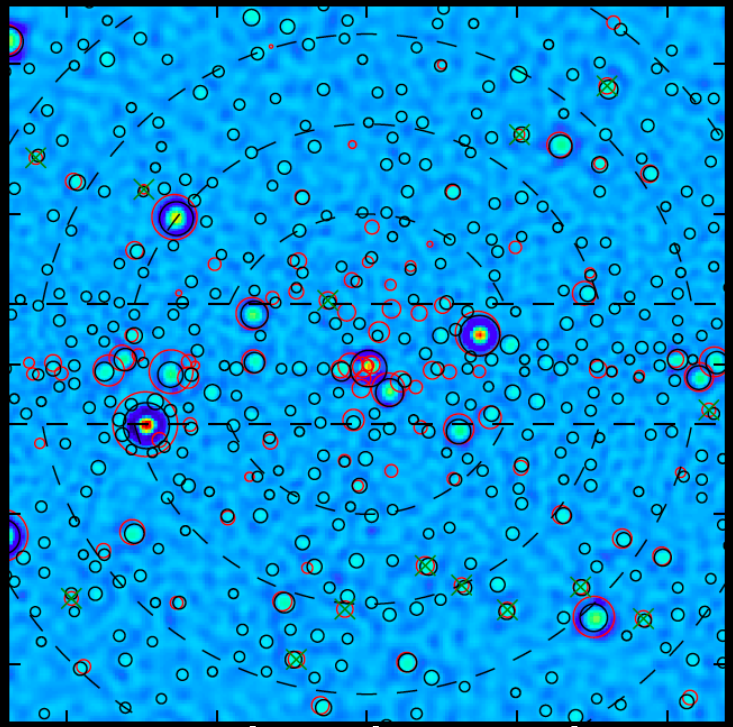
Wavelet Analysis of the Galactic Center: Strong Support for the MSP Interpretation

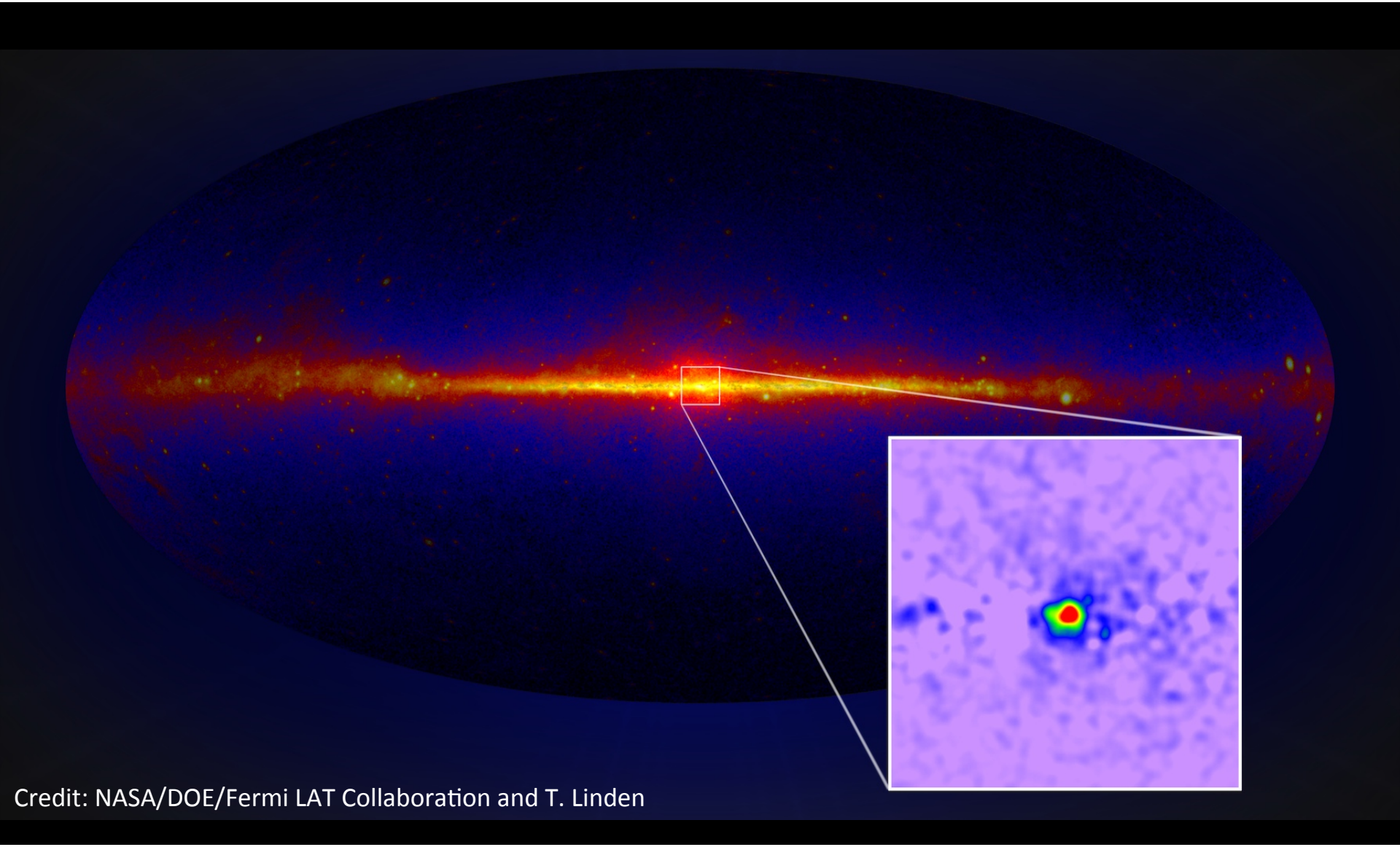


Richard Bartels

S. Krishnamurthy and C. Weniger

arXiv: 1506.05104

One Minute on the GeV Excess

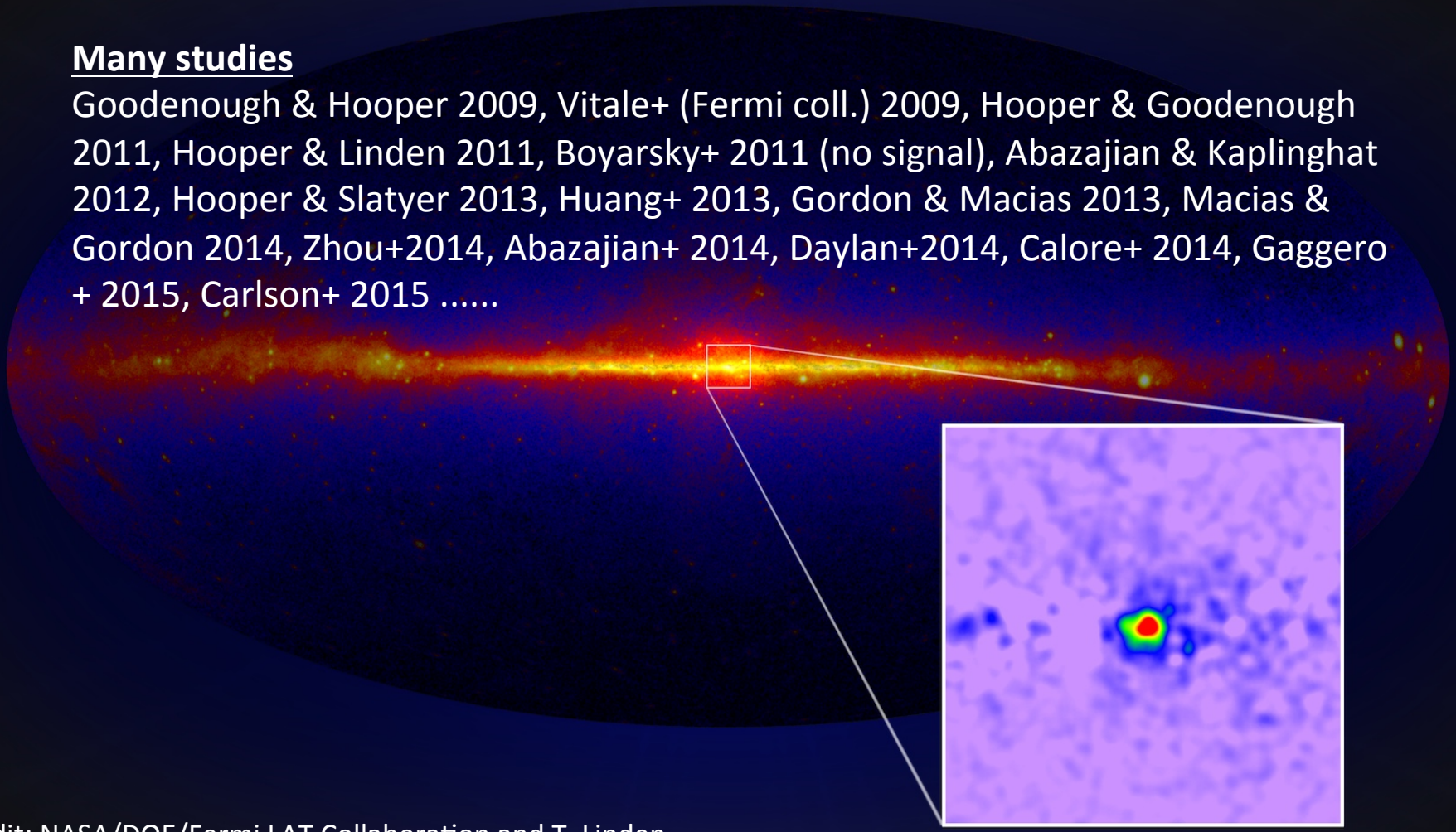


Credit: NASA/DOE/Fermi LAT Collaboration and T. Linden

One Minute on the GeV Excess

Many studies

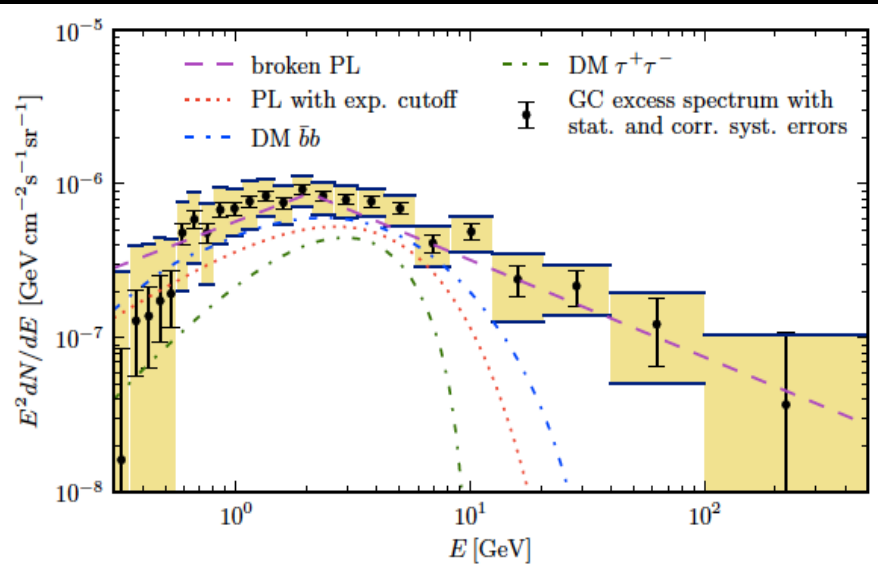
Goodenough & Hooper 2009, Vitale+ (Fermi coll.) 2009, Hooper & Goodenough 2011, Hooper & Linden 2011, Boyarsky+ 2011 (no signal), Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Huang+ 2013, Gordon & Macias 2013, Macias & Gordon 2014, Zhou+2014, Abazajian+ 2014, Daylan+2014, Calore+ 2014, Gaggero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



