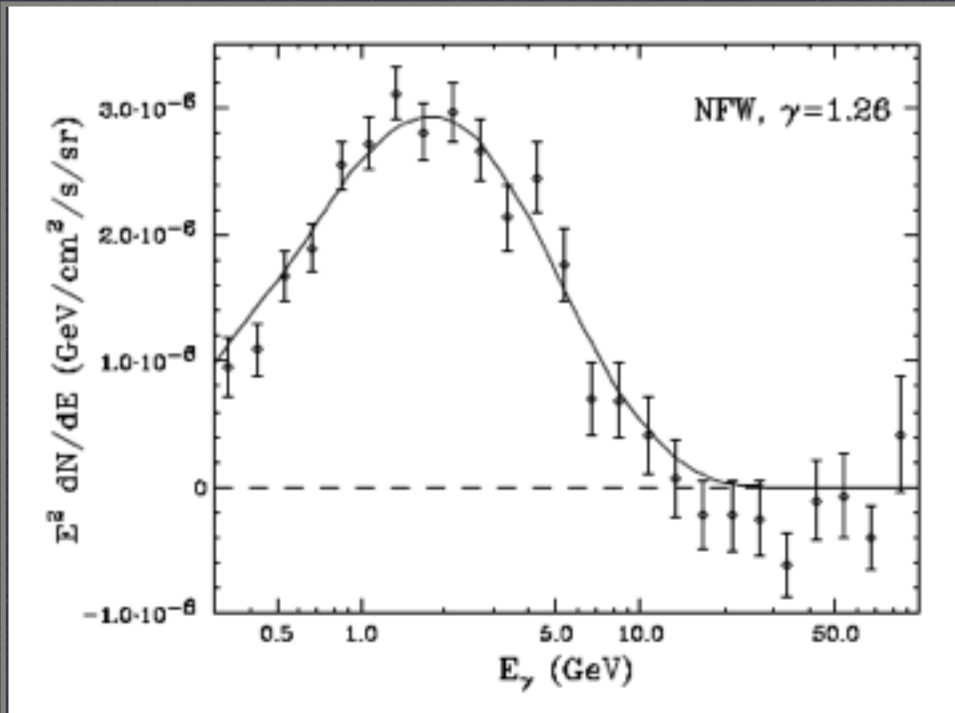
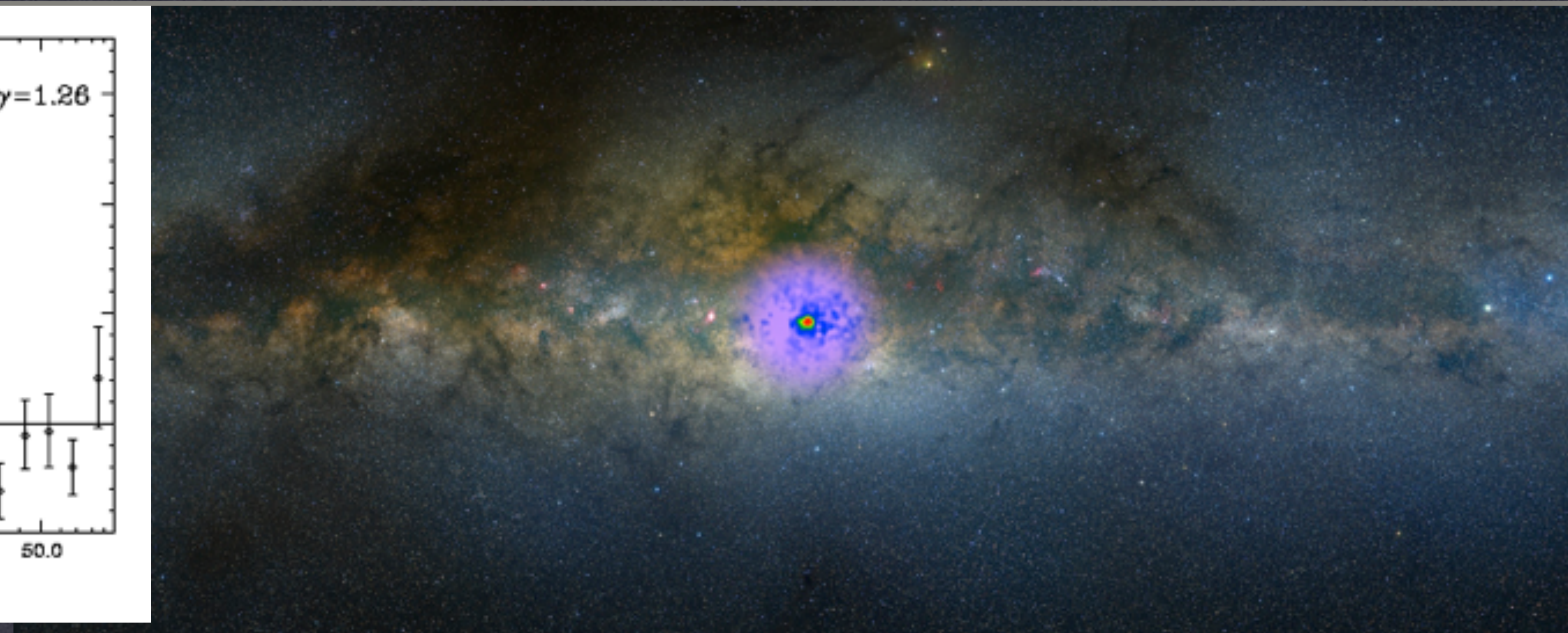


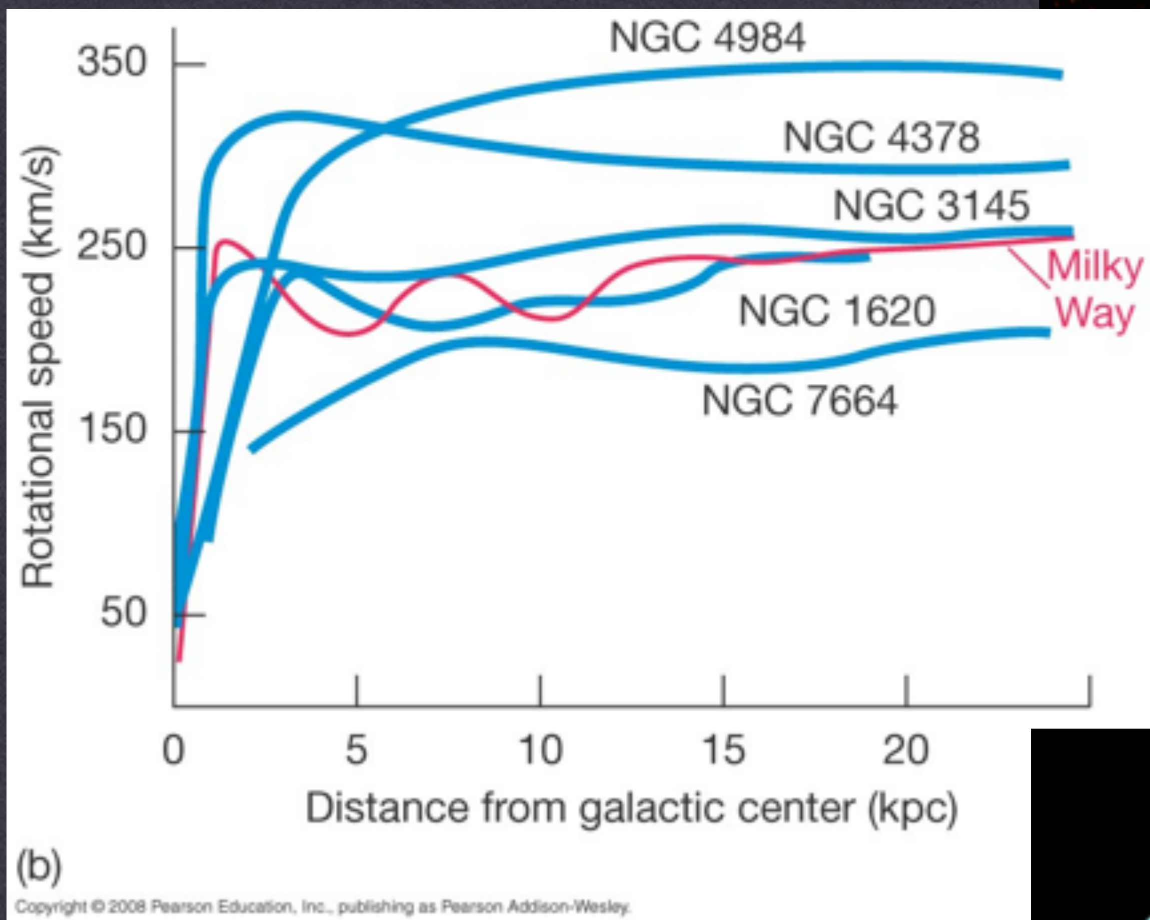


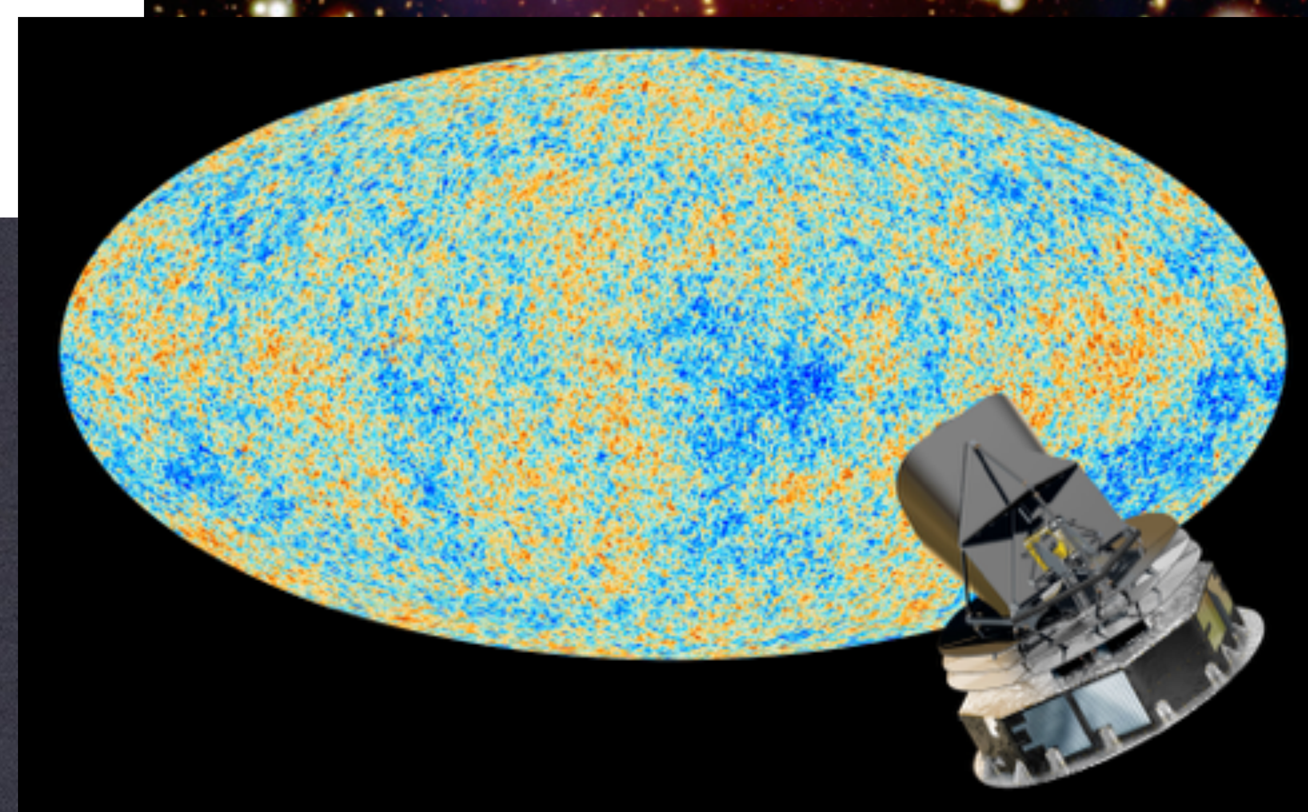
THE SEARCH FOR DARK MATTER ANNIHILATION IN THE GAMMA-RAY SKY

TIM LINDEN

WITH: TANSU DAYLAN, DOUG FINKBEINER, DAN HOOPER, STEPHEN PORTILLO, NICK RODD, TRACY SLATYER, ILIAS CHOLIS, MANOJ KAPLINGHAT, HAIBO YU, PHILIPP MERTSCH AND OTHERS

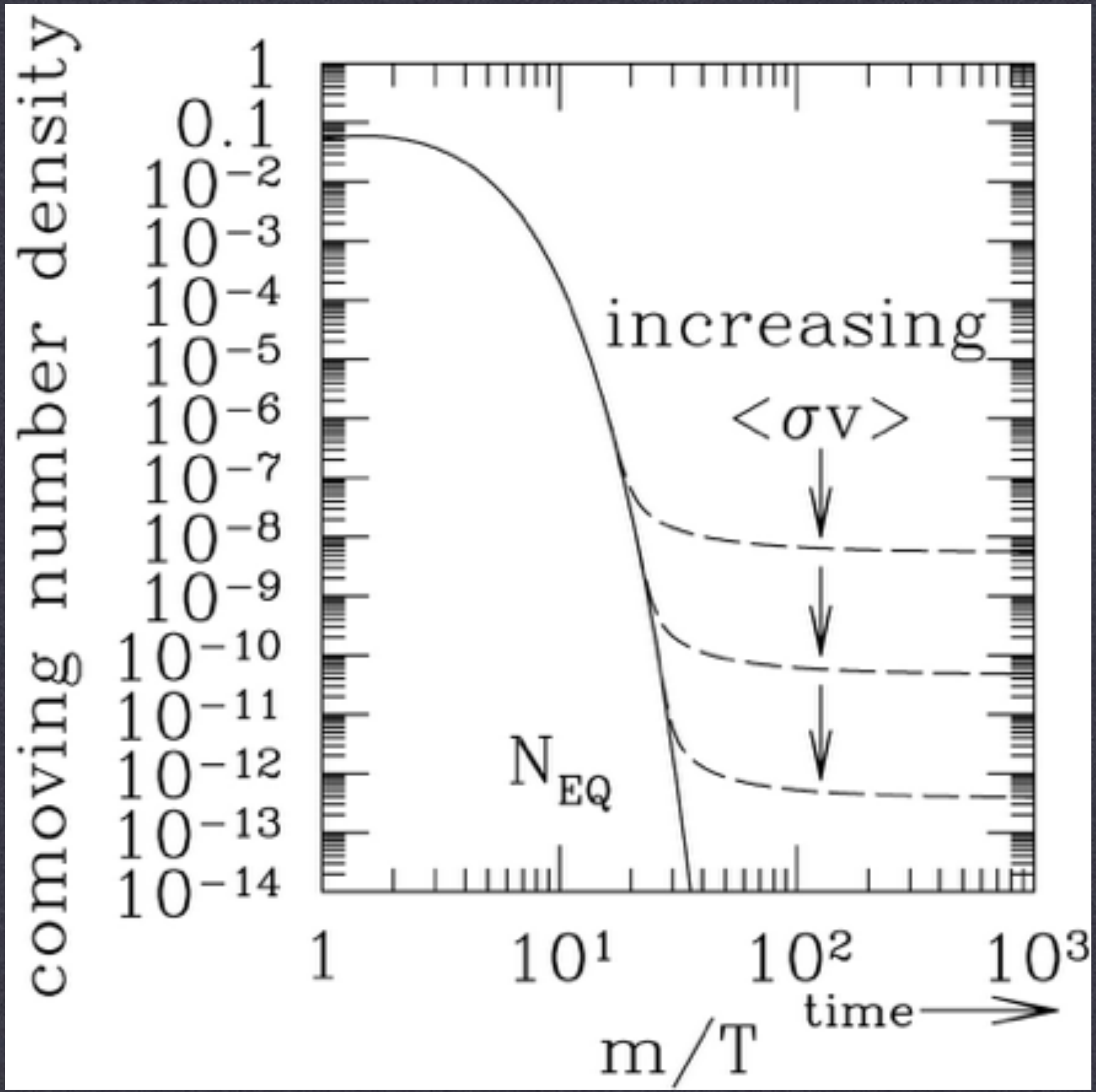
GRAVITATIONAL DARK MATTER





DARK MATTER

WEAKLY INTERACTING MASSIVE PARTICLES



Ignoring several possible complications, a particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the early universe

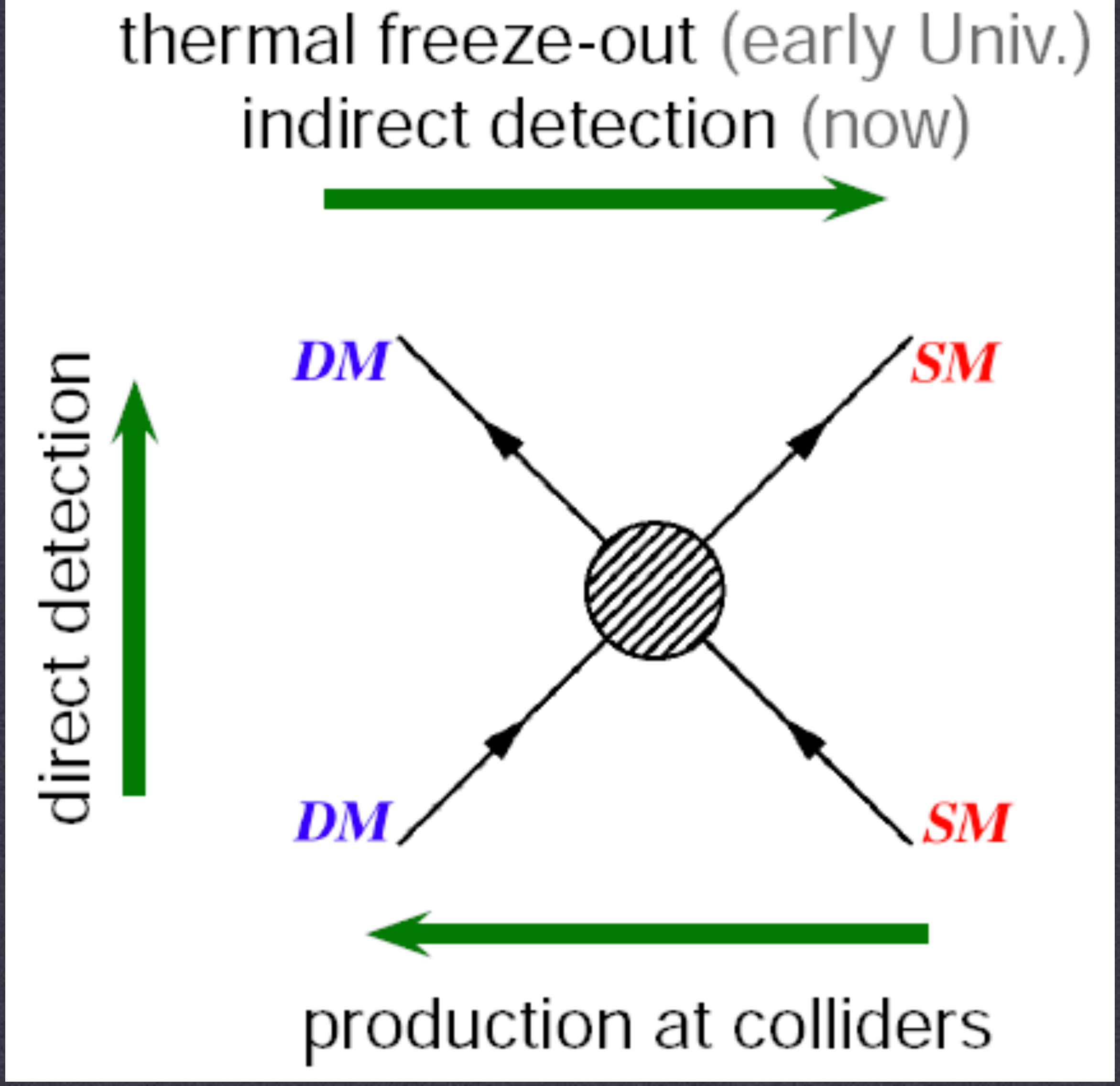
$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\mathrm{f.o.}}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

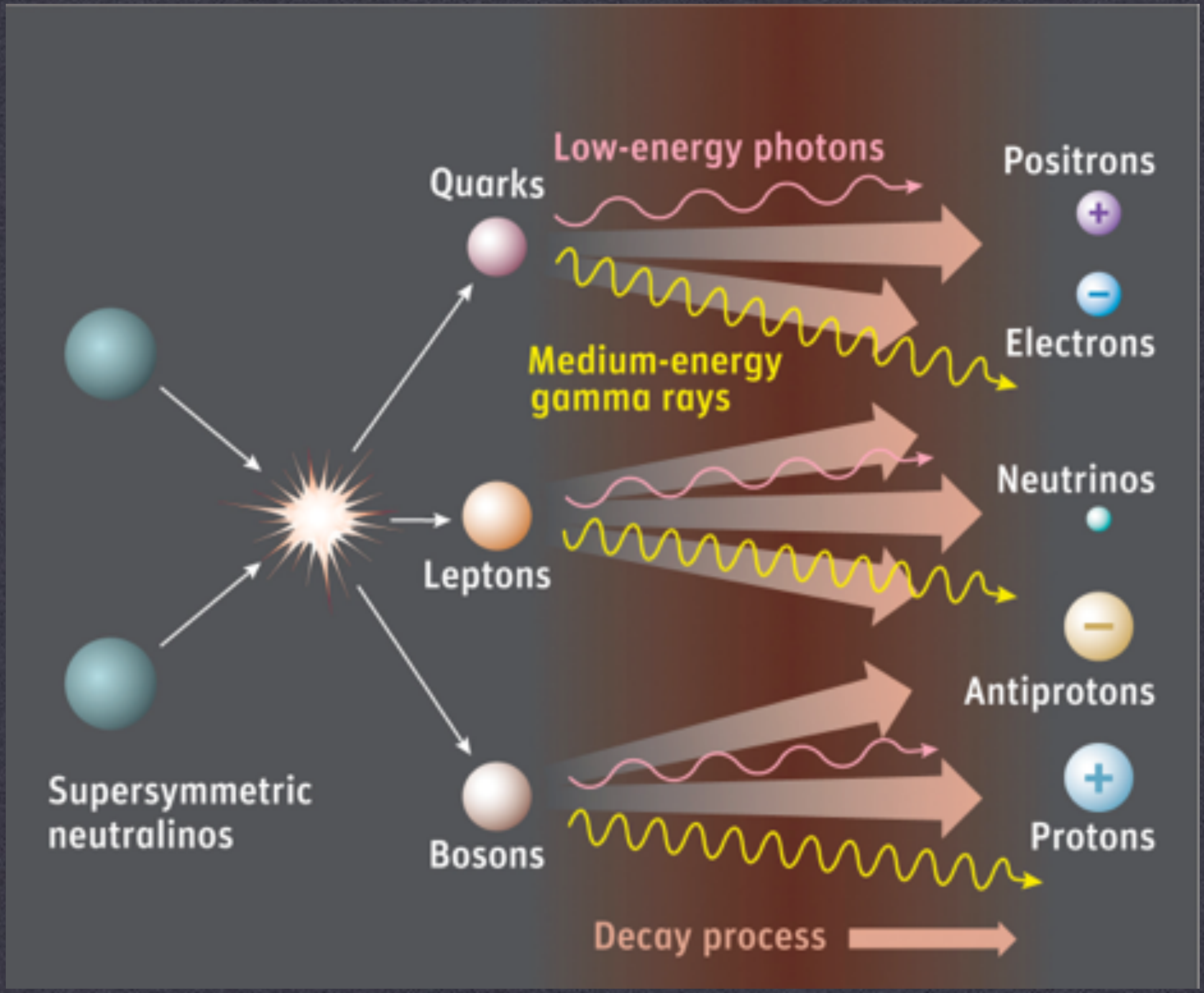
$$\langle\sigma v\rangle \sim 10^{-8}\ \mathrm{GeV}^{-2}\left(3\times10^{-28}\ \mathrm{GeV}^2\ \mathrm{cm}^2\right)\ 10^{10}\ \frac{\mathrm{cm}}{\mathrm{s}} = 3\times10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

DARK MATTER

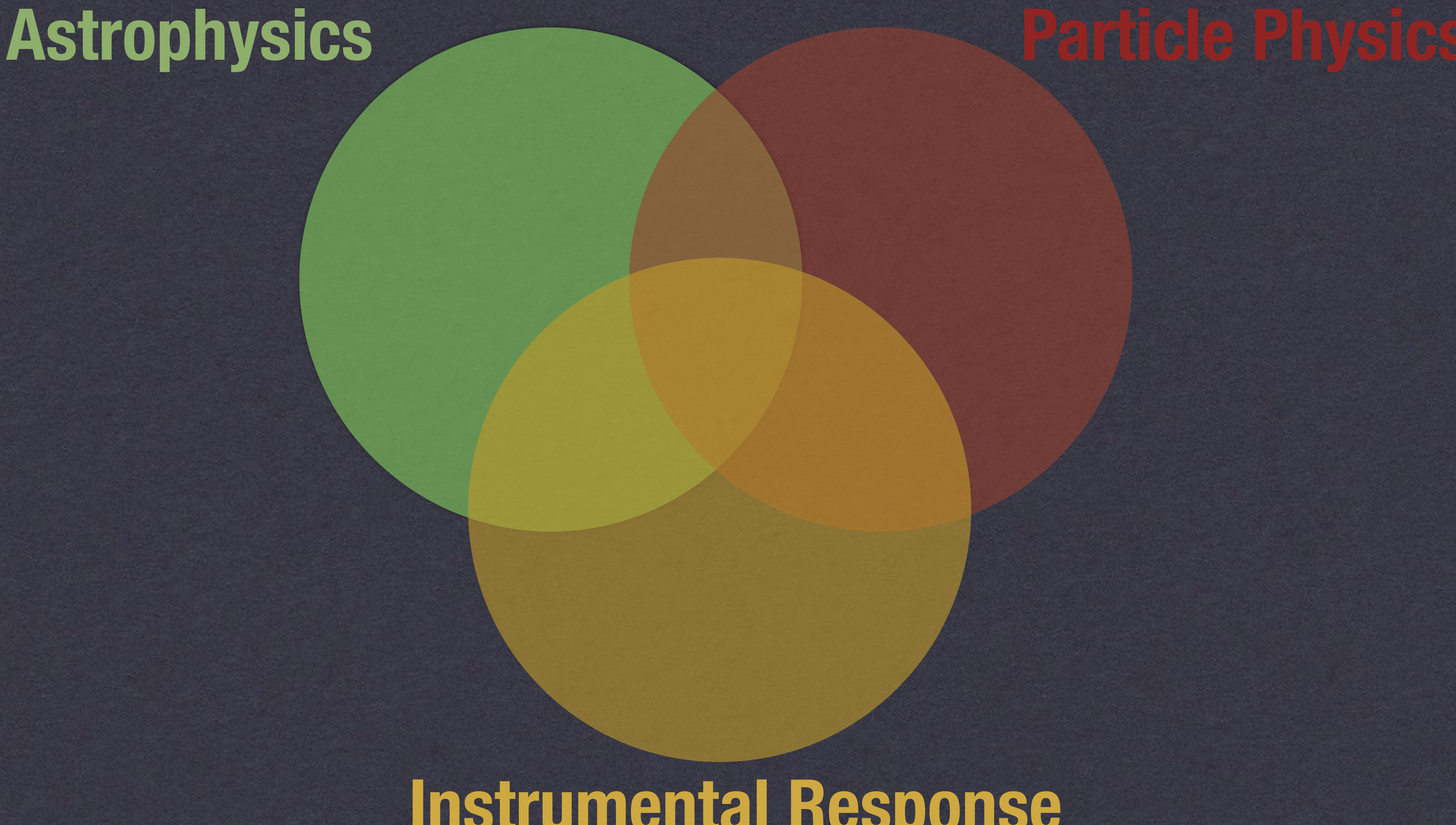
WEAKLY INTERACTING MASSIVE PARTICLES

INDIRECT DETECTION OF WIMPS





INDIRECT DETECTION OF WIMPS

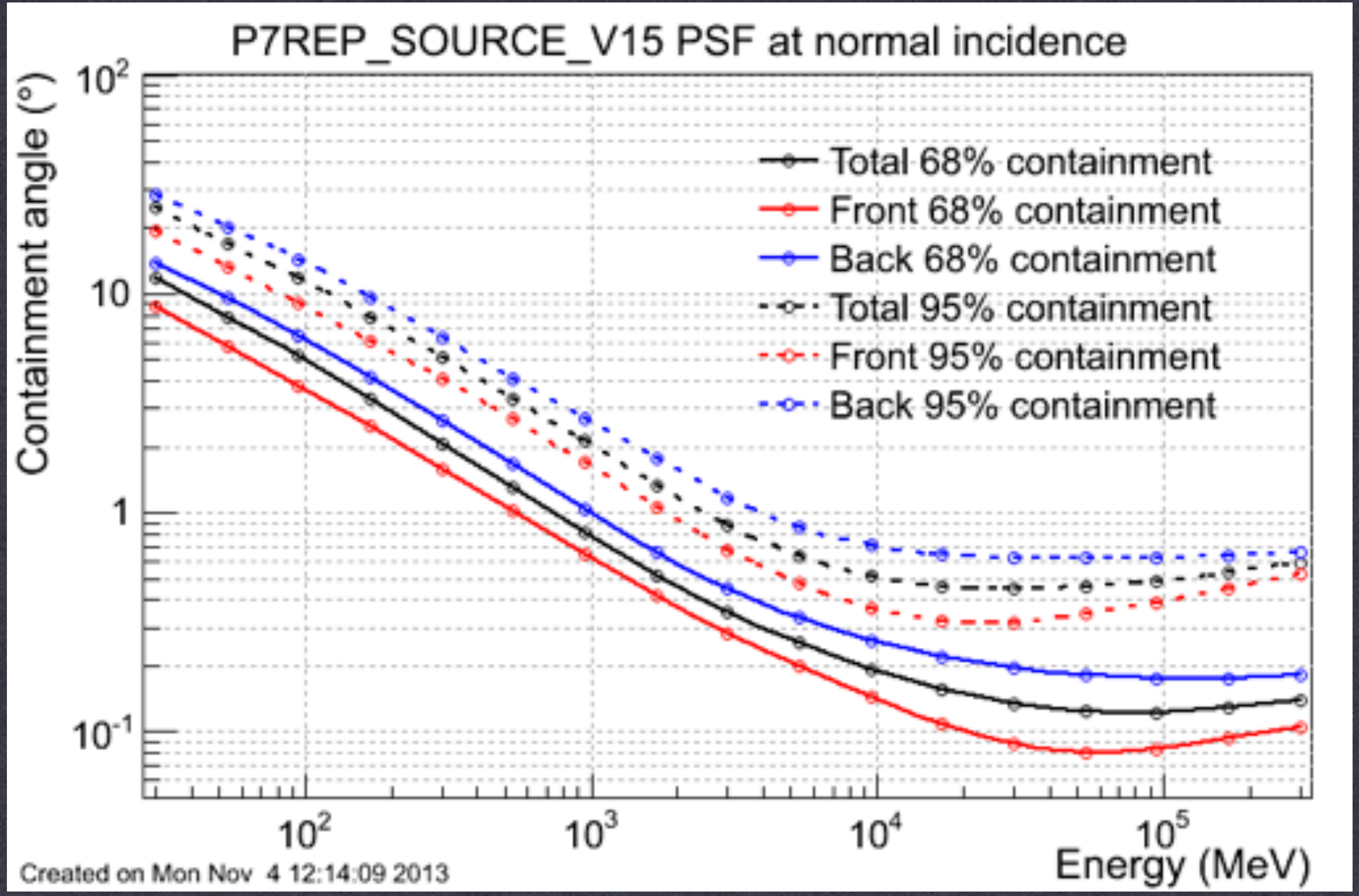


INDIRECT DETECTION OF WIMPS

WE HAVE AN INSTRUMENT! THE FERMI-LAT

Launched in June 2008 and has been taking science data for > 6 yr

Detects γ-rays between ~30 MeV - 1 TeV



Effective Area ~ 0.8 m^2

Field of View ~ 2.4 sr

Energy Resolution ~ 10%

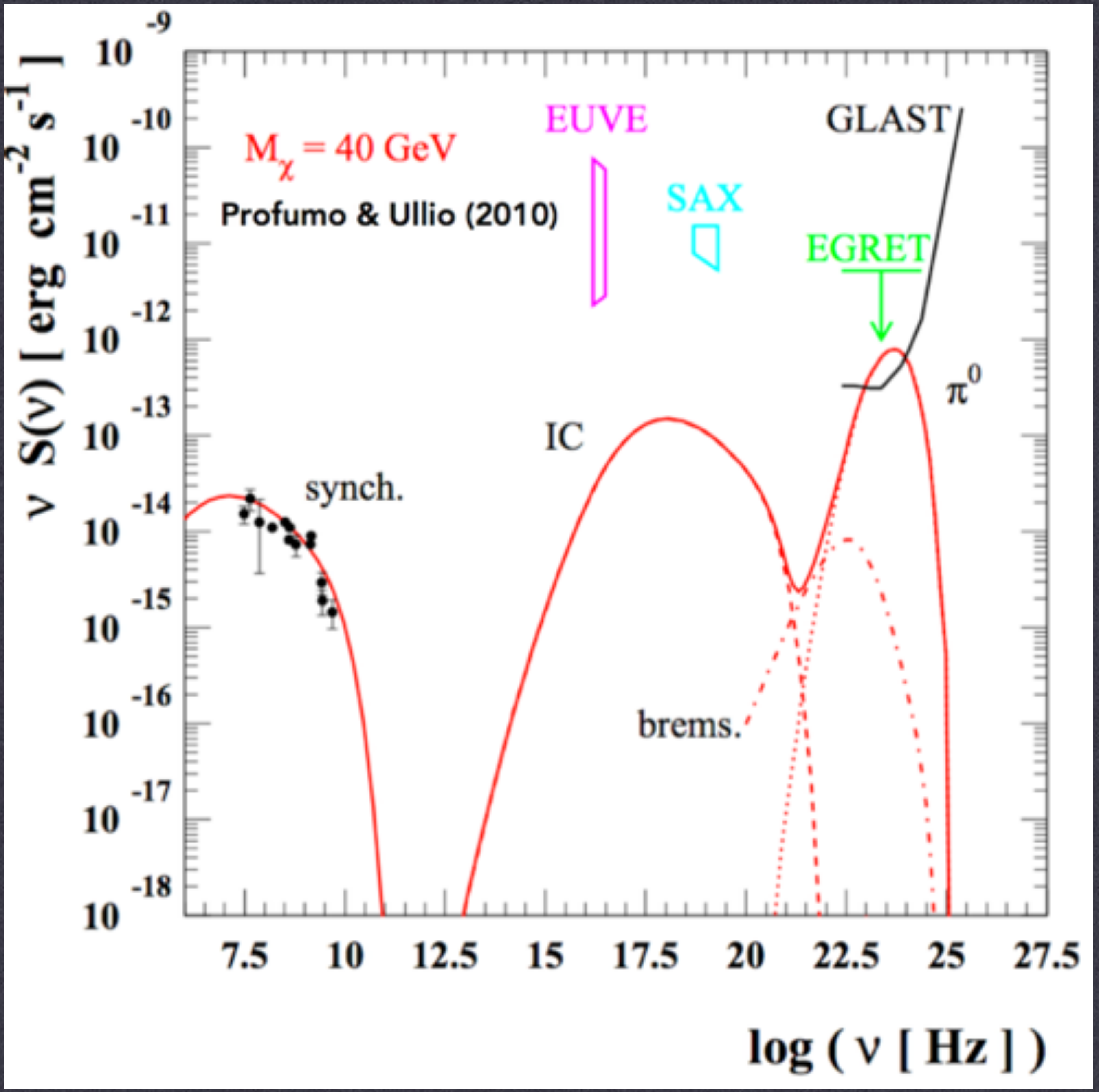
Angular Resolution is highly Energy Dependent

INDIRECT DETECTION OF WIMPS

PARTICLE PHYSICS

Why Do We Search in Gamma-Rays?

For a dark matter particle with a mass of ~100 GeV, the standard model annihilation products tend to have energy in the 10 GeV range



INDIRECT DETECTION OF WIMPS

DARK MATTER DENSITY PROFILES

$$\rho_{\mathrm{NFW}} = \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-3+\gamma}$$

A simple analytic formula has been found that provides a reasonable fit to the observed density distribution of dark matter over halos of widely varying masses.

In the standard NFW scenario, $\gamma = 1$

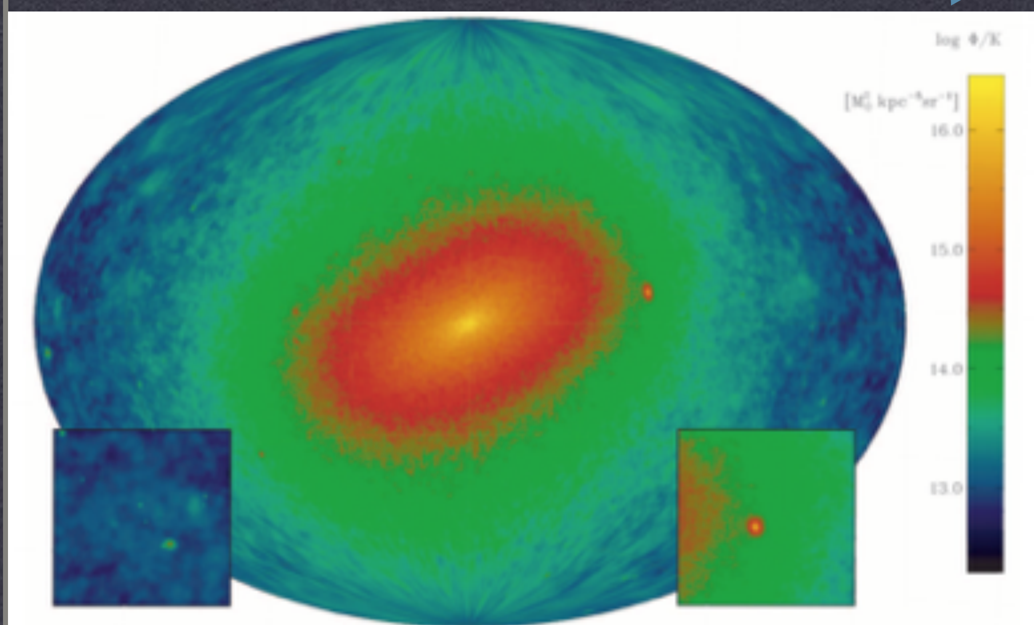
Navarro, Frenk, White (1996)

Springel et al. (2008, 0809.0898)

INDIRECT DETECTION OF WIMPS

DARK MATTER DENSITY PROFILES

THE GALACTIC CENTER



Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\overline{\log_{10}(J^{NFW})}^{a}$ ($\log_{10}[\mathrm{GeV}^2\,\mathrm{cm}^{-5}\,\mathrm{sr}]$)
Bootes I	358.1	69.6	66	18.8 ± 0.22
Bootes II	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Canis Major	240.0	-8.0	7	–
Carina	260.1	-22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25
Draco	86.4	34.7	76	18.8 ± 0.16
Fornax	237.1	-65.7	147	18.2 ± 0.21
Hercules	28.7	36.9	132	18.1 ± 0.25
Leo I	226.0	49.1	254	17.7 ± 0.18
Leo II	220.2	67.2	233	17.6 ± 0.18
Leo IV	265.4	56.5	154	17.9 ± 0.28
Leo V	261.9	58.5	178	–
Pisces II	79.2	-47.1	182	–
Sagittarius	5.6	-14.2	26	–
Sculptor	287.5	-83.2	86	18.6 ± 0.18
Segue 1	220.5	50.4	23	19.5 ± 0.29
Segue 2	149.4	-38.1	35	–
Sextans	243.5	42.3	86	18.4 ± 0.27
Ursa Major I	159.4	54.4	97	18.3 ± 0.24
Ursa Major II	152.5	37.4	32	19.3 ± 0.28
Ursa Minor	105.0	44.8	76	18.8 ± 0.19
Willman 1	158.6	56.8	38	19.1 ± 0.31

For typical parameters from an NFW profile:

$$J \sim 10^{21}\ \mathrm{GeV}^2\ \mathrm{cm}^{-5}$$

INDIRECT DETECTION OF WIMPS

DARK MATTER DENSITY PROFILES

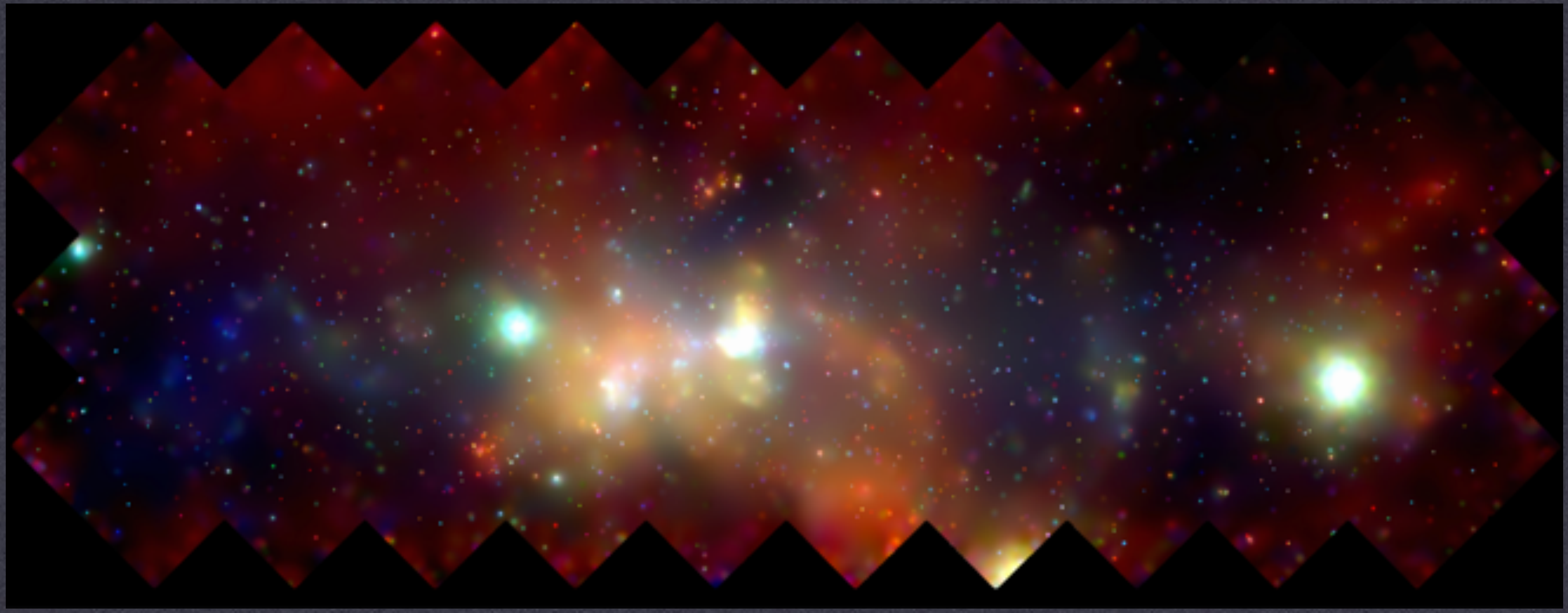
THE GALACTIC CENTER

Put Another Way:

The Fermi-LAT telescope observes a flux in the inner 1^o between 1-3 GeV of approximately 1 x 10^{-10} erg cm^{-2} s^{-1}

A Generic Dark Matter Scenario predicts a flux of 2 x 10^{-11} erg cm^{-2} s^{-1}

Unfortunately, the backgrounds are not negligible.



