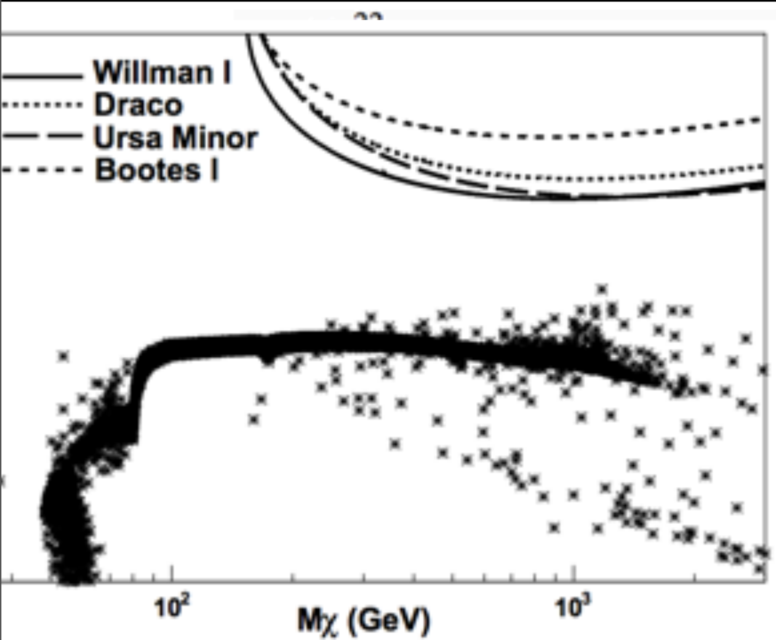
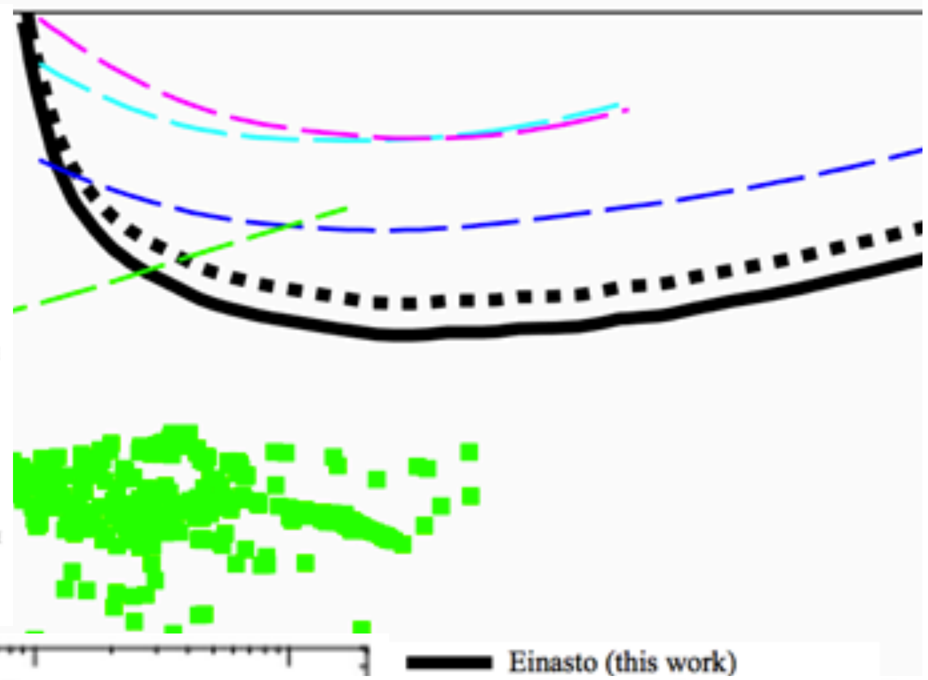
Indirect Dark Matter Searches with Gamma-Ray Telescopes





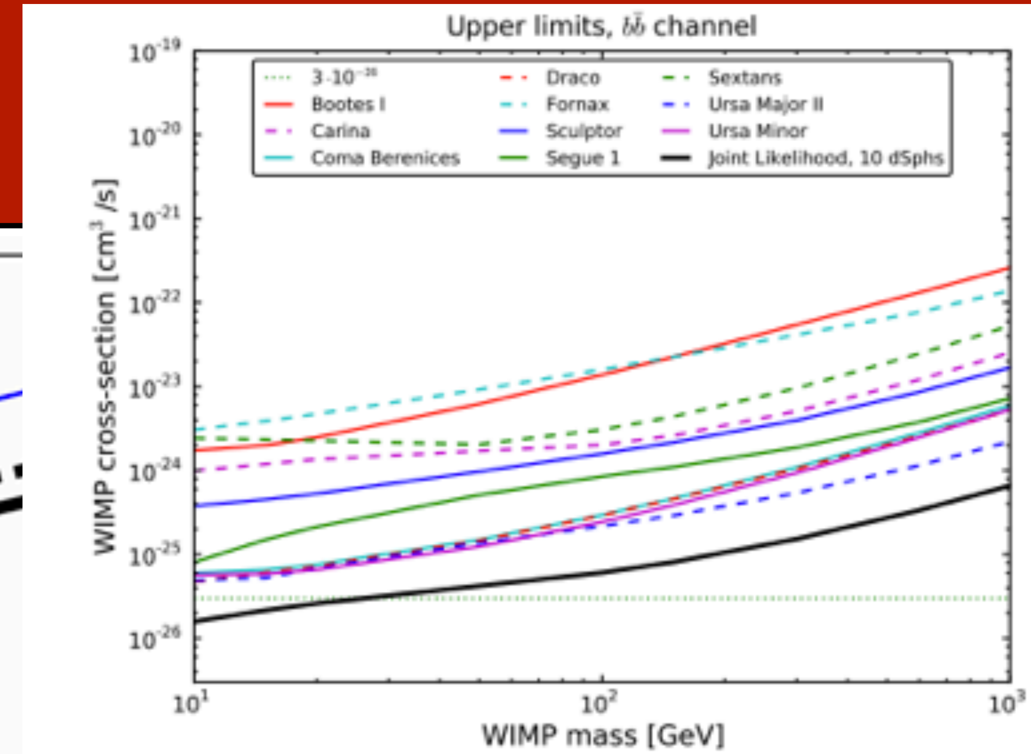
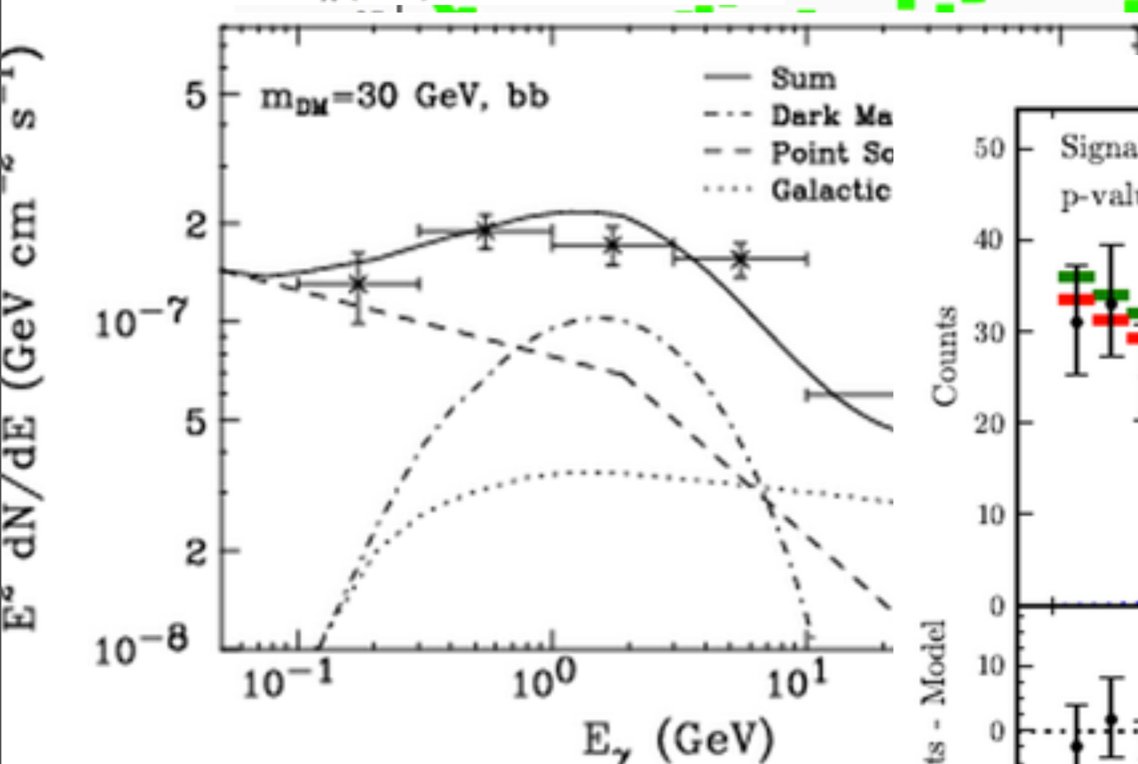
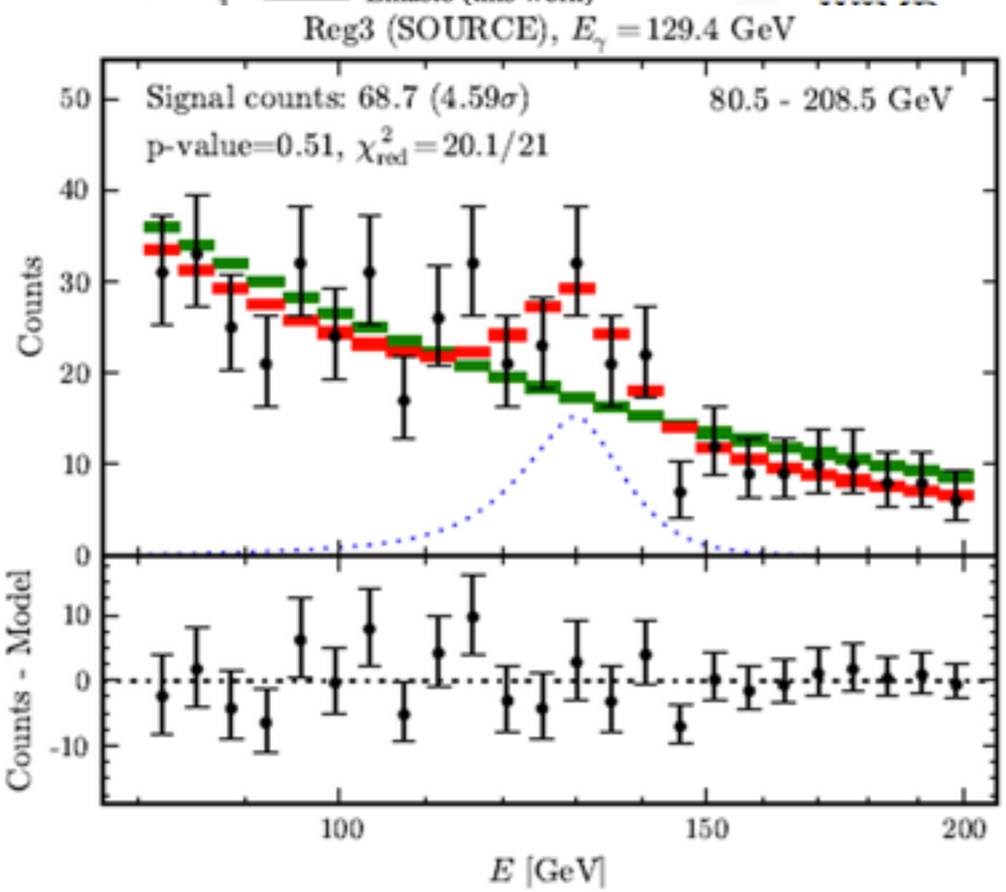
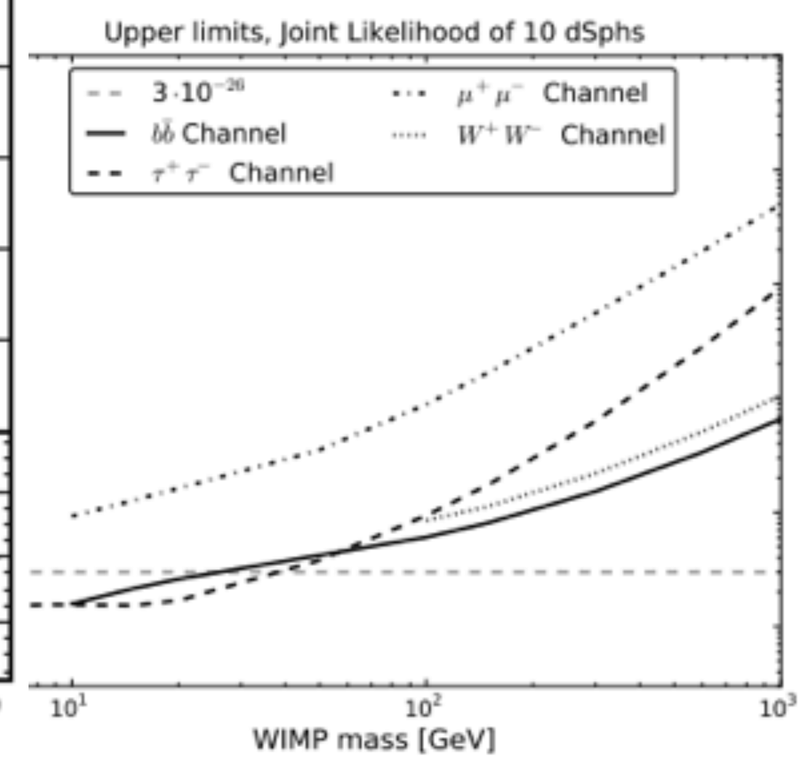


FIG. 1. 95% Upper limits on WIMP annihilation cross sec tion for annihilation into 100% $b\bar{b}$. The expected therma ss-section is plotted as a reference.







Tim Linden
UC - Santa Cruz

INPAC Workshop Asilomar, CA April 27, 2013

What Instruments are We Talking About?

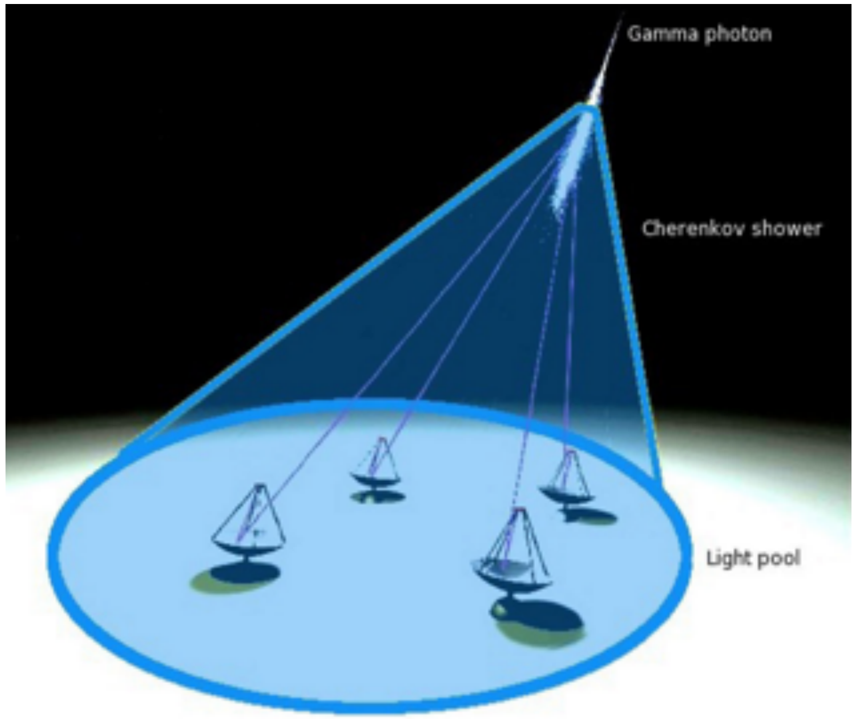
Fermi-LAT

Effective Area ~ 1 m^2

Angular Acceptance ~ 2 sr

Observation Time ~ 10 yr

Energy Range > 0.1 MeV



VERITAS

H.E.S.S.

