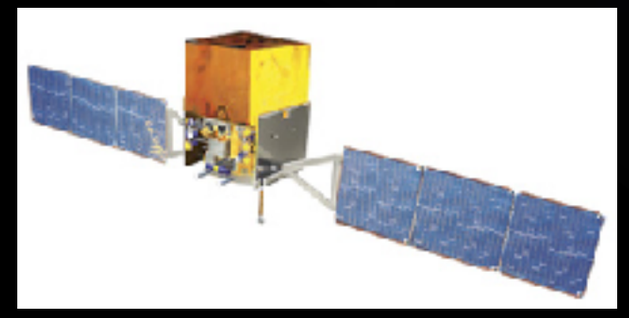
Testing the Galactic Center Excess with the Known Catalogue of Gamma-Ray Point Sources

In collaboration with
Yi-Ming Zhong (KICP), Sam McDermott (Fermilab) & Patrick Fox (Fermilab), arXiv:1911.12369

Ilias Cholis, 4/19/2020

third dimension (not shown) — energy

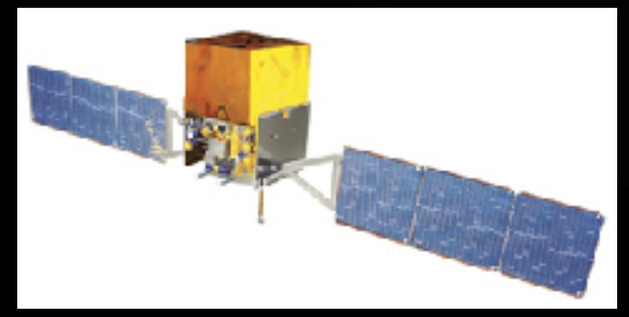


latitude, b ⟶

Fermi-LAT gamma-ray sky

⟵Galactic longitude, ℓ

third dimension (not shown) — energy



latitude, b ⟶

Inner Galaxy

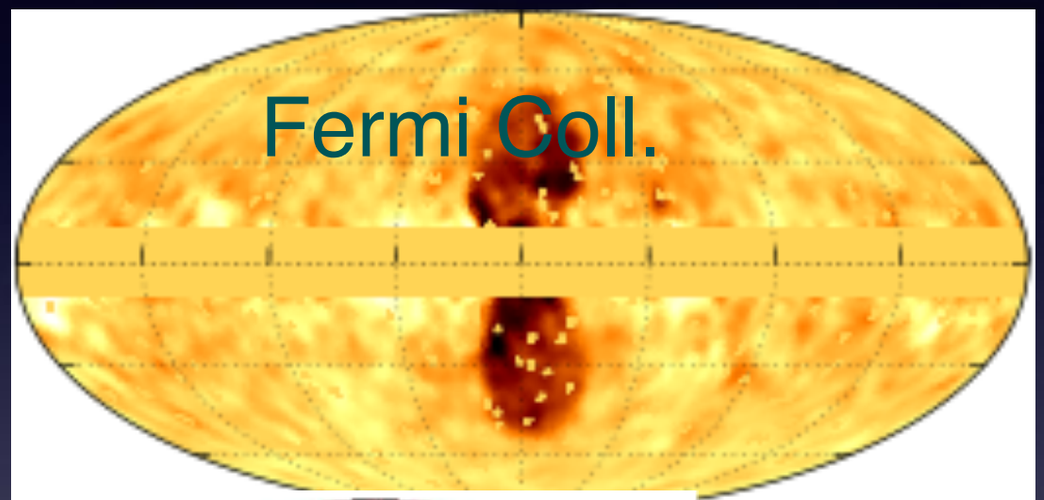
Galactic Center

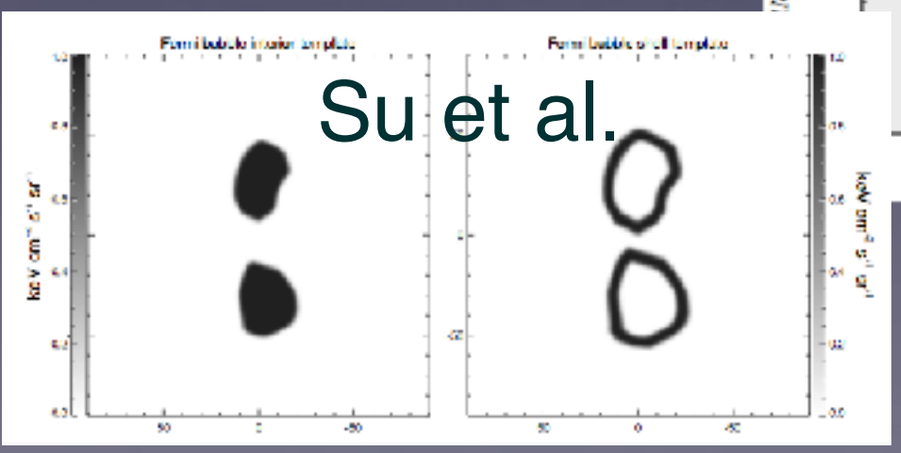
Fermi-LAT gamma-ray sky

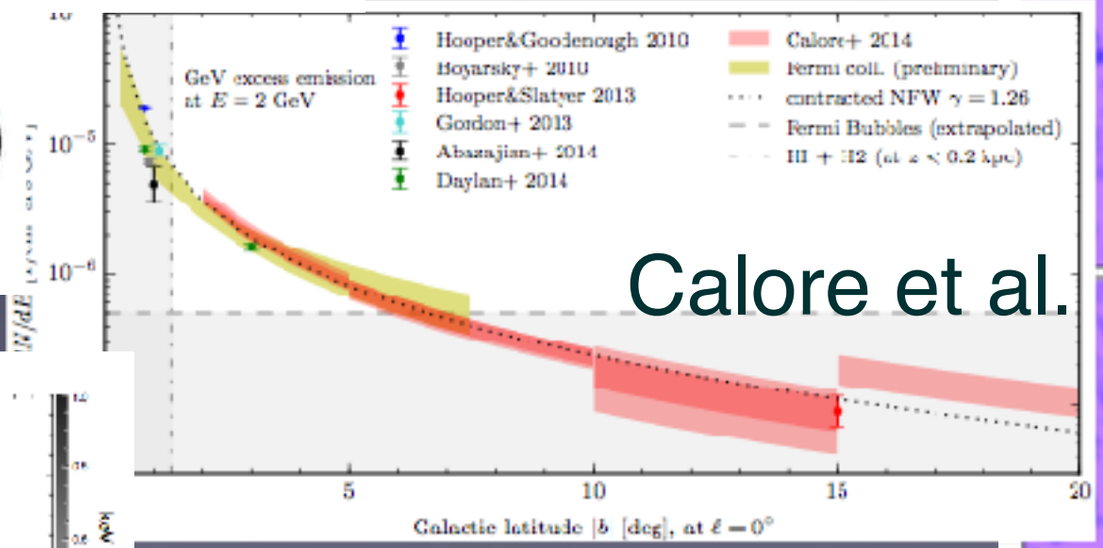
⟵Galactic longitude, ℓ

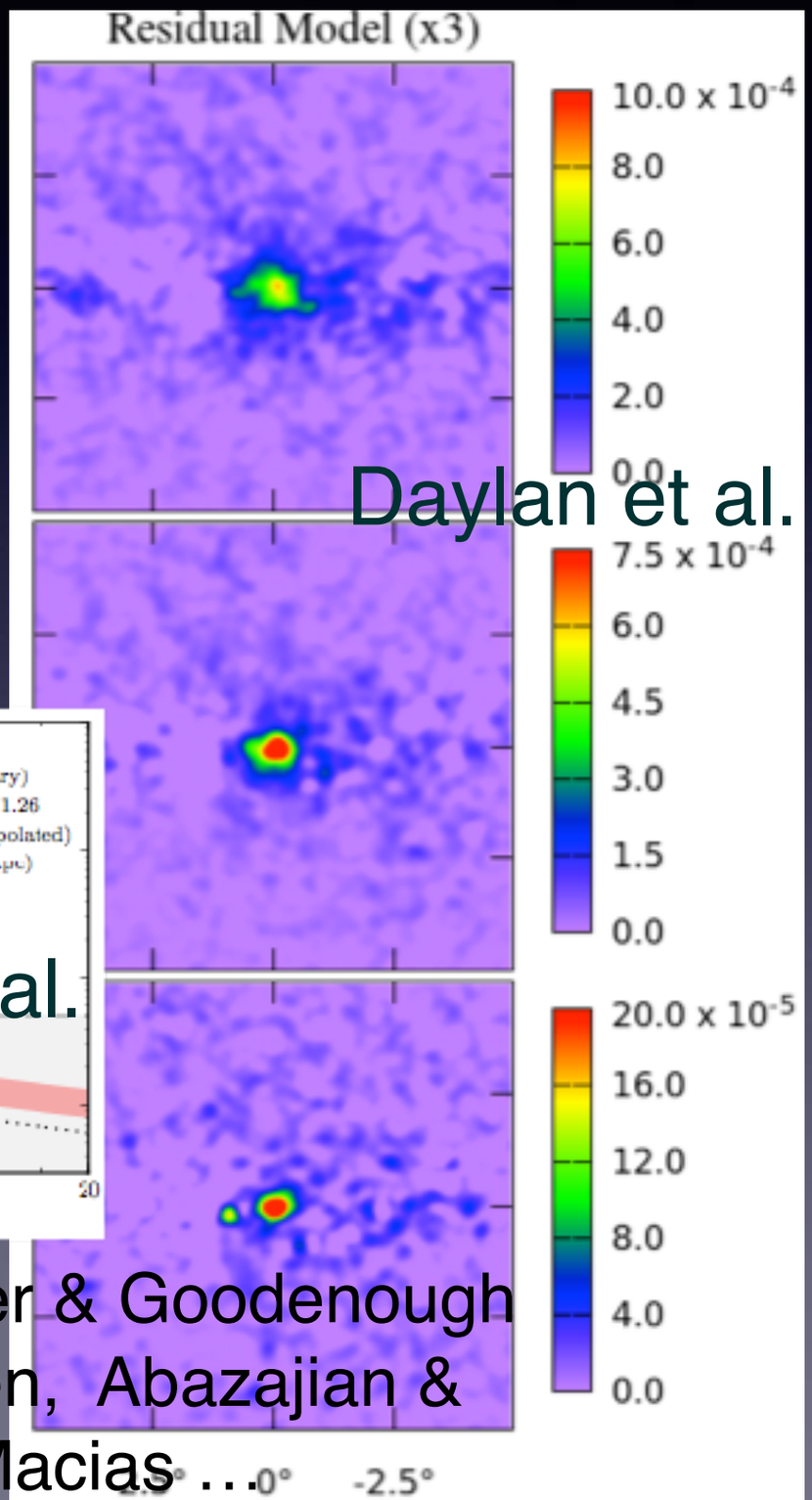
Studies of the Fermi Data

The galactic center and inner galaxy is a very interesting region.
Interesting CR activity. Burst? Point Sources.
A possible signal of Dark Matter Annihilation?



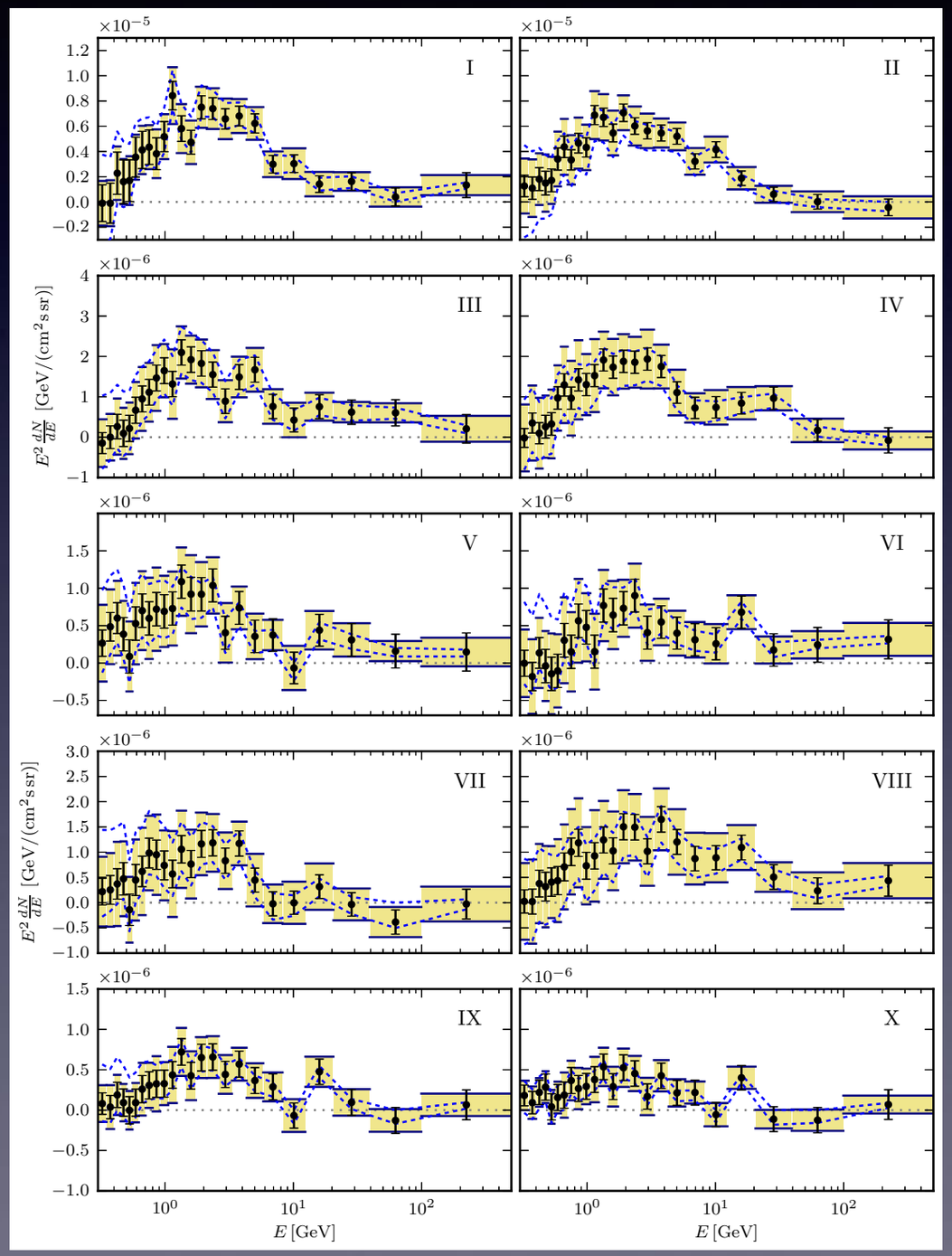




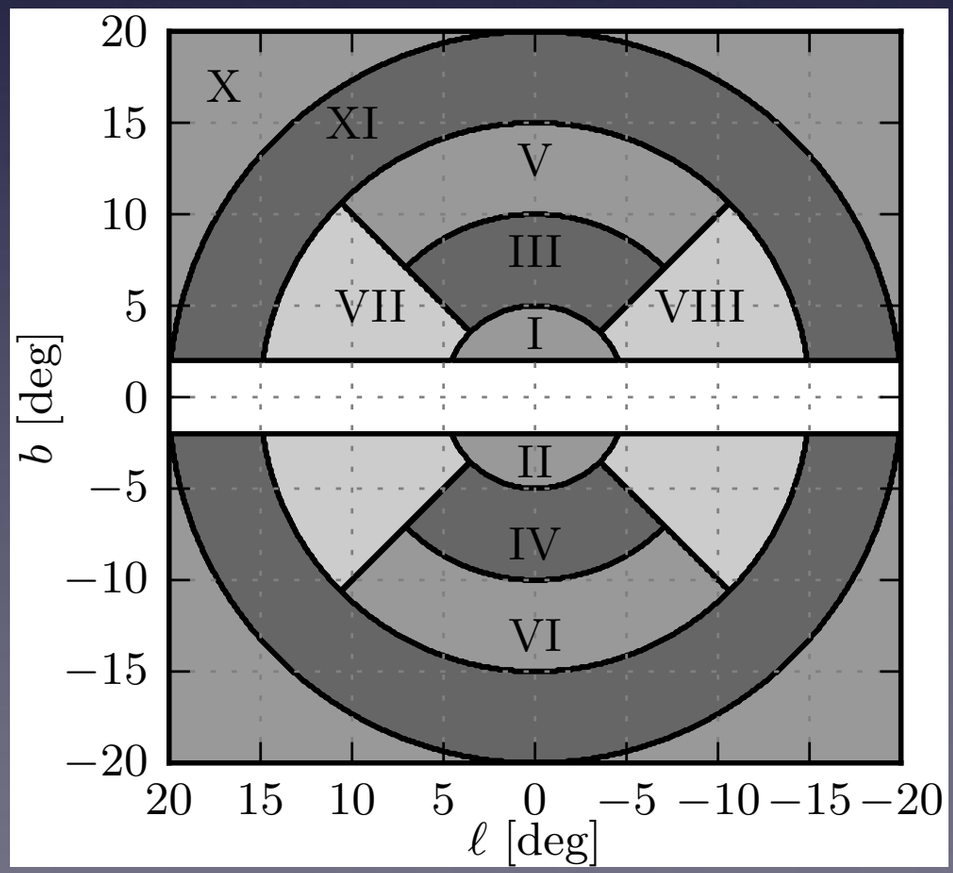


Also works from Hooper & Goodenough 2009-10, Hooper Linden, Abazajian & Kaplinghat,Gordon & Macias …

Robust to diffuse gamma-ray emission uncertainties



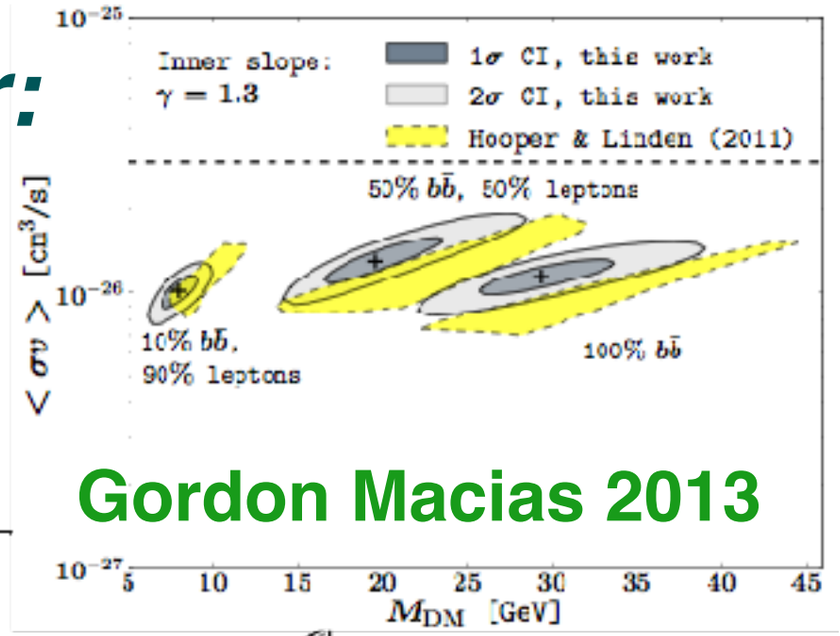
The GCE is present everywhere in the inner galaxy



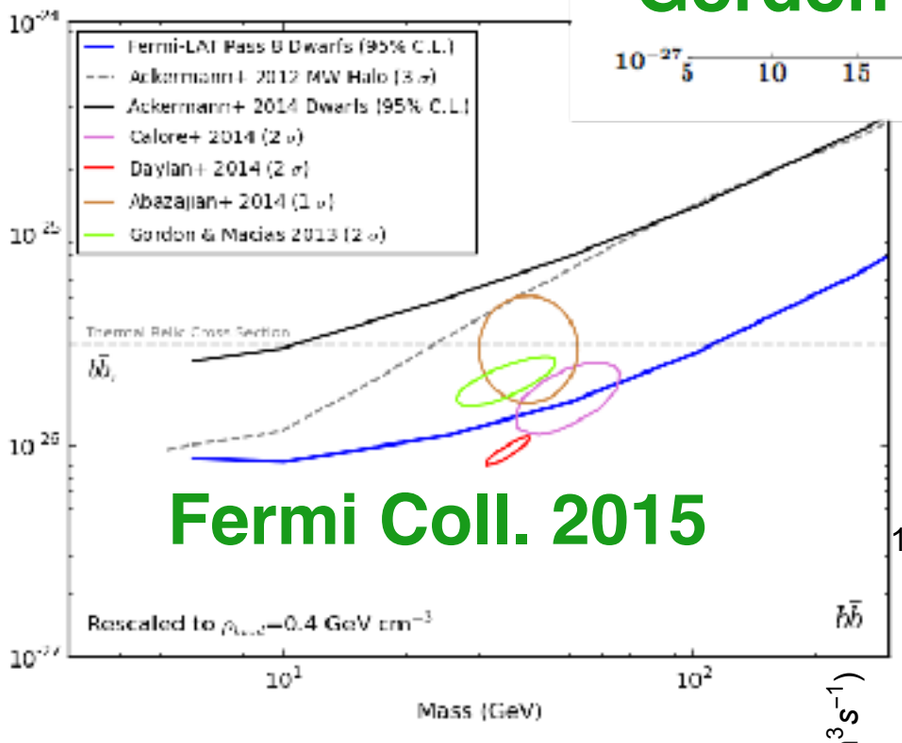
Calore, Cholis, Weniger, JCAP 2015

What are the explanations?