Chandra image of Galactic Center

INDIRECT DETECTION OF WIMPS

DARK MATTER DENSITY PROFILES

THE GALACTIC CENTER: BACKGROUNDS

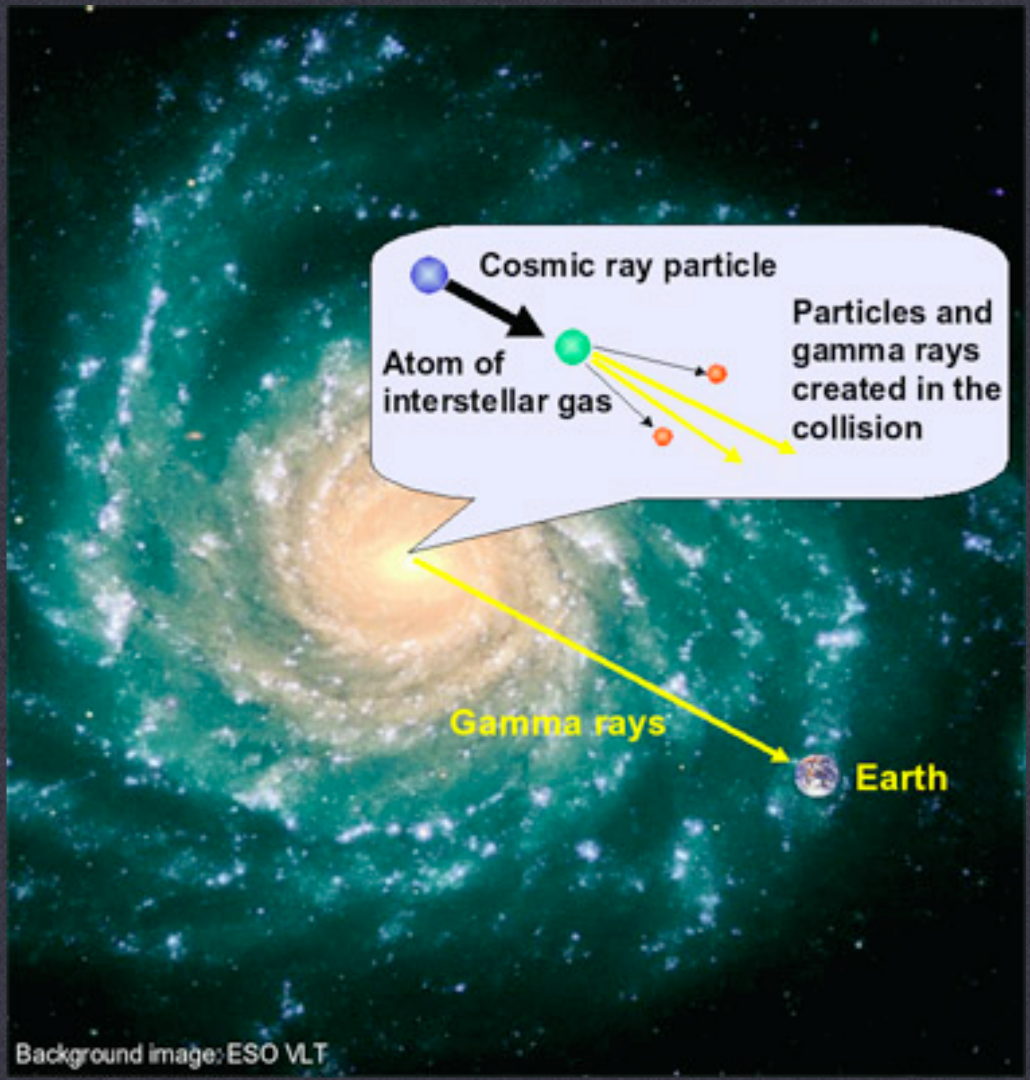
What Are These Backgrounds?

* Point Sources (SNR, pulsars, etc.)

* Hadronic Interactions (pp -> π^0 -> $\gamma\gamma$)

* Bremsstrahlung

* Inverse Compton Scattering



INDIRECT DETECTION OF WIMPS

PUTTING IT ALL TOGETHER

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\mathrm{DM}}^2}\int_{E_{\min}}^{E_{\max}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\Phi_{\mathrm{PP}}} \times \underbrace{\int_{\Delta\Omega}\left\{\int_{\mathrm{l.o.s.}}\rho^2(\boldsymbol{r})\mathrm{d}l\right\}\mathrm{d}\Omega'}_{\text{J-factor}}$$

Fortunately, these terms are separable for standard CDM

WHY WE'RE DOING WHAT WE'RE DOING

1.) Dark Matter is one of the most mysterious, but important extensions to the standard model

2.) WIMPs are among the most well-motivated models for dark matter annihilation

3.) The observation of dark matter annihilation products offers the capability to observe/understand the WIMP particle

4.) The Milky Way Galactic Center is a promising target for indirect detection studies.

5.) The Fermi-LAT has provided us with an unparalleled ability to detect WIMPs annihilating at the thermal cross-section

PREVIOUS WORK

Many Analyses of the Galactic Center over the past 5 years:

Goodenough & Hooper (2009)	0910.2998
Hooper & Goodenough (2011, PLB 697 412)	1010.2752
Hooper & TL (2011, PRD 84 12)	1110.0006
Abazajian & Kaplinghat (2012, PRD 86 8)	1207.6047
Hooper & Slatyer (2013, PDU 2 18)	1302.6589
Gordon & Macias (2013, PRD 8 8)	1306.5725
Macias & Gordon (2013, PRD 89 6)	1312.6671
Abazajian et al. (2014, PRD 90 2)	1402.4090
Daylan et al. (2014)	1402.6703
Calore et al. (2014)	1409.0042

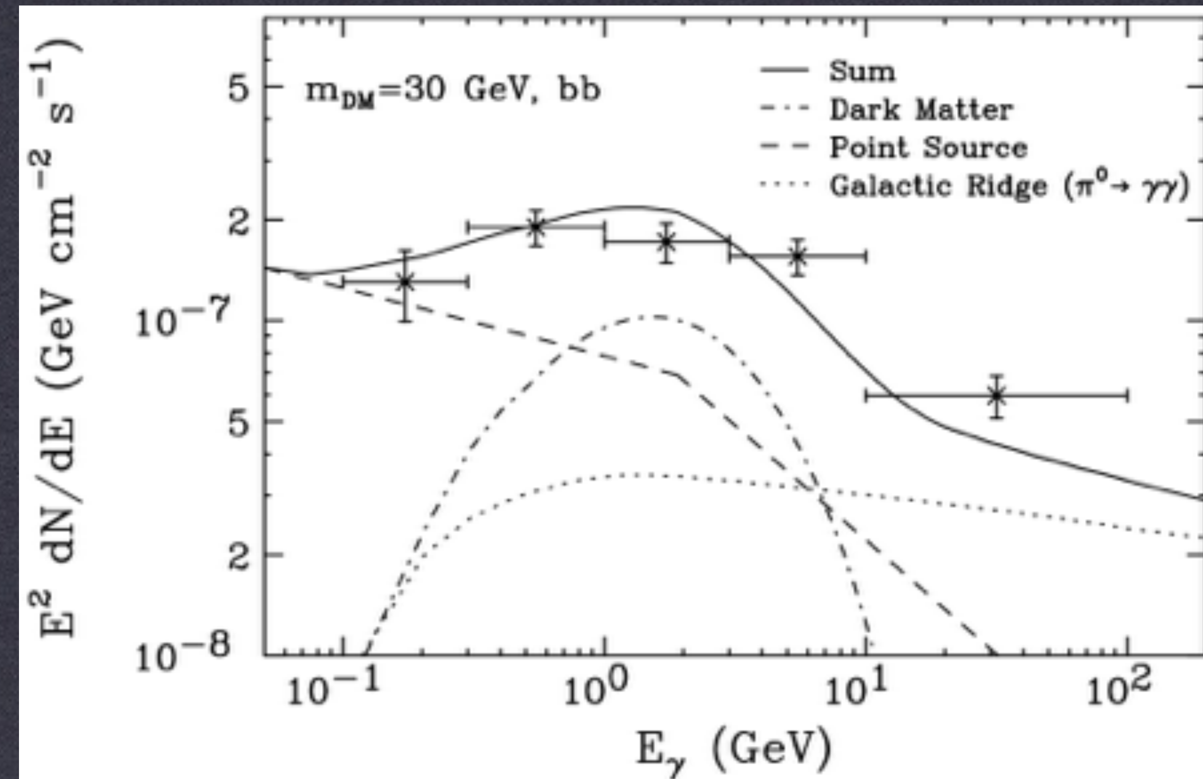
Different studies have used various techniques and regions of interest, but have obtained consistent results!

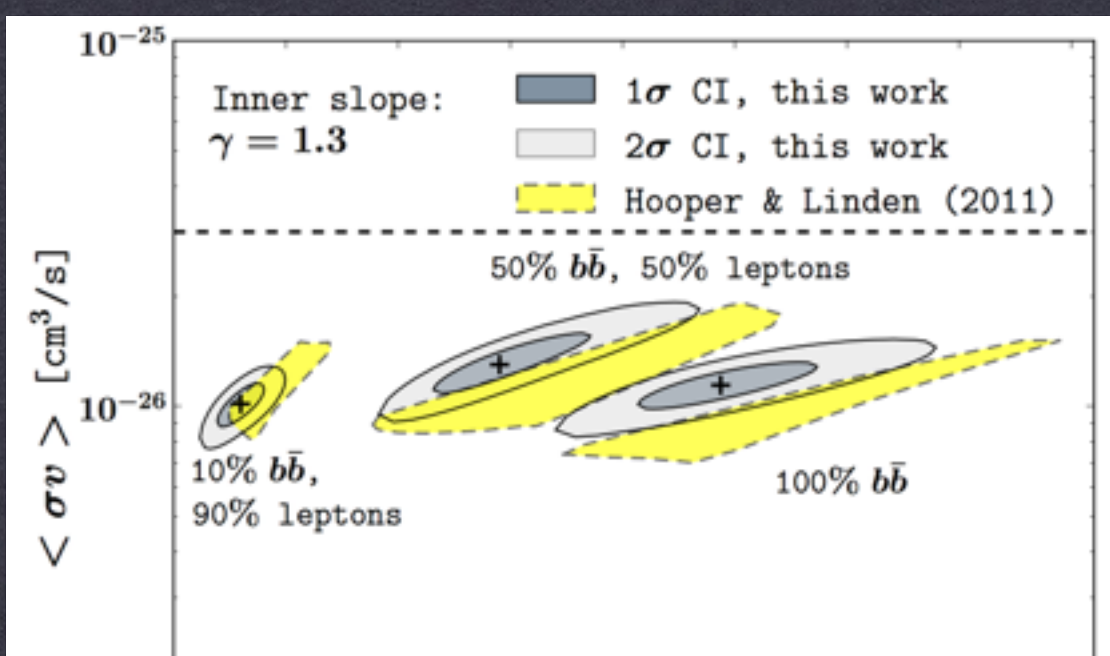
PREVIOUS WORK

CONSISTENCY!

Despite different background models, ROIs, and degrees of freedom, the results of each analysis are statistically consistent

Hooper & TL (2011)





Gordon & Macias (2013)

channel, m_χ	$TS_\approx$	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 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

Abazajian & Kaplinghat (2012)

IMPORTANT CAVEAT

I have discussed "dark matter fits" to the γ-ray data.

But this does NOT mean that the mechanism producing the excess has a dark matter origin

The data analysis tells us that the model of γ-ray data improves when we add a template with:

- A spherically symmetric, radially falling emission profile with $r^{-2.0 \text{ to } -2.8}$
- A spectrum which peaks at an energy of ~2 GeV and has a hard low-energy spectrum compared to known astrophysical emission mechanisms

CURRENT RESULTS

ABAZAJIAN ET AL.

1402.4090

Astrophysical and dark matter interpretations of extended gamma-ray emission from the Galactic Center

Kevork N. Abazajian,* Nicolas Canac,† Shunsaku Horiuchi,‡ and Manoj Kaplinghat§
Center for Cosmology, Department of Physics and Astronomy,
University of California, Irvine, Irvine, California 92697 USA

We construct empirical models of the diffuse gamma-ray background toward the Galactic Center. Including all known point sources and a template of emission associated with interactions of cosmic rays with molecular gas, we show that the extended emission observed previously in the Fermi Large Area Telescope data toward the Galactic Center is detected at high significance for all permutations of the diffuse model components. However, we find that the fluxes and spectra of the sources in our model change significantly depending on the background model. In particular, the spectrum of the central Sgr A* source is less steep than in previous works and the recovered spectrum of the extended emission has large systematic uncertainties, especially at lower energies. If the extended emission is interpreted to be due to dark matter annihilation, we find annihilation into pure b-quark and τ-lepton channels to be statistically equivalent goodness of fits. In the case of the pure b-quark channel, we find a dark matter mass of $39.4\left(^{+3.7}_{-2.9}\text{ stat.}\right)(\pm 7.9\text{ sys.})$ GeV, while a pure $\tau^+\tau^-$-channel case has an estimated dark matter mass of $9.43\left(^{+0.63}_{-0.52}\text{ stat.}\right)(\pm 1.2\text{ sys.})$ GeV. Alternatively, if the extended emission is interpreted to be astrophysical in origin such as due to unresolved millisecond pulsars, we obtain strong bounds on dark matter annihilation, although systematic uncertainties due to the dependence on the background models are significant.

DAYLAN ET AL. (2014)

1402.6703

The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

[1]Department of Physics, Harvard University, Cambridge, MA
[2]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA
[3]Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, IL
[4]University of Chicago, Department of Astronomy and Astrophysics, Chicago, IL
[5]University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL
[6]Center for Theoretical Physics, Massachusetts Institute of Technology, Boston, MA
[7]School of Natural Sciences, Institute for Advanced Study, Princeton, NJ

Past studies have identified a spatially extended excess of ~1-3 GeV gamma rays from the region surrounding the Galactic Center, consistent with the emission expected from annihilating dark matter. We revisit and scrutinize this signal with the intention of further constraining its characteristics and origin. By applying cuts to the *Fermi* event parameter CTBCORE, we suppress the tails of the point spread function and generate high resolution gamma-ray maps, enabling us to more easily separate the various gamma-ray components. Within these maps, we find the GeV excess to be robust and highly statistically significant, with a spectrum, angular distribution, and overall normalization that is in good agreement with that predicted by simple annihilating dark matter models. For example, the signal is very well fit by a 31-40 GeV dark matter particle annihilating to $b\bar{b}$ with an annihilation cross section of $\sigma v = (1.4 - 2.0) \times 10^{-26}$ cm^3/s (normalized to a local dark matter density of 0.3 GeV/cm^3). Furthermore, we confirm that the angular distribution of the excess is approximately spherically symmetric and centered around the dynamical center of the Milky Way (within ~0.05° of Sgr A*), showing no sign of elongation along or perpendicular to the Galactic Plane. The signal is observed to extend to at least $\simeq 10°$ from the Galactic Center, disfavoring the possibility that this emission originates from millisecond pulsars.

PACS numbers: 95.85.Pw, 98.70.Rz, 95.35.+d; FERMILAB-PUB-14-032-A, MIT-CTP 4533

I. INTRODUCTION

Weakly interacting massive particles (WIMPs) are a

tons), other explanations have also been proposed. In particular, it has been argued that if our galaxy's central stellar cluster contains several thousand unresolved mil-

CALORE ET AL.

1409.0042

Background model systematics for the Fermi GeV excess

Francesca Calore,[a] **Ilias Cholis**[b] **and Christoph Weniger**[a]

[a]GRAPPA, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, Netherlands
[b]Fermi National Accelerator Laboratory, Center for Particle Astrophysics, Batavia, IL 60510, USA

E-mail: f.calore@uva.nl, cholis@fnal.gov, c.weniger@uva.nl

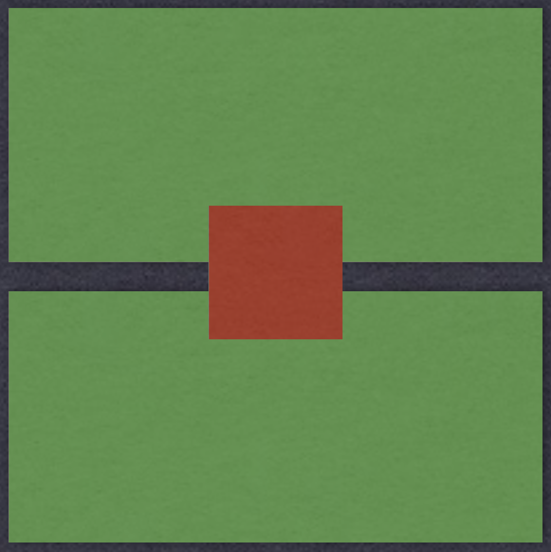
Abstract. The possible gamma-ray excess in the inner Galaxy and the Galactic center (GC) suggested by *Fermi*-LAT observations has triggered a large number of studies. It has been interpreted as a variety of different phenomena such as a signal from WIMP dark matter annihilation, gamma-ray emission from a population of millisecond pulsars, or emission from cosmic rays injected in a sequence of burst-like events or continuously at the GC. We present the first comprehensive study of model systematics coming from the Galactic diffuse emission in the inner part of our Galaxy and their impact on the inferred properties of the excess emission at Galactic latitudes $2^\circ < |b| < 20^\circ$ and 300 MeV to 500 GeV. We study both theoretical and empirical model systematics, which we deduce from a large range of Galactic diffuse emission models and a principal component analysis of residuals in numerous test regions along the Galactic plane. We show that the hypothesis of an extended spherical excess emission with a uniform energy spectrum is compatible with the *Fermi*-LAT data in our region of interest at 95% CL. Assuming that this excess is the extended counterpart of the one seen in the inner few degrees of the Galaxy, we derive a lower limit of 10.0° (95% CL) on its extension away from the GC. We show that, in light of the large correlated uncertainties that affect the subtraction of the Galactic diffuse emission in the relevant regions, the energy spectrum of the excess is equally compatible with both a simple broken power-law of break energy $E_{\rm break} = 2.1 \pm 0.2\,\mathrm{GeV}$, and with spectra predicted by the self-annihilation of dark matter, implying in the case of $\bar{b}b$ final states a dark matter mass of $m_\chi = 49^{+6.4}_{-5.4}\,\mathrm{GeV}$.

TWO REGIONS OF INTEREST

INNER GALAXY

- Mask galactic plane (e.g. $|b| > 1^{\circ}$), and consider 40° x 40° box
- Bright point sources masked at 2°
- Allow diffuse templates (galactic diffuse, isotropic, Fermi bubbles, dark matter) to float independently in each of 30 energy bins

DAYLAN ET AL.
CALORE ET AL.



GALACTIC CENTER

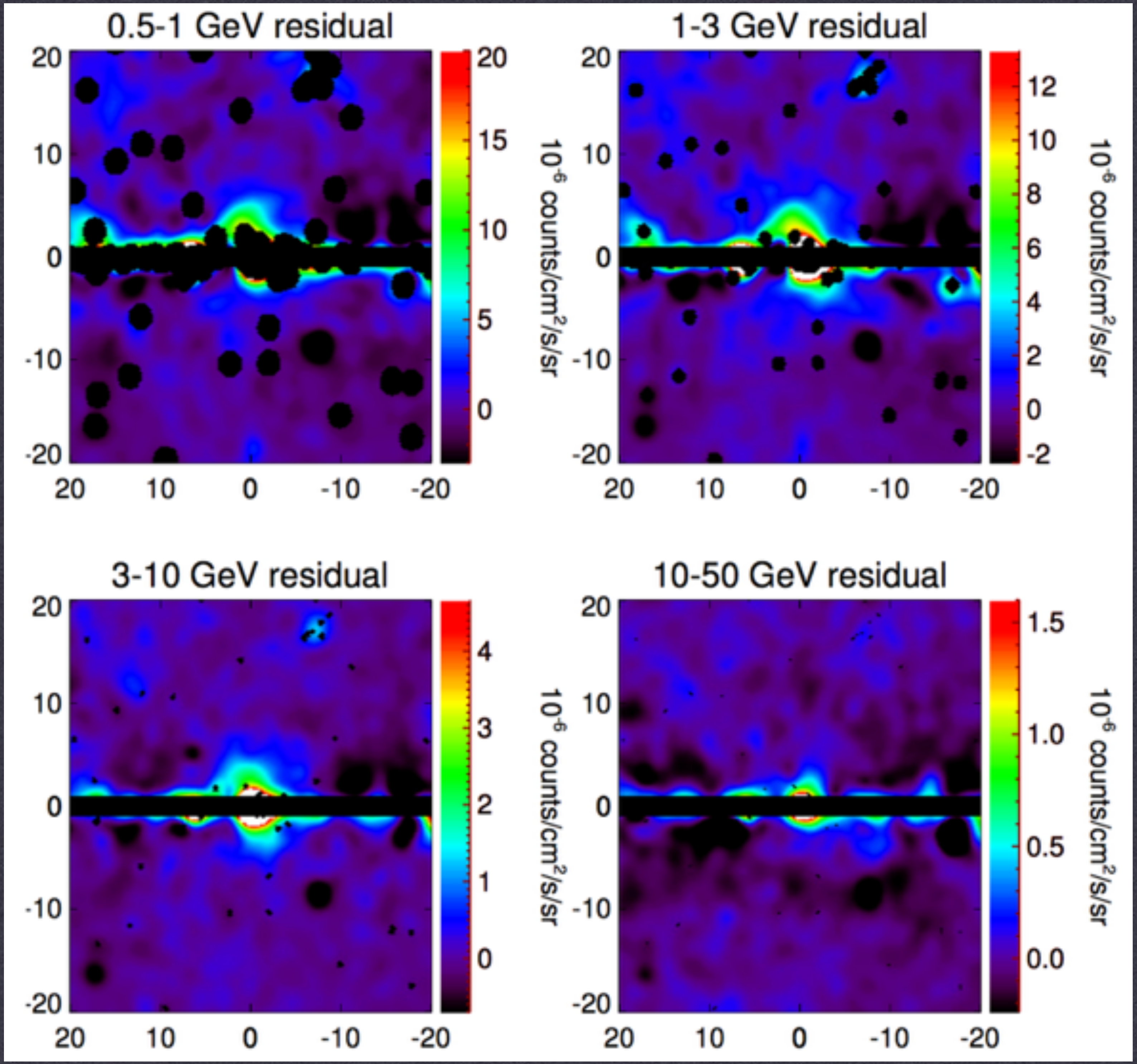
- Box around the GC (10° x 10°)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source component
- Calculate log-likelihood to determine significance

DAYLAN ET AL.
ABAZAJIAN ET AL.

RESIDUAL MAPS

INNER GALAXY

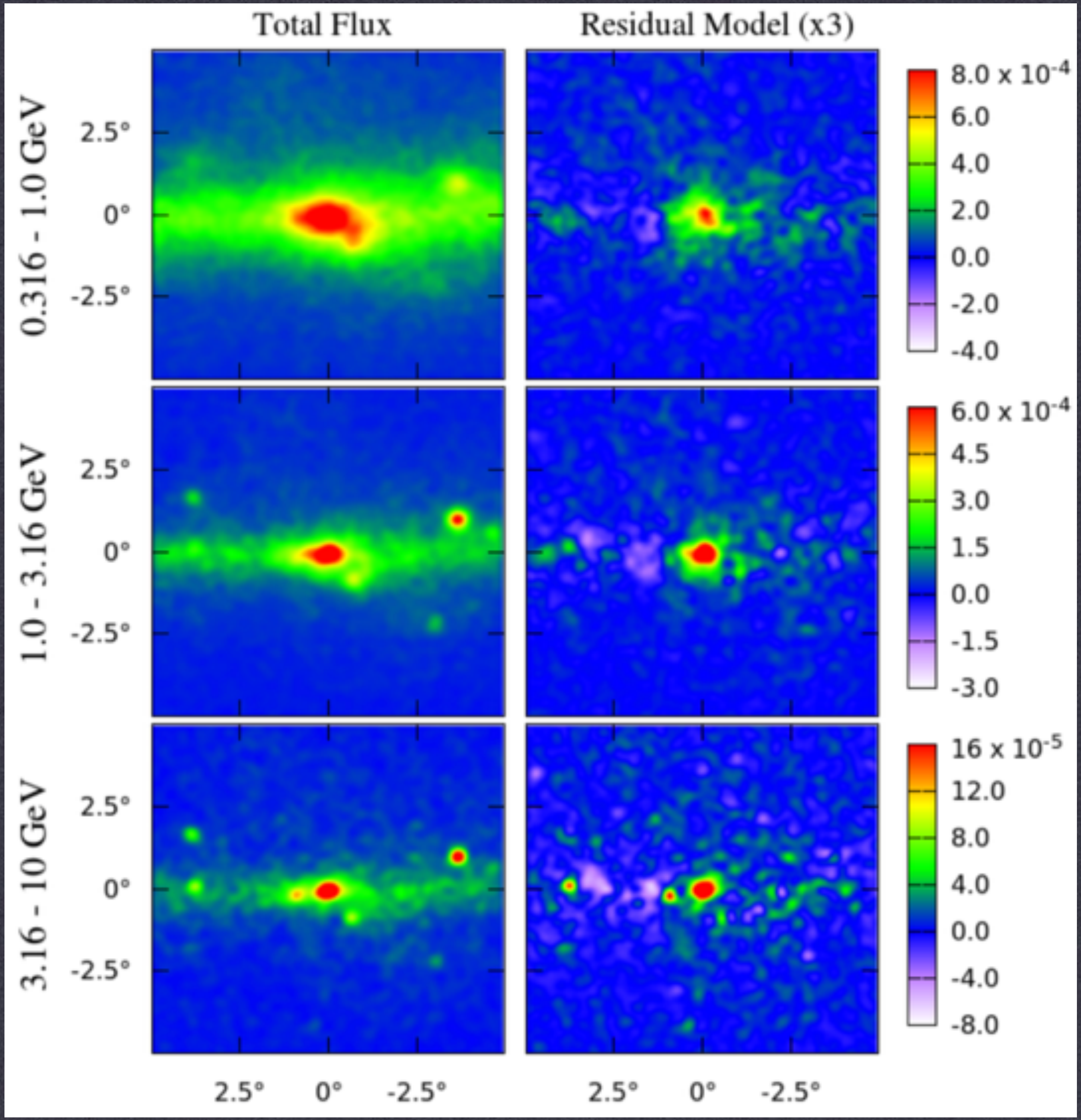
DAYLAN ET AL. (2014)



RESIDUAL MAPS

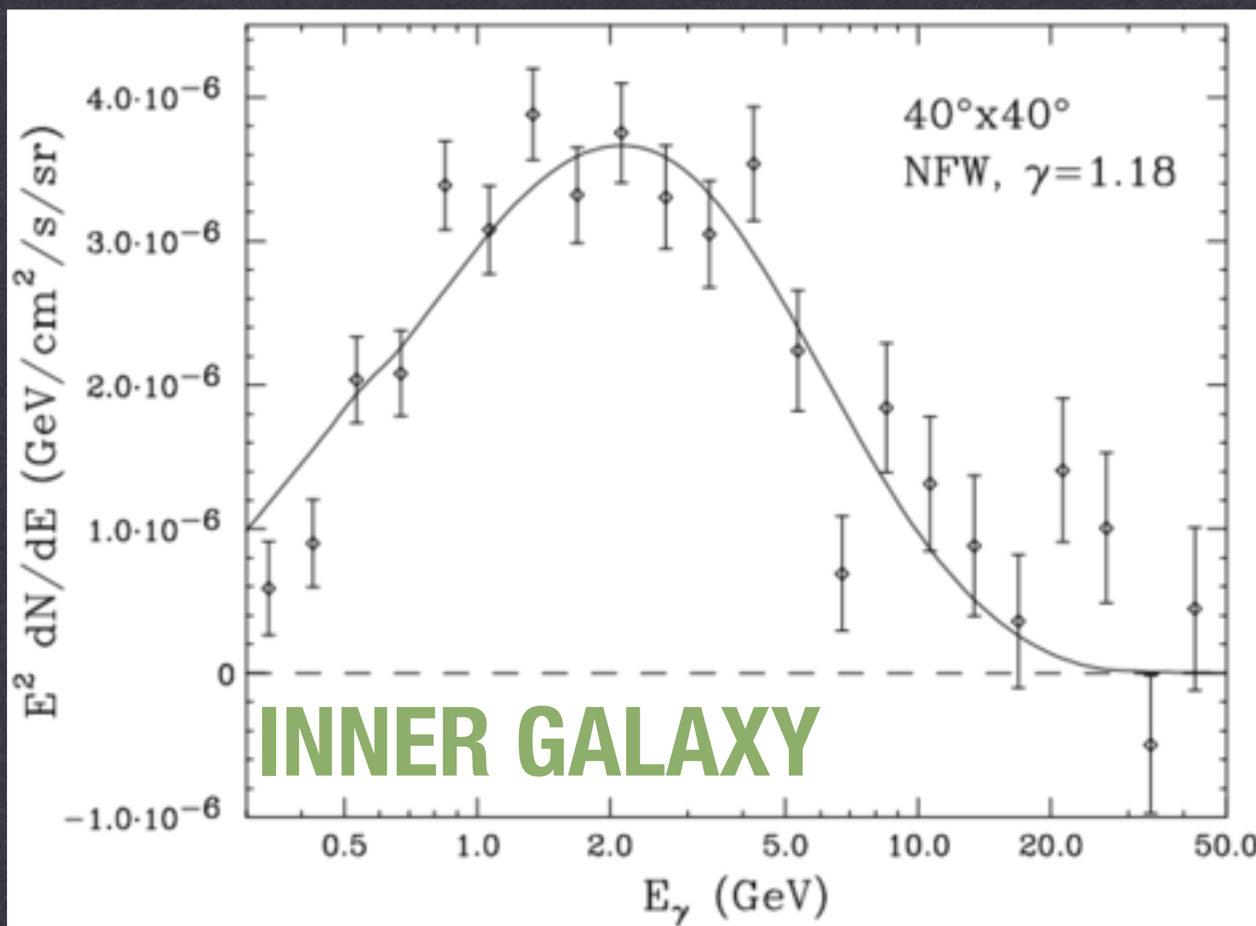
GALACTIC CENTER

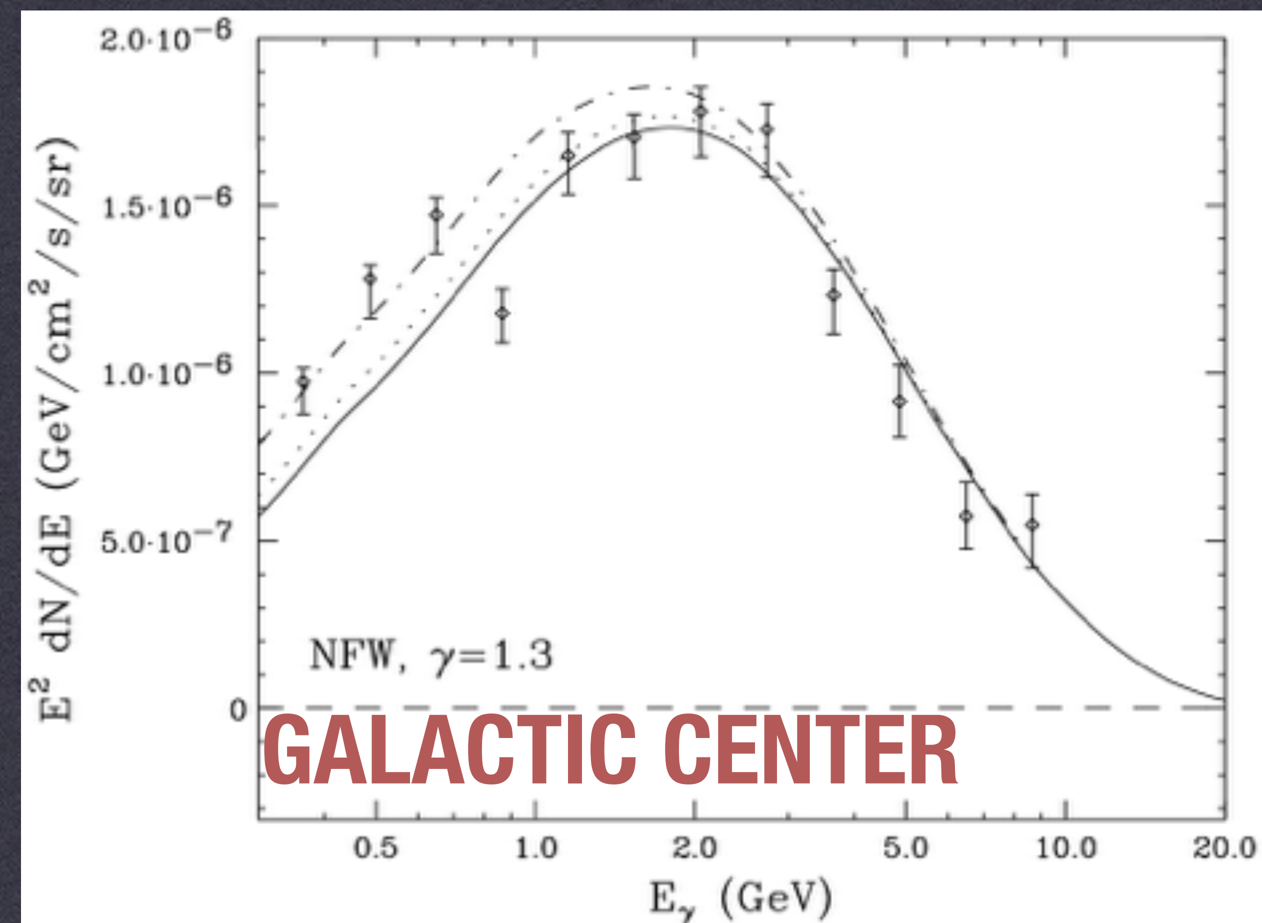
DAYLAN ET AL. (2014)



EXCESS SPECTRUM

DAYLAN ET AL. (2014)





Spectra show a consistent peak at ~2 GeV.

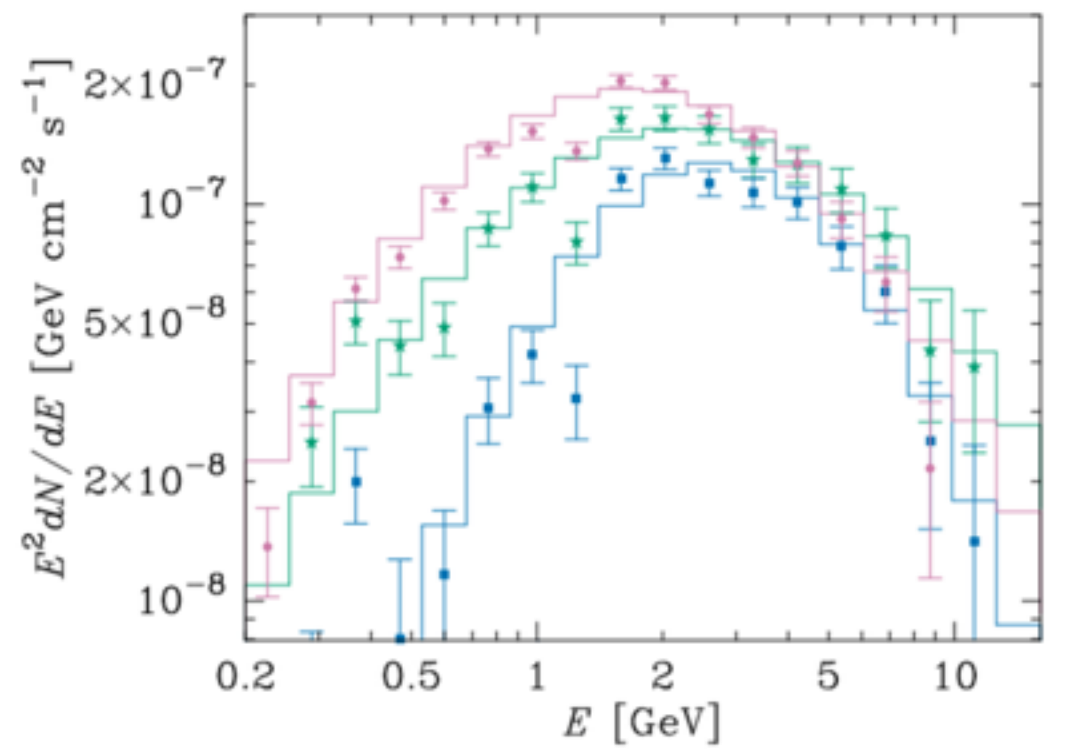
Low energy spectrum in GC may be either systematic modeling or due to bremsstrahlung emission from DM produced electrons

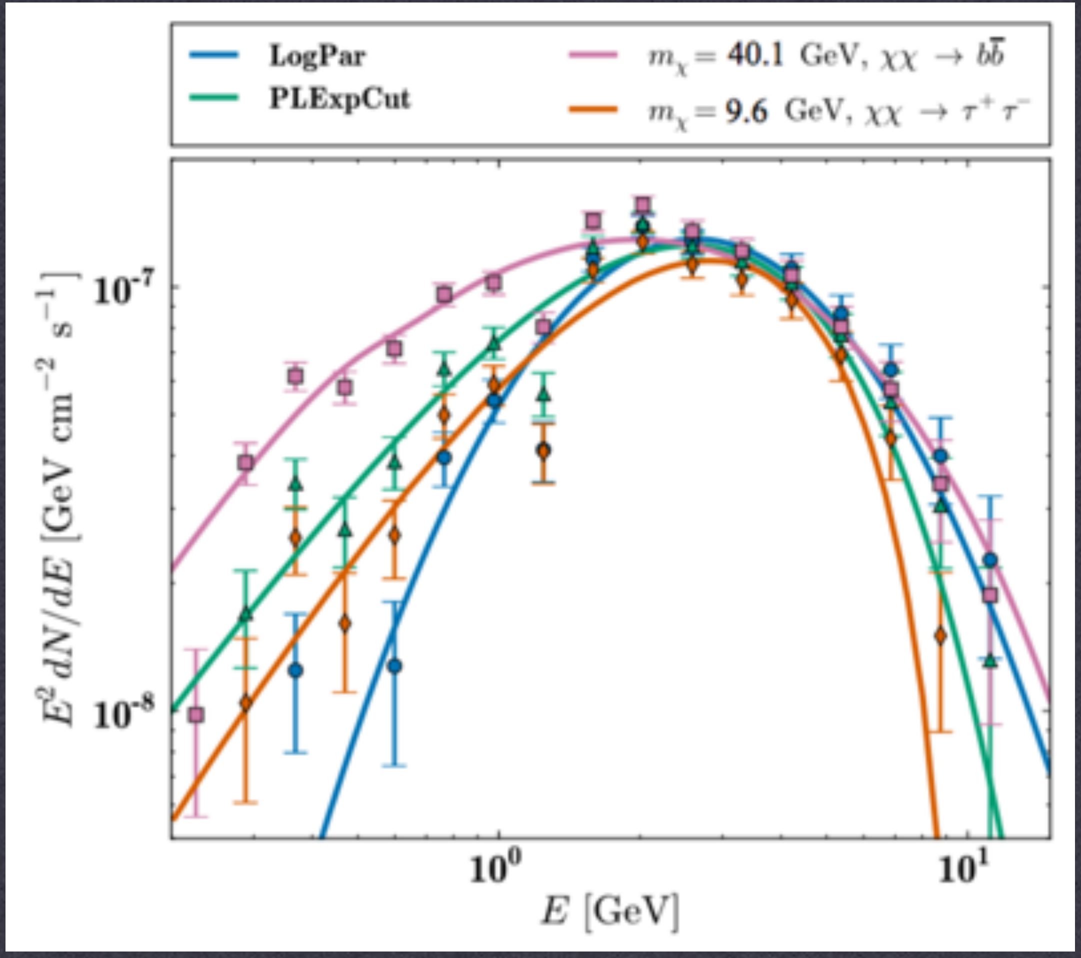
EXCESS SPECTRUM

ABAZAJIAN ET AL. (2014)

By adding extra degrees of freedom near the position of the GC - different input dark matter models can provide similar fits to the data.

The many degrees of freedom from point sources near the GC help accommodate the different spectral fits.



