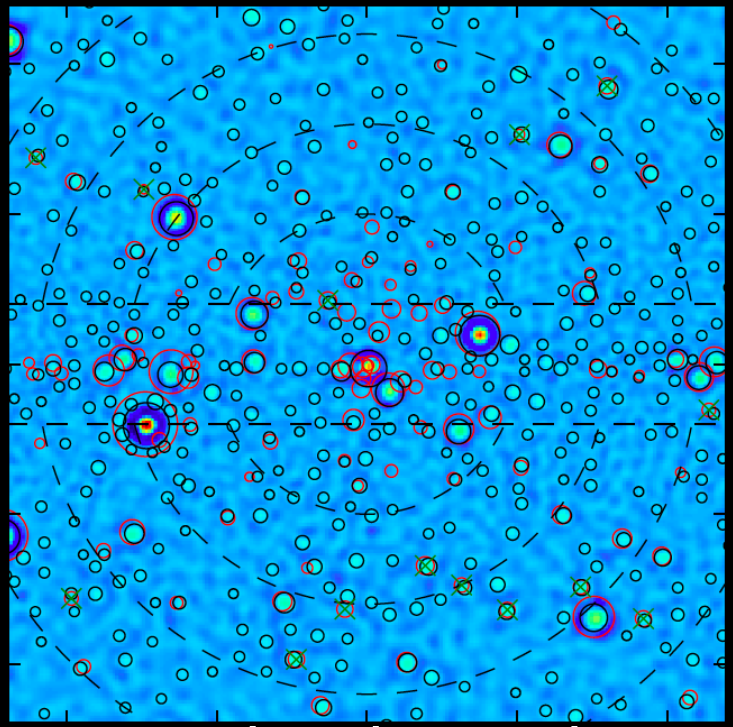
# The GeV Excess: A Compelling Case for Millisecond Pulsars



Richard Bartels

S. Krishnamurthy and C. Weniger

arXiv: 1506.05104

University of Amsterdam

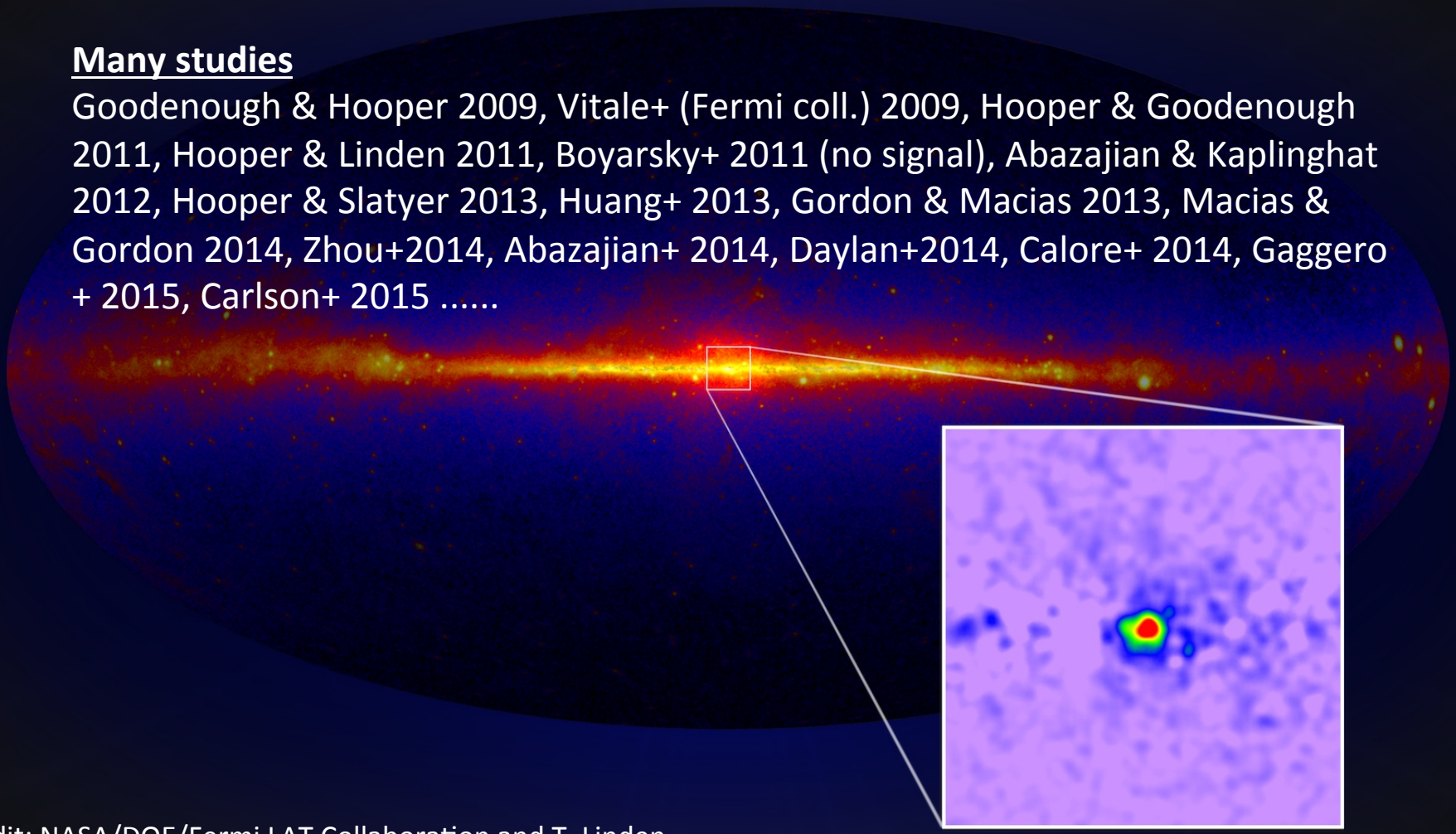
9 December 2015
Obergurgl

GRAPPA
GRavitation AstroParticle Physics Amsterdam

# The GeV Excess

**Many studies**

Goodenough & Hooper 2009, Vitale+ (Fermi coll.) 2009, Hooper & Goodenough 2011, Hooper & Linden 2011, Boyarsky+ 2011 (no signal), Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Huang+ 2013, Gordon & Macias 2013, Macias & Gordon 2014, Zhou+2014, Abazajian+ 2014, Daylan+2014, Calore+ 2014, Gaggero + 2015, Carlson+ 2015 .....



Credit: NASA/DOE/Fermi LAT Collaboration and T. Linden

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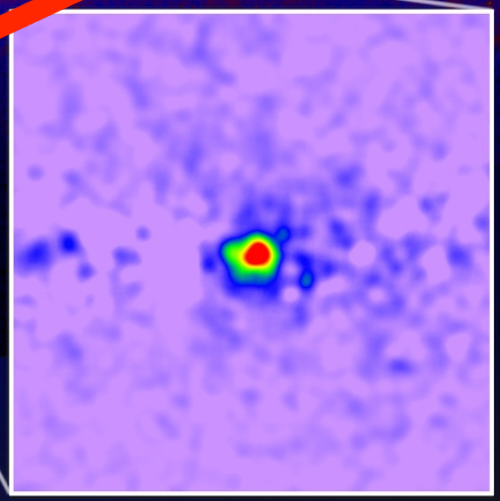
Discussed!



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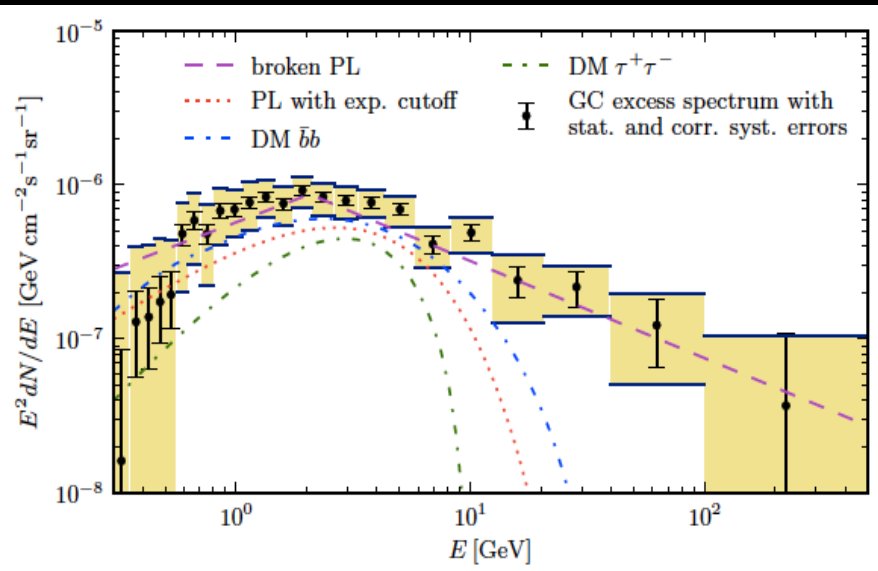
Fermi Approved ✓

