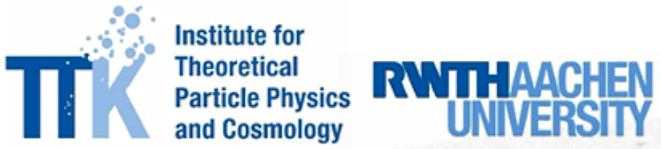


Dissecting the inner Galaxy with gamma-ray pixel count statistics

Silvia Manconi (TTK, RWTH Aachen) with F. Calore and F. Donato

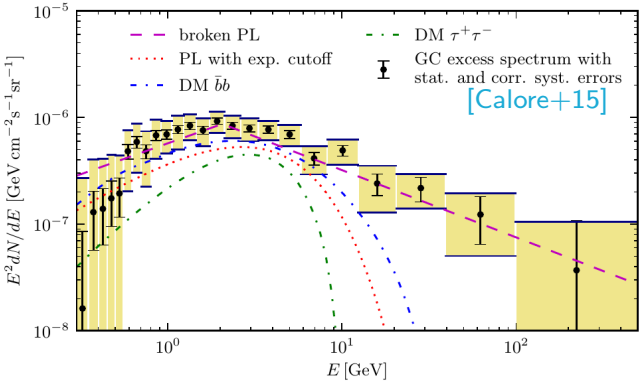
July, 2021

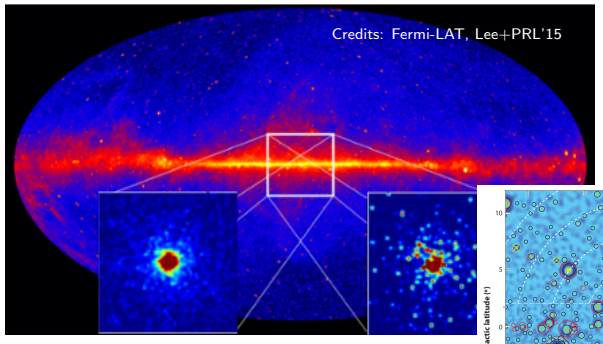
Contributed Talk @ ICRC 2021 Berlin (online)

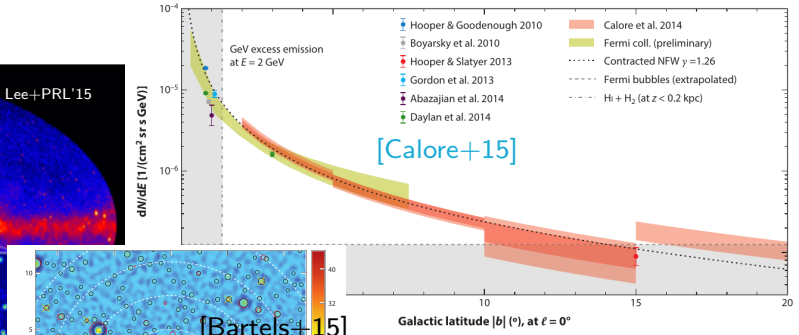
Gamma-rays from the Galactic center (and debated excess)

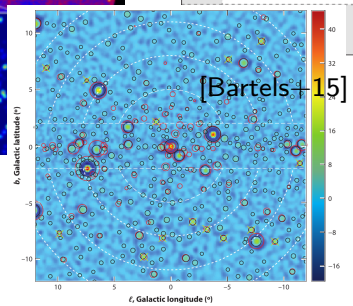
Excess in Fermi-LAT data, inner Galaxy: emission above astrophysical foregrounds and backgrounds, i.e. Galactic diffuse emission and catalog point sources

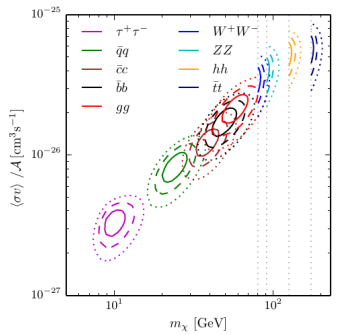
- Peculiar spectrum peaked at a few GeV
- Extended up to $\sim$ 10 degrees ($\sim$ 1.5 kpc)
- Morphology: many recent works (and this one): bulge-like, others: spherical











Leading interpretations (still debated):

- Unresolved, sub-threshold point sources, millisecond pulsar-like
- Dark matter annihilation in Galactic halo

10+ years of works: challenging to acknowledge all references. Review: [S.Murgia ARNPS'20]

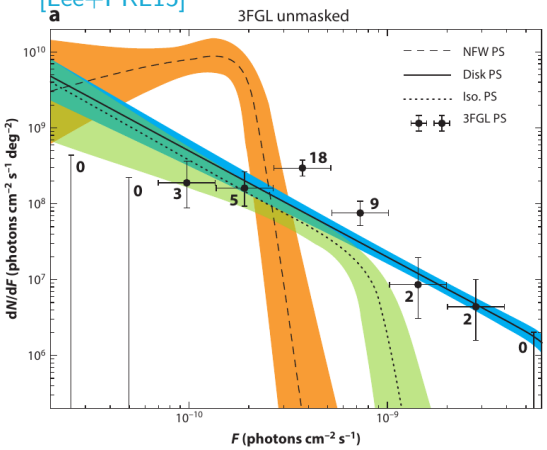
see also ICRC discussion session # 41

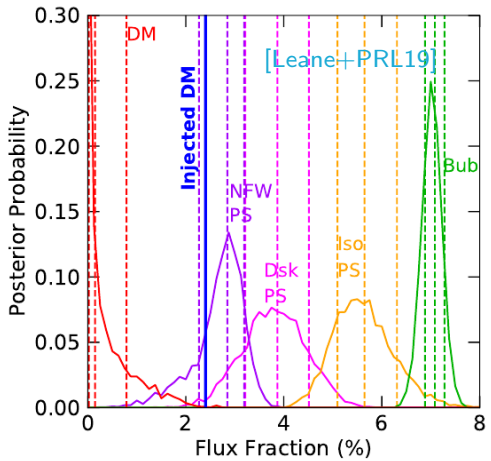
Faint sources of γ-rays at low latitudes

To model inner Galaxy in Fermi-LAT data *is a challenge*

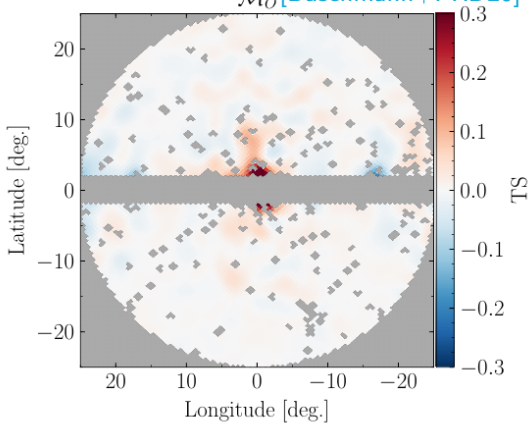
- Large uncertainties from the Galactic diffuse emission
- Many unassociated sources, many more not detected/unresolved

[Lee+PRL15]





$\mathcal{M}_O$ [Buschmann+PRD20]