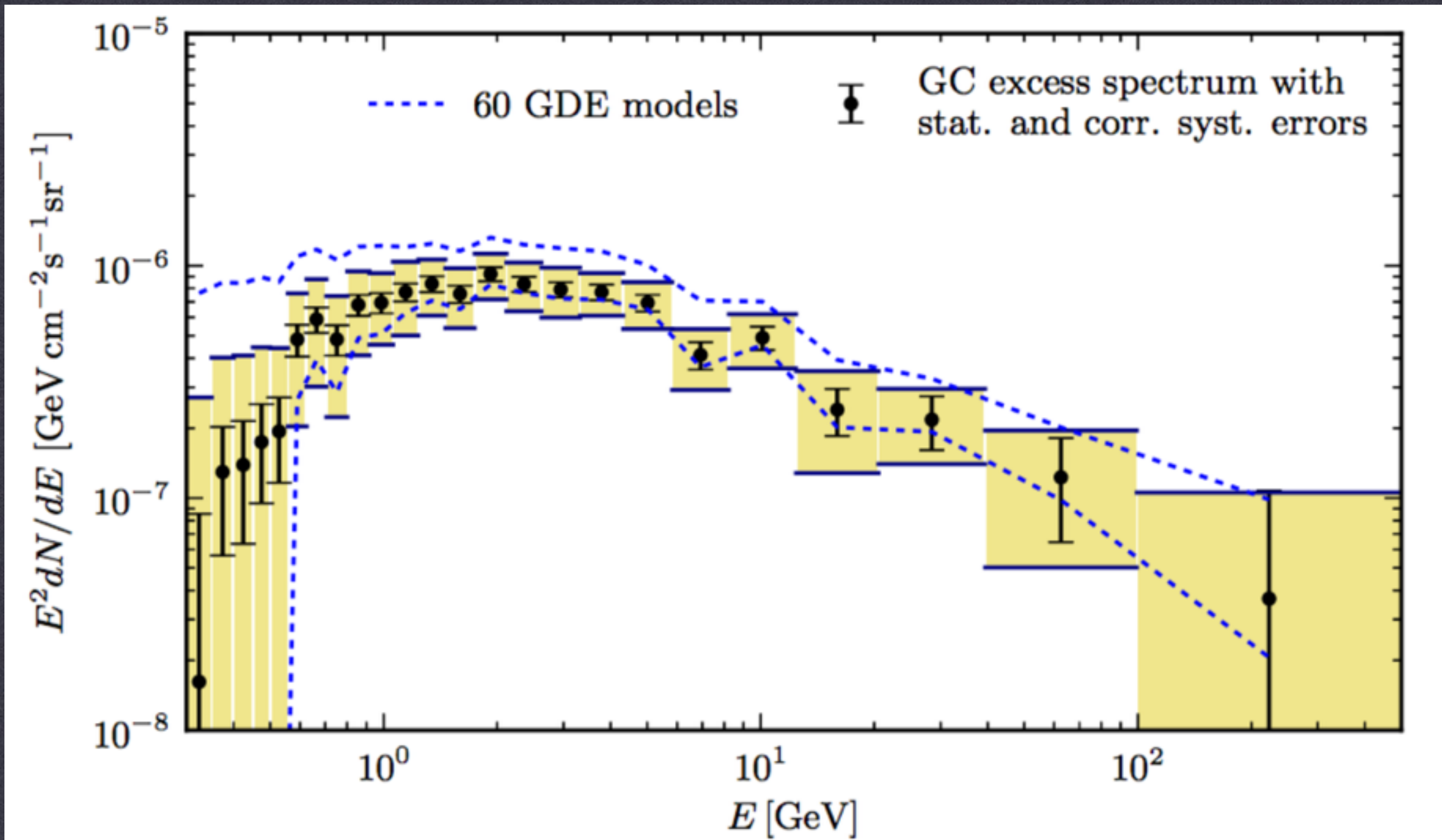


GALACTIC CENTER

EXCESS SPECTRUM

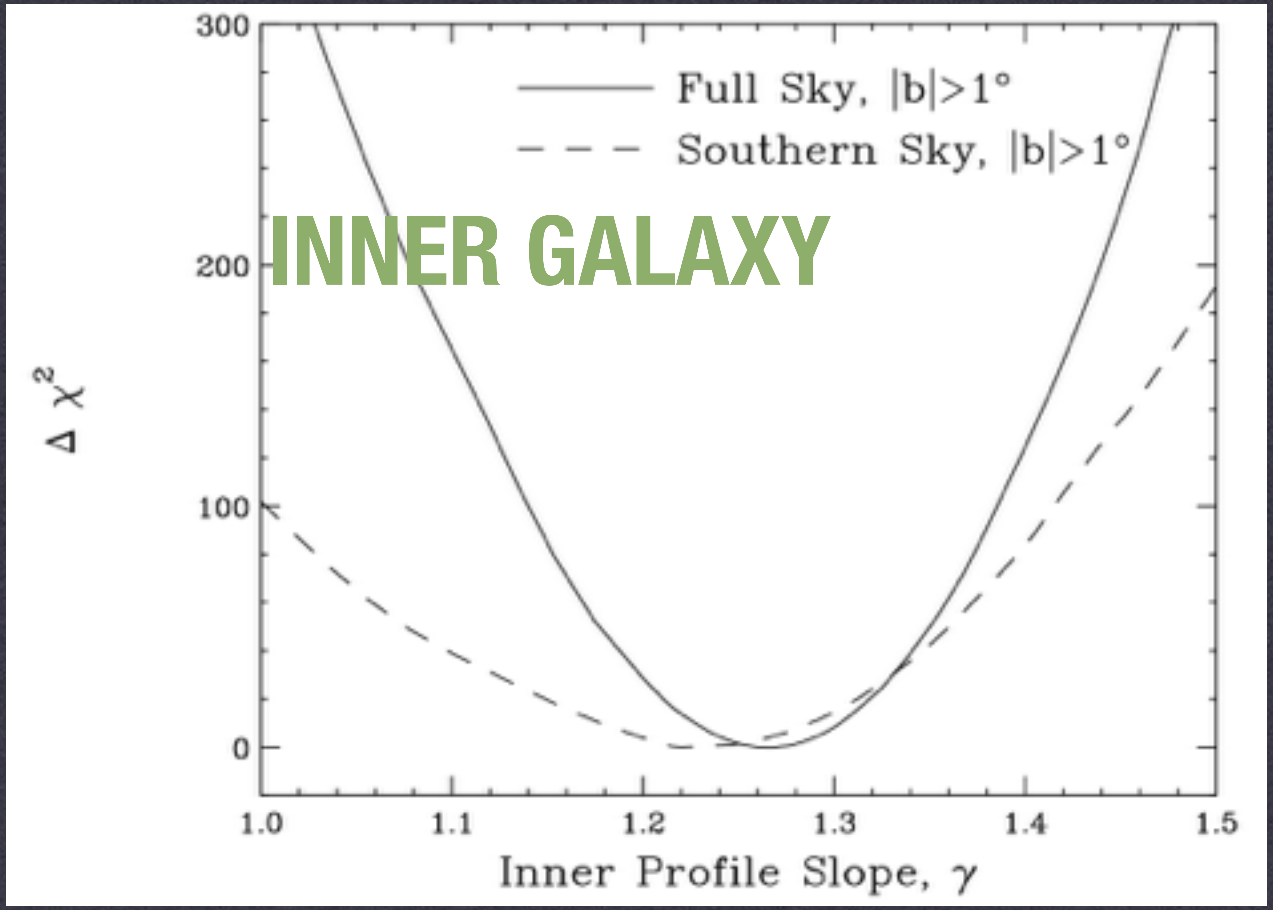
INNER GALAXY

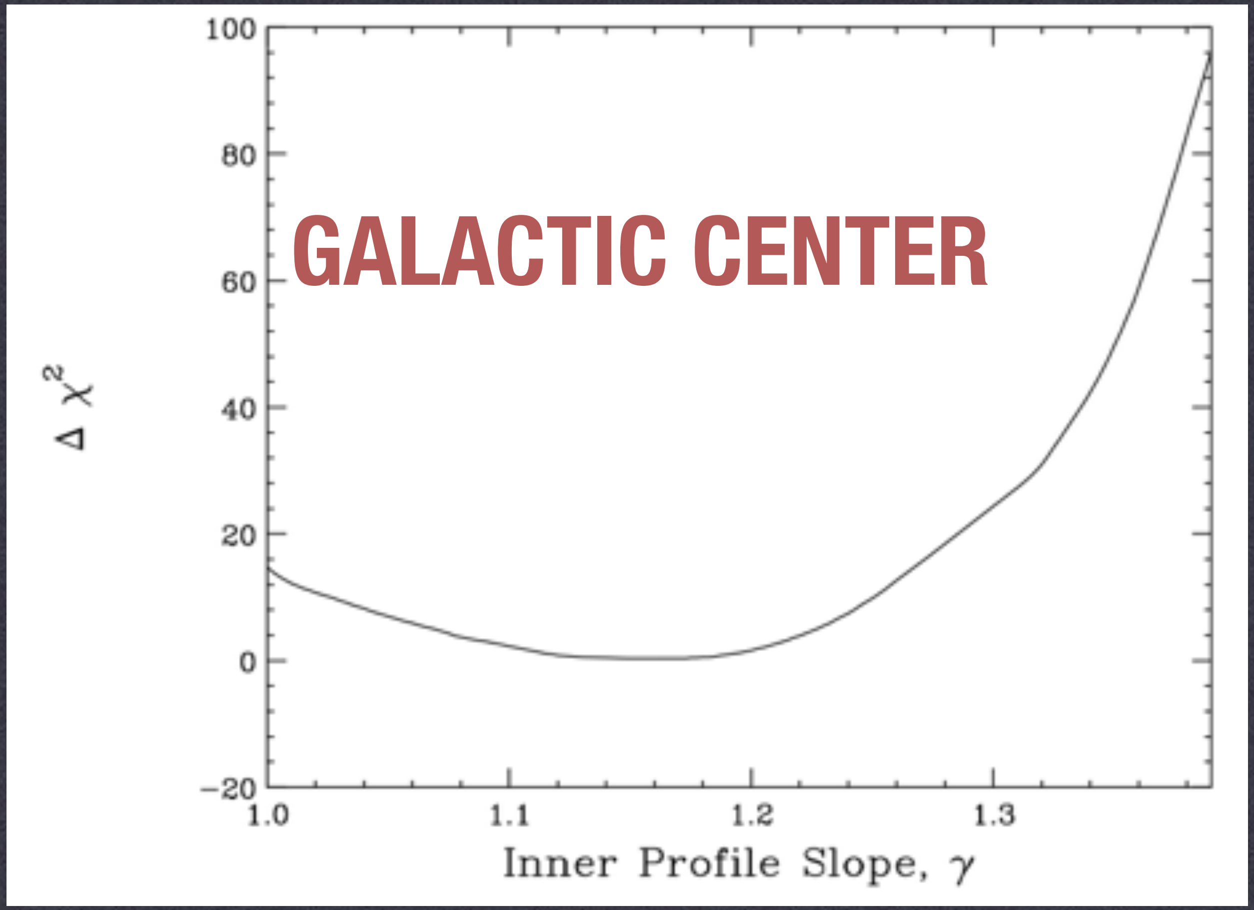
CALORE ET AL. (2014)



EXCESS MORPHOLOGY

RESULTS: MORPHOLOGY





Inner galaxy prefers density profile γ = 1.18

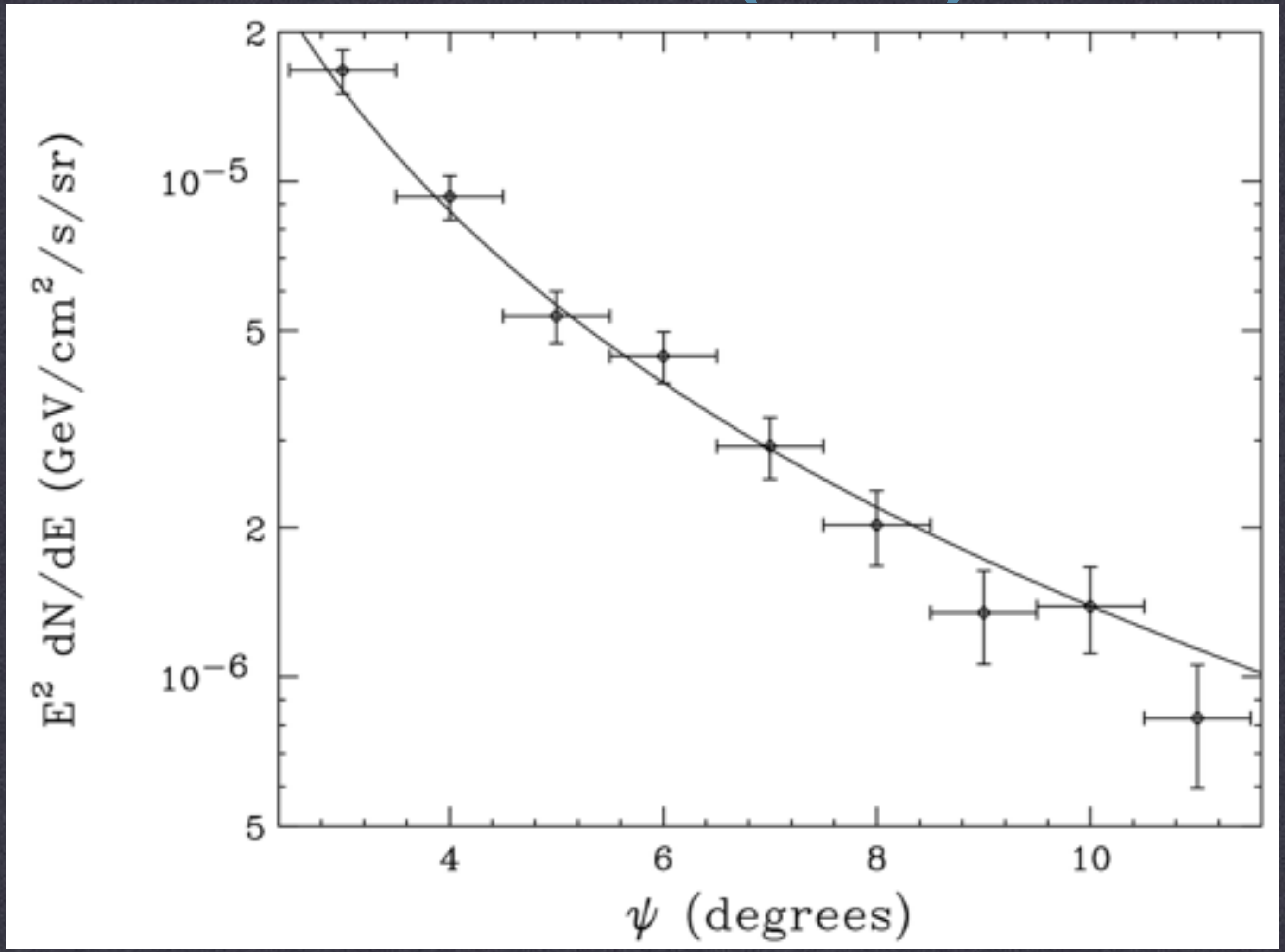
Galactic Center prefers γ = 1.17

γ = 1.26 is consistent with both, profile may also vary with radius

EXCESS MORPHOLOGY

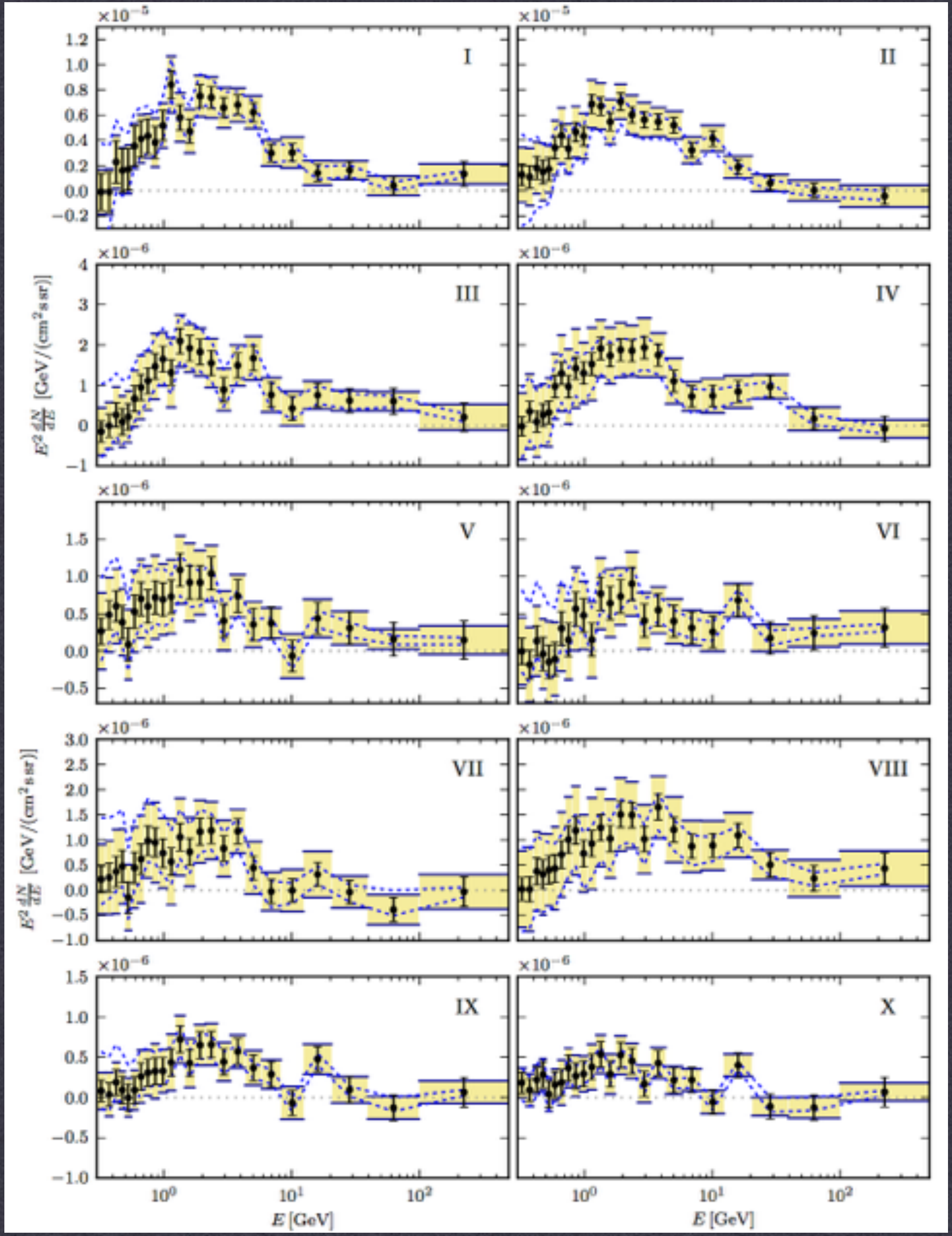
DAYLAN ET AL. (2014)

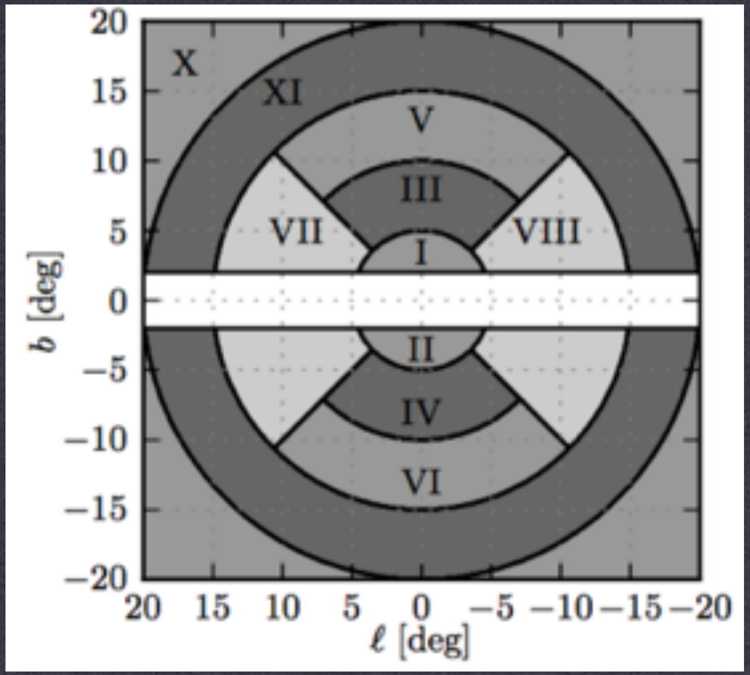
INNER GALAXY



Can additionally fix the spectrum and allow the normalization to float independently in different radial bins. In this case we find γ = 1.4, which provides some evidence that the profile is steepening with distance.

EXCESS MORPHOLOGY





Calore et al. (2014) independently fit the gamma-ray excess in 10 different sky regions.

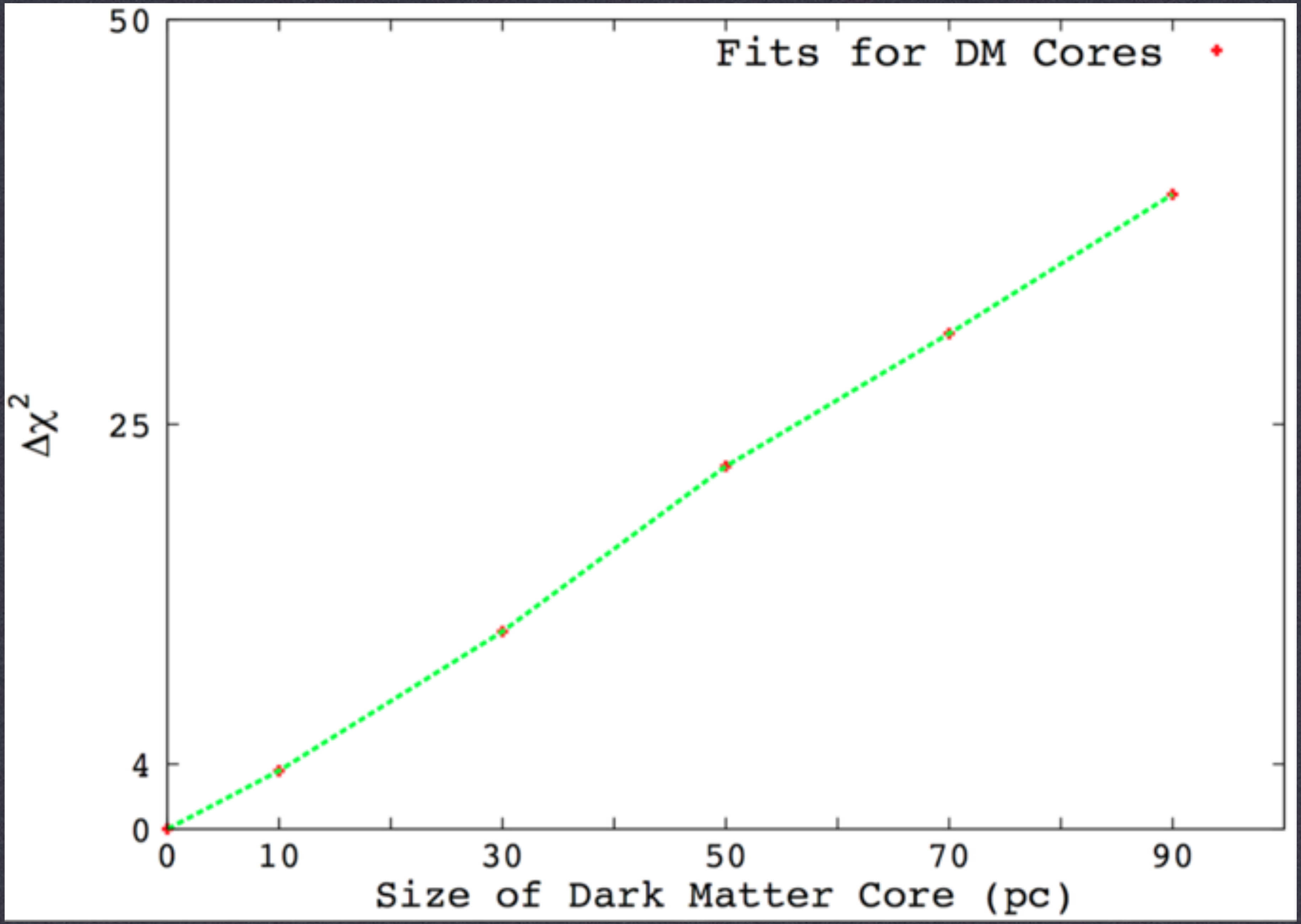
INNER GALAXY

This technique also allows us to compare the spectral shape of the fit in different sky regions. They show remarkable similarity.

A PROFILE CORE?

GALACTIC CENTER

DAYLAN ET AL. (2014)

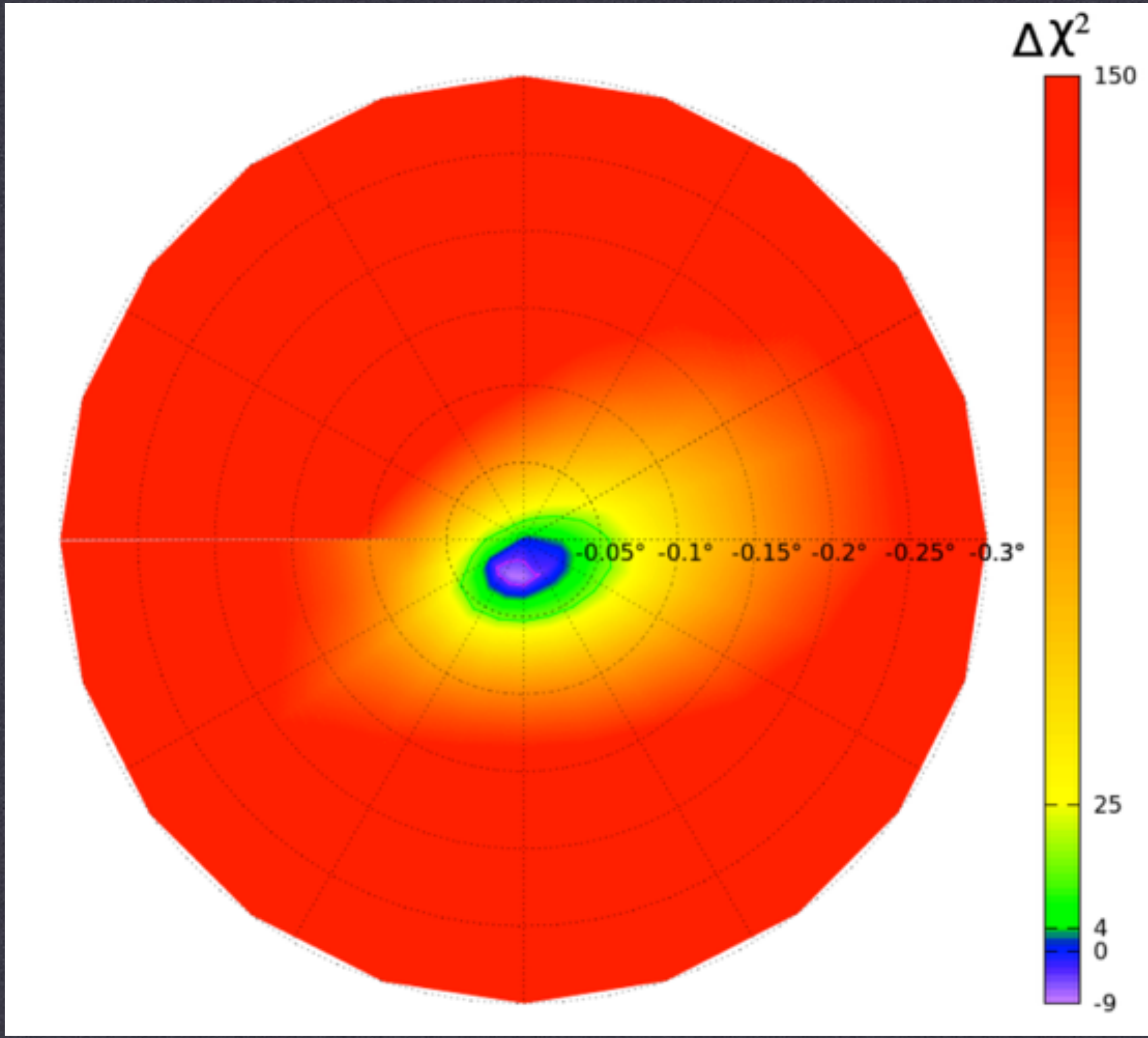


The emission intensity continues to rise to within 10 pc of the GC.

CENTERED-NESS?

GALACTIC CENTER

DAYLAN ET AL. (2014)



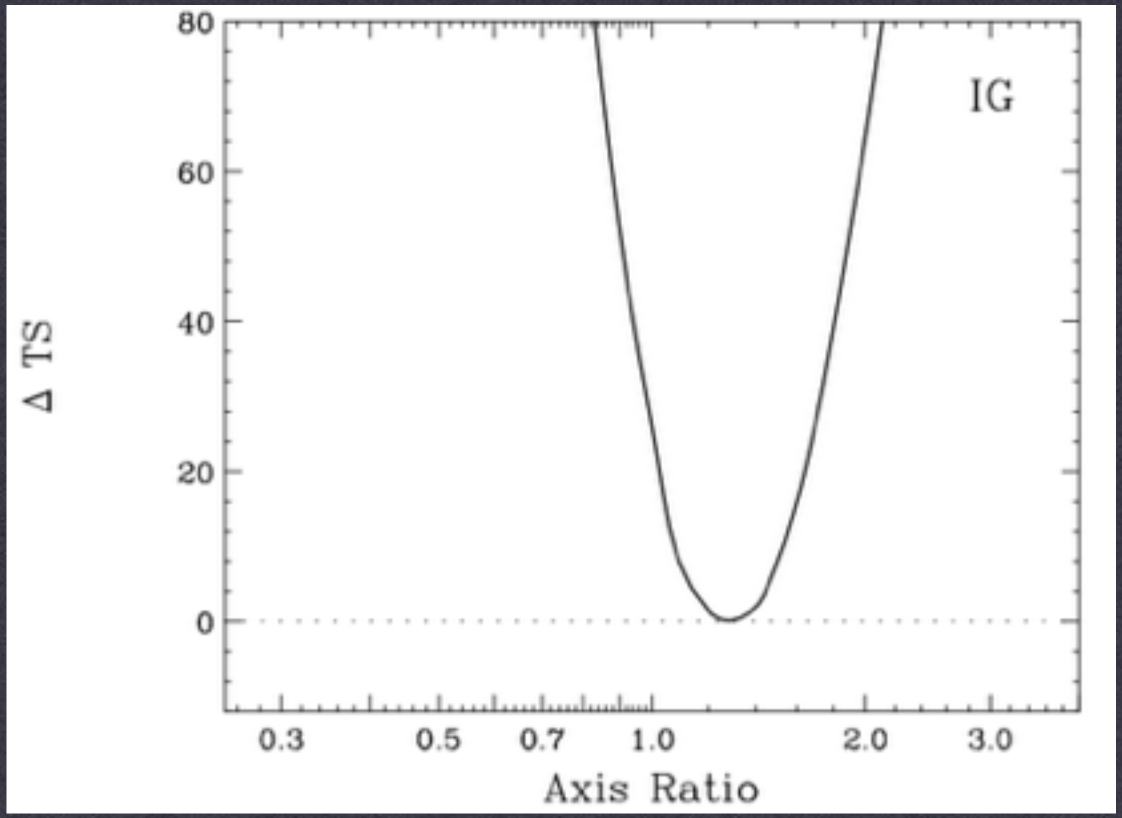
The center of the emission profile is located to within 0.05º of Sgr A*.

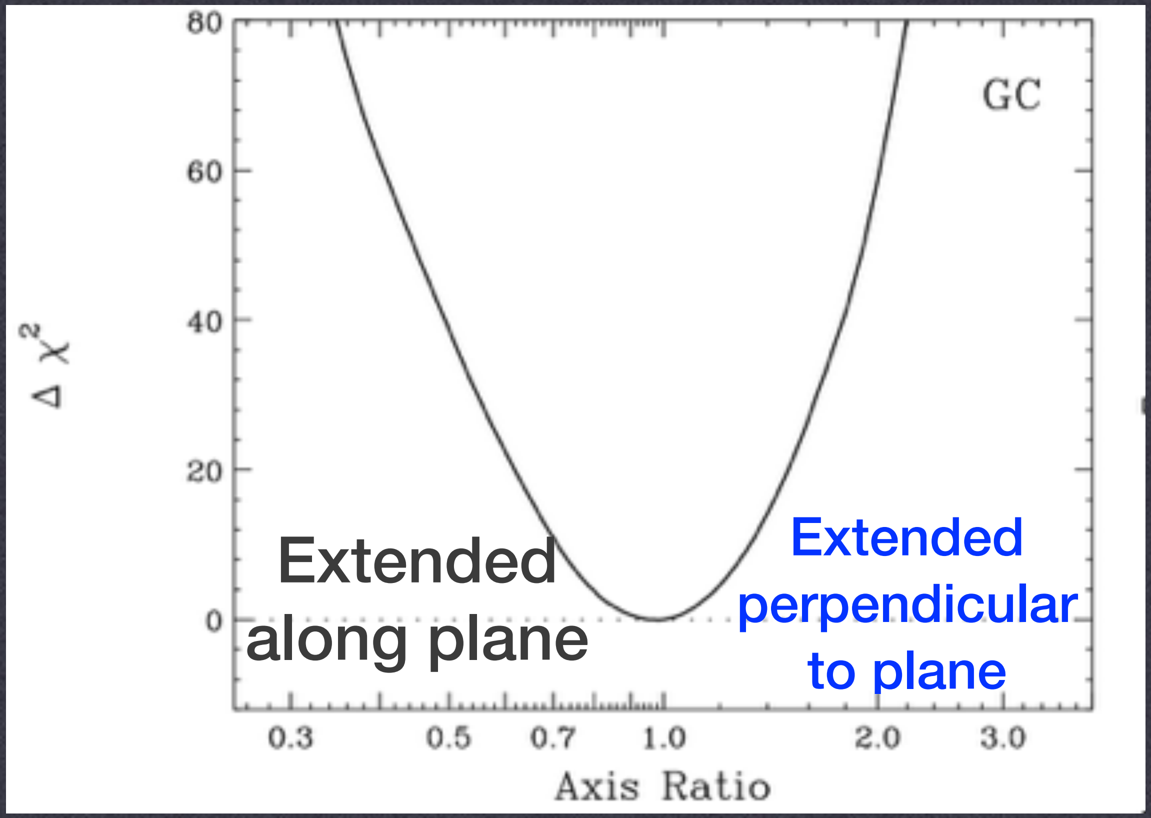
This disfavors Sgr A East as the source of the γ-ray excess (though only at 2σ).

ELLIPTICITY?

DAYLAN ET AL. (2014)

INNER GALAXY **GALACTIC CENTER**





The ellipticity serves as a powerful discriminator of baryonic mechanisms, which tend to be much more luminous along the plane.

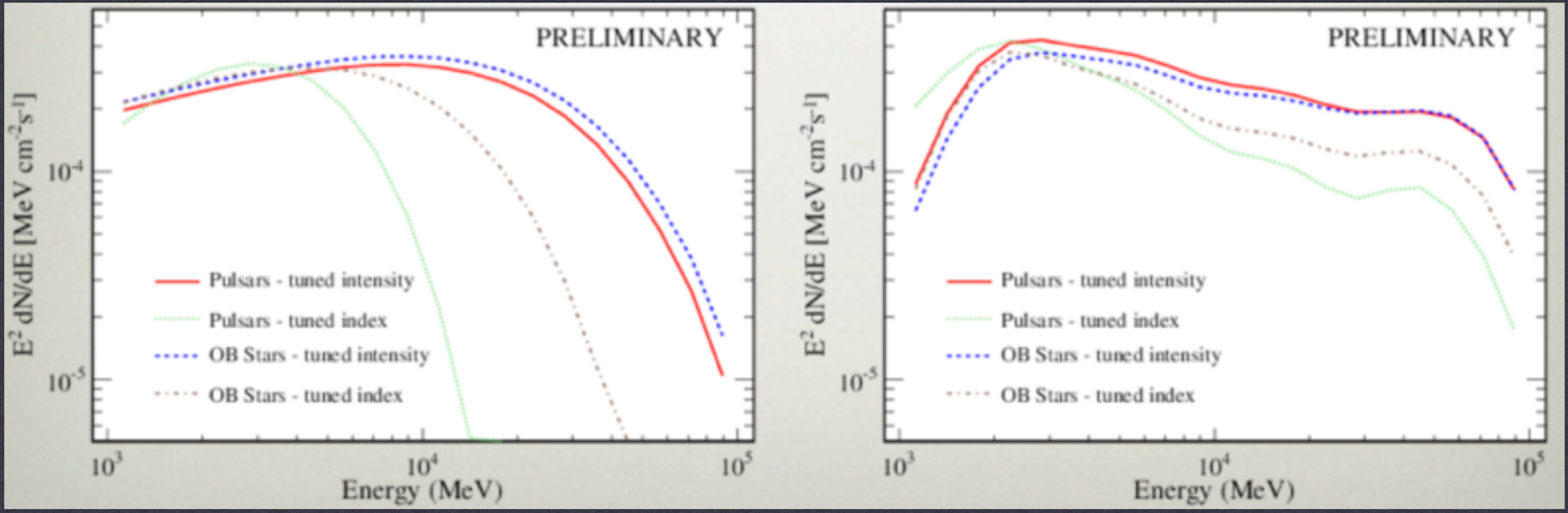
Hint of ellipticity in the IG analysis is thought to be due to over-subtraction of the galactic plane.

FERMI-LAT COLLABORATION

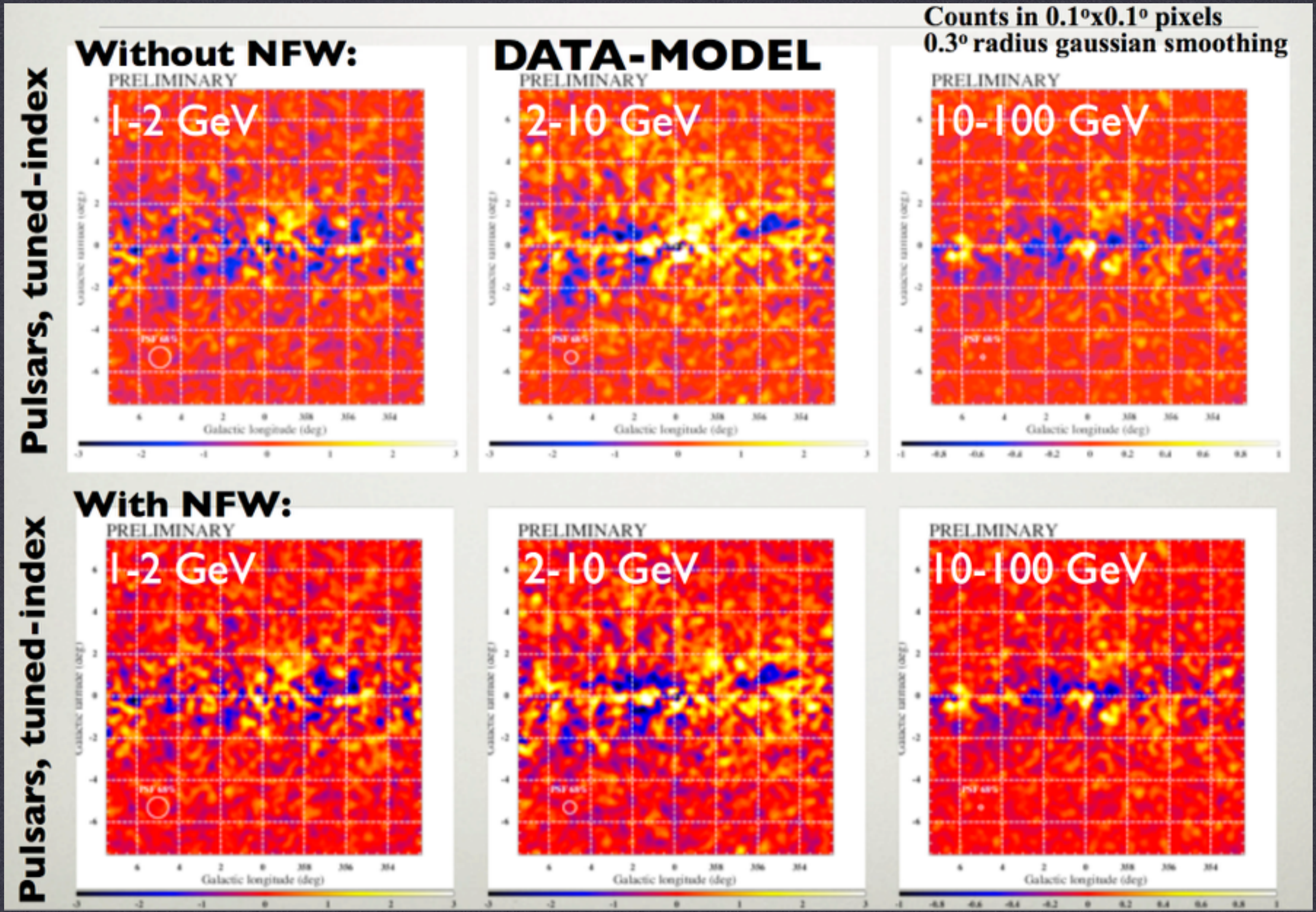
Though no Fermi-LAT publication on the GC has yet been published, the preliminary results were shown at 2014 Fermi Symposium.

They also find improved fits when an NFW template is added, the spectral details of the additional component depend on the modeling of the astrophysical diffuse emission.

Simona Murgia, 2014 Fermi Symposium



FERMI-LAT COLLABORATION



CURRENT STATE OF MEASUREMENTS

All published studies agree:

- The spectrum of the excess is peaked at an energy of ~2 GeV, and falls off at low energies with a spectrum that is harder than expected for astrophysical pion emission

- The excess extends to at least 10^{o} away from the galactic center, following a 3D profile which falls in intensity as $r^{-2.2 \text{ to } -2.8}$

IMPORTANT CAVEAT

I have discussed "dark matter fits" to the γ-ray data.

