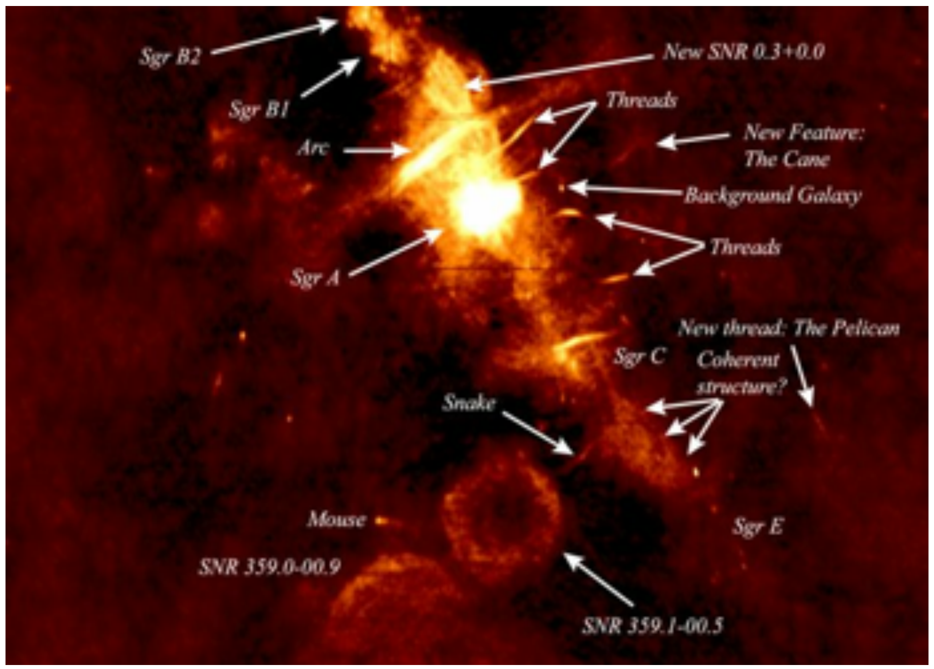
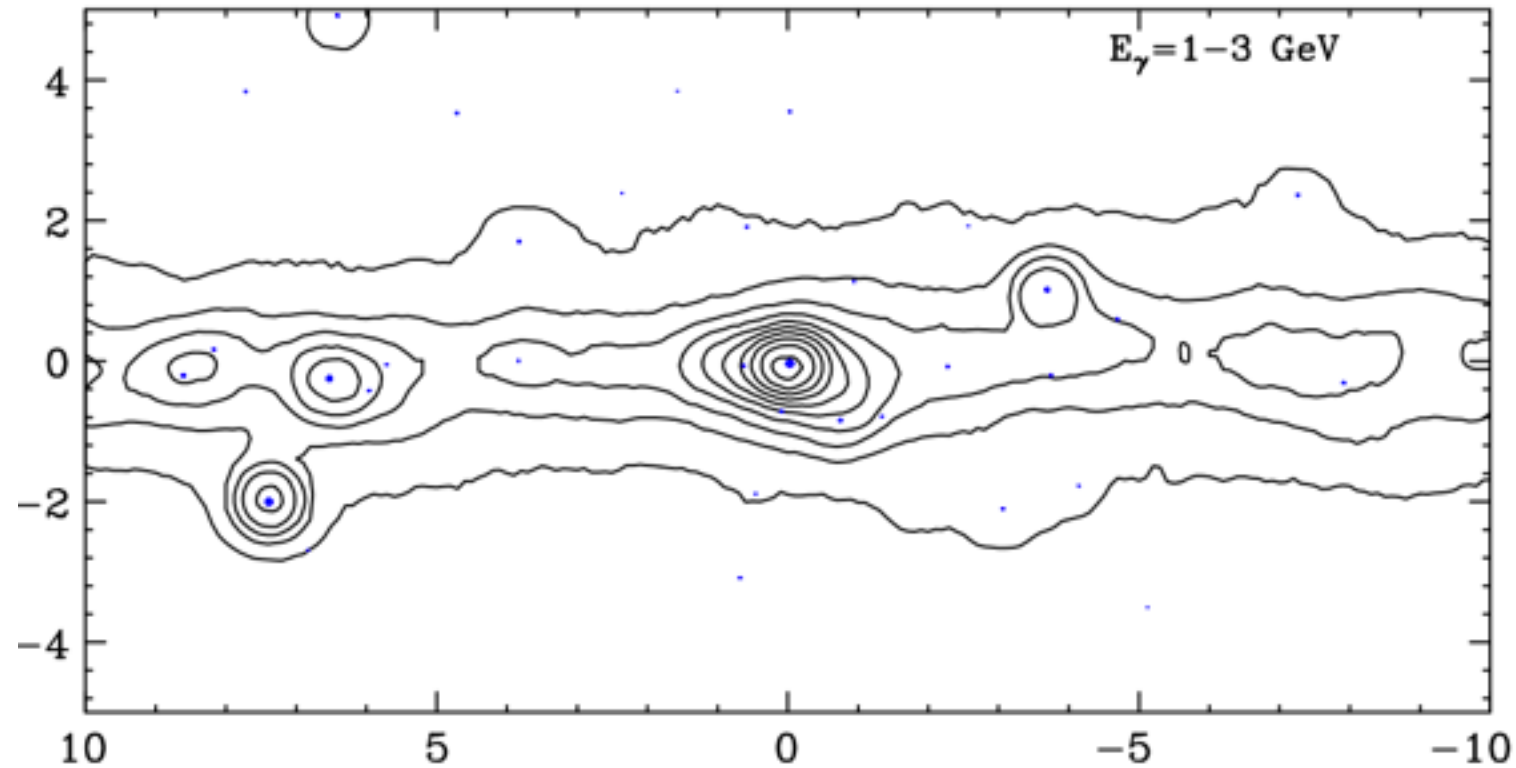
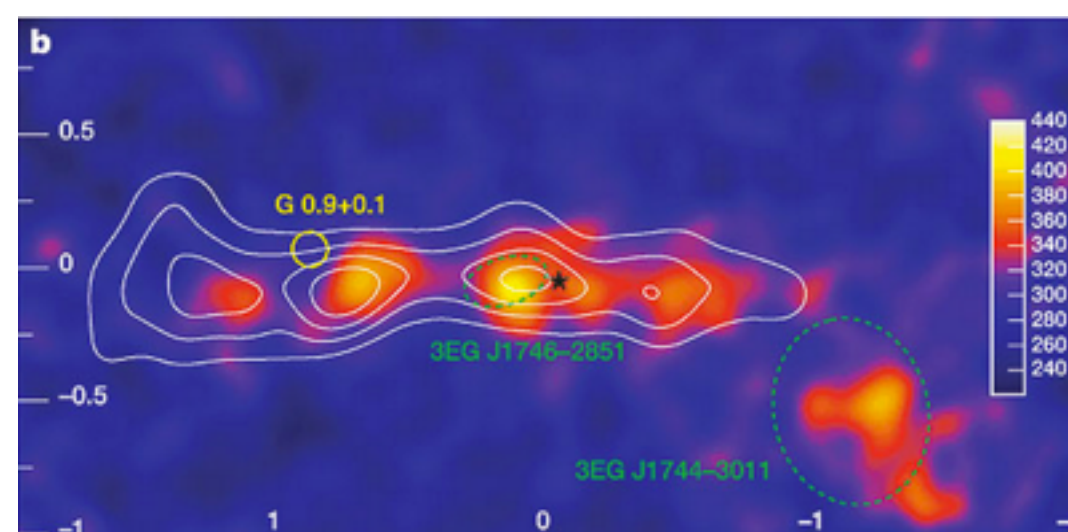
Dark Matter Annihilation At the Galactic Center



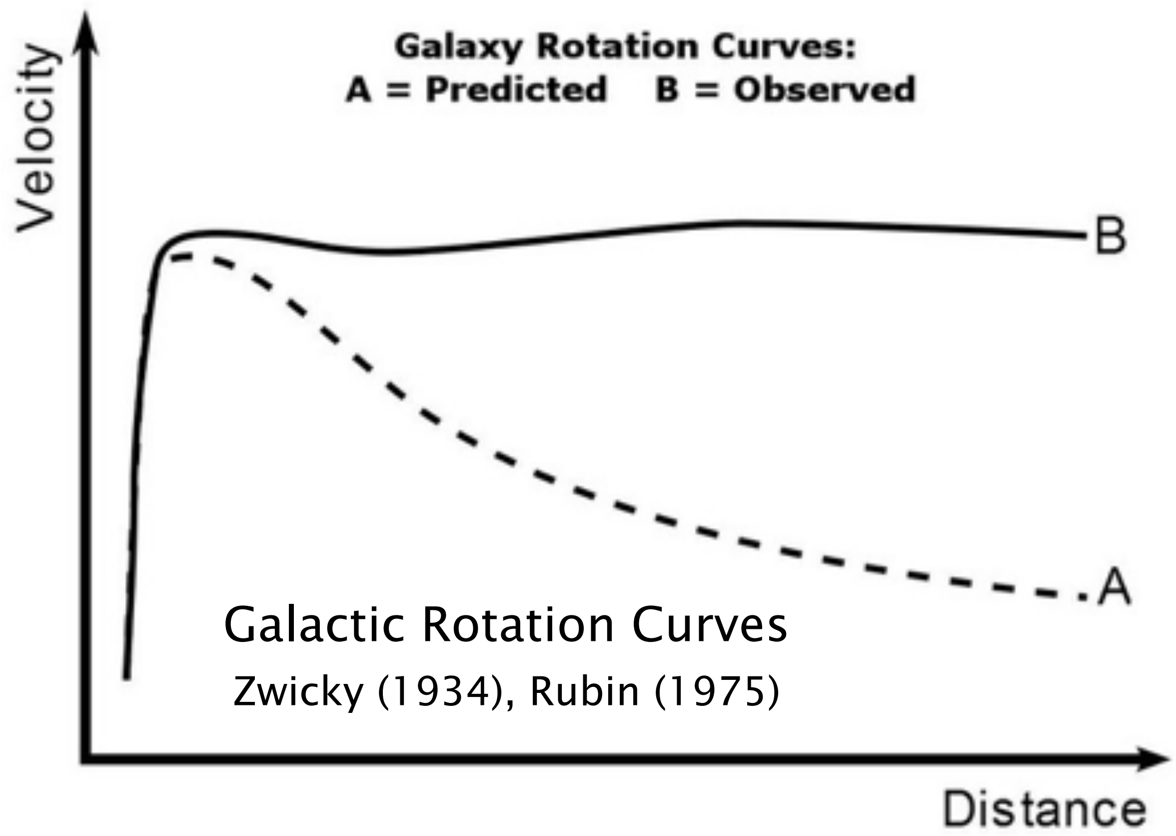


Tim Linden
UC - Santa Cruz



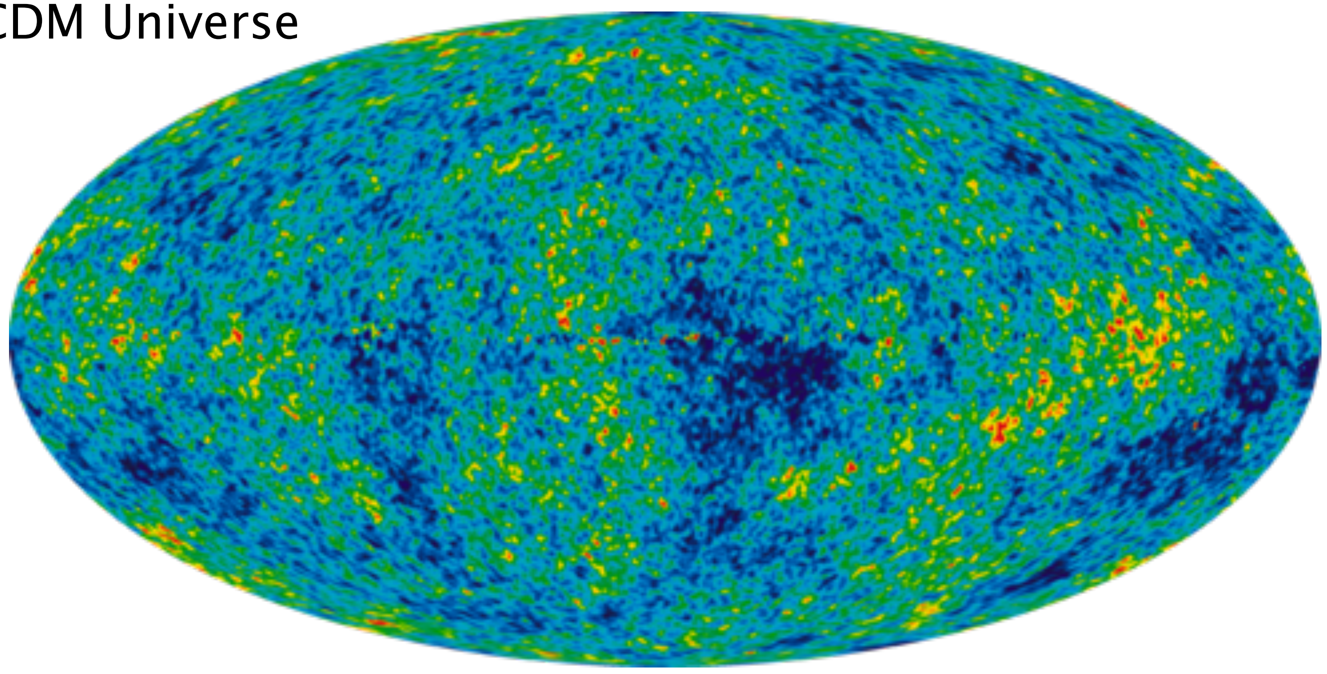
Dissertation Defense May 7, 2013

Motivating Question: Particle Dark Matter



8σ rejection of some modified gravity theories (2006)

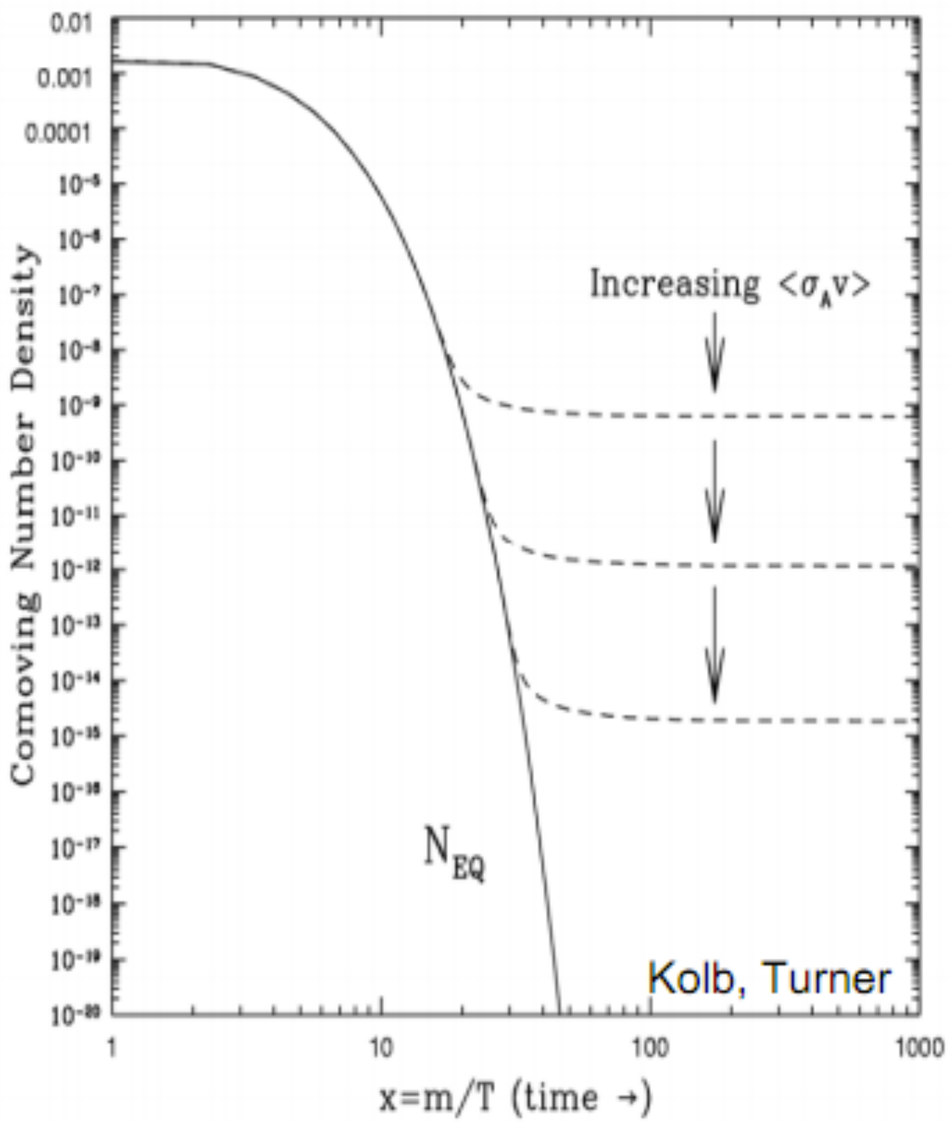
Cosmic Microwave Background is consistent with ΛCDM Universe



Also:

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

Motivating Question: WIMP Dark Matter Detection

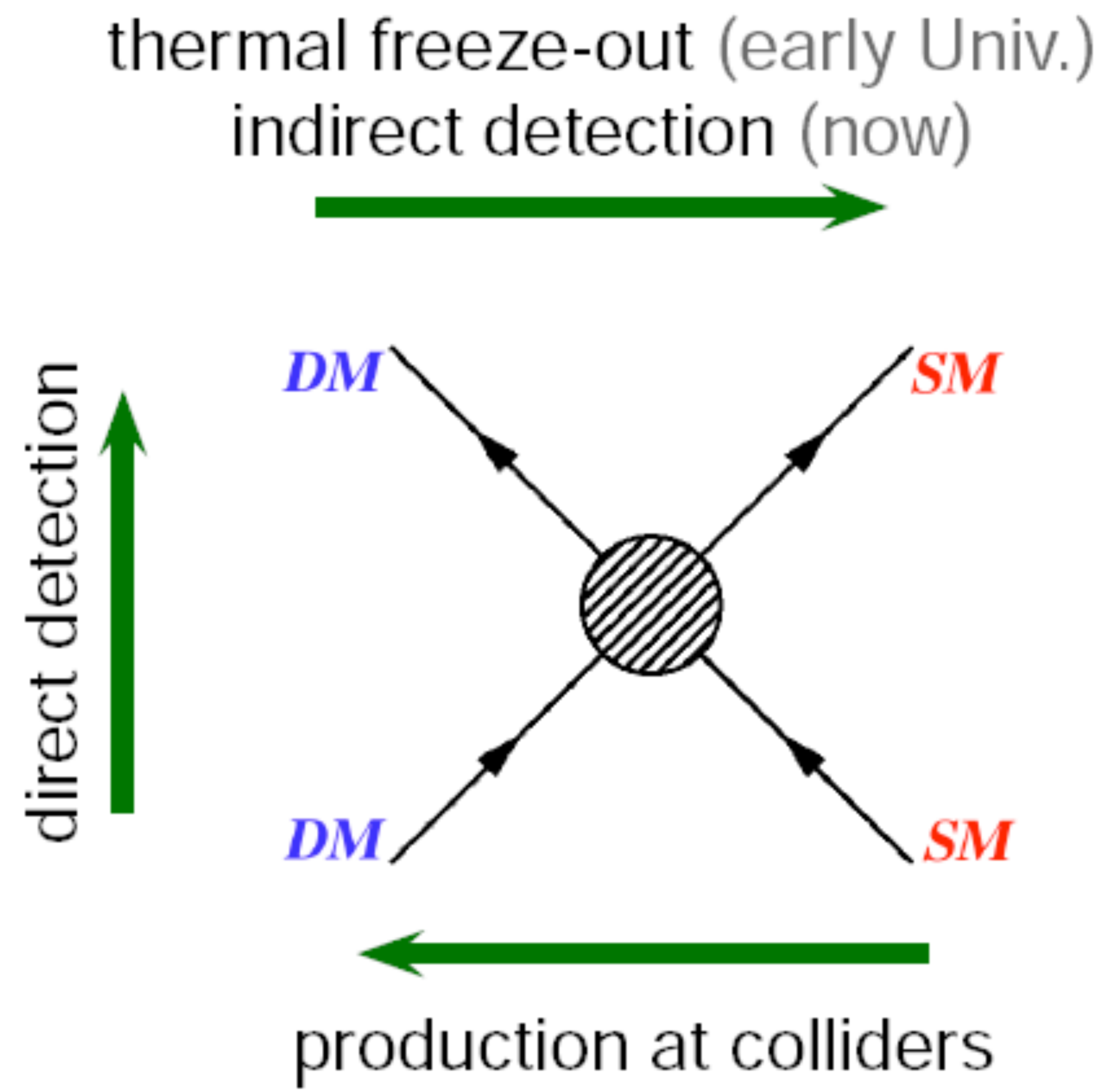


$$\Omega_h \propto <\sigma v>^{-1} \propto \frac{M_X^2}{g_X^4}$$

$M_X^2 = 100$ GeV

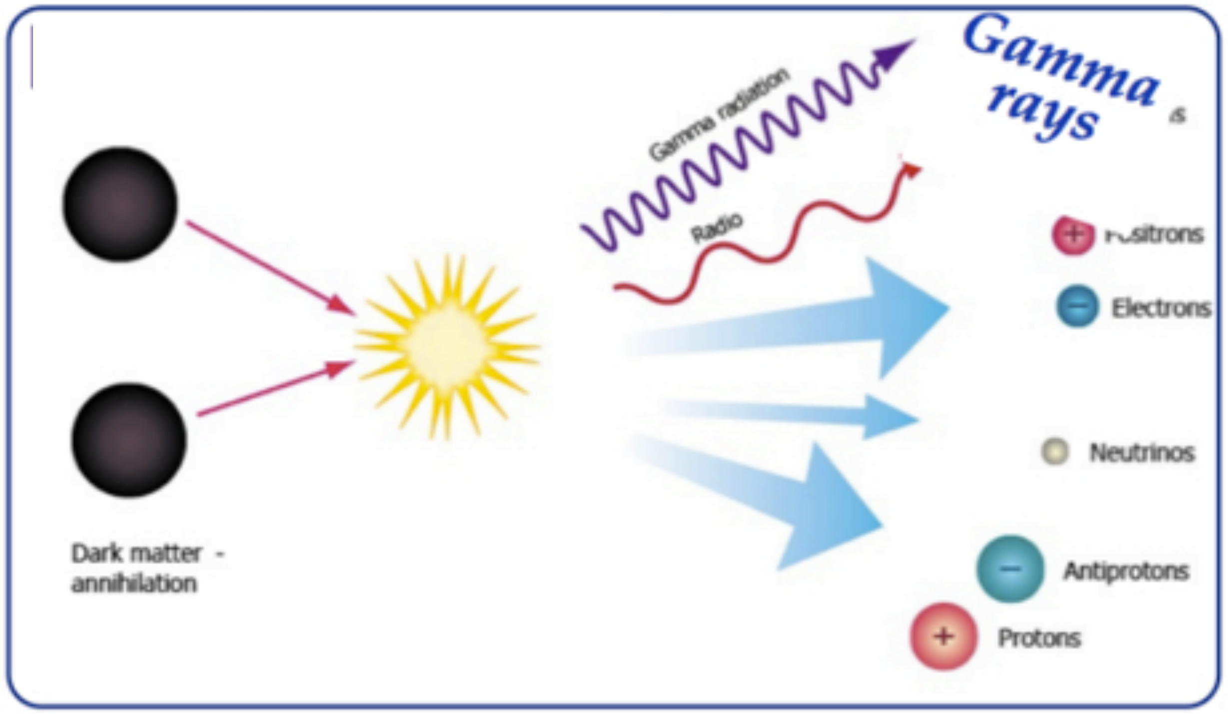
$g_X^4 = 0.6$

$\Omega_h \sim 0.1$



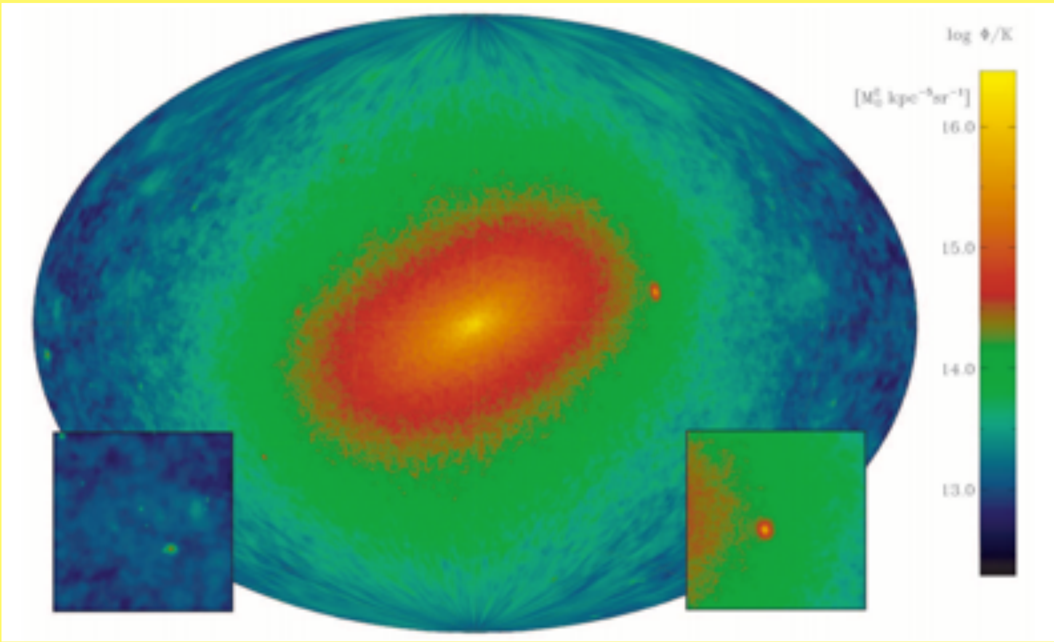
Motivating Question: Dark Matter Indirect Detection

Particle Physics

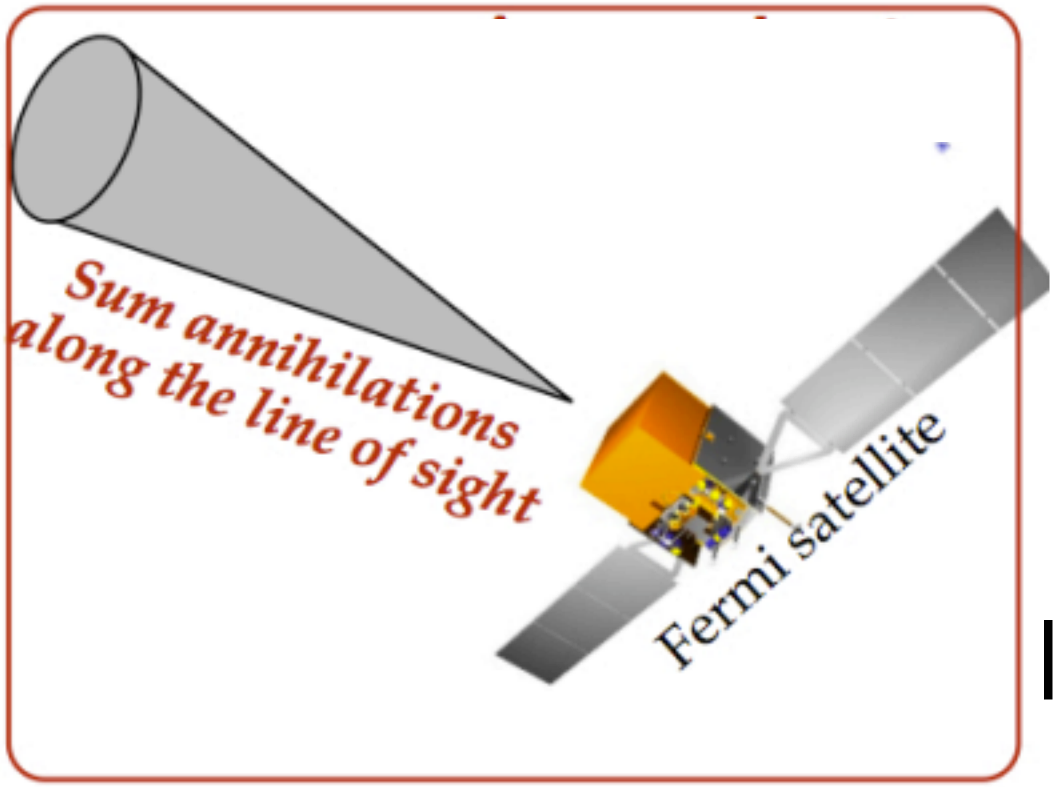


Slides Courtesy of G. Zaharijas

Astrophysics



Diemand et al. 2008



Instrumental Response

Dark Matter Indirect Detection

Motivating Question:

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

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

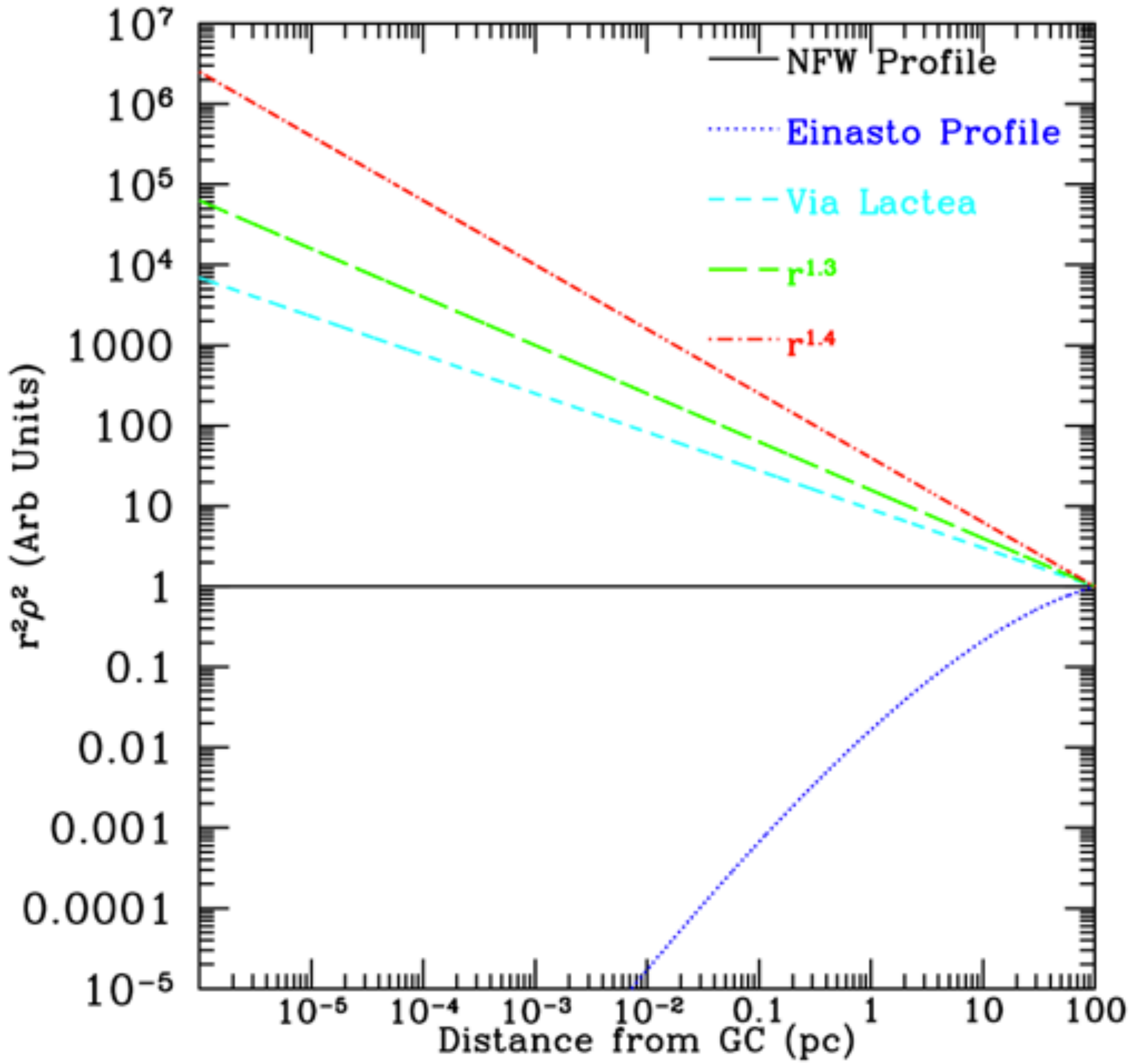
$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int d\Omega \int_{\mathrm{l.o.s.}} \rho^2(l)\,dl(\psi)$$

- 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

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

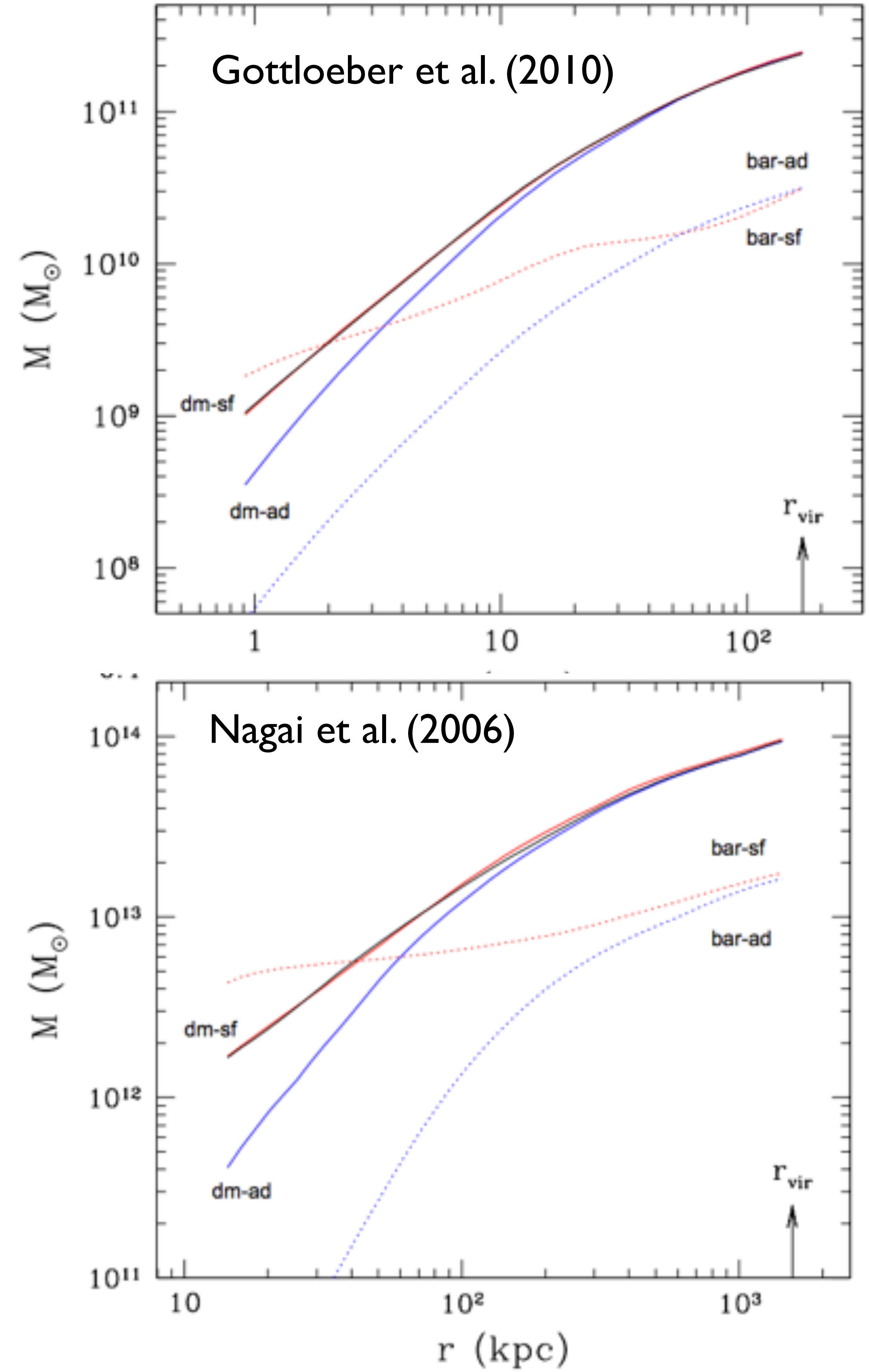
- Dark Matter is not a dominant gravitational source near the galactic center, so there are few observational handles on the dark matter density in the GC region

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

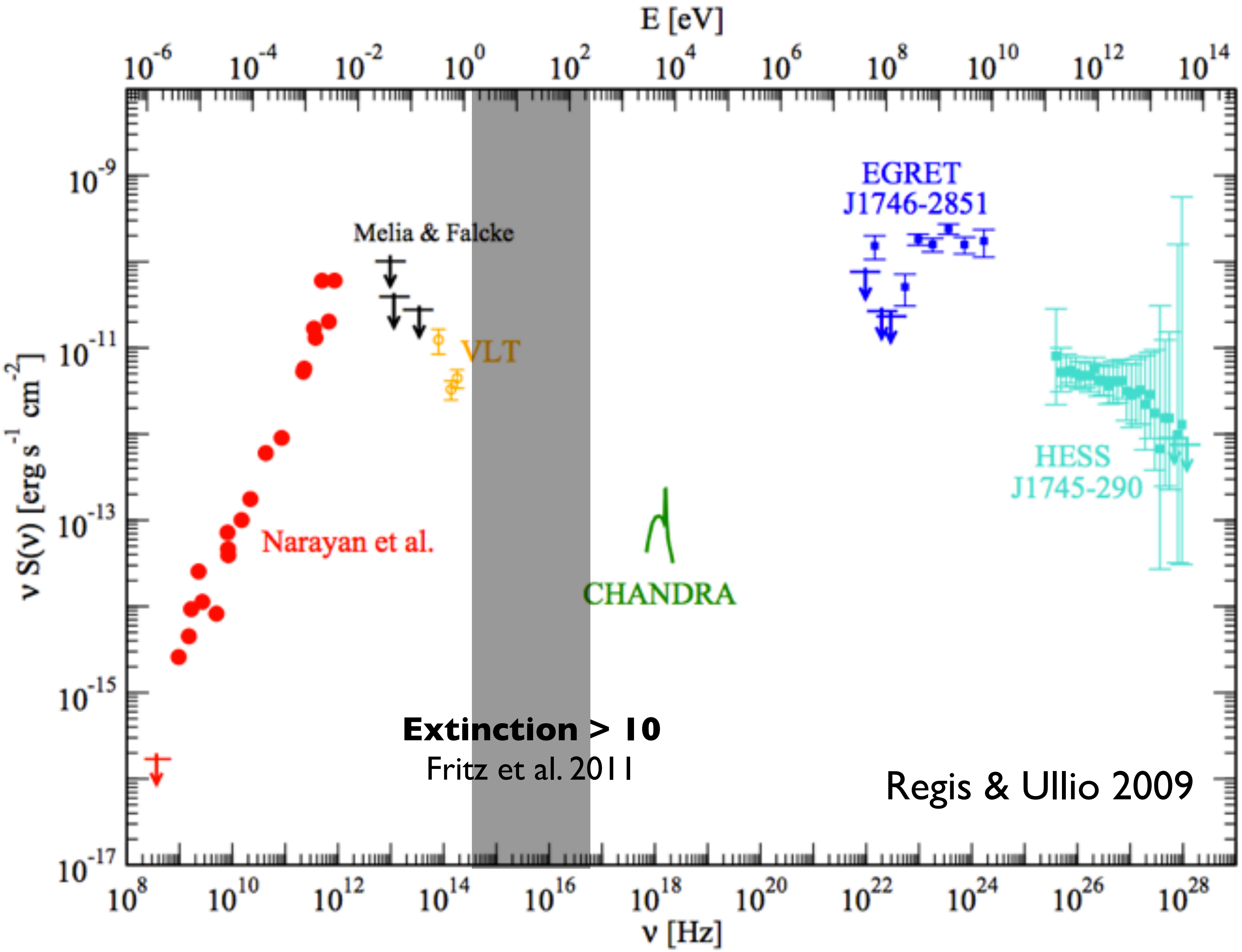
- Much more work is required to understand the dark matter content of the GC region

