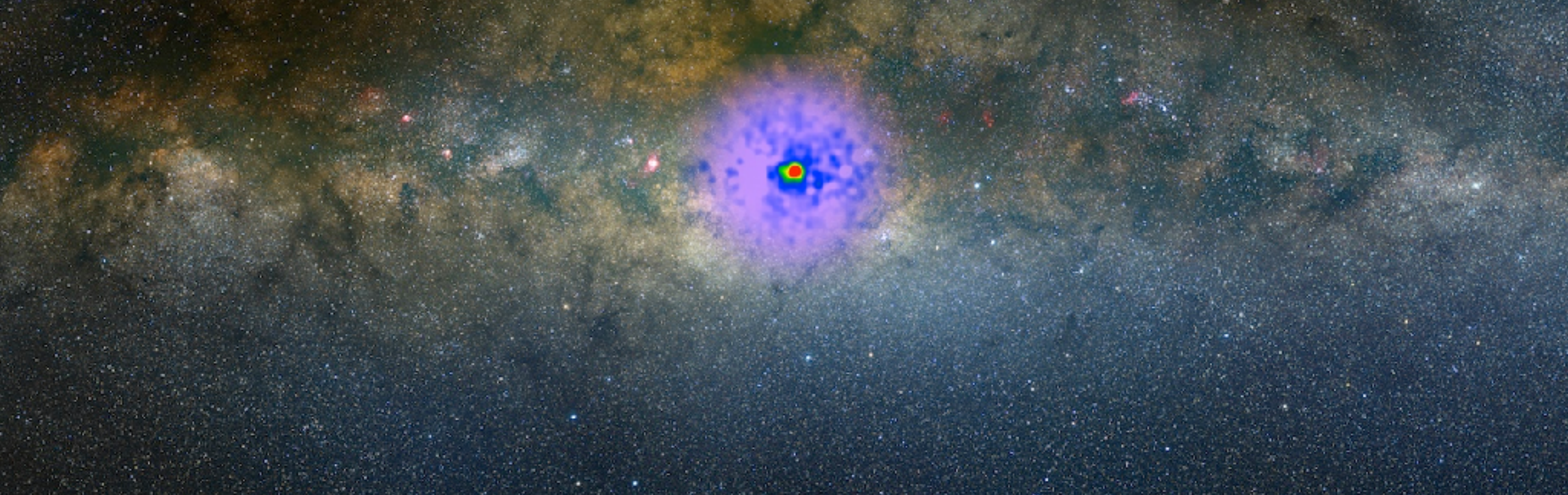
Pulsar Interpretations of the Galactic Center Excess



with emphasis on: “Characterizing the population of pulsars in the Galactic bulge with the Fermi Large Area Telescope”, arXiv: 1705.00009

Tim Linden

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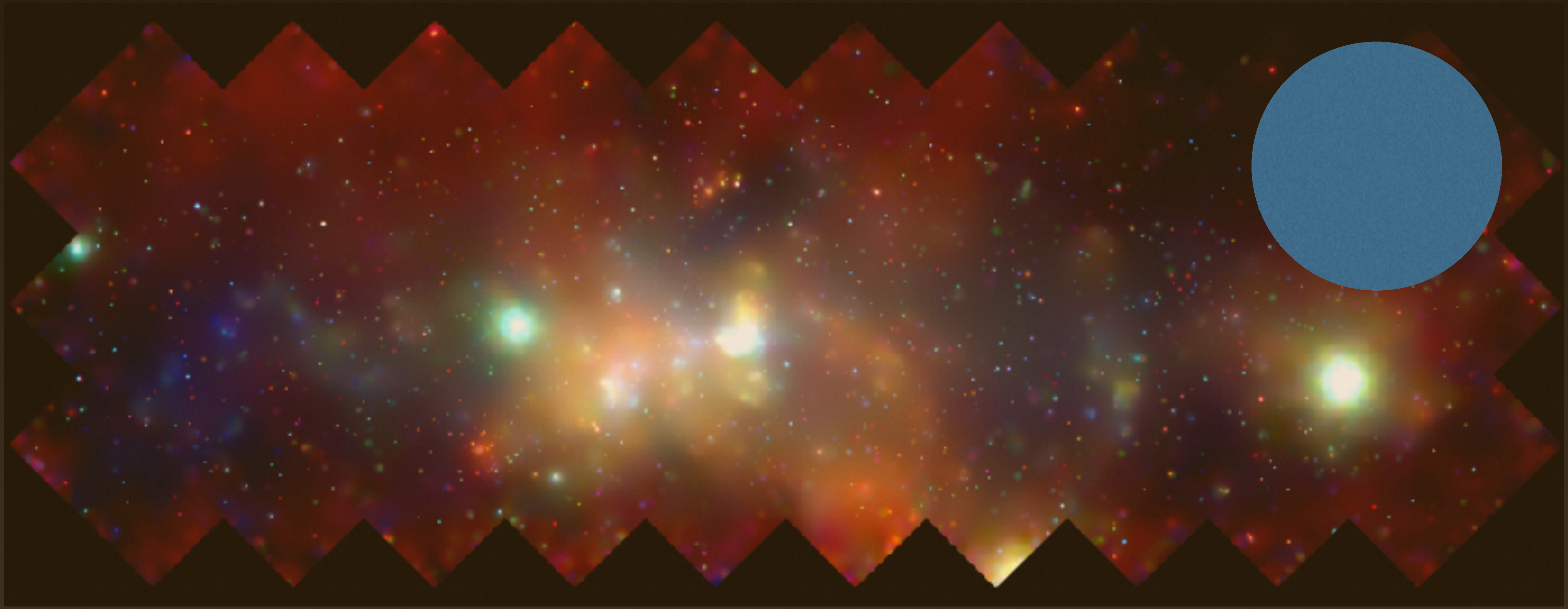
LHC Results Forum 6/14/17

Interpreting the Origin of a Gamma-Ray Source



Associating a gamma-ray source with a specific object is hard:

1.) Angular Resolution is poor (PSF ~1.0°, source localization ~0.1°)
  a.) Overlapping astrophysical sources within error bars
  b.) No morphological information for most sources
2.) No spectral lines
3.) New source classes, not bright at other wavelengths (radio-quiet pulsars, dark matter?)

Understanding the Origin of a Gamma-Ray Source

1.) Flux (Luminosity)

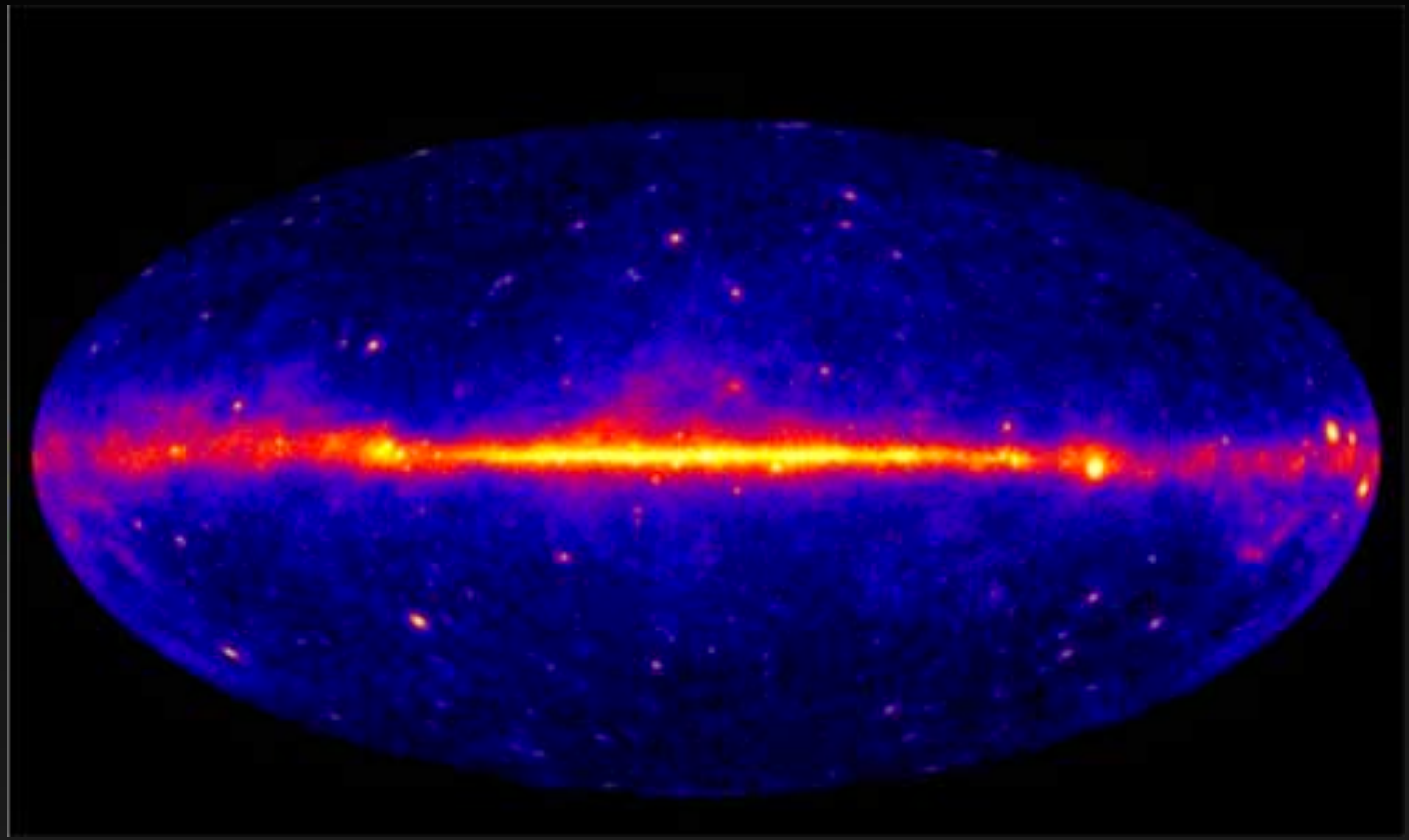
2.) Spectrum

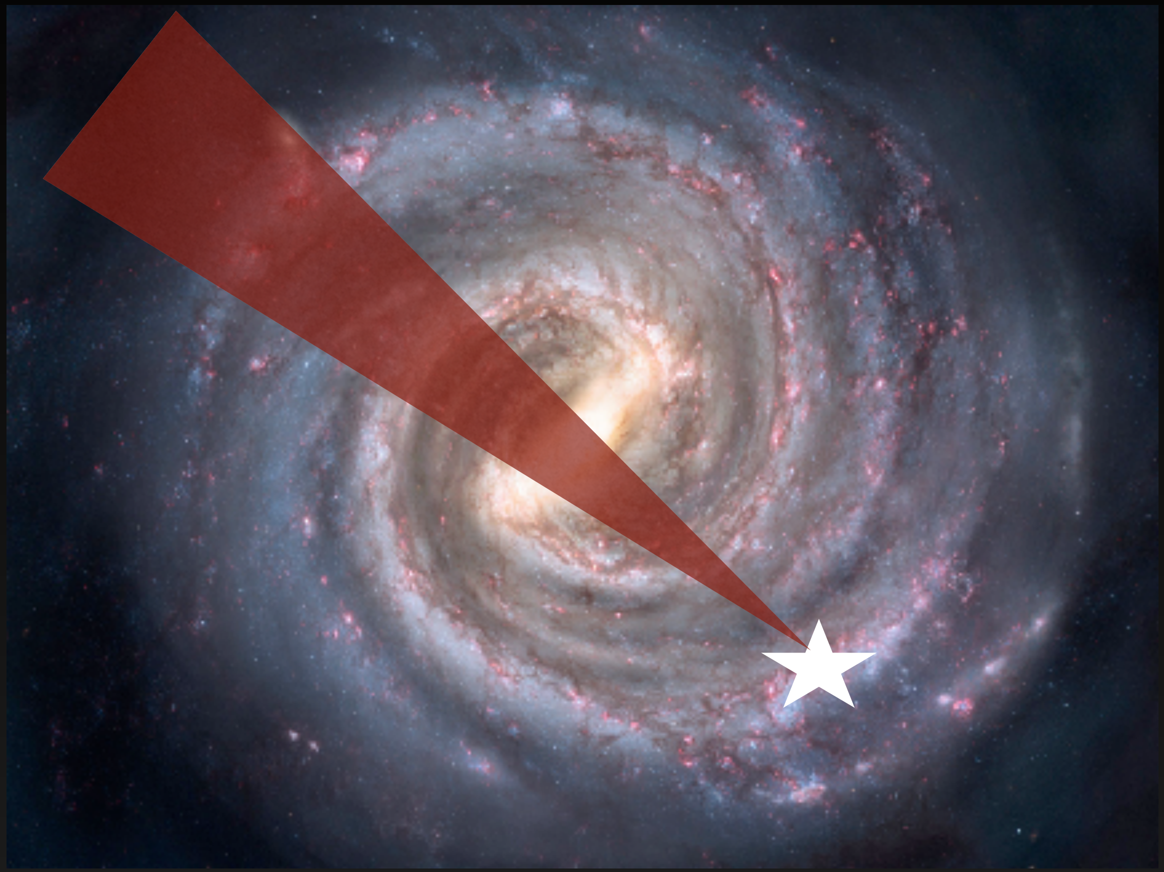
3.) Morphology
   a.) Global Morphology
   b.) Flux Variations

4.) Multi-wavelength Correlations
   a.) Time variability

Part Ia:
The gamma-ray flux from the Galactic Center

Fermi-LAT Flux from The Galactic Center





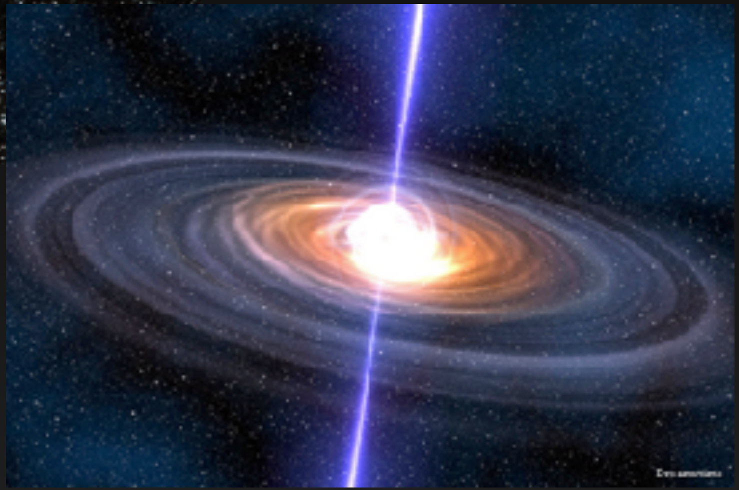
Total Gamma-Ray Flux (>1 GeV) in inner 1° is **1.1×10^{-9} erg cm^{-2} s^{-1}**

Approximately half of this emission is produced along the line of sight towards the GC, and thus we approximate the total gamma-ray luminosity of the central one degree to be **5×10^{36} erg s^{-1}**

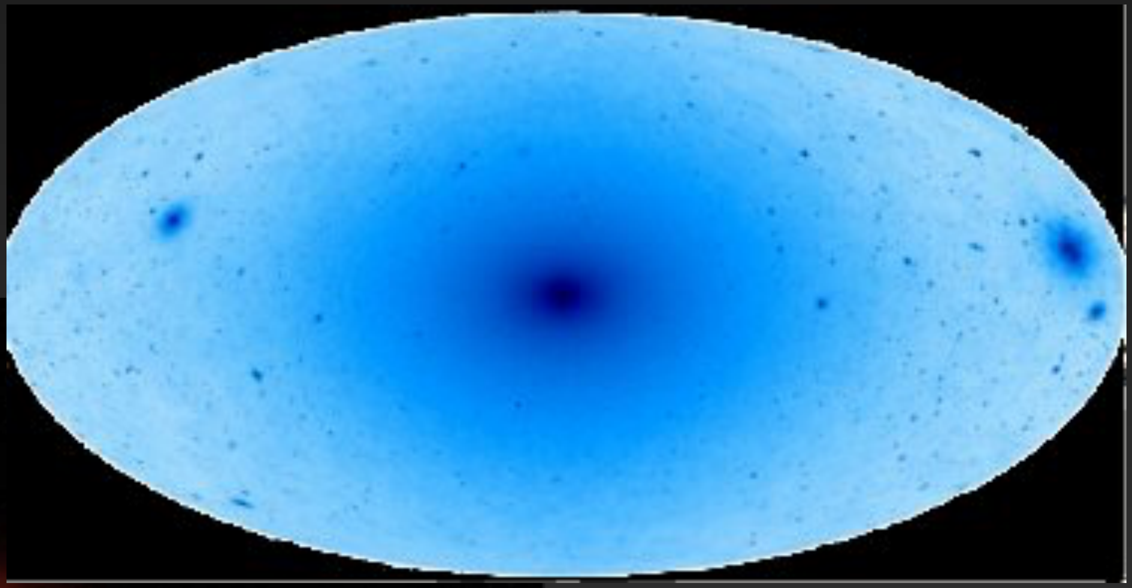
What models can power this emission?

What Gamma-Ray Sources Exist?

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

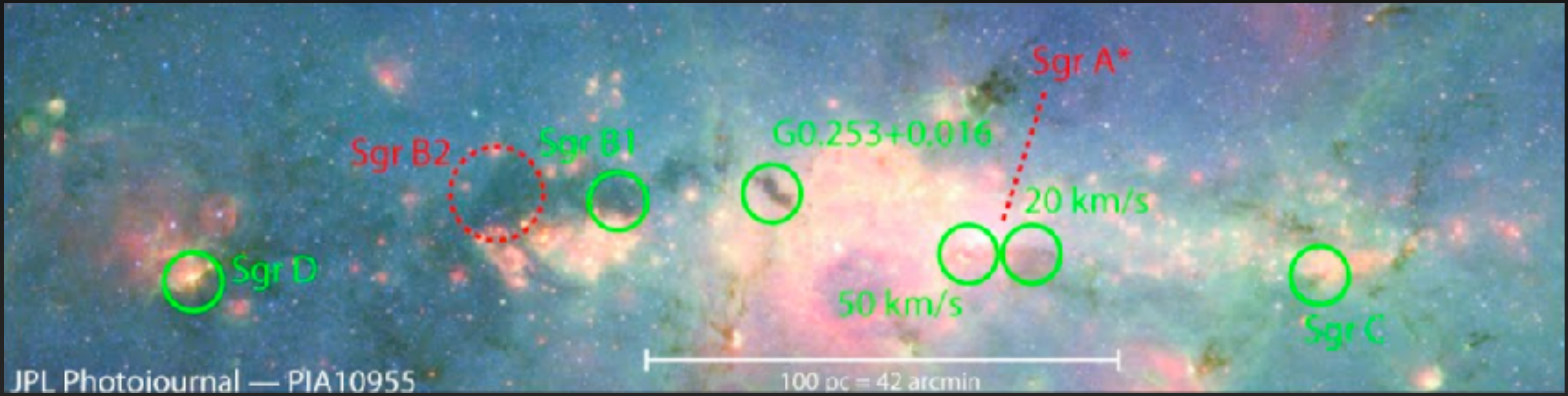


1.) Supernovae
2.) Pulsars
3.) Sgr A*
4.) Reacceleration
5.) Dark Matter Annihilation?



The Central Molecular Zone

- 400 pc x 80 pc
- 10^7 M_o of gas in Molecular Clouds
- Conditions similar to nearby starburst galaxies



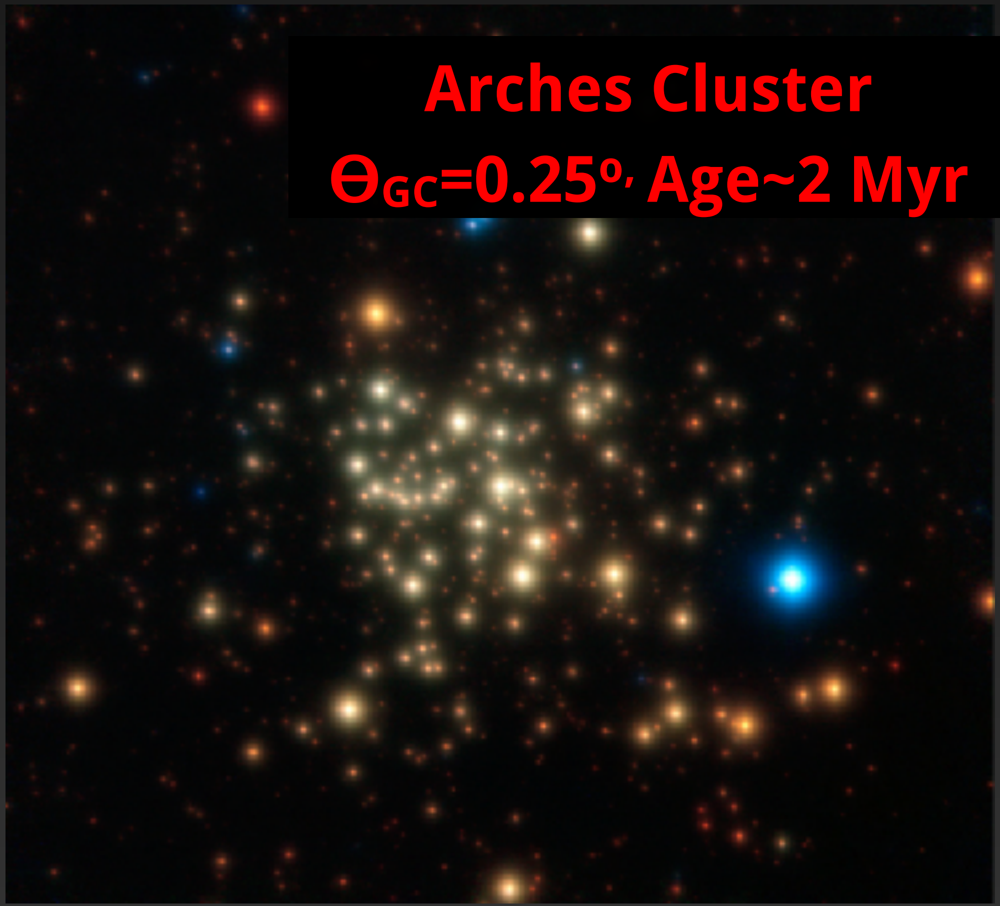
- Molecular Gas clouds in the Central Molecular Zone are hot (~50-100K)
- Indicative of heating by a significant cosmic-ray population confined in the central molecular zone. (Yusef-Zadeh et al. 2013)

The Galactic Center Supernovae

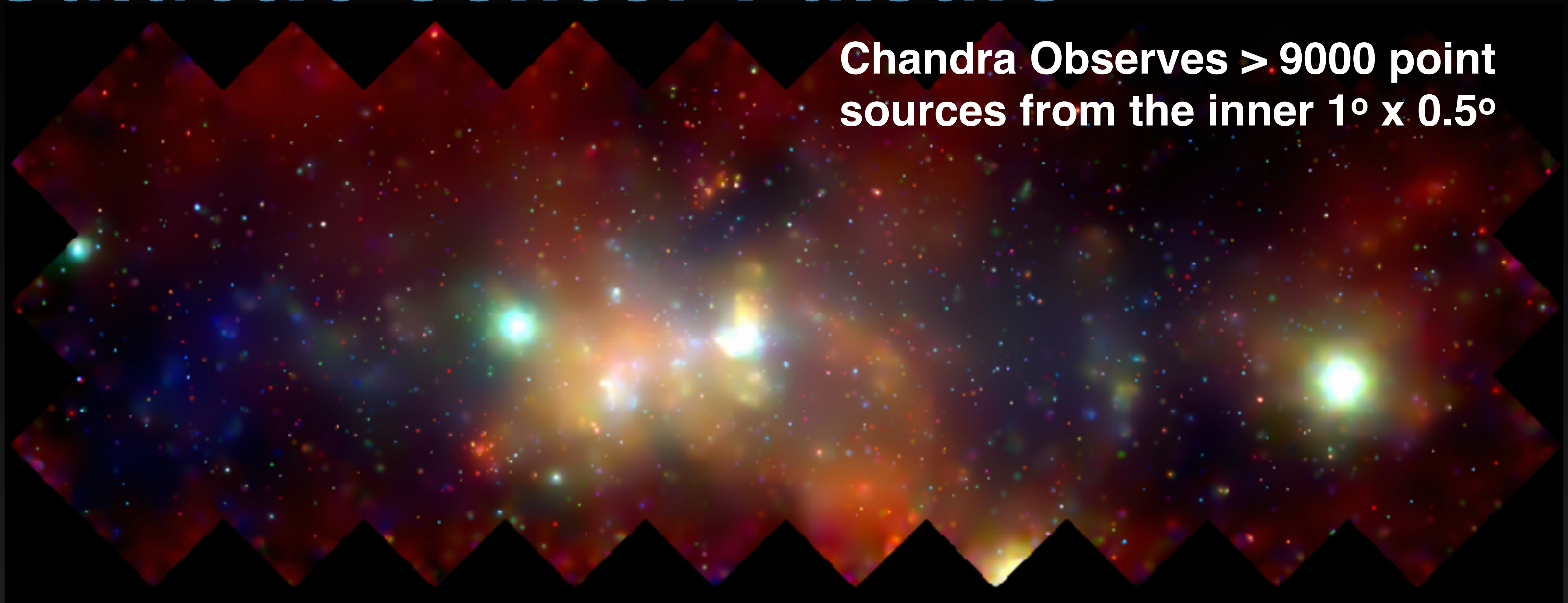
Multiwavelength observations indicate that the Galactic Center is a dense star-forming environment.

3-20% of the total Galactic Star Formation 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)



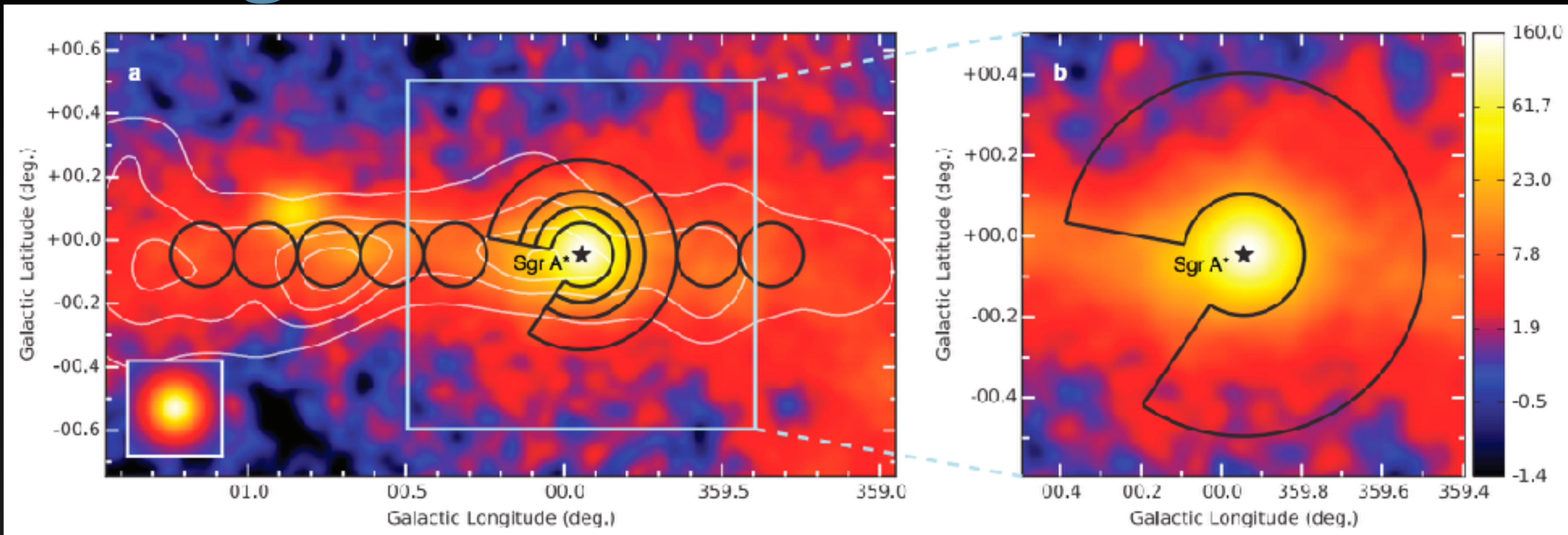
Galactic Center Pulsars



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, $\sim 10^{49}$ erg of energy our released, primarily in the form of relativistic e^+e^- pairs.

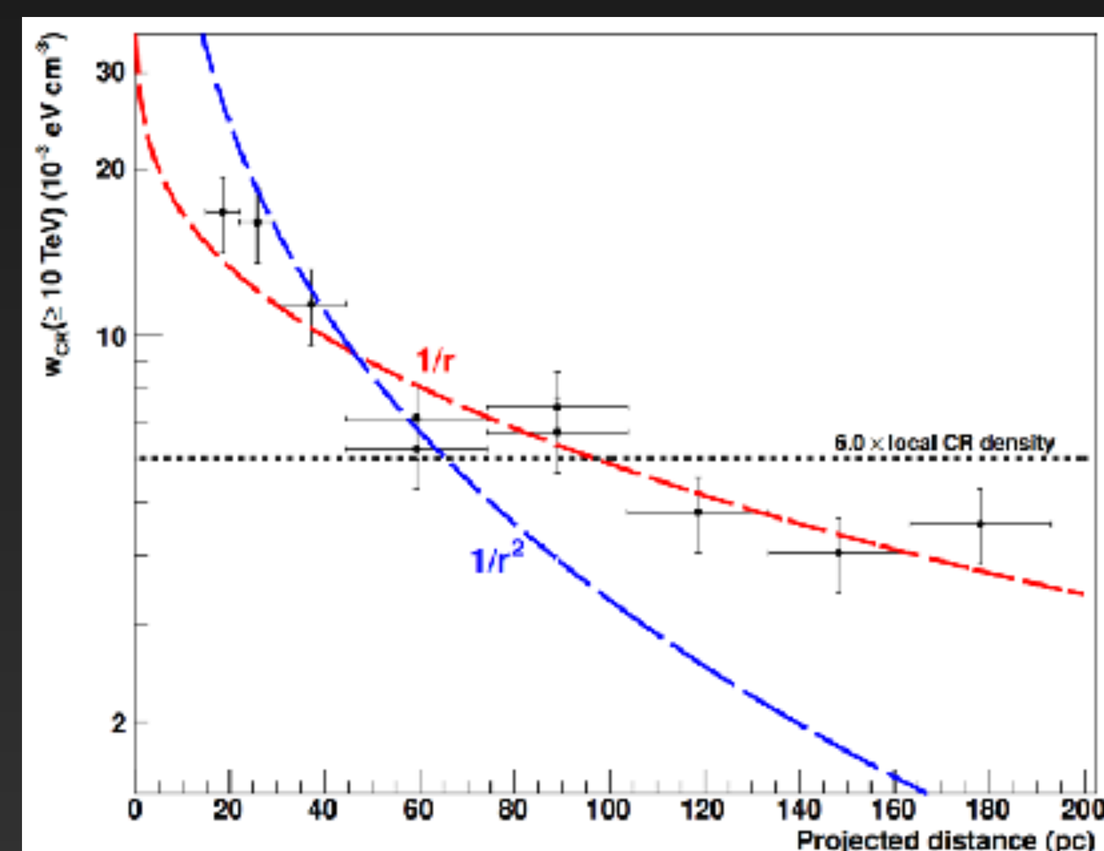
The Sgr A* Source



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

This is not observed in even the youngest supernova remnants.

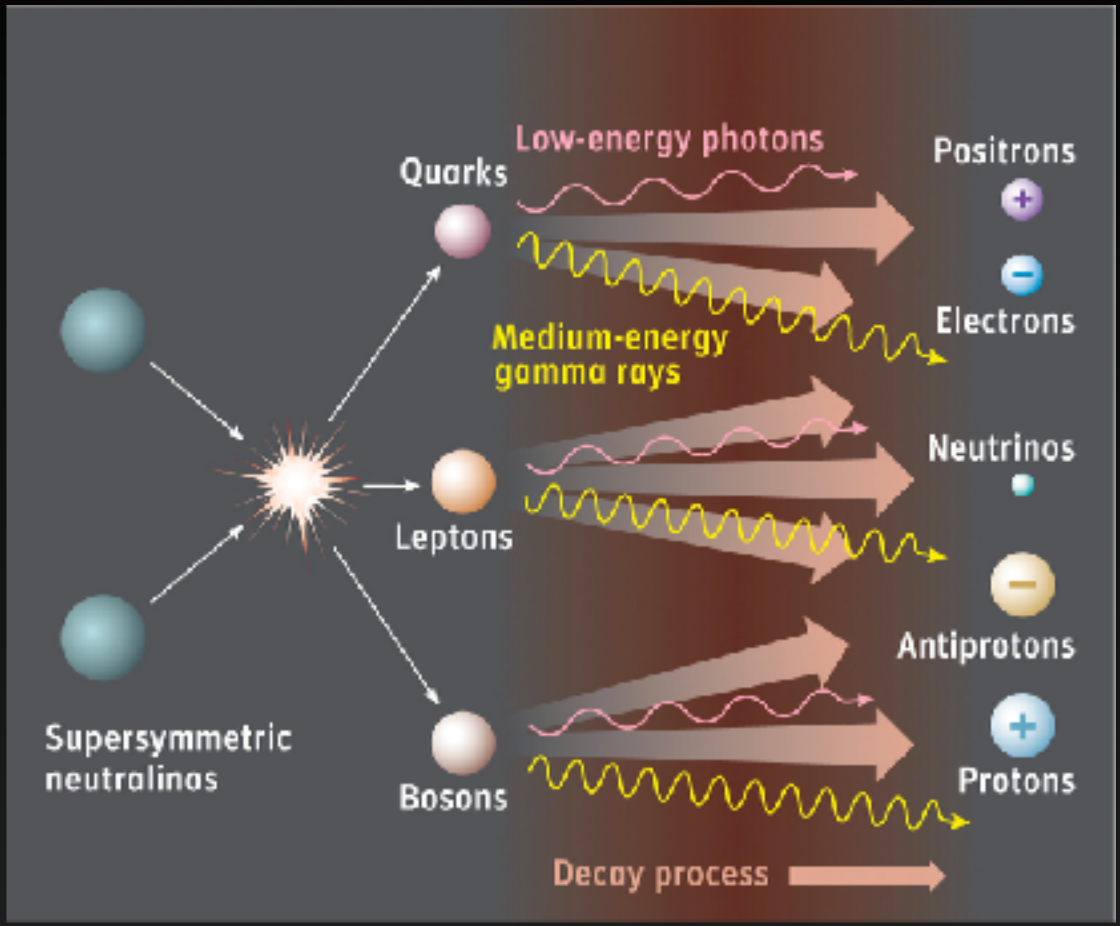
The emission profile is indicative of diffusion from the central BH.

