A New Mask for An Old Suspect

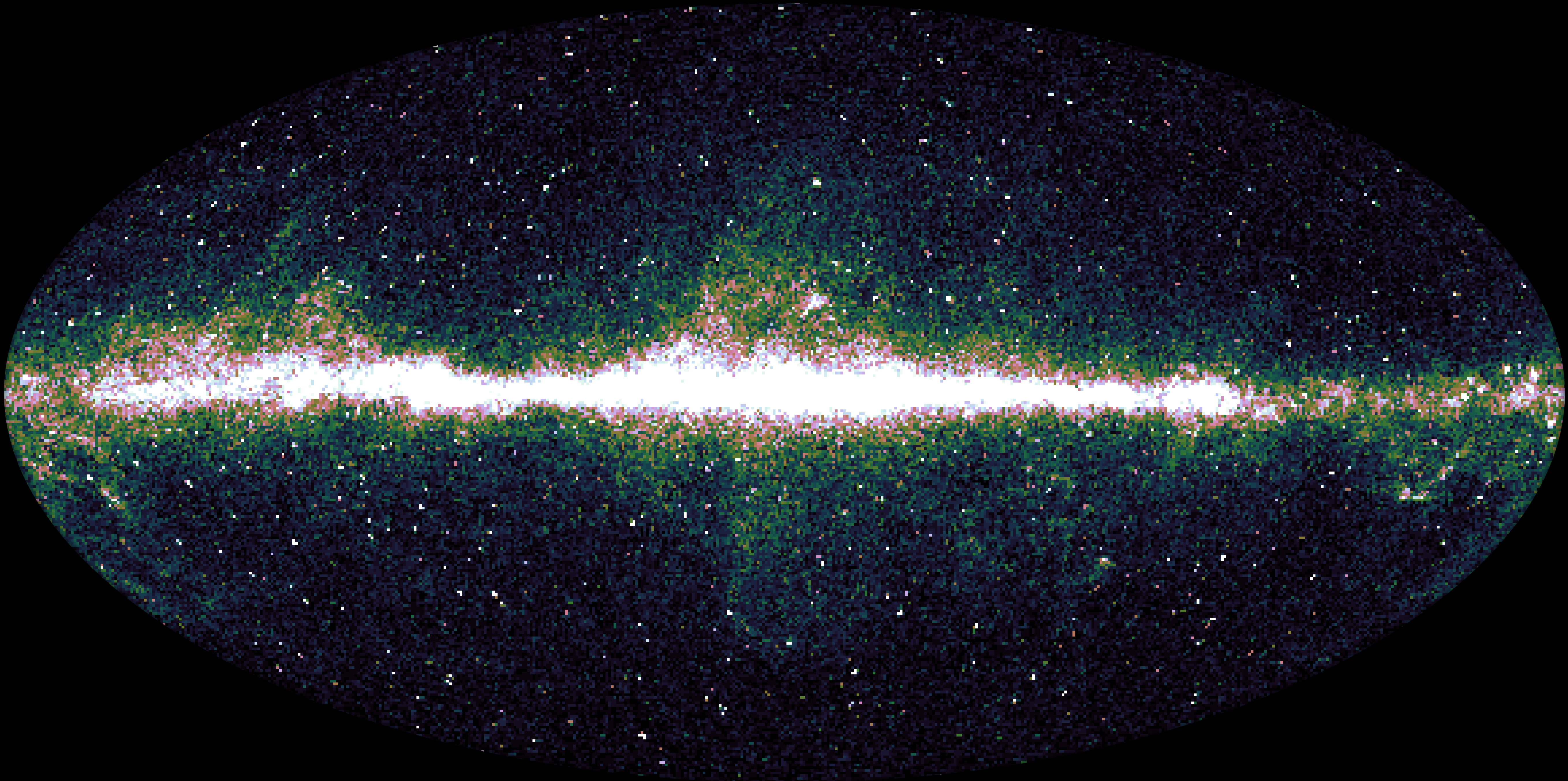
Testing the sensitivity of the Galactic Center Excess to the point source mask

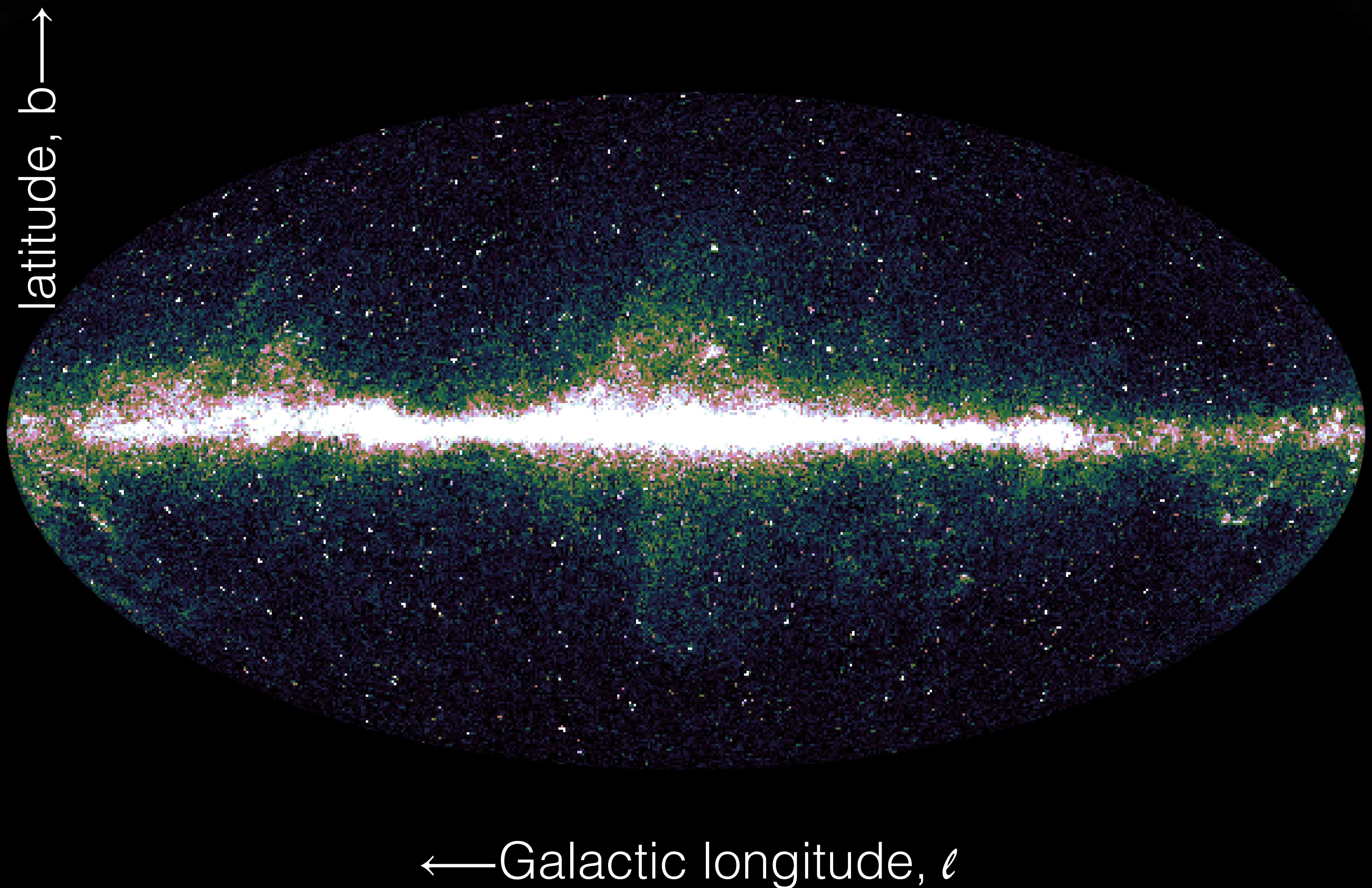
Samuel D. McDermott

In collaboration w/
Yi-Ming Zhong, Ilias Cholis & Patrick Fox, arXiv:1911.12369

CERN 18 Mar 2020

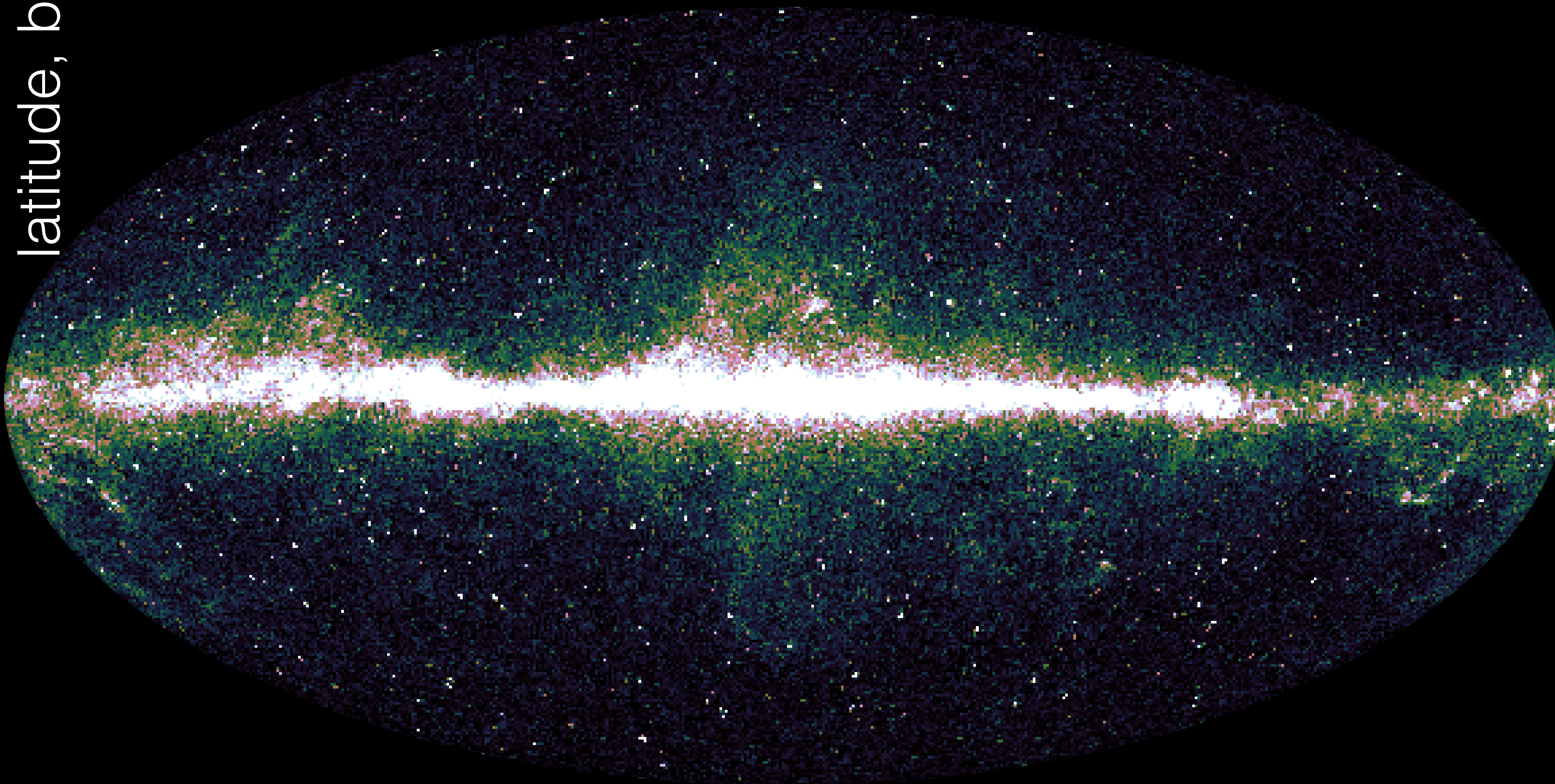
Fermilab



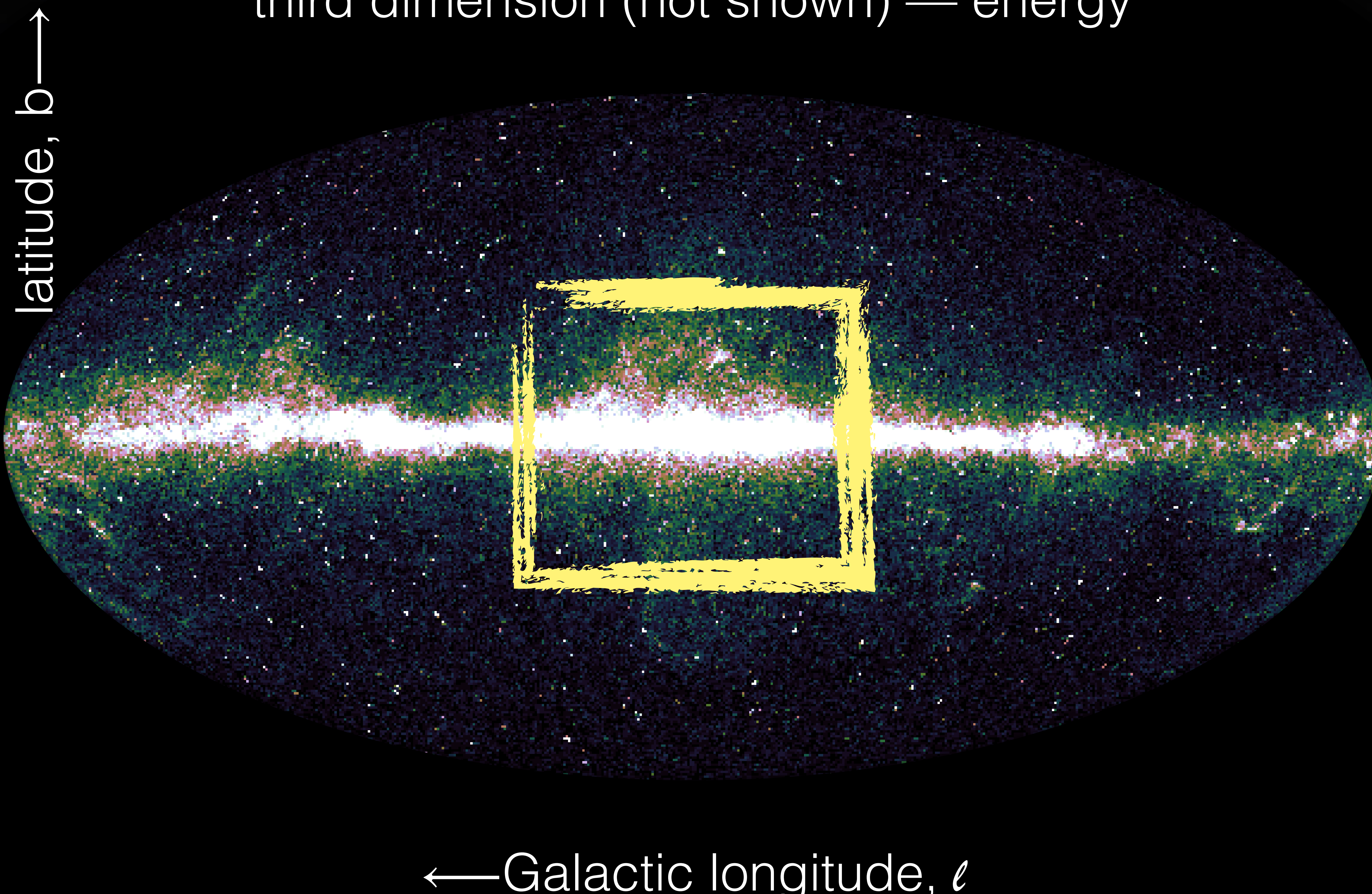

latitude, b ⟶
⟵Galactic longitude, ℓ

third dimension (not shown) — energy

latitude, b ⟶



⟵ Galactic longitude, ℓ



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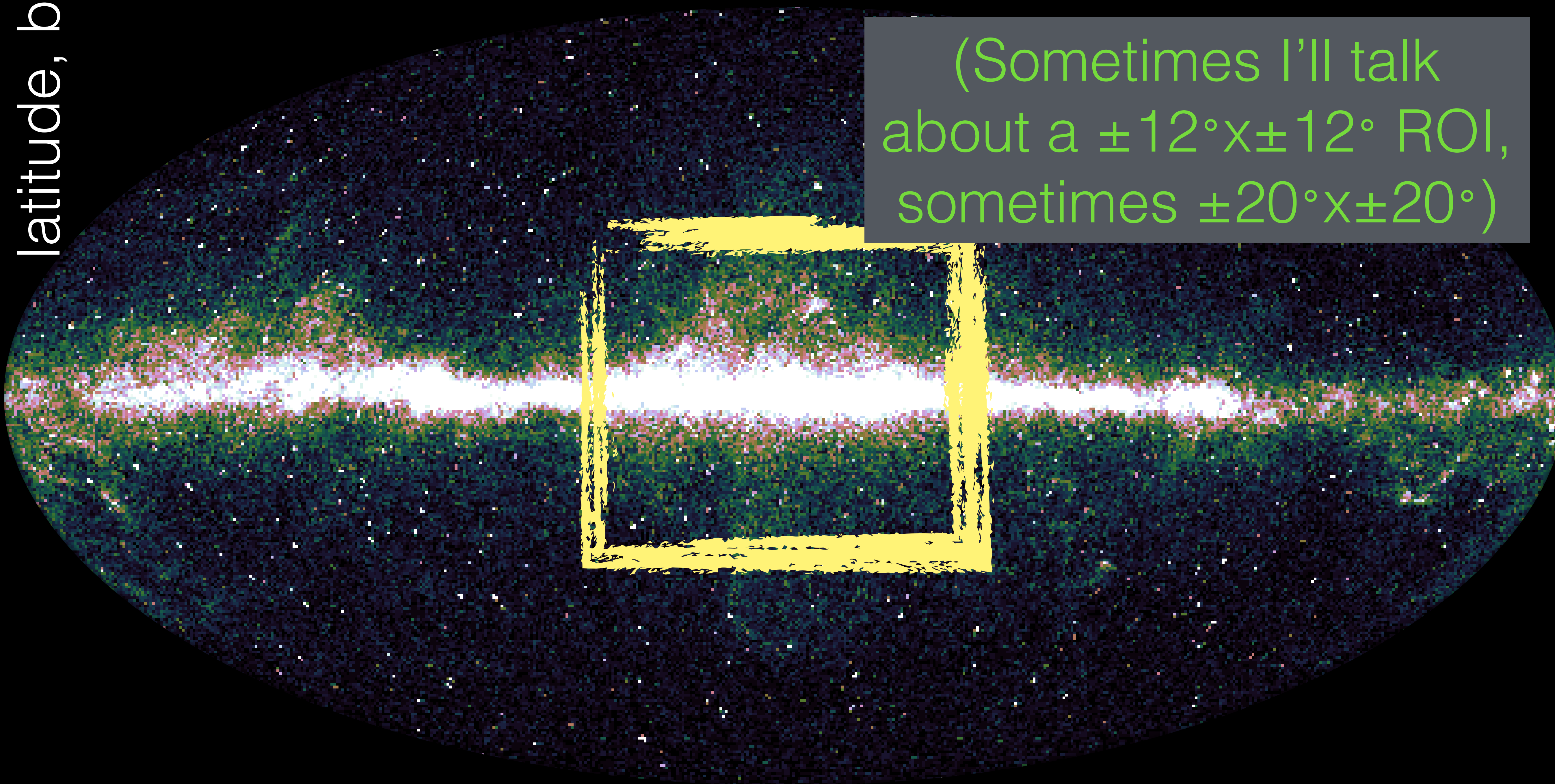


⟵Galactic longitude, ℓ

Outline

1. Things most people agree on ("introduction")
    - how many photons? (roughly) how are they distributed across the sky?

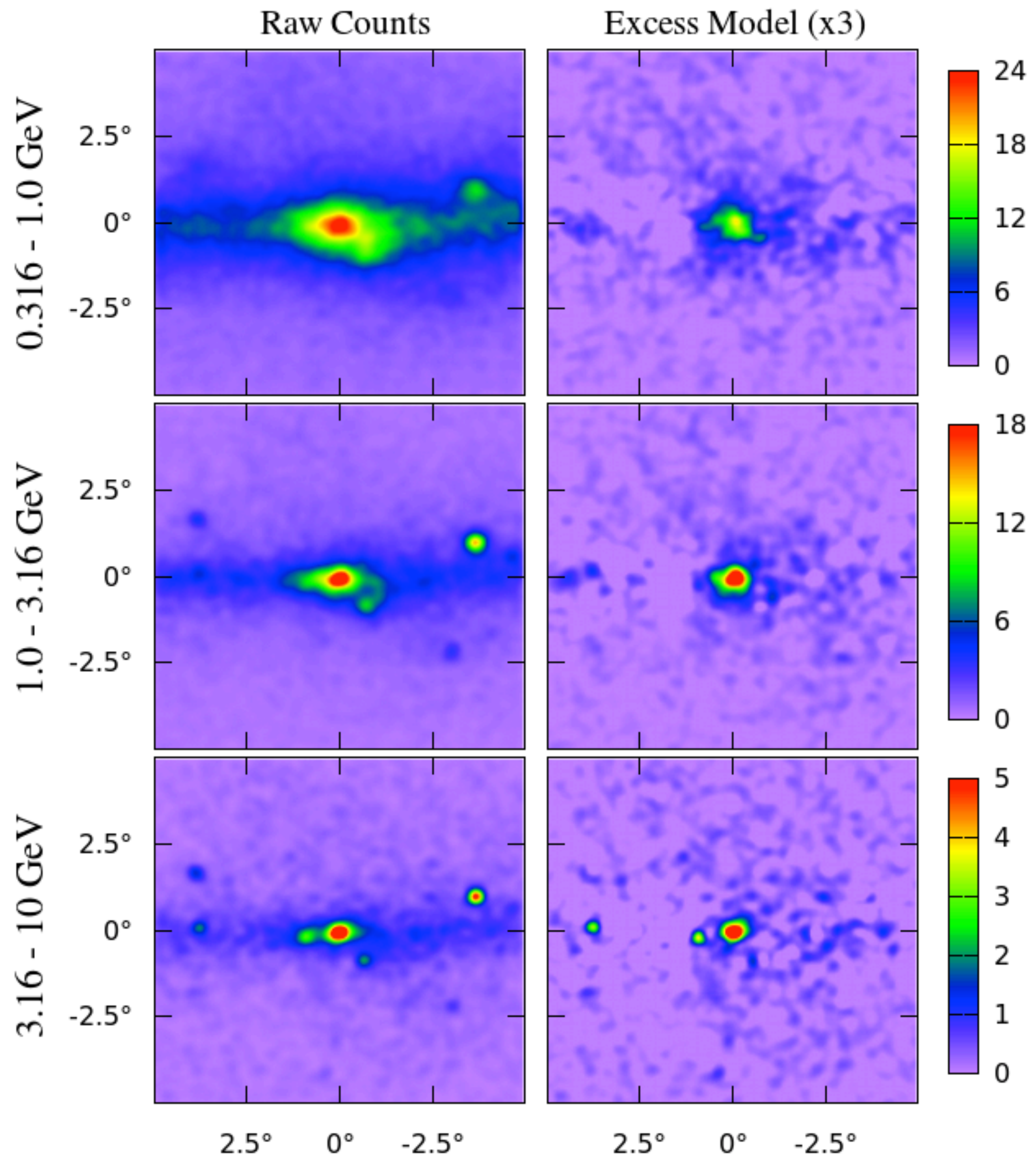
2. Things that are up for debate
    - what produces these photons?

3. New results
    - (in)sensitivity of two tests to point source masks

Part 1

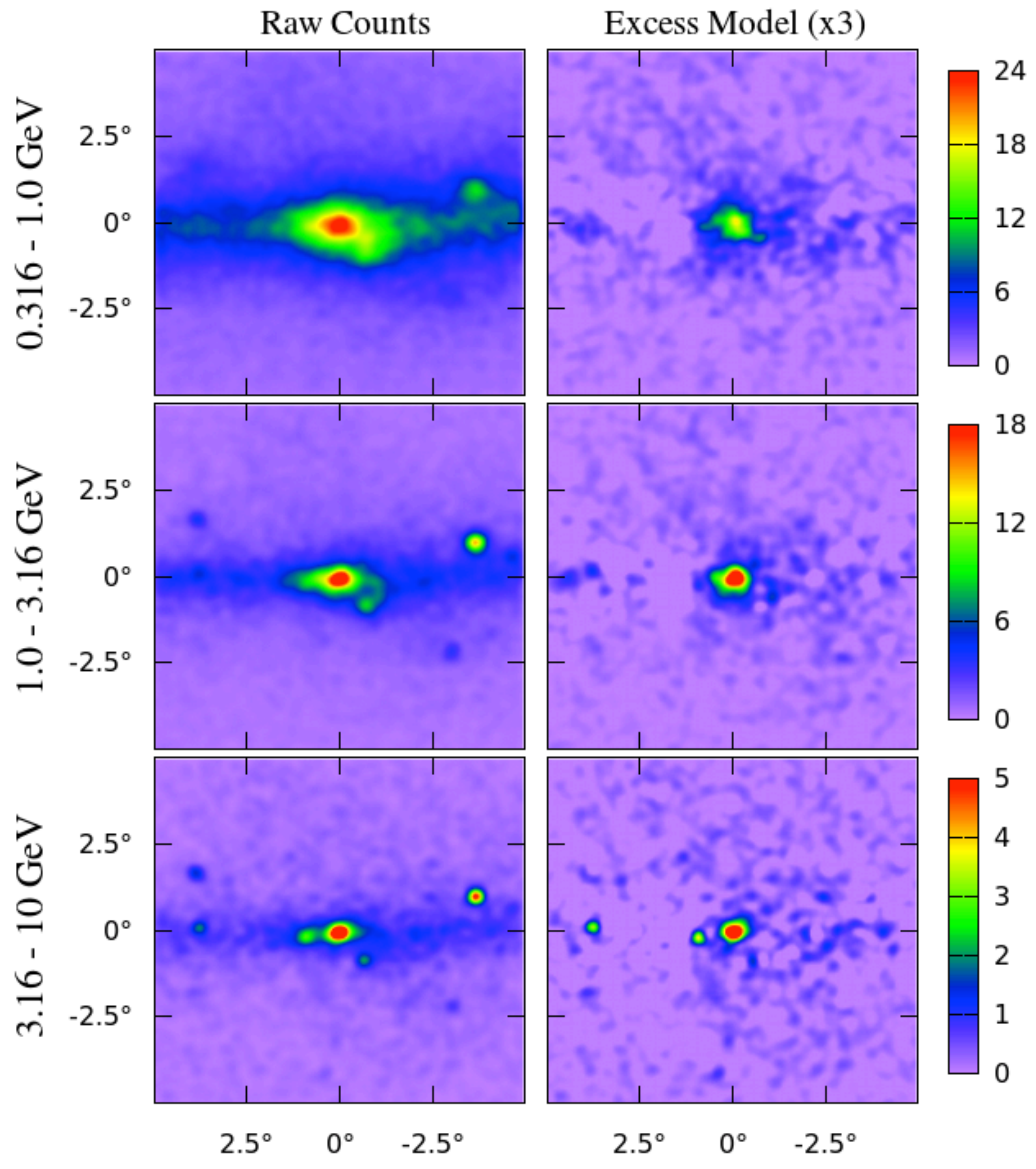
Features of the Galactic Center Excess

Galactic Center



Daylan et al., 1402.6703

Galactic Center



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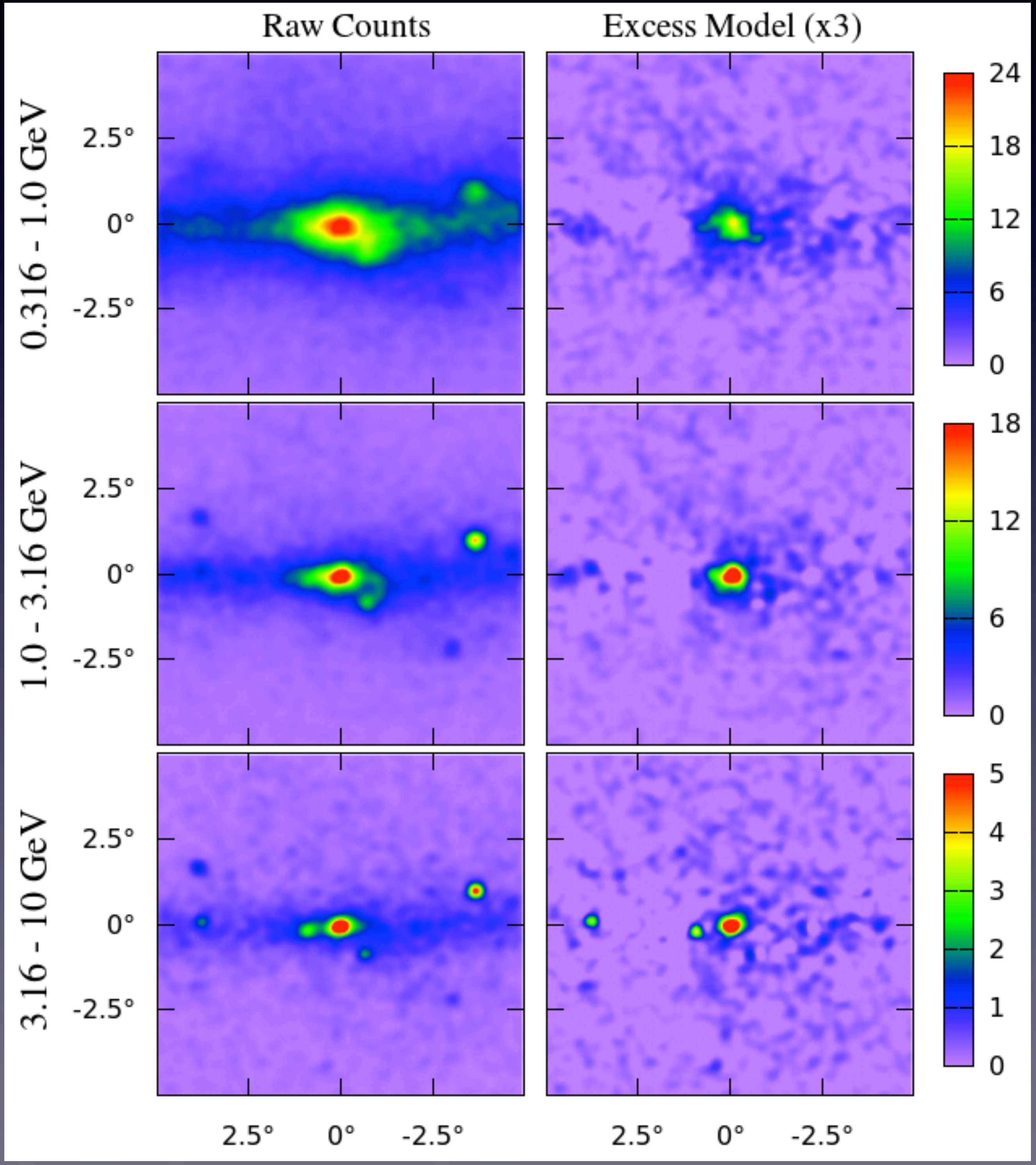
excess with normalization ~ 30% of raw!

Galactic Center

point sources; isotropic; diffuse emission; map of 20 cm synchrotron



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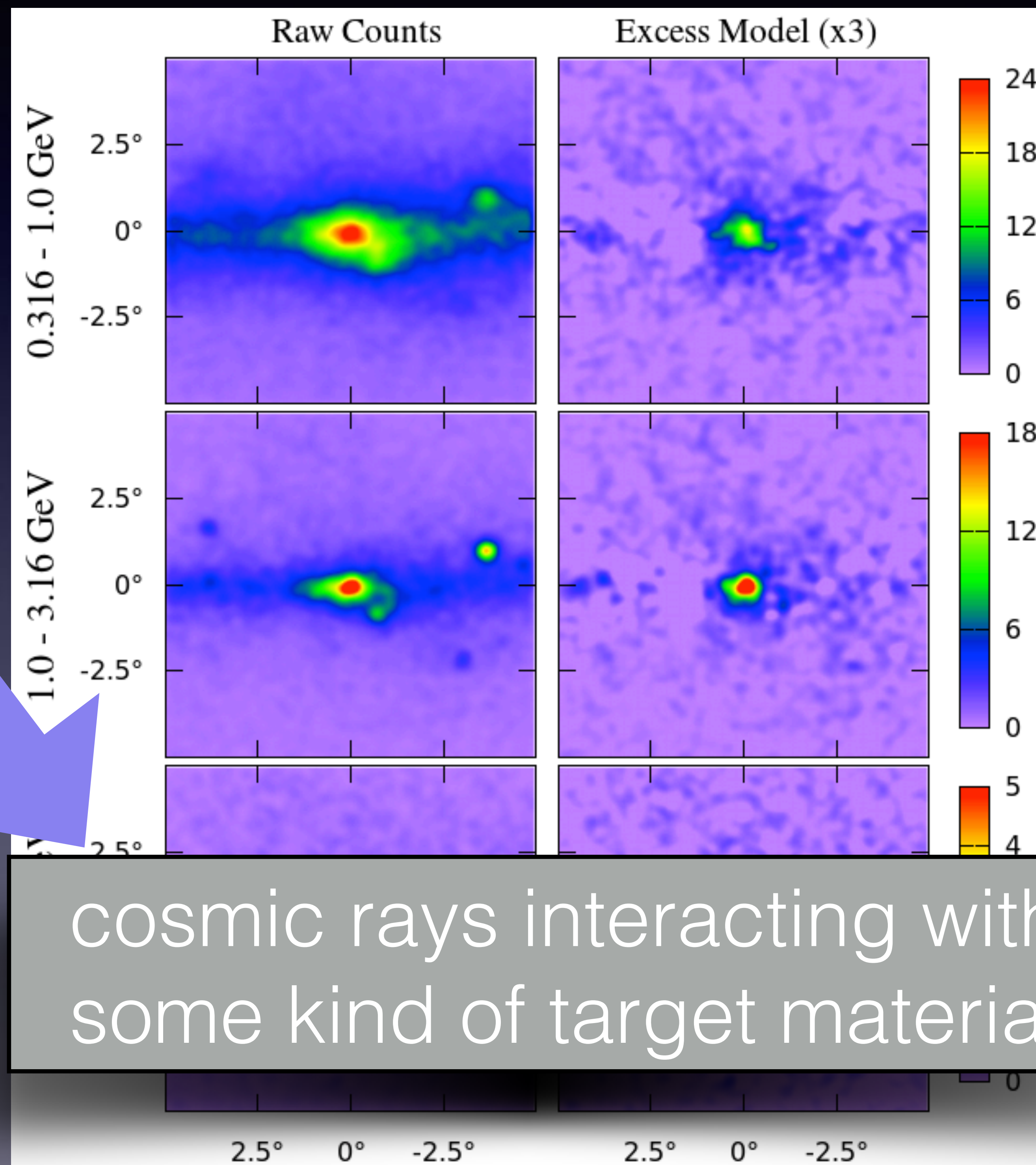

cosmic rays interacting with some kind of target material

excess with normalization ~ 30% of raw!