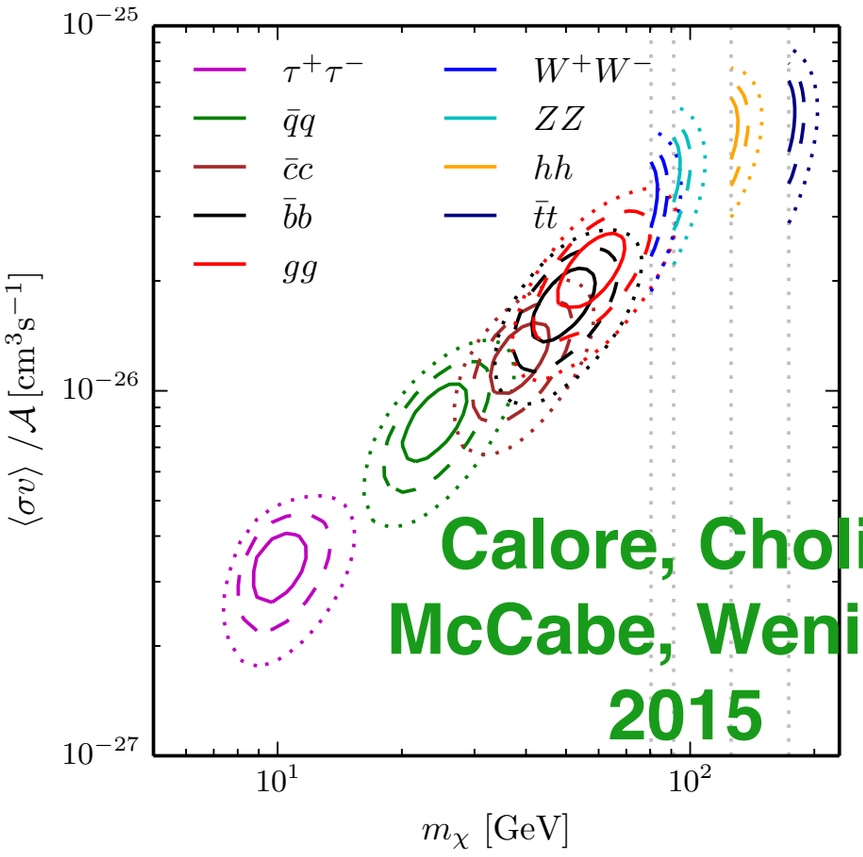
Dark Matter:



Gordon Macias 2013

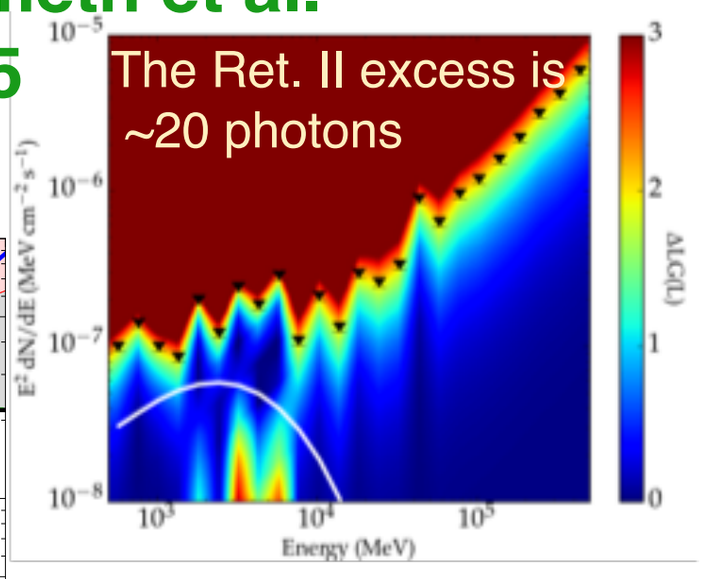


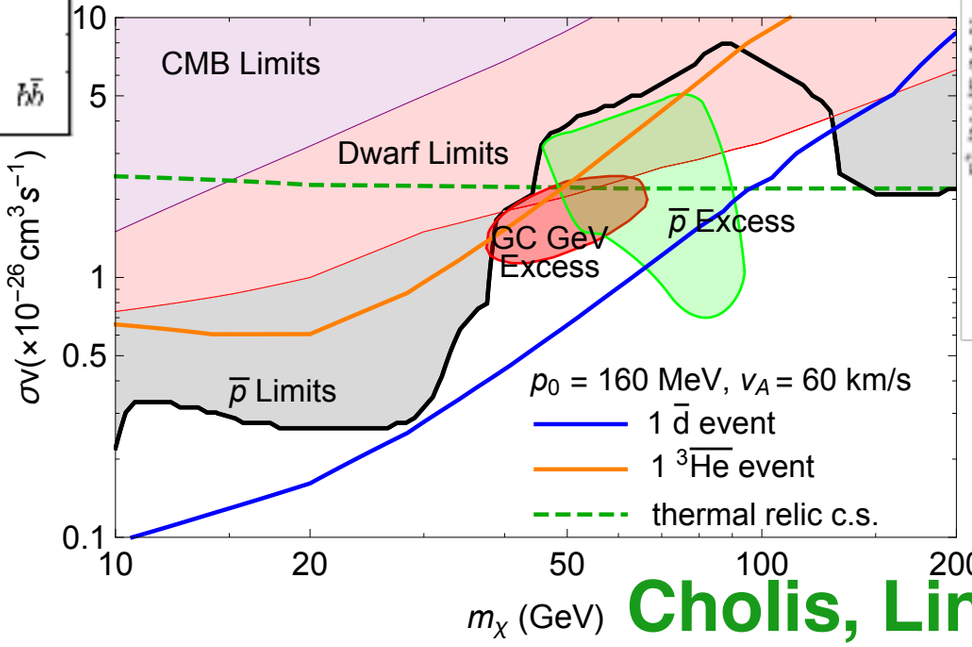
Fermi Coll. 2015



Calore, Cholis, McCabe, Weniger, 2015

Geringer-Sameth et al. 2015



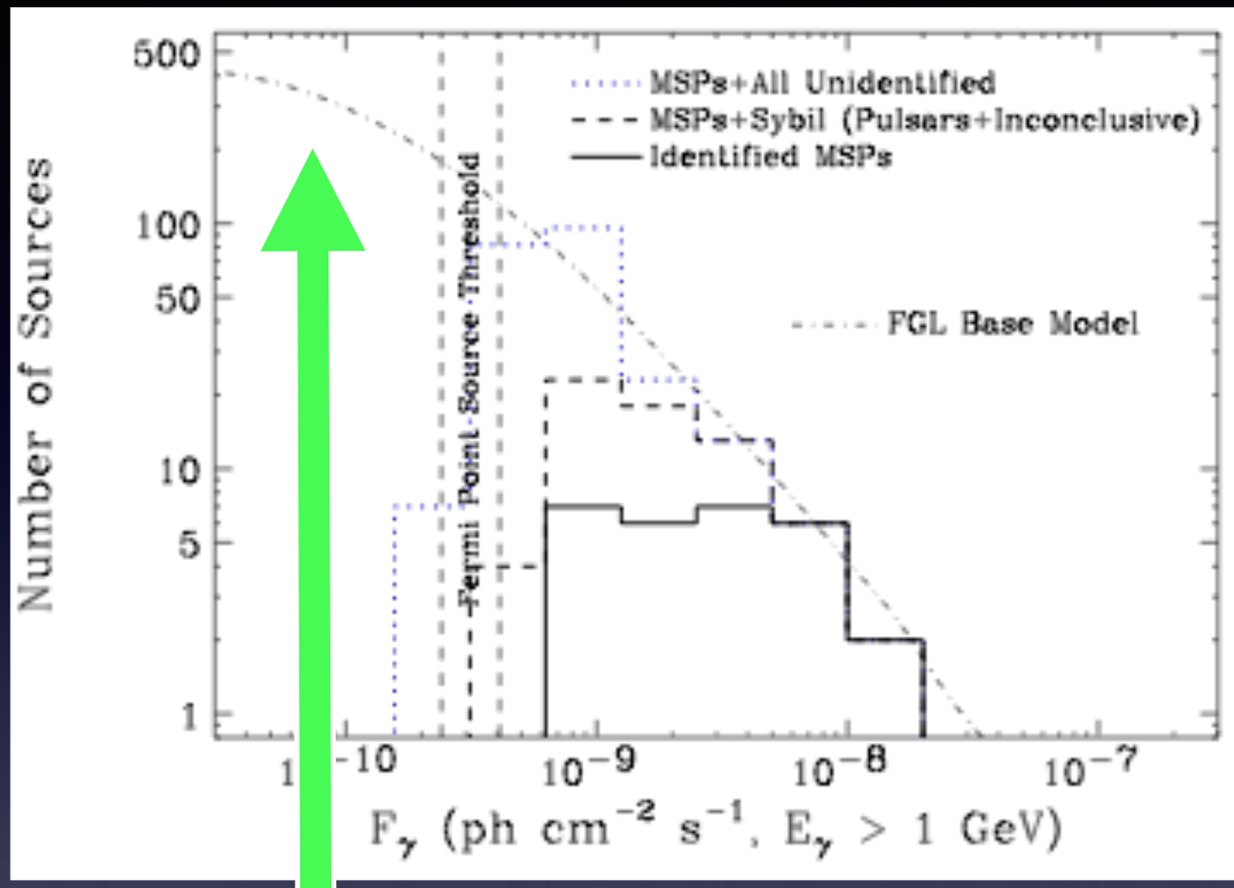


Cholis, Linden, Hooper 2020

Alternative work related to the Galactic Center the GeV excess and it's interpretations

Millisecond Pulsars:

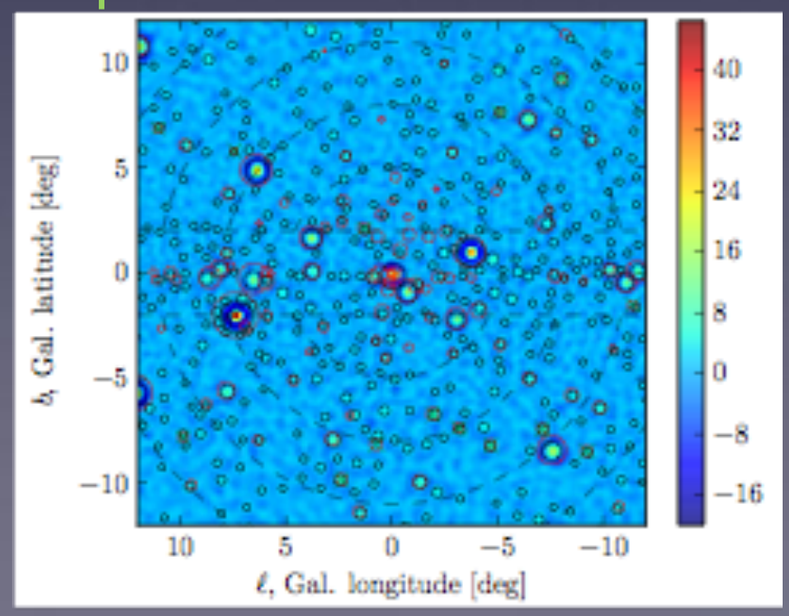
Hooper, IC, Linden, Siegal-Gaskins & Slatyer PRD 2013 (1305.0830), (<10% of total)
Calore, Di Mauro, Donato ApJ 2014 (1406.2706) (<10%)
IC, Hooper, Linden JCAP 2015 (1407.5625) NOT REALLY ABOVE 5deg
Calore, Di Mauro, Donato, Hessels, Weniger (1512.06825) MAYBE YES
Brandt, Cocsis ApJ 2015 YES BUT SPECIAL MSPs
O'Leary, Kistler, Kerr, Dexter 2016 PROBABLY



As reference we need 1-3x10^3 MSPs in the inner 2 kpc bellow threshold

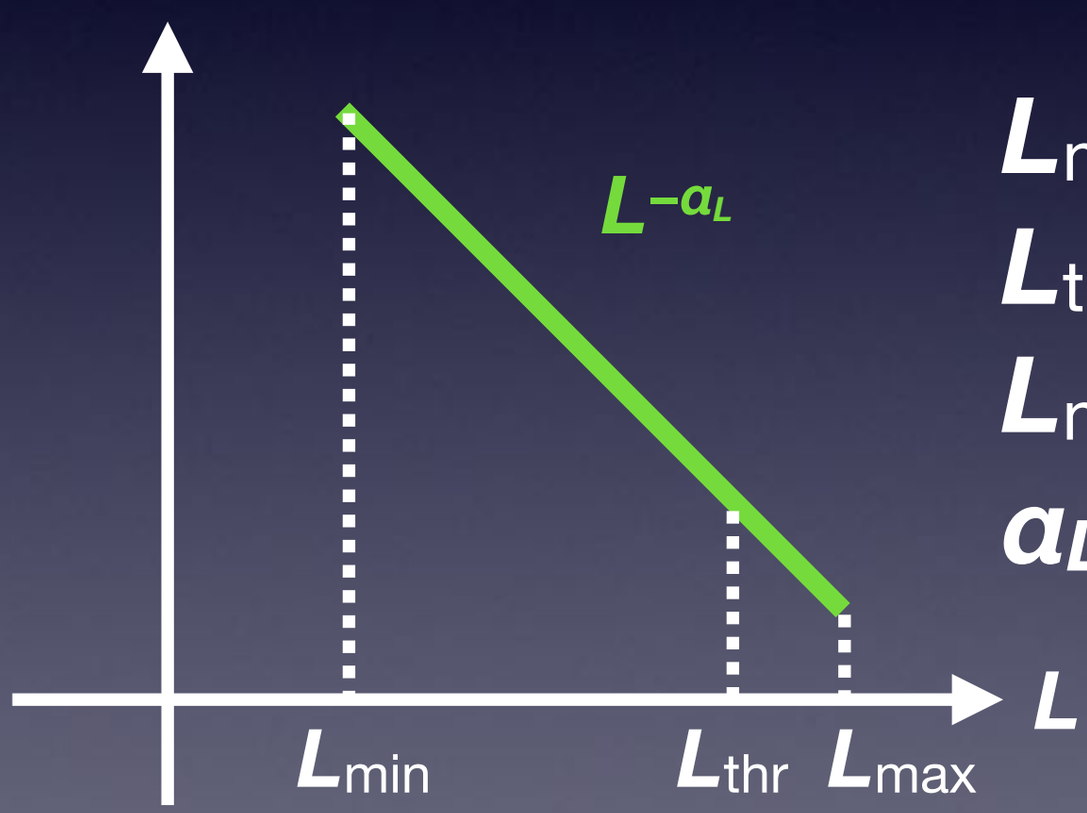
Sensitivity analyses on point-sources and astrophysics modeling:

Bartels, Krishnamurthi, Weniger PRL 2016
Lee, Lisanti, Safdi, Slatyer, Xue PRL 2016
Huang, Ensslin, Selig JPCS 2016.



A Central Source Population

How to characterize a Central Source Population?



L_{min} → gamma-ray physics

L_{thr} → detection threshold

L_{max} → gamma-ray physics

α_L → theory prior

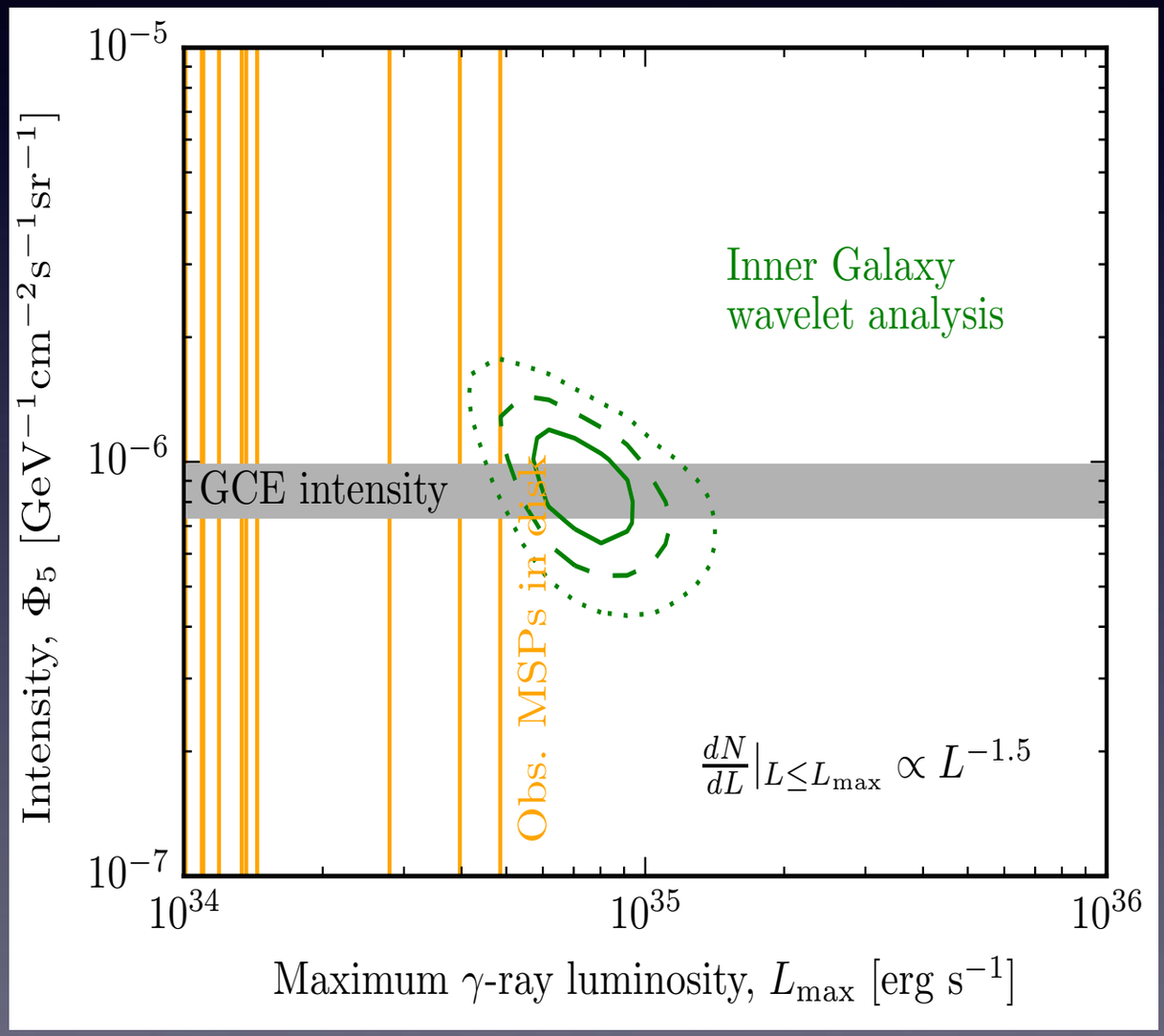
Prior peaked at $\alpha_L \sim 1$; strong preference for $\alpha_L \leq 1.5$ (various arguments)

0609359, 0610649, 1407.5583, 1411.0559, 1411.2980, …

A simple Question: Can the CSP Be Bright Enough?