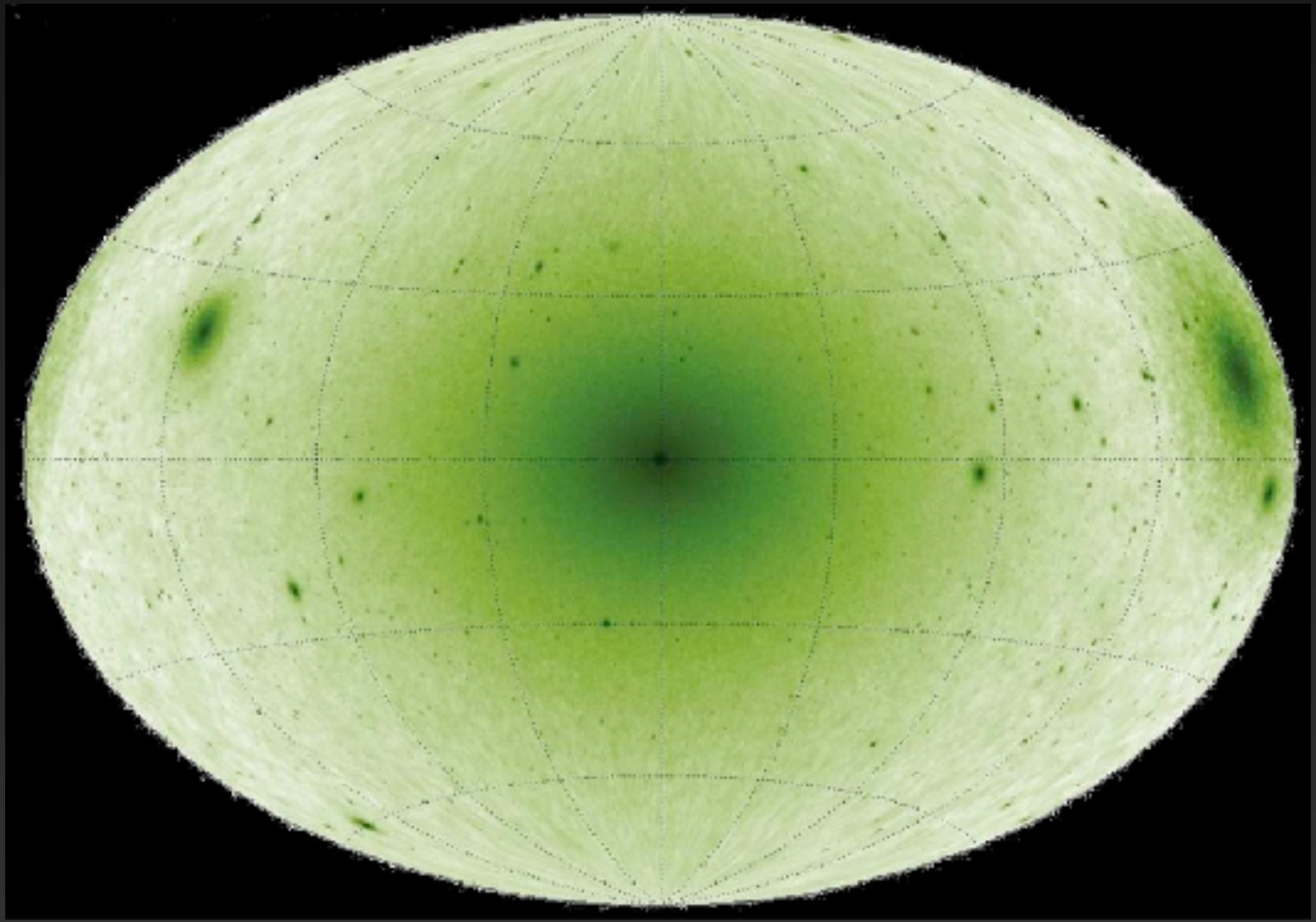


Dark Matter Annihilation in the Galactic Center

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.

Fitting the Gamma-Ray Luminosity

Total Gamma-Ray Flux (>1 GeV) in inner 1° is 1.1×10^{-9} erg cm^{2} s^{-1}

Approximately half of this emission is produced along the line of sight towards the GC, and thus we approximate the total gamma-ray luminosity of the central one degree to be 5×10^{36} erg s^{-1}

Supernovae:

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

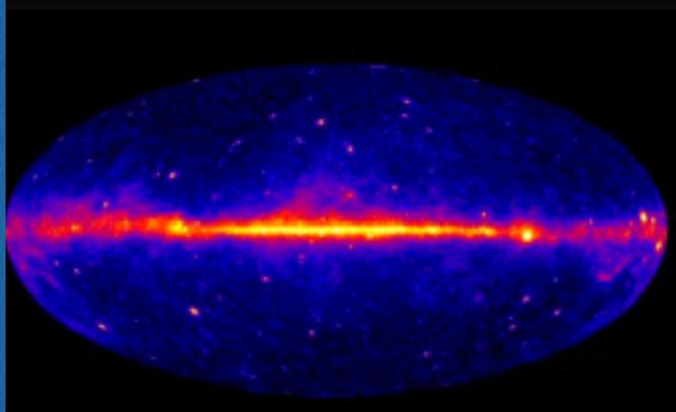
~10% to CR protons.

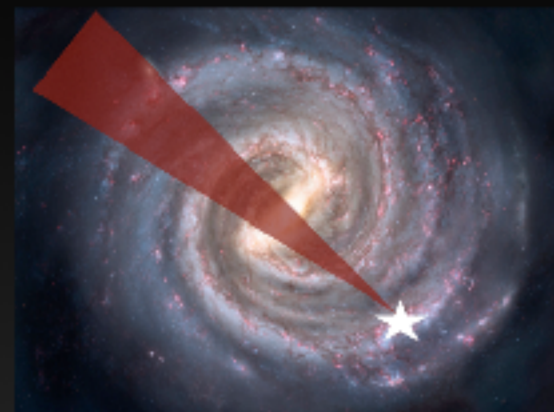
Assuming 1 Galactic center SN every 250 years (10% the Galactic Rate), this provides an energy flux of 1.3×10^{40} erg s^{-1}.

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

$$6.7 \times 10^{37} \text{ erg s}^{-1}$$ ✔

Fitting the Gamma-Ray Luminosity





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Sgr A*:

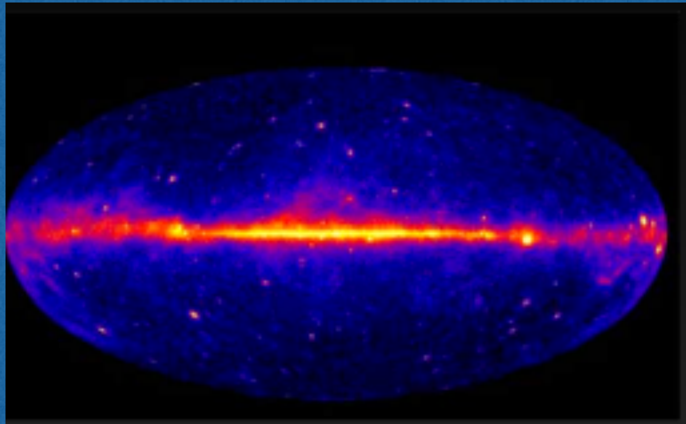
A tidal disruption event releases ~10^{45} erg s^{-1} for a period of ~0.2 yr.

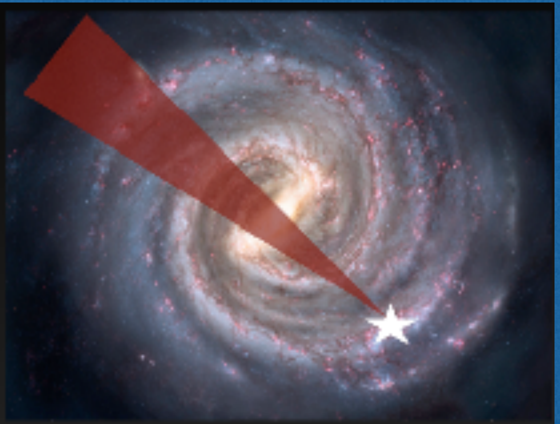
Sgr A* is expected to produce a tidal disruption event every ~10^5 yr, producing a time-averaged energy output of 2×10^{39} erg s^{-1}.

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:

$$8.0 \times 10^{37} \text{ erg s}^{-1} \quad ✔$$

Fitting the Gamma-Ray Luminosity





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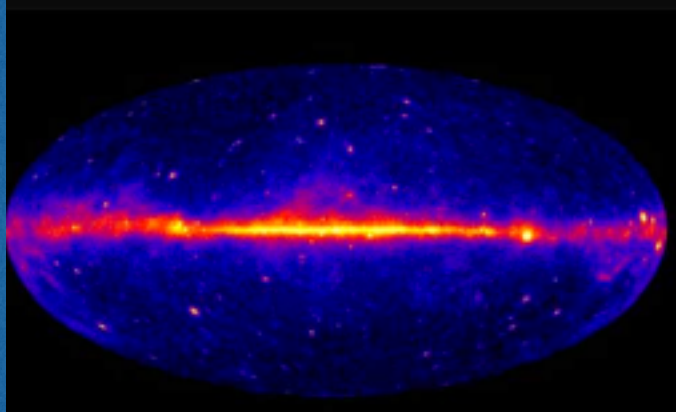
Pulsars

MSPs observed in the galactic field are fit by a population with a mean gamma-ray luminosity 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 x 10^7 $M_\odot$). For the 1 x 10^9 $M_\odot$ of stars formed in the inner degree of the Milky Way, we get:

$$7.7 \times 10^{37} \text{ erg s}^{-1}$$ ✔

Fitting the Gamma-Ray Luminosity



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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.

The dark matter annihilation rate is 8.6×10^{38} ann s^{-1}, which produces a gamma-ray flux of:

6.9×10^{36} erg s^{-1} ✔

Part I:
What can produce the luminosity of the emission at the Galactic Center?

Answer: Basically everything

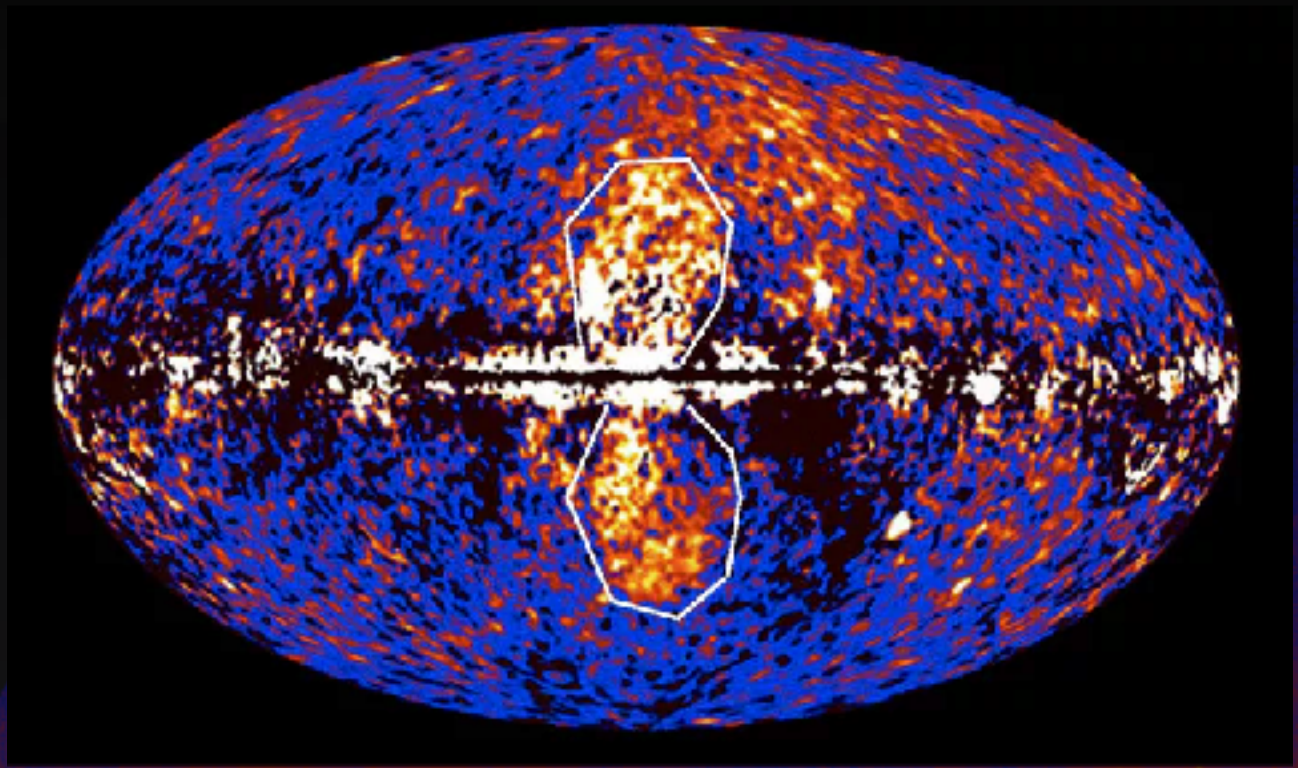
Conclusion:
Every Model is Correct

Part IIa:
Modeling the Morphology and Spectrum of the Galactic Center Gamma-Ray Excess

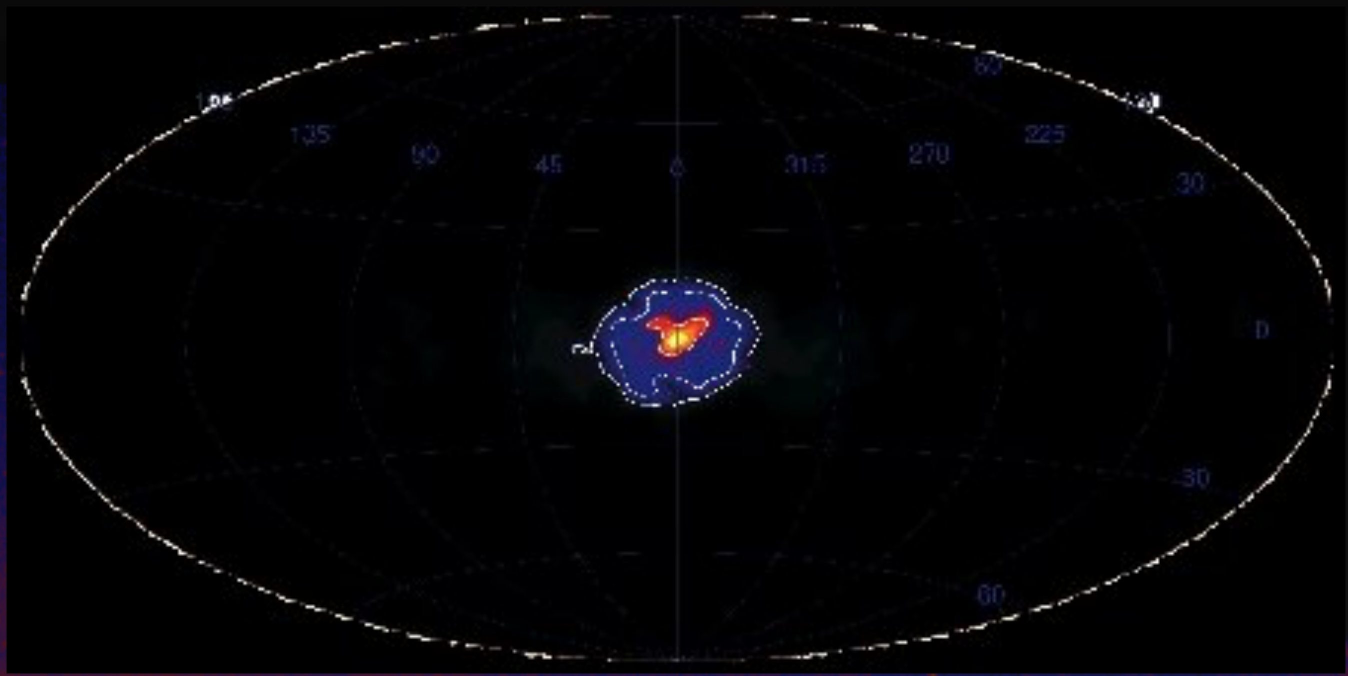
1.) Hard Gamma-Ray Spectrum peaking at ~2 GeV
2.) Spherically Symmetric Emission Morphology
3.) Extension to >10° from the GC.

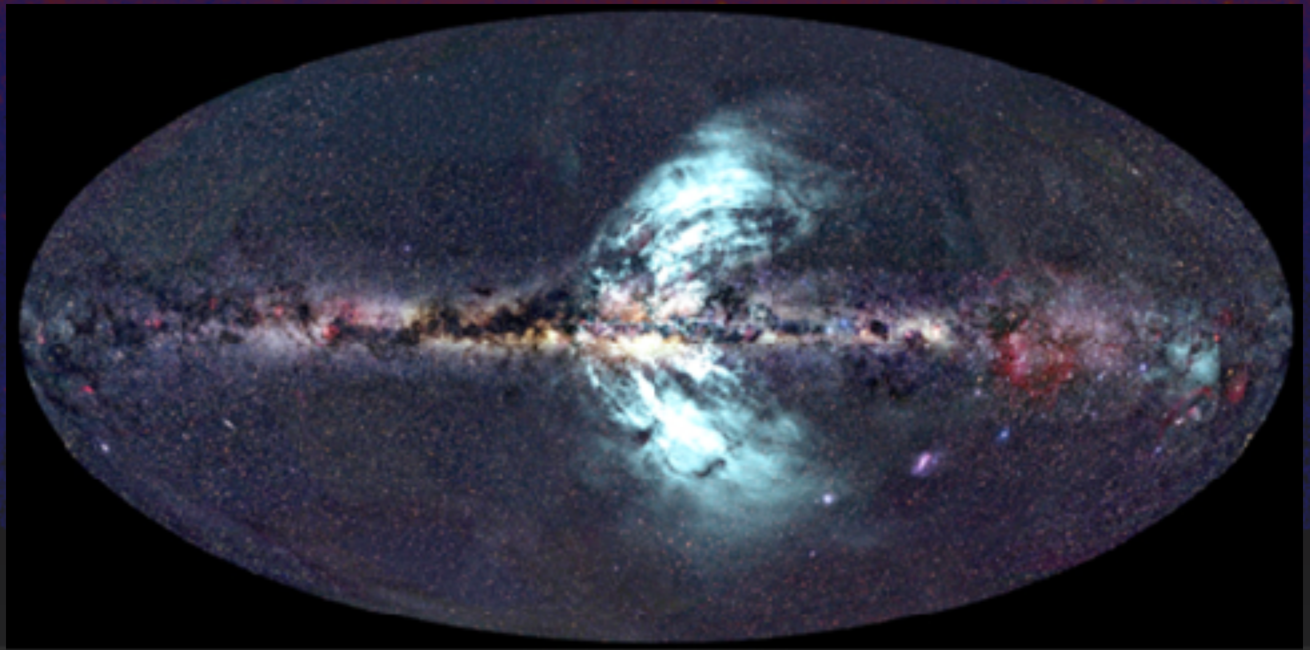
Morphology of Galactic Center Emission

Fermi Bubbles



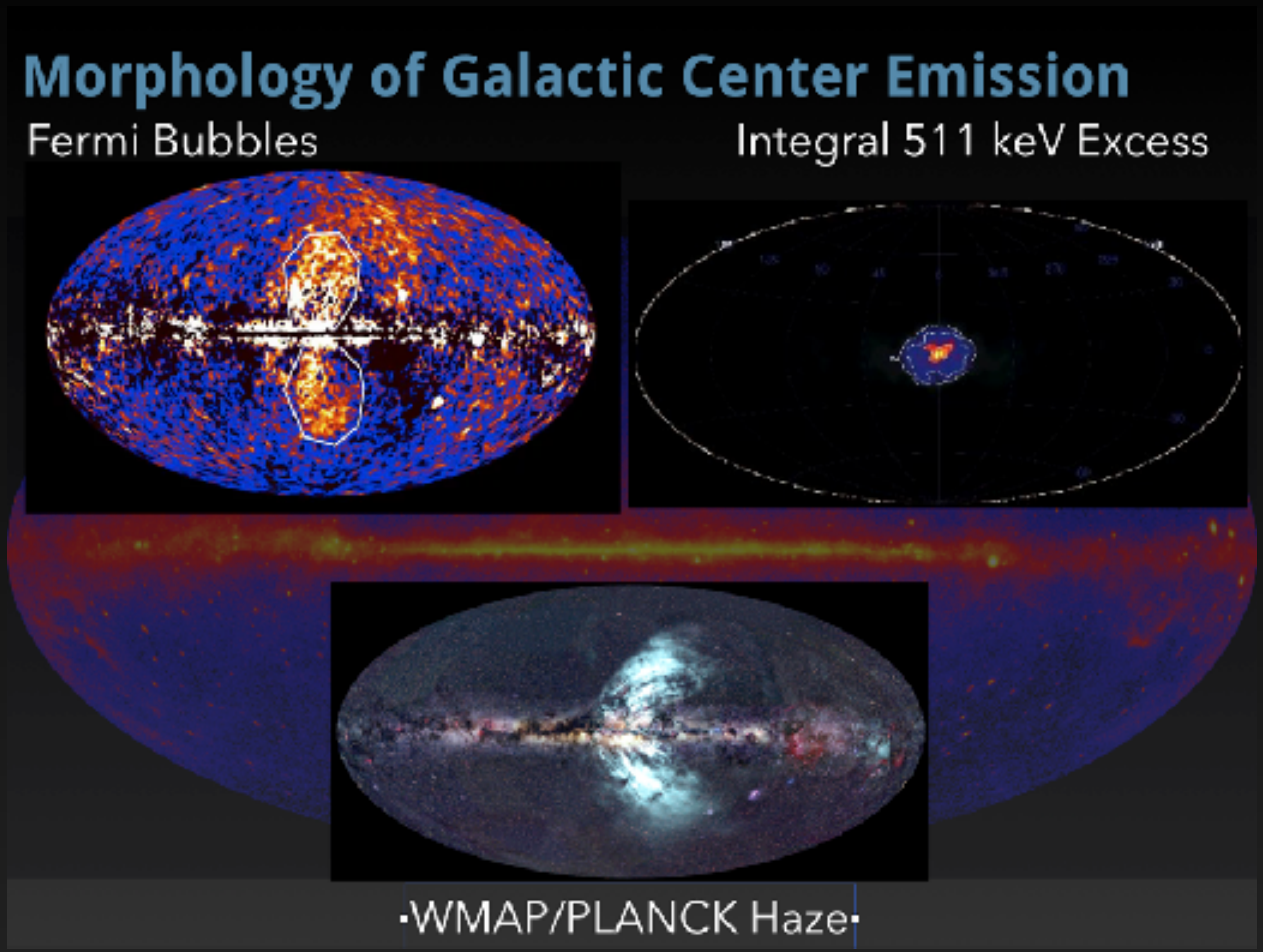
Integral 511 keV Excess





WMAP/PLANCK Haze

Morphology of Galactic Center Emission

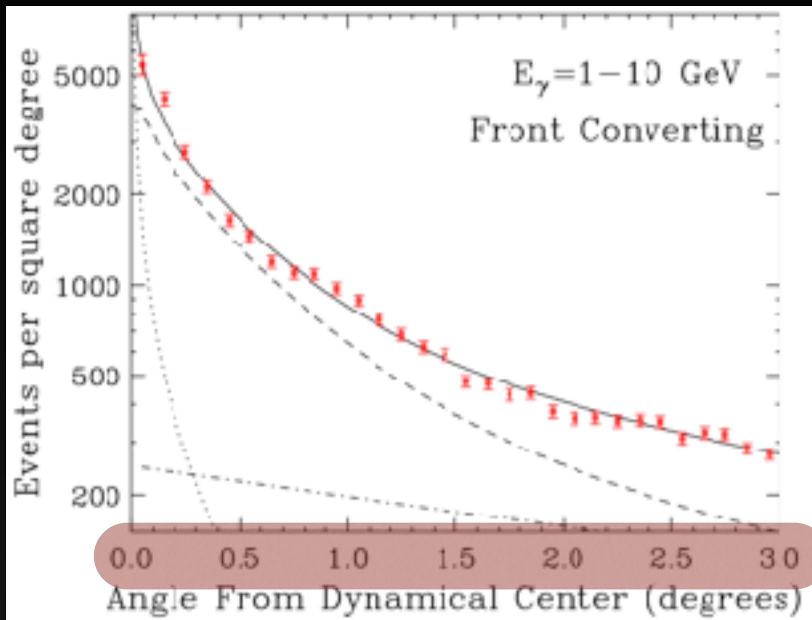


The photon excesses extend very far from the central molecular region!

This:

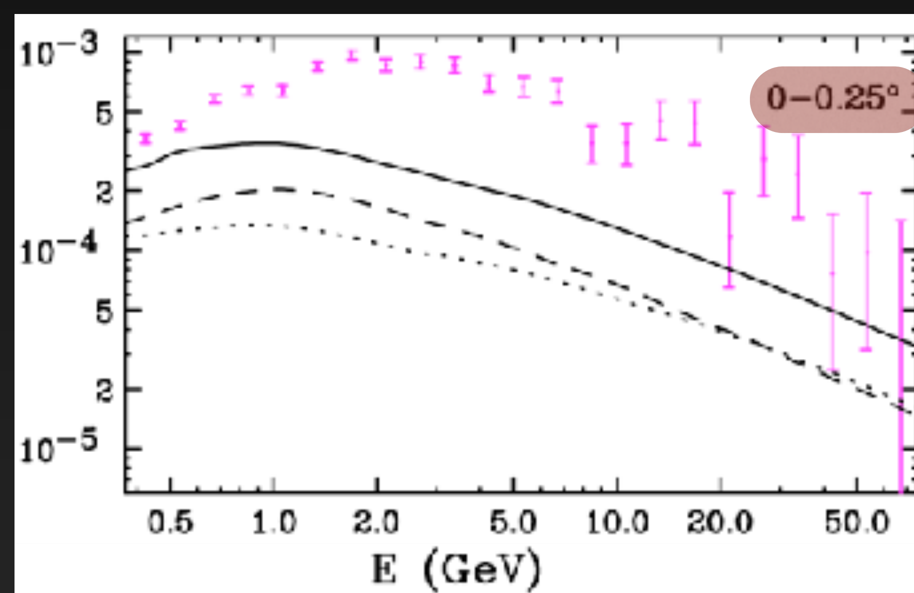
(a) Indicates the relative power of Galactic center accelerators, compared to the Galactic plane.
(b) Provides a large field of view for studies of GC emission.
(c) Implies that propagation is important!

Early Analyses of the Galactic Center Excess



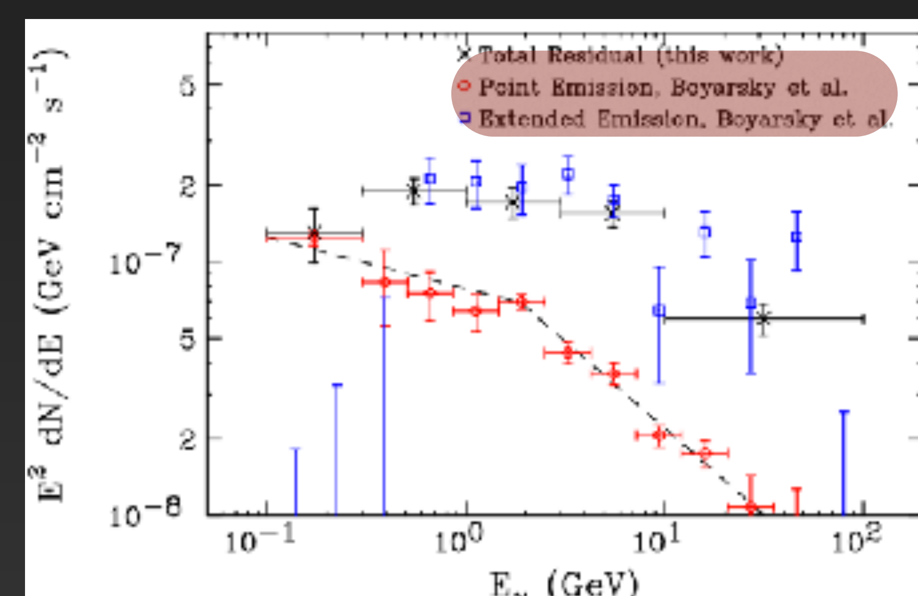
Goodenough & Hooper (2009)

Early analyses of the Galactic center focused on emission within ~2° of the Galactic center.



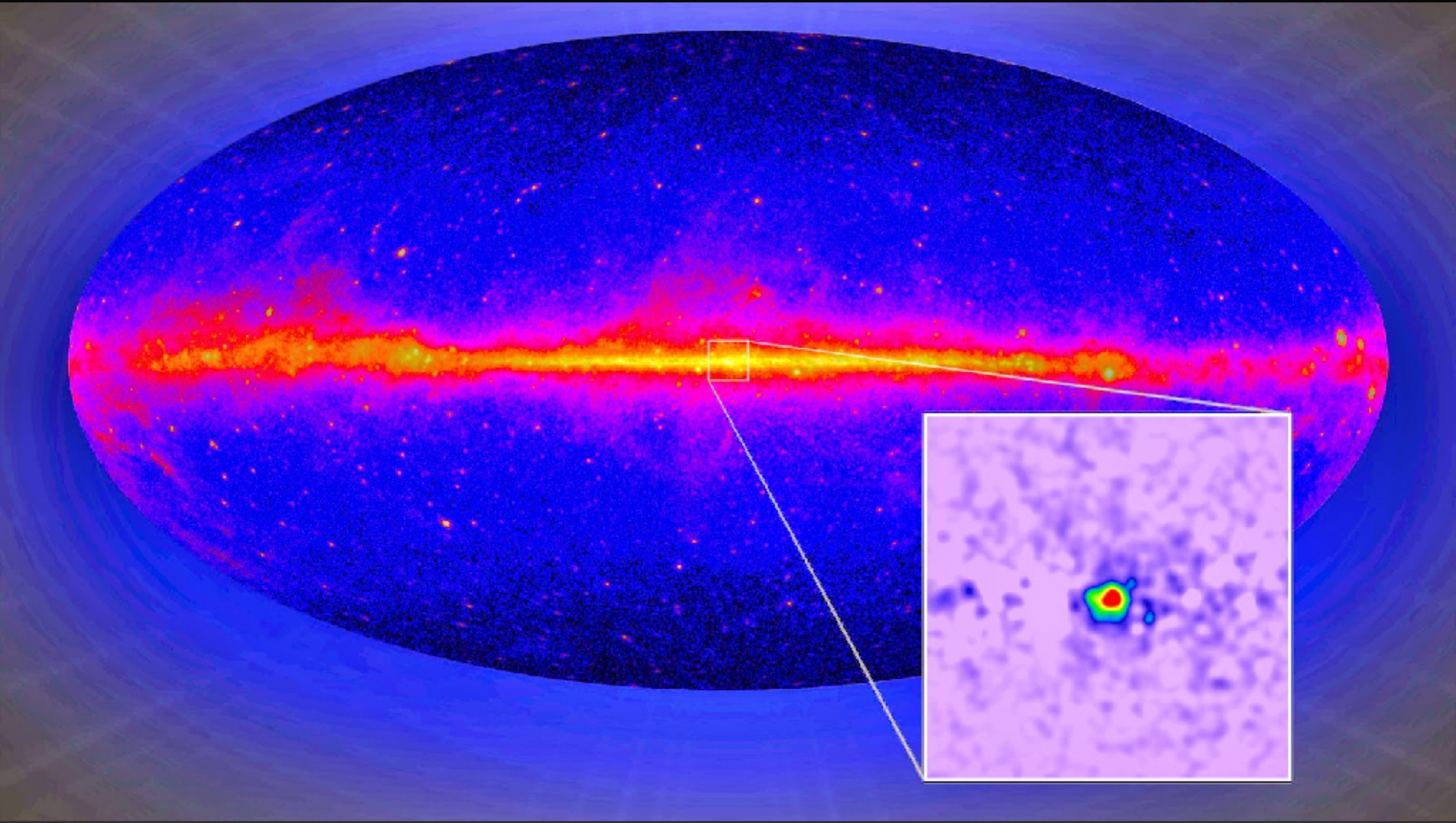
Hooper & Goodenough (2010)

Hooper & Linden (2011)