Photon count statistics measure collective properties of faint sources (see later): modeling of diffuse emissions can bias results when residuals are large [Leane+PRL'19,20, Buschmann+PRD'20]

Faint sources of γ-rays at low latitudes

To model inner Galaxy in Fermi-LAT data *is a challenge*

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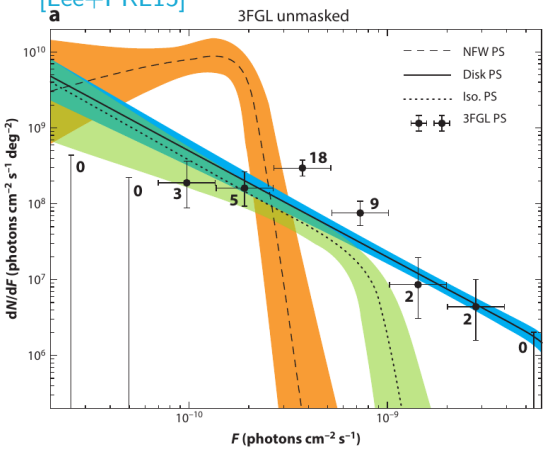
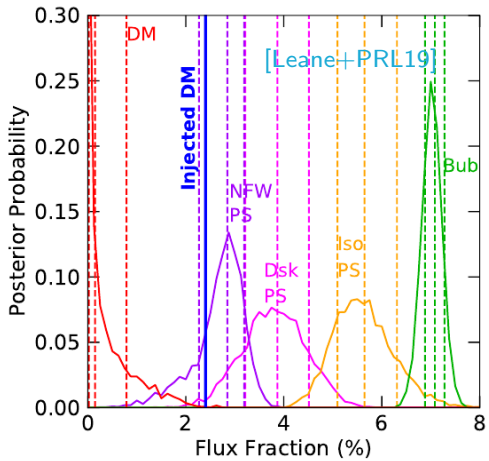
[Lee+PRL15]





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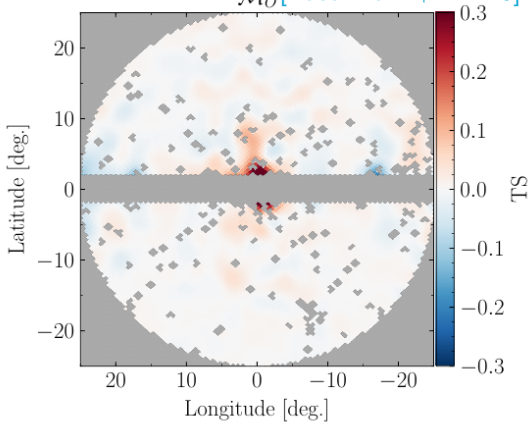


Photon count statistics measure collective properties of faint sources (see later): modeling of diffuse emissions can bias results when residuals are large [Leane+PRL'19,20, Buschmann+PRD'20]

Main roads ahead to shed light on the excess:

- **Better background models for Galactic diffuse emission** $\rightarrow$ Adaptive template fitting
- **Detect/ associate more sources** $\rightarrow$ Photon count statistics /machine learning techniques
- Complementary techniques/ wavelenghts: X-ray, gravitational waves, radio [Calore+ApJ16,PRL19,Berteaud+20], CTA [Macias+21], cosmic rays [DiMauro PRD21]

This work: arXiv:2102.12497

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?

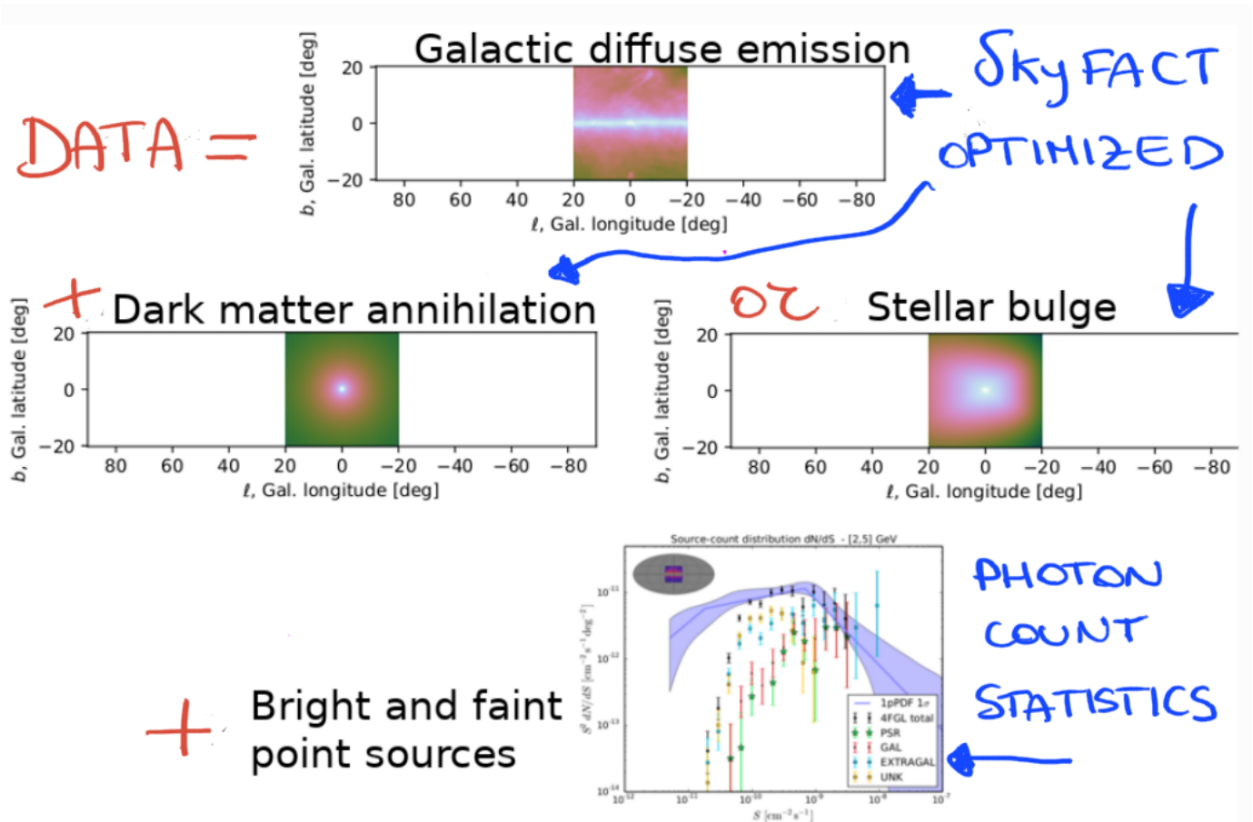
This work: arXiv:2102.12497

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?