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

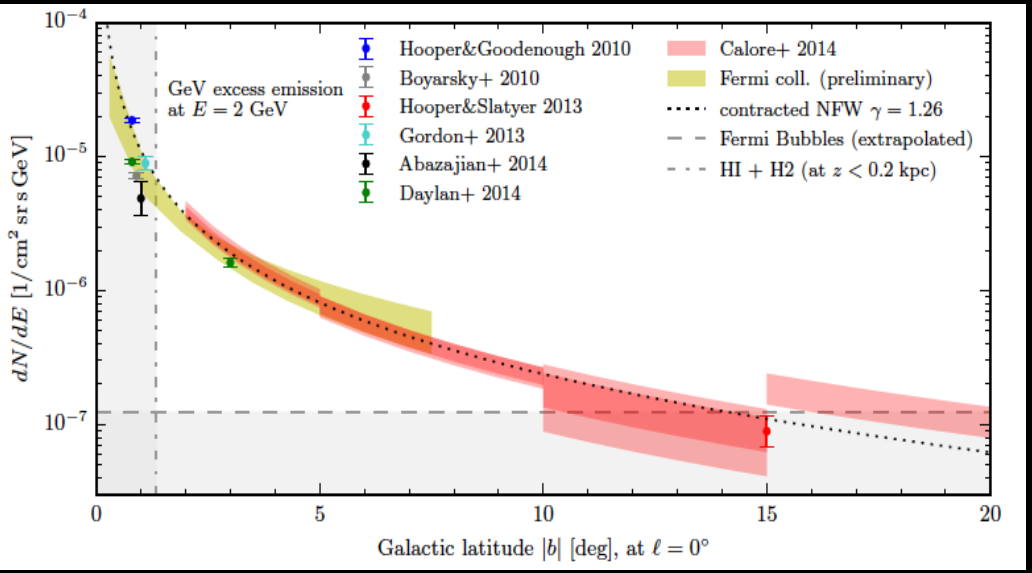
One more minute…

Spectrum



Calore, Cholis & Weniger, 2014

Radial Profile



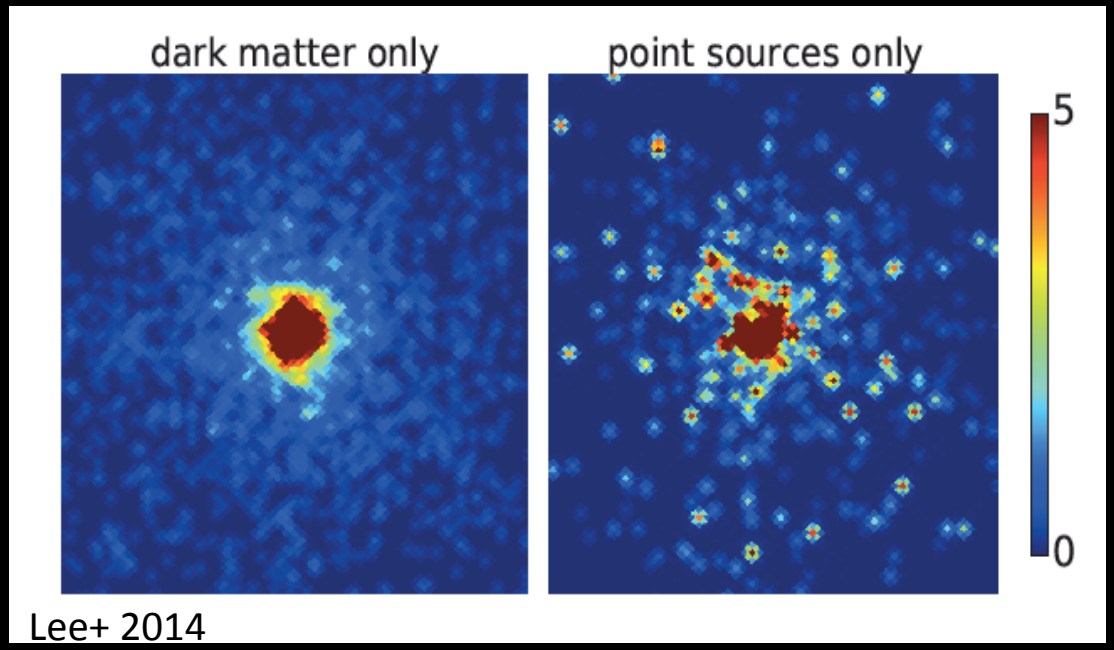
Calore, Cholis, McCabe & Weniger, 2015

Testing the DM (or point source) interpretation

Methods

- **Wavelet Decomposition [HERE]**

Testing the DM (or point source) interpretation

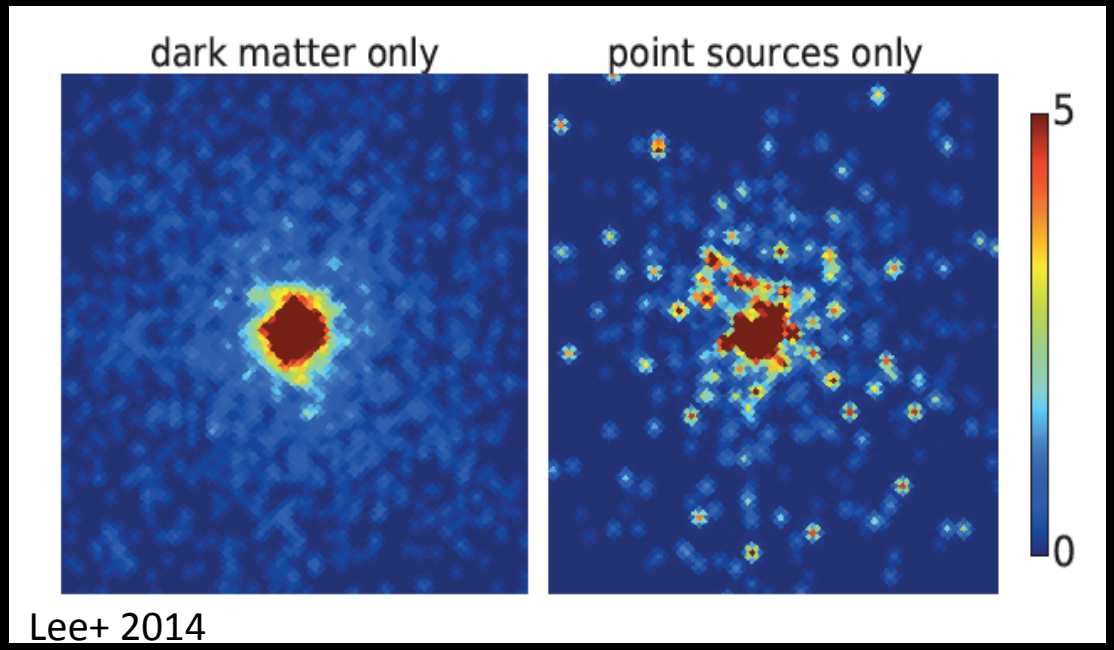


Lee+ 2014

Methods

- **Wavelet Decomposition [HERE]**
- One point Statistiscs (non-poissonian noise for PSCs) [Lee+ 2014]

Testing the DM (or point source) interpretation



Lee+ 2014

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]

But first: what point sources?

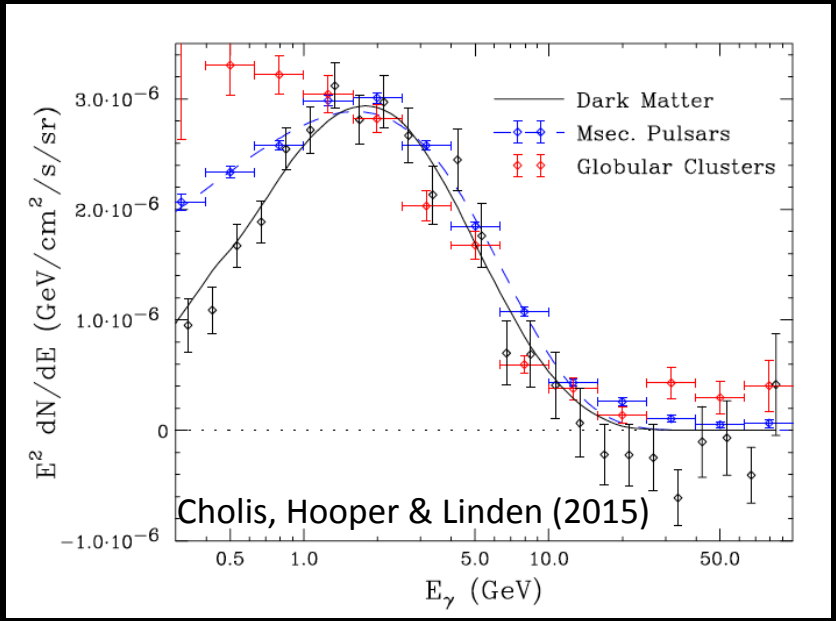
Millisecond Pulsars

[e.g. Abazijan 2011, Gordon & Macias 2013, Hooper+ 2013, Yuan and Zhang 2014, Cholis+ 2015, Calore+ 2015, Petrovic+ 2015]