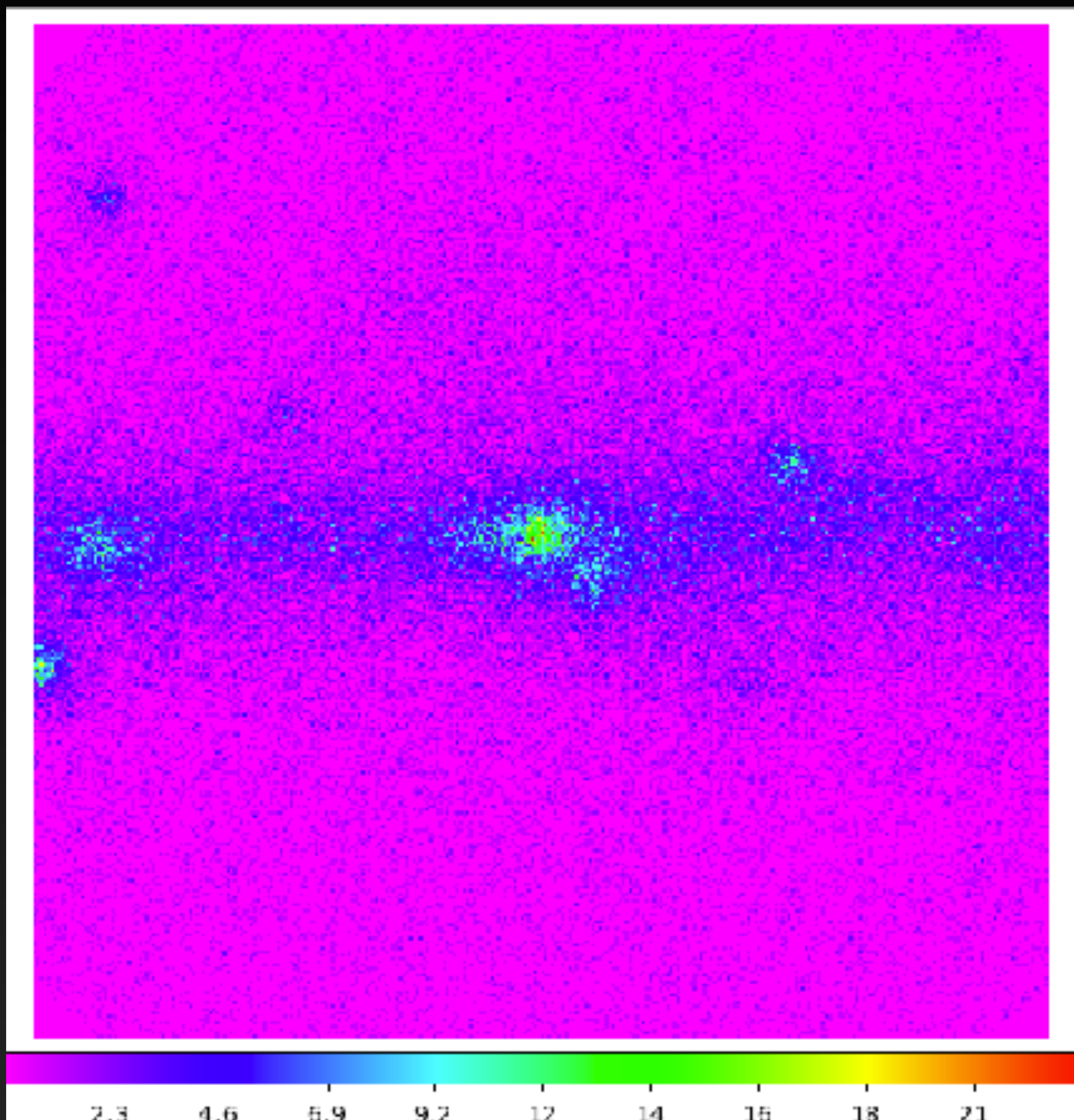


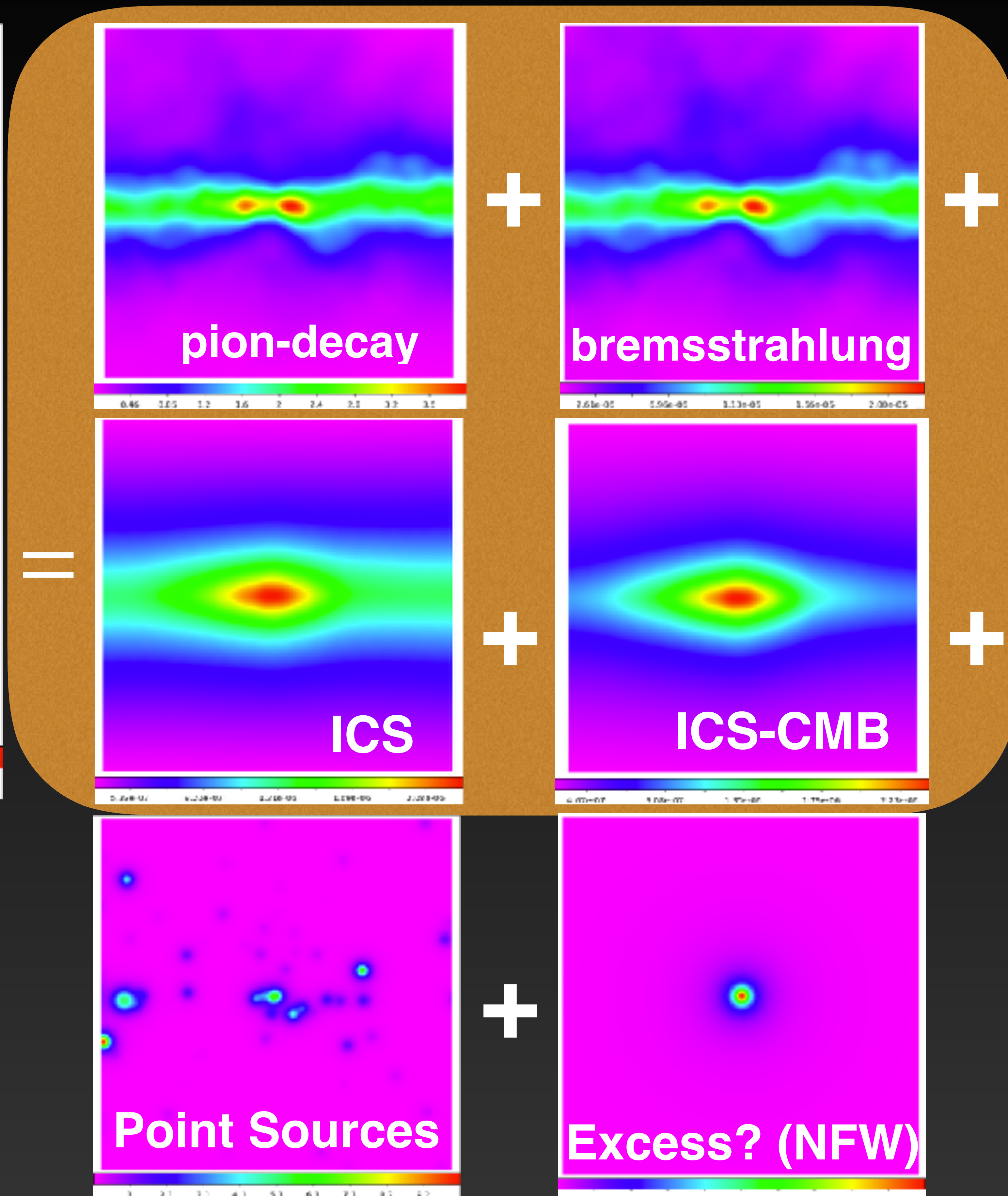
Only pronounced spectral feature was a bump at ~3 GeV.

A More Detailed Fermi-LAT Analysis



Modeling the Galactic Center





Data

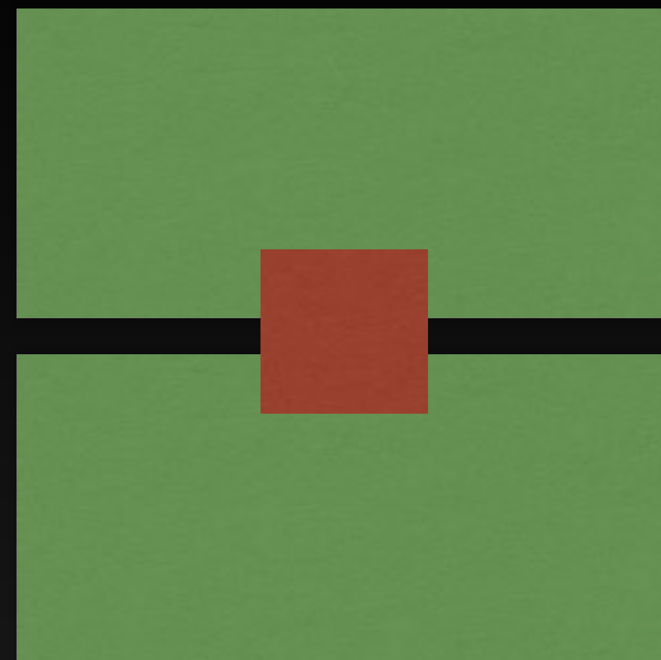
750 — 950 MeV

Best Angular Resolution Cut

10º x 10º ROI

$$\mathcal{L} = \prod_k \frac{m_k^{n_k} e^{-m_k}}{n_k!}$$

Two Analyses of the Gamma-Ray Excess



INNER GALAXY

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

GALACTIC CENTER

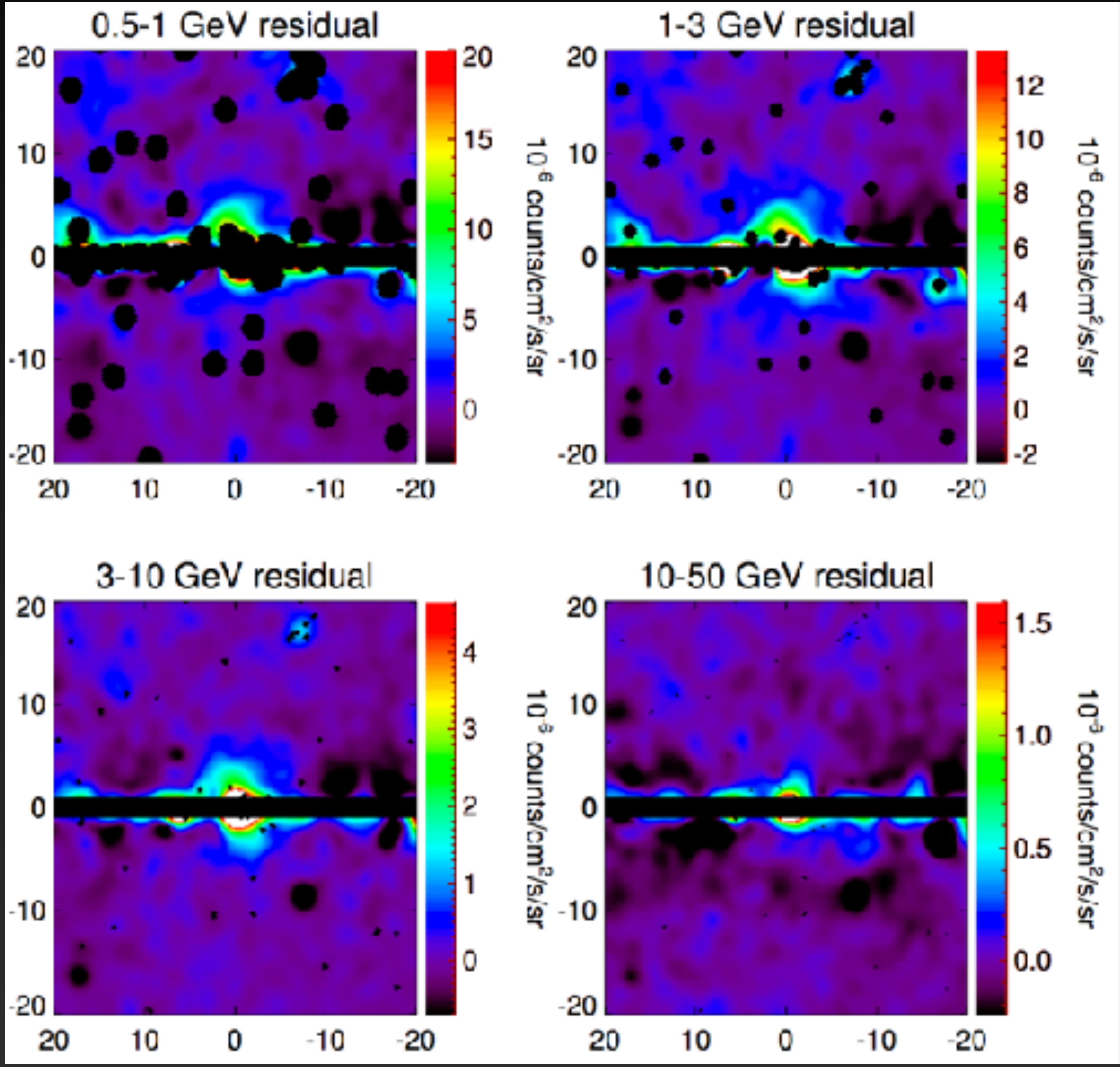
- Box around the GC (15° x 15°)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source
- Bright Signal

The Galactic Center Excess

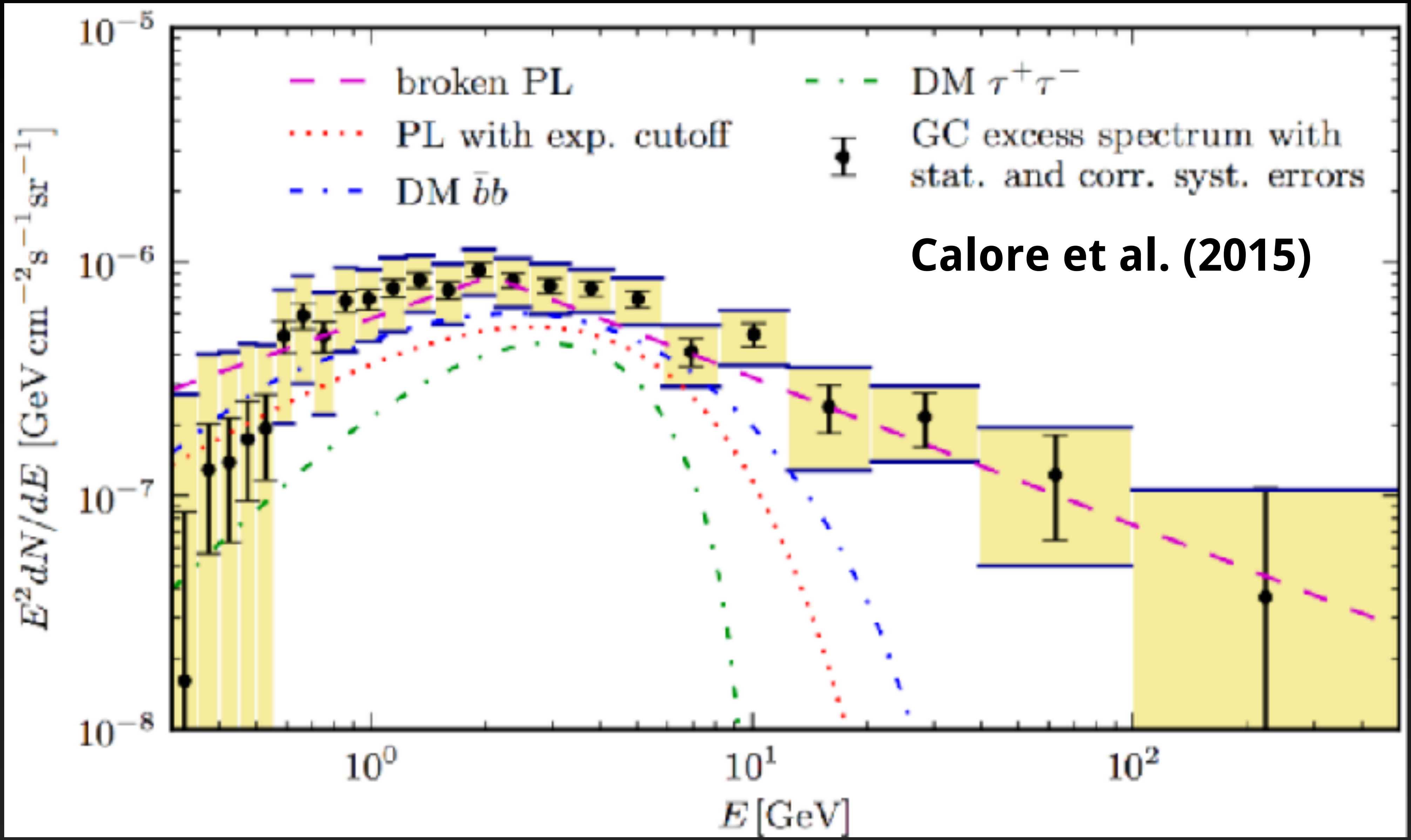
Utilizing different models for removing astrophysical and point source foregrounds. Multiple studies have consistently observed a gamma-ray excess.

Goodenough & Hooper (2009, 0910.2998)
Hooper & Goodenough (2010, 1010.2752)
Hooper & Linden (2011, 1110.0006)
Abazajian & Kaplinghat (2012, 1207.6047)
Gordon & Macias (2013, 1306.5725)
Gordon & Macias (2013, 1312.6671)
Abazajian et al. (2014, 1402.4090)
Daylan et al. (2014, 1402.6703)
Calore et al. (2014, 1409.0042)
Abazajian et al. (2014, 1410.6168)
Bartels et al. (2015, 1506.05104)
Lee et al. (2015, 1506.05124)
Gaggero et al. (2015, 1507.06129)
Carlson et al. (2015, 1510.04698)
The Fermi-LAT Collaboration (2015, 1511.02938)
Yang & Aharonian (2016, 1602.06764)
Carlson et al. (2016, 1603.06584)
Linden et al. (2016, 1604.01026)
Horiuichi et al. (2016, 1604.01402)
Karwin et al. (2016, 1612.05687)
Ackermann et al. (2017, 1704.03910)

Daylan et al. (2014)



The Gamma-Ray Excess Spectrum

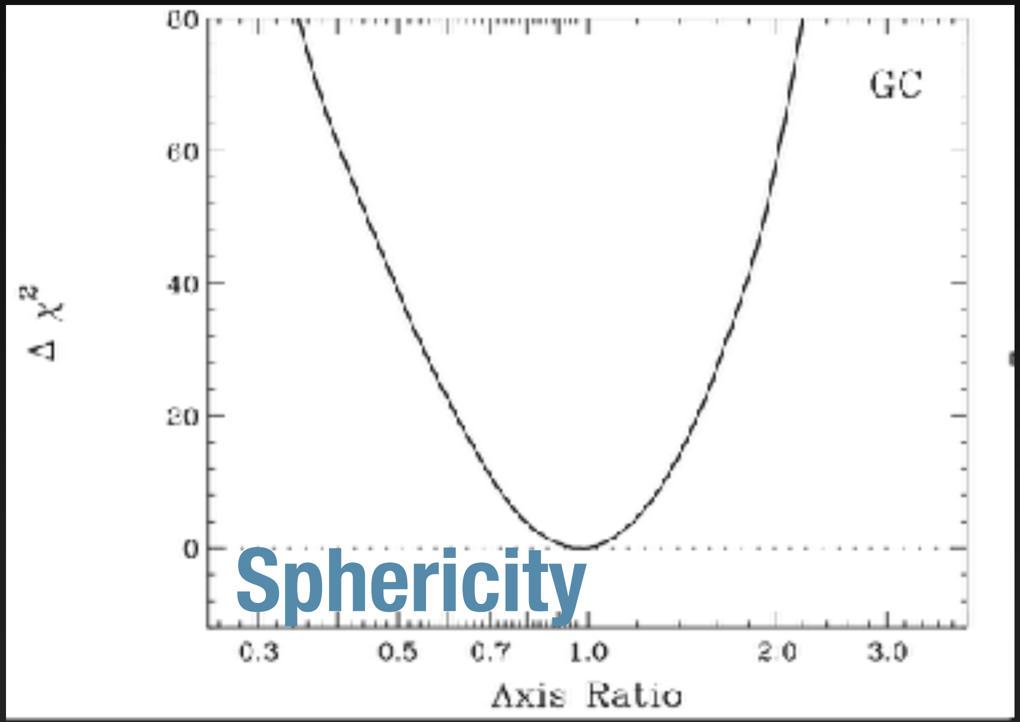


The excess has an unusual spectrum - highly peaked at an energy of ~2 GeV.

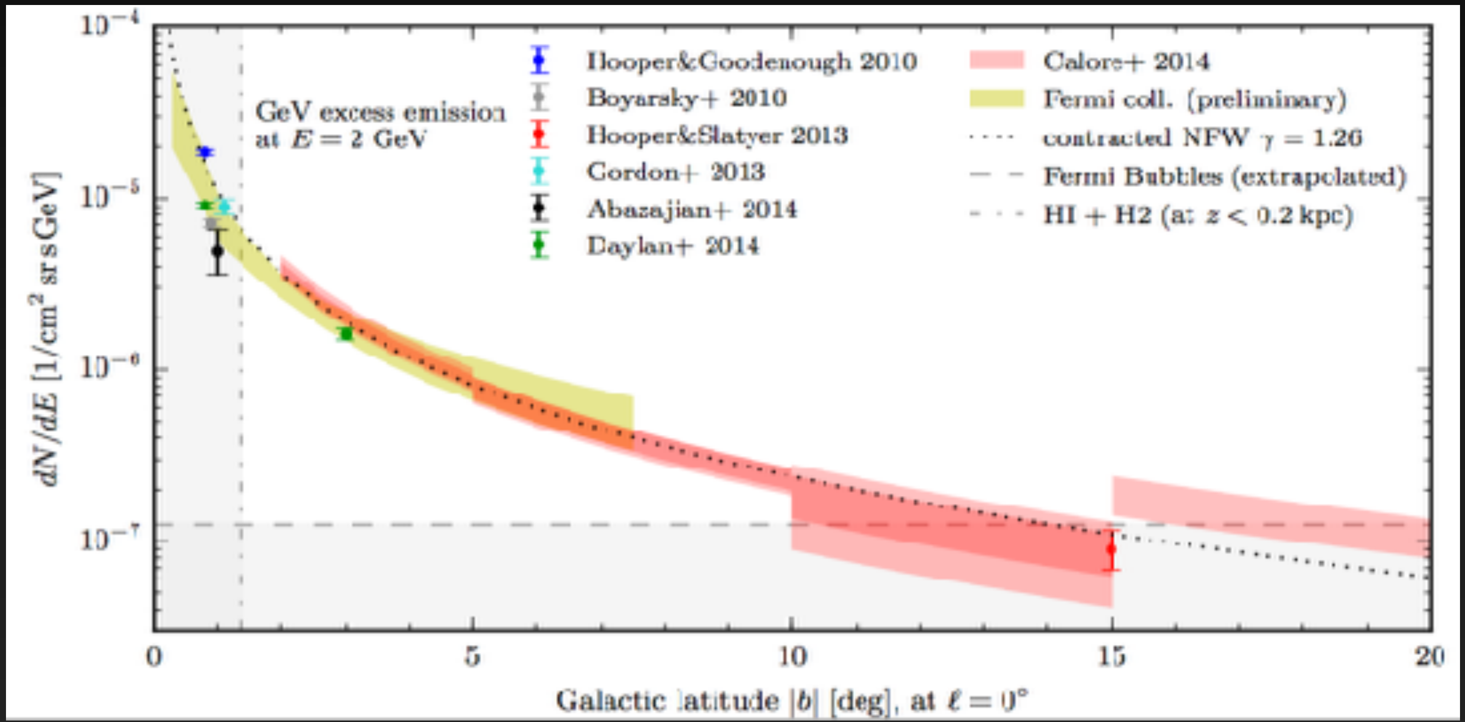
This spectrum is significantly harder than expected from astrophysical diffuse emission.

The Gamma-Ray Excess Morphology

Daylan et al. (2014)



Calore et al. (2014b)



The GeV excess spherically symmetric, and is statistically significant from 0.1° – 10° from the Galactic Center.

Observational Results Overview

These are the three resilient features of the GeV Excess:

1.) Hard Gamma-Ray Spectrum peaking at ~2 GeV

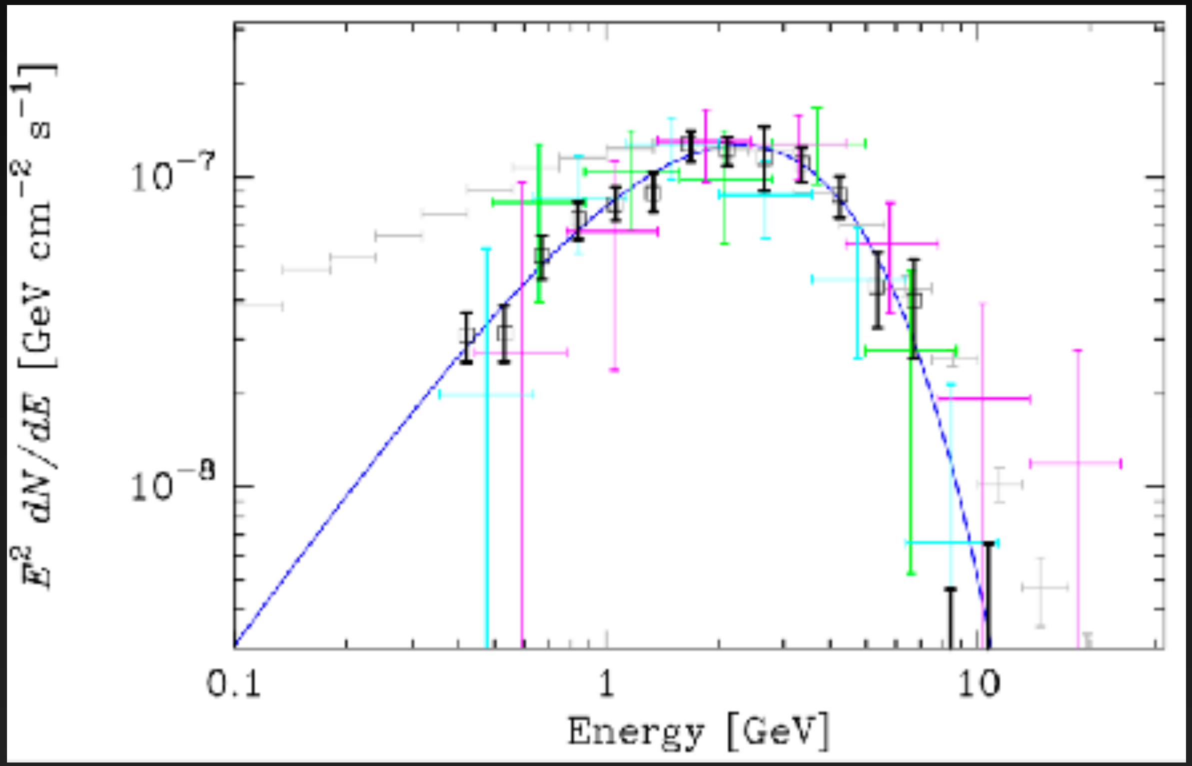
2.) Spherically Symmetric Emission Morphology

3.) Extension to >10° from the GC.

How Do Pulsars Match these Three Observables?

These are the three resilient features of the GeV Excess:

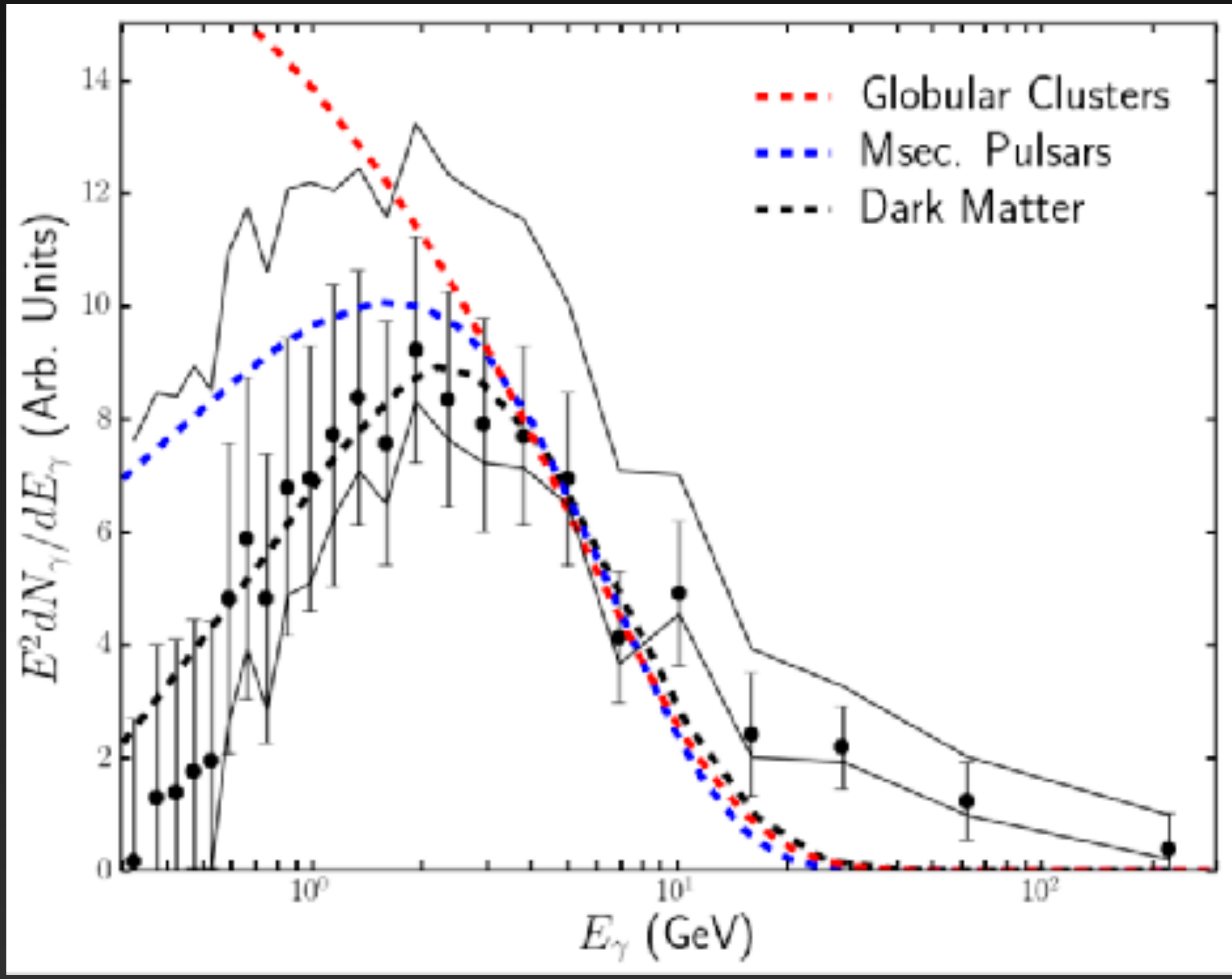
1.) Hard Gamma-Ray Spectrum peaking at ~2 GeV



Abazajian (2010)

Pulsars match the GCE spectral peak.

Fit of low-energy spectrum disputed.

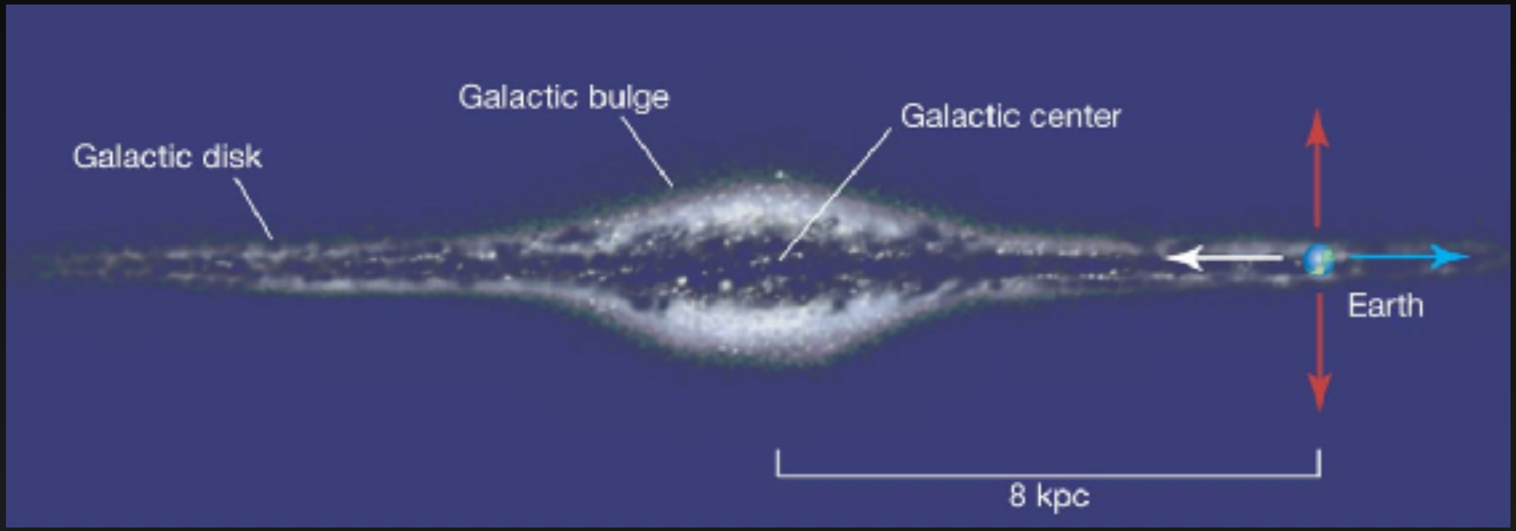


Cholis et al. (2014)

How Do Pulsars Match these Three Observables?

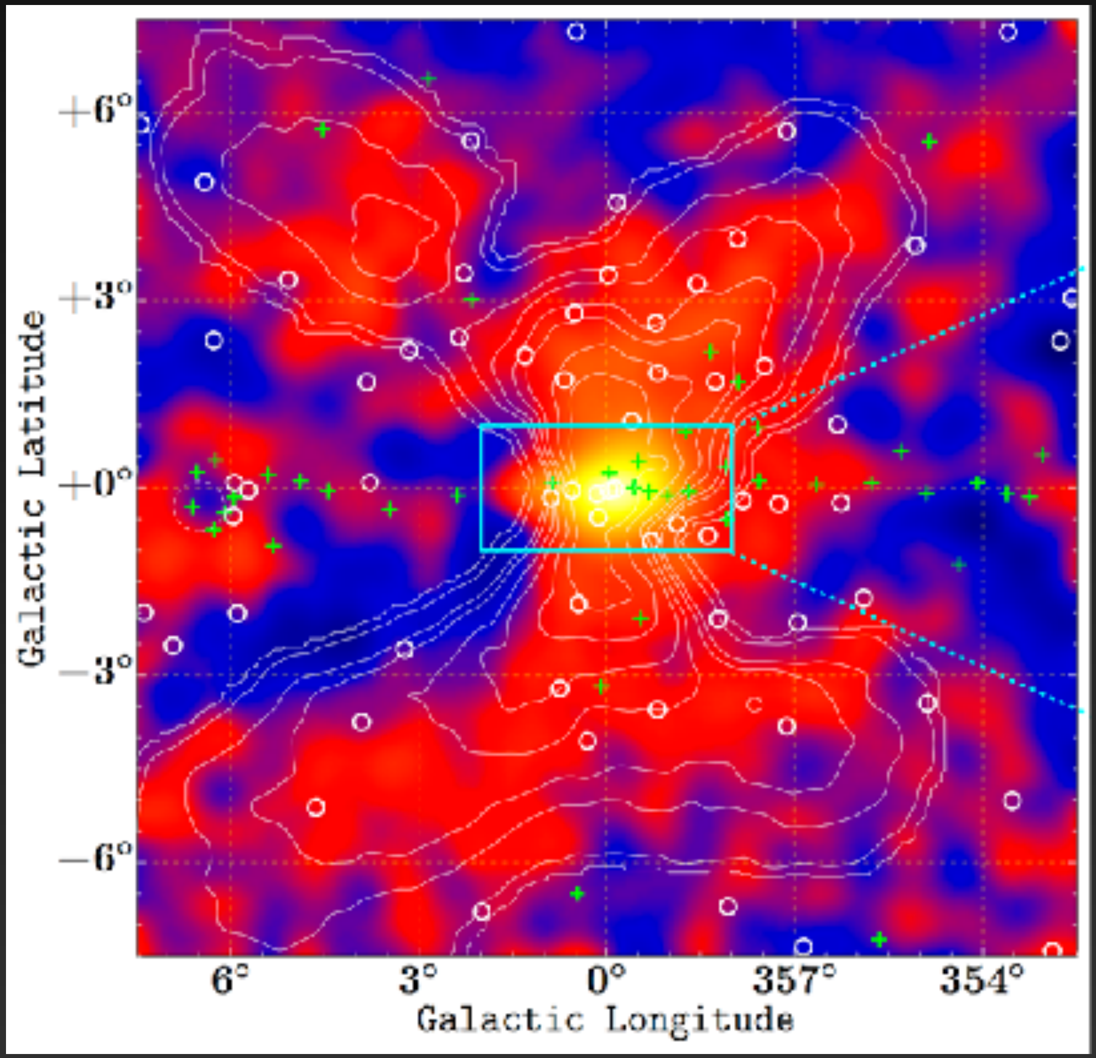
These are the three resilient features of the GeV Excess:

2.) Spherically Symmetric Emission Morphology



Pulsars in the Galactic bulge expected to have spherically symmetric morphology.

