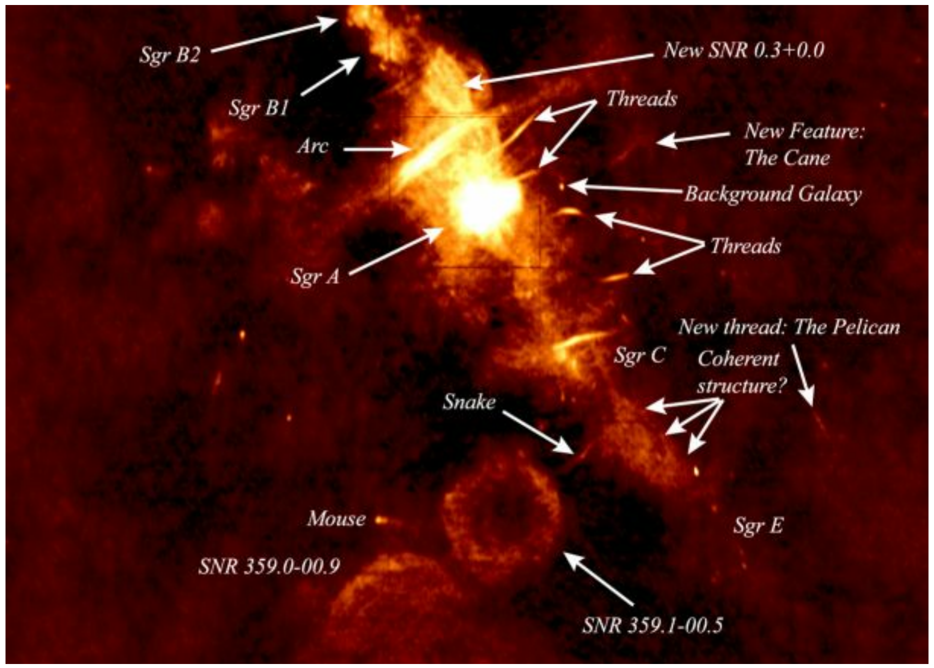
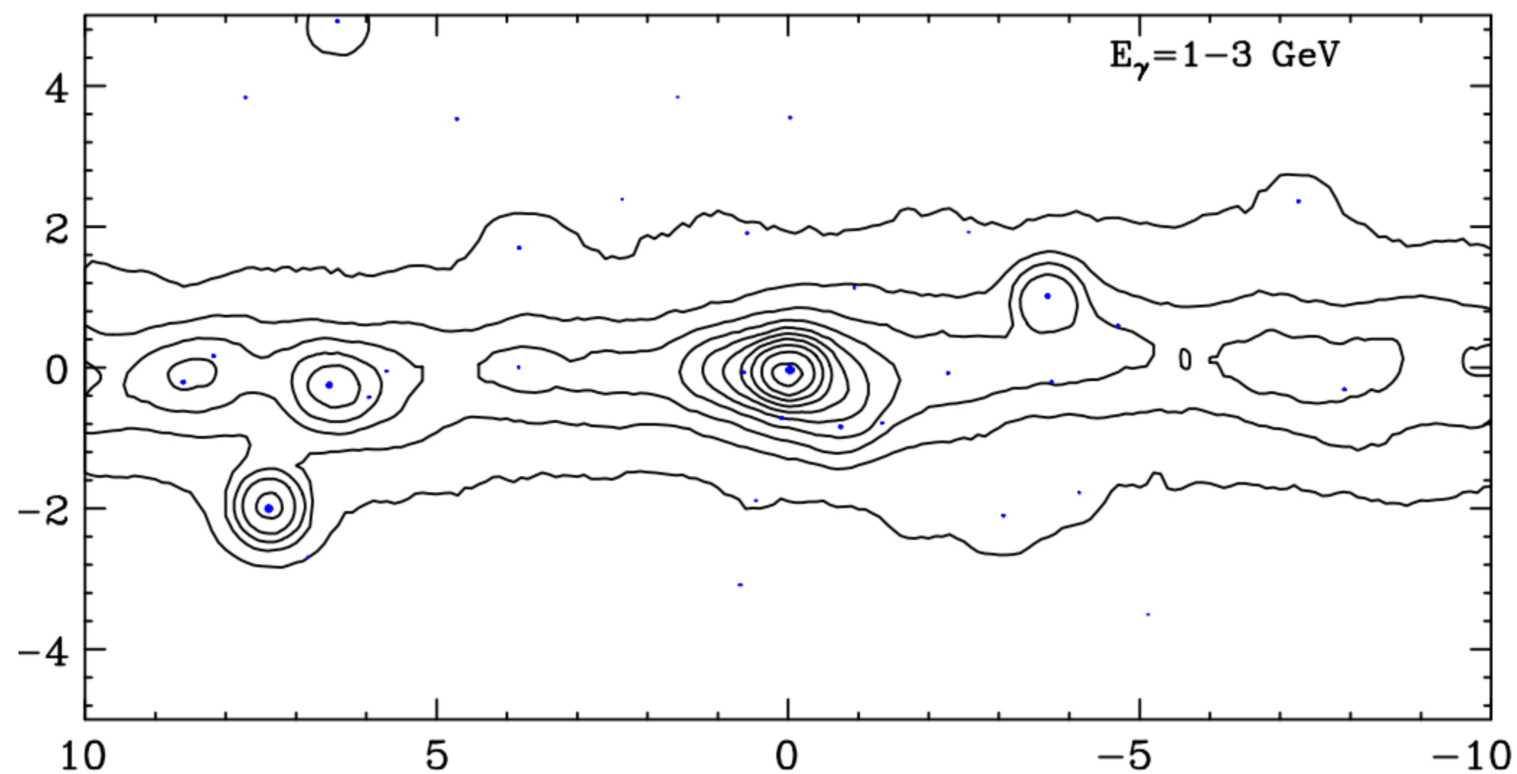
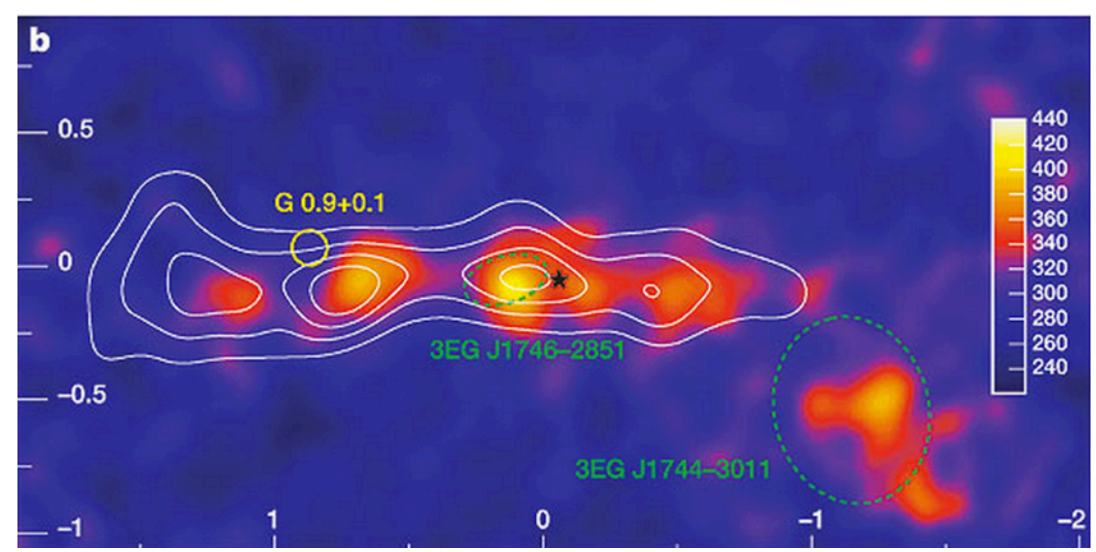
Understanding High Energy Emission from the Galactic Center: 3 Convincing Stories





