Dissecting the Inner Galaxy with gamma-ray pixel count statistics

EPS-HEP Conference 2021, DESY, Hamburg (online)

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The Galactic center GeV excess

Signal:

- *Well-established excess* of Fermi-LAT GeV photons from the inner Galaxy**
- Peculiar spectrum peaked at a few GeV
- Extended emission up to ~10 degrees (~1.5 kpc), almost spherically symmetric (but not quite so)

Interpretations:

- *Diffuse emission* from electrons/positrons at the Galactic centre (enhanced SF or activity GC)

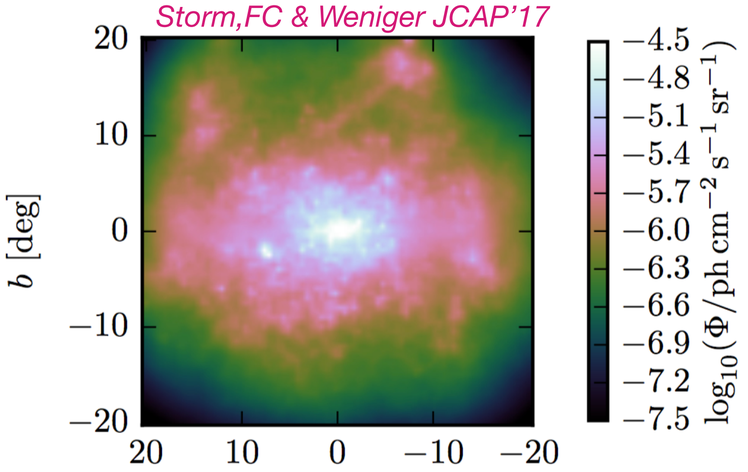
  Gaggero+ JCAP'15; Carlson+PRD'15; Petrovic+ JCAP'14; Cholis,FC+JCAP'15

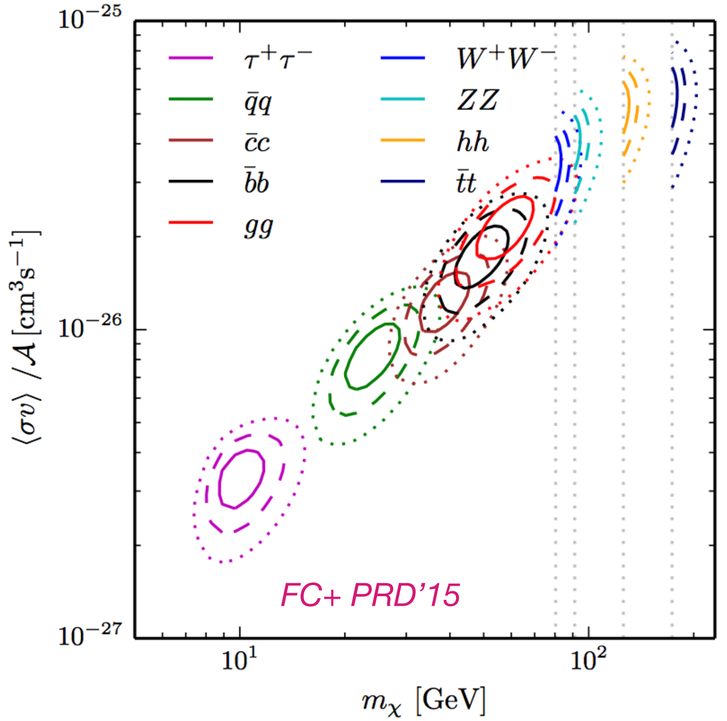
- *Sub-threshold* millisecond pulsar-like point *sources*

  Bartels+PRL'16; Lee+PRL'16; Ackermann+'17

- *Dark matter annihilation*: large freedom in channel/masses thanks to syst uncertainties

  FC+ PRD'15; Agrawal+JCAP'15

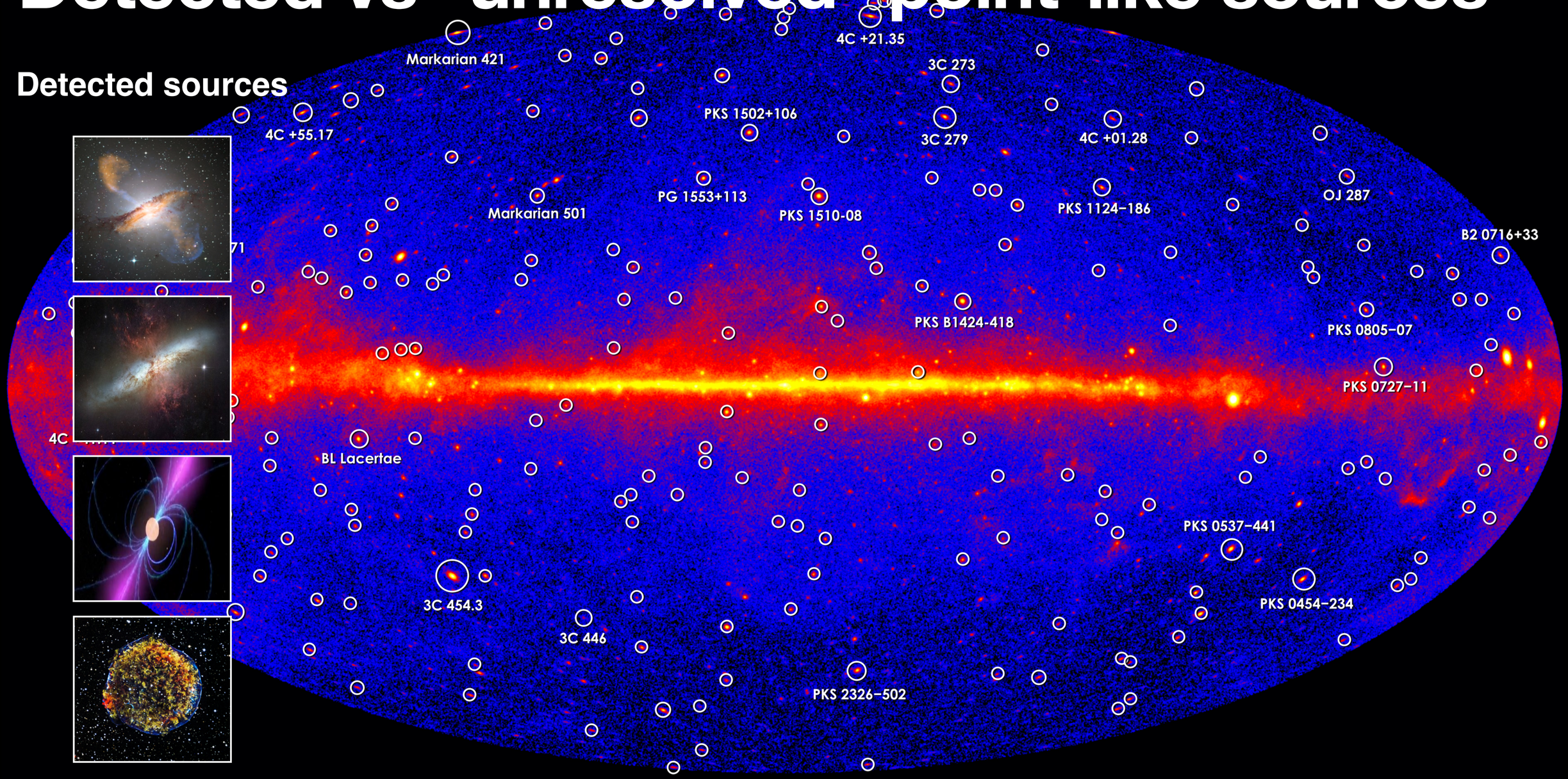




**Some Refs. since 2009: *Hooper&Goodenough '09; Vitale&Morselli '09; Abazajian&Kaplinghat PRD'12; de Boer+'16; Macias+'16; Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ '14; FC+ JCAP'15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15; Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; Leane & Slatyer'19; Di Mauro PRD'20*