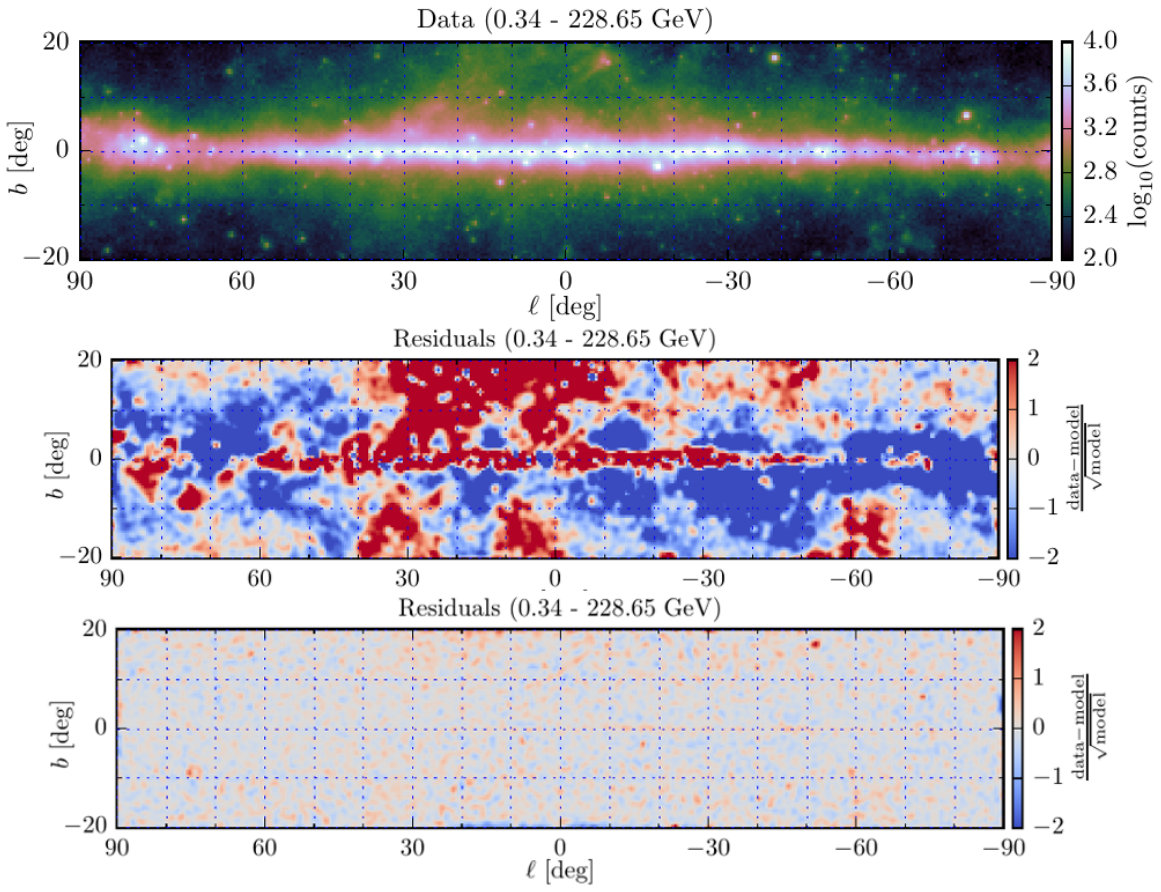
Old question, *new techniques* combining for the first time:

1. Adaptive template fitting of diffuse emissions and dark matter/stellar bulge with skyFACT
2. Photon-count statistic analysis of faint sources with optimized diffuse models



Sky Factorisation with Adaptive Constraining Templates

Model to fit Fermi-LAT data: Σ_{pixels} energy spectrum x spatial morphology



- Standard fitting techniques: up to 30% residuals!
- **SkyFACT** [Storm+JCAP'17]: account for intrinsic uncertainties in spectral/spatial predictions by introducing very large number of parameters w/ regularisation conditions for the likelihood
- *Still not modeling unresolved faint sources...*

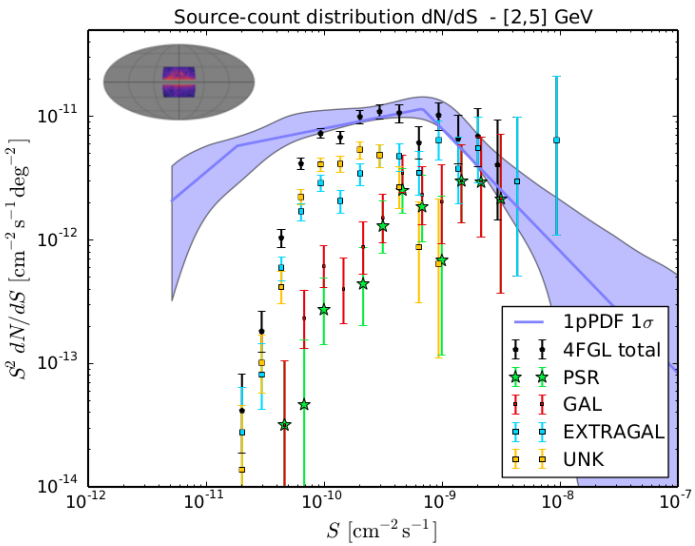
Photon count statistics with the 1-point Probability Distribution Function (1pPDF)

Statistical analysis of photon counts to decompose the γ-ray sky and measure dN/dS

Developed in: Zechlin+ApJS'16,+ApJL'16, Zechlin,SM+PRD'18

The 1-point probability distribution function (1pPDF):

- **Measures** the source count distribution dN/dS as a function of the γ-ray flux
- **Extends** the sensitivity for dN/dS **below** catalog flux threshold
- **Decomposes** the γ-ray sky into:
  1. point sources
  2. Galactic diffuse emission
  3. isotropic diffuse background
  4. additional components (dark matter?)

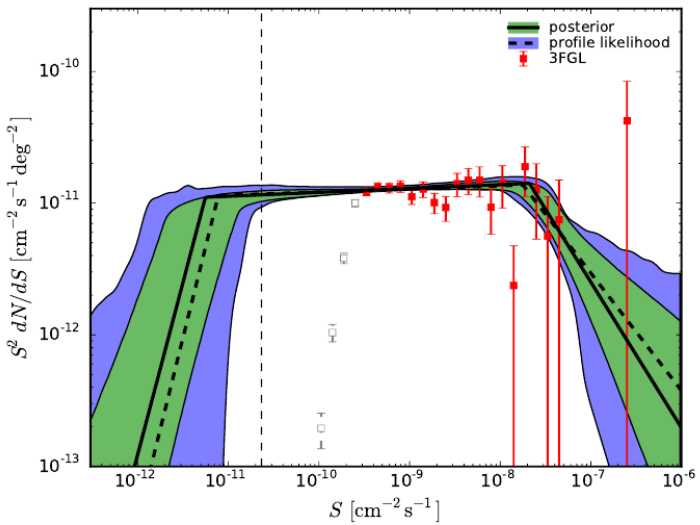


Method applied to γ-rays: [Dodelson+2009], [Malyshev,Hogg 2011]
NPTF, mainly applied at Galactic Center: [Lee+2015,2016], [Lisanti+2016], [Leane+2019], [Chang+2019]
Similar methods used also in radio [Vernstrom+MNRAS2015] and X-ray [Soltan+A&A2011]