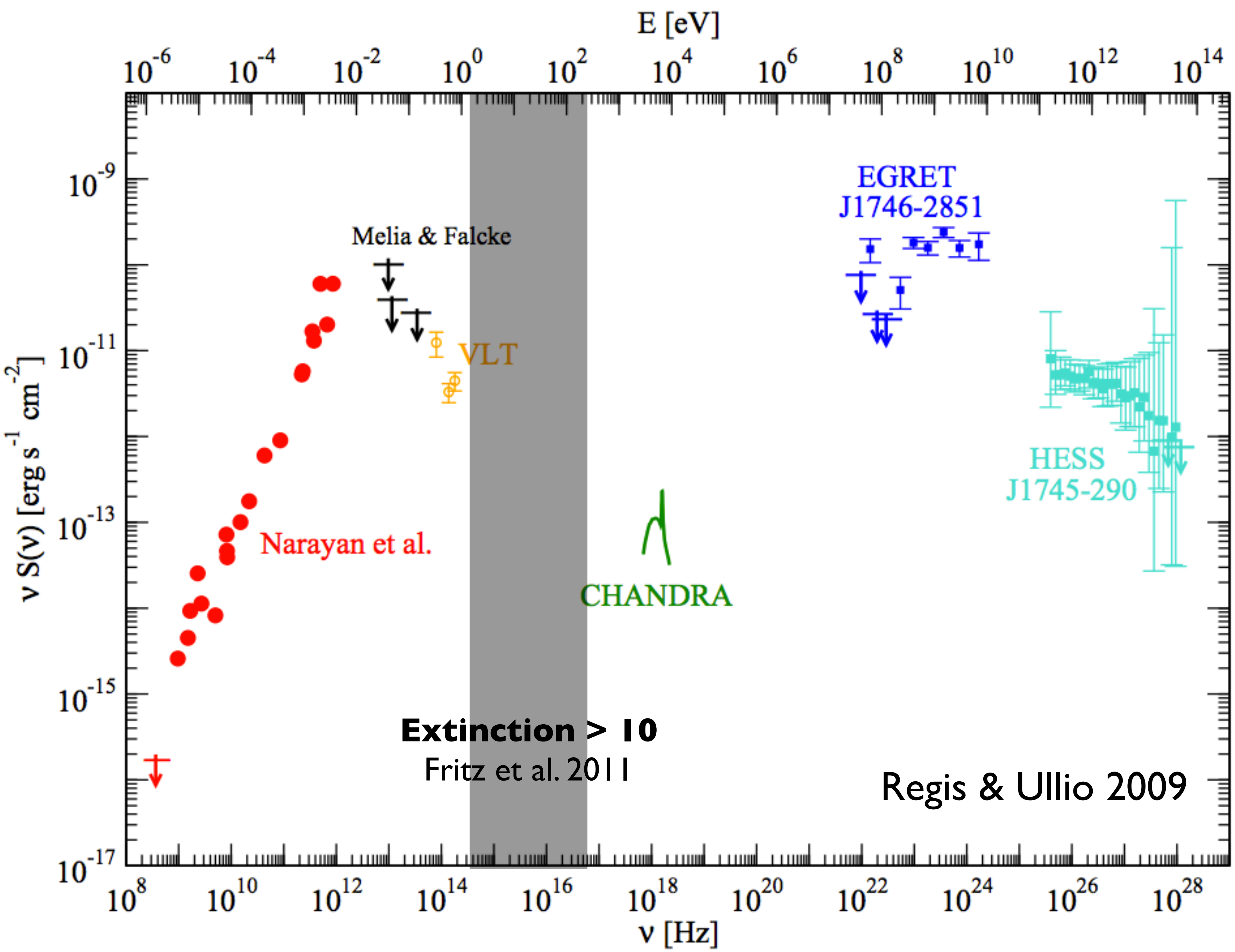
Tim Linden
UC - Santa Cruz



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

4th International Fermi Symposium November 2, 2012

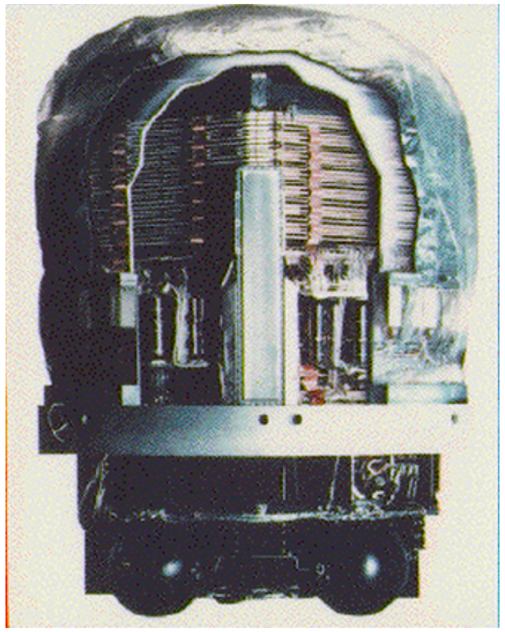
The Multi-wavelength Galactic Center



VLA

Chandra

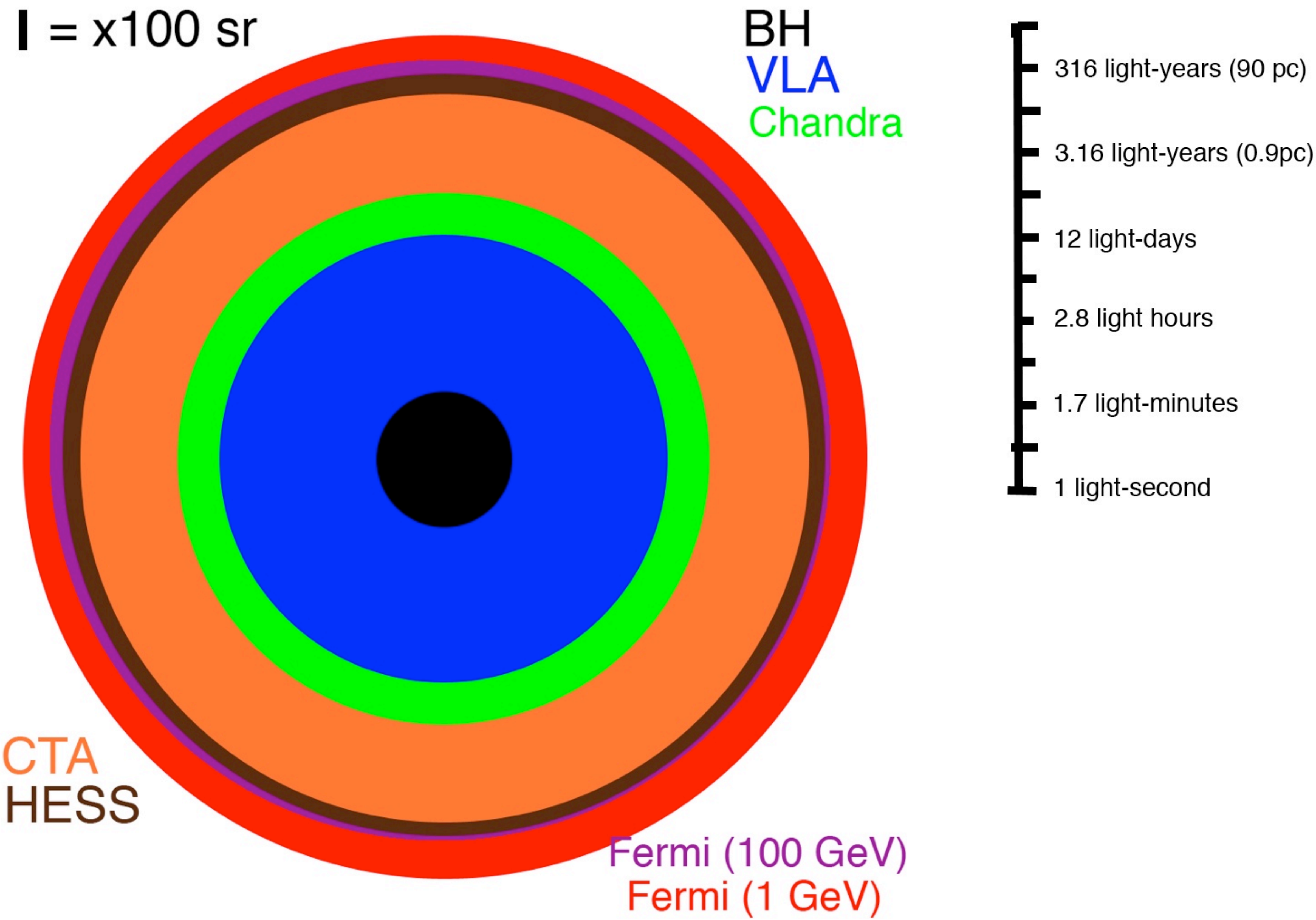
EGRET



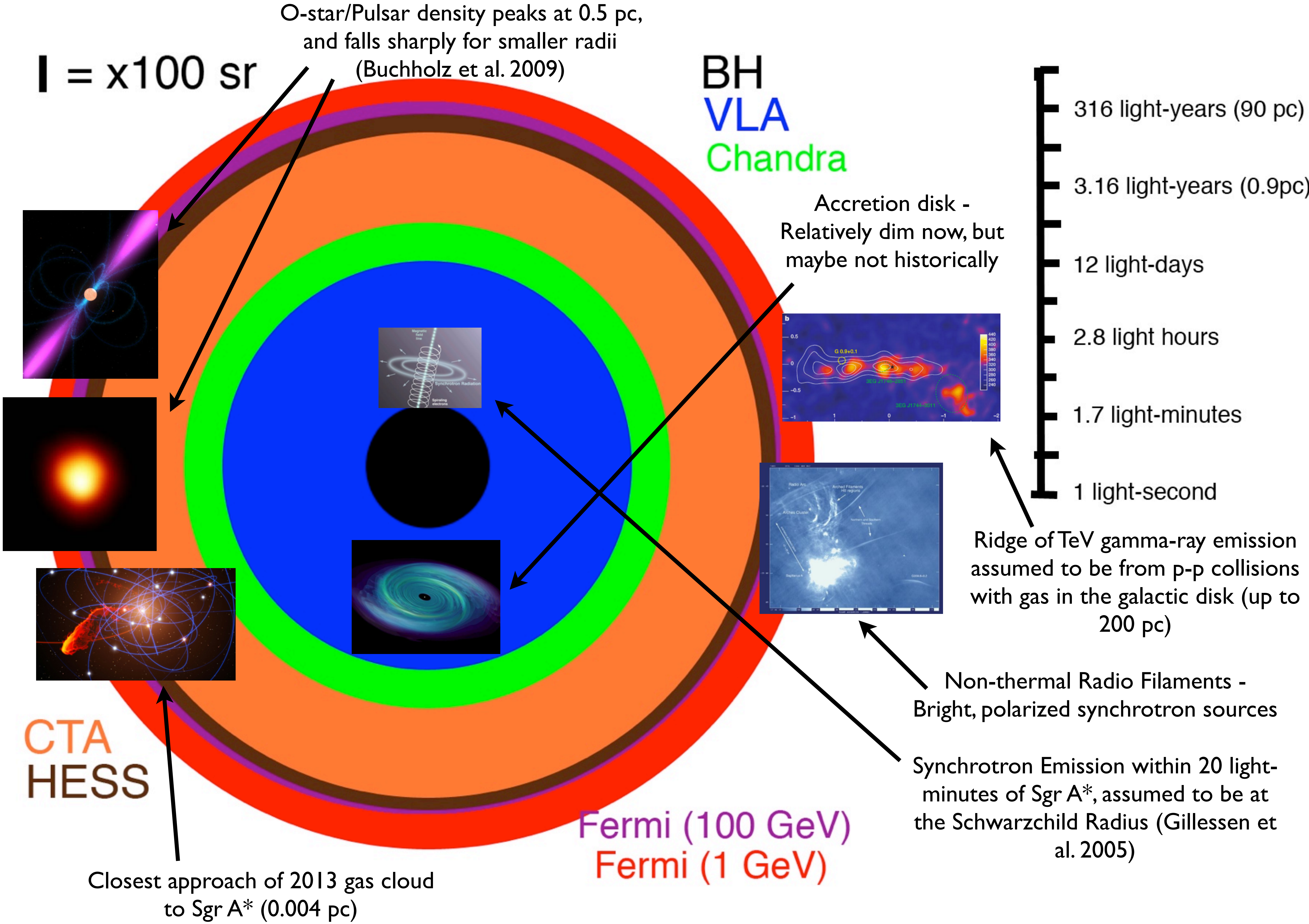
HESS

Fermi-LAT

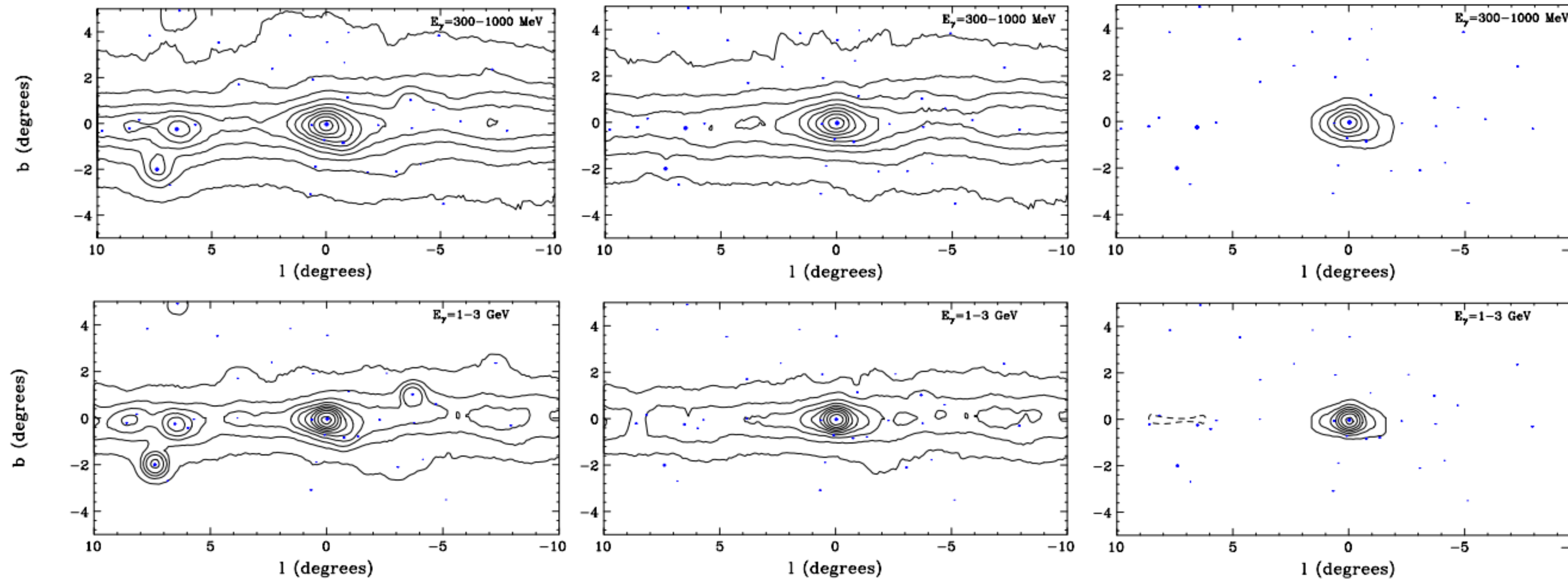
Angular Scales of the Galactic Center

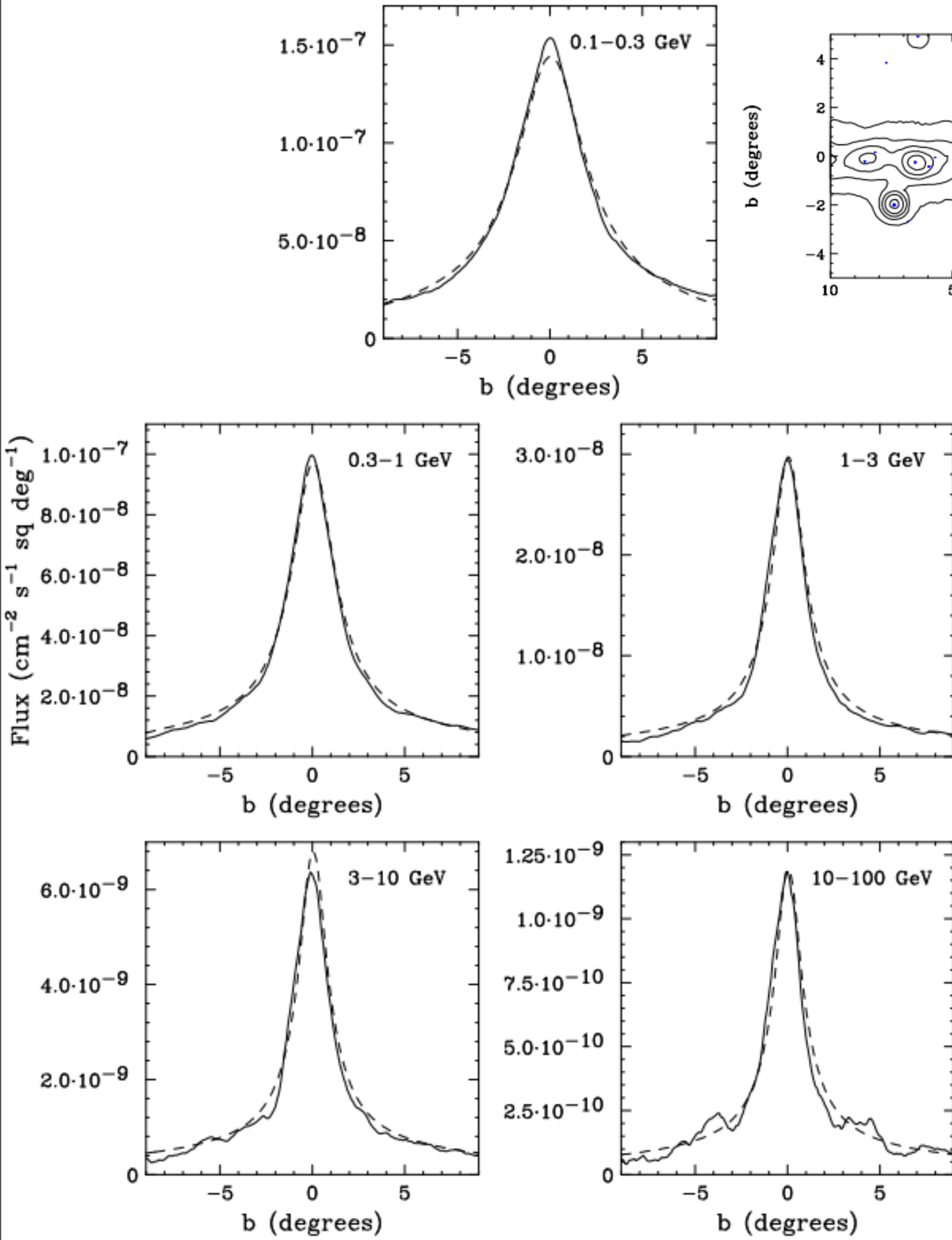


The Galactic Center “Zoo”



Subtracting the Astrophysical Background: Fermi





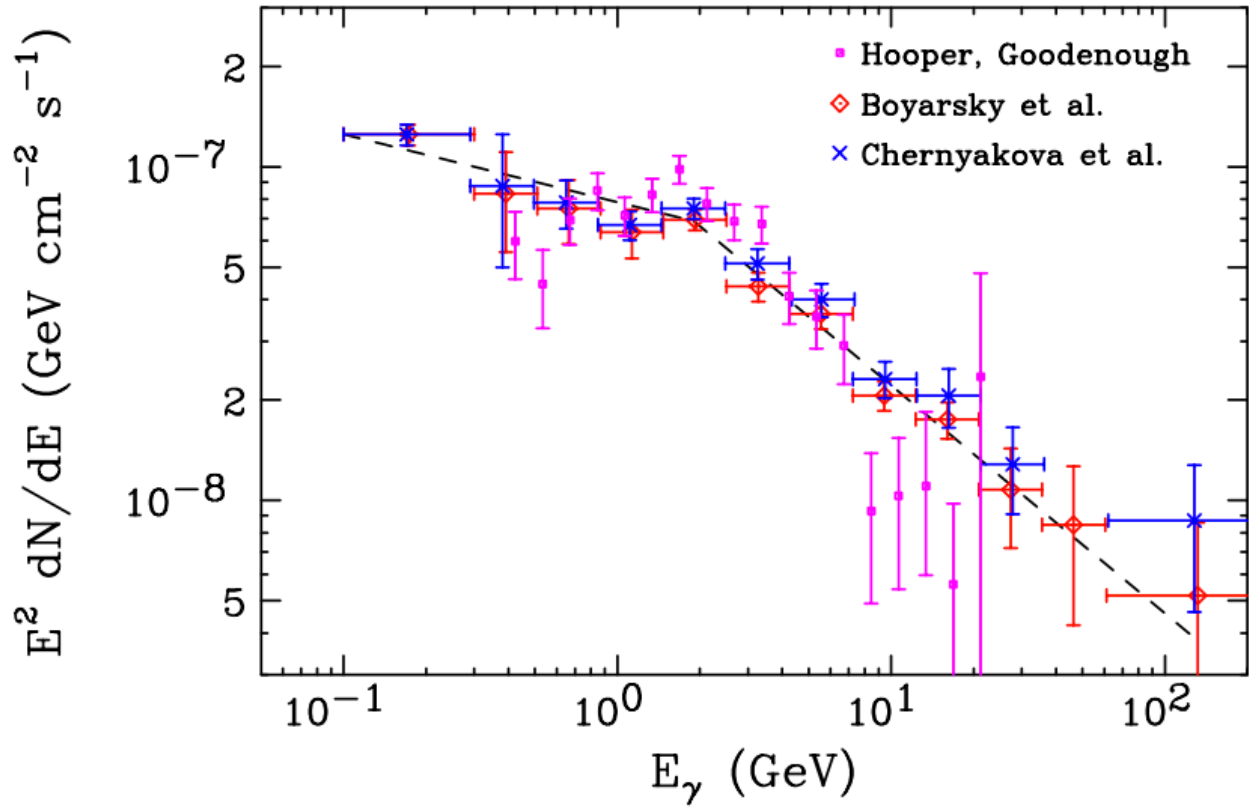
- We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.
- This emission template provides a superb match to the total emission spectrum
- This large residual at the center of the galaxy is a factor of 10 brighter than anything else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

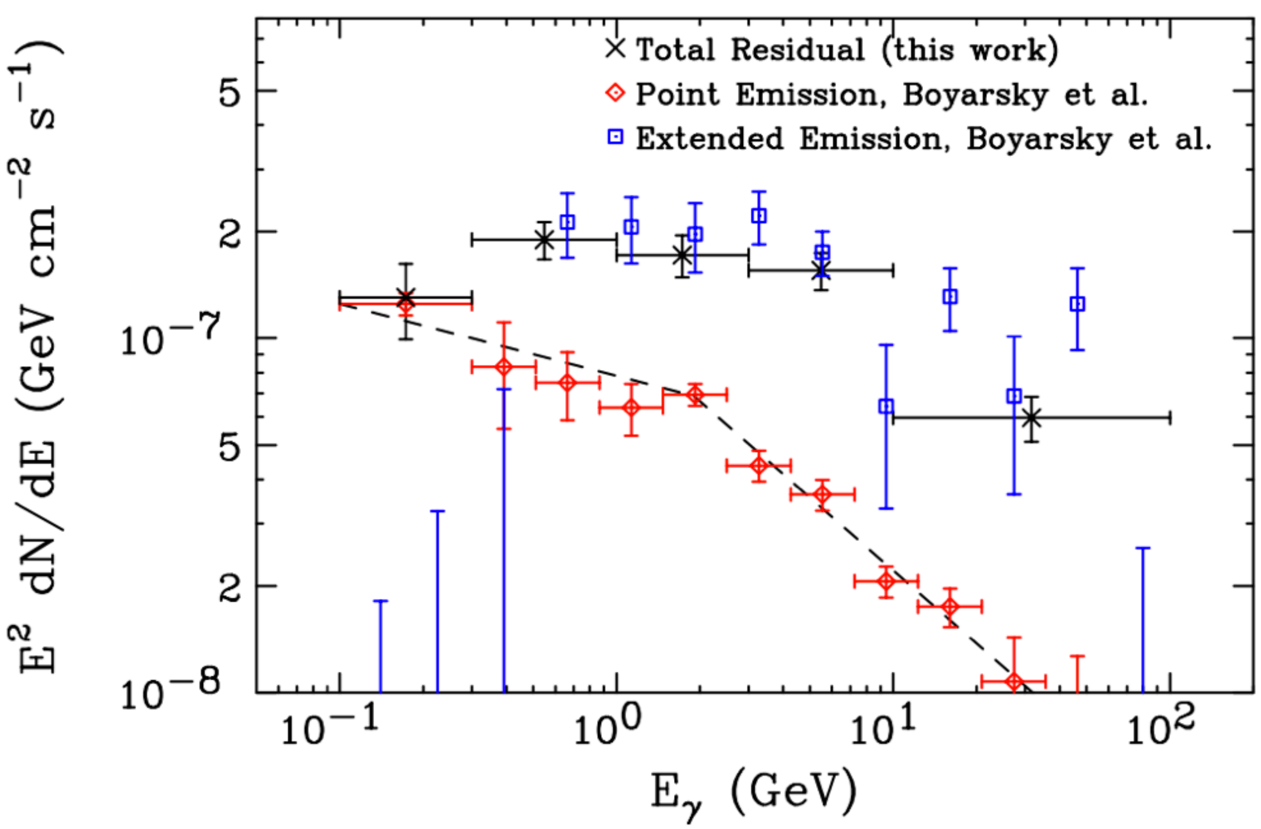
Hooper & Linden (2011)

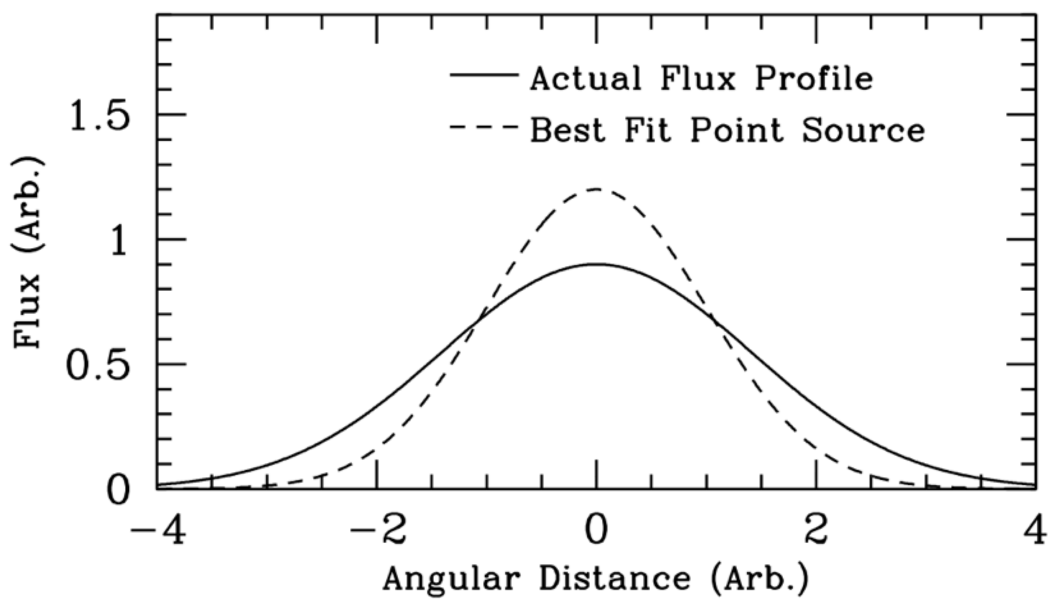
Understanding the GC Point Source: Fermi

- 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





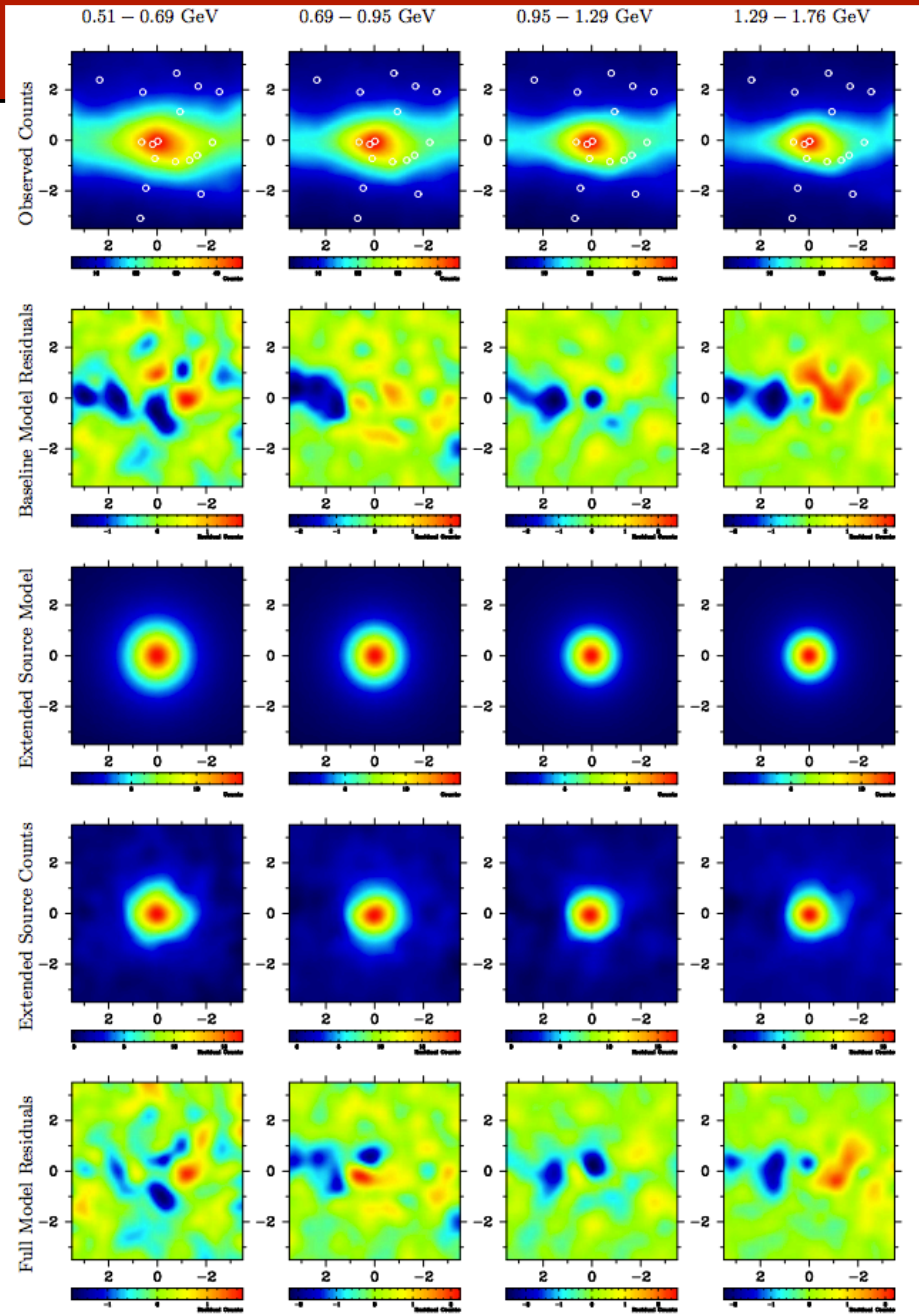


Hooper & Linden (2011)

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)

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?

