Unresolved gamma-ray point sources in the inner Galaxy at $E > 10$ GeV

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September 14, 2023

TeVPA 2023, Naples (IT)

The gamma ray Galactic Center Excess (GCE)

Statistically significant excess in Fermi-LAT data [talk by D.Hooper]
few % of inner Galaxy flux

Debated nature:
Millisecond pulsar-like (MSP) in Galactic Bulge vs. Dark Matter (DM)

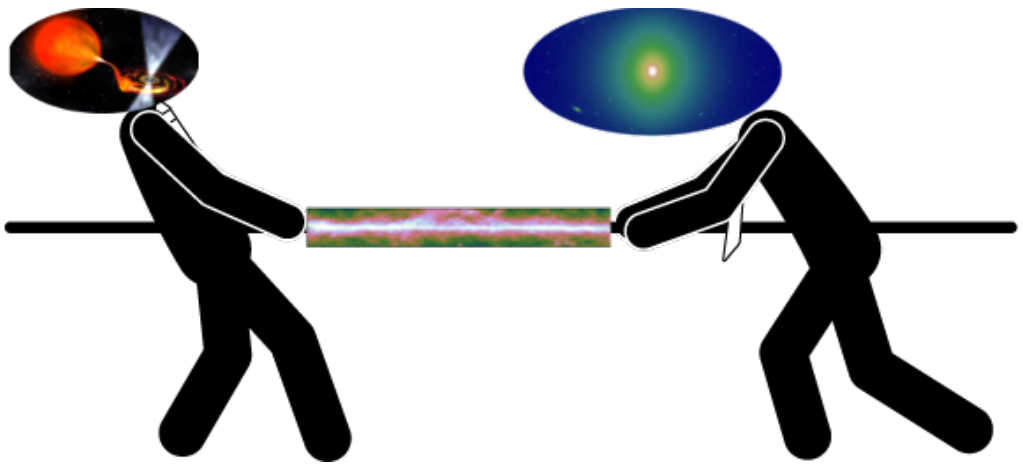

image credits: CLUMPY (J factor map), diffuse model [Storm+17], spectra [Gautam+21, Calore+14], morphology maps, [Storm+17], sim statistics [Lee+15]. *[Blame me for this collage]*

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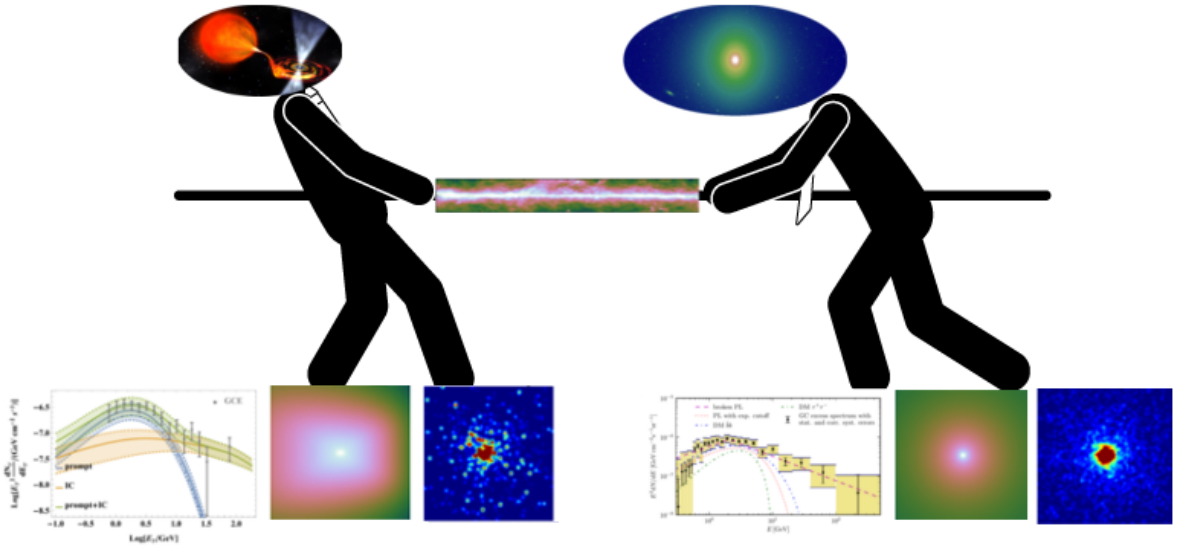

