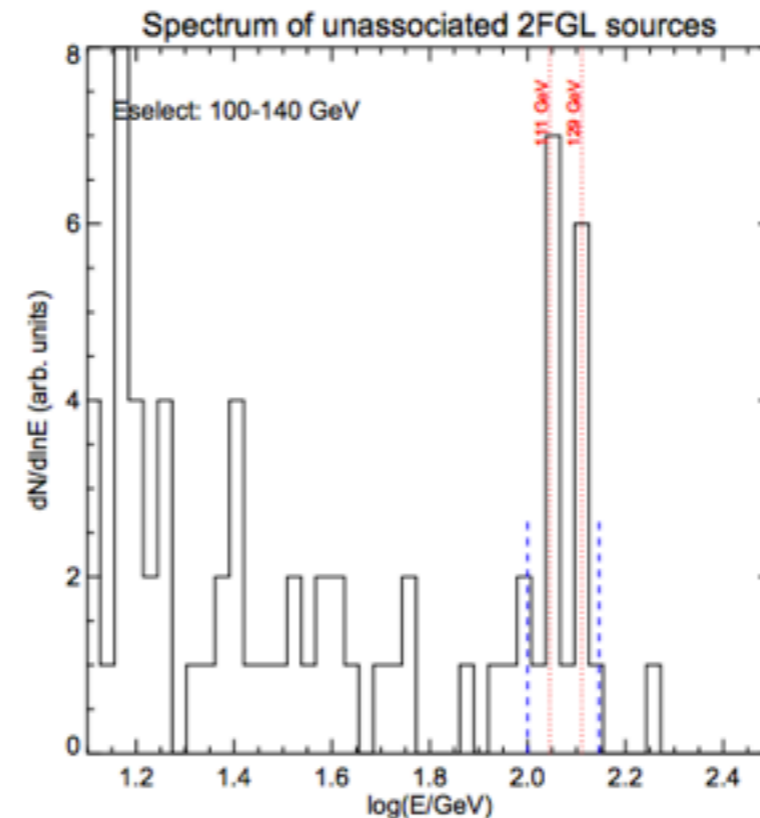


Hektor et al.
(2012)

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

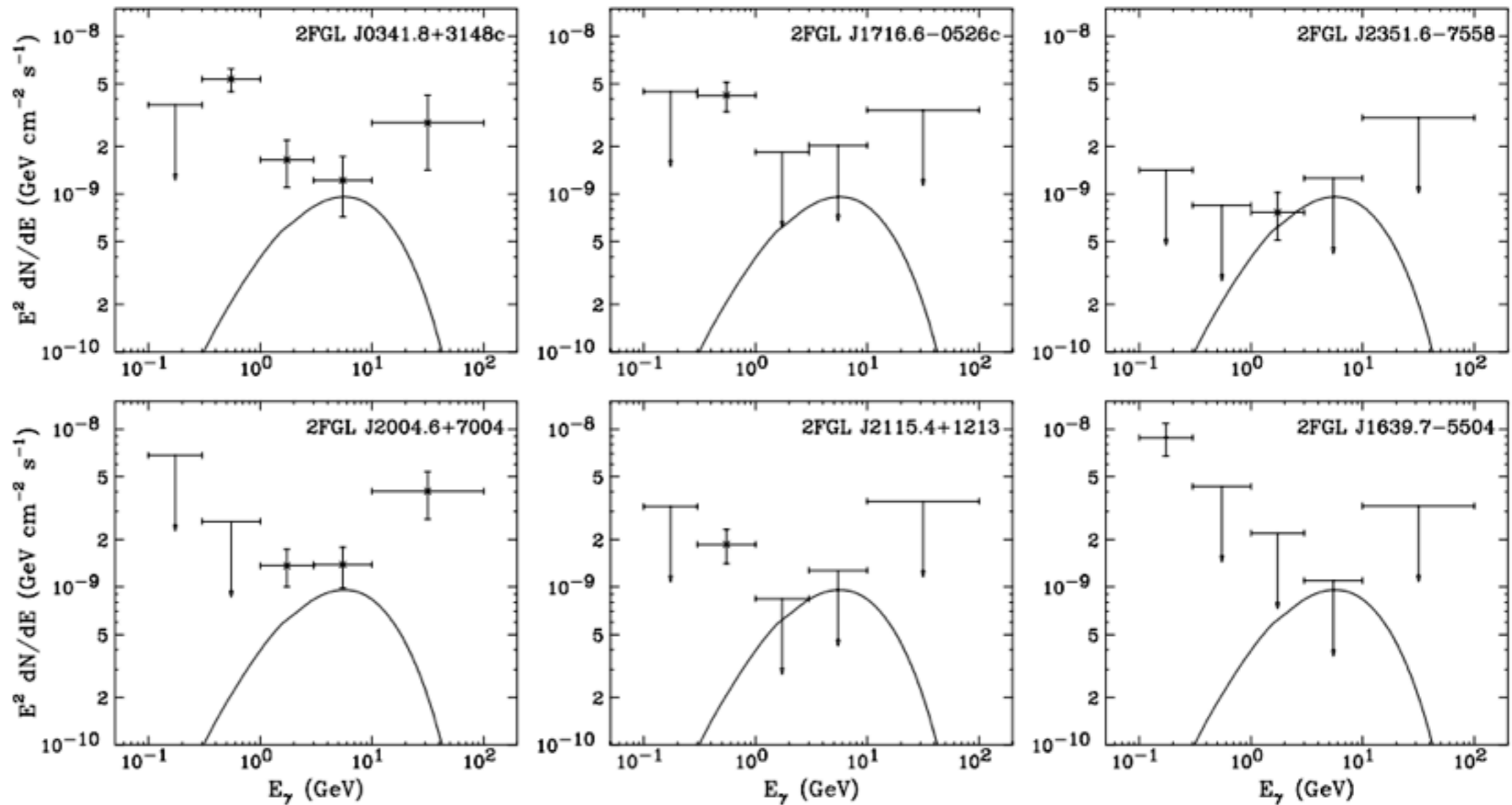
Is the Line Anywhere Else?

- 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)

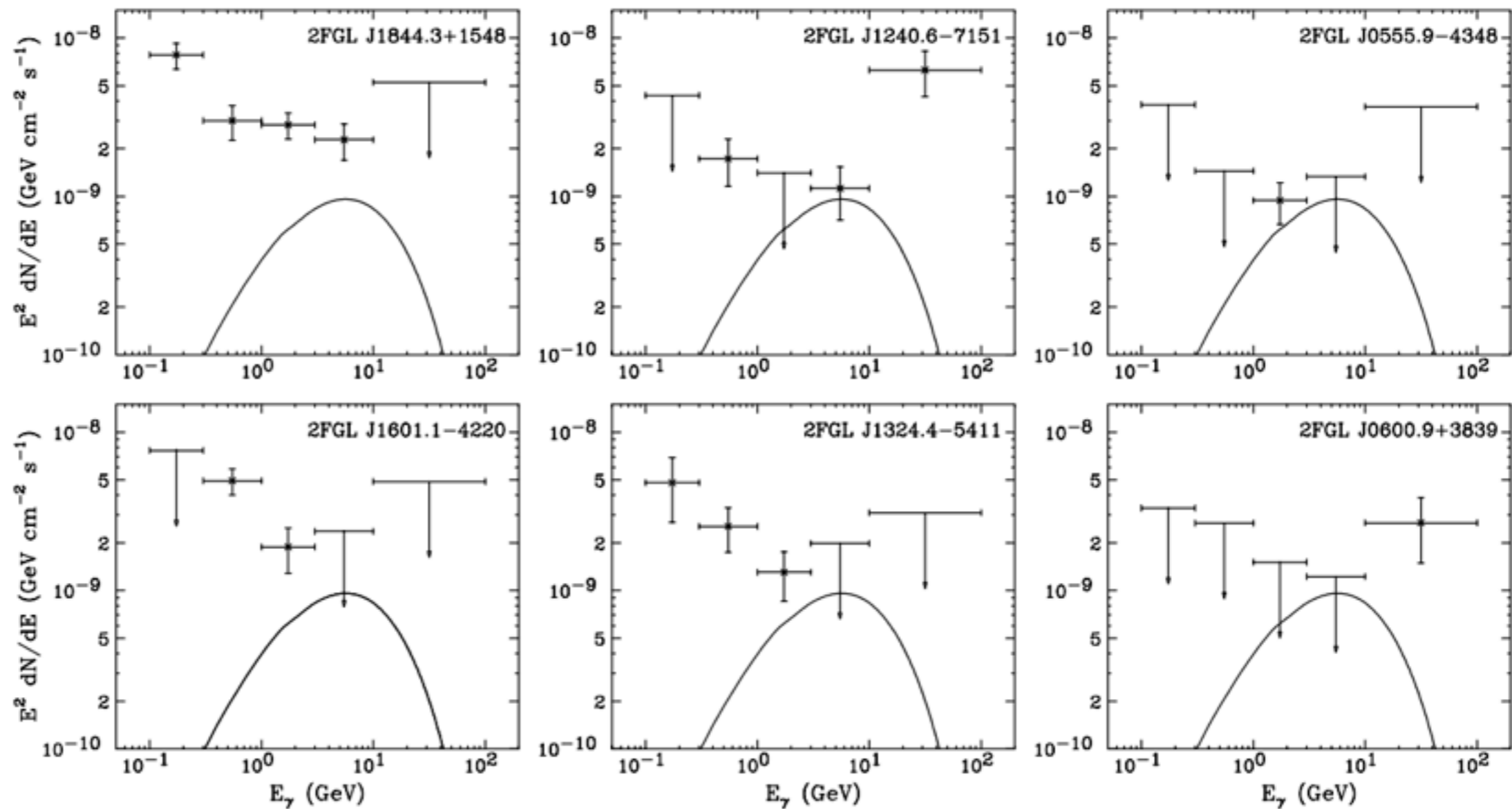
Is the Line Anywhere Else?



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?

