The Galactic Center GeV Excess

Tim Linden

CCAPP Postdoctoral Fellow
Center for Cosmology and Astro-Particle Physics
The Ohio State University

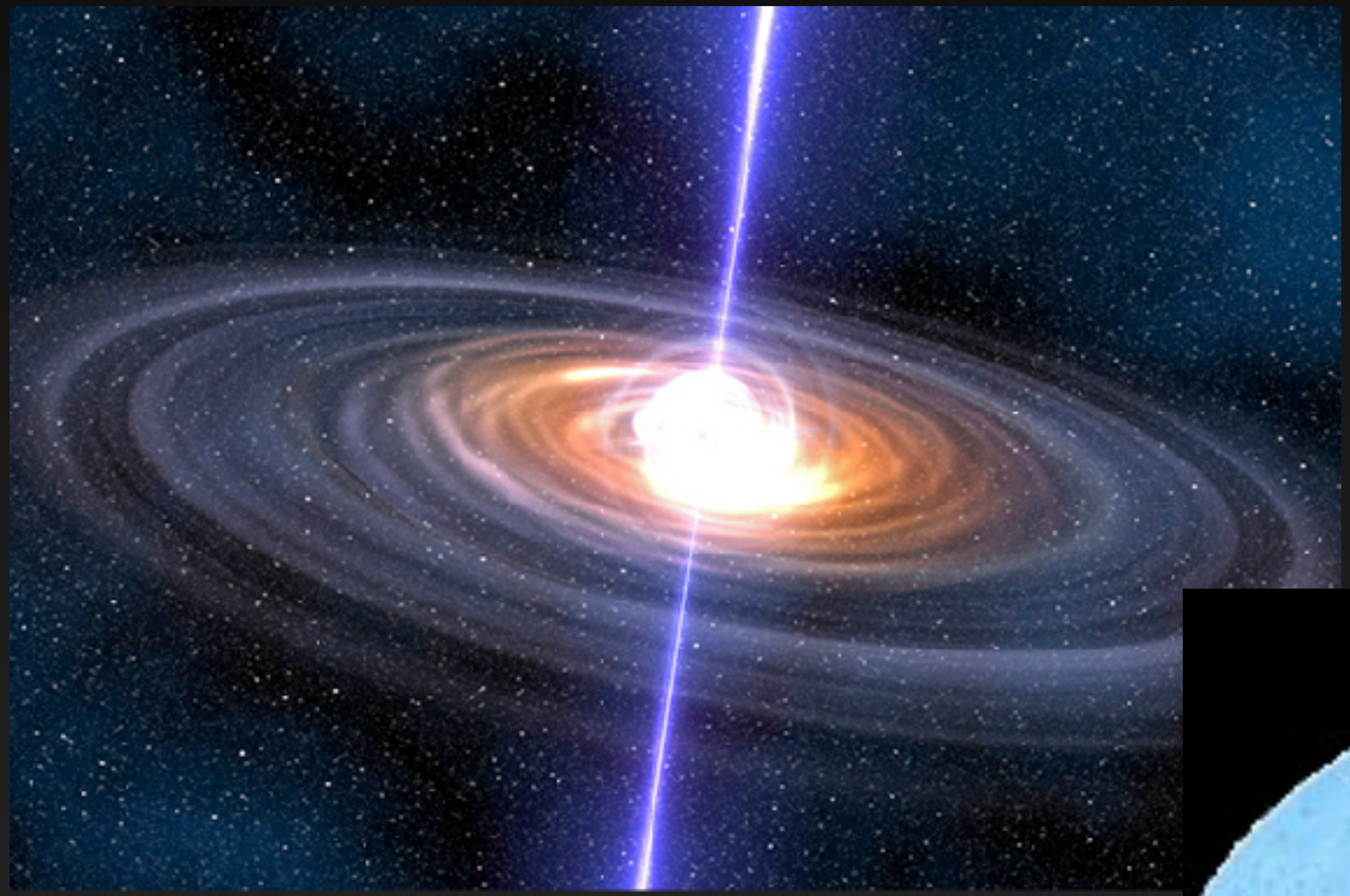
Models of the GeV Excess

These are the four resilient features of the GeV Excess:

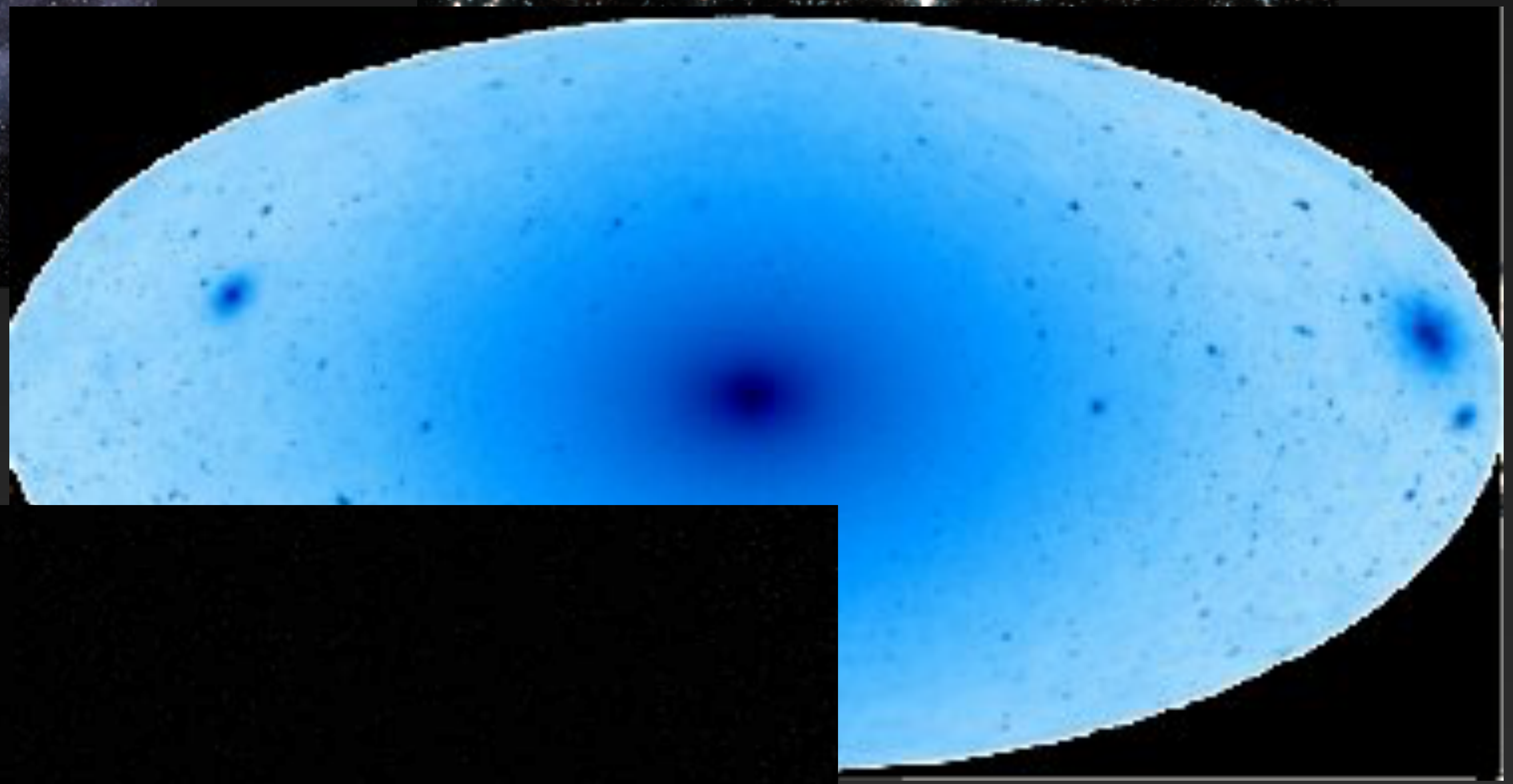
1.) High Luminosity of ~2×10^{37} erg s^{-1}
2.) Hard Gamma-Ray Spectrum peaking at ~2 GeV
3.) Spherically Symmetric Emission Morphology
4.) Extension from 0.1° to 10° from the GC.

Cosmic-Ray Sources in the Galactic Center

The Galactic center region is known to contain nearly every known cosmic-ray acceleration mechanism.



1.) Supernovae
2.) Pulsars
3.) Sgr A*
4.) Reacceleration
5.) Dark Matter Annihilation?



The Central Molecular Zone

- 400 pc x 80 pc
- 10^7 $M_\odot$ of gas in Molecular Clouds

Dense Molecular Clouds

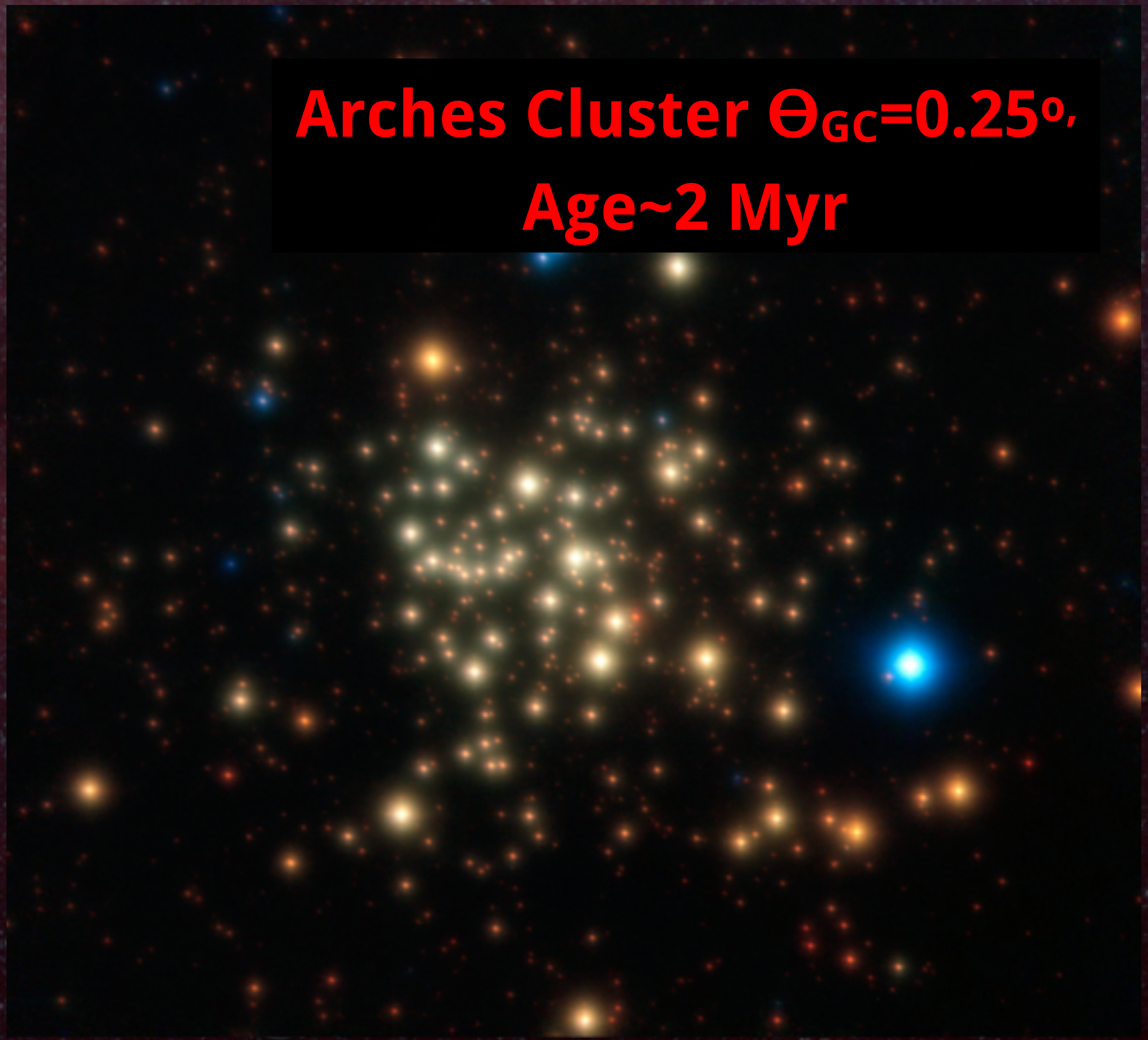
>9000 *Chandra* Point Sources

The Result

Multiwavelength observations indicate that the GC is a dense star-forming environment.

2-20% of the total Galactic Star Formation Rate (and thus SN rate) is contained within the Central Molecular Zone.

- 2-4% - ISOGAL Survey Immer et al. (2012)
- 2.5-5% - Young Stellar Objects Yusef-Zadeh et al. (2009)
- 5-10% - Infrared Flux Longmore et al. (2013)
- 10-20% - Wolf-Rayet Stars Rosslowe & Crowther (2014)
- 2% - Far-IR Flux Thompson et al. (2007)
- 2.5-6% - SN1a Schanne et al. (2007)



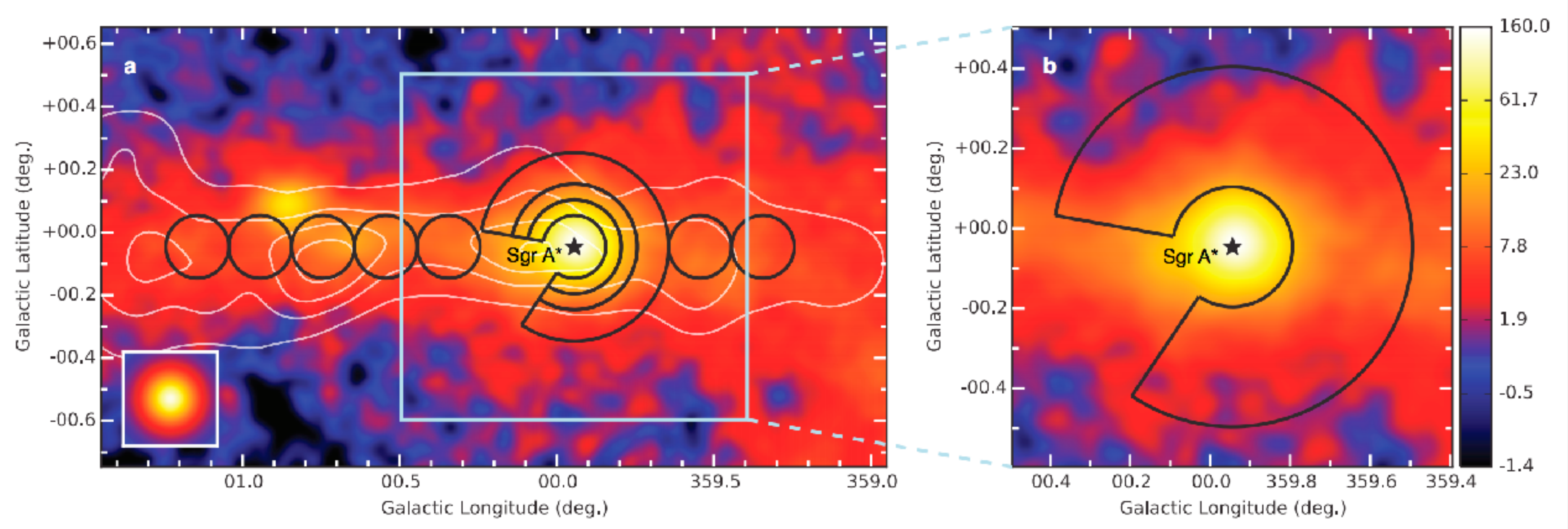
Galactic Center Pulsars

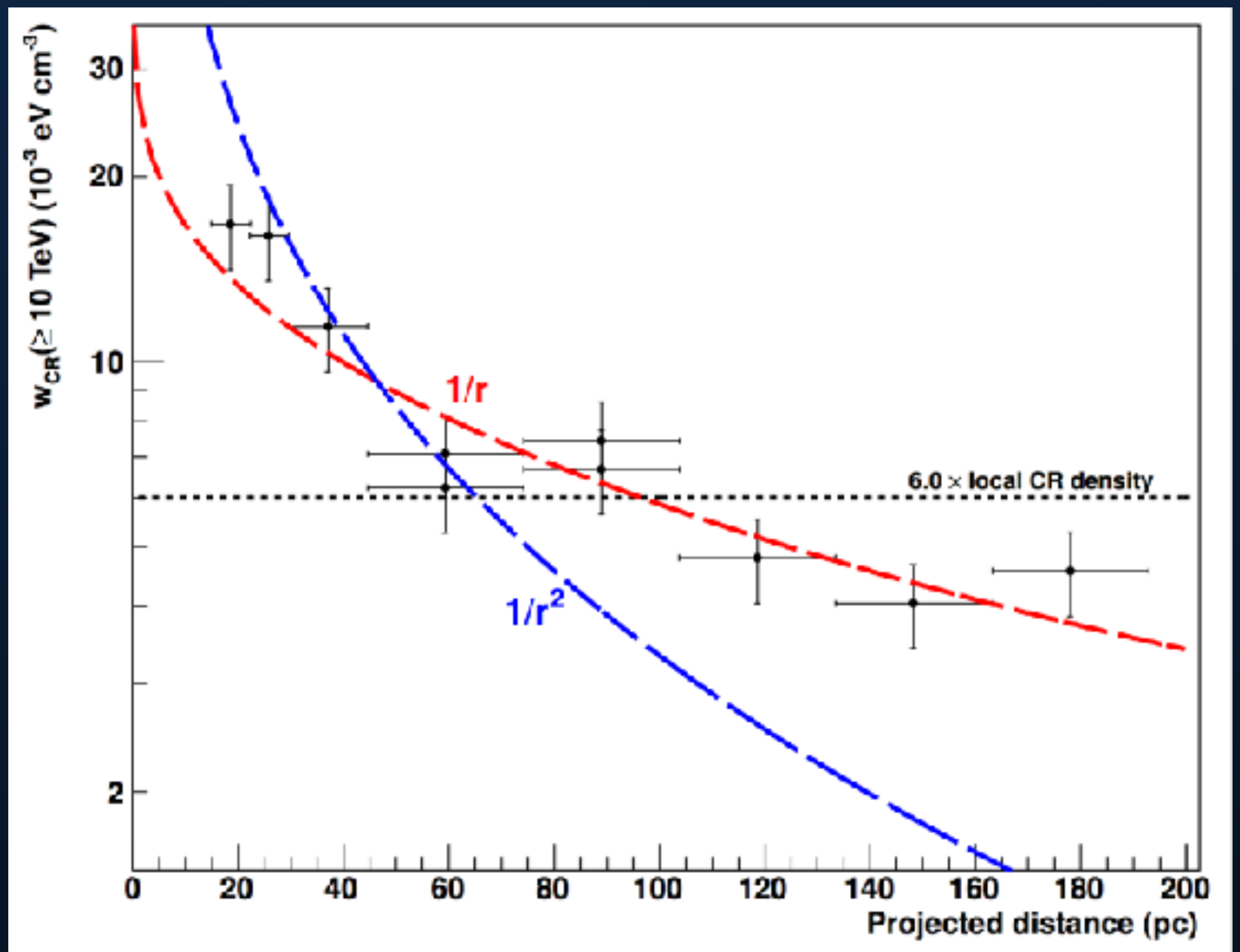
The Galactic Center is expected to host a significant population of both young pulsars (due to its high SFR), and millisecond pulsars (in part from the disruption of Globular Clusters).

Over the lifetime of a young (recycled) pulsar, ~10^{50} erg of energy our released, primarily in the form of relativistic e^+e^- pairs.

The Sgr A* Source

Abramowki et al. (2016; 1603.07730)



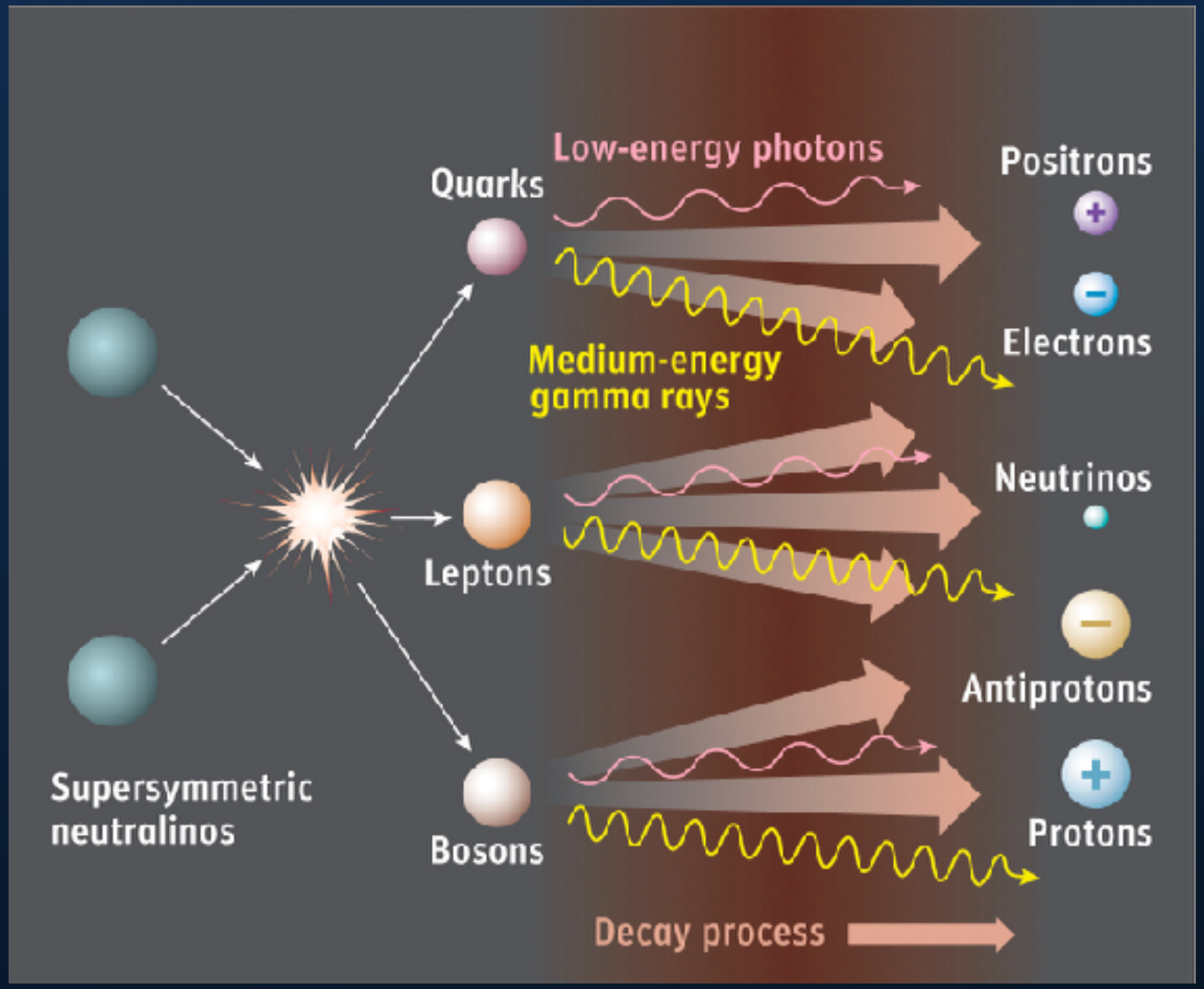


HESS has detected diffuse gamma-ray emission at energies ~100 TeV.

This is not observed in even the youngest supernova remnants.

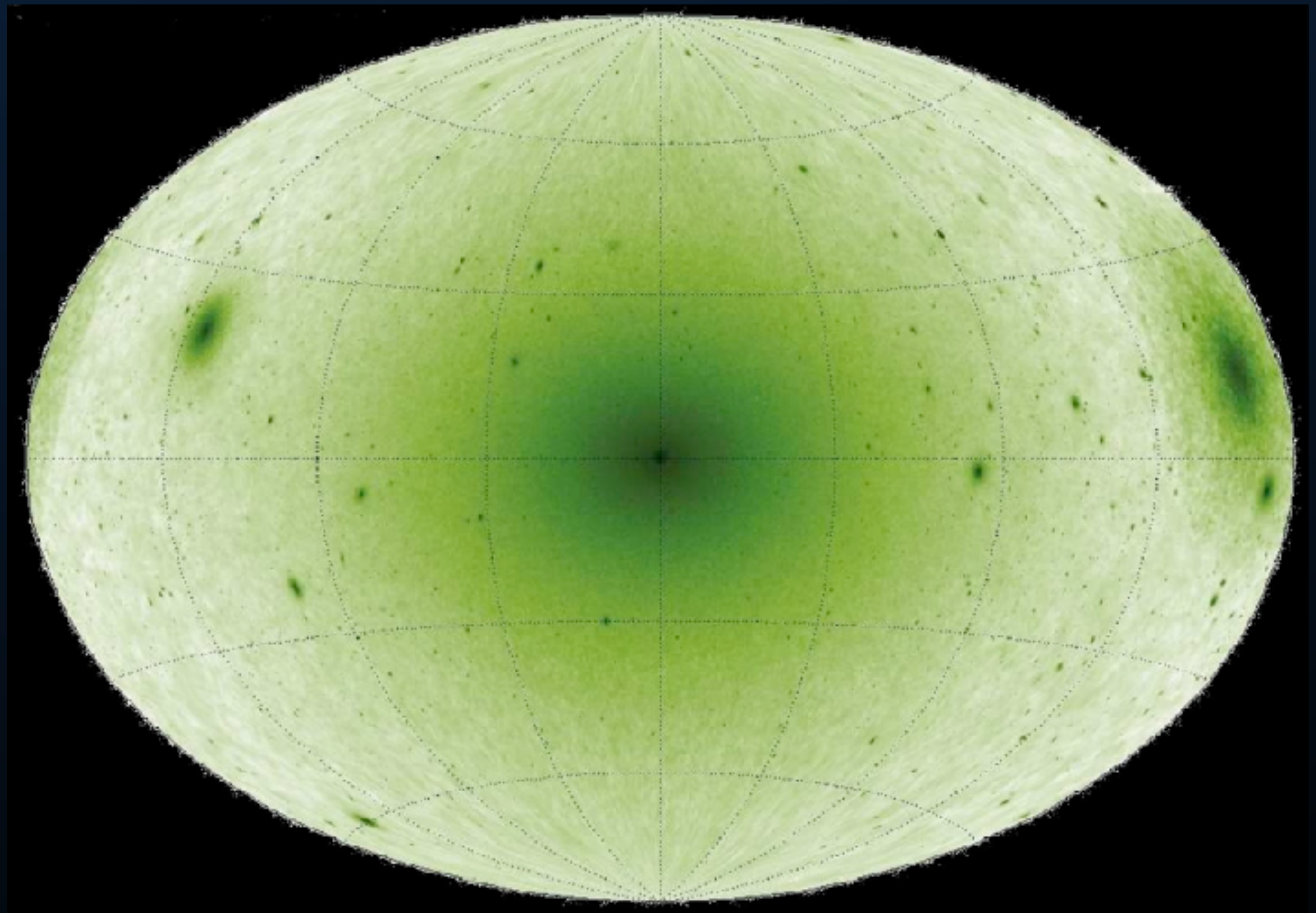
The emission profile is indicative of diffusion from the central BH.

Dark Matter Annihilation?



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

WIMP annihilation naturally produces a significant cosmic-ray (and gamma-ray) flux.

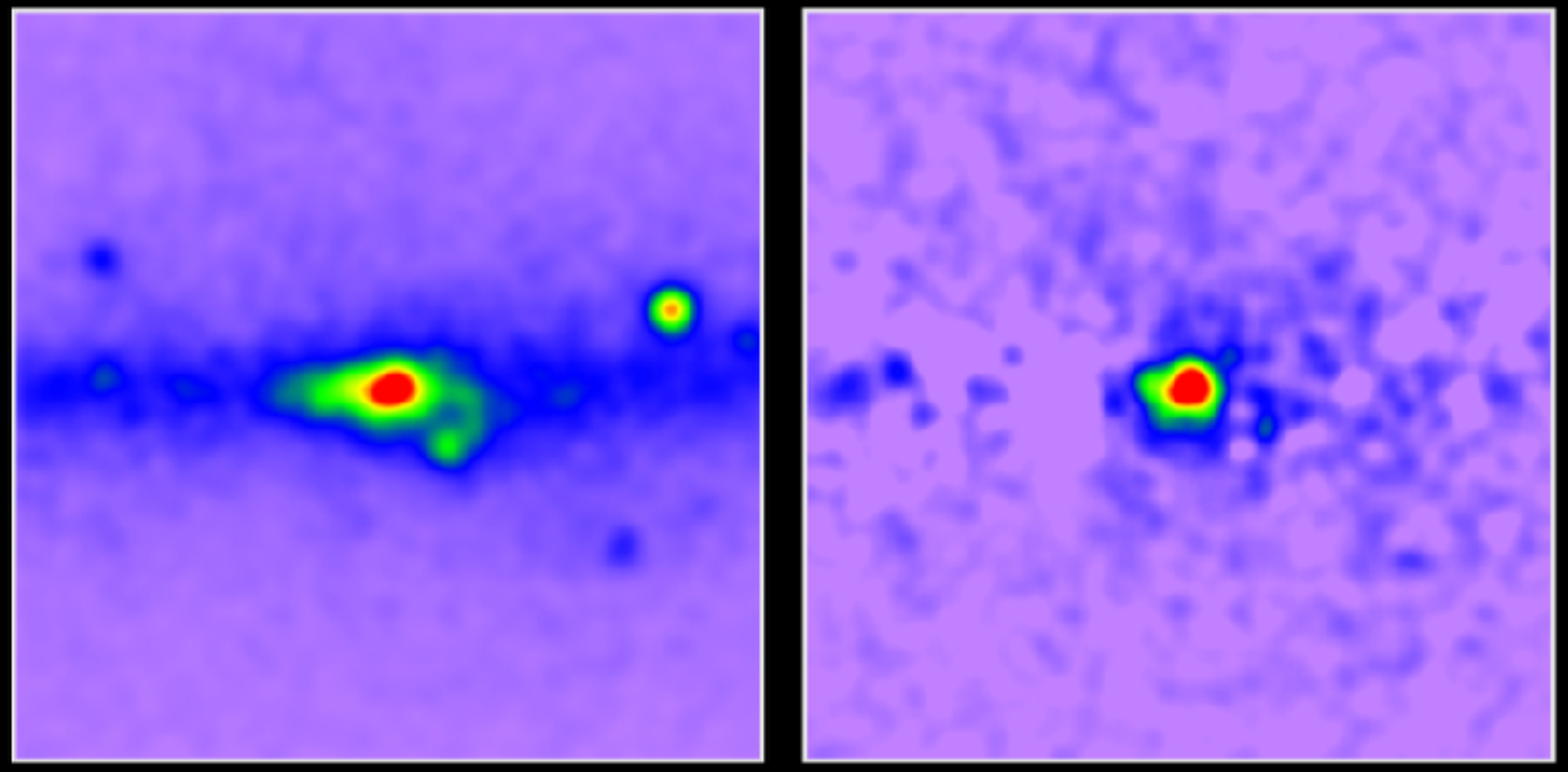


Dark Matter structure simulations uniformly predict that the GC is the brightest source of WIMP annihilations.

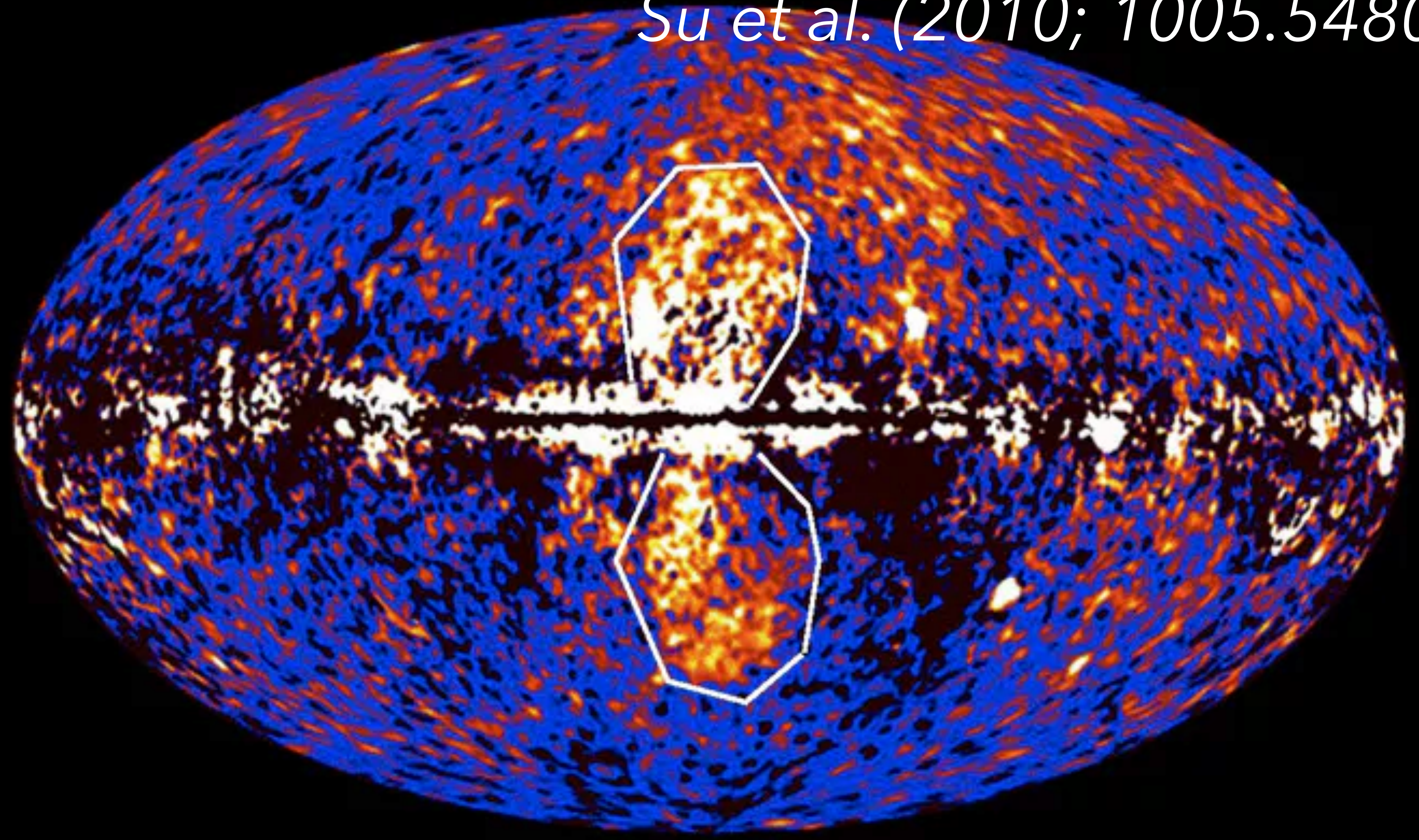
Standard scenarios predict the flux from the GC exceeds dSphs by a factor of ~100 — 1000.

Galactic Center Excesses

GeV Excess *Daylan et al. (2016; 1402.6703)*



Fermi Bubbles *Su et al. (2010; 1005.5480)*



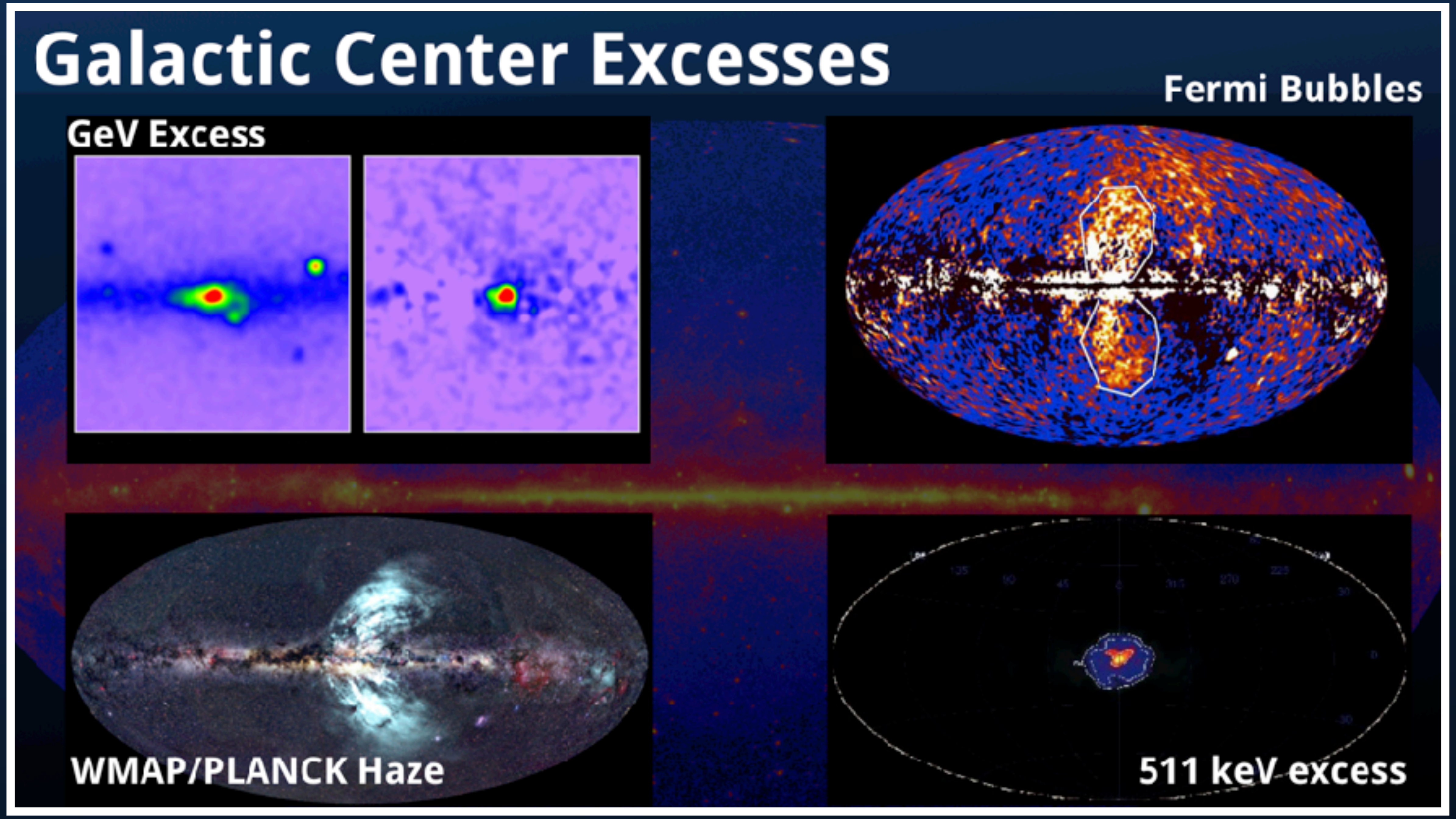
Finkbeiner (2003; 0311547)

WMAP/PLANCK Haze

Knodlseder et al. (2005; 0506026)

511 keV excess

Galactic Center Excesses



The photon excesses extend very far from the central molecular region!

This:

(a) Indicates the extreme power of Galactic Center accelerators.
(b) Provides a region of interest for studies of Galactic Center emission.
(c) Implies that propagation is important!

Models of the GeV Excess

How could we model this with:

1.) Diffuse Emission from Supernovae
2.) Leptonic Outbursts from Sgr A*
3.) Pulsars
4.) Dark Matter Models

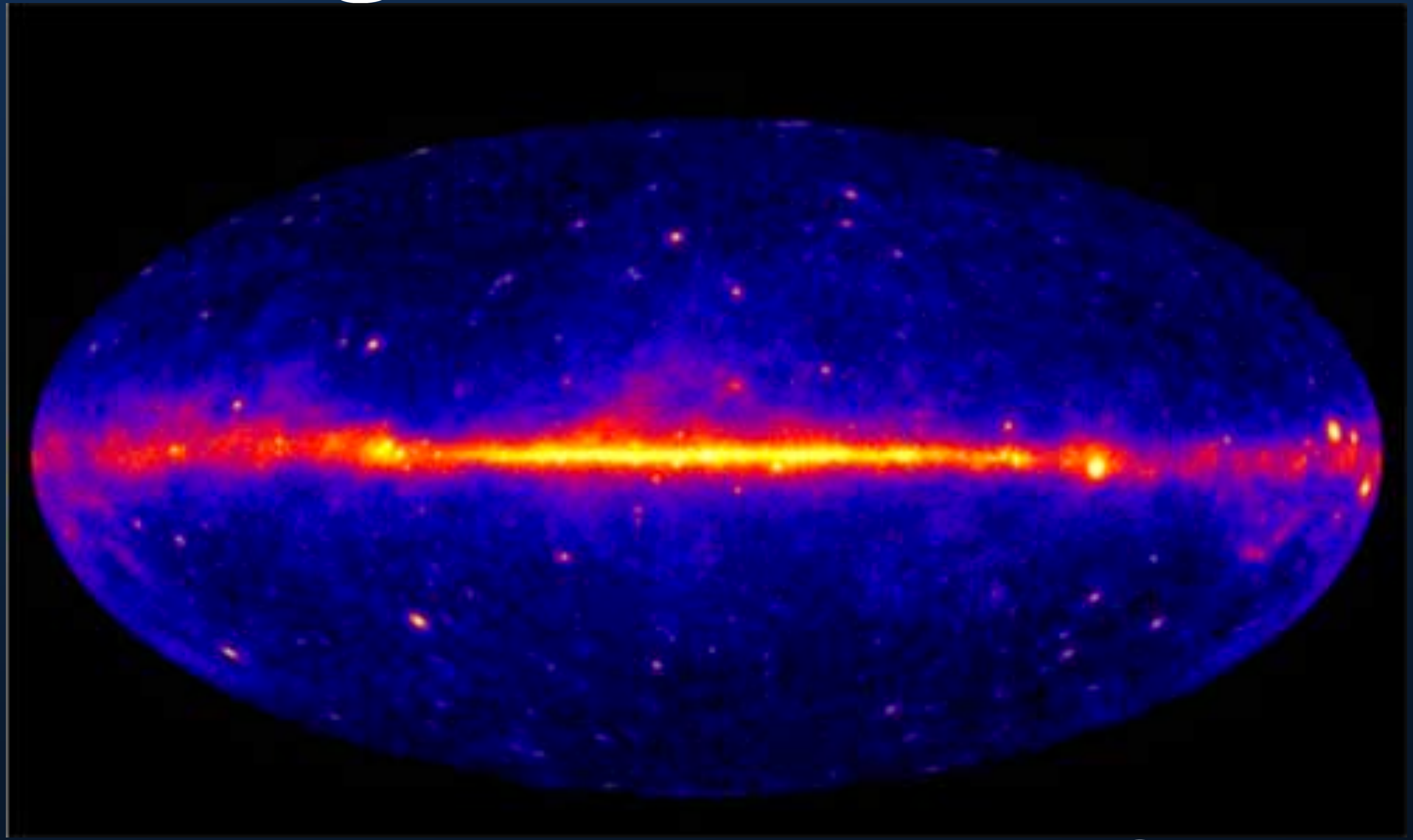
Modeling Approach to Gamma-Ray Excesses

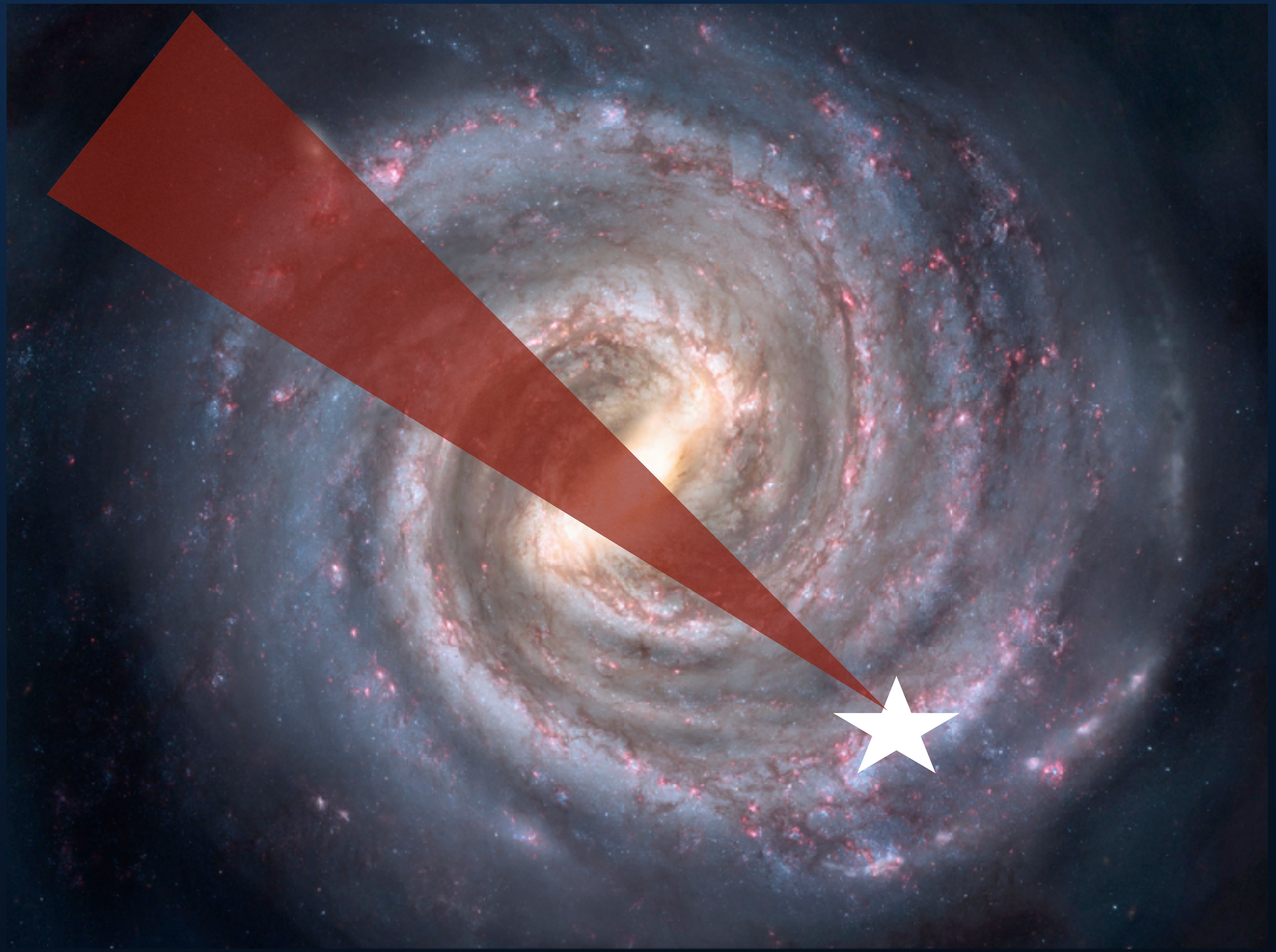
1.) Energetics - Most astrophysical accelerators can't produce the luminosities (at GeV energies) necessary to produce the emission.