Characteristics: spectrum, morphology, photon statistics

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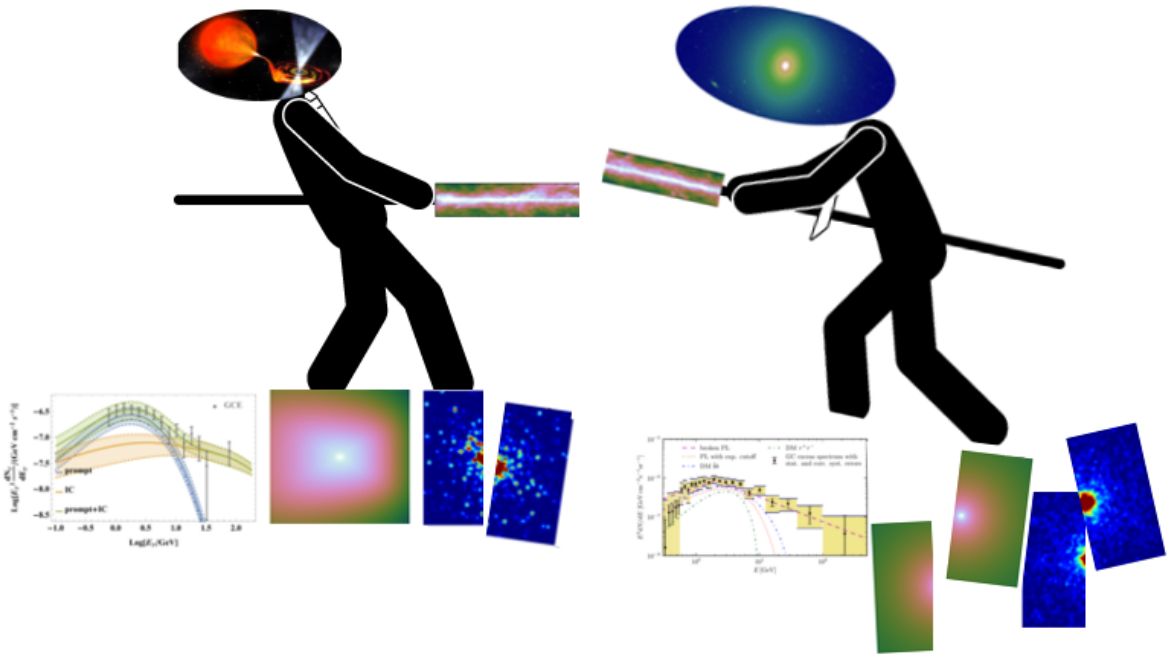
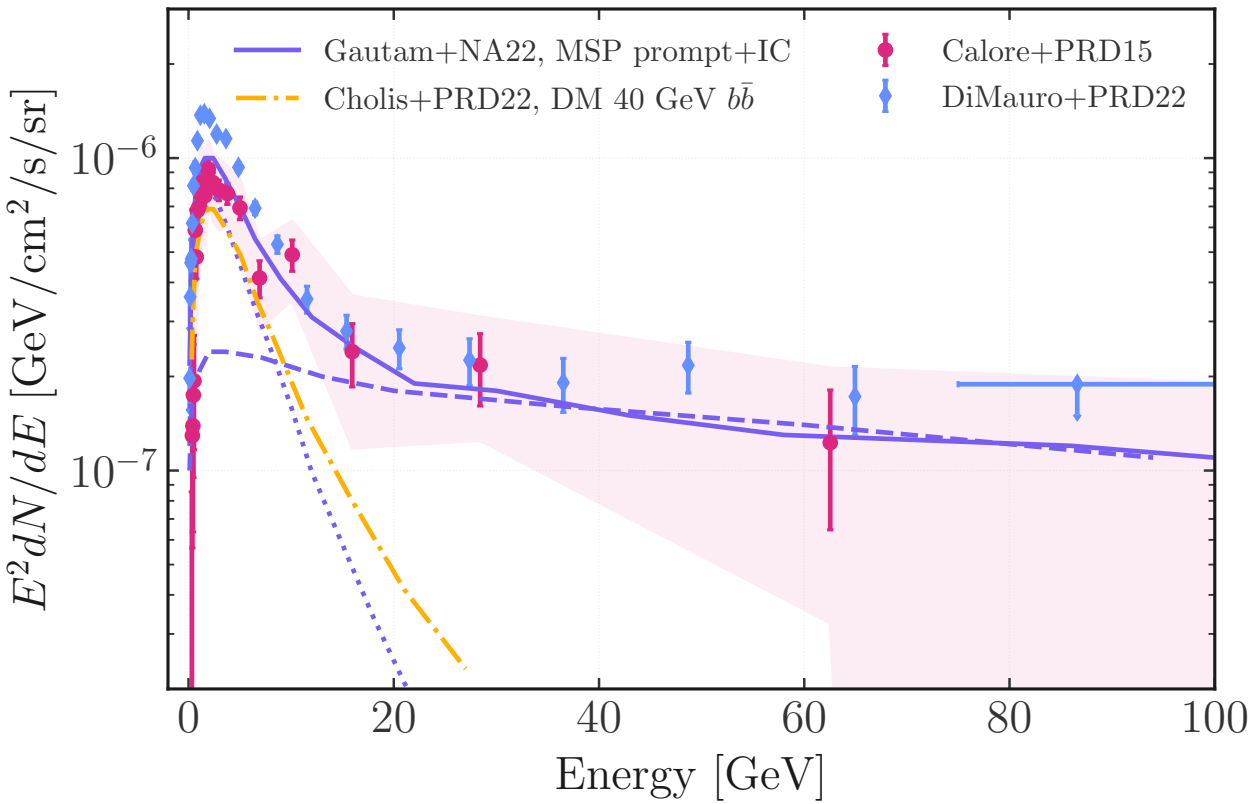