CTA*

ACTs

Effective Area ~ 5 x 10^4 m^2

Angular Acceptance ~ 0.002 sr

Observation Time ~ 1000 hr/yr

Energy Range > 100 GeV

Water Cherenkov Telescopes

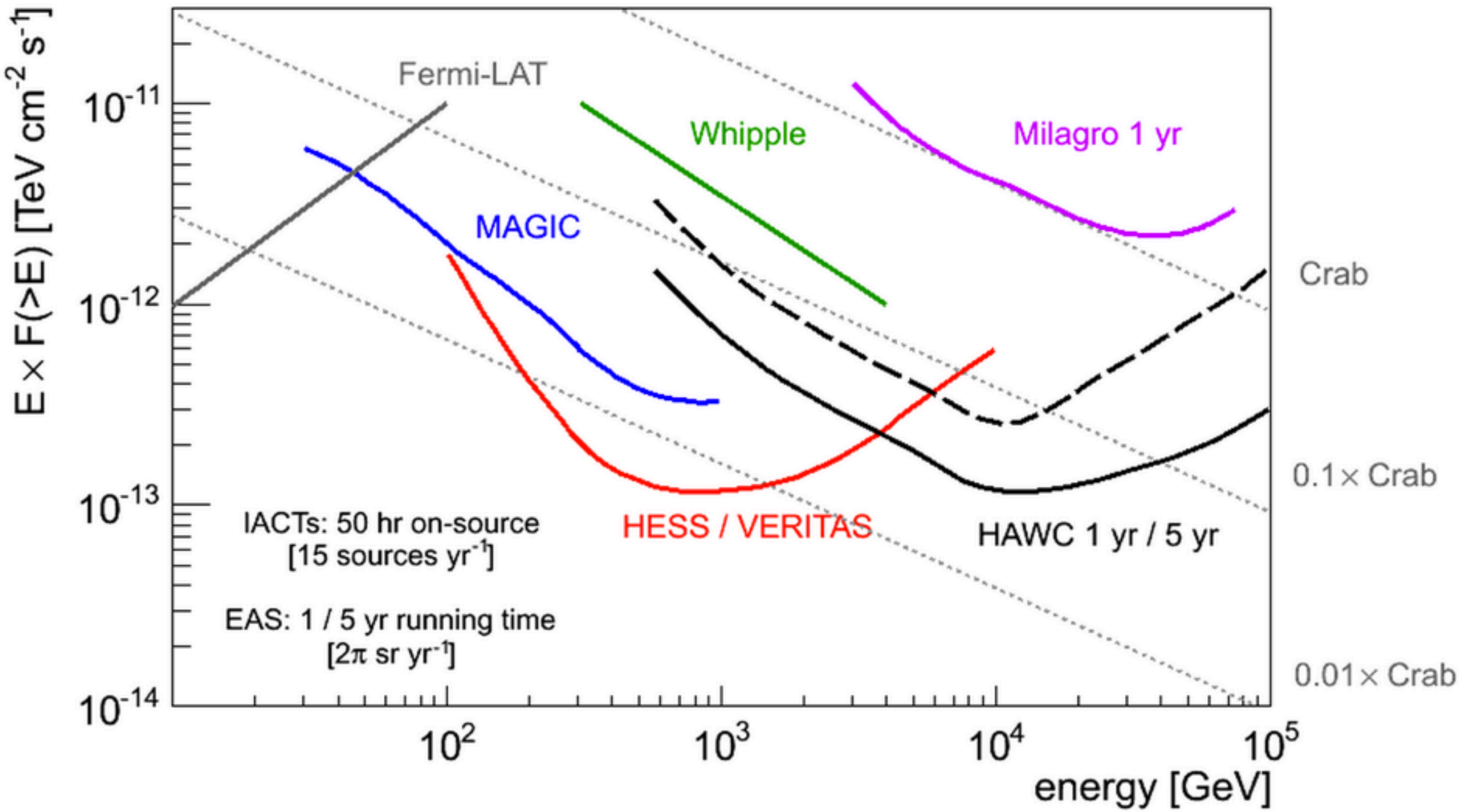
Effective Area ~ 2 x 10^4 m^2

Angular Acceptance ~ 6 sr

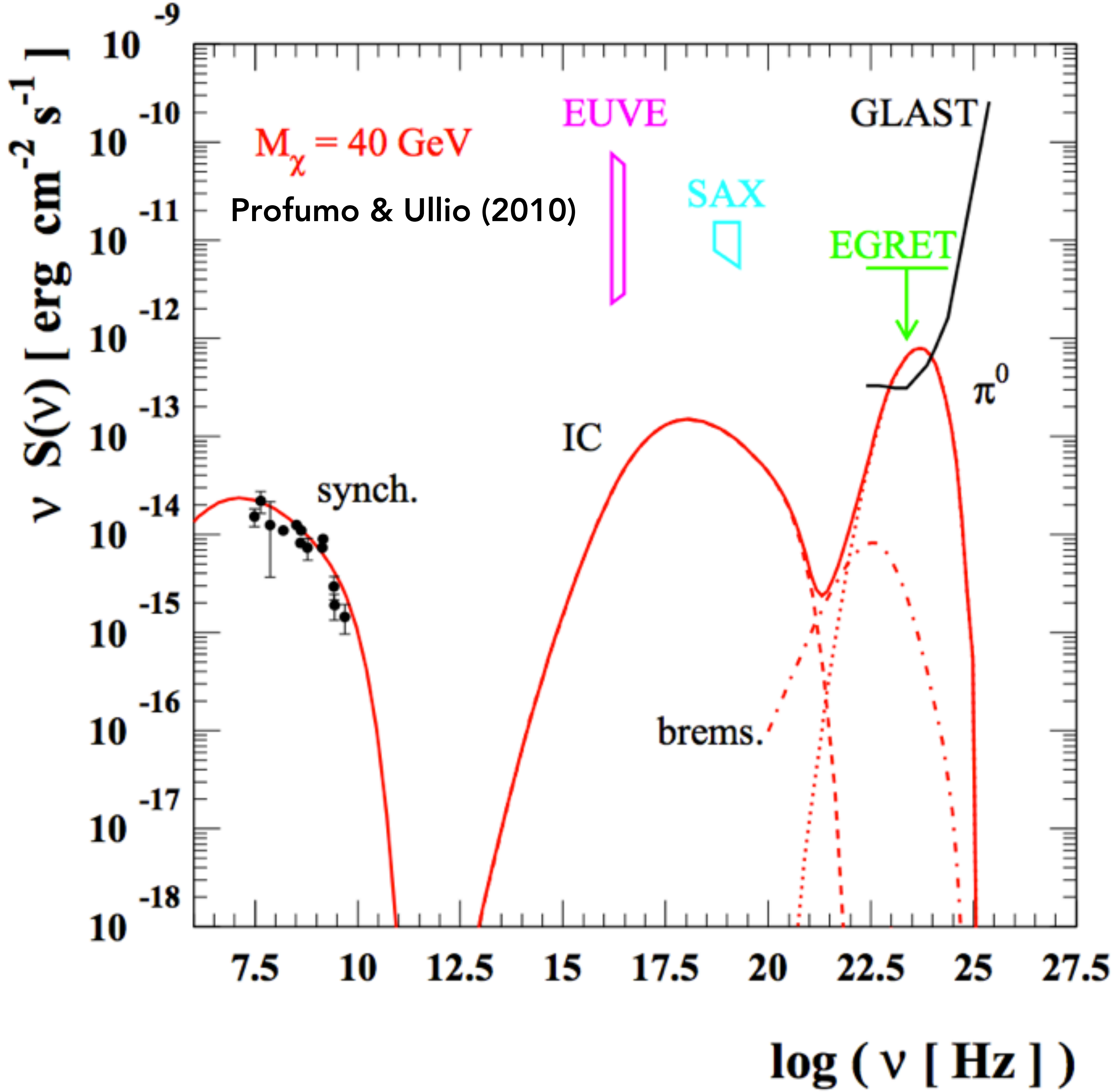
Total Observation Time ~ 3000h / yr

Energy Range > 1000 GeV

What Instruments are We Talking About

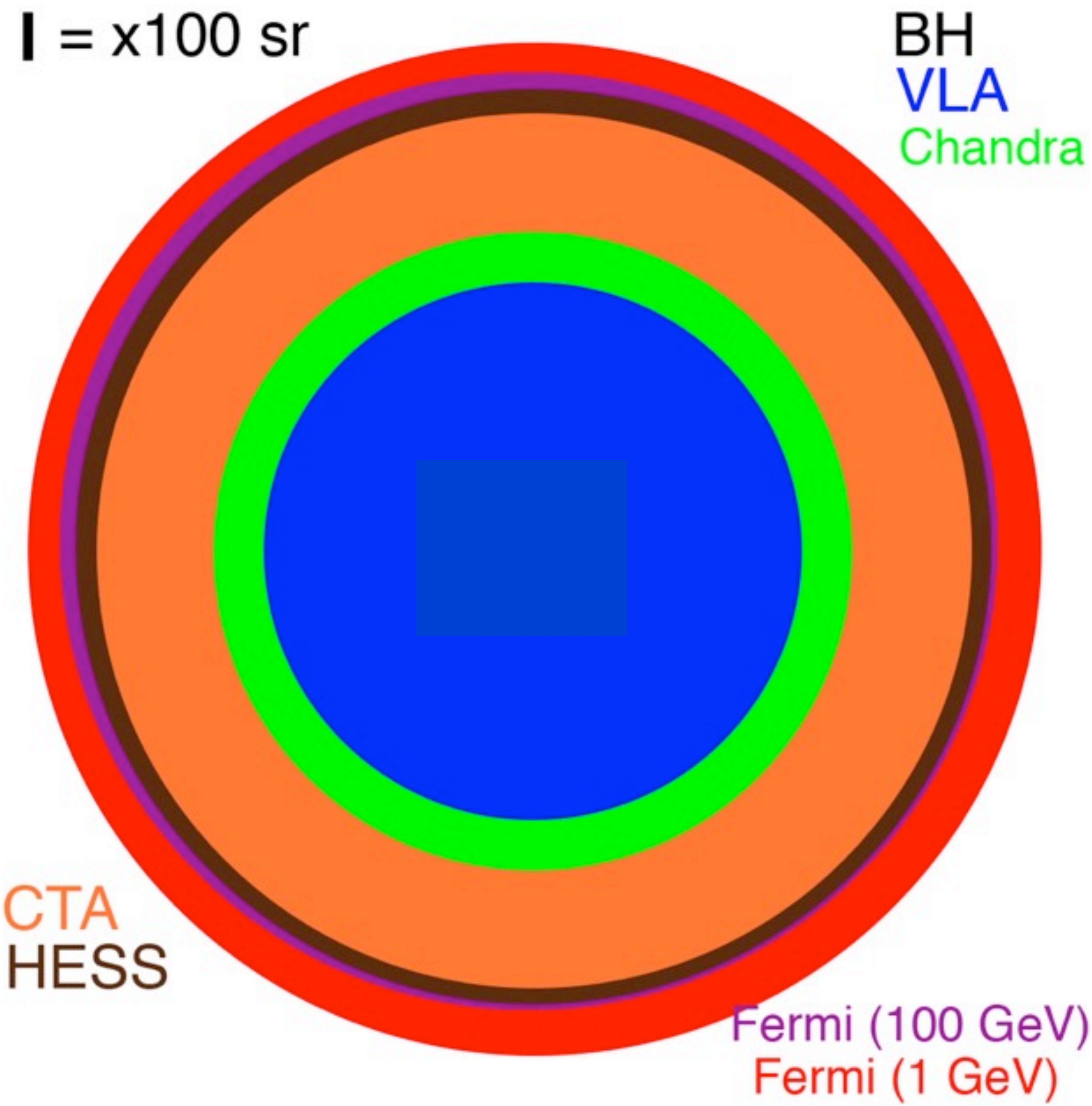


Why Do We Search for Dark Matter in Gamma-Rays

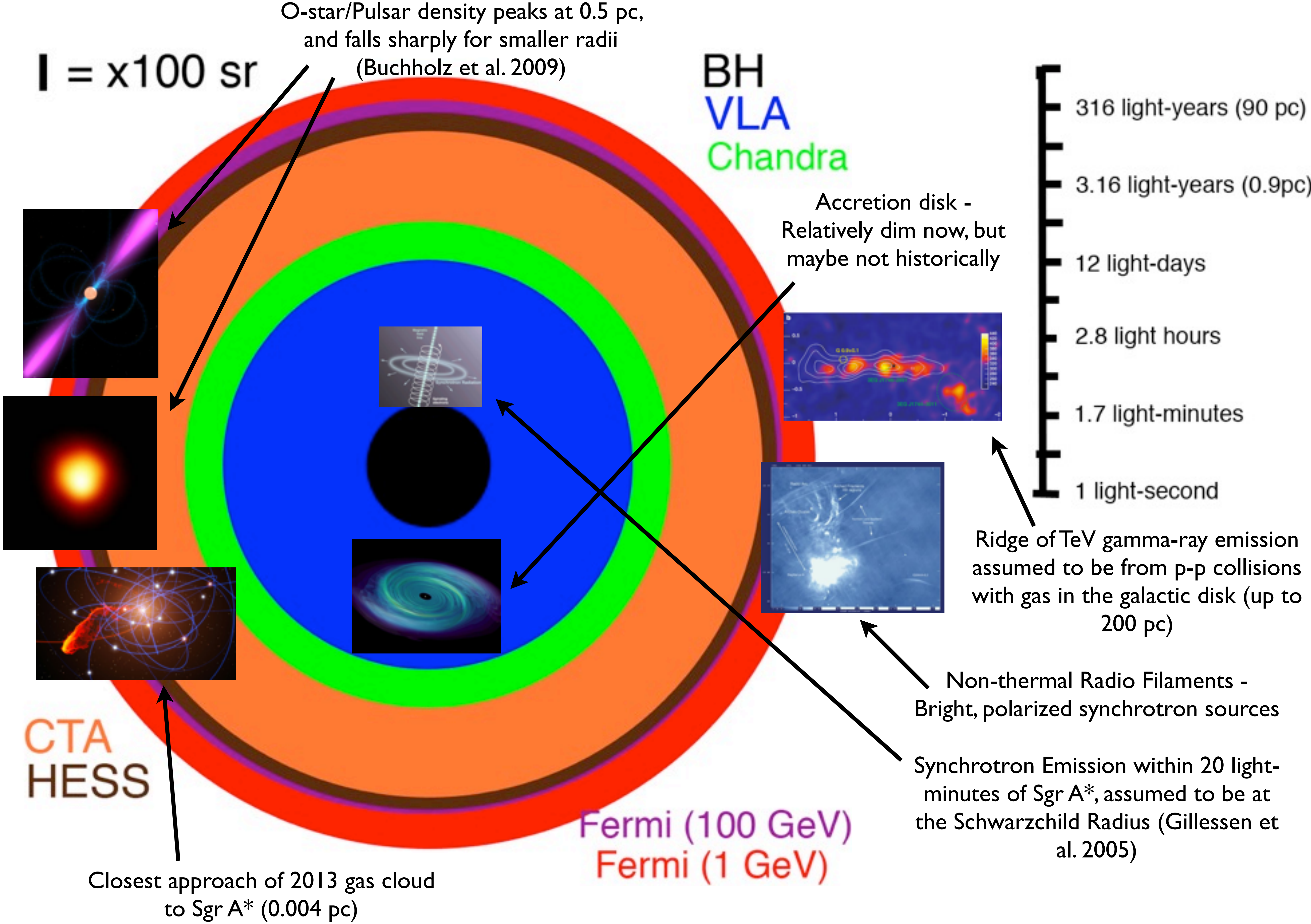


Saturday, April 27, 2013

Angular Scales at Various Energies



What this looks like in the Galactic Center



The Flux Sensitivity (to point sources) are Lower

- **VLA - 6 x 10^{-21} erg s^{-1} cm^{-2} (10 hour exposure, 1.4 GHz, 75 MHz Band)**

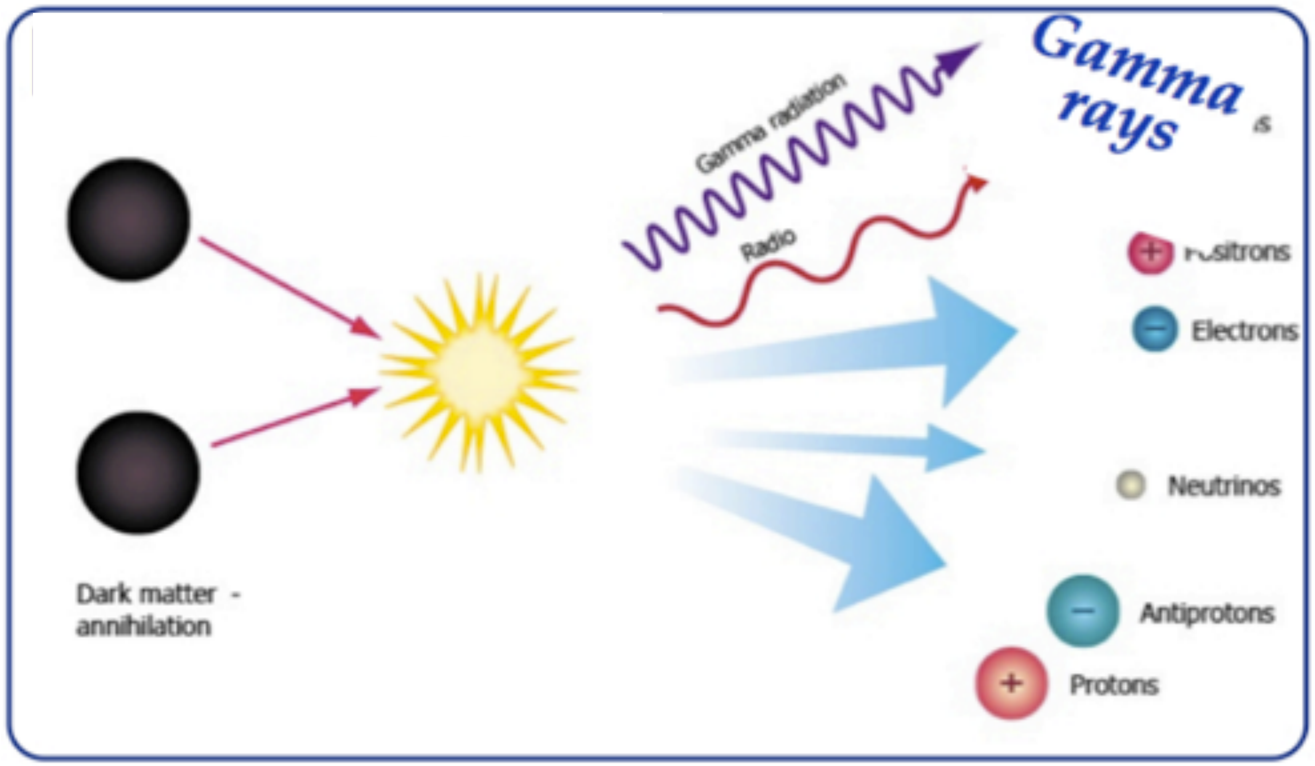
- **Chandra - 1 x 10^{-17} erg s^{-1} cm^{-2} (1 Ms exposure, 0.5-10 keV)**

- **Fermi - 8 x 10^{-13} erg s^{-1} cm^{-2} (2 year survey mode, 1 GeV)**
- **H.E.S.S. / VERITAS - 2 x 10^{-13} erg s^{-1} cm^{-2} (50 hours, 1 TeV)**
- **HAWC - 4.8 x 10^{-13} erg s^{-1} cm^{-2} (1 year, 10 TeV)**

So Maybe gamma-ray telescopes aren’t the optimal instruments?

So, Why are gamma-ray telescopes setting the best limits for indirect detection?

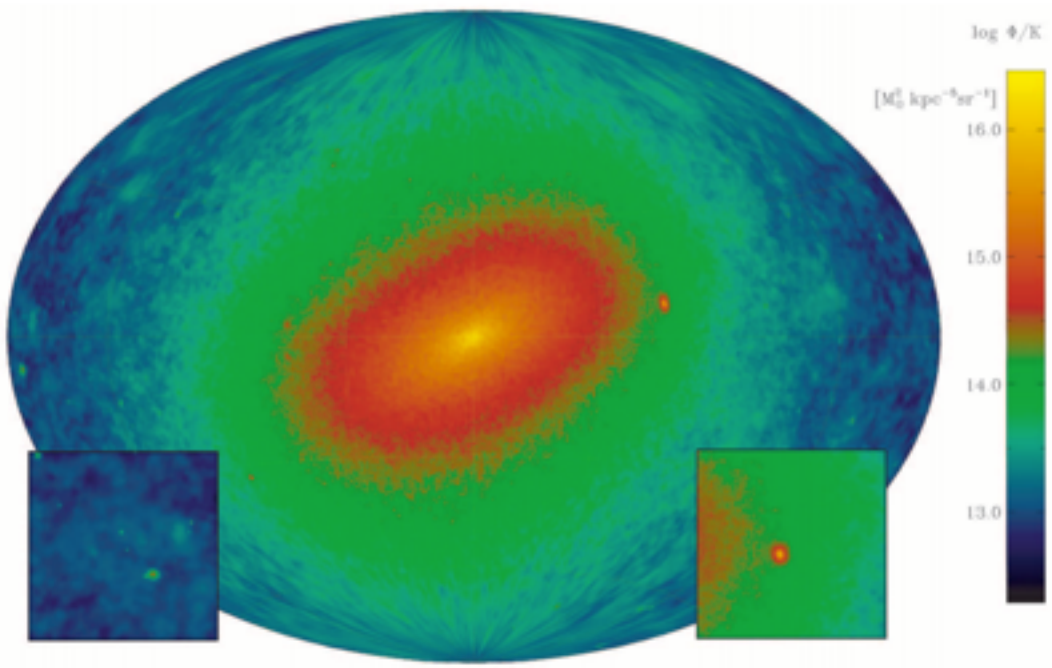
Dark Matter Indirect Detection



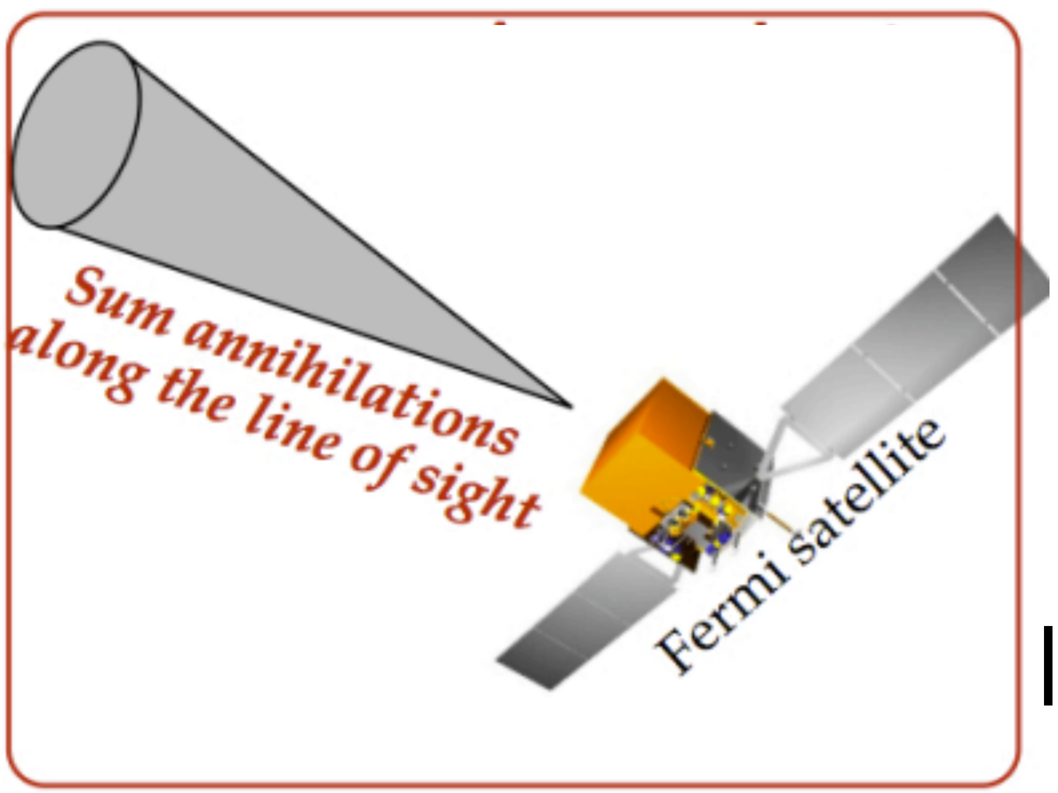
Particle Physics

Slides Courtesy of G. Zaharijas

Astrophysics



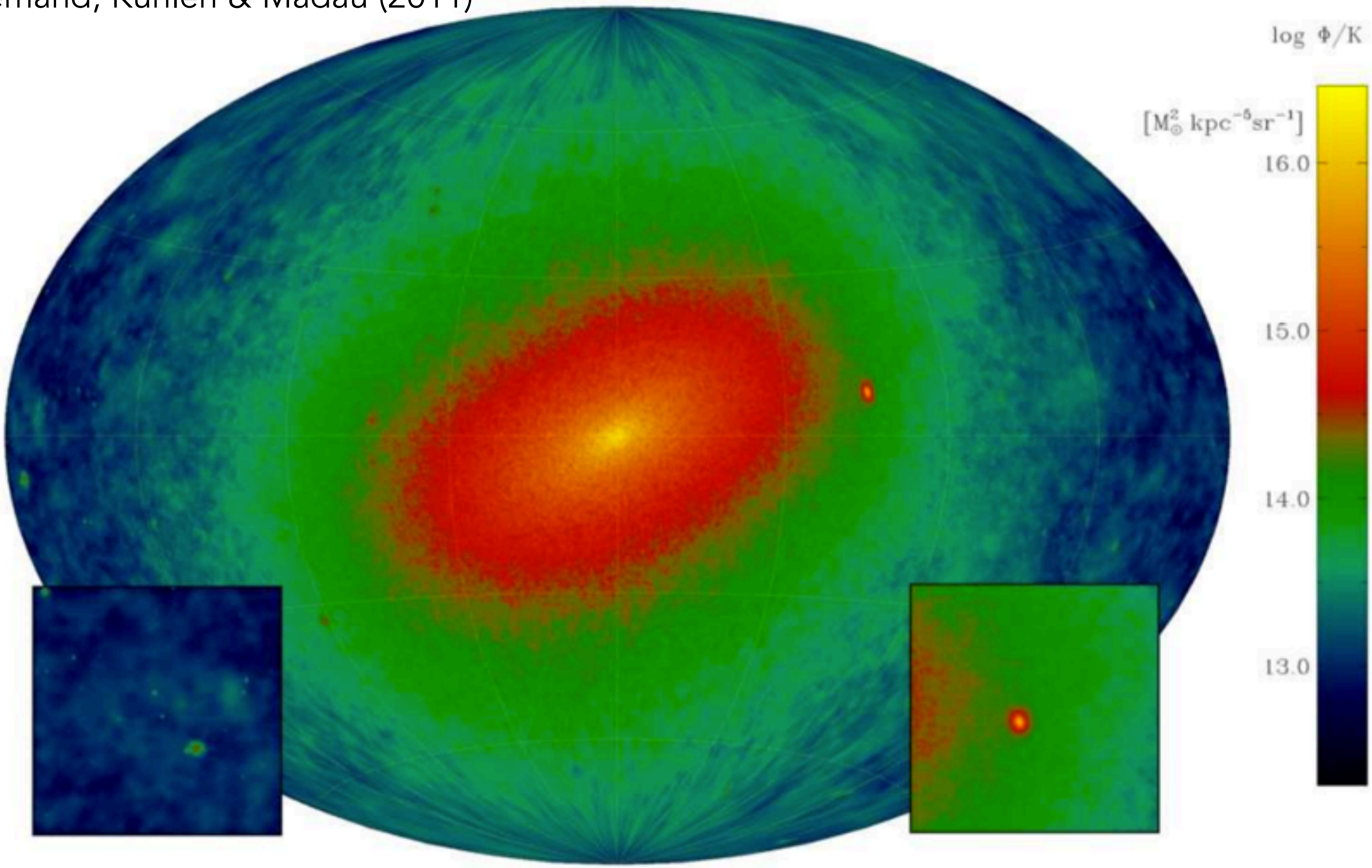
Diemand et al. 2008



Instrumental Response

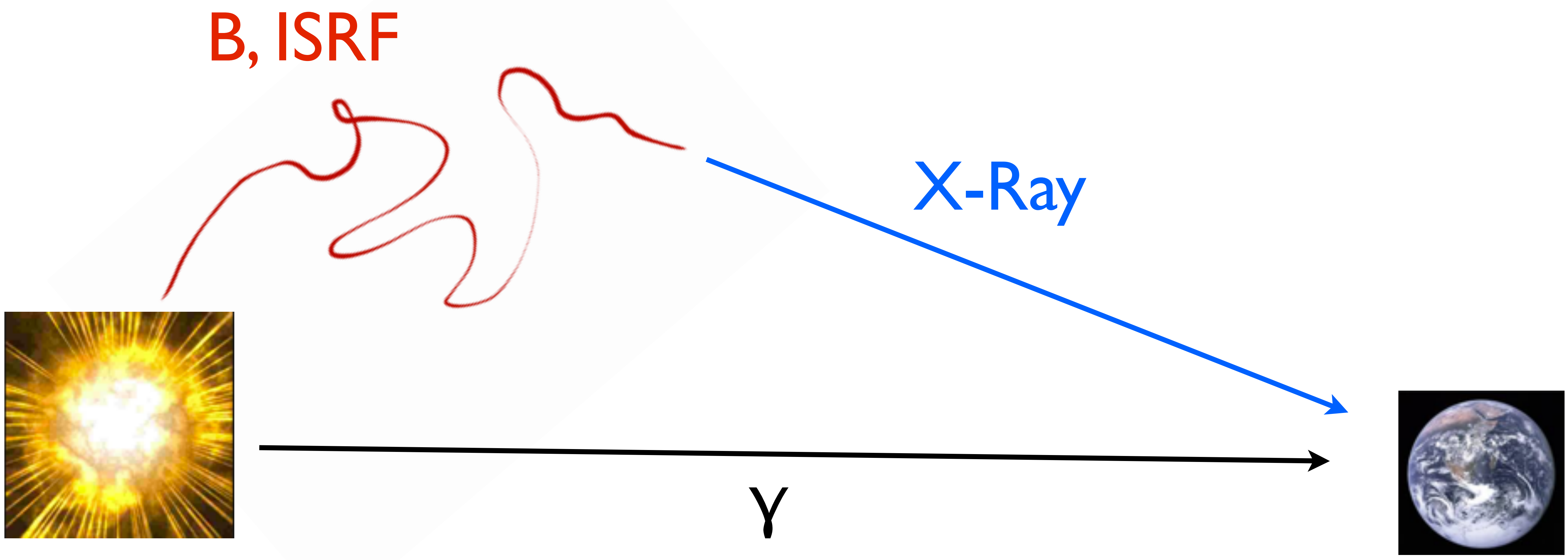
Gamma-Ray Flux Follows the Density Profile

Diemand, Kuhlen & Madau (2011)



- The primary gamma-ray signal from dark matter annihilations is produced promptly - so the gamma-ray flux is calculable if we know the dark matter density

Low Energy Processes and Diffusion



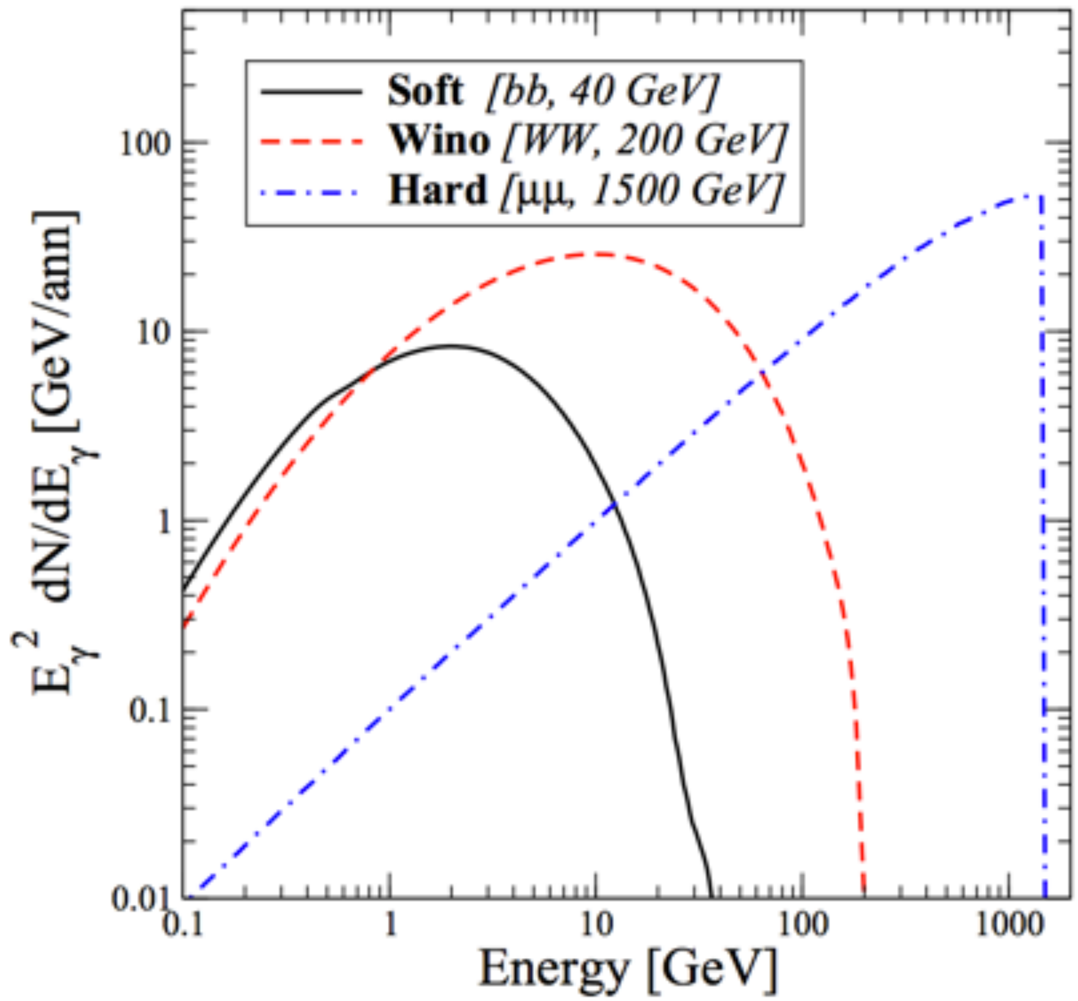
- At low energy, propagation can carry the particles which create the observed signal far from the annihilation event, before they produce anything that is seen at the Earth