But could be X-shaped. Might be hard to distinguish.

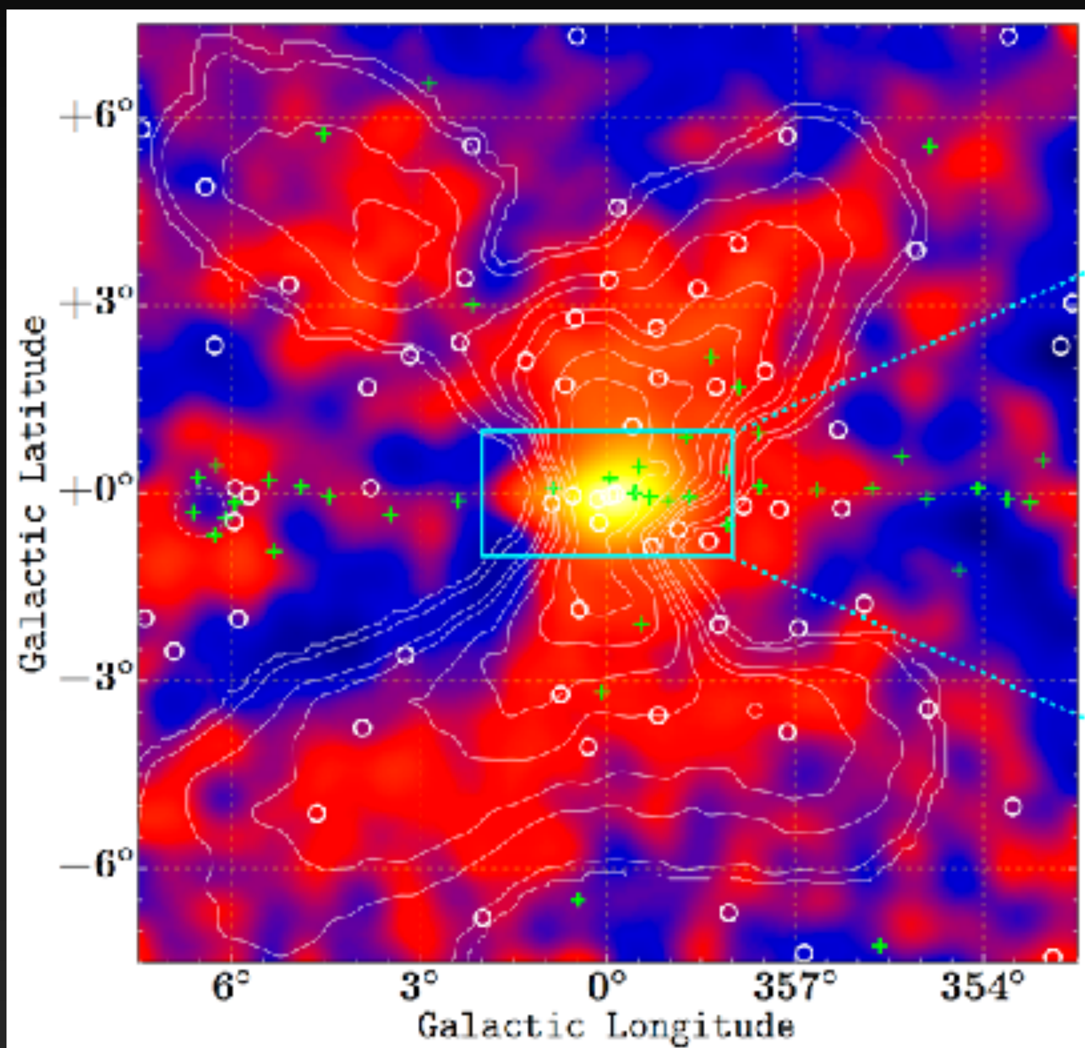


Macias et al. (2016)

How Do Pulsars Match these Three Observables?

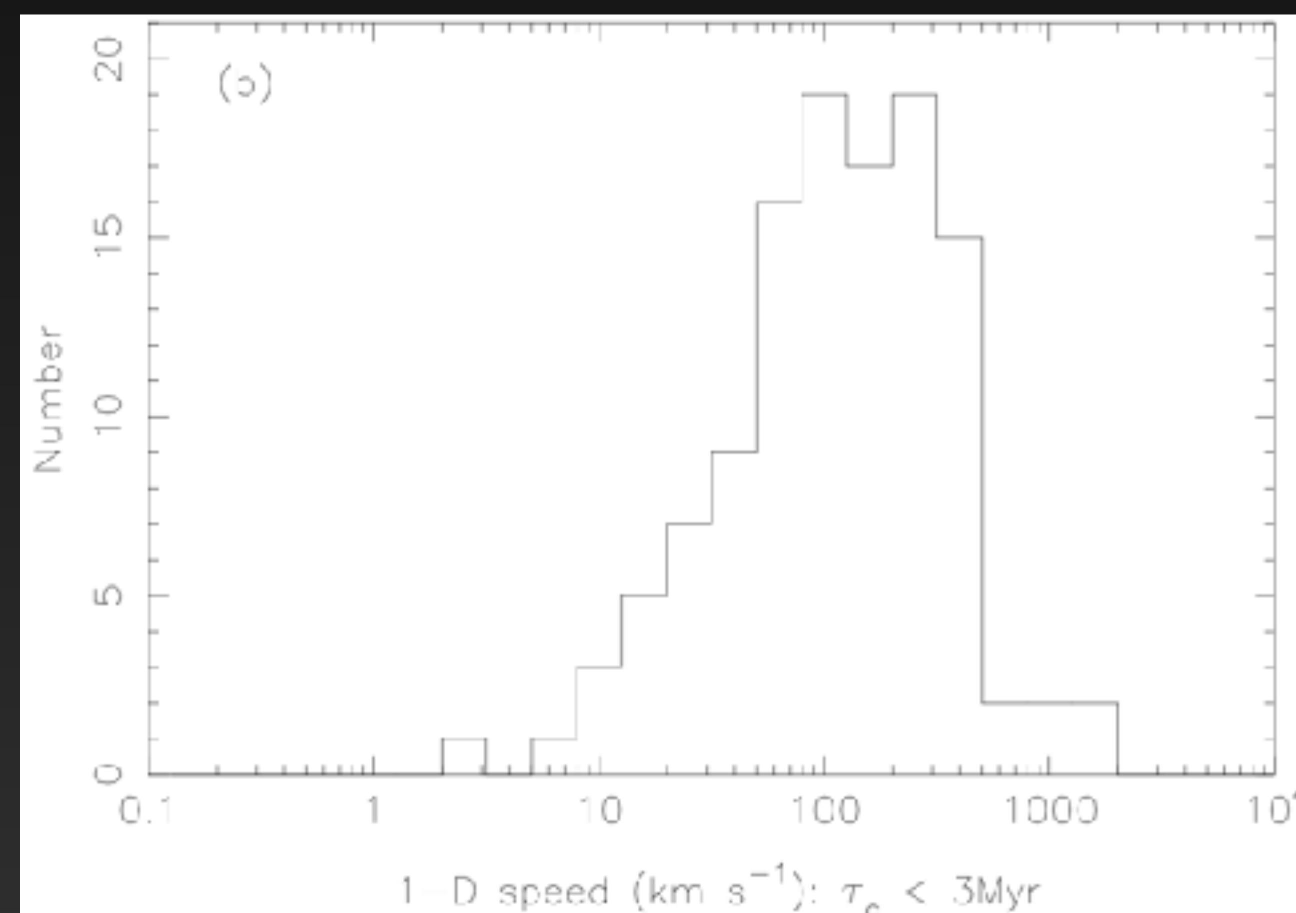
These are the three resilient features of the GeV Excess:

3.) Extension to >10° from the GC.



Macias et al. (2016)

Bulge does not extend out to 10°.

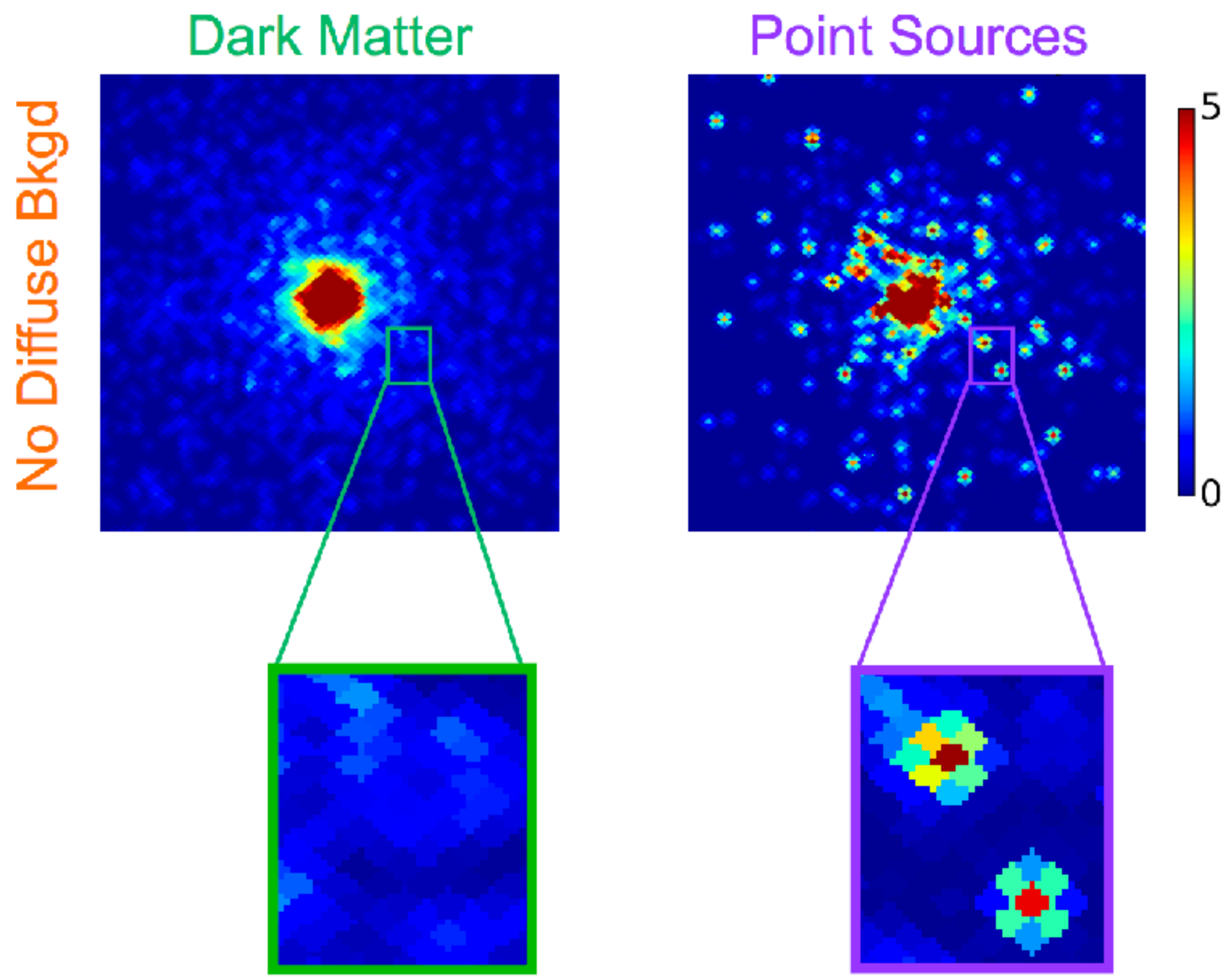


Hobbs et al. (2005)

But 10° signal is weak and pulsars get kicks

Part IIb:
Flux Variations in the Galactic Center Excess

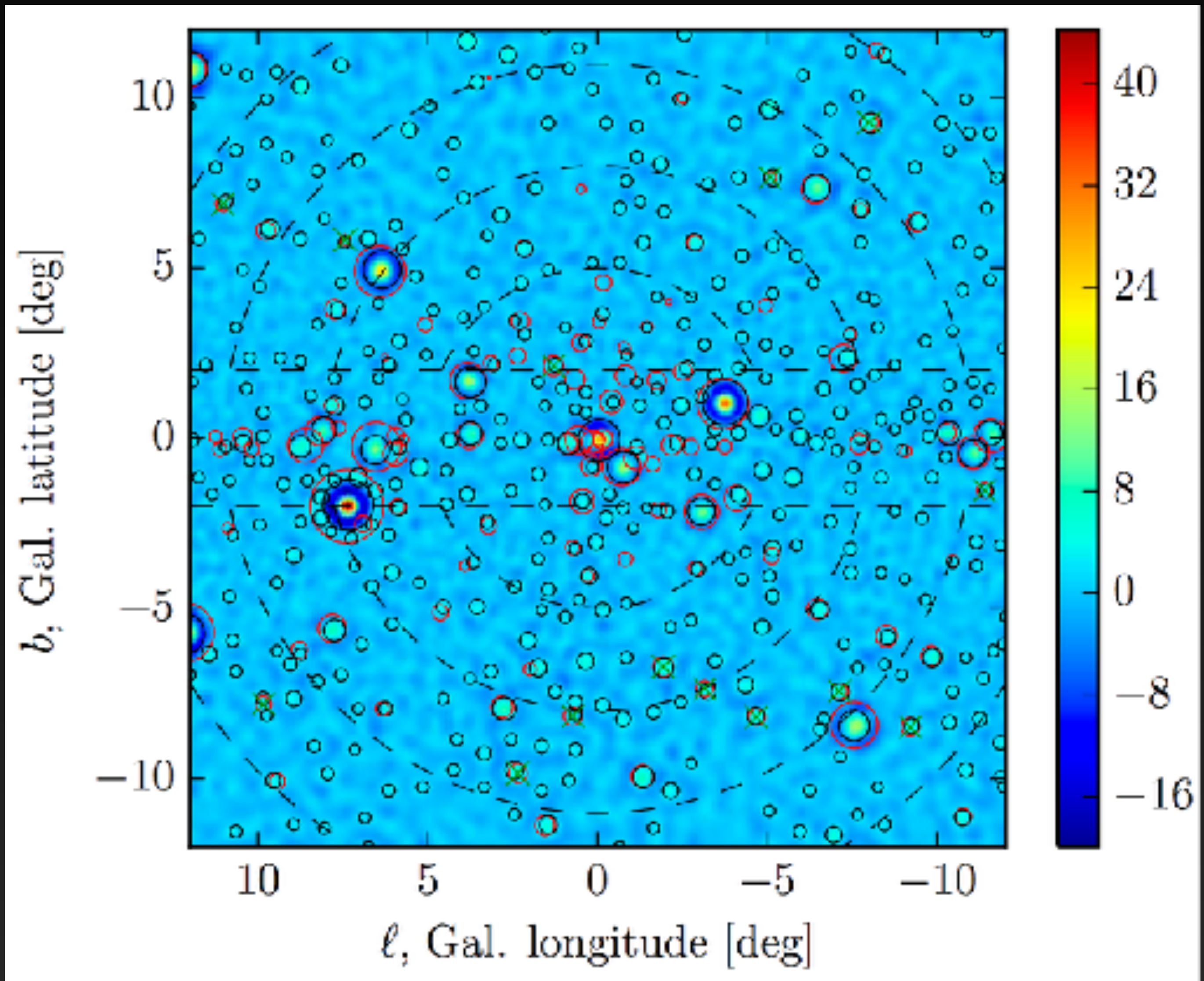
Looking for Flux Variations



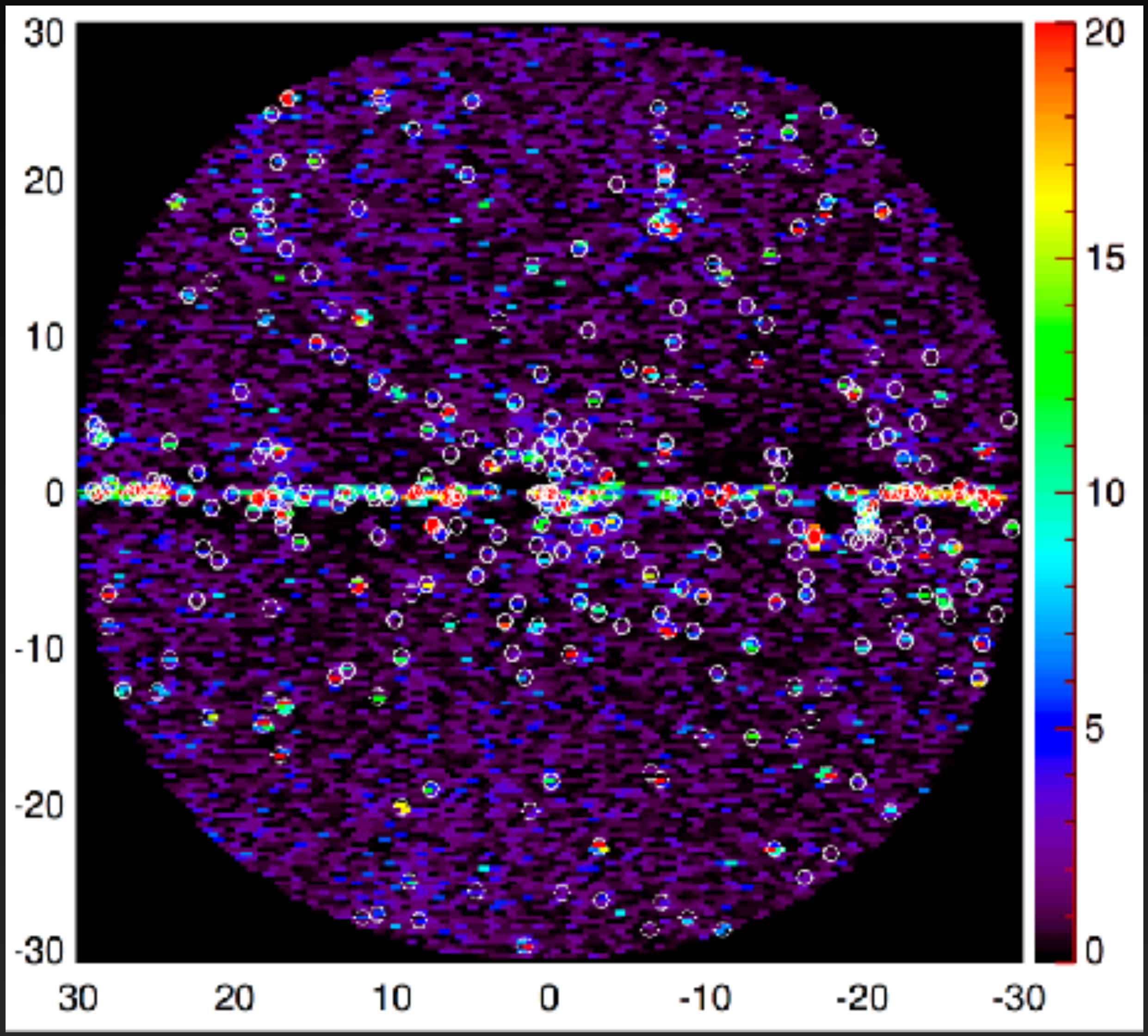
slide from Mariangela Lisanti

Wavelets and Non-Poissonian Template Fitting

Bartels et al. (2015)

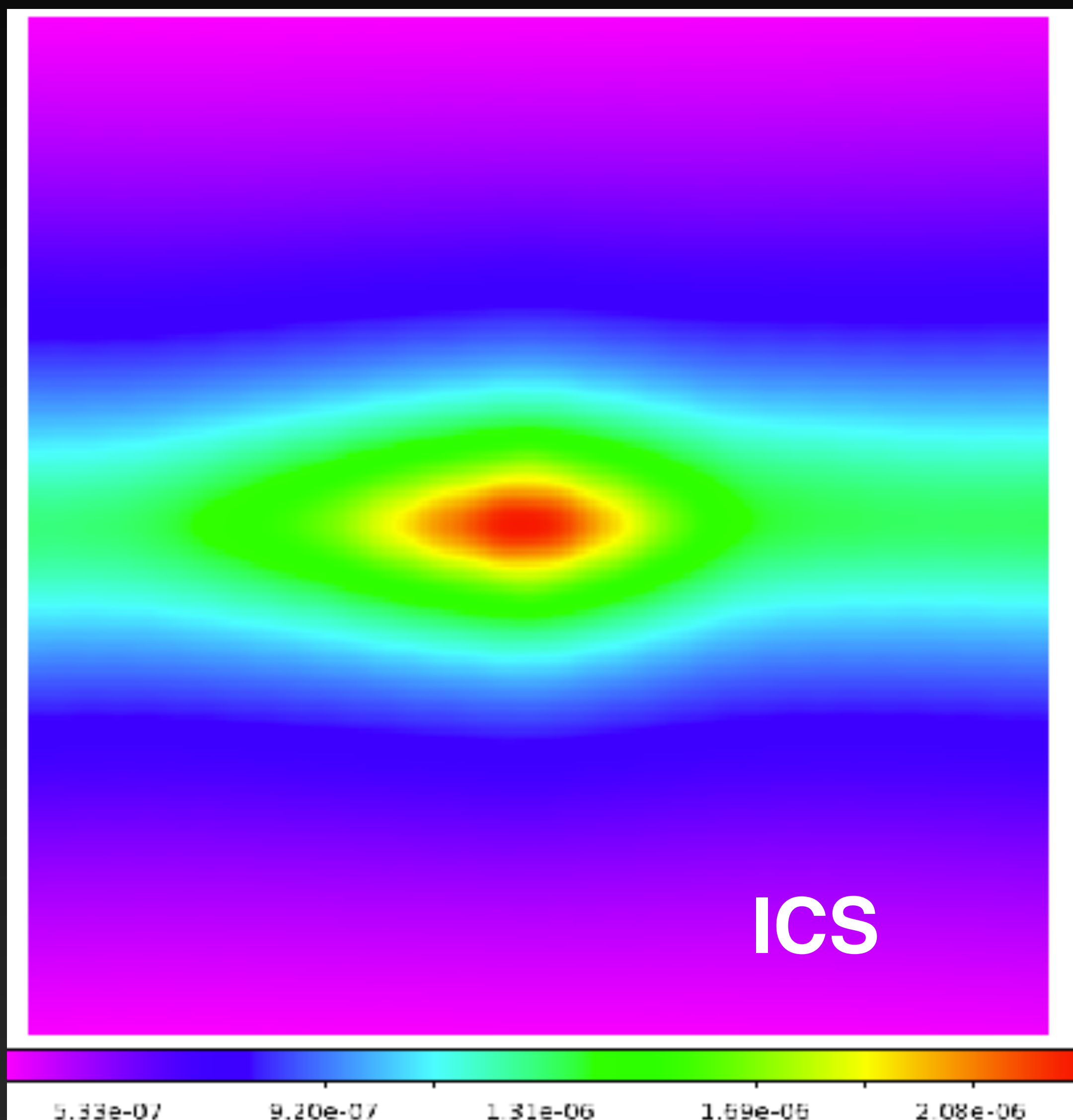


Lee et al. (2015)

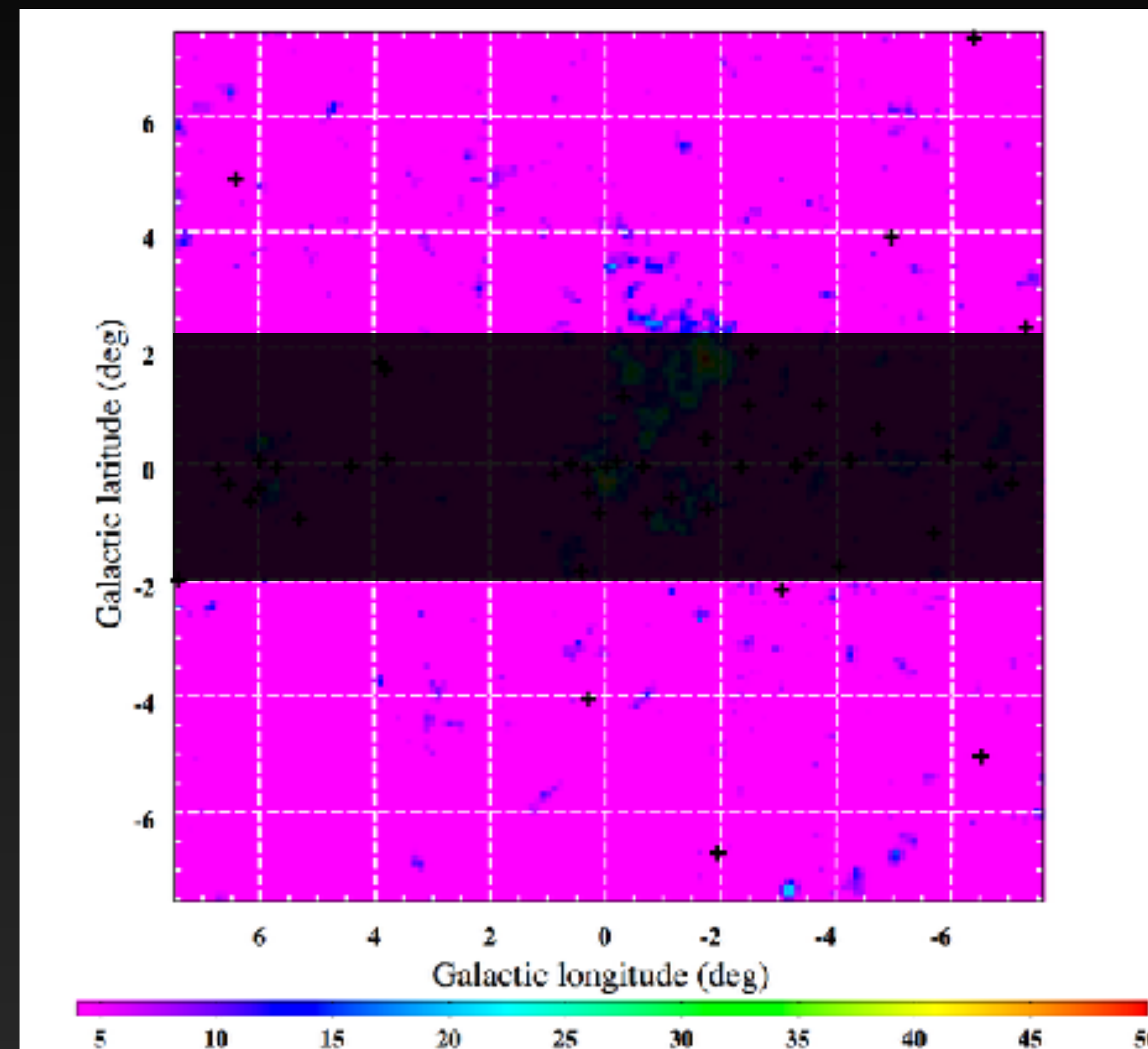


- **Recent analyses of hot-spots and cold spots in the GC region find evidence for the presence of a population of sub-threshold point sources.**

Systematic Background Uncertainties

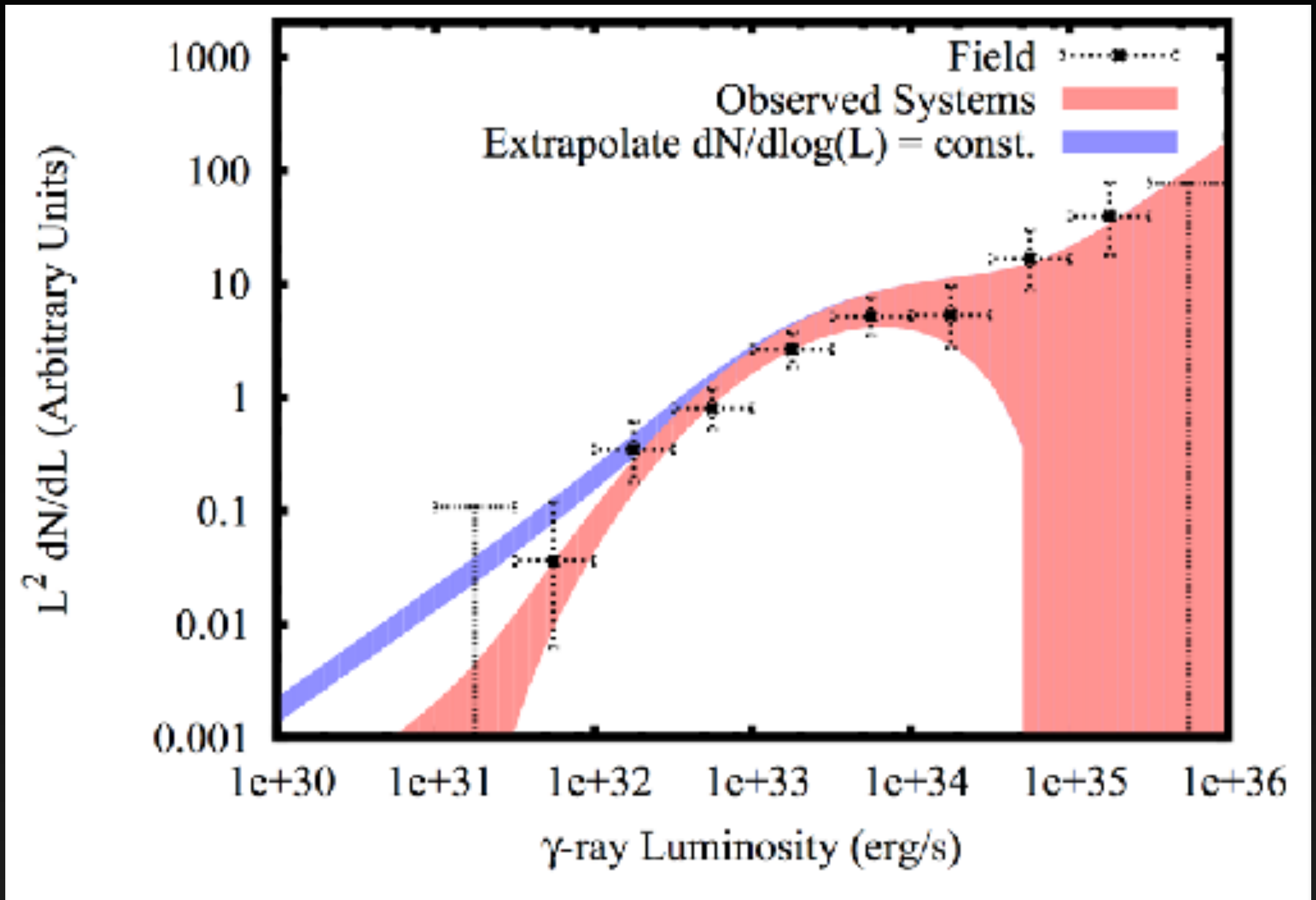


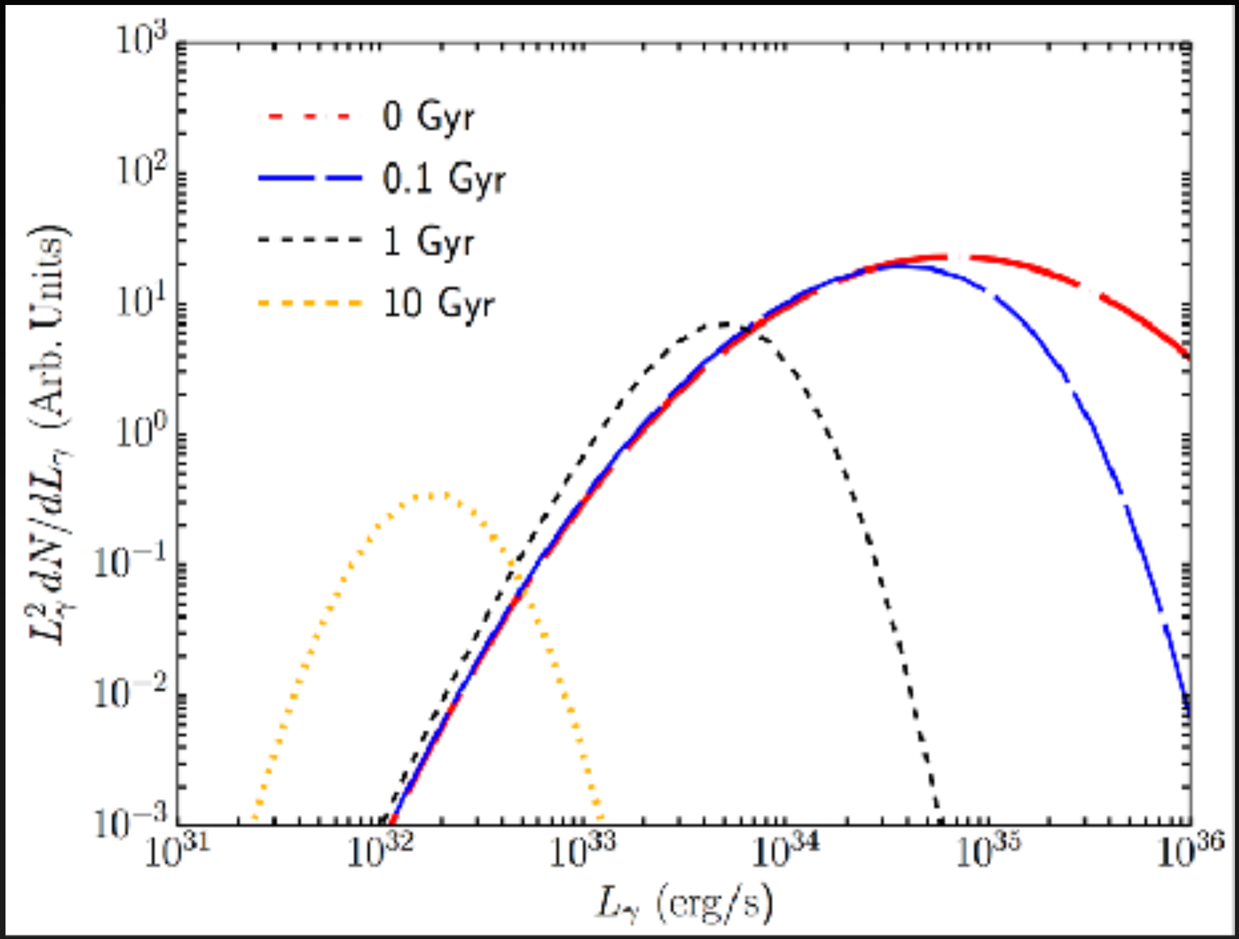
Ajello et al. (2015)



- However, these residuals are found once an extremely smooth diffuse emission model is subtracted - it remains to be seen whether the residuals are resilient to diffuse model changes.