Interstellar diffuse emission mismodeling

image credits: CLUMPY (J factor map), diffuse model [Storm+17], spectra [Gautam+21, Calore+14], morphology maps, [Storm+17], sim statistics [Lee+15]. *[Blame me for this collage]*

Focus: the GCE high energy tail



Crucial discrimination power: naturally explained by inverse Compton of $e^{\pm}$ in MSP (see [GRA Monday session]), DM annihilation needs more tuning

Last dedicated work: [Linden+PRD'16] 7y of data using standard template fitting + photon count statistics (NPTF), likely same issues as [Lee+PRL'15] as pointed in [Leane+PRL'19] (see backup)

Goals & Outline

in collaboration with:

Francesca Calore (LAPTh, CNRS) Fiorenza Donato (University & INFN, Torino)

Assess GCE significance and measure characteristics of inner Galaxy gamma rays at > 10 GeV

1 Combining *state-of-the-art methods*, as pioneered in [Calore,SM+PRL'21]

* *Photon count statistics*: Measure faint point sources

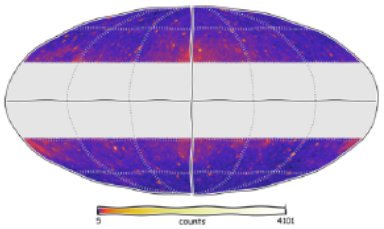
* *Adaptive template fitting* : Minimize/study diffuse emission model systematics, crucial for photon count statistics