- This is imperative for understanding the signals from indirect detection



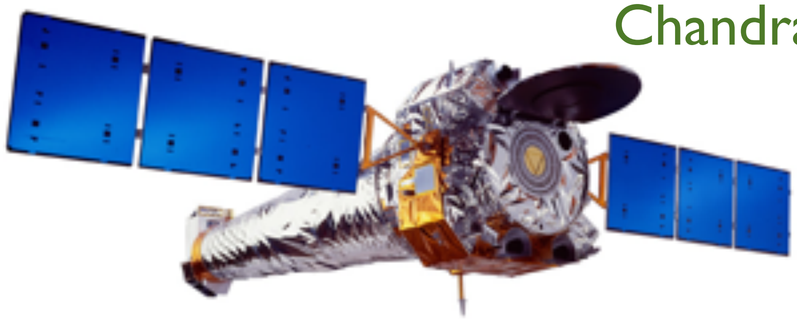
as reported in Gnedin et al. 2011

The Multi-wavelength Galactic Center

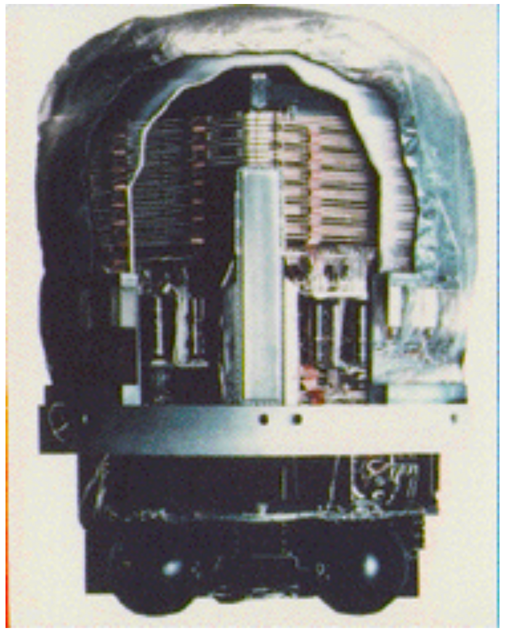


VLA

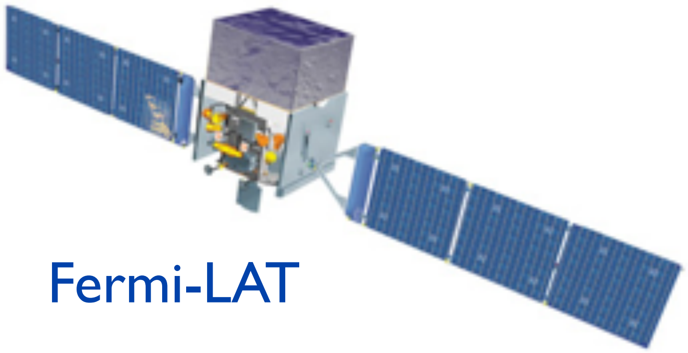
Chandra



EGRET

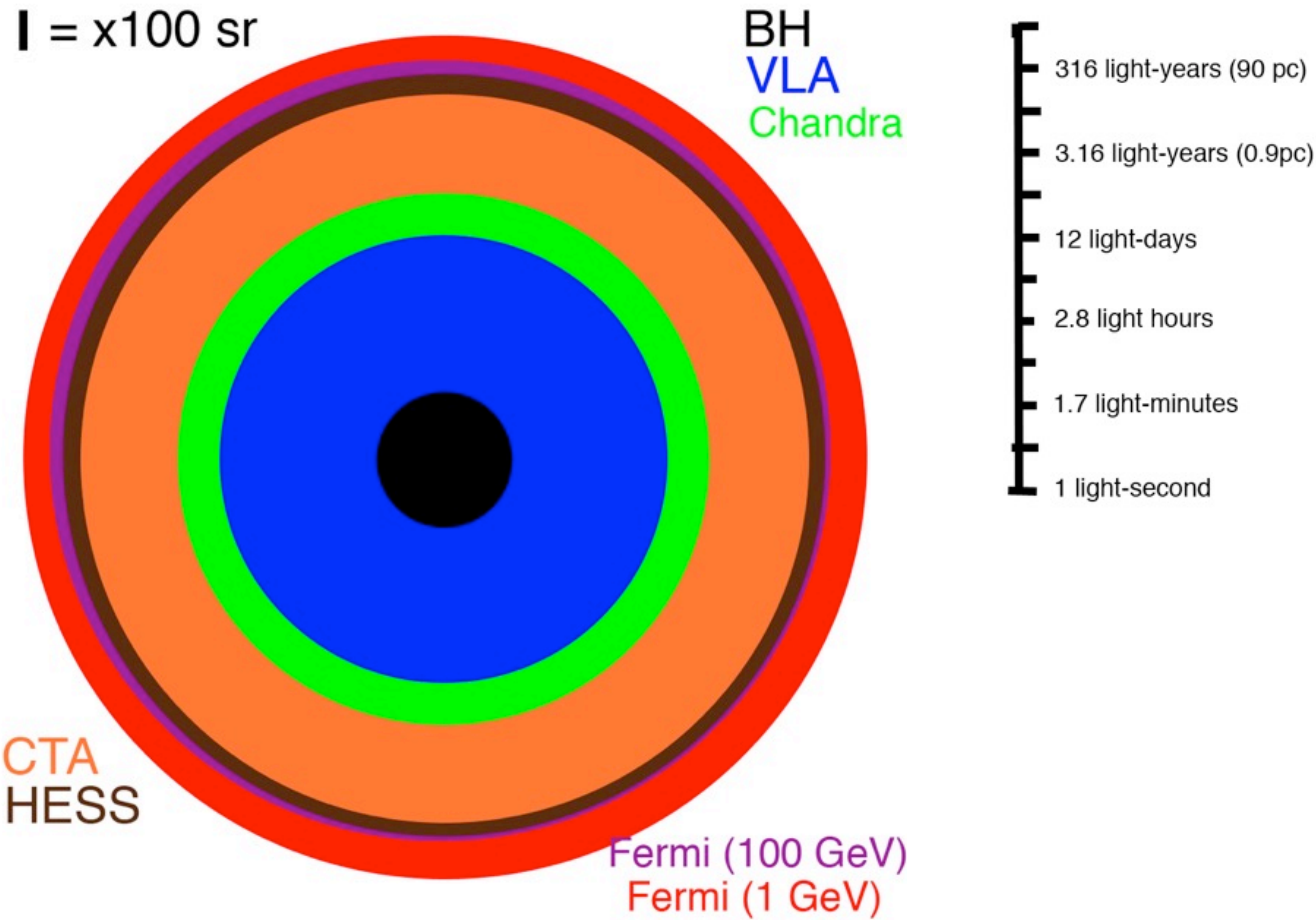


HESS

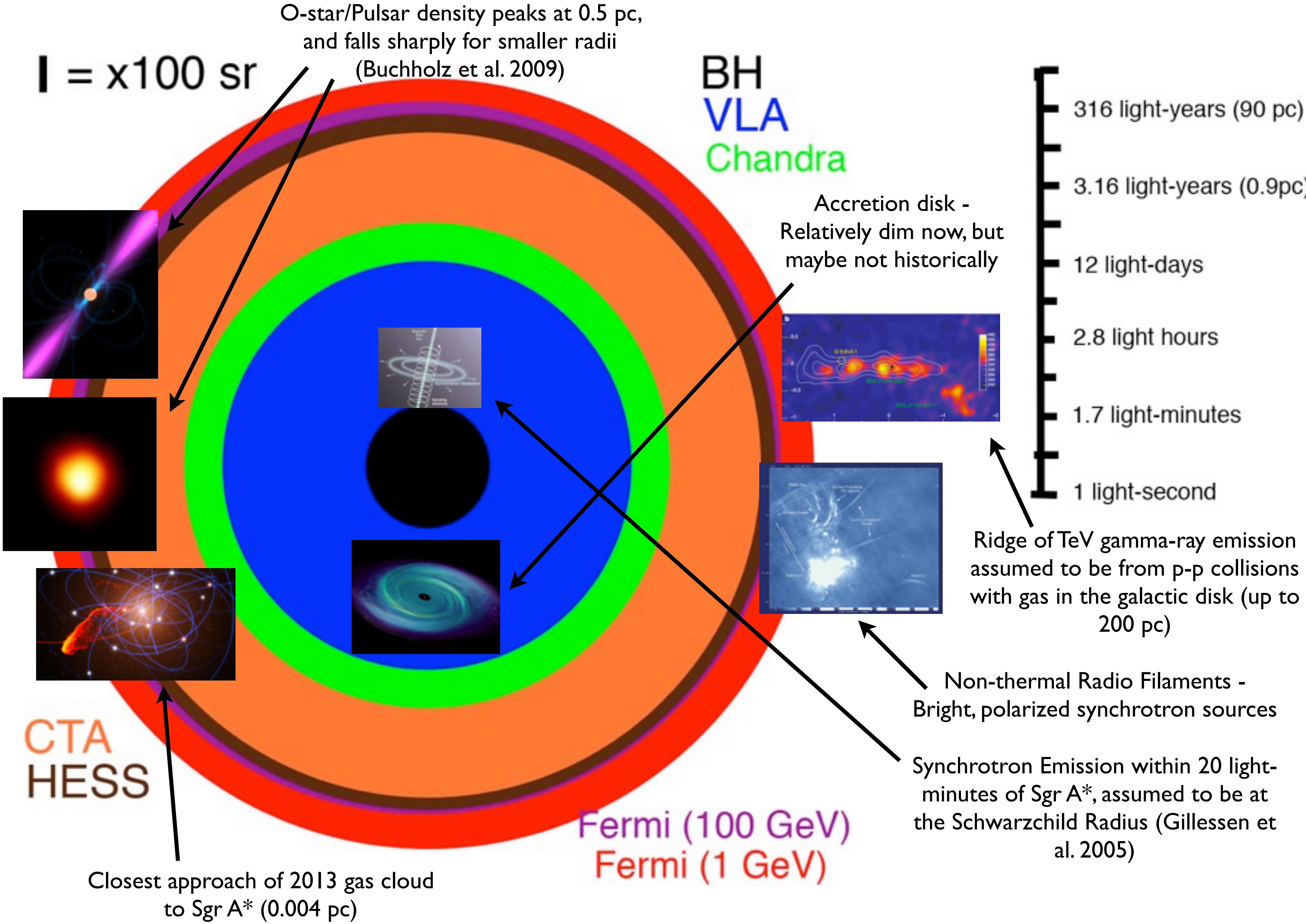


Fermi-LAT

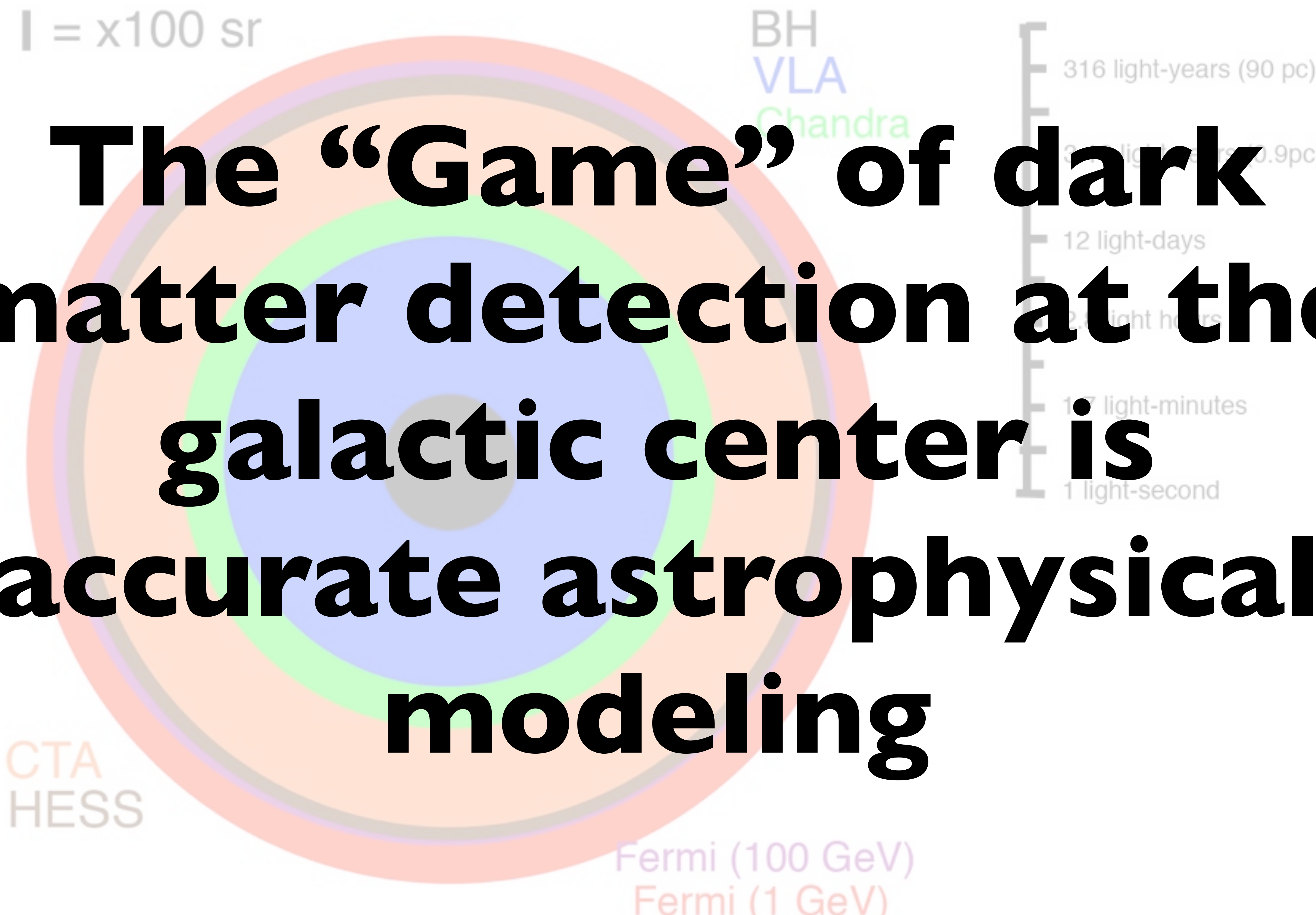
Angular Scales of the Galactic Center



The Galactic Center "Zoo"

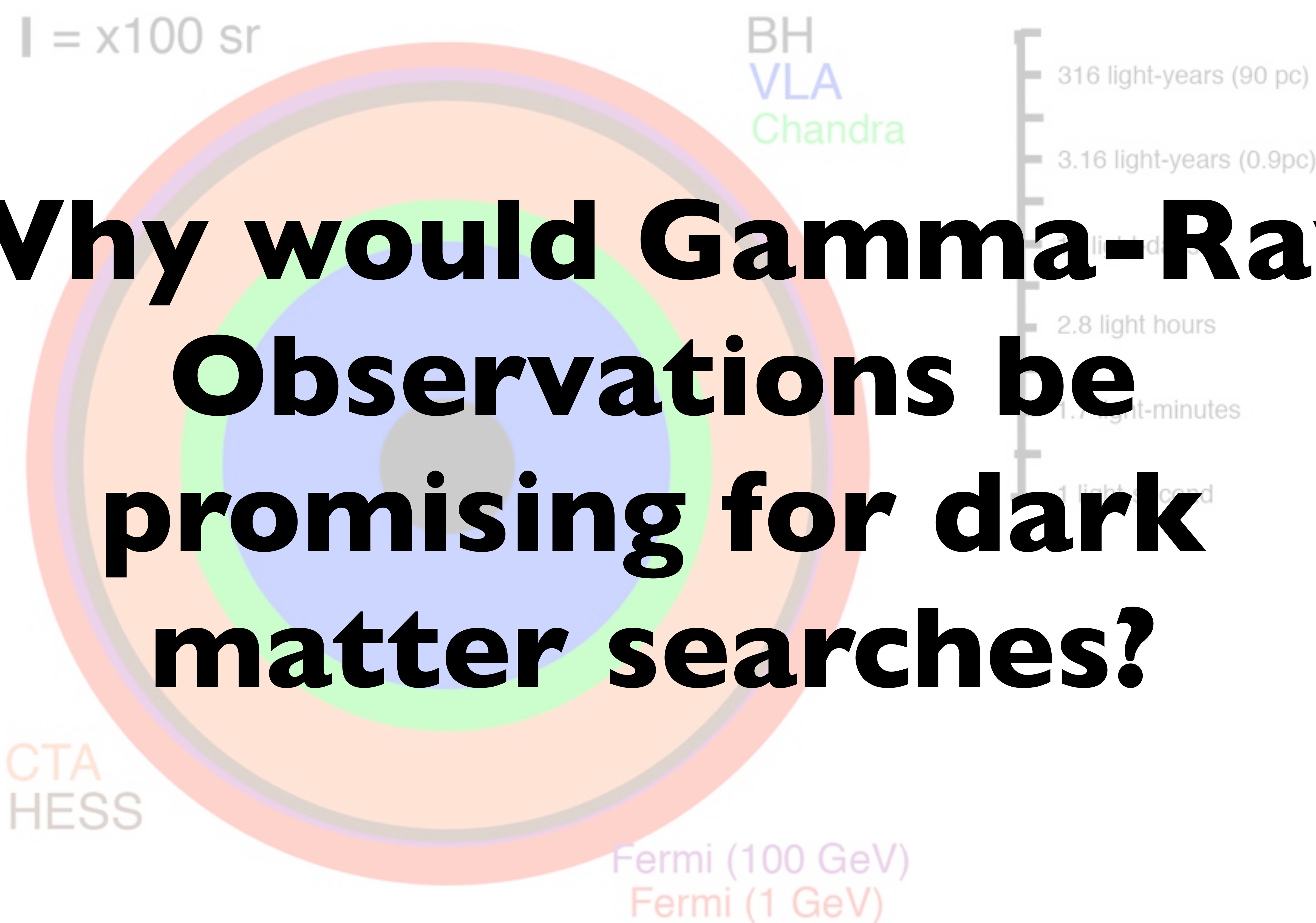


Angular Scales of the Galactic Center



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

Angular Scales of the Galactic Center



Why would Gamma-Ray Observations be promising for dark matter searches?

Why is the Galactic Center Interesting?

Back of the Envelope Calculation

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

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

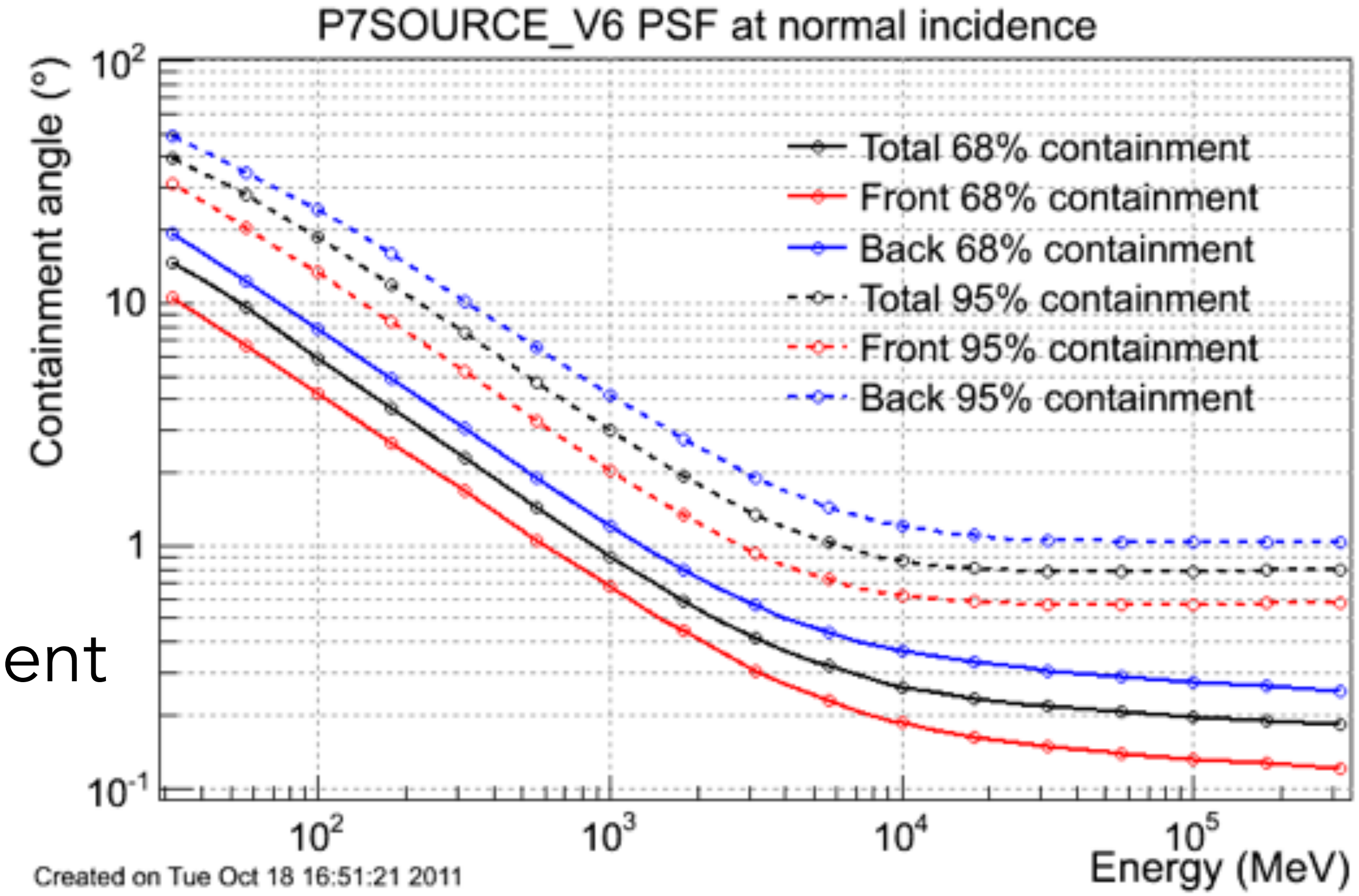
- This is equivalent to the number of photons expected in this energy bin from a "vanilla" 100 GeV dark matter candidate annihilating to bb with a cross-section **$\langle\sigma v\rangle = 1.6 \times 10^{-25}$ cm^3 s^{-1}**

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

Fermi Telescope (2008-Present)

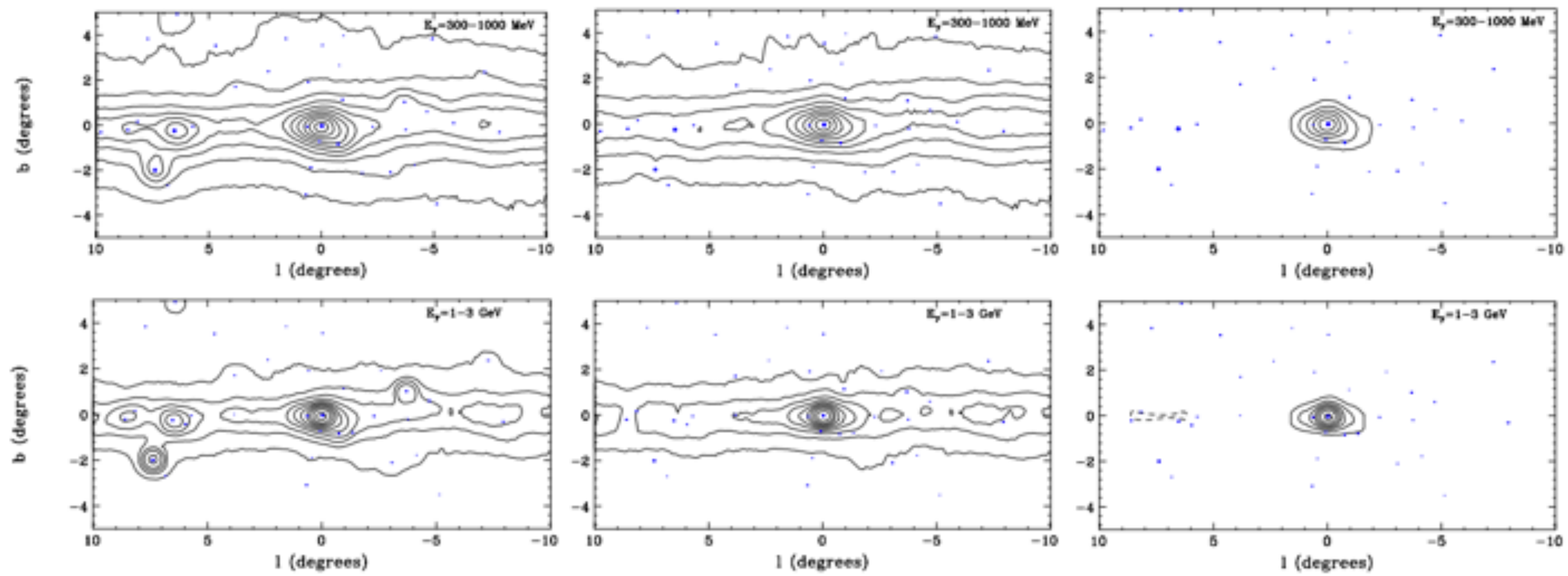
- Fermi-LAT is a space based gamma-ray detector with an effective energy range of 20 MeV-300 GeV

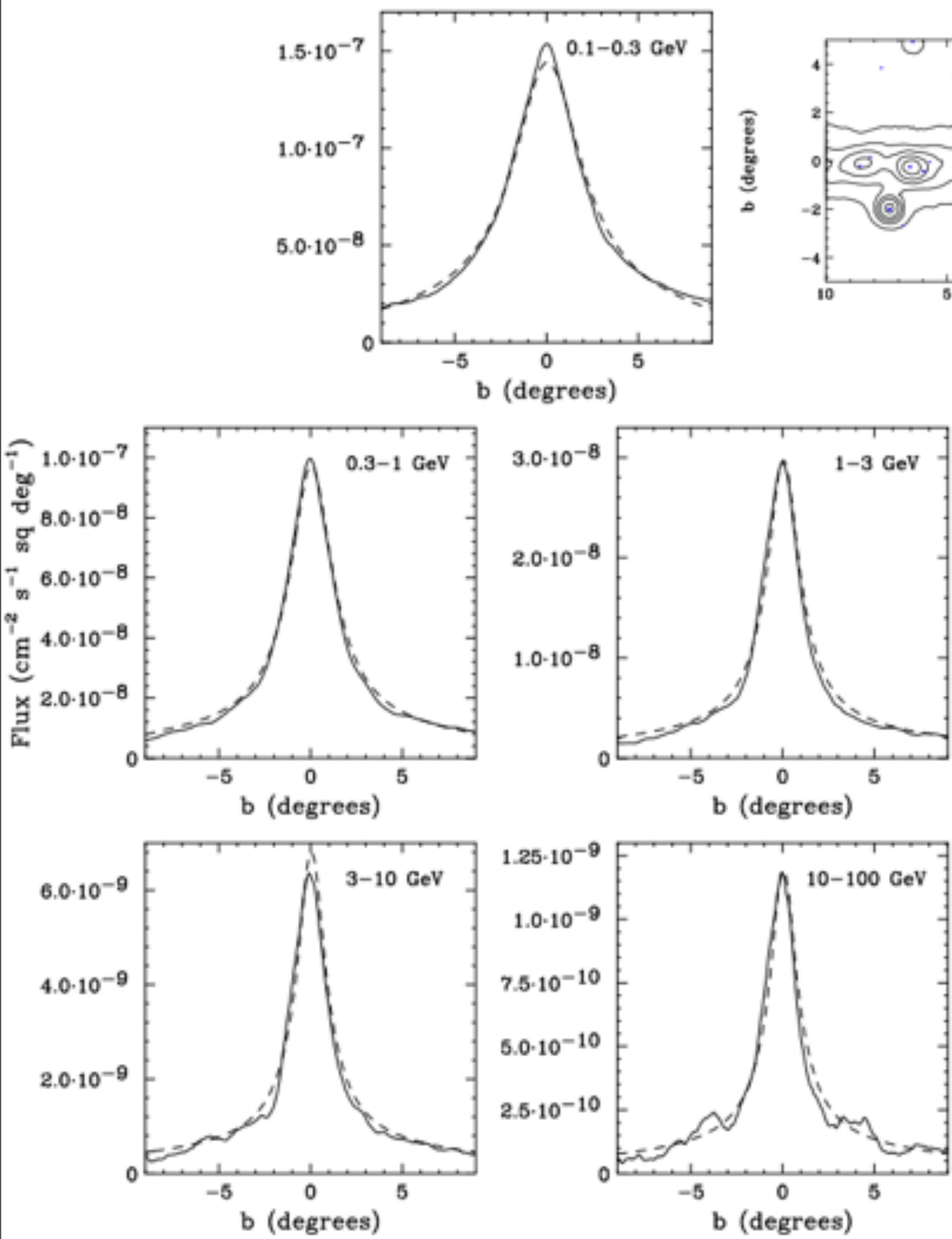
- Effective Area ~ 0.8 m^2
- Field of View ~ 2.4 sr
- Energy Resolution ~ 10%
- Angular Resolution: Energy Dependent



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

Subtracting the Astrophysical Background: Fermi

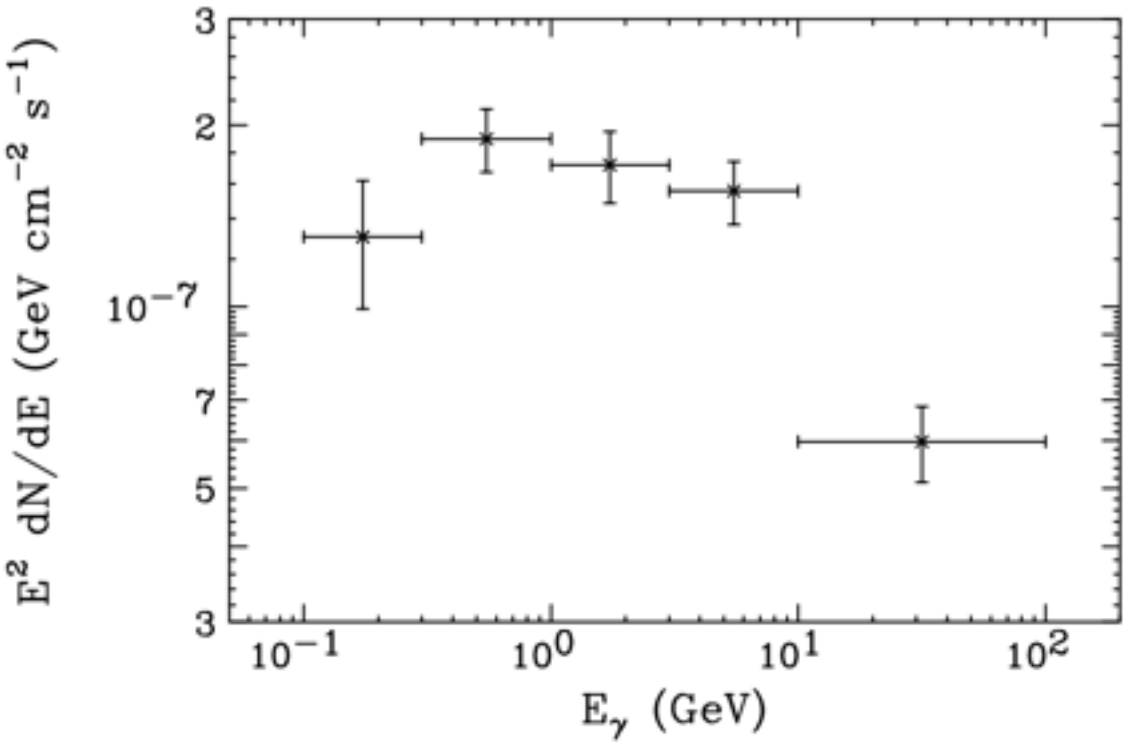




- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum
- This large residual at the center of the galaxy is a factor of 10 brighter than anything else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

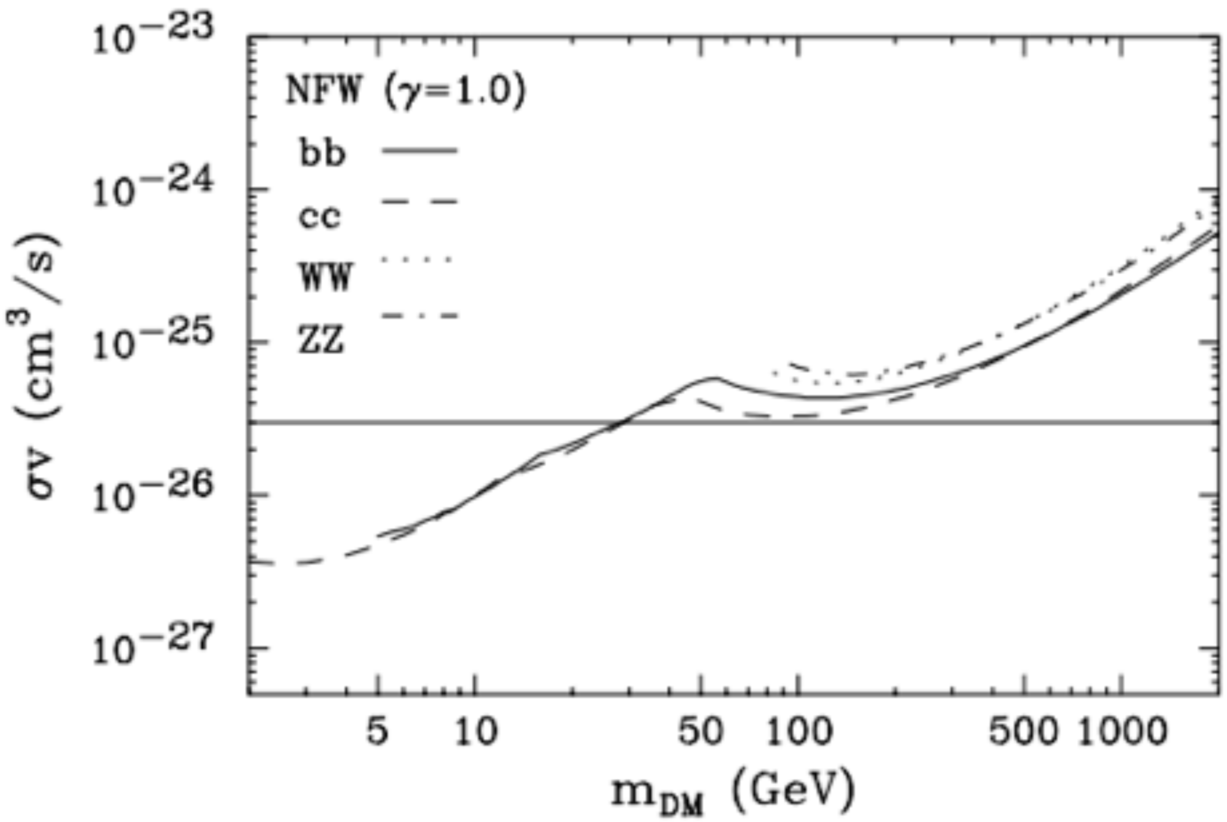
Hooper & Linden (2011)

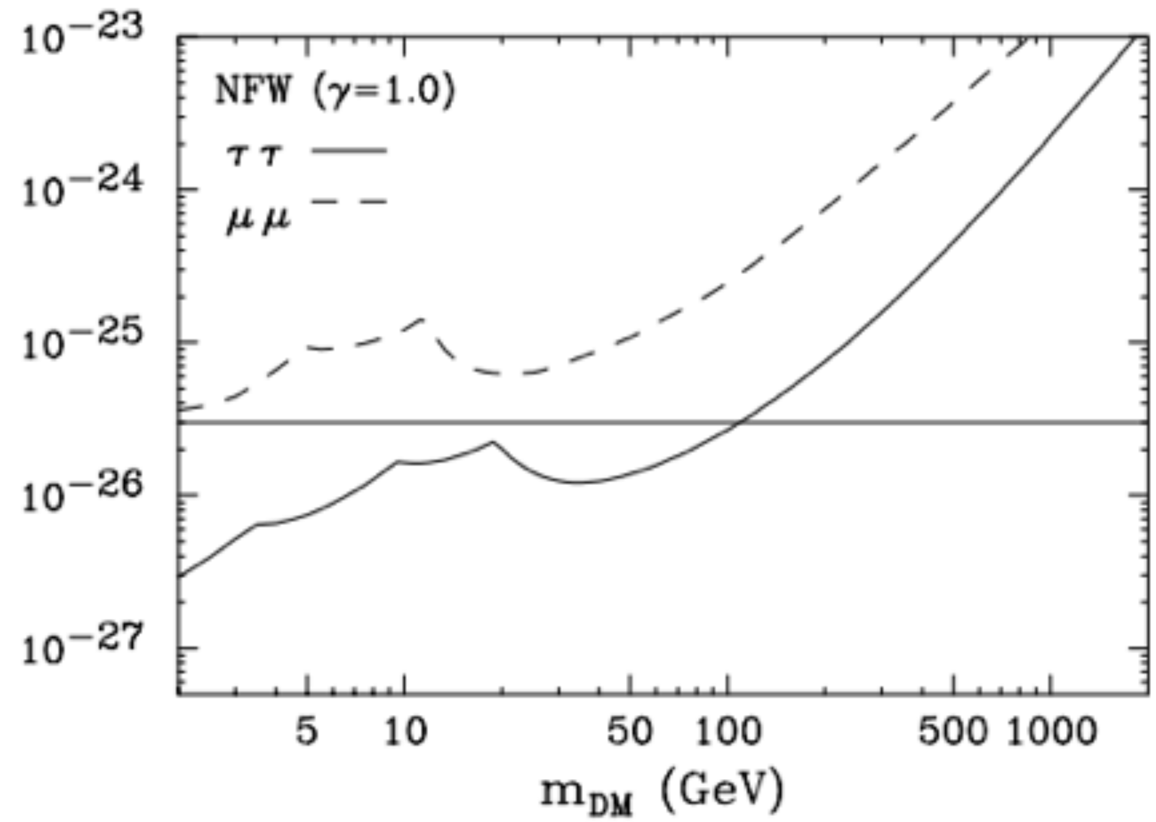
Dark Matter Limits in the Simplest Way Possible



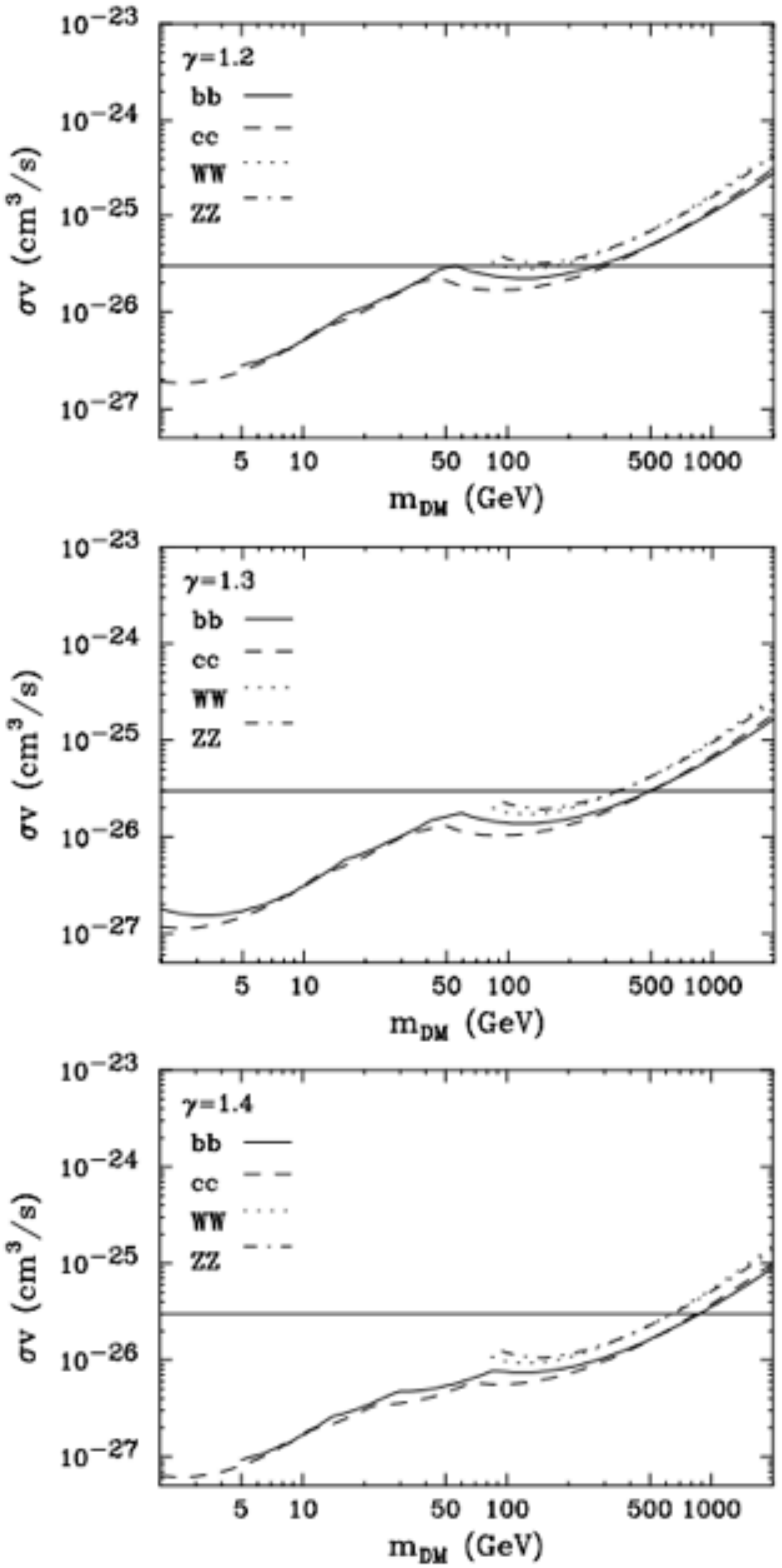
Hooper & Linden (2011)

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



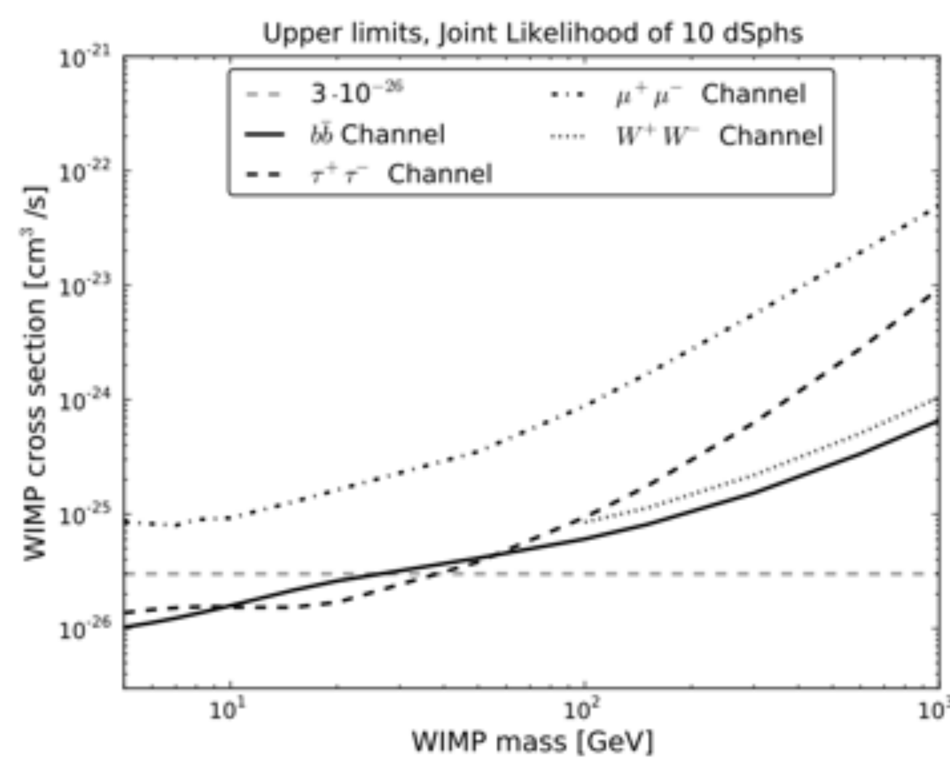


Comparison to Other Indirect Detection Regimes



Hooper & Linden (2011)

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

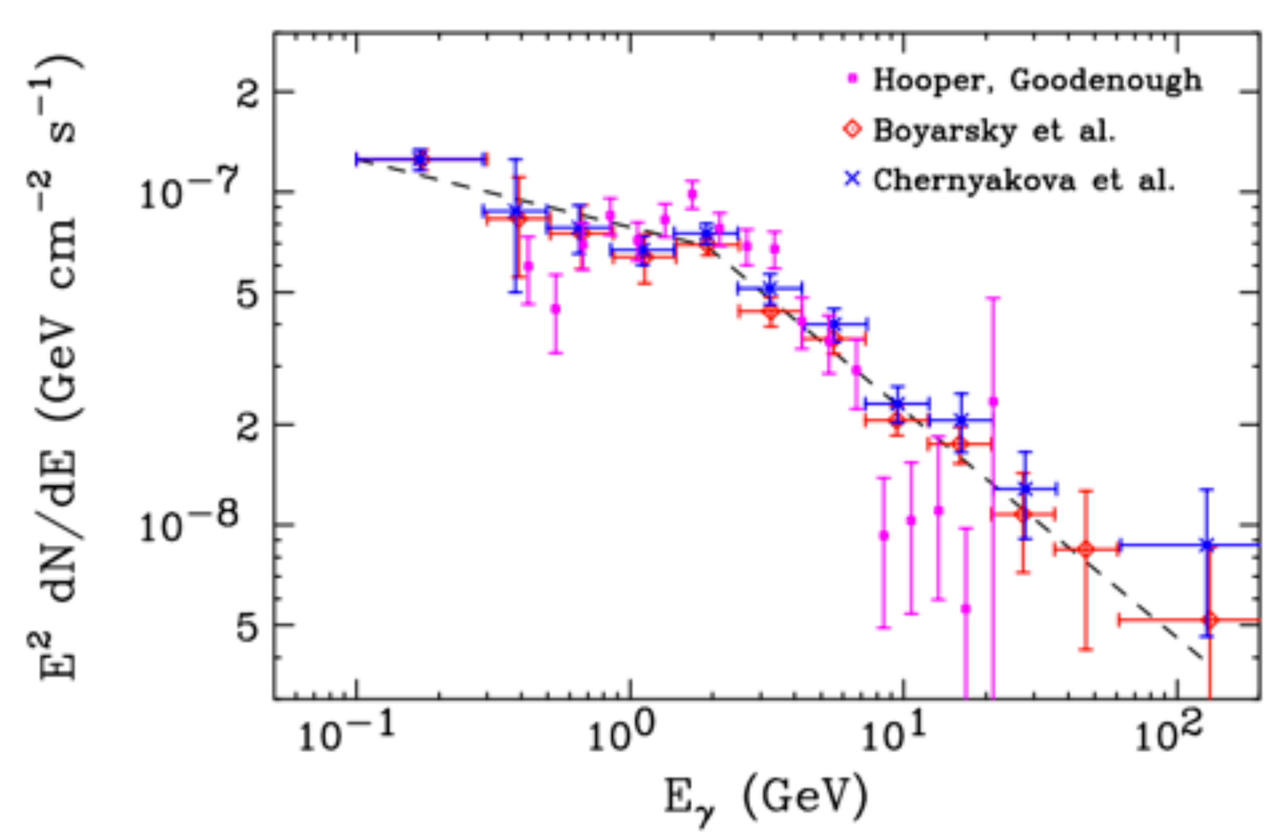


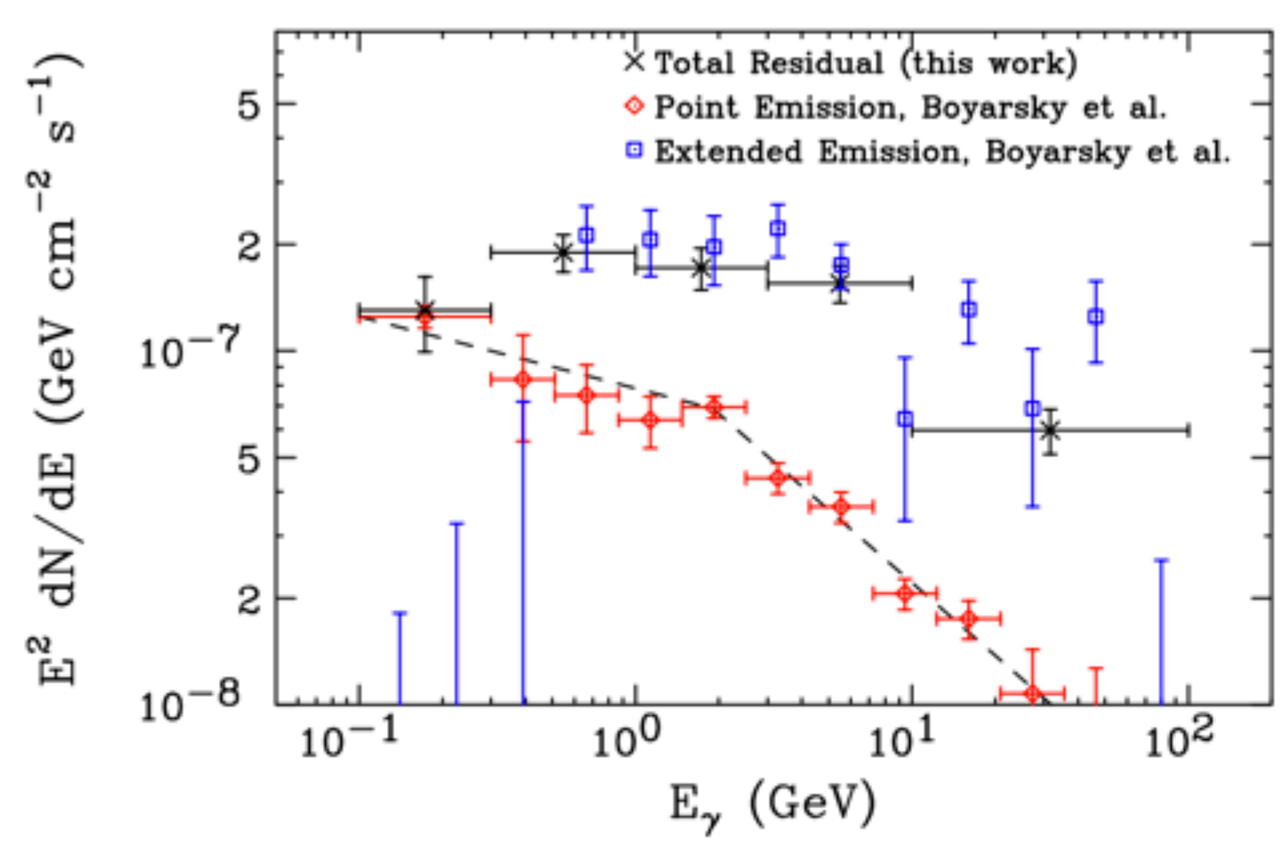
Ackermann et al. (2011)

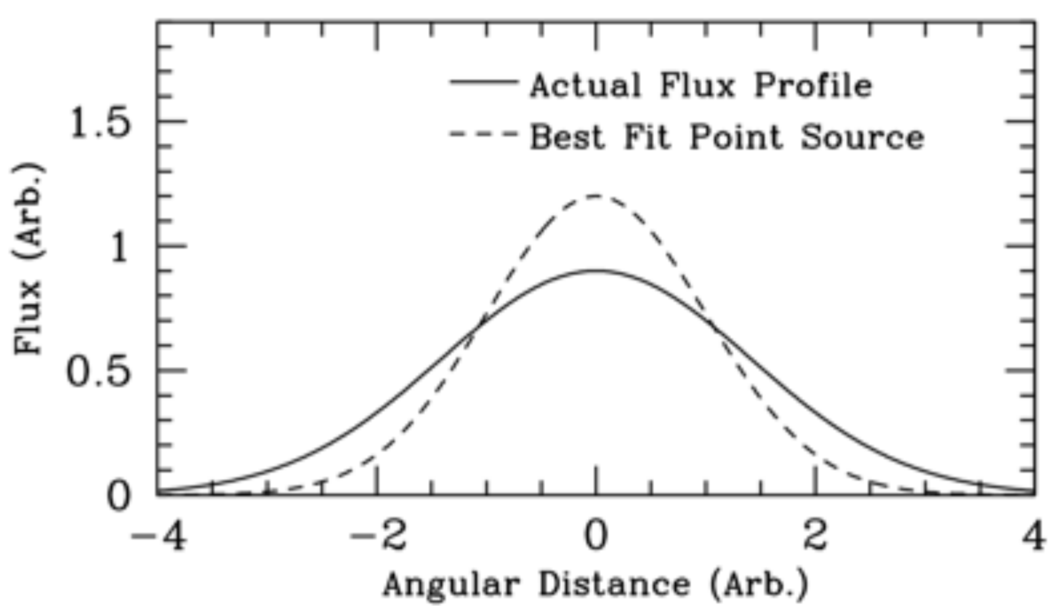
Understanding the GC Point Source: Fermi

- 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)

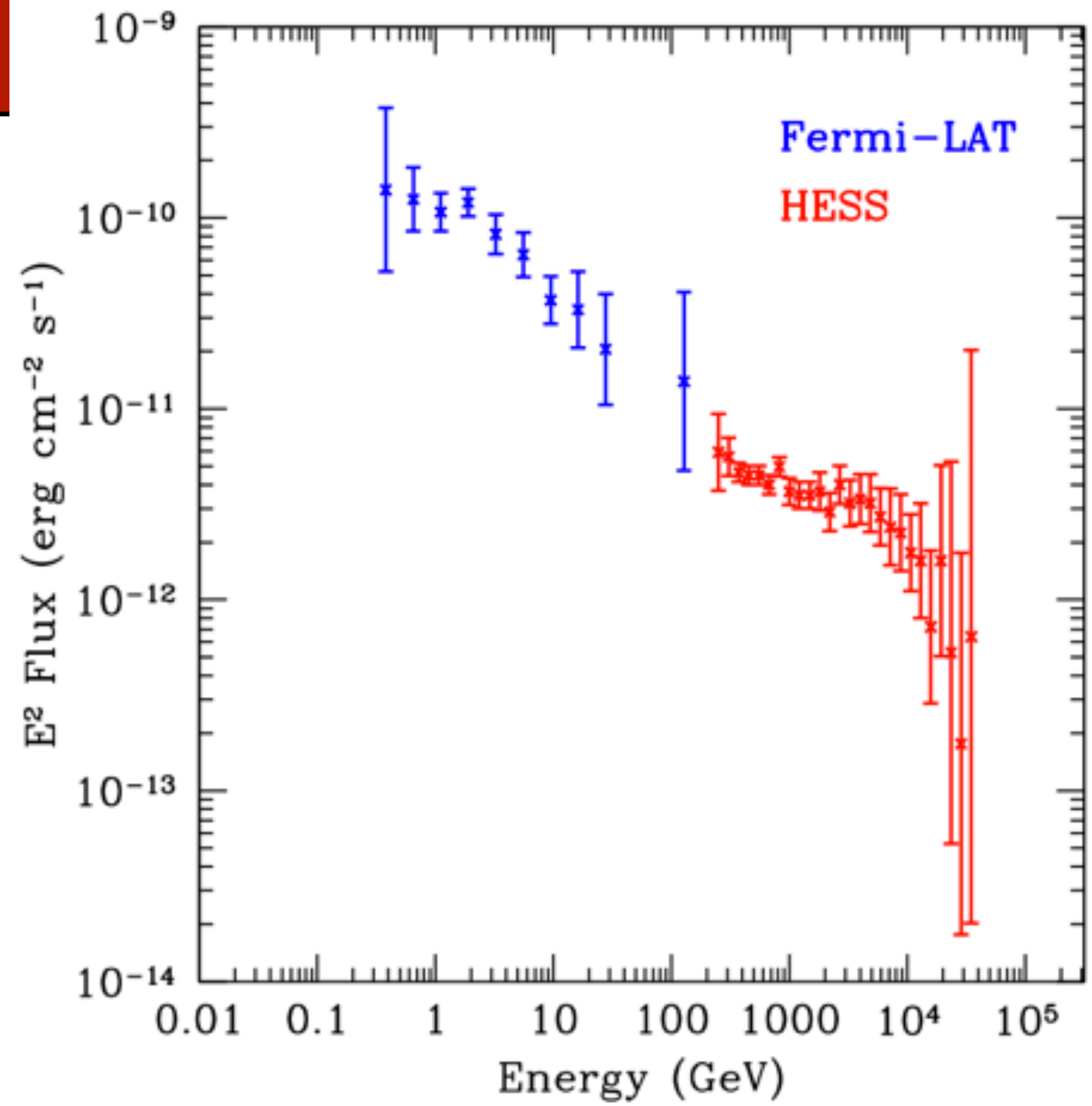
So You Think You've Found An Excess?

