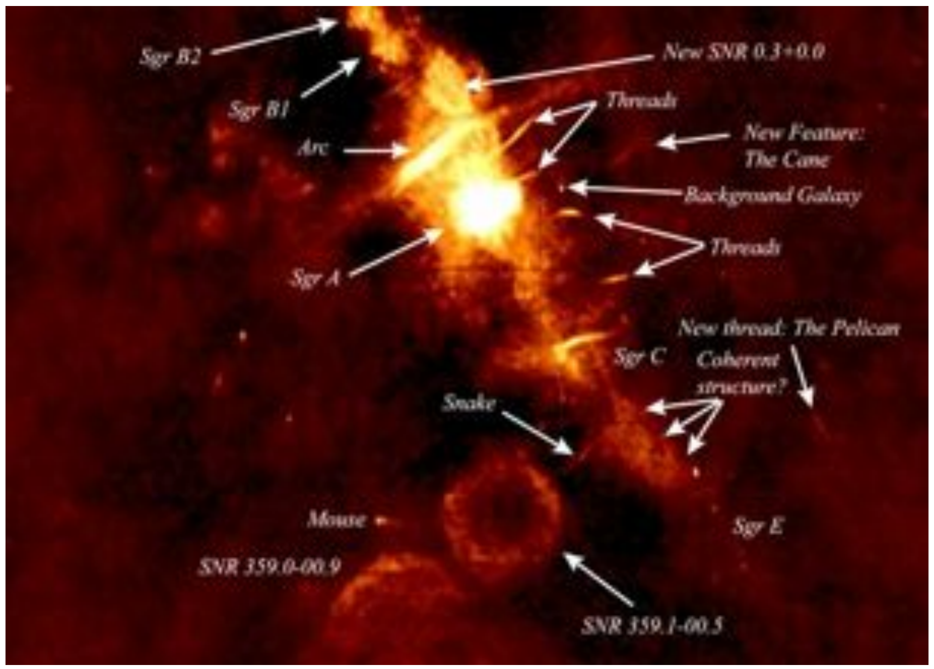
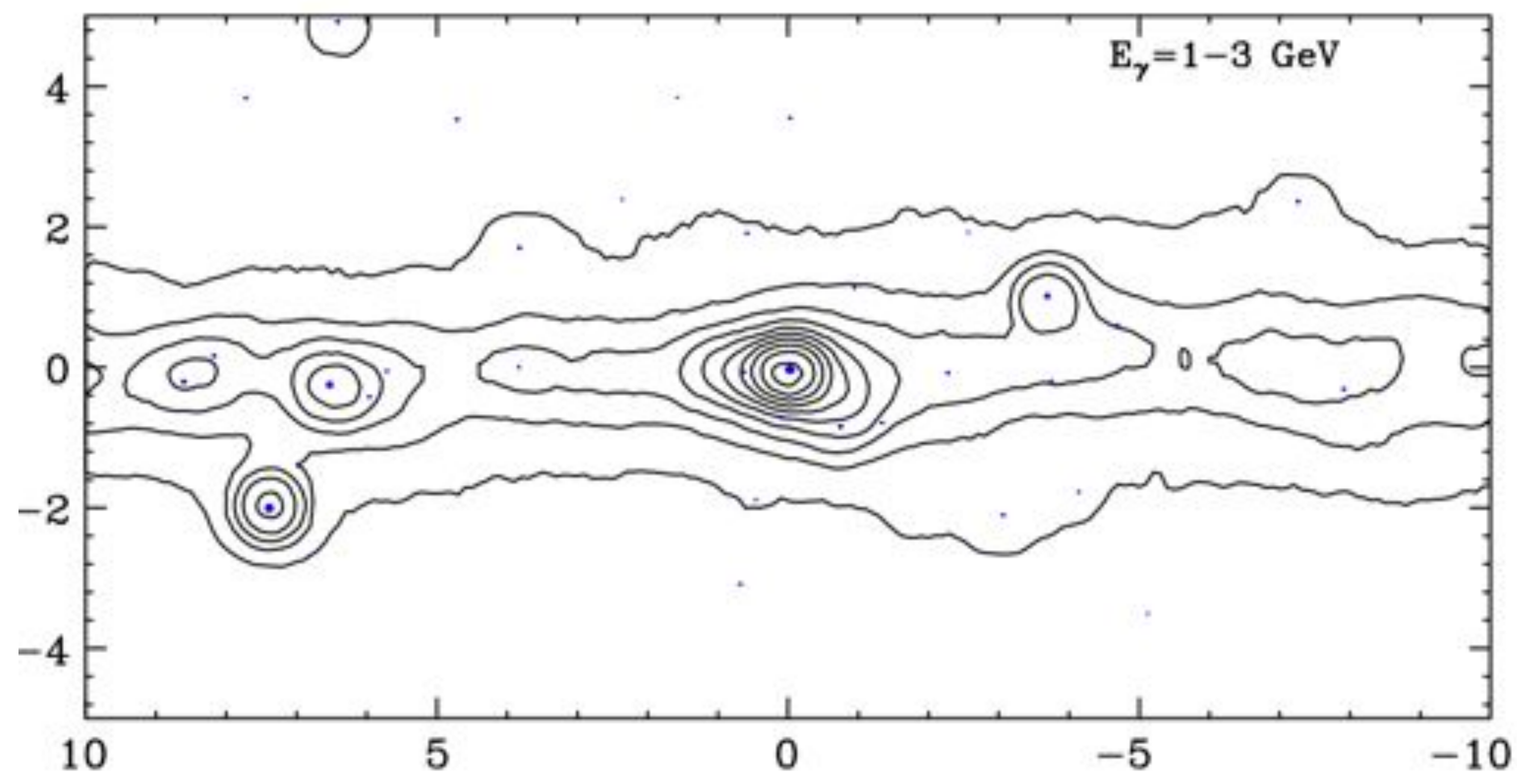
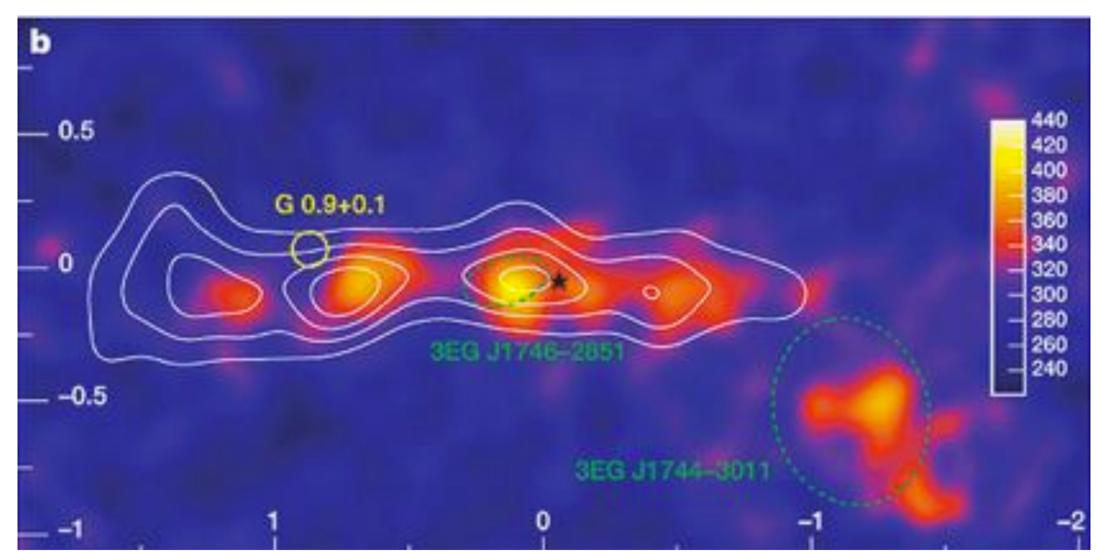
Understanding High Energy Emission from the Galactic Center: 3 Convincing Stories





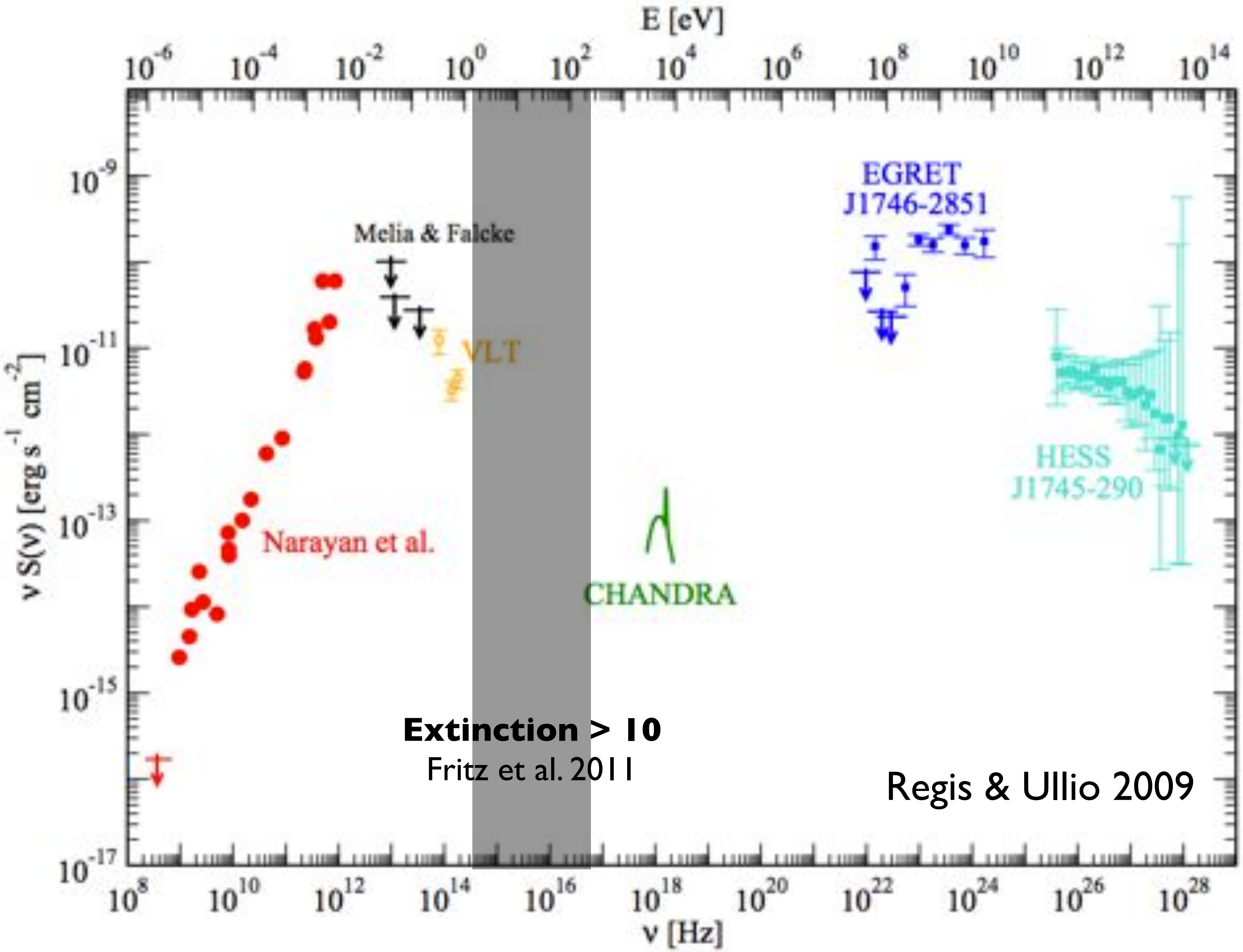
Tim Linden
UC - Santa Cruz



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

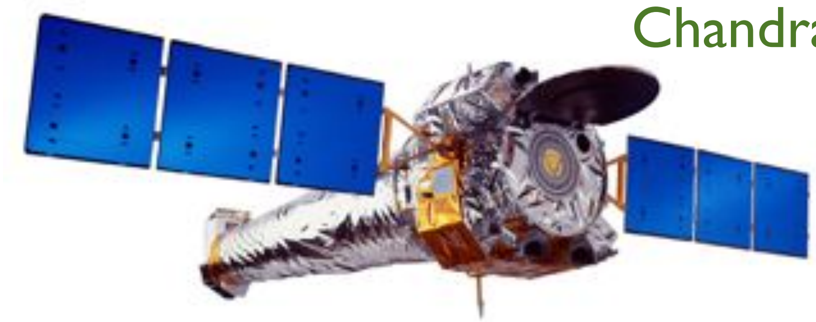
4th International Fermi Symposium November 2, 2012

The Multi-wavelength Galactic Center

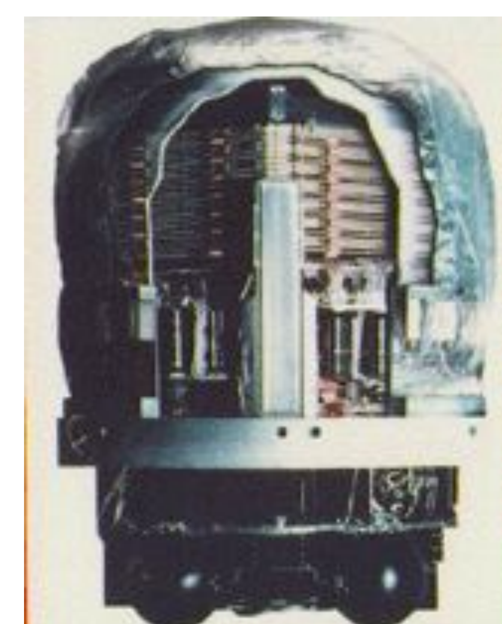


VLA

Chandra



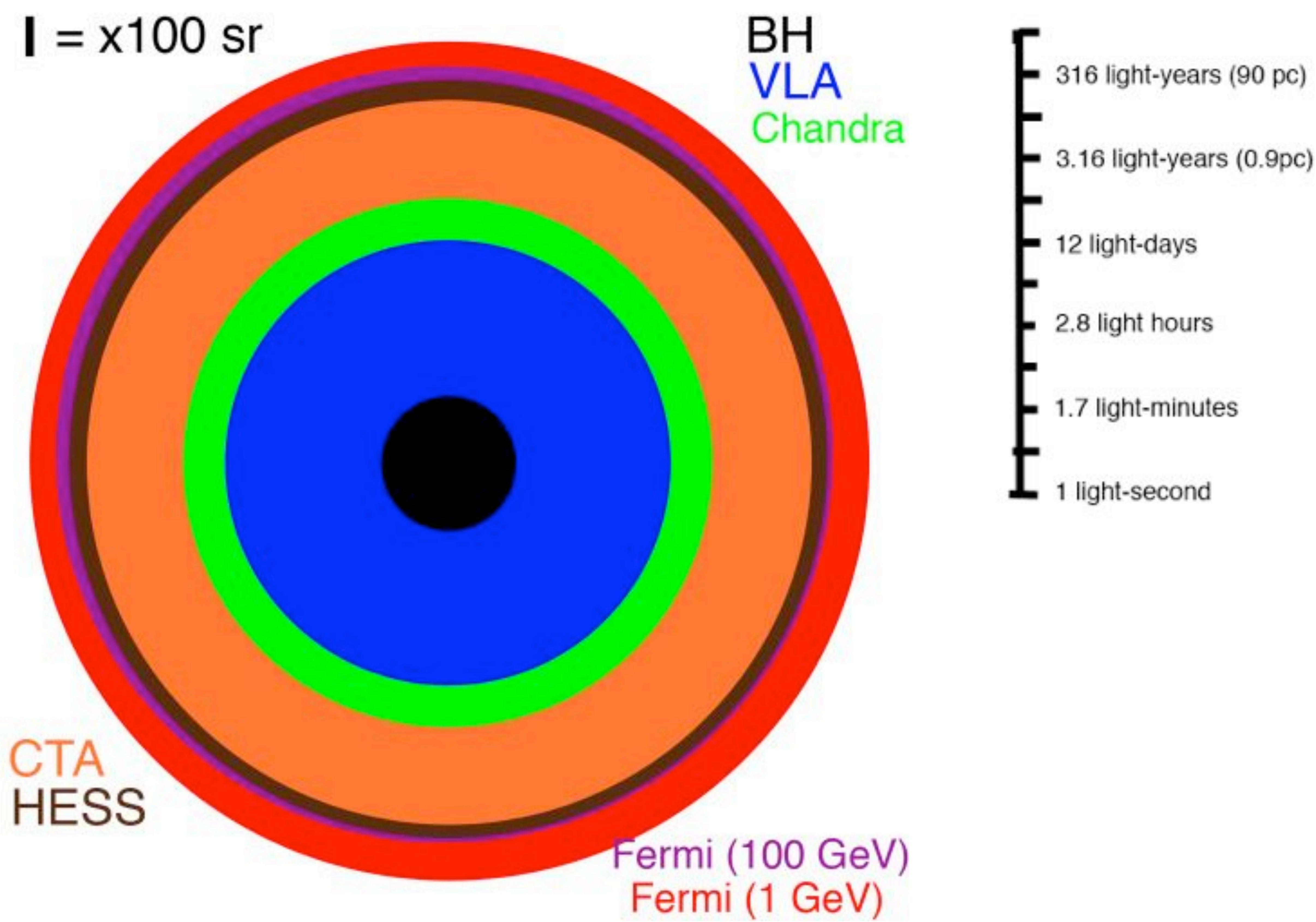
EGRET



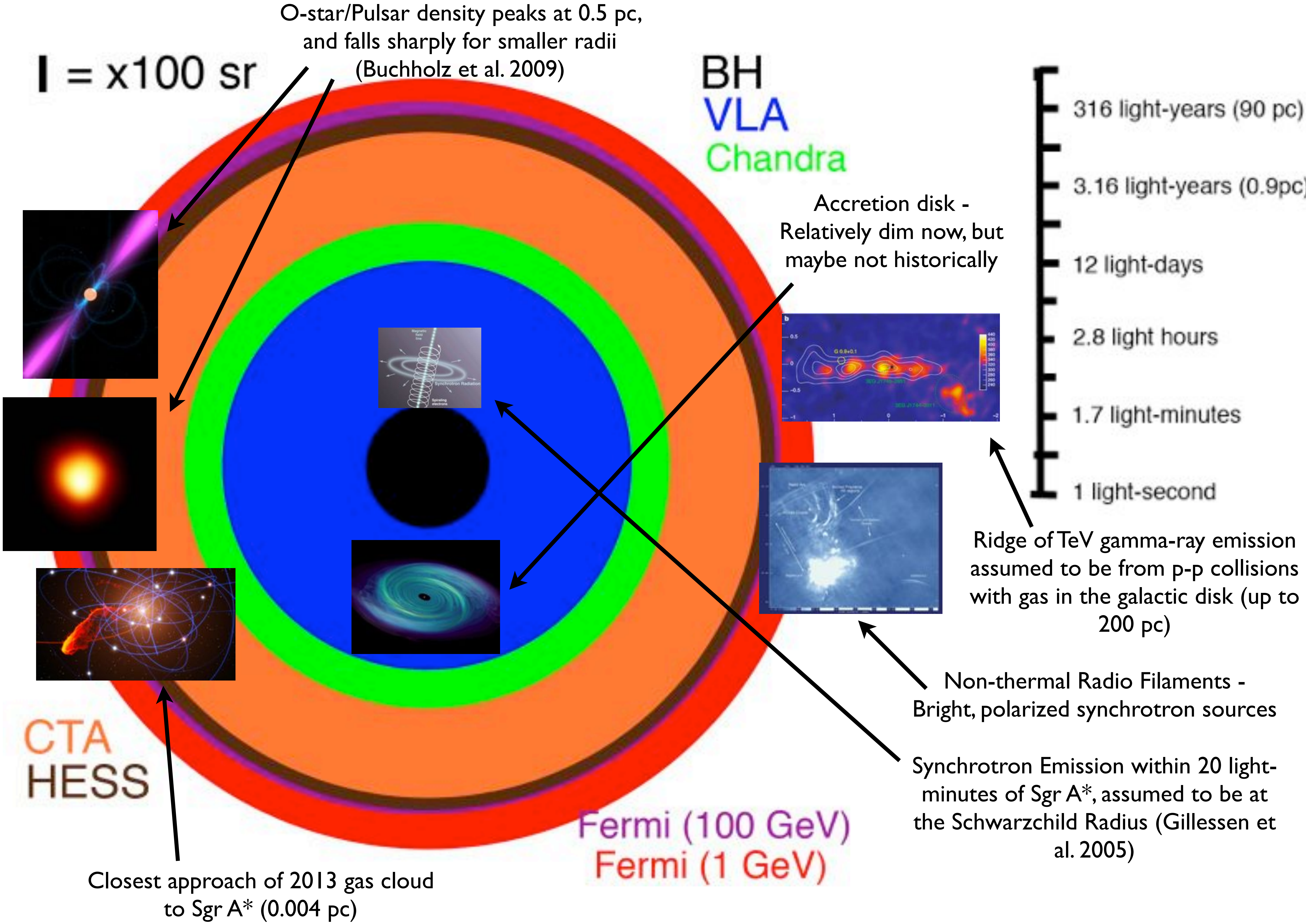
HESS

Fermi-LAT

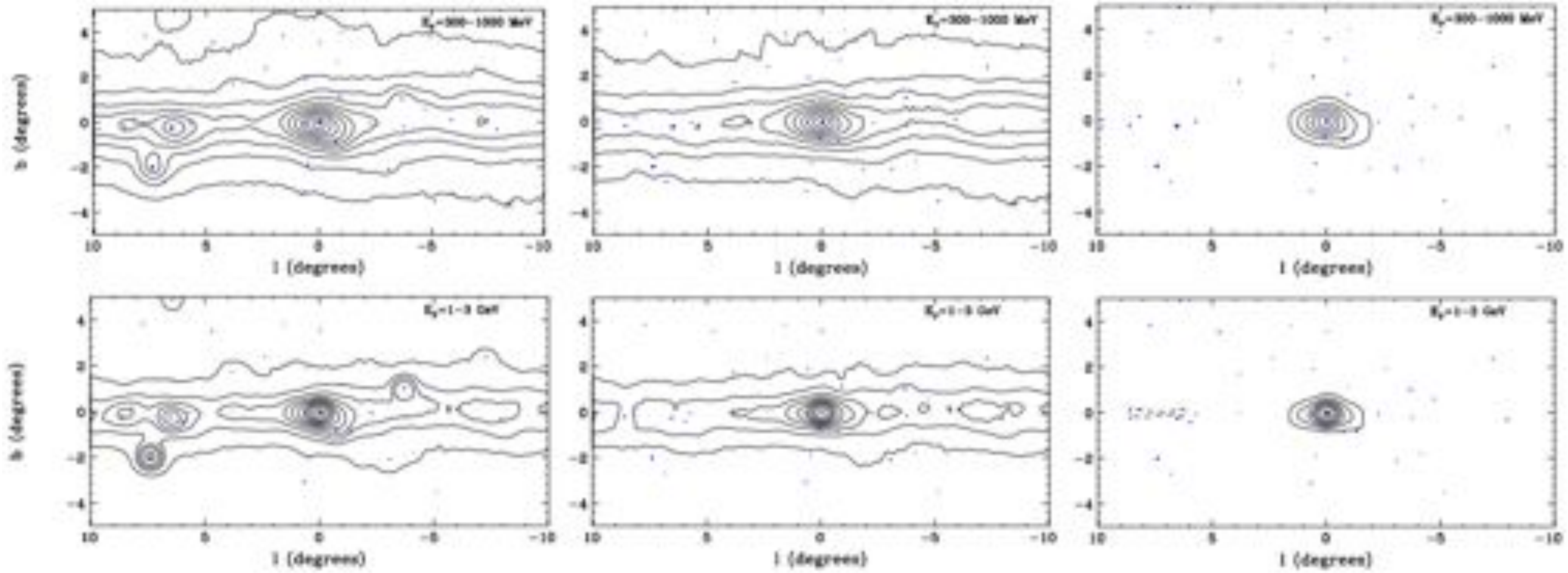
Angular Scales of the Galactic Center

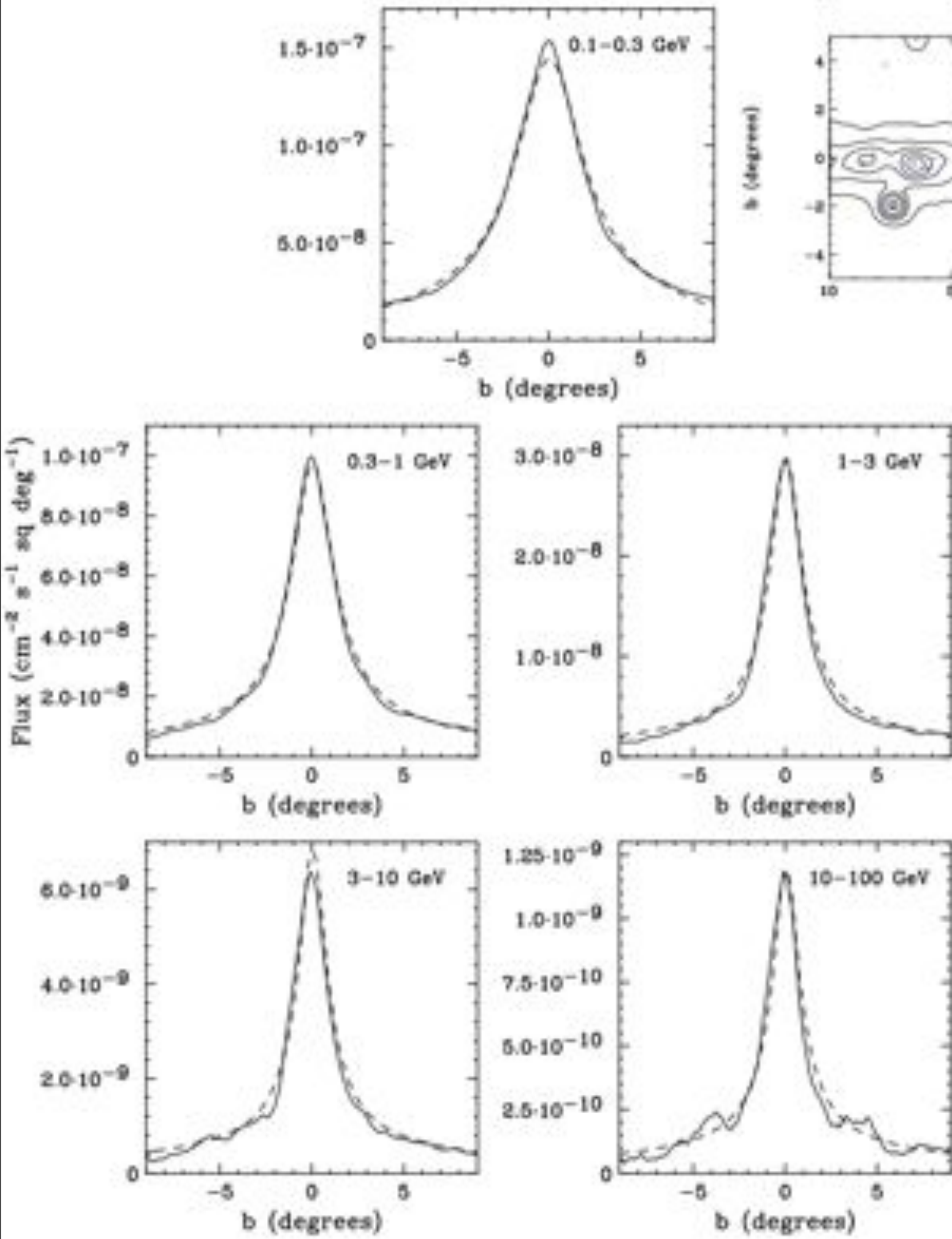


The Galactic Center "Zoo"



Subtracting the Astrophysical Background: Fermi





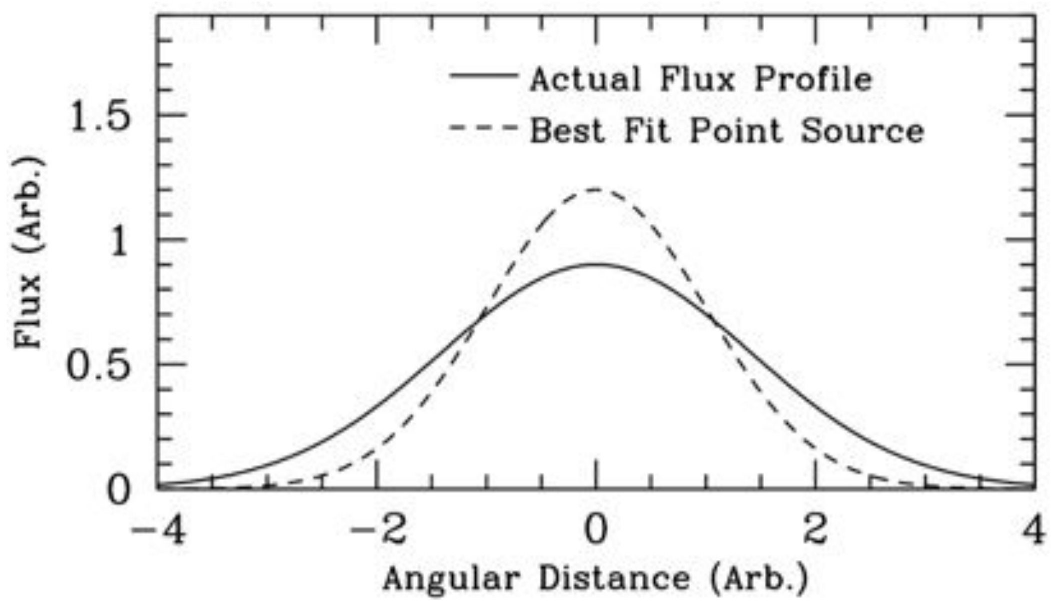
- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum
- This large residual at the center of the galaxy is a factor of 10 brighter than anything else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

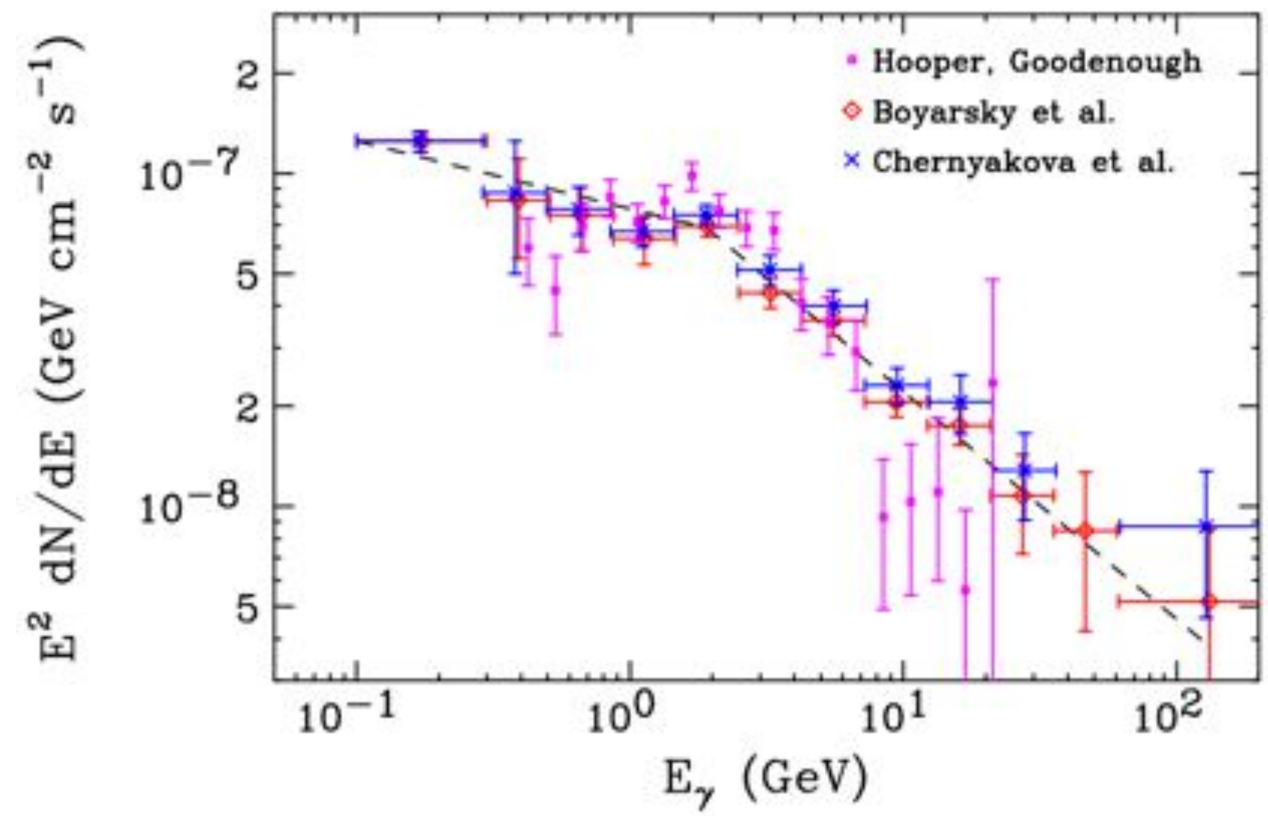
Hooper & Linden (2011)

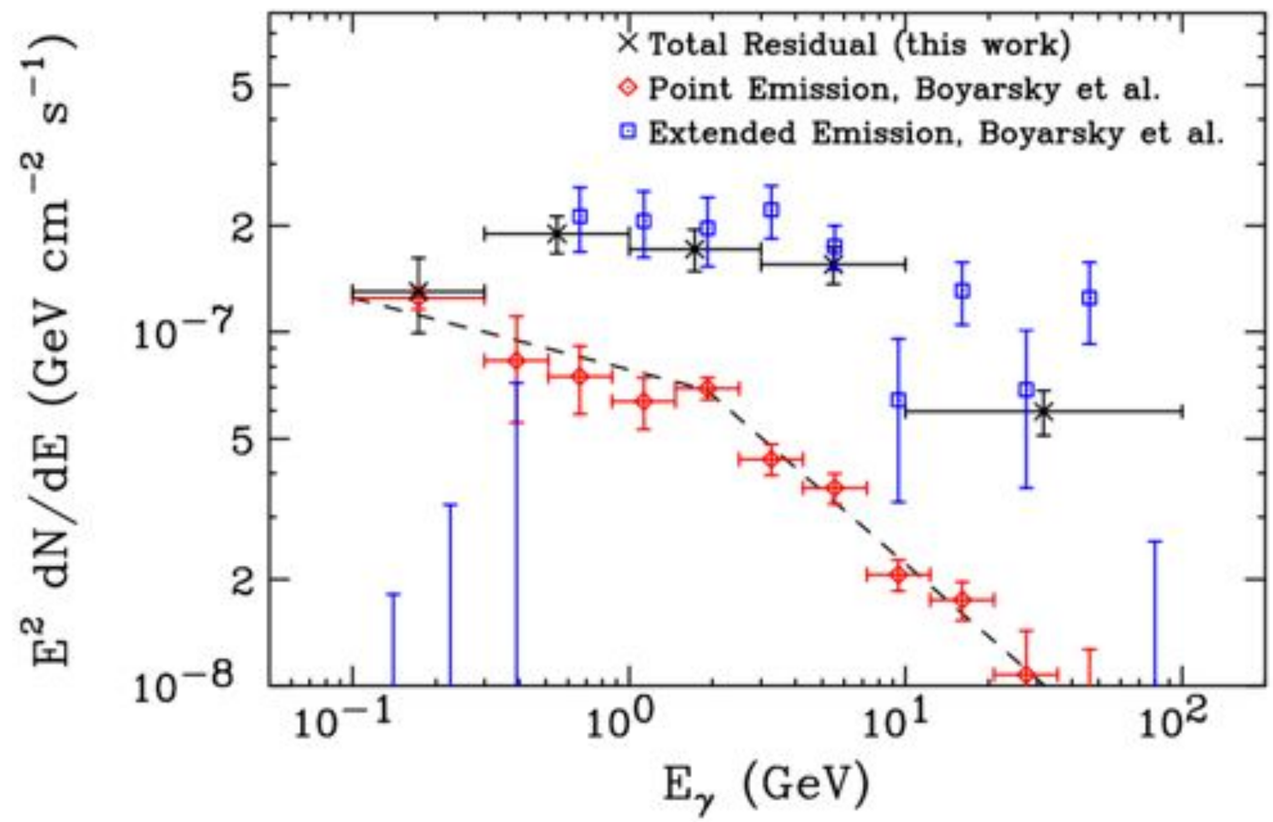
Understanding the GC Point Source: Fermi

- 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





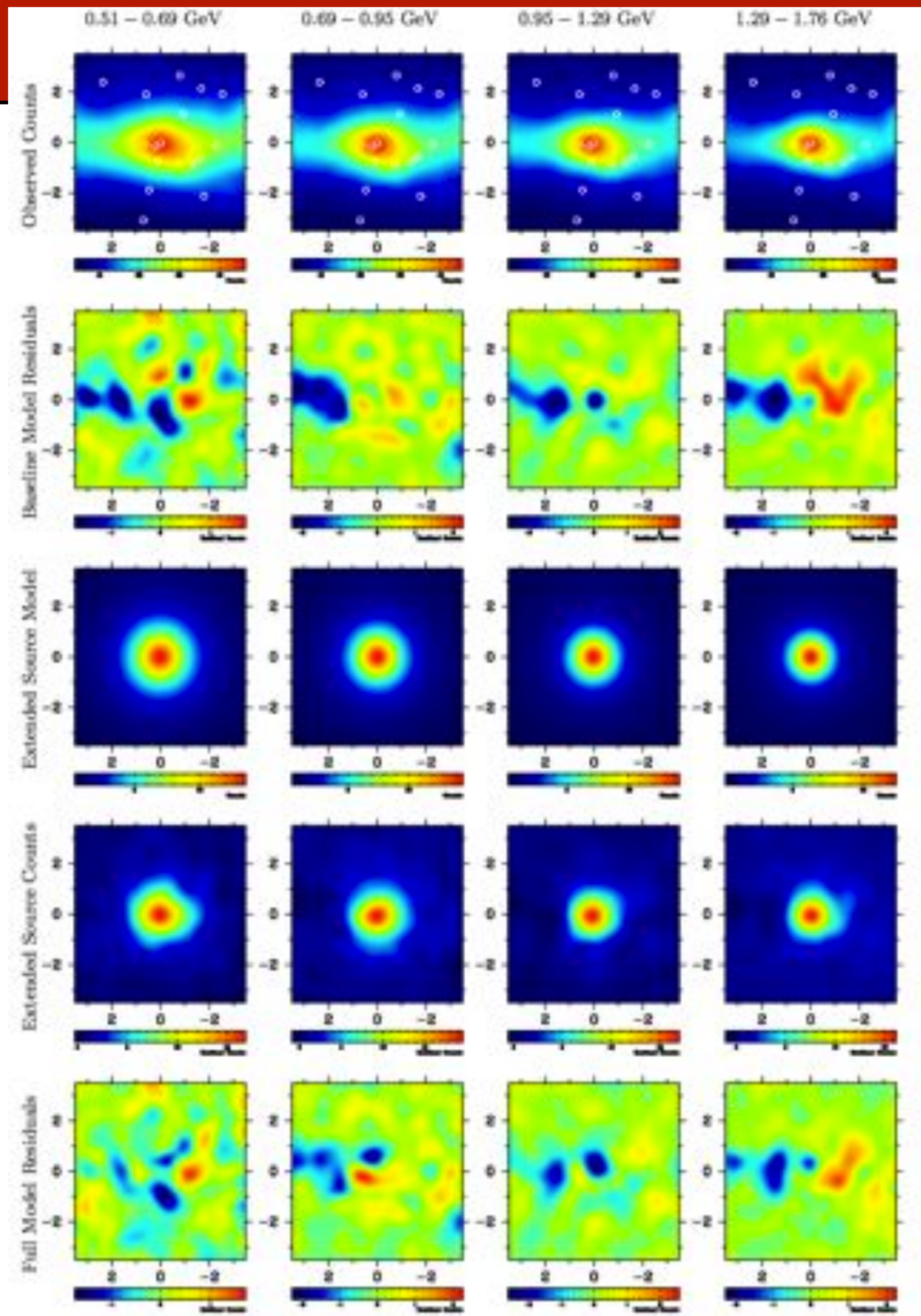


Hooper & Linden (2011)

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
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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?