But this does NOT mean that the mechanism producing the excess has a dark matter origin

The data analysis tells us that the model of γ-ray data improves when we add a template with:

- A spherically symmetric, radially falling emission profile with $r^{-2.0 \text{ to } -2.8}$
- A spectrum which peaks at an energy of ~2 GeV and has a hard low-energy spectrum compared to known astrophysical emission mechanisms

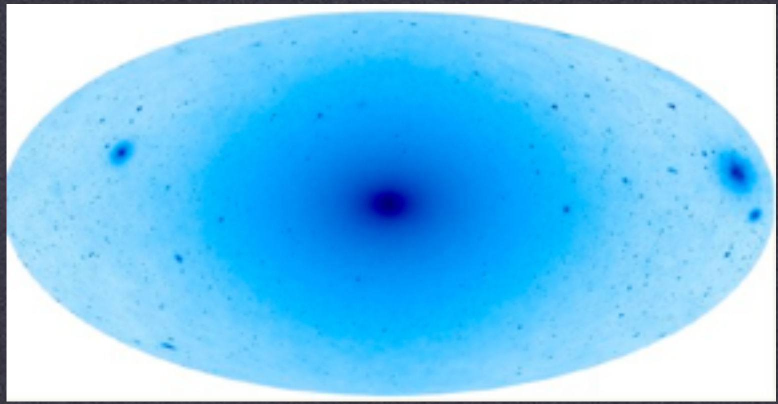
INTERPRETATIONS

Three Interpretations Have Been Proposed So Far:

1.) A Population of GC Millisecond Pulsars

2.) An Outburst of Hadronic or Leptonic Emission from the Galactic Center

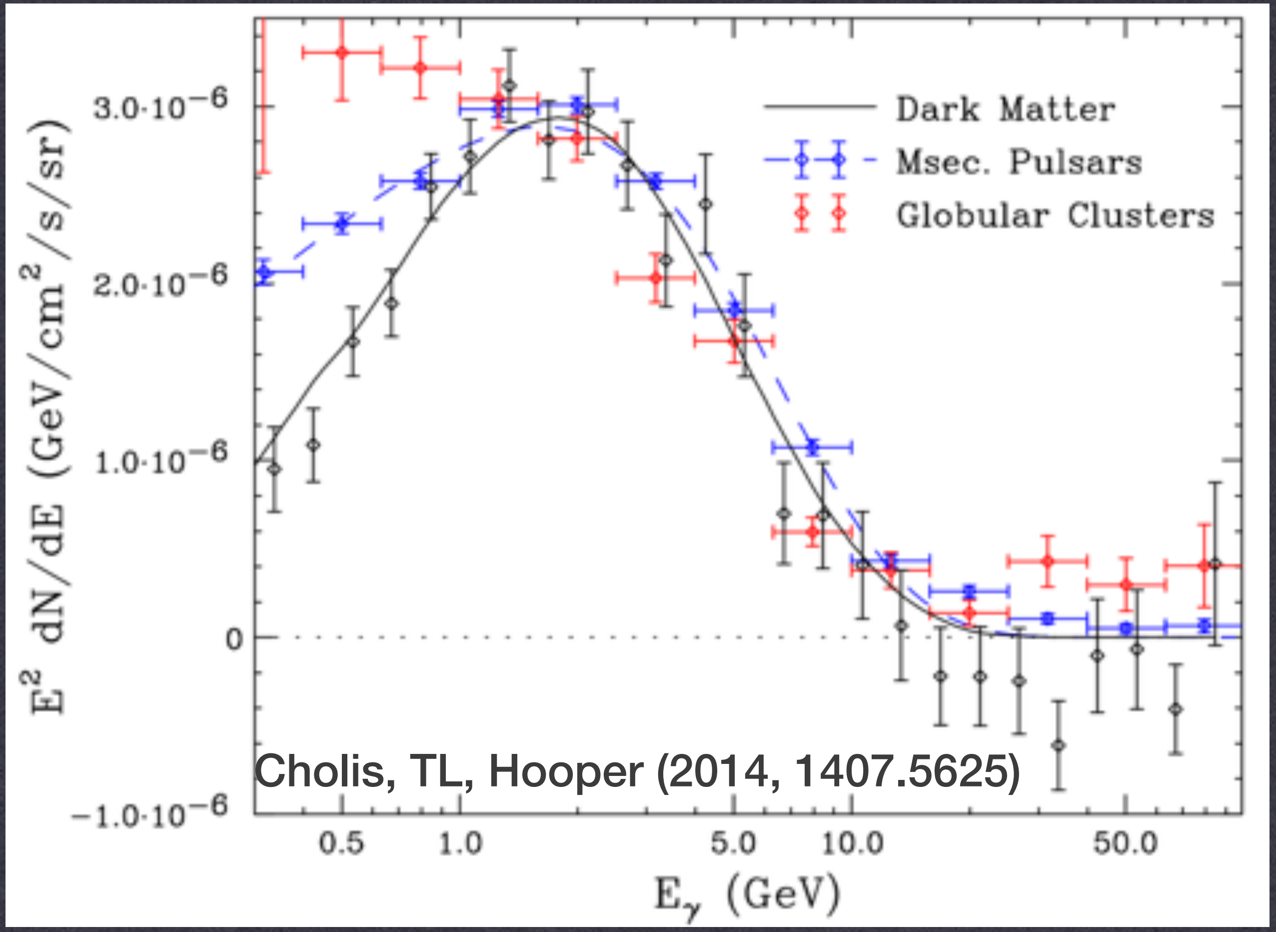
3.) Dark Matter Annihilation



INTERPRETATIONS

MILLISECOND PULSARS

- To first order, the peak of the MSP energy spectrum matches the peak of the observed excess
- MSPs are thought to be overabundant in dense star-forming regions (like globular clusters, and potentially the galactic center)

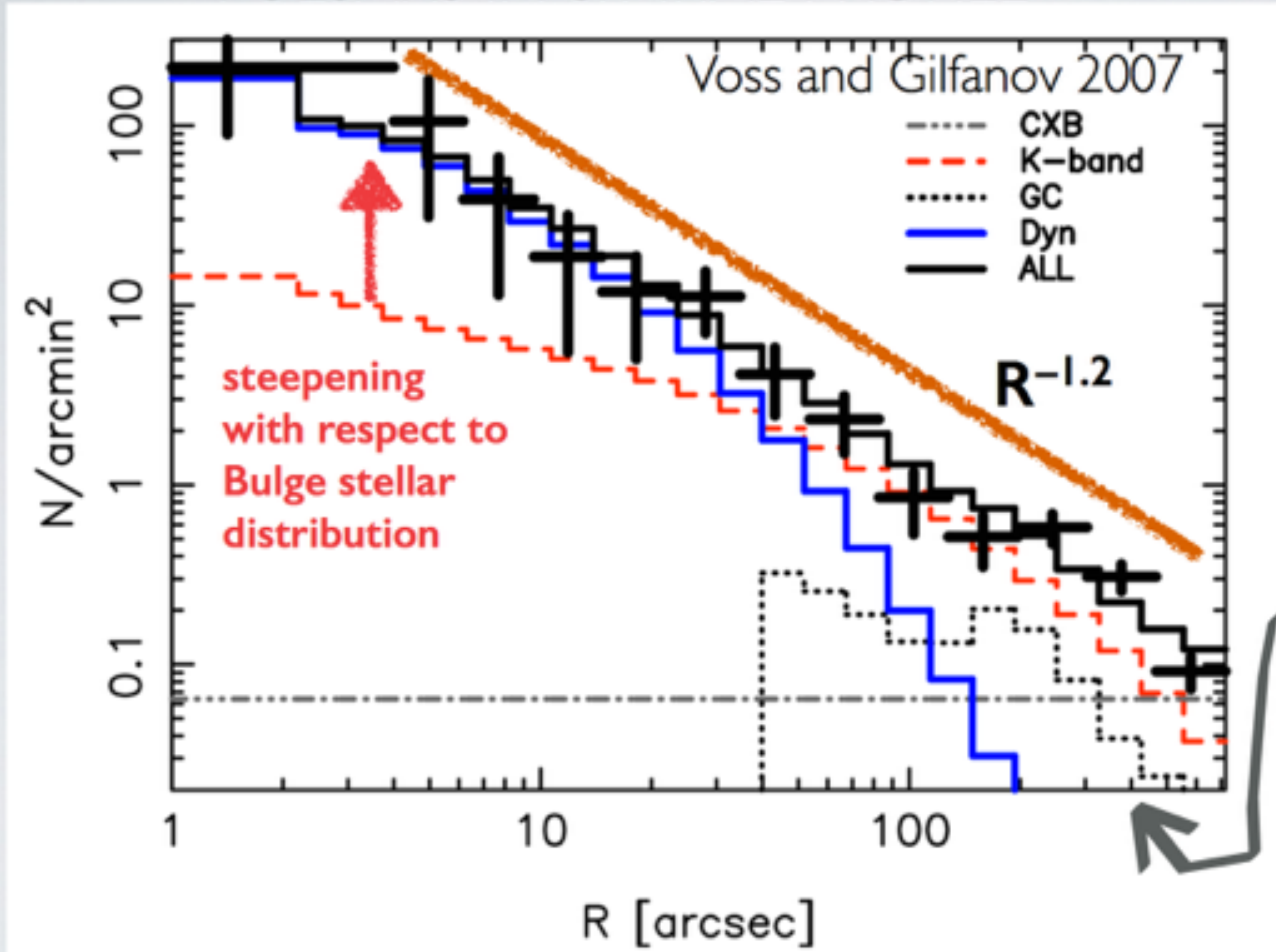


ABAZAJIAN (2011, 1011.4275)
ABAZAJIAN & KAPLINGHAT (2012, 1207.6047)
PETROVIC ET AL. (2014, 1411.2980)

INTERPRETATIONS

MILLISECOND PULSARS: M31

DEGENERACY WITH MILLI-SECOND PULSARS IN SPATIAL PROFILE



We make the reasonable assumption that Low-Mass X-ray Binaries have the same spatial distribution as MSPs

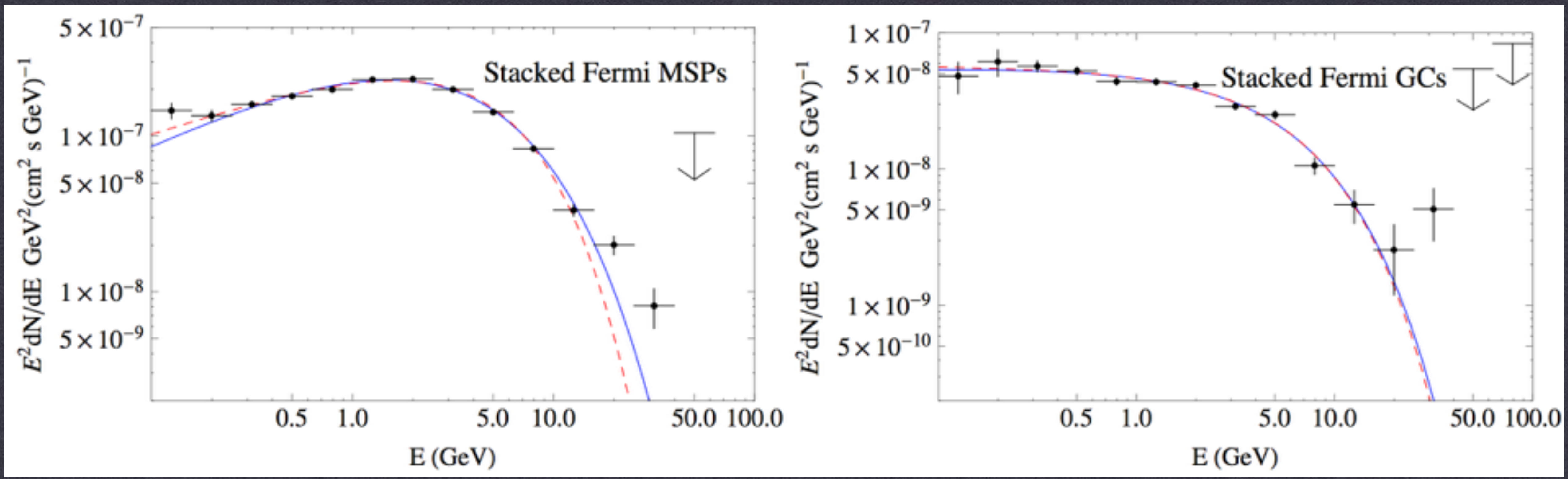
400" towards M31 center = 1.5 kpc distance from center = 10 degrees towards MW center

Orange line is same as best-fit excess template ($R^{-1.2}$ in projection implies $r^{-2.2}$ de-projected)!

Slide from Manoj Kaplinghat

INTERPRETATIONS

MILLISECOND PULSARS

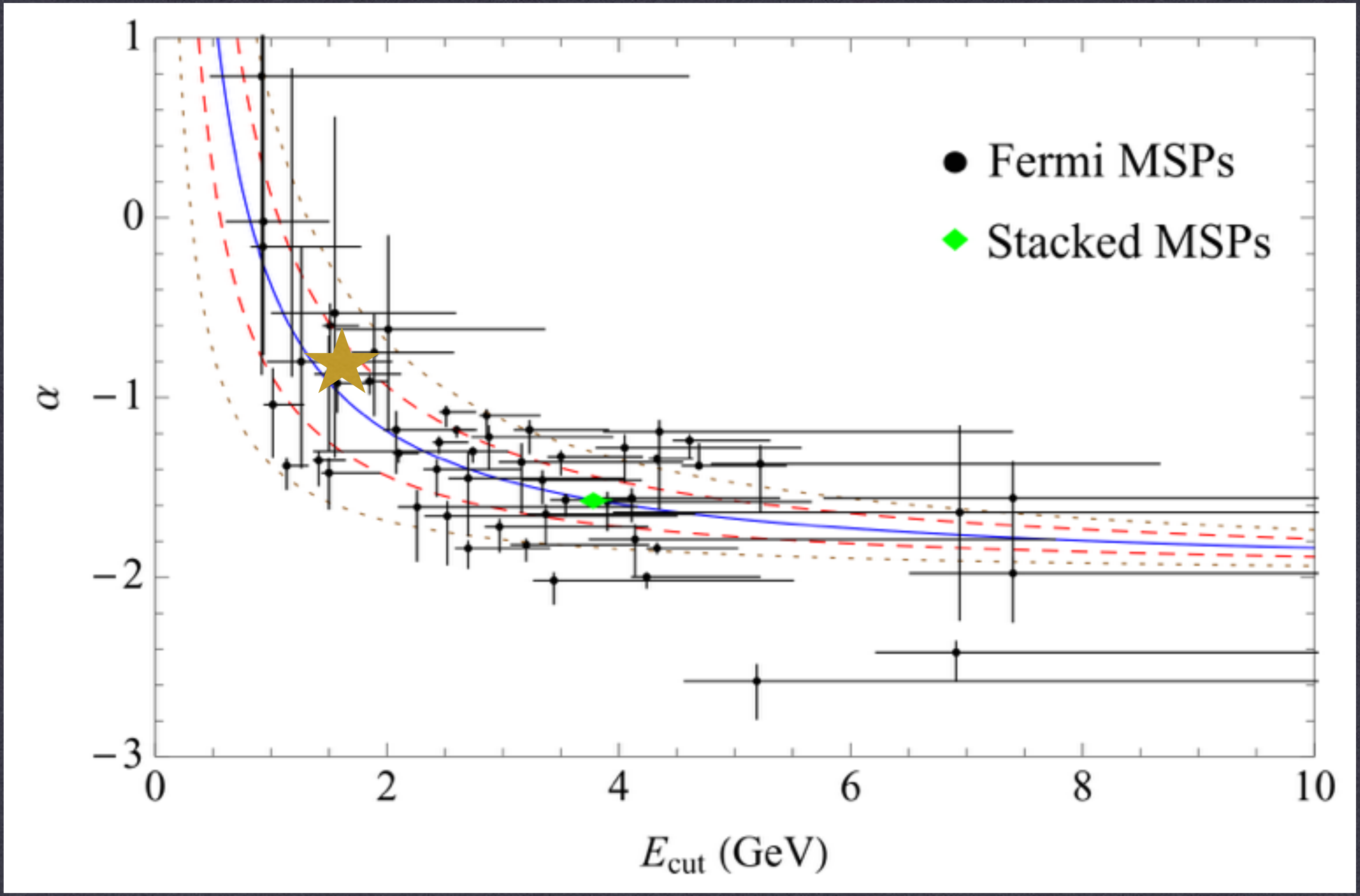


- **Analyze the average spectrum and luminosity of the Fermi MSP and globular cluster populations:**
  - **5.5 years of data**
  - **P7 Reprocessed Photons**
  - **15 energy bins, no spectral model assumed**

CHOLIS, TL, HOOPER (2014, 1407.5583)
CHOLIS, TL, HOOPER (2014, 1407.5625)

INTERPRETATIONS

MILLISECOND PULSARS



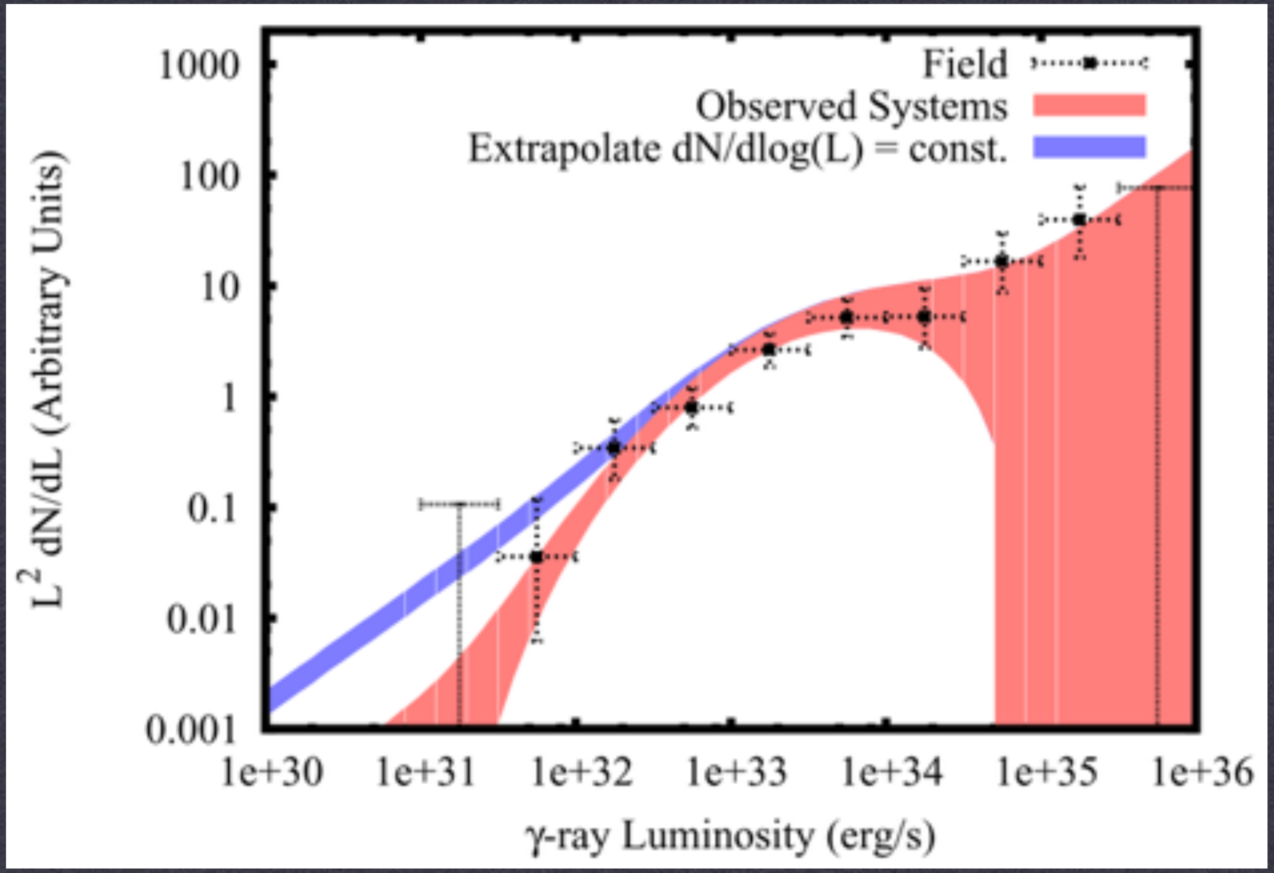
CHOLIS, TL, HOOPER (2014, 1407.5583)
CHOLIS, TL, HOOPER (2014, 1407.5625)

INTERPRETATIONS

MILLISECOND PULSARS

- There would need to be 226 (+91/-67) MSPs with luminosity > 10^{34} erg s^{-1} in the circular region, and 61.9 (+60/-33.7) with luminosity > 10^{35} erg s^{-1}.

- These should be detectable by the Fermi-LAT as bright point sources

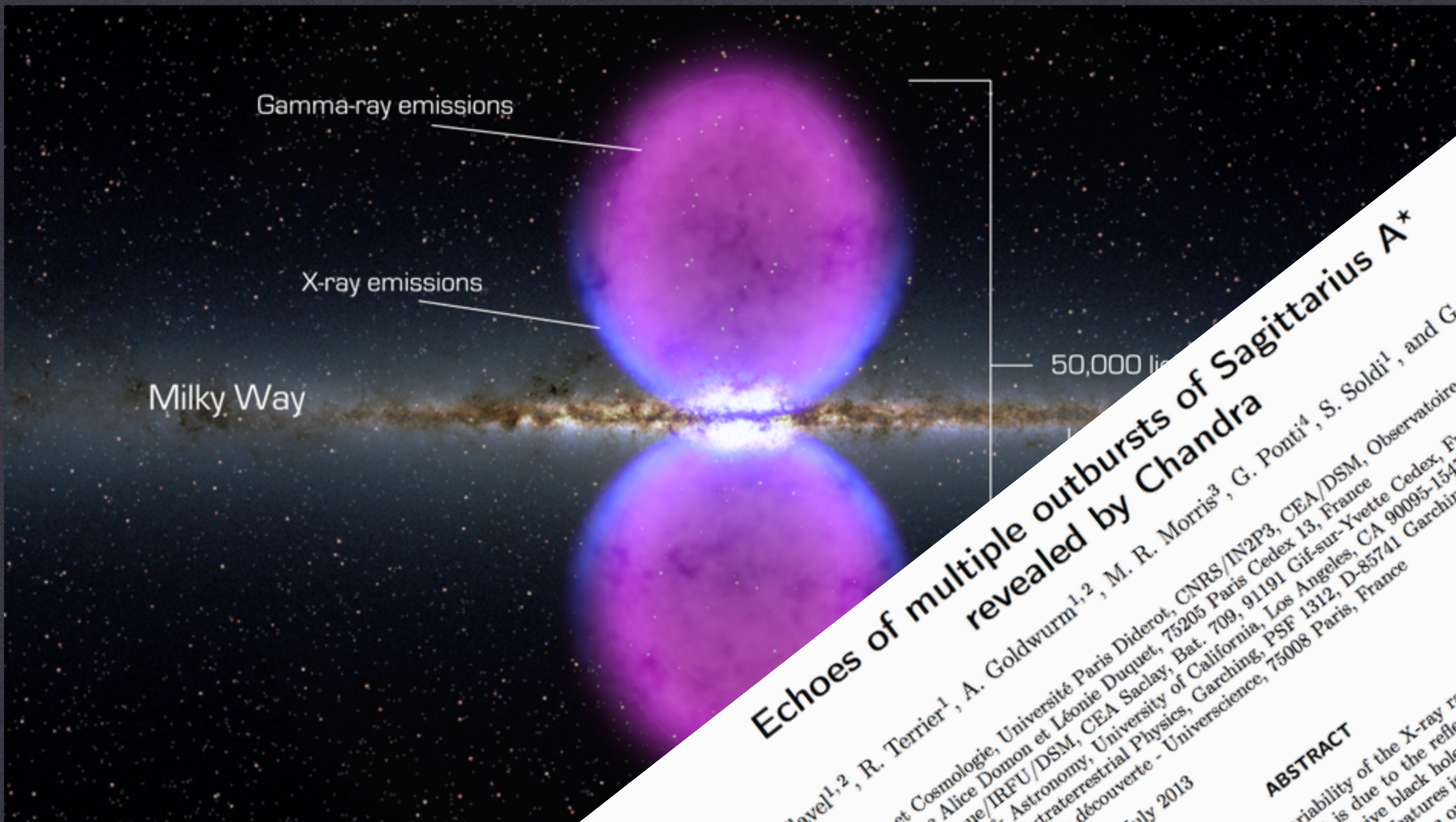


- We can also compare the MSP population to observed LMXBs. The ratio of LMXBs to the MSP luminosity of globular clusters, predicts a population of 103 (+70/-45) LMXBs in the GC in order to produce the GC excess. Only 6 are observed.

CHOLIS, TL, HOOPER (2014, 1407.5583)
CHOLIS, TL, HOOPER (2014, 1407.5625)

INTERPRETATIONS

HADRONIC OUTBURSTS



Echoes of multiple outbursts of Sagittarius A* revealed by Chandra

M. Clavel[1,2], R. Terrier[1], A. Goldwurm[1,2], M. R. Morris[3], G. Ponti[4], S. Soldi[1], and G. Trap[5,1]

AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/DSM, Observatoire de Paris
Paris Cité ; 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France
ice d'Astrophysique/IRFU/DSM, CEA Saclay, Bat. 709, 91191 Gif-sur-Yvette Cedex, France
ent of Physics & Astronomy, University of California, Los Angeles, CA 90095-1547, USA
-Institute for Extraterrestrial Physics, Garching, PSF 1312, D-85741 Garching, Germa
ique, Palais de la découverte - Universcience, 75008 Paris, France

/ Accepted 12 July 2013

ABSTRACT

and temporal variability of the X-ray radiation f
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ntral supermassive black hole, Sagitta
loud reflection features is therefo
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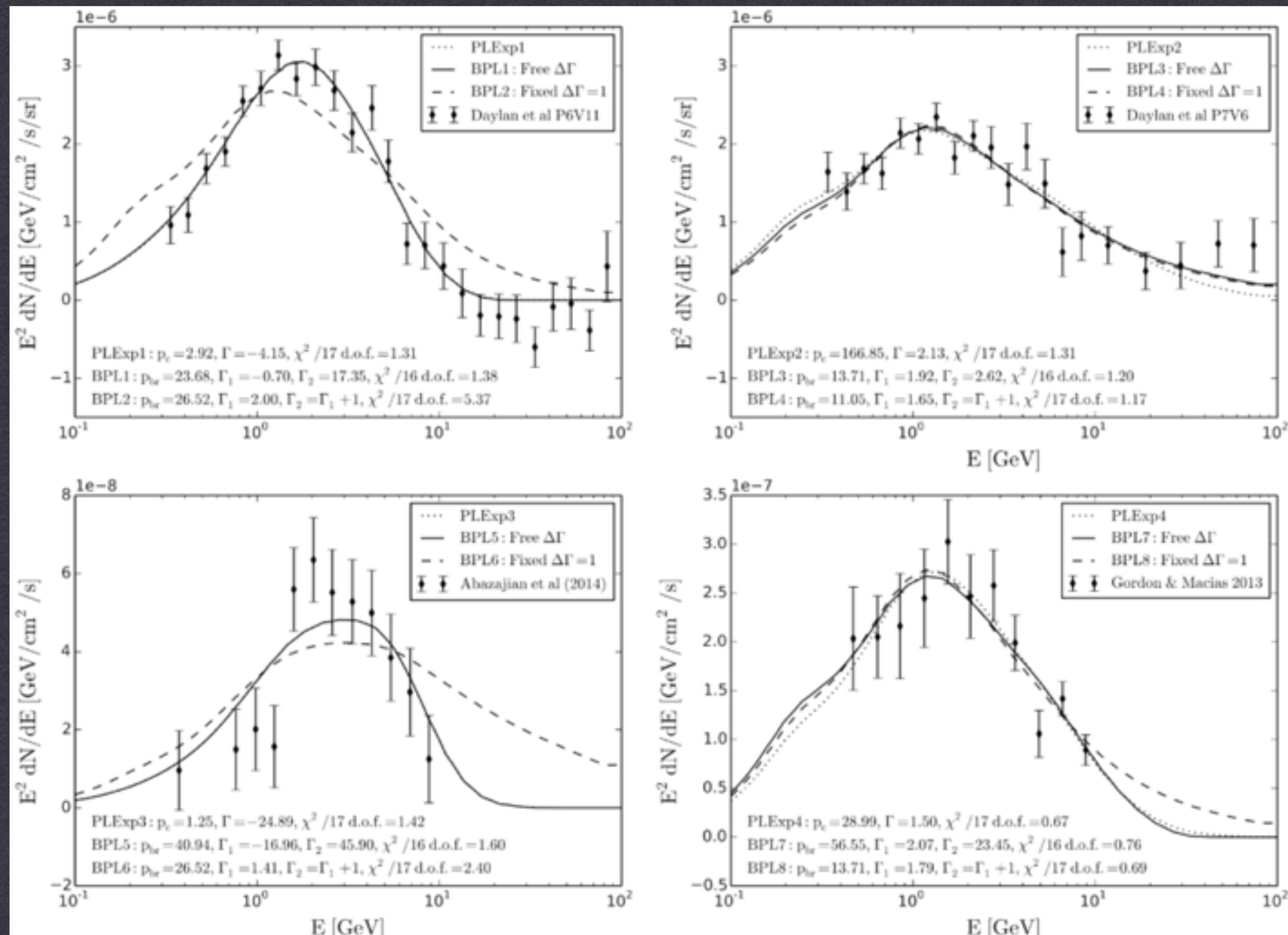
t 6.4 k

CARLSON & PROFUMO (2014, 1405.7685)

INTERPRETATIONS

HADRONIC OUTBURSTS

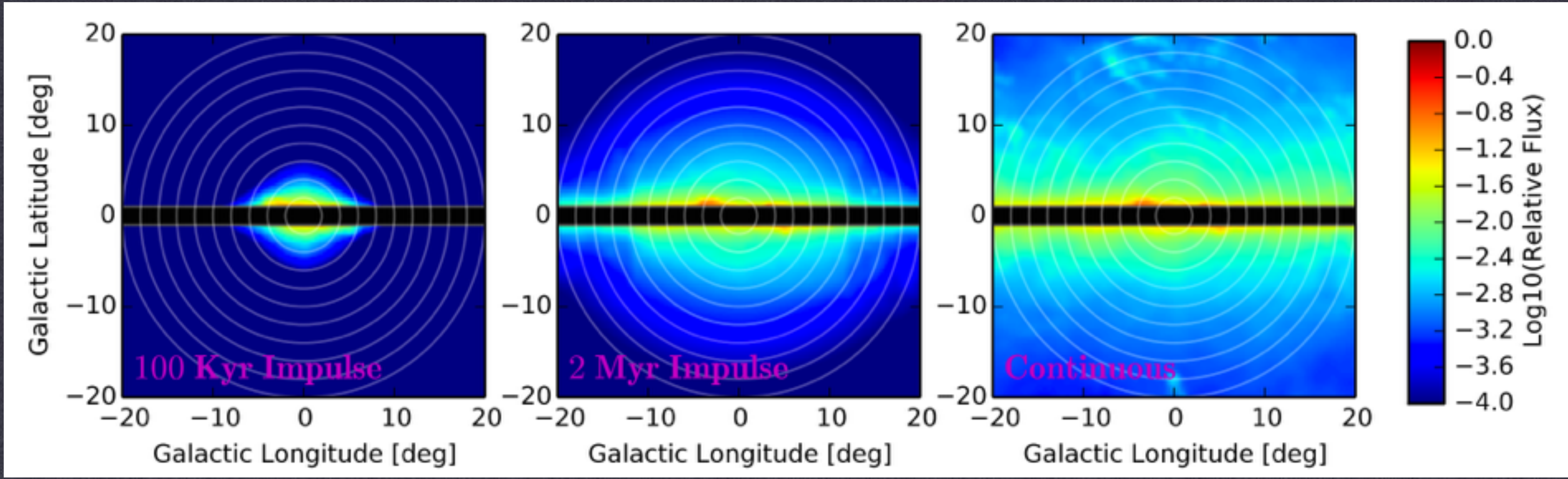


Difficult to explain the low-energy spectrum without introducing highly peaked proton injection spectra

CARLSON & PROFUMO (2014, 1405.7685)

INTERPRETATIONS

HADRONIC OUTBURSTS

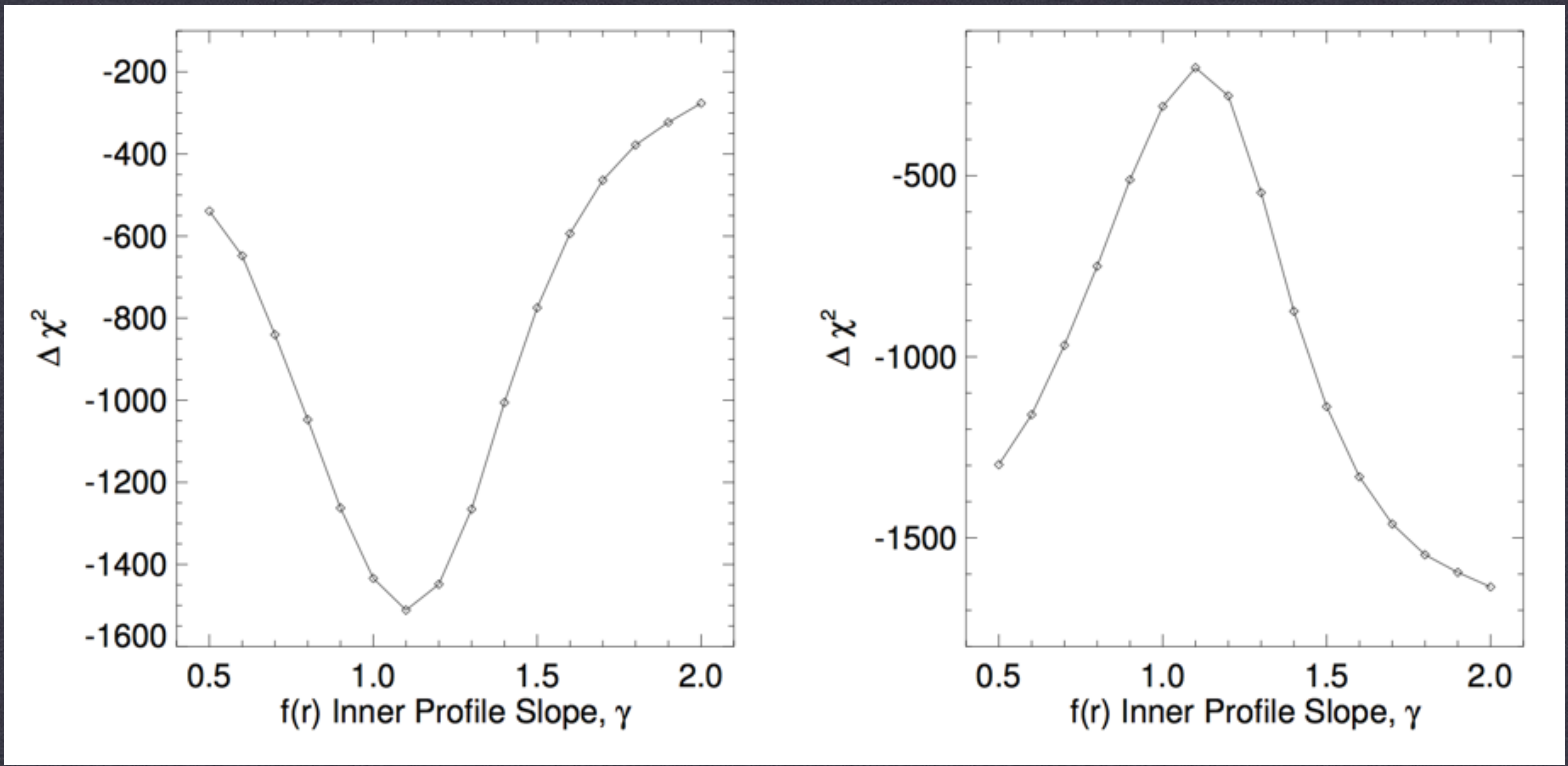


Best Fitting Linear Combination of Hadronic Outburst Models:	TS=51 (14 d.o.f)
Best Fitting NFW Template	TS=315 (5 d.o.f)

CARLSON & PROFUMO (2014, 1405.7685)

DAYLAN ET AL. (2014)

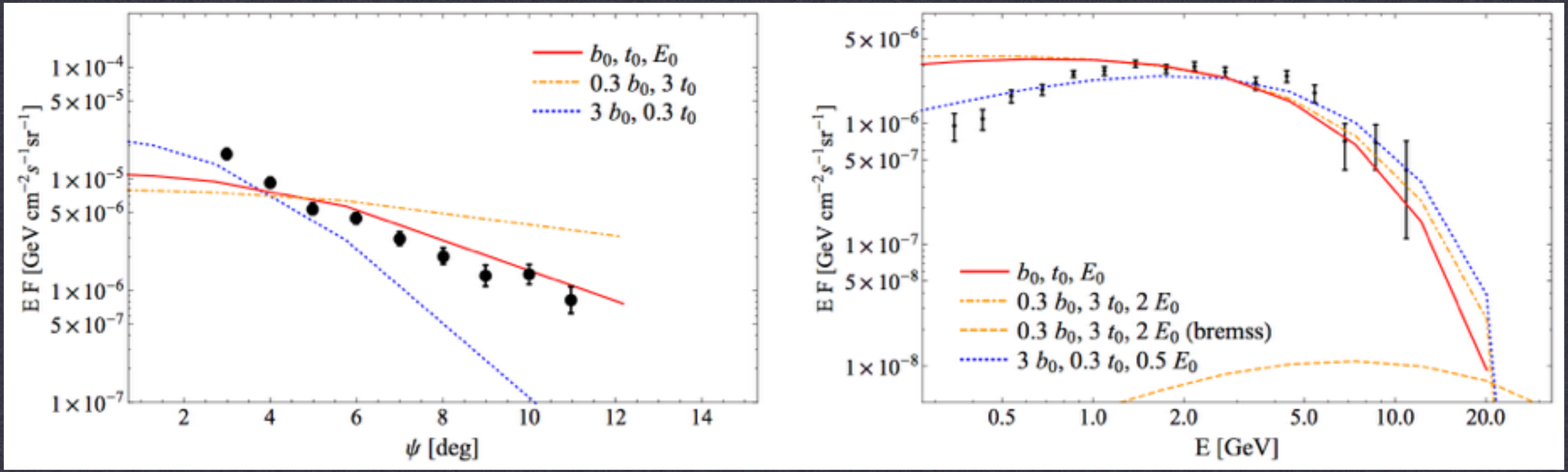
RESULTS: CORRELATION WITH GAS



Can add in the SFD dust map, integrated over the line of sight, and globally bias each ring by $r^{-2.4}$ in order to test the fit to local peaks in the gas density

INTERPRETATIONS

LEPTONIC OUTBURSTS



Electron Cooling is a significant issue — the models which correctly fit the morphology of the GC excess are poor fits to the spectrum of the GC excess, and vice versa.

PETROVIC, SERPICO, ZAHARIJAS (2014)

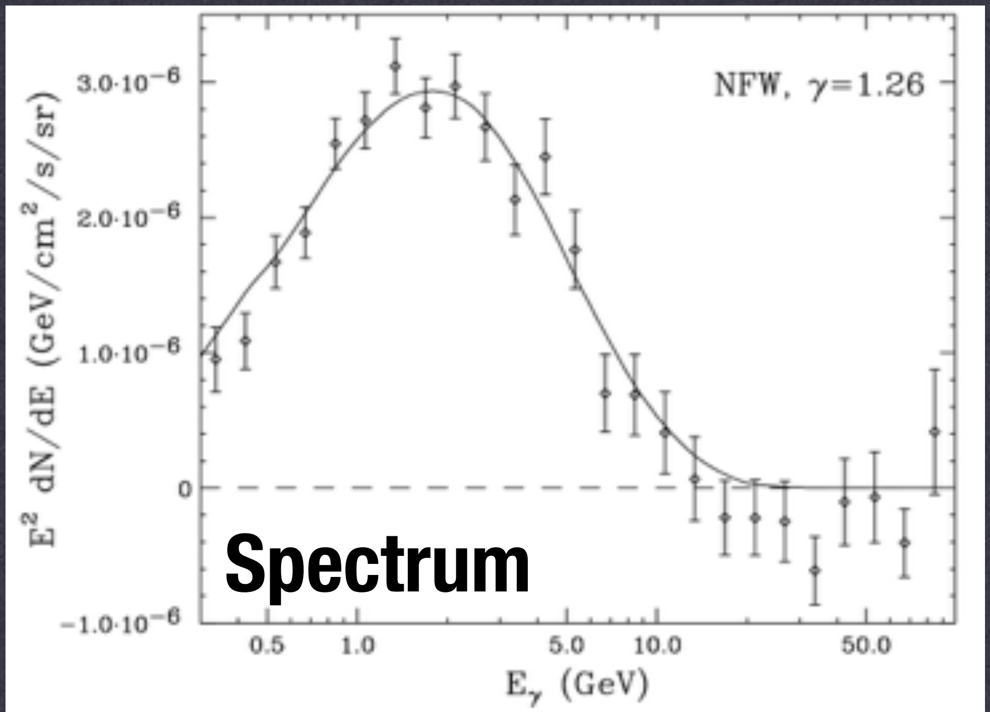
INTERPRETATIONS

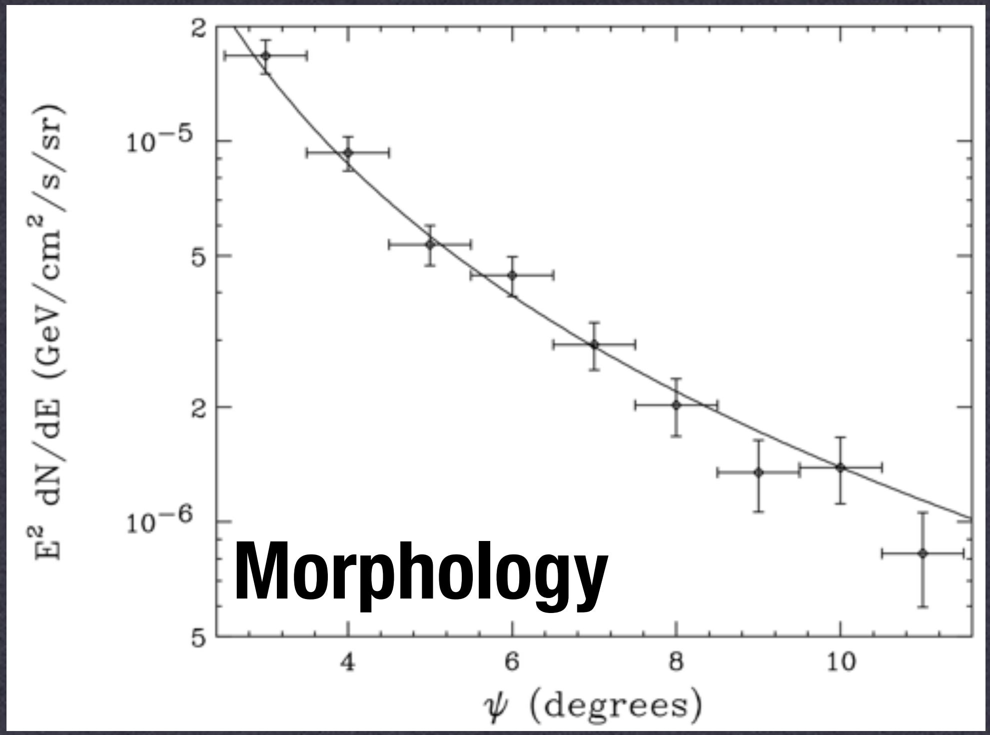
ASTROPHYSICAL MECHANISMS: BAYESIAN VIEW

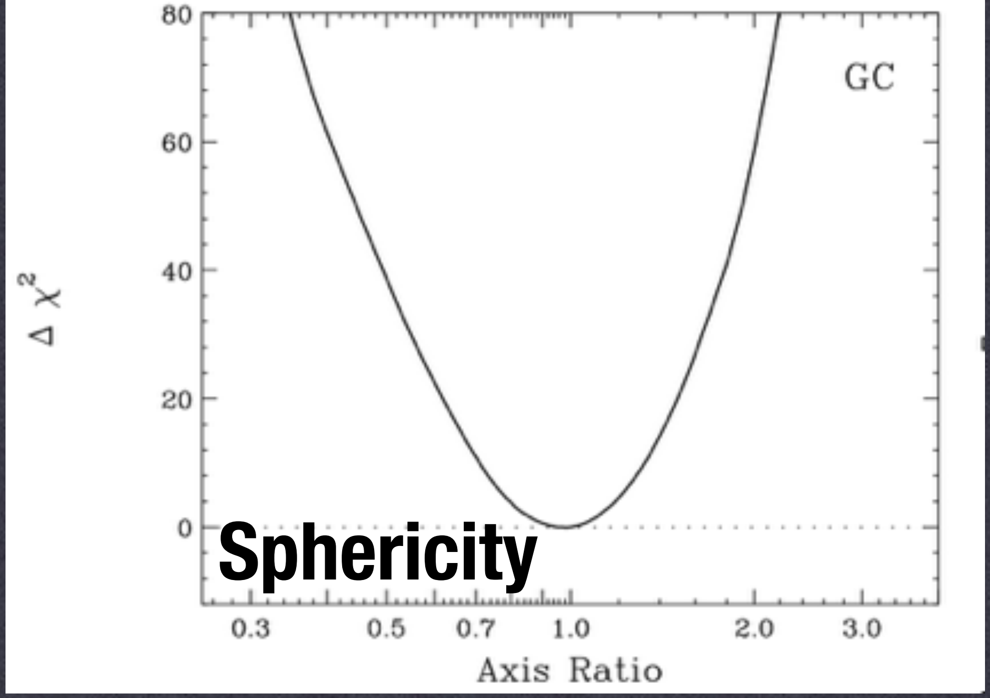
- Astrophysical models form a relatively poor fit to the spectrum and morphology of the GC excess.
- However, the Bayesian prior on the existence of these emission mechanisms is quite high.
- More refined models are coming! There is some hope that diffuse emission models could provide a testable explanation for the GC excess.