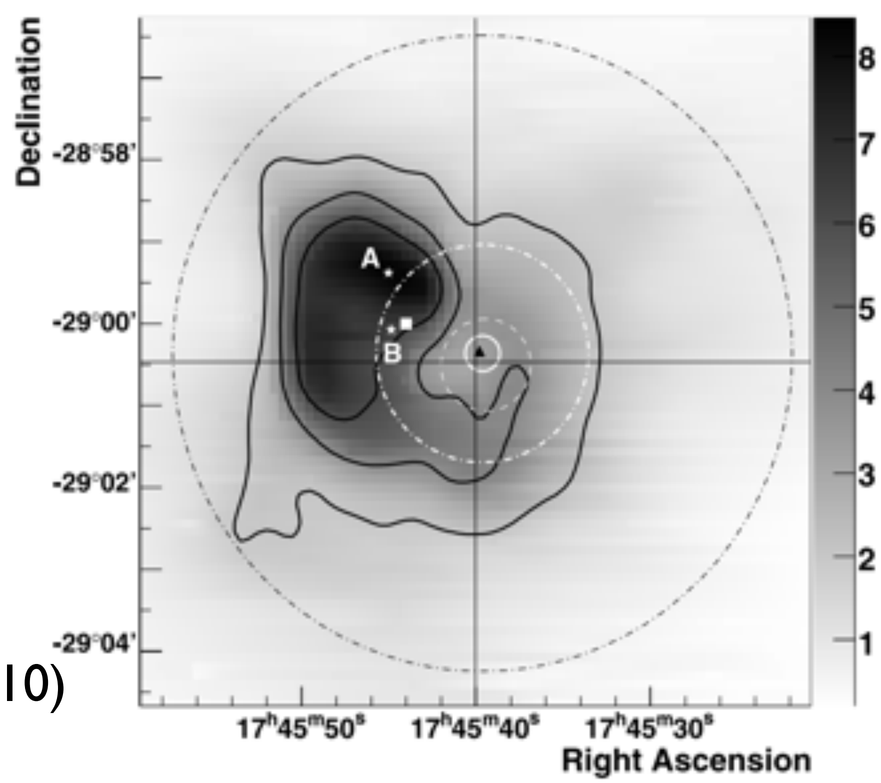
- These observations have yielded strong evidence for a bright, extended, spherically symmetric gamma-ray residual around the galactic center

- What can we learn about physics from these observations?

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

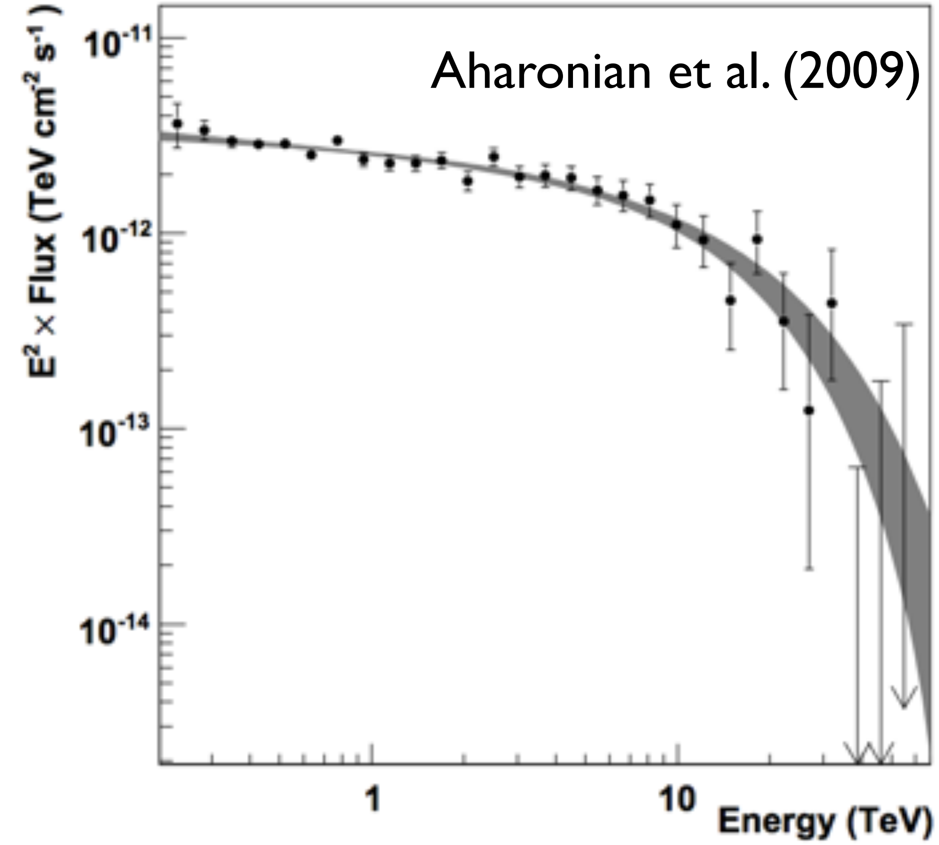




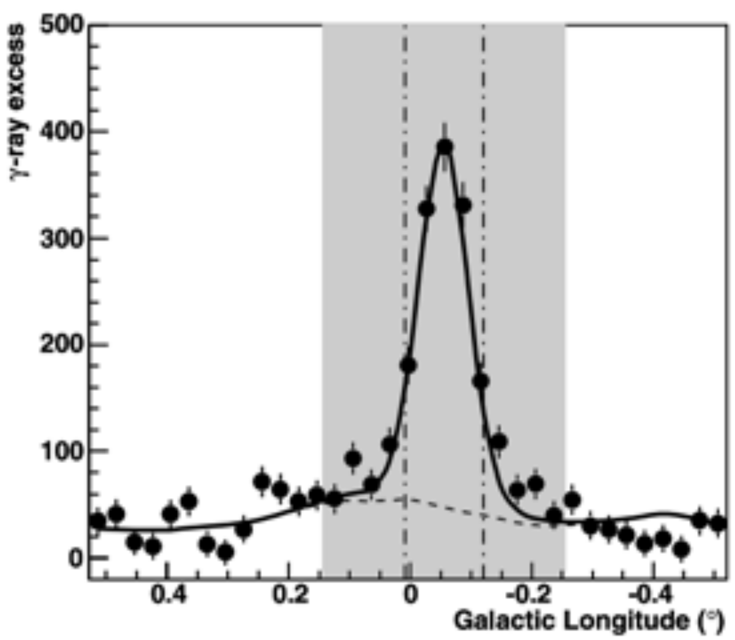
Acero et al. (2010)

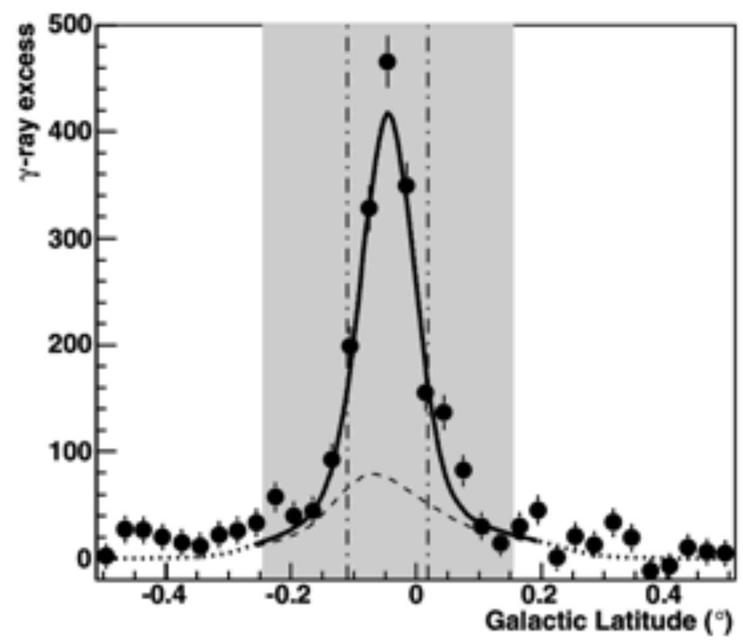
Understanding Astrophysical Backgrounds: HESS

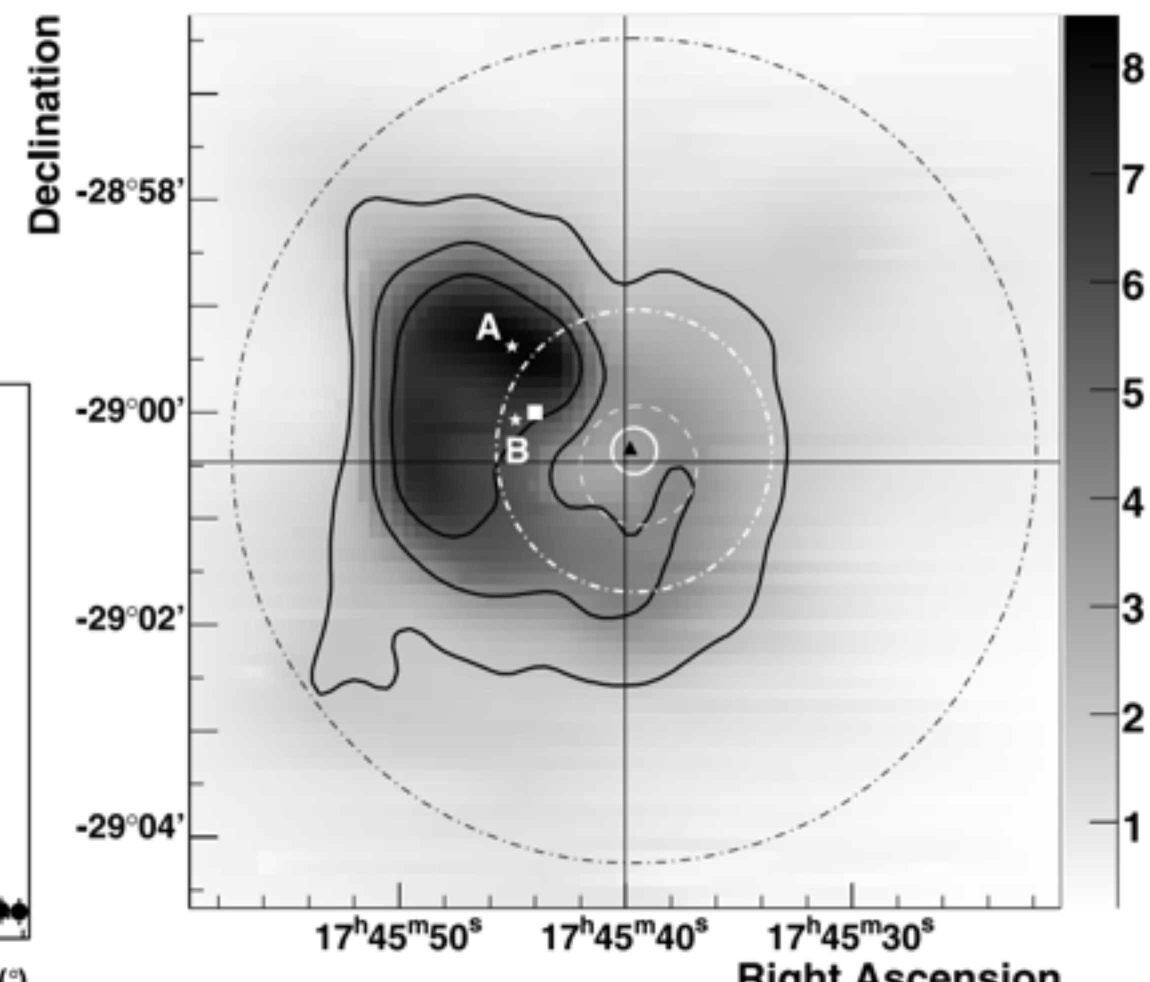
- HESS spectrum well matched by flat E^{-2} spectrum, up to energies of ~10 TeV, where an exponential cutoff is observed



- 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



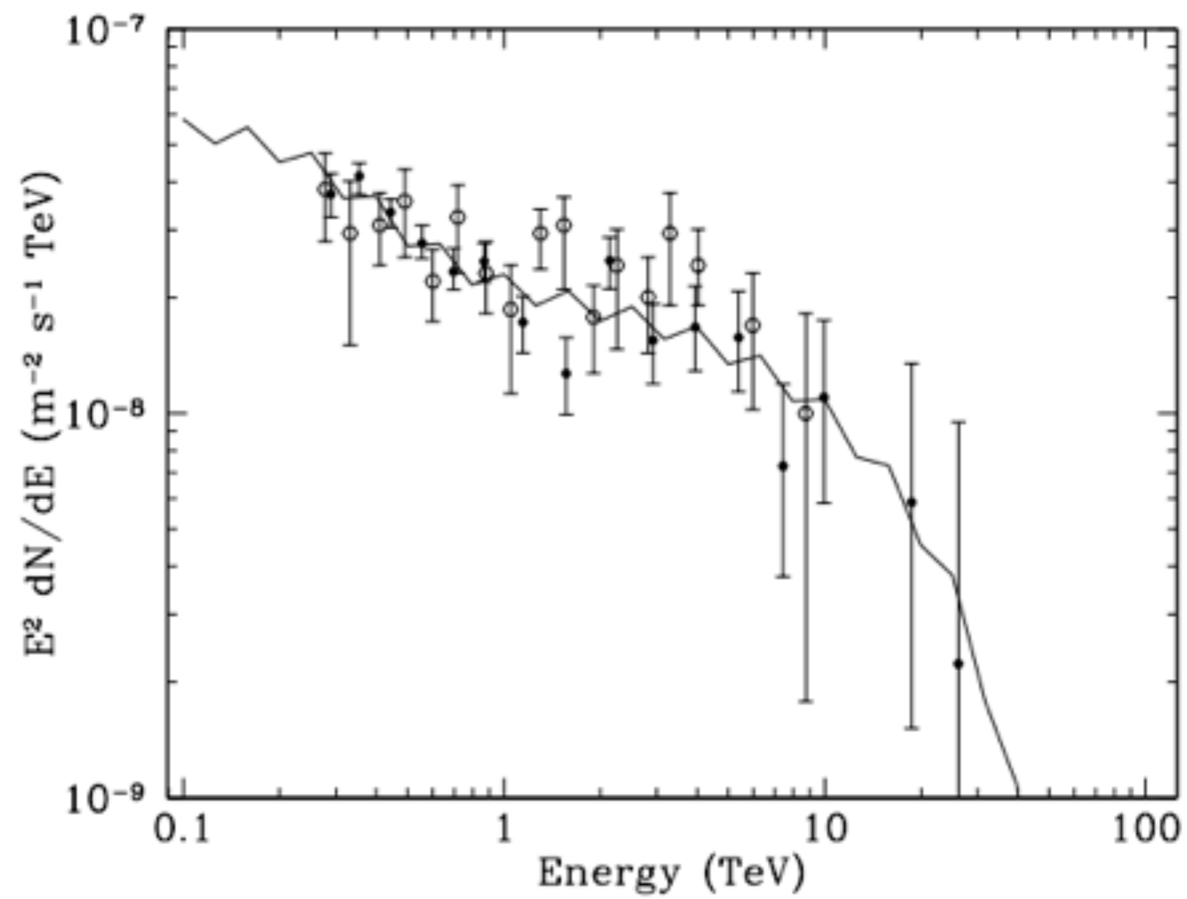


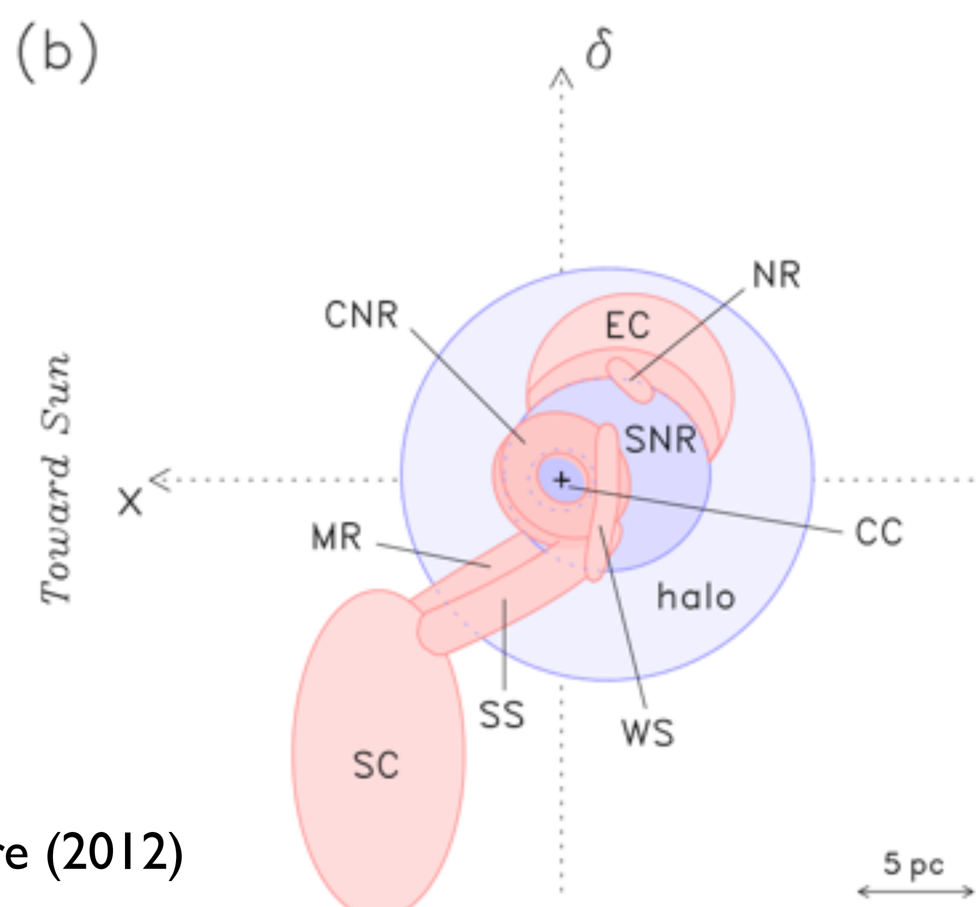


Acero et al. (2010)

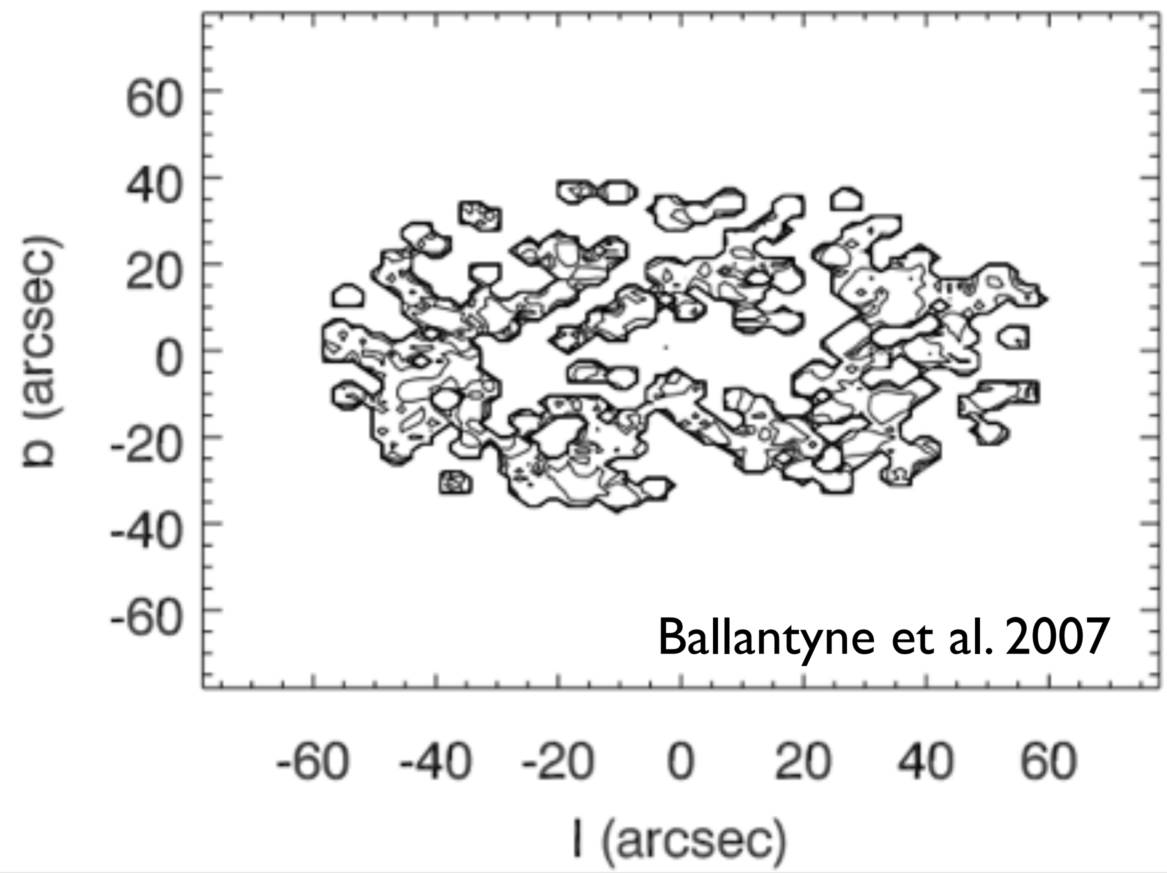
Fitting the Residual: Hadronic Processes

- 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





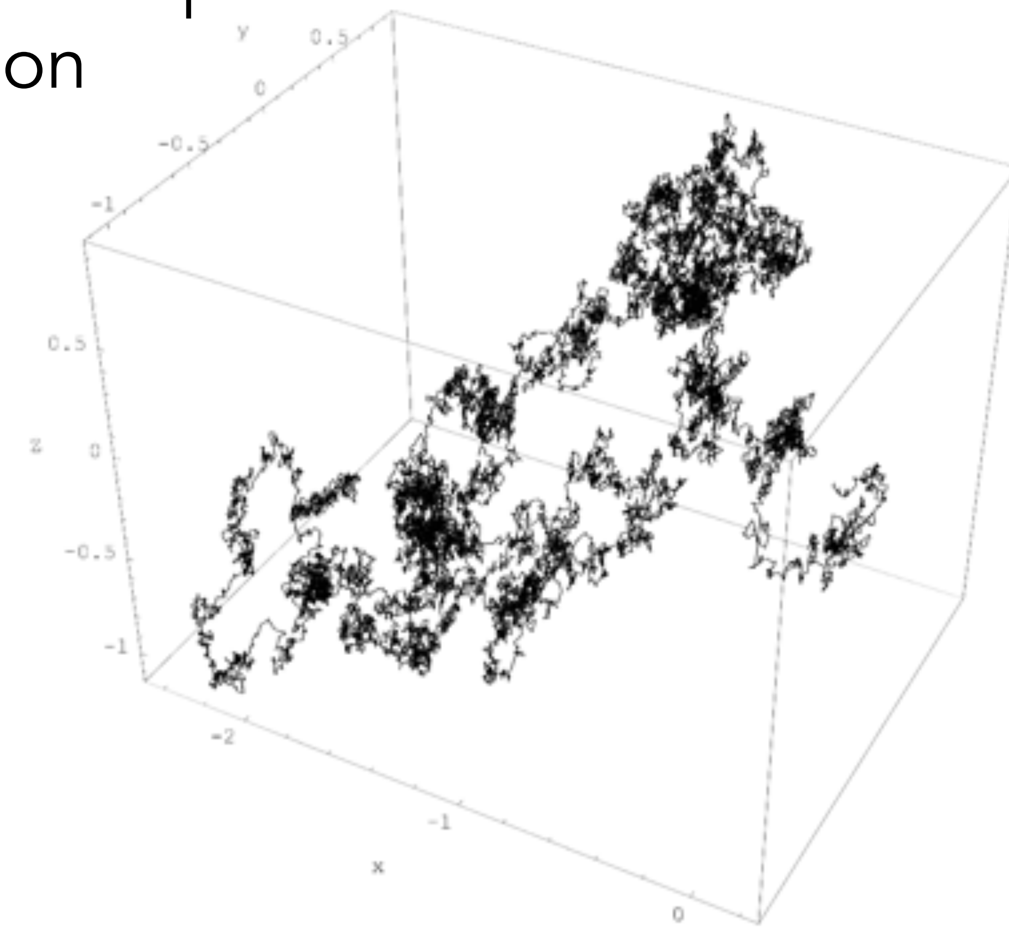
Ferriere (2012)



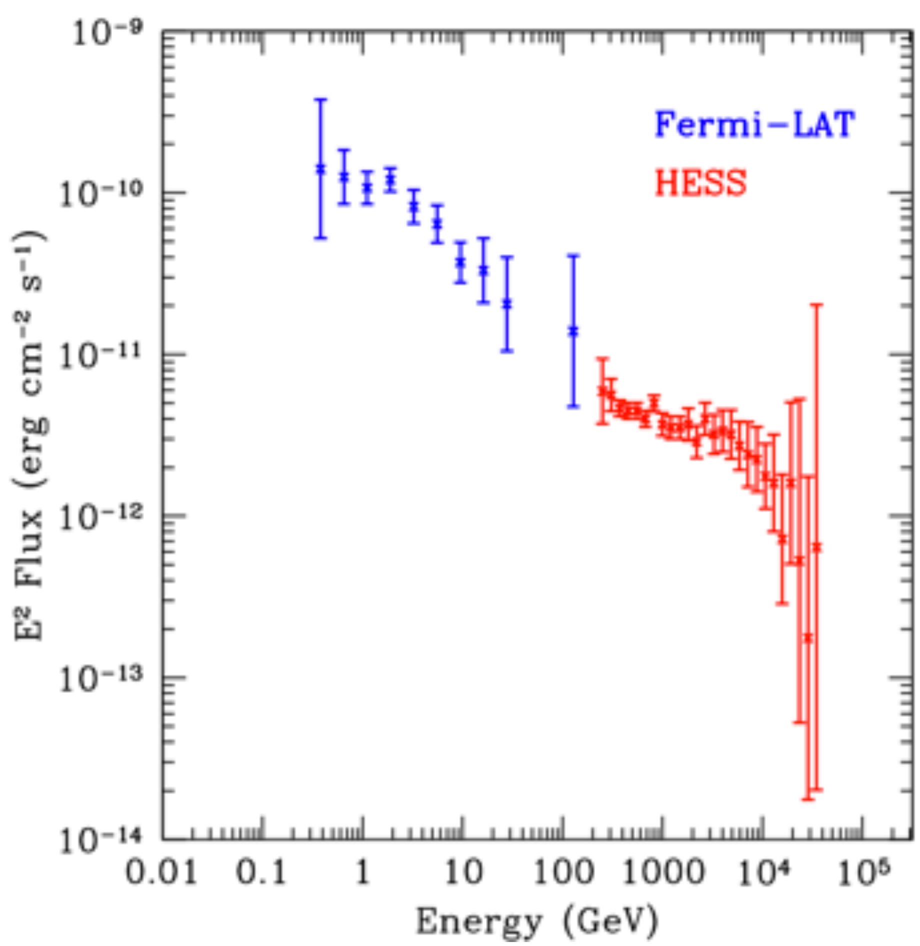
Ballantyne et al. 2007

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

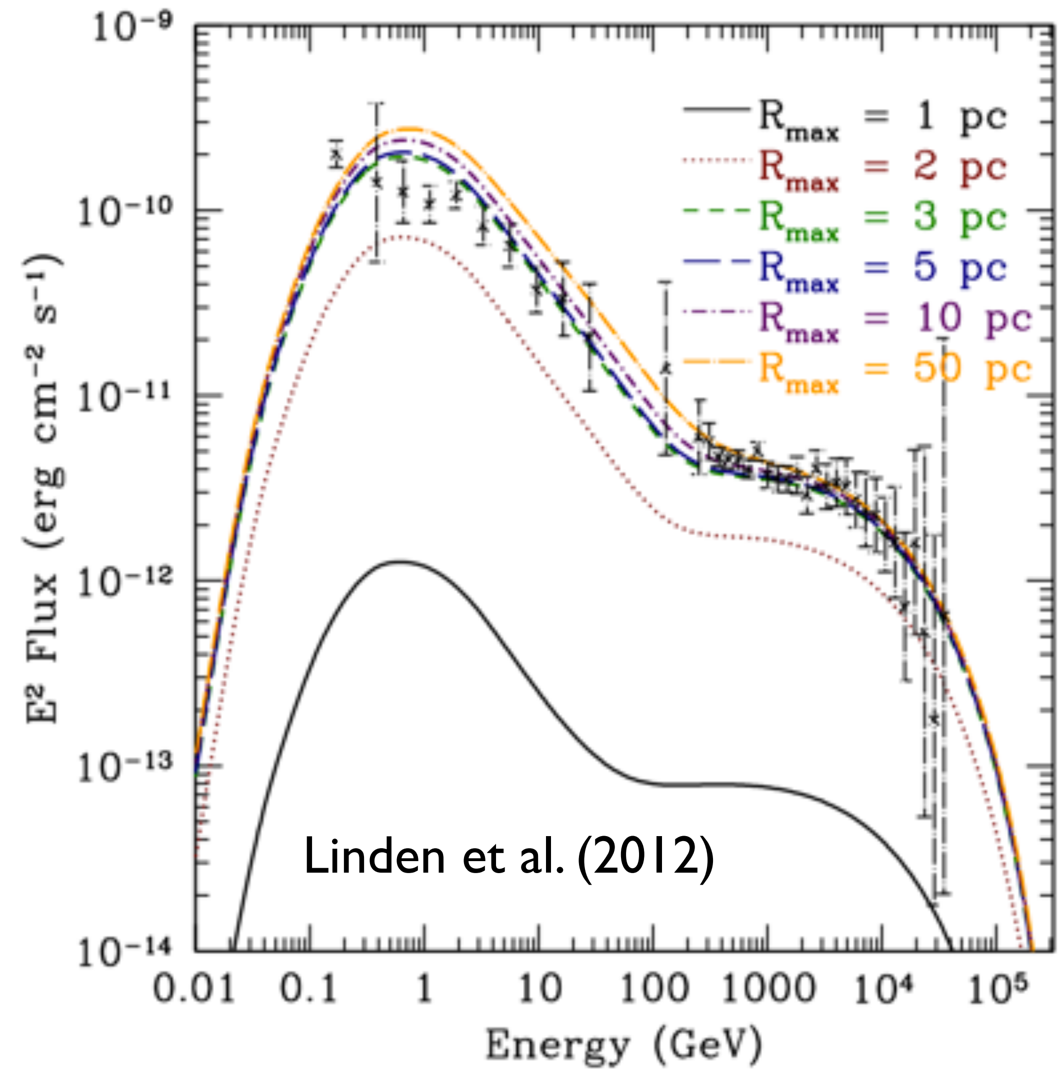


- In the regime where the diffusion step is small, then the emission intensity depends linearly on the time the particle spends within the diffusion region

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:

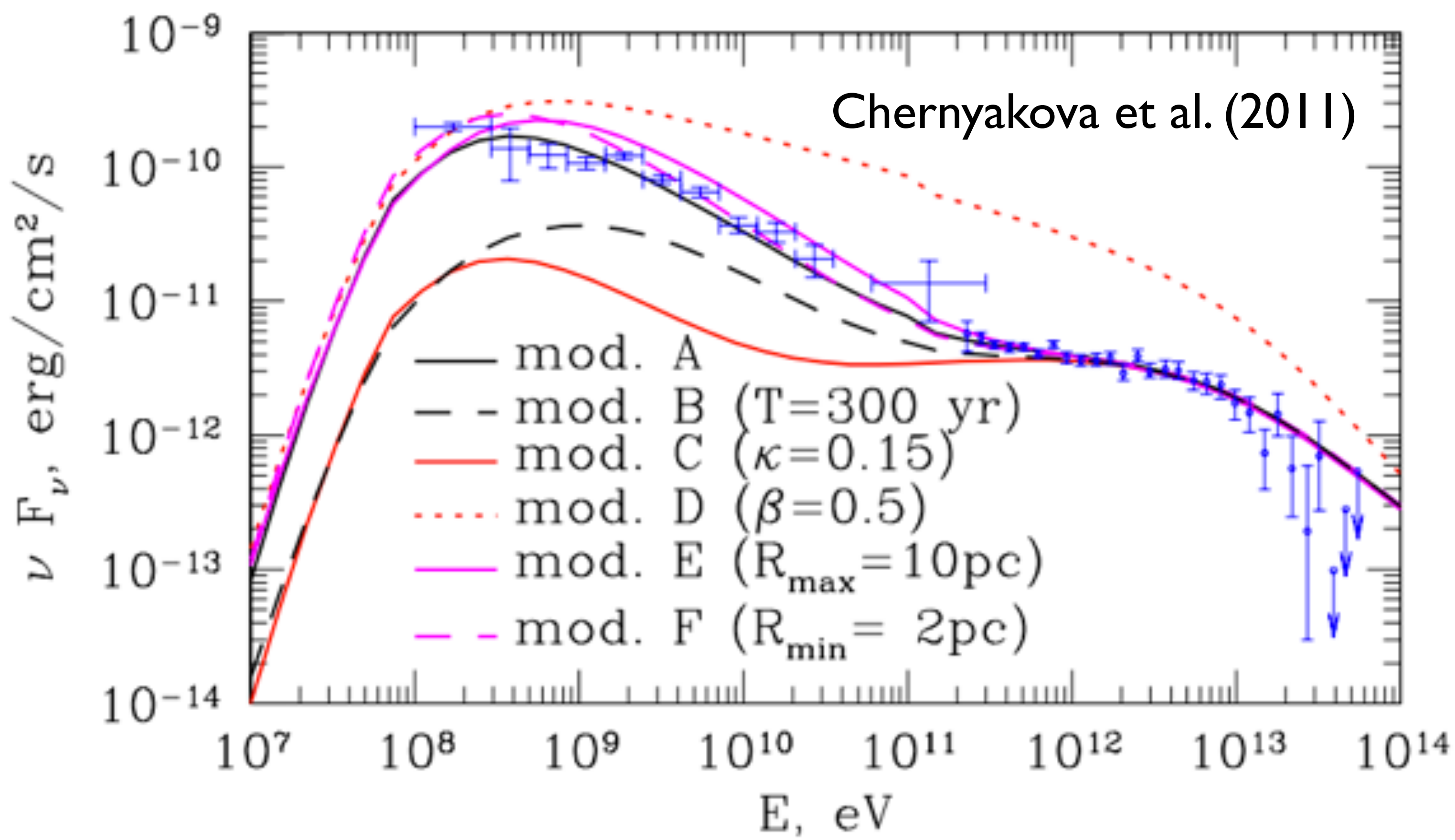
$$D_0 = 1.2 \times 10^{26} (E/1 \text{ GeV})^{0.91}$$



- 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.

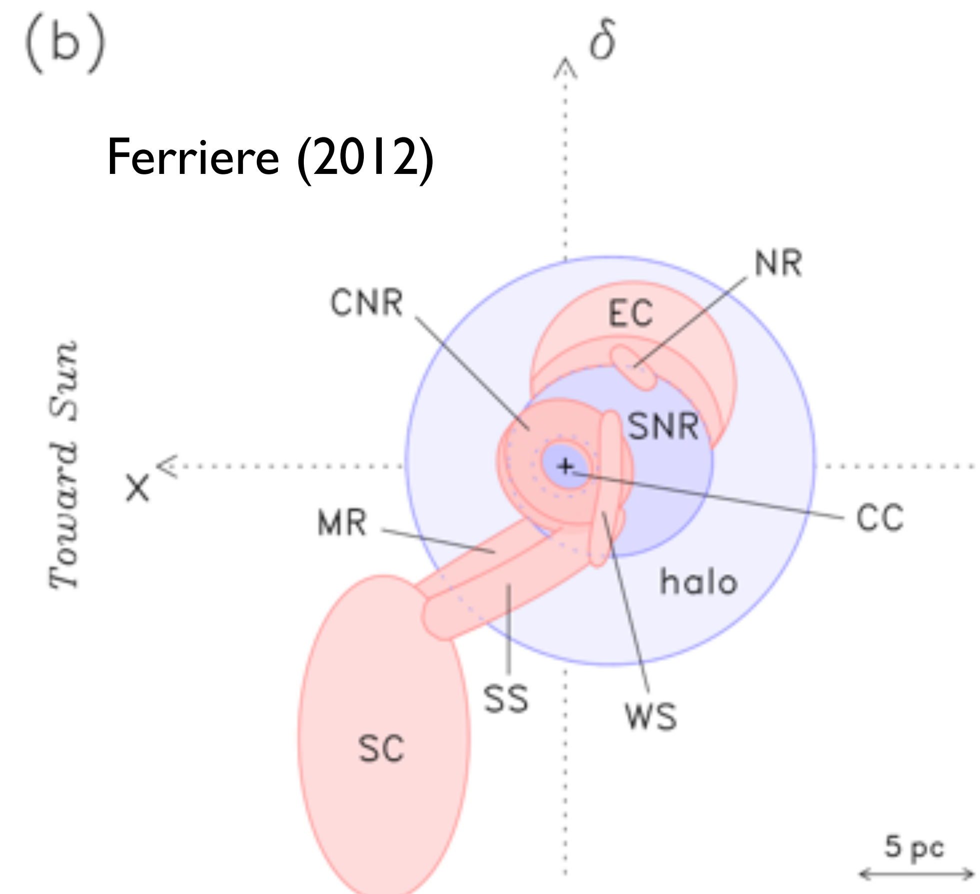
- Models are formed with a step-function gas density profile (1000 n_H/cm^{-3} within 3 pc of the galactic center, and 0 n_H/cm^{-3} outside)

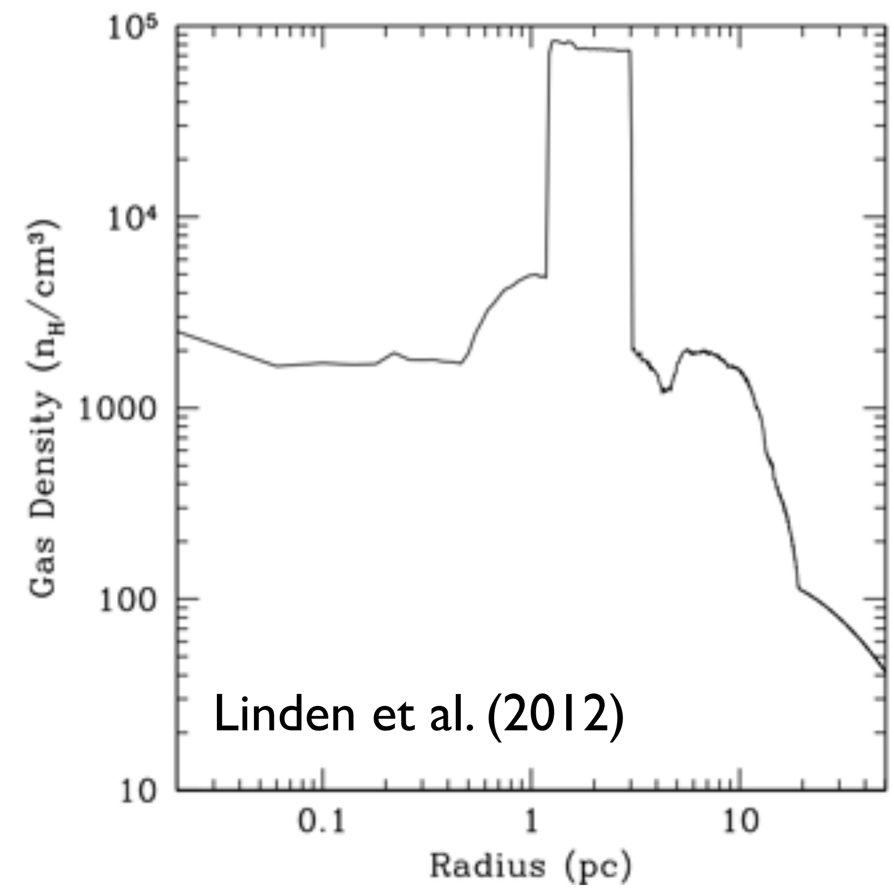
Employing a Realistic Gas Model

- 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

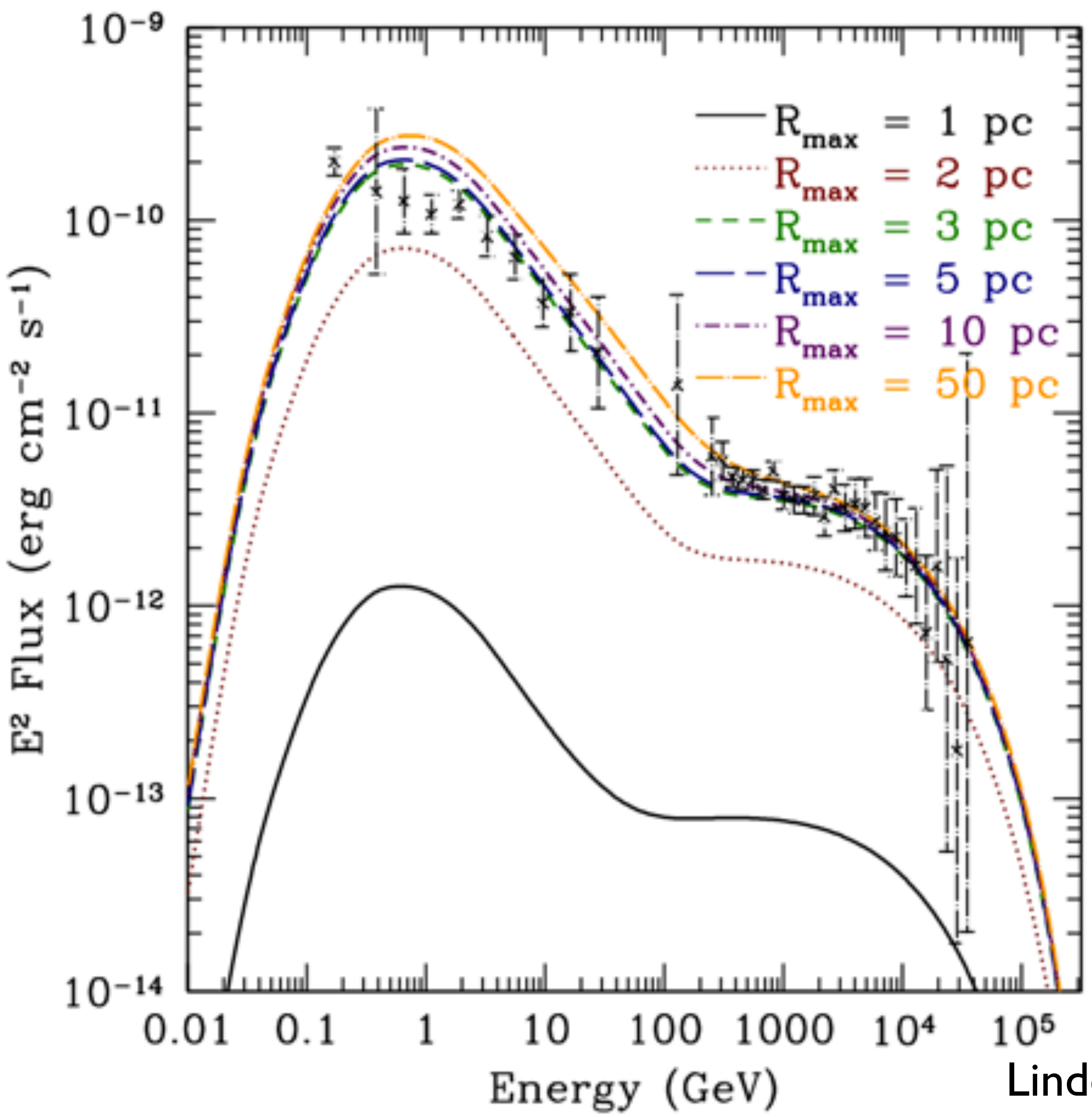
- By far the dominant feature is the Circumnuclear ring between 1-3 pc from the GC