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} GeV^2 cm^{-5})
AWM 7	43.6229	41.5781	0.0172	$1.4^{+0.1}_{-0.1}$
Fornax	54.6686	-35.3103	0.0046	$6.8^{+1.0}_{-0.9}$
M49	187.4437	7.9956	0.0033	$4.4^{+0.2}_{-0.1}$
NGC 4636	190.7084	2.6880	0.0031	$4.1^{+0.3}_{-0.3}$
Centaurus (A3526)	192.1995	-41.3087	0.0114	$2.7^{+0.1}_{-0.1}$
Coma	194.9468	27.9388	0.0231	$1.7^{+0.1}_{-0.1}$

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

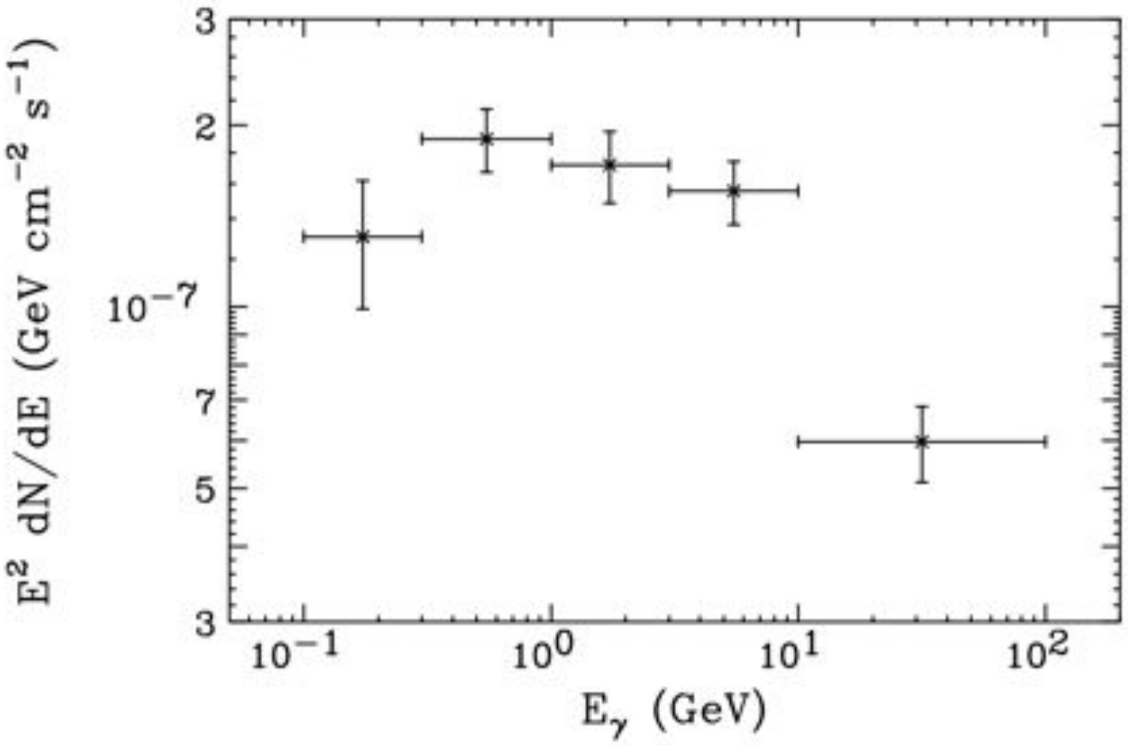
$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \rho^2(l)\mathrm{d}l(\psi)$$

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

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

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

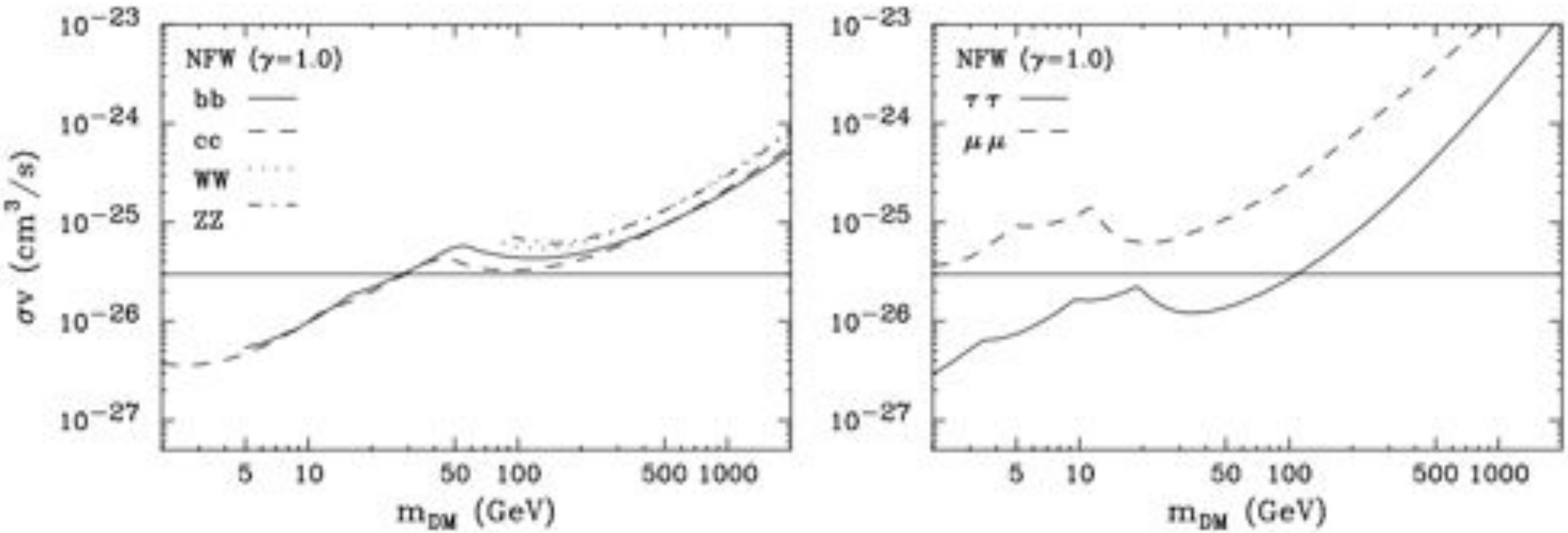
Dark Matter Limits in the Simplest Way Possible



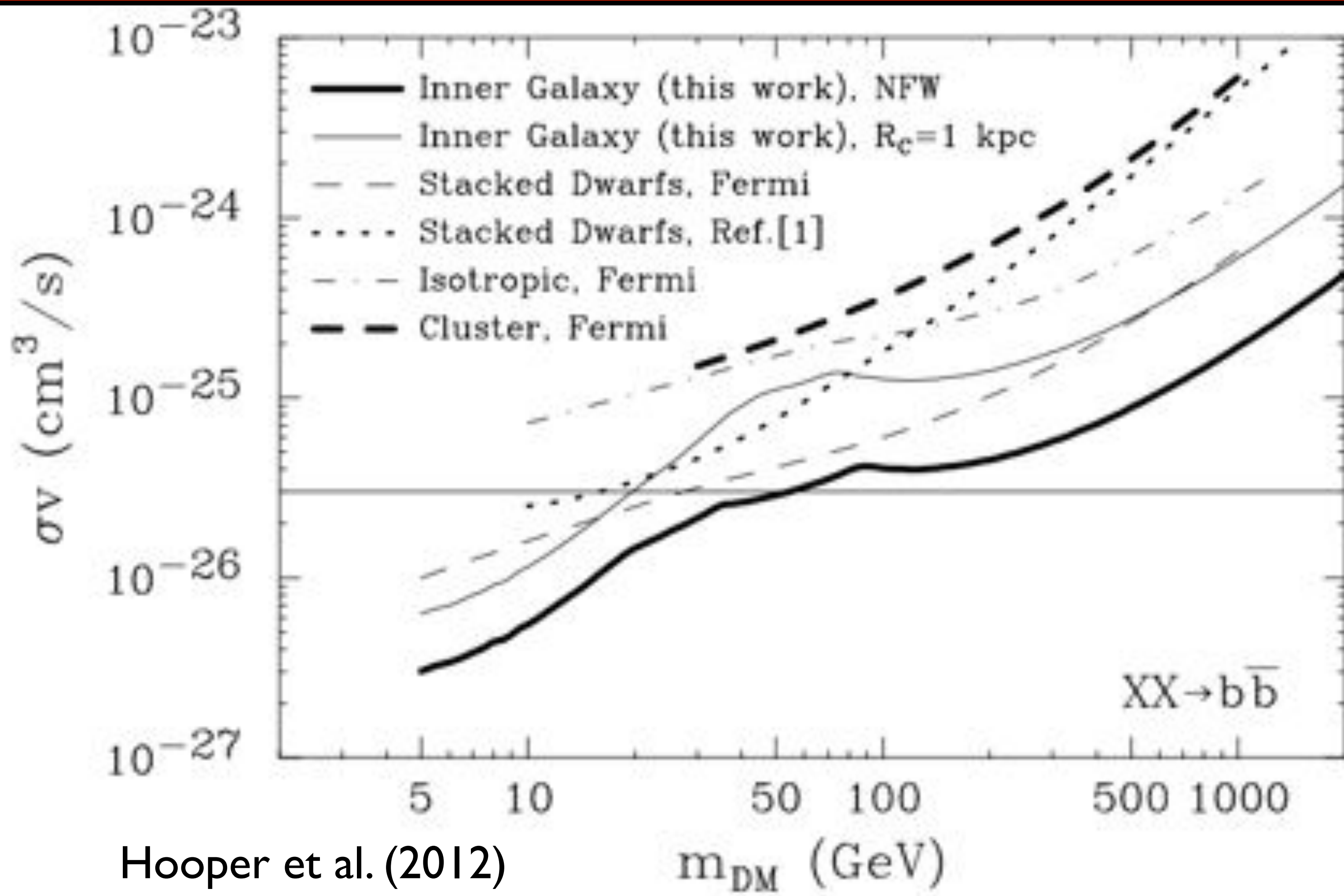
Hooper & Linden (2011)

- 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

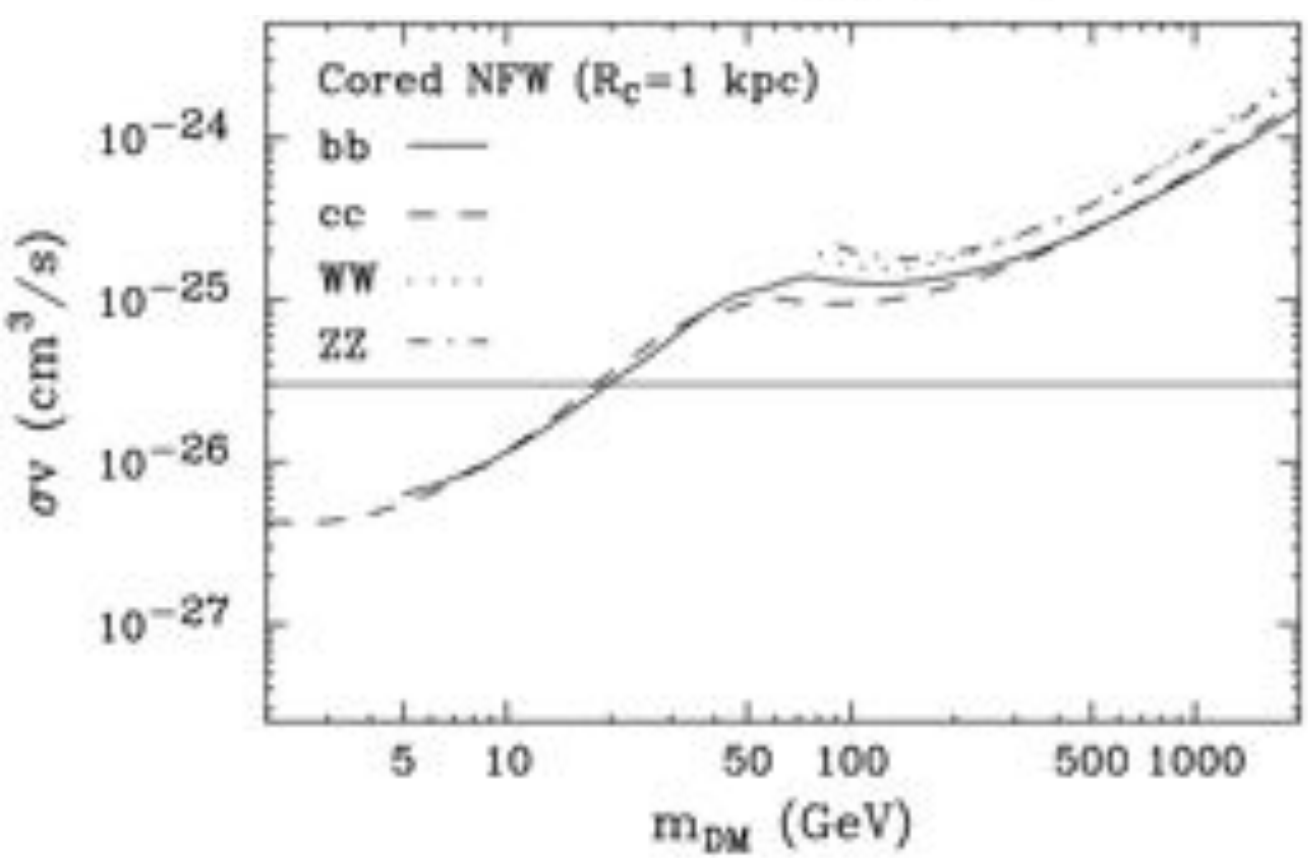


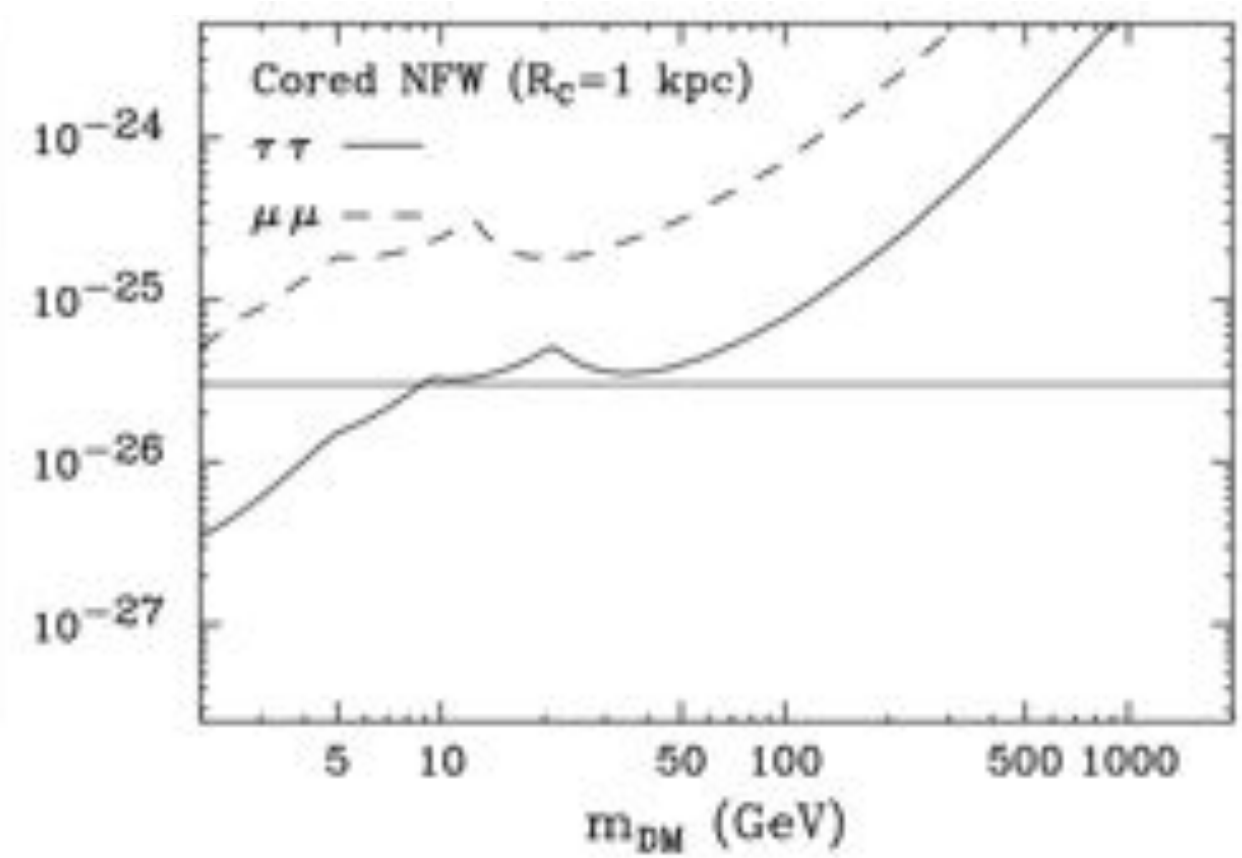
Comparison to Other Indirect Detection Regimes



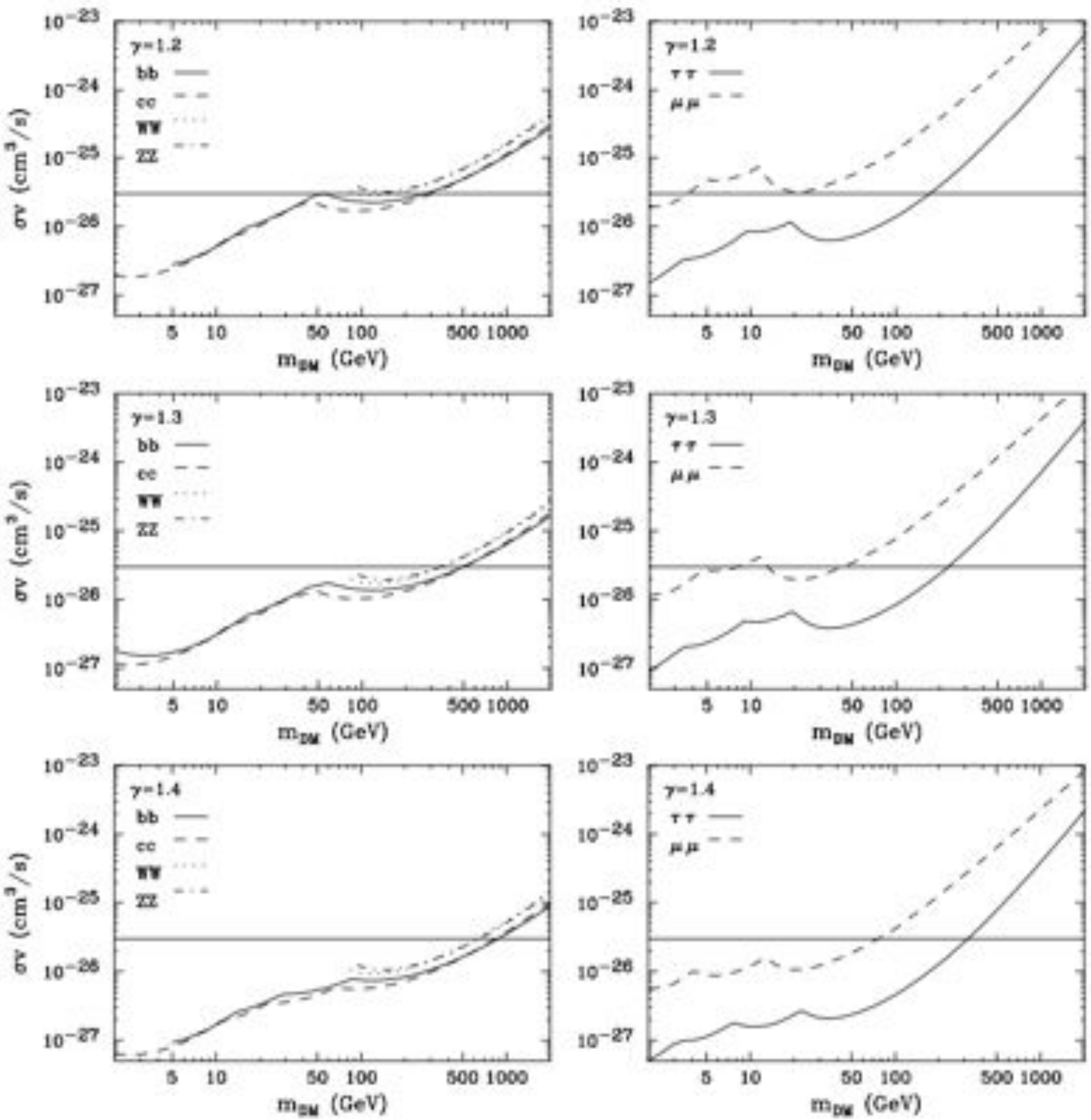
Hooper et al. (2012)

- 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



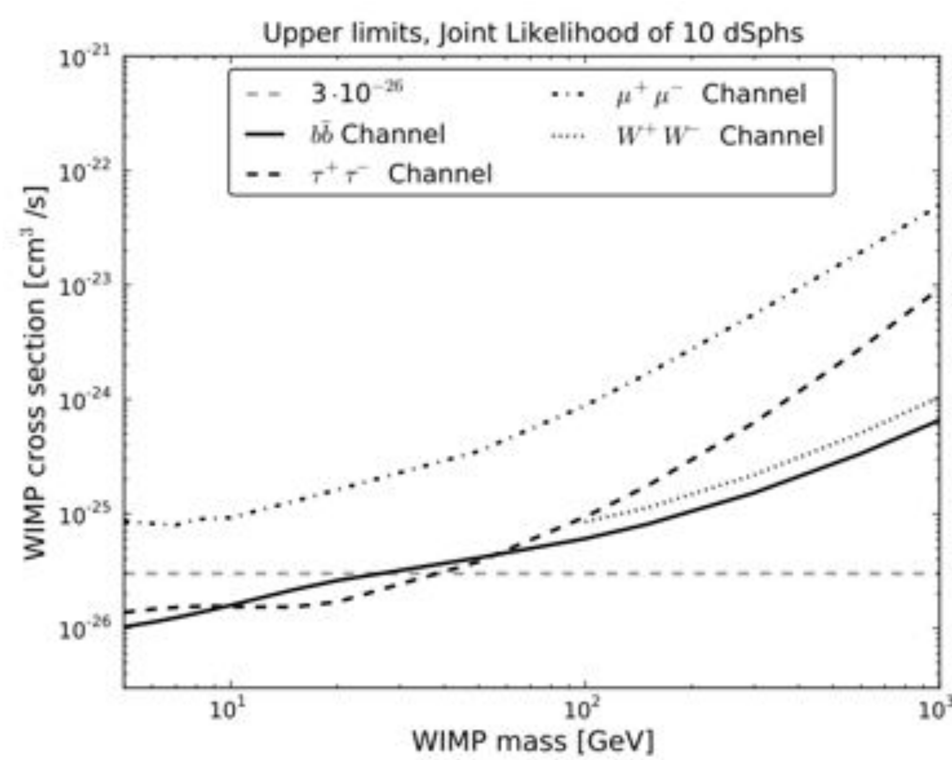


Comparison to Other Indirect Detection Regimes



Hooper & Linden (2011)

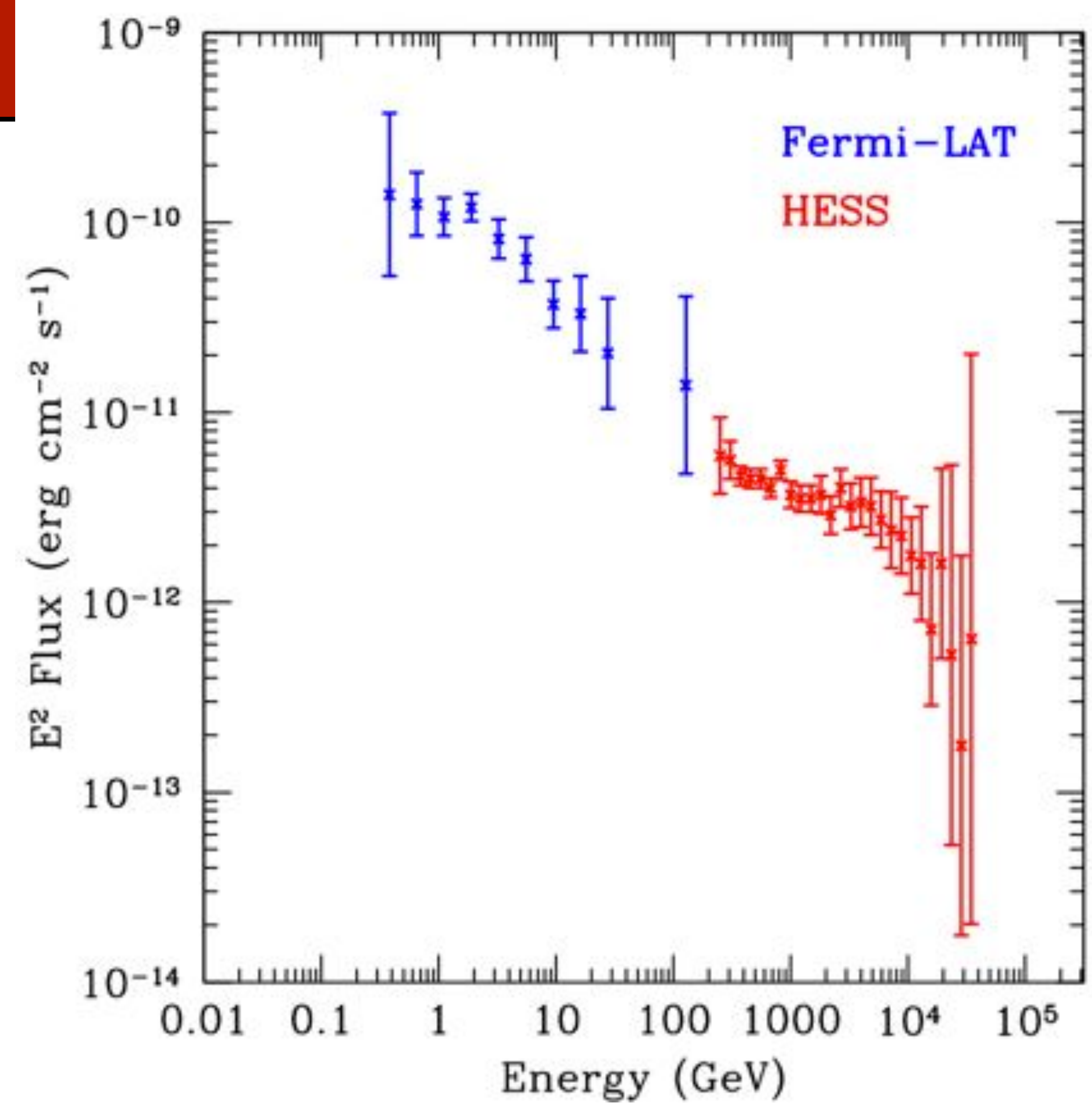
- With some adiabatic contraction of the inner dark matter profile, these limits can become substantially stronger than any other indirect detection limit

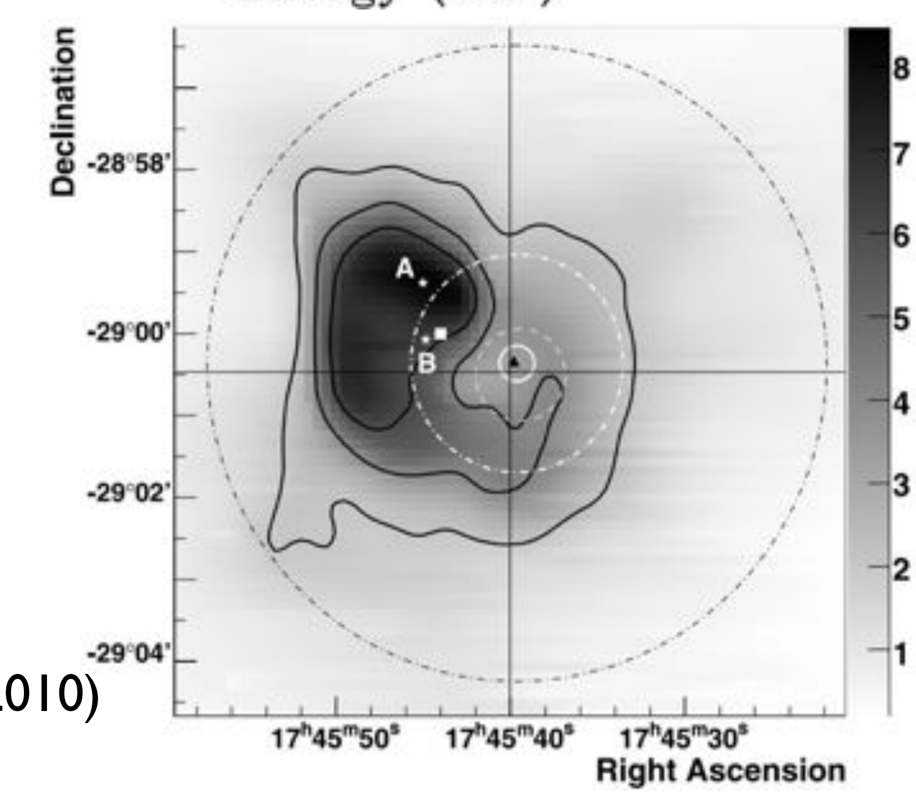


Ackermann et al. (2011)

A 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 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

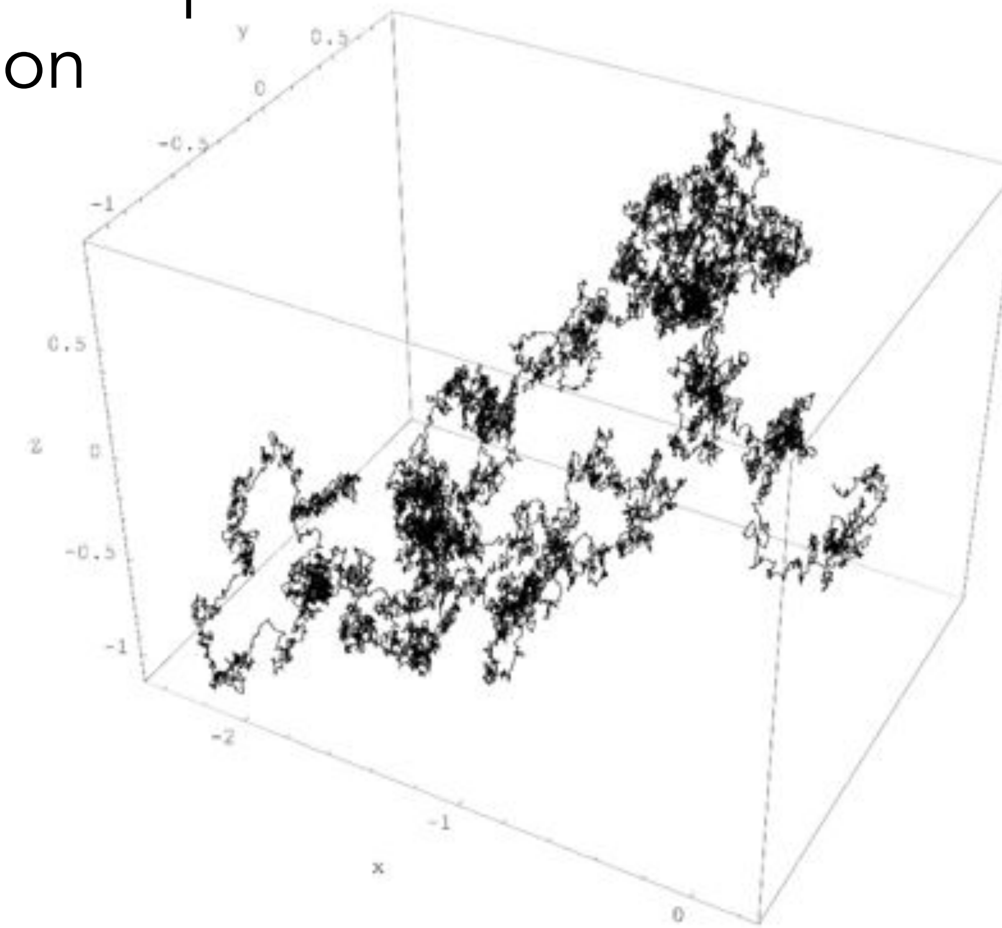




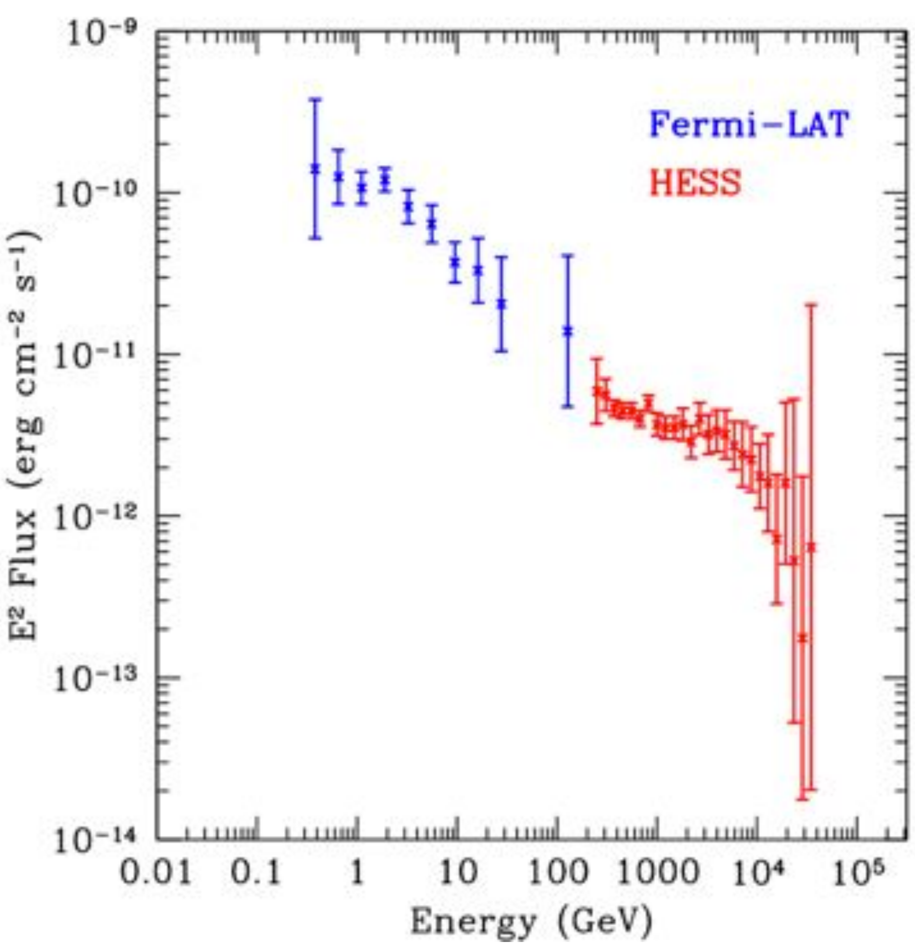
Acero et al. (2010)

Controlling the Emission Spectrum with Diffusion

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



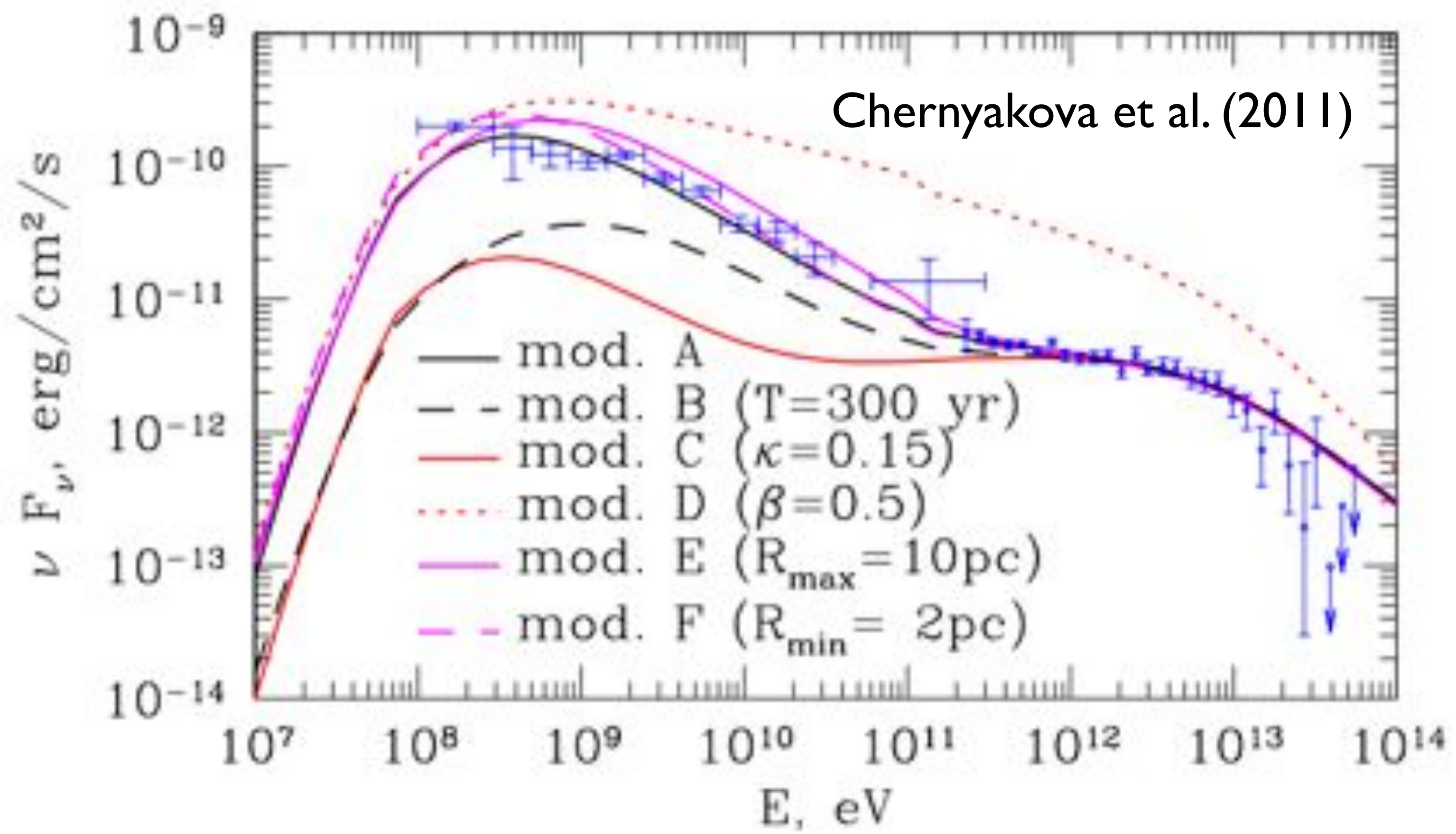
- In the regime where the diffusion stepsize exceeds the diffusion region, the emission intensity is energy independent, and an E^{-2} proton injection spectrum corresponds directly to an E^{-2} gamma-ray spectrum



- 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.