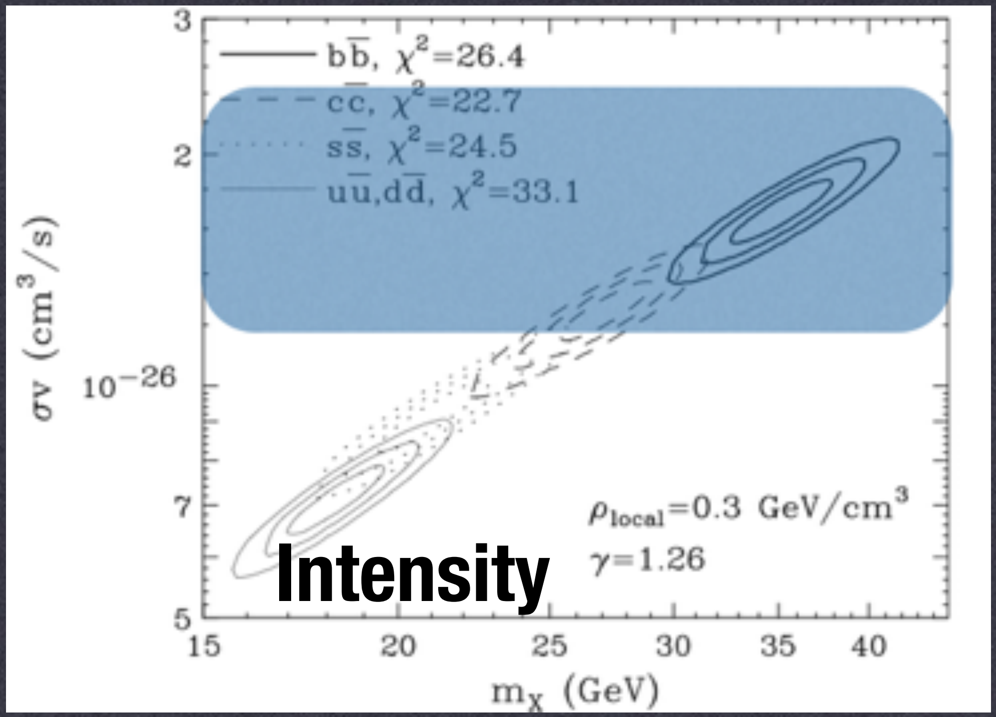
INTERPRETATIONS

DARK MATTER





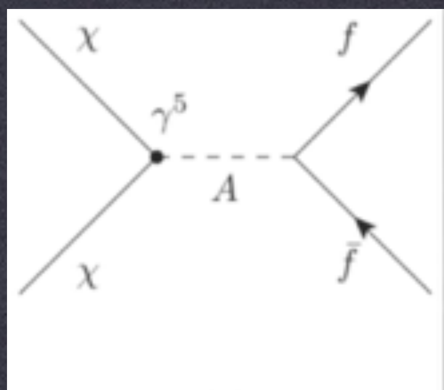




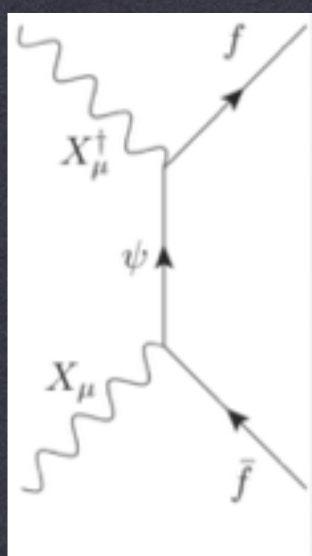
INTERPRETATIONS

DARK MATTER

BERLIN, HOOPER, MCDERMOTT (2014)



(1)



(8)

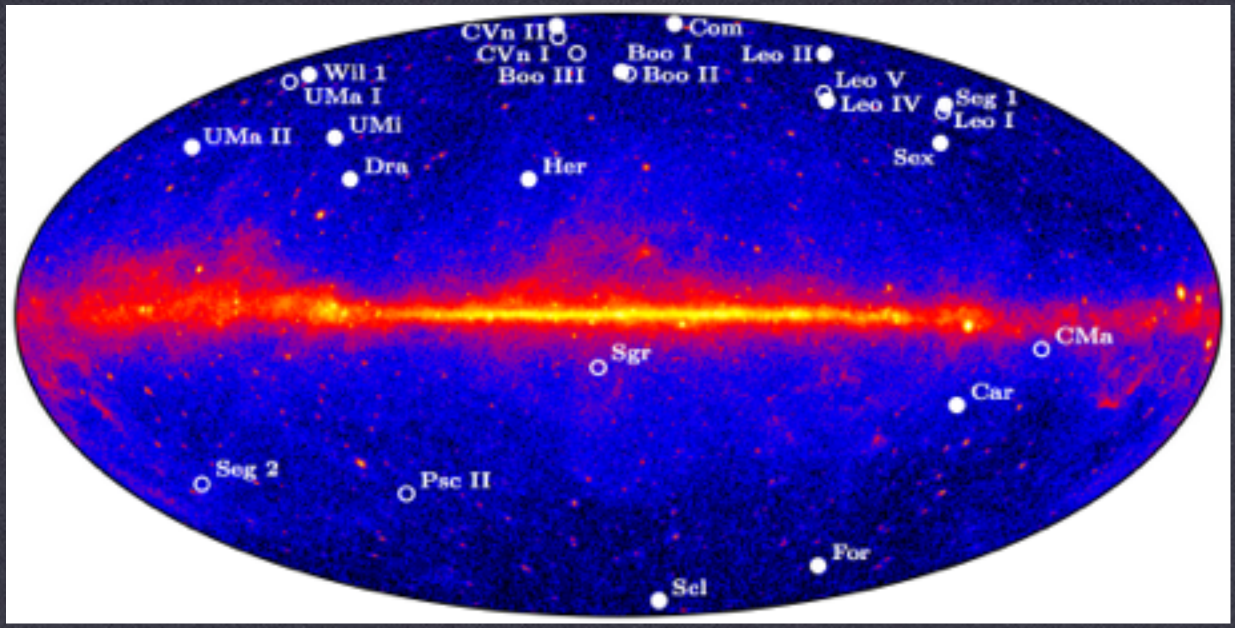
Model Number	DM	Mediator	Interactions	Elastic Scattering	Near Future Reach? Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

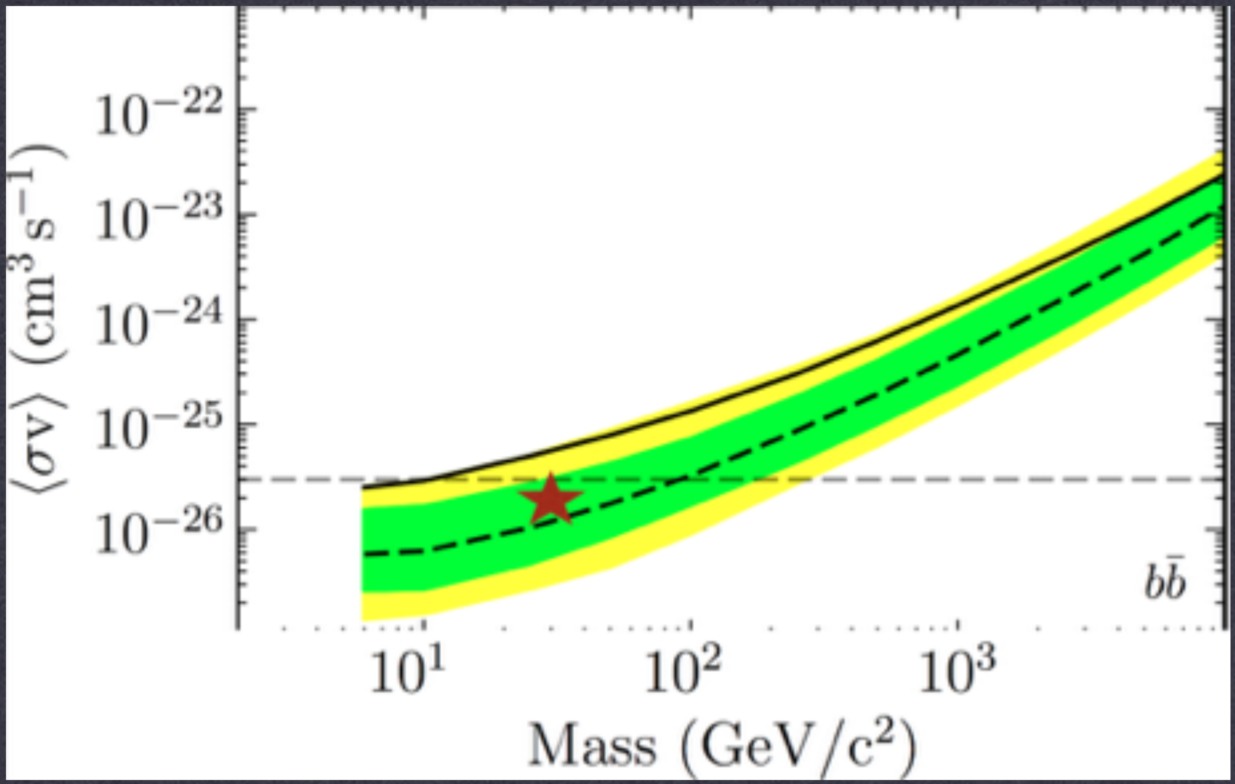
About half of the tree-level diagrams producing the GC signal are currently compatible with direct detection and collider constraints.

More than 100 papers considering specific models have been submitted.

FUTURE TESTS OF DARK MATTER

DWARF GALAXIES





Dwarf Galaxies can also produce a significant γ-ray signal from dark matter annihilation.

Latest published results showed a TS = 8.7 local excess at the mass of the GC signal.

FERMI-LAT COLLABORATION (2013, 1310.0828)

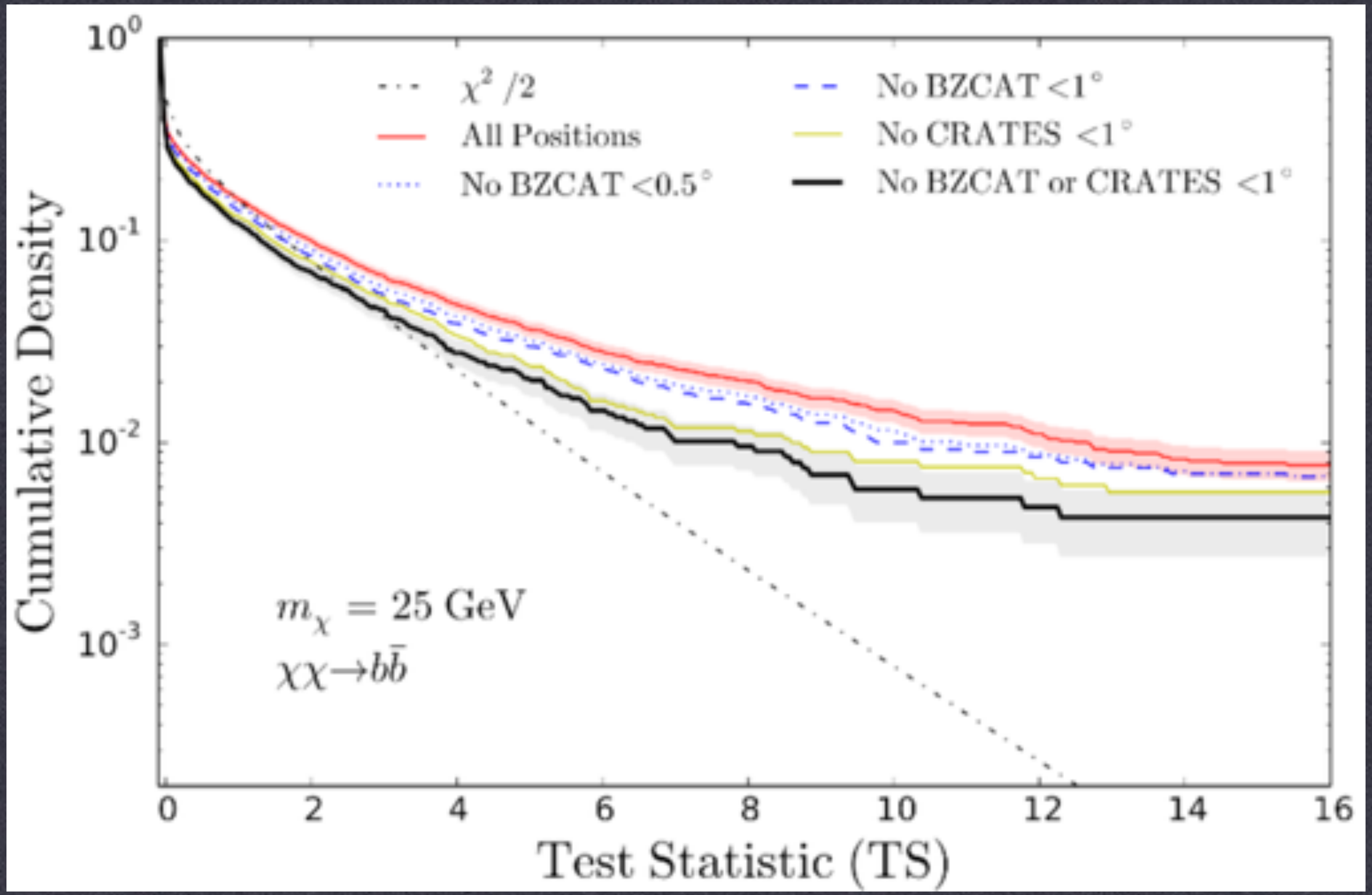
FUTURE TESTS OF DARK MATTER

DWARF GALAXIES

How can this test statistic be translated into a significance?

Can cross-correlate hotspots in the Fermi-LAT data with the positions of known high-energy blazars and radio galaxies.

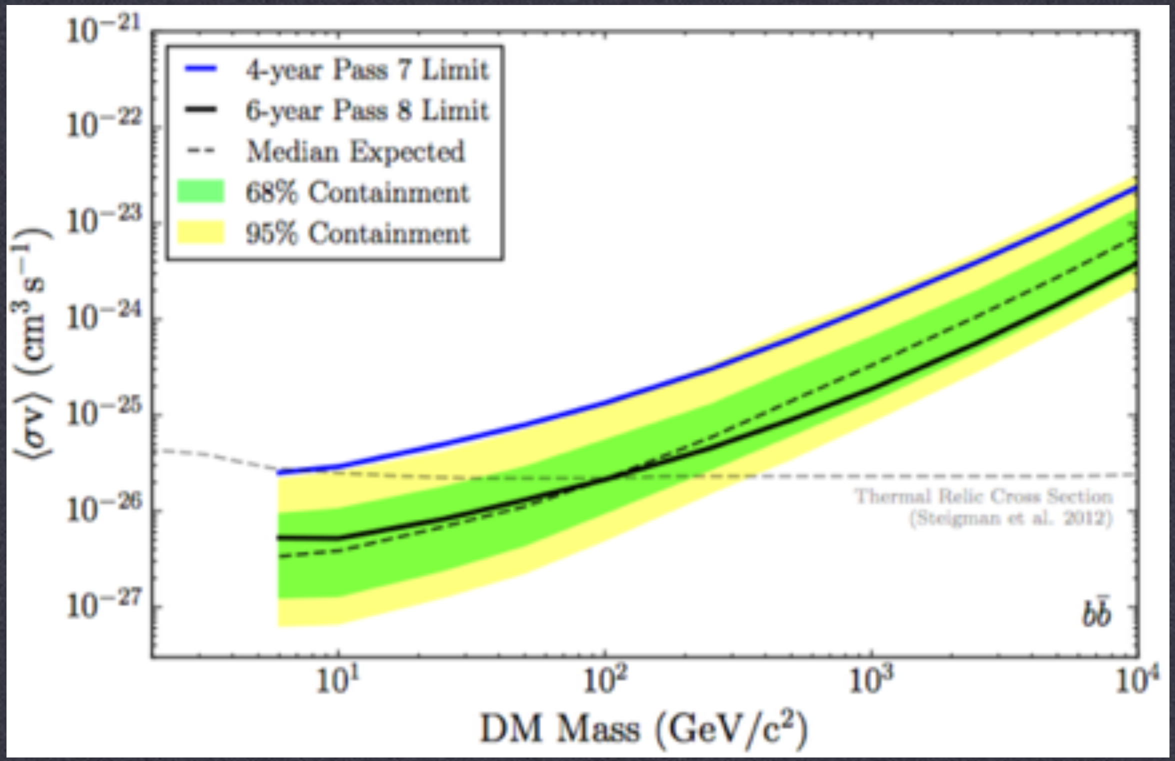
This allows for a determination of the significance, which was nearly 2.7σ



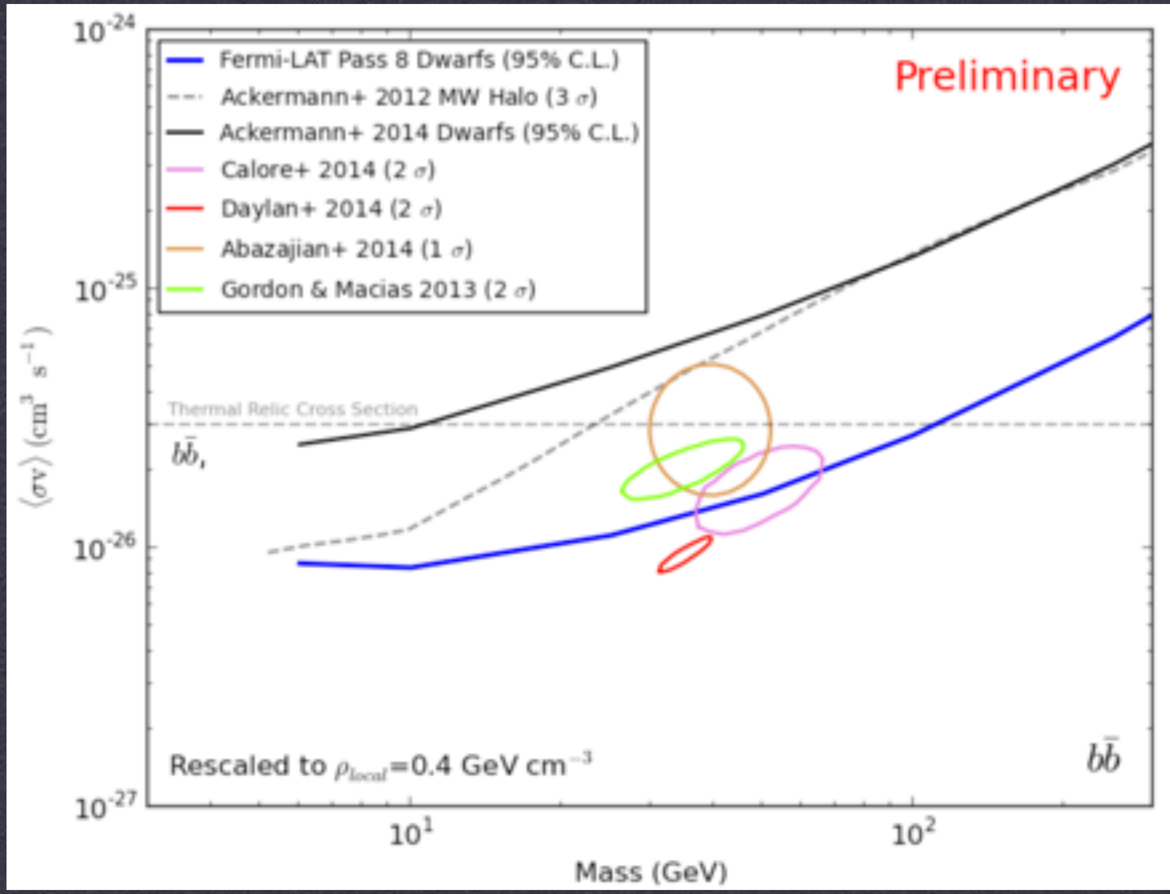
CARLSON, TL, HOOPER (2014, 1409.1572)

FUTURE TESTS OF DARK MATTER

DWARF GALAXIES



However, a new analysis of the Fermi-LAT data was recently presented at the Fermi Symposium (not yet published)

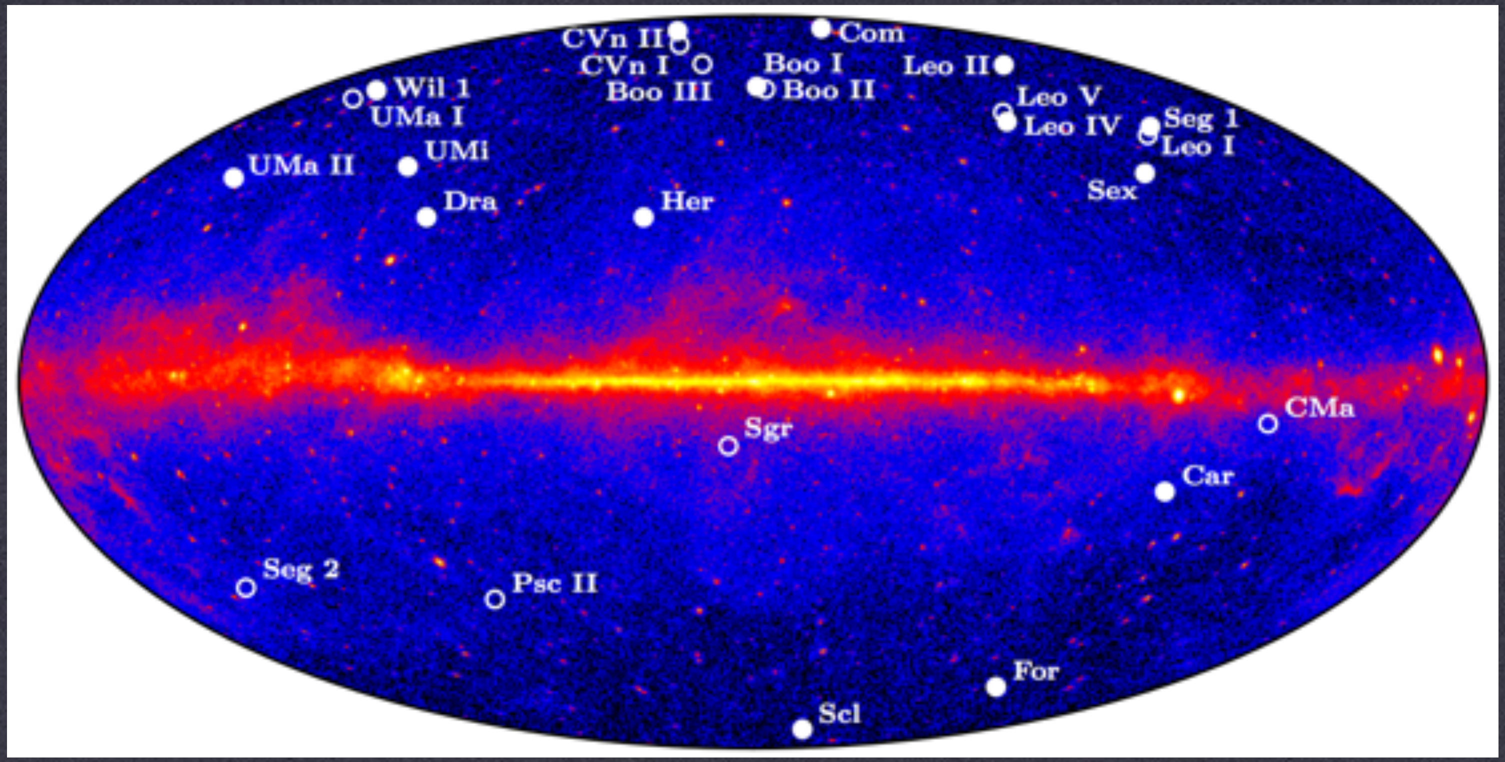


The observed excess has disappeared, and the new limit is now in mild tension with some models of the GC excess

ACKERMANN ET AL. (2015)
BRANDON ANDERSON (2014 FERMI-LAT SYMPOSIUM)

FUTURE TESTS OF DARK MATTER

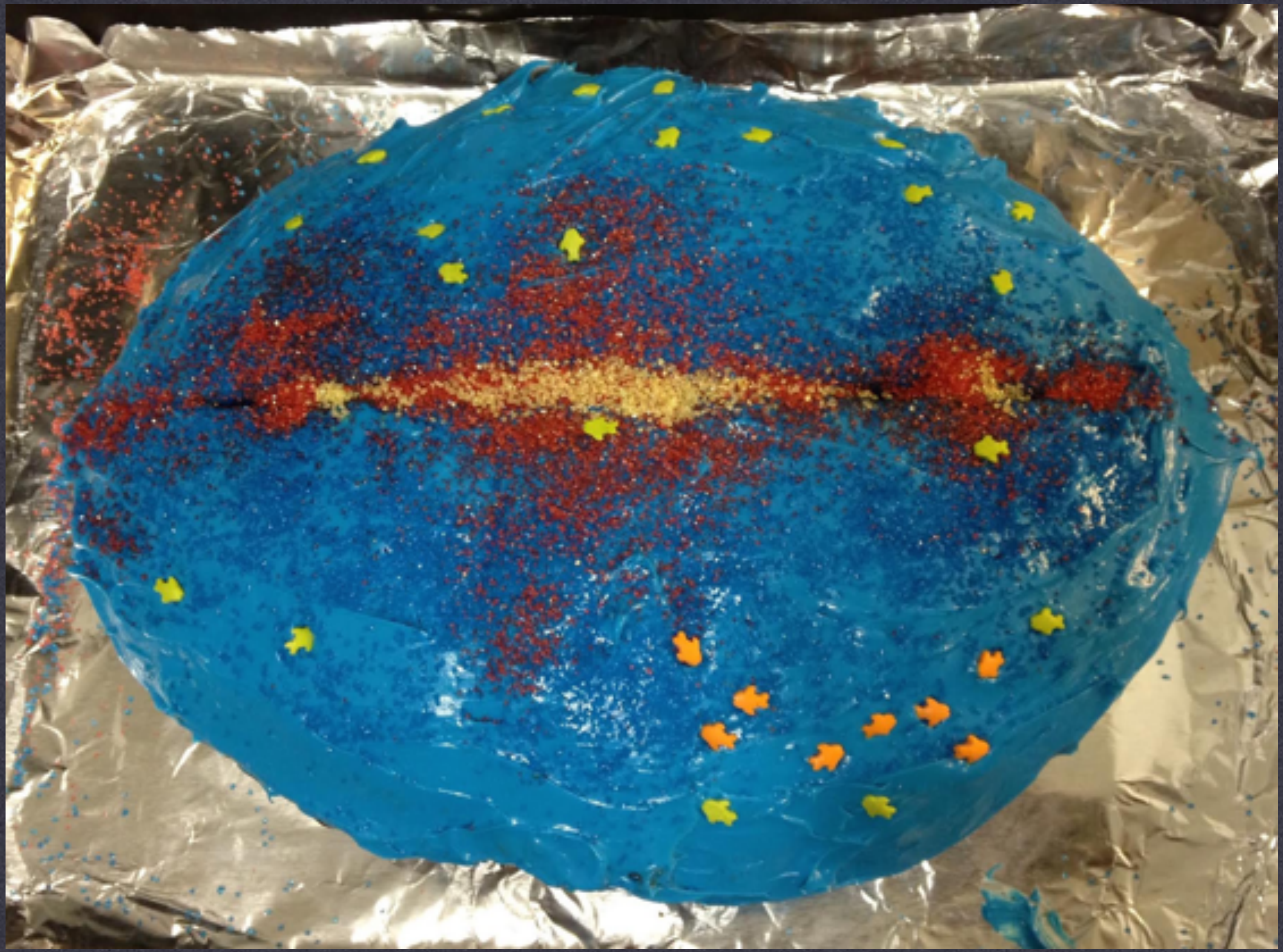
DWARF GALAXIES - FUTURE



The Dark Energy Survey is likely to greatly improve the detection of dwarf spheroidal galaxies in the Southern Hemisphere. Future limits may improve drastically if nearby dwarfs are discovered.

FUTURE TESTS OF DARK MATTER

NEW DWARFS!



Analyses of the DES, and Pan-Starrs Data have recently observed 11 (and counting) new dwarf candidates in the Southern Hemisphere.

FUTURE TESTS OF DARK MATTER

RETICULUM 2

STELLAR KINEMATICS AND METALLICITIES IN THE ULTRA-FAINT DWARF GALAXY RETICULUM II

J. D. SIMON,[1] A. DRLICA-WAGNER,[2] T. S. LI,[3] B. NORD,[2] M. GEHA,[4] K. BECHTOL,[5] E. BALBINOT,[6,7] E. BUCKLEY-GEER,[2] H. LIN,[2] J. MARSHALL,[3] B. SANTIAGO,[8,7] L. STRIGARI,[3] M. WANG,[3] R. H. WECHSLER,[9,10,11] B. YANNY,[2] T. ABBOTT,[12] A. H. BAUER,[13] G. M. BERNSTEIN,[14] E. BERTIN,[15,16] D. BROOKS,[17] D. L. BURKE,[10,11] D. CAPOZZI,[18] A. CARNERO ROSELL,[7,19] M. CARRASCO KIND,[20,21] C. B. D'ANDREA,[18] L. N. DA COSTA,[7,19] D. L. DEPOY,[3] S. DESAI,[22] H. T. DIEHL,[2] S. DODELSON,[2,5] C. E CUNHA,[10] J. ESTRADA,[2] A. E. EVRARD,[23] A. FAUSTI NETO,[7] E. FERNANDEZ,[24] D. A. FINLEY,[2] B. FLAUGHER,[2] J. FRIEMAN,[2,5] E. GAZTANAGA,[13] D. GERDES,[23] D. GRUEN,[25,26] R. A. GRUENDL,[20,21] K. HONSCHEID,[27,28] D. JAMES,[12] K. KUEHN,[29] N. KUROPATKIN,[2] O. LAHAV,[17] M. A. G. MAIA,[7,19] M. MARCH,[14] P. MARTINI,[27,30] C. J. MILLER,[31,23] R. MIQUEL,[24] R. OGANDO,[7,19] A. K. ROMER,[32] A. ROODMAN,[10,11] E. S. RYKOFF,[10,11] M. SAKO,[14] E. SANCHEZ,[33] M. SCHUBNELL,[23] I. SEVILLA,[33,20] R. C. SMITH,[12] M. SOARES-SANTOS,[2] F. SOBREIRA,[2,7] E. SUCHYTA,[27,28] M. E. C. SWANSON,[21] G. TARLE,[23] J. THALER,[34] D. TUCKER,[2] V. VIKRAM,[35] A. R. WALKER,[12] AND W. WESTER[2]
(THE DES COLLABORATION)

galaxy known. Although Ret II is the third-closest dwarf galaxy to the Milky Way, the line-of-sight integral of the dark matter density squared is $\log_{10}(J) = 18.8 \pm 0.6\,\mathrm{GeV}^2\,\mathrm{cm}^{-5}$ within $0.2°$, indicating that the predicted gamma-ray flux from dark matter annihilation in Ret II is lower than that of several other dwarf galaxies.

Yeoman's work by several optical spectroscopers has given us two estimations of the J-factors for Reticulum 2

FUTURE TESTS OF DARK MATTER

RETICULUM 2

DARK MATTER ANNIHILATION AND DECAY PROFILES FOR THE RETICULUM II DWARF SPHEROIDAL GALAXY

Vincent Bonnivard[1], Céline Combet[1], David Maurin[1], Alex Geringer-Sameth[2], Savvas M. Koushiappas[3], Matthew G. Walker[2], Mario Mateo[4], Edward W. Olszewski[5], and John I. Bailey III[4]

Draft version April 14, 2015

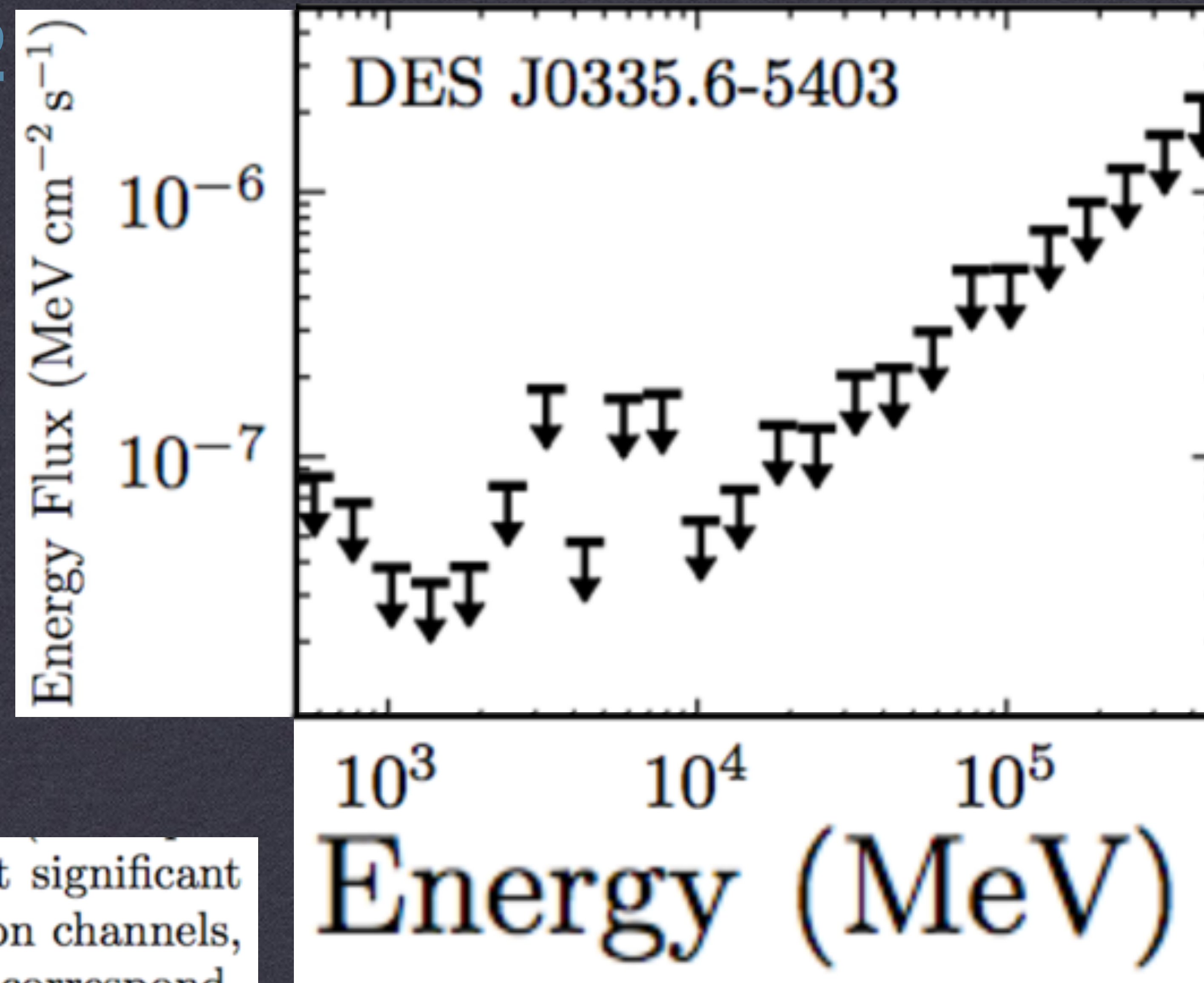
$\alpha_{\rm int}$ [deg]	$\log_{10}(J(\alpha_{\rm int}))$ $[J/{\rm GeV}^2\,{\rm cm}^{-5}]^{\rm a}$
0.01	$16.9^{+0.5(+1.1)}_{-0.4(-0.8)}$
0.05	$18.2^{+0.5(+1.0)}_{-0.4(-0.7)}$
0.1	$18.6^{+0.6(+1.1)}_{-0.4(-0.8)}$
0.5	$19.5^{+1.0(+1.6)}_{-0.6(-1.3)}$
1	$19.7^{+1.2(+2.0)}_{-0.9(-1.5)}$

against several of its ingredients. We find that Ret II presents one of the largest annihilation J-factors among the Milky Way's dSphs, possibly making it one of the best targets to constrain the DM particle properties. However, it is important to obtain follow-up photometric and spectroscopic data in order to test the assumptions of dynamical equilibrium as well as a negligible fraction of binary stars in the kinematic sample. Nevertheless, the proximity of Ret II and its potential large dark matter content make it the most interesting object from the newly discovered dwarf galaxies.

Yeoman's work by several optical spectroscopers has given us two estimations of the J-factors for Reticulum 2

FUTURE TESTS OF DARK MATTER

RETICULUM 2



Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data

A. Drlica-Wagner,[1,2,*] A. Albert,[3,†] K. Bechtol,[1,4,‡] M. Wood,[3,§] L. Strigari,[5,¶] M. Sánchez-Conde,[6,7] L. Baldini,[8] R. Essig,[9] J. Cohen-Tanugi,[10] B. Anderson,[11] R. Bellazzini,[12] E. D. Bloom,[3] R. Caputo,[13] C. Cecchi,[14,15] E. Charles,[3] J. Chiang,[3] J. Conrad,[7,6,11,16] A. de Angelis,[17] S. Funk,[3] P. Fusco,[18,19] F. Gargano,[19] N. Giglietto,[18,19] F. Giordano,[18,19] S. Guiriec,[20,21] M. Gustafsson,[22] M. Kuss,[12] F. Loparco,[18,19] P. Lubrano,[14,15] N. Mirabal,[20,21] T. Mizuno,[23] A. Morselli,[24] T. Ohsugi,[23] E. Orlando,[3] M. Persic,[25,26] S. Rainò,[18,19] F. Spada,[12] D. J. Suson,[27] G. Zaharijas,[28,29] and S. Zimmer[7,6]
(The Fermi-LAT Collaboration)

tion 6 in Ackermann *et al.* [19]). The most significant excess for any of the DM masses, annihilation channels, and targets we consider here was TS = 6.7, corresponding to a local signficance[6] of 1.5σ ($p = 0.06$) and a global significance of 0.26σ ($p = 0.40$). This coincides with

Reticulum 2 also has an excess!

FUTURE TESTS OF DARK MATTER

RETICULUM 2

Evidence for Gamma-ray Emission from the Newly Discovered Dwarf Galaxy Reticulum 2

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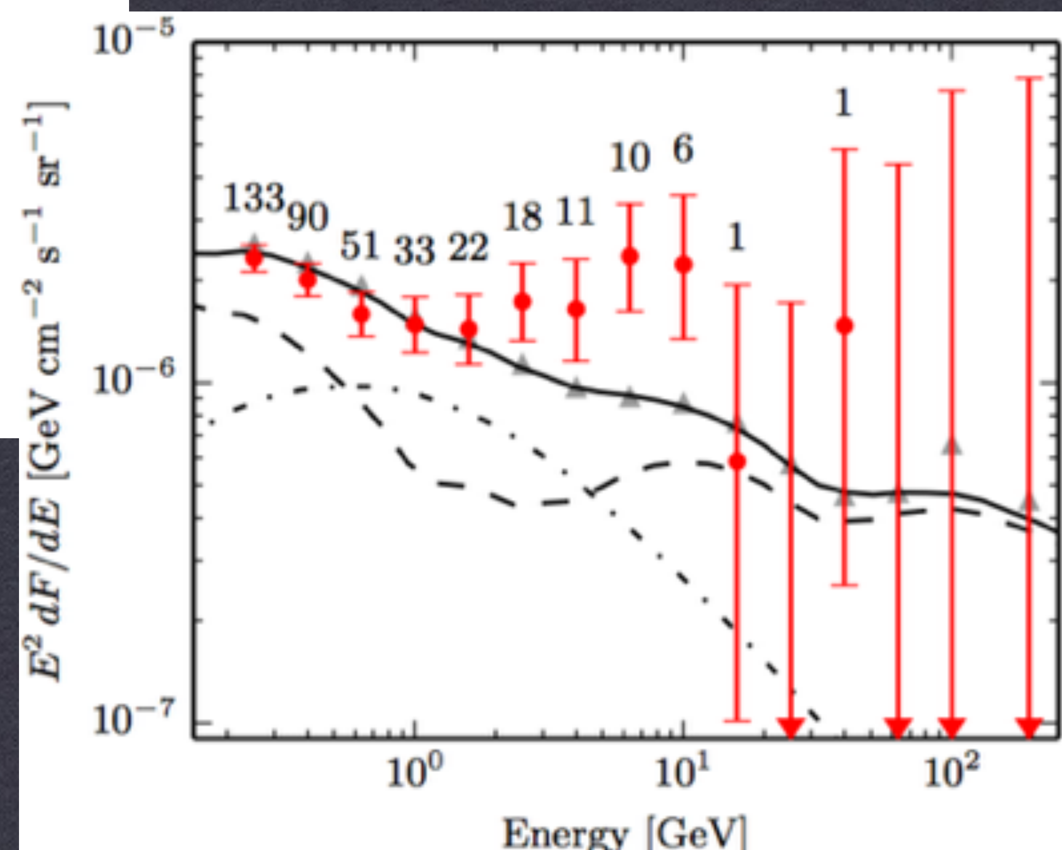
(Dated: March 10, 2015)

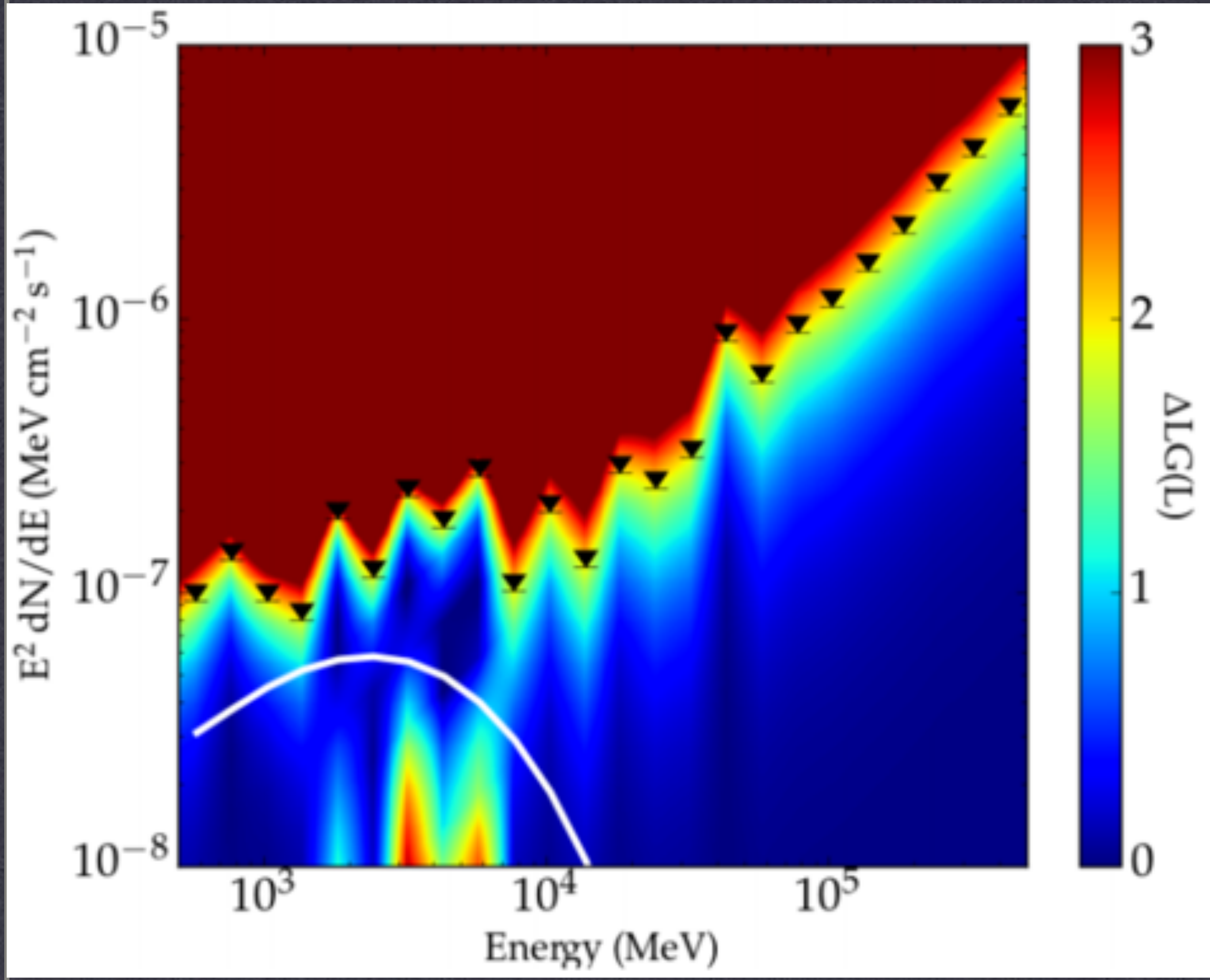
We present a search for γ-ray emission from the direction of the newly discovered dwarf galaxy Reticulum 2. Using Fermi-LAT data, we detect a signal that exceeds expected backgrounds between $\sim 2-10$ GeV and is consistent with annihilation of dark matter for particle masses less than a few $\times 10^2$ GeV. Modeling the background as a Poisson process based on Fermi-LAT diffuse models, and taking into account trials factors, we detect emission with p-value less than 9.8×10^{-5} ($> 3.7\sigma$). An alternative, model-independent treatment of background reduces the significance, raising the p-value to 9.7×10^{-3} (2.3σ). Even in this case, however, Reticulum 2 has the most significant γ-ray signal of any known dwarf galaxy. If Reticulum 2 has a dark matter halo that is similar to those inferred for other nearby dwarfs, the signal is consistent with the s-wave relic abundance cross section for annihilation.