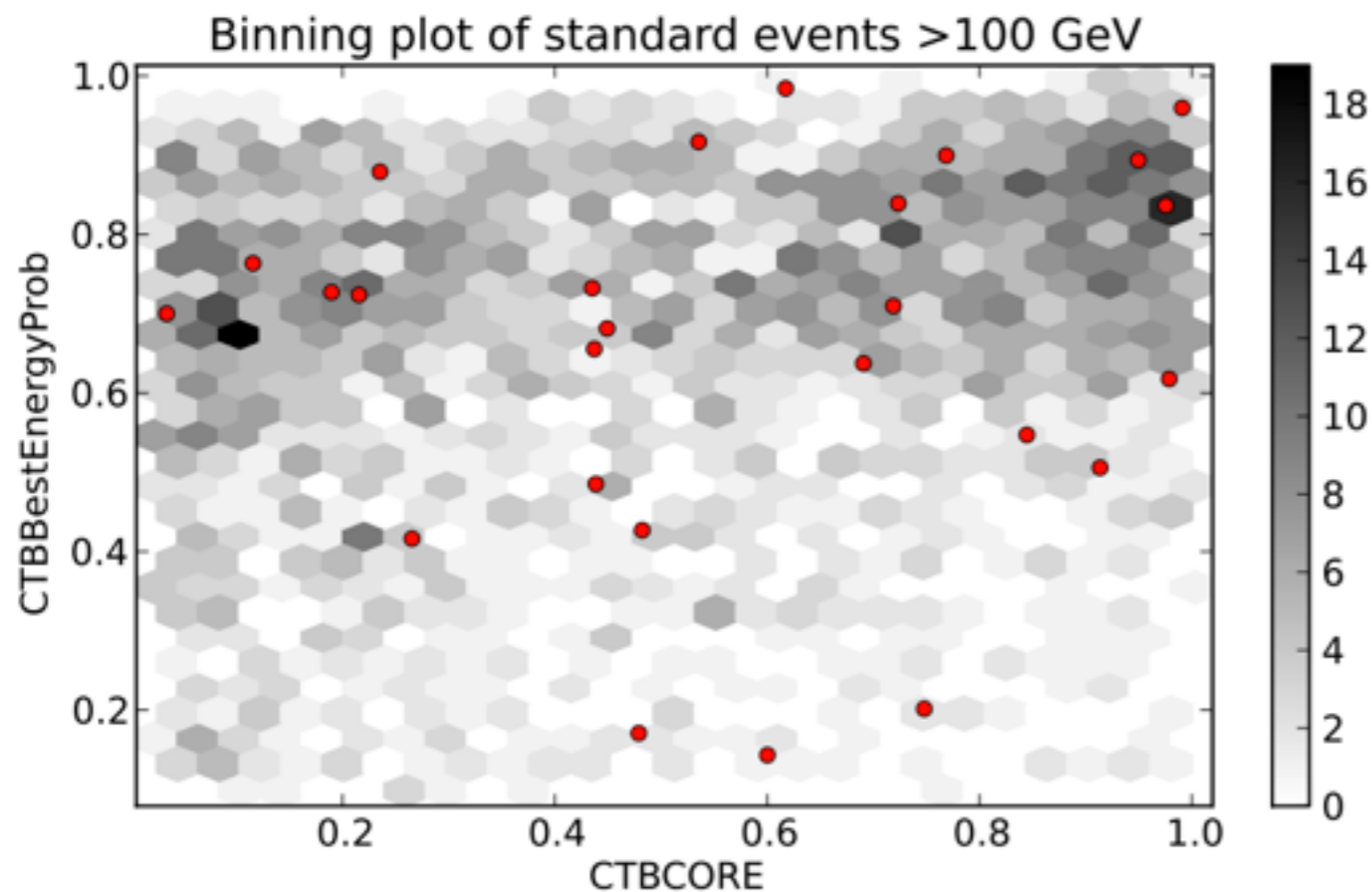
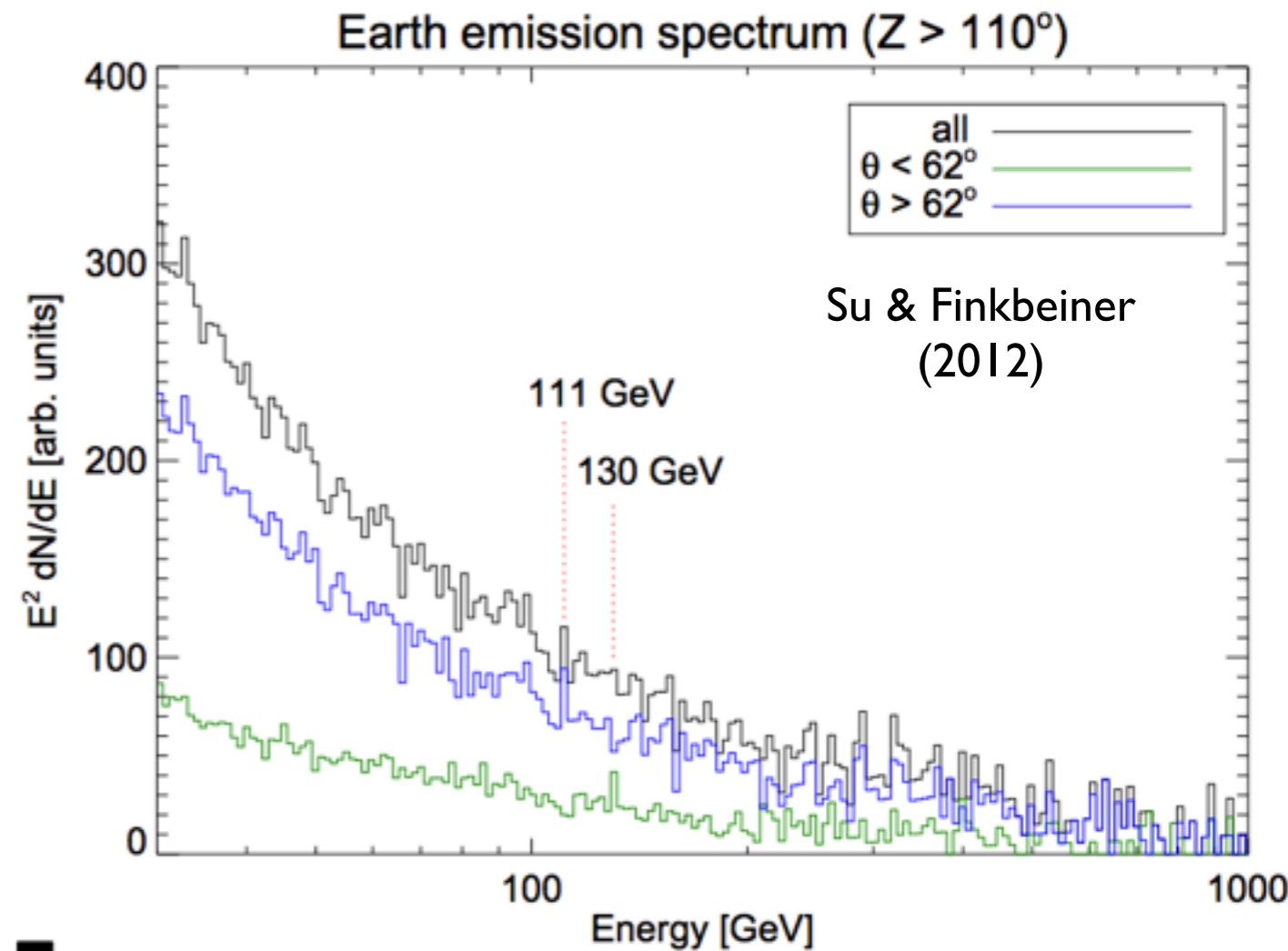


Hooper & Linden
(2012)

- 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

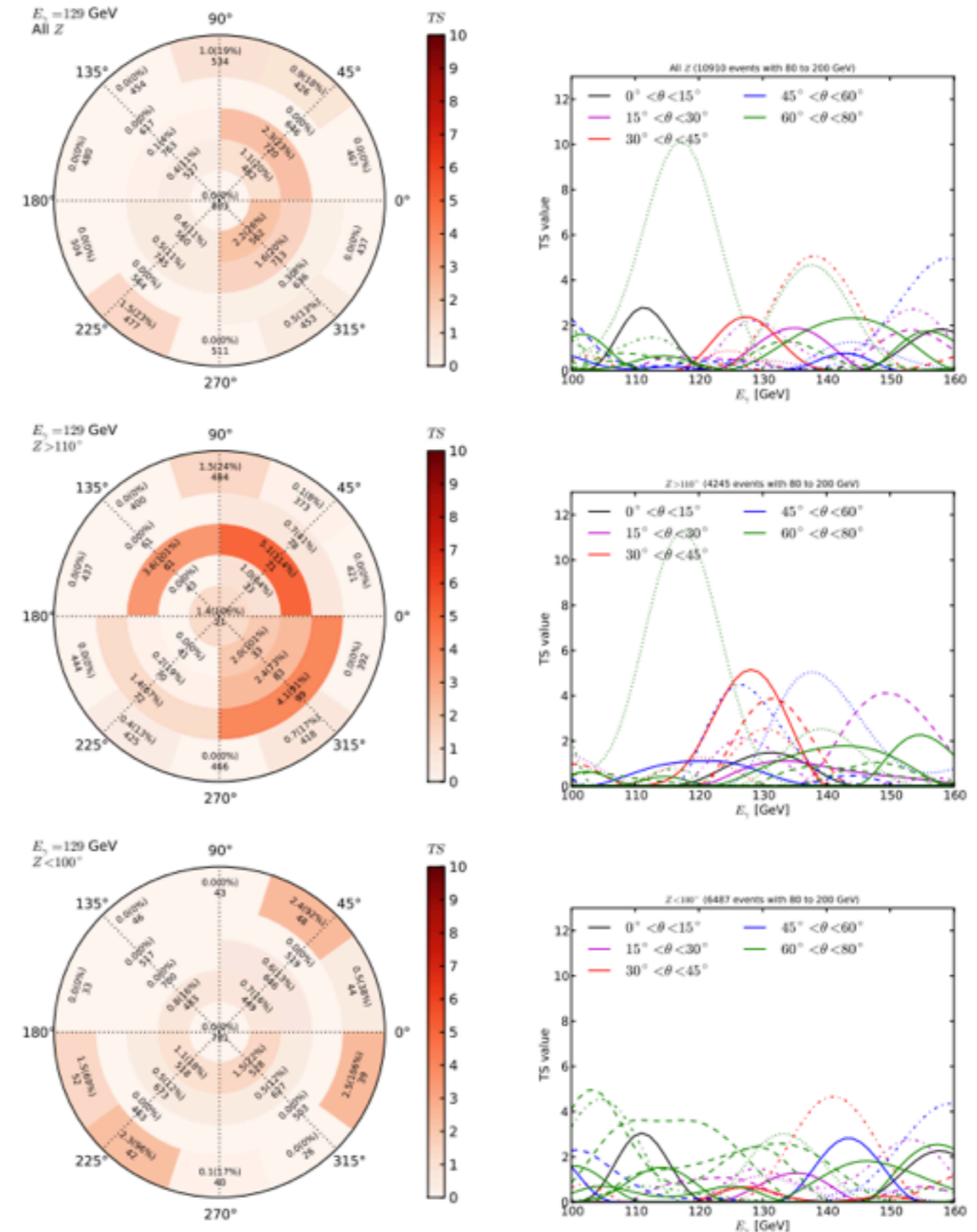
Is the Line Instrumental?