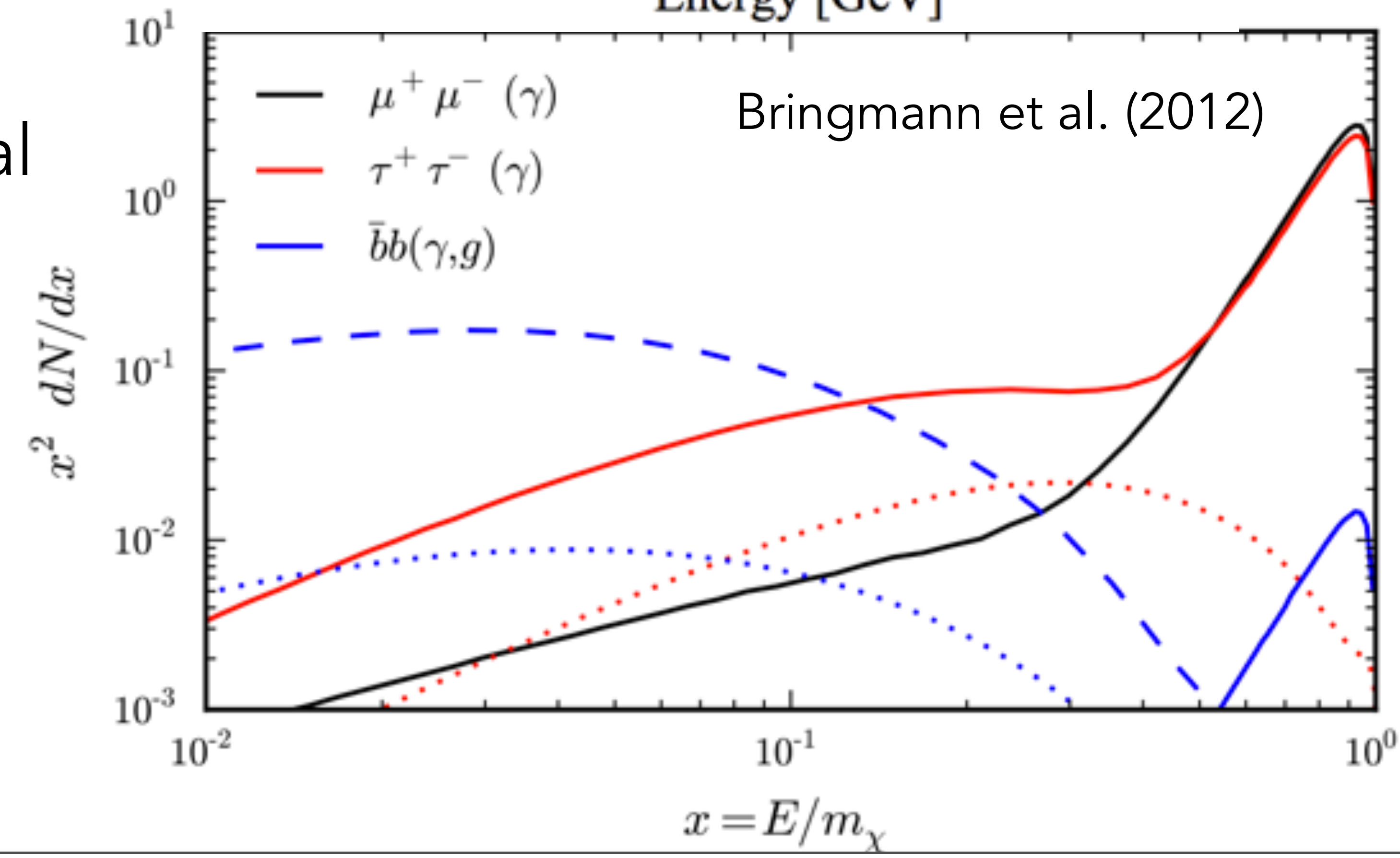
Gamma-Ray Spectrum May Have Known Features

- Once a dark matter annihilation proceeds to standard model particles, it's spectrum is calculable

- The observed spectrum tells us something about the dark matter mass and annihilation products

- We may even find unique special features -- like bumps and lines!





Why is the Galactic Center Interesting?

Back of the Envelope Calculation

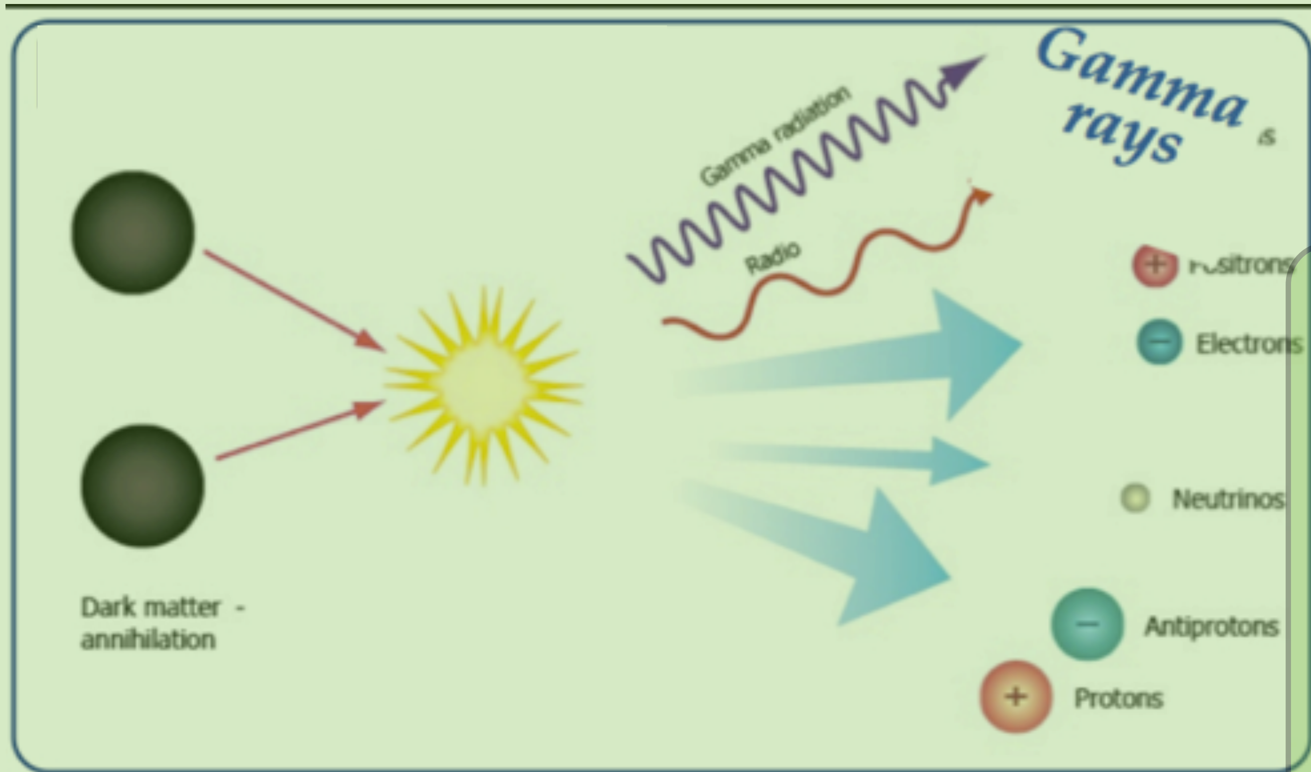
- Total Gamma-Ray Flux from 1-3 GeV within 1° of Galactic Center is

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

- 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

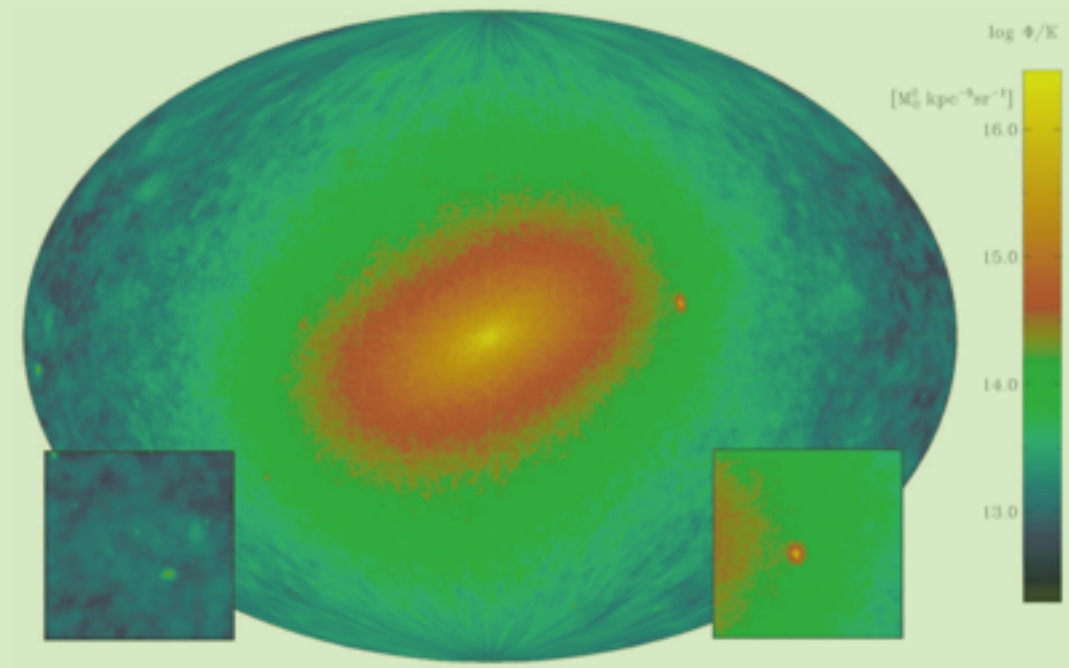
Dark Matter Indirect Detection



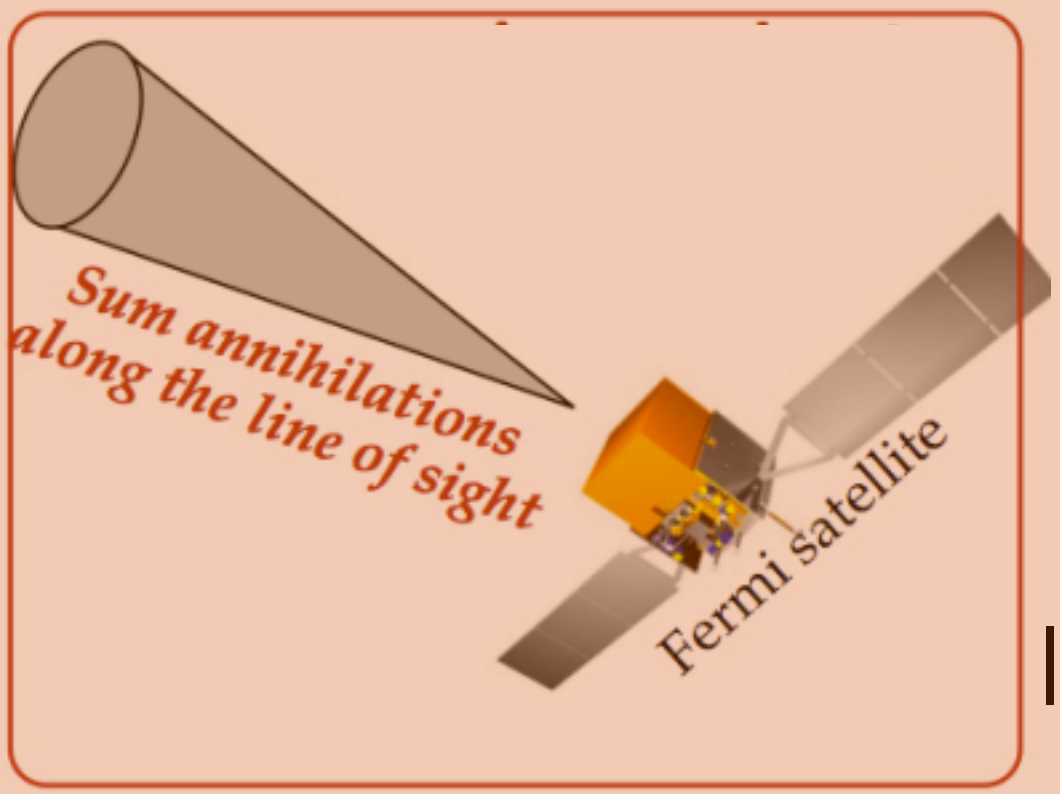
Particle Physics

Slides Courtesy of G. Zaharijas

Astrophysics



Diemand et al. 2008



Instrumental Response

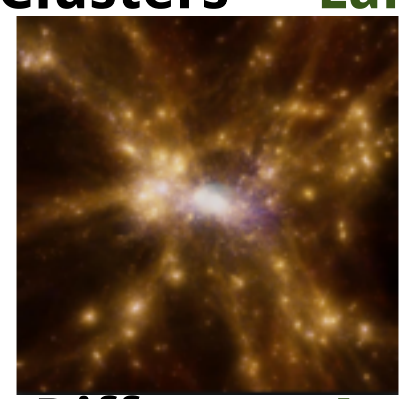
Where can we look for dark matter with gamma-ray instruments?

Flux Sensitivity

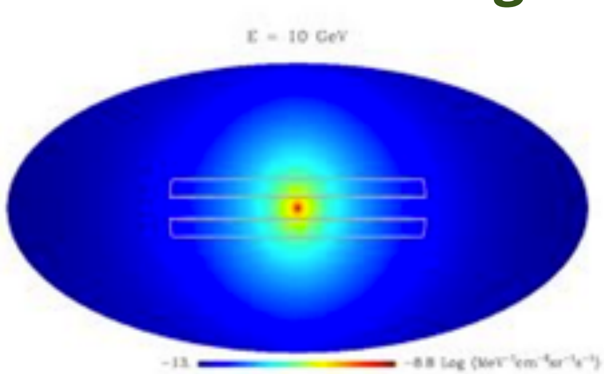
- **Galactic Center --- High Annihilation Rate --- Lots of Background, DM Profile Unmeasured**

- **Dwarf Galaxies --- Low Background, Well Measured DM Profile --- Low Annihilation Rate**

- **Galaxy Clusters --- Large Annihilation Rate --- Distant, Point Source Confusion**



- **Galactic Diffuse --- Angular Resolution Unimportant --- Diffusion, Backgrounds Important**



- **Extragalactic Diffuse --- Angular Resolution Unimportant --- Astrophysical Subtraction?**

The Astrophysical J-Factor

Ackermann et al. 2012

Dwarfs

Name	l	b	d	$\log_{10}(J)$	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

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

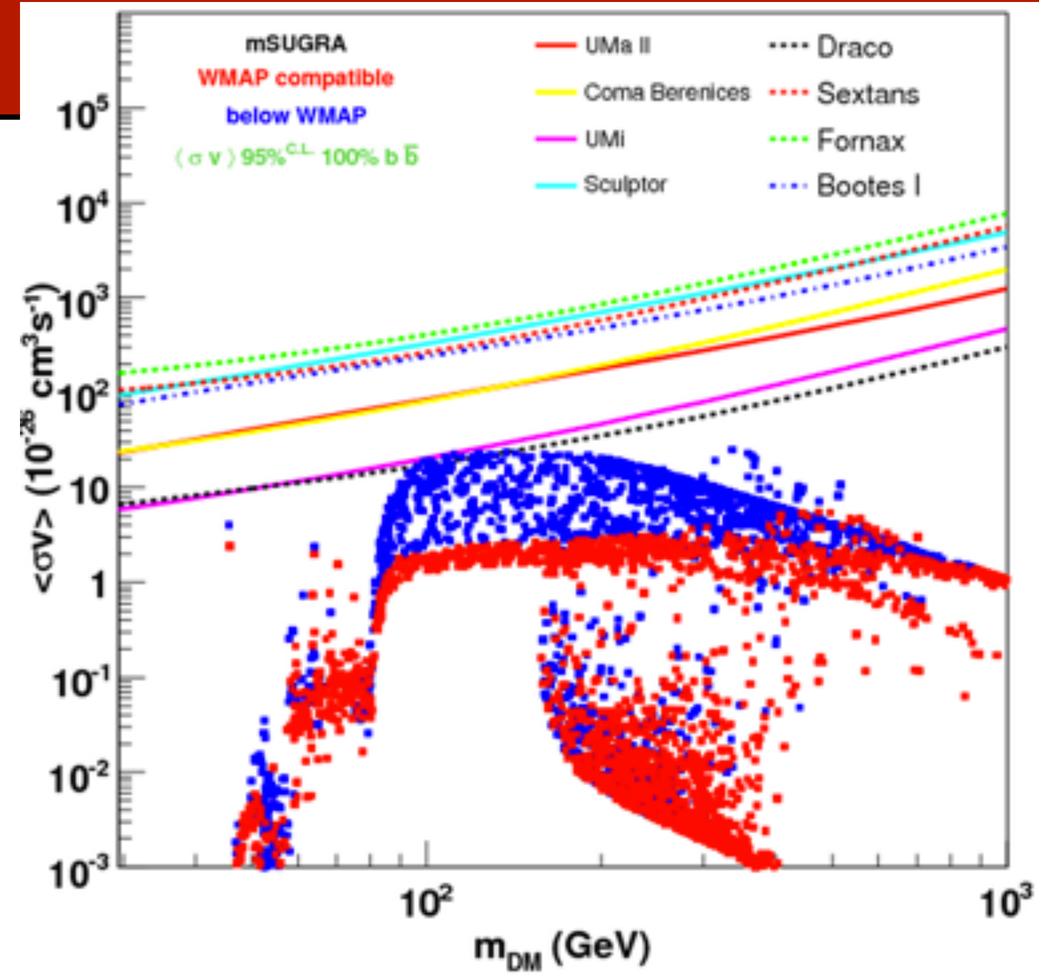
- The J-factor of the galactic center is approximately:

$\log_{10}(J) = 21.0$

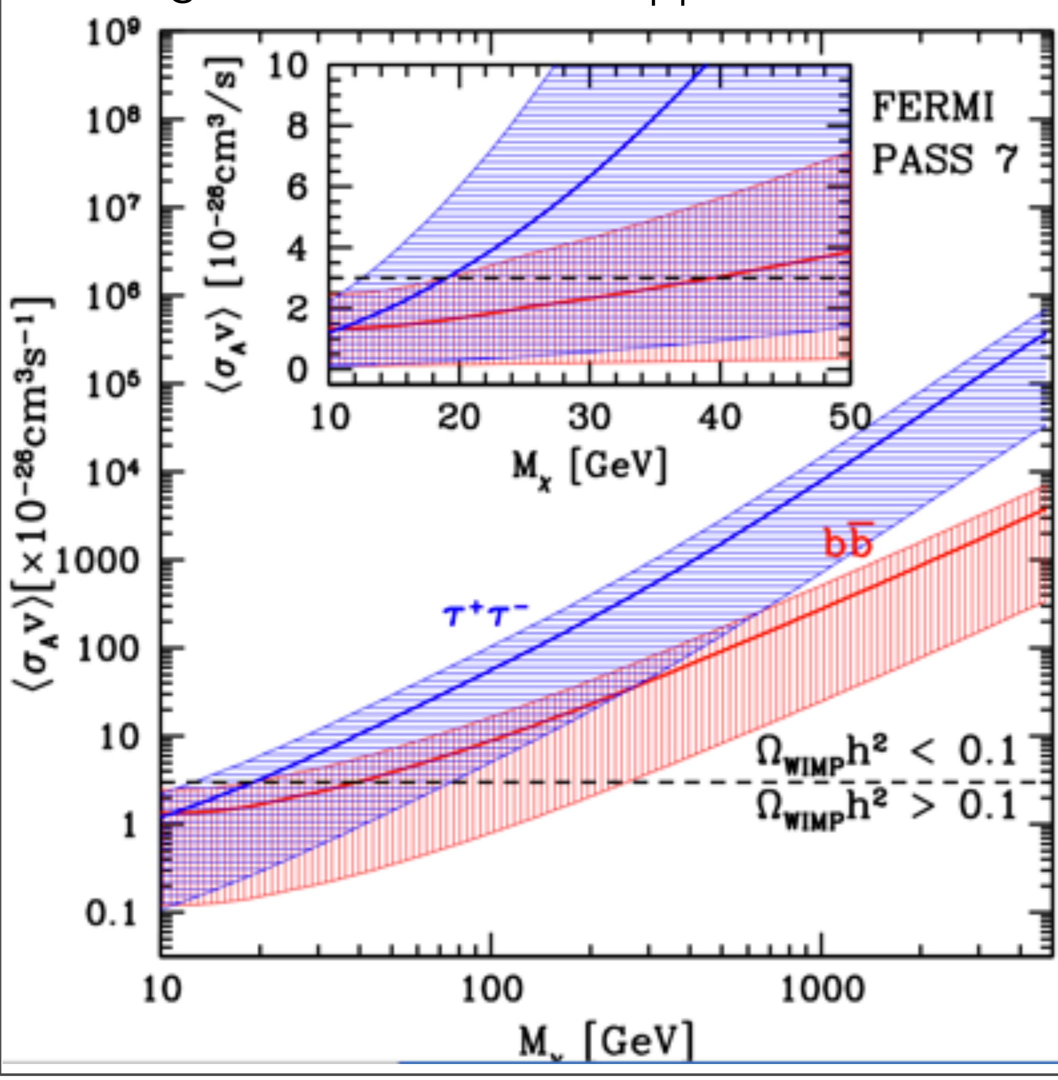
for a region within 1° of the Galactic center and an NFW profile

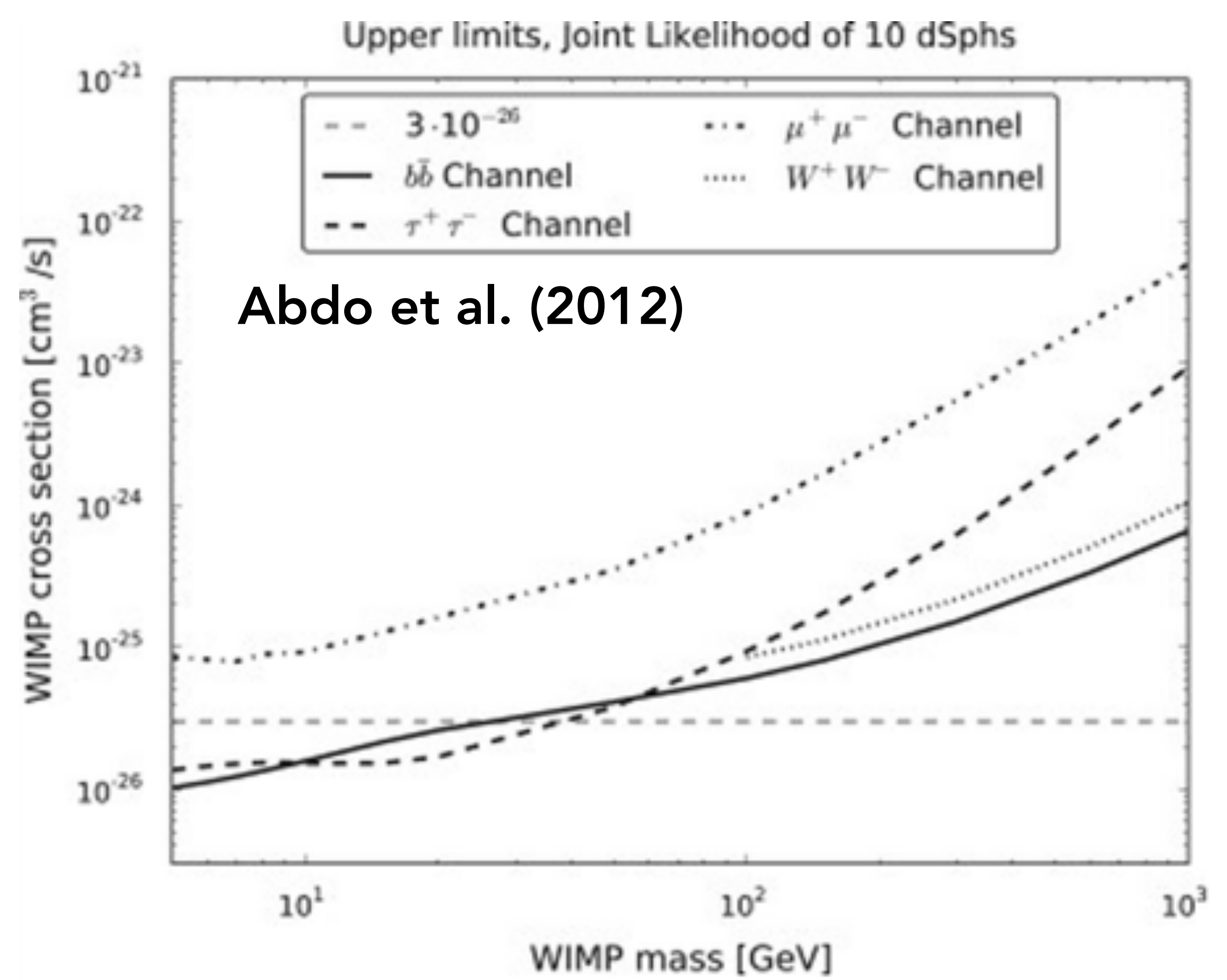
Dwarf Galaxies

- Dwarf Galaxies are highly DM dominated (if you have a signal, good chance its DM)
- Low ISRF, small magnetic fields -> Prompt Gamma-Rays only way to detect signal