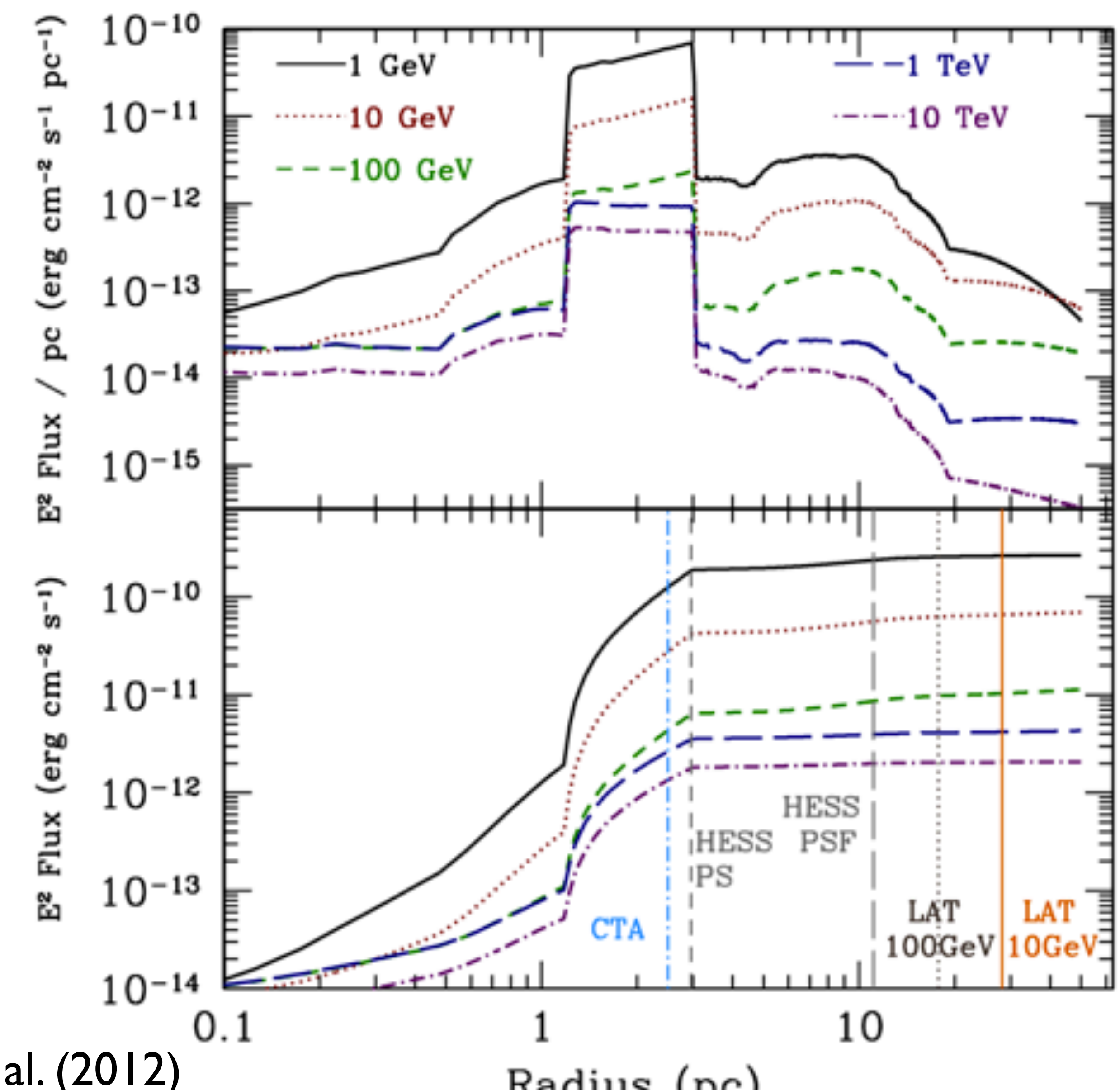




Employing a Realistic Gas Model

- 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

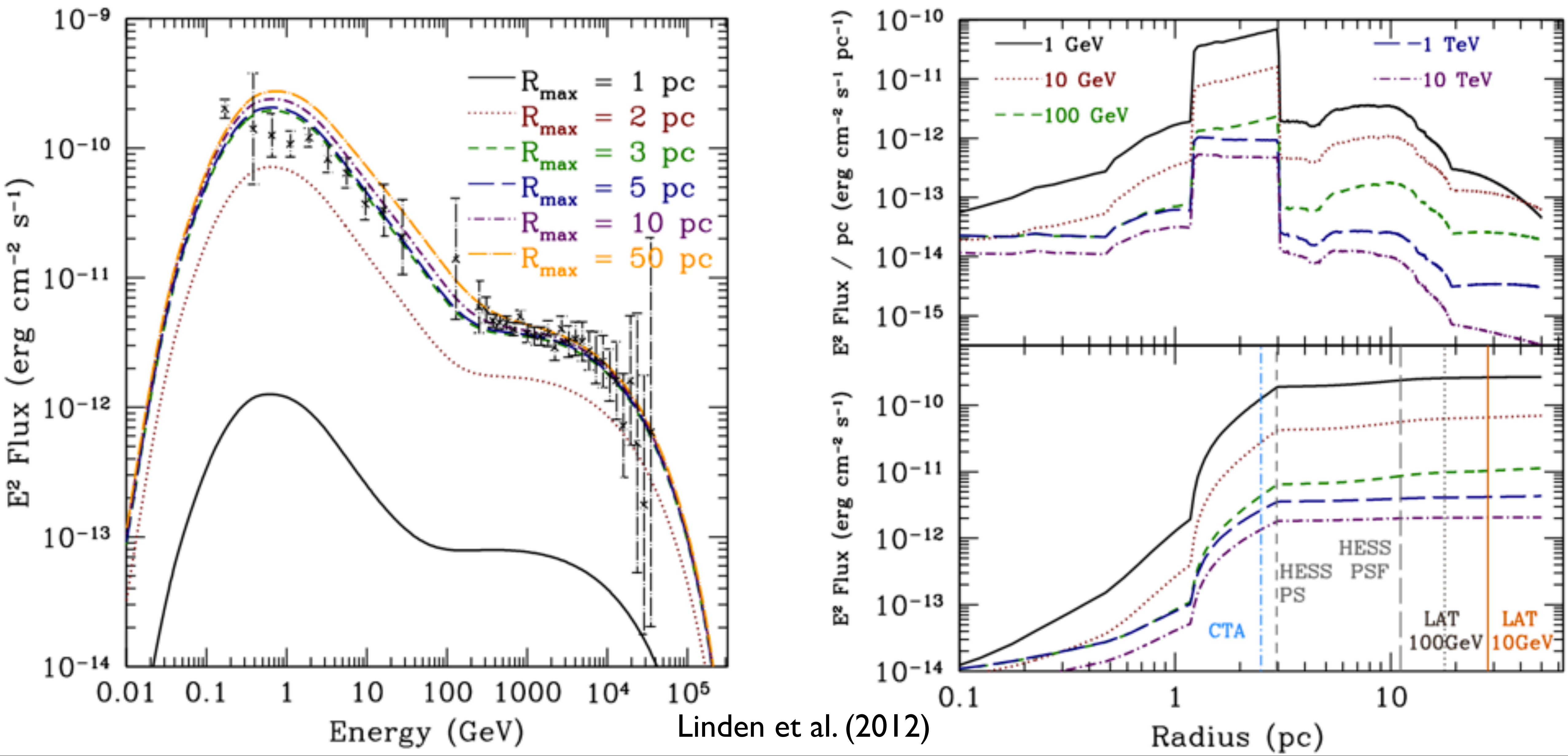




Linden et al. (2012)

The Gas Morphology Dominates the Gamma-Ray Morphology From Proton Emission

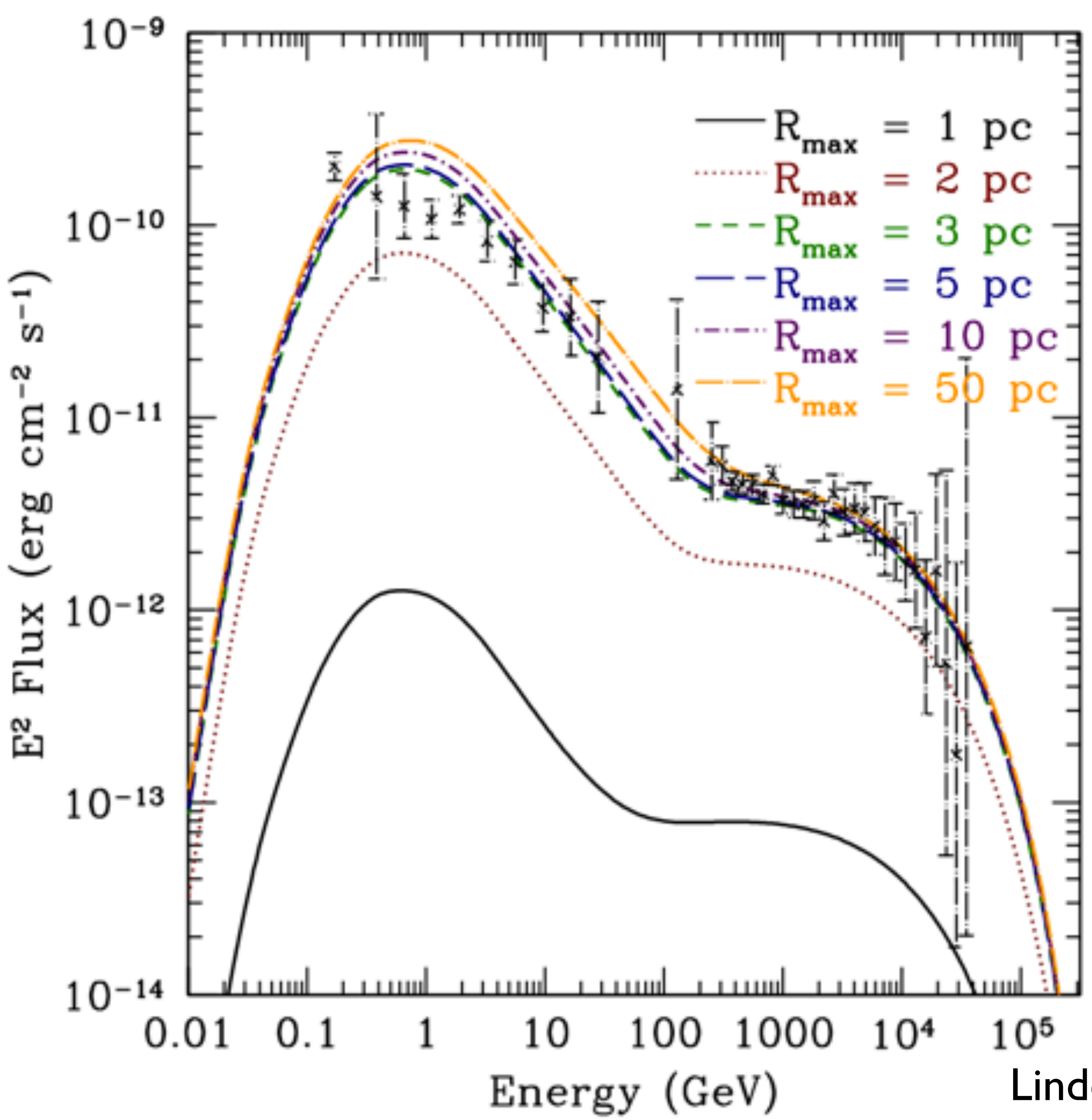
Thus Hadronic Emission Can't Explain the GeV Excess

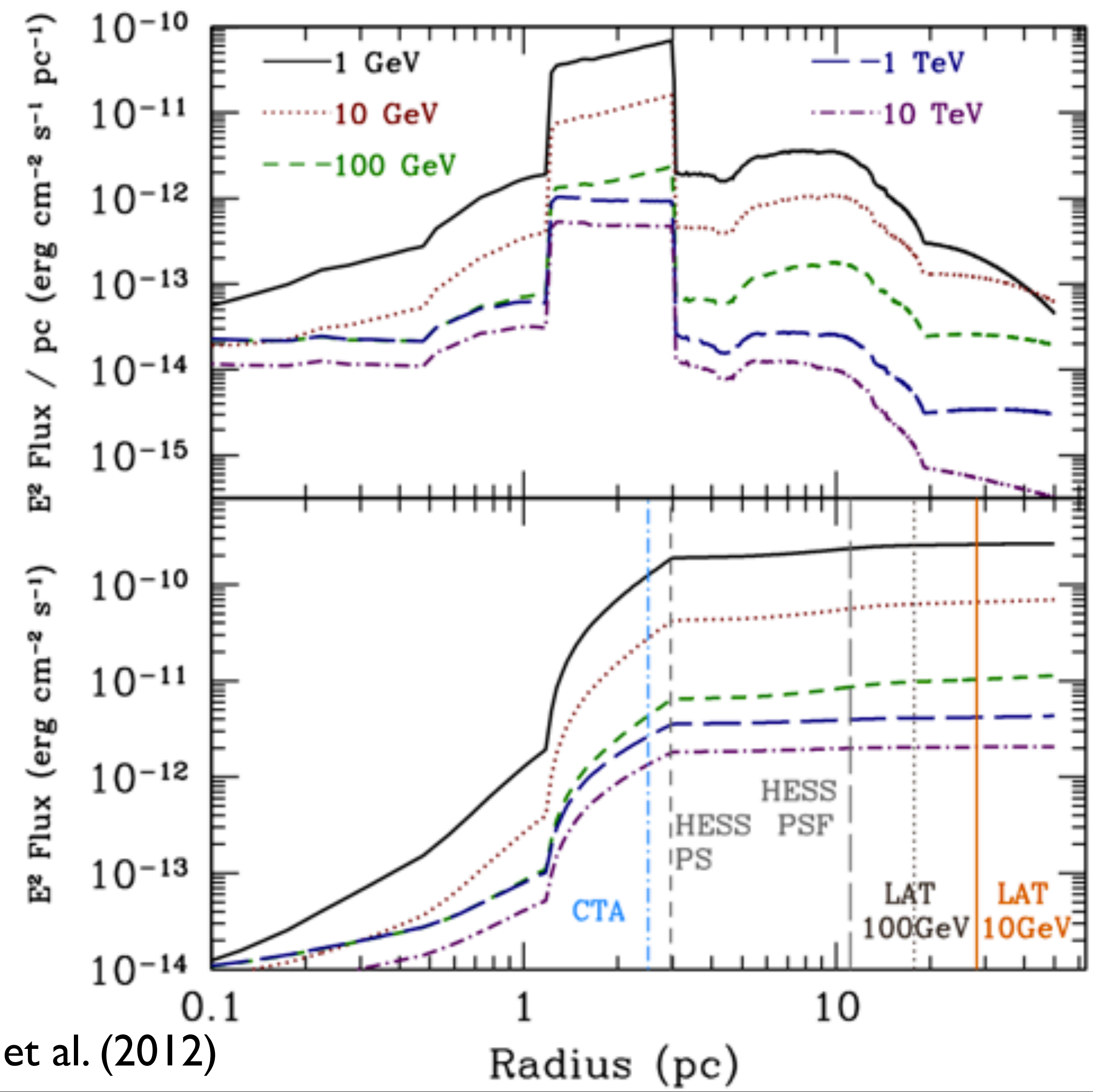


Linden et al. (2012)

CTA and the Galactic Center

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



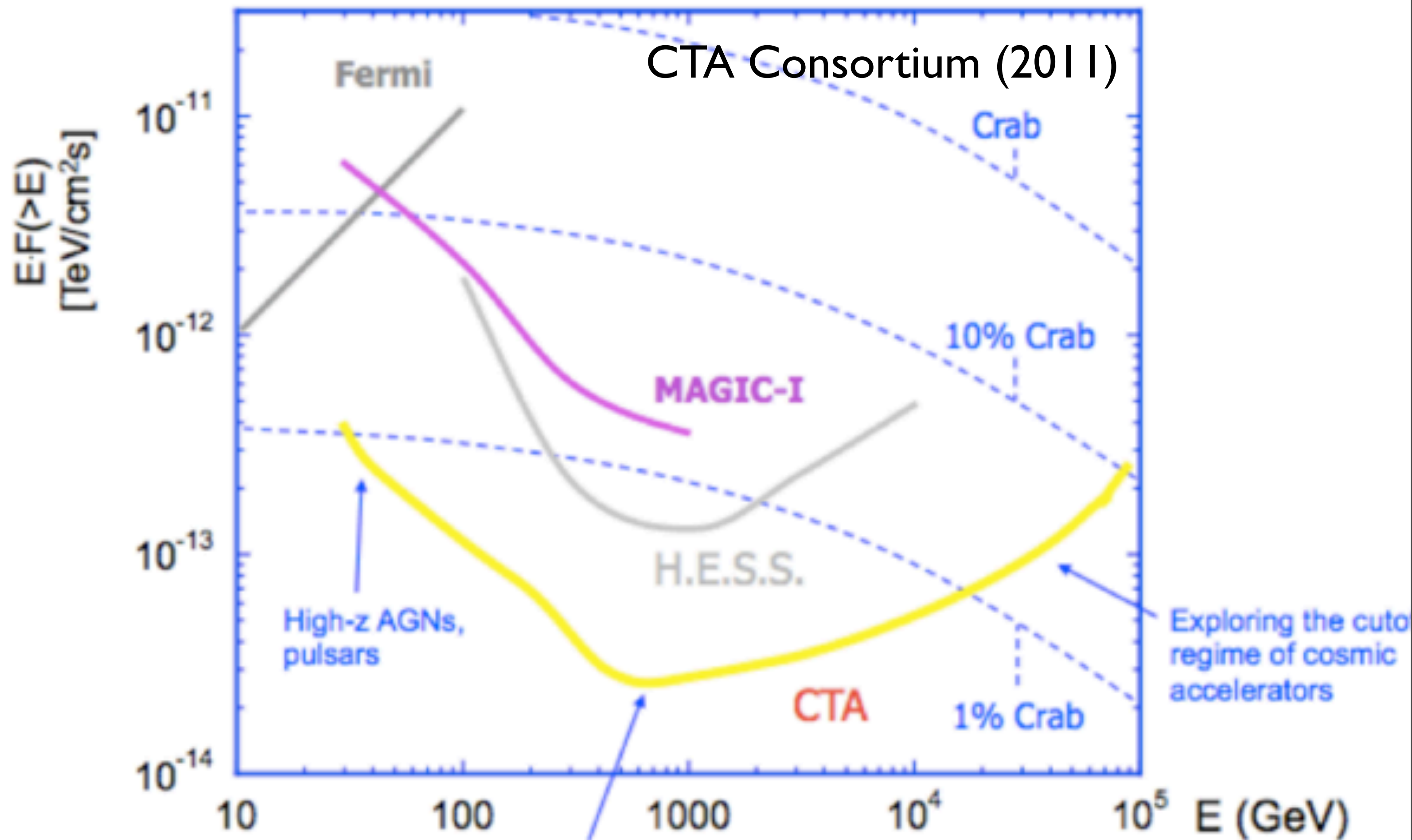


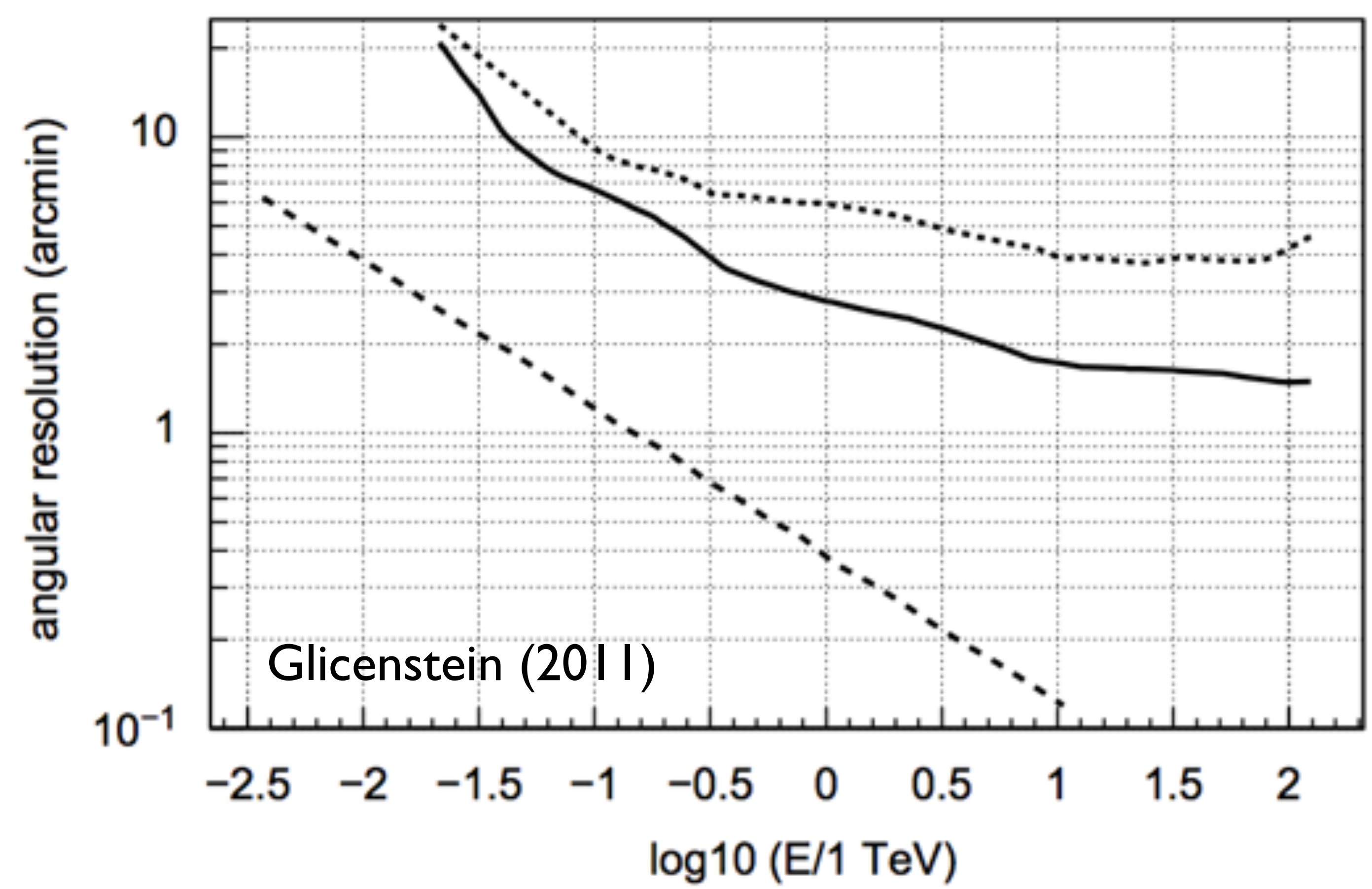
Linden et al. (2012)

CTA and the Galactic Center

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

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

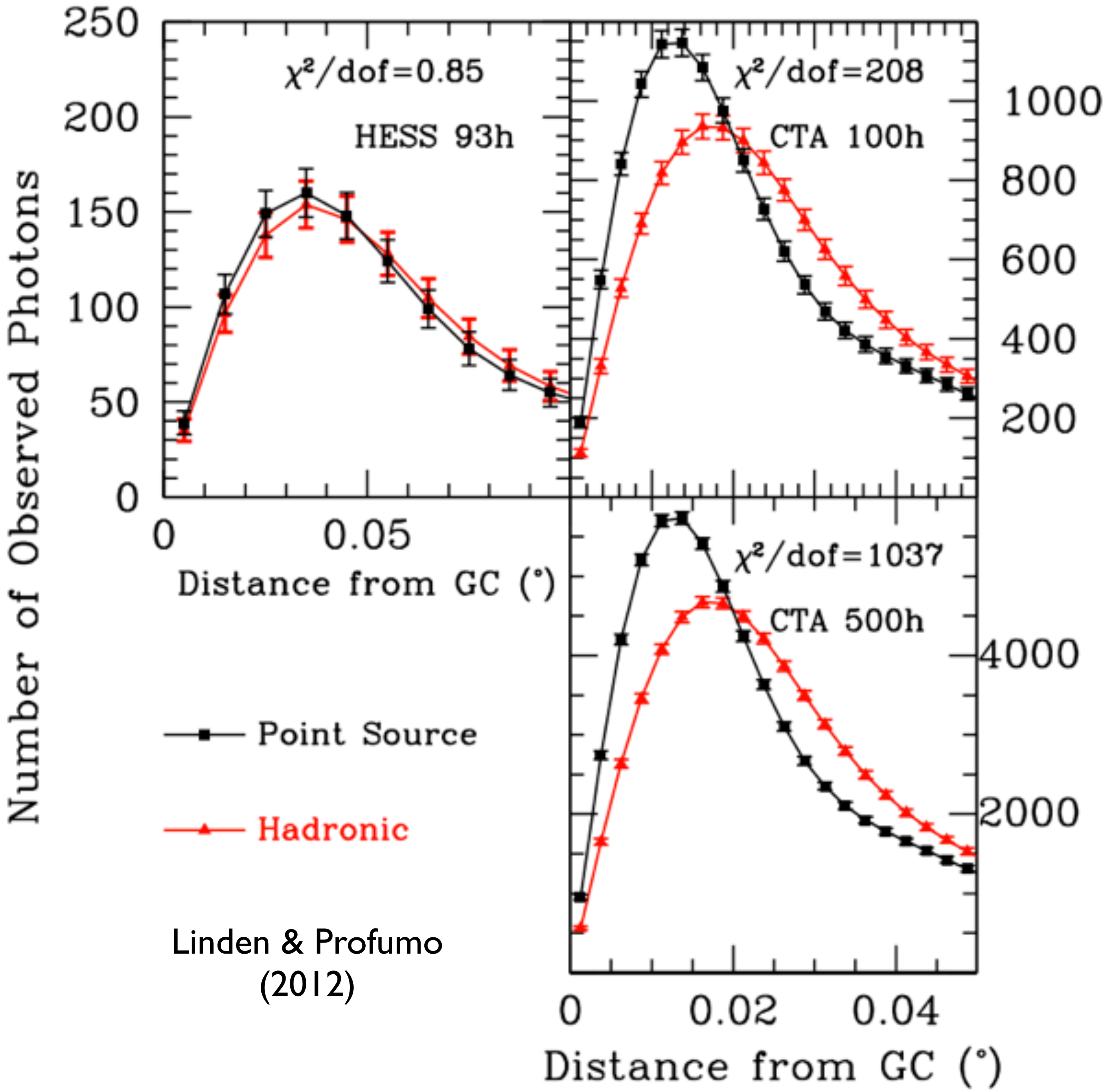




CTA and the Galactic Center

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

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



Linden & Profumo (2012)

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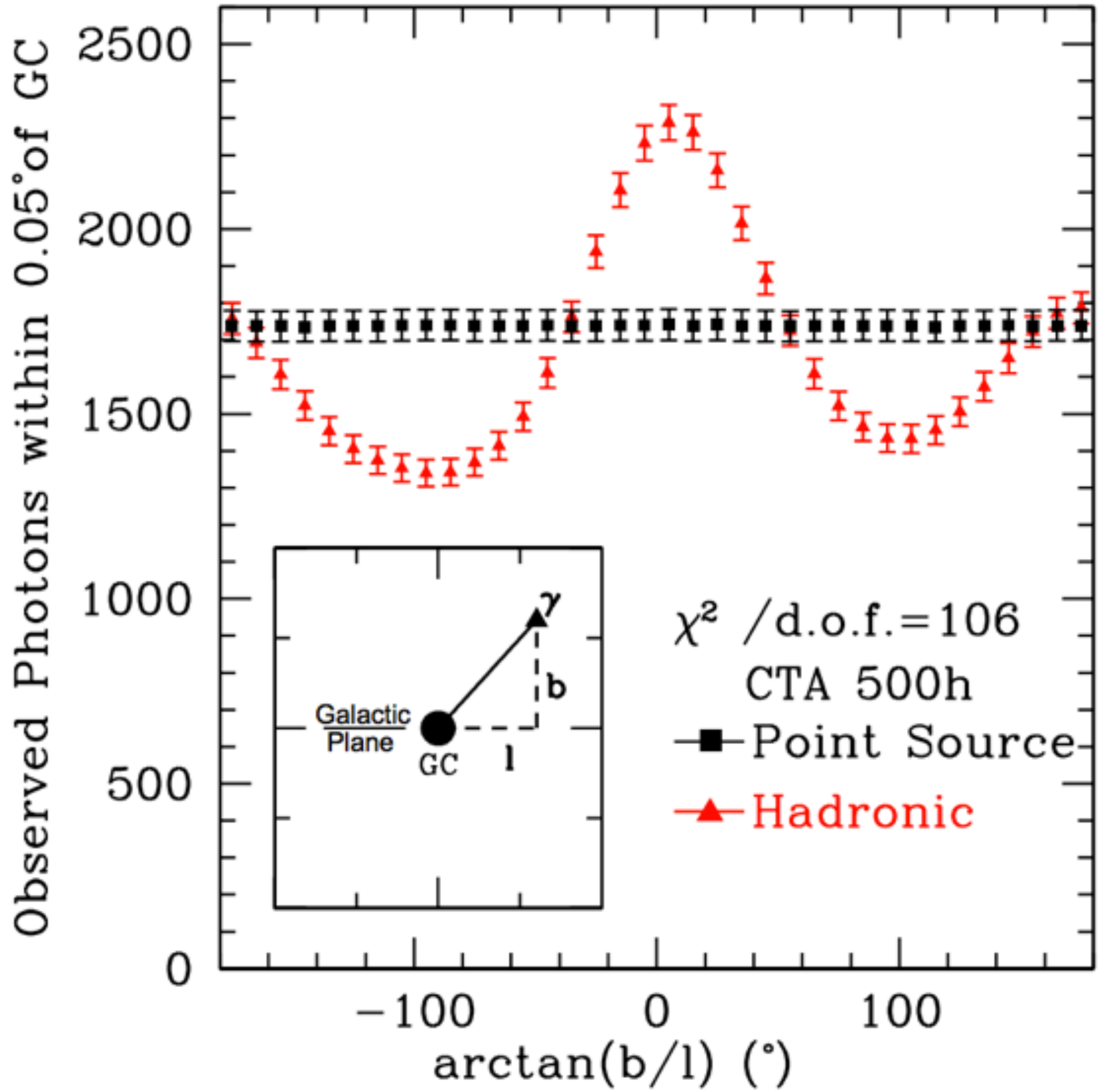
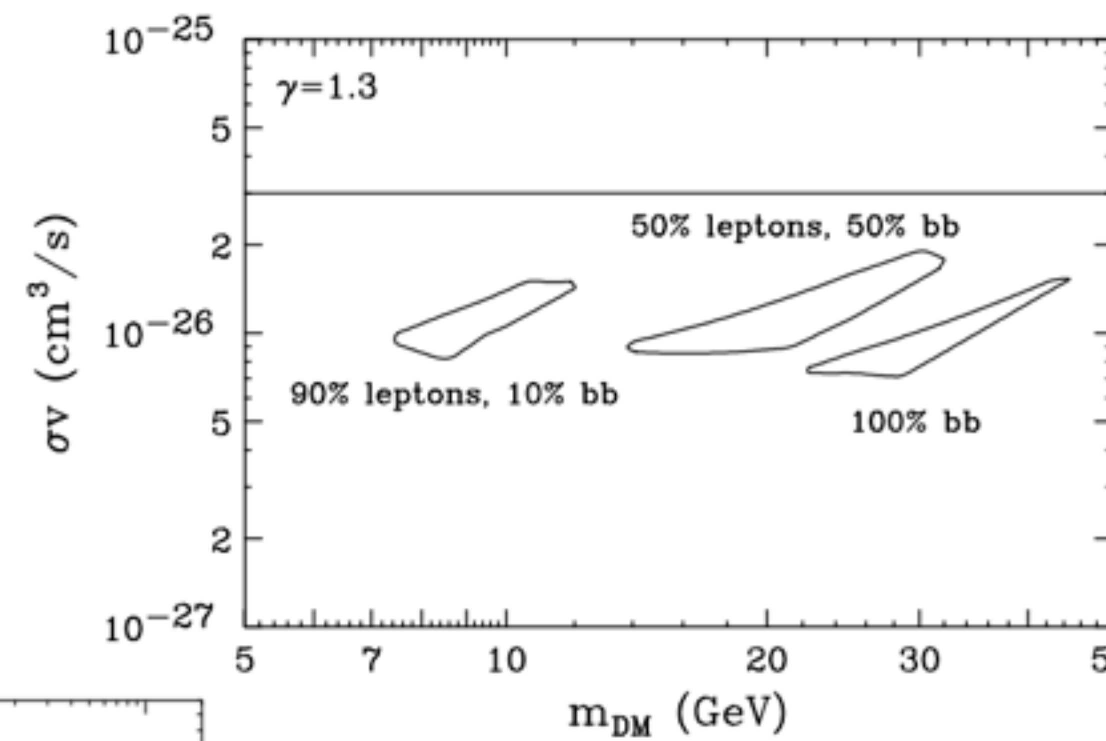


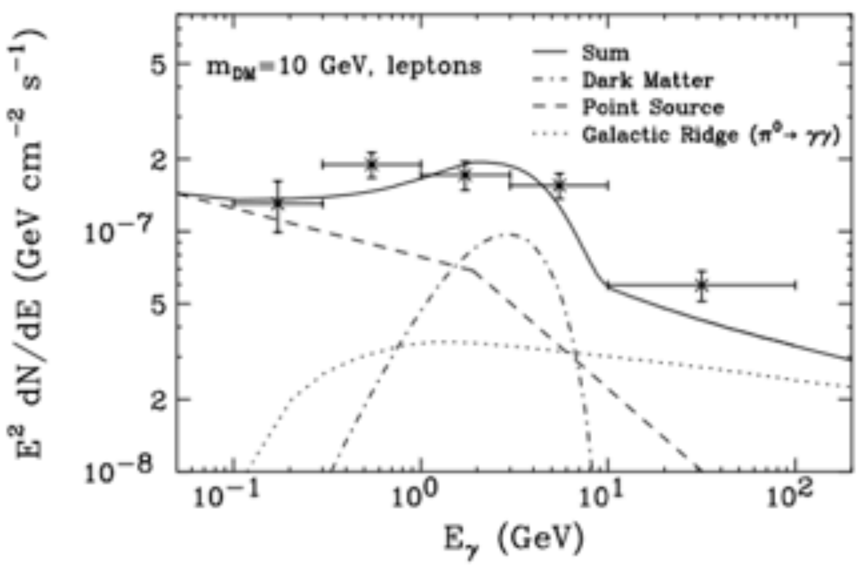
Linden & Profumo (2012)

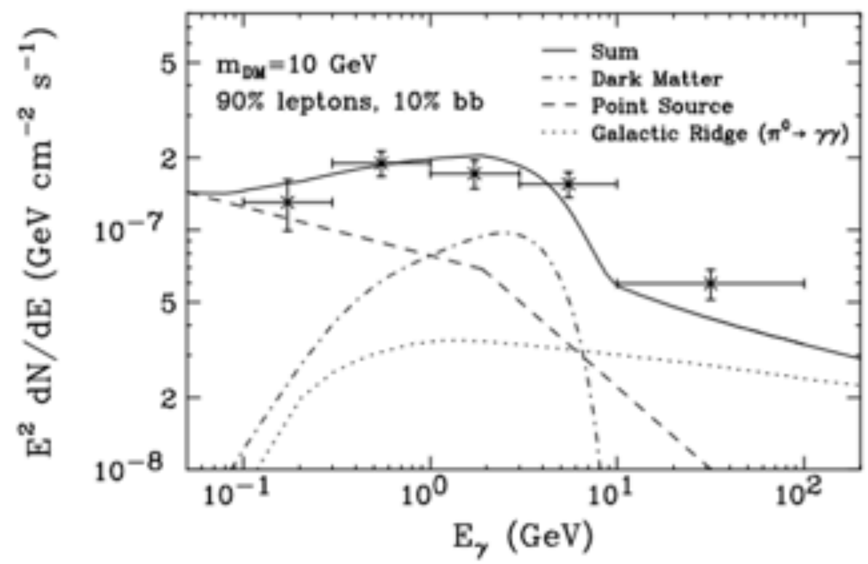
A Dark Matter Interpretation of the Excess

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

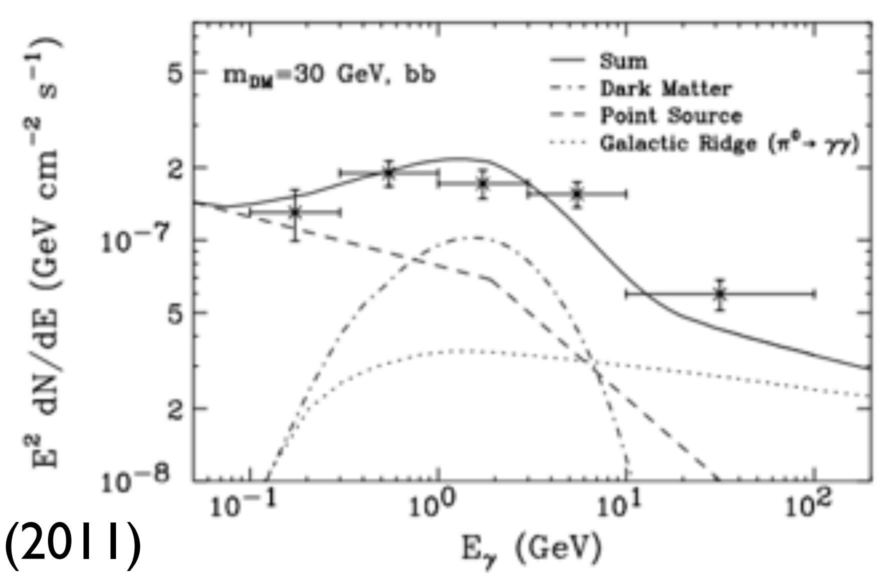


- These models are compatible with estimates for the relic density of dark matter





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

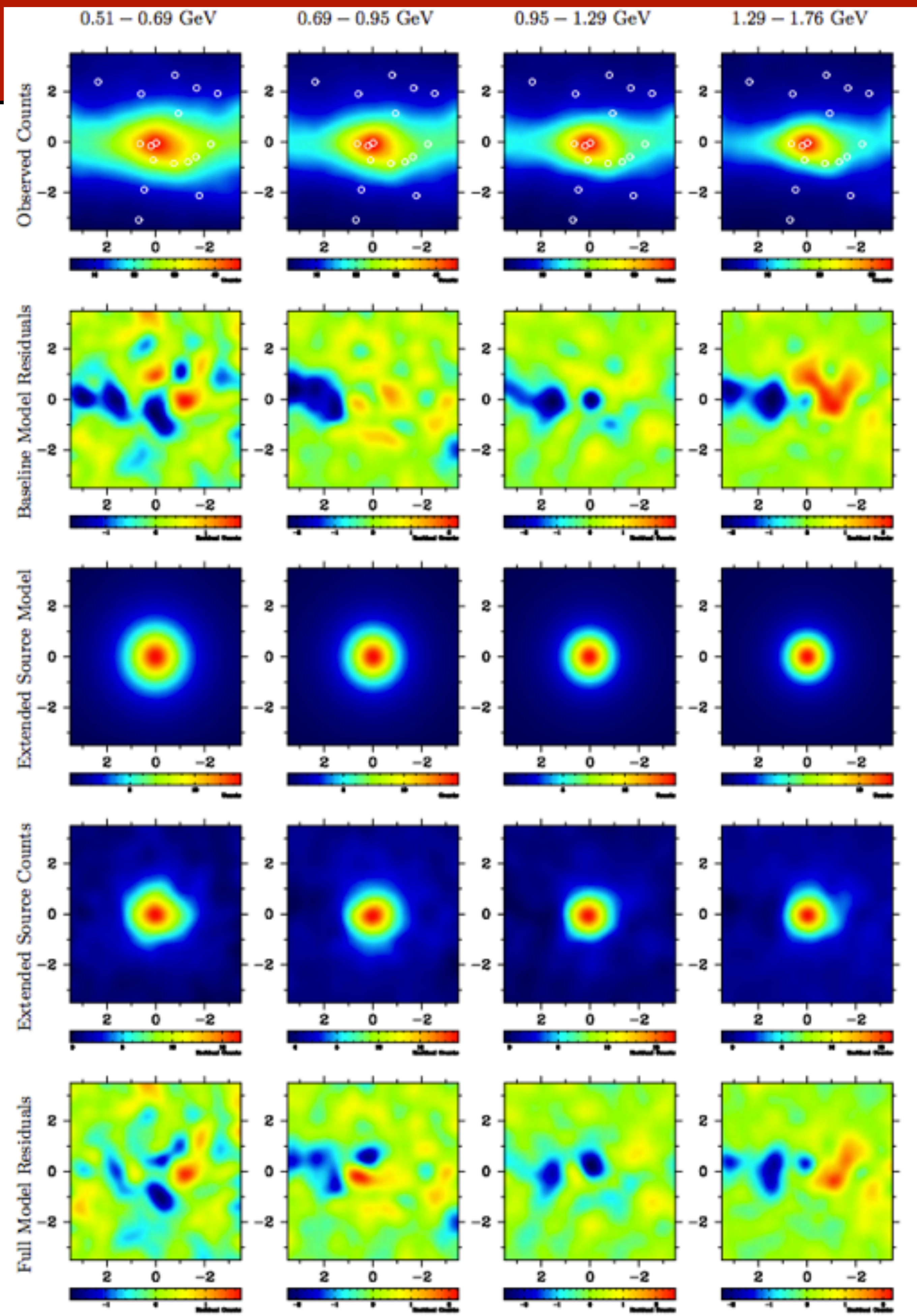


Hooper & Linden (2011)

Independent Confirmation!

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

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



Abazajian & Kaplinghat (2012)

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Spatial Model	Spectrum	TS	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
Baseline	–	–	140070.2	–
Density $\Gamma = 0.7$	LogPar	1725.5	139755.5	314.7
Density^2 $\gamma = 0.9$	LogPar	1212.8	139740.0	330.2
Density^2 $\gamma = 1.0$	LogPar	1441.8	139673.3	396.9
Density^2 $\gamma = 1.1$	LogPar	2060.5	139651.8	418.3
Density^2 $\gamma = 1.2$	LogPar	4044.9	139650.9	419.2
Density^2 $\gamma = 1.3$	LogPar	7614.2	139686.8	383.4
Density^2 Einasto	LogPar	1301.3	139695.7	374.4
Density^2 $\gamma = 1.2$	PLCut	3452.5	139663.2	407.0

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

channel, m_χ	TS	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 10 GeV	2385.7	139913.6	156.5
$b\bar{b}$, 30 GeV	3460.3	139658.3	411.8
$b\bar{b}$, 100 GeV	1303.1	139881.1	189.0
$b\bar{b}$, 300 GeV	229.4	140056.6	13.5
$b\bar{b}$, 1 TeV	25.5	140108.2	−38.0
$b\bar{b}$, 2.5 TeV	7.6	140114.2	−44.0
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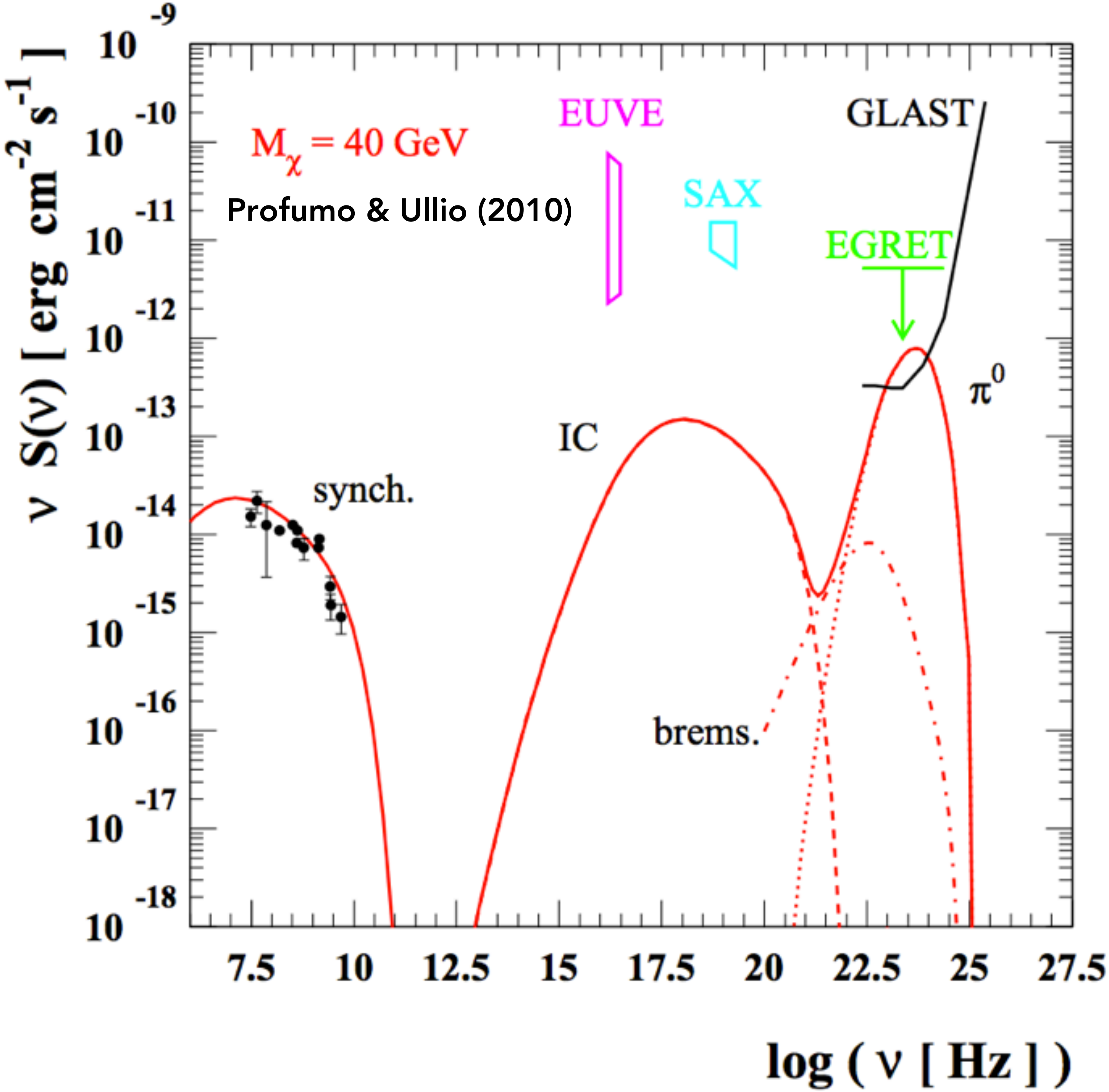
Abazajian & Kaplinghat (2012)

What Can We See With Radio Observations?