2 Preliminary results

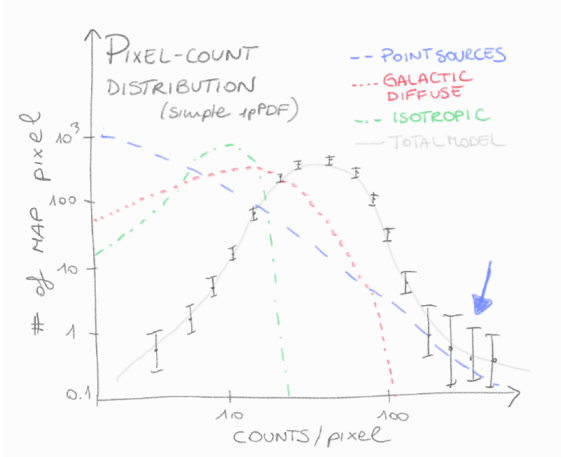
3 Summary & Outlook

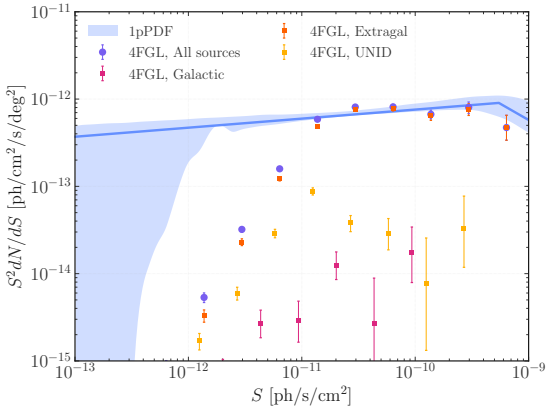
Photon count statistics of gamma rays

Statistical analysis of photon counts[1] to decompose the gamma-ray sky and measure source count distribution dN/dS below catalog flux threshold



1p-PDF





Main application: isotropic, extragalactic sources

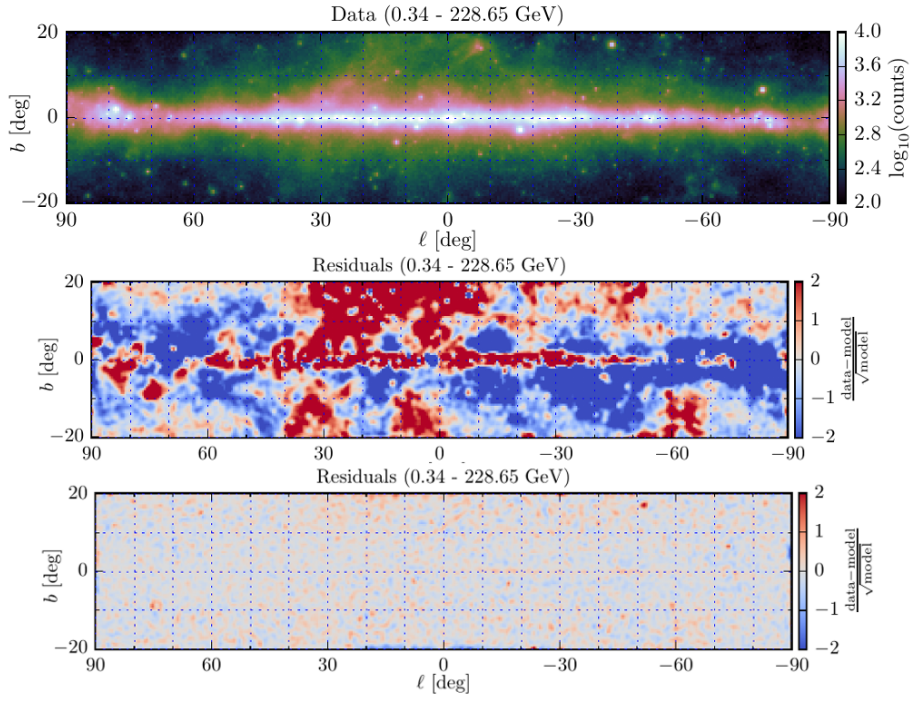
Bright diffuse backgrounds + mis-modeling could bias method at low latitudes

[Leane&Slatyer PRL'19,PRD'20,Buschmann+PRD'20,Calore,SM+PRL'21]

[1] Two main implementations: NPTF [Lee+PRL16,Mishra-Sharma+AJ'17]; 1pPDF [Zechlin+ApJS'16,+ApJL'16] based on formalism introduced in [Malyshev+ApJ2011]. Main applications include: extragalactic sources [Lisanti+Apj2016,DiMauro,SM+ApJ'18], blazar models [SM+PRD'20], DM halo, subhalo constraints [Zechlin,SM+PRD'18,Somalwar+ApJ'21], ...