2.) Spectrum - The precise energy resolution of the Fermi-LAT distinguishes the ``2 GeV" bump.

3.) Morphology - While the Fermi-LATs angular resolution is unprecedented at GeV energies, it smears out much of the dynamics of the Galactic center.

Energetics





The total luminosity of the Galactic center gamma-ray excess is approximately 2×10^{37} erg s^{-1}.

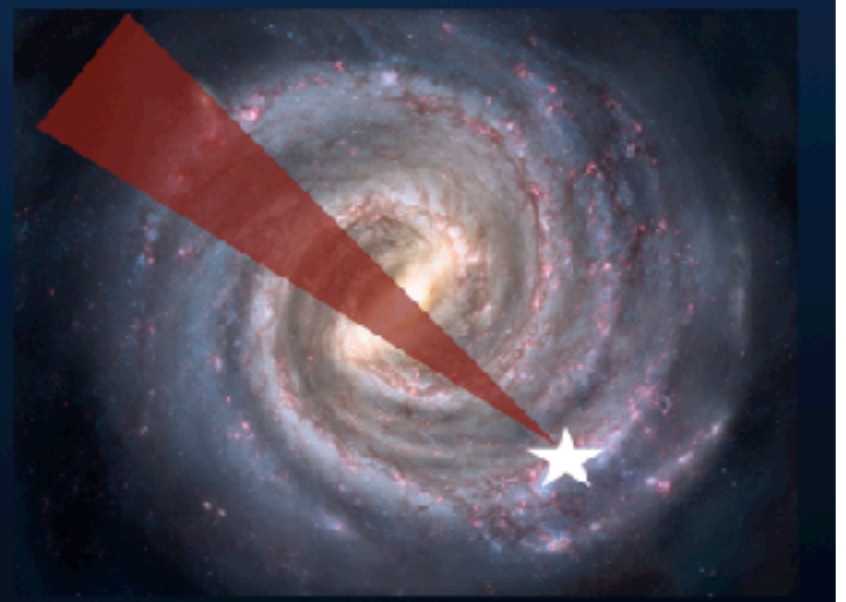
Which models are capable of producing this emission?

Supernovae

A Supernovae produces ~10^{51} erg of kinetic energy.

Approximately 10% in cosmic-ray protons.

Energetics



The total luminosity of the Galactic center gamma-ray excess is approximately 10^{37} erg s^{-1}.

Which models are capable of producing this emission?

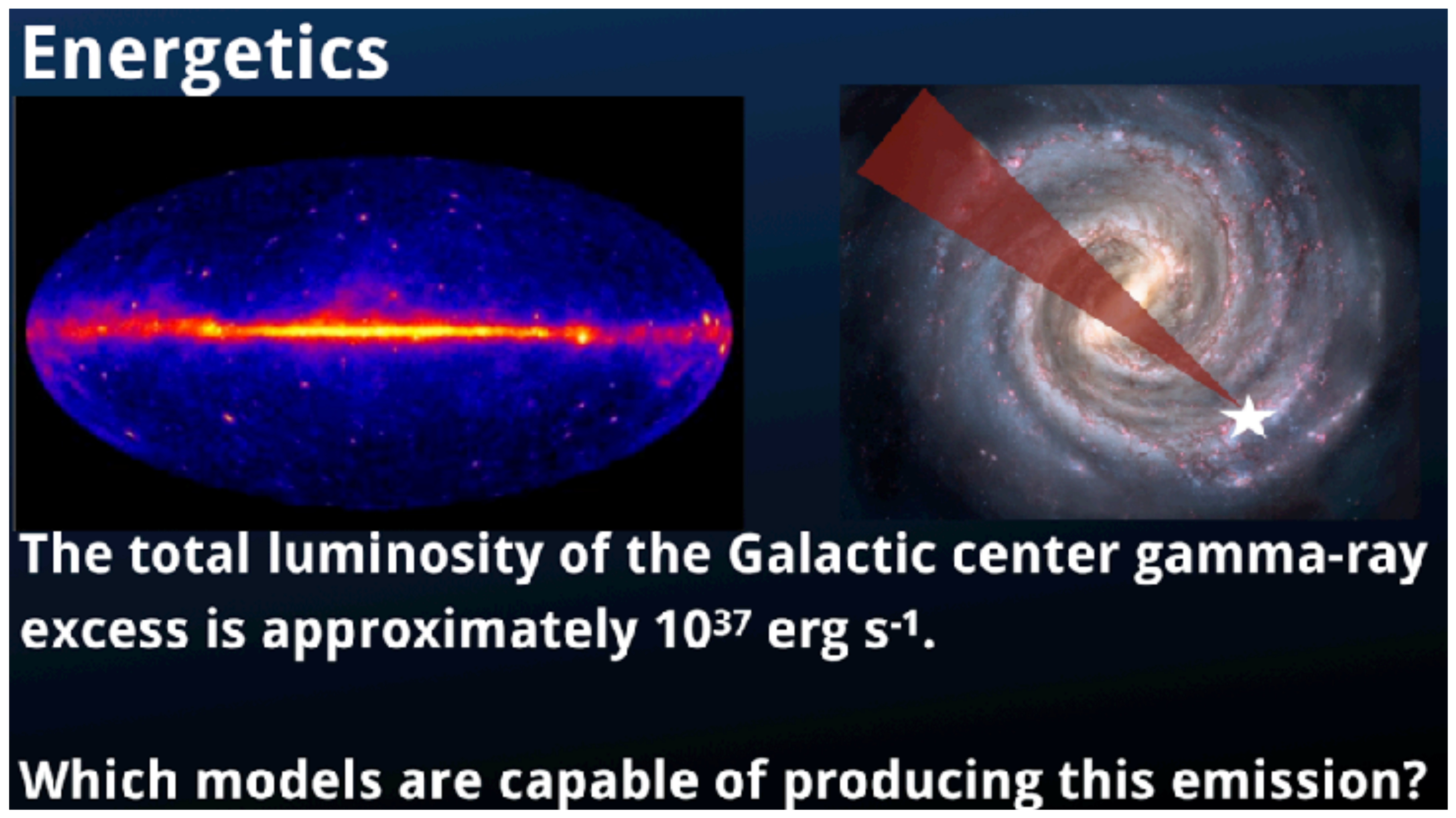
Assuming 1 Galactic center SN every 250 years (10% the Galactic Rate), this provides an energy flux of 1.3 x 10^{40} erg s^{-1}.

If these cosmic-rays are trapped for 10 kyr in a 100 pc box (D_0 = 5 x 10^{28} cm^2 s-1), filled with Hydrogen gas at density 100 cm^{-2}, this will produce a total gamma-ray emission:

6.7 x 10^{37} erg s^{-1} ✔

Leptonic Outbursts

A tidal disruption event releases $\sim 10^{45}$ erg s^{-1} for a period of ~0.2 yr.

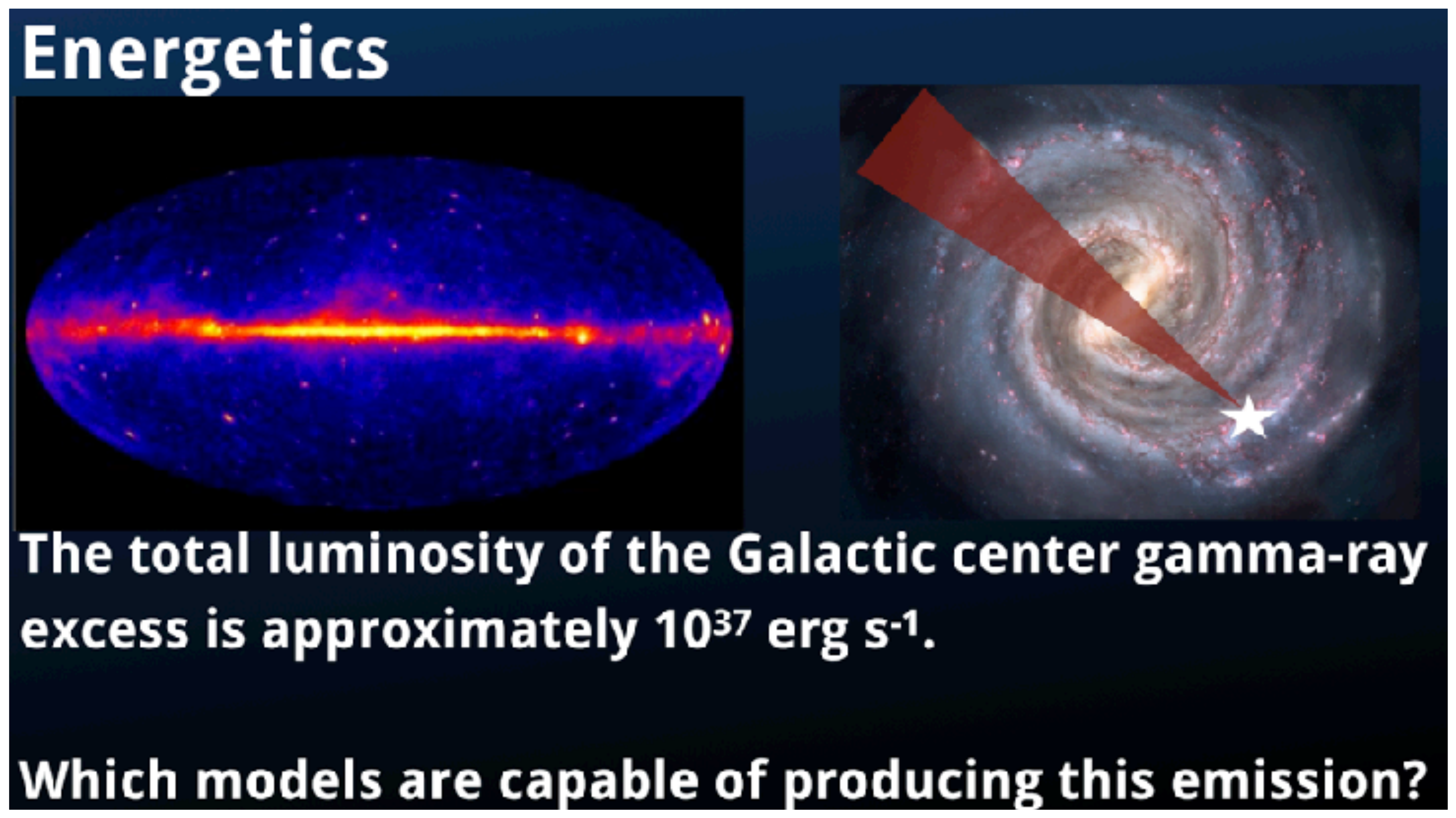


Sgr A* is expected to produce a tidal disruption event every $\sim 10^{5}$ yr, producing a time-averaged energy output of 2×10^{39} erg s^{-1}.

If these CRs are primarily leptonic, and the electrons remain trapped in a region with a 40 eV cm^{-3} ISRF and a 200 μG magnetic field the gamma-ray flux from inverse Compton scattering is:

7.0×10^{37} erg s^{-1} ✔

Pulsars



MSPs observed in the galactic field are fit by a population with a mean gamma-ray flux of 3×10^{34} erg s^{-1}. (Hooper & Mohlabeng 2015)

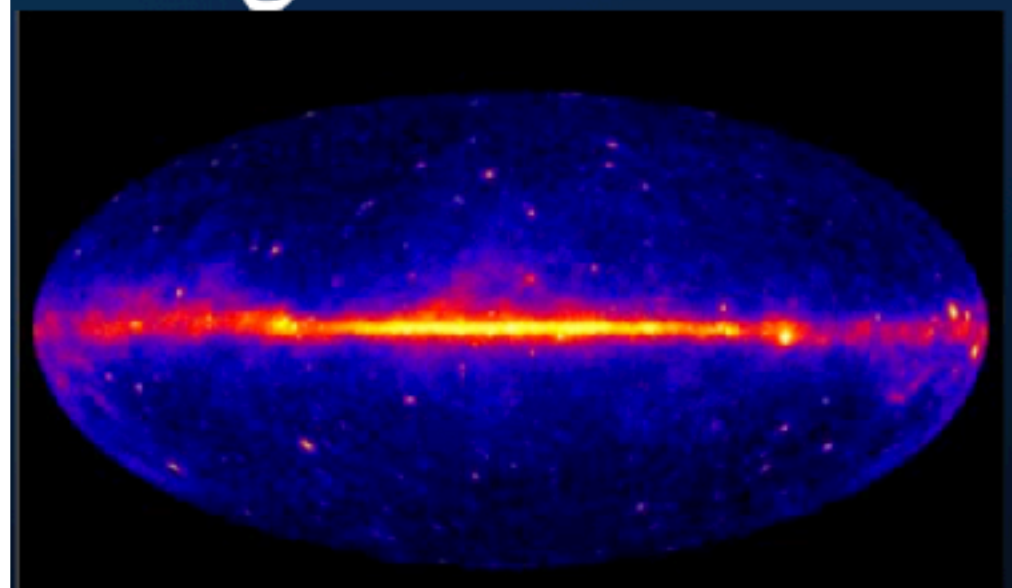
Given the population of 129 MSPs among 124 globular clusters (with a total stellar mass ~5×10^{7} M_{o}).
For the 1×10^{9} M_{o} of stars formed in the inner degree of the Milky Way, we get:

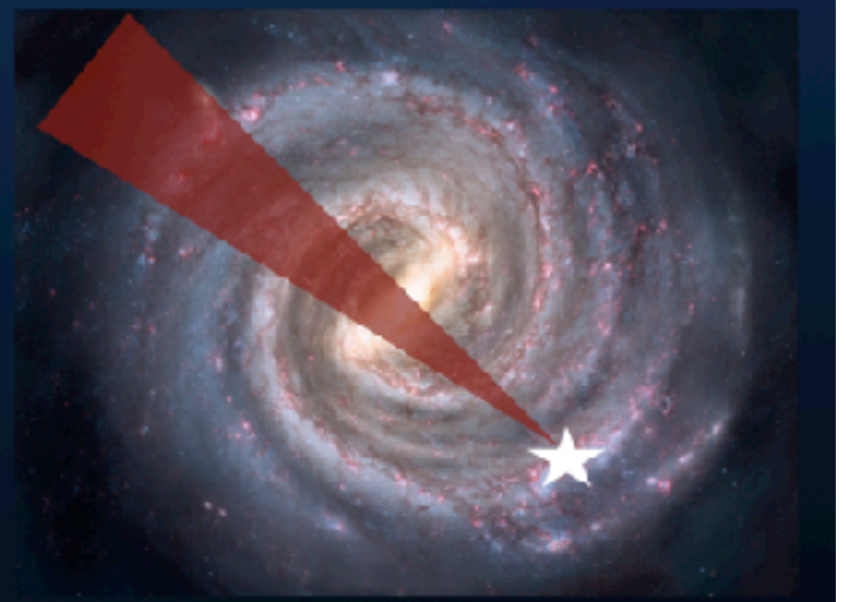
7.7×10^{37} erg s^{-1} ✔

Dark Matter

For a 35 GeV dark matter particle annihilating at the thermal cross-section to bb, and a slightly adiabatically contracted $r^{-1.35}$ density profile.

Energetics





The total luminosity of the Galactic center gamma-ray excess is approximately 10^{37} erg s^{-1}.

Which models are capable of producing this emission?

The dark matter annihilation rate is 2.25 x 10^{39} ann s^{-1}, which produces a gamma-ray flux of:

2.4 x 10^{37} erg s^{-1} ✔

Energetics ✓

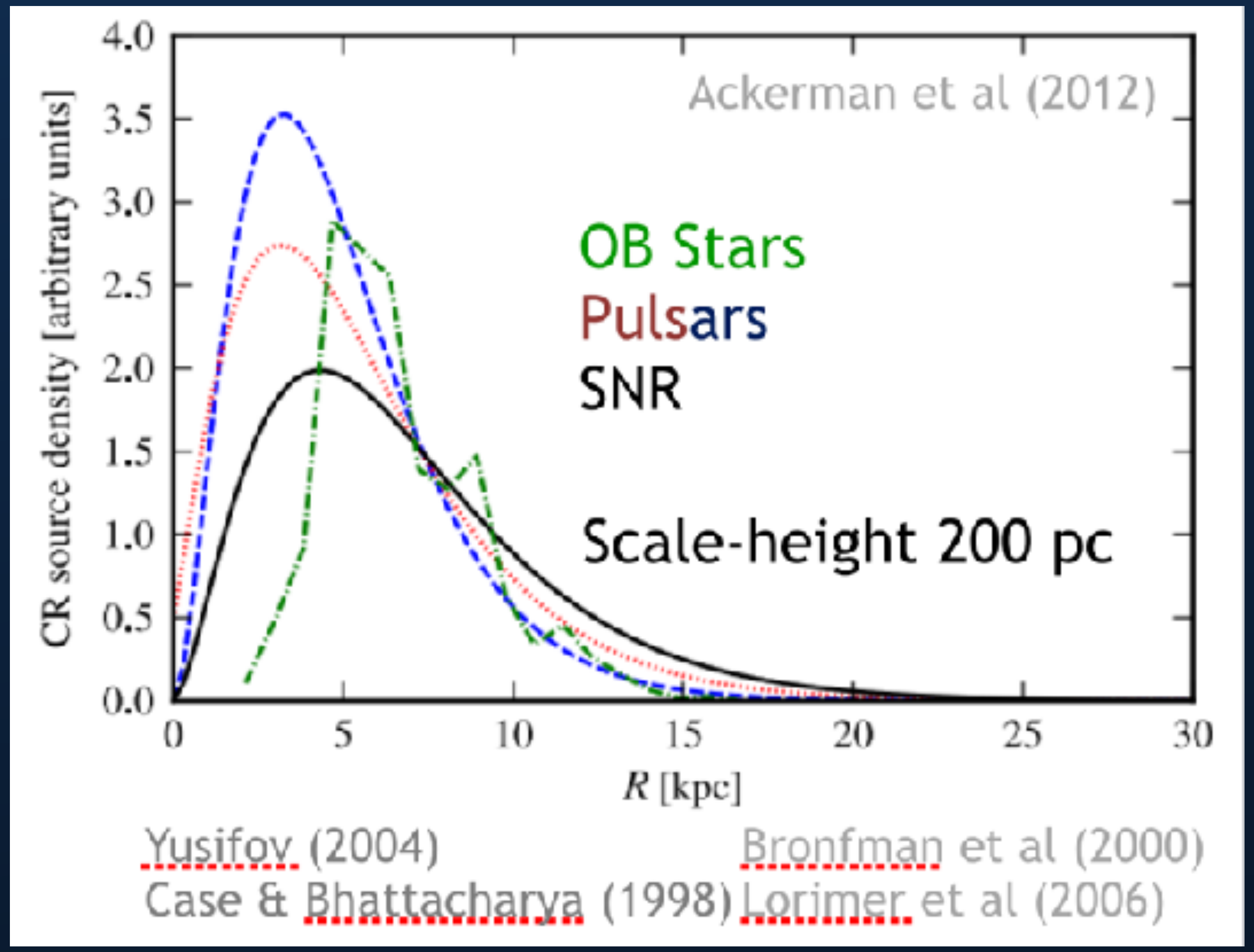
All models can potentially explain the energetics of the GC excess.

This is more challenging problem than it seems — most gamma-ray sources are associated based on energetics (or time variability).

Need to examine each model in much more detail.

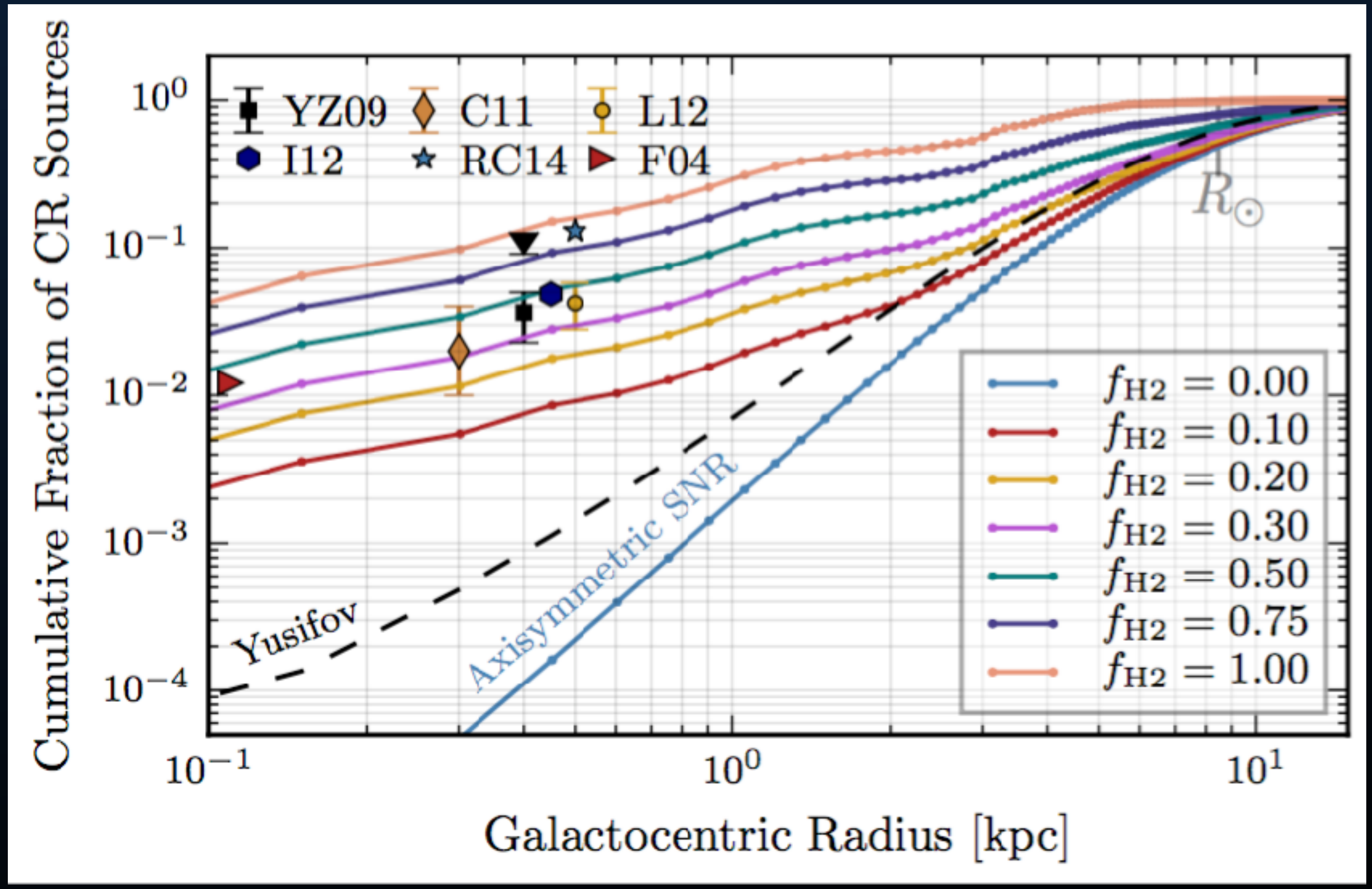
Supernovae Models

More than uncertainties - previous models used to calculate the supernova rate in the Galactic center are wrong.



Most reasonable model - we know there is more energy injection from supernova than we include.

Using H_2 as a tracer of star formation - and subsequent supernovae, provides a significantly more accurate model of the Galactic center supernova rate.



Carlson et al. (2016; 1603.06584)

Supernovae Models

Carlson et al. (2016; 1603.06584)

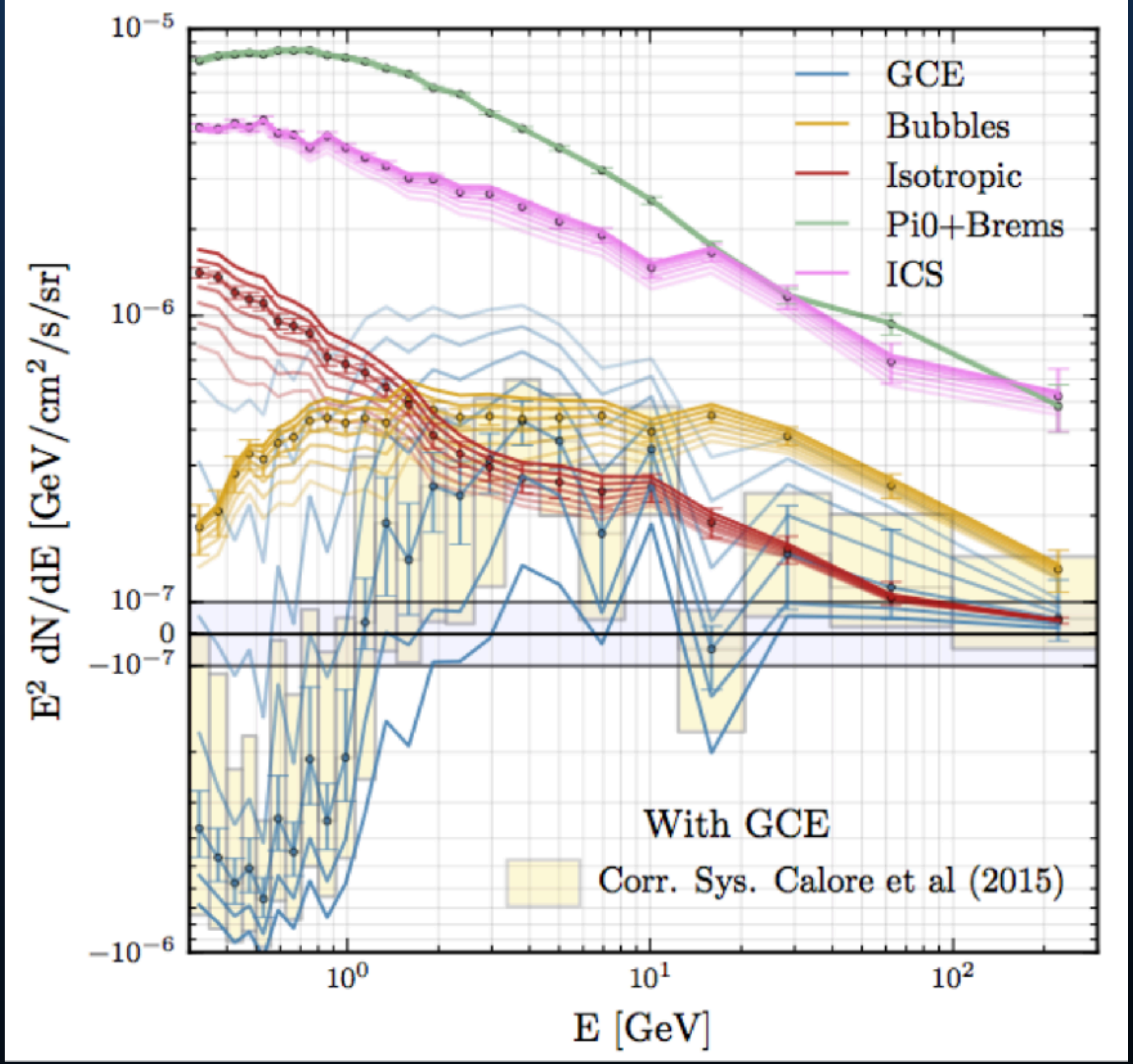
A model where 20% of the total cosmic-ray injection traces the H2 density provides a better fit to the data, and also decreases the intensity of the excess.

Supernovae Models

However, this over-subtracts the low-energy emission.

Inevitable, because π^0-decay spectrum is softer than the excess.

Note: The total intensity of the excess appears reasonably consistent, it has just been significantly zero-point subtracted.



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Supernovae Models

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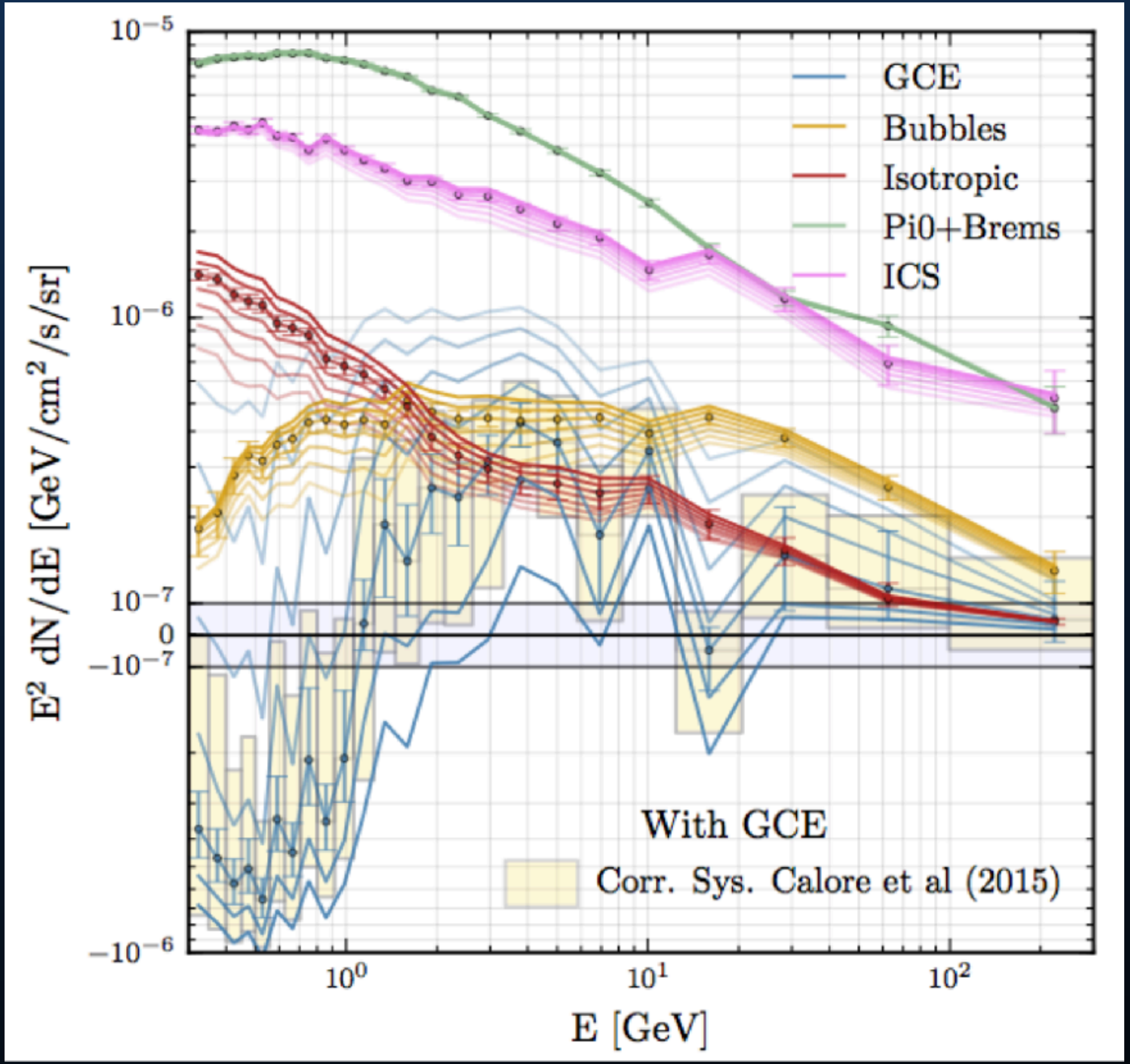


Carlson et al. (2016; 1603.06584)

Changes in the supernova injection rate affect the calculation of the excess - but cannot entirely eliminate it.

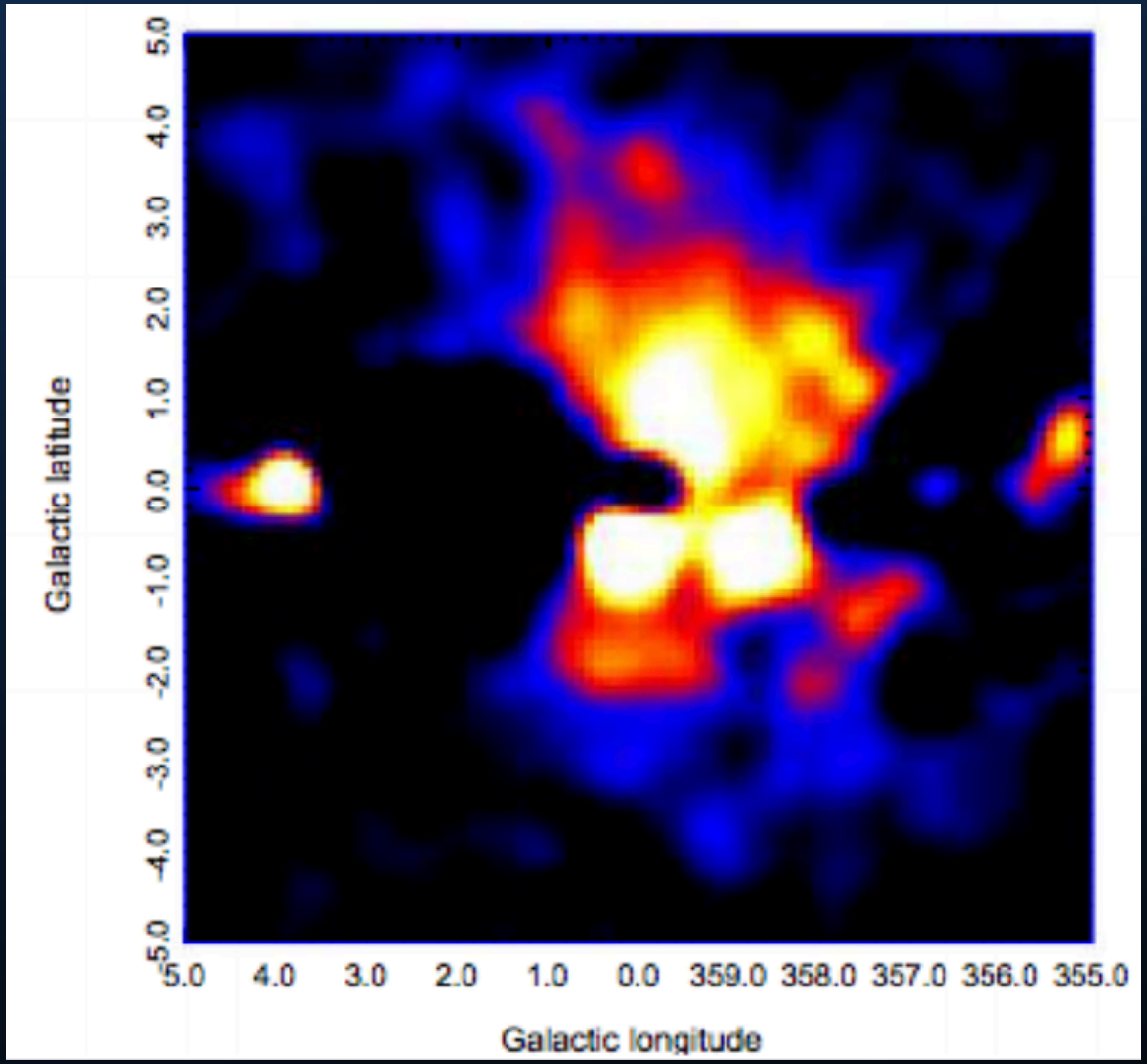
Supernovae Models

Energetics ✓

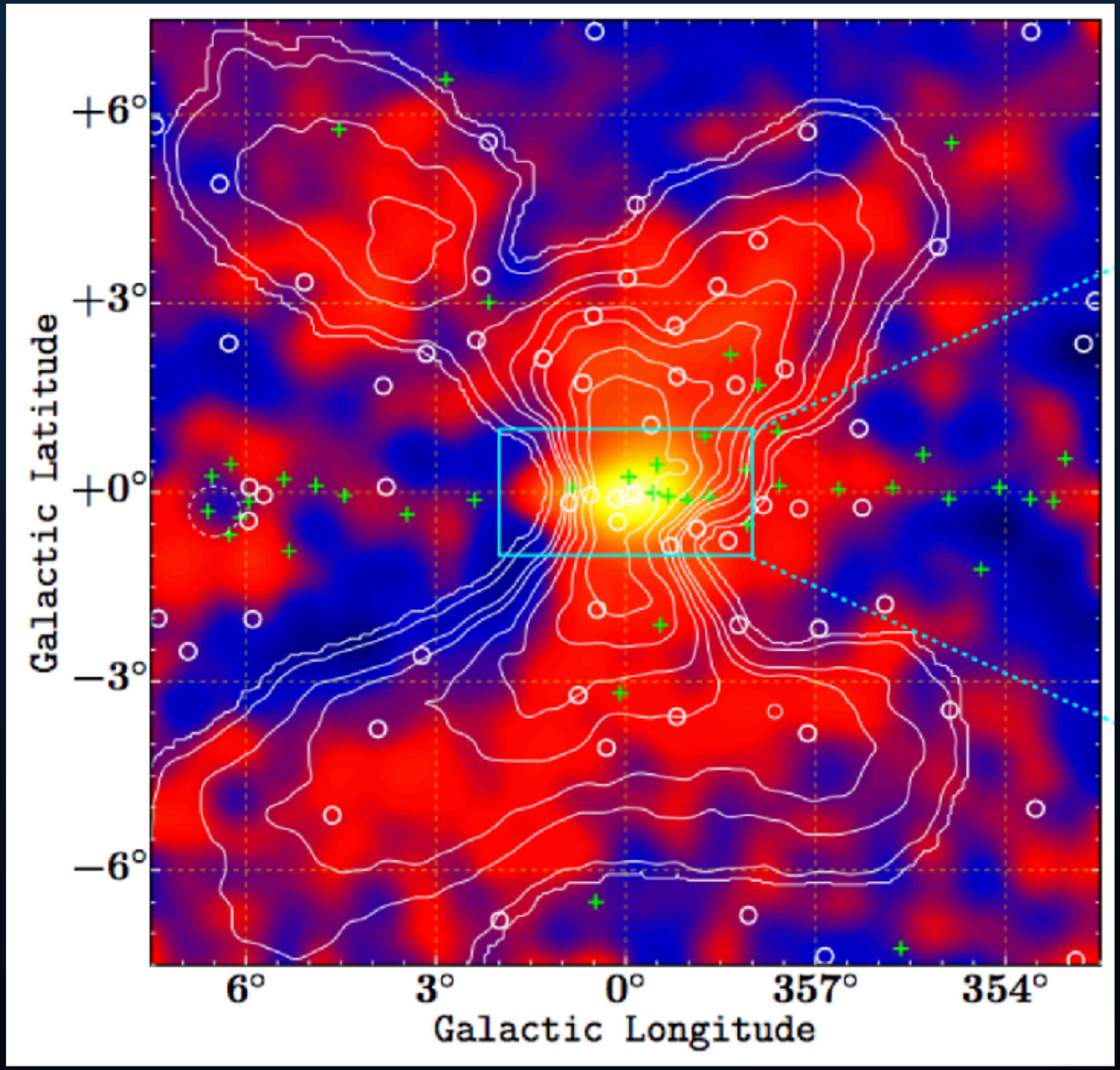
Spectrum ✗

Supernovae Models

Yang & Aharonian (2016)



Macias et al. (2016; 1611.06644)



see next talk by Chris Gordon!