- 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

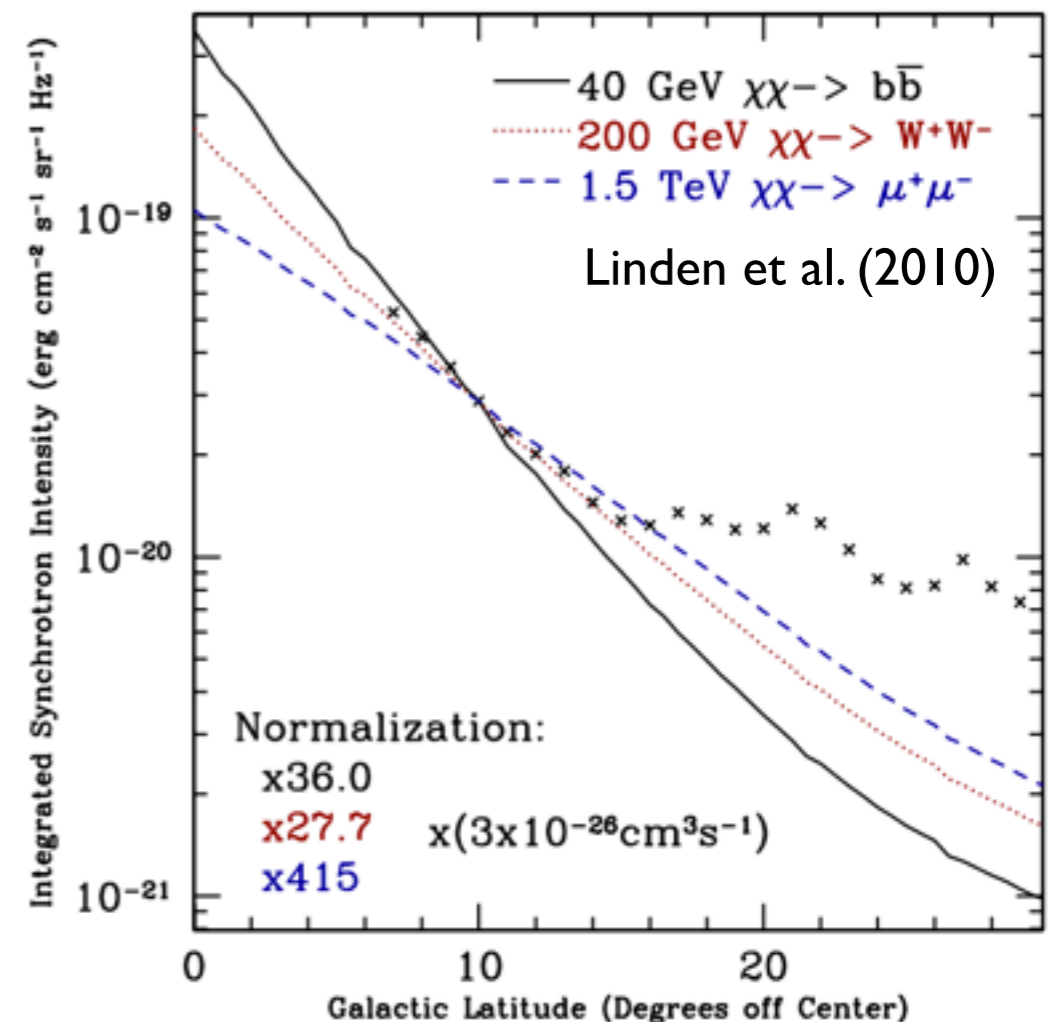
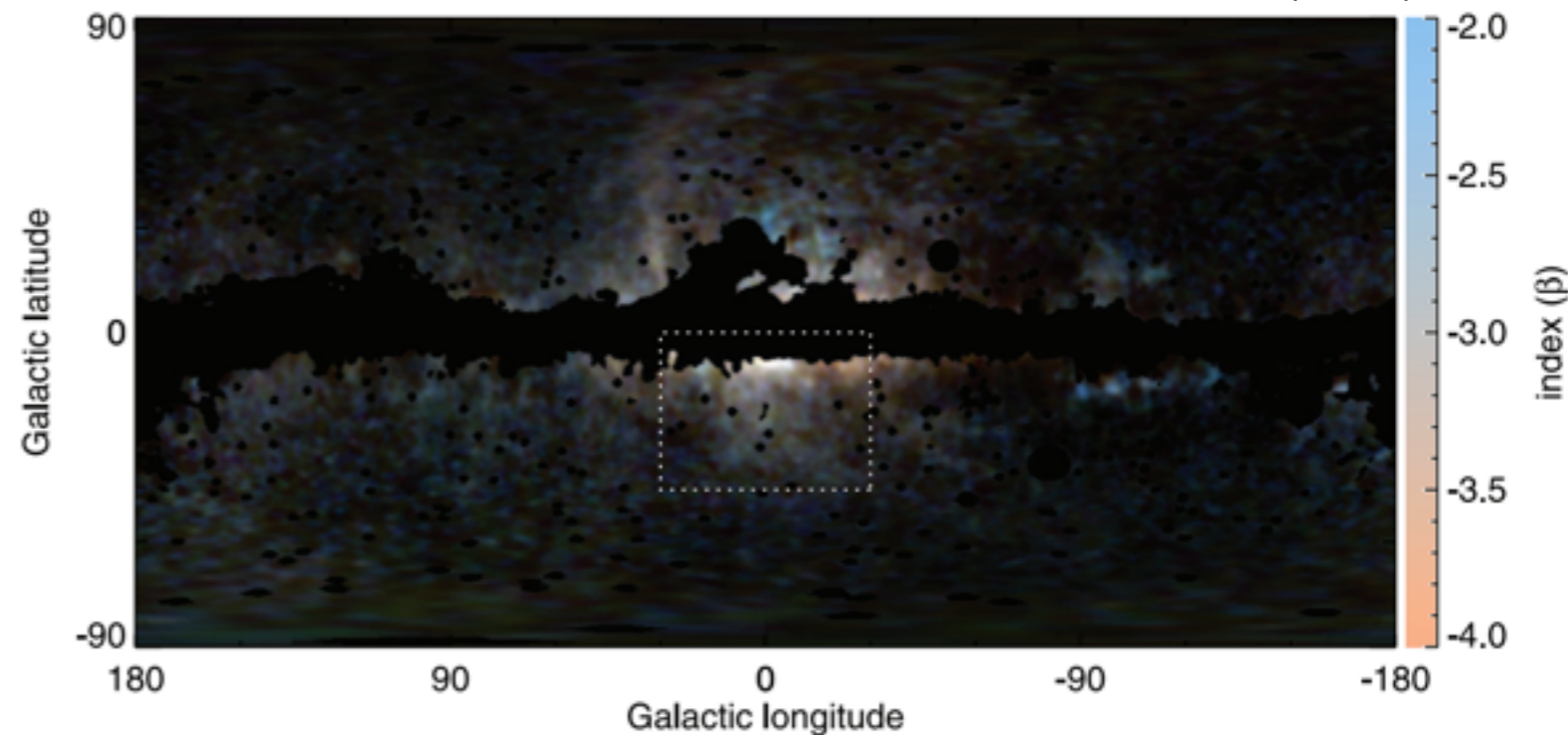
- The galactic center is one of the most exciting places to search for a dark matter signal
- Present observatories are capable of both making exciting discoveries, and setting stringent limits on the properties of WIMP dark matter
- Upcoming instruments are likely to make exciting discoveries of both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

Extra Slides

What is the WMAP Haze?