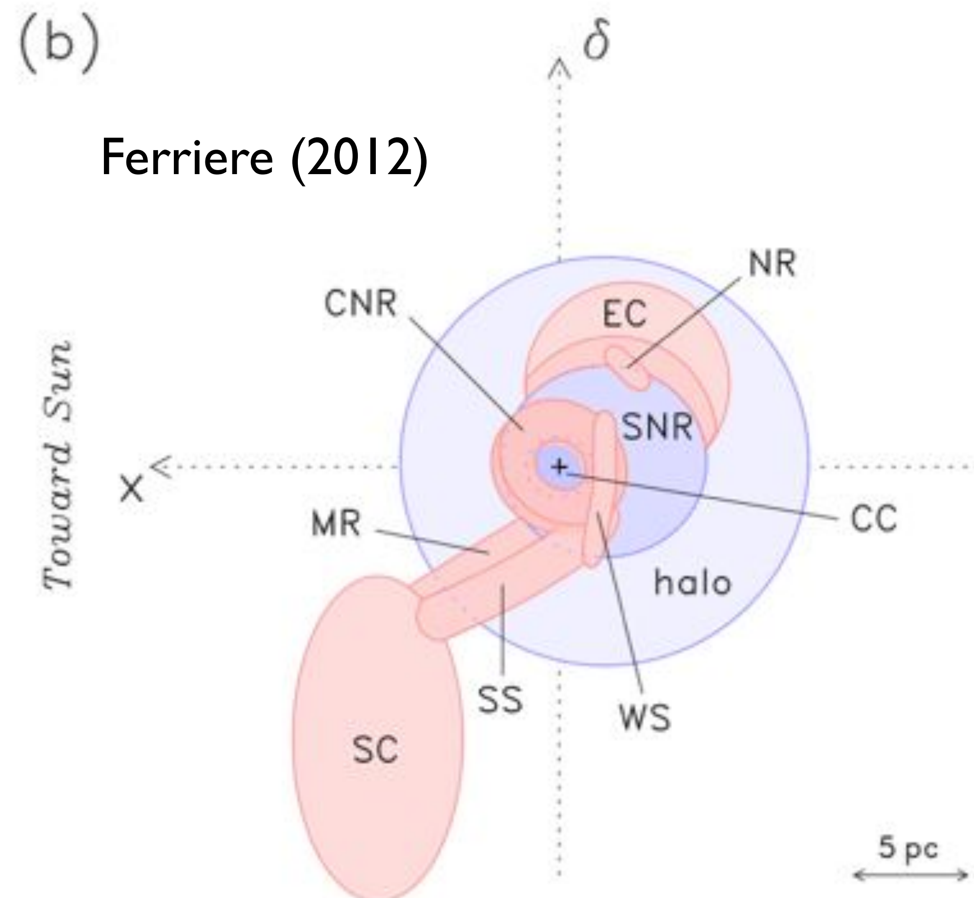
- Models are formed with a step-function gas density profile (1000 n_H/cm^{-3} within 3 pc of the galactic center, and 0 n_H/cm^{-3} outside)

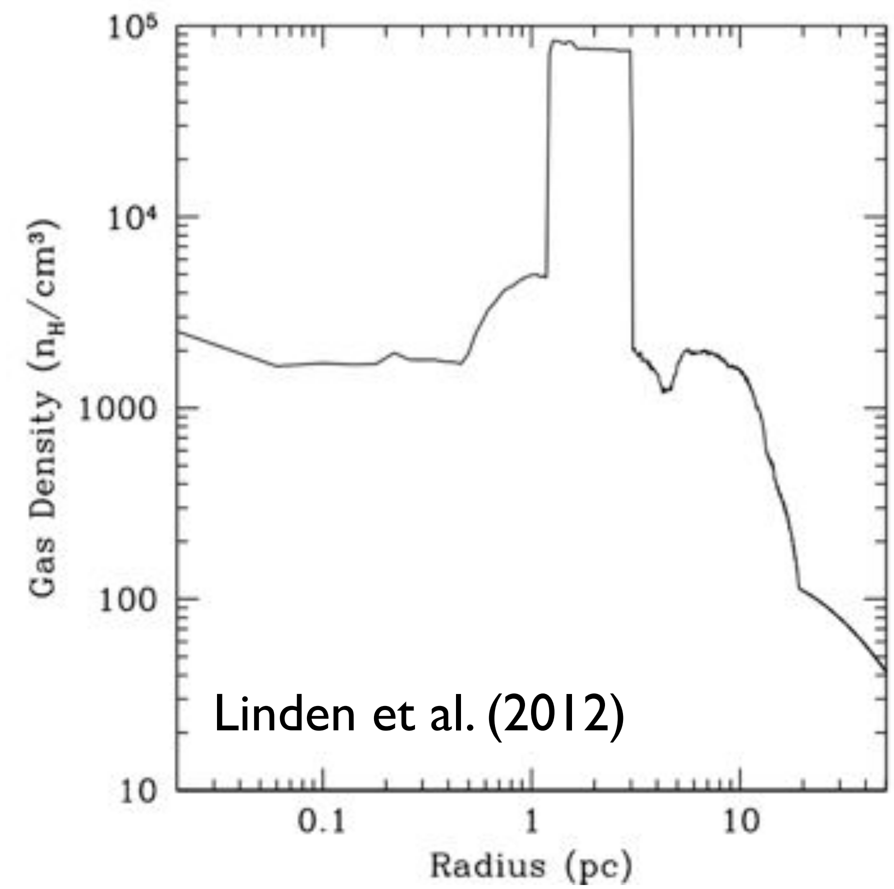
Employing a Realistic Gas Model

- 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

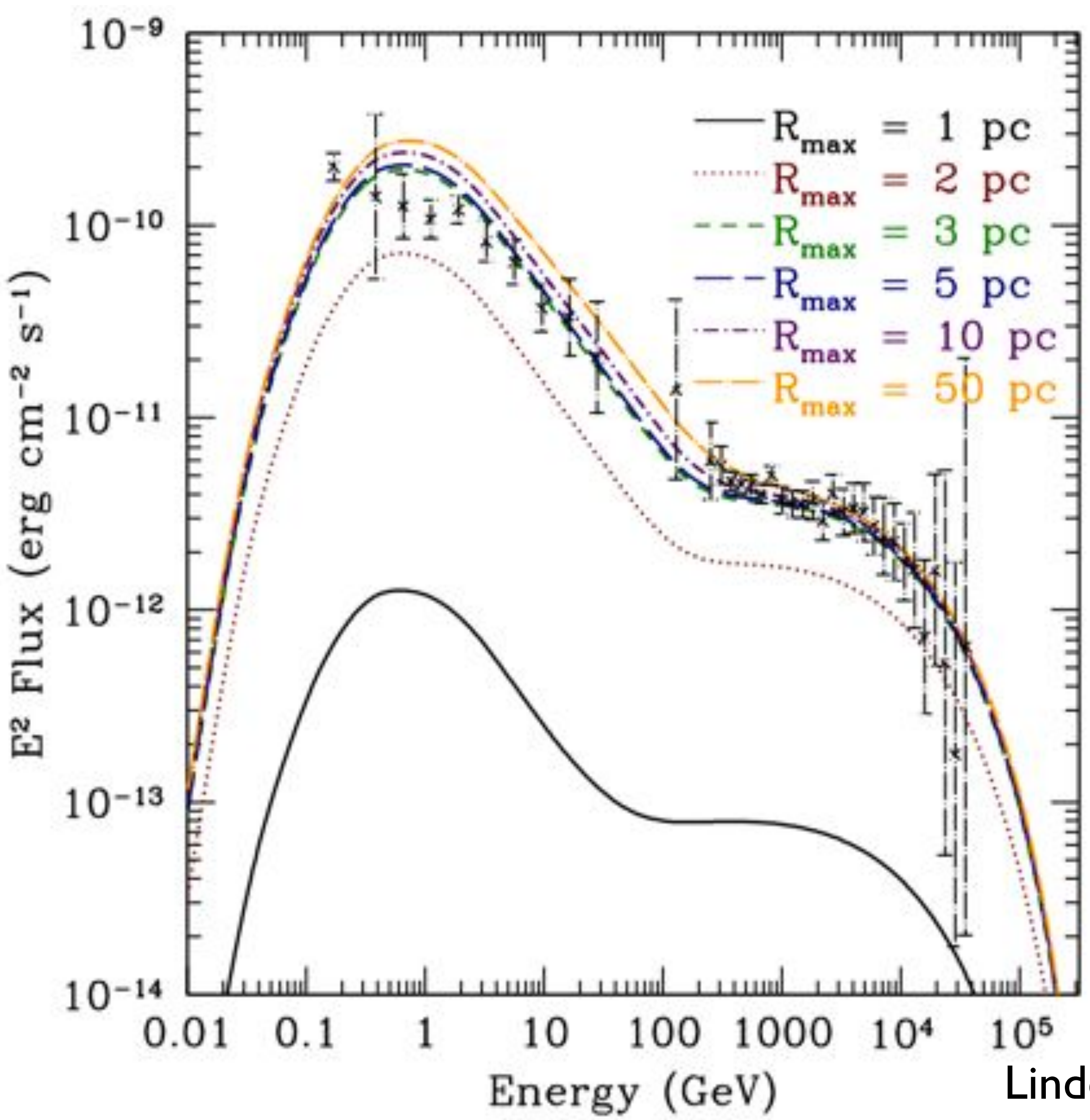
- By far the dominant feature is the Circumnuclear ring between 1-3 pc from the GC

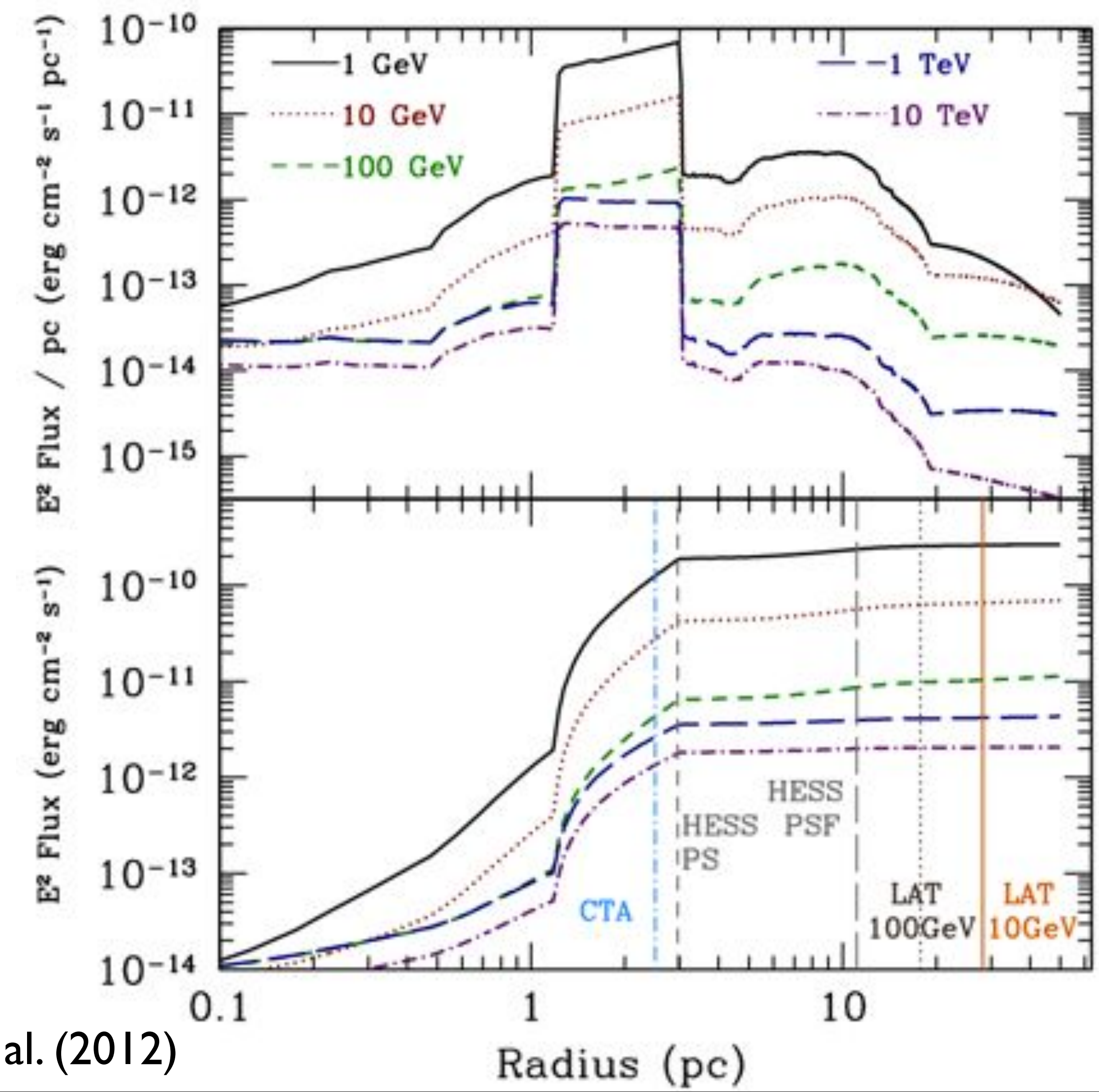




Employing a Realistic Gas Model

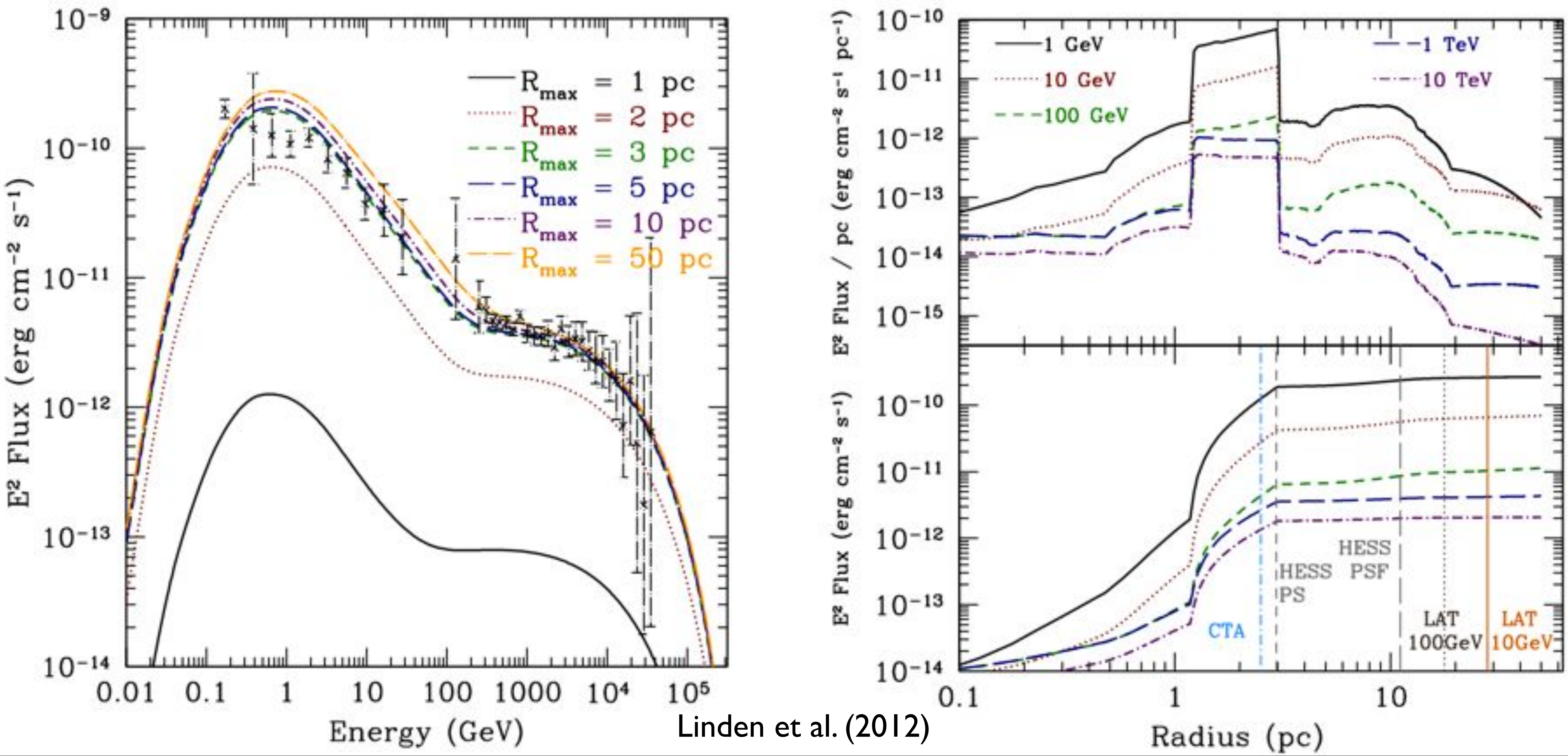
- The vast majority of emission stems from within 3 pc of the galactic center at all energies
- This lies below the PSF of all current gamma-ray instruments
- This effectively rules out hadronic interactions from Sgr A* as the source of the Fermi-LAT excess





Linden et al. (2012)

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

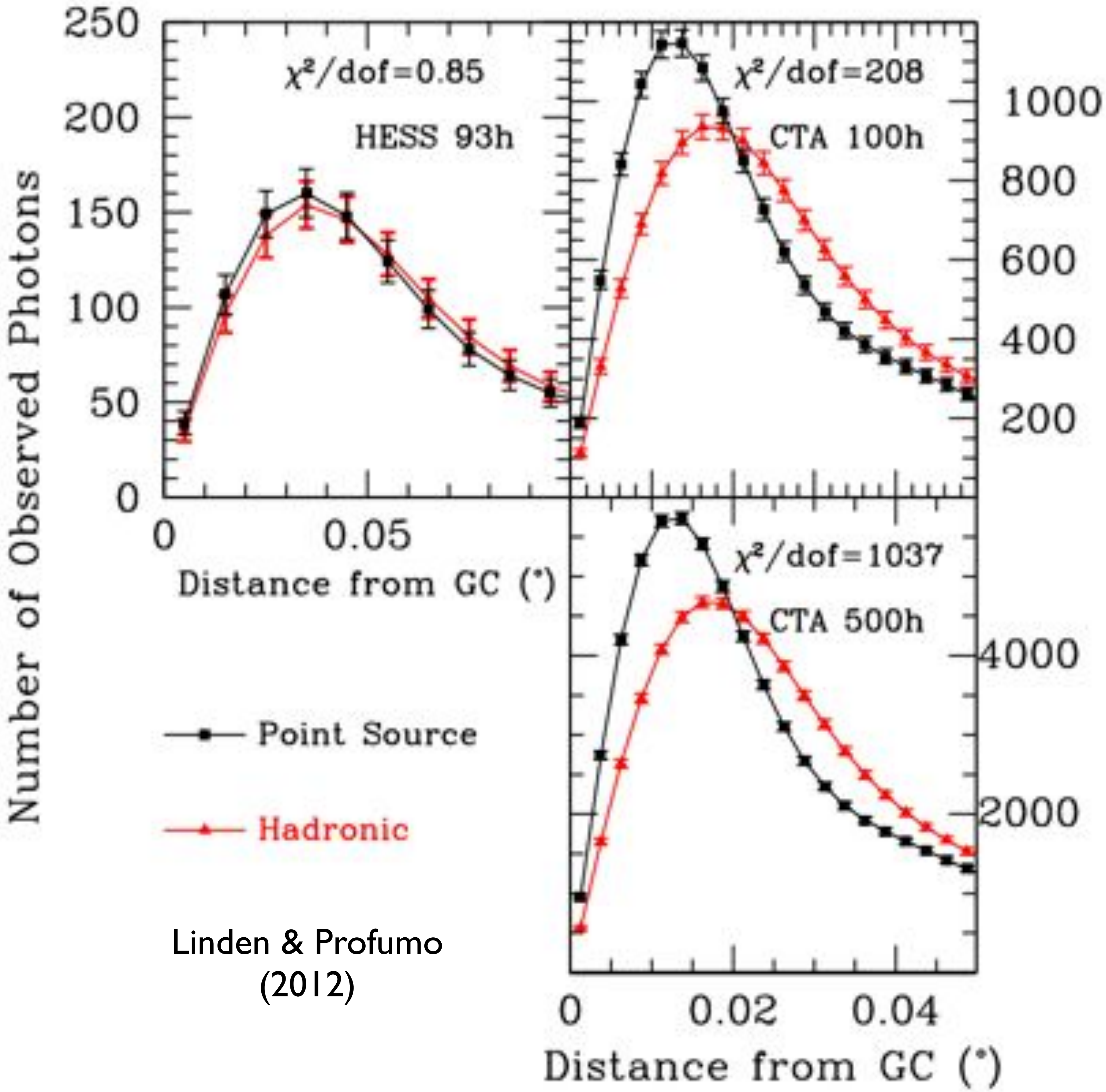


Linden et al. (2012)

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

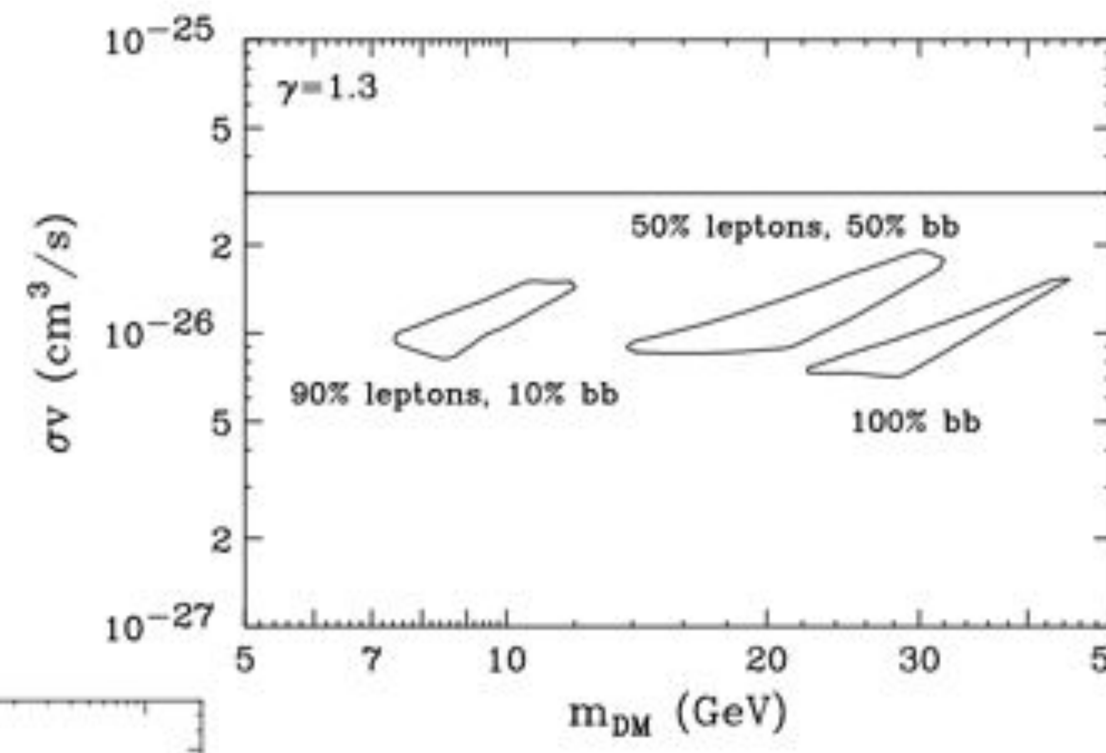
- CTA will conclusively determine whether the galactic center source stems from a hadronic emission channel



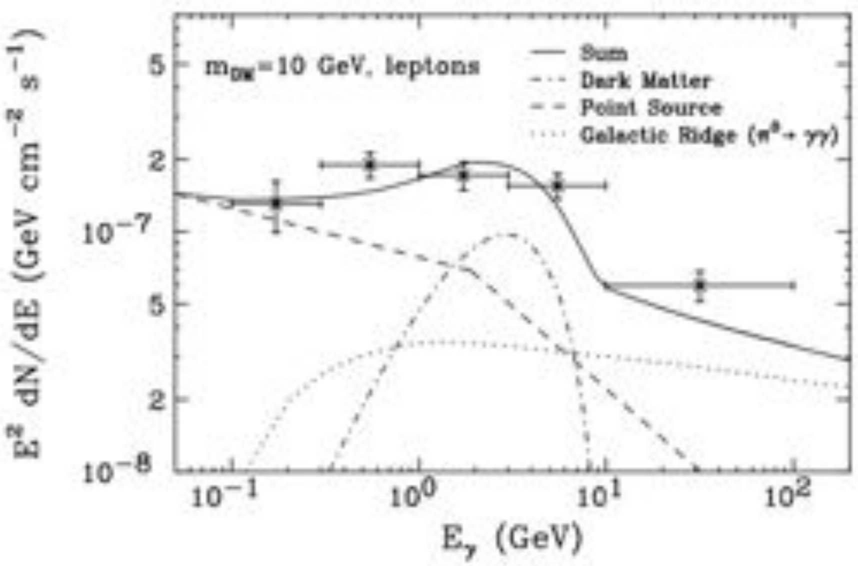
Linden & Profumo (2012)

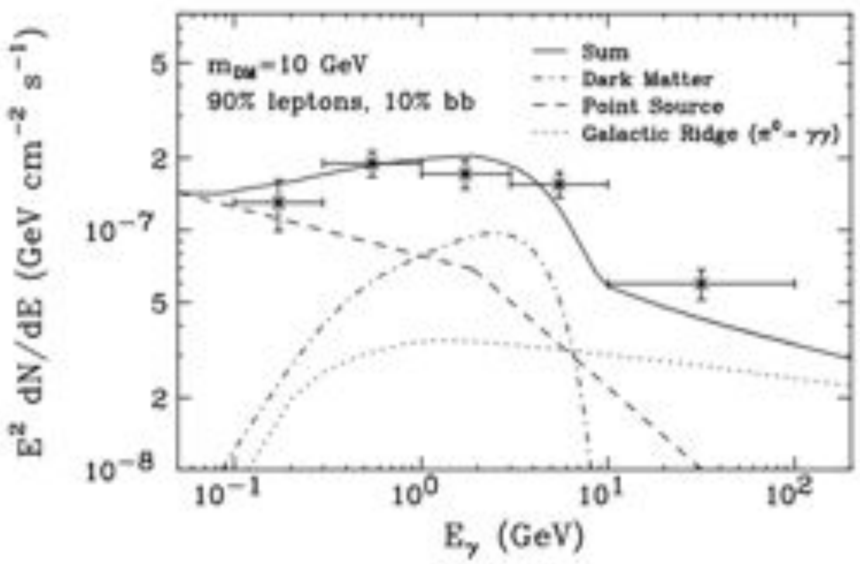
Story 2: Low-Mass Dark Matter

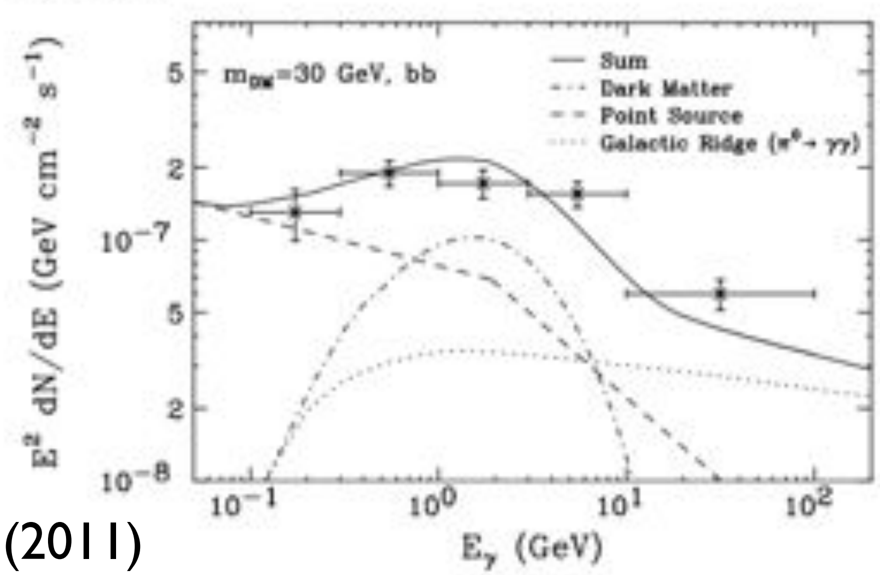
- For a best fitting profile γ = 1.3, we find an available parameter space for dark matter models which match the observed GC excess



- 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

- 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	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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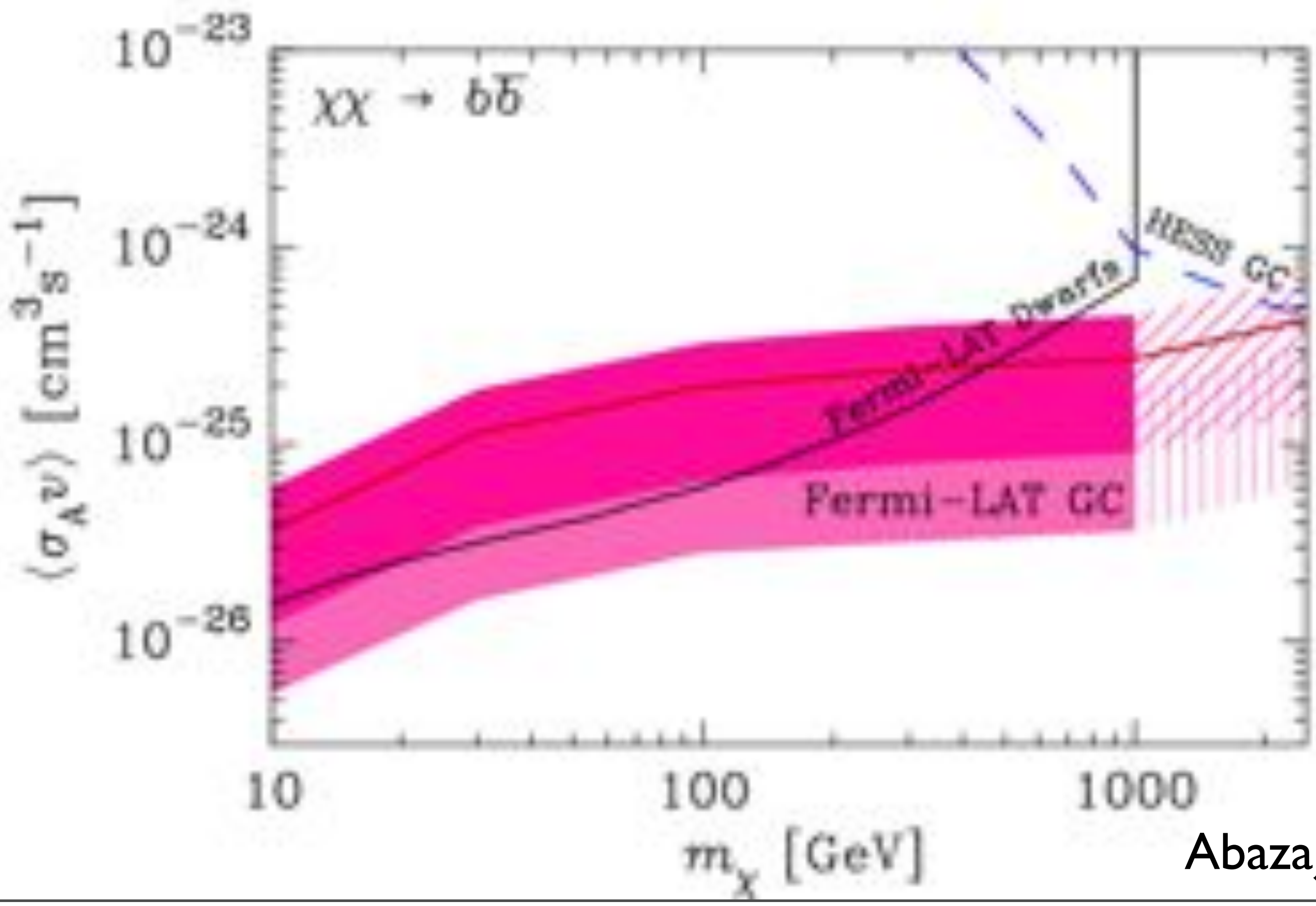
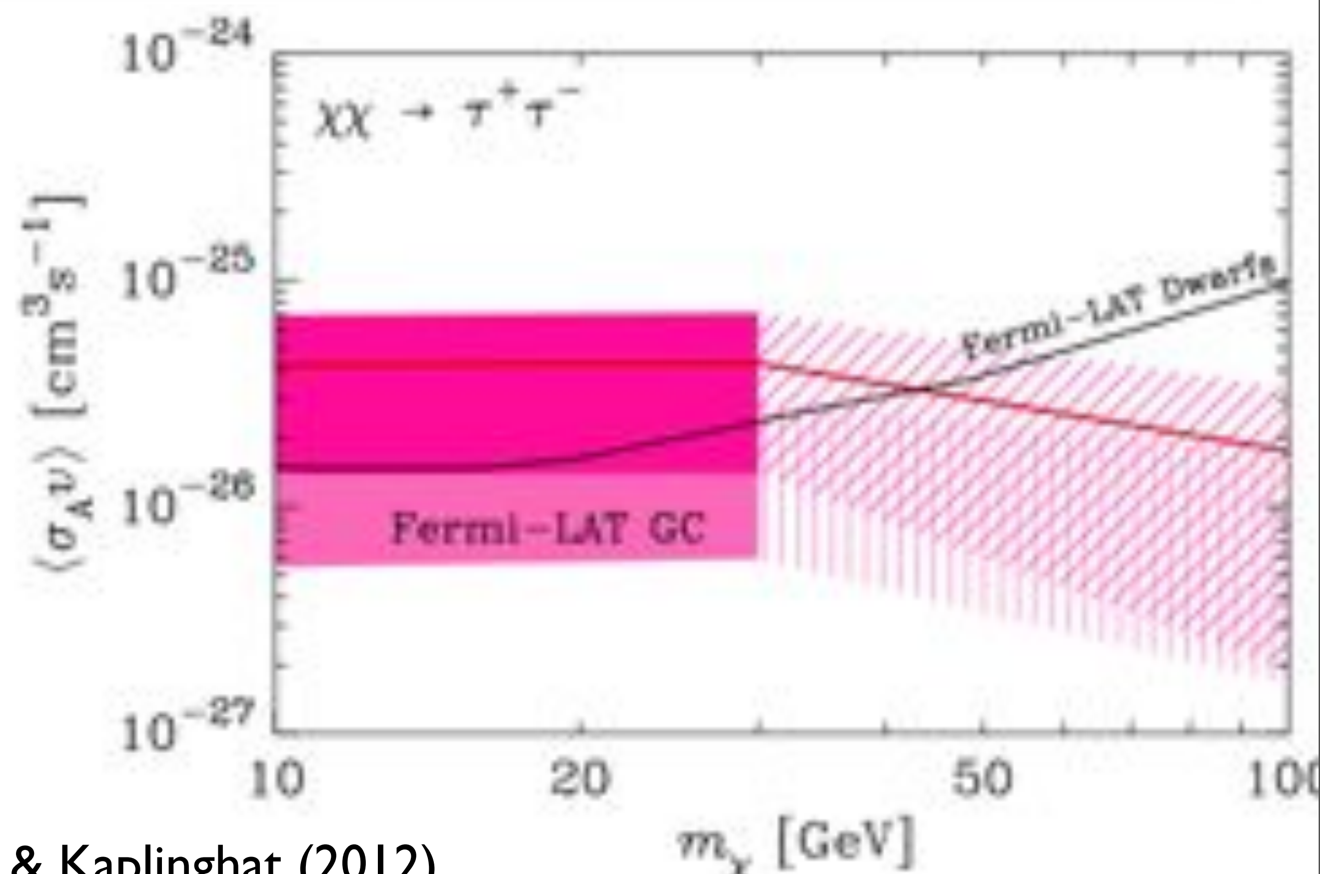
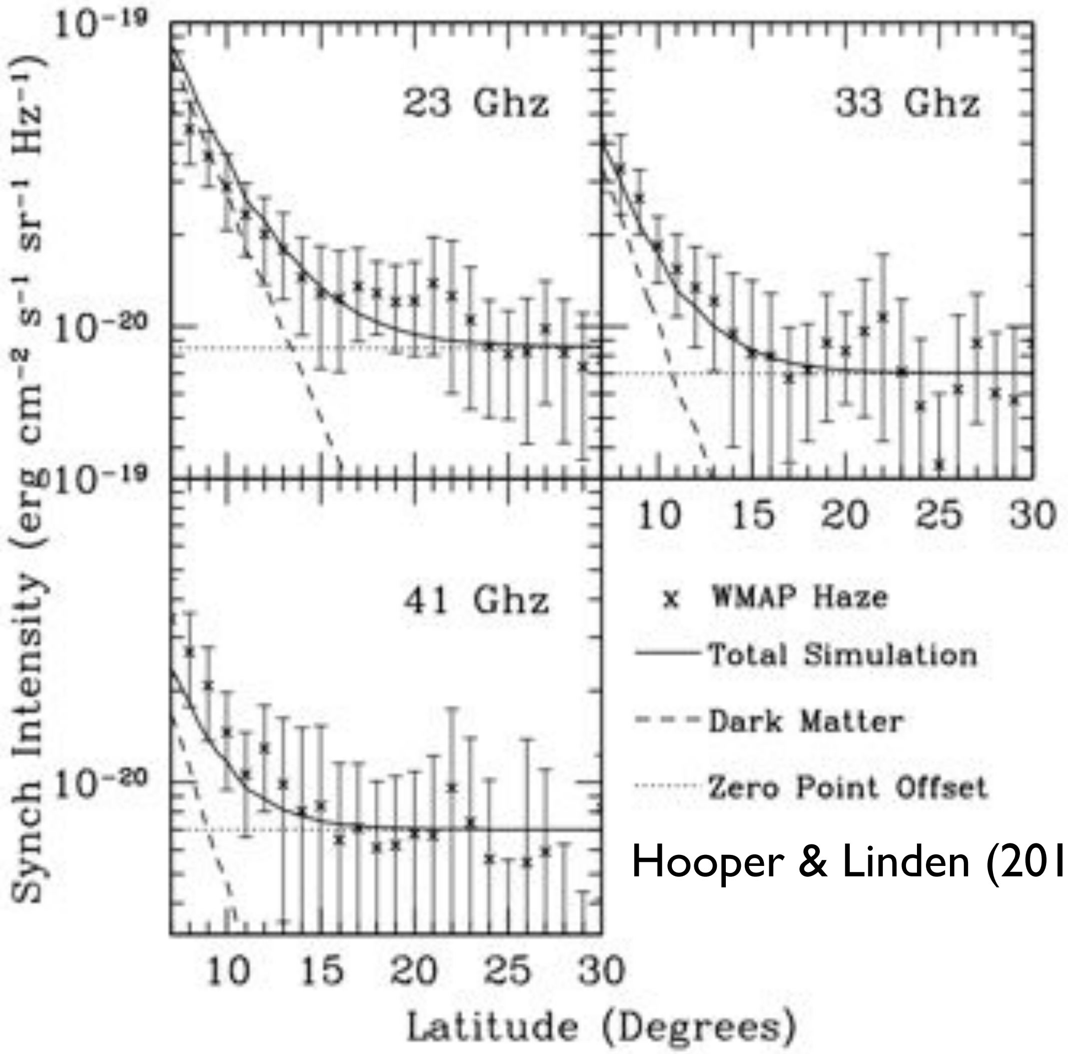