Credit: NASA/DOE/Fermi LAT Collaboration and T. Linden

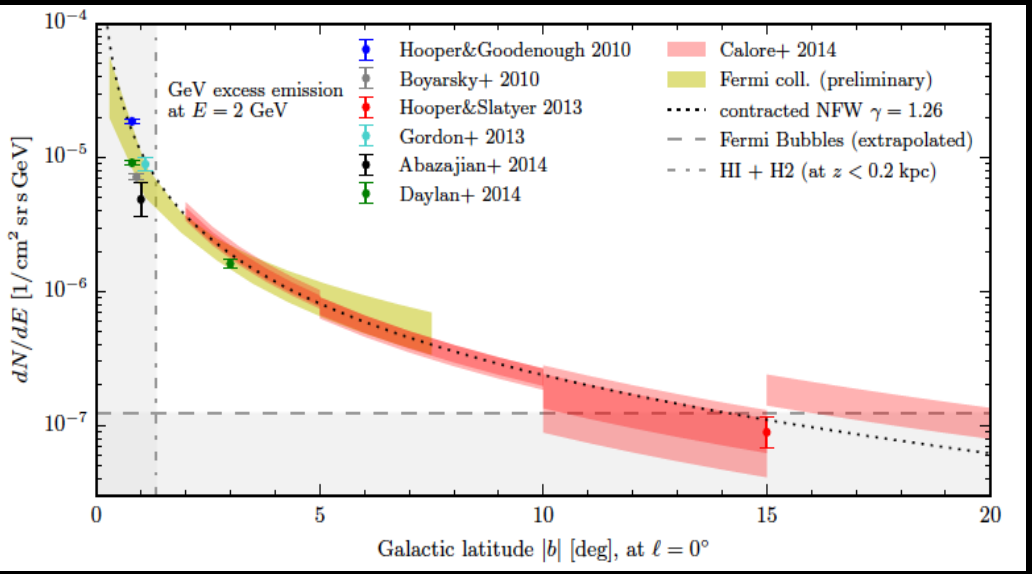
# Just One Reminder…

## Spectrum




Calore, Cholis & Weniger, 2014

## Radial Profile

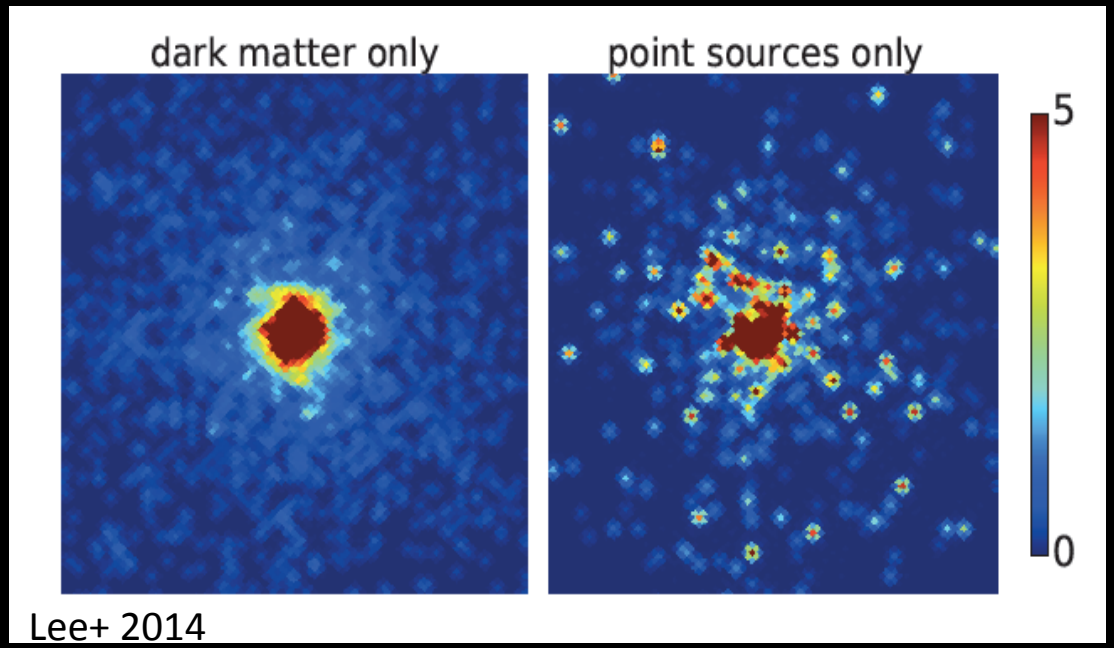



Calore, Cholis, McCabe & Weniger, 2015

# Today

- Wavelet analysis
- Why Bulge Millisecond Pulsars

# But first: Testing the DM/point source interpretation




Lee+ 2014

Methods

- **Wavelet Decomposition [HERE]**

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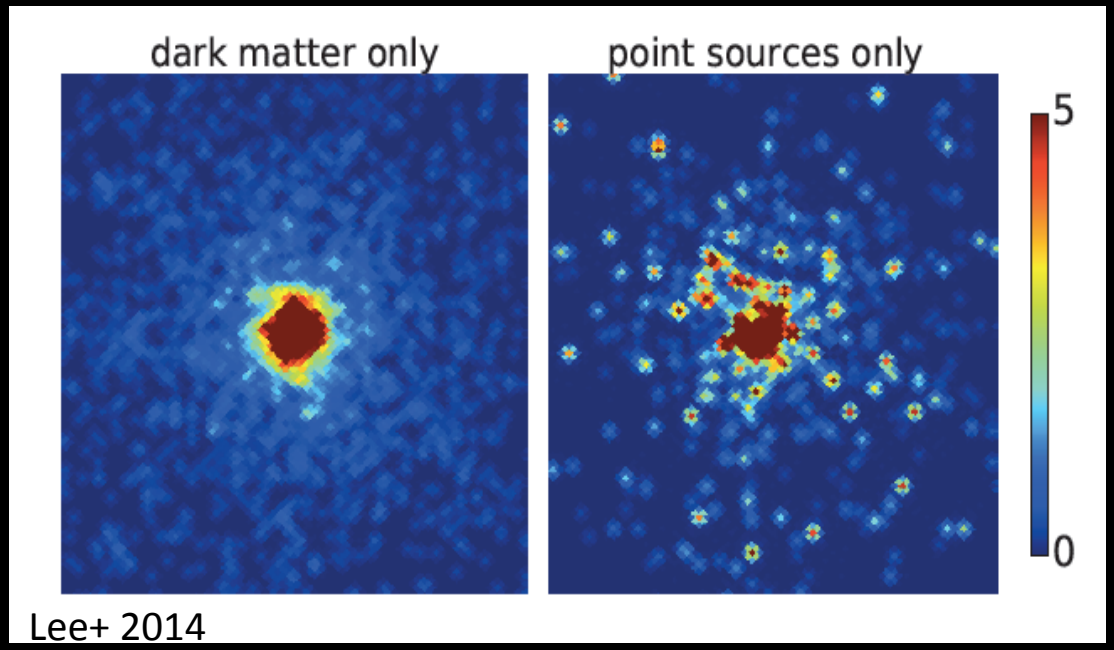

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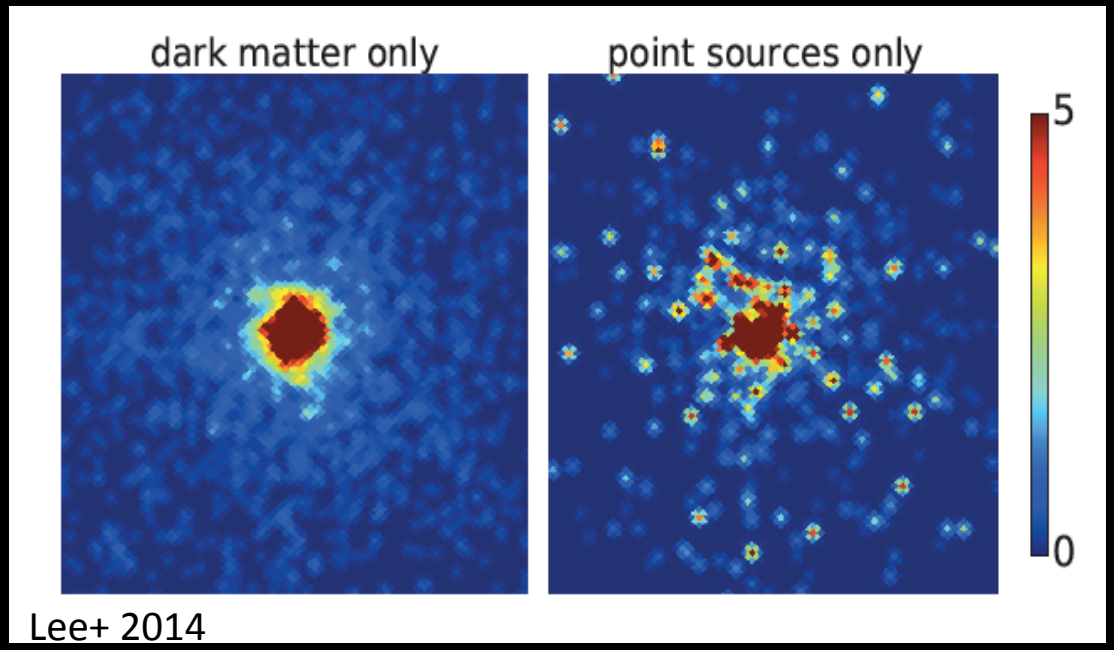

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Methods

- **Wavelet Decomposition [HERE]**
- One point Statistiscs (non-poissonian noise for PSCs) [Lee+ 2014]
- Template fit including non-poissonian noise [Lee, Lisanti, Safdi, Slatyer & Xue, 2015]

# Our Method: Wavelet Analysis

## Wavelet Transform:

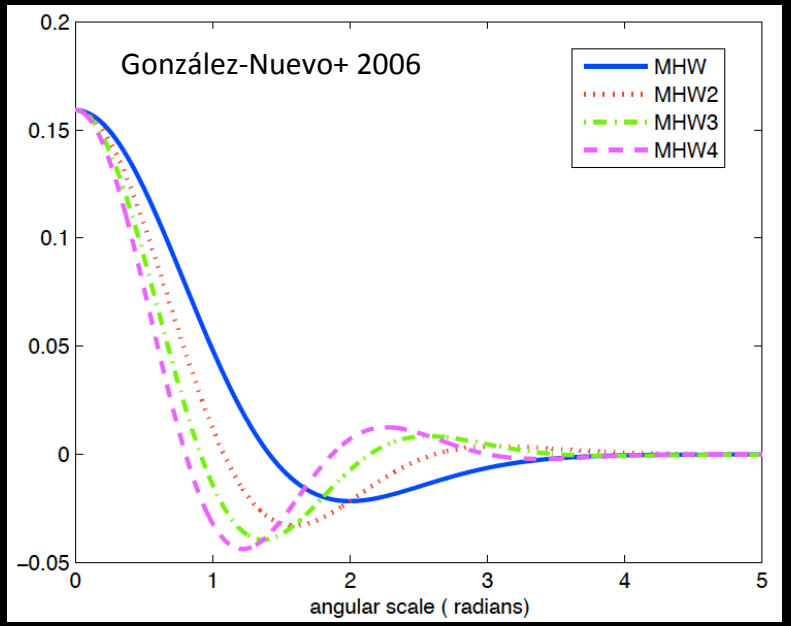
$$\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega) \equiv \int d\Omega' \, \mathcal{W}(\Omega - \Omega')\mathcal{C}(\Omega')$$

Wavelet Kernel

Count map (1-4 GeV)

with:

$$\int d\Omega \, \mathcal{W}(\Omega) = 0$$

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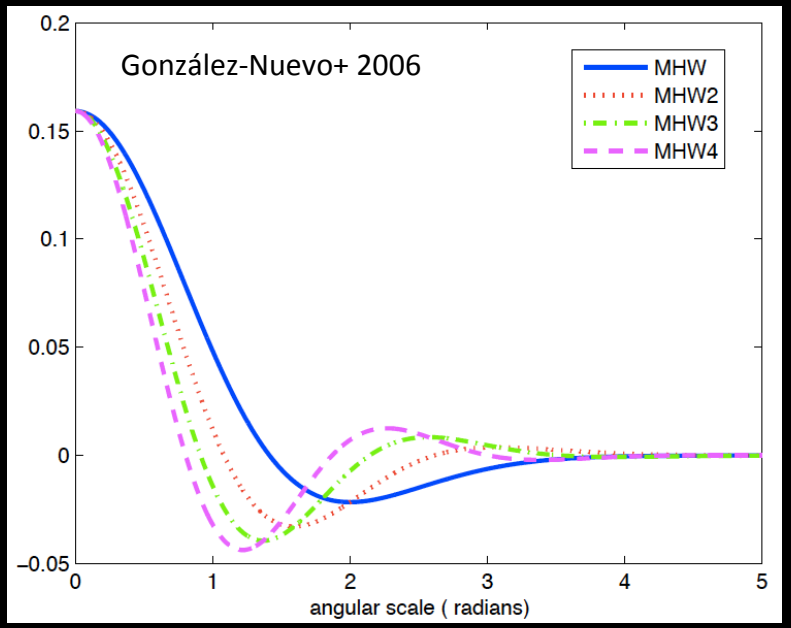


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## Signal-to-noise Ratio:

We consider:

$$\mathcal{S}(\Omega) \equiv \frac{\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega)}{\sqrt{\mathcal{F}_{\mathcal{W}^2}[\mathcal{C}](\Omega)}}$$

- On smooth datasets with enough photons: *Gaussian random field*

# Monte Carlo

- Fermi Diffuse & Isotropic Model + statistical noise

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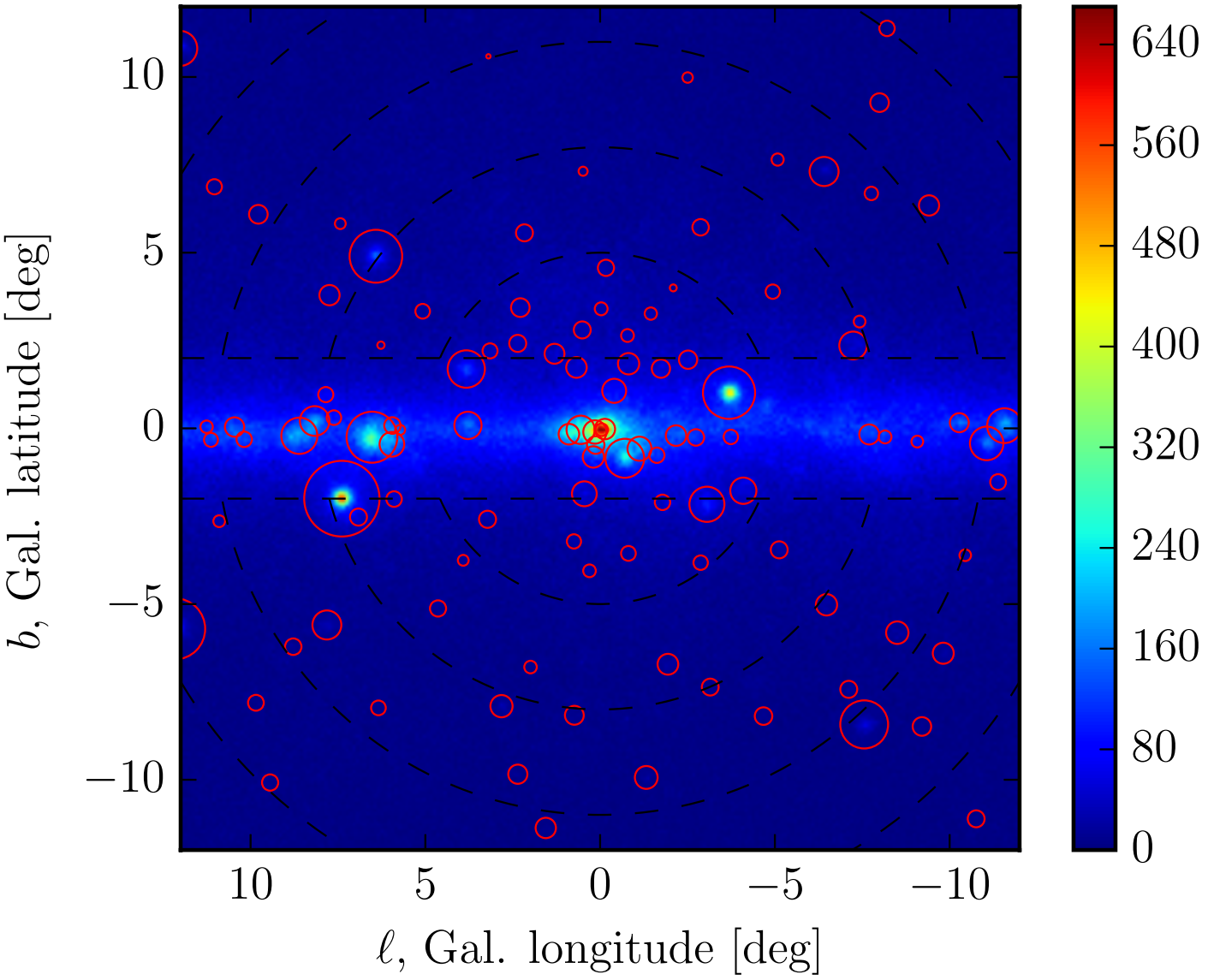
- Fermi Diffuse & Isotropic Model + statistical noise
- Add MSP-like point sources
  - Luminosity function: $\frac{dN}{dL} \propto L^{-1.5}$ hard cutoff $L_{\rm max}$
  - Spatial Distribution: Radial Power law with $\Gamma = -2.5$
  - Vary: $N_{\rm msp}$ and $L_{\rm max} = 10^{34}$–$10^{36}\,{\rm erg\,s^{-1}}$