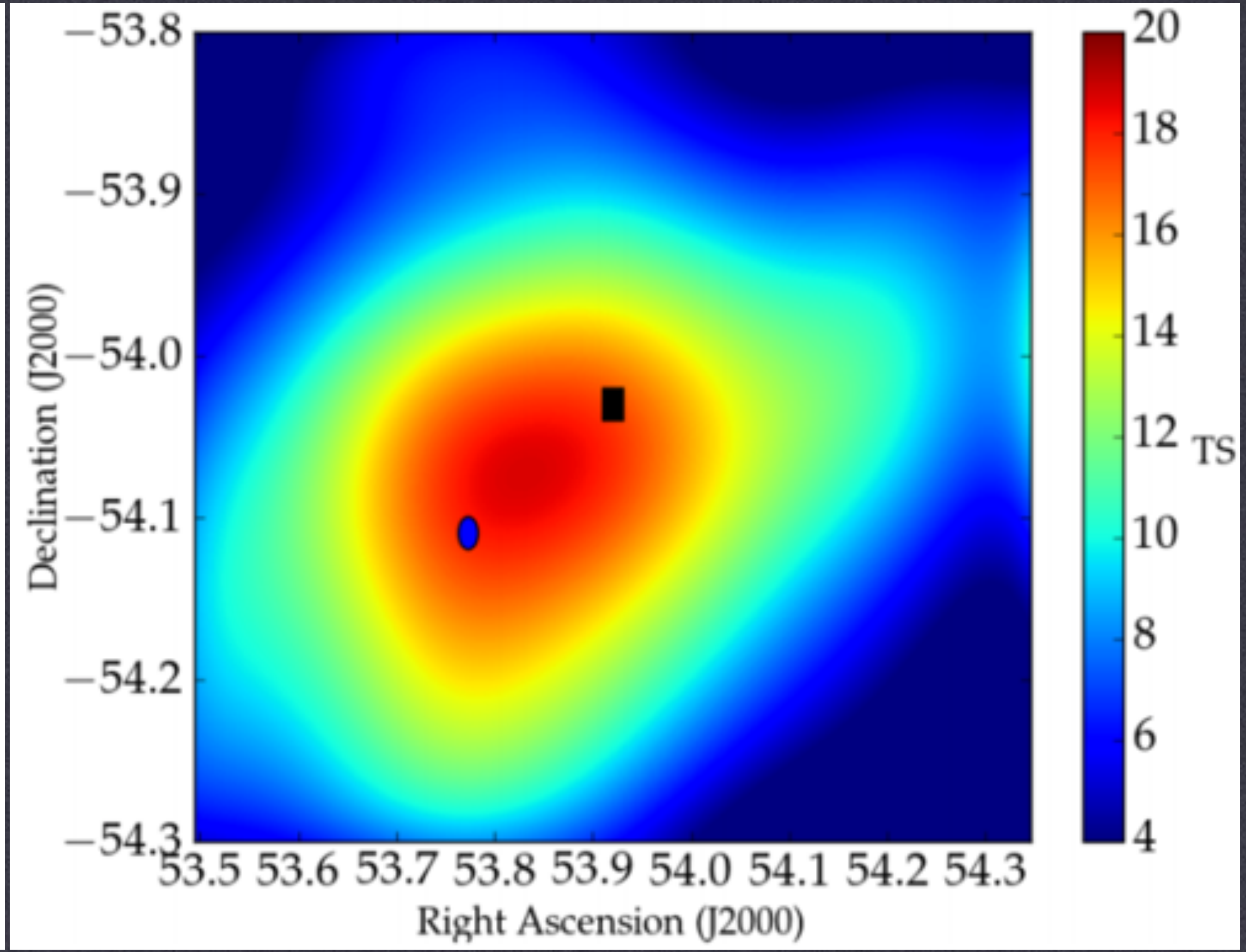


Reticulum 2 also has an excess!

FUTURE TESTS OF DARK MATTER

RETICULUM 2

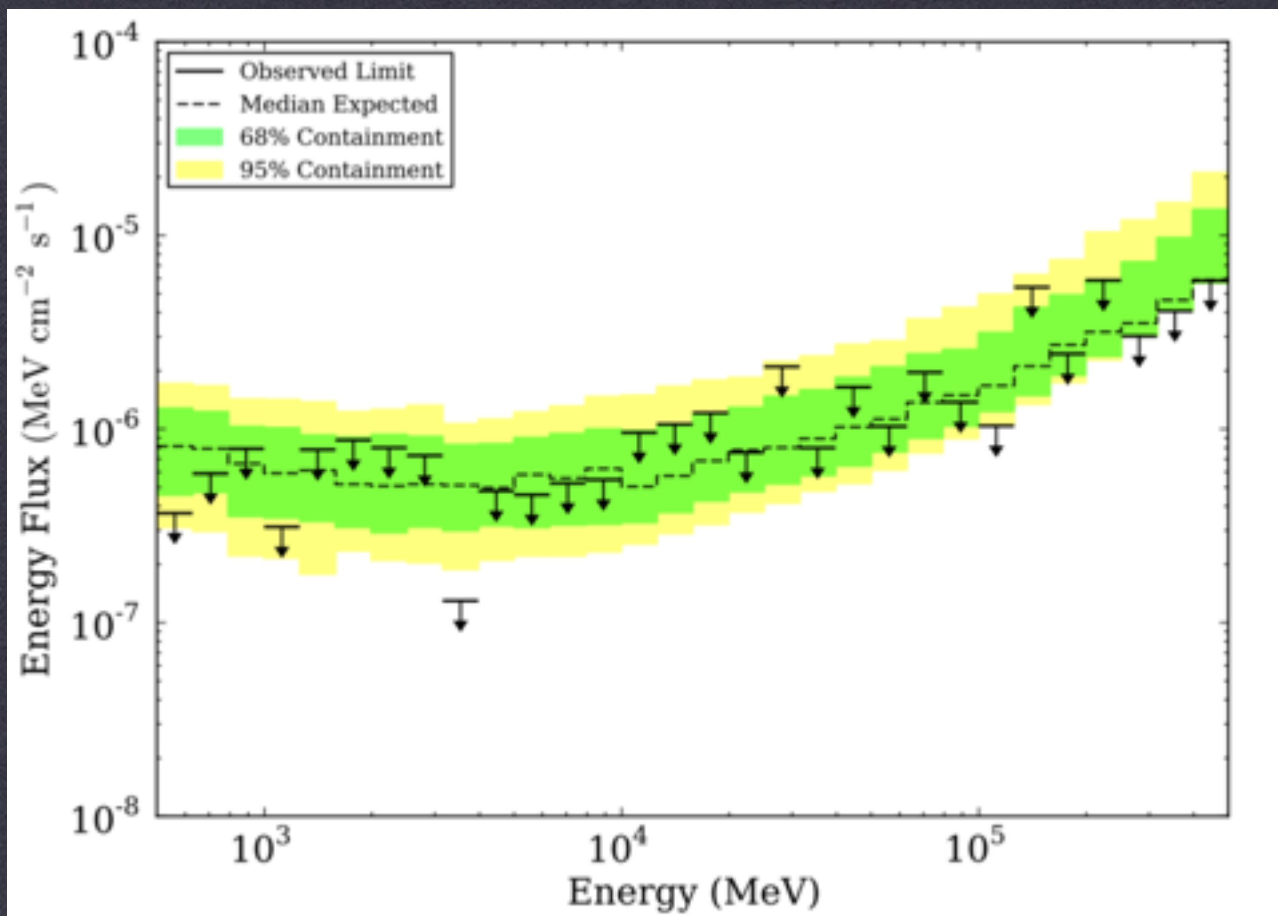


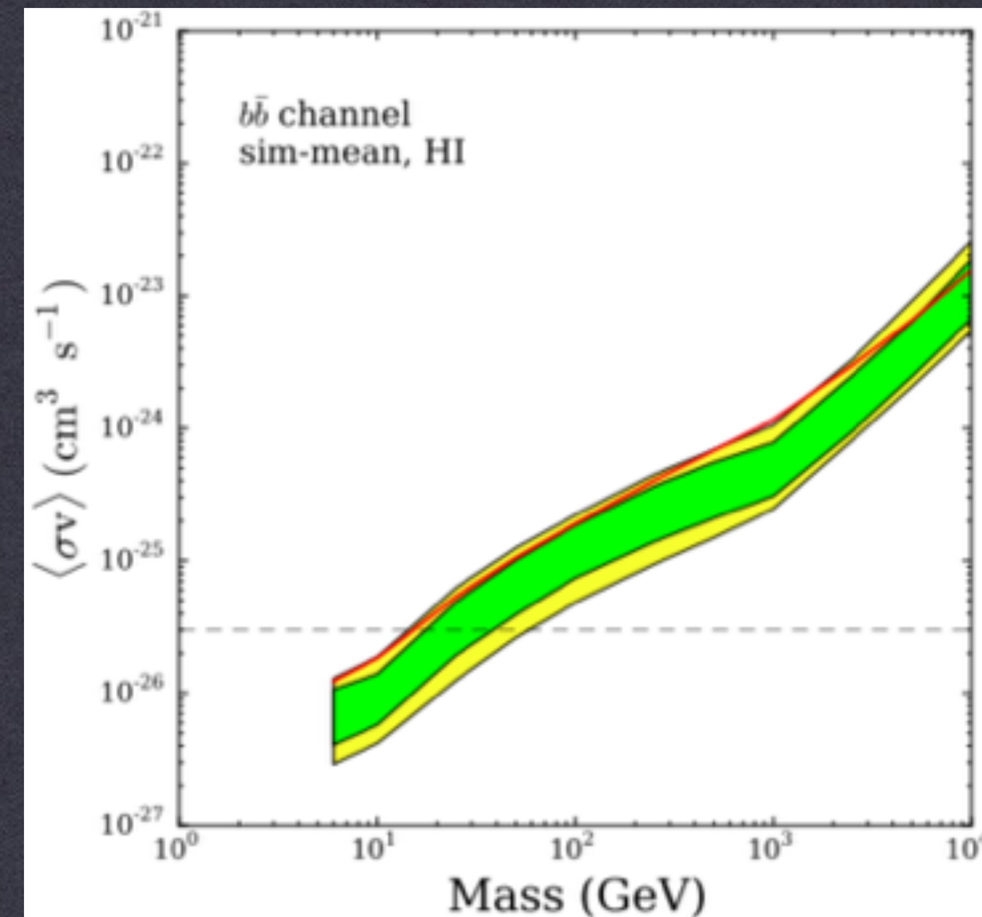


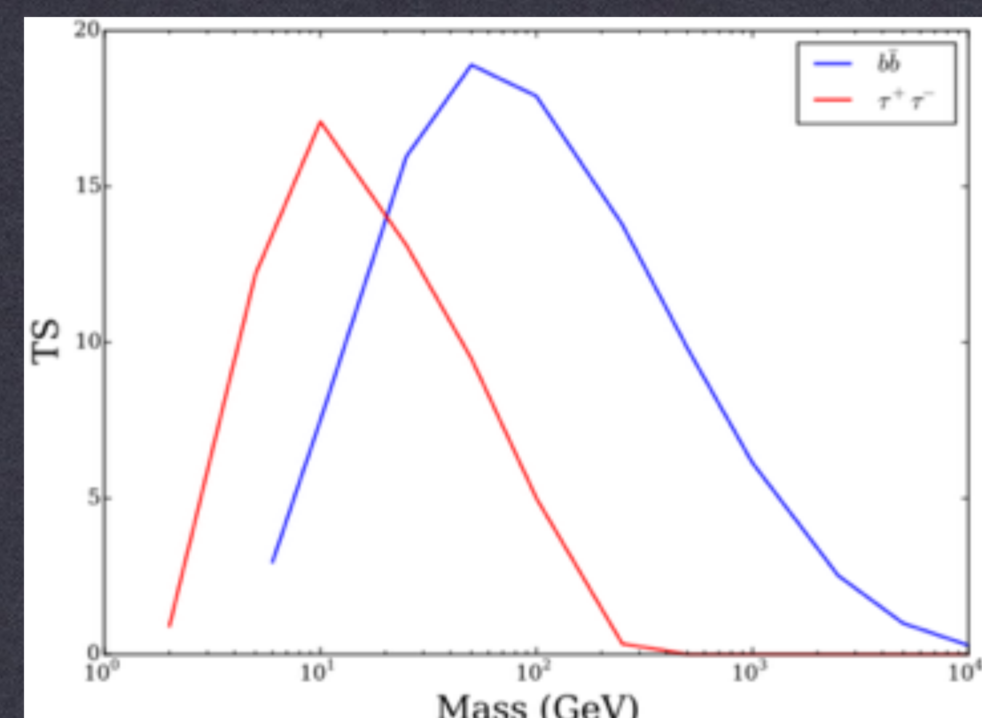
Reticulum 2 also has an excess!

FUTURE TESTS OF DARK MATTER

LMC







The LMC also shows hints of a dark matter excess

However, there are considerable backgrounds here as well.

Buckley et al. (2015)

FUTURE TESTS OF DARK MATTER

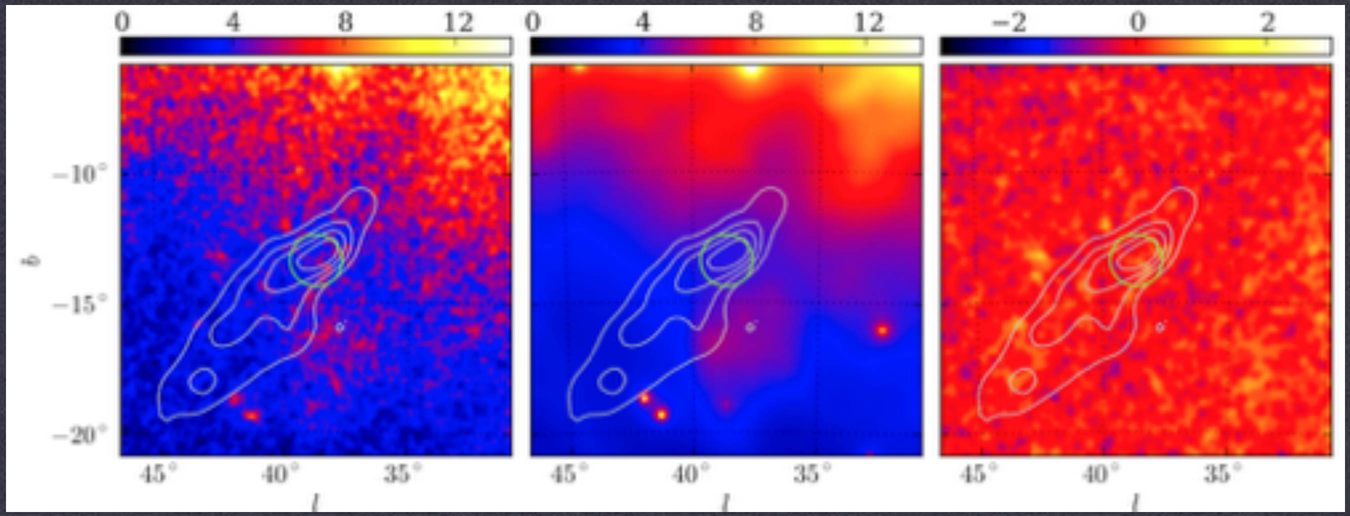
OTHER GAMMA-RAY TARGETS

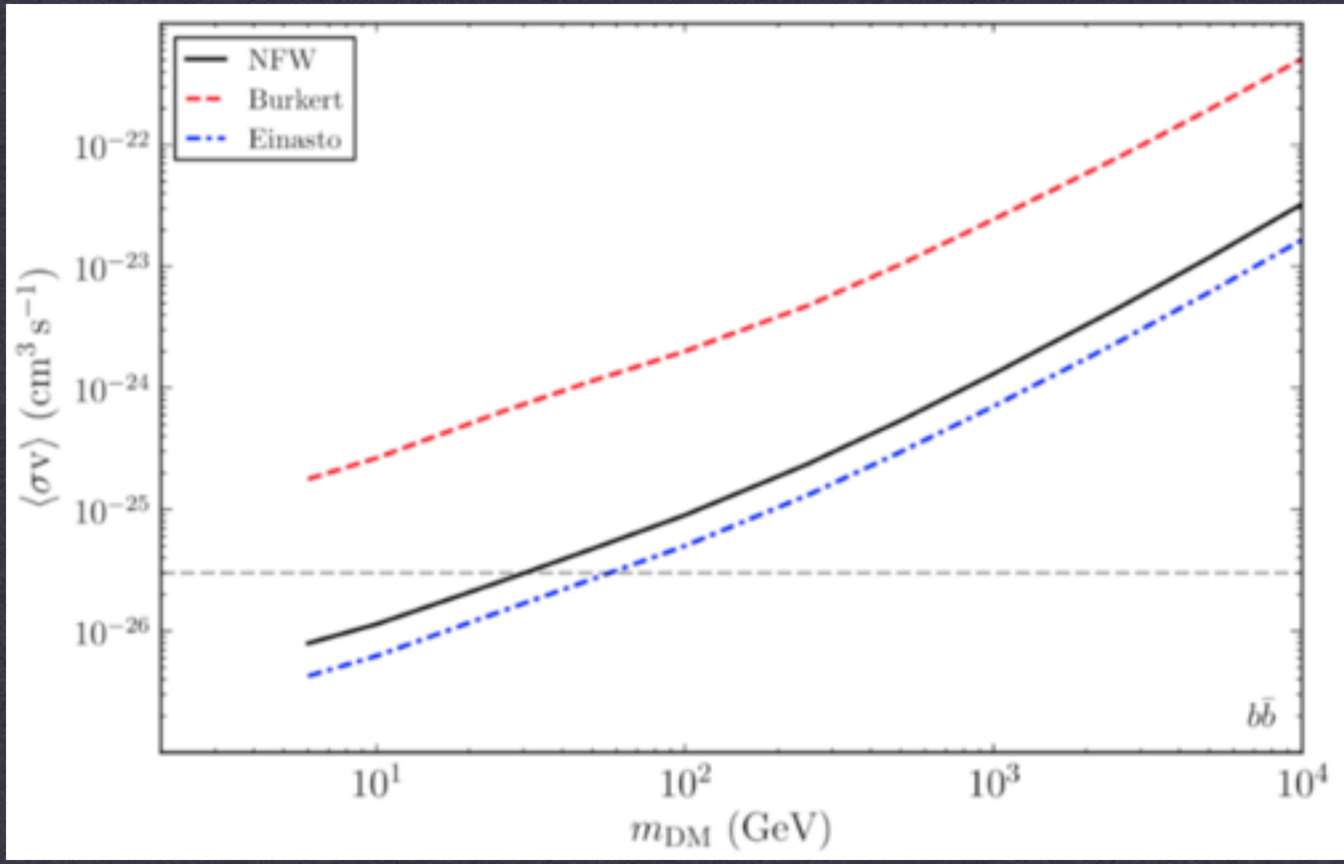
May find other bright indirect detection targets.

One possibility is the population of High Velocity Clouds orbiting the Milky Way

Some may be confined by dark matter halos

However, no γ-ray excess is observed in these systems





NICHOLS & BLAND-HAWTHORN (2009, 0911.0684)
NICHOLS ET AL. (2014, 1404.3209)
DRLICA-WAGNER ET AL. (2014, 1405.1030)

A DARK MATTER STORY?

- There is a comprehensive dark matter interpretation of the story:

  - The J-factor of the GC exceeds all dwarf spheroidal galaxies by more than 2 orders of magnitude
  - A relatively significant detection should appear in the LMC and SMC (study forthcoming)
  - The stacked analysis of the dwarfs should begin to show a statistical excess - starting with the brightest object

A DARK MATTER STORY?

- For the skeptics, there are many ways this story could fall apart:
  - Improved J-factor measurements may indicate that Reticulum II is not the brightest dwarf
  - The significance of the dwarf analysis might go down with P8 data
  - Astrophysical explanations for excesses in the Galactic Center and the LMC may be produced

- The next few years promise to present significant hints (or significant constraints on) the dark matter particle models that can explain the GeV excess.

ONE CAVEAT (OF COURSE)

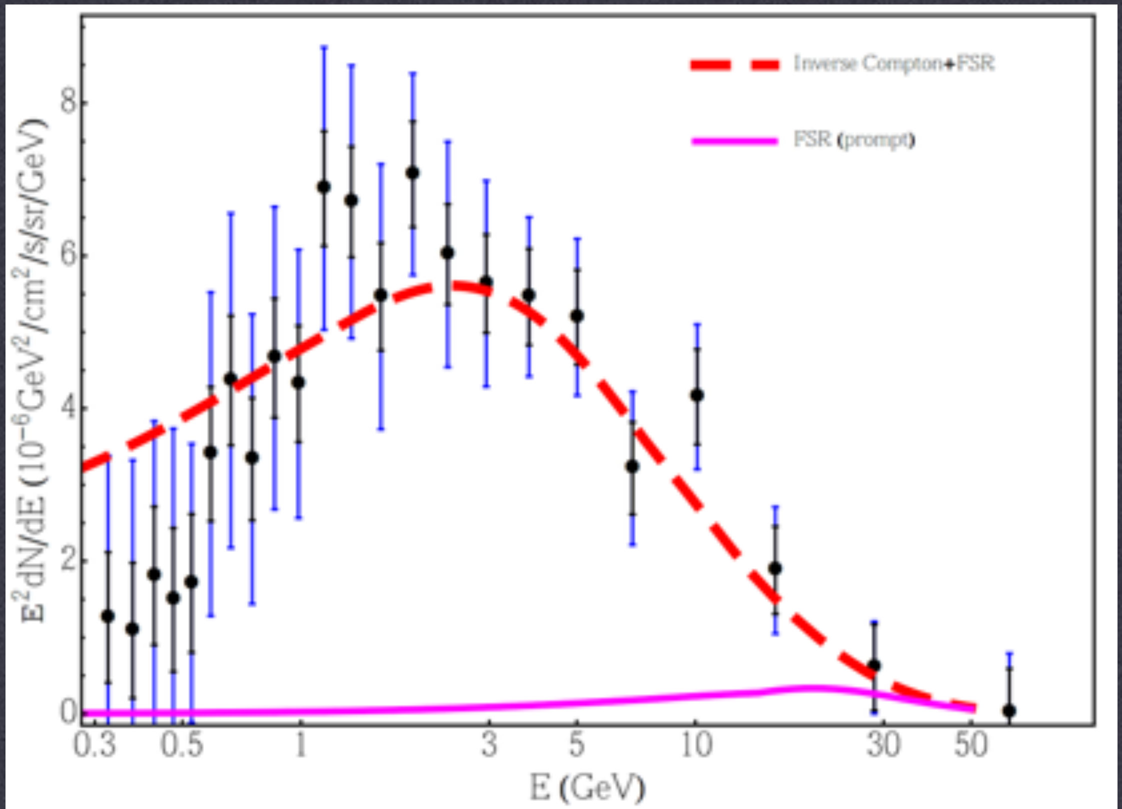
MODEL BUILDING

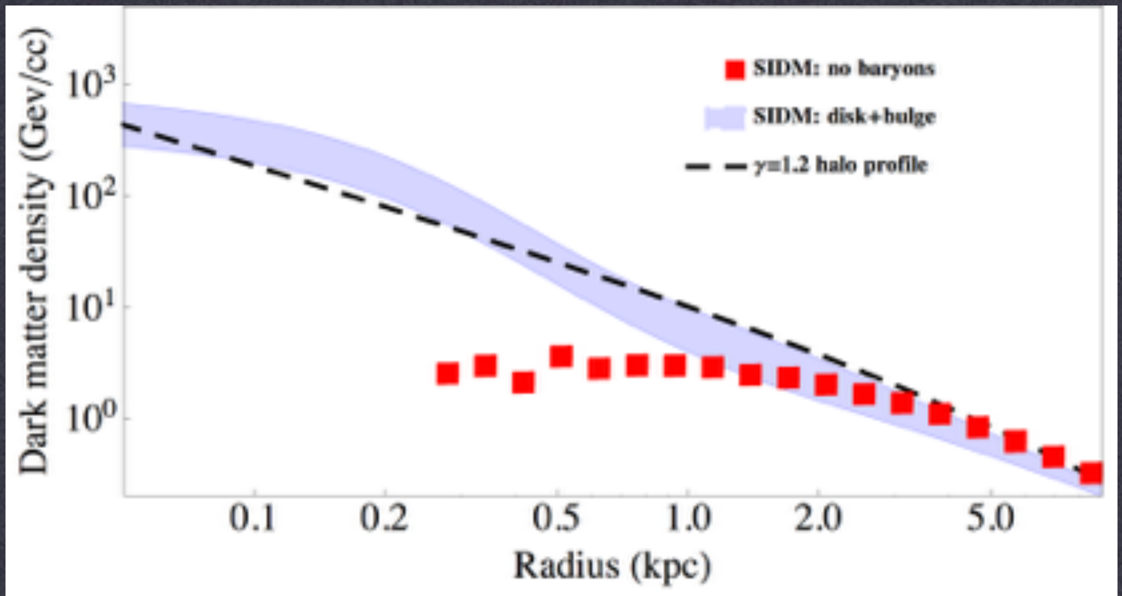
If the tension between the GC and dwarf observations persists, this could be addressed via secondary emission models:

$$\chi\,\chi \to \phi\,\phi \to e^+e^-$$

The spectrum and morphology of the signal can then be reproduced through the secondary up-scattering of the ISRF.

This is a natural solution in models of self-interacting dark matter.





KAPLINGHAT, TL, YU (2014, 1311.6524)
KAPLINGHAT, TL, YU (2015, 1501.03507)

CONCLUSIONS

1.) A bright, spherically symmetric, hard spectrum excess has been observed coincident with the dynamical center of the Milky Way.

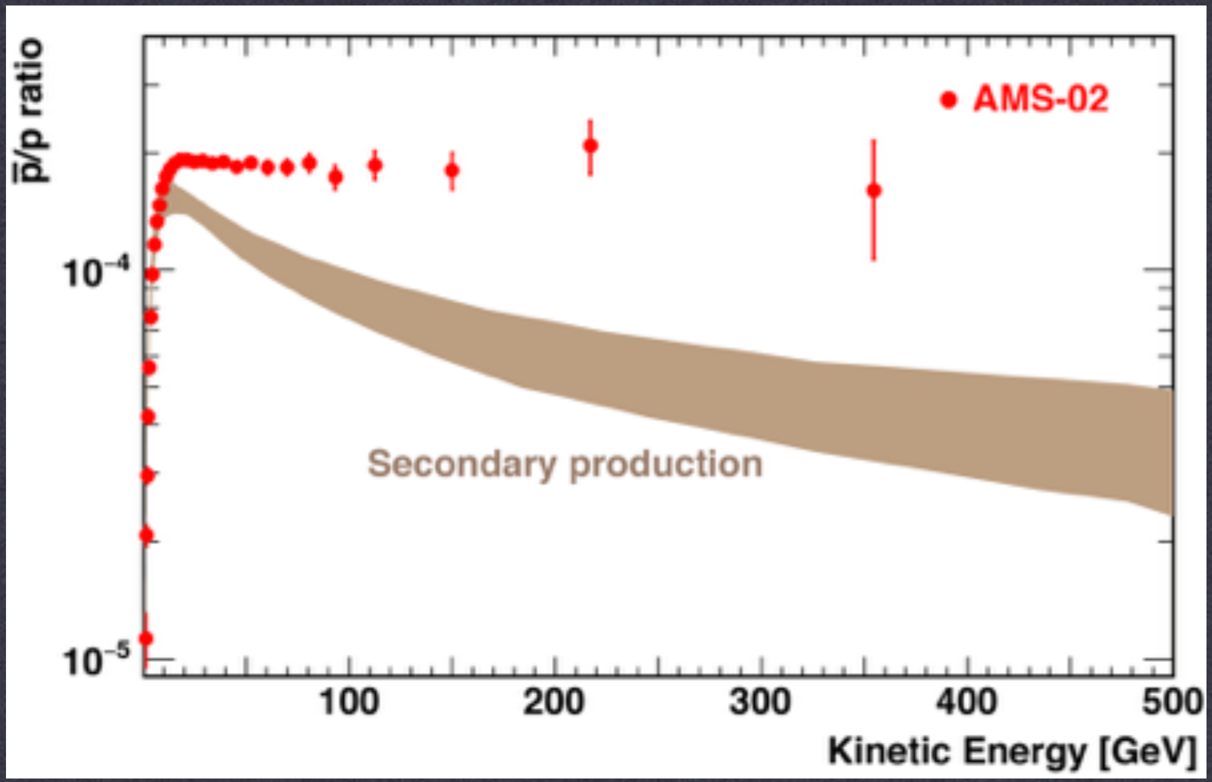
2.) This excess is difficult to explain with known astrophysical source mechanisms, such as MSPs and galactic outbursts.

3.) Dark matter provides a natural fit to the characteristics of the GC excess

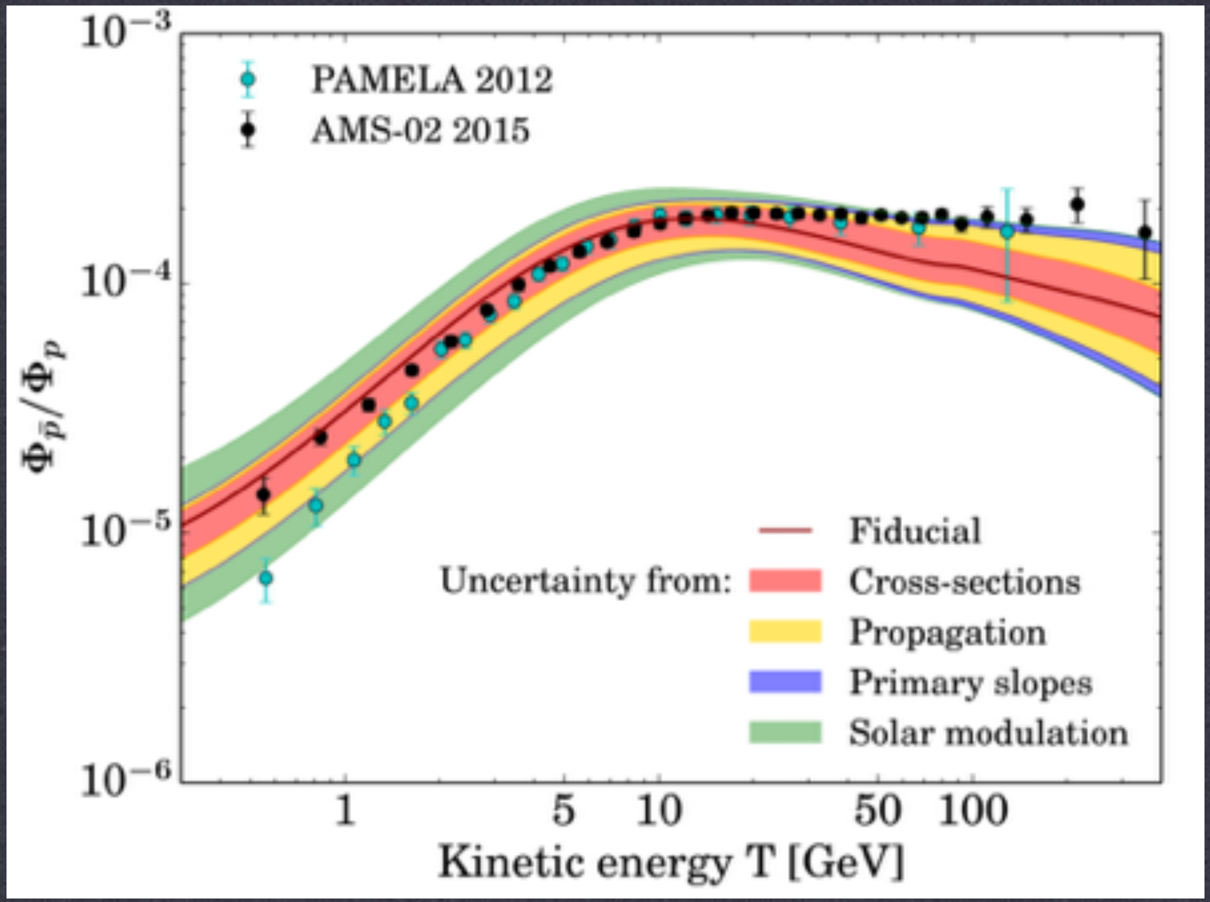
4.) However, any dark matter claim must be backed up by redundant observations. Significant work must still be done to test out or confirm our models of the GC excess.

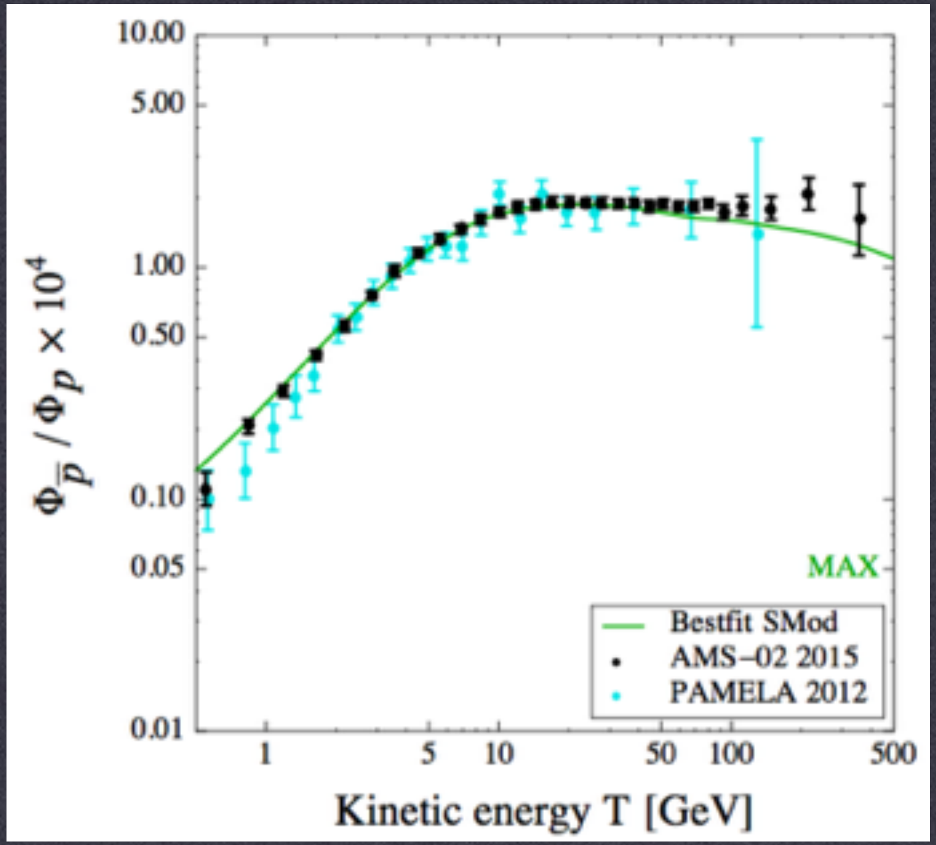
FUTURE TESTS OF DARK MATTER

AMS-02 DATA



AMS-02 data has lead to strong limits on dark matter annihilation - however their current strength is overestimated in the literature



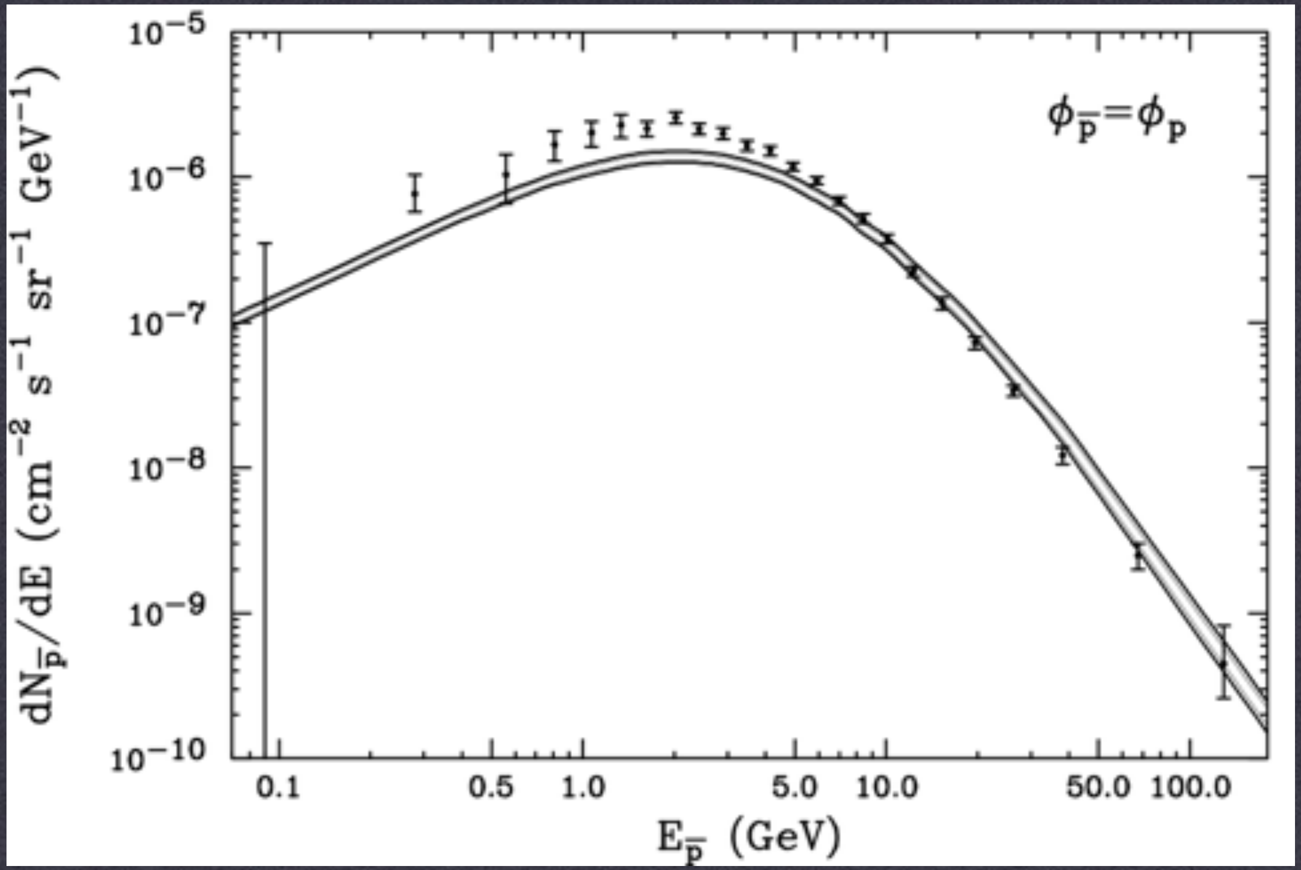


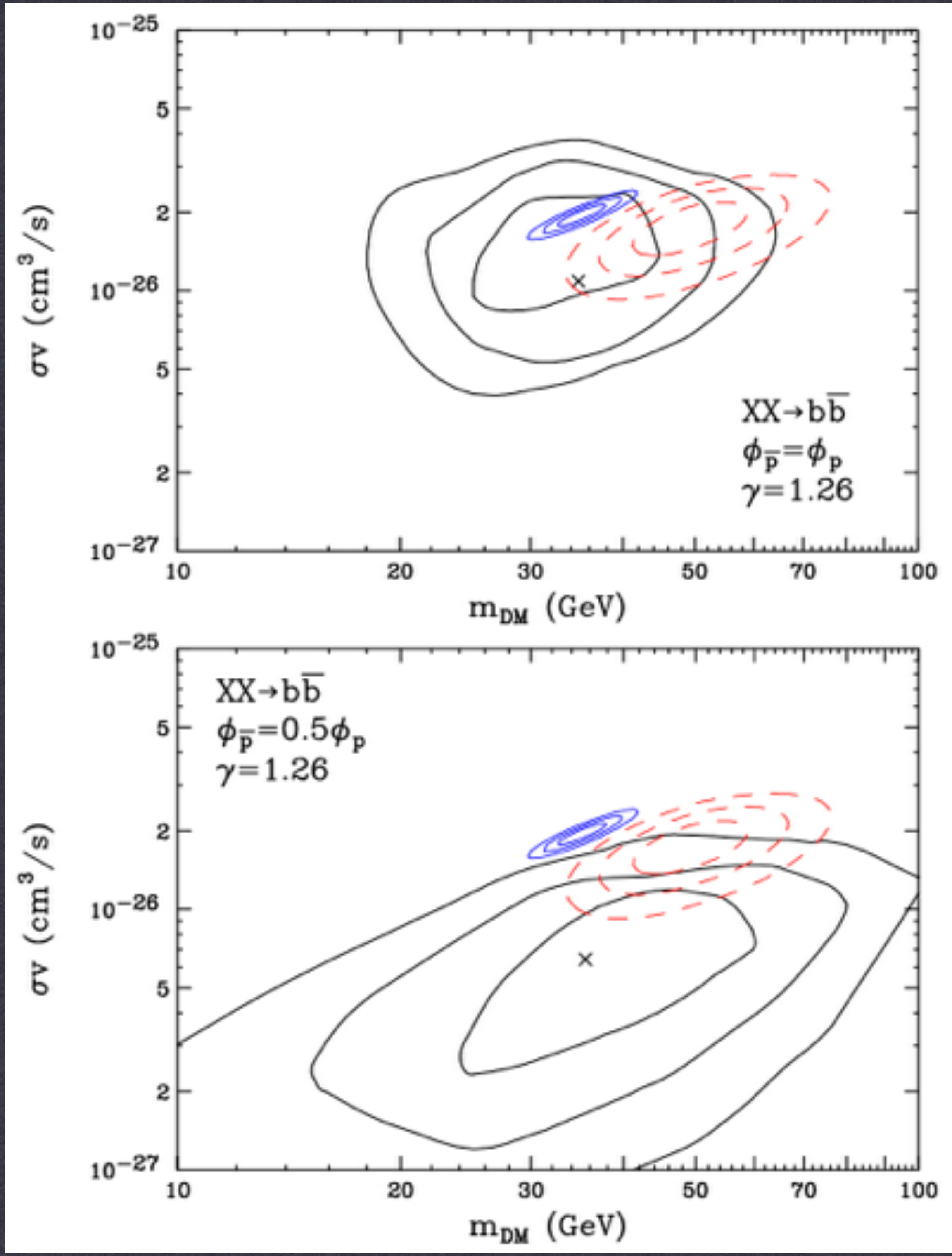
FUTURE TESTS OF DARK MATTER

COSMIC-RAY SEARCHES

HOOPER, TL, MERTSCH (2014, 1410.1527)

Observations of Cosmic-Ray Antiproton Fluxes show some evidence for an excess compared to astrophysical models, which can be fit by a dark matter candidate.