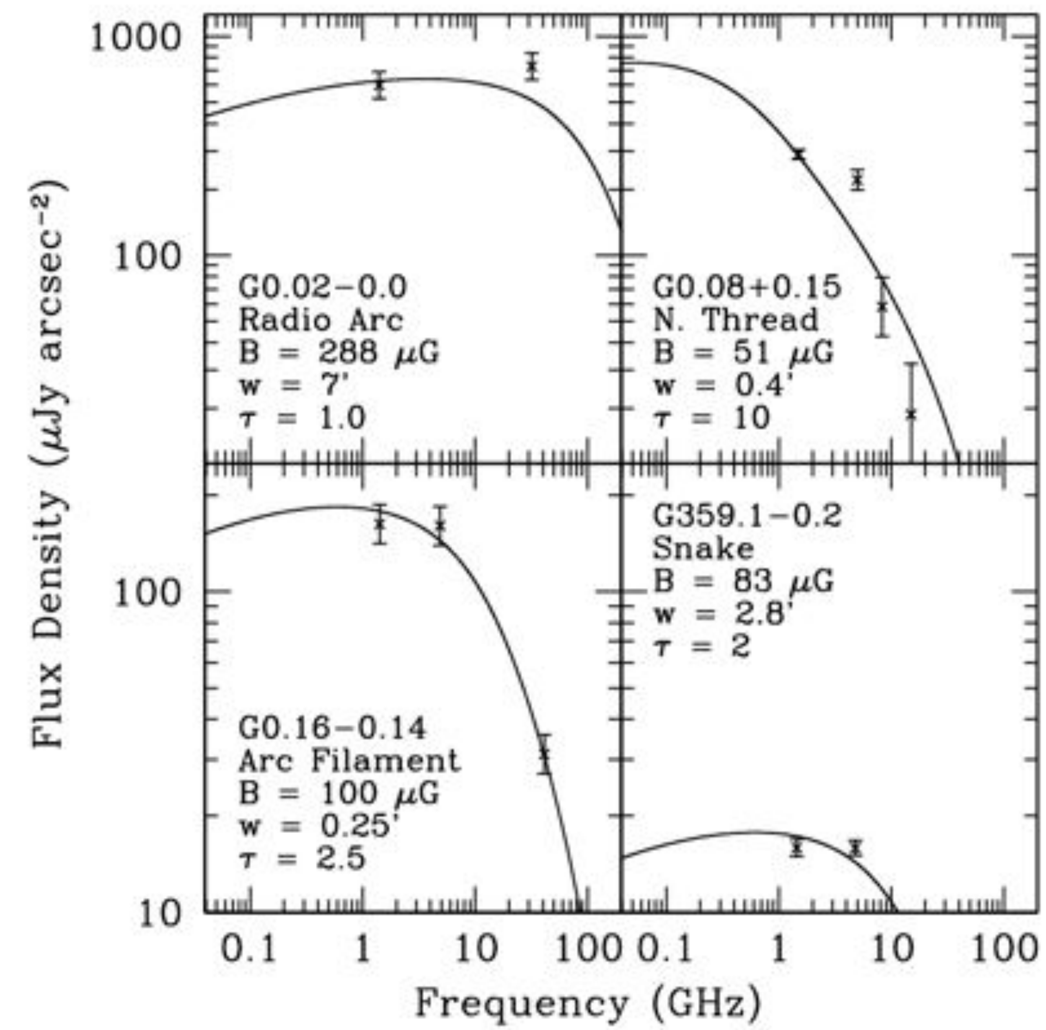
Abazajian & Kaplinghat (2012)

Other Observations Fitting Light DM: Indirect



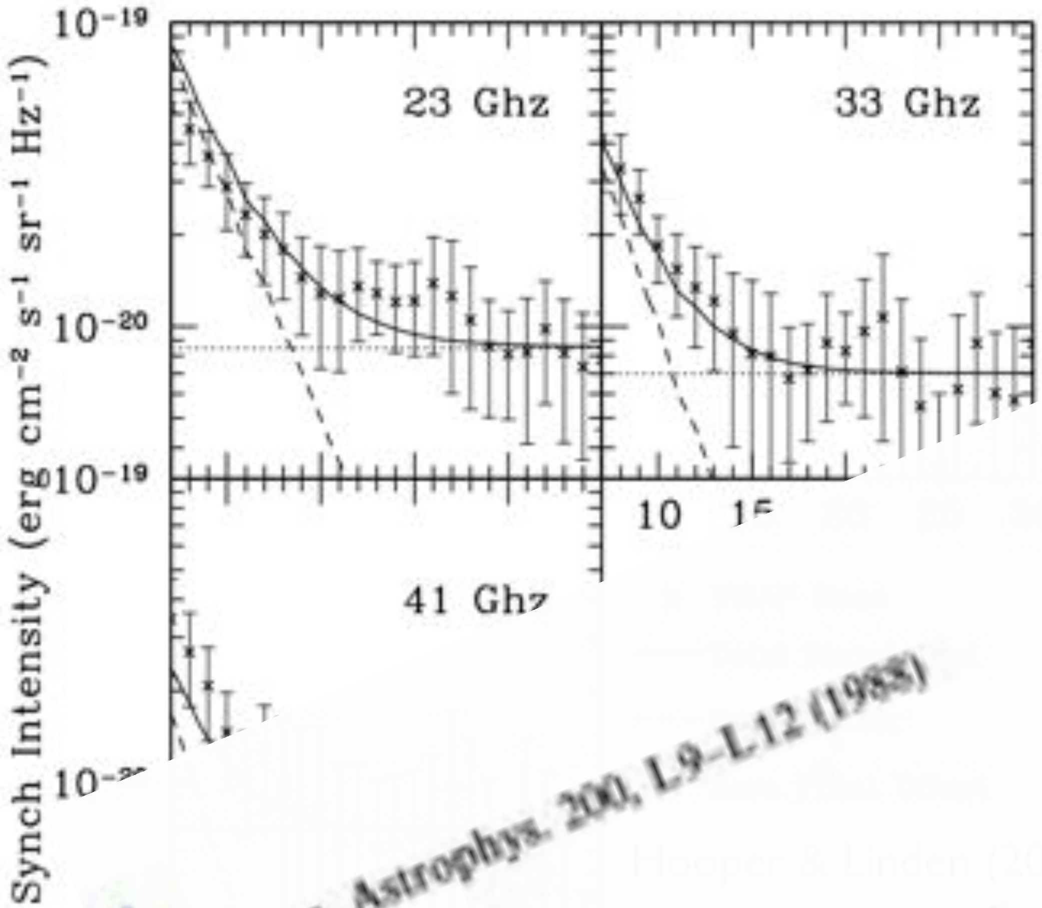
Hooper & Linden (2011)

- 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: Indire



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Hooper & Linden (2011)

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ASTRONOMY AND ASTROPHYSICS

Astron. Astrophys. 200, L9–L12 (1988)

Letter to the Editor

Monoenergetic relativistic electrons in the galactic center

H. Lesch*, R. Schlickeiser, and A. Crusius
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Federal Republic of Germany

Received March 29, accepted May 27, 1988

Summary
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 ... nor due to thermal absorption. A ... in which Sgr A* represents ... which propagate with ... function into the

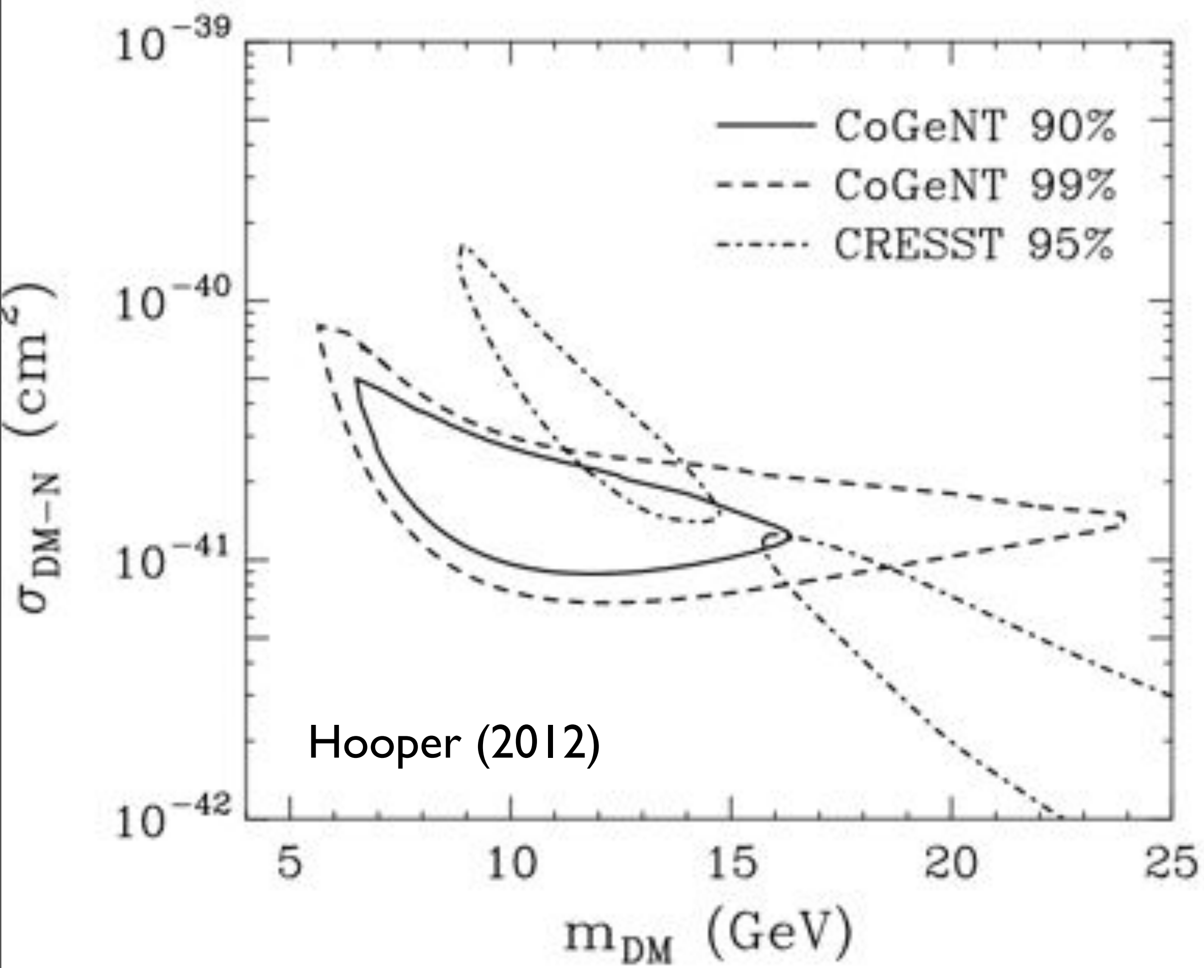
θ_{crit} = 2.6·10^{9} $S_M^{1/2}$ $\nu_M^{-5/4}$ $B^{1/4}$ arcse

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^{-3} G (Sofue and Fujimoto, 1988)

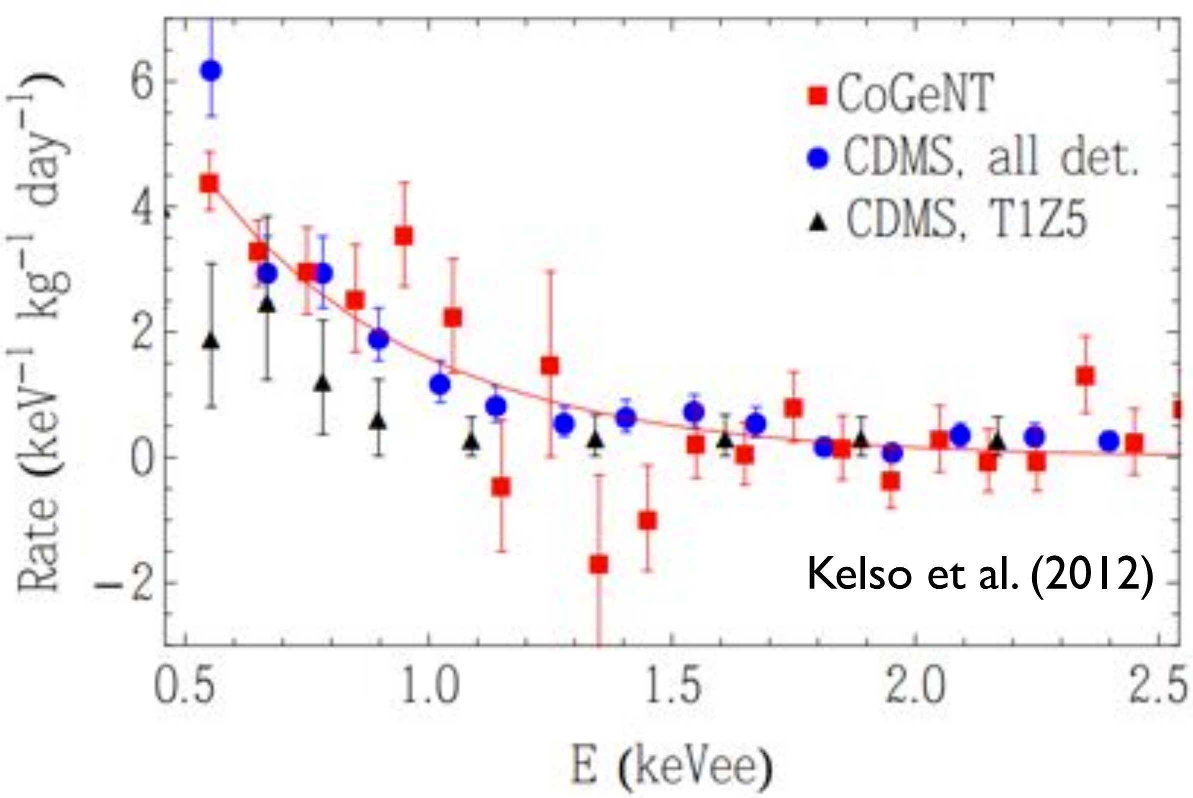
θ_{crit} = 4·10^{-4} arcseconds

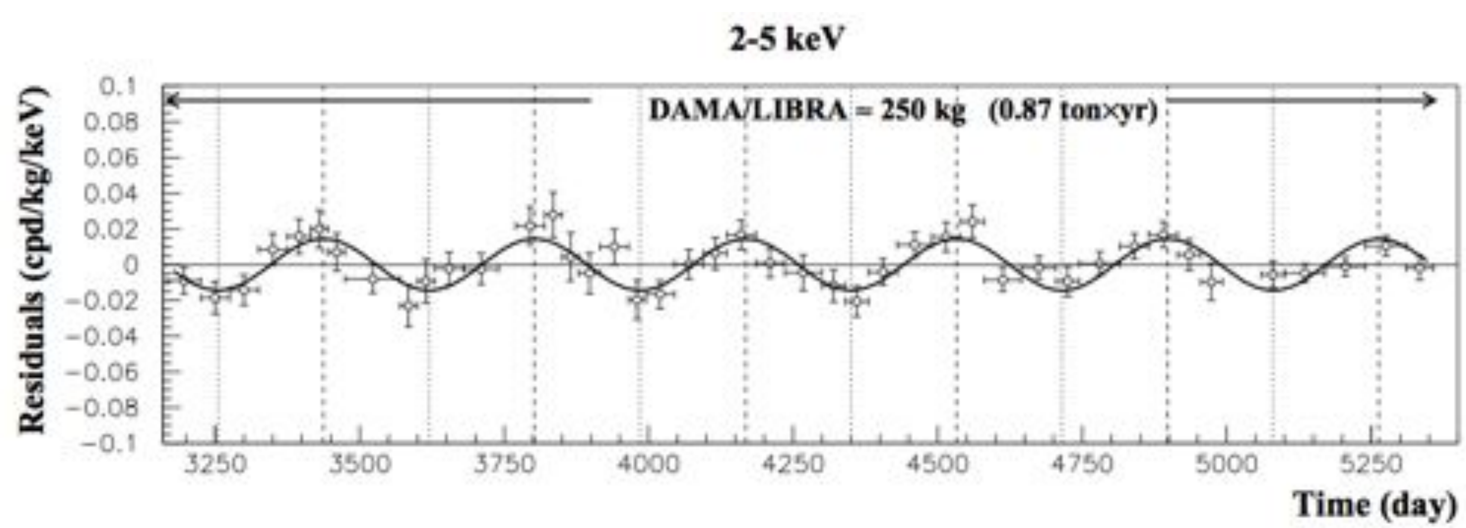
The source is resolved with an ... arcseconds (Reich et al., 198... reasonably small structures

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





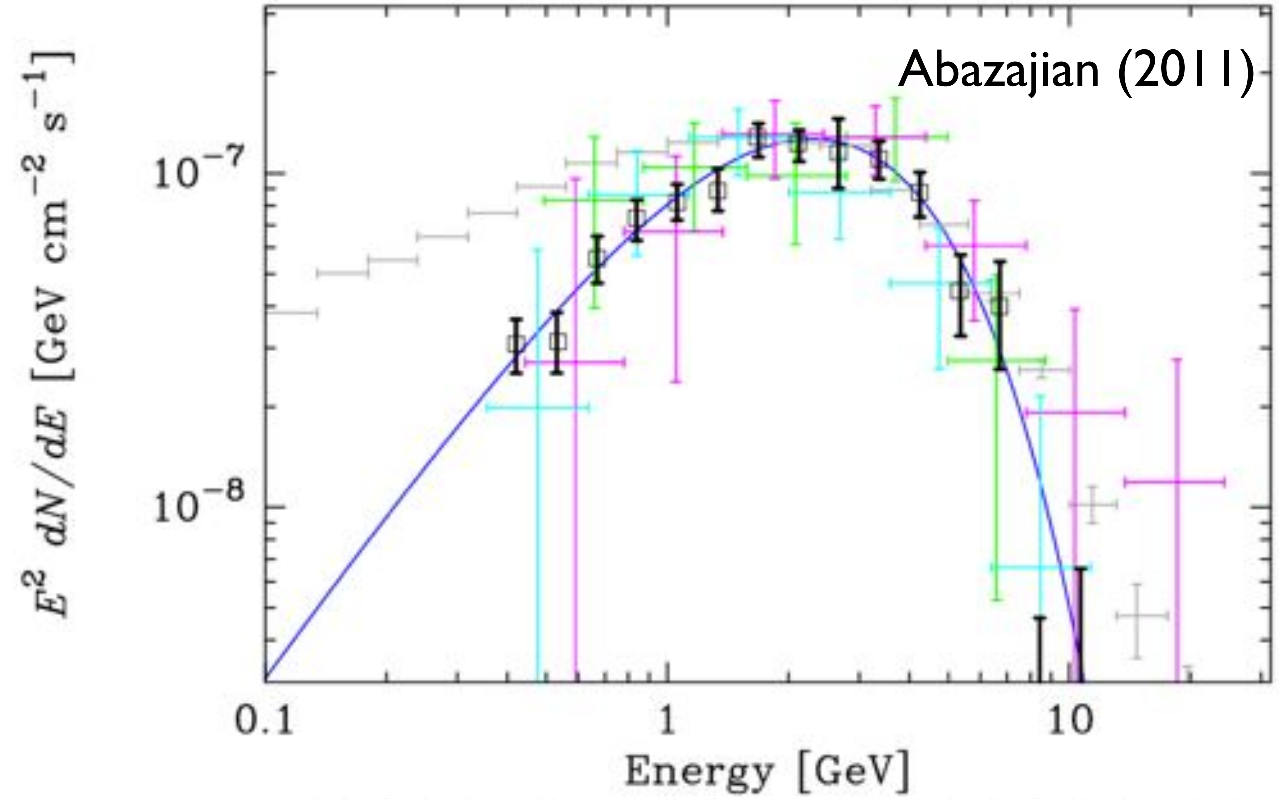
Story 3: Milli-second Pulsars

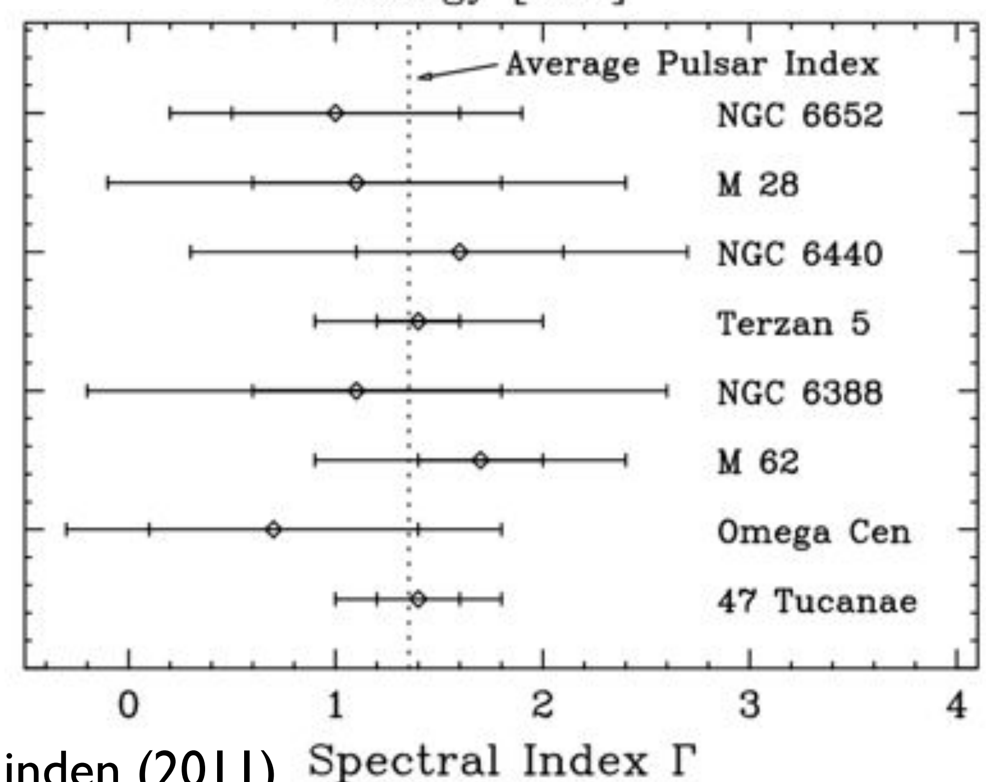
- Populations of Millisecond pulsars have been observed in multiple globular clusters (Terzan 5, Omega Cen, NGC 6388, M 28)

- GC source is ~200 brighter than Omega Cen - which correlates nicely with the 1000x larger mass of the GC region

- Spectrum of MSP population is very similar to the observed gamma-ray excess

Hooper & Goodenough (black)
Omega Cen (green)
NGC 6388 (cyan)
M 28 (magenta)
Geminga (light gray)

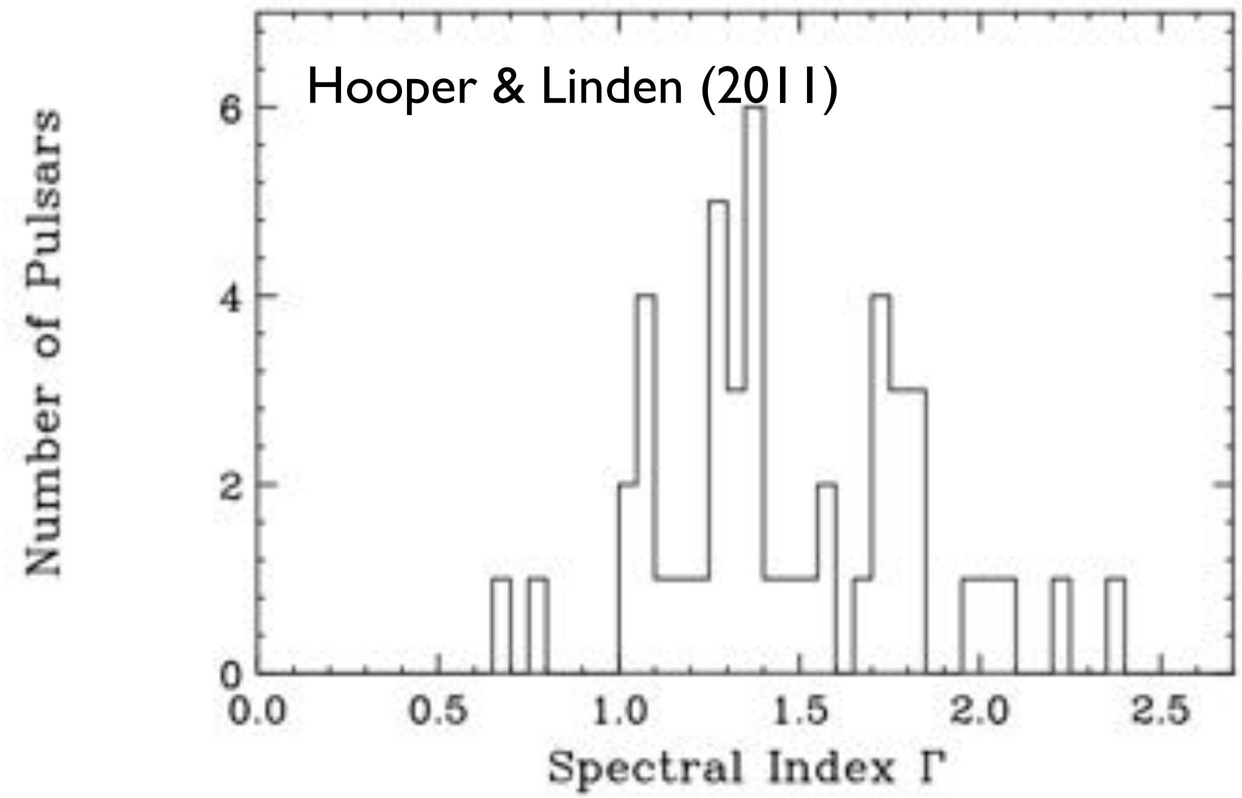




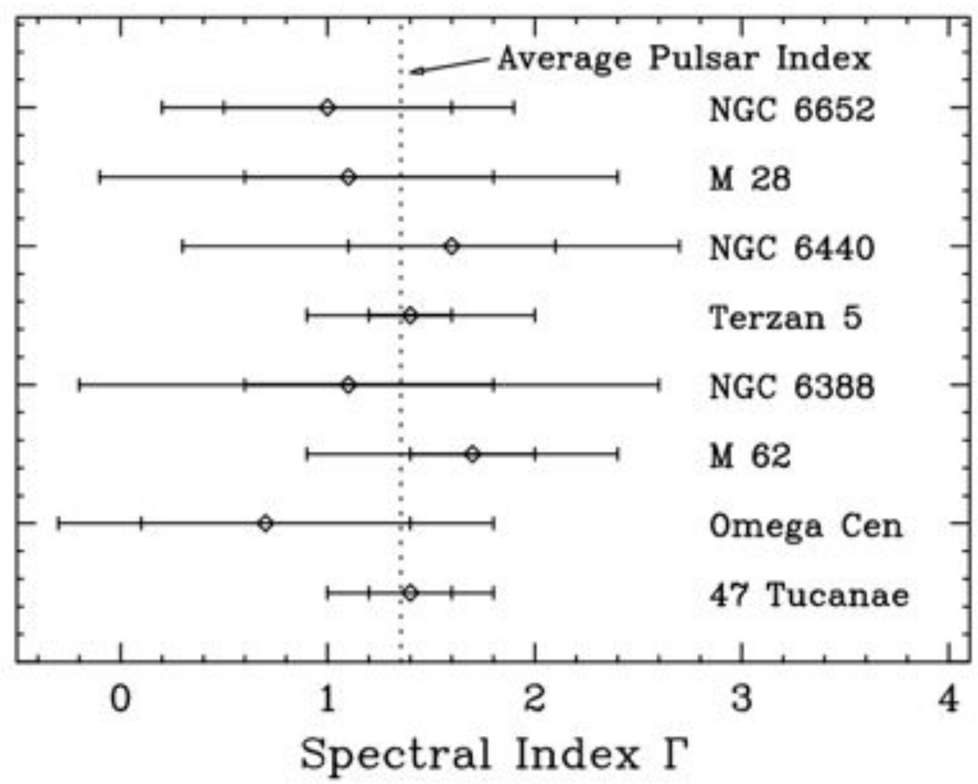
Hooper & Linden (2011)

Story 3: Milli-second Pulsars

- The galactic center residual spectrum ($\Gamma <\approx 1.0$) is somewhat harder than the population of observed pulsars - though uncertainties in the astrophysical spectrum which is subtracted are uncertain



- Must explain the high density of pulsars near the Galactic Center ($\sim r^{-2.6}$)
  - Two body interactions in the densest clusters?
  - Mass segregation?



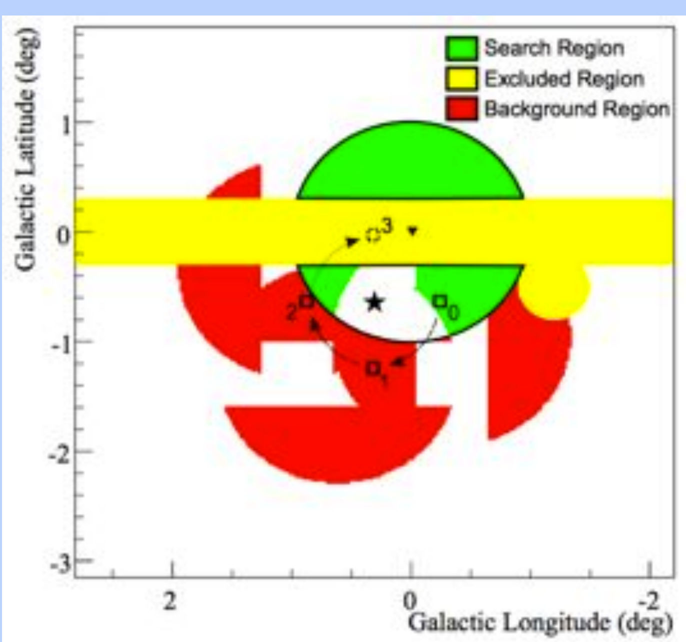
Conclusions

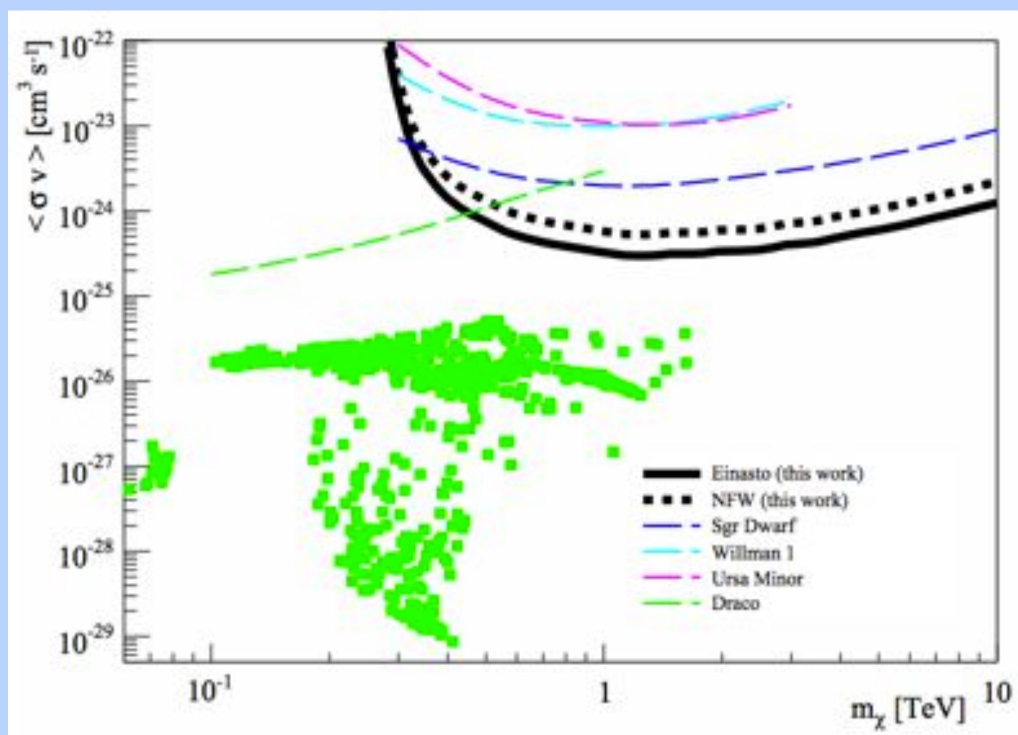
- There is **strong** evidence for an extended, spherically symmetric, excess in ~1 GeV gamma-ray emission surrounding the galactic center
- This excess is not easily accounted for by any known astrophysical model - and the background subtraction models used indicate that it is not correlated with galactic gas
- Dark Matter Annihilation and Pulsars both provide plausible models for this excess
- New observations, and also novel models, are needed to separate these components

Extra Slides

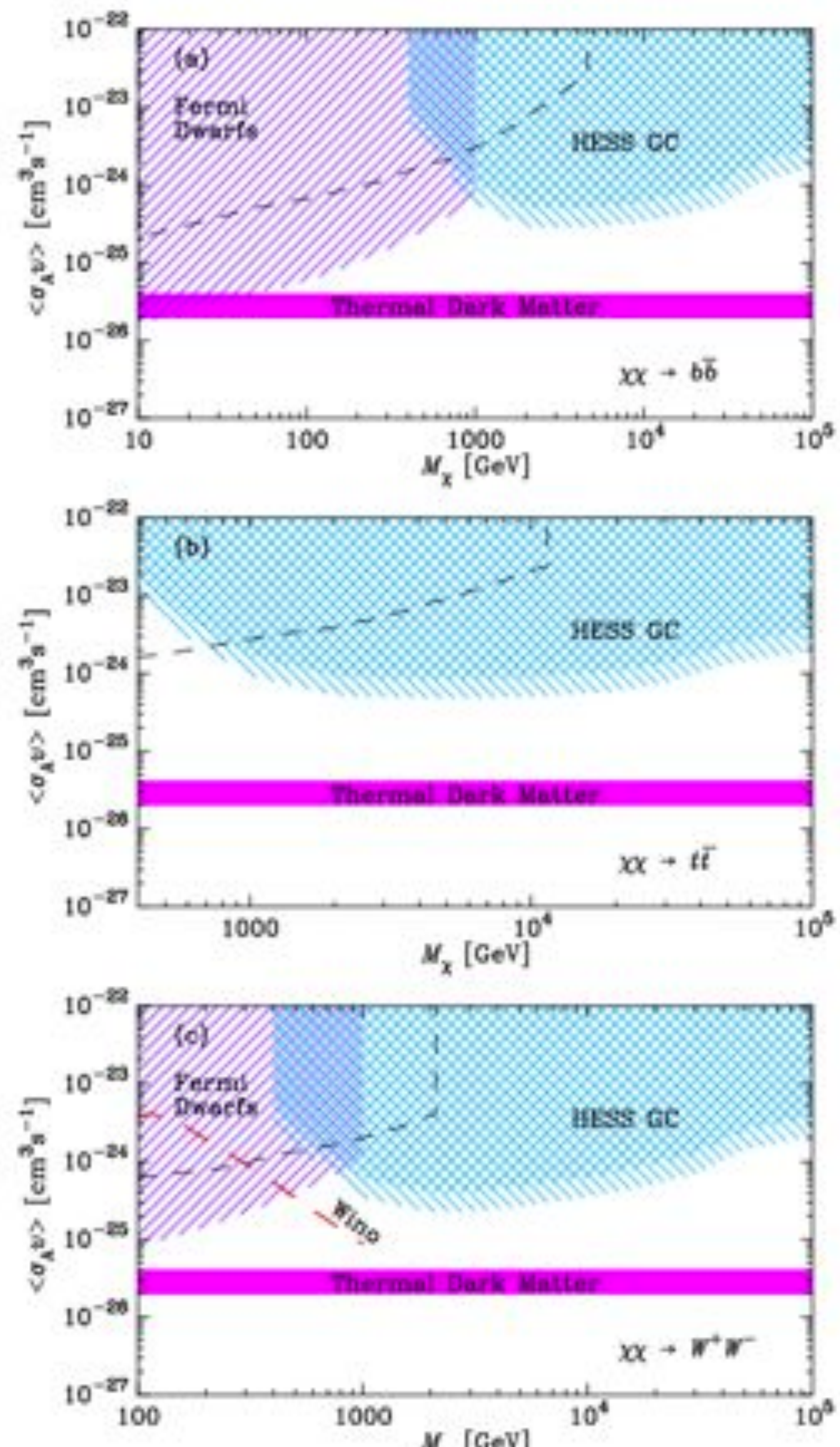
HESS Limits on TeV Dark Matter

- 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)