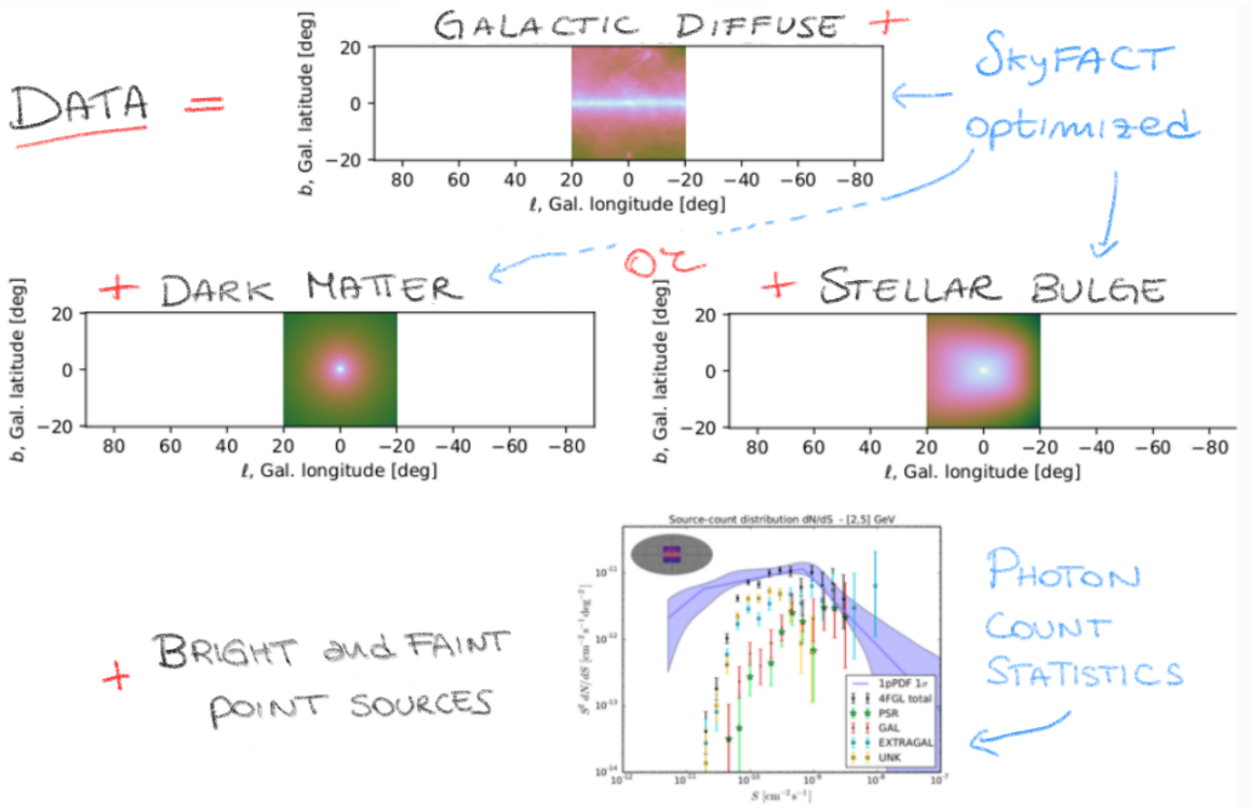
SkyFACT: overcoming diffuse emission mismodeling

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



- Standard fitting techniques: up to 30% residuals [Cholis+PRD'22,Pohl+PRD'22]
- Mismodeling at low angular scales: *spurious evidence* for new components such as point sources [Leane&Slatyer PRD'20, Karwin+22]
- **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 [→ C.Eckner's talk]