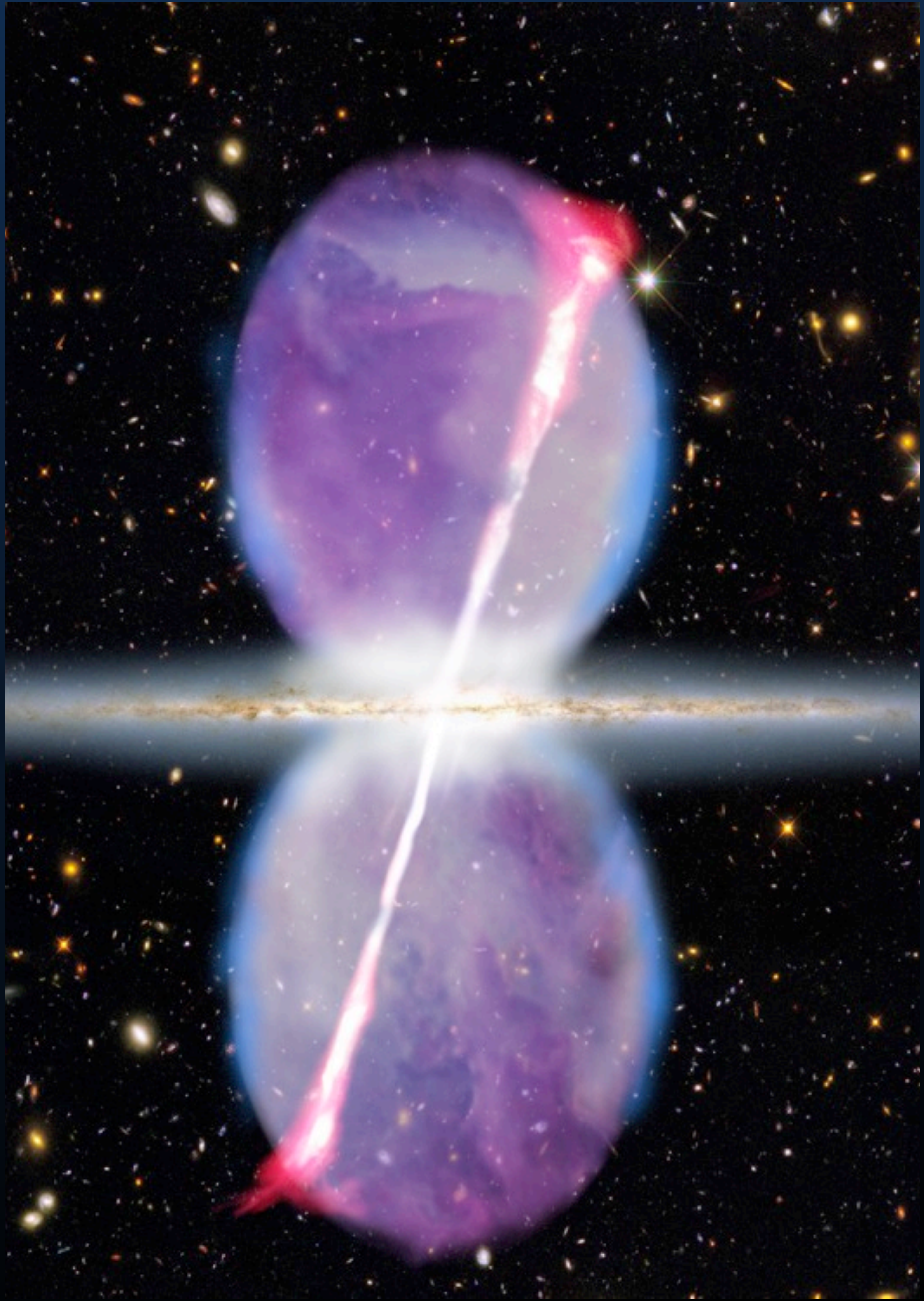
Leptonic Outbursts

Can fix spectral errors (to some degree) by invoking time-dependent emission.

This is well motivated by the Fermi bubbles and WMAP/PLANCK haze.

Similar to the supernovae model, we know this is an uncertainty, but can it explain all the emission?

Petrovic et al. (2014, 1405.7928)
Cholis et al. (2015, 1506.05119)



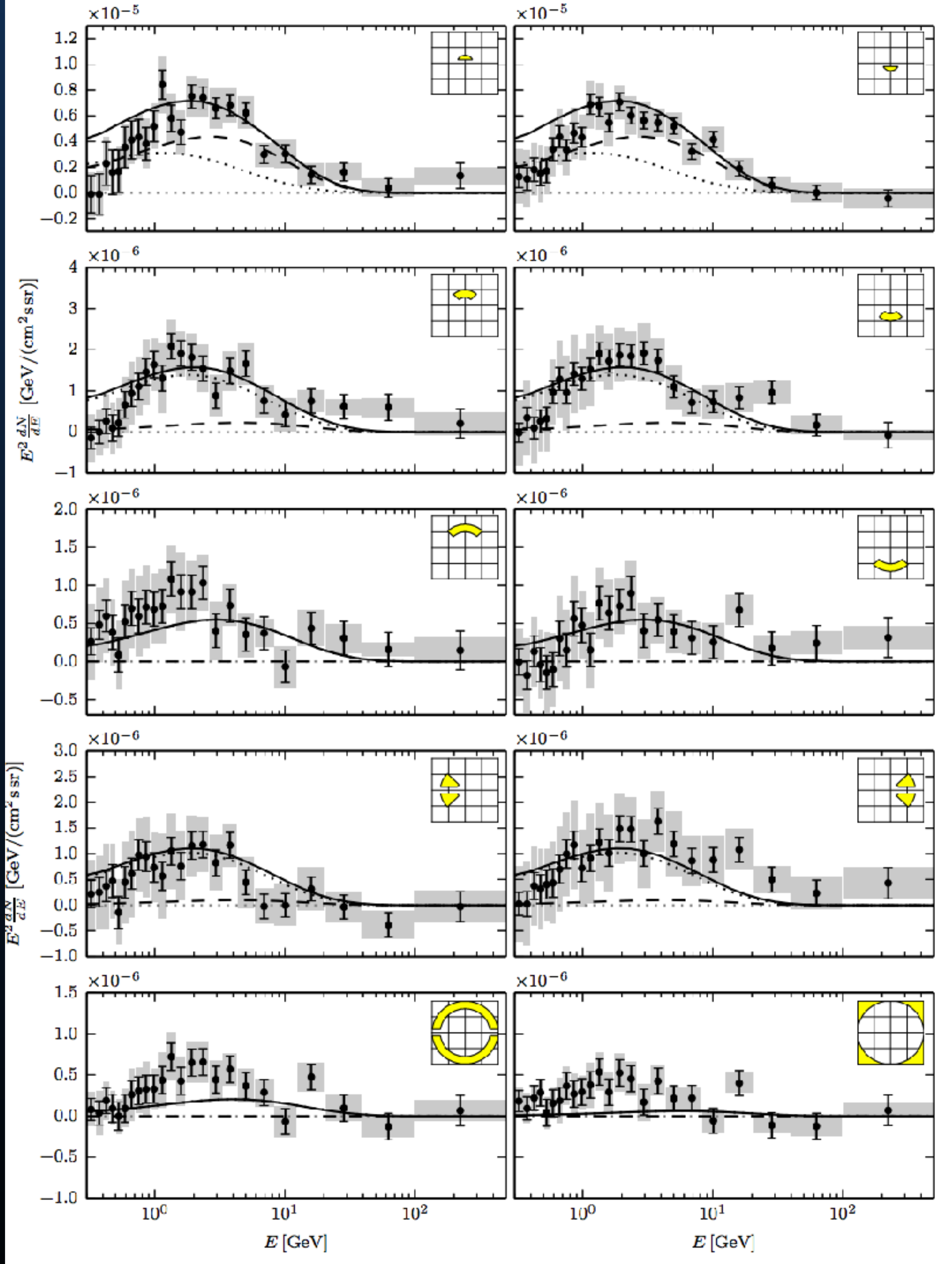
Leptonic Outbursts

Can fix spectral errors (to some degree) by invoking time-dependent emission.

In particular, the energy loss rate from leptons scales linear with electron energy.

However, morphology becomes an issue:

> Require multiple outbursts to produce intensity over full ROI.
>
> Electrons cool rapidly, spectrum should change.



Cholis et al. (2015, 1506.05119)

Leptonic Outbursts

Again, we know that this emission must exist to some extent.

And models exist where this can explain the entirety of the excess.

Parameter	Model A	Model B	Model C
α_1	1.2	2.0	1.1
α_2	NA	NA	1.0
$E_{\mathrm{cut},1}$	1 TeV	1 TeV	20 GeV
$E_{\mathrm{cut},2}$	NA	NA	60 GeV
τ_1 (Myr)	0.83	0.46	0.1
τ_2 (Myr)	NA	NA	1.0
N_1 (10^{51} erg)	2.89	9.87	0.1
N_2 (10^{51} erg)	NA	NA	0.88
δ	0.20	0.23	0.3
D_0 (10^{28} cm^2/s)	5.08	9.12	9.0
D_{zz}/D_{xx}	1.12	0.87	NA
v_A (km/s)	176	122	150
B_0 (μG)	11.5	11.5	11.7
r_c (kpc)	10.0	10.0	10.0
z_c (kpc)	2.0	2.0	0.5
dv_c/dz (km/s/kpc)	0.0	0.0	0.0
ISRF	1.0, 1.0	1.0, 1.0	1.8, 0.8
χ^2 (p−value)	277 (0.04)	317 (0.0004)	261 (0.14)

Leptonic Outburst Models can fit the excess - but they are fine-tuned.

Corresponding emission should be observed at radio energies.

Cholis et al. (2015, 1506.05119)

Leptonic Outburst Models

Energetics ✓

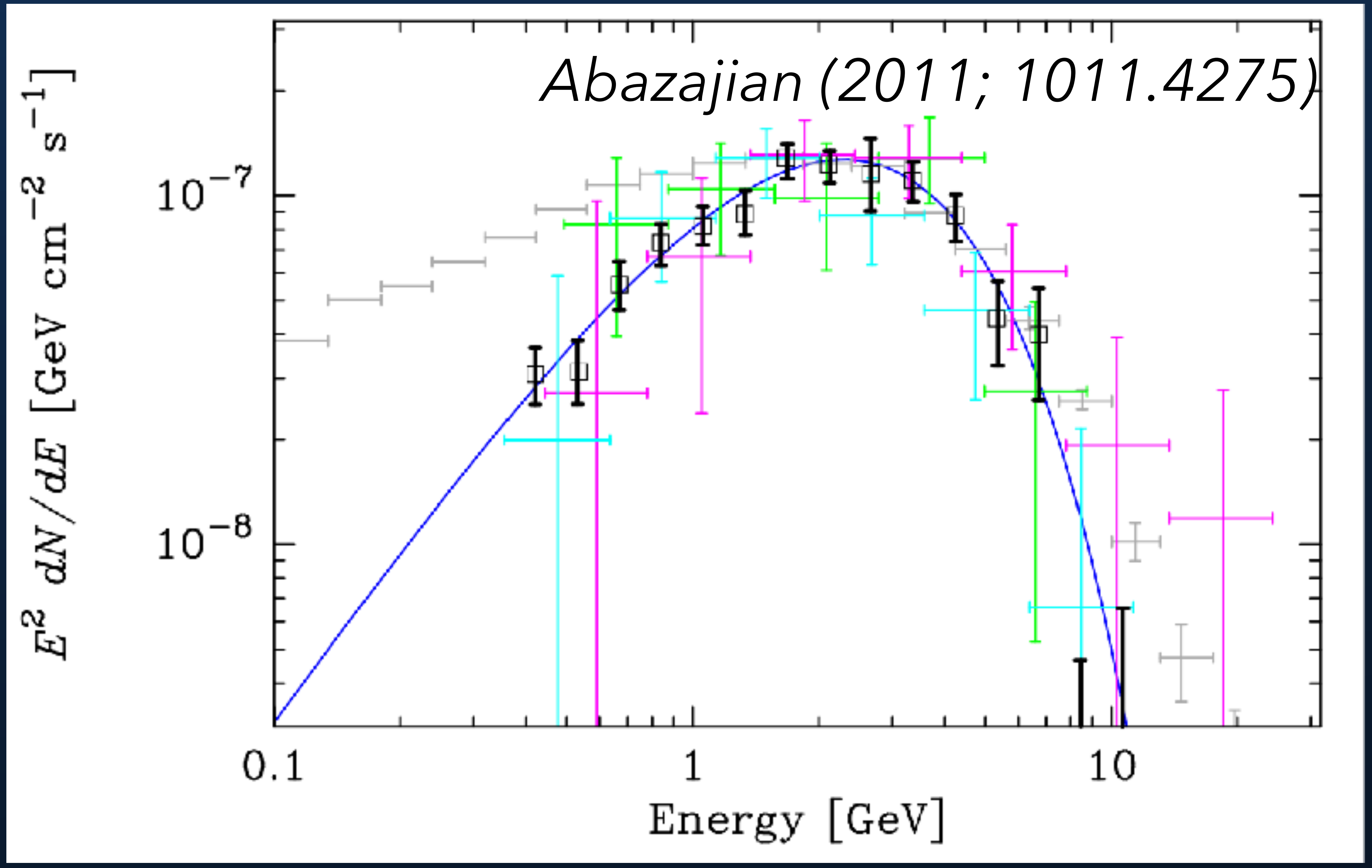
Spectrum ?

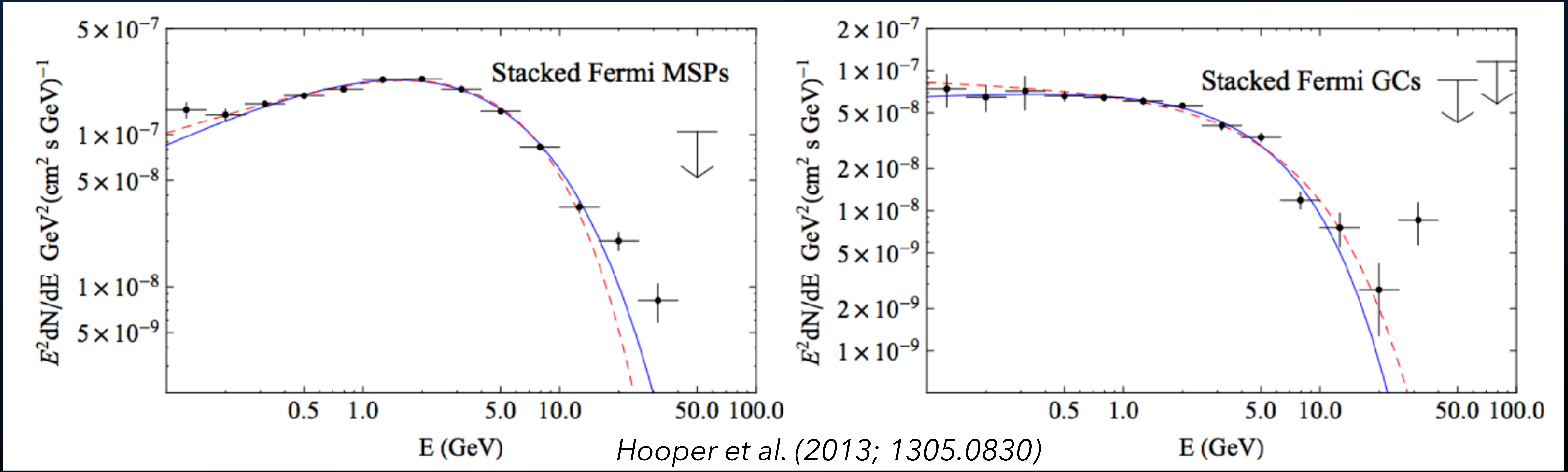
Morphology ?

Pulsar Spectra

Pulsar spectra are broadly consistent with the properties of the excess.

Some deviations at low-energies.

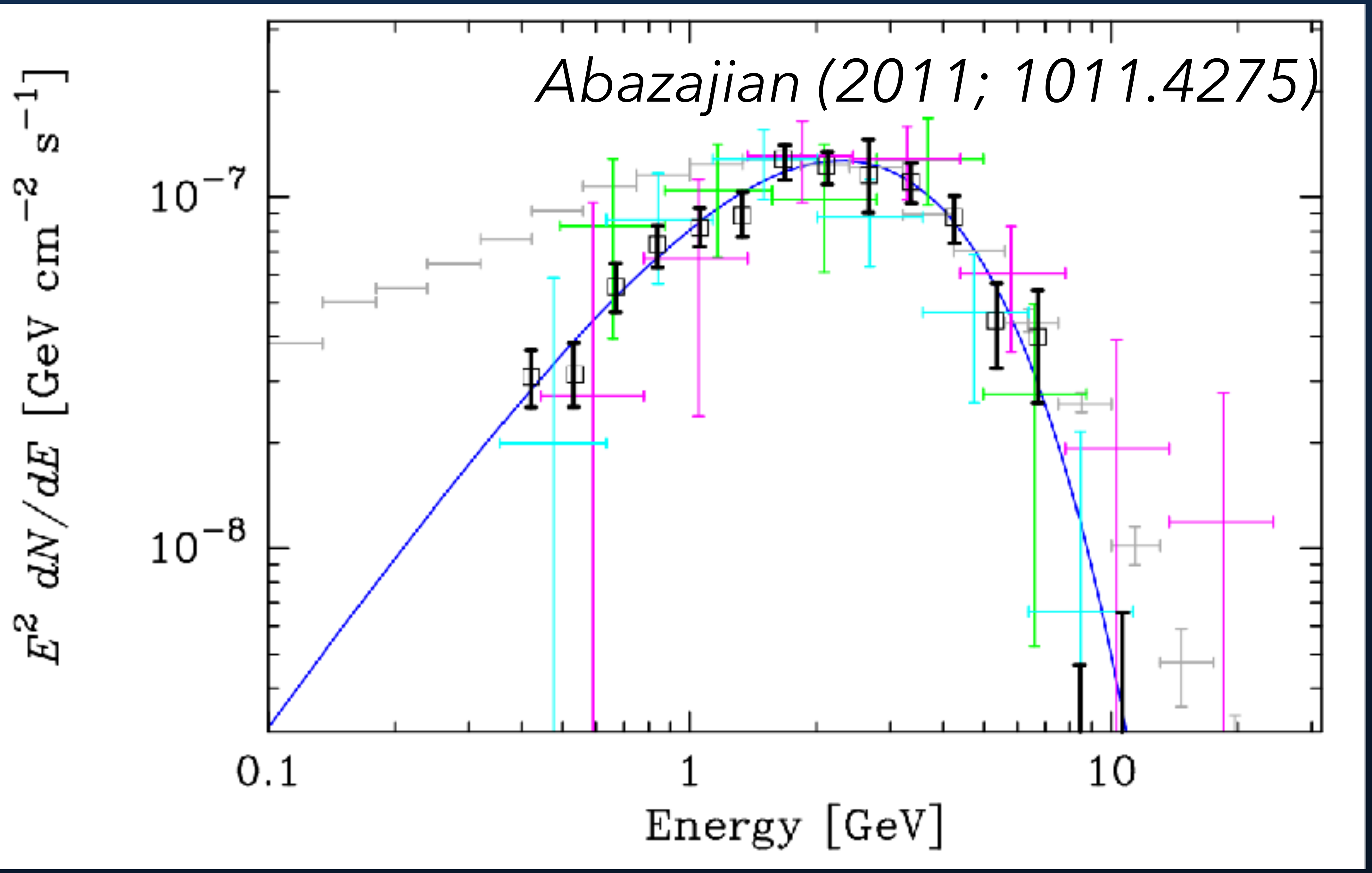




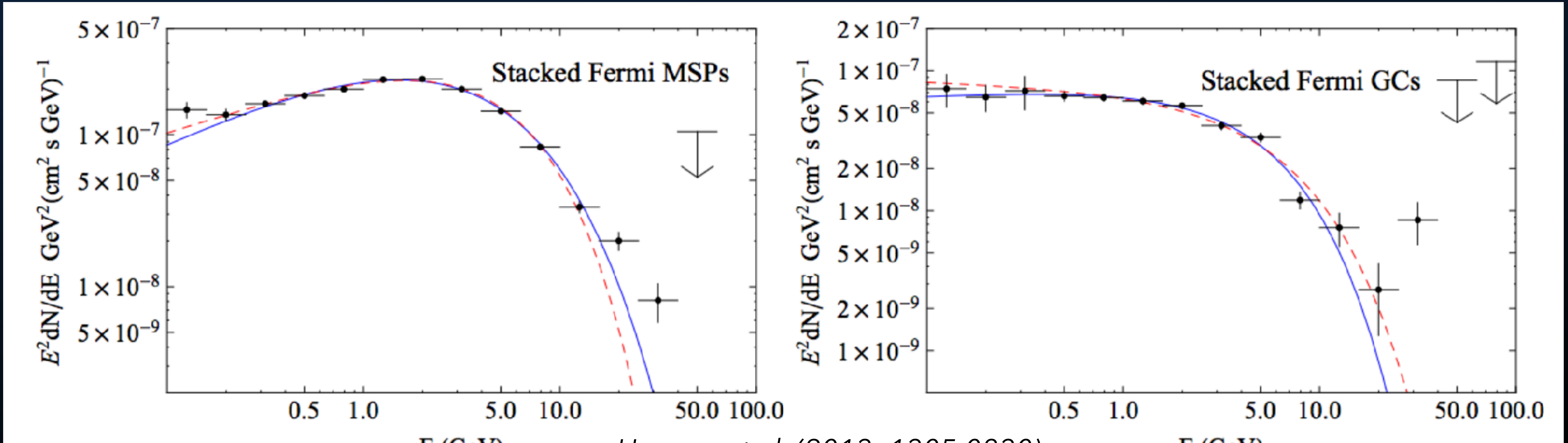
Pulsar Spectra

Note: No degrees of freedom here!

Much better evidence than possible spectral matches from other models.



Abazajian (2011; 1011.4275)



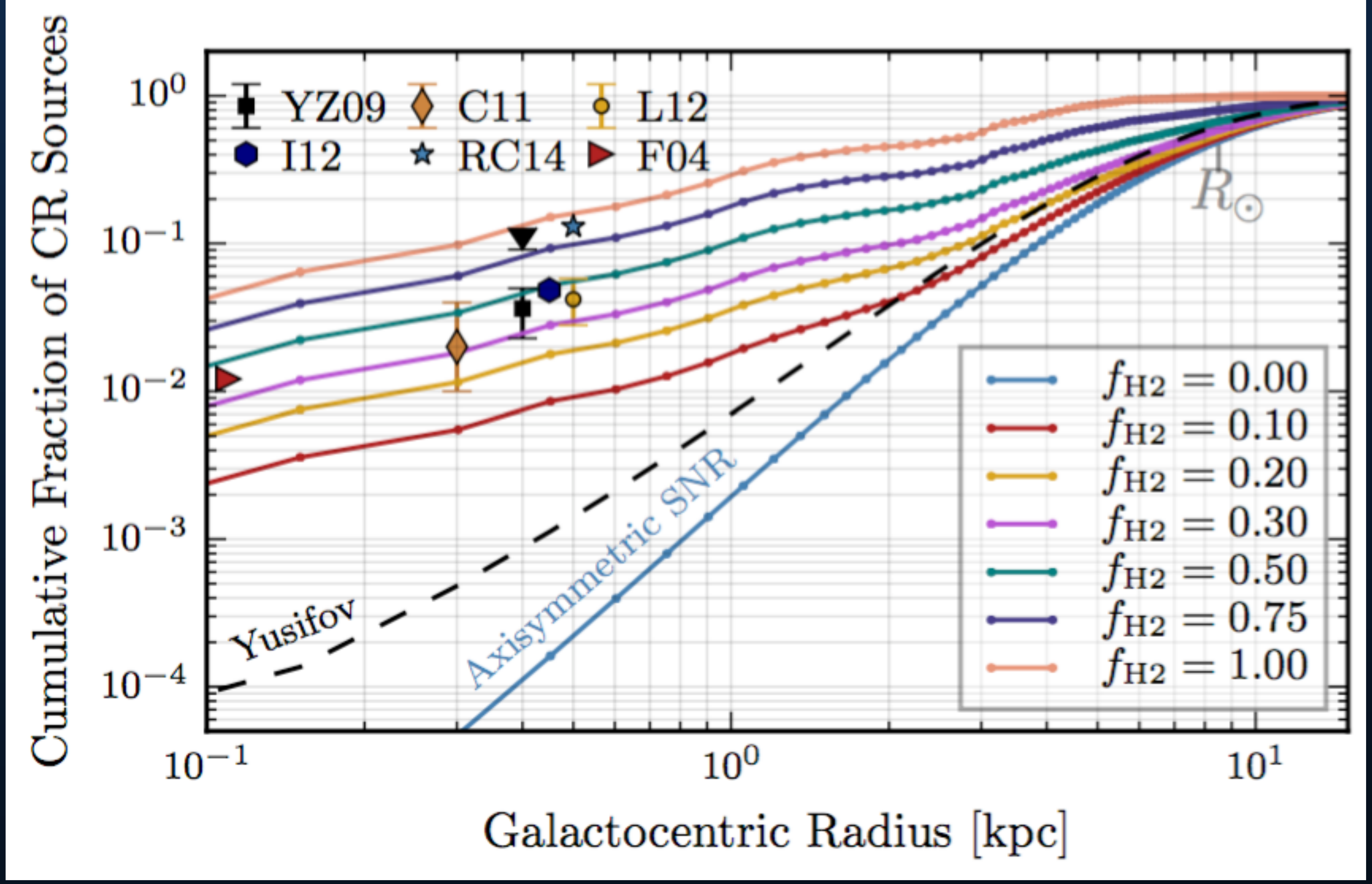
Hooper et al. (2013; 1305.0830)

Pulsar Morphology

More challenging:

The stellar distribution near the Galactic Center is approximately n α $r^{-1.4}$, significantly less peaked than the Galactic center excess.

Pulsars should be more diffuse, due to their high natal kicks (v_k ~ 400 km/s)



Carlson et al. (2016; 1603.06584)

Millisecond pulsars potentially produce a dense emission morphology, through two different mechanisms.

Multiple Pulsar Interpretations

Young Pulsars - Motivated by recent start formation near Galactic center. Difficult to explain spatial extent and lack of bright, detectable systems.

Millisecond Pulsars - Several advantages over young pulsars

1.) Millisecond pulsars formed in the Galactic bulge, or can be kicked to high latitudes.

2.) Systems are individually dimmer.

3.) Can produce morphology that falls as stellar density squared near the GC.

Two Classes of MSPs

1.) MSPs formed near Galactic Center

2.) MSPs formed in Globular Clusters and subsequently disrupted by the Galactic Center.

Two Classes of MSPs

1.) MSPs formed near Galactic Center

Approximately 3-20% of star-formation occurs in the CMZ

This is insufficient to power the excess, unless MSPs are dynamically produced in the GC.

However, the density of the Galactic Center is much smaller than in globular clusters, except for the central parsec.

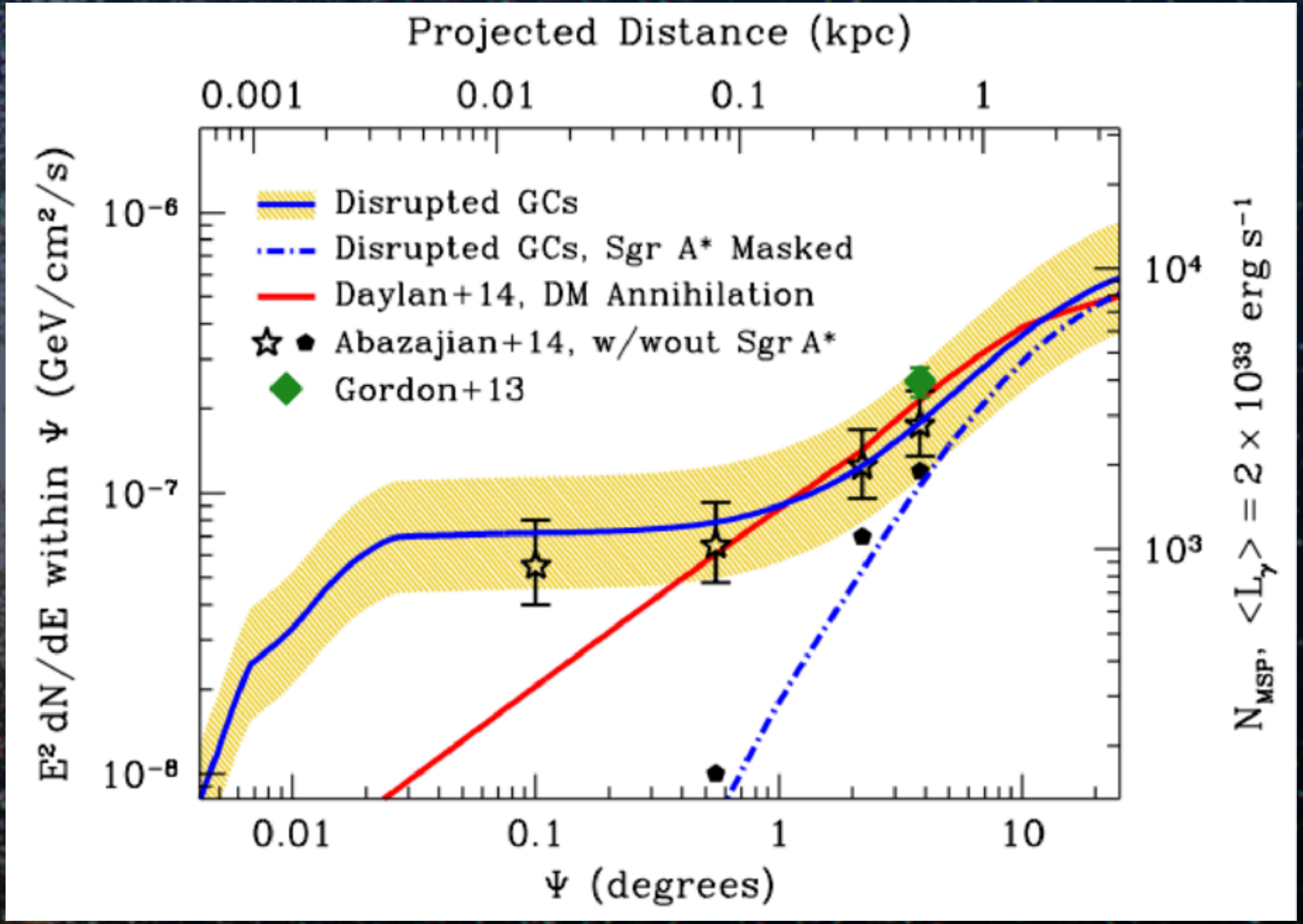
MSPs would need to be produced very efficiently in the Galactic Center and kicked to large distances.

Two Classes of MSPs

2.) MSPs formed in Globular Clusters and subsequently disrupted by the Galactic Center.

Models of the dynamical friction and tidal stripping of globular clusters by the Milky Way galactic center predict a peaked profile.

We know that MSP production is efficient in globular clusters.



Brandt & Kocsis (2015; 1507.05616)

Arguments Against the Pulsar Interpretation

Arguments against the pulsar interpretation are based on intensity:

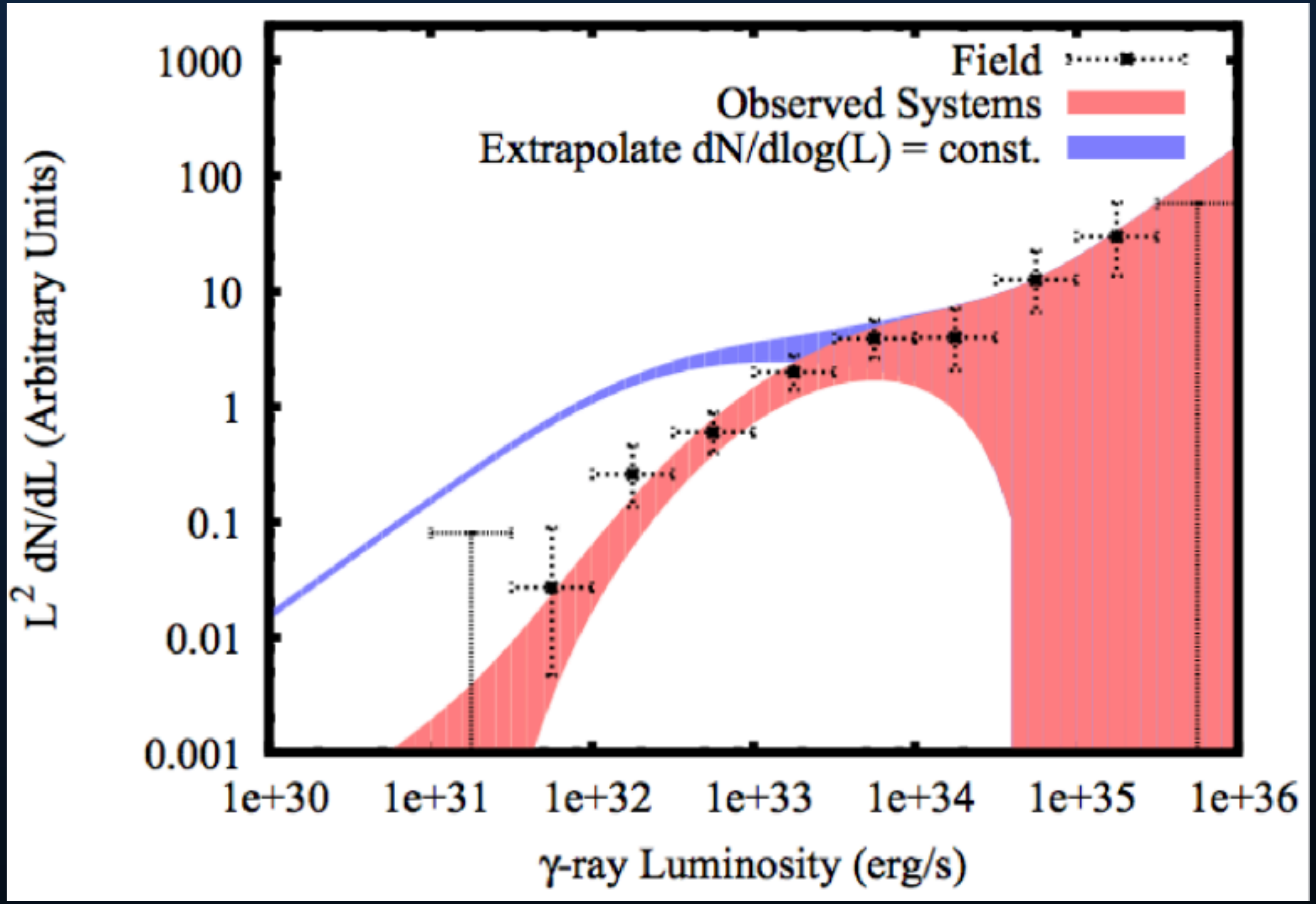
1.) How many pulsars are necessary to produce the excess?

2.) Why haven't we seen the brightest pulsars that contribute to the excess?

MSP Luminosity Function

Can determine the flux distribution of pulsars contributing to the Galactic center excess by calculating the luminosity distribution of galactic MSPs.

Early results found very hard spectra.



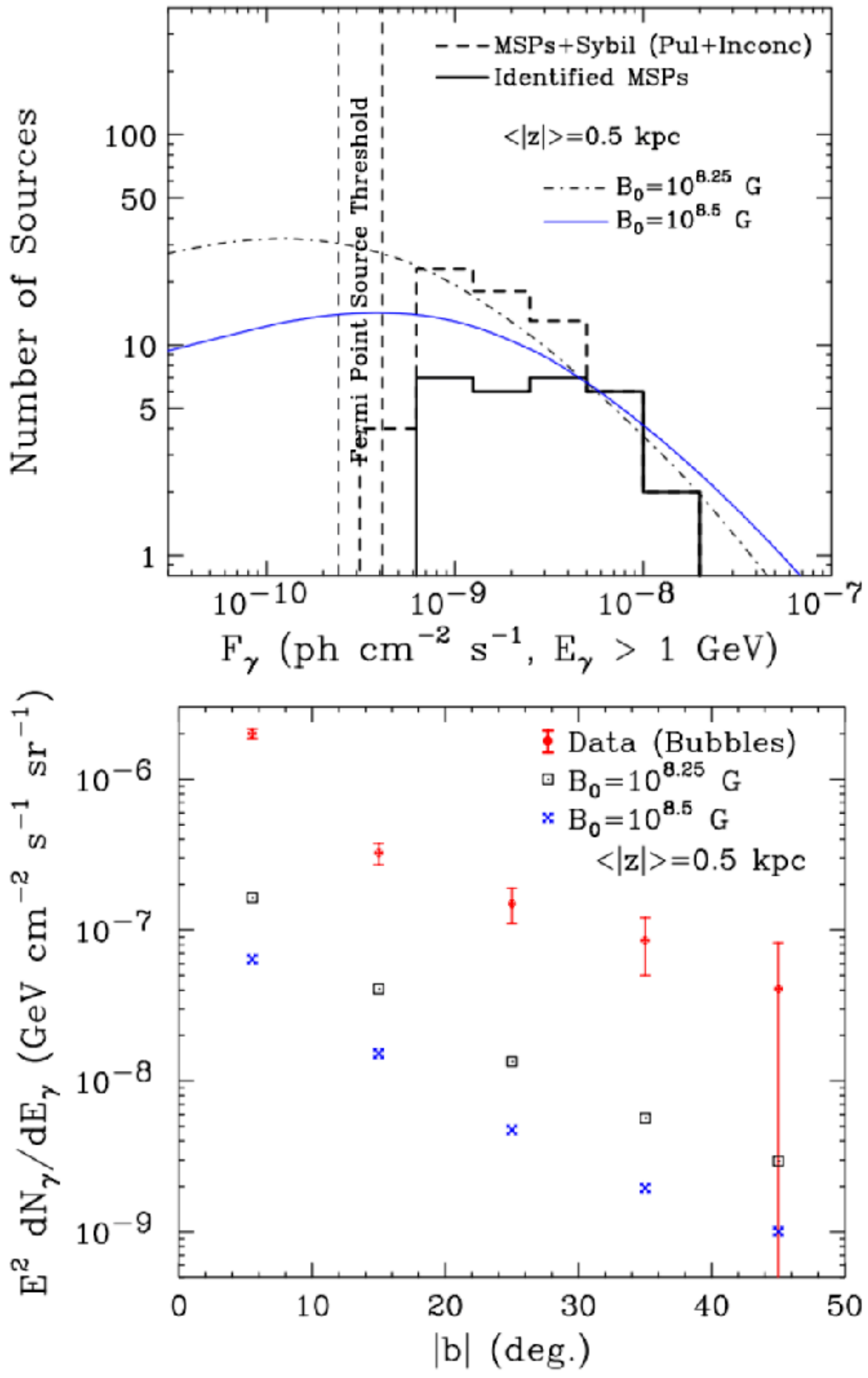
Hooper et al. (2014; 1407.5583)

Constraints on Bright Pulsars

Models with luminosity functions similar to those of observed MSPs saturate the number of observed 3FGL sources while only producing 5-10% of the excess.

More serious constraints on young pulsars - because more systems are even brighter.

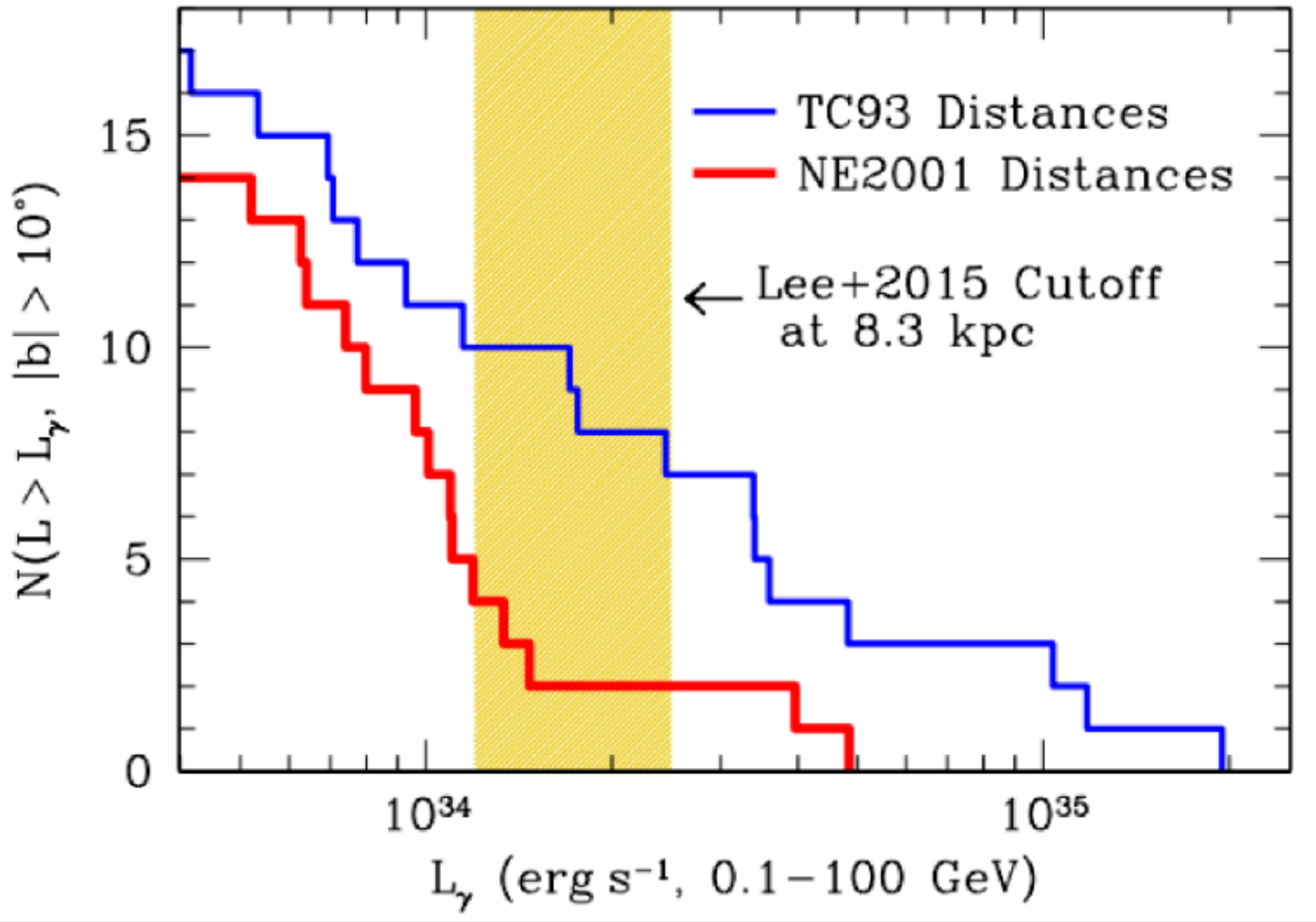
Requires a re-tuning of the MSP luminosity function for systems near the Galactic center.



Hooper et al. (2013; 1305.0830)

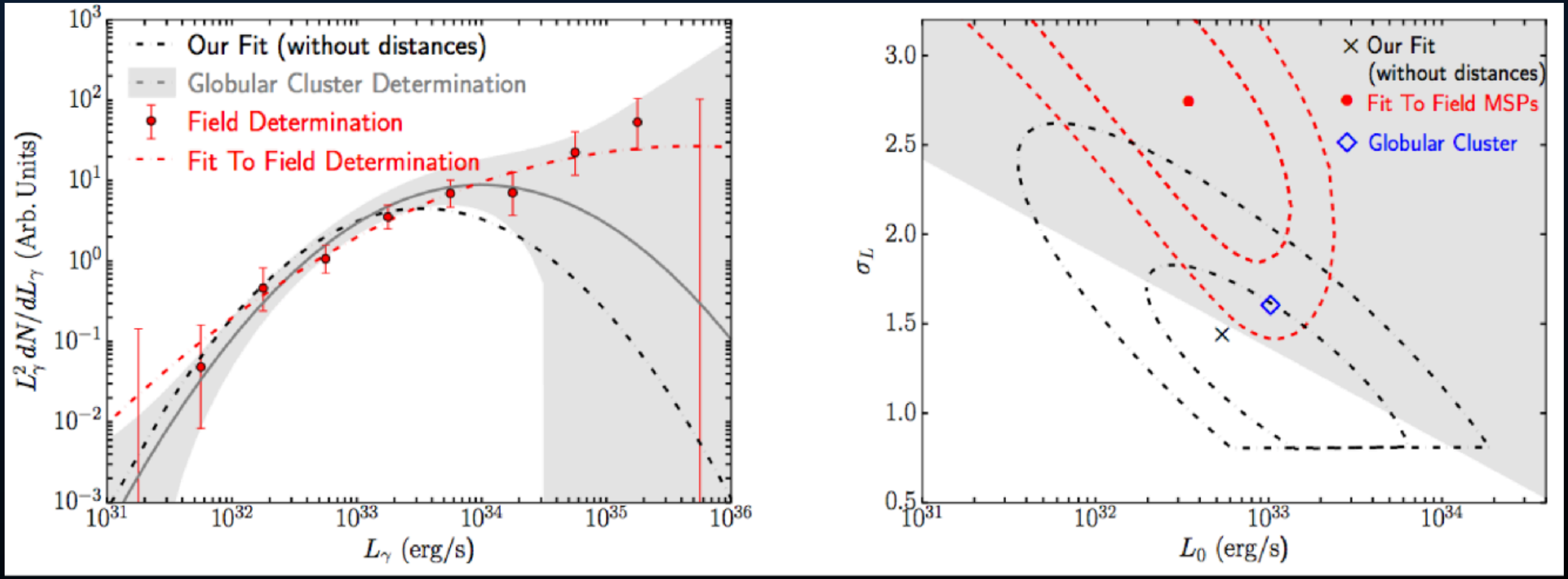
MSP Luminosity Function

More recent results using the NE2001 catalog (right) or the latitude distribution of pulsars (bottom) find fewer very bright sources.