Geringer-Sameth & Koushiappas (2012)



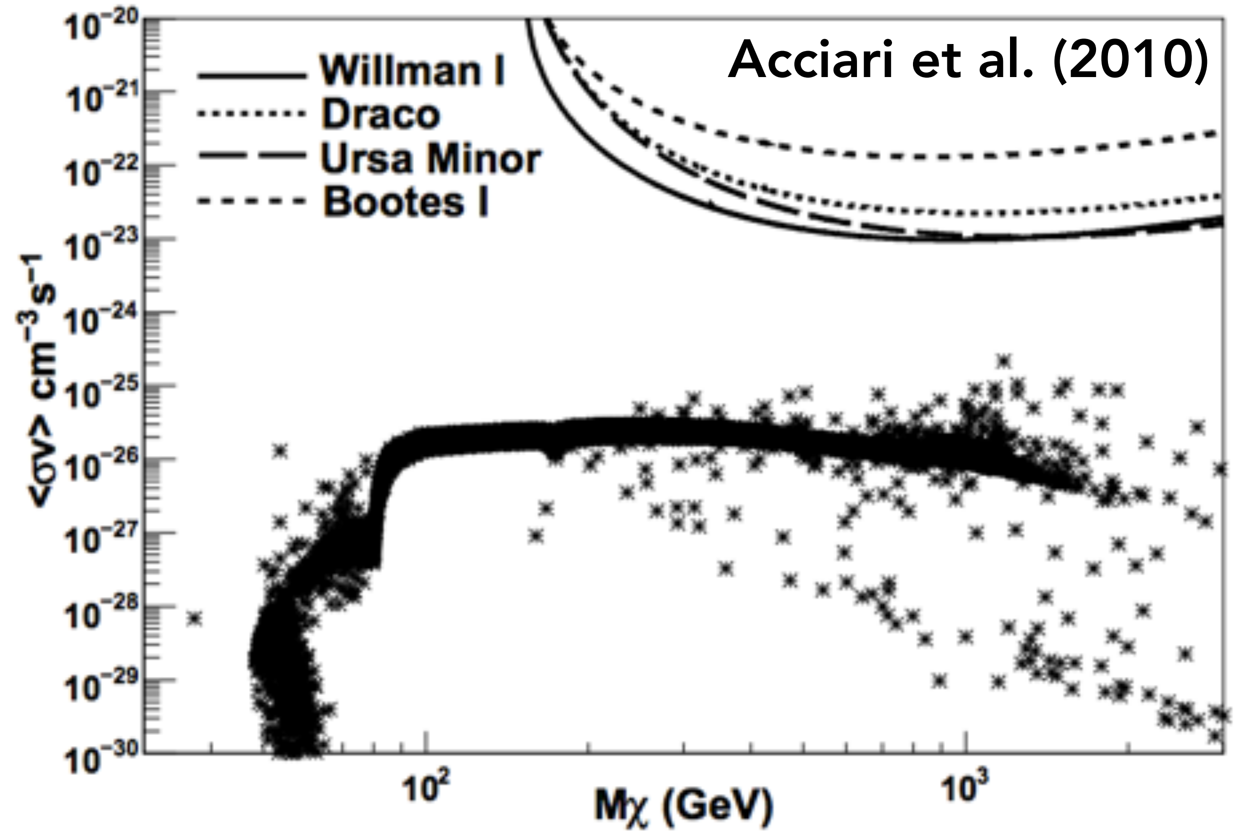


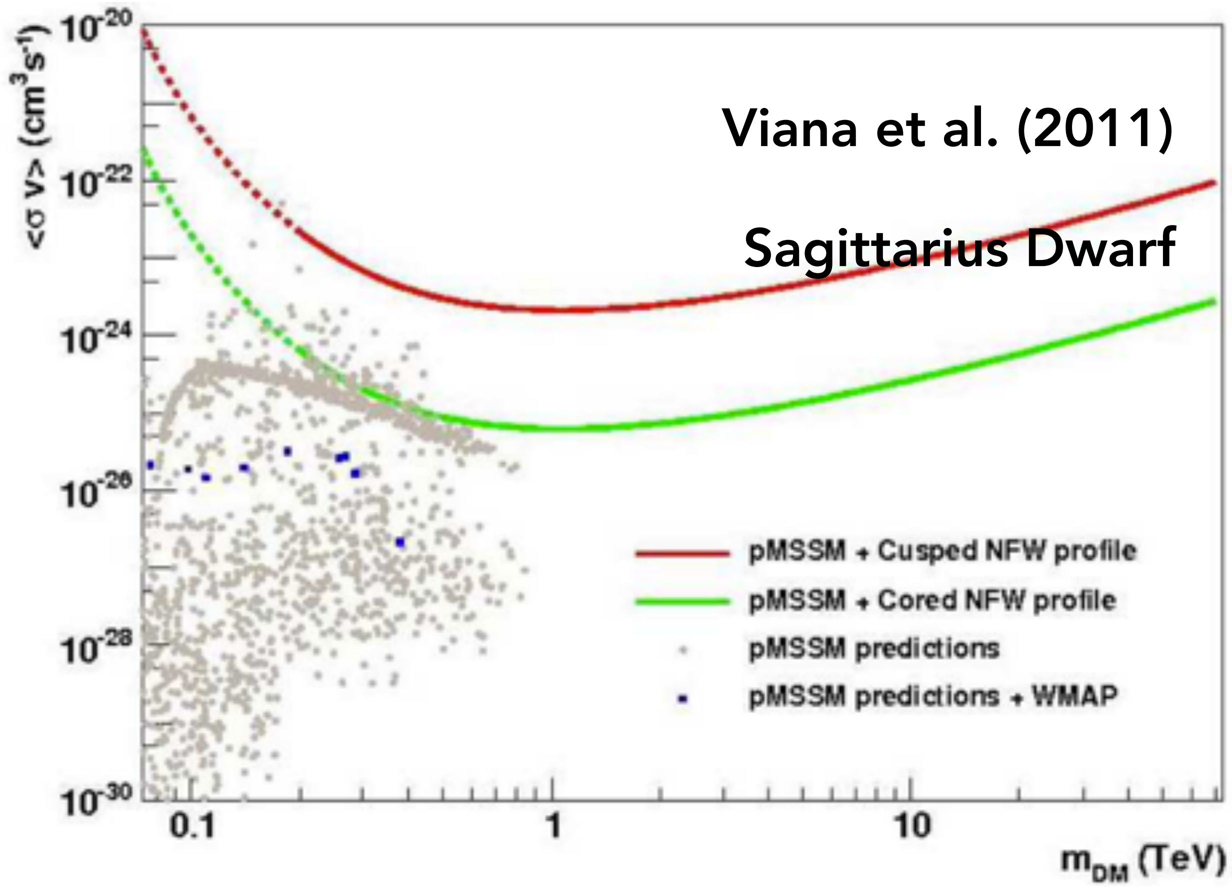
Dwarf Galaxies

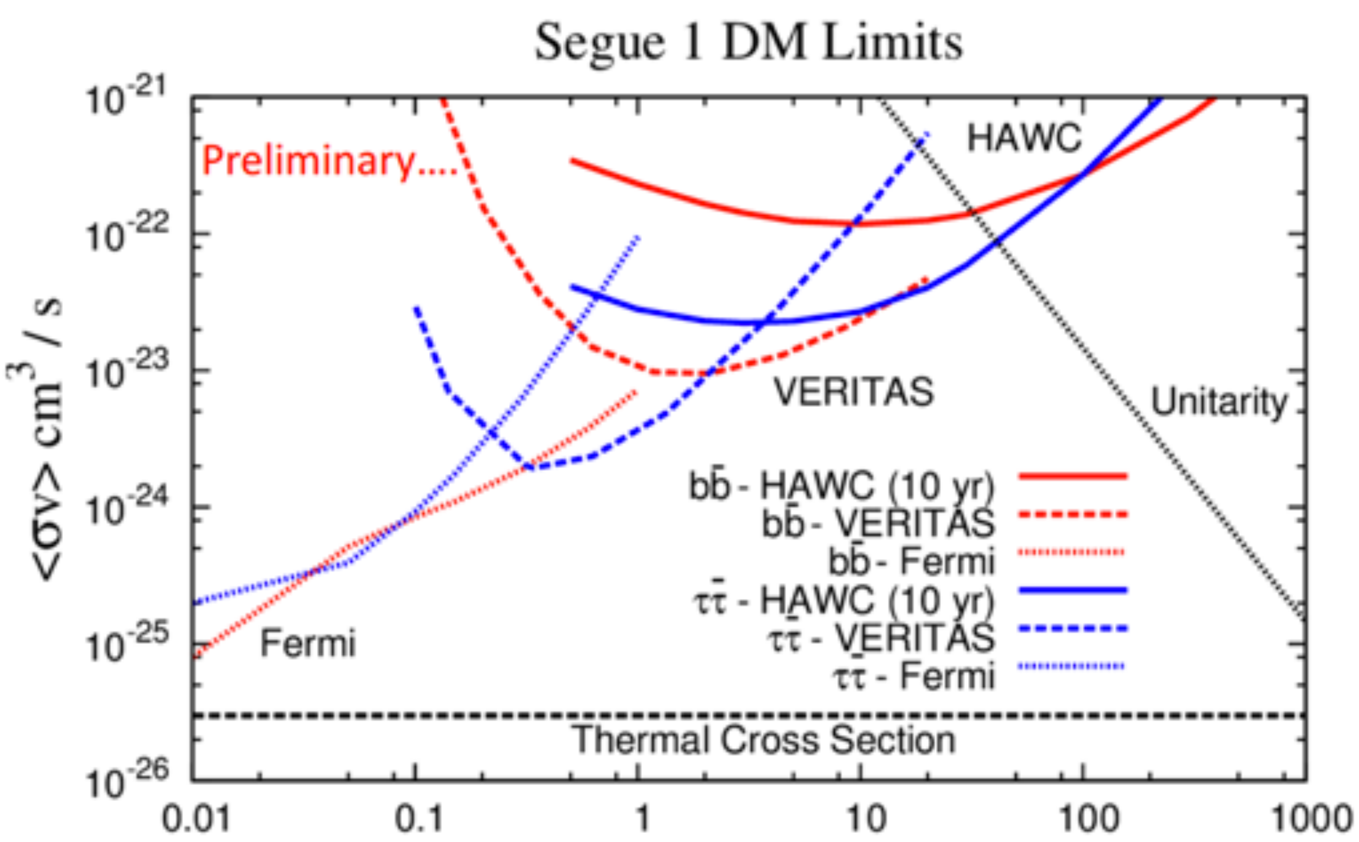
- High Energy Observations beginning to probe interesting parameter space

- Still very difficult to put limits on high mass dark matter particles

- Best place for a **convincing detection** of dark matter





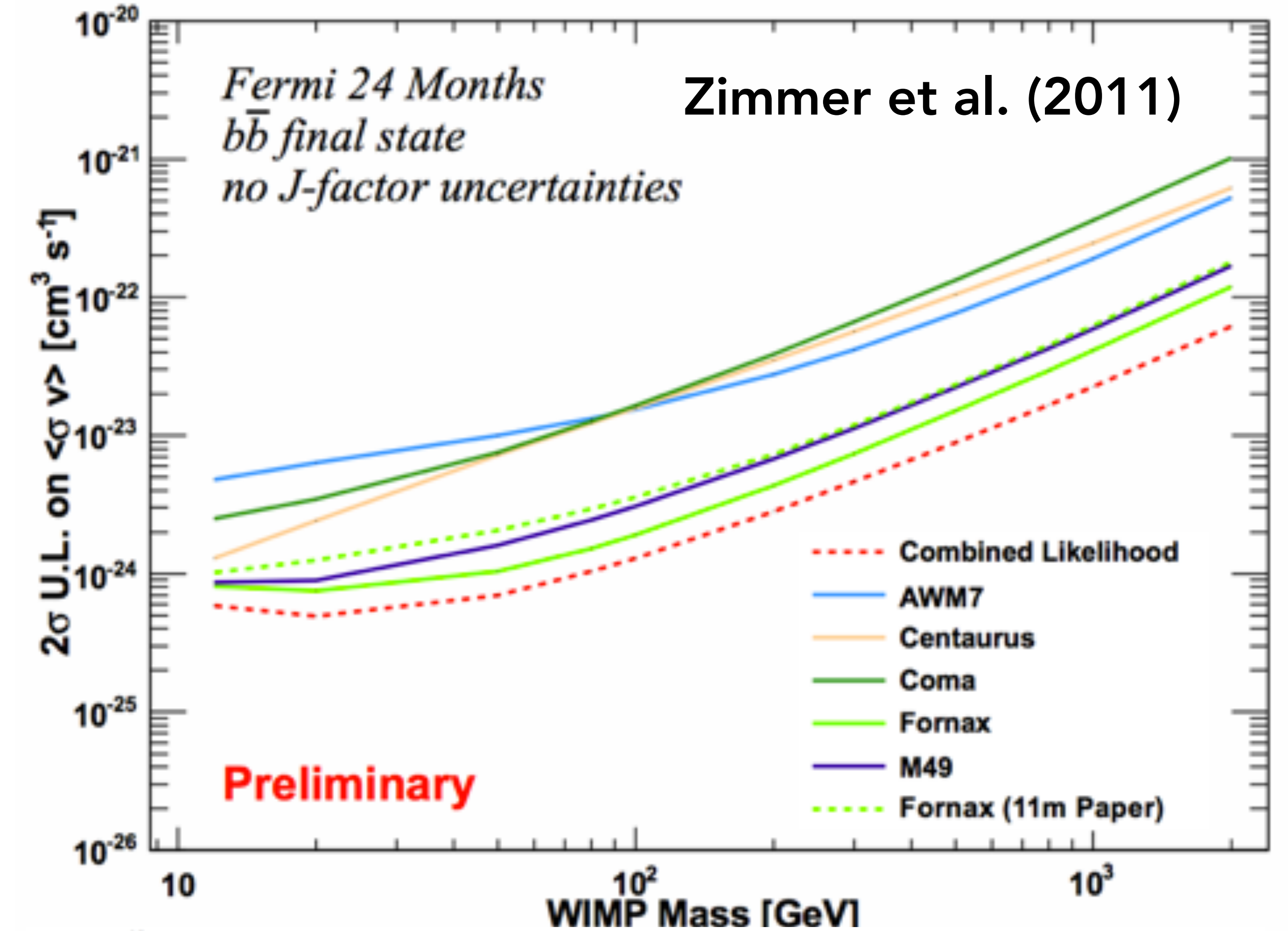


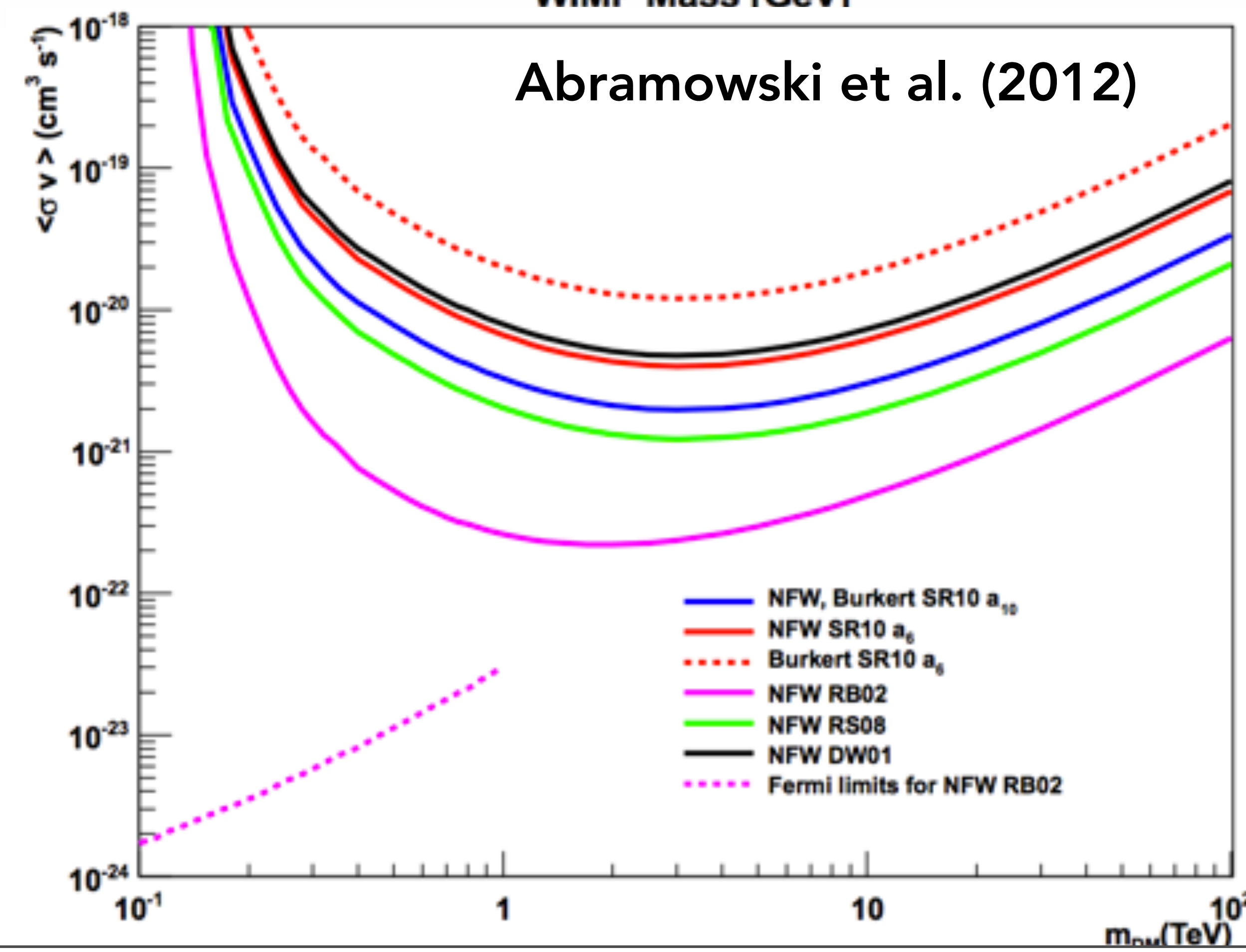
Limits on Dark Matter Annihilation from Clusters

- Can also look at Galaxy Clusters

- While the J-factor shown above are small, uncertainties due to substructure can be large

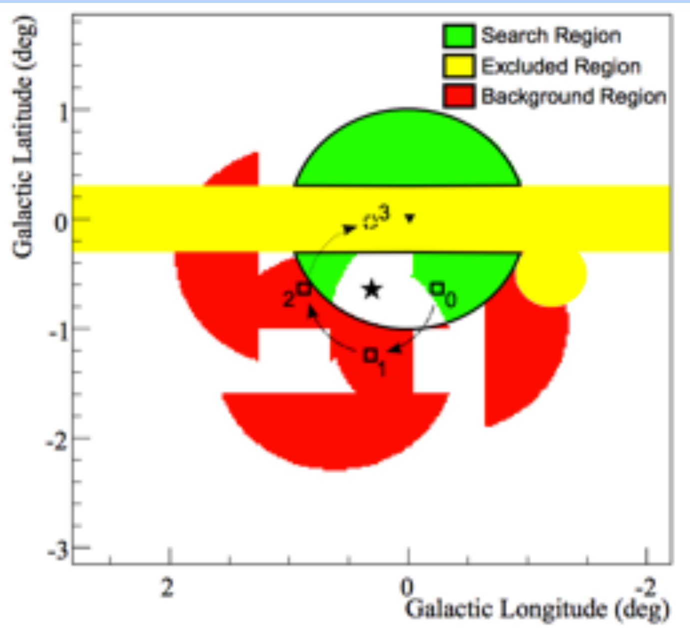
- Probably a better way to detect dark matter, than to put limits on it

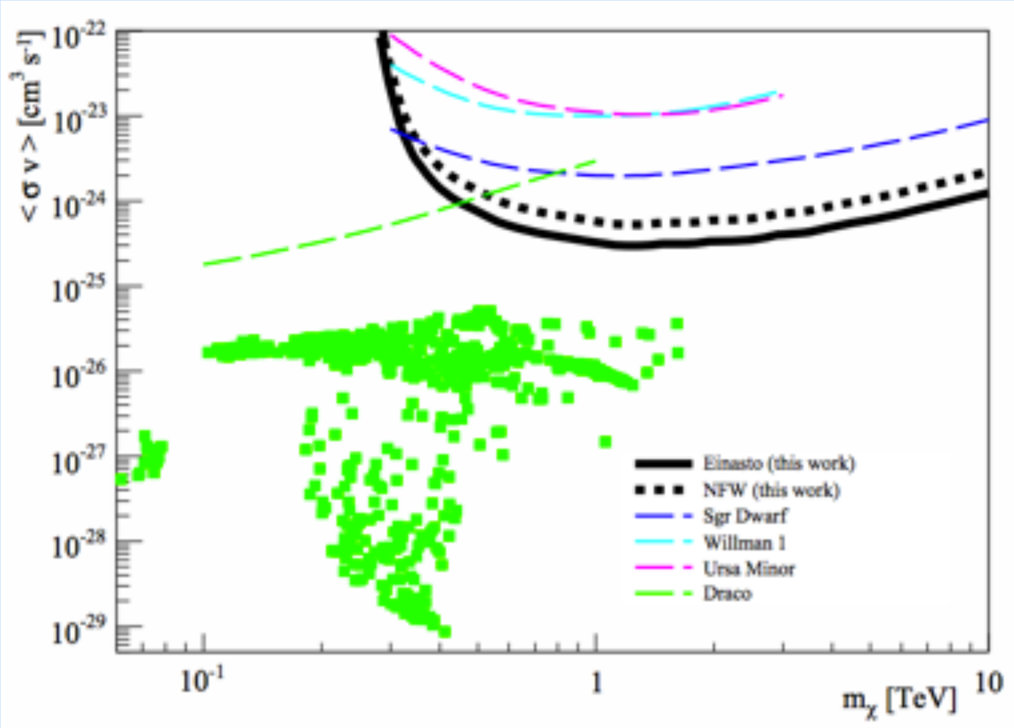




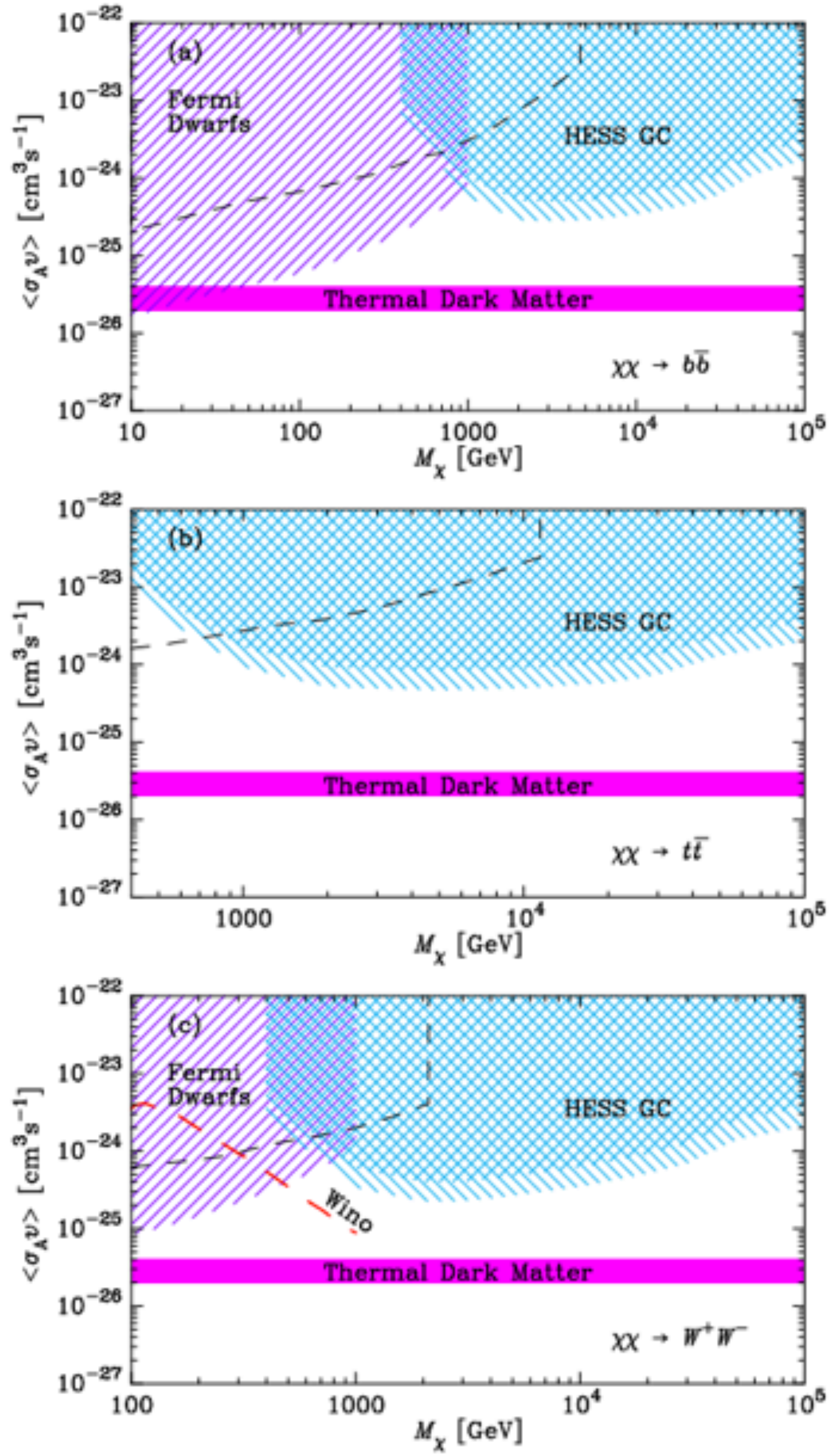
Limits on Dark Matter from the Galactic Center