- Given an assumption about the "luminosity function" (the dependence of N_{PS} on L_{PS}), can ask if "point source-y" PSs are compatible with unresolved PSs accounting for the GCE

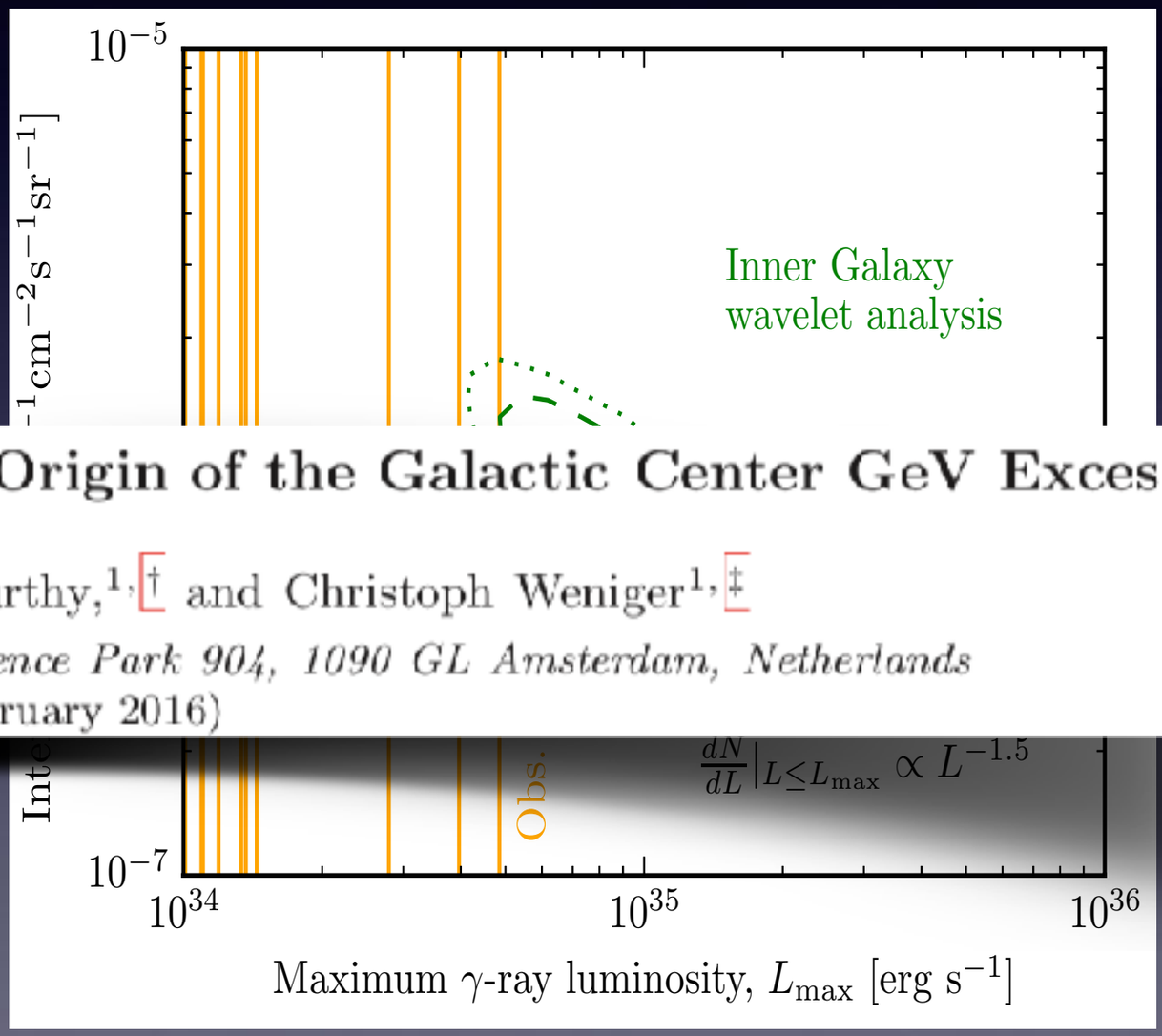
- Claim in 2015 was "yes" if the luminosity function had a power-law index α_L=1.5



Bartels et al., **1506.05104**

Yes, a CSP Can Be Bright Enough

- Given an assumption about the "luminosity function" (the dependence of N_{PS} on L_{PS}), can ask if "point source-y" PSs luminosity function had a power-law index α_L=1.5



Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

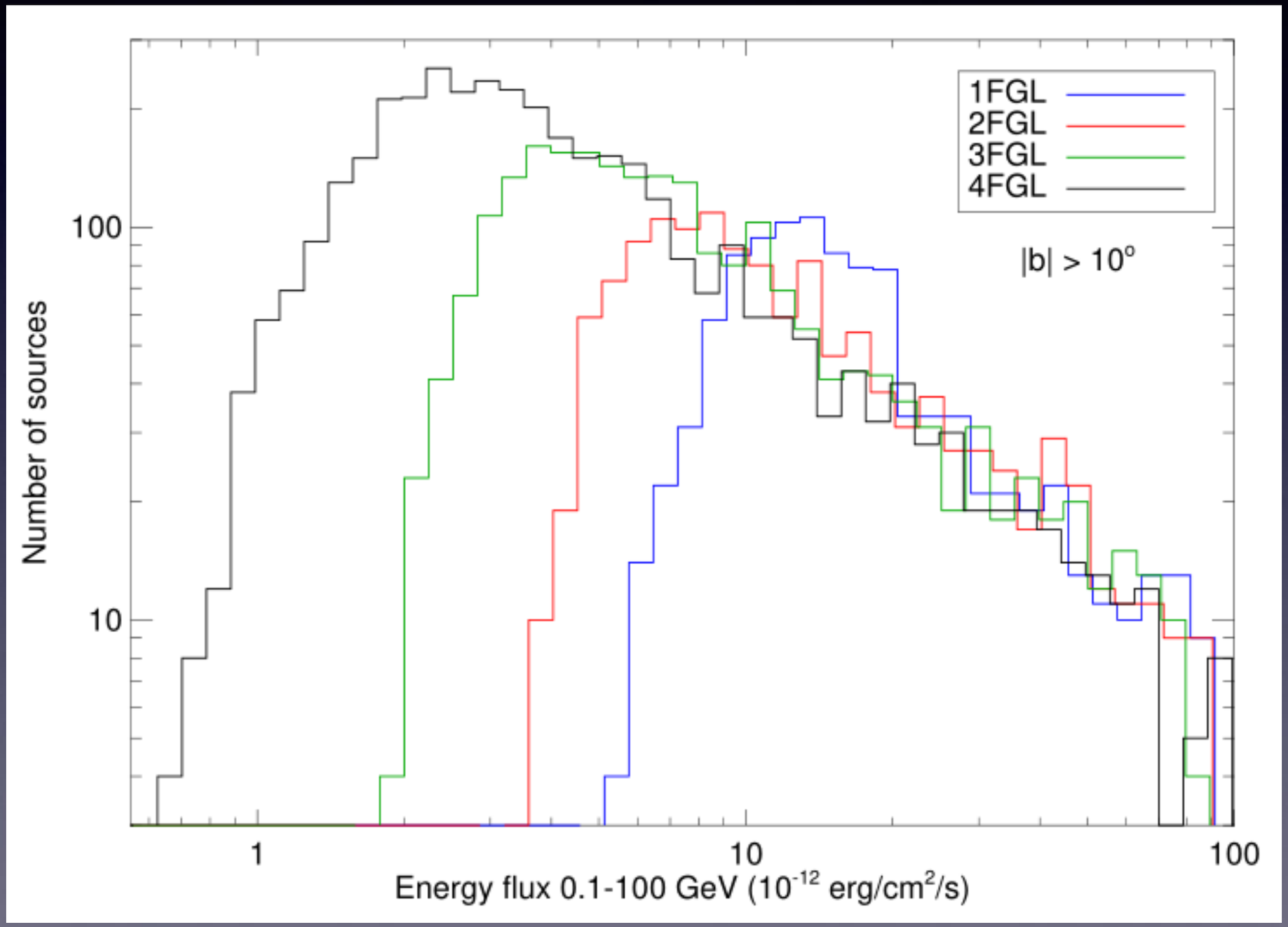
Richard Bartels,[1,*] Suraj Krishnamurthy,[1,†] and Christoph Weniger[1,‡]

[1] *GRAPPA Institute, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, Netherlands*

(Dated: 4 February 2016)

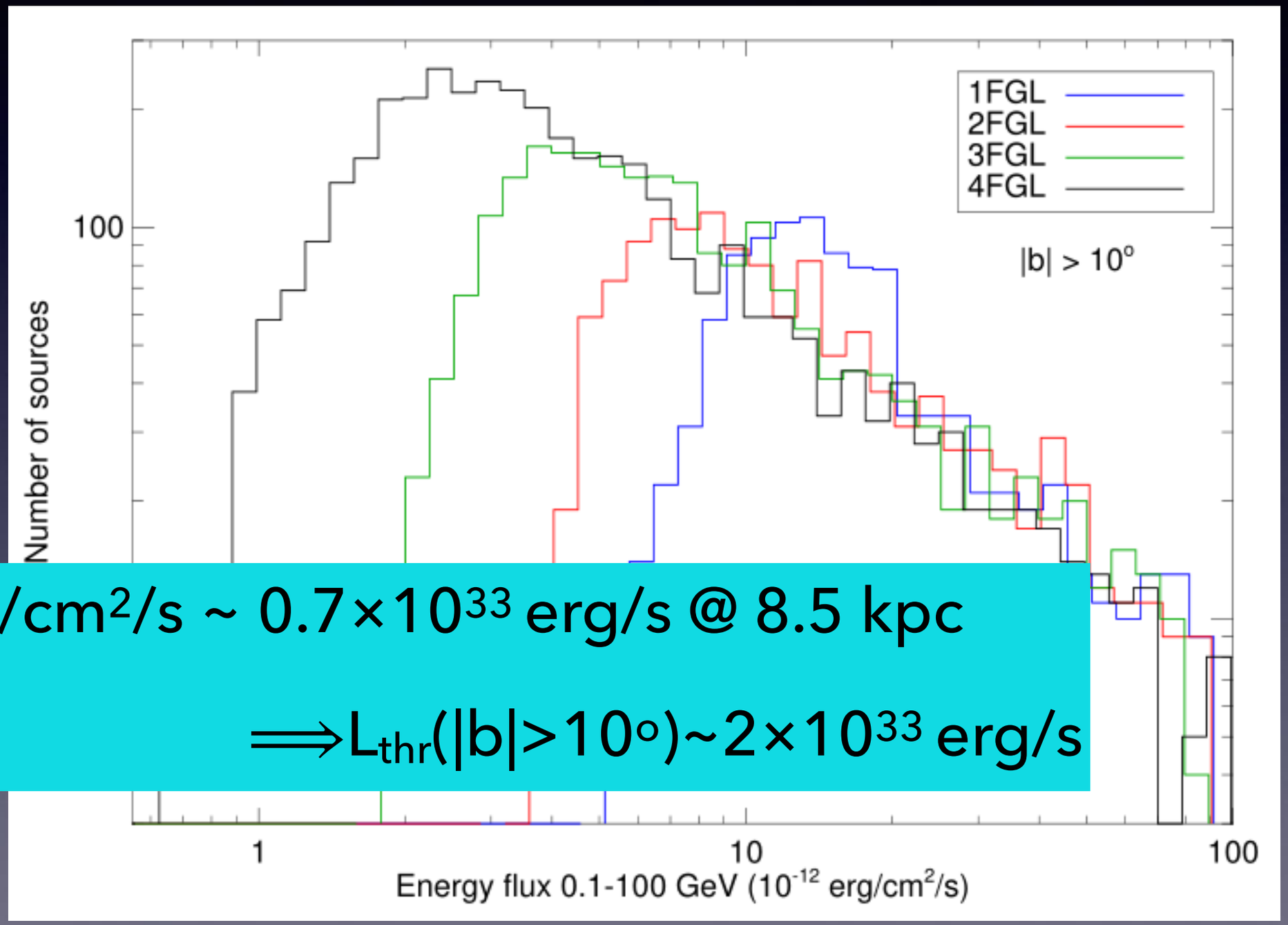
Bartels et al., **1506.05104**

The 4FGL Catalog



Abdollahi et al., **1902.10045**

The 4FGL Catalog

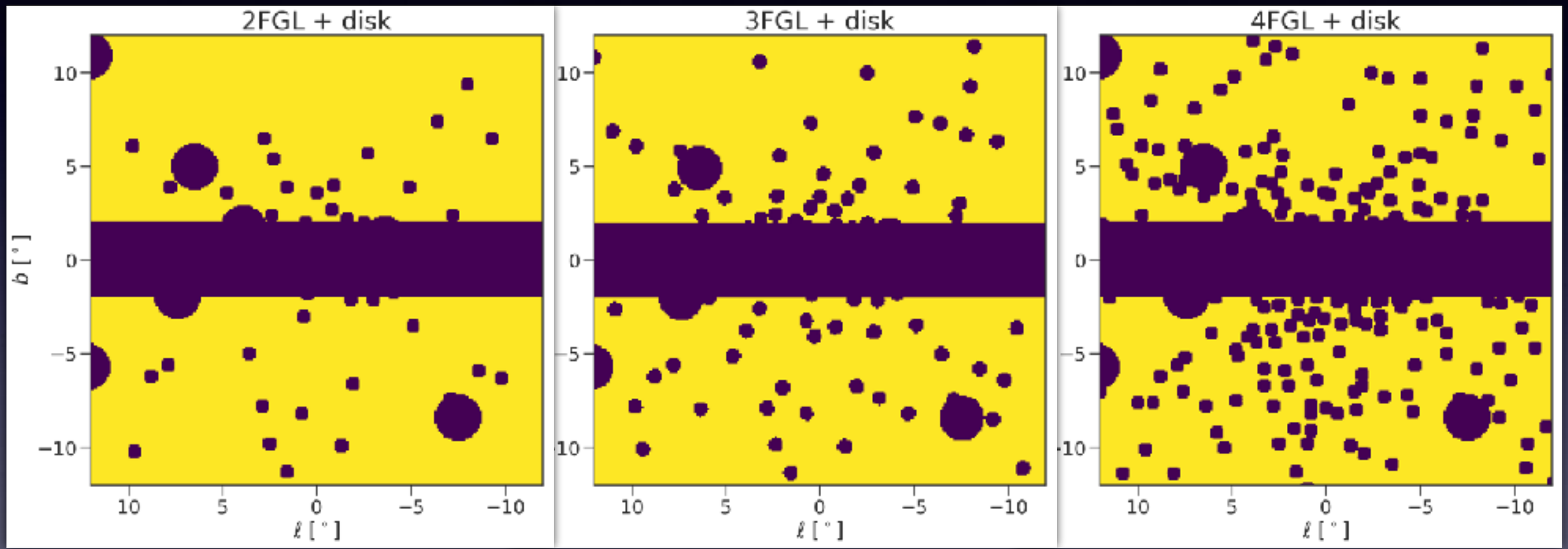


10^{-12} erg/cm^2/s ~ 0.7×10^{33} erg/s @ 8.5 kpc

$\Longrightarrow L_{thr}(|b|>10^{\circ})\sim 2\times10^{33}$ erg/s

Abdollahi et al., **1902.10045**

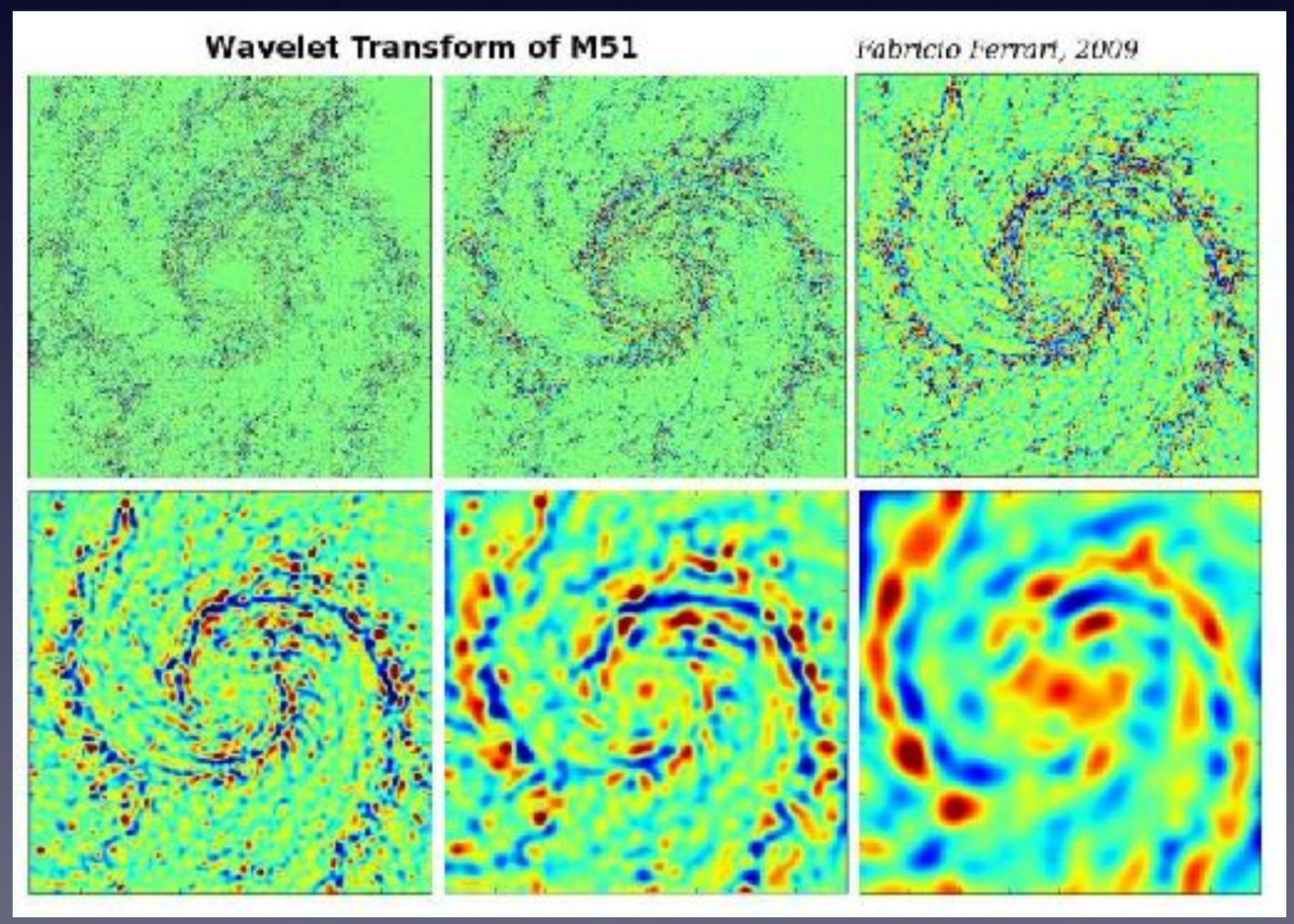
The Masks of different Fermi Catalogs (#FGL)



What are wavelets?

Wavelets have been used in image compression (JPEG), de-noising, fast signal identification, even in HEP data

Allow analysis of data in both time/space and frequency space

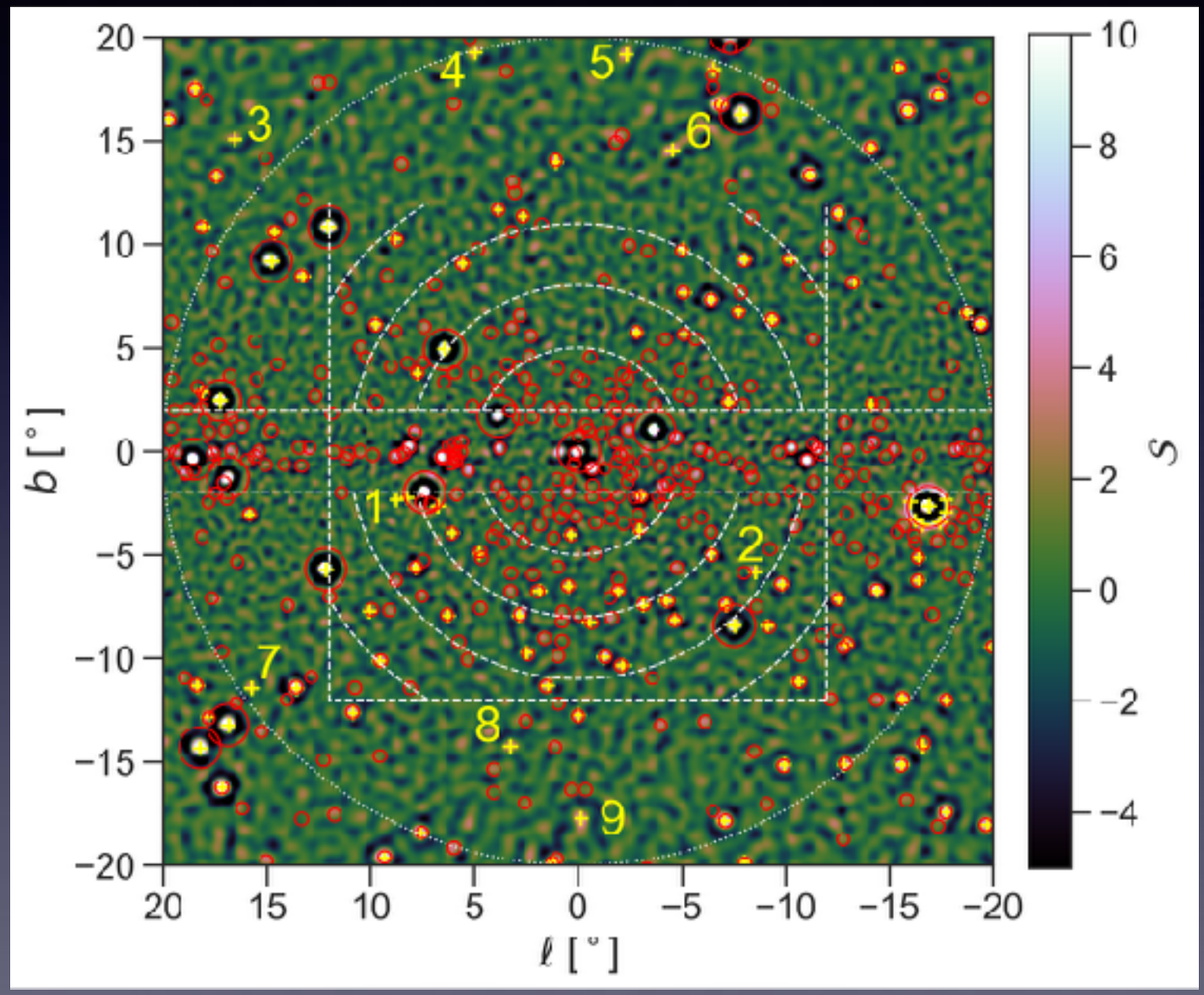


Different type of structures will have a different power at different levels of the decomposition (e.g. edges and other small scale structures vs larger scale variations).

Wavelets can find these different structures.

