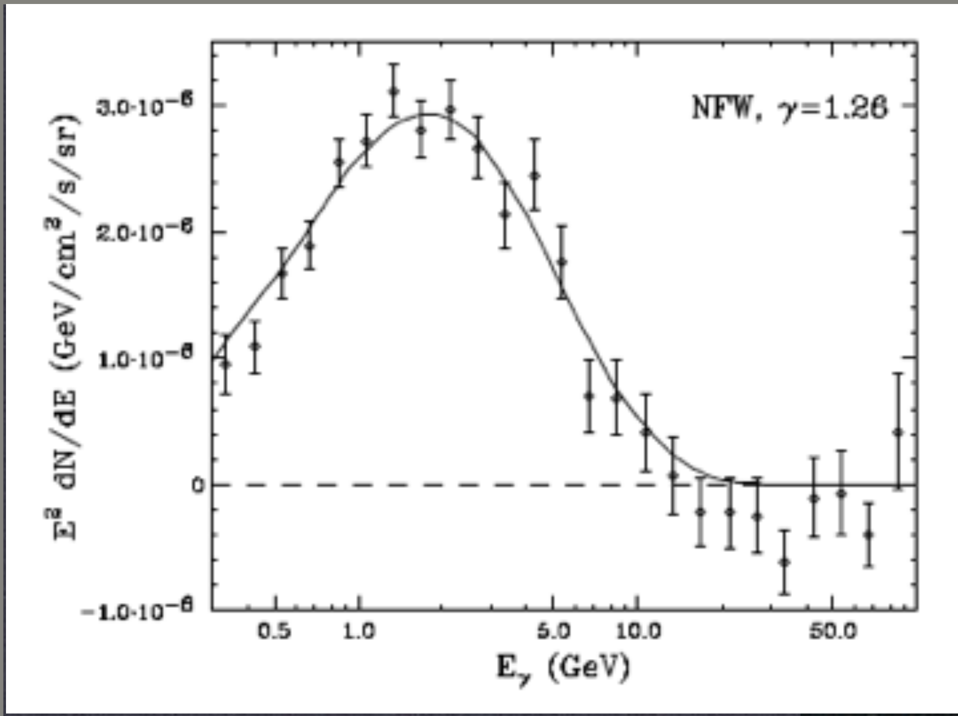
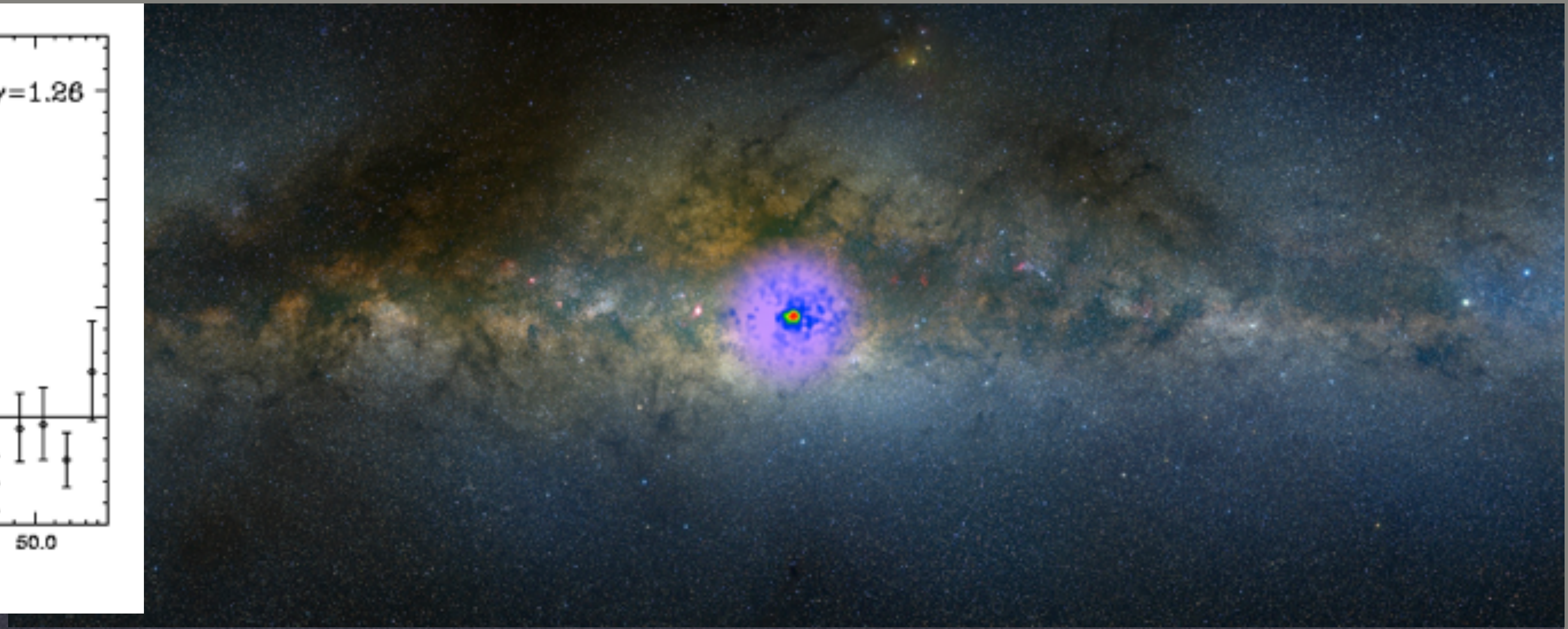




ASTROPHYSICAL MODELS FOR THE GALACTIC CENTER GEV EXCESS

TIM LINDEN

WITH: TANSU DAYLAN, DOUG FINKBEINER, DAN HOOPER, STEPHEN PORTILLO, NICK RODD, TRACY SLATYER, ILIAS CHOLIS, CHRISTOPH WENIGER, FRANCESCA CALORE, CARMELO EVOLI, STEFANO PROFUMO, ERIC CARLSON

CETUP 2015

INDIRECT DETECTION OF WIMPS

DARK MATTER DENSITY PROFILES

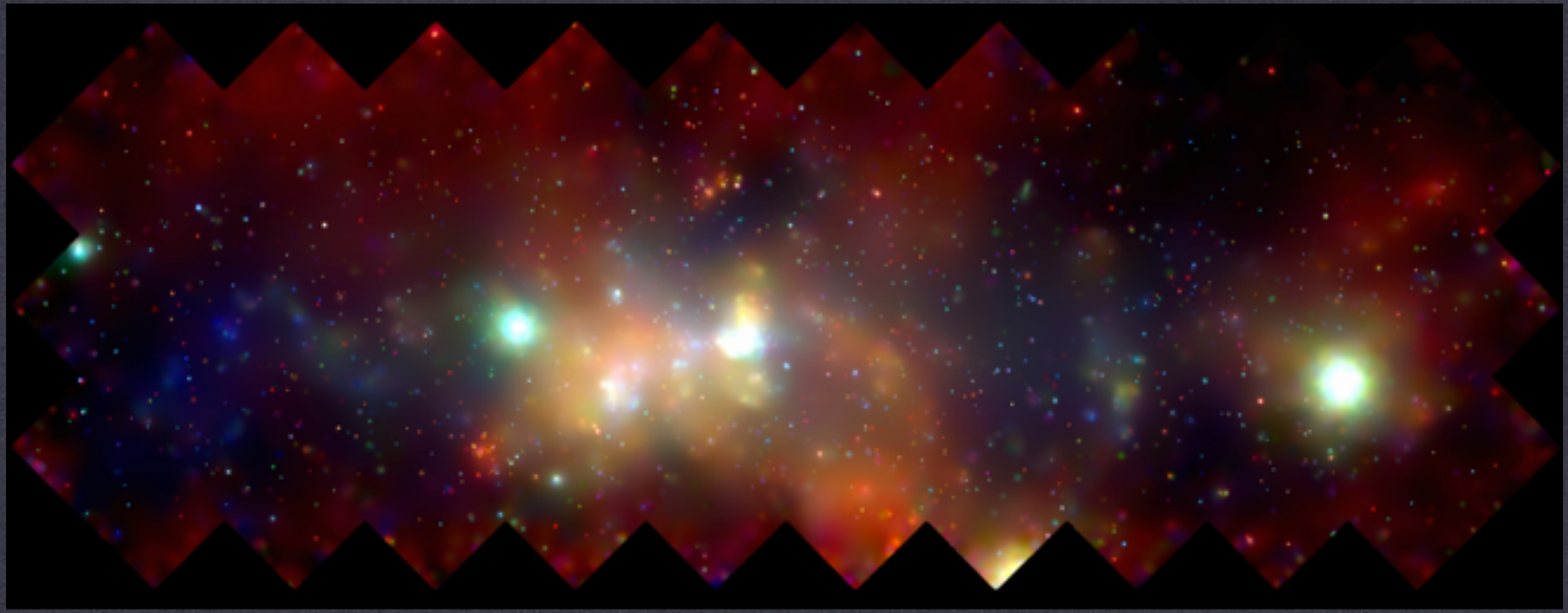
THE GALACTIC CENTER

A Coincidence!

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

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

Unfortunately, the backgrounds are not negligible.



Chandra image of Galactic Center

WHY WE'RE DOING WHAT WE'RE DOING

1.) Dark Matter is one of the guaranteed extensions to the standard model

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

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

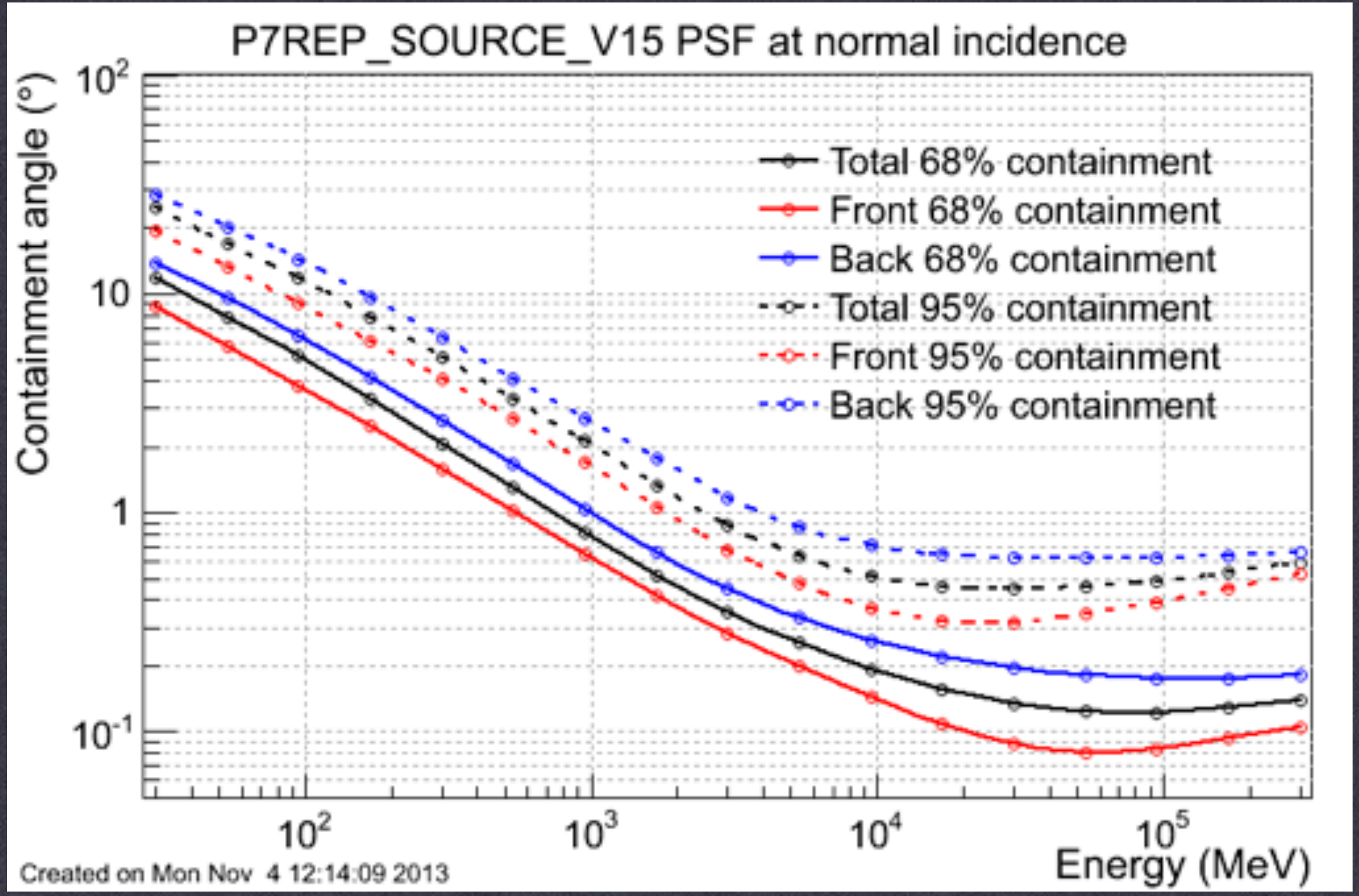
Different studies have used various techniques and regions of interest, but have obtained consistent results!

INDIRECT DETECTION OF WIMPS

WE HAVE AN INSTRUMENT!

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

TWO REGIONS OF INTEREST

INNER GALAXY

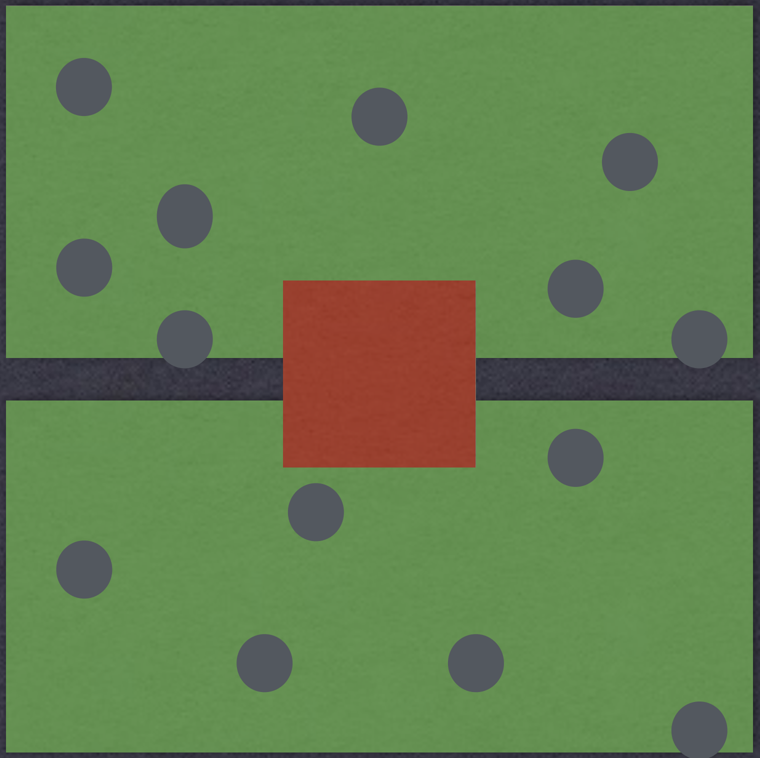
- Mask galactic plane (e.g. $|b| > 1^\circ$), and consider $40^\circ \times 40^\circ$ box
- Bright point sources masked at 2°
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin

DAYLAN ET AL.
CALORE ET AL.

GALACTIC CENTER

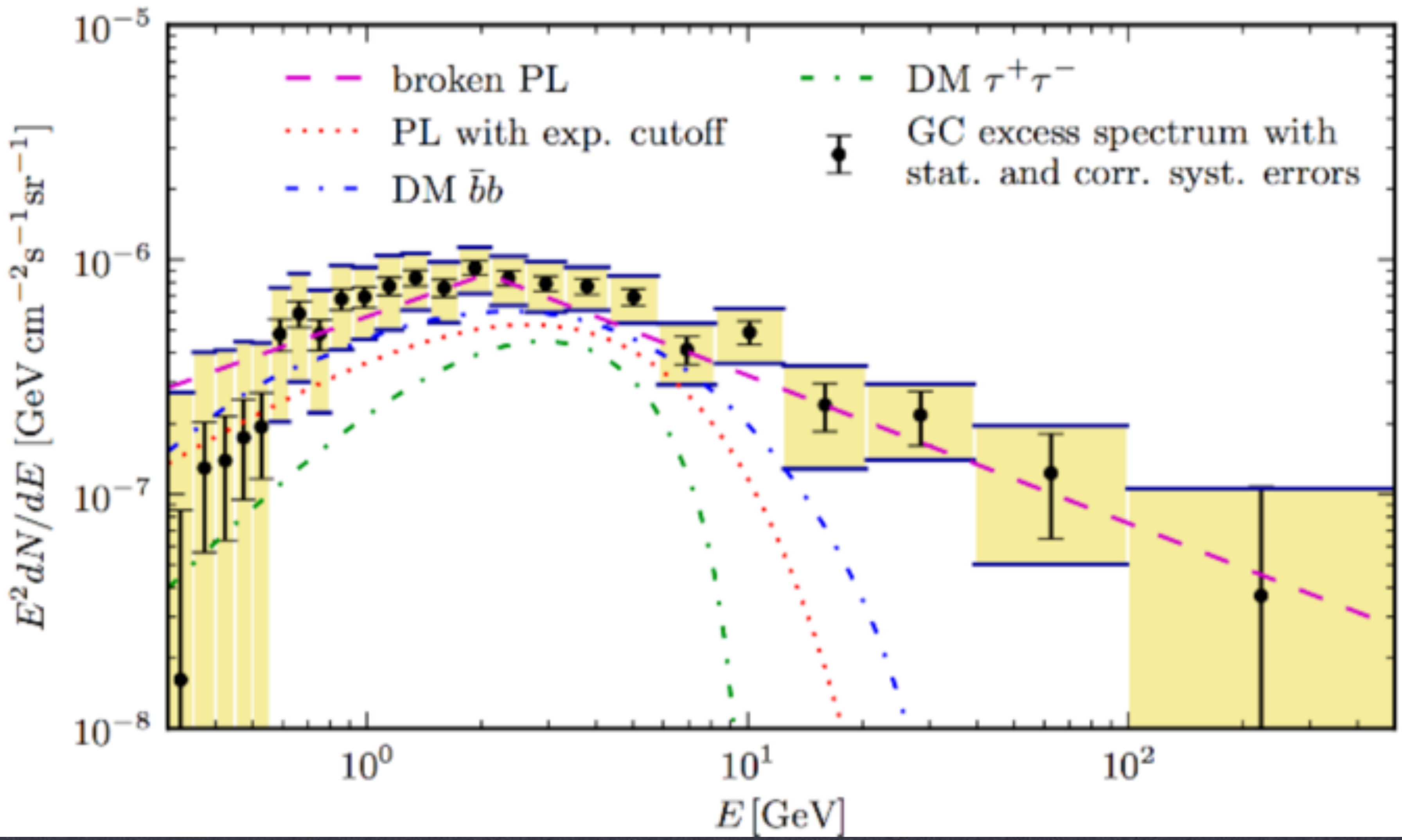
- Box around the GC ($10^\circ \times 10^\circ$)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source

DAYLAN ET AL.



EXCESS SPECTRUM

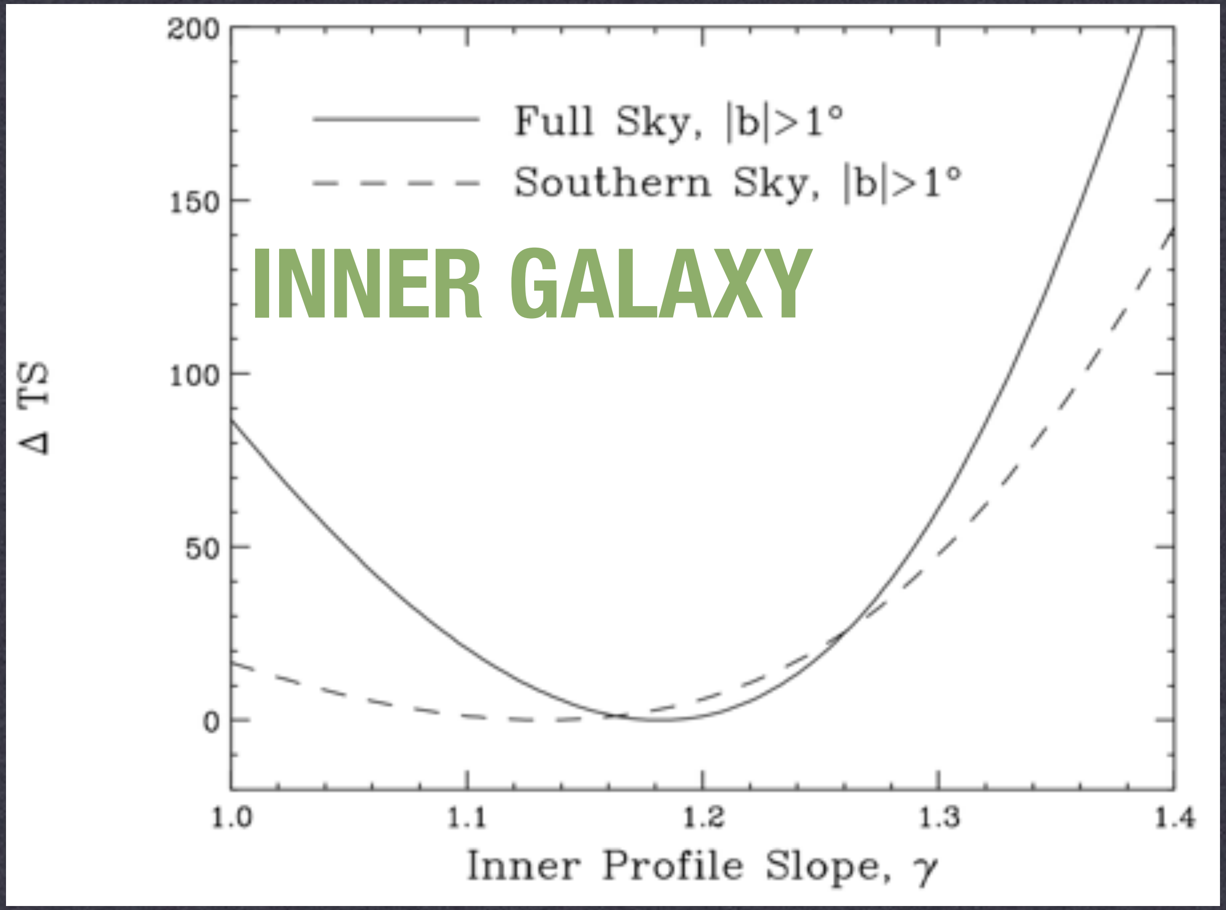
Calore et al. (2014, 1409.0042)

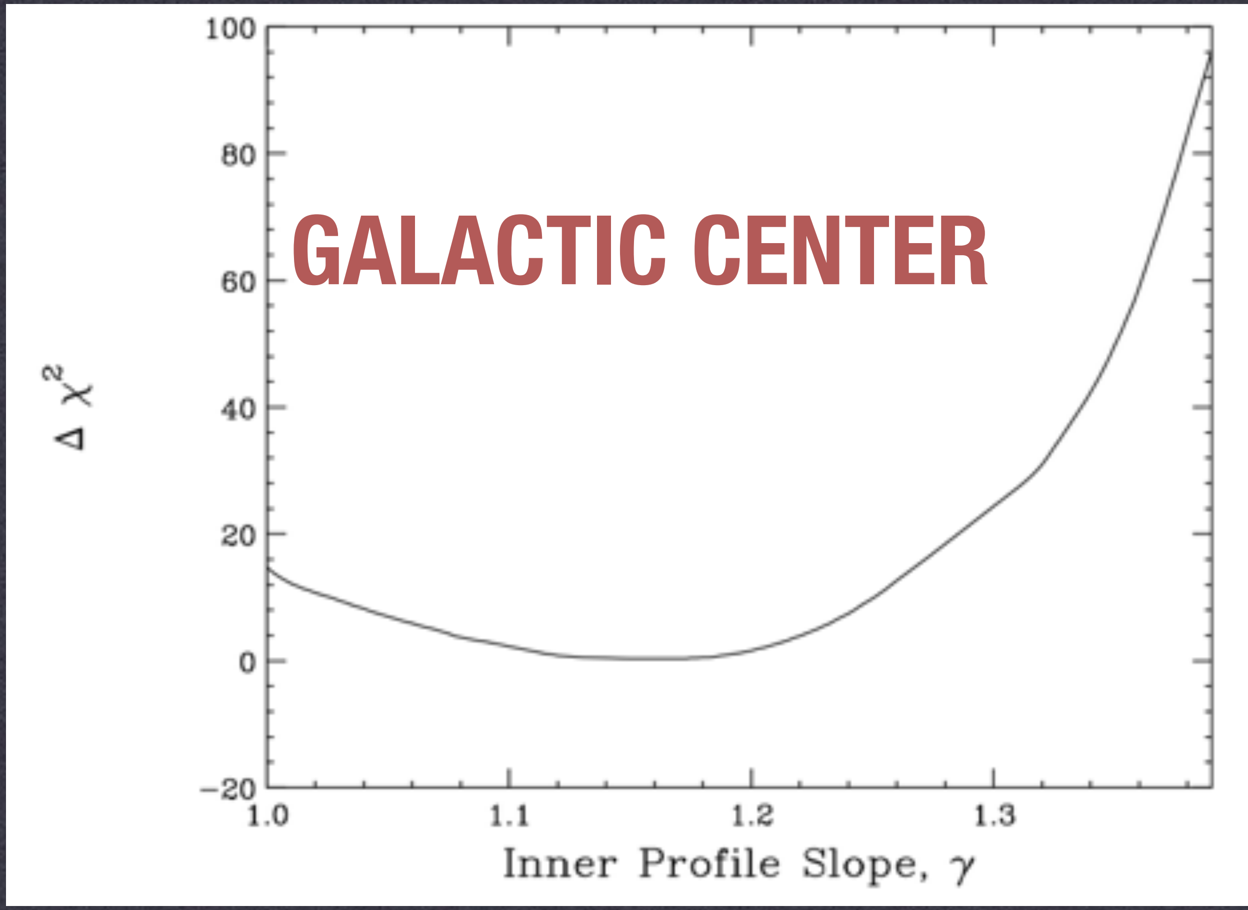


Spectral Model highly resilient to changing systematic background models ~300 models considered here.

Low energy spectrum hard to constrain due to systematics
High energy spectrum difficult due to statistics

MORPHOLOGY

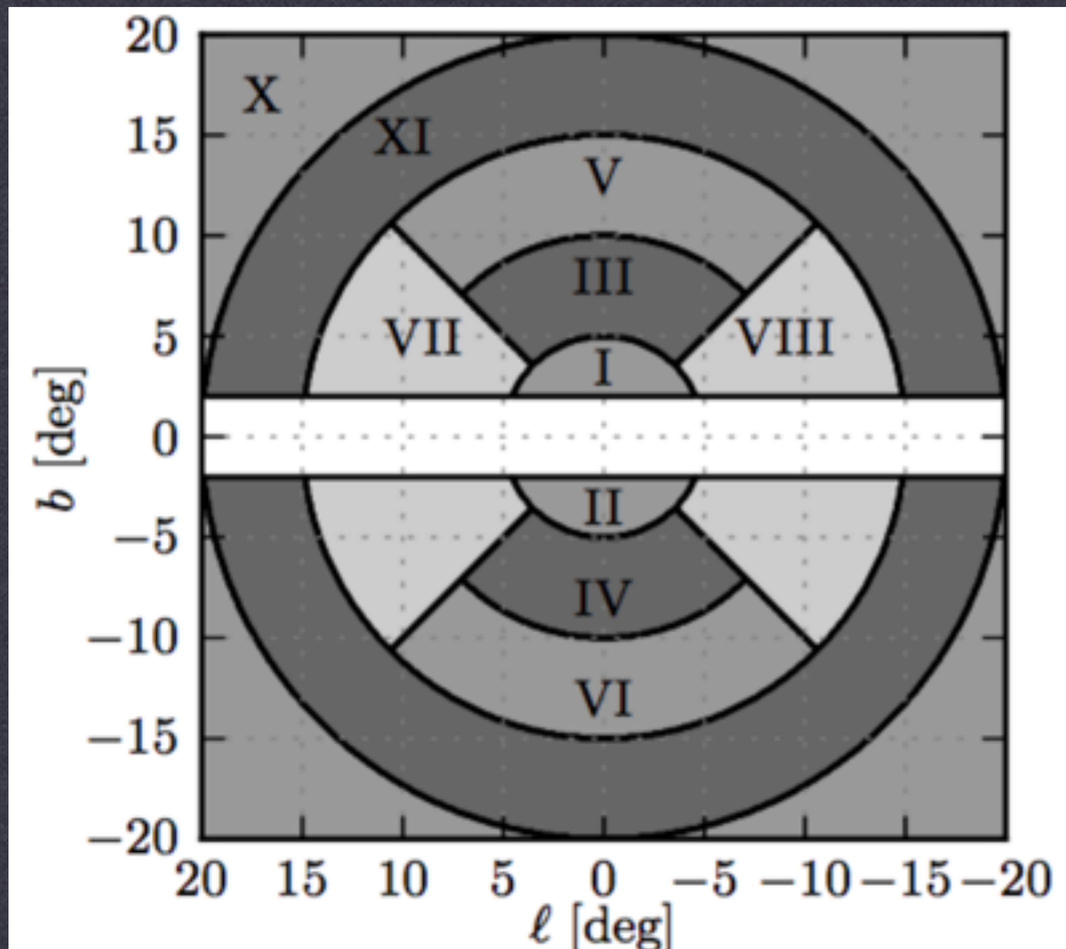


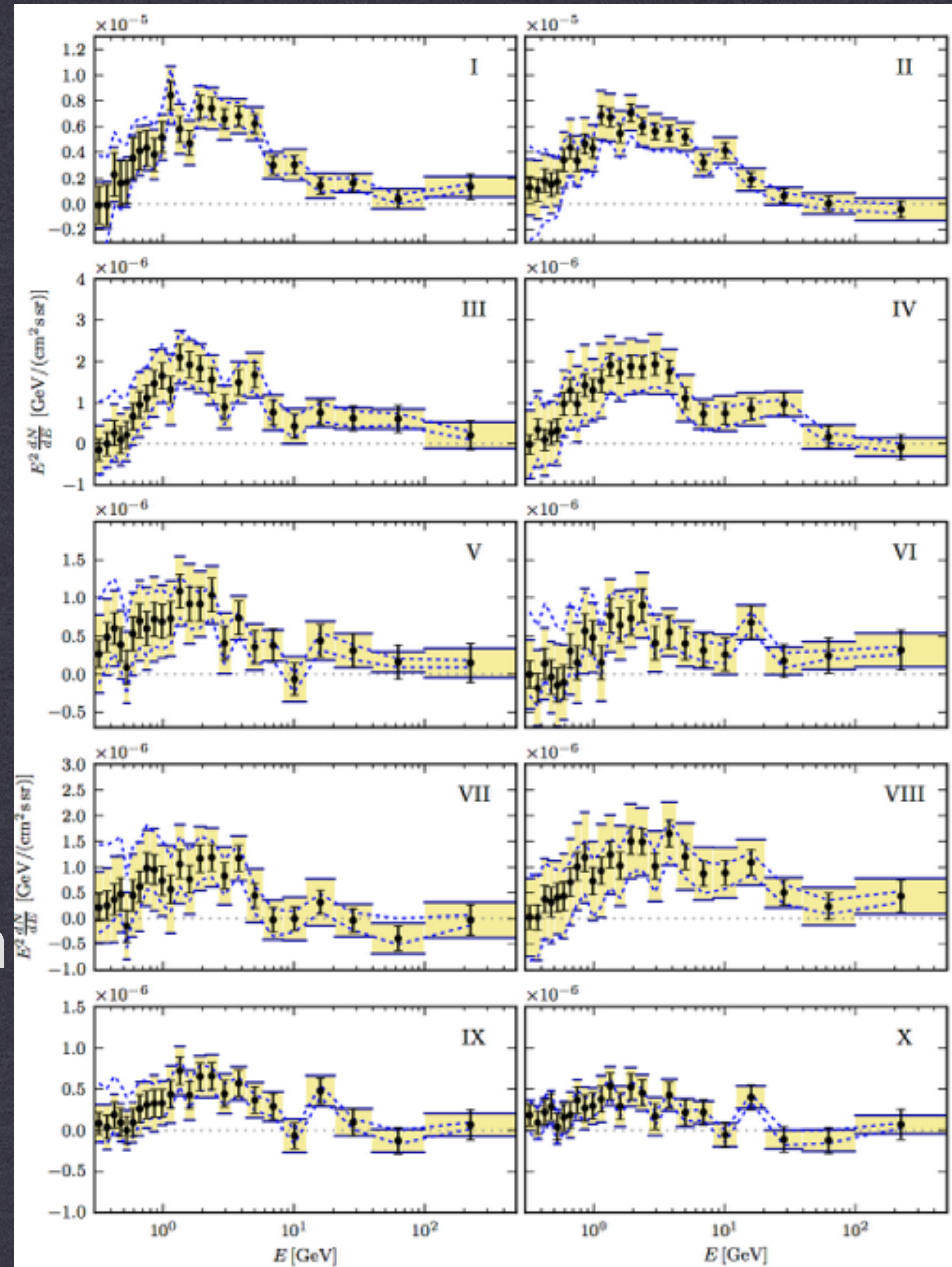


Inner galaxy prefers density profile $\gamma = 1.18$

Galactic Center prefers $\gamma = 1.17$

COMBINATION



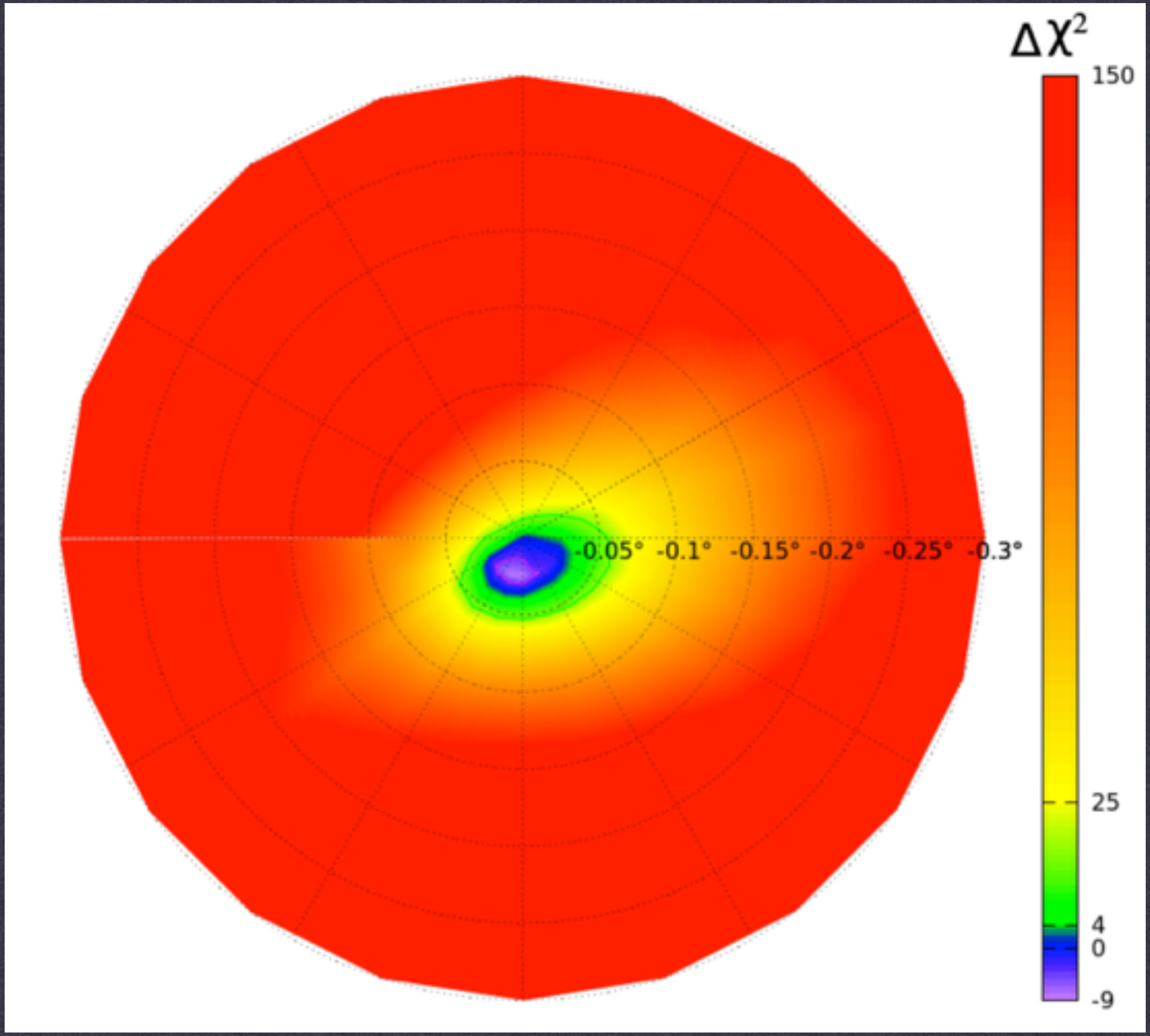


Calore et al (2014) also find evidence for excess emission in morphological bins that extend far from the GC.

Consistent spectrum!

CENTERED-NESS?

GALACTIC CENTER

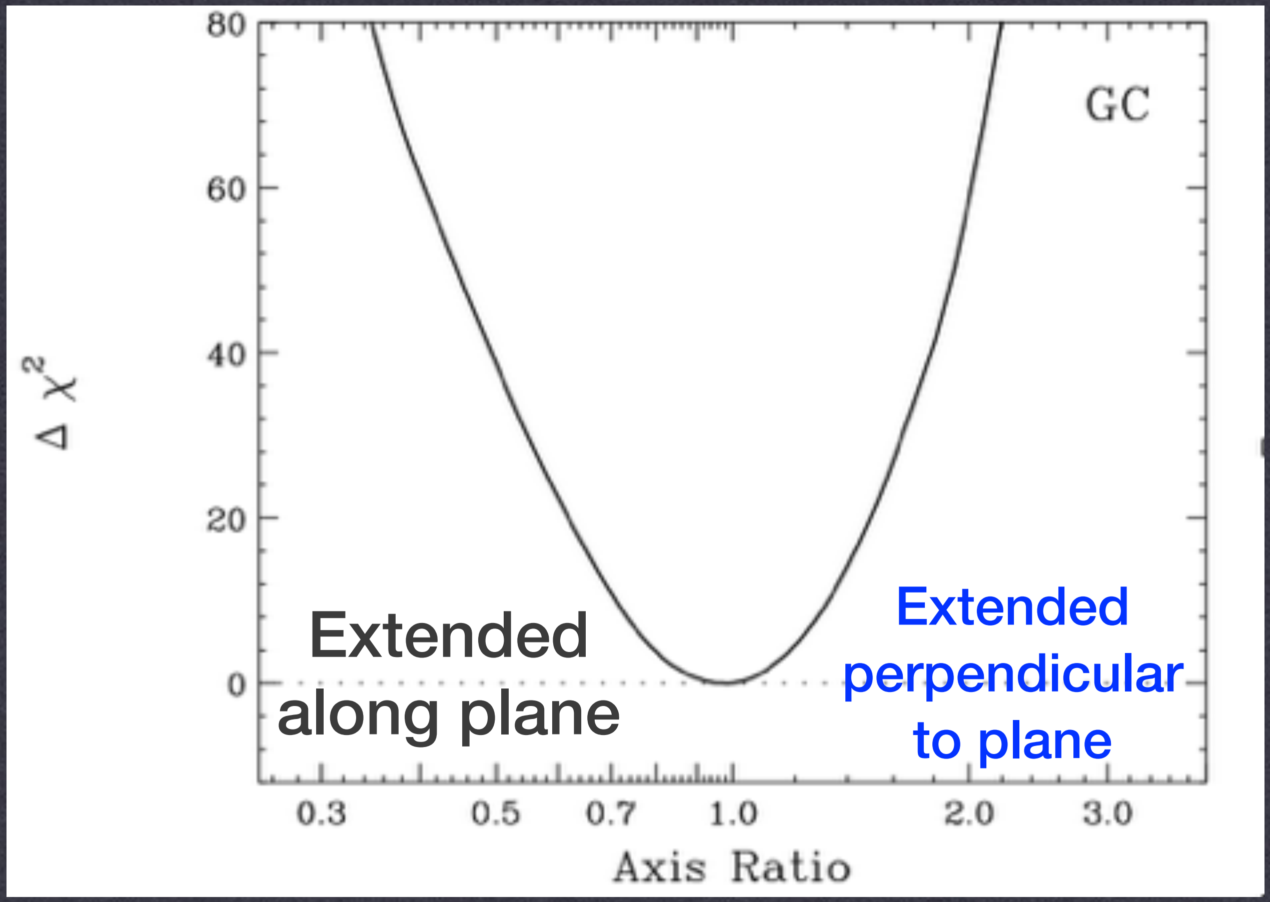


The center of the emission profile is located to within 0.05º of Sgr A*.

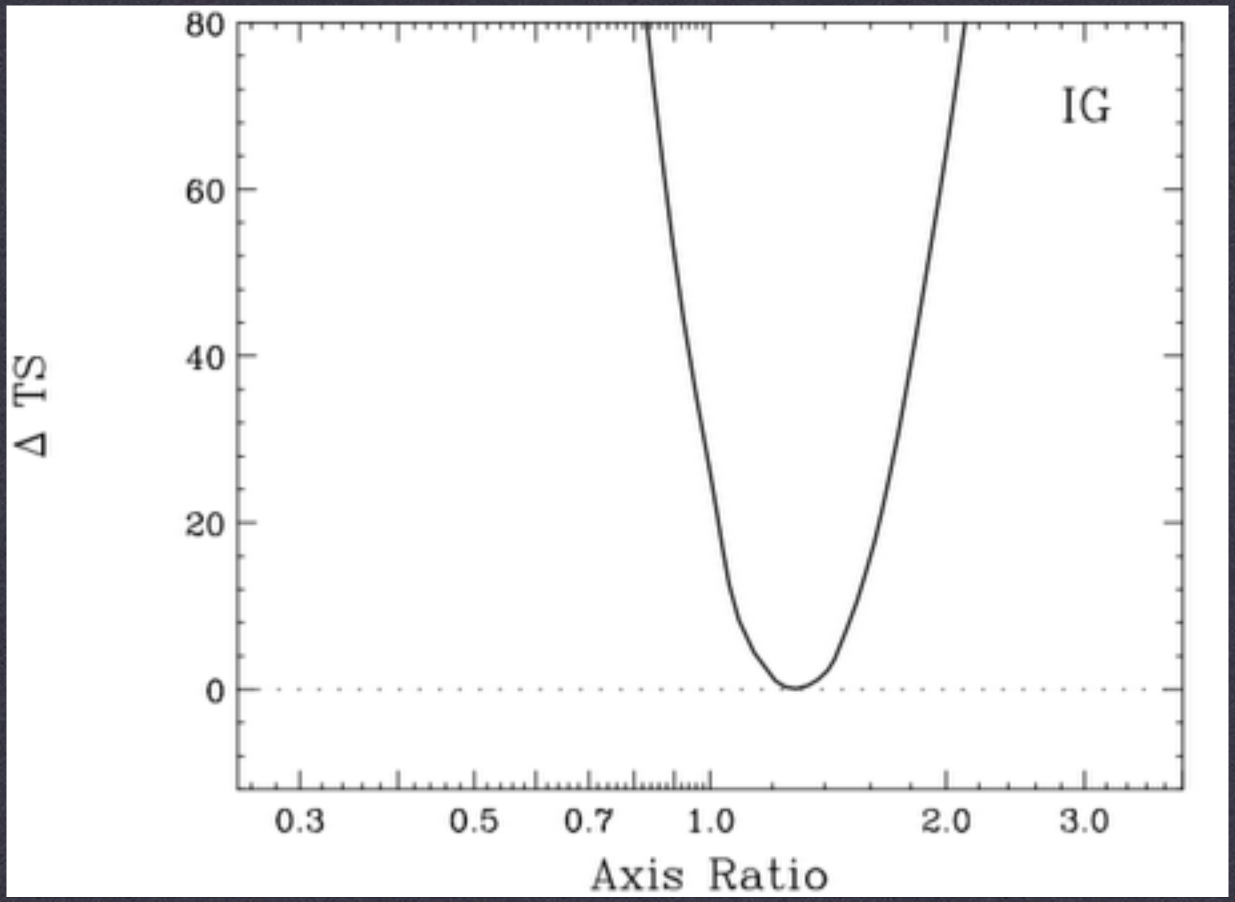
This disfavors Sgr A East as the source of the γ-ray excess (though only at 2σ).