- 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



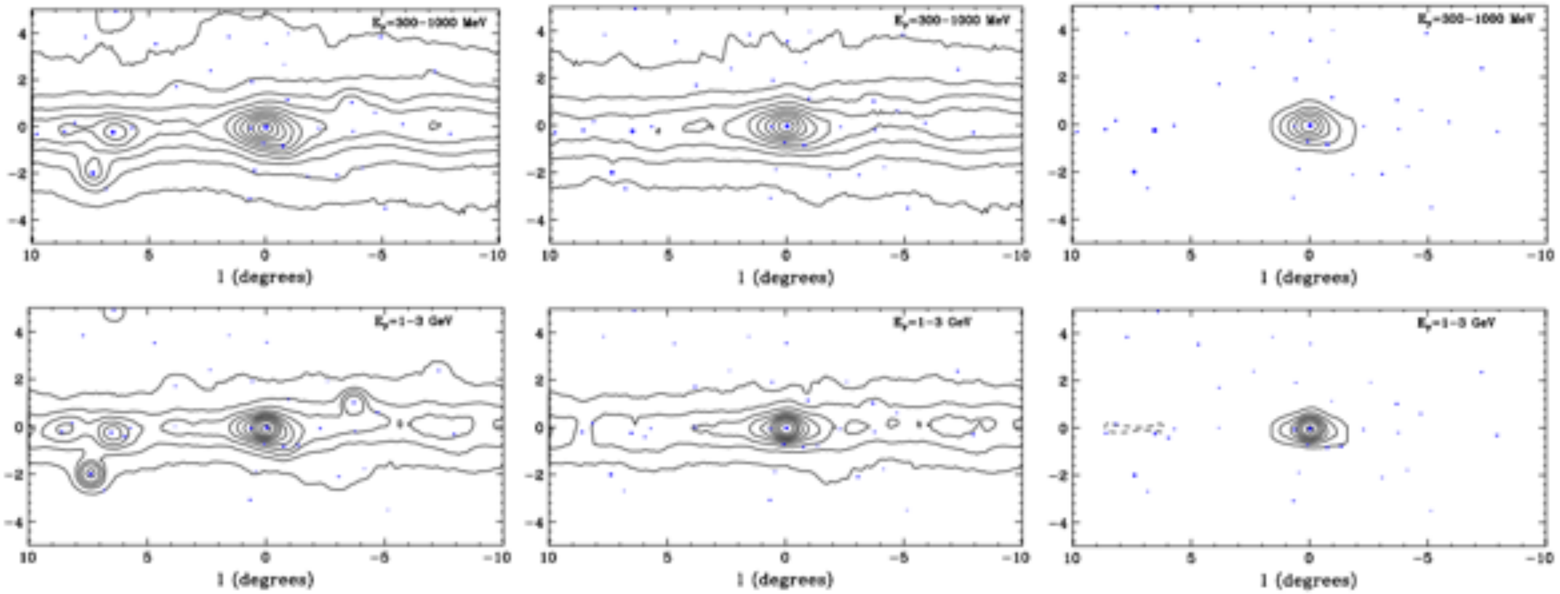


Abramowski et al. (2011)



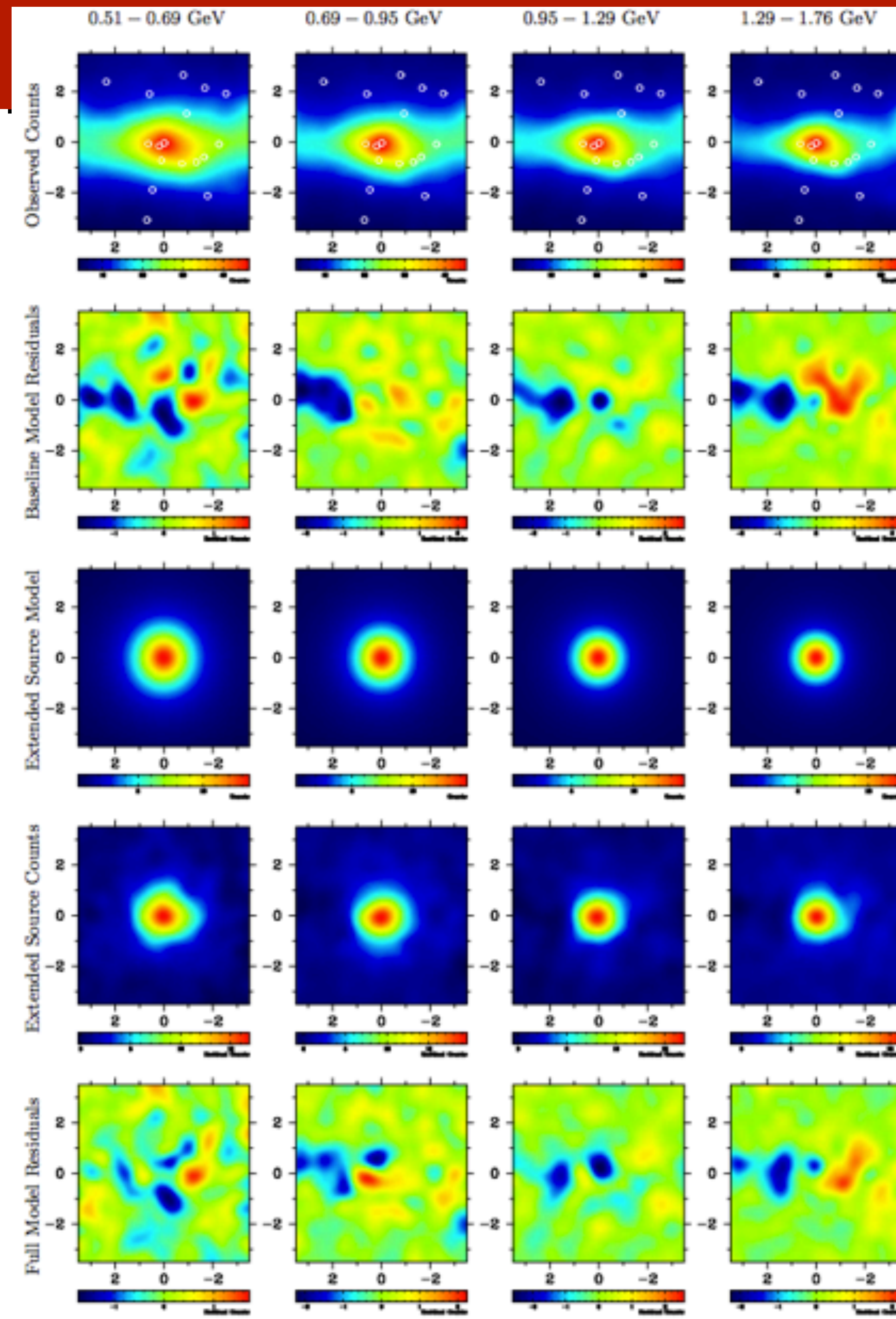
Abazajian & Harding (2011)

A Signal in the GC?



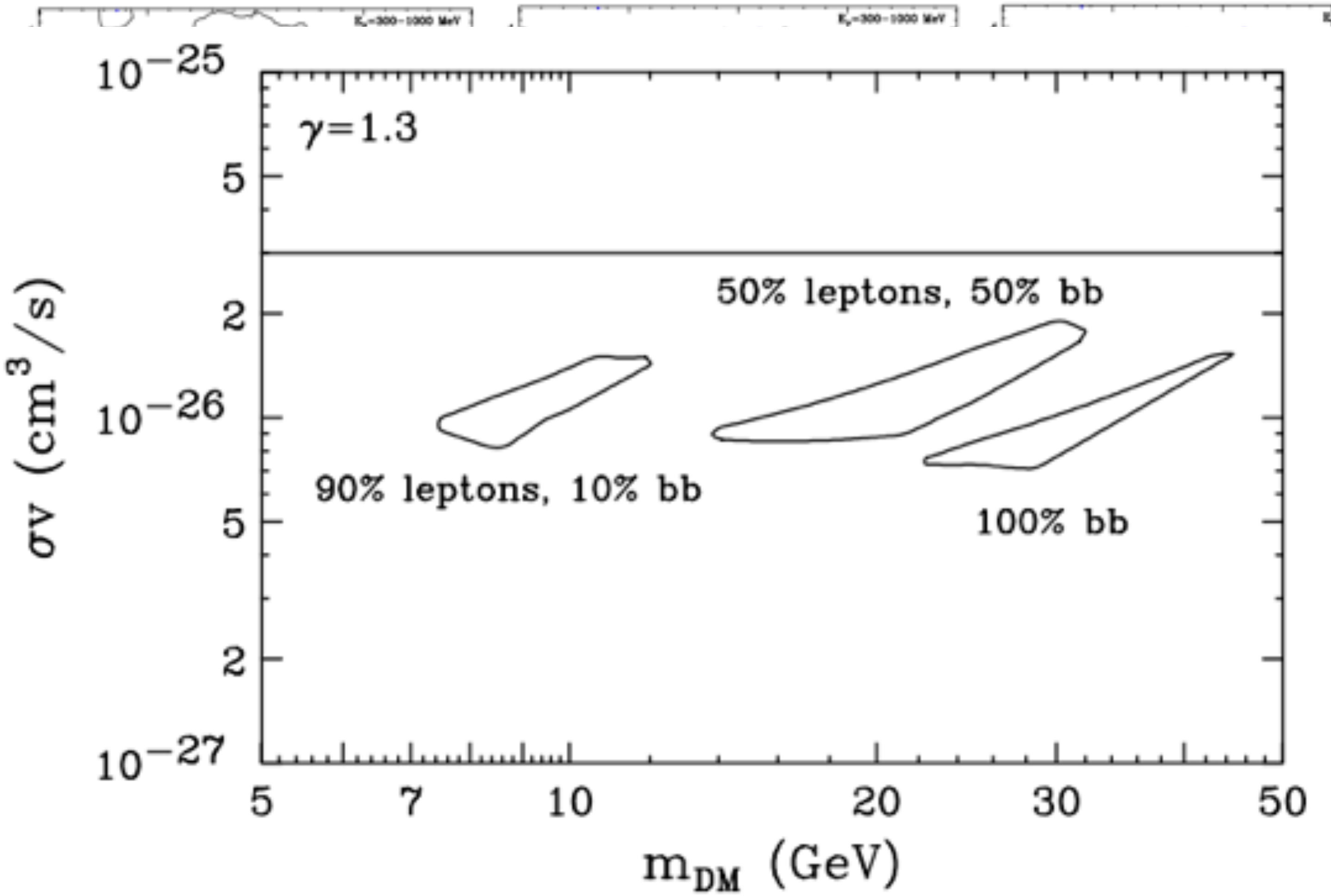
Hooper & Linden (2011)

- Two different models yield strong statistical preferences for a spherically symmetric, extended source at the Galactic center



Abazajian & Kaplinghat (2012)

A Signal in the GC?



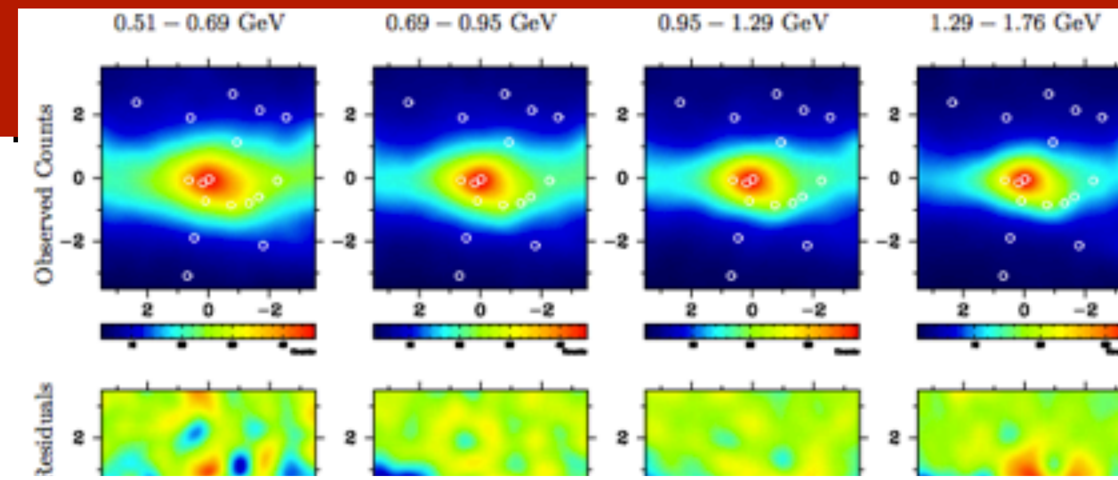
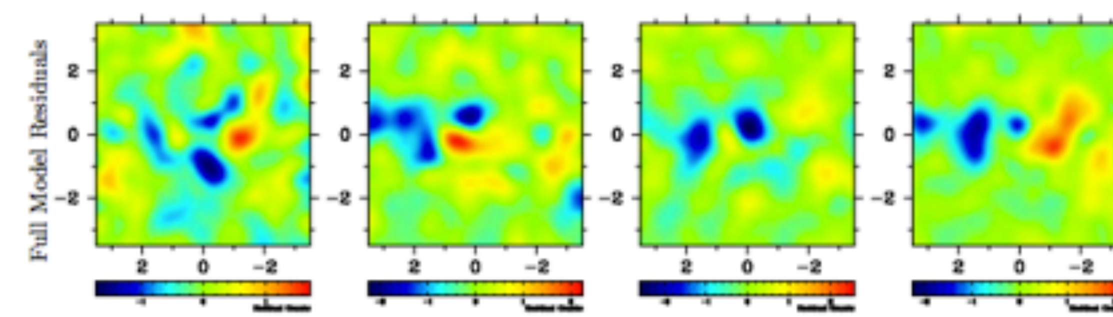


TABLE II. The best-fit TS, negative log likelihoods, and $\Delta\mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

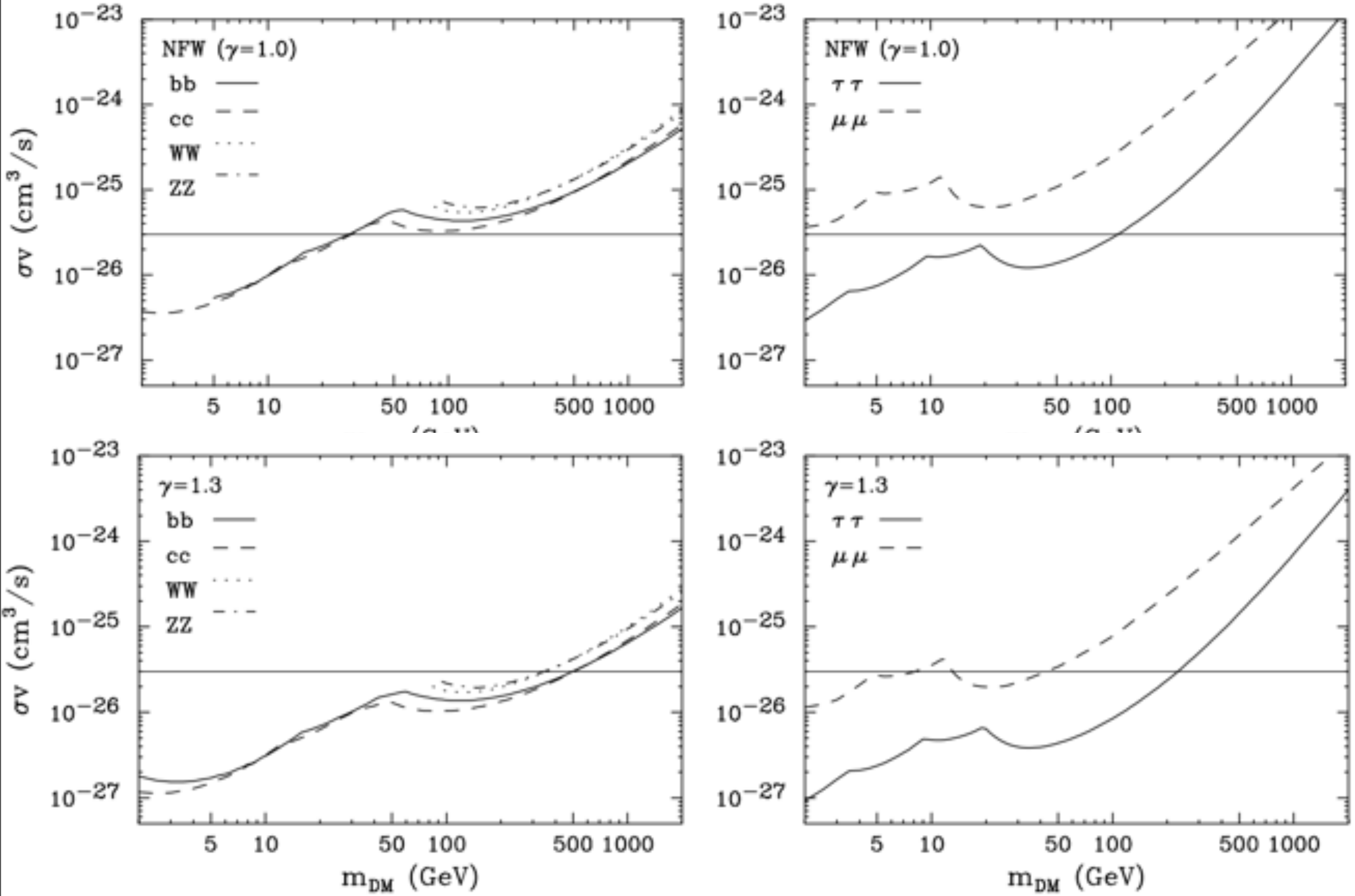
channel, m_χ	TS	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 10 GeV	2385.7	139913.6	156.5
$b\bar{b}$, 30 GeV	3460.3	139658.3	411.8
$b\bar{b}$, 100 GeV	1303.1	139881.1	189.0
$b\bar{b}$, 300 GeV	229.4	140056.6	13.5
$b\bar{b}$, 1 TeV	25.5	140108.2	−38.0
$b\bar{b}$, 2.5 TeV	7.6	140114.2	−44.0
$\tau^+\tau^-$,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



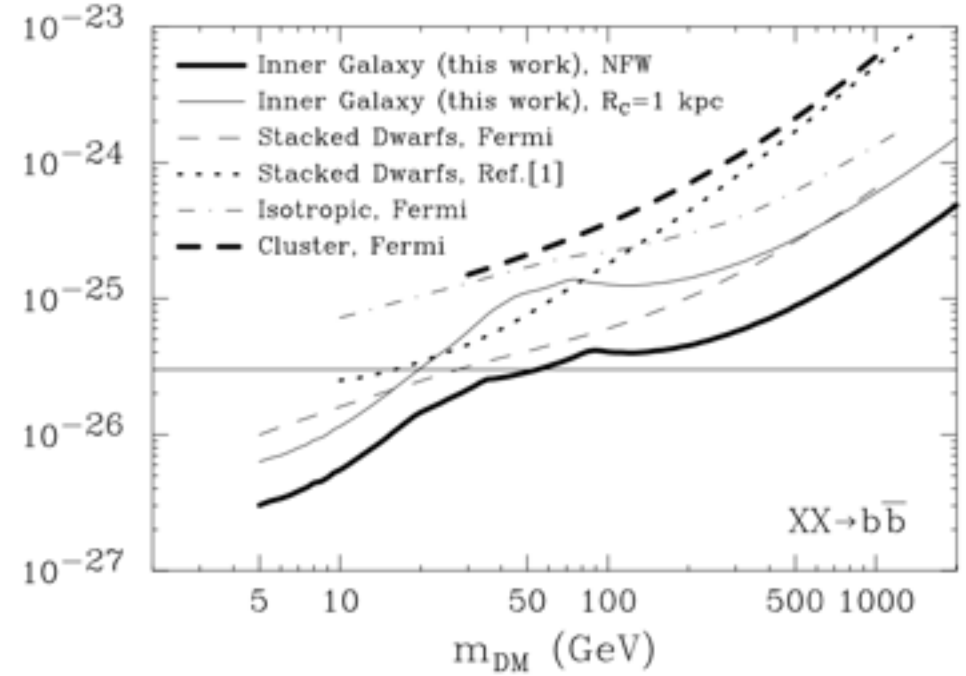
statistical preferences for a spherically symmetric, extended source at the Galactic center

Abazajian & Kaplinghat (2012)

Strong Limits from the GC



Hooper & Linden (2011)



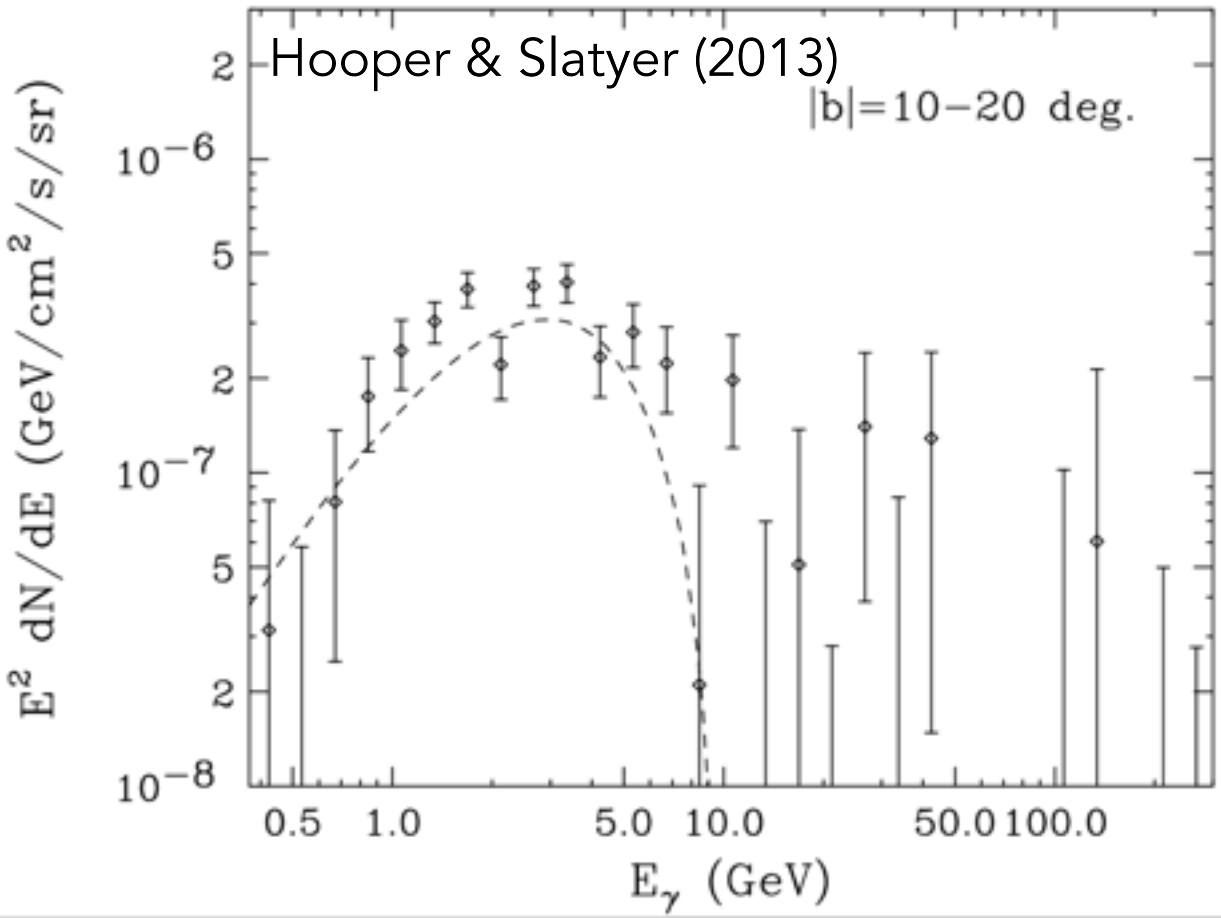
Hooper et al (2012)