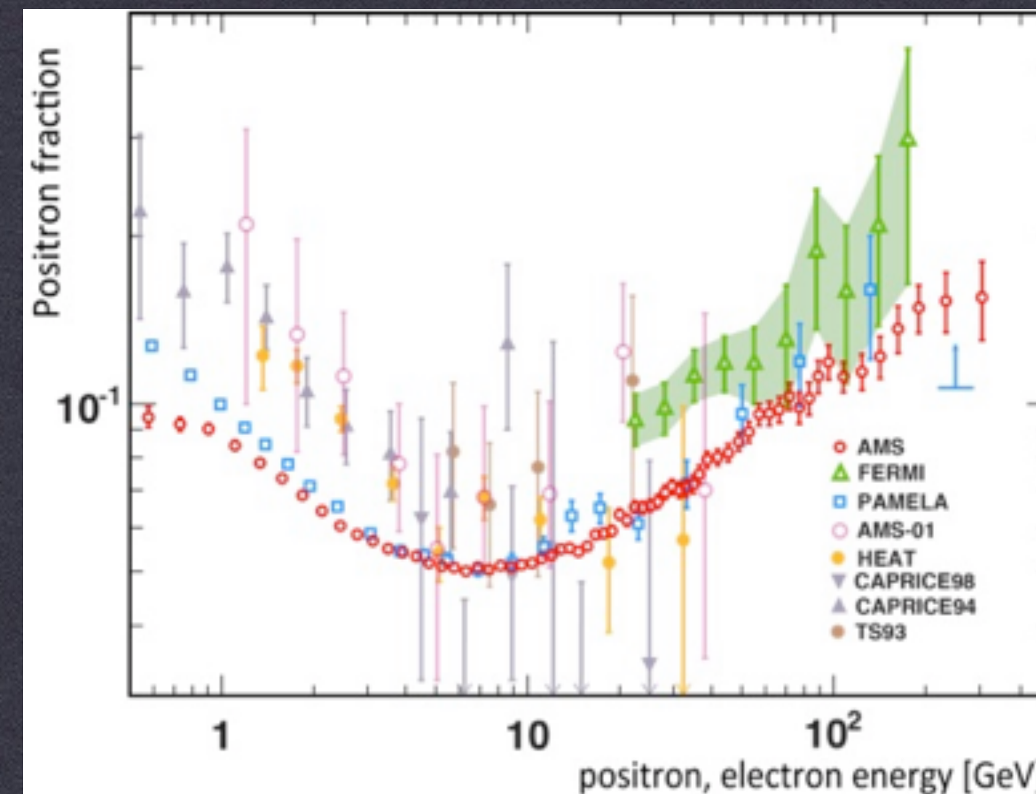


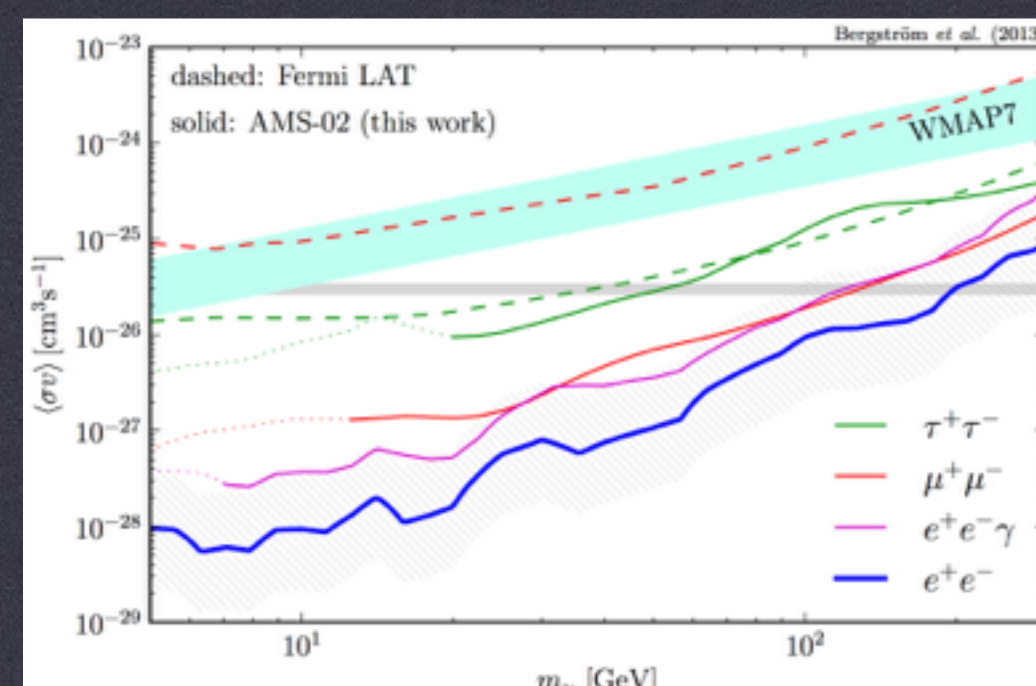
FUTURE TESTS OF DARK MATTER

COSMIC-RAY SEARCHES

Observations of the cosmic-ray positron spectrum by the AMS-02 instrument can place strong constraints on the annihilation to leptonic final states.

In some cases (i.e. direct annihilation to e^+e^-) these can fall below the thermal cross-section by two orders of magnitude.

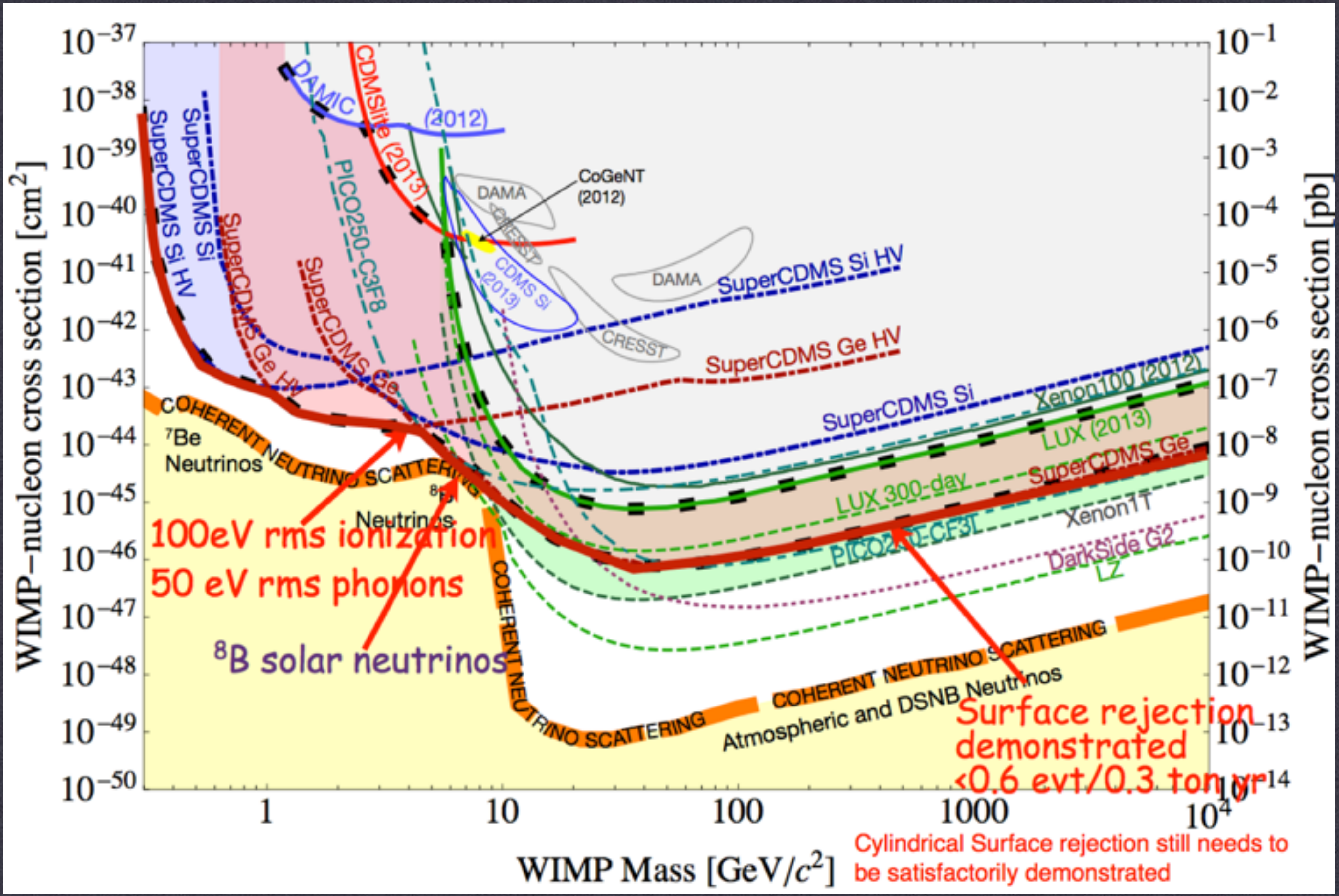




BERGSTROM ET AL. (2013, 1306.3983)

FUTURE TESTS OF DARK MATTER

DIRECT DETECTION SEARCHES



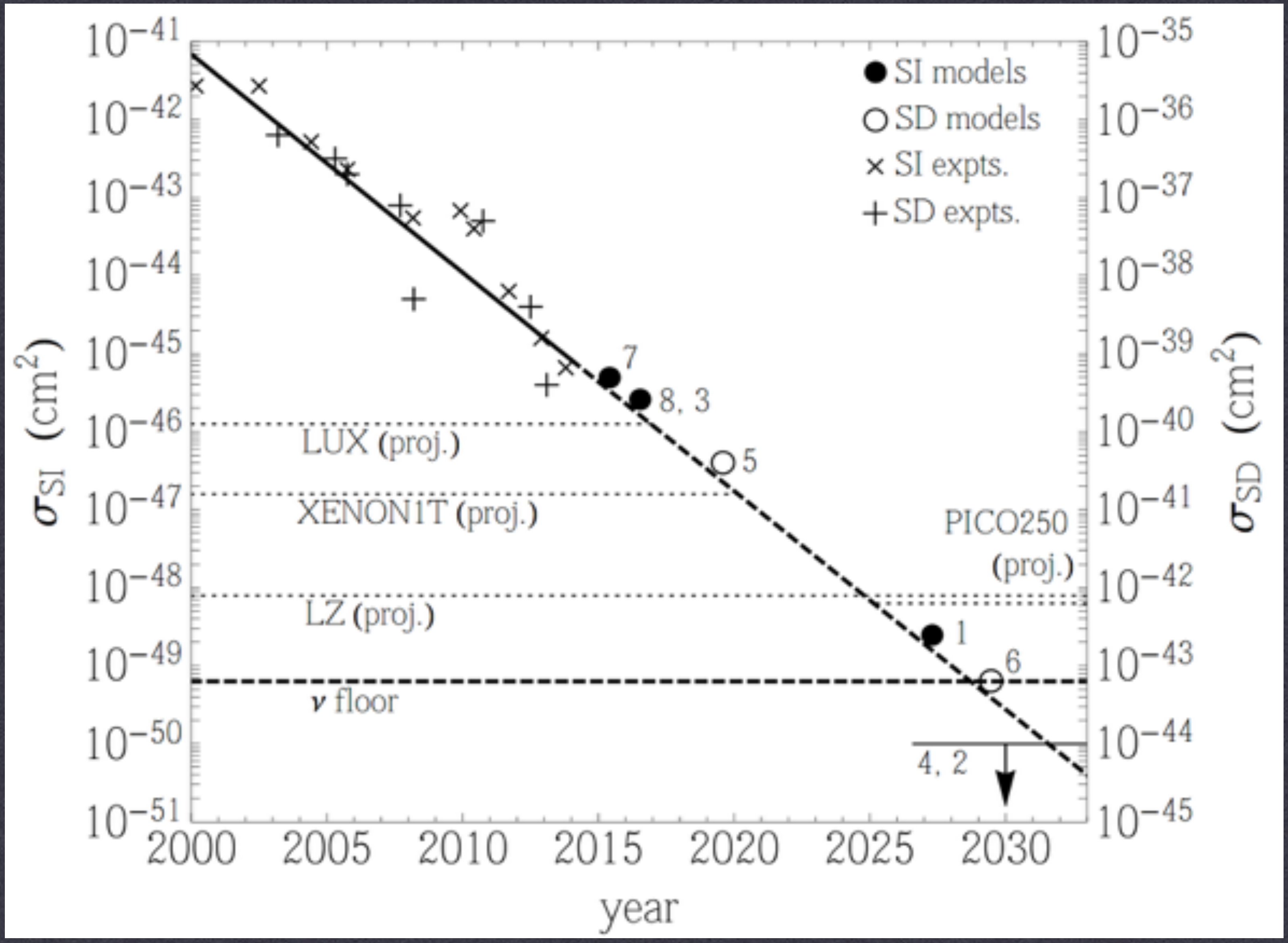
The 20 - 60 GeV Mass Range is optimal for direct detection searches.

FUTURE TESTS OF DARK MATTER

DIRECT DETECTION SEARCHES

However, these limits are model dependent.

Annihilations through a pseudo-scaler mediator will be unobservable with direct detection

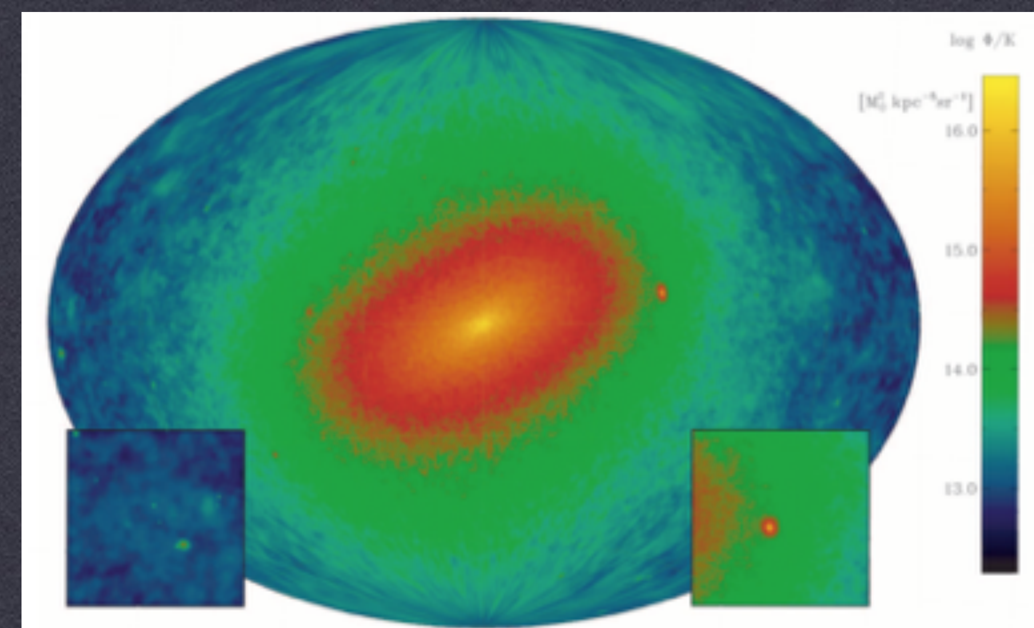


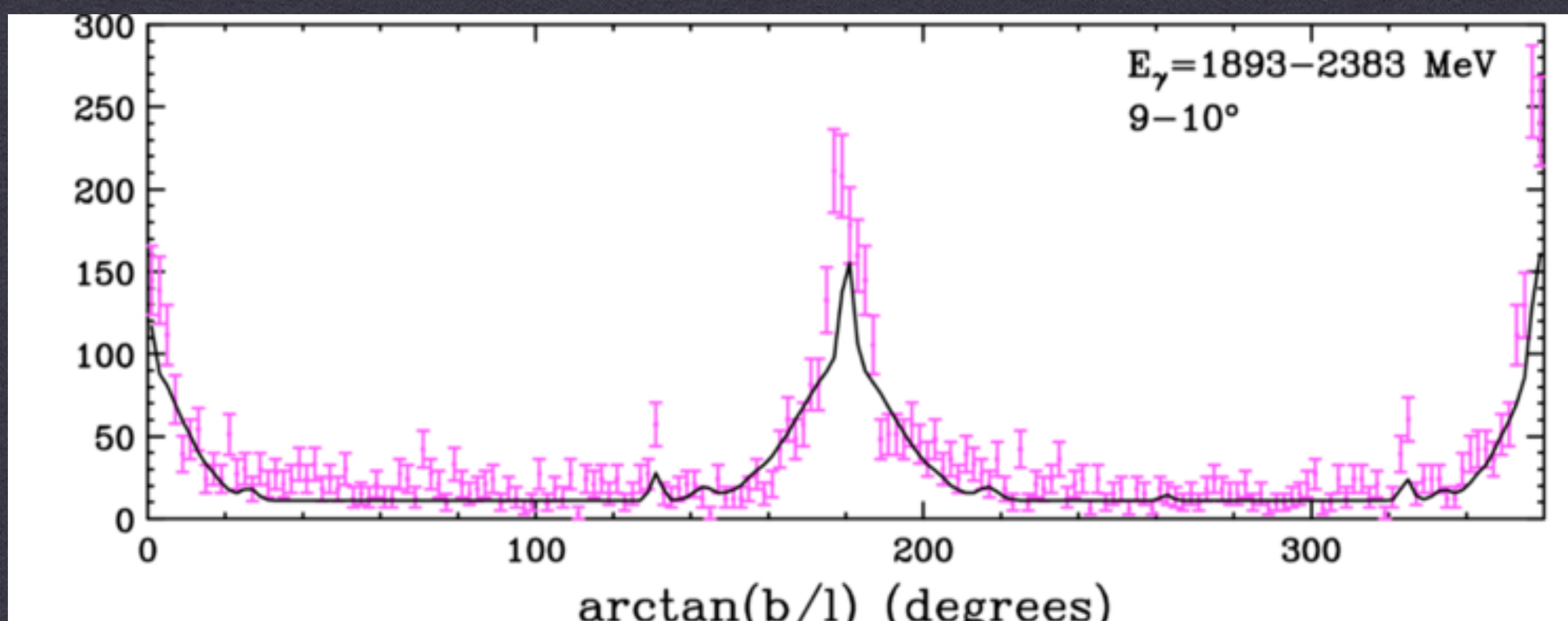
BERLIN, HOOPER, MCDERMOTT (2014)

EXTRA SLIDES

PREVIOUS WORK

GOODENOUGH & HOOPER (2009), HOOPER & GOODENOUGH (2011)



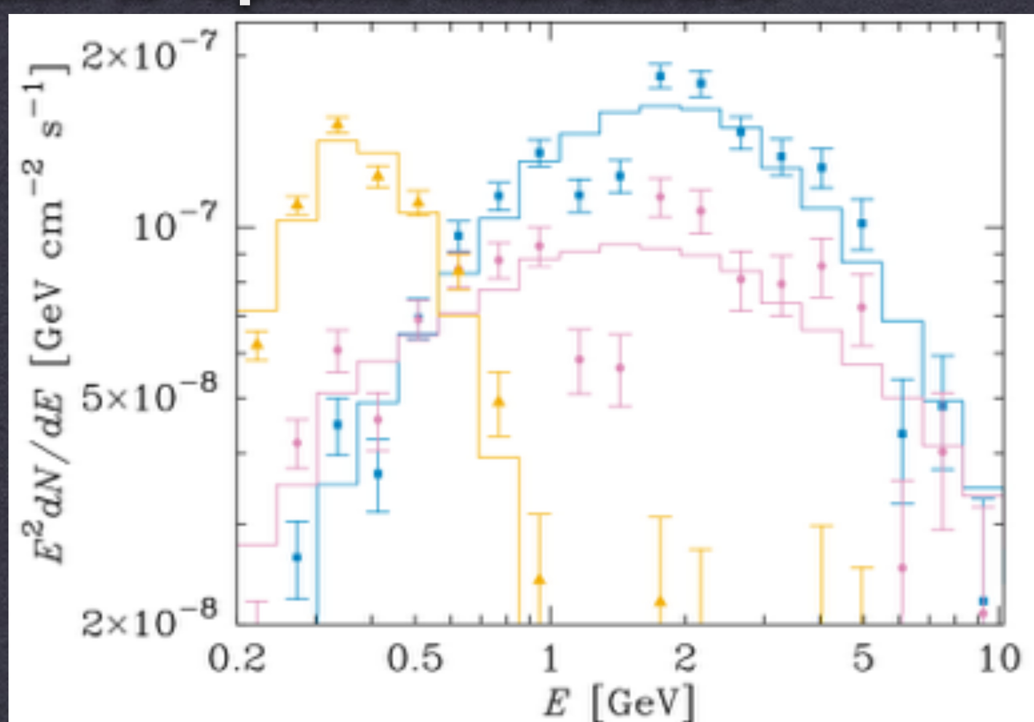


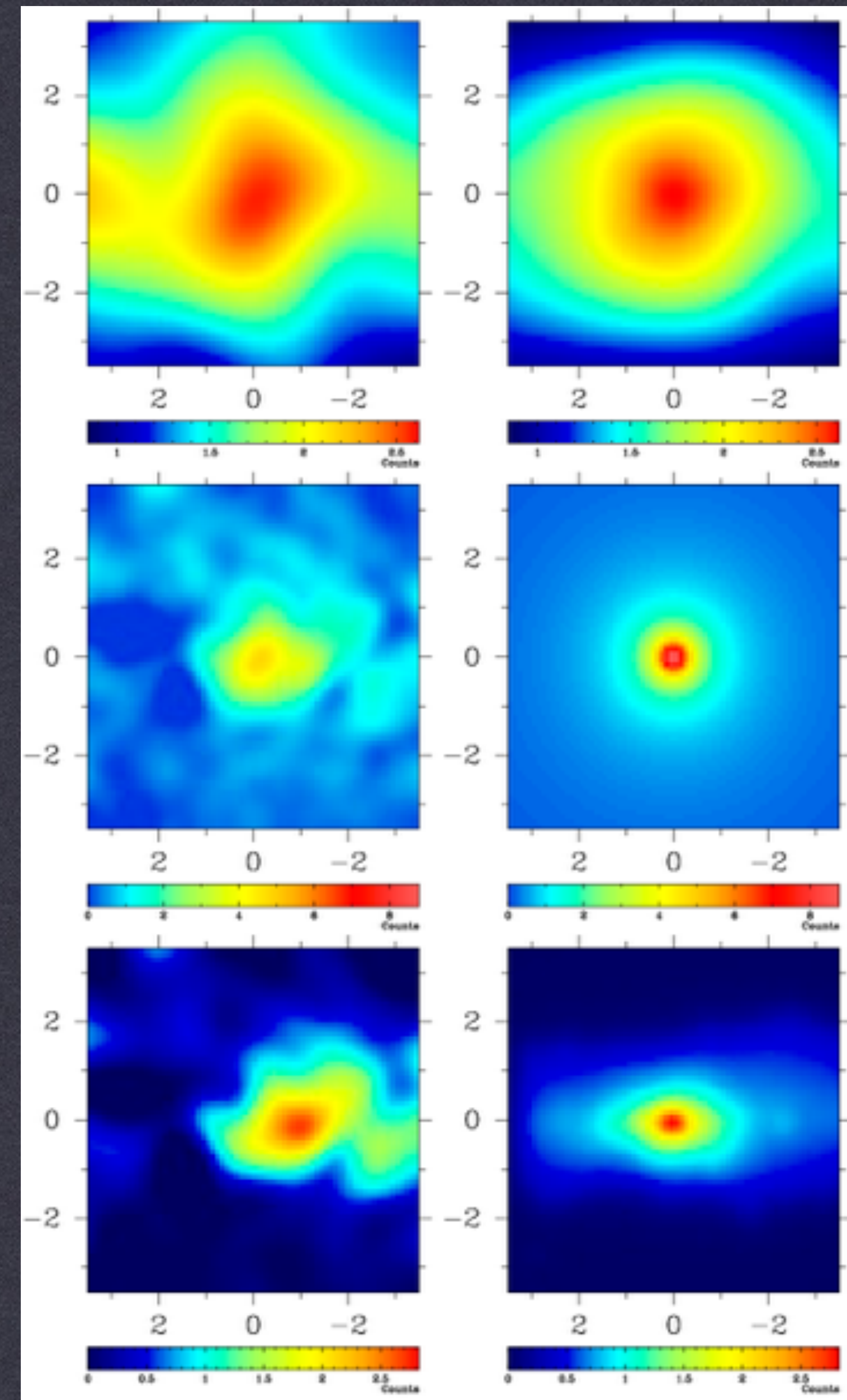
FUTURE TESTS OF DARK MATTER

THE GALACTIC CENTER

Better constraints on the spherical symmetry, spatial extension, and low-energy spectrum of the GC excess can support a DM interpretation.

One interesting analysis has found evidence of a secondary inverse-Compton component with an intensity matching that expected by dark matter annihilation to leptonic final states.

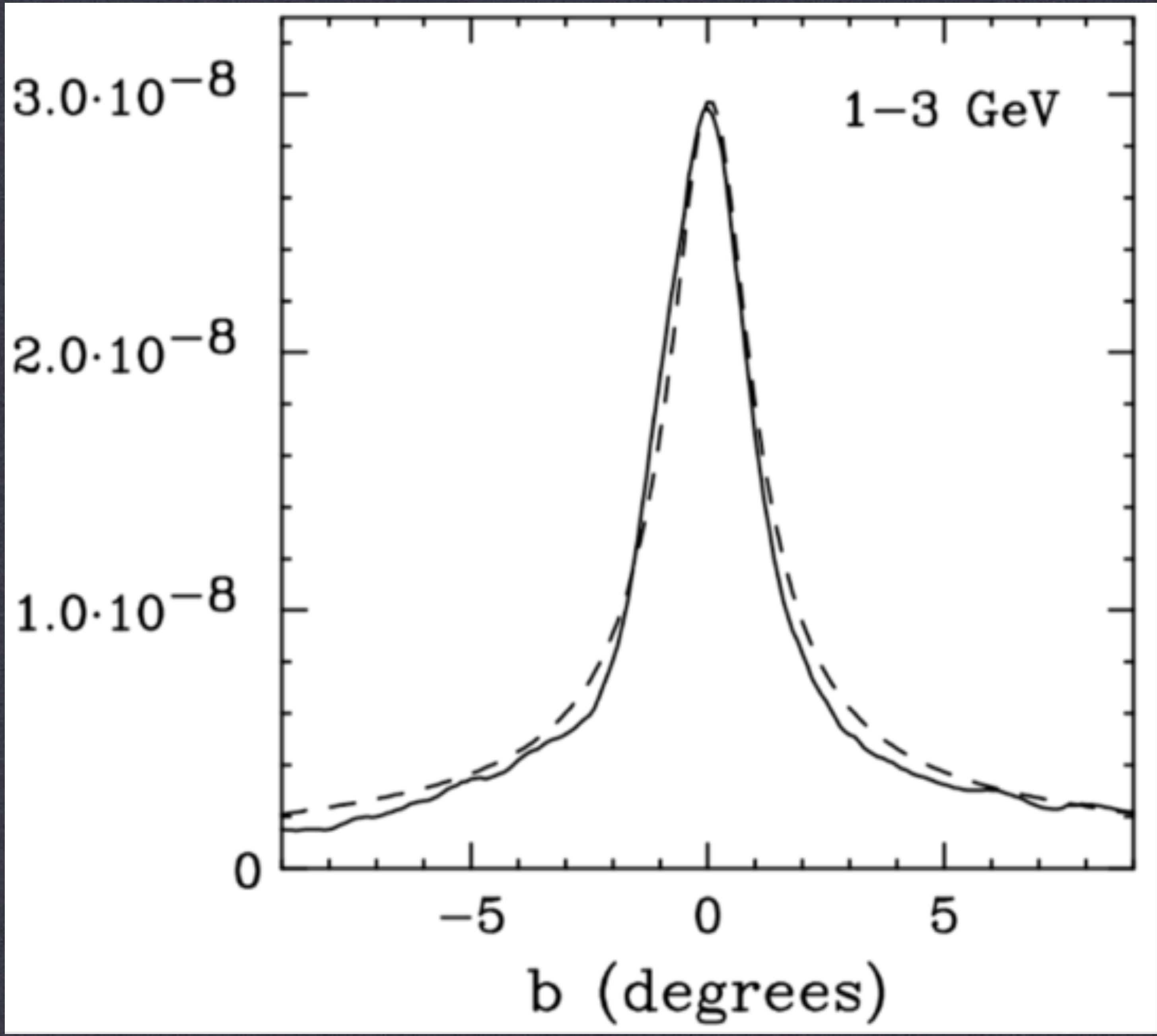




ABAZAJIAN ET AL. (2014B, 1410.6168)

PREVIOUS WORK

HOOPER & TL (2011)



Employ analytic model for the integrated gas density near the galactic center (Kalberla & Kerp 2009)

Fit the emission in regions far from the galactic center ($|l| > 5^{o}$), and extrapolate into center

Remove emission correlating with gas, and examine intensity and spectrum of remaining emission

PREVIOUS WORK

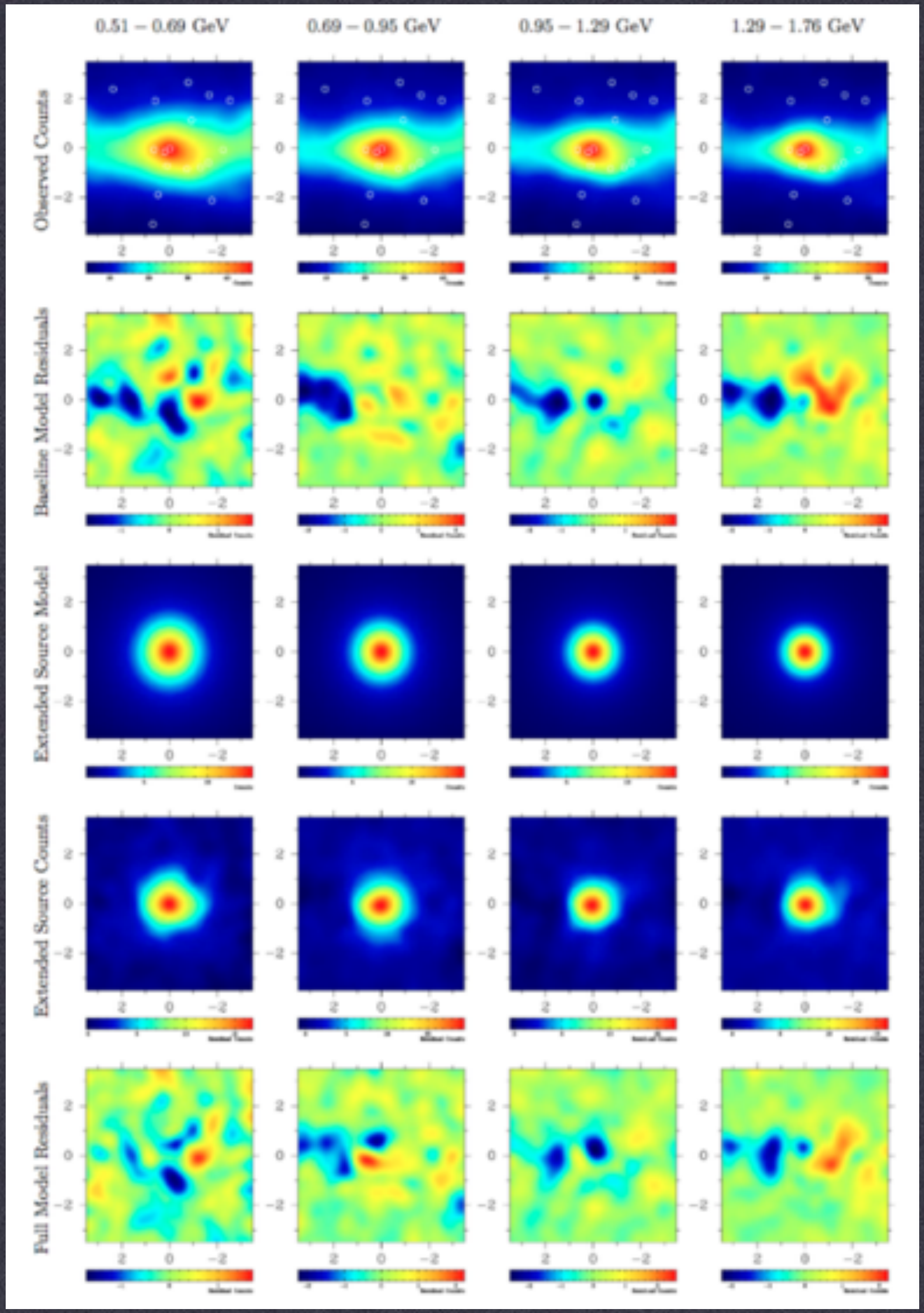
ABAZAJIAN & KAPLINGHAT (2011)

Produce full model of γ-ray emission in the GC, including all point sources and diffuse emission models

Fit data with, and without, a dark matter component, use log-likelihood to determine best fit

$$\ln \mathcal{L} = \sum_i k_i \ln \mu_i - \mu_i - \ln (k_i!)$$

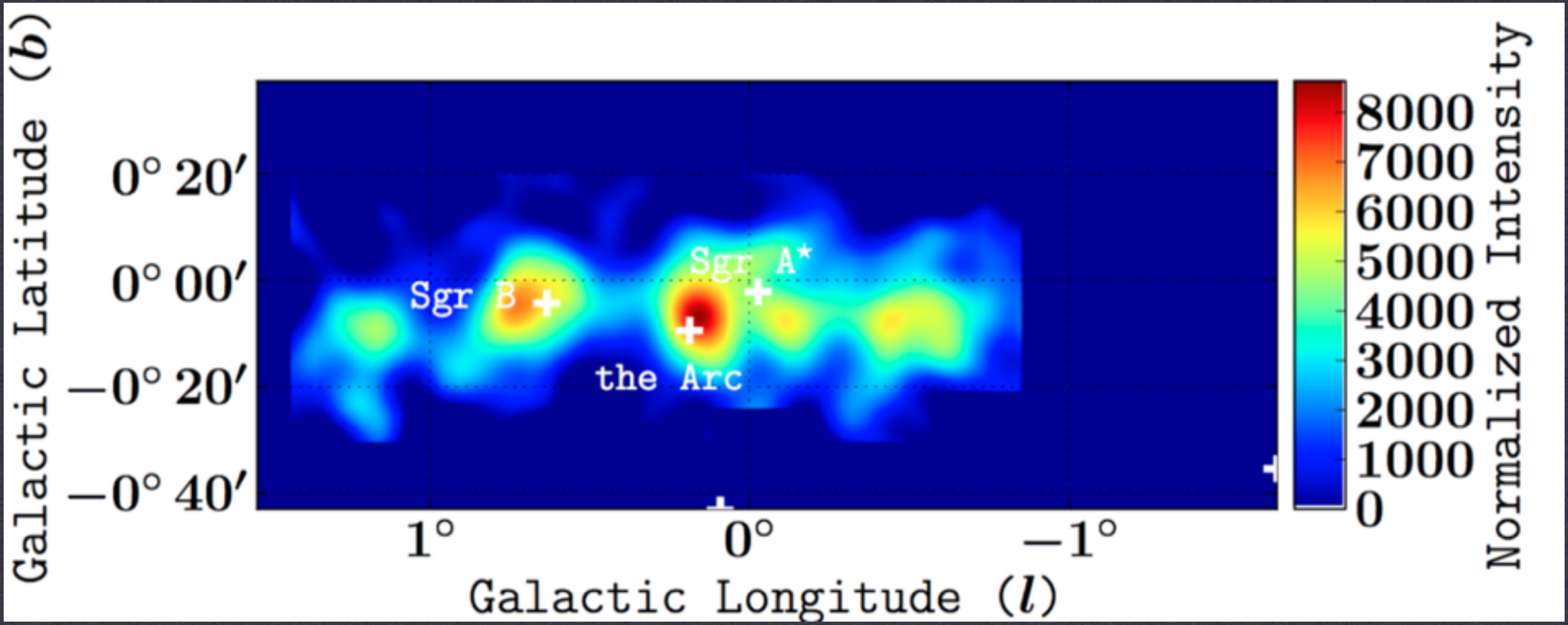
μ_i = model counts $\quad$ k_i=data counts



PREVIOUS WORK

GORDON & MACIAS (2013), MACIAS & GORDON (2013)

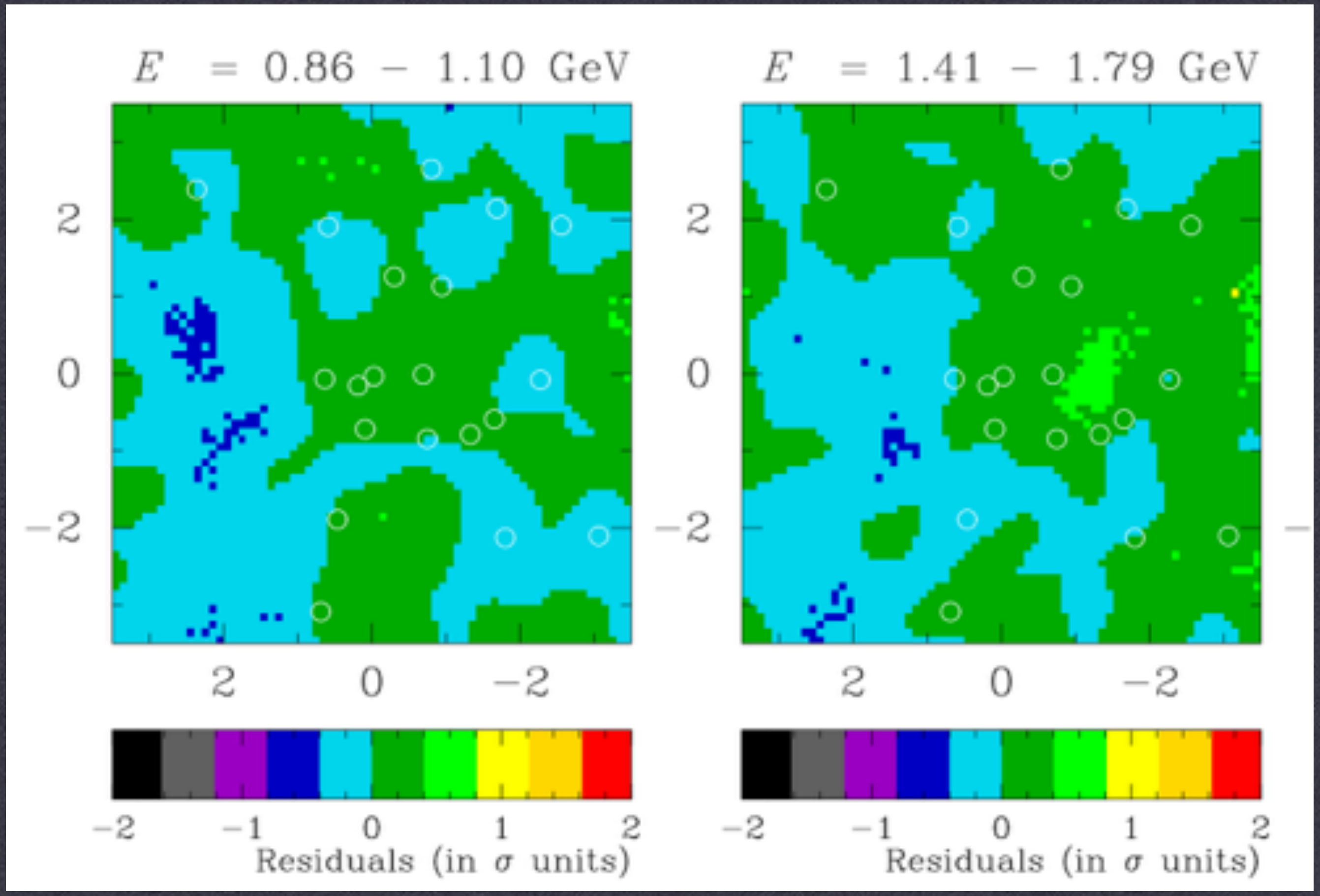
Use Log-Likelihood Formulation, but add additional components corresponding to known high-energy emission sources (20 cm lines, H.E.S.S. ridge)

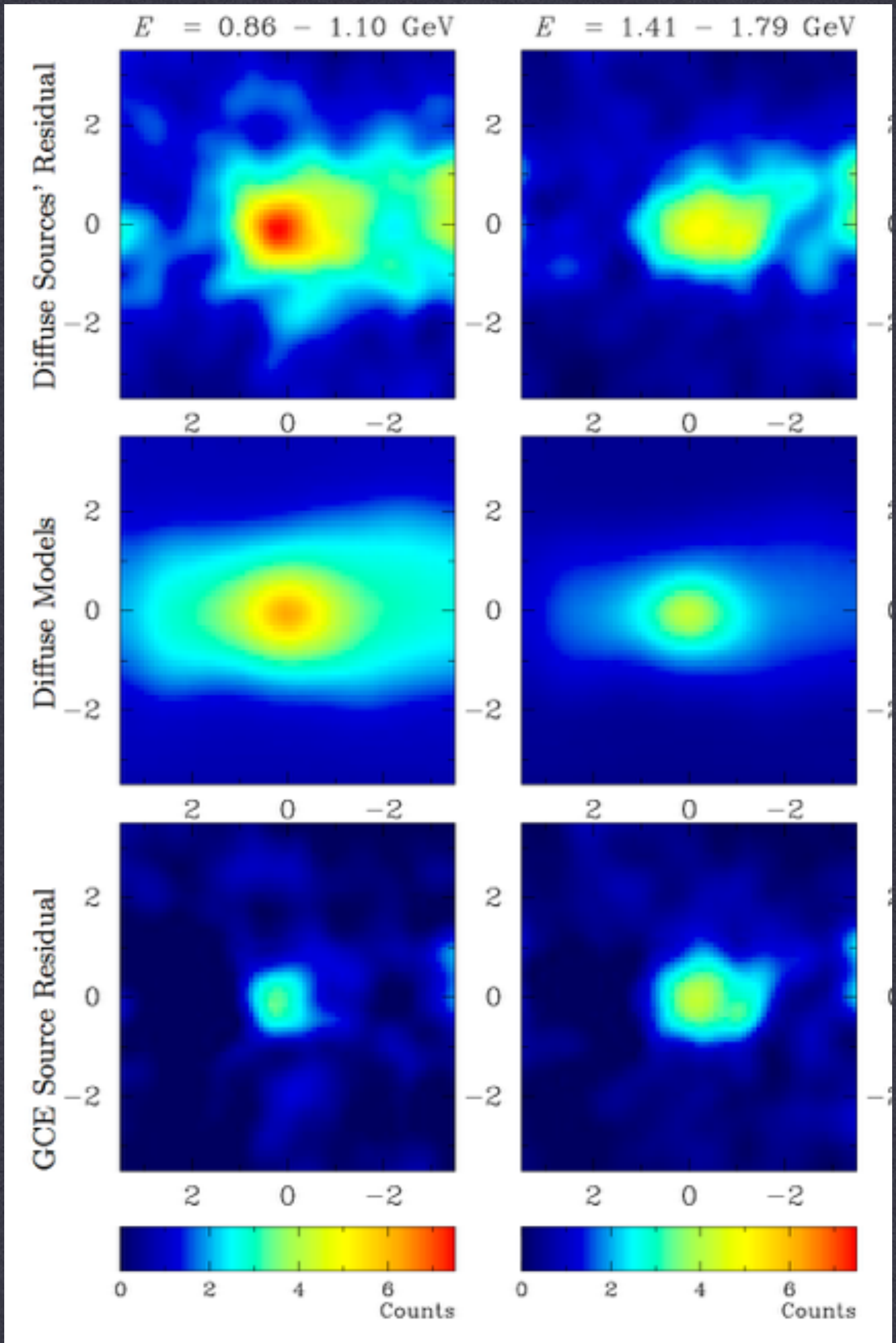


PREVIOUS WORK

ABAZAJIAN ET AL. (2014)

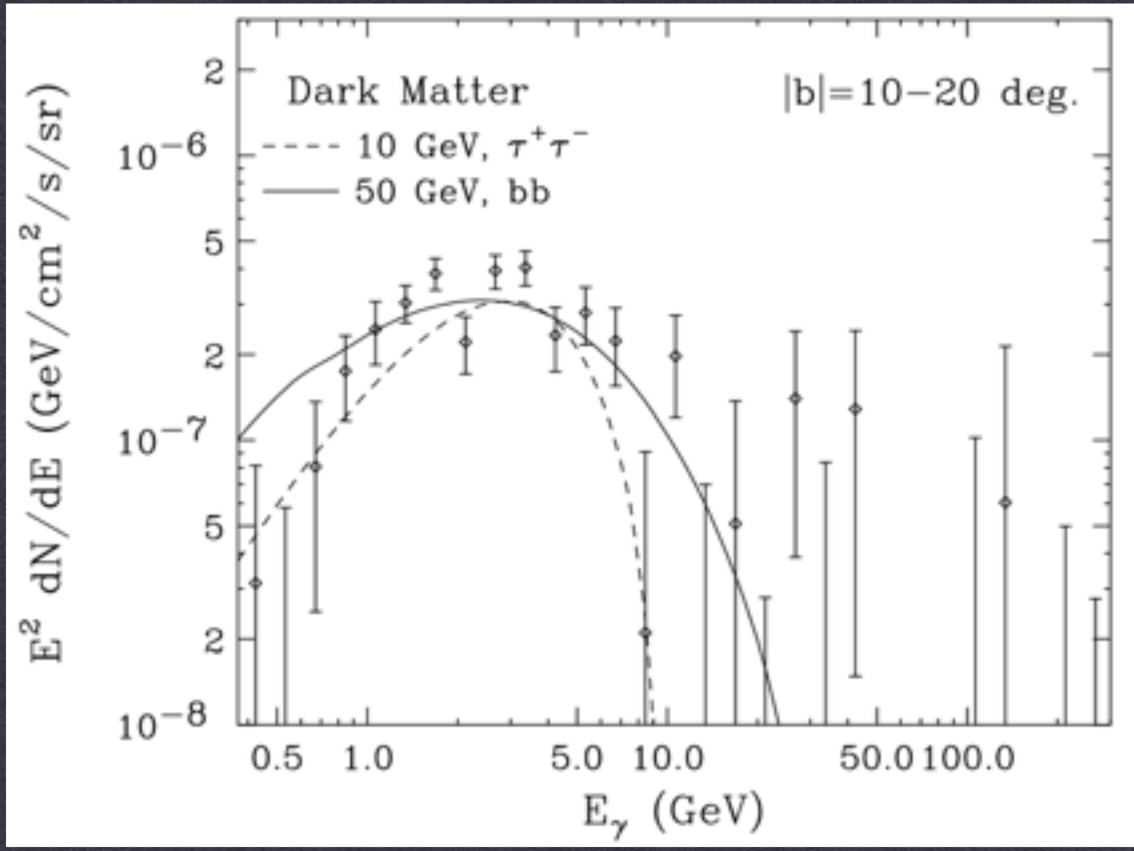
Examined the variation in the low-energy spectrum of the GC Excess for different choices in the diffuse background modeling.