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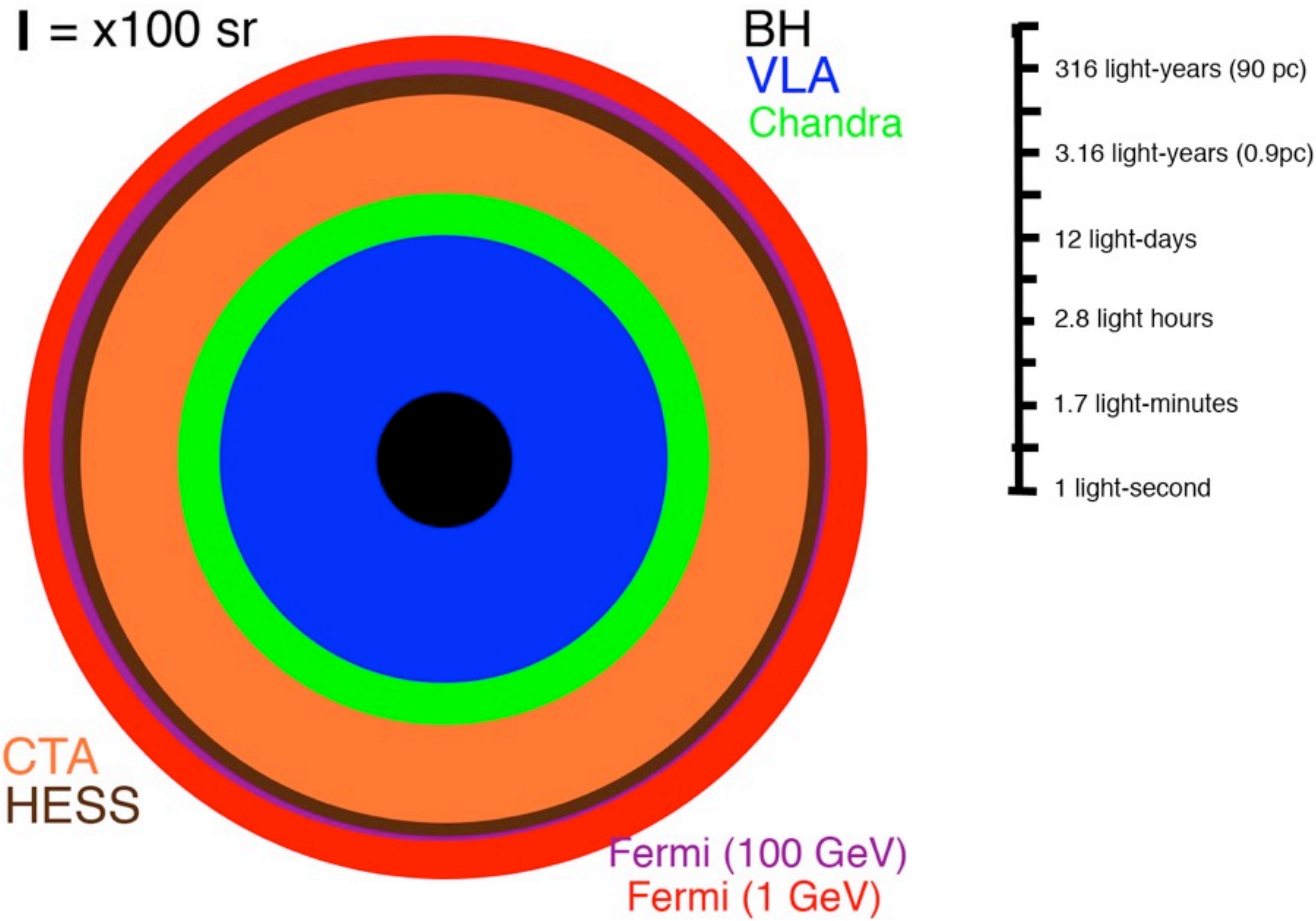
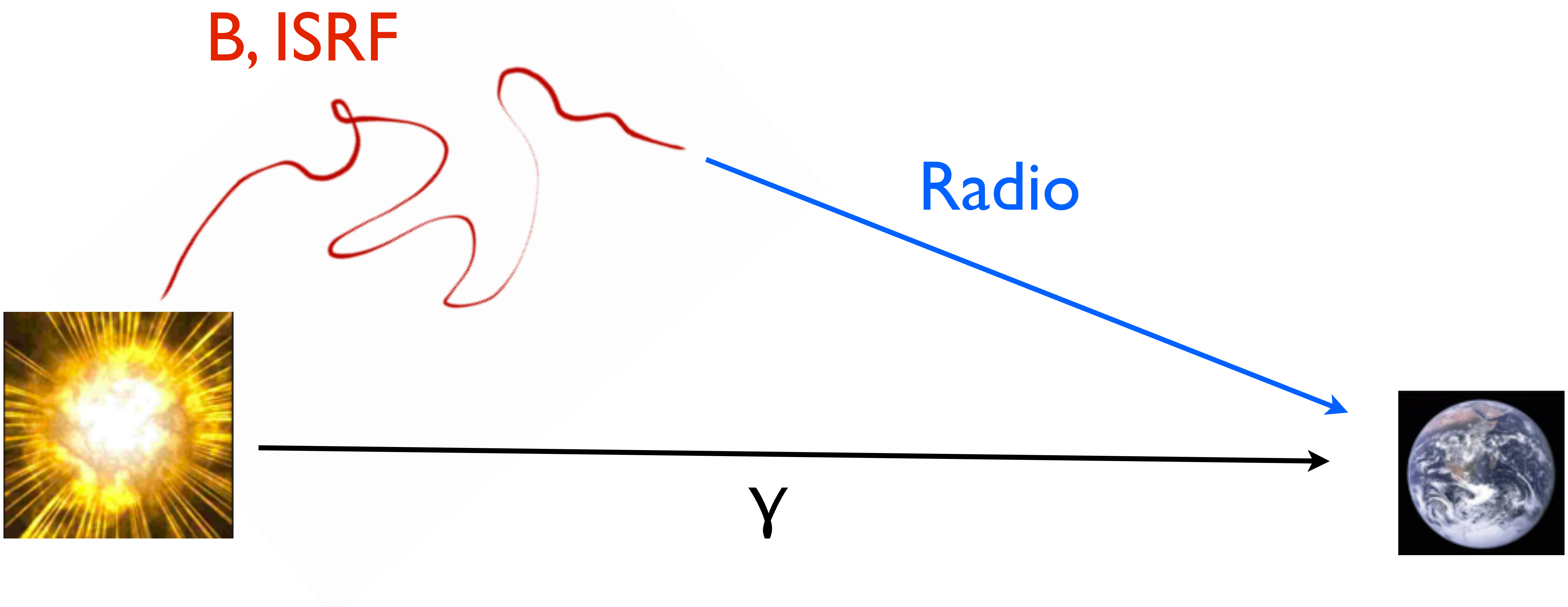


Complications From Particle Diffusion



- At low energy, propagation can carry the particles which create the observed signal far from the annihilation event, before they produce anything that is seen at the Earth

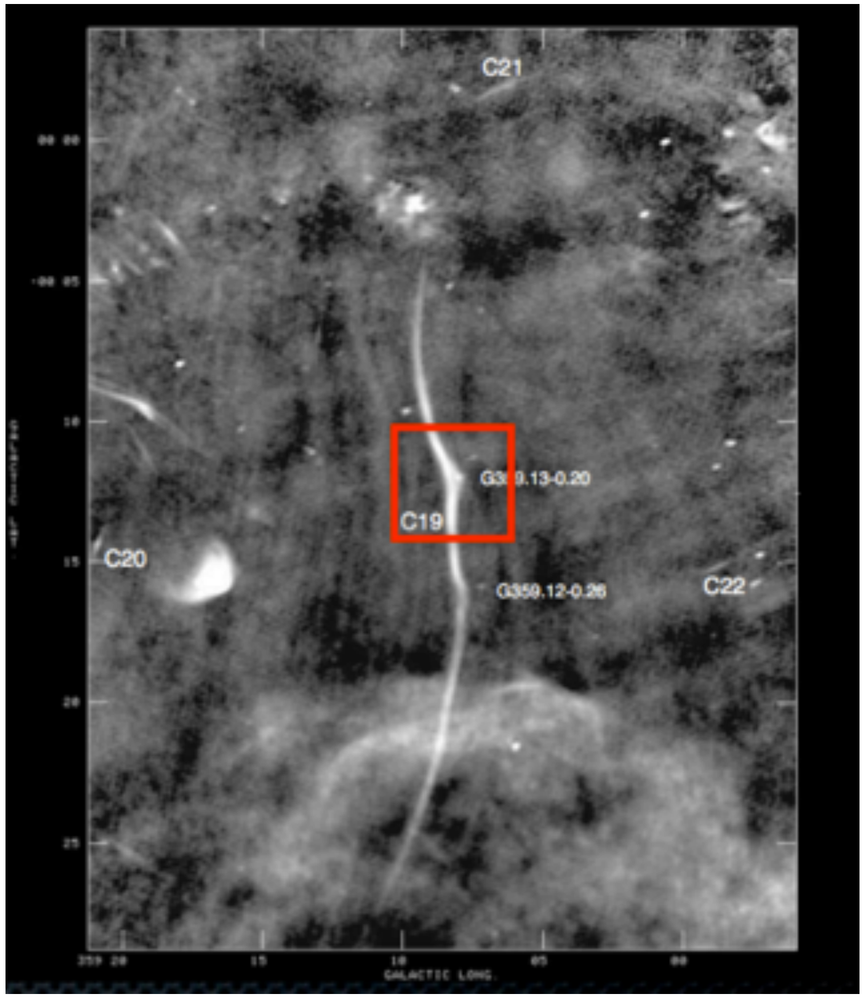
Complications From Particle Diffusion

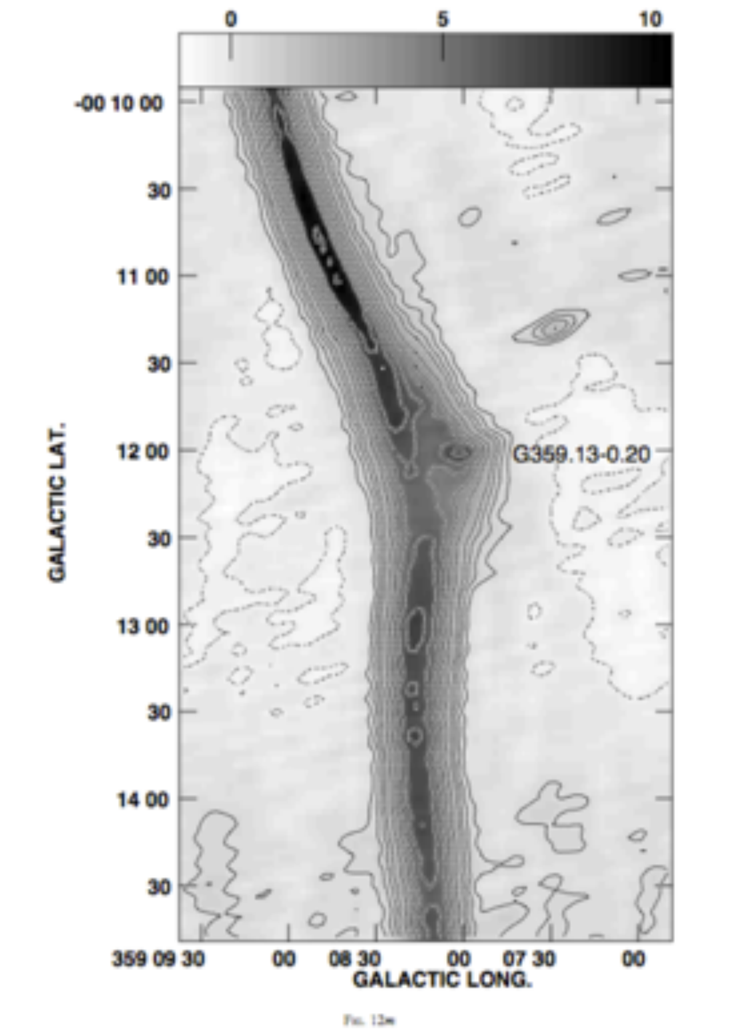
Is there a region where the diffusion and magnetic field are “predictable”

- At low energy, propagation can carry the particles which create the observed signal far from the annihilation event, before they produce anything that is seen at the Earth

Nonthermal Radio Filaments

- Non-Thermal Filaments
  - Long (~30 pc)
  - Thin (< 1 pc)
  - Synchrotron Sources
  - Strong B-Field





Yusef-Zadeh et al. (2004)

- Polarization -> Ordered B-Field

$$\frac{B_{ord}}{B_{tot}} > 0.6$$

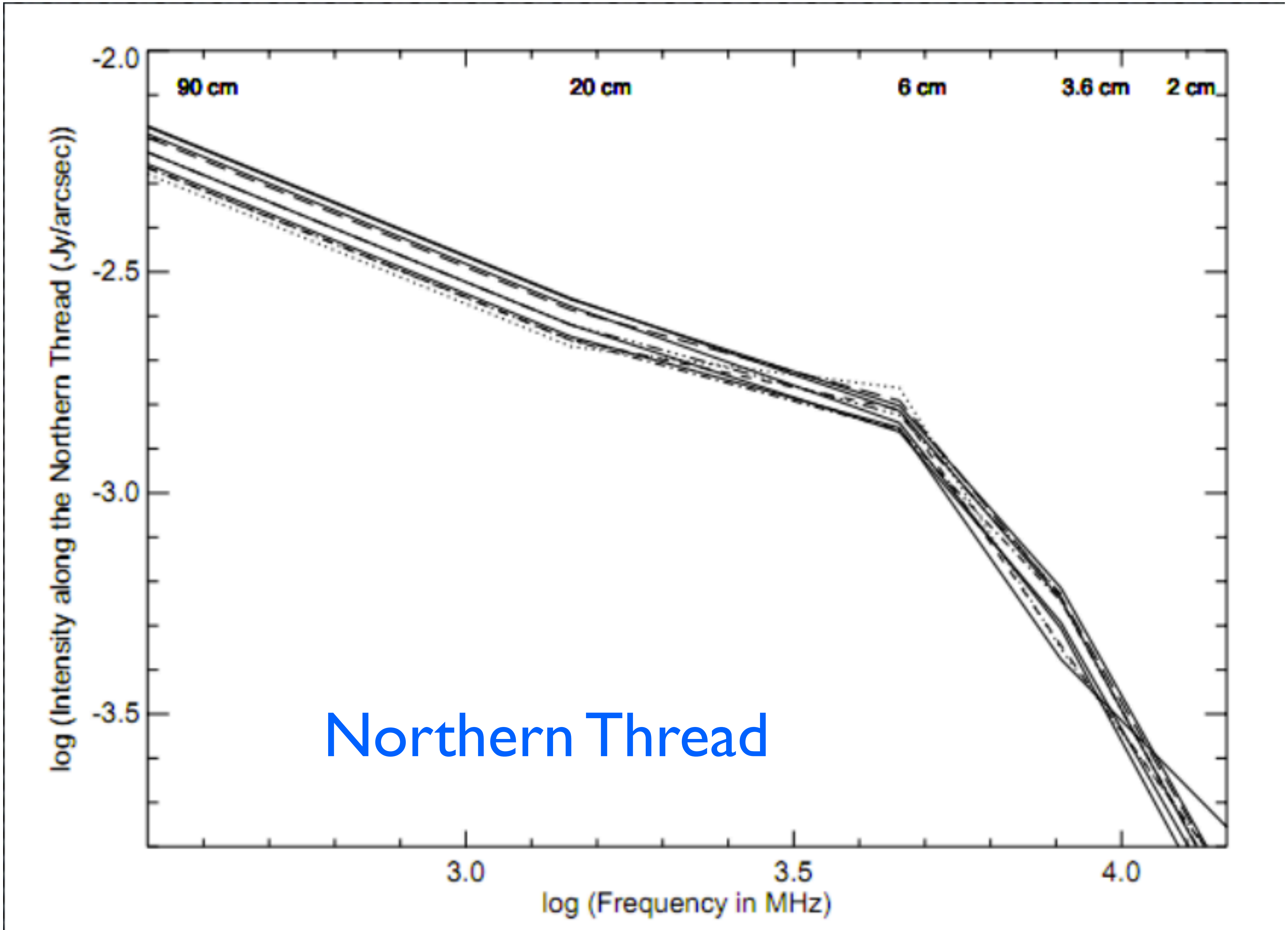
- Spectrum -> Hard Electron Spectrum

$$p + 1 = 2\alpha$$

α = Synchrotron Spectrum

p = Electron Spectrum

The Hard Spectrum of NTFs



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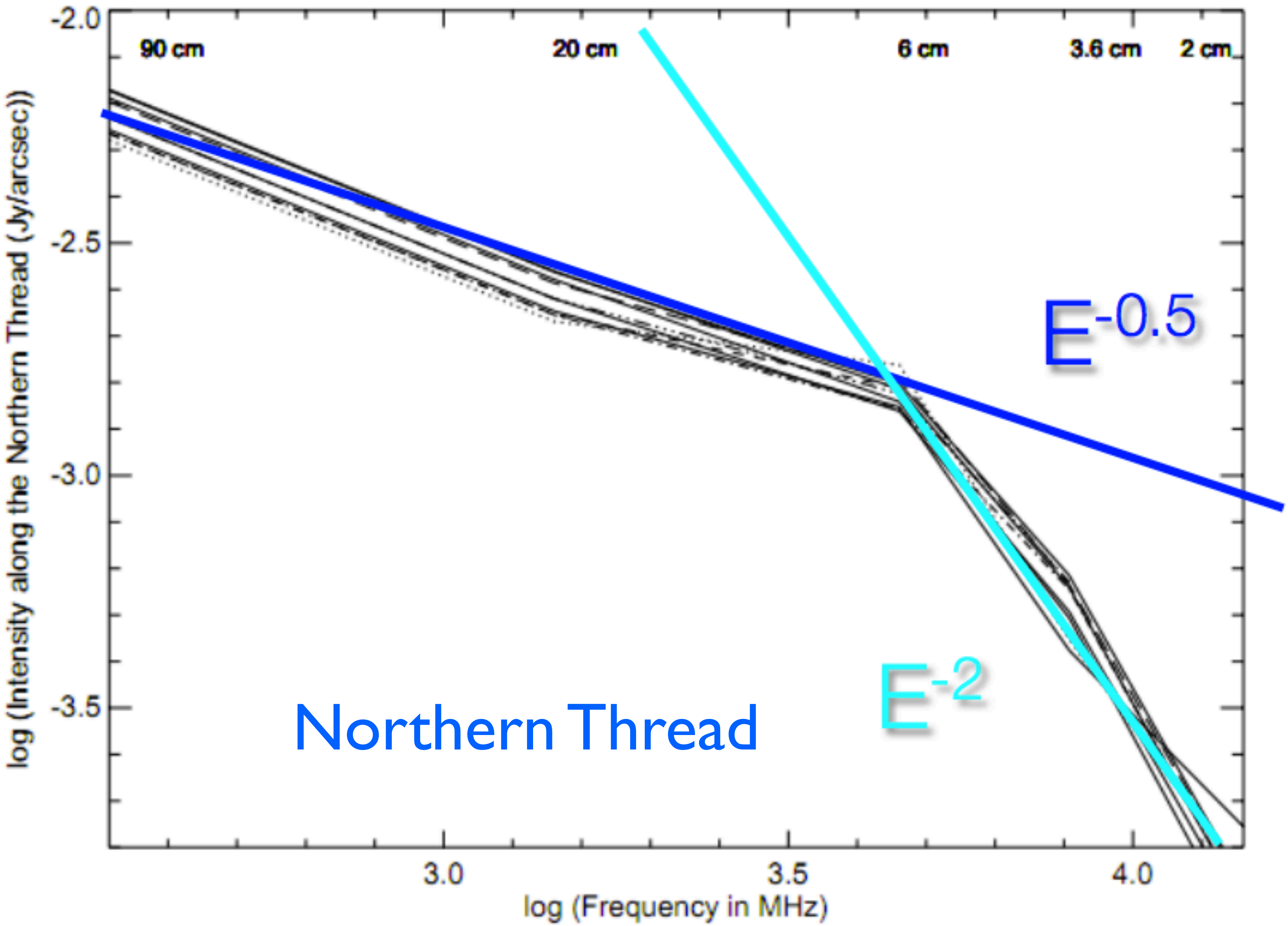


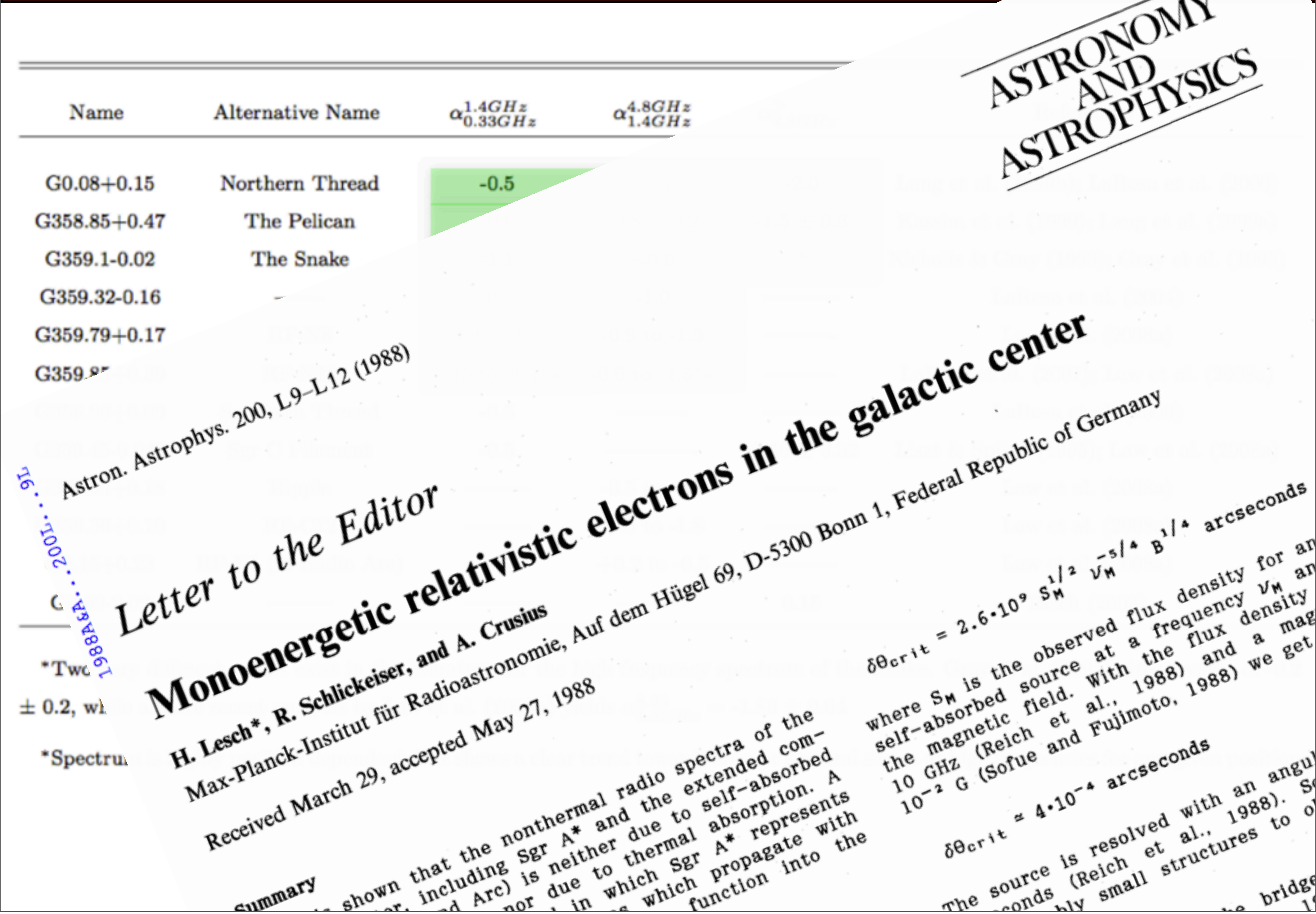
The Hard Spectrum of NTFs

Name	Alternative Name	$\alpha^{1.4GHz}_{0.33GHz}$	$\alpha^{4.8GHz}_{1.4GHz}$	$\alpha^{>}_{4.8GHz}$	References
G0.08+0.15	Northern Thread	-0.5	-0.5	-2.0	Lang et al. (1999b); LaRosa et al. (2000)
G358.85+0.47	The Pelican	-0.6	-0.8 ± 0.2	-1.5 ± 0.3	Kassim et al. (1999); Lang et al. (1999a)
G359.1-0.02	The Snake	-1.1	~0.0	*	Nicholls & Gray (1993); Gray et al. (1995)
G359.32-0.16	——	-0.1	-1.0	——	LaRosa et al. (2004)
G359.79+0.17	RF-N8	-0.6 ± 0.1	-0.9 to -1.3	——	Law et al. (2008a)
G359.85+0.39	RF-N10	0.15 to -1.1*⋆	-0.6 to -1.5*⋆	——	LaRosa et al. (2001); Law et al. (2008a)
G359.96+0.09	Southern Thread	-0.5	——	——	LaRosa et al. (2000)
G359.45-0.040	Sgr C Filament	-0.5	——	-0.46 ± 0.32	Liszt & Spiker (1995); Law et al. (2008a)
G359.54+0.18	Ripple	——	-0.5 to -0.8	——	Law et al. (2008a)
G359.36+0.10	RF-C12	——	-0.5 to -1.8	——	Law et al. (2008a)
G0.15+0.23	RF-N1 (in Radio Arc)	——	+0.2 to -0.5	——	Law et al. (2008a)
G0.09-0.09	——	——	——	0.15	Reich (2003)

*Two very different values exist in the literature for the high frequency spectrum of the Snake. Gray et al. (1995) cites a value of -0.2 ± 0.2, while a more recent analysis by Law et al. (2008b) yields $\alpha^{8.33}_{4.8GHz} = -1.86 \pm 0.64$

*Spectrum is highly position dependent, but shows a clear trend towards steeper spectral slopes at high frequencies for any given position

The Hard Spectrum of NTFs



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G359.32-0.16			
G359.79+0.17			

*Two

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*Spectru

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

Astron. Astrophys. 200, L9–L12 (1988)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Monoenergetic relativistic electrons in the galactic center

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

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Federal Republic of Germany

Received March 29, accepted May 27, 1988

Summary

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

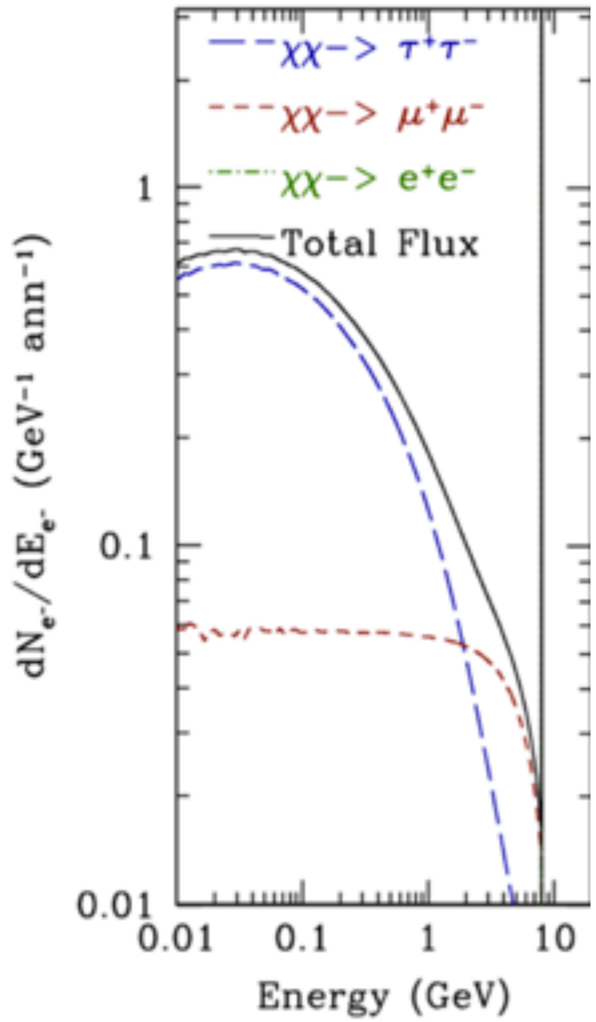
$\delta\theta_{crit} = 2.6 \cdot 10^{9}\ S_M^{1/2}\ \nu_M^{-5/4}\ B^{1/4}$ arcseconds

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

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

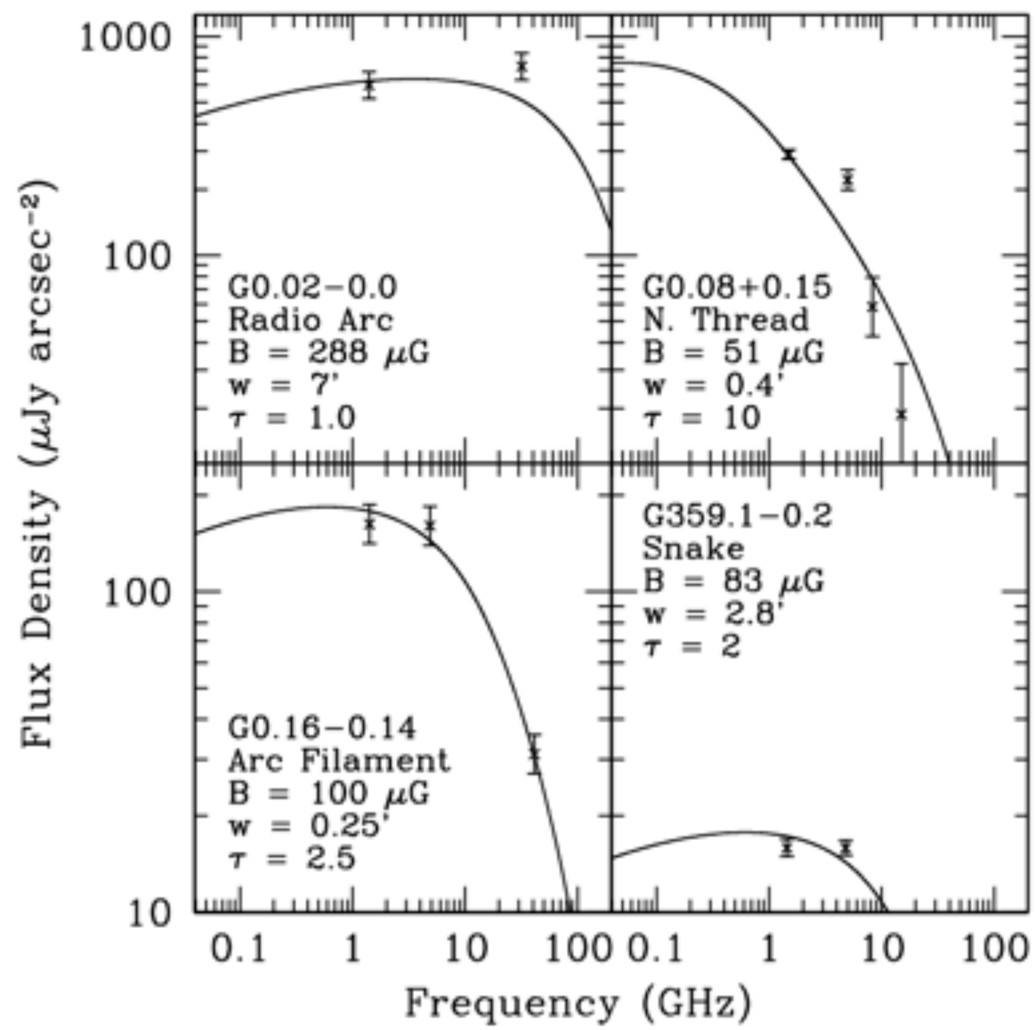
The source is resolved with an angu ... conds (Reich et al., 1988). S ... bly small structures to o ... bridge

Dark Matter Interpetations of the NTFs



- Dark Matter Annihilation Provides a very hard (non power-law) electron spectrum to produce synchrotron radiation
-

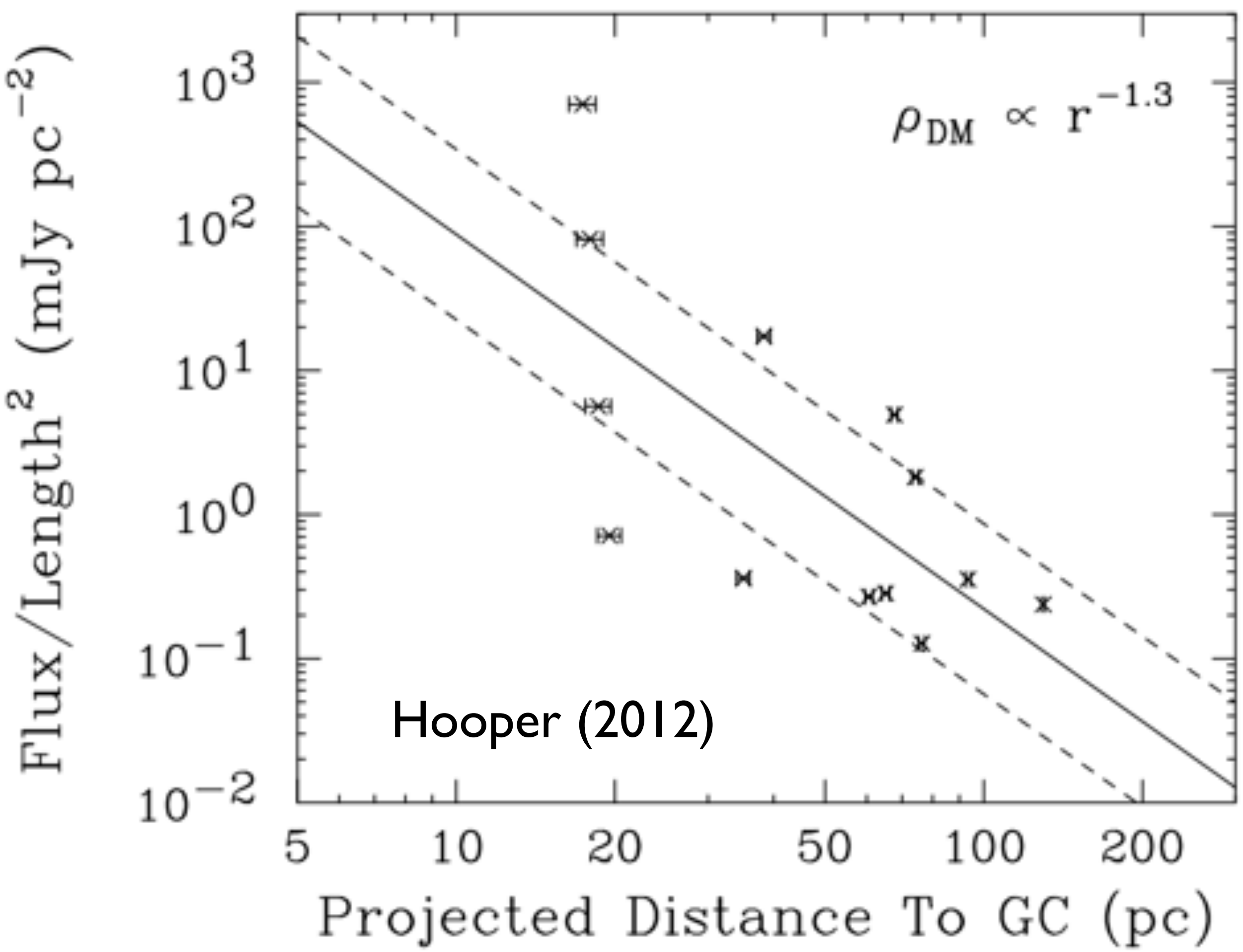
- Light dark matter annihilation naturally fits the observed spectrum of multiple non-thermal radio filaments

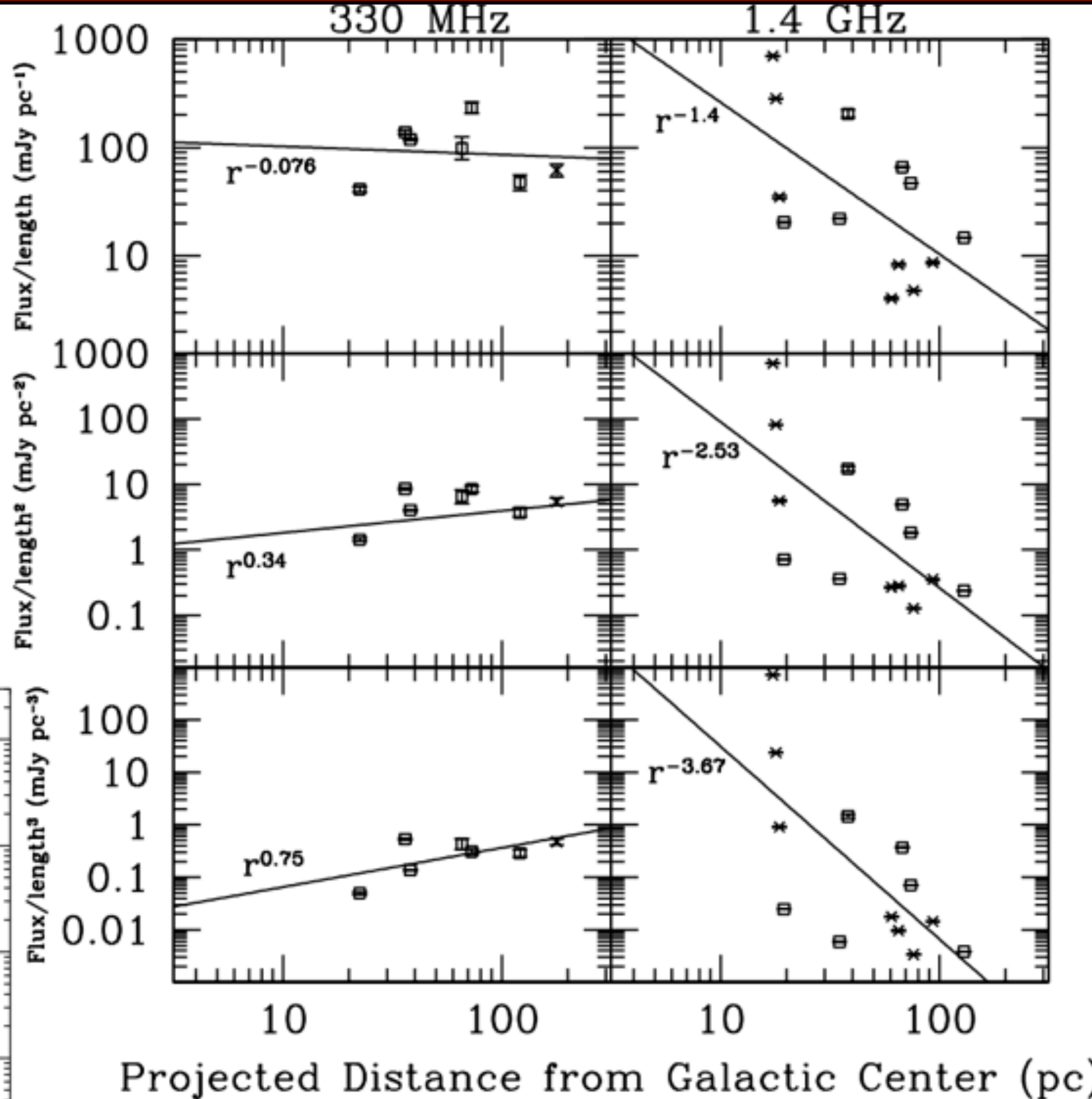


Linden et al. (2011)

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





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 Provides a convincing explanation for this excess

- Secondary emission can be used to test this result - in regions where the magnetic field and diffusion constant may be determined

Thanks!

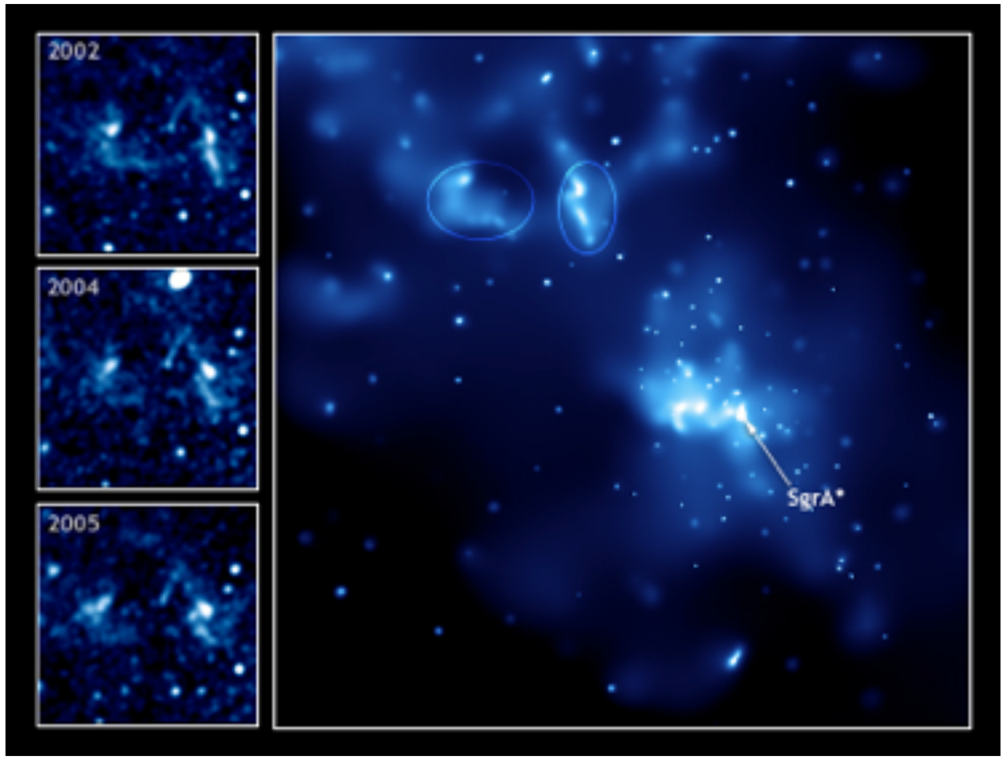
- Thanks go to my committee: Tesla Jeltema, Stefano Profumo, Steve Ritz
- Collaborators: Brandon Anderson, Eric Carlson, Dan Hooper, Tesla Jeltema, Vicky Kalogera, Elizabeth Lovegrove, Andrea Prestwich, Jennifer Siegal-Gaskins, Jeremy Sepinsky, Tracy Slatyer, Francesca Valsecchi, Christoph Weniger, Farhad Yusef-Zadeh and others
- Special thanks to my advisor Stefano Profumo
- and to all my fellow grad students - especially my lab-mates: Chris, Laura, Lauren, Max
- and especially to Colleen!