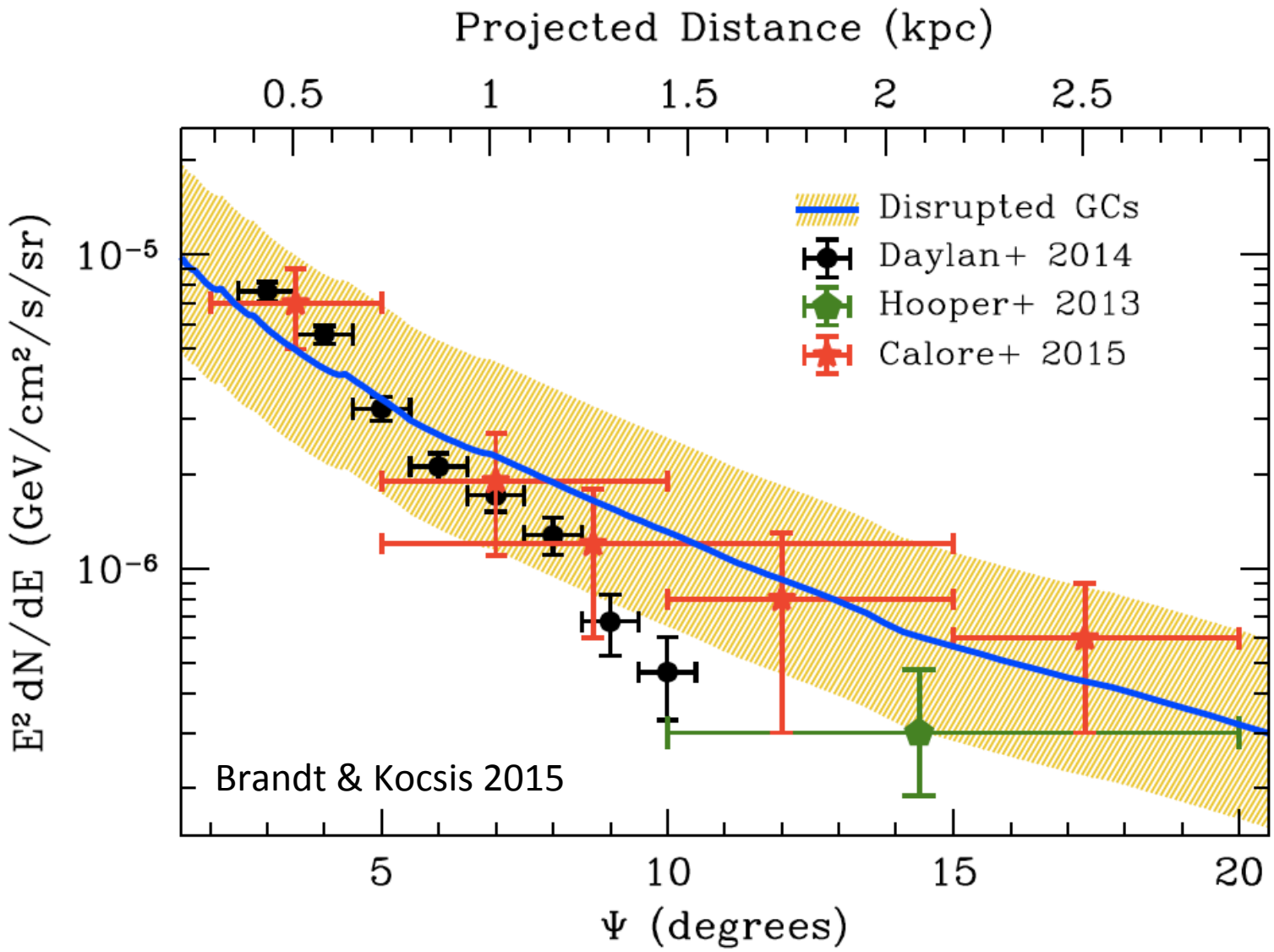
- Compatible Spectrum
- Luminosity function:

$$\frac{dN}{dL} \sim L^{-\alpha},\ \alpha \sim 1\text{–}2$$

But consistent?



MSPs from Disrupted Globular Clusters?



Wavelet Analysis

Wavelet Transform:

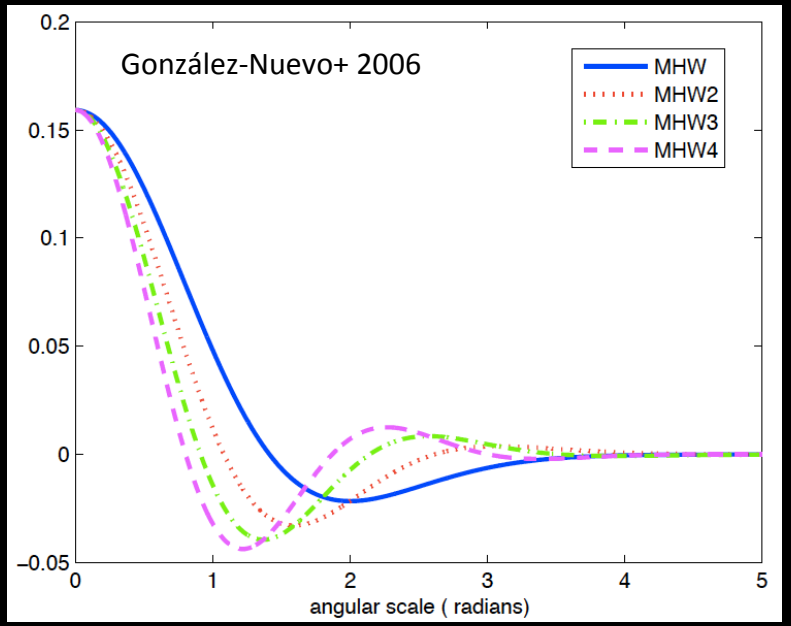
$$\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega) \equiv \int d\Omega' \, \mathcal{W}(\Omega - \Omega')\mathcal{C}(\Omega')$$

with:

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

Wavelet Kernel

Count map (1-4 GeV)



We optimize the wavelet scale to detect Fermi point sources

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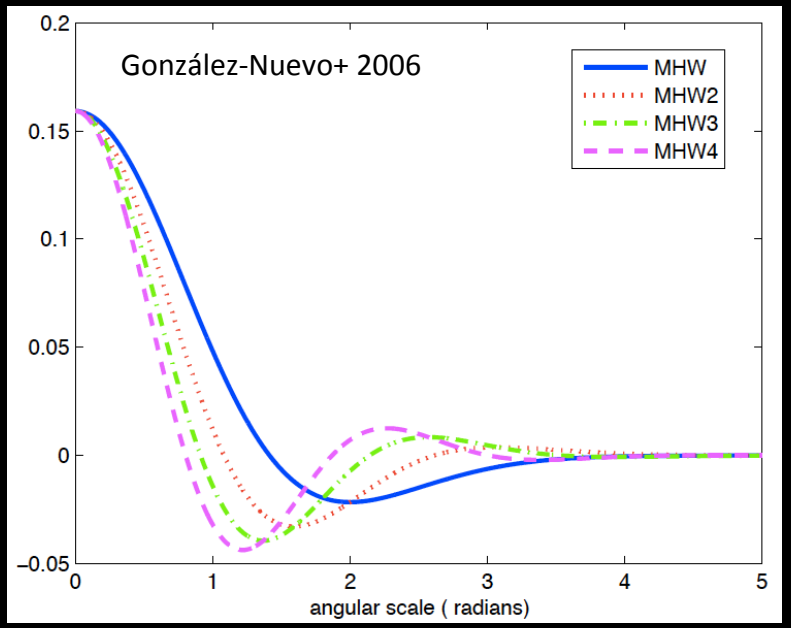

Signal-to-noise Ratio:

We consider:

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

We optimize the wavelet scale to detect Fermi point sources

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

Wavelet Analysis

Contributions to Wavelet Peaks:

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

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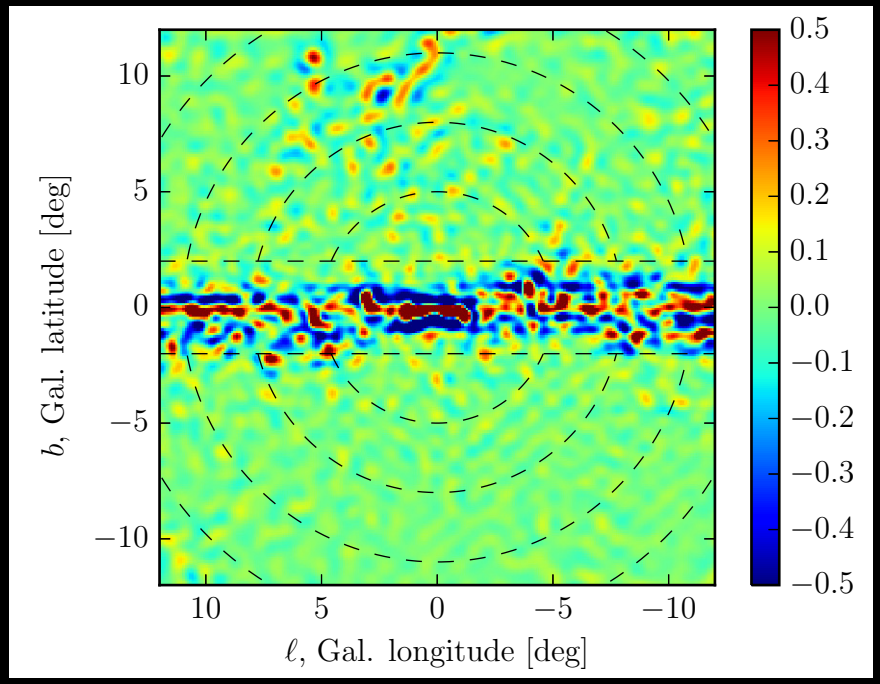
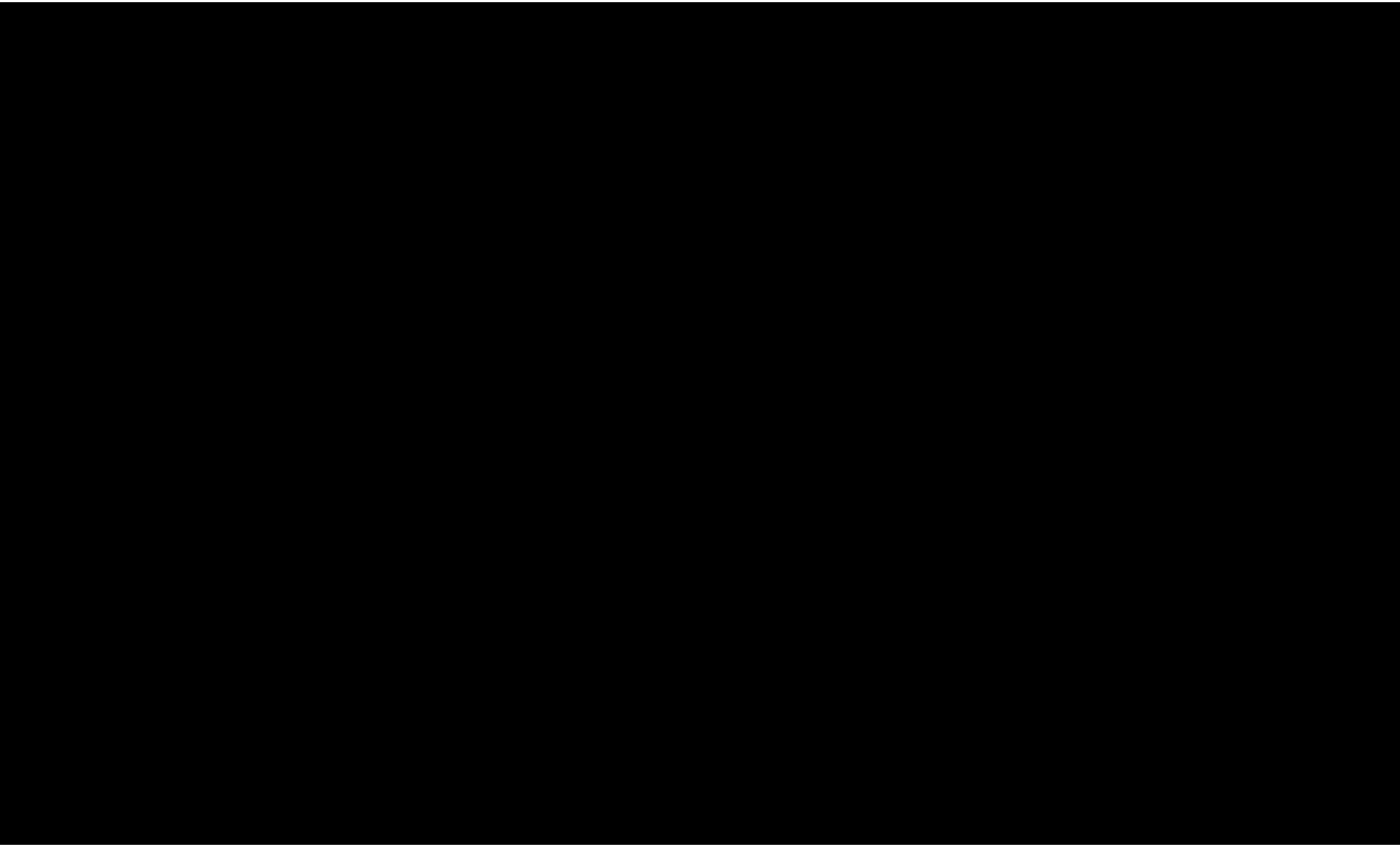


Wavelet transform of Fermi LAT PASS8 diffuse emission model (v06)

Monte Carlo



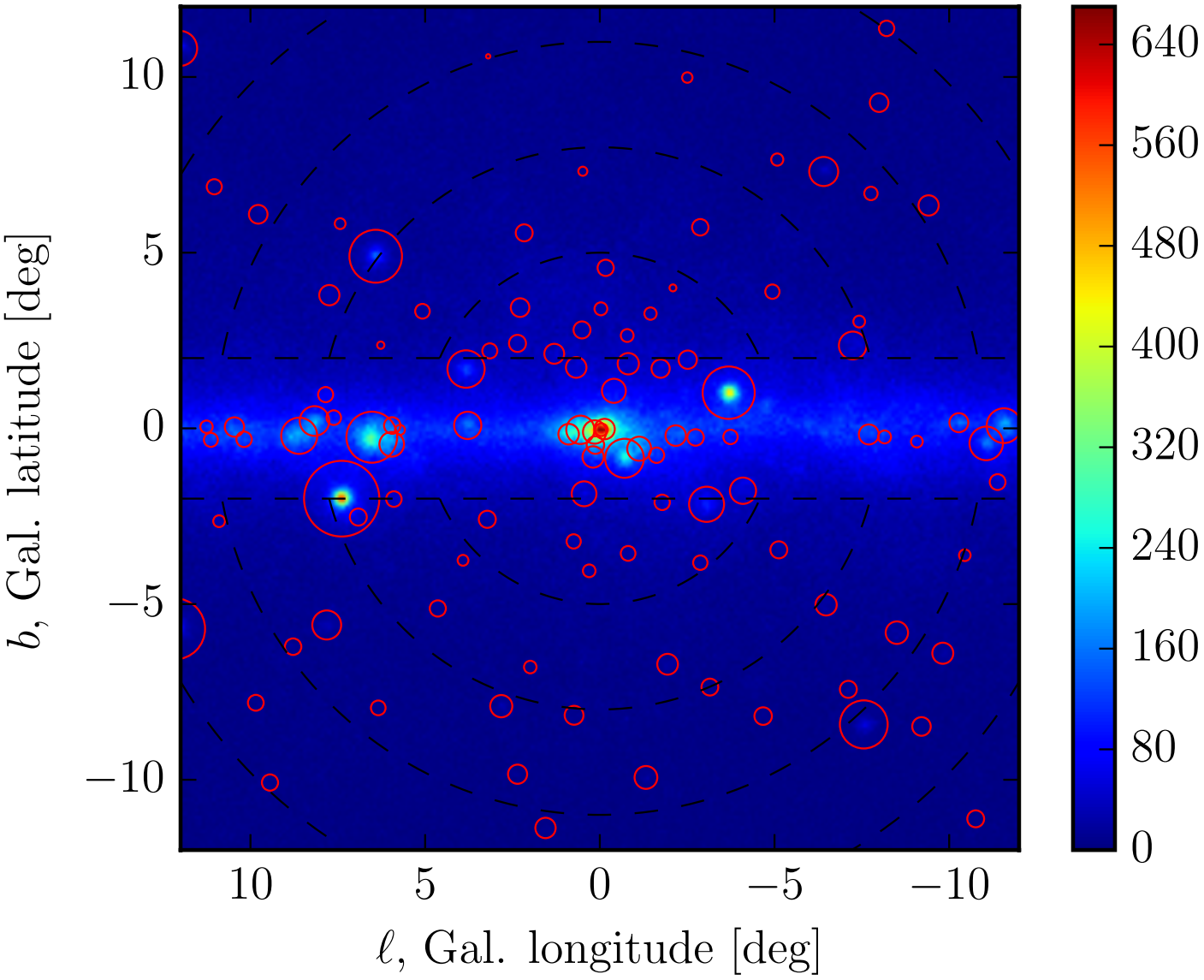
Monte Carlo

- Fermi Diffuse & Isotropic Model + statistical noise

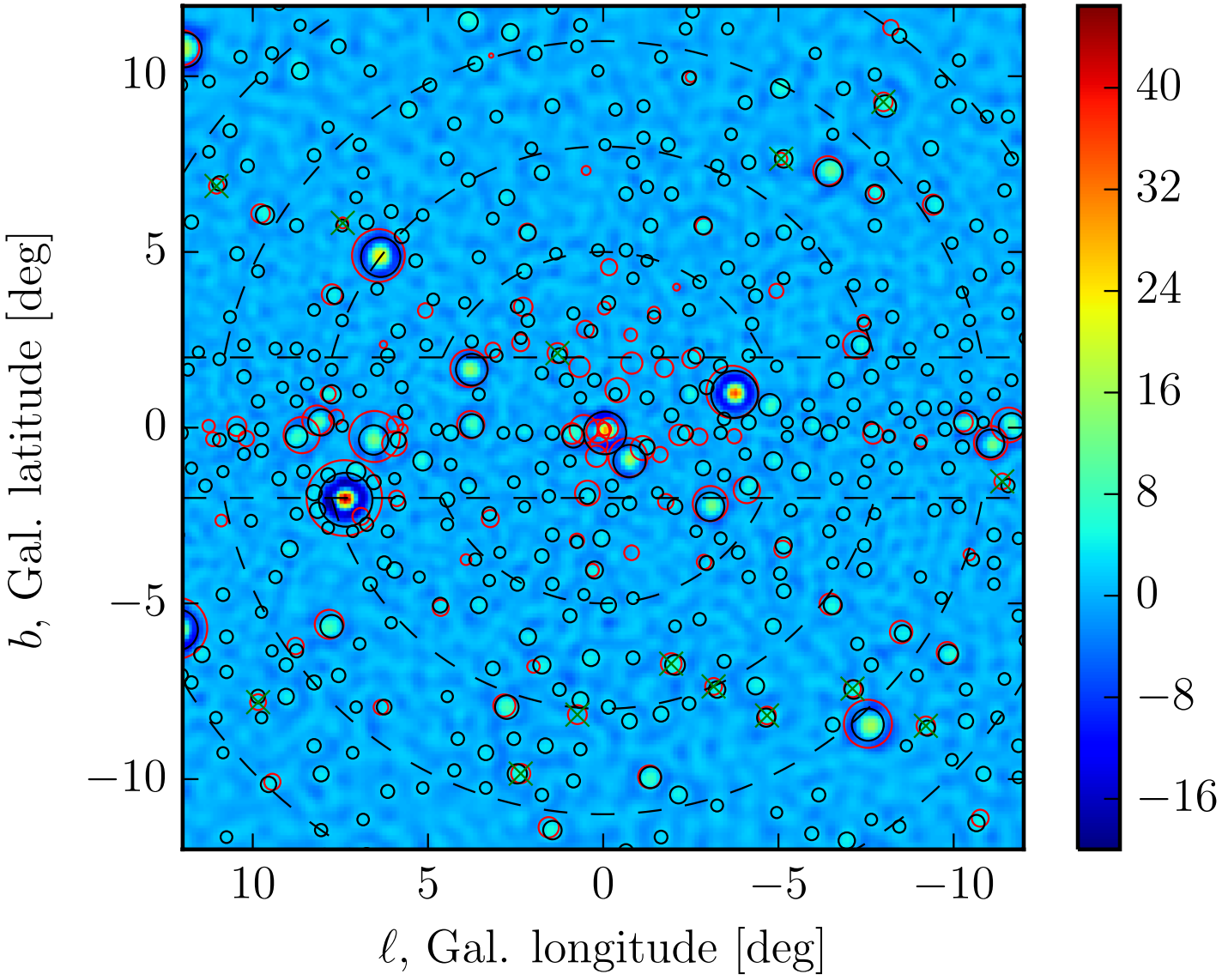
Monte Carlo

- 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 $L_{\rm max} = 10^{34}$–$10^{36}\,{\rm erg\,s^{-1}}$

