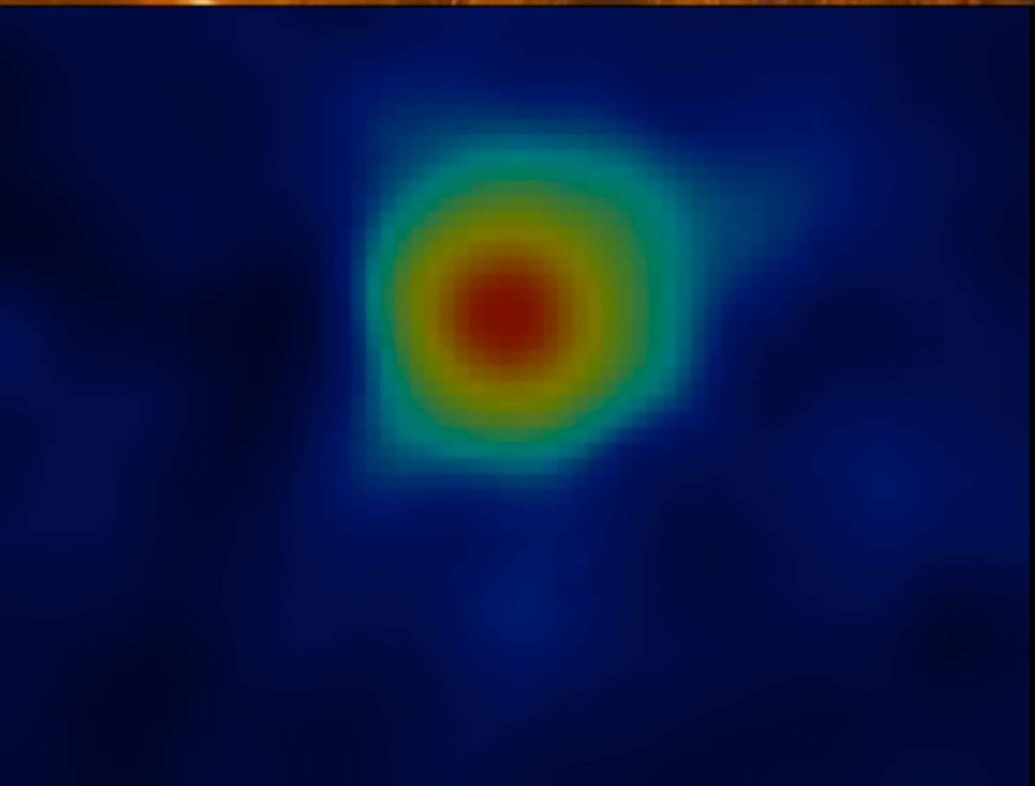
An Unexpected Journey

Detection of Continuum γ-rays from Dark Matter Annihilation in the Galactic Center?



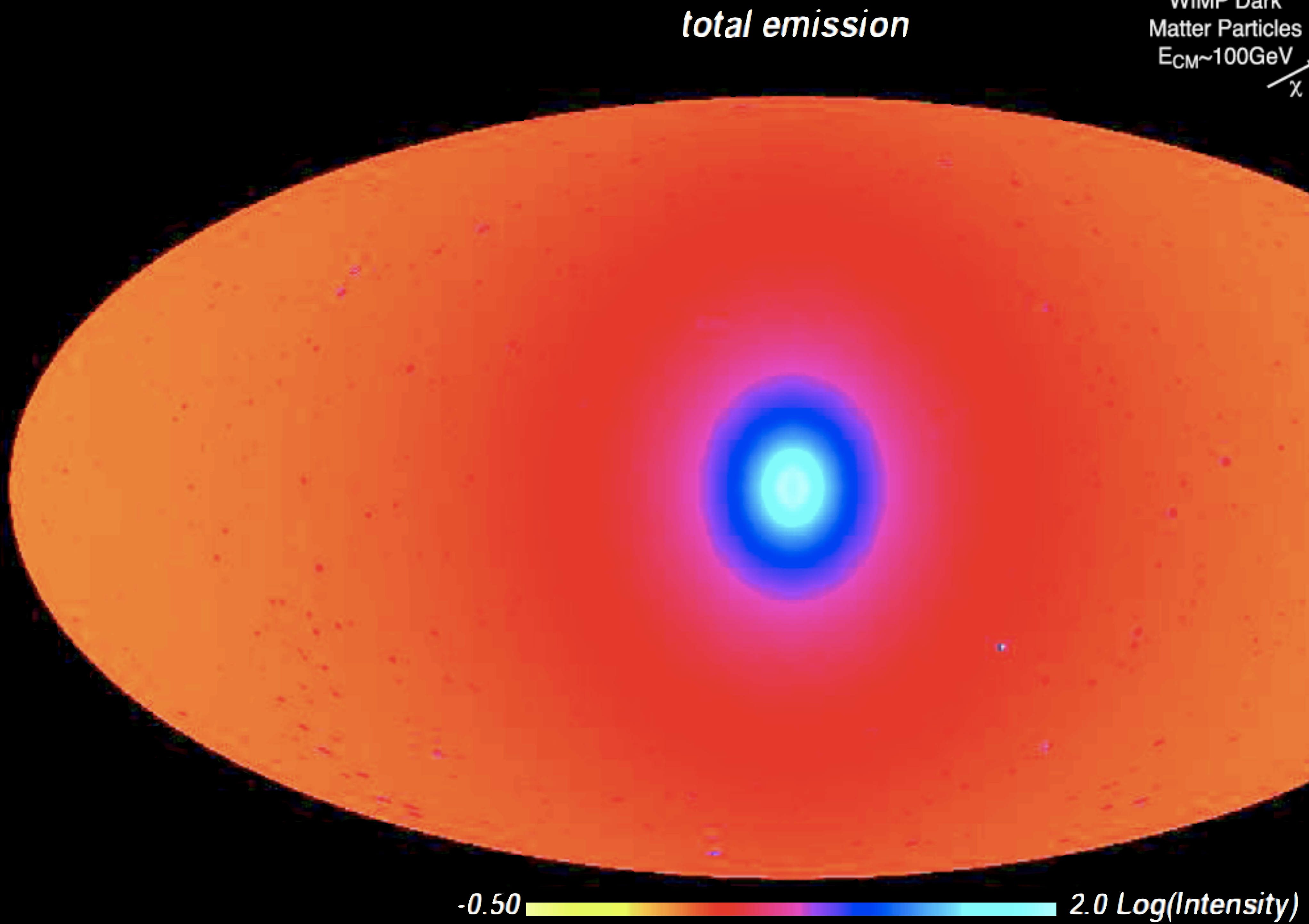
Kevork Abazajian

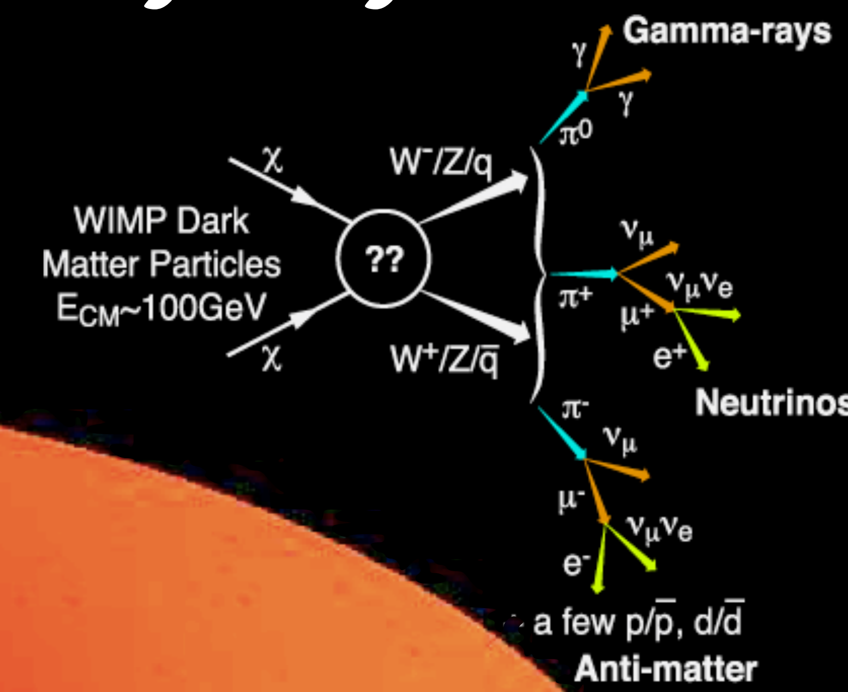
University of California, Irvine

Aspen Workshop: Closing in on Dark Matter?

February 1, 2013

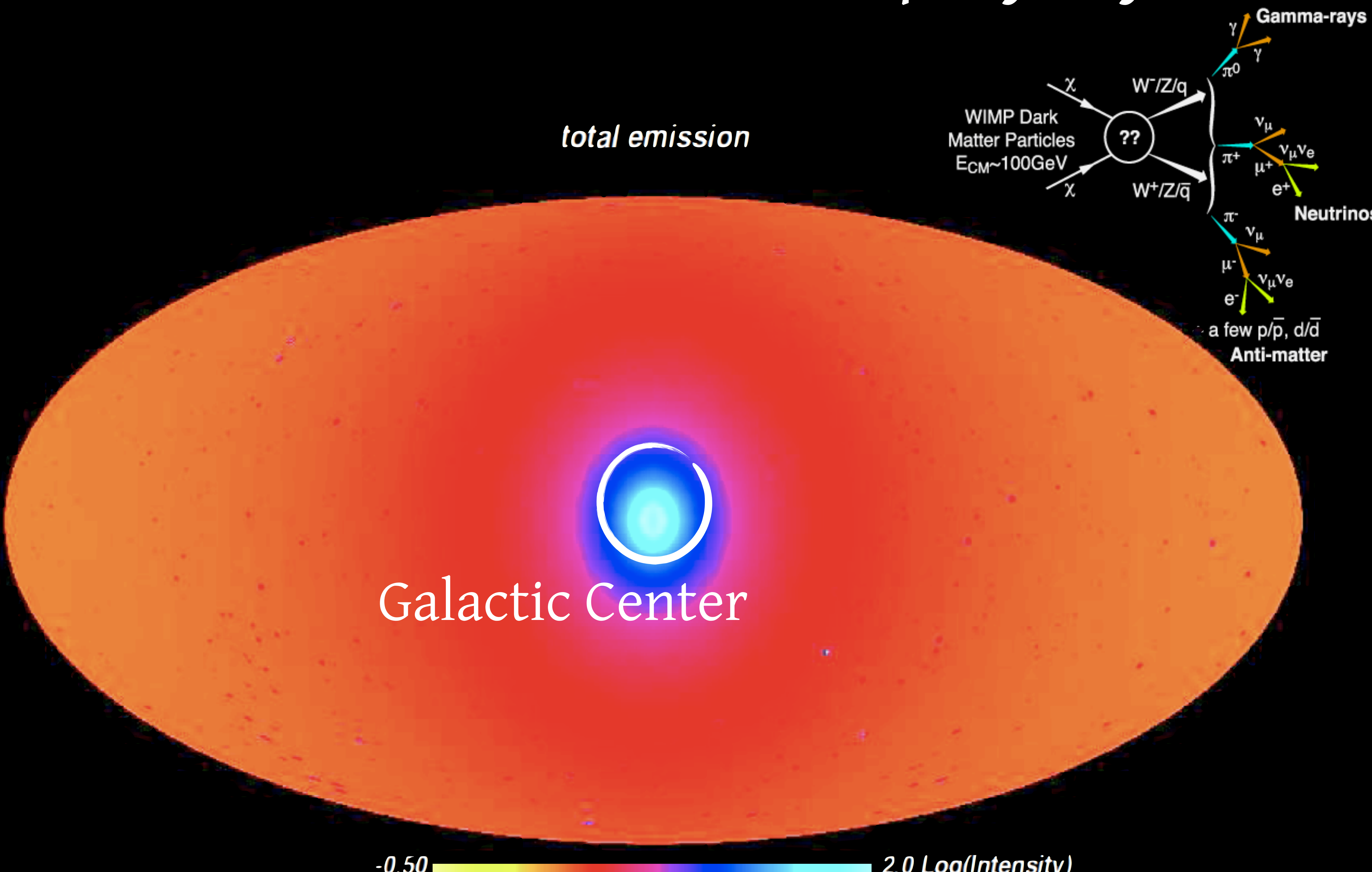
The Dark Matter Hunter's γ-ray Sky





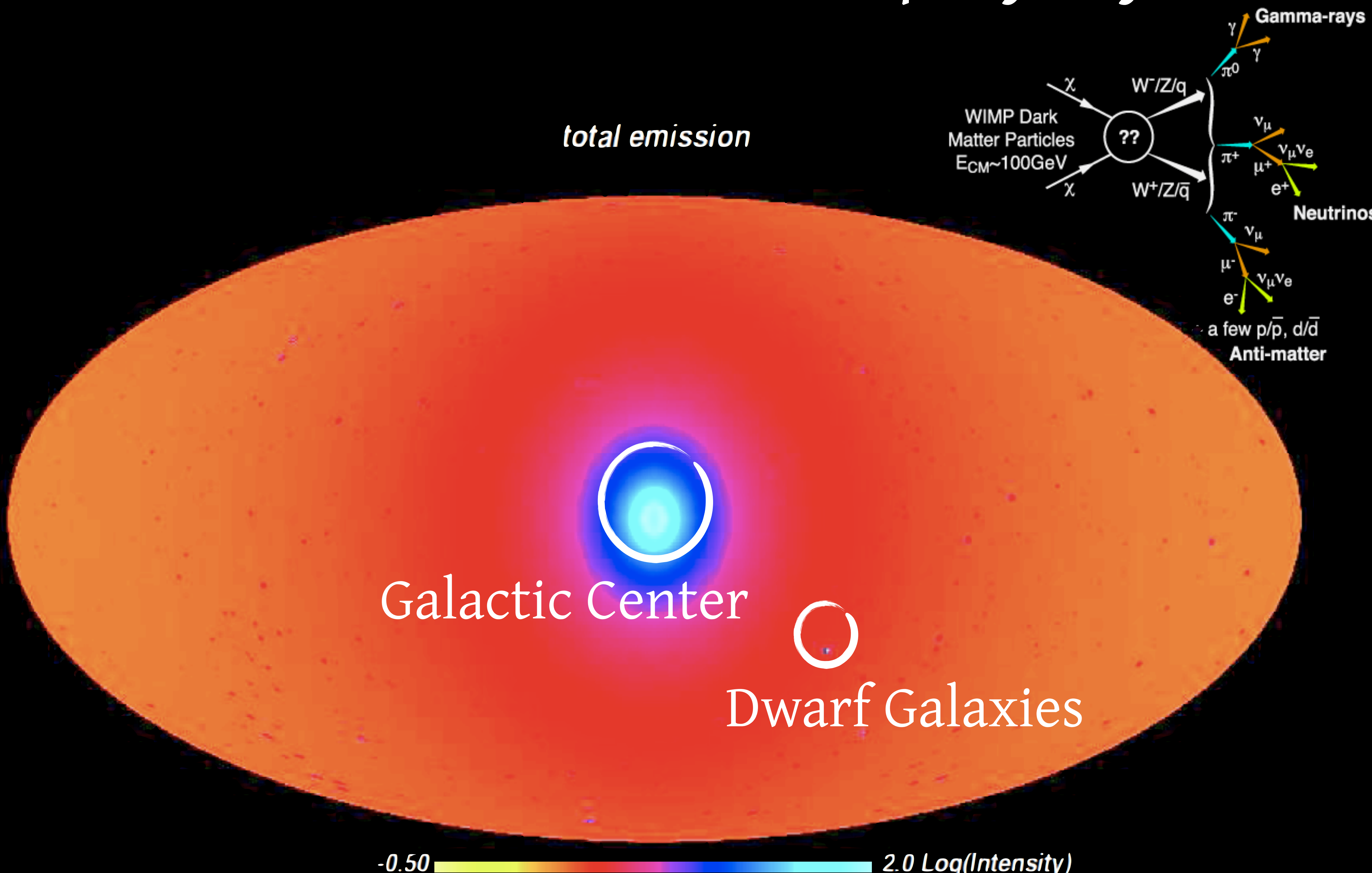
Springel et al 2008

The Dark Matter Hunter's γ-ray Sky



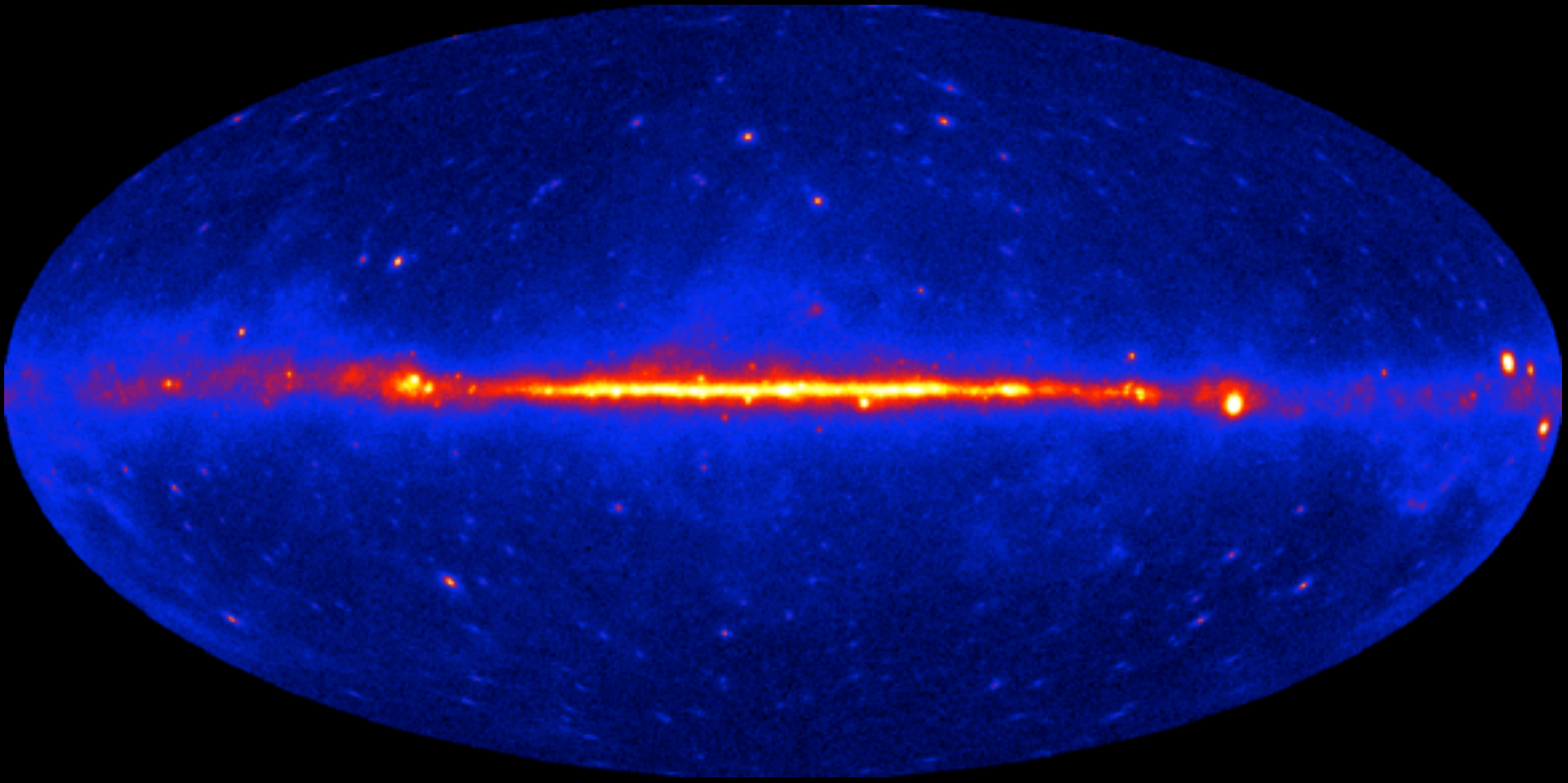
Springel et al 2008

The Dark Matter Hunter's γ-ray Sky

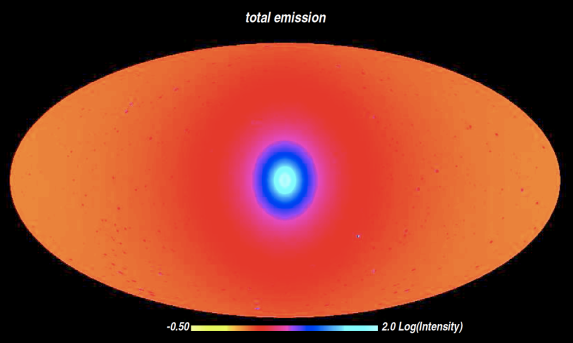


Springel et al 2008

The Observed Fermi-LAT γ-Ray Sky



Dark Matter Annihilation in the Sky: Galactic and Extragalactic Contributions



Galactic:

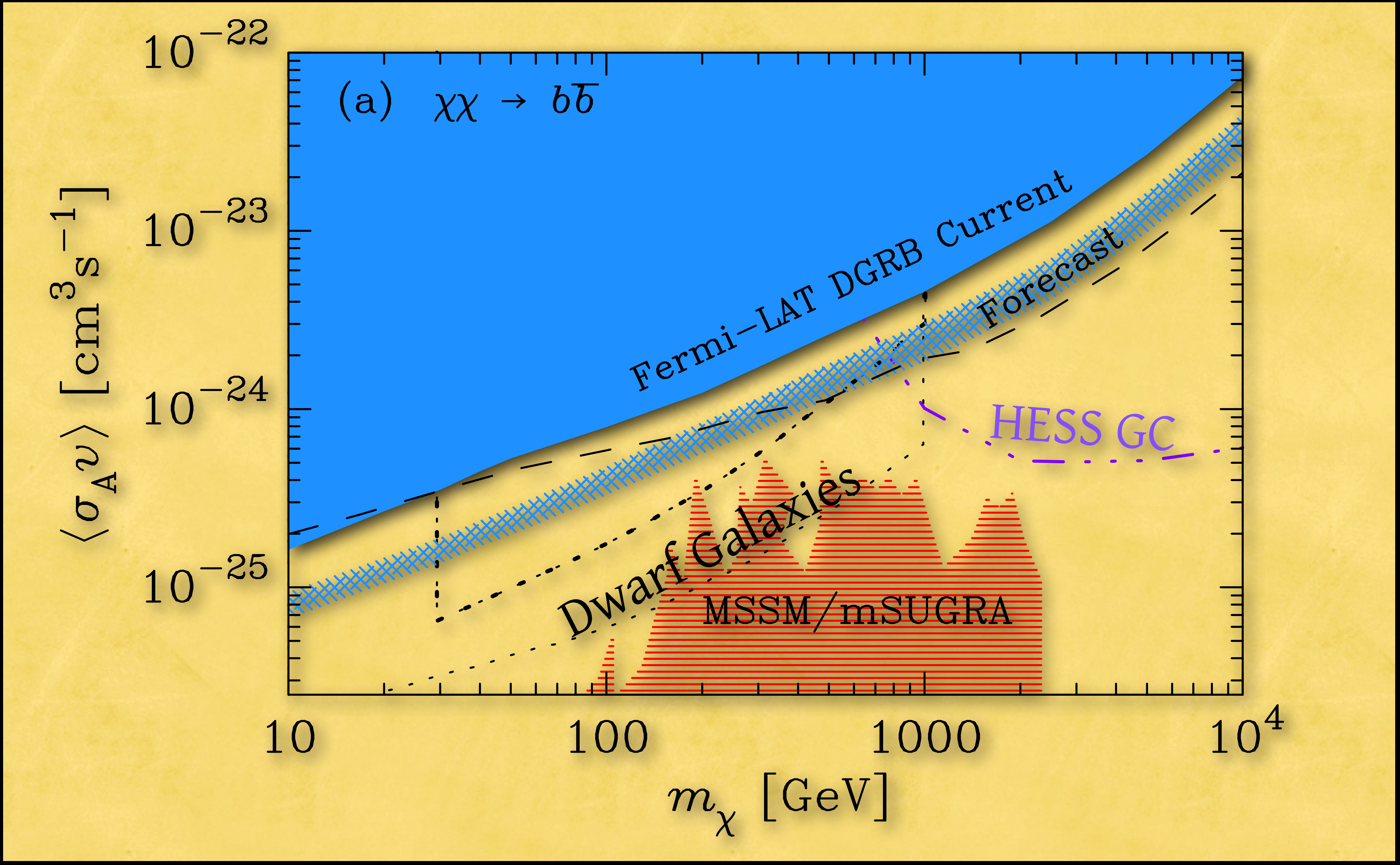
$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{\mathcal{J}_{\Delta\Omega}}{J_0} \frac{1}{4\pi m_\chi^2} \frac{dN_\gamma}{dE}$$

$$\mathcal{J}(b,\ell) = \mathrm{J}_0 \int_{x_{\rm min}}^{x_{\rm max}} \rho^2 \left(r_{\rm gal}(b,\ell,x)\right) dx$$

Extragalactic:

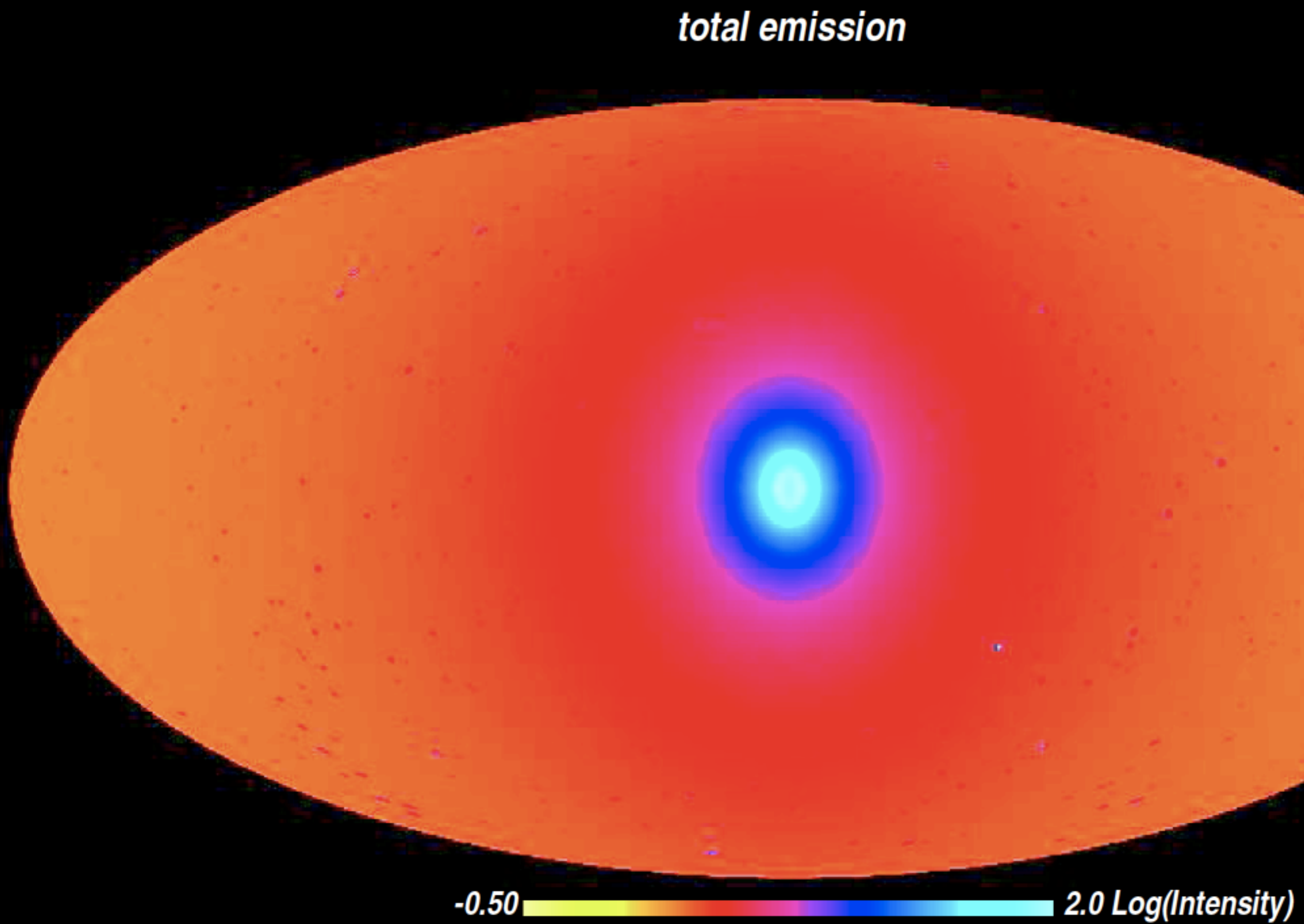
$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{c}{4\pi H_0} \frac{(f_{\rm DM}\Omega_m)^2 \rho_{\rm crit}^2}{m_\chi^2} \int_0^{z_{\rm up}} \frac{f(z)(1+z)^3}{h(z)} \frac{dN_\gamma(E')}{dE'} e^{-\tau(z,E')} dz$$

Annihilation Channel Status & Forecasts: DGRB



Abazajian, Blanchet & Harding 2012

Galactic Center is the brightest DM source...

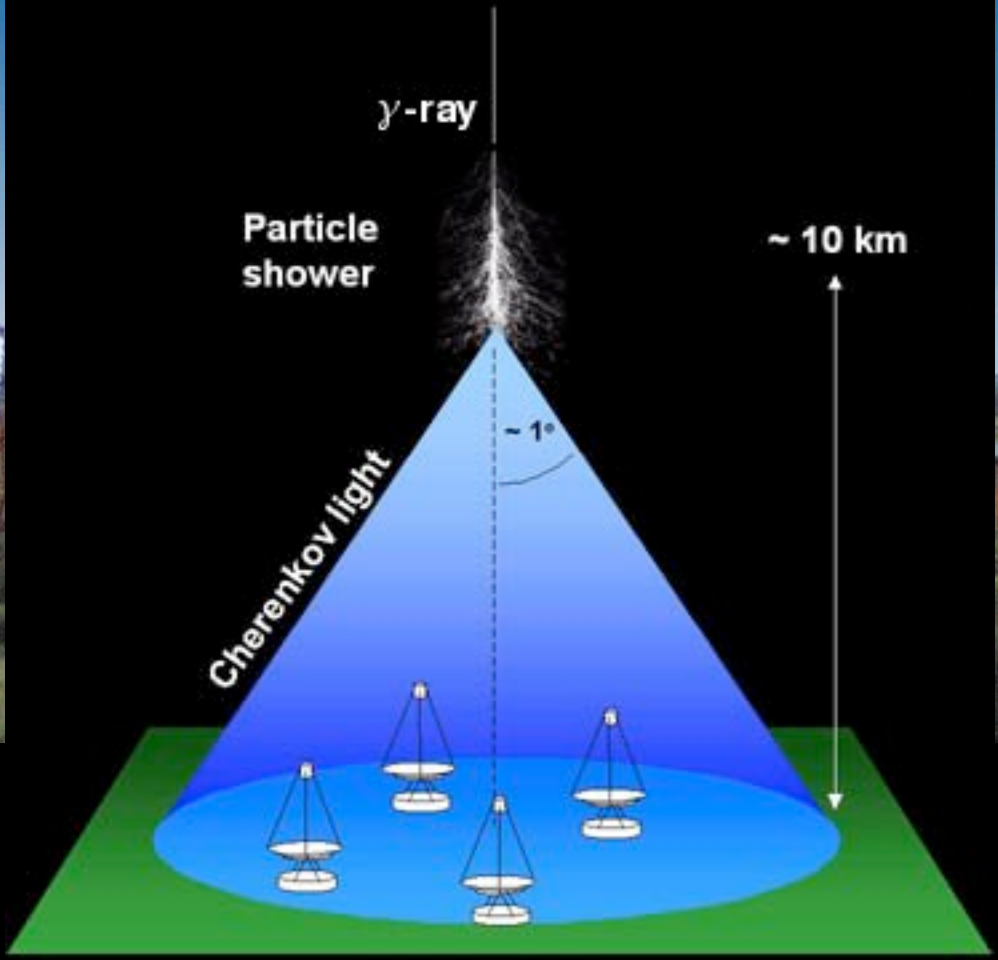


Springel et al 2008

High Energy Spectroscopic Survey (HESS) Gamma-Ray Telescope in Namibia

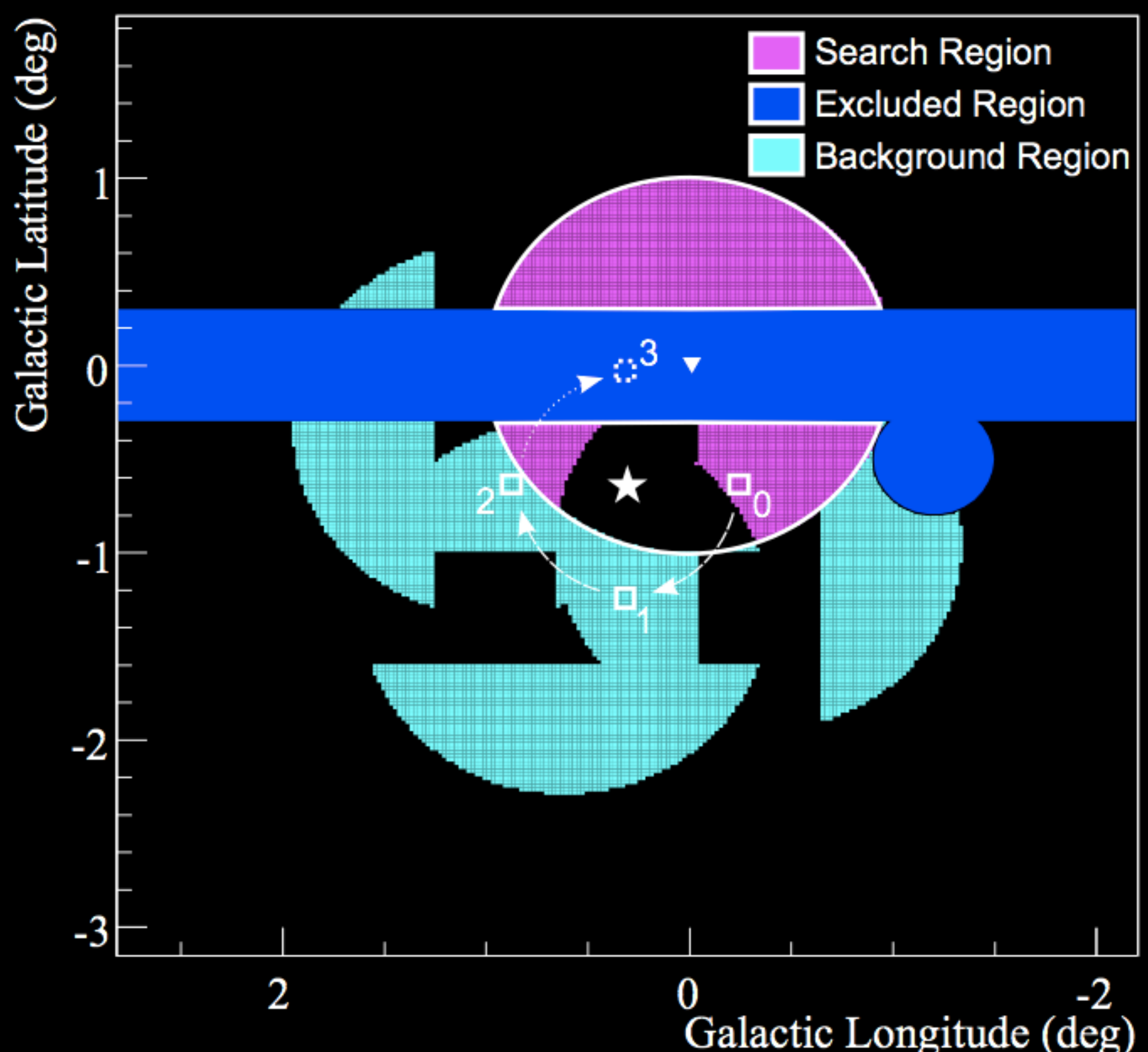
Would detect gamma-rays from annihilation products in High-Mass Dark Matter Models

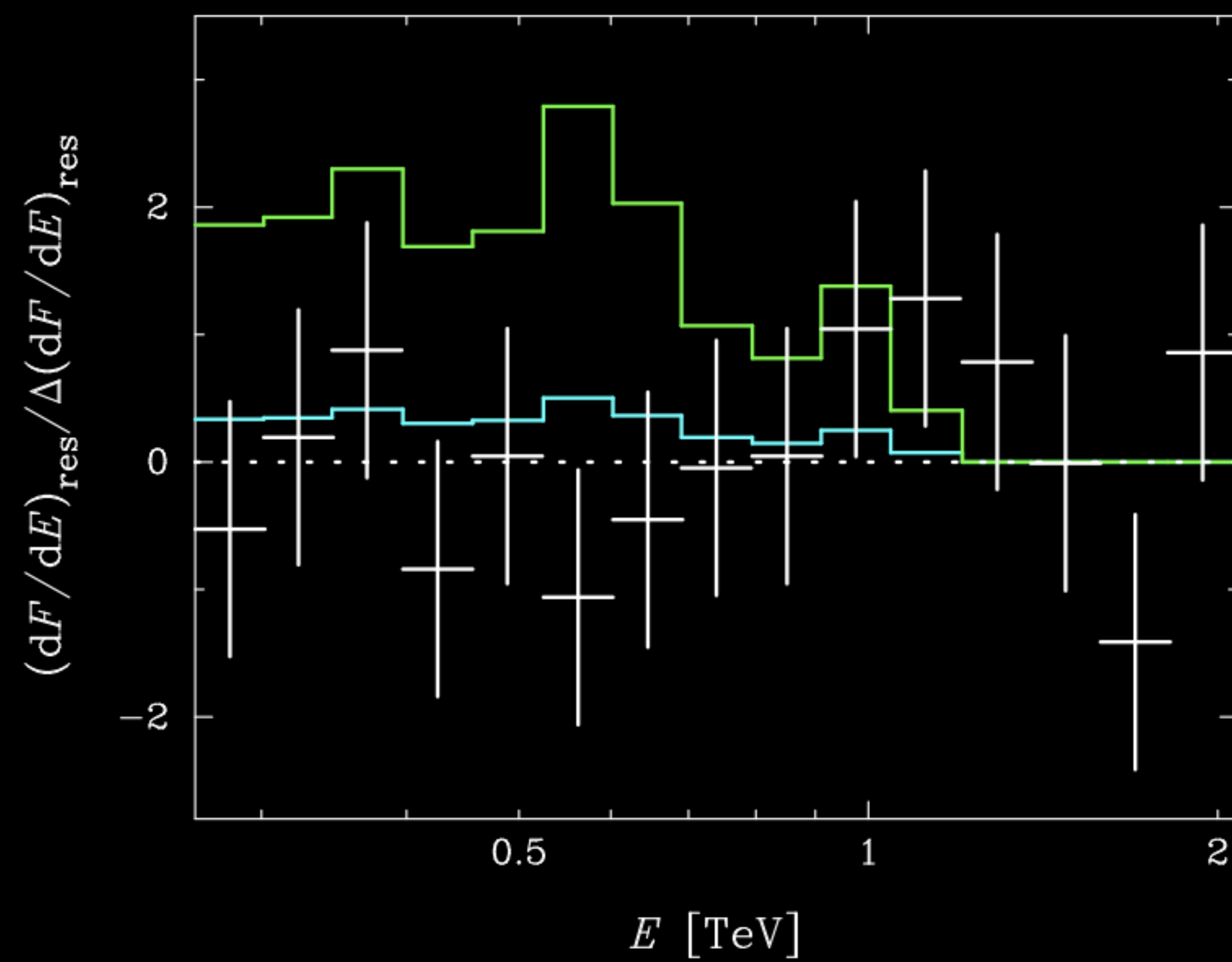
High Energy Spectroscopic Survey (HESS)
Gamma-Ray Telescope in Namibia

Would detect gamma-rays from annihilation products in High-Mass Dark Matter Models