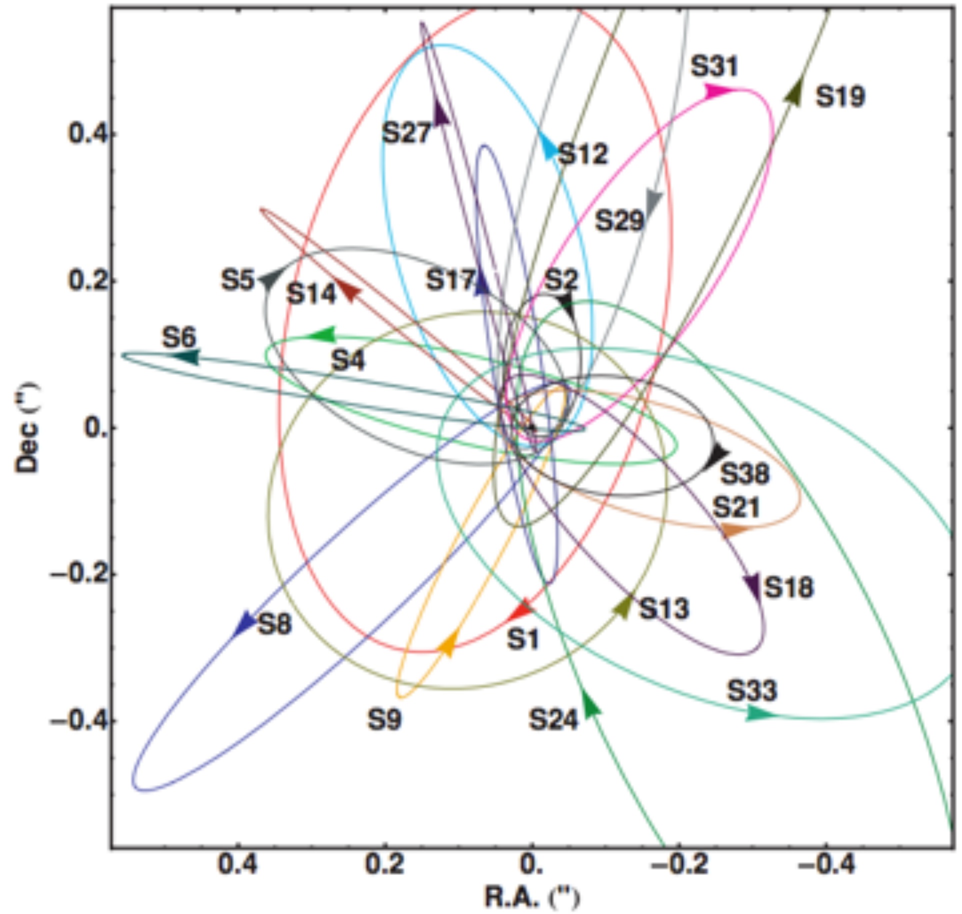
Extra Slides

History of Galactic Center Observations (in 60 seconds)

- 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)

Muno et al. 2007





Gillissen et al. 2009

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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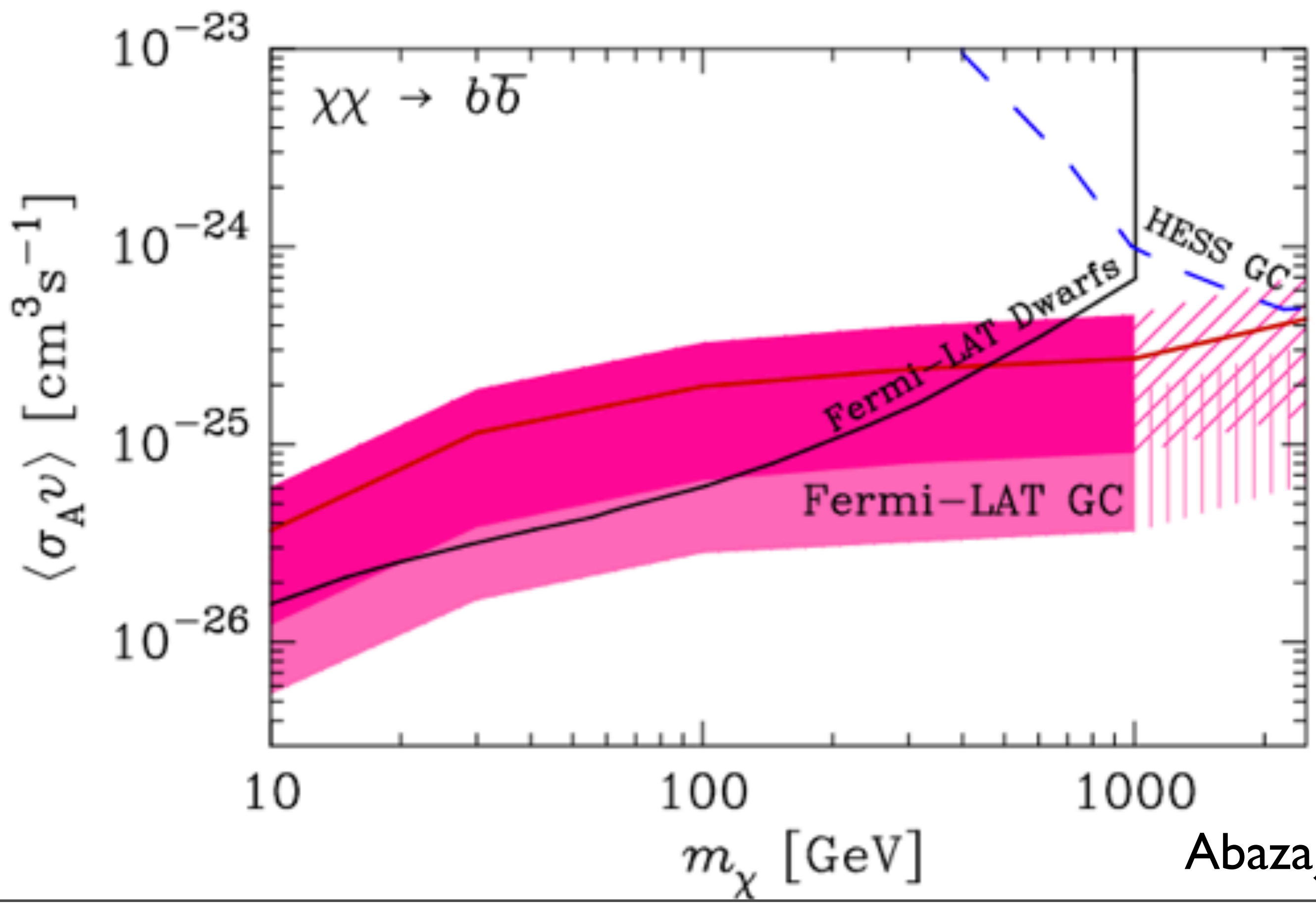
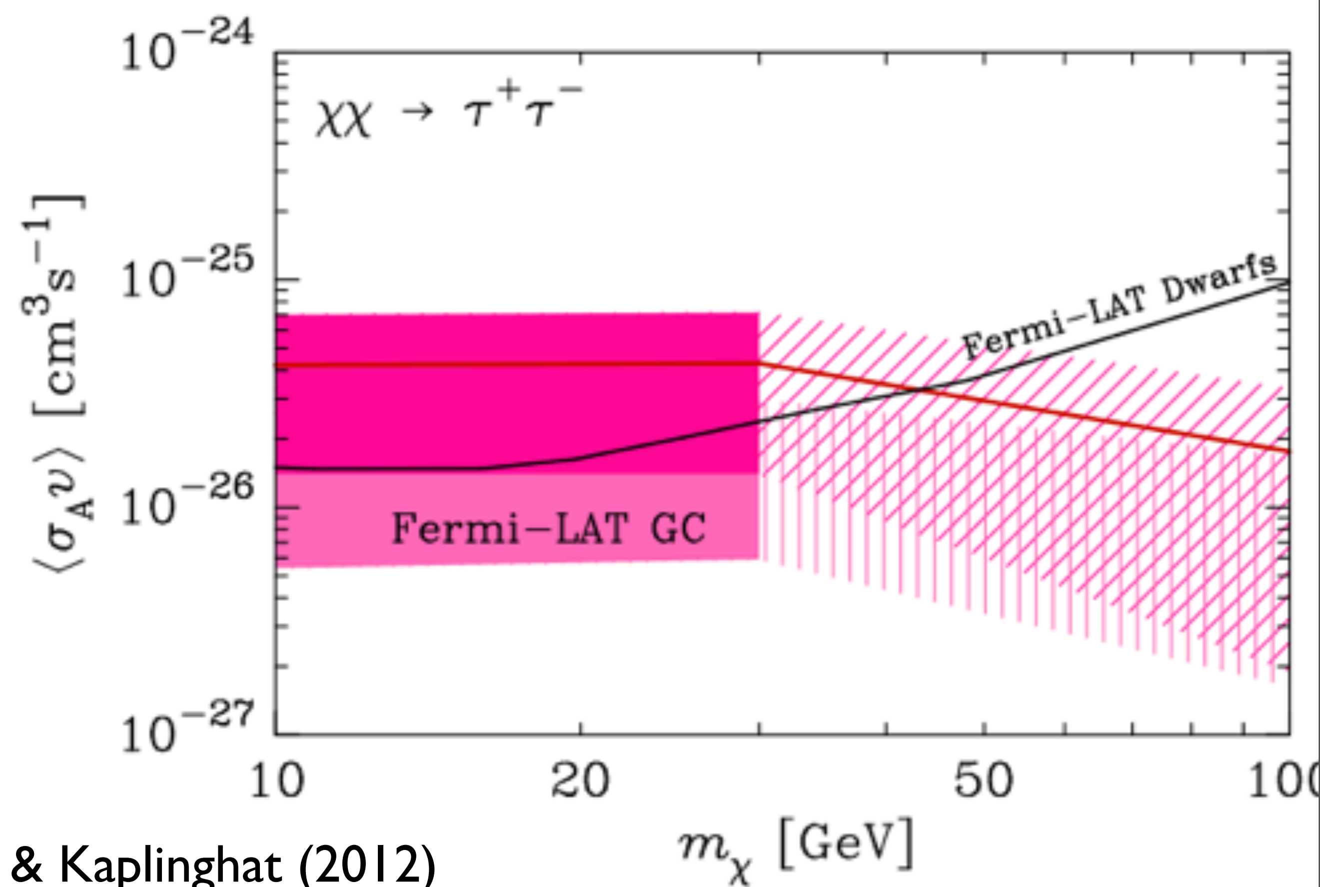
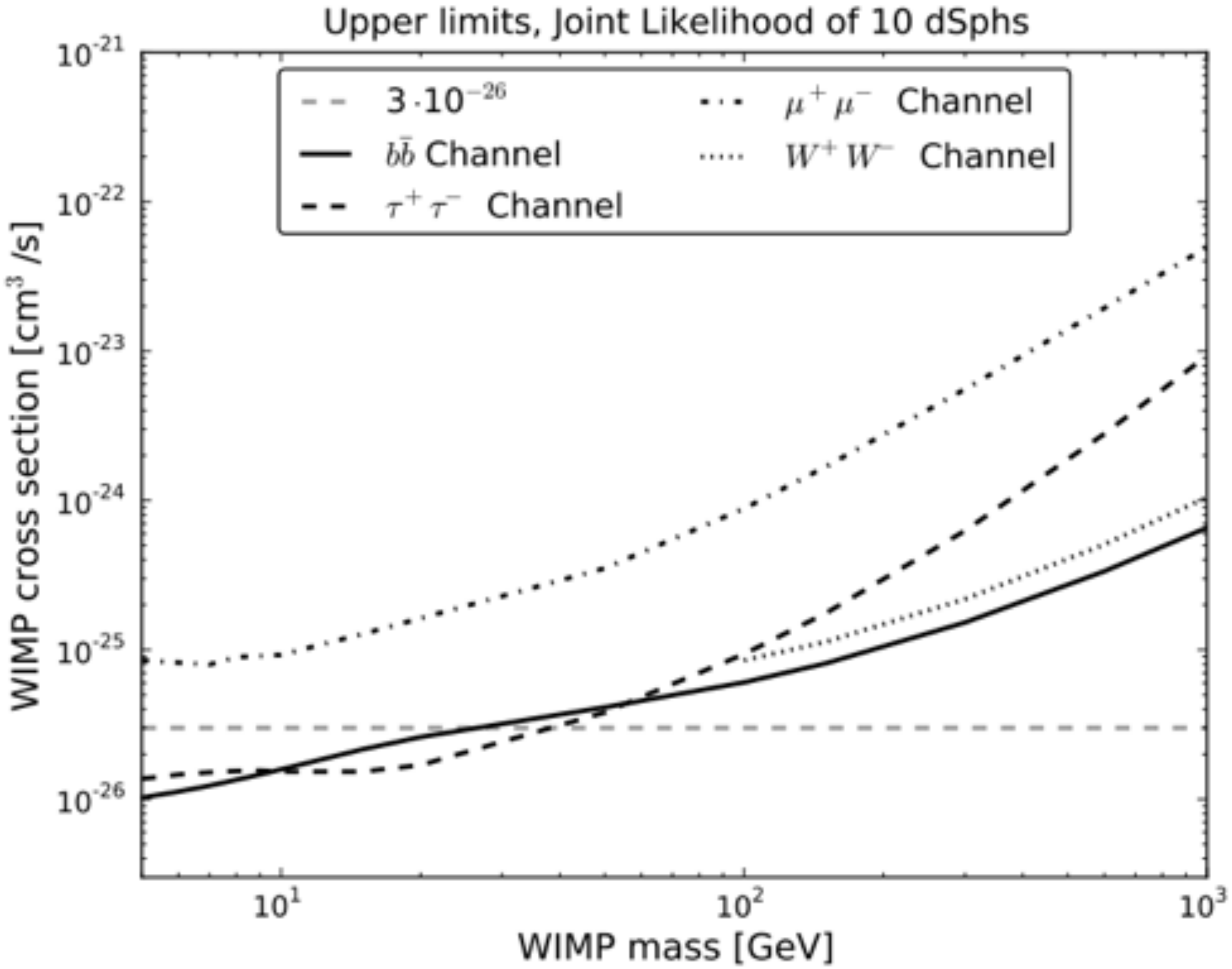




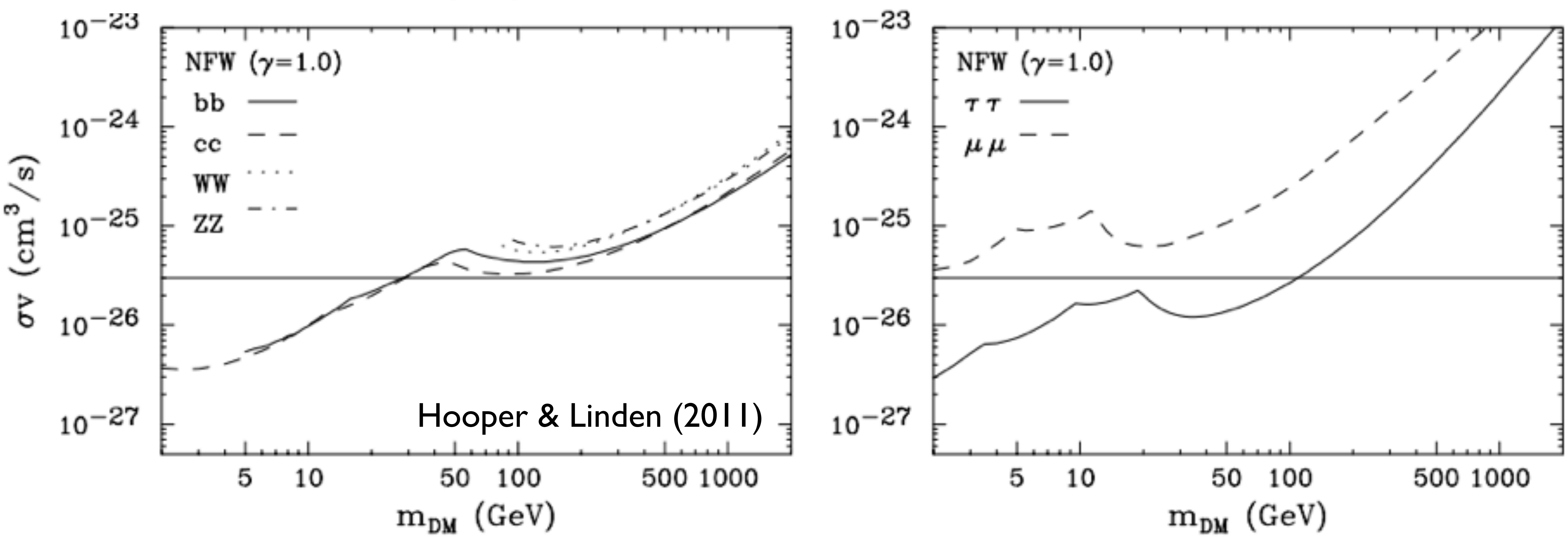
Abazajian & Kaplinghat (2012)

Comparison to Other Indirect Detection Regimes

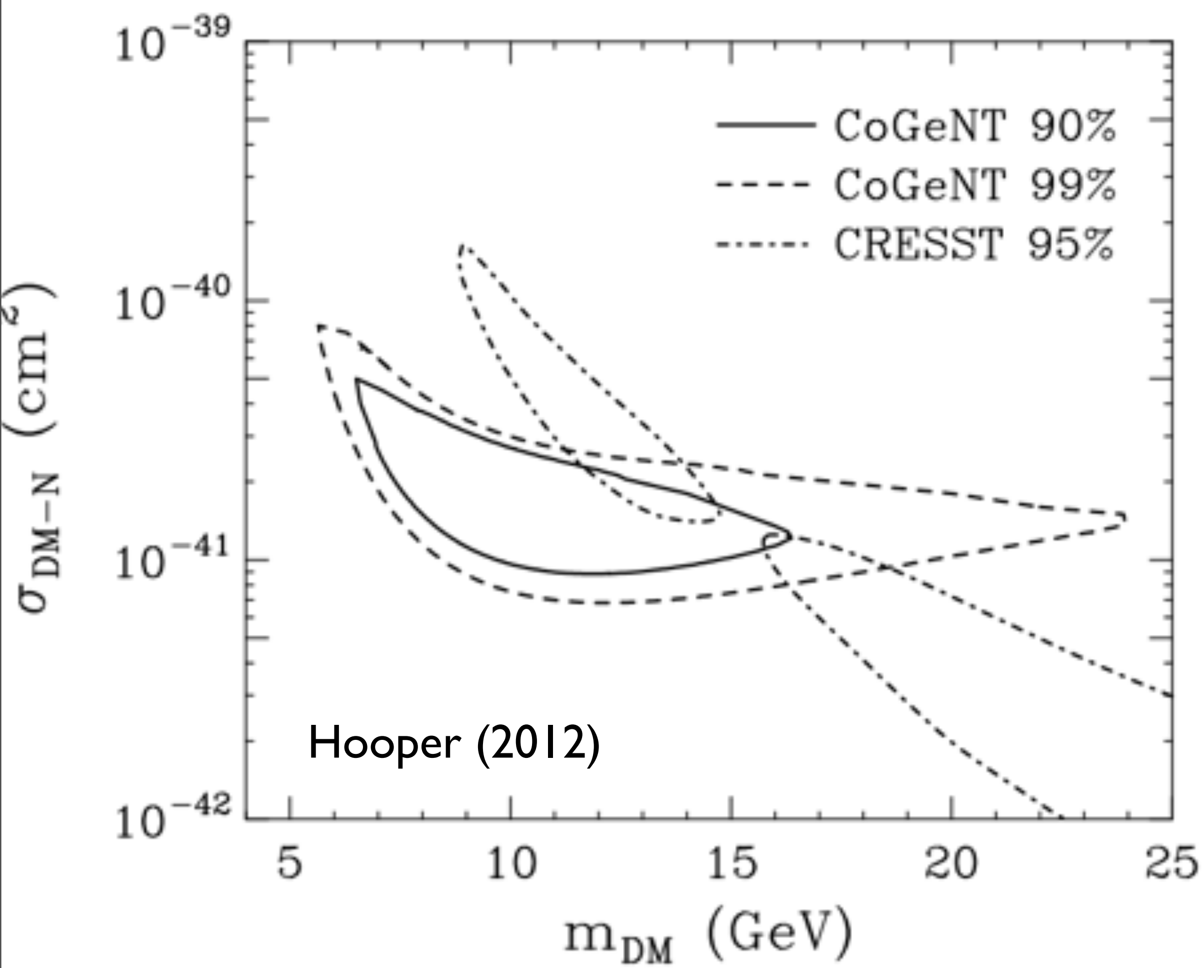


- Under the assumption of an NFW profile, the 95% confidence limits are as good or better than those from dwarf-spheroidals

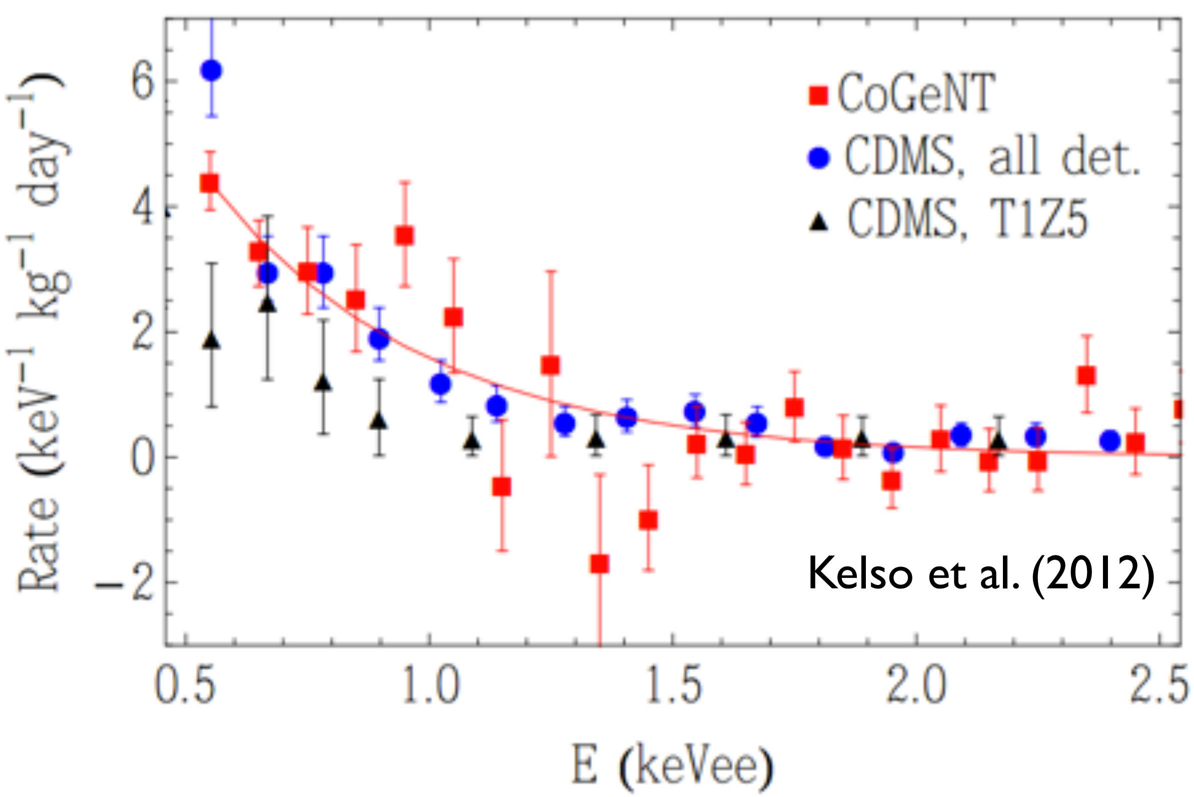
- They are especially stronger for leptophilic annihilation paths

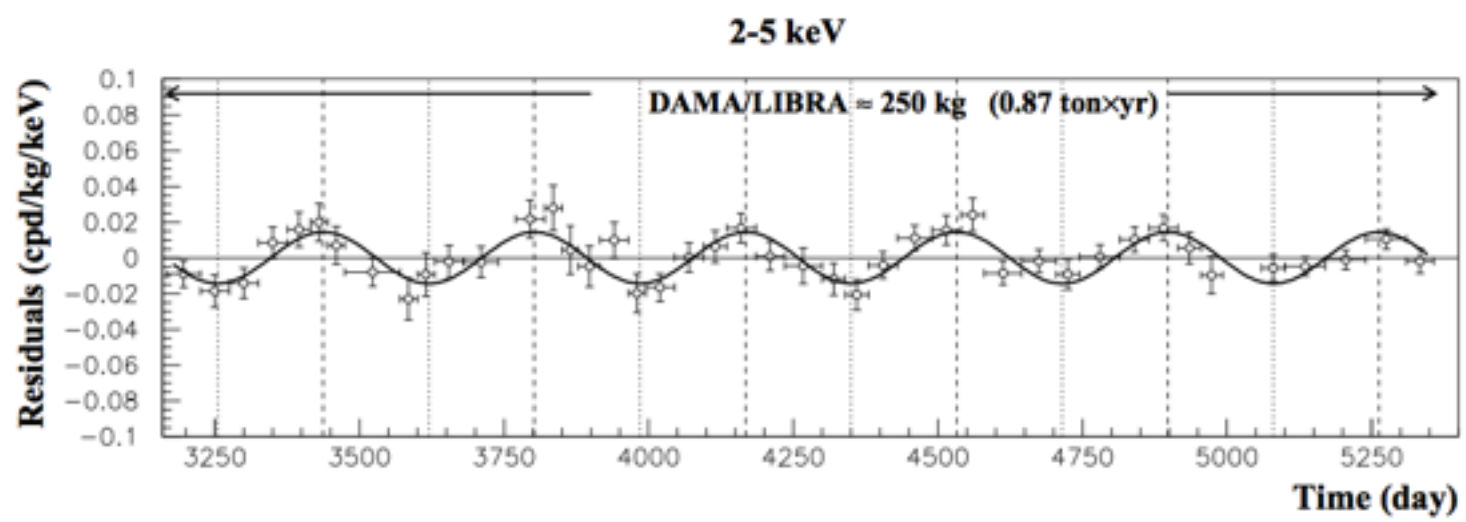


Other Observations Fitting Light DM: Direct

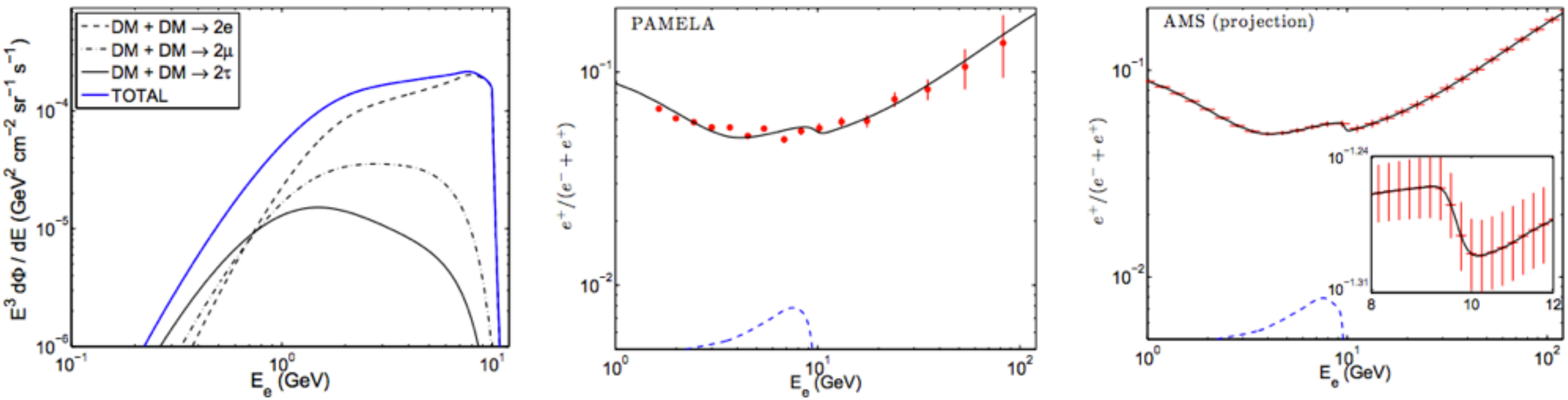


- Light Dark Matter (~10 GeV) provides a compelling fit to the excesses currently observed by DAMA, CoGeNT and CRESST
- Light Dark Matter may also be compatible with observed signal/limits at CDMS
- This issue will be resolved on the experimental side, with current and upcoming data





Other Observations Fitting Light DM: Indirect



Hooper & Xue (2012)

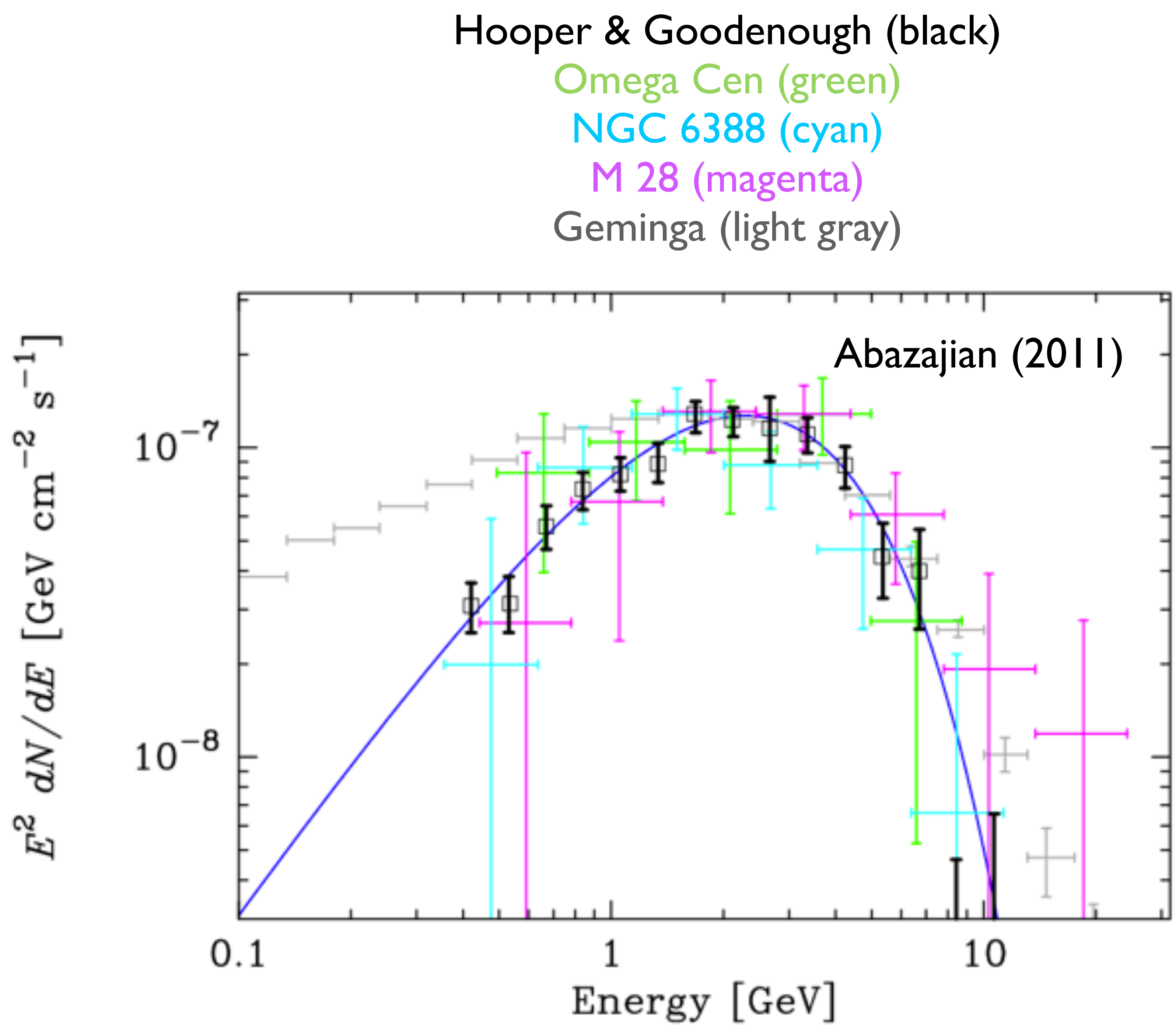
- Light, leptophilic Dark Matter models will be observable by AMS.

- Solar Modulation must be taken into account (marginally) at these energy levels

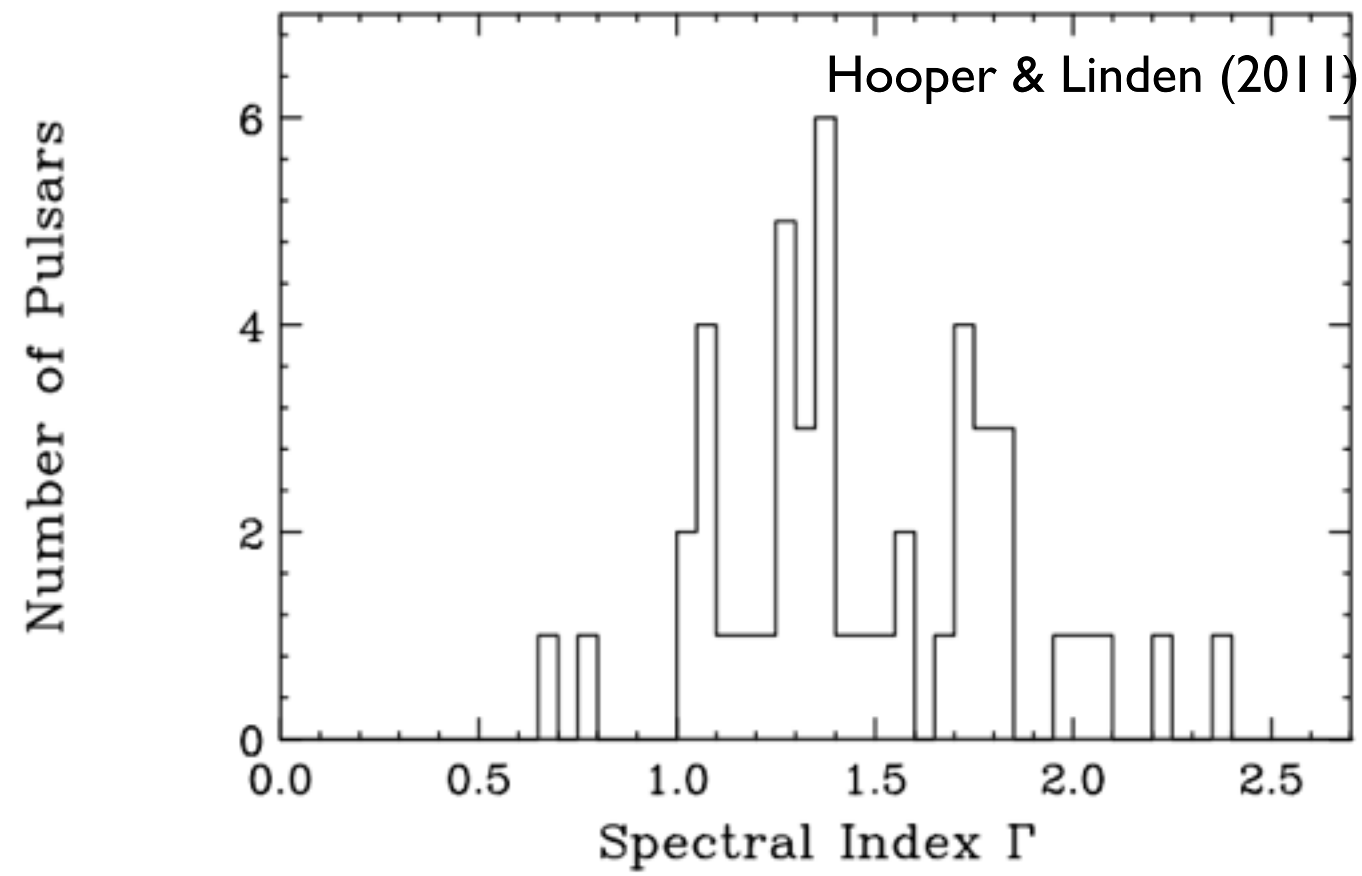
Story 3: Milli-second Pulsars

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

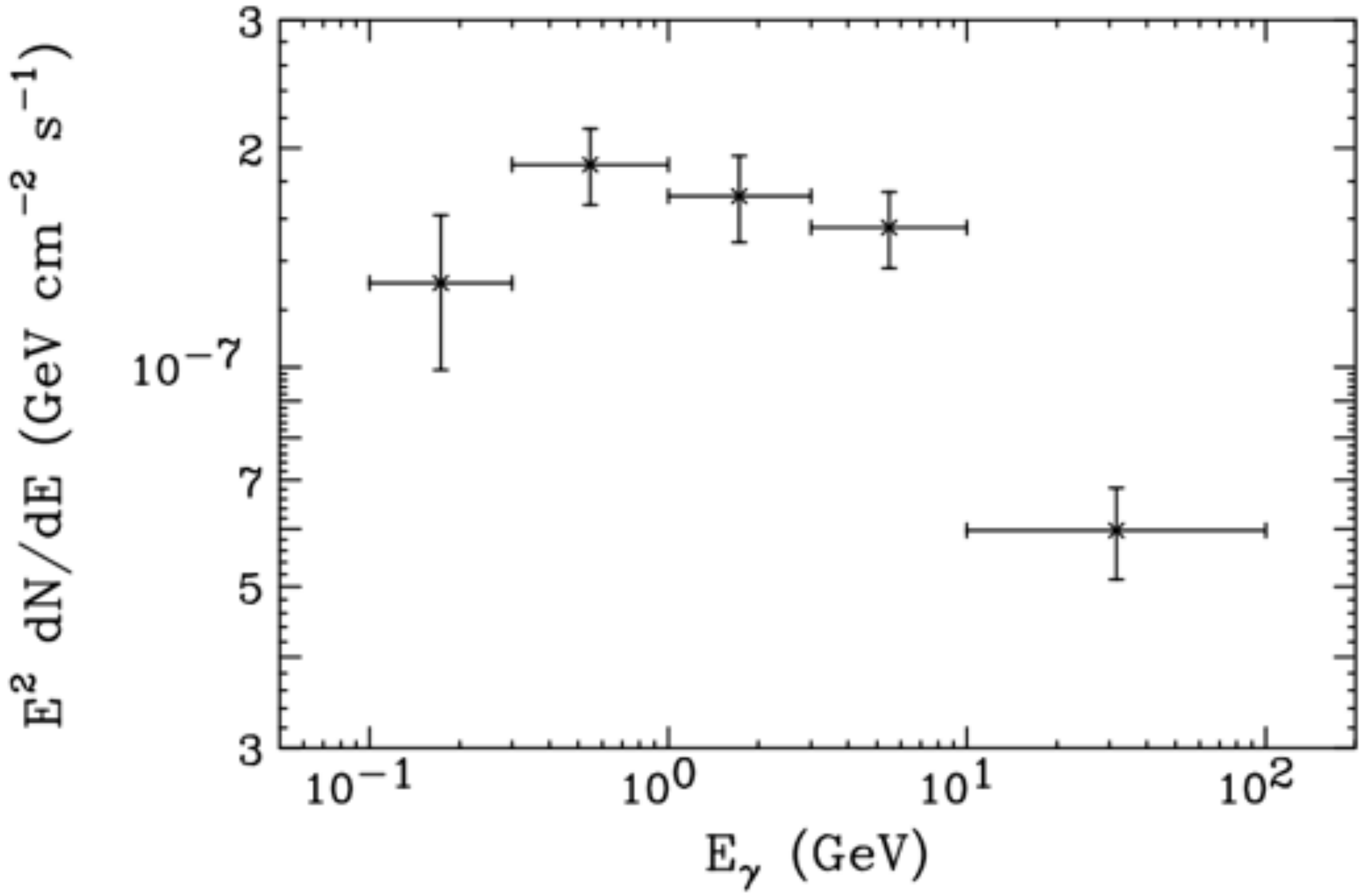
- GC source is ~200 brighter than Omega Cen - which correlates nicely with the 1000x larger mass of the GC region

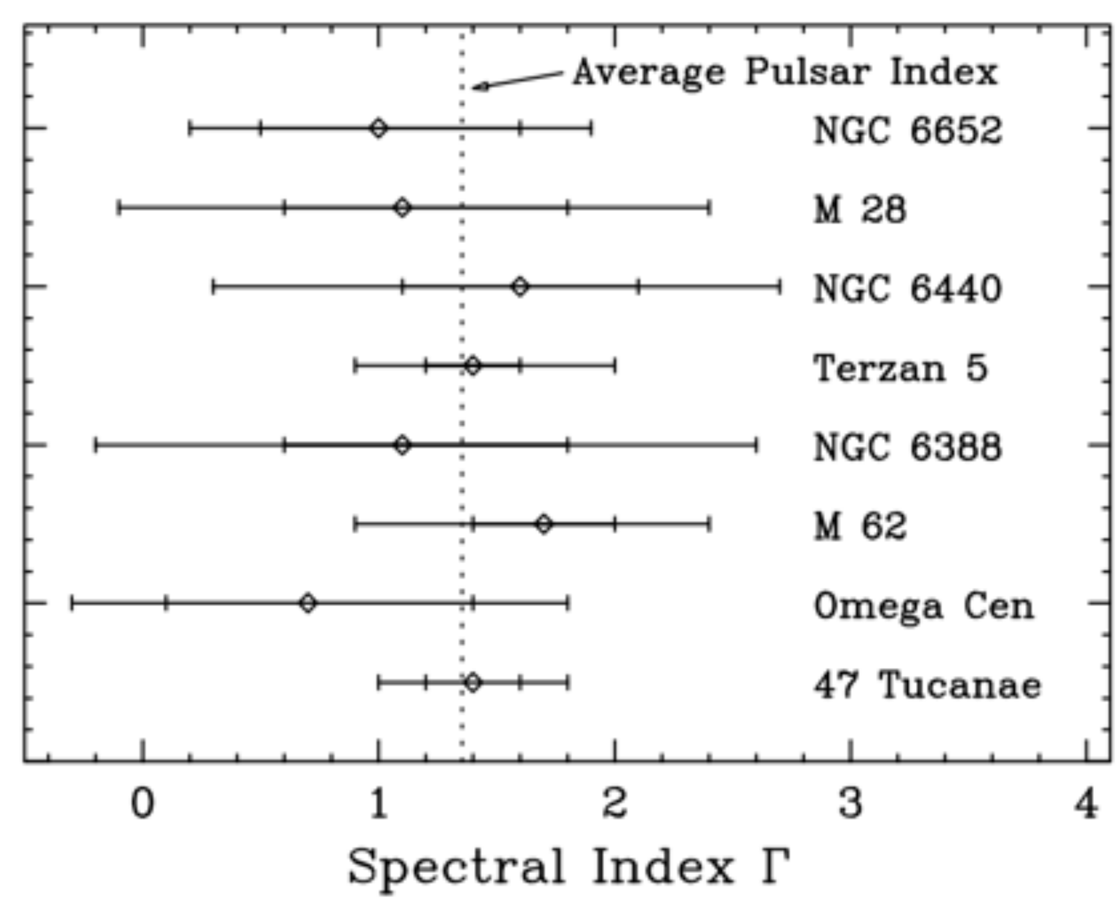


Millisecond Pulsar Spectrum



- But is the spectrum of the observed residual (Γ <≈ 1.0) too hard below 1 GeV?

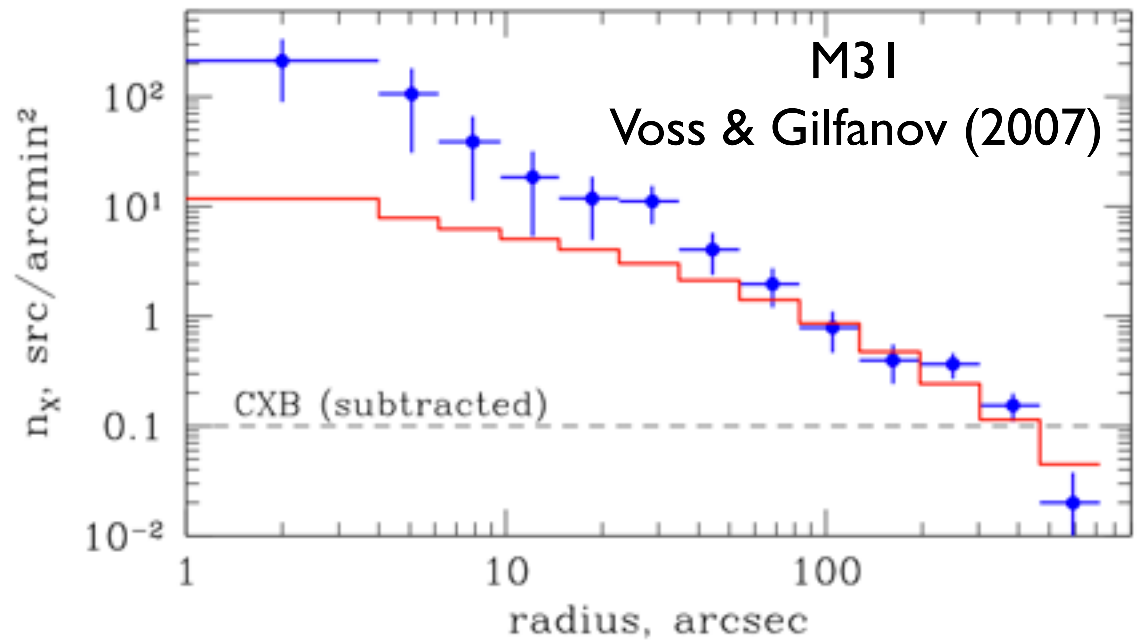


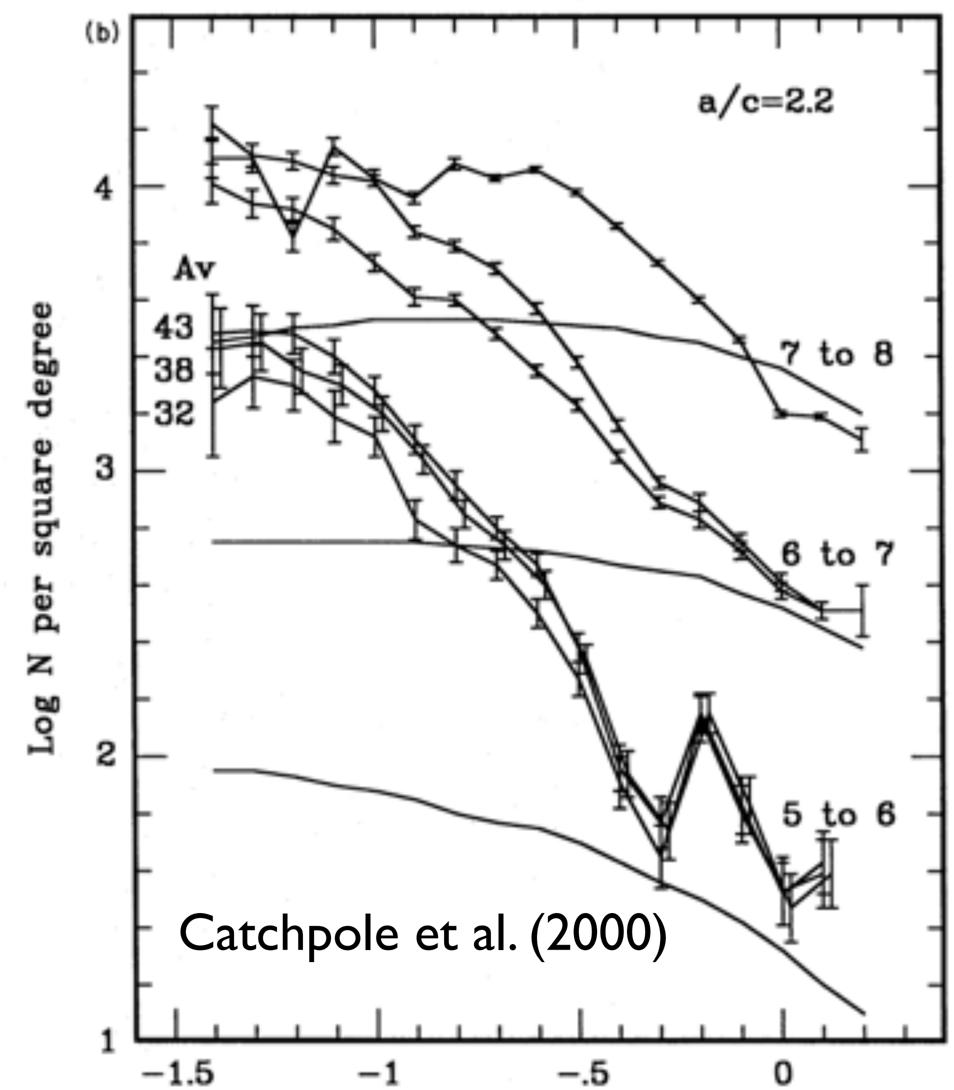


Millisecond Pulsar Density

- 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?