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Single Slide on Diffuse Emission

Diffuse gamma ray emission arises when cosmic rays collide with background “target” material

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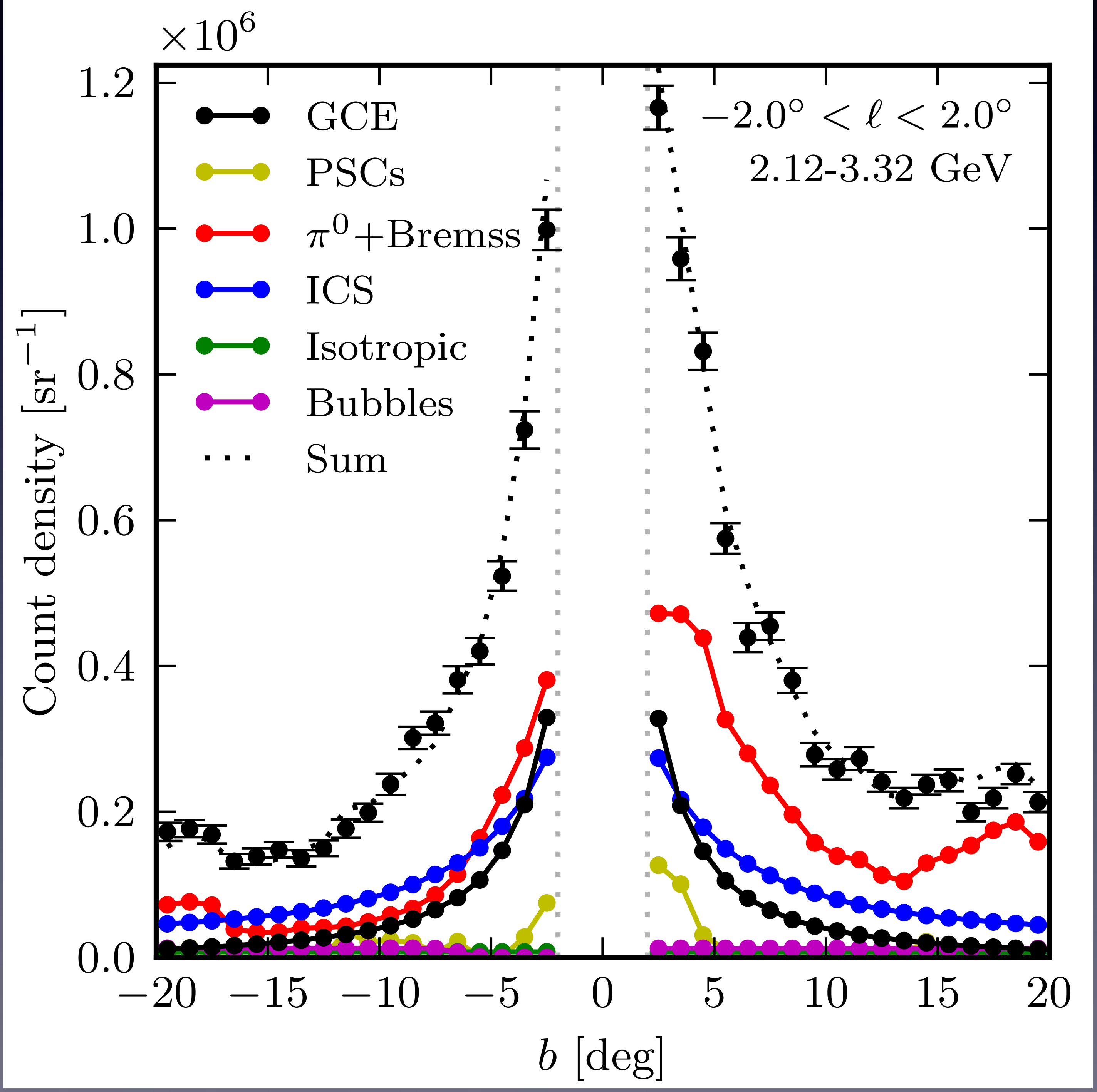
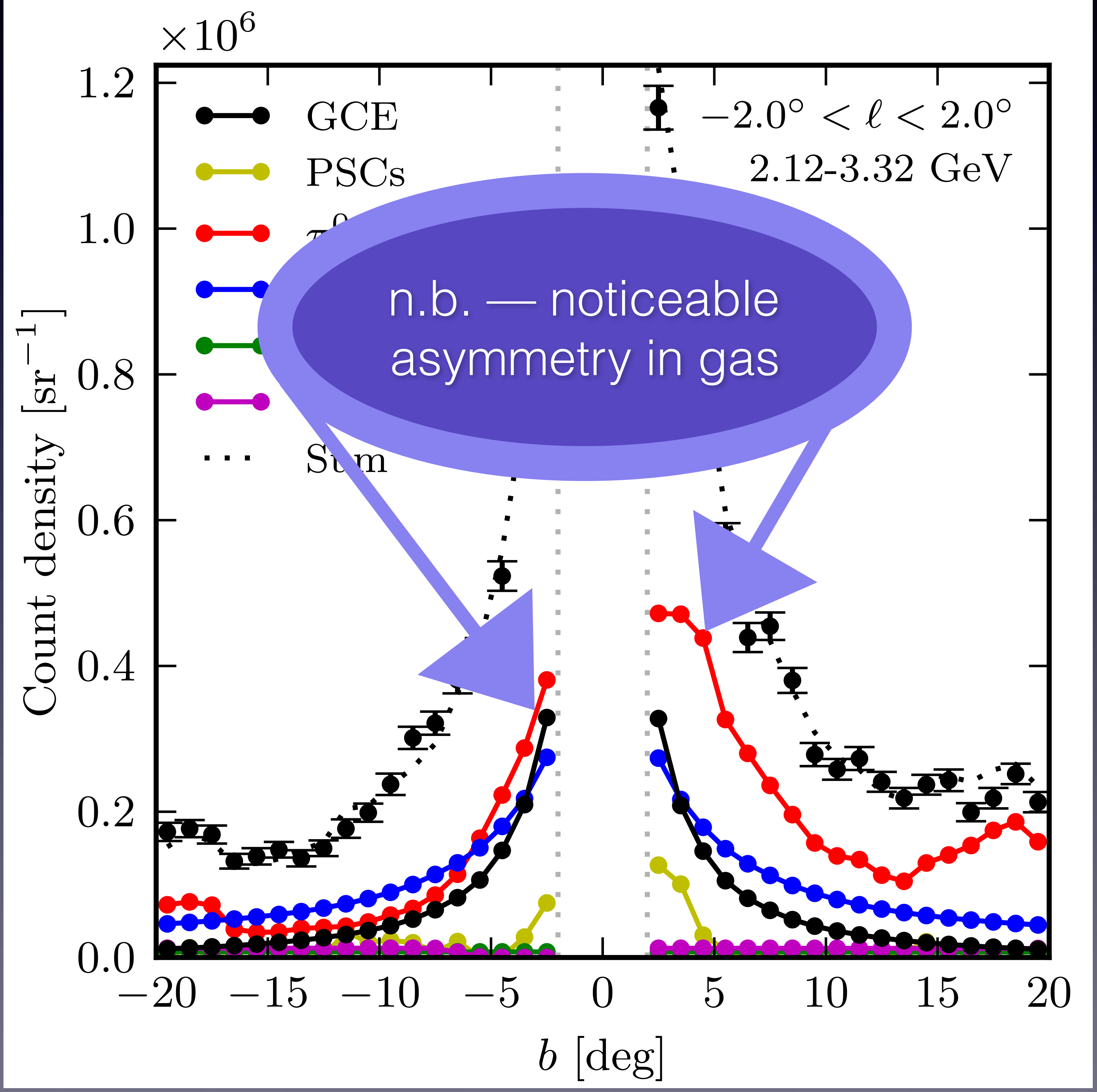
"π^0's" = hadronic CRs interacting with gas
"bremsstrahlung" = leptonic CRs interacting with gas
"ICS" = leptonic CRs interacting with background light

Latitude dependence



1409.0042

Total Normalization

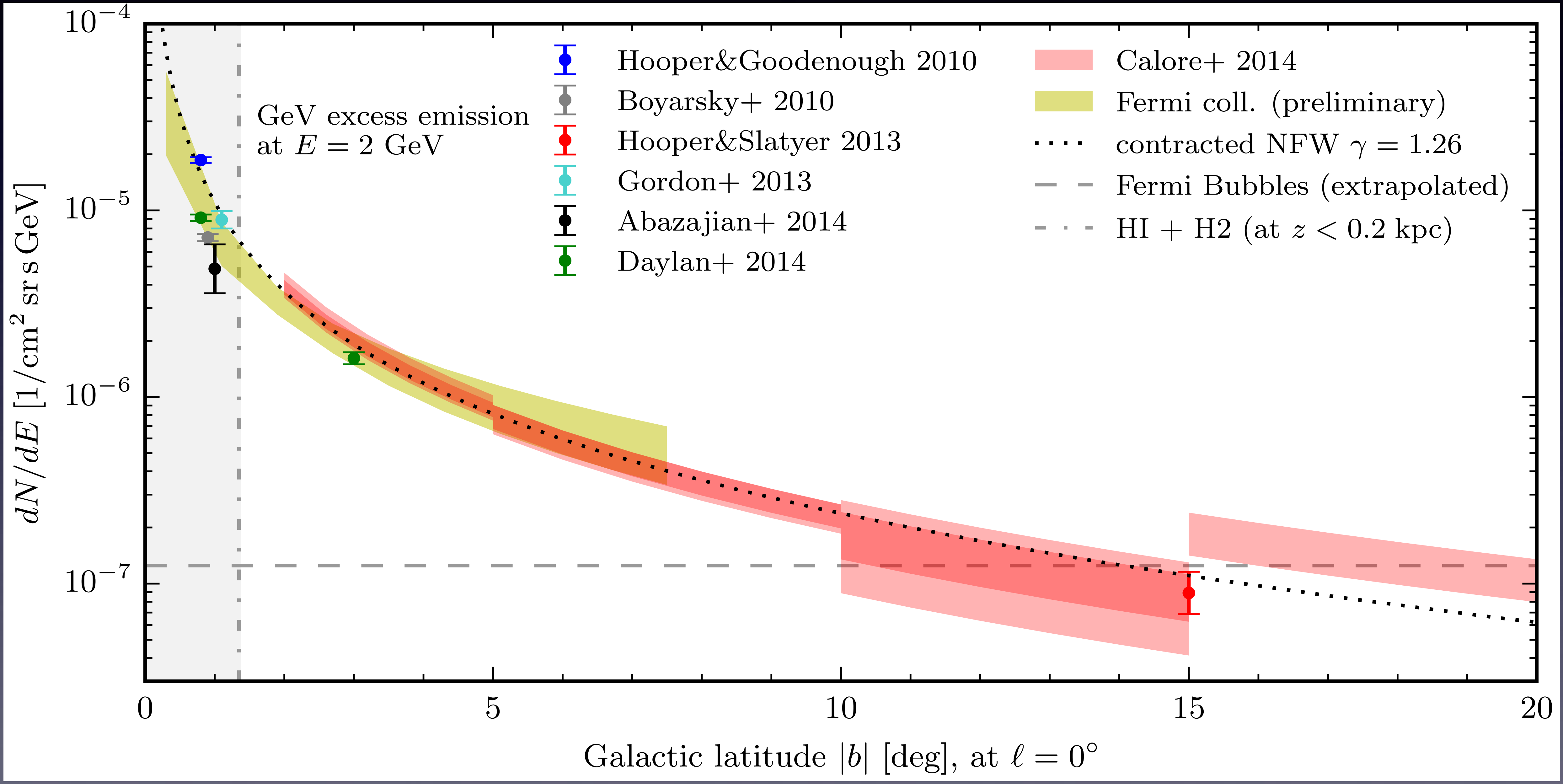


1409.0042

cf Leane & Slatyer
2002.12370

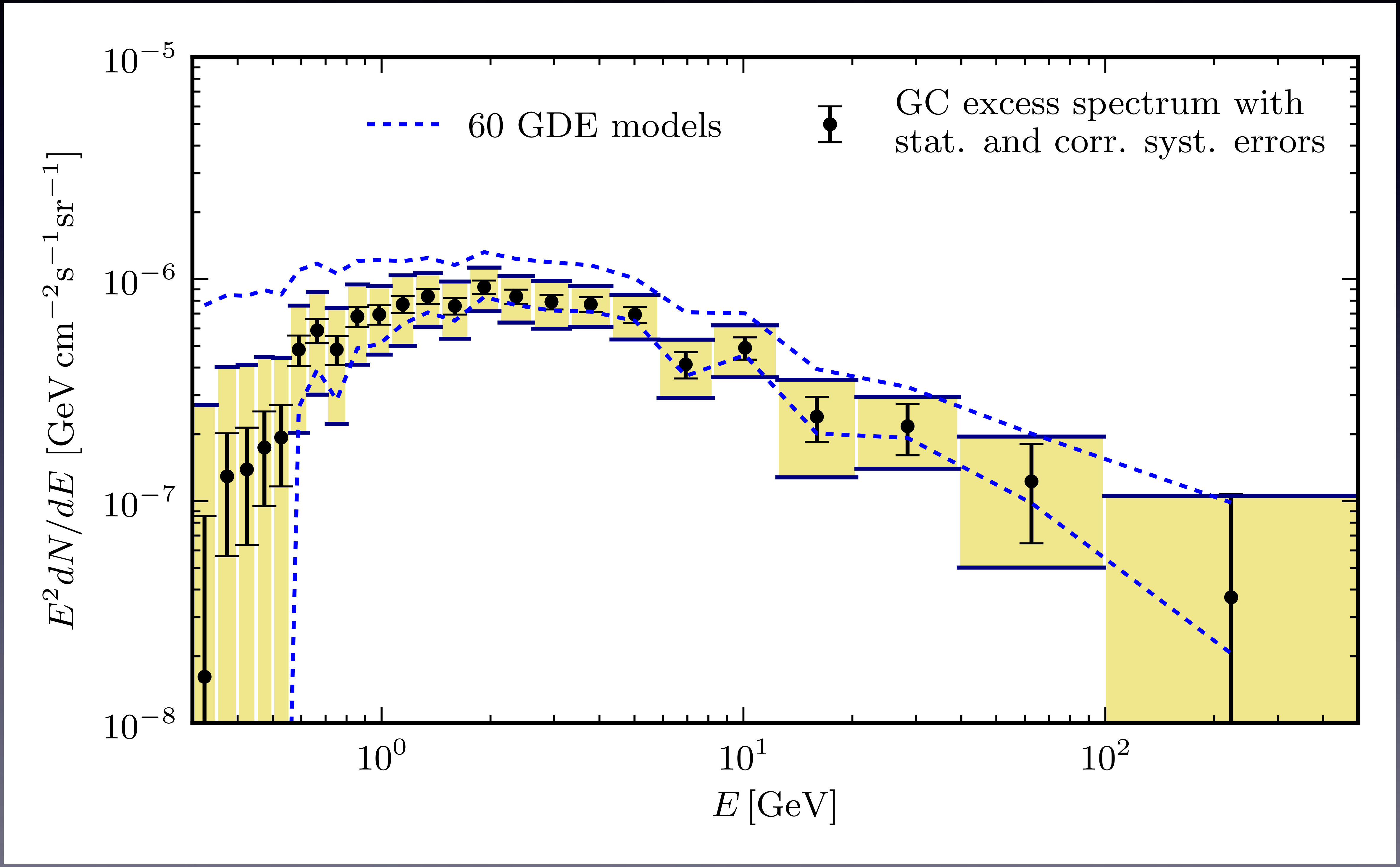
Seen out to > 10°

1411.4647



dotted line: $\rho_{gNFW} = \rho_s\,(r/r_s)^{-\gamma}\,[1+(r/r_s)]^{-3+\gamma}$ and $\gamma \sim 1.2$

Robust to diffuse map



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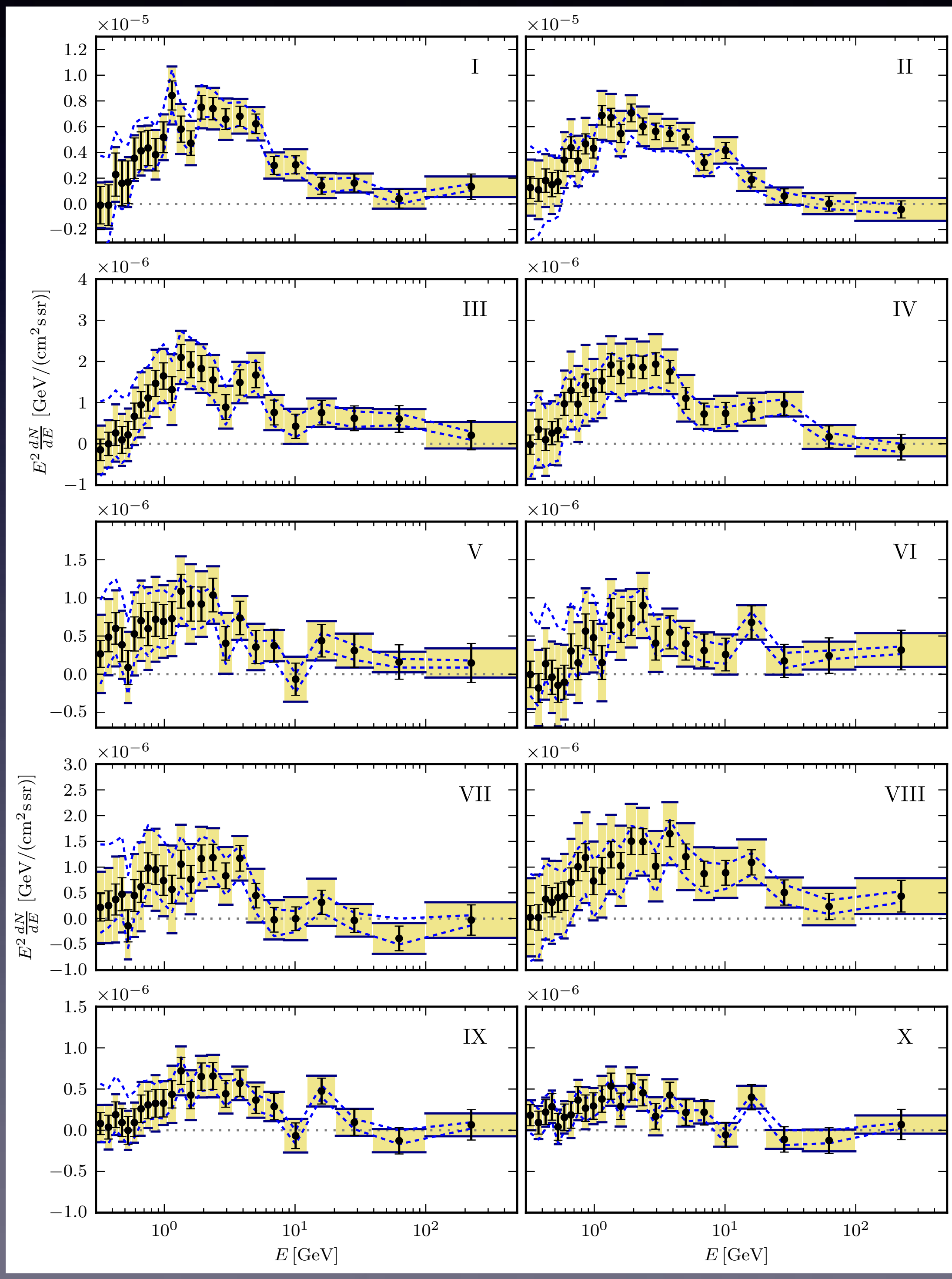
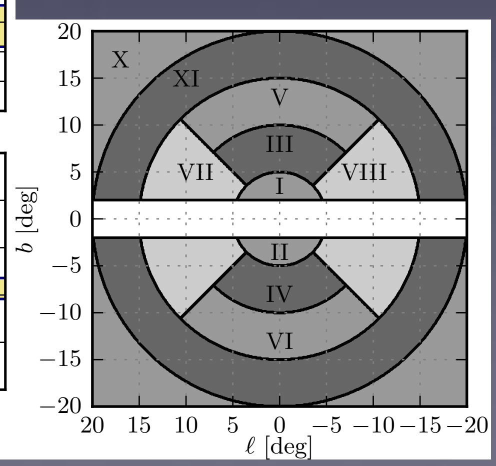


And present everywhere on the sky

1409.0042



Part 2

Where Does It Come From?

Two Primary Candidate Explanations

1. Dark Matter Annihilation
   - expected DM spatial distribution ($\sim\rho_{gNFW}^2$) is a good fit
   - thermal relic cross-section and ~ weak scale mass match observed brightness and energy spectrum

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in this talk, I'm going to focus on this possibility

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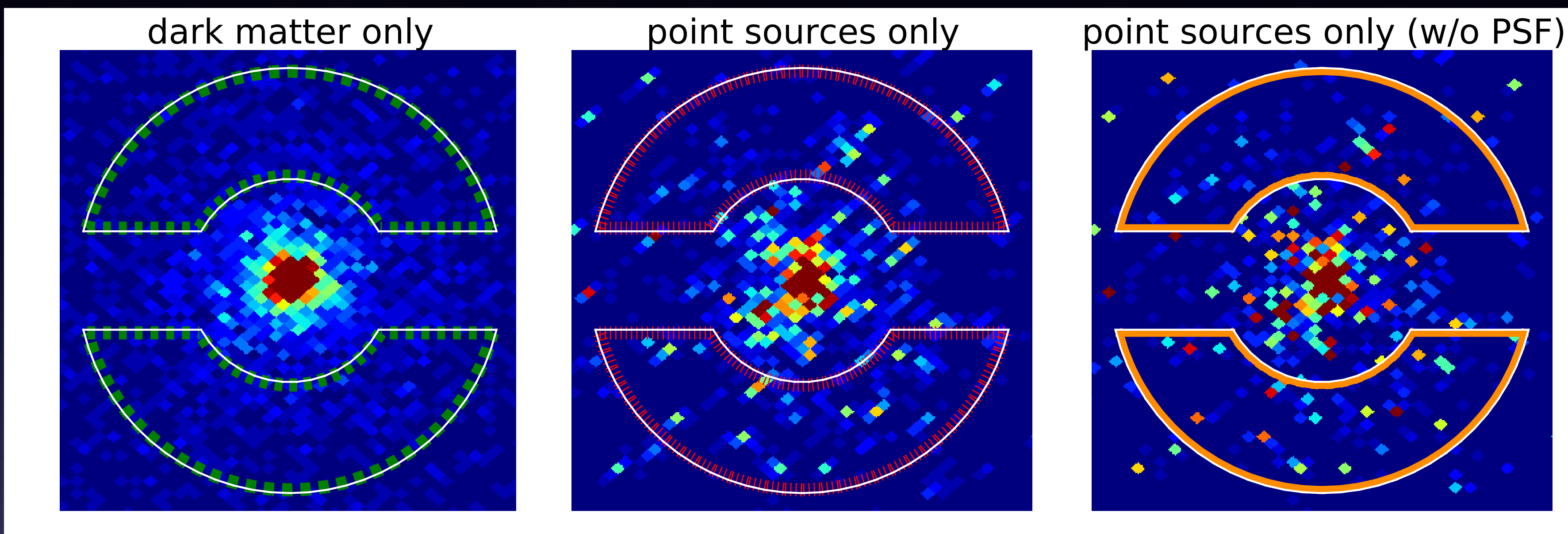
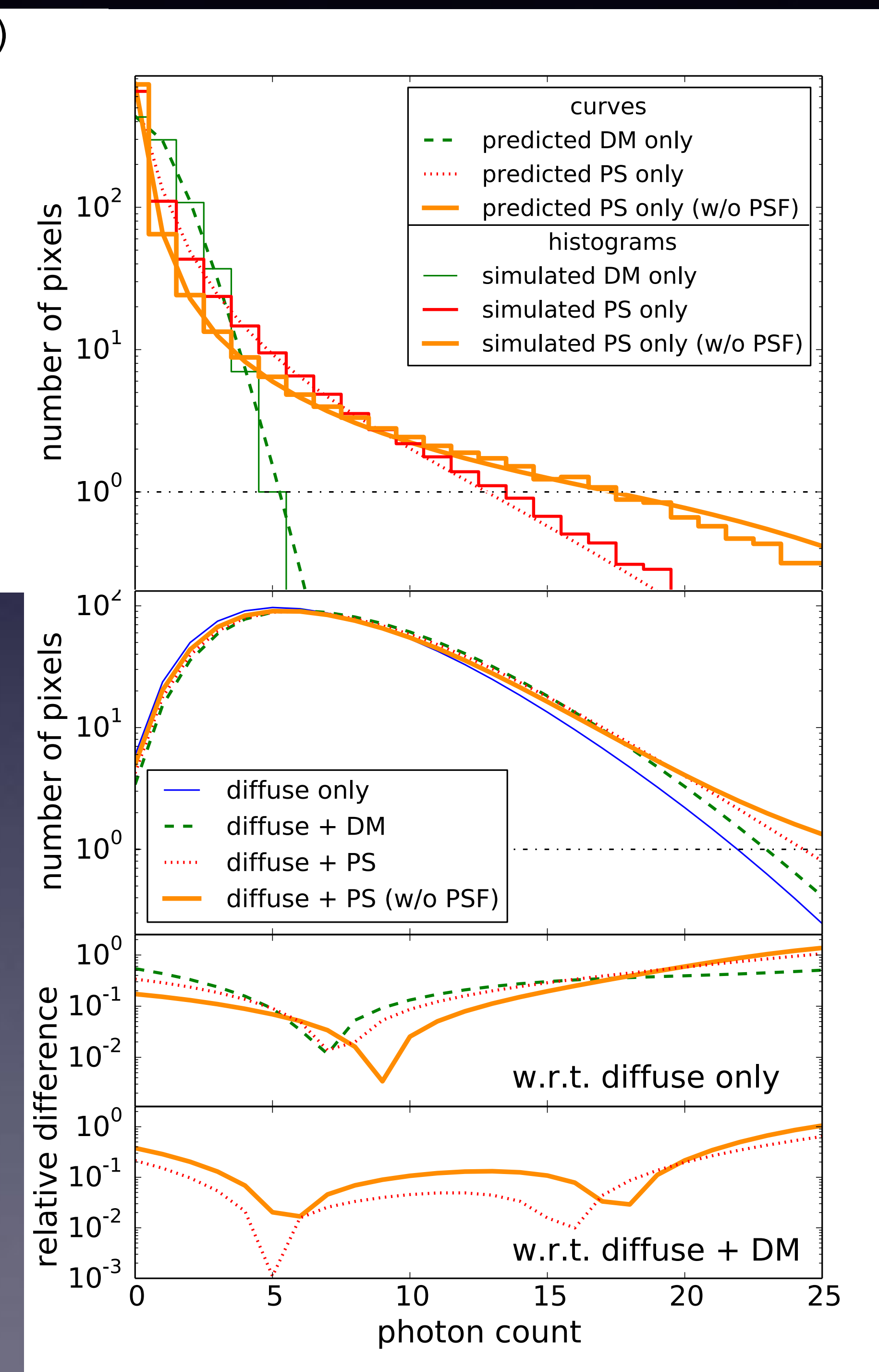
Point Source Statistics





Lee, Lisanti, Safdi **1412.6099**

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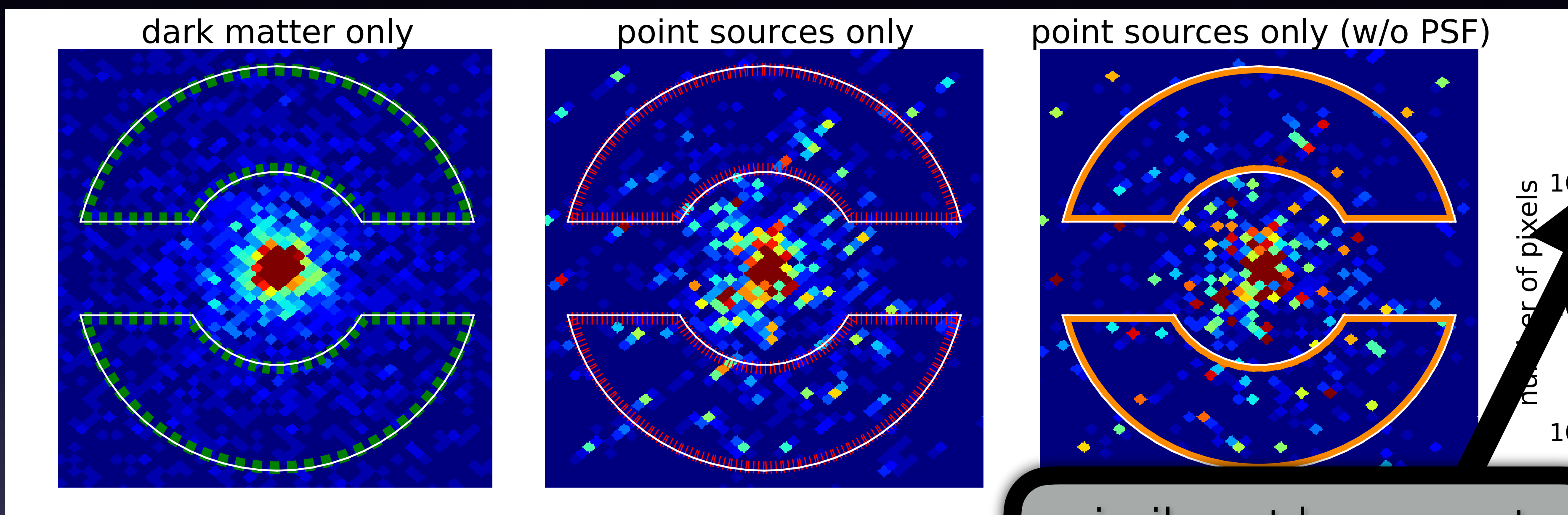

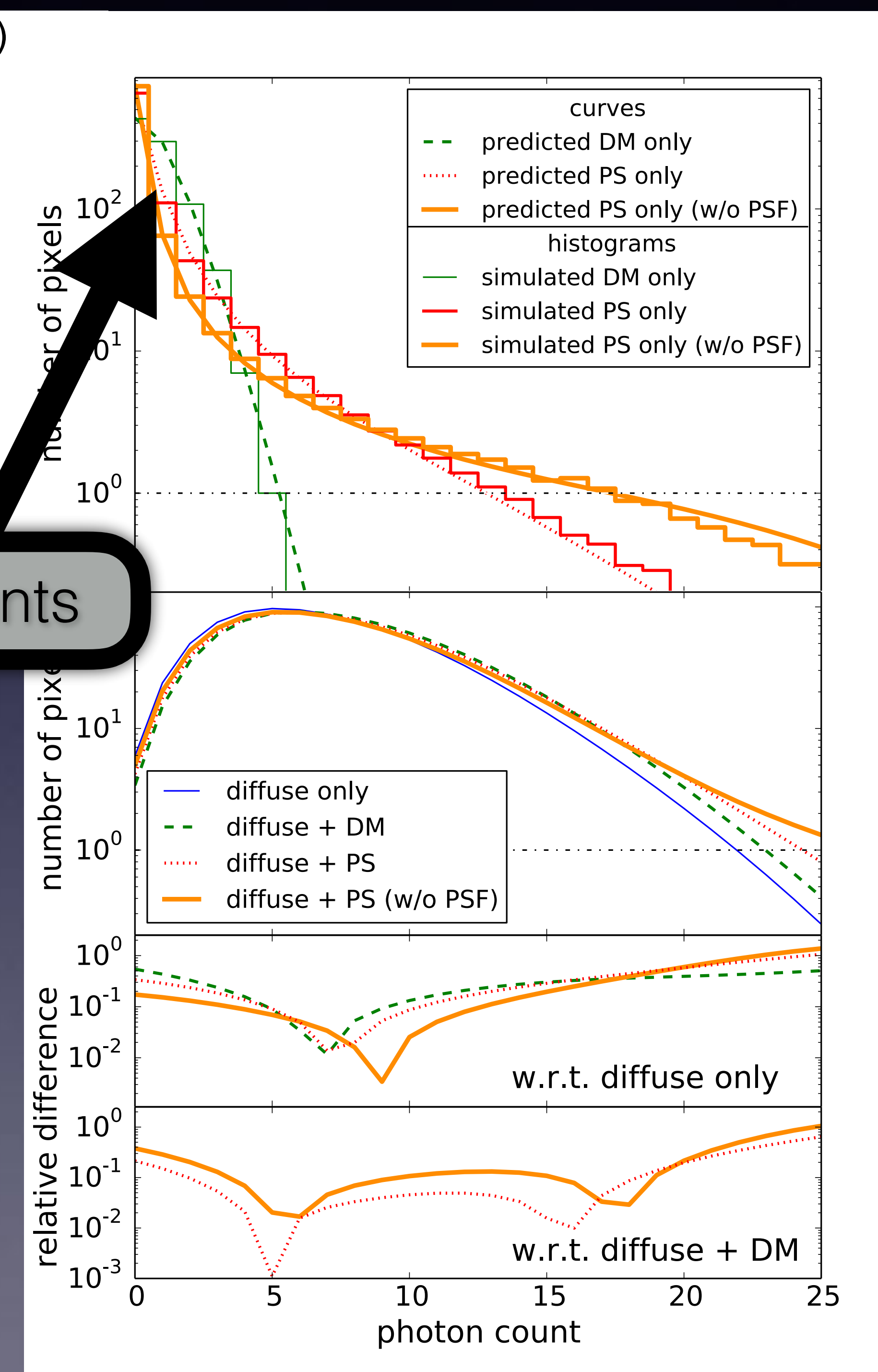

similar at low counts

Lee, Lisanti, Safdi 1412.6099

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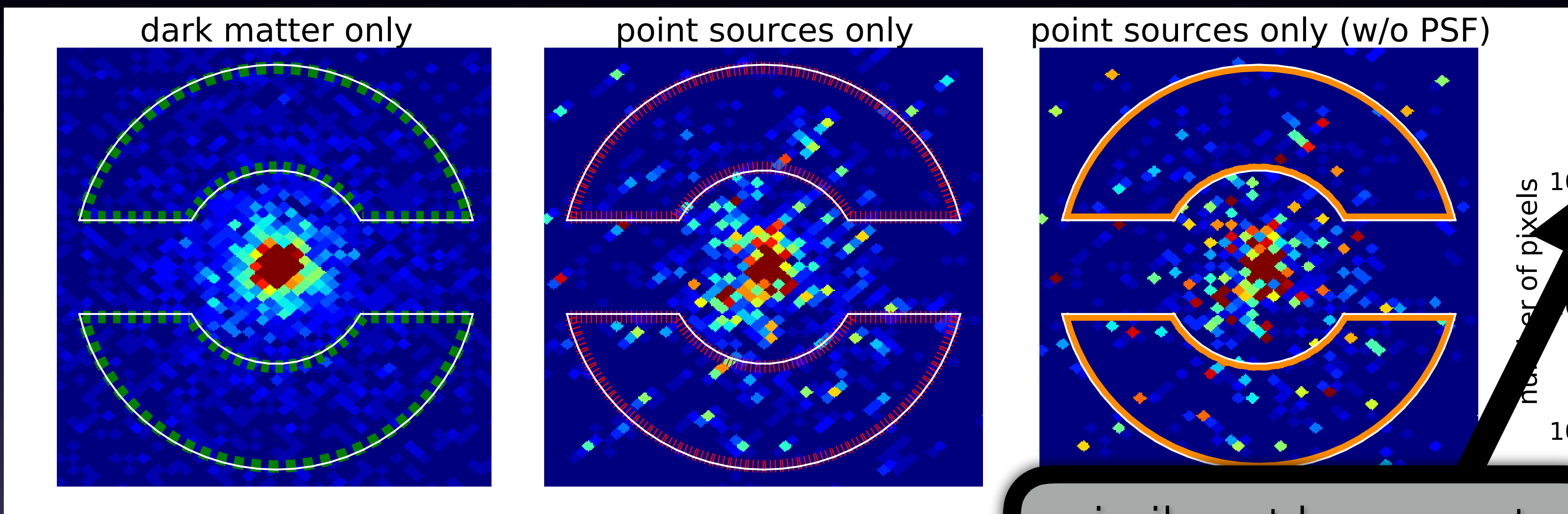

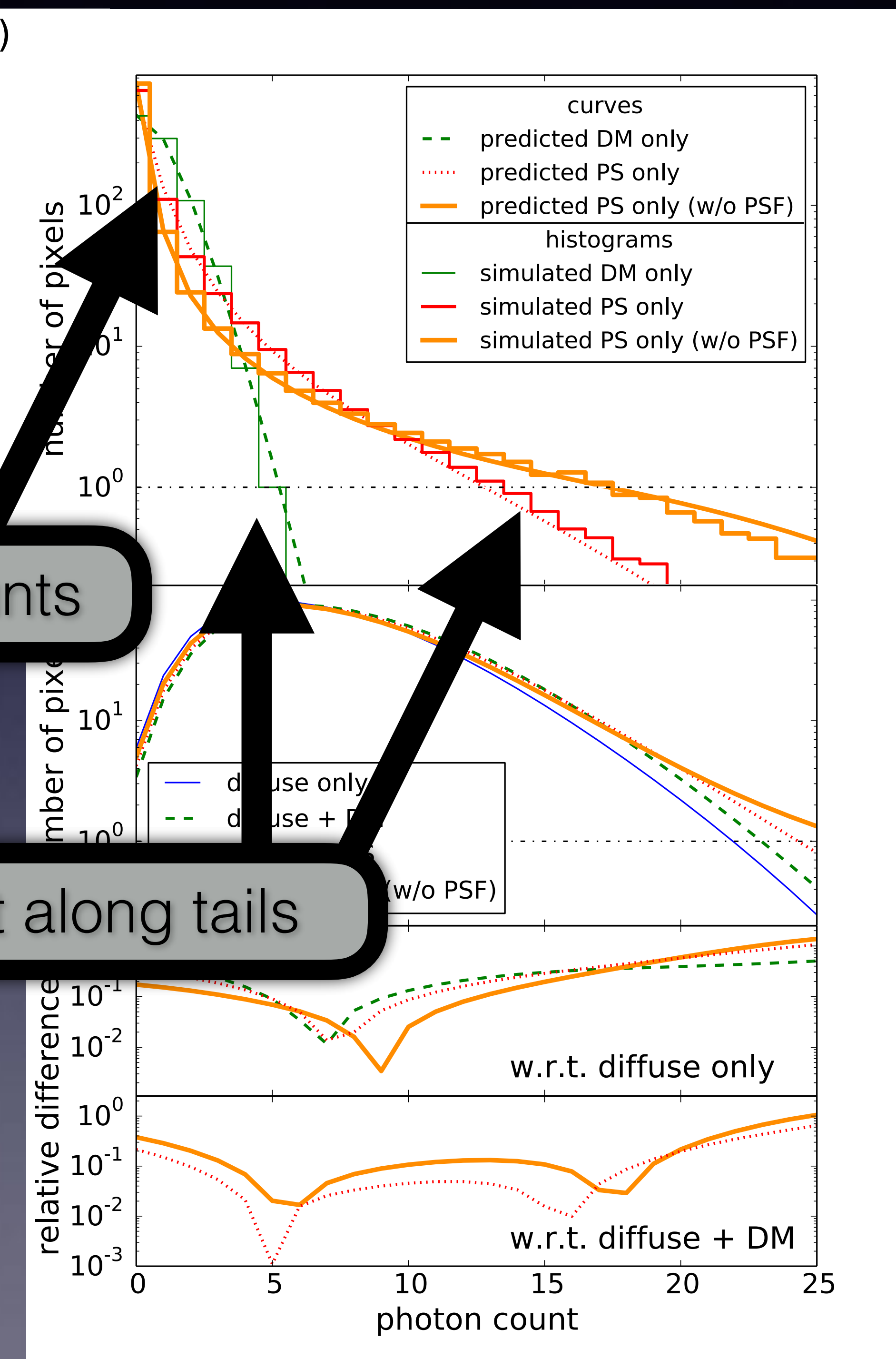

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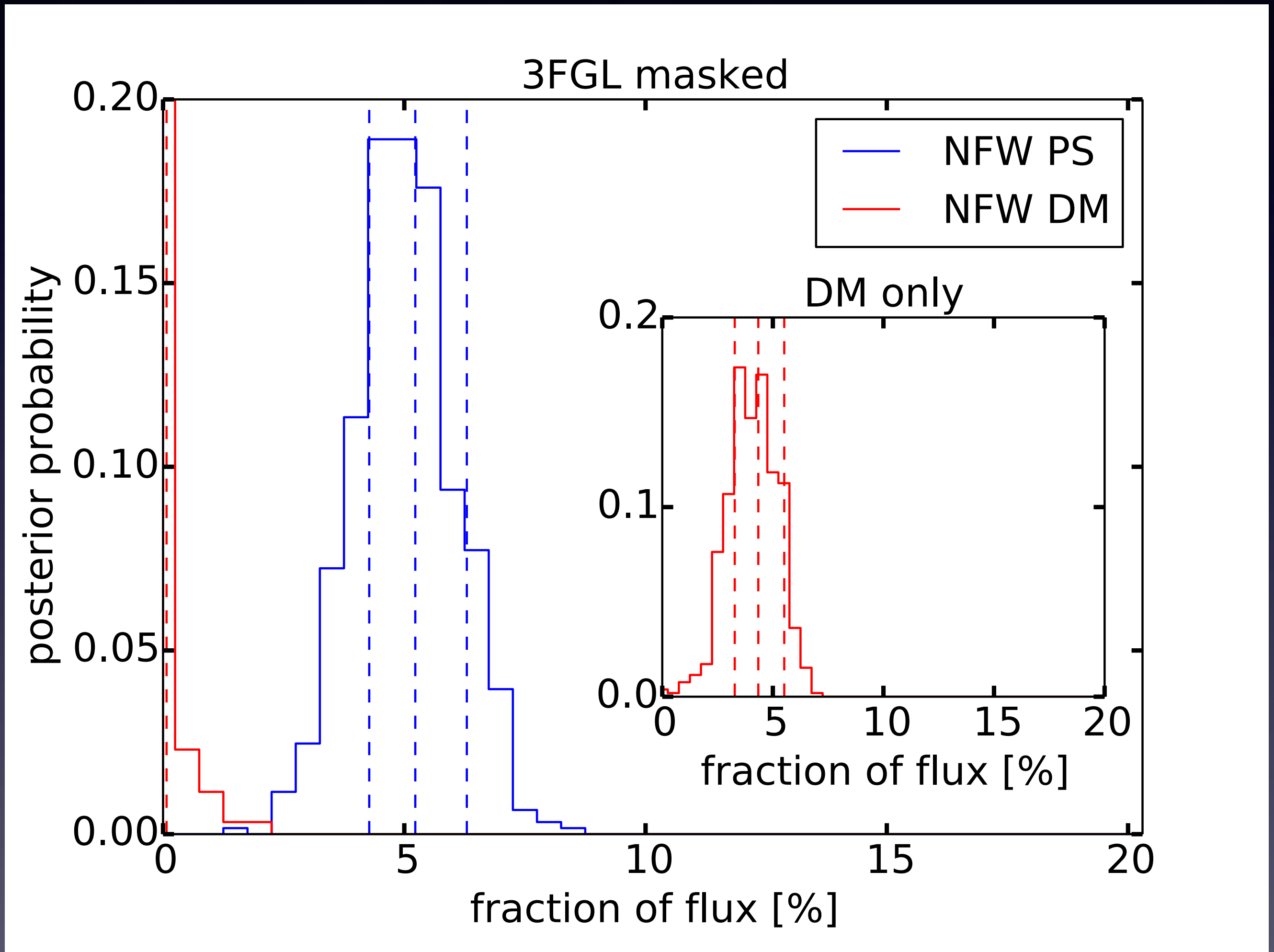
Point Source Fits