Detectable Sources?





- Utilizing the luminosity distribution of pulsars in the field produces too many bright (detectable) pulsars, compared to observations. (Hooper et al. 2013, 2015)

- Evolving the pulsars (compared to the replenished field population) decreases the number of bright pulsars, but requires too many systems to explain the total luminosity. (Hooper & TL 2016)

The Answer is In the Sources

- Definitively finding (or not finding) these sources, and comparing their spectrum to the gamma-ray excess can provide strong evidence for or against pulsar interpretations of the gamma-ray excess

TL (2015)

- Conclusively cross-correlating these sources with observed radio pulsars could definitively prove pulsar interpretations of the excess.

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CHARACTERIZING THE POPULATION OF PULSARS IN THE GALACTIC BULGE WITH THE *FERMI* LARGE AREA TELESCOPE.

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Draft version May 2, 2017

ABSTRACT

An excess of γ-ray emission from the Galactic Center (GC) region with respect to predictions based on a variety of interstellar emission models and γ-ray source catalogs has been found by many groups using data from the *Fermi* Large Area Telescope (LAT). Several interpretations of this excess have been invoked. In this paper we test the interpretation that the excess is caused by an unresolved population of γ-ray pulsars located in the Galactic bulge. We use cataloged LAT sources to derive criteria that efficiently select pulsars with very small contamination from blazars. We search for point sources in the inner $40^\circ \times 40^\circ$ region of the Galaxy, derive a list of approximately 400 sources, and apply pulsar selection criteria to extract pulsar candidates among our source list. We also derive the efficiency of these selection criteria for γ-ray pulsars as a function of source energy flux and location. We demonstrate that given the observed spatial and flux distribution of pulsar candidates, a model that includes a population with about 2.7 γ-ray pulsars in the Galactic disk (in our $40^\circ \times 40^\circ$ analysis region) for each pulsar in the Galactic bulge is preferred at the level of 7 standard deviations with respect to a disk-only model. The properties of these disk and bulge pulsar populations are consistent with the population of known γ-ray pulsars as well as with the spatial profile and energy spectrum of the GC excess. Finally, we show that the dark matter interpretation of the GC excess is strongly disfavored since a distribution of dark matter is not able to mimic the observed properties of the population of sources detected in our analysis.

Three Key Components

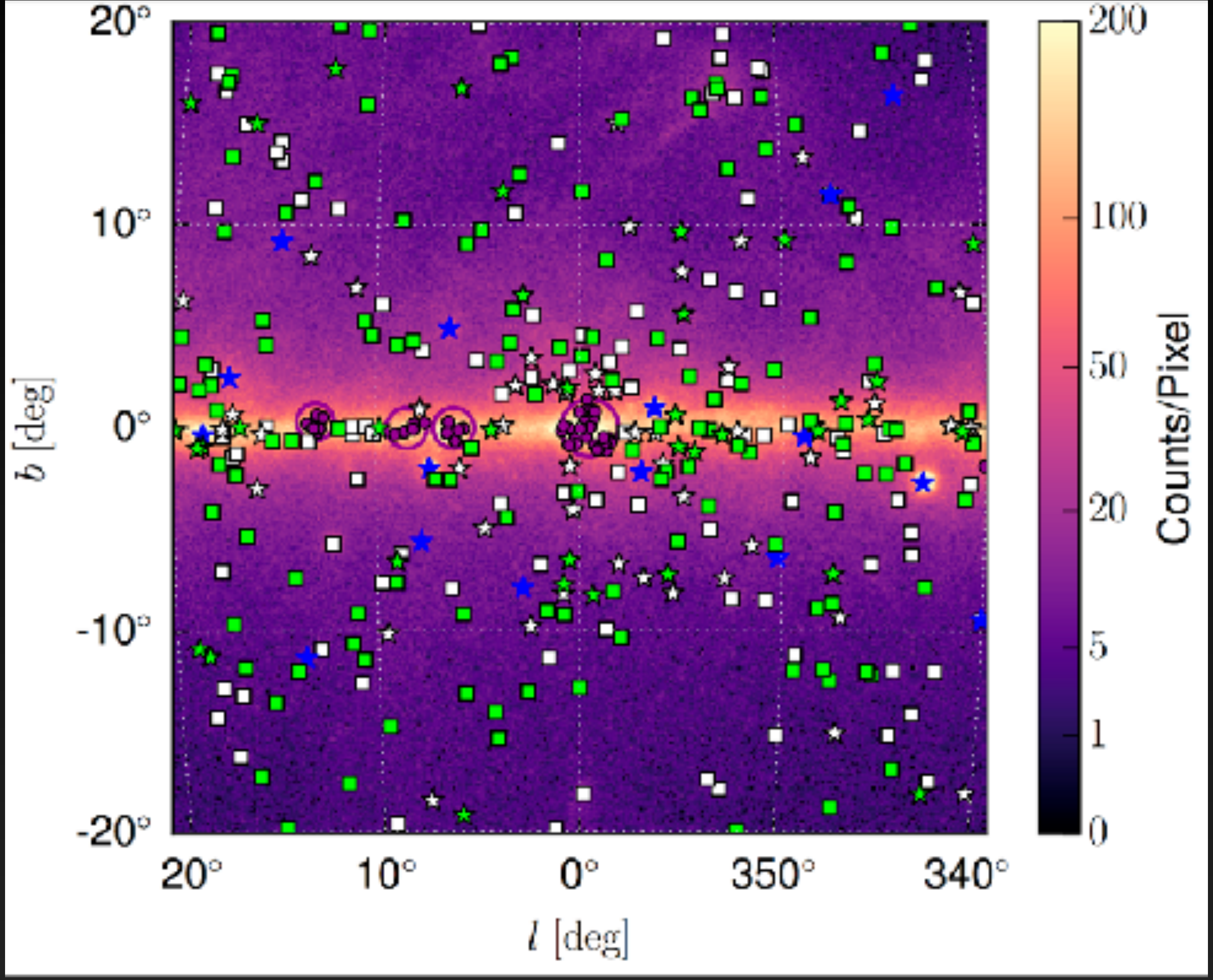
- 1.) A new analysis of point sources in the Galactic center, using customized diffuse emission models and 7.5 years of P8 data.

- 2.) A method to categorize sources as either blazars or potential pulsars, based on their gamma-ray spectra.

- 3.) Using newly detected sources to calibrate the total contribution of unresolved pulsars to the gamma-ray excess.

Building a Point Source Model

- 40° x 40° ROI
    - Divided into 64 different 8°x8° ROIs (3° overlaps)
- Iteratively build a point source model of the region, compared to a specific background model.



- Iteratively build a point source model of the region, compared to a specific background model.

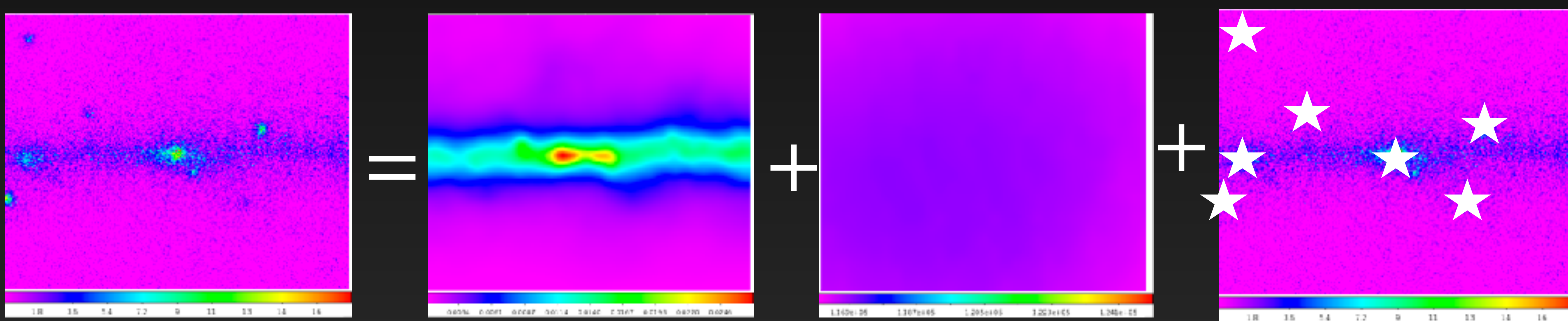
Building a Point Source Model

1.) Start with:

a.) Galactic Diffuse Model

b.) Isotropic Background Model (extragalactic + cosmic-ray contamination).

c.) All 3FGL sources identified at TS > 49 (~7σ)

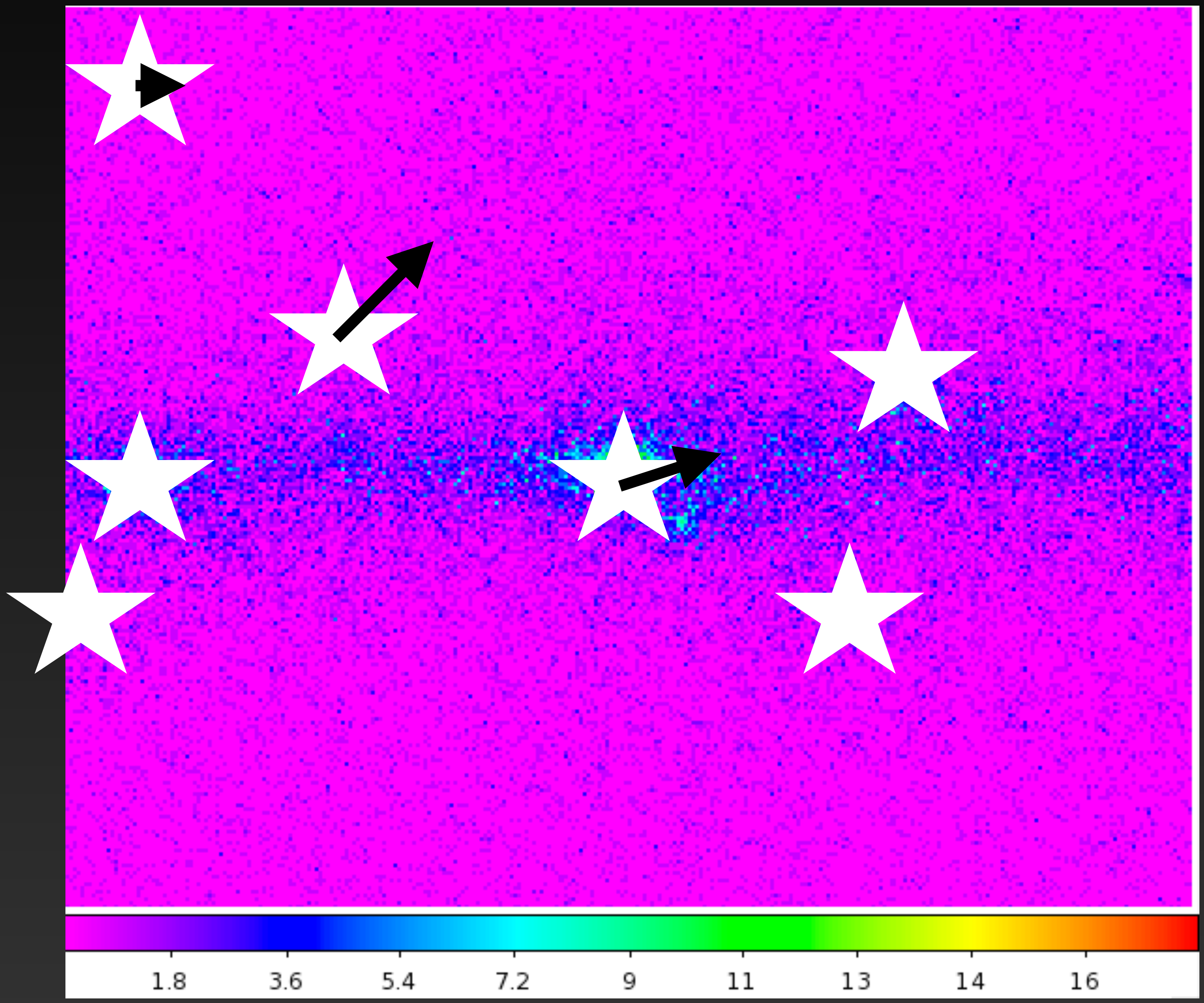


Data Diffuse Isotropic Bright Sources

$$\mathcal{L} = \prod_k \frac{m_k^{n_k} e^{-m_k}}{n_k!}$$

Find New Point Sources

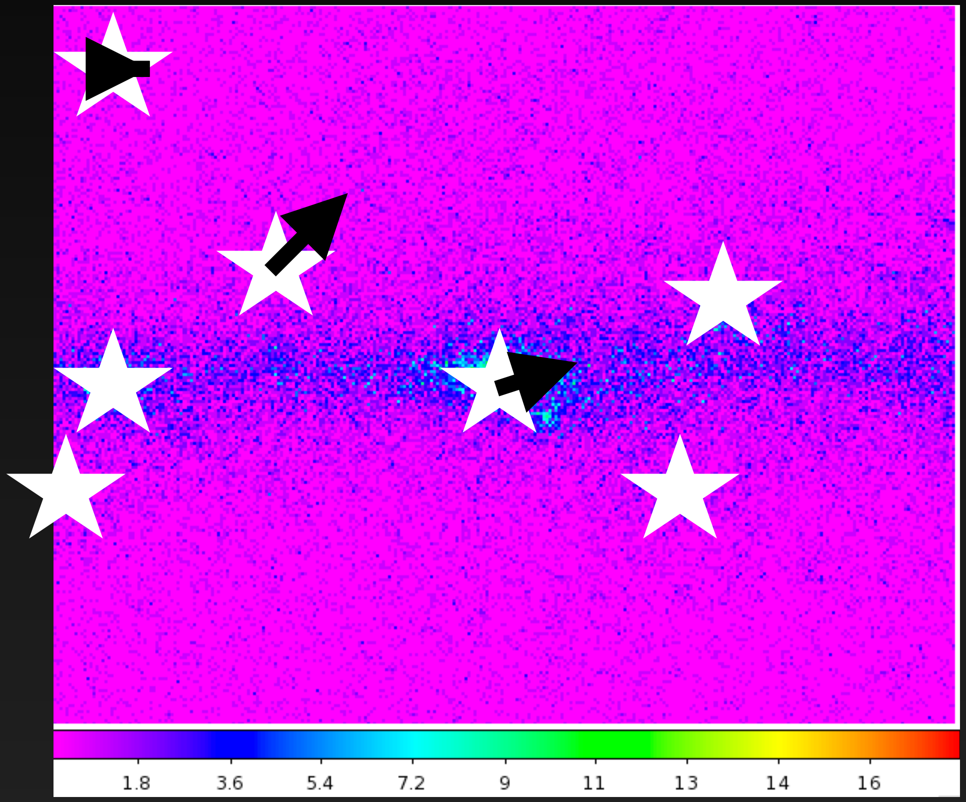
Step 1: Recenter Point Sources based on new diffuse data/ model:

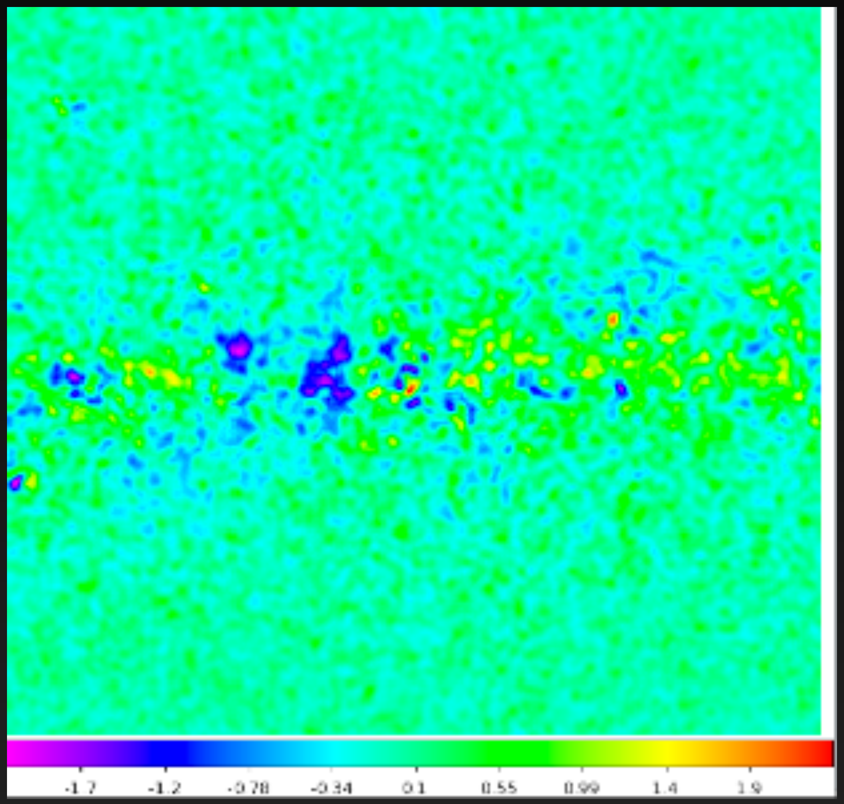


*not to scale

Find New Point Sources:

Step 2: Calculate a Test Statistic for this Model:



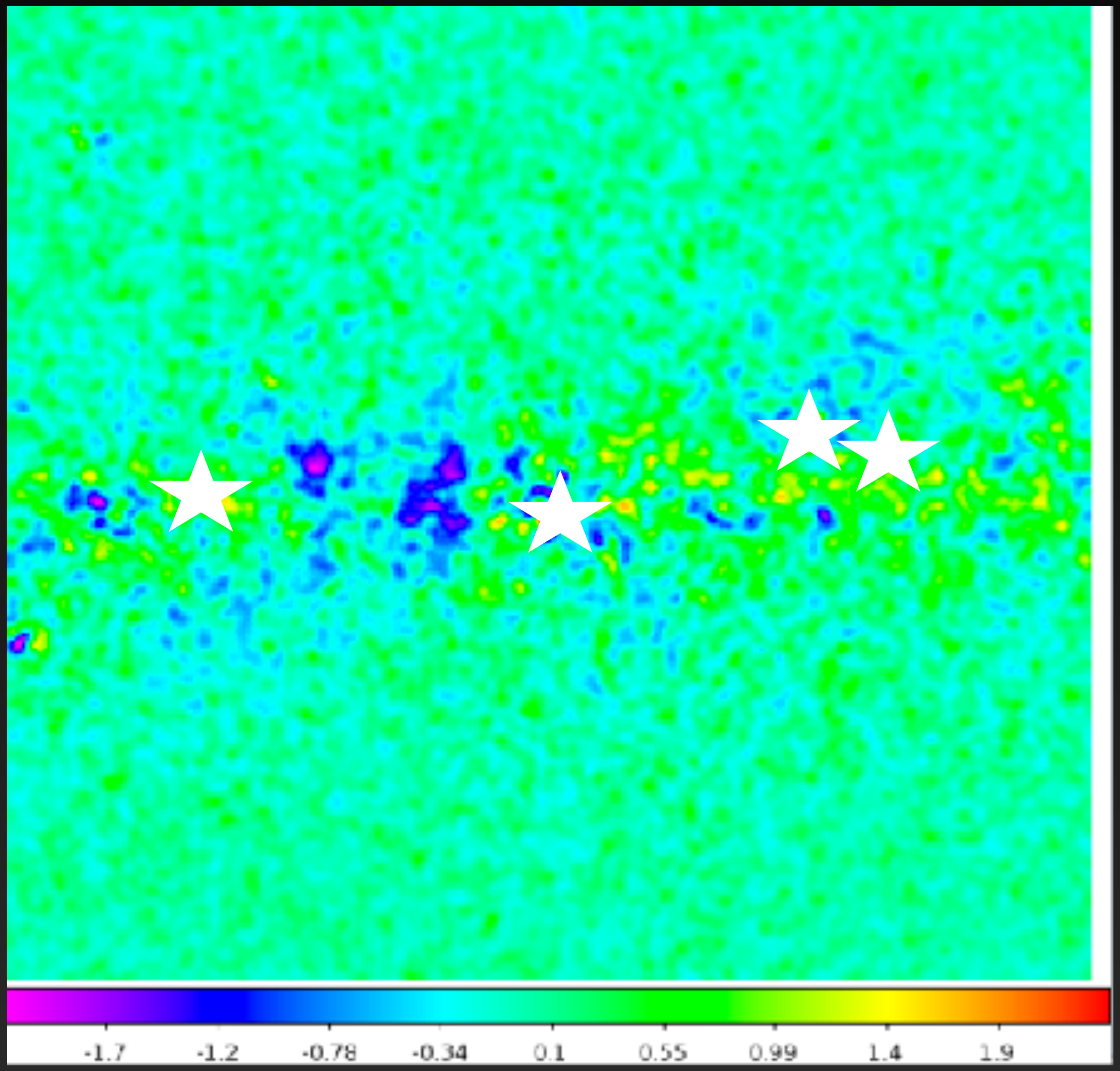


- Fit the model to the binned data, calculating the likelihood of obtaining the observed number of photons in each bin, using Poisson statistics:

$$\mathcal{L} = \prod_k \frac{m_k^{n_k} e^{-m_k}}{n_k!}$$

Find New Point Sources:

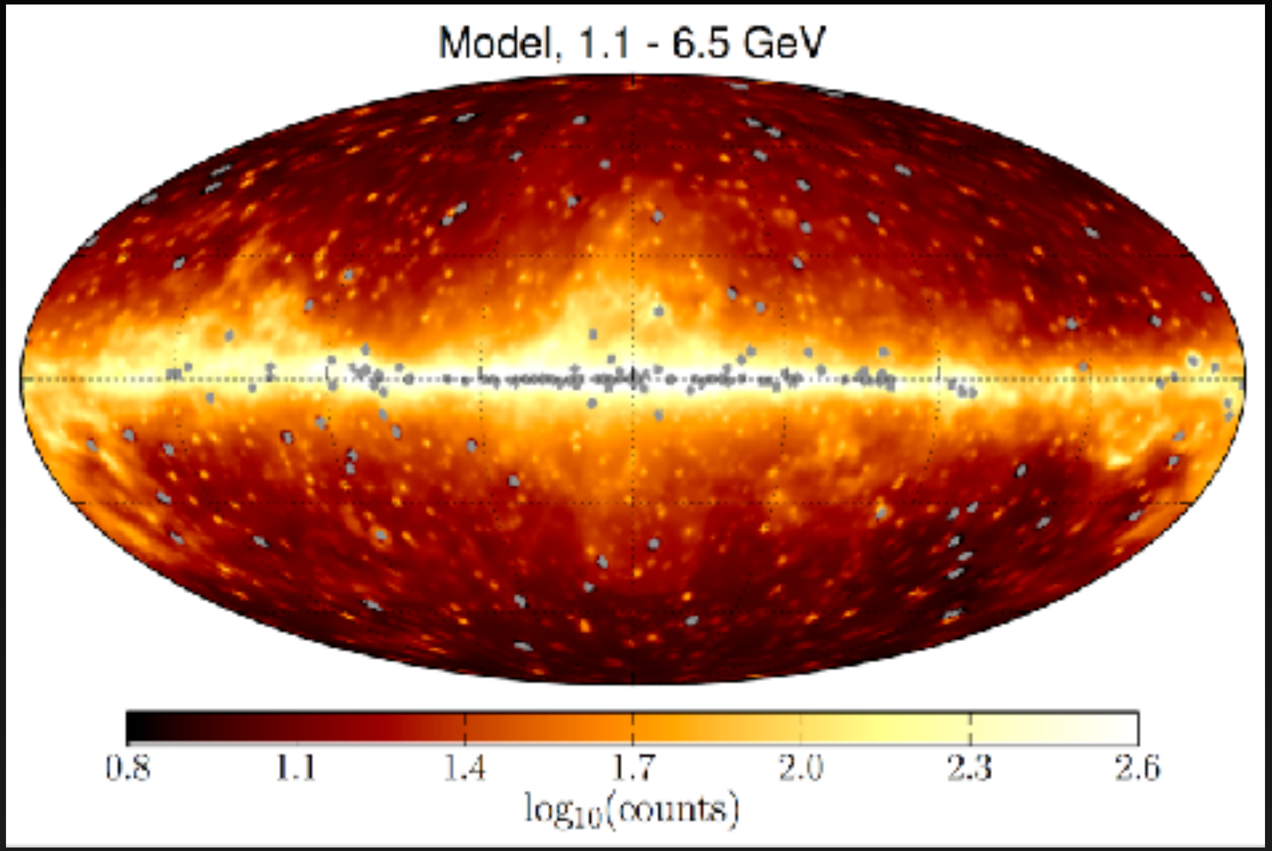
Step 3: Find new point sources iteratively by building a TS map of the residual:



- Declare an object to be a new source, if adding a point source at the location improves the LG(L) by at least 12.5

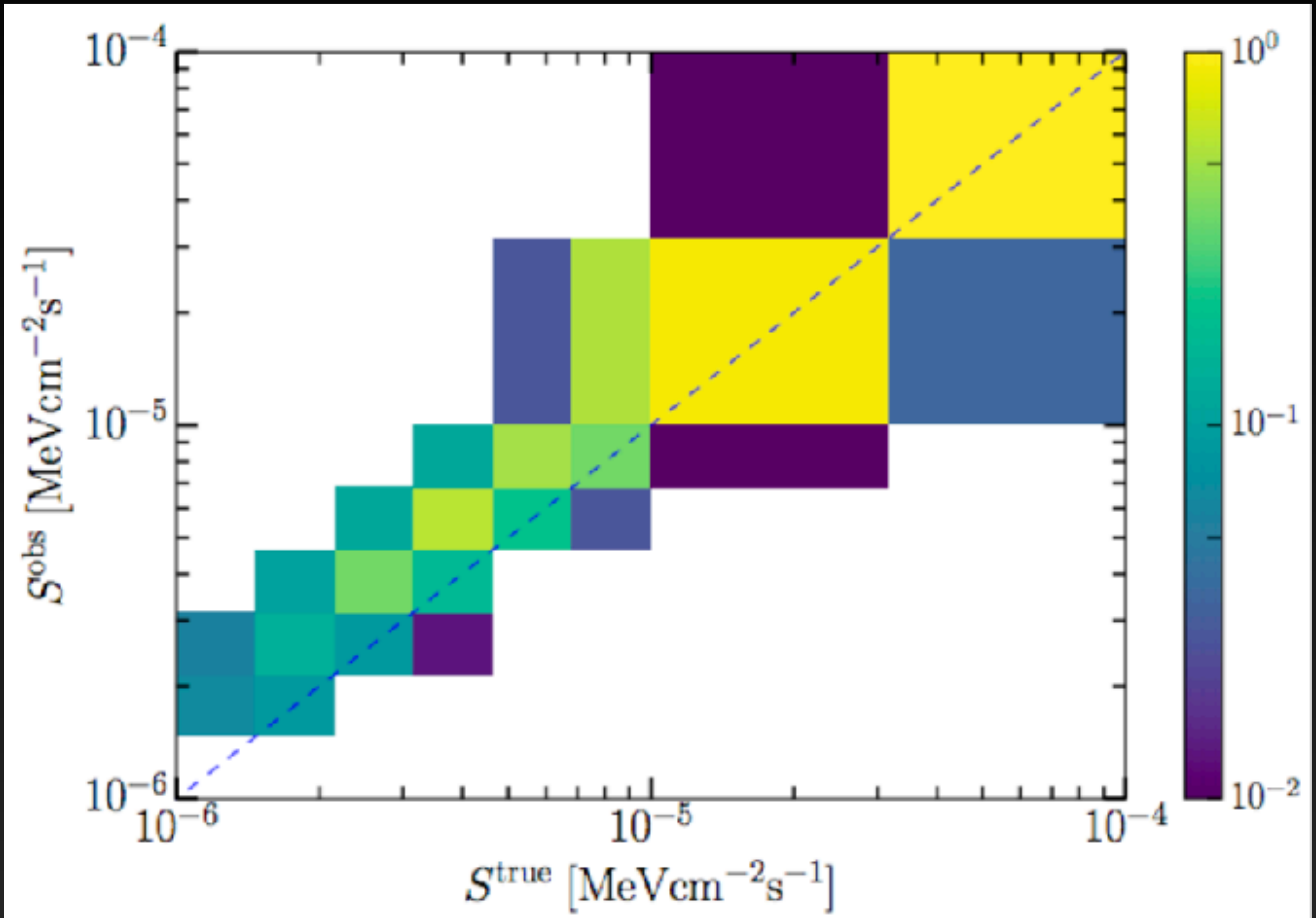
Diffuse Emission Models

- Point sources are calculated and modeled assuming two different diffuse backgrounds:
  - Default 3FGL diffuse model
  - Alternative diffuse emission model designed to model the galactic center region. (Ackermann et al. 2017)



- Because diffuse emission in the Galactic center is bright (and challenging to model), this can affect point source determinations and properties.

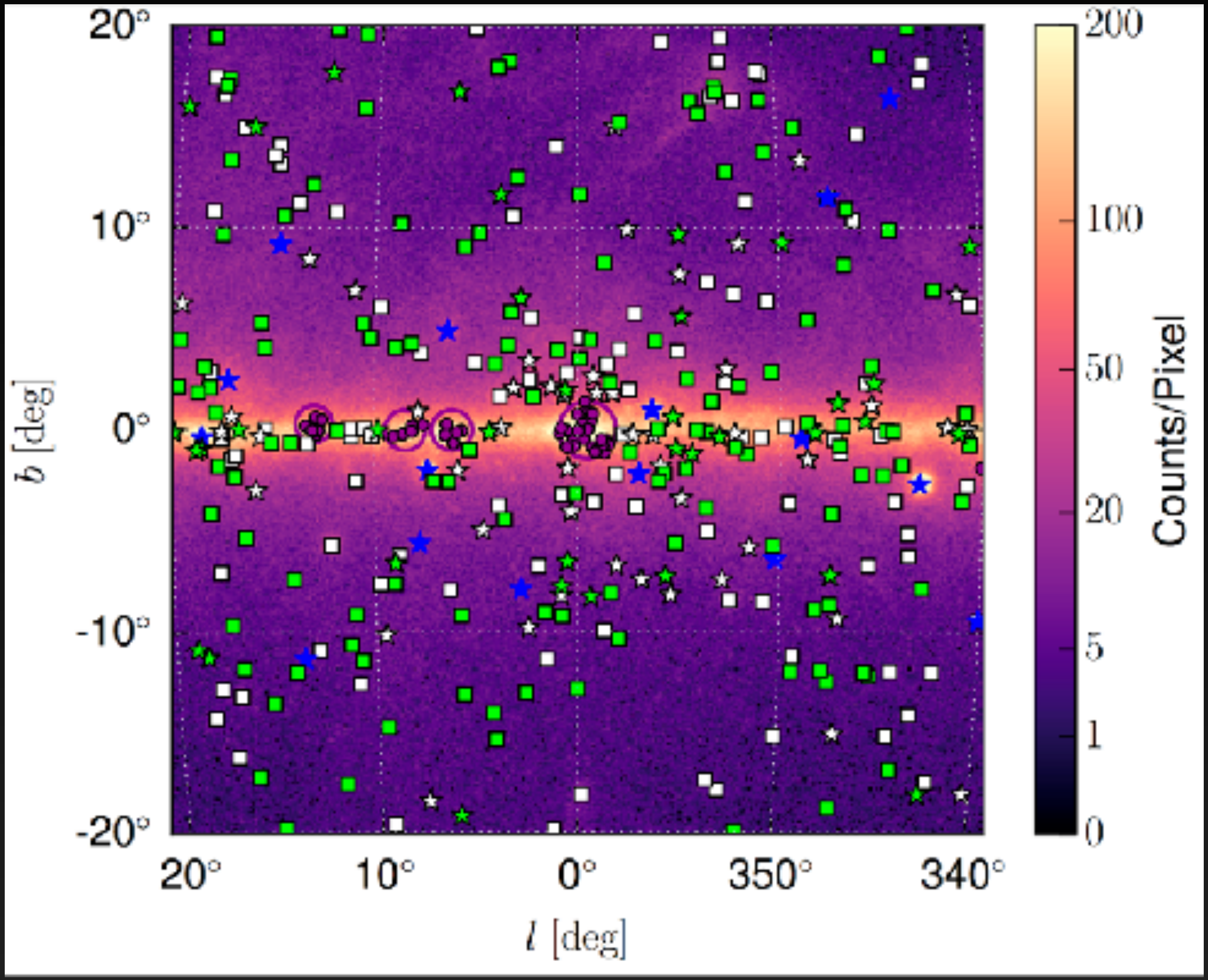
Background Fluctuations and Point Sources



- An example of this effect from Monte Carlo:
  - While most luminosities are reconstructed accurately, there is a tendency for pulsar fluxes to be overestimated.