Detected vs “unresolved” point-like sources

Detected sources



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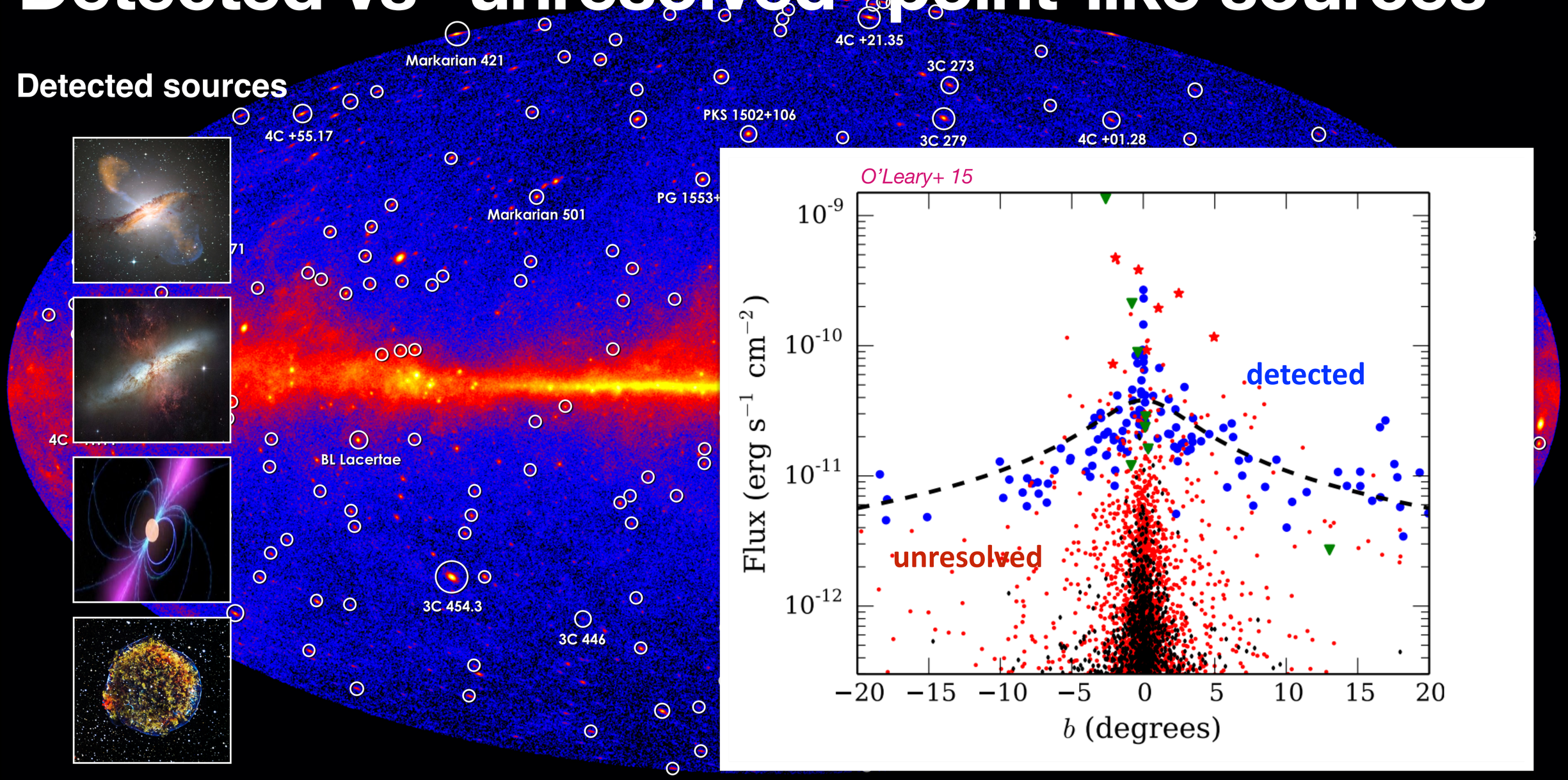
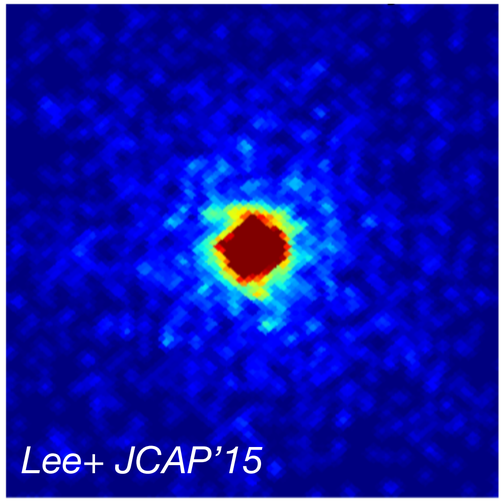


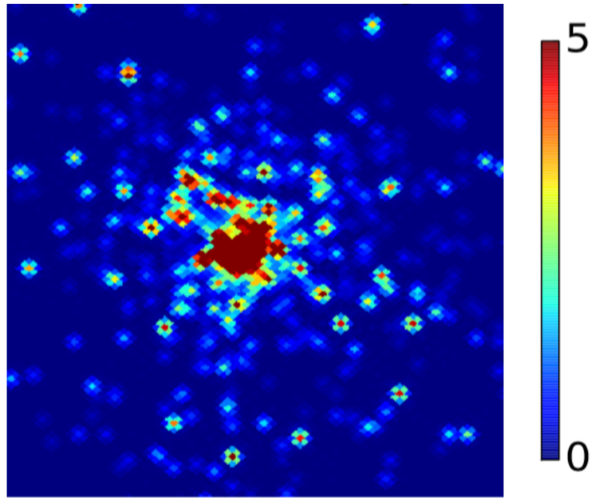
Diffuse vs point-source emission

Truly diffuse emission



dark matter,
enhanced star-formation, leptonic bursts

Unresolved point sources



millisecond or young pulsars

Difference in the **statistics of the photon counts**

Bartels+ PRL'16, Lee+ PRL'16; Zhong+PRL'19; Leane&Slatyer PRL'20, PRD'20; Chang+ PRD'20, Buschmann+PRD'20; FC+ 2102.12497

Correlations with stellar tracers

Macias+ Nat. Astron.'18, Bartels, FC+ Nat. Astron.'18

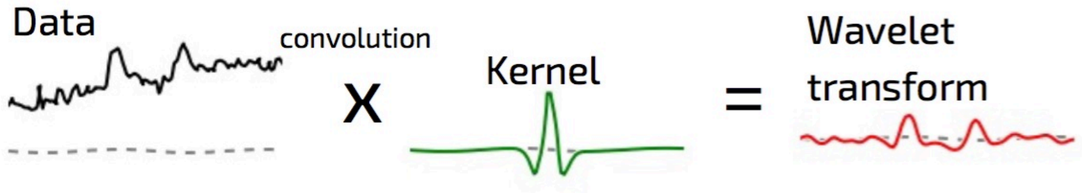
Multi-messenger signals (radio surveys, X-ray catalogs, GW stochastic bkg)

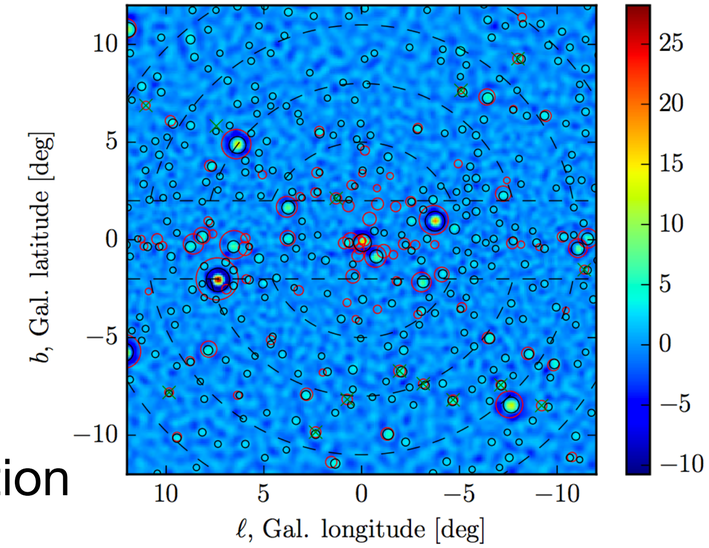
FC+ApJ'16; FC+PRL'19;
Berteaud, FC+ 2012.03580