ELLIPTICITY

GALACTIC CENTER



INNER GALAXY



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

CURRENT STATE OF MEASUREMENTS

<u>All</u> 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

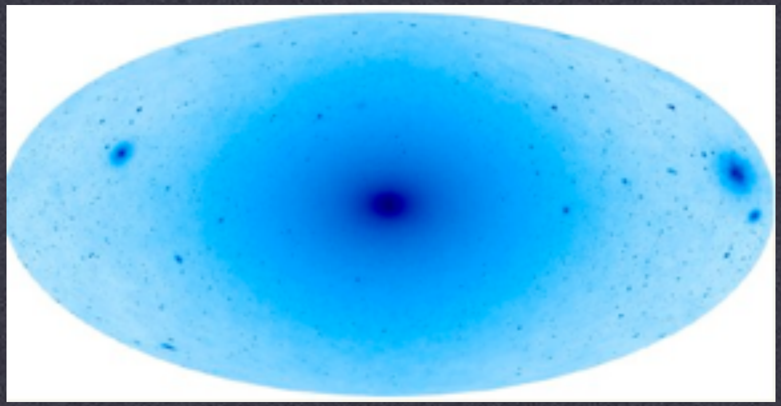
INTERPRETATIONS

Three Classes of Interpretations Have Been Proposed So Far:

1.) A Population of GC Millisecond Pulsars

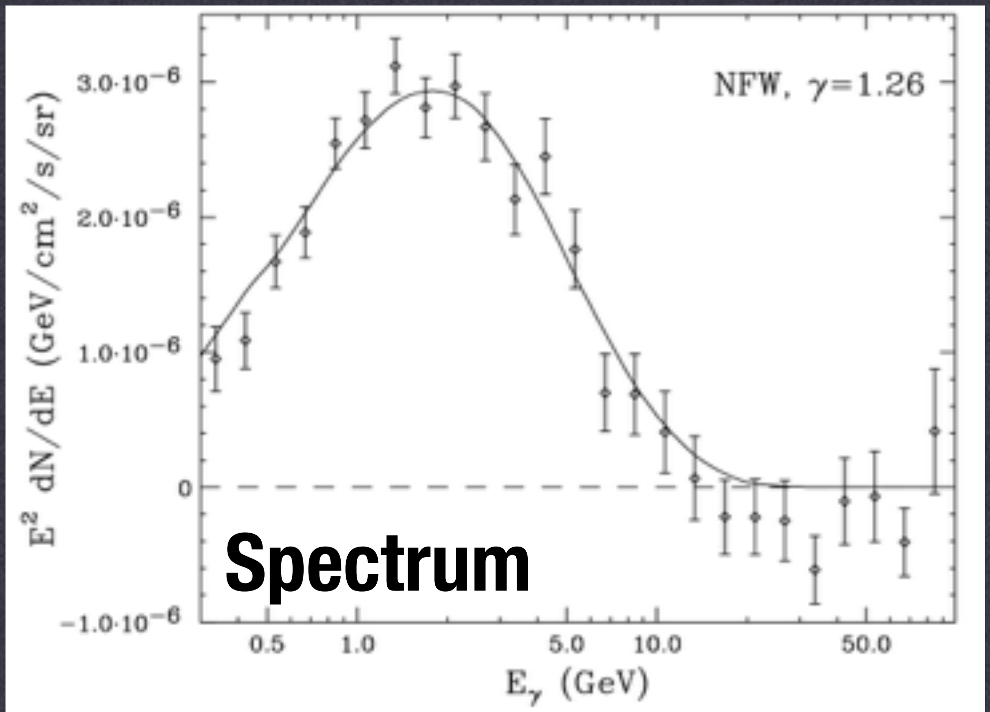
2.) An Outburst of Hadronic or Leptonic Emission from the Galactic Center

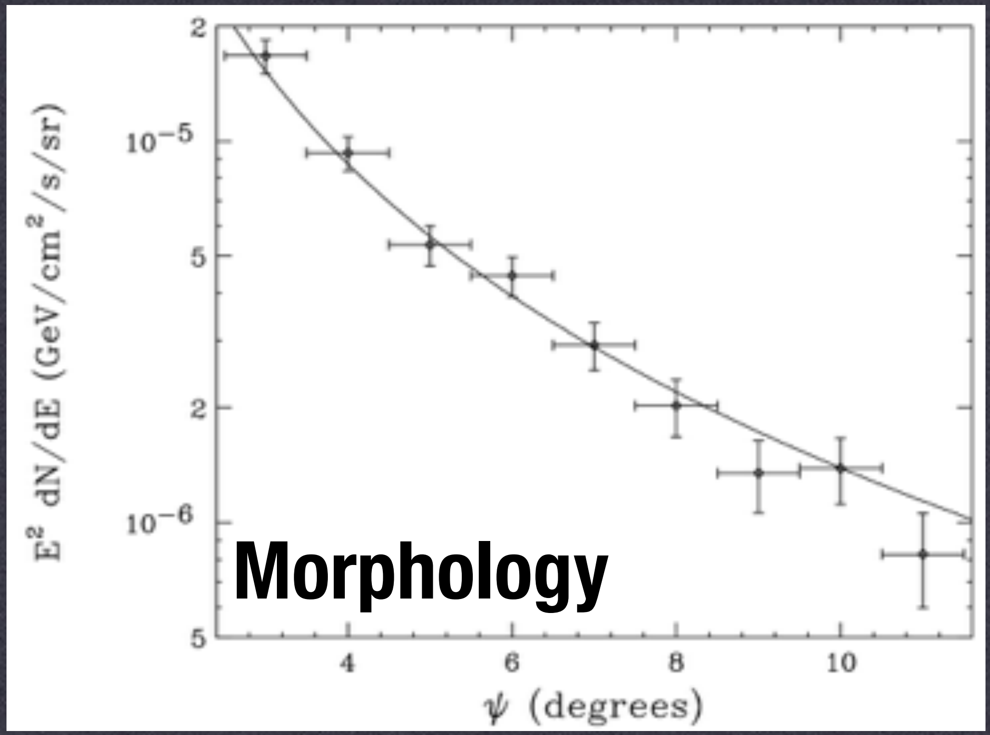
3.) Dark Matter Annihilation

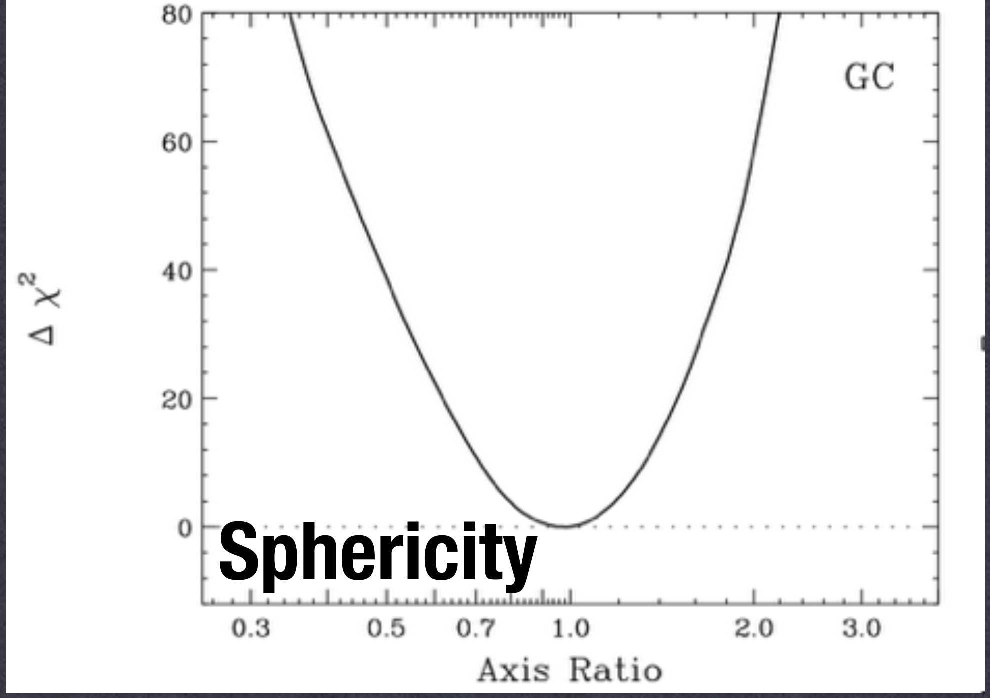


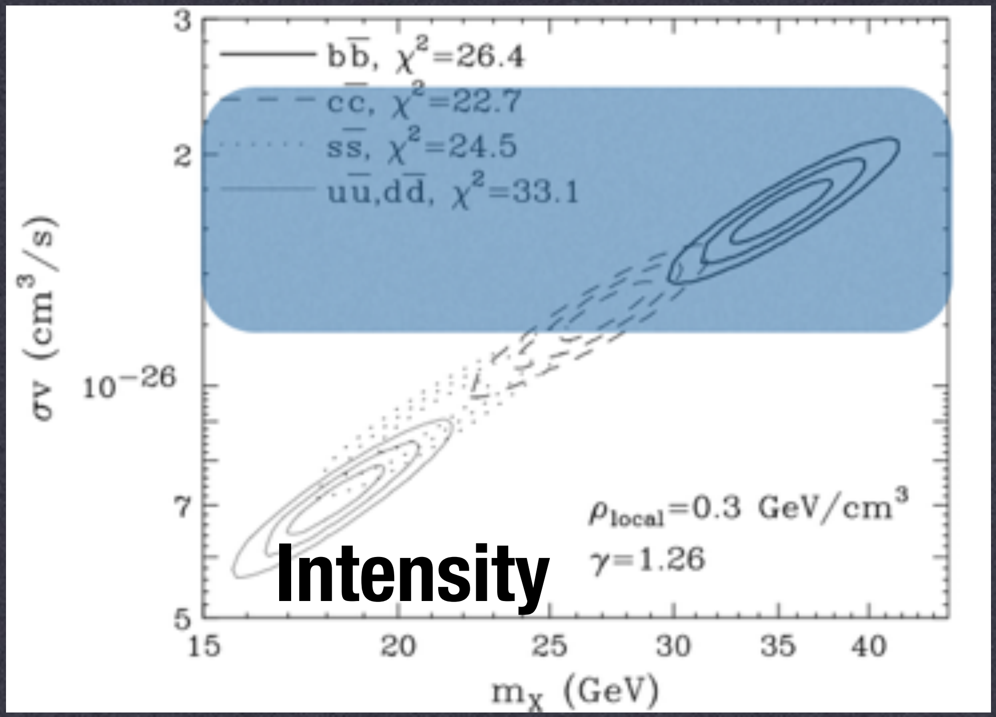
INTERPRETATIONS

DARK MATTER









WARNING

Everything after this slide is new and unpublished:

1.) Results may change

2.) Conclusions may shift

3.) My slide quality <u>will</u> rapidly deteriorate

INTERPRETATIONS

LEPTONIC OUTBURSTS

FERMILAB-PUB-15-255-A

PREPARED FOR SUBMISSION TO JCAP

Appearing Tonight!

The Galactic Center GeV Excess from a Series of Leptonic Cosmic-Ray Outbursts

Ilias Cholis[a] Carmelo Evoli[b] Francesca Calore[c] Tim Linden[d] Christoph Weniger[c] and Dan Hooper[a,e]

[a]Fermi National Accelerator Laboratory, Center for Particle Astrophysics, Batavia, IL 60510, USA

[b]Institüt für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, D-22761, Hamburg, Germany

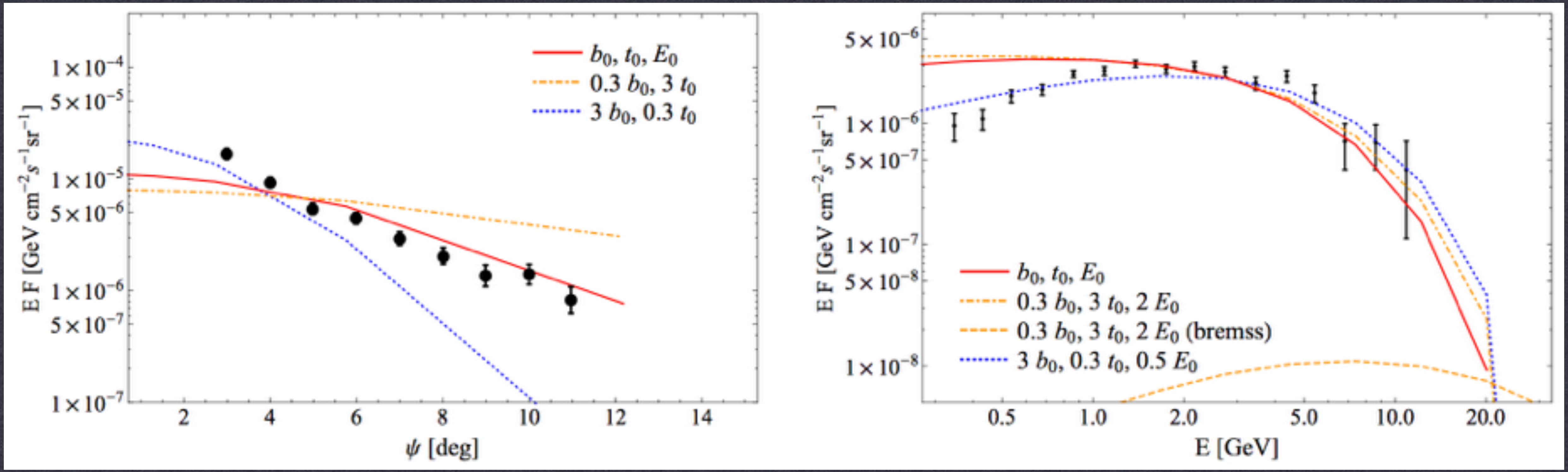
[c]GRAPPA, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, Netherlands

[d]University of Chicago, Kavli Institute for Cosmological Physics, 933 E. 56th St., Chicago, IL 60637 USA

[e]University of Chicago, Department of Astronomy and Astrophysics, 5640 S. Ellis Ave., Chicago, IL 60637 USA

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

LEPTONIC OUTBURSTS

New Goal:

1.) Use numerical methods in order to calculate the inverse-Compton scattering spectrum stemming from leptonic outbursts (Dragon, Galprop)

2.) Allow the diffusion coefficients, reacceleration models, Outburst Properties to vary

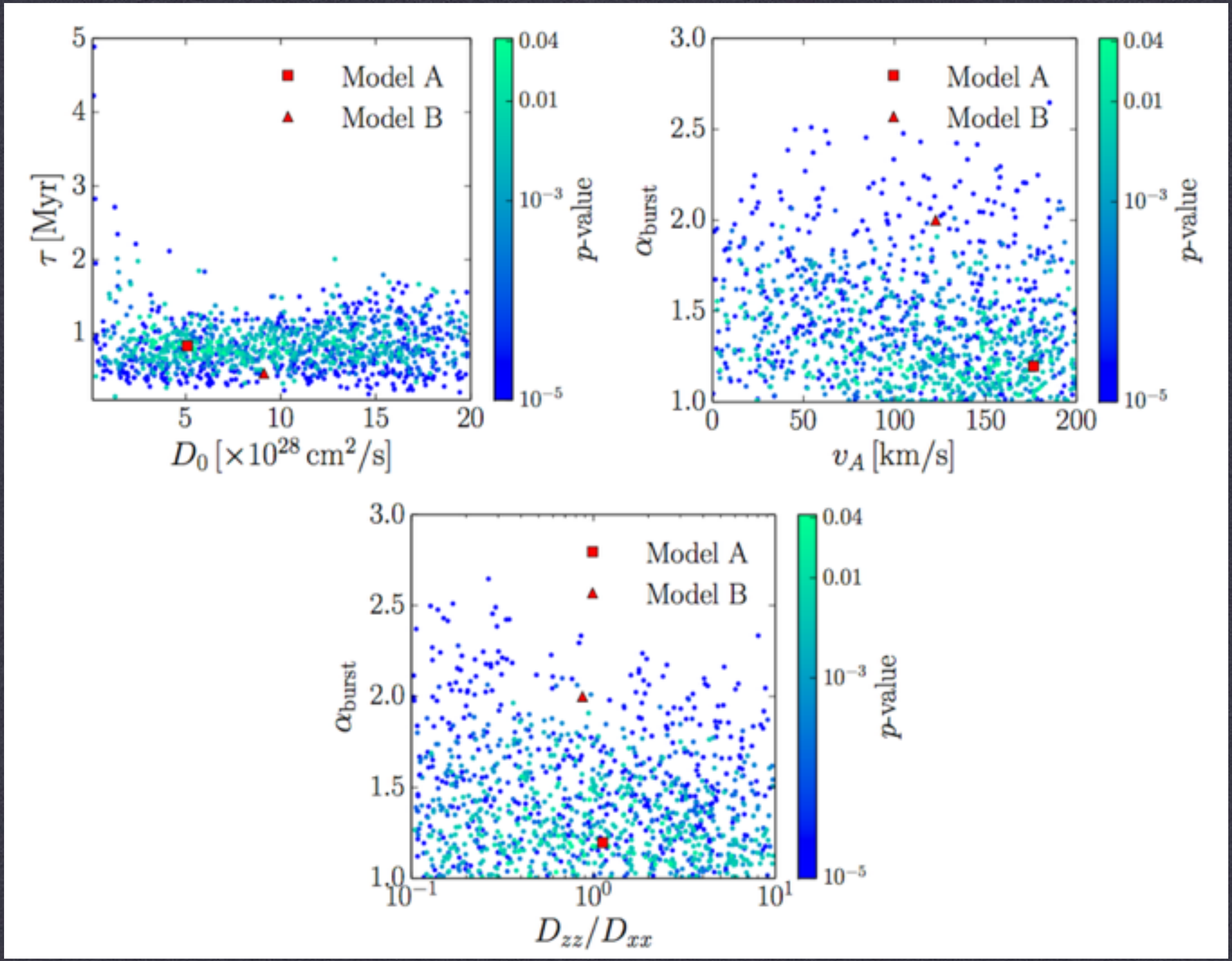
3.) Use MCMC Methods to systematically fit the excess in 10 spatial regions, comparing to Calore et al. (2014) and Daylan et al. (2014)

4.) Also consider two outburst models, with one burst 1 Myr old, and a second 100 kyr burst

CHOLIS ET AL. (2015)

LEPTONIC OUTBURSTS

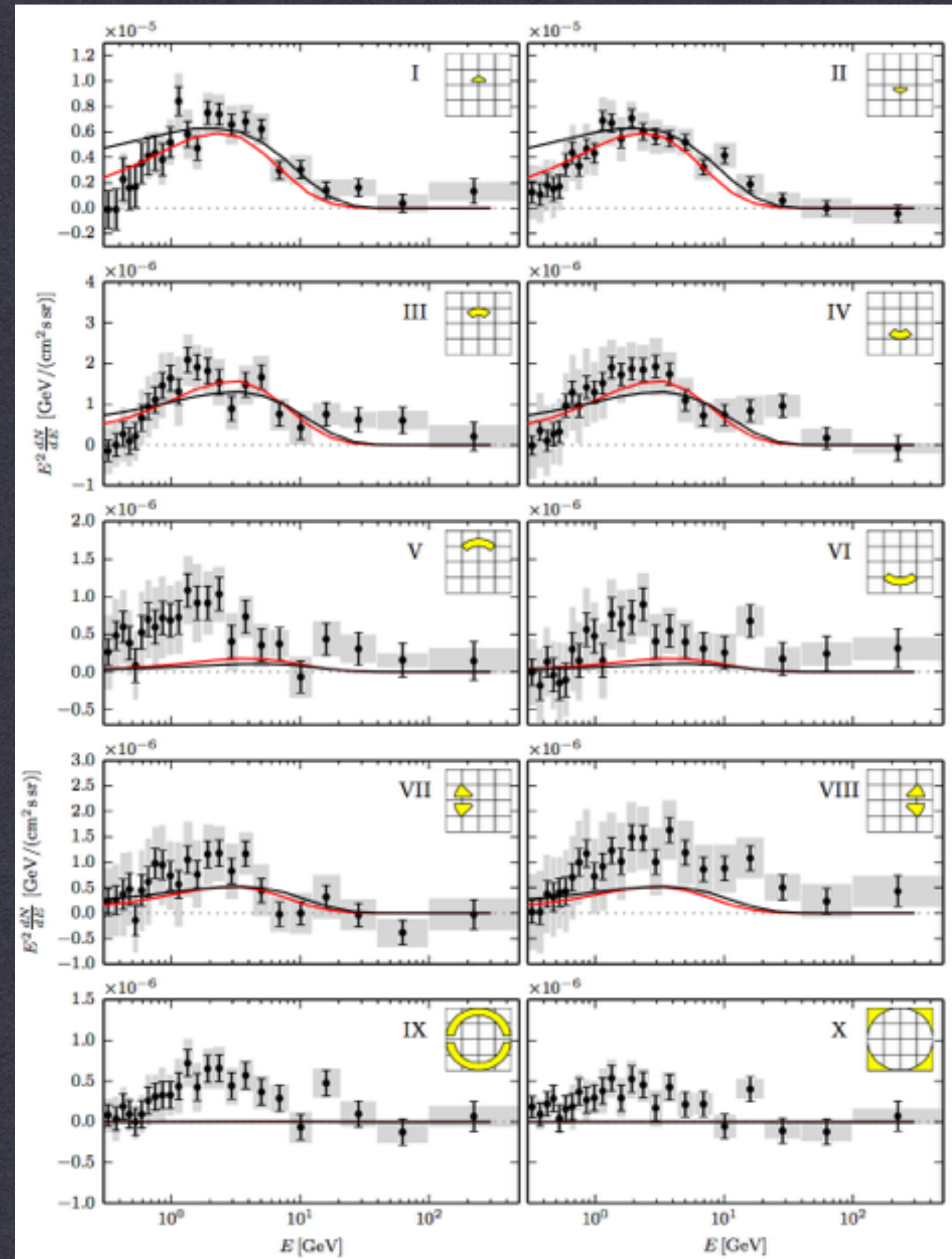
One Burst Models



CHOLIS ET AL. (2015)

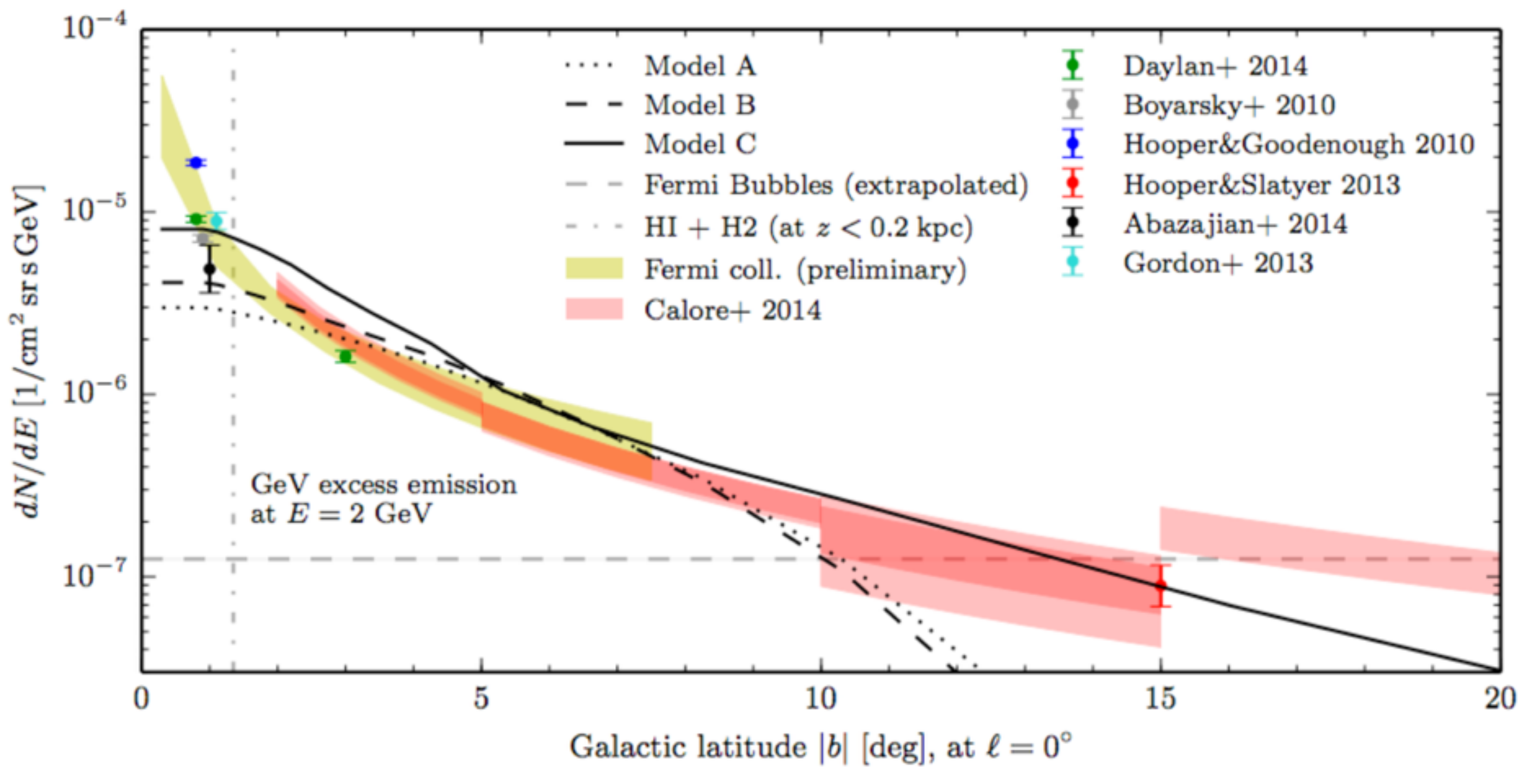
LEPTONIC OUTBURSTS

Parameter	Model A	Model B
α_1	1.2	2.0
α_2	NA	NA
$E_{\text{cut},1}$	1 TeV	1 TeV
$E_{\text{cut},2}$	NA	NA
τ_1 (Myr)	0.83	0.46
τ_2 (Myr)	NA	NA
N_1 (10^{51} erg)	2.89	9.87
N_2 (10^{51} erg)	NA	NA
δ	0.20	0.23
D_0 (10^{28} cm^2/s)	5.08	9.12
D_{zz}/D_{xx}	1.12	0.87
v_A (km/s)	176	122
B_0 (μG)	11.5	11.5
r_c (kpc)	10.0	10.0
z_c (kpc)	2.0	2.0
dv_c/dz (km/s/kpc)	0.0	0.0
ISRF	1.0, 1.0	1.0, 1.0
χ^2 ($p-$value)	277 (0.04)	317 (0.0004)



CHOLIS ET AL. (2015)

LEPTONIC OUTBURSTS



CHOLIS ET AL. (2015)

LEPTONIC OUTBURSTS

CONCLUSIONS

1.) Leptonic Outbursts are Capable of producing reasonable fits to the key parameters of the GeV Excess, a combination of two outbursts seems sufficient to match the intensity of the excess from 1-15^{o} from the GC.

2.) The outbursts can produce emission that is roughly spherically symmetric.

3.) The history of our galaxy is likely to have many such outbursts.

4.) The injection spectrum for such an outbursts must be extremely hard (compared say, to observed blazar electron injection spectra).

5.) The intensity and spectral changes of the outbursts must be carefully chosen in order to avoid spectral or morphological distortions.

6.) A new mechanism (or a third outburst) is still necessary in order to explain the inner degree around the GC.

CHOLIS ET AL. (2015)

DIFFUSE MODELING

New Goal:

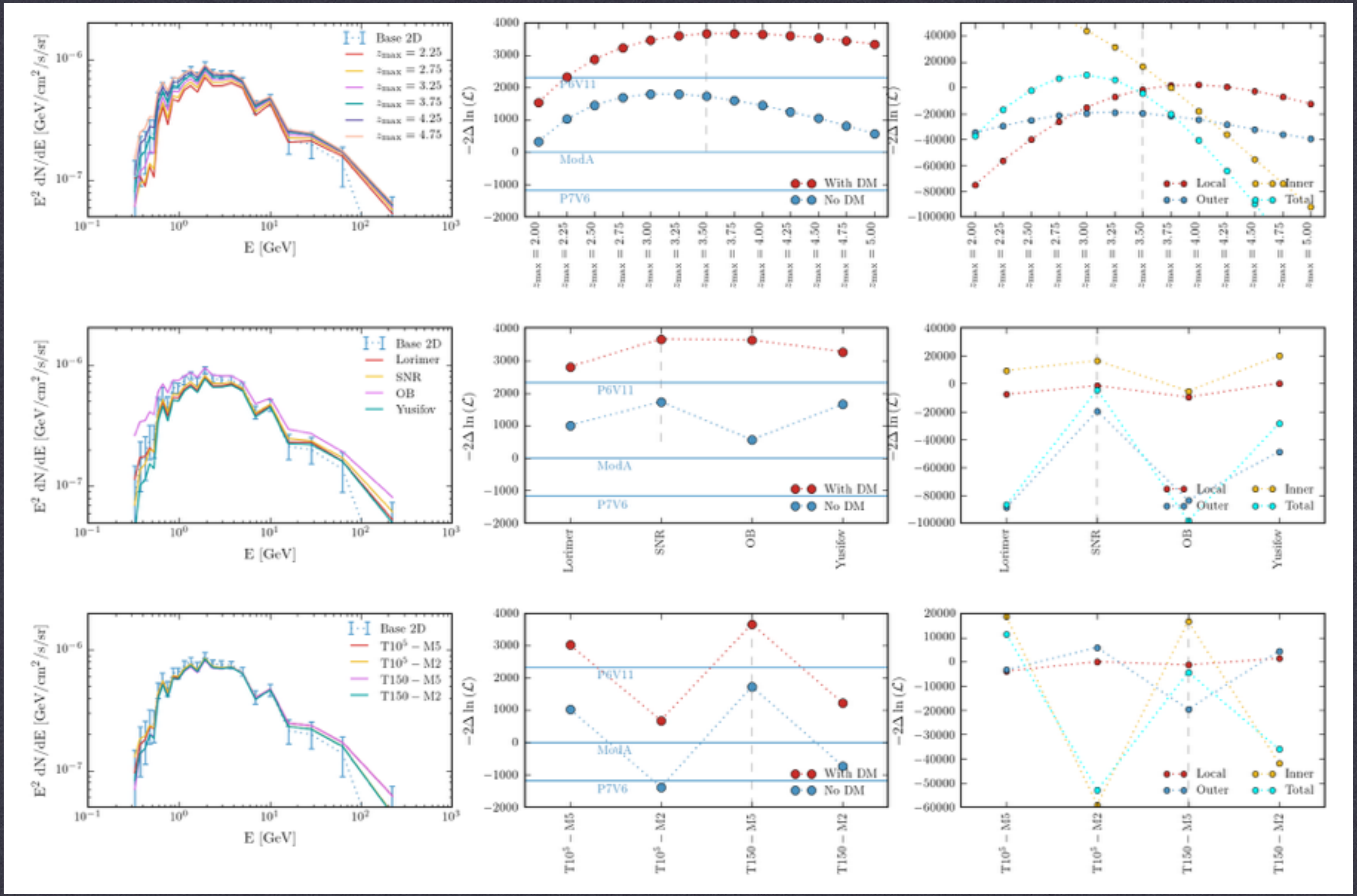
1.) Fermi Diffuse Models are not optimized for the Galactic Center Region

2.) Build new models of diffuse emission that fit the GC Region Better, and see how these affect the parameters of the GeV excess

3.) Utilize 3D Galprop models, new models for ionized and molecular gas, and new particle injection morphologies

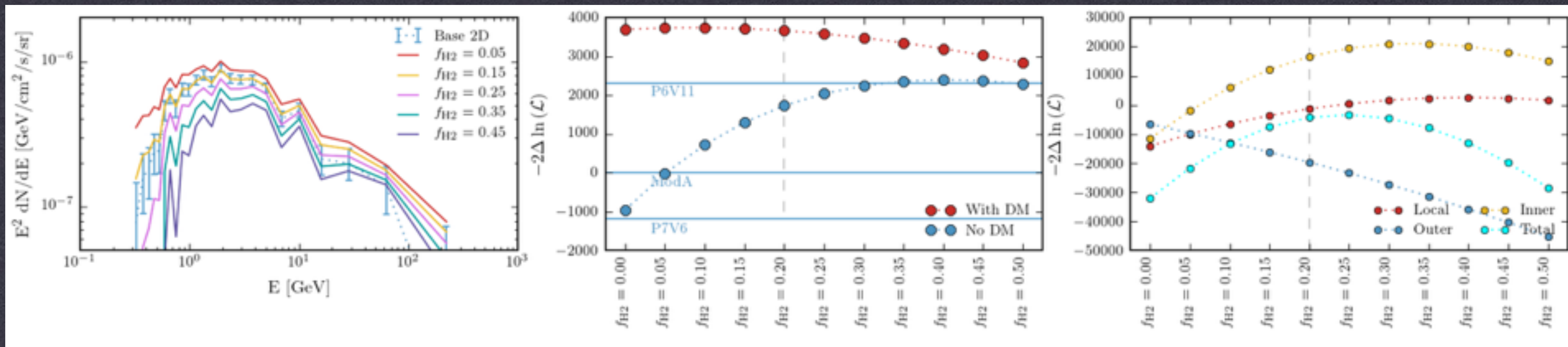
CARLSON ET AL. (2015)

DIFFUSE MODELING



CARLSON ET AL. (2015)

DIFFUSE MODELING

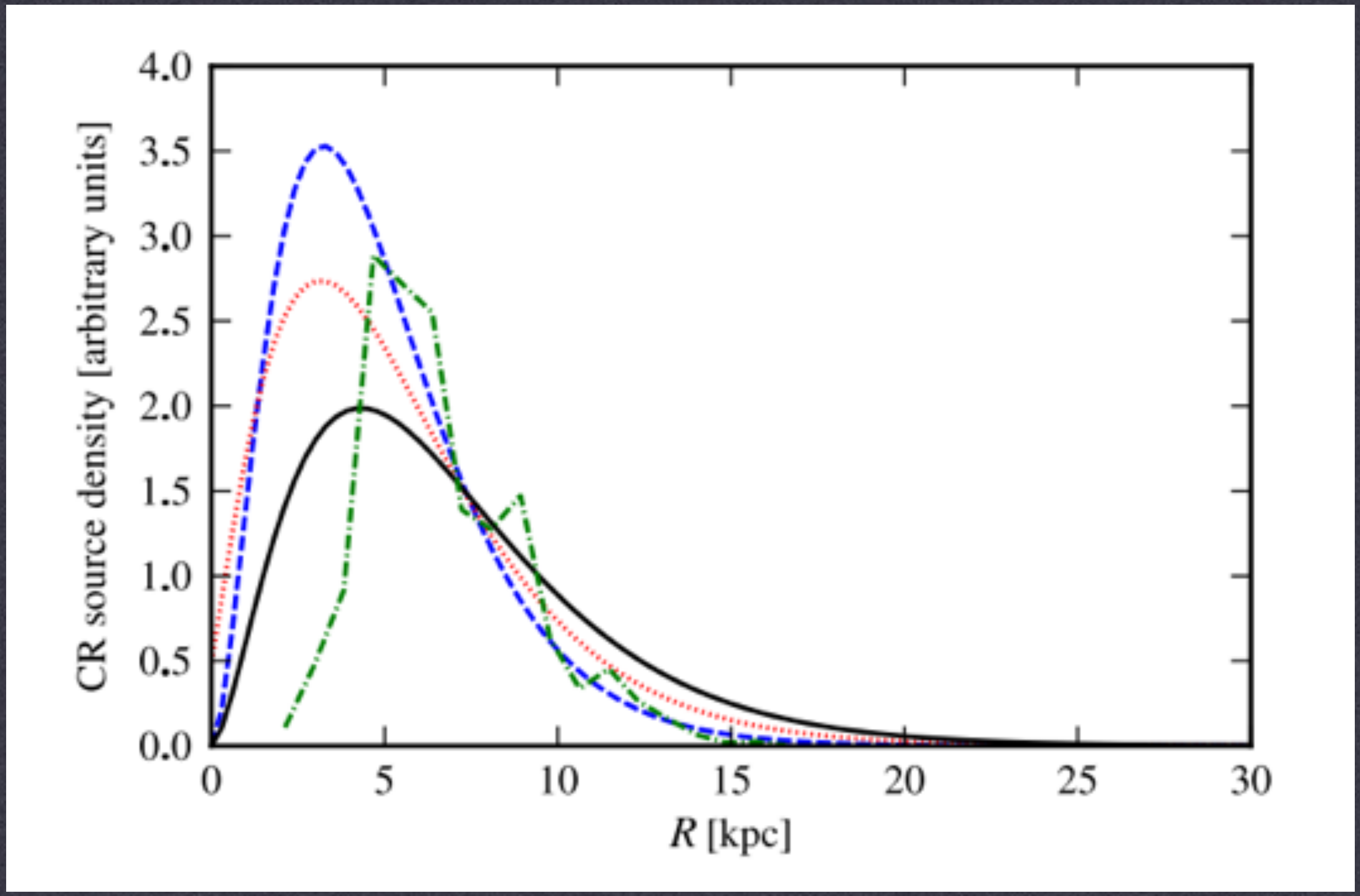


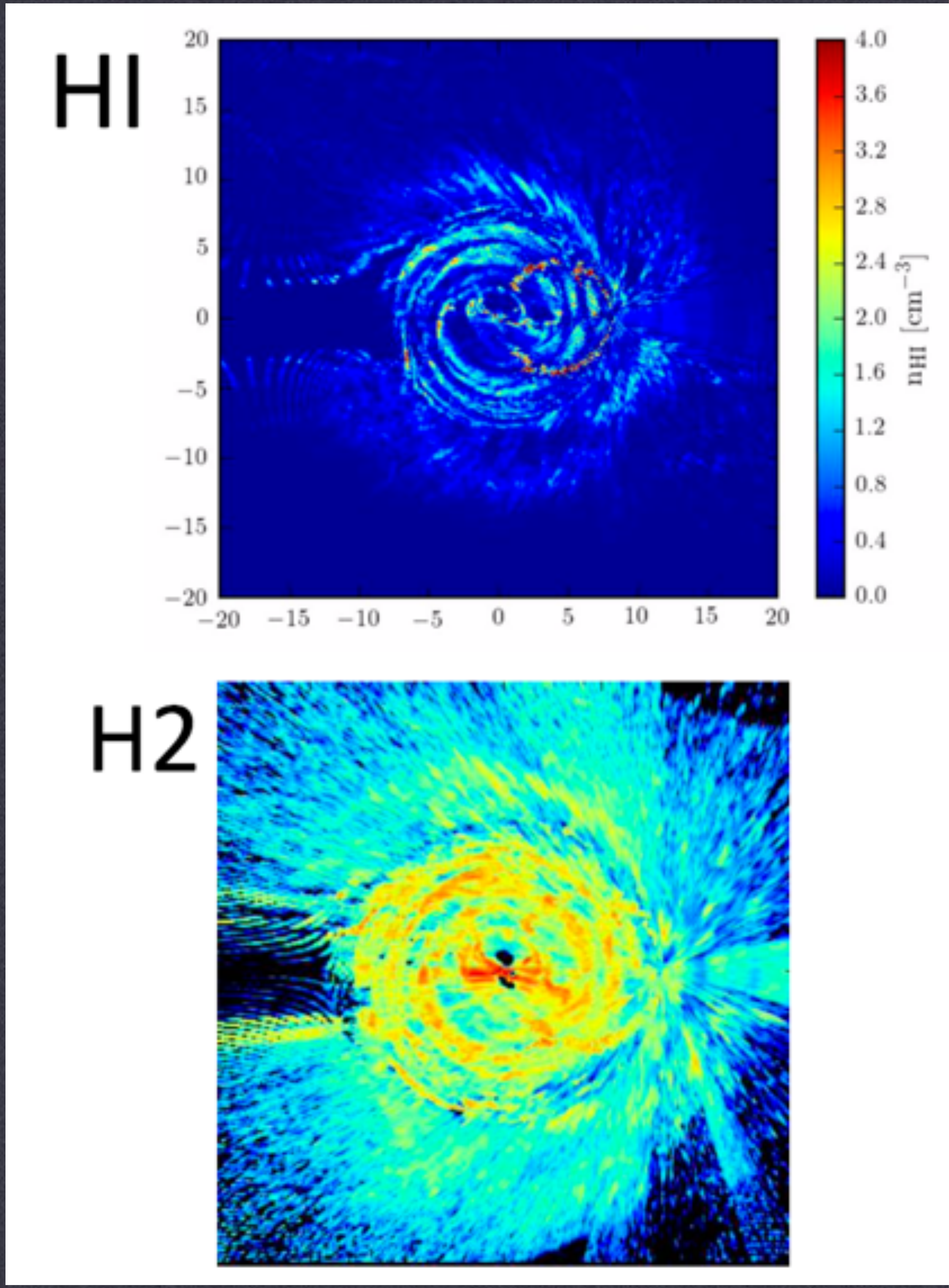
1.) One modification that does appear to greatly affect the excess is the fraction of emission which traces the H2 density, rather than the pulsar or OB star density

2.) This is a reasonable physical model, since star formation traces H2

CARLSON ET AL. (2015)

DIFFUSE MODELING

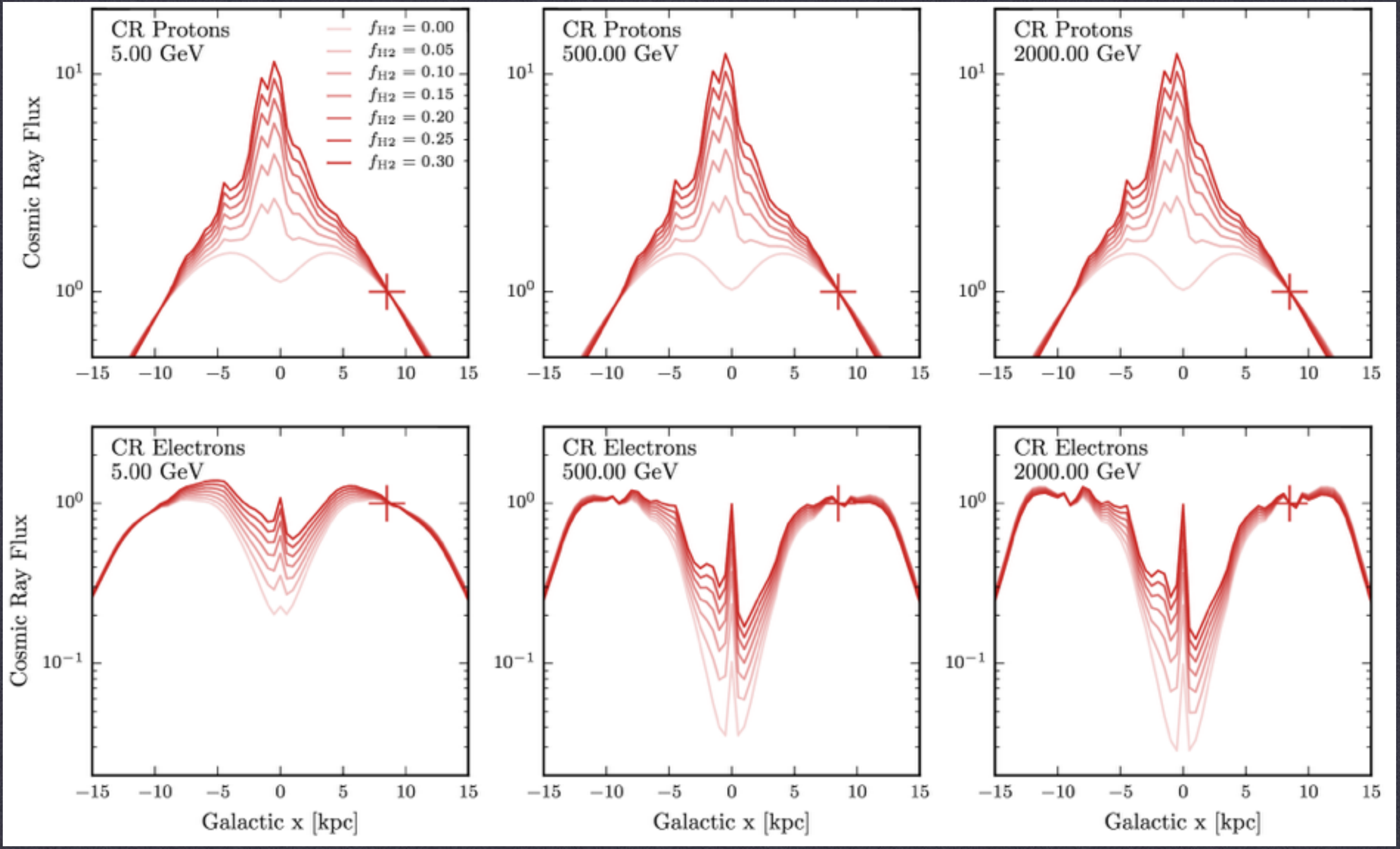




OB and Pulsar Models have very little emission near the GC, H1 and H2 maps provide significantly more flux in this region

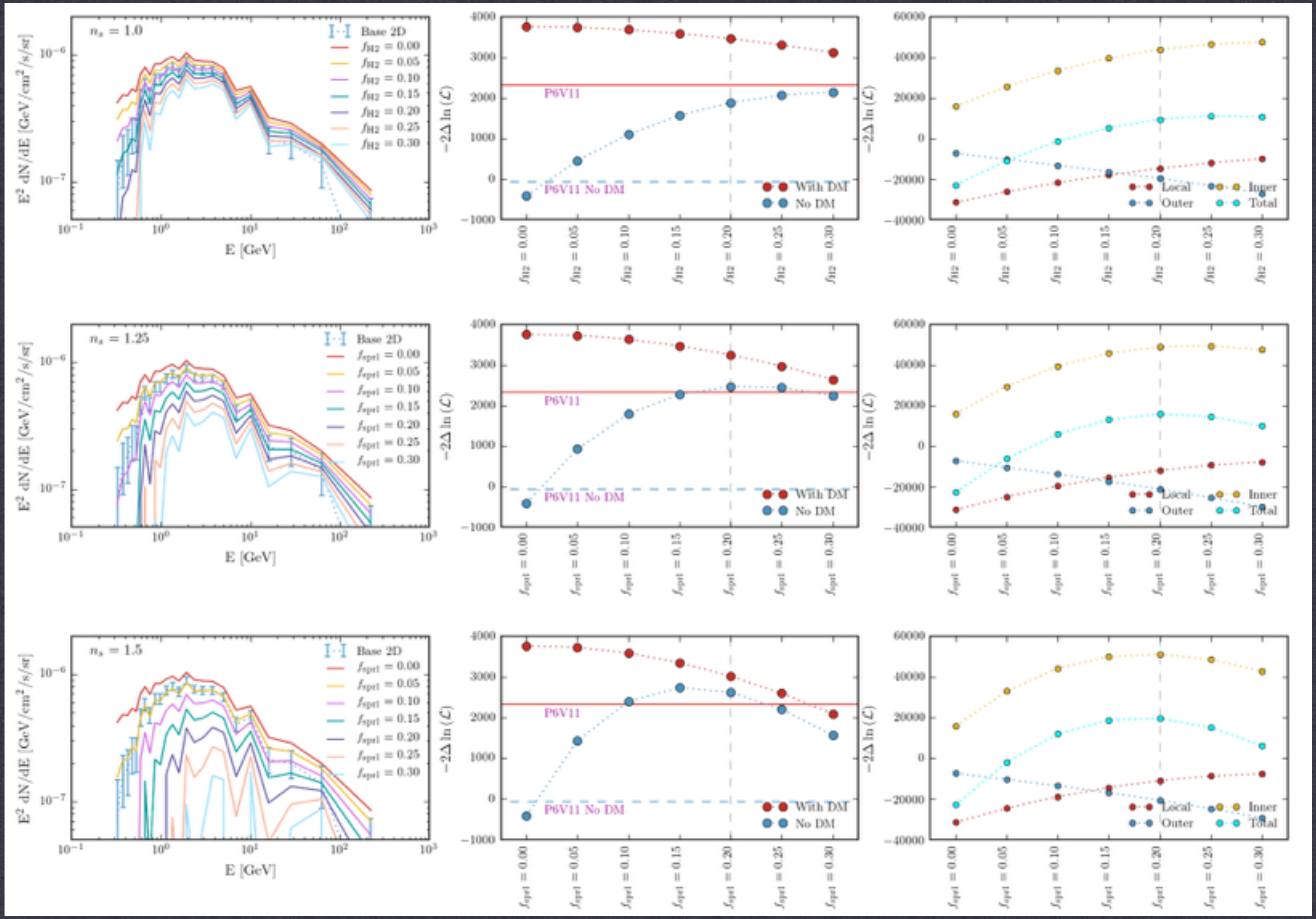
CARLSON ET AL. (2015)

DIFFUSE MODELING



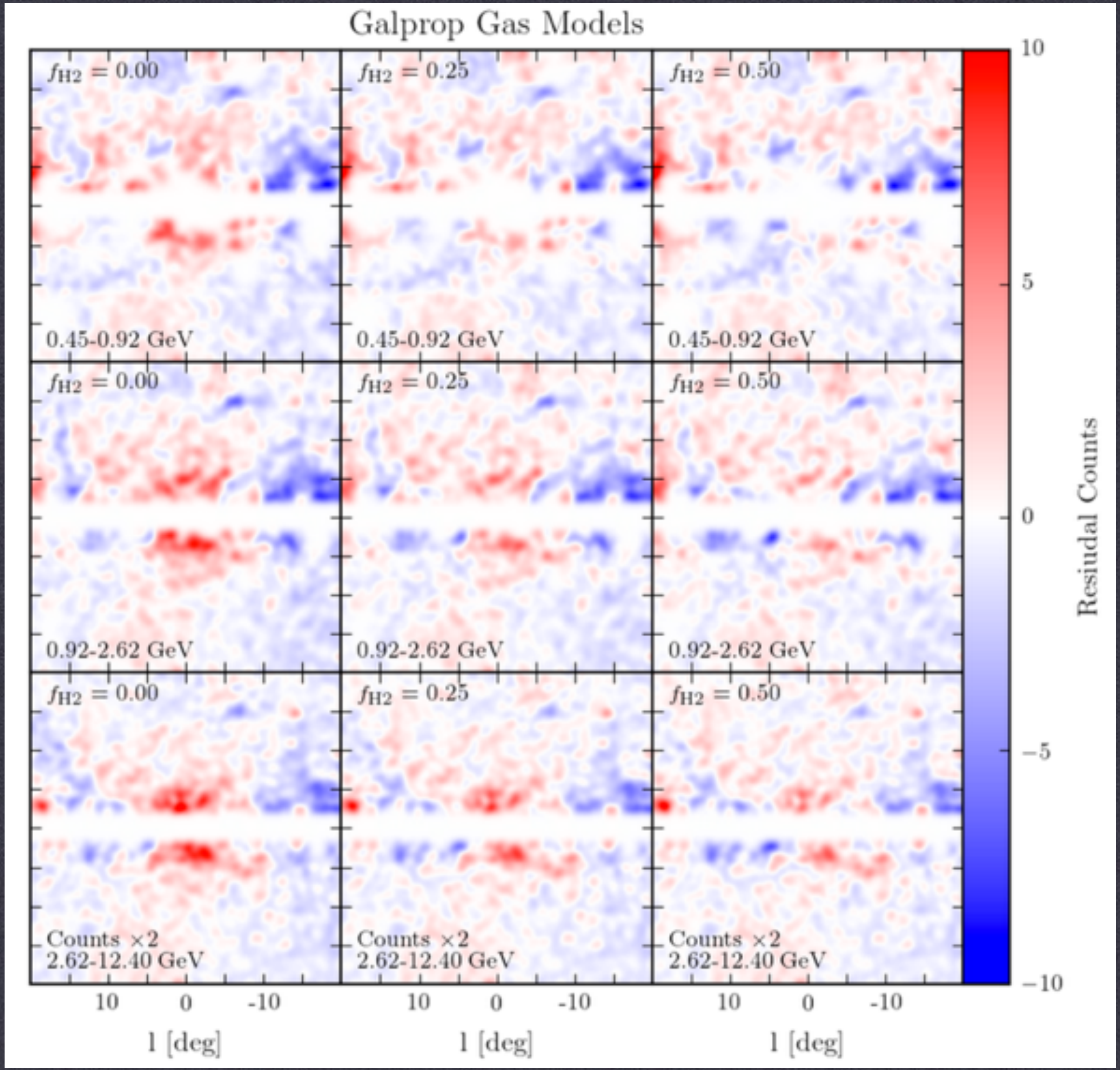
CARLSON ET AL. (2015)

DIFFUSE MODELING



Can float the correlation between gas density and the proton injection rate. n_s = 1.5 is predicted by the Kennicutt-Schmidt Relation

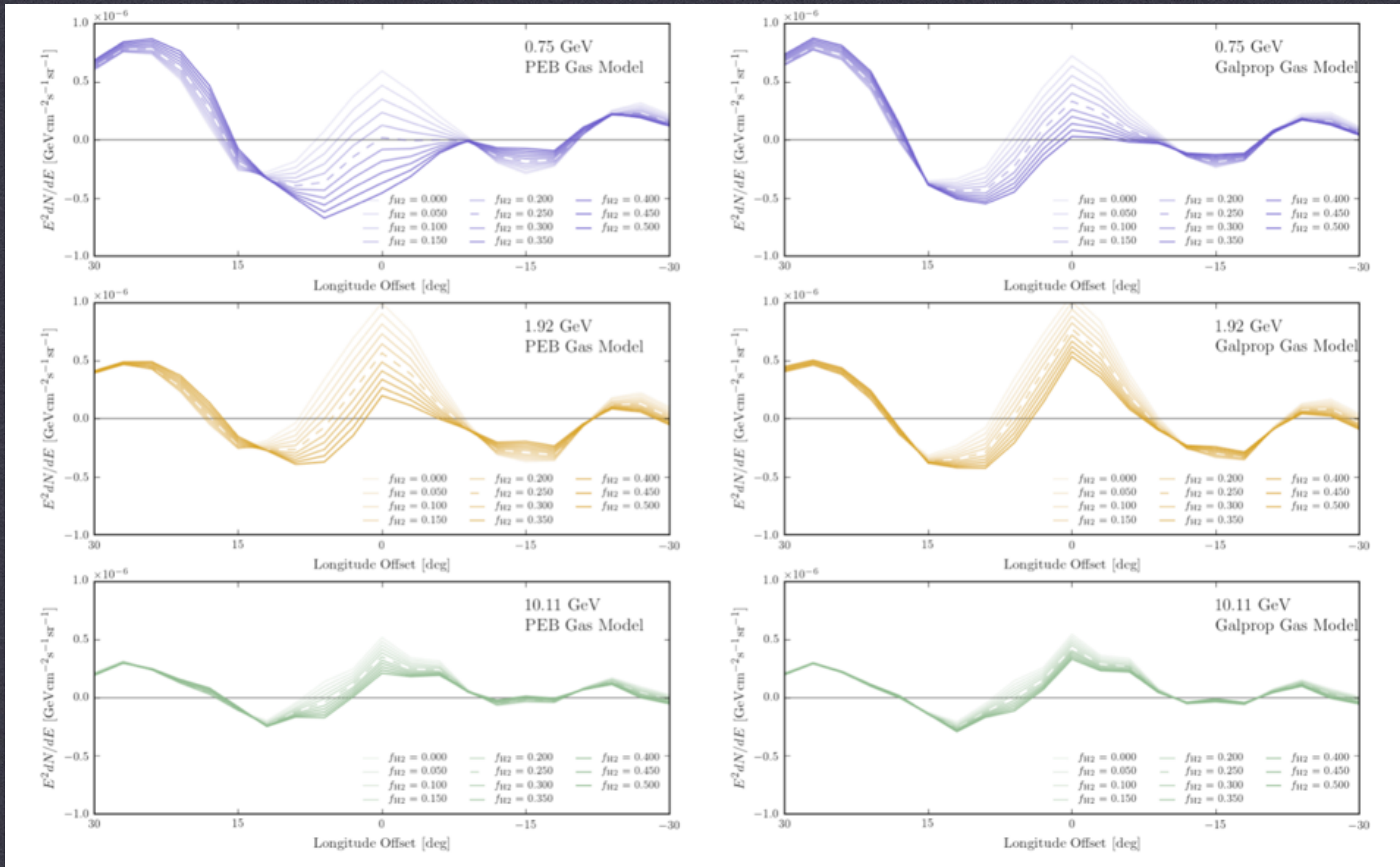
DIFFUSE MODELING



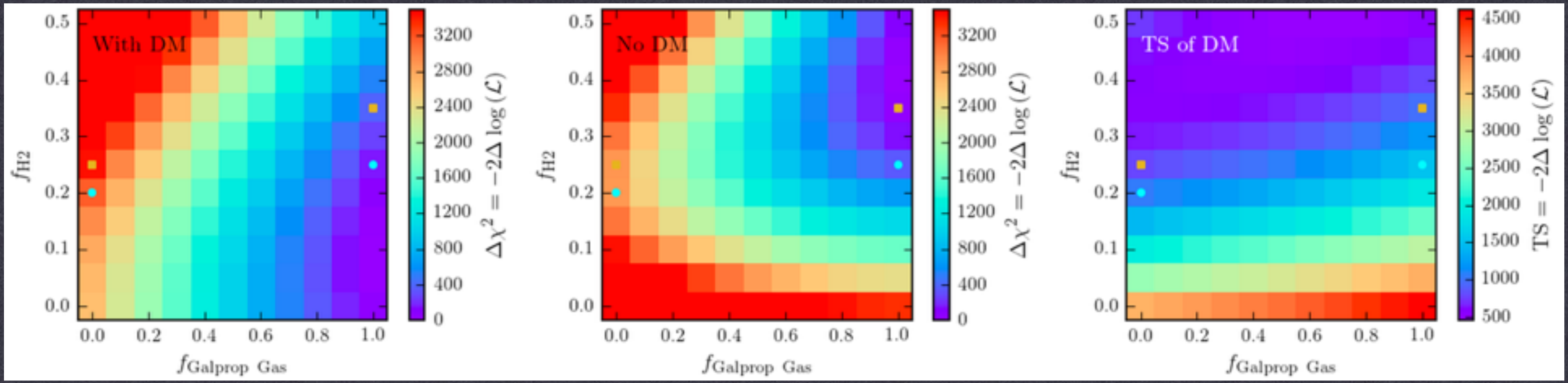
This does have the effect of decreasing the residuals which are usually attributed to the GC excess.