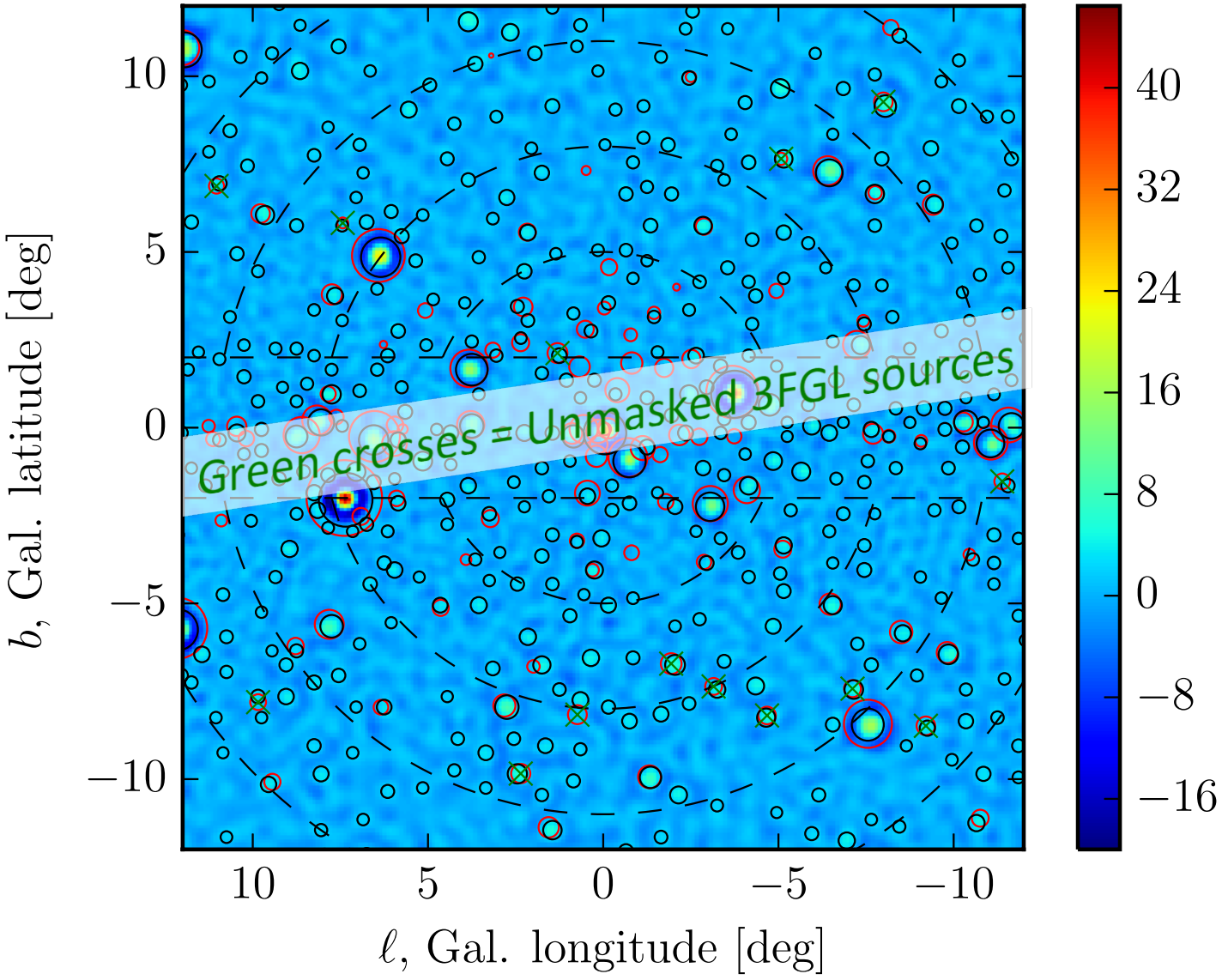
Compare with data



Compare with data



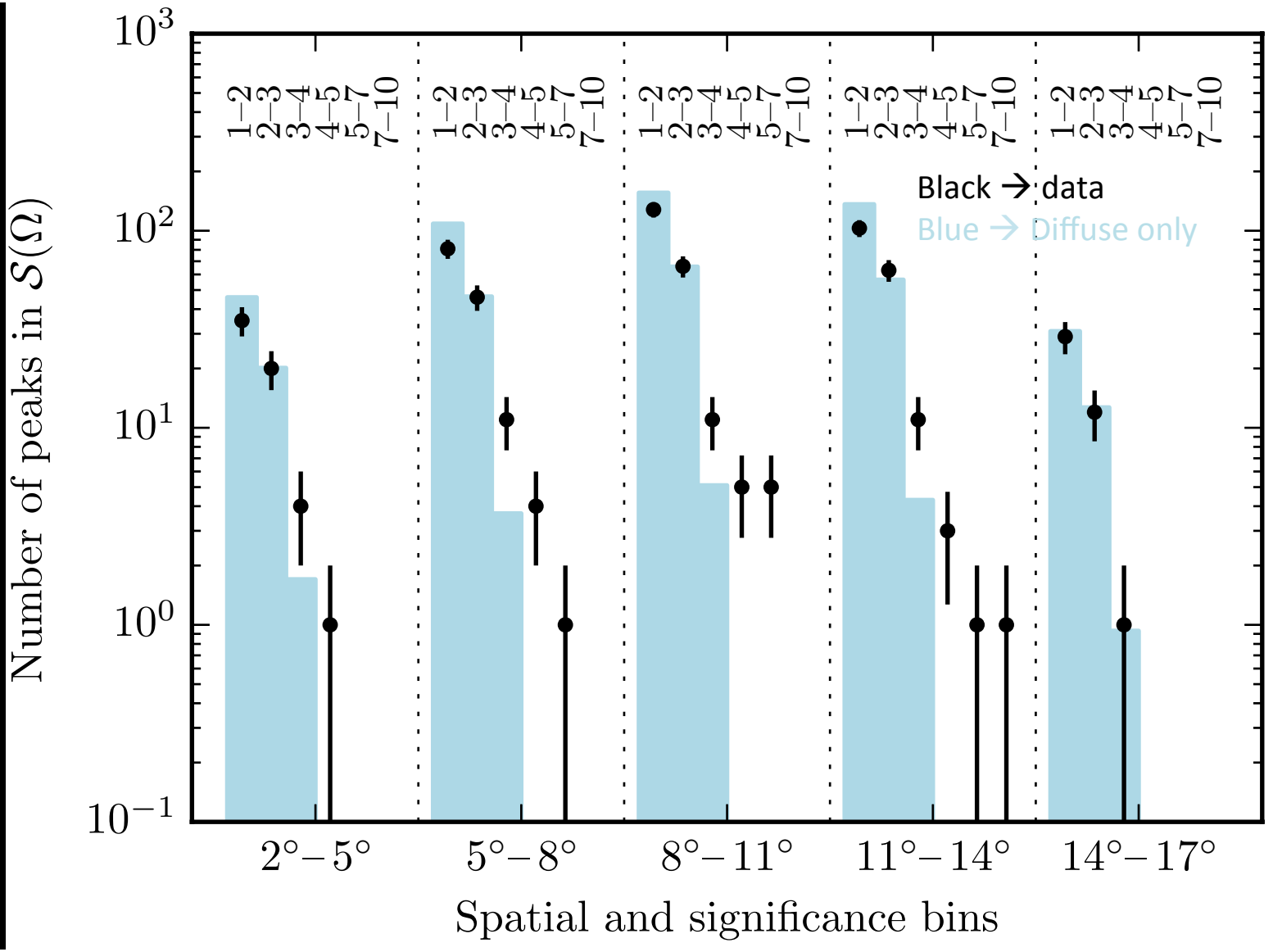
Compare with data



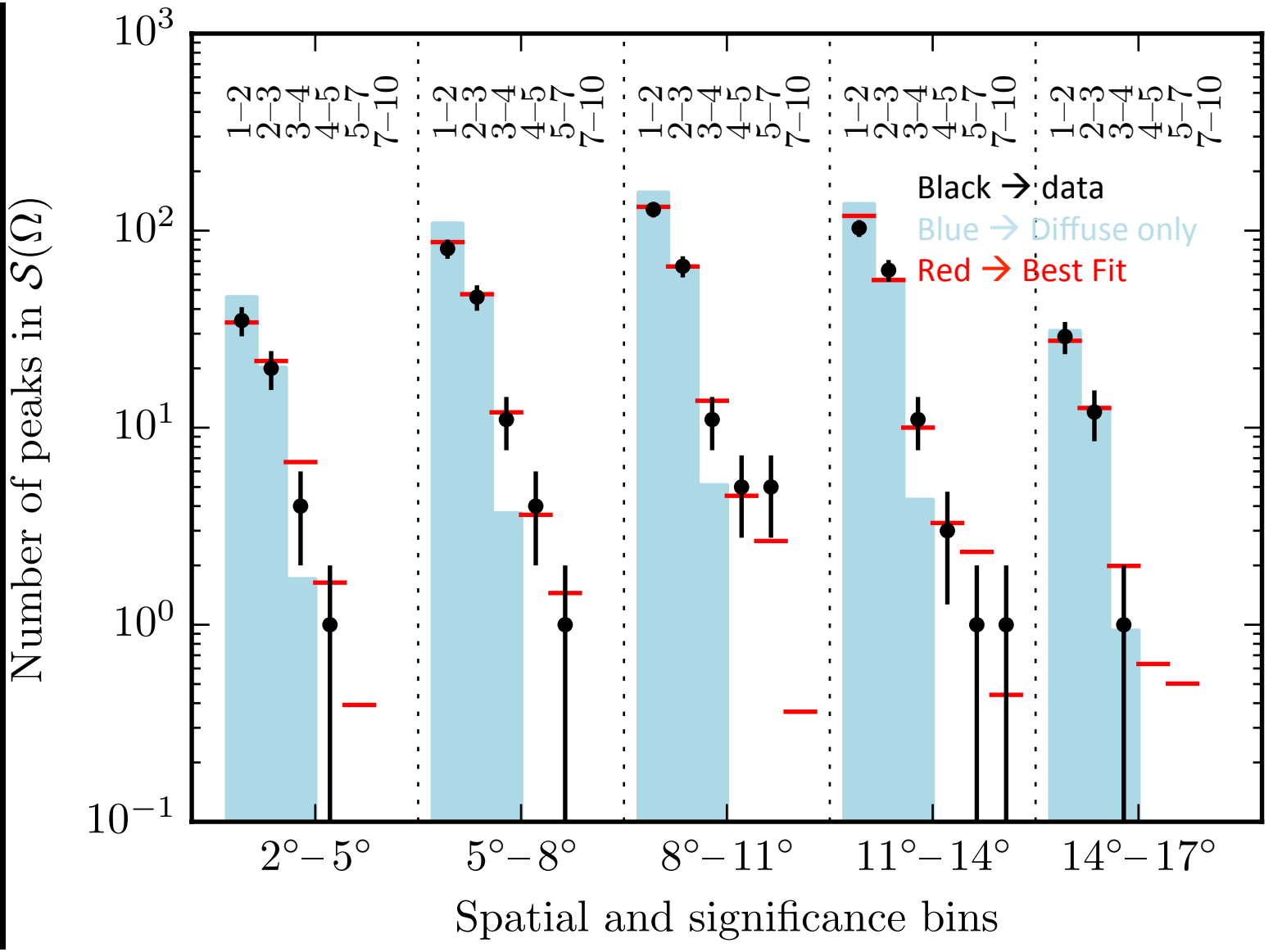
3FGL Sources

- All masked
- Except unassociated sources that might be part of the central MSP population → around 13 in ROI
- However, our results do not critically depend on masking these 13 sources or not

Results


Number of peaks in $\mathcal{S}(\Omega)$
10^3
10^2
10^1
10^0
10^{-1}
1–2
2–3
3–4
4–5