Brandt & Kocsis (2015; 1507.05616)

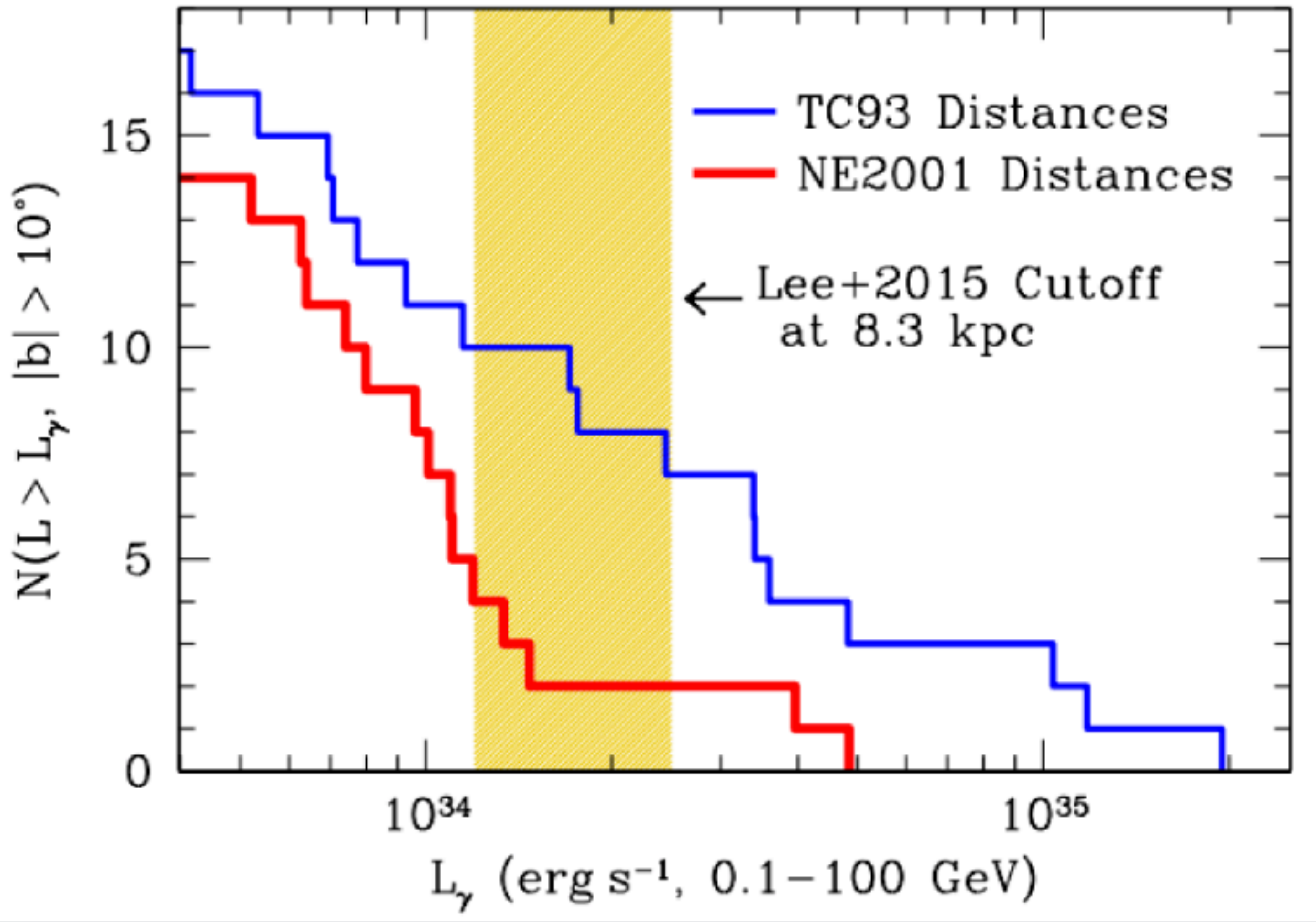
Hooper & Mohlabeng (2015; 1512.04966)



MSP Luminosity Function

<u>Tension Still Exists:</u>

The luminosity function of MSPs in the Galactic Center must be somewhat softer than either the field or globular clusters.



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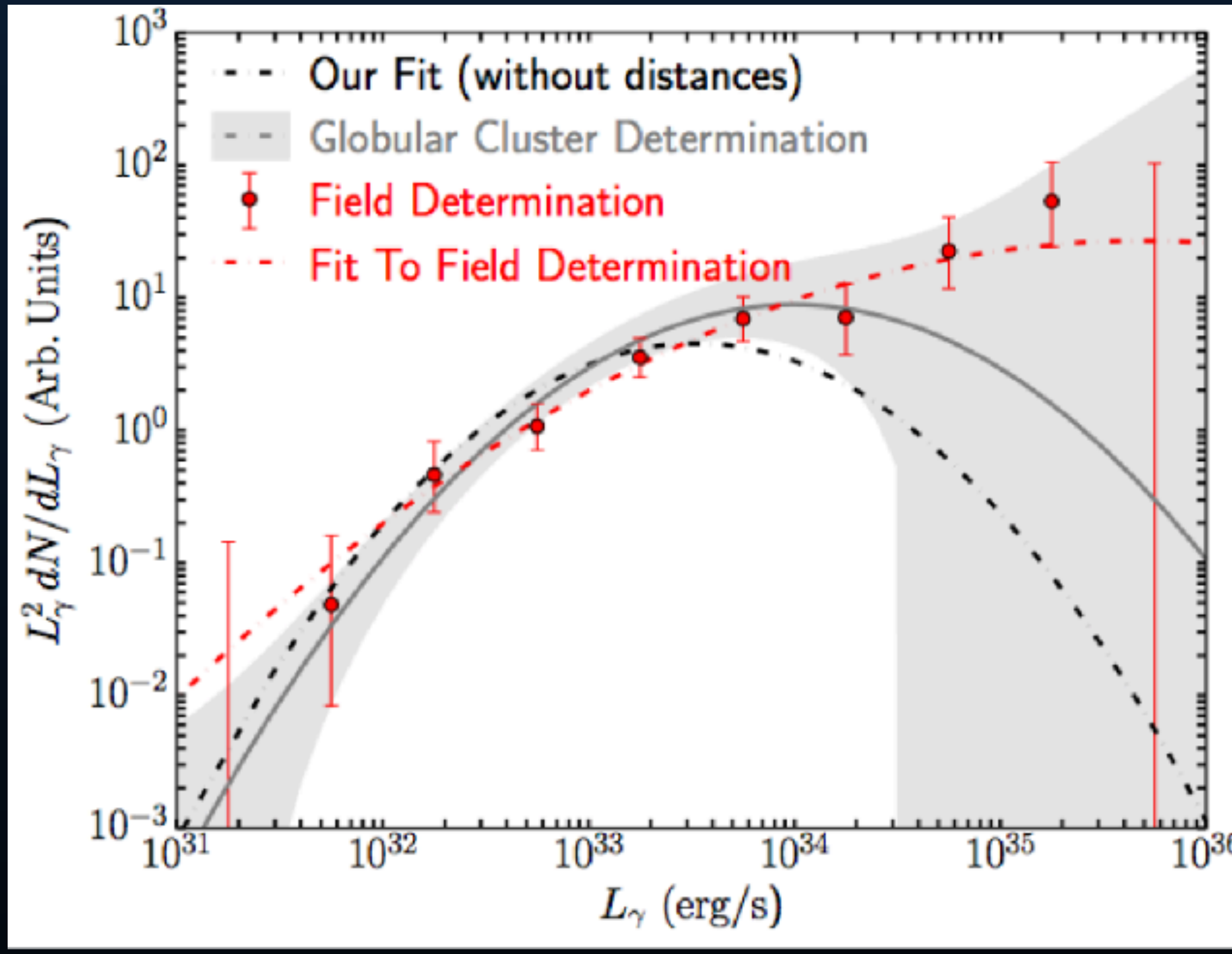
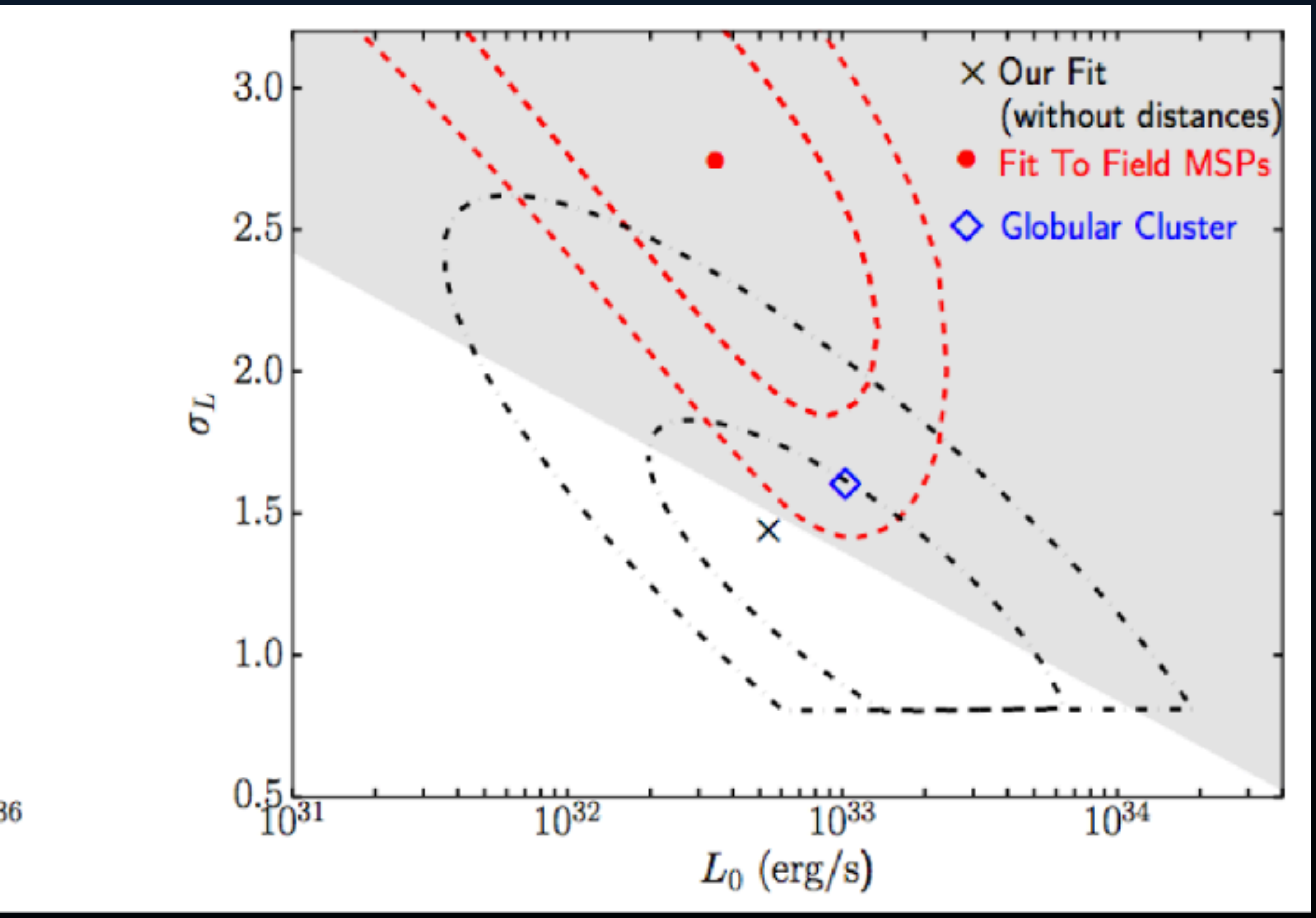


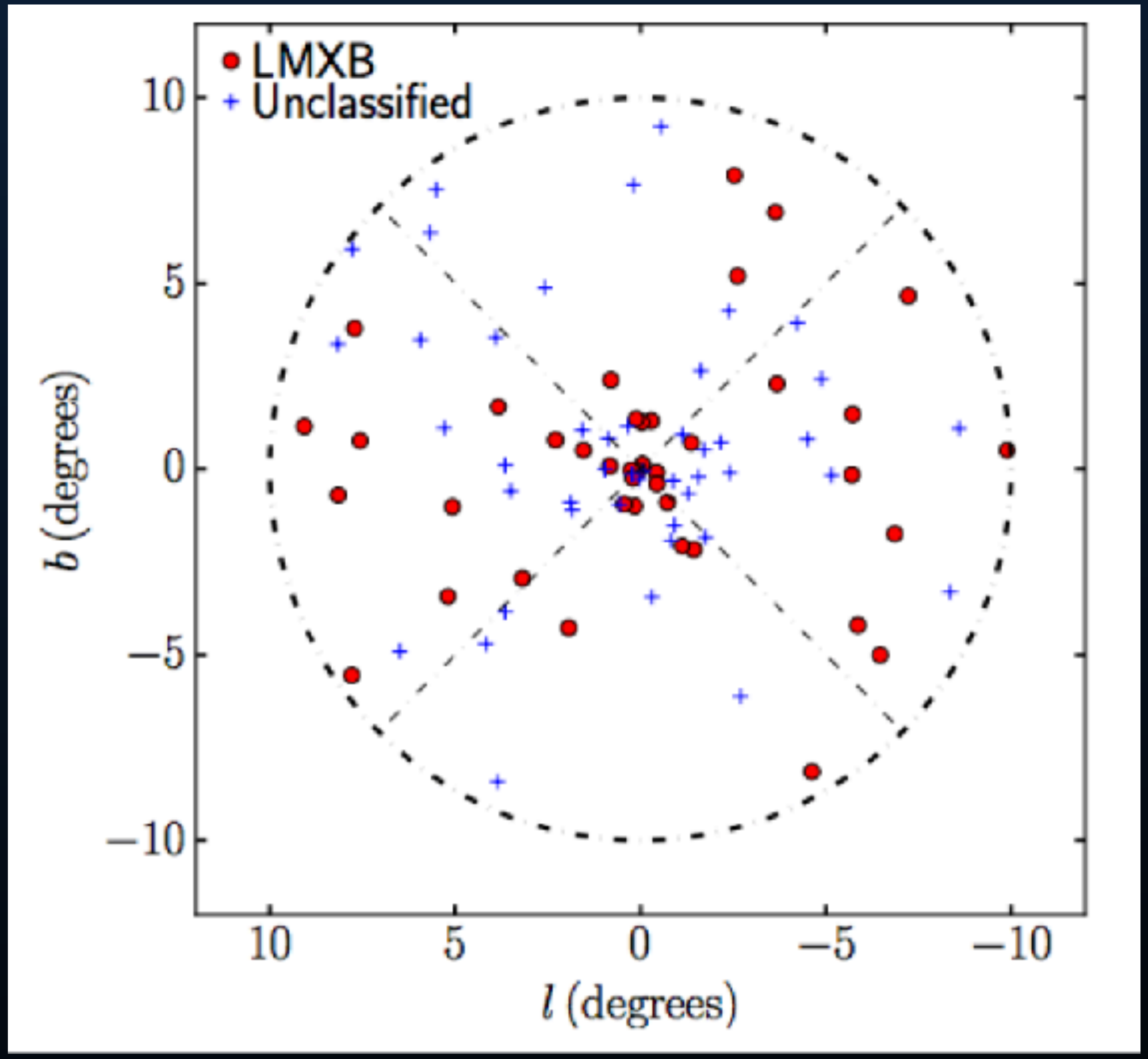


The LMXB Problem

LMXBs are the progenitors of MSPs.

$$L_\gamma^{\rm IG} = L_\gamma^{\rm clusters} \times \left(\frac{N_{\rm LMXB}^{\rm IG}}{N_{\rm LMXB}} \right)$$

Haggard et al. (2017; 1701.02726)



Globular Cluster	Alternate Name	Flux (erg/cm^2/s)	α	$E_{\rm cut}$(GeV)	TS
NGC 104	47 Tuc	$2.436^{+0.062}_{-0.062} \times 10^{-11}$	1.18	2.51	4055.9
NGC 2808		$3.546^{+0.602}_{-0.486} \times 10^{-12}$	1.36	3.16	97.4
NGC 5139	Omega Centauri	$5.900^{+0.468}_{-0.453} \times 10^{-12}$	-0.12	1.26	301.3
NGC 5904	M5	$2.131^{+0.539}_{-0.600} \times 10^{-12}$	1.86	3.98	39.6
NGC 6093	M80	$3.986^{+0.596}_{-0.705} \times 10^{-12}$	1.38	5.01	96.9
NGC 6139		$5.330^{+1.310}_{-0.936} \times 10^{-12}$	2.28	19.95	40.6
NGC 6218	M12	$2.969^{+0.655}_{-0.844} \times 10^{-12}$	2.24	≥ 100	31.0
NGC 6266	M62	$1.710^{+0.074}_{-0.070} \times 10^{-11}$	1.36	3.16	855.7
NGC 6316		$1.091^{+0.124}_{-0.120} \times 10^{-11}$	2.00	7.94	163.5
NGC 6342		$4.339^{+1.046}_{-1.015} \times 10^{-12}$	2.16	15.85	37.8
NGC 6388		$1.732^{+0.124}_{-0.099} \times 10^{-11}$	1.52	3.16	779.6
NGC 6397		$6.390^{+0.734}_{-0.727} \times 10^{-12}$	2.90	50.12	81.5
Palomar 6		$5.489^{+1.455}_{-1.324} \times 10^{-12}$	0.94	1.26	29.9
Terzan 5	Terzan 11	$5.973^{+0.203}_{-0.147} \times 10^{-11}$	1.16	2.51	2742.3
NGC 6440		$2.392^{+0.178}_{-0.105} \times 10^{-11}$	2.32	10.00	390.6
NGC 6441		$1.252^{+0.088}_{-0.144} \times 10^{-11}$	2.04	10.00	217.8
NGC 6541		$3.251^{+0.748}_{-0.667} \times 10^{-12}$	1.16	2.51	77.7
2MASS-GC01		$2.476^{+0.217}_{-0.196} \times 10^{-11}$	1.06	1.26	179.8
2MASS-GC02		$8.846^{+2.051}_{-2.065} \times 10^{-12}$	1.08	1.26	28.2
GLIMPSE 02		$1.630^{+0.228}_{-0.242} \times 10^{-11}$	1.94	7.94	67.3
NGC 6652		$4.495^{+0.805}_{-0.495} \times 10^{-12}$	1.38	3.16	128.5
GLIMPSE 01		$9.020^{+1.205}_{-1.345} \times 10^{-12}$	-0.74	1.58	68.7
NGC 6717	Palomar 9	$1.816^{+0.543}_{-0.386} \times 10^{-12}$	0.38	2.51	42.3
NGC 6752		$2.866^{+0.503}_{-0.327} \times 10^{-12}$	0.12	0.79	144.8
NGC 7078	M15	$3.160^{+0.587}_{-0.604} \times 10^{-12}$	2.42	6.31	41.8

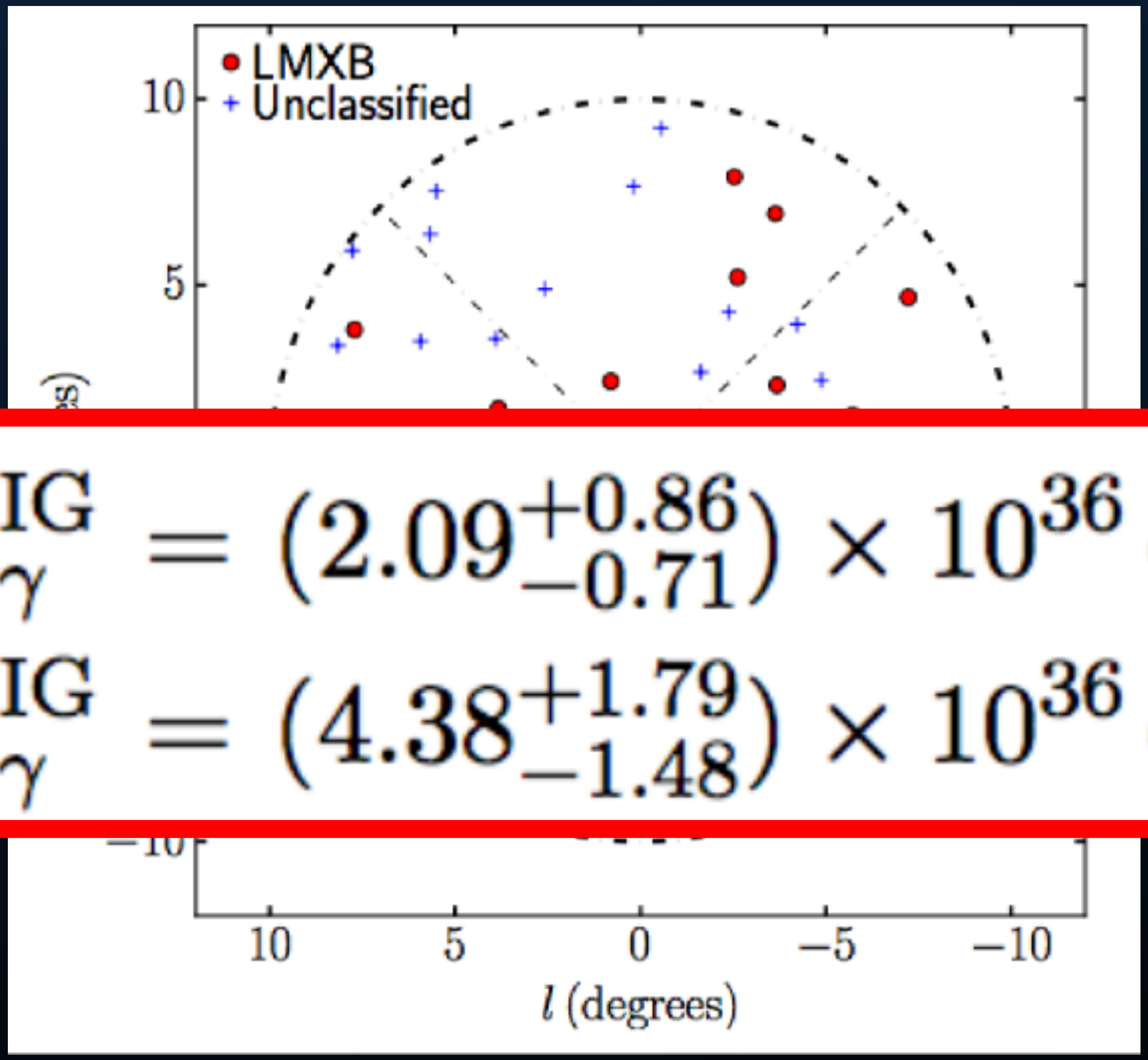
Hooper & Linden (2016; 1606.09250)

The LMXB Problem

LMXBs are the progenitors of

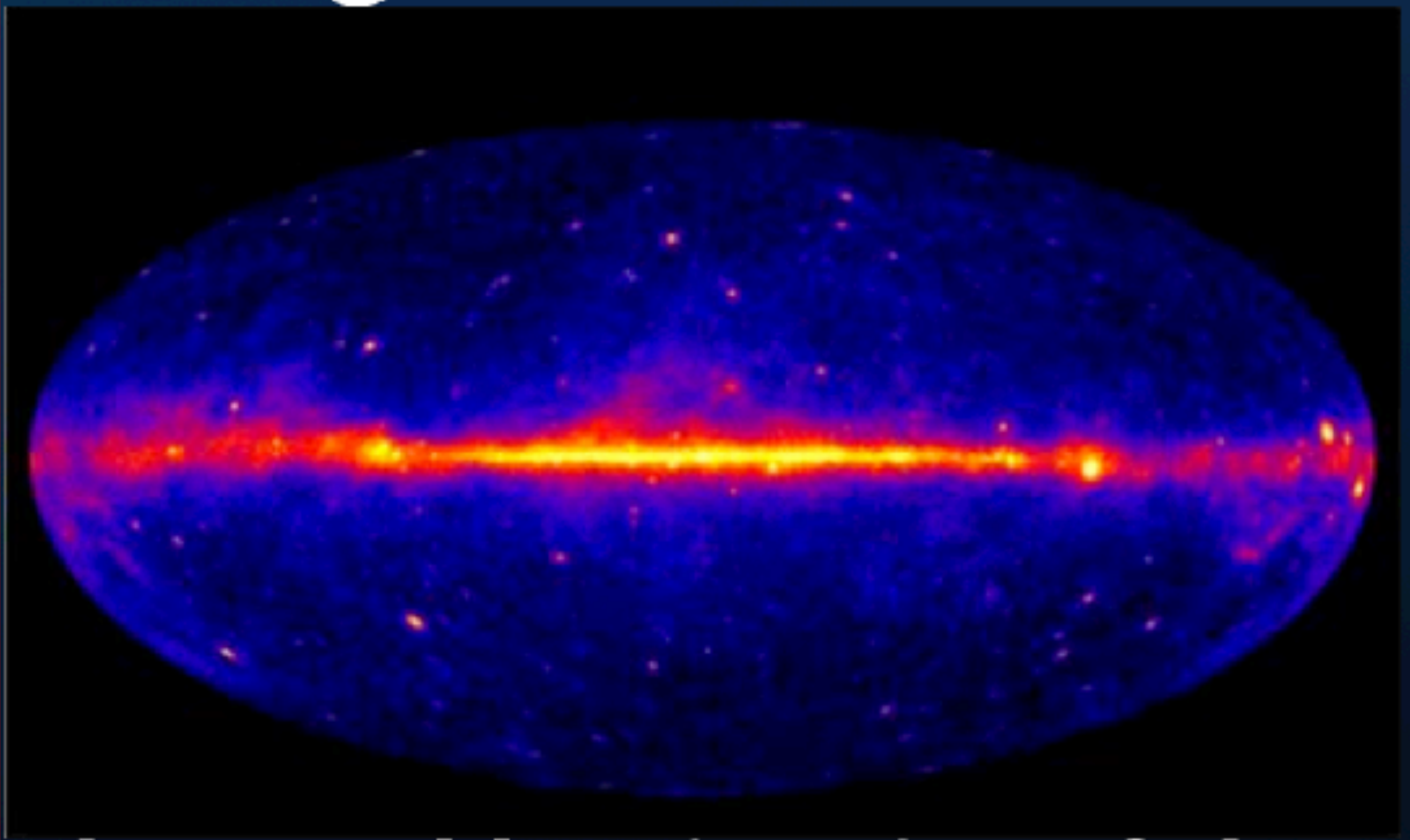
$$L_\gamma^{\rm IG} = L_\gamma^{\rm clusters} \times \left(\frac{N^{\rm IG}_{\rm LM}}{N_{\rm LM}} \right.$$

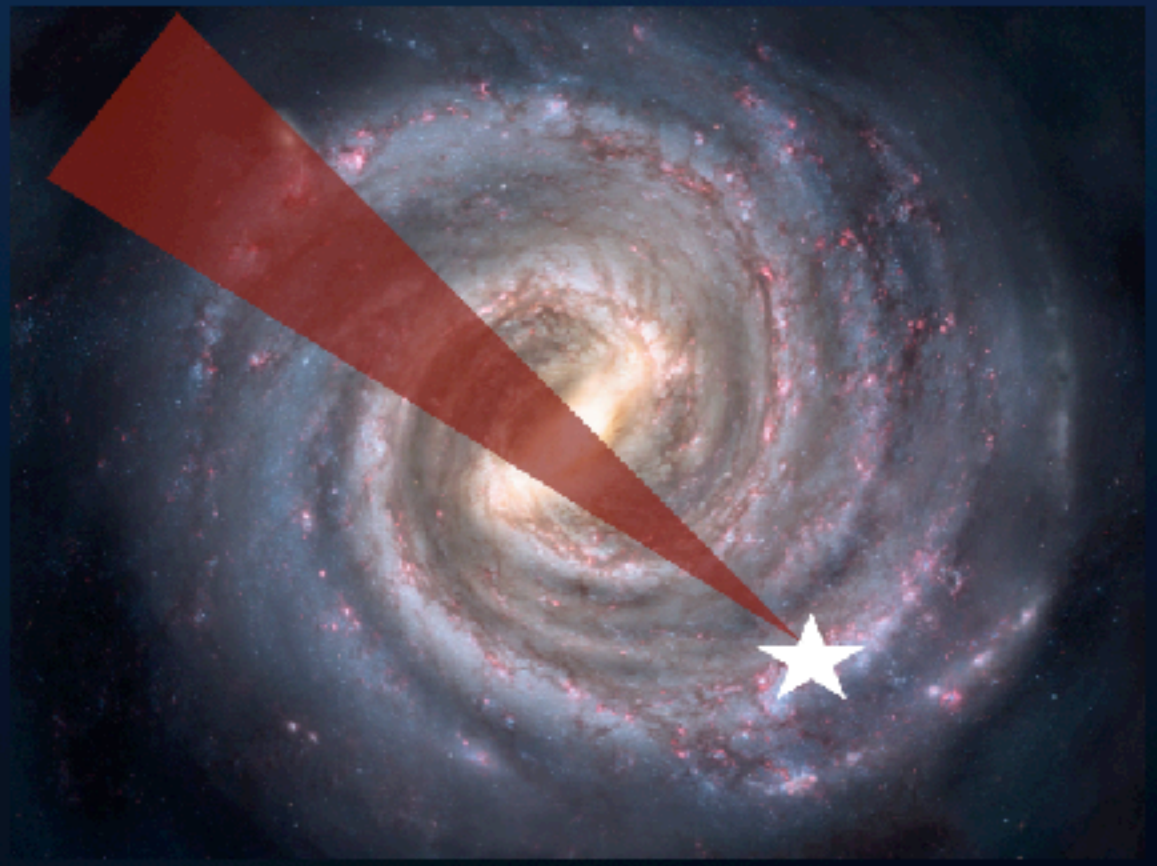
Haggard et al. (2017; 1701.02726)



Globular Cluster	Alternate Name	Flux (erg/cm^2/s)	α	$E_{\rm cut}$(GeV)	TS
NGC 104	47 Tuc	$2.436^{+0.062}_{-0.062} \times 10^{-11}$	1.18	2.51	4055.9
NGC 7078	M15	$3.160^{+0.587}_{-0.604} \times 10^{-12}$	2.42	6.31	41.8

Energetics





The total luminosity of the Galactic center gamma-ray excess is approximately 2 x 10^{37} erg s^{-1}.

Which models are capable of producing this emission?

$$L_\gamma^{\rm IG} = (2.09^{+0.86}_{-0.71}) \times 10^{36}\,{\rm erg/s}, \quad \text{Only Sources Classified as LMXBs}$$

$$L_\gamma^{\rm IG} = (4.38^{+1.79}_{-1.48}) \times 10^{36}\,{\rm erg/s}, \quad \text{Including All Unclassified Sources}$$

Hooper & Linden (2016; 1606.09250)

Solution: Disrupted Globular Clusters

Solves both MSP luminosities and LMXBs:

1.) LMXB and MSP formation occur normally in globular cluster

2.) The disruption of the globular cluster ends binary formation, moving the system out of steady state.

As the systems leave steady state:

Individual MSPs get dimmer

LMXB phases end

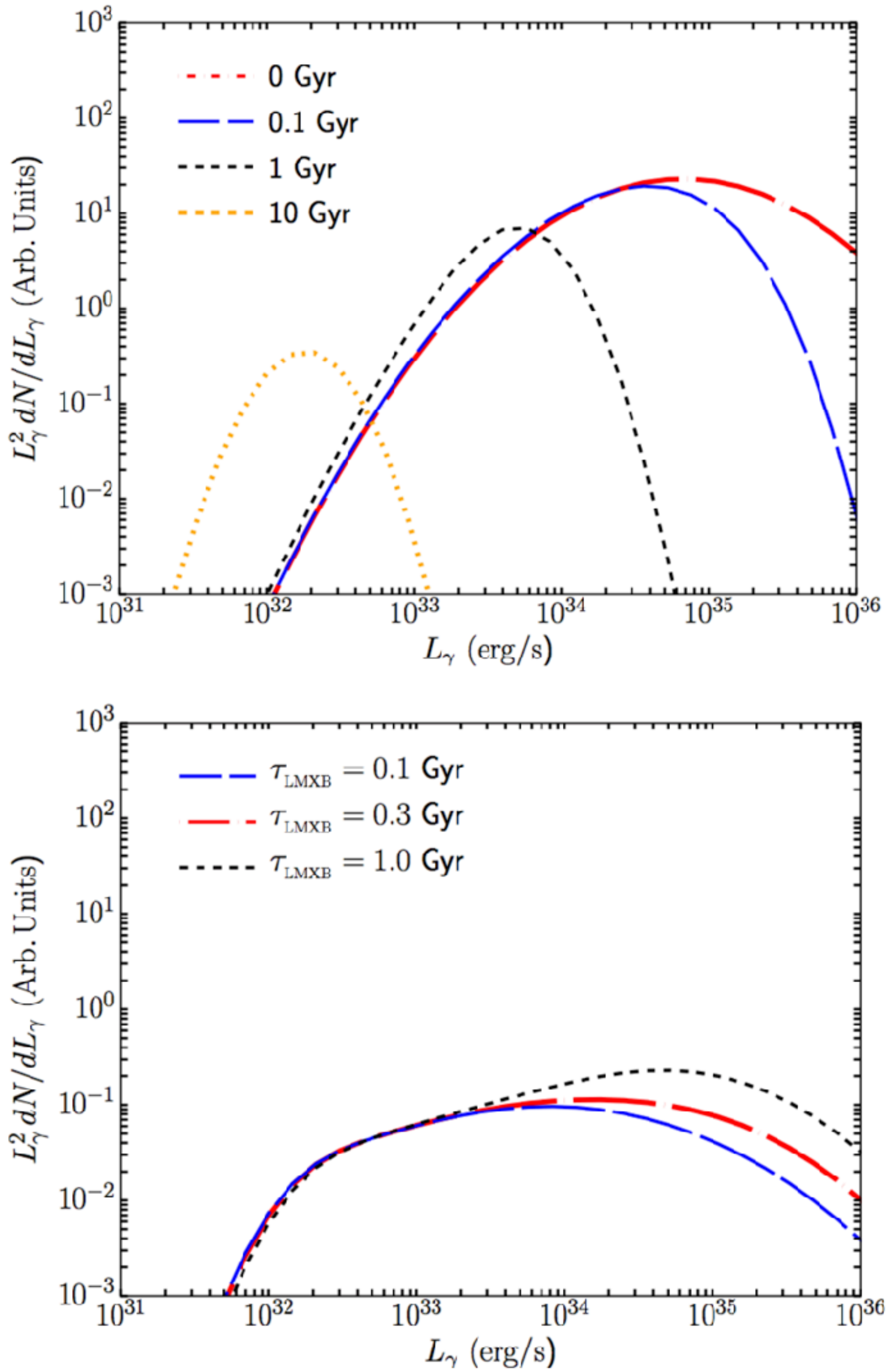
Too Bright or Too Many?

MSPs also spin-down rapidly:

$$\tau = \frac{3c^3 I P_0^2}{4\pi^2 B_0^2 R^6}$$

For most MSPs, τ ~ 100 Myr - 1 Gyr

$$\begin{aligned} L_\gamma &= \eta_\gamma \dot{E} \\ &= \eta_\gamma \frac{4\pi^2 I \dot{P}}{P^3} \\ &\simeq 9.6 \times 10^{33}\,\mathrm{erg/s} \left(\frac{\eta_\gamma}{0.2}\right) \left(\frac{B}{10^{8.5}\,\mathrm{G}}\right)^2 \left(\frac{3\,\mathrm{ms}}{P}\right)^4 \end{aligned}$$



Hooper & Linden (2016; 1606.09250)

Enough with the theory - let’s just look for these things.

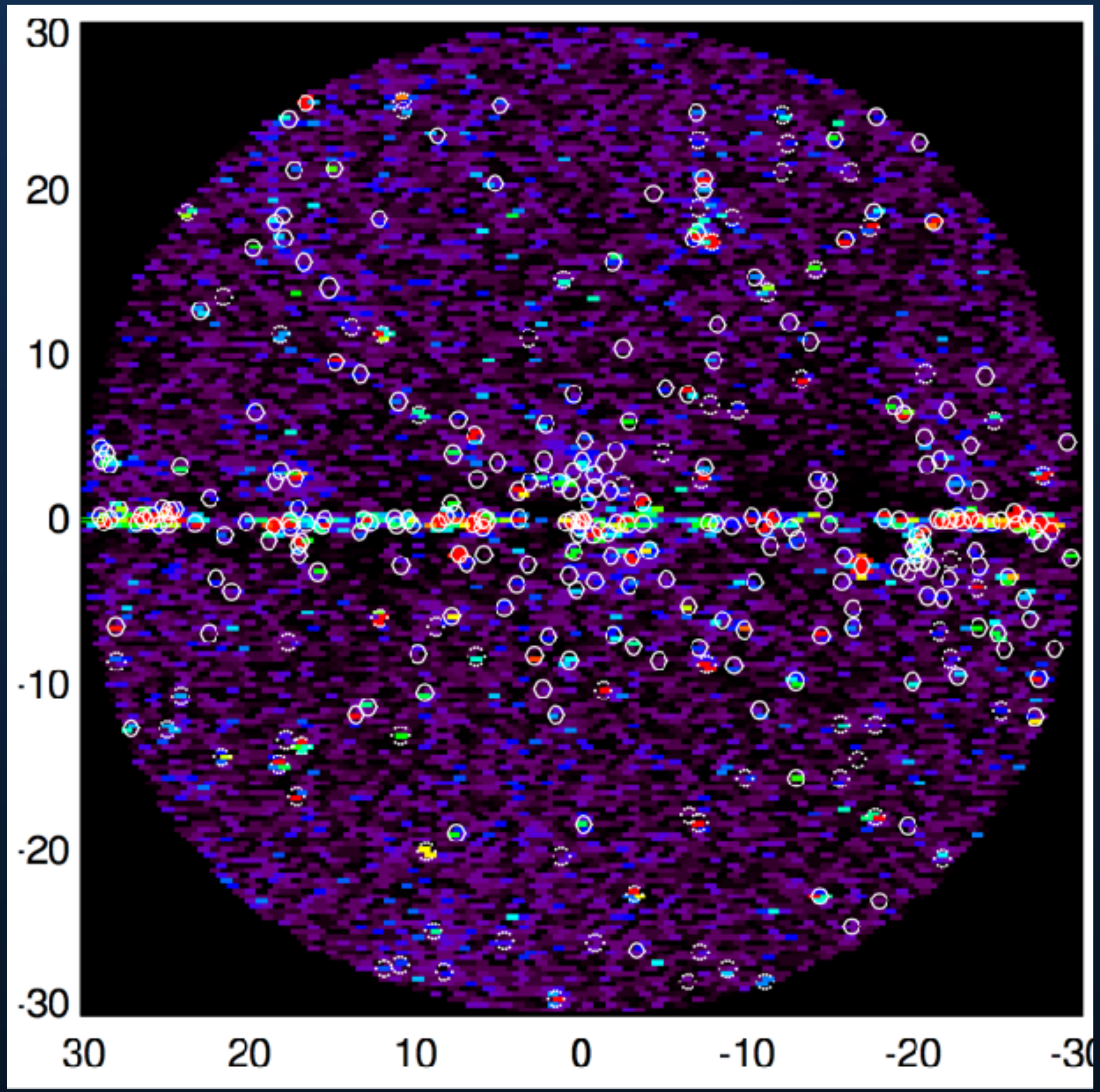
Non-Poissonian Fluctuations

Two Methods:

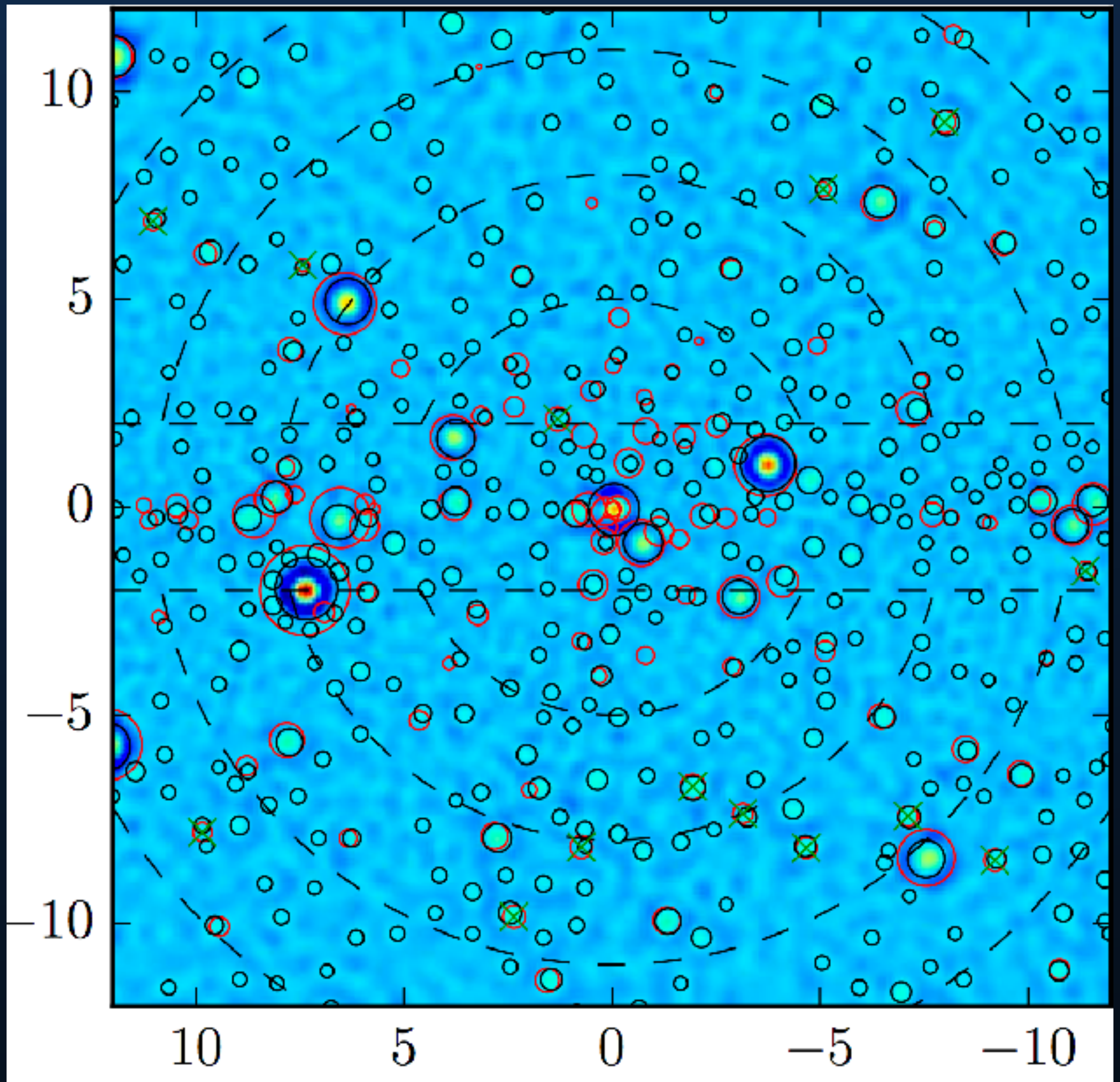
1.) Find pulsars as individual gamma-ray point sources in the Fermi data

2.) Find radio pulsars that are correlated with the positions of the non-Poissonian fluctuations in the Fermi-LAT data.