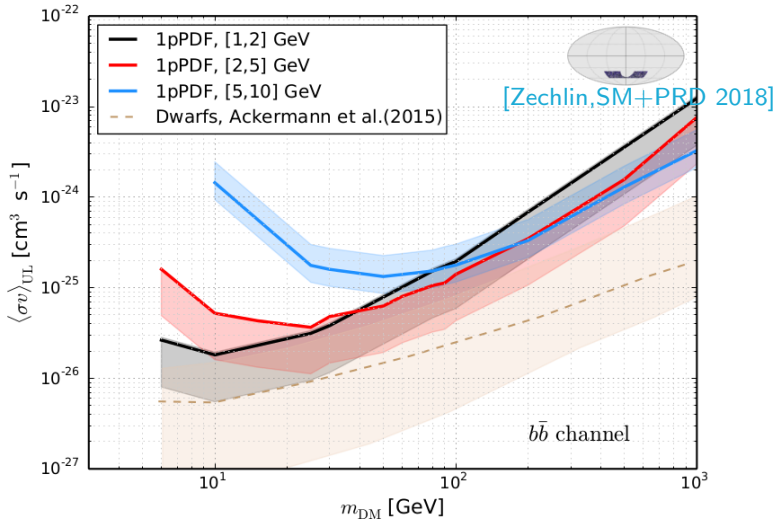
Test of 1pPDF method with Fermi-LAT data

In 1-10 GeV

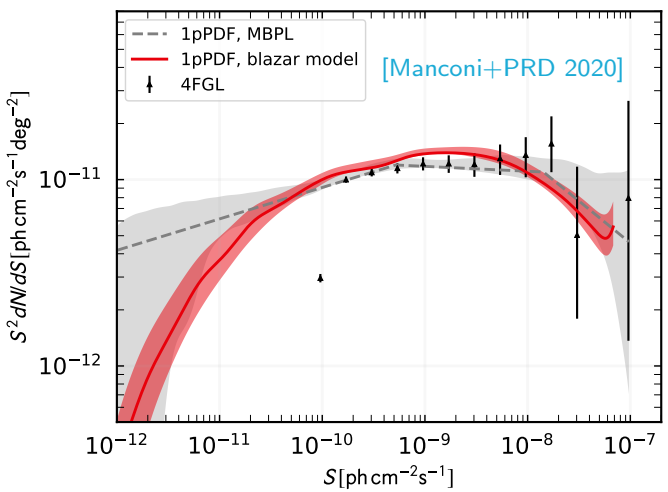
[Zechlin+ApjS 2016]



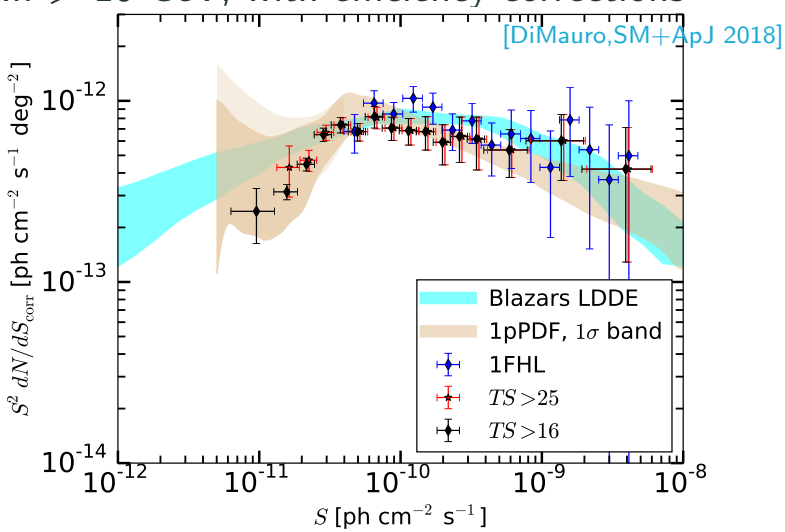
Adding a galactic dark matter template



To constrain blazar models

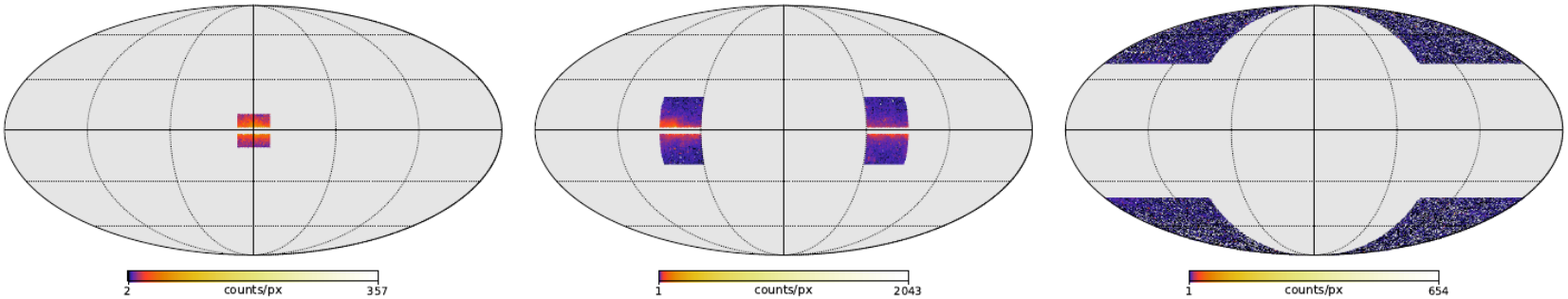


In $>$ 10 GeV, with efficiency corrections

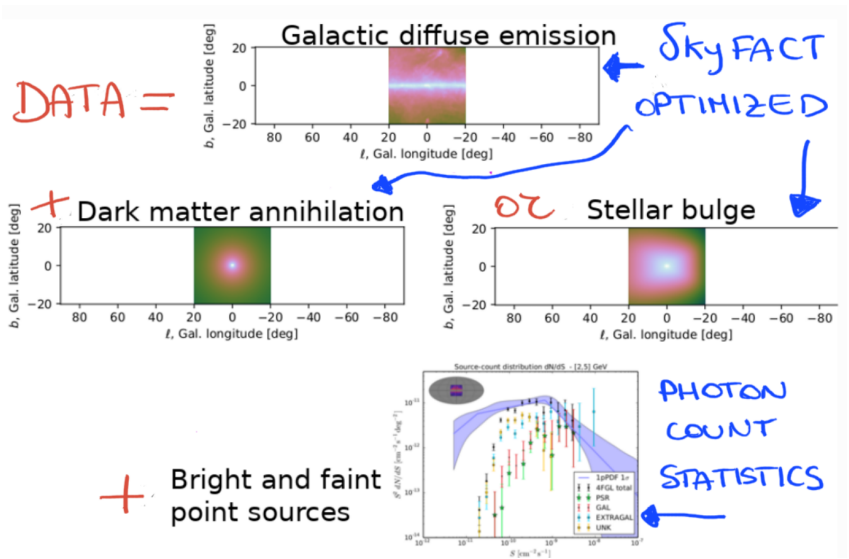


Photon count statistics+SkyFACT applied to inner Galaxy

Using 12 years of Fermi-LAT data 2-5GeV:

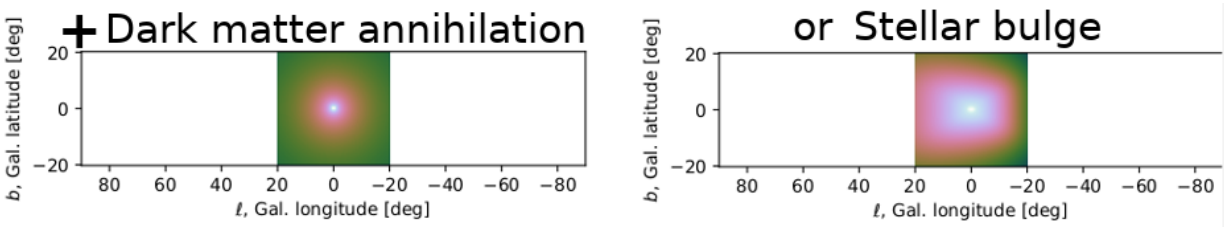


and comparing results in different regions of interests.