Lee et al., **1506.05124**



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

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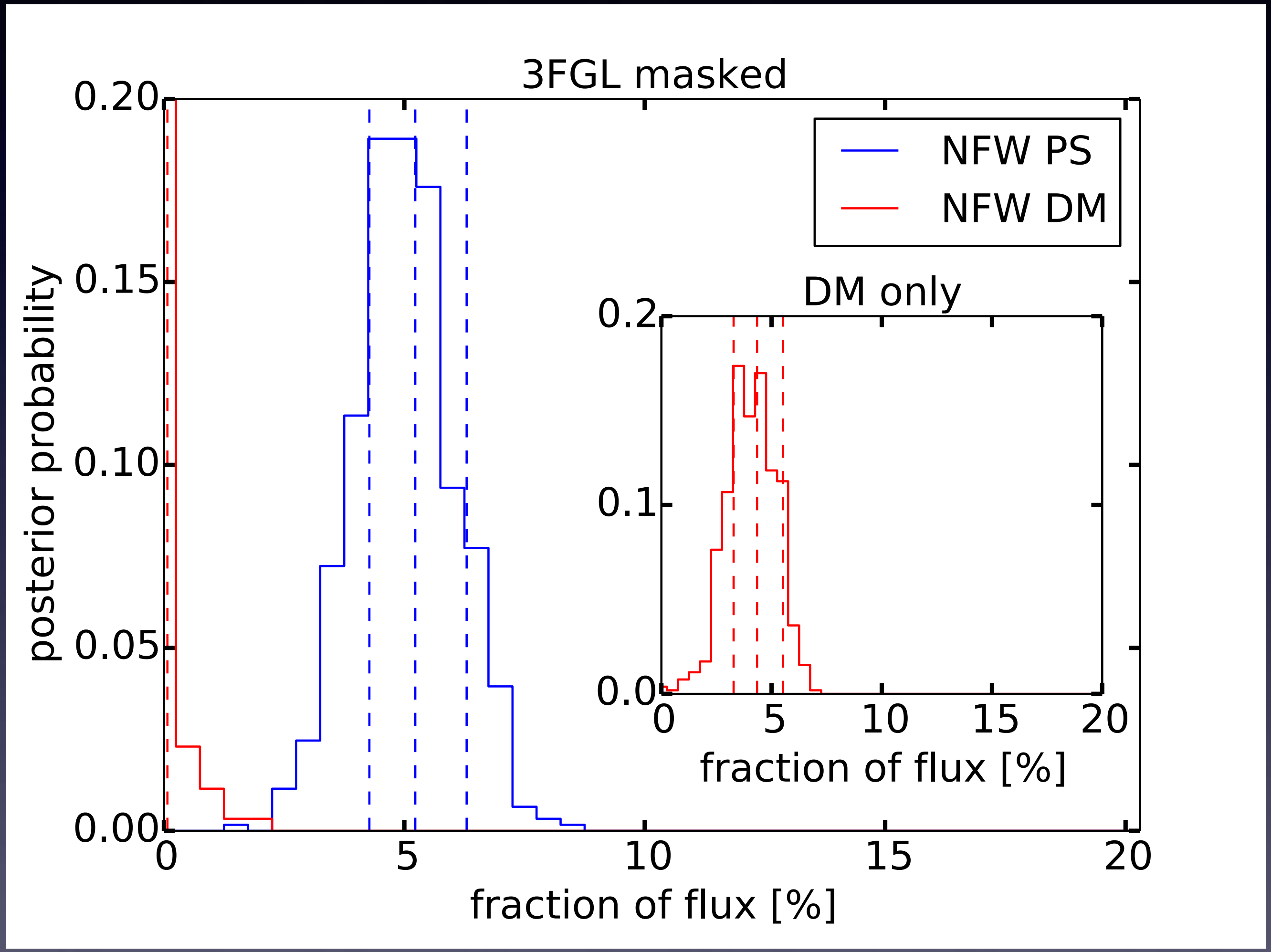
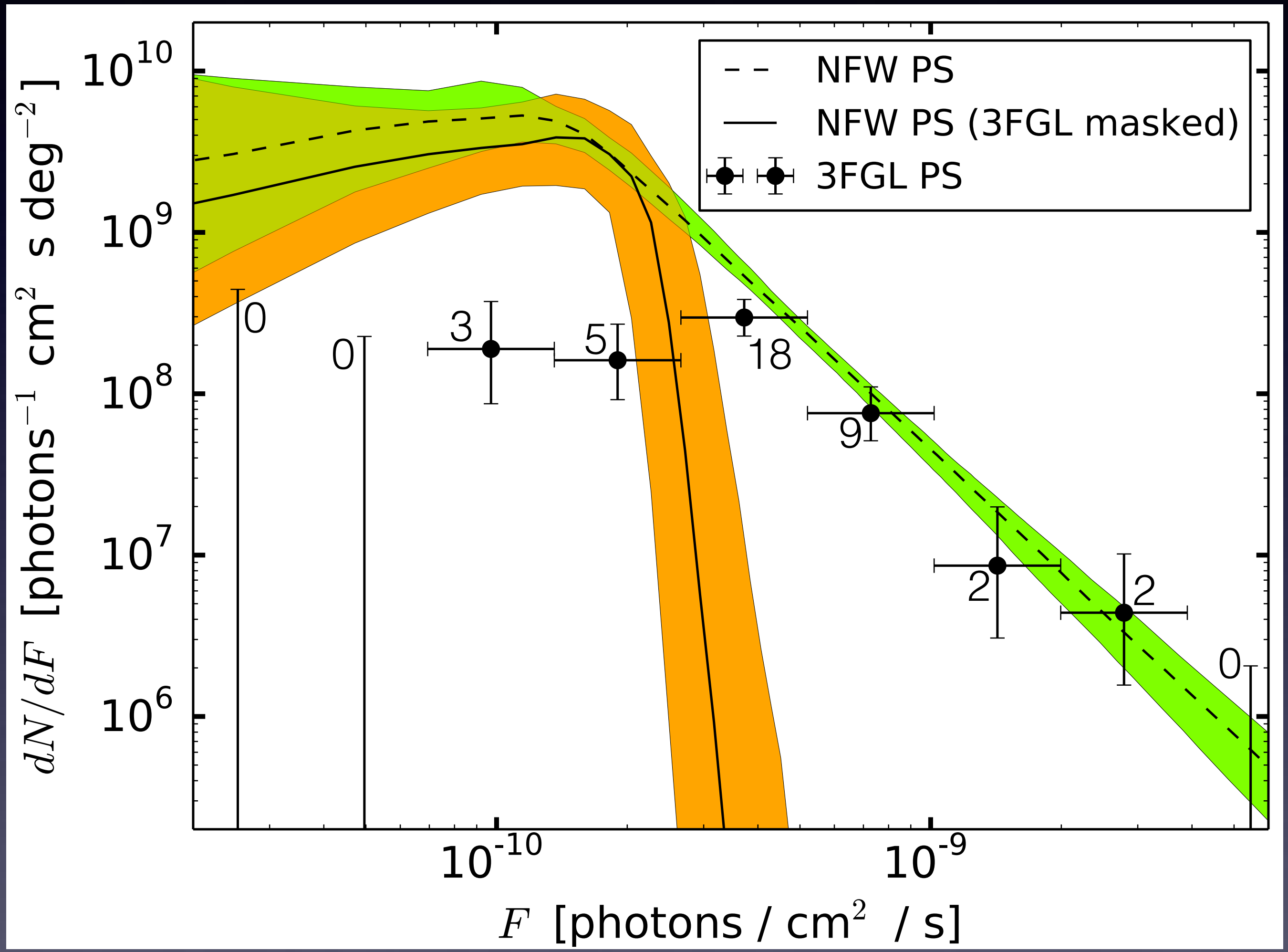




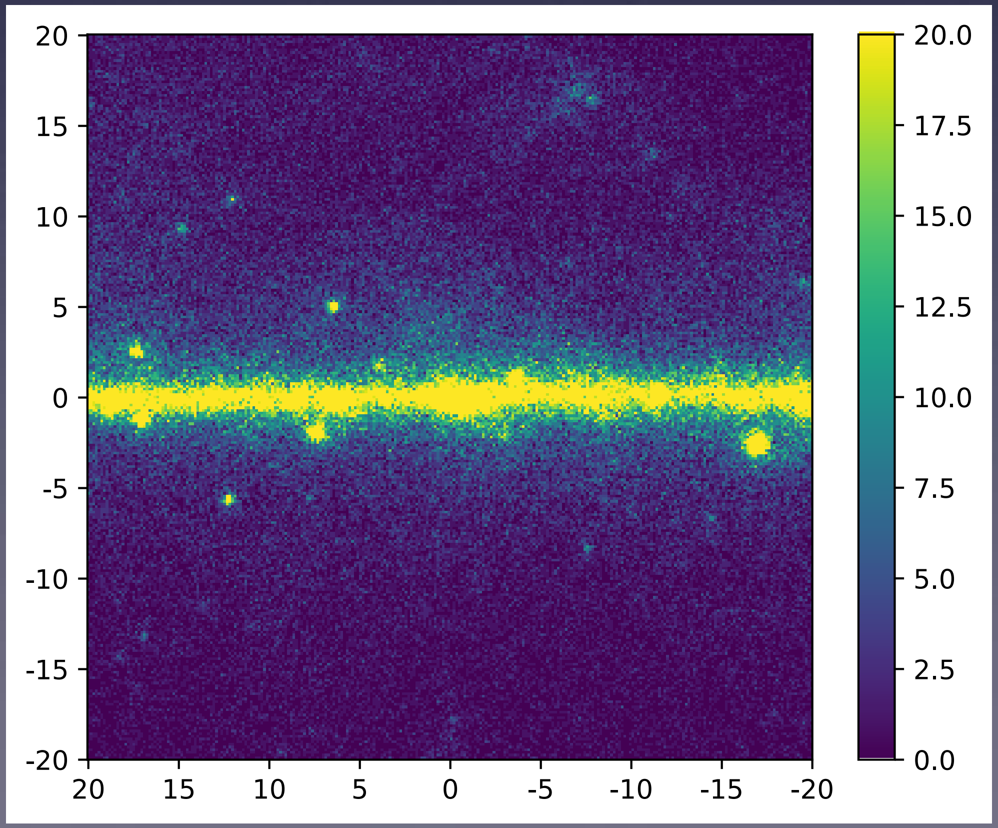
based on non-Poissonian (vs. Poissonian) template fit, excess "preferred" to be from point sources

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

Looking for Point Sources

"Wavelet" — convolve data with shape functions of increasing size

- break down sky into structures of different angular size to form a partition of the data (single scale = matched filter)
- look for excess and ask: does it add up?



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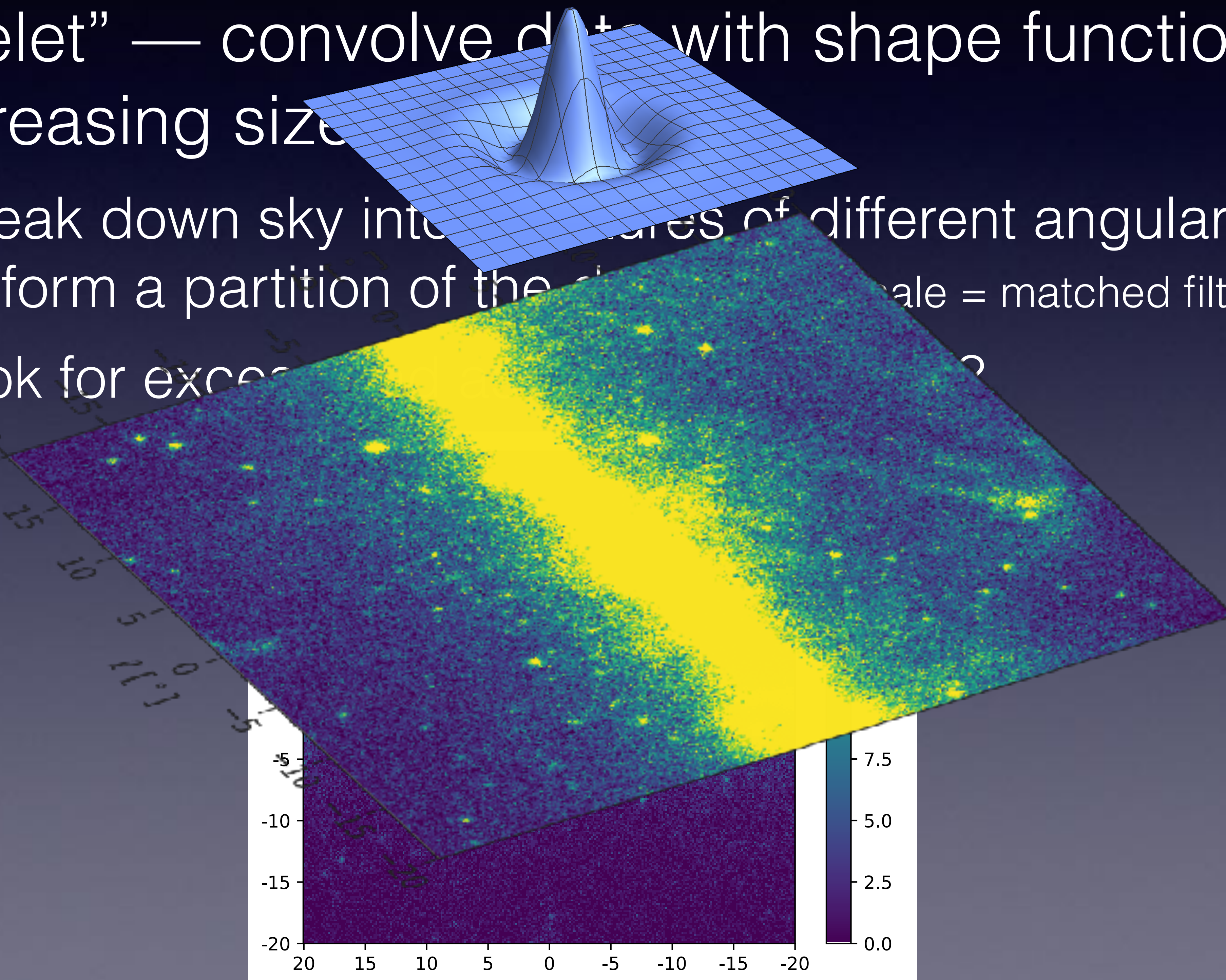
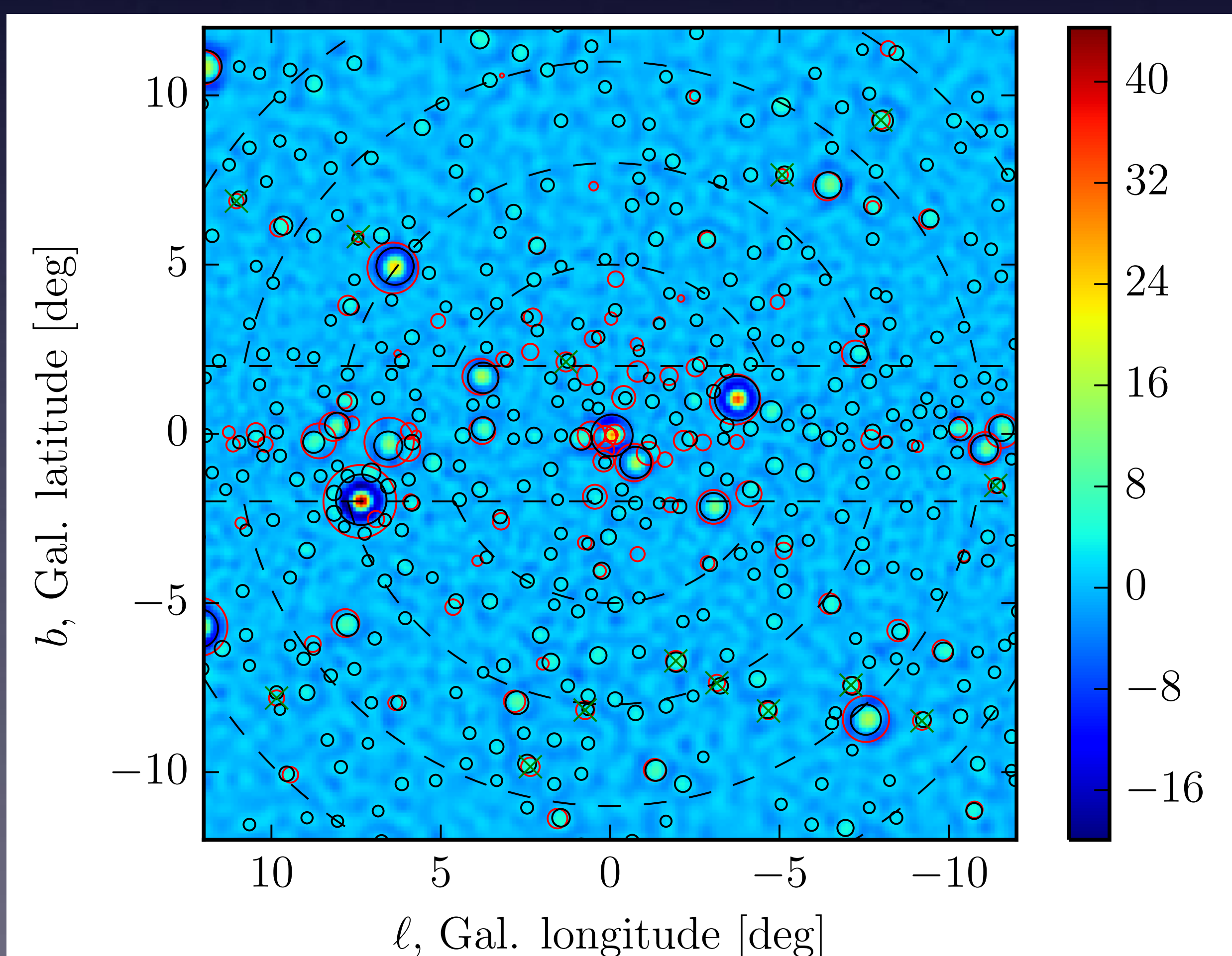


Point Source Search, 2015

$$\mathcal{S} = \frac{M_2 \otimes \mathcal{C}}{\sqrt{M_2^2 \otimes \mathcal{C}}}$$



Bartels et al., **1506.05104**

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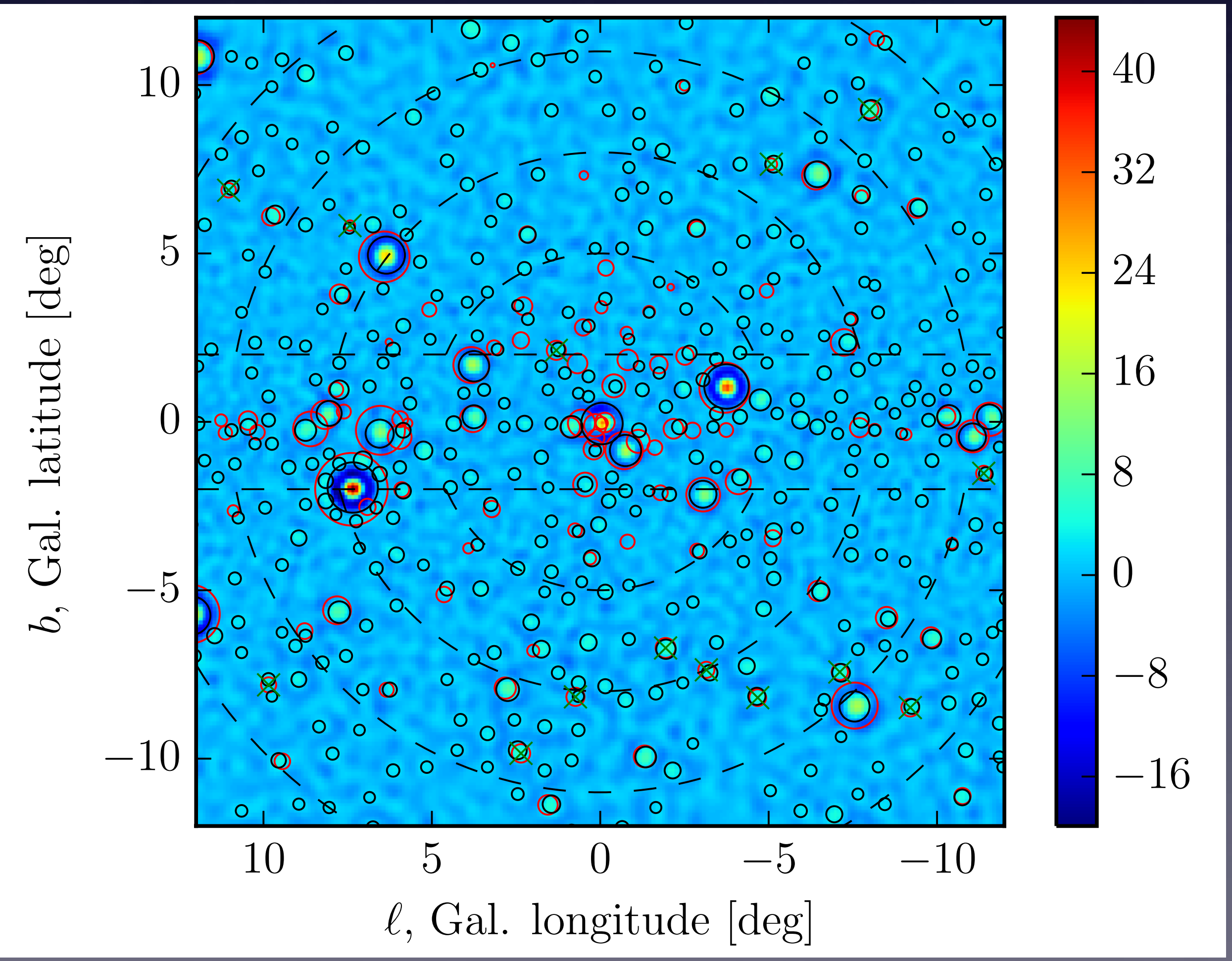
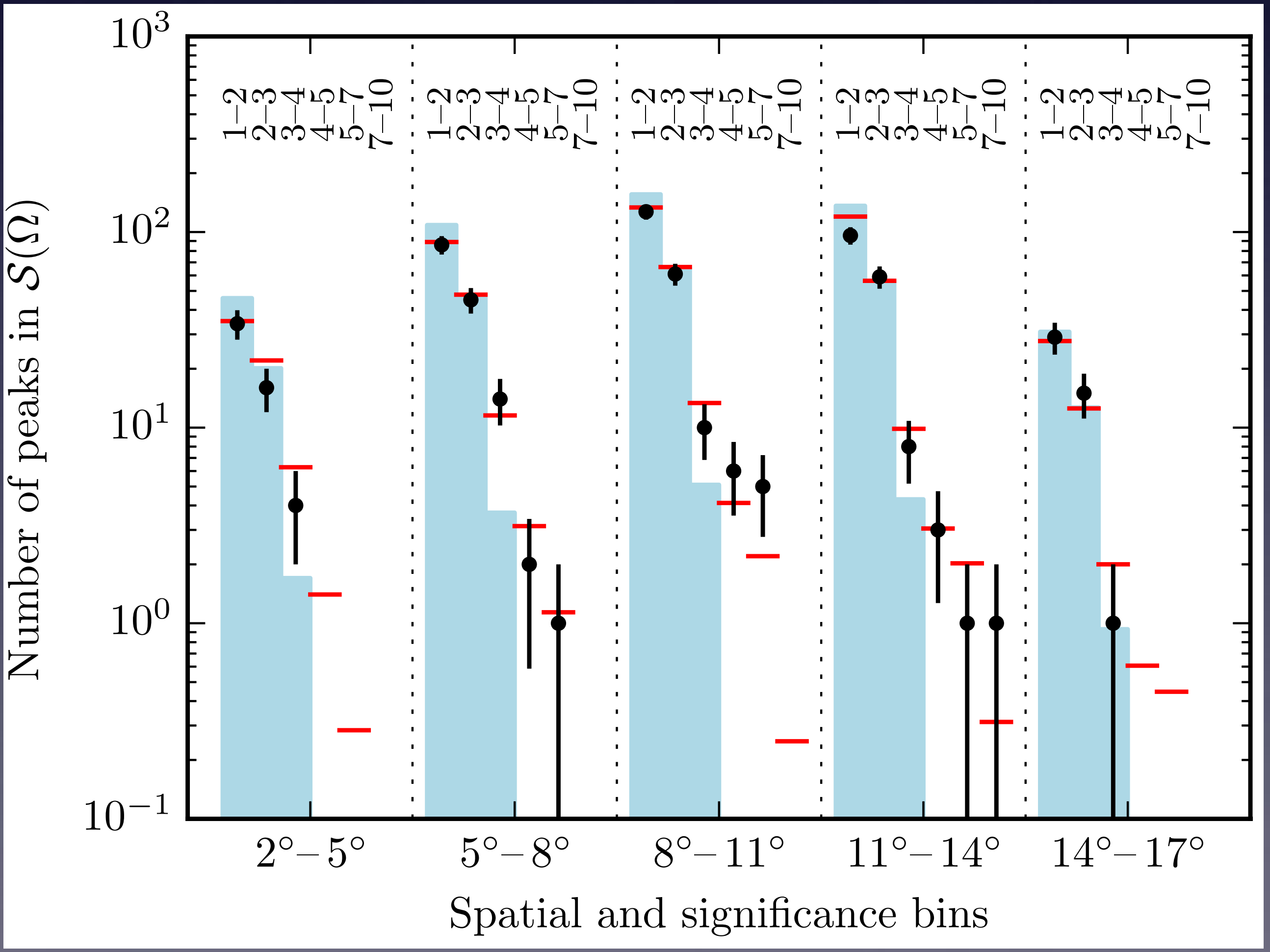
bin in *S* and location





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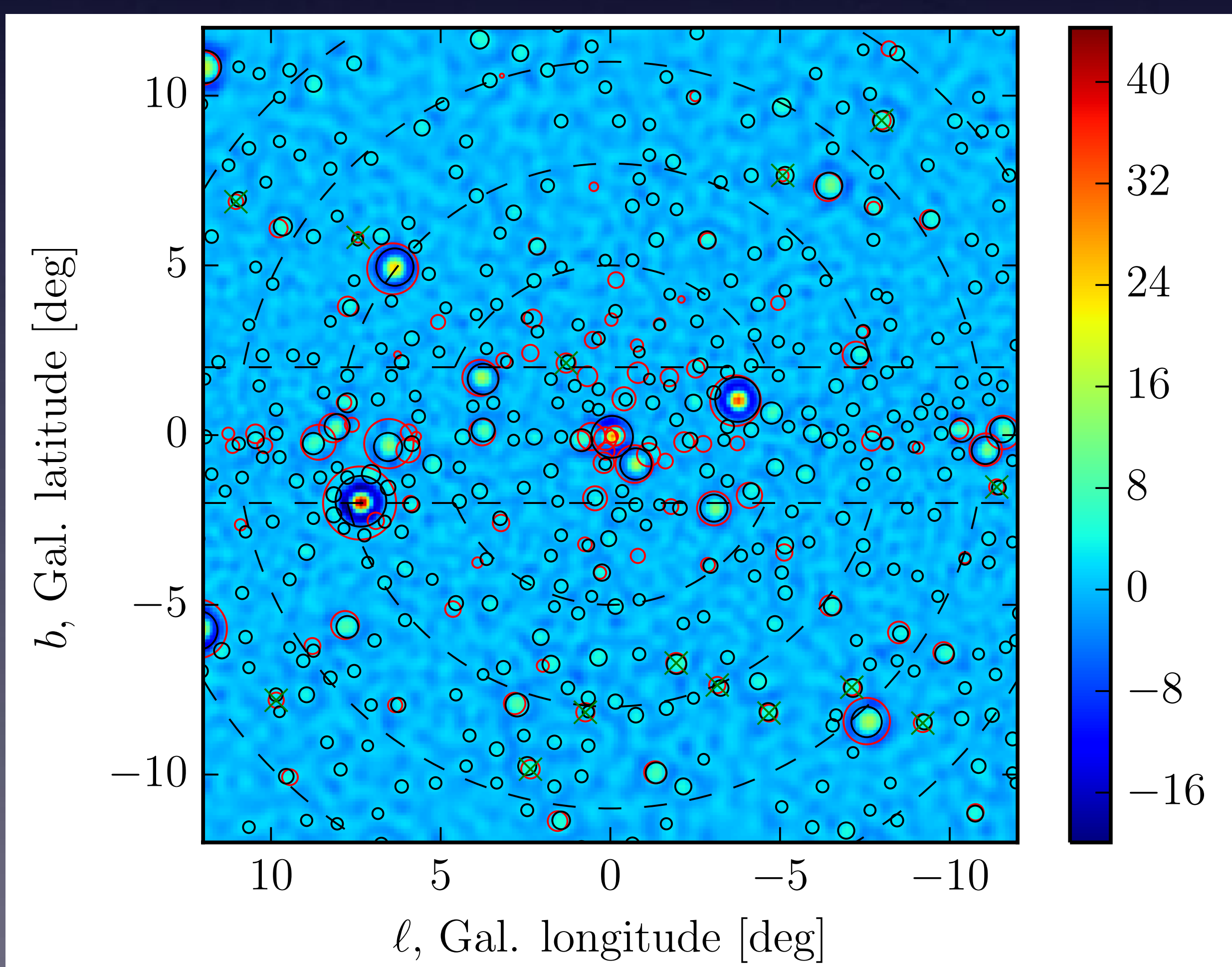

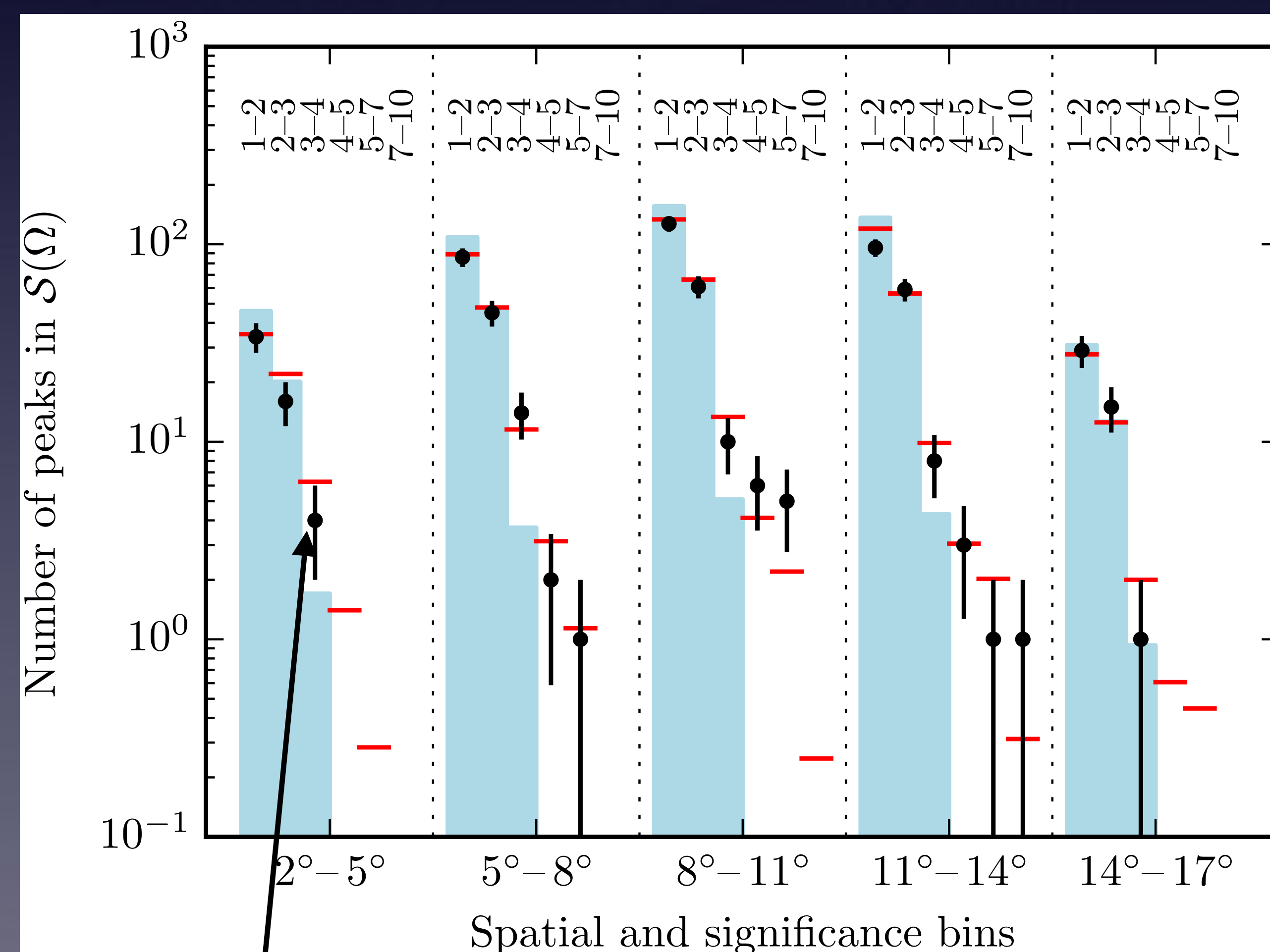

data

Bartels et al., **1506.05104**

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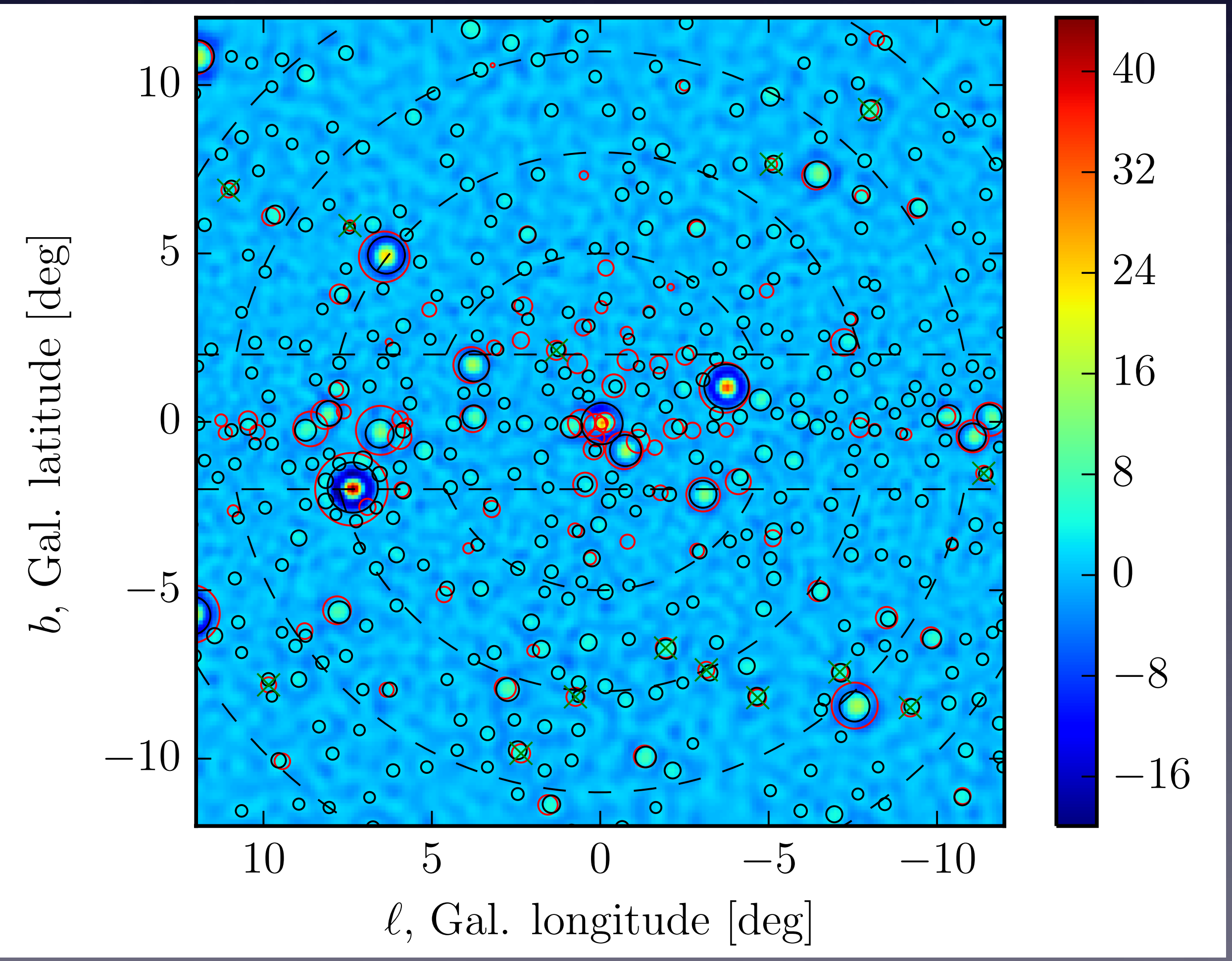