The J-Factor of the Galactic Center

Ackermann et al. 2012

Dwarfs

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

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

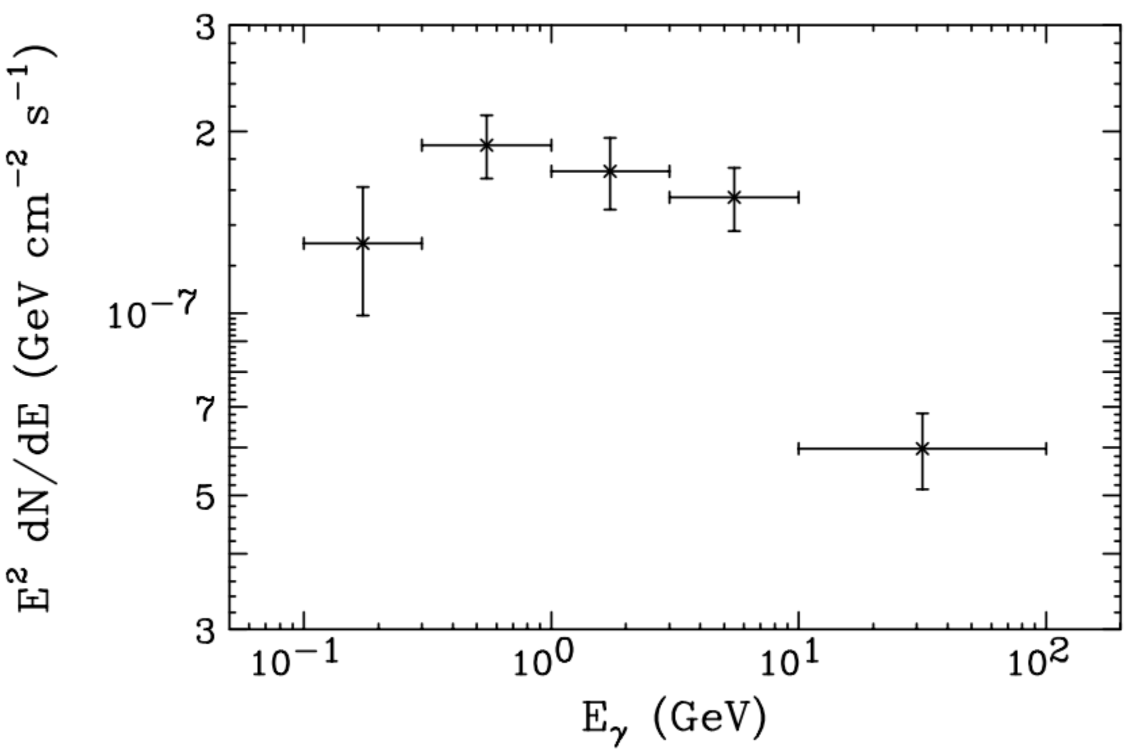
$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \rho^2(l)\mathrm{d}l(\psi)$$

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

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

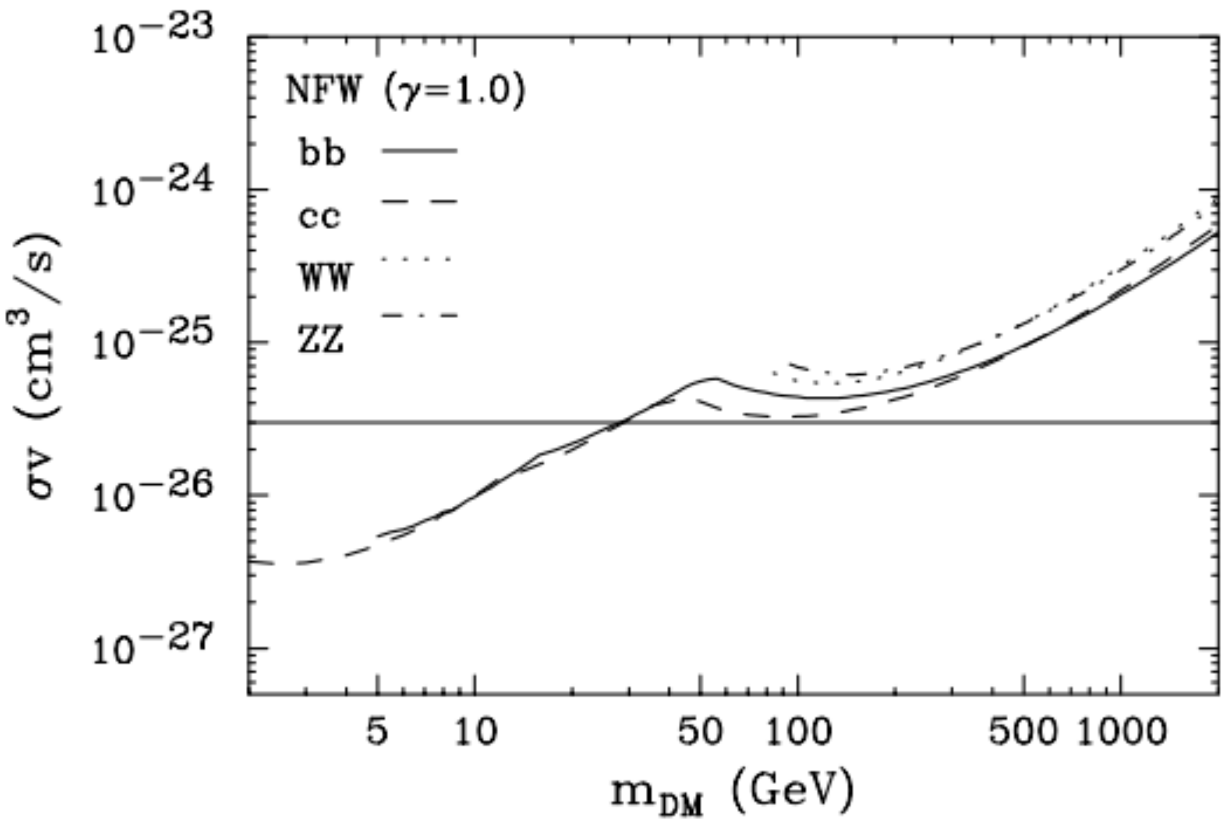
for a region within 100 pc of the Galactic center and an NFW profile

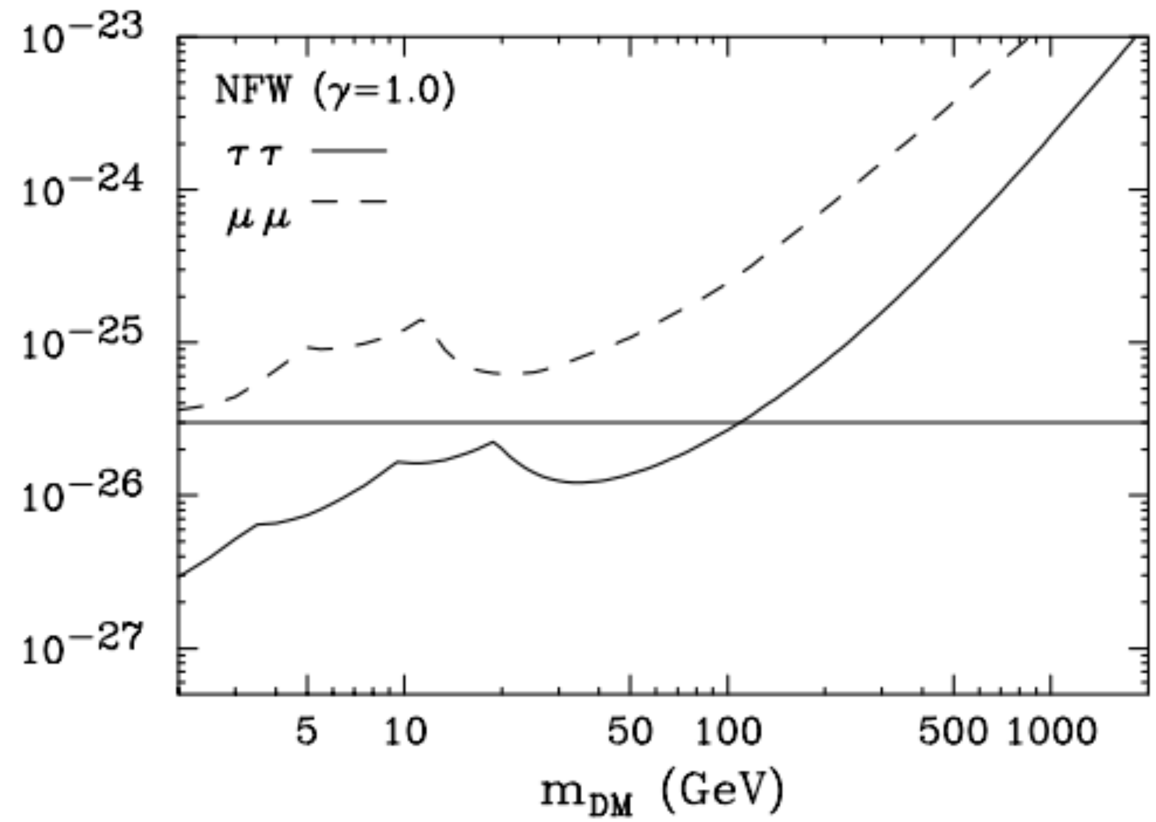
Dark Matter Limits in the Simplest Way Possible



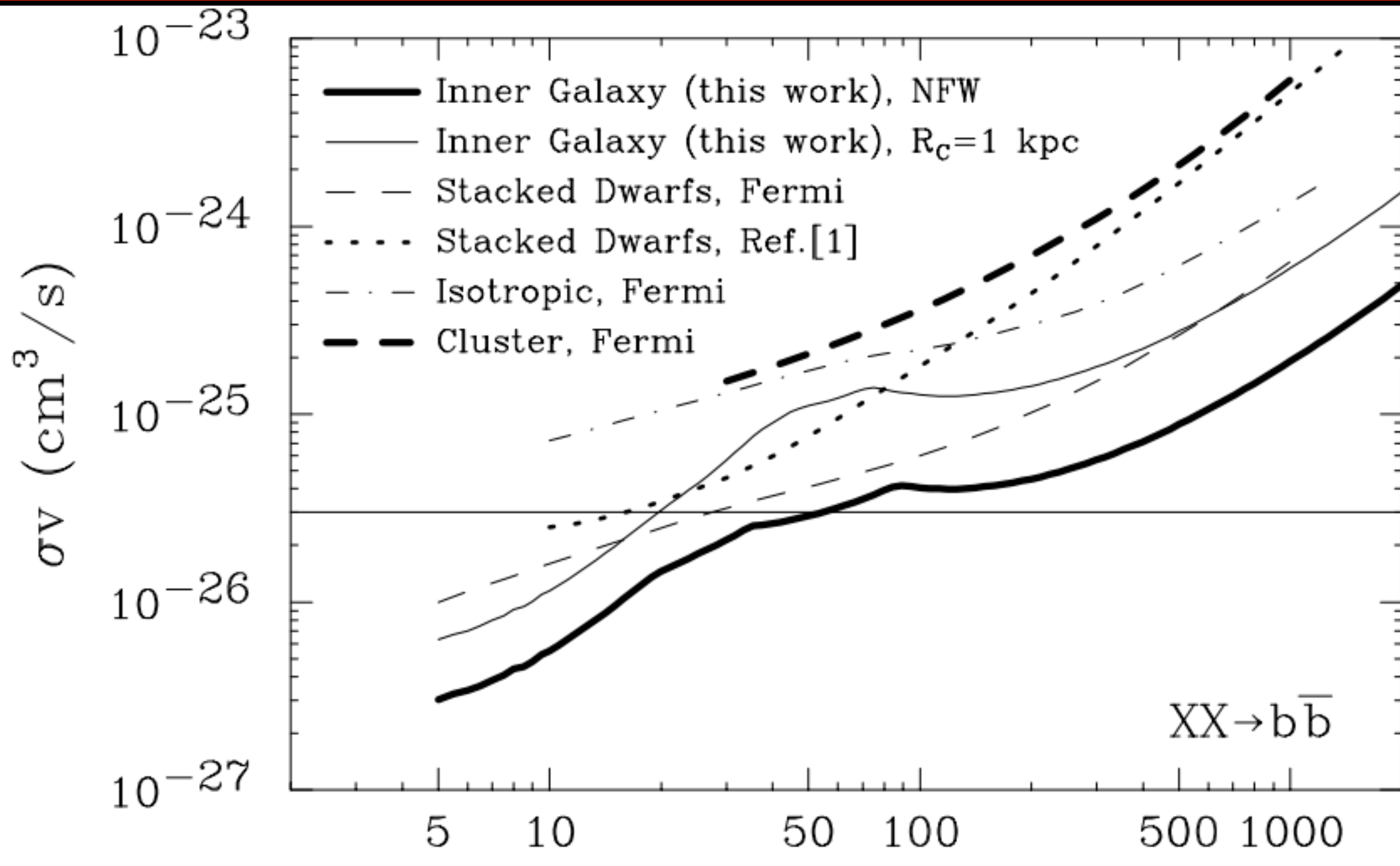
Hooper & Linden (2011)

- 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



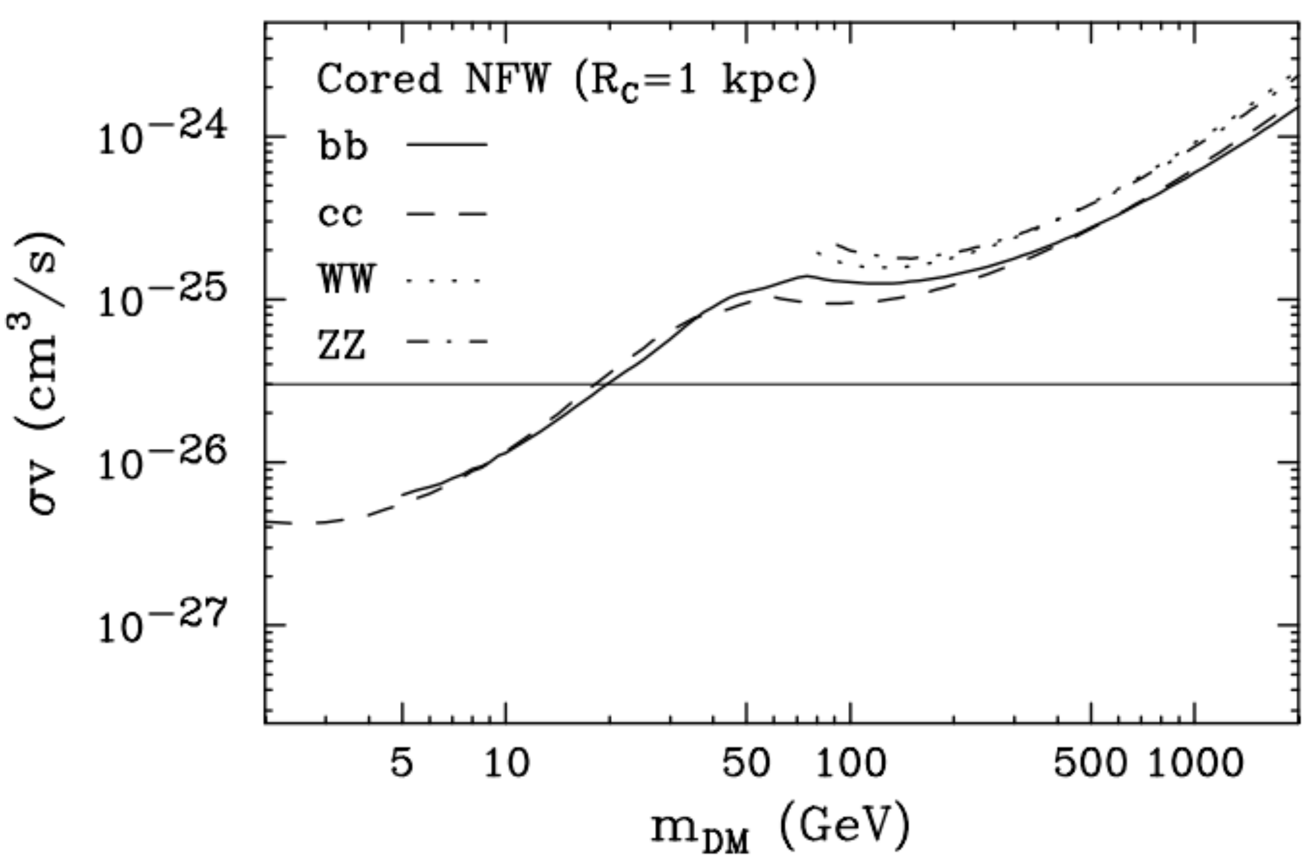


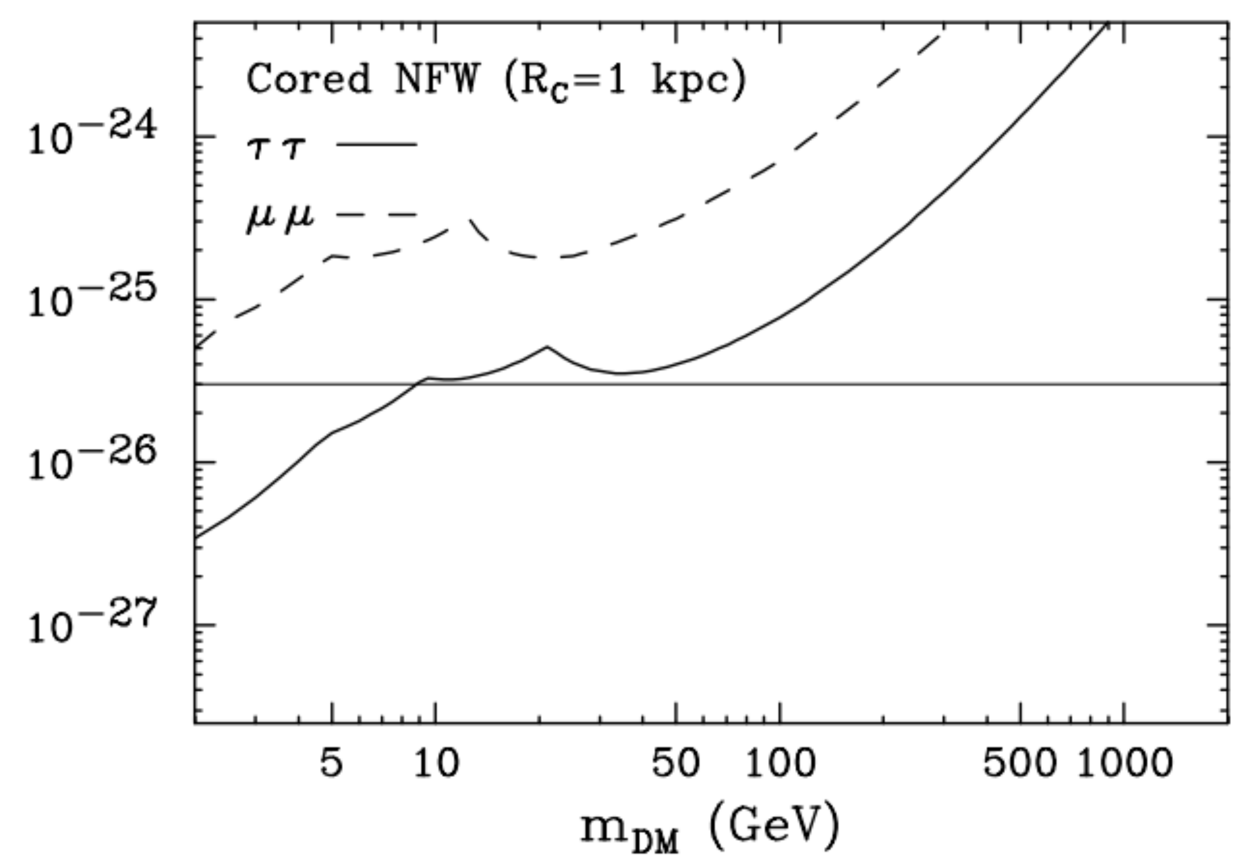
Comparison to Other Indirect Detection Regimes