At the very least, it is fair to say that f_H2 is degenerate with the GeV Excess template

DIFFUSE MODELING



DIFFUSE MODELING



However when given the following choices:

1.) Allow f_H2 to float to high values

2.) Allow for an NFW template

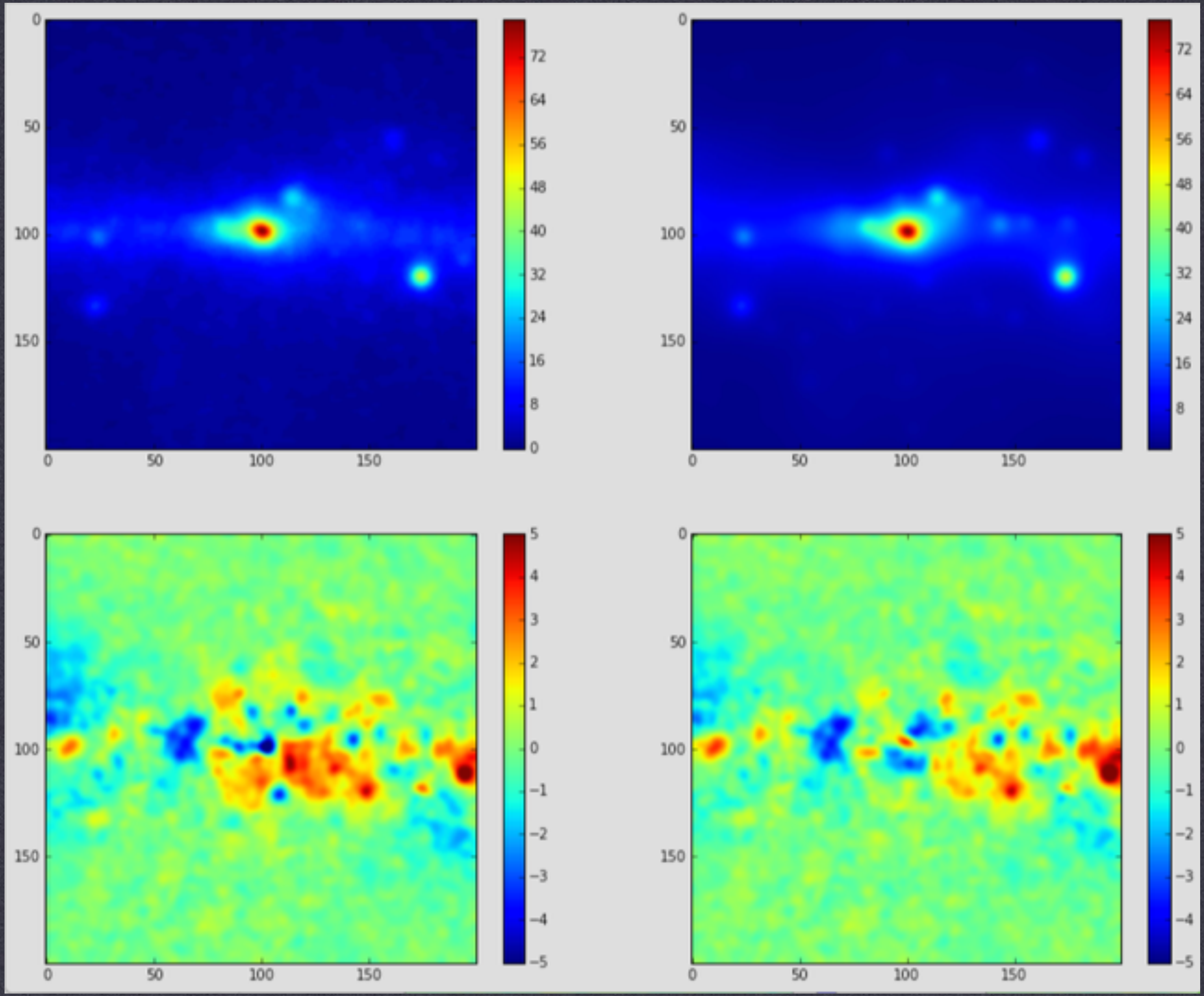
The NFW template is preferred, with f_H2 = 0 in the Inner Galaxy

CARLSON ET AL. (2015)

DIFFUSE MODELING

The NFW template is also still strongly preferred in the GC region (10ºx10º)

In fact, profiles with f_H2 in this region increase the significance of the NFW template



CARLSON ET AL. (2015)

DIFFUSE MODELING

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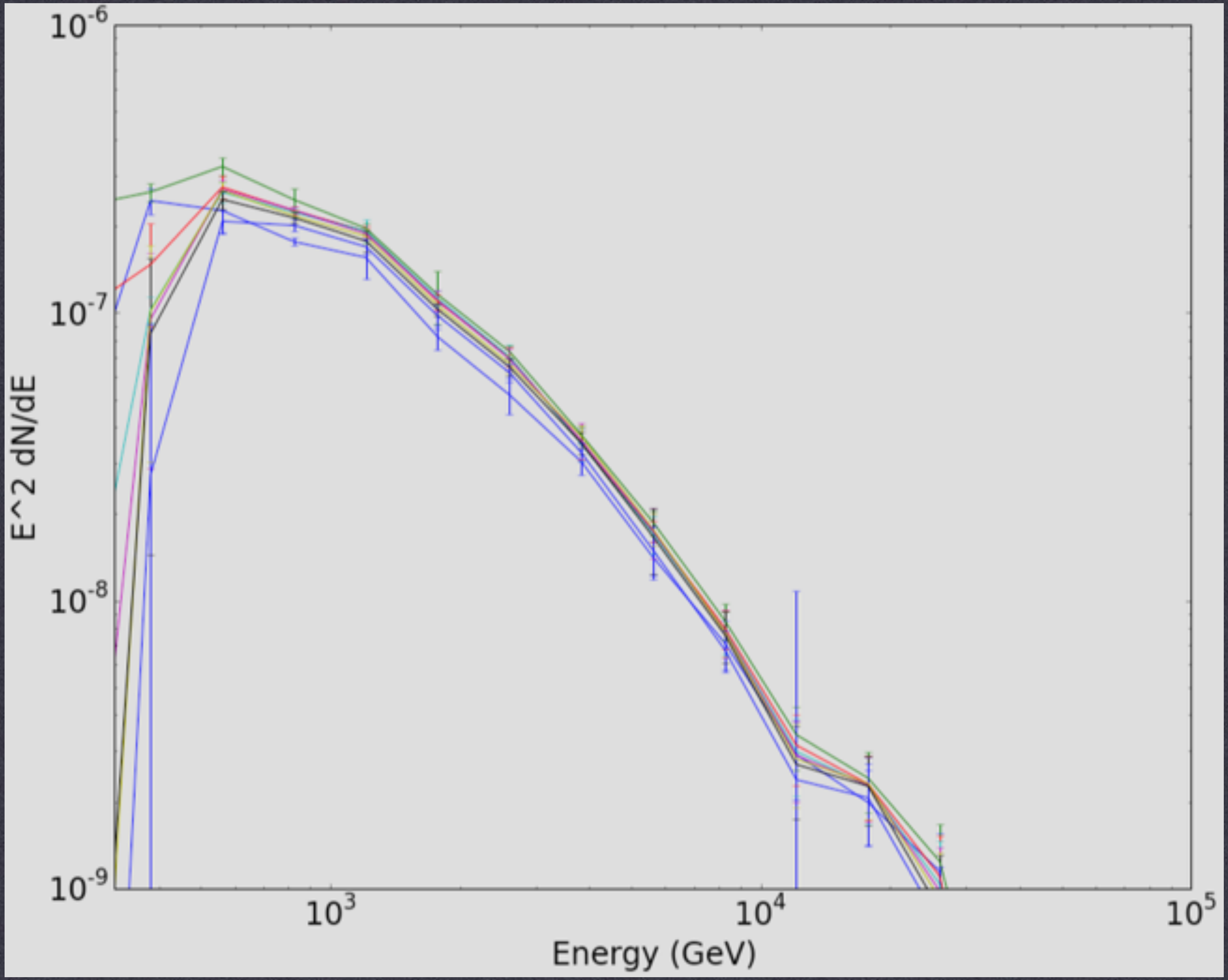


CARLSON ET AL. (2015)

DIFFUSE MODELING

1.) Adding a cosmic-ray injection source tracing the H2 density is theoretically motivated, and leads to much better fits for the entire diffuse sky.

2.) This also adds significant hadronic emission in the IG region, and appears roughly degenerate with the NFW template, taking a high value for H2 as a prior, the significant of GeV excess is significantly reduced.

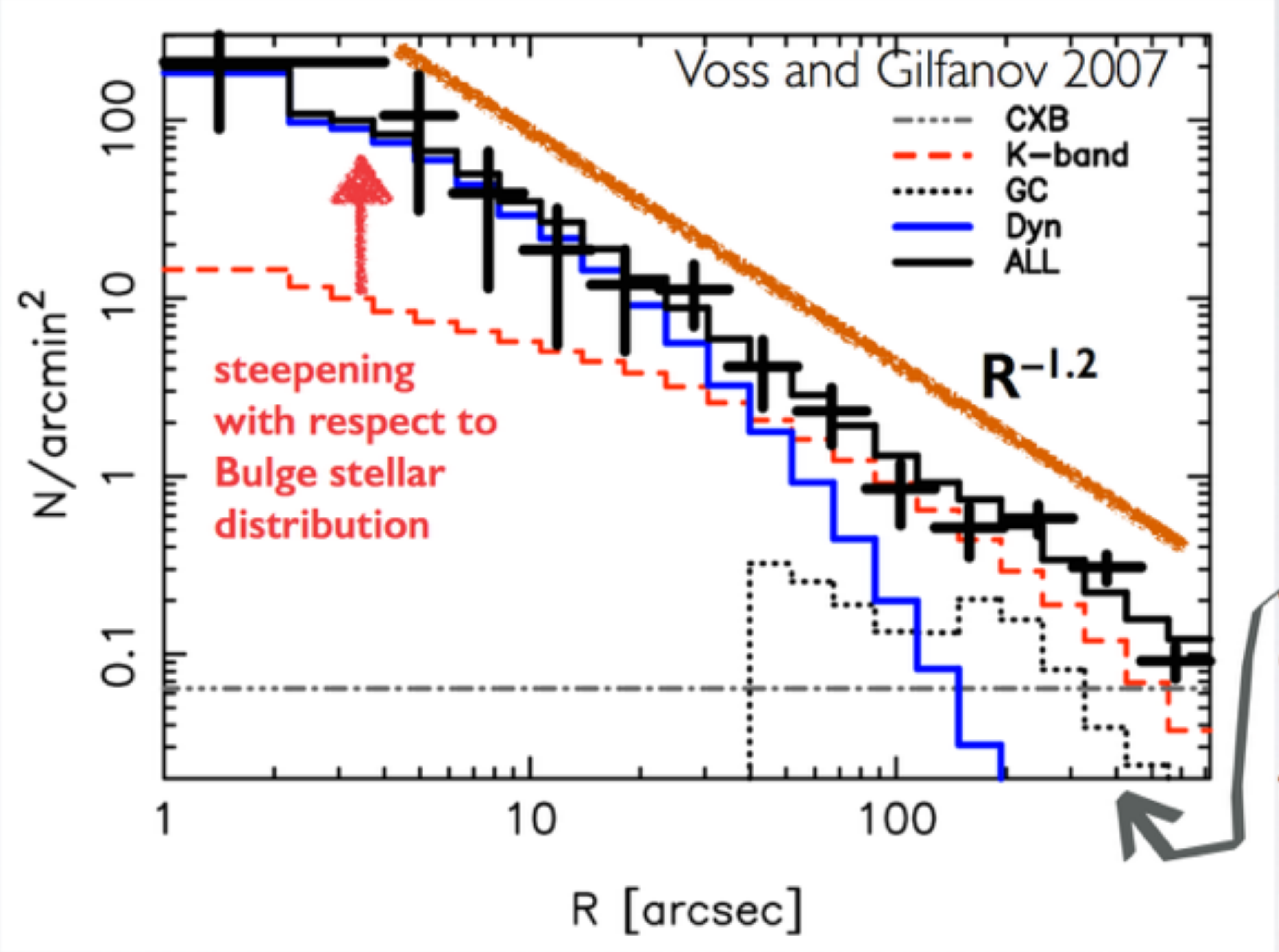
3.) However, if you ask the fit whether it prefers a spherically symmetric NFW template or cosmic-ray injection which traces H2, the NFW profile is preferred and the fraction of sources tracing H2 goes to 0.

4.) Furthermore, the current models offer poor fits to the GC region, where the NFW profile actually becomes more preferred than for default Fermi Diffuse models.

CARLSON ET AL. (2015)

MILLISECOND PULSARS

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

MILLISECOND PULSARS

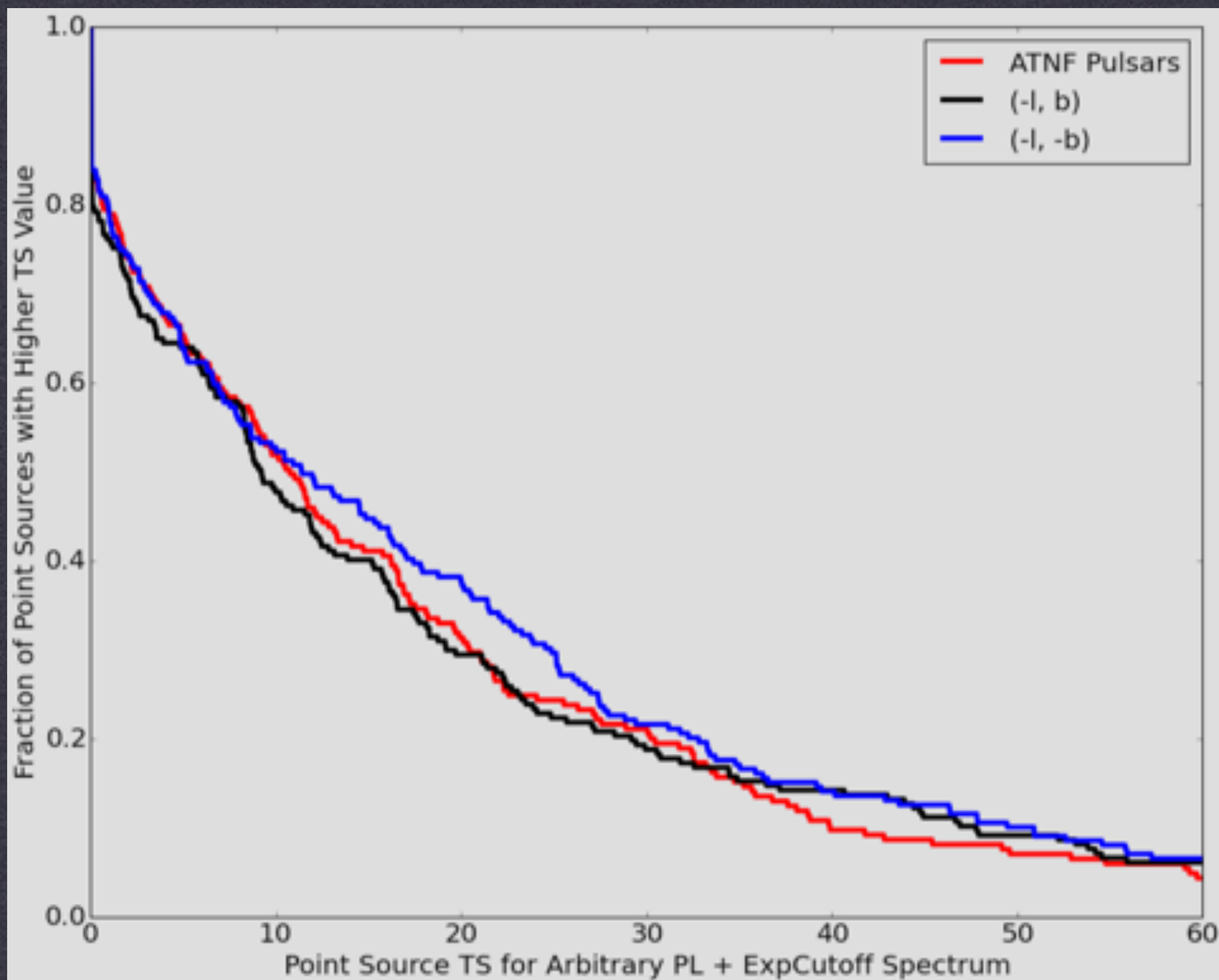
Methodology:

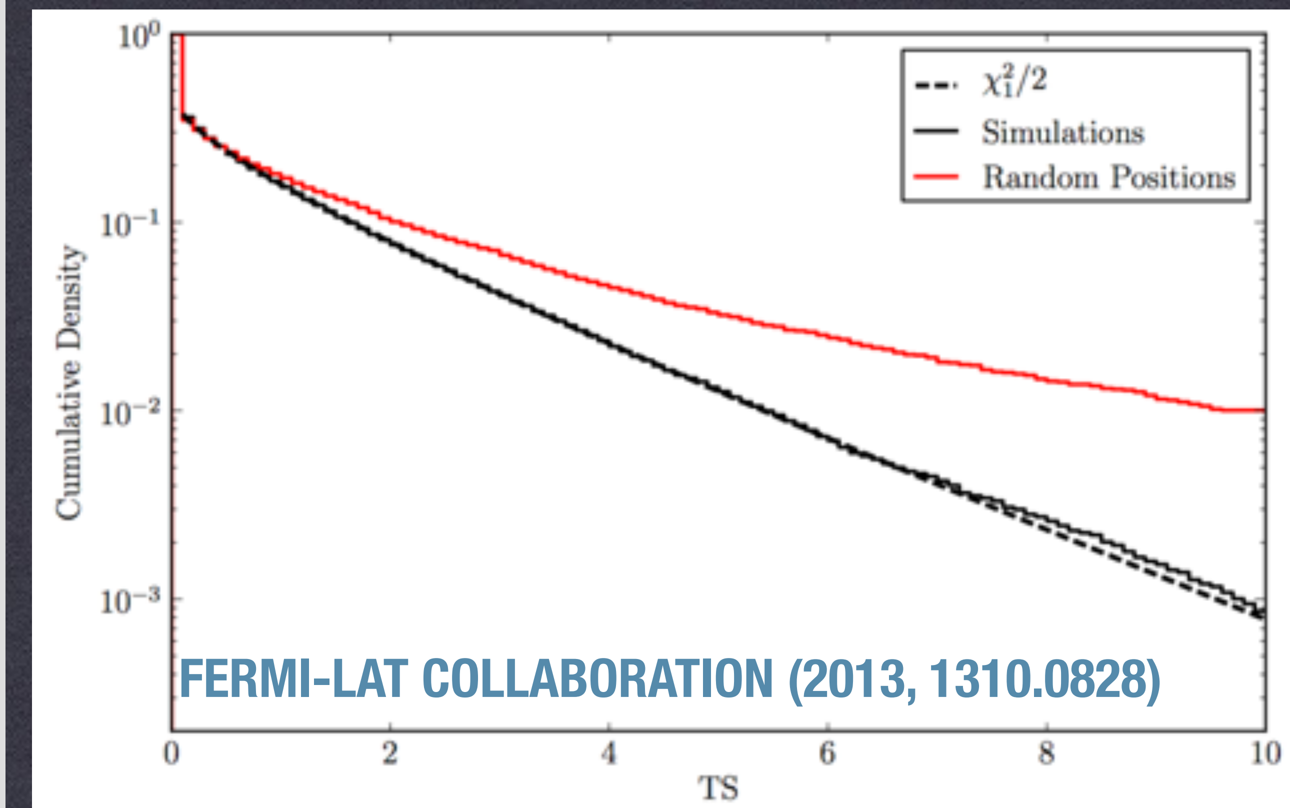
1.) Produce models of the Fermi-LAT sky in a 10x10 box around each candidate pulsar

2.) Calculate the fit to the gamma-ray data with and without a pulsar present

3.) Calculate the luminosity function and TS distribution of these locations to look for evidence of pulsars.

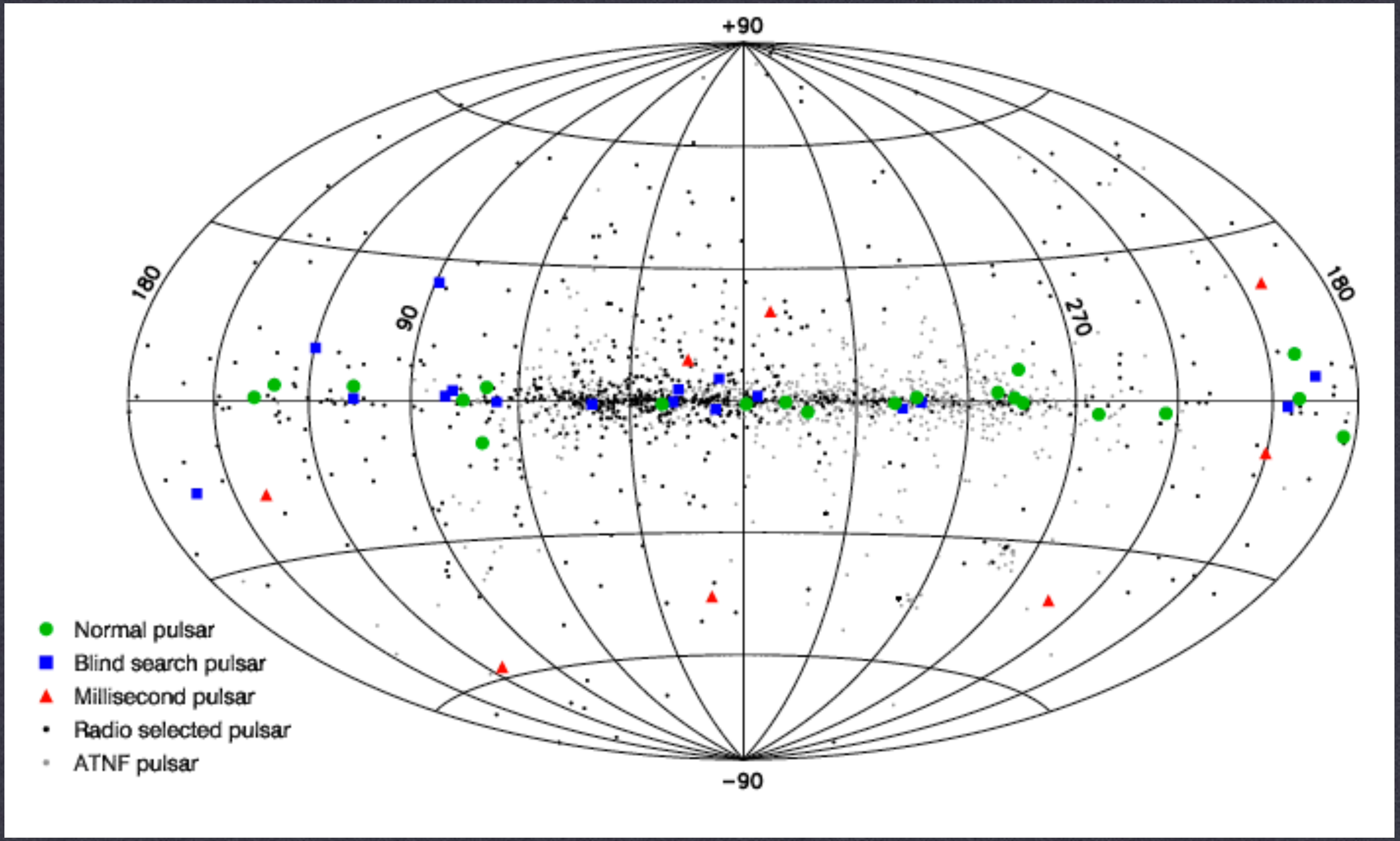
MILLISECOND PULSARS





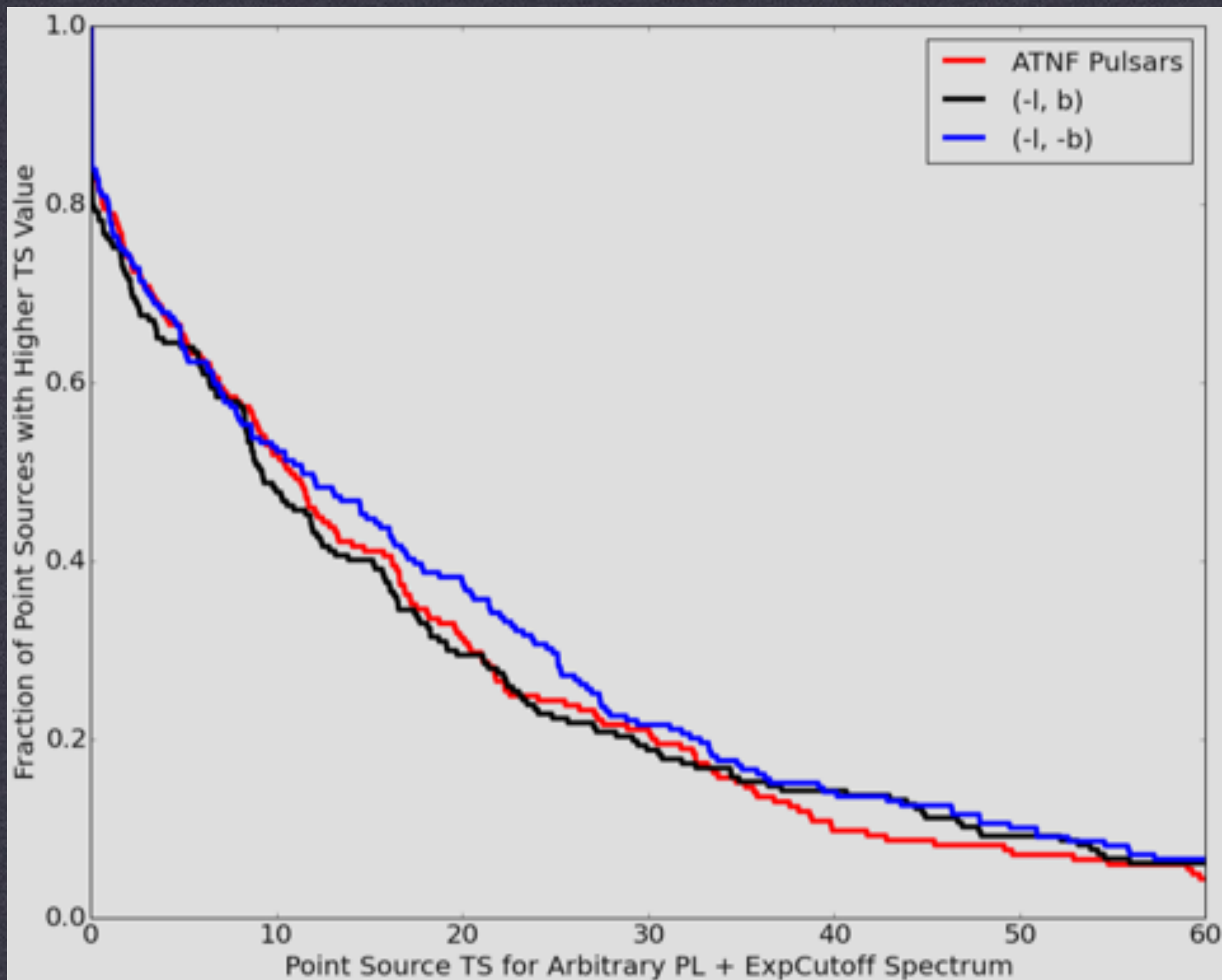
Can add "mock" point sources in the GC, they naturally pick up a high TS, compared to point sources added far from the galactic plane (see Mariangela's Talk)

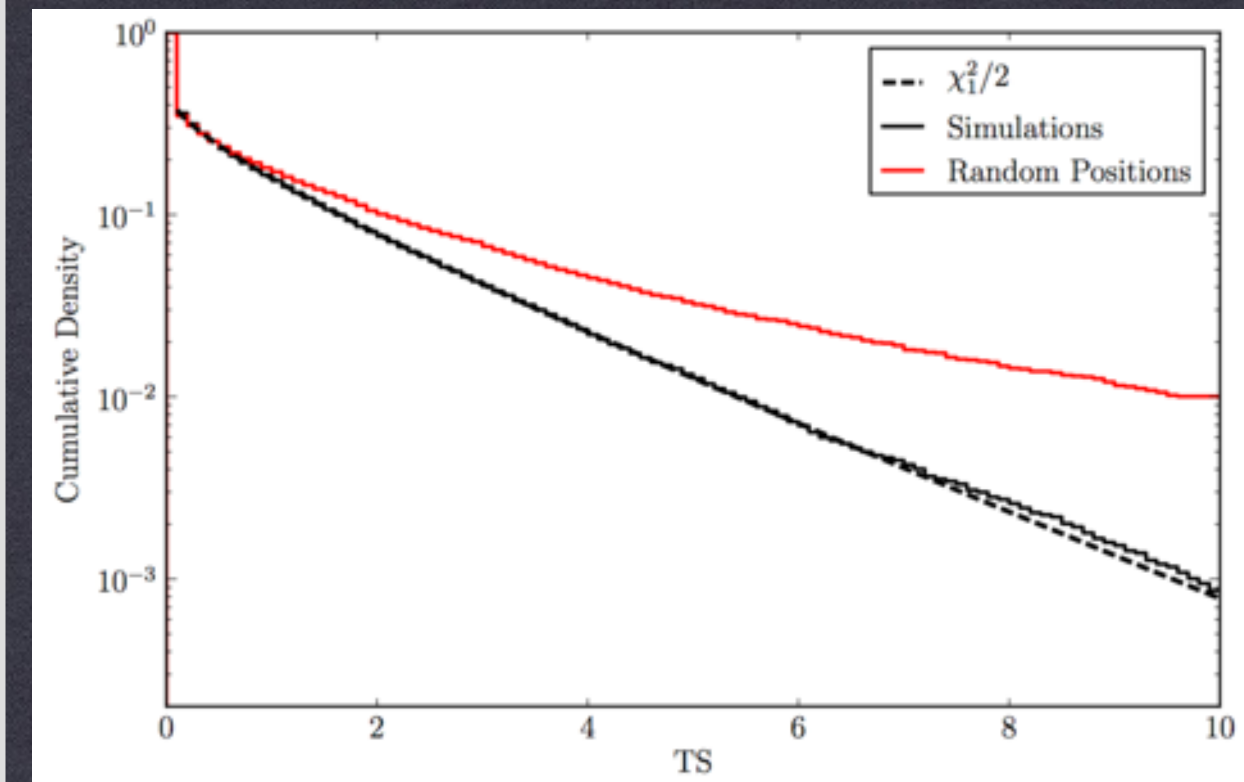
MILLISECOND PULSARS



Radio observations (such as those by ATNF) have found a multitude of pulsars (185 in the inner 10ºx10º that are currently unobserved (as point sources) in gamma-rays

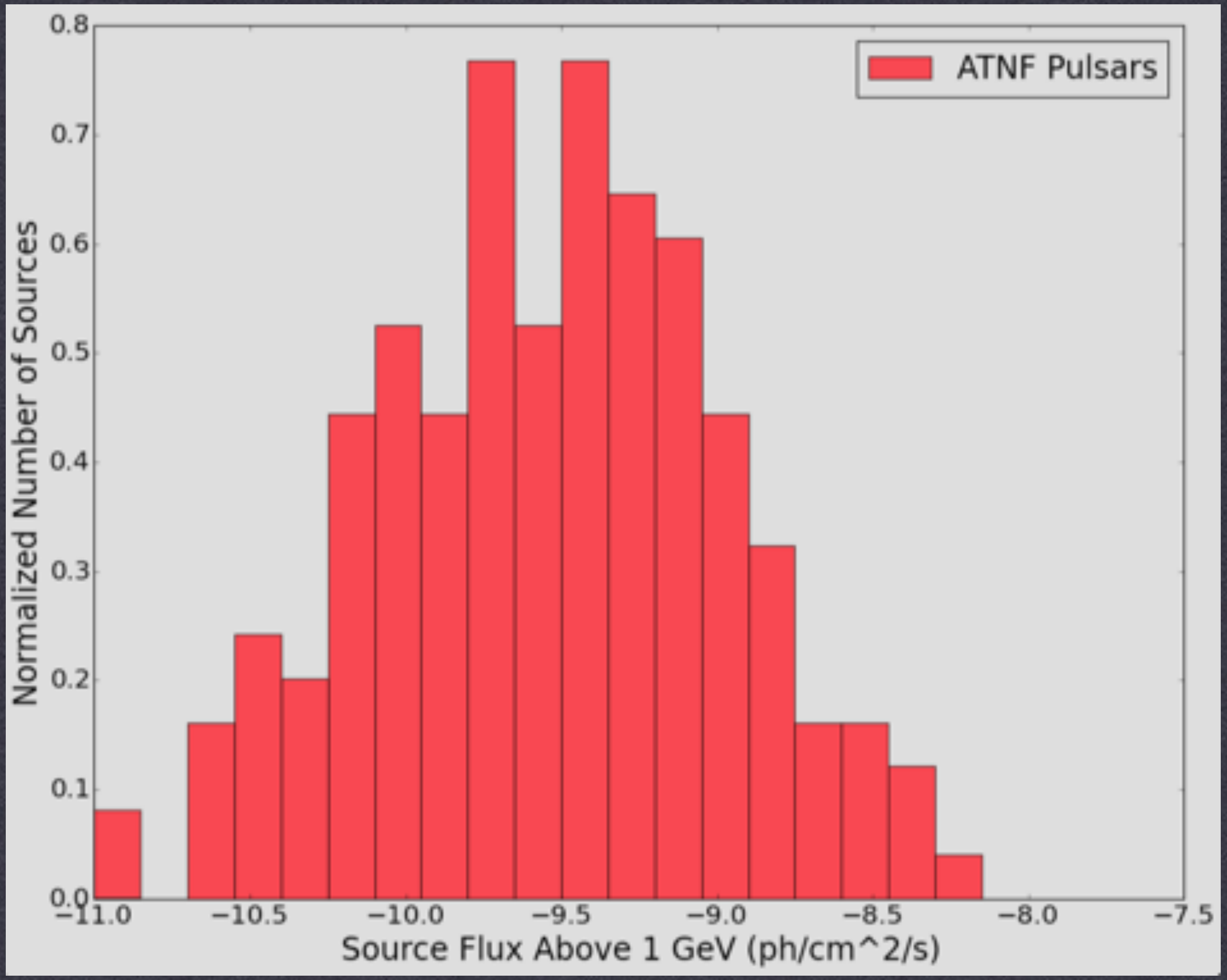
MILLISECOND PULSARS

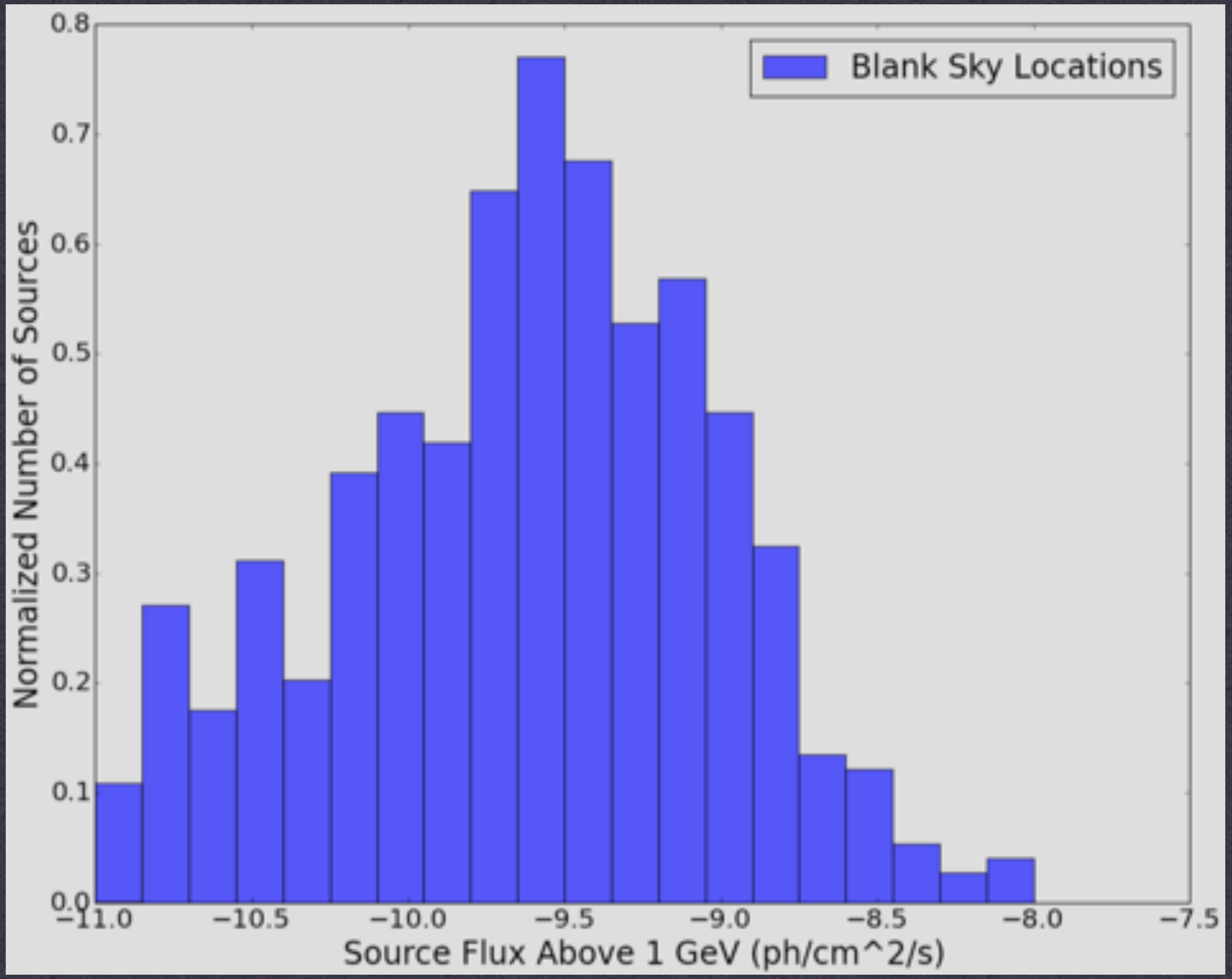




While these mock point sources pick up a high TS (indicating that there is "point source like" emission at these locations. The TS coincident with real pulsar locations is consistent with null sky positions that do not have a pulsar.

MILLISECOND PULSARS





The source flux distribution is highly peaked to source that are just below the Fermi-LAT detection threshold. This is a somewhat odd distribution of point-source luminosities

LINDEN (2015)

MILLISECOND PULSARS

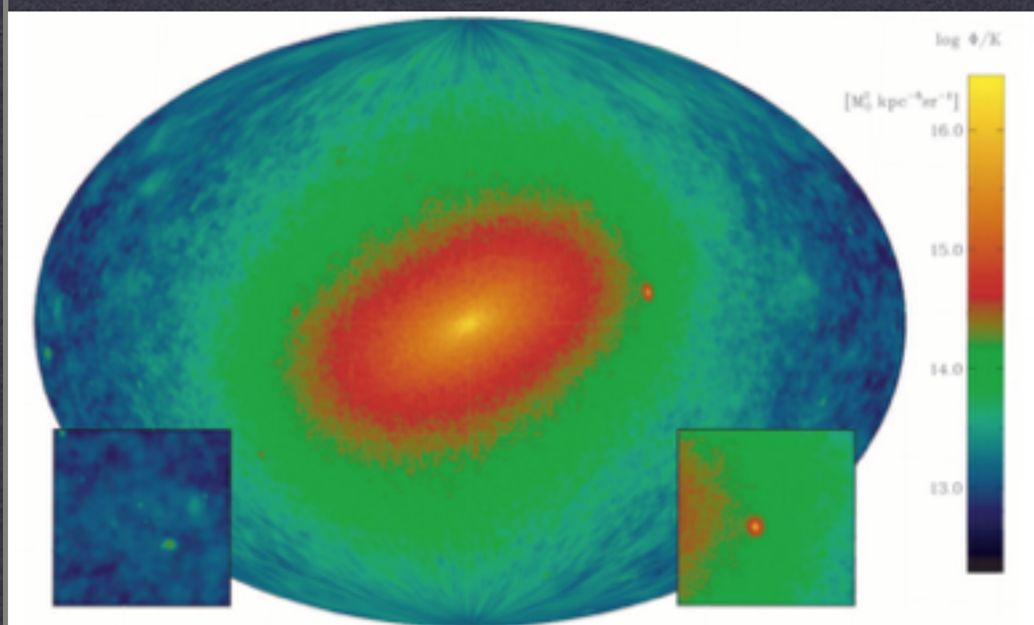
1.) It appears that adding point source degrees of freedom in the GC region picks up significant emission — see papers by Lee et al. and Bartels et al. tonight

2.) The emission does not appear to trace known radio pulsars.

LINDEN (2015)

FUTURE TESTS OF DARK MATTER

DWARF GALAXIES



For typical parameters from an NFW profile:

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

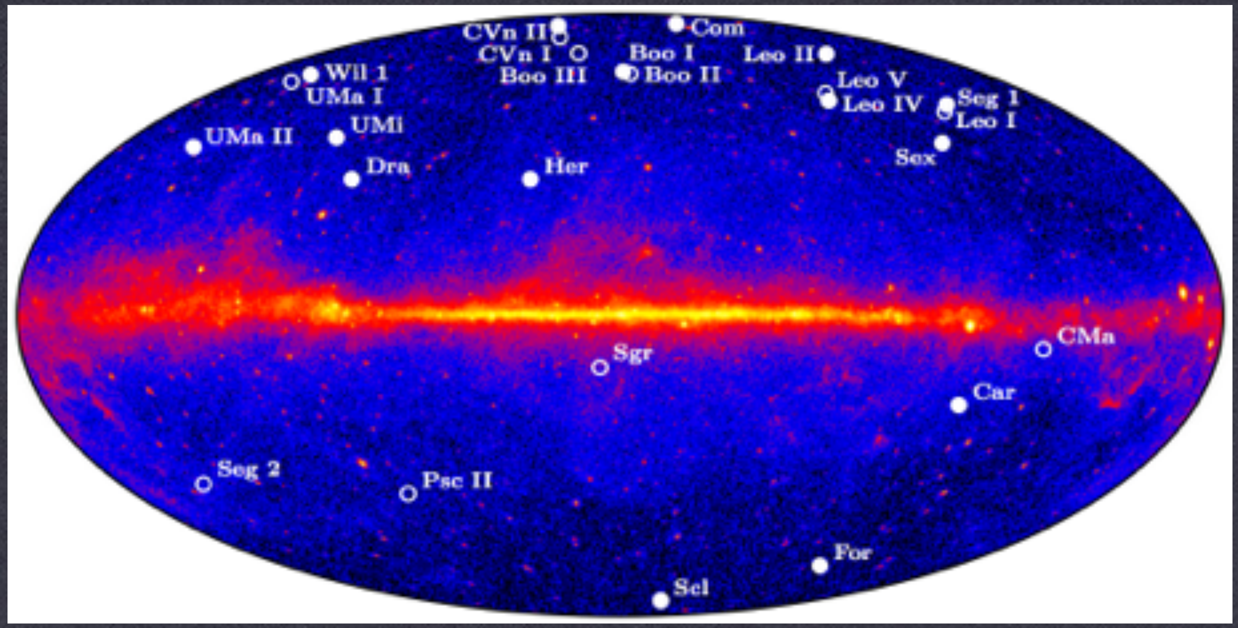
Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\overline{\log_{10}(J^{NFW})}^a$ ($\log_{10}$[GeV^2 cm^{-5} sr])
Bootes I	358.1	69.6	66	18.8 ± 0.22
Bootes II	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Canis Major	240.0	-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

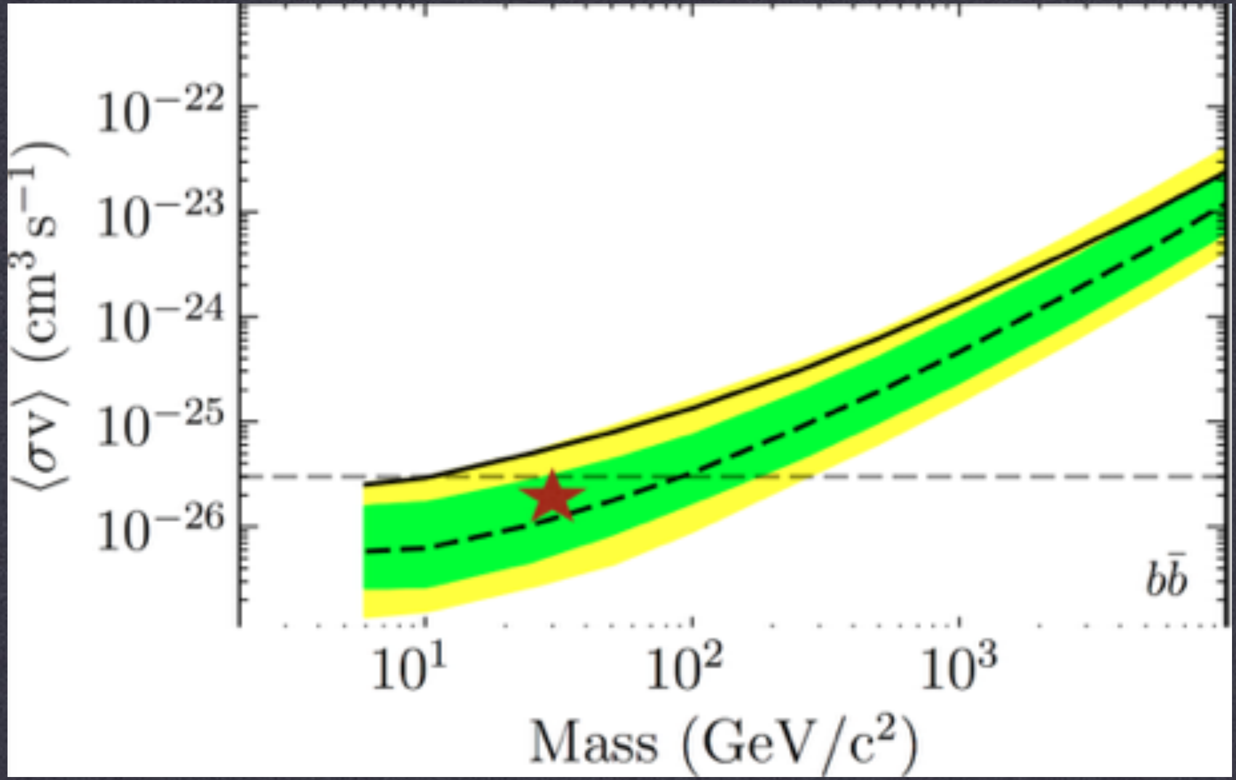
FUTURE TESTS OF DARK MATTER

DWARF GALAXIES

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

Results from the 4-year, P7 Analysis of the Fermi-LAT data showed a TS=8.7 excess!