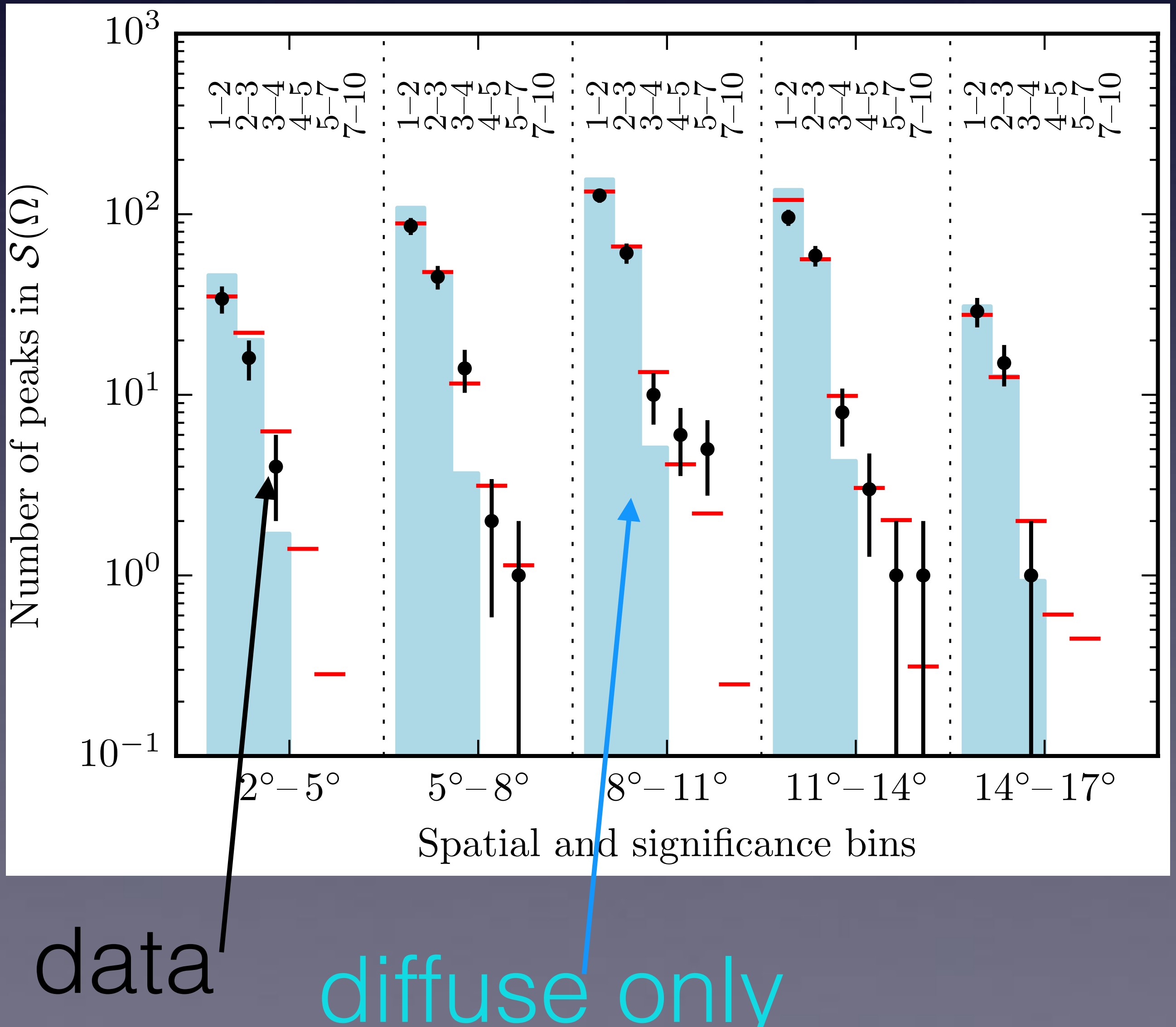

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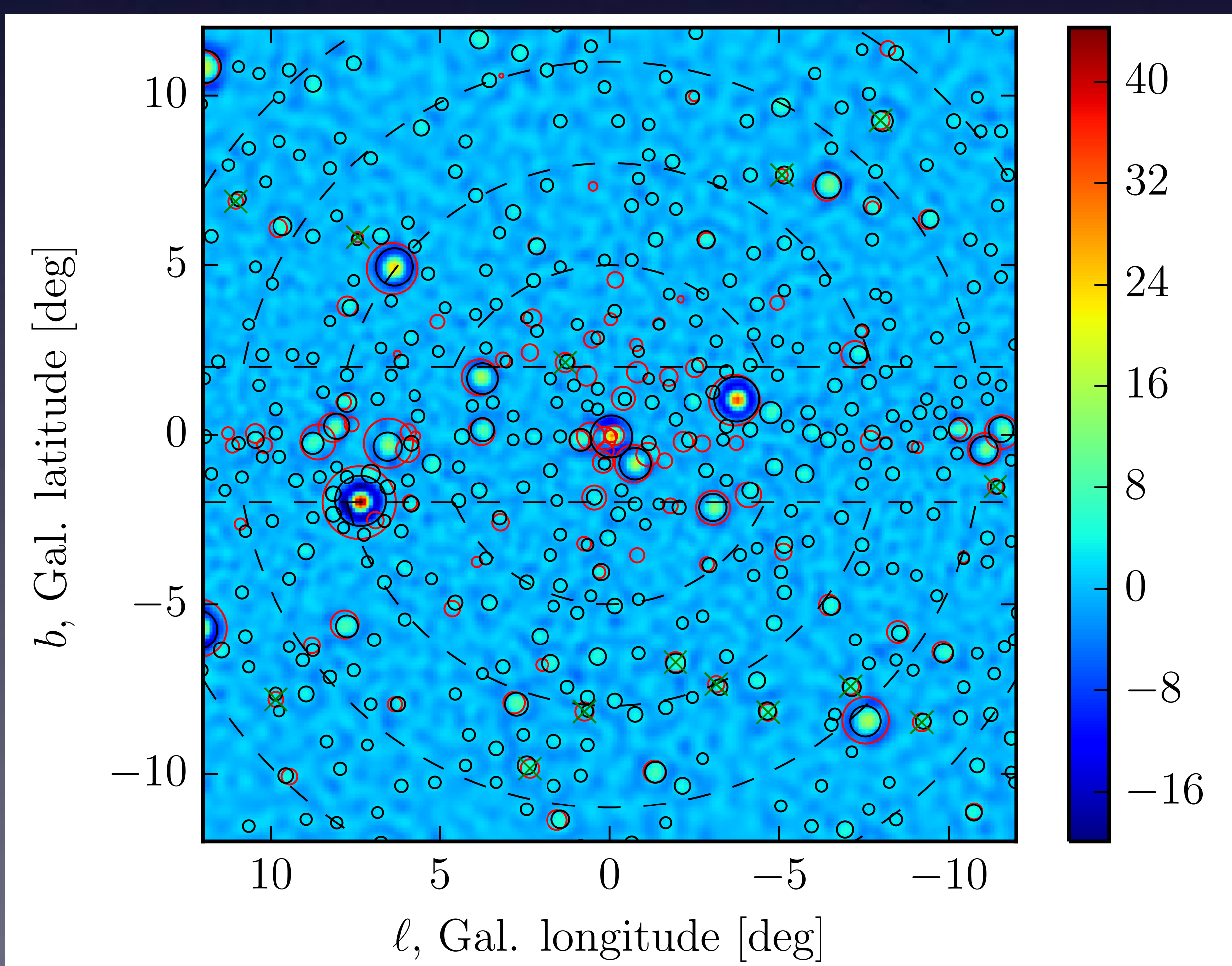
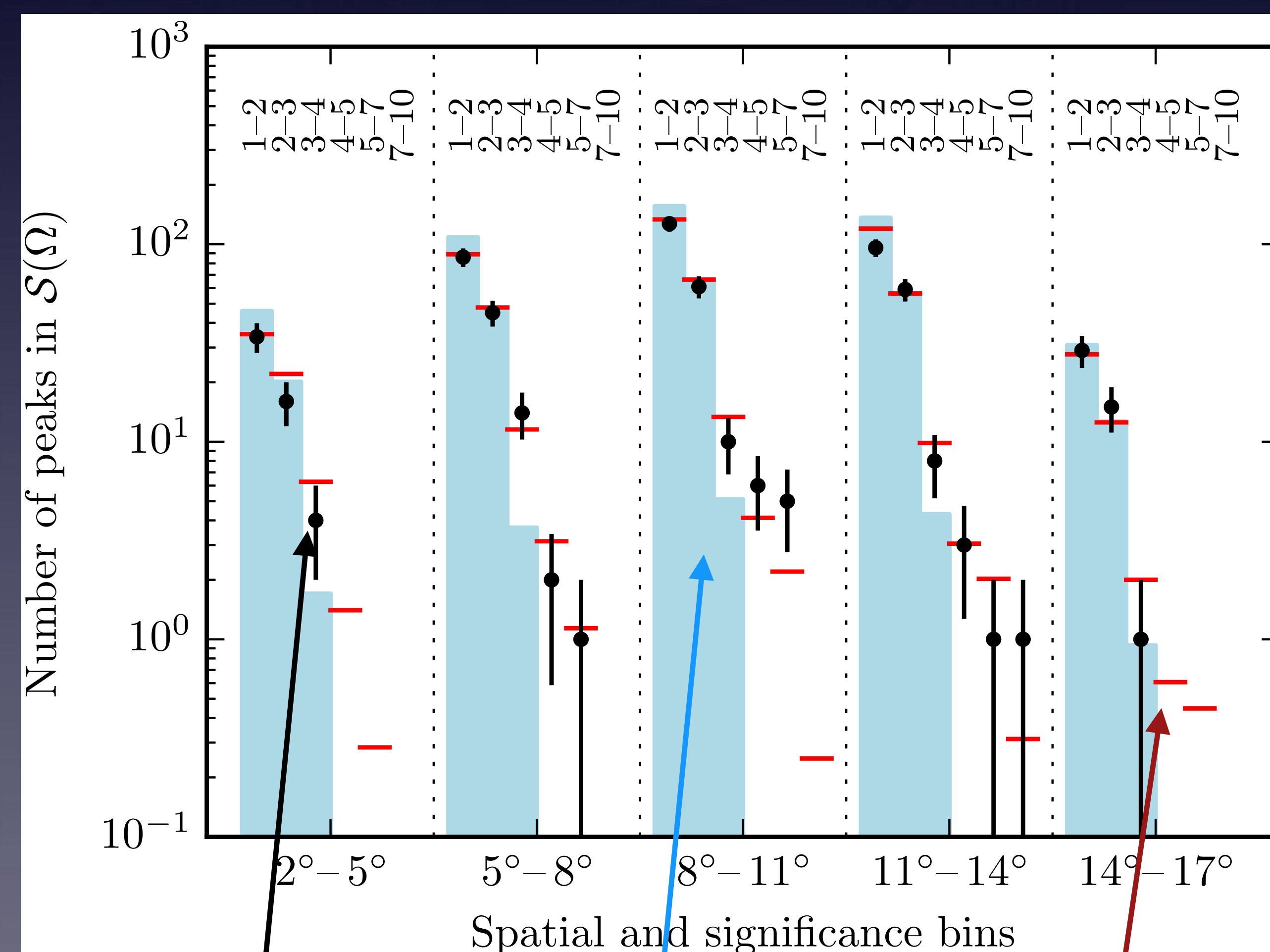
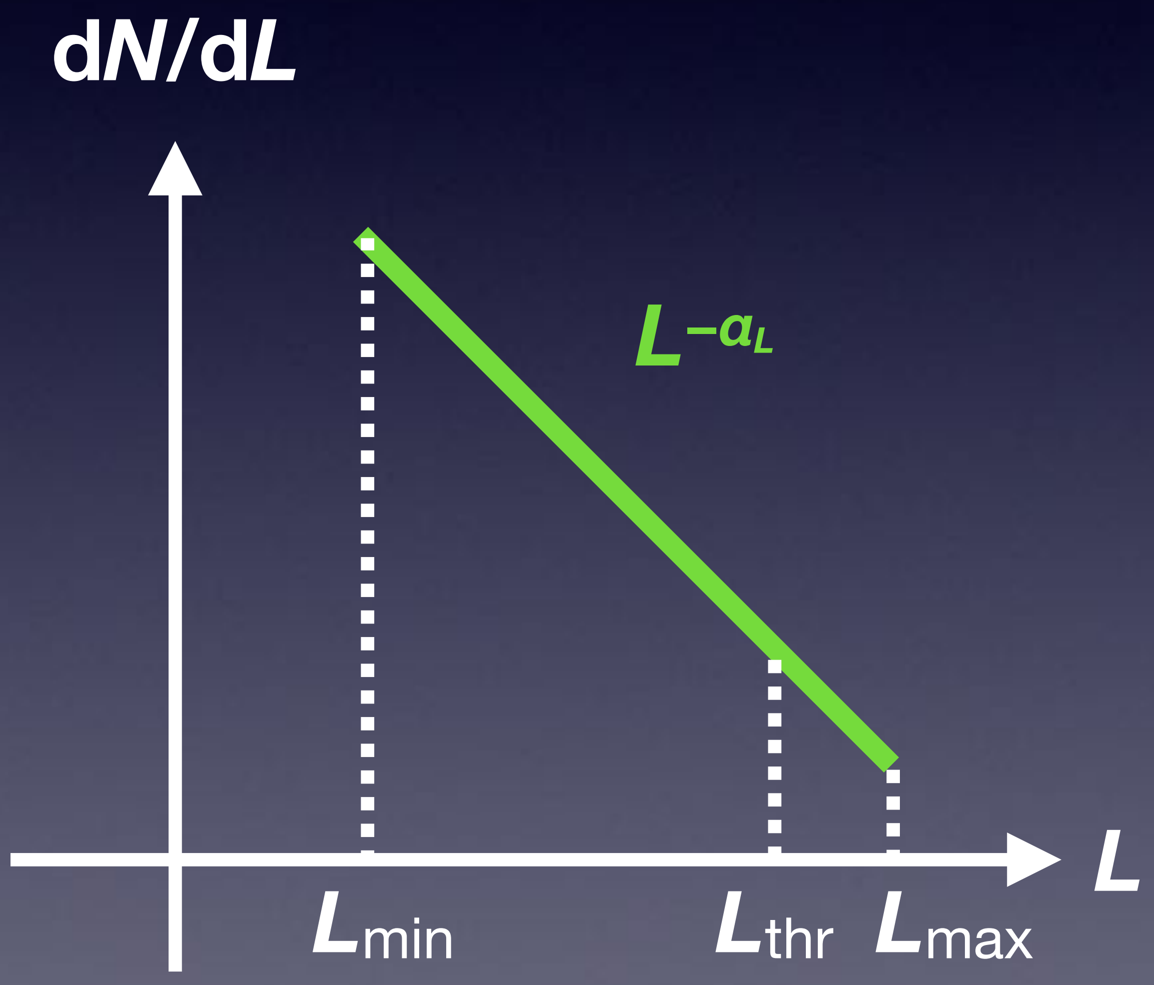




Bartels et al., **1506.05104**

How to characterize CSP?



L_{min} → CR physics
L_{thr} → detection threshold
L_{max} → CR physics
α_L → theory prior

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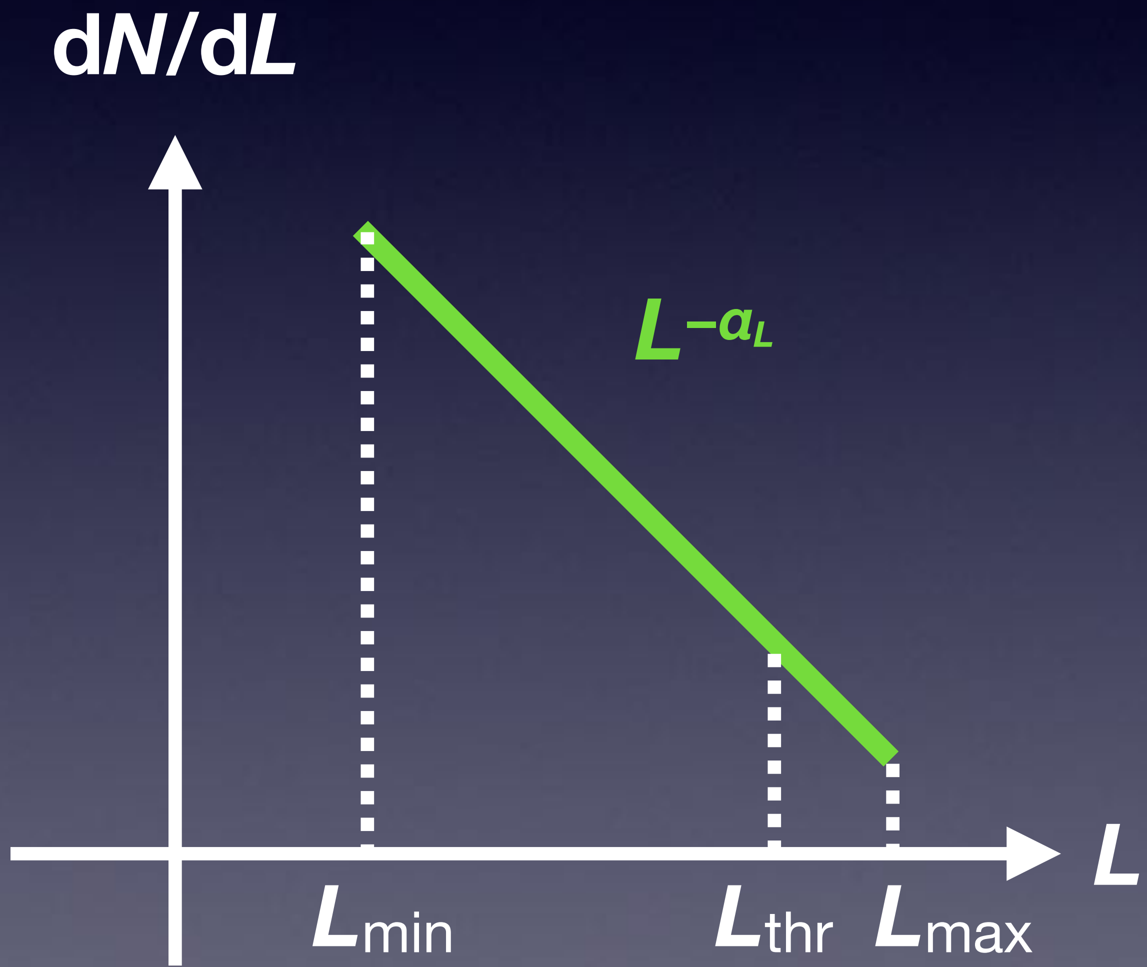


L_{min} → CR physics

L_{thr} → detection threshold

L_{max} → CR physics

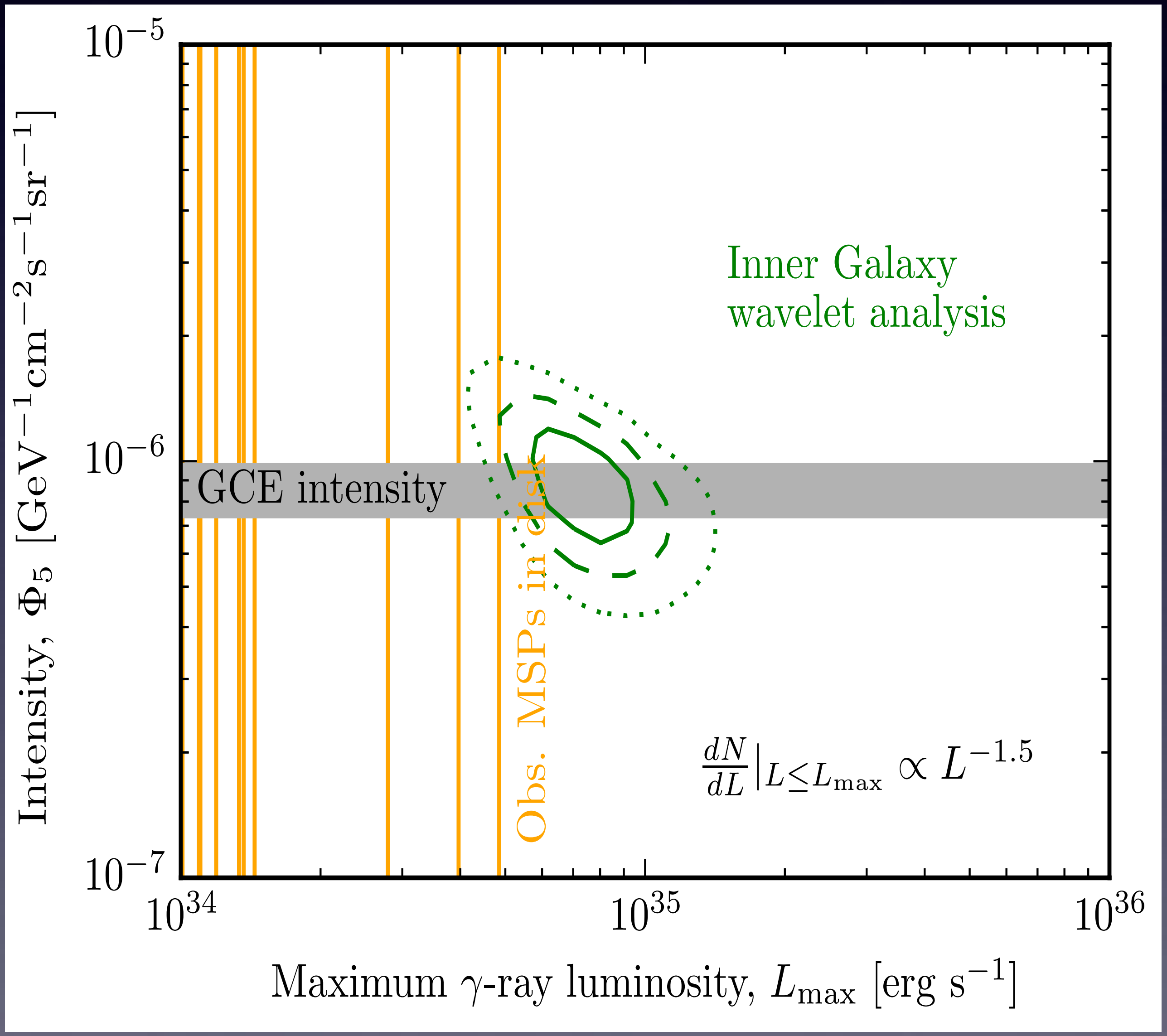
α_L → theory prior

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, …

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 are compatible with unresolved PSs accounting for the GCE



Bartels et al., **1506.05104**

CSP Can Be Bright Enough

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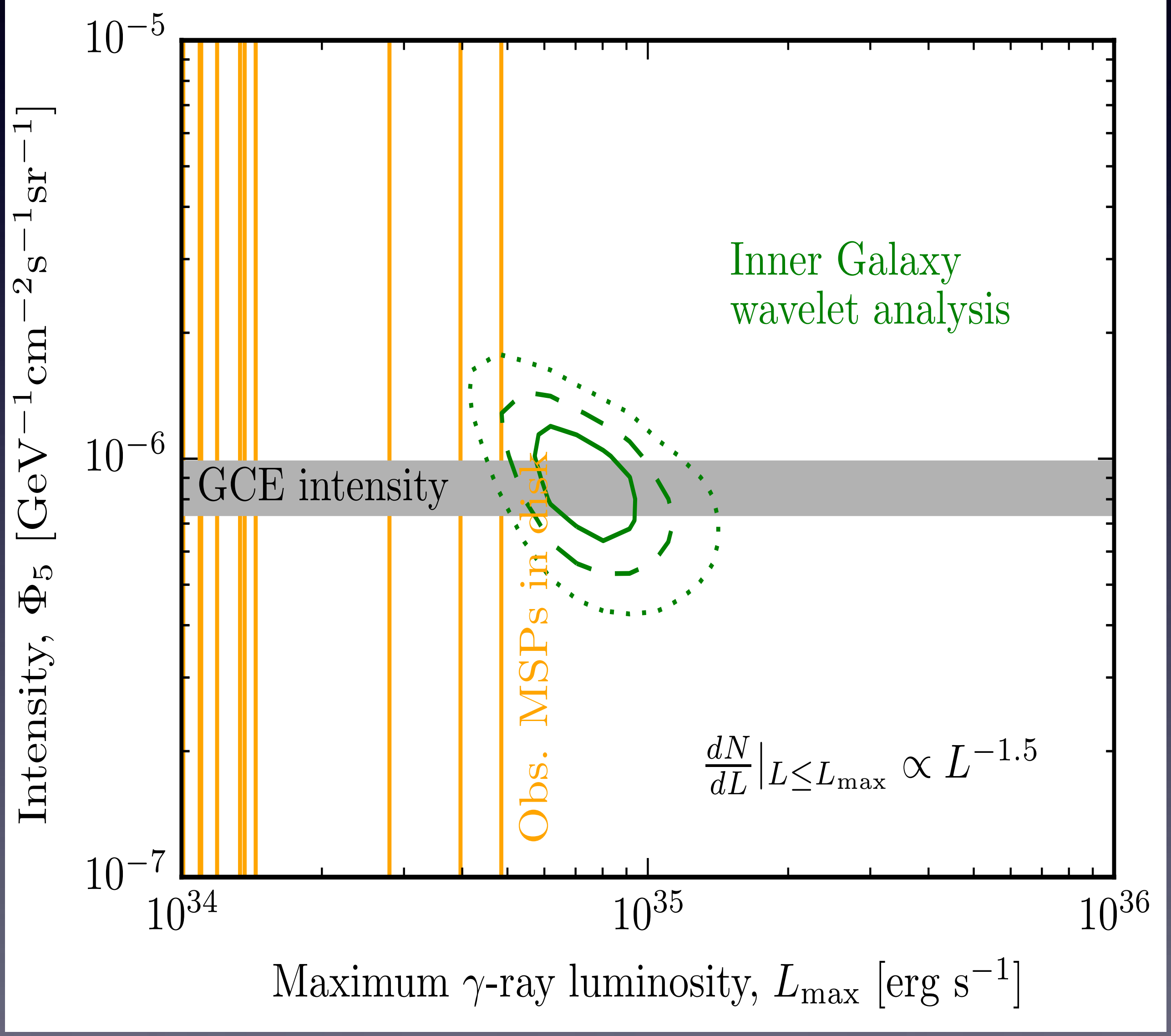
- Claim in 2015 was "yes" if the luminosity function had a power-law index α_L=1.5



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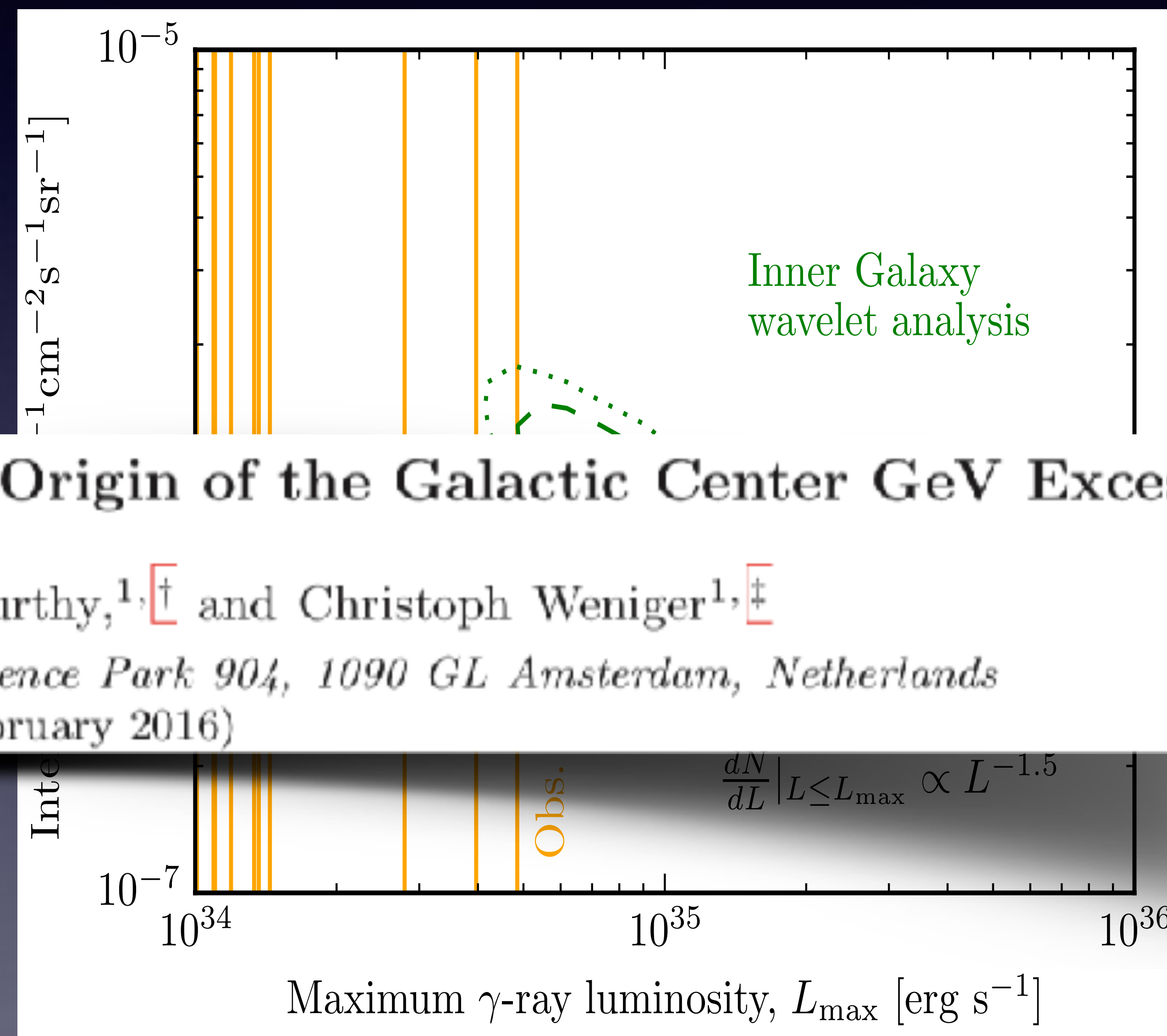


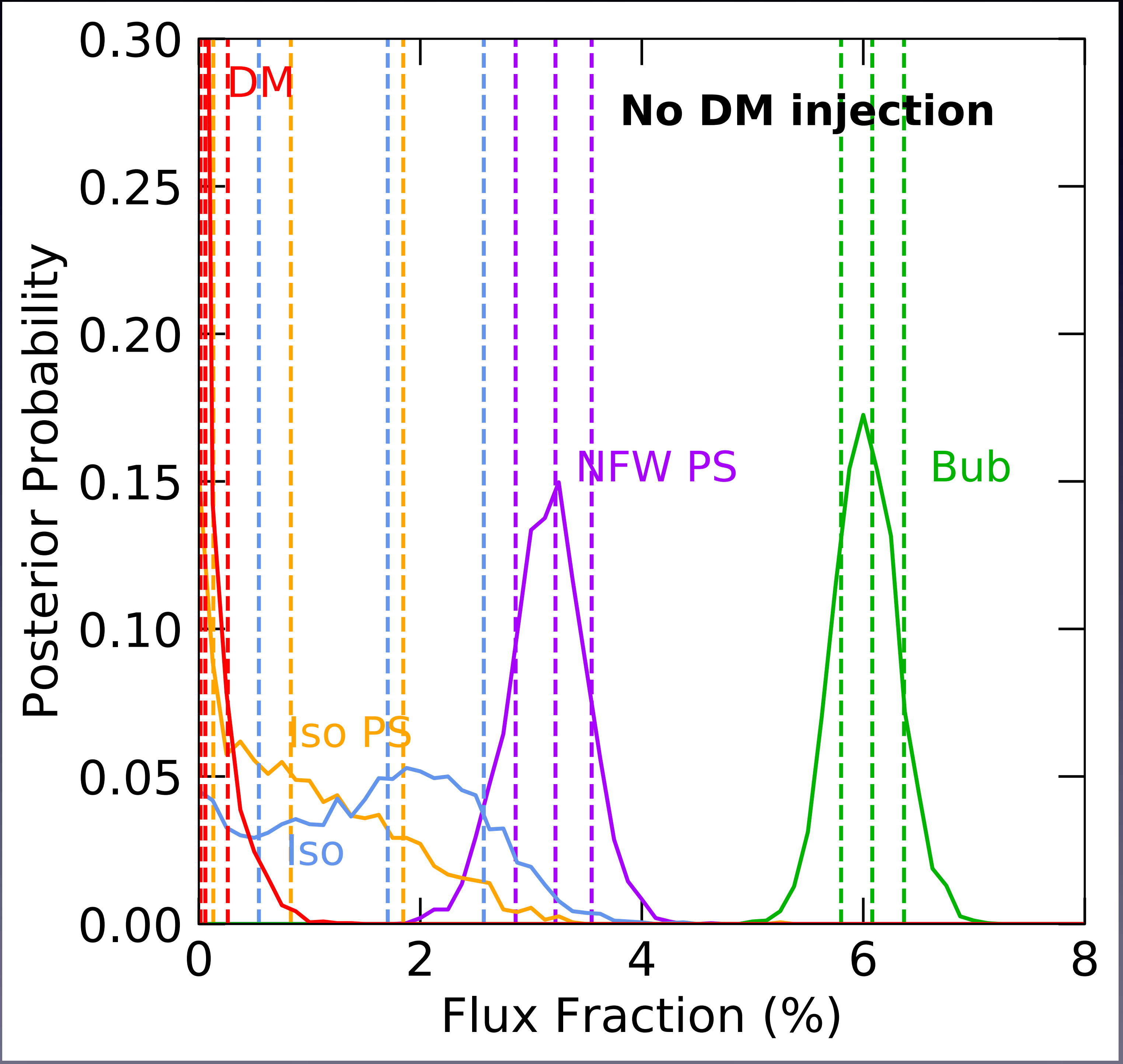
Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

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**

… but trouble for NPTF



Leane and Slatyer, **1904.08430**

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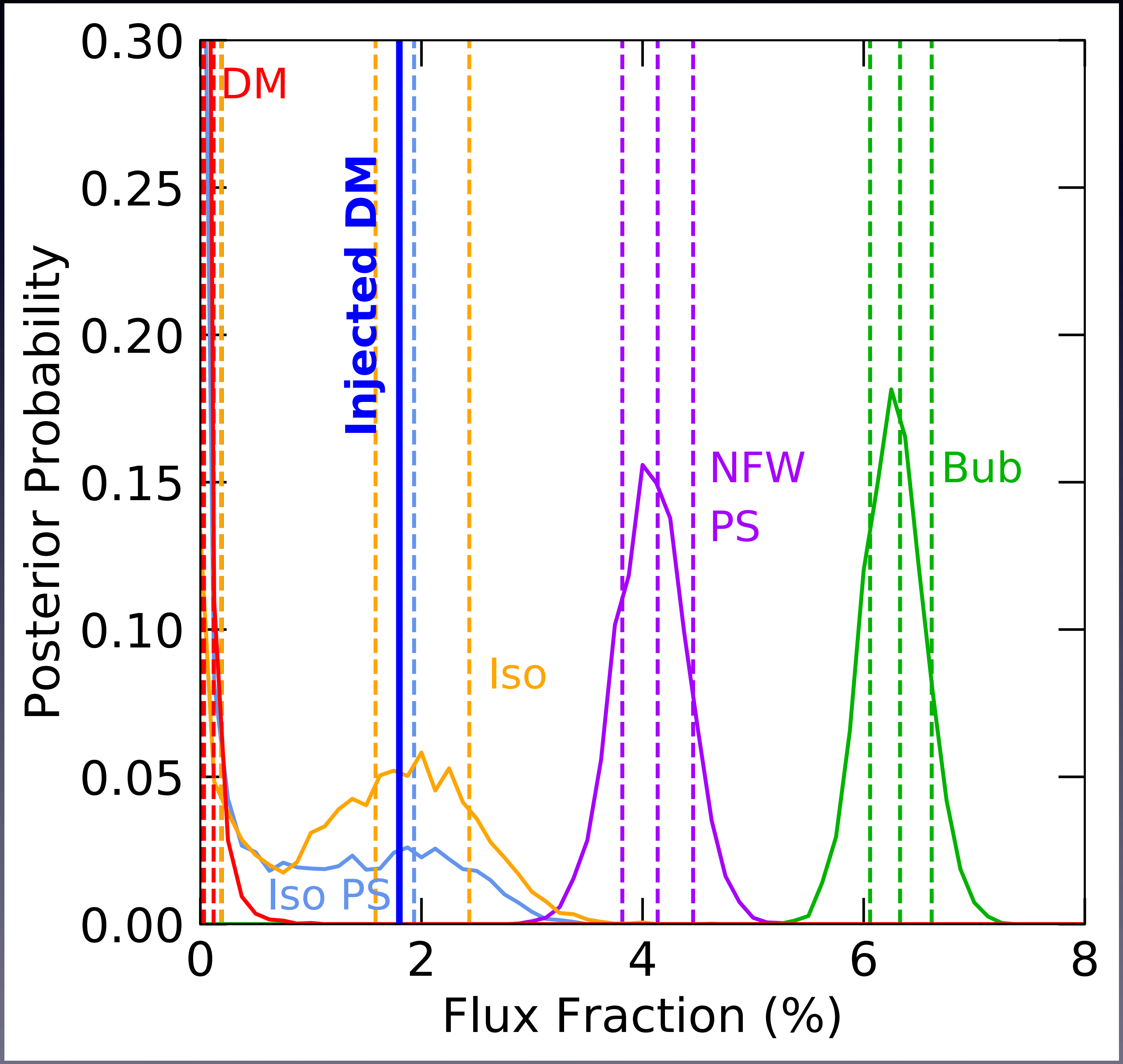