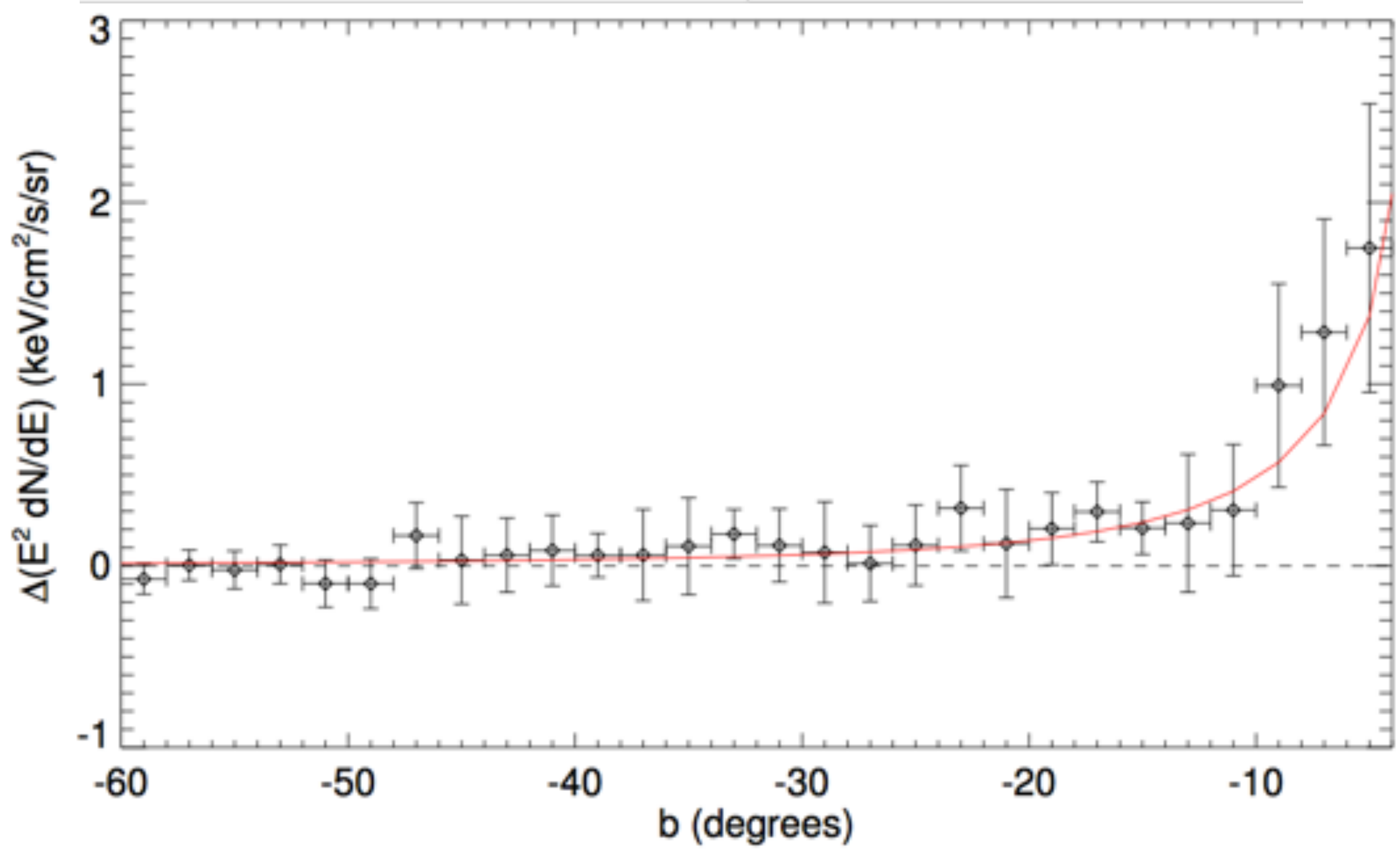
- Despite an observation of a bright signal - the galactic center can also set very strong limits

- GC is the best location in which to set limits on dark matter annihilation

Have we observed a signal?

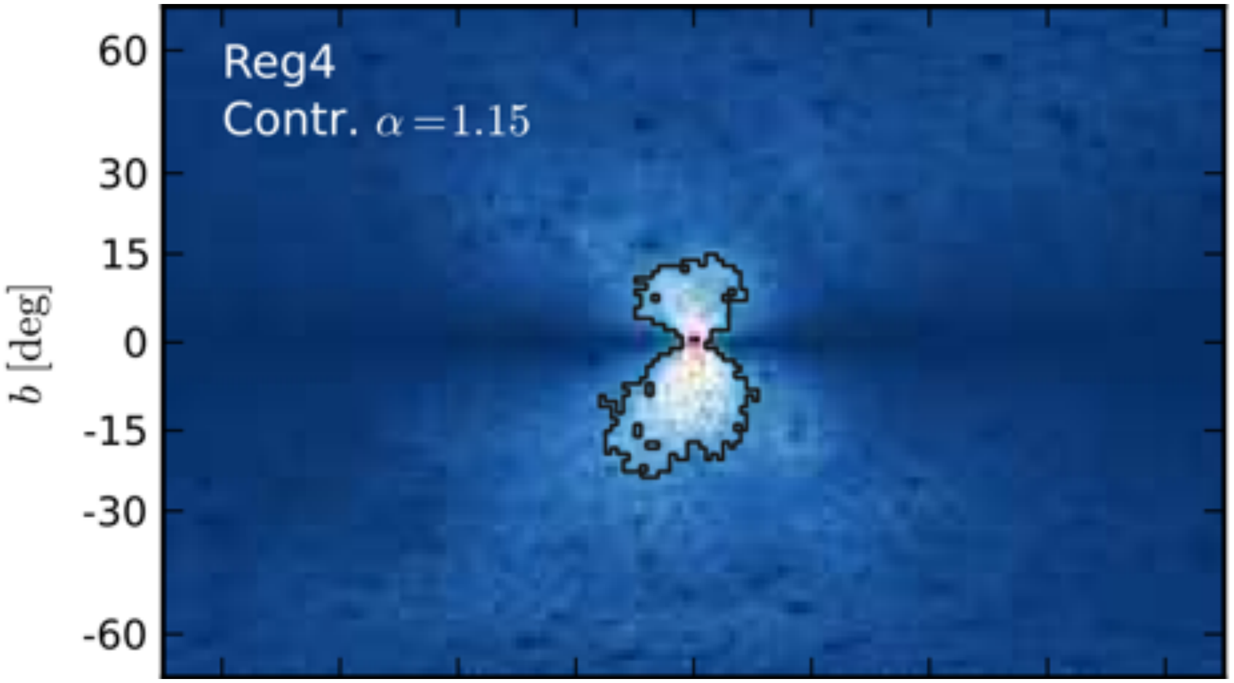
- New evidence shows this signal may extend to high latitudes
- If so, it follows a profile consistent with dark matter annihilation in the inner galaxy

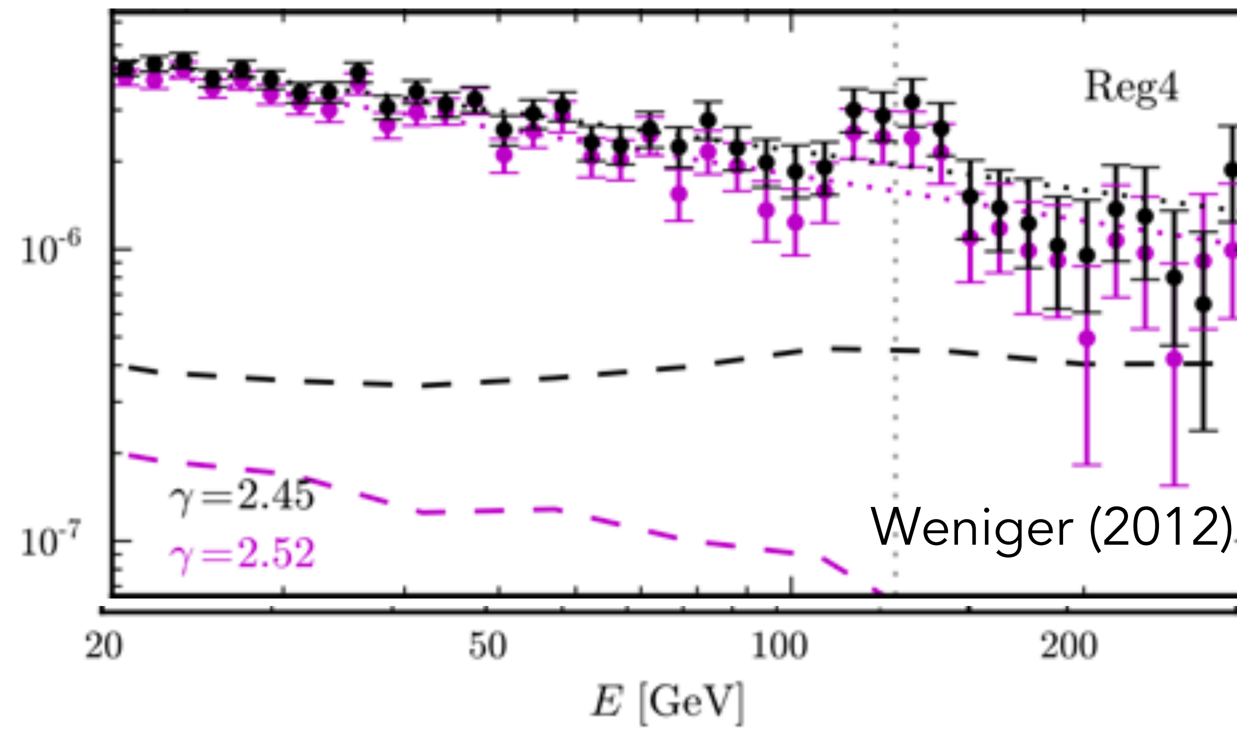




Stay Tuned!

A Gamma-Ray Line !!??

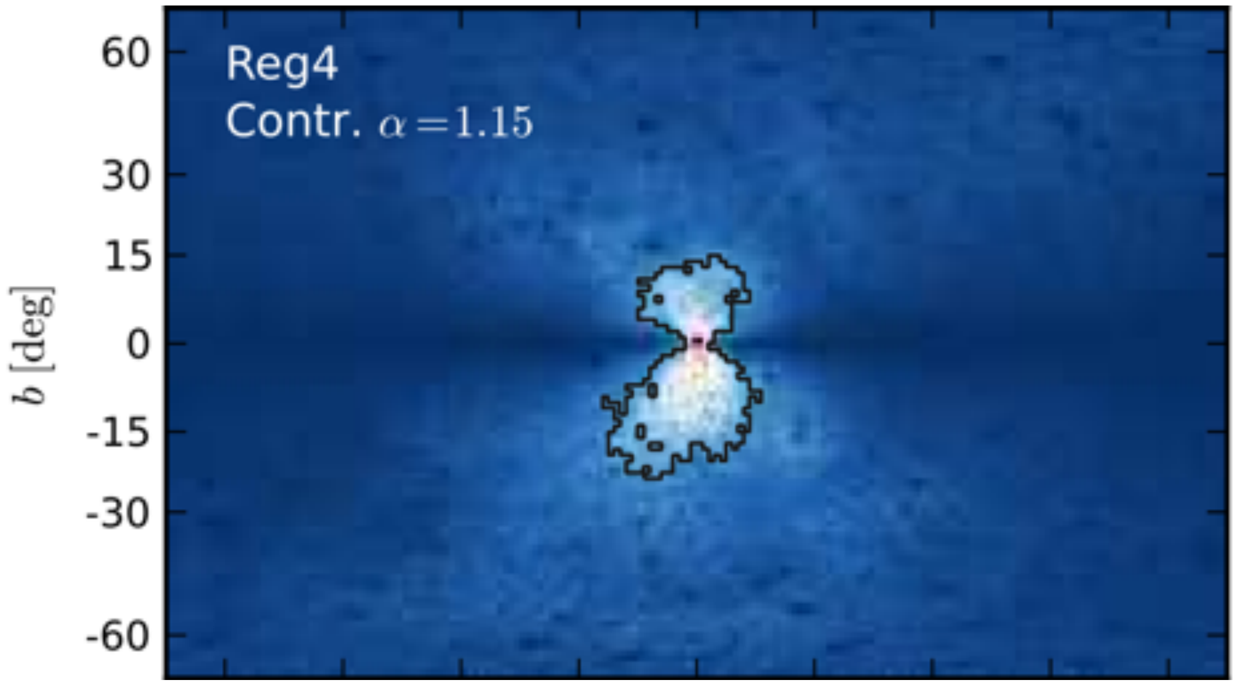


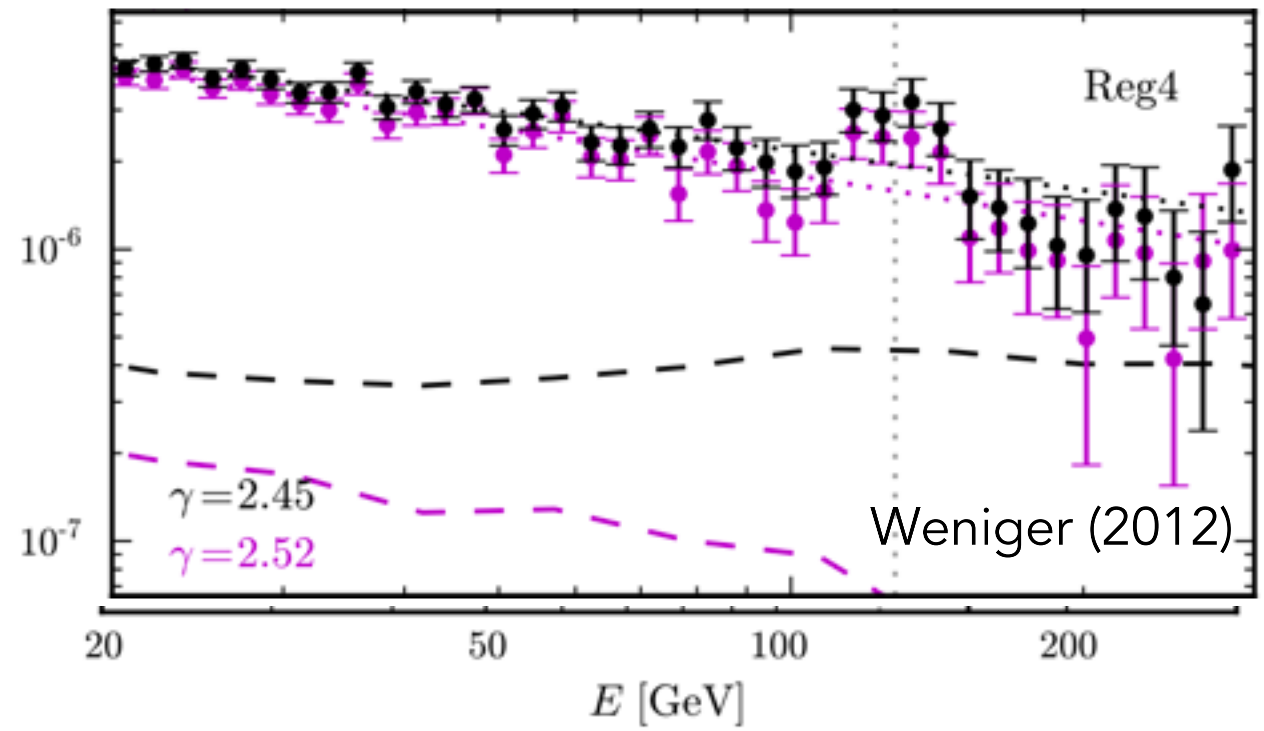


- Weniger (2012) examined the Fermi-LAT data and found evidence for a gamma-ray line at an energy of 130 GeV!

- This had a profound effect on the dark matter indirect-detection community

A Gamma-Ray Line !!??





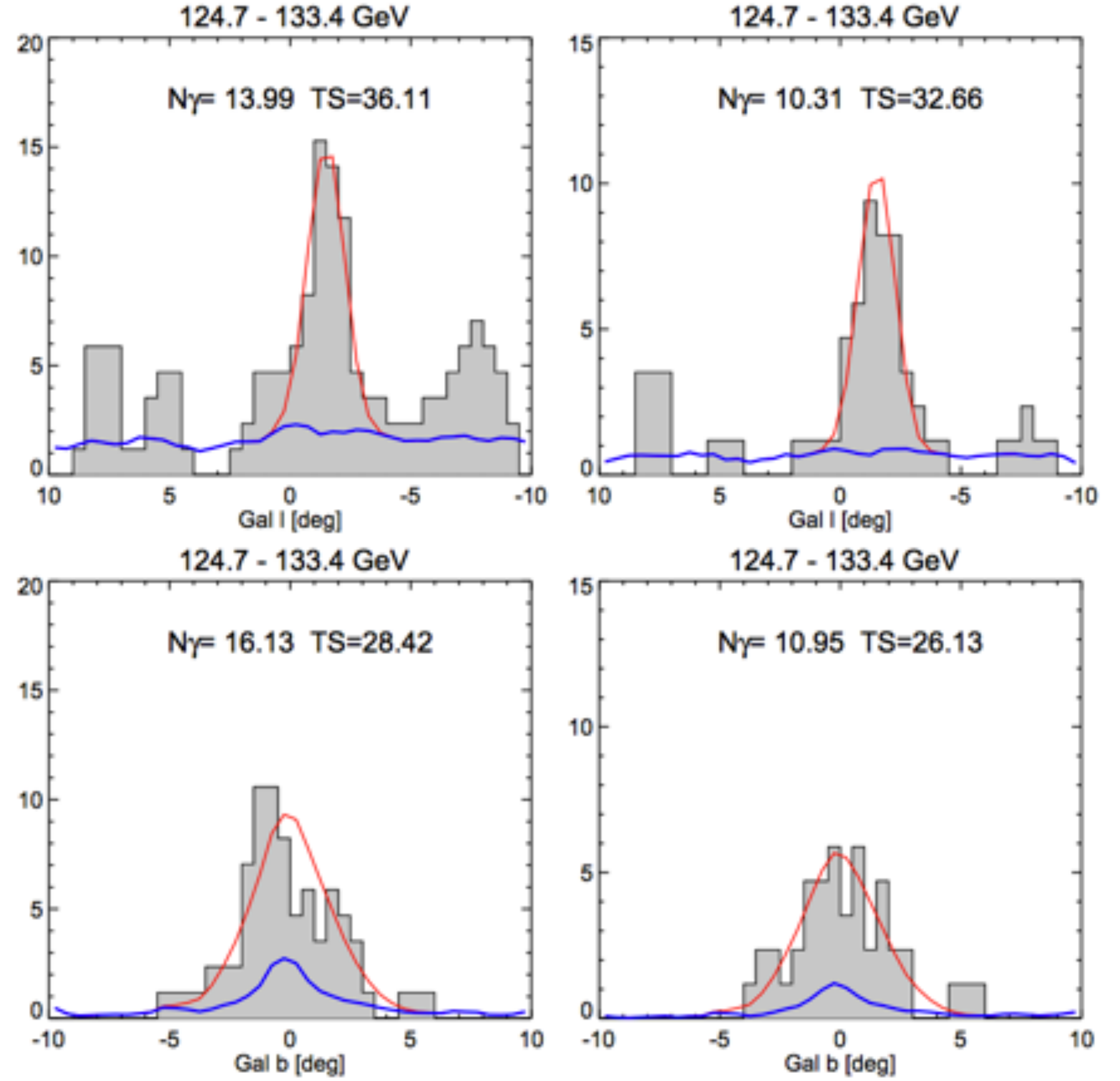
- Weniger (2012) examined the Fermi-LAT data and found evidence for a gamma-ray line at an energy of 130 GeV!

- **Unofficial Poll of Experts:**
  - **CCAPP Symposium (2011) - 100% believed this was a smoking-gun for dark matter**
  - **SLAC (October 2012) - 5% believed this was a smoking gun for dark matter**

A Gamma-Ray Line !!??

- Follow up analysis (Su & Finkbeiner) finds evidence for two lines

- Finds an extremely high significance (as high as 5σ) after a trials factor is applied



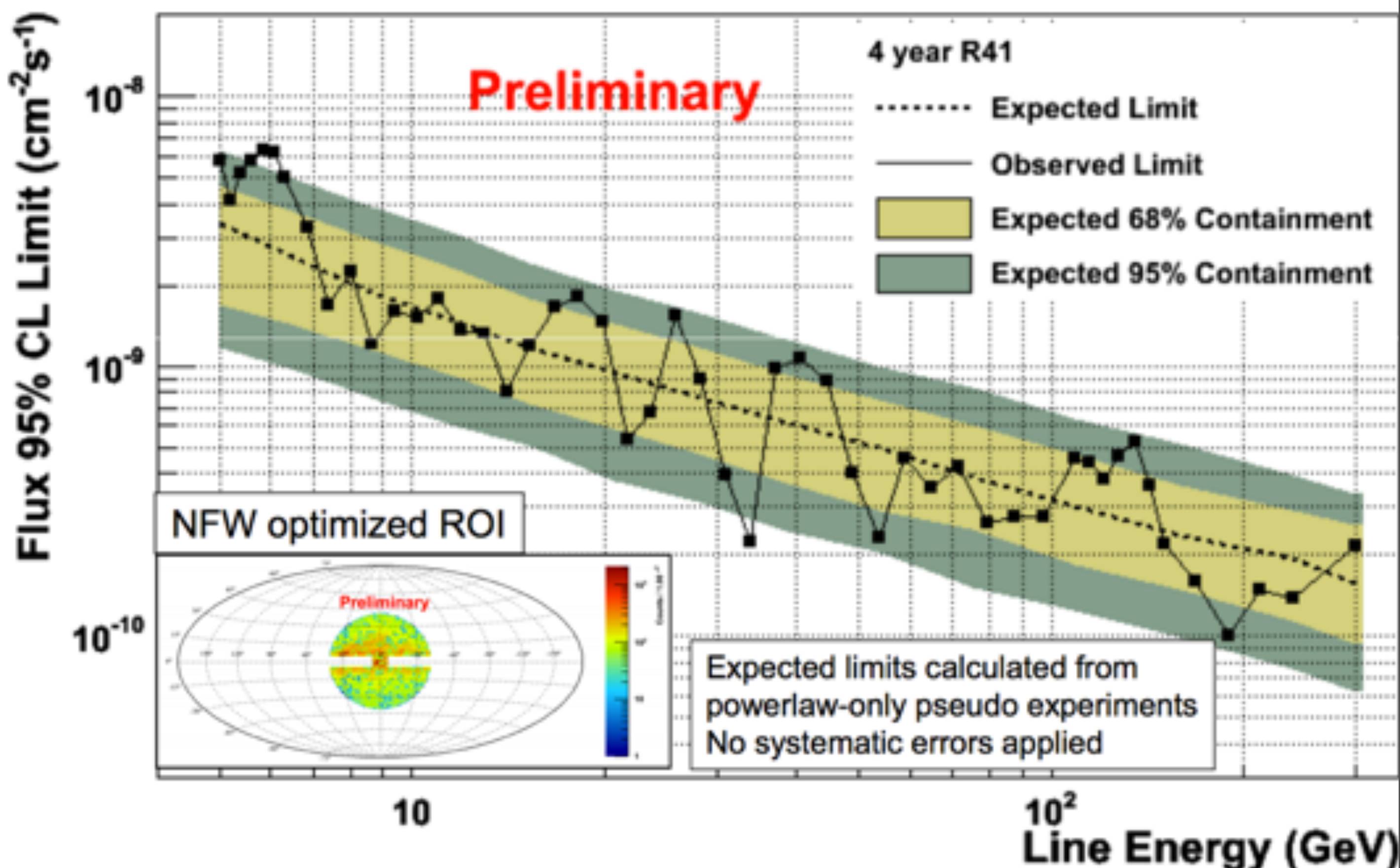
Models	Before trials	After trials (one line)	Trials factor (one line)
Gaussian (centered)	5.0σ	3.7σ	300
Gaussian (off center, $\theta > 40°$)	5.5σ	3.7σ	6000
unbinned ℓ	5.2σ	3.2σ	6000
unbinned ℓ ($\theta > 40°$)	4.9σ	2.8σ	6000
unbinned b	4.8σ	3.5σ	300
unbinned b ($\theta > 40°$)	4.6σ	3.2σ	300
NFW $\alpha = 1.0$ (off center)	6.1σ	4.5σ	6000
NFW $\alpha = 1.2$ (off center)	6.5σ	5.0σ	6000
NFW $\alpha = 1.3$ (off center)	6.0σ	4.4σ	6000
NFW $\alpha = 1.4$ (off center)	5.6σ	3.8σ	6000
NFW $\alpha = 1.5$ (off center)	5.2σ	3.2σ	6000
Einasto (off center)	**6.6σ**	**5.1σ**	**6000**

Su & Finkbeiner (2012)

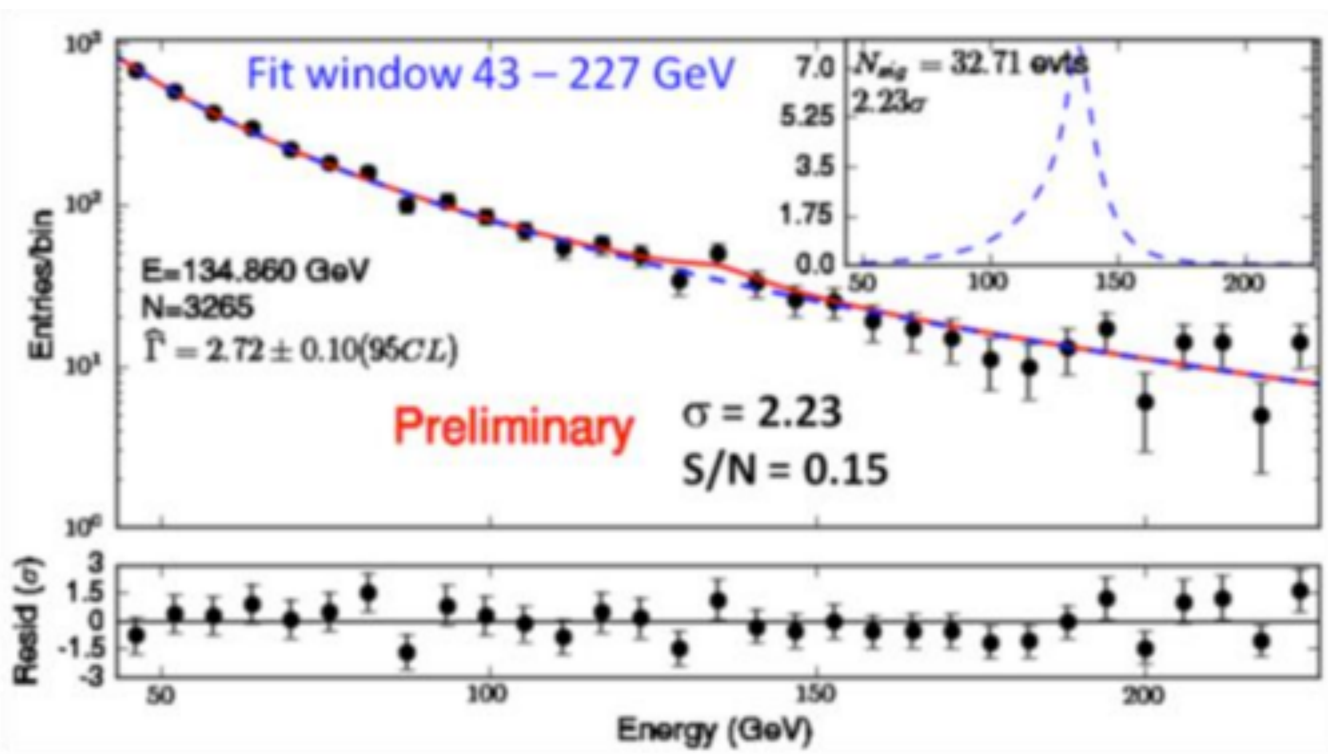
A Gamma-Ray Line !!??