*MSPs and the GeV excess? See:*
[e.g. Abazijan 2011, Gordon & Macias 2013, Hooper+ 2013,
Yuan and Zhang 2014, Cholis+ 2014, Calore+ 2014,
Petrovic+ 2015]

# Compare with data



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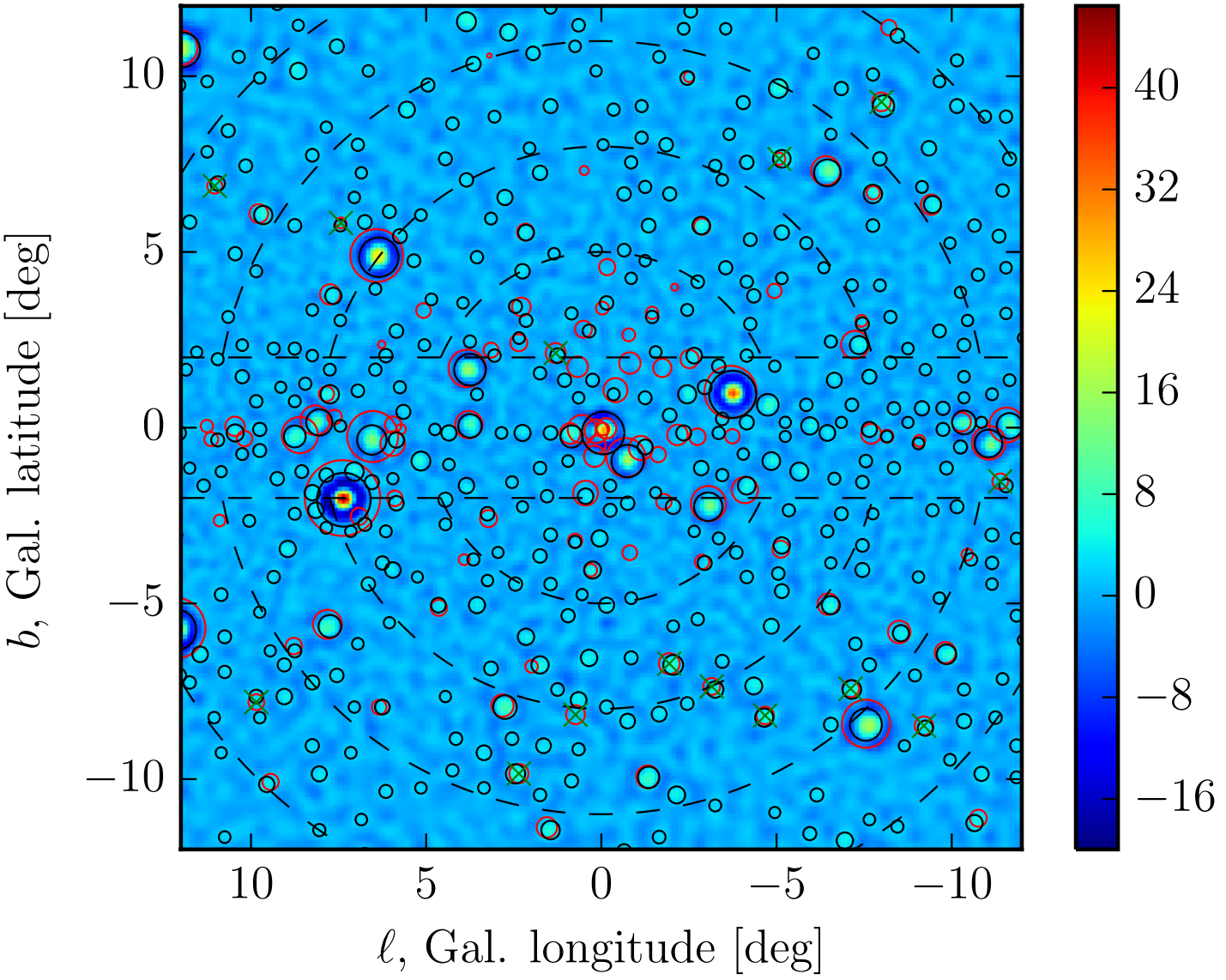
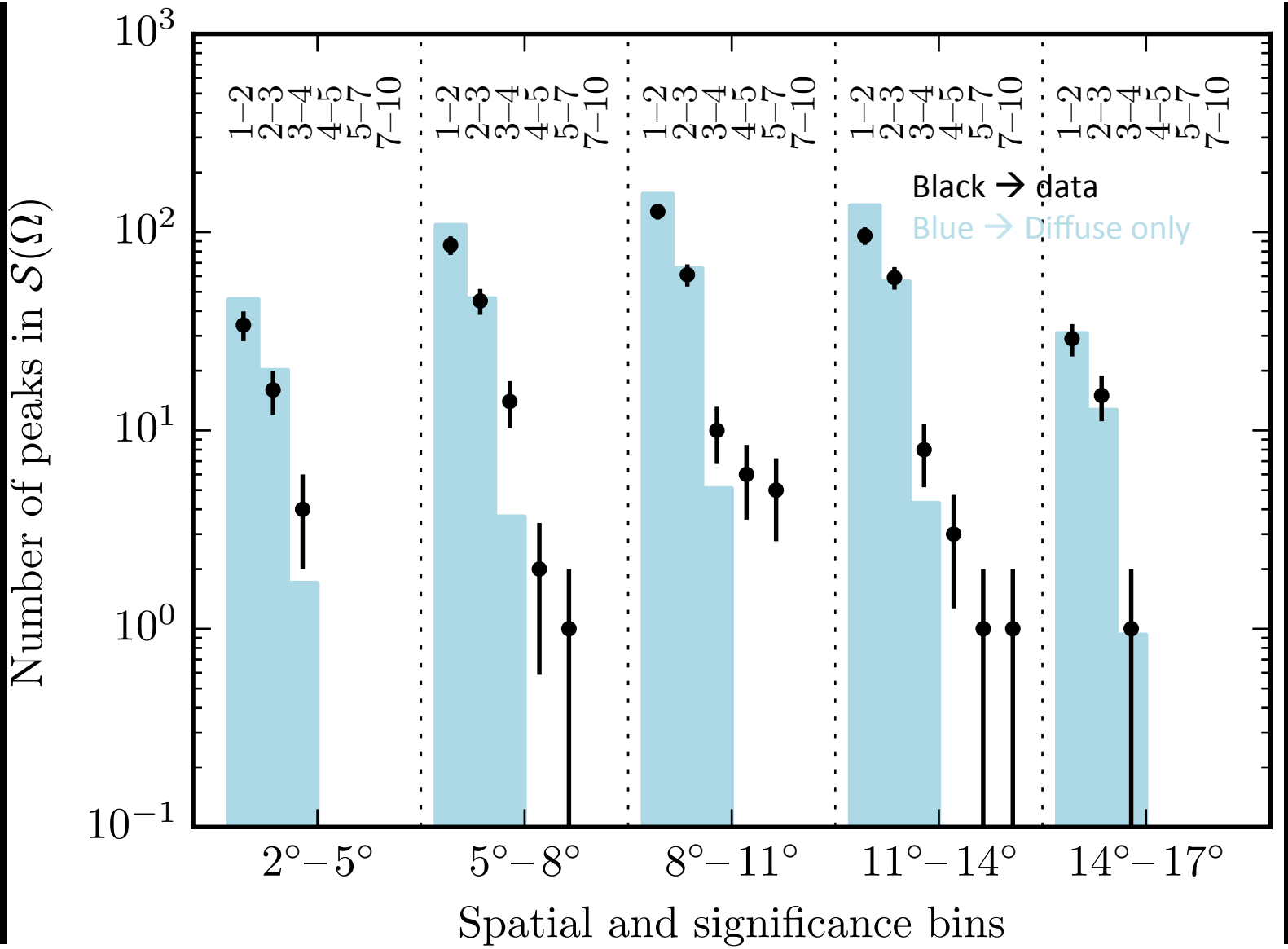