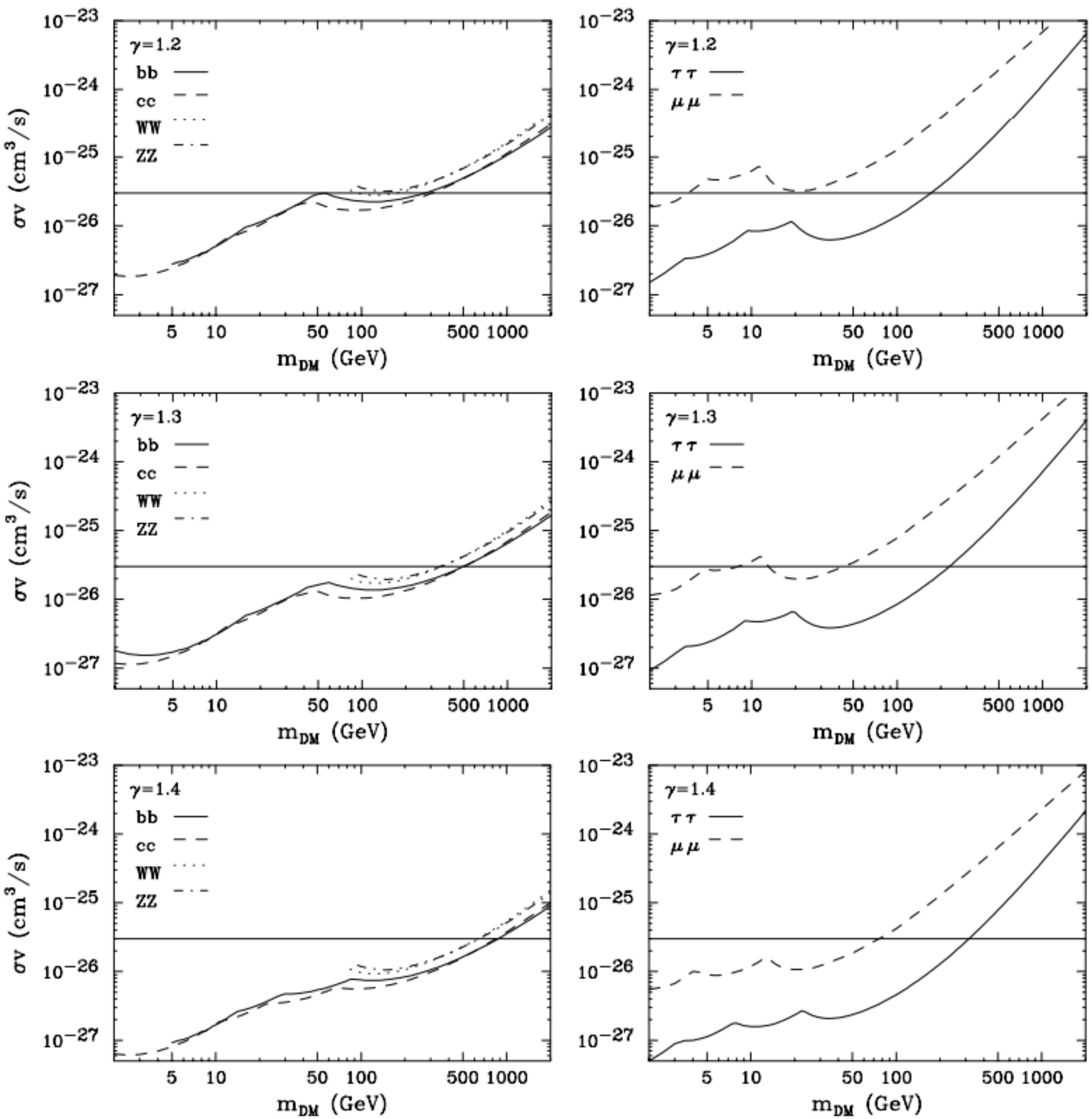
Hooper et al. (2012)

- 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



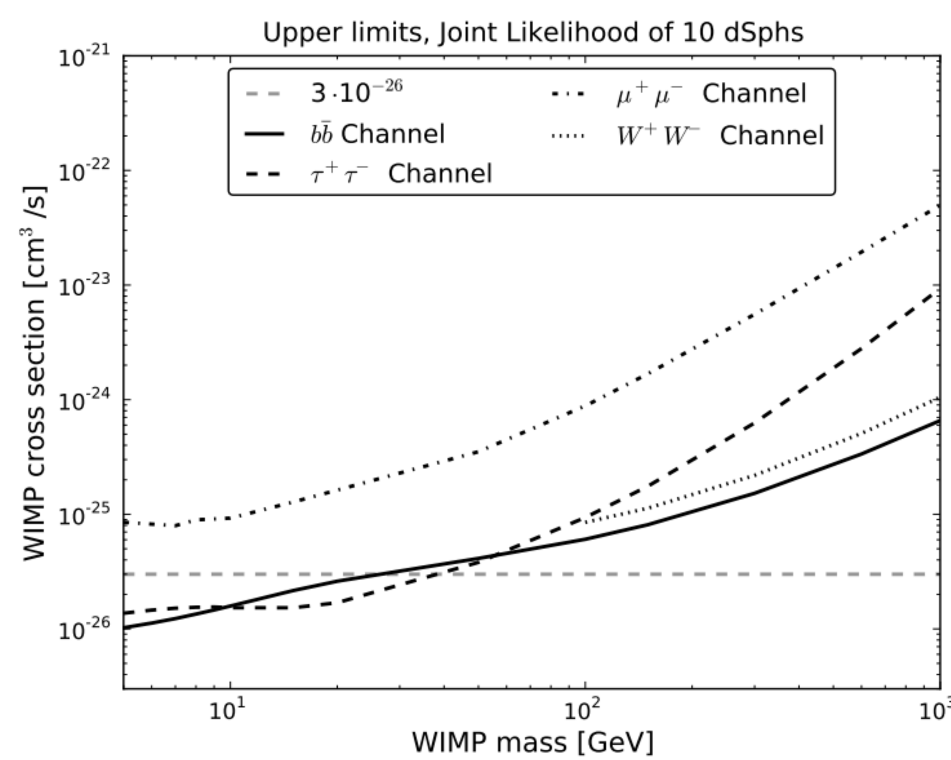


Comparison to Other Indirect Detection Regimes



Hooper & Linden (2011)

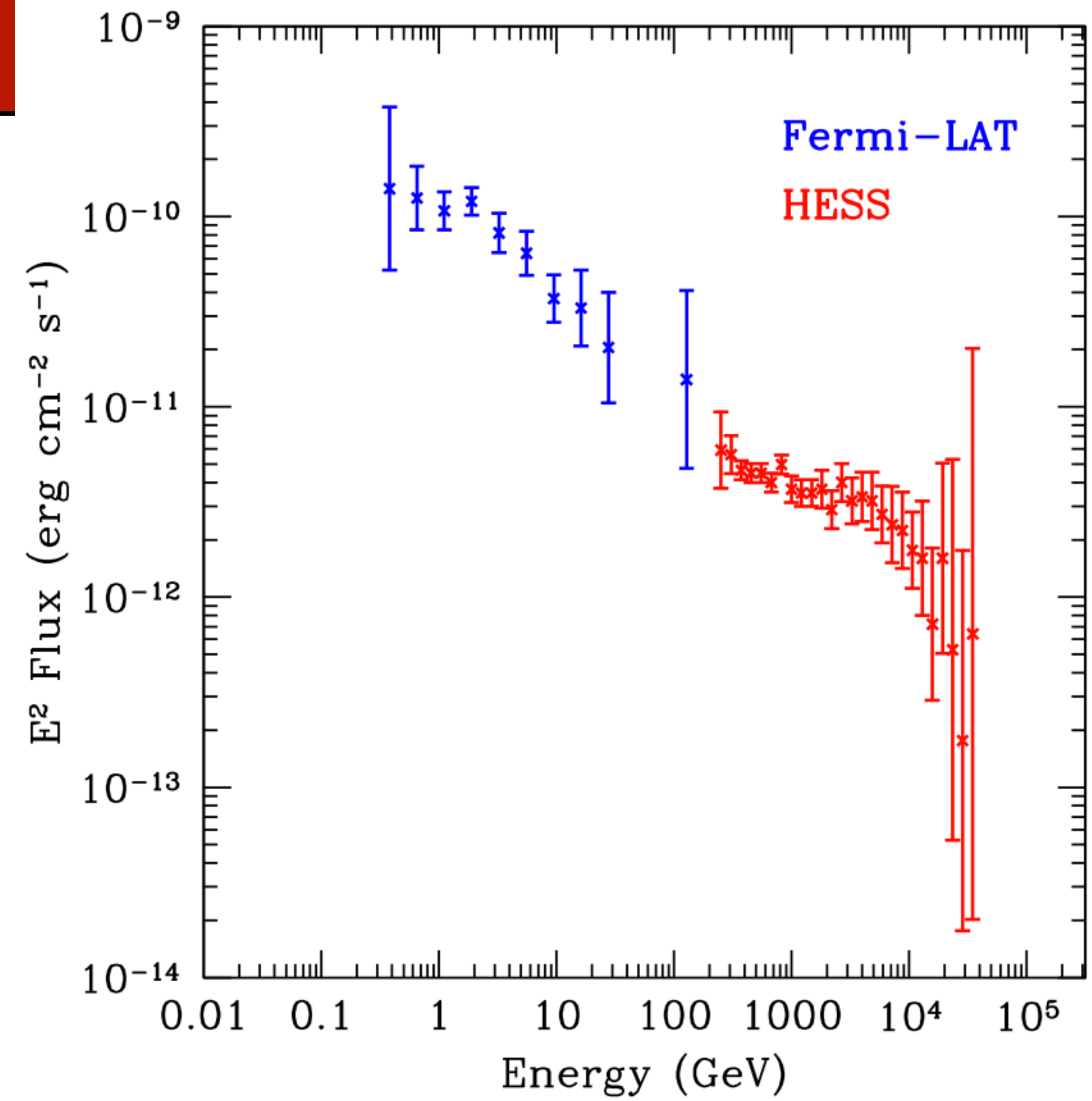
- With some adiabatic contraction of the inner dark matter profile, these limits can become substantially stronger than any other indirect detection limit

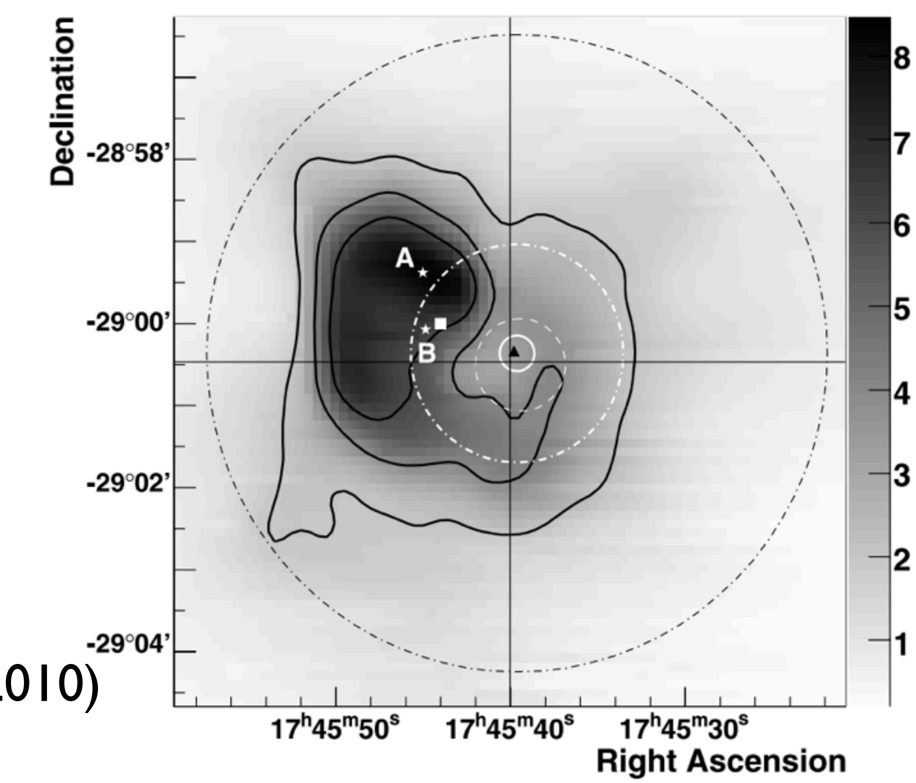


Ackermann et al. (2011)

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



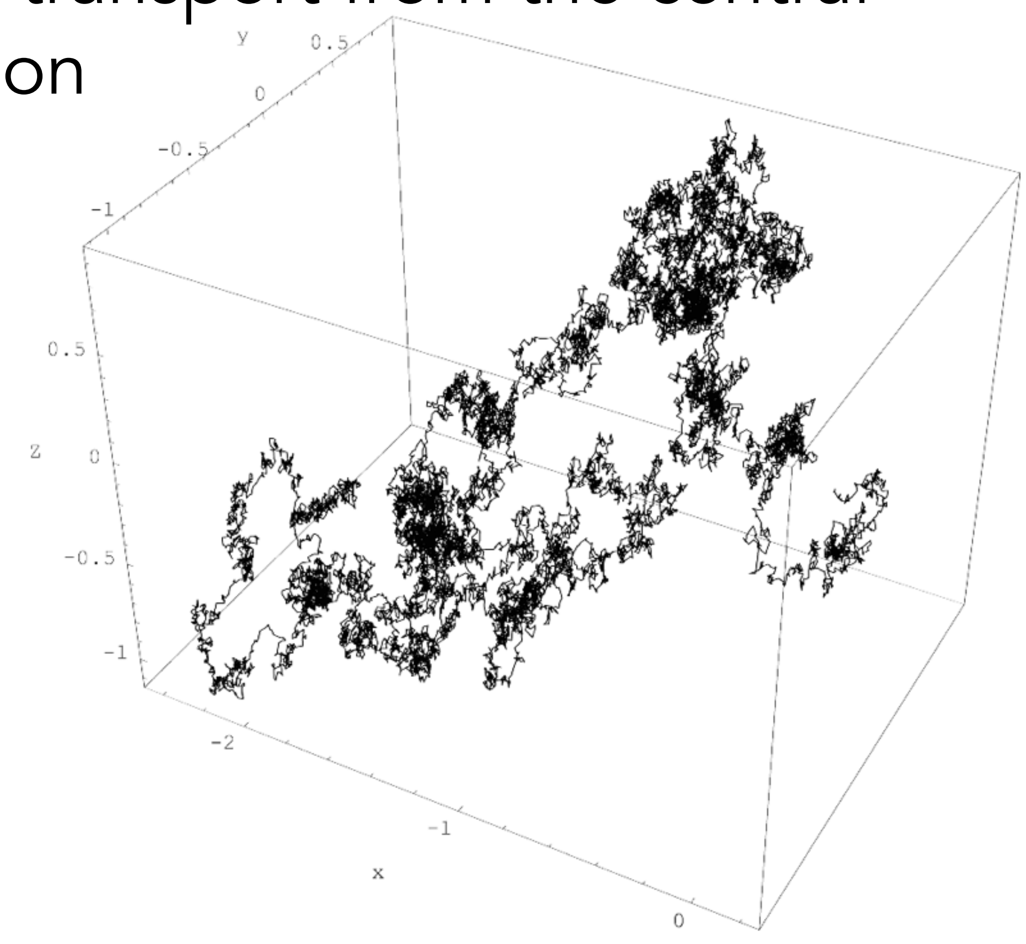


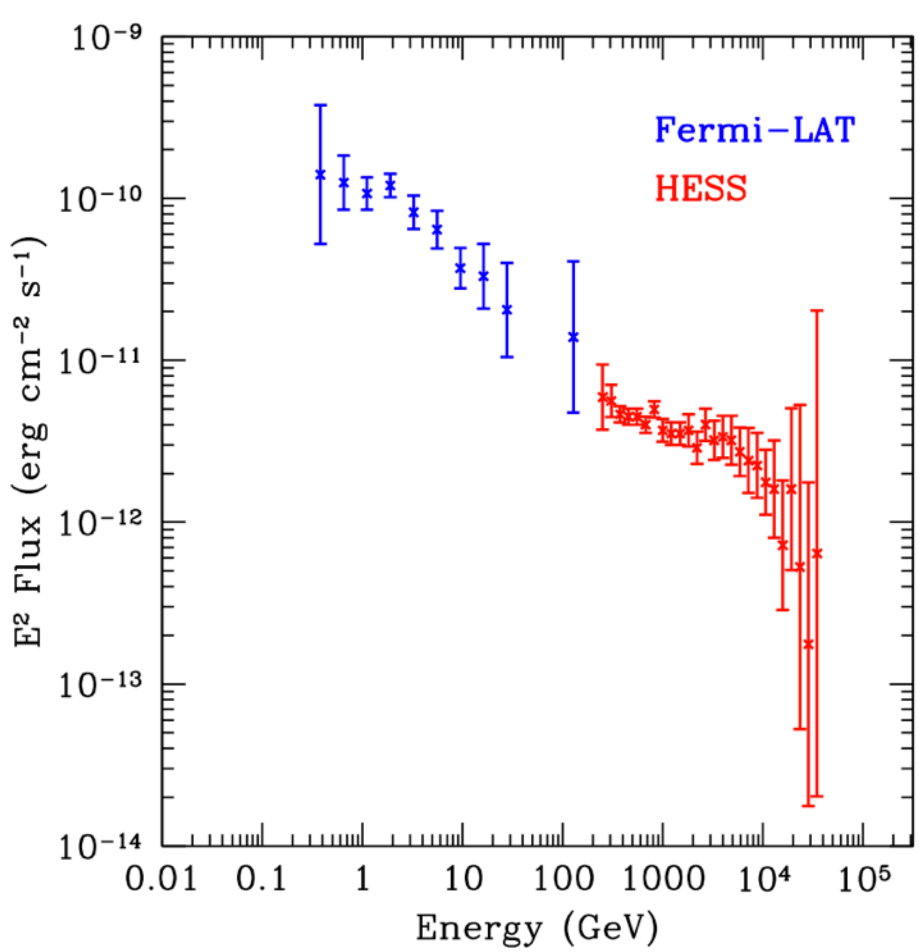
Acero et al. (2010)