5–7
7–10
Black → data
Blue → Diffuse only
2°–5°
5°–8°
8°–11°
11°–14°
14°–17°
Spatial and significance bins

Results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10^3
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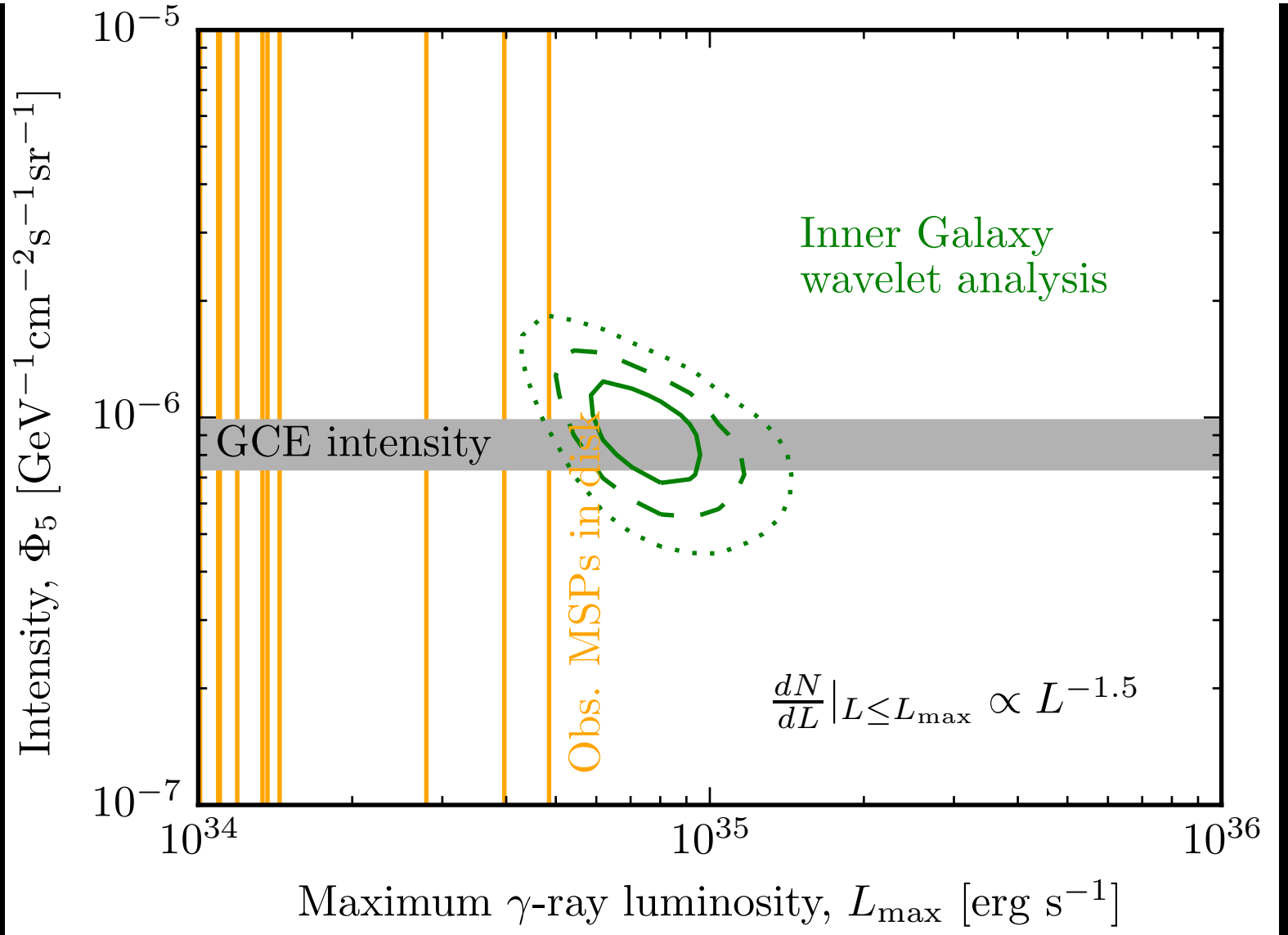
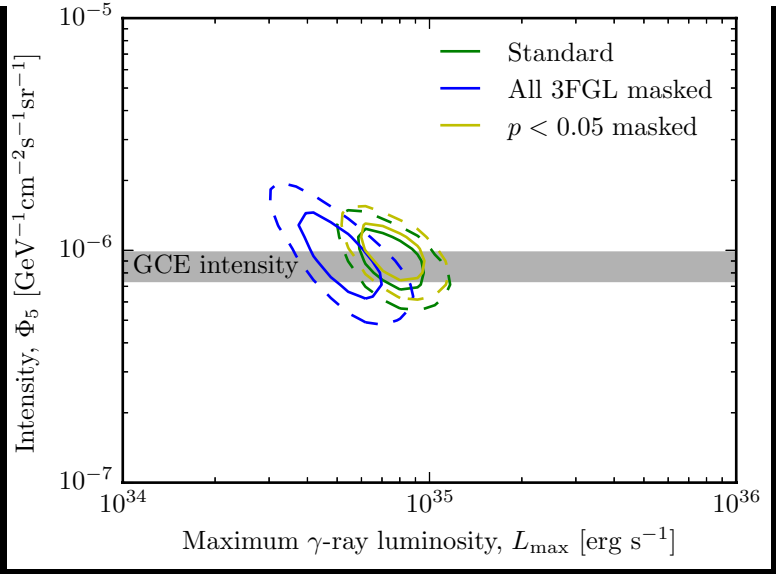
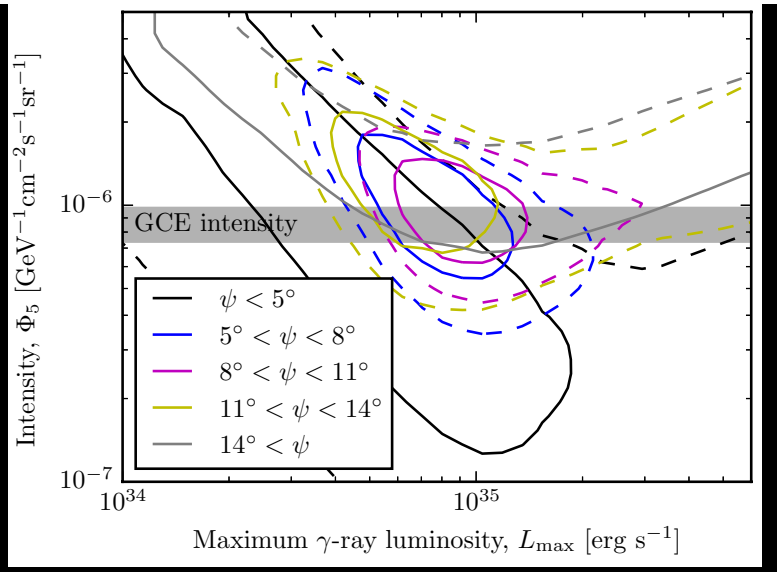
1–2
2–3
3–4
4–5
5–7
7–10
Black → data
Blue → Diffuse only
Red → Best Fit
2°–5°
5°–8°
8°–11°
11°–14°
14°–17°
Spatial and significance bins