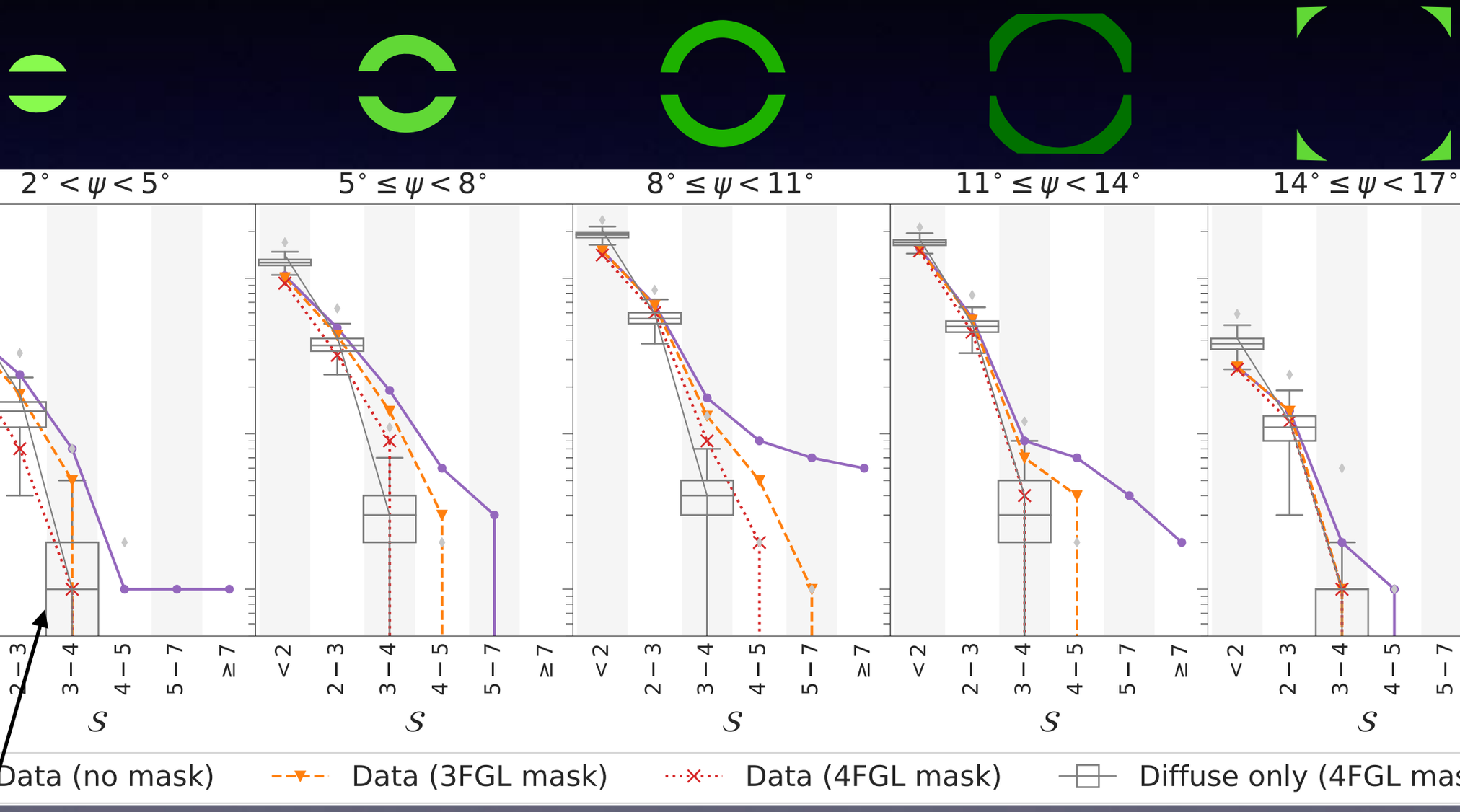
GCE: “Wavelet” Results

Zhong, McDermott, Cholis, Fox, 1911.12369



117 peaks (w/ S>4) ⊃ 109 peaks near 4FGL

Counting “Wavelet” Peaks



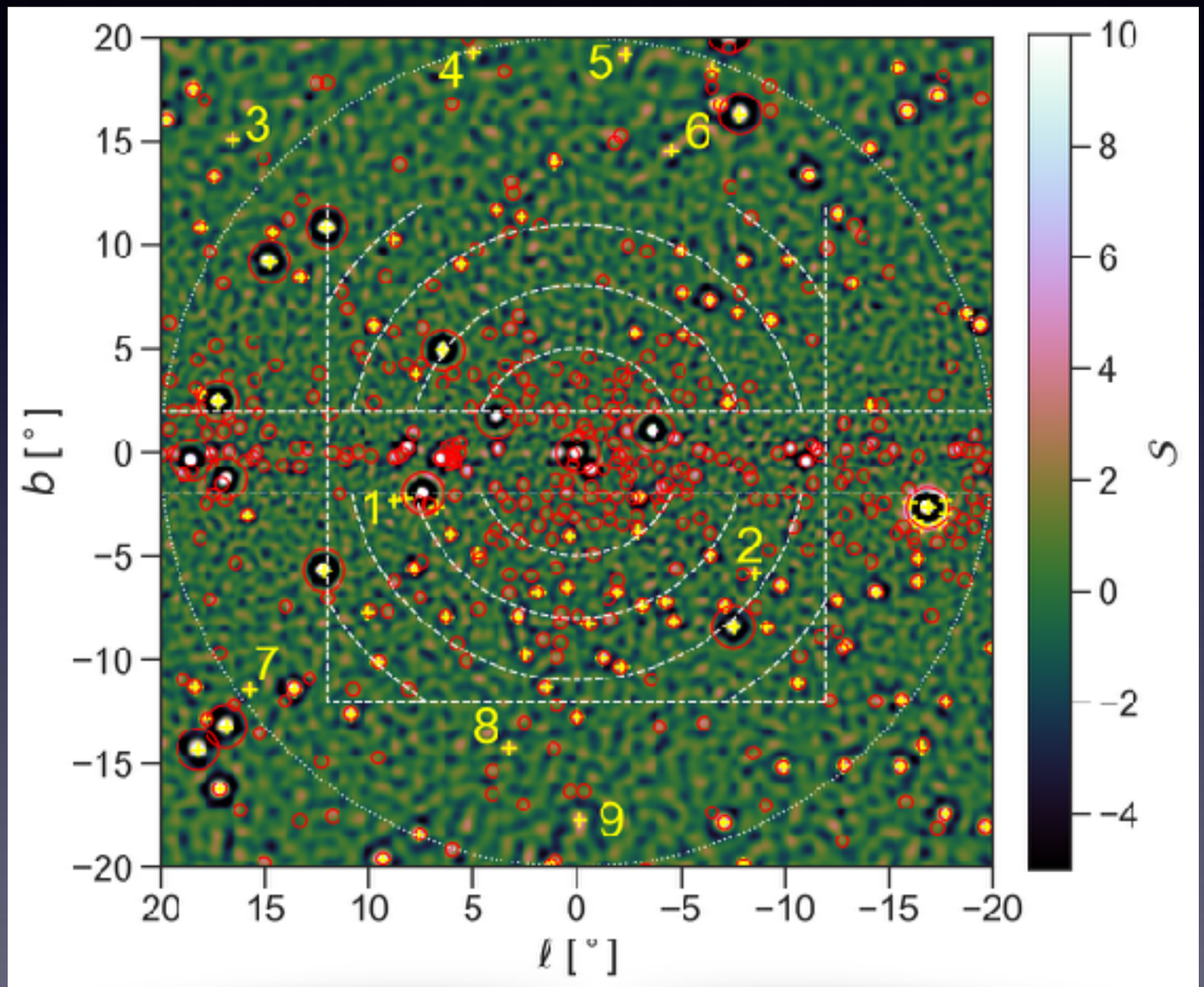
60 diffuse models × 100 trials

Zhong, McDermott, Cholis, Fox, 1911.12369

wavelet statistics change qualitatively with 4FGL!

High-*S* Sources

Zhong, McDermott, Cholis, Fox, 1911.12369

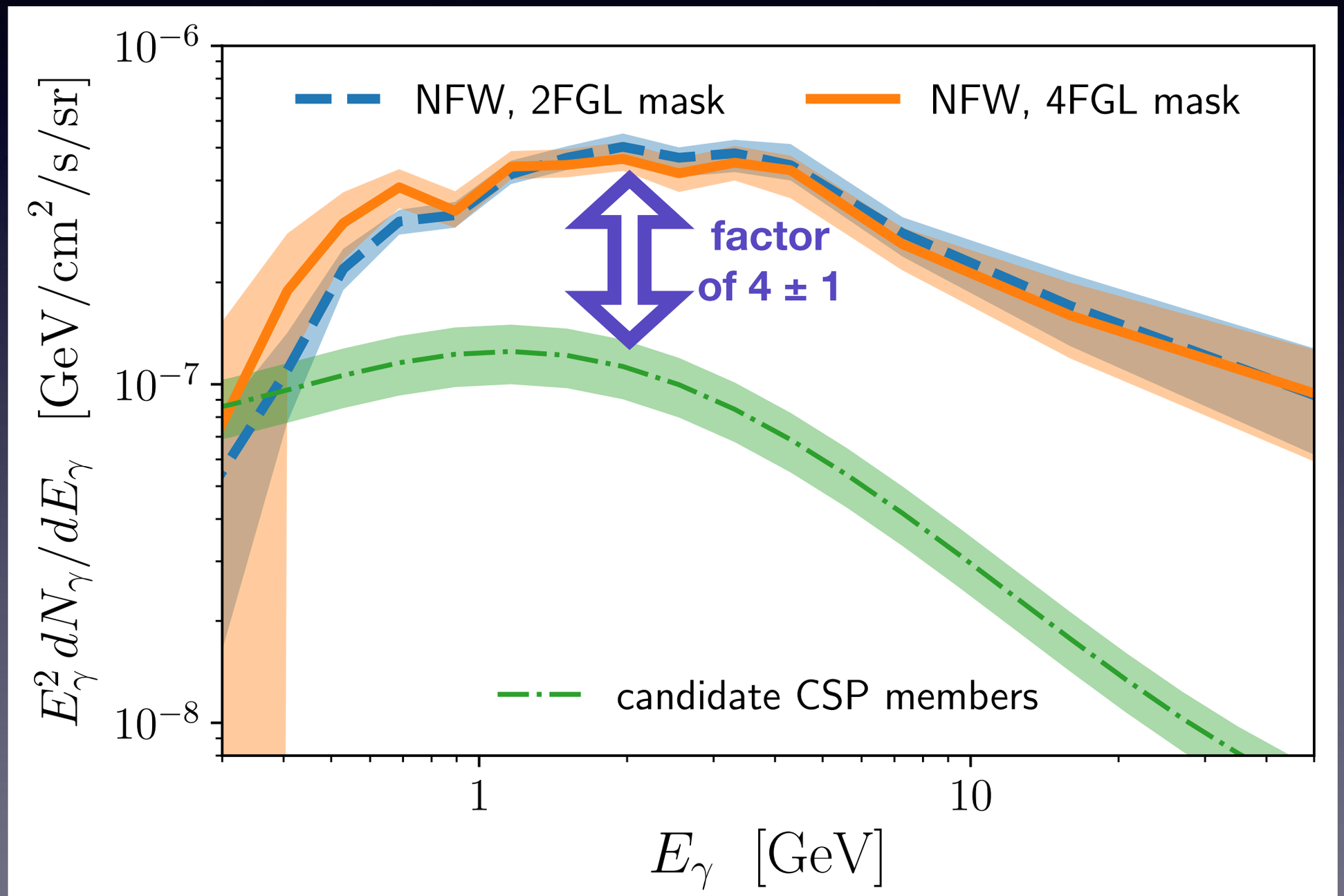


117 peaks (w/ *S*>4) ⊃ 109 peaks near 4FGL ⊃ 47 are unknown/unassociated

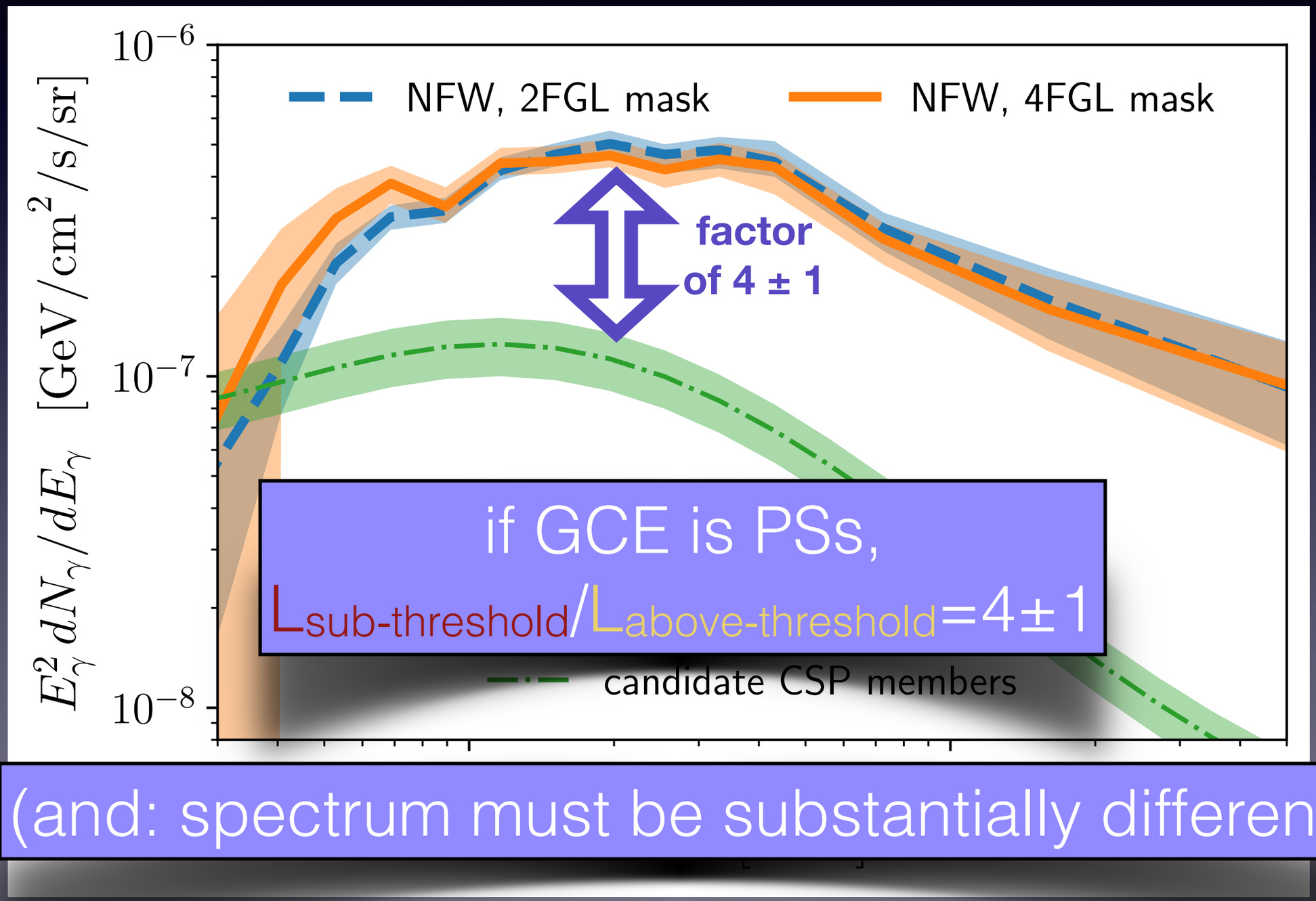
We have access to all of those spectra in 4FGL!

Compare Spectra

Zhong, McDermott, Cholis, Fox, 1911.12369

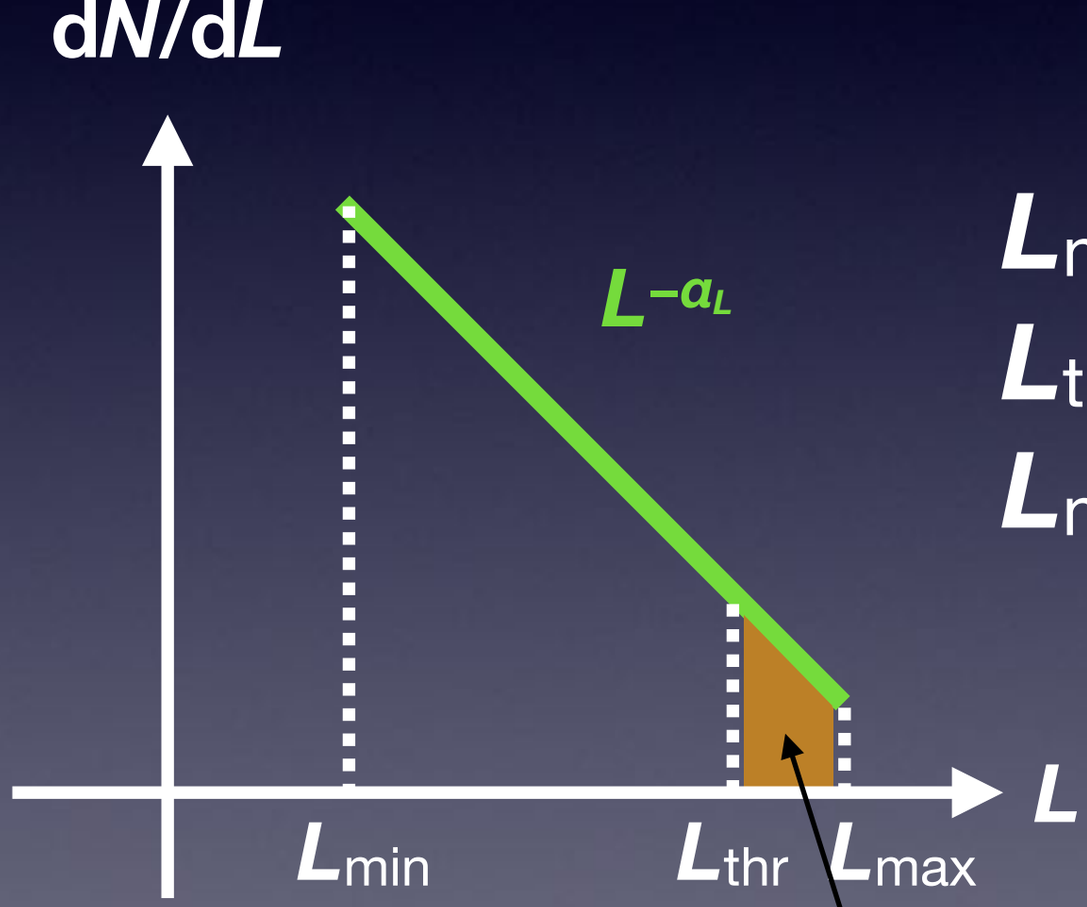


Implications for GCE



(and: spectrum must be substantially different)

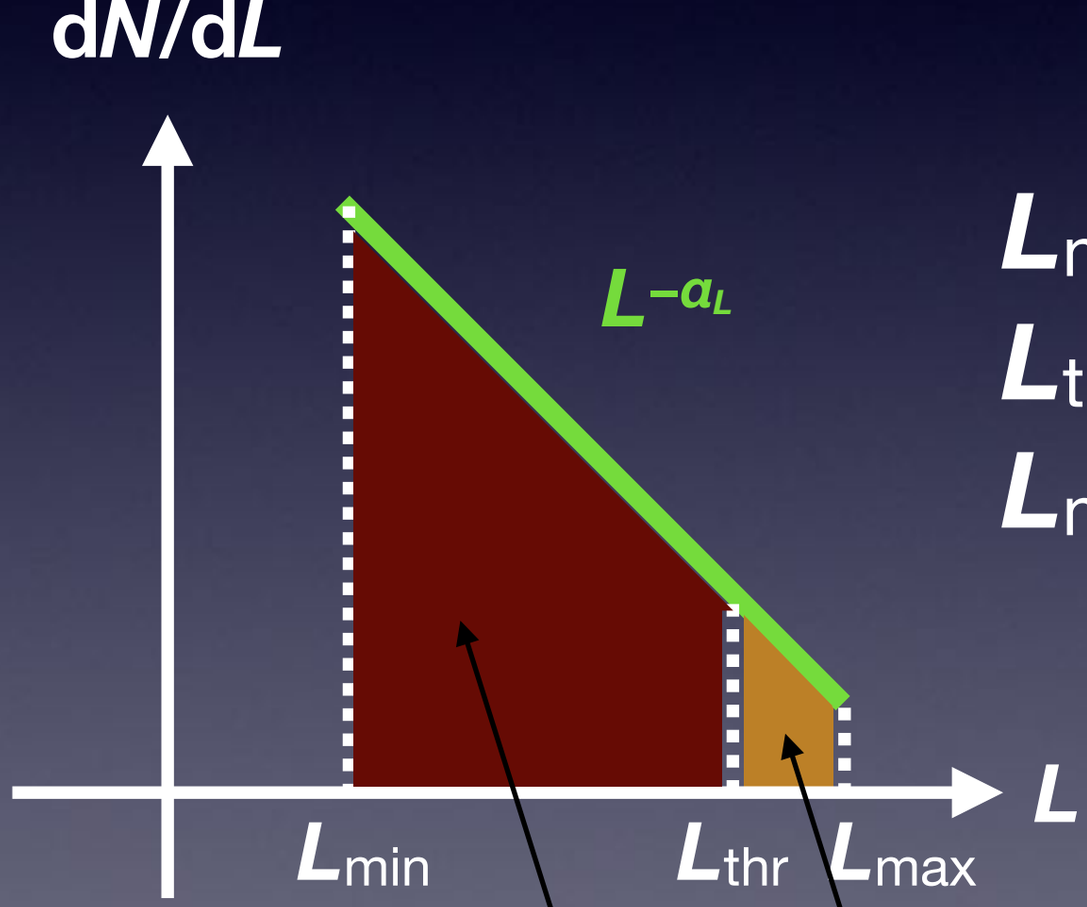
Luminosity Function



L_{min} → gamma-ray physics
L_{thr} → detection threshold
L_{max} → gamma-ray physics