Support for unresolved point sources (PS)

Local maxima of normalised wavelet transform

Bartels+ PRL'16

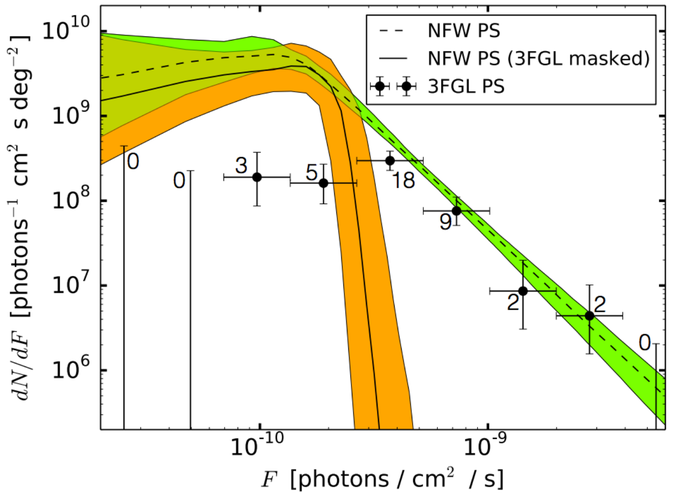


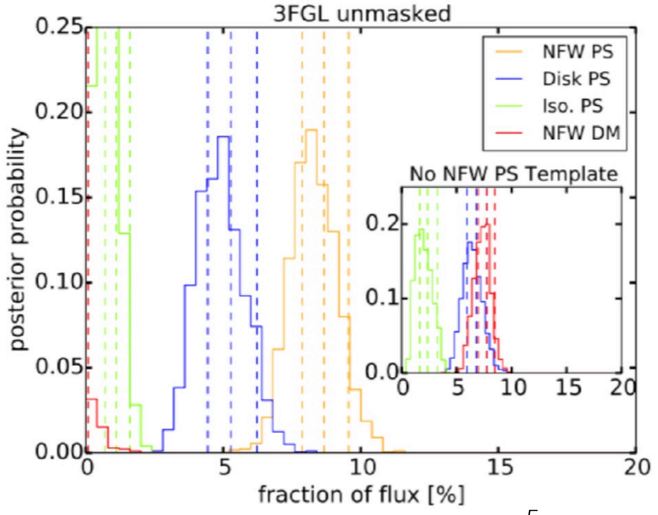


- Wavelet transform to look for **peaks** in data
- Enough peaks were found to explain the cumulative excess emission
- Evidence for unresolved PS population and constraints on luminosity function
- No modelling of diffuse emission required

Non-Poissonian template fitting

Lee+ PRL'16





- Exploits difference in photon statistics: smooth signal (DM) vs larger variance across pixels (PS)
- PS fluctuations follow non-Poissonian statistics
- Sensitivity to spatial distribution and luminosity function of PS
- Required modelling of diffuse emission

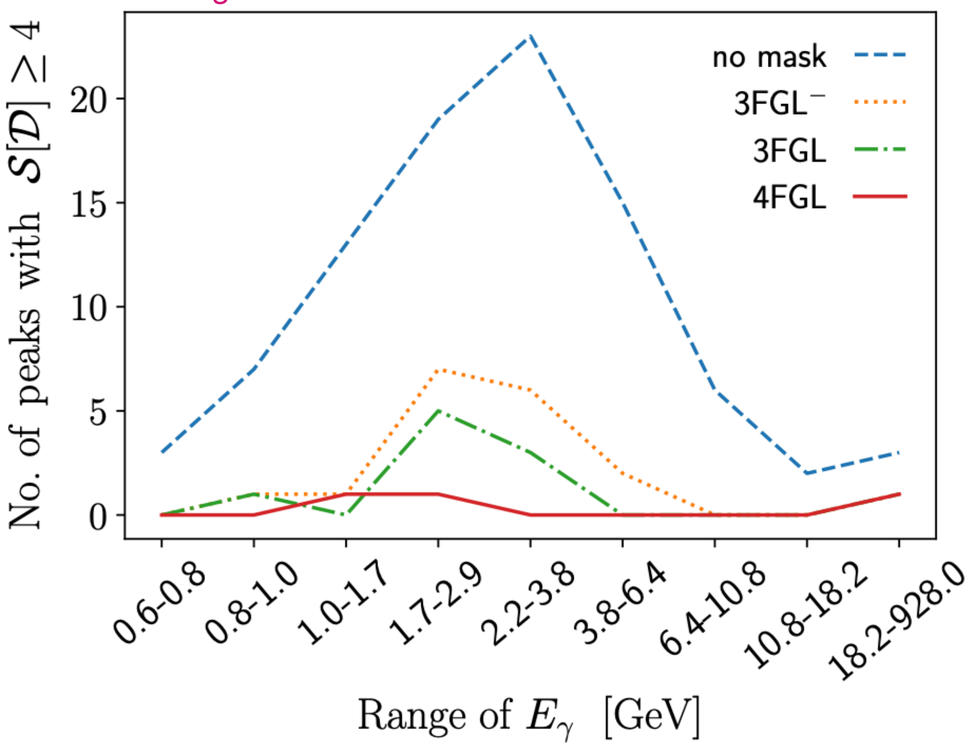
A yet to be solved debate

“Dark matter strikes back at the Galactic center?”

Measure of **power @ small scales**:

Real sources or residual structures from mis-modelling of diffuse components?

Zhong+PRL’19



Wavelets

- Analysis update with latest Fermi-LAT catalog (4FGL)
- Reduced number of wavelet peaks means more “just-below-threshold” resolved sources in new catalog
- The bulk of the excess disappears and non-resolved peaks cannot reproduce cumulative GCE emission

A yet to be solved debate

“Dark matter strikes back at the Galactic center?”

Measure of **power @ small scales**:

Real sources or residual structures from mis-modelling of diffuse components?

Non-Poissonian template fitting

- Strong effects of yet unexplored systematics

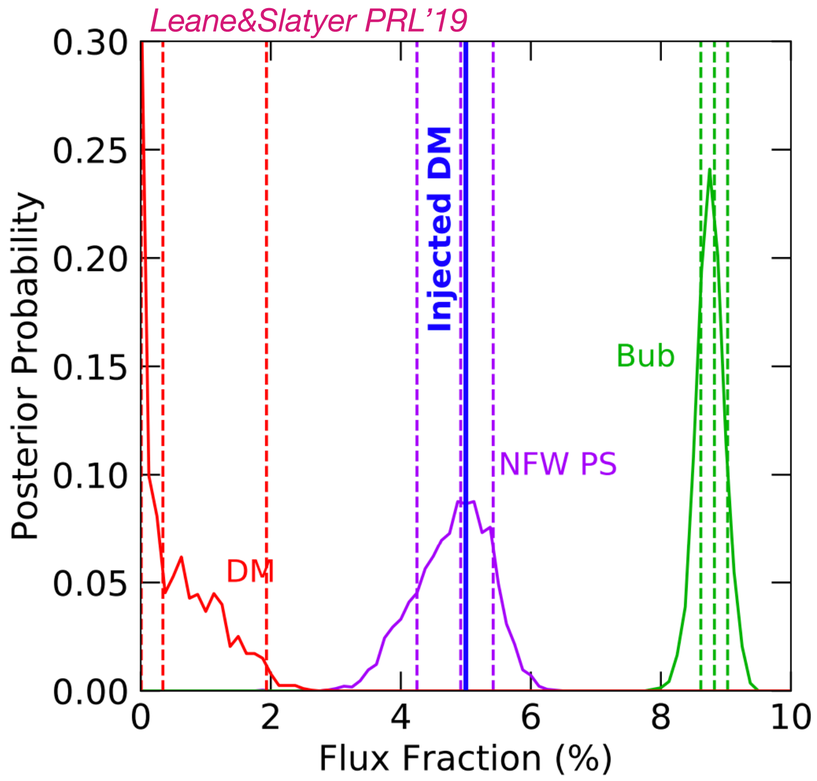
  Leane&Slatyer PRL’19; Chang+ PRD’20

- Mis-modelling of background templates
  => Mitigation of diffuse mis-modelling
  => Evidence for PS population decreased to 3σ