- Troubling that a 2D energy analysis decreases the significance of the line

- However, there may be important systematic issue (lines appear in the Earth atmosphere)



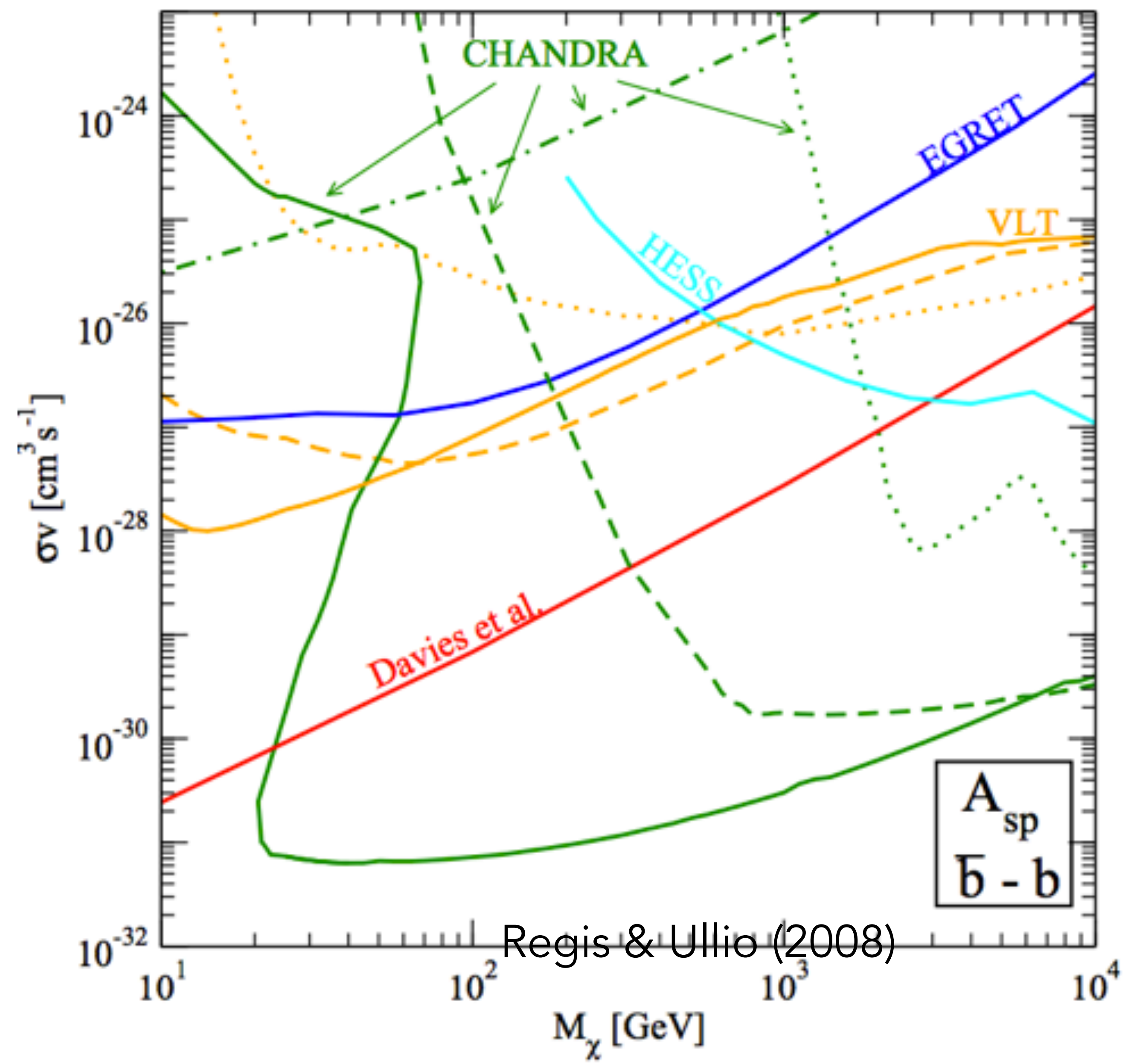
Andrea Albert (Fermi Symposium)



Bloom et al. (2013)

Multiwavelength Studies - A Dangerous Path

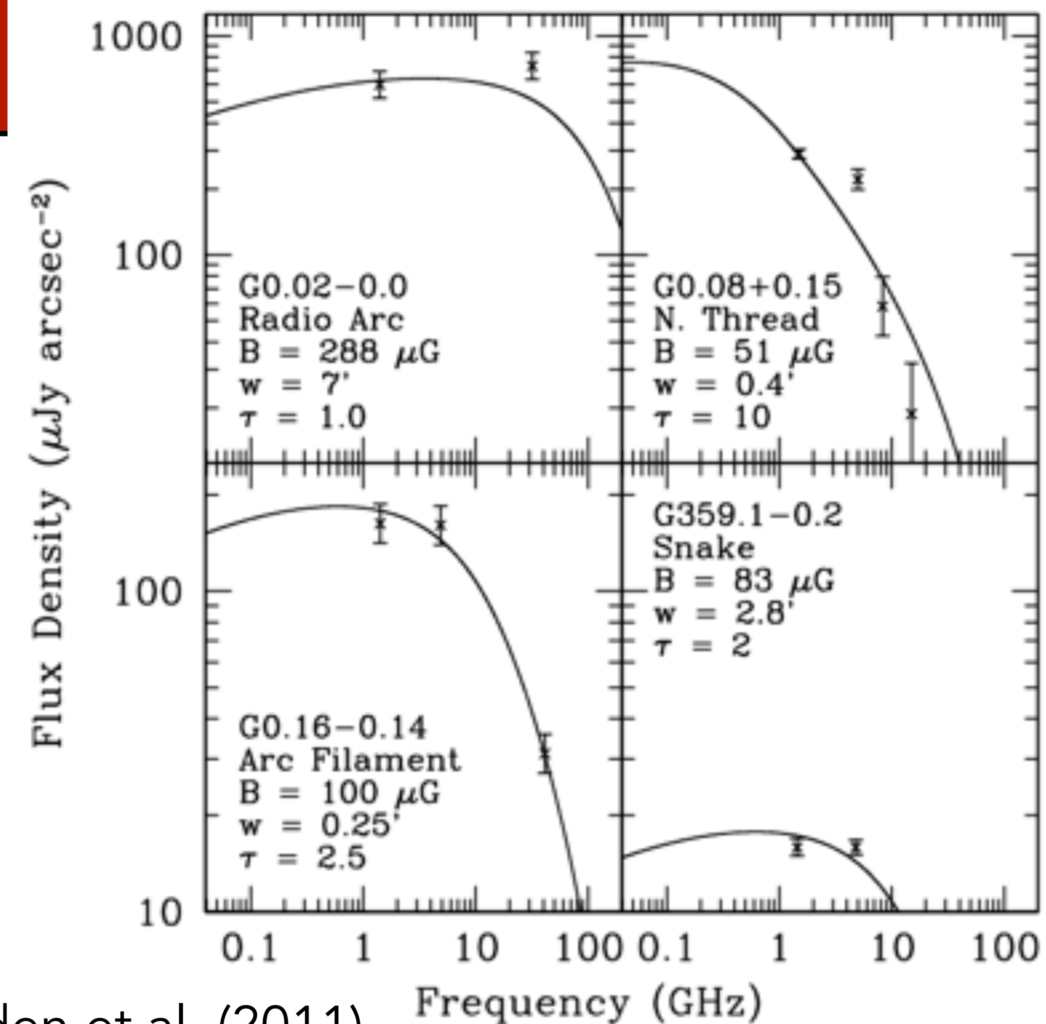
- You can use the superior angular resolution of radio and X-Ray telescopes
- However, this requires an extrapolation of our knowledge by orders of magnitude
  - Dark Matter density distribution
  - Magnetic Fields and diffusion
- Beware strong limits with (relatively honest looking) extrapolations



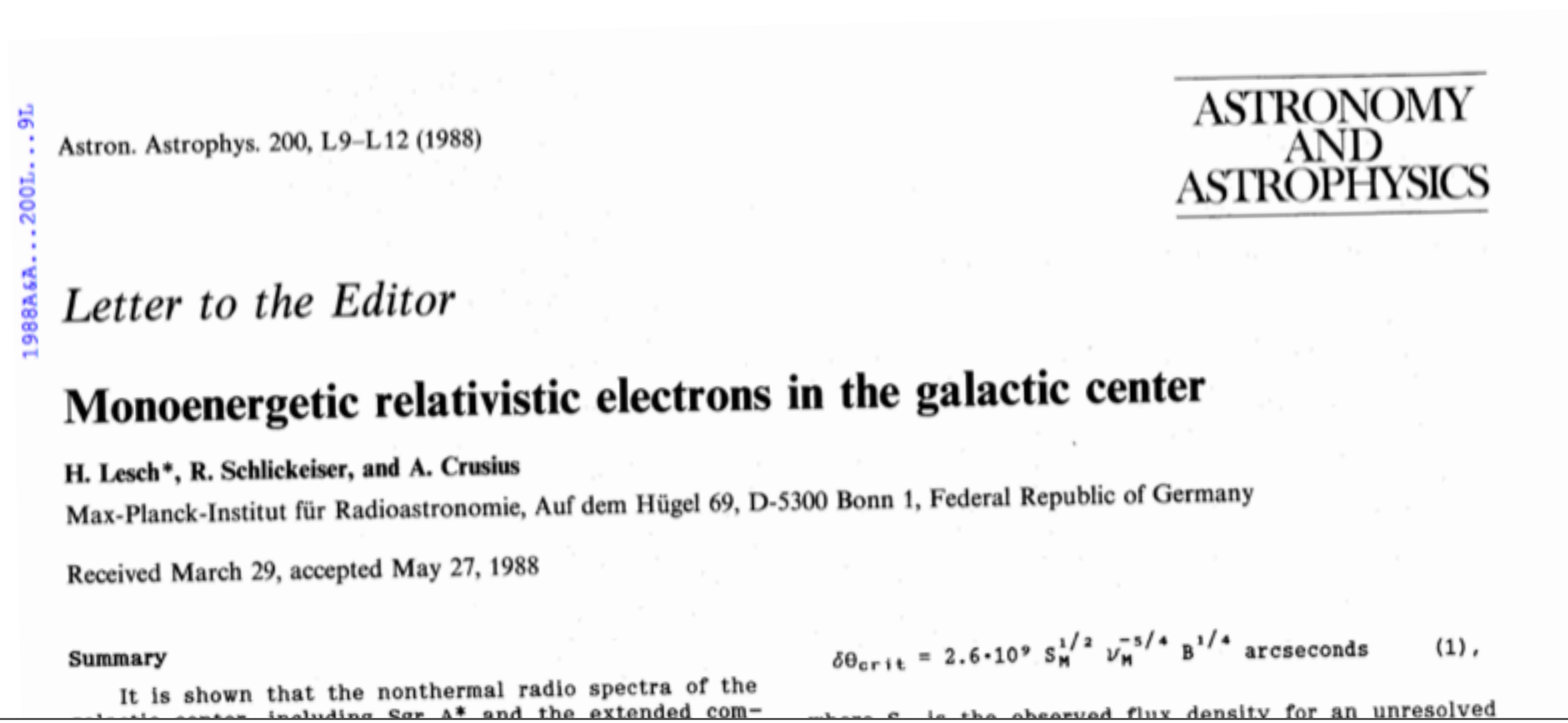
Regis & Ullio (2008)

Convincing Low Energy Studies

- Can also place constraints (or find signals) in certain regions of space where you think you understand the magnetic fields better (e.g. the filamentary arcs)



Linden et al. (2011)



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

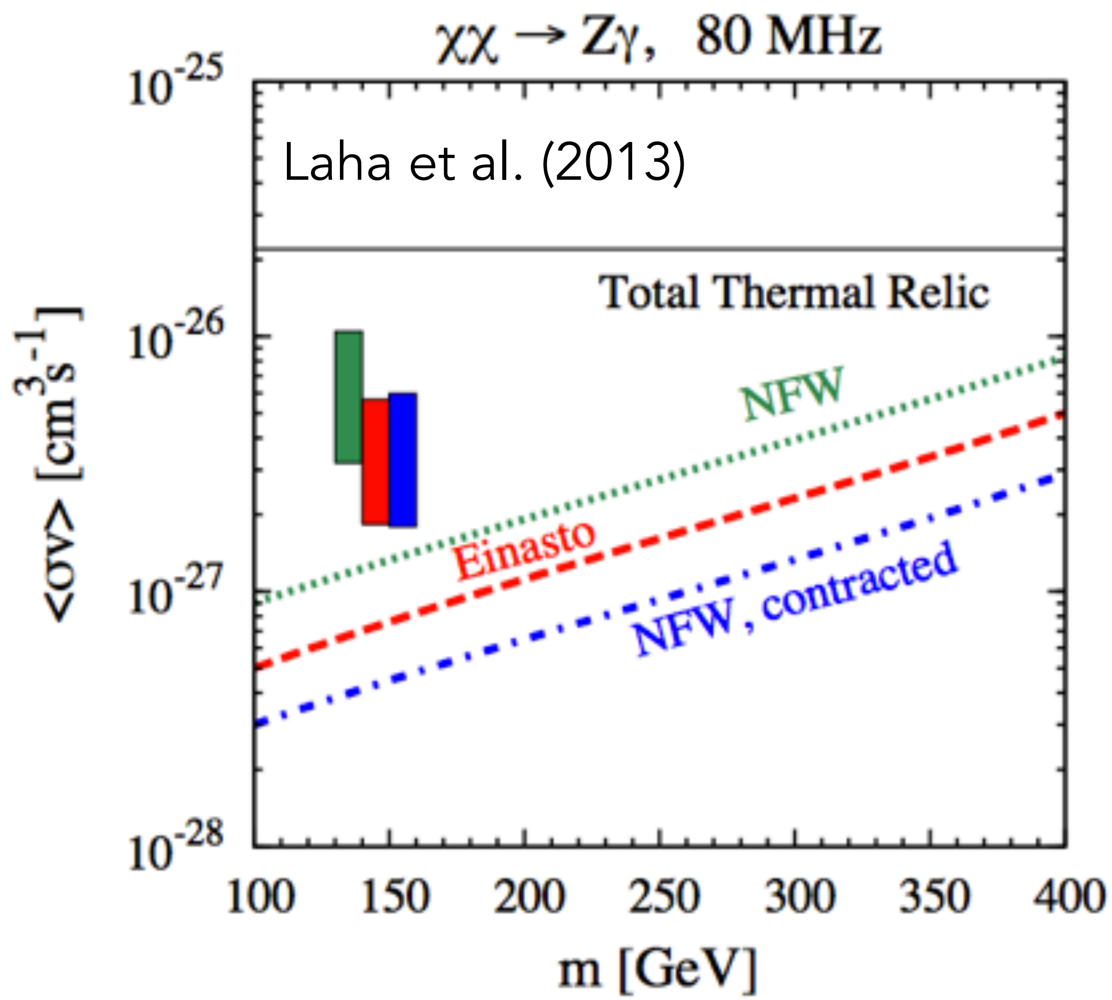
Received March 29, accepted May 27, 1988