$\int_{>thr} L\, dN/dL\, dL$ = stacked spectra

Luminosity Function



L_{min} → gamma-ray physics

L_{thr} → detection threshold

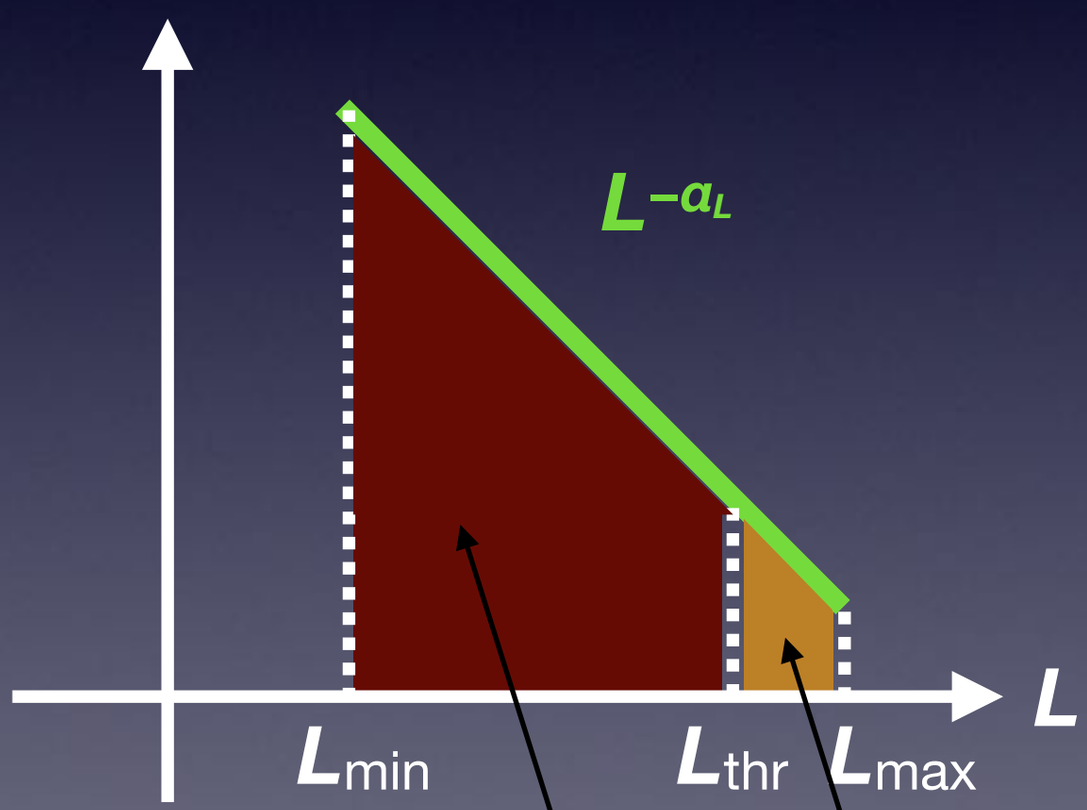
L_{max} → gamma-ray physics

$\int_{<thr} L\, dN/dL\, dL$ "= GCE"

$\int_{>thr} L\, dN/dL\, dL$ = stacked spectra

Luminosity Function

if GCE is PSs,
$L_{\text{sub-threshold}}/L_{\text{above-threshold}}=4\pm1$



$\int_{<thr} L\, dN/dL\, dL$ "= GCE"

$\int_{>thr} L\, dN/dL\, dL$ = stacked spectra

$L_{\text{min}} \rightarrow 10^{29}$ erg/s

$L_{\text{thr}} \rightarrow 10^{34}$ erg/s

$L_{\text{max}} \rightarrow 10^{35}$ erg/s

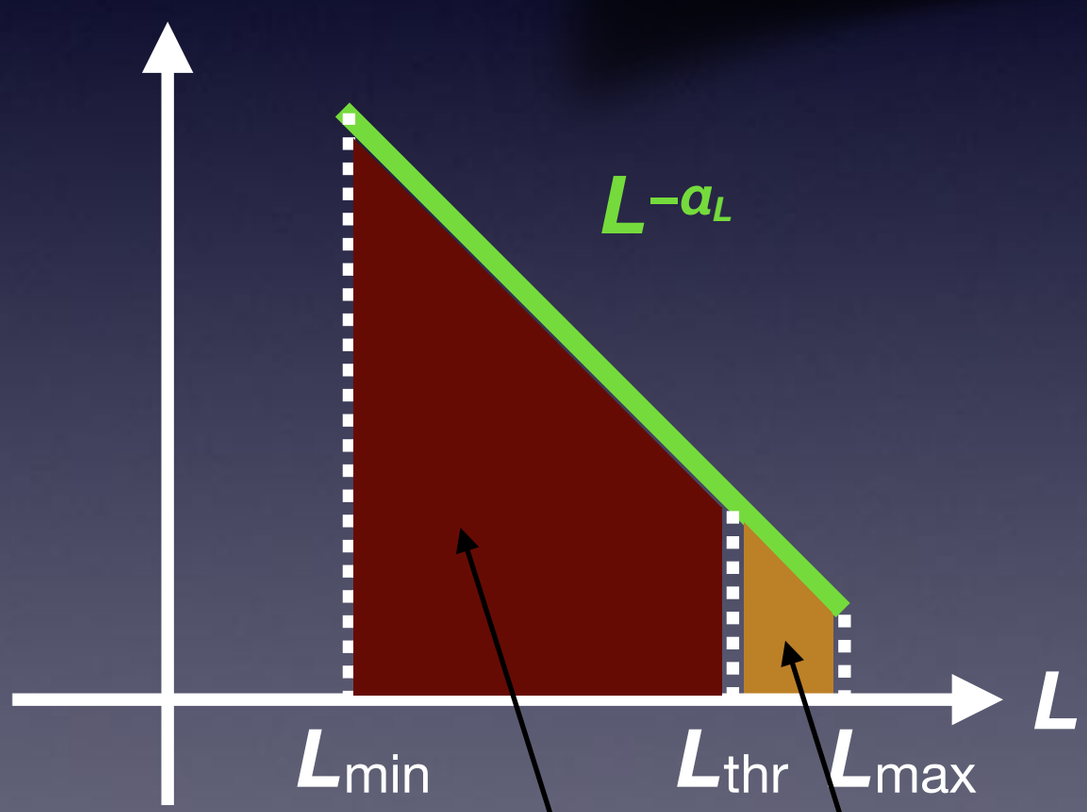
$\Longrightarrow \alpha_L \rightarrow 1.95 \pm 0.05$

$N_{sub} \rightarrow (3.5 \pm 1.7)*10^6$

(compare to $N_{vis} \sim 47$)

Luminosity Function?

if GCE is PSs,
$L_{\text{sub-threshold}}/L_{\text{above-threshold}}=4\pm1$



$L_{\text{min}} \rightarrow 0$

$L_{\text{thr}} \rightarrow 3\times10^{34}$ erg/s

$L_{\text{max}} \rightarrow 10^{35}$ erg/s

$\Longrightarrow \alpha_L \rightarrow 1.8 \pm 0.05$

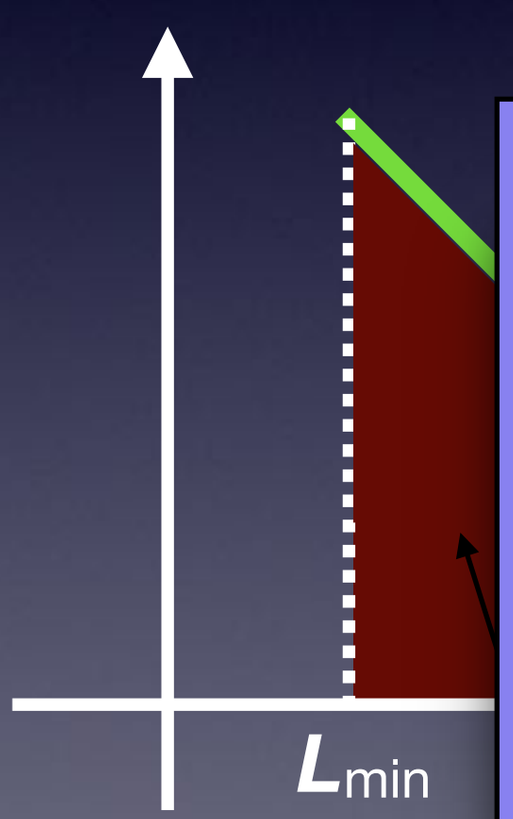
(N_{sub} diverges)

$\int_{<\text{thr}} L\, dN/dL\, dL$ "= GCE"

$\int_{>\text{thr}} L\, dN/dL\, dL$ = stacked spectra

Luminosity Function

if GCE is PSs,
$L_{\text{sub-threshold}}/L_{\text{above-threshold}}=4\pm1$



bottom line: $\alpha_L<1.5$ is strongly disfavored under any reasonable set of assumptions

$\Longrightarrow$

the GCE is not a large population of MSPs

g/s

/s

0.05

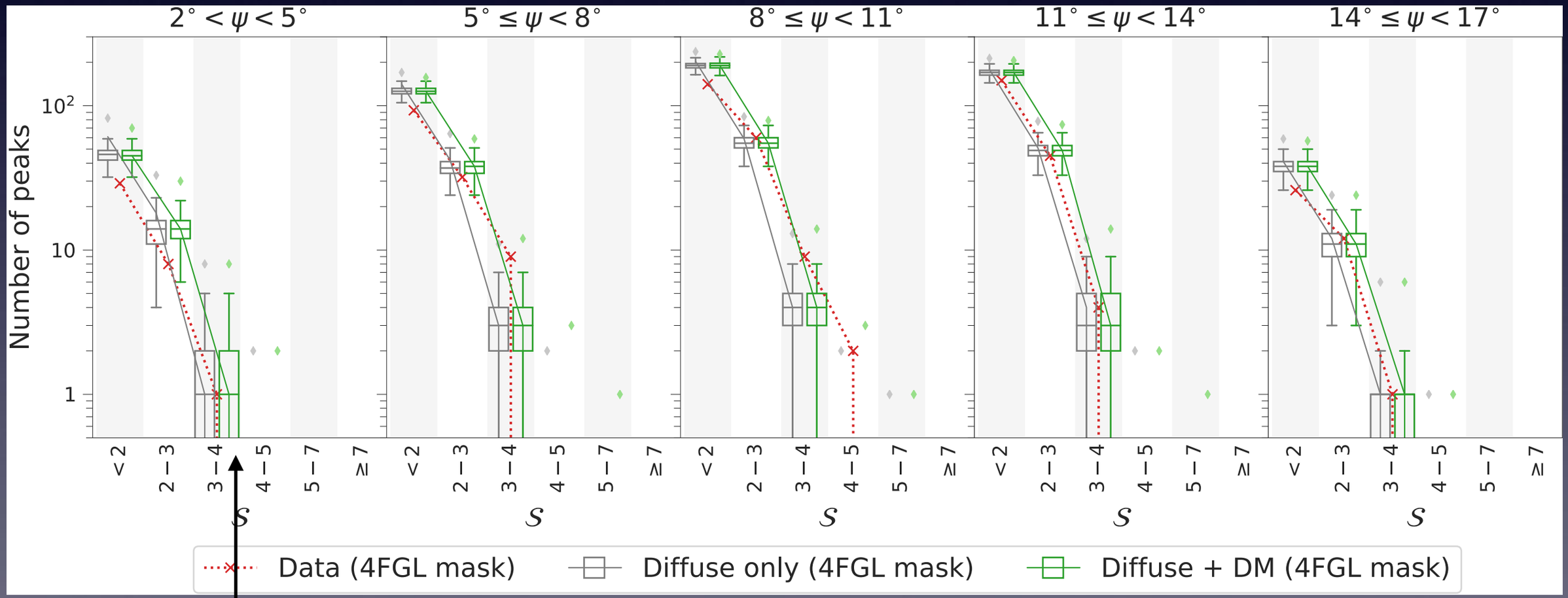
, diverges!)

$\int_{<thr} L\, dN/dL\, dL$ "= GCE"

$\int_{>thr} L\, dN/dL\, dL$ = stacked spectra

DM or Cosmic-Ray Burst activity still work

No additional small-scale structure,
so it looks just as good as diffuse-only



3 DM models × 60 diffuse models × 100 trials

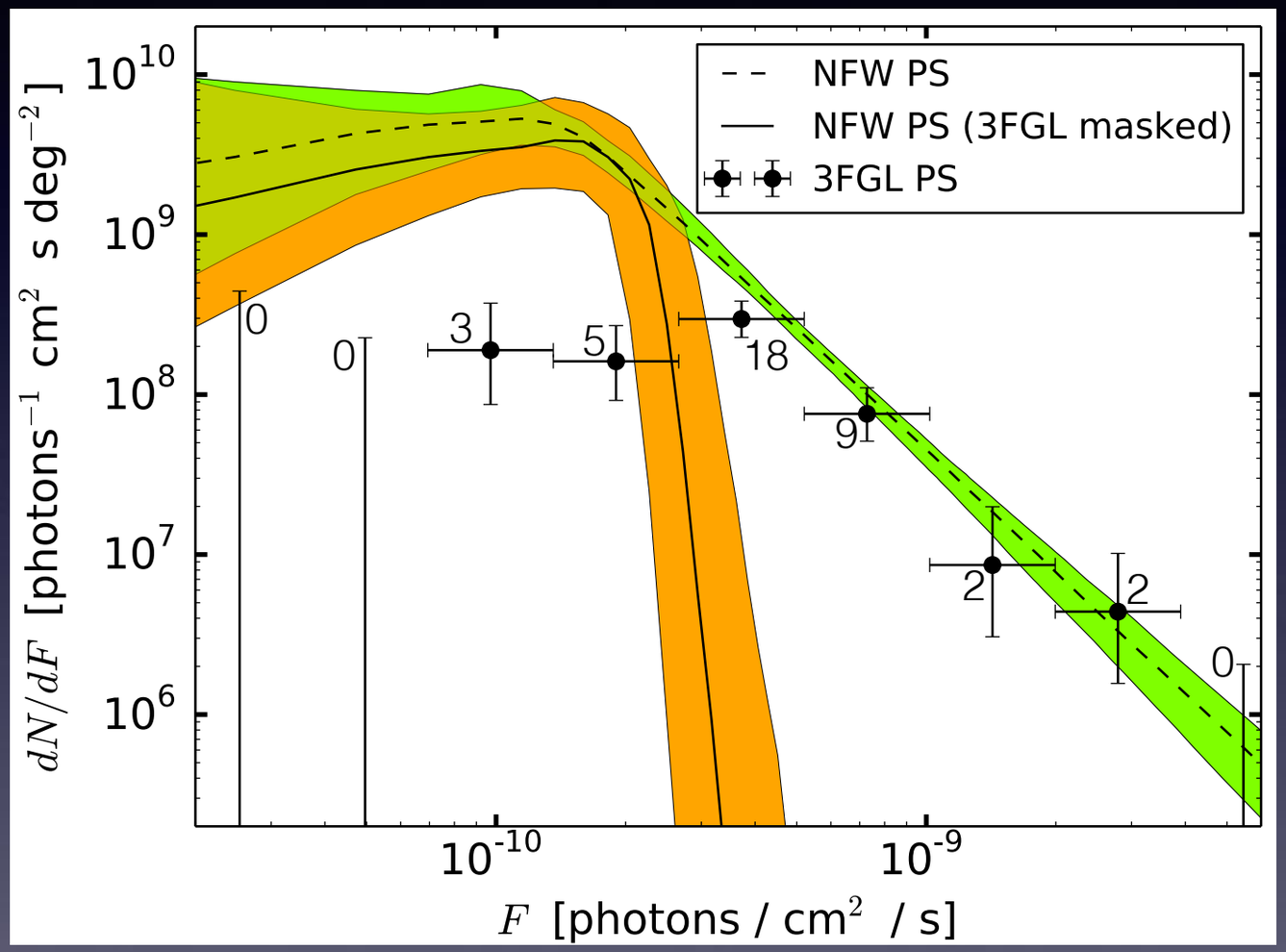
Zhong, McDermott, Cholis, Fox, 1911.12369

Thanks!