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

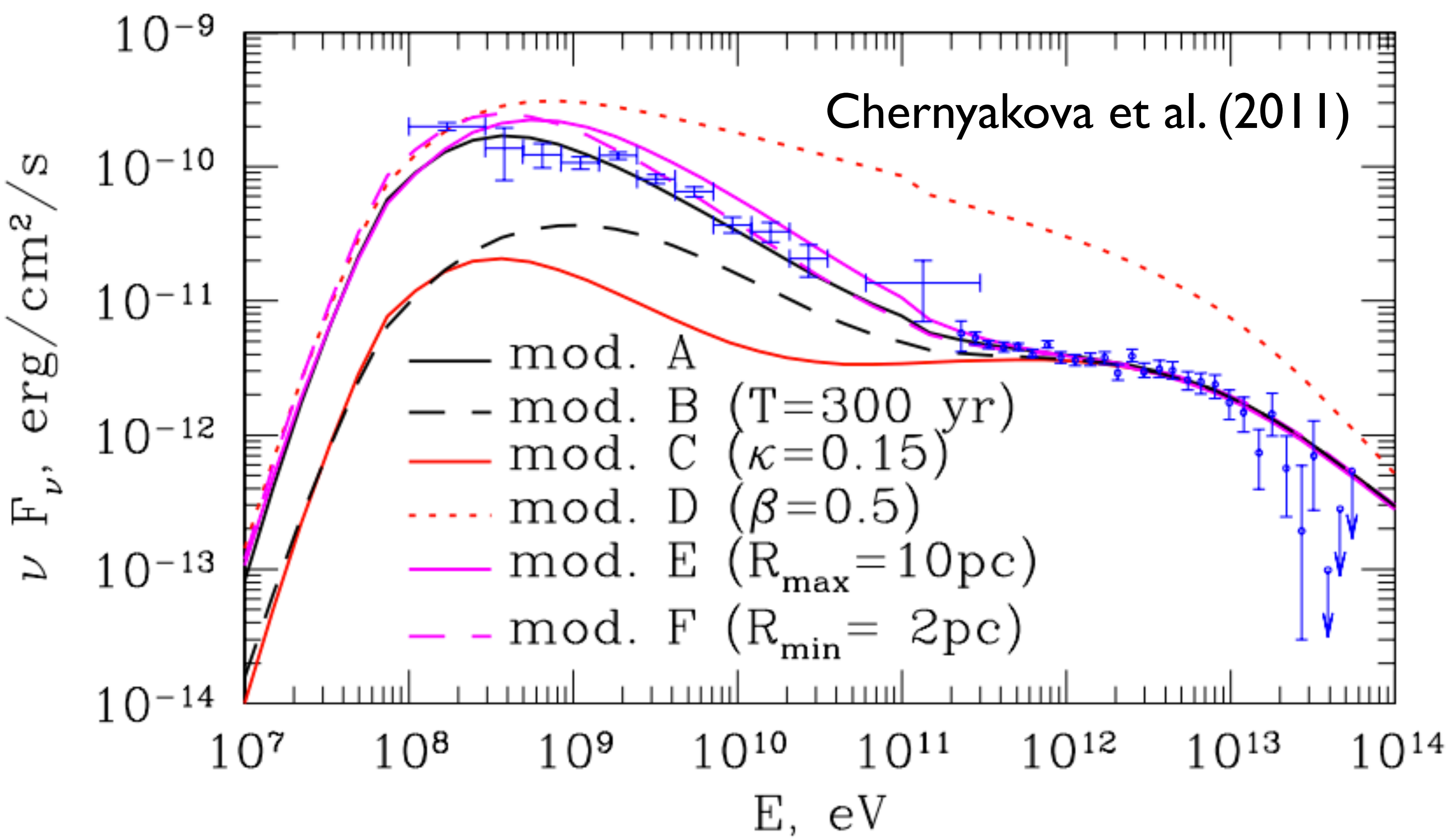




- In the regime where the diffusion step is small, then the emission intensity depends linearly on the time the particle spends within the diffusion region

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

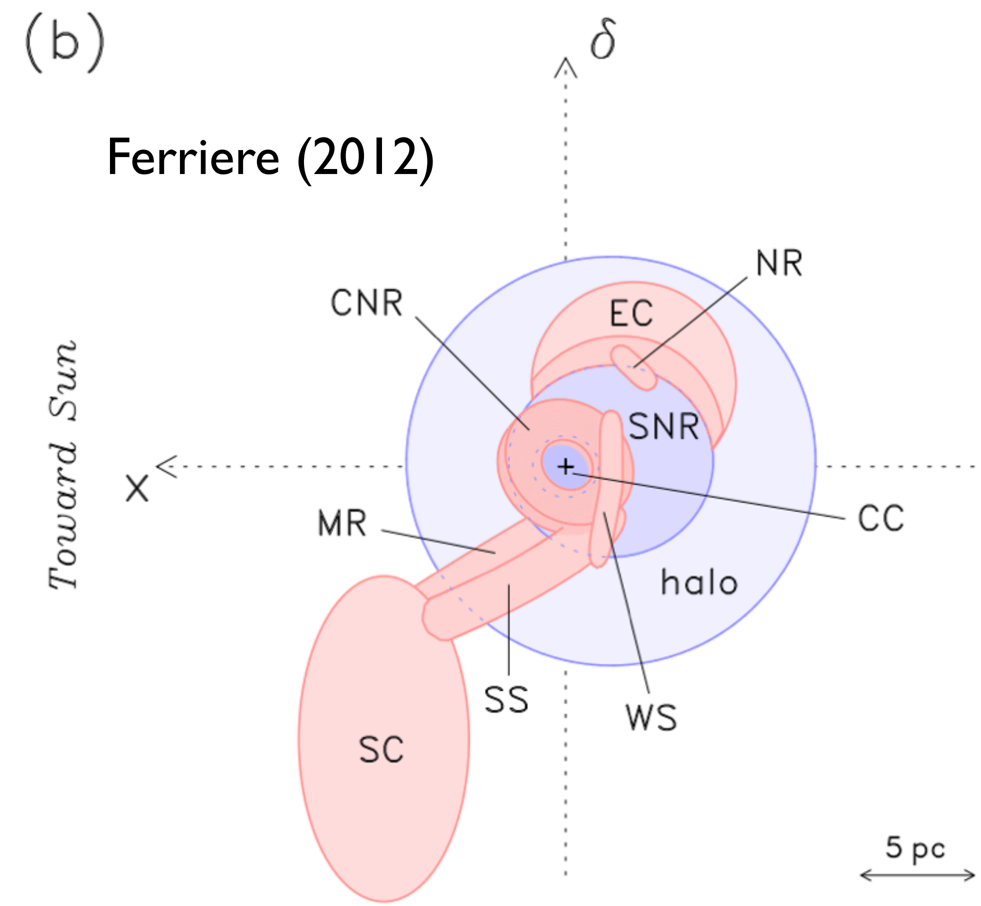


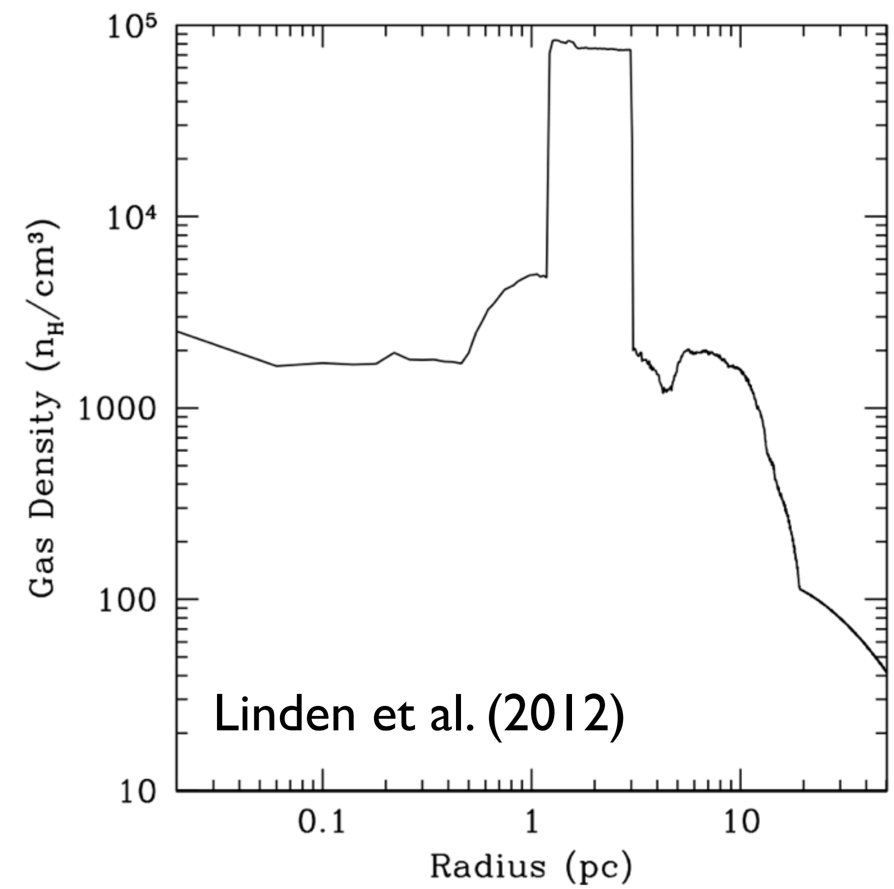
- Several model parameters can also be adjusted, such as the duration of particle injection, the occurrence of recent flares, the maximum radius for diffusion etc.

- 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

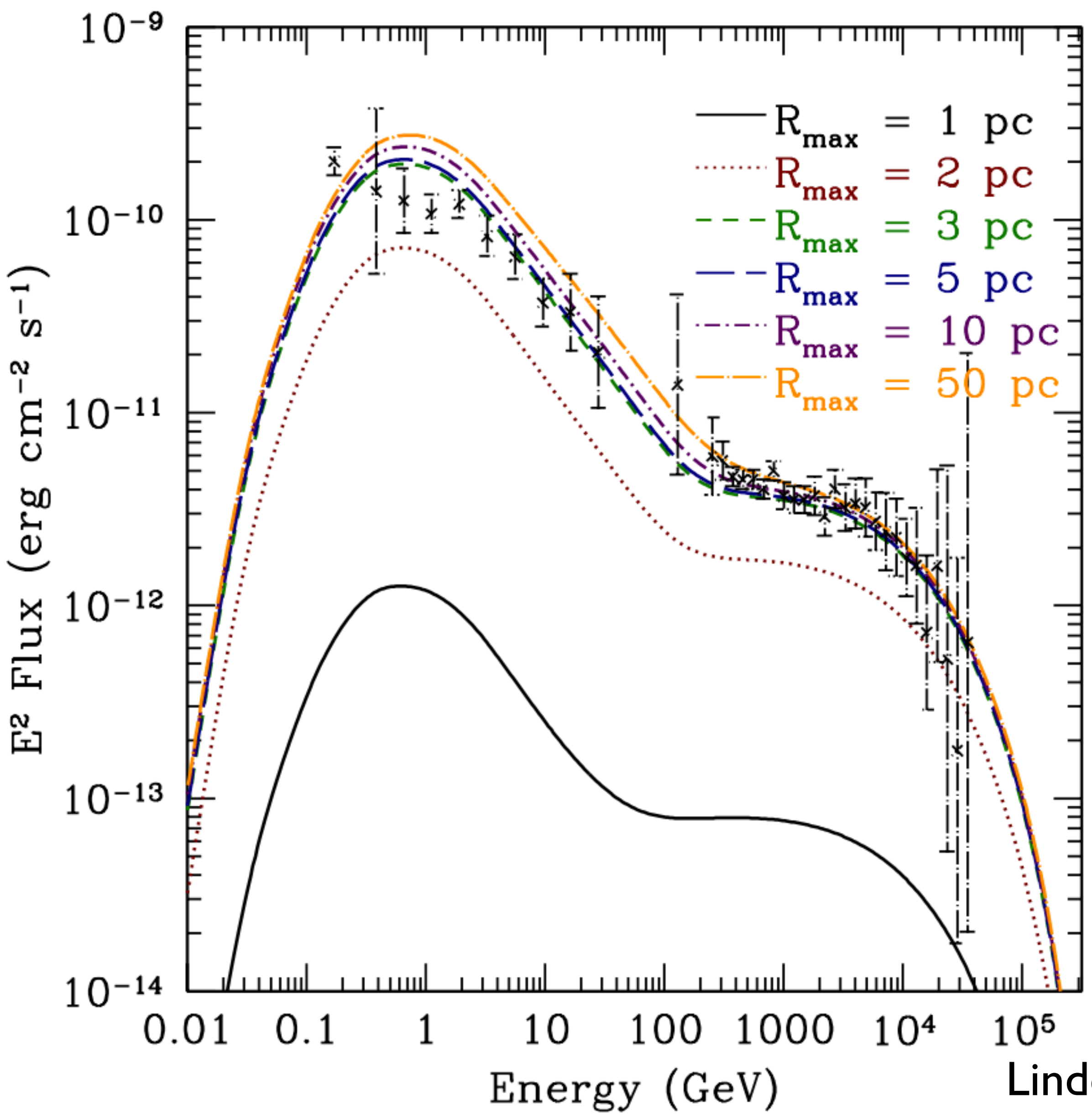
- Detailed models of the galactic gas density exist in the literature
- We employ a spherically symmetric model for galactic gas, and use this to calculate the morphology of the gamma-ray emission as a function of energy
- By far the dominant feature is the Circumnuclear ring between 1-3 pc from the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

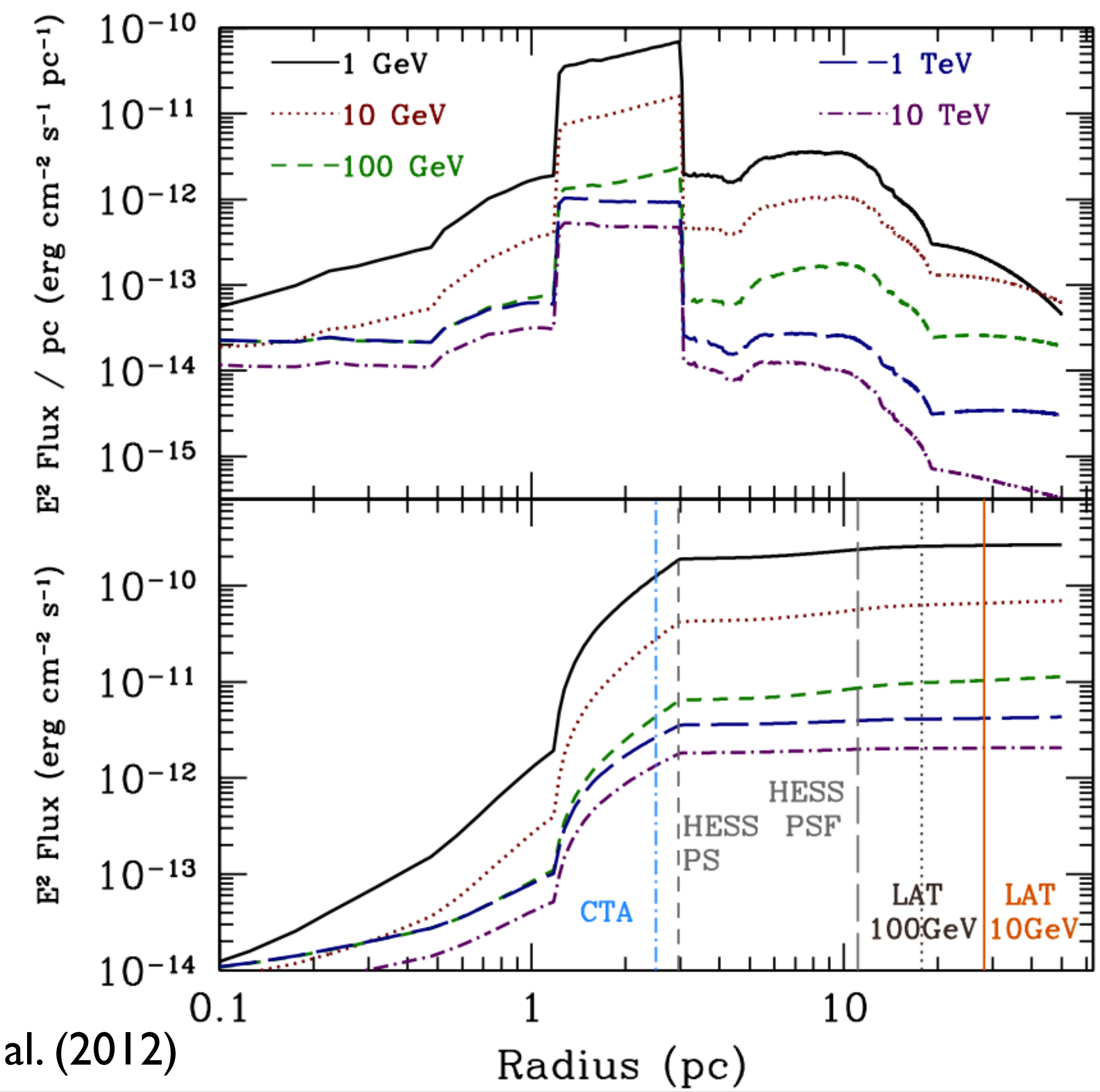




Employing a Realistic Gas Model

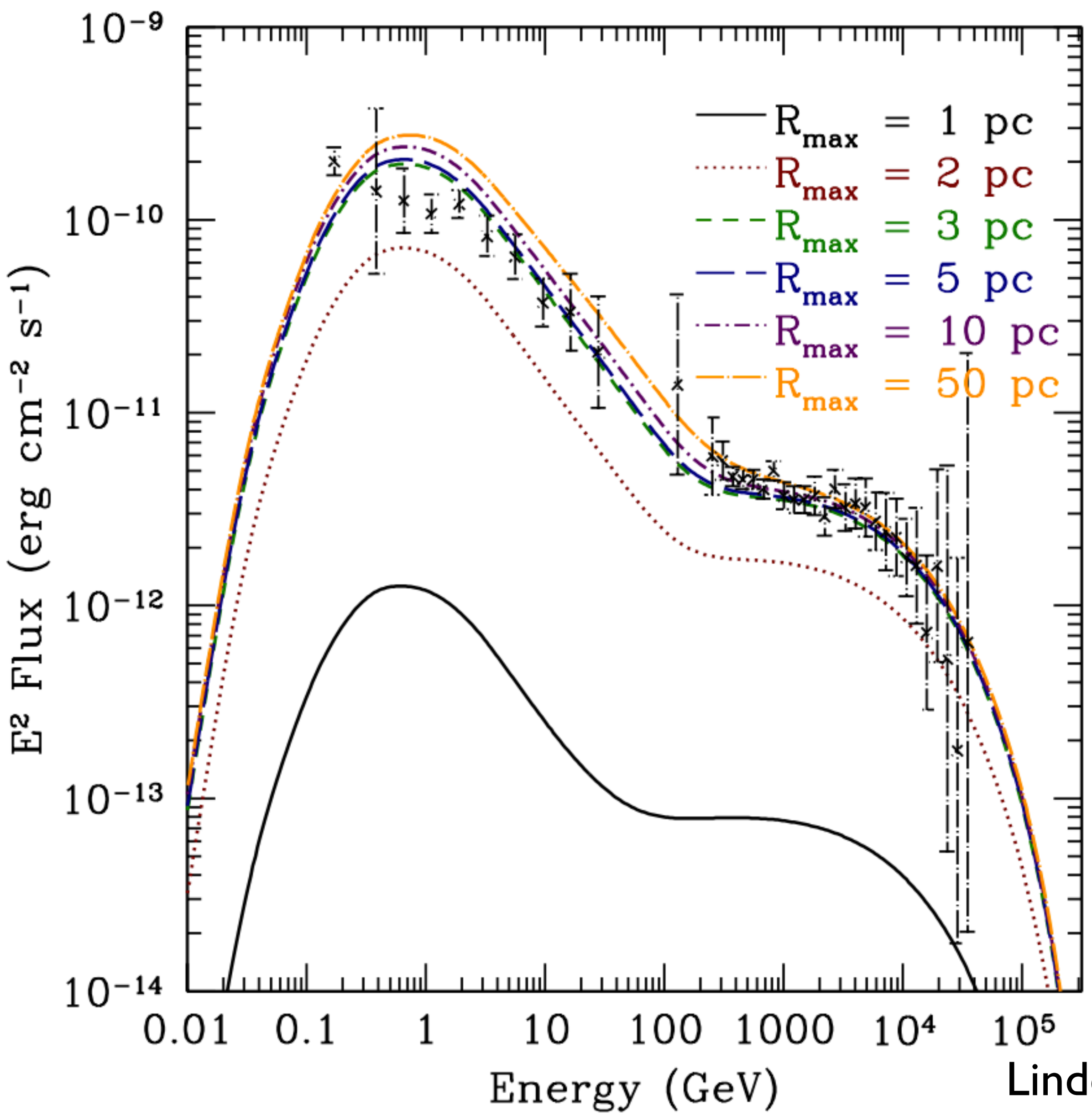
- The vast majority of emission stems from within 3 pc of the galactic center at all energies
- This lies below the PSF of all current gamma-ray instruments
- This effectively rules out hadronic interactions from Sgr A* as the source of the Fermi-LAT excess