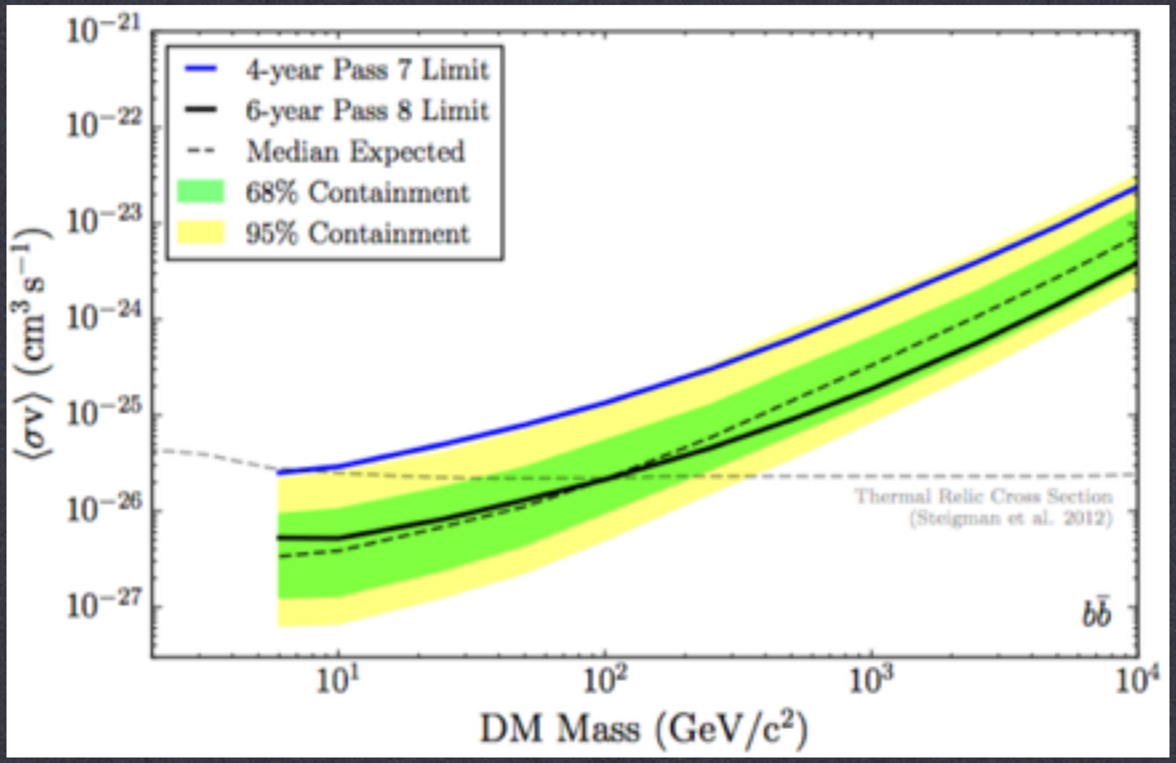
FERMI-LAT COLLABORATION (2013, 1310.0828)

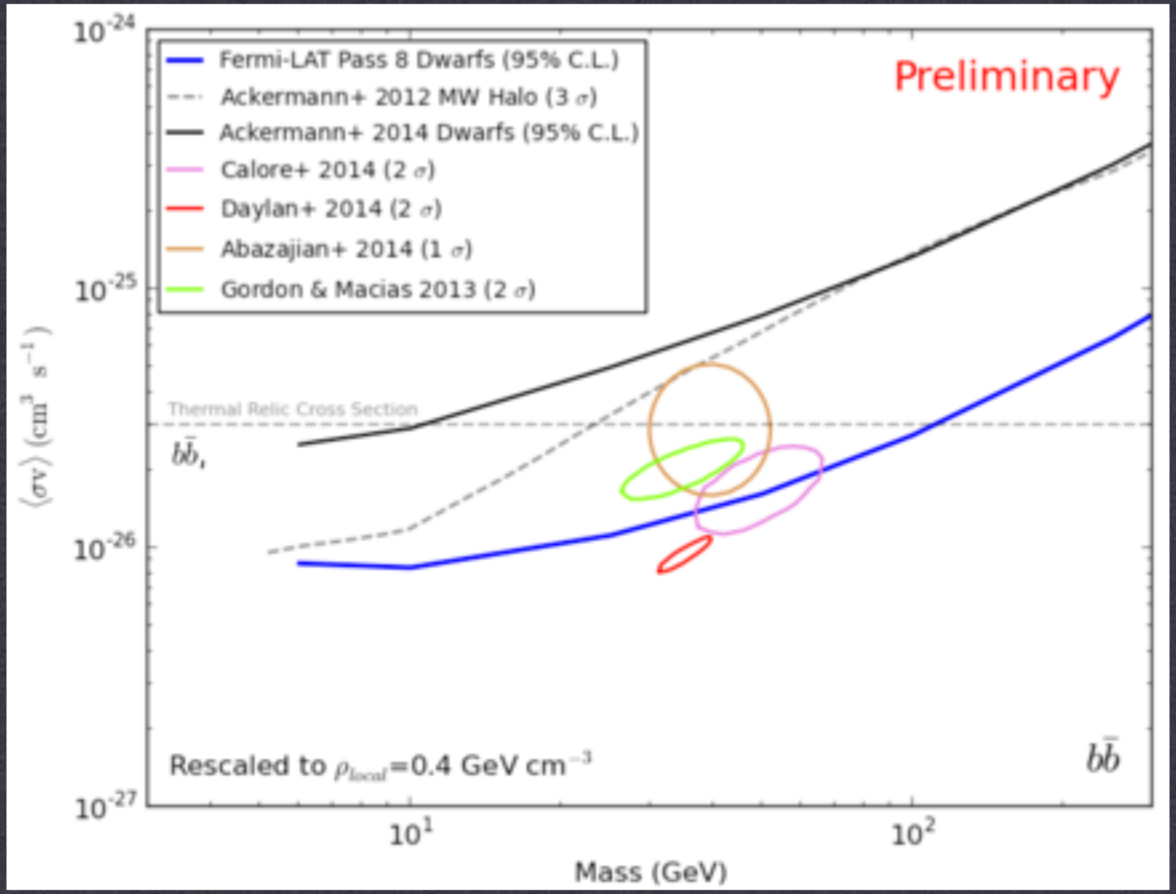
FUTURE TESTS OF DARK MATTER

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

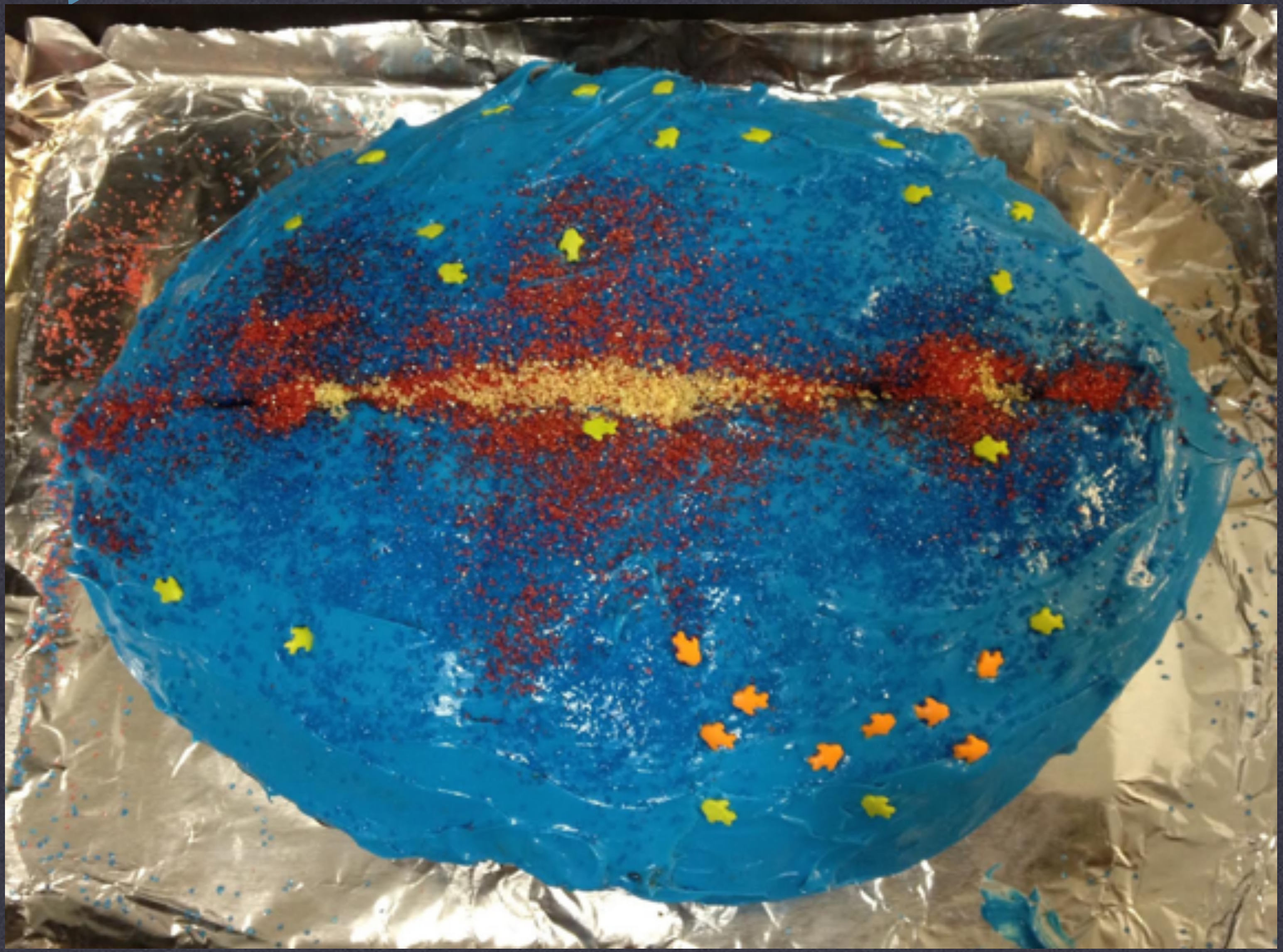




BRANDON ANDERSON, 2014 FERMI-LAT SYMPOSIUM

FUTURE TESTS OF DARK MATTER

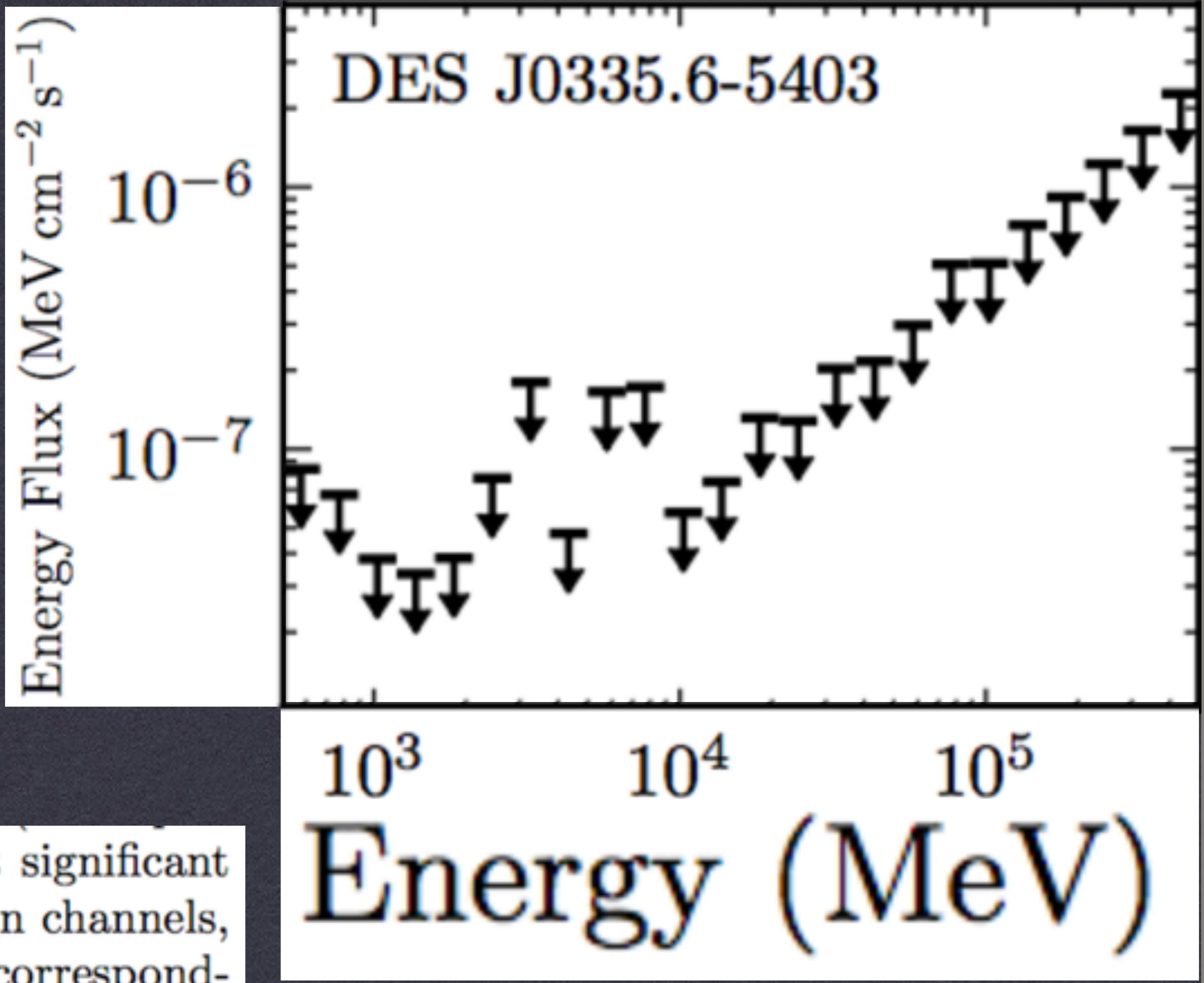
NEW DWARFS!



Analyses of the DES, and Pan-Starrs Data have recently observed 12 (and counting) new dwarf candidates in the Southern Hemisphere.

FUTURE TESTS OF DARK MATTER

RETICULUM 2



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

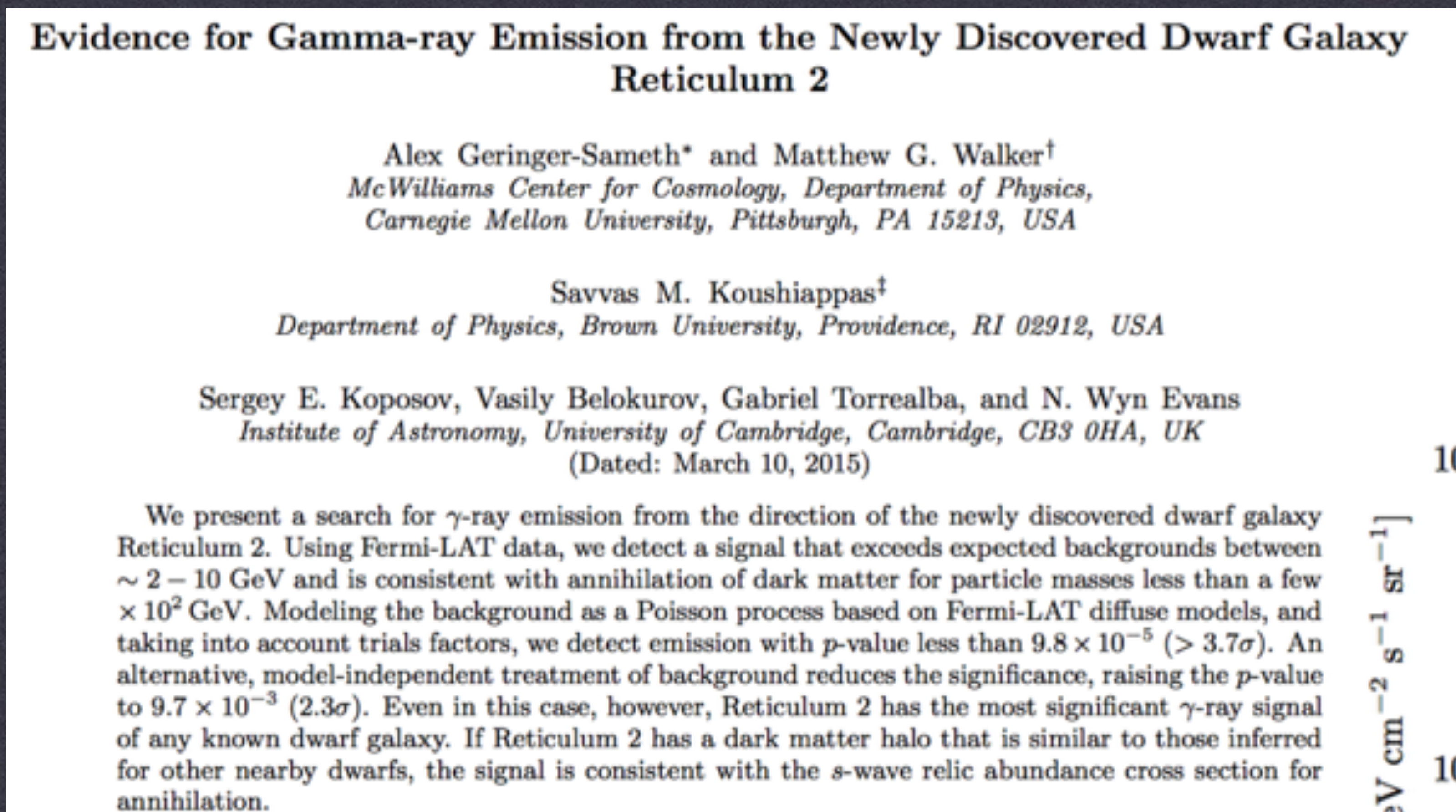
A. Drlica-Wagner,[1,2,*] A. Albert,[3,†] K. Bechtol,[1,4,‡] M. Wood,[3,§] L. Strigari,[5,¶] M. Sánchez-Conde,[6,7] L. Baldini,[8] R. Essig,[9] J. Cohen-Tanugi,[10] B. Anderson,[11] R. Bellazzini,[12] E. D. Bloom,[3] R. Caputo,[13] C. Cecchi,[14,15] E. Charles,[3] J. Chiang,[3] J. Conrad,[7,6,11,16] A. 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

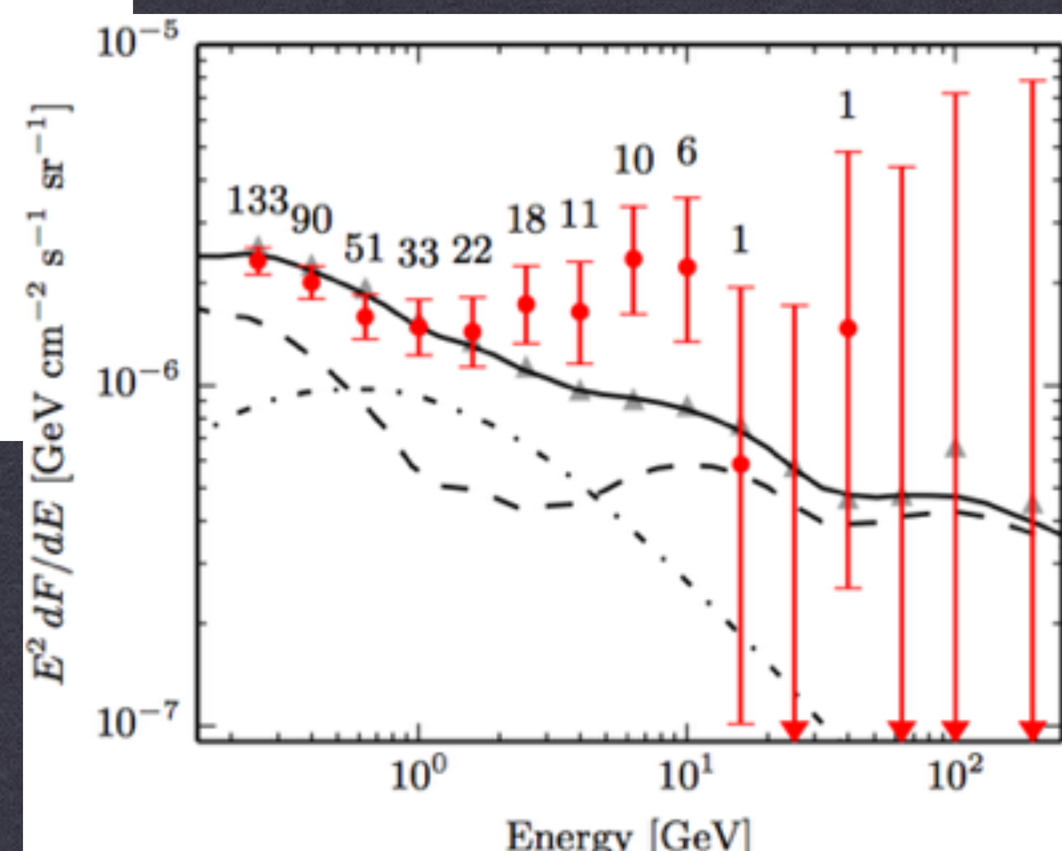
Alex Geringer-Sameth* and Matthew G. Walker†
McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Savvas M. Koushiappas‡
Department of Physics, Brown University, Providence, RI 02912, USA

Sergey E. Koposov, Vasily Belokurov, Gabriel Torrealba, and N. Wyn Evans
Institute of Astronomy, University of Cambridge, Cambridge, CB3 0HA, UK

(Dated: March 10, 2015)

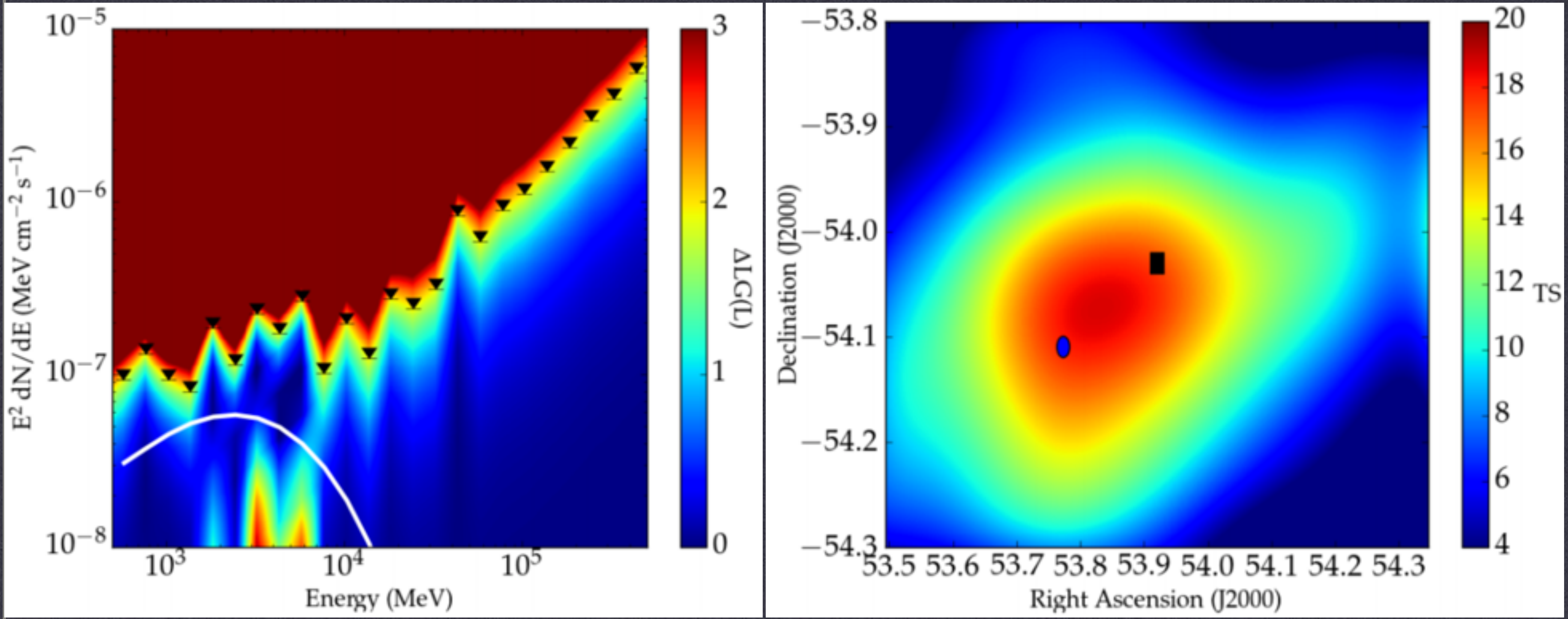
We present a search for γ-ray emission from the direction of the newly discovered dwarf galaxy Reticulum 2. Using Fermi-LAT data, we detect a signal that exceeds expected backgrounds between $\sim 2-10$ GeV and is consistent with annihilation of dark matter for particle masses less than a few $\times 10^2$ 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!

A CONSISTENT PICTURE?

HANGING BY A THREAD?

1.) The observed (modeled) J-factors of Galactic Center, the LMC/SMC, and Dwarf Spheroidal Galaxies imply that any dark matter signal should be observed in that order

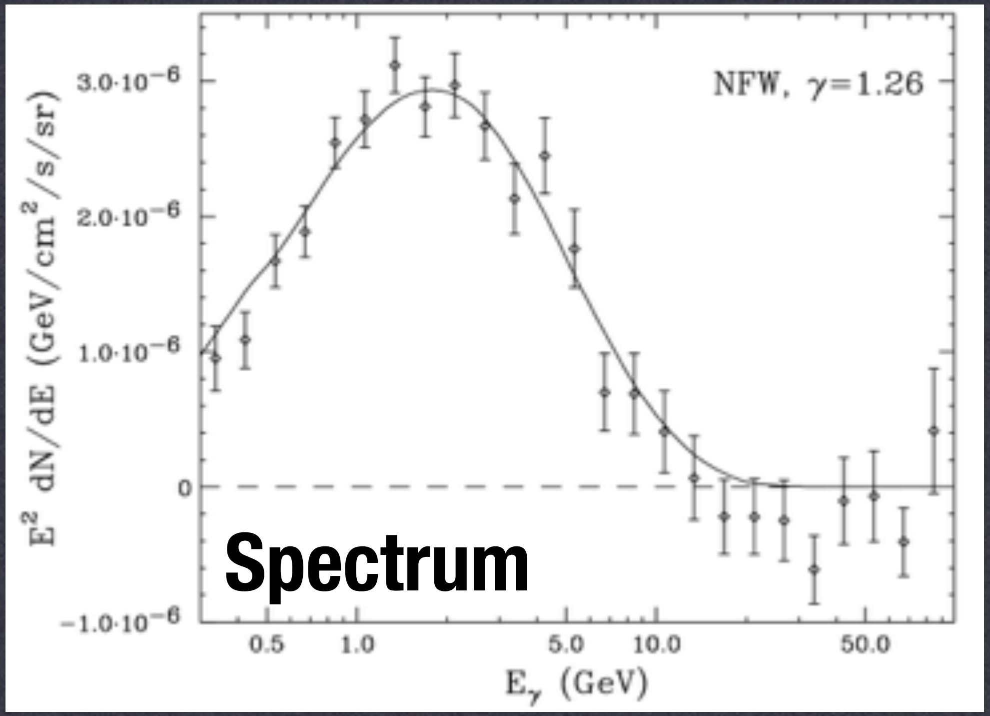
2.) A high significance excess exists in the Galactic Center, a low-significance excess in the LMC (not discussed here), and very low-significance excesses exist in several dwarfs.

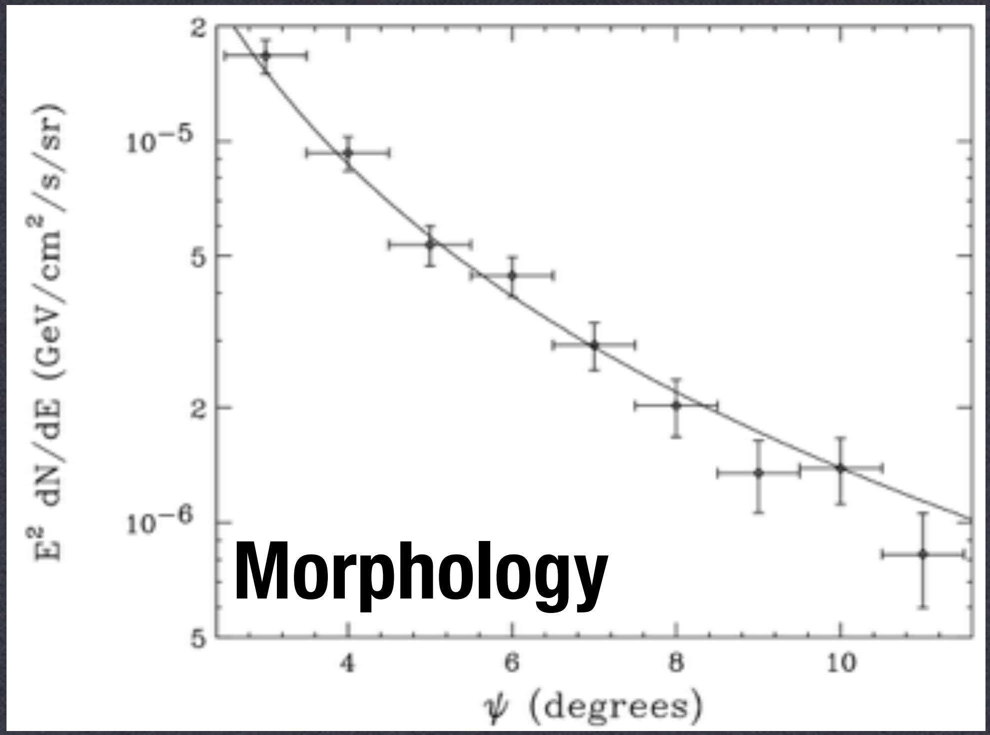
3.) Most importantly, this model can be disproved:

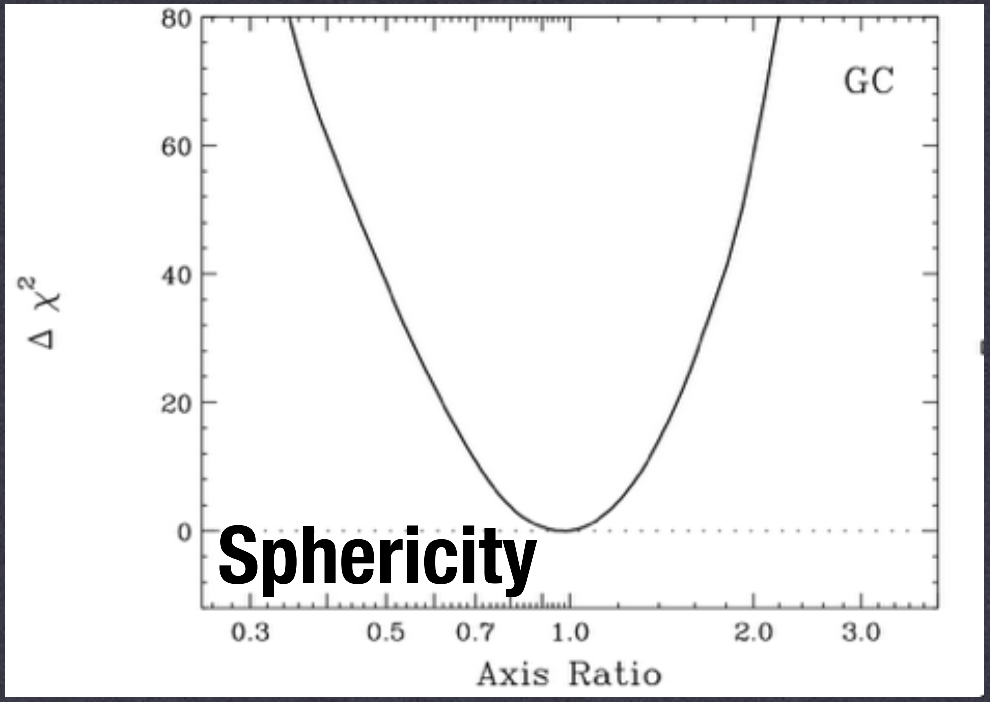
- Lack of future dwarf detections will challenge the Dark Matter interpretation of the Galactic Center Excess
- Improved Astrophysical Models may provide convincing explanations for the GC data.

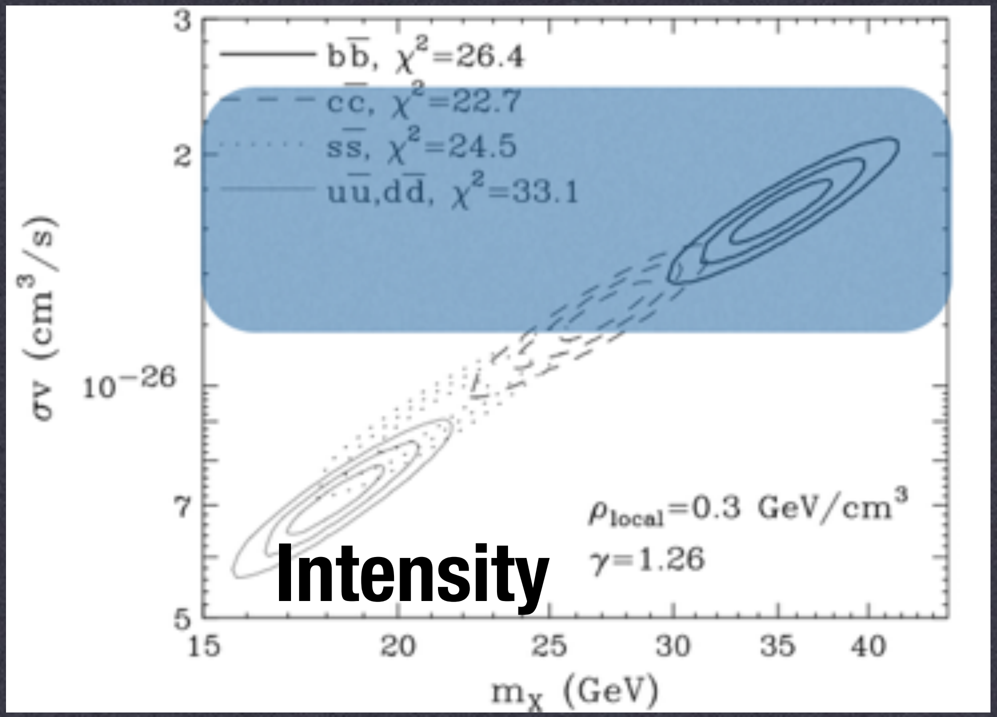
INTERPRETATIONS

DARK MATTER







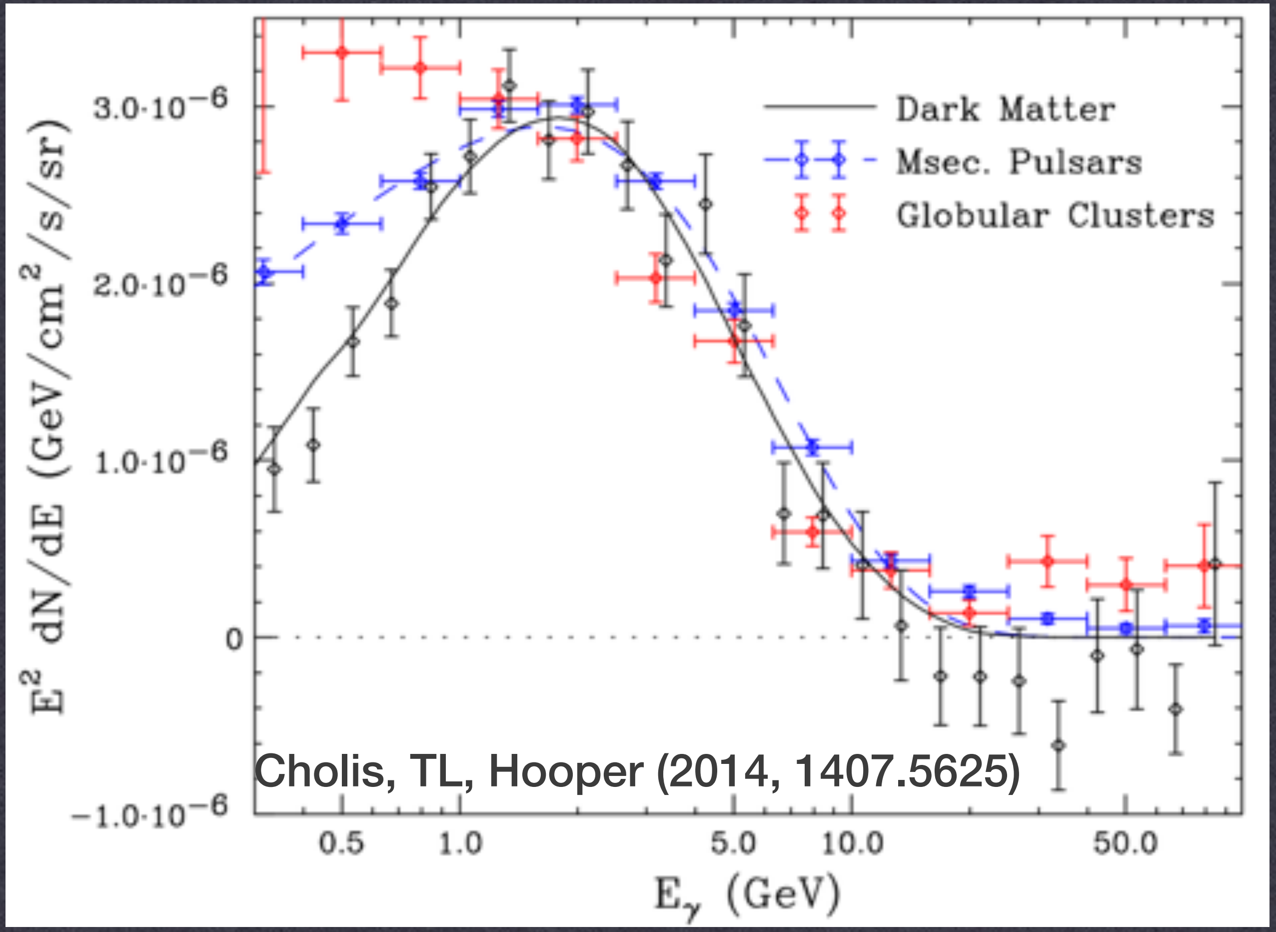


EXTRA SLIDES

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)

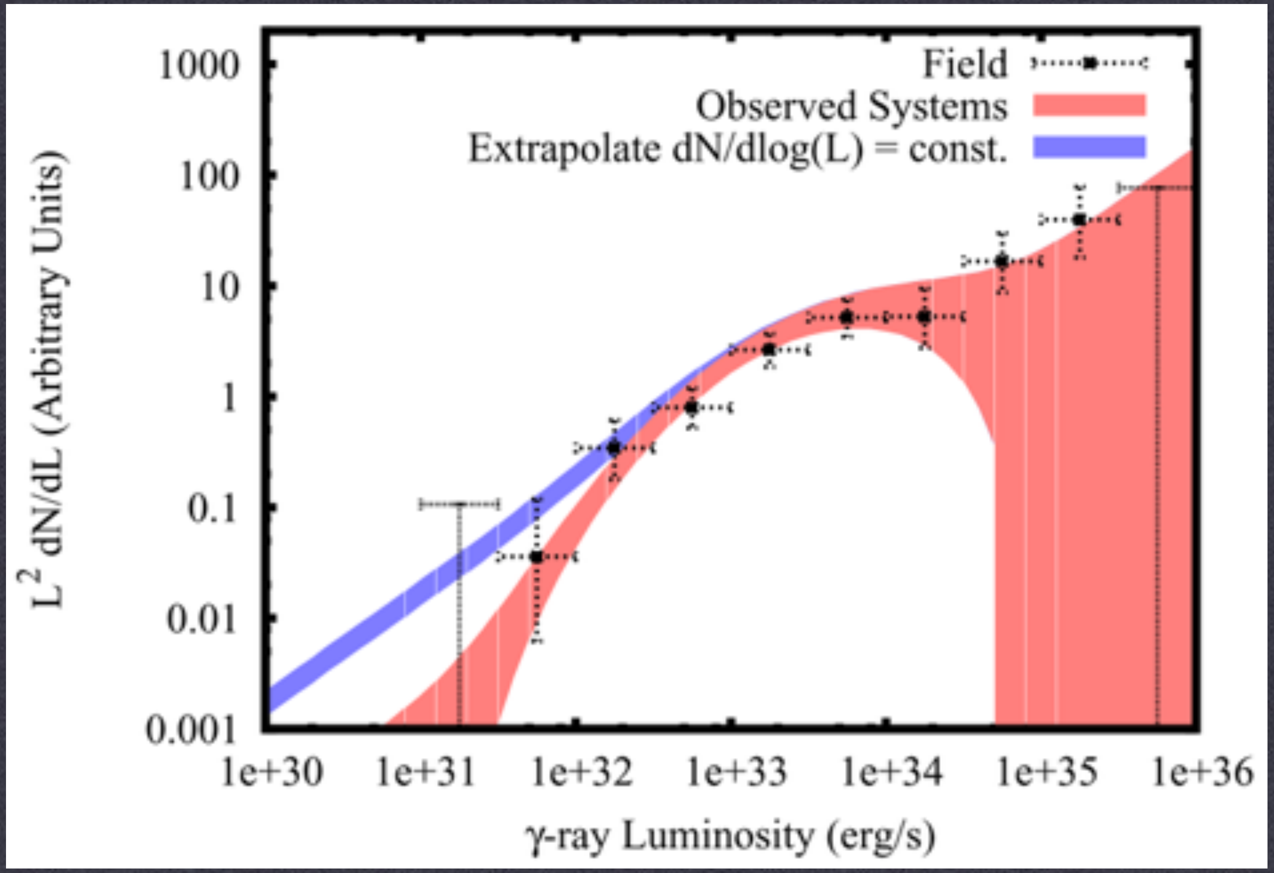


ABAZAJIAN (2011, 1011.4275)
ABAZAJIAN & KAPLINGHAT (2012, 1207.6047)
PETROVIC ET AL. (2014, 1411.2980)

INTERPRETATIONS

MILLISECOND PULSARS

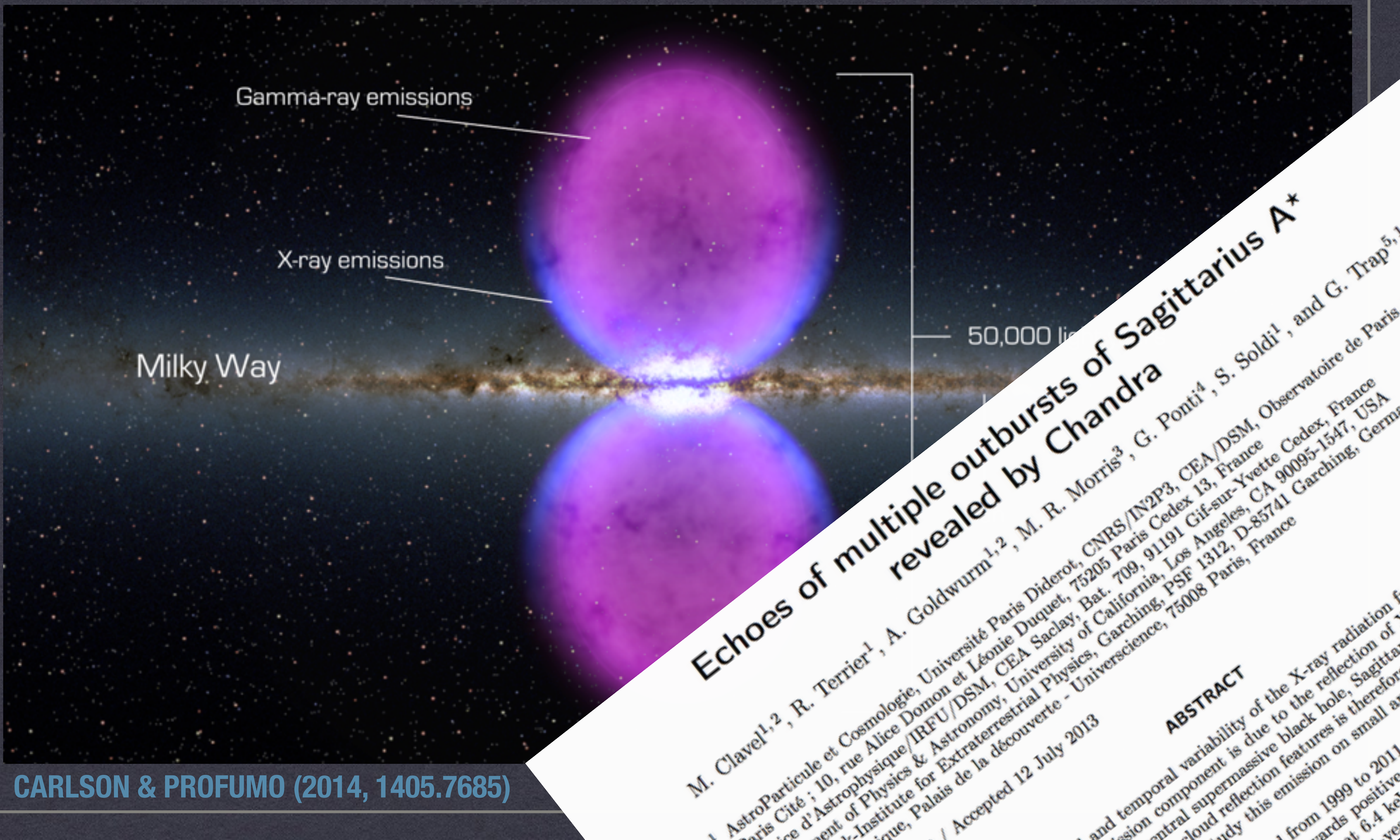
- There would need to be 226 (+91/-67) MSPs with luminosity > 10^{34} erg s^{-1} in the GC region, and 62(+60/-33.7) with luminosity > 10^{35} erg s^{-1}.
- These should be detectable by the Fermi-LAT as bright point sources
- We only see 7 MSPs or potential MSPs



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

INTERPRETATIONS

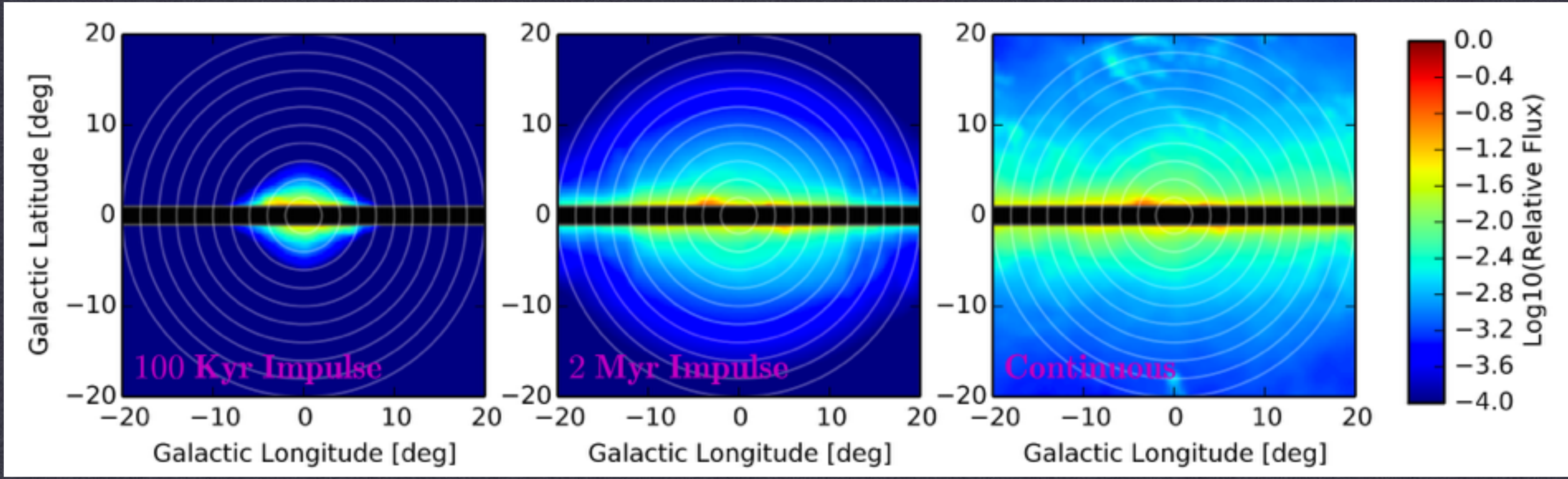
OUTBURSTS



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)

INTERPRETATIONS

ASTROPHYSICAL MECHANISMS: BAYESIAN VIEW

- Current astrophysical models form a relatively poor fit to the excess.
- However, the Bayesian prior on the existence of these emission mechanisms is quite high.
- Preview - More nuanced astrophysical models should be coming soon, and may provide reasonable fits to the data. Stay tuned!

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.