Resulting Point Source Population

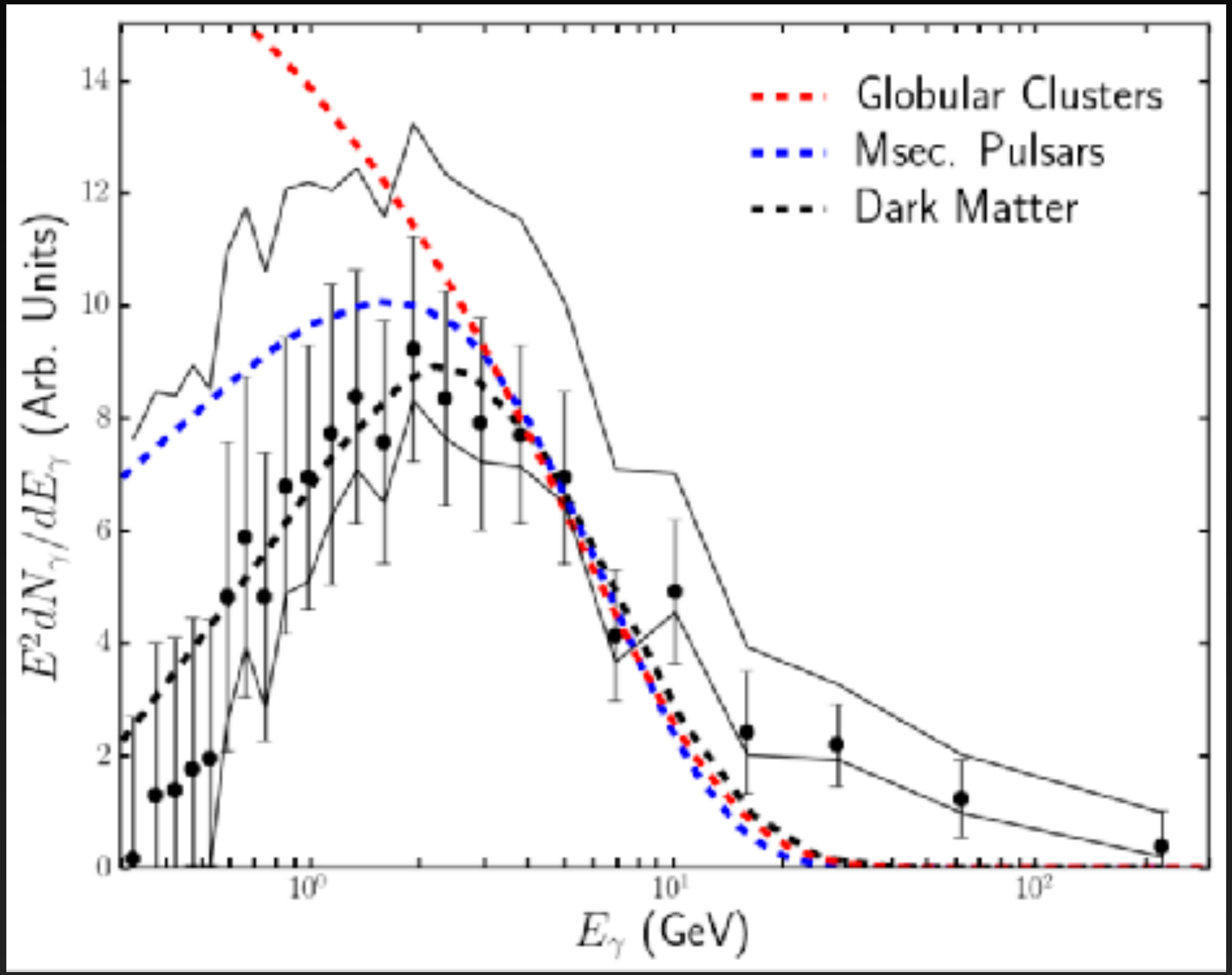
- Detect 374 (385) sources using the default (alternative) background model
- 469 total sources are detected (~100 sources are only in one model or the other)
- This nearly doubles the 202 sources found in 3FGL. 189 (182) of these sources are found here.



- The 1FIG catalog investigated a smaller 15° x 15° region, and found 48 sources, 38 (41) are found here.

Source Spectra

- Can use spectral information to determine whether these sources are pulsars



Cholis et al. (2014)

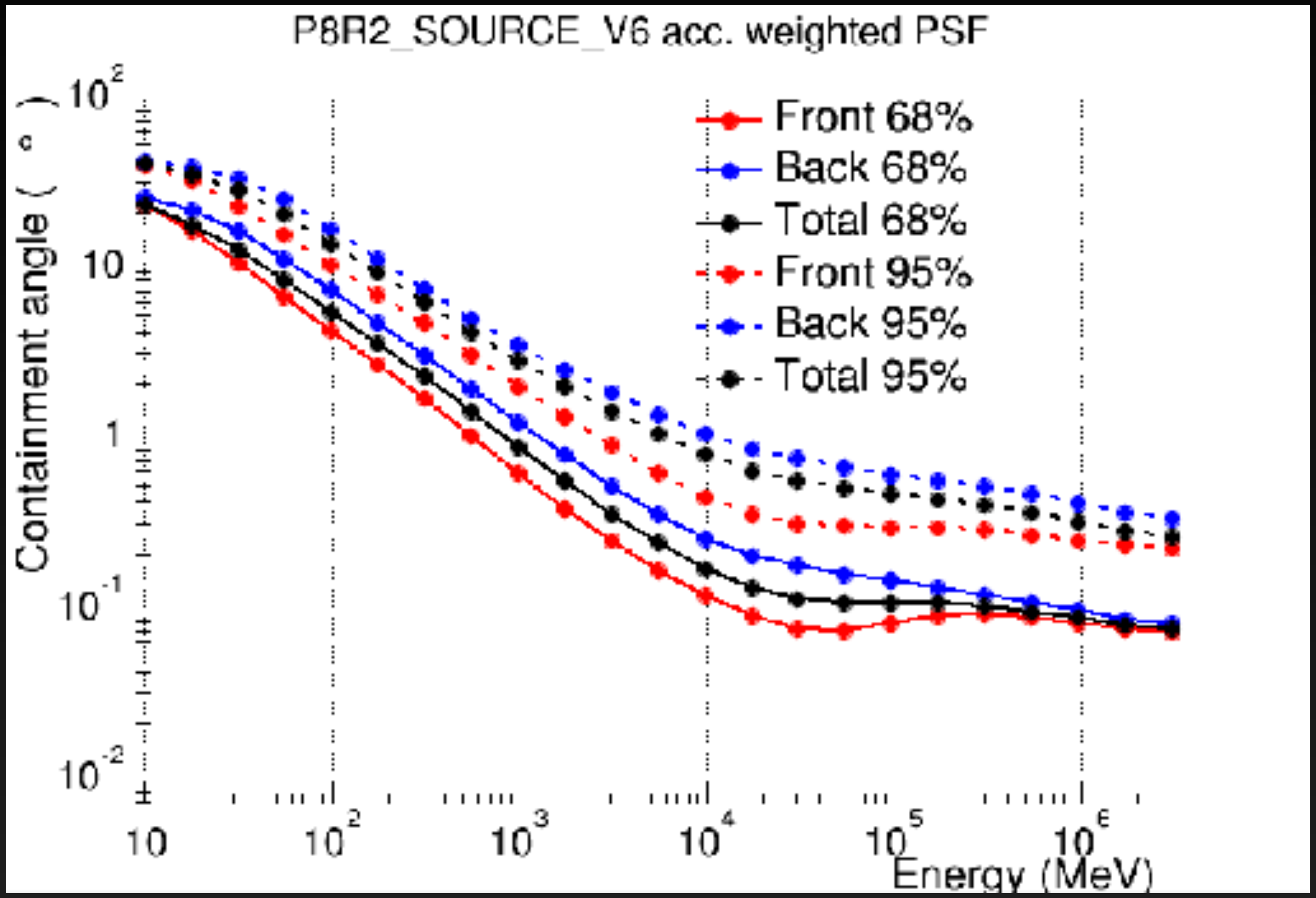
- Pulsars have a hard spectrum peaking at 2 GeV, background blazars, on the other hand, have power-law spectra.

- Need to be careful considering threshold effects - sources that are near the detection threshold are less likely to show non-power law behavior.

Source Spectra - Threshold Effects

- Moreover, issues may arise in regions with dense source populations:

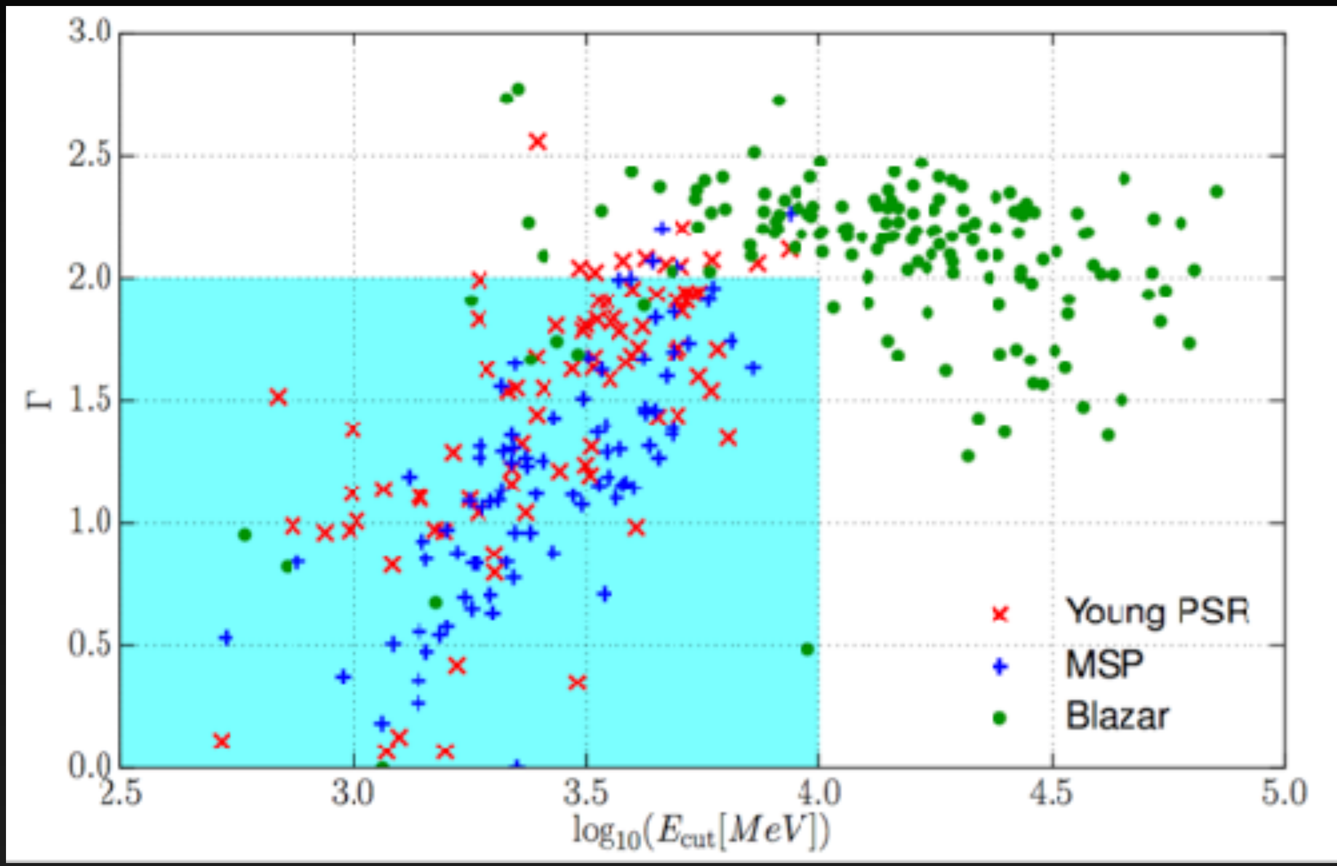
- At low energies, source localization is difficult, and sources significantly overlap.



- This can potentially affect the intensity of low-significance sources in an energy dependent way, thus affecting their spectrum.

Treating Spectral Systematics

Several Techniques utilized to minimize these systematic effects:



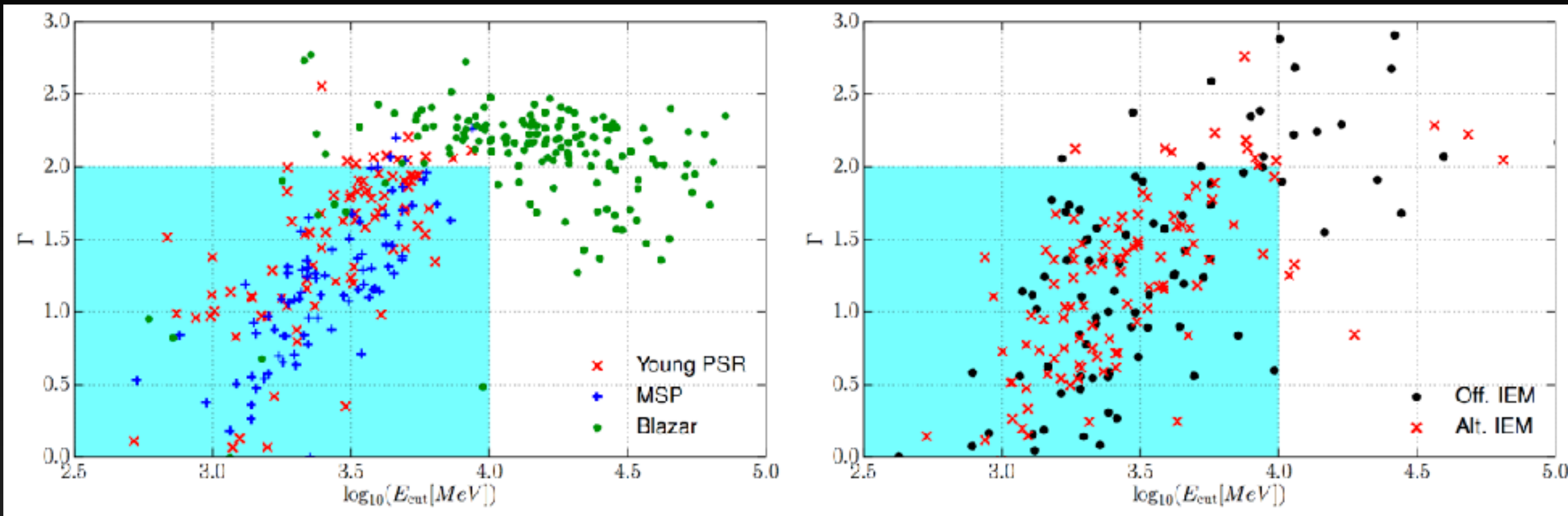
Compare only sources that have evidence for non power-law behavior (removing very dim sources, or those with very soft spectra).

Allow the spectra of all sources within 3° of a putative source to floa
when a new source is added to the fit.

Remove "clumps" of sources which appear to be diffuse mis-modeling.

Treating Spectral Systematics - Results

only sources with TS$_{curve}$ > 9



- The majority of sources in the Galactic center are seen to have power-law + exponential cutoff spectra which are compatible with pulsars, rather than with blazar activity.

IEM	N_{PSR}	Γ	$\log_{10}(E_{cut}[\mathrm{MeV}])$
Off.	86	1.03 ± 0.52	3.28 ± 0.33
Alt.	115	1.05 ± 0.50	3.27 ± 0.31
Alt. ∩ Off. (Off.)	66	1.02 ± 0.52	3.27 ± 0.32
Alt. ∩ Off. (Alt.)	66	1.01 ± 0.51	3.26 ± 0.30
Known PSRs (Off.)	172	1.33 ± 0.54	3.43 ± 0.24
Young PSRs (Off.)	86	1.46 ± 0.53	3.44 ± 0.26
MSPs(Off.)	86	1.20 ± 0.50	3.42 ± 0.23

error bars are the 68% containment of central values

Simulating a Population of Pulsars

- Build simulated models of pulsar emission to compare with data.

- Need:

  - 1.) Spectrum of Pulsars - Average of observed pulsars

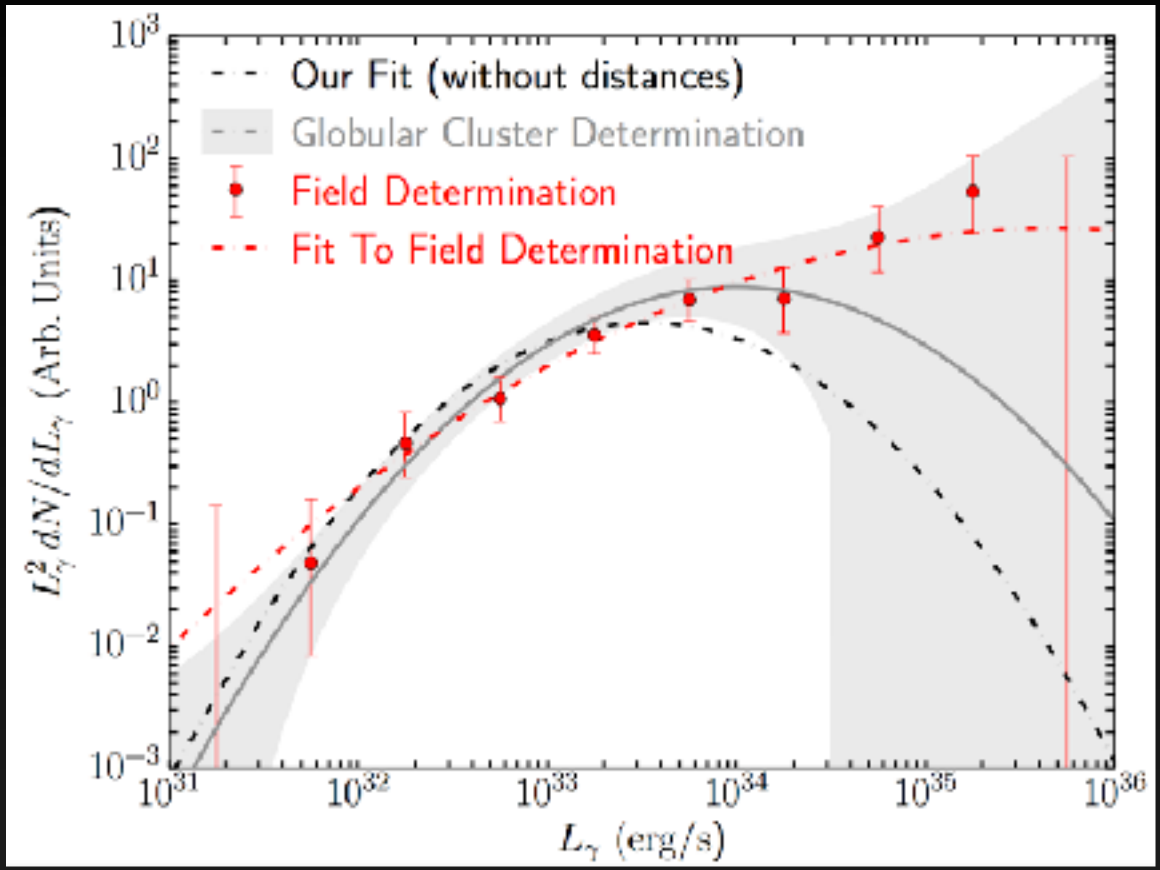
  - 2.) Luminosity Distribution of Galactic Center pulsars.

  - 3.) Expected morphology of pulsars

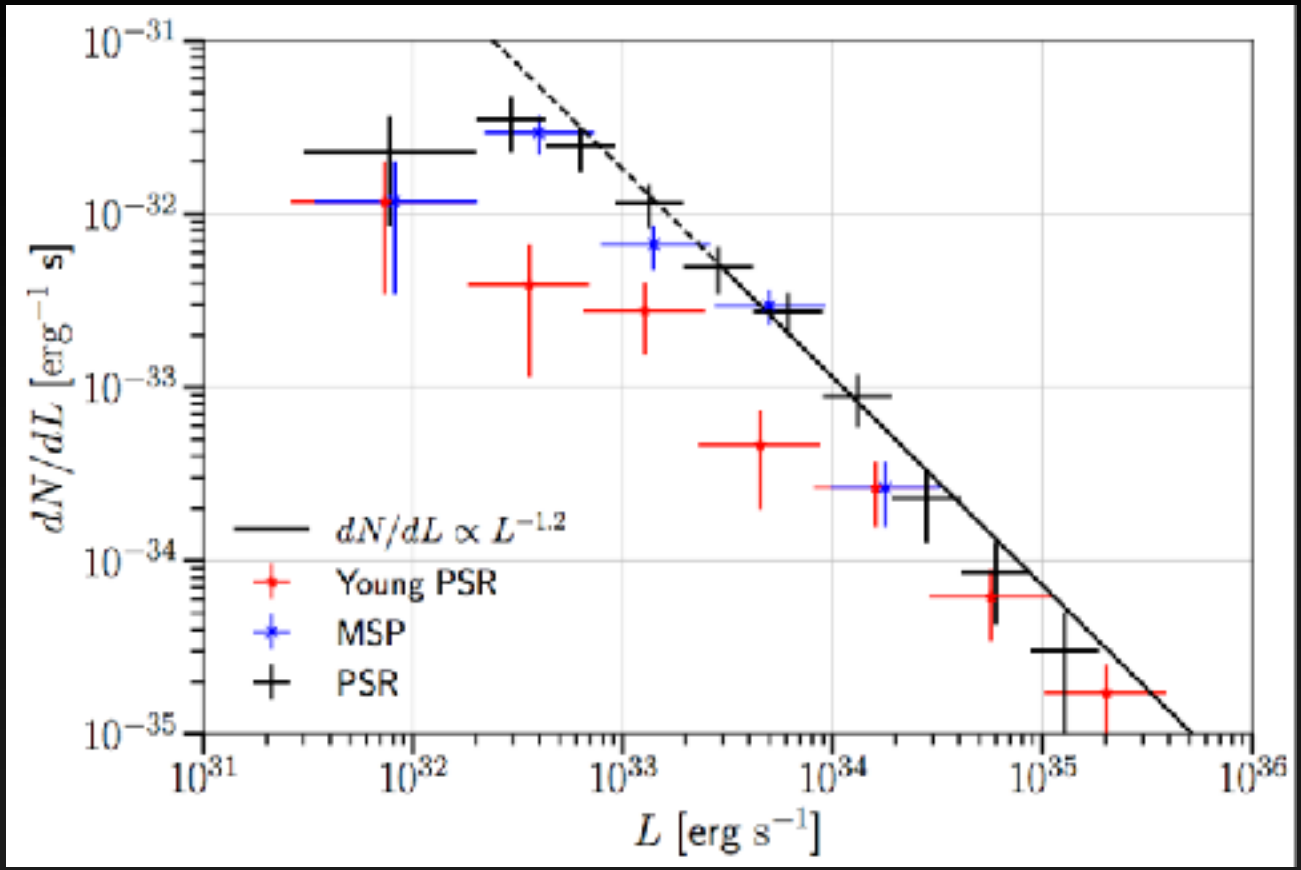
    - a.) Pulsars in the Milky Way disk

    - b.) Pulsars in the Galactic Bulge

Luminosity Distribution of Pulsars



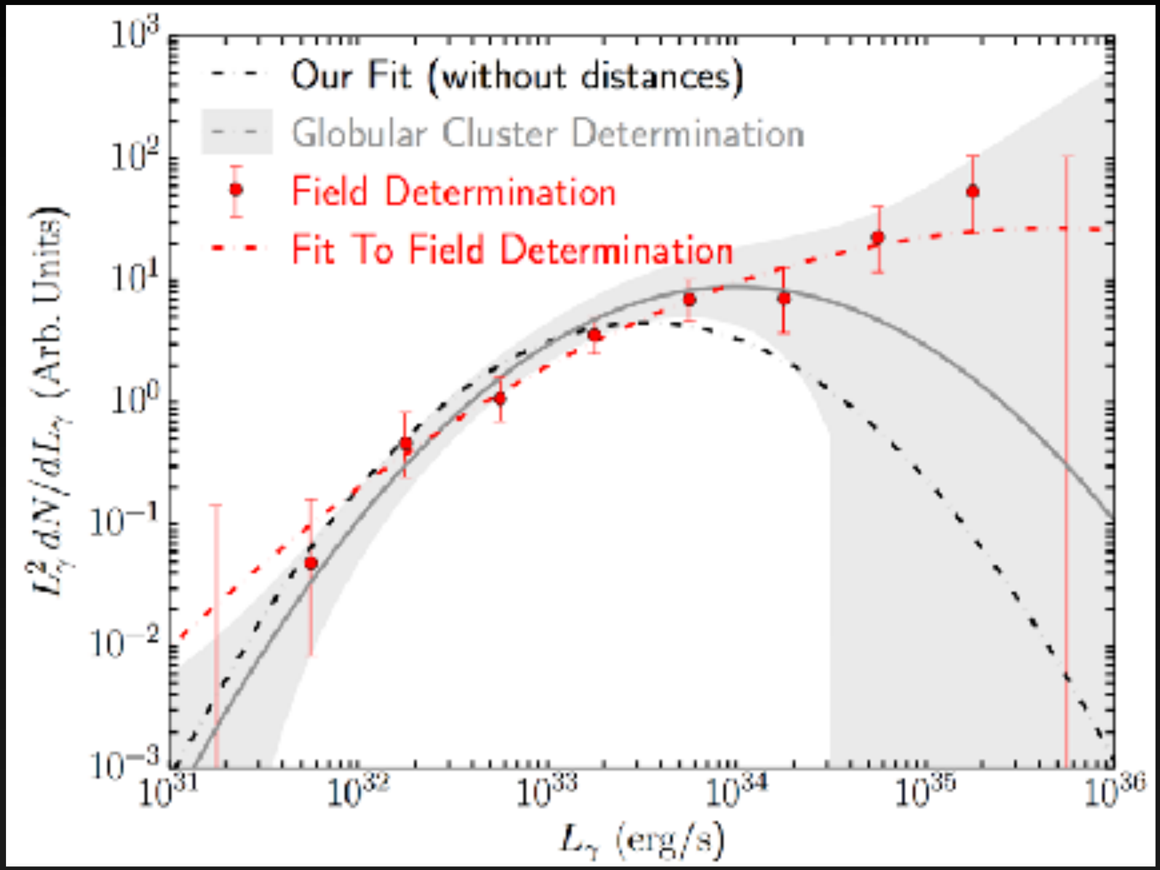
Hooper & Mohlabeng (2015)



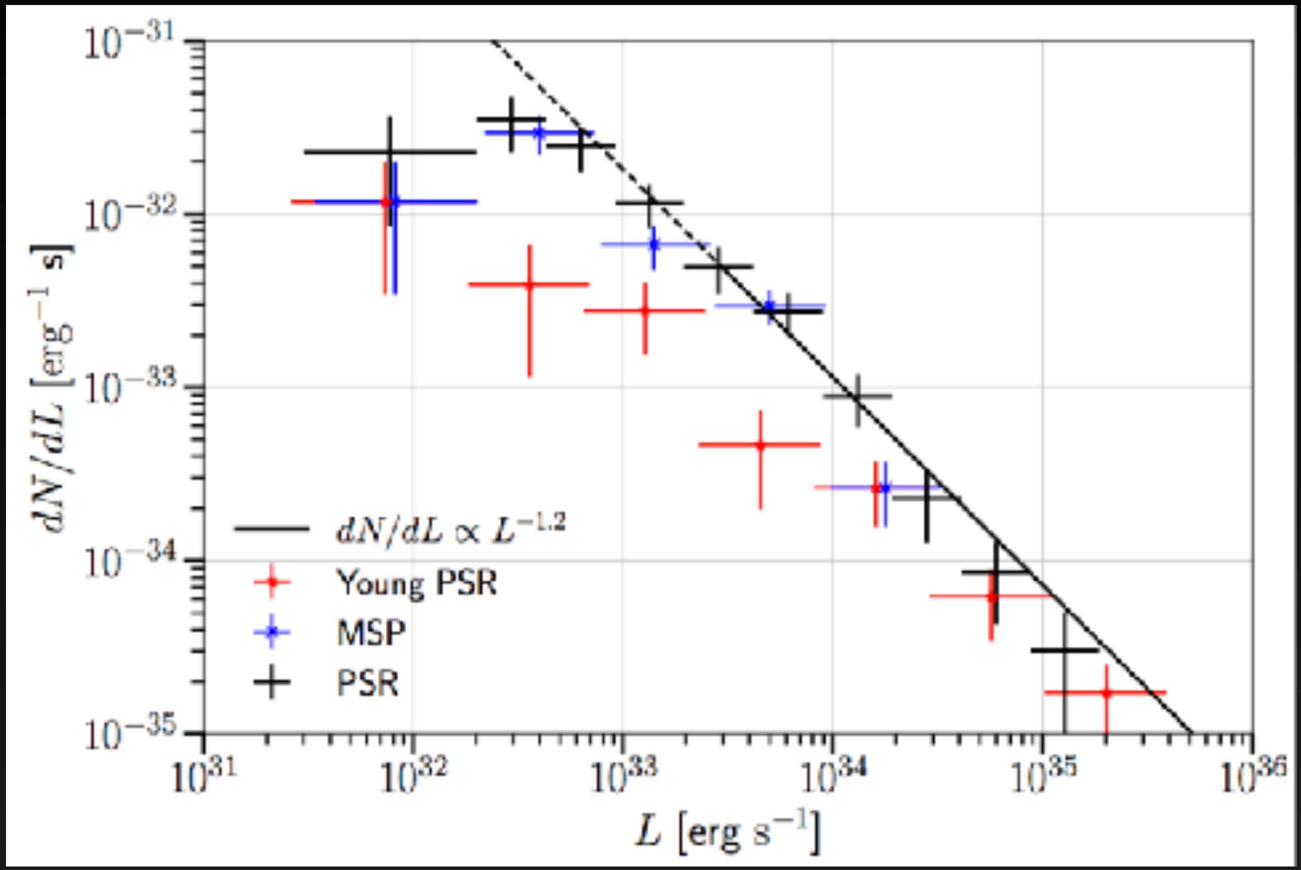
Fermi-LAT Analysis

- Using the population of detected radio-pulsars within 3kpc of Earth, a model for the luminosity distribution of pulsars is established.
- Unlike previous results (Hooper & Mohlabeng 2015, Cholis, Hooper, & Linden 2014, Bartels et al. 2016), no turnover at low luminosities is modeled, but this effect is marginal.

Luminosity Distribution of Pulsars

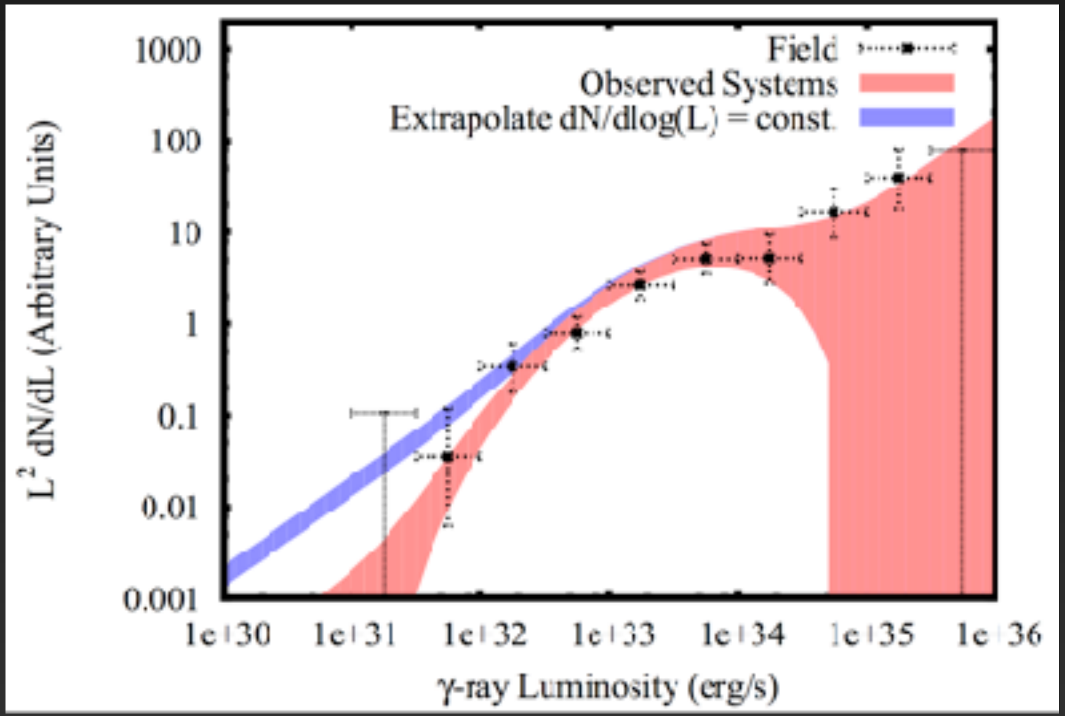


Hooper & Mohlabeng (2015)



Fermi-LAT Analysis

- Most of the luminosity is provided by the brightest pulsars.
- In fact, this is somewhat more true in the Fermi-LAT analysis than in previous works.



Cholis et al. (2014)

Disk vs. Bulge Pulsars

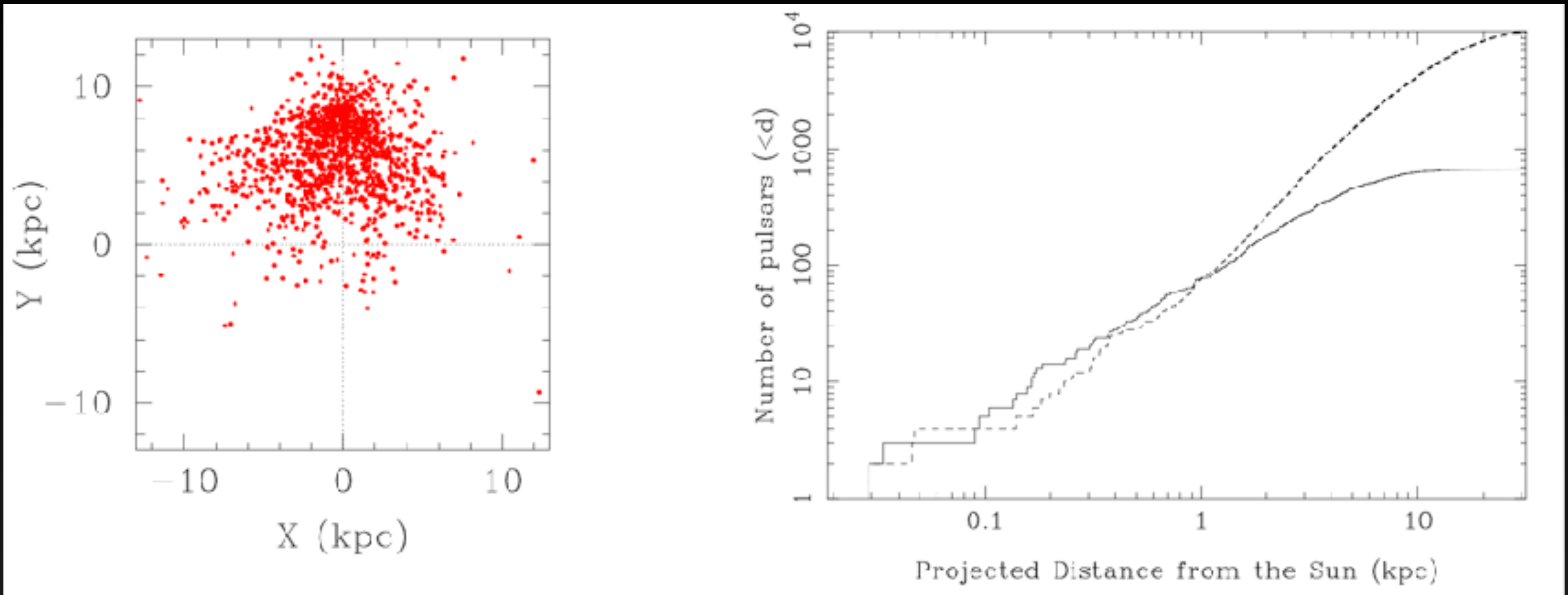
- Two primary populations of stars in the Milky Way:
  - Stars in the thin disk of the galaxy (relatively young, relatively high metallicity)
  - Stars in the *spherical* galactic bulge surrounding the Milky Way (relatively old, relatively low metallicity)

Disk vs. Bulge Pulsars

- Build Models for the global morphologies of pulsars from both the disk and the bulge.
- Then use the spatial and luminosity distribution of observed sources to determine the normalization of each component.