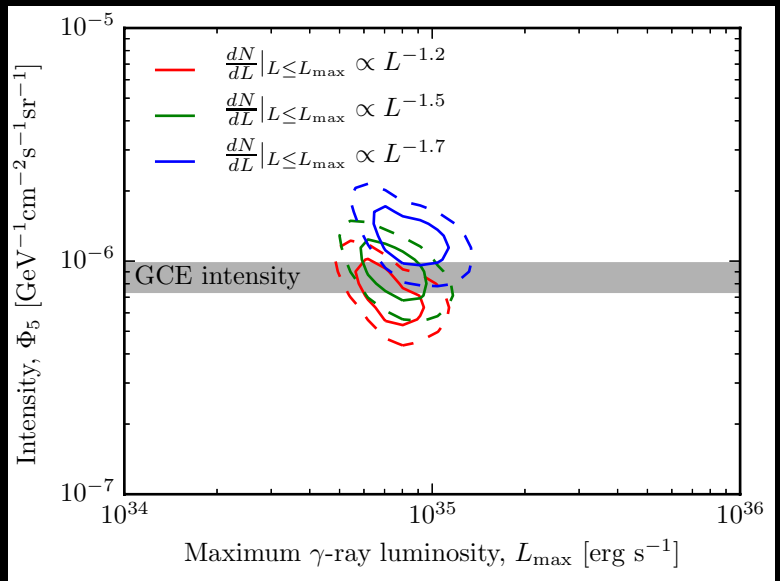
Results: Limits

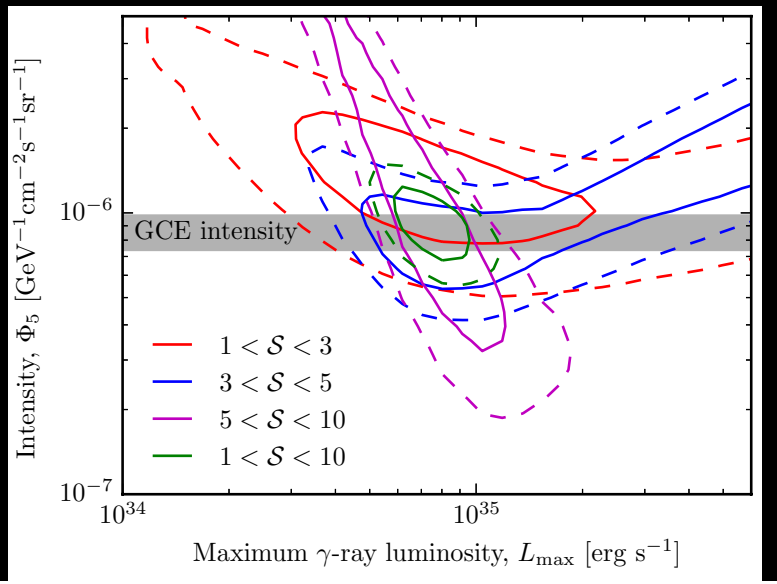


Results: Limits (checks)

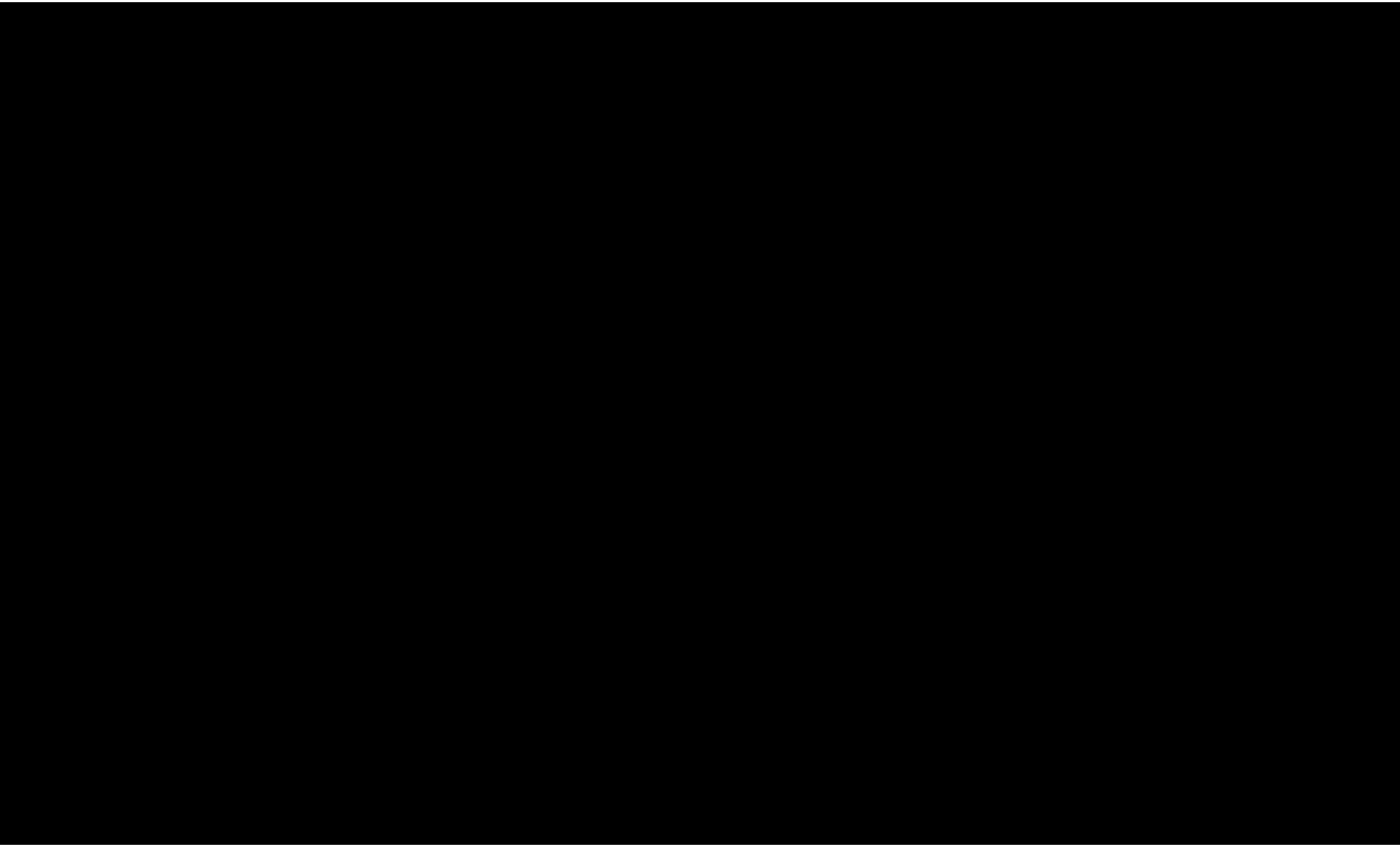








Is this really a characteristic of the GC?



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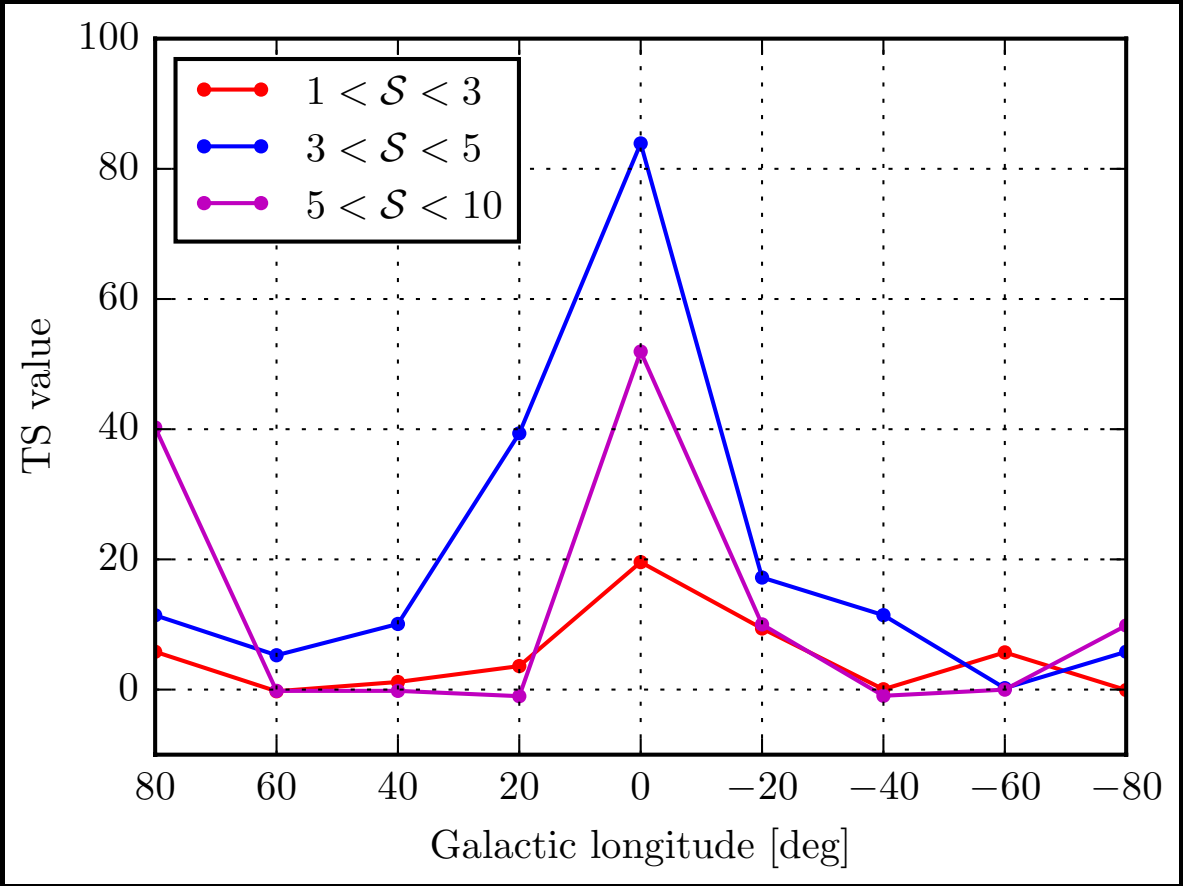
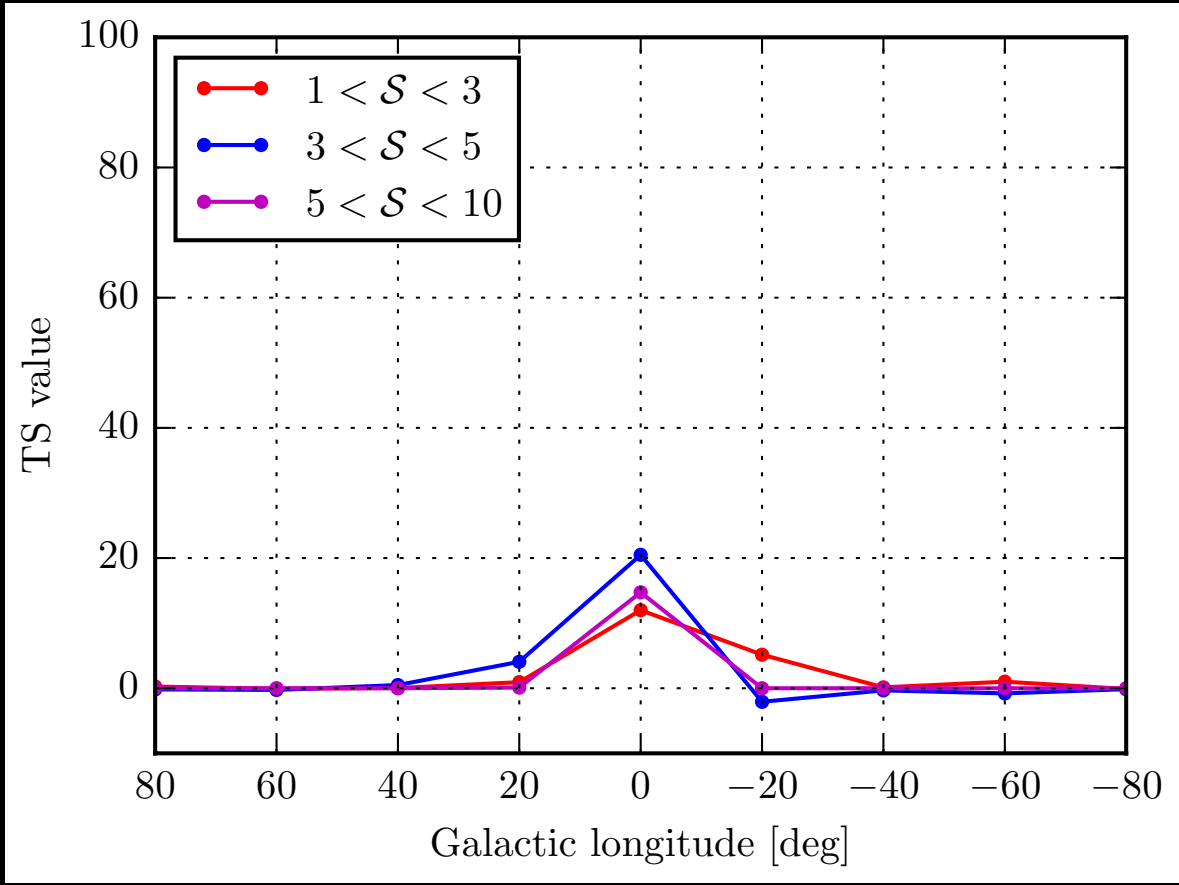