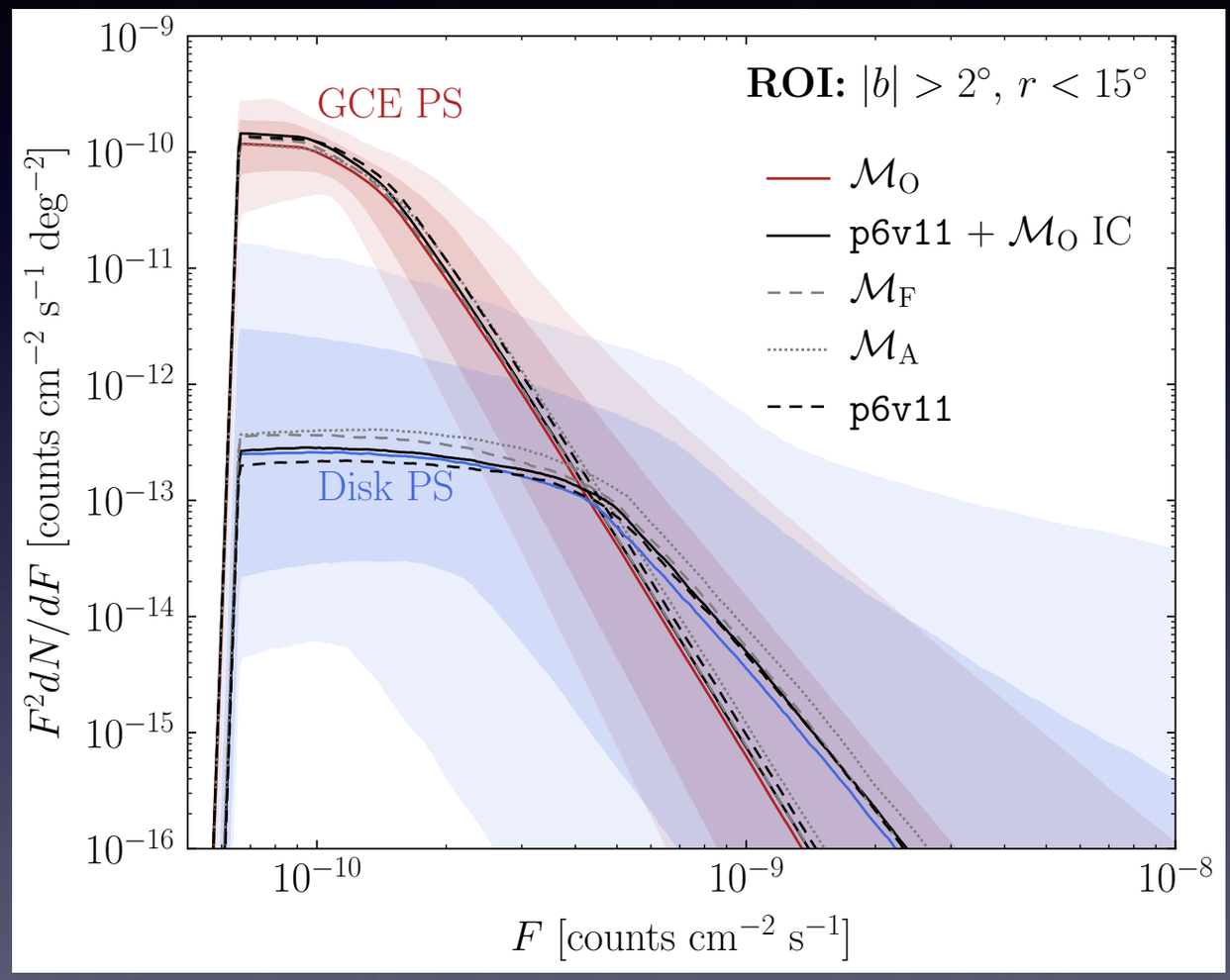
Extra

Point Source Fit Update

Lee et al., **1506.05124**



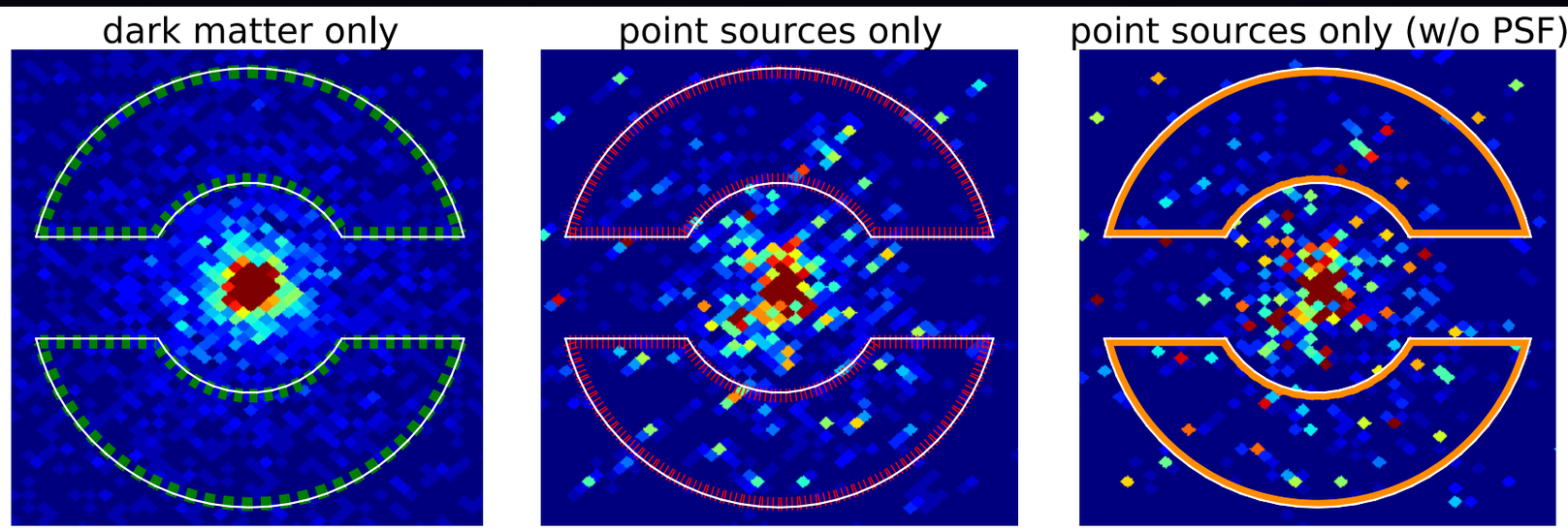
Buschmann et al., **2002.12373**

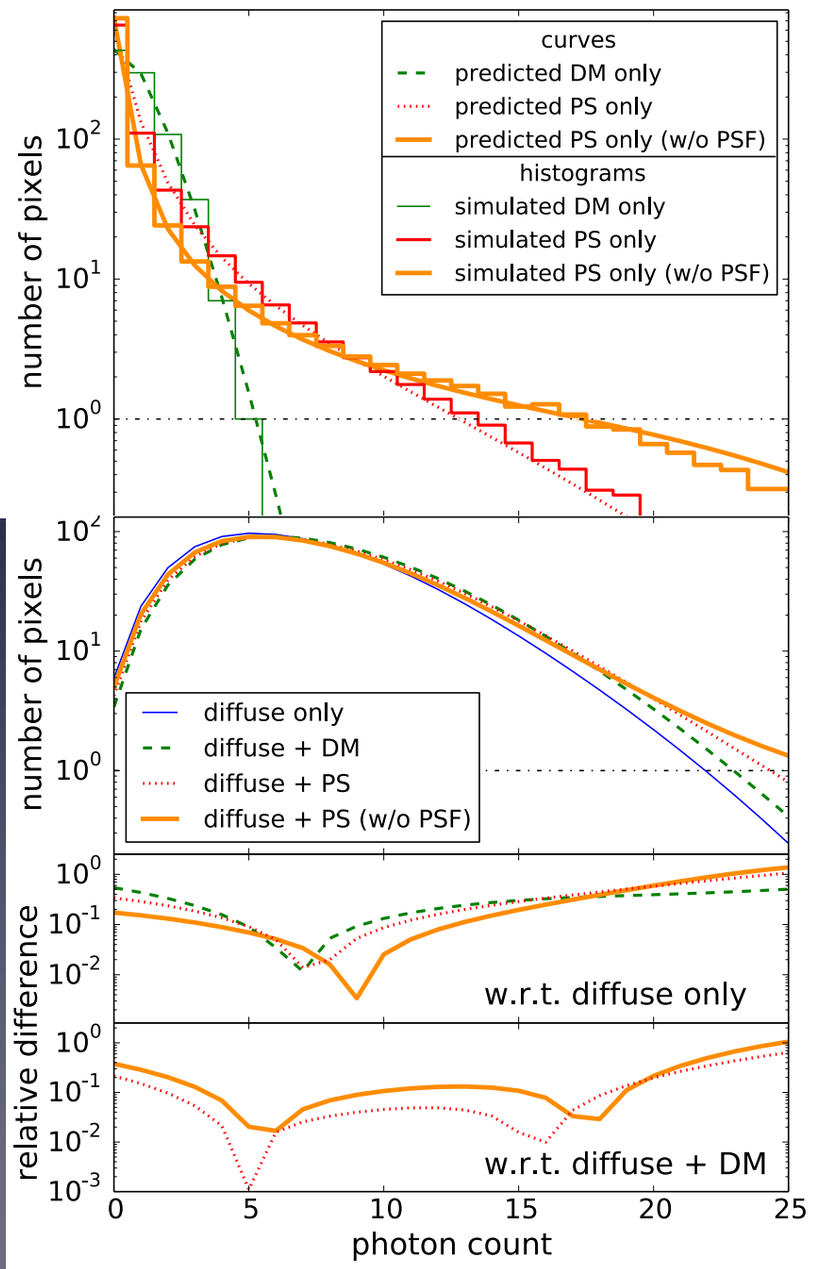


most of the brightness should have been just below the (ca. 2015) point source detection threshold

(time invariant statement)

Point Source Statistics





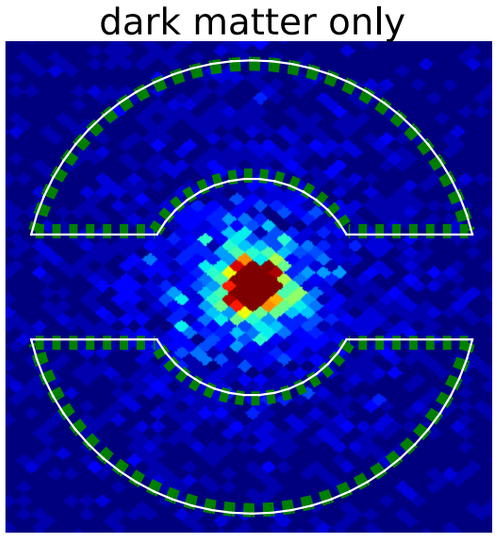
Lee, Lisanti, Safdi 1412.6099

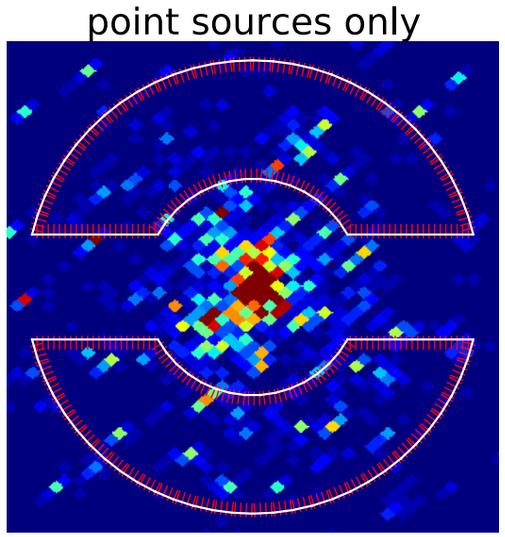
$n_{PS} \sim r^{-\delta}$

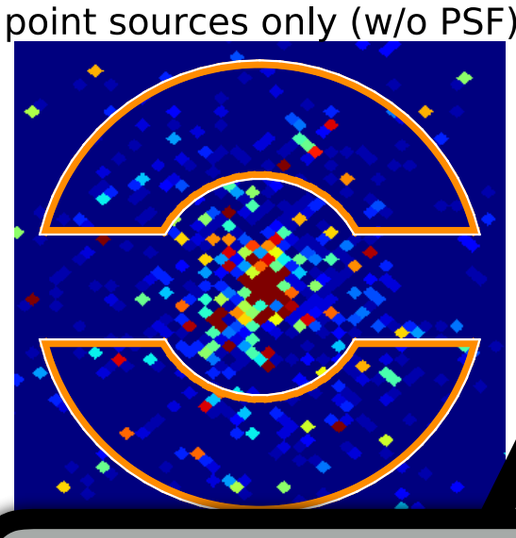
$\delta \sim 2.5$ observed (in Andromeda)

cf. $\rho_{gNFW}^2 \sim r^{-2\gamma}$ with $\gamma \sim 1.2$

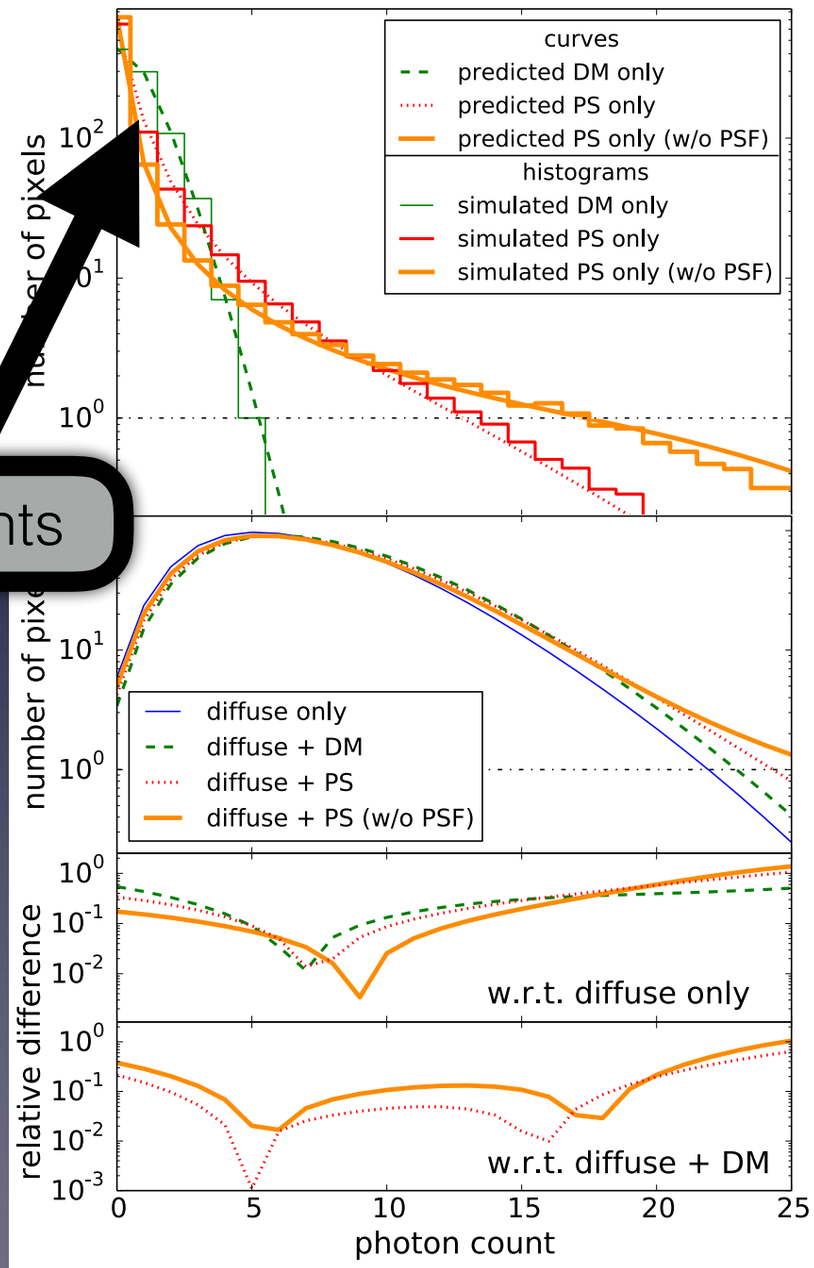
Point Source Statistics







similar at low counts



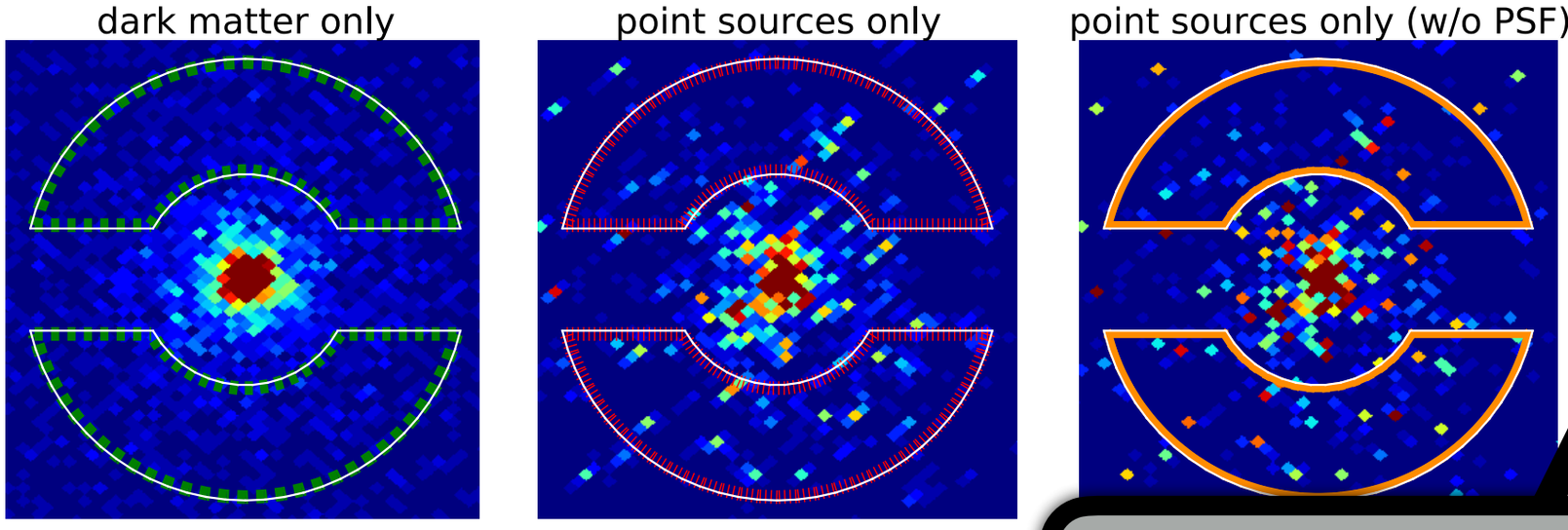
Lee, Lisanti, Safdi 1412.6099

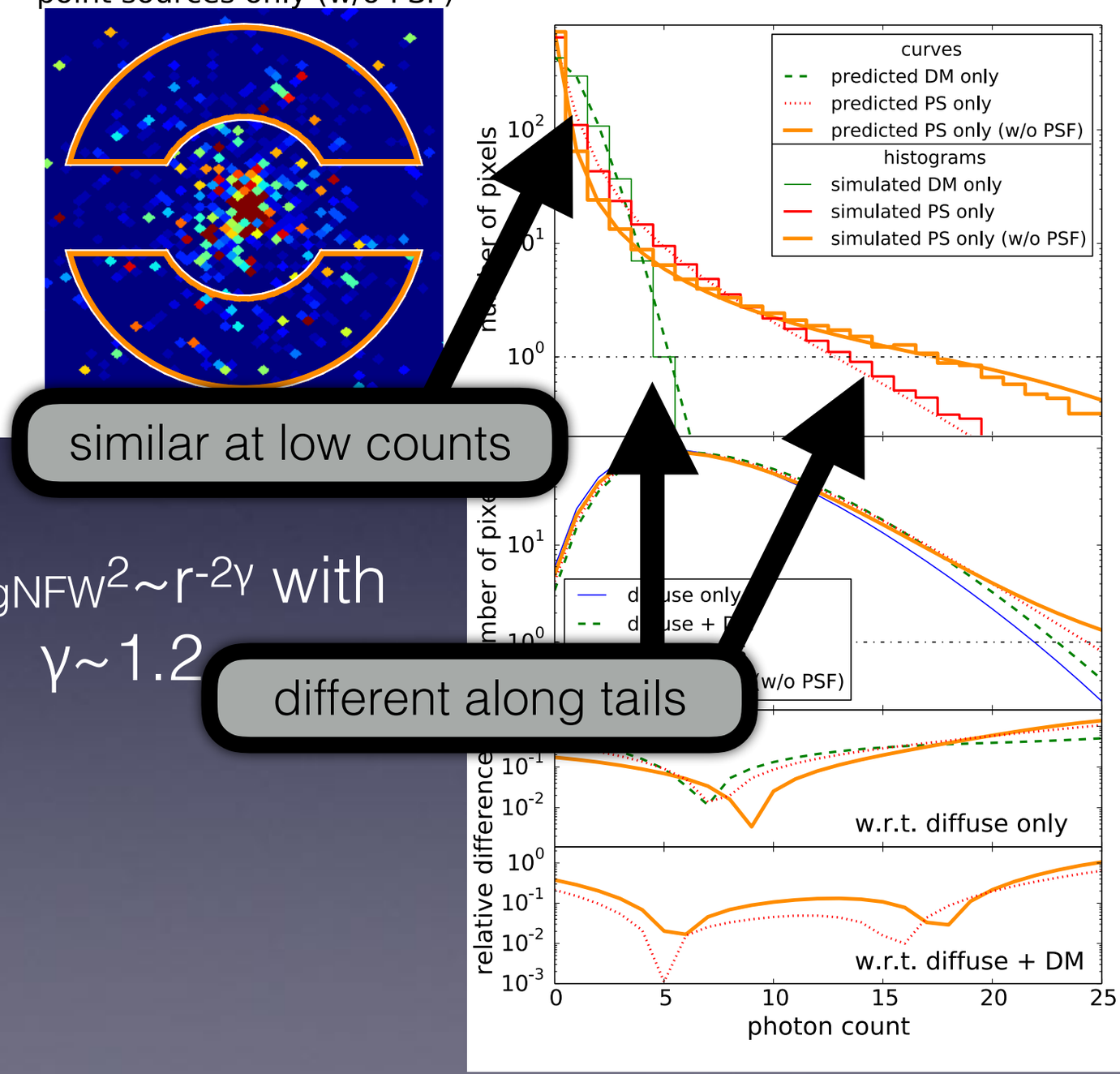
$n_{PS} \sim r^{-\delta}$

$\delta \sim 2.5$ observed (in Andromeda)

cf. $\rho_{gNFW}^2 \sim r^{-2\gamma}$ with $\gamma \sim 1.2$

Point Source Statistics





similar at low counts

different along tails

Lee, Lisanti, Safdi 1412.6099

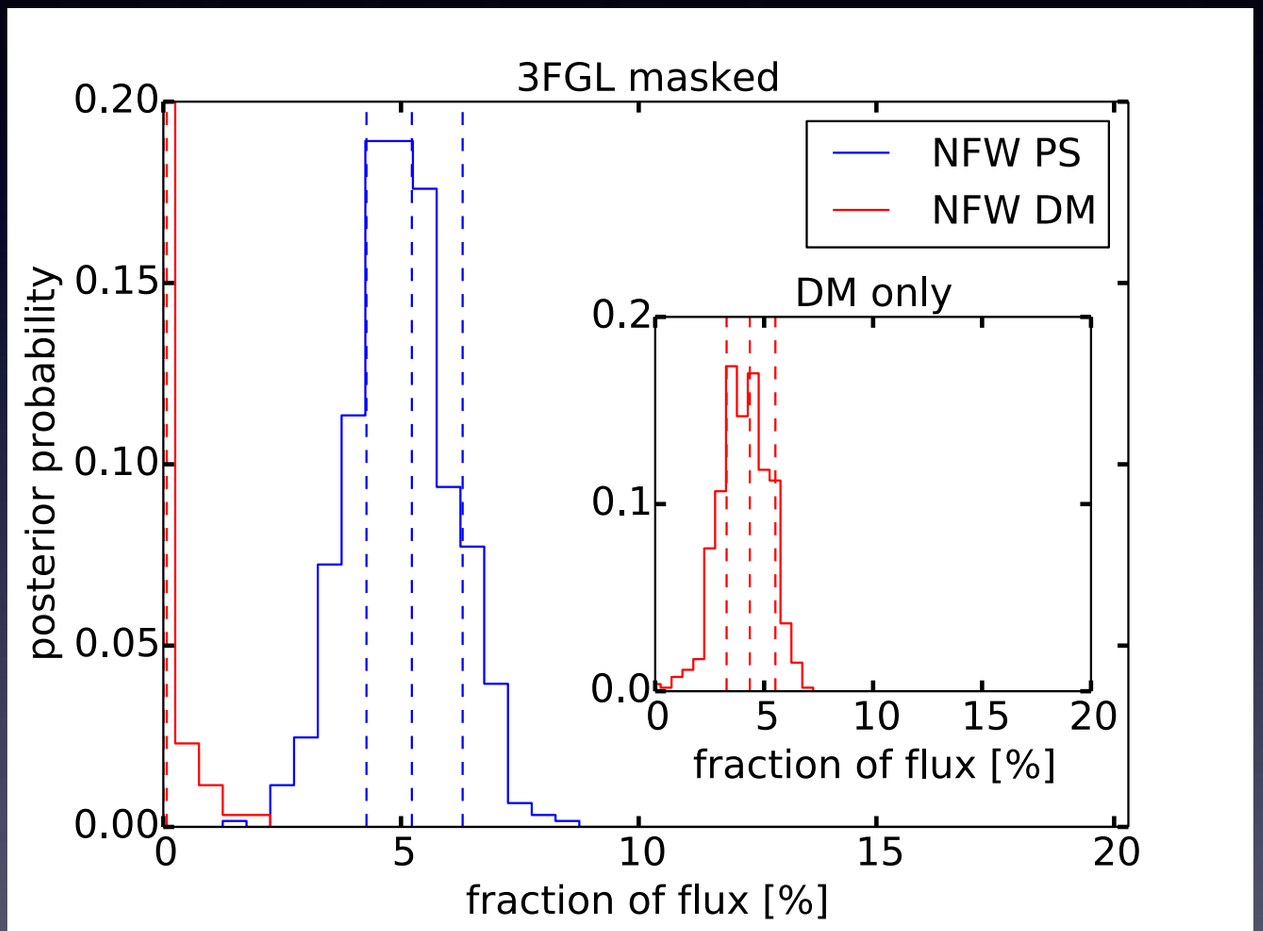
$n_{PS} \sim r^{-\delta}$

$\delta \sim 2.5$ observed (in Andromeda)