Residual Spectrum Toward the Galactic Center

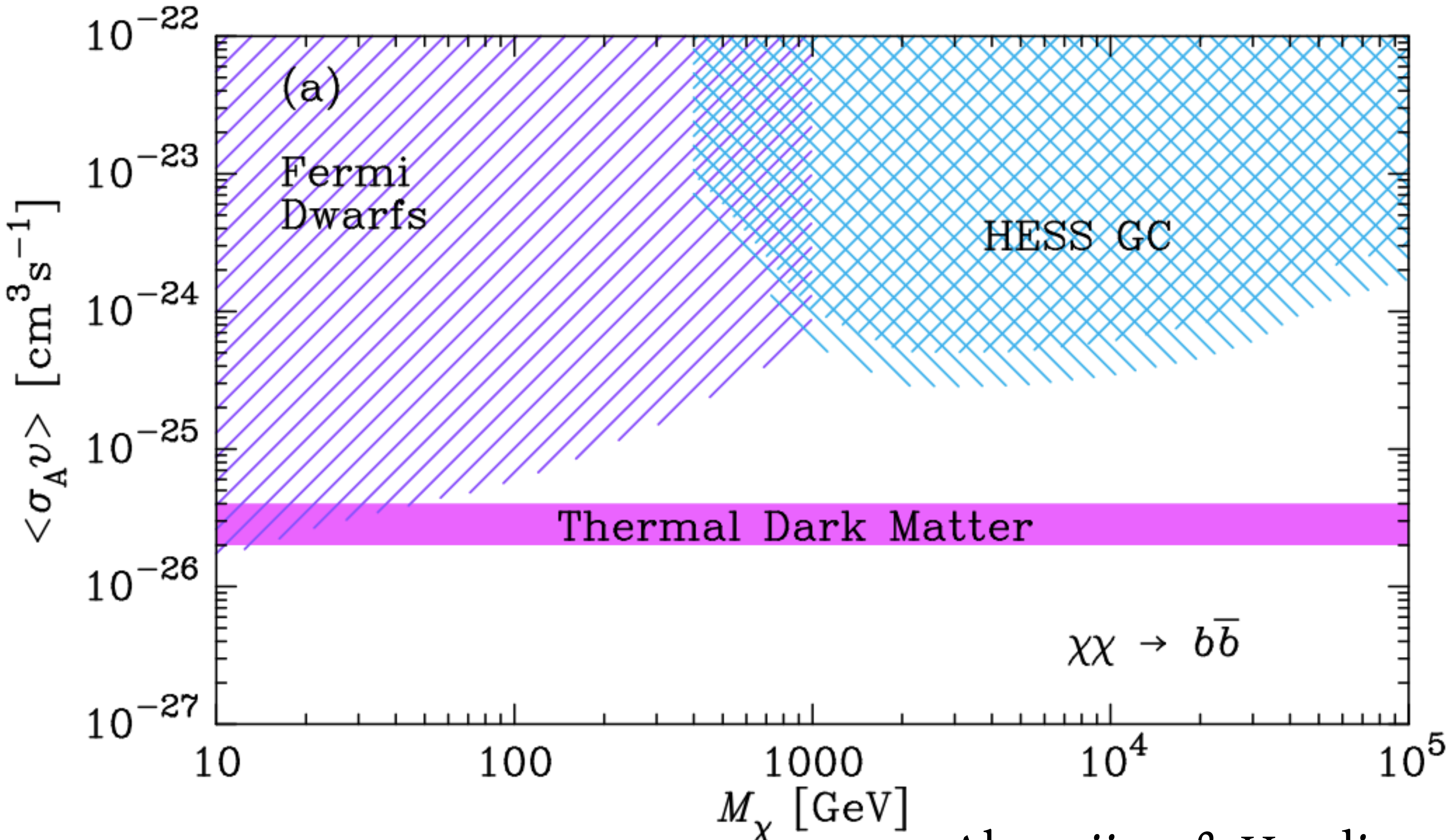




Abramowski et al 2011

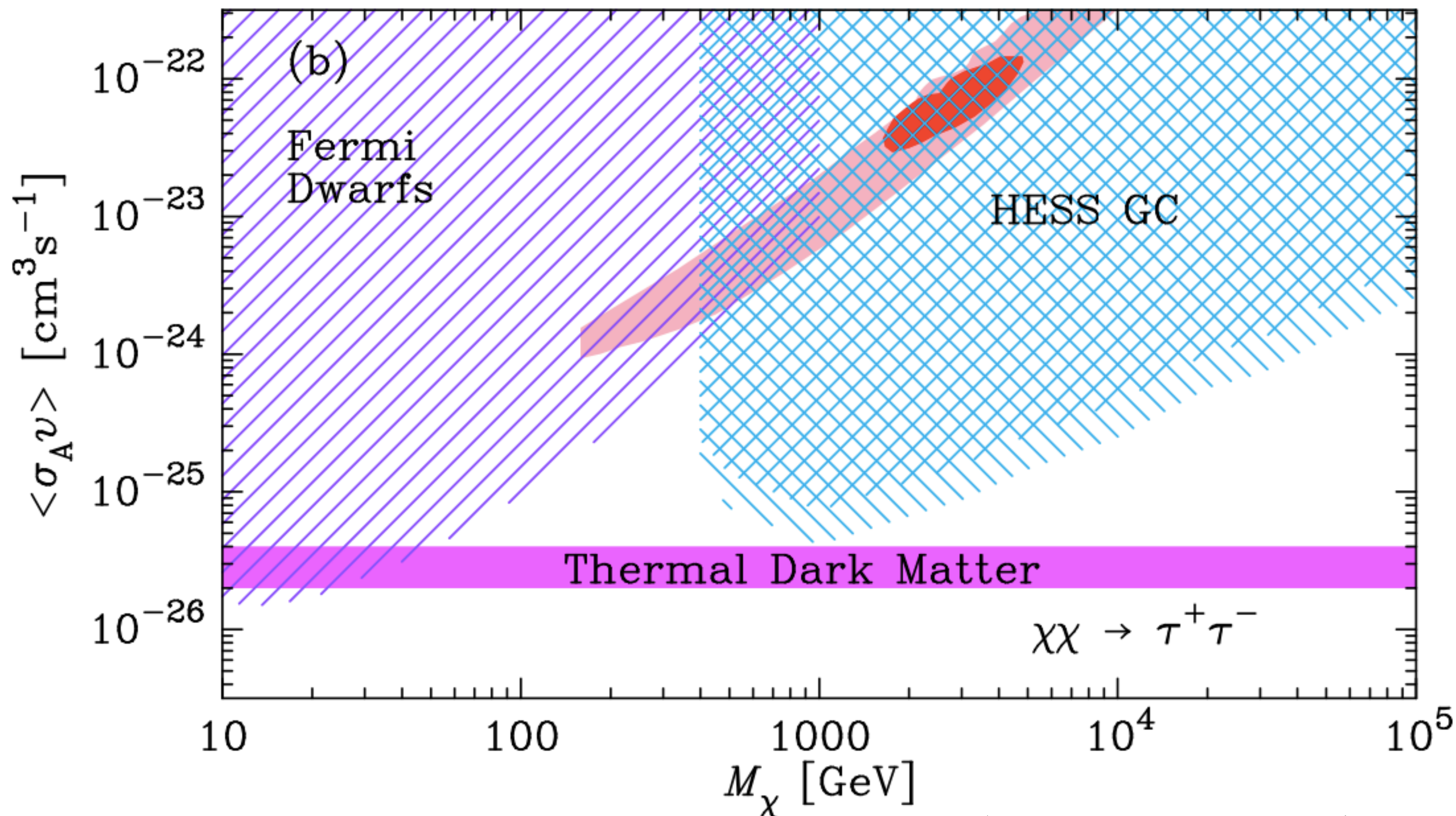
Abazajian & Harding 2011

Fermi-LAT & HESS: The Best Current Constraints on Annihilating Dark Matter



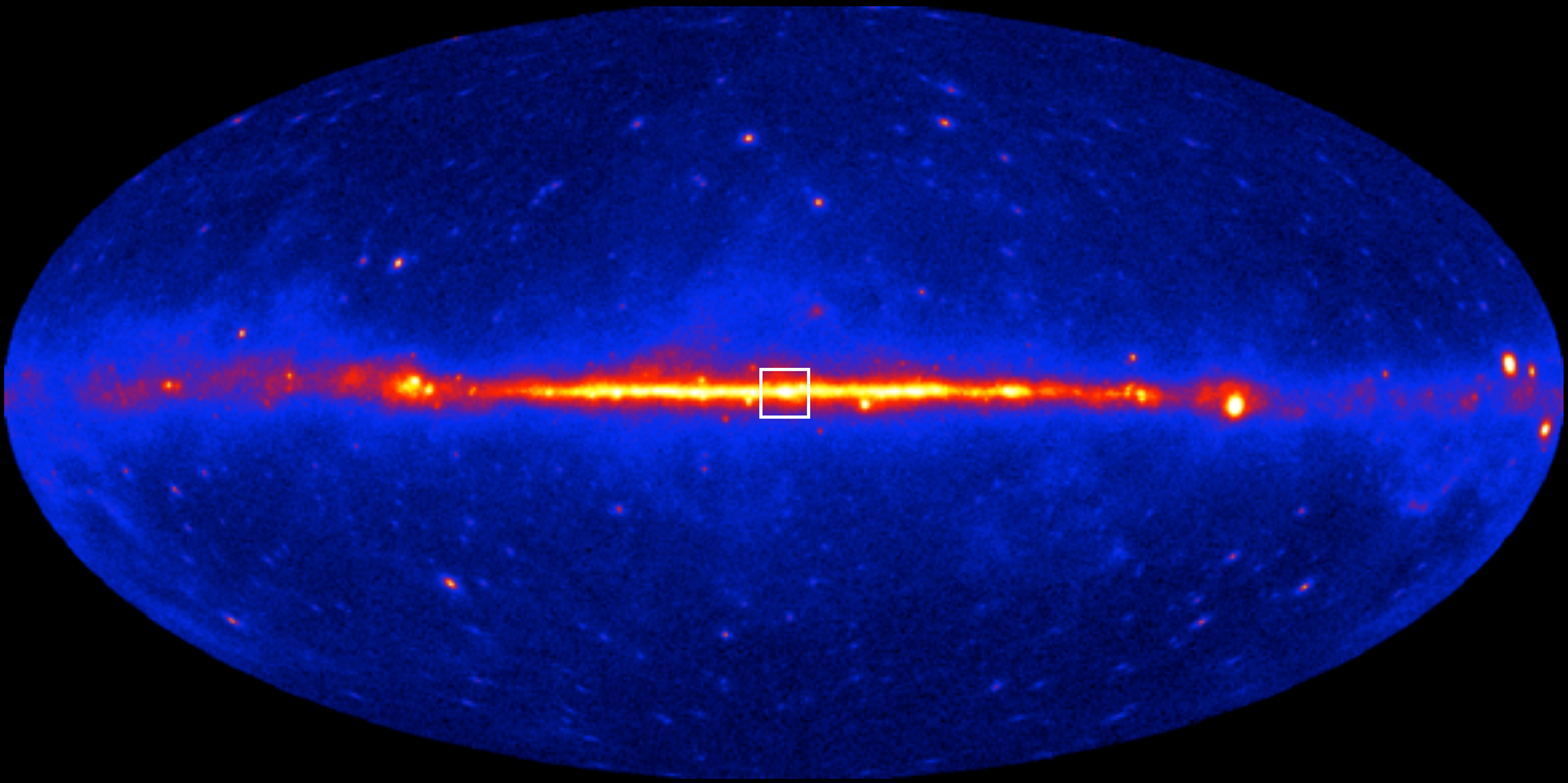
Abazajian & Harding 2012

Fermi-LAT & HESS: The Best Current Constraints on Annihilating Dark Matter

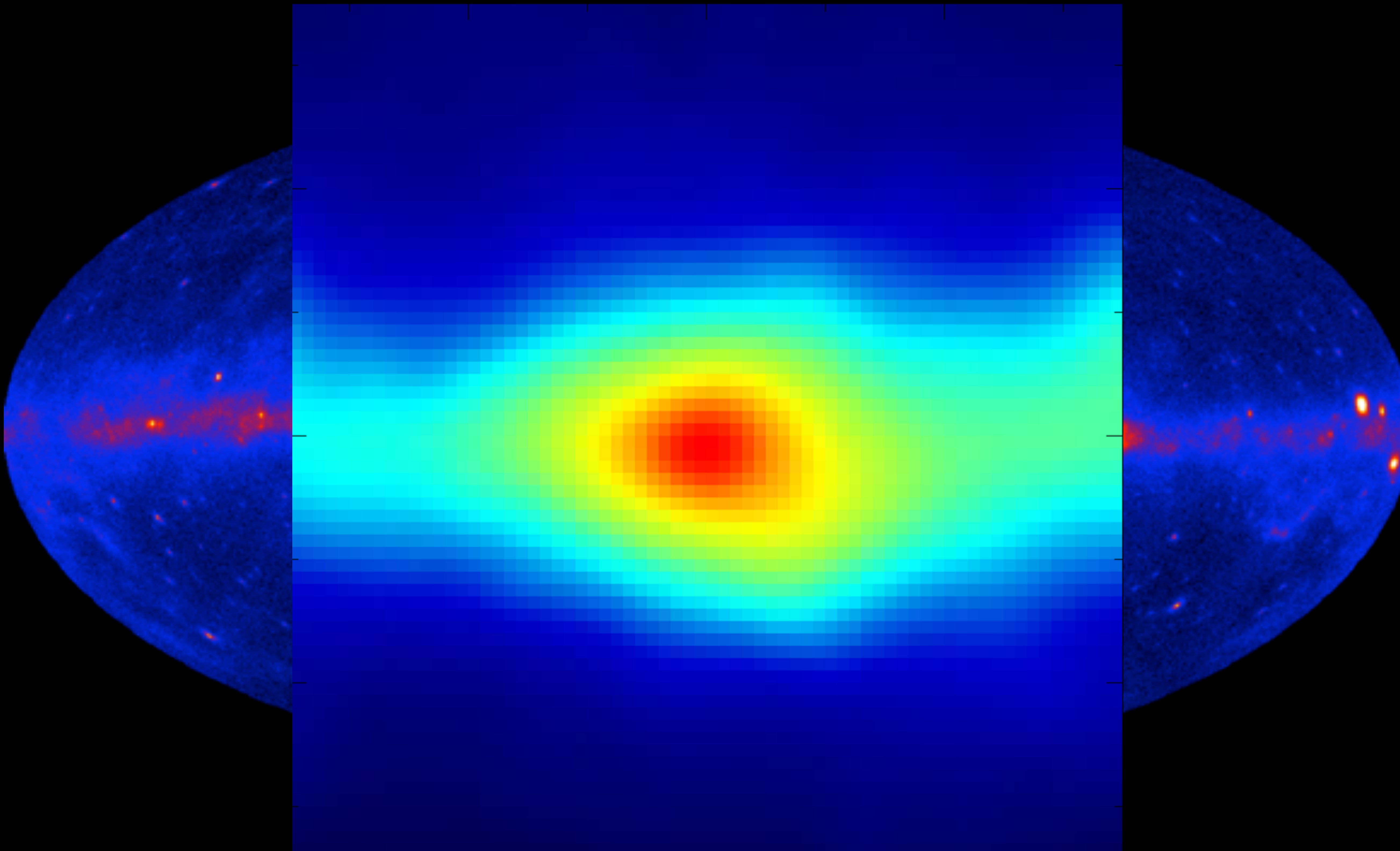


Abazajian & Harding 2012

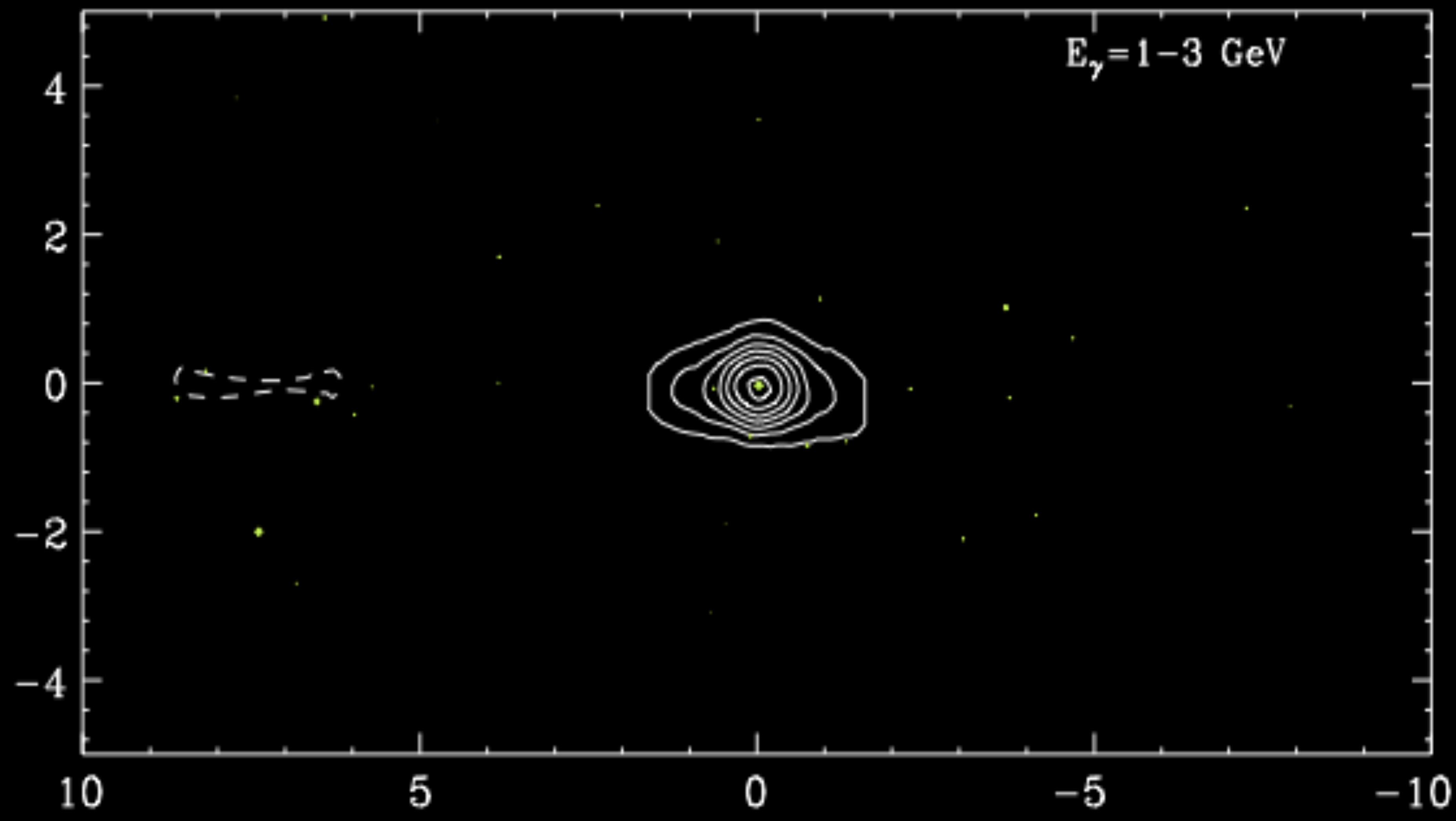
The Observed Fermi-LAT Gamma-Ray Sky



The Observed Fermi-LAT Gamma-Ray Sky



Dark Matter Annihilation in the Galactic Center?



Yes it's extended!

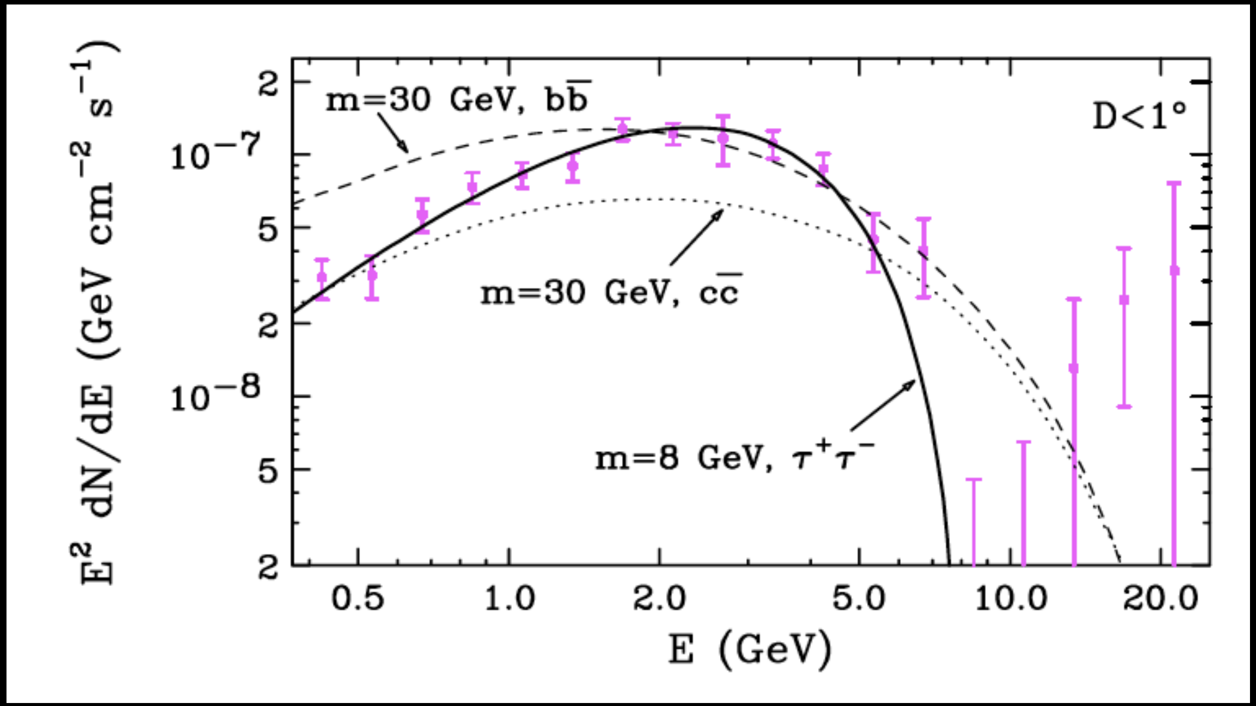
Hooper & Goodenough, 2010
Hooper & Linden, 2011

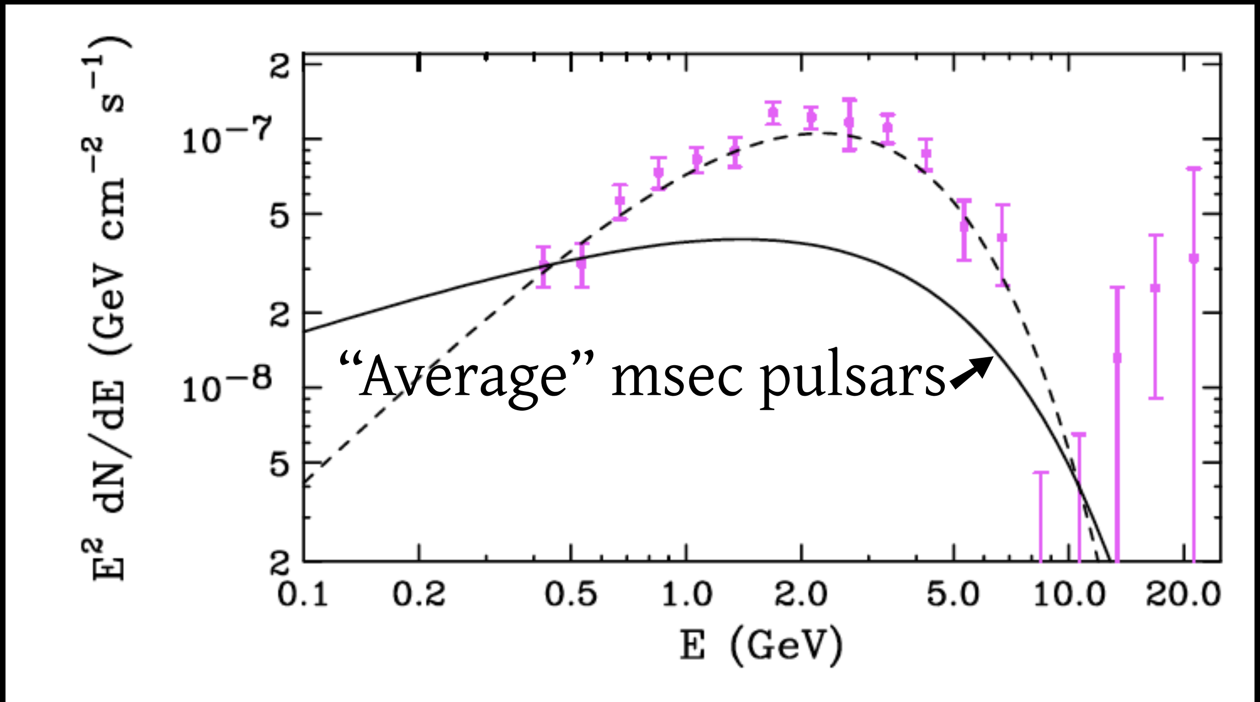
No, it's point sources!

Boyarsky et al. 2011

Dark Matter Annihilation in the Galactic Center?