  Buschmann+ PRD’20

- Mis-modelling of smooth and/or PS signal
  => Increased pixel-to-pixel variance
  => Appearance of spurious PS population

  Leane&Slatyer PRL, PRD'20



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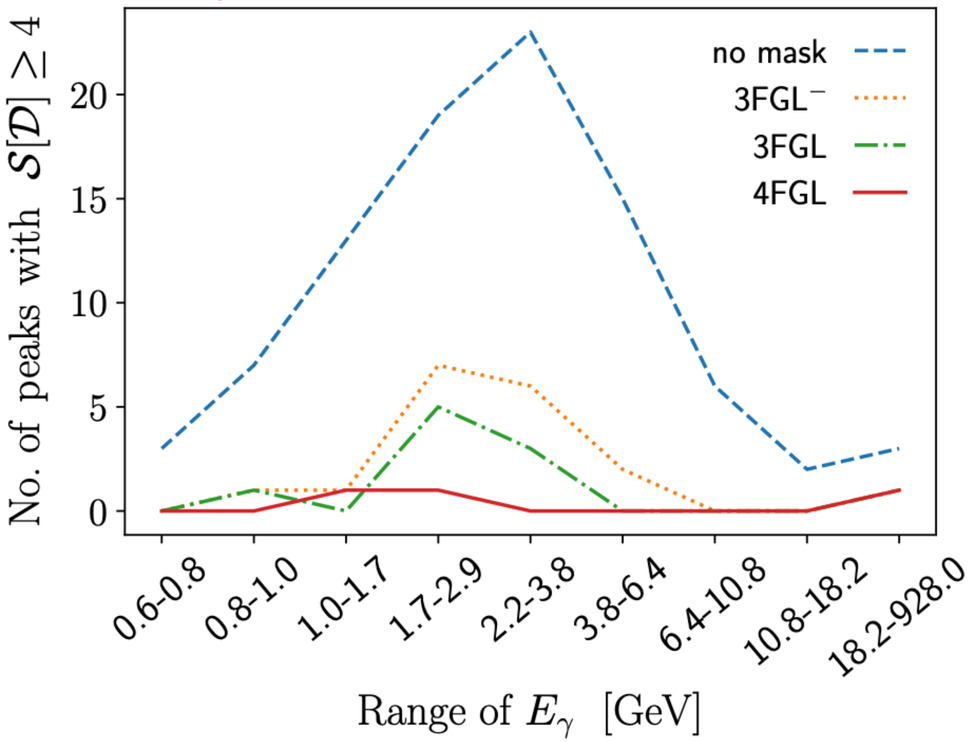
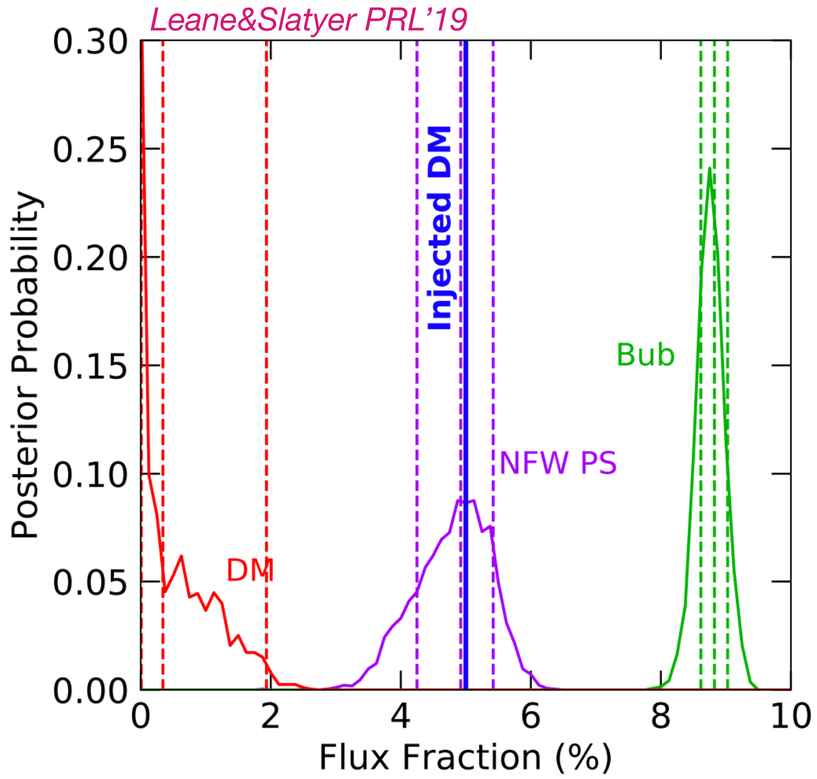


Leane&Slatyer PRL'19



[For alternative methods see: *Caron+JCAP'18* (Deep learning); *List+ 2006.12504, 2107.09070* (CNN)]

Old methods combined in a new approach

arXiv: 2102.12497

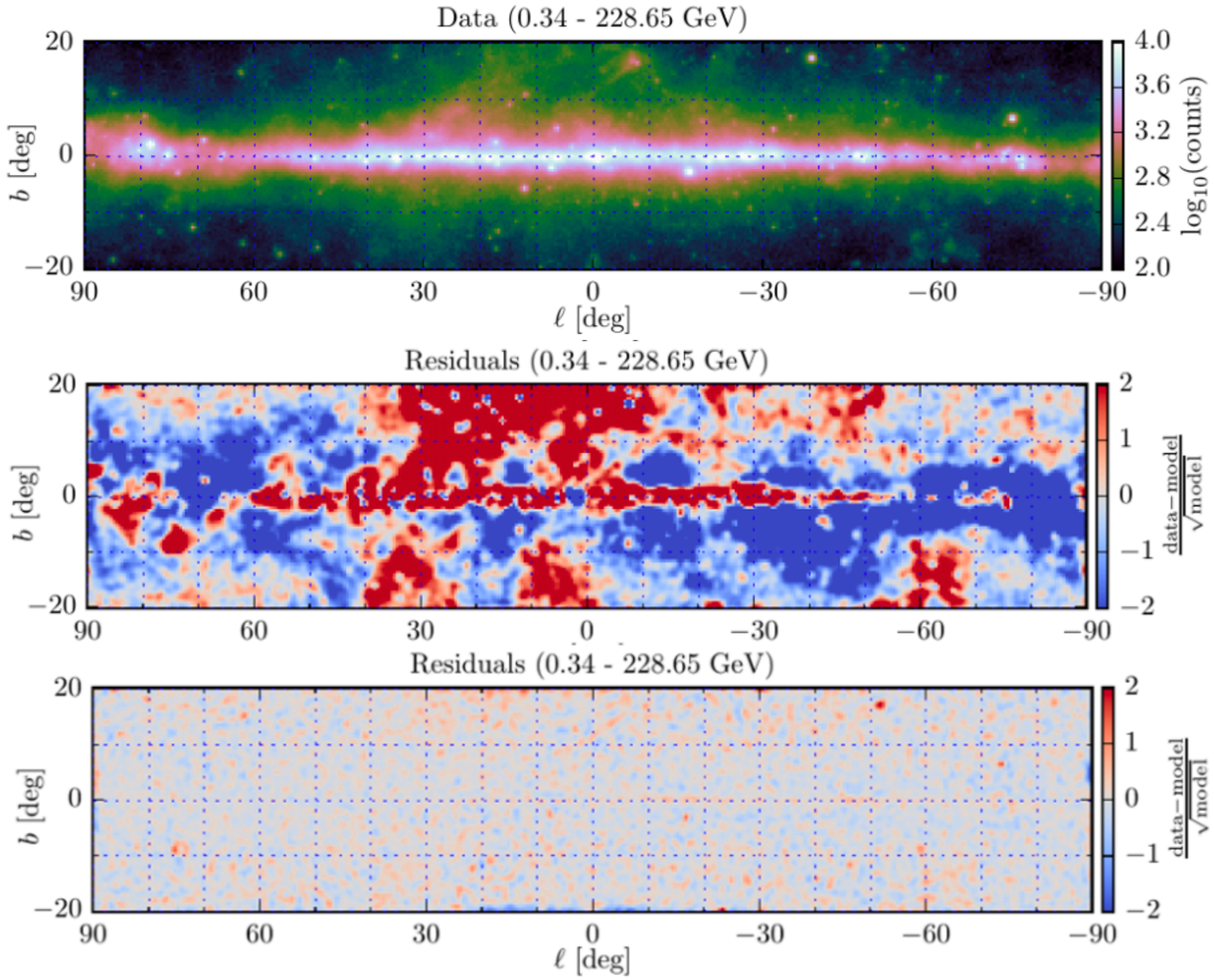
1. **Adaptive template fitting** => Better background models for the Galactic diffuse emission
2. **Photon count statistics** => Resolve more sources through the characterisation of their statistical properties

- Is all (or fraction) of Galactic Center excess coming from unresolved point sources?
- Is the morphology of the excess compatible with a bulge-like or dark matter-like emission?