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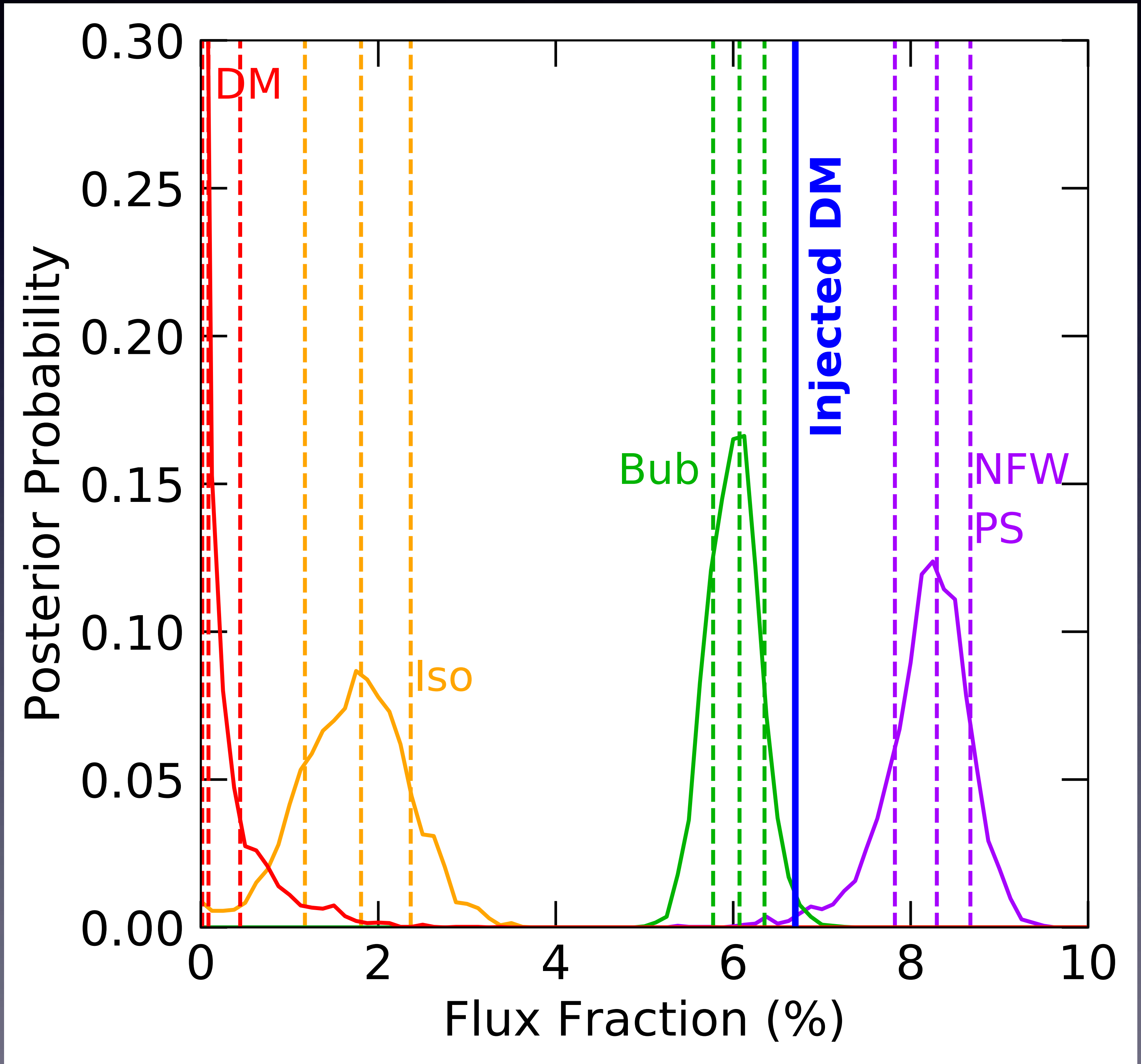

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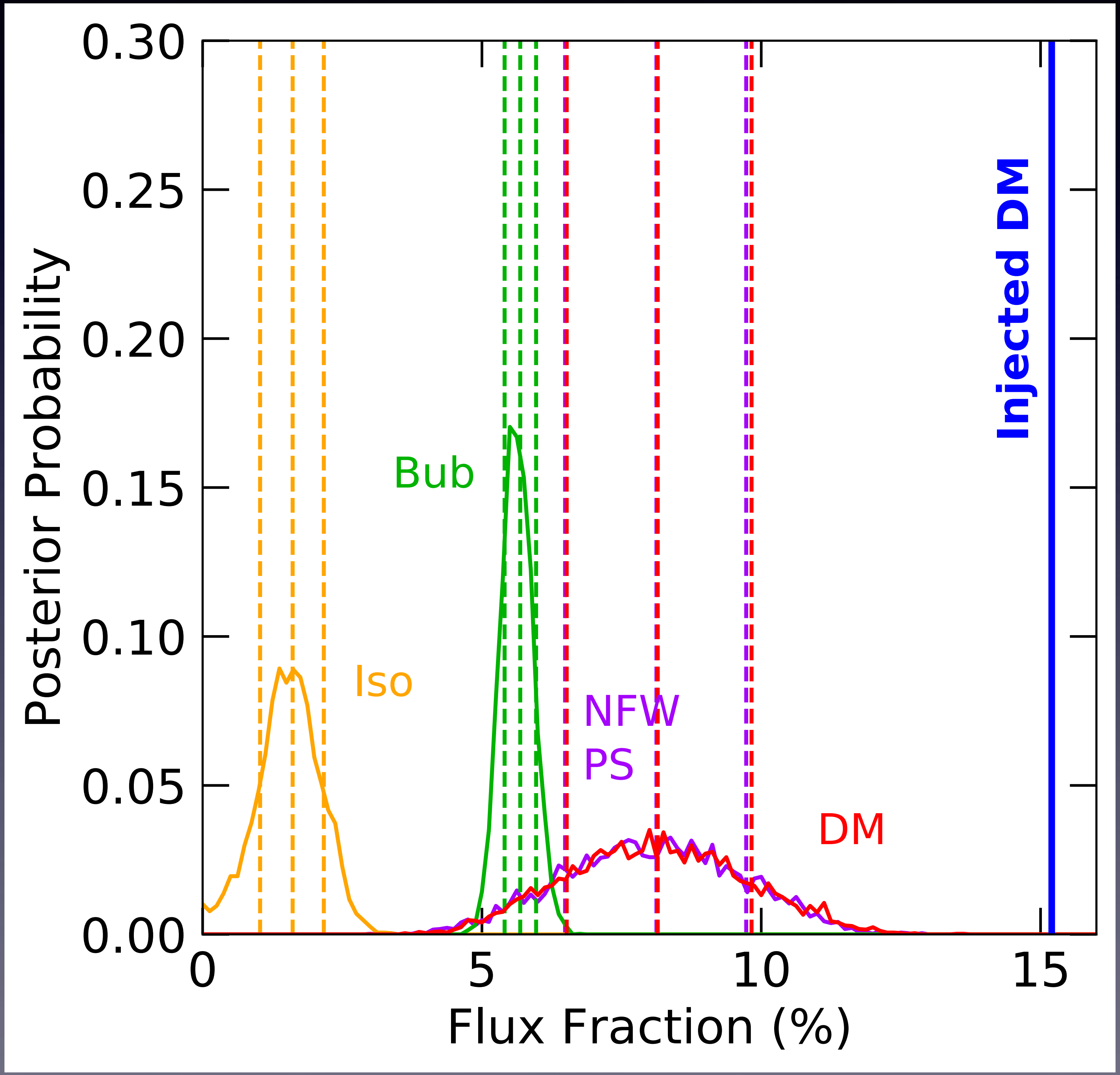

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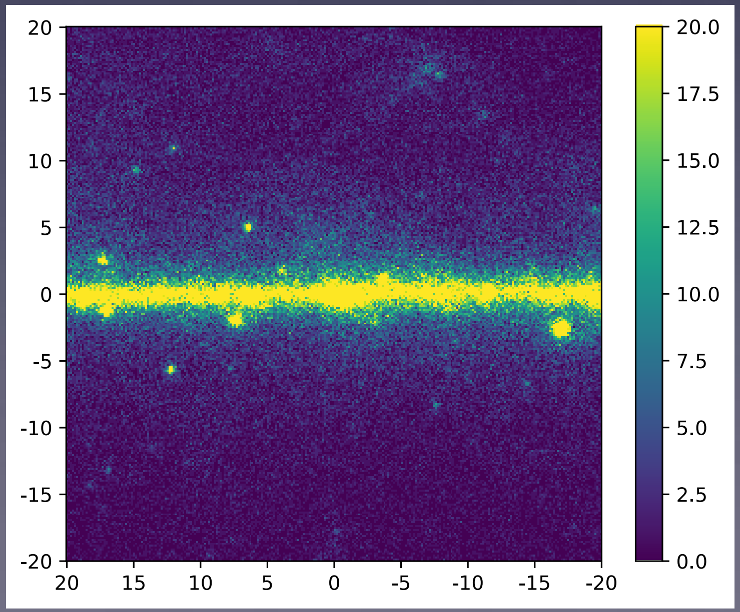
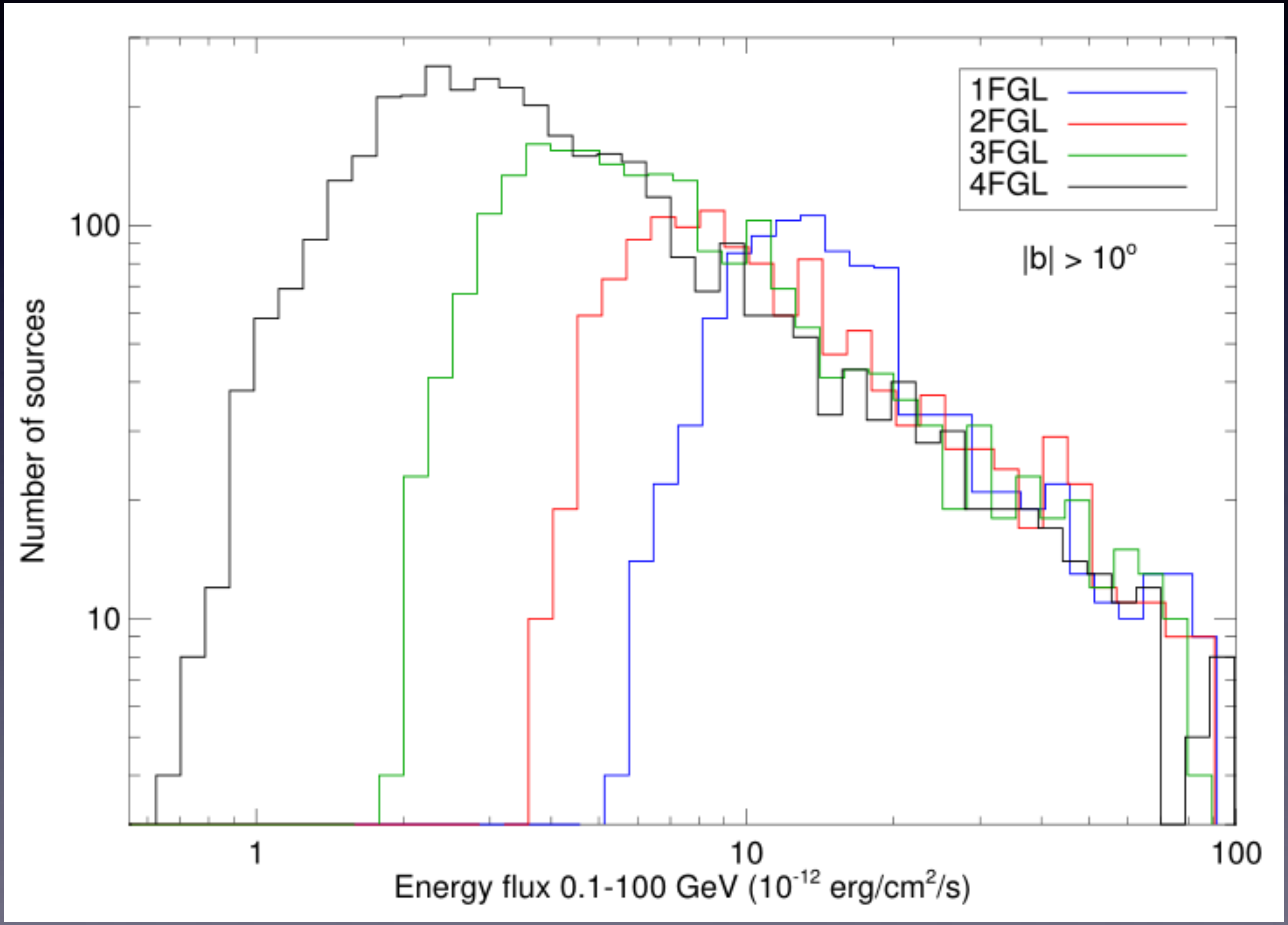
Part 3

Template and Wavelet Results After 4FGL

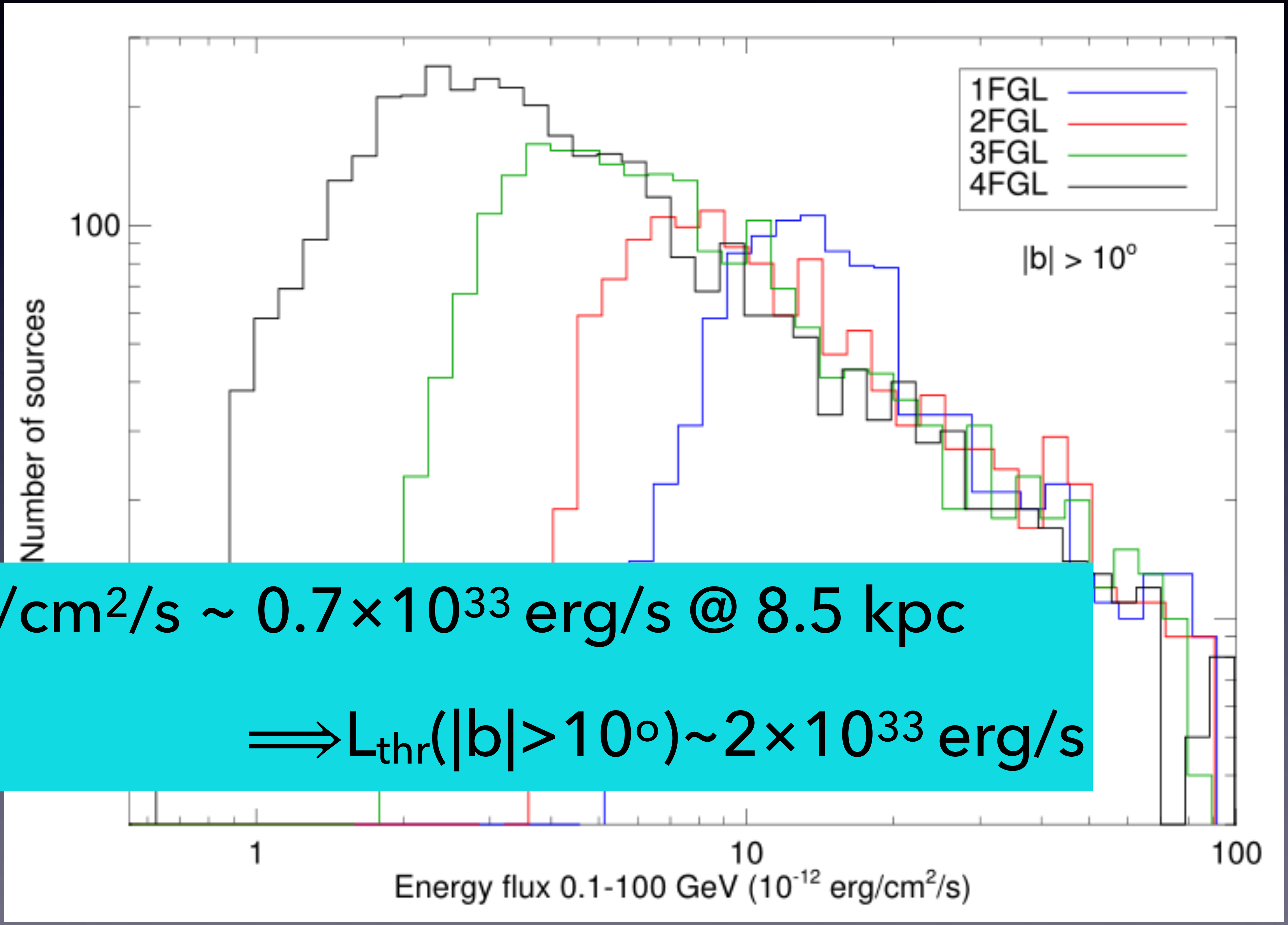


The 4FGL Catalog



Abdollahi et al., **1902.10045**

The 4FGL Catalog

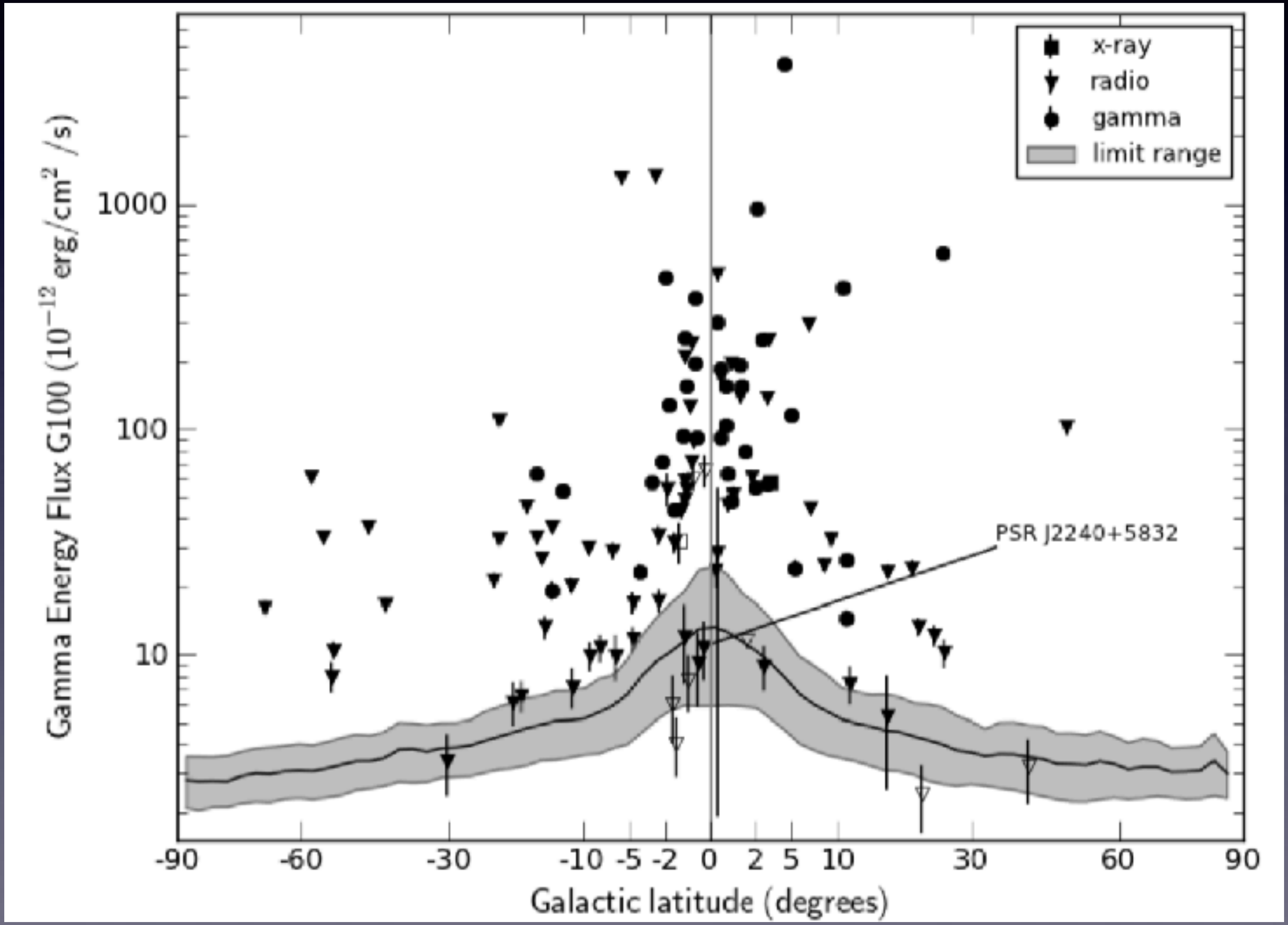


10^{-12} erg/cm^2/s ~ 0.7×10^{33} erg/s @ 8.5 kpc

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

Abdollahi et al., **1902.10045**

b-dependence of detection

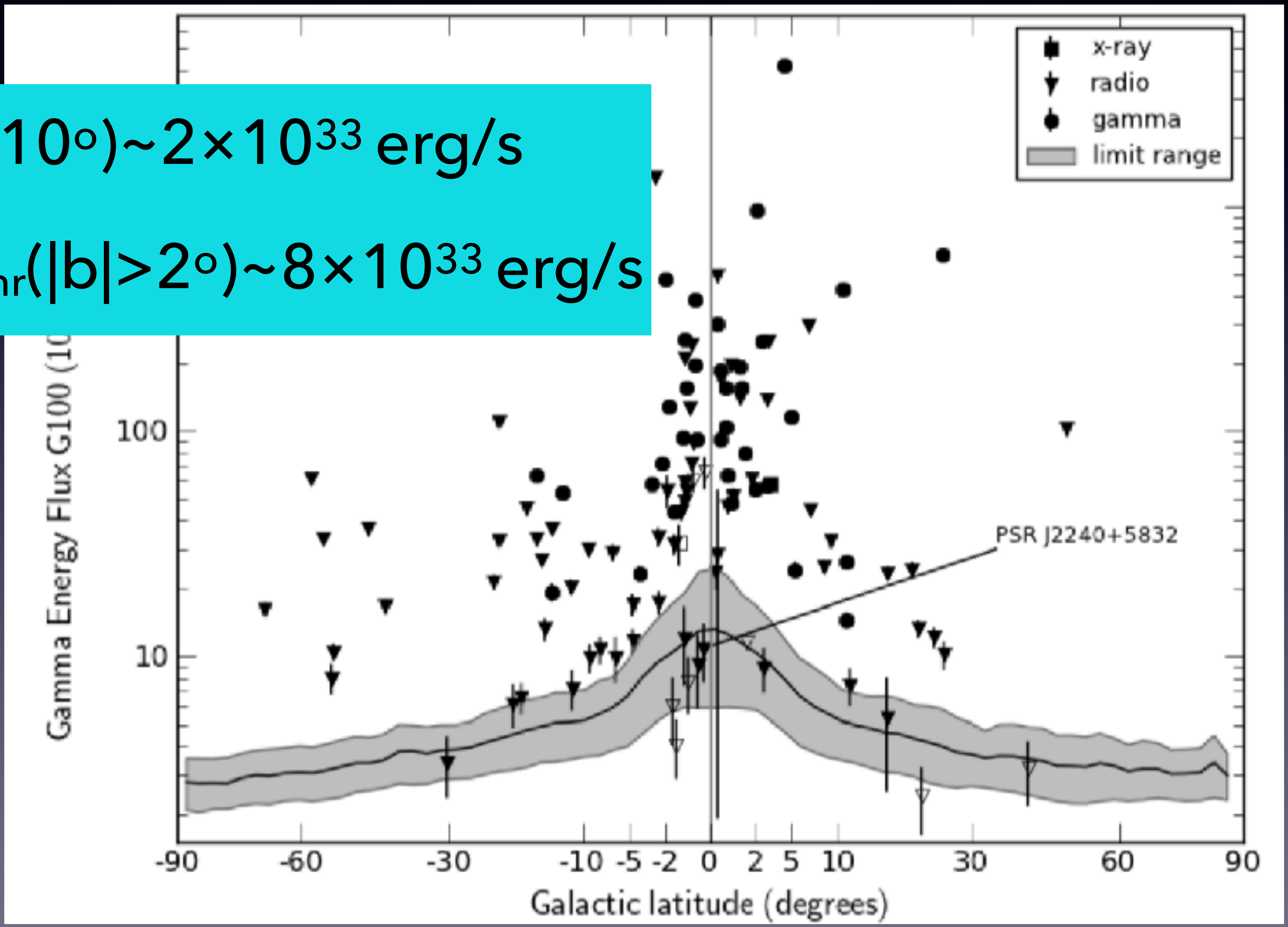


Abdo et al., **1305.4385**

b-dependence of detection

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

$\Longrightarrow L_{thr}(|b|>2^{\circ}) \sim 8\times10^{33}$ erg/s



Abdo et al., **1305.4385**

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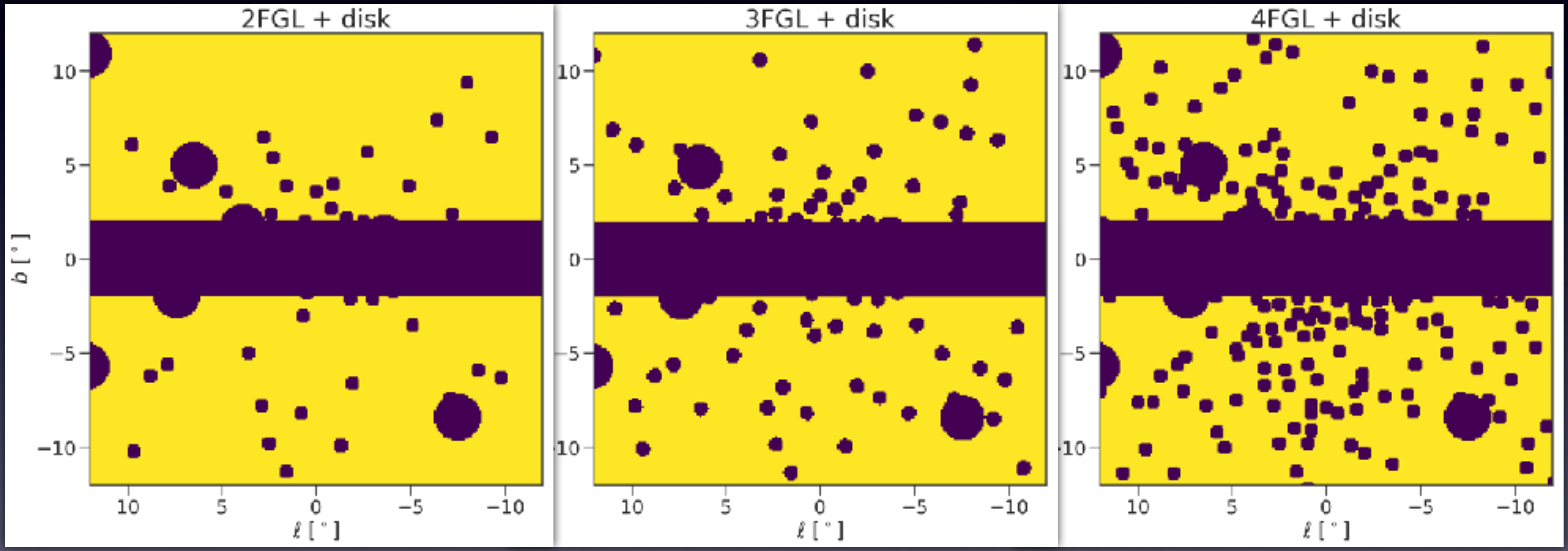
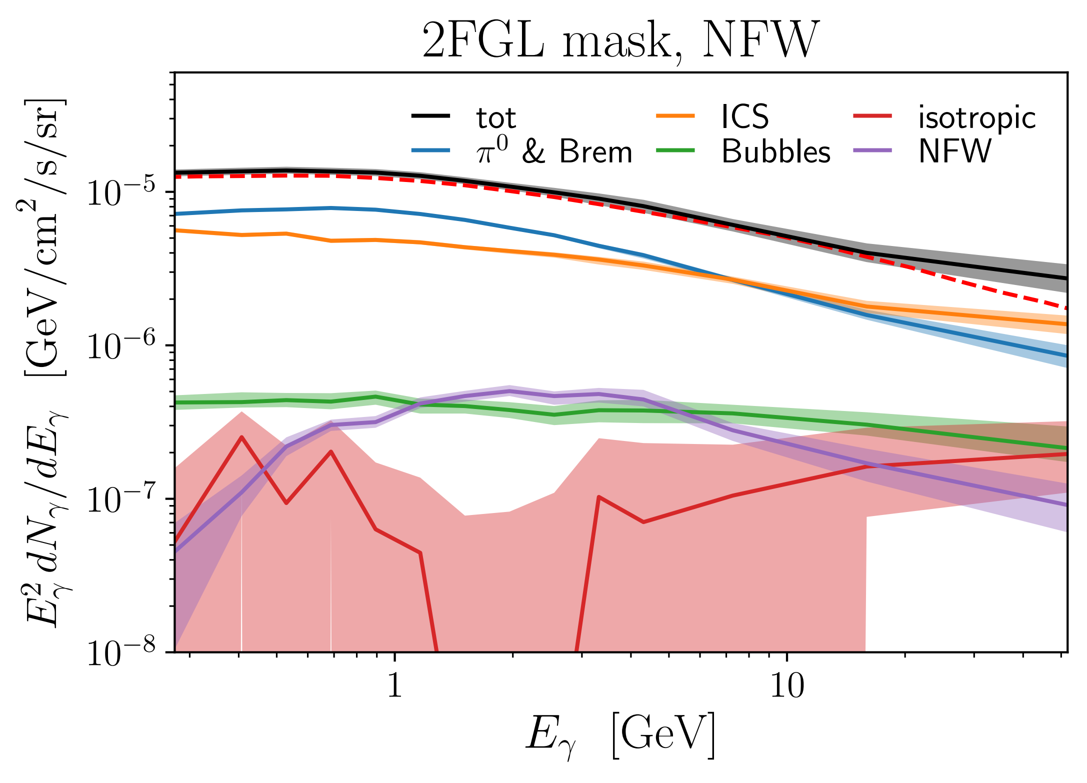


additional solid angle under the mask depends on location: about 3x larger than 2FGL in innermost region, down to about 50% more in outer regions

GCE: Template Fit Results

Zhong, McDermott, Cholis, Fox, 1911.12369



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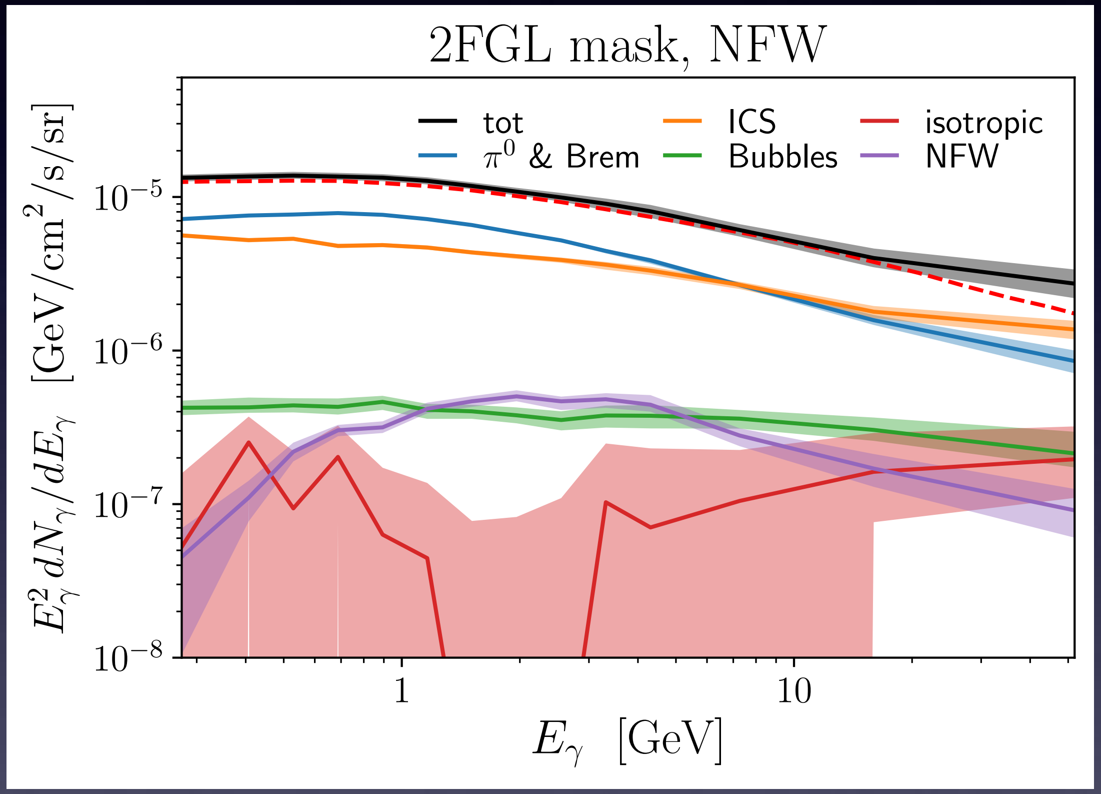

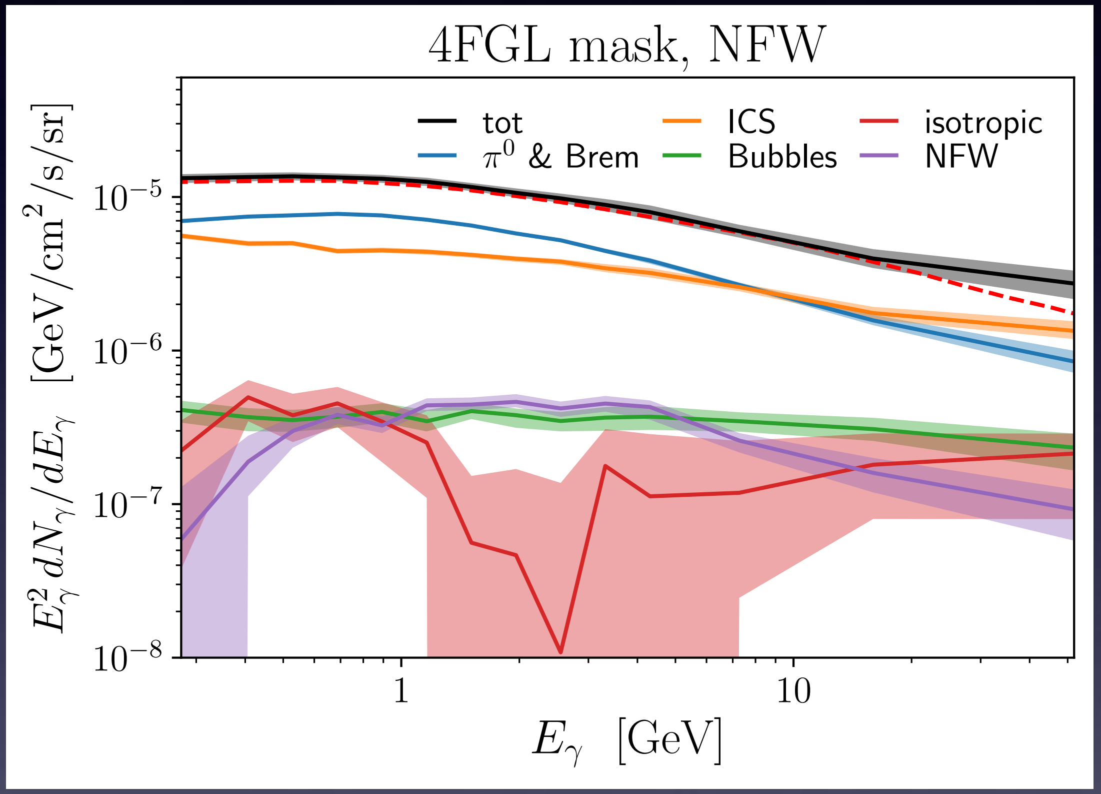

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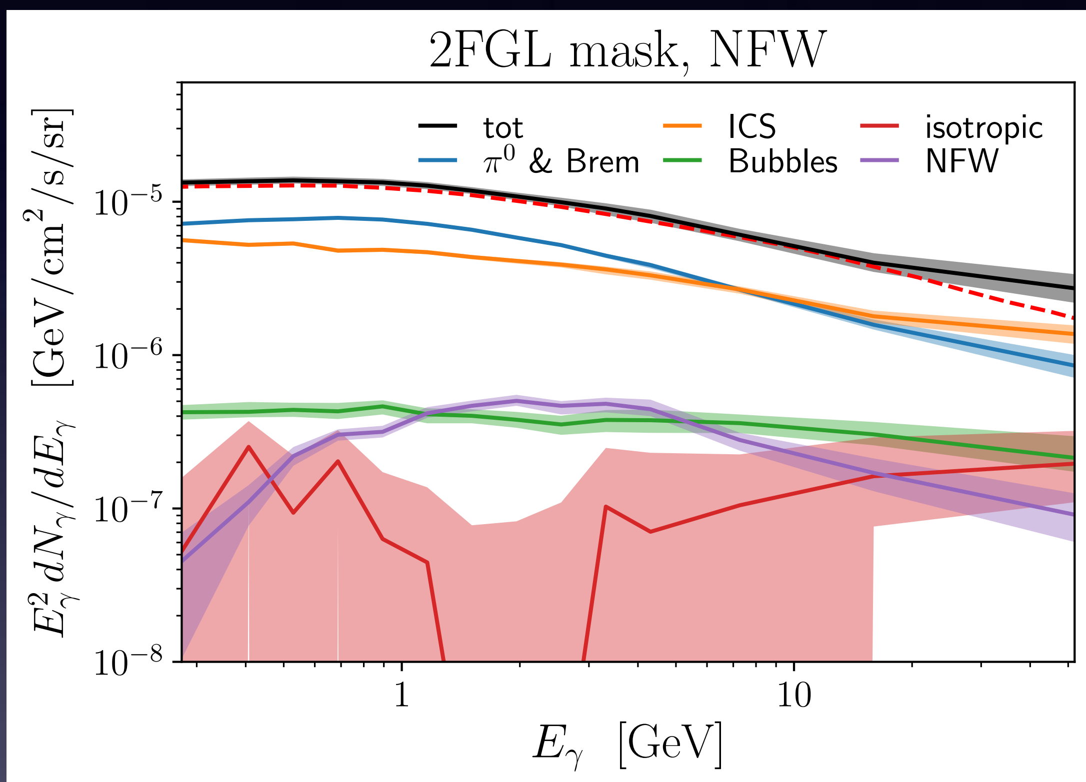

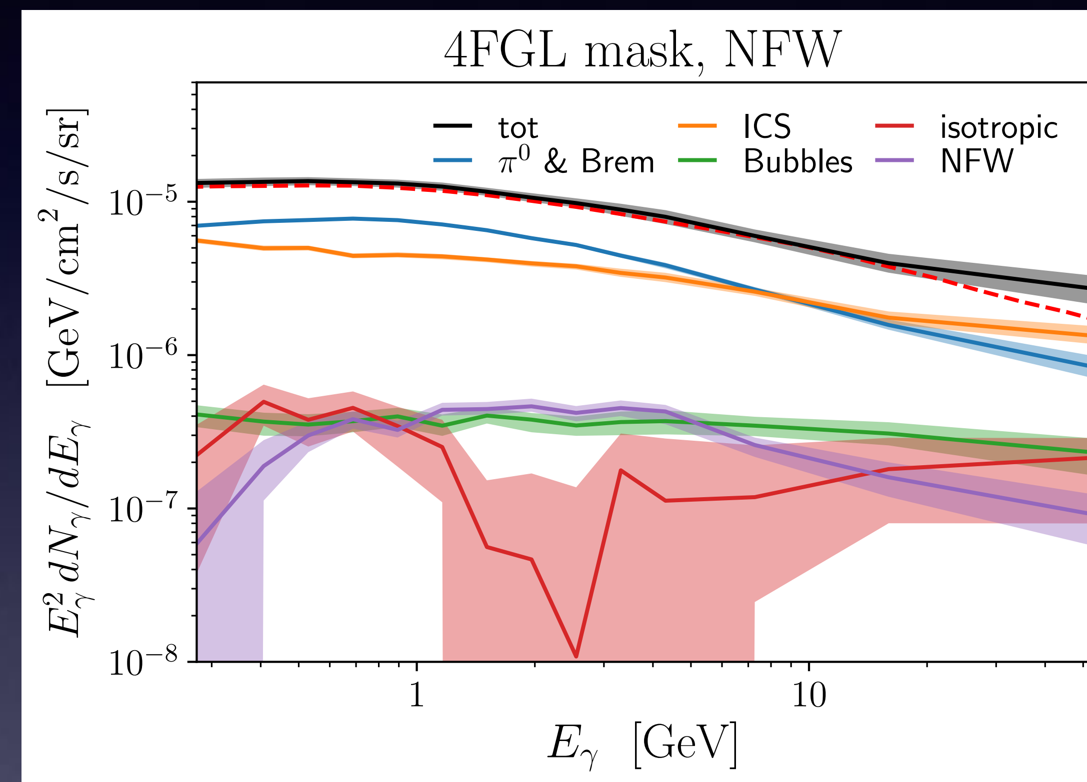

preference slightly smaller (fewer photons)