Combining 1pPDF and SkyFACT

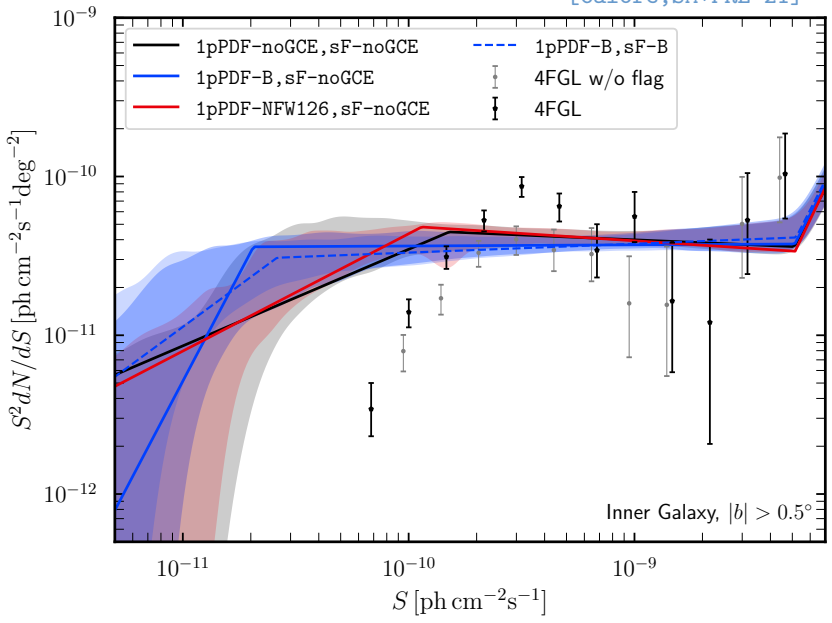


- SkyFACT: *reduce diffuse mis-modeling*
- Photon-count statistic: model faint sources *after reducing residuals*

First application to inner Galaxy [Calore,SM+PRL21, arXiv:2102.12497] at energies 2-5 GeV

Inner Galaxy, energies 2–5 GeV: results

[Calore,SM+PRL'21]



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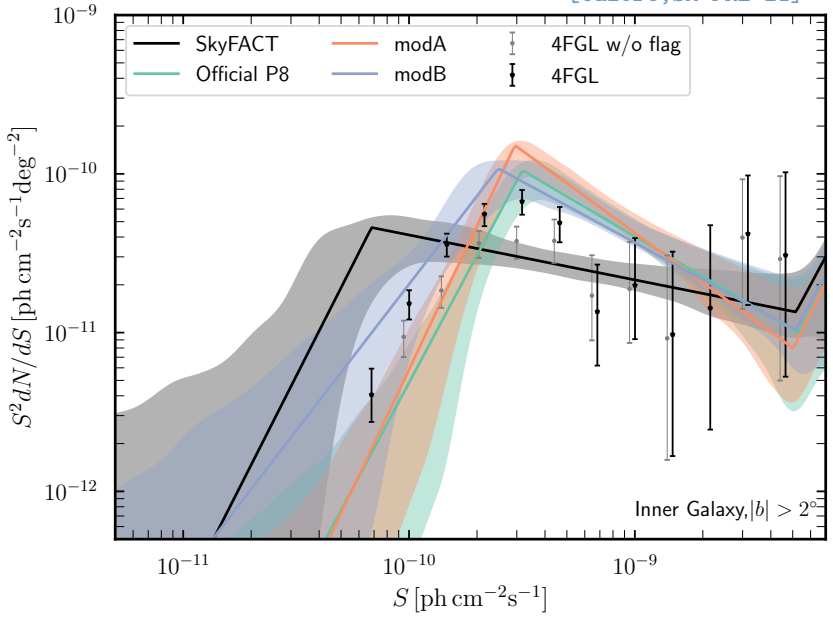
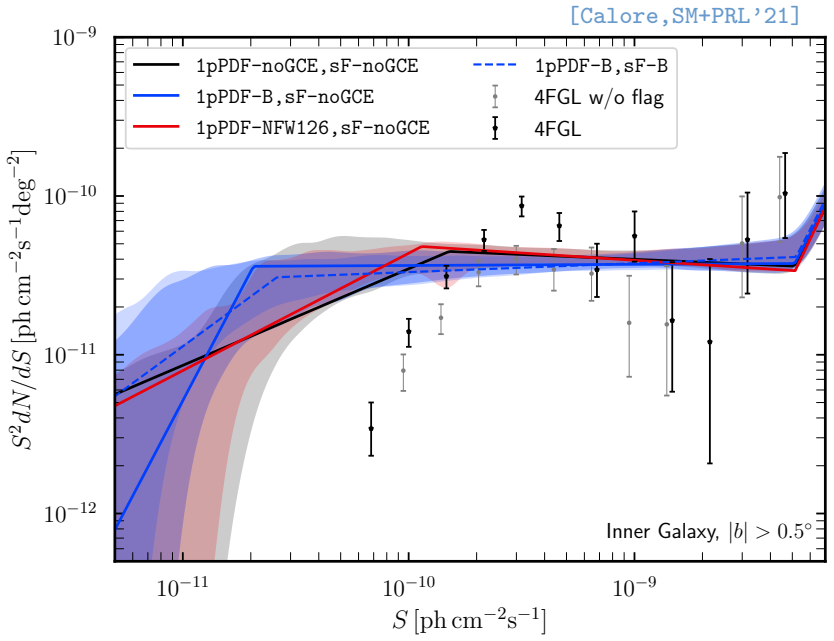
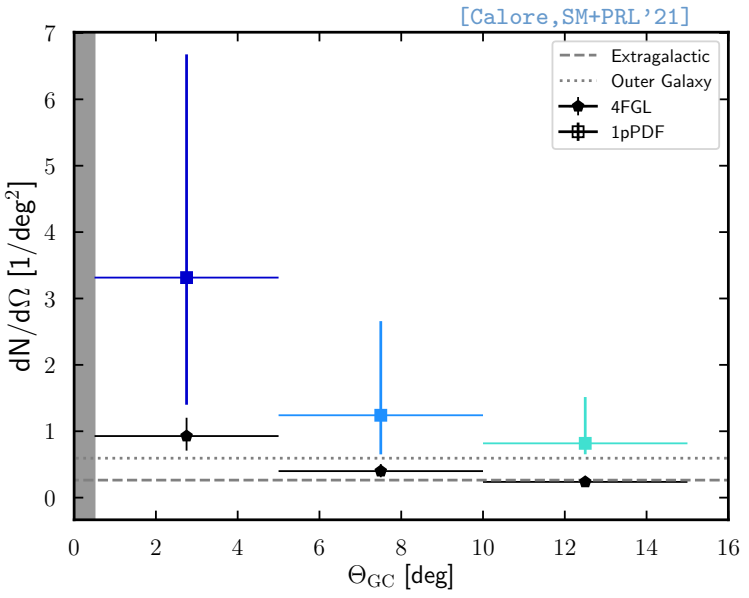