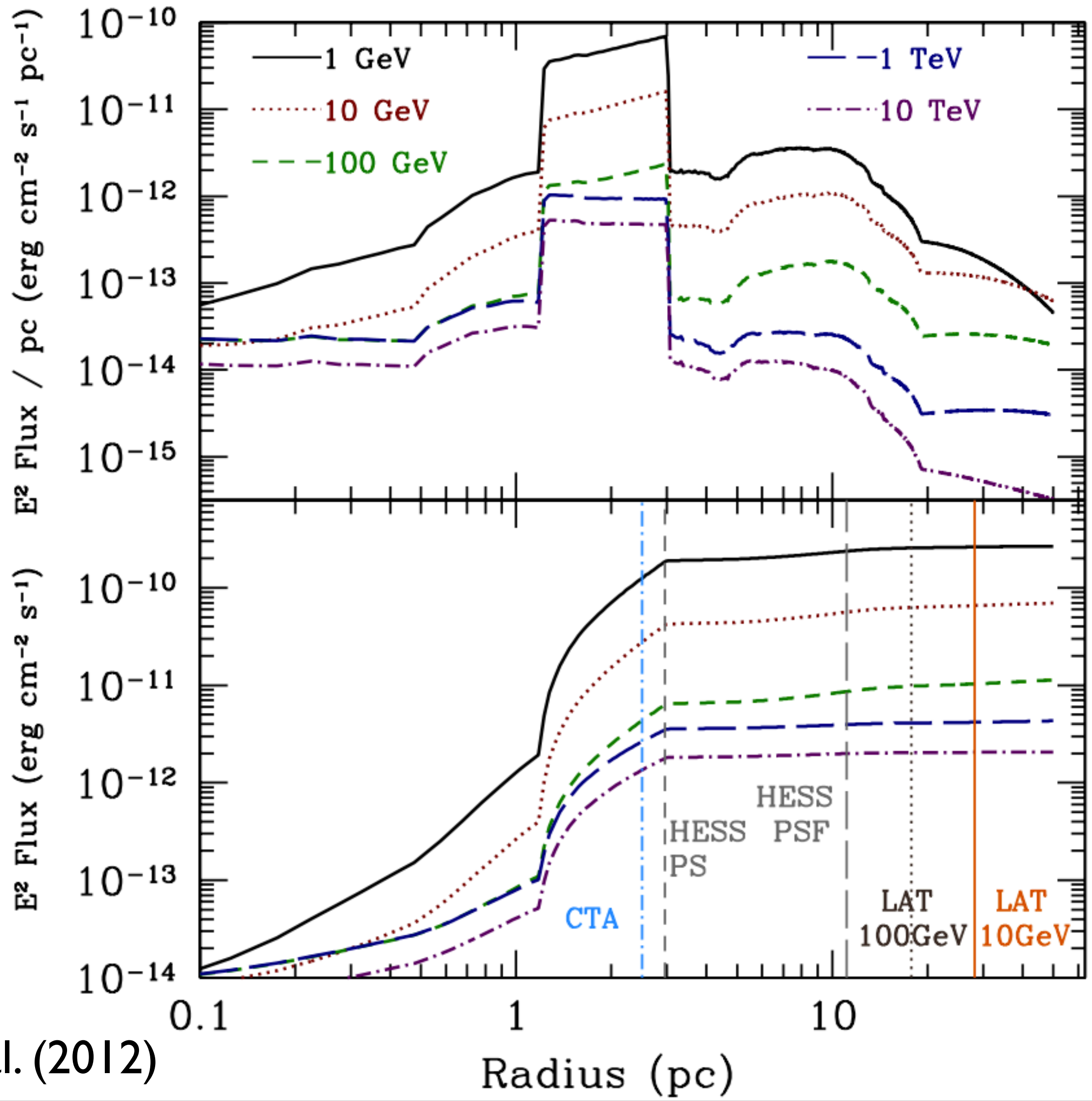




Linden et al. (2012)

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



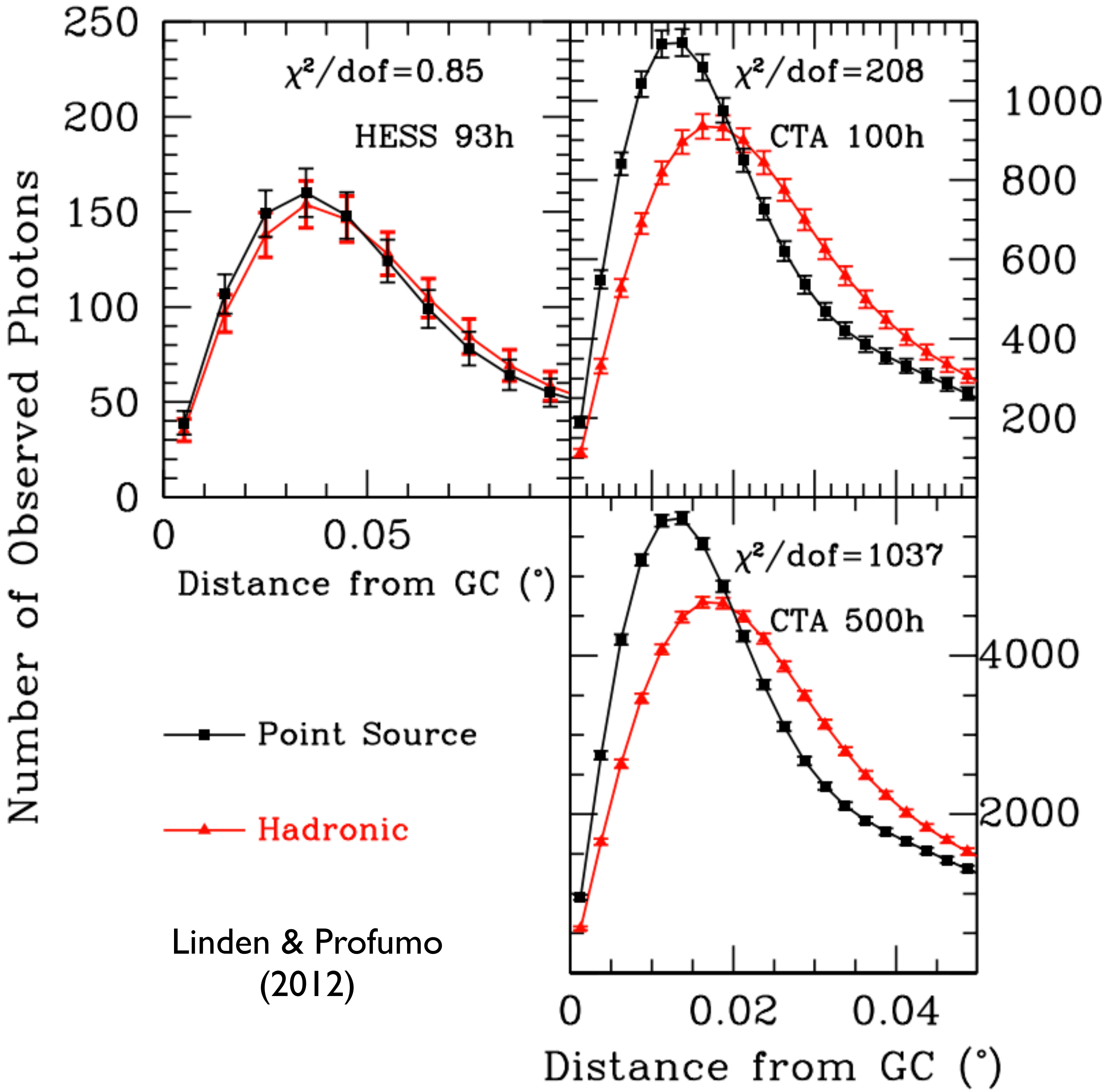


Linden et al. (2012)

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

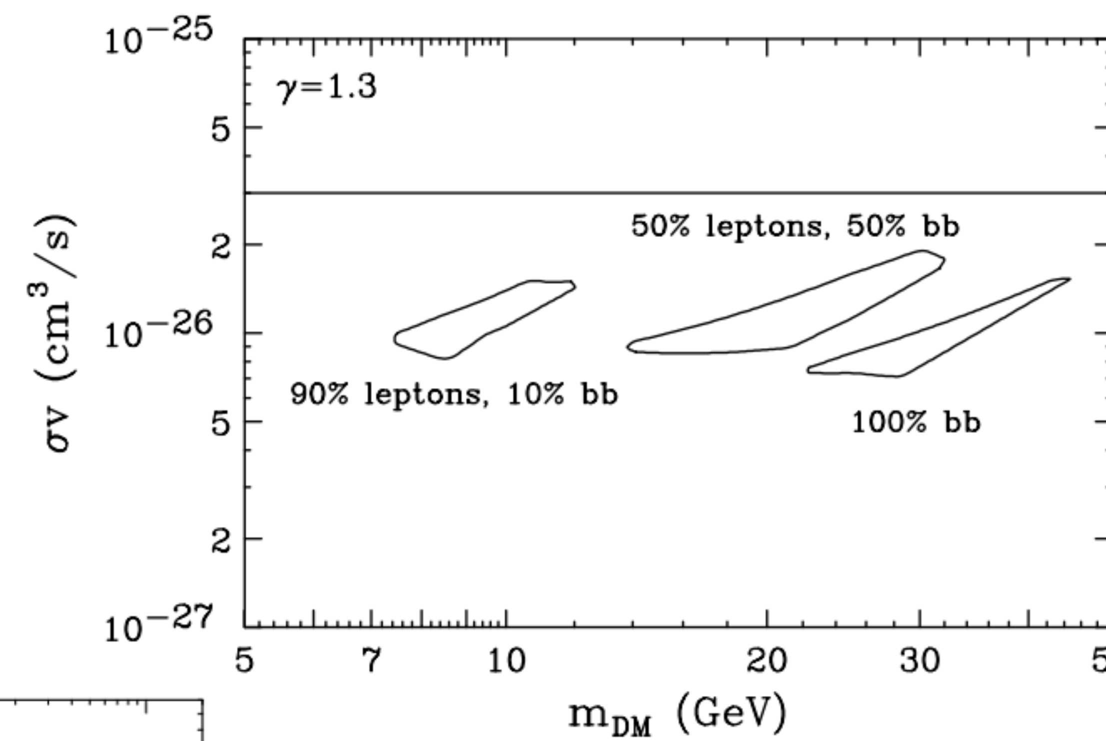
- CTA will <u>conclusively</u> determine whether the galactic center source stems from a hadronic emission channel



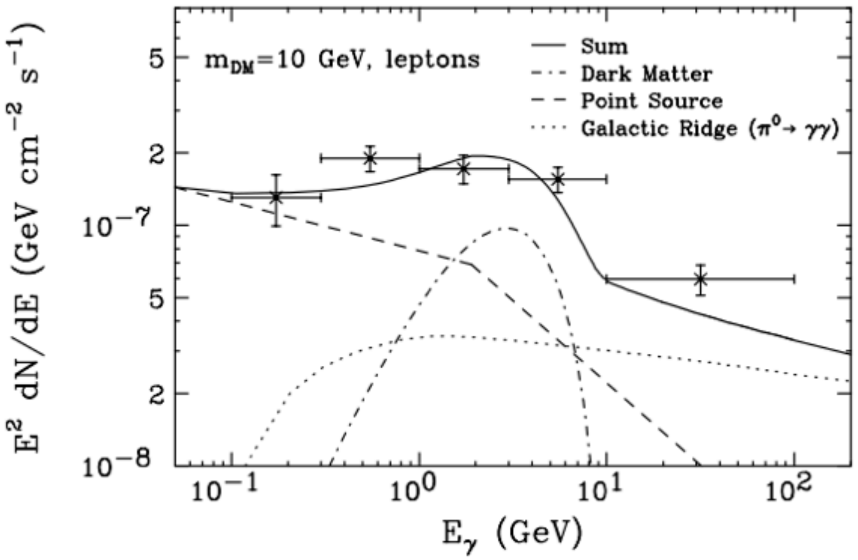
Linden & Profumo (2012)

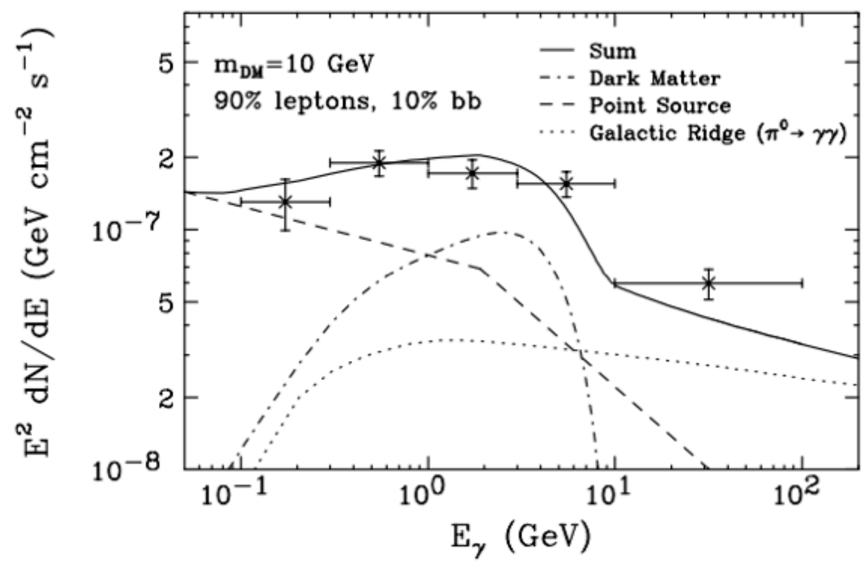
Story 2: Low-Mass Dark Matter

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

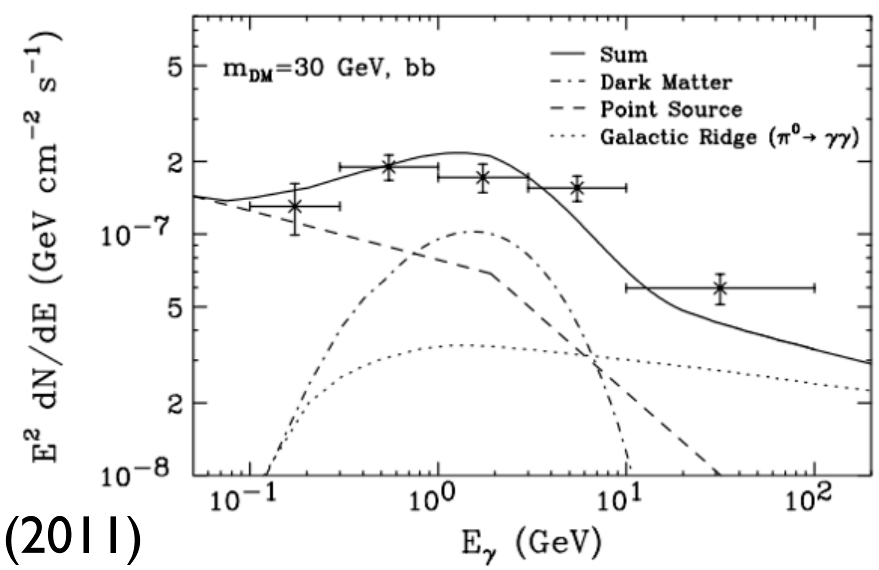


- These models are compatible with estimates for the relic density of dark matter





- 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)

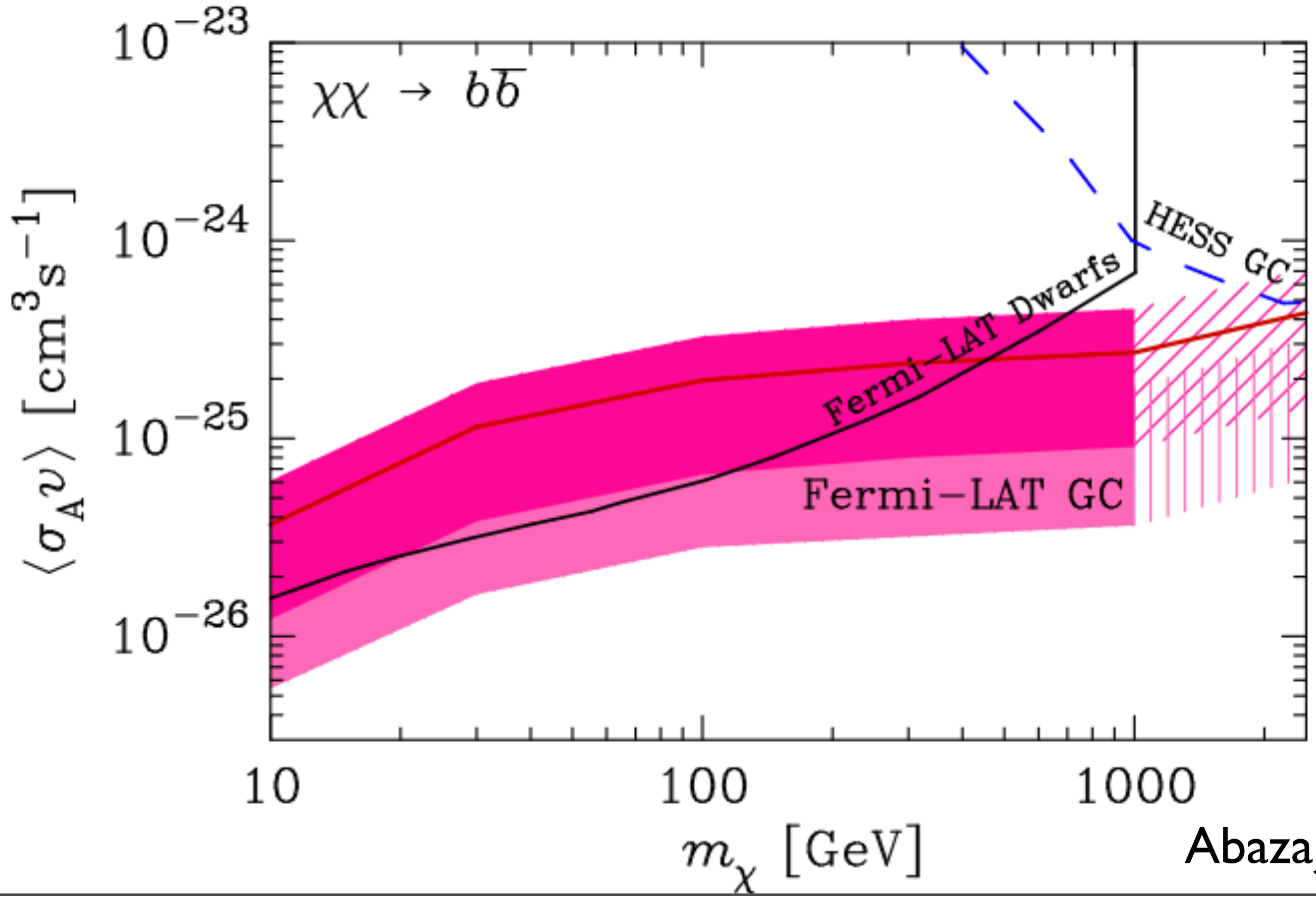
Best fitting Models for Low-Mass Dark Matter