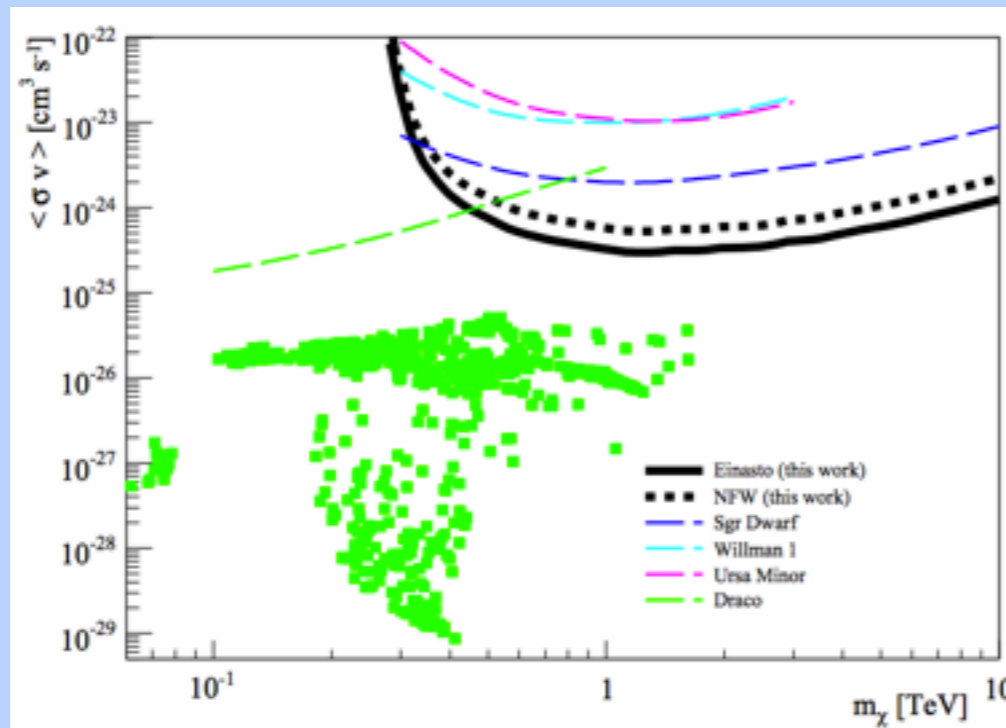
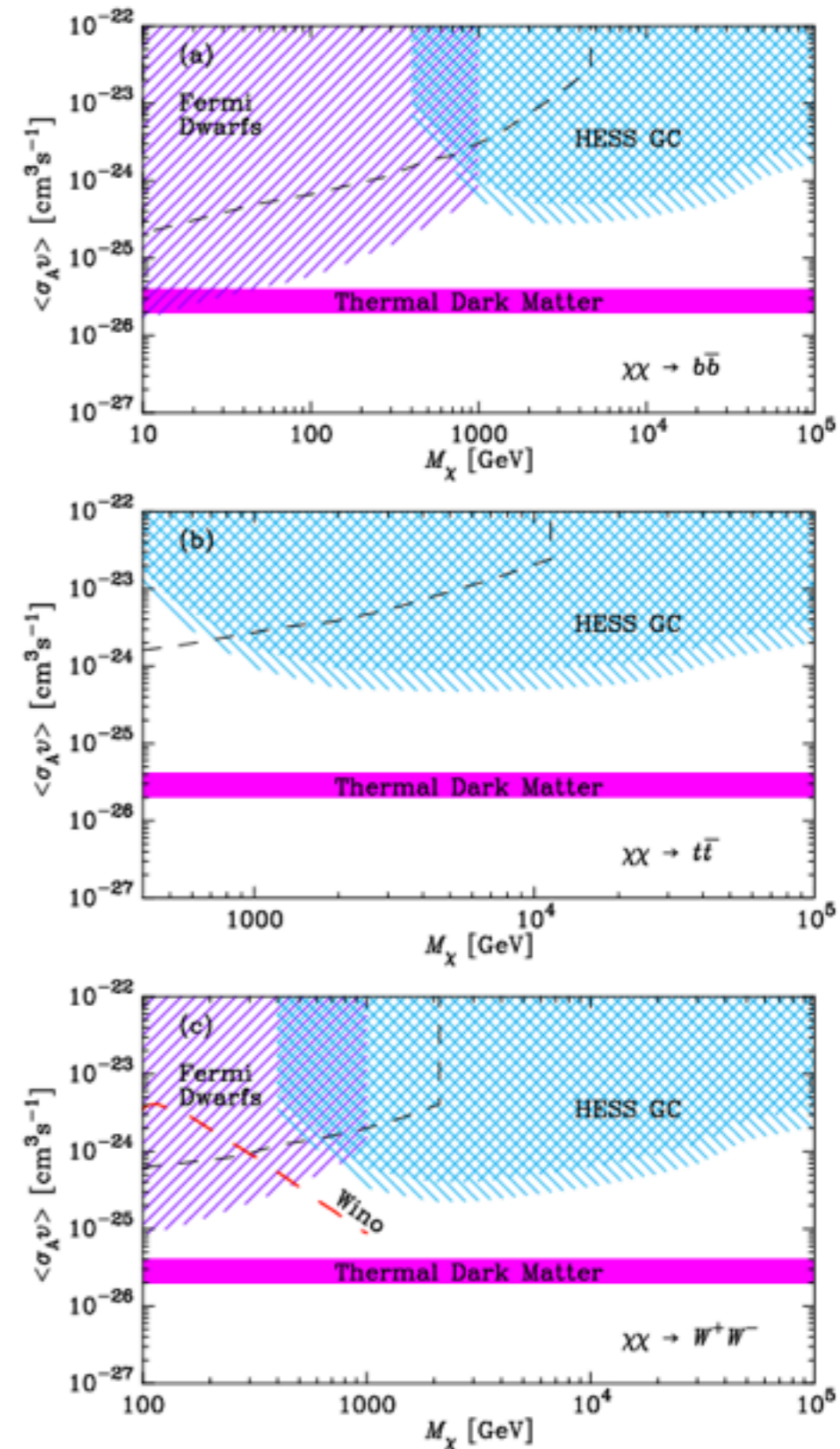
- Discovered by Doug Finkbeiner in 2004
- Synchrotron origin determined by subsequent observations
- Hard spectrum difficult to fit with lepton injection spectra typical of astrophysical phenomena
- Well fit by dark matter models with typical annihilation cross-sections and spectra
- However, modifications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

Dobler et al. (2008)



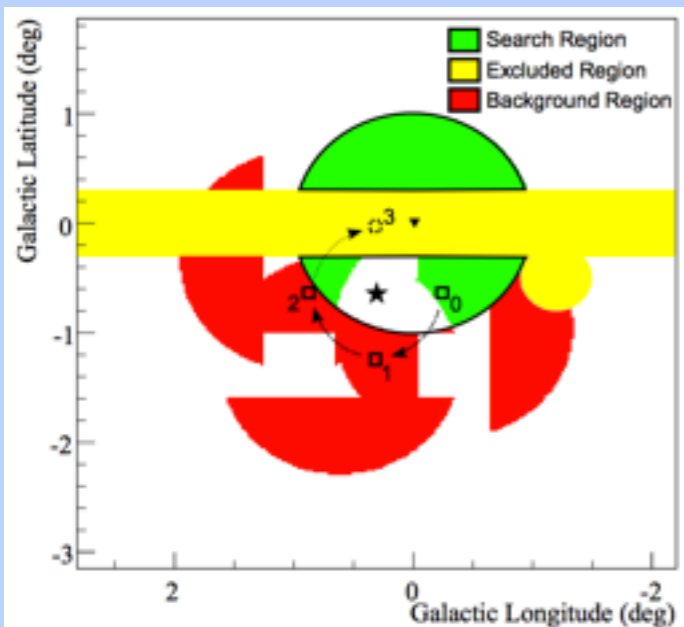
HESS Limits on TeV Dark Matter

- 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



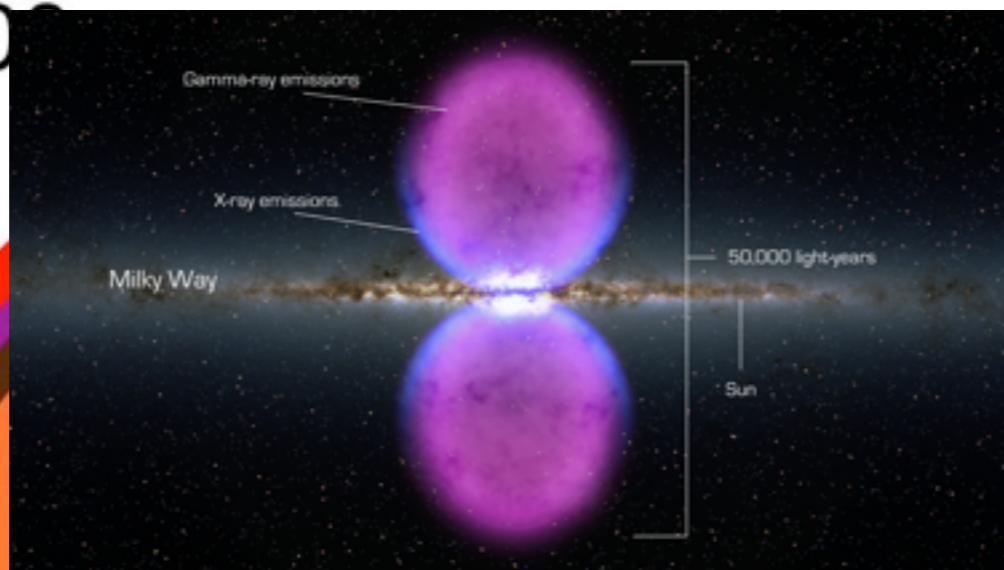
Abramowski et al. (2011)

Abazajian & Harding (2011)