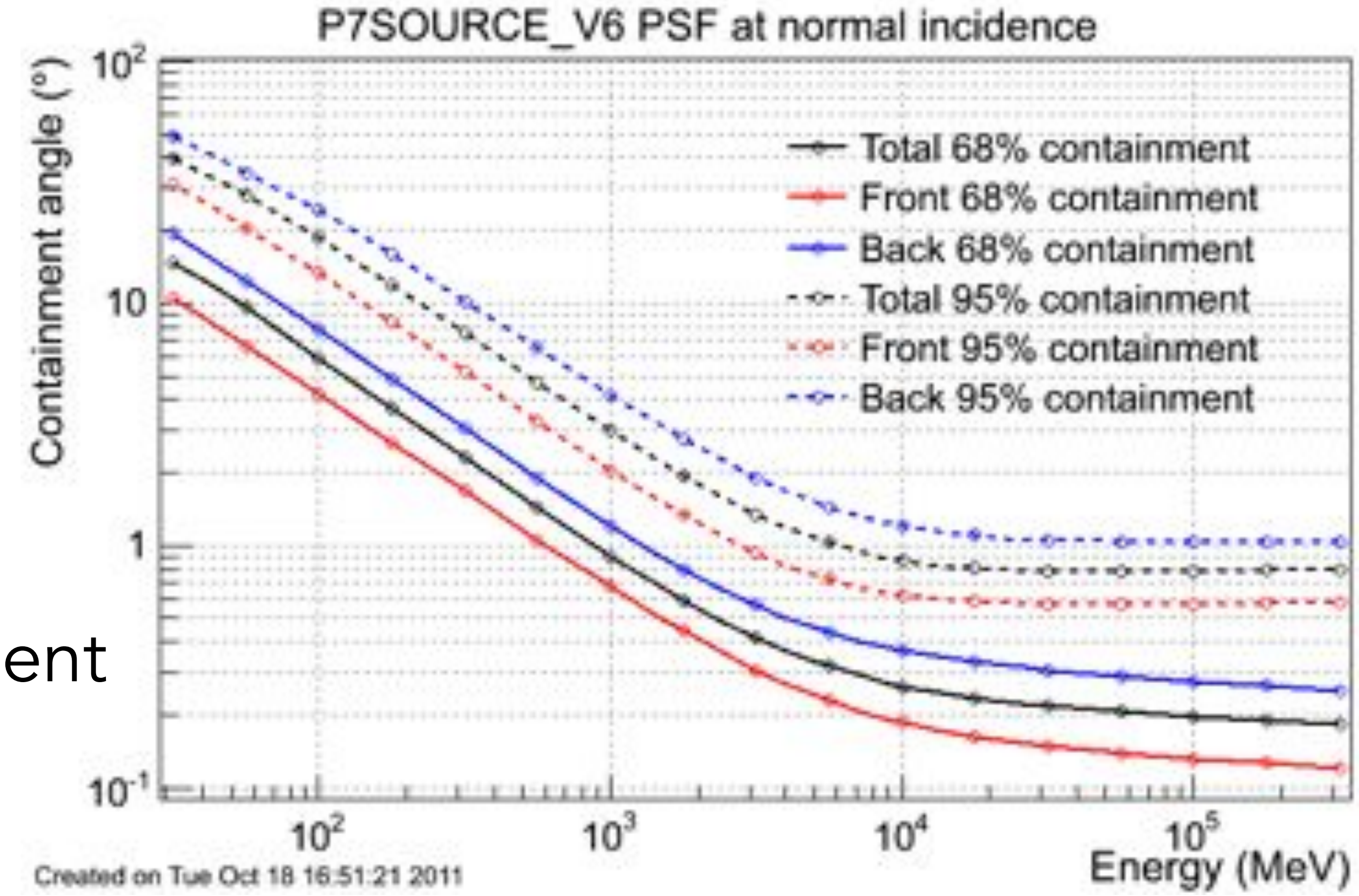


Abazajian & Harding (2011)

Fermi Telescope (2008-Present)

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

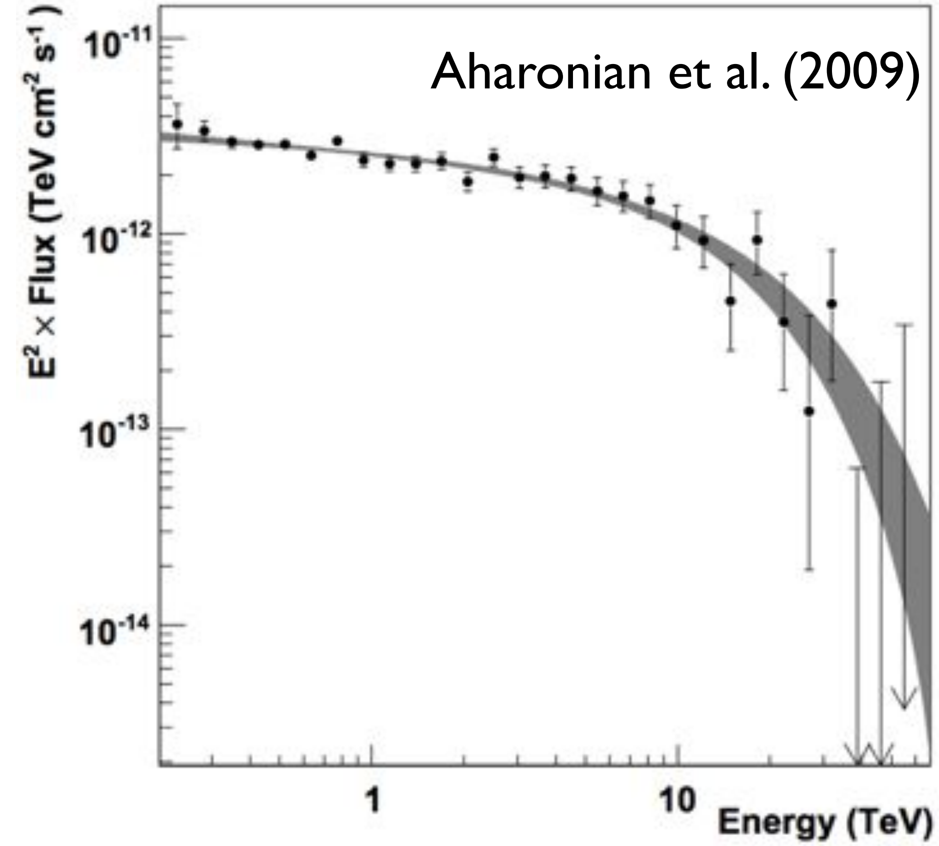
- Effective Area ~ 0.8 m^2
- Field of View ~ 2.4 sr
- Energy Resolution ~ 10%
- Angular Resolution: Energy Dependent



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

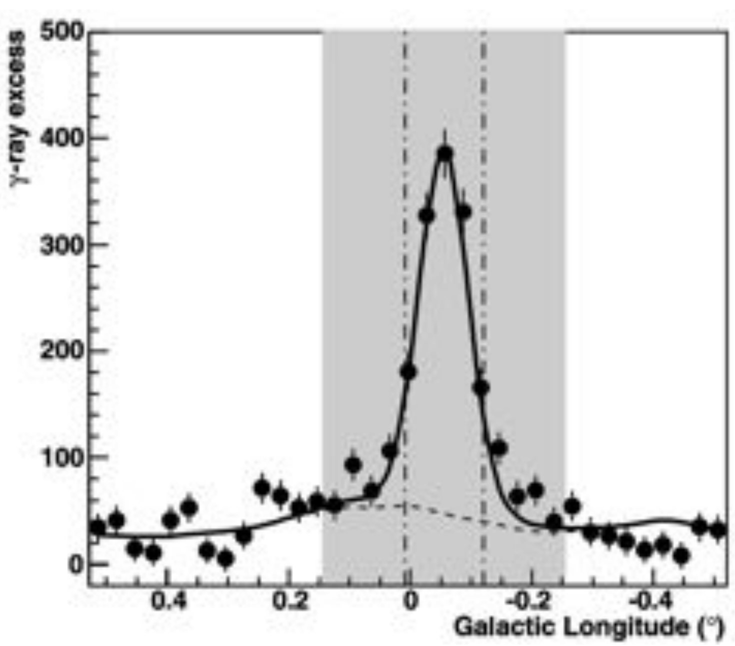
Understanding Astrophysical Backgrounds: HESS

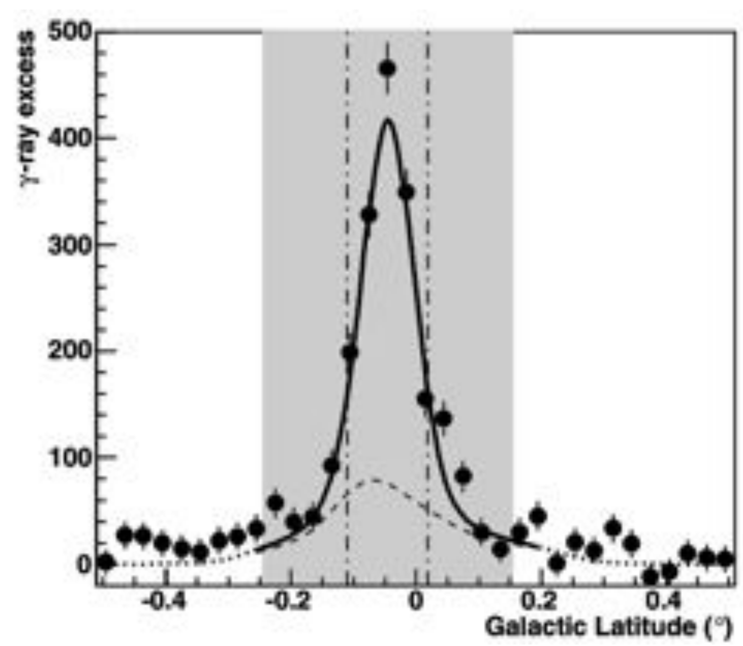
- HESS spectrum well matched by flat E^{-2} spectrum, up to energies of ~10 TeV, where an exponential cutoff is observed

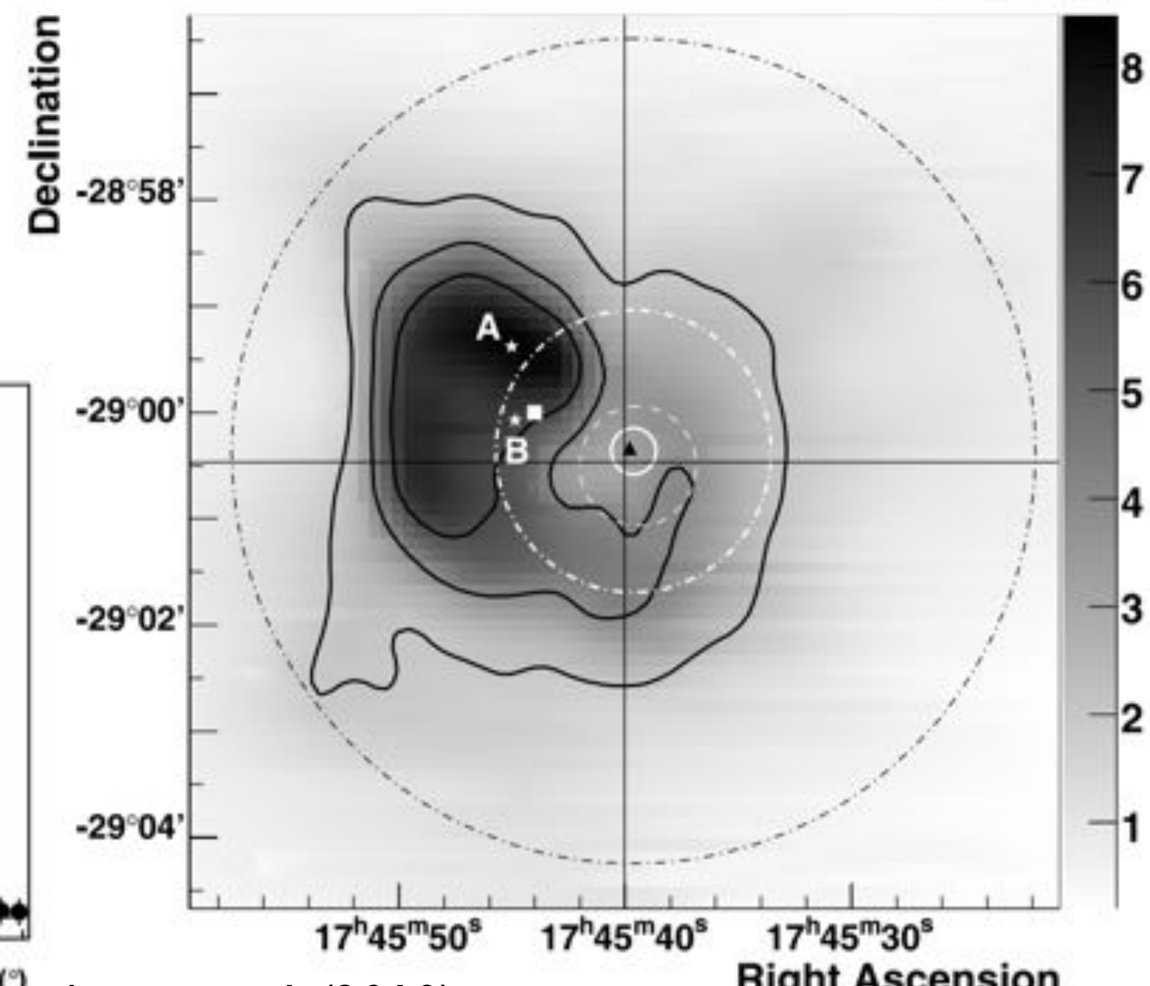


Aharonian et al. (2009)

- 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





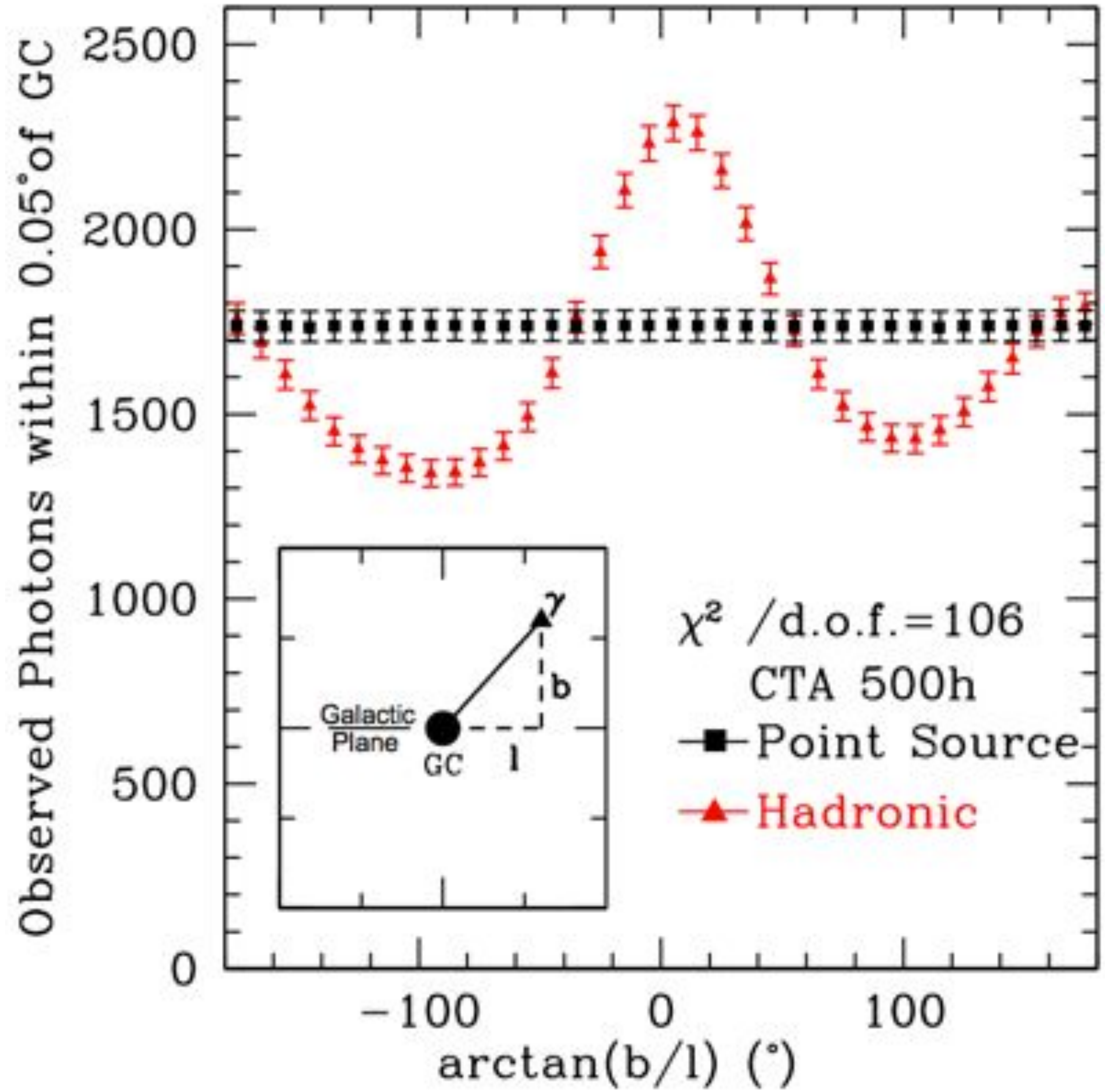


Acero et al. (2010)

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

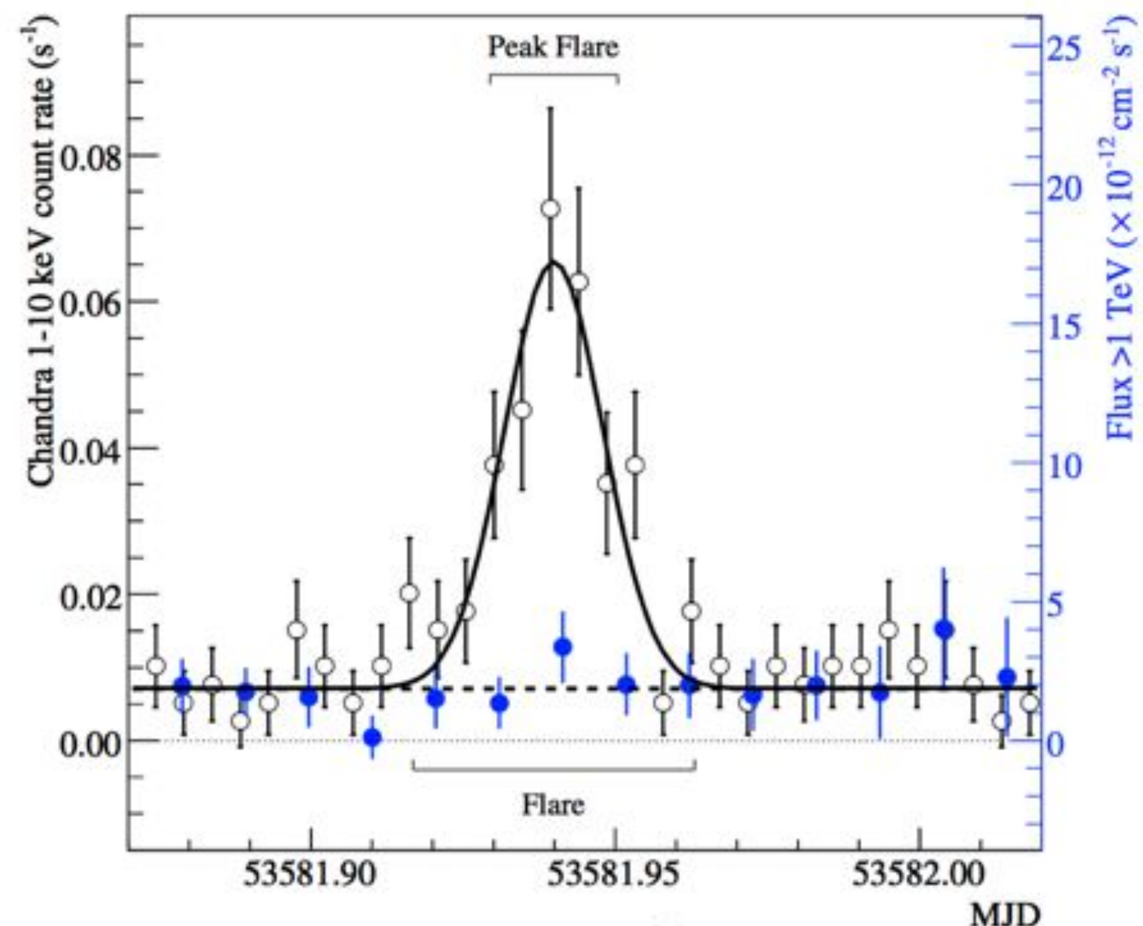
- CTA will <u>conclusively</u> determine whether the galactic center source stems from a hadronic emission channel



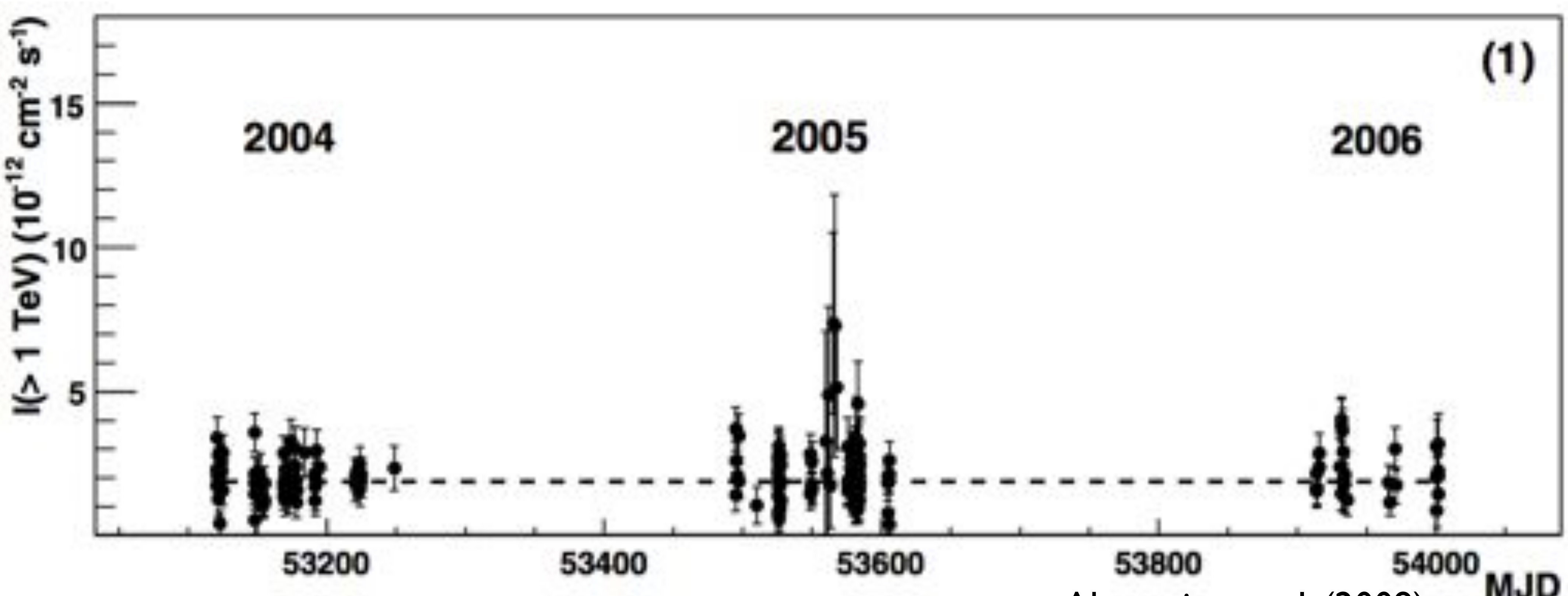
Linden & Profumo (2012)

Understanding Astrophysical Backgrounds: HESS

Aharonian et al. (2008)

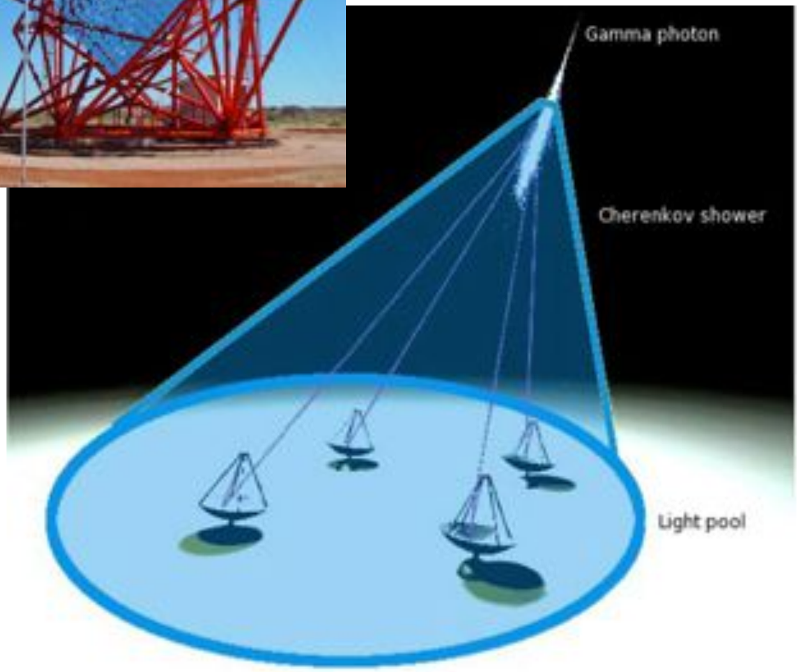


- However, HESS shows no variability, even during outbursts observed by Chandra
- This implies that the source of the emission is spatially distinct from lower energy sources

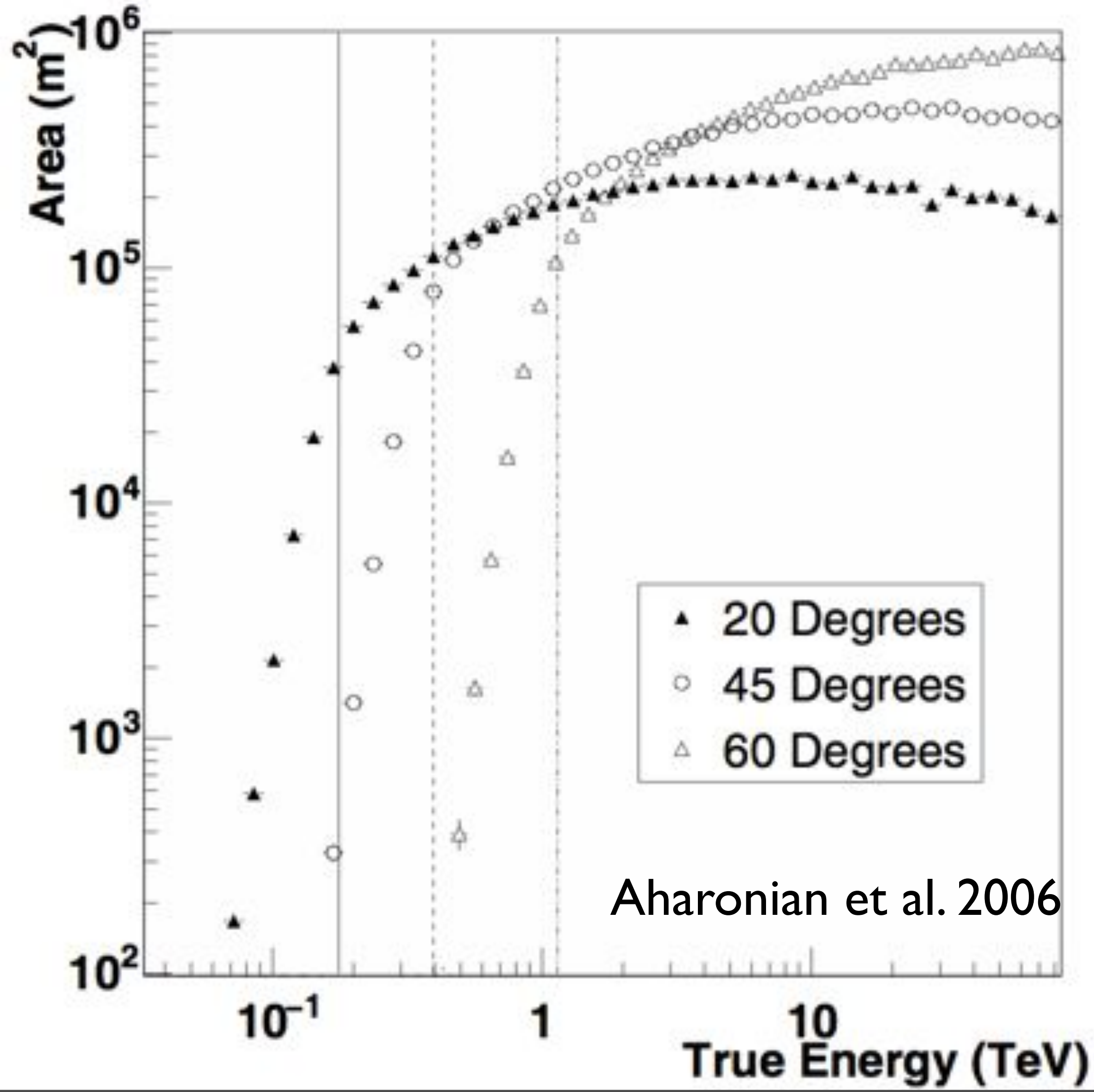


Aharonian et al. (2009)

HESS Telescope (2004-Present)

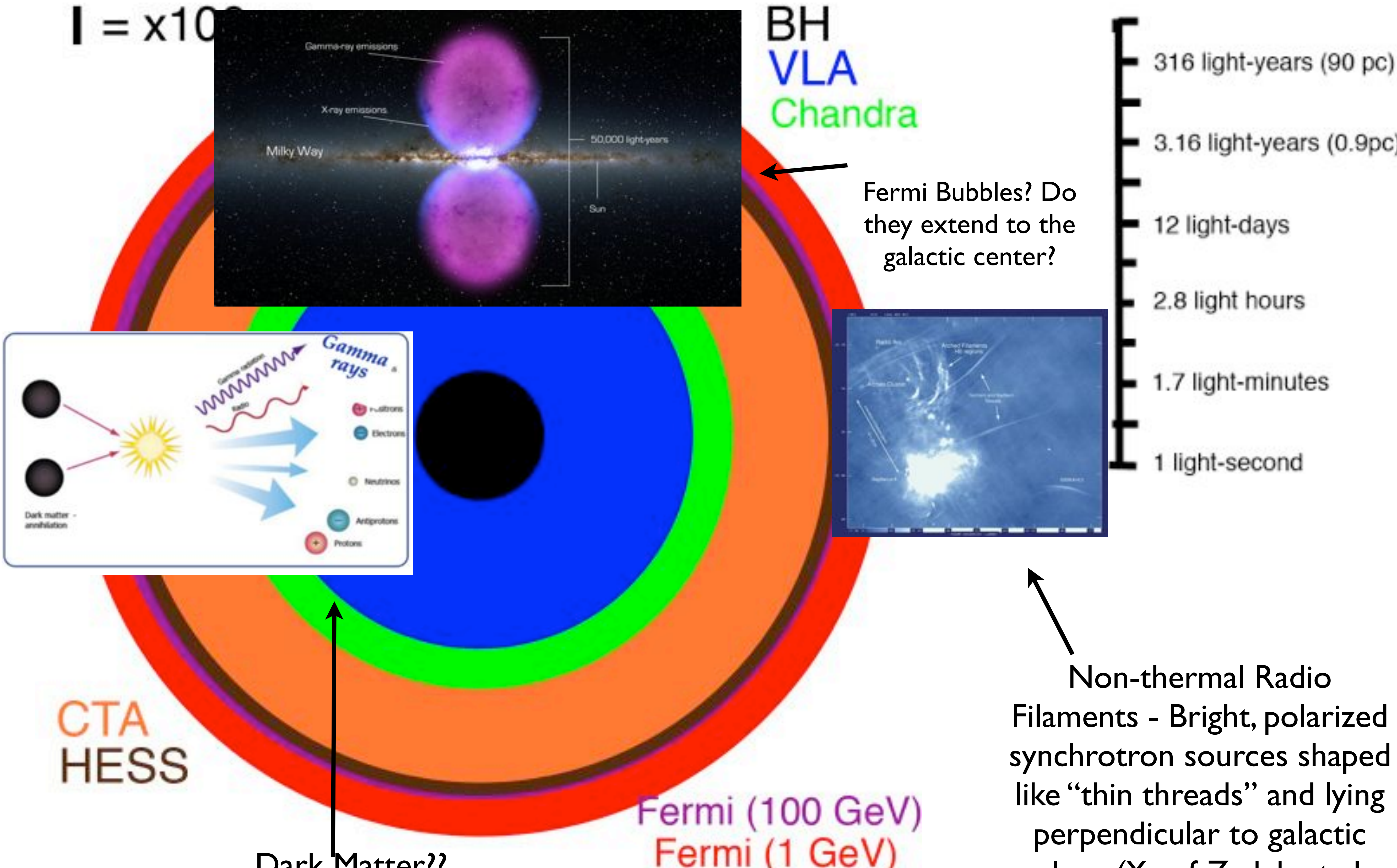


- HESS is an Atmospheric Cherenkov Telescope built in Namibia
- Effective over the energy range ~500 GeV - 100 TeV with an effective area on the order of 10^5 m^2.
- Energy Resolution ~ 10%
- Angular Resolution (>1 TeV) ~ 0.075°.
- Total Observation of the Galactic Center: 93h/112h



Aharonian et al. 2006

And some surprises!

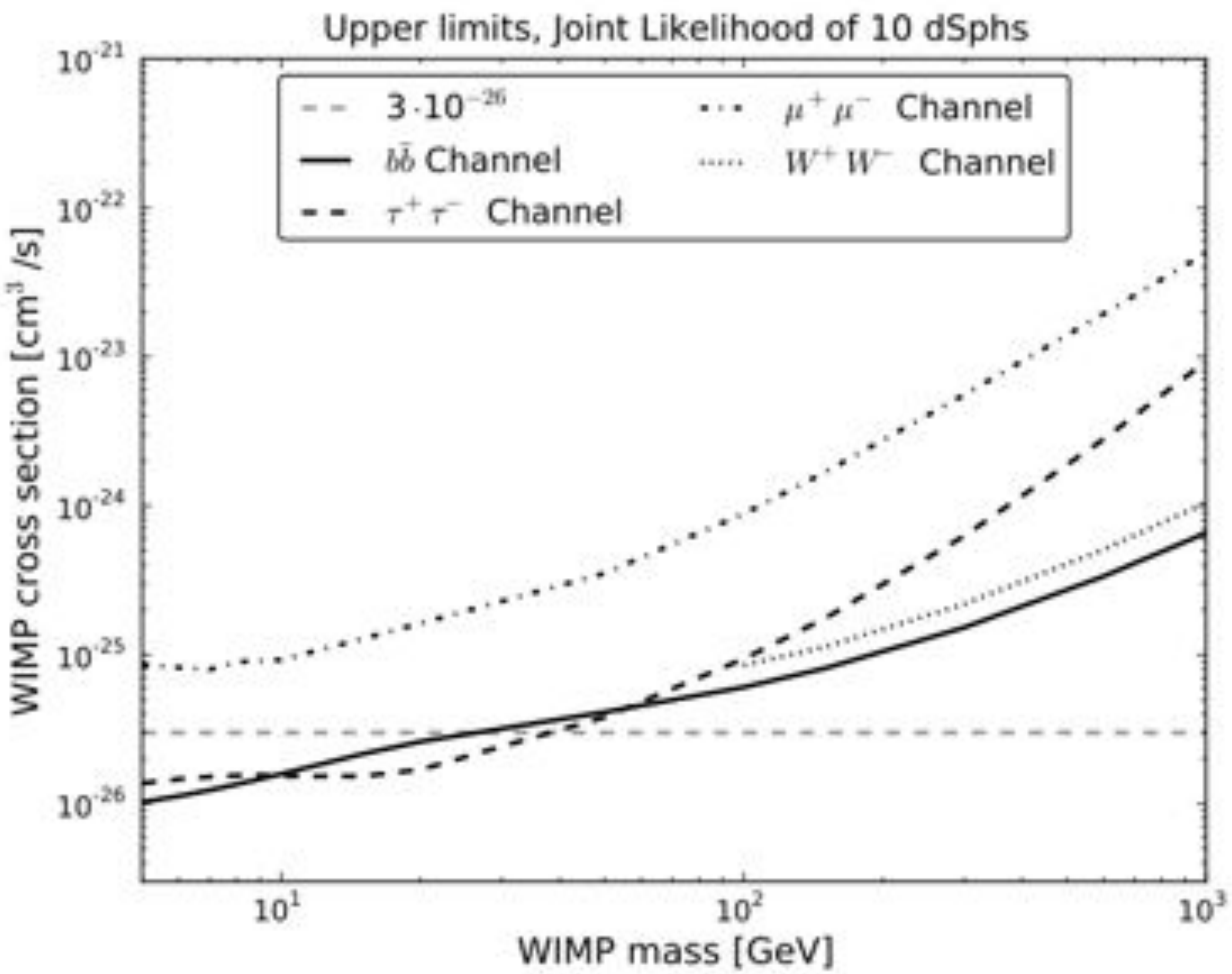


Fermi Bubbles? Do they extend to the galactic center?

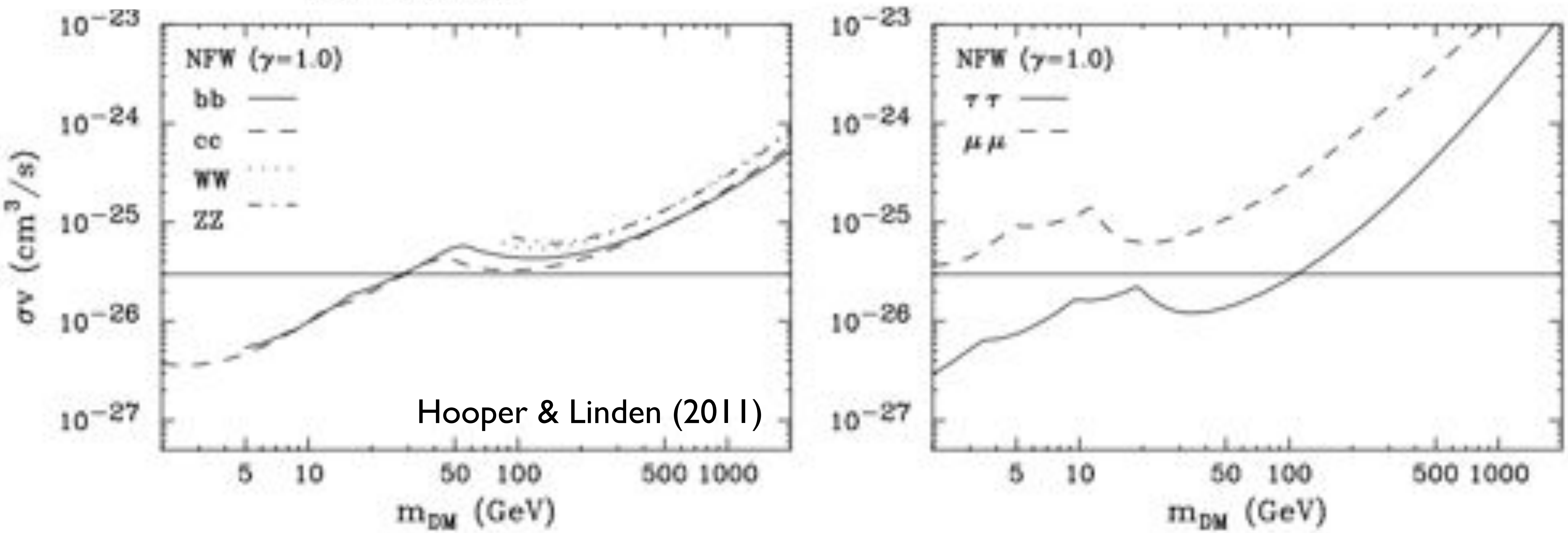
Dark Matter??