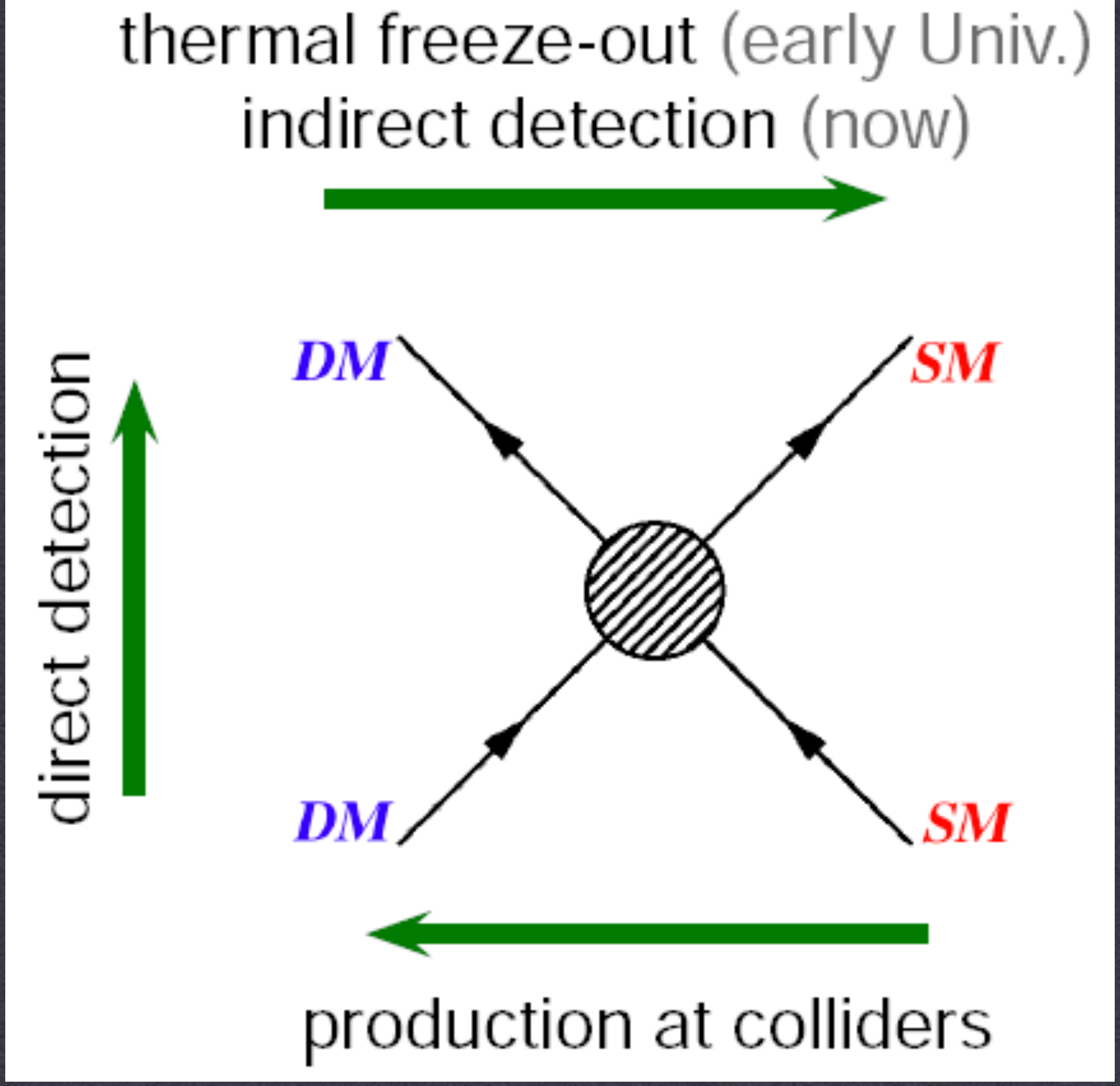
3.) Dark matter provides a natural fit to the characteristics of the GC excess

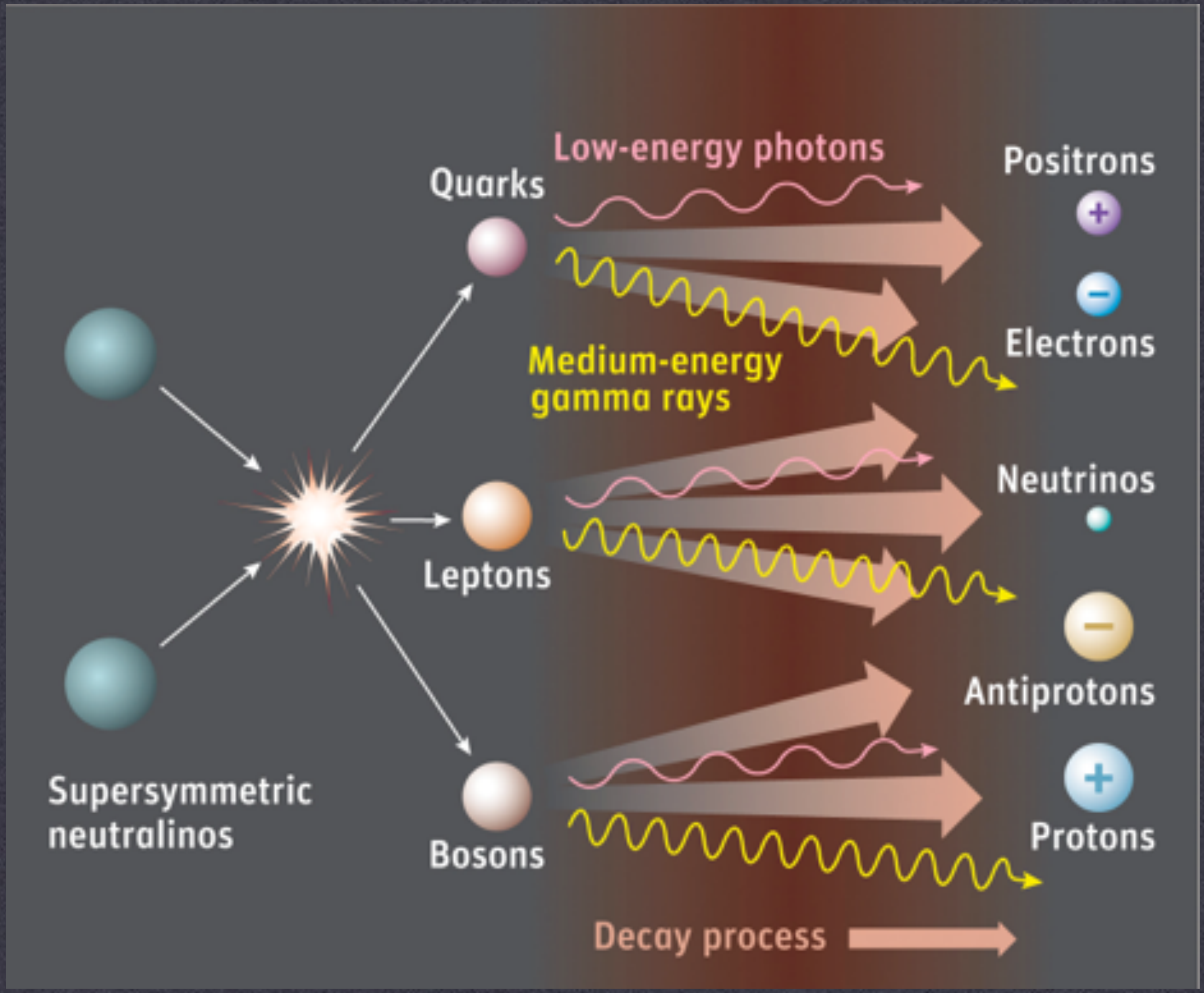
4.) However, any dark matter claim must be backed up by redundant observations. Significant work must still be done to test out or confirm our models of the GC excess.

DARK MATTER

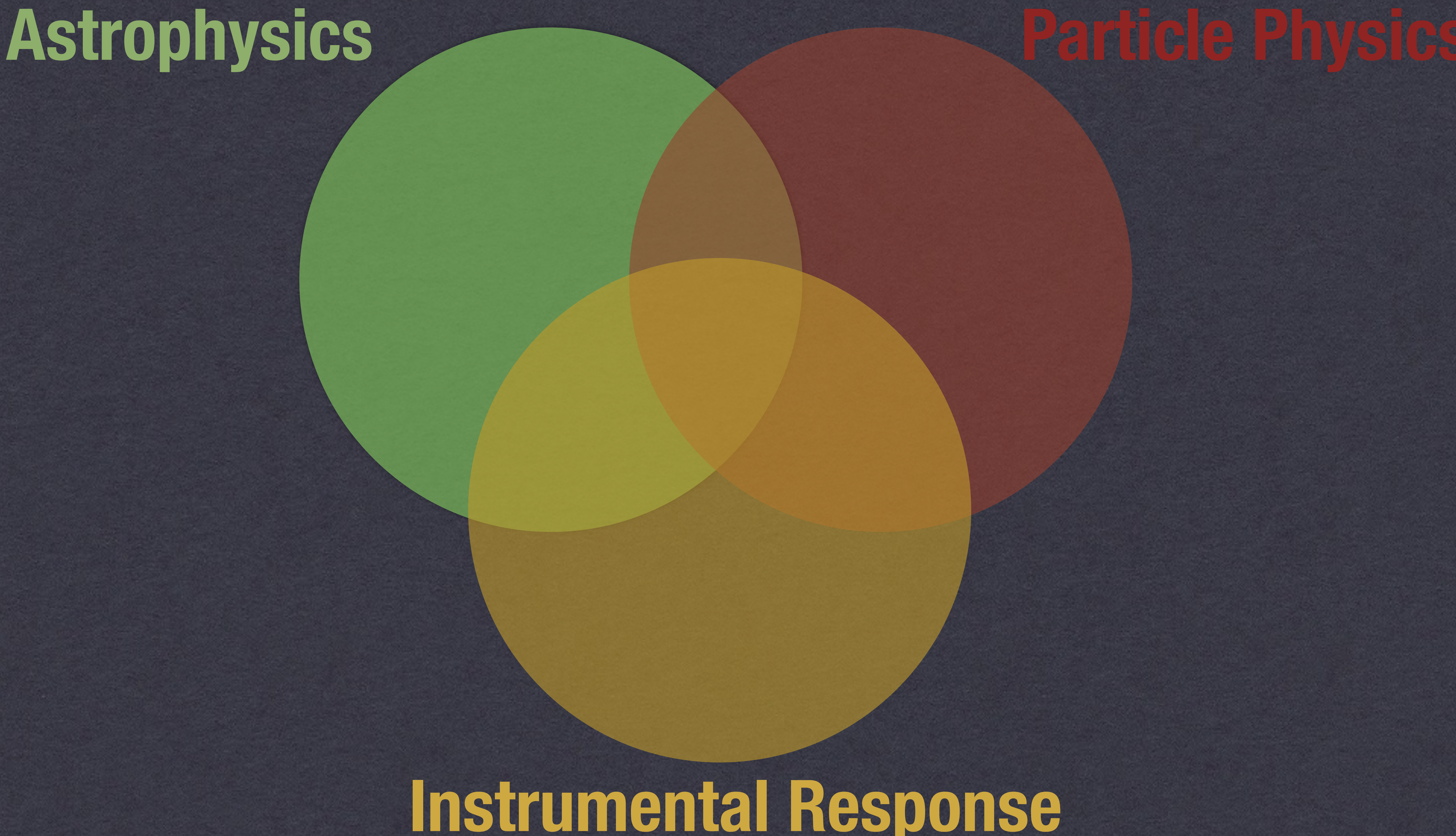
WEAKLY INTERACTING MASSIVE PARTICLES

INDIRECT DETECTION OF WIMPS





INDIRECT DETECTION OF WIMPS

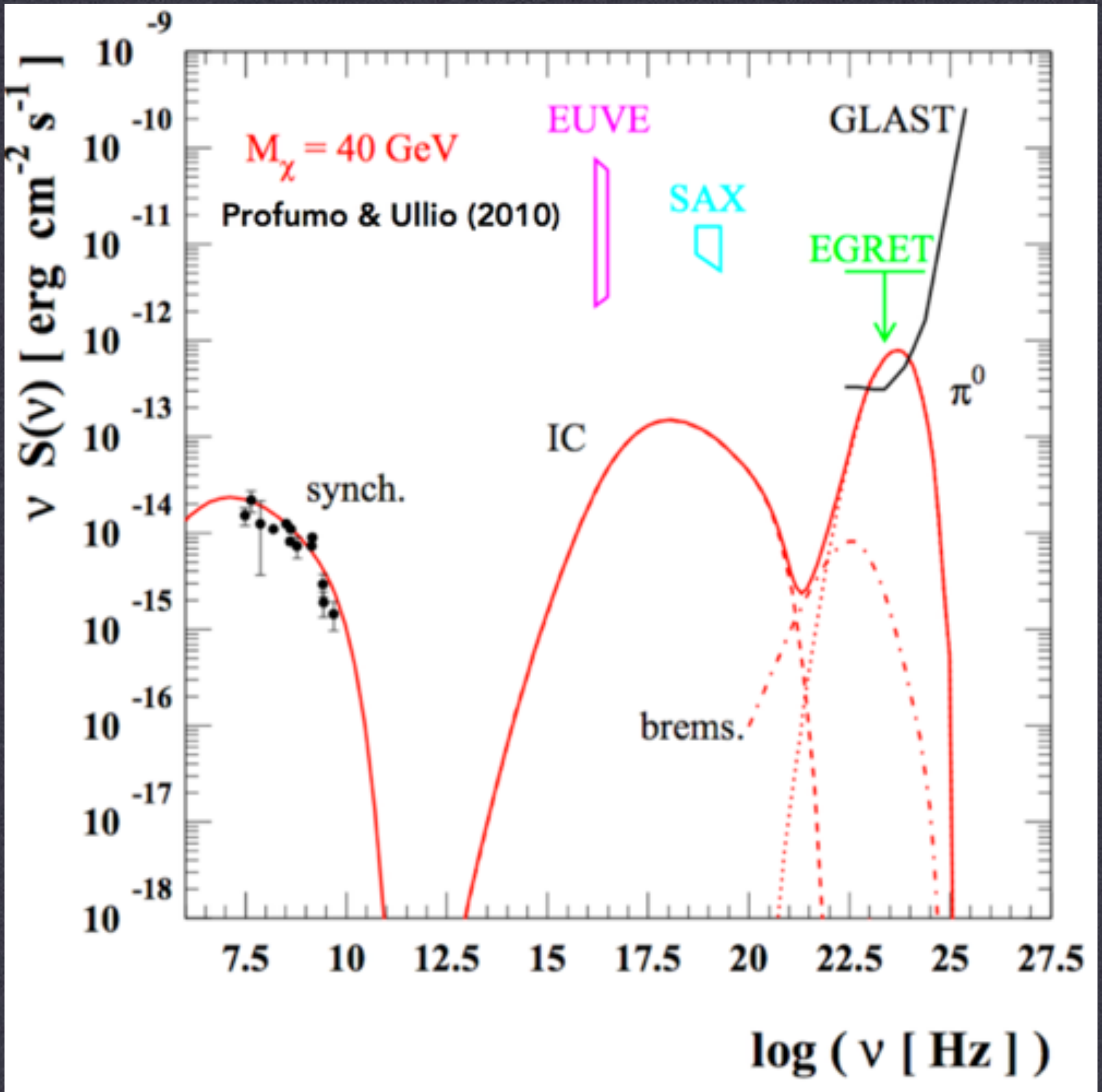


INDIRECT DETECTION OF WIMPS

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

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

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.

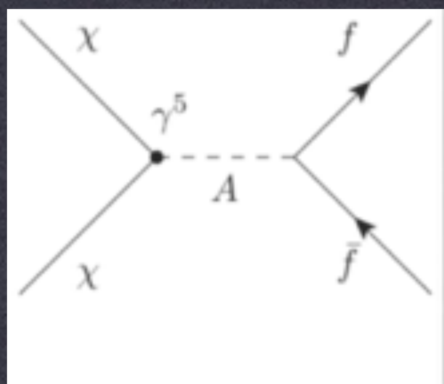
In the standard NFW scenario, $\gamma = 1$

Navarro, Frenk, White (1996)
Springel et al. (2008, 0809.0898)

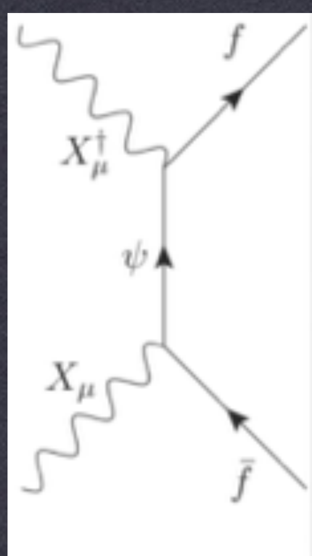
INTERPRETATIONS

DARK MATTER

BERLIN, HOOPER, MCDERMOTT (2014)



(1)



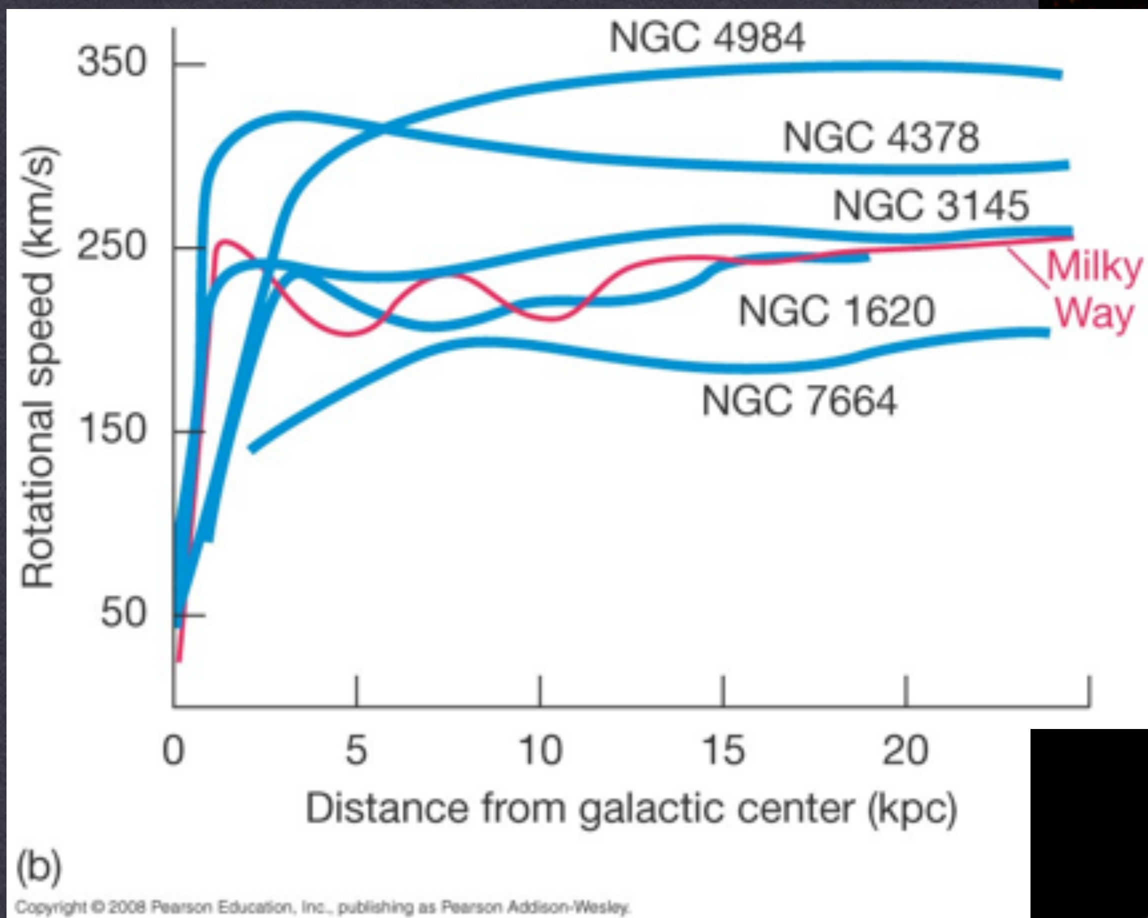
(8)

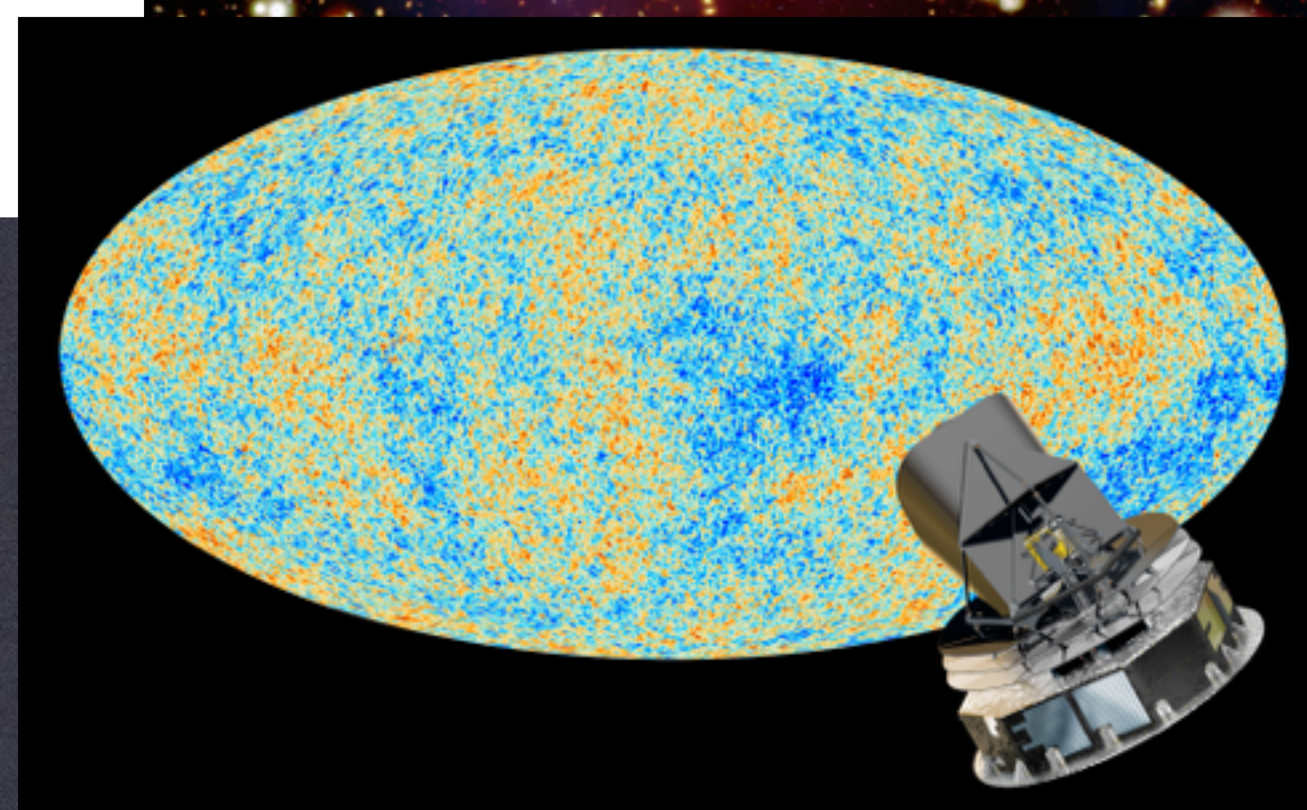
Model Number	*DM*	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach? Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (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	$B_\mu^\dagger B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	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.)	$X_\mu^\dagger\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ 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.

DARK MATTER


NGC 4984
NGC 4378
NGC 3145
Milky Way
NGC 1620
NGC 7664
Rotational speed (km/s)
350
250
150
50
0
5
10
15
20
Distance from galactic center (kpc)
(b)
Copyright © 2008 Pearson Education, Inc., publishing as Pearson Addison-Wesley.



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

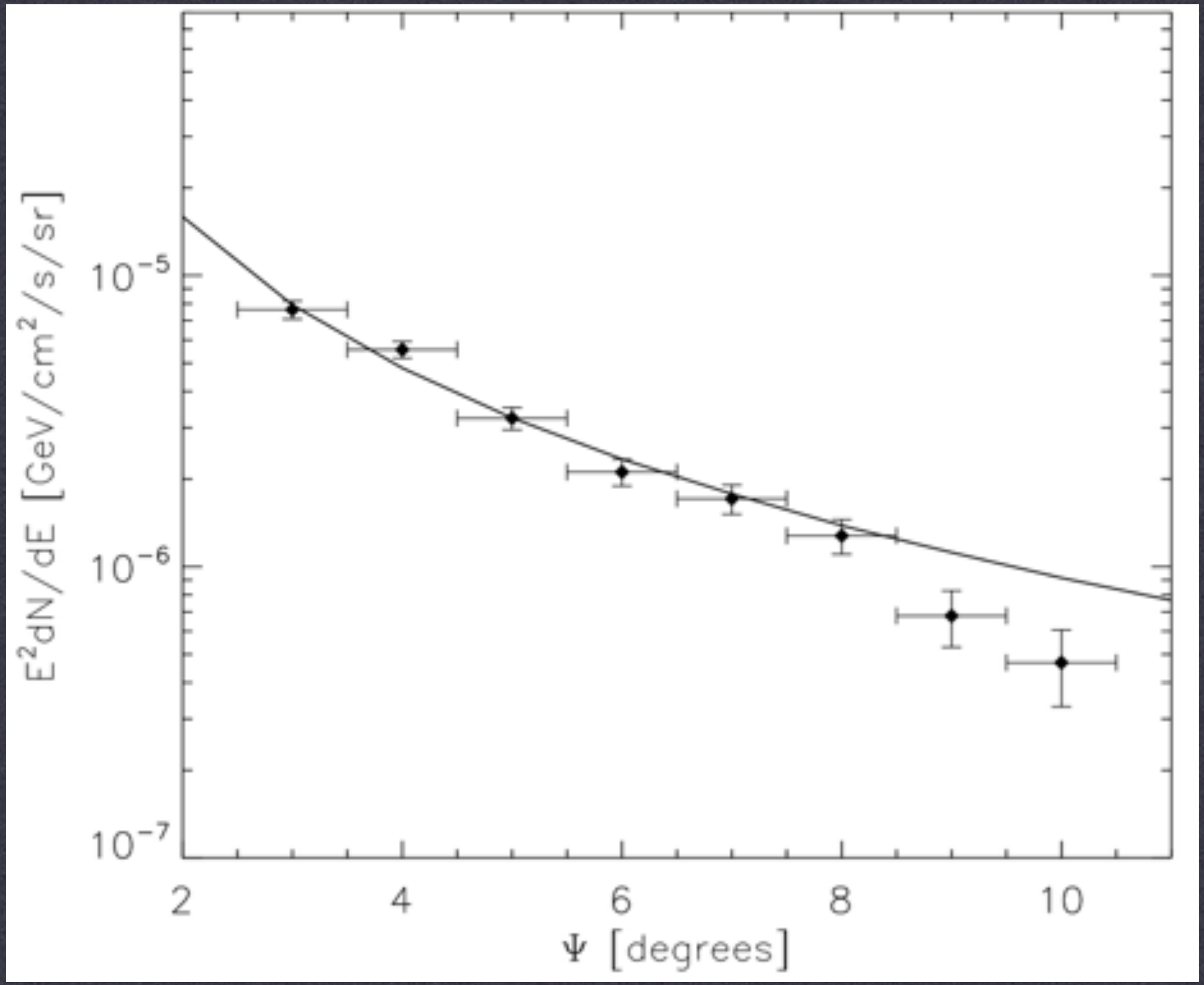
$\alpha_{\rm int}$ [deg]	$\log_{10}(J(\alpha_{\rm int}))$ $[J/{\rm GeV}^2\,{\rm cm}^{-5}]$[a]
0.01	$16.9^{+0.5(+1.1)}_{-0.4(-0.8)}$
0.05	$18.2^{+0.5(+1.0)}_{-0.4(-0.7)}$
0.1	$18.6^{+0.6(+1.1)}_{-0.4(-0.8)}$
0.5	$19.5^{+1.0(+1.6)}_{-0.6(-1.3)}$
1	$19.7^{+1.2(+2.0)}_{-0.9(-1.5)}$

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

MORPHOLOGY

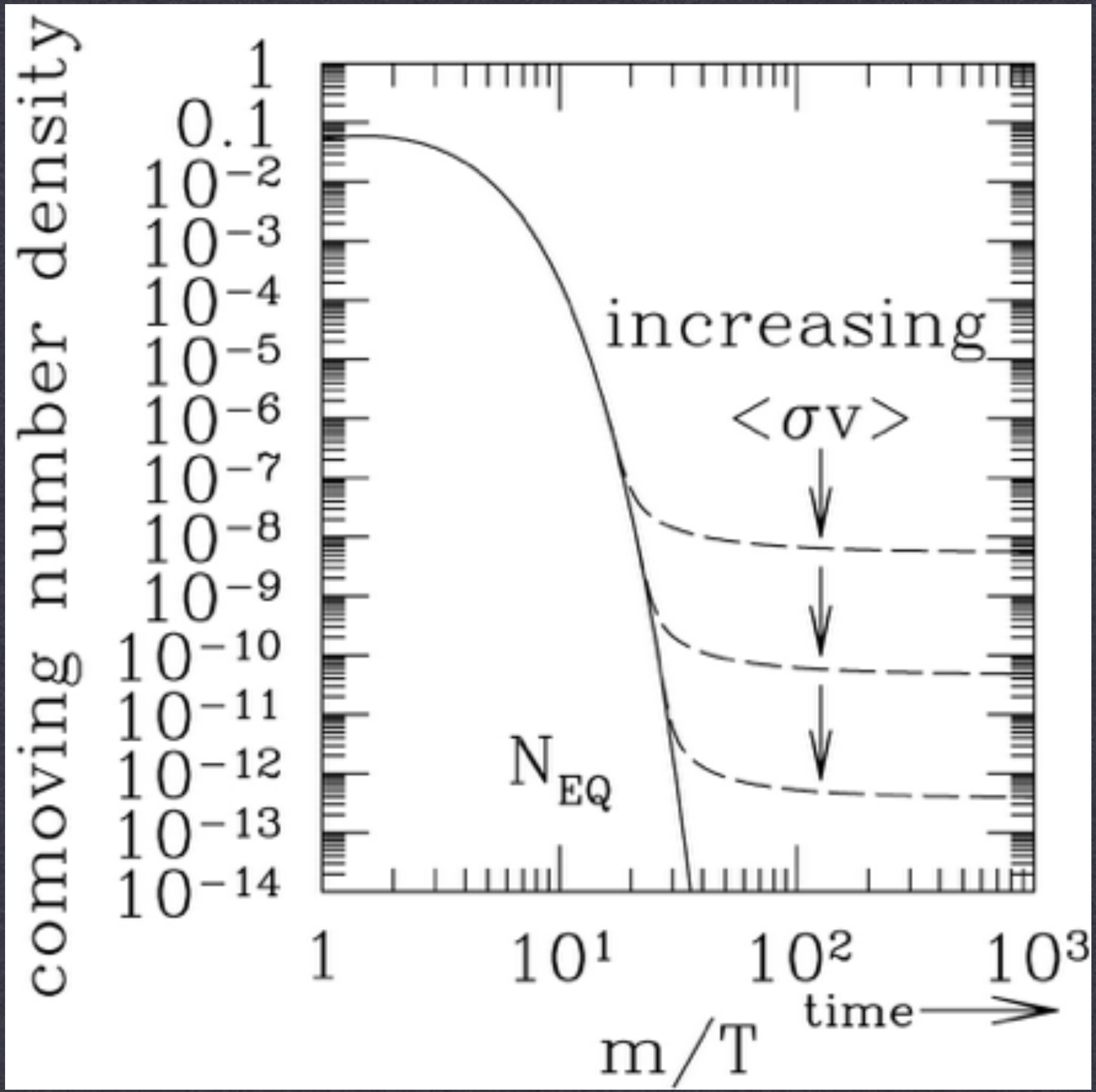
INNER GALAXY



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.

DARK MATTER

WEAKLY INTERACTING MASSIVE PARTICLES



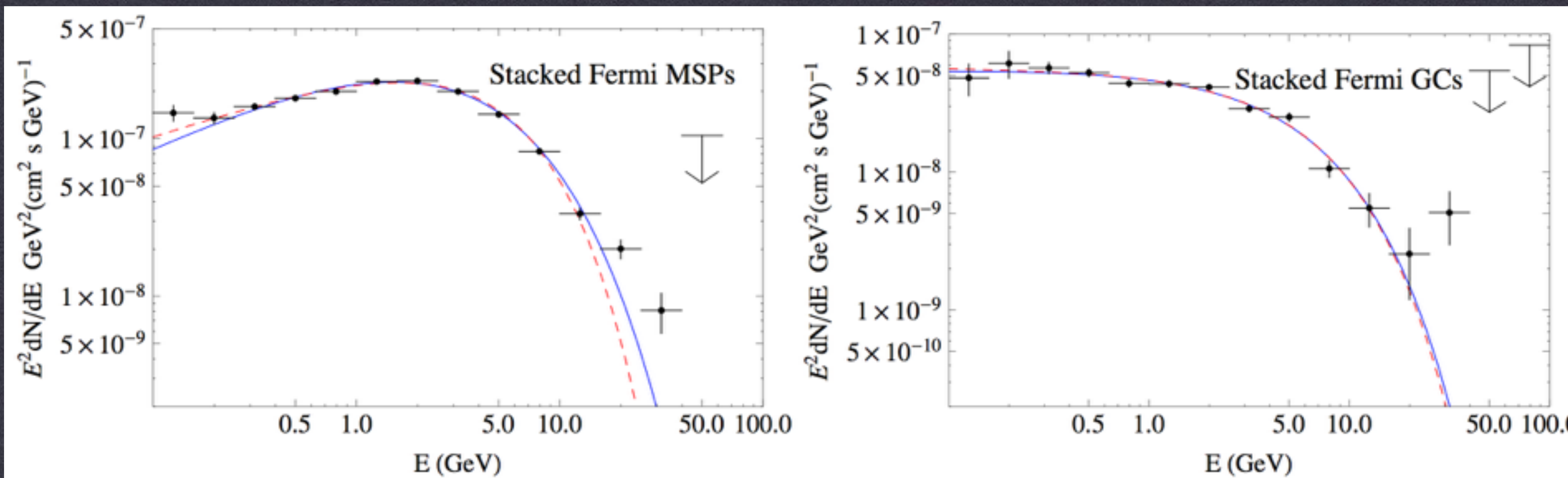
Ignoring several possible complications, a particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the early universe

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

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

INTERPRETATIONS

MILLISECOND PULSARS

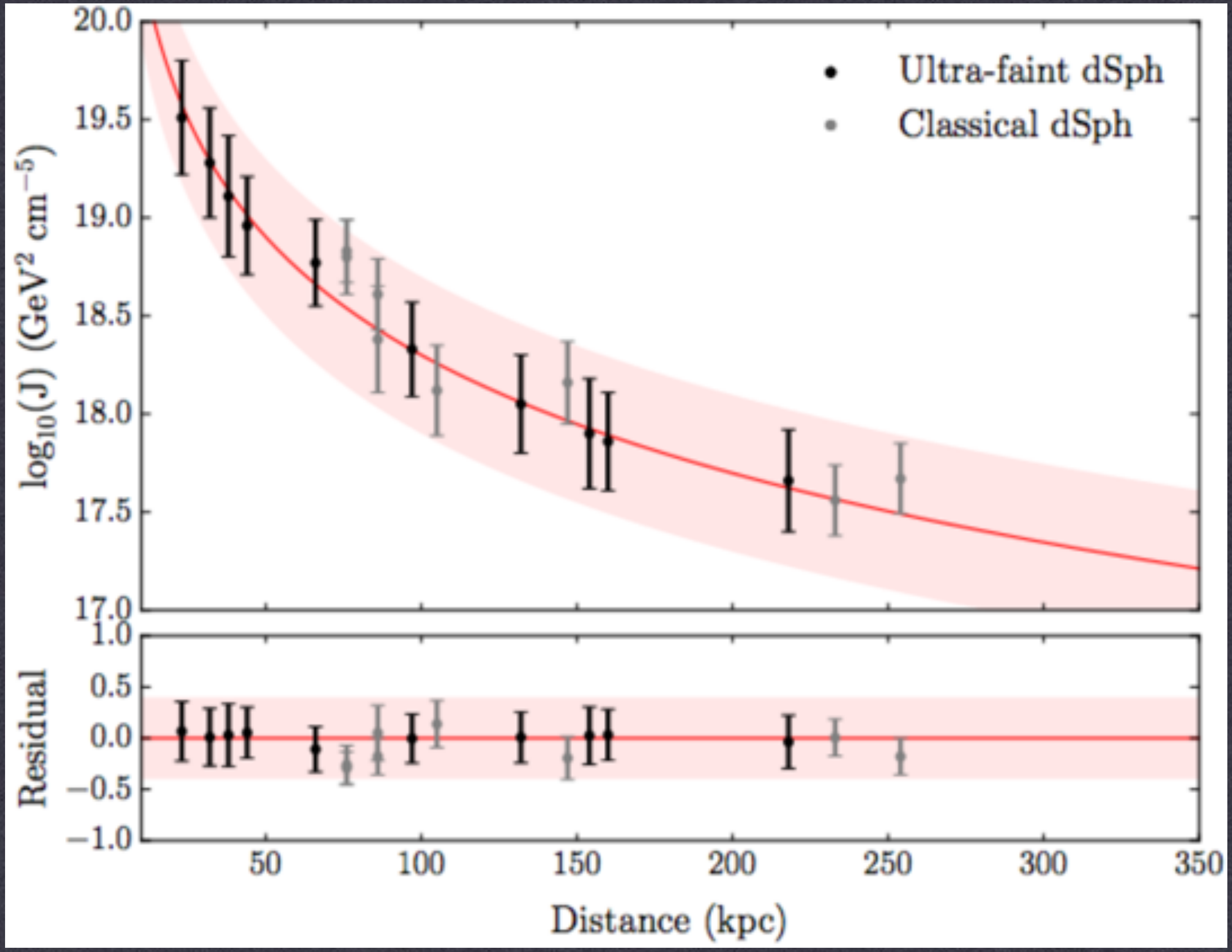


- Analyze the average spectrum and luminosity of the Fermi MSP and globular cluster populations:
  - 5.5 years of data
  - P7 Reprocessed Photons
  - 15 energy bins, no spectral model assumed

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

FUTURE TESTS OF DARK MATTER

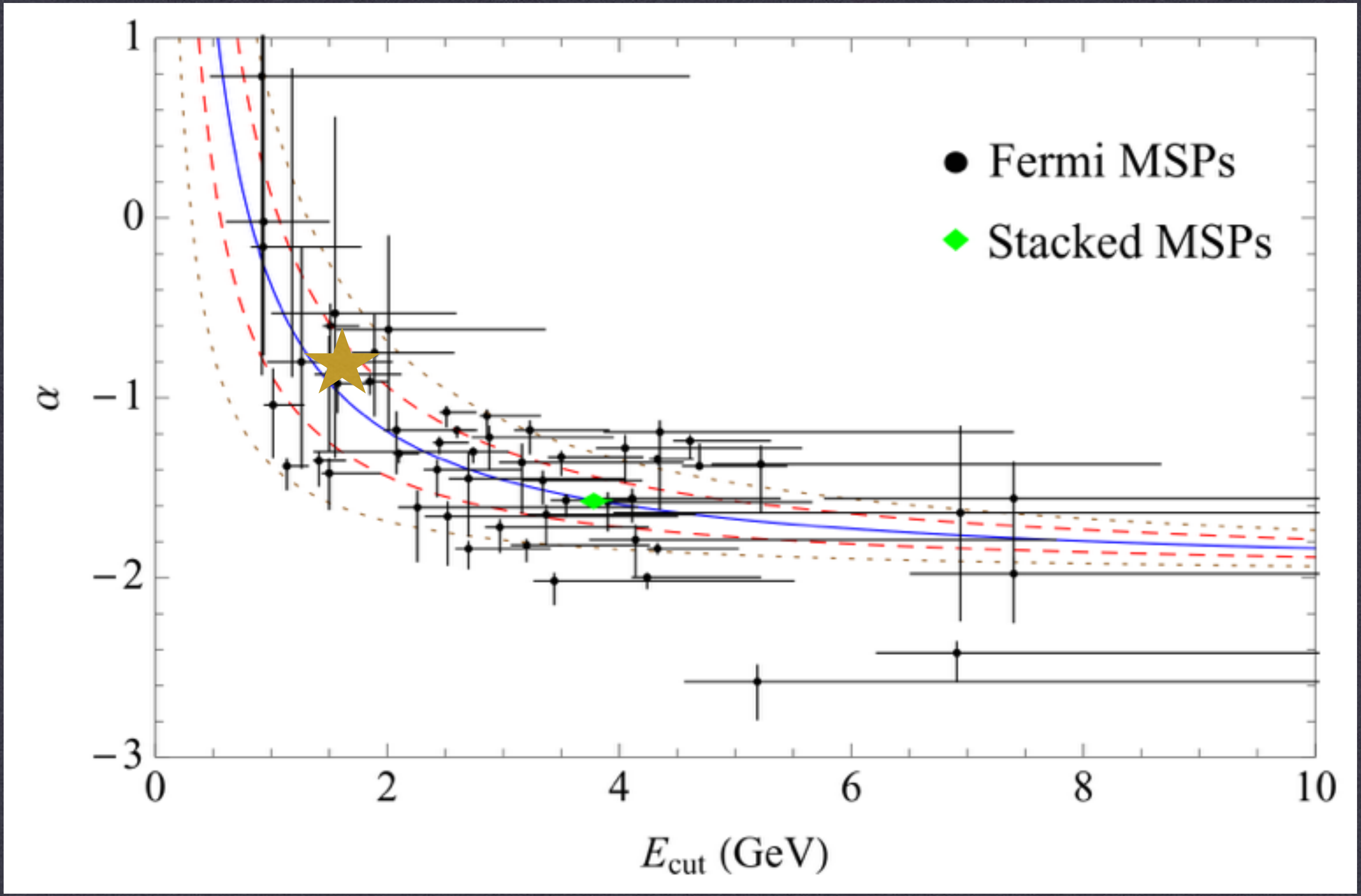
RETICULUM 2



Several of these dwarfs (Reticulum 2 and possibly Triangulum 2) are close enough to be important targets for dwarf galaxy searches

INTERPRETATIONS

MILLISECOND PULSARS



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

FUTURE TESTS OF DARK MATTER

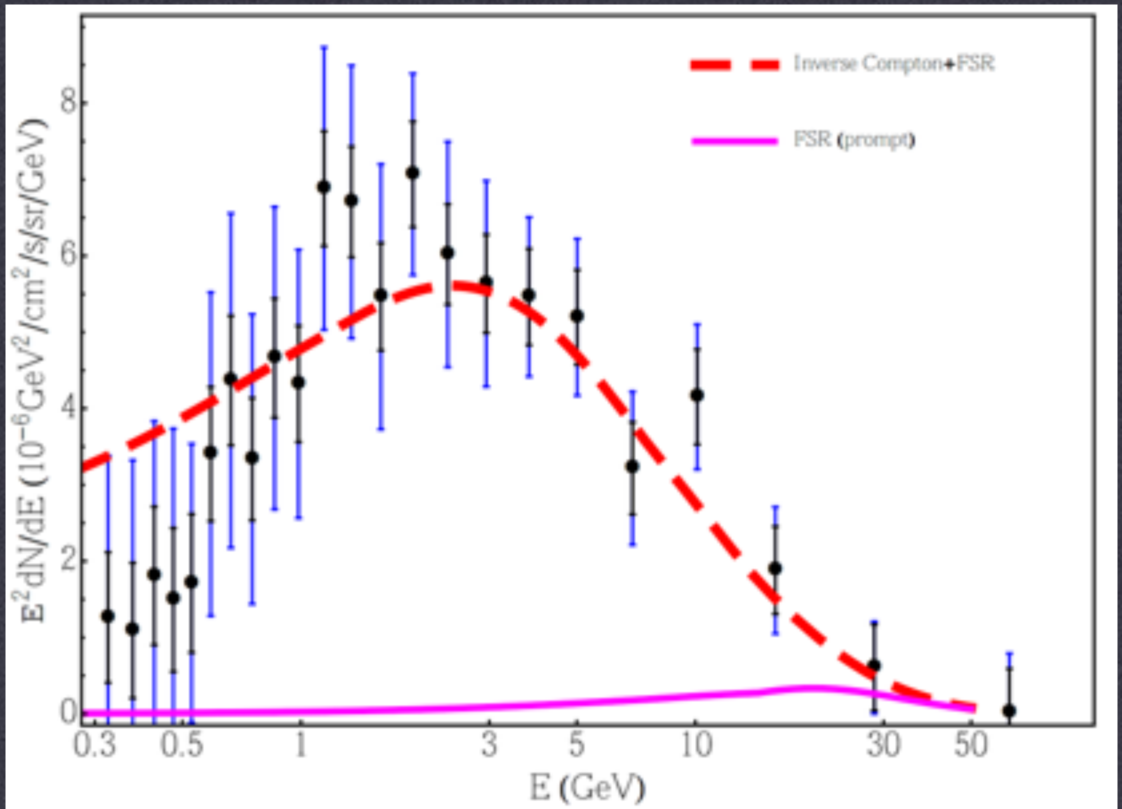
DWARF GALAXIES: MODEL BUILDING

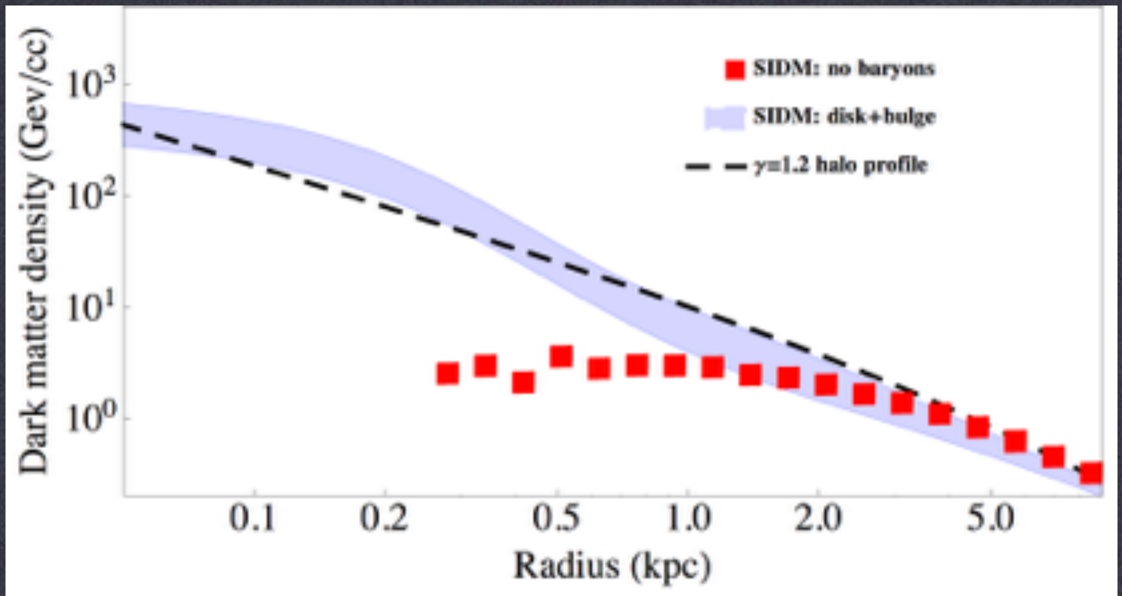
If the tension between the GC and dwarf observations persists, this could be addressed via secondary emission models:

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

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.





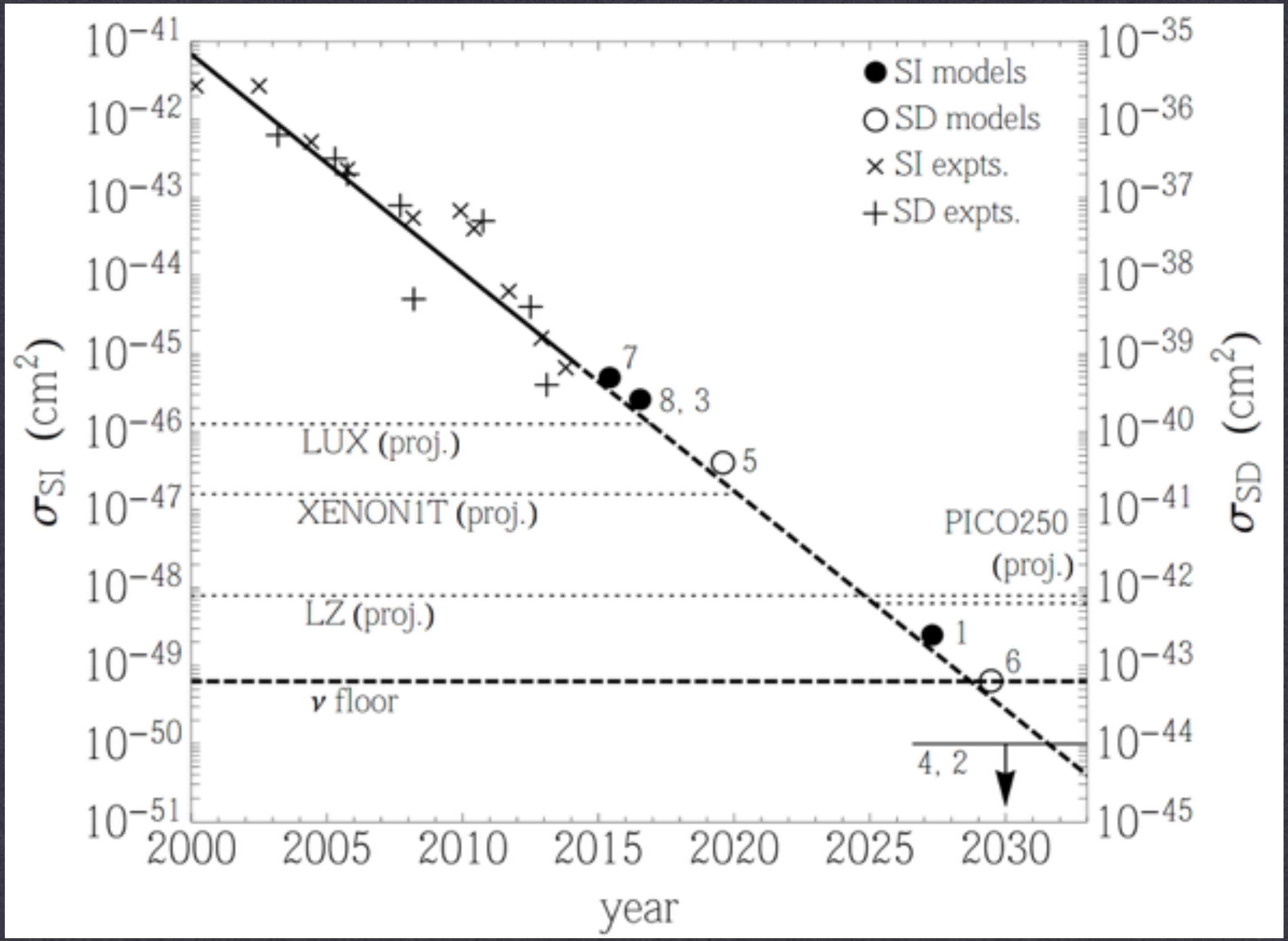
KAPLINGHAT, TL, YU (2014, 1311.6524)
KAPLINGHAT, TL, YU (2015, 1501.03507)

FUTURE TESTS OF DARK MATTER

DIRECT DETECTION SEARCHES

However, these limits are model dependent.