cf. $\rho_{gNFW}^2 \sim r^{-2\gamma}$ with $\gamma \sim 1.2$

Point Source Fits

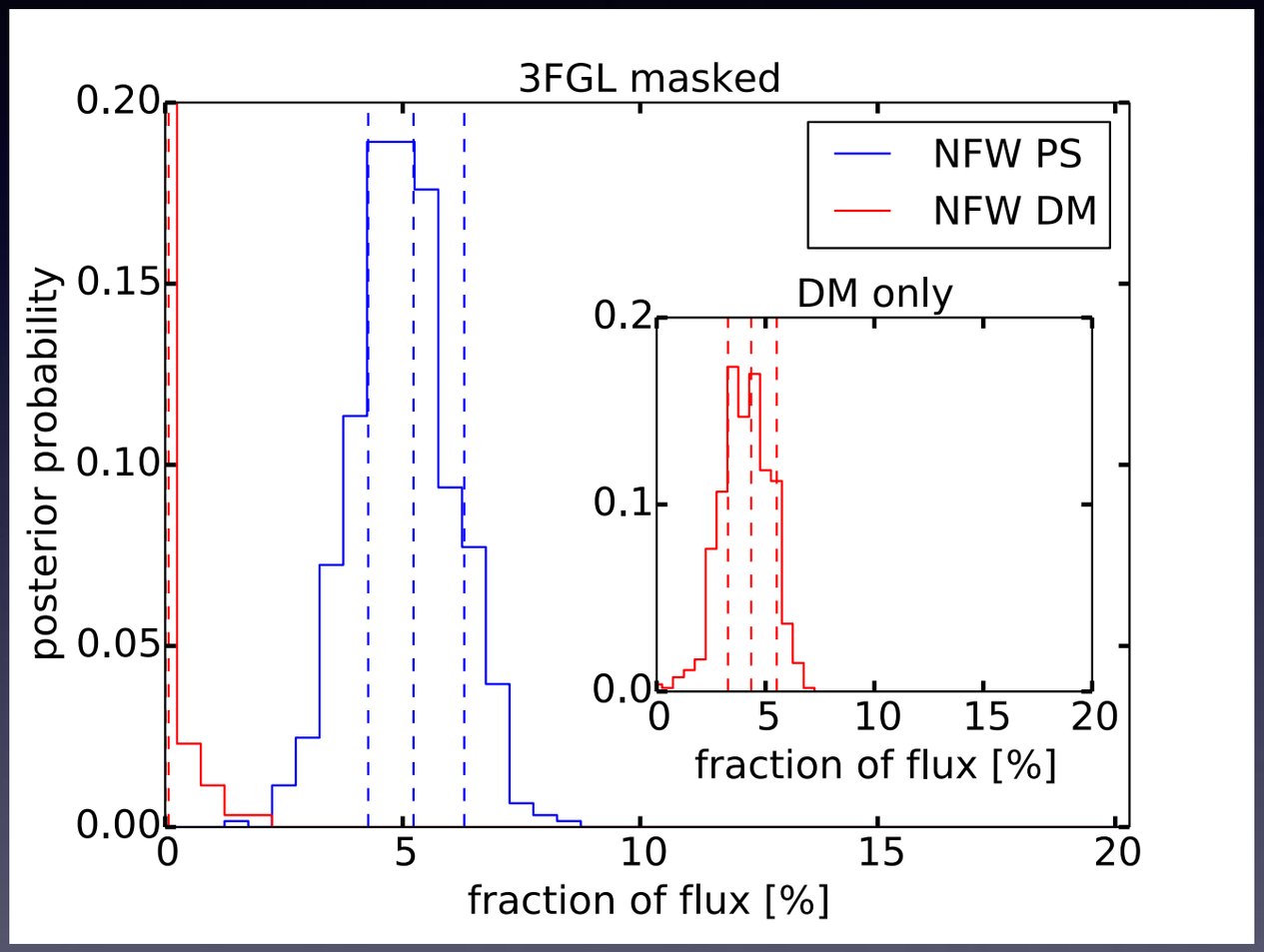
Lee et al., **1506.05124**



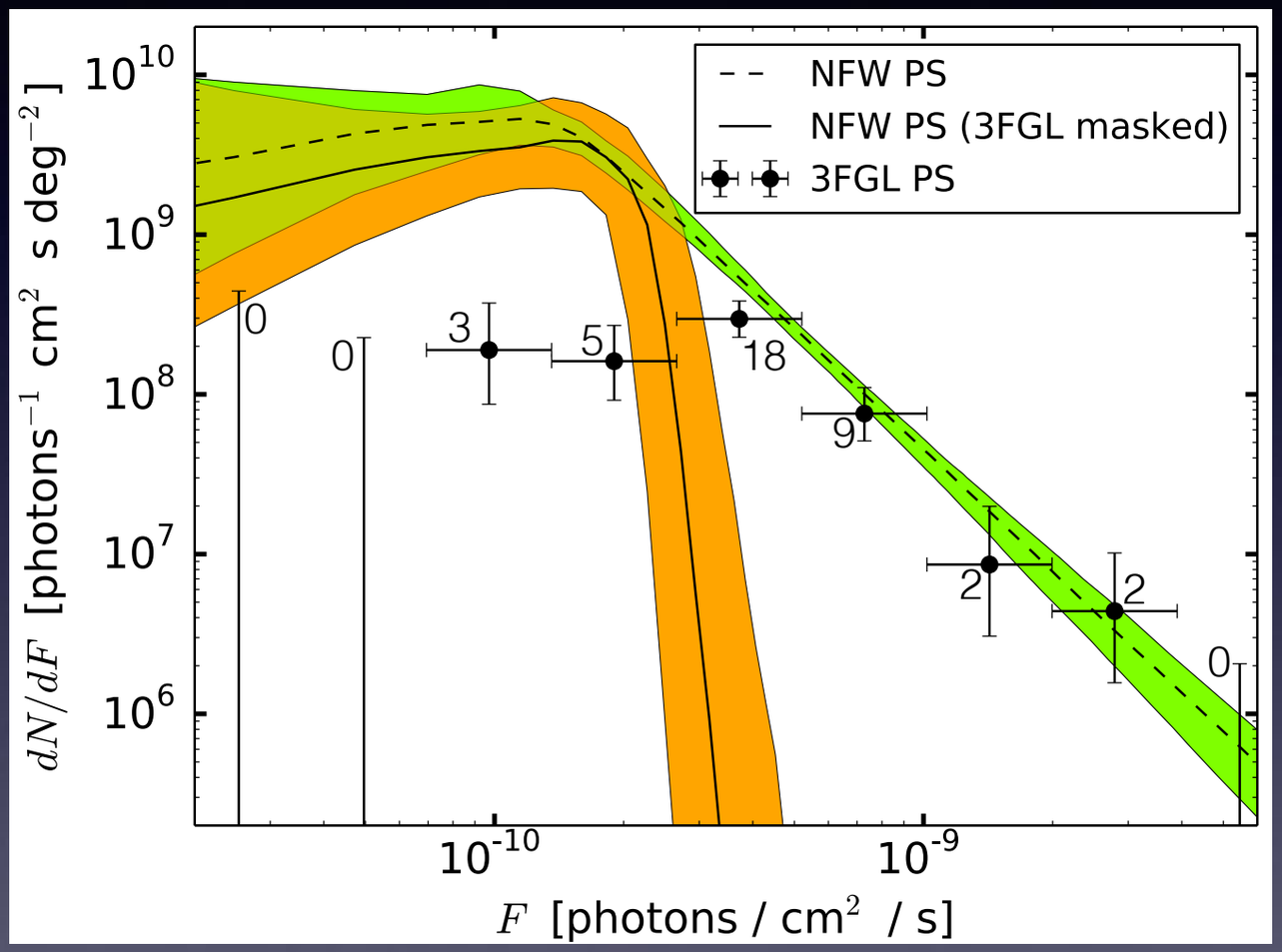
based on non-Poissonian (vs. Poissonian) template fit, excess “preferred” to be from point sources

Point Source Fits

Lee et al., **1506.05124**

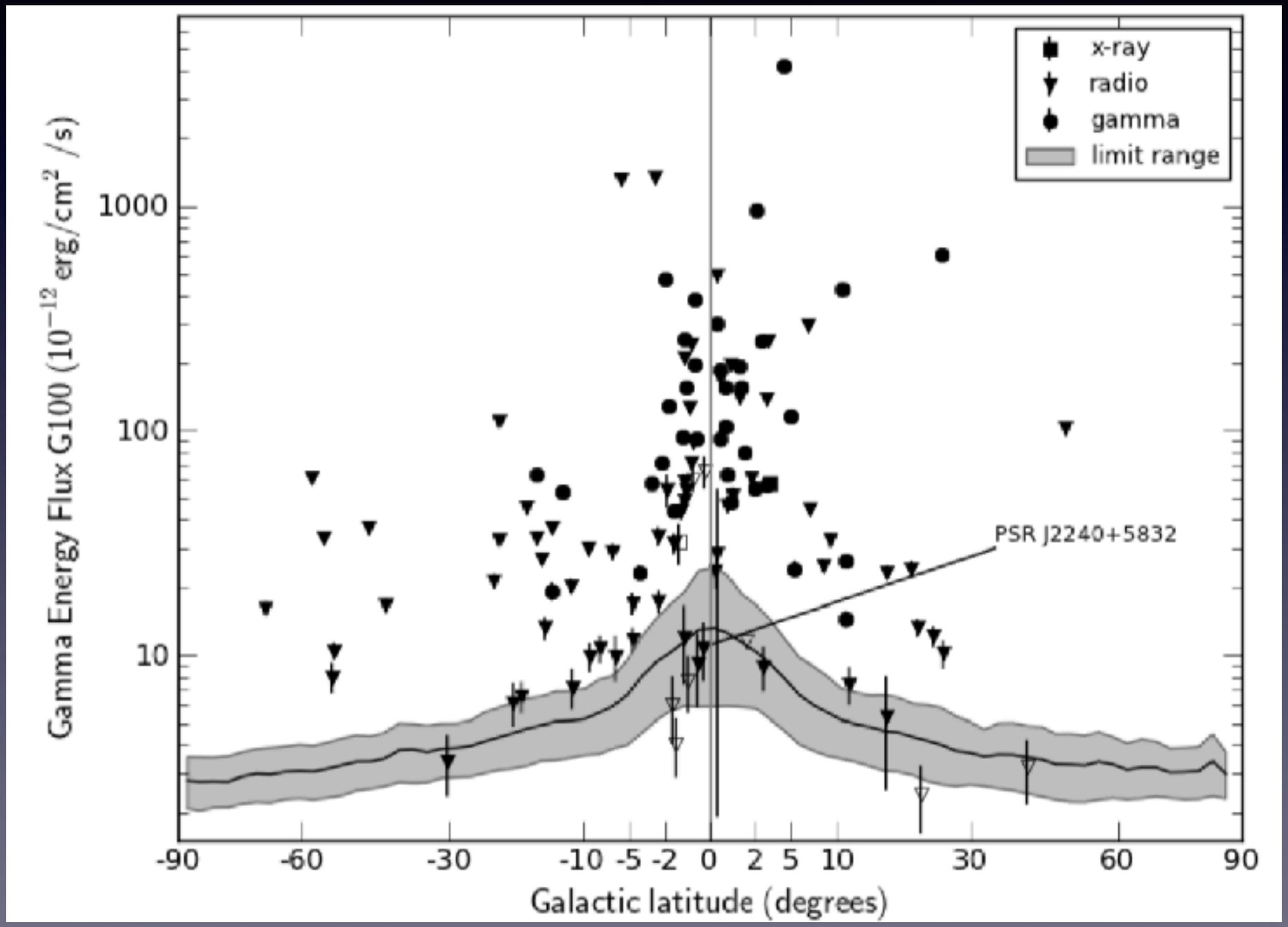


based on non-Poissonian (vs. Poissonian) template fit, excess “preferred” to be from point sources



but most of the brightness must be just below the (ca. 2015) point source detection threshold

b-dependence of detection

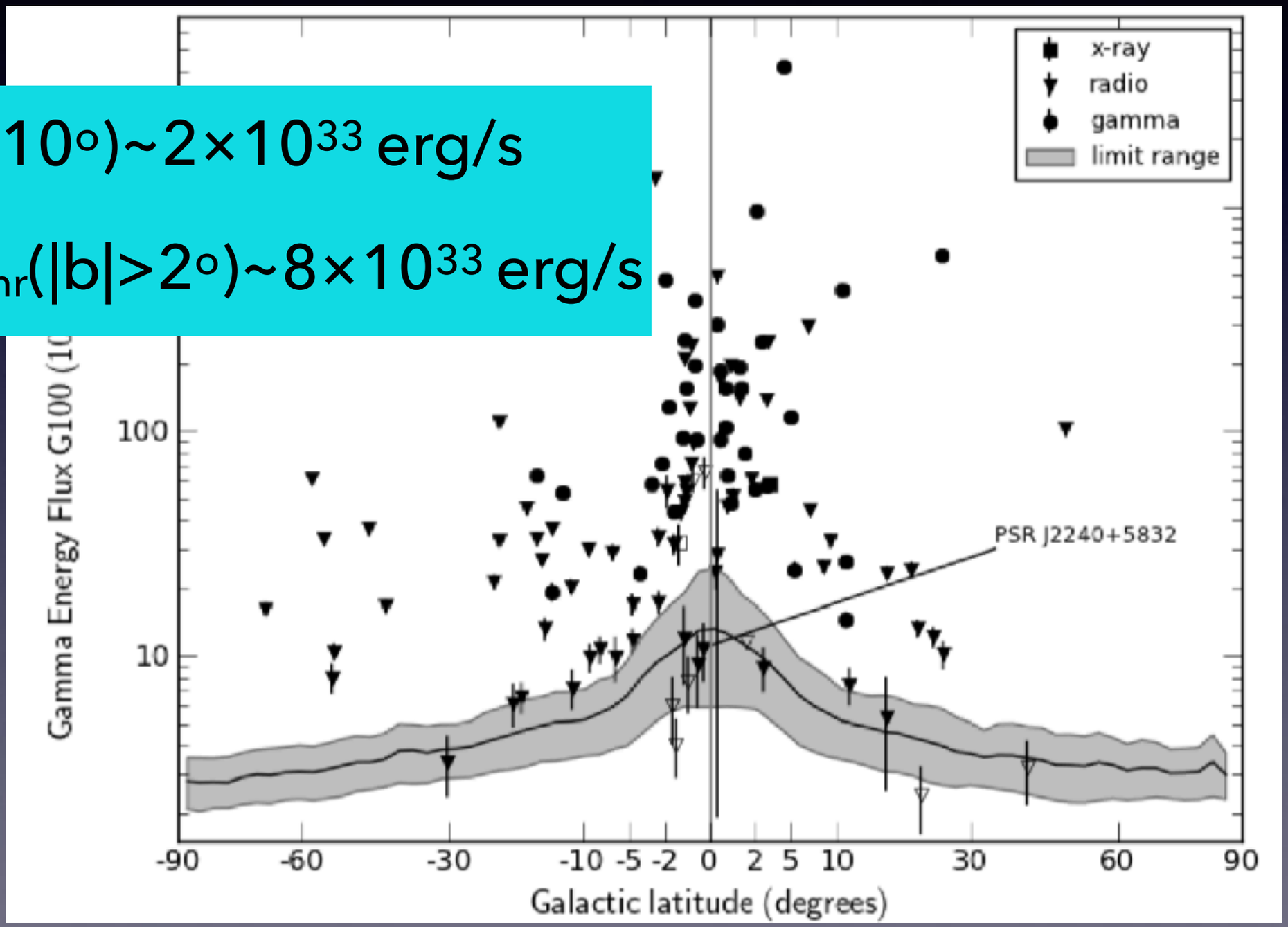


Abdo et al., **1305.4385**

b-dependence of detection

$L_{thr}(|b|>10°)\sim 2\times 10^{33}$ erg/s

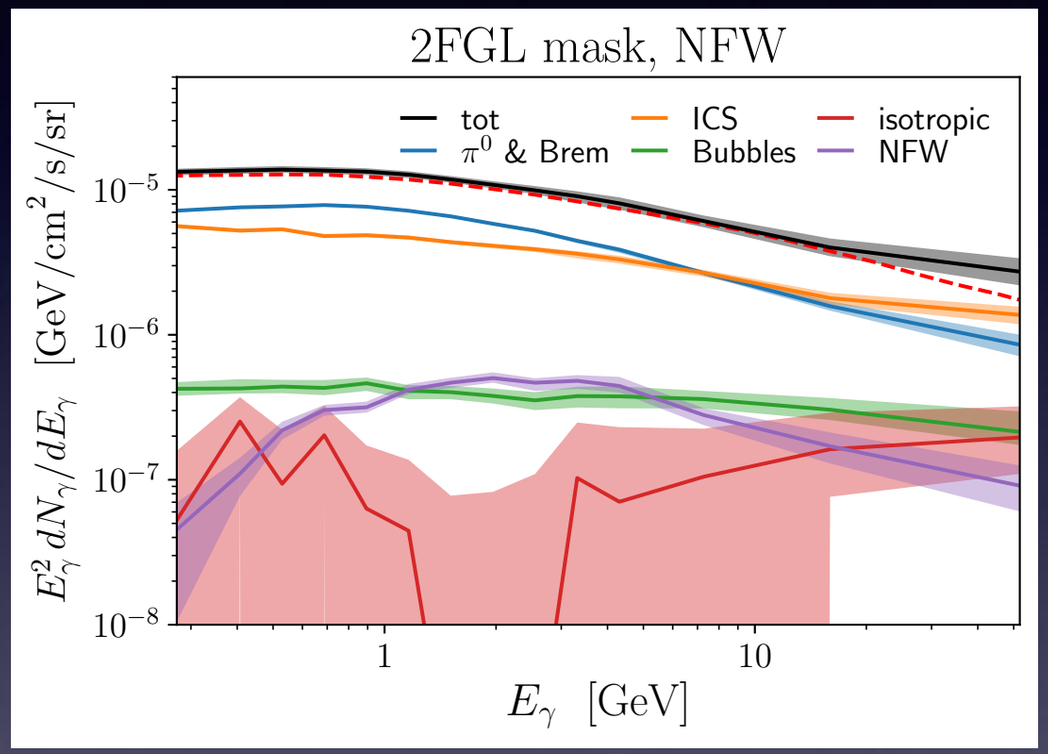
$\Longrightarrow L_{thr}(|b|>2°)\sim 8\times 10^{33}$ erg/s



Abdo et al., 1305.4385

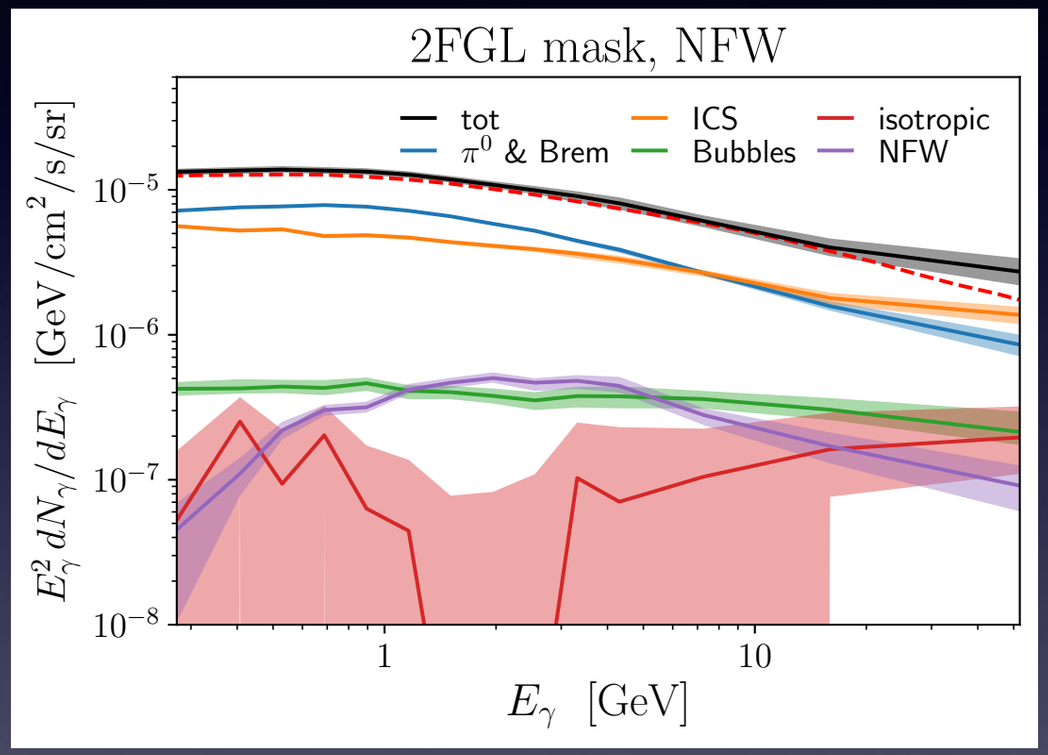
GCE: Template Fit Results

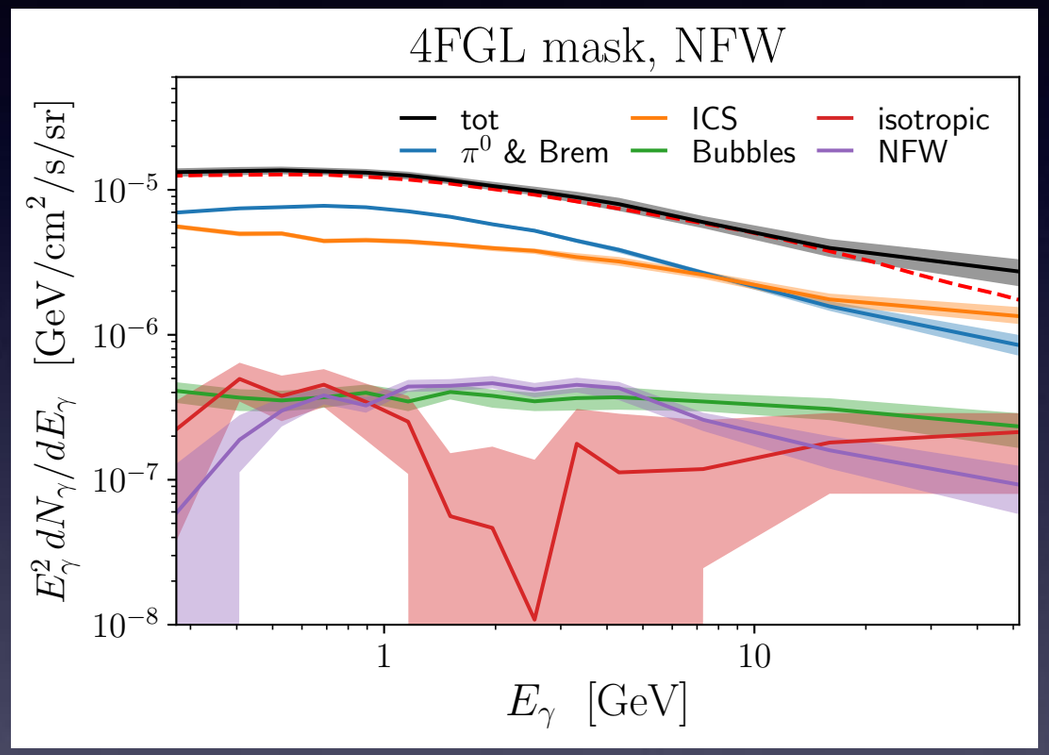
Zhong, McDermott, Cholis, Fox, 1911.12369