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

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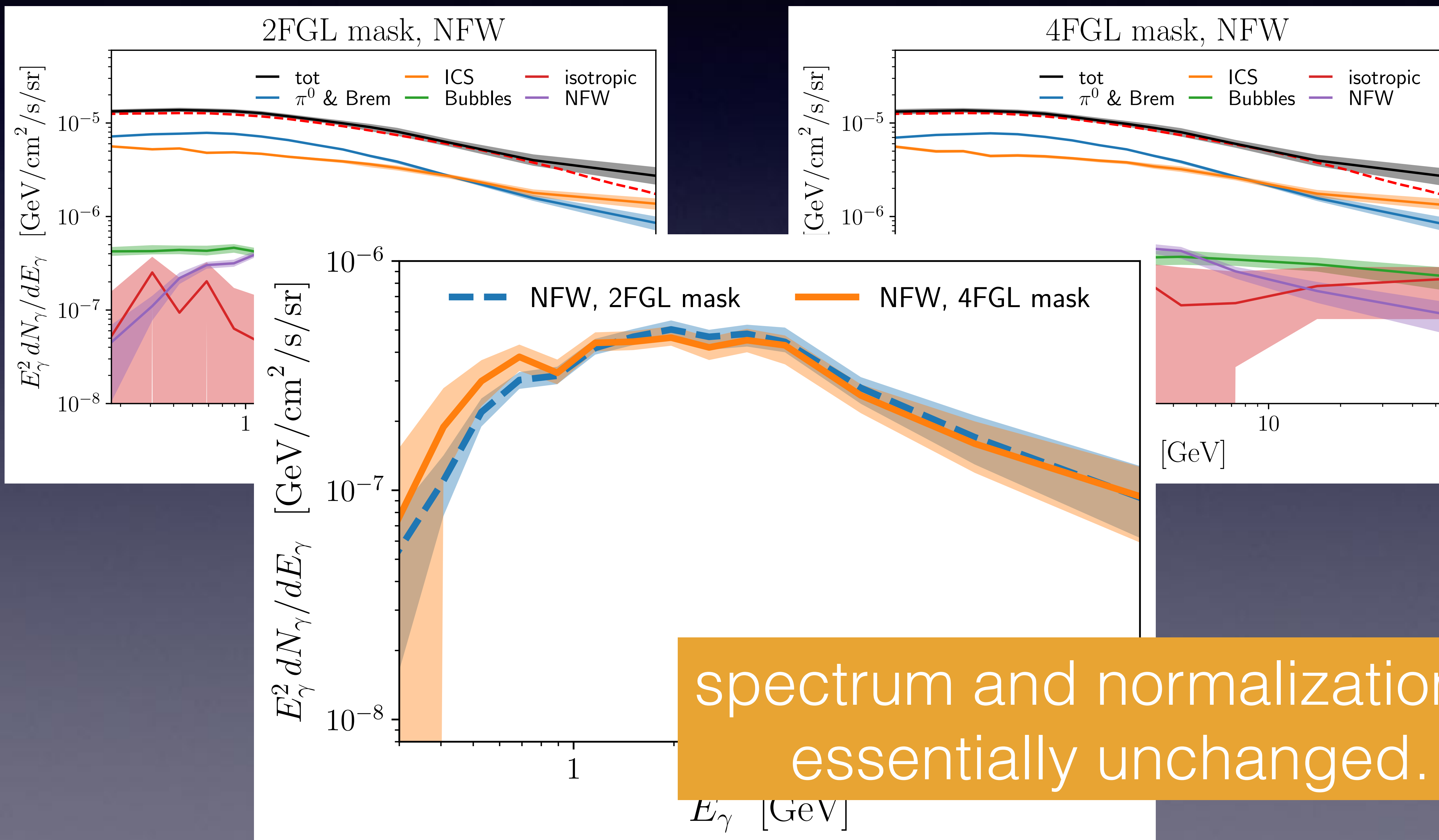
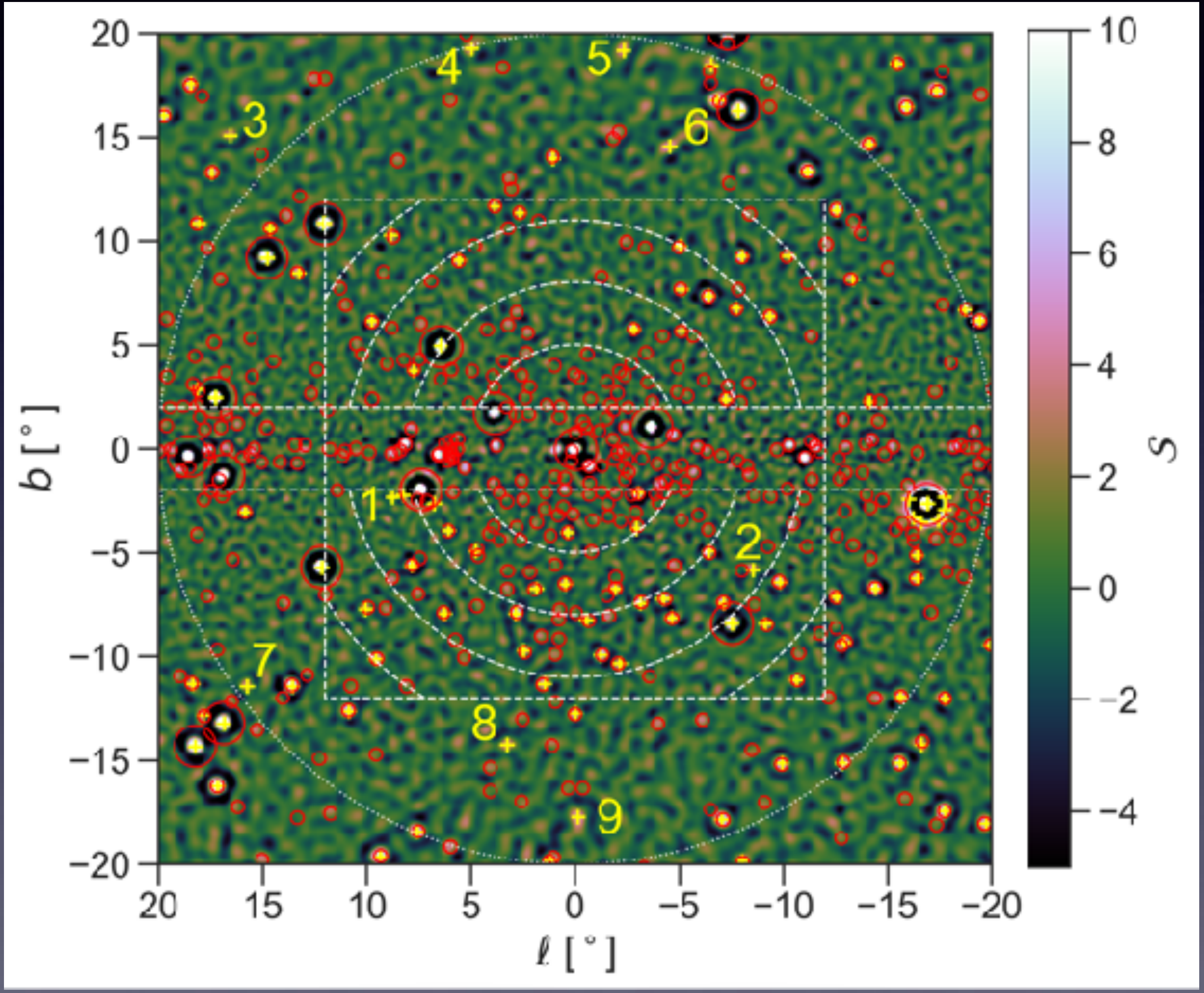


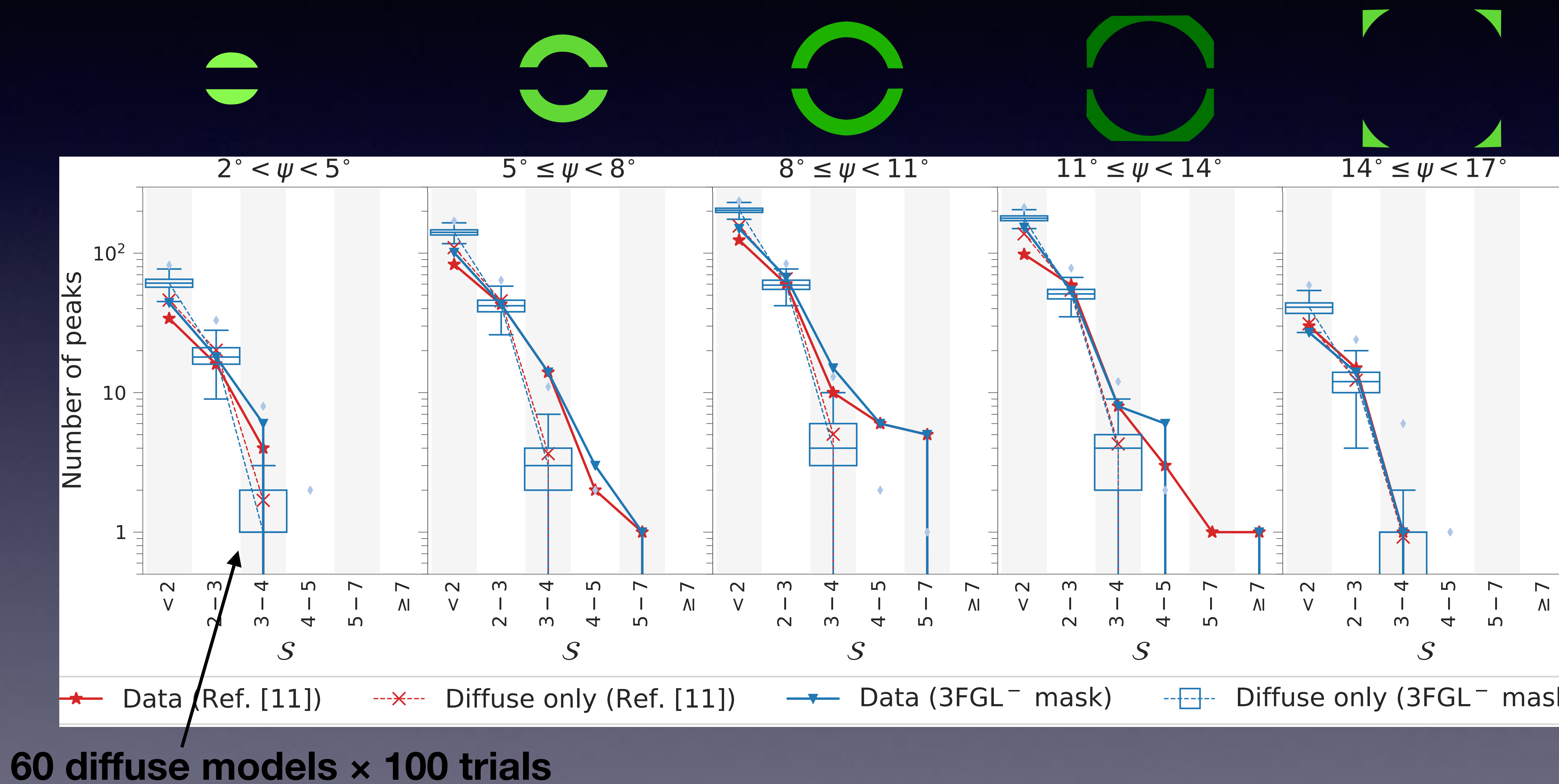
spectrum and normalization essentially unchanged…

GCE: “Wavelet” Results



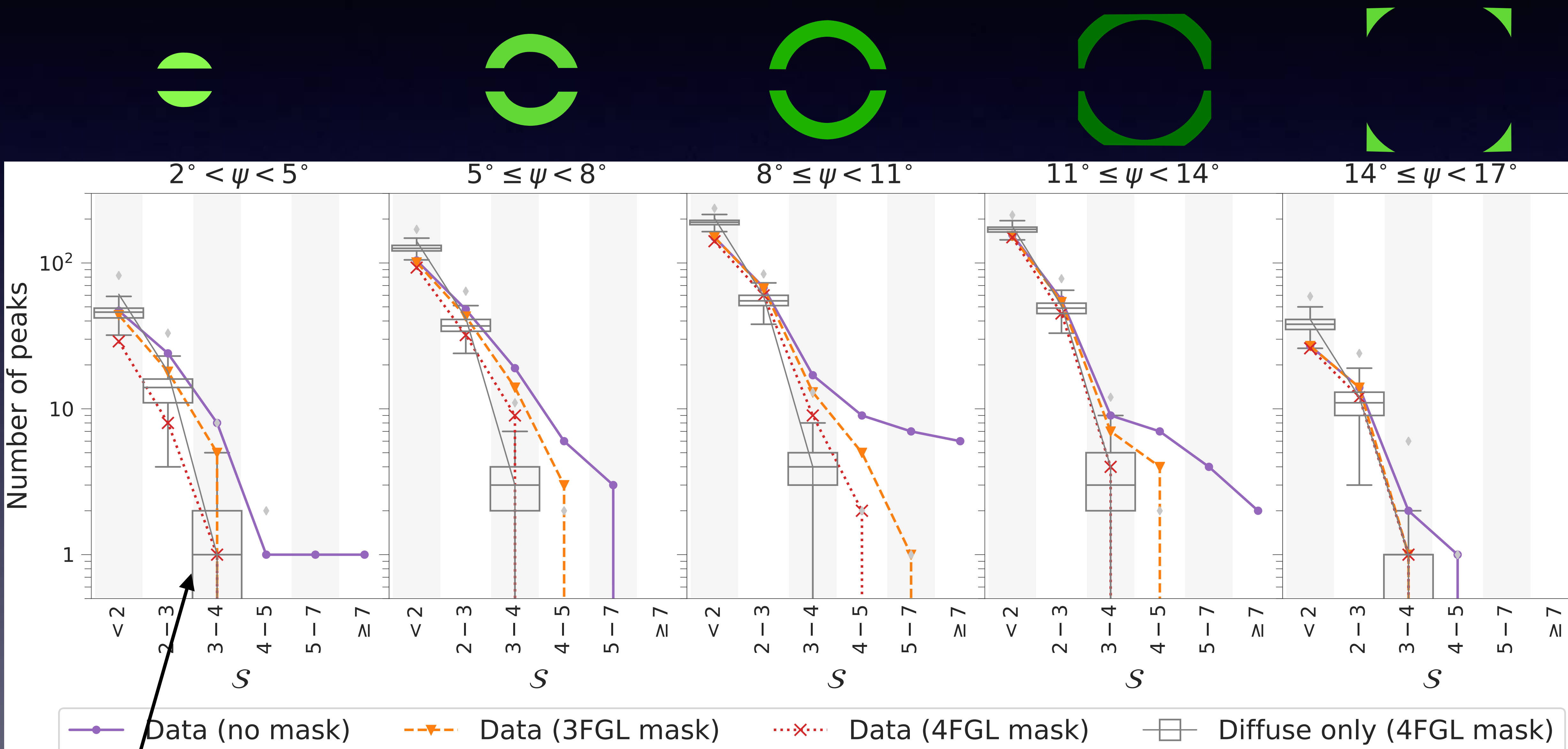
117 peaks (w/ S>4) ⊃ 109 peaks near 4FGL

Counting "Wavelet" Peaks



replicating Bartels et al

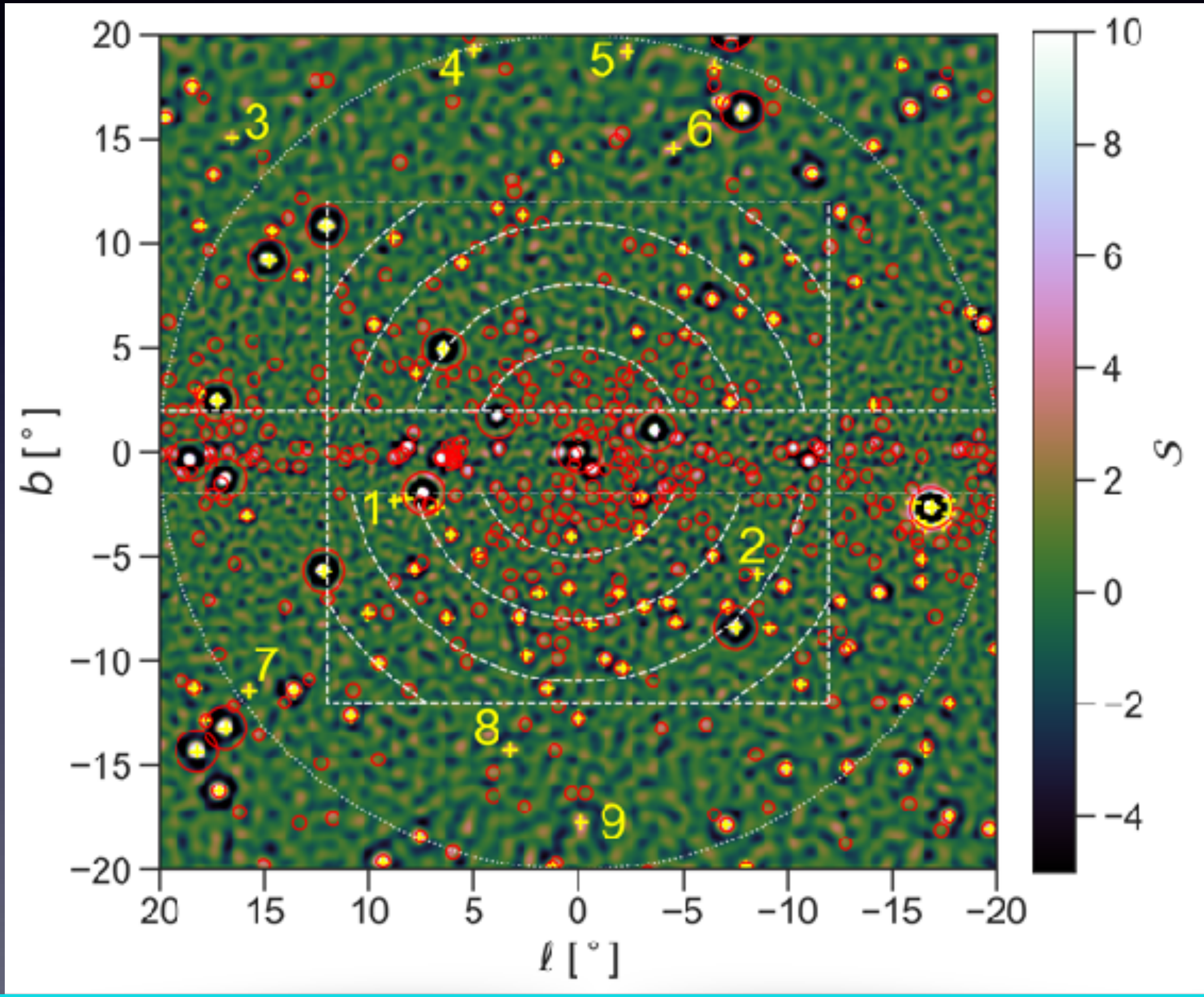
Counting “Wavelet” Peaks



60 diffuse models × 100 trials

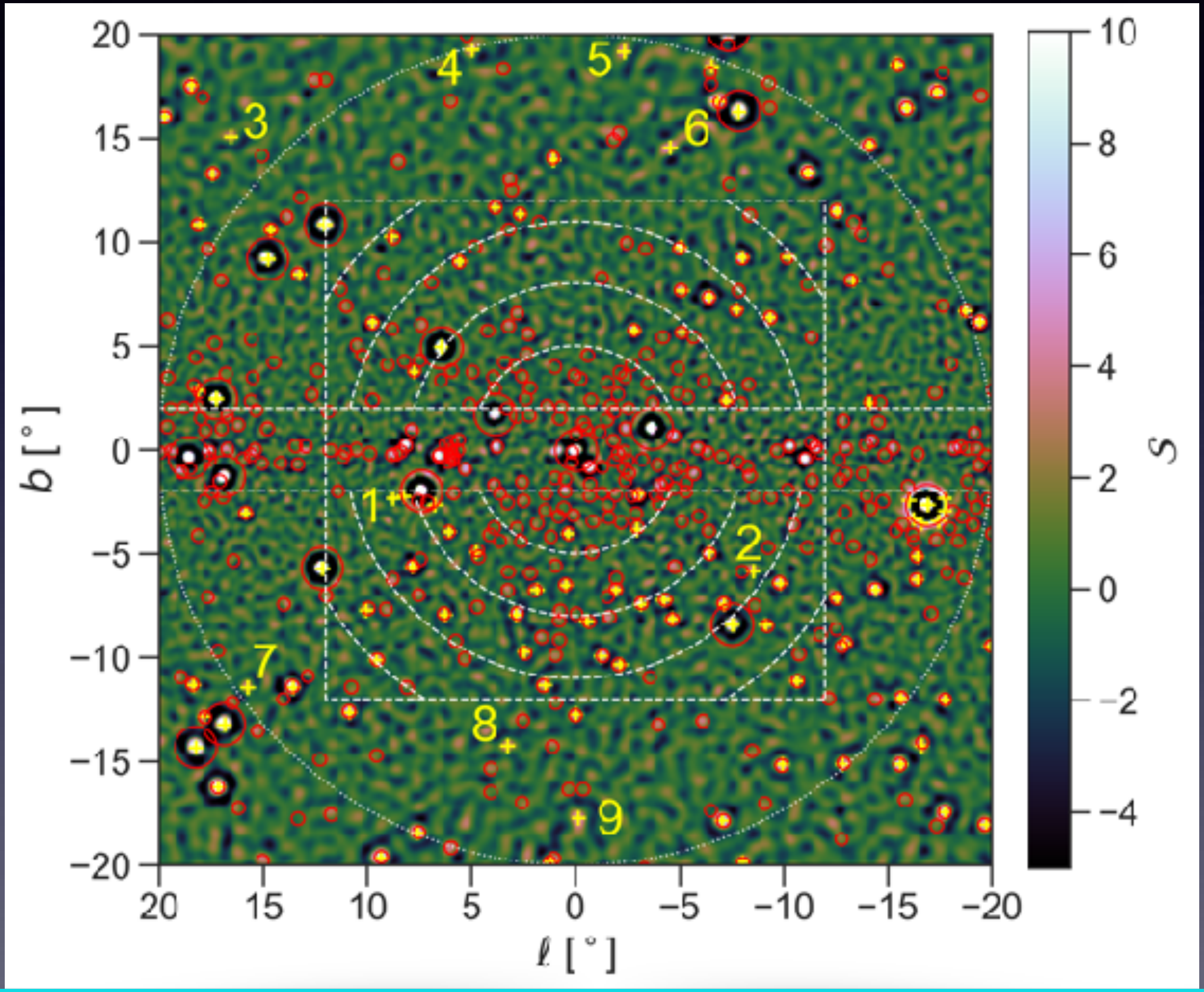
wavelet statistics change qualitatively with 4FGL!

High-S Sources



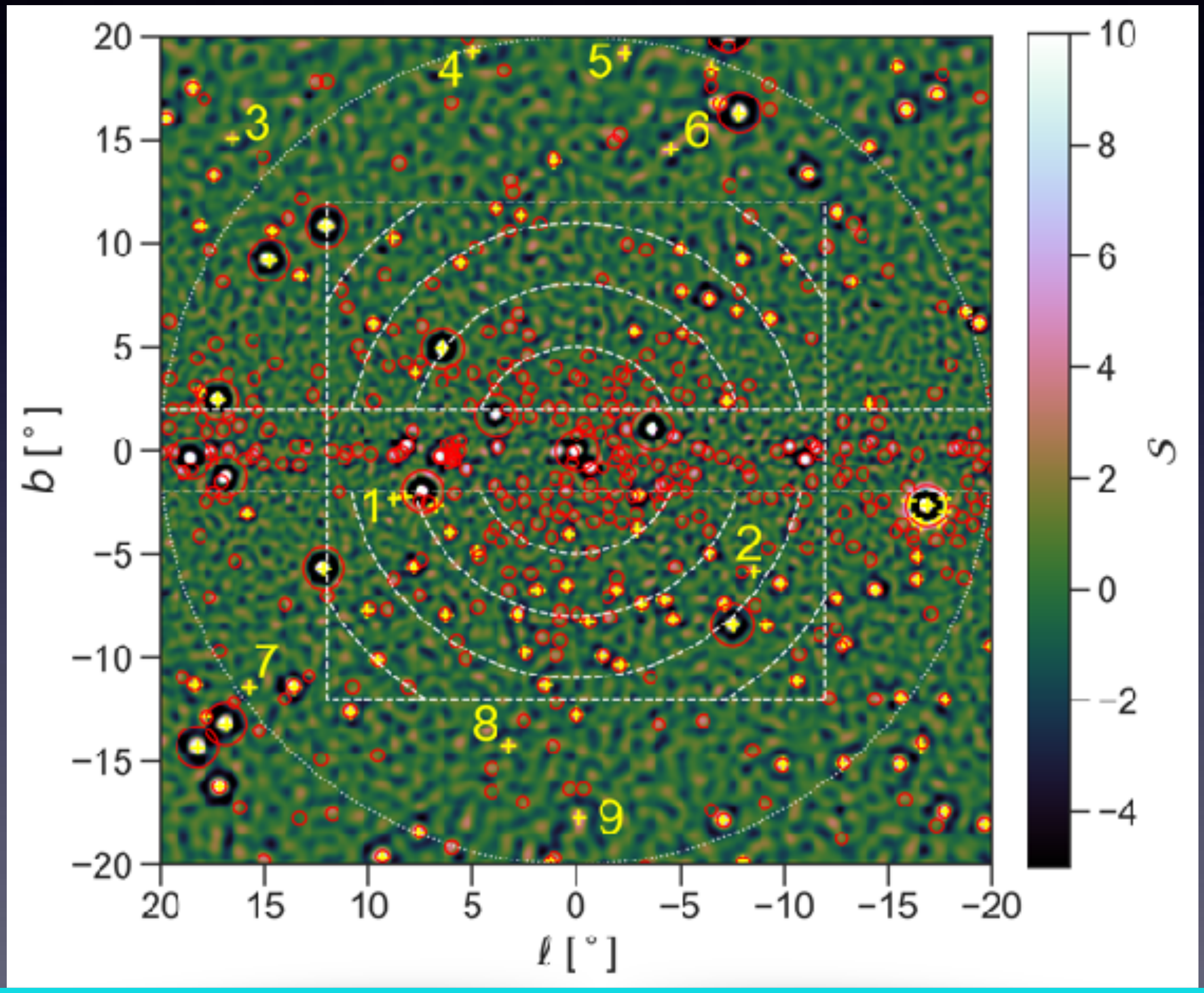
117 peaks (w/ S>4)

High-*S* Sources



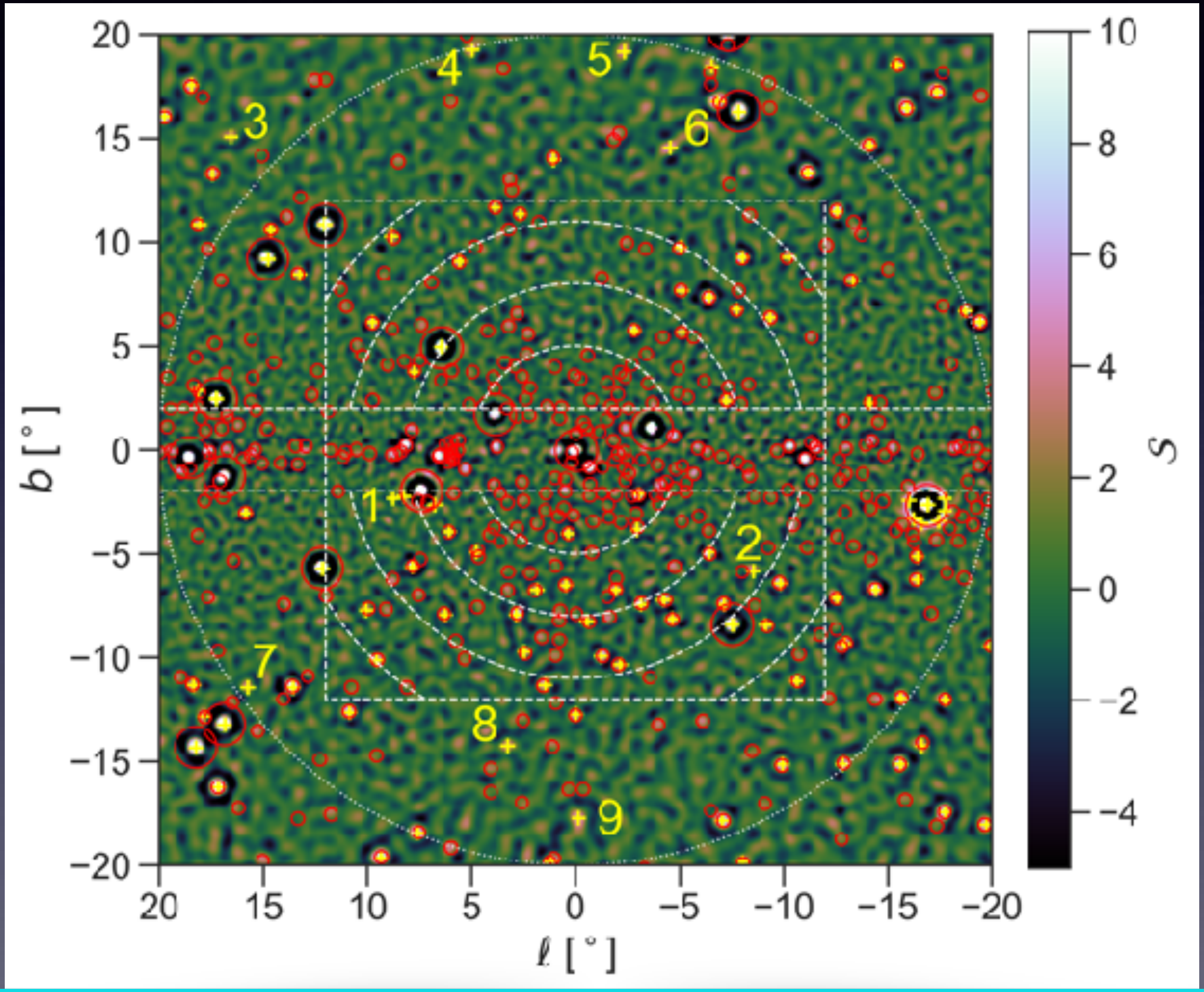
117 peaks (w/ *S*>4) ⊃ 109 peaks near 4FGL

High-*S* Sources



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

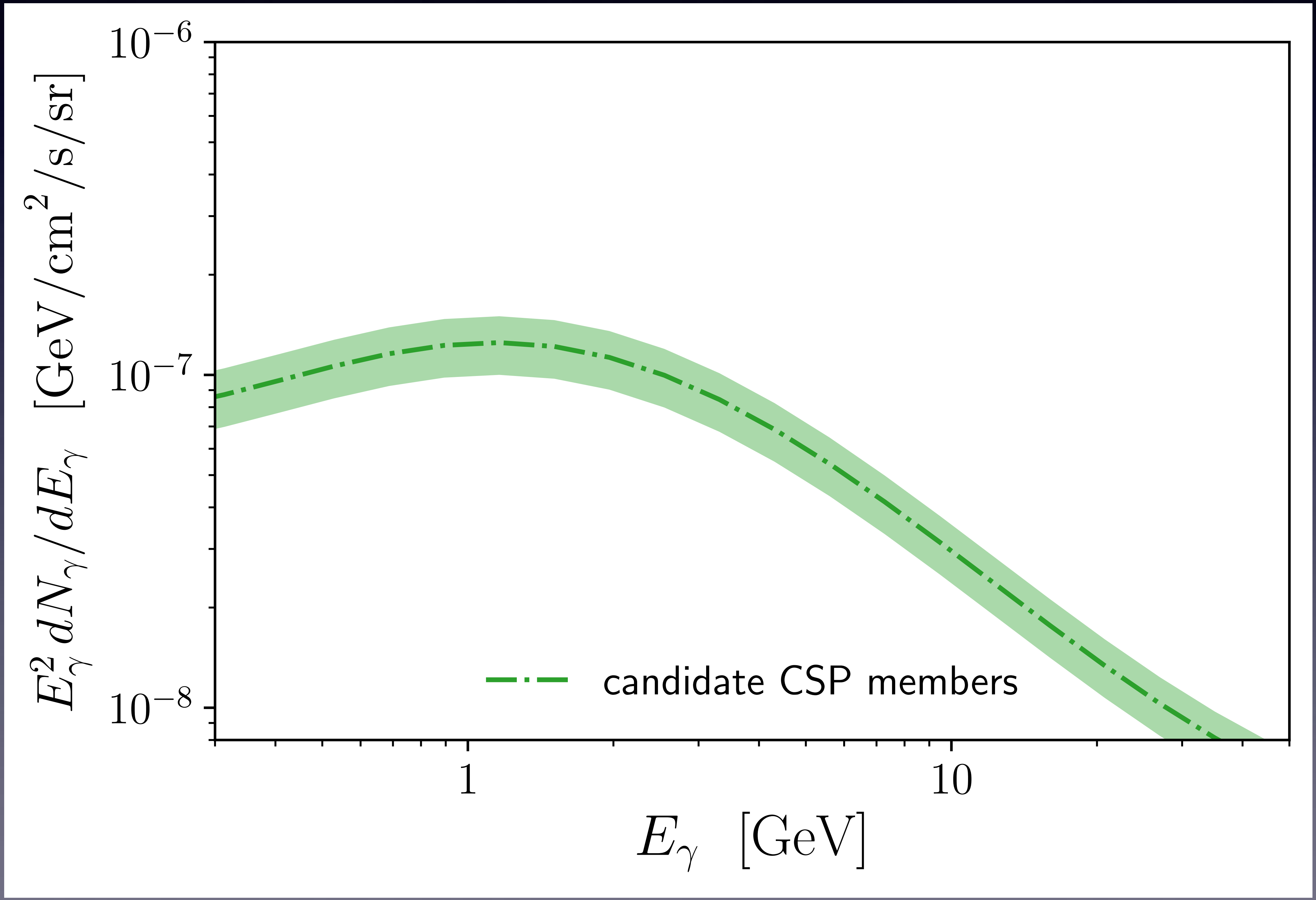
High-*S* Sources



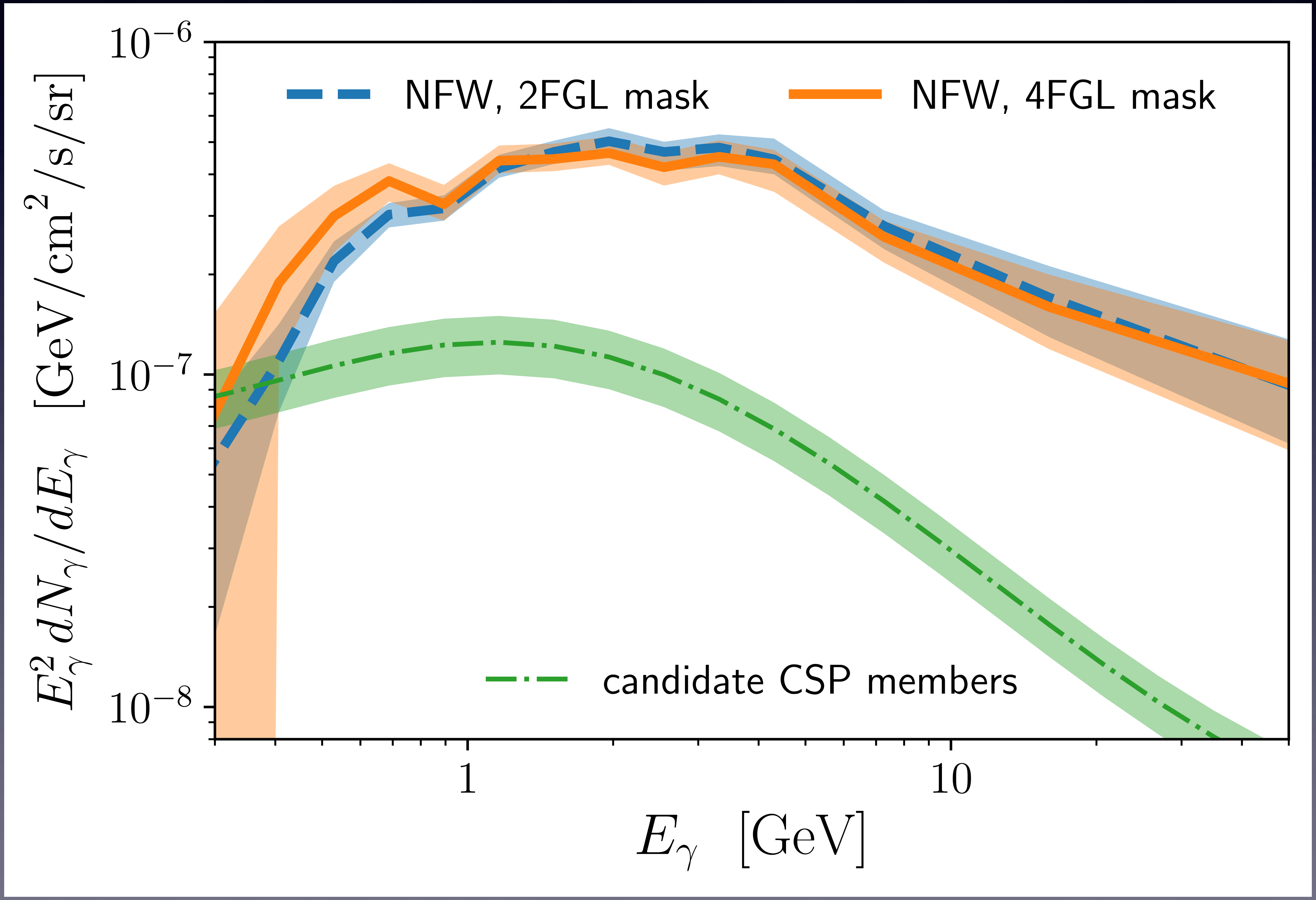
117 peaks (w/ *S*>4) ⊃ 109 peaks near 4FGL ⊃ 47 are unknown/unassociated