Non-Poissonian Fluctuations



Bartels et al (2015; 1506.05104)



Lee et al (2015; 1506.05124)

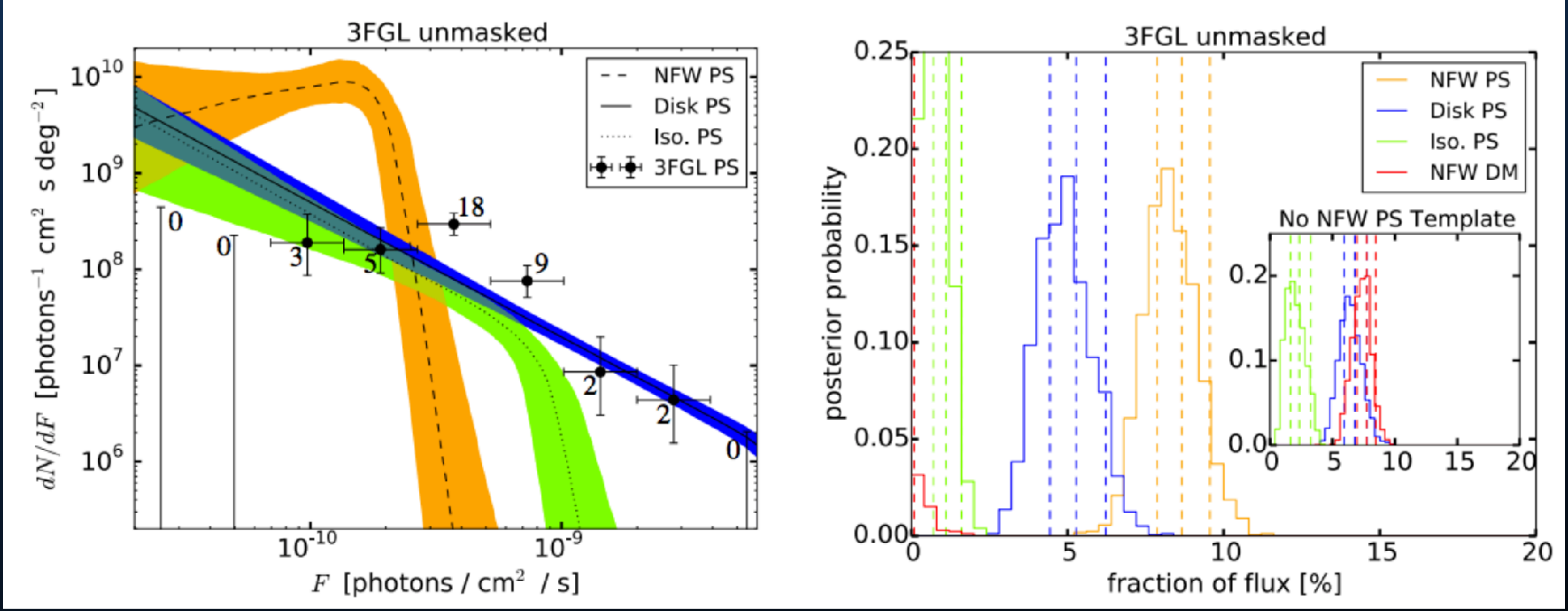
Two Simultaneous Analyses Found fluctuations exceeding Poisson noise in the Fermi-LAT data:

Non-Poissonian Template Fitting (Lee et al.)

Wavelet Analyses (Bartels et al.)

Non-Poissonian Fluctuations

Lee et al (2015; 1506.05124)

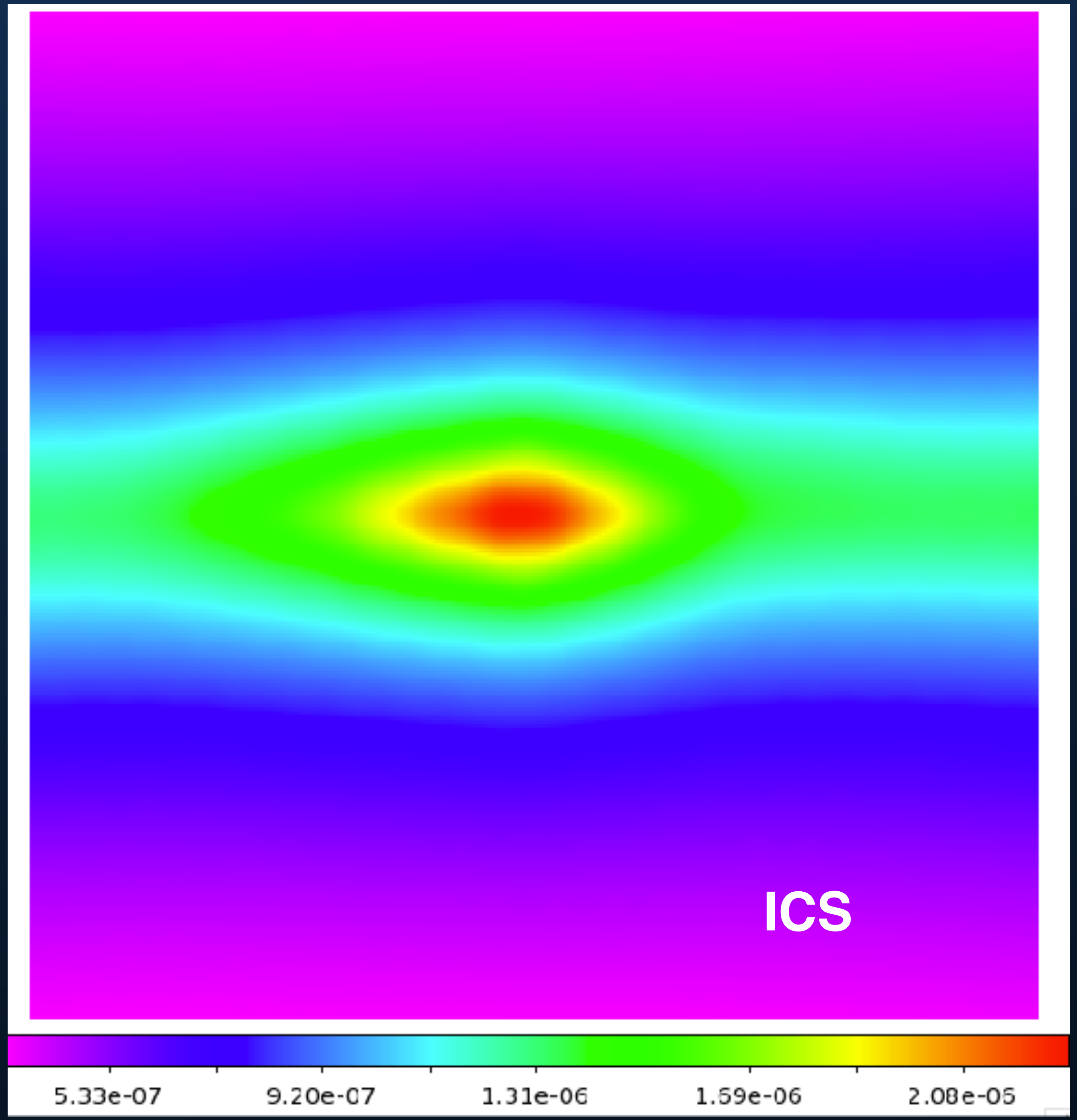


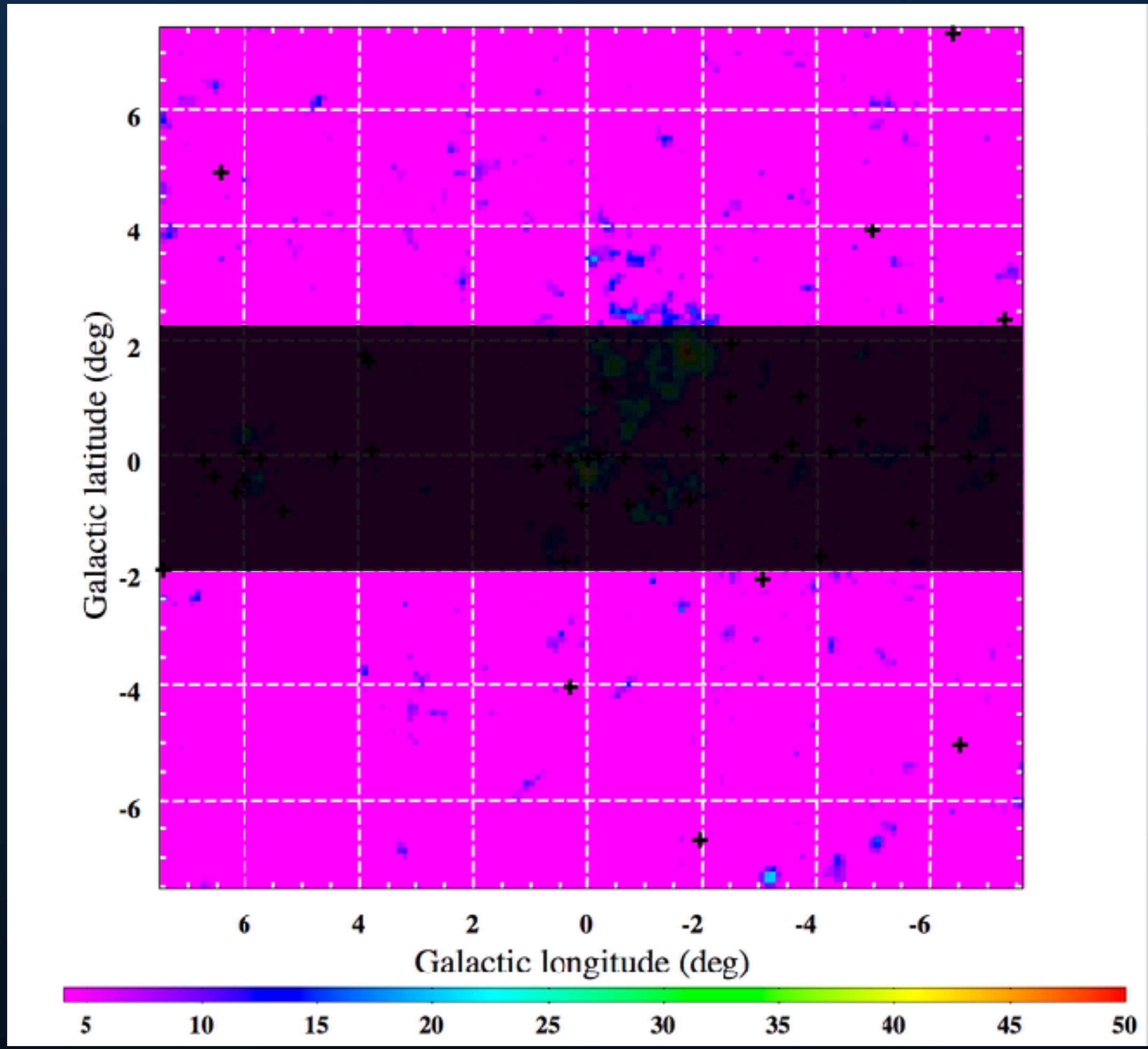
Number of sources peaks just below the Fermi-LAT detection threshold.

Sub-threshold point sources absorb the majority of the Galactic Center flux.

Smooth Diffuse Models

Ajello et al. (2016; 1511.02938)



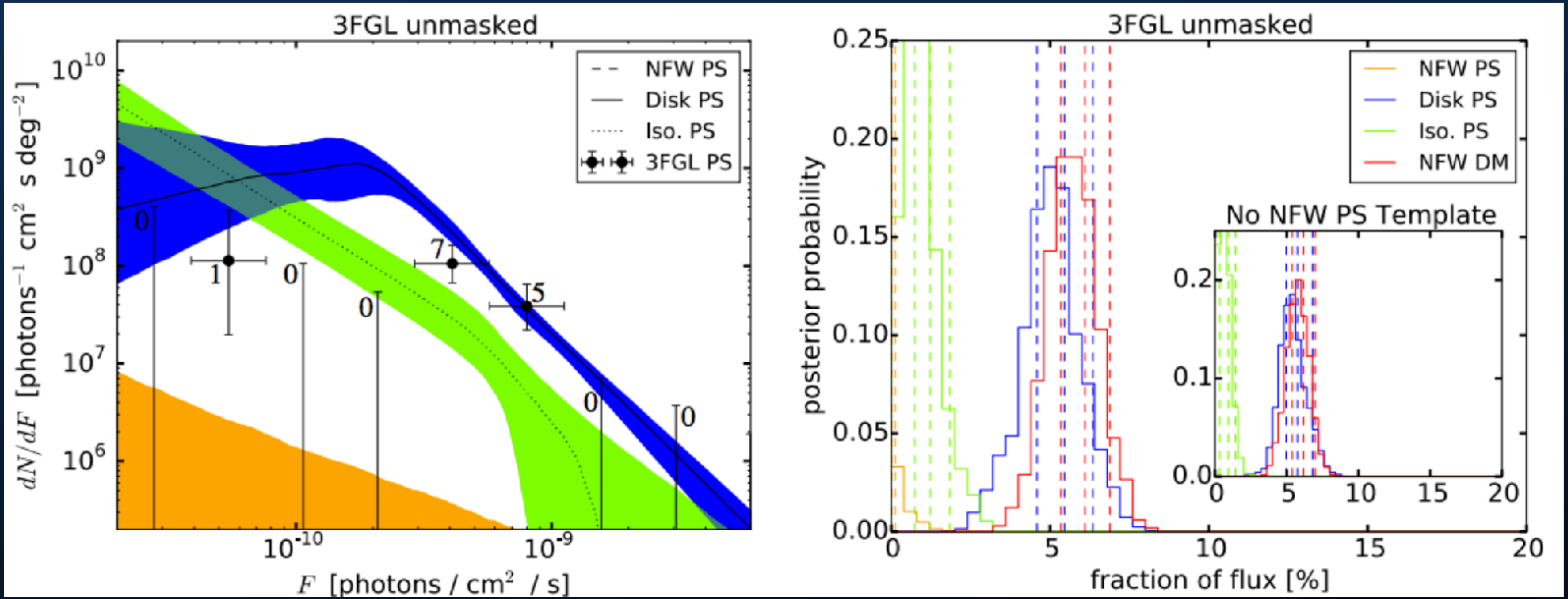


The models used for foreground subtraction of diffuse emission are very smooth, while the astrophysical emission is not smooth.

Can this induce point-source fluctuations in the excess?

Smooth Diffuse Models

Lee et al (2015; 1506.05124)



Can test this by looking elsewhere along the plane.

But the Galactic center is a unique place.

Definitively Proving the Pulsar Interpretation

Second Issue:

The NPTF and Wavelet analyses only work on the population level — cannot identify individual point sources.

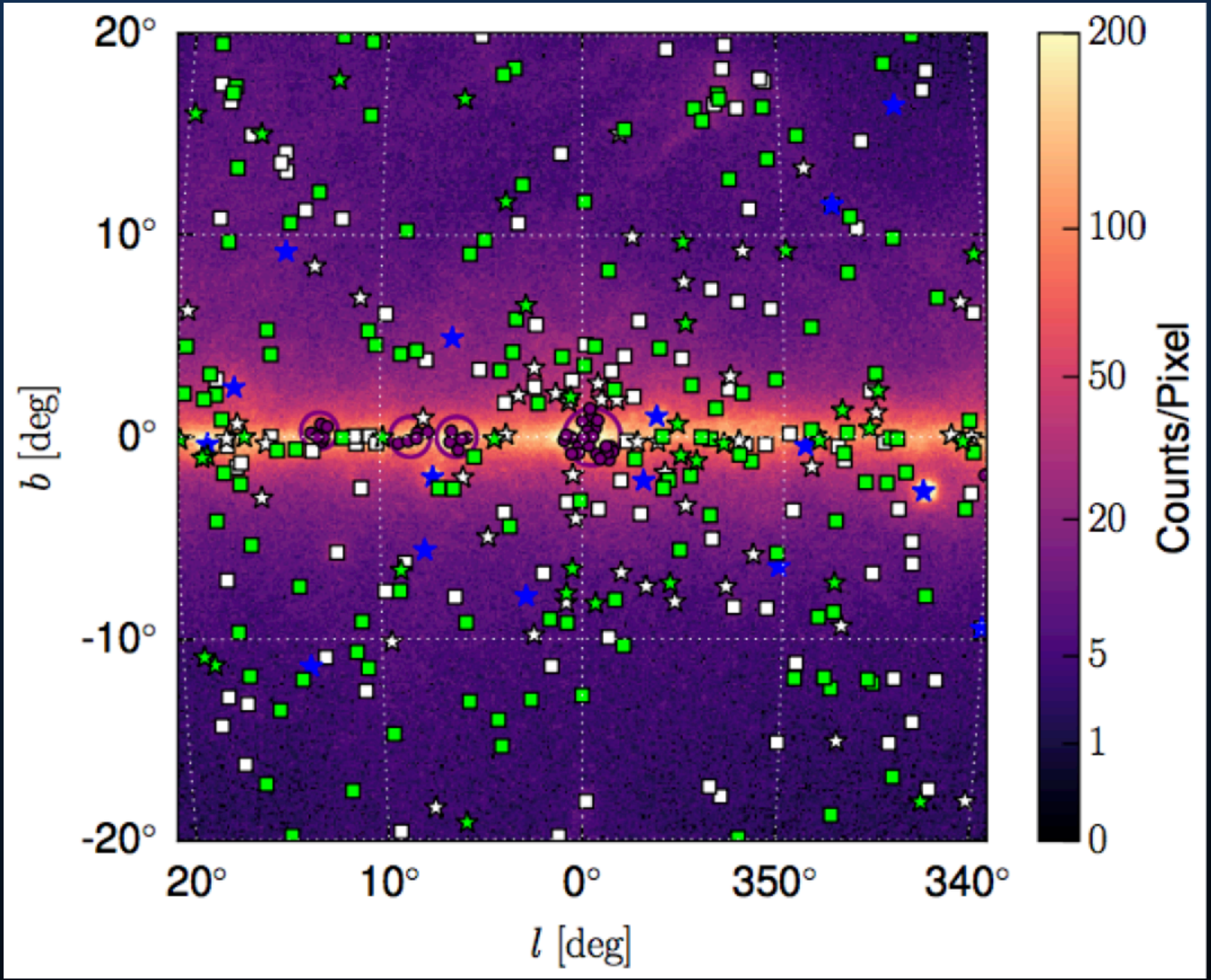
What if we find high-significance gamma-ray point sources?

2FIG Catalog

Deepest catalog of gamma-ray point sources in the Galactic center region - far more sensitive than 3FGL.

7.5 years of data (4 yr)
400 point sources (200 PS)

Spectral determination used to separate probable blazars from probable pulsars.



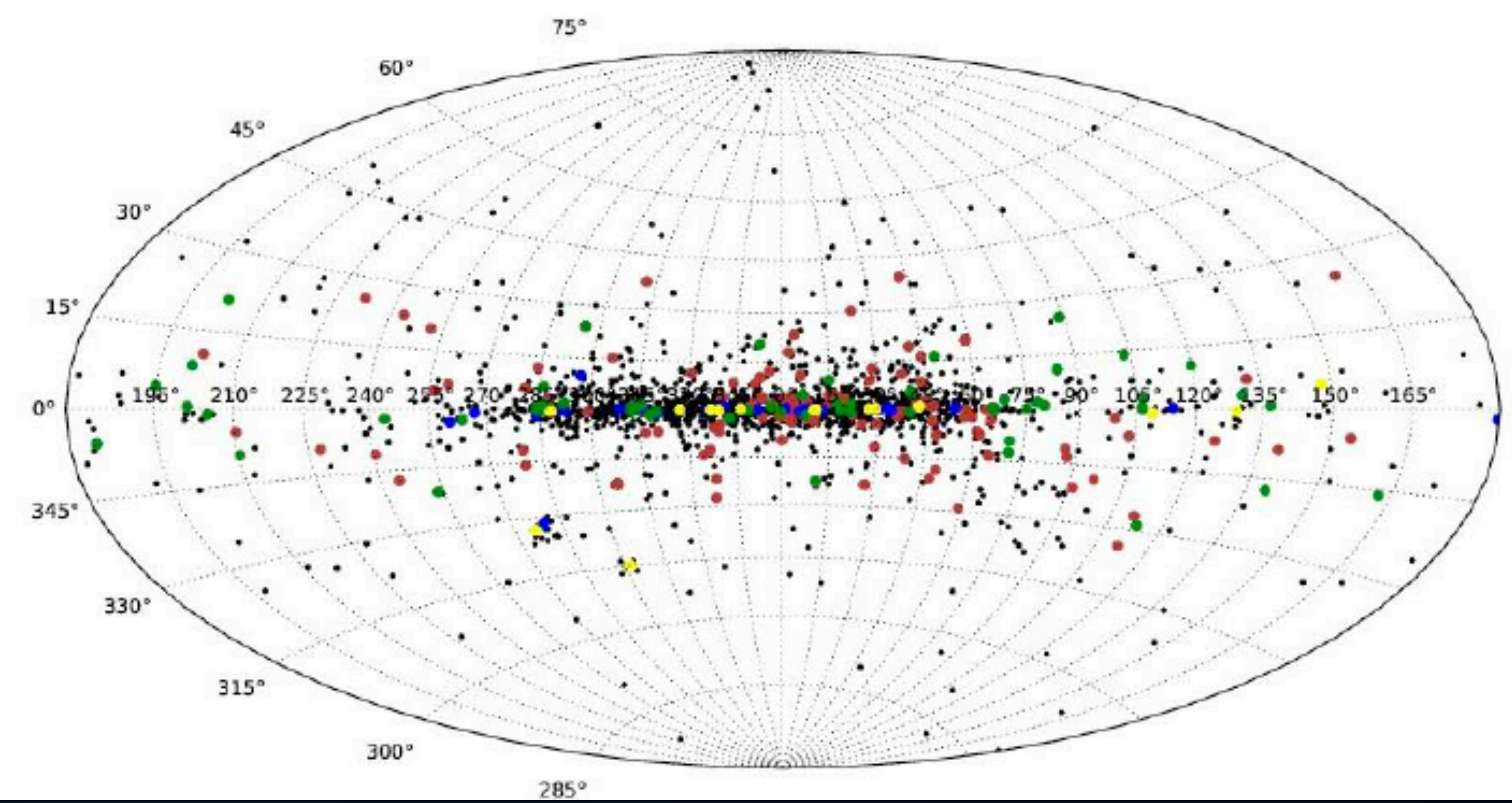
Ajello et al. (2017, 1705.00009)

see talk by Eric Charles

Finding a Bulge Pulsar Population

Use the morphology and flux distribution of 2FIG selected pulsars to search for bulge contribution.

Disk Distribution (Lorimer 2004)



Bulge Distribution (Spherical)

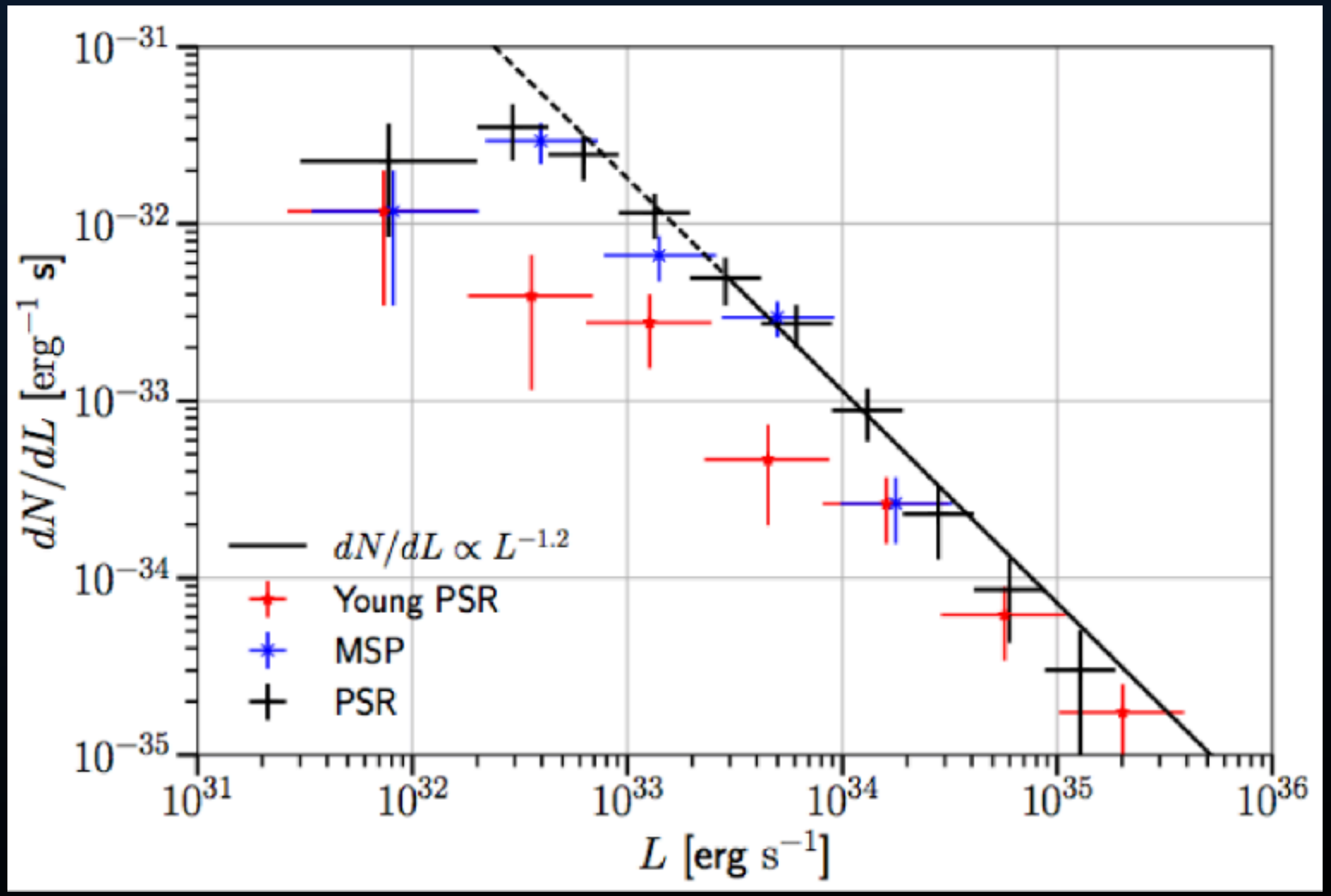
$$N_{i,j,k}^{\mathrm{model}} = \sum_{m} \Omega_{i,j,k,m} \int_{\Delta\Omega_{i,j}} dl \cos b db \int_{0}^{\infty} ds \rho(r(l,b,s)) s^2 \times \int_{L_m^{\mathrm{min}}}^{L_m^{\mathrm{max}}} \frac{dN}{dL} dL, \quad (3)$$

2FIG Catalog

	Alternate IEM						Official IEM					
A	$N_{\rm disk}$	z_0[kpc]	β	$N_{\rm bulge}$	α	TS	$N_{\rm disk}$	z_0[kpc]	β	$N_{\rm bulge}$	α	TS
1	23500^{+5500}_{-5000}	$0.63^{+0.14}_{-0.14}$	$1.35^{+0.07}_{-0.07}$	0	$\cdots$	0	22500^{+5200}_{-4800}	$0.71^{+0.16}_{-0.16}$	$1.34^{+0.07}_{-0.07}$	0	$\cdots$	0
2	3740^{+1030}_{-940}	$0.66^{+0.14}_{-0.14}$	$1.23^{+0.06}_{-0.06}$	1580^{+330}_{-270}	2.60	60	3560^{+980}_{-870}	$0.72^{+0.17}_{-0.17}$	$1.24^{+0.06}_{-0.06}$	1330^{+270}_{-210}	2.60	63
3	3960^{+1070}_{-970}	$0.70^{+0.16}_{-0.16}$	$1.24^{+0.07}_{-0.07}$	1660^{+350}_{-300}	$2.55^{+0.24}_{-0.24}$	65	3610^{+1010}_{-930}	$0.75^{+0.18}_{-0.18}$	$1.25^{+0.07}_{-0.07}$	1370^{+280}_{-220}	$2.57^{+0.23}_{-0.23}$	69
B	$N_{\rm disk}$	z_0[kpc]	β	$N_{\rm bulge}$	α	TS	$N_{\rm disk}$	z_0[kpc]	β	$N_{\rm bulge}$	α	TS
1	25600^{+5900}_{-5200}	$0.72^{+0.22}_{-0.22}$	$1.37^{+0.13}_{-0.13}$	0	$\cdots$	0	24500^{+5700}_{-5000}	$0.76^{+0.23}_{-0.23}$	$1.33^{+0.14}_{-0.14}$	0	$\cdots$	0
2	4670^{+1350}_{-1230}	$0.69^{+0.21}_{-0.21}$	$1.25^{+0.12}_{-0.12}$	1380^{+370}_{-310}	2.60	53	3710^{+1270}_{-1150}	$0.75^{+0.23}_{-0.23}$	$1.26^{+0.12}_{-0.12}$	1310^{+350}_{-290}	2.60	54
3	4360^{+1370}_{-1180}	$0.68^{+0.20}_{-0.20}$	$1.24^{+0.11}_{-0.11}$	1430^{+380}_{-320}	$2.57^{+0.27}_{-0.27}$	58	3660^{+1210}_{-1110}	$0.73^{+0.22}_{-0.22}$	$1.25^{+0.12}_{-0.12}$	1350^{+330}_{-300}	$2.65^{+0.28}_{-0.28}$	59

>7σ evidence found for a bulge component:

- **Very hard gamma-ray spectrum ($L^{-1.2}$), or $L^2\, dN/dL \sim L^{0.8}$**
  - **Most emission produced by extremely bright pulsars.**



2FIG Catalog

We recently attempted to reproduce this result from Ajello et al. (2017), but were unable.

A paper detailing this work will be released at the end of the month.

For maximum transparency, all numerical codes and calculations employed in this work are publicly available at:

https://github.com/bsafdi/GCE-2FIG

COMMENT ON "CHARACTERIZING THE POPULATION OF PULSARS IN THE GALACTIC BULGE WITH THE *FERMI* LARGE AREA TELESCOPE" [ARXIV:1705.00009]

RICHARD BARTELS,[1] DAN HOOPER,[2,3,4] TIM LINDEN,[5] SIDDHARTH MISHRA-SHARMA,[6] NICHOLAS L. RODD,[7] BENJAMIN R. SAFDI,[8] TRACY R. SLATYER[7]

Draft version October 10, 2017

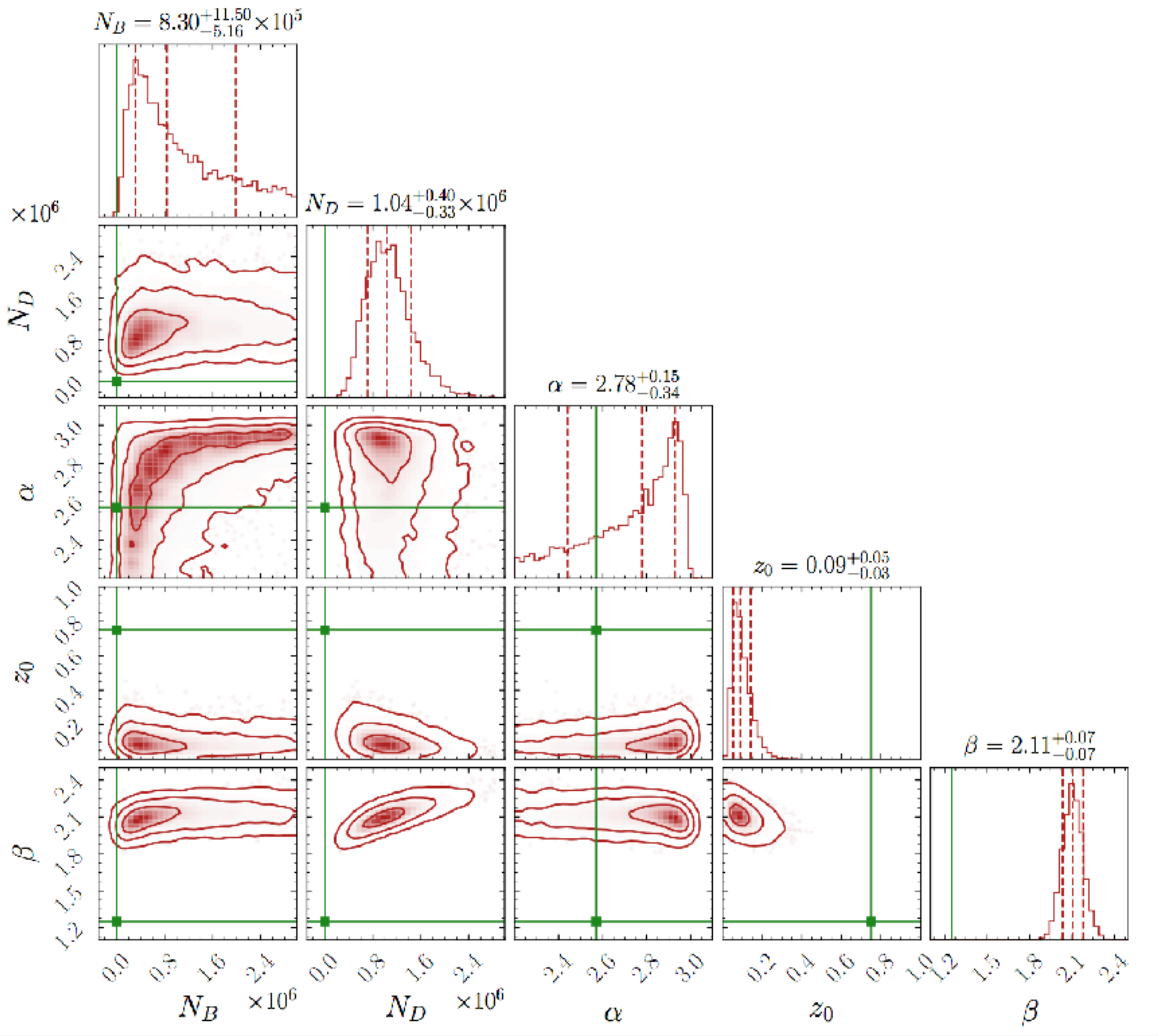
ABSTRACT

The *Fermi*-LAT Collaboration recently presented a new catalog of gamma-ray sources located within the

2FIG Catalog

Our analysis does not confirm the result from Ajello et al. (2017):

- **Much softer luminosity function**
- **No significant preference for a Galactic bulge component.**



Results of Ajello et al. (2017)

N_D	z_0[kpc]	β	N_B	α	TS
22500^{+5200}_{-4800}	$0.71^{+0.16}_{-0.16}$	$1.34^{+0.07}_{-0.07}$	0	...	0
3560^{+980}_{-870}	$0.72^{+0.17}_{-0.17}$	$1.24^{+0.06}_{-0.06}$	1330^{+270}_{-210}	2.60	63
3610^{+1010}_{-930}	$0.75^{+0.18}_{-0.18}$	$1.25^{+0.07}_{-0.07}$	1370^{+280}_{-220}	$2.57^{+0.23}_{-0.23}$	69

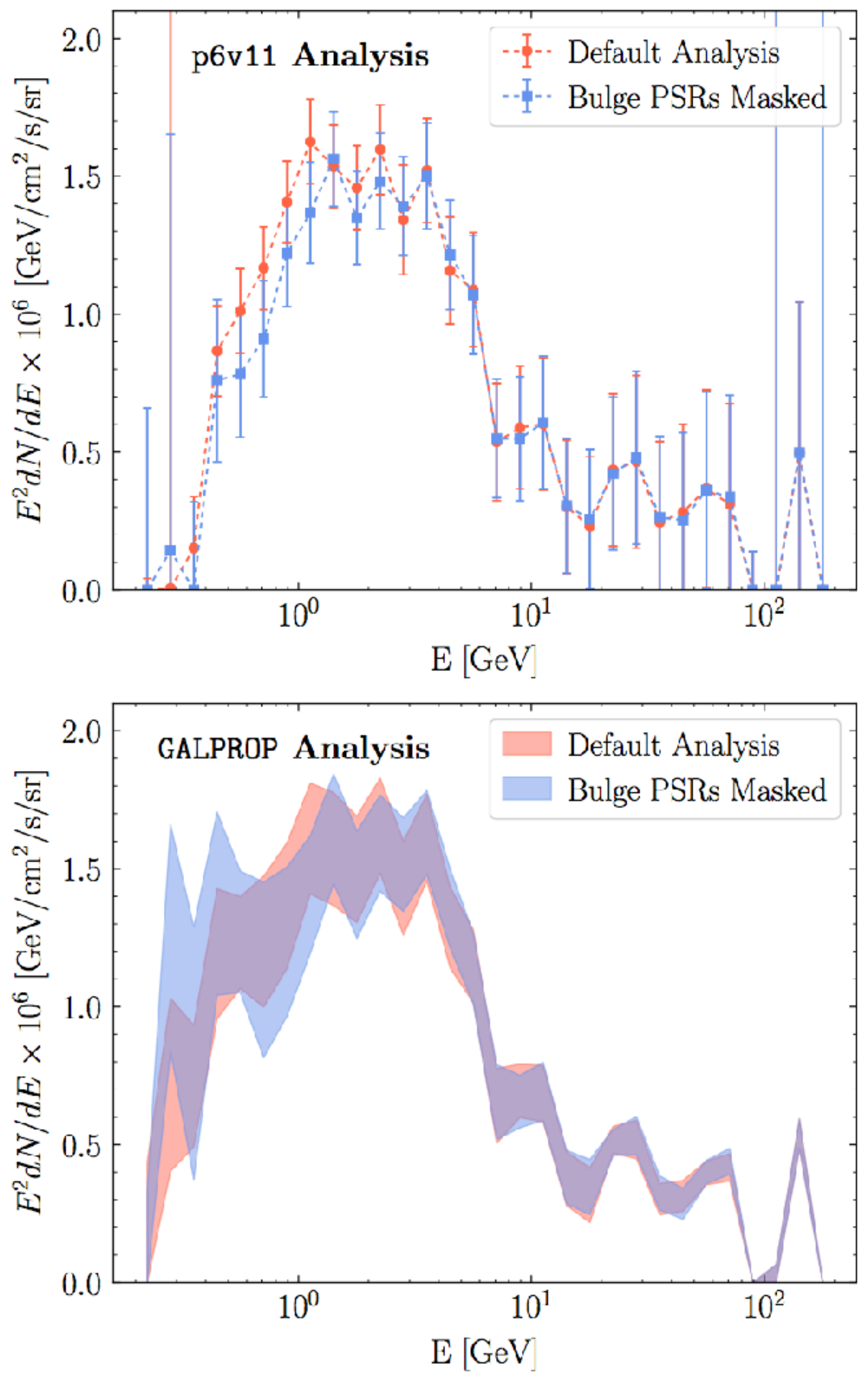
Results of This Study

N_D	z_0[kpc]	β	N_B	α	TS
$(1.26^{+0.48}_{-0.40})\times 10^6$	$0.13^{+0.06}_{-0.04}$	$2.08^{+0.07}_{-0.07}$	0	...	0
$(1.06^{+0.42}_{-0.34})\times 10^6$	$0.08^{+0.05}_{-0.03}$	$2.11^{+0.08}_{-0.07}$	$(5.03^{+4.89}_{-2.52})\times 10^5$	2.60	8.3
$(1.04^{+0.40}_{-0.34})\times 10^6$	$0.09^{+0.05}_{-0.03}$	$2.11^{+0.07}_{-0.07}$	$(8.30^{+11.50}_{-5.16})\times 10^5$	$2.78^{+0.15}_{-0.34}$	8.5

2FIG Catalog

Additionally, masking 2FIG sources identified as pulsars does not significantly change the parameters of the excess.

The sources identified in the 2FIG catalog do not provide evidence for a pulsar interpretation of the excess.



2FIG Catalog

Through recent dialog with the corresponding authors of Ajello et al. (2017), an error was found in a portion of their analysis script.