...or millisecond pulsars? (Abazajian 2011)

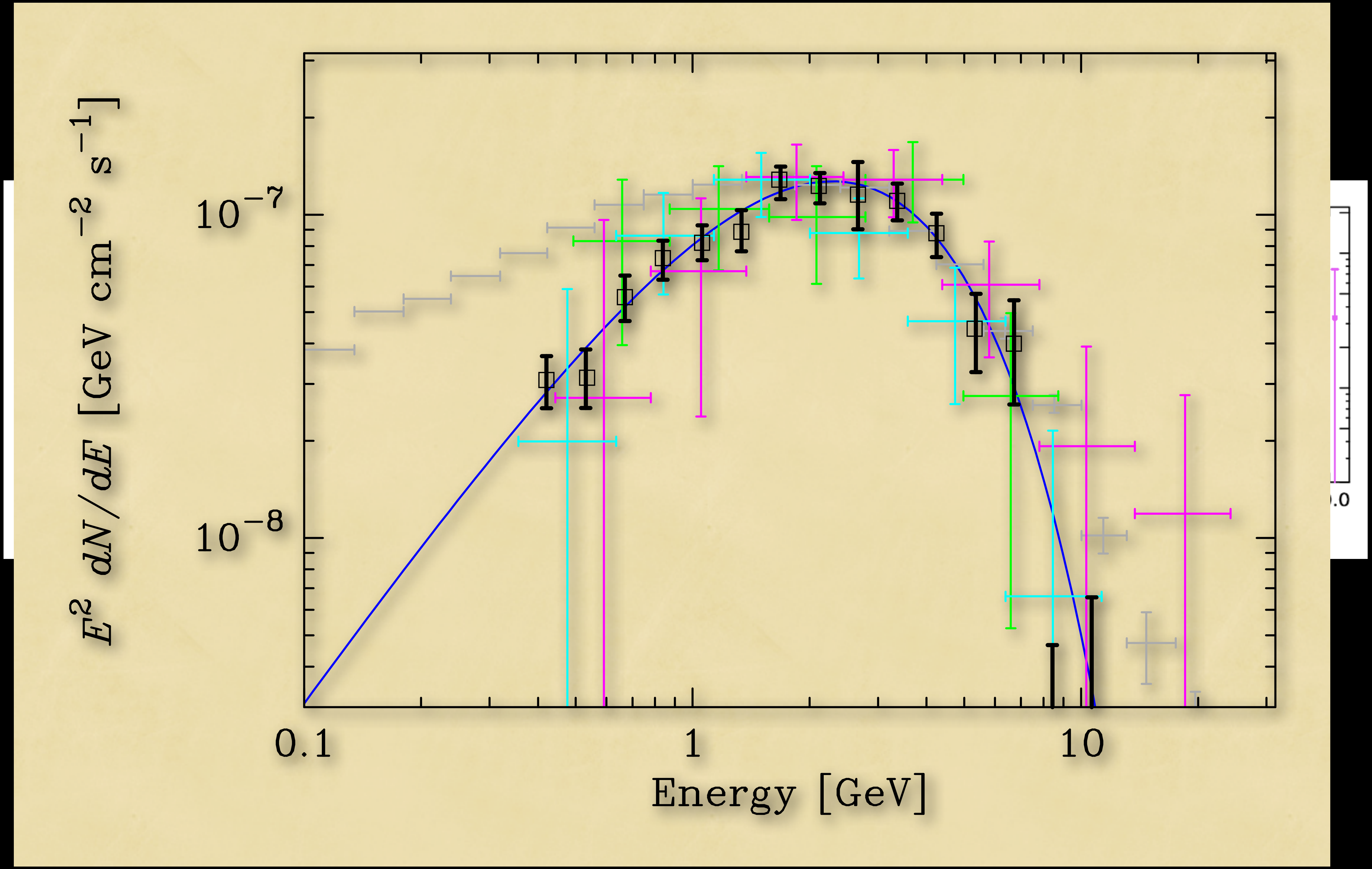




Hooper & Goodenough, arXiv:1010.2752

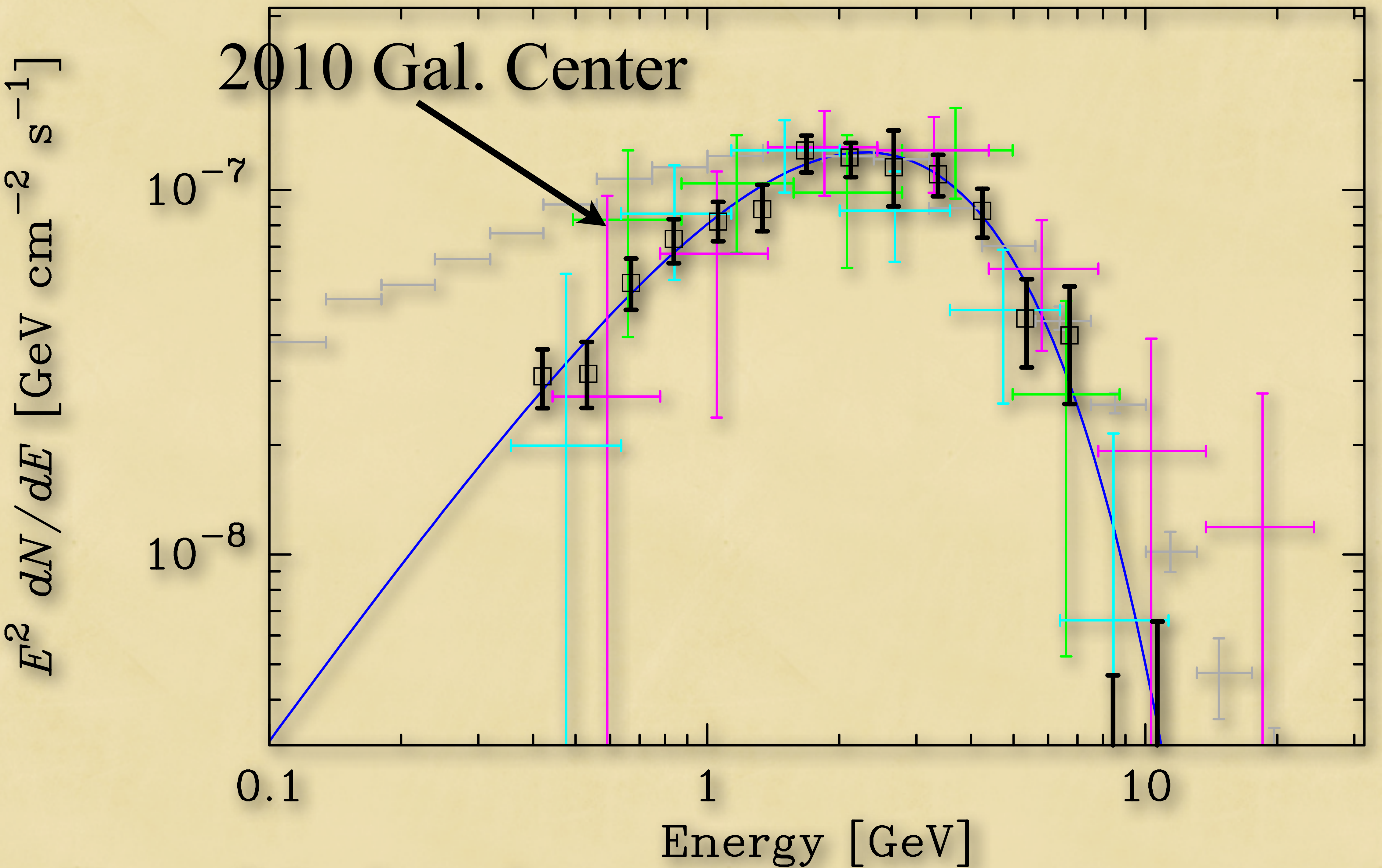
Dark Matter Annihilation in the Galactic Center?

...or millisecond pulsars? (Abazajian 2011)



Dark Matter Annihilation in the Galactic Center?

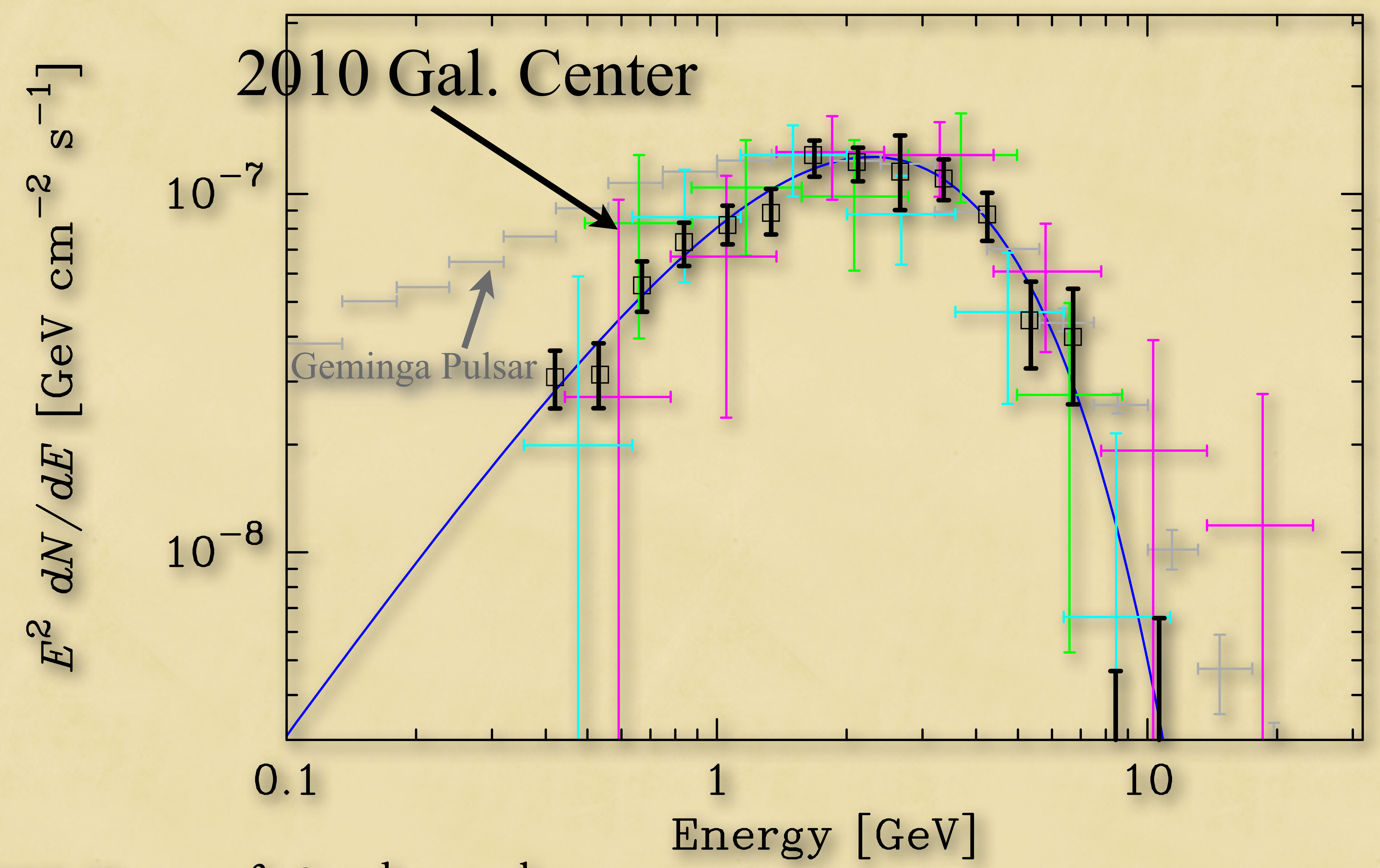
...or millisecond pulsars? (Abazajian 2011)



2010: Hooper & Goodenough

Dark Matter Annihilation in the Galactic Center?

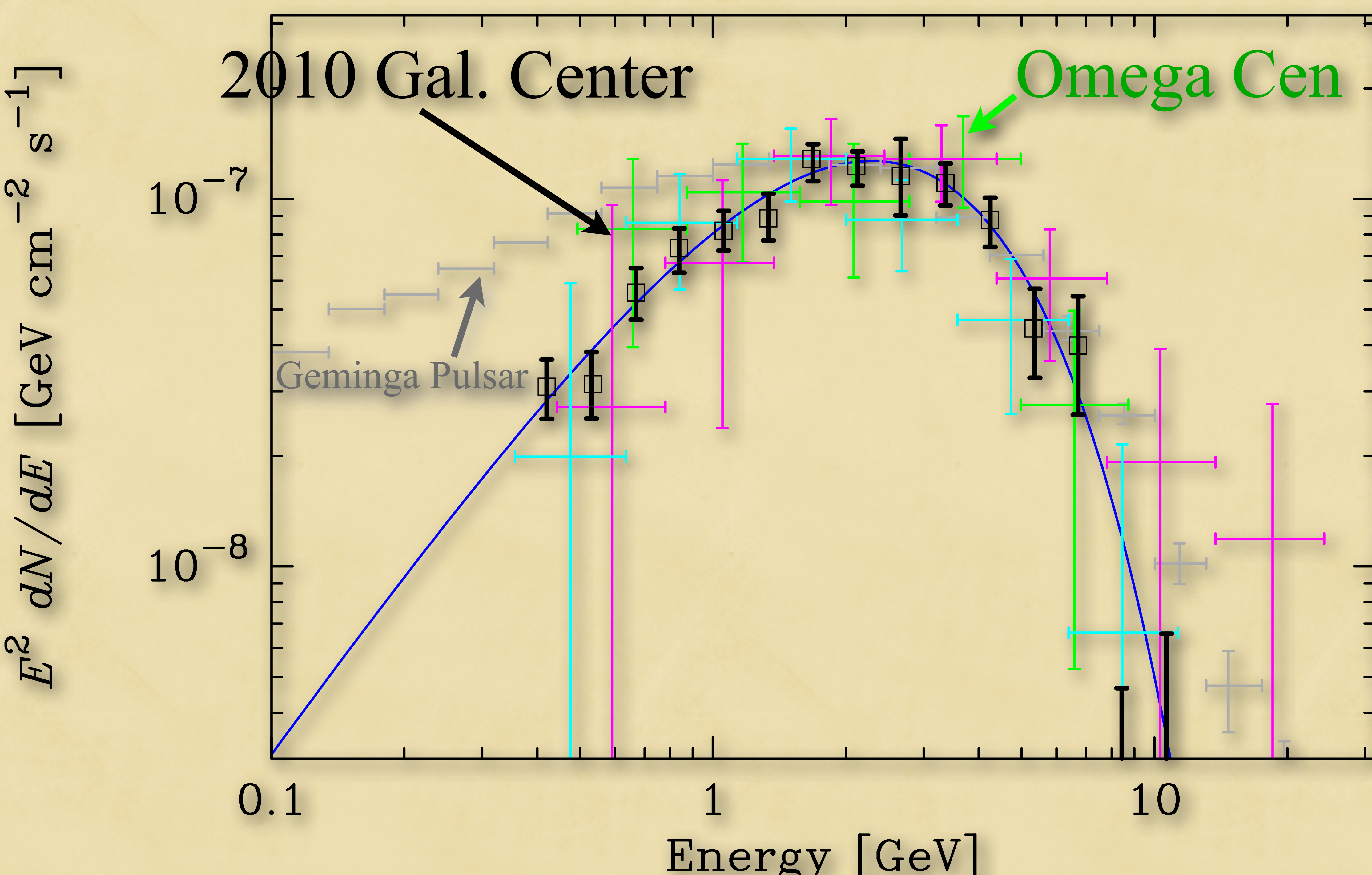
...or millisecond pulsars? (Abazajian 2011)



2010: Hooper & Goodenough

Dark Matter Annihilation in the Galactic Center?

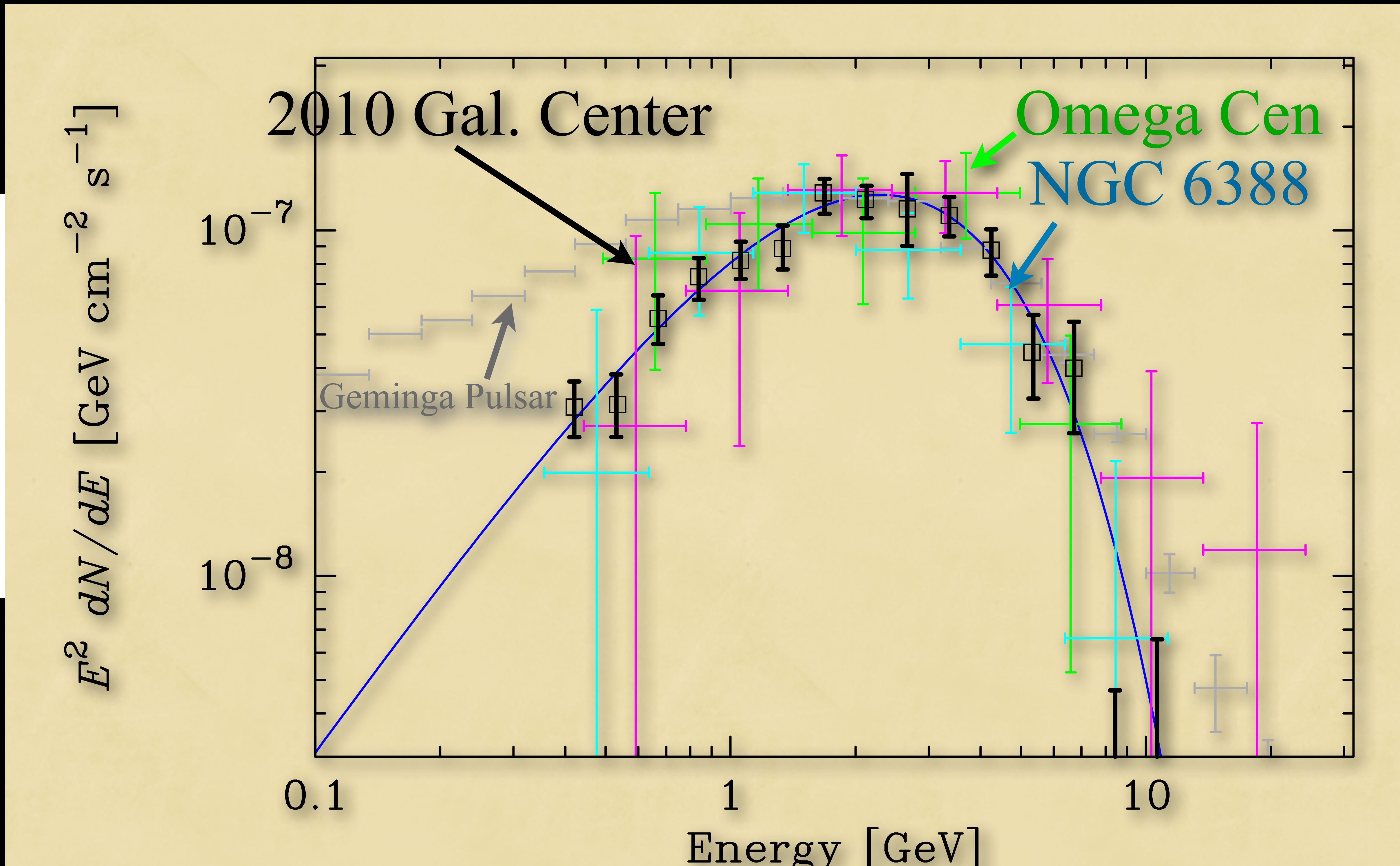
...or millisecond pulsars? (Abazajian 2011)



2010: Hooper & Goodenough

Dark Matter Annihilation in the Galactic Center?

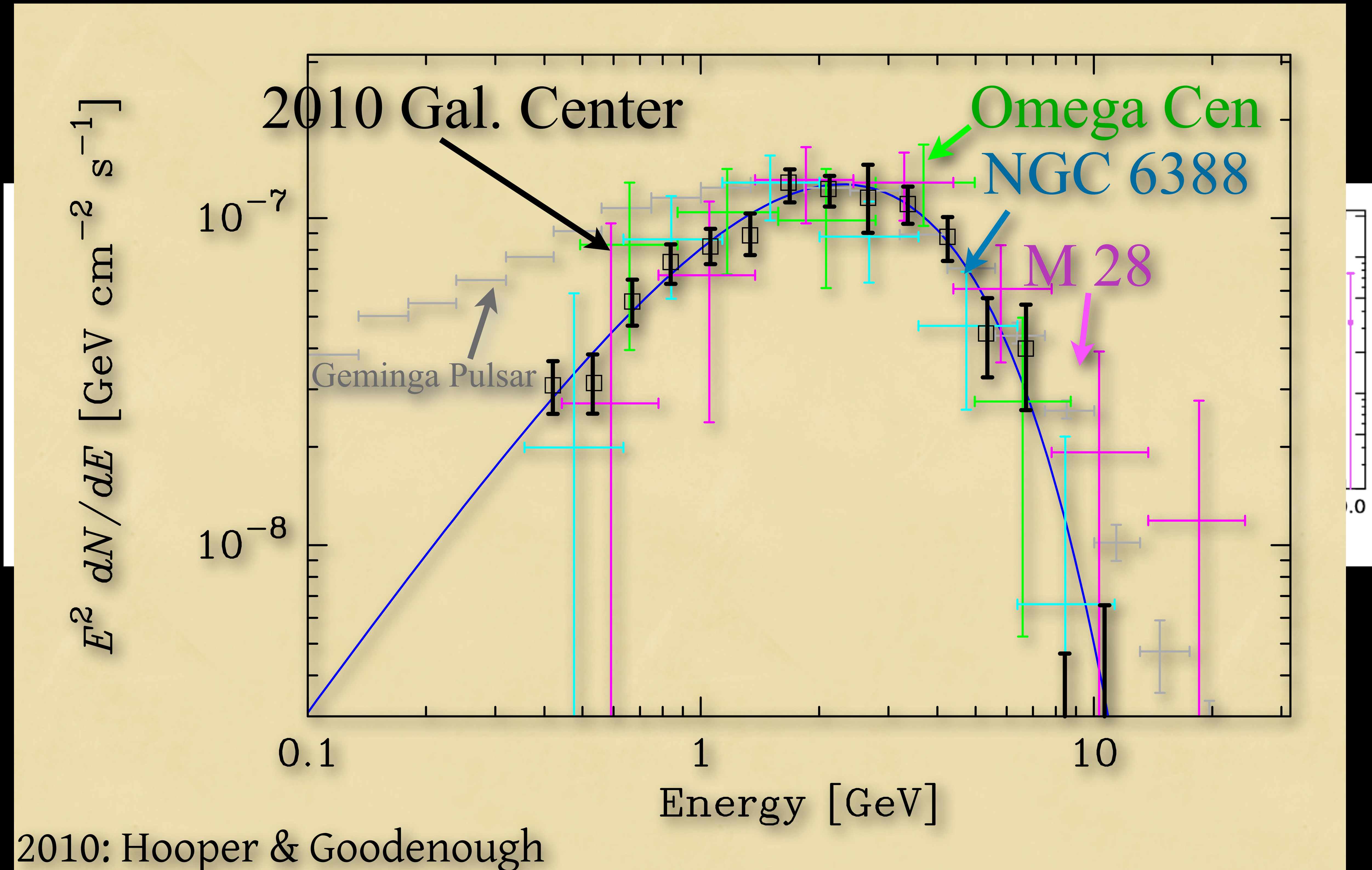
...or millisecond pulsars? (Abazajian 2011)



2010: Hooper & Goodenough

Dark Matter Annihilation in the Galactic Center?