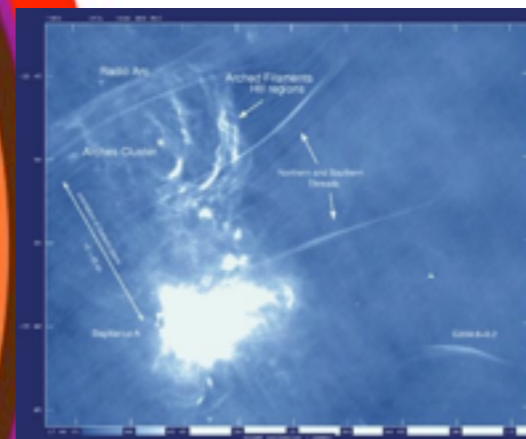
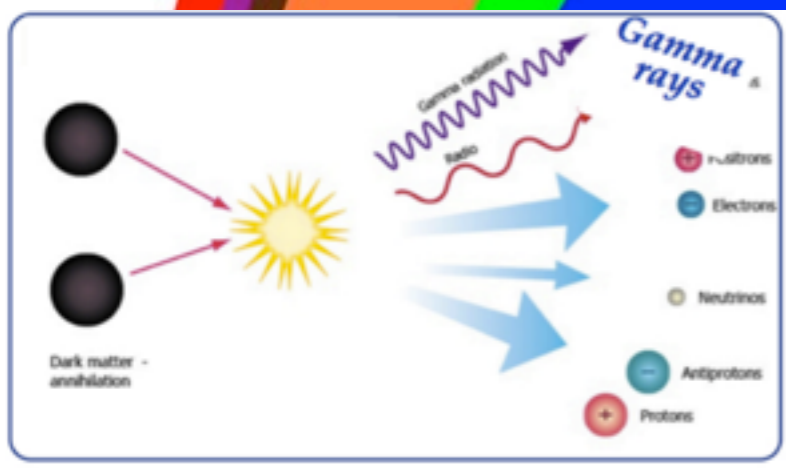
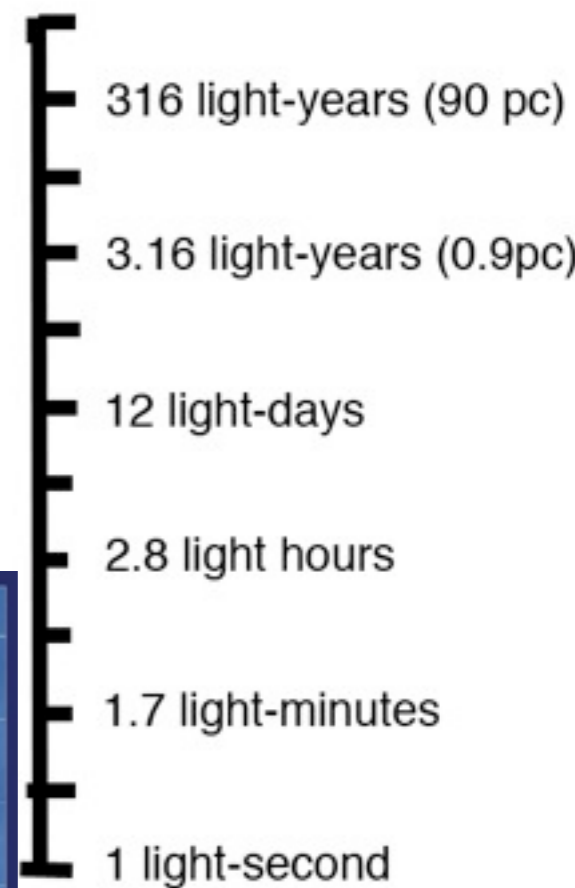
And some surprises!

$I = x10^{22}$



BH
VLA
Chandra

Fermi Bubbles? Do they extend to the galactic center?



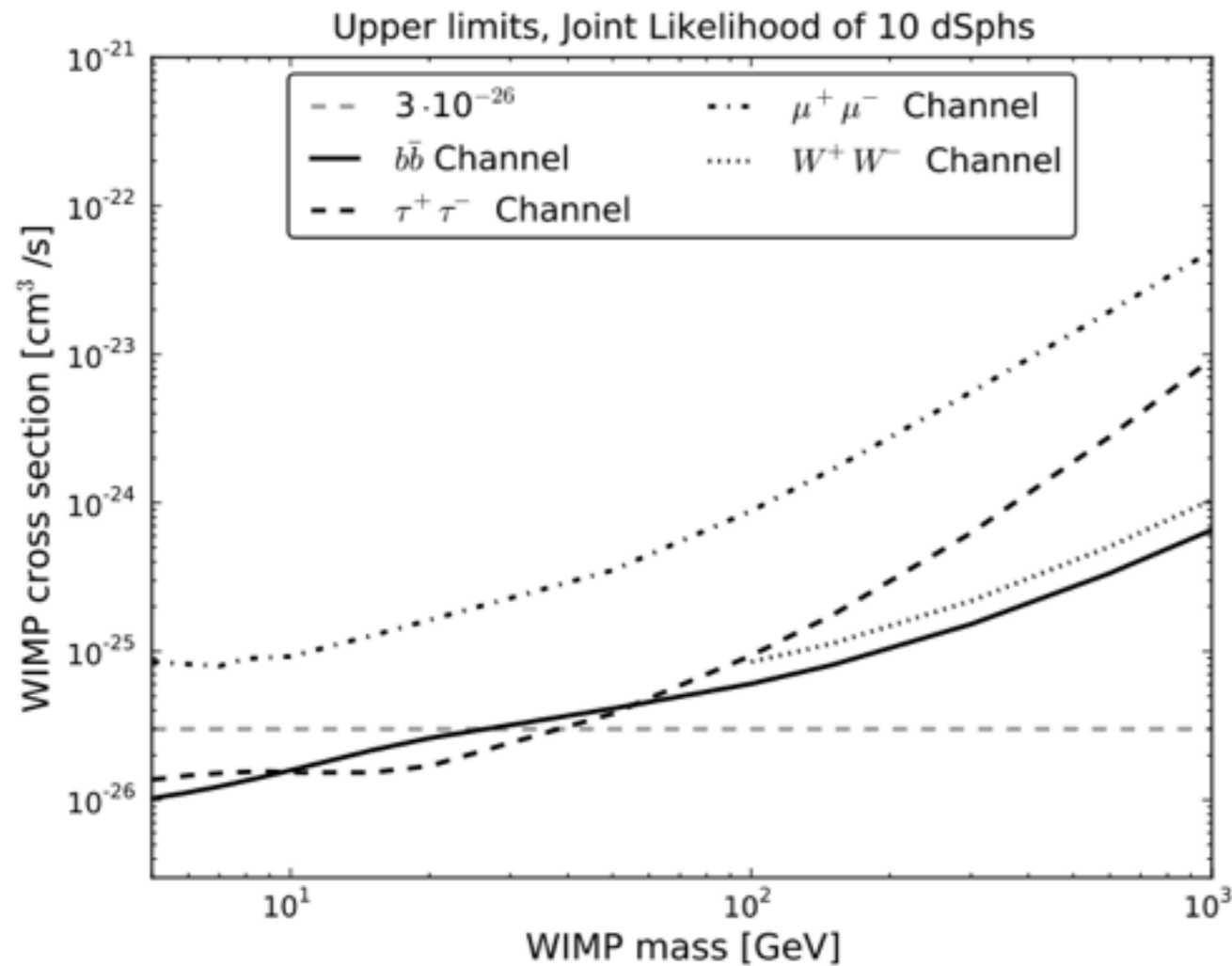
Non-thermal Radio Filaments - Bright, polarized synchrotron sources shaped like "thin threads" and lying perpendicular to galactic plane (Yusef-Zadeh et al. 1984)

CTA
HESS

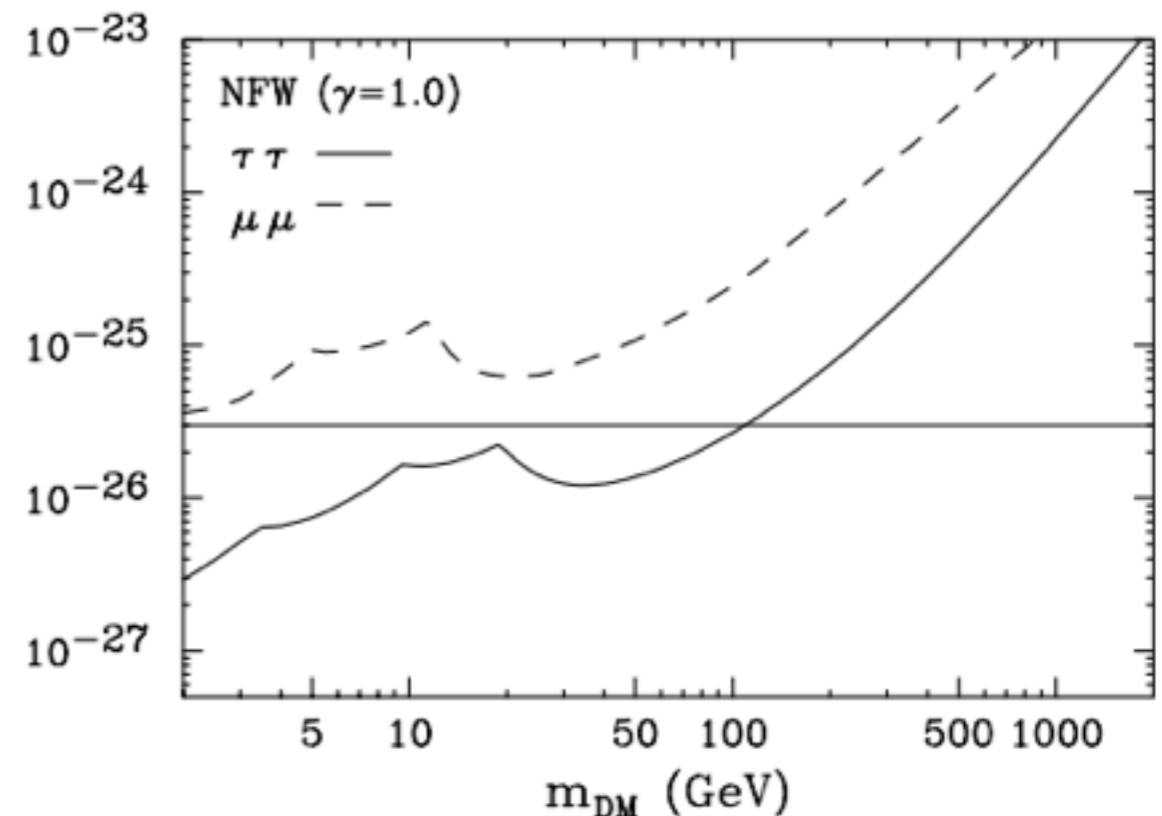
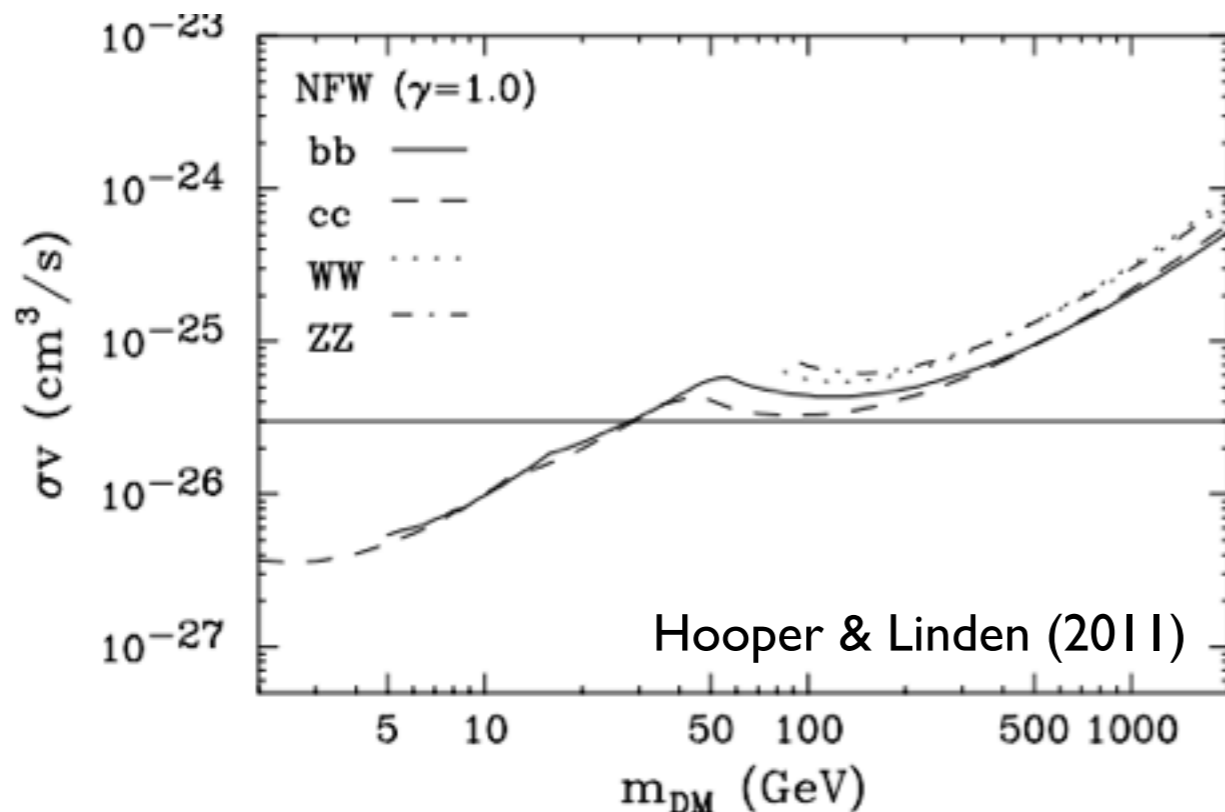
Dark Matter??