# Results


Number of peaks in $\mathcal{S}(\Omega)$
$10^3$
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1–2
2–3
3–4
4–5
5–7
7–10
Black → data
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2°–5°
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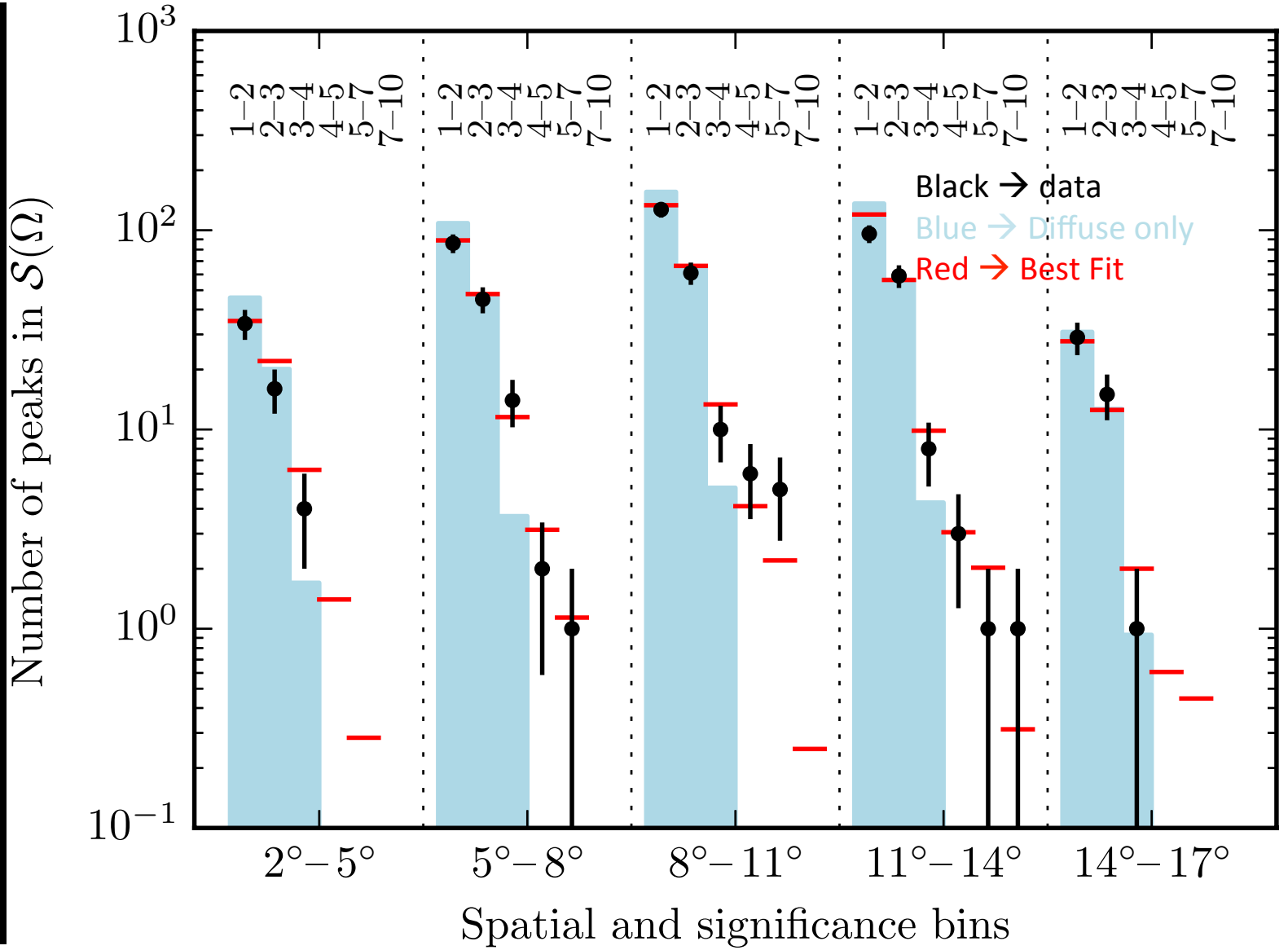
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Black → data
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Red → Best Fit
2°–5°
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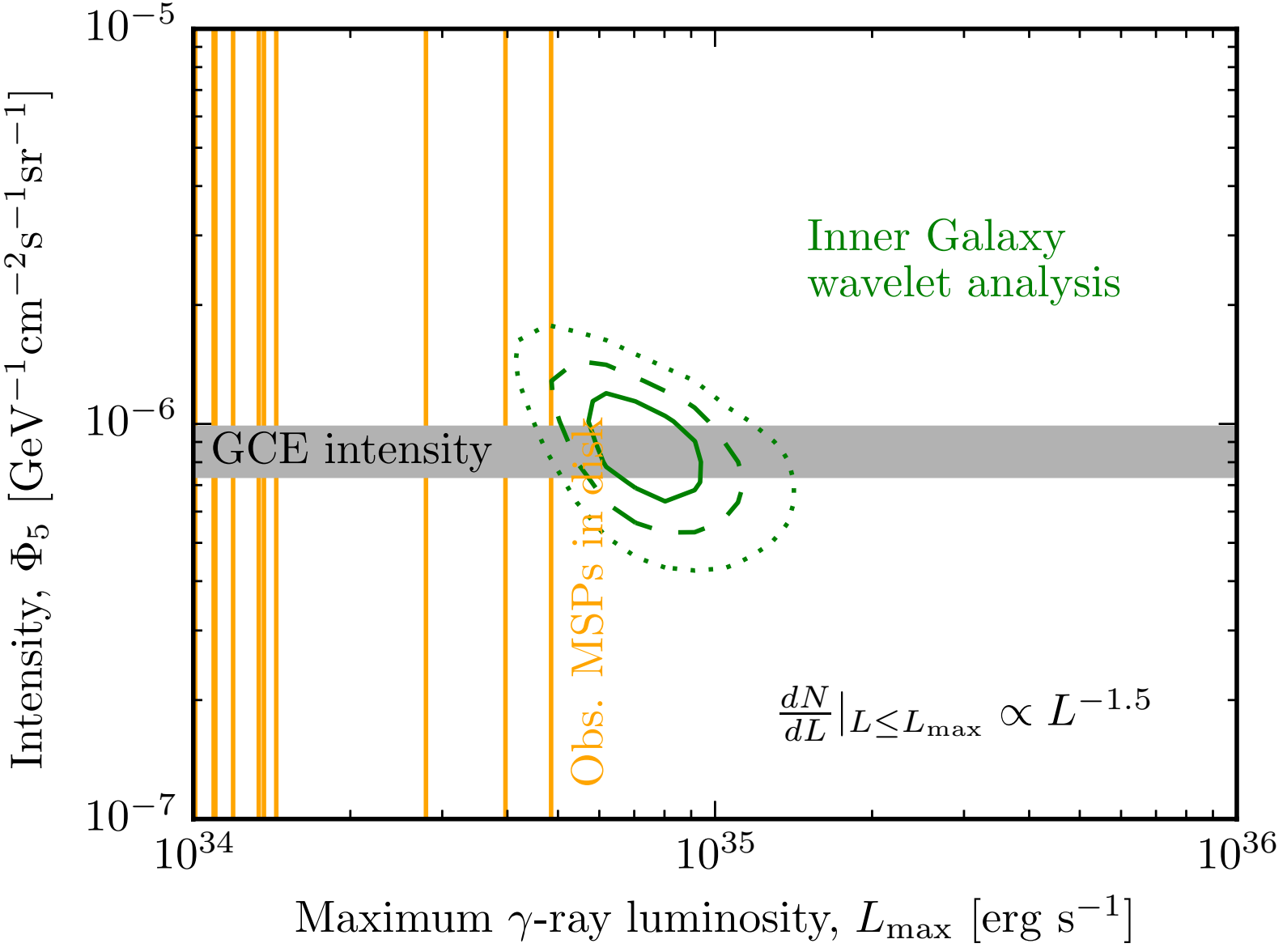
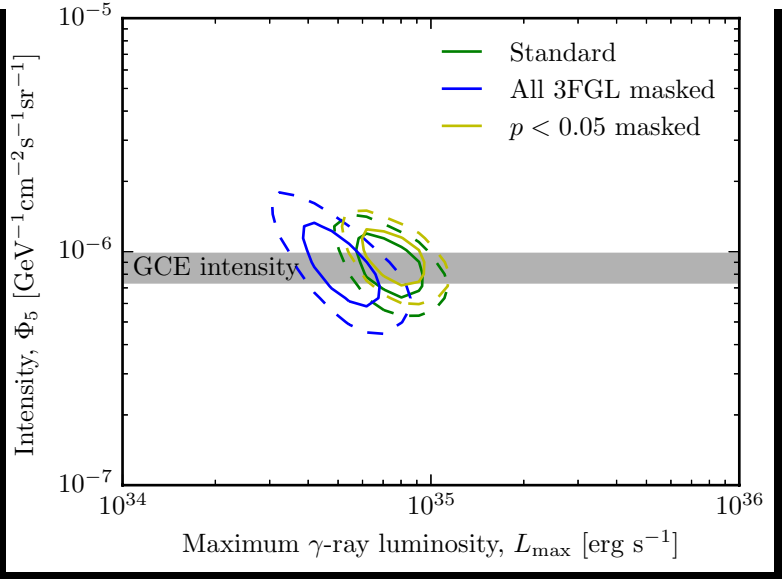
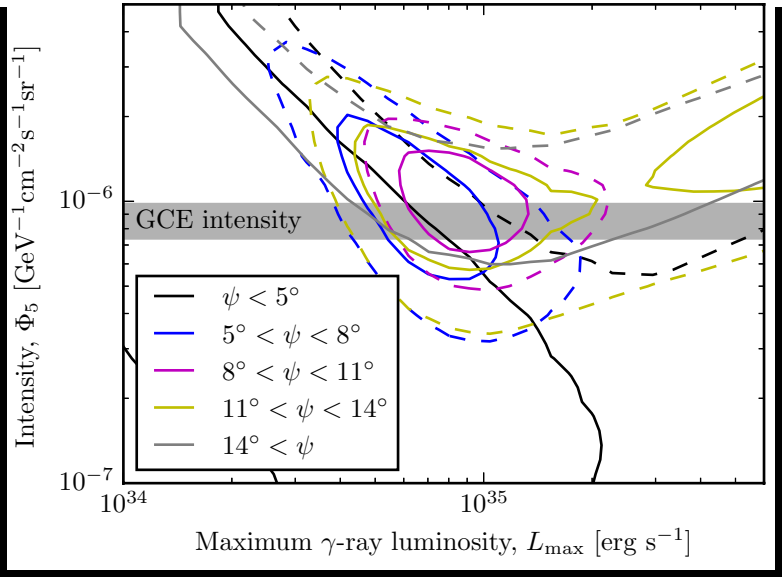
Spatial and significance bins

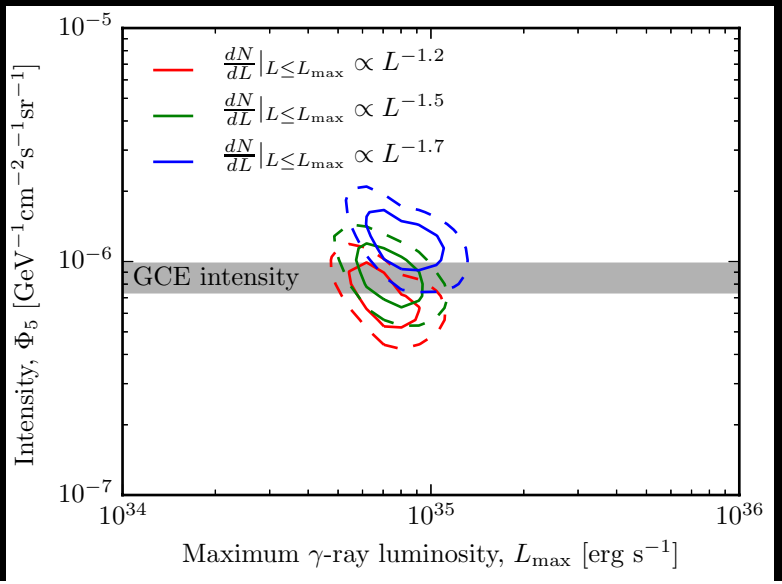
# Results: Limits

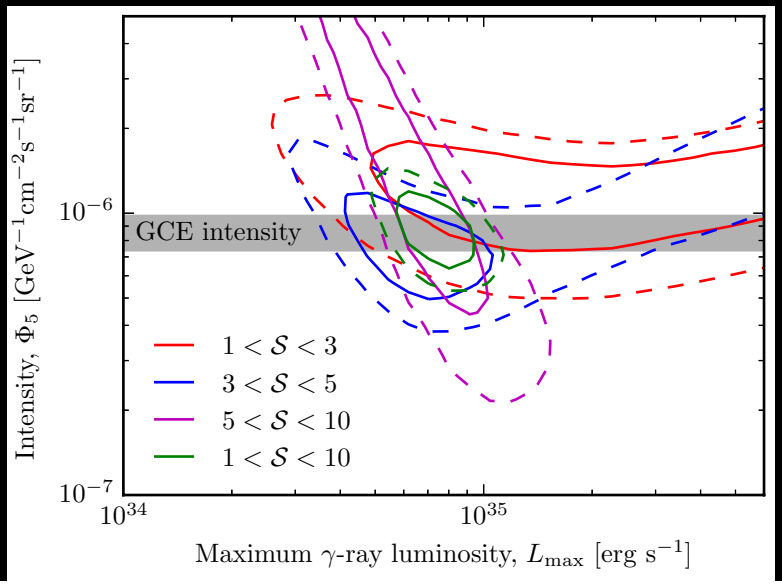


# Results: Limits (checks)



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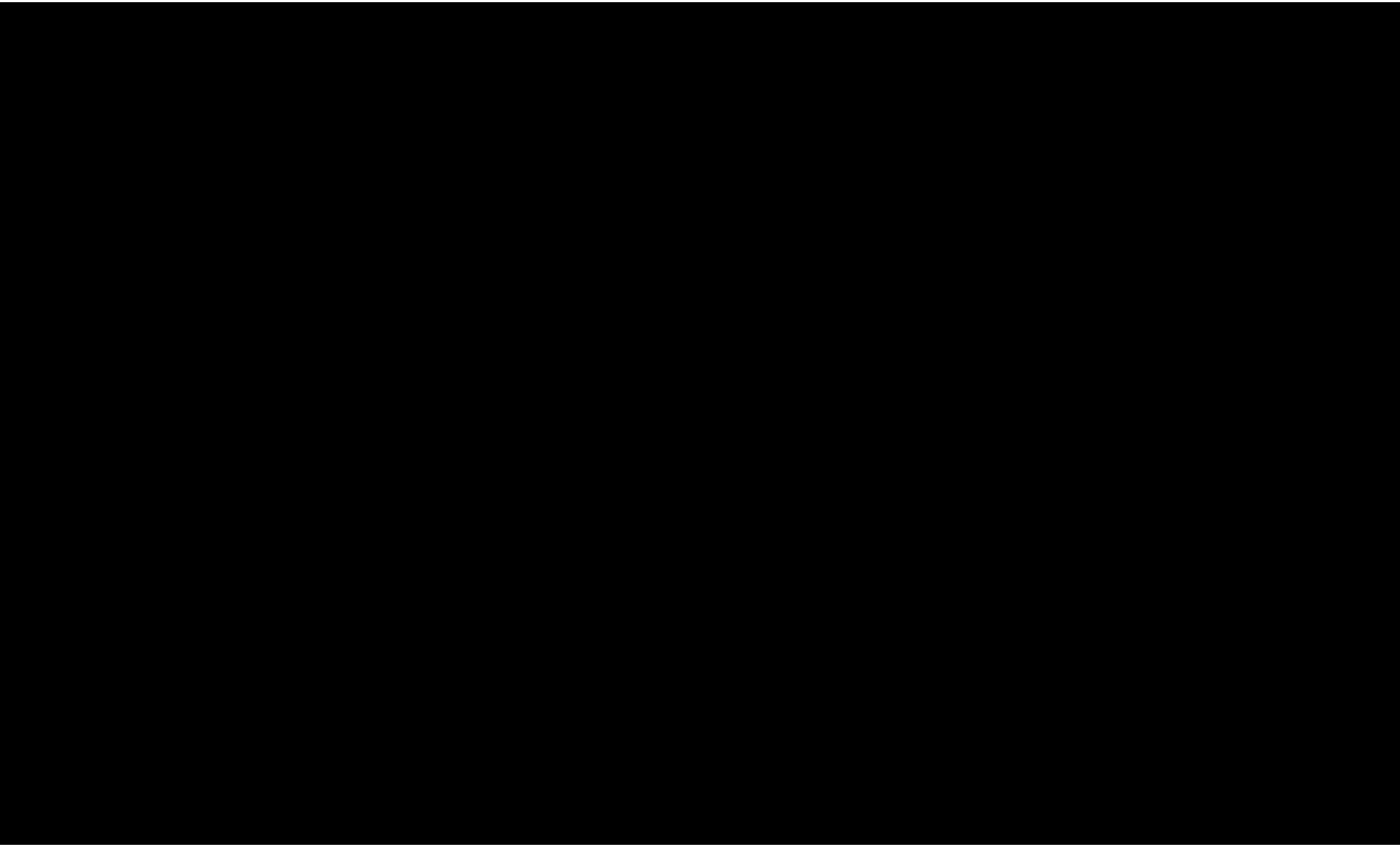