NO similar source population outside the inner Galaxy!

Is this really a characteristic of the GC?



A thick disk population that absorbs all counts outside the GC: 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
- Signal probably not caused by:
  - Disk population of MSPs
  - Other point source classes
  - Gas
- For plausible luminosity functions MSPs can account for 100% of the GeV excess
- However, not yet conclusive evidence:
  - More detailed analysis
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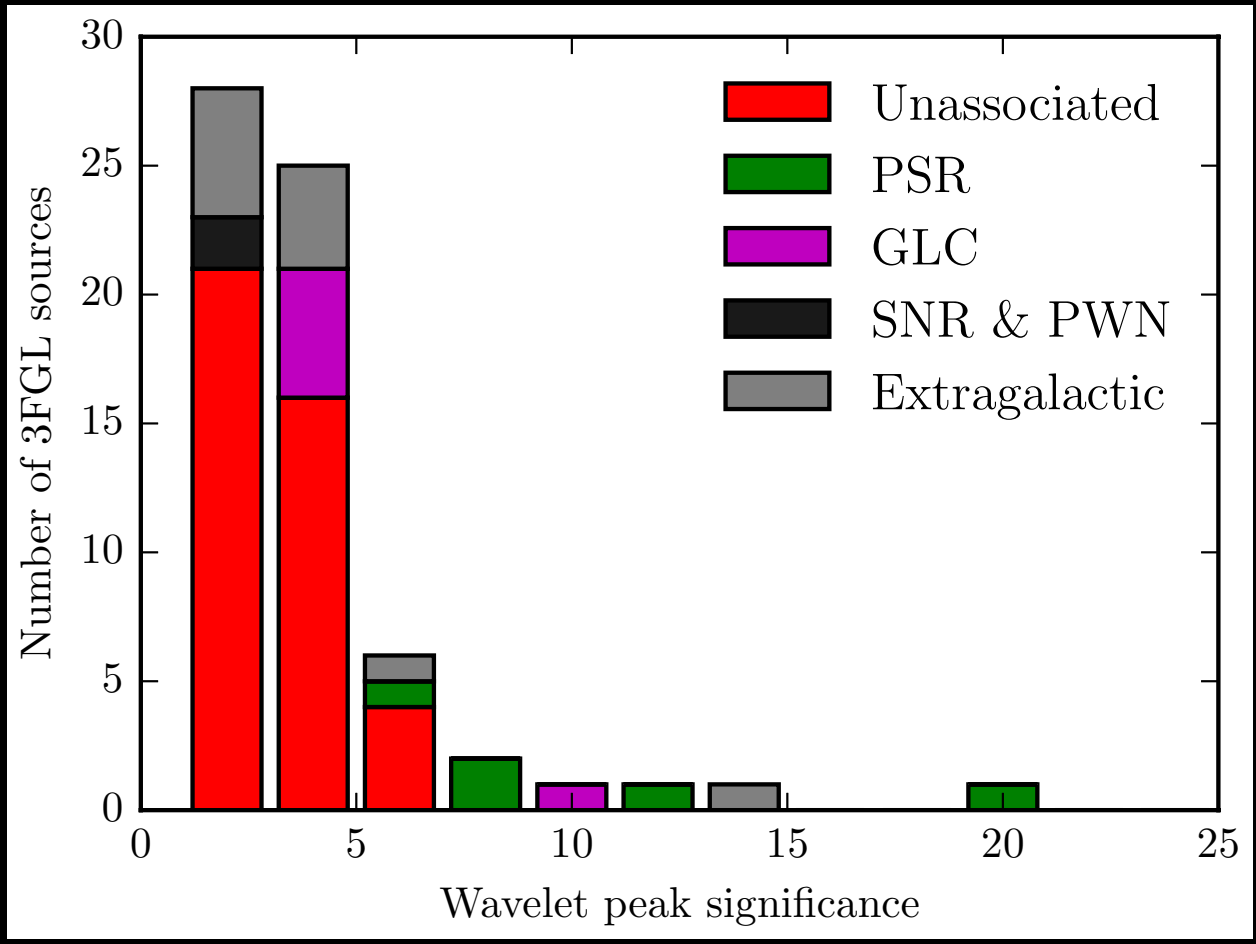
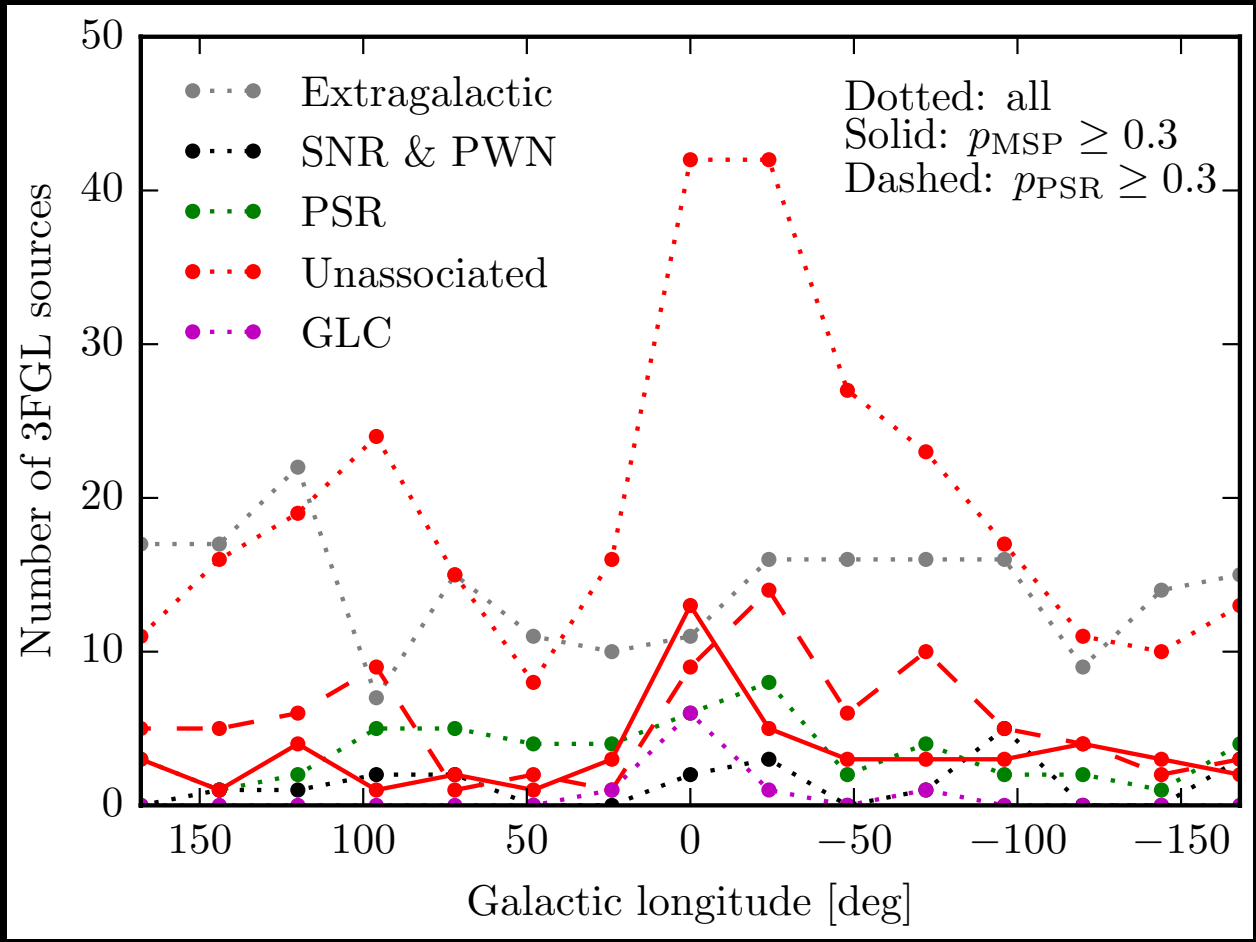
see: **F. Calore @ 17:50**

Thank you ☺

Backup


Number of 3FGL sources
Wavelet peak significance
Unassociated
PSR
GLC
SNR & PWN
Extragalactic
0
5
10
15
20
25
30

Backup


Extragalactic
SNR & PWN
PSR
Unassociated
GLC
Dotted: all
Solid: $p_{\rm MSP} \geq 0.3$
Dashed: $p_{\rm PSR} \geq 0.3$
Number of 3FGL sources
Galactic longitude [deg]
50
40
30
20
10
0
150
100
50
0
−50
−100
−150

Backup

@ 1GeV:

Giant molecular

$3 \times 10^5\,\mathrm{M}_\odot$

$\updownarrow$

$10^7\,\mathrm{erg\,s}^{-1}$

MSP

CO (tracer for HI)

$\mathcal{O}(10-100)\,\mathrm{K\,km\,s}^{-1}$ → probably already seen