GCE: Template Fit Results

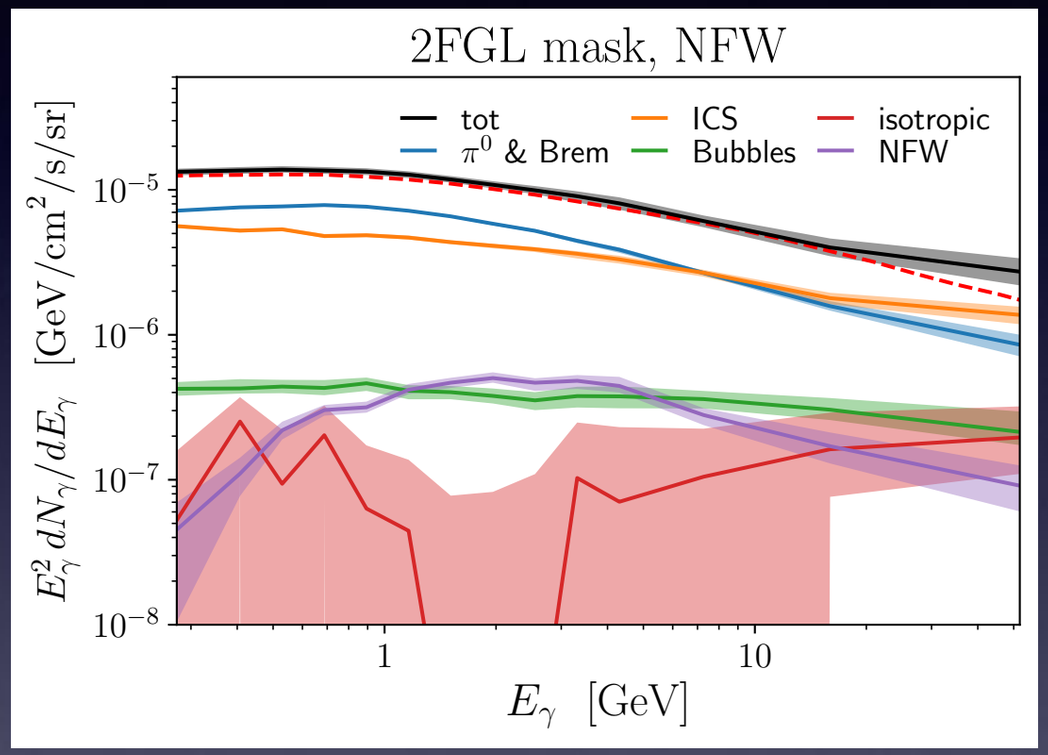
Zhong, McDermott, Cholis, Fox, 1911.12369

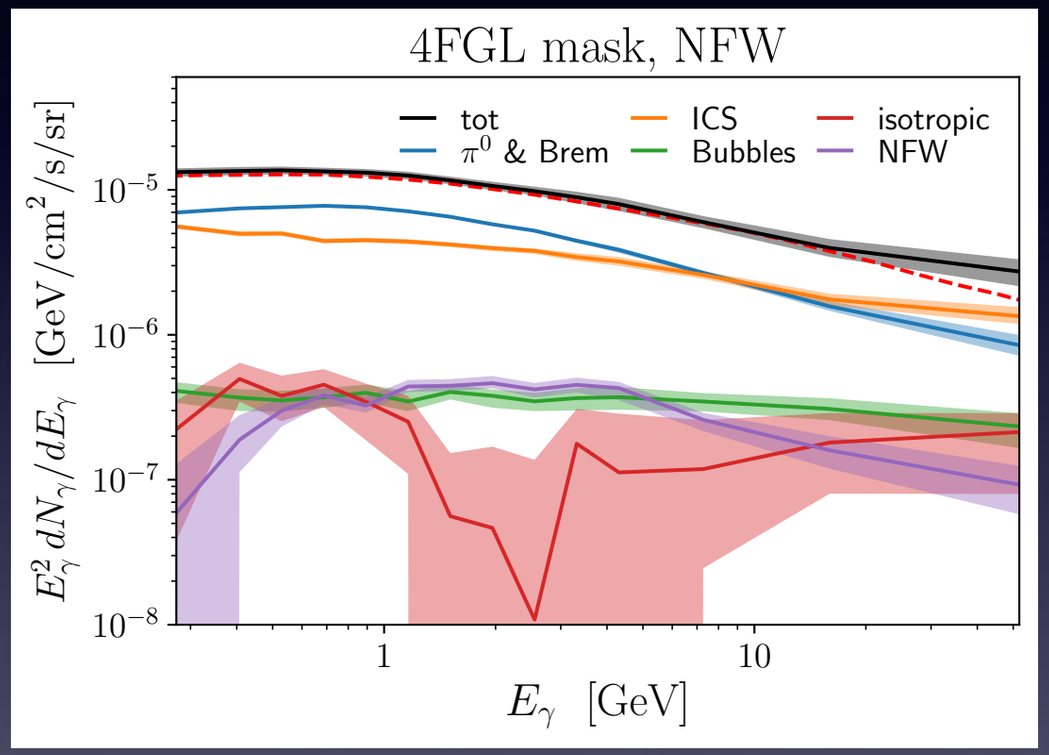




GCE: Template Fit Results

Zhong, McDermott, Cholis, Fox, 1911.12369





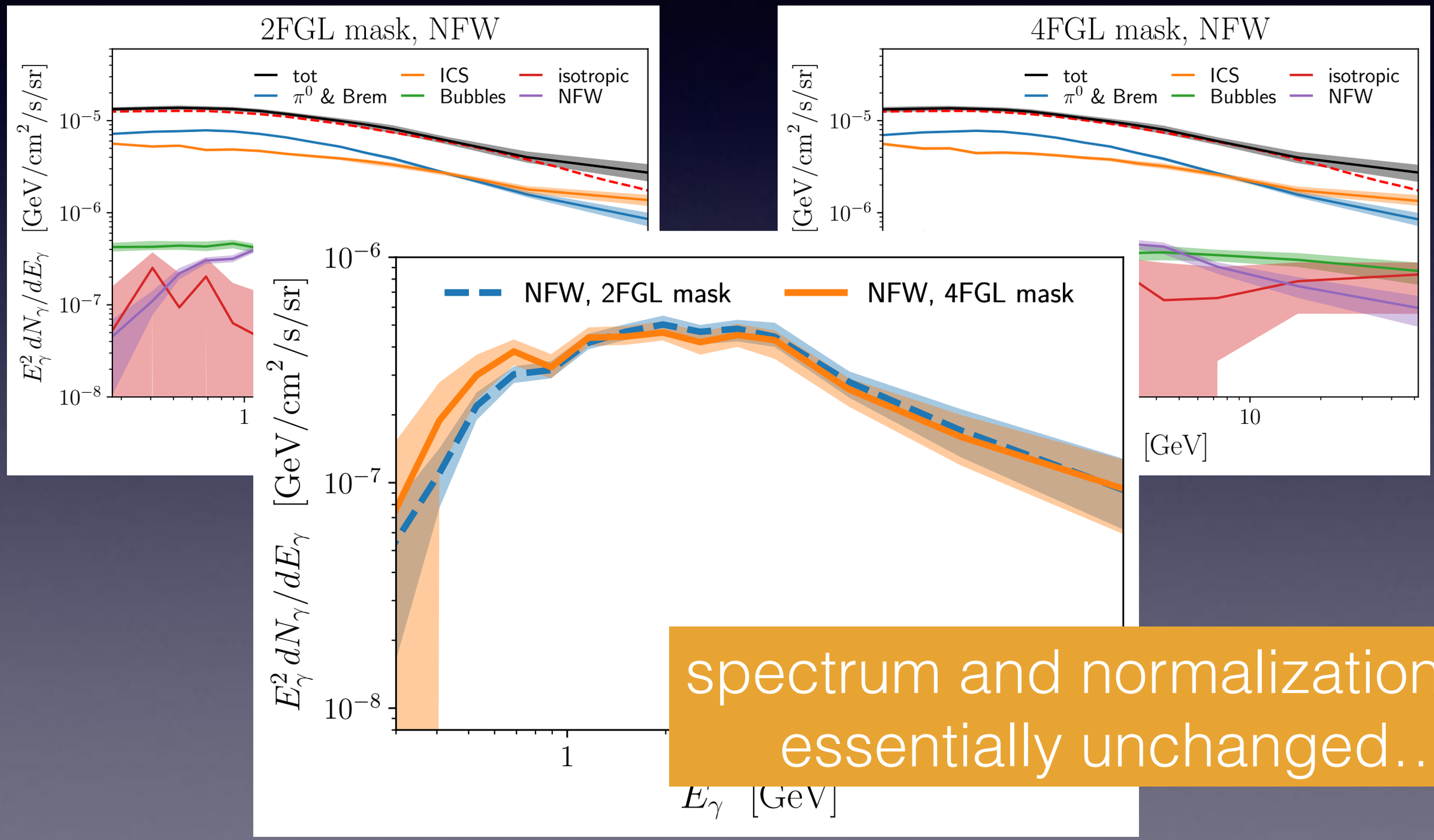
preference slightly smaller (fewer photons)

TABLE I. Difference in $-2\ln\lambda$ (lower numbers are better) at the best fit points of each model, summed over energy bins, compared to our best fit for each mask.

Type of Mask	NFW	gNFW	no excess
2FGL	-	476	5430
4FGL	-	368	3600

GCE: Template Fit Results

Zhong, McDermott, Cholis, Fox, 1911.12369



spectrum and normalization essentially unchanged…

What are wavelets?

wavelet coefficients

original signal

$$W(a,b) = \frac{1}{\sqrt{a}} \int f(x)\psi^* \left(\frac{x-b}{a} \right) dx$$

scale

position

mother wavelet
(different choices)

$$\int \psi(x)dx = 0$$

$$\int |\psi(x)|^2 dx = 1$$

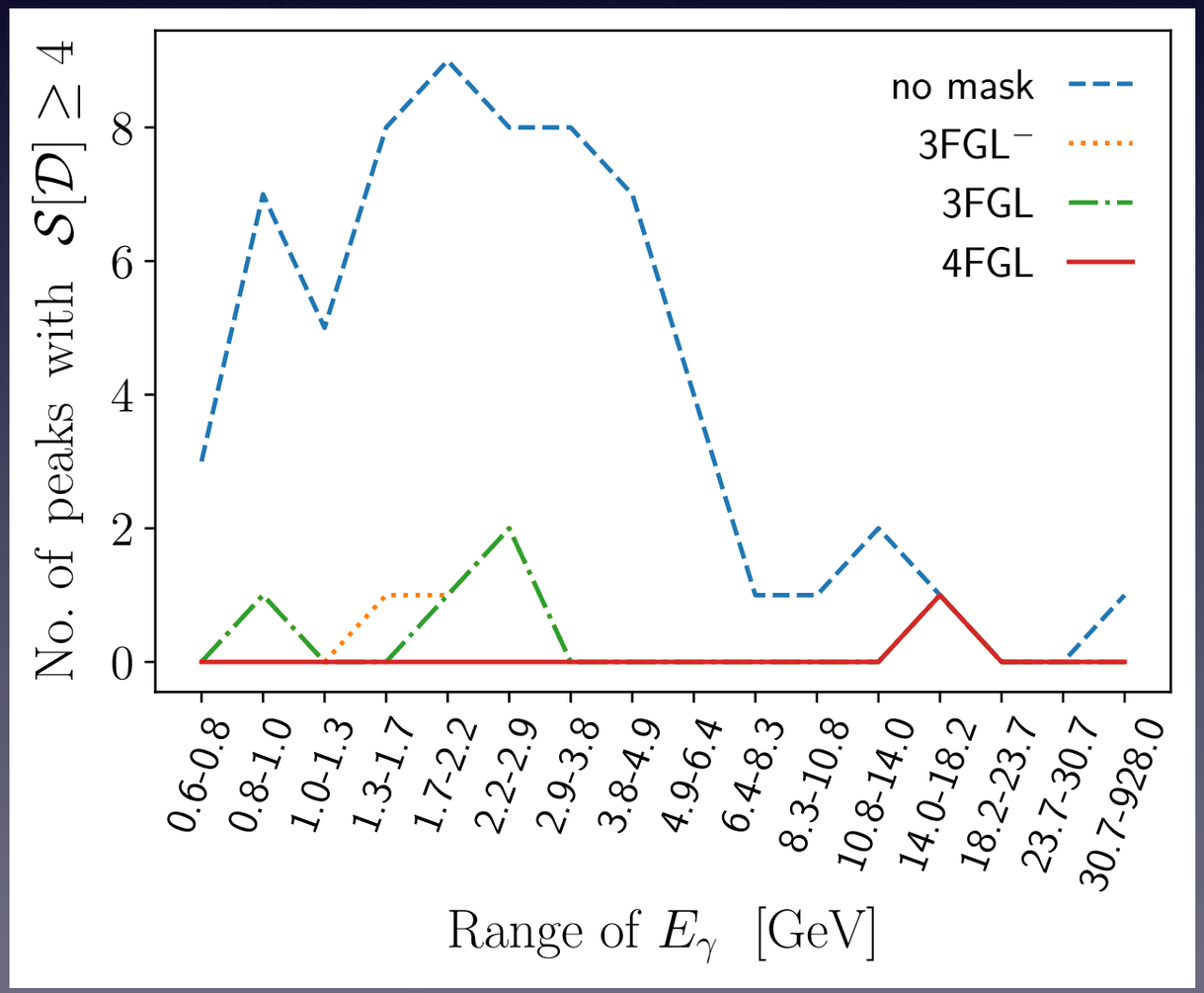
$$\psi(x) \in \mathbb{L}^2(\mathbb{R}) \text{ and}$$

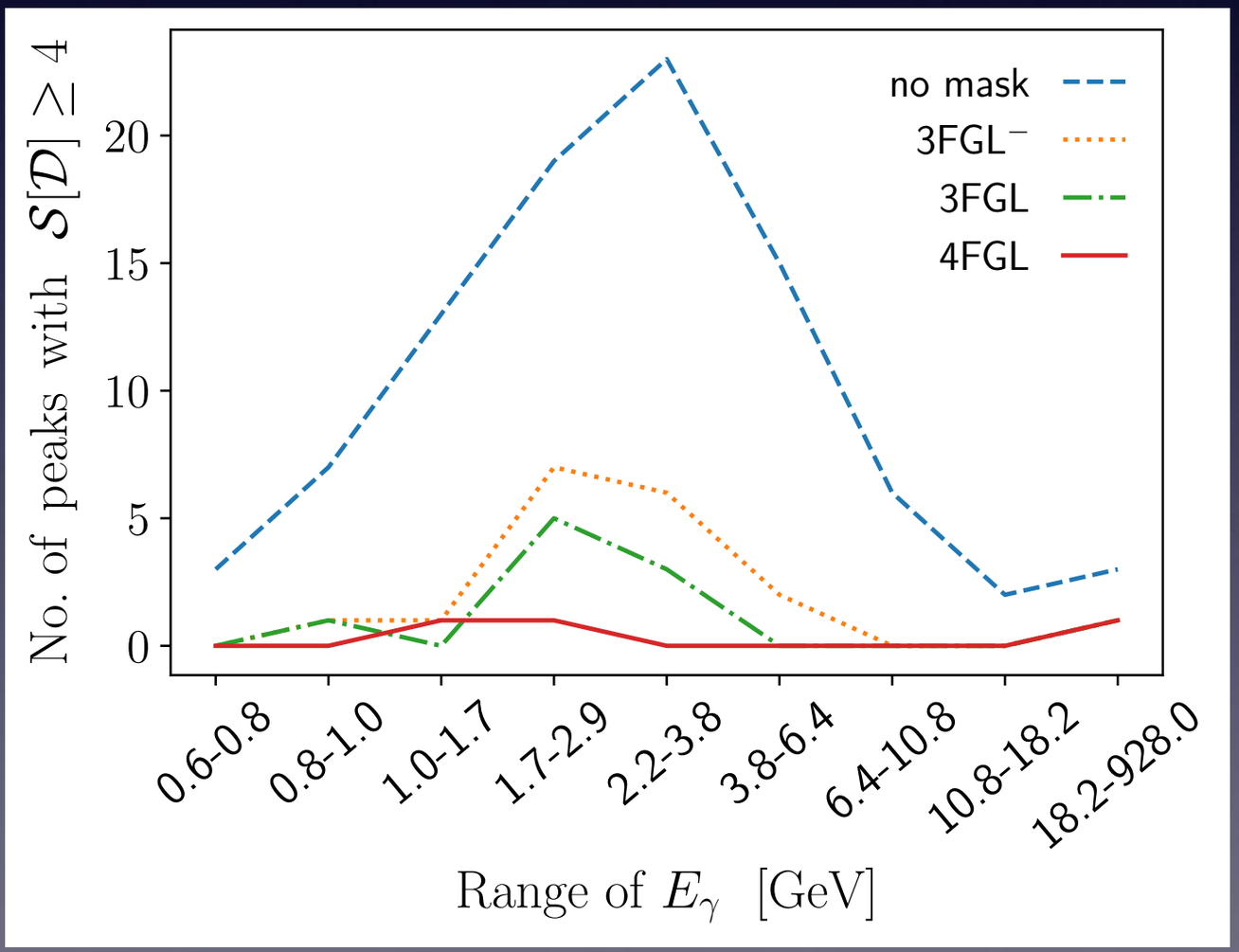
$$\frac{1}{\sqrt{a}}\psi \left(\frac{x-b}{a} \right) \in \mathbb{L}^2(\mathbb{R})$$

$$\text{for } a, b \in \mathbb{Z}$$

Other Energy Binnings

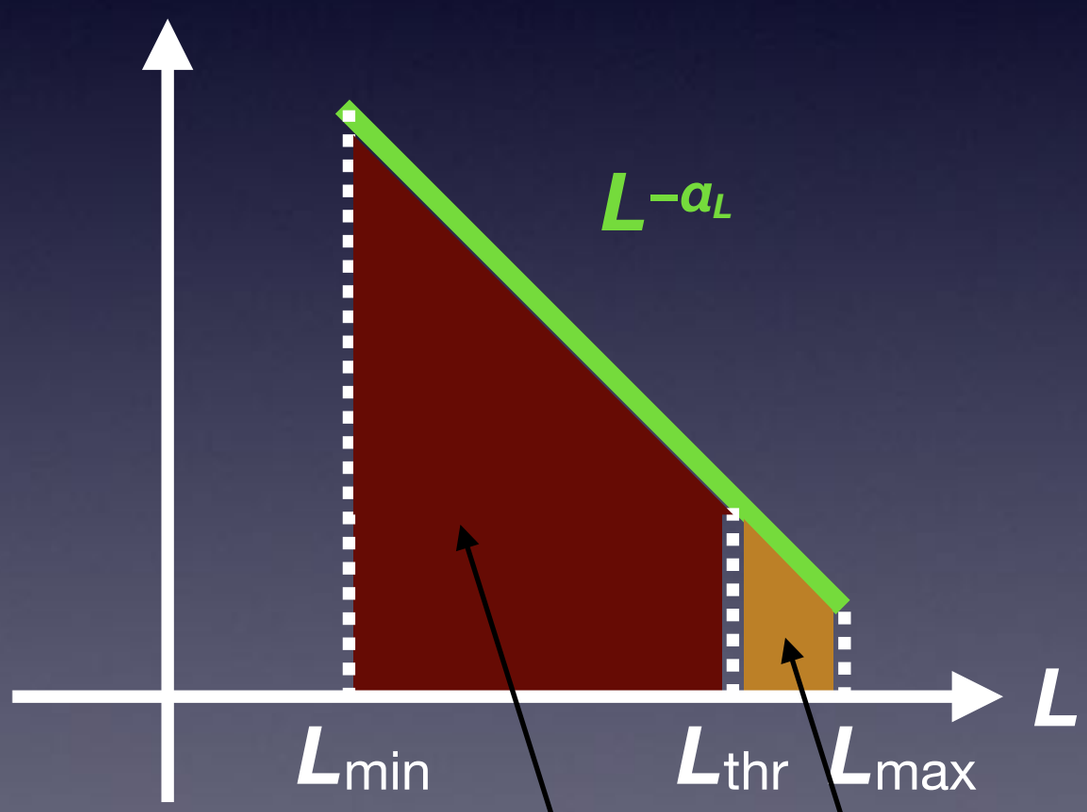
S is a nonlinear function of counts/binning — but 4FGL always captures entire relevant population





Luminosity Function

if GCE is PSs,
$L_{\text{sub-threshold}}/L_{\text{above-threshold}}=4\pm1$



$L_{min} \rightarrow 10^{31}$ erg/s
$L_{thr} \rightarrow 10^{34}$ erg/s
$L_{max} \rightarrow 10^{35}$ erg/s
$\Longrightarrow \alpha_L \rightarrow 2.06 \pm 0.04$
$N_{sub} \rightarrow (1.7 \pm 0.5)*10^3$

(compare to $N_{vis} \sim 47$)

$\int_{<thr} L\, dN/dL\, dL$ "= GCE"

$\int_{>thr} L\, dN/dL\, dL$ = stacked spectra