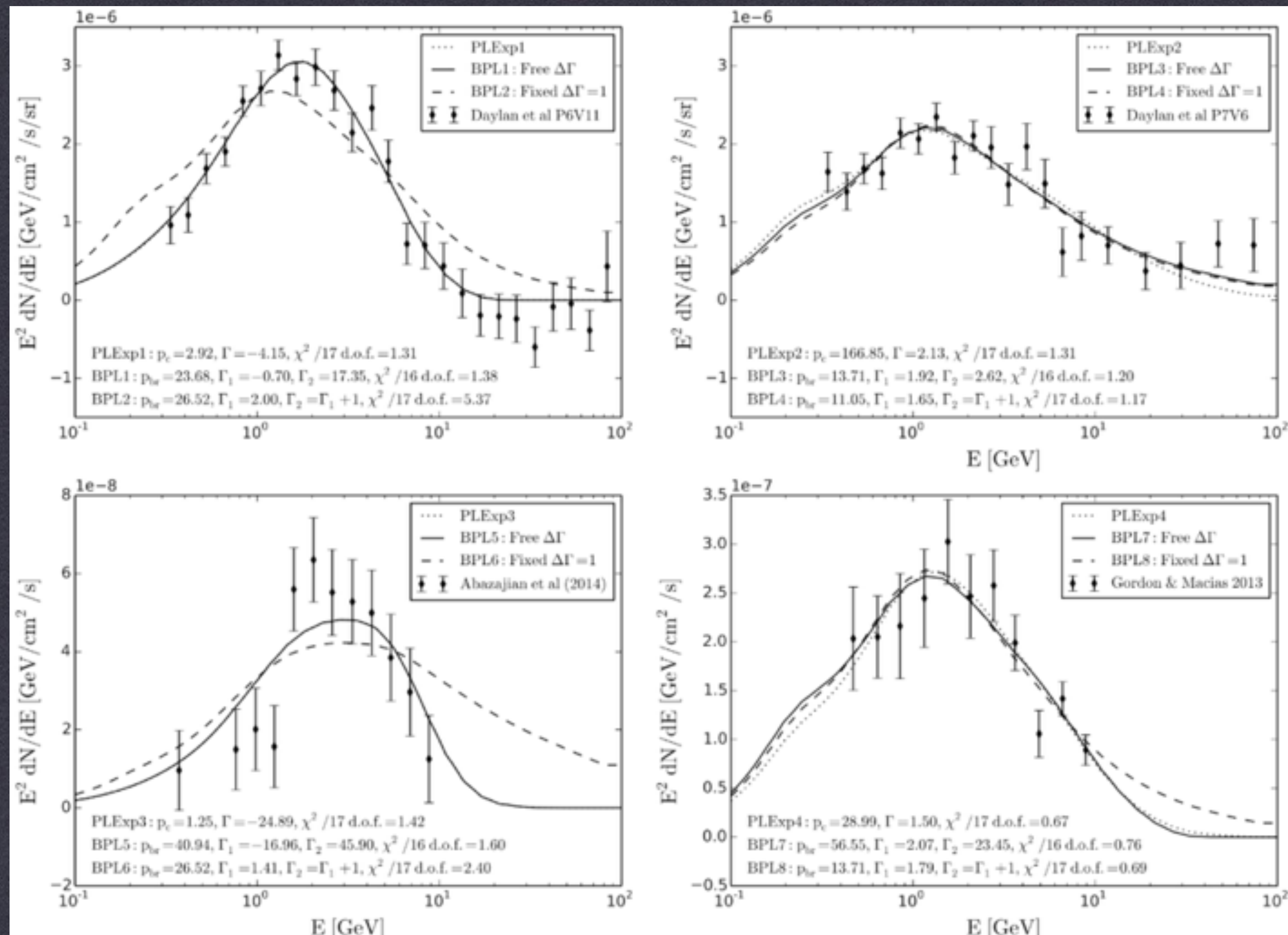
Annihilations through a pseudo-scaler mediator will be unobservable with direct detection



BERLIN, HOOPER, MCDERMOTT (2014)

INTERPRETATIONS

HADRONIC OUTBURSTS



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

CARLSON & PROFUMO (2014, 1405.7685)

INDIRECT DETECTION OF WIMPS

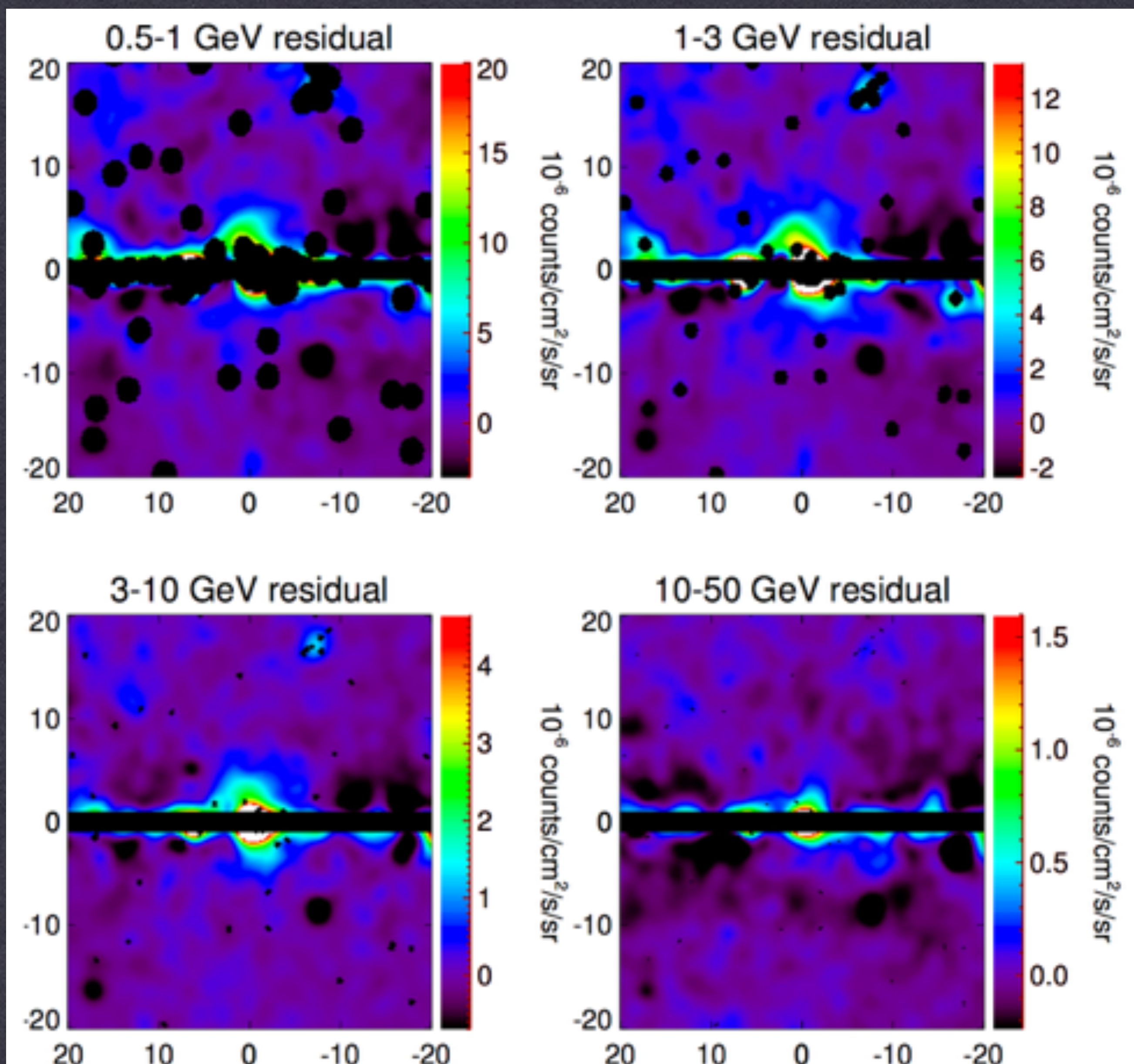
PUTTING IT ALL TOGETHER

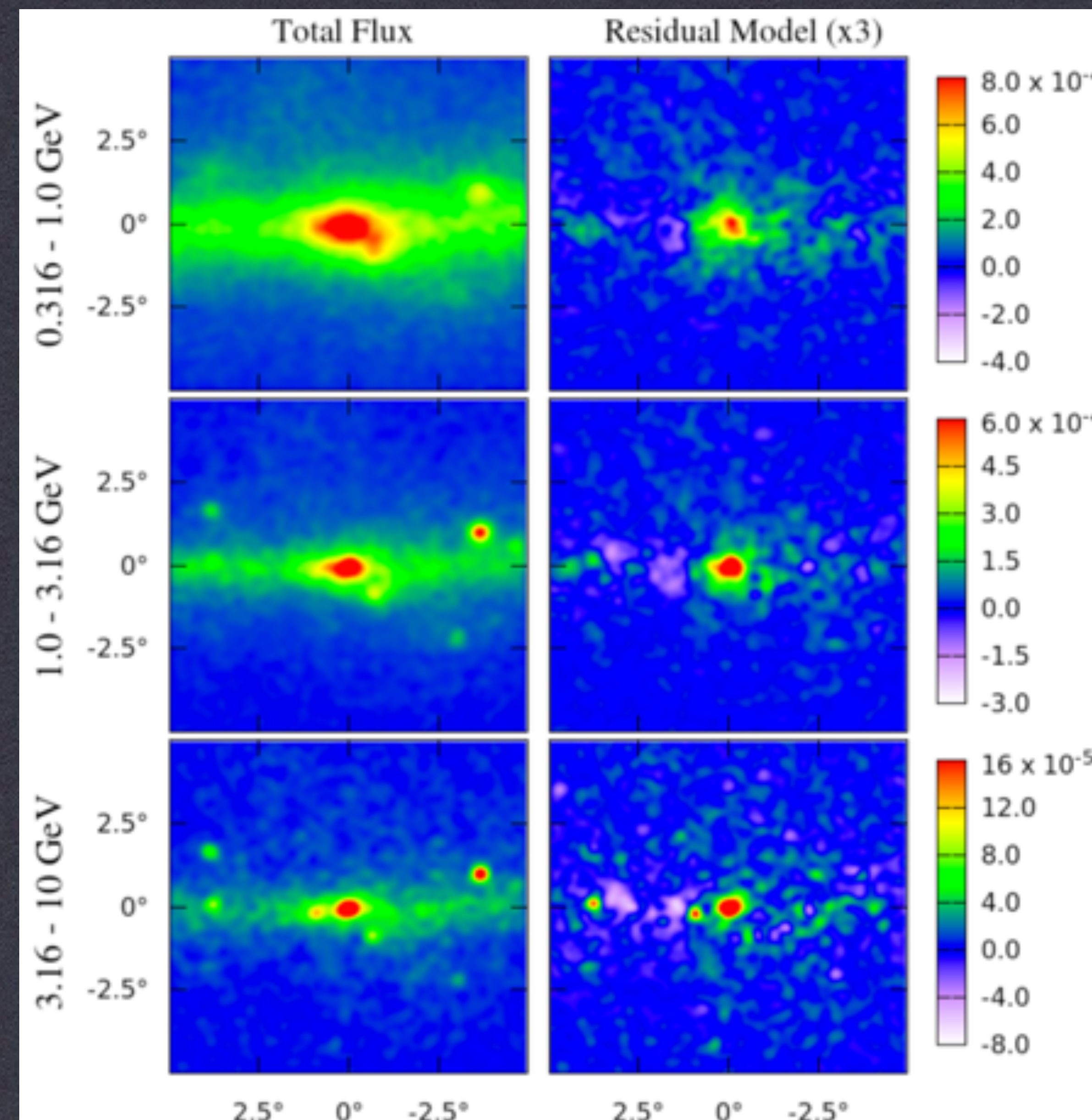
$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}}$$

$$\times \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(\boldsymbol{r}){\rm d}l\right\}{\rm d}\Omega'}_{\text{J-factor}}$$

Fortunately, these terms are separable for standard CDM

EMISSION MAPS





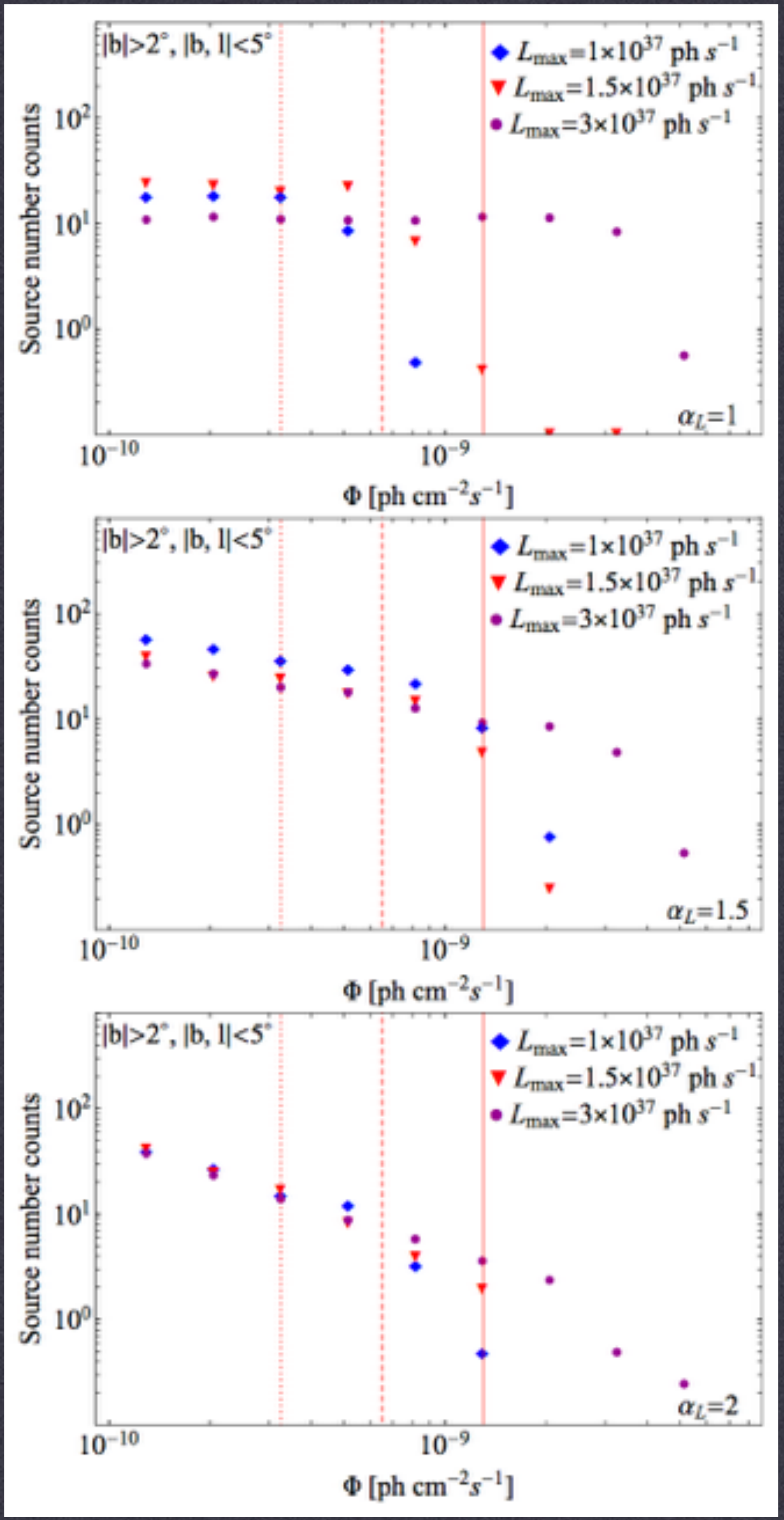
INNER GALAXY

GALACTIC CENTER

INTERPRETATIONS

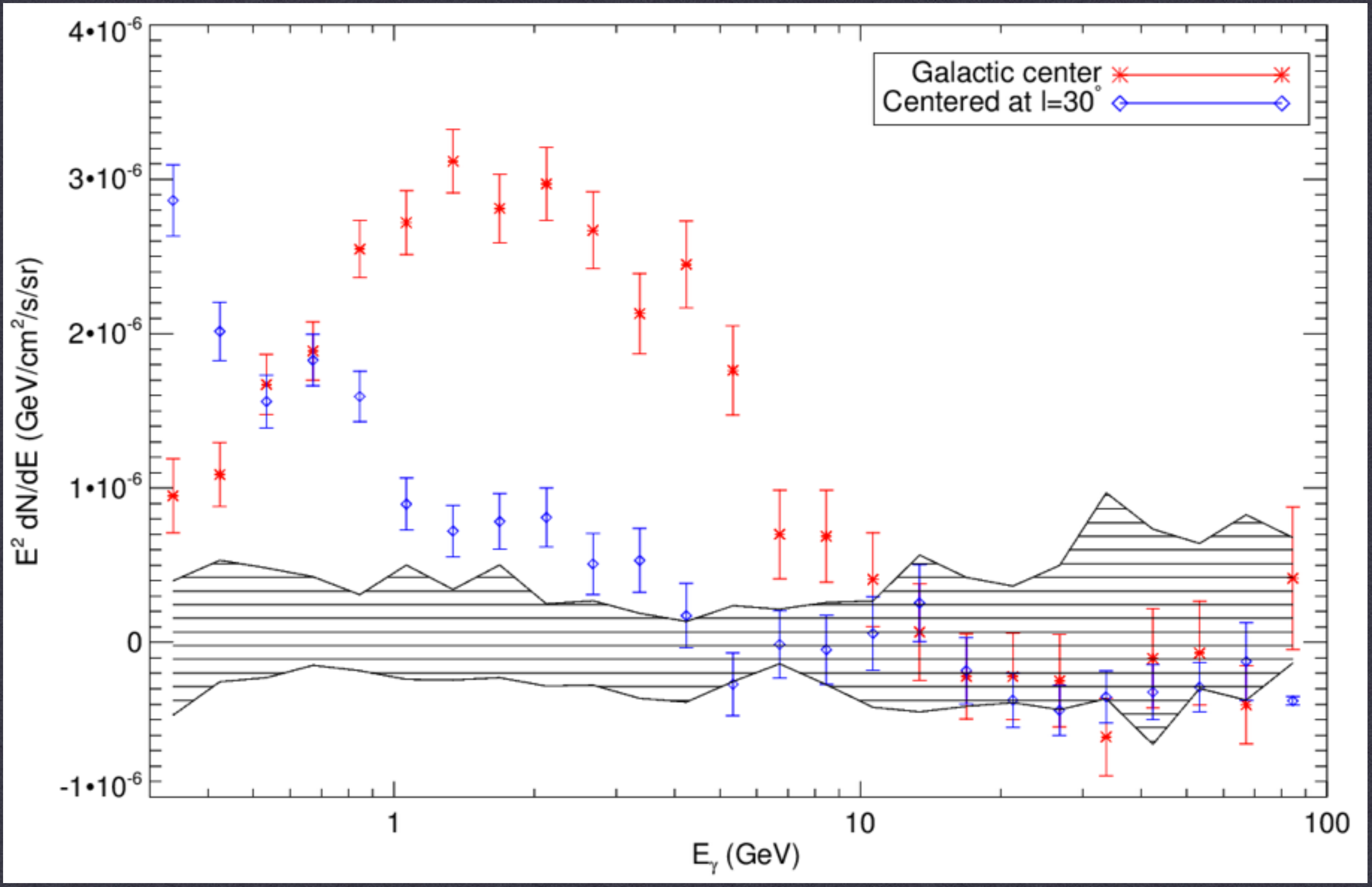
MILLISECOND PULSARS

- 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.

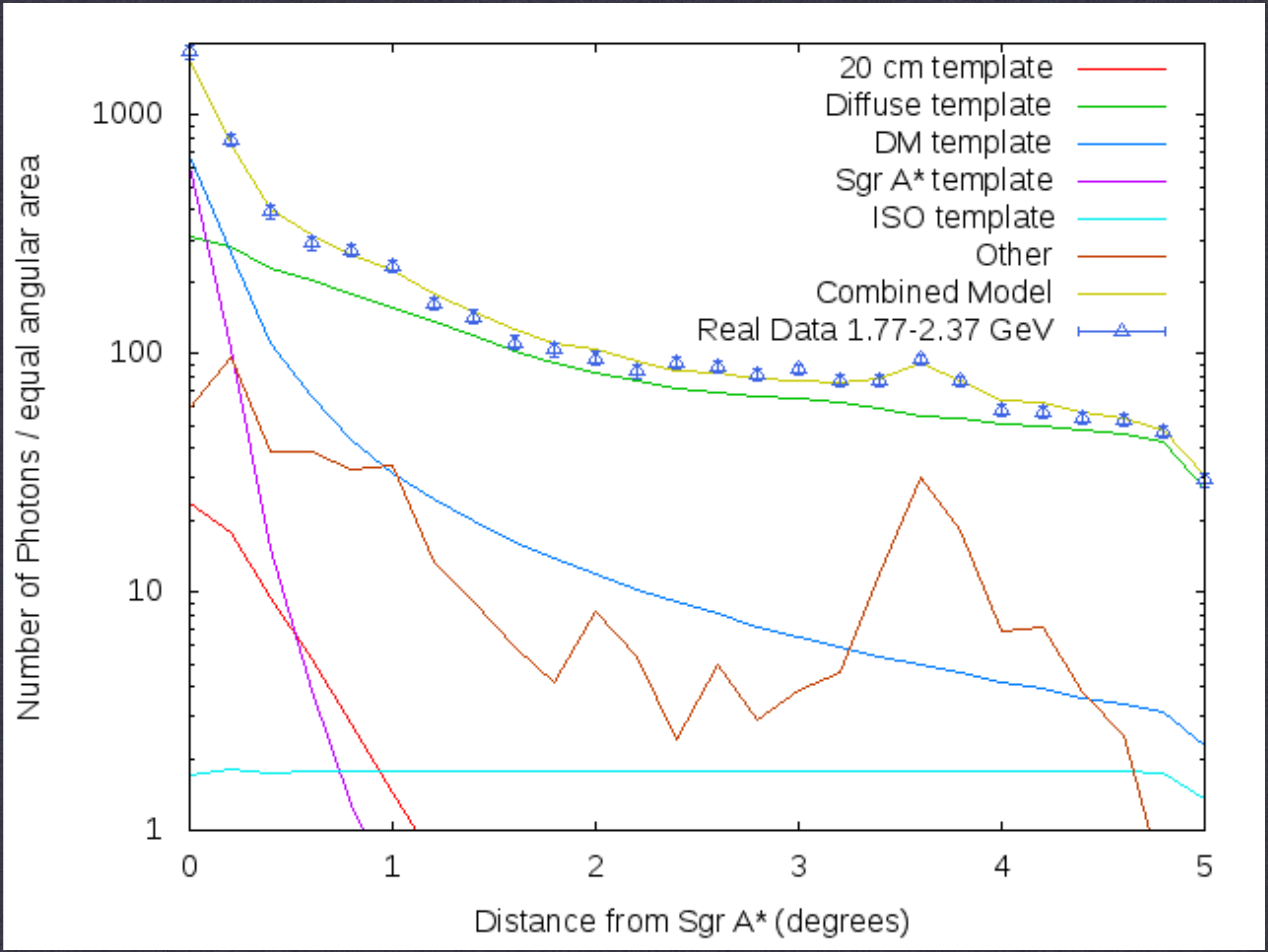


PETROVIC, SERPICO, ZAHARIJAS (2014, 1411.2980)

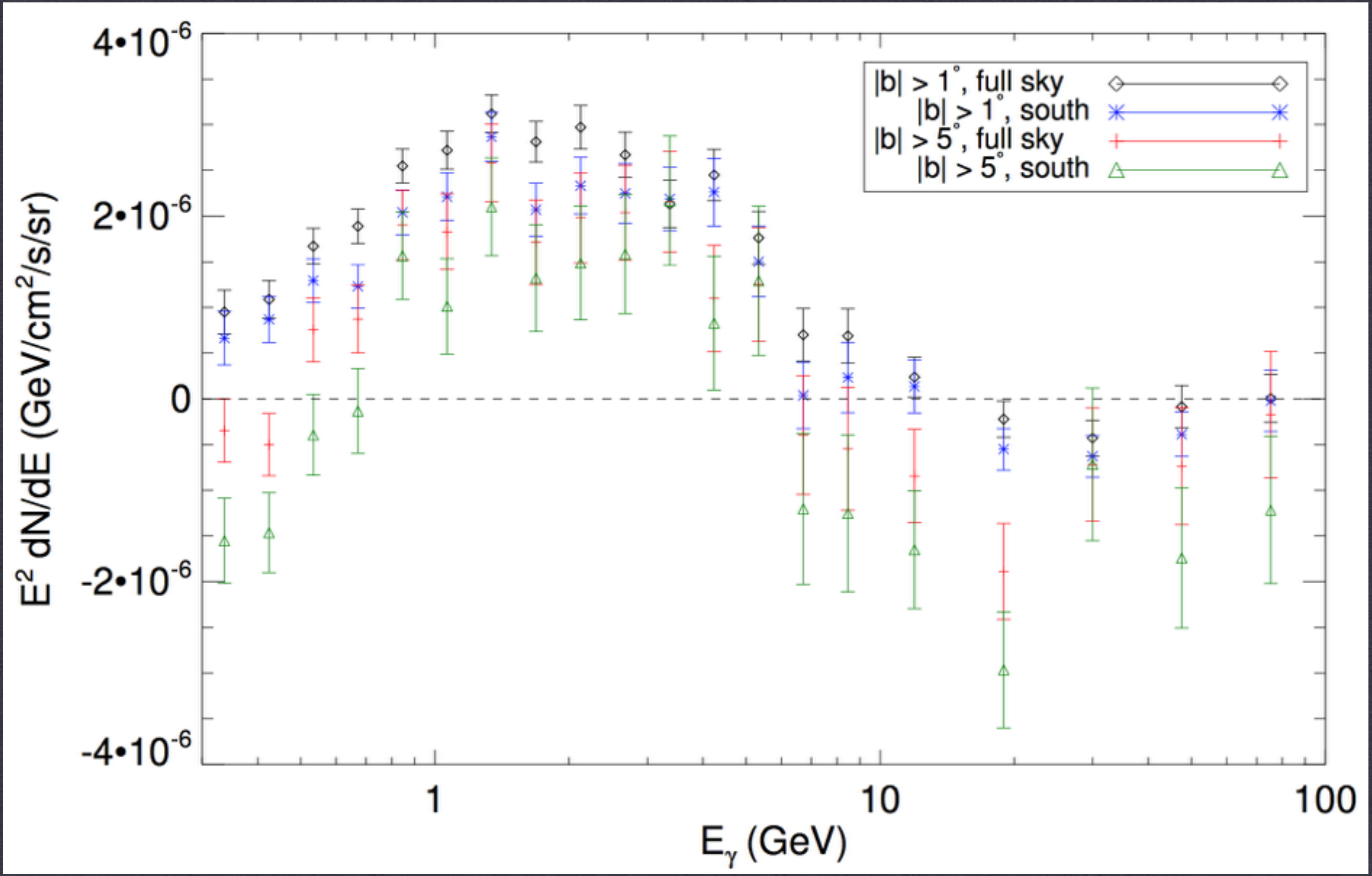
COMPARISON TO OTHER RESIDUALS



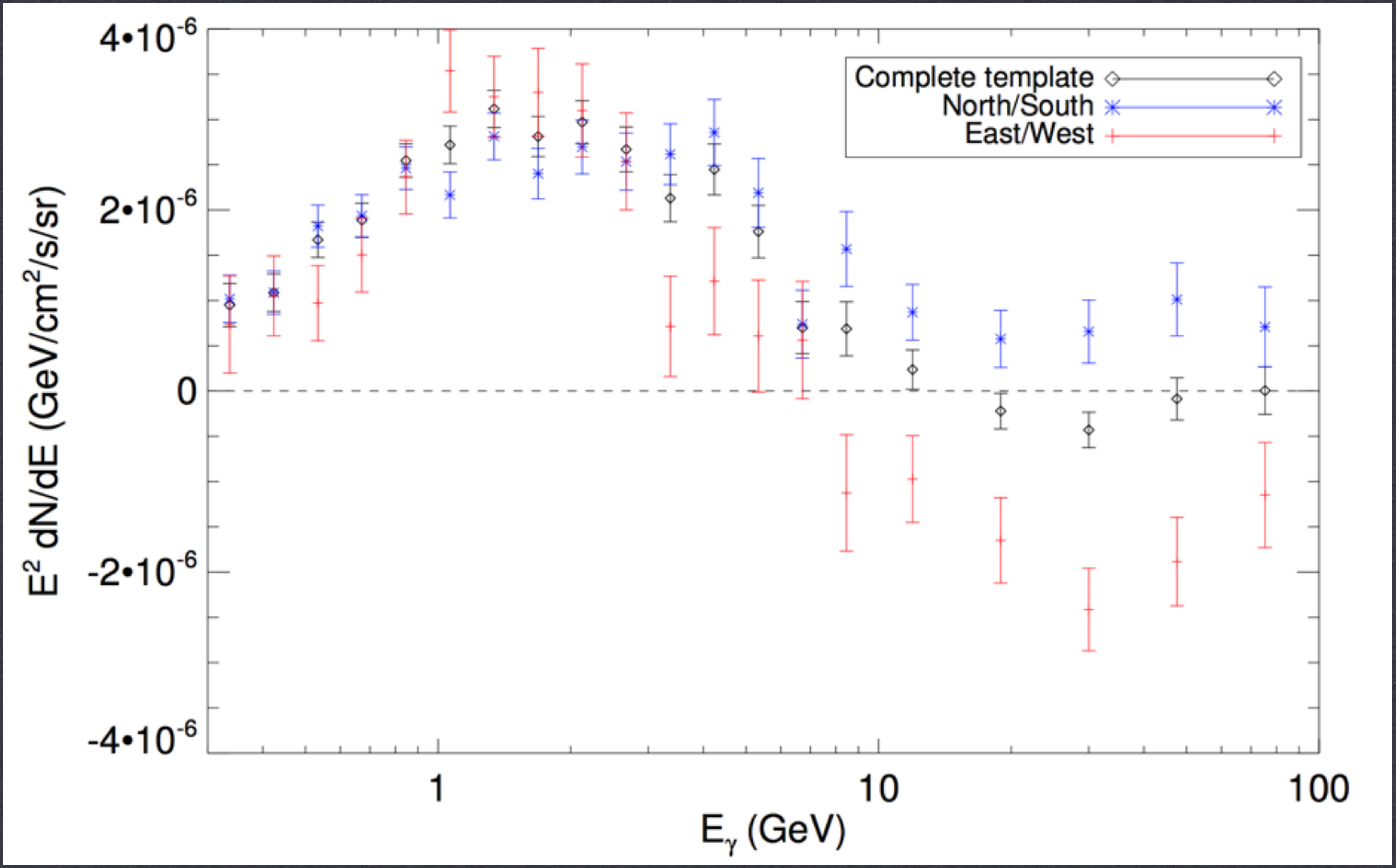
FRACTIONAL INTENSITY



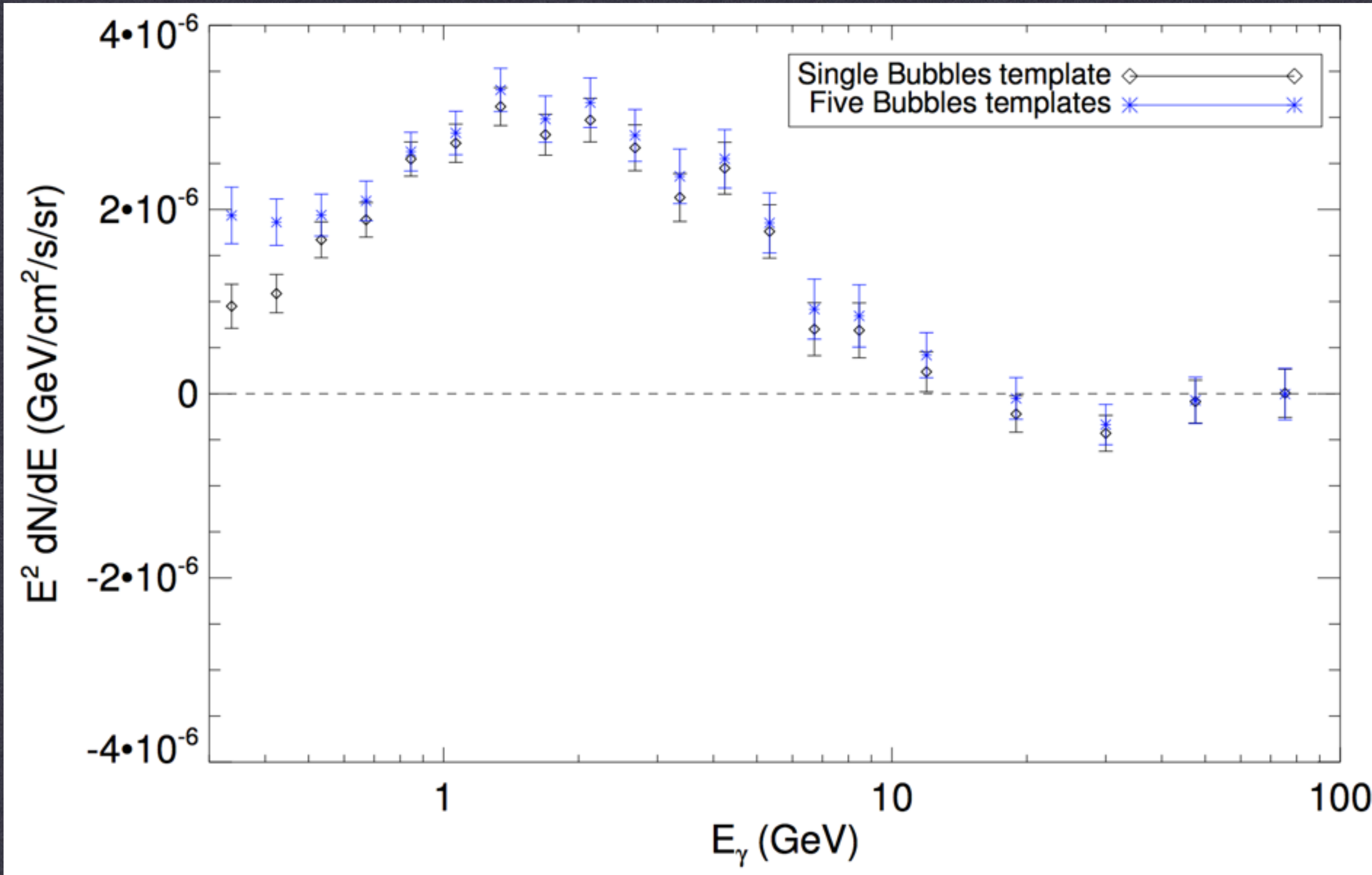
IG EXCESS WITH GC EVENTS REMOVED



SPECTRUM INSIDE/OUTSIDE BUBBLES

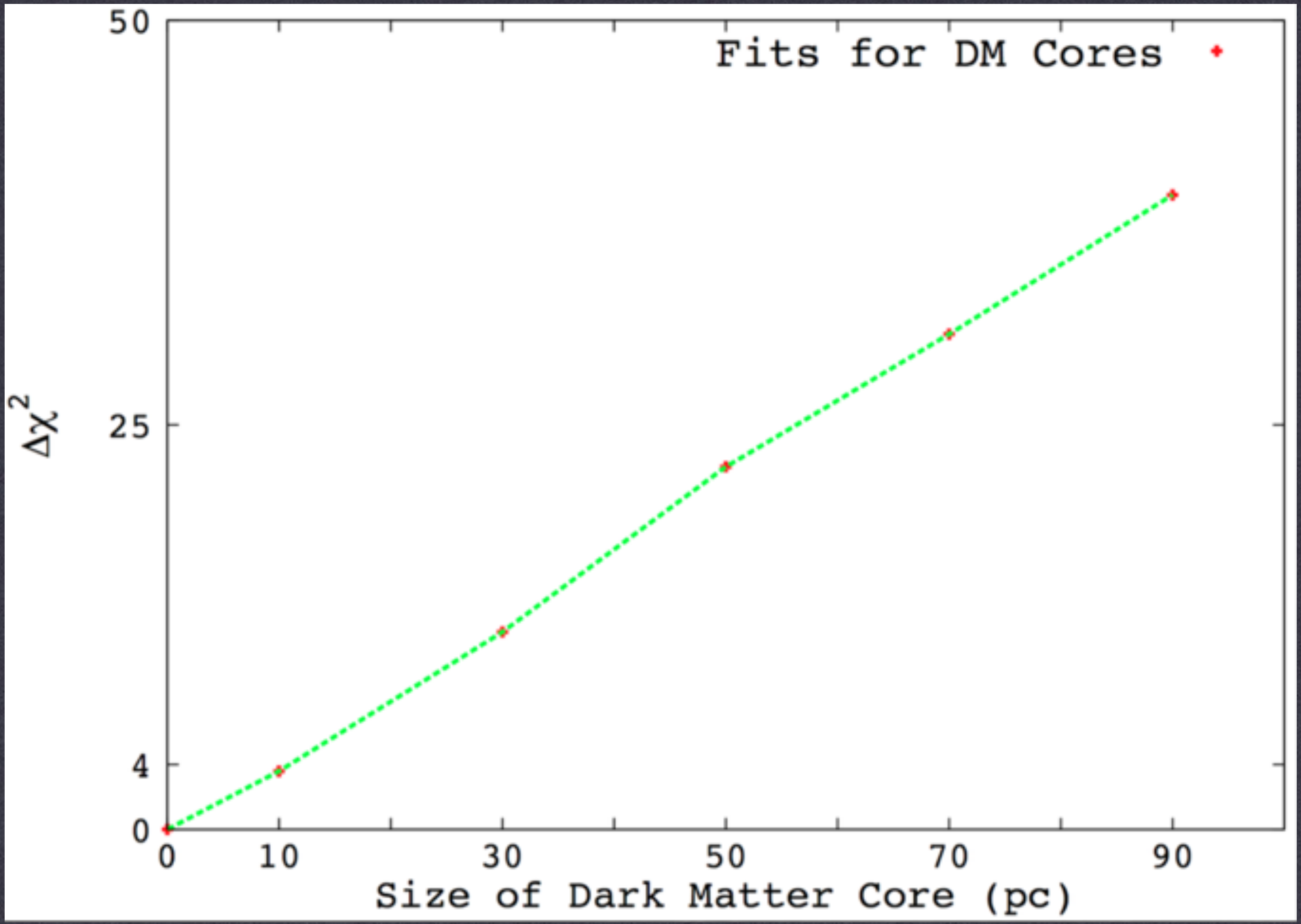


SPECTRAL VARIATION INSIDE BUBBLES



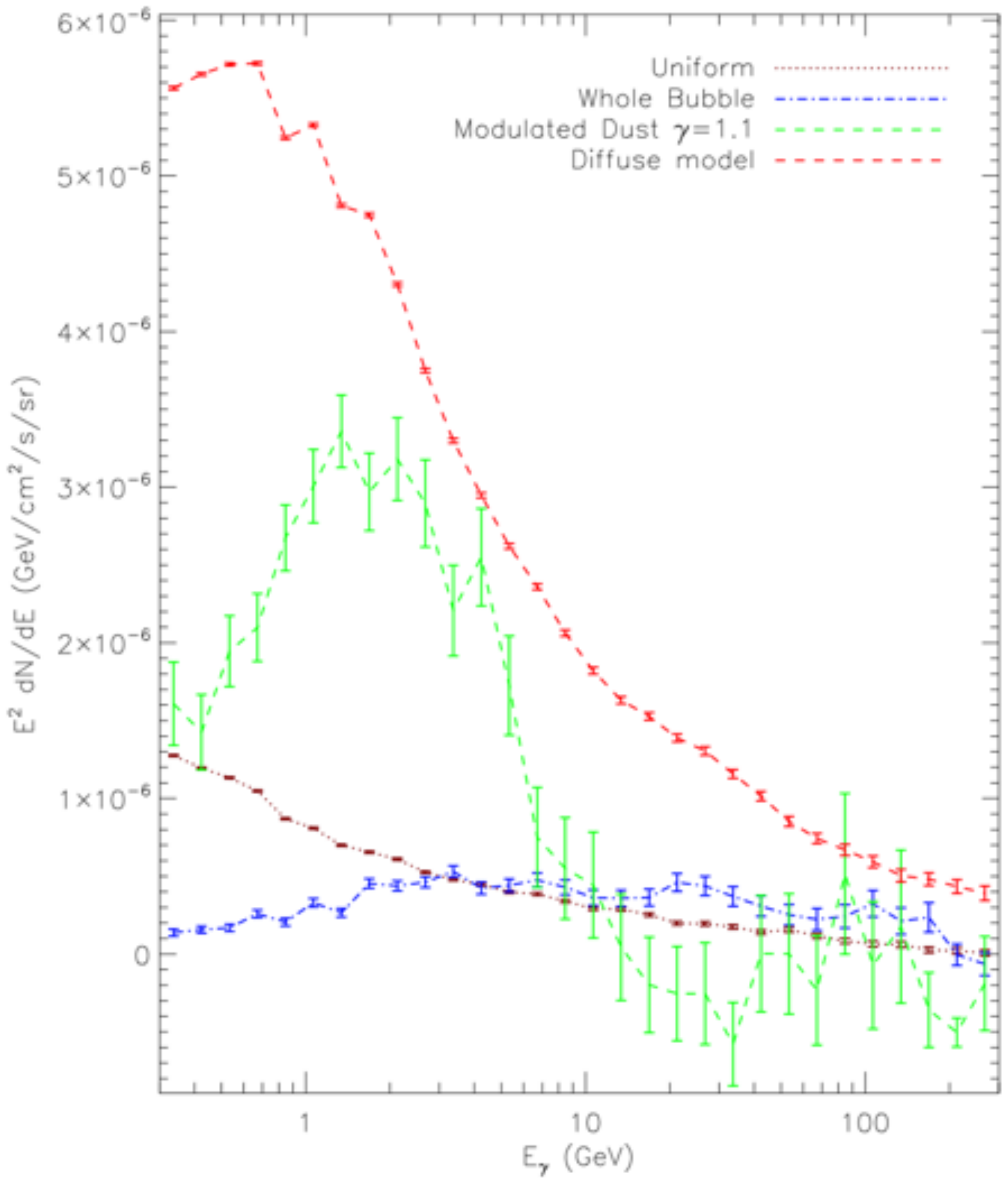
PROFILE CORES

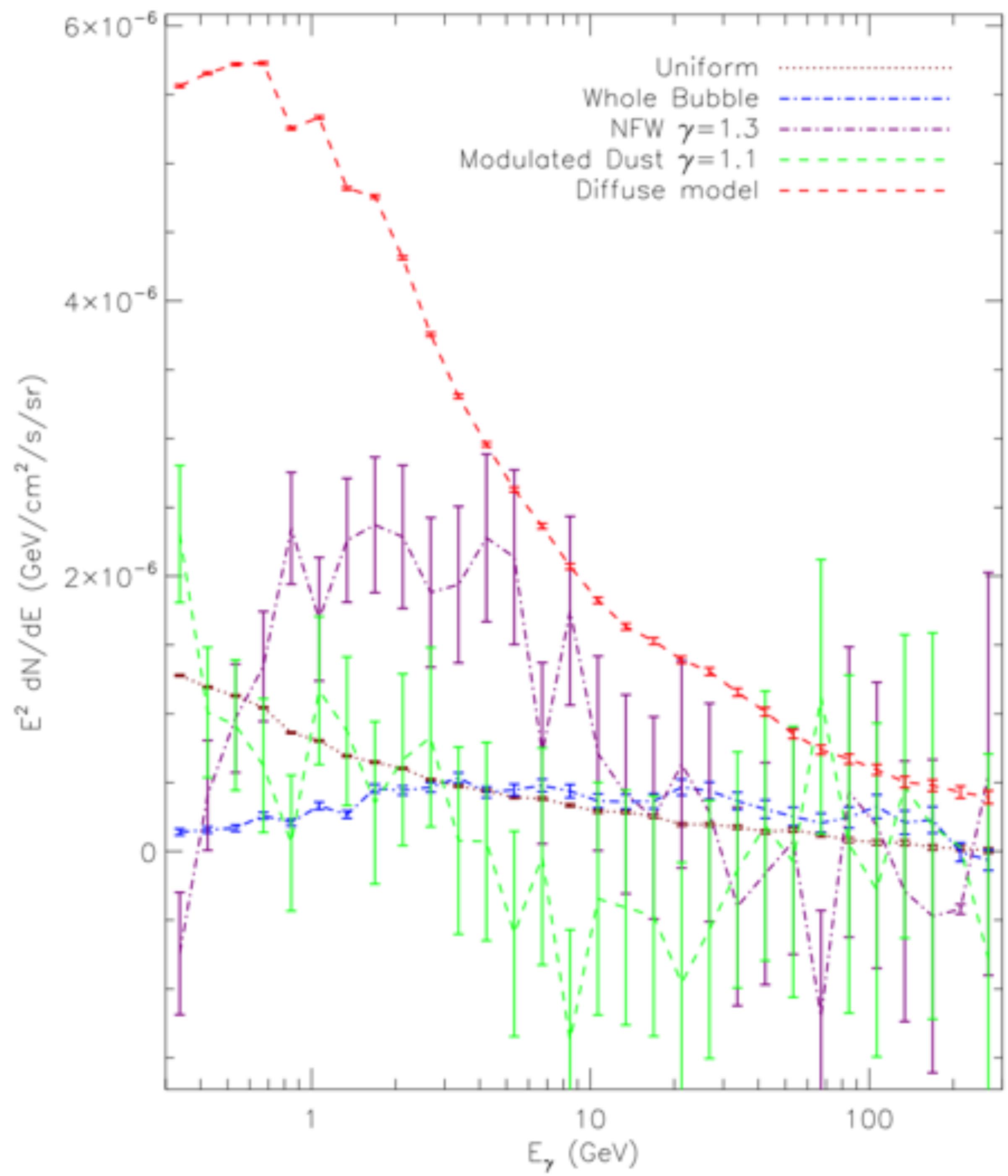
GALACTIC CENTER



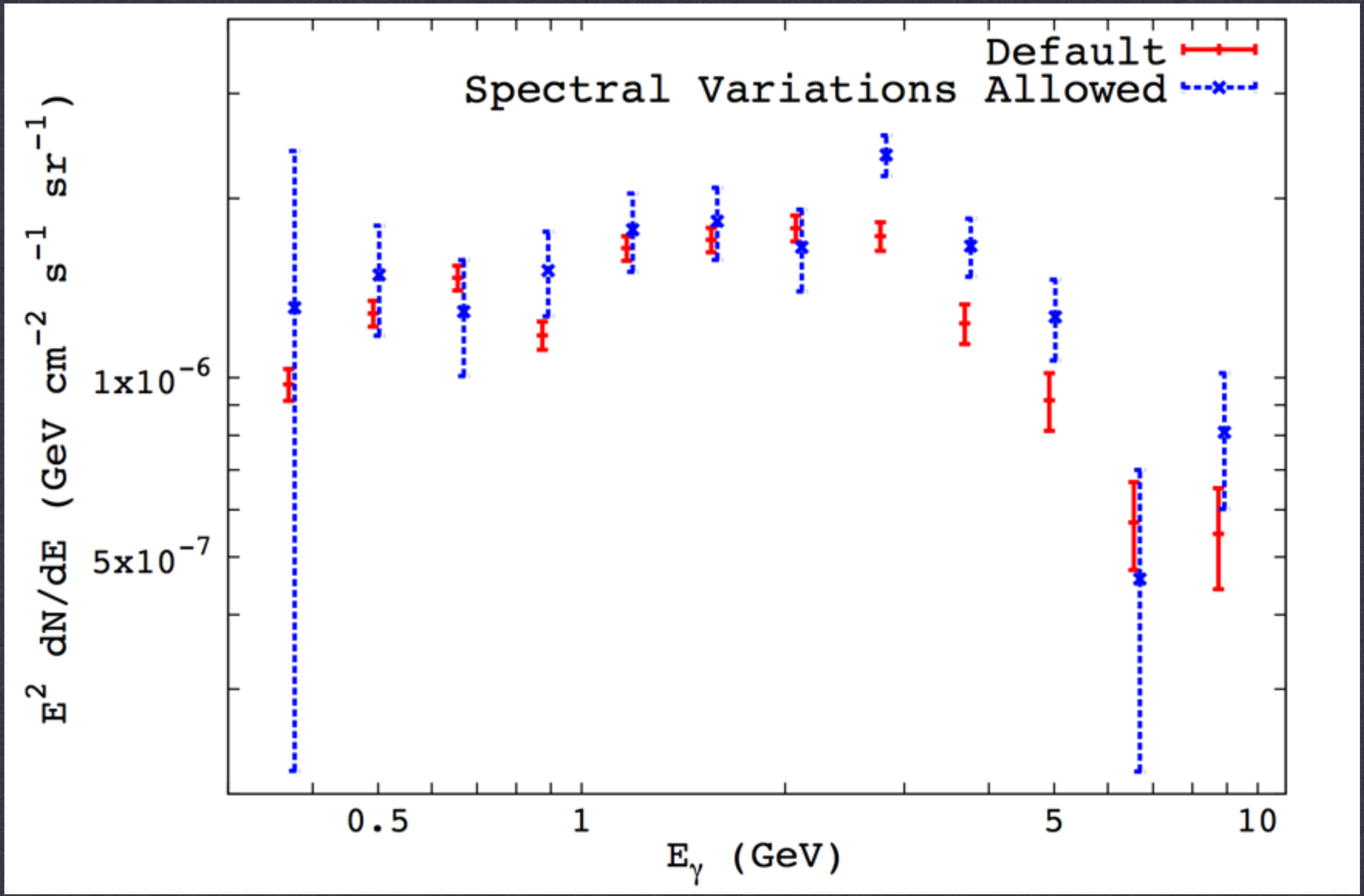
The emission intensity continues to rise to within 10 pc of the GC.