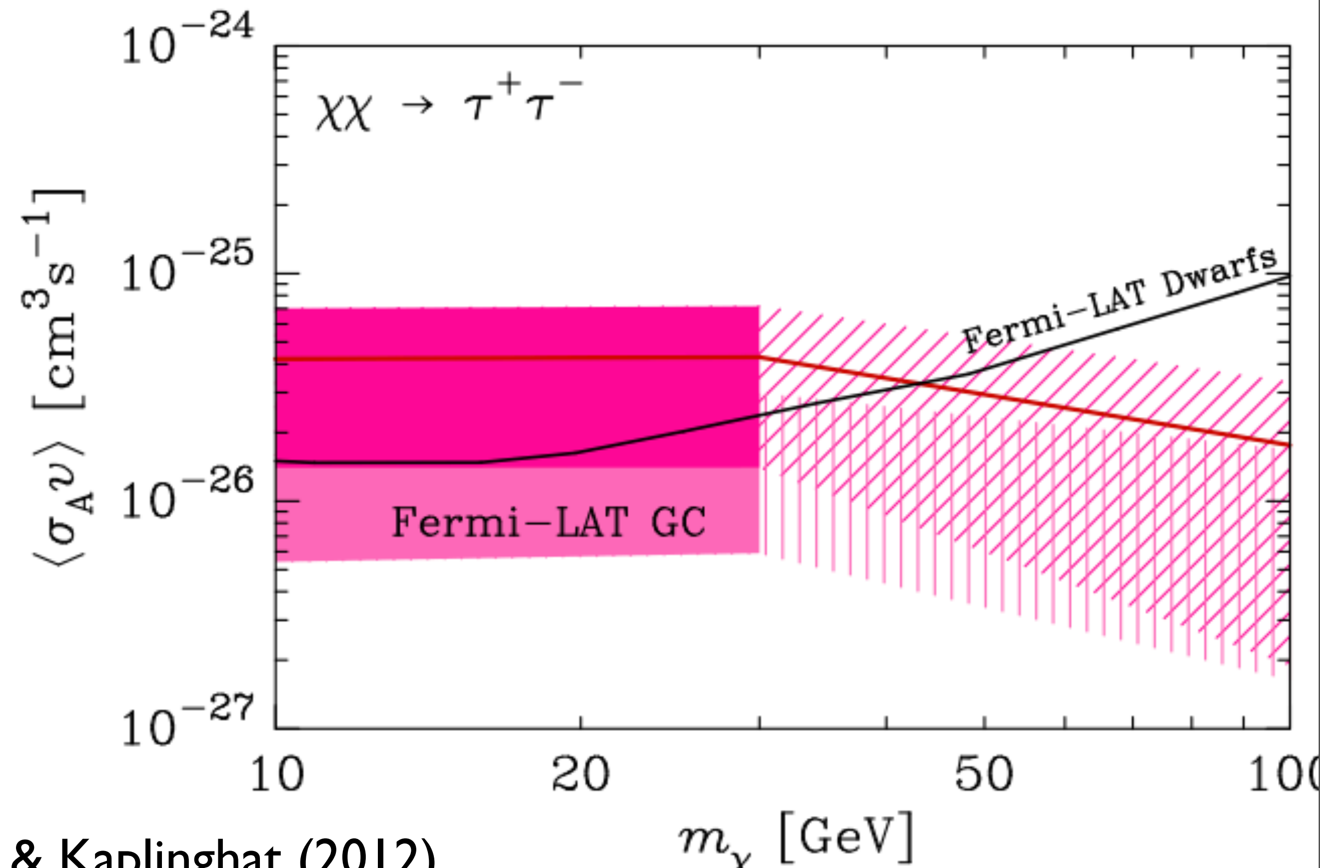
- Abazajian & Kaplinghat find a wider range of dark matter masses which provide improved fits to the data

- 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 $\alpha = 1, \beta = 3, \gamma = 1.2$.

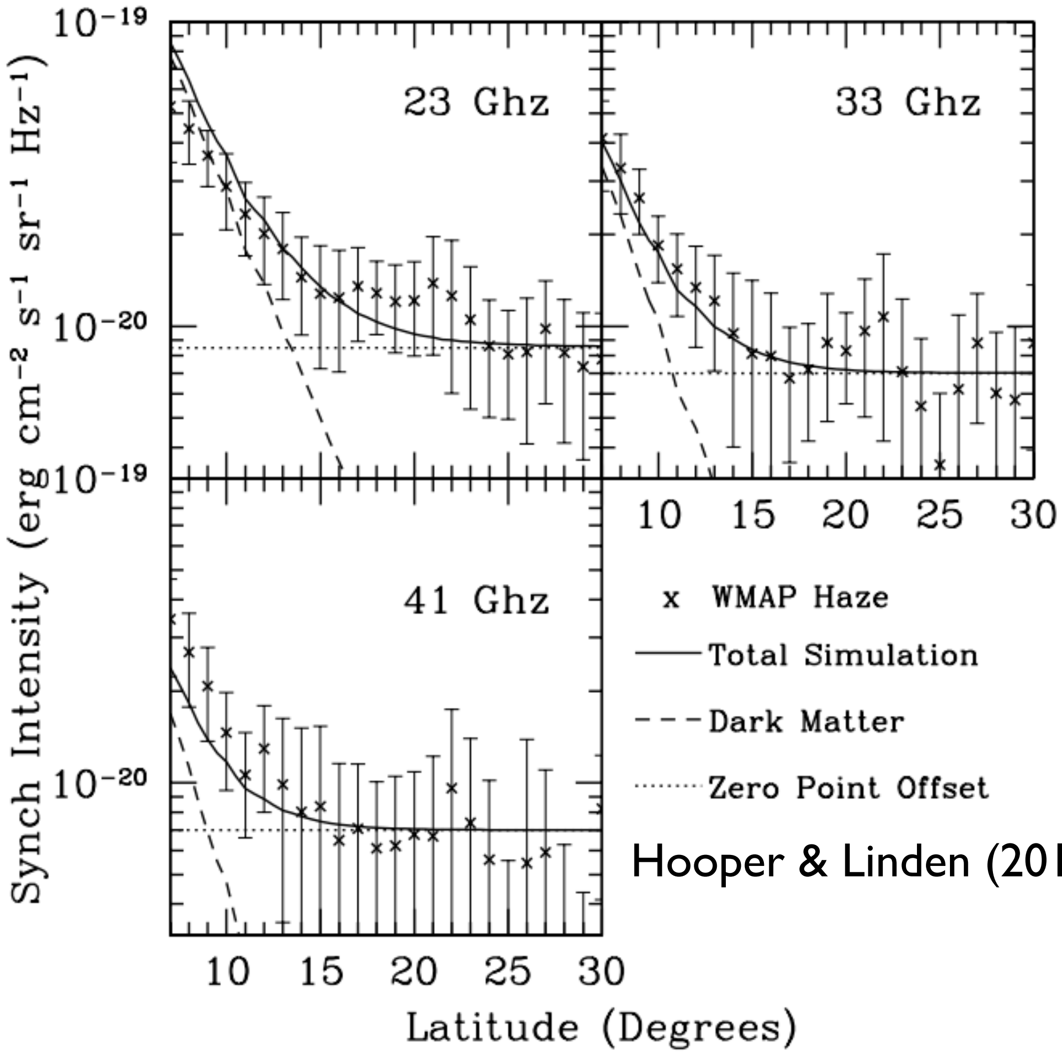
channel, m_χ	TS	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 10 GeV	2385.7	139913.6	156.5
$b\bar{b}$, 30 GeV	3460.3	139658.3	411.8
$b\bar{b}$, 100 GeV	1303.1	139881.1	189.0
$b\bar{b}$, 300 GeV	229.4	140056.6	13.5
$b\bar{b}$, 1 TeV	25.5	140108.2	−38.0
$b\bar{b}$, 2.5 TeV	7.6	140114.2	−44.0
$\tau^+\tau^-$,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

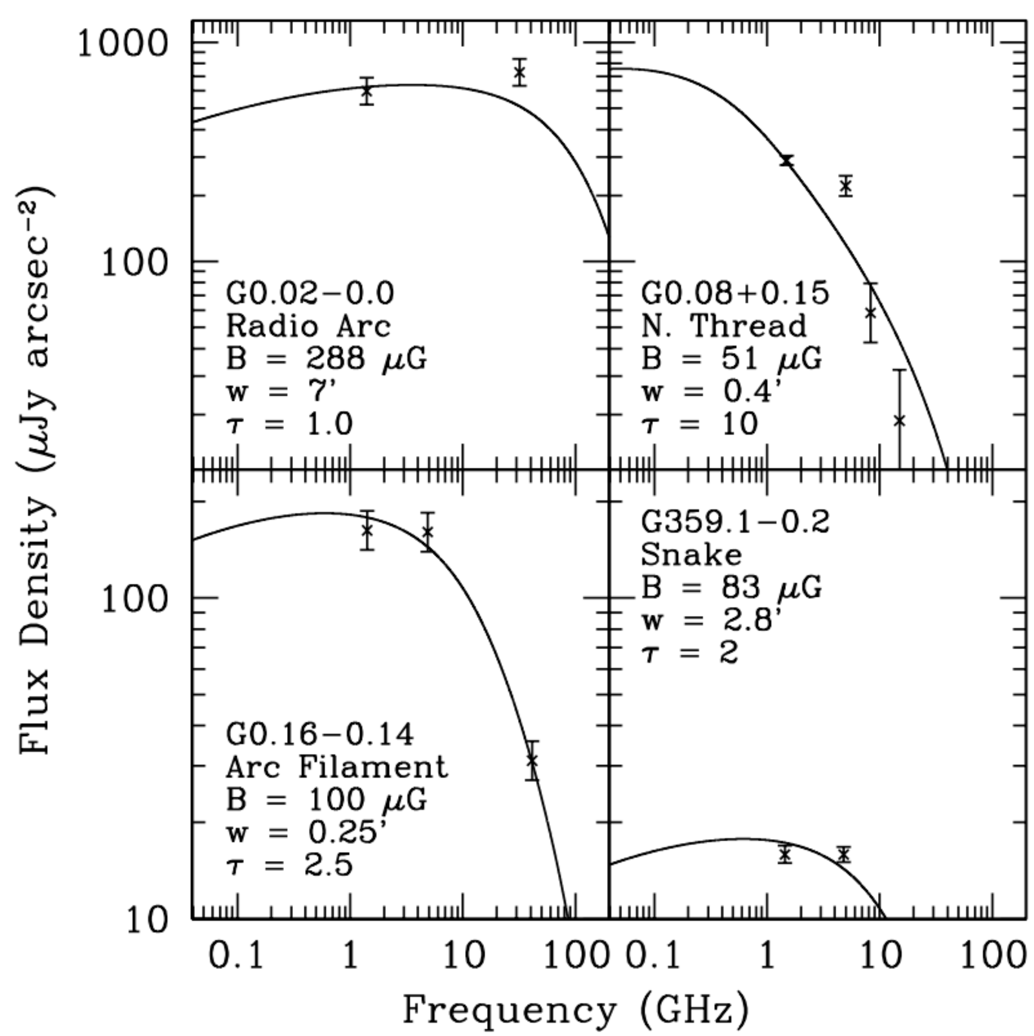
Other Observations Fitting Light DM: Indirect



Hooper & Linden (2011)

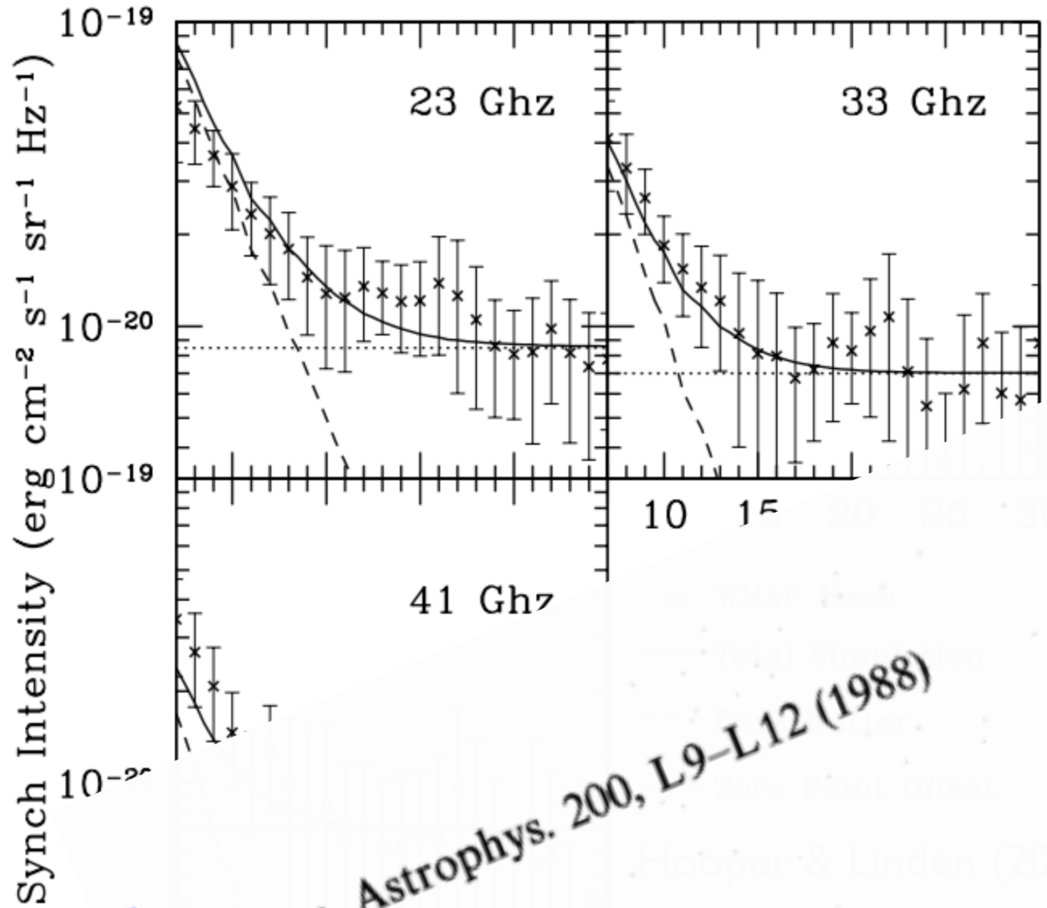
- The same dark matter model provides a reasonable explanation to the intensity and morphology of the WMAP haze
- The magnetic field must be slightly stronger above the galactic plane than usually assumed

- 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)

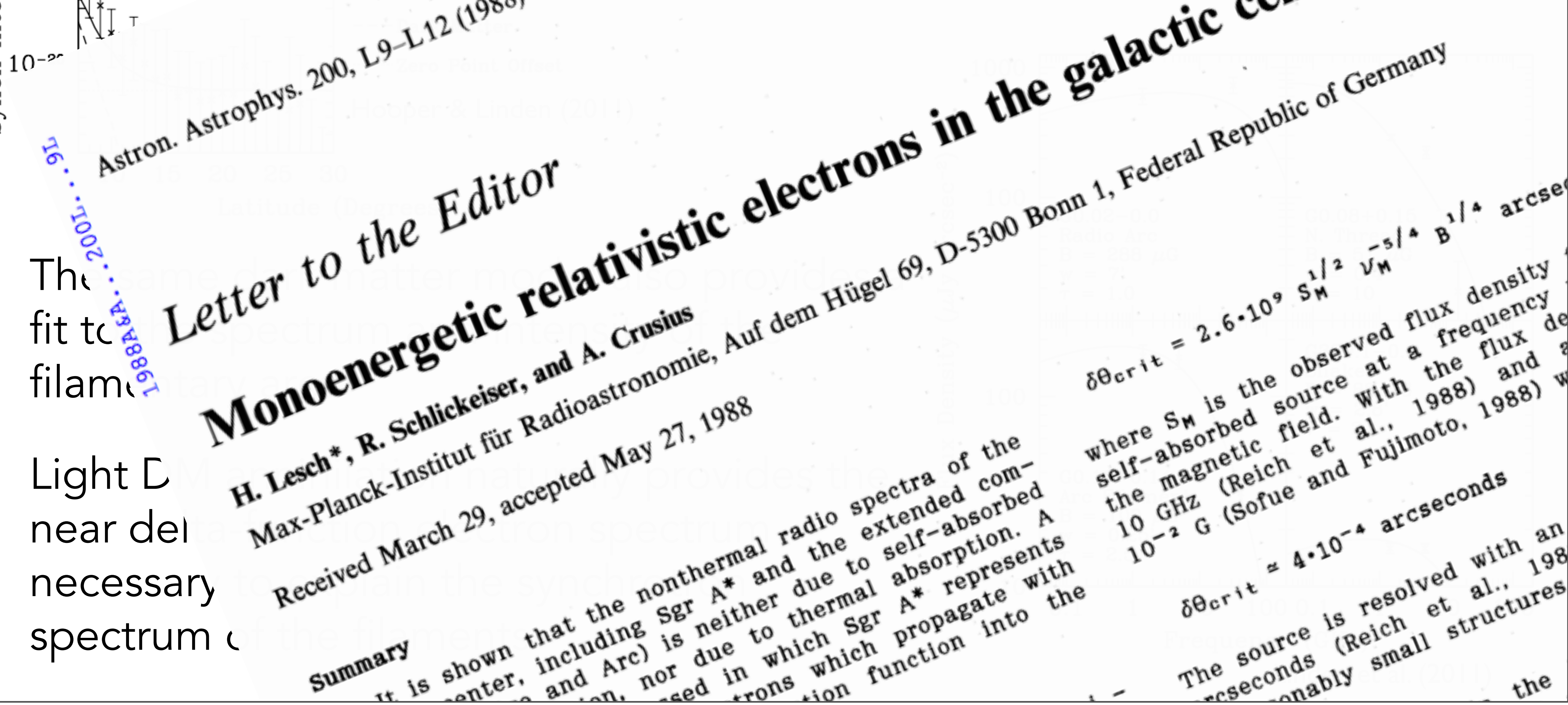
Other Observations Fitting Light DM: Indire