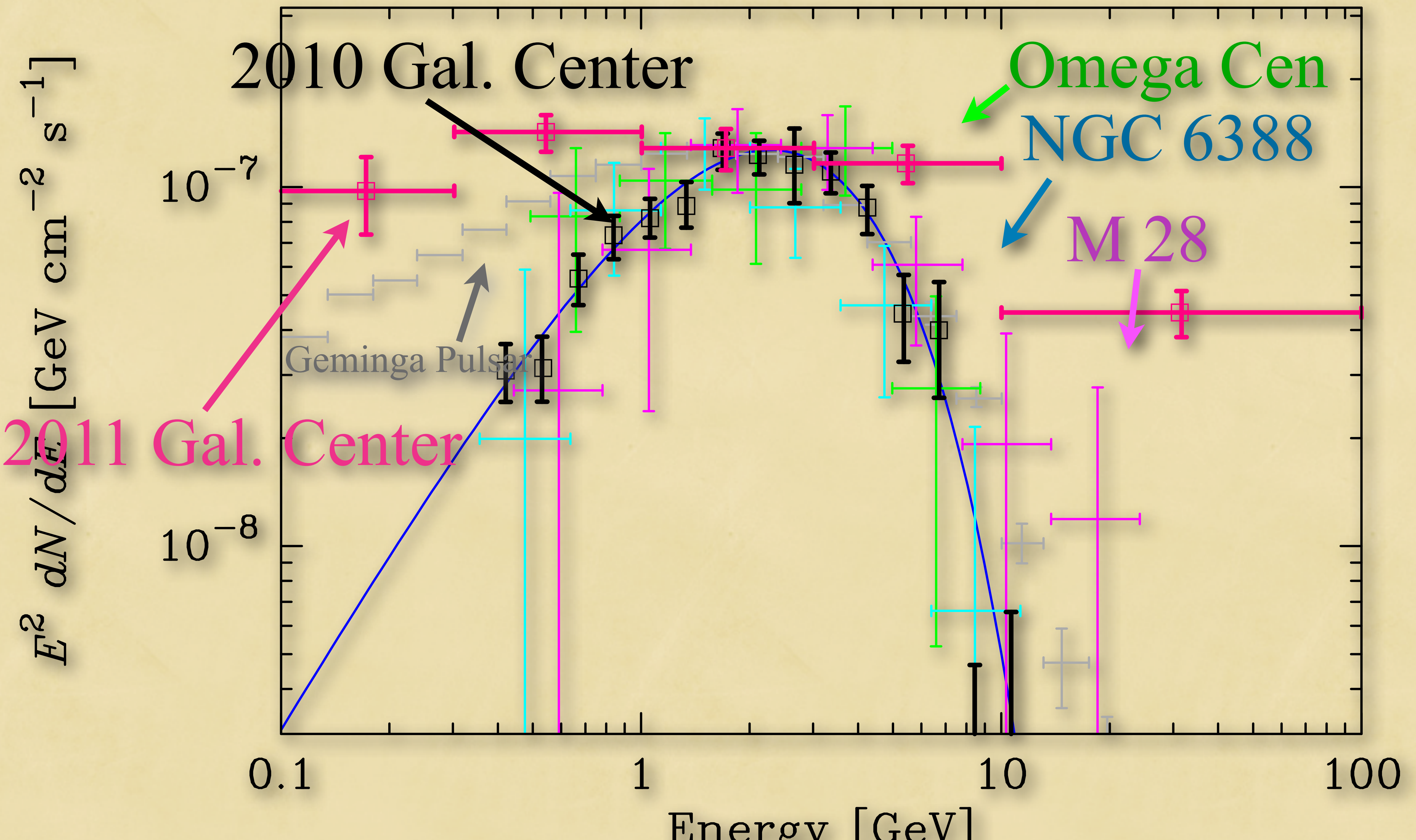
...or millisecond pulsars? (Abazajian 2011)



2010: Hooper & Goodenough

Dark Matter Annihilation in the Galactic Center?

...or millisecond pulsars? (Abazajian 2011)

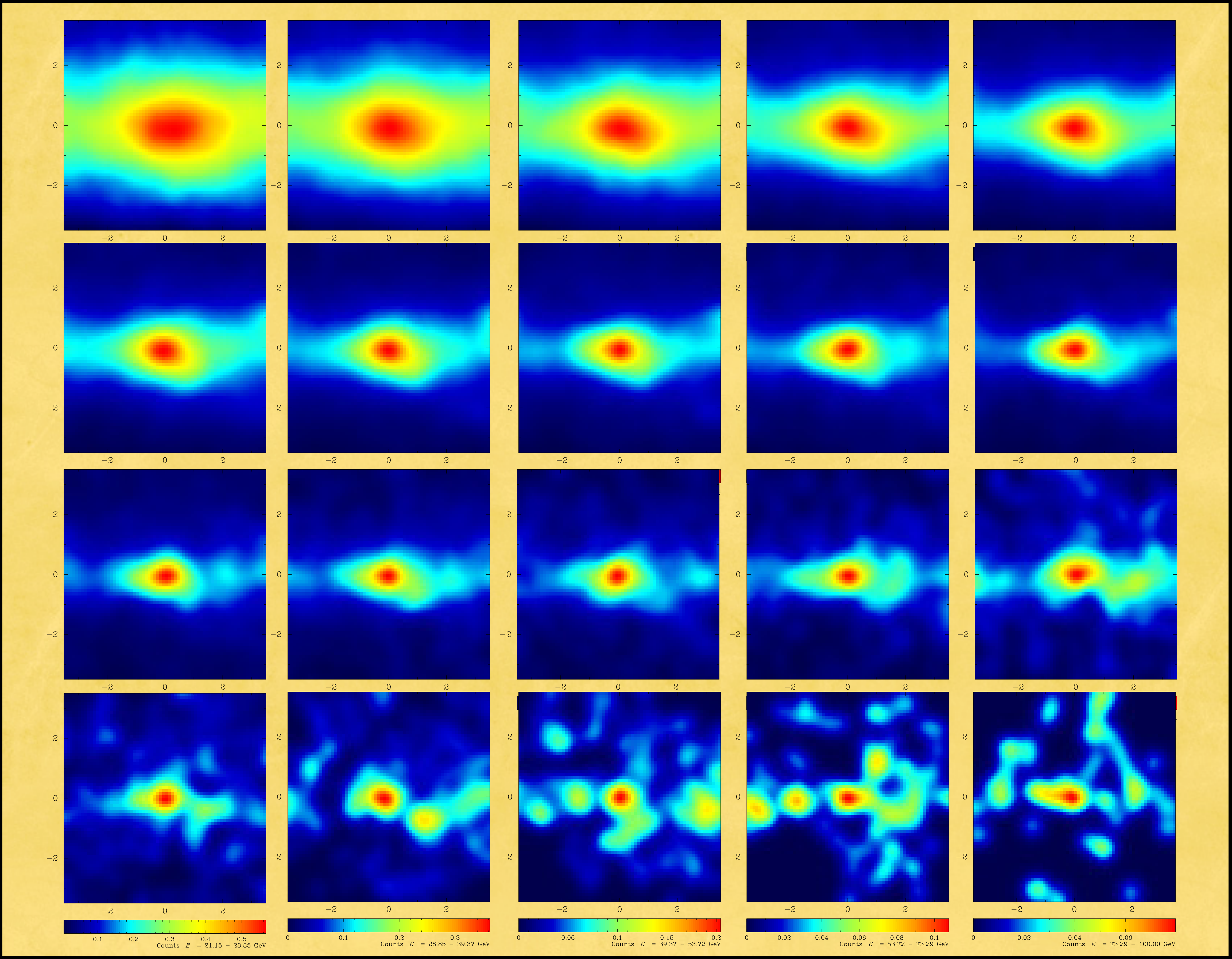


2010: Hooper & Goodenough

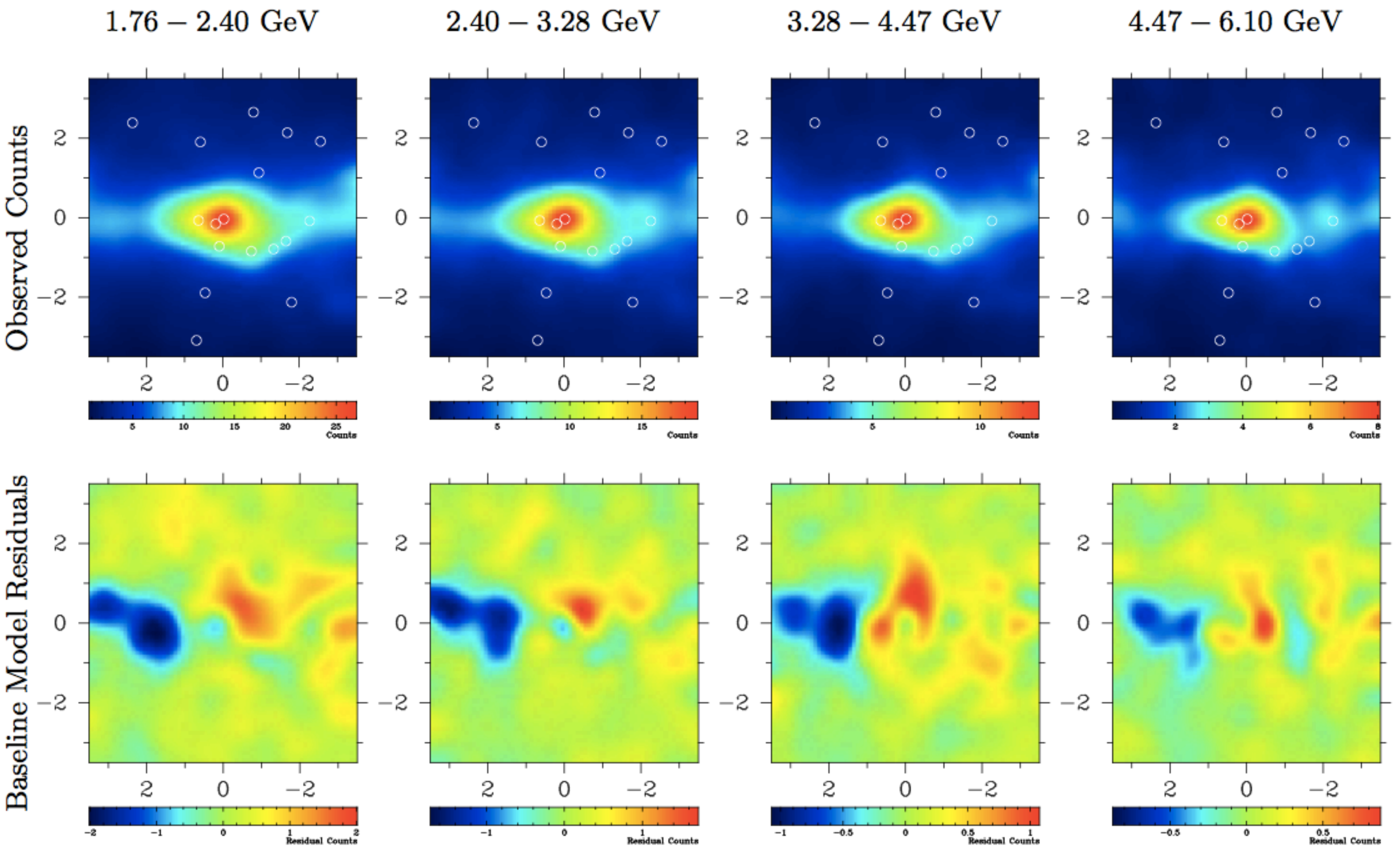
2011: Hooper & Linden

Sources in the Galactic Center: Spatial-Spectral Degeneracy

Abazajian & Kaplinghat, 2012



Fermi-LAT 2 Year Point Sources and Diffuse Galactic & Extragalactic Fit Subtraction



Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	$\mathrm{TS}_{\mathrm{approx}}$	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
Baseline	—			

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
Baseline	–	-	140070.2	–

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
Baseline	—	-	140070.2	—
Density $\Gamma = 0.7$	LogPar			

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
Baseline	–	-	140070.2	–
Density $\Gamma = 0.7$	LogPar	1725.5	139755.5	314.7

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
Baseline	–	-	140070.2	–
Density $\Gamma = 0.7$	LogPar	1725.5	139755.5	314.7
Density^2 $\gamma = 0.9$	LogPar			

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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			

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	$TS_{\rm approx}$	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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			

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
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

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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			

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
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			

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
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			

Method & Results

- Fit all of the 17 point sources in the ROI iteratively, starting from the central sources, also varying the Galactic & Isotropic Diffuse Backgrounds
- Add central extended sources with several morphologies & spectra, repeating the step above for each case

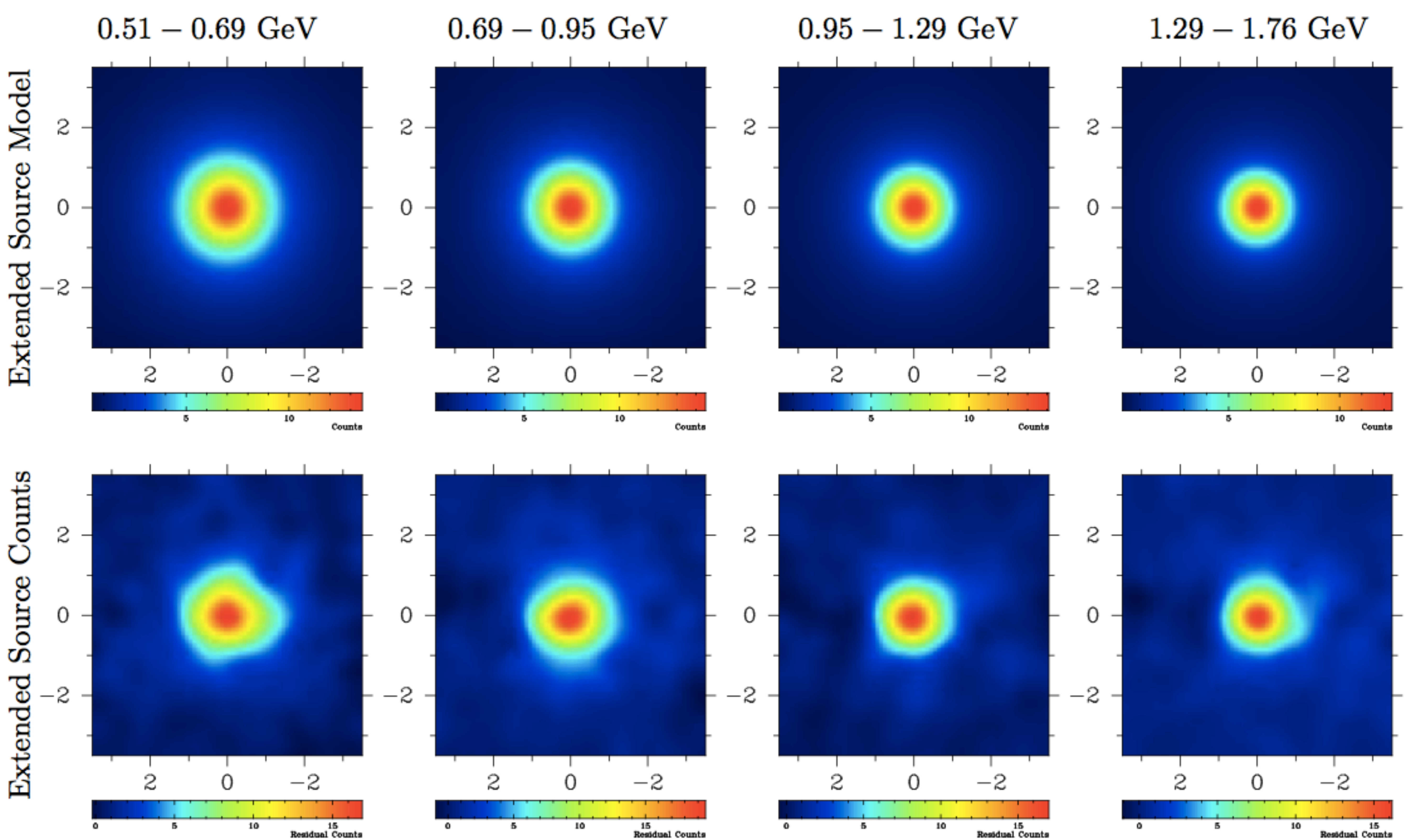
Spatial Model	Spectrum	TS_{approx}	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
Baseline	–	-	140070.2	–
Density $\Gamma = 0.7$	LogPar	1725.5	139755.5	314.7
Density^2 $\gamma = 0.9$	LogPar	1212.8	139740.0	330.2
Density^2 $\gamma = 1.0$	LogPar	1441.8	139673.3	396.9
Density^2 $\gamma = 1.1$	LogPar	2060.5	139651.8	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

Dark Matter Annihilation Channel Fits

channel, m_χ	$\mathrm{TS}_{\mathrm{approx}}$	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
$b\bar{b}$, 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

Dark Matter in the Galactic Center?

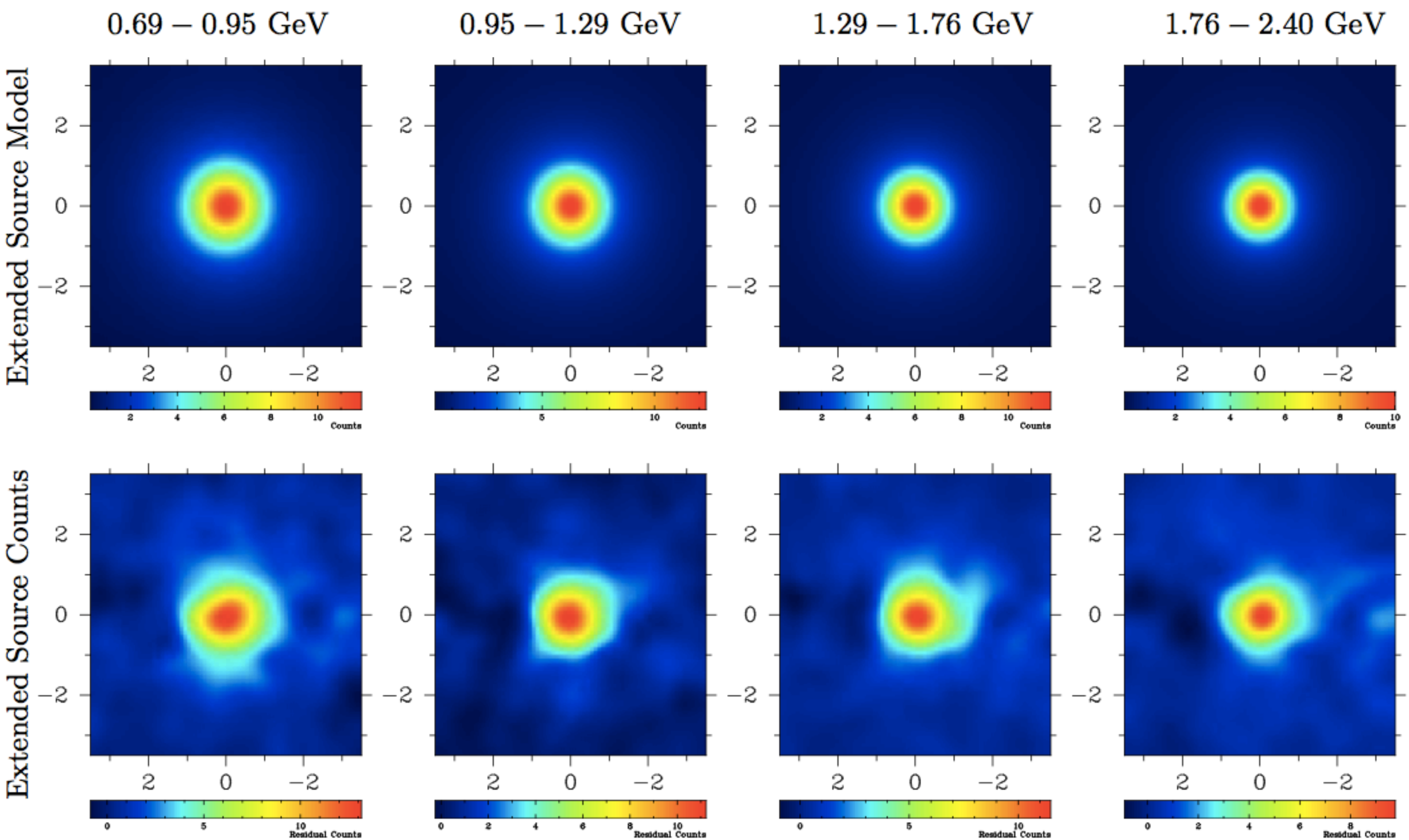
General Log-Parabola Spectrum — NFW $\gamma = 1.3$



Dark Matter in the Galactic Center?