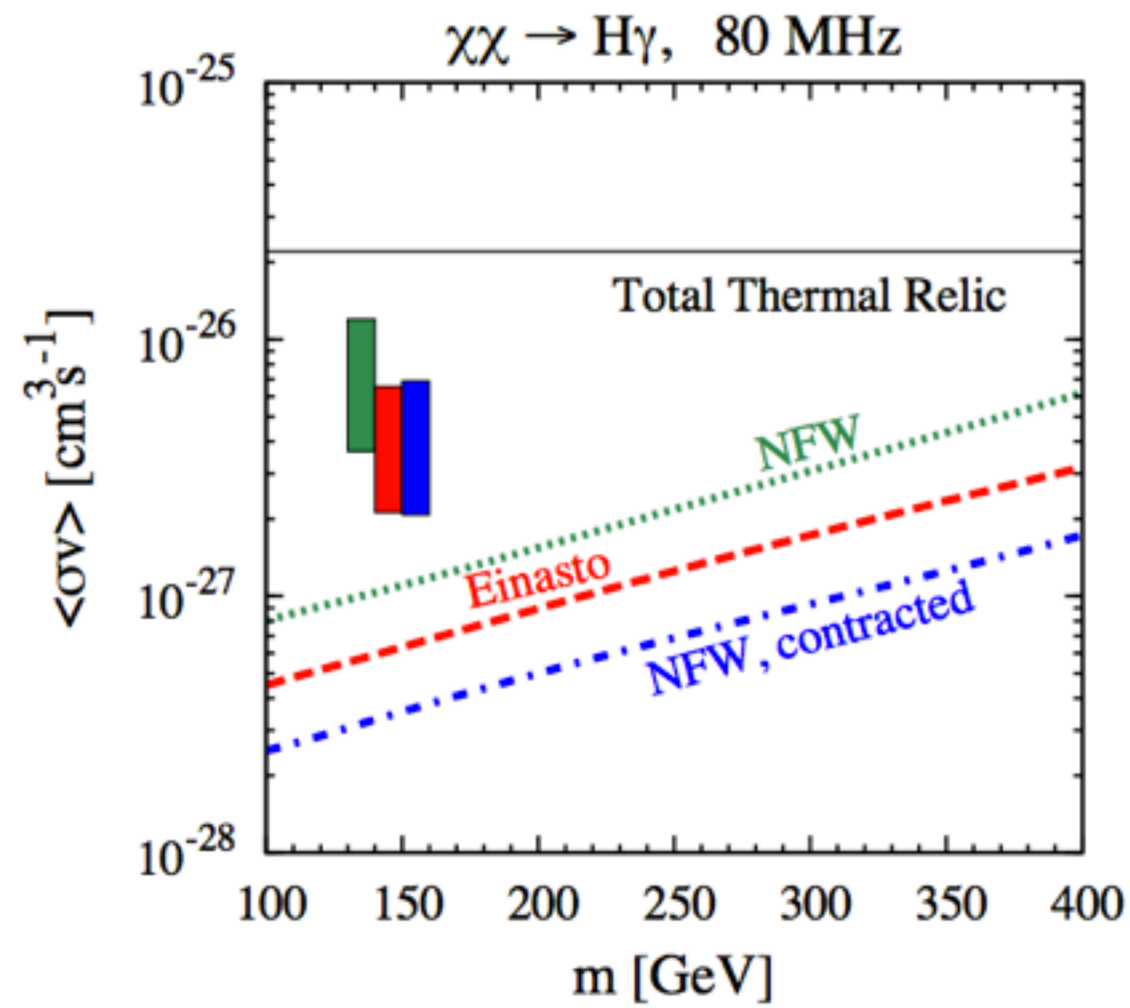
Summary

It is shown that the nonthermal radio spectra of the

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

Convincing Low Energy Studies

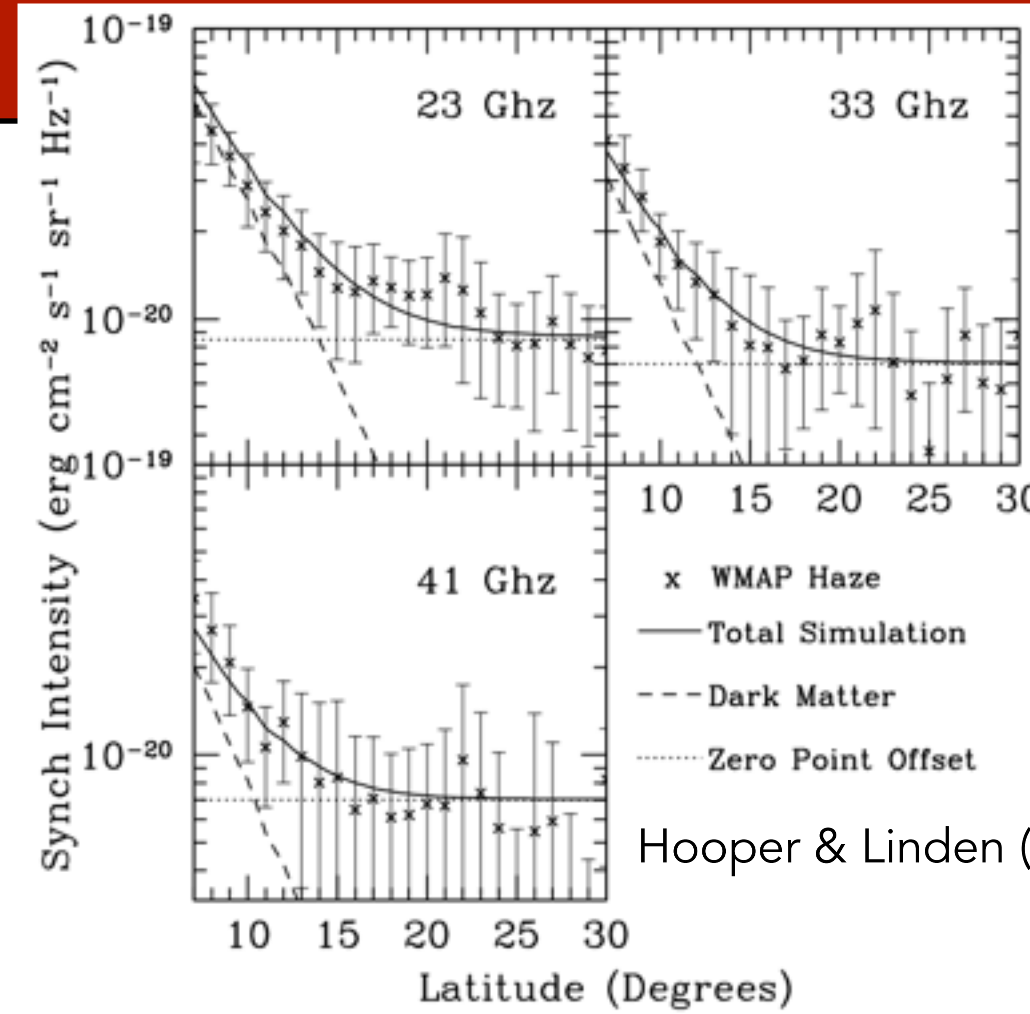




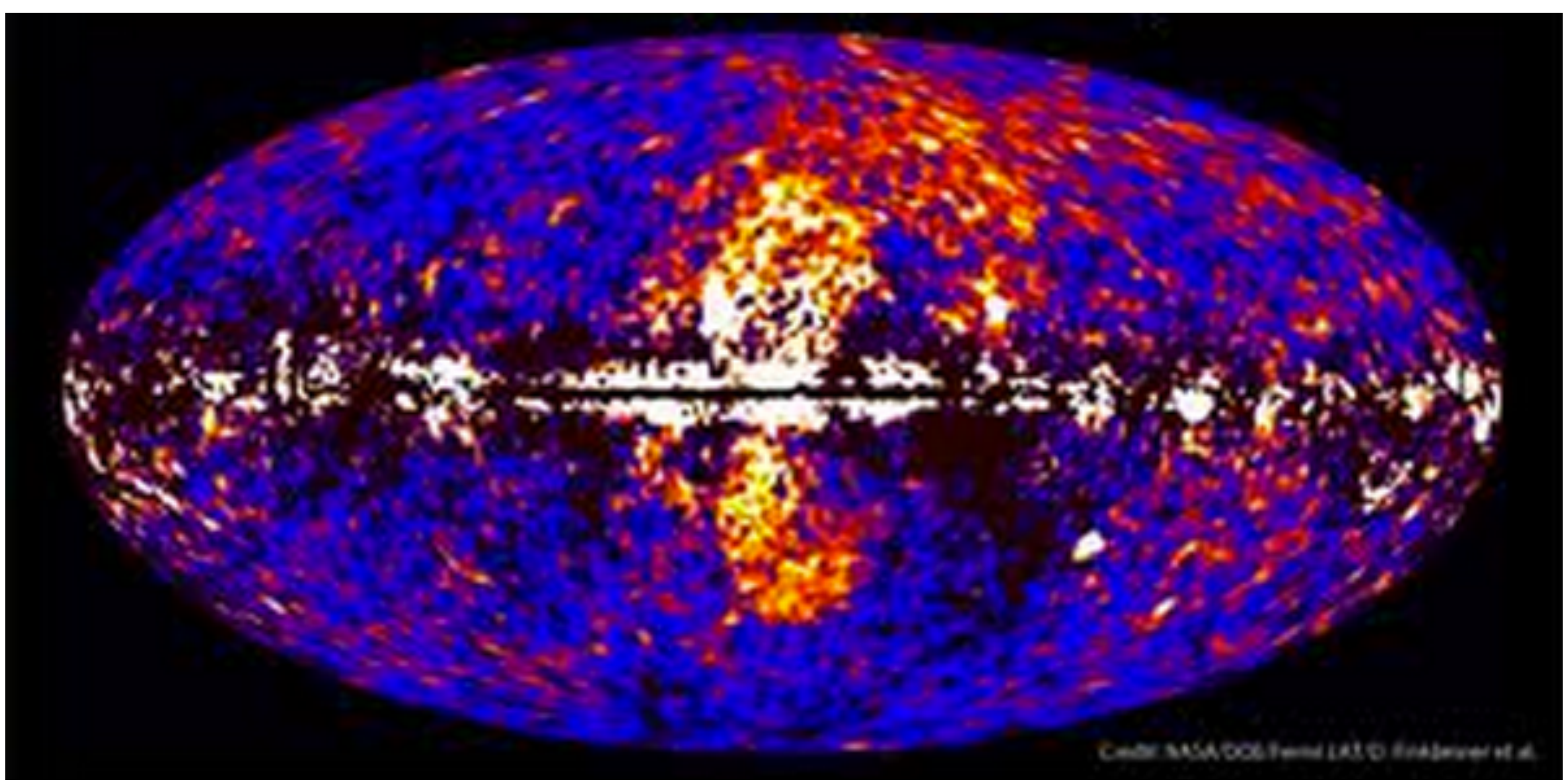
- Can go to regions where the astrophysical background is much much smaller (i.e. low energy surveys)

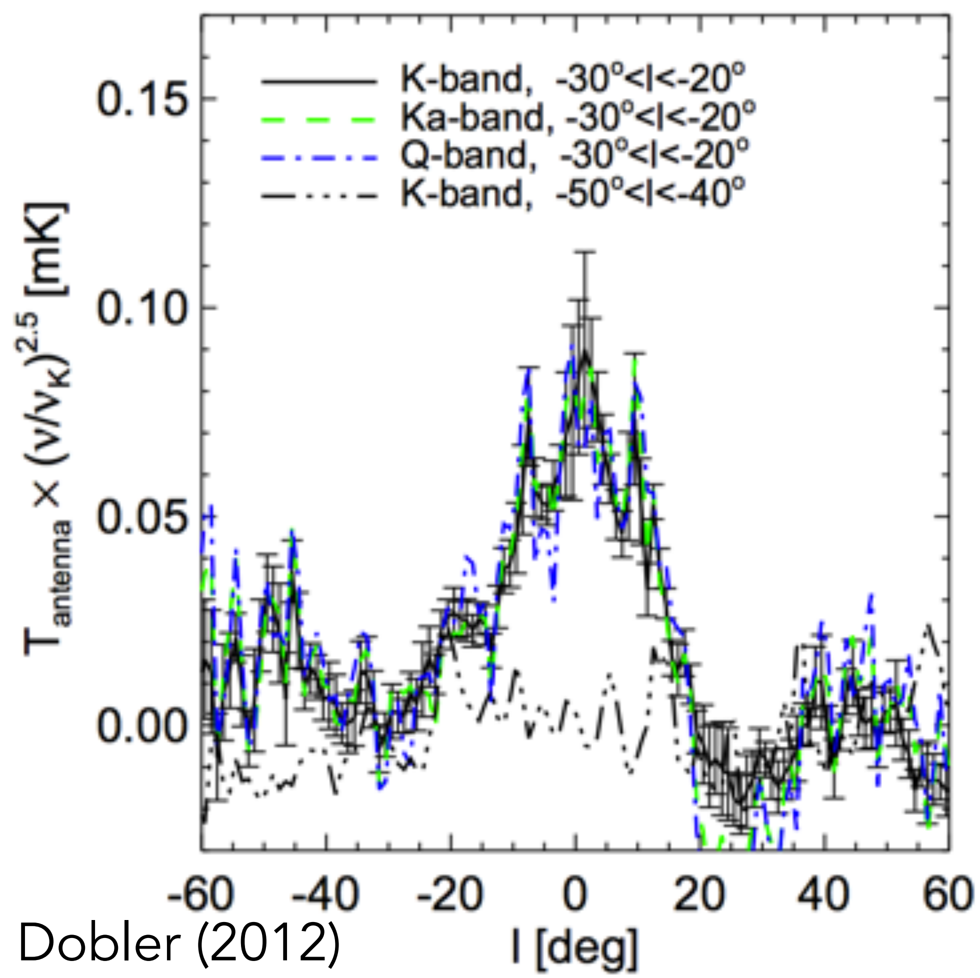
Multiwavelength Studies?

- Story of the WMAP Haze shows how multiwavelength observations can help understand supposed dark matter signals



Hooper & Linden (2011)



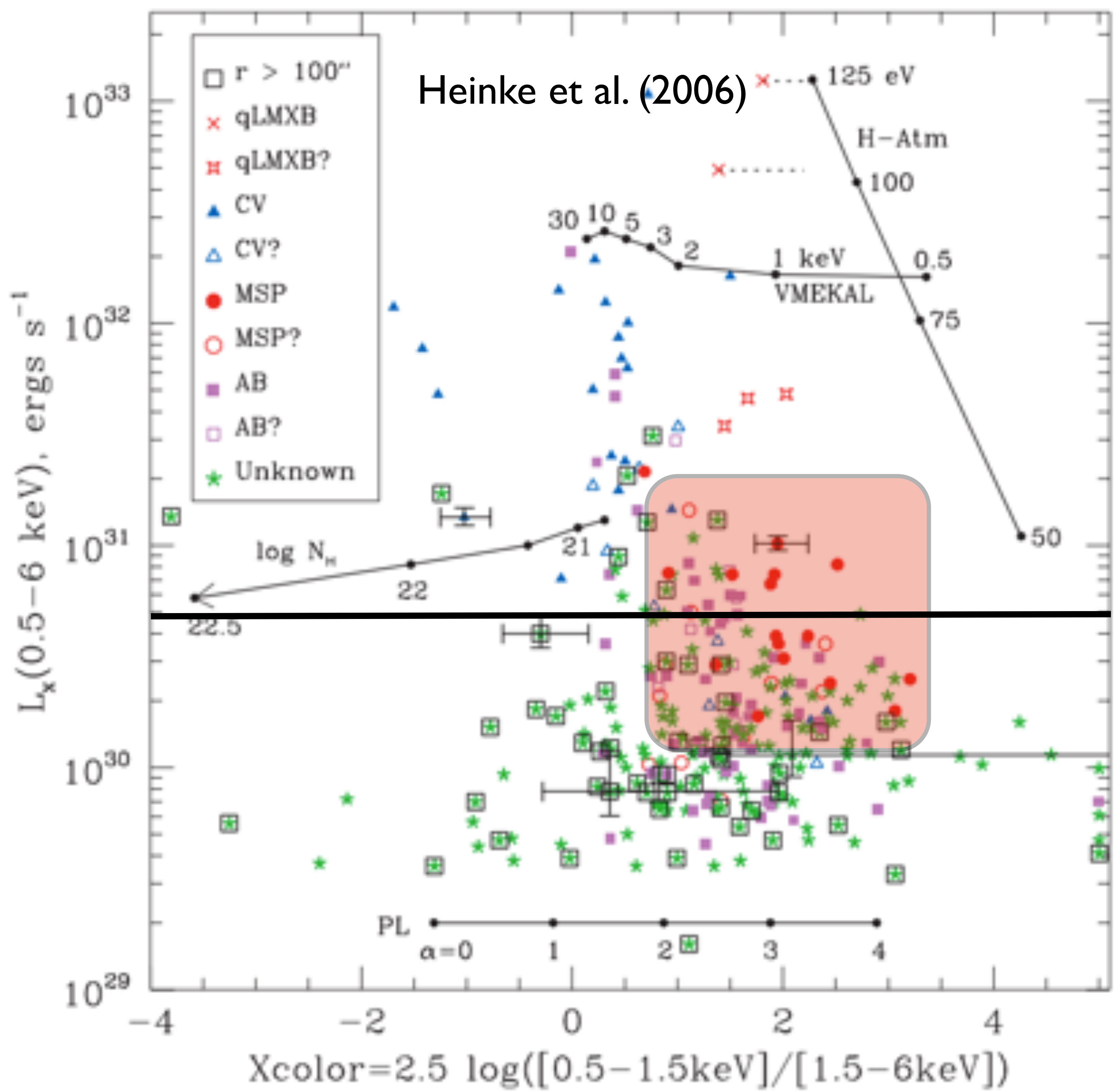


Dobler (2012)

Multiwavelength Studies

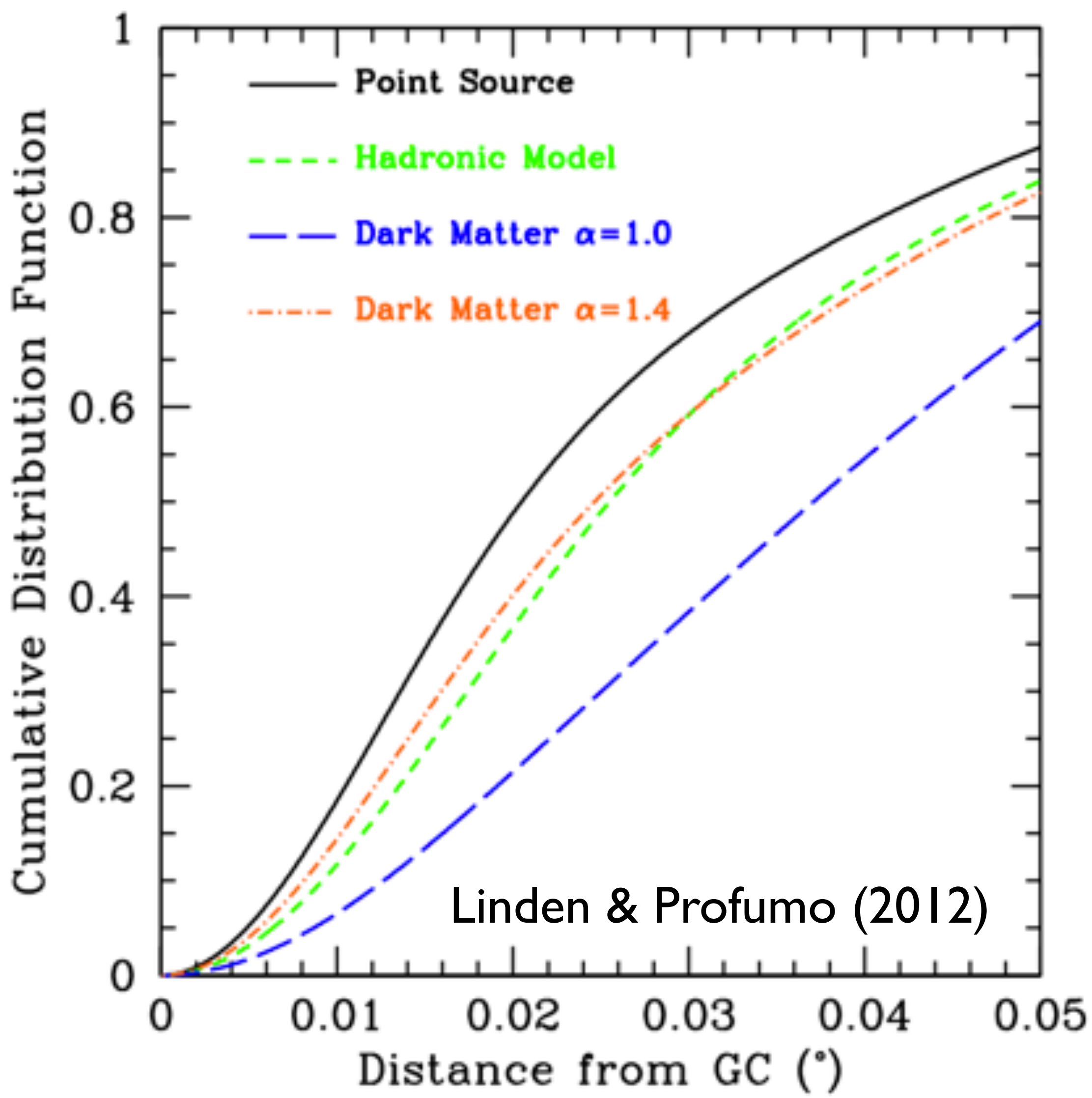
- While Fermi-LAT observes 2 point sources within 50 pc of the GC, Chandra observes ~2400

- Understanding these point sources, and their likely gamma-ray energy spectrum, can inform our models of the galactic center gamma-ray spectrum

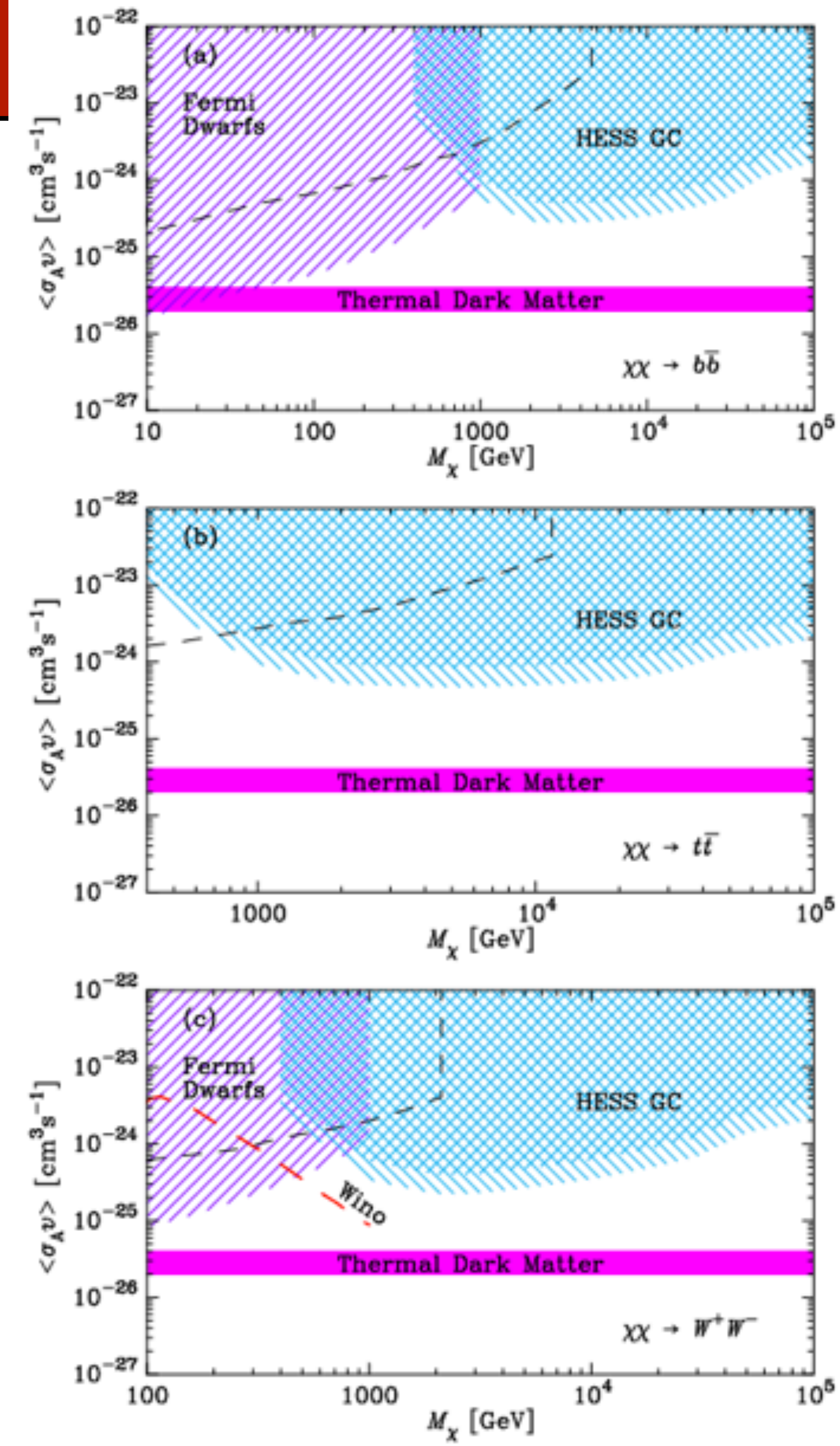


Cherenkov Telescope Array

- Will improve the H.E.S.S. effective area by a factor of 10
- Could provide extremely interesting limits, especially at the galactic center



Linden & Profumo (2012)



Abazajian & Harding (2011)

Conclusions

- Gamma-Ray Instruments are quickly cutting into the thermal cross-section for dark matter annihilation (Funny that theoretical prejudice for large cross-sections has suddenly disappeared)

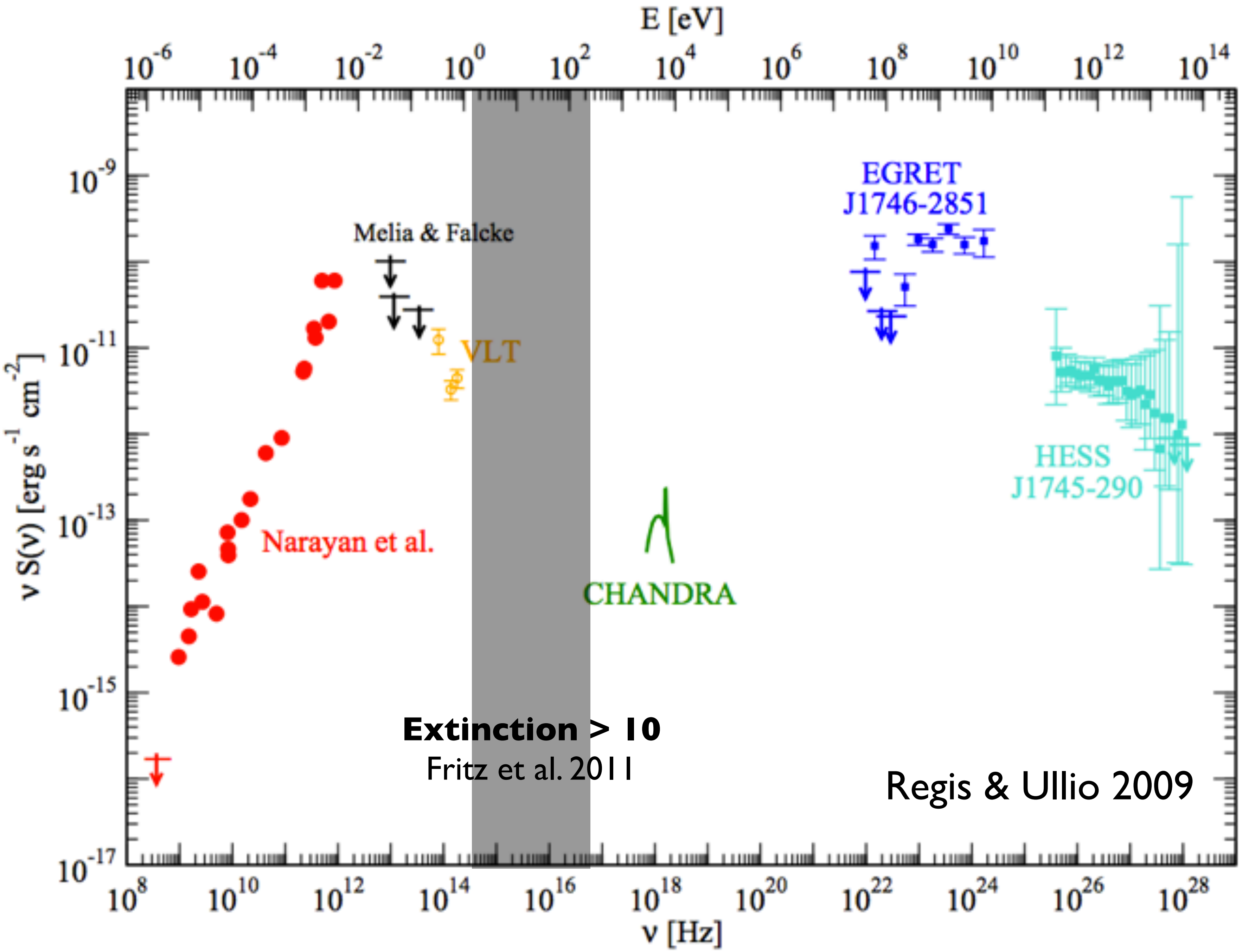
- Studies of the Galactic Center have a high discovery potential -- but low background observations are necessary! (Theorists can convince themselves of anything)

- Stay tuned on the story of spectral lines (You're sure to hear more)

- Multiwavelength analyses are key (But difficult)

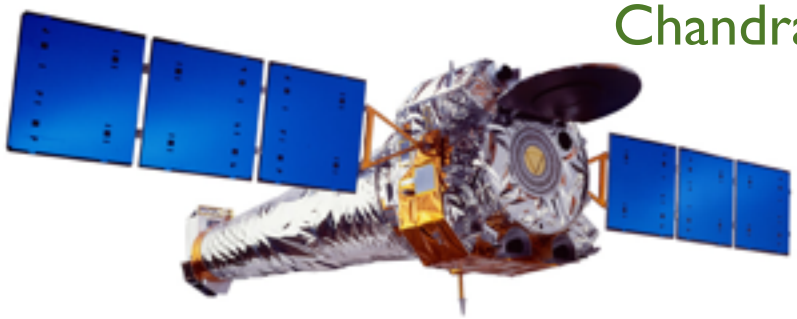
Extra Slides

The Multi-wavelength Galactic Center

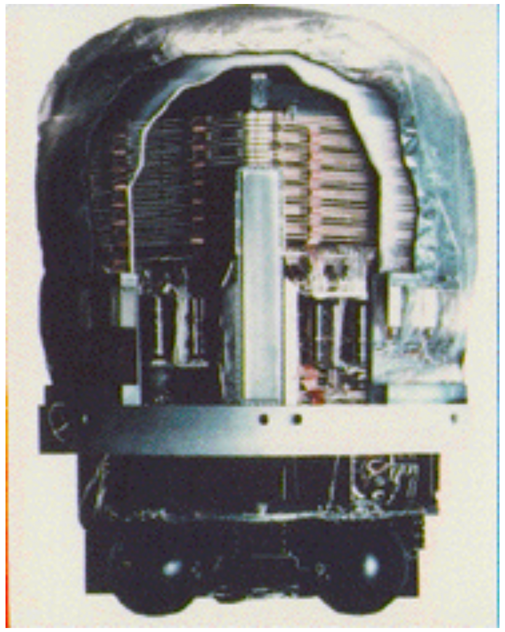


VLA

Chandra



EGRET



HESS

Fermi-LAT