Fermi (100 GeV)
Fermi (1 GeV)

Comparison to Other Indirect Detection Regimes

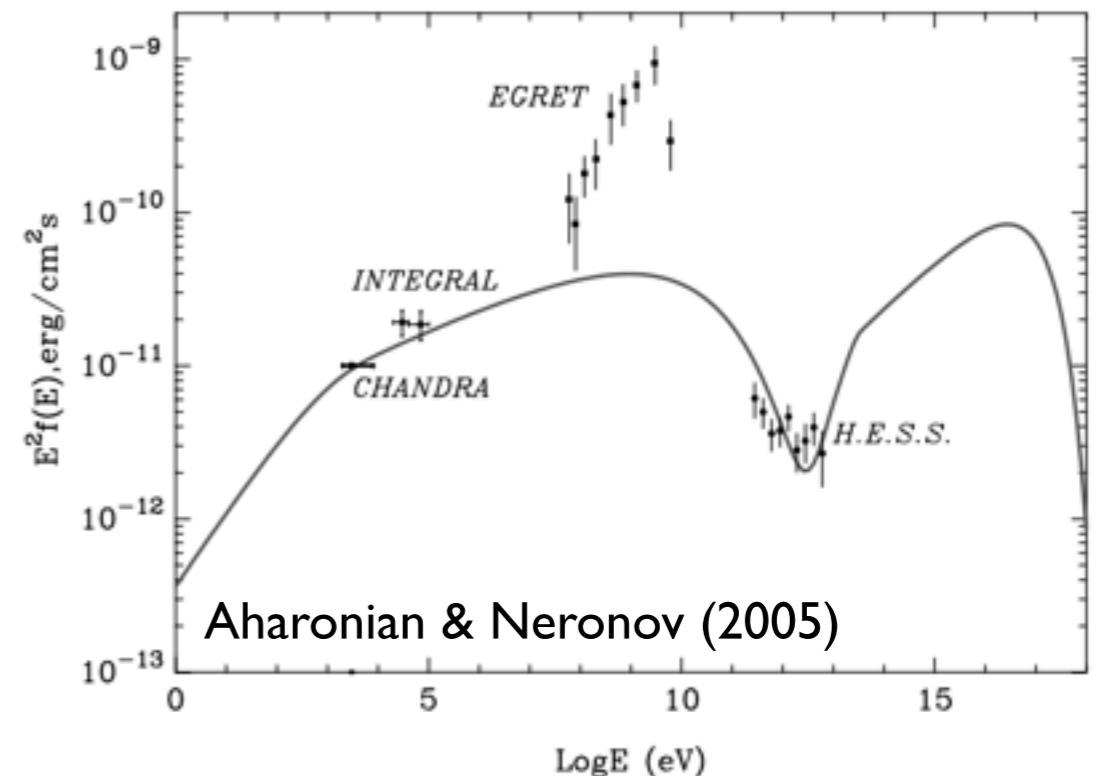
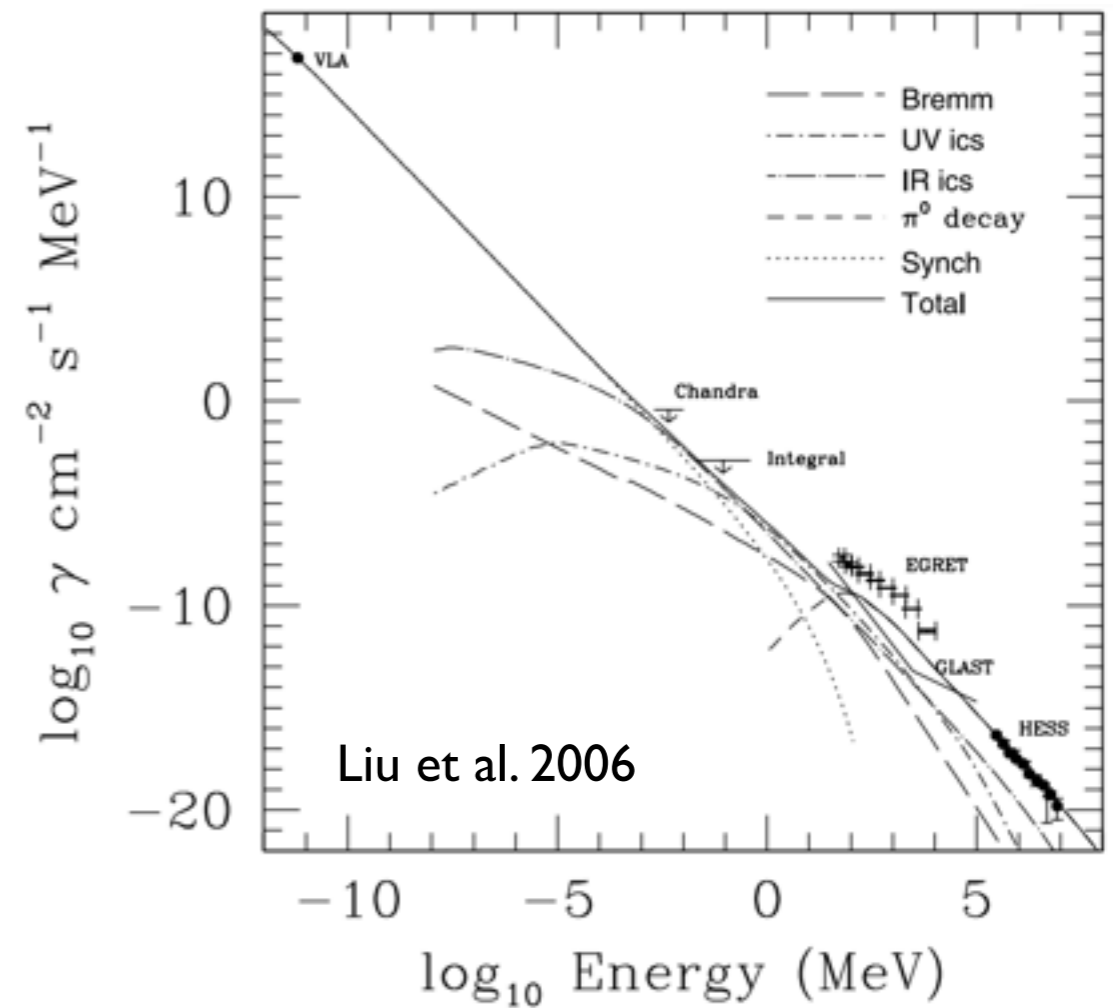


- Under the assumption of an NFW profile, the 95% confidence limits are as good or better than those from dwarf-spheroidals
- They are especially stronger for leptophilic annihilation paths