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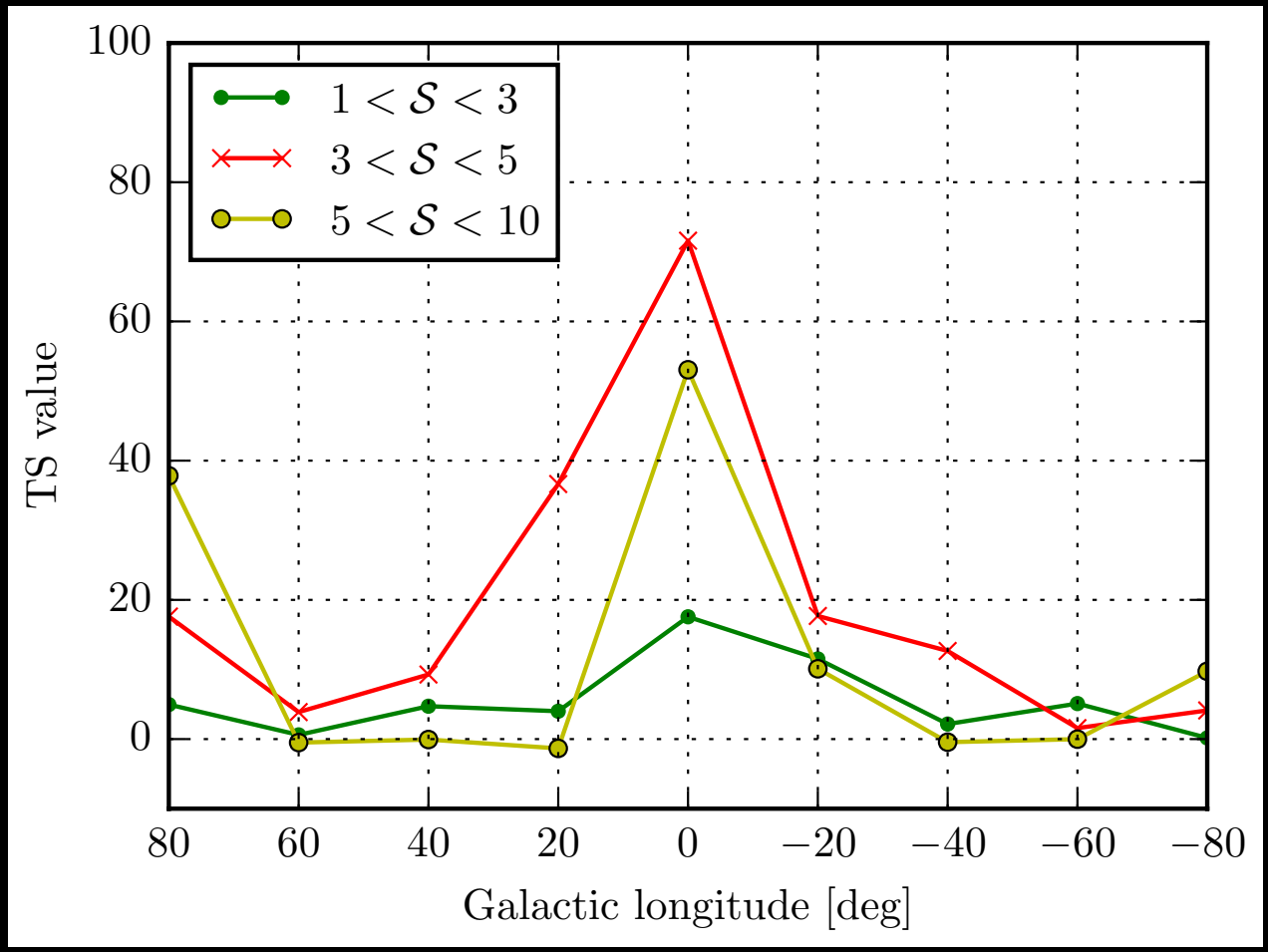


NO clustering of photons outside the inner Galaxy!

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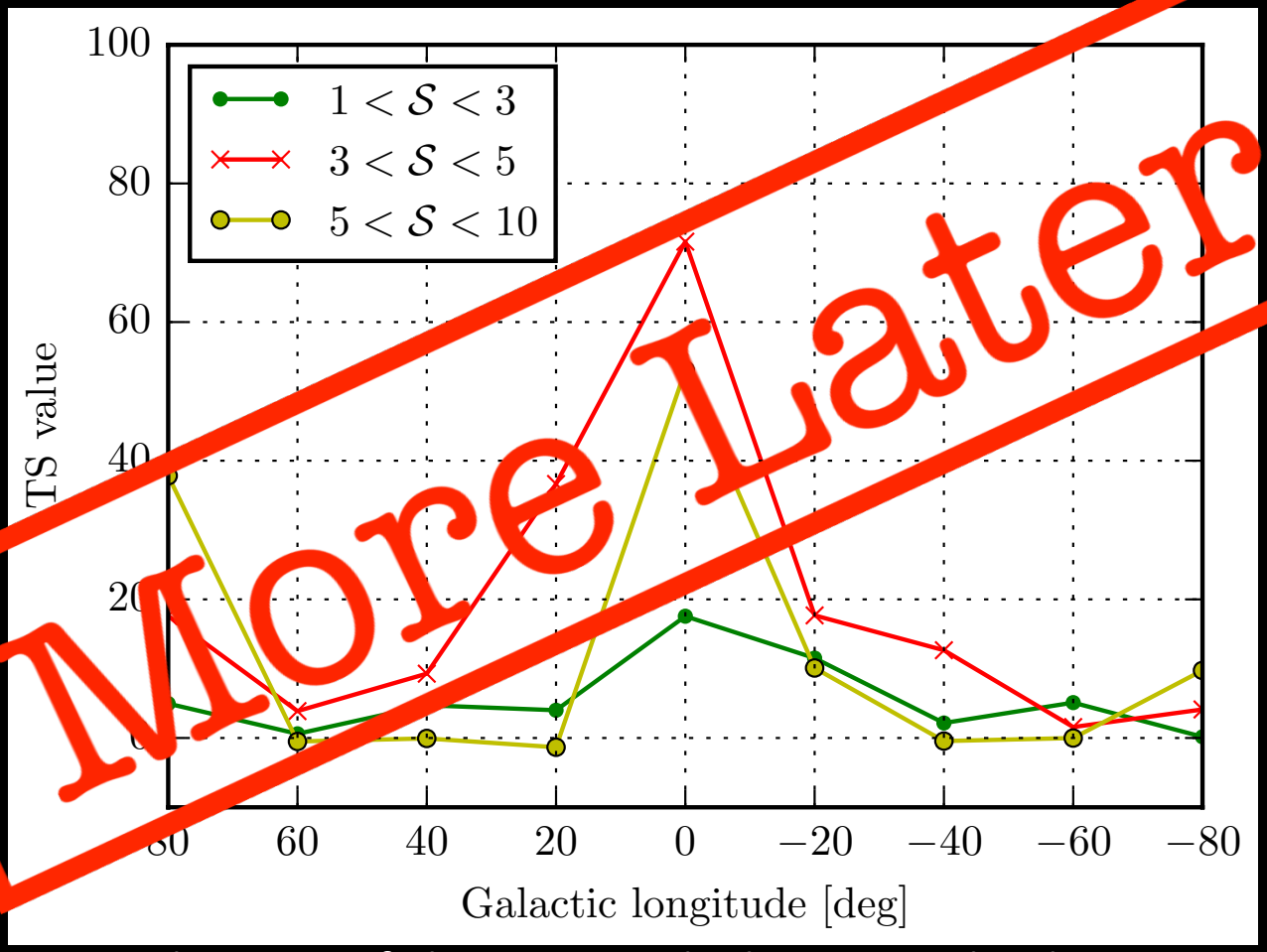


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- Other source populations?

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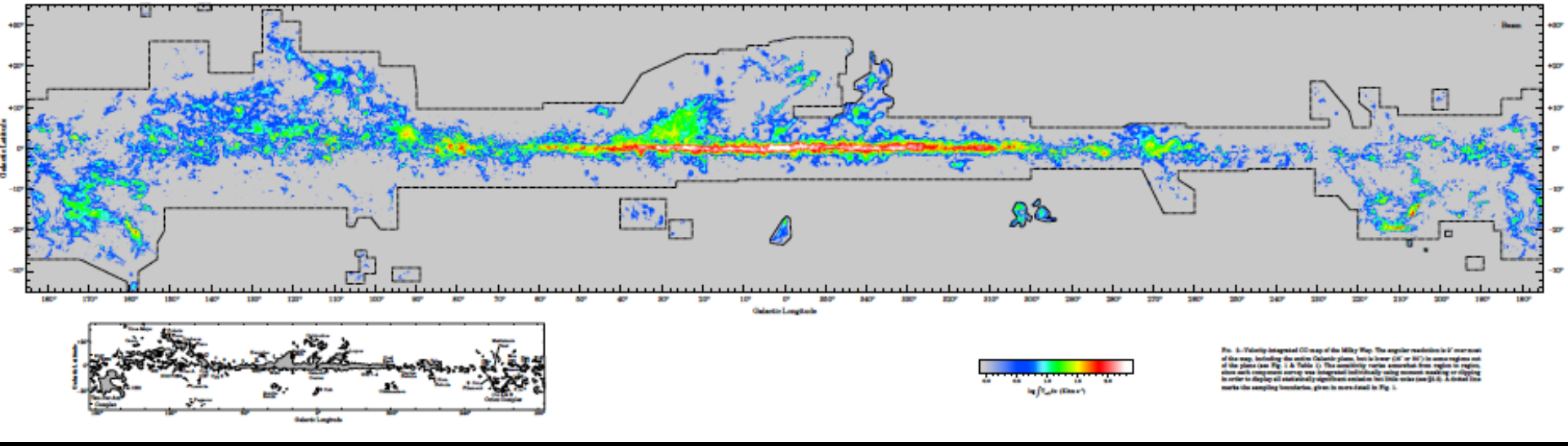
But also CO emission:

$$\mathcal{O}\,(10\text{–}100)\ \mathrm{K\,km\,s}^{-1}$$

# 1) Giant Molecular Clouds

## But no indication in the CO map:

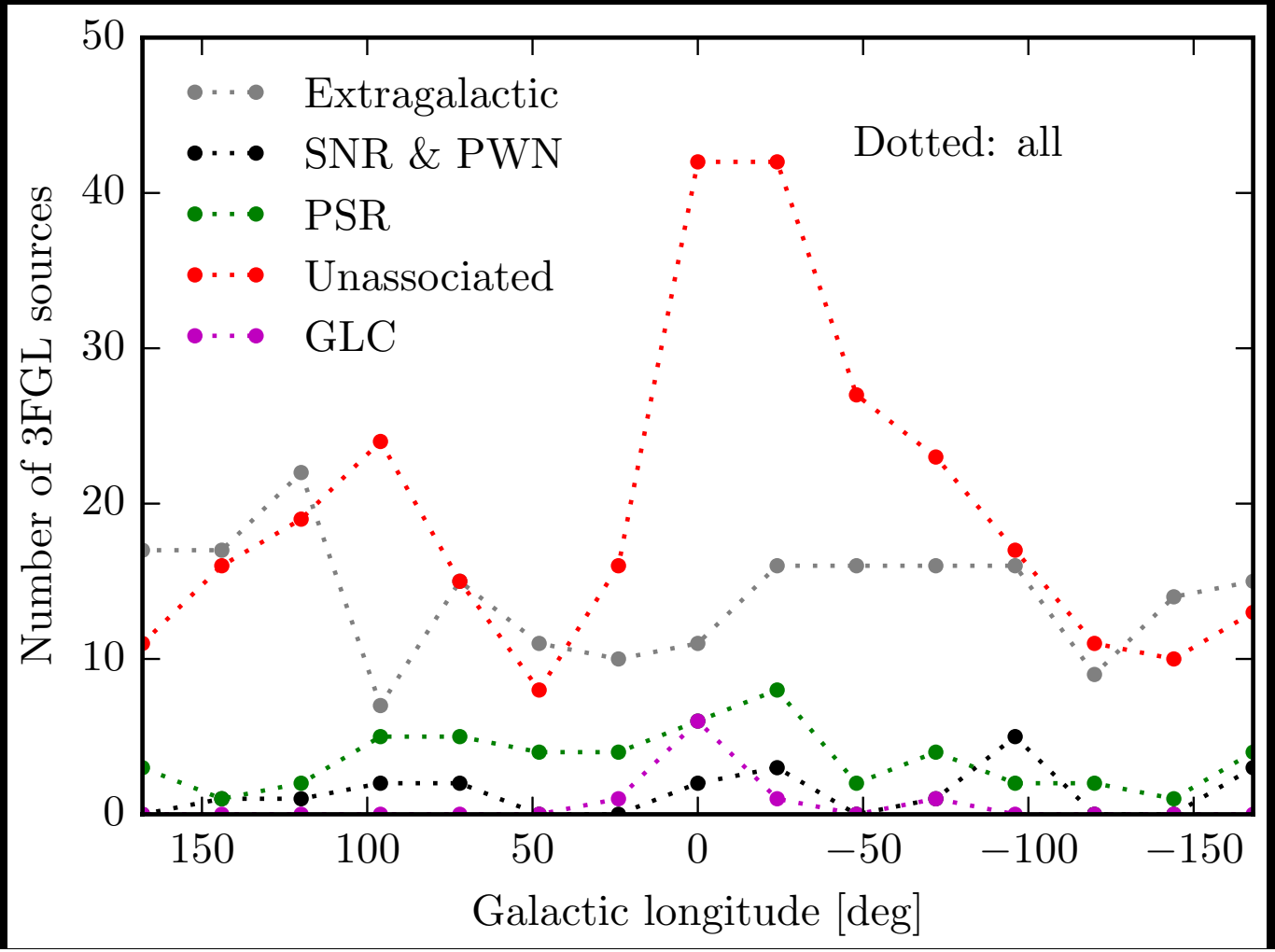


Dame, Hartmann & Thaddeus, 2000

# 2) Point Source Populations

## Point sources in all ROIs along the disk

24° x 24°
|b| < 2° masked



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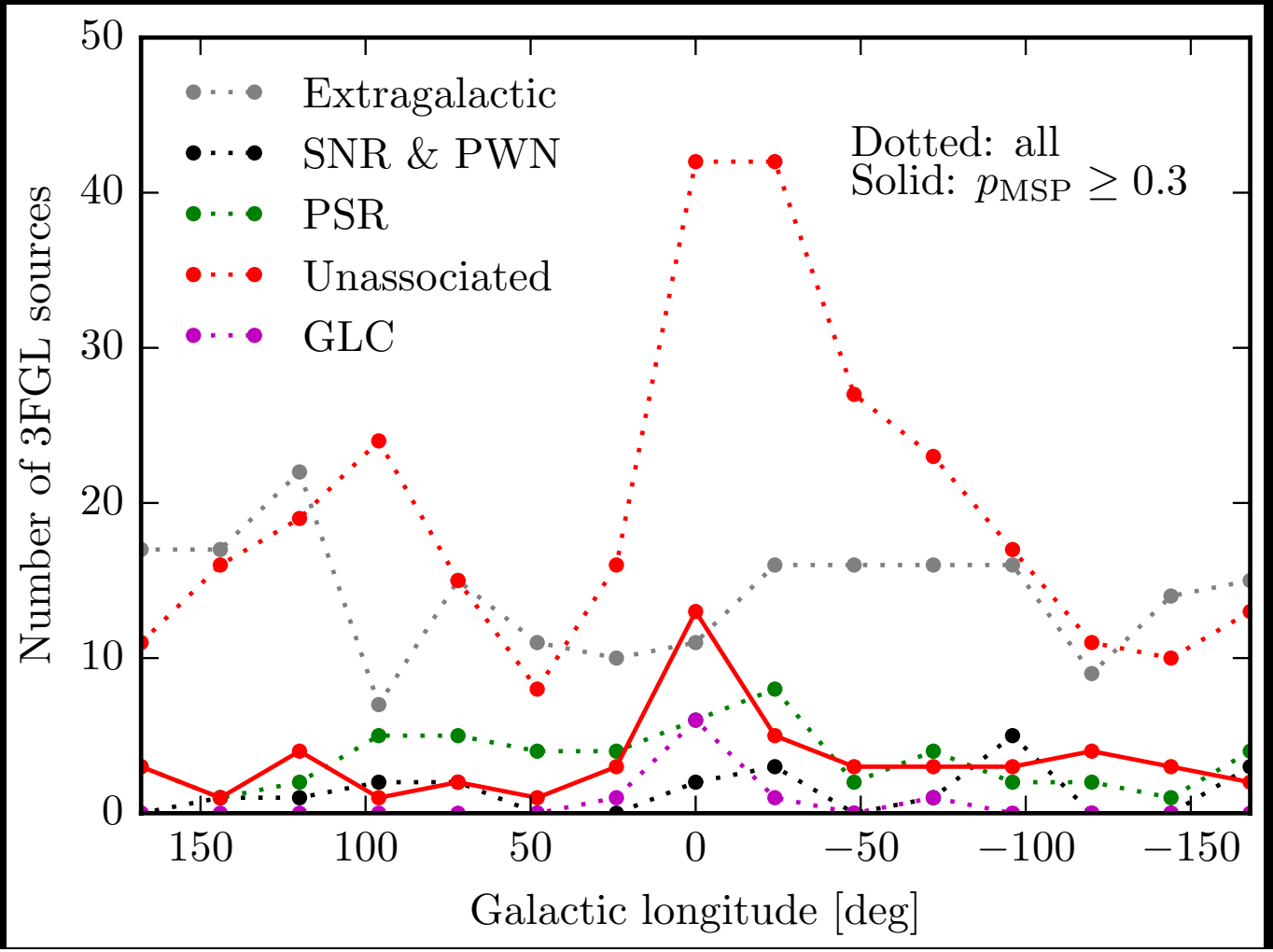

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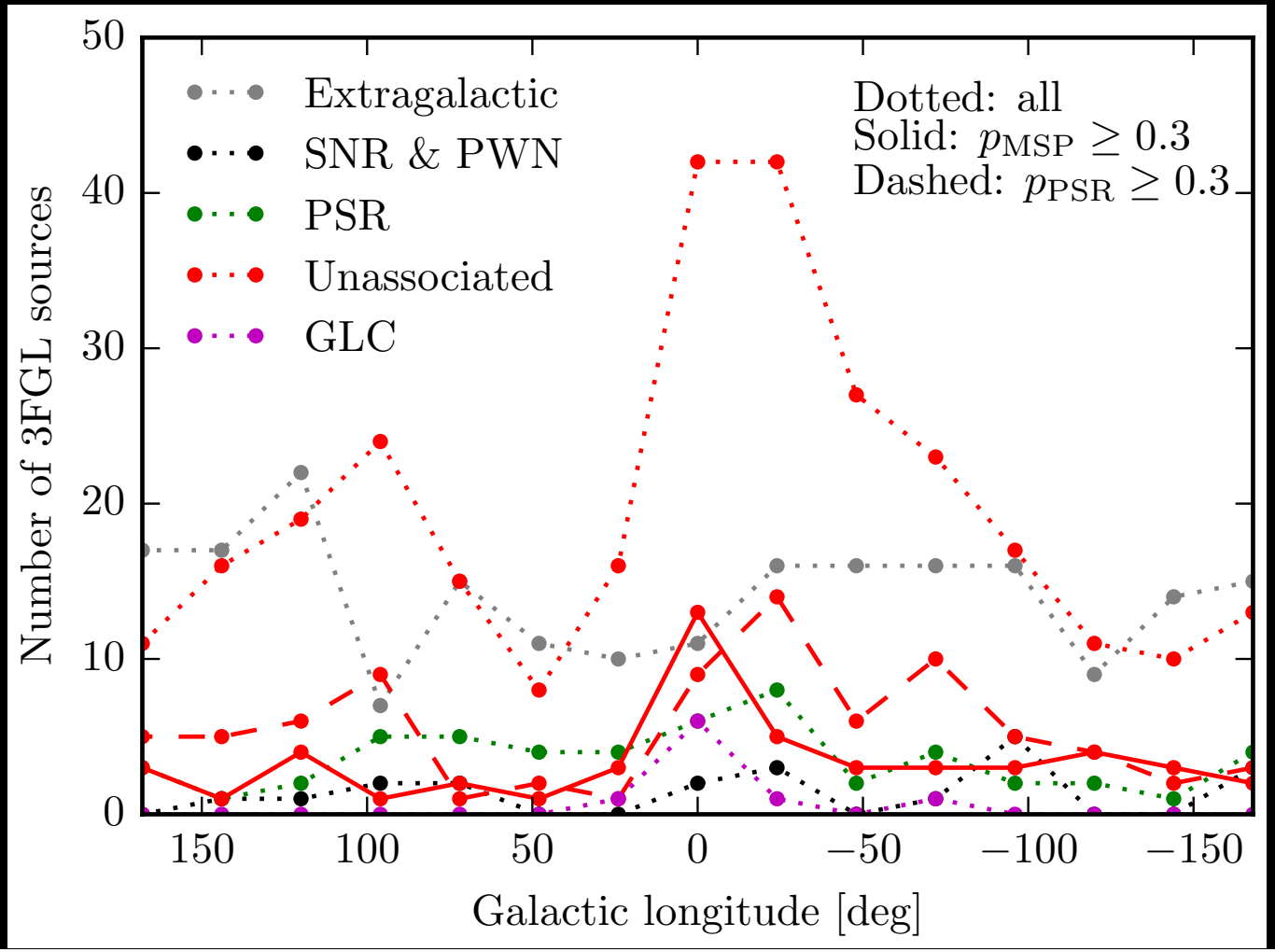