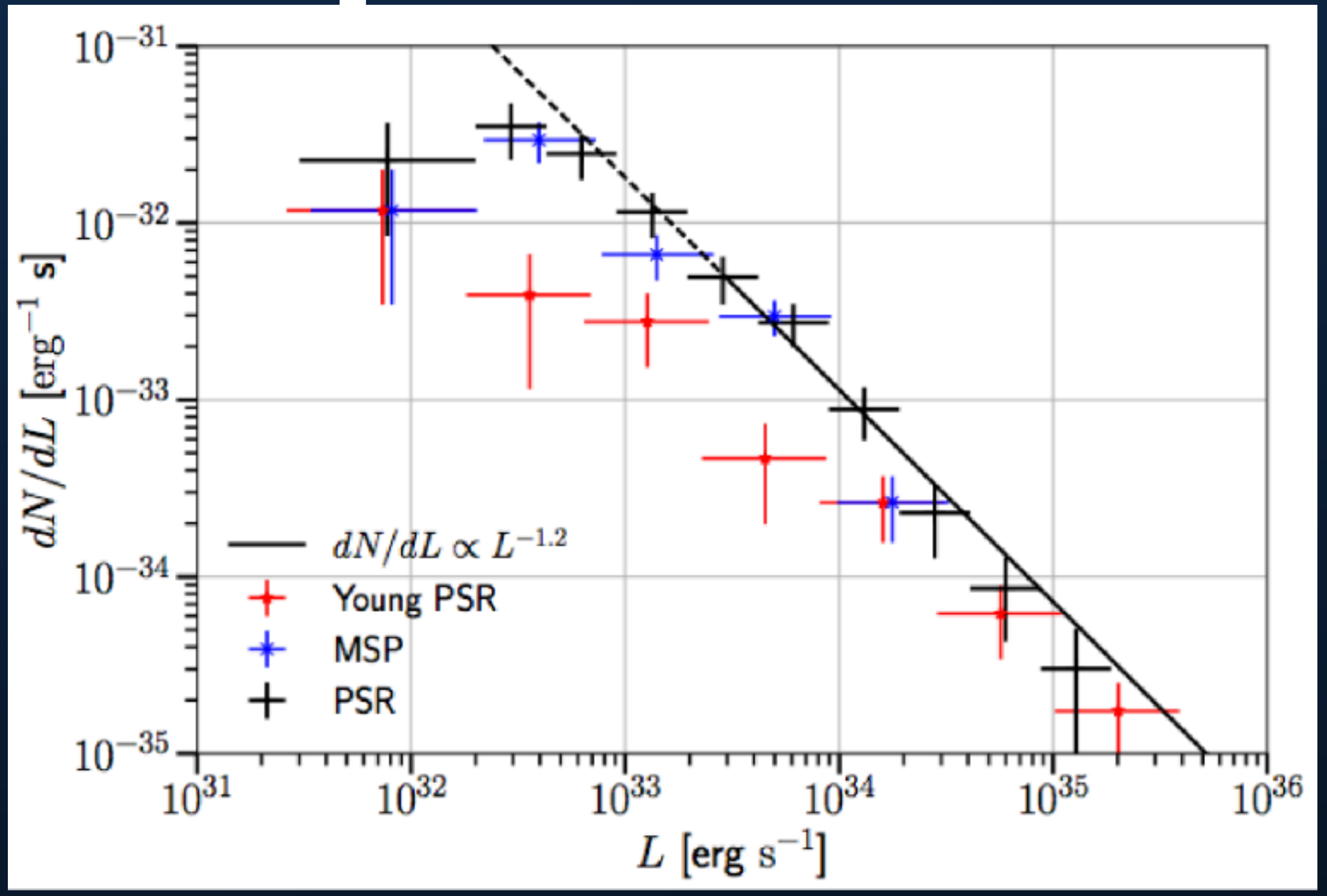
When corrected, preliminary results are consistent with Bartels et al. (2017) - in particular preliminary results indicate a TS of around 10 (5-15?) and a luminosity function which falls as $L^{-2.x}$

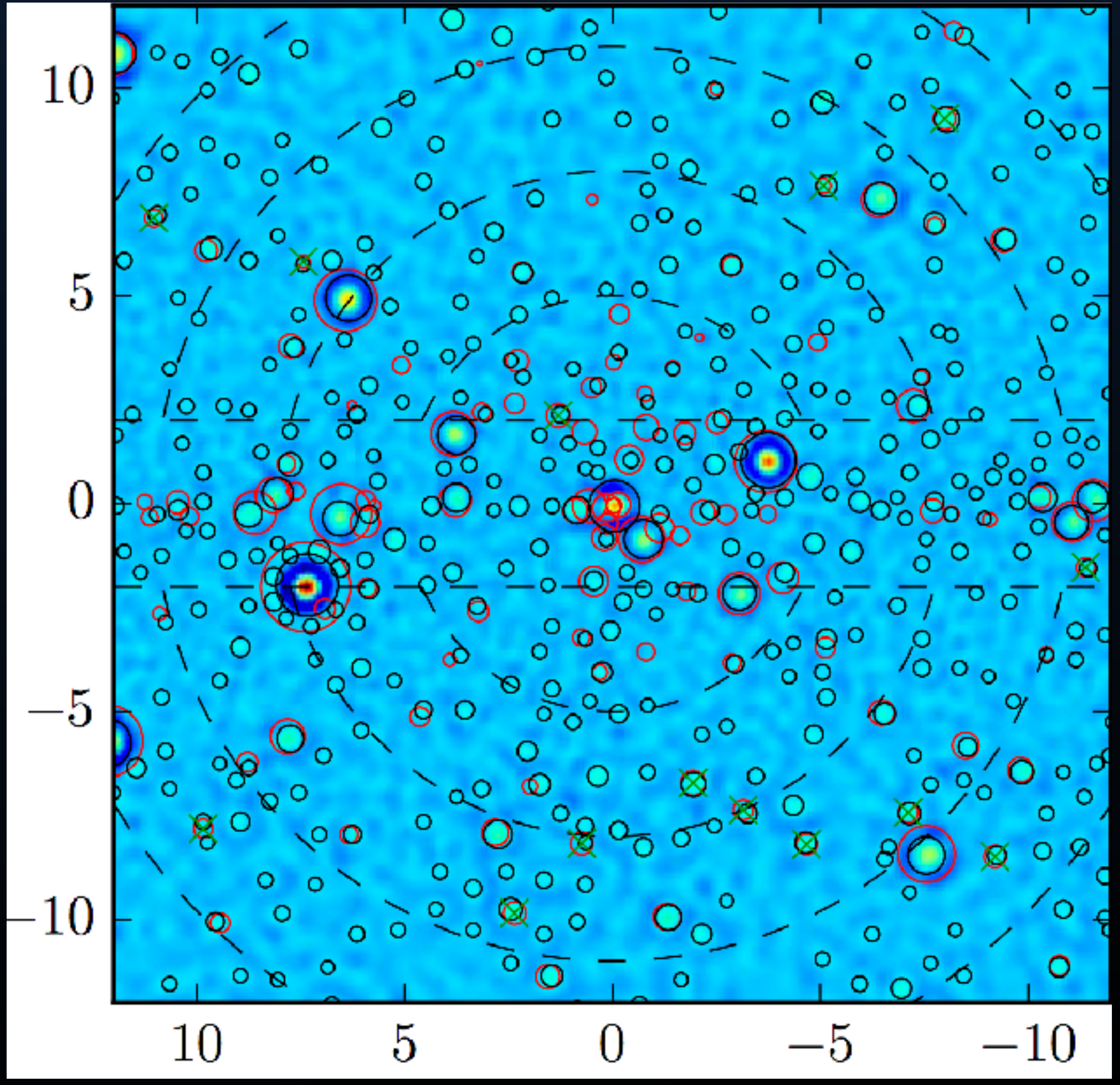
A revised version of Ajello et al. (2017) will be released near the end of the month.

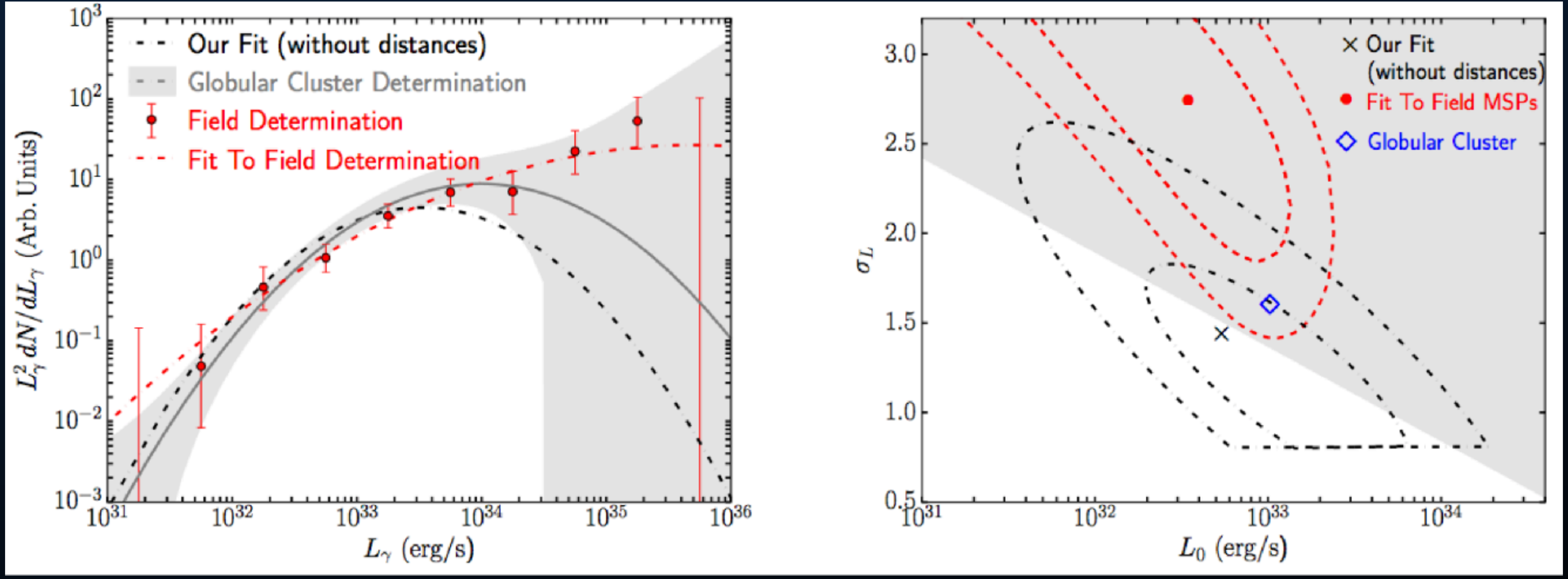
This Does Not Rule Out the Pulsar Interpretation

Both models and Wavelet/NPTF analyses expected the bulge pulsar distribution to be dimmer.

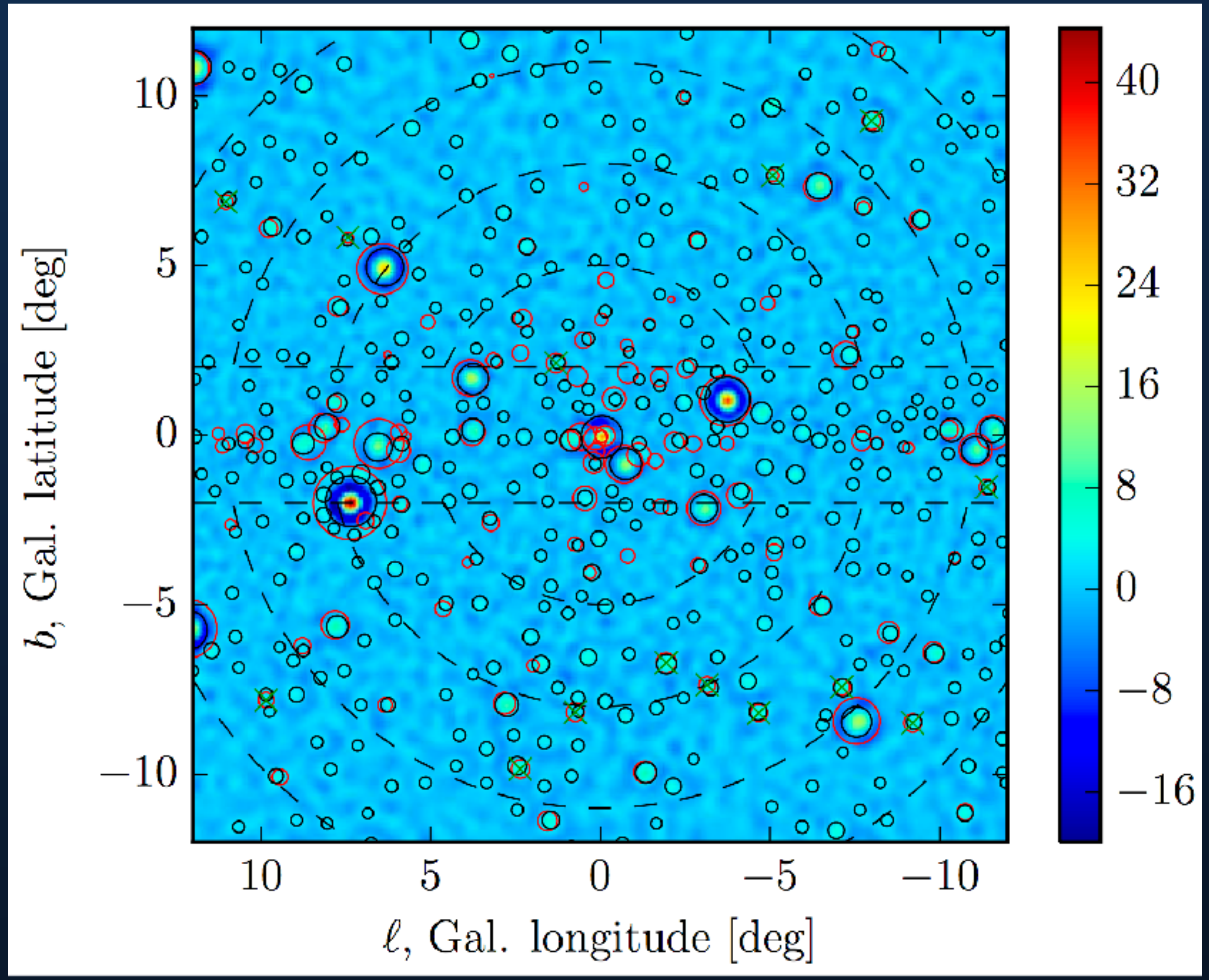
The viability of pulsar interpretations are not affected by these results.

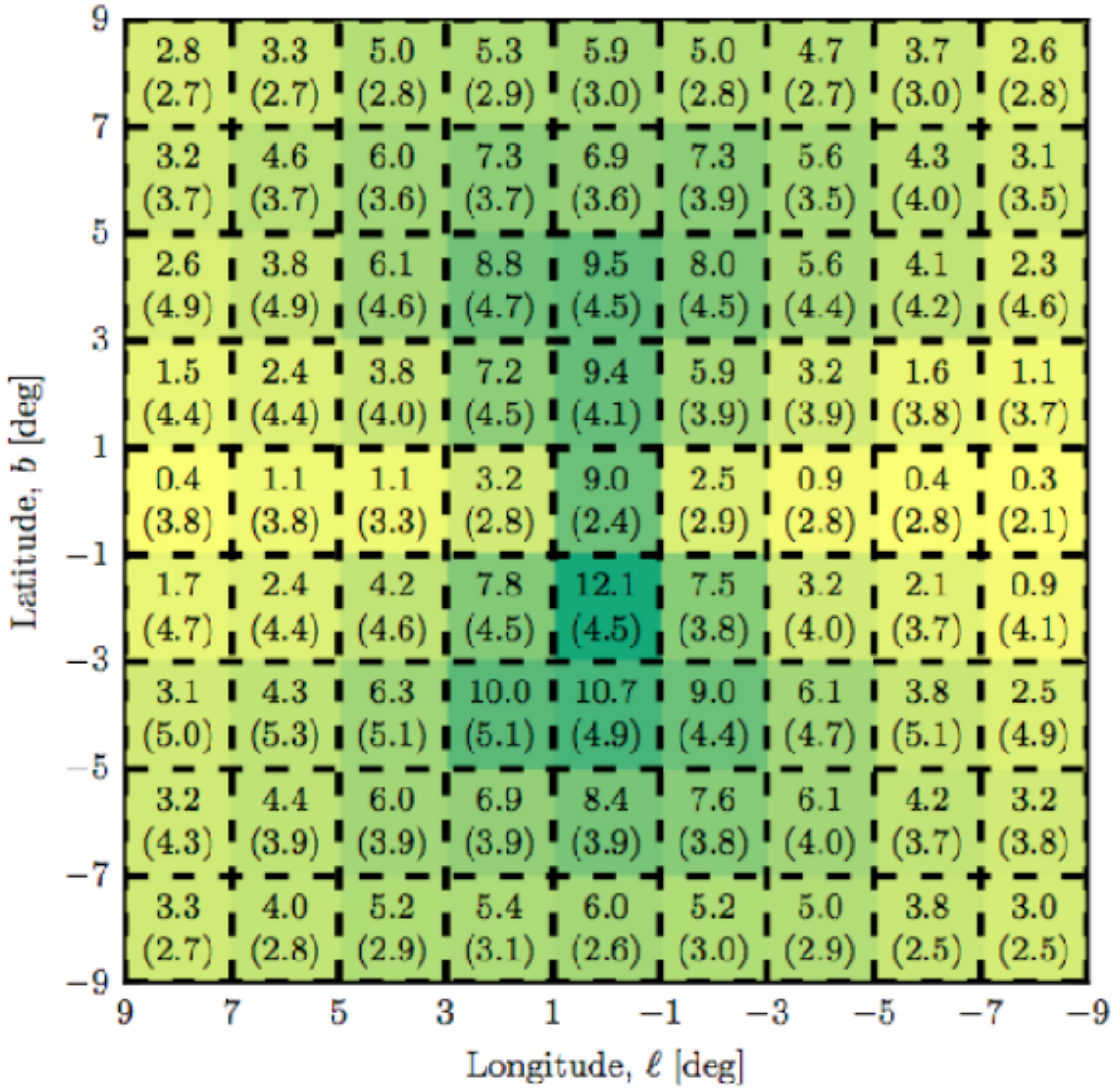


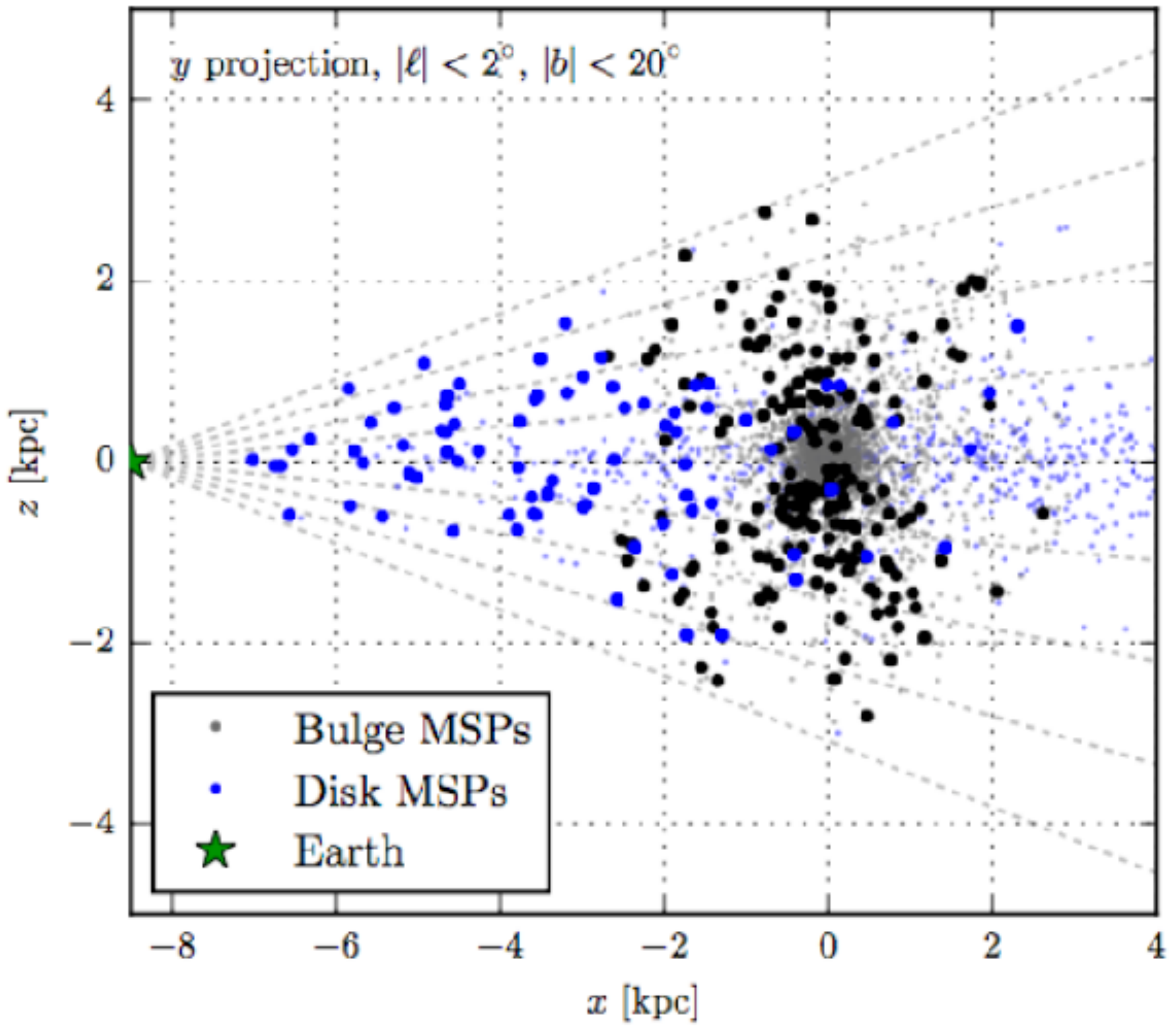




Radio Surveys







Radio surveys can find pulsars coincident with the positions of known gamma-ray hotspots.

Only a handful of sources necessary to provide definitive evidence for a pulsar interpretation.

Calore et al. (2016; 1512.06825)

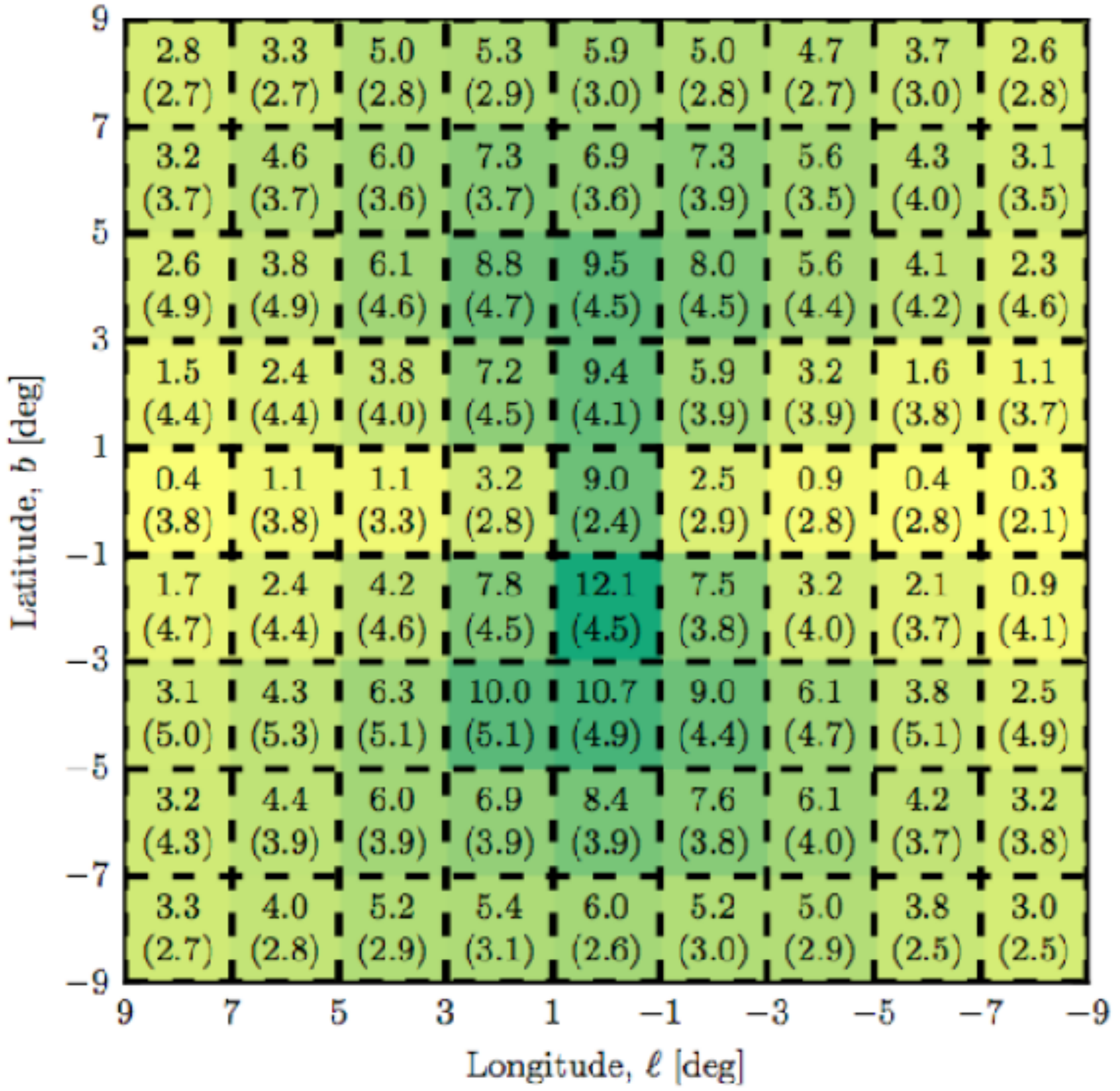
Radio Surveys

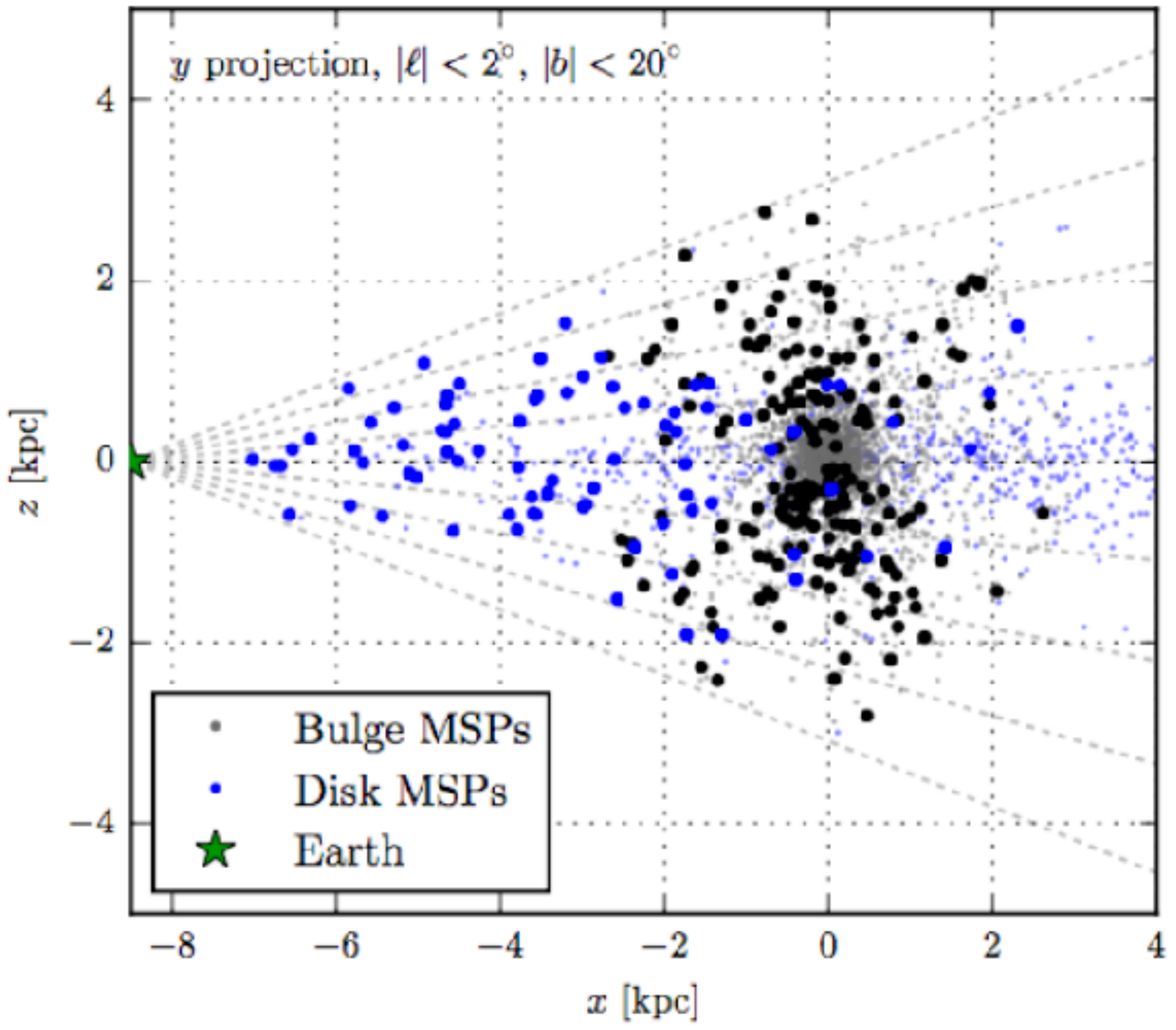
Current Radio Surveys - 100 hour commitment is expected to find ~5 radio pulsars near the GC.

MeerKAT/SKA - 100 hour commitment is expected to find ~100 pulsars near the GC.

Extremely promising method to definitively prove or disprove the pulsar interpretation in the upcoming years.

Calore et al. (2016; 1512.06825)





Pulsars - Summary

Pulsar Interpretations have a high Bayesian Prior, and are well motivated by spectral fits.

Observations indicating point-source fluctuations in the excess provide data-driven evidence validating this interpretation.

However, the pulsars in the galactic center must be categorically dimmer and more numerous than elsewhere in the Galaxy — need a model building explanation.

Pulsar Models

Energetics ?

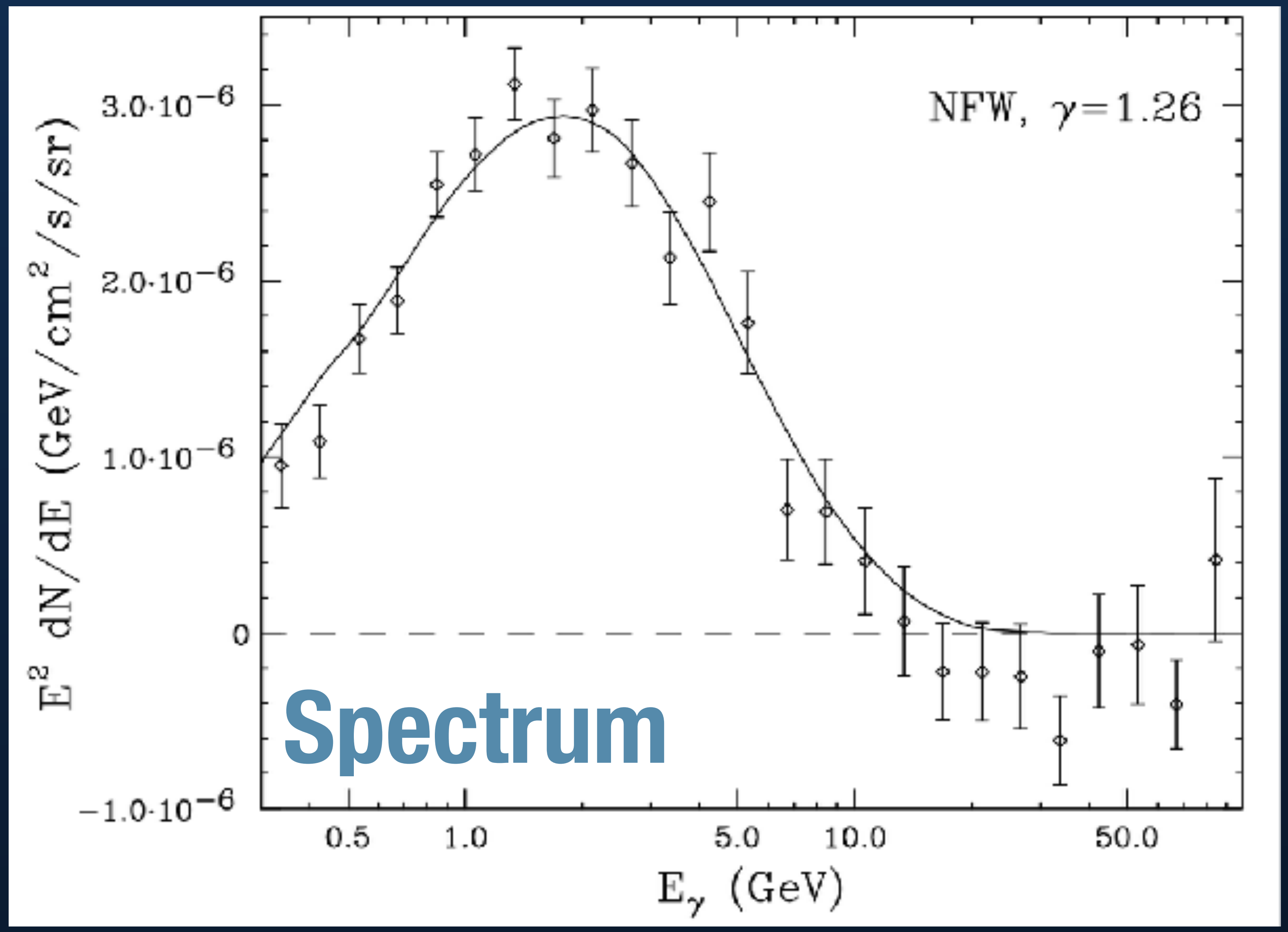
Spectrum ✓

Morphology ?

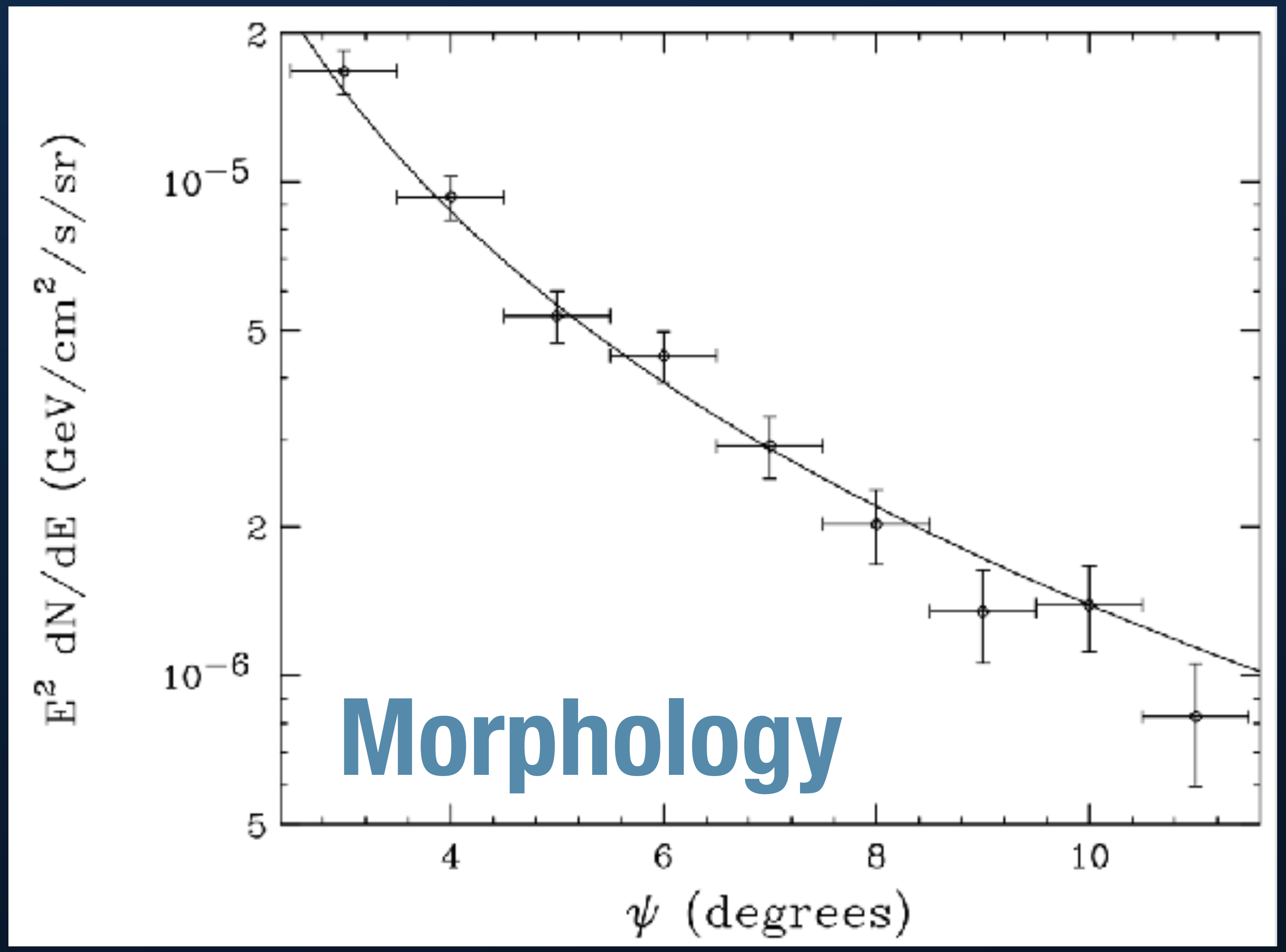
Dark Matter

Daylan et al. (2016; 1402.6703)

Significant Freedom



Constrained



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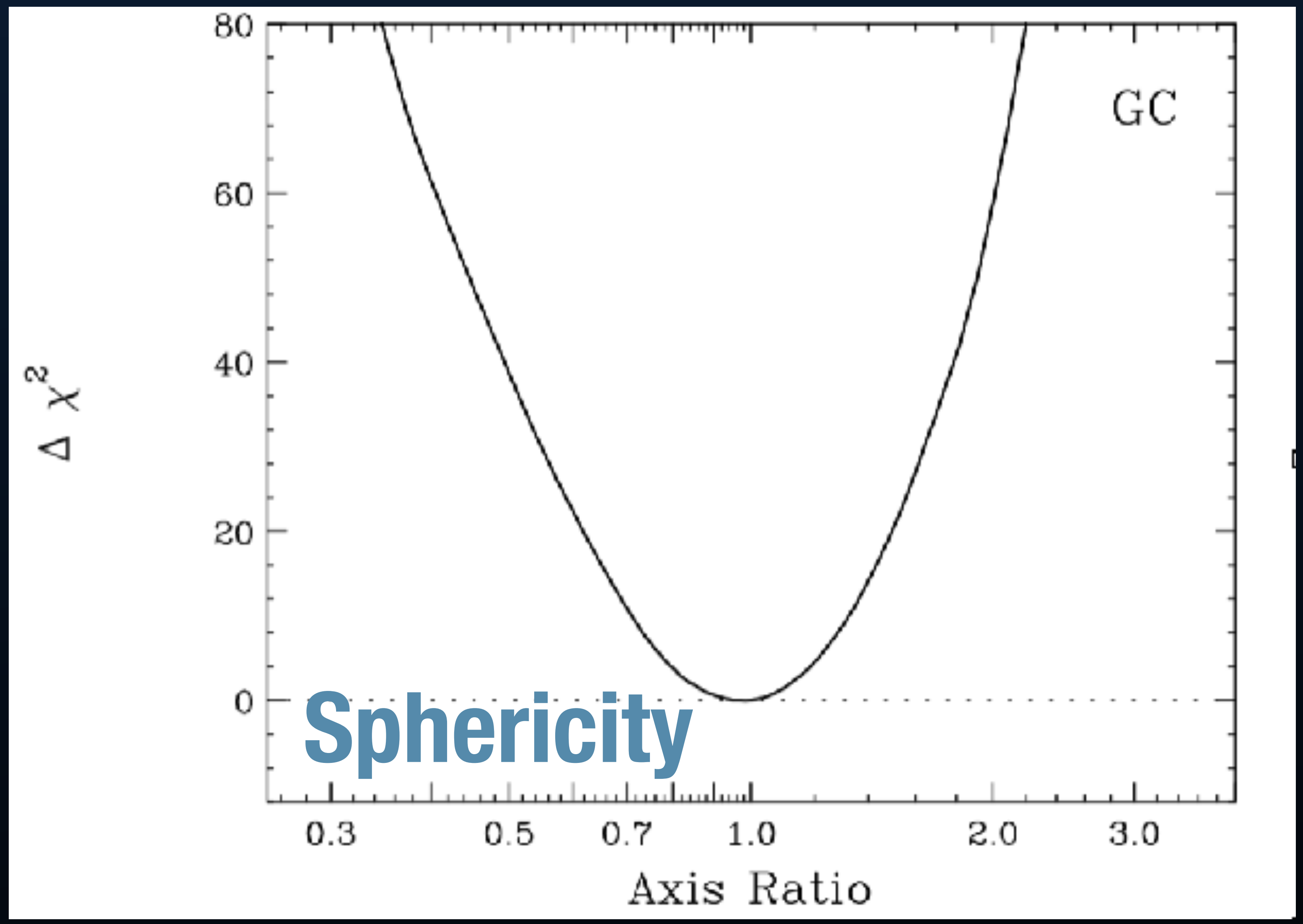
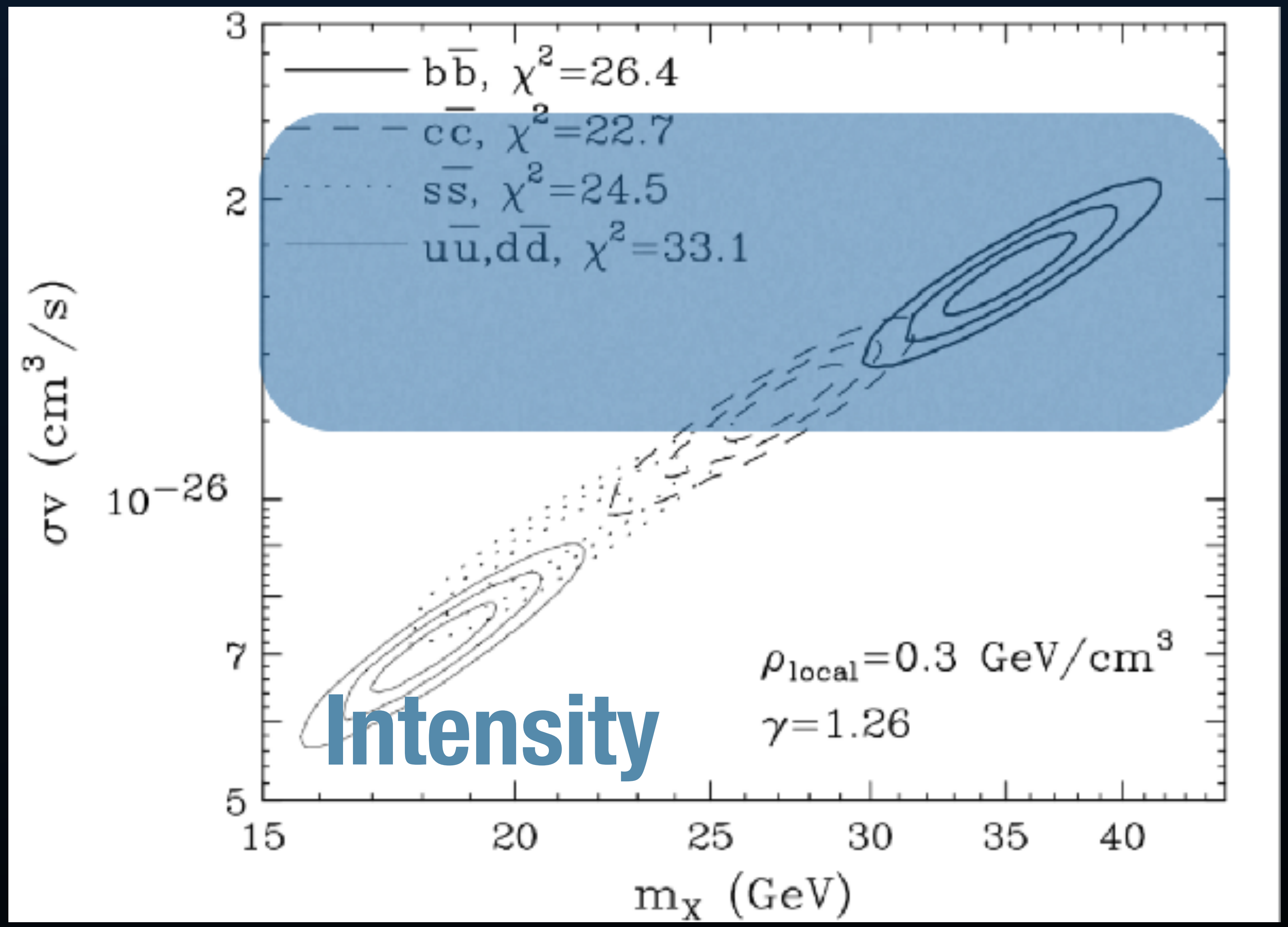
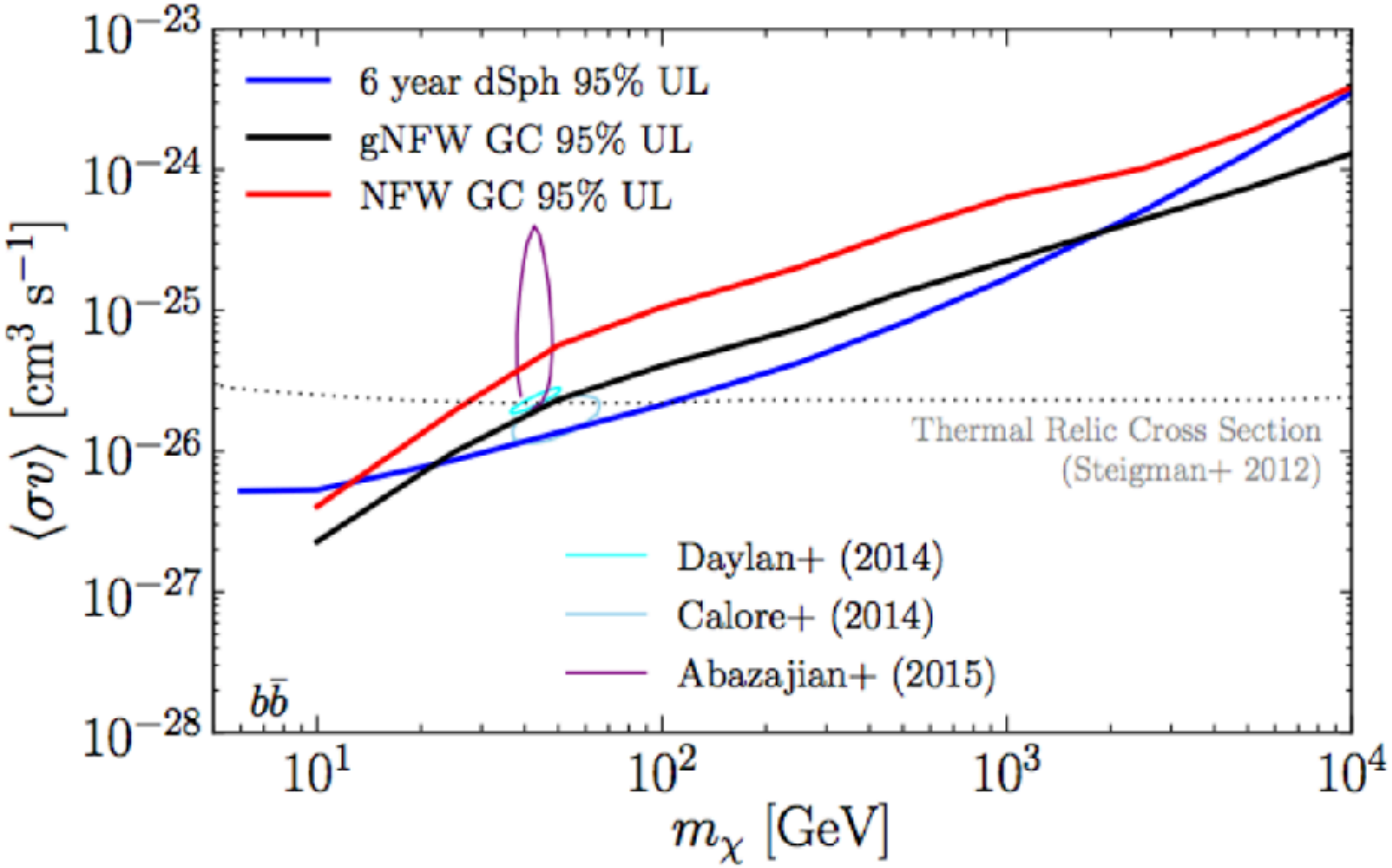