- Stellar-bulge morphology *preferred over dark matter*: SkyFACT only (10σ) and modeling faint sources (lnB$>$ 20), confirms [Bartels+NA'18,Macias+NA'18,JCAP'19]
- *Unresolved* point sources resolved down to $\sim 5 \cdot 10^{-11}$ ph cm^{-2} s^{-1}
- Diffuse mismodeling *strongly affects faint source reconstruction*

Inner Galaxy, energies 2–5 GeV: results





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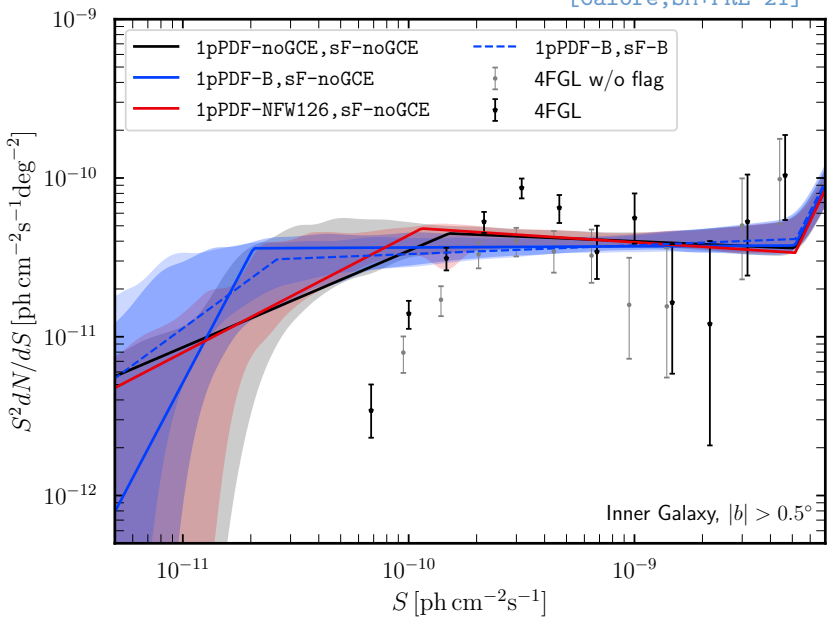