Inner Galaxy: morphology of the excess

Is the Galactic center excess better described by a dark matter or stellar bulge morphology?



Results:

- skyFACT only (without unresolved sources): **stellar bulge at** 11σ**!** [Bartels+Nature'18]
- Photon-count statistics: **stellar bulge at** $\mathit{ln}(B) \sim 95$
  (13% of emission) + unresolved sources ($> 3\%$)

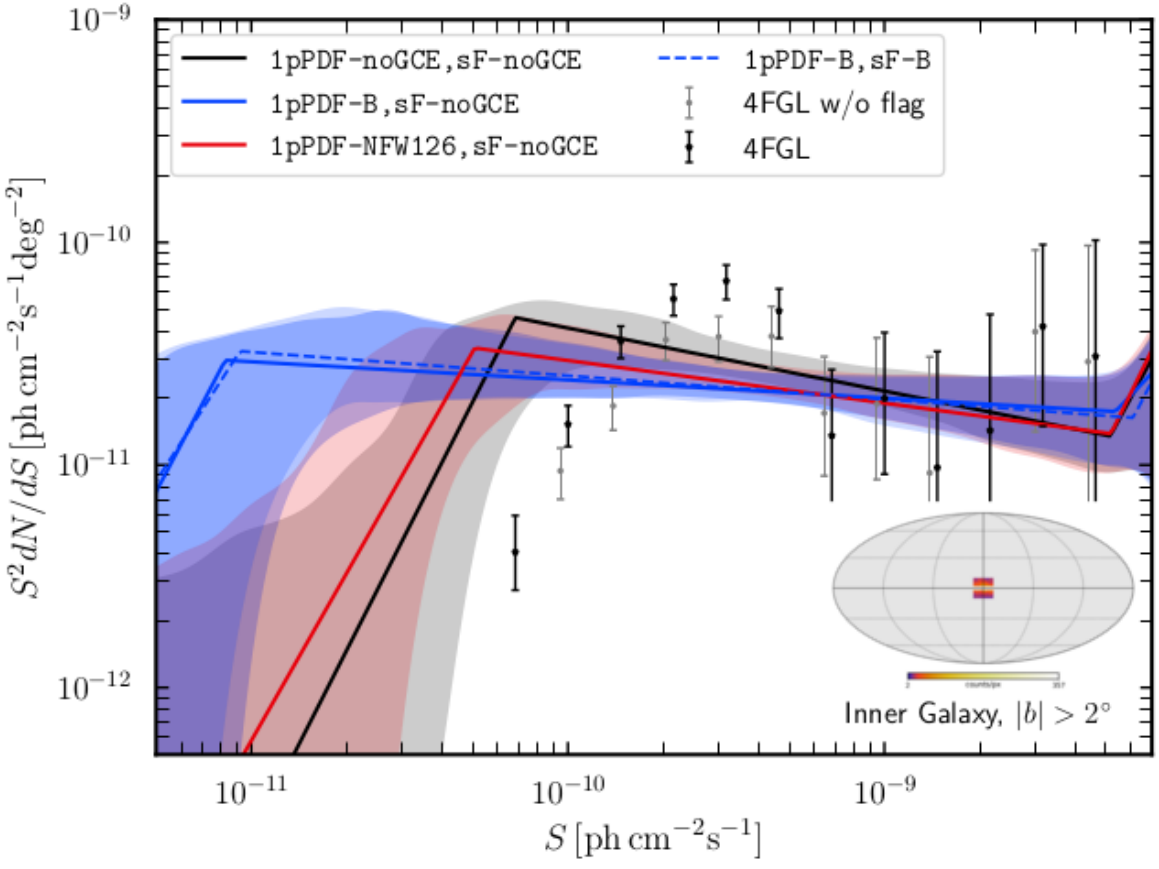
Description	$\ln(\mathcal{Z})$	Point sources/diffuse/GCE %
No GCE (both)	−6113	12/89/−
Bulge (`1pPDF` only)	−6076	13/81/7
DM (`1pPDF` only)	−6084	10/84/6
Bulge (`skyFACT` only)	−6169	11/89/−
Bulge (both)	−6074	13/77/10
DM (both)	−6084	11/82/7

Stellar-bulge morphology preferred over dark matter also when modeling faint point sources!

Inner Galaxy: results for source count distribution

Measurement of dN/dS below catalog flux threshold:

[Calore,SM+2102.12497]



- skyFACT-optimized Galactic diffuse emission: dNdS results stable wrt all tested sistematics

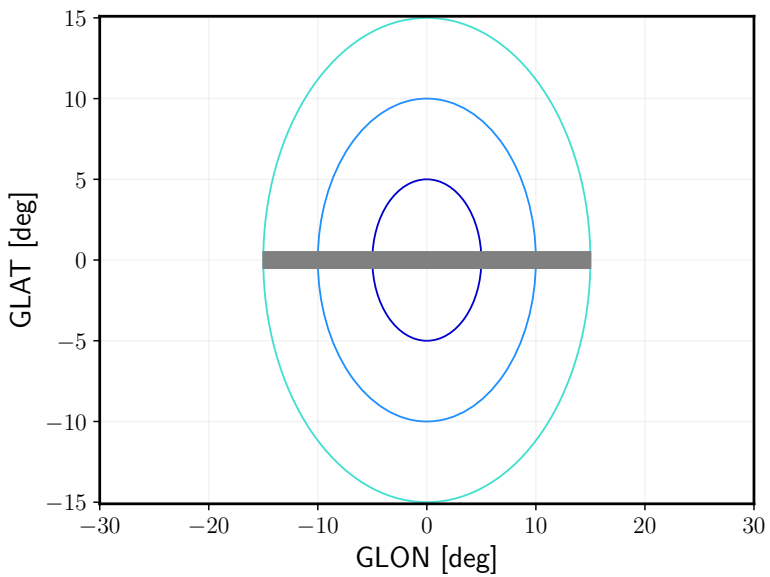
Unresolved point sources in the inner Galaxy resolved down to $\sim 5 \cdot 10^{-11}$ ph cm^{-2} s^{-1}