Adaptive template fitting

Sky Factorisation with Adaptive Constraining Templates (SkyFACT)

Storm, Weniger & FC JCAP'17



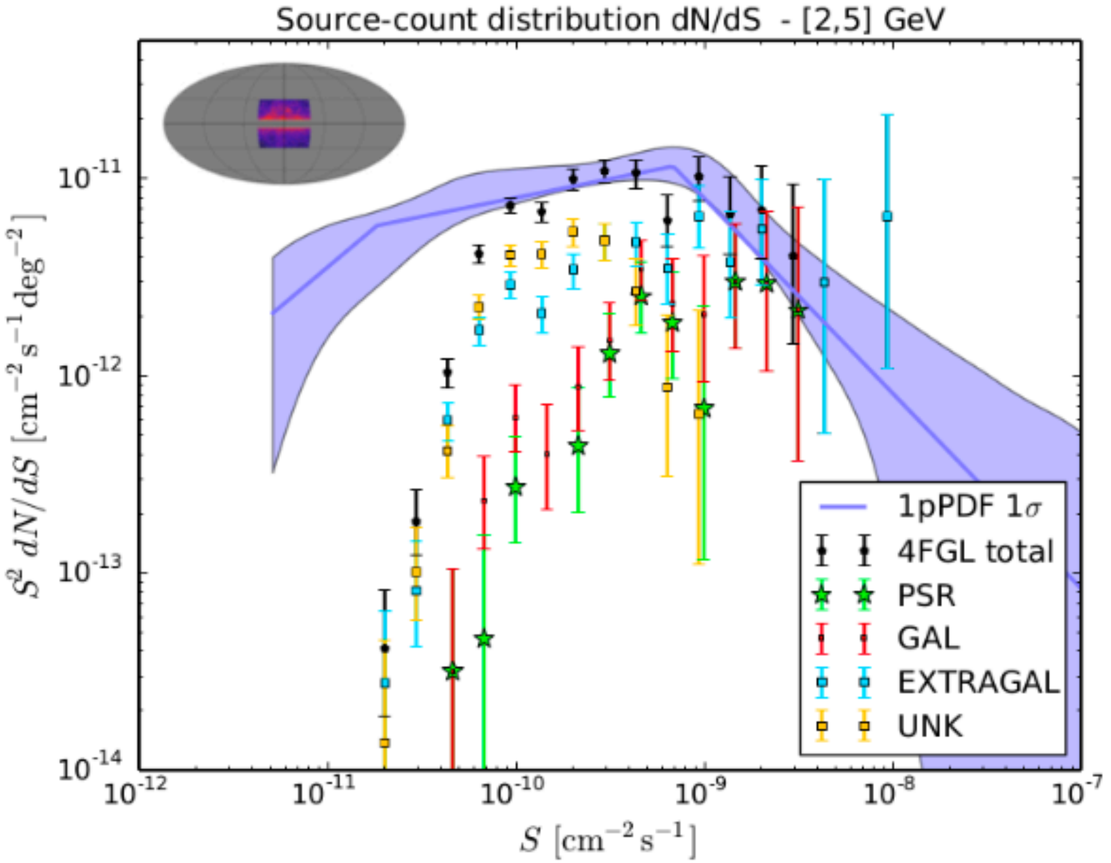
- *Standard fitting techniques*: up to 30% residuals
- **SkyFACT**: Hybrid approach combining template fitting and image reconstruction
- Can account for intrinsic uncertainties in spectral/spatial predictions by introducing *very large number of parameters* w/ regularisation conditions for the likelihood
- Still *not modelling unresolved faint sources*!

1-point probability distribution function (1p-PDF)

Statistical analysis of photon counts to decompose the gamma-ray sky and measure the source count distribution (dN/dS)

Zechlin+ApJS'16,+ApJL'16, Zechlin+PRD'18

- *Measures* the source count distribution dN/dS as a function of the gamma-ray flux
- *Extends* the sensitivity for dN/dS below the nominal Fermi-LAT catalog flux threshold
- *Decomposes* the gamma-ray sky into: point sources + Galactic diffuse emission + isotropic diffuse background + additional components (e.g. DM)

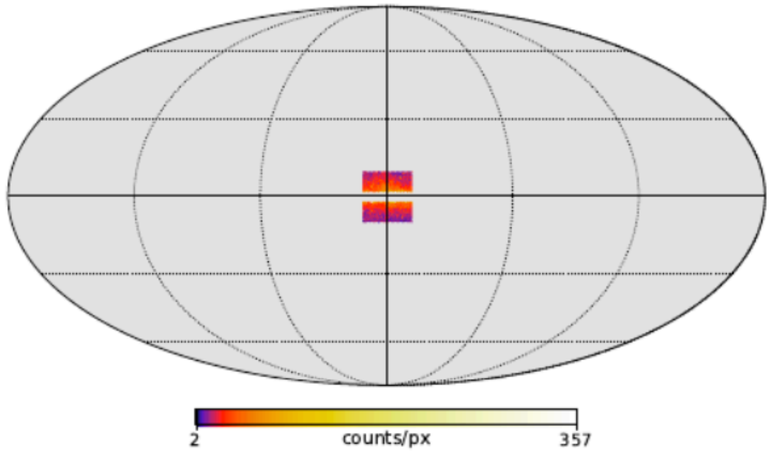


Method thoroughly tested on Fermi-LAT data

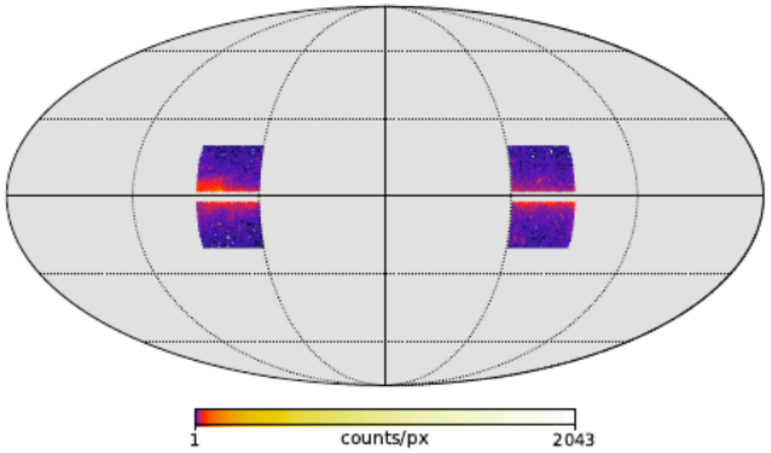
Zechlin+ApJS'16,+ApJL'16, Zechlin+PRD'18, Manconi+PRD'20, DiMauro+ApJ'18

SkyFACT+1p-PDF in the Inner Galaxy

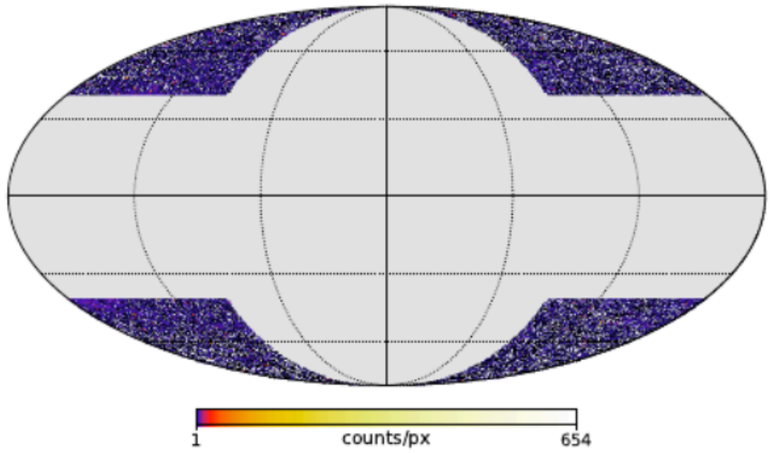
12yr of Fermi-LAT data, 2-5 GeV energy range