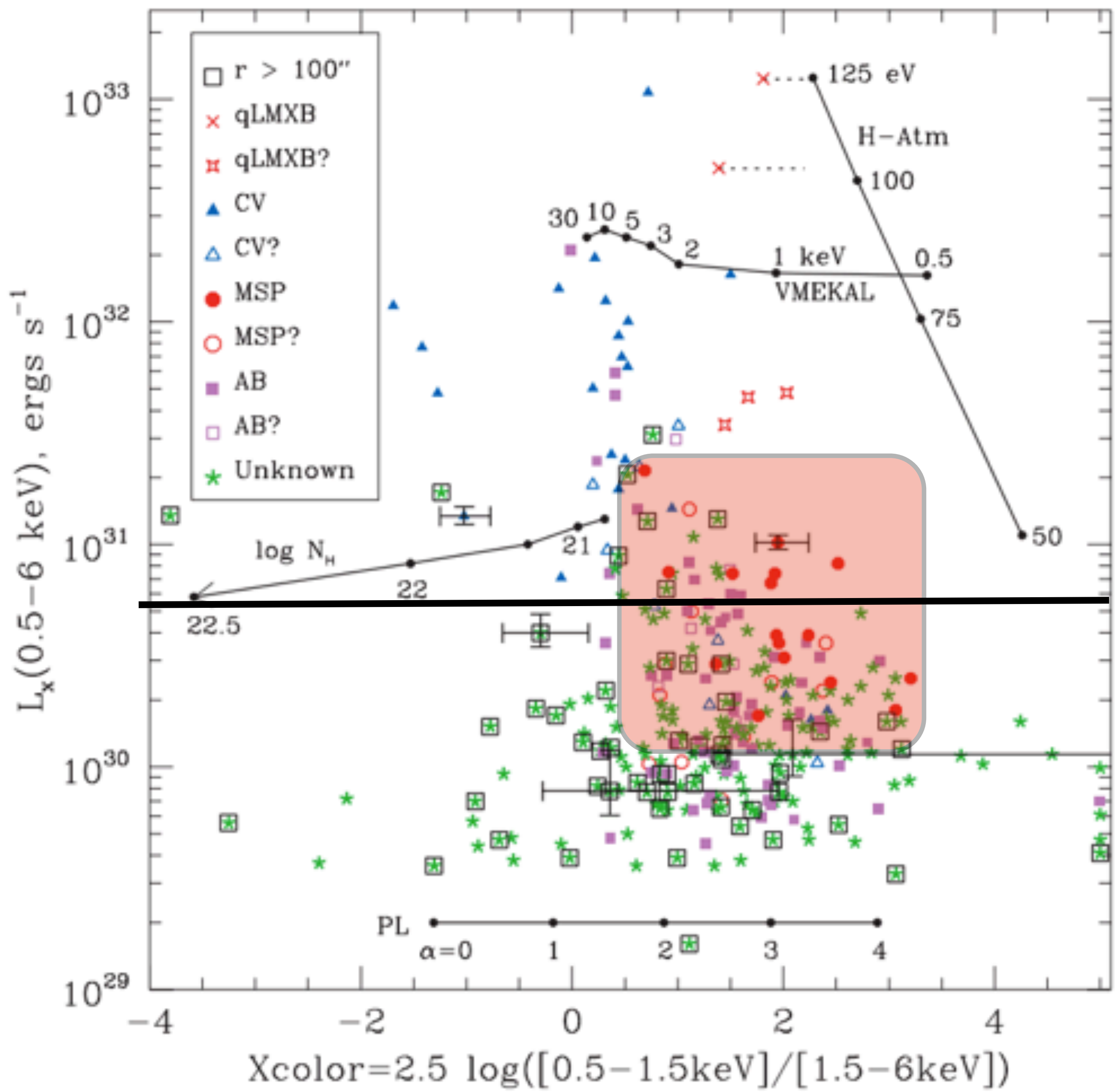




Can the Distribution of GC MSPs be Determined?

- X-Ray observations find a total of 2347 point sources within 40 pc of the GC - this could include a large population of MSPs

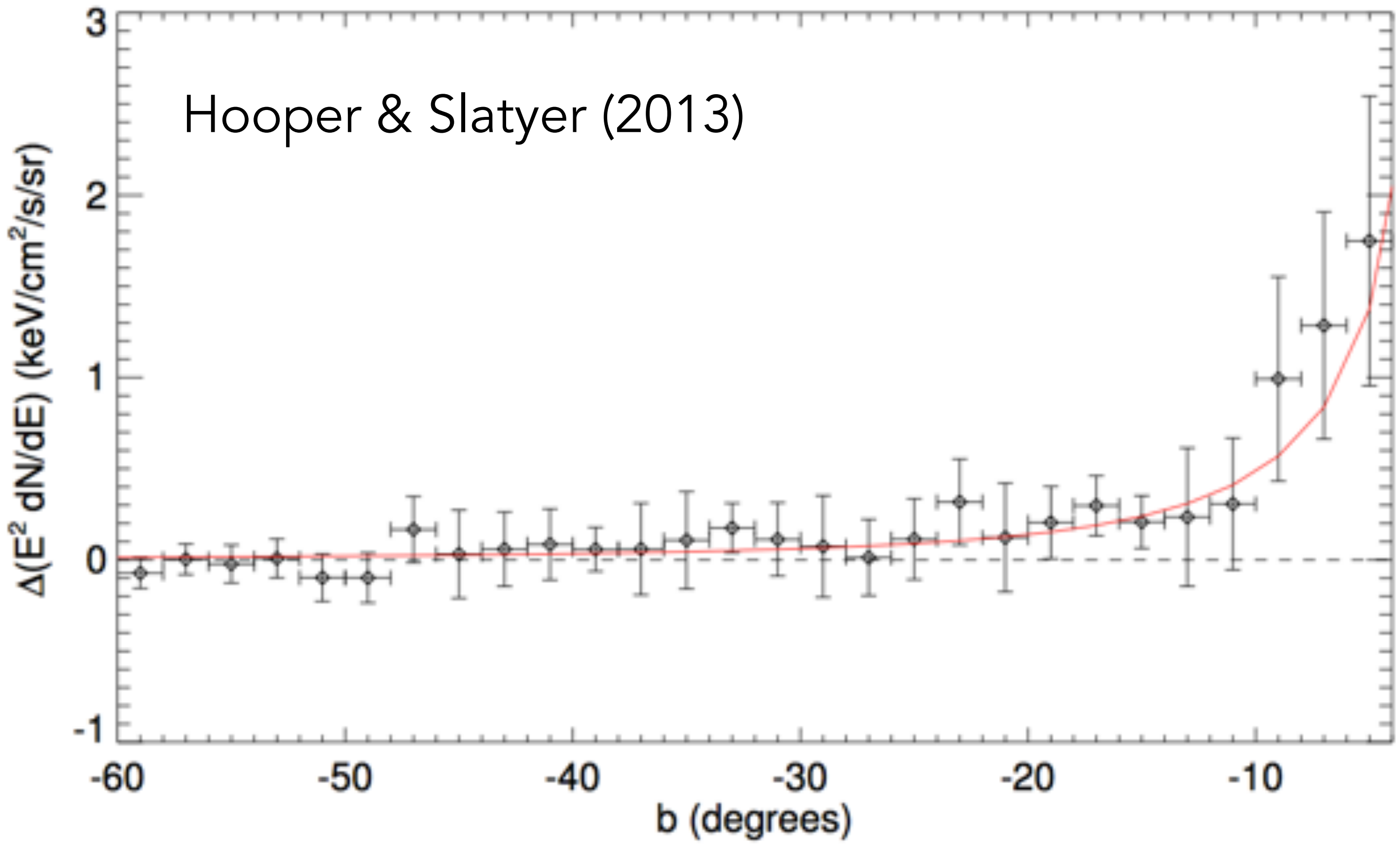
- MSPs exist in a particular location on the luminosity-color diagram in 47 Tuc



Heinke et al. (2006)

Have we observed a signal?

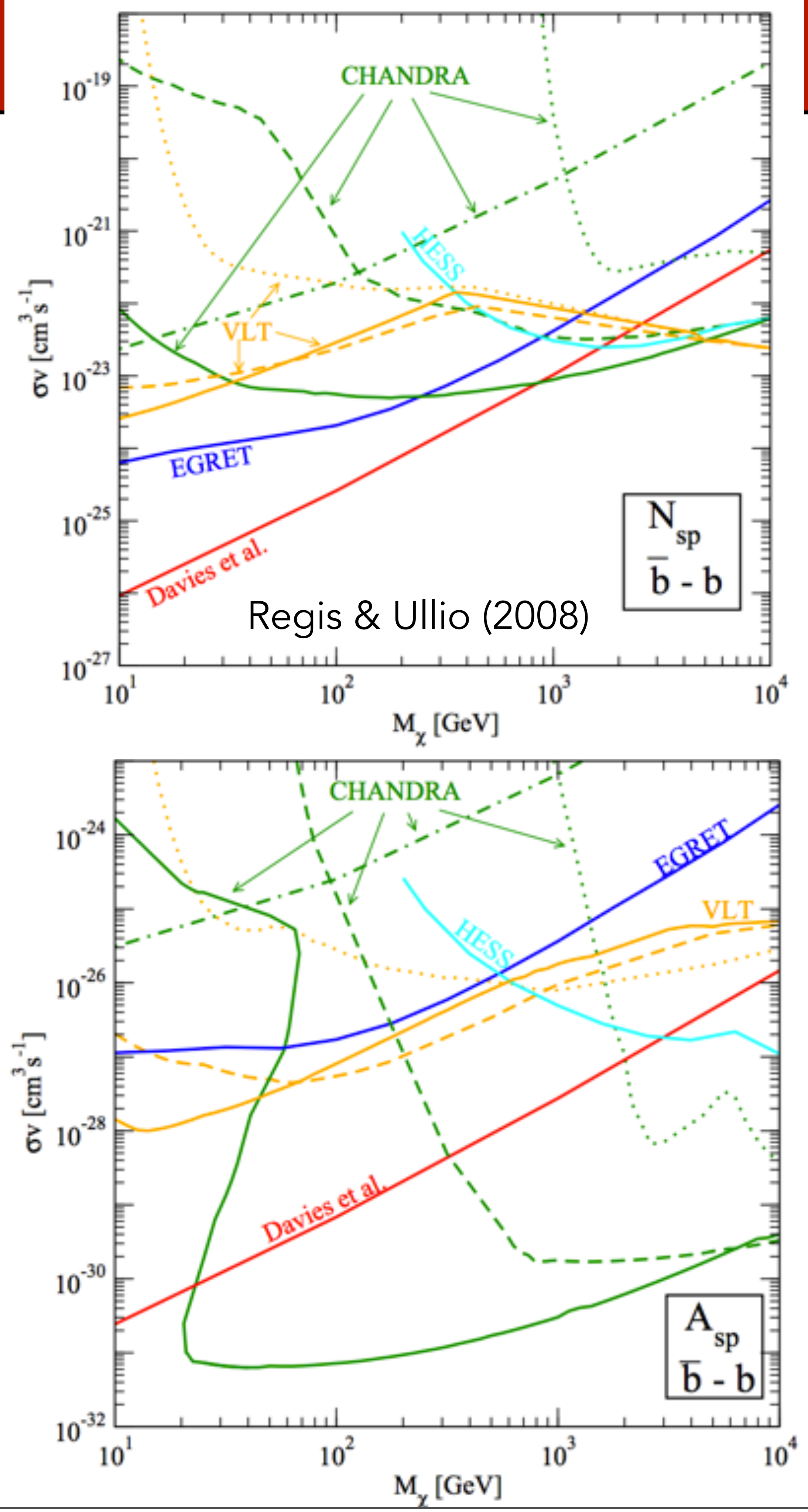
- New evidence shows this signal may extend to high latitudes



Stay Tuned!

Radio and X-Ray Observations

- Very strong constraints can be placed on dark matter annihilation through radio and X-Ray observations
- Current techniques have focused on regions **very** close to the central black hole, utilizing the high density of dark matter expected there
- Two issues:
  - Dependent on diffusion parameters
  - High Resolution requires extrapolation of dark matter density profiles



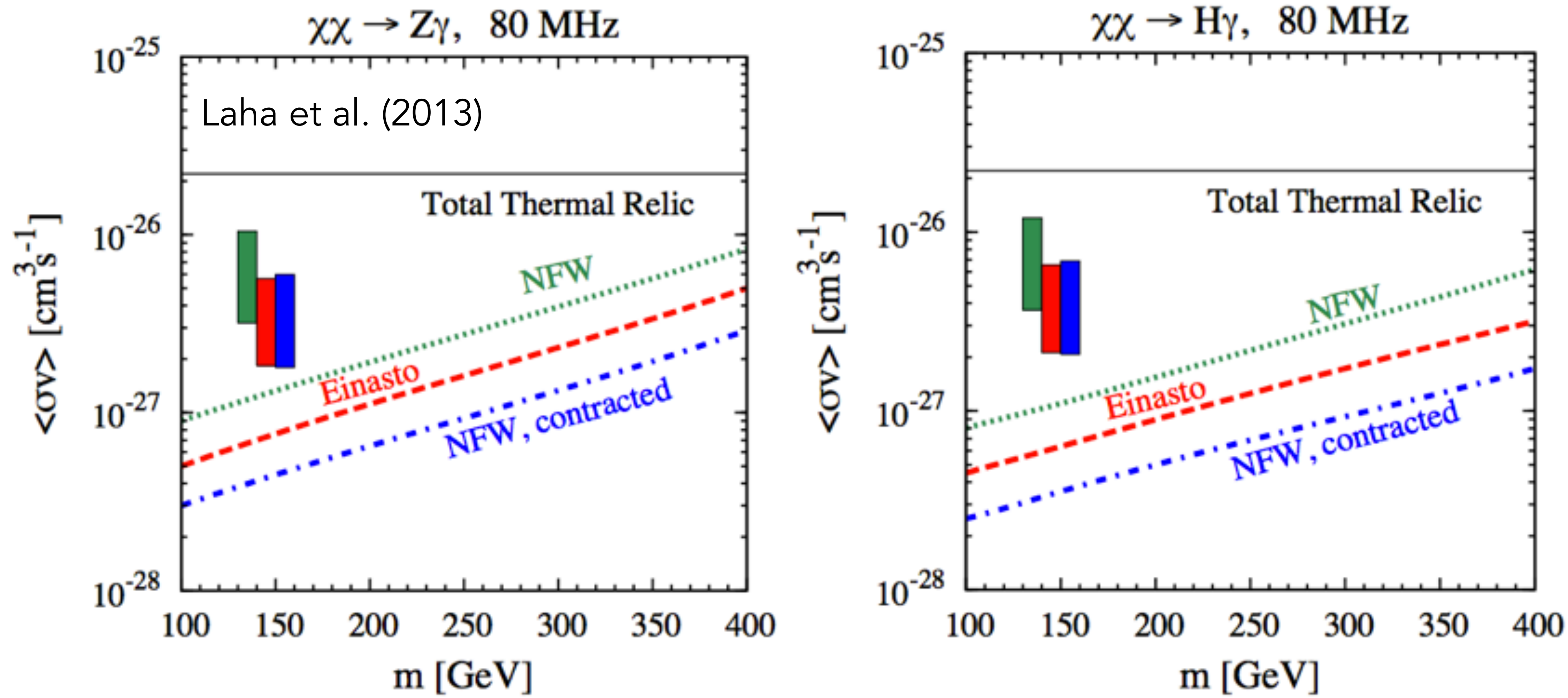
Necessary Observational Advances

- Observational capabilities over the next decade are relatively set.

- **Angular Resolution** is the key to understanding the Galactic Center
    - Long Wavelength Array (<100 MHz) - 8″
    - ALMA (84-720 GHz) - 0.1″
    - JWST (0.04 - 2 eV) - < 0.1″
    - NuSTAR (5 - 80 keV) - 18″
    - Gamma400 (100 MeV - 3 TeV) - 0.01° (> 100 GeV)
    - CTA (>20 GeV) - 0.03° (> 1 TeV)

- We have great observational advantages in the Galactic Center - telescopes at every wavelength spend a significant portion of their time staring at it.

Future Radio and X-Ray Observations

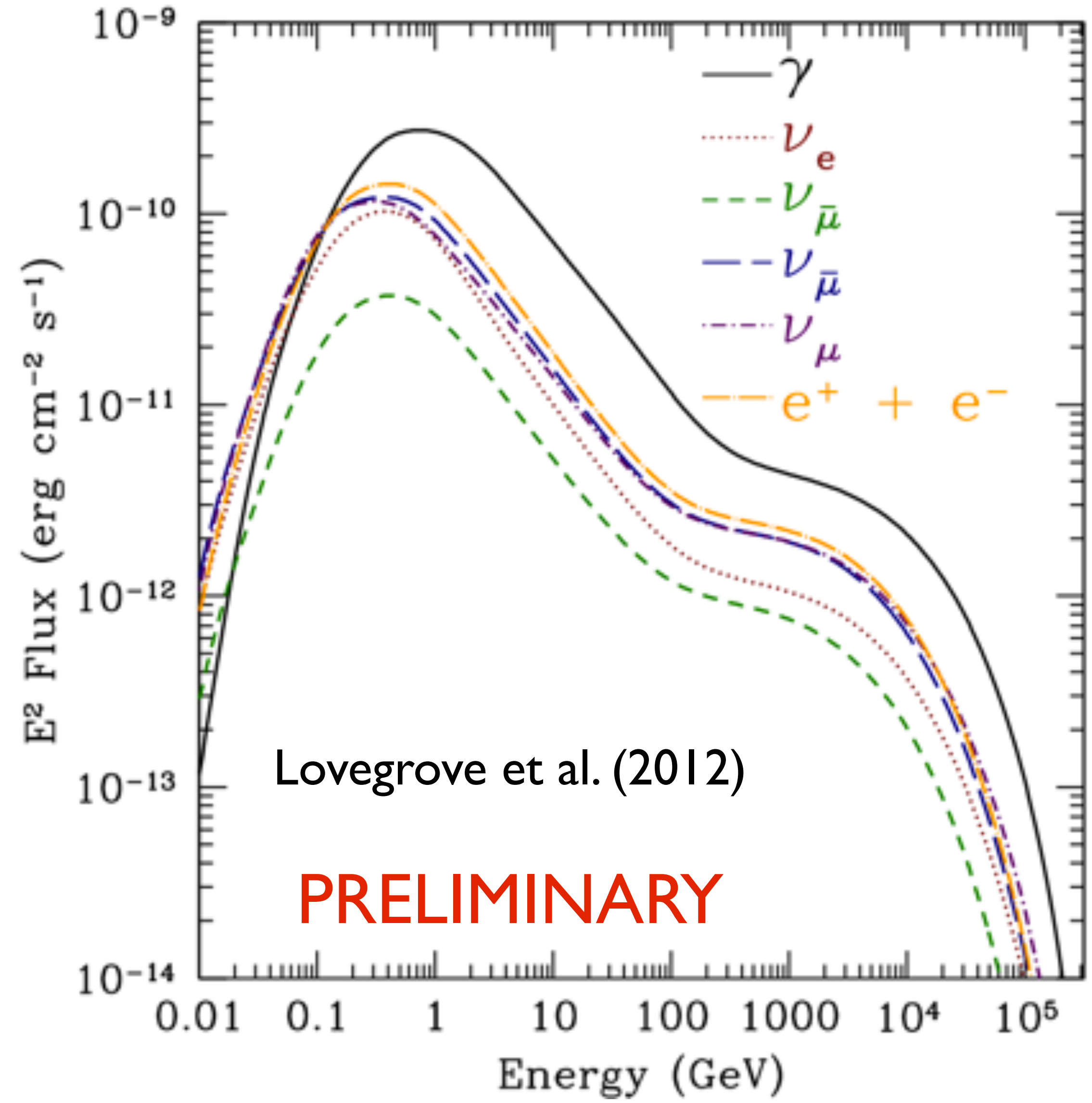


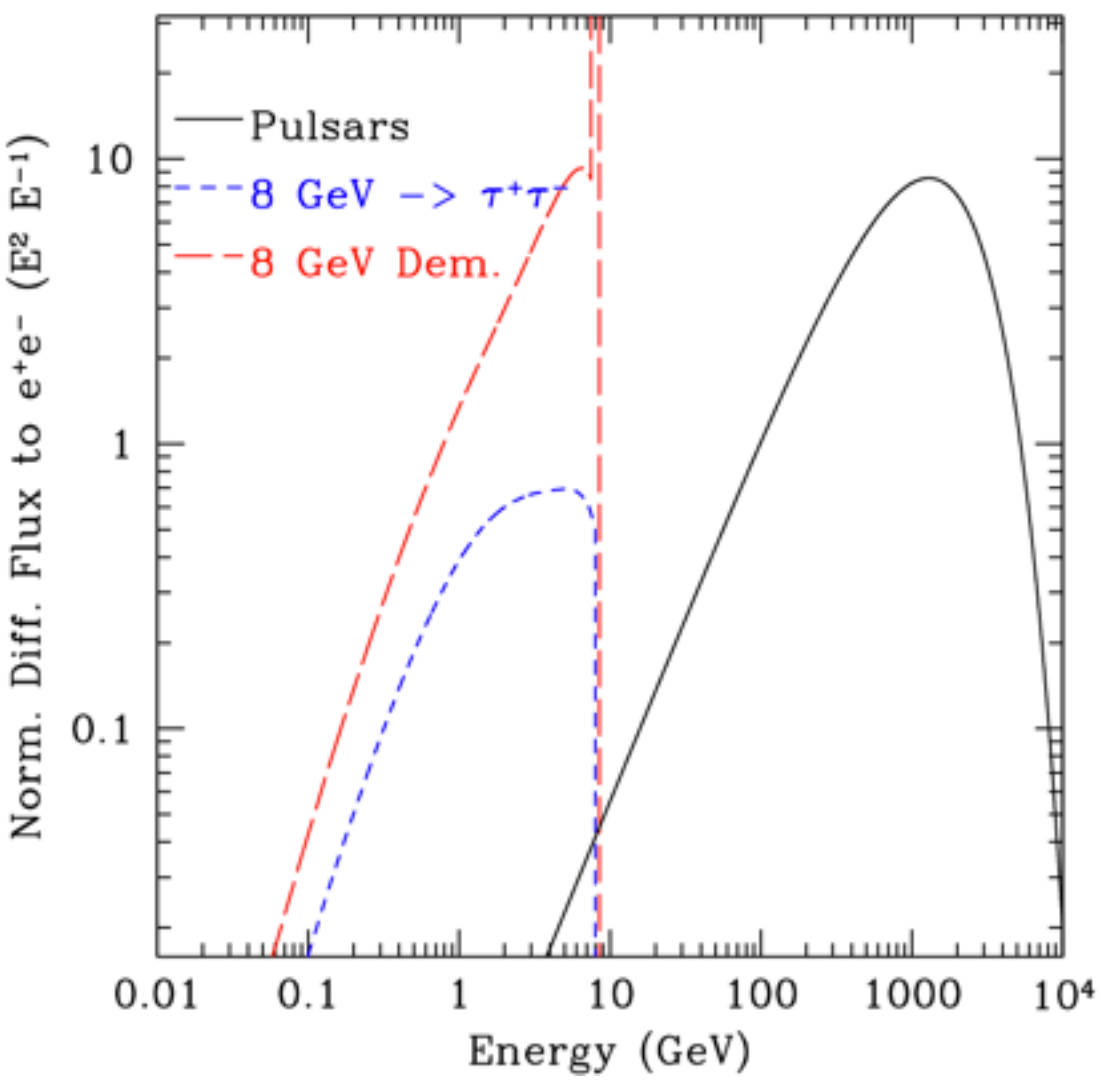
- Can also put constraints on certain gamma-ray models (like the 130 GeV line)

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



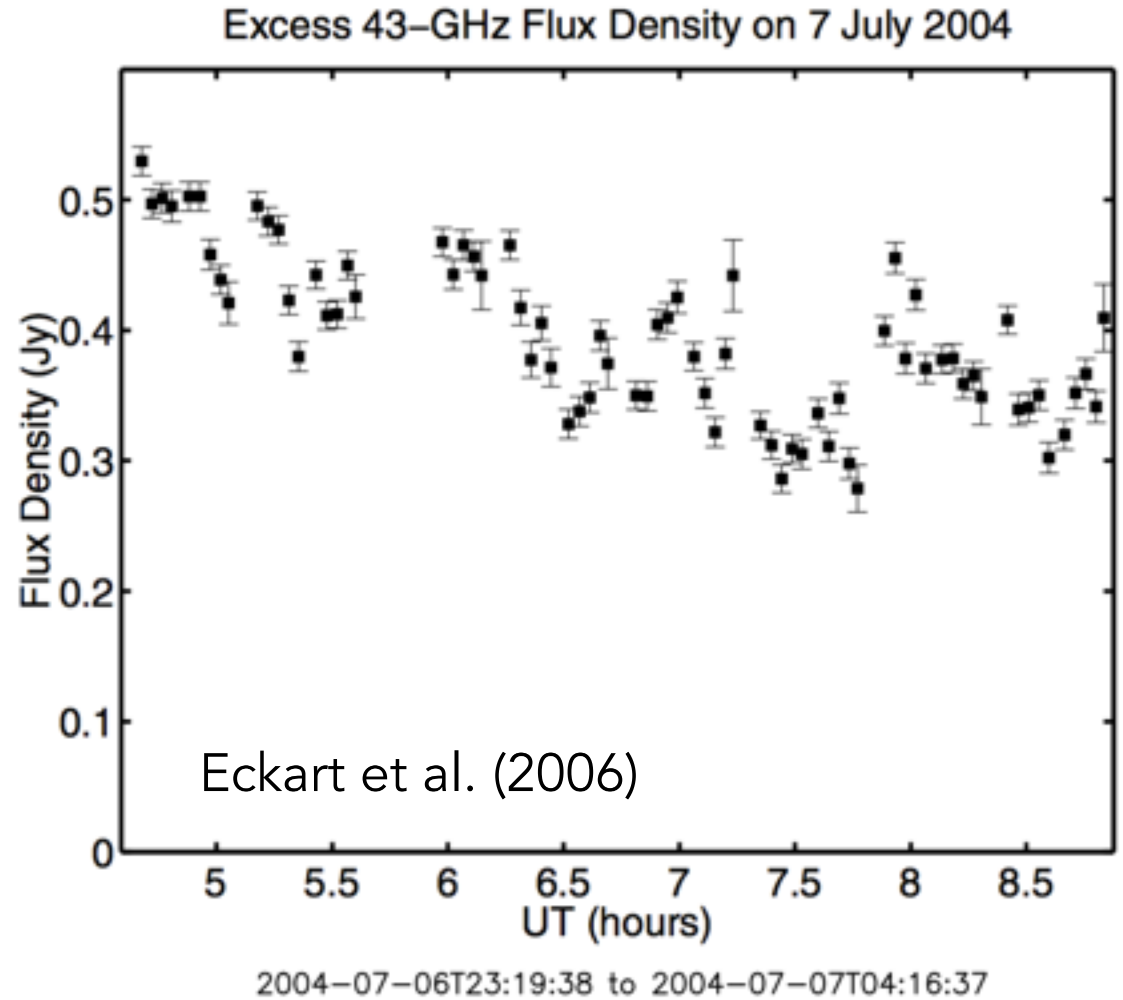


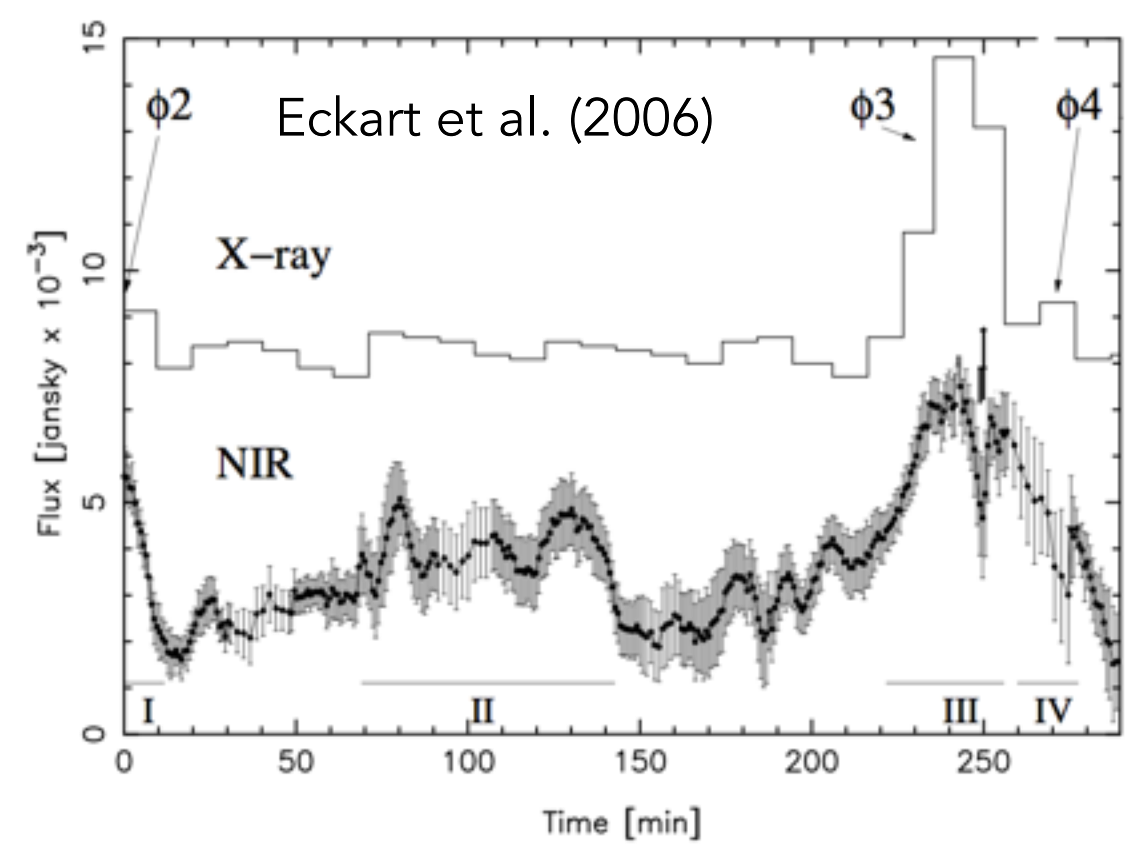
Positive: The angular resolution of radio telescopes is significantly greater than gamma-ray observatories

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

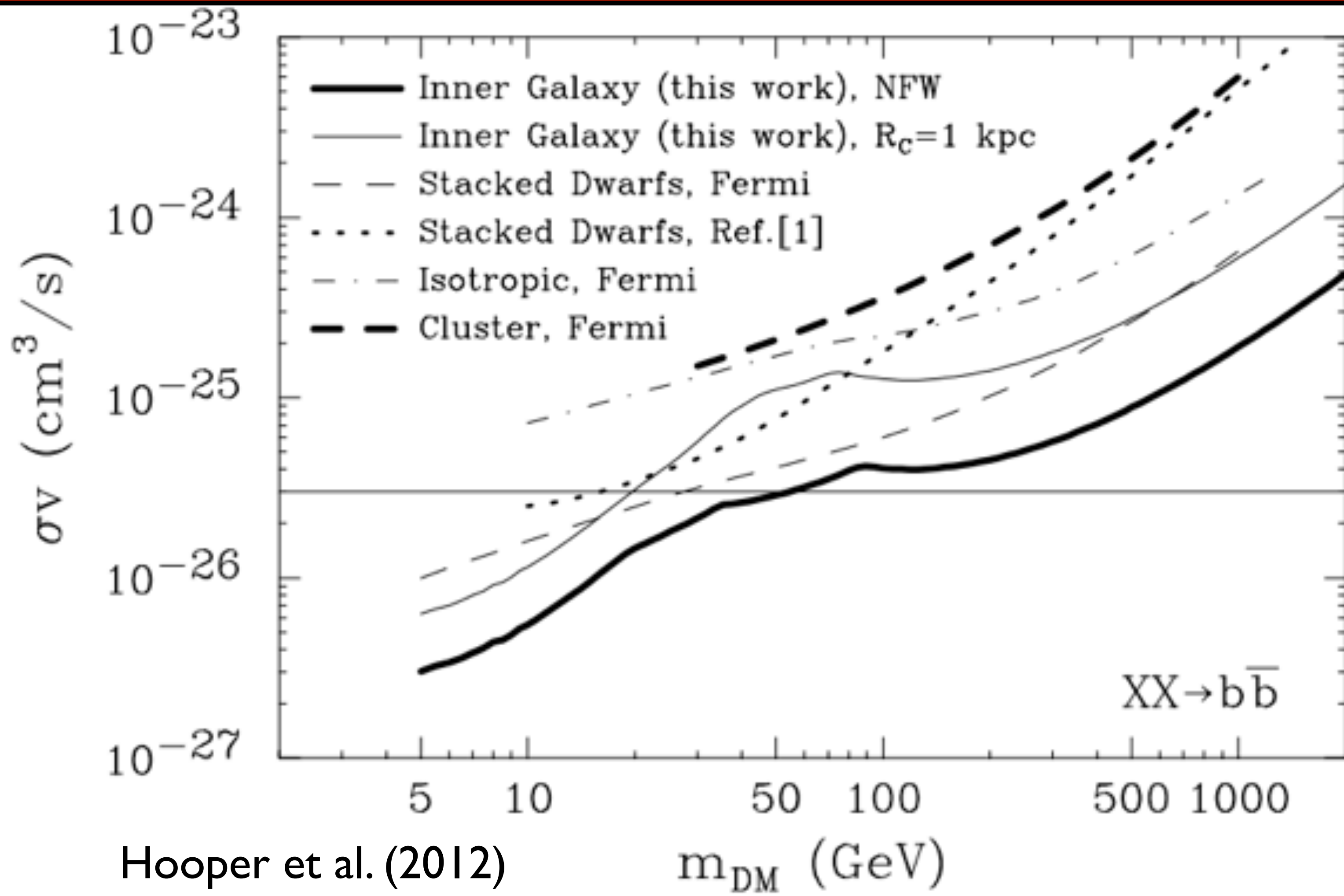
Variability at the Galactic Center

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



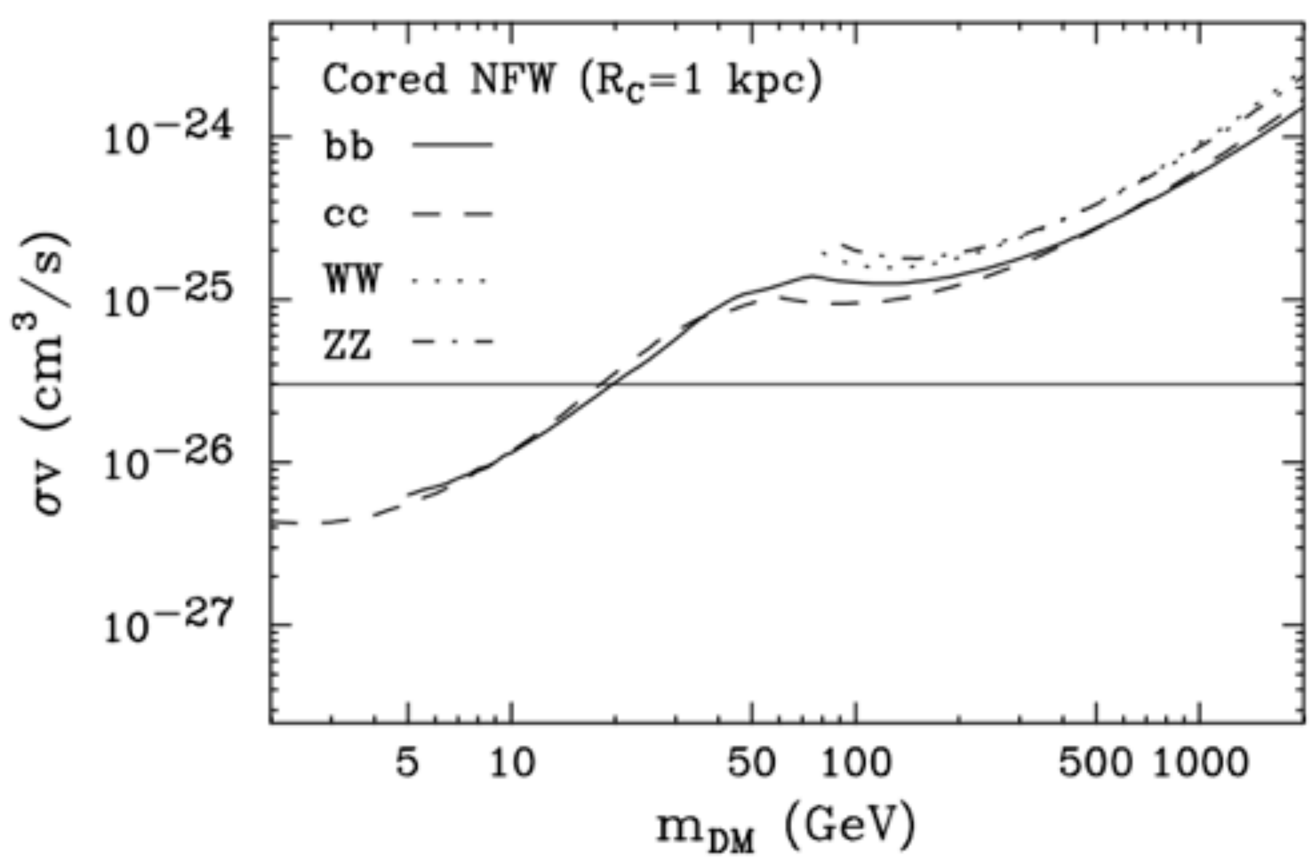


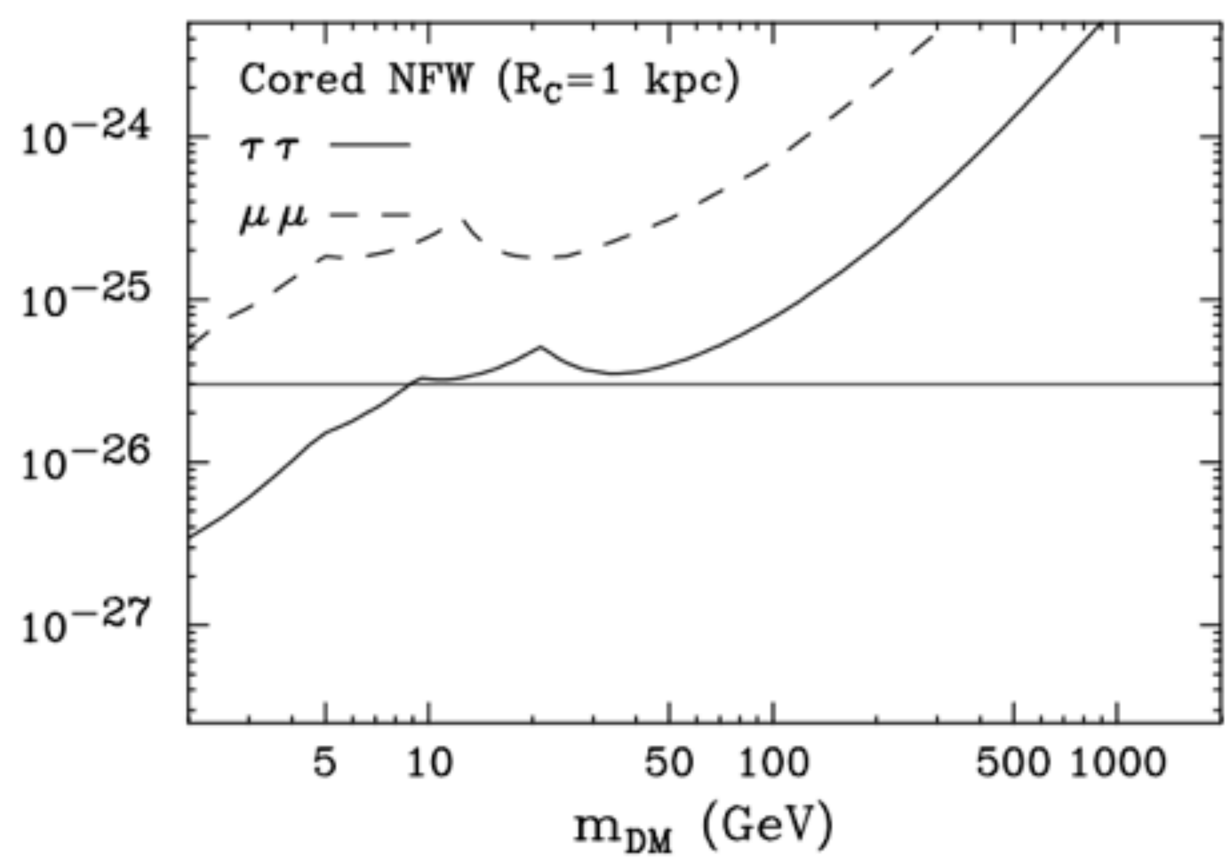
Comparison to Other Indirect Detection Regimes



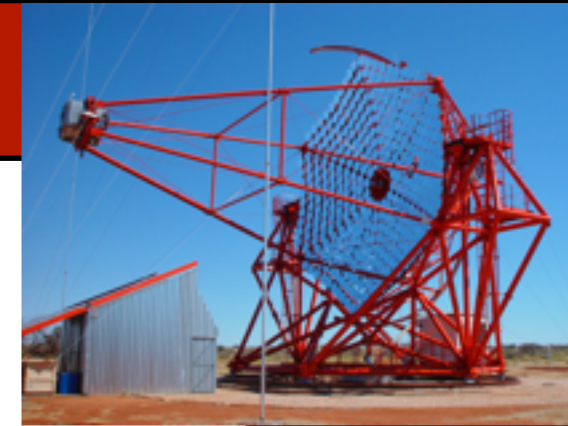
Hooper et al. (2012)

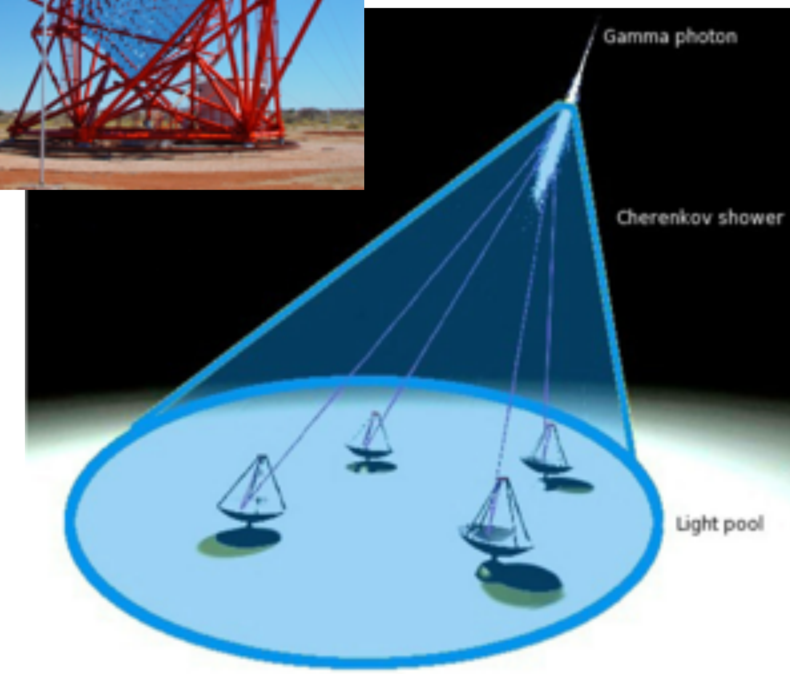
- Hooper et al. (2012) further tweaked the methods used to derive these limits, deriving rigorous constraints under a wide variety of assumptions
- These are the strongest gamma-ray limits on the cross-section for dark matter annihilation



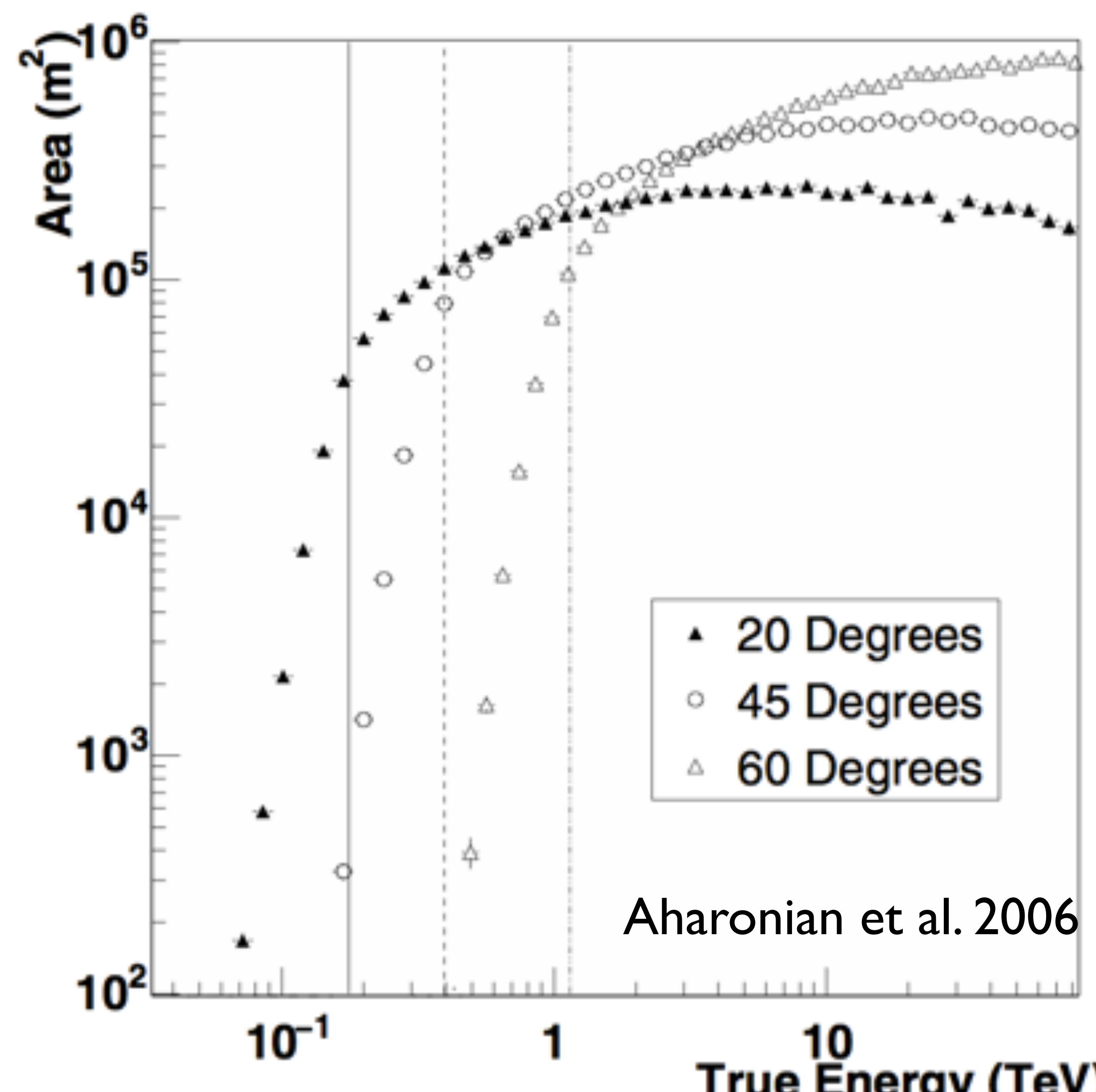


HESS Telescope (2004-Present)