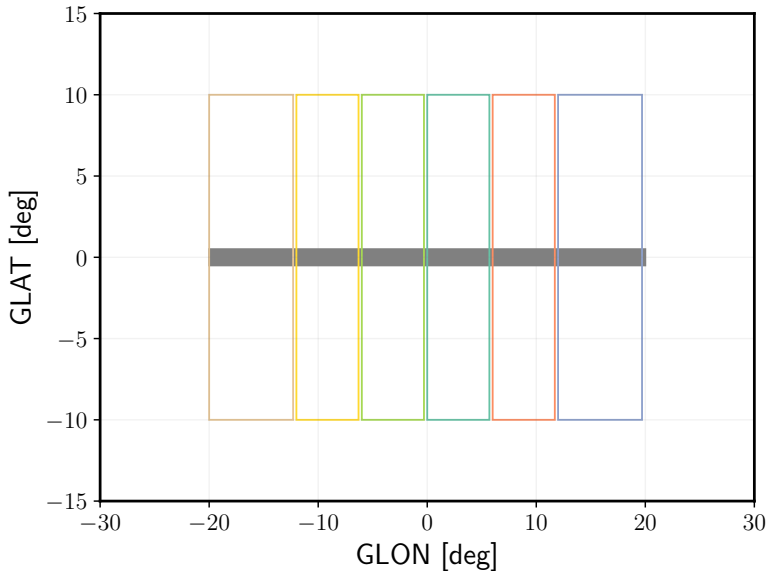
Inner Galaxy: spatial distribution of unresolved sources

1pPDF not sensitive to spatial distribution of point sources.

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

[Calore,SM+2102.12497]





- Faint point sources are not purely isotropic: *Galactic origin* likely

Corroborating a possible, (at least) partial stellar origin of the Galactic center excess

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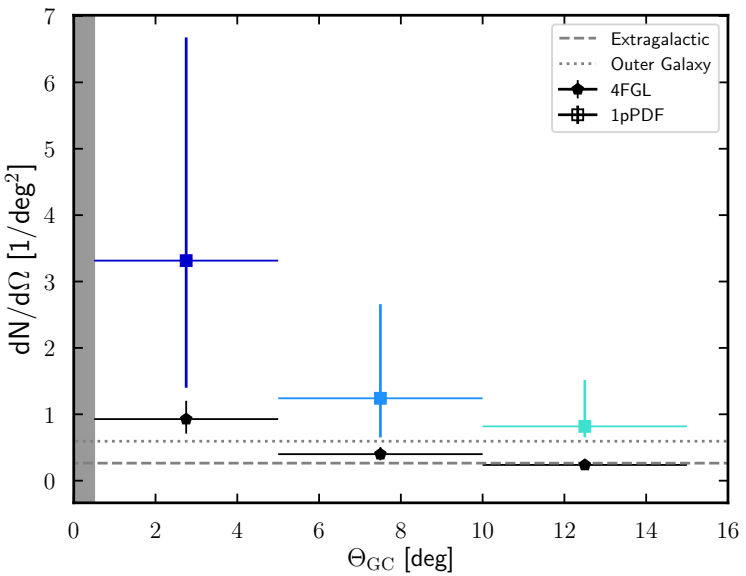
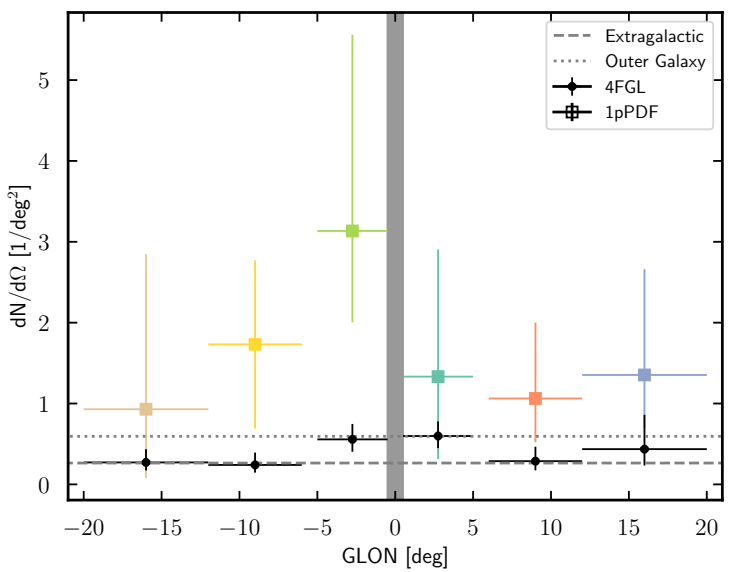
[Calore,SM+2102.12497]





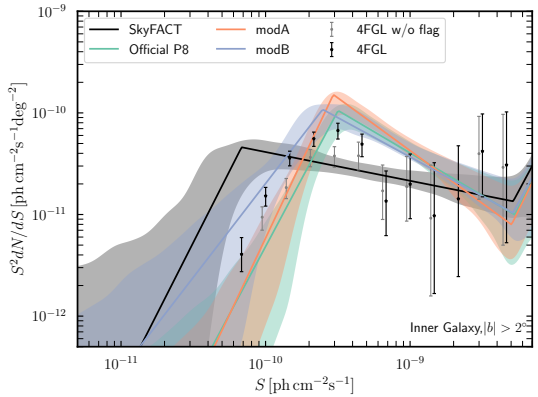
- Faint point sources are not purely isotropic: *Galactic origin* likely

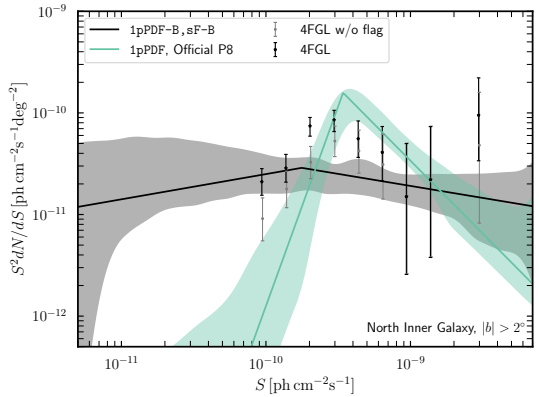
Corroborating a possible, (at least) partial stellar origin of the Galactic center excess

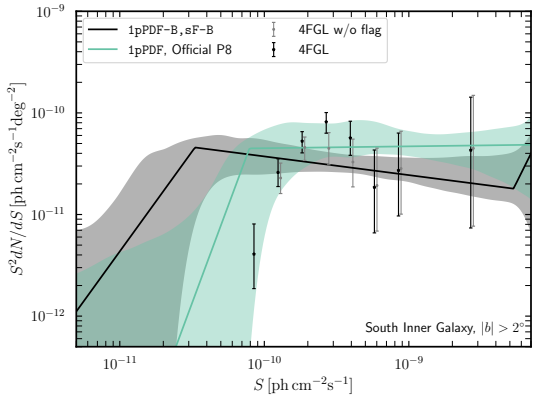
Source count distribution: systematics

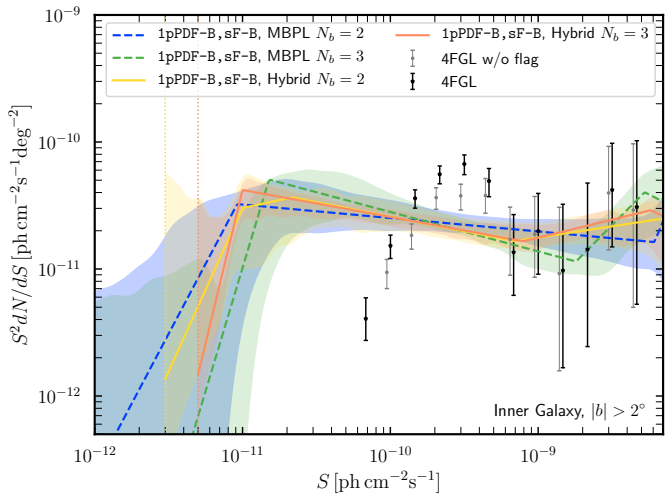
Stability of results tested against many systematics