Inner galaxy (IG)



Outer Galaxy (OG)



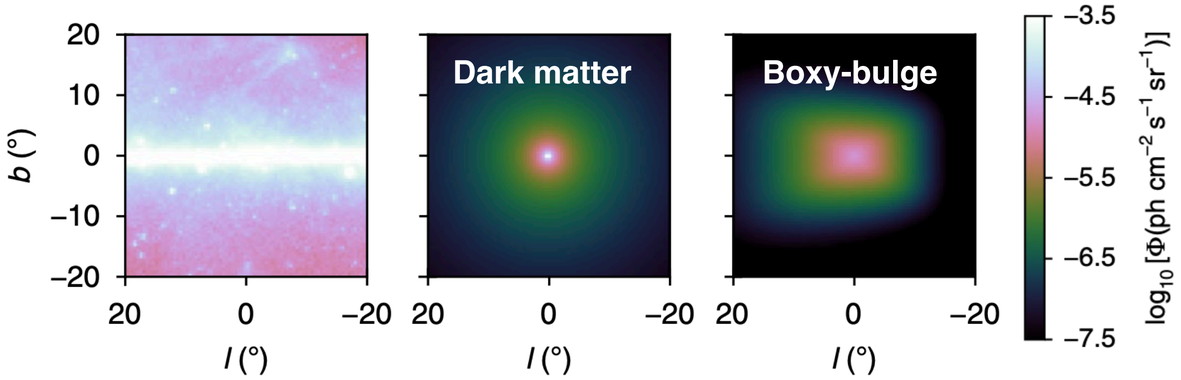
Extra-galactic (EG)

3 *regions of interest* where we characterise:

1. Diffuse Galactic emission, including a *smooth* excess template
2. Source count distribution of point sources

Results 1: Morphology of the Fermi excess

Dark matter vs stellar bulge-like distribution



Description	ln(𝒵)	Point sources/diffuse/GCE %
No GCE (both)	−6113	12/89/−
Bulge (1pPDF only)	−6076	13/81/7
DM (1pPDF only)	−6084	10/84/6
Bulge (skyFACT only)	−6169	11/89/−
Bulge (both)	−6074	13/77/10
DM (both)	−6084	11/82/7

- SkyFACT only (without unresolved sources): Stellar bulge preferred over DM at 11σ!

  Macias+ Nature Astronomy'18; Macias+ JCAP'19

- 1p-PDF: Stellar bulge + unresolved sources (> 3% of total ROI emission) at *ln(B)* ~ 95

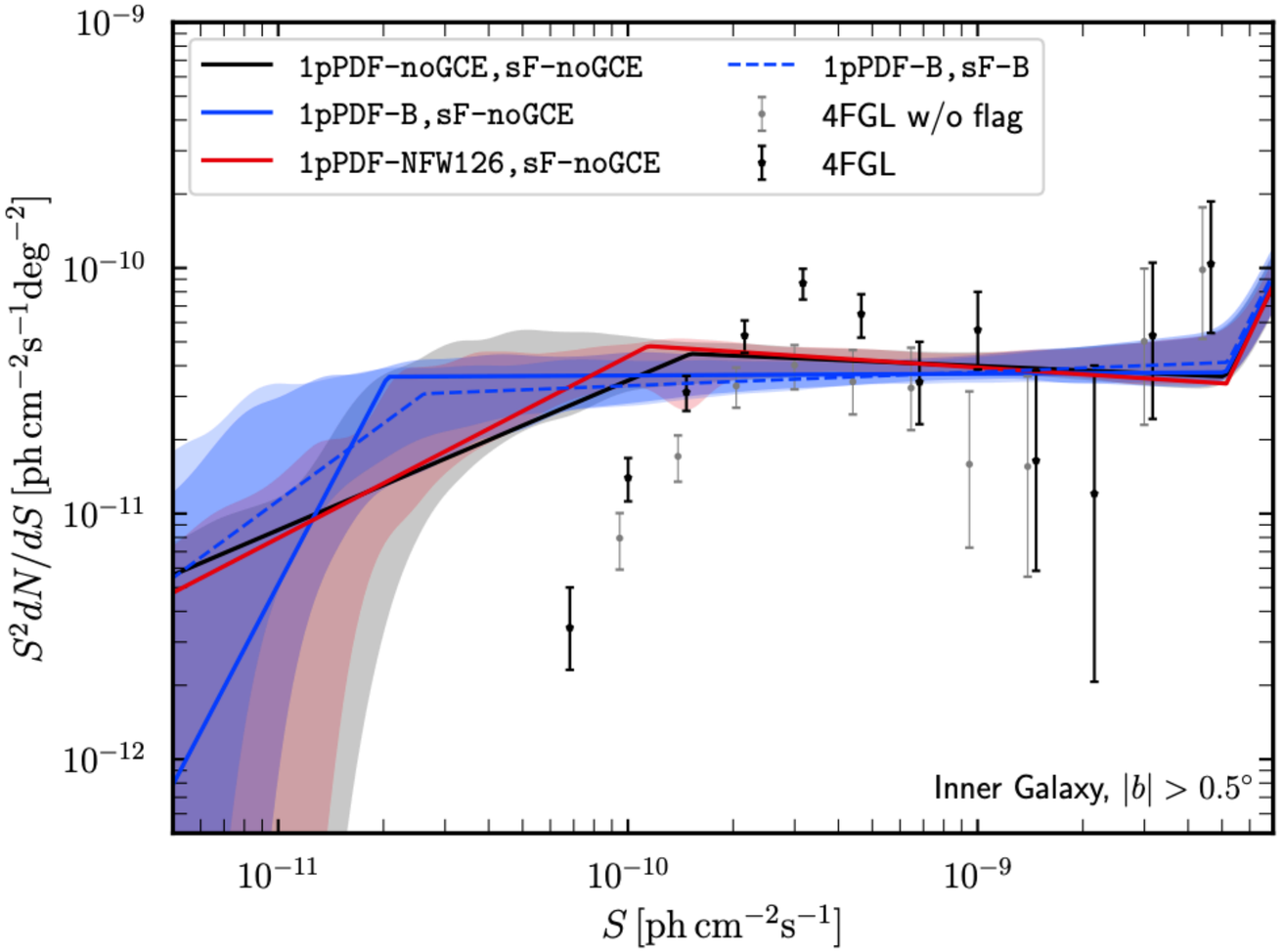
Stellar bulge morphology preferred over DM also when modelling faint point sources!

Results 2: Evidence for unresolved PS

Characterise the source count distribution of faint PS

Measure of dN/dS *below catalog flux threshold*:

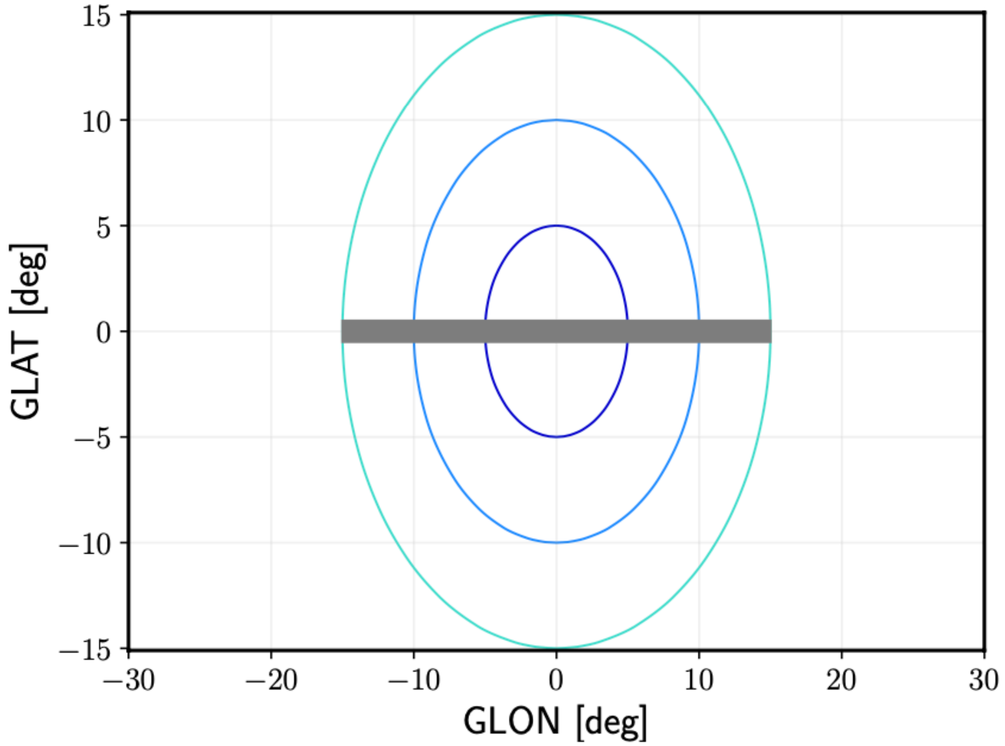
- skyFACT-optimised Galactic diffuse emission: dNdS results stable w.r.to all tested systematics
- Unresolved point sources in the inner Galaxy *resolved* down to ~ $5 \cdot 10^{-11}$ ph cm^{-2} s^{-1}

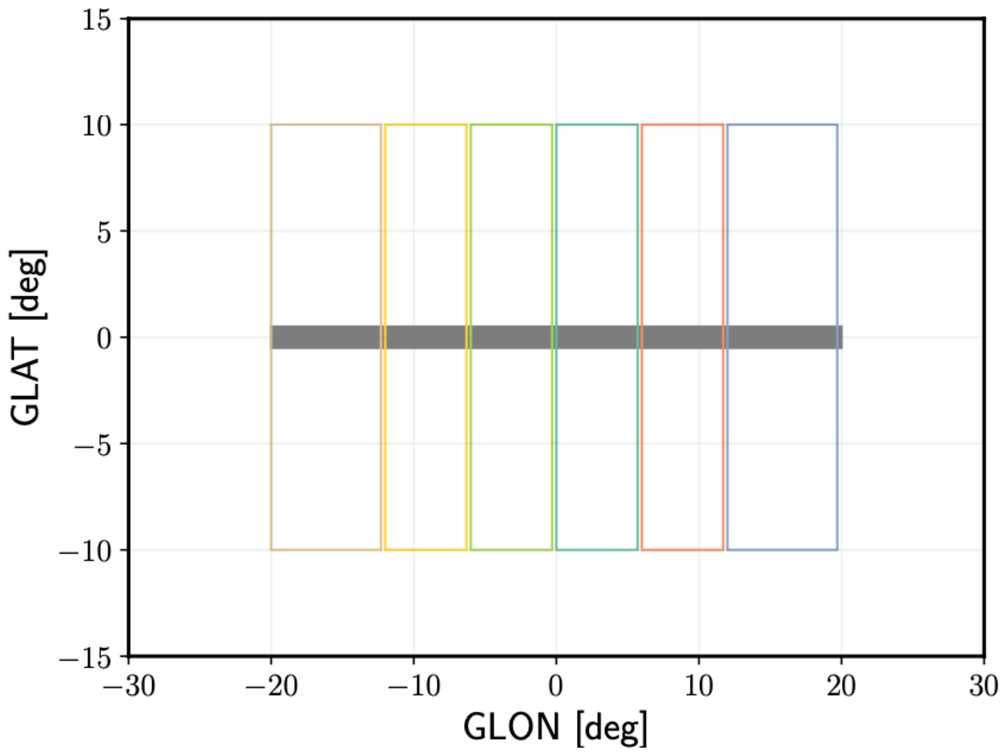


Results 3: Spatial distribution of unresolved PS

Characterise the source count distribution of faint PS

Latitude/longitude profiles: source density by integrating dN/dS in [10^{-11} ,10^{-9}] ph cm^{-2} s^{-1}





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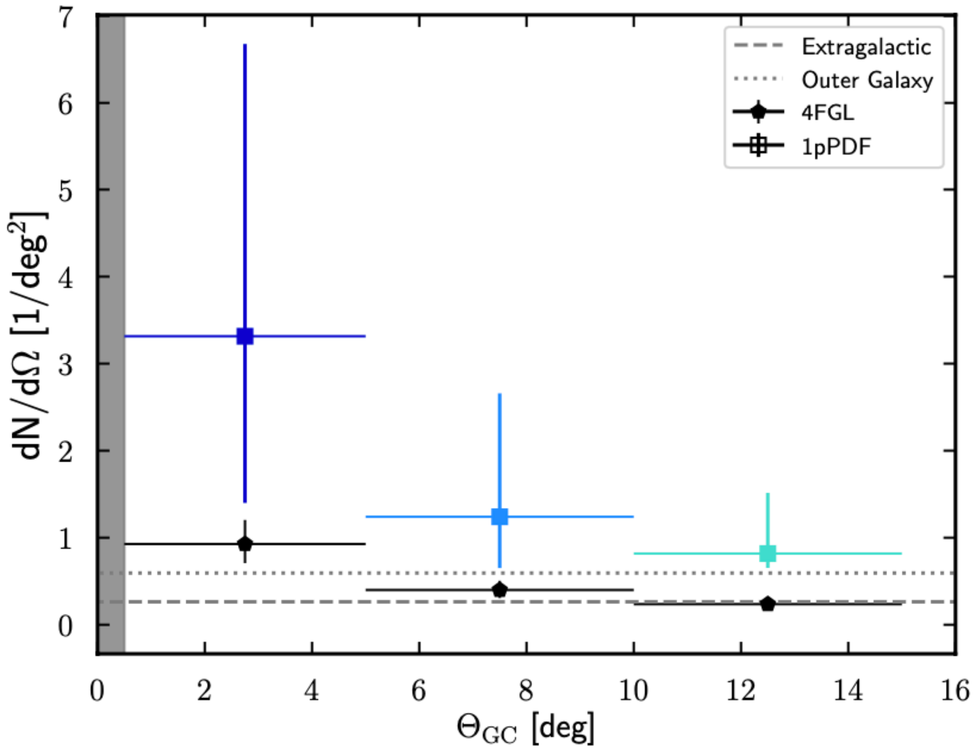

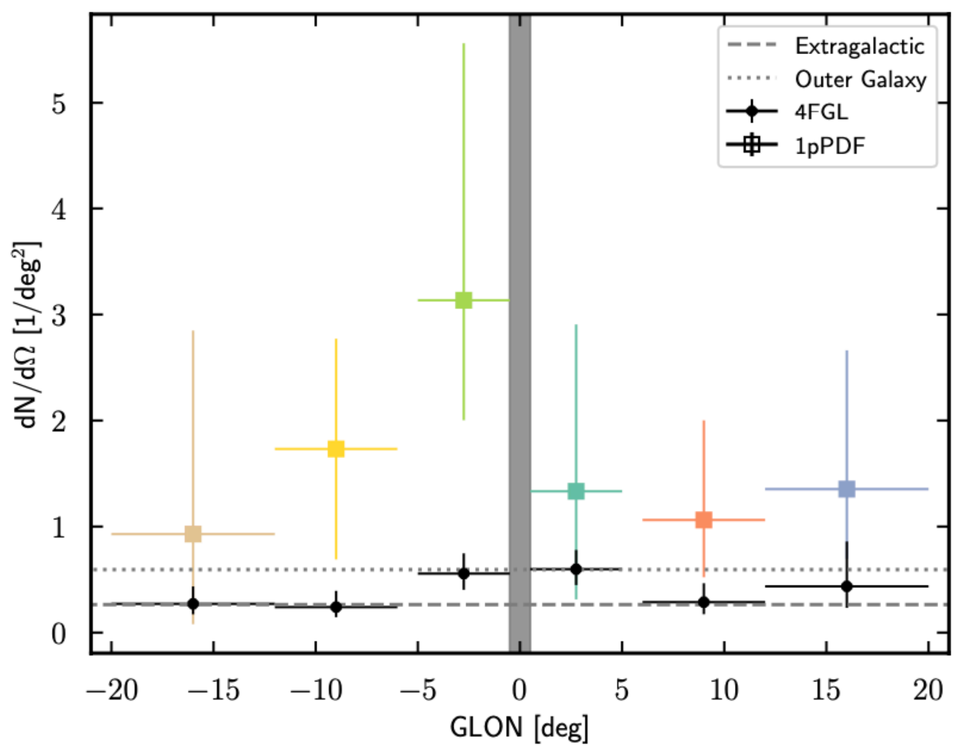

- Faint point sources are not purely isotropic: *Galactic origin*
- Corroborating a *(at least) partial stellar origin of the Galactic center excess*