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

Comparison to Other Indirect Detection Regimes



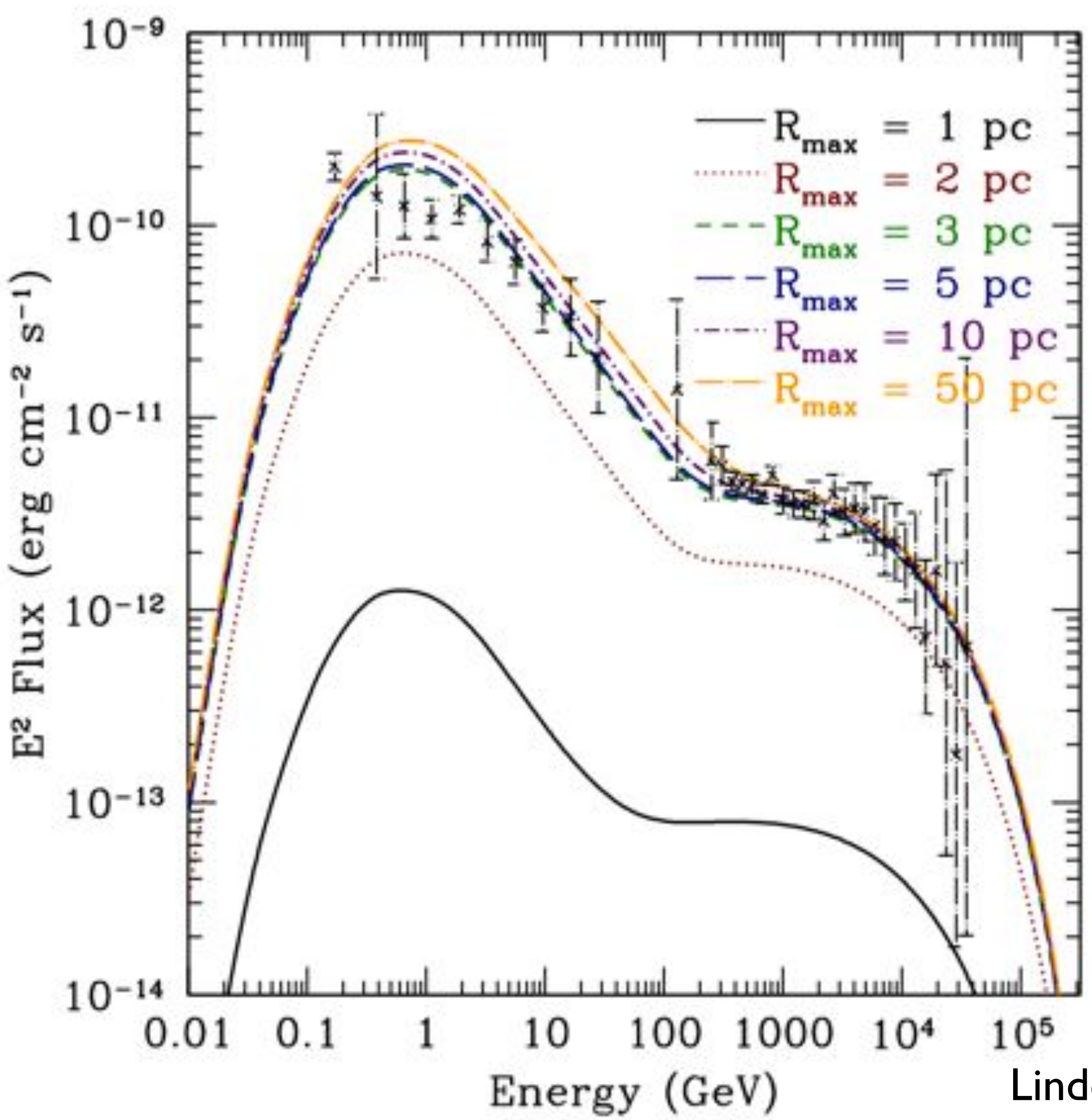
- Under the assumption of an NFW profile, the 95% confidence limits are as good or better than those from dwarf-spheroidals
- They are especially stronger for leptophilic annihilation paths

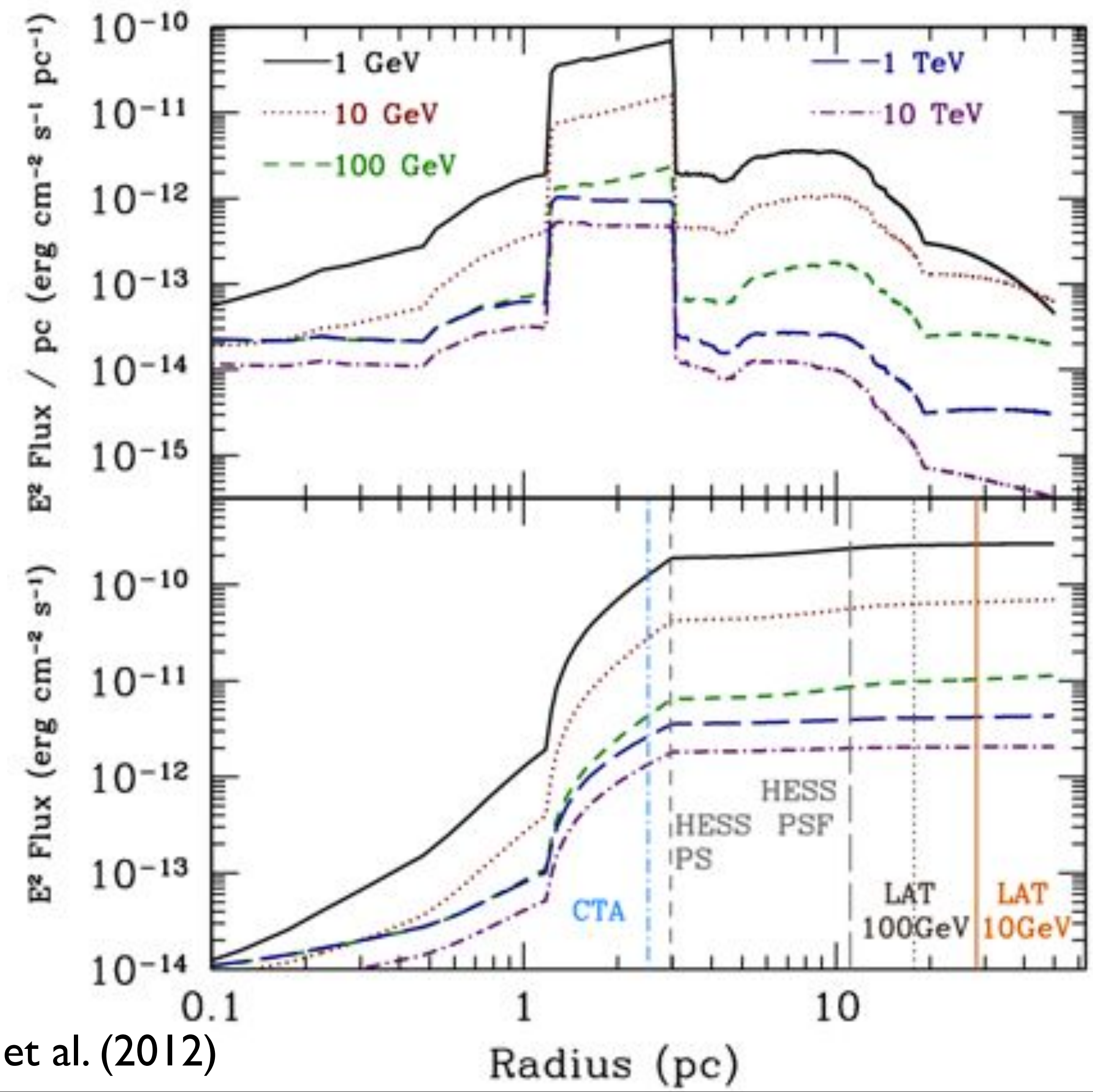


Hooper & Linden (2011)

Employing a Realistic Gas Model

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



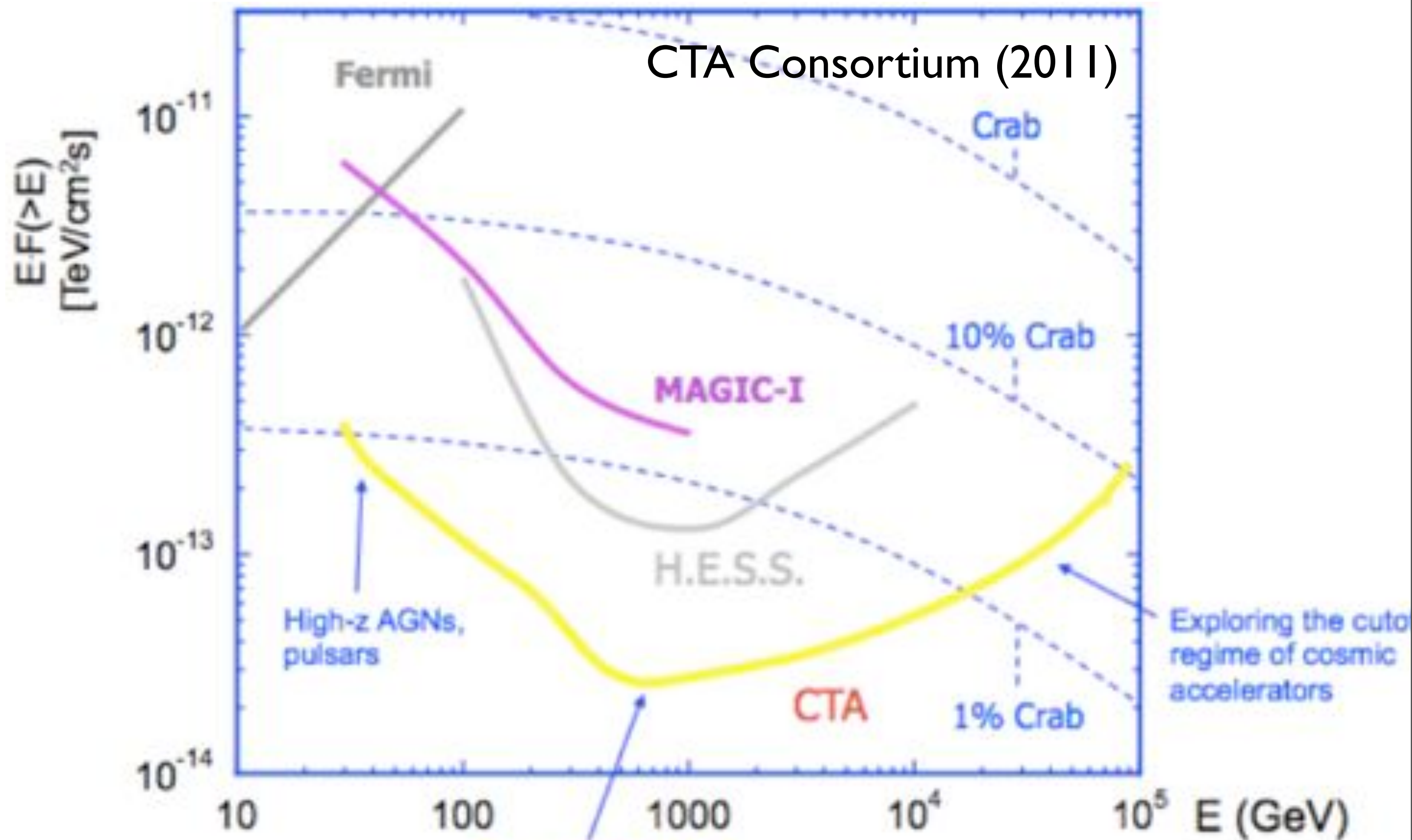


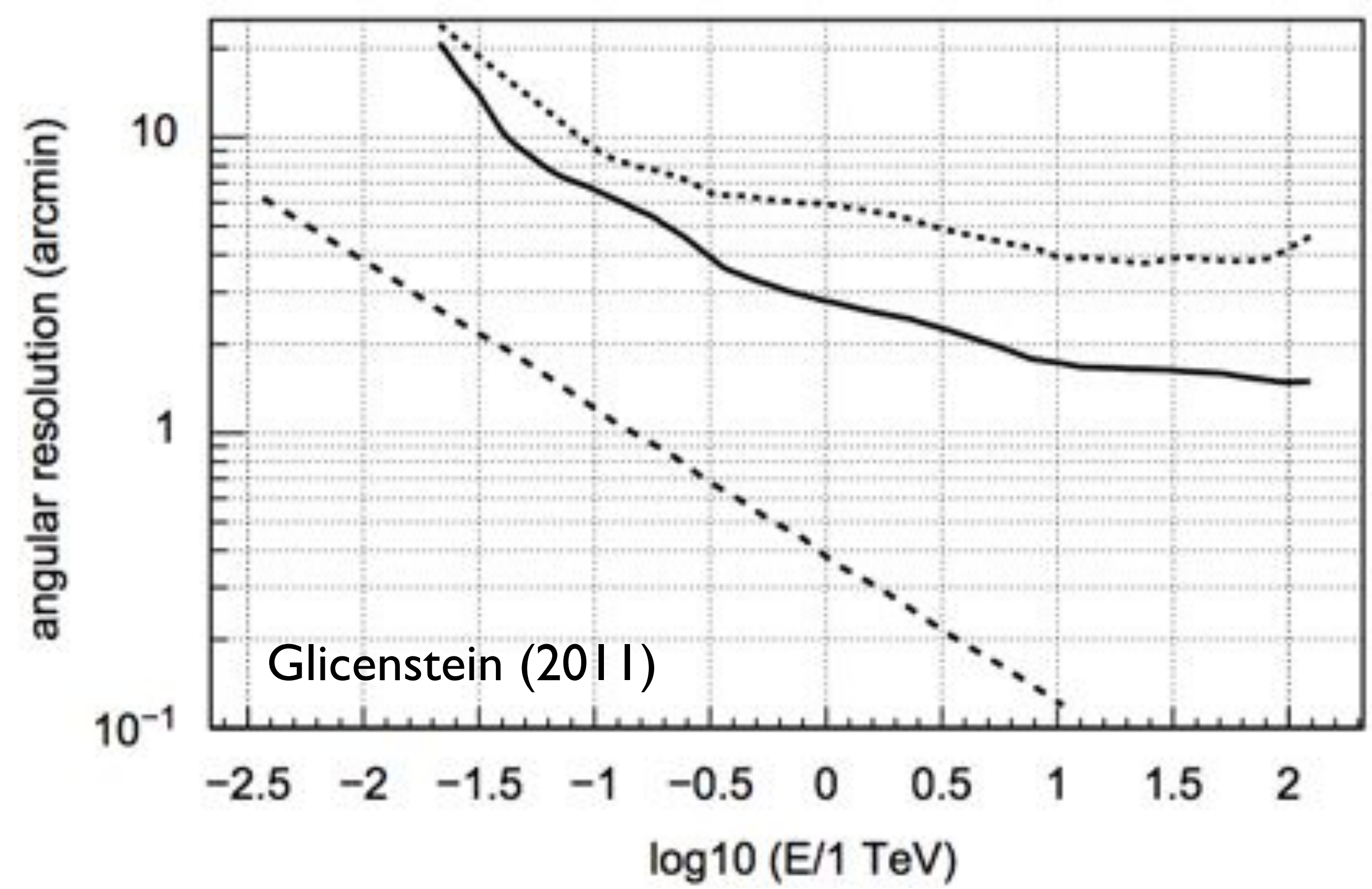
Linden et al. (2012)

CTA and the Galactic Center

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

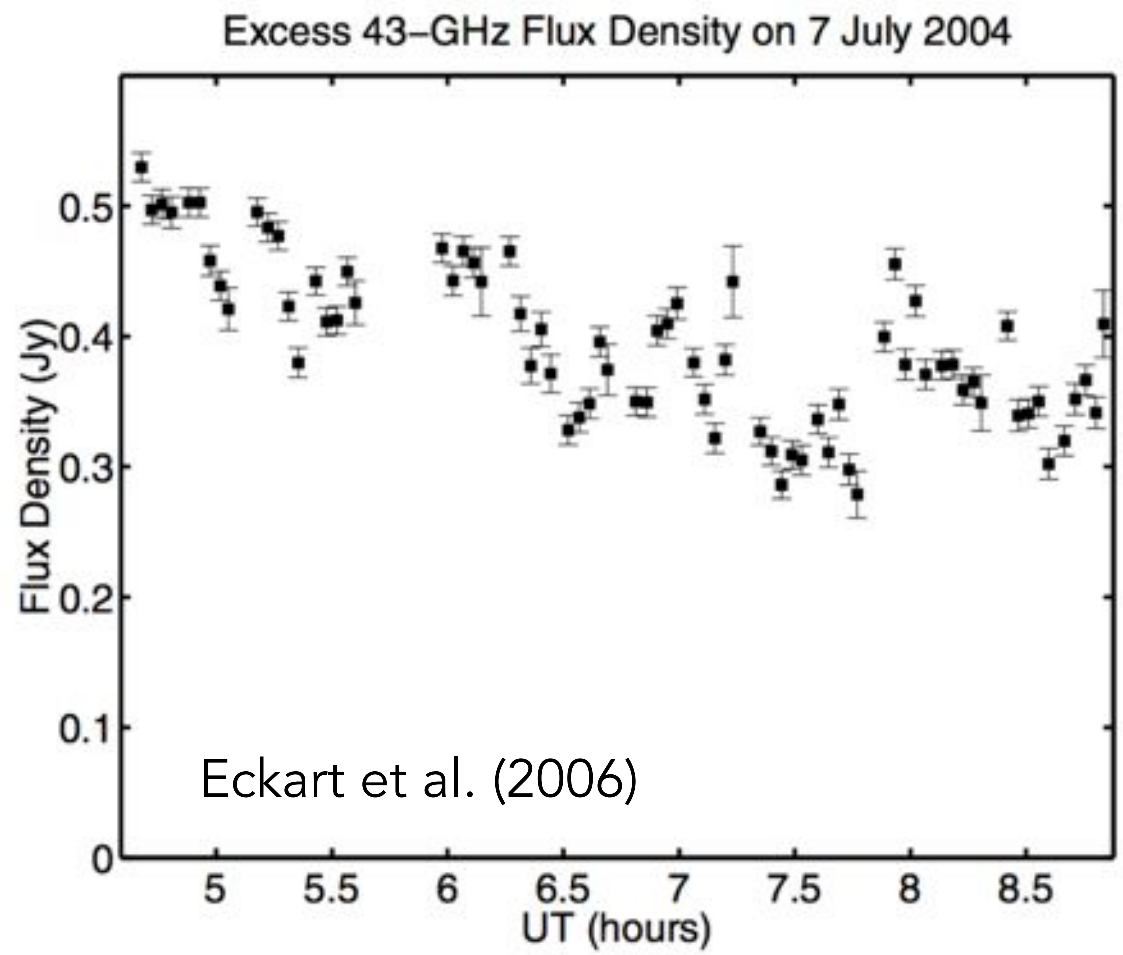
- The instrument specifications for CTA are not yet entirely known, so we employ the following:
  - An order of magnitude improvement in the effective area over HESS
  - A reduction in the PSF from 1-10 TeV from 0.075° to 0.03°

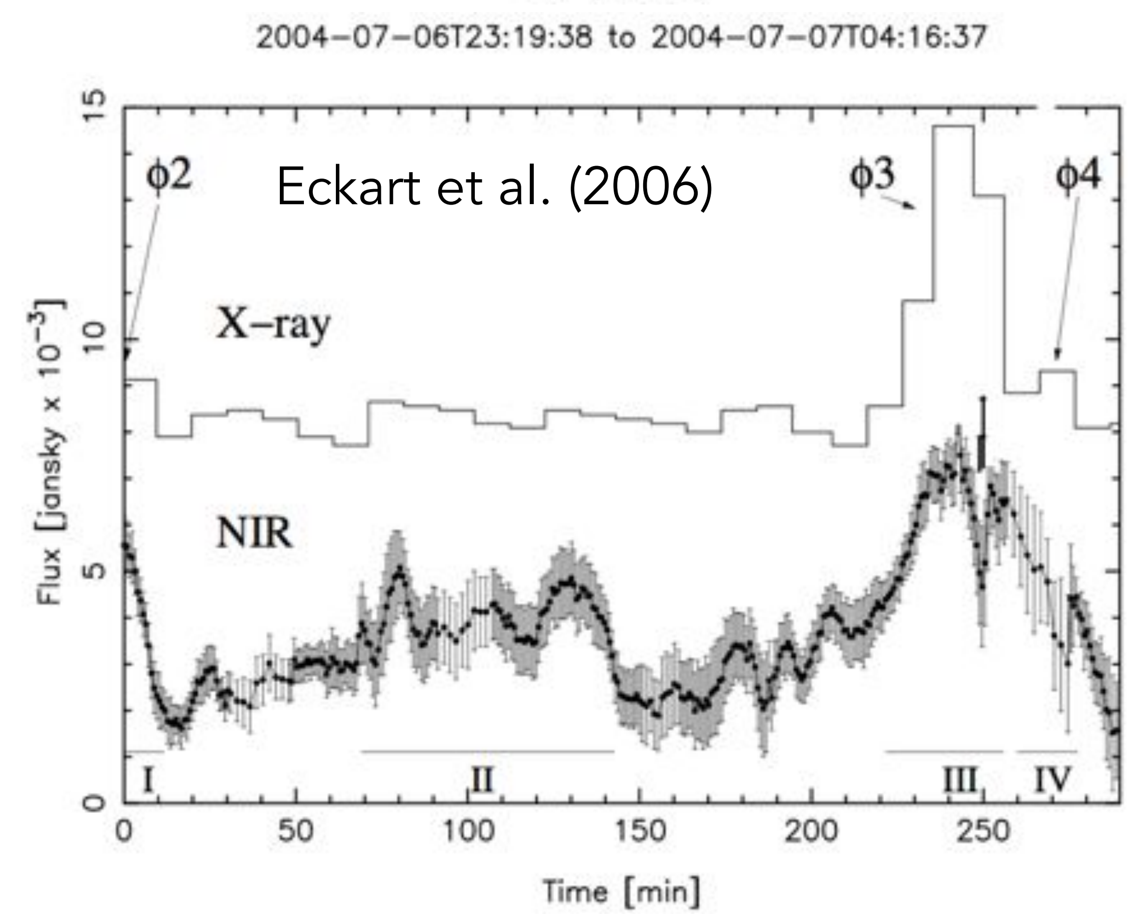




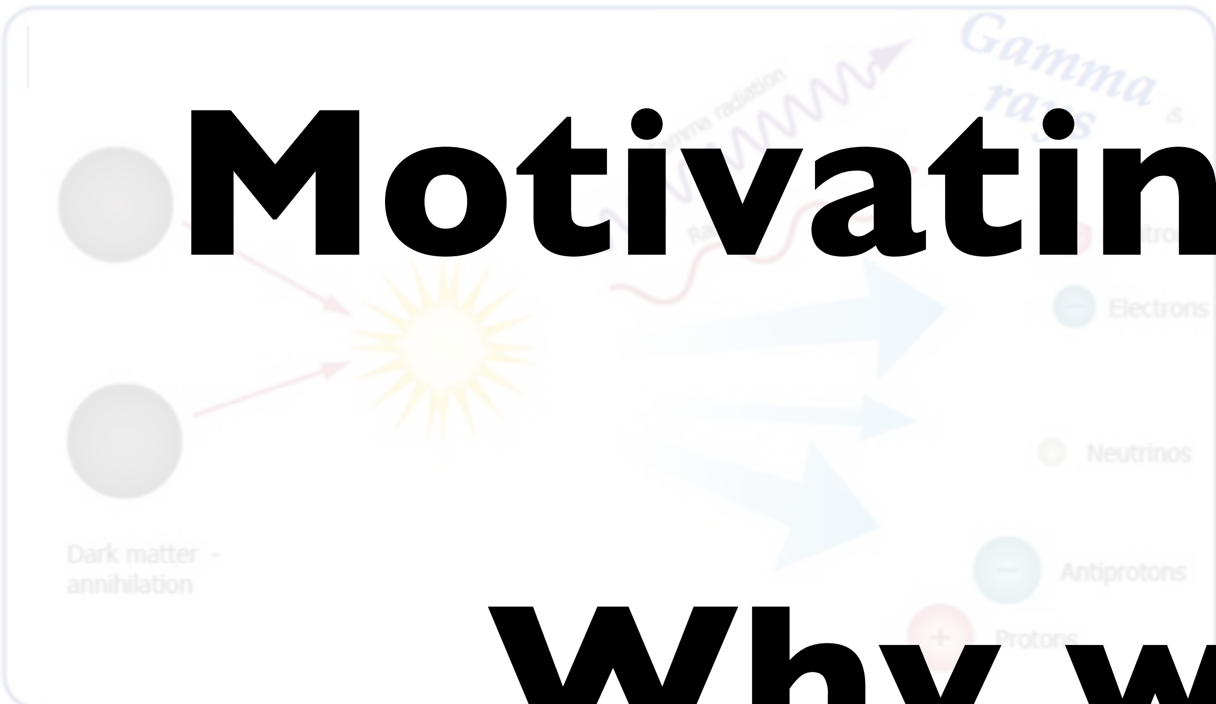
Variability at the Galactic Center

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



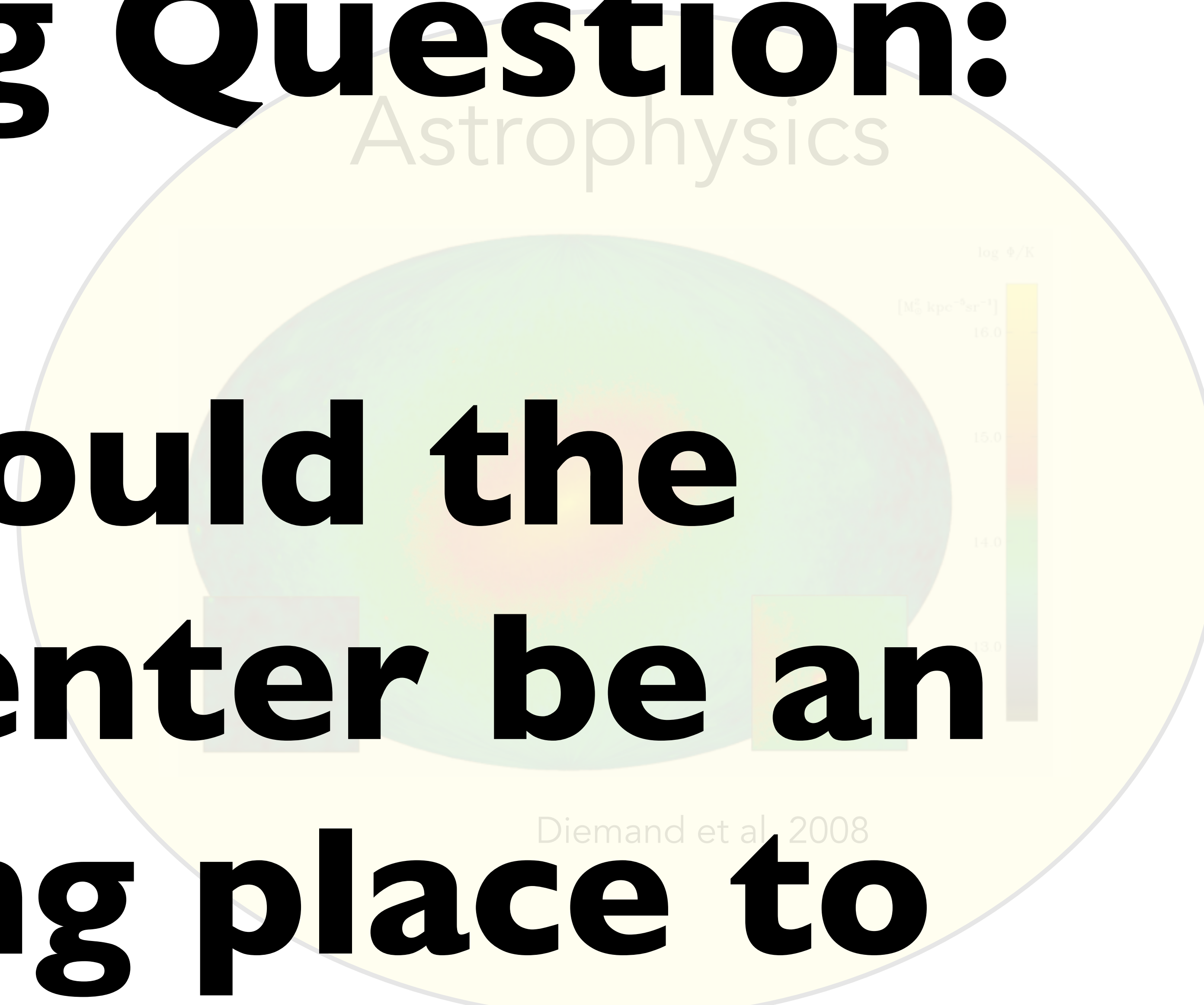


Particle Physics



Motivating Question:

Astrophysics



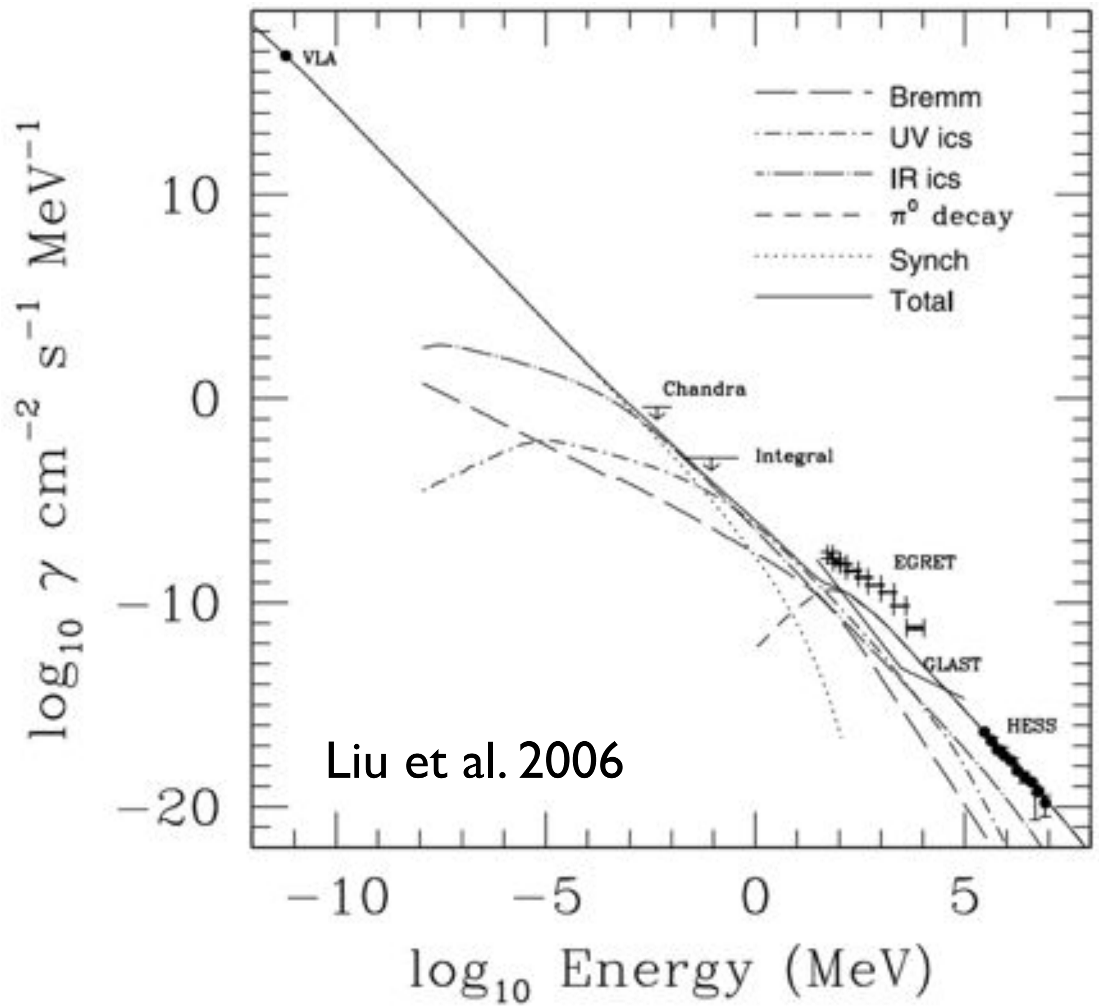
Why would the galactic center be an interesting place to look for Dark Matter?

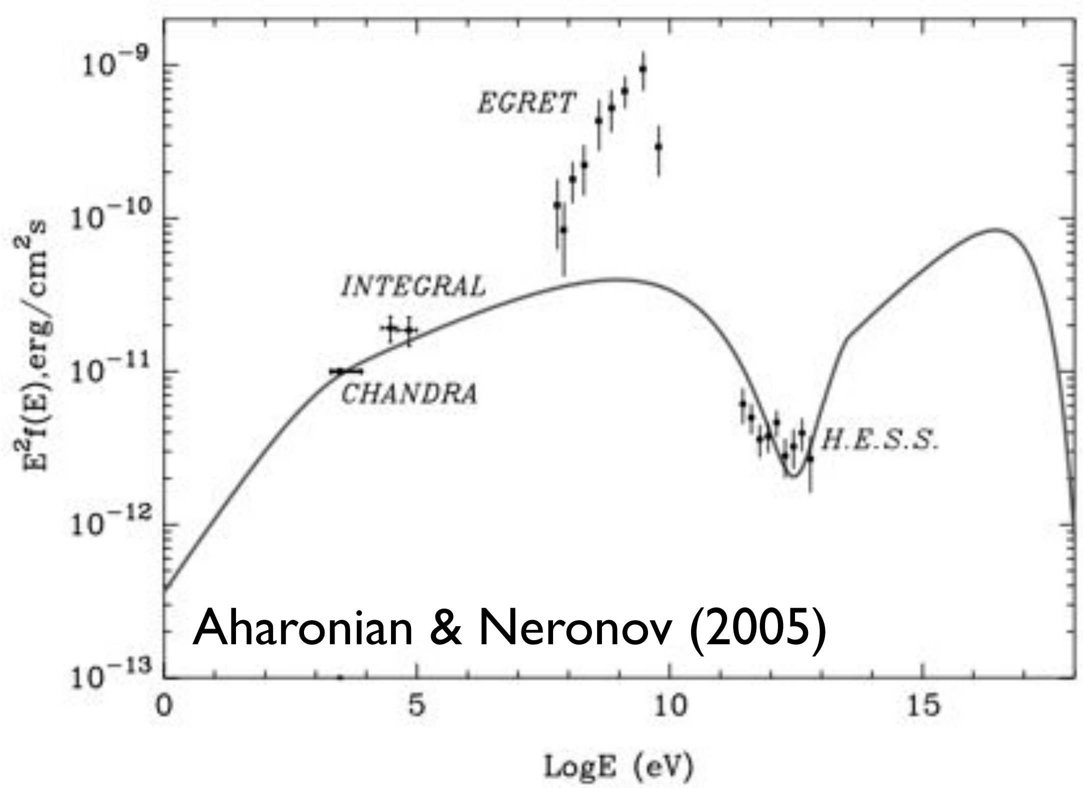
Slides Courtesy of G. Zaharijas

Instrumental Response

Fitting the Residual: Hadronic Processes

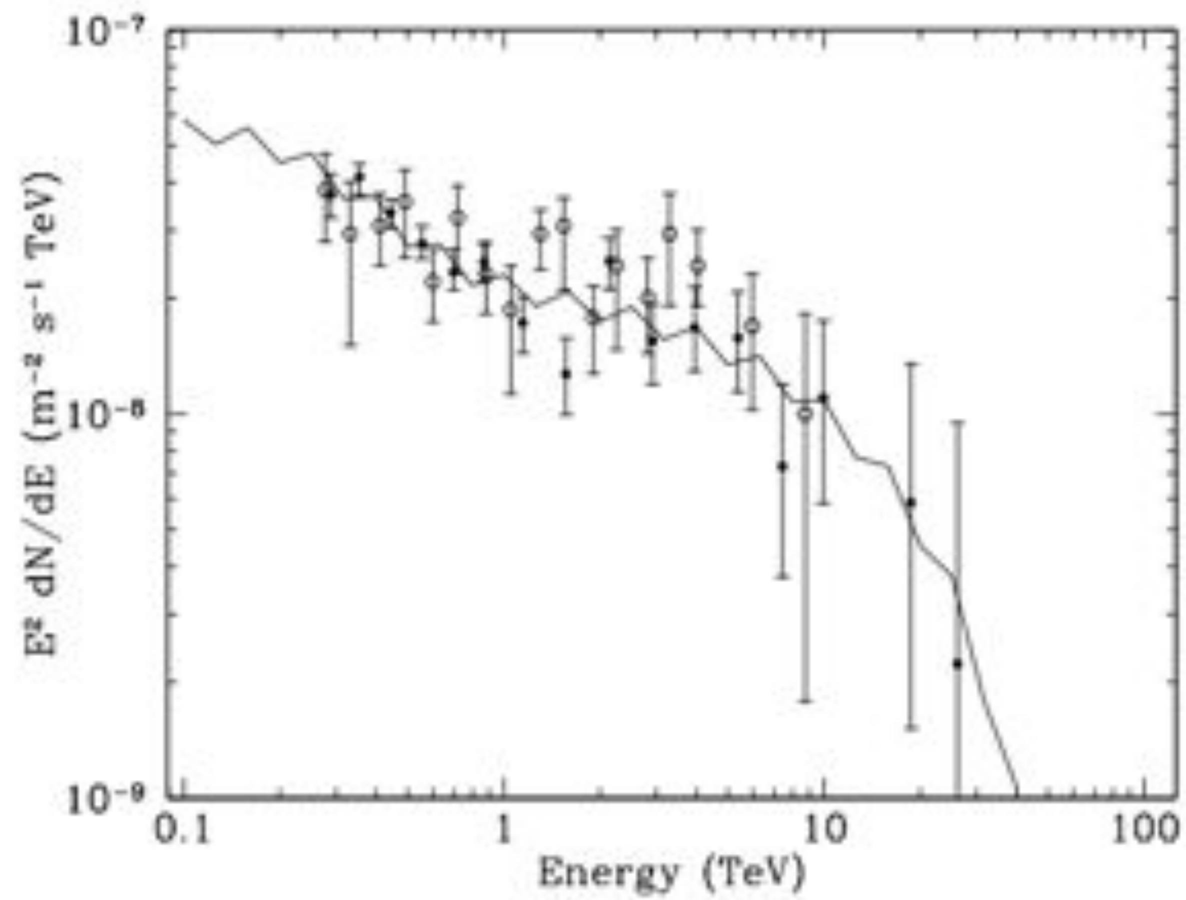
- The lack of variability indicates that the emission may be stemming from a region farther away from the GC itself
- A recent model examined the possibility that protons emitted from the galactic center produce gamma-rays through their subsequent interaction with galactic gas
- This has the potential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