Disk Pulsars

Lorimer (2004)

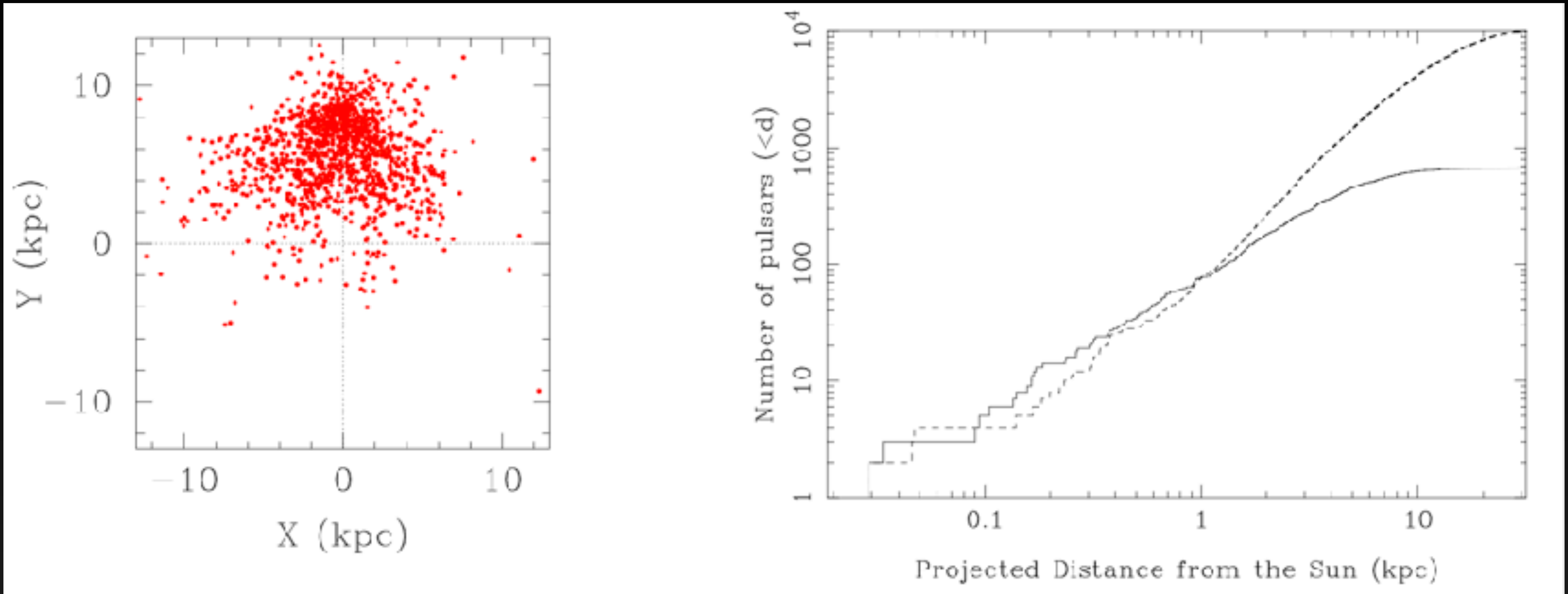


- For the disk population, the radial distribution of pulsars is normalized to the results of Lorimer 2004.

- This is of some concern, as the Lorimer distribution is based on observations that have sensitivity issues near the galactic center – and thus appears to systematically underproduce the number of observed pulsars in this region.

Disk Pulsars

Lorimer (2004)



Specifically, Lorimer (2004) produces an analytic fit to the pulsar data, of the form:

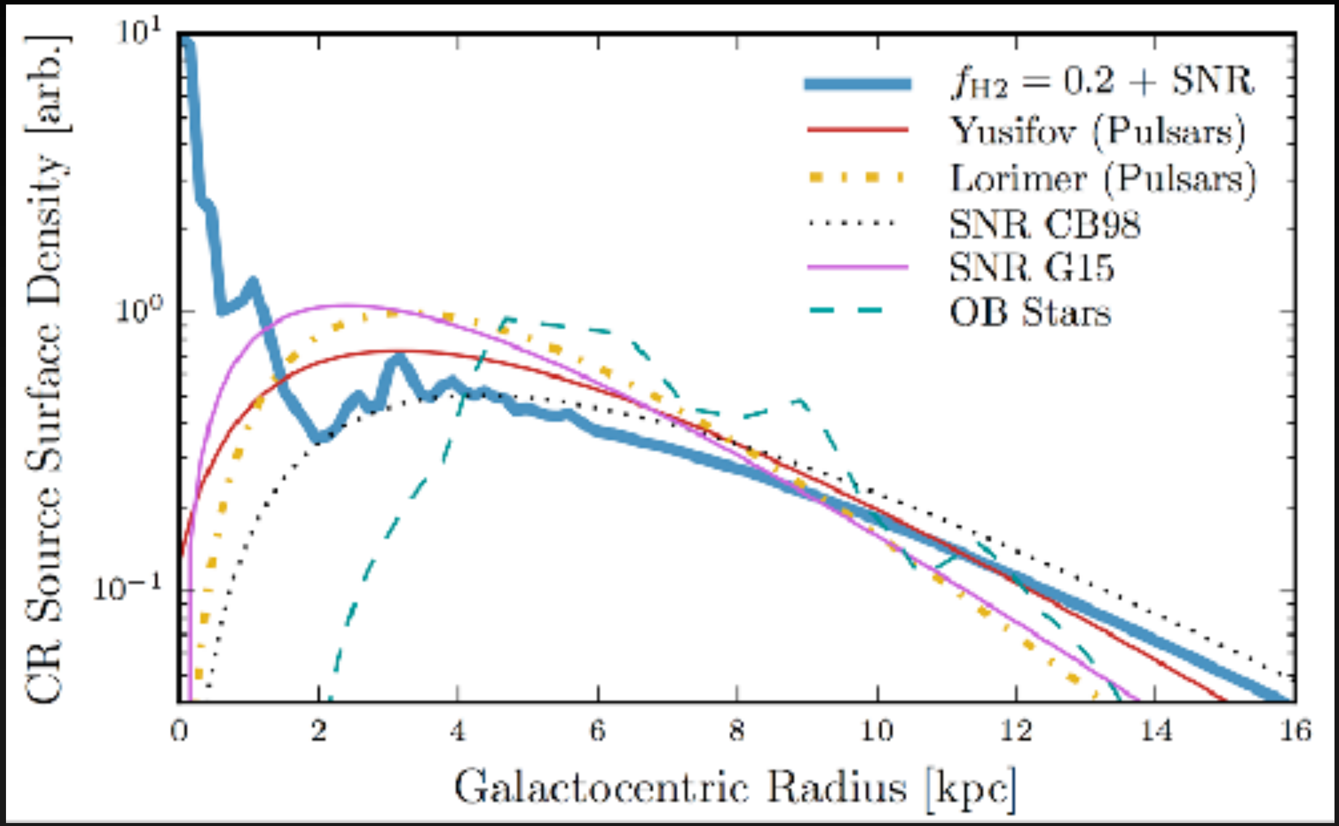
$$\rho(R) = R^n \exp(-R/\sigma)$$

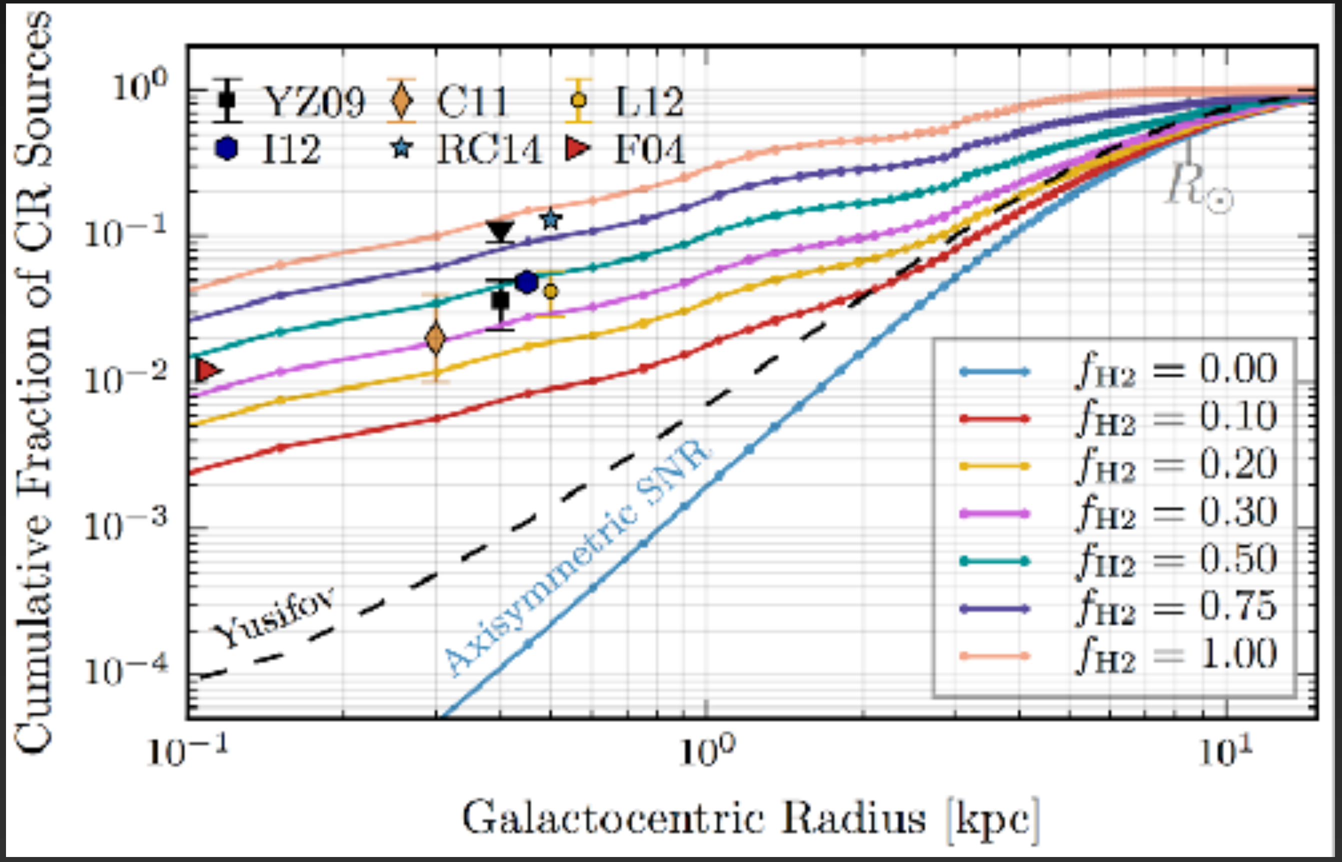
with $n = 2.35$, **and** $\sigma = 1.53$ kpc.

An Alternative Disk Pulsar Model

- Recent models (self-biased) have tried to employ observations of dense molecular clouds (the seeds of star formation) in order to calibrate the number of pulsars formed near the galactic center.

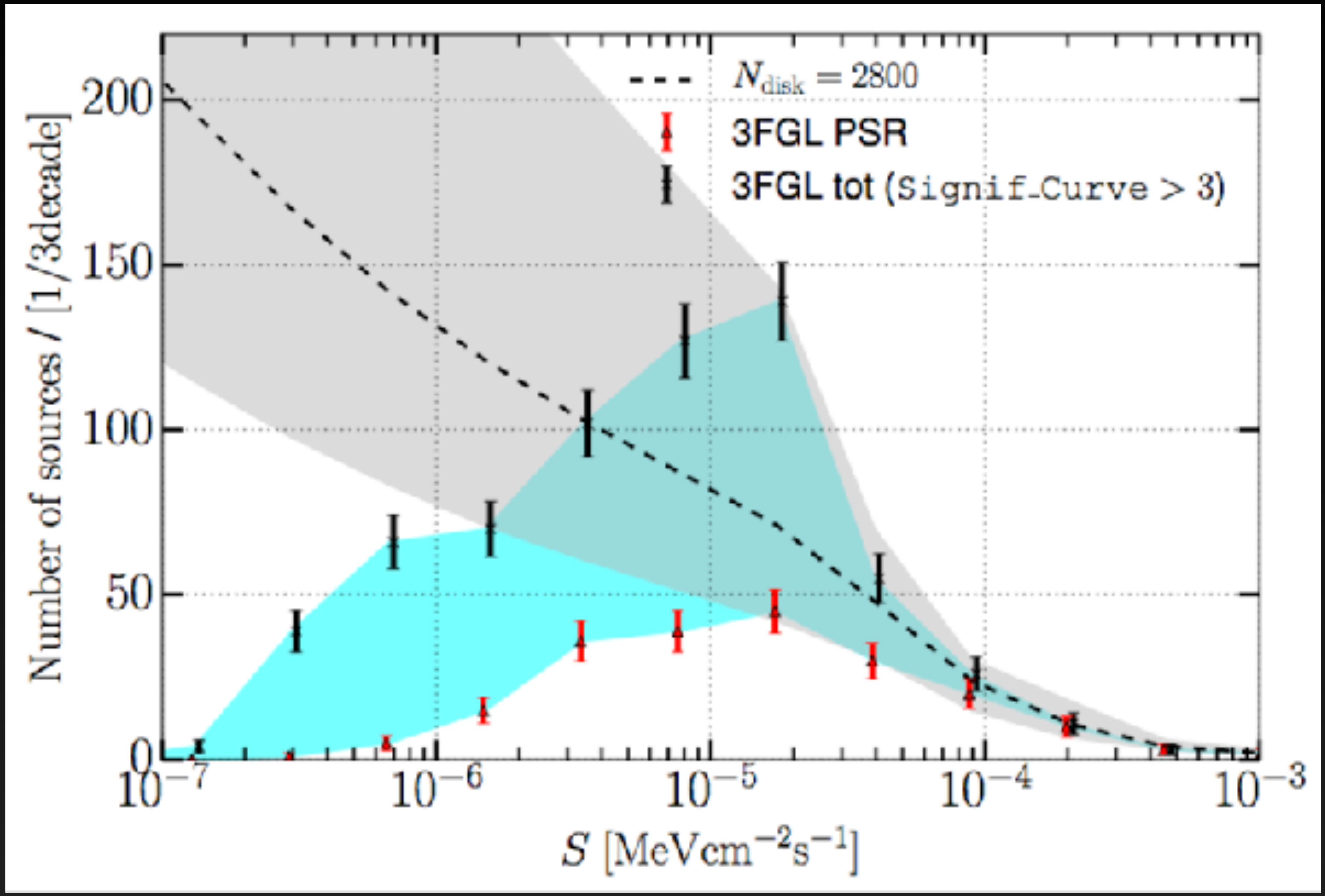
- This produces an extremely different pulsar population in the central kpc, which is a better fit to observations.





Carlson, TL, Profumo (2016)

Disk Pulsar Fits



- These results do provide a good fit to the luminosity distribution of observed 3FGL pulsars (which are nearly all from the disk).

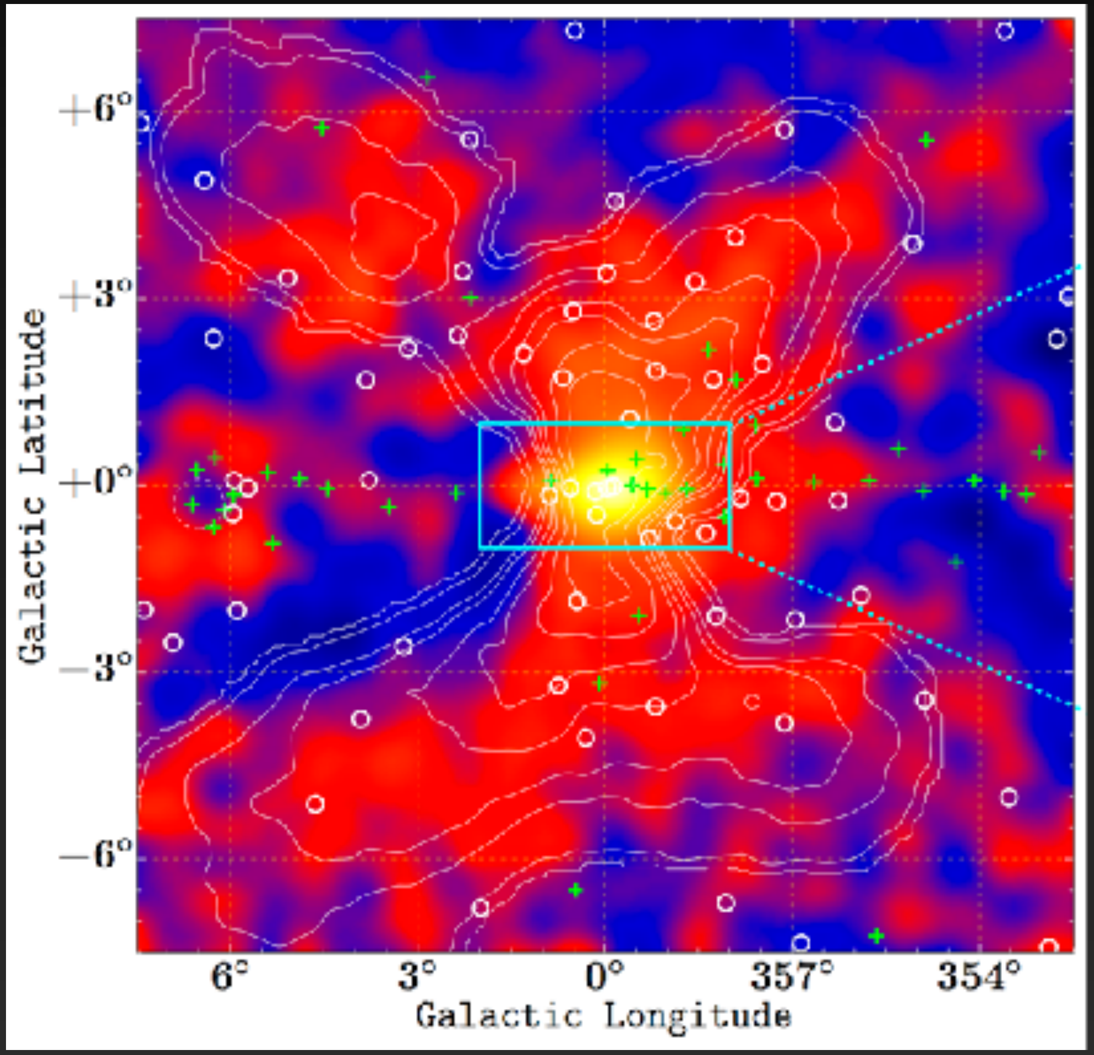
- Also, allowing n and σ to float independently do not provide good fits to the data.

Bulge Pulsars

- For the bulge population, a radial density profile of $r^{-2.6}$ is fit to the observed parameters of the galactic center excess.

- This radial distribution is assumed to extend out to 3 kpc from the Galactic center

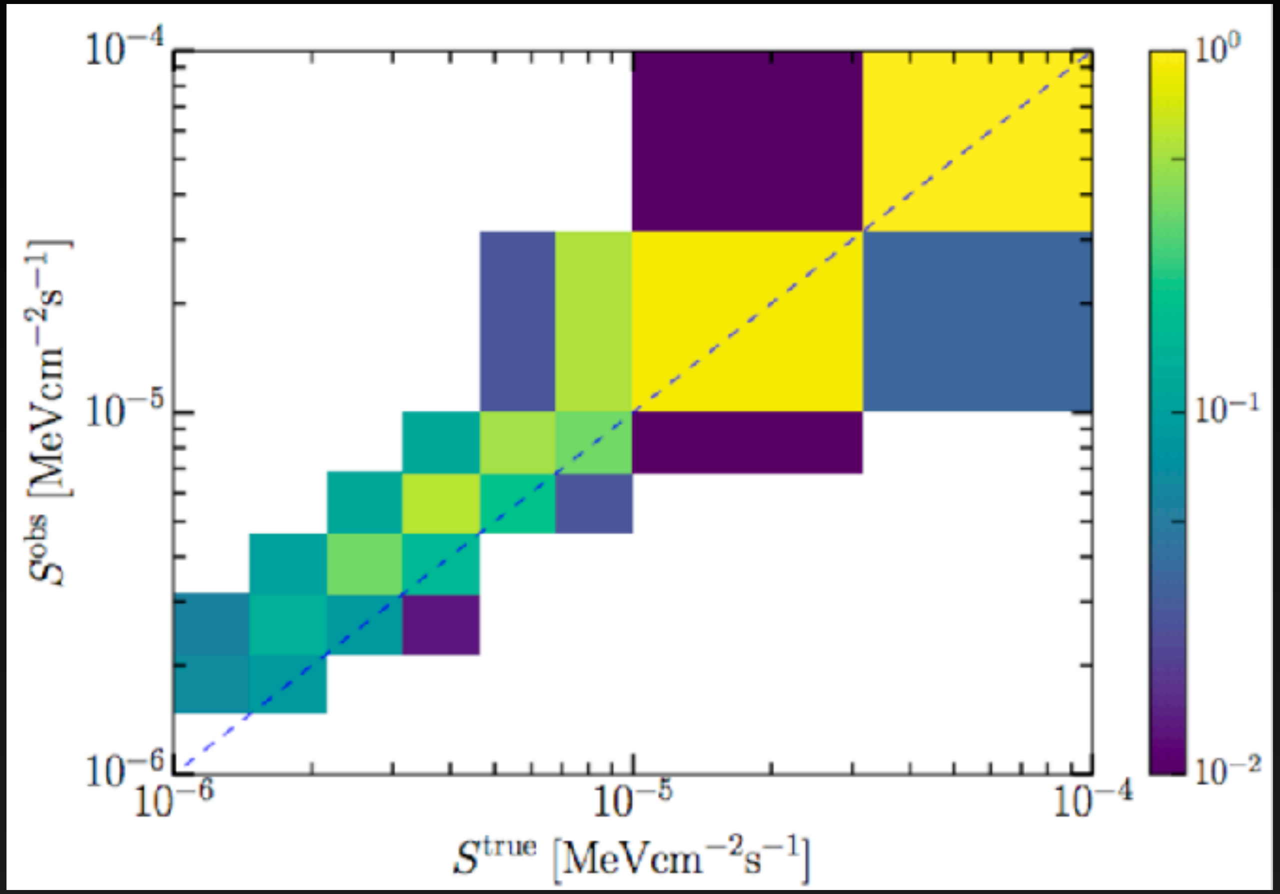
- Note that the bulge is not actually this large (approximately 1 kpc), but neutron star natal kicks may be important.

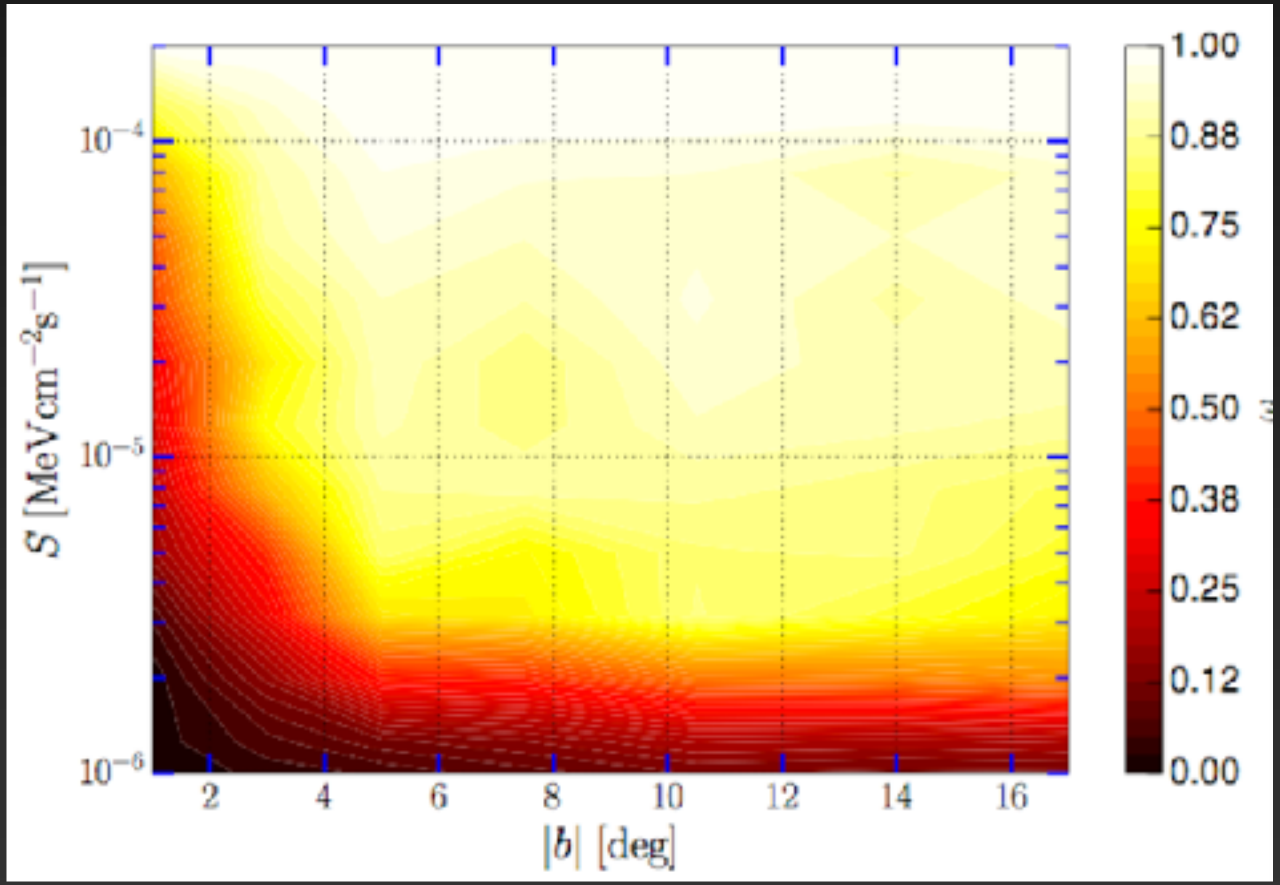


Macias et al. (2016)

Uncertainties in the Detection Probability

- The spatially variable detection probability of point sources must be carefully considered.
- Dim sources near the galactic center will never be observed.
- Bright distant sources will always be observed.
- By building a sensitivity map in flux space and as a function of angular position, the number of detected pulsars in each location and flux bin can be quickly calculated based on the modeled number.





Calculating the Likelihood Fit

$$N^{\text{obs}}_{i,j,k} = \sum_m \Omega_{i,j,k,m} \cdot N^{\text{model}}_{i,j}(S^{\text{true}}_m)$$

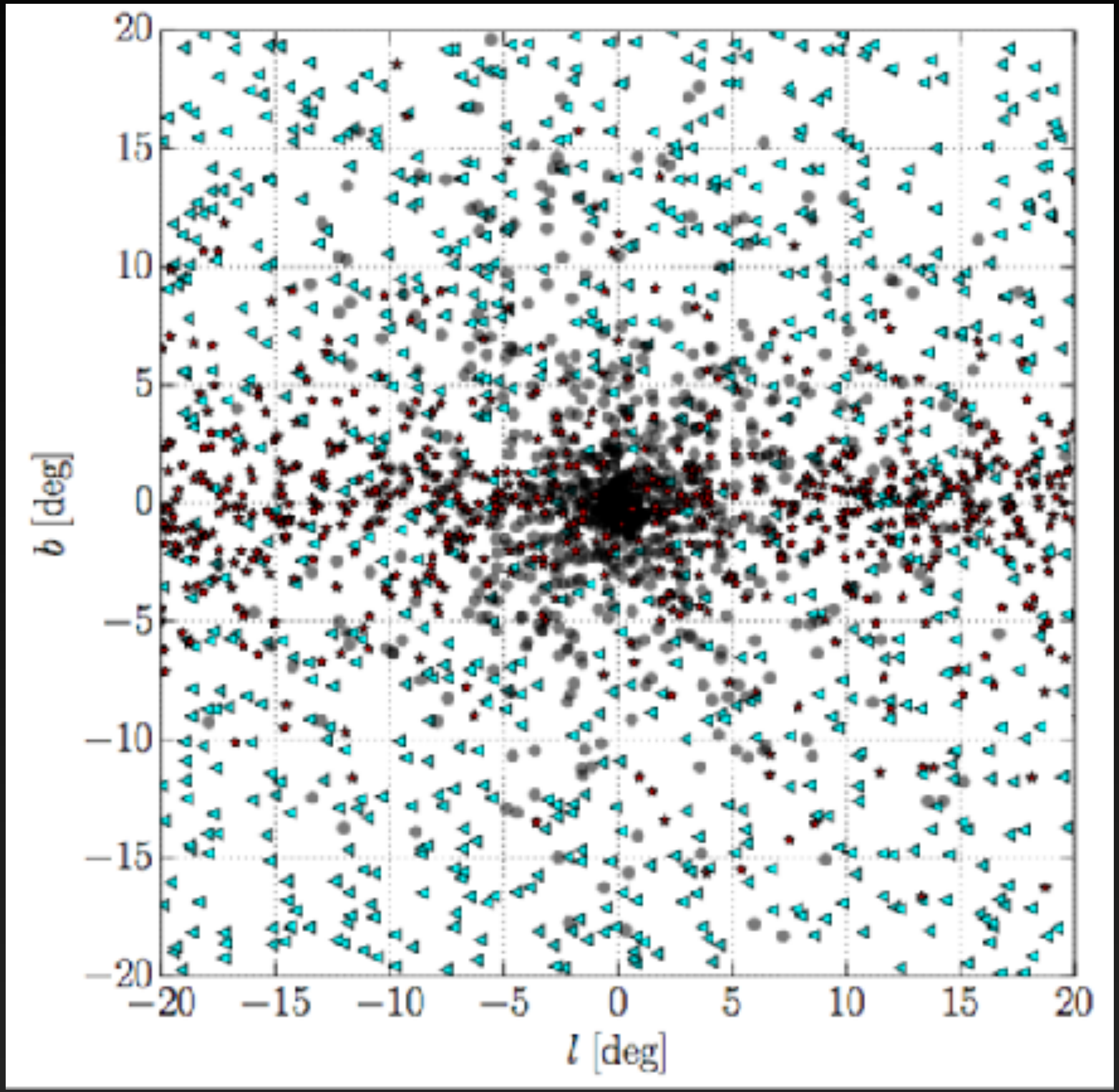
$$N^{\text{model}}_{i,j,k} = \sum_m \Omega_{i,j,k,m} \int_{\Delta\Omega_{i,j}} dl \cos b db \int_0^\infty ds \rho(r(l,b,s)) s^2 \times \int_{L^{\min}_m}^{L^{\max}_m} \frac{dN}{dL} dL, \quad (3)$$

$$\log(\mathcal{L}) = \sum_{i,j,k} N^{\text{obs}}_{i,j,k} \log(N^{\text{model}}_{i,j,k}(\lambda)) + N^{\text{model}}_{i,j,k}(\lambda) + \mathcal{L}_{\text{prior}},$$

- Calculate log-likelihood of simulated model by determining number of observable pulsars in each angular bin (i,j), and energy flux bin (k), comparing this to the new point source catalog.
- These results are calculated in spatial bins of either 3.3° or 6°
- This produces fits and uncertainties on the values N^{model} for the disk, bulge, and blazar components.