$m_\chi = 30$ GeV
NFW $\gamma = 1.2$

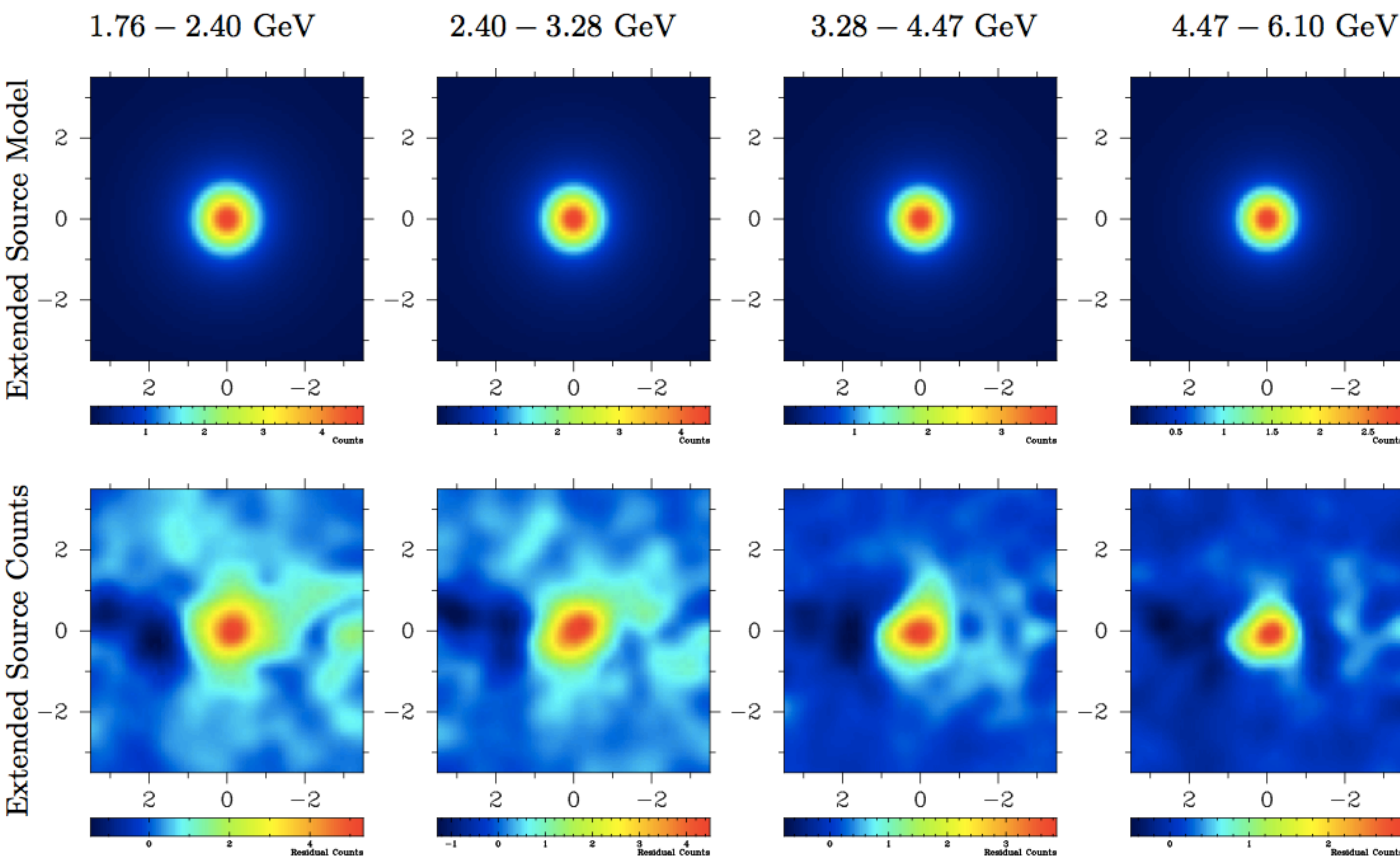
$$\mathrm{TS_{true}} = 2\Delta \ln \mathcal{L} = 824,\ \ 28.7\sigma,\ \ p = 4 \times 10^{-181}$$



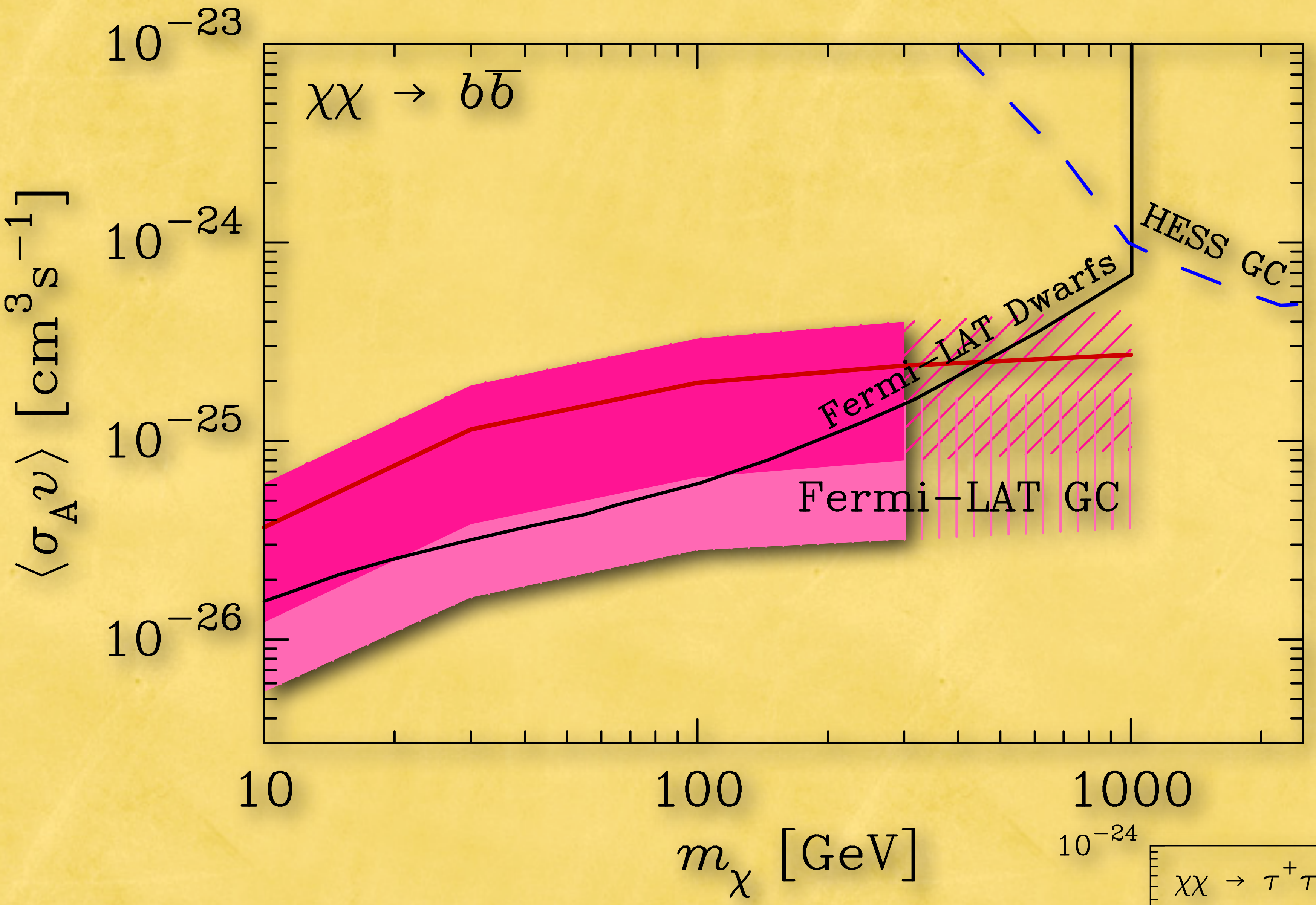
$m_\chi = 100$ GeV

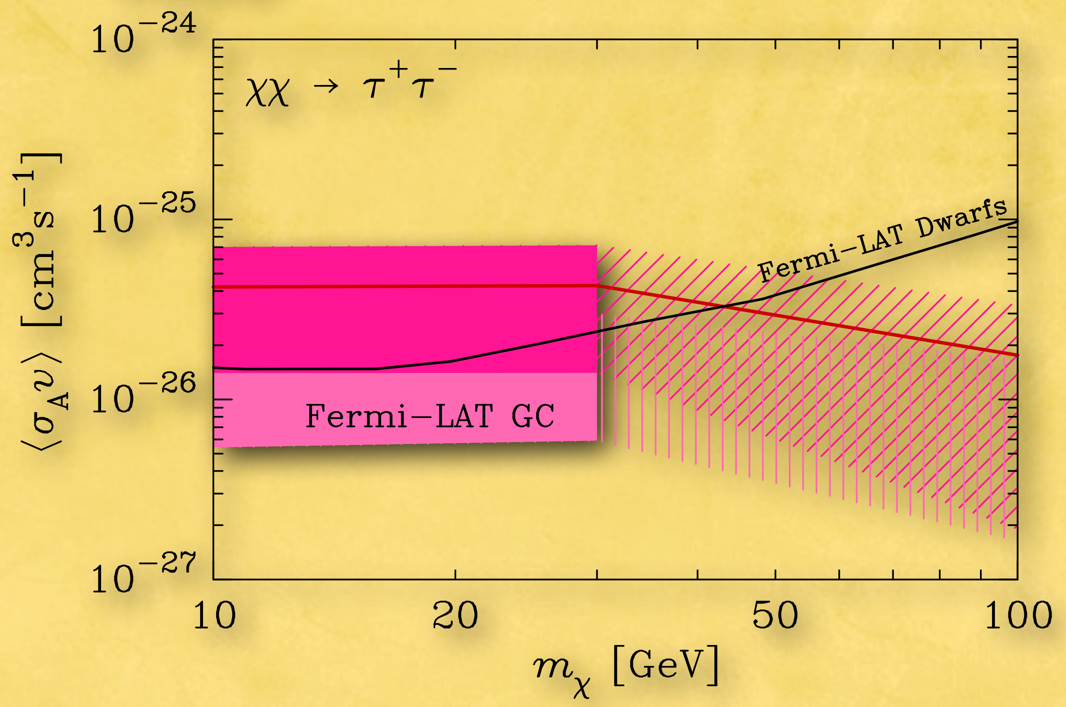
NFW $\gamma = 1.2$

$TS_{true} = 2 \ln \mathcal{L} = 378;\ 19.4\sigma,\ p = 3 \times 10^{-84}$

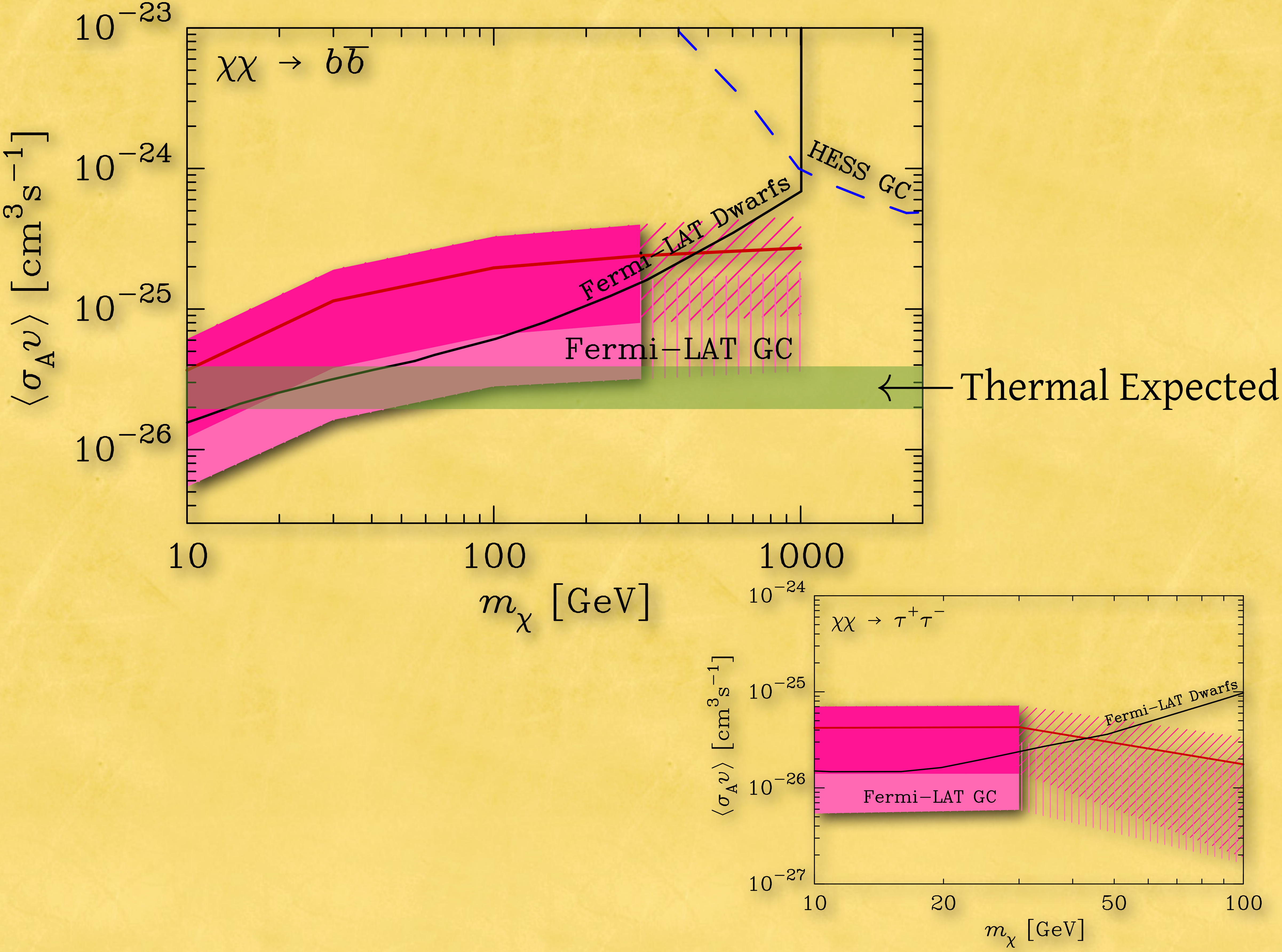


Signal Parameters

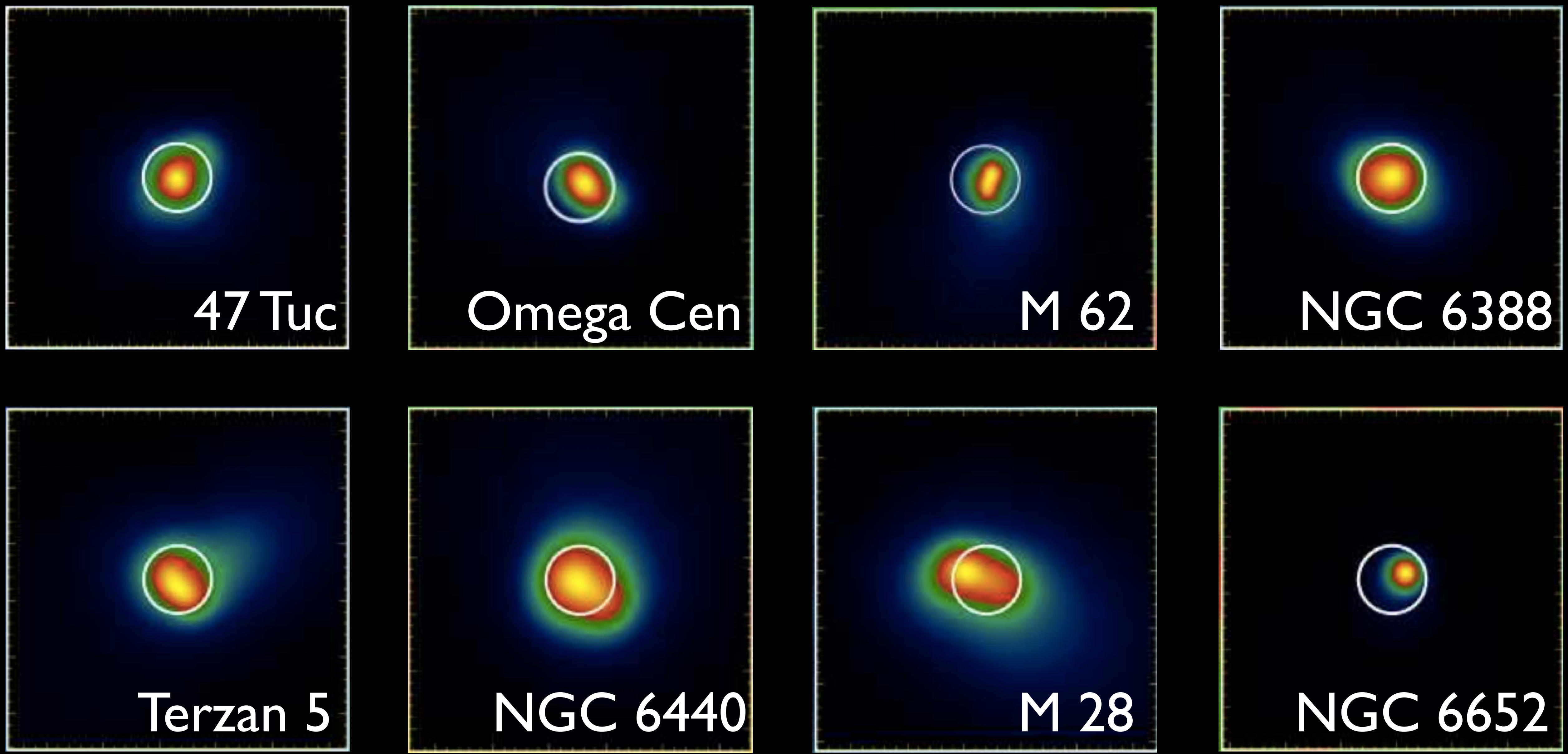




Signal Parameters



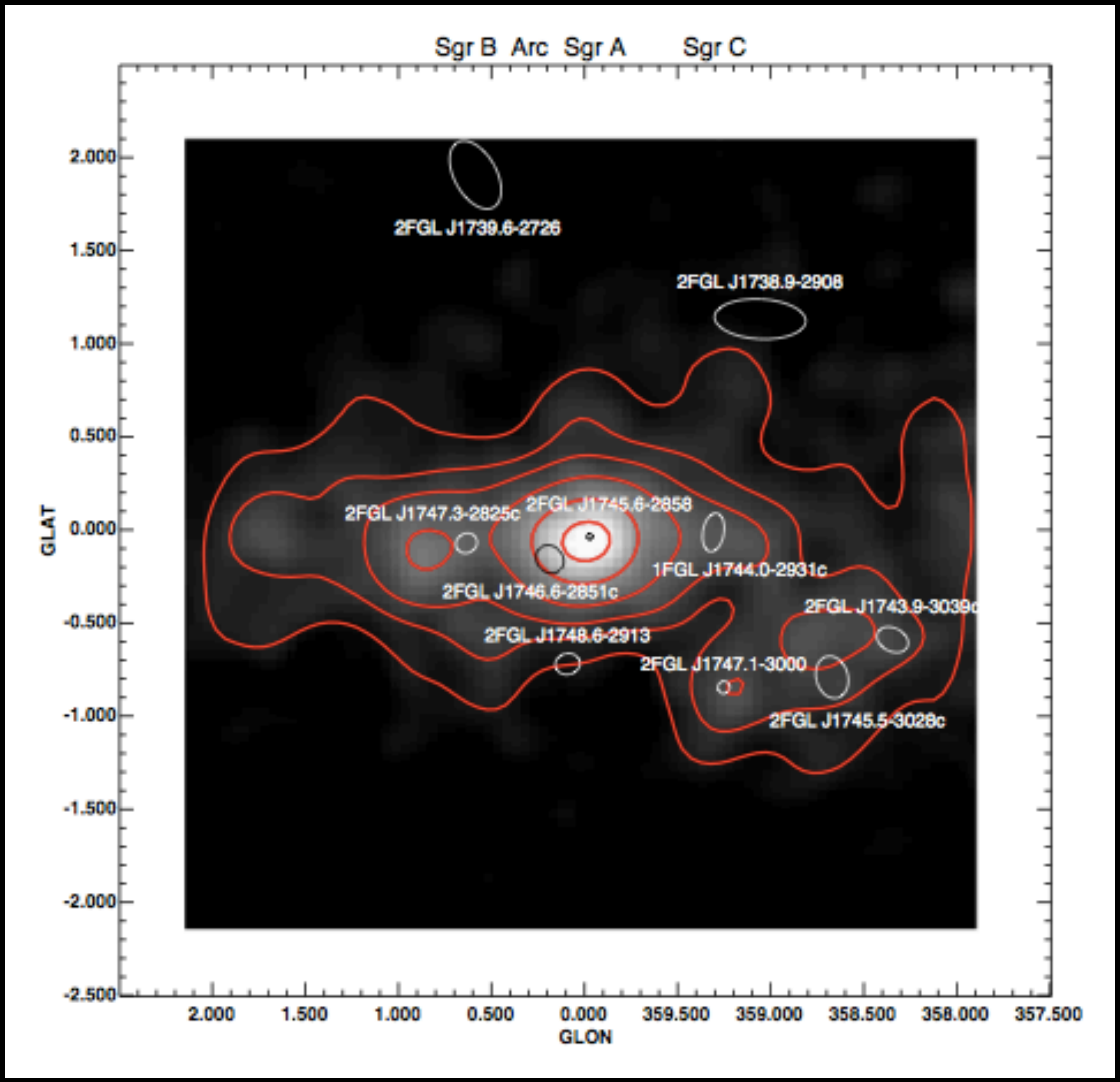
Is it dark matter?
Millisecond Pulsars in Stellar & Globular Clusters