Diffuse emission mismodeling

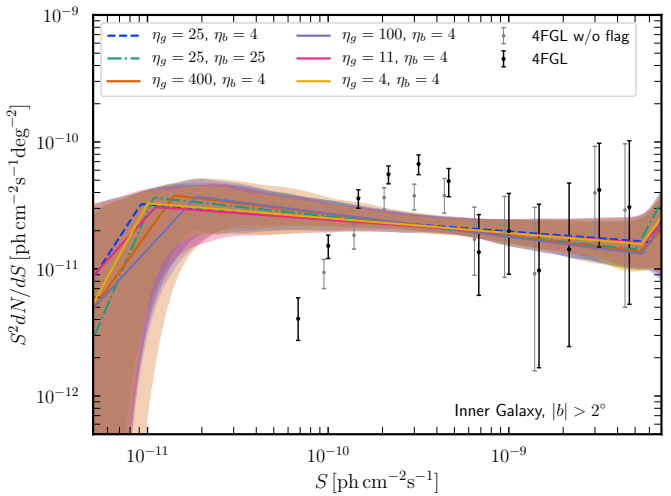








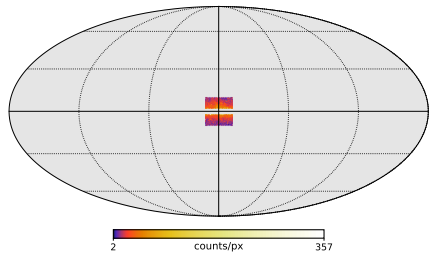
1pDPF modeling: flux cuts, dNdS breaks



skyFACT: smoothing scale of templates

Conclusions

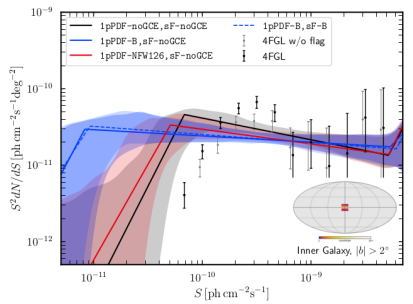
Combine adaptive template fitting (skyFACT) and photon count statistics in the inner Galaxy to understand origin of Galactic center excess

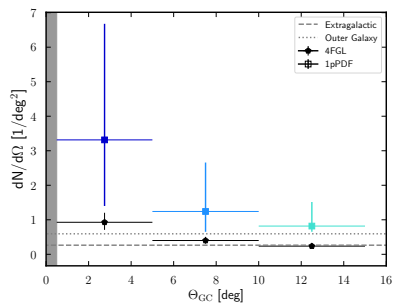


Using 12 years of Fermi-LAT data, 2-5 GeV

Properties of unresolved point sources in the inner Galaxy:

- ⋆ skyFACT background models stabilize photon count statistics analysis
- ⋆ resolved down to $\sim 5 \cdot 10^{-11}$ ph cm^{-2} s^{-1}
- ⋆ not purely isotropic: likely of Galactic origin
- ⋆ Stellar-bulge + unresolved point sources preferred over dark matter
- ⋆ Results stable against many systematics





Corroborating a possible, (at least) partial stellar origin of the Galactic center excess in Fermi-LAT data

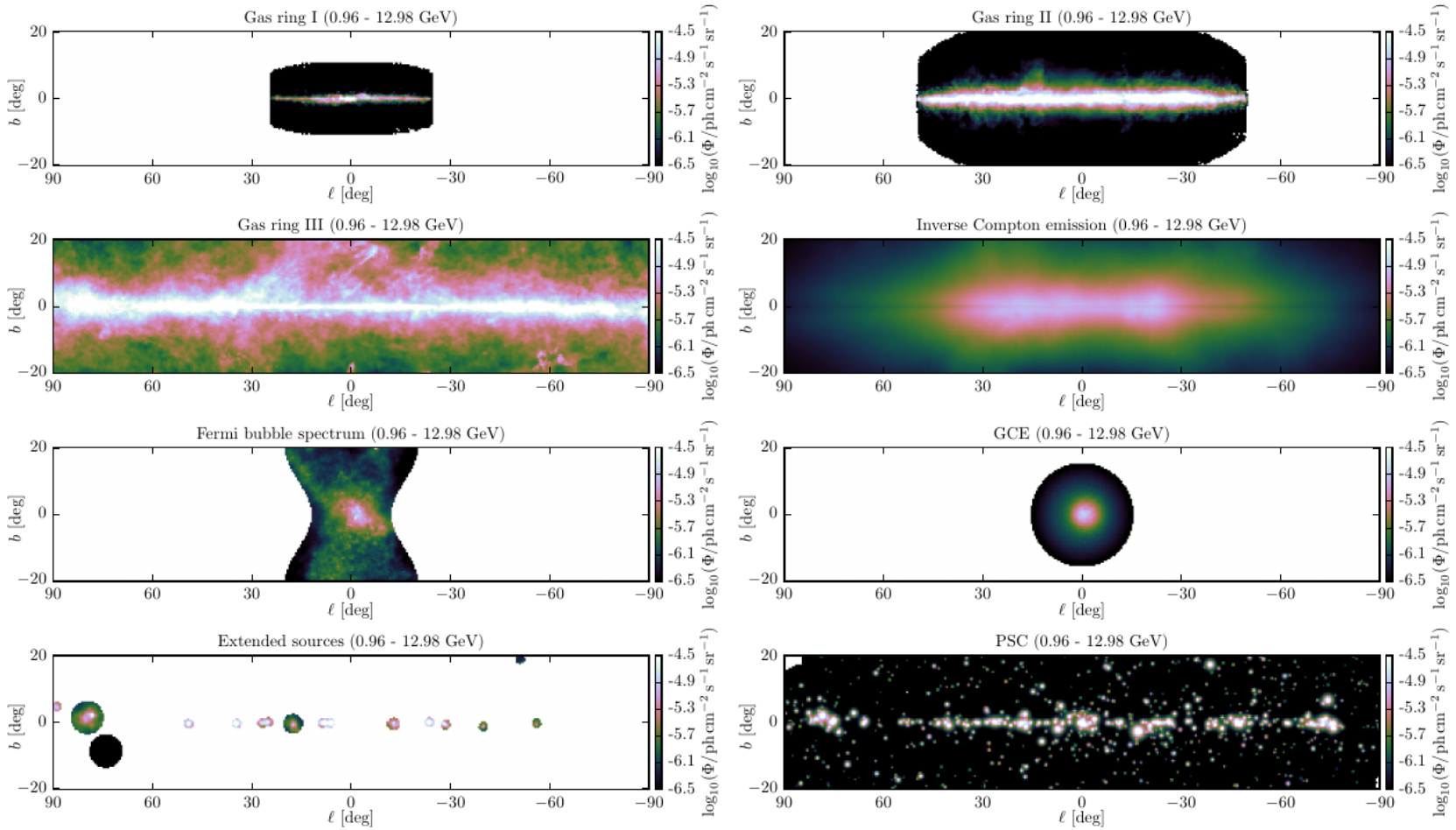
thank you for the (virtual) attention!