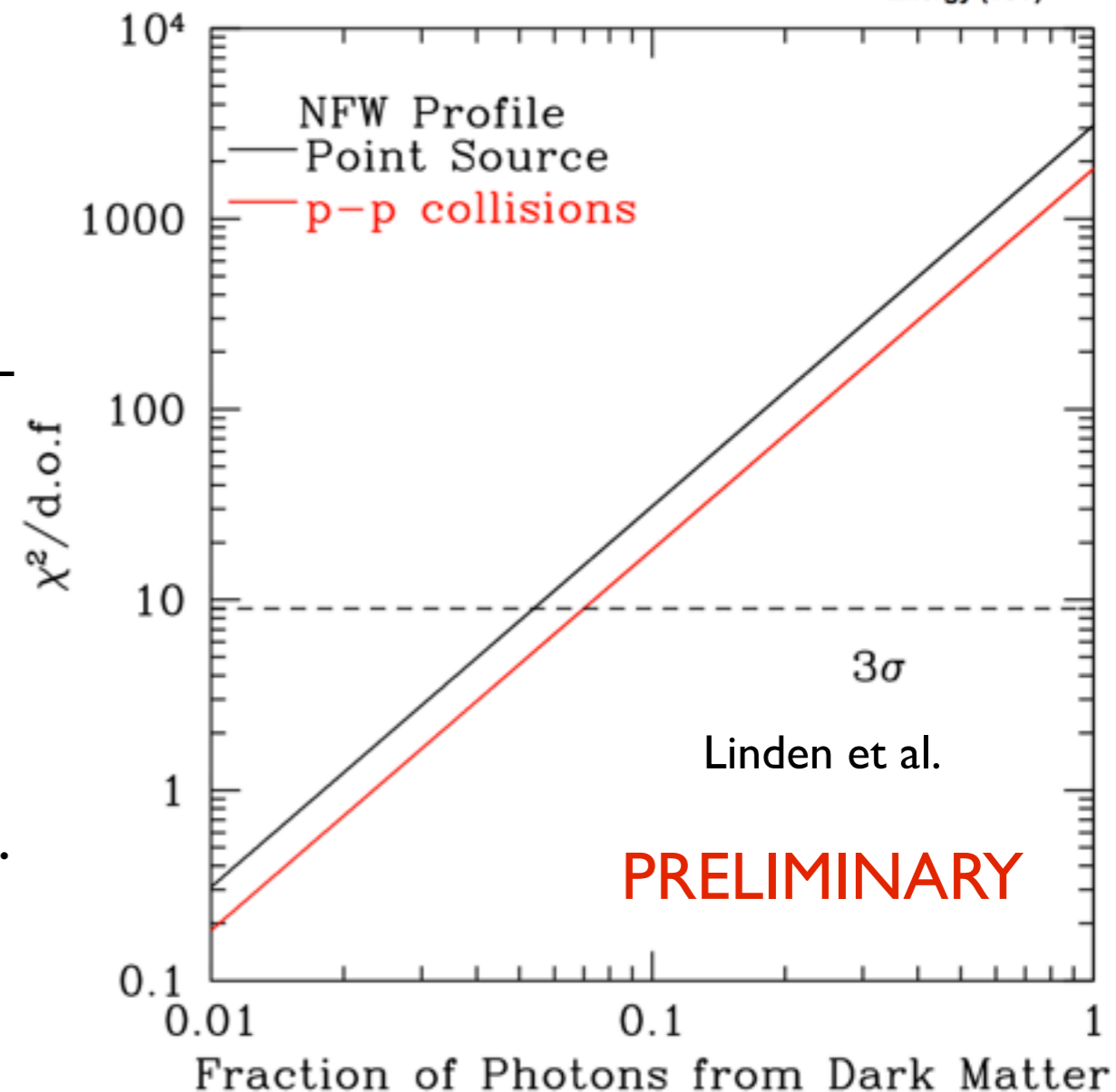
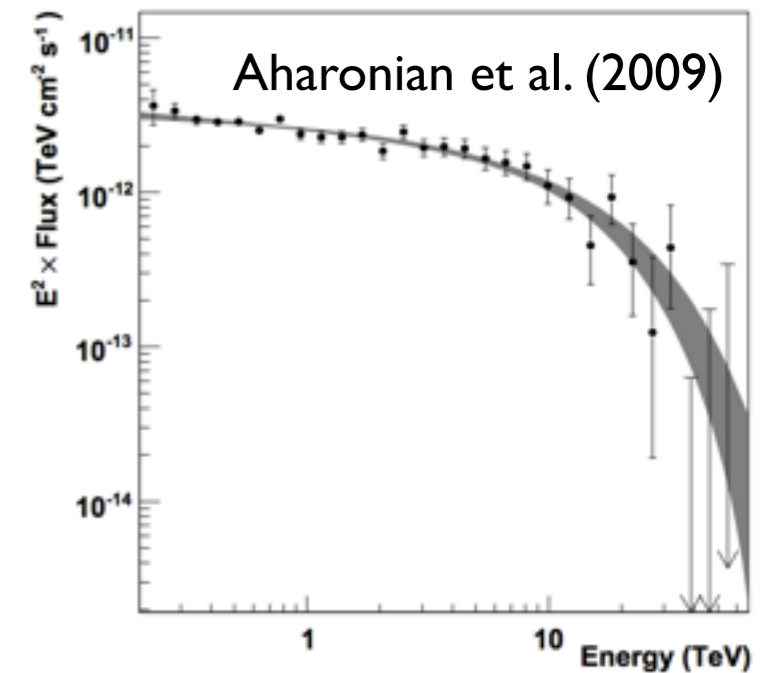
Fitting the Residual: Hadronic Processes

- 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!**)

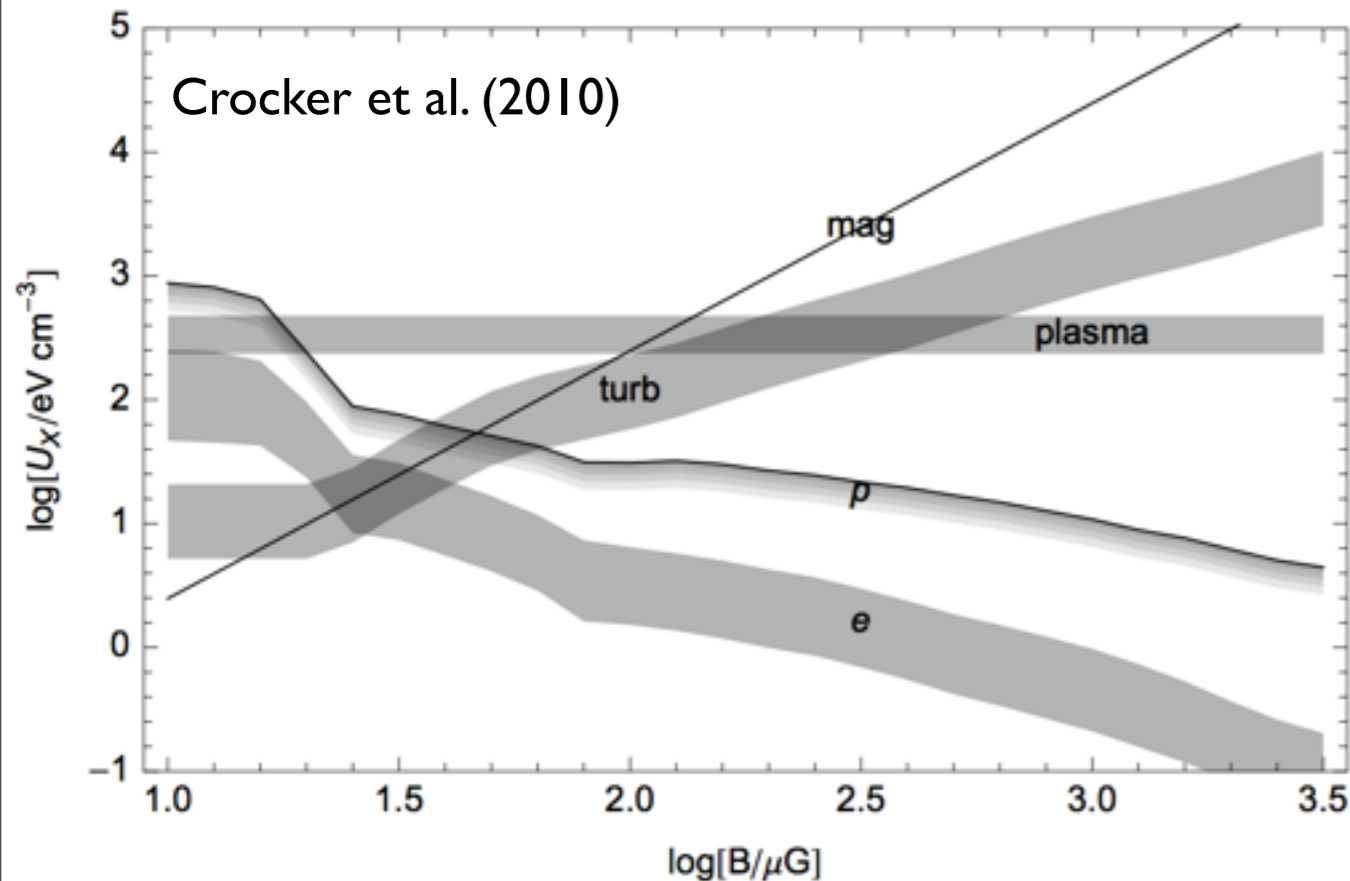
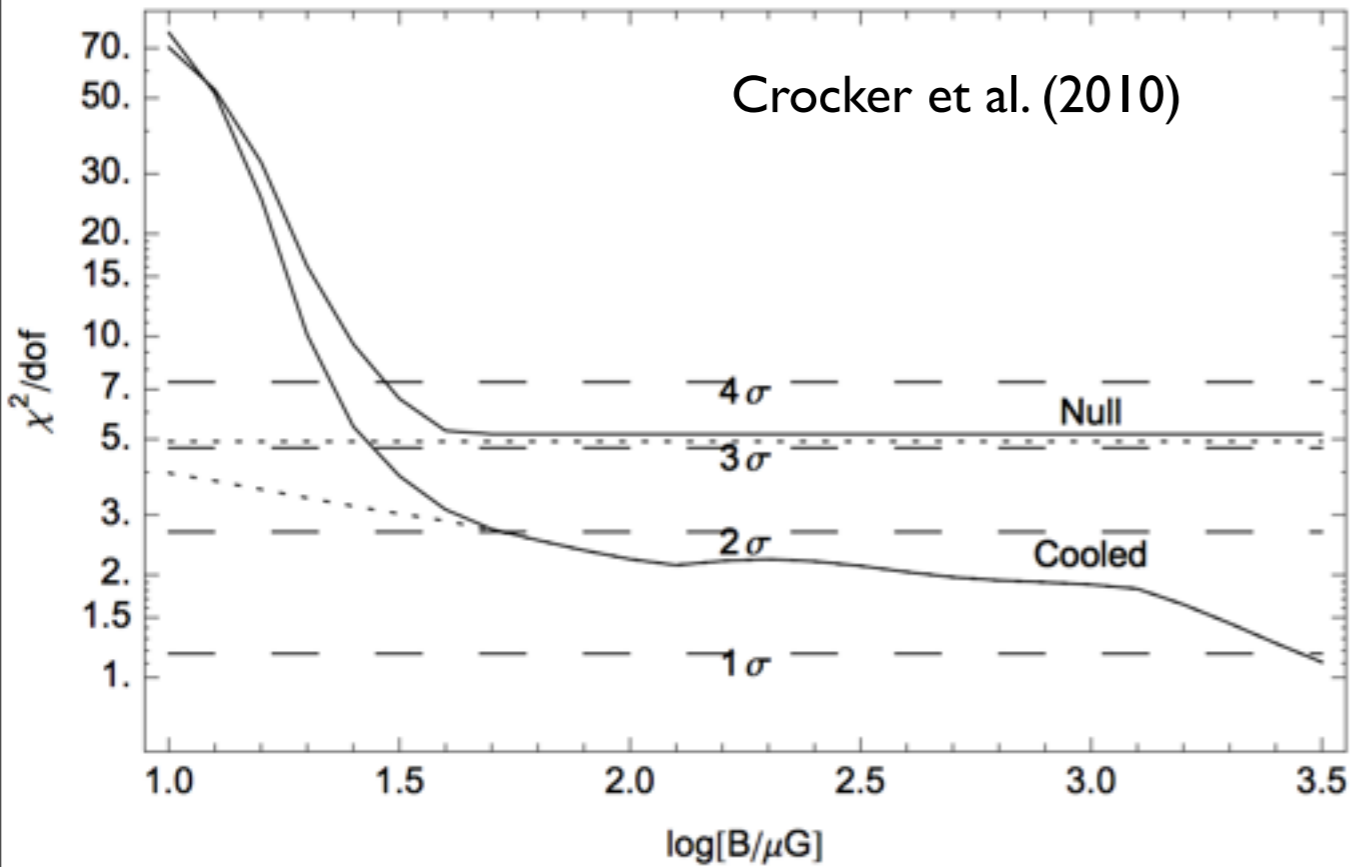