# 3FGL Point sources in inner-galaxy ROI and their wavelet signal

24° x 24°
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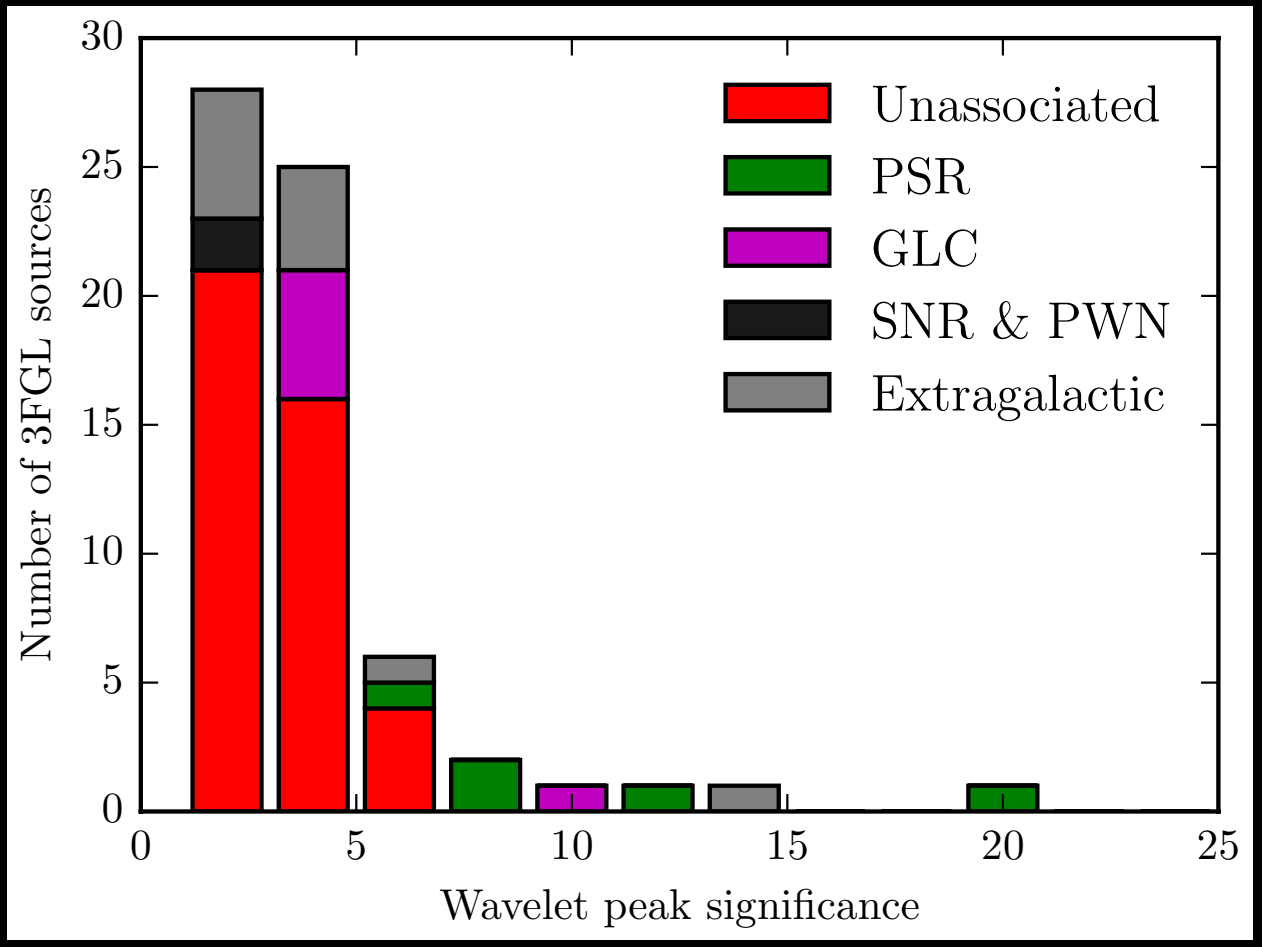


Likely MSPs


But what about their distribution …

# Distribution: Bulge vs Thick Disk

We model a thick disk distribution:

- Normalization: match # of 3FGL MSPs at |b|>15°

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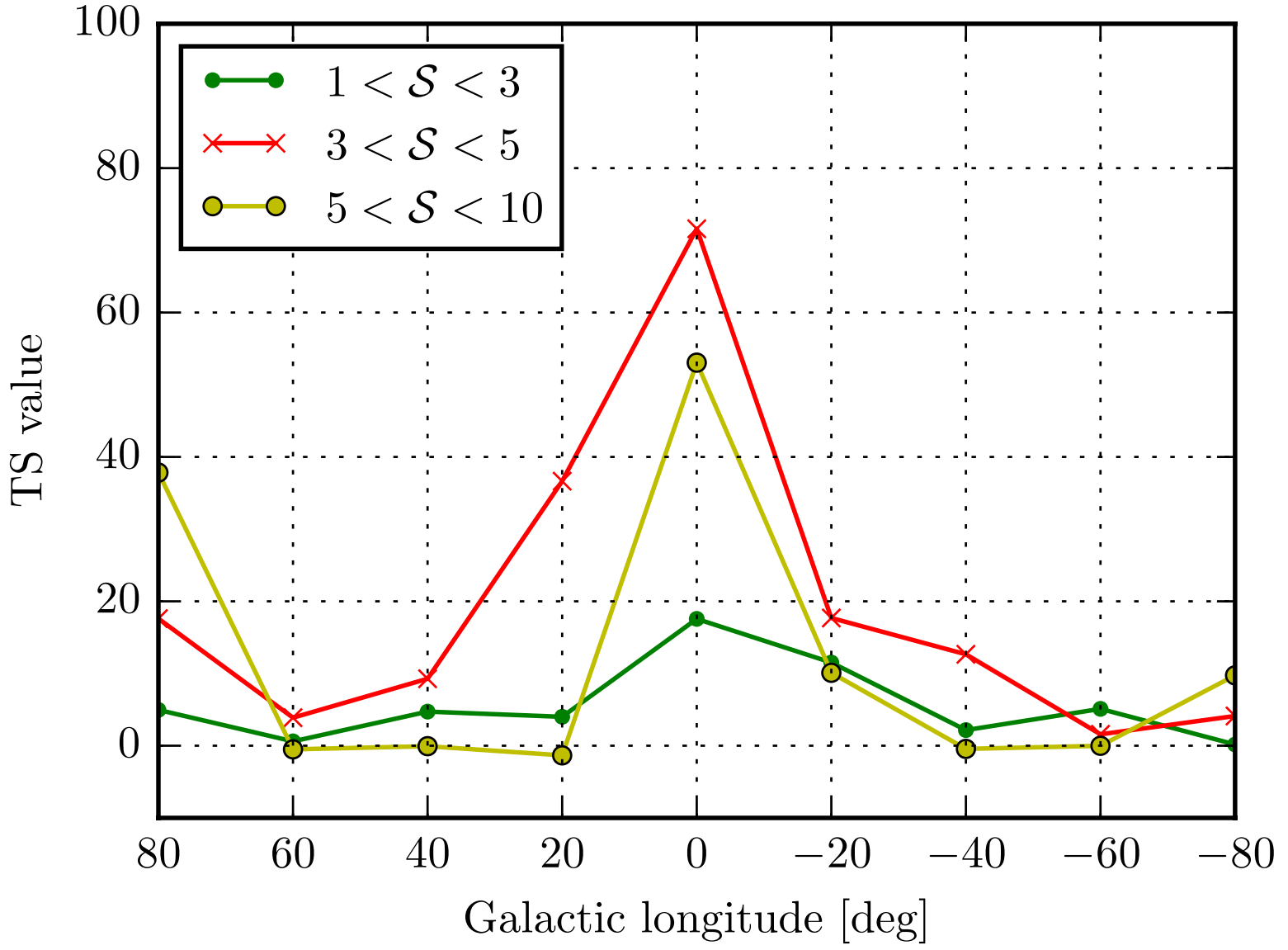
We model a thick disk distribution:

- Normalization: match # of 3FGL MSPs at |b|>15°
- But then : Factor $\mathcal{O}(10)$ too few sources in inner 2 kpc to explain the wavelet signal there.
- Cannot modify the disk population to account for this …

# Distribution: Bulge + Thick Disk



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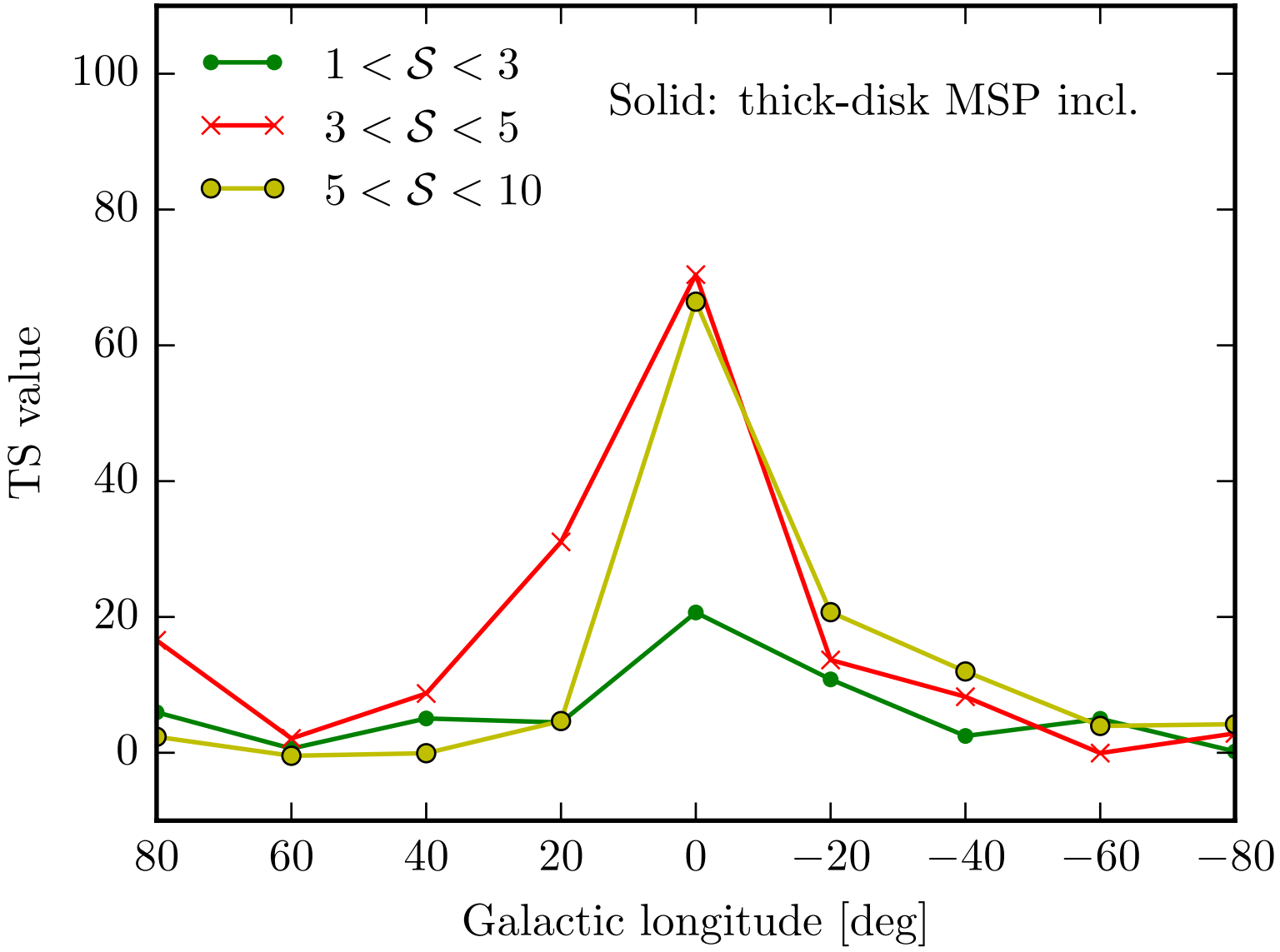

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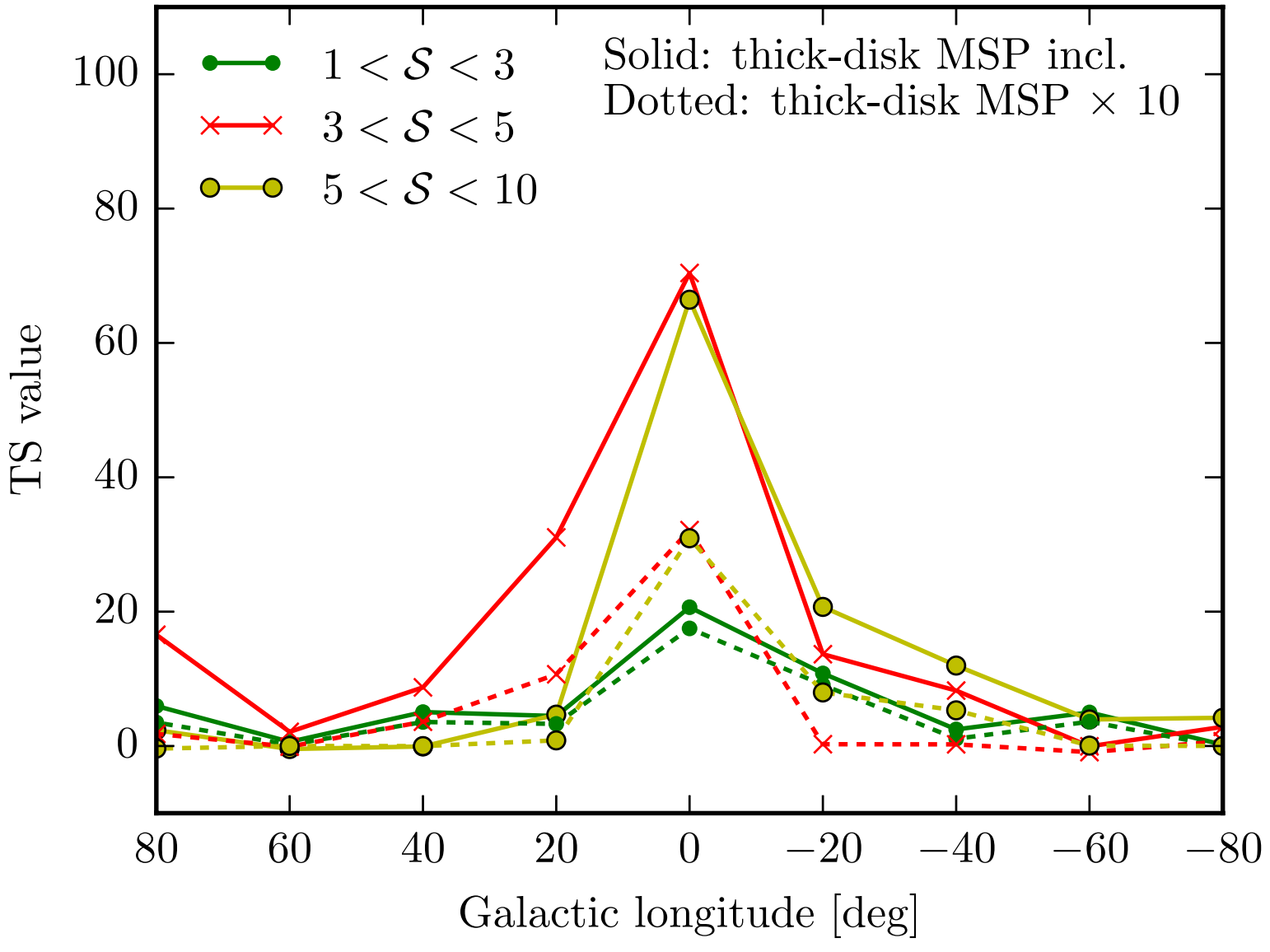