BACKUP

Sky Factorisation with Adaptive Constraining Templates

Model to fit Fermi-LAT data: Σ_{pixels} energy spectrum x spatial morphology

Templates: map-cube with spectrum and morphology: [Storm+JCAP'17]

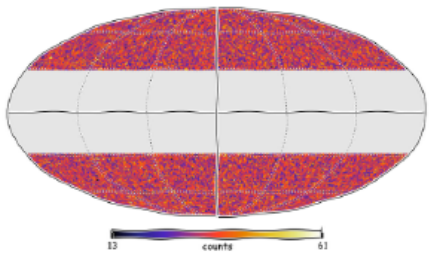


Photon count statistics of Fermi-LAT data

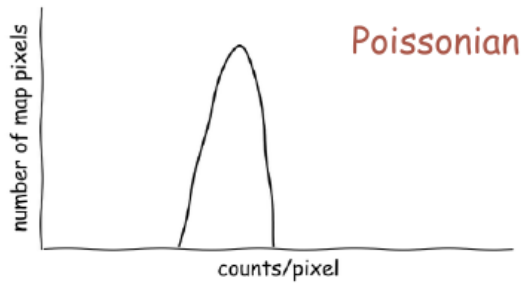
Separate sources based on statistical properties of their photon counts

Examples: courtesy of H. Zechlin

(A) diffuse isotropic background

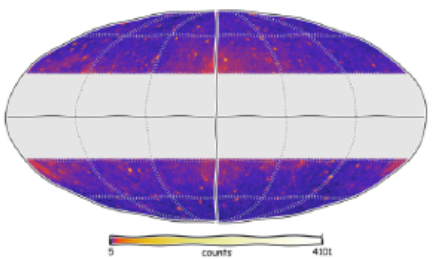


1p-PDF

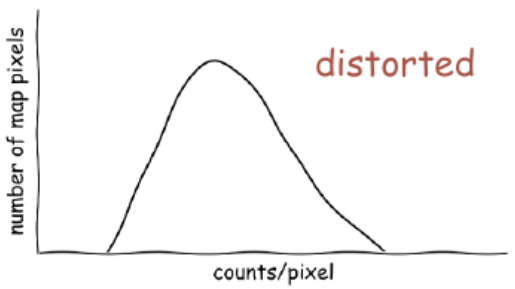


- not to scale -

(B) adding point sources, Galactic foreground, …



1p-PDF



The 1pPDF analysis - (technical)

1p-PDF= $p_k^{(p)}$, probability to find k photons in a given pixel p; n_k= # pixels counting k photons
Exploting the method of generating functions introduced in [Malyshev+ApJ2011]

Modeling: *probability generating functions* $\mathcal{P}^{(p)}(t)$*:*

$$p_k^{(p)} = \frac{1}{k!} \left. \frac{\mathrm{d}^k \mathcal{P}^{(p)}(t)}{\mathrm{d}t^k} \right|_{t=0}$$

OBSERVED
Probability distribution of photon counts in pixels $p_k^{(p)}$

$\Longleftrightarrow$

WANTED
Decompose γ-ray sky in:
-Point sources dN/dS
-Diffuse contributions

$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k = \exp\left(\sum_{m=1}^{\infty} x_m^{(p)} (t^m - 1) \right)$$

$x_m^{(p)}$ = **expected number of sources contributing** m **photons per pixel** p:

- point sources (dN/dS)
- Galactic diffuse emission
- Diffuse isotropic background
- Dark matter

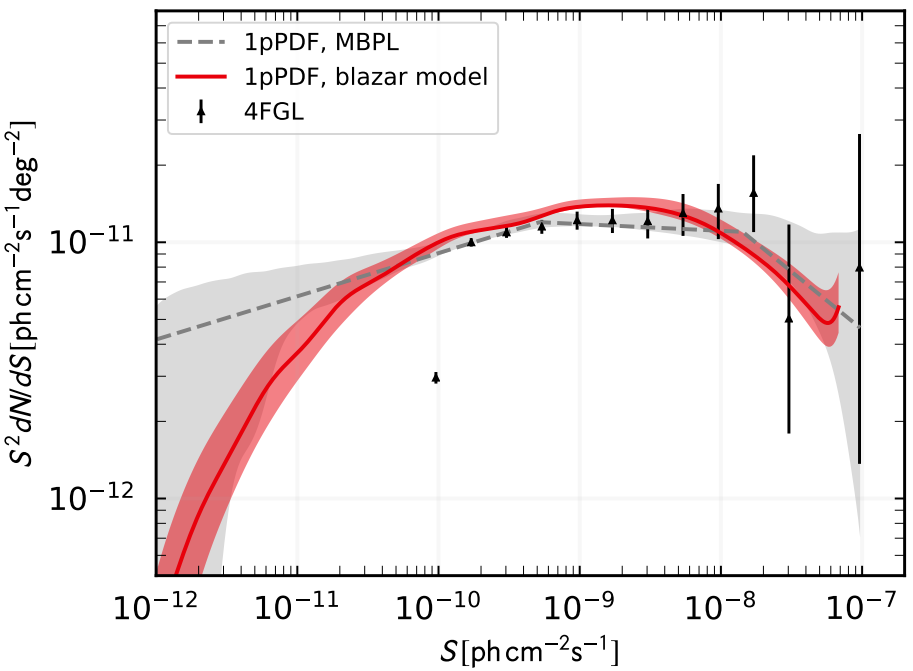
1pPDF constraints to Blazar model

Fit to Fermi-LAT observed photon counts with 1pPDF, blazar source counts:

$$\frac{dN}{dS} = \int_{0.01}^{5.0} dz \int_{1}^{3.5} d\Gamma \Phi[L_\gamma(S_{\rm E}, z, \Gamma), z, \Gamma] \frac{dV}{dz} \frac{dL_\gamma}{dS}$$

10 yrs data, $|b| > 30$ deg, 1-10 GeV

[Manconi+PRD101 (2020)]



- 1pPDF measures point sources below catalog flux threshold
- Blazar model is a good fit for observed photon counts down to $S \sim 10^{-12}$ph cm^{-2} s^{-1} deg^{-2}
- dN/dS from blazar model and MBPL are compatible

$\Rightarrow$ We extend understanding of Blazar model to unresolved γ-rays with 1pPDF