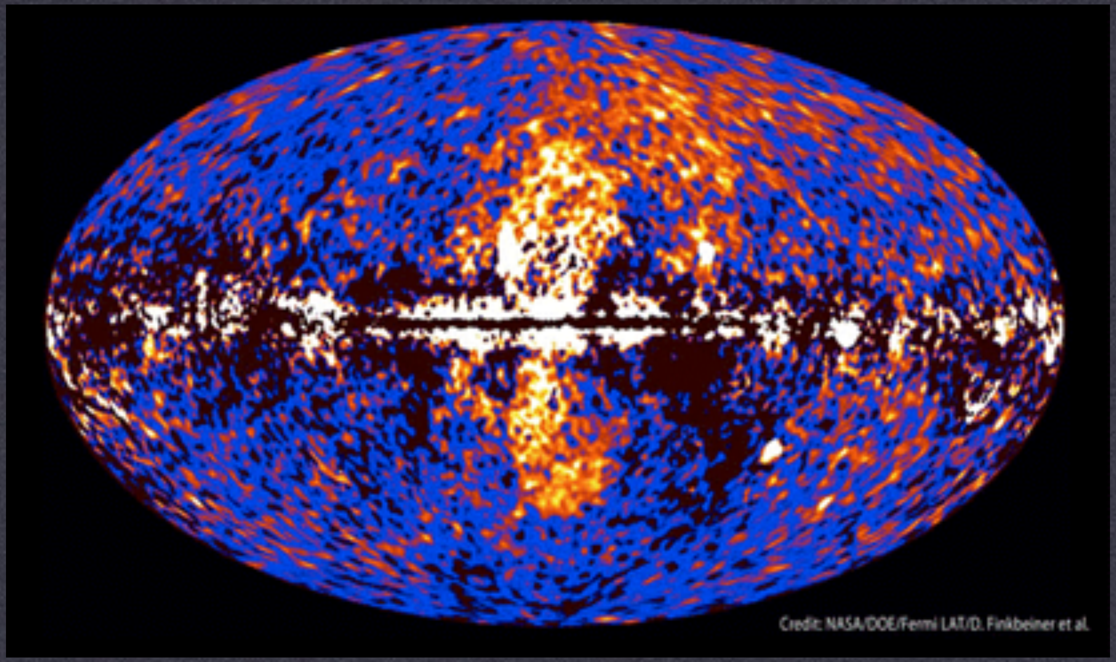


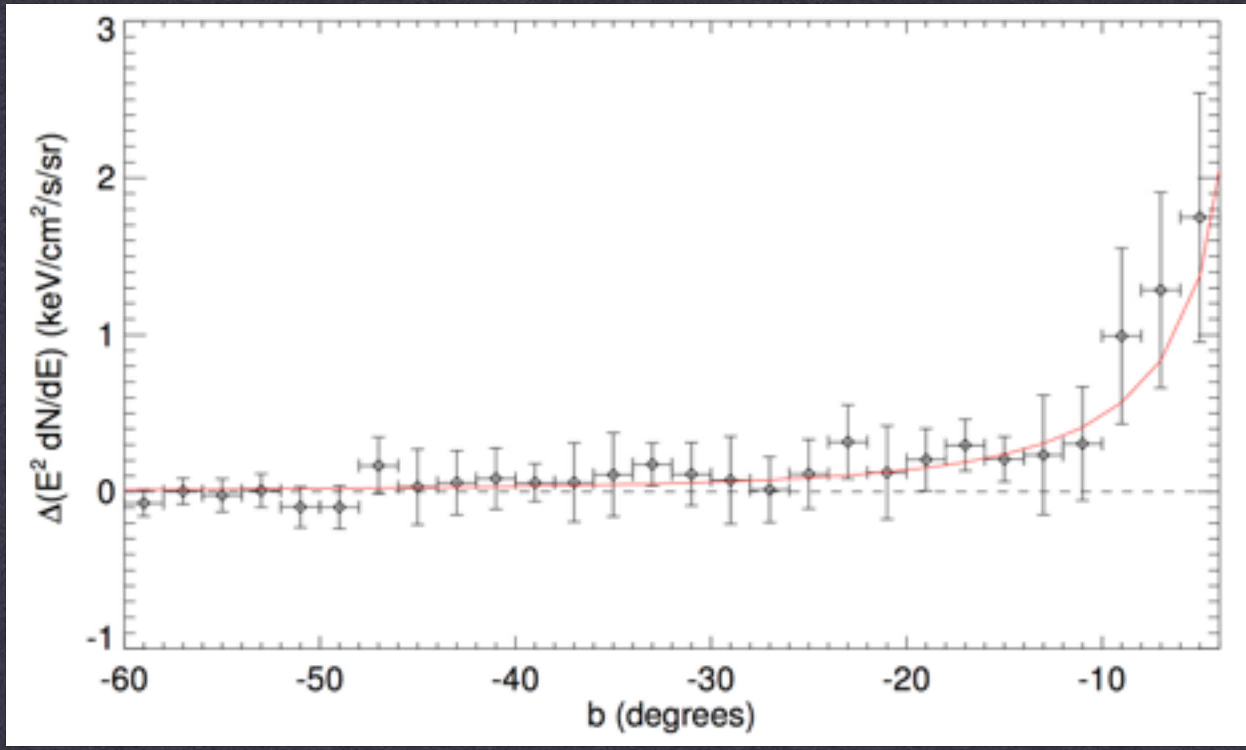
PREVIOUS WORK

HOOPER & SLATYER (2013)



Instead analyzed the Fermi bubbles. They found an excess low-energy emission which fell of with increasing distance from the GC.



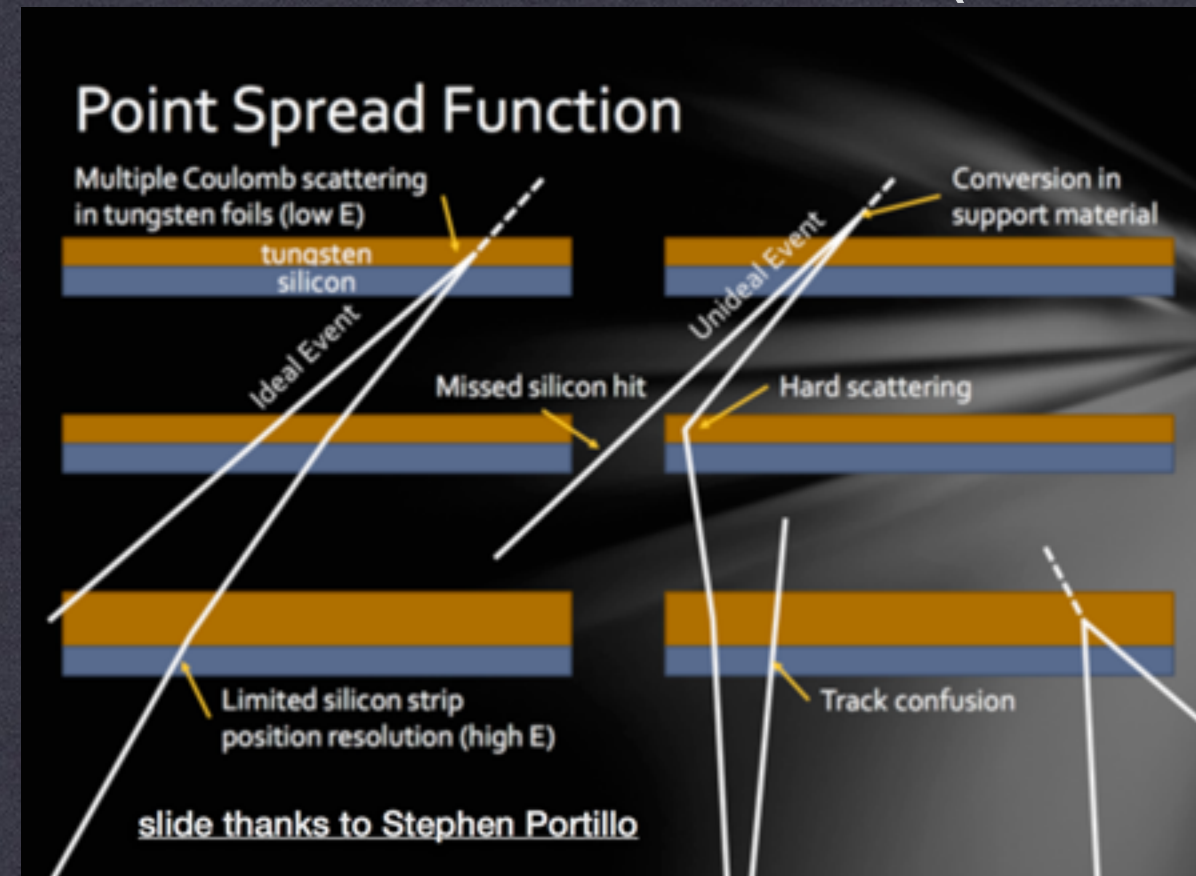


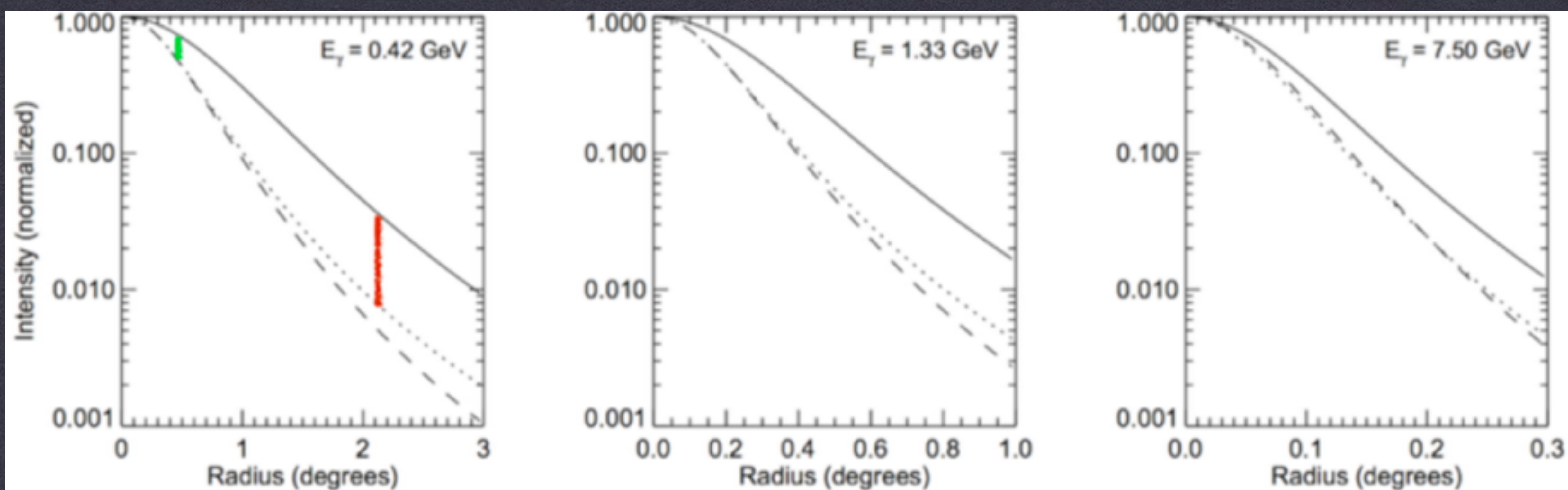
DAYLAN ET AL. (2014)

see Portillo & Finkbeiner (1406.0507)

CTBCORE

Use additional information to classify each photon event based on the accuracy of its directional reconstruction



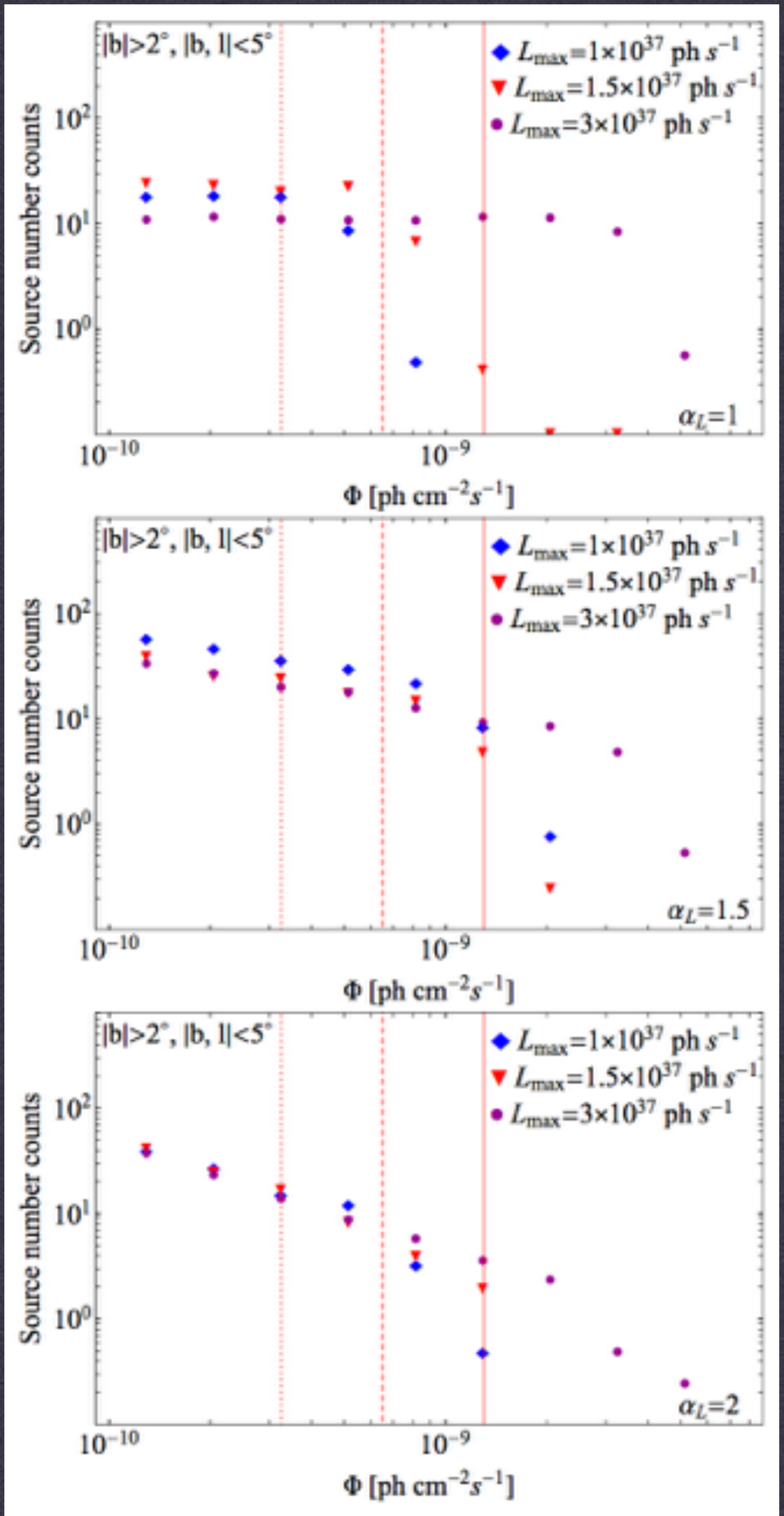


INTERPRETATIONS

MILLISECOND PULSARS

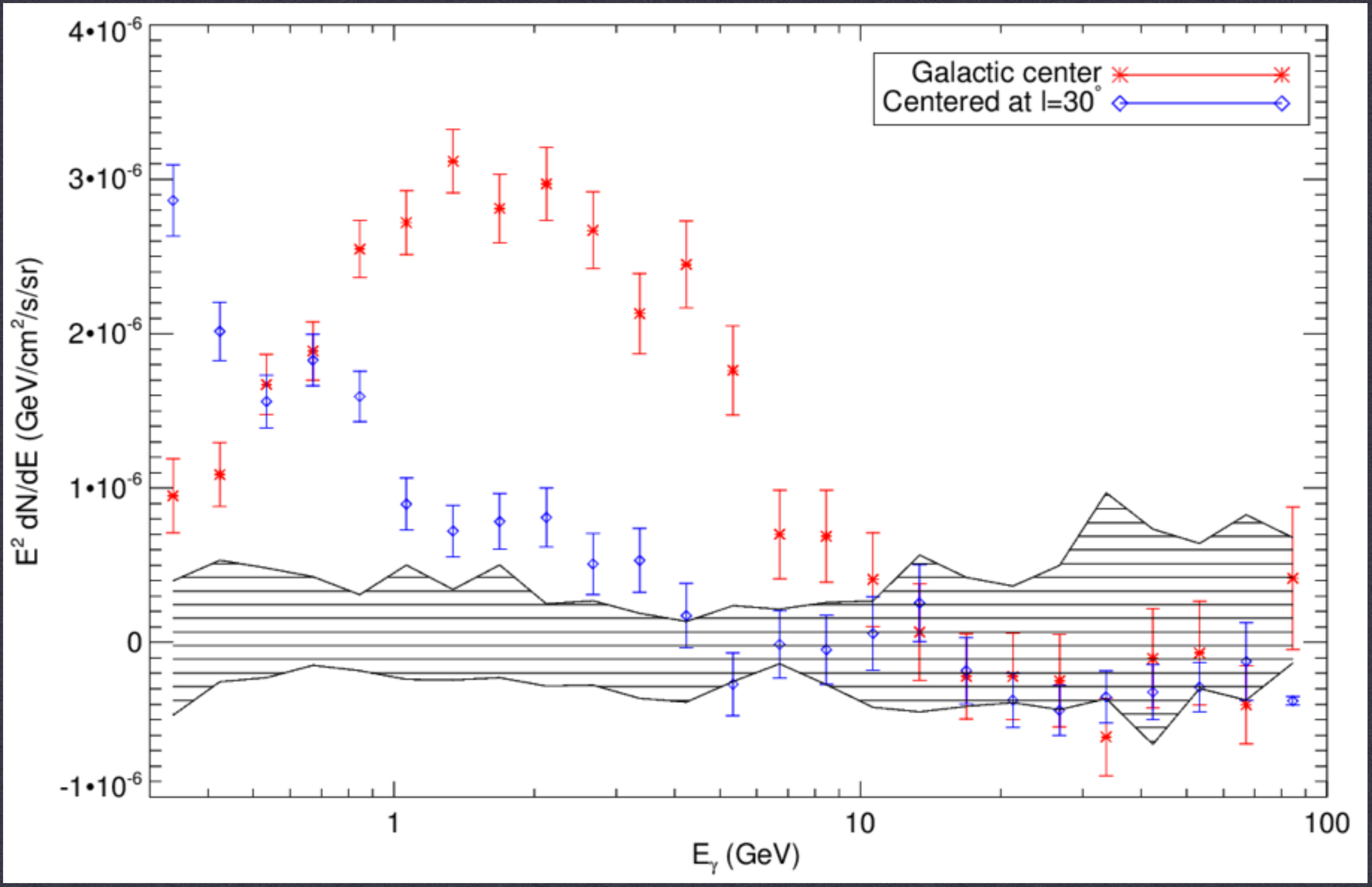
- Petrovic et al. argue that this may still be consistent with the data, if a break in the MSP luminosity function is added in order to decrease the number of bright systems.

- It is not clear how this new cutoff is affected by non-isotropic emission “beaming”, which is expected to exist in most pulsars.

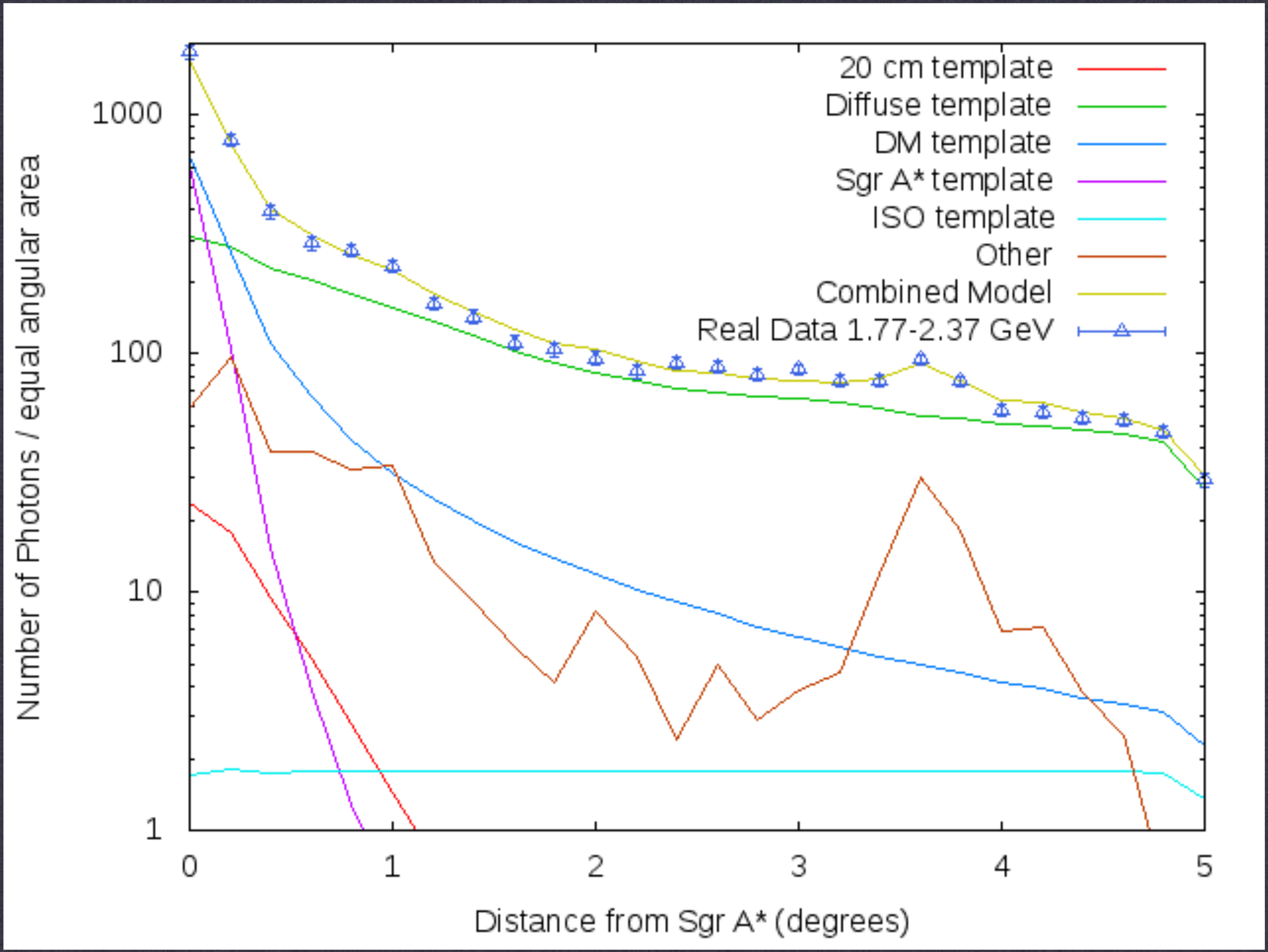


PETROVIC, SERPICO, ZAHARIJAS (2014, 1411.2980)

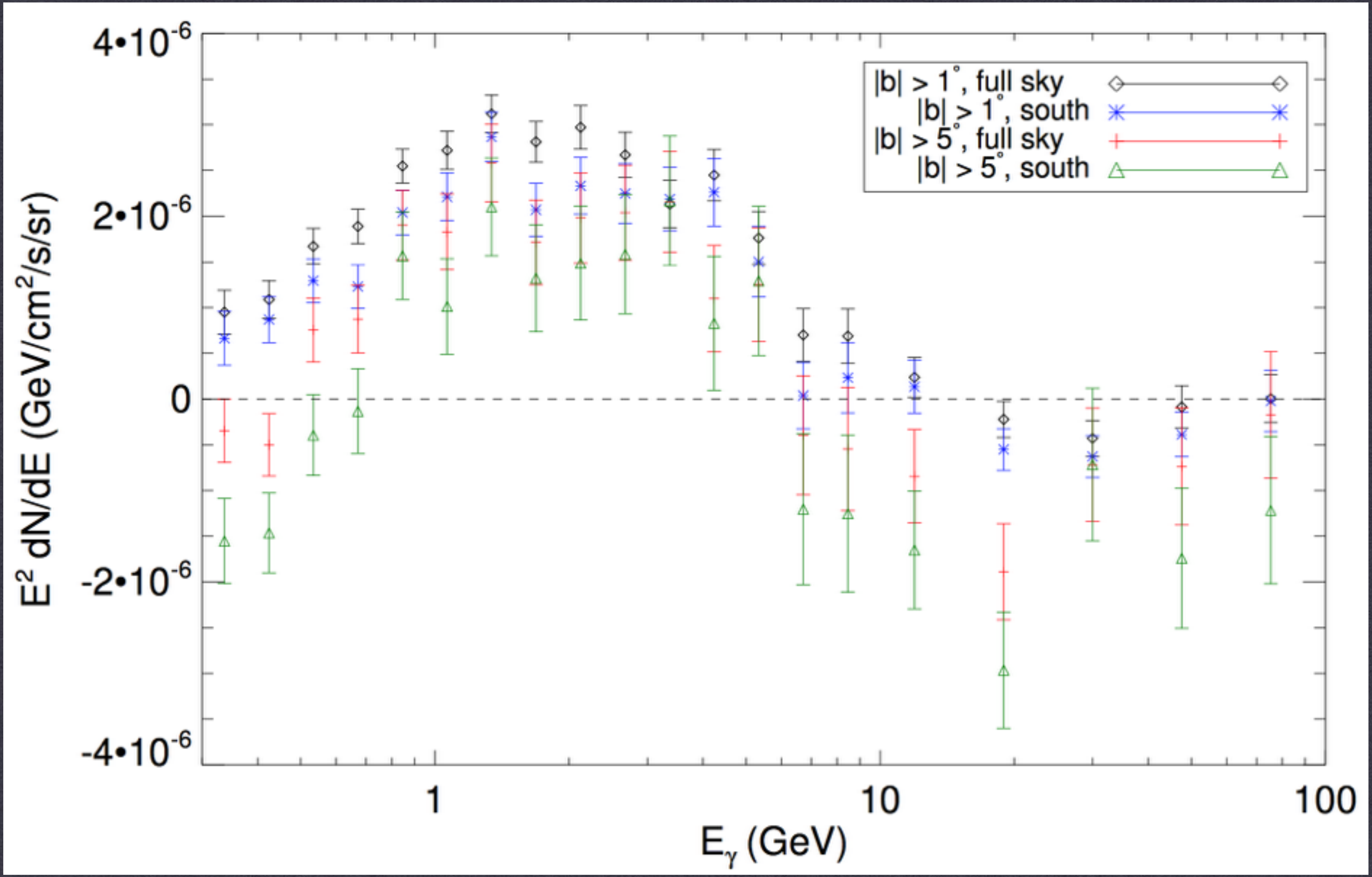
COMPARISON TO OTHER RESIDUALS



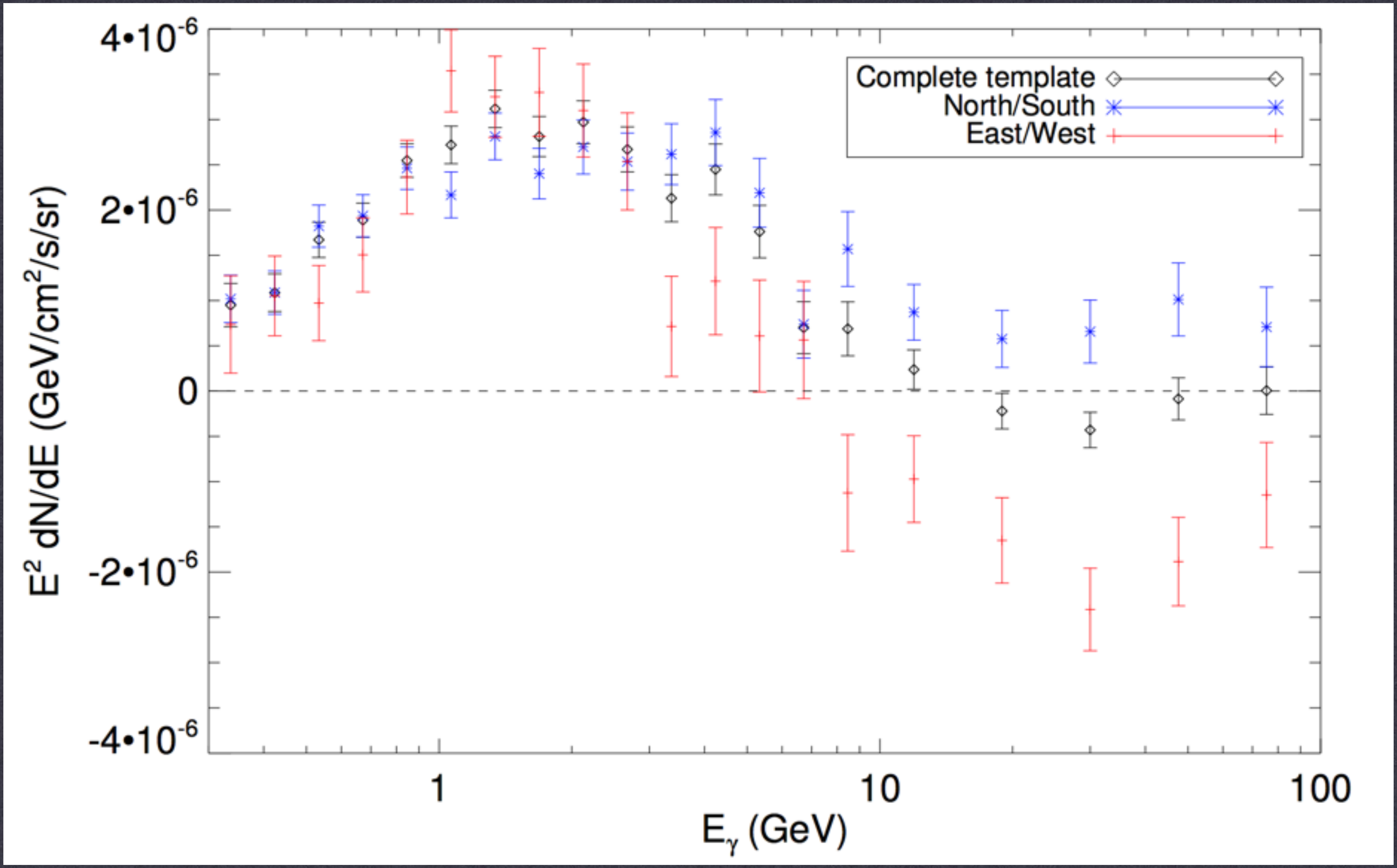
FRACTIONAL INTENSITY



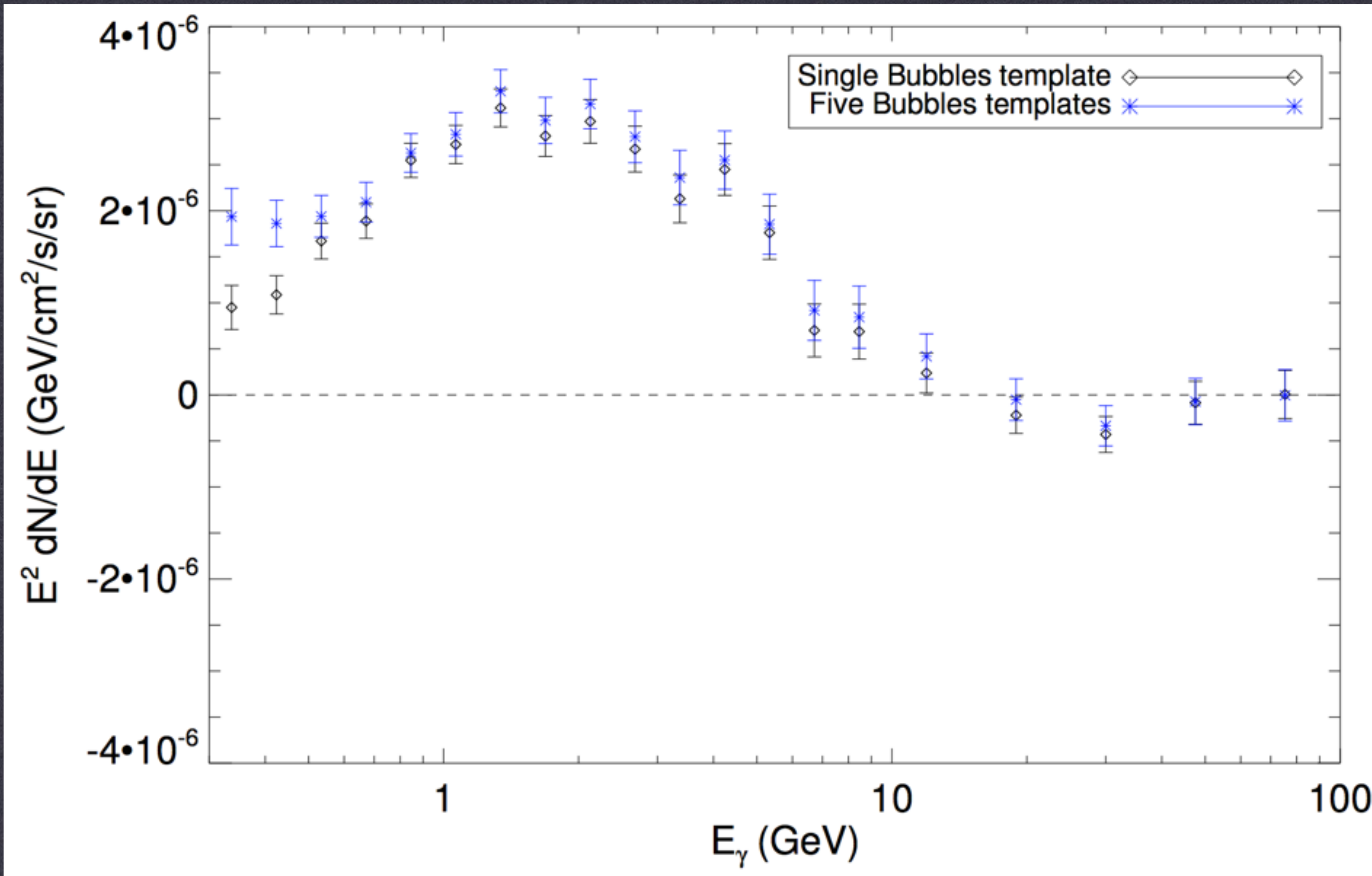
IG EXCESS WITH GC EVENTS REMOVED



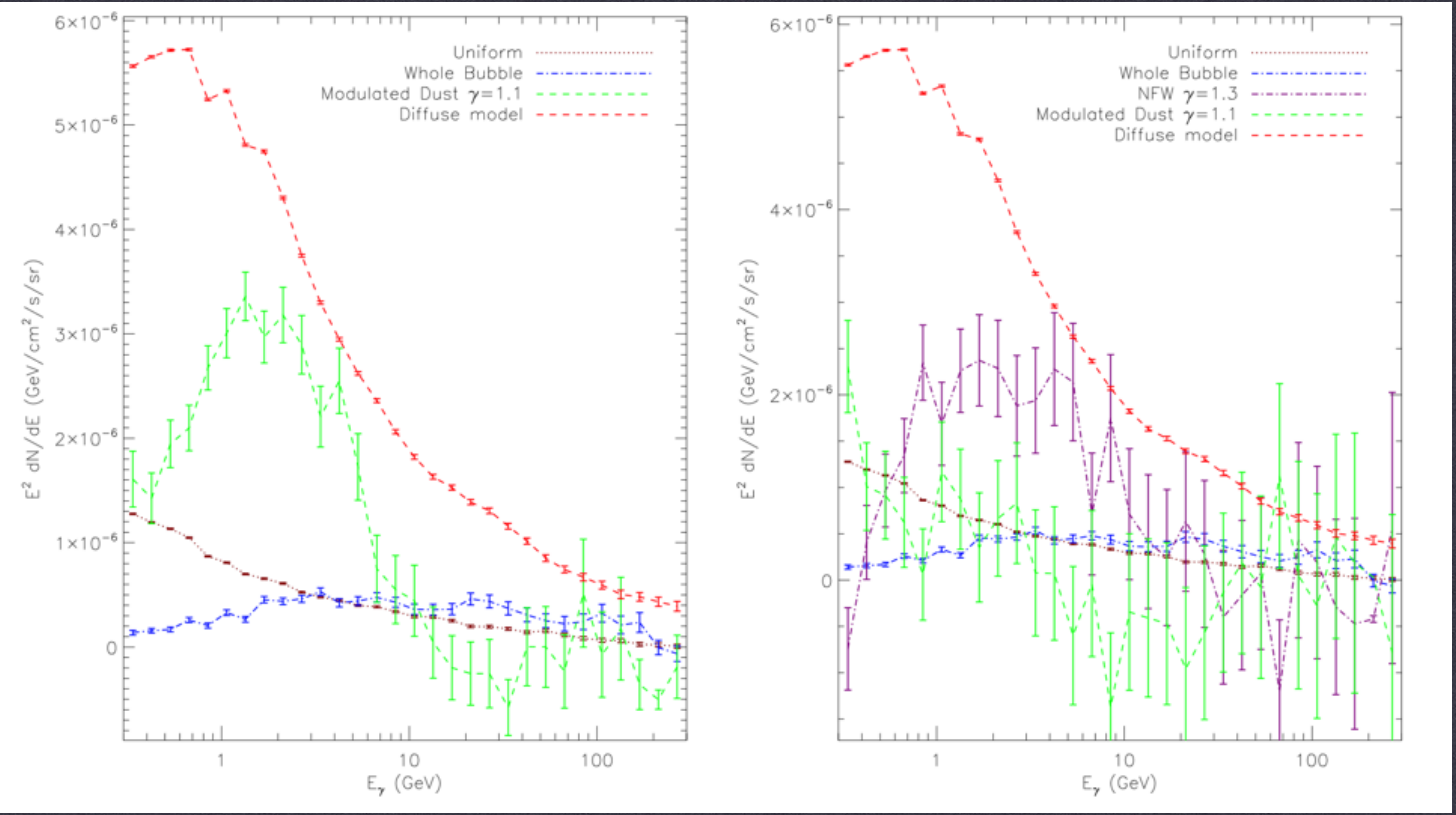
SPECTRUM INSIDE/OUTSIDE BUBBLES



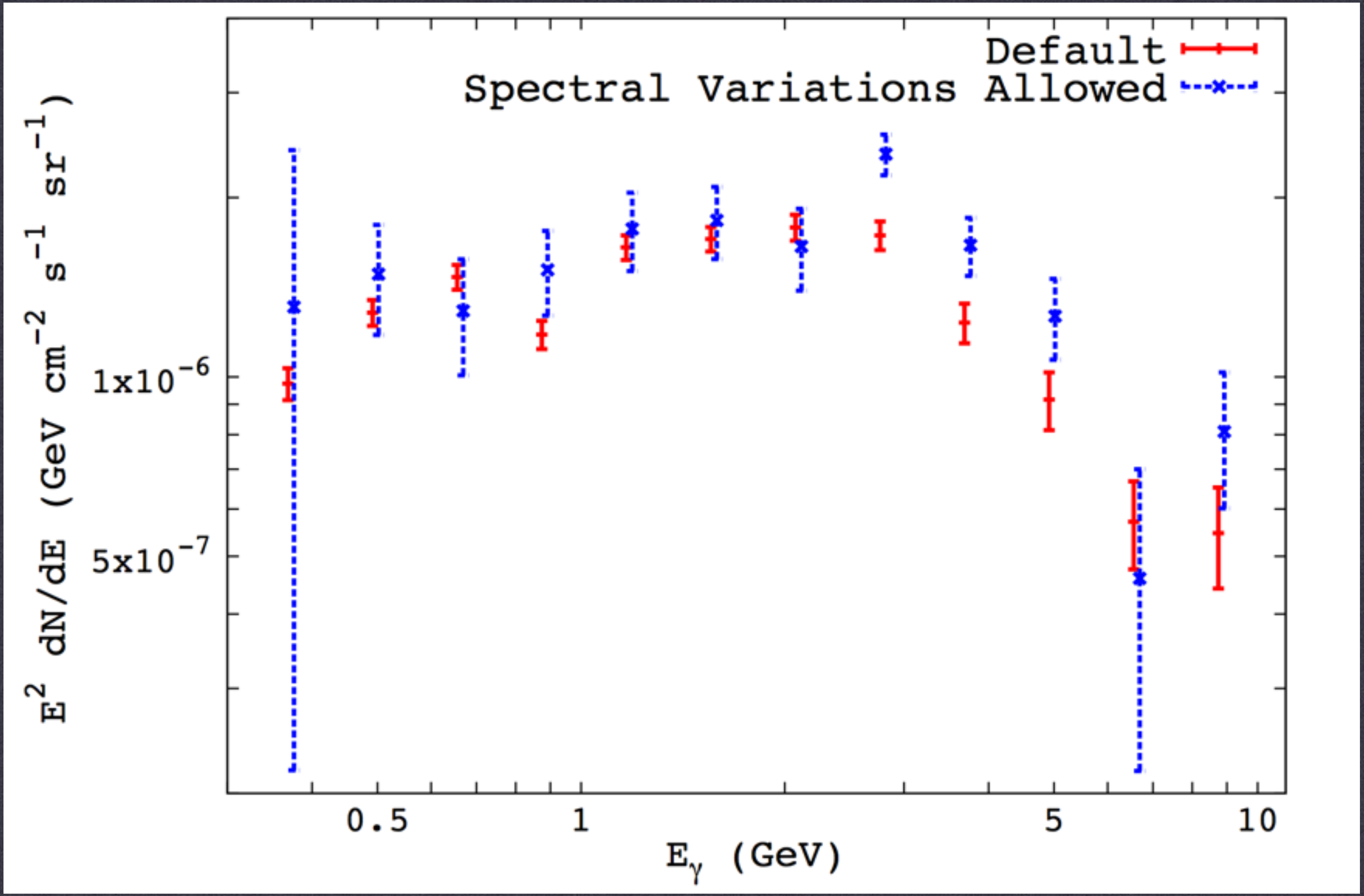
SPECTRAL VARIATION INSIDE BUBBLES



CORRELATION WITH GAS



SPECTRAL VARIATIONS IN DIFFUSE MODEL



ELLIPTICITY IN GENERAL DIRECTION