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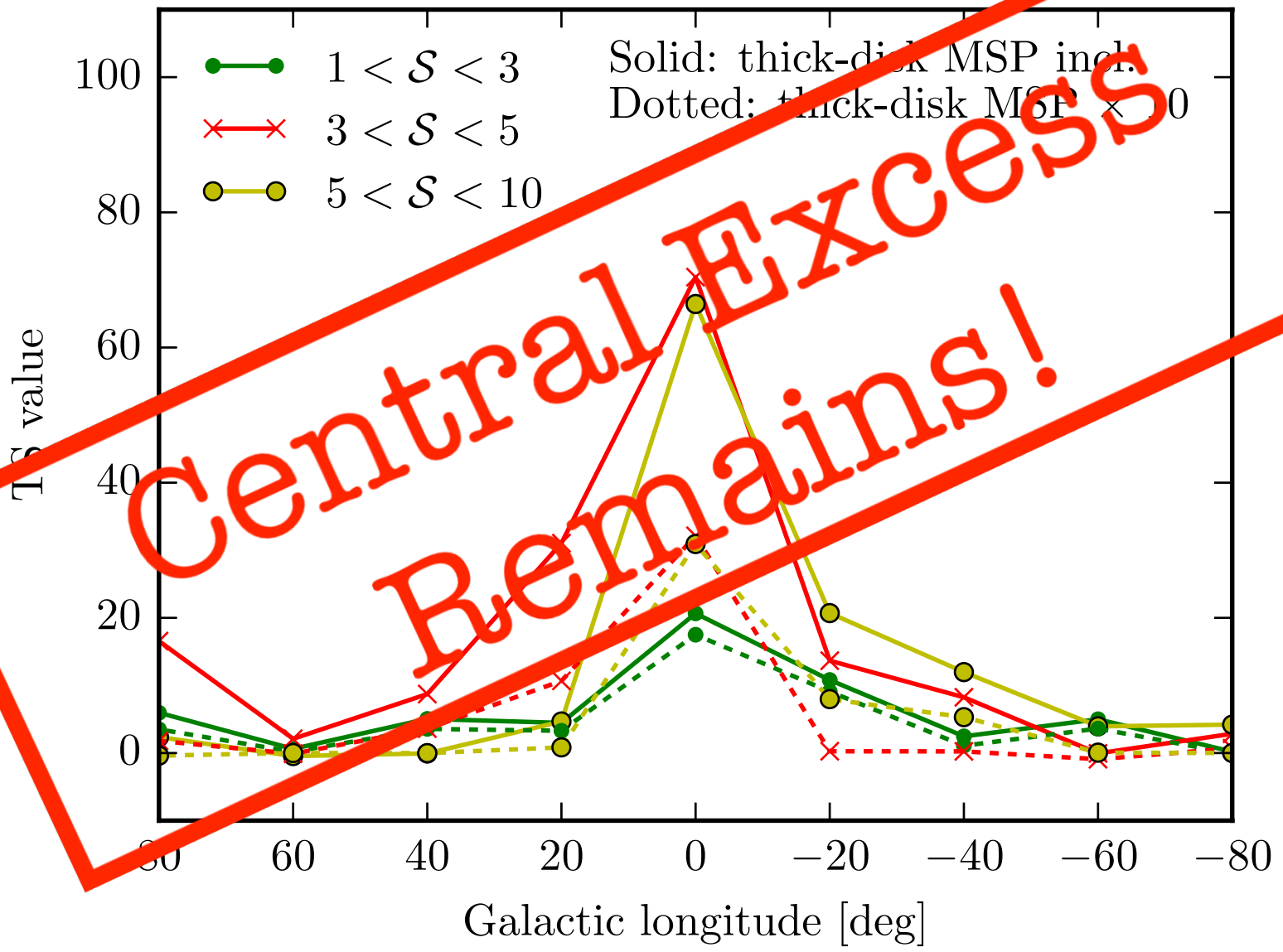



Central Excess Remains!

# Conclusion

- We apply a novel technique on γ-ray data to look for sub-threshold point sources
- We detect at $\sim 10\sigma$ a clustering of photons in the inner galaxy, as predicted for sub-threshold MSPs
- For plausible luminosity functions MSPs can account for 100% of the GeV excess
- Signal unlikely to be caused by:
  - Other point source classes
  - Gas
  - Disk population of MSPs
- However, not yet conclusive evidence:
  - More detailed analysis
  - X-ray and radio follow-up

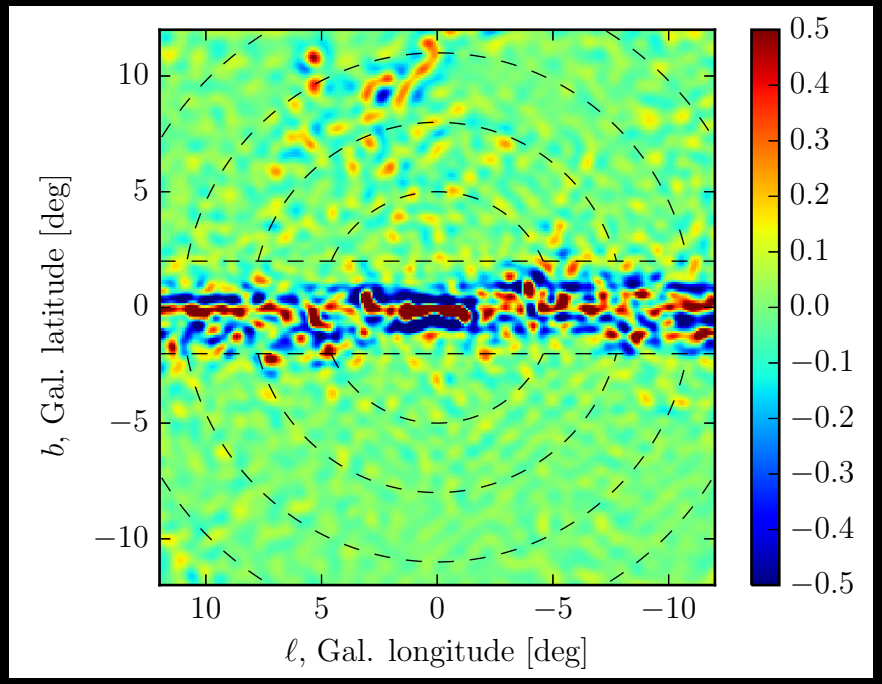
# Thank you ☺

# Backup: Wavelet Analysis

## Contributions to Wavelet Peaks:

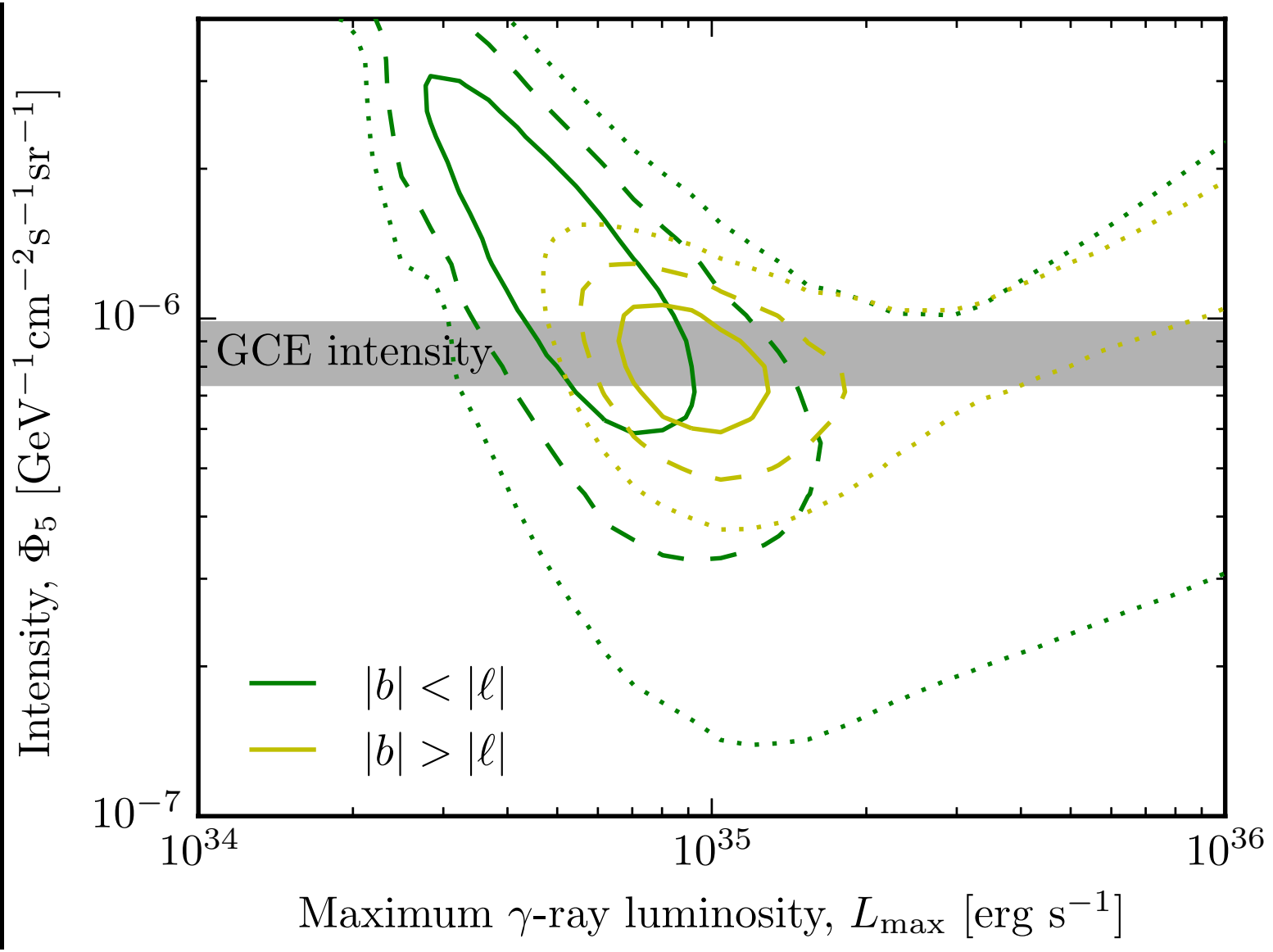
- Point sources
- Irregularities in the diffuse emission
- Statistical Noise: $\lesssim 3\sigma$

$$\mathcal{S}(\Omega) \equiv \frac{\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega)}{\sqrt{\mathcal{F}_{\mathcal{W}^2}[\mathcal{C}](\Omega)}}$$




Wavelet transform of Fermi LAT PASS8 diffuse emission model (v06)

# Backup: Sphericity



# Backup: CO Map vs Wavelet