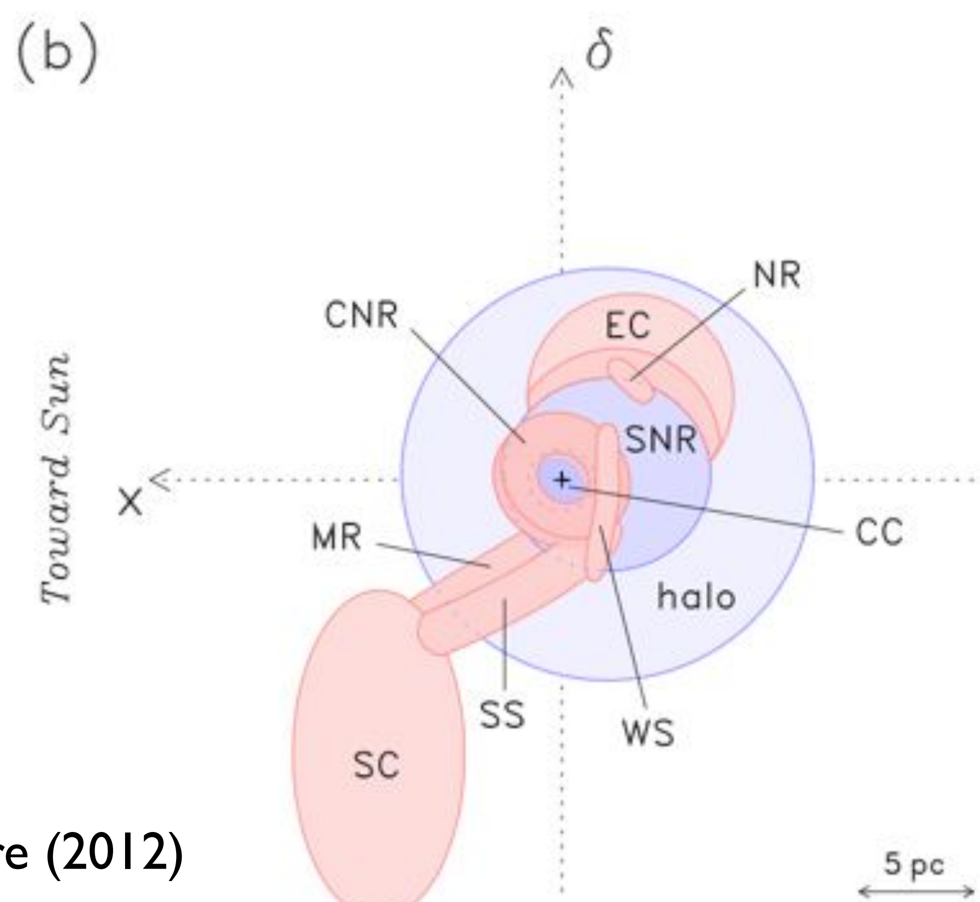




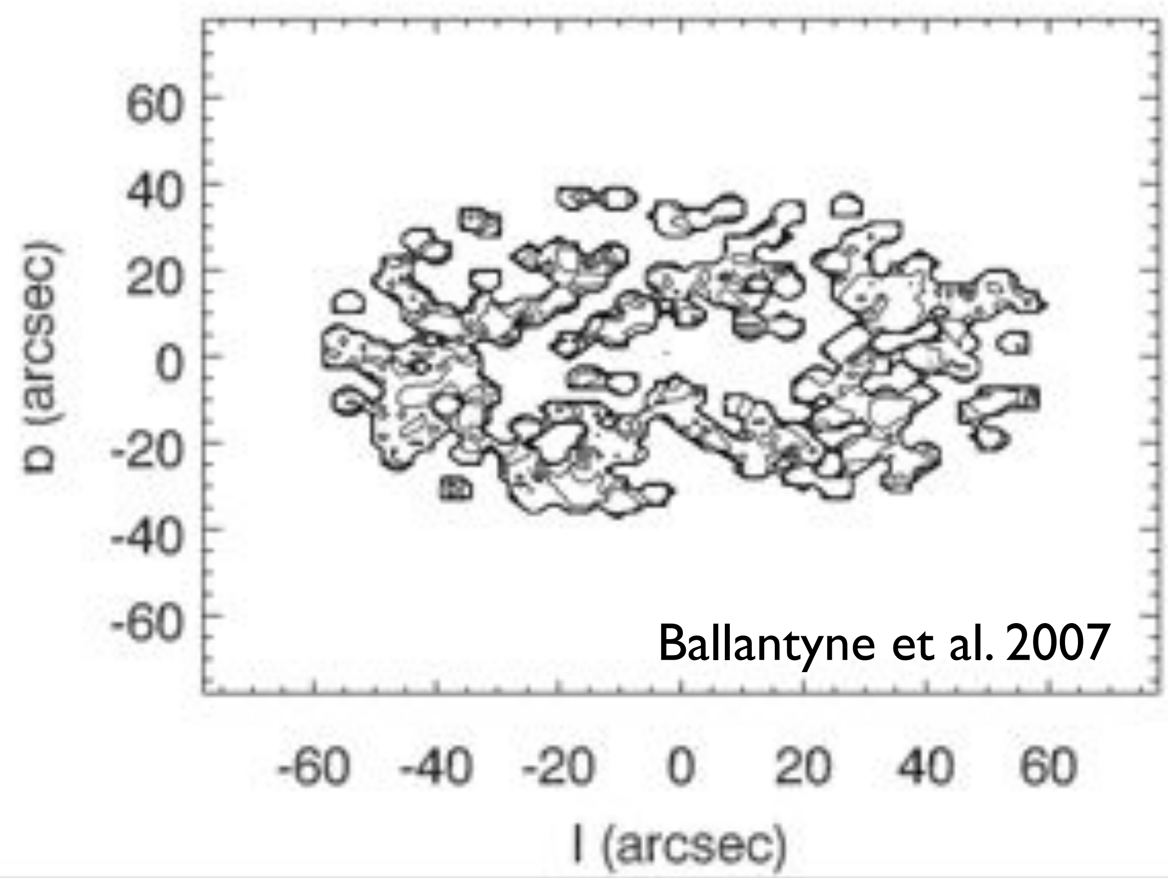
Fitting the Residual: Hadronic Processes

- 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



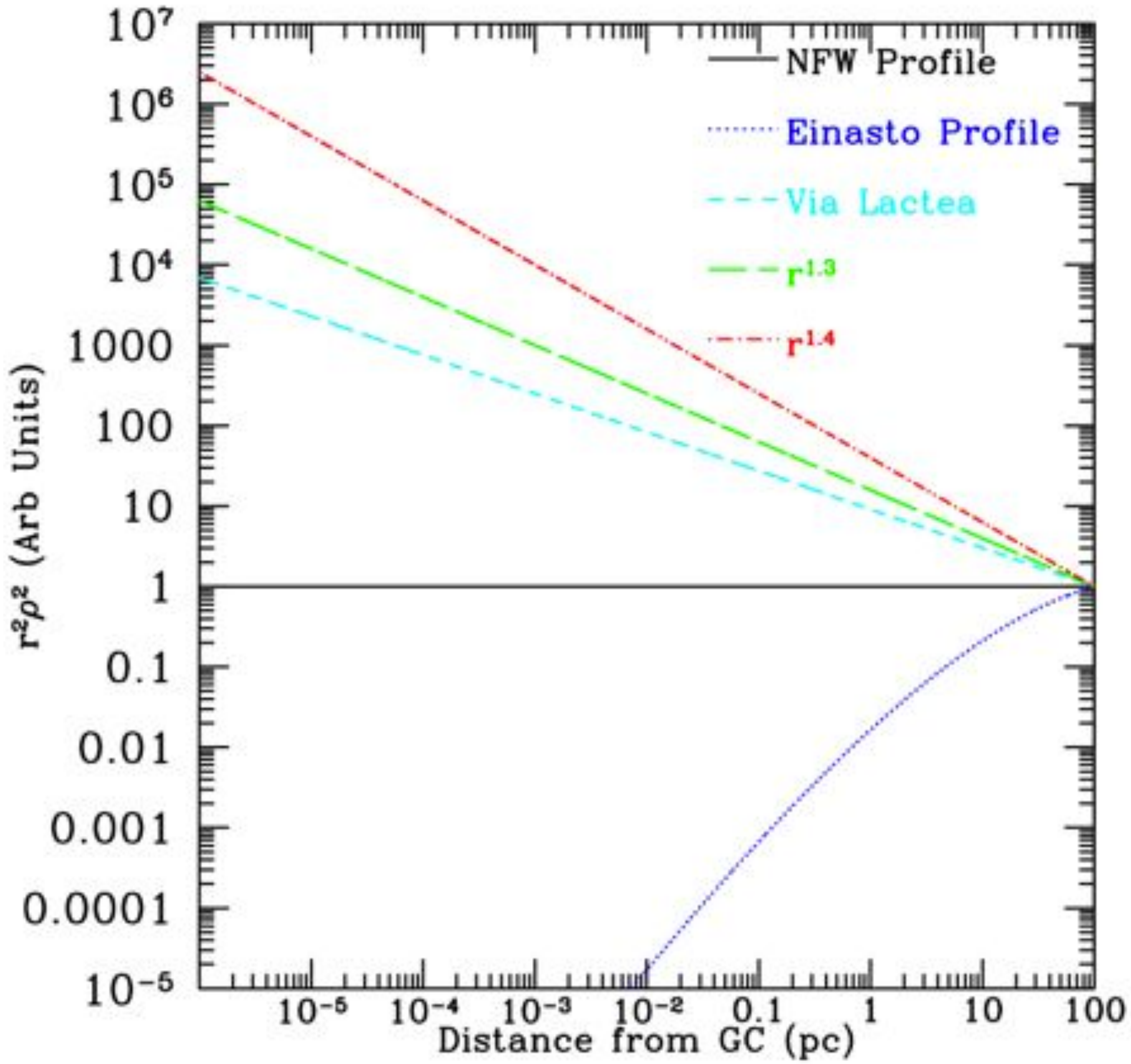


Ferriere (2012)



Ballantyne et al. 2007

Negative: The Profile Dependence



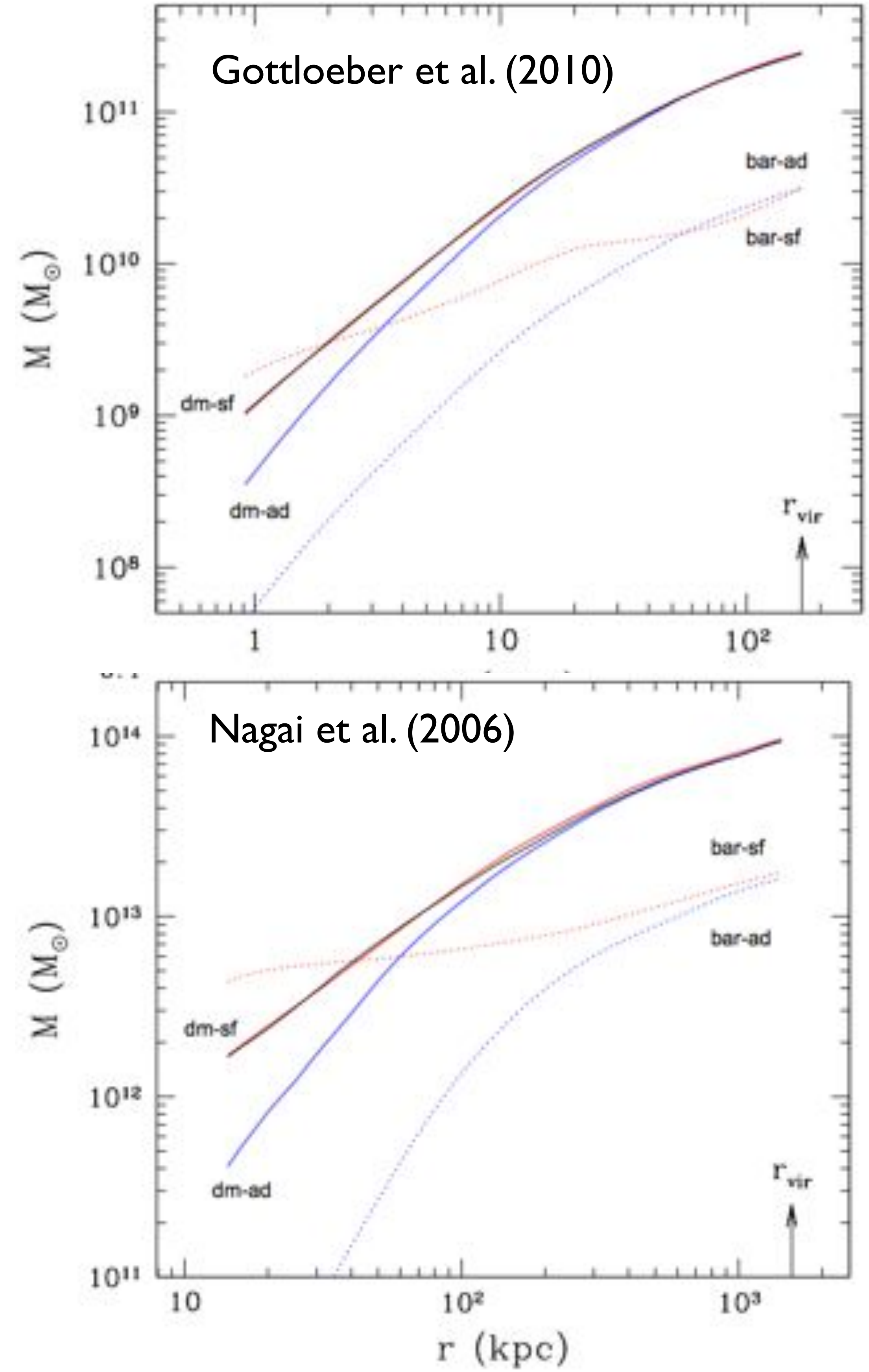
- Assumptions for the slope of the inner dark matter profile can make **orders of magnitude** differences in the expected dark matter annihilation rate
- Dark Matter is not a dominant gravitational source near the galactic center, so there are few observational handles on the dark matter density in the 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

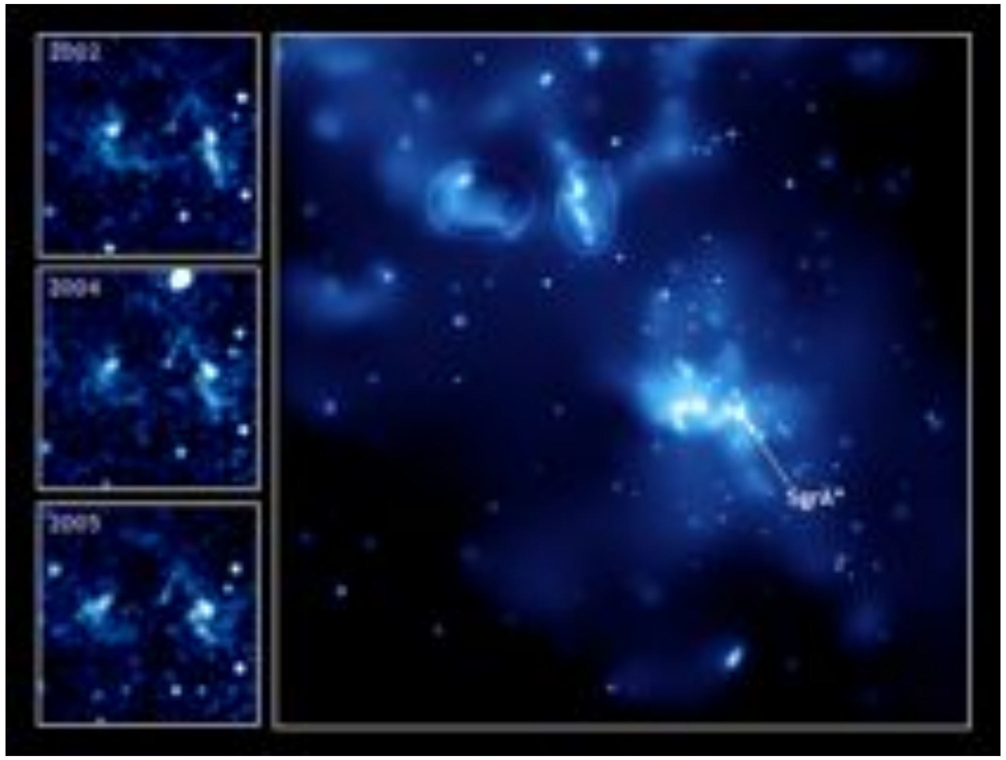
- This is imperative for understanding the signals from indirect detection



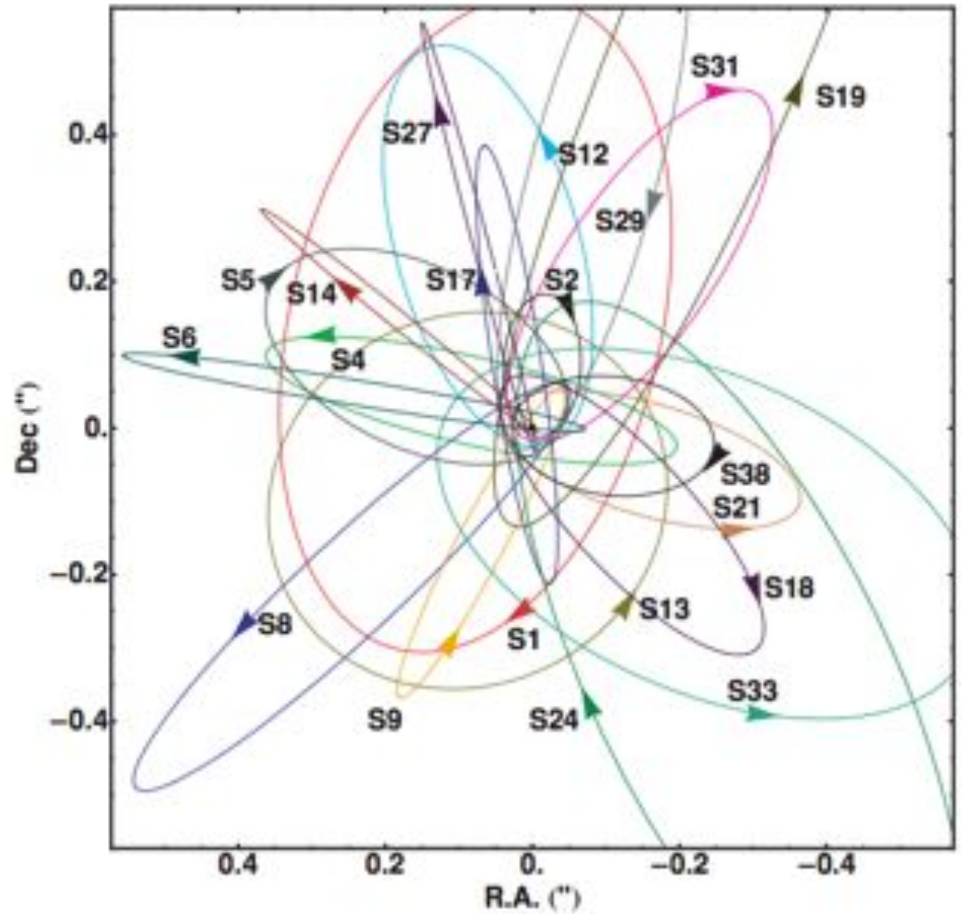
as reported in Gnedin et al. 2011

History of Galactic Center Observations (in 60 seconds)

Muno et al. 2007

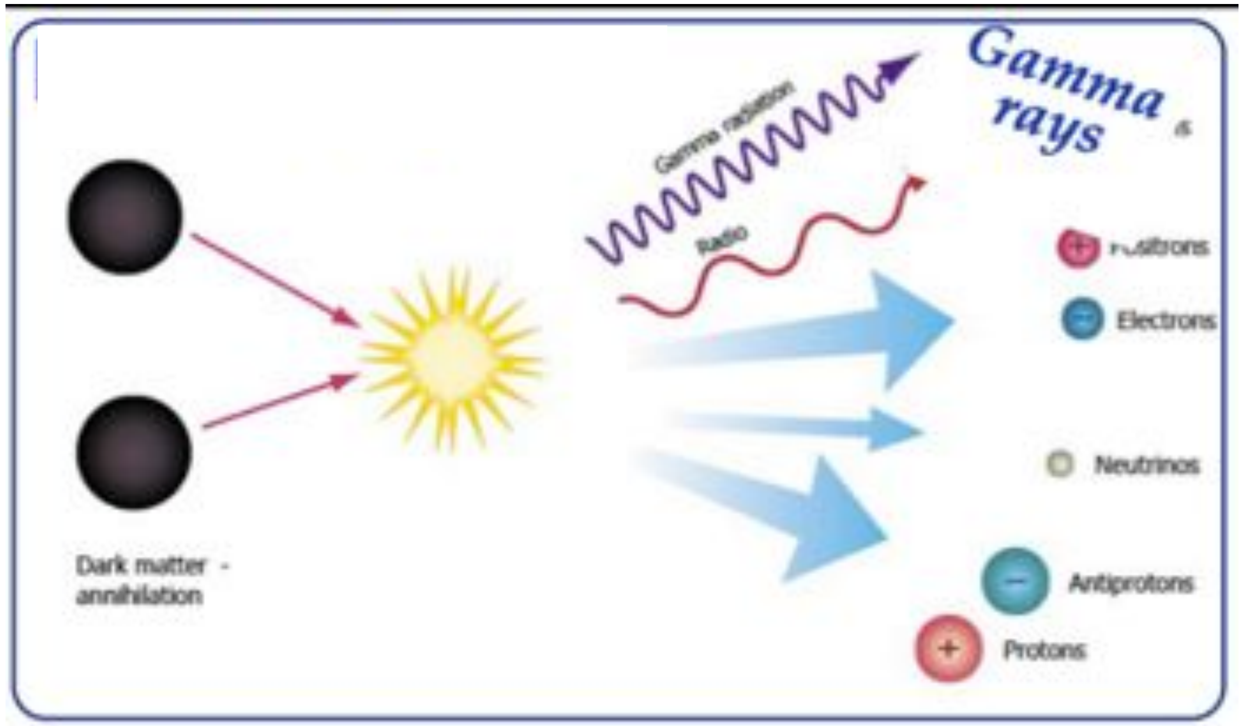


- Sgr A* Discovered via radio observations in 1974
- Measurements of stellar motion confirm the status of the central object as a black hole (Gillissen et al. 2009)
- Majority of radio emission thought to stem from accretion disk, rather than at BH event horizon (Doeleman et al. 2008)



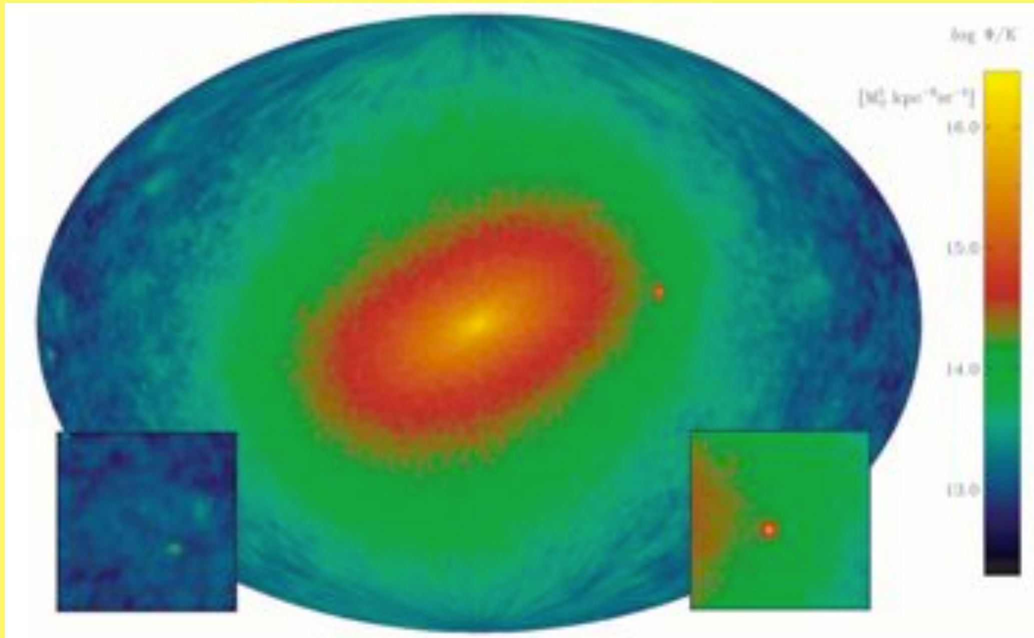
Gillissen et al. 2009

Dark Matter Indirect Detection



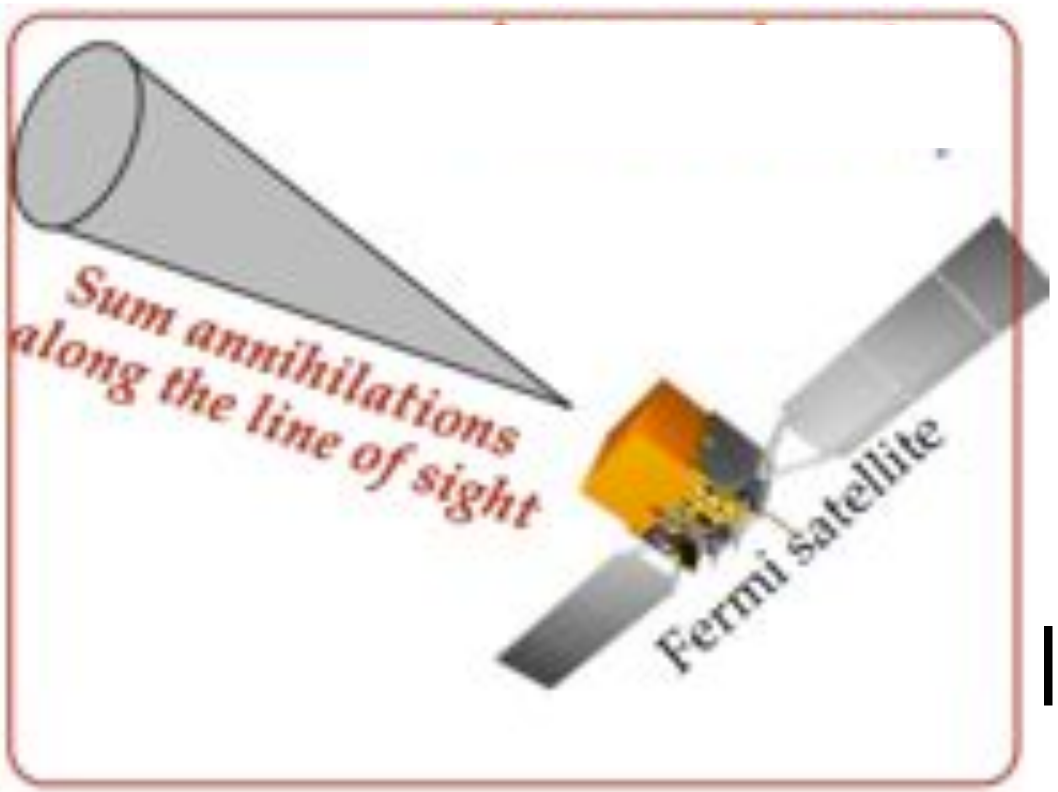
Particle Physics

Astrophysics



Diemand et al. 2008

Slides Courtesy of G. Zaharijas



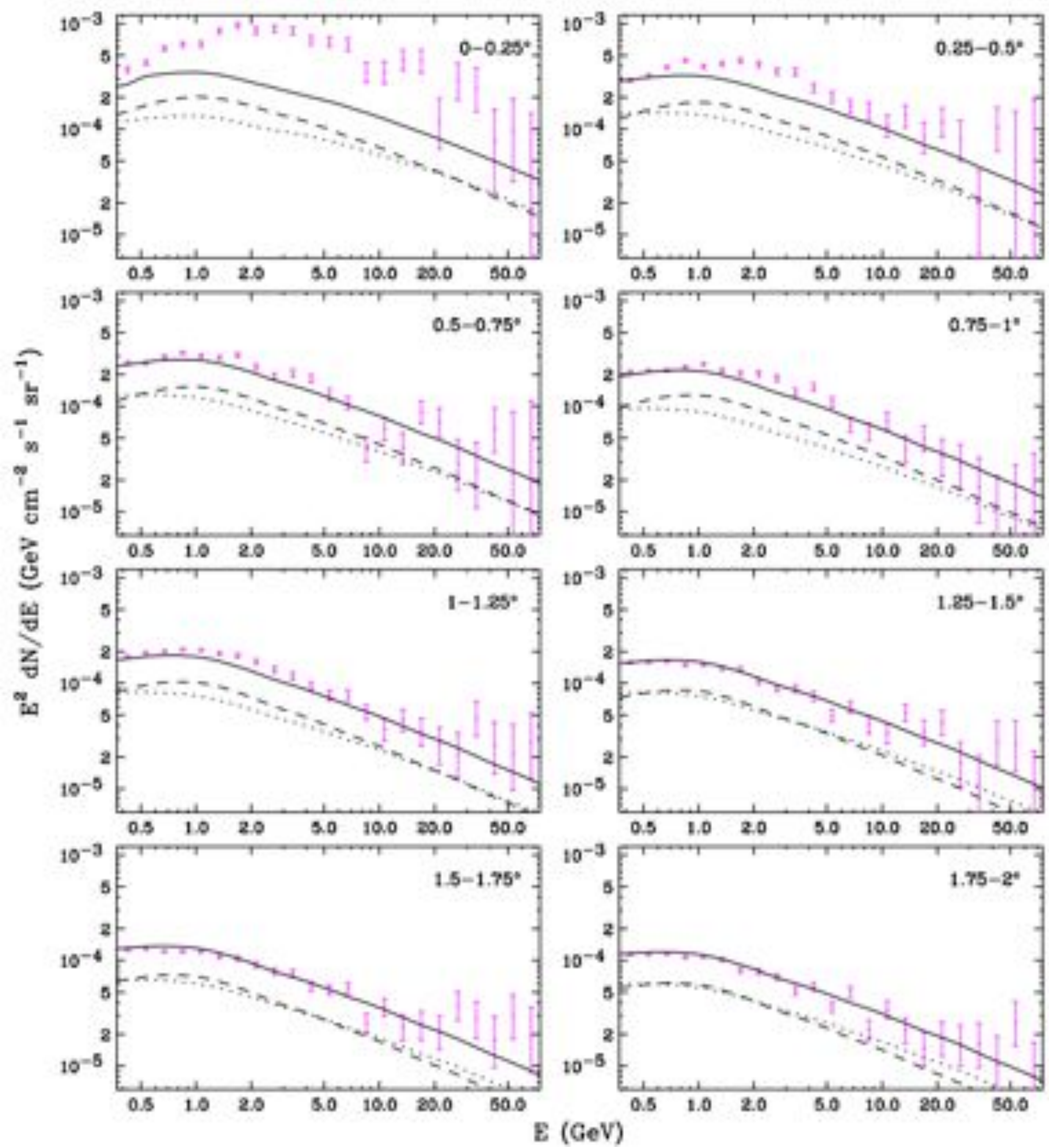
Instrumental Response

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

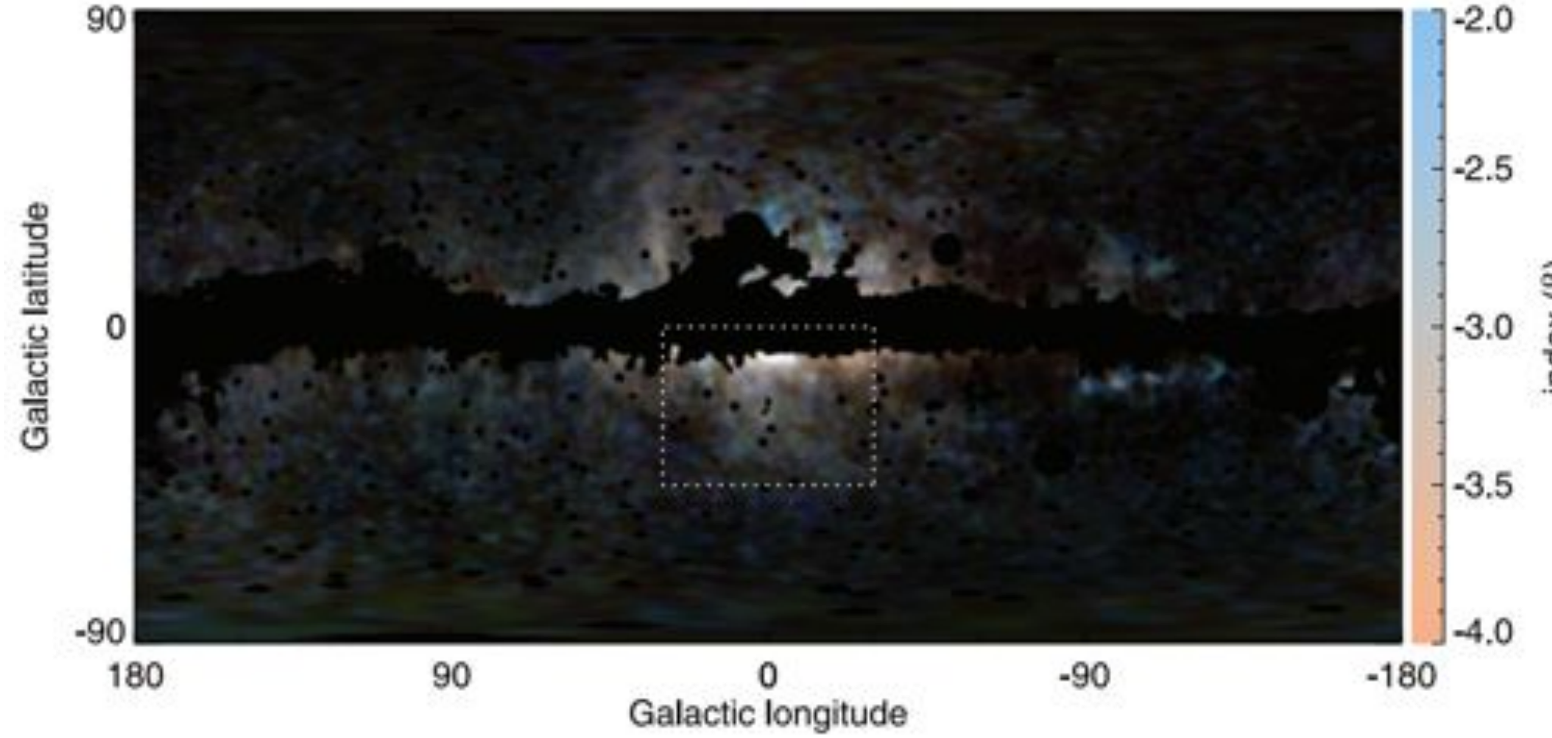
Hooper & Goodenough (2011)

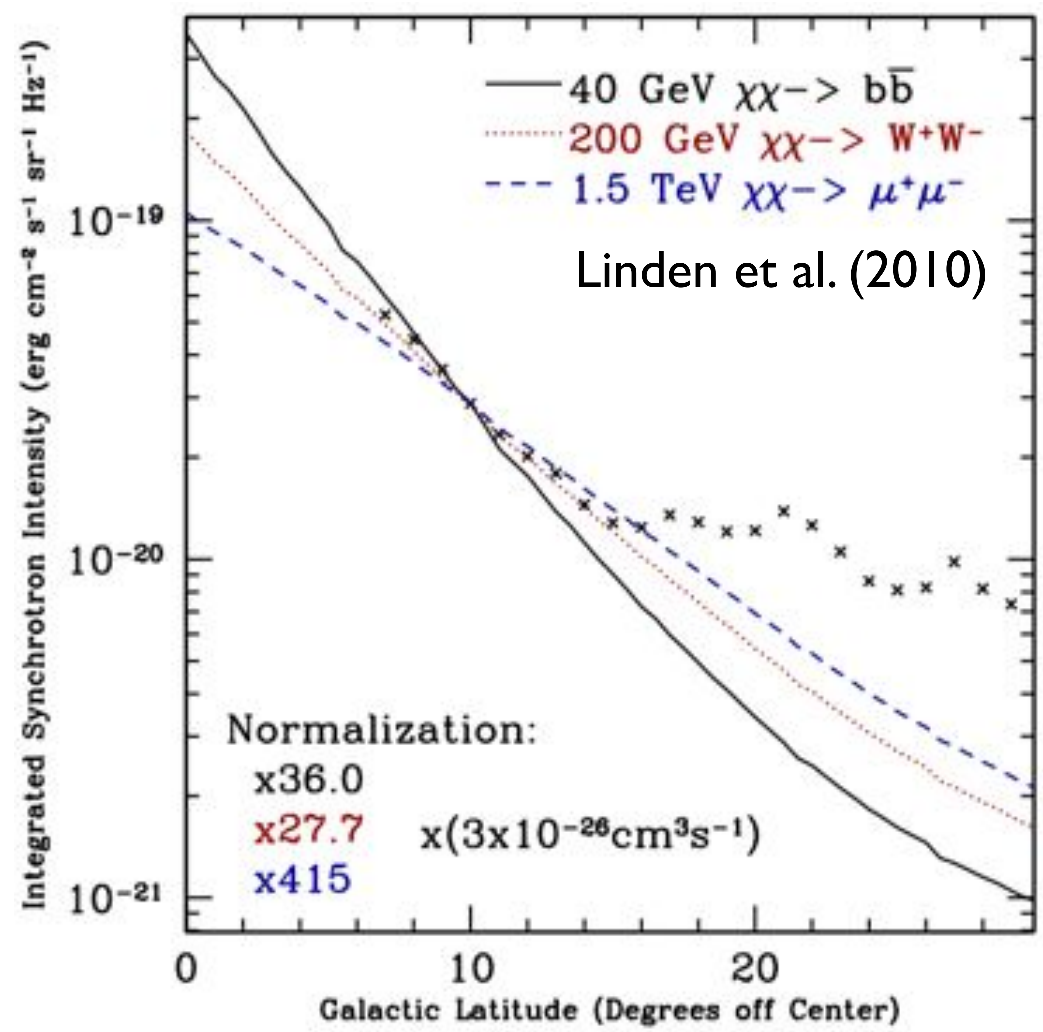


What is the WMAP Haze?