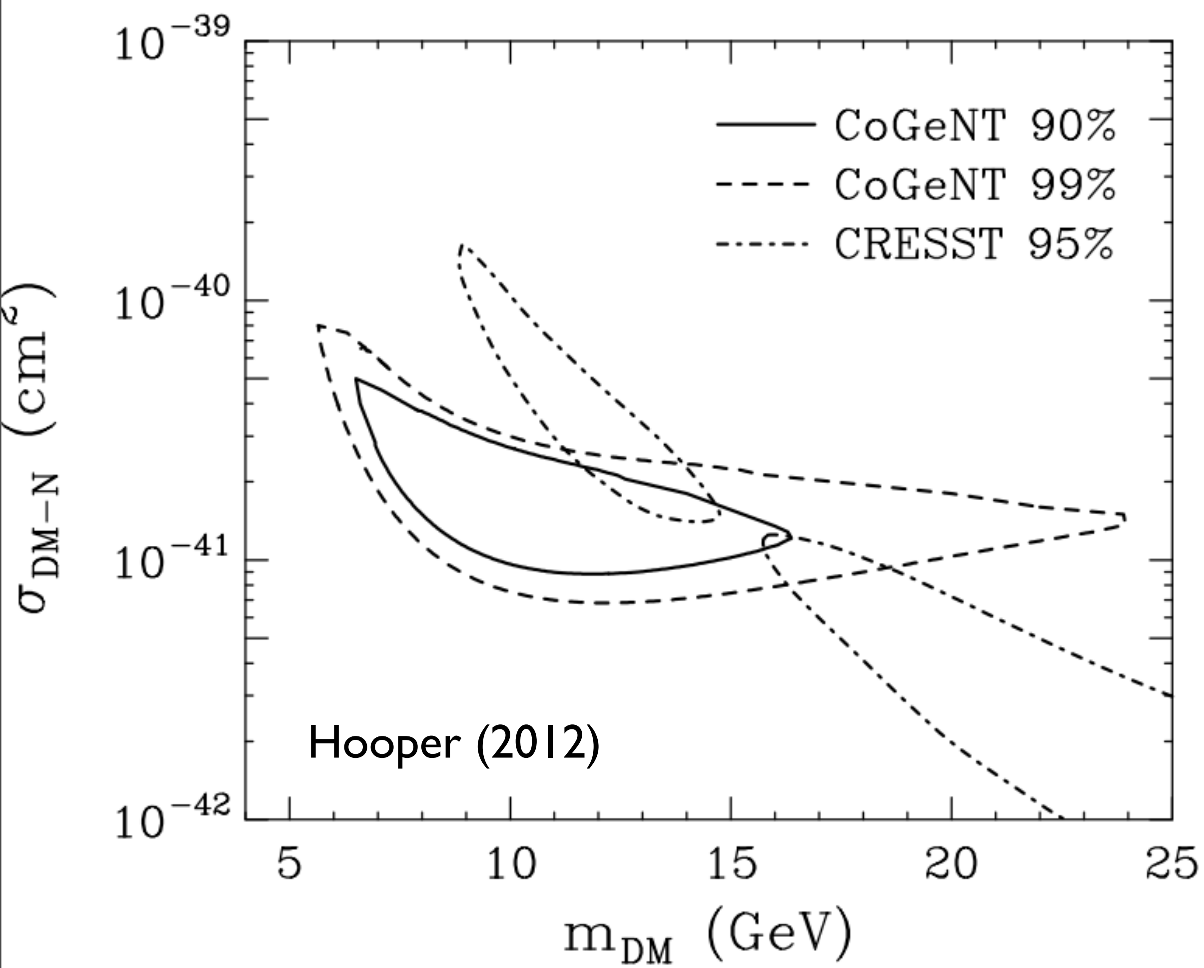
- The same dark m
reasonable
and

- The
fit to
filame

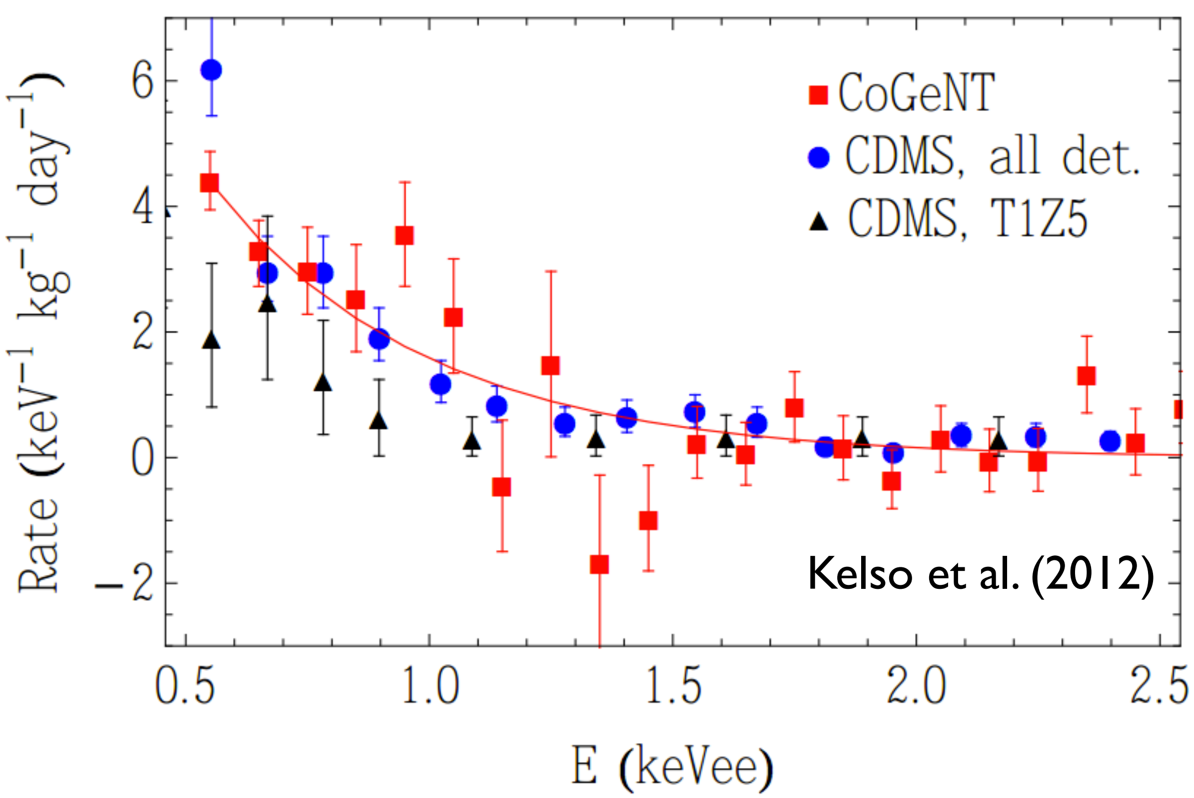
- Light D
near del
necessary
spectrum

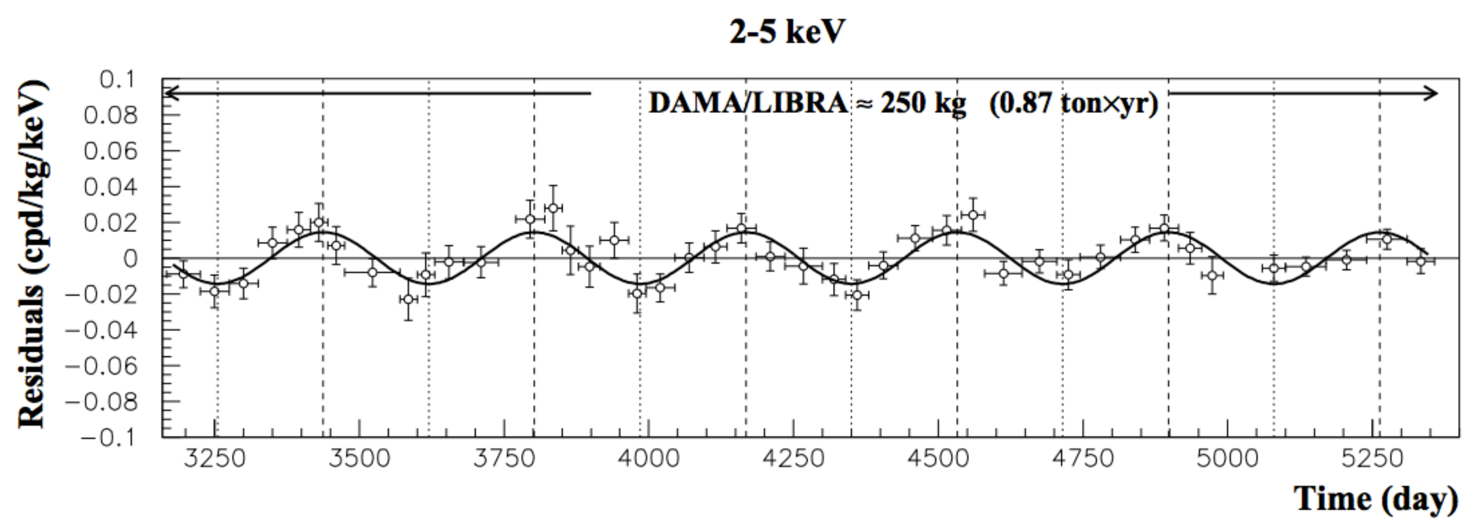


Other Observations Fitting Light DM: Direct



- 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



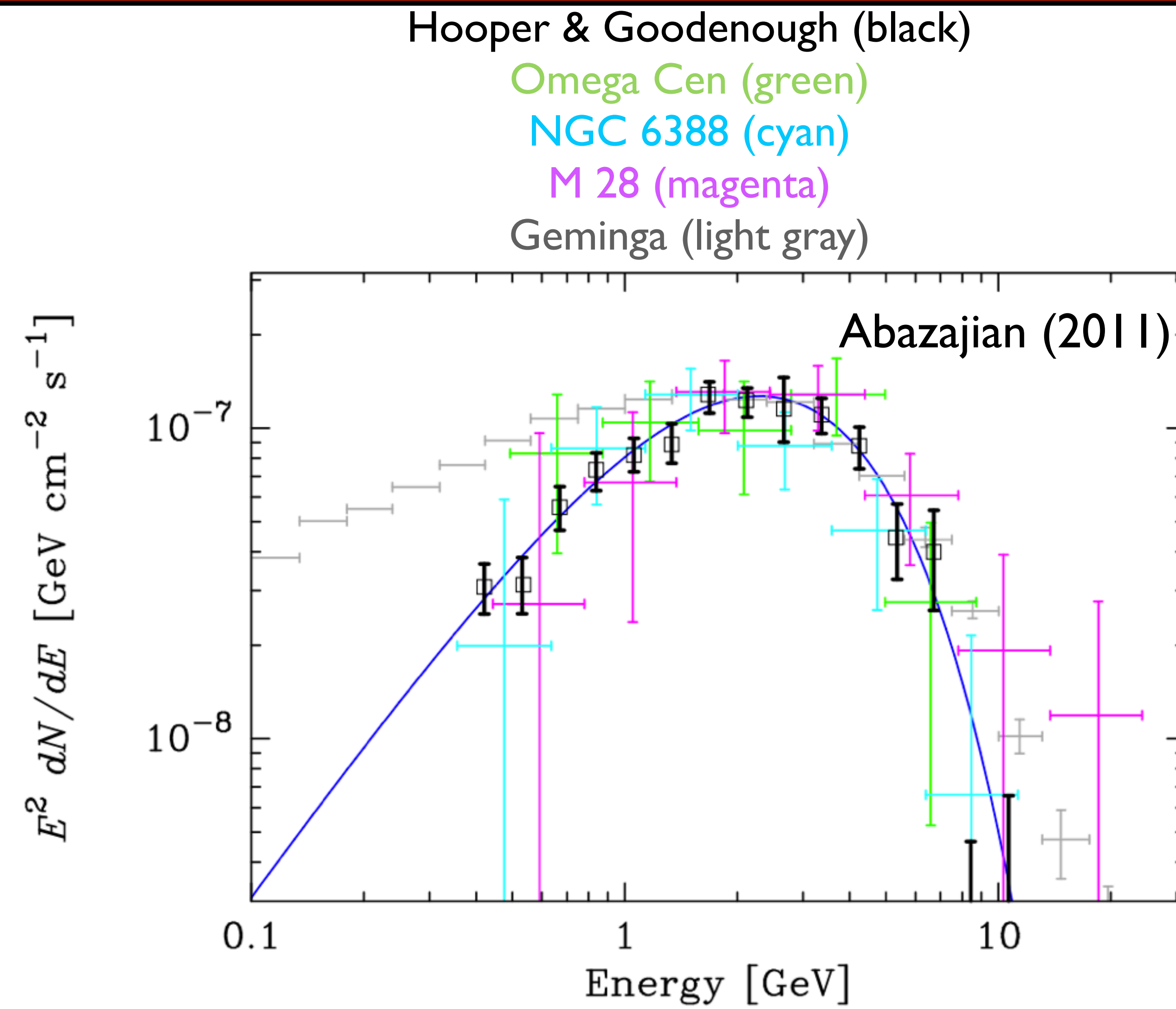


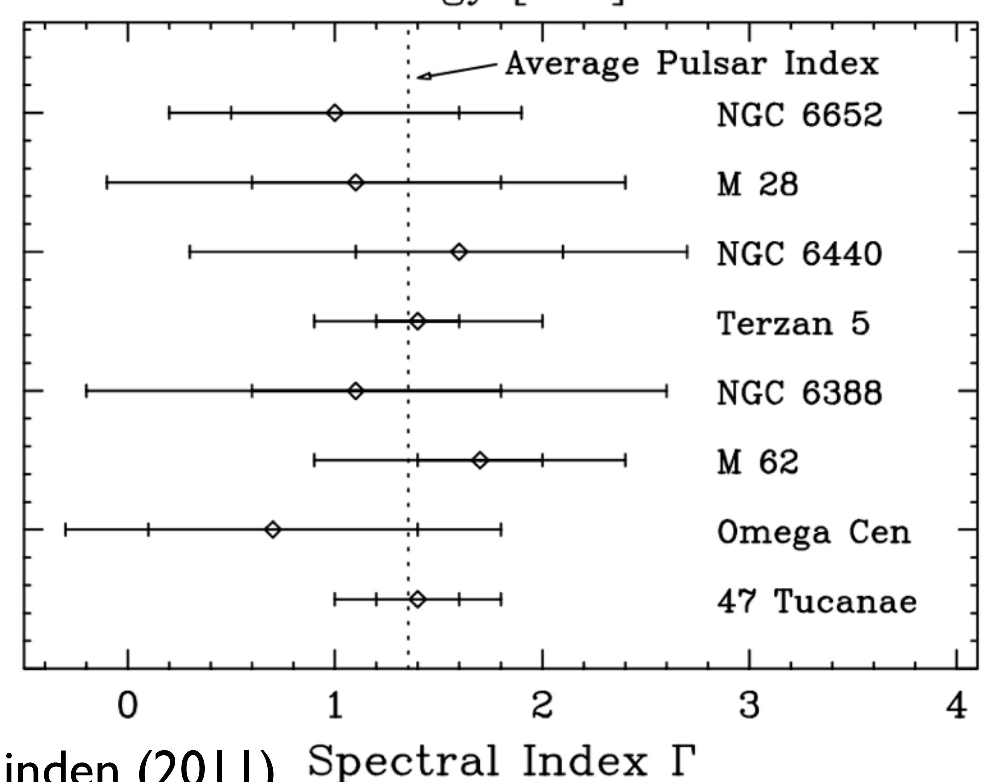
Story 3: Milli-second Pulsars

- 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

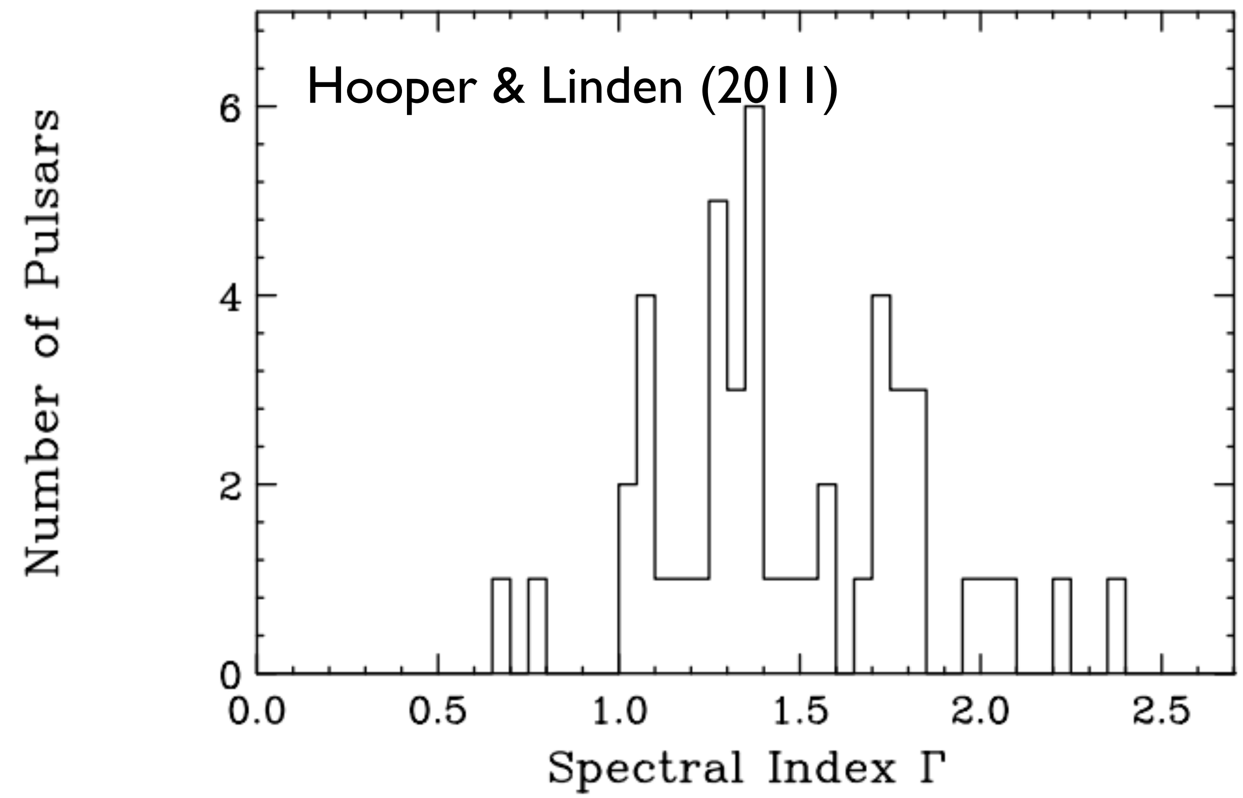




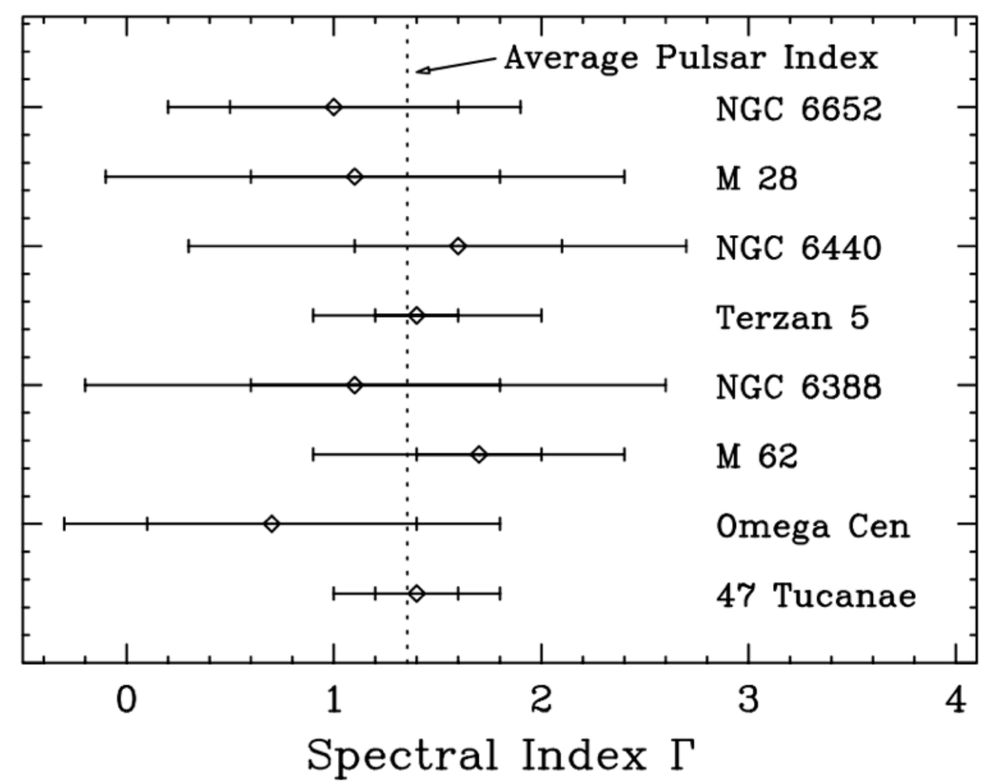
Hooper & Linden (2011)

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