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

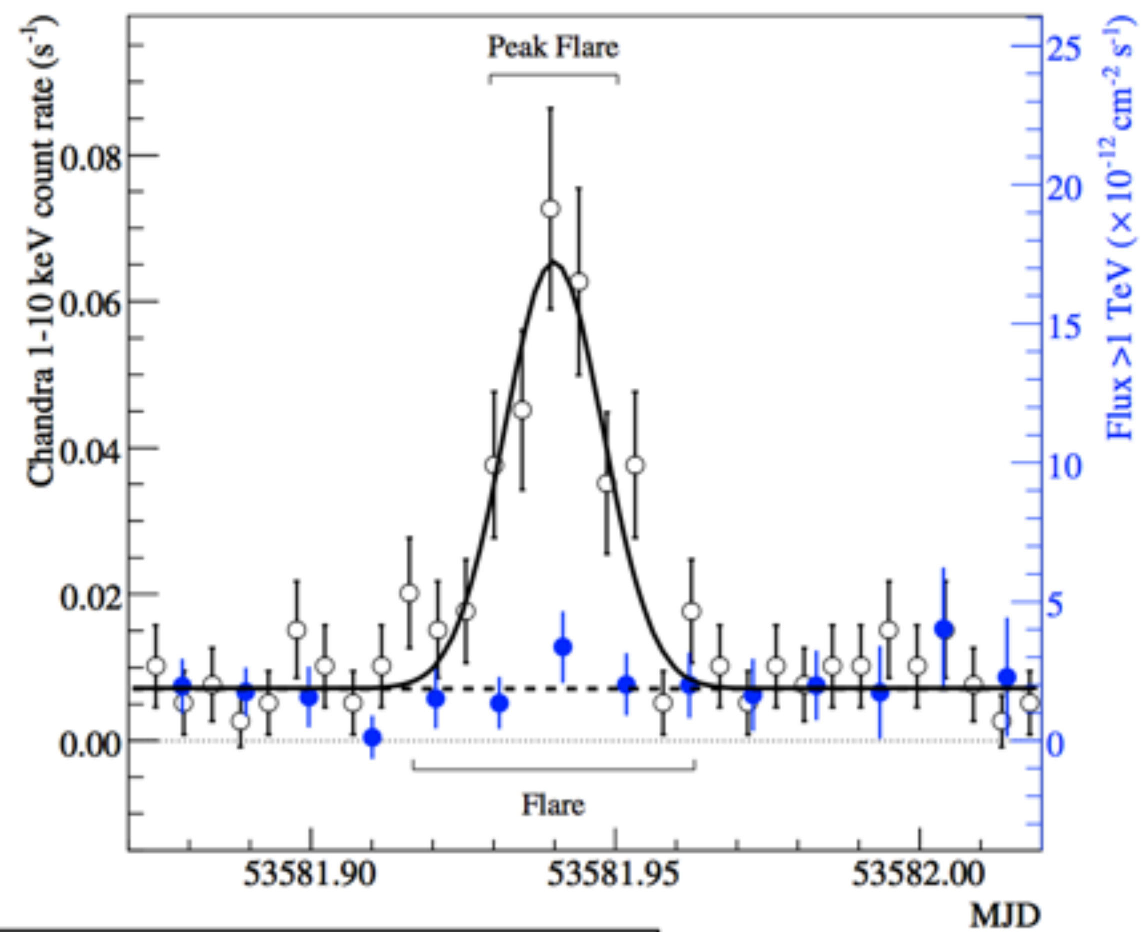


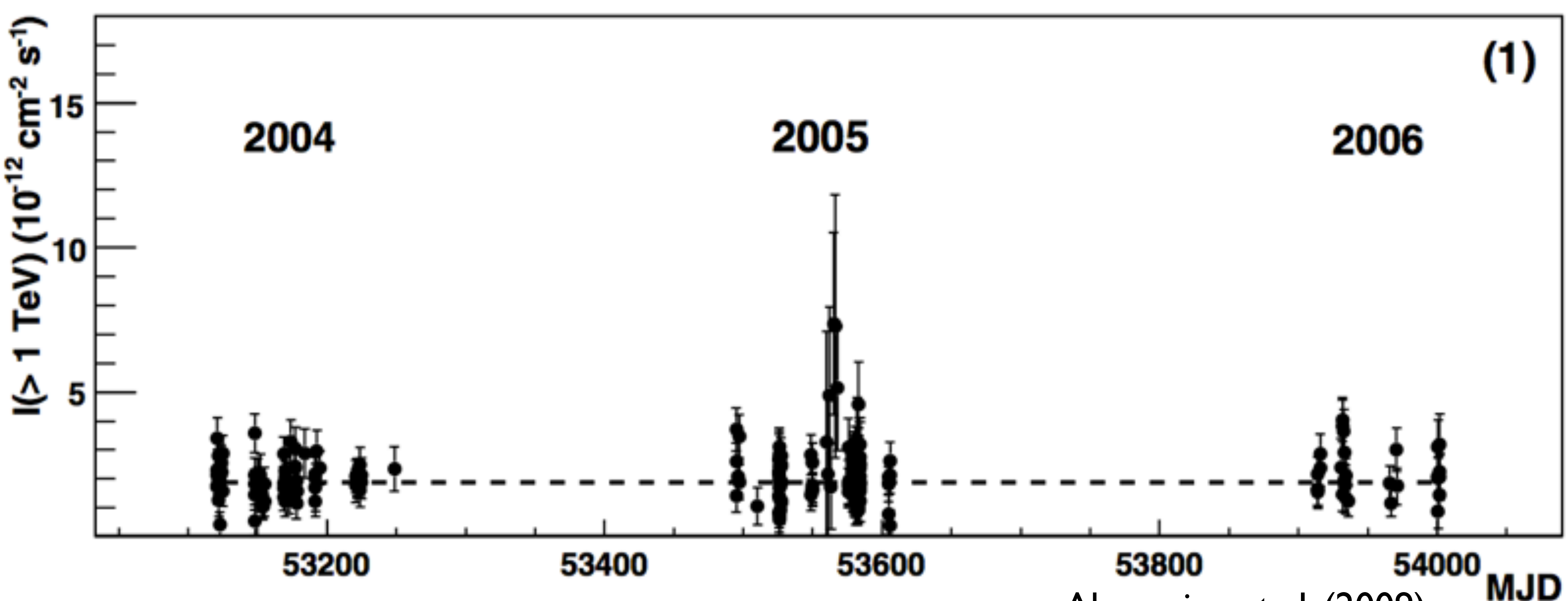
Understanding Astrophysical Backgrounds: HESS

- 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)



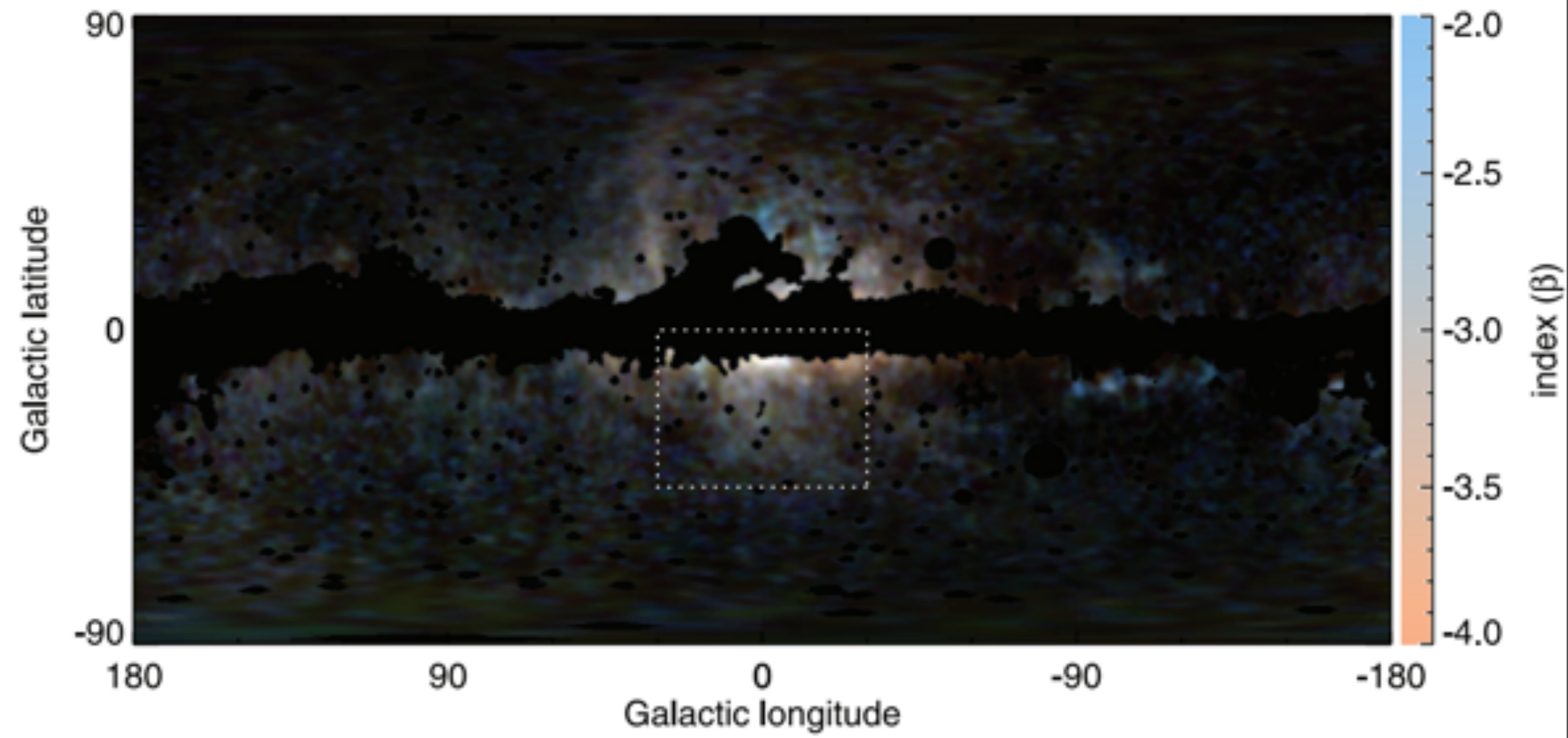


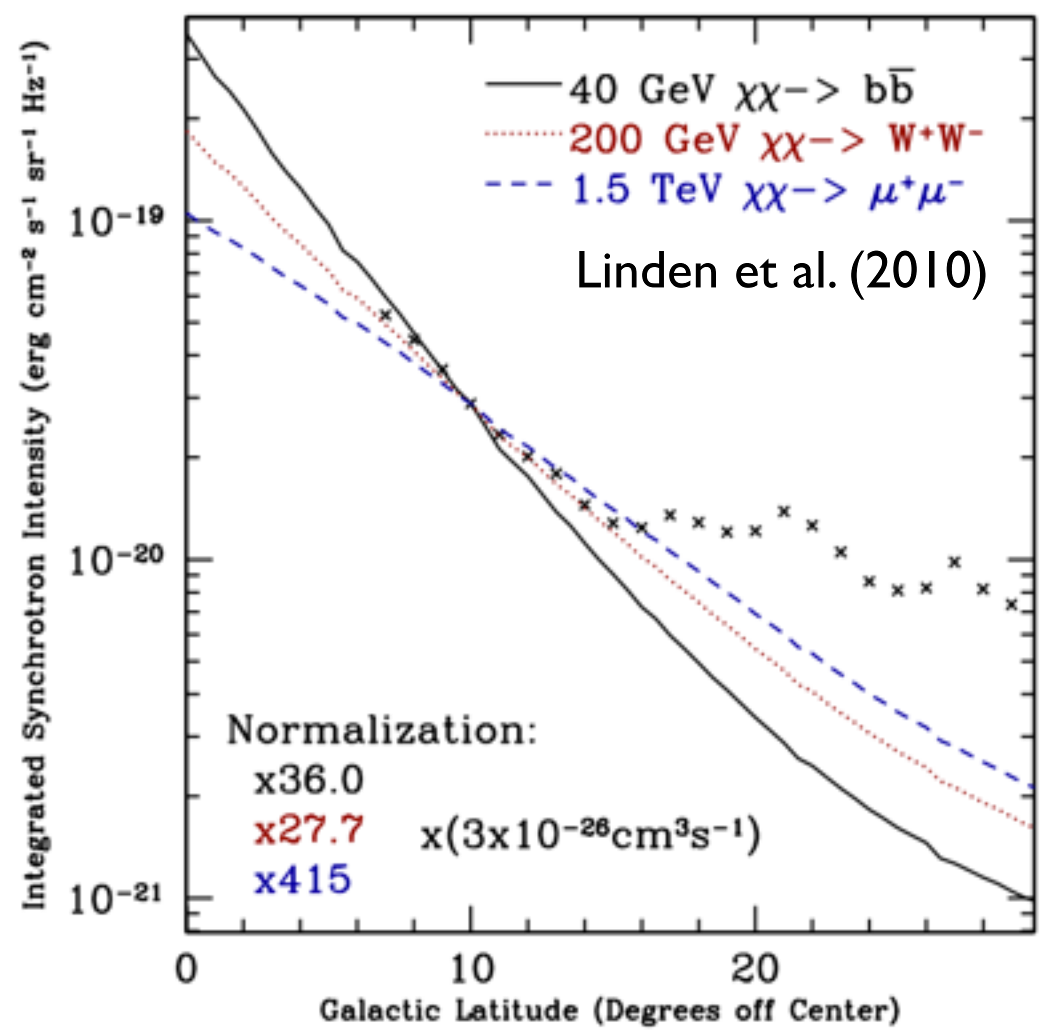
Aharonian et al. (2009)

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

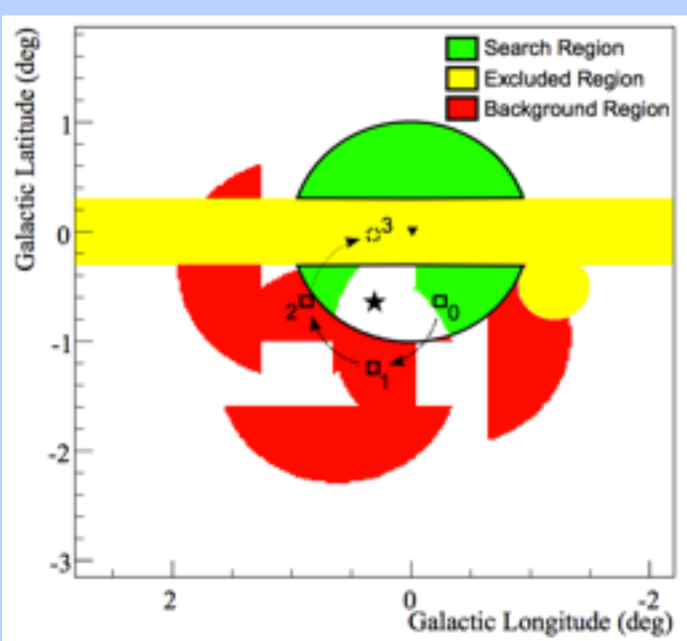
Dobler et al. (2008)

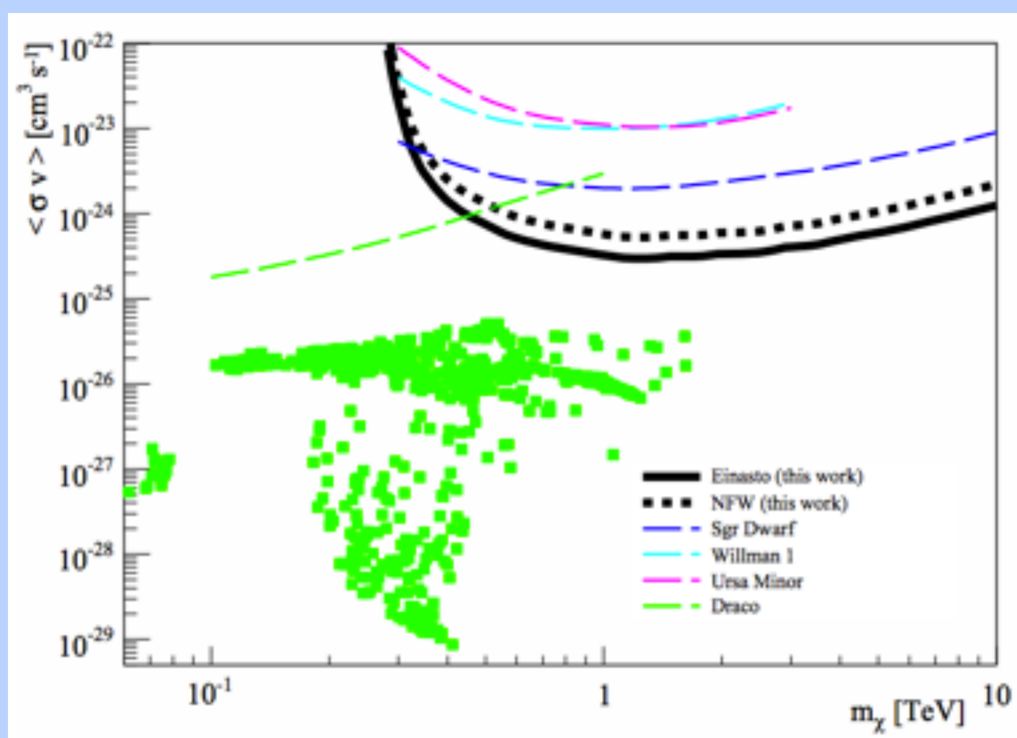




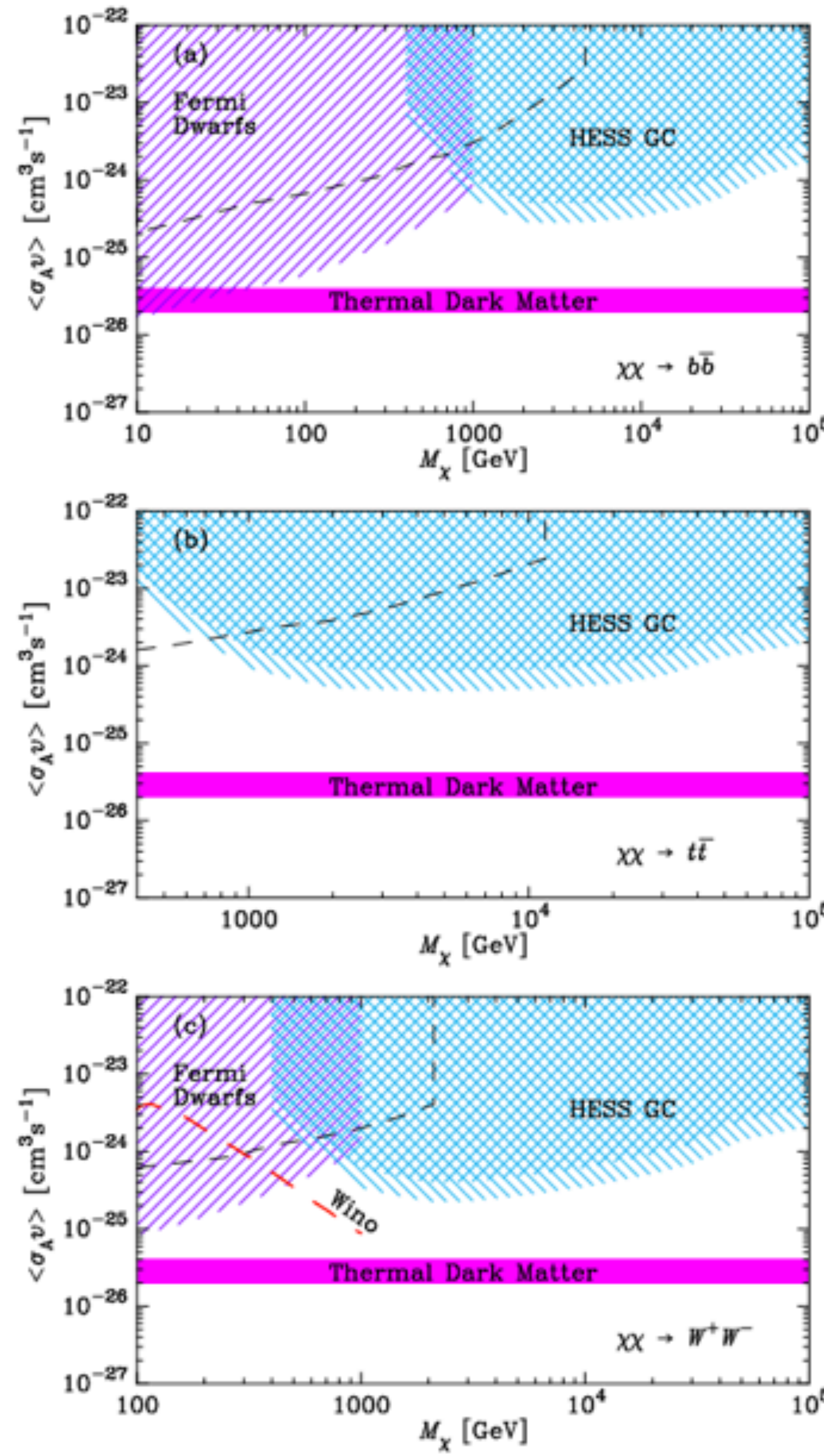
HESS Limits on TeV Dark Matter

- 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





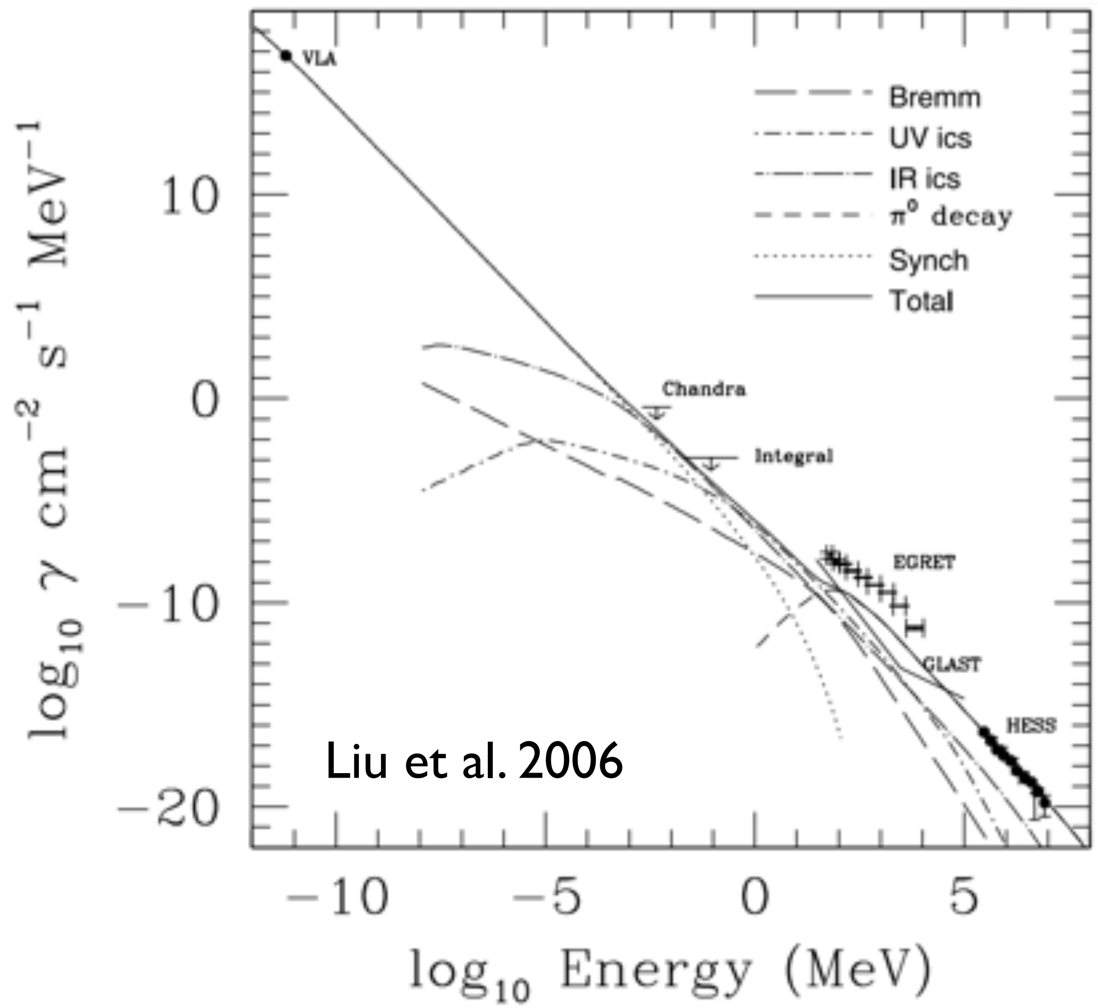
Abramowski et al. (2011)

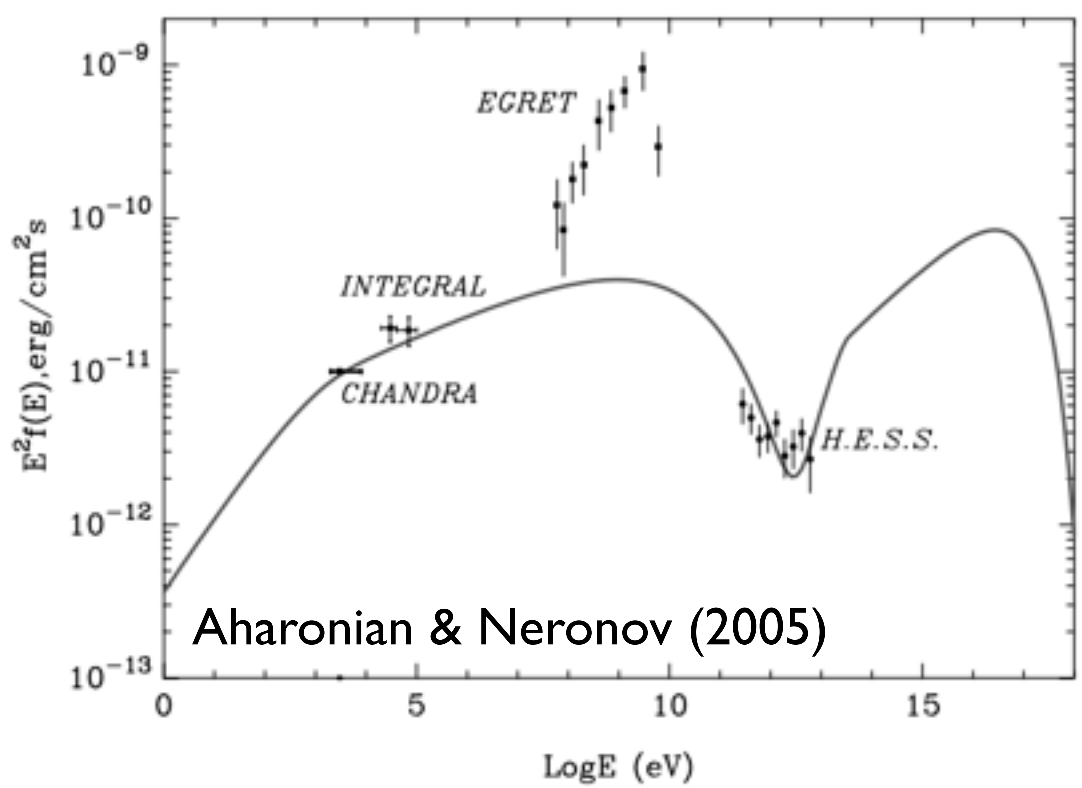


Abazajian & Harding (2011)

Fitting the Residual: Hadronic Processes

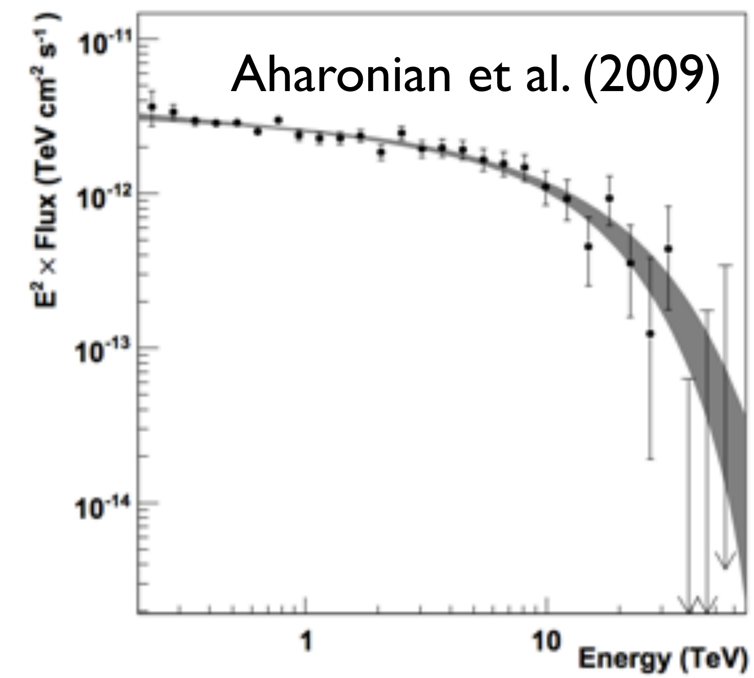
- The lack of variability indicates that the emission may be stemming from a region farther away from the GC itself
- A recent model examined the possibility that protons emitted from the galactic center produce gamma-rays through their subsequent interaction with galactic gas
- This has the potential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

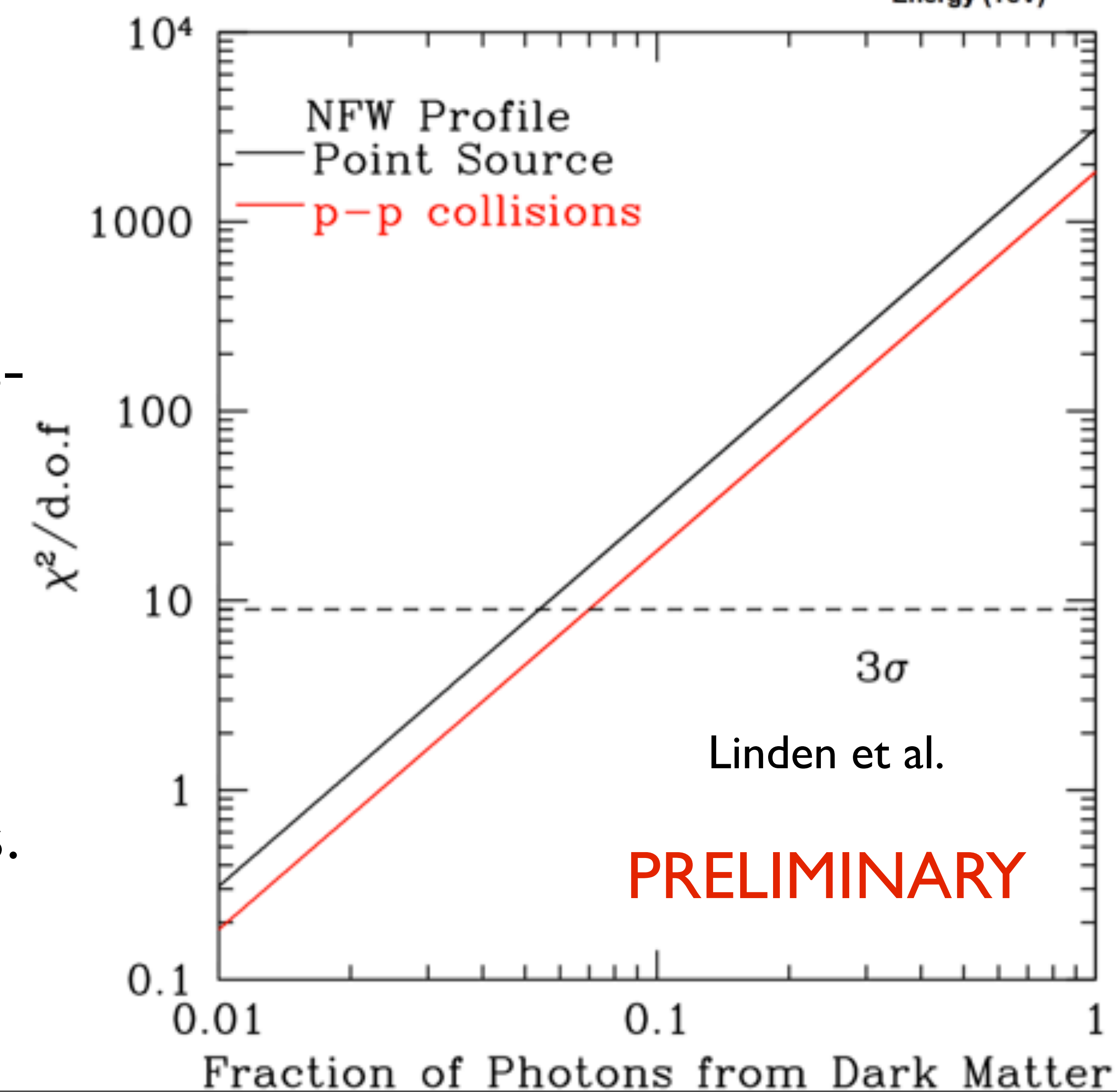




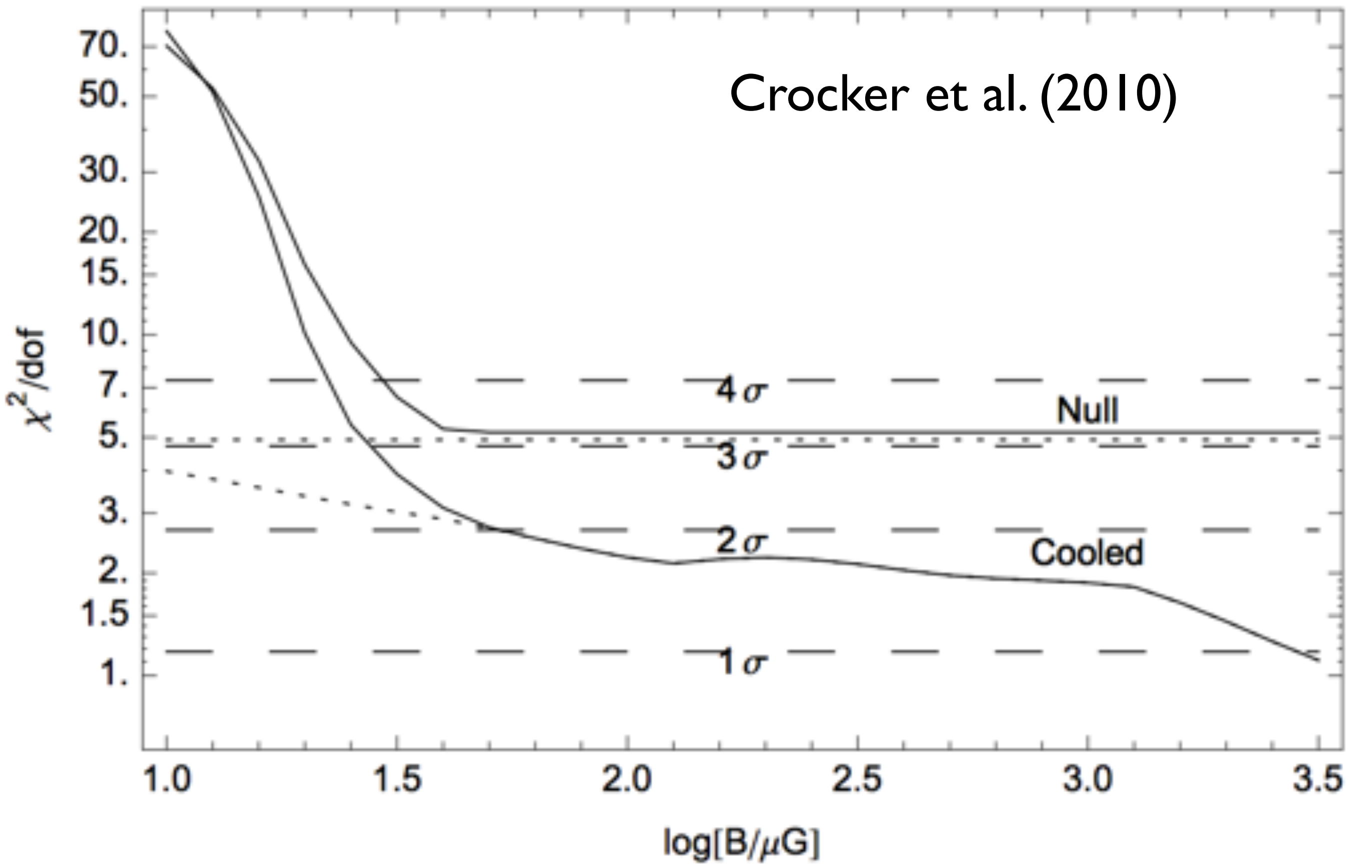
Dark Matter at the Galactic Center

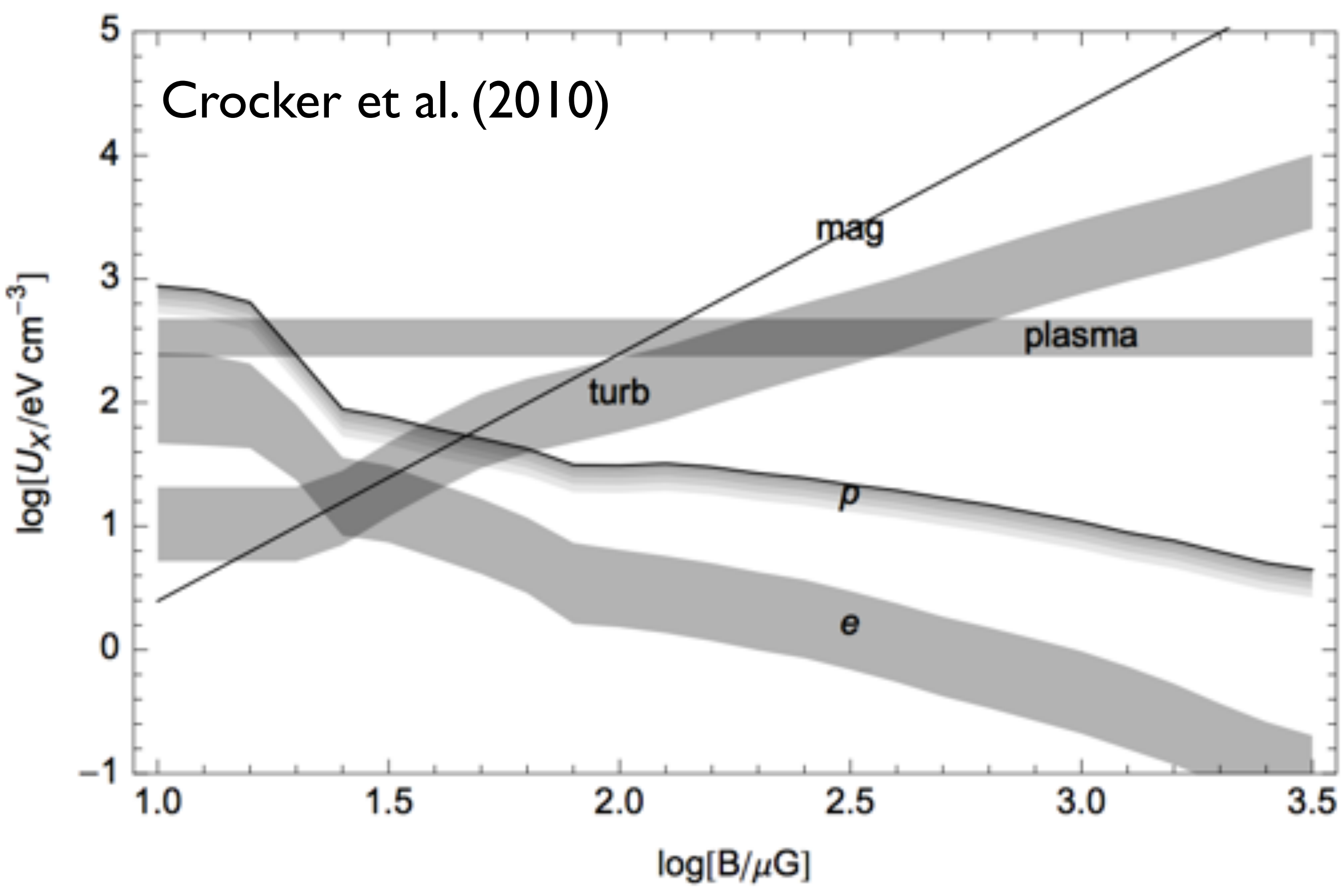
- Can use a Kolmogorov-Smirnov test after finding the CDF for the radial profile of dark matter annihilation
- Since the CDFs for dark matter and the background point-source can be compared linearly, strong limits can quickly be set on dark matter annihilation
- Limits on photon counts can then be translated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

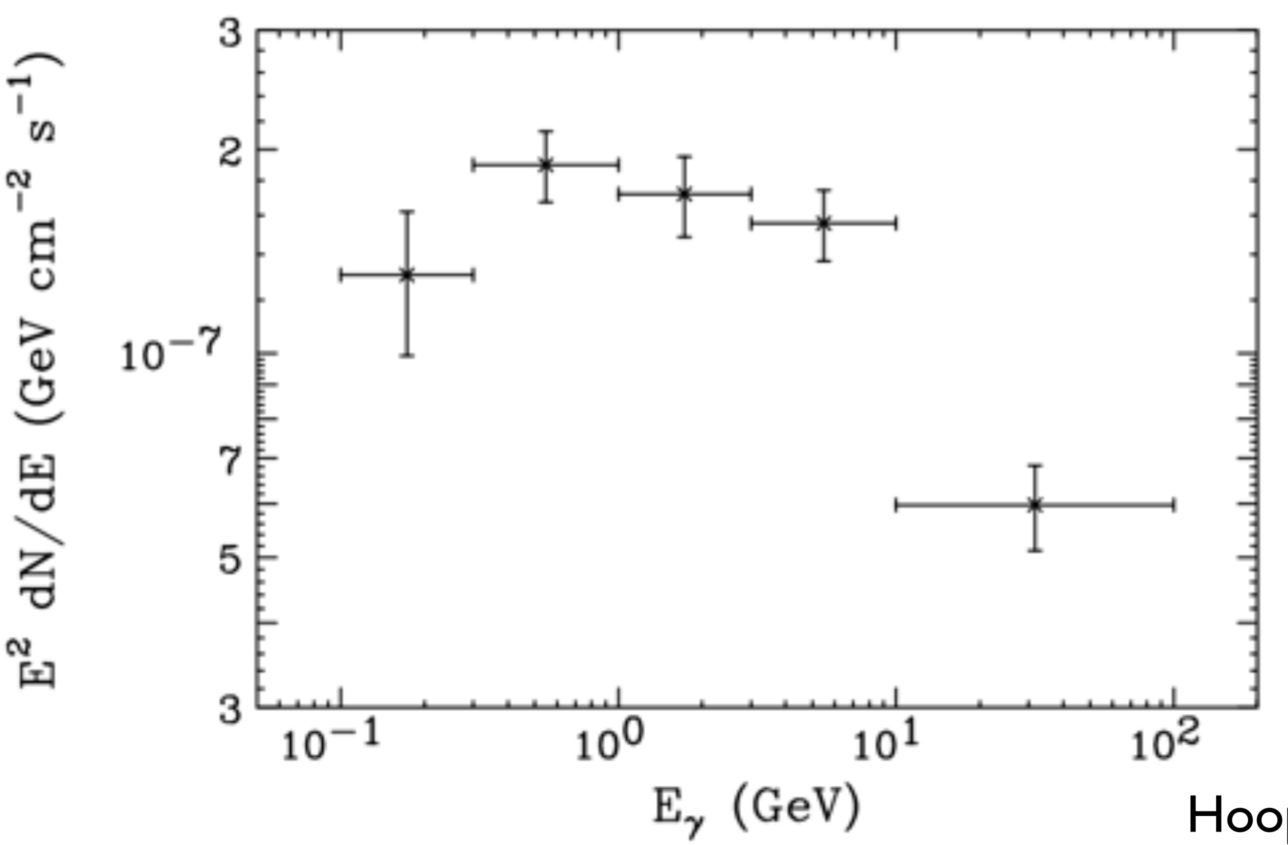


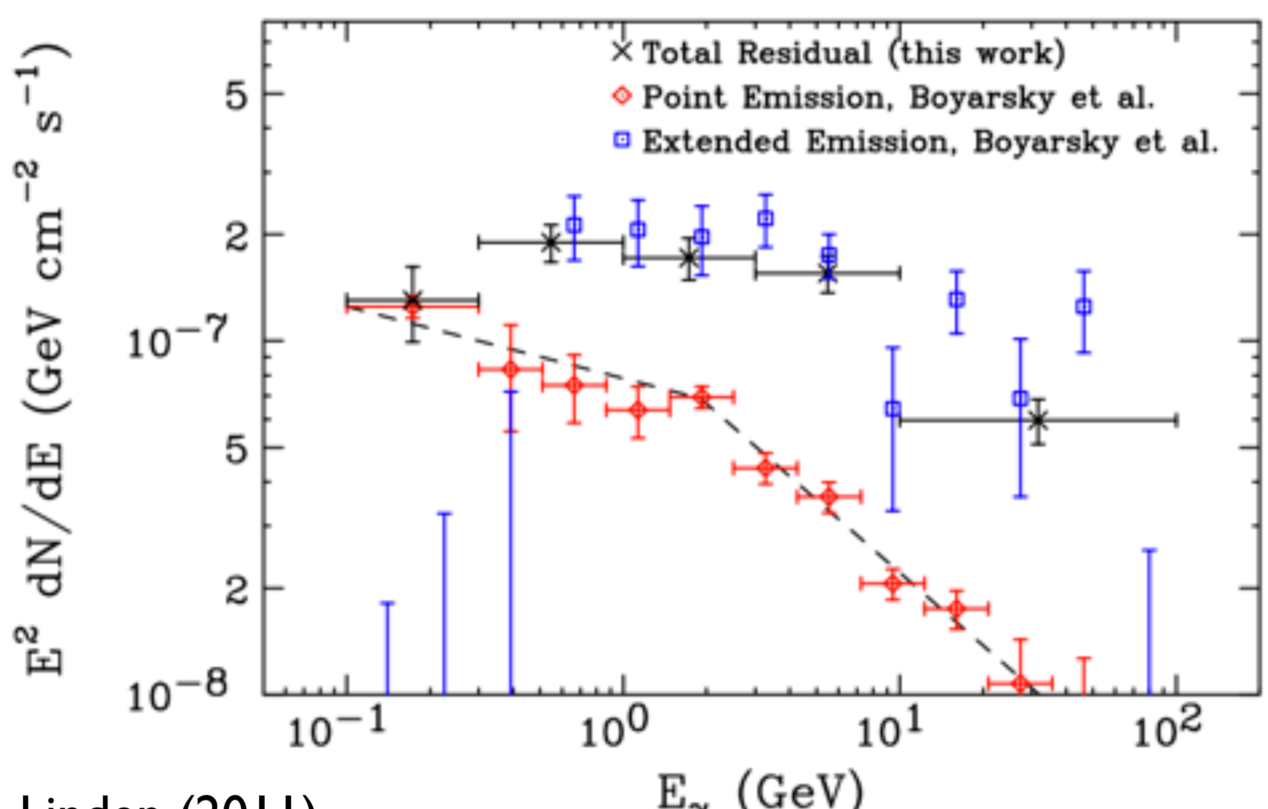


- This is particularly interesting in light of recent models which have set a minimum strength of 50 μG on the magnetic fields in the galactic center (best fit range 100-300 μG)
- This almost ensures that synchrotron is the dominant energy loss mechanism for high energy electrons
- In the hadronic scenario,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