Conclusions and outlook

- We apply, through a new methodological approach, adaptive template fitting (SkyFACT) *and* photon-count statistics (1p-PDF) to the inner Galaxy Fermi-LAT data
- We found evidence of stellar bulge-like morphology preferred over dark matter-based templates w/o and w/ including addition point sources
- We characterise the properties of point sources in the inner Galaxy (dN/dS and longitude/latitude profiles)
- Our results corroborate a *(at least)* partial stellar origin of the Galactic center excess

➡ Complementary techniques and multi-wavelength searches to test the excess nature:

- ✳ X-ray, gravitational waves, radio searches — *FC+ApJ'16; FC+PRL'19; Berteaud, FC+ 2012.03580*
- ✳ Very high-energy photons with CTA — *Macias+ MNRAS'21*
- ✳ DM constraints from cosmic rays — *Di Mauro & Winkler PRD'21*

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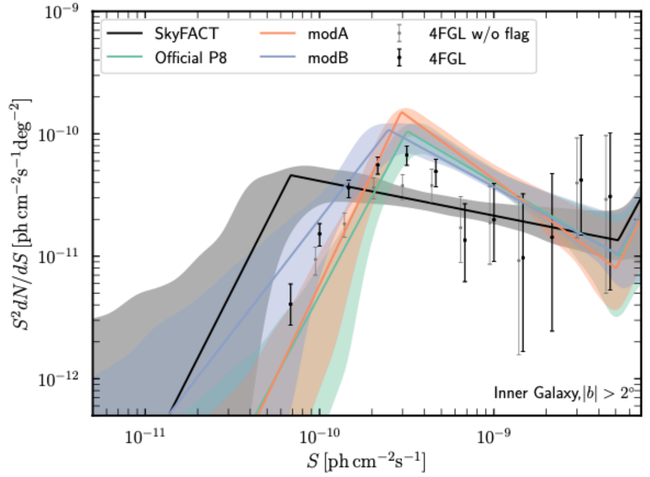
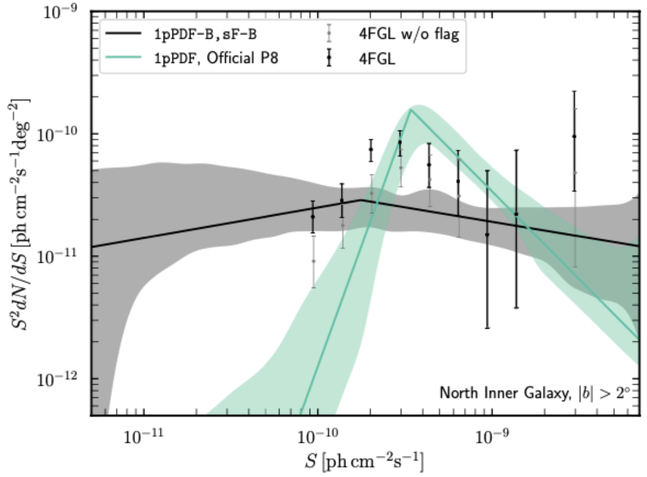
Thank you

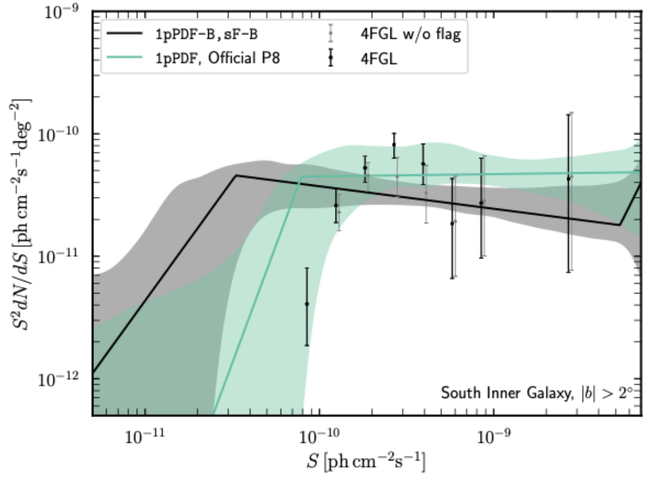
Backup

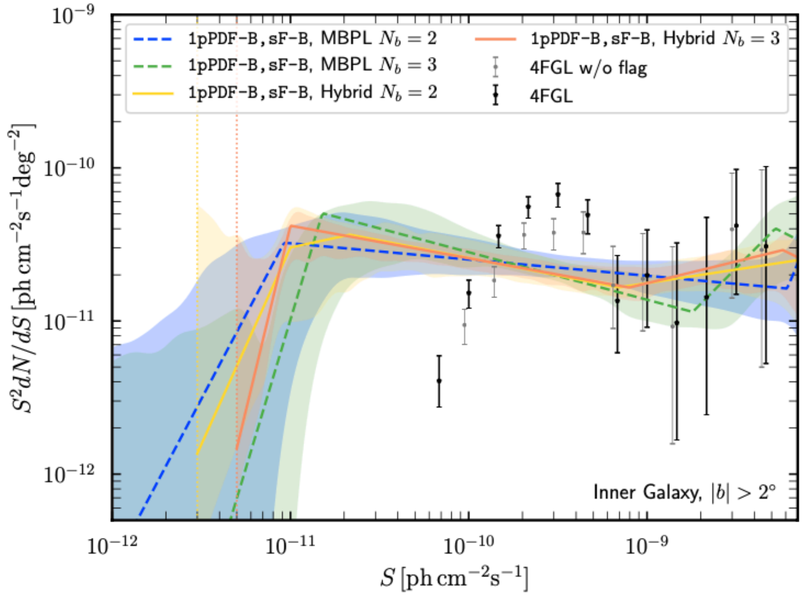
Results stability against ystematics

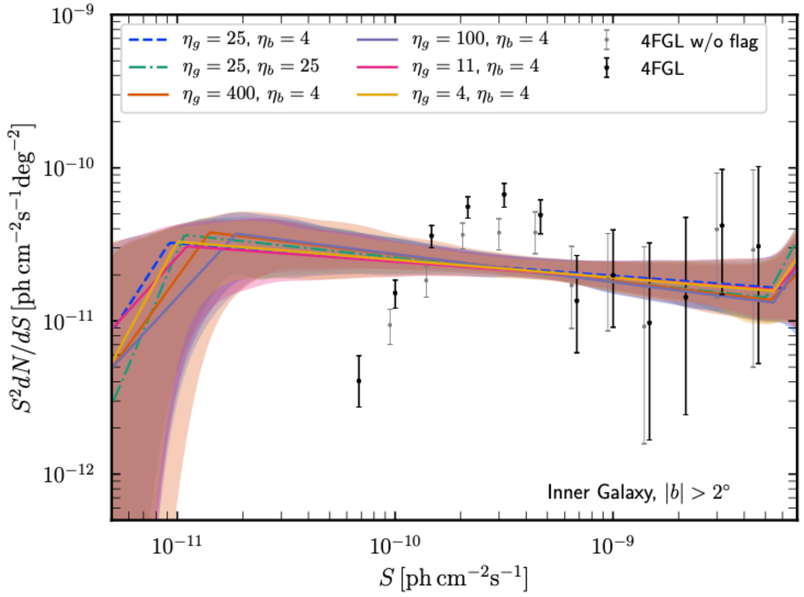
Diffuse emission mismodeling











1pDPF modeling: flux cuts, dNdS breaks

skyFACT: smoothing scale of templates