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

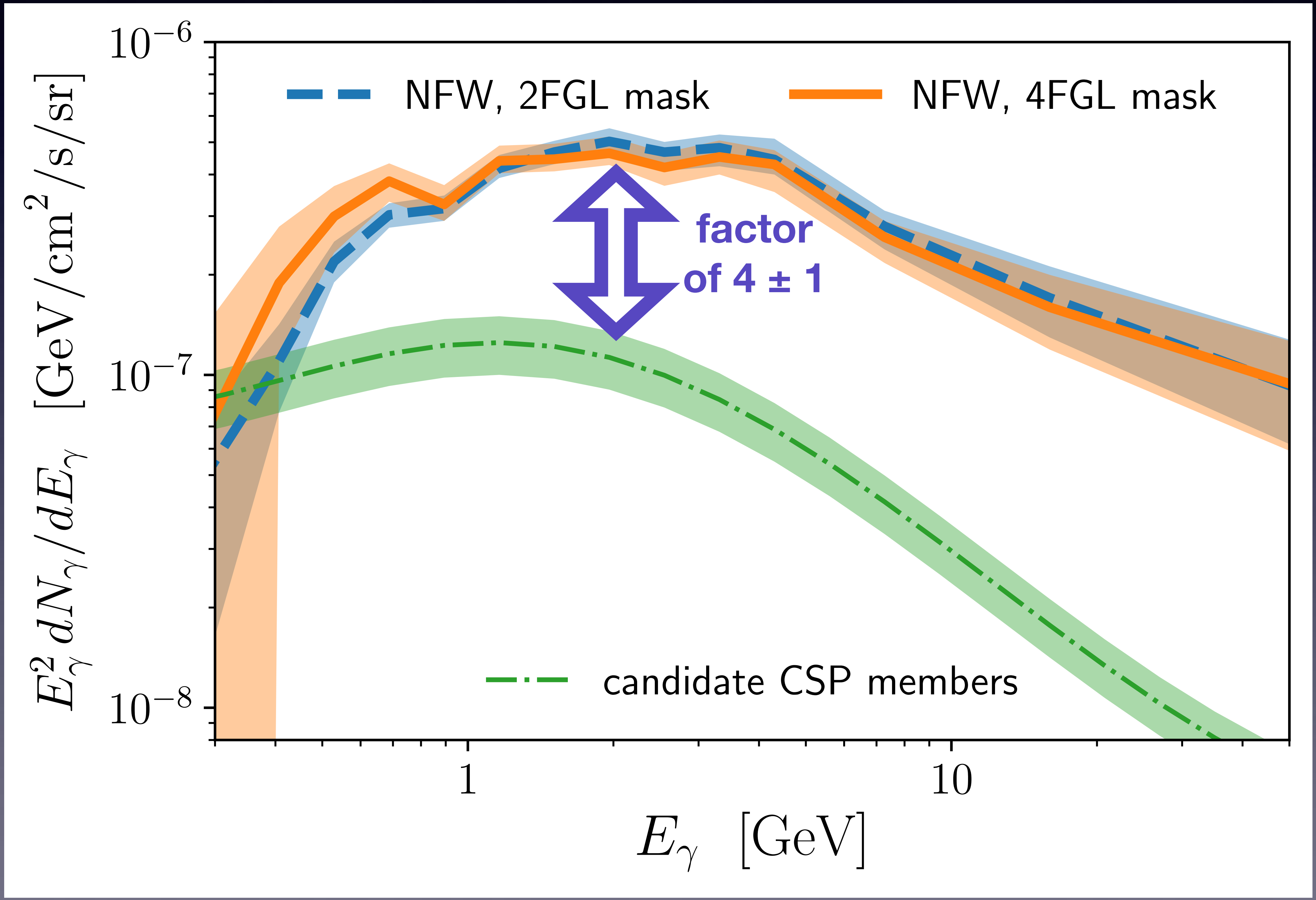
Stacked CSP Spectra



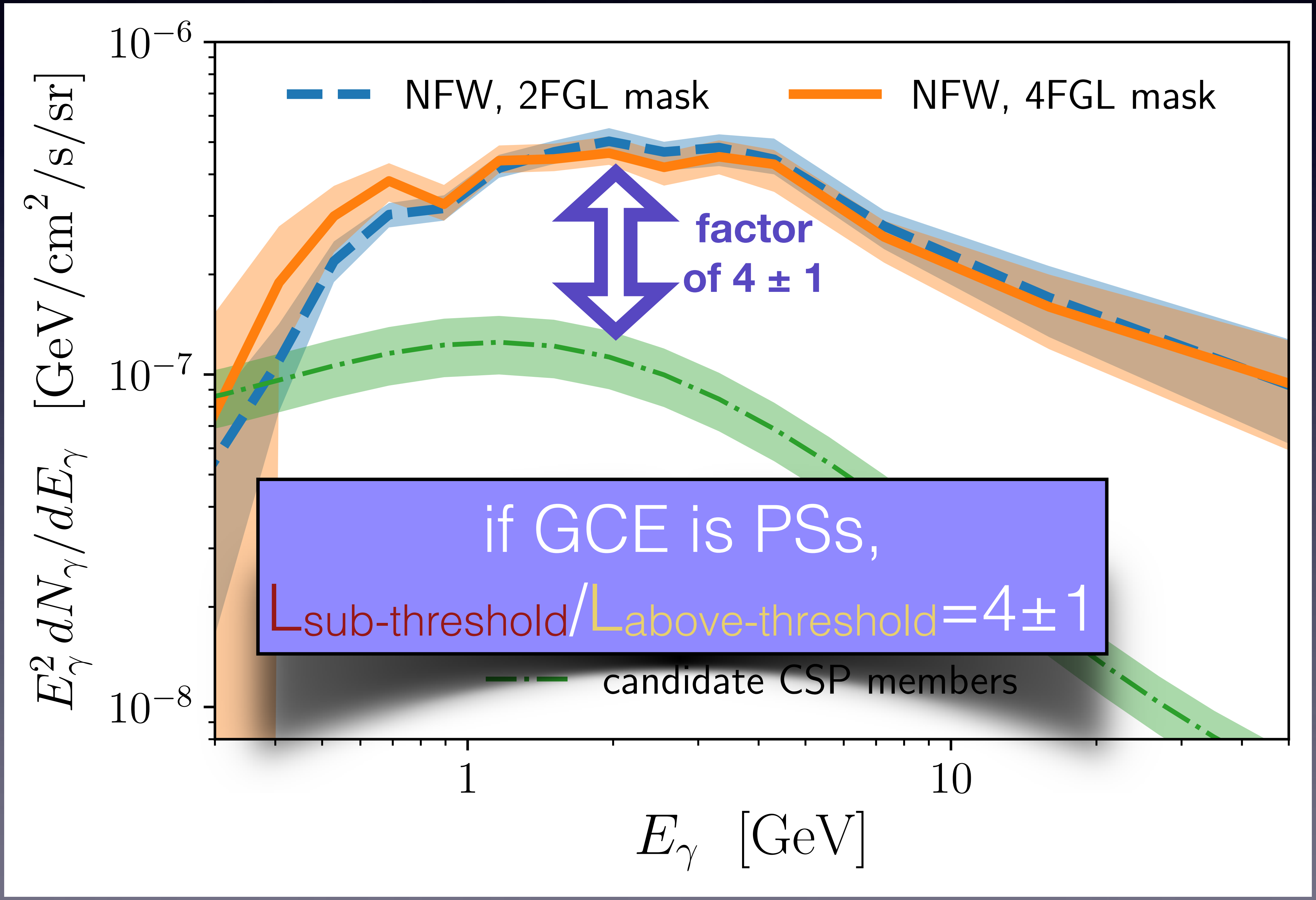
Compare Spectra



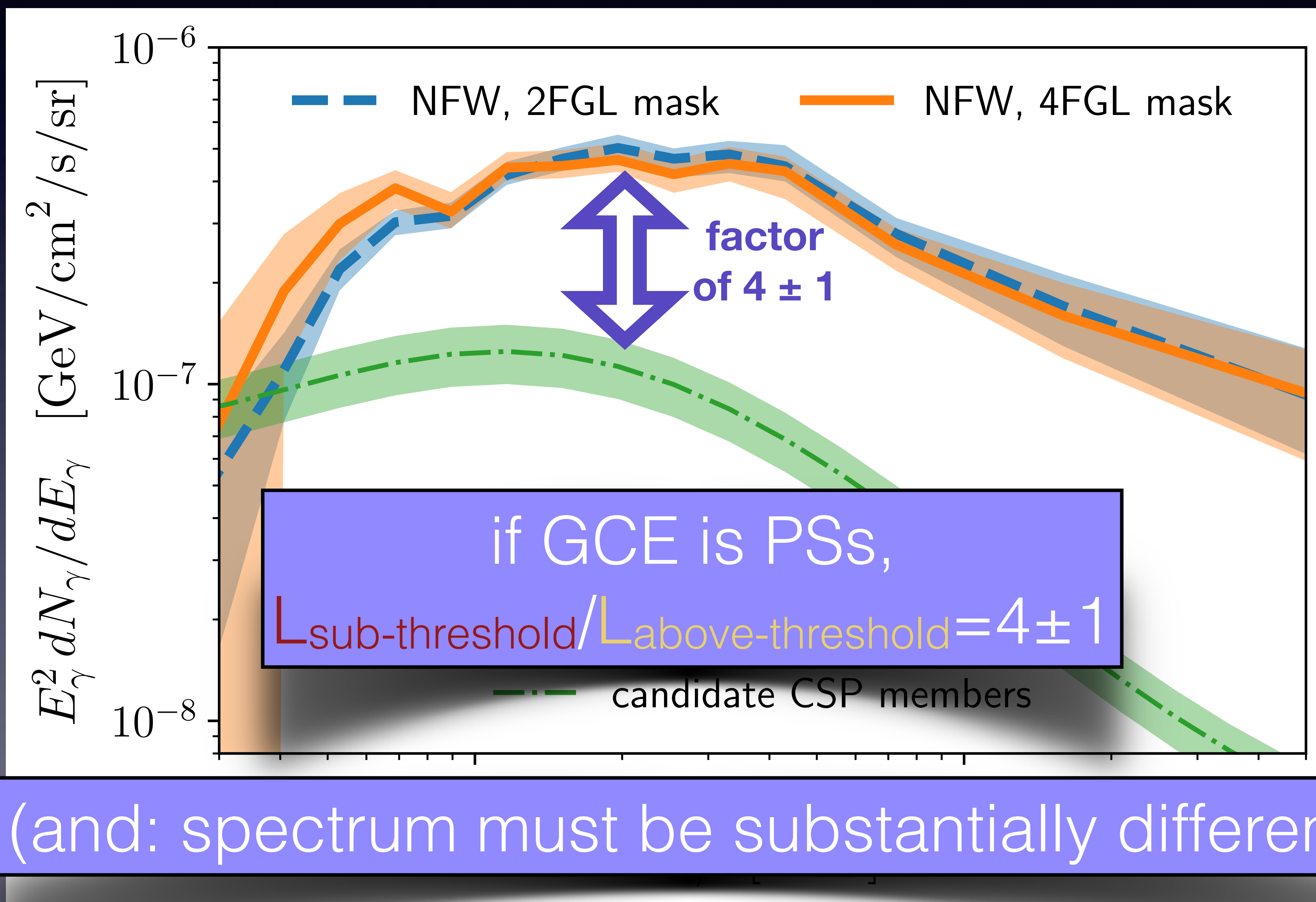
Compare Spectra



Implications for GCE



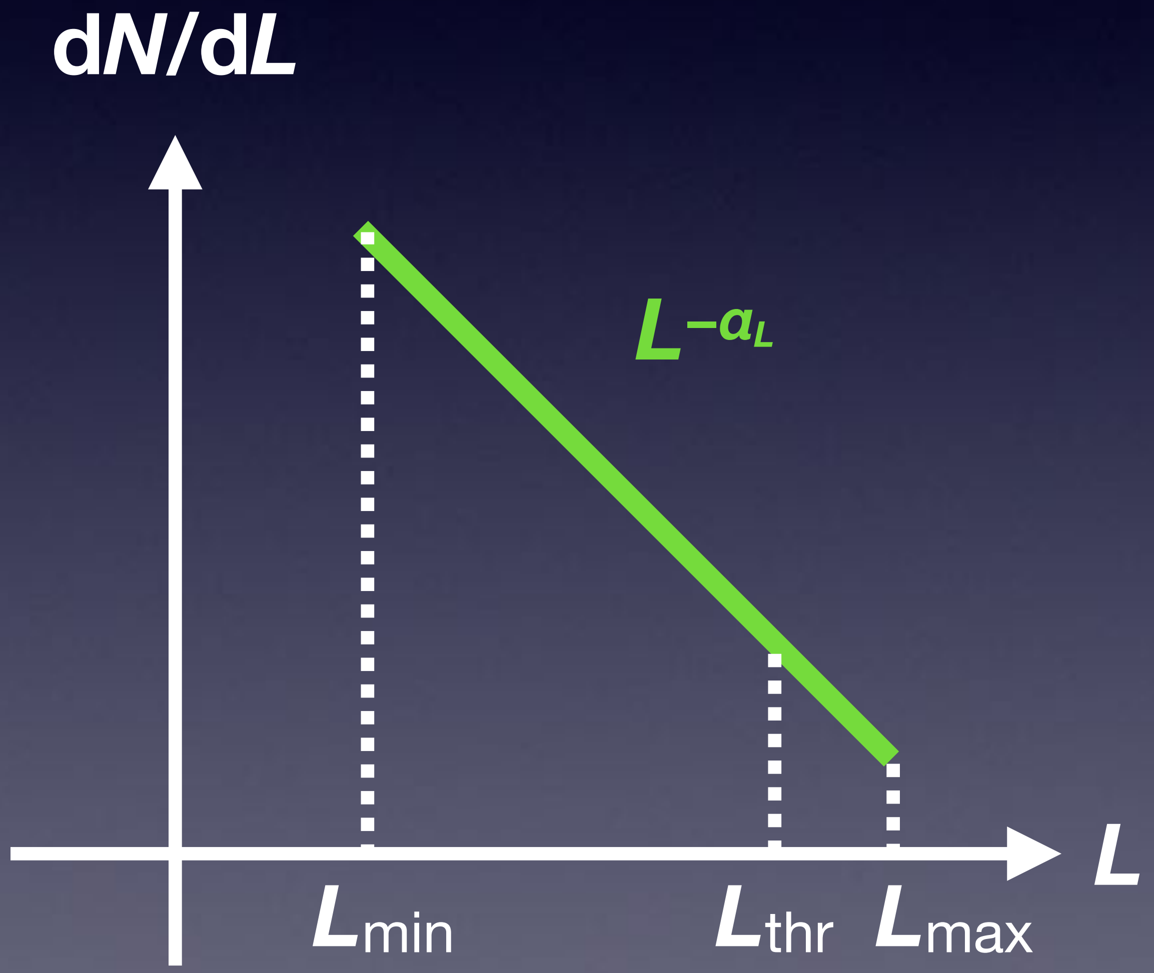
Implications for GCE



if GCE is PSs,
$L_{\text{sub-threshold}} / L_{\text{above-threshold}} = 4 \pm 1$

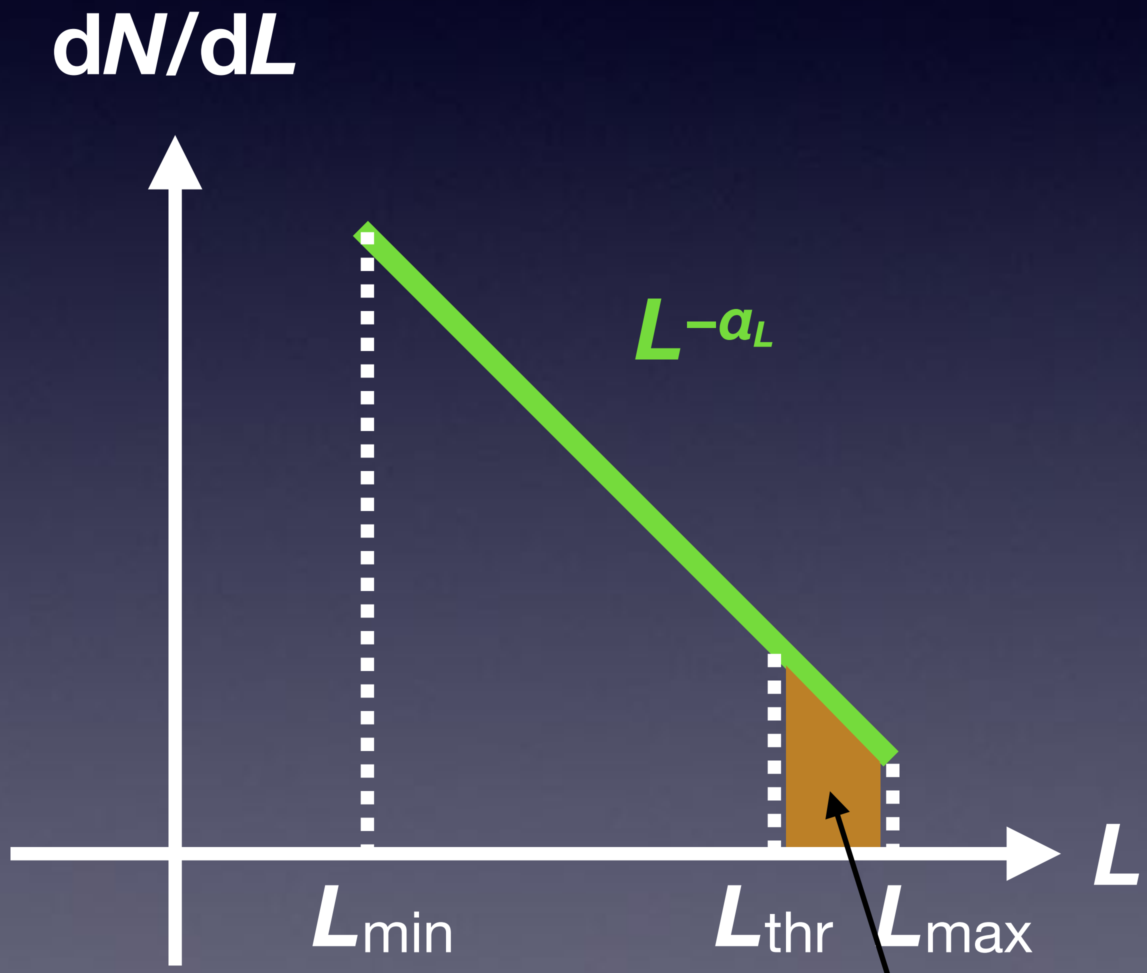
(and: spectrum must be substantially different)

Luminosity Function



L_{min} → CR physics
L_{thr} → detection threshold
L_{max} → CR physics

Luminosity Function



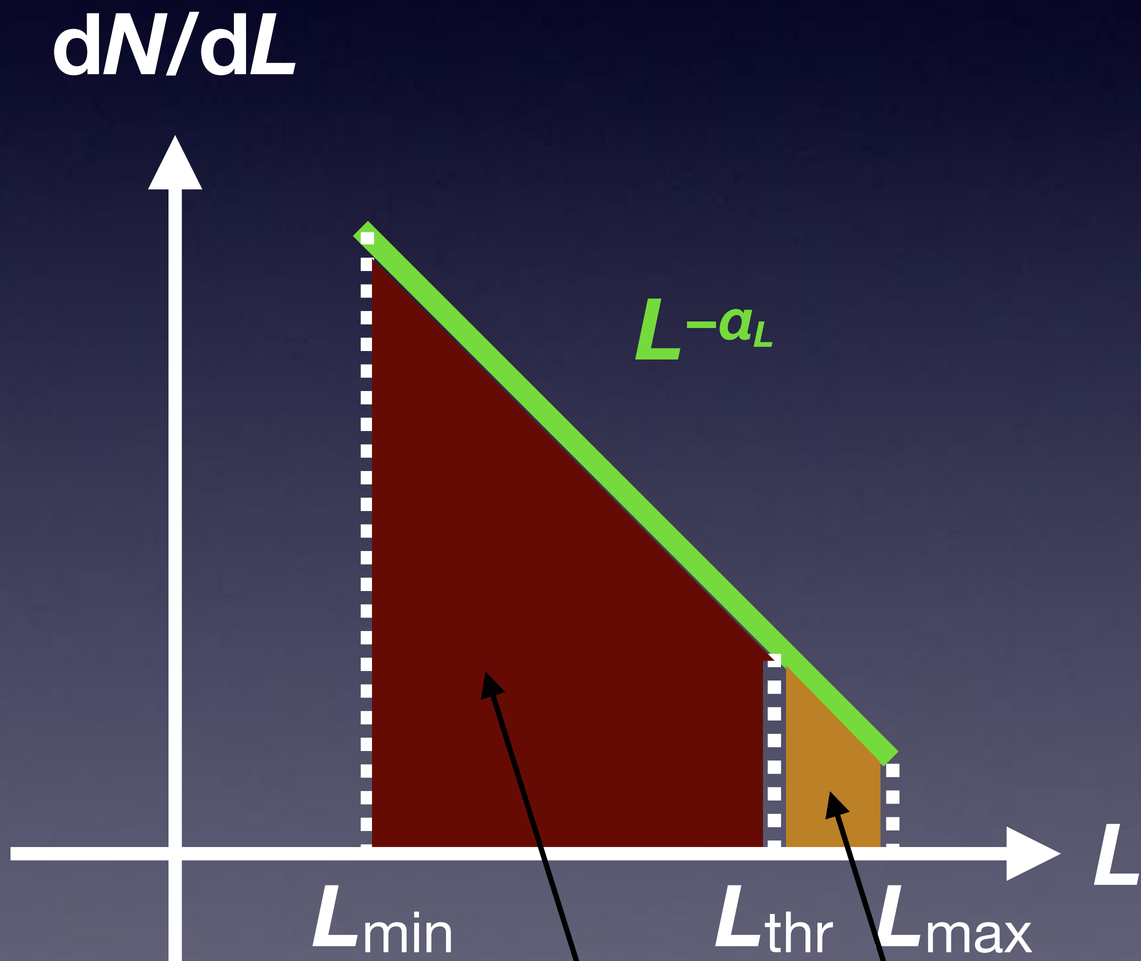
L_{min} → CR physics

L_{thr} → detection threshold

L_{max} → CR physics

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

Luminosity Function



L_{min} → CR physics

L_{thr} → detection threshold

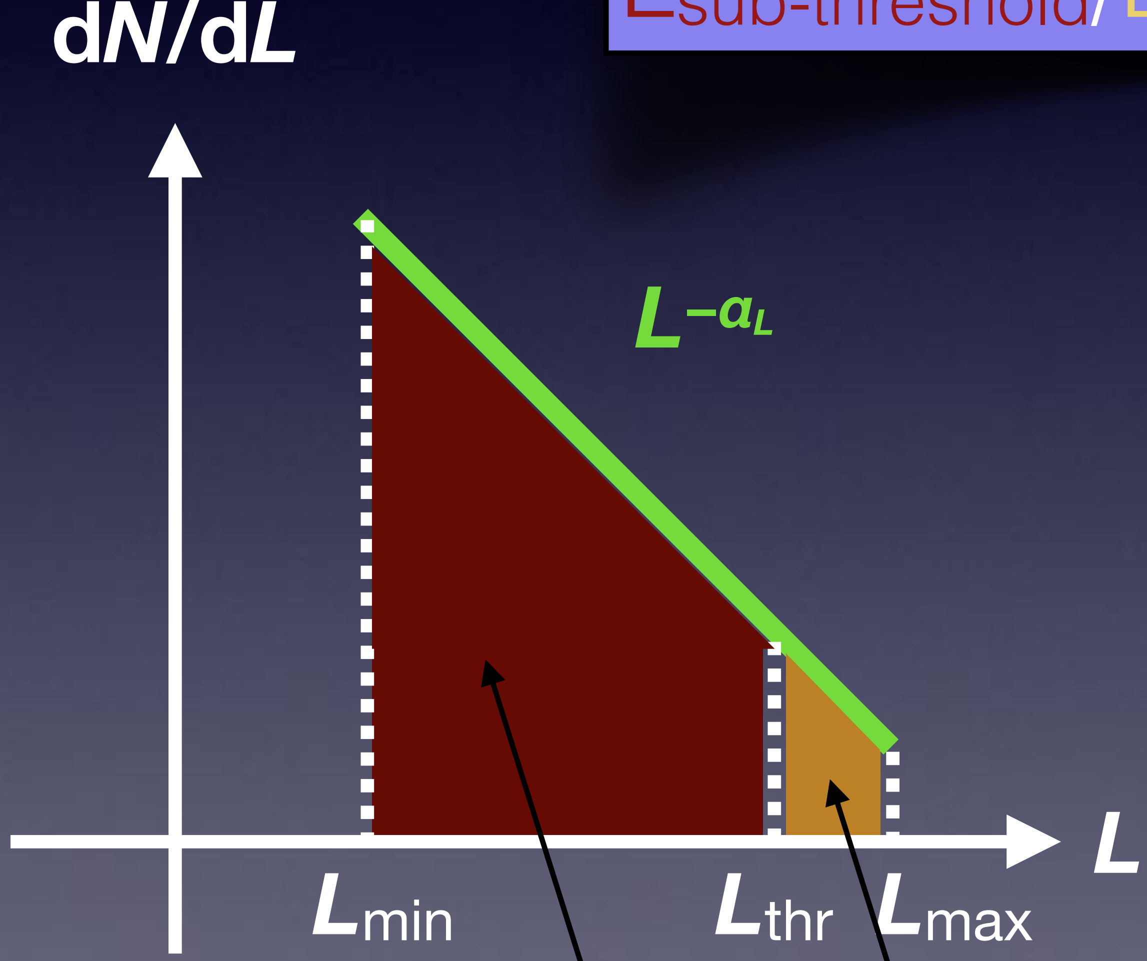
L_{max} → CR physics

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

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

Luminosity Function

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



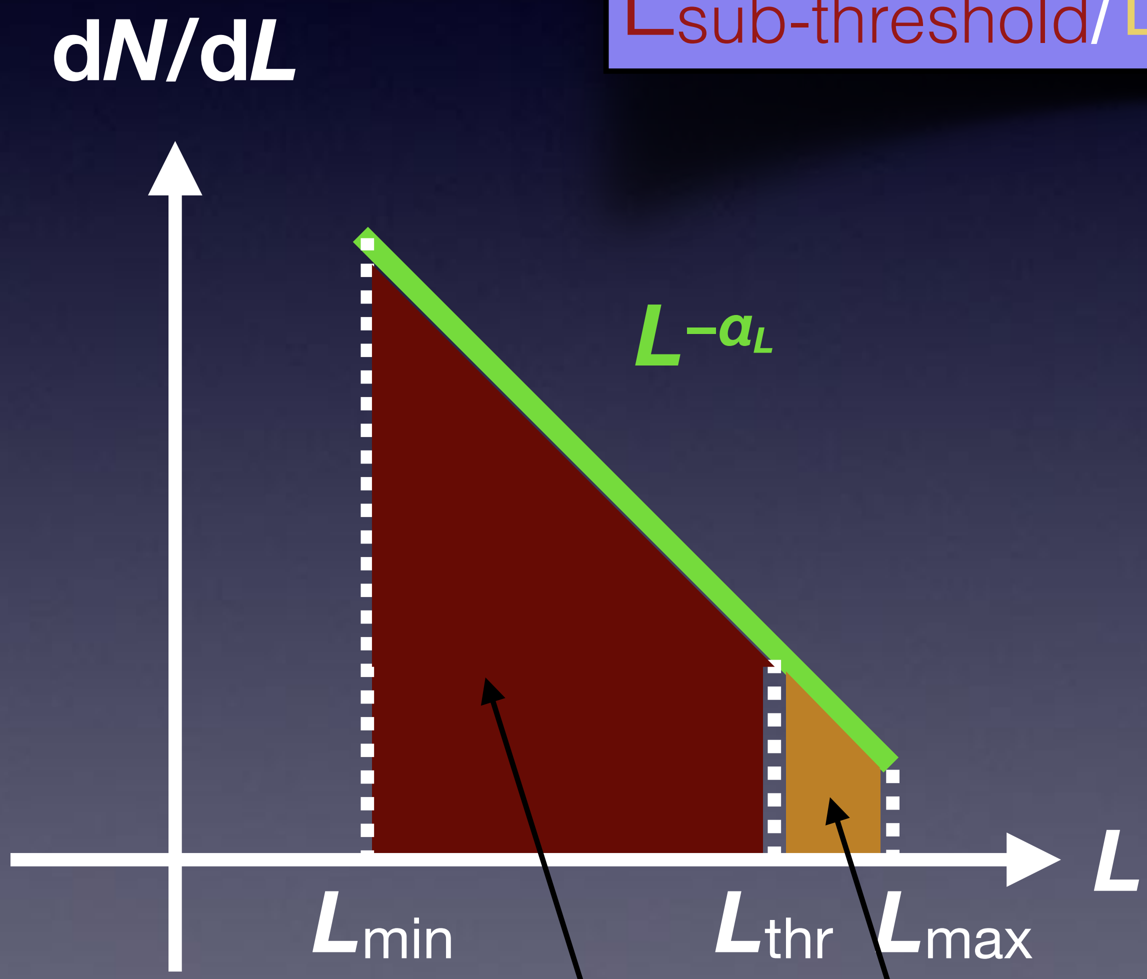
L_{min} → CR physics
L_{thr} → detection threshold
L_{max} → CR physics

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

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

Luminosity Function

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



L_{min} → CR physics

L_{thr} → detection threshold

L_{max} → CR physics

Given $L_{\text{sub-threshold}}$, $L_{\text{above-threshold}}$, and $N_{\text{above-threshold}}$

$\Longrightarrow$ α_L, N_{sub} output

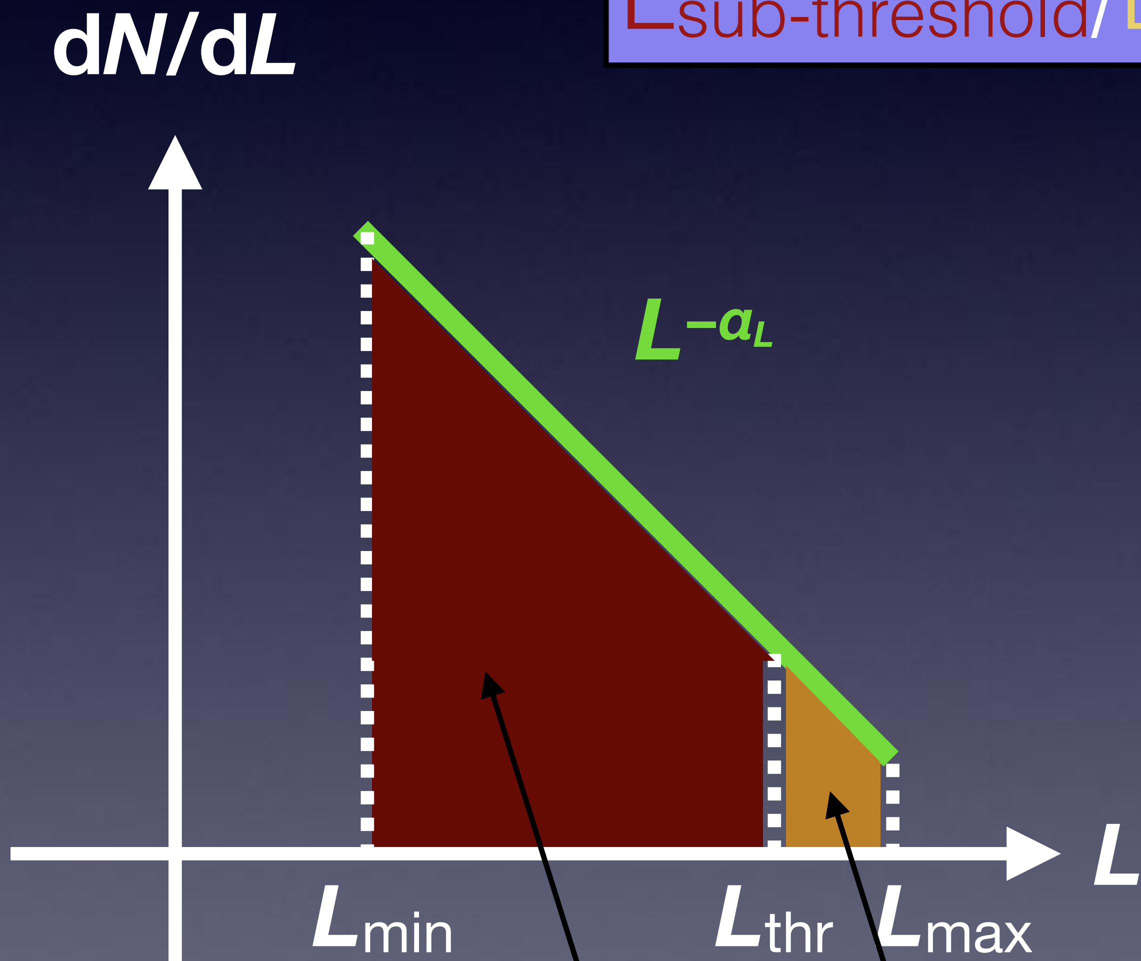
$\int_{<\text{thr}} L\, dN/dL\, dL$ "= GCE"

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

Luminosity Function

if GCE is PSs,

$L_{\text{sub-threshold}} / L_{\text{above-threshold}} = 4 \pm 1$



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

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

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

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

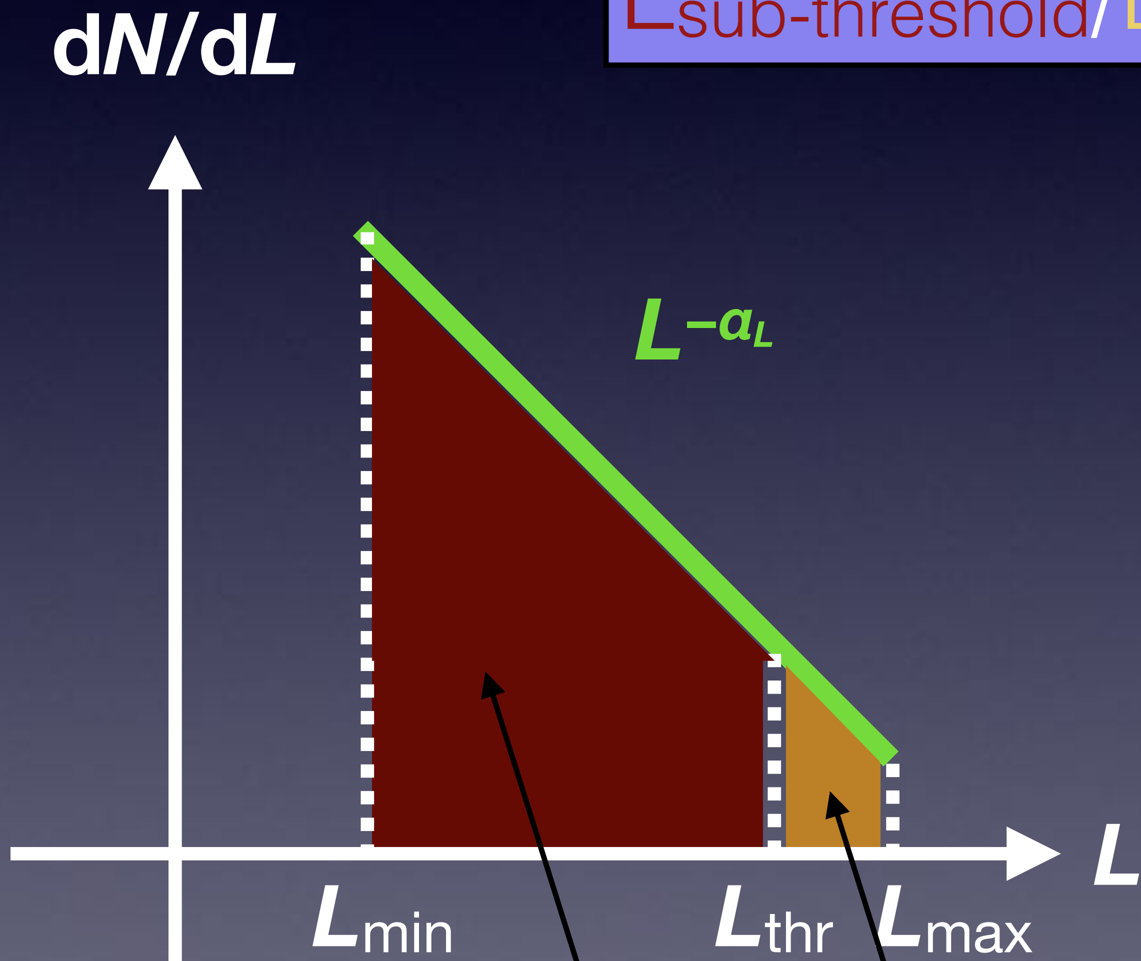
$N_{sub} \rightarrow (3.5 \pm 1.7)*10^6$

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

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

Luminosity Function

if GCE is PSs,
$L_{\text{sub-threshold}} / L_{\text{above-threshold}} = 4 \pm 1$



$L_{min} \rightarrow 10^{29}$ erg/s
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$L_{max} \rightarrow 10^{35}$ erg/s
$\Longrightarrow \alpha_L \rightarrow 1.95 \pm 0.05$
$N_{sub} \rightarrow (3.5 \pm 1.7)*10^6$