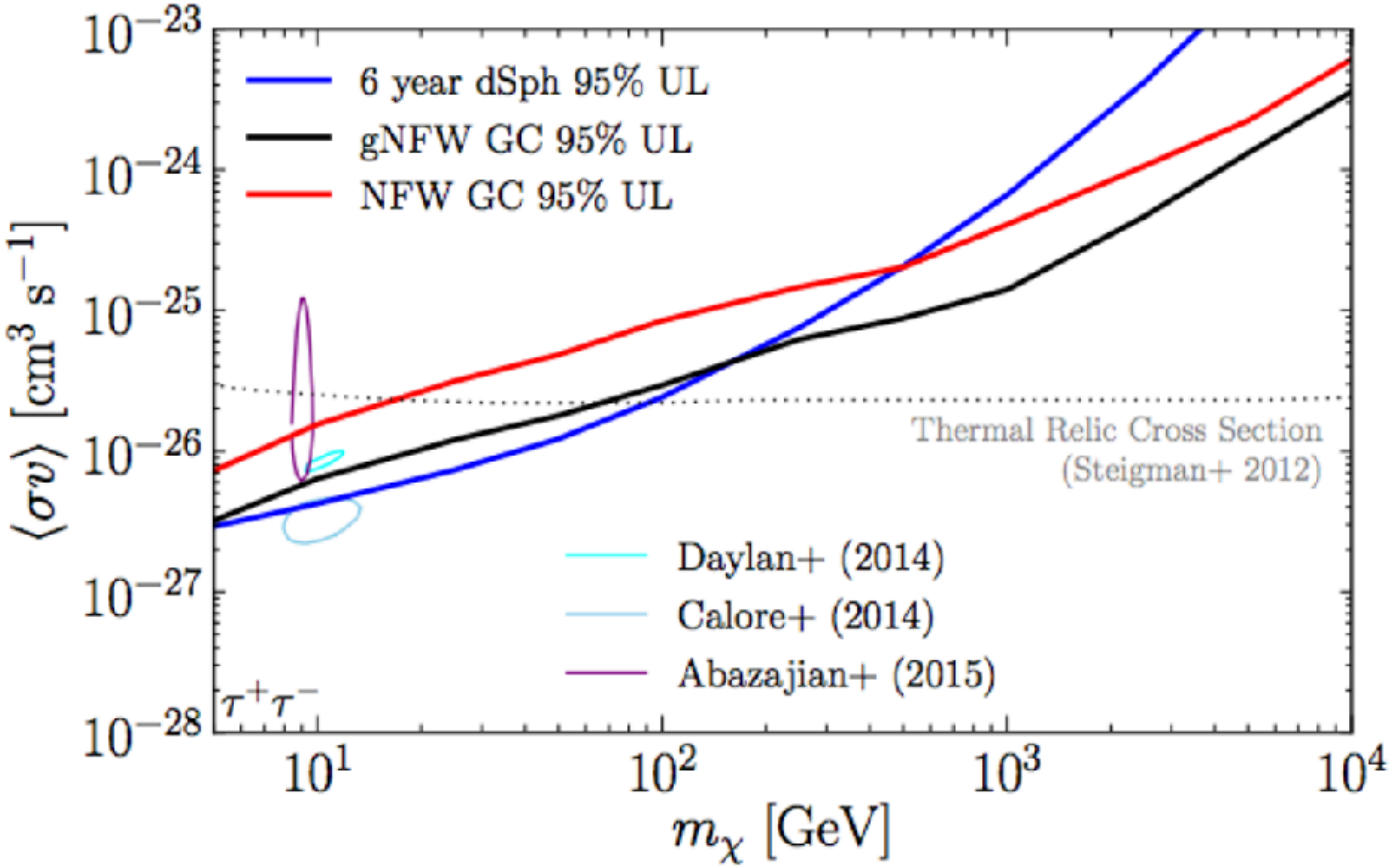
Constrained



Dark Matter

Ackermann et al. (2017; 1704.03910)





Dark Matter Mass:

30 - 70 GeV (annihilation to quarks)

8 - 15 GeV (annihilation to $\tau^+\tau^-$)

Dark Matter Cross-Section:

Approximately Thermal, for an NFW Profile

Particle Physics Models Exist

Chan (1607.02246)
Jia (1607.00737)
Barrau et al. (1606.08031)
Huang et al. (1605.09018)
Cui et al. (1605.08138)
Krauss et al. (1605.05327)
Kumar et al. (1605.00611)
Biswas et al. (1604.06566)
Sage et al. (1604.04589)
Choquette et al. (1604.01039)
Cuoco et al. (1603.08228)
Chao et al. (1602.05192)
Horiuchi et al. (1602.04788)
Hektor et al. (1602.00004)
Freytsis et al. (1601.07556)
Kim et al. (1601.05089)
Huang et al. (1512.08992)
Kulkami et al. (1512.06836)
Tang et al. (1512.02899)
Cox et al. (1512.00471)
Cai et al. (1511.09247)
Agrawal et al. (1511.06293)
Duerr et al. (1510.07562)
Drozd et al. (1510.07053)
Arcadi et al. (1510.02297)
Williams (1510.00714)
Cai & Spray (1509.08481)
Freese et al. (1509.05076)
Bhattacharya et al. (1509.03665)
Algeri et al. (1509.01010)
Fox & Tucker-Smith (1509.00499)
Dutta et al. (1509.05989)
Liu et al. (1508.05716)
Berlin et al. (1508.05390)
Fan et al. (1507.06993)
Hektor et al. (1507.05096)
Achterbeg et al. (1507.04644)
Biswas et al. (1507.04543)

Butter et al. (1507.02288)
Mondal et al. (1507.01793)
Cao et al. (1506.06471)
Banik et al. (1506.05665)
Ipek (1505.07826)
Buchmueller et al. (1505.07826)
Balazs et al. (1505.06758)
Medina (1505.05565)
Kim et al. (1505.04620)
Ko et al. (1504.06944)
Ko & Tang (1504.03908)
Ghorbani & Ghorbani (1504.03610)
Fortes et al. (1503.08220)
Cline et al. (1503.08213)
Rajaraman et al. (1503.05919)
Bi et al. (1503.03749)
Kopp et al. (1503.02669)
Elor et al. (1503.01773)
Gherghetta et al. (1502.07173)
Berlin et al. (1502.06000)
Achterberg et al. (1502.05703)
Modak et al. (1502.05682)
Guo et al. (1502.00508)
Chen & Nomura (1501.07413)
Kozaczuk & Martin (1501.07275)
Berlin et al. (1501.03496)
Kaplinghat et al. (1501.03507)
Alves et al. (1501.03490)
Biswas et al. (1501.02666)
Biswas et al. (1501.02666)
Ghorbani & Ghorbani (1501.00206)
Cerdeno et al. (1501.01296)
Liu et al. (1412.1485)
Hooper (1411.4079)
Arcadi et al. (1411.2985)
Cheung et al. (1411.2619)
Agrawal et al. (1411.2592)
Kile et al. (1411.1407)

Buckley et al. (1410.6497)
Heikinheimo & Spethmann (1410.4842)
Freytsis et al. (1410.3818)
Yu et al. (1410.3347)
Cao et al. (1410.3239)
Guo et al. (1409.7864)
Yu (1409.3227)
Cahill-Rowley et al. (1409.1573)
Banik & Majumdar (1408.5795)
Bell et al. (1408.5142)
Ghorbani (1408.4929)
Okada & Seto (1408.2583)
Frank & Mondal (1408.2223)
Baek et al. (1407.6588)
Tang (1407.5492)
Balazs & Li (1407.0174)
Huang et al. (1407.0038)
McDermott (1406.6408)
Cheung et al. (1406.6372)
Arina et al. (1406.5542)
Chang & Ng (1406.4601)
Wang & Han (1406.3598)
Cline et al. (1405.7691)
Berlin et al. (1405.5204)
Mondal & Basak (1405.4877)
Martin et al. (1405.0272)
Ghosh et al. (1405.0206)
Abdullah et al. (1404.5503)
Park & Tang (1404.5257)
Cerdeno et al. (1404.2572)
Izaguirre et al. (1404.2018)
Agrawal et al. (1404.1373)
Berlin et al. (1404.0022)
Alves et al. (1403.5027)
Finkbeiner & Weiner (1402.6671)
Boehm et al. (1401.6458)
Kopp et al. (1401.6457)
Modak et al. (1312.7488)

Alves et al. (1312.5281)
Fortes et al. (1312.2837)
Banik et al. (1311.0126)
Arhrib et al. (1310.0358)
Kelso et al. (1308.6630)
Kozaczuk et al. (1308.5705)
Kumar (1308.4513)
Demir et al. (1308.1203)
Buckley et al. (1307.3561)
Cline et al. (1306.4710)
Cannoni et al. (1205.1709)
An et al. (1110.1366)
Buckley et al. (1106.3583)
Boucenna et al. (1106.3368)
Ellis et al. (1106.0768)
Cheung et al. (1104.5329)
Marshall et al. (1102.0492)
Abada et al. (1101.0365)
Tytgat (1012.0576)
Logan (1010.4214)
Barger et al. (1008.1796)
Raklev et al. (0911.1986)

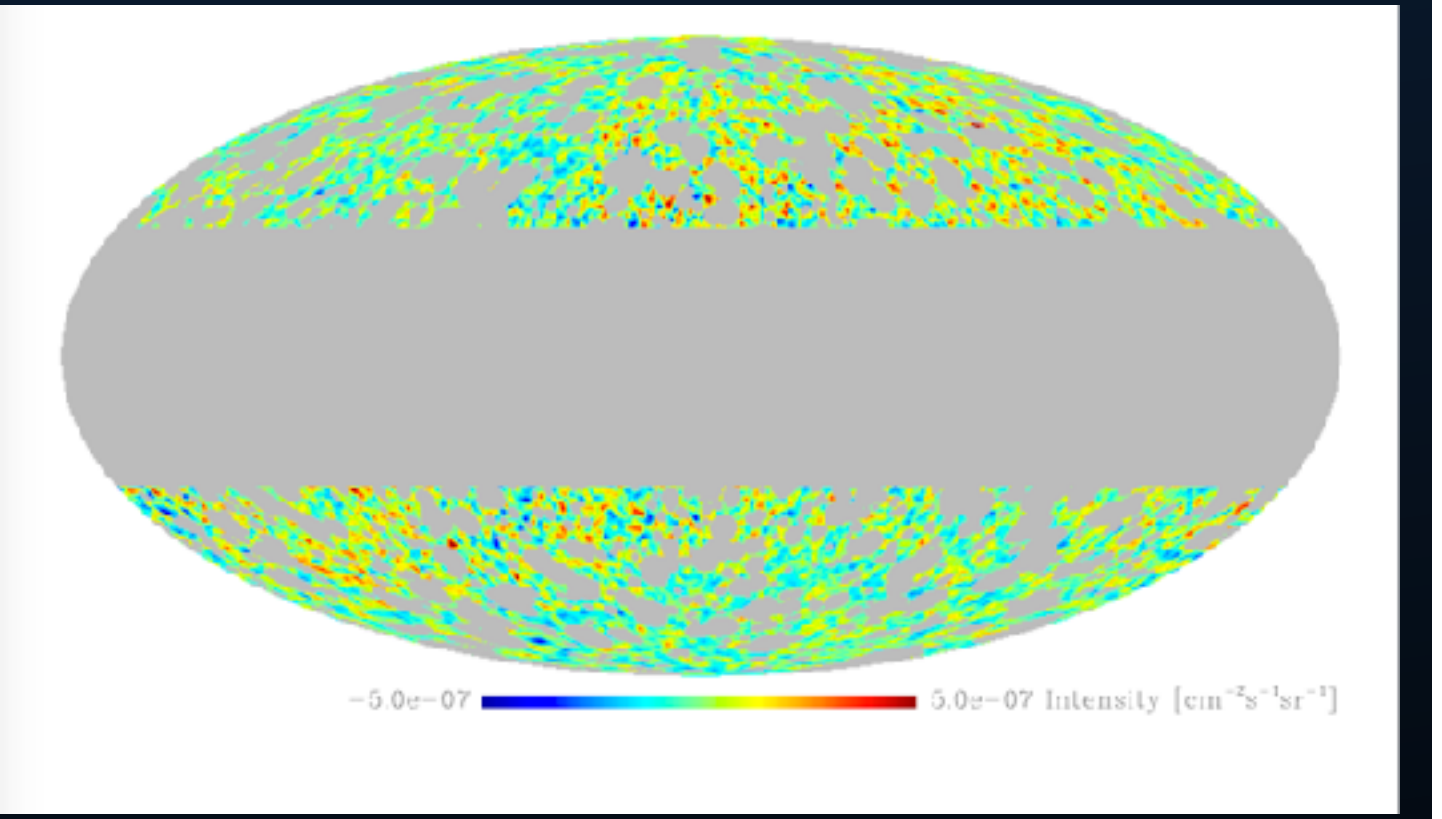
Finding Dark Matter Elsewhere

The Galactic Center is a terribly messy place.

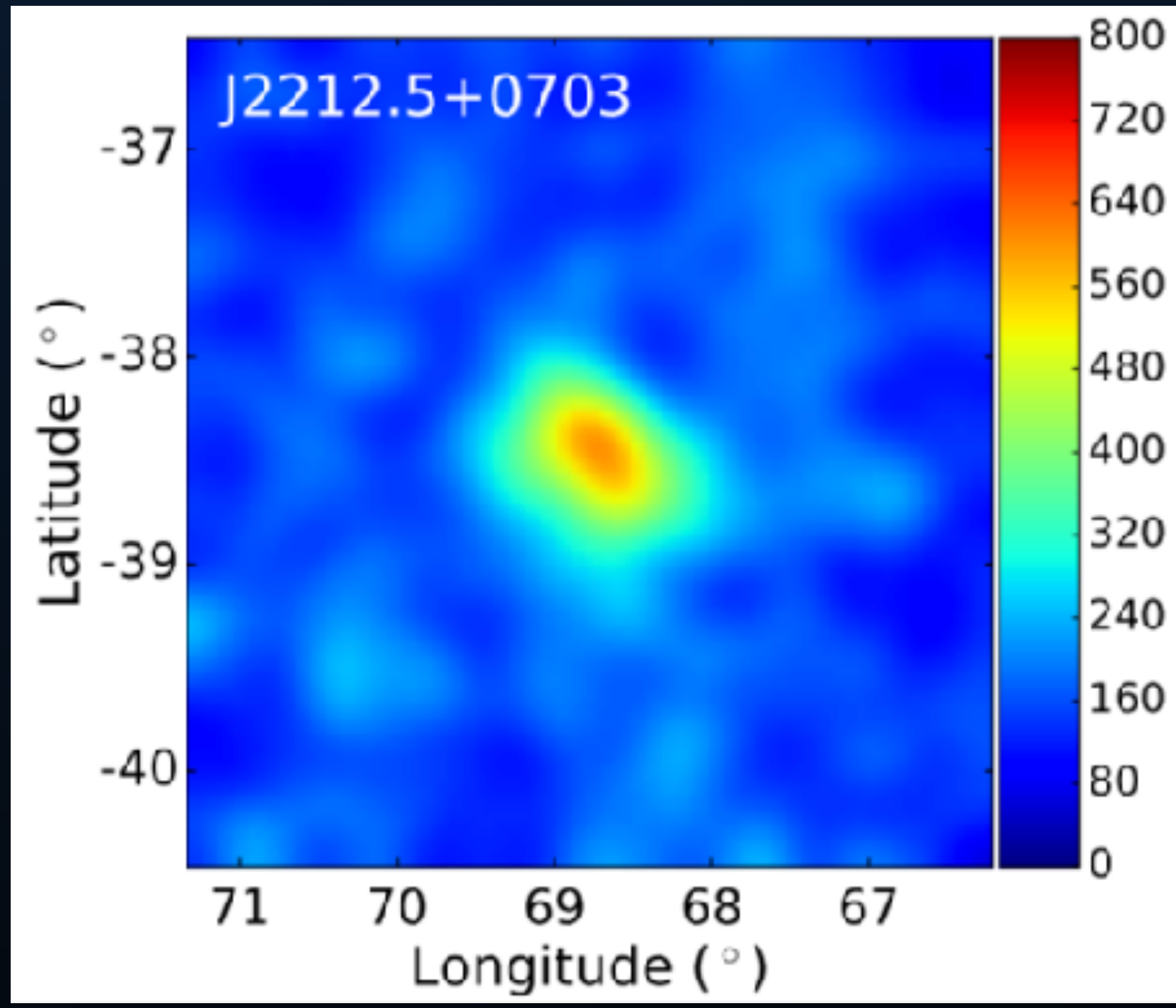
The Bayesian Prior on a given excess being produced by dark matter is …. low.

Need to verify elsewhere:

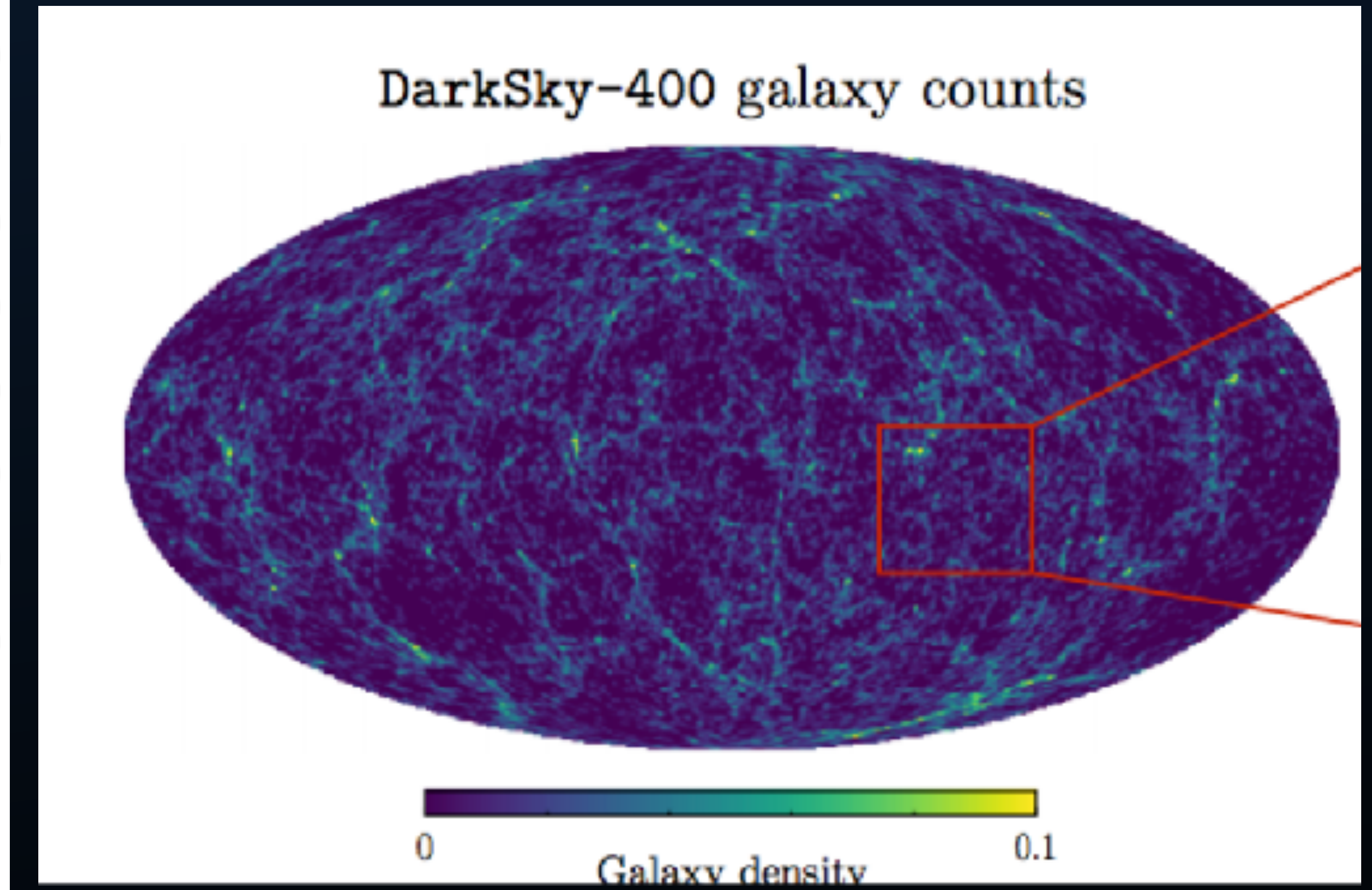
dSphs



IGRB



Unassociated Sources



Galaxies

Finding Dark Matter Elsewhere

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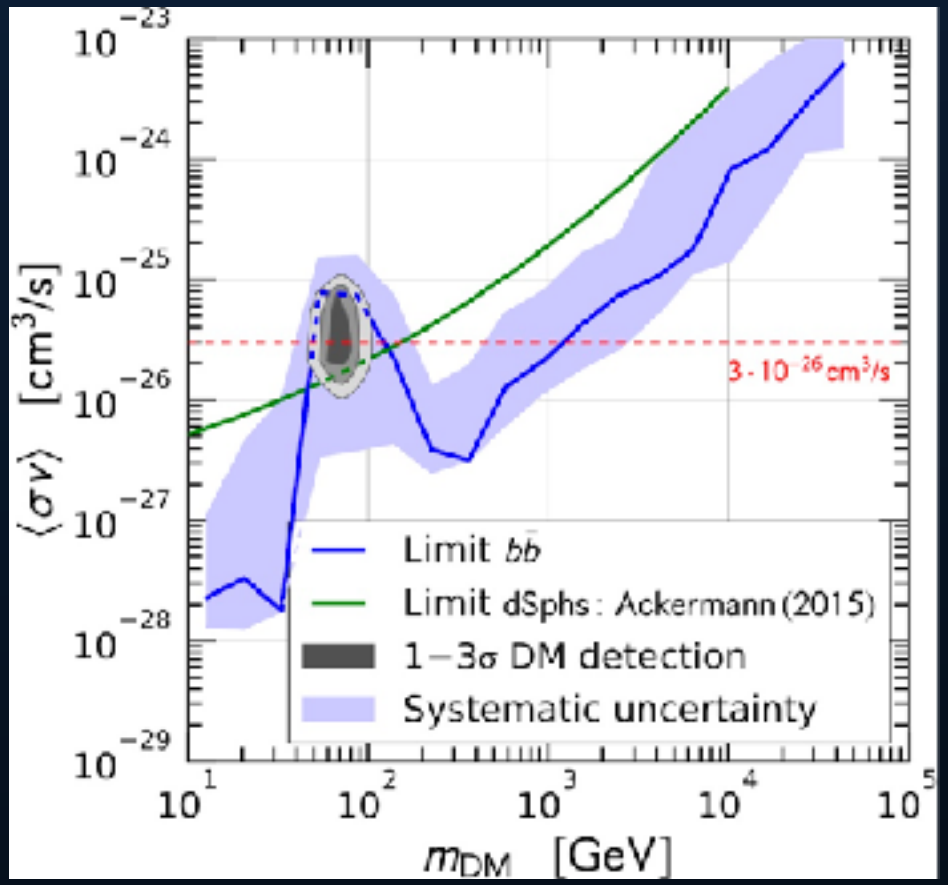
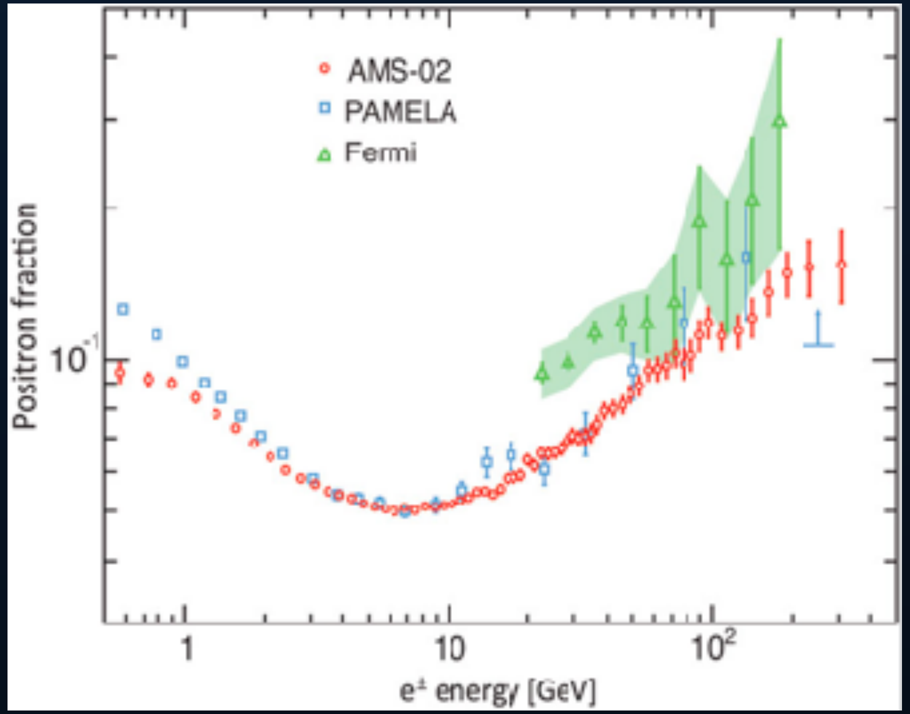
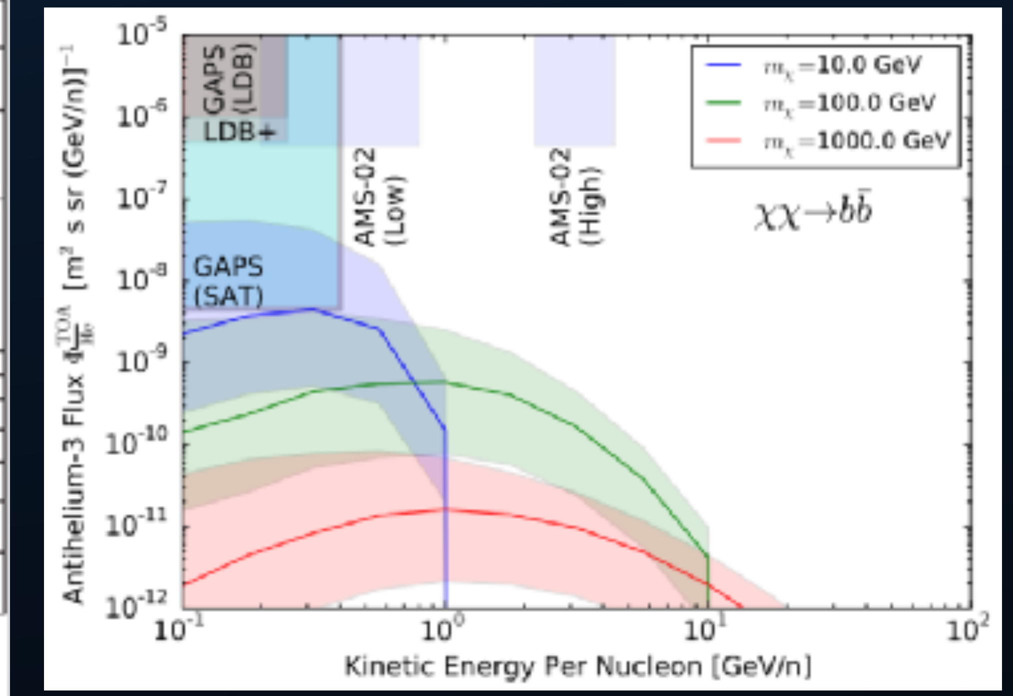
Need to verify elsewhere:



Antiprotons

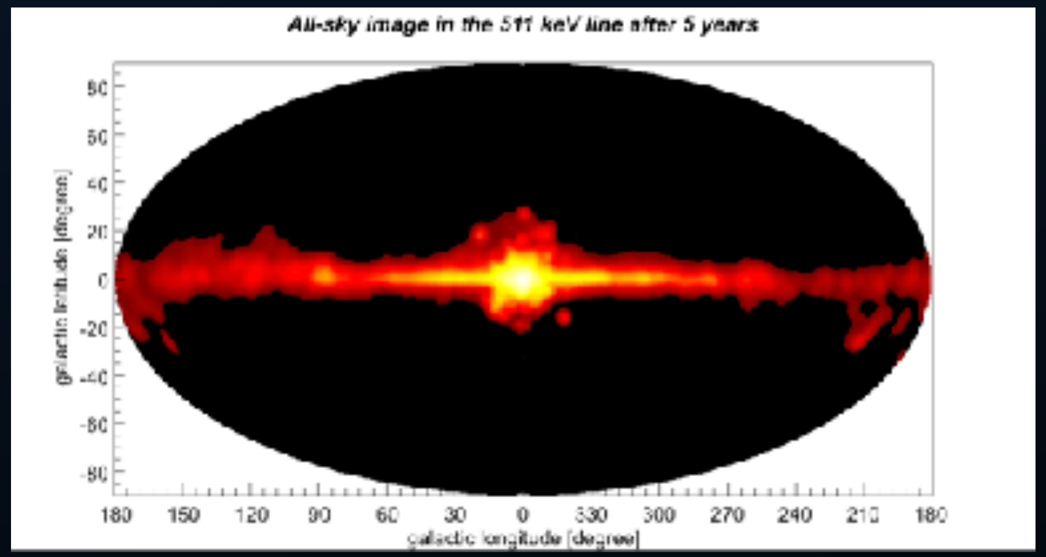


Positrons



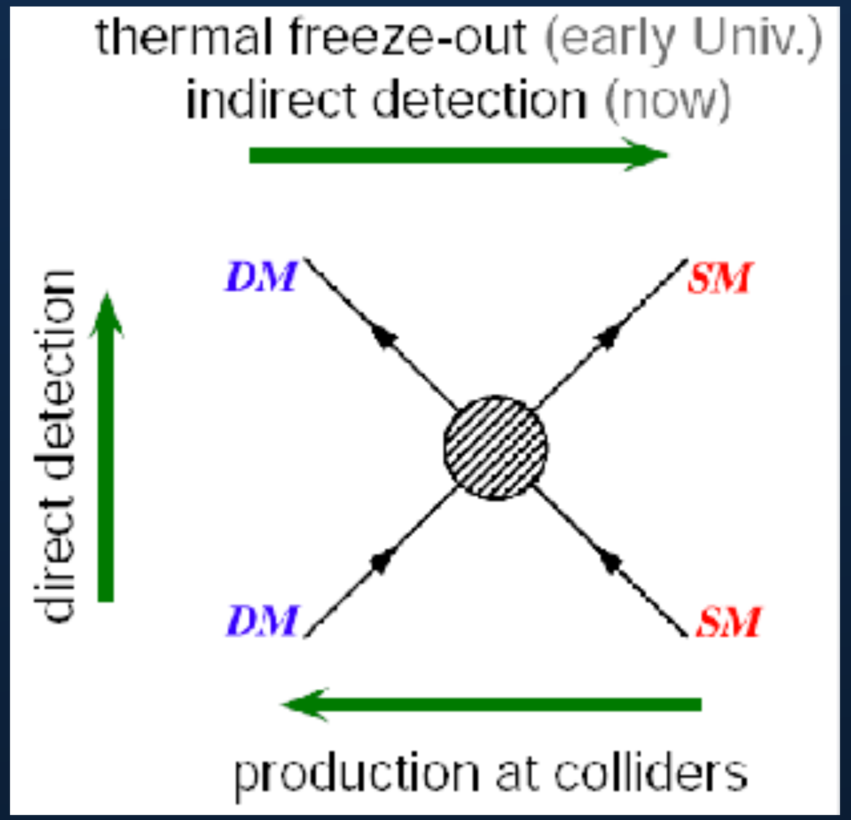
Antihelium

Isotropic Radio



511 keV line

Finding Dark Matter Elsewhere

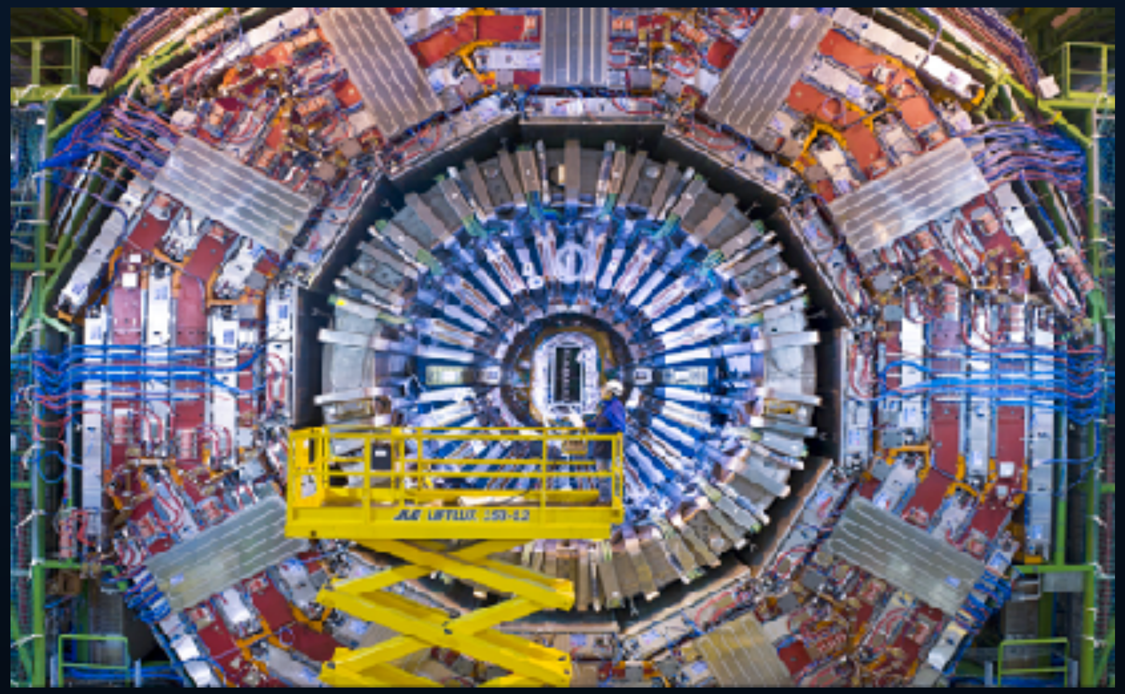


The Galactic Center is a terribly messy place.

The Bayesian Prior on a given excess being produced by dark matter is .... low.