CORRELATION WITH GAS

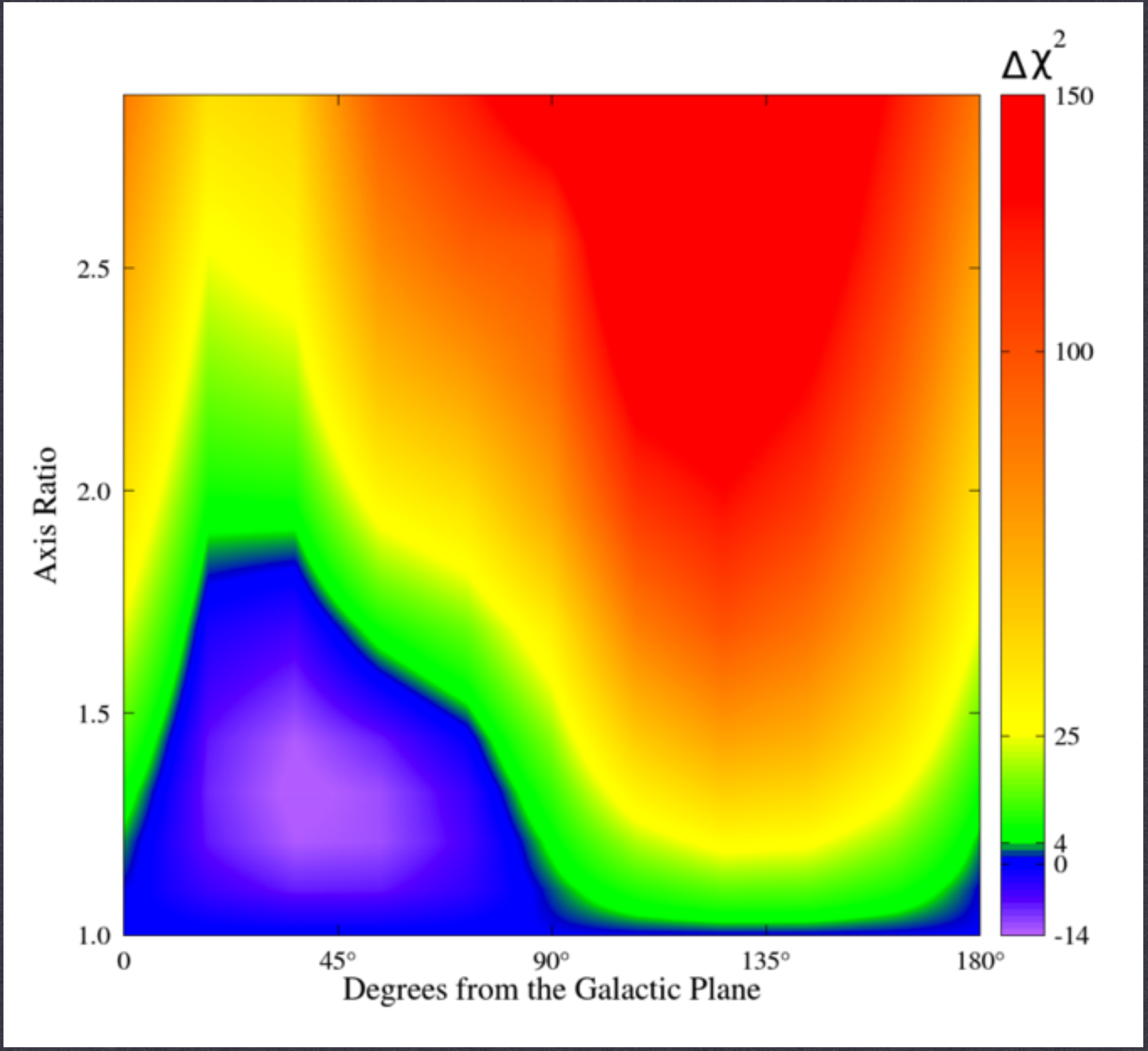




SPECTRAL VARIATIONS IN DIFFUSE MODEL

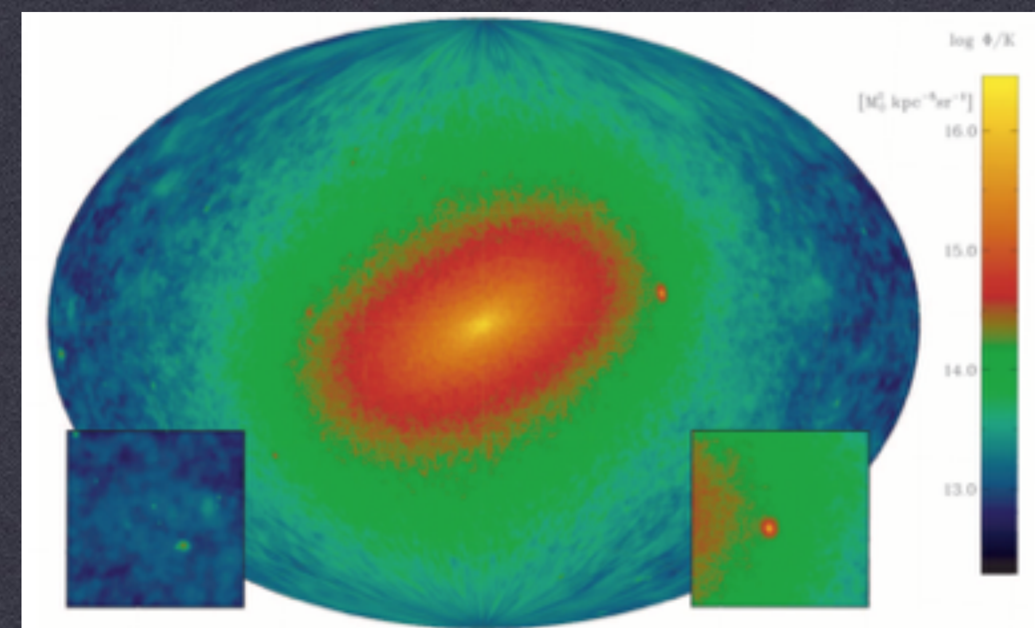


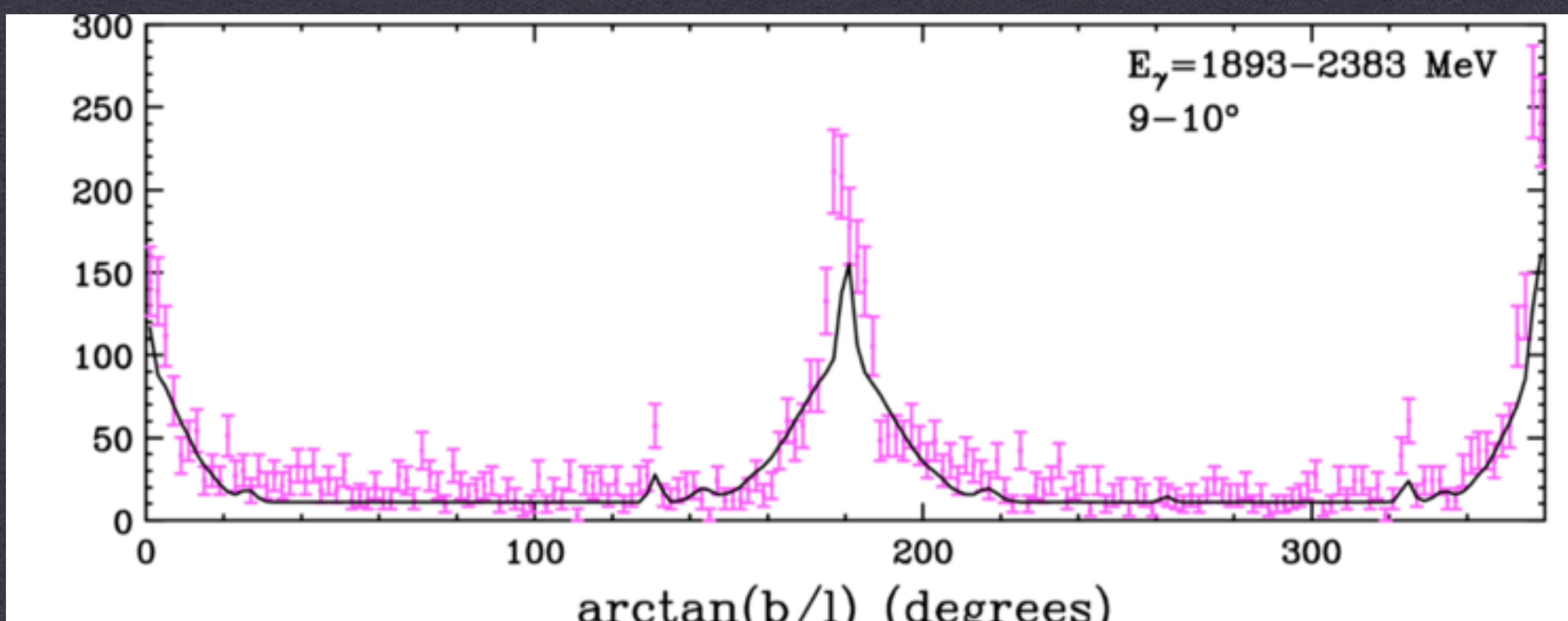
ELLIPTICITY IN GENERAL DIRECTION



PREVIOUS WORK

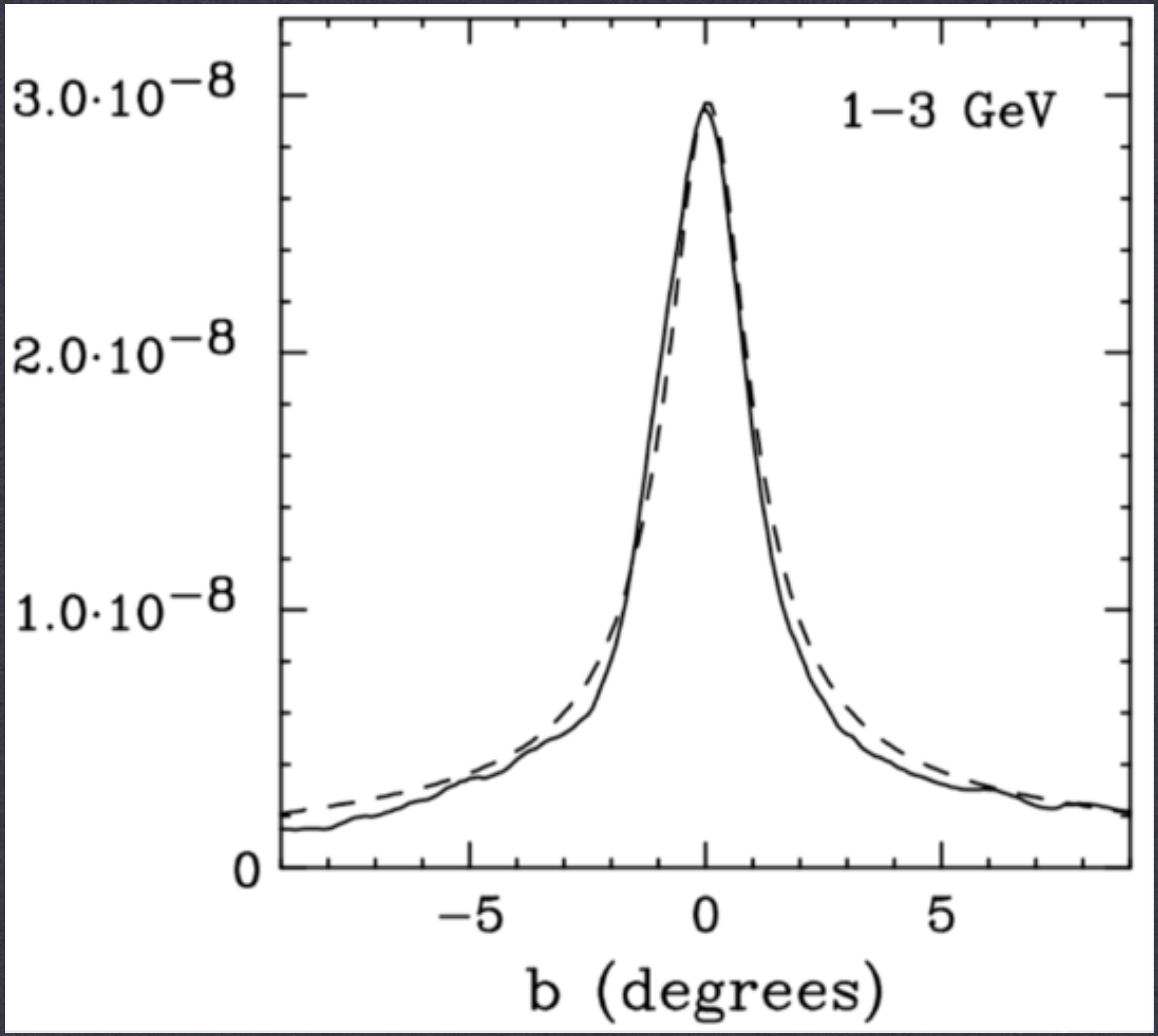
GOODENOUGH & HOOPER (2009), HOOPER & GOODENOUGH (2011)





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

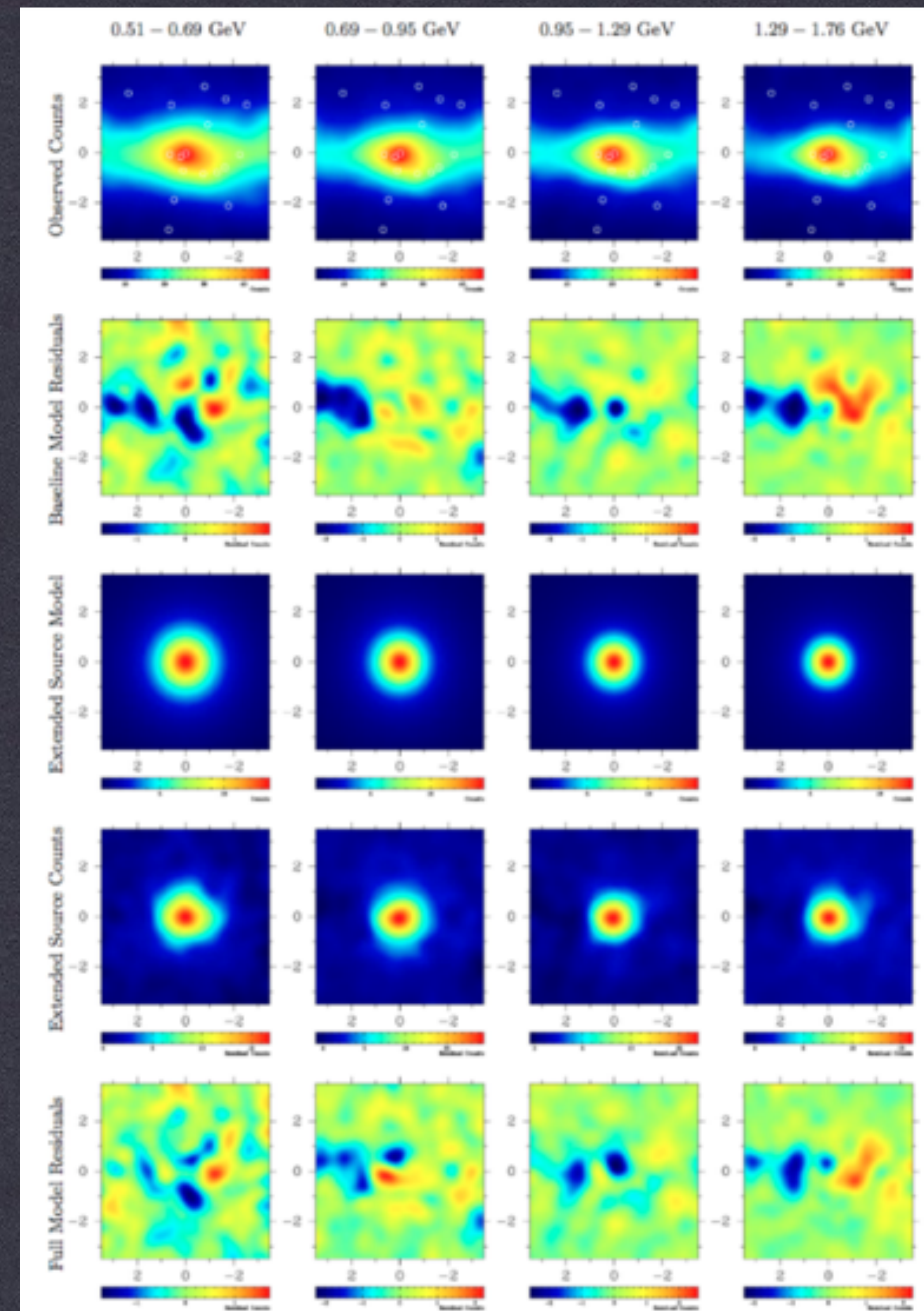
ABAZAJIAN & KAPLINGHAT (2011)

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

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

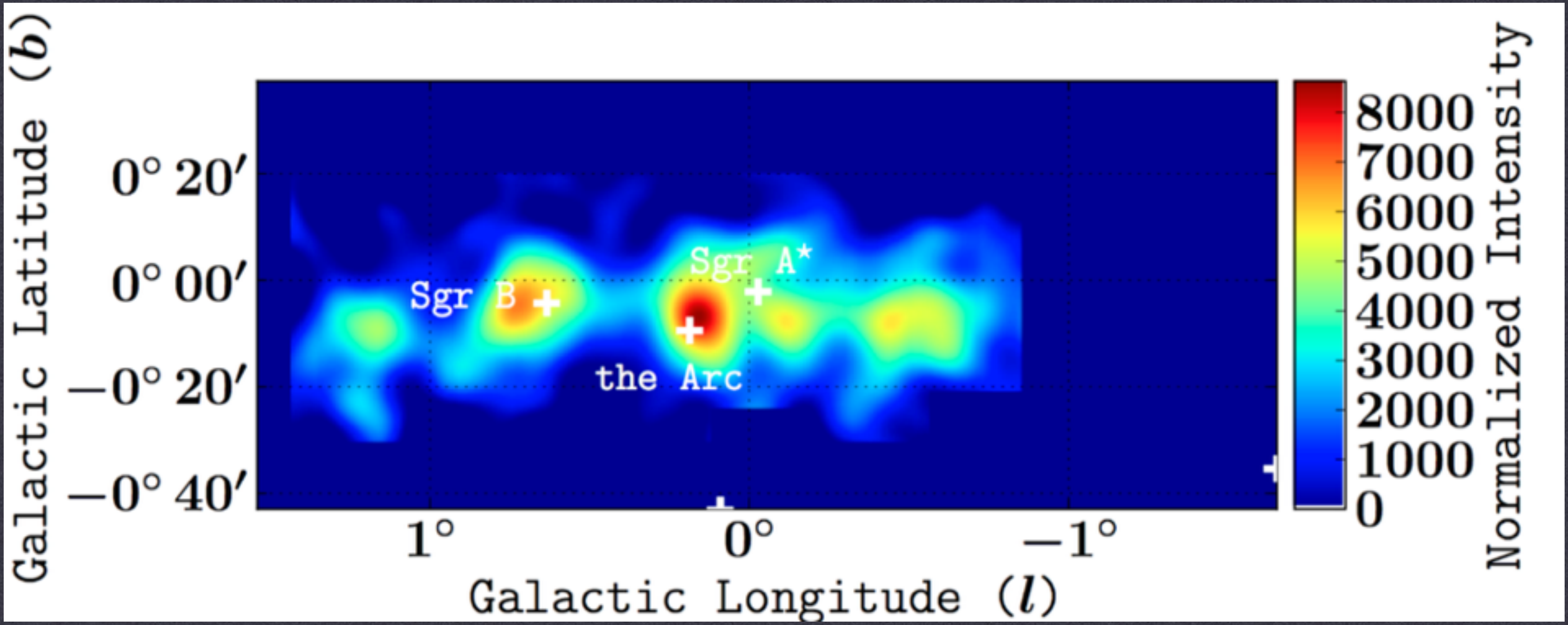
μ_i = model counts $\quad$ k_i=data counts



PREVIOUS WORK

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

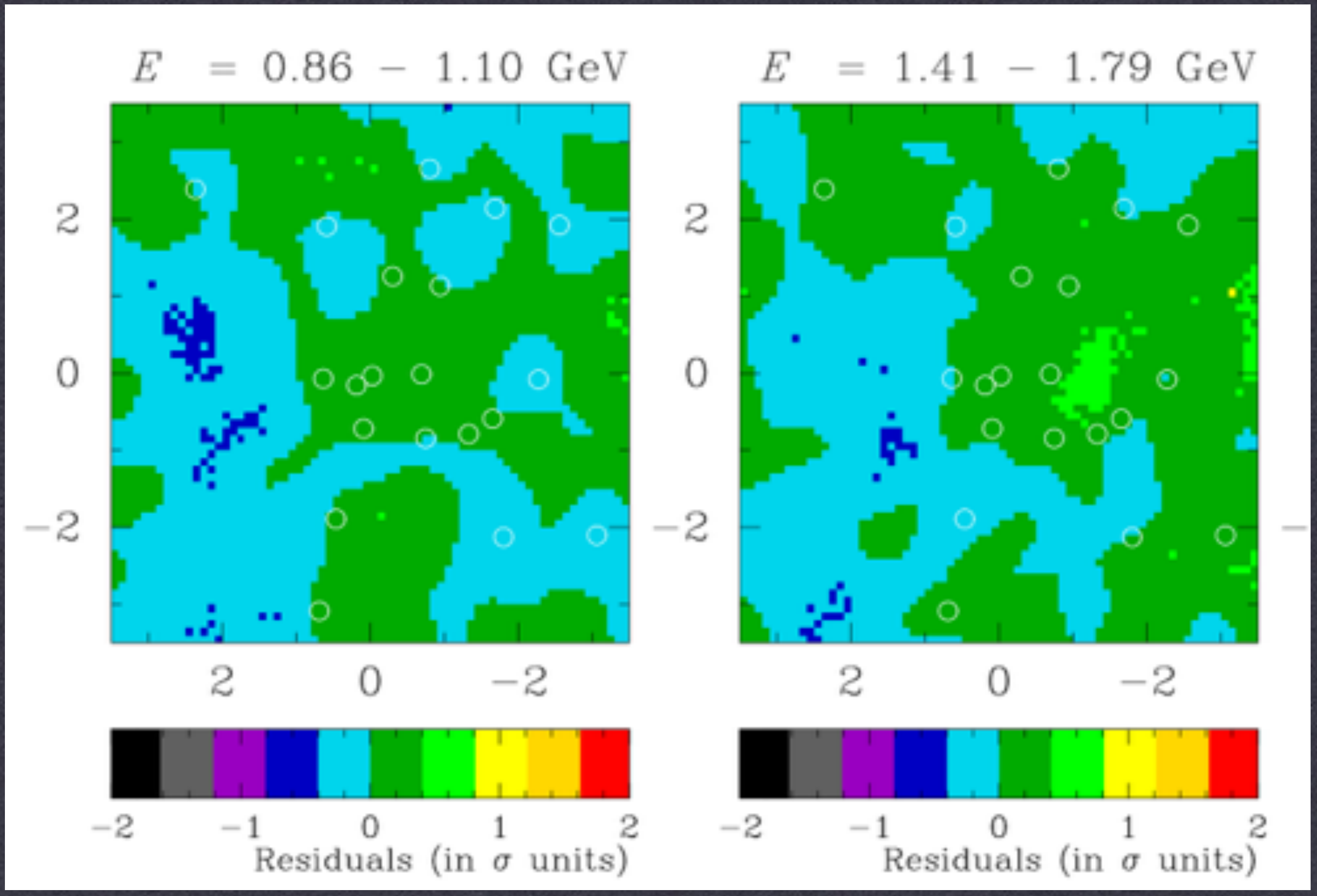
Use Log-Likelihood Formulation, but add additional components corresponding to known high-energy emission sources (20 cm lines, H.E.S.S. ridge)

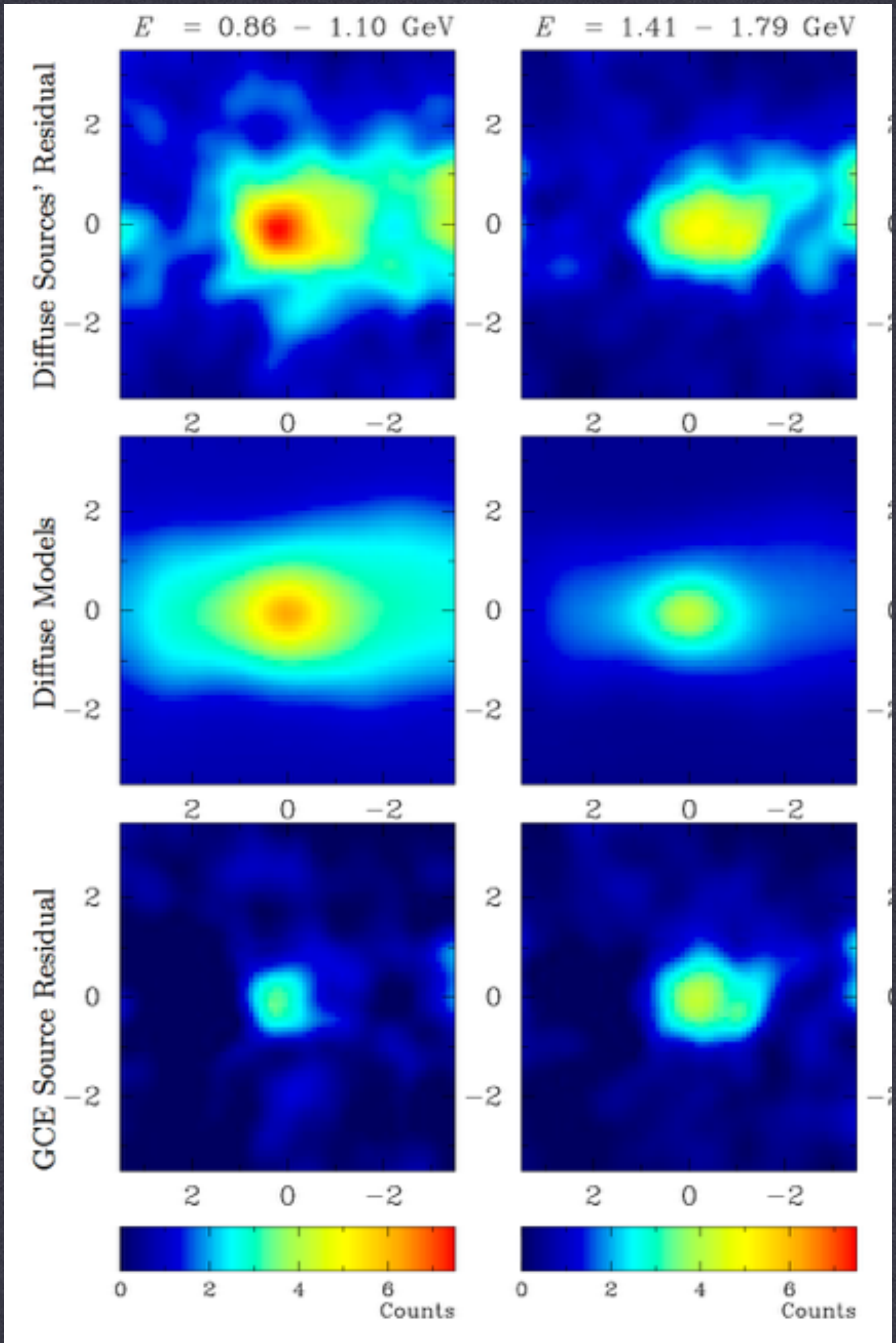


PREVIOUS WORK

ABAZAJIAN ET AL. (2014)

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





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 ≃ 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-

DAYLAN ET AL. (2014)

TWO ANALYSIS METHODS

INNER GALAXY

- Mask galactic plane (e.g. |b| > 1º)
- Bright point sources masked at 2º
- Allow diffuse templates (galactic diffuse, isotropic, Fermi bubbles, dark matter) to float independently in each of 30 energy bins

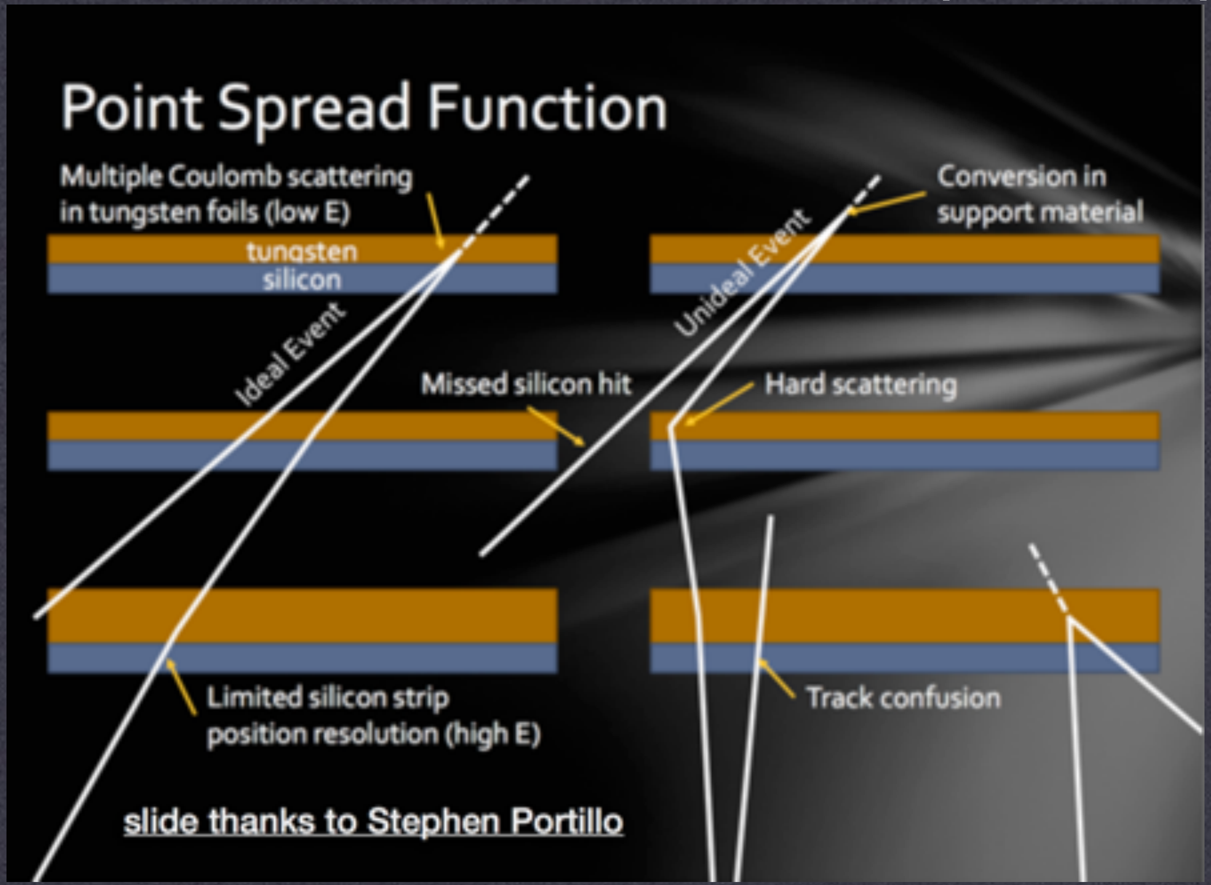
GALACTIC CENTER

- Box around the GC (10º x 10º)
- 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

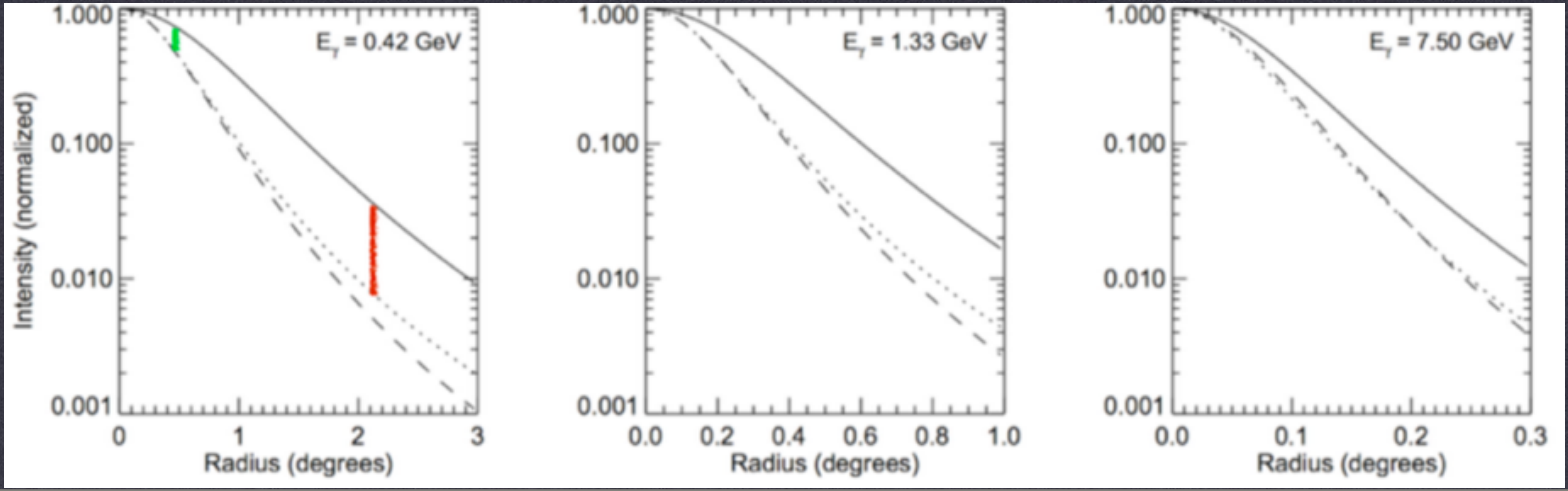
DAYLAN ET AL. (2014)

CTBCORE

see Portillo & Finkbeiner (1406.0507)

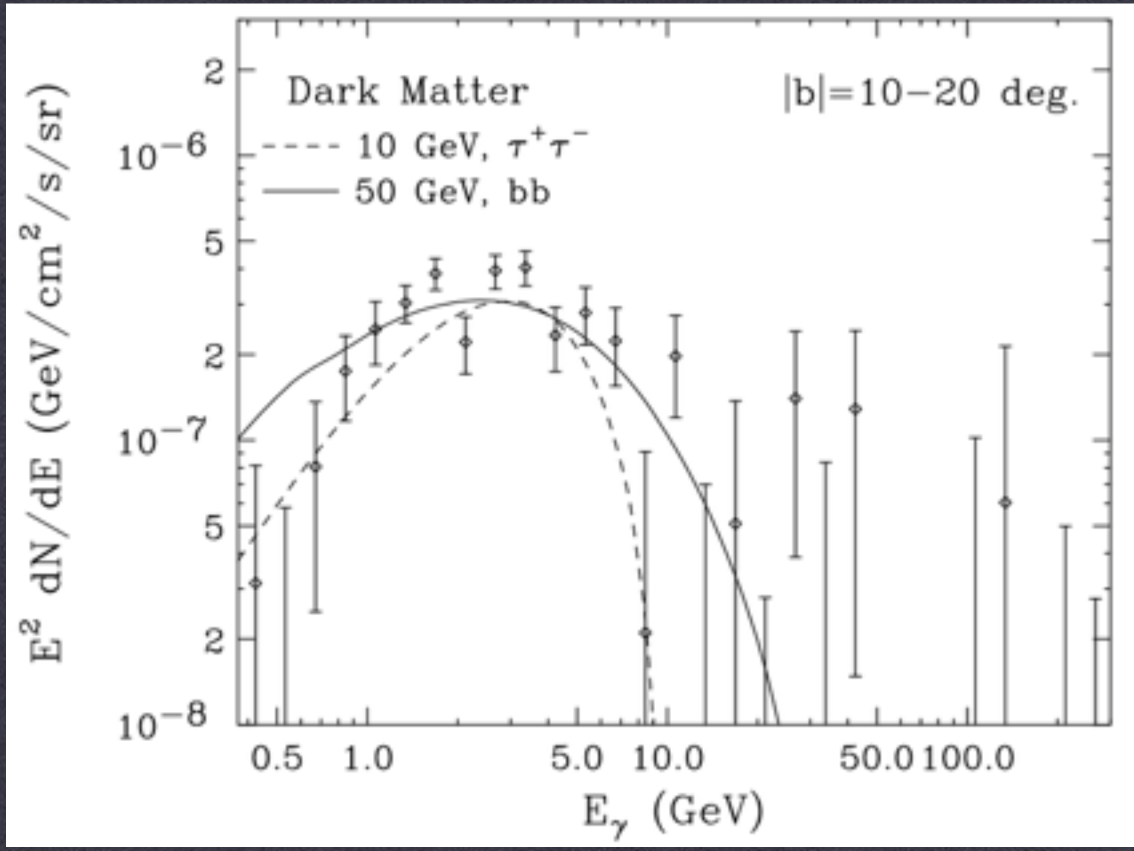


Use additional information to classify each photon event based on the accuracy of its directional reconstruction

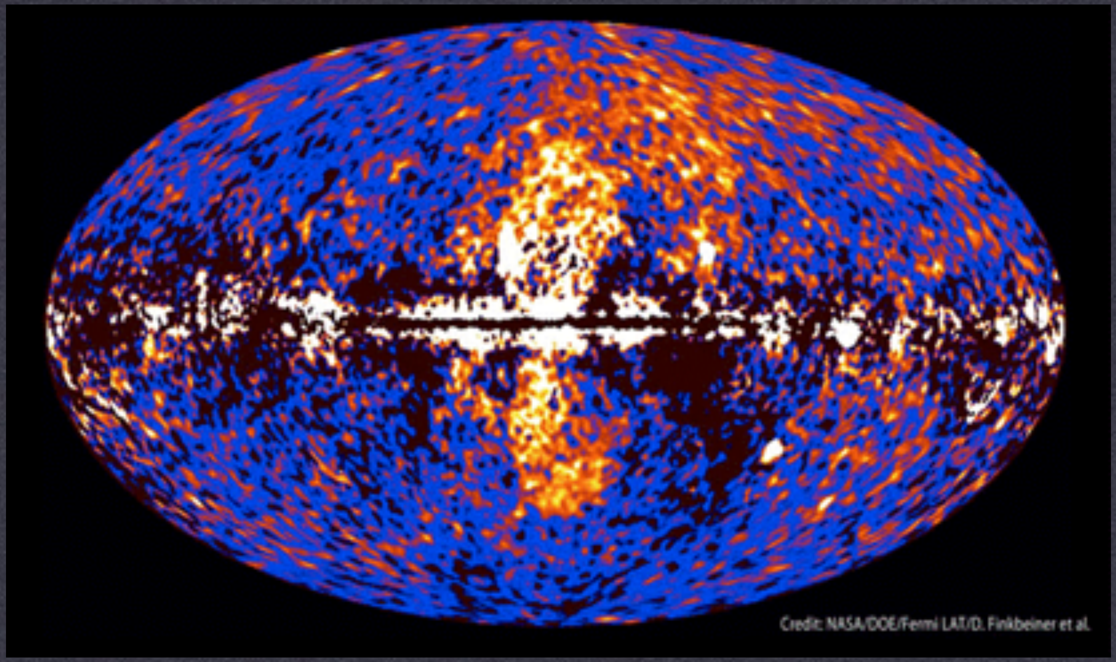


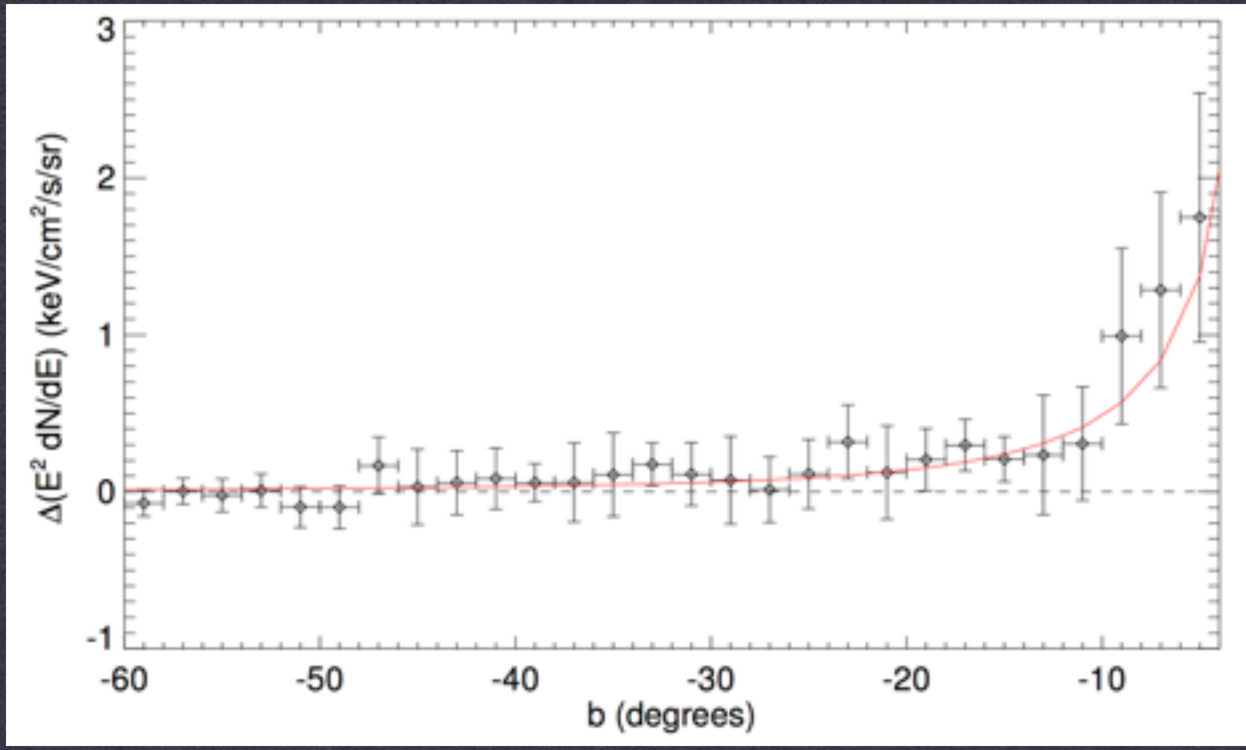
PREVIOUS WORK

HOOPER & SLATYER (2013)



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



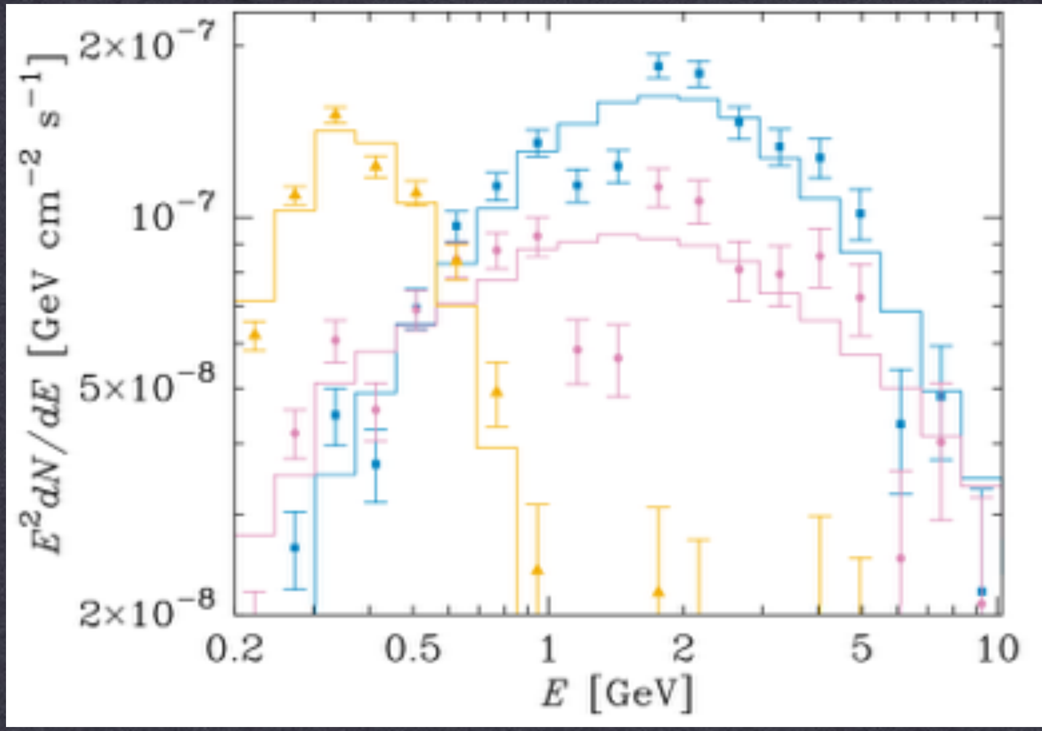


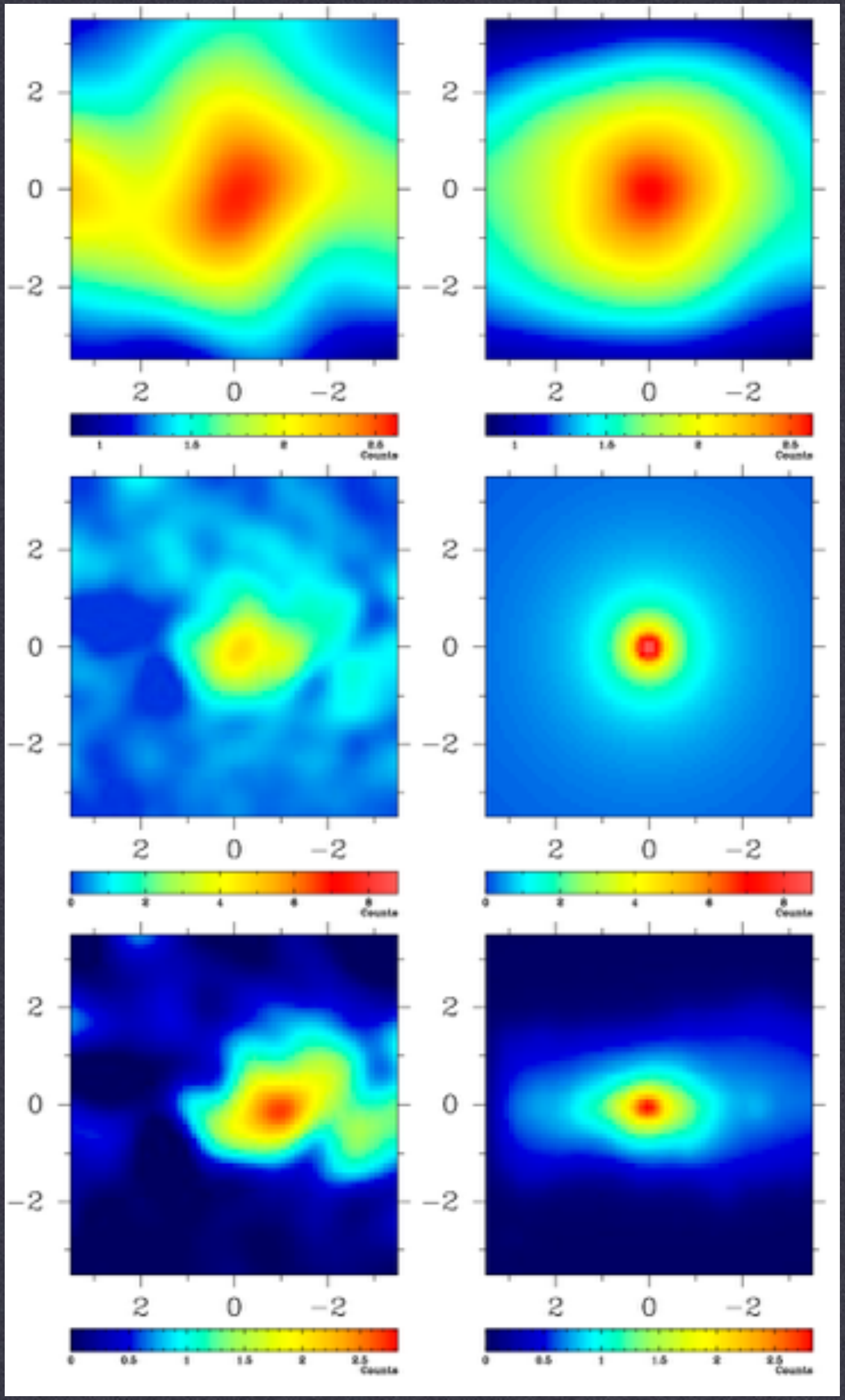
FUTURE TESTS OF DARK MATTER

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.