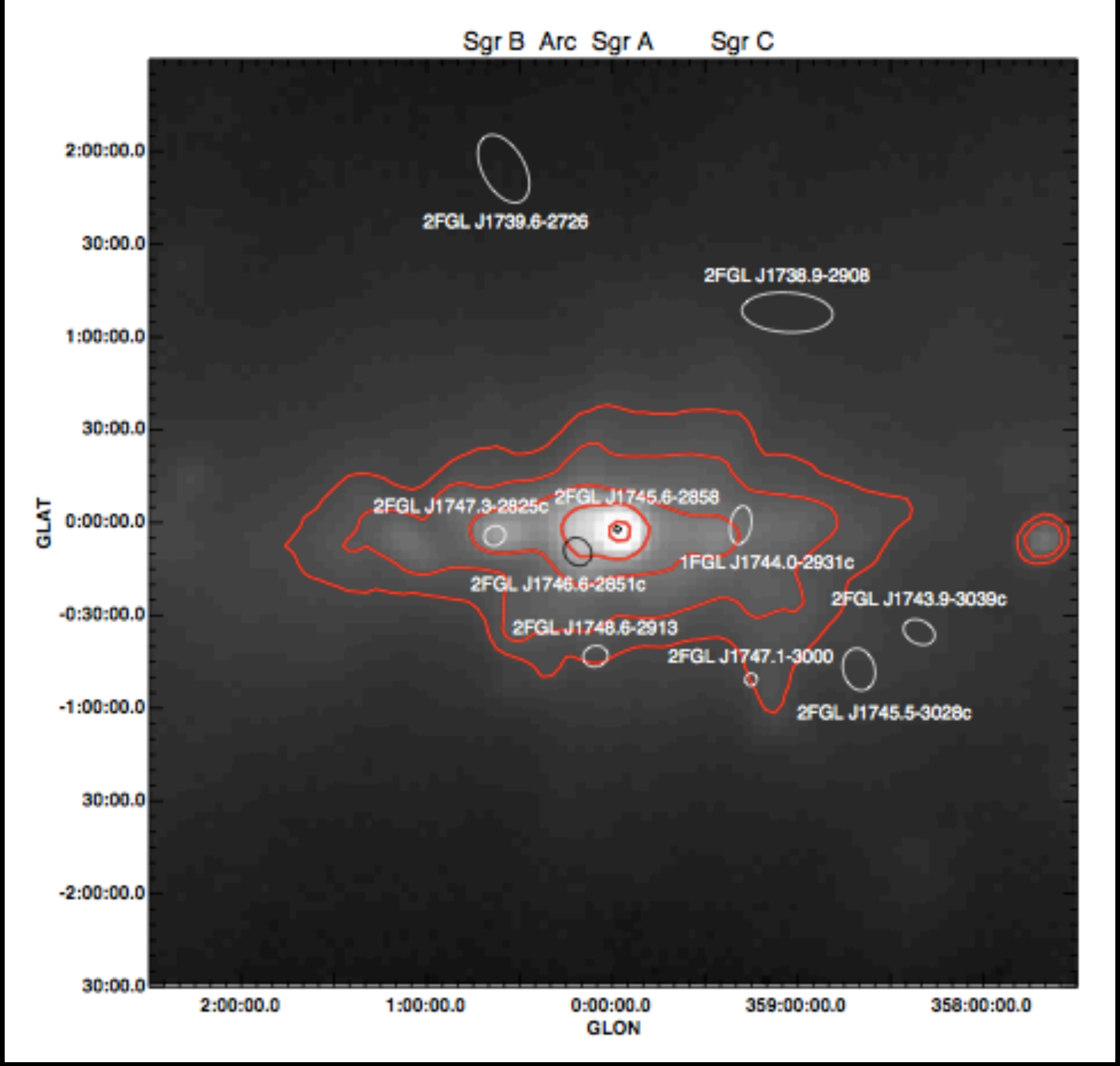


- Requires the flux from the GC MSPs to be ~200 times that in Omega Cen - reasonable stellar mass is ~800 times
- Requires ~1000 MSPs in the GC region - again reasonable scale
- Requires a centrally concentrated density profile $n \sim r^{-2.6}$, which is seen for the central density distribution of LMXBs in M31 (see also Wharton et al 2012)

Cosmic-Ray e^- Bremsstrahlung on Molecular Gas

Yusef-Zadeh et al 2012



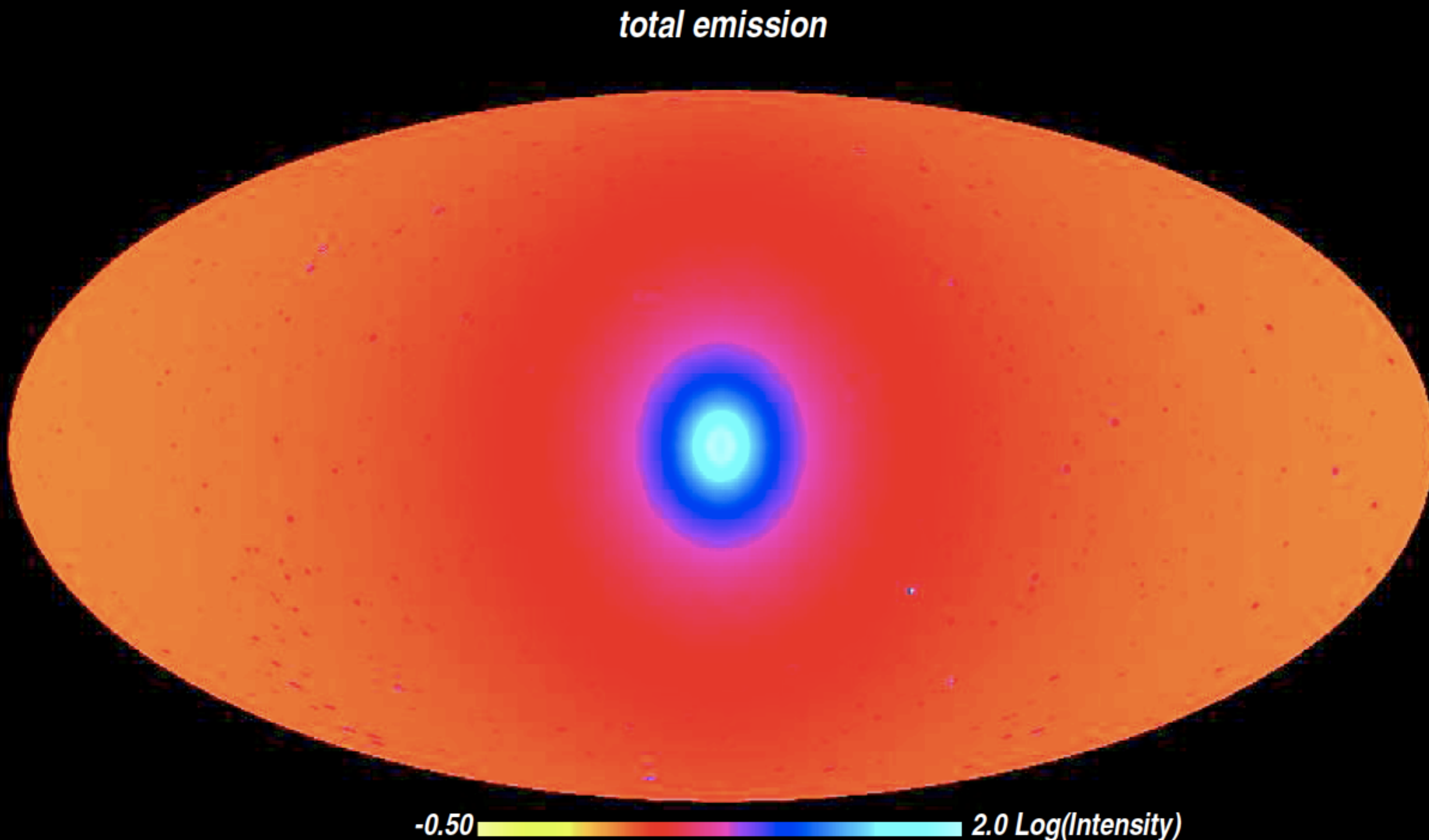


Gamma-Ray

1.4 GHz Radio

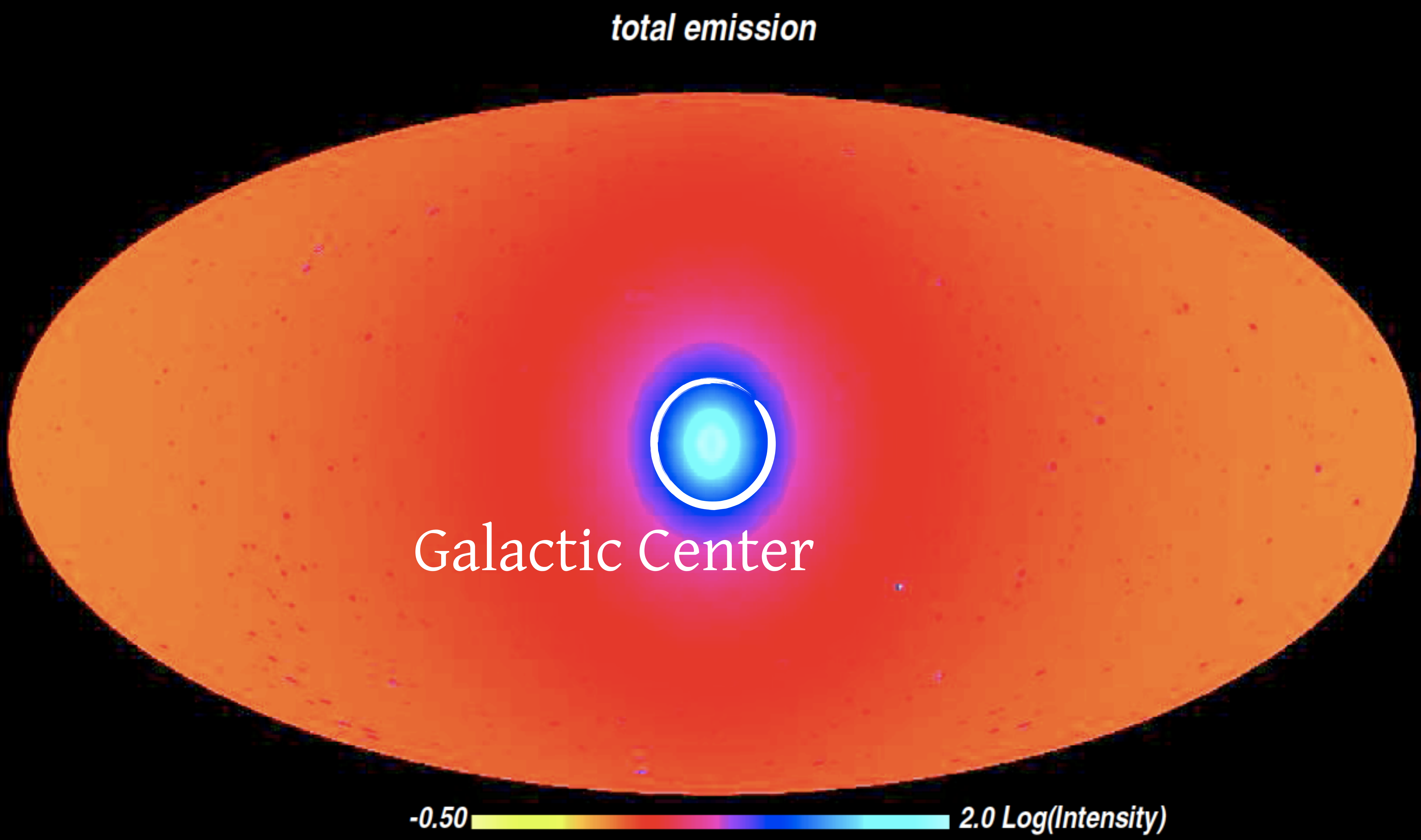
However, 2Δln(Like) is better for NFW γ =1.2 maps
than the radio map analysis (210 vs 113).

Low-Background Sources Will Differentiate...



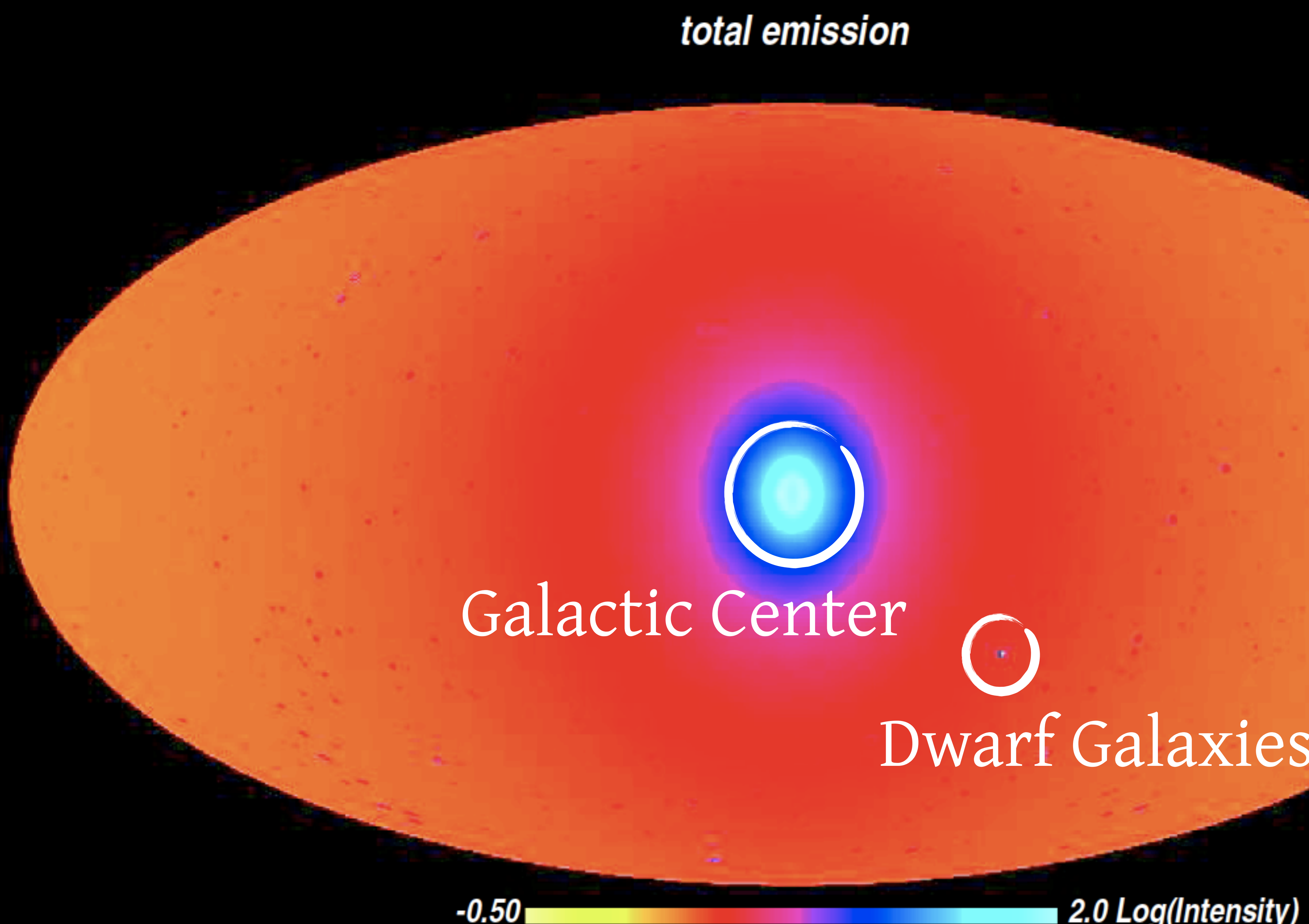
Springel et al 2008

Low-Background Sources Will Differentiate...



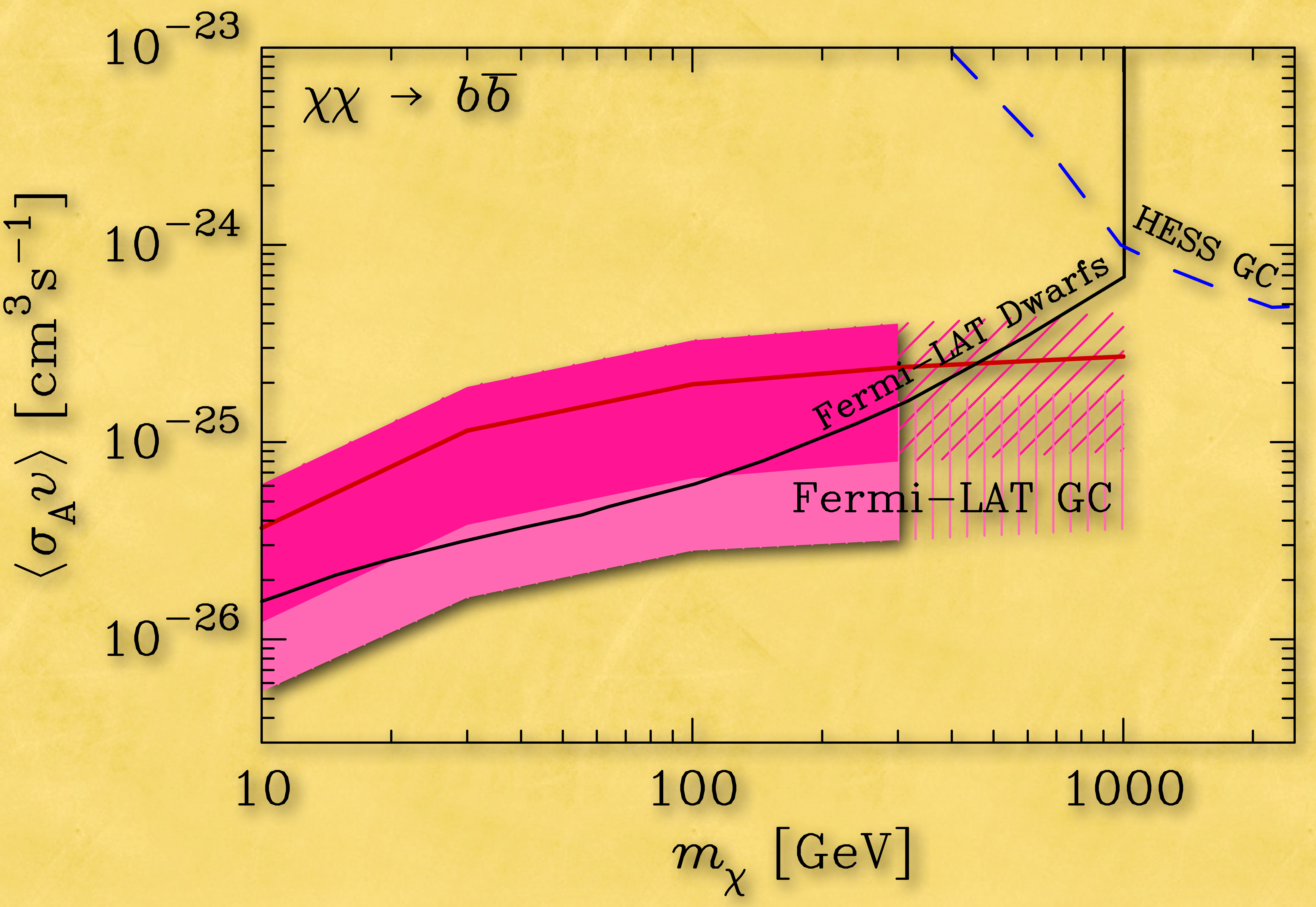
Springel et al 2008

Low-Background Sources Will Differentiate...

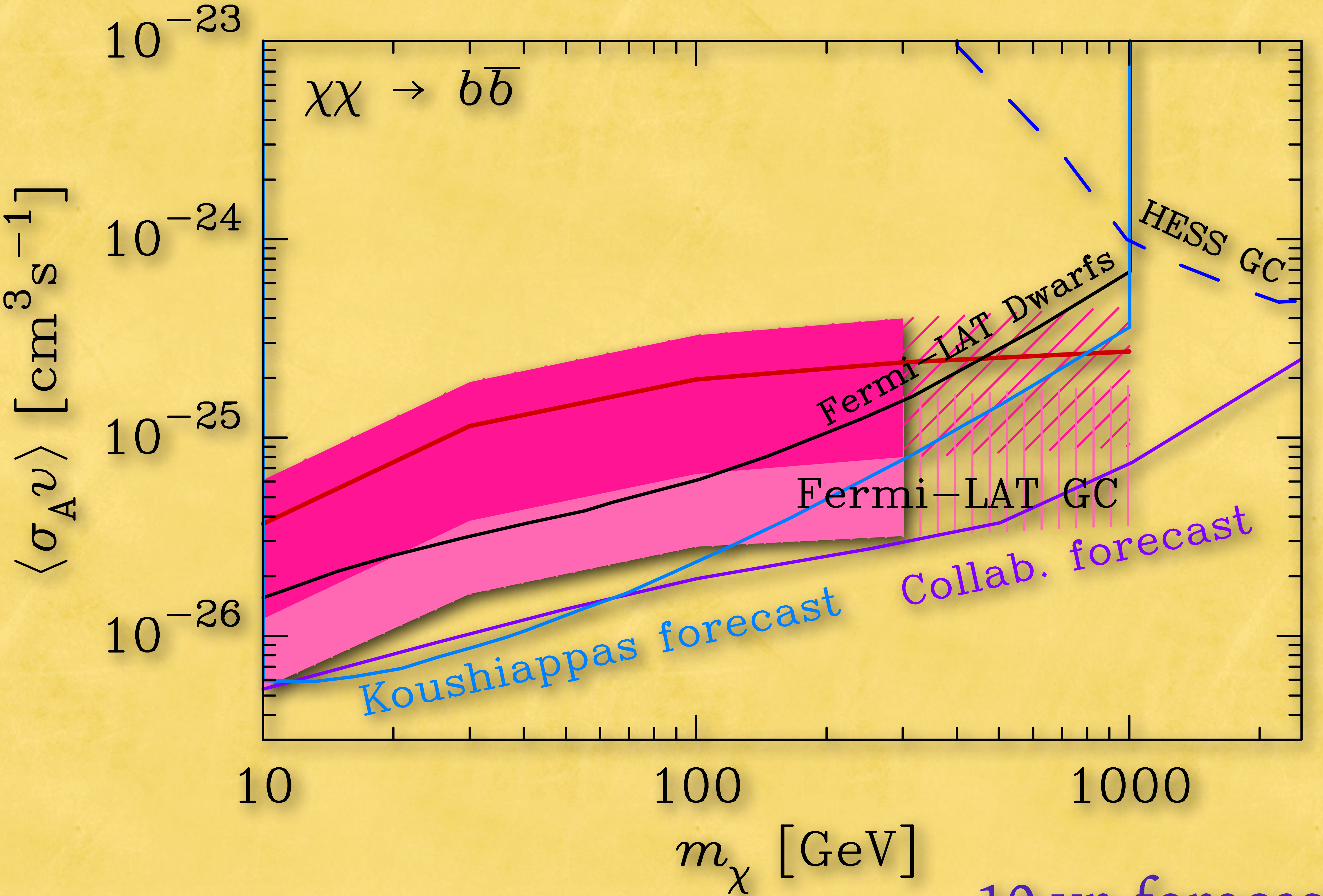


Springel et al 2008

Low-Background Sources Will Differentiate...