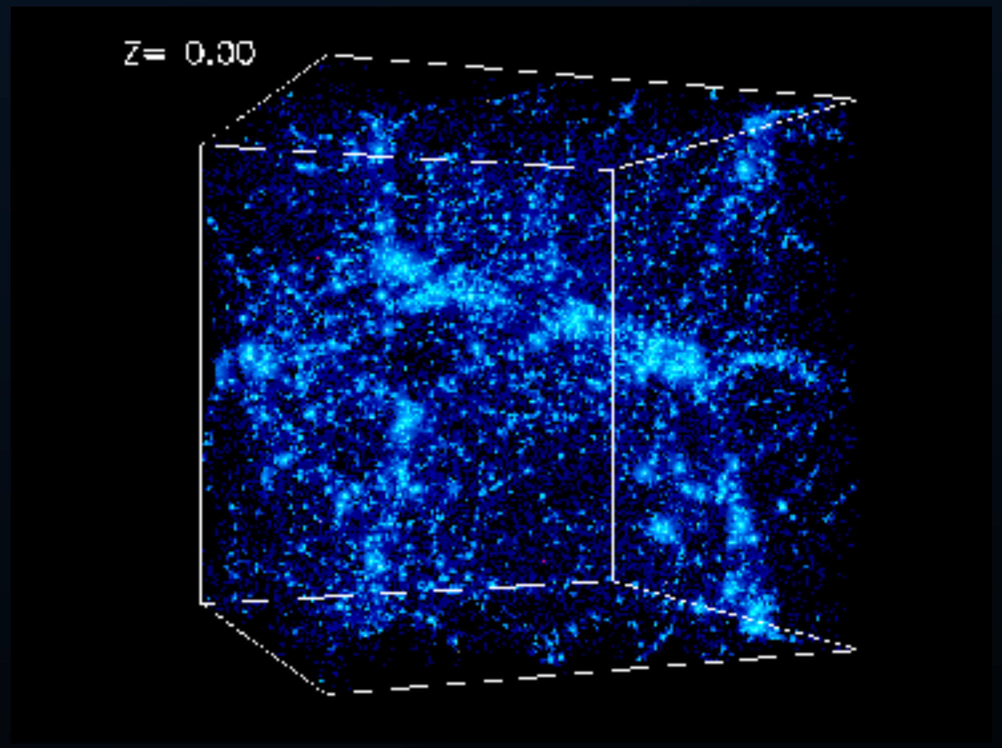
Need to verify elsewhere:

Direct Detection



Collider

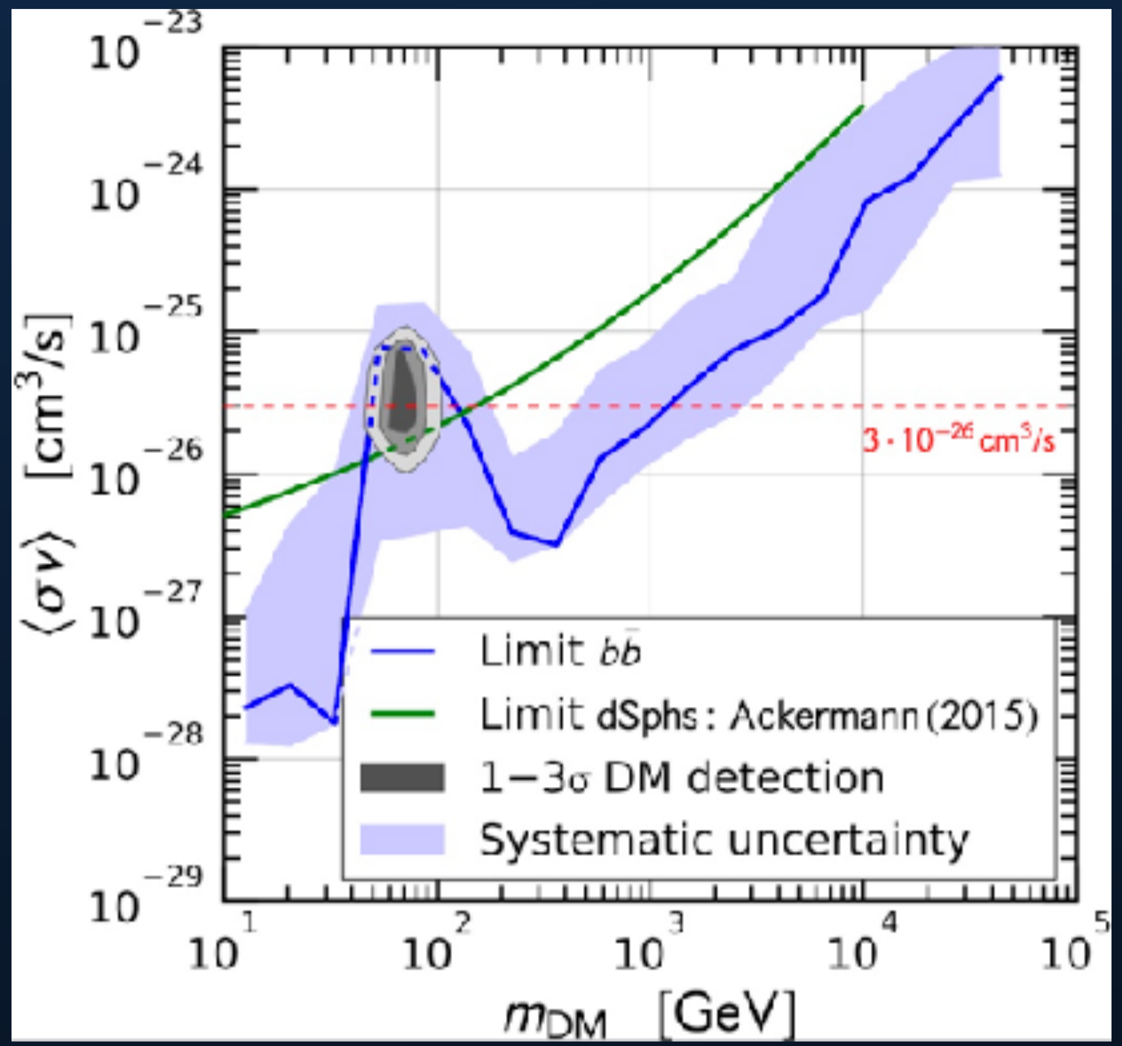
Precision Frontier



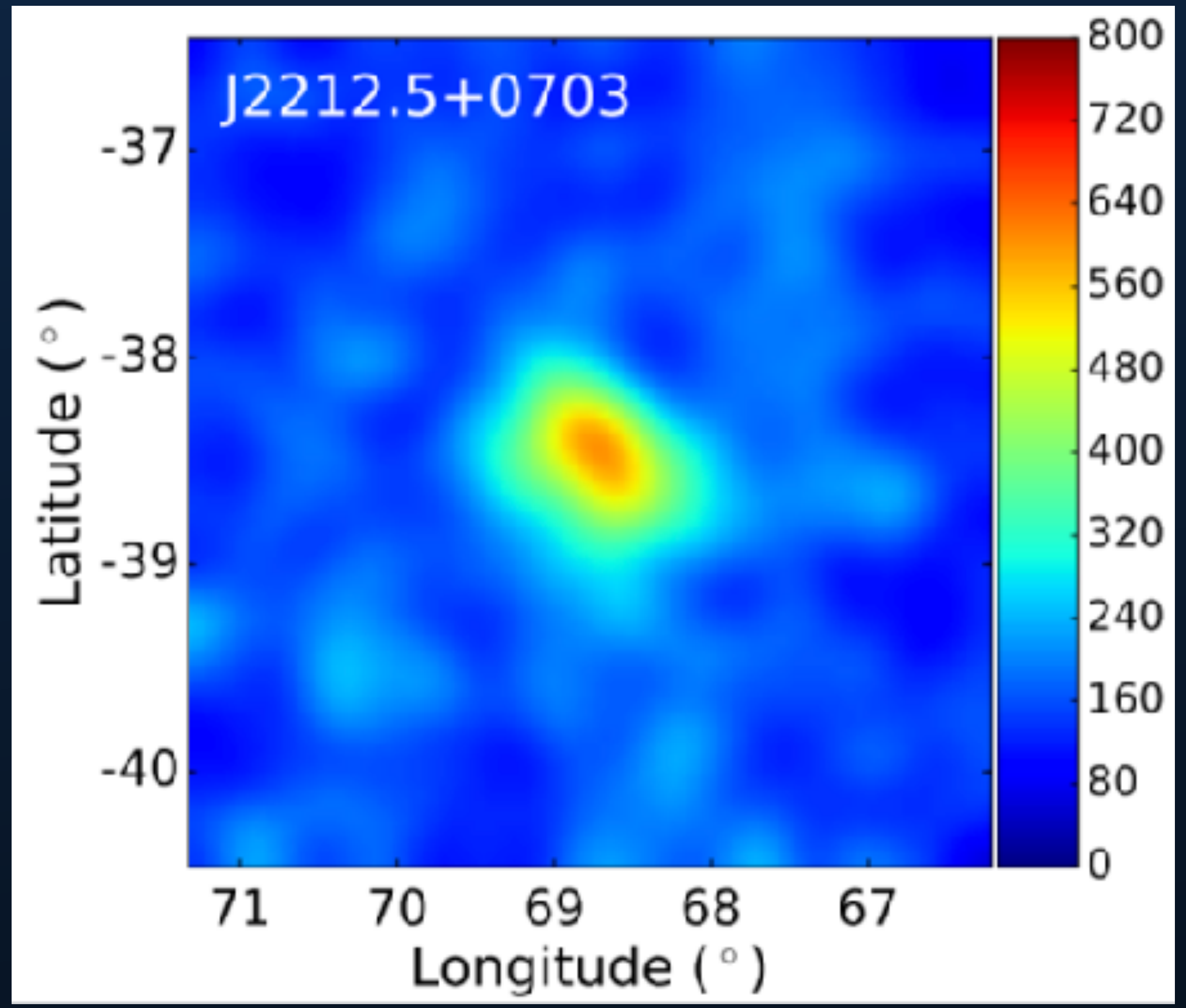
Structure Formation

Detections - The Optimistic Case

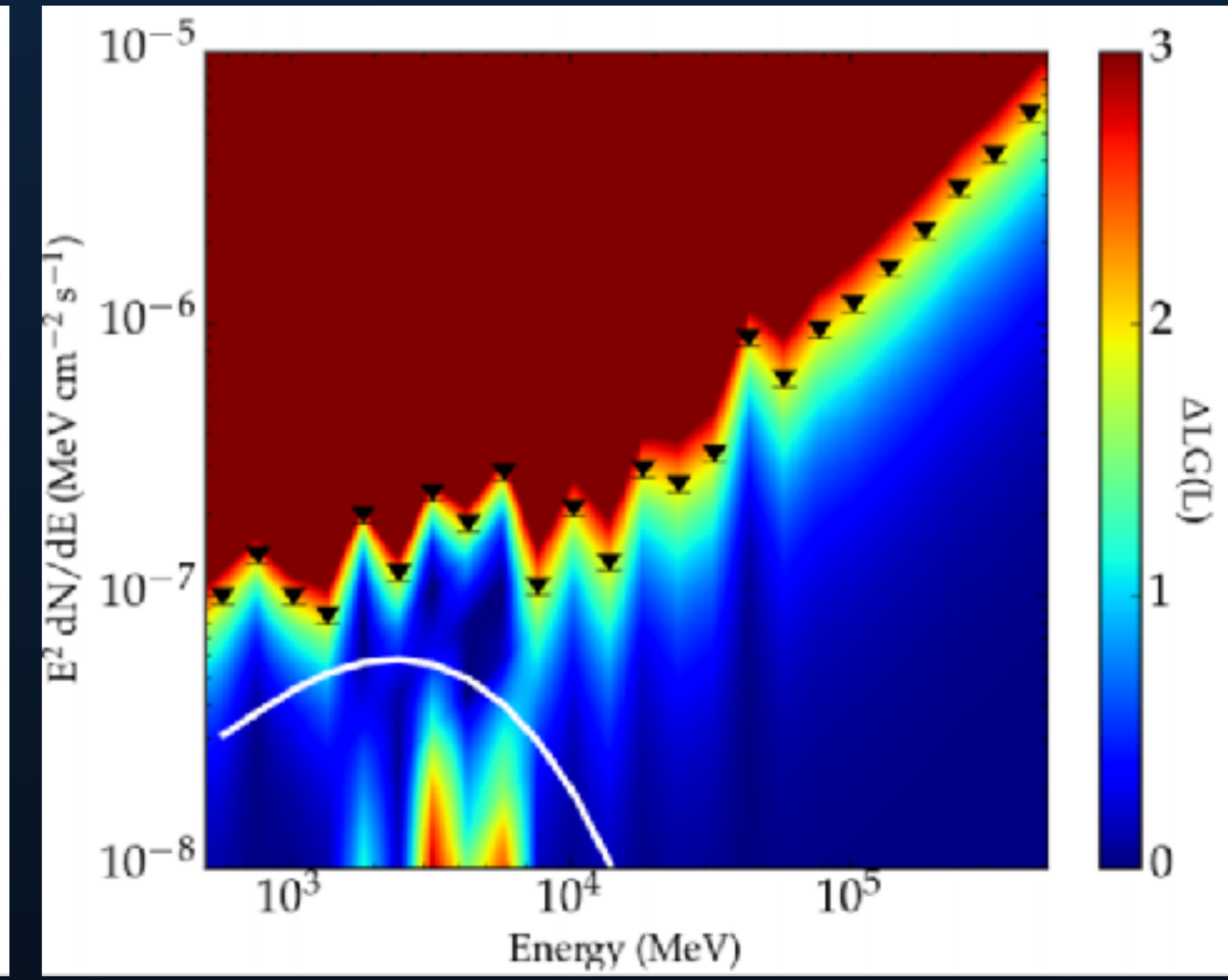
A number of excesses have been observed that are consistent with a dark matter interpretation of the gamma-ray excess.



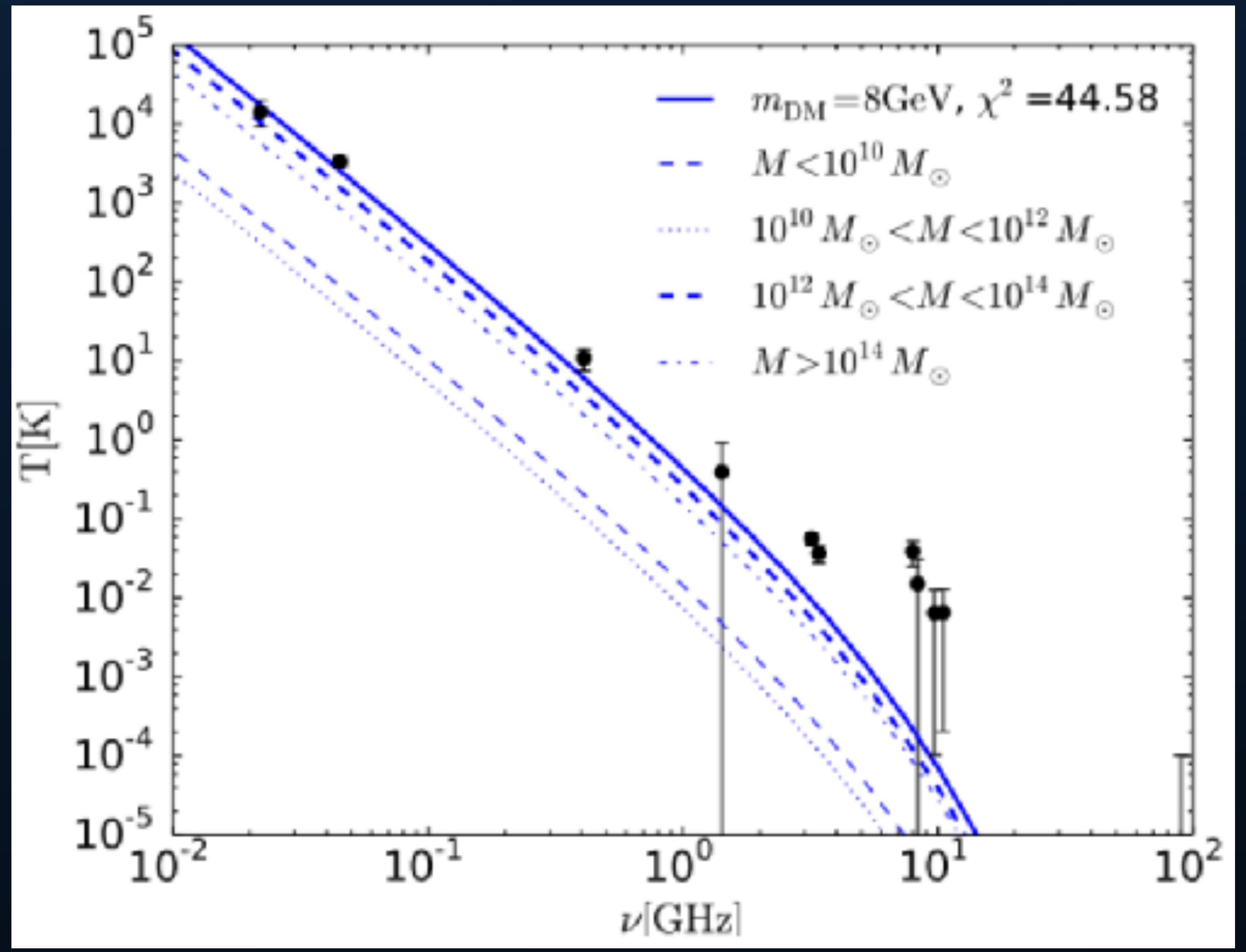
Antiproton Excess



Unassociated Source



Reticulum II



ARCADE-II Excess

Detections - The Pessimistic Case

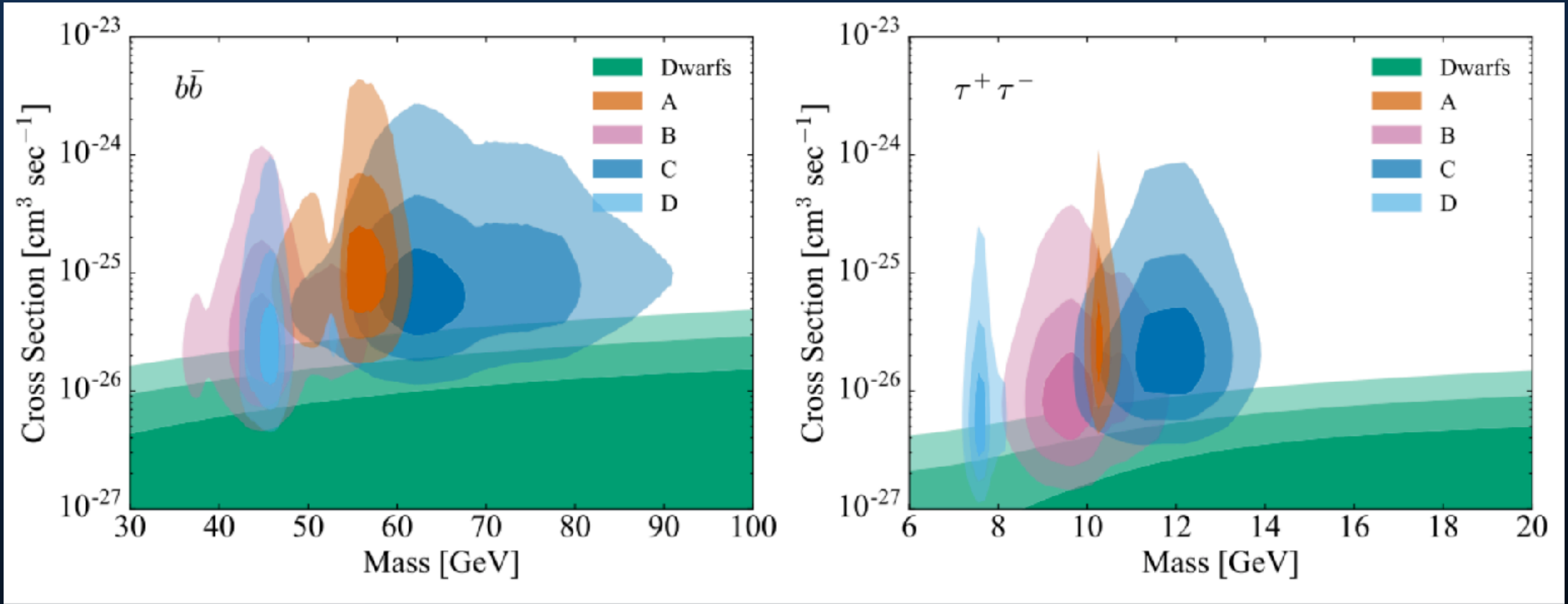
Current Instrumentation:

1.) Has been sensitively probing the GeV energy range

2.) Has been probing intensities similar to the thermal cross-section

Any excess that is found has a high probability of being consistent with the GeV excess.

Detections - The Optimistic (?) Case

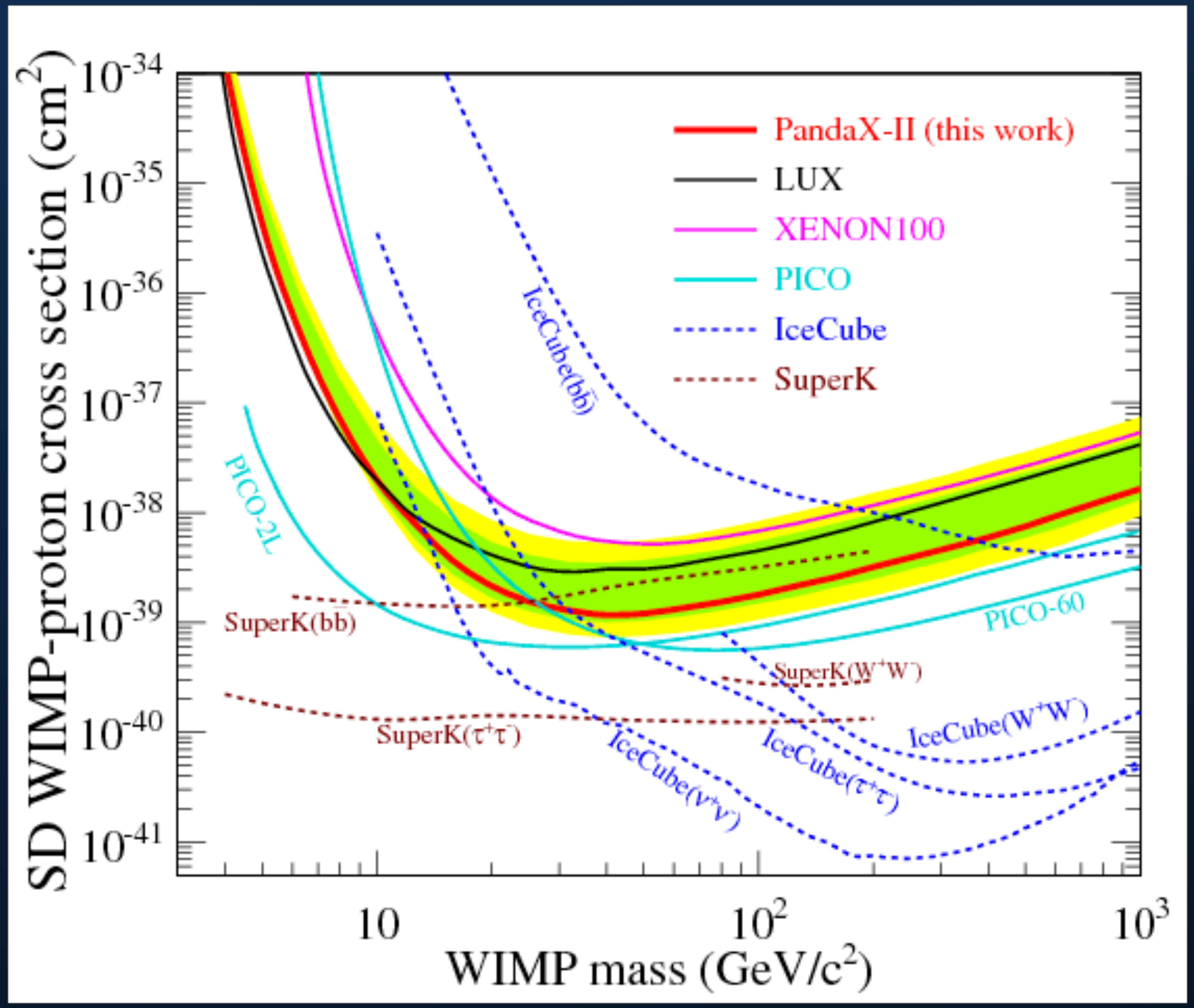


The parameter spaces allowed by dwarf searches and the Galactic center excess are somewhat inconsistent.

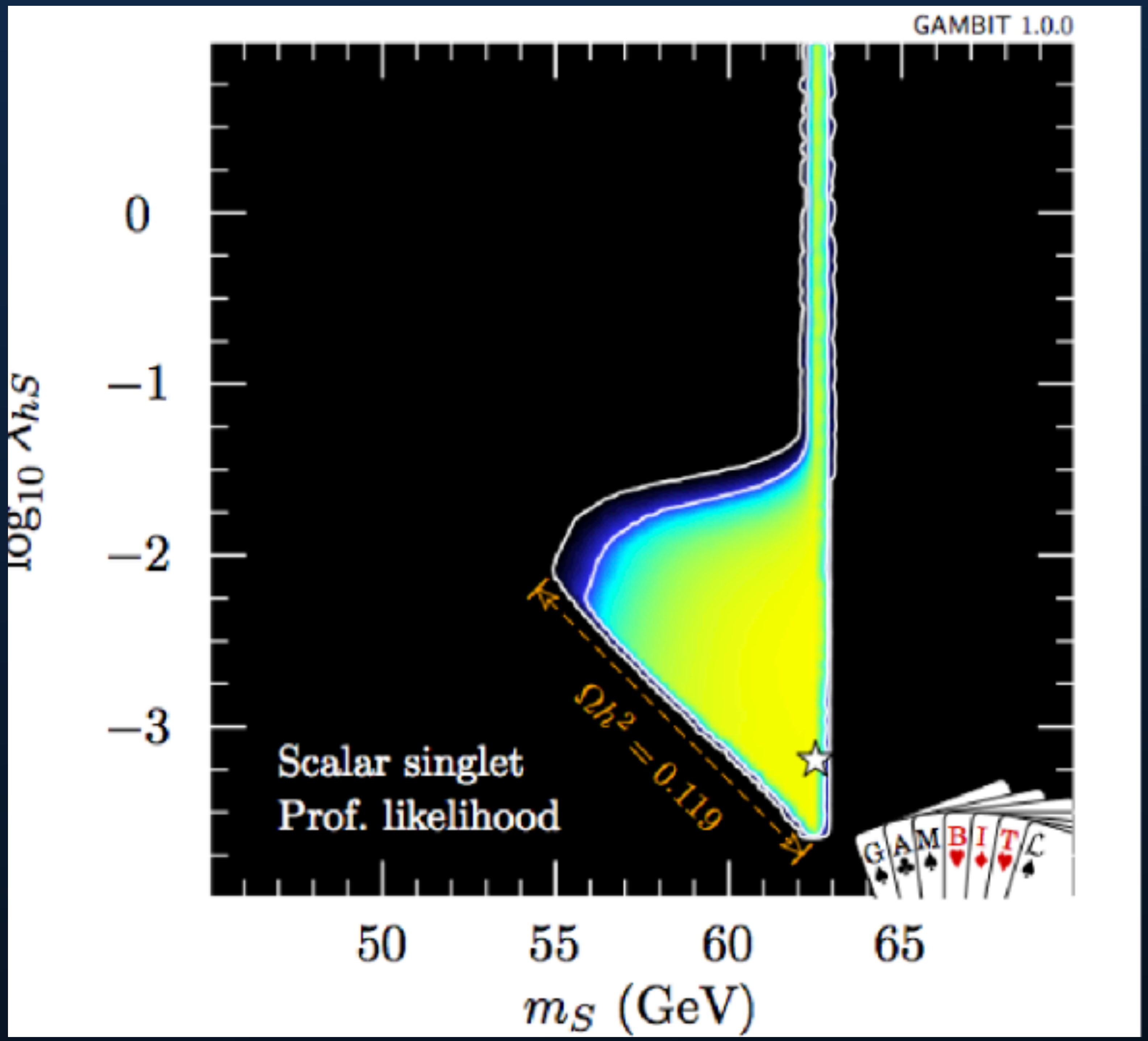
Dwarf constraints are likely to improve.

Keeley et al. (2017; 1710.03215)

Detections - The Optimistic (?) Case



Tan et al. (2016; 1607.07400)

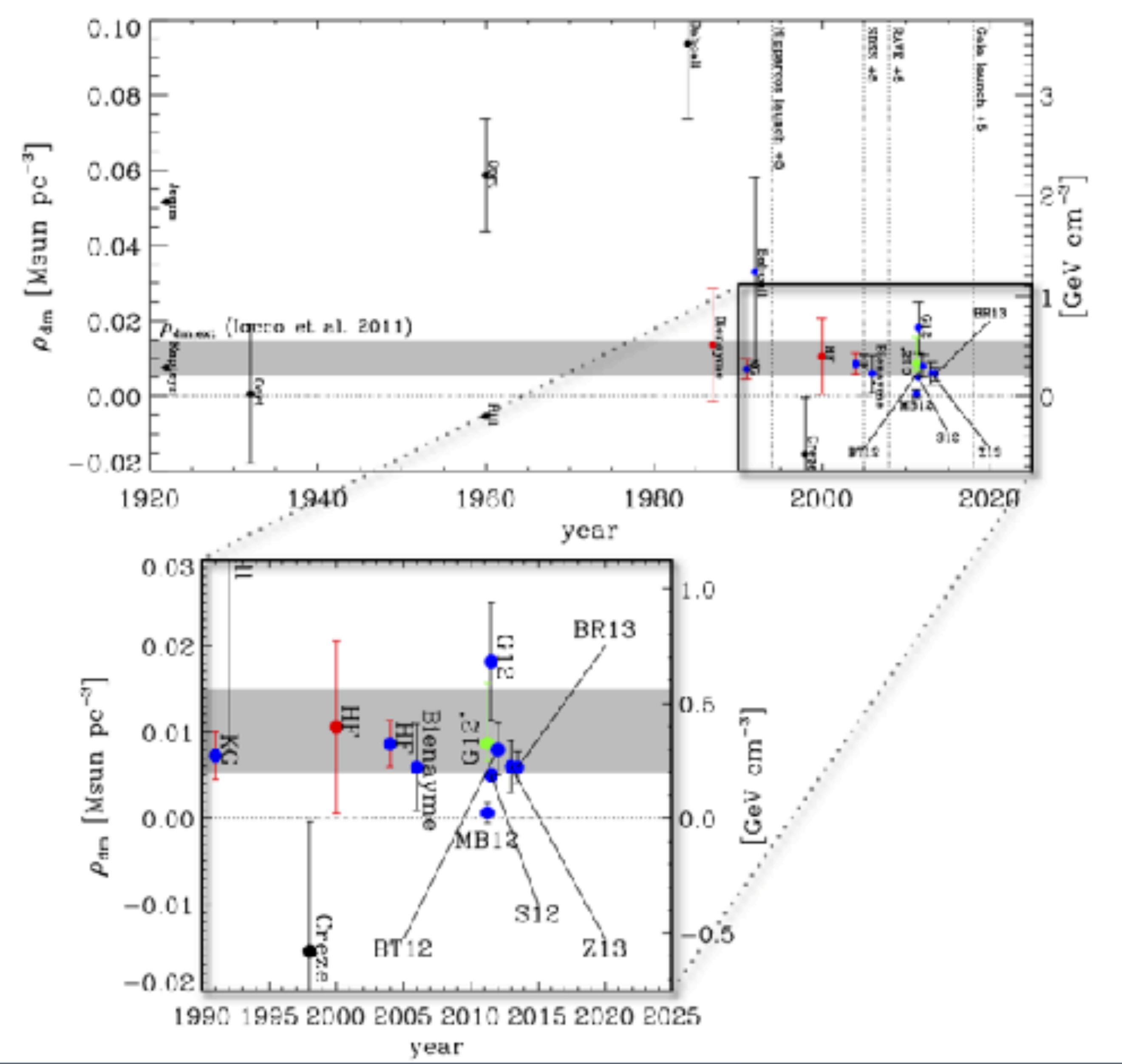


Athron et al. (2017; 1705.07931)

Direct Detection experiments are highly sensitive to the 30-50 GeV dark matter mass range.

Multidimensional scans of supersymmetric parameter space also constraining a significant range of dark matter model building.

Detections - The Pessimistic (?) Case



Read (2014; 1404.1938)

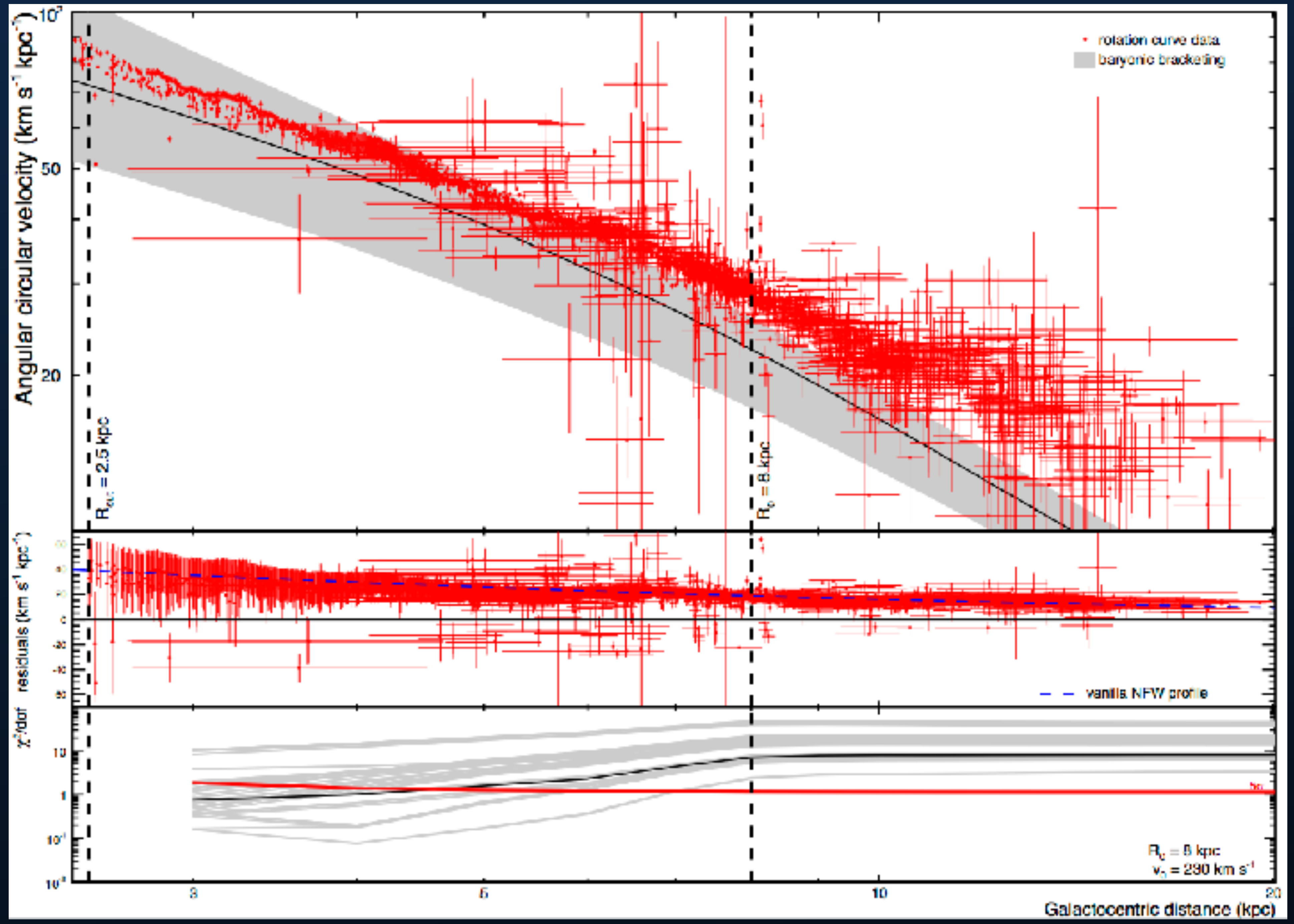
Component	Σ^{∞} $M_{\odot}$ pc^{-2}	$\pm$ (%)		$\pm(M_{\odot}$ $pc^{-2})$
Visible stars	27.0 (M15)	15% (M15, text)	→	4.05
White dwarfs	4.7 (S17)	17% (M15)	→	0.80
Brown dwarfs	1.2 (M15)	30% (M15)	→	0.36
Neutron stars	0.2 (M15)	30% (M15)	→	0.06
Black holes	0.1 (M15)	30% (M15)	→	0.03
Stellar sum	**33.2**			**5.30**
H2	0.95 (S17)	30% (M15)	→	0.29
HI	10.9 (M15)	20% (S17)	→	2.18
HII	1.8 (M15)	17% (S17)	→	0.31
Gas sum	**13.65**			**2.78**
Total baryon	**46.85**	**13 %**	←	**5.98**

Sivertsson et al. (2017; 1708.07836)

The comparison of these constraints to other indirect detection models are highly dependent on the local dark matter density - modeled cross-section can change by a factor of almost 4.

Most recent results point to high dark matter densities, which would decrease the necessary cross-section.

Detections - The Optimistic (!) Case



Iocco et al. (2015; 1502.03821)

Upcoming observations are closing this significant source of uncertainty.

Dark Matter Models

Energetics ✓

Spectrum ✓

Morphology ✓

Dark Matter Models

Energetics ✓

Spectrum ✓

Morphology ✓

Bayesian Prior ✗

Conclusions

1.) The Galactic Center excess can be explained by several physical mechanisms.

2.) Likely that more than one mechanism produces >~ 10% of the total emission.

3.) Pulsars remain a leading candidate - and will be tested in the next few years.

4.) Dark Matter remains a viable model — hard to rule out with additional Galactic center observations.

Supernovae Models

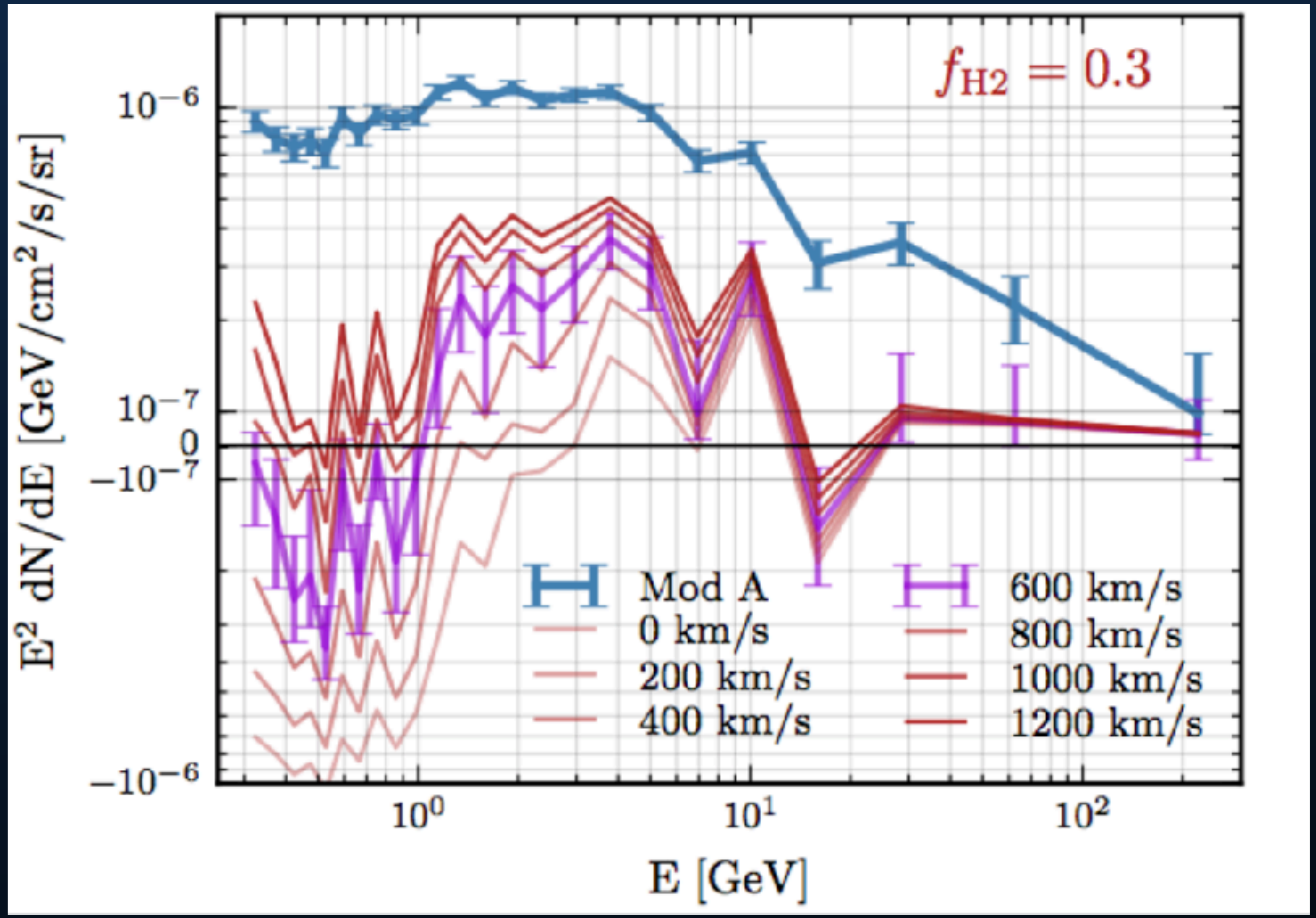
Carlson et al. (2016; 1603.06584)

However, this over-subtracts the low-energy emission.

Inevitable, because π^0-decay spectrum is softer than the excess.

Add winds!

But some excess returns.



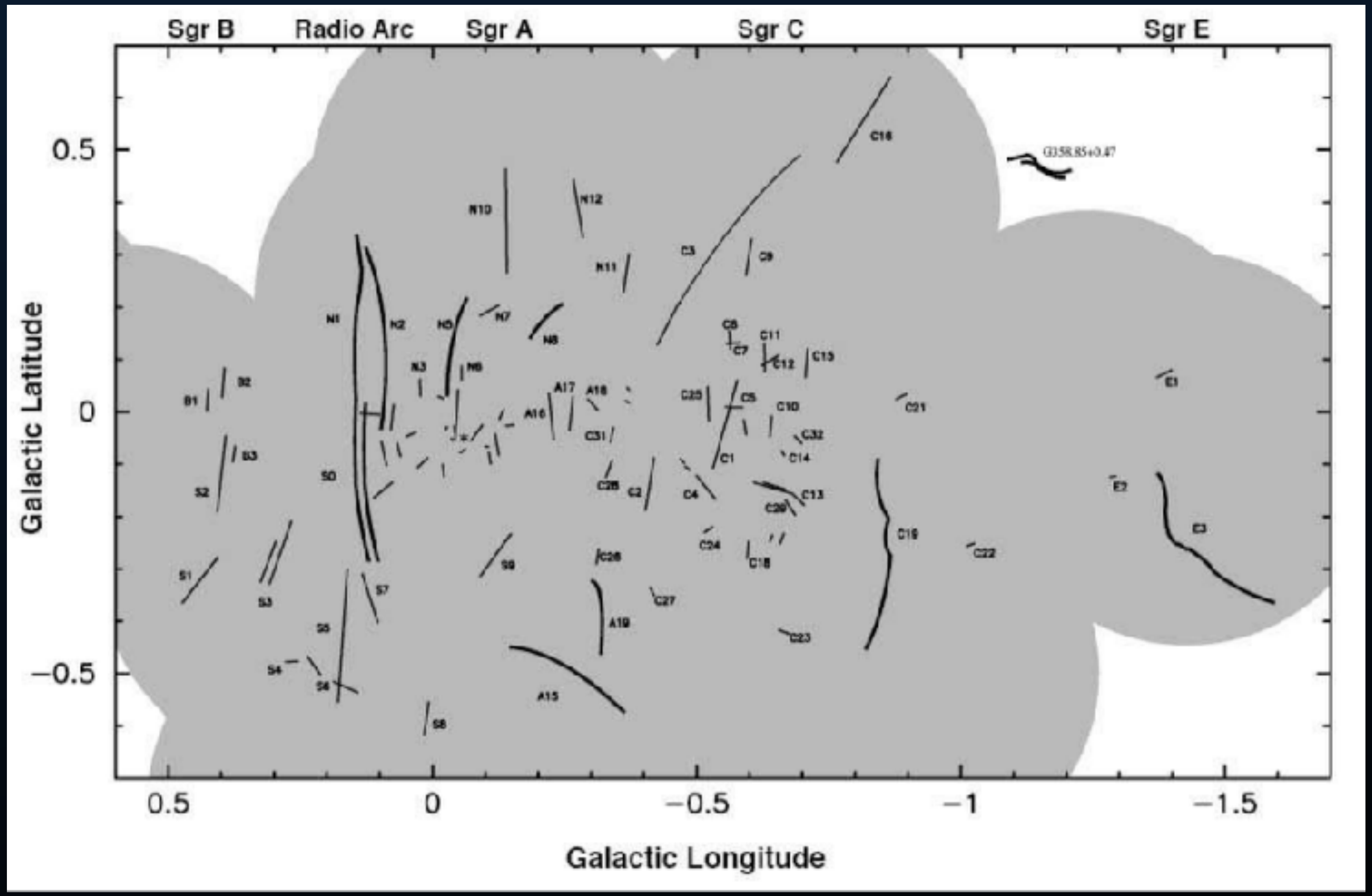
Changes in the supernova injection rate affect the calculation of the excess - but cannot entirely eliminate it.

Reacceleration

More than 80 filamentary structures identified in the central 2° x 1° .

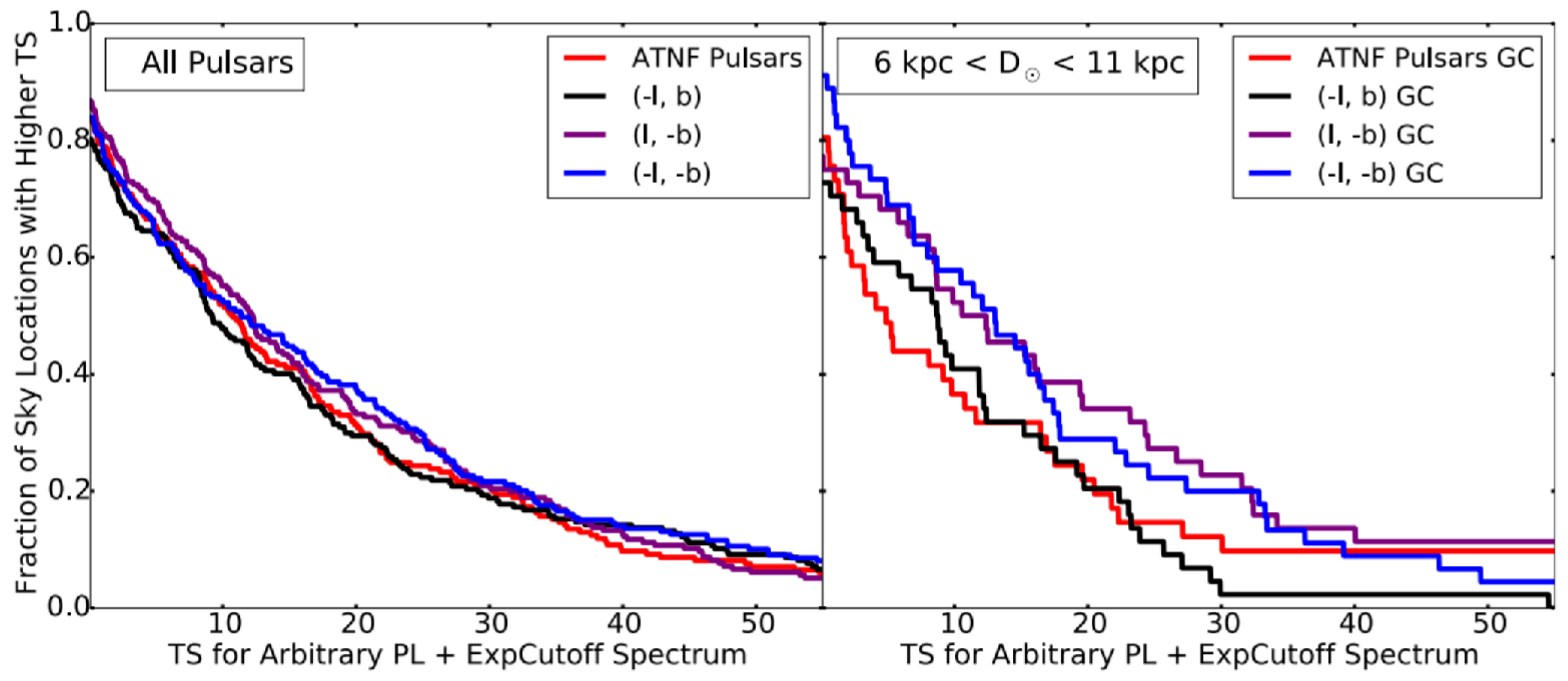
The filaments are observed as highly polarized, hard-spectrum synchrotron sources — indicative of strongly ordered magnetic fields and hard injected electron spectra.

The best astrophysical explanation involves significant re-acceleration via magnetic reconnection (Lesch & Riech 1992, Lieb et al. (2004).



Yusef-Zadeh et al. (2004)

Known Radio Pulsars Do Not Produce the Excess



The locations of known of ATNF radio pulsars near the Galactic center do not correspond to excesses in the gamma-ray data.

Linden (2016; 1509.02928)