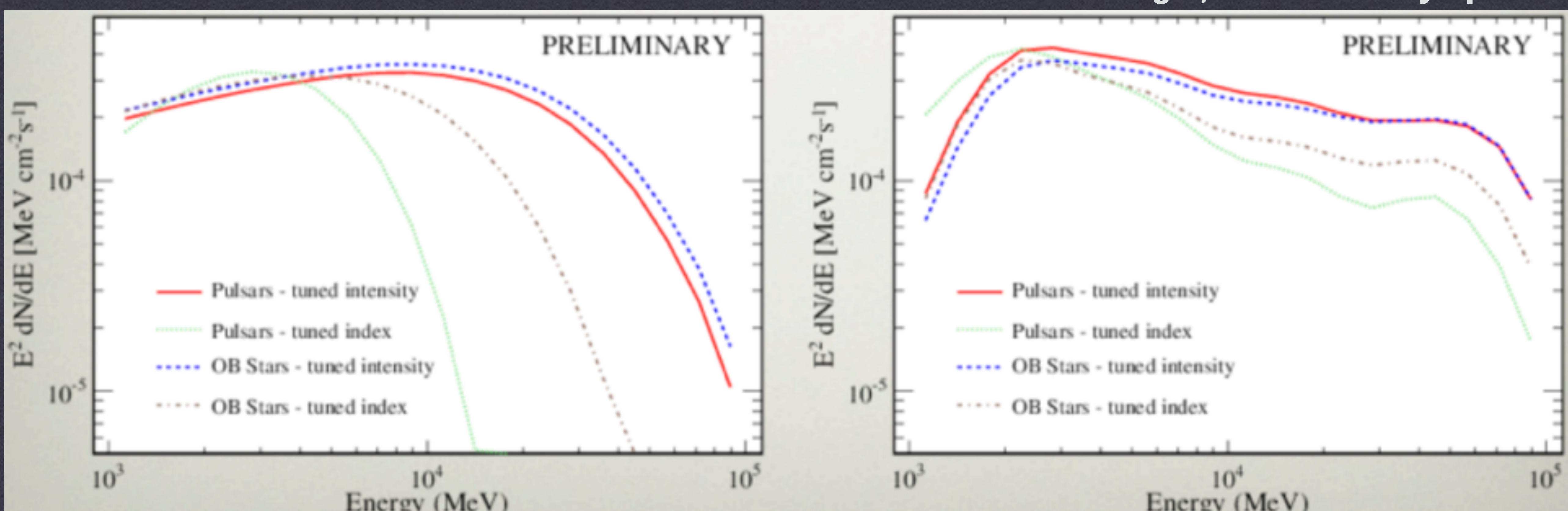
ABAZAJIAN ET AL. (2014B, 1410.6168)

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



FUTURE TESTS OF DARK MATTER

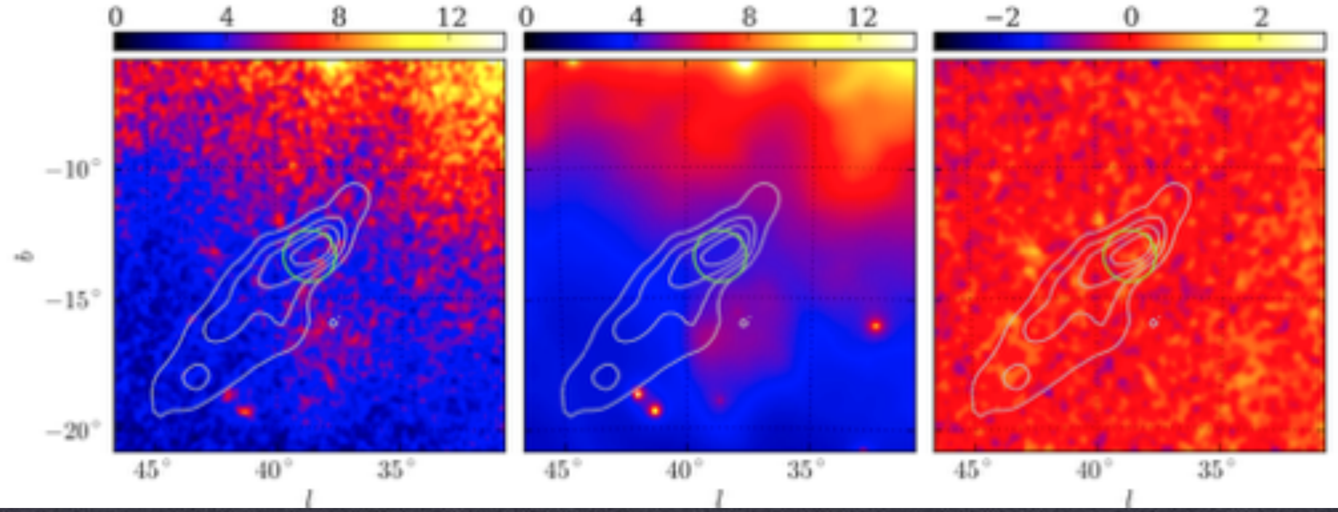
OTHER GAMMA-RAY TARGETS

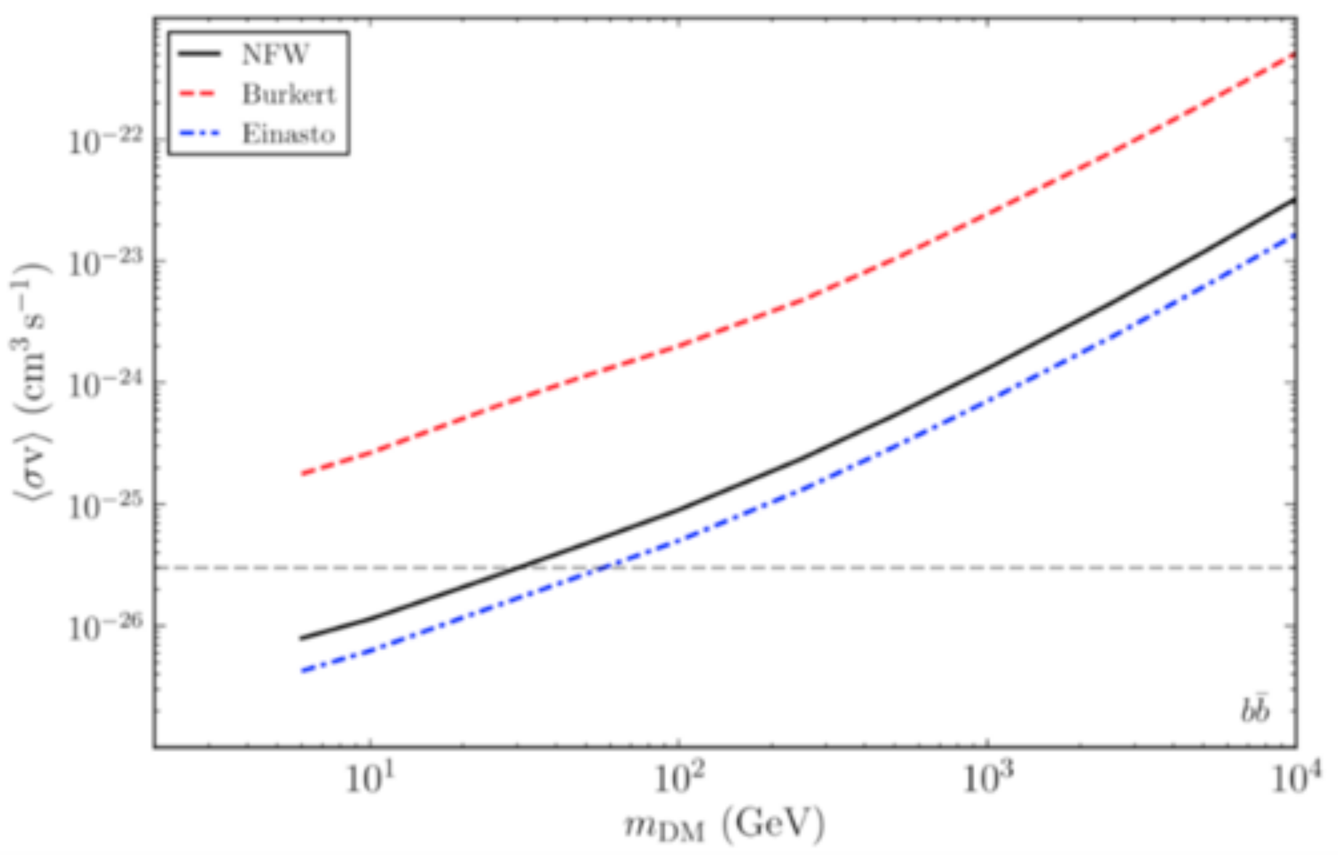
May find other bright indirect detection targets.

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





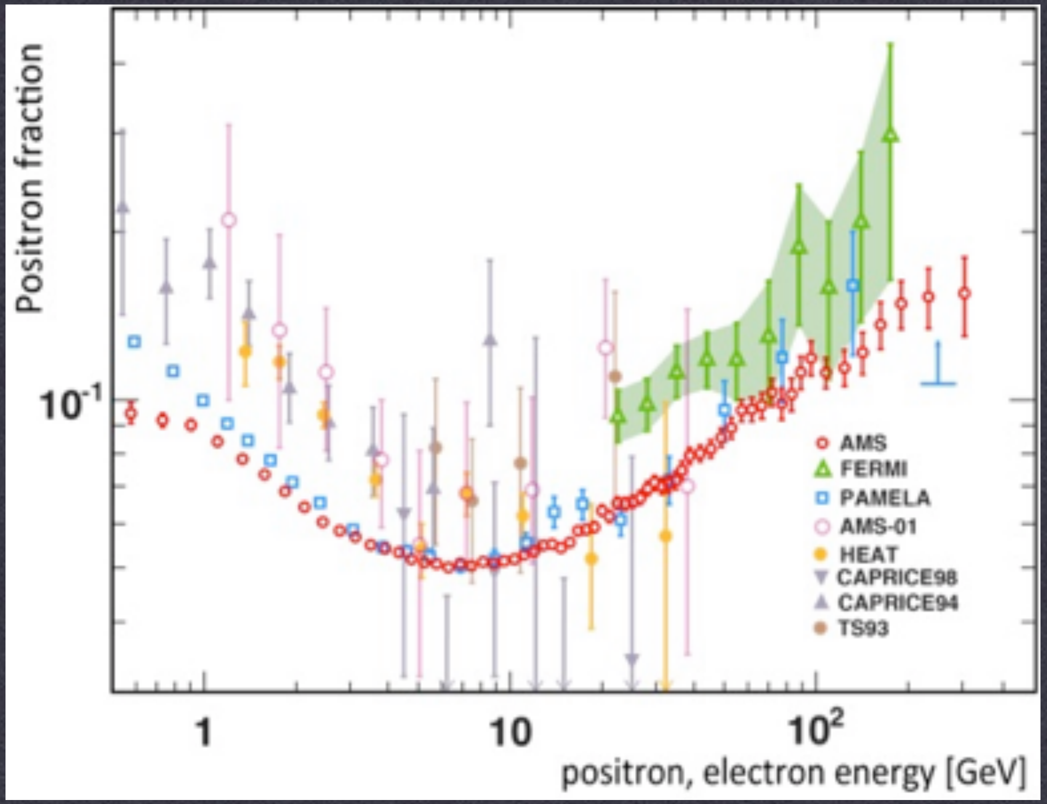
NICHOLS & BLAND-HAWTHORN (2009, 0911.0684)
NICHOLS ET AL. (2014, 1404.3209)
DRLICA-WAGNER ET AL. (2014, 1405.1030)

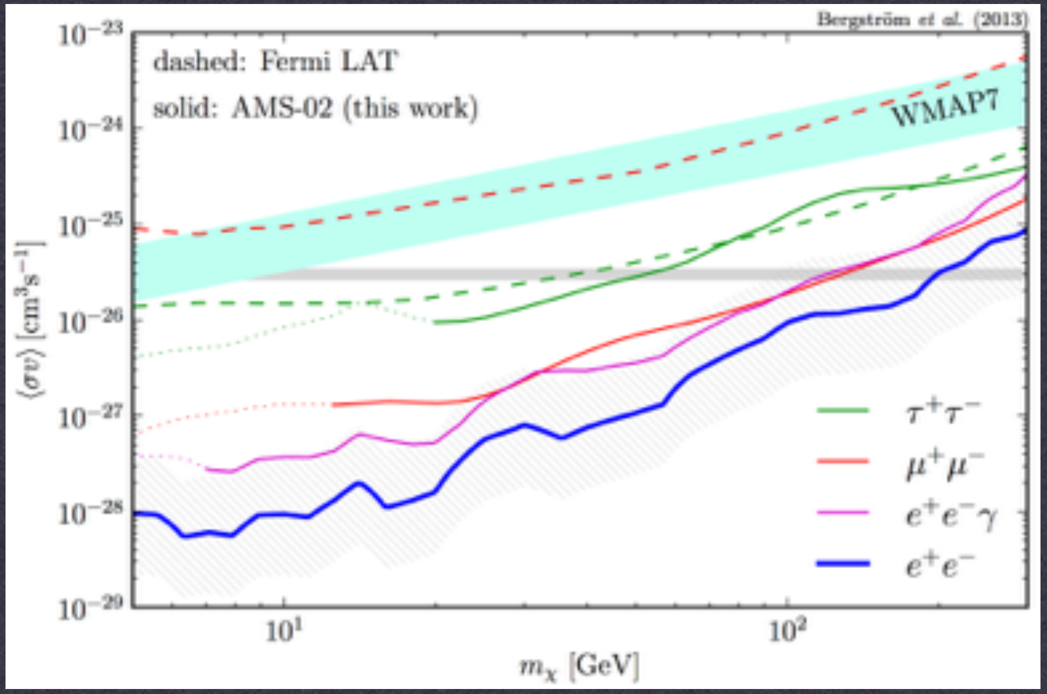
FUTURE TESTS OF DARK MATTER

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.





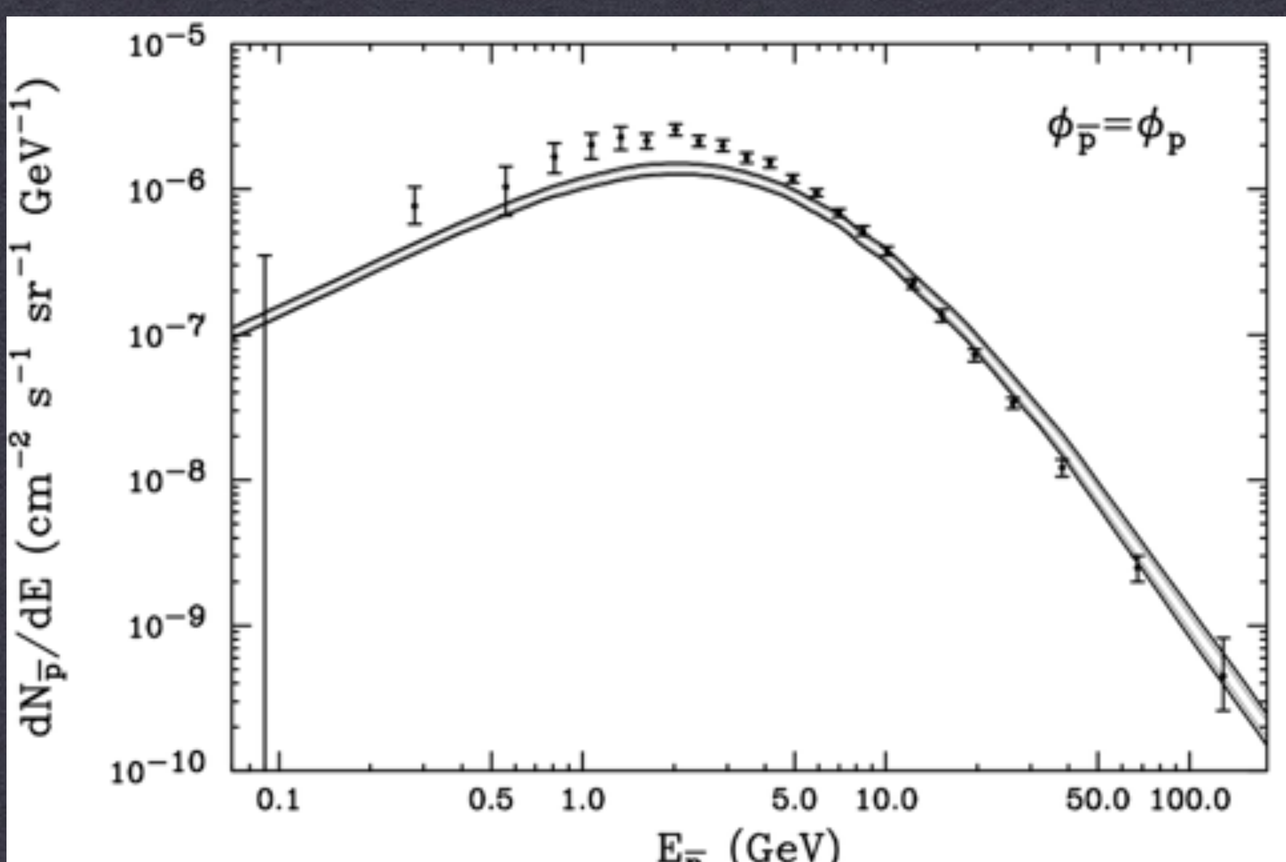
BERGSTROM ET AL. (2013, 1306.3983)

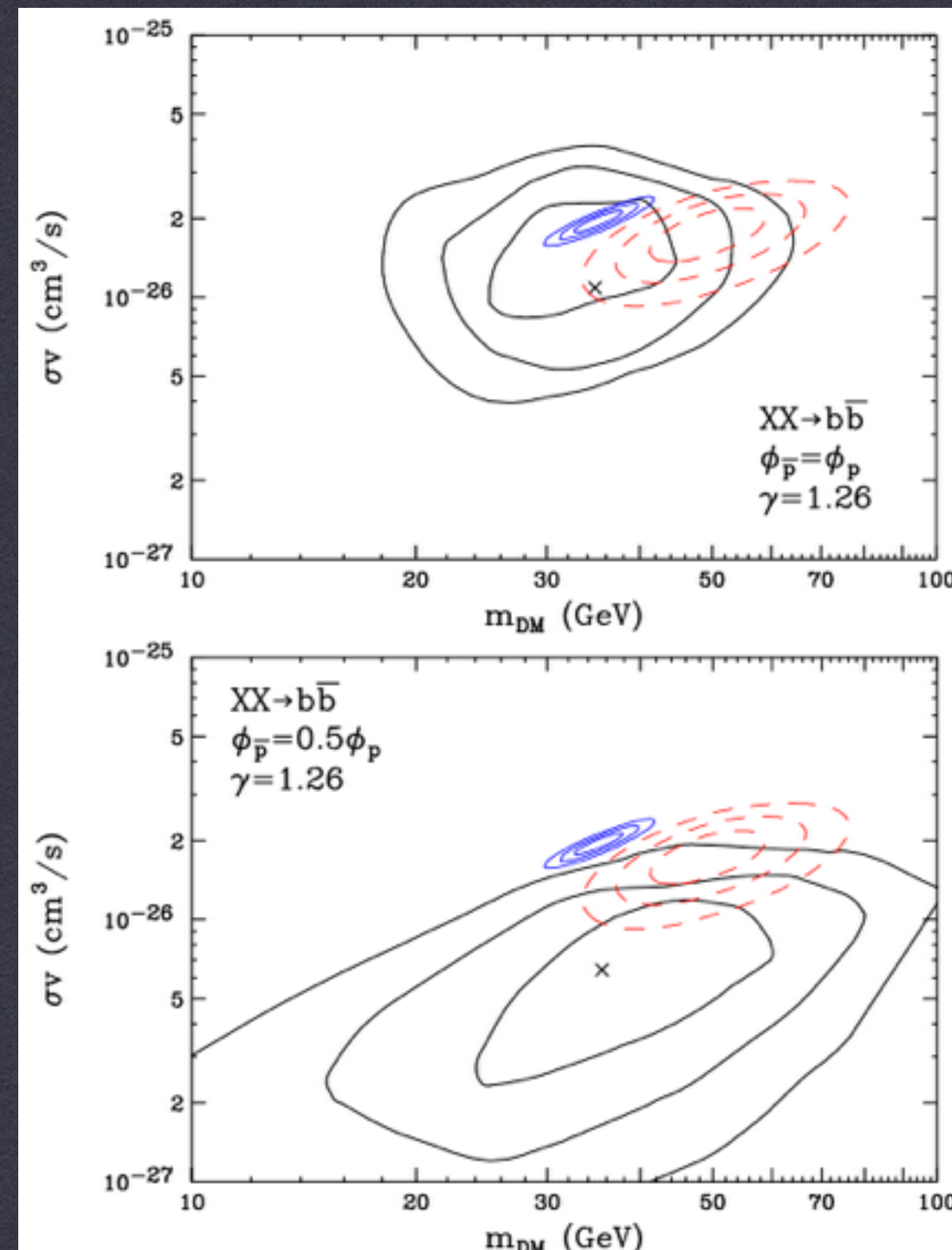
FUTURE TESTS OF DARK MATTER

COSMIC-RAY SEARCHES

HOOPER, TL, MERTSCH (2014, 1410.1527)

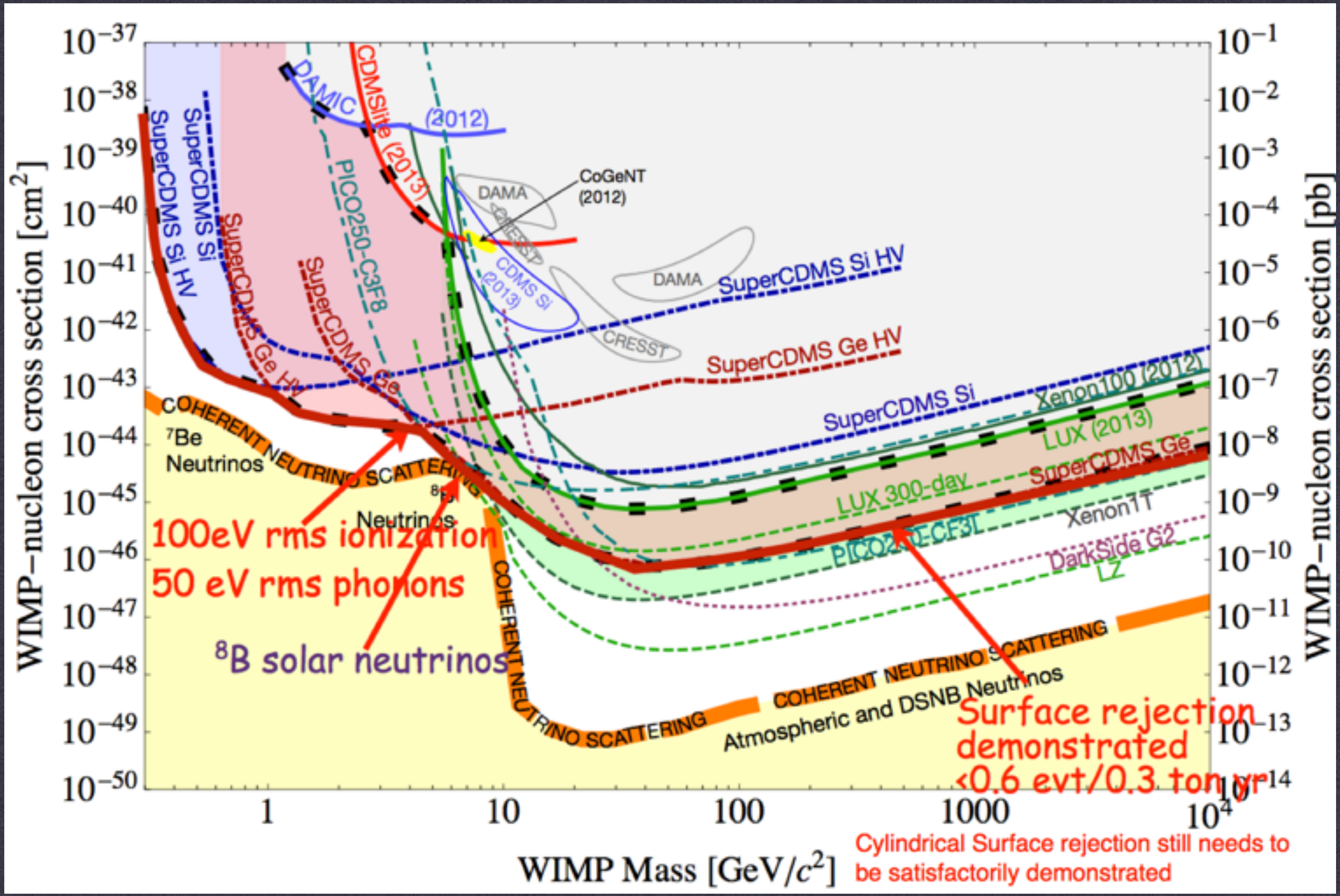
Observations of Cosmic-Ray Antiproton Fluxes show some evidence for an excess compared to astrophysical models, which can be fit by a dark matter candidate.





FUTURE TESTS OF DARK MATTER

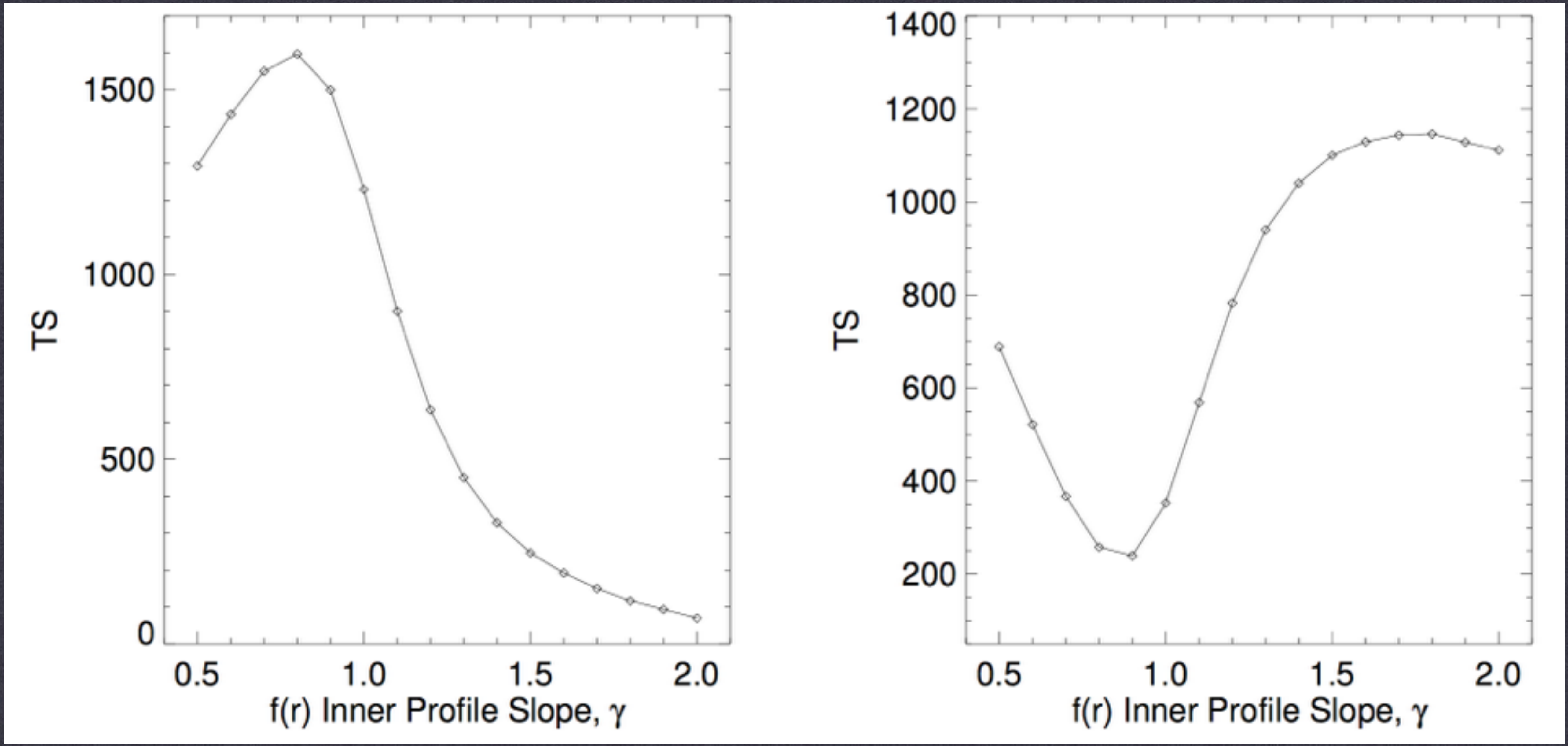
DIRECT DETECTION SEARCHES



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

DAYLAN ET AL. (2014)

RESULTS: CORRELATION WITH GAS



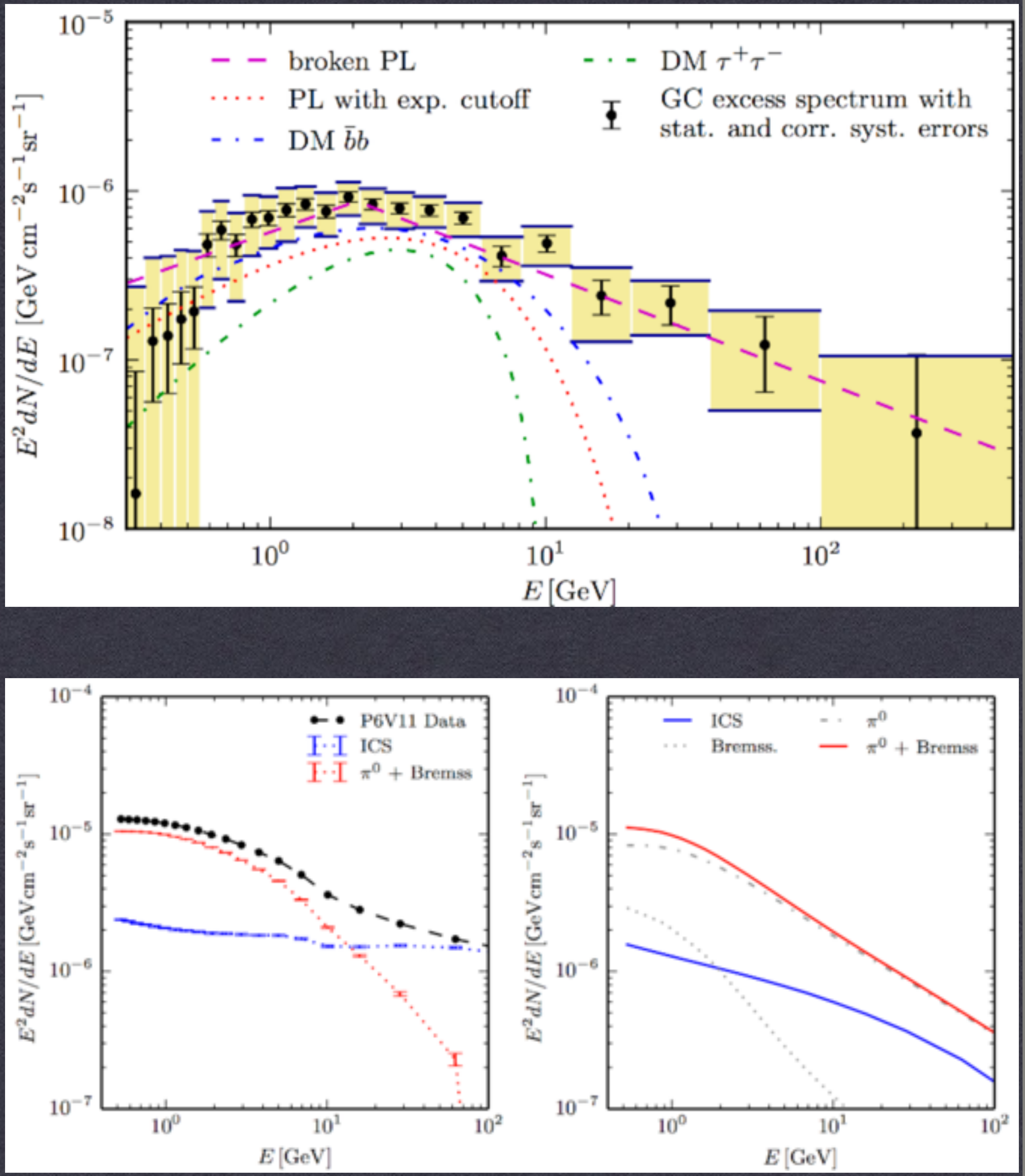
Can add in the SFD dust map, integrated over the line of sight, and globally bias each ring in order to test the fit to local peaks in the gas density

CALORE ET AL. (2014) (1409.0042)

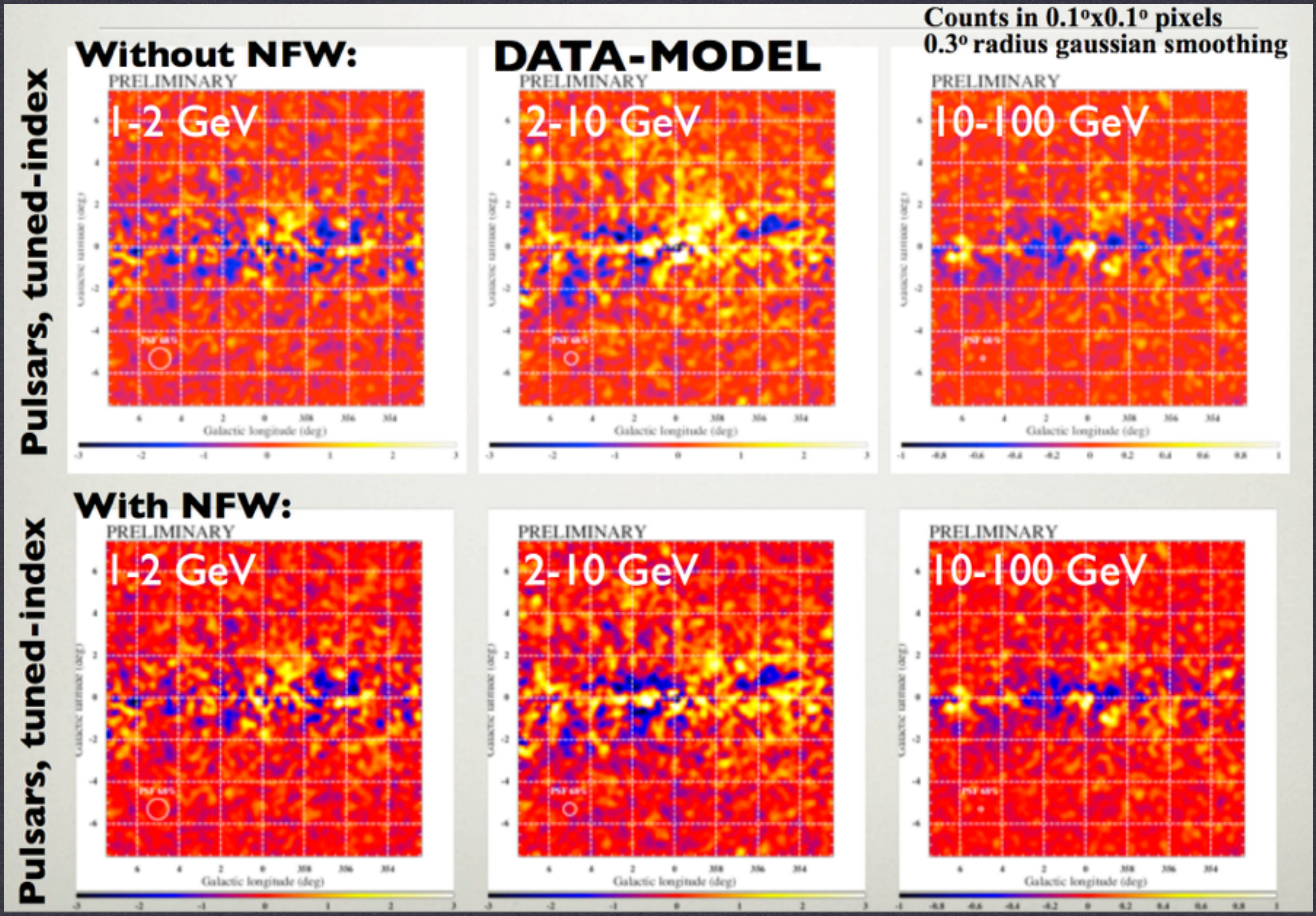
Tour de force paper which investigates the resiliency of the γ-ray excess to changes in the astrophysical diffuse model.

Tests over 300 diffuse models and finds the GC excess to be a resilient feature

Finds some evidence for extra high energy emission compared to Daylan et al. (2014)



FERMI-LAT COLLABORATION



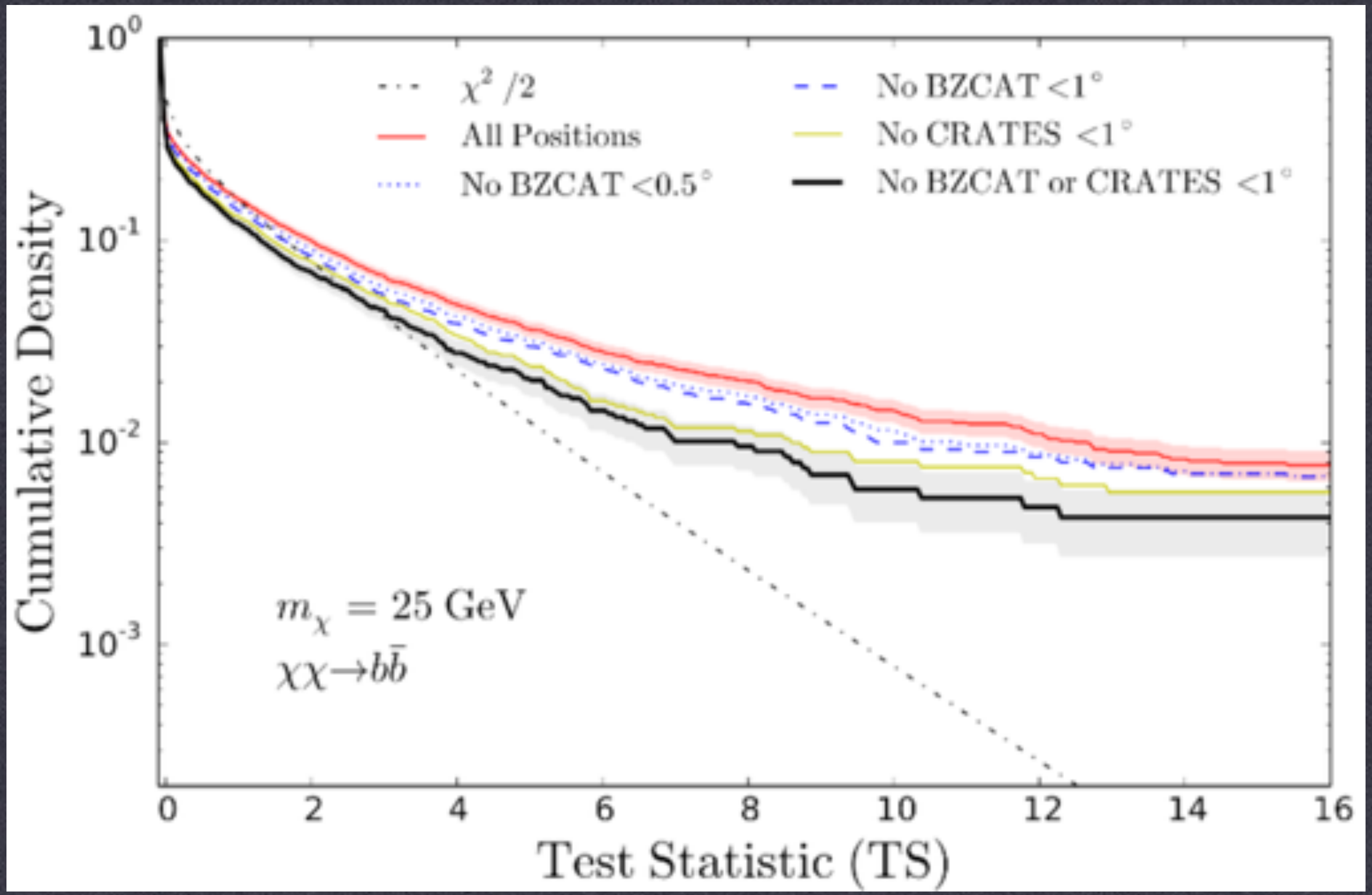
FUTURE TESTS OF DARK MATTER

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)

INDIRECT DETECTION OF WIMPS

DARK MATTER DENSITY PROFILES

THE GALACTIC CENTER: BACKGROUNDS

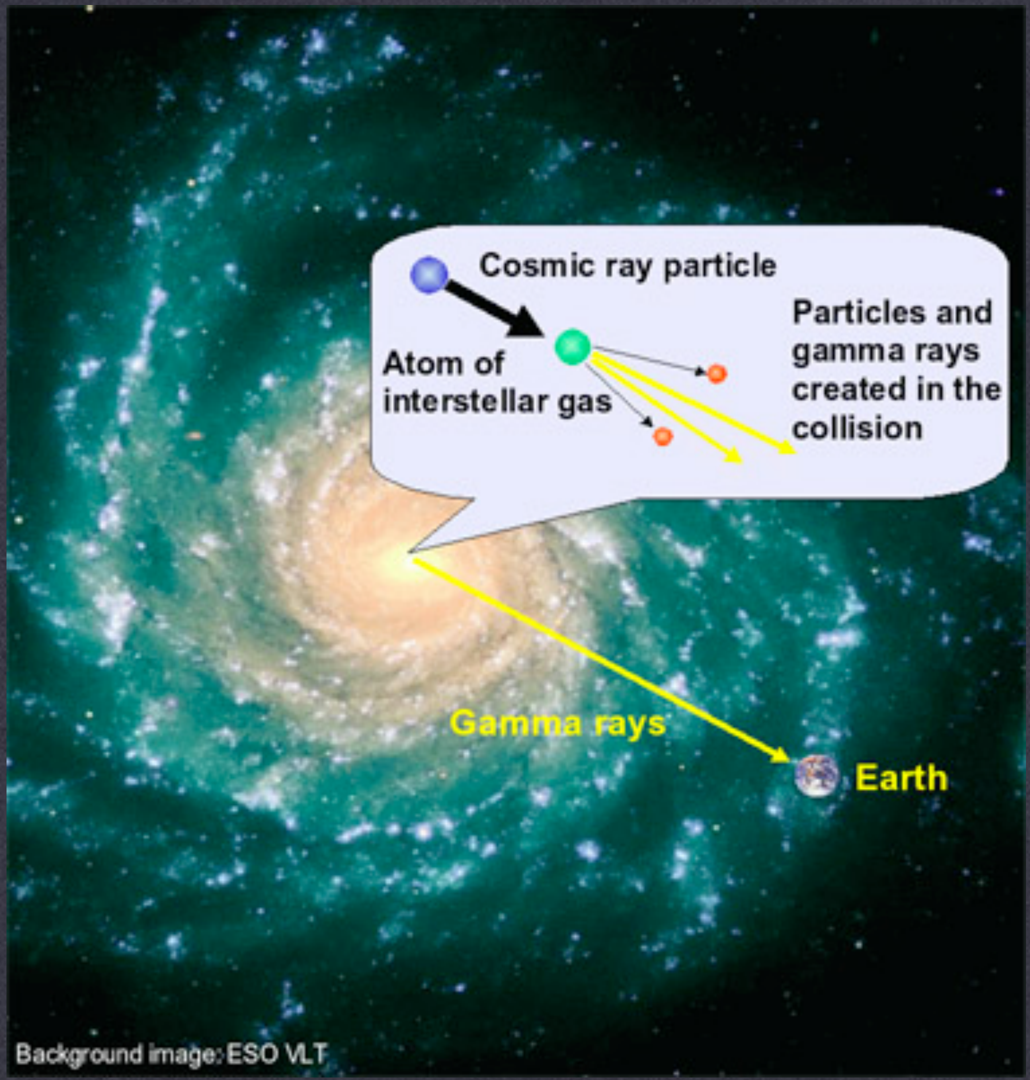
What Are These Backgrounds?

* Point Sources (SNR, pulsars, etc.)

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

* Bremsstrahlung

* Inverse Compton Scattering

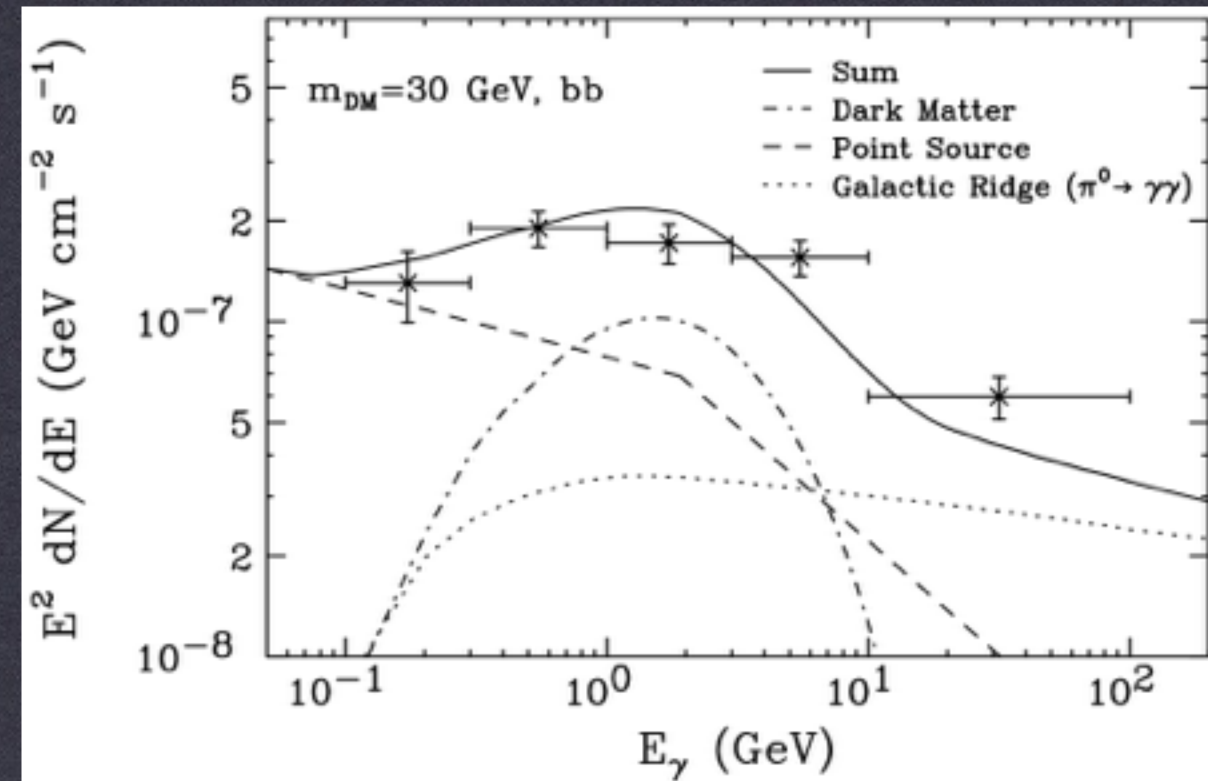


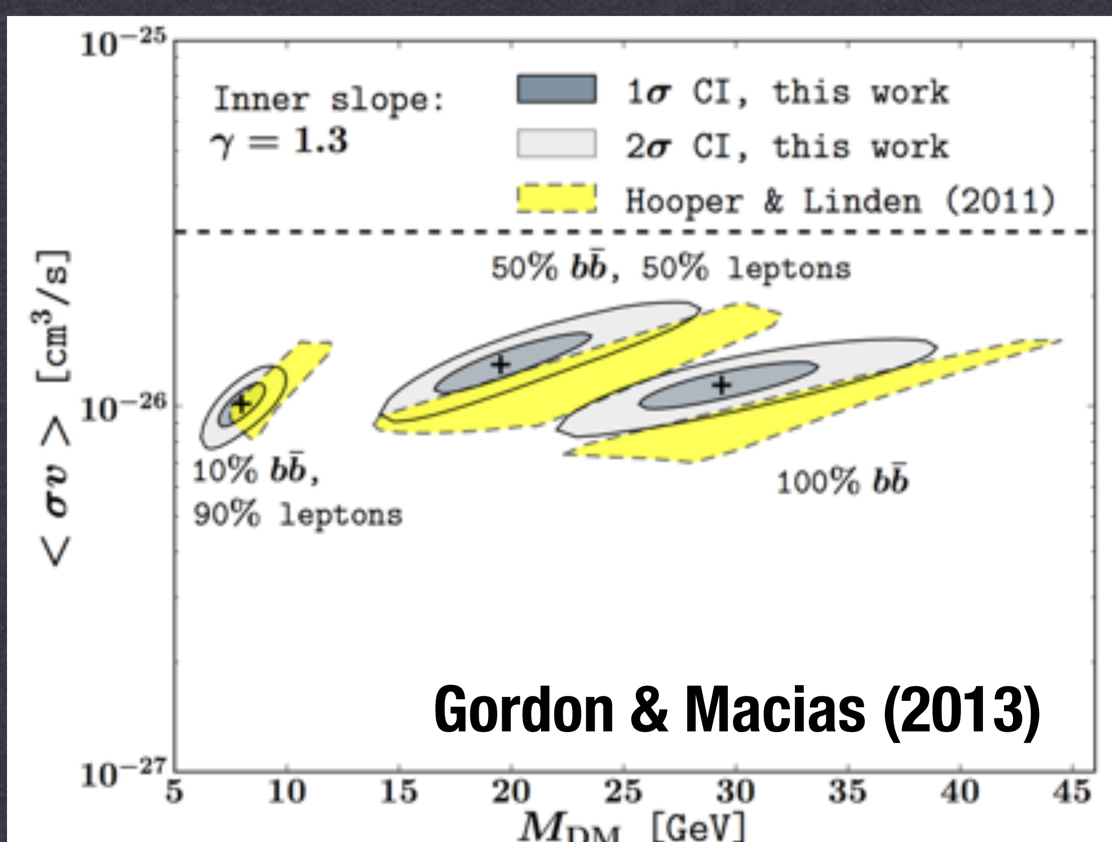
PREVIOUS WORK

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)