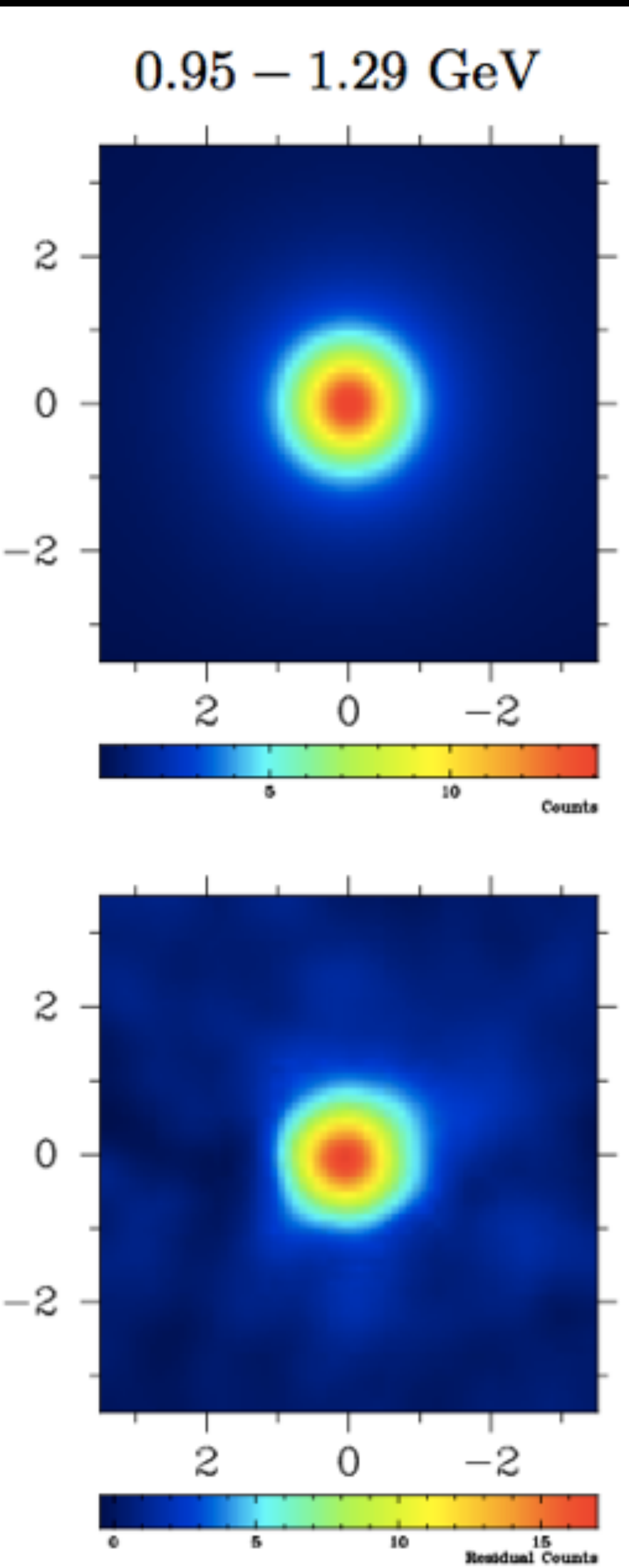


Low-Background Sources Will Differentiate...

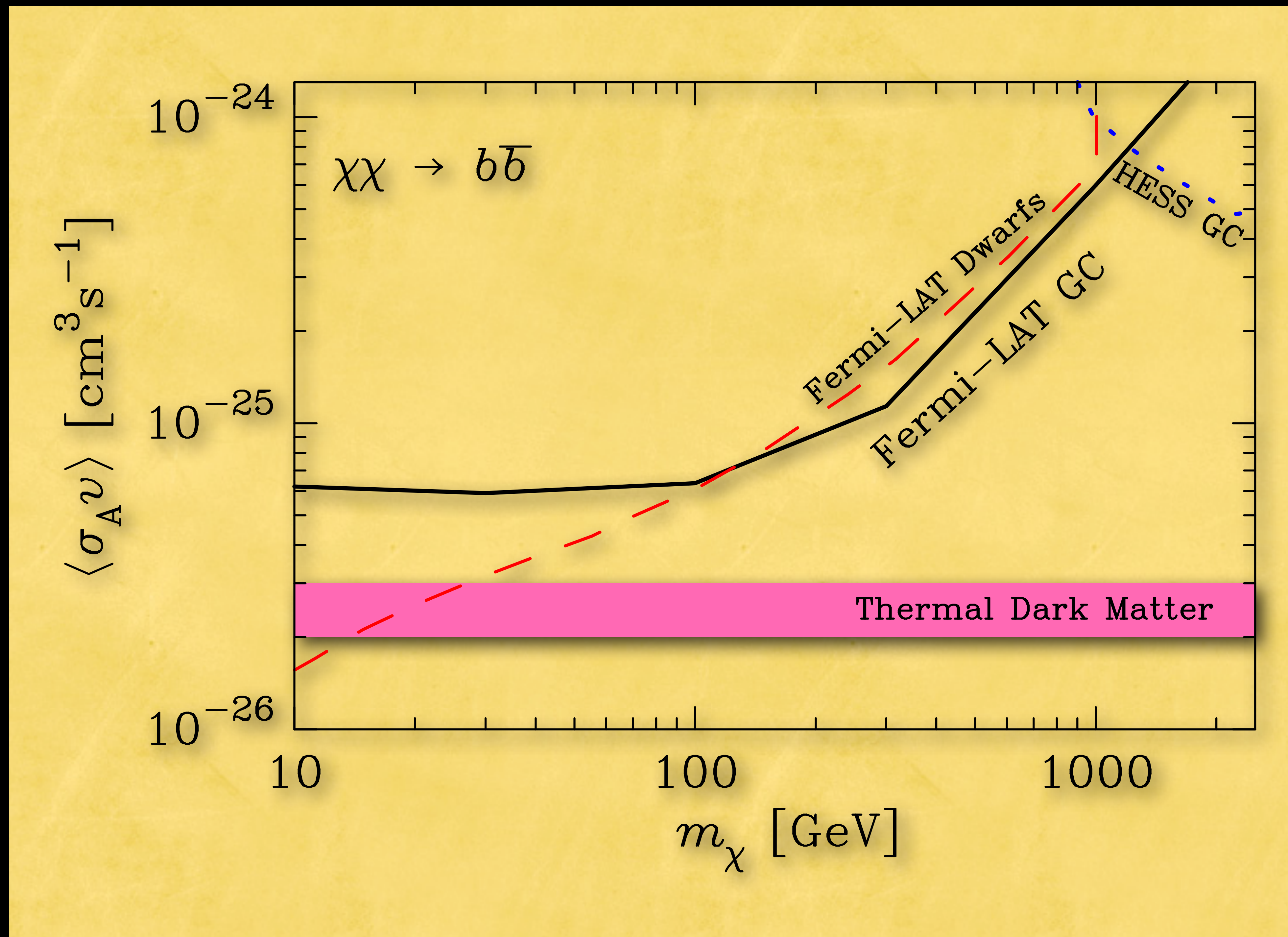


10 yr. forecasts

$\gamma_\rho = 2.4$, LogPar

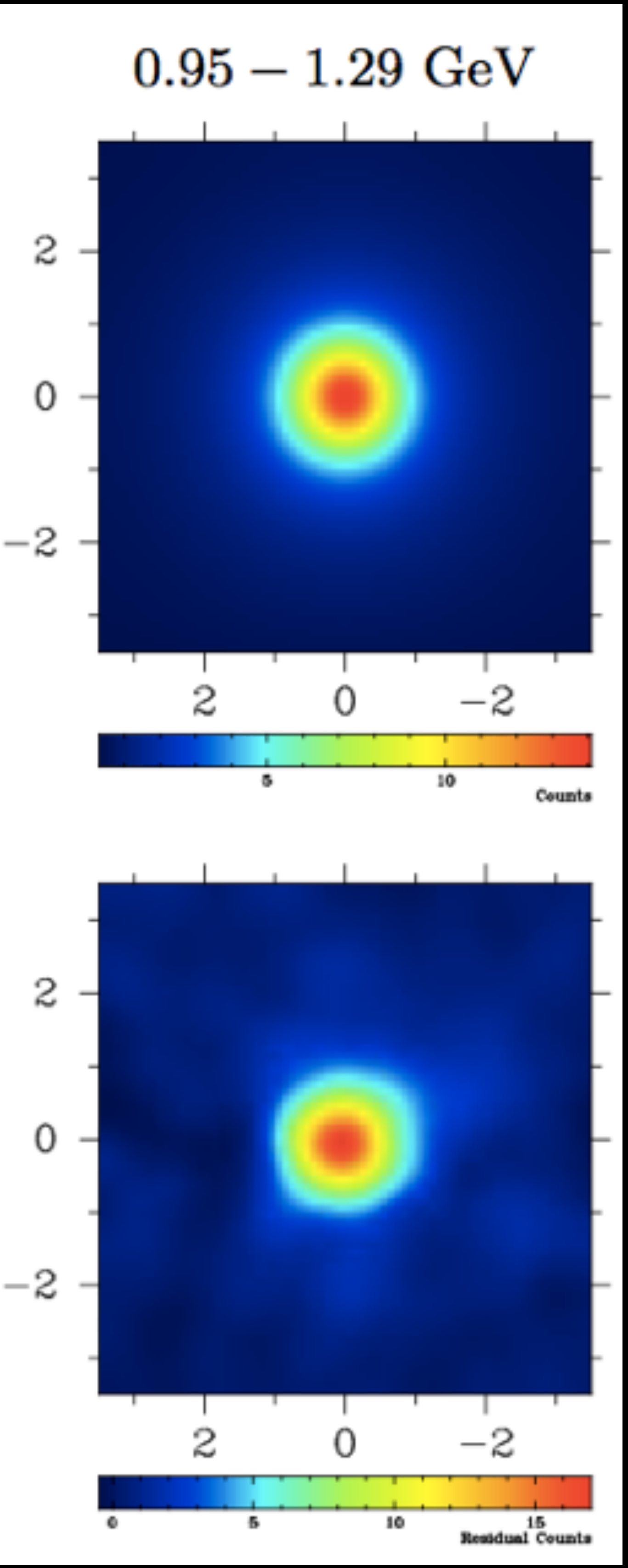


Let's be conservative (*pessimistic?*) and model the central source as an astrophysical source and test what can room can be left for dark matter

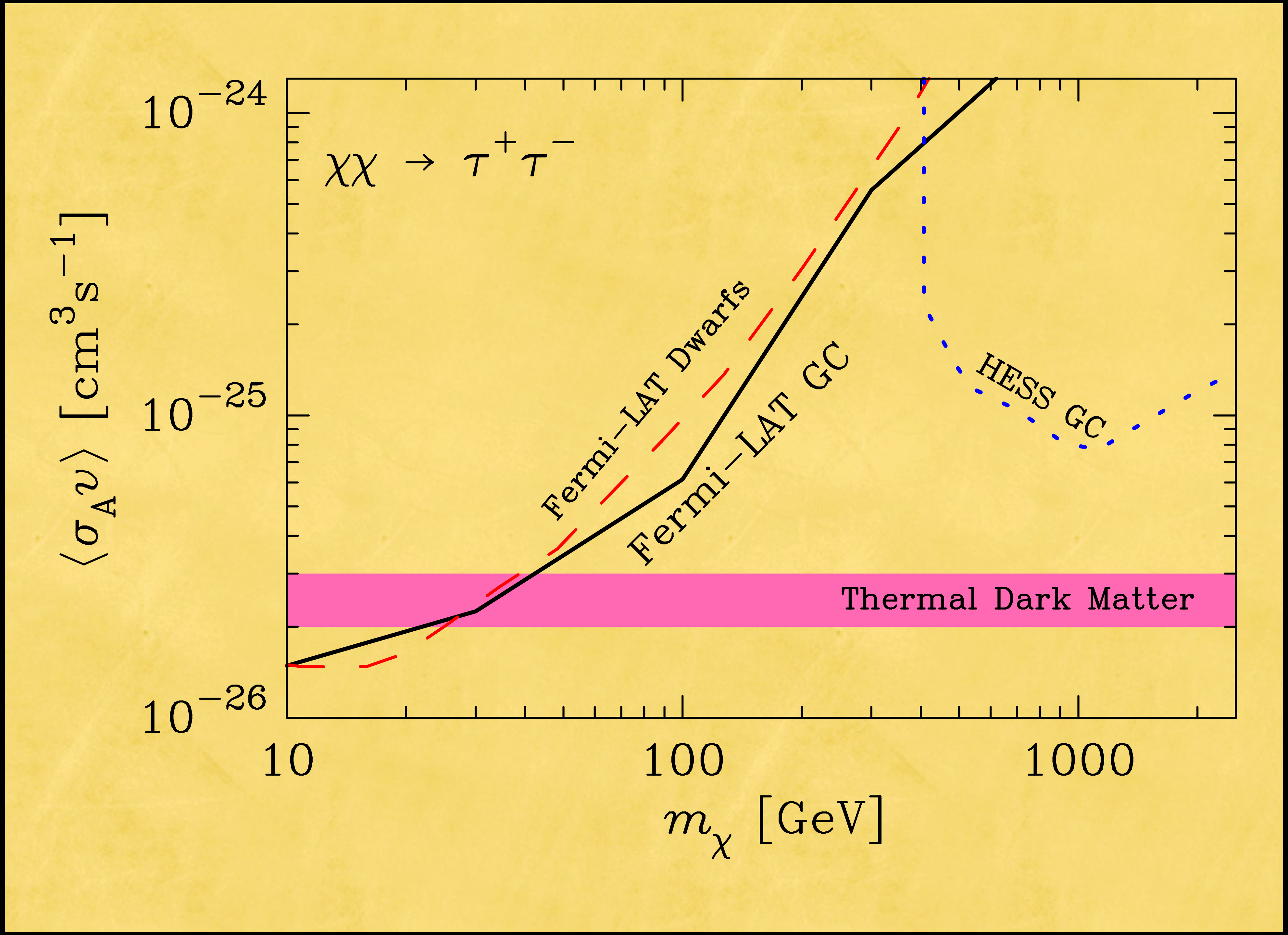


Abazajian, Canac & Kaplinghat, in prep

$\gamma_\rho = 2.4$, LogPar

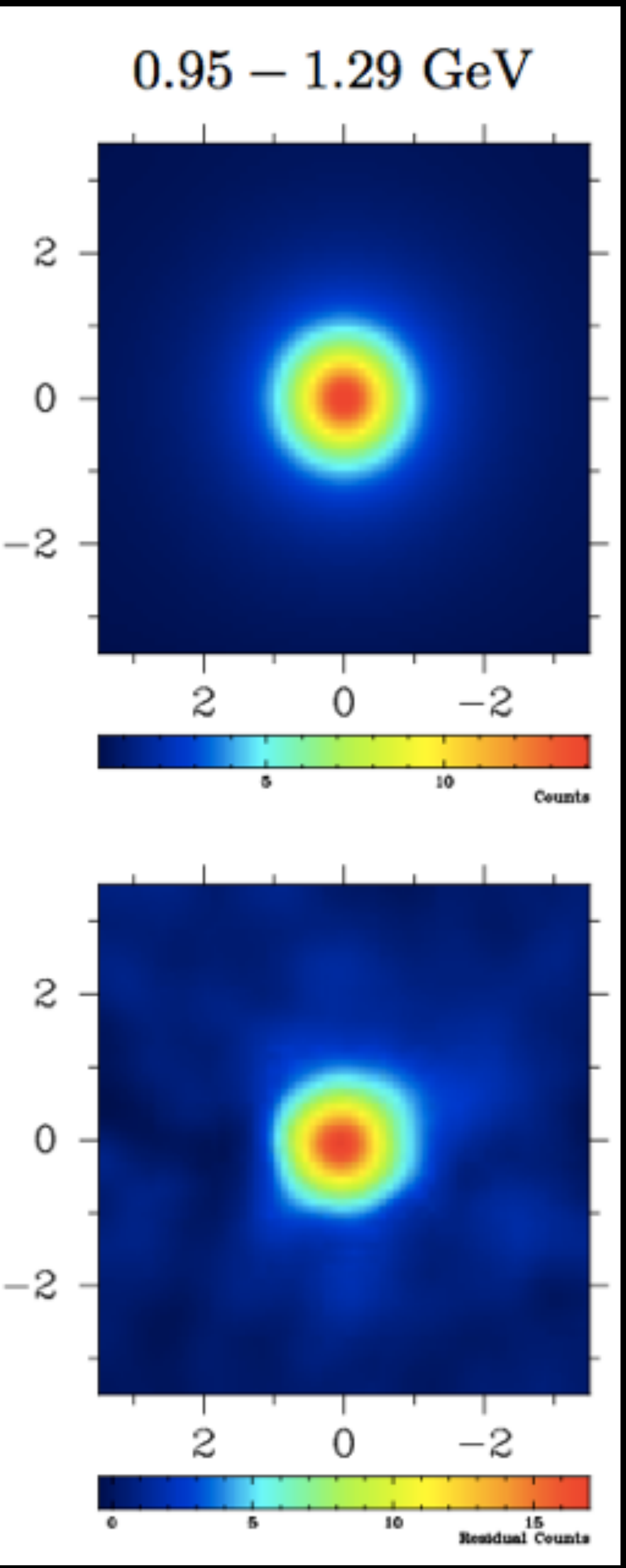


Let's be conservative (*pessimistic?*) and model the central source as an astrophysical source and test what can room can be left for dark matter

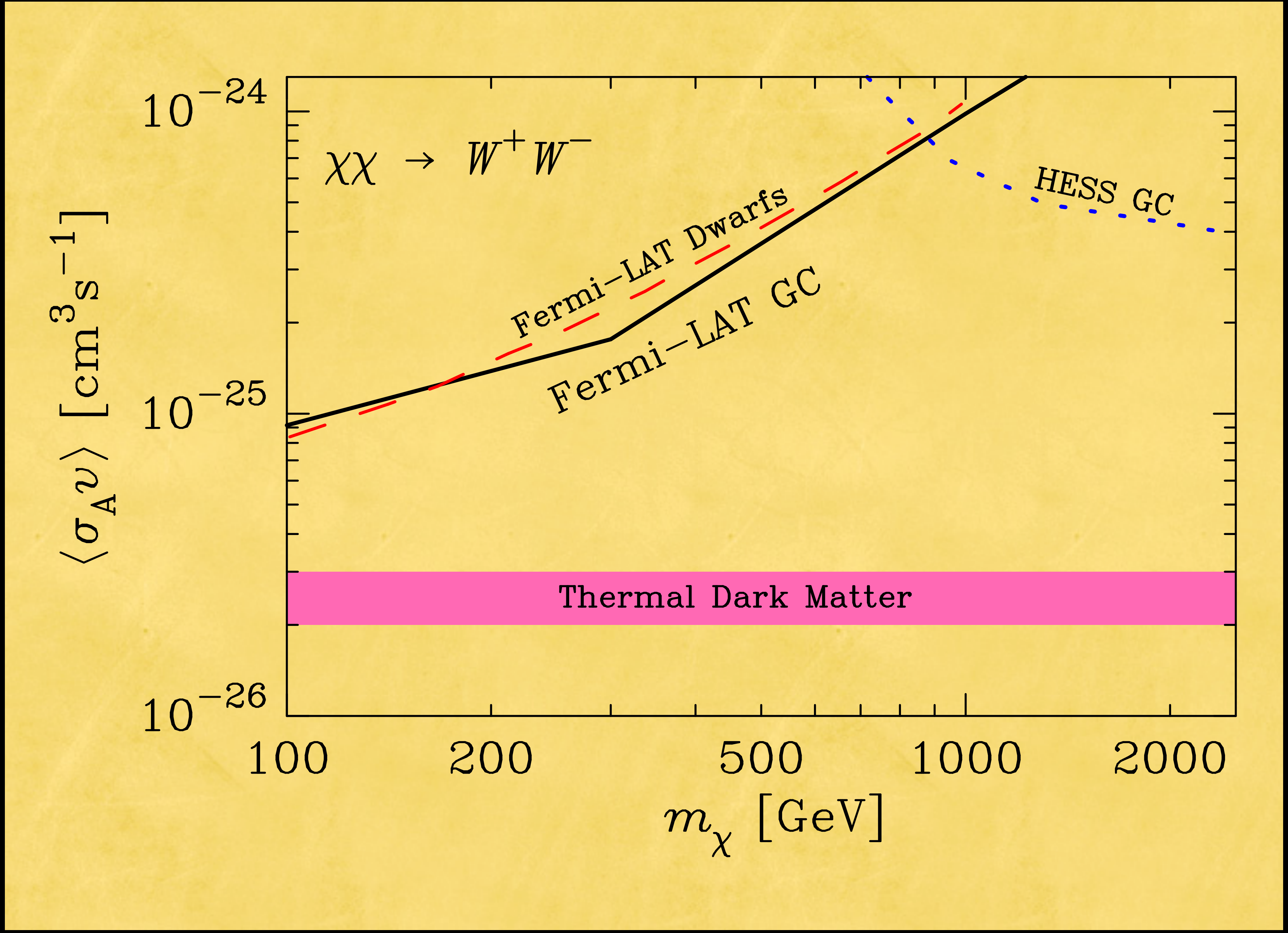


Abazajian, Canac & Kaplinghat, in prep

$\gamma_\rho = 2.4,$ LogPar



Let's be conservative (*pessimistic?*) and model the central source as an astrophysical source and test what can room can be left for dark matter



Abazajian, Canac & Kaplinghat, in prep

Galactic Center Dark Matter Summary

Galactic Center has a new source consistent with extended emission.

- The source is has a triplet of consistency with a dark matter annihilation source:

    1. Morphology: NFW-like profile

    2. Rate: flux is consistent with the weak rate expected with thermal WIMP decoupling

    3. Spectrum: the spectrum is consistent with a broad range of particle masses, 10 GeV to 1 TeV, annihilating to $b\bar{b}$.

- The source is also consistent with the morphology, intensity and spectrum with millisecond pulsars existing in dense stellar clusters (e.g., globular clusters) and traced by LMXBs in Andromeda

- The source is also consistent with the morphology, intensity and spectrum of electron cosmic-ray bremsstrahlung on molecular gas, which is also mapped out by its synchrotron radio emission and the induced FeI 6.4 keV X-ray line (Yusef-Zadeh et al. 2012)