Results

- The best fit model is found to include:
  - 1300 bulge PSRs in 40°x40° ROI
  - 2800 disk PSRs in 40°x40° ROI
- Statistical preference of TS 54-69 for a bulge pulsar population.
- This model predicts the detection of:
  - 77 bulge PSRs
  - 128 disk PSRs
  - 92 background blazars



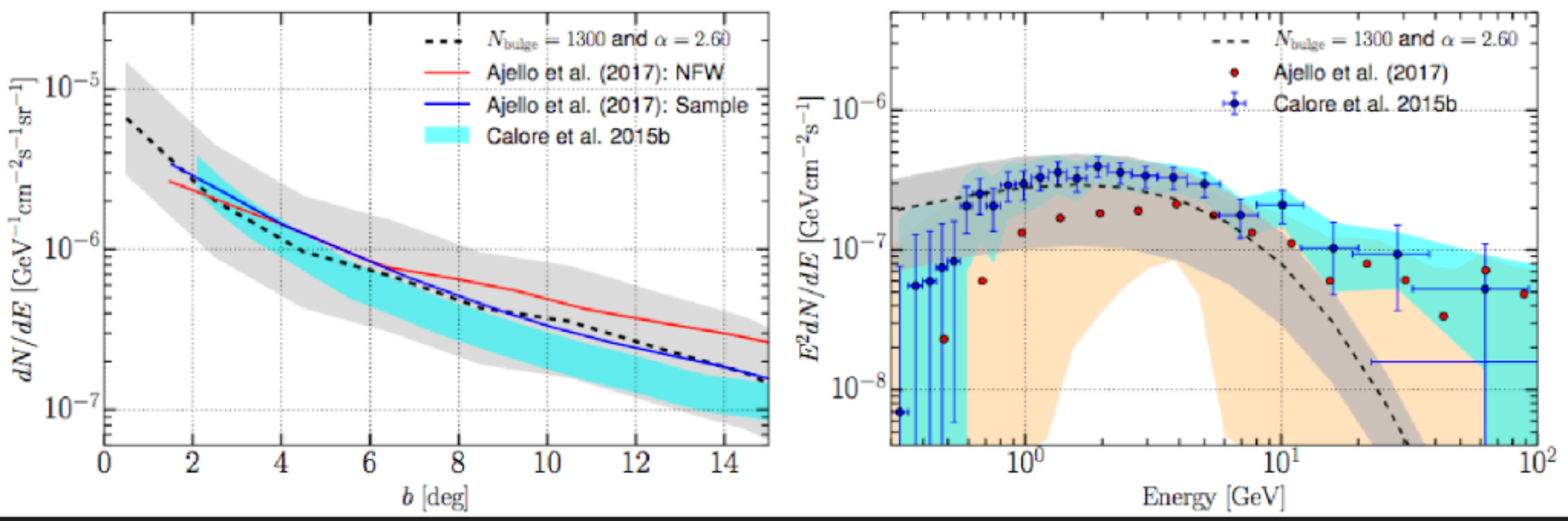
one realization:
blazars = cyan triangles
disk PSRs = red stars
bulge PSRs = black stars

Complete Results

	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

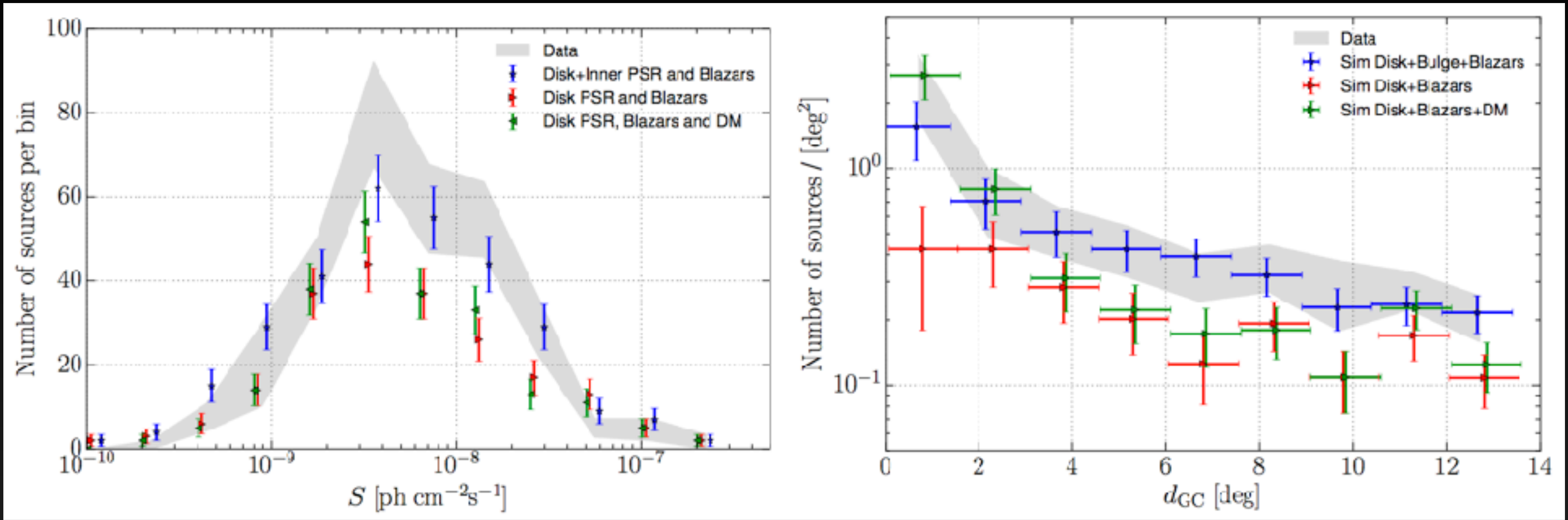
- Best fit results and uncertainties on the entire model.
  - z0 is the scale height of the Lorimer pulsar distribution
  - β is the luminosity distribution (dN/dL for pulsars).
  - α is the inner slope of the bulge population
- The top and bottom blocks use spatial bins of 3.3° and 6°

Spectrum and Luminosity Function



- These models recover the key pulsar observables:
    - Radial dependence (though this is partially by fiat)
    - Pulsar Spectrum

Fitting the Number of Observed Sources

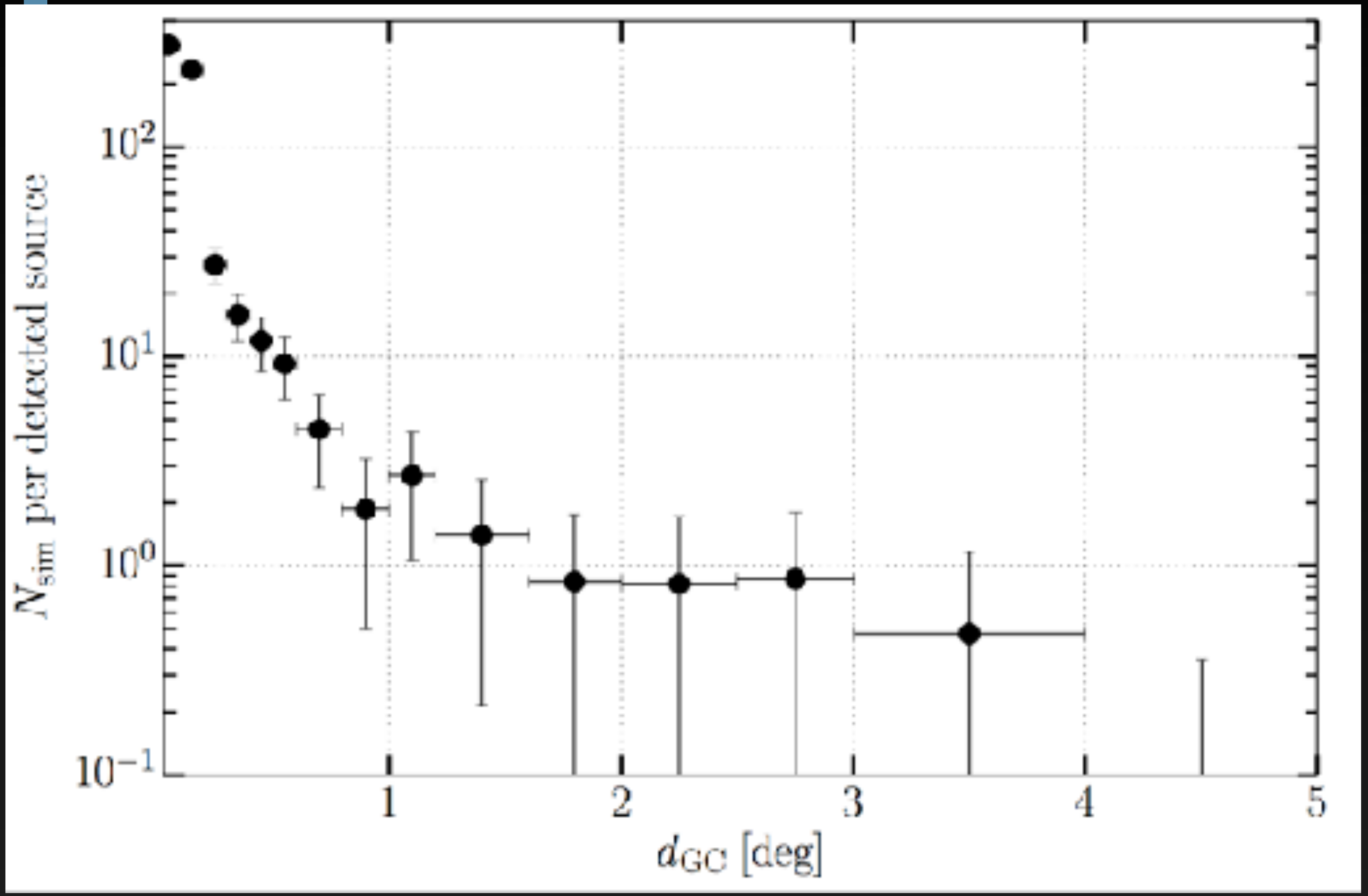


- Models that utilize bulge pulsars provide a better fit to the number of sources observed in both luminosity space, and as a function of galactic-center distance.

- On the other hand, models that use only the disk population, along with the expected number of background blazars and dark matter annihilation, do not produce the observed point source population.

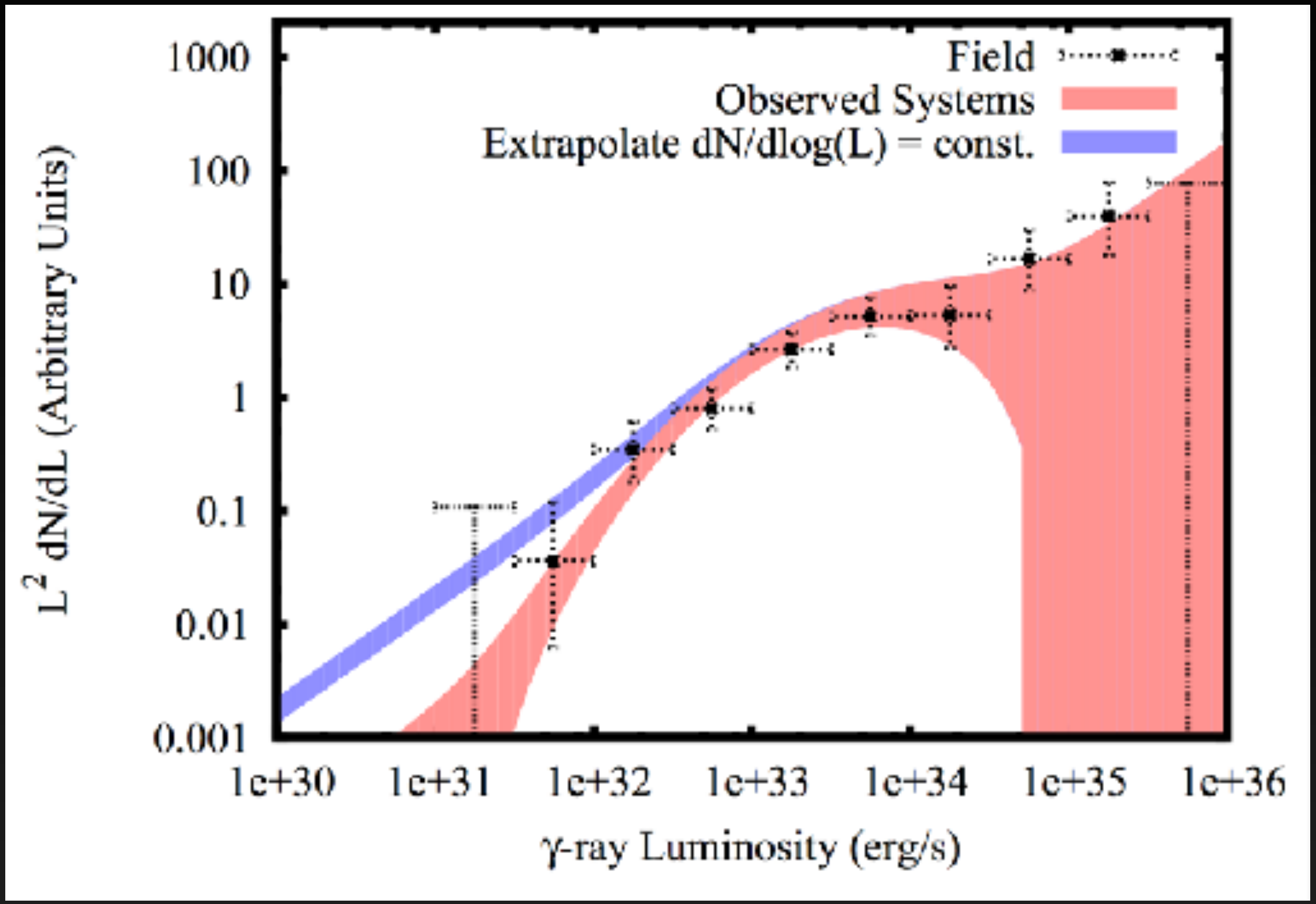
Producing a Complete Model

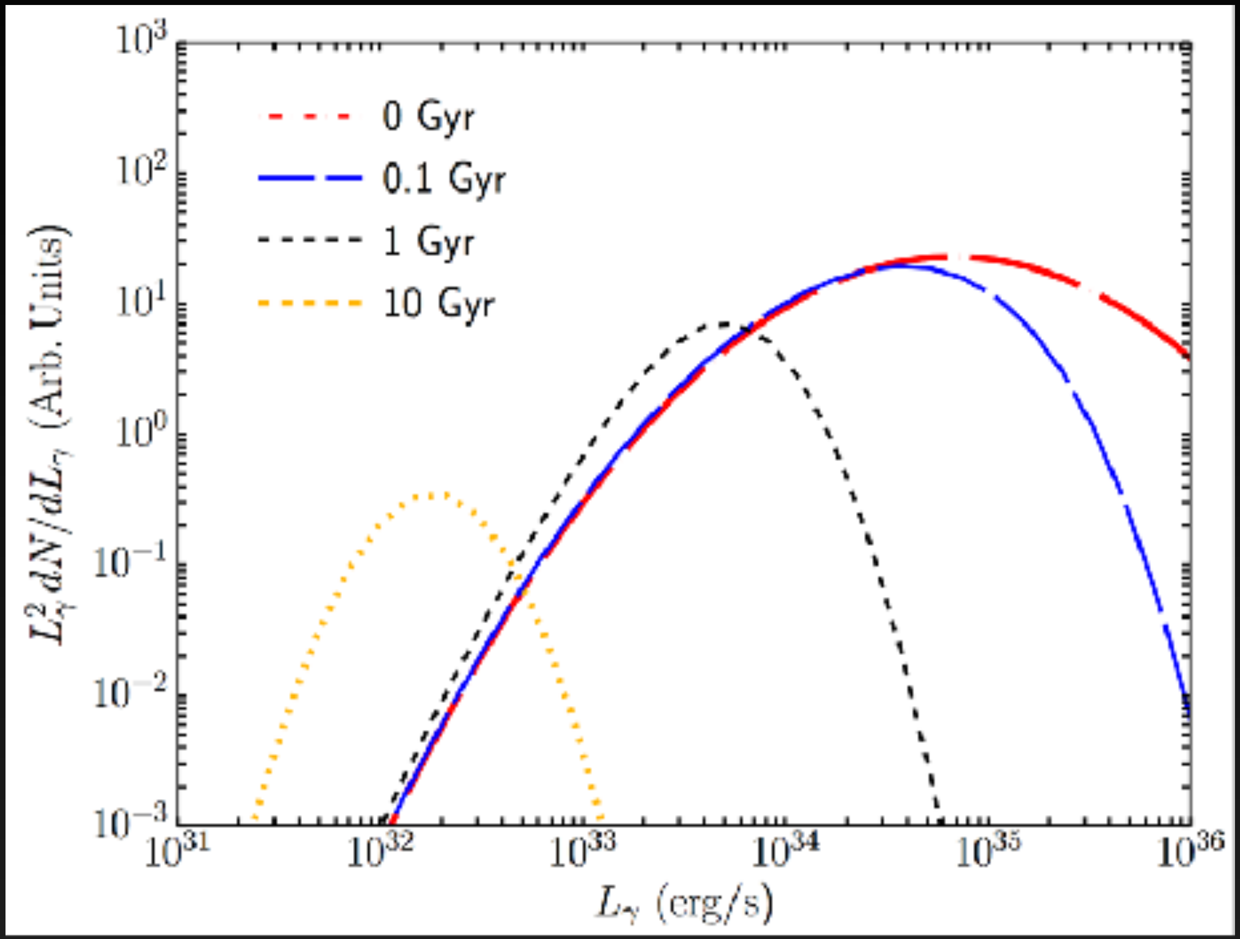
- Near the galactic center, most observed pulsars include contributions from many sources in the simulation.



- Outside of the galactic center - most detected pulsars are compatible with the location of only one simulated pulsar, bringing credence to the idea that the source luminosity function is being properly reconstructed.

Going Back - Detectable Sources?





- Utilizing the luminosity distribution of pulsars in the field produces too many bright (detectable) pulsars, compared to observations. (Hooper et al. 2013, 2015)

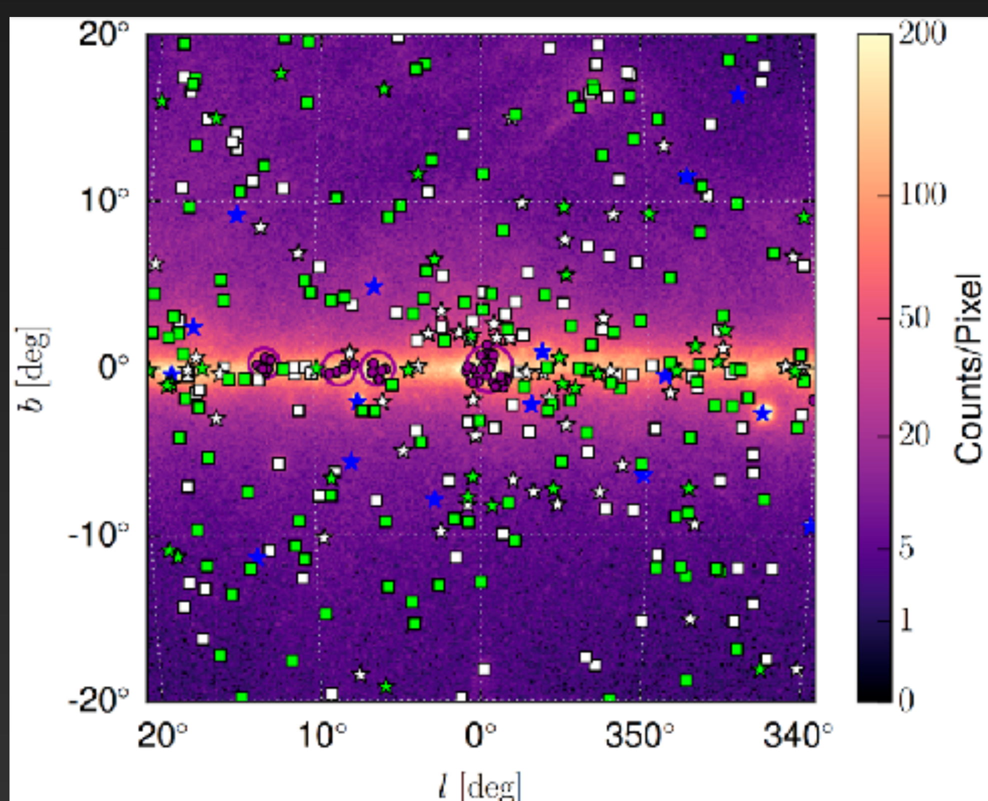
- This puts us into a new regime, with regard to previous literature. Previous papers have argued that ~100 bulge pulsars would be expected to be detected - are they being detected now?

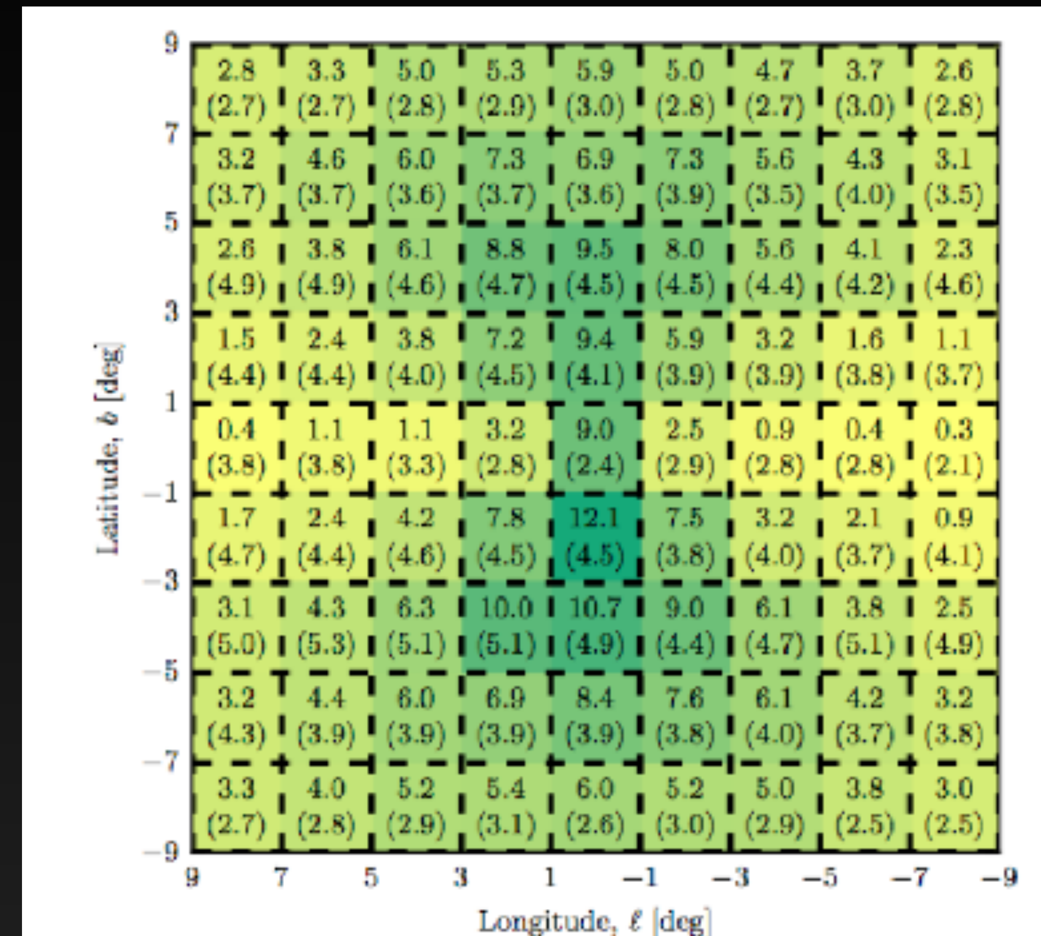
Calore et al. (2015)

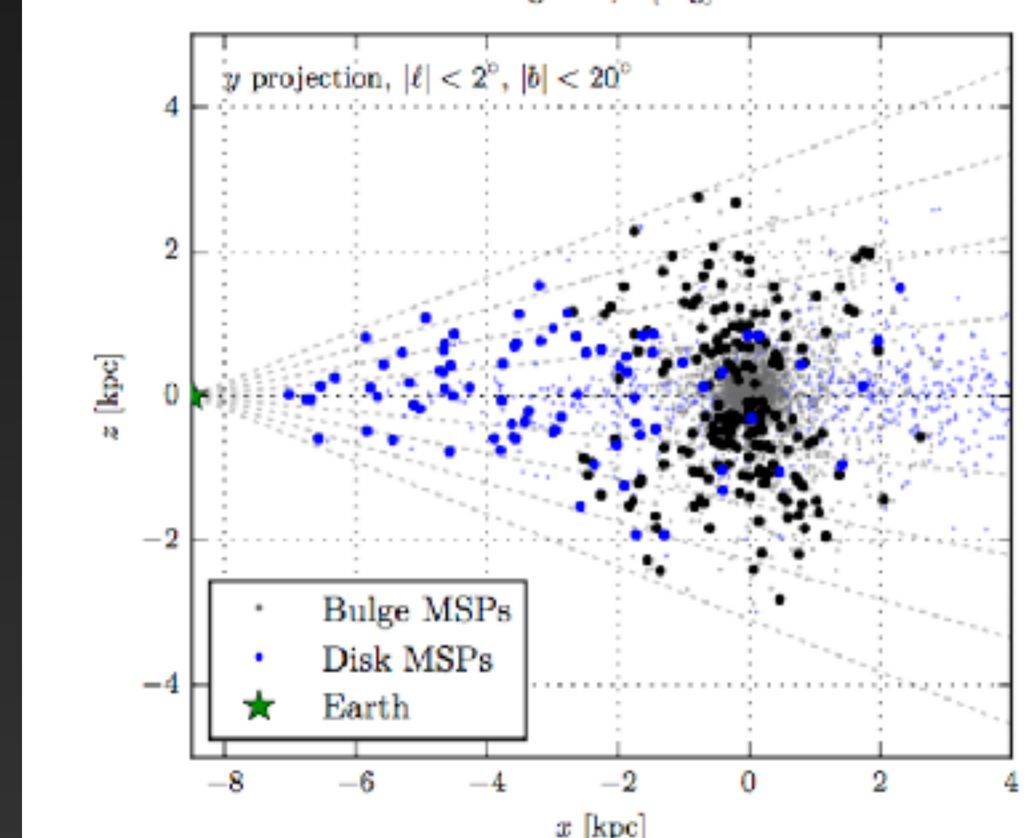
Fortunately the Pulsar Hypothesis is Testable

- Radio Observations with GBT targeted at gamma-ray hotspots would be expected to find ~5-10 MSPs with a 200 hr commitment.

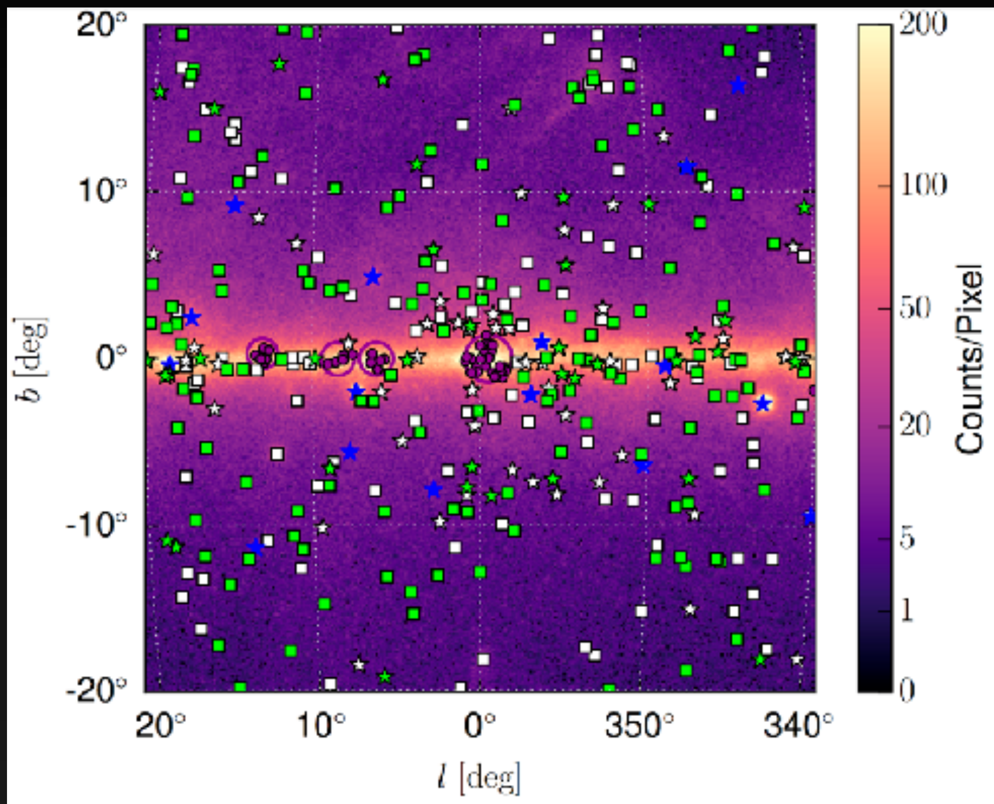
- Fortunately, SKA observations are likely to conclusively find MSPs in the GC, or rule out this scenario.

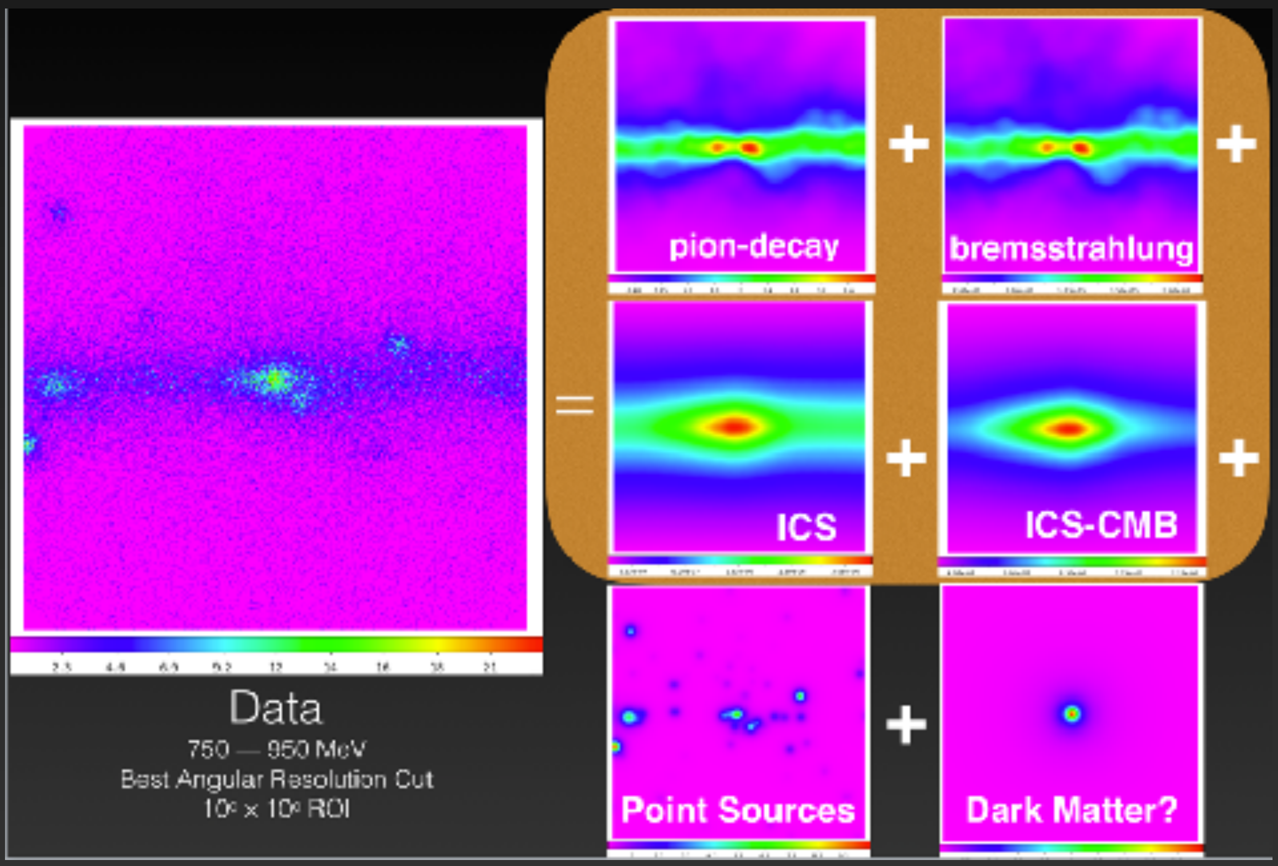




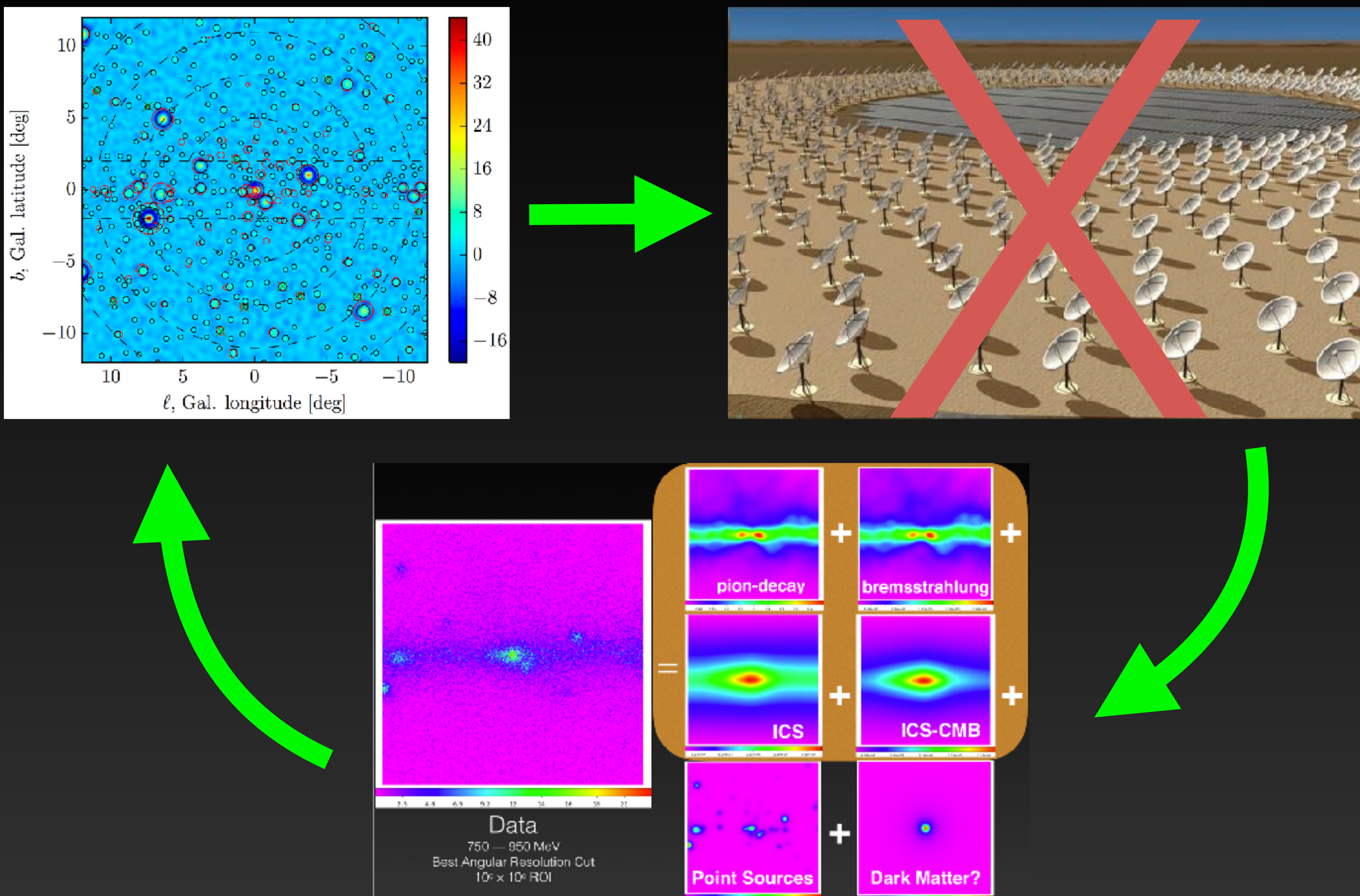


Proving the Pulsar Interpretation





Can this be proven in the negative?



Conclusion

1.) The Fermi-LAT collaboration has built a sophisticated model for the point source population near the galactic center. This has detected nearly 200 new point sources, and has provided spectral information indicating that a large number of these sources are pulsars.

2.) By breaking down this population into a morphology representative of the galactic disk, and a new morphology representative of the galactic bulge, they have shown that many of the new sources appear to be produced by the bulge population.

3.) The smoking gun signal would be to correlate these new point sources with radio pulsars that can be placed in the galactic bulge. This will require follow-up with sensitive radio instruments. However, the gamma-ray source locations are important in motivating follow-up radio surveys.