- 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

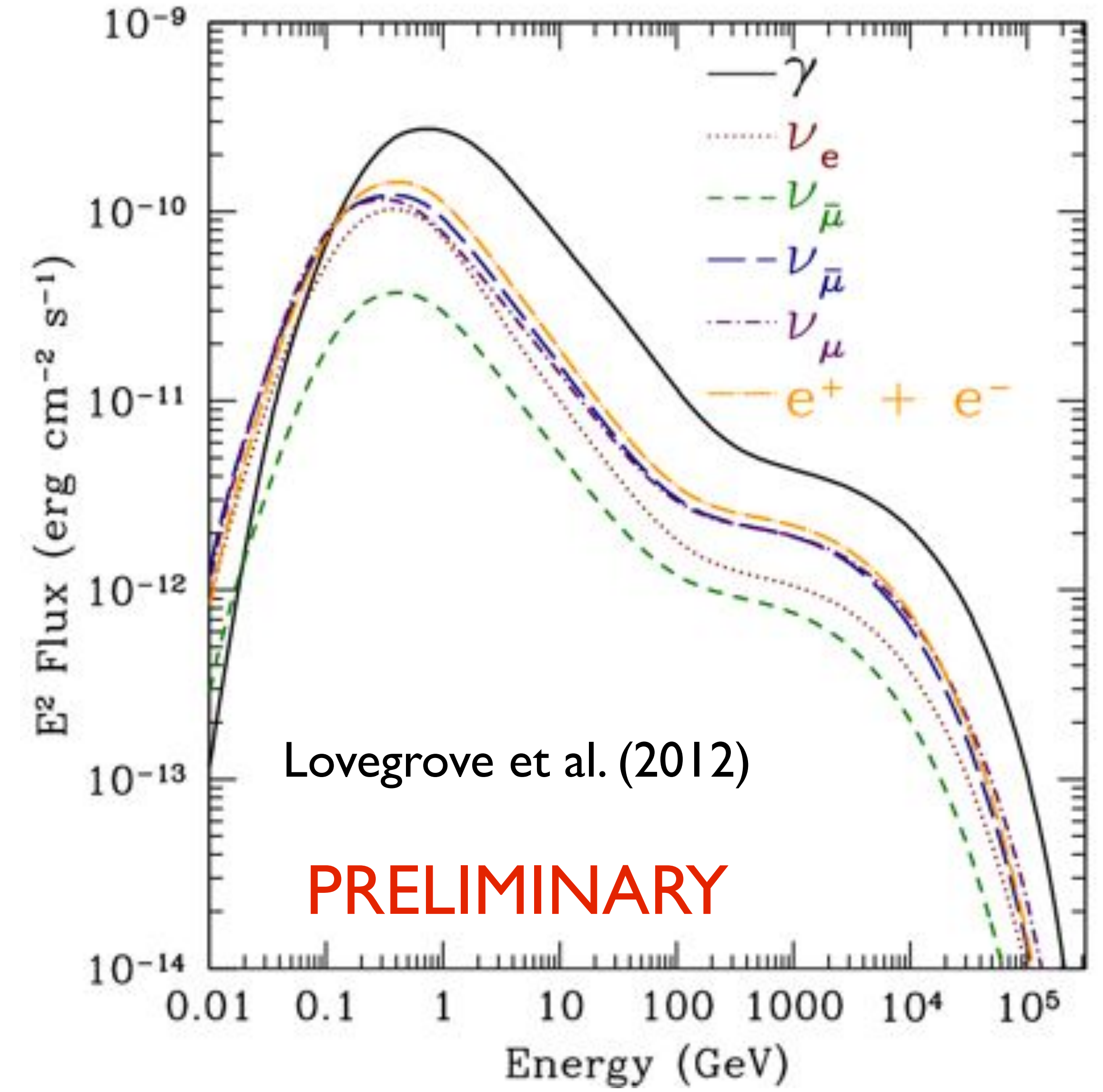
Dobler et al. (2008)

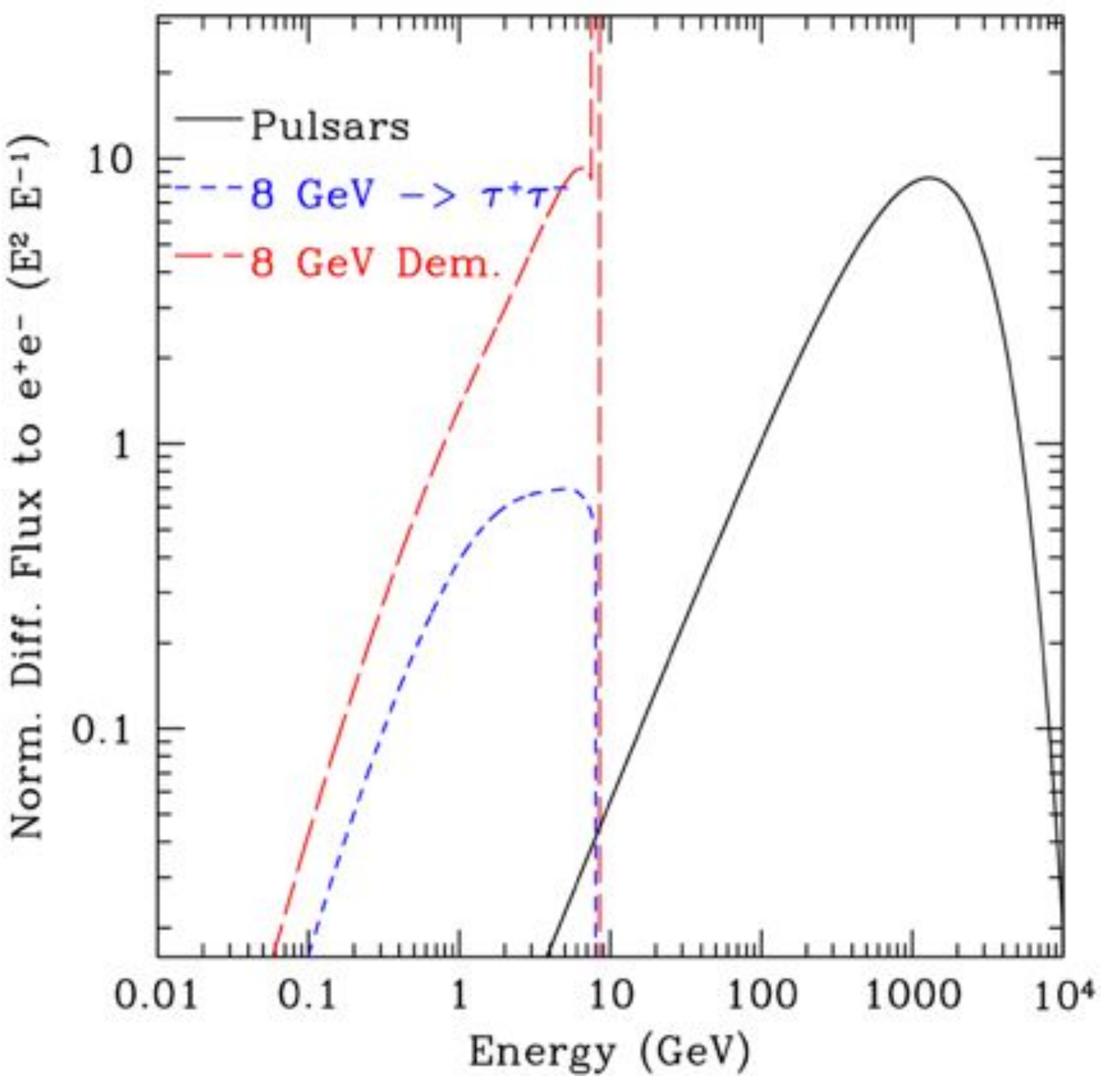




Understanding the Secondary Emission

- 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



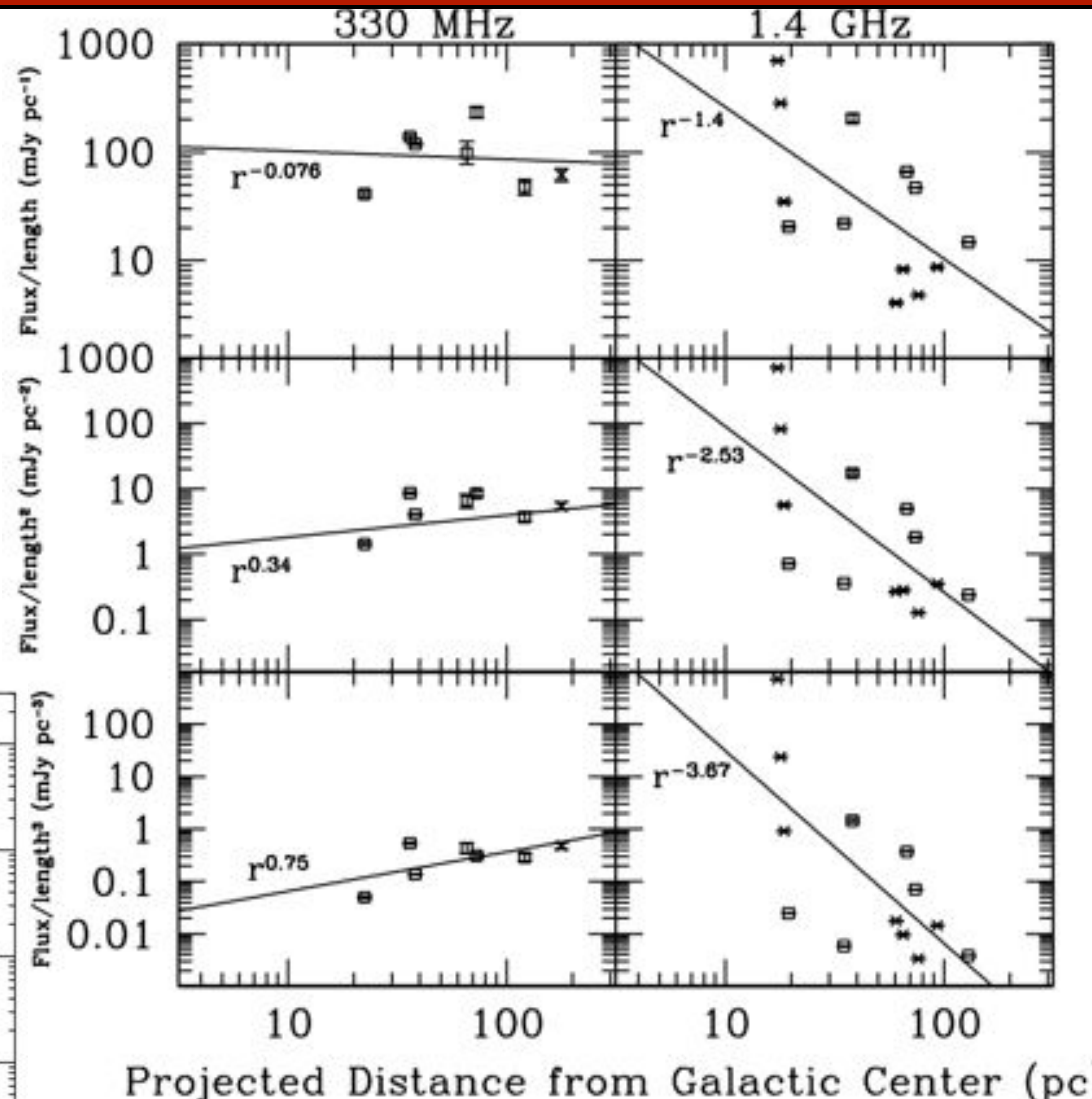


Positive: The angular resolution of radio telescopes is significantly greater than gamma-ray observatories

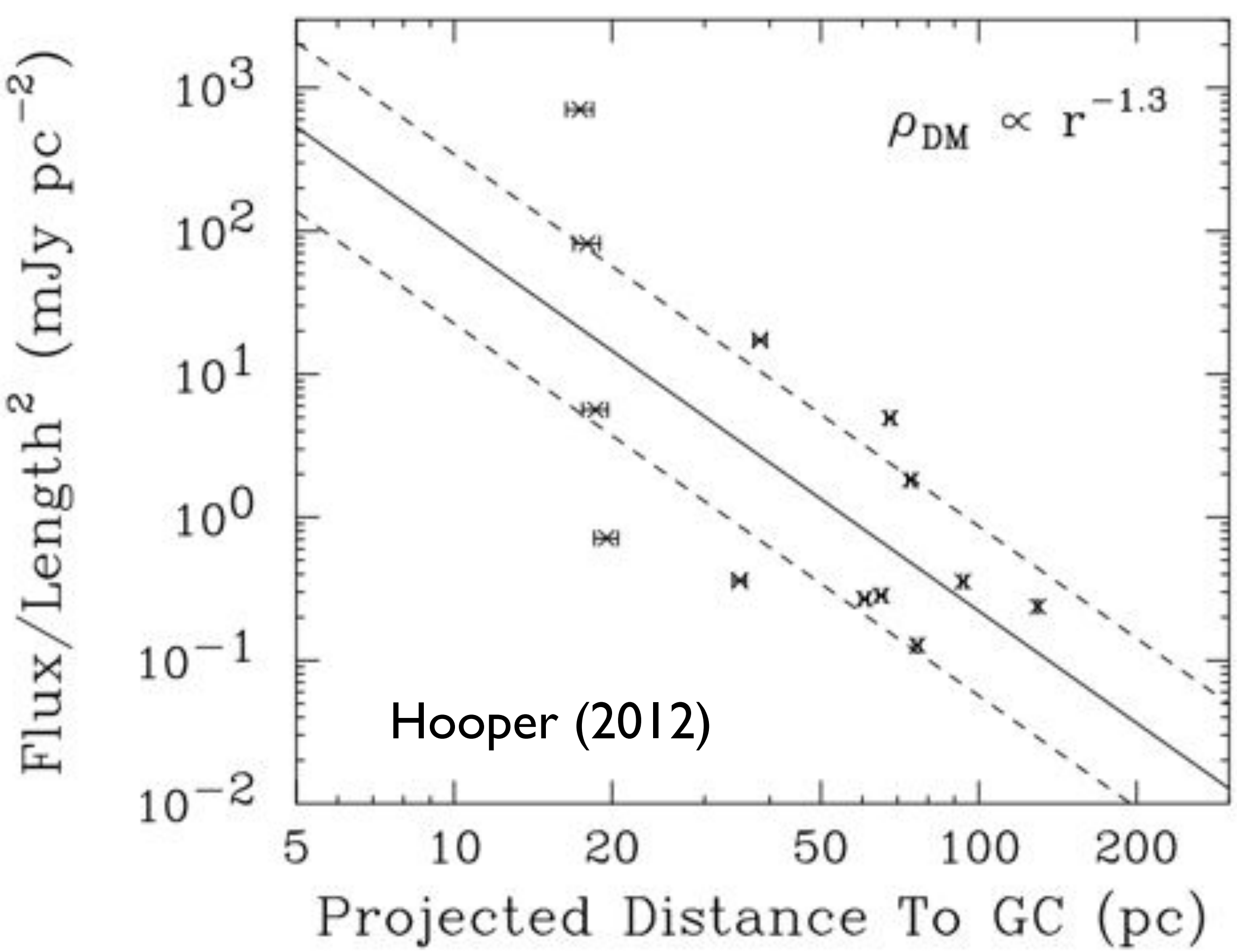
Negative: The diffusion and energy loss time of charged electrons adds additional uncertainties to the model

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

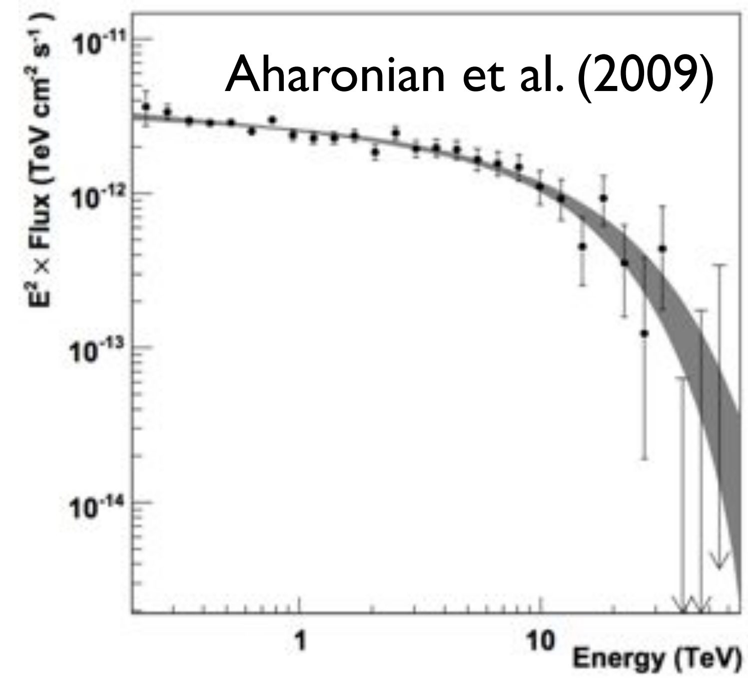


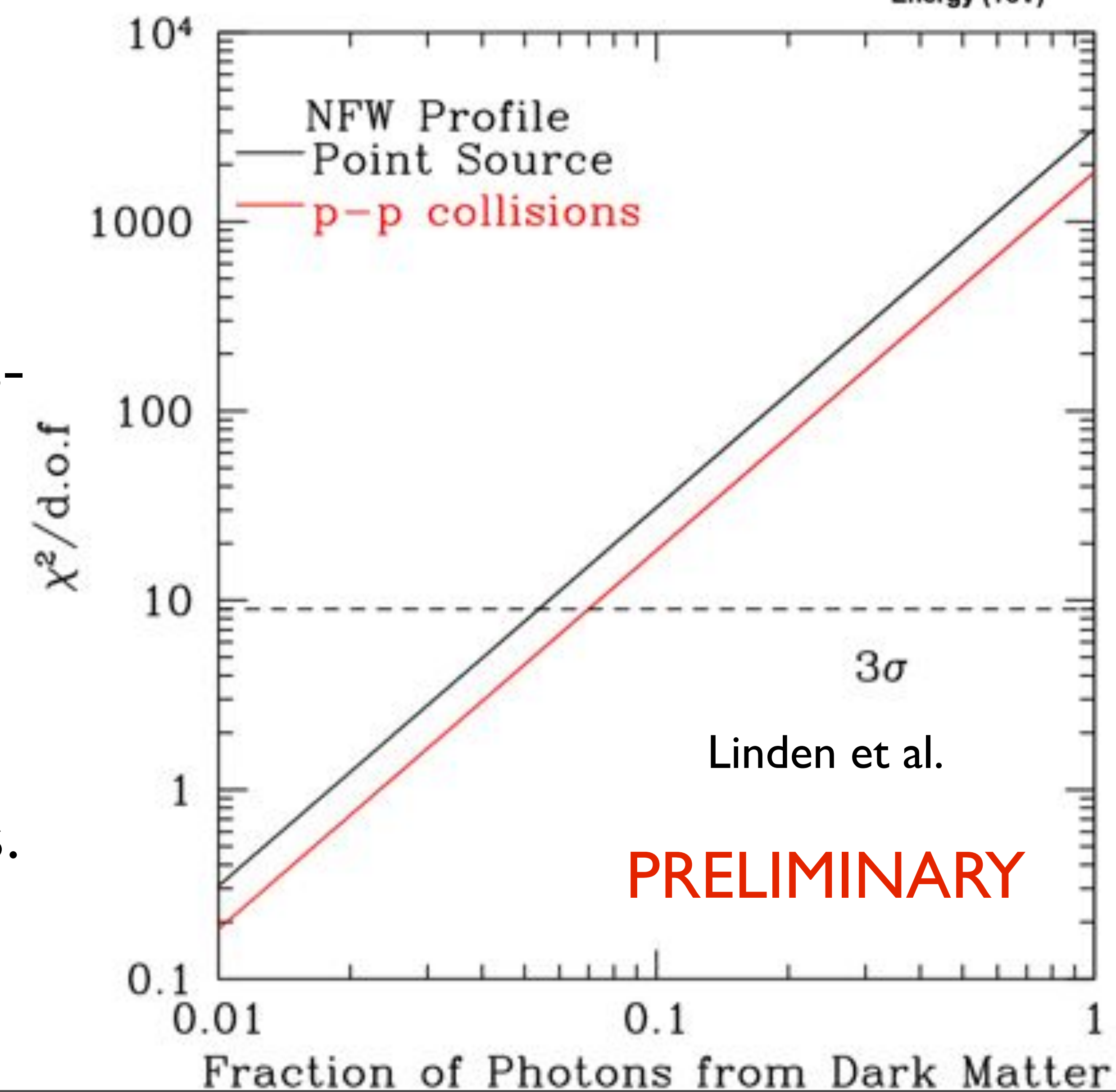
Linden et al. (2011)



Dark Matter at the Galactic Center

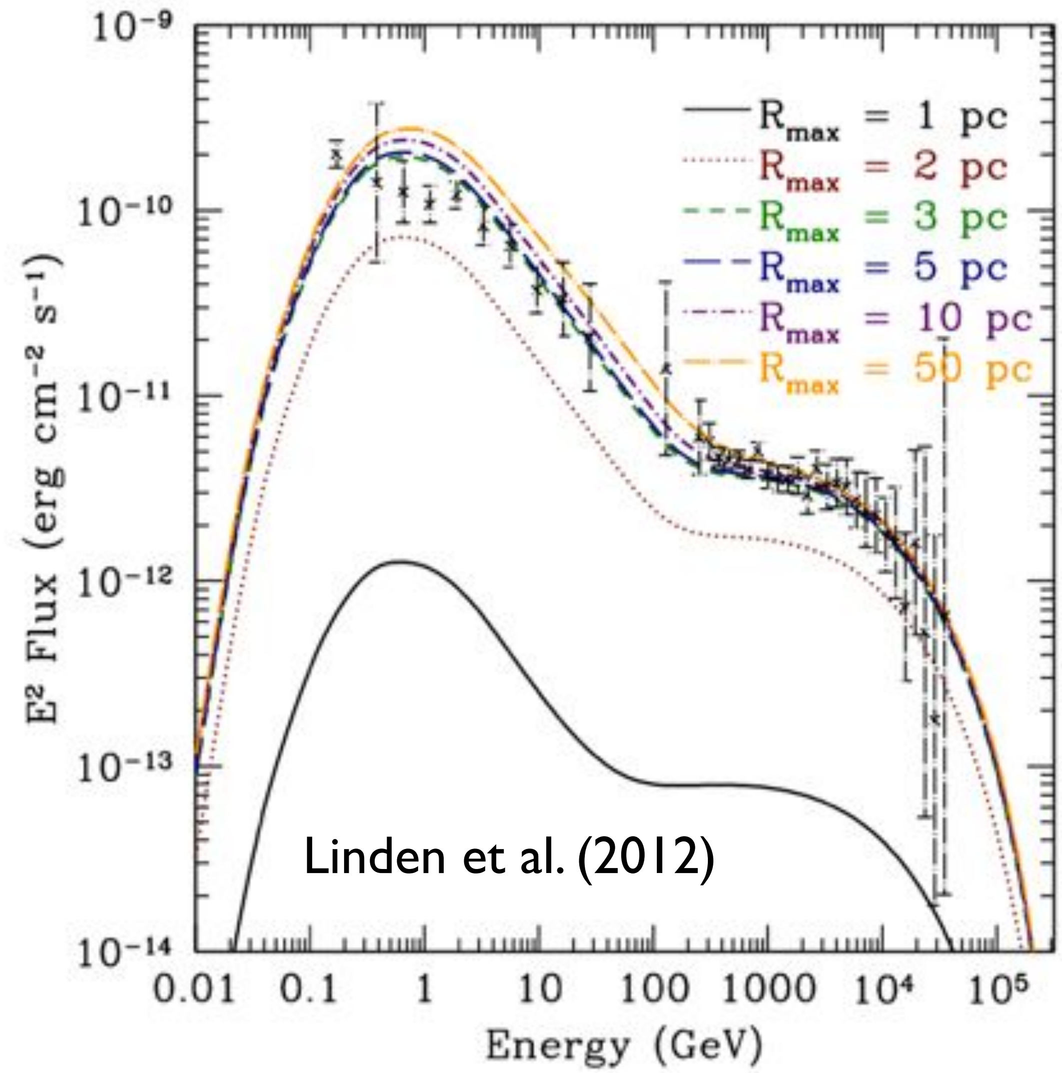
- Can use a Kolmogorov-Smirnov test after finding the CDF for the radial profile of dark matter annihilation
- Since the CDFs for dark matter and the background point-source can be compared linearly, strong limits can quickly be set on dark matter annihilation
- Limits on photon counts can then be translated 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





Modeling Benefits of the Hadronic Scenario!

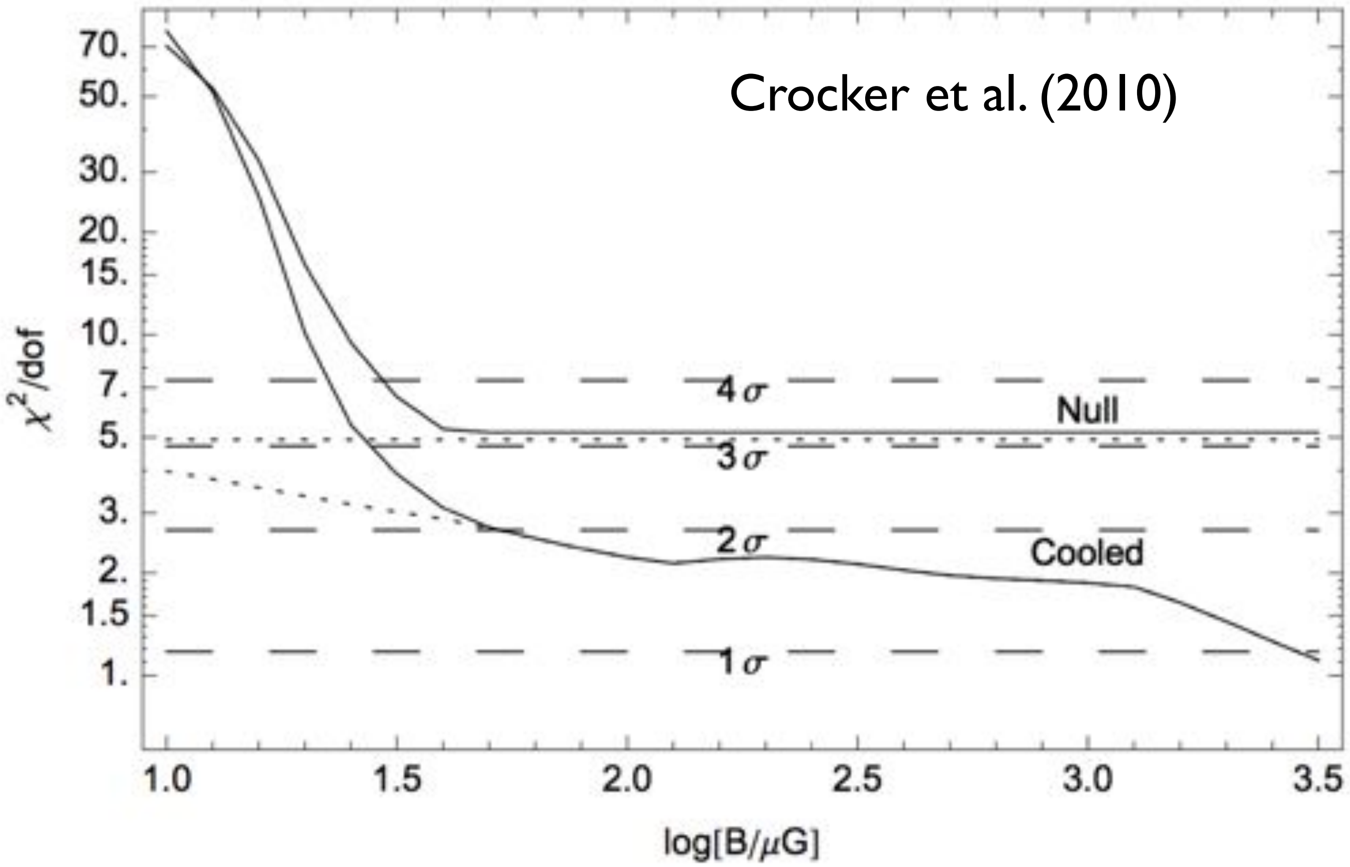
- Under the assumption that the proton source has a power-law spectrum and is in steady-state, then the slope of gamma-ray emission strongly constrains the diffusion constant in the galactic center region:

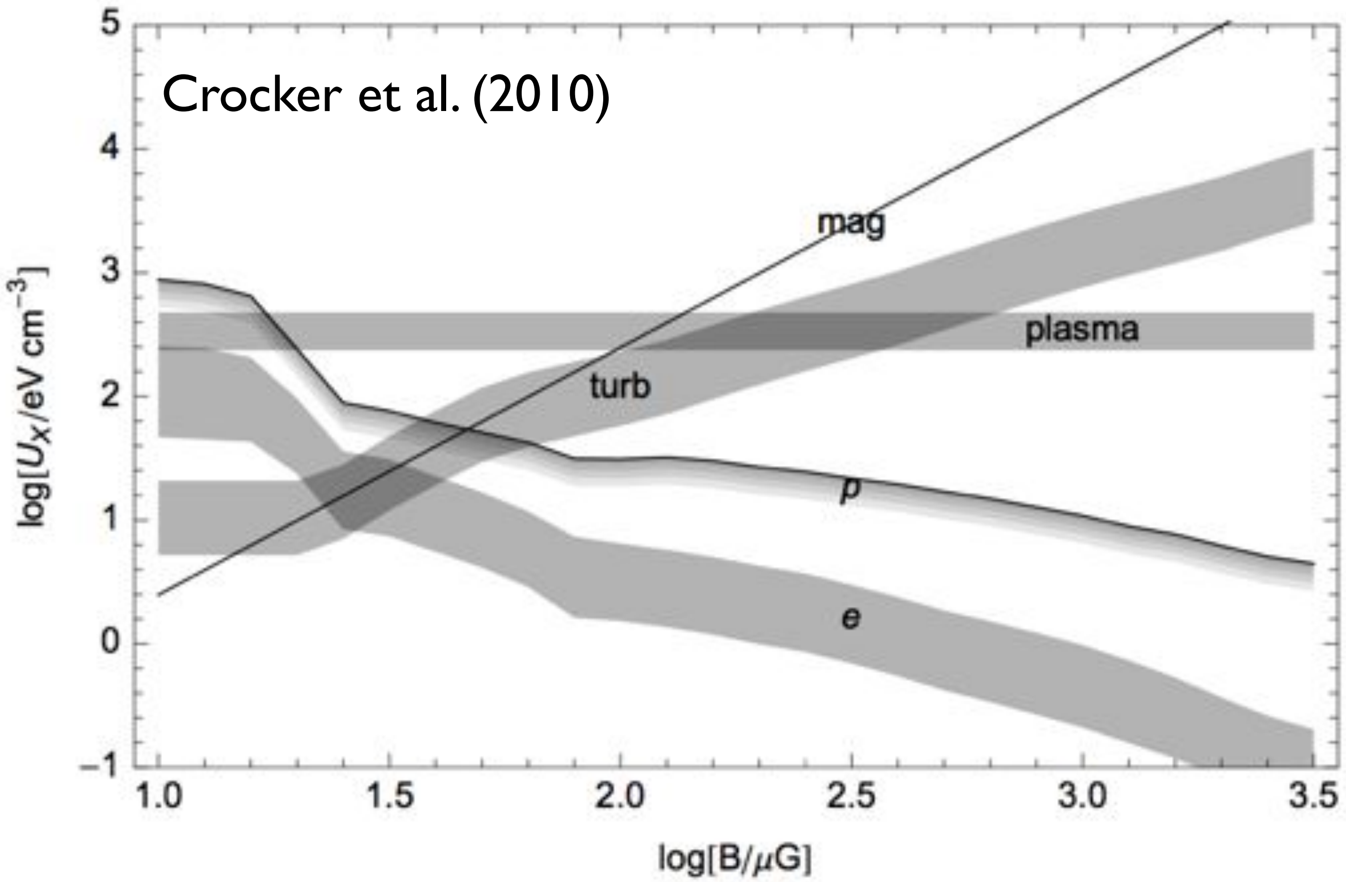


$$D_0 = 1.2 \times 10^{26}\ (E/1\ \text{GeV})^{0.91}$$

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

Models of the Galactic Center Magnetic Field

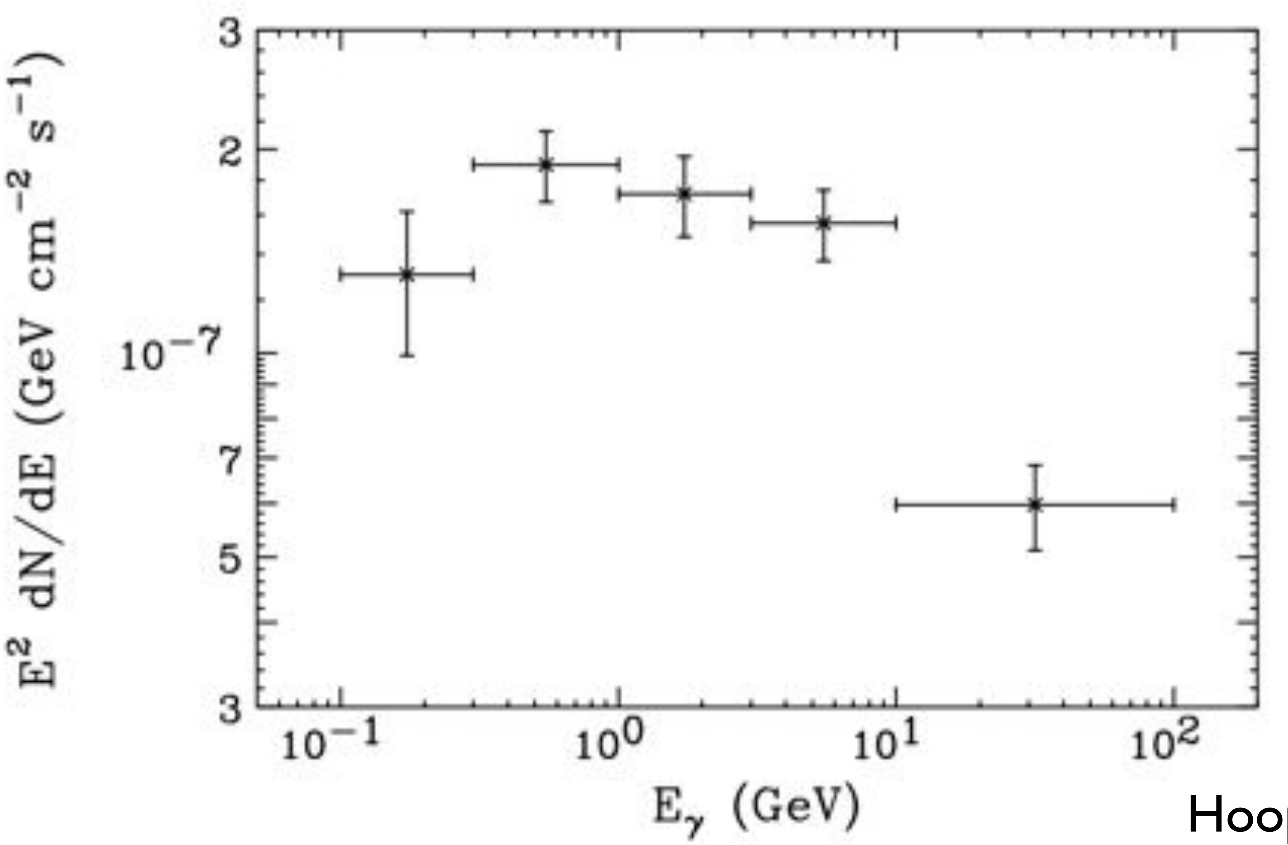


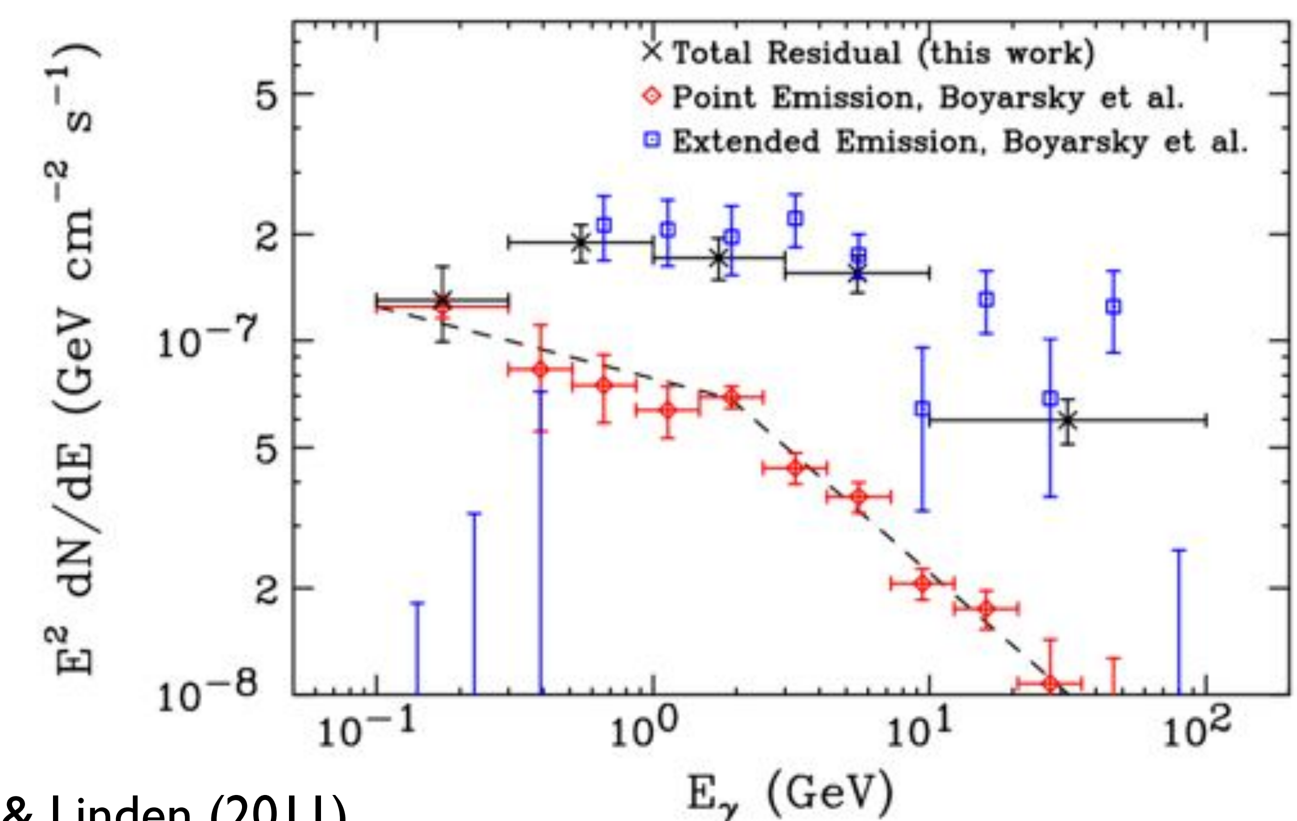


- This is particularly interesting in light of recent models which have set a minimum strength of 50 μG on the magnetic fields in the galactic center (best fit range 100-300 μG)
- This almost ensures that synchrotron is the dominant energy loss mechanism for high energy electrons
- In the hadronic scenario,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

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

- 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