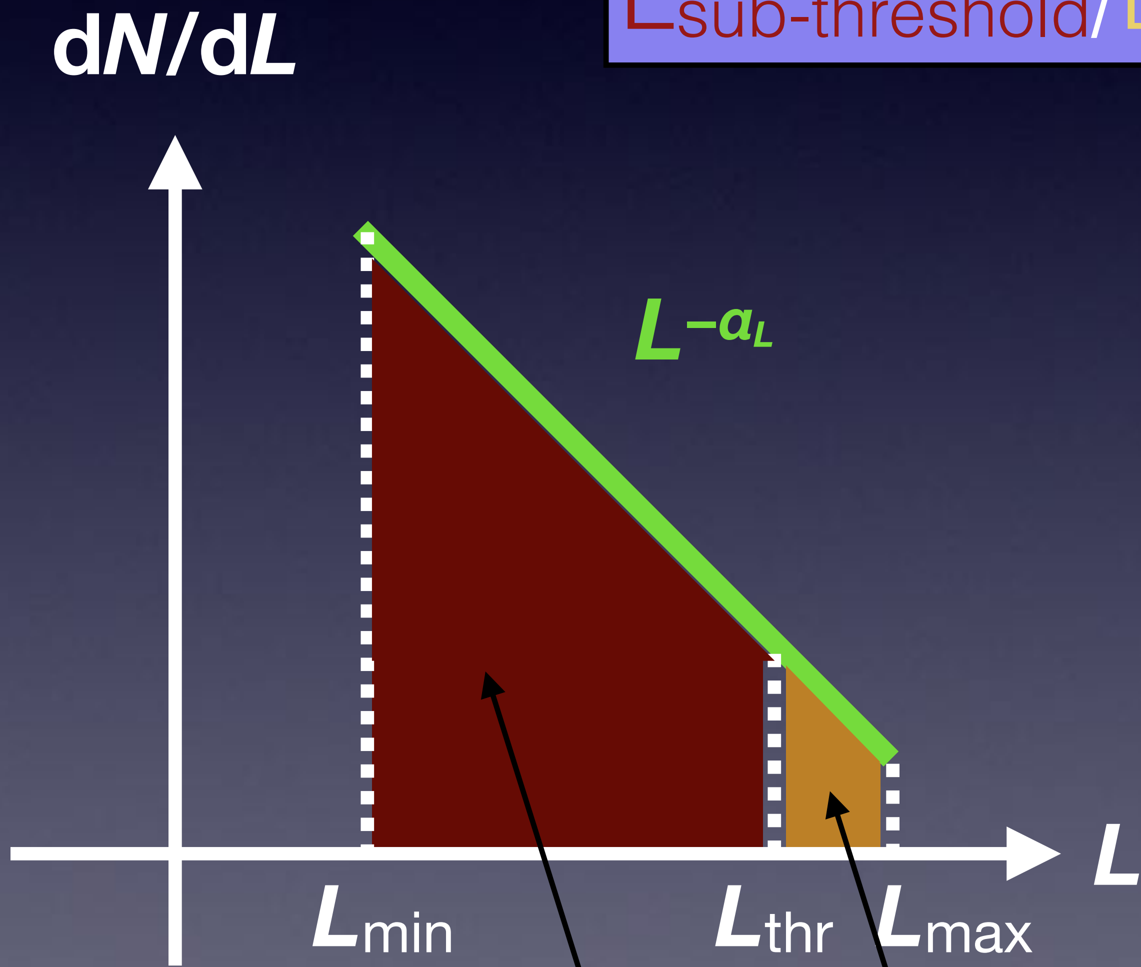
(compare to $N_{vis} \sim 47$)

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

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

Luminosity Function

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



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

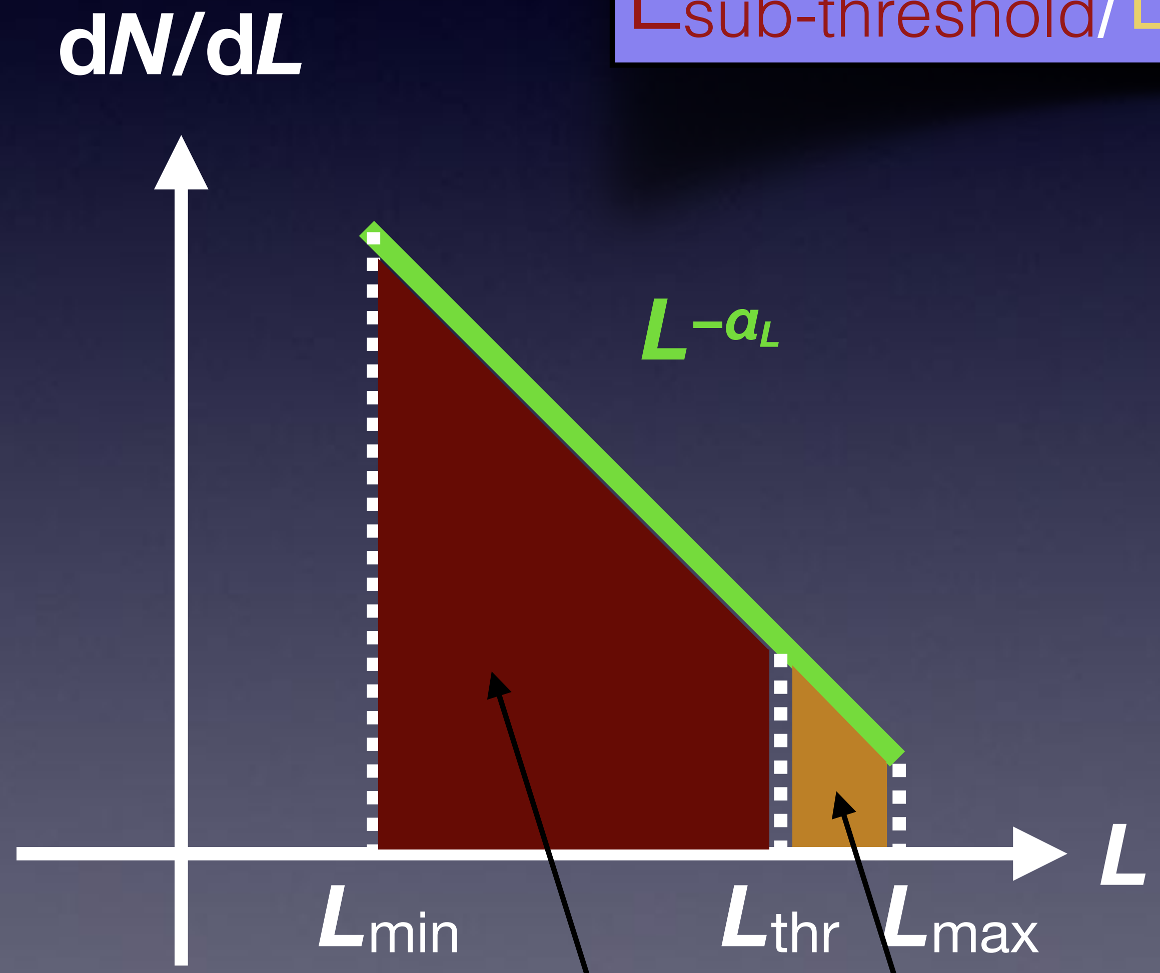
(compare to N_{vis} ~ 47)

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

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

Luminosity Function?

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



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

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

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

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

(N_{sub} diverges!)

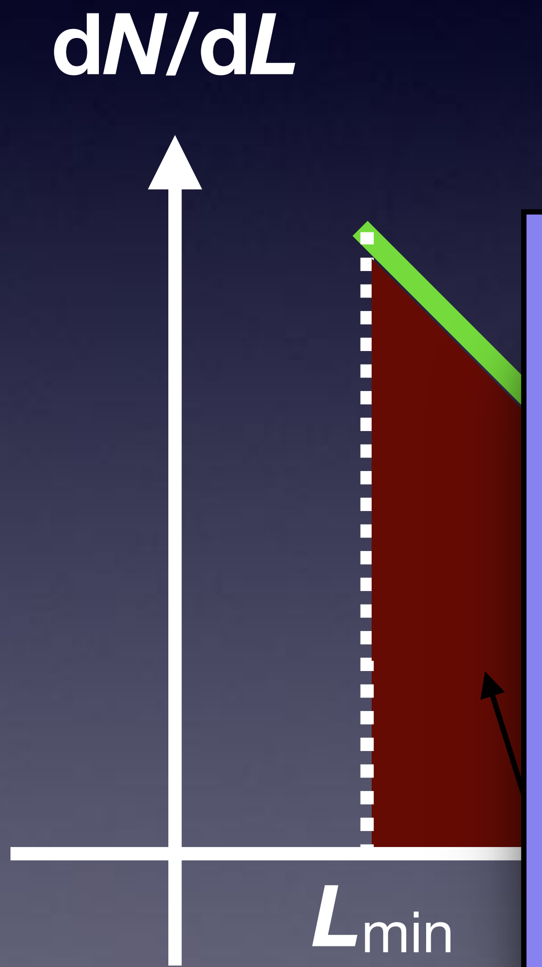
$\int_{<\text{thr}} L\, dN/dL\, dL$ "= GCE"

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

.05

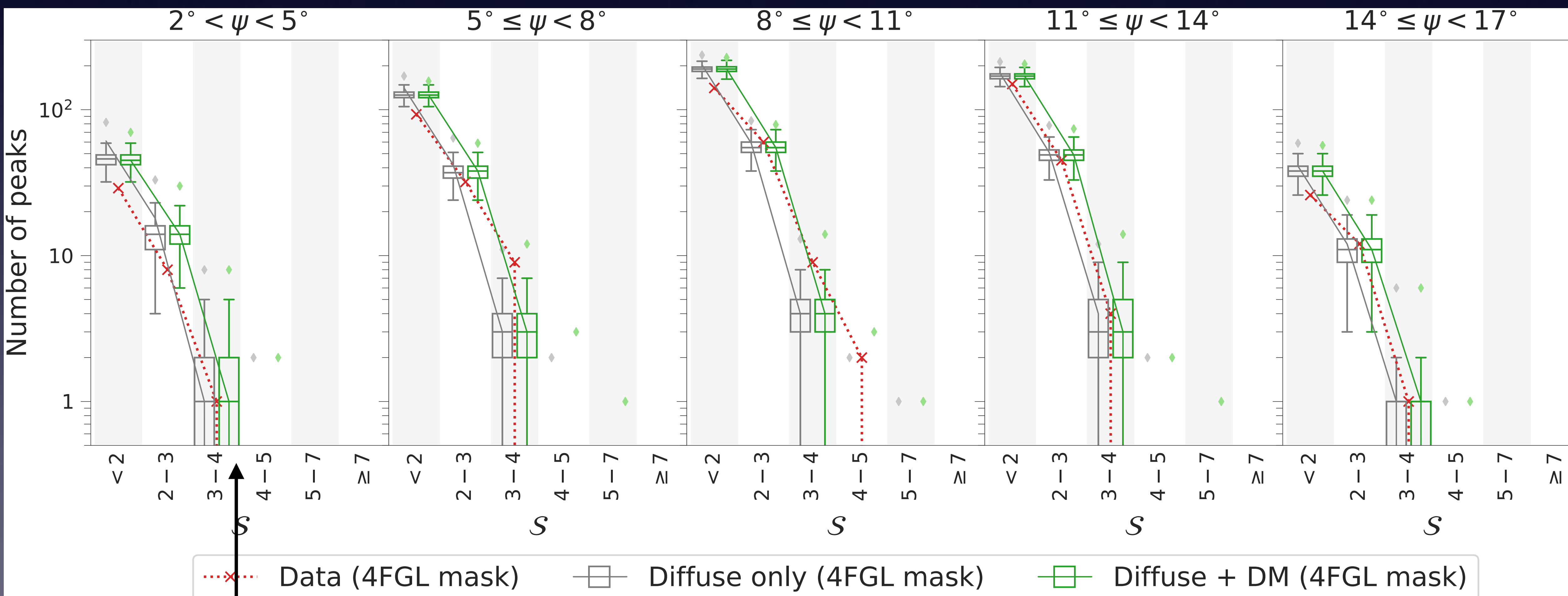
diverges!)

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

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

Does DM still work?

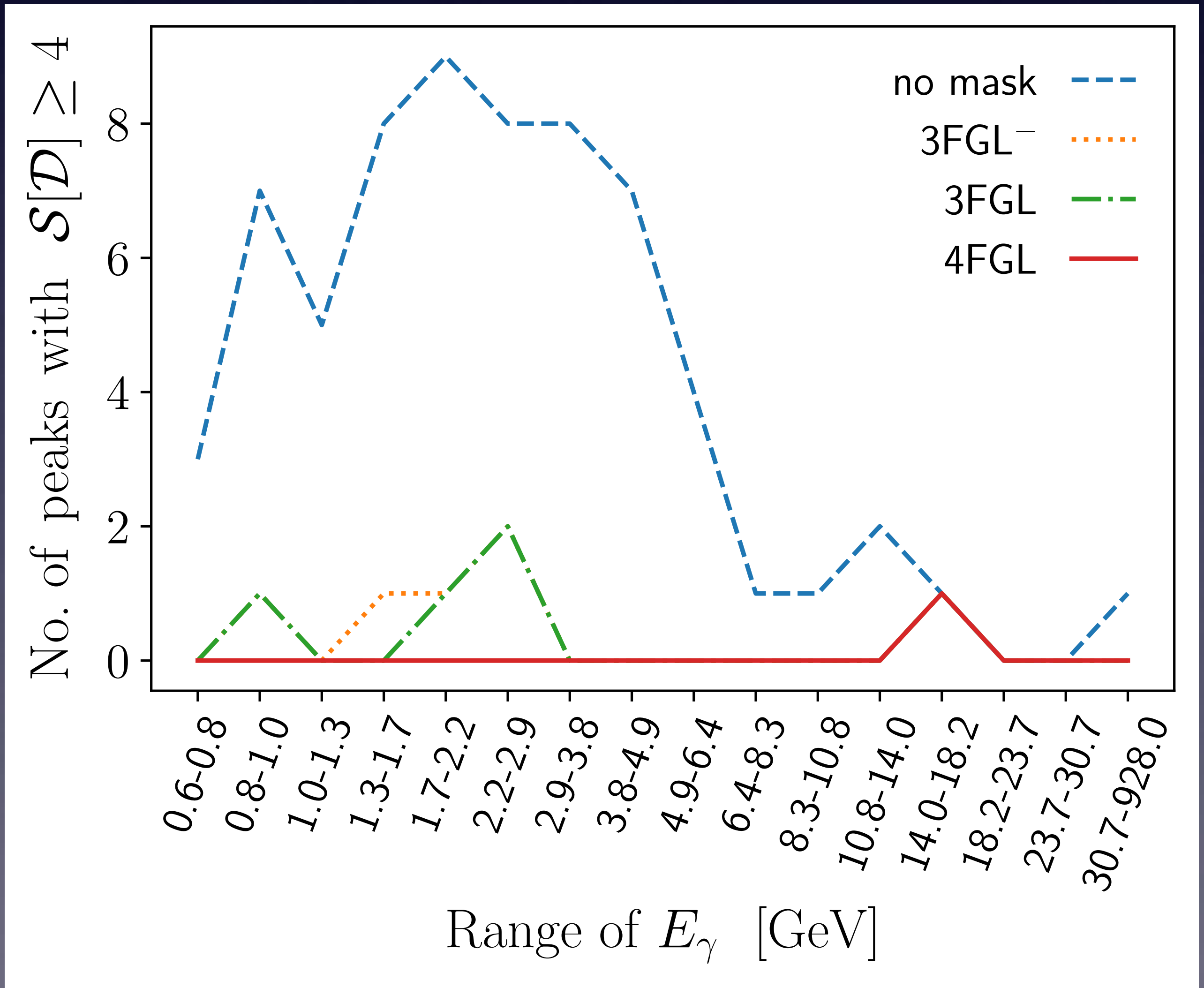
No additional small-scale structure,
so it looks just as good as diffuse-only

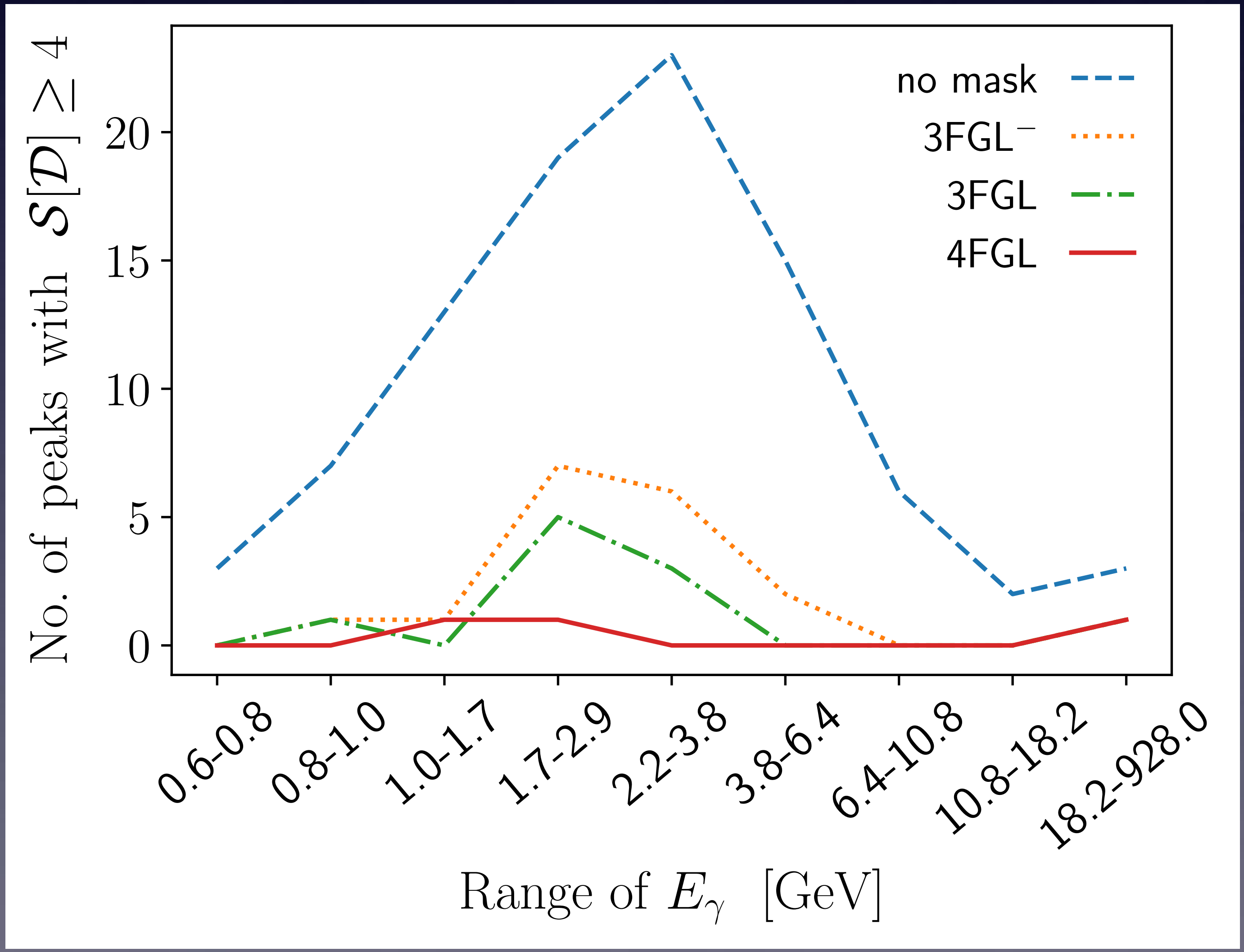


3 DM models × 60 diffuse models × 100 trials

Other Energy Binnings

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





Future Steps

- Template fit improvements:
  - incorporate 4FGL mask (which takes up so much solid angle near GCE) in a more sophisticated way
  - consider more diffuse models
- Wavelet analysis:
  - look at larger angular scales
  - do some “GC-optimization”
  - can we find *model-independent support* for DM?

Conclusions

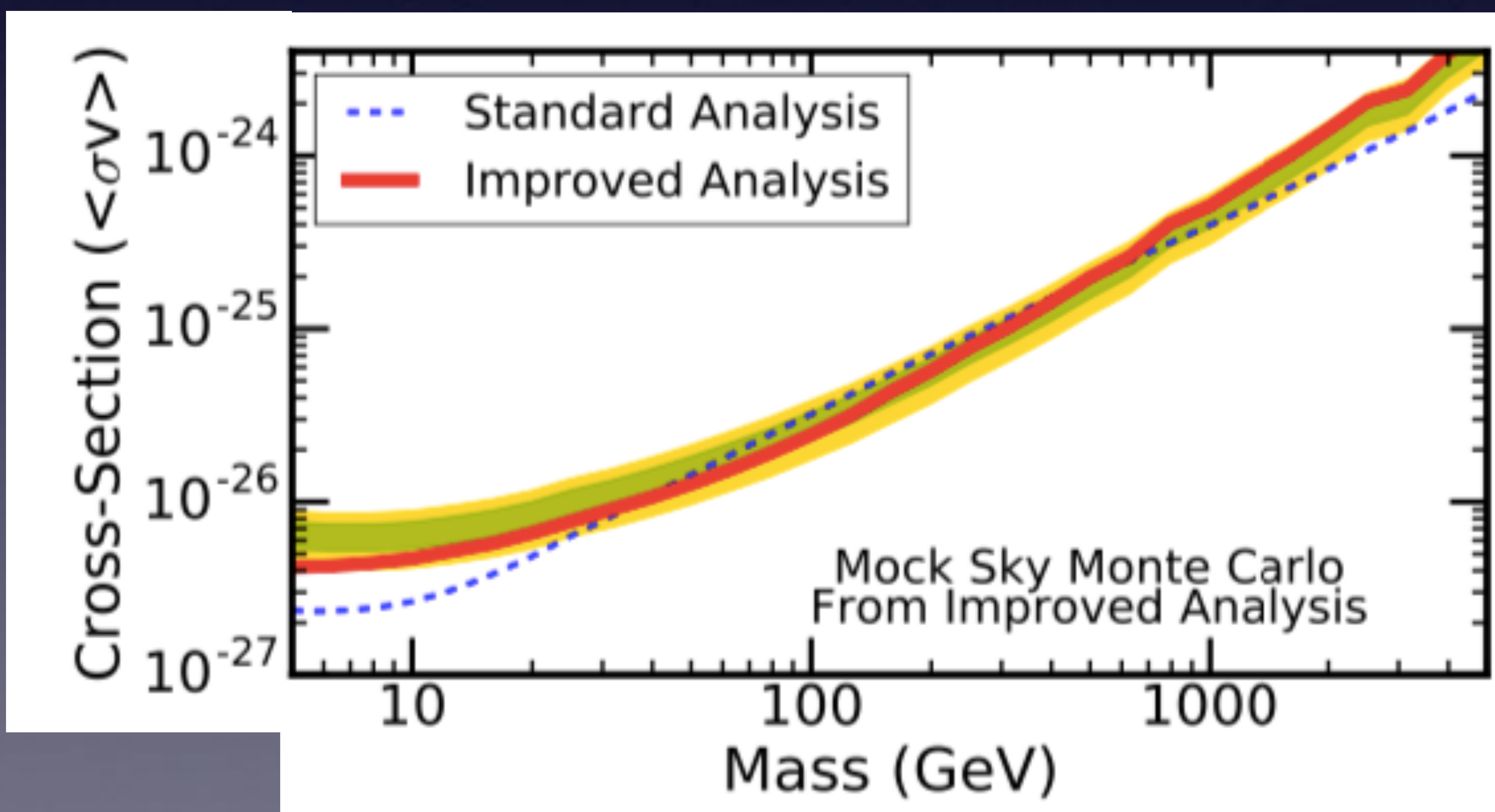
- GCE is in a peculiar position…
    - very confident it's there
    - seems to be very hard to independently substantiate either of the two most popular explanations
- Future is "bright"
    - 1506.05104 "predicted" 4FGL $\implies$ we predict that our "extra 8" are "real" sources
    - Cartesian-specific wavelet analysis may be able to get rid of some of those "extra sigmas" while retaining some discriminating evidence

Thanks!

Extra

Other Searches

Gamma rays from dwarf galaxies (~null)
Antiprotons from AMS (~pro)



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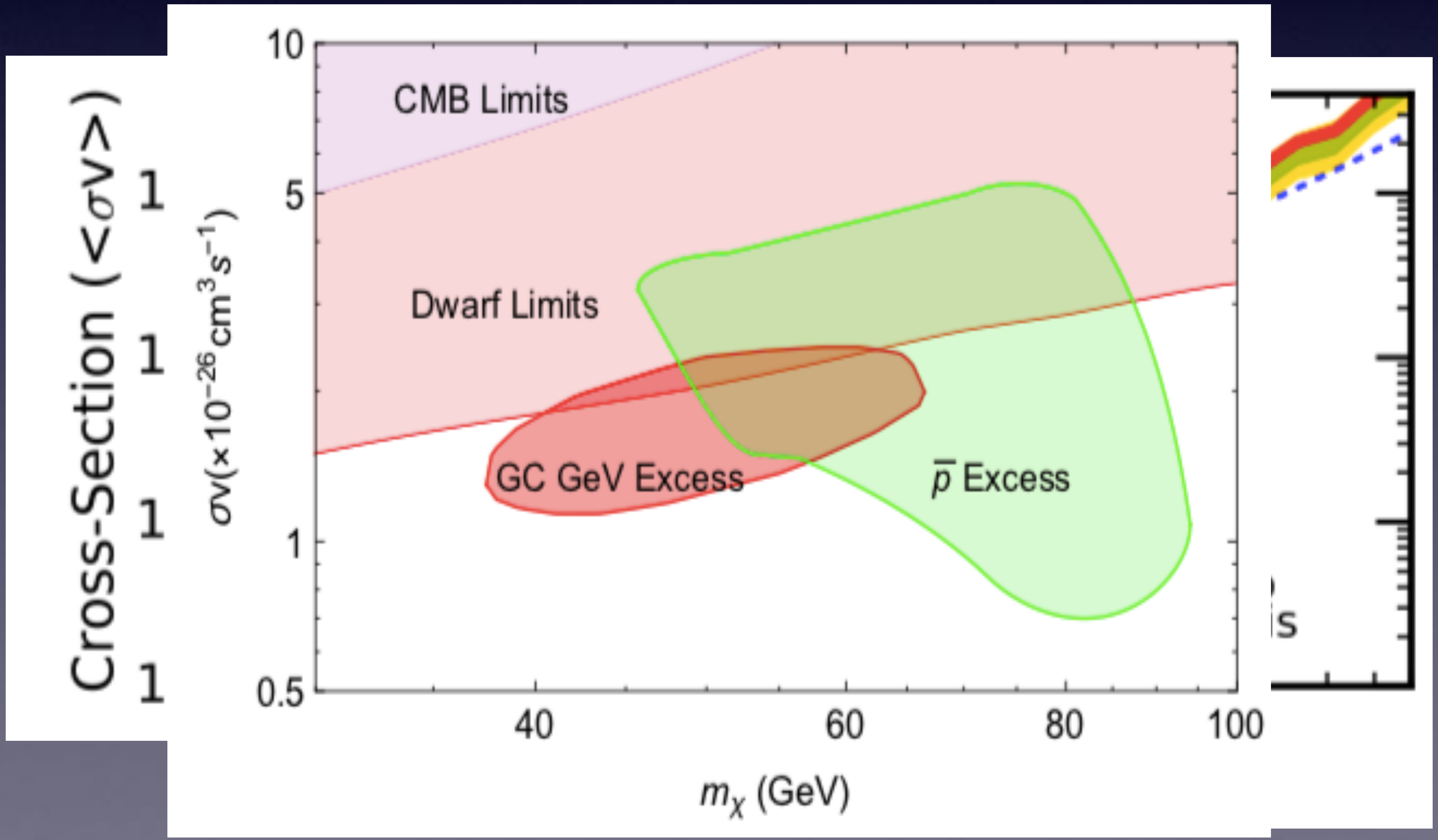

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Gamma rays from dwarf galaxies (~null)
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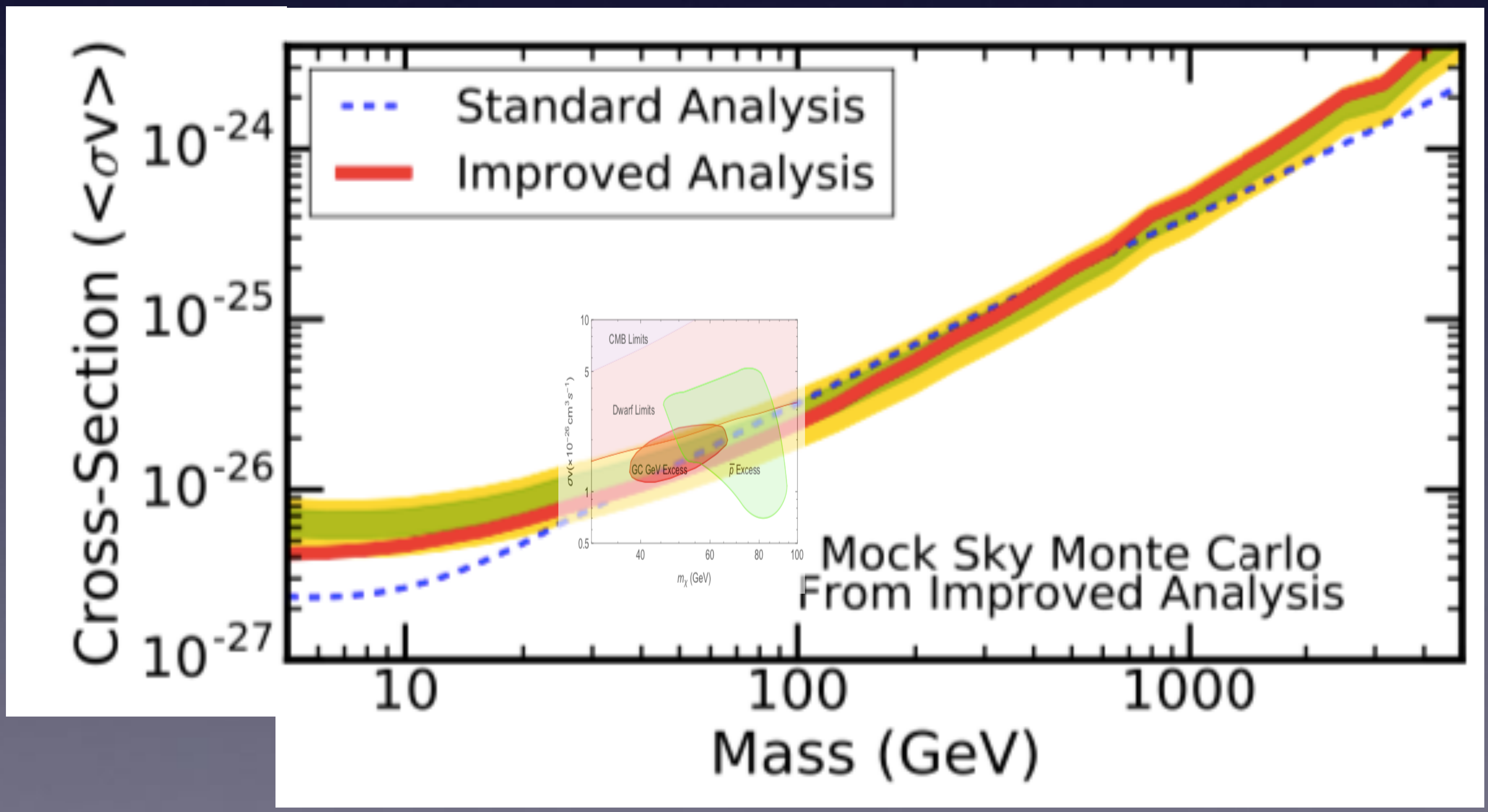
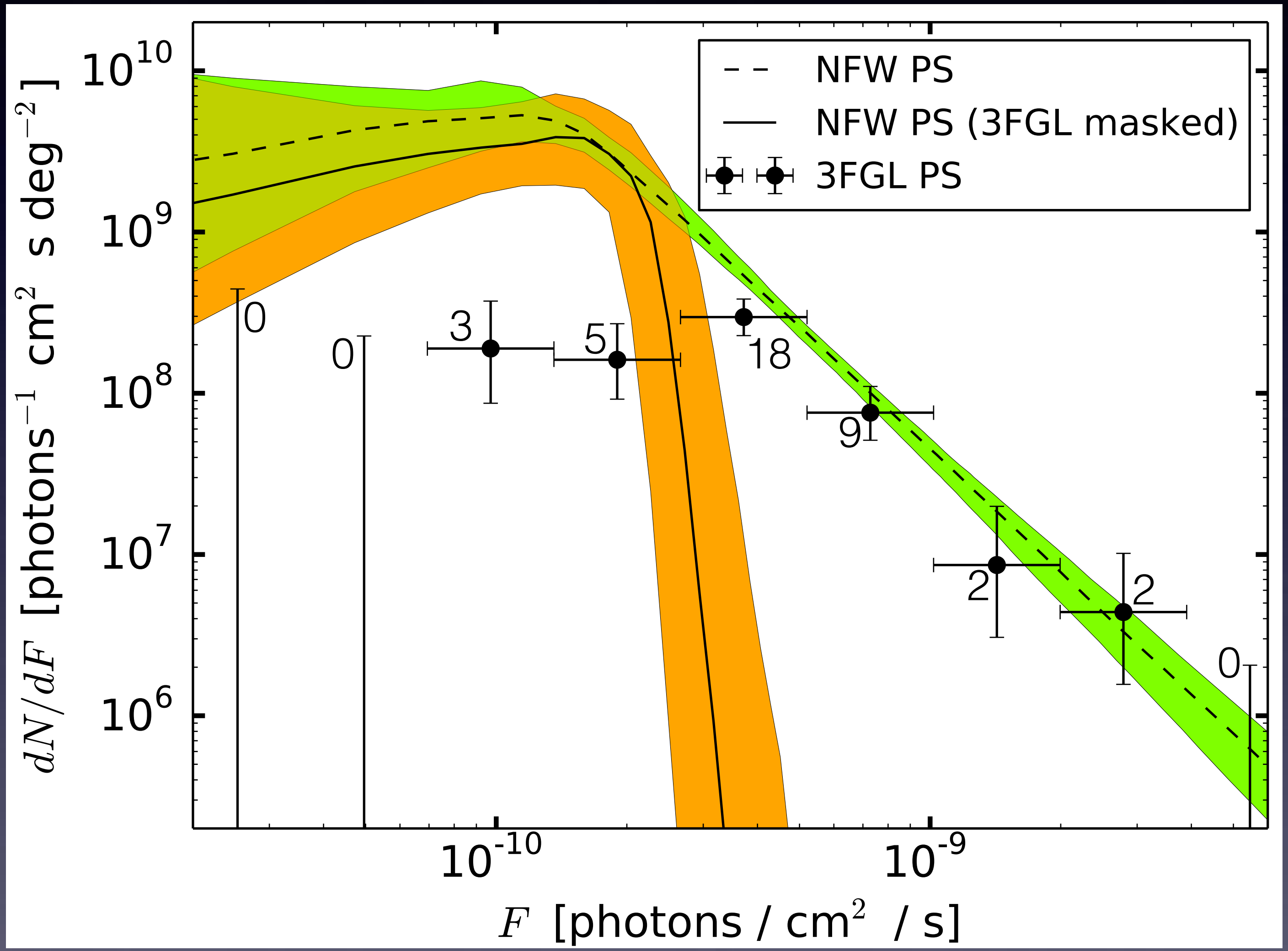
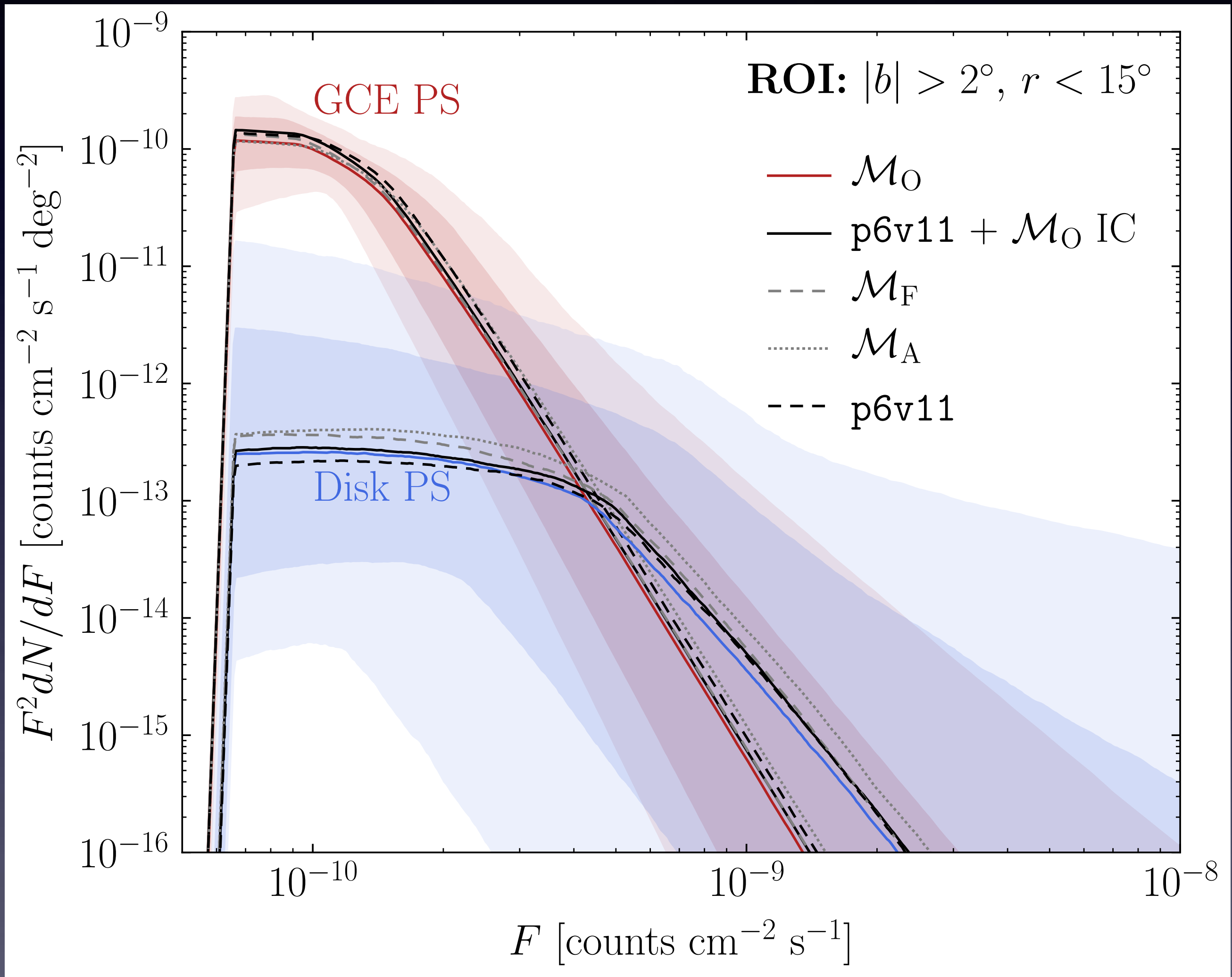


Point Source Fit Update

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)