Dark Matter at the Galactic Center

- 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



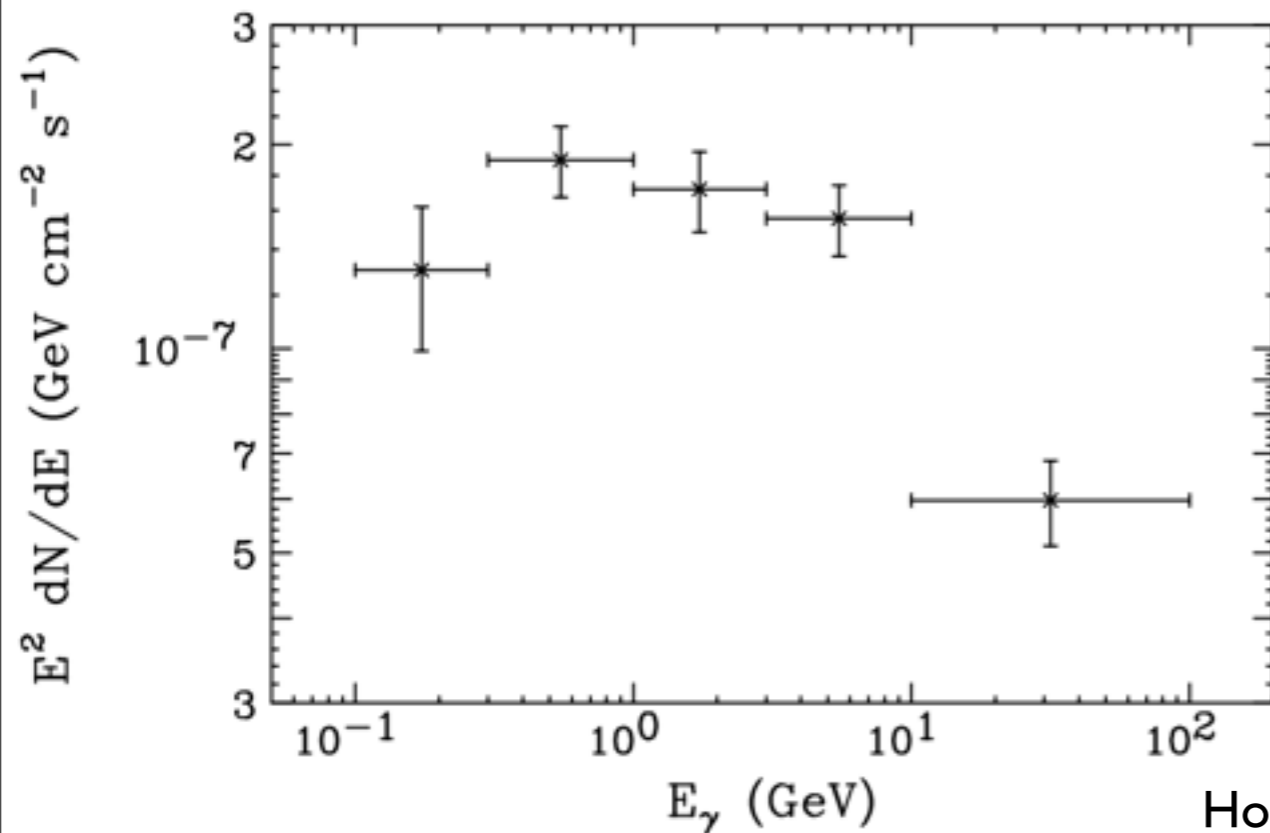
Models of the Galactic Center Magnetic Field



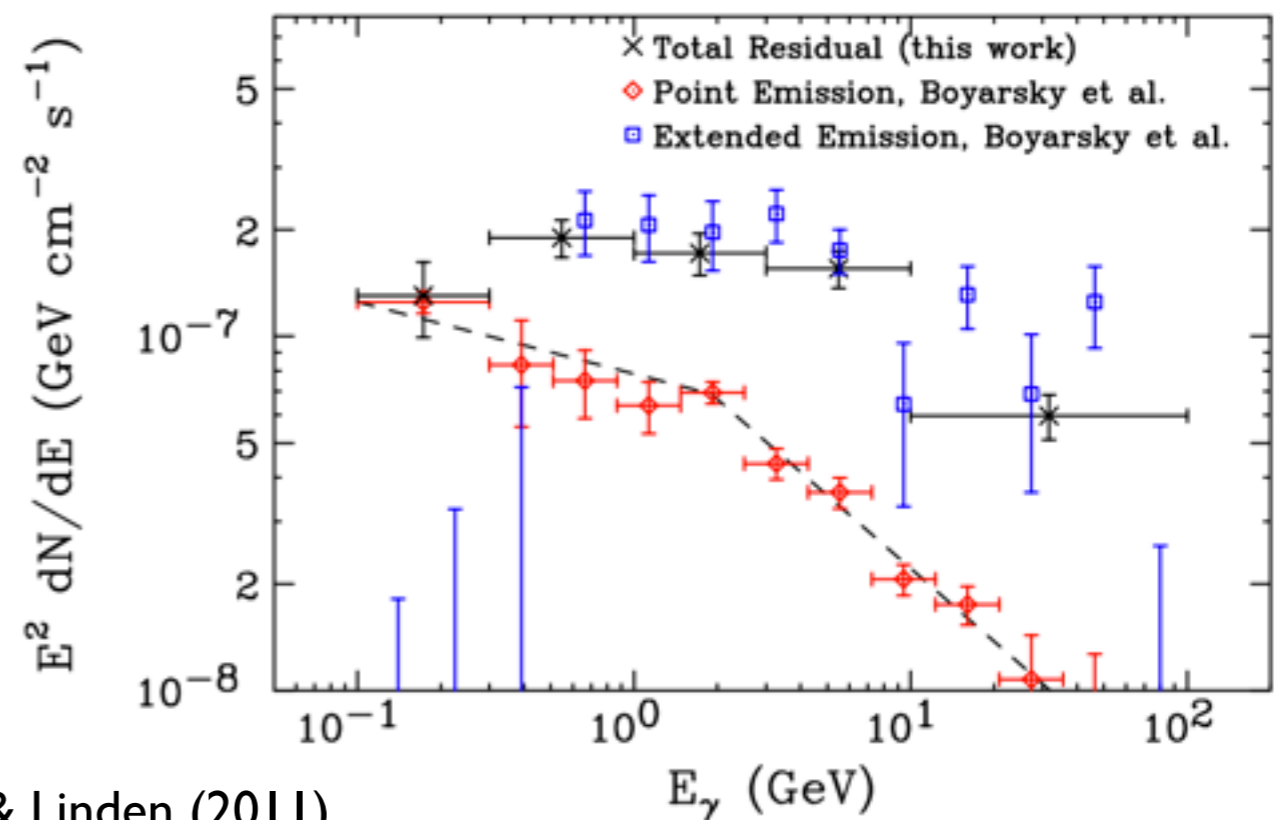
- This is particularly interesting in light of recent models which have set a minimum strength of $50 \mu\text{G}$ on the magnetic fields in the galactic center (best fit range $100\text{-}300 \mu\text{G}$)
- This almost ensures that synchrotron is the dominant energy loss mechanism for high energy electrons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

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)



Conclusions - Galactic Center

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- Upcoming instruments are likely to make exciting discoveries of both the astrophysical and dark matter properties of the galactic center region