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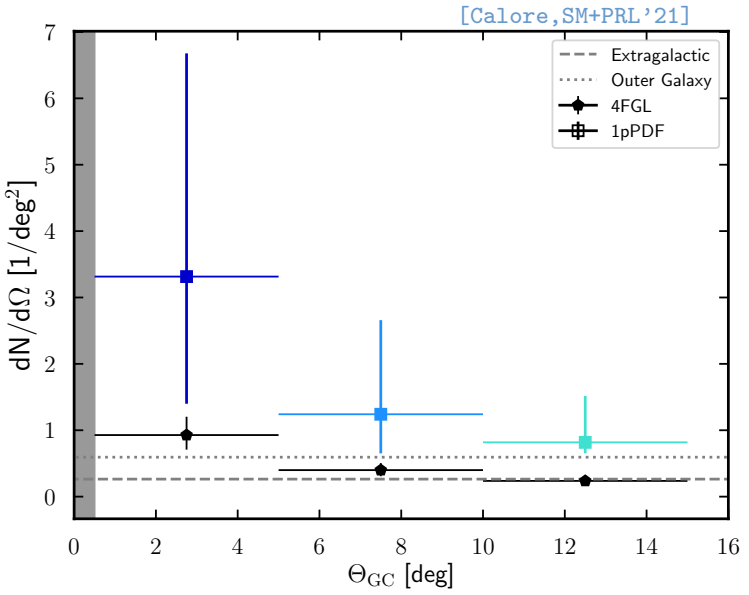

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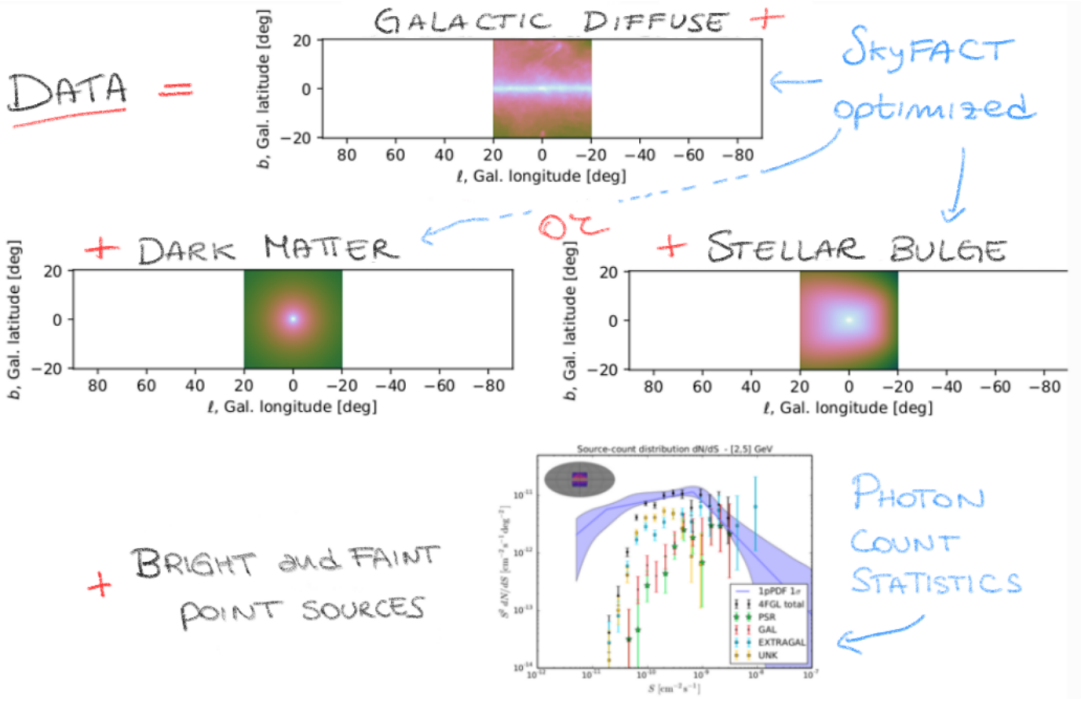
Corroborating a possible, (at least) partial stellar origin of the Galactic center excess

see also [List+PRD'21,Mishra-Sharma+PRD'22]

Extending to energies > 10 GeV

Fermi-LAT data selection: ULTRACLEANVETO, all PSF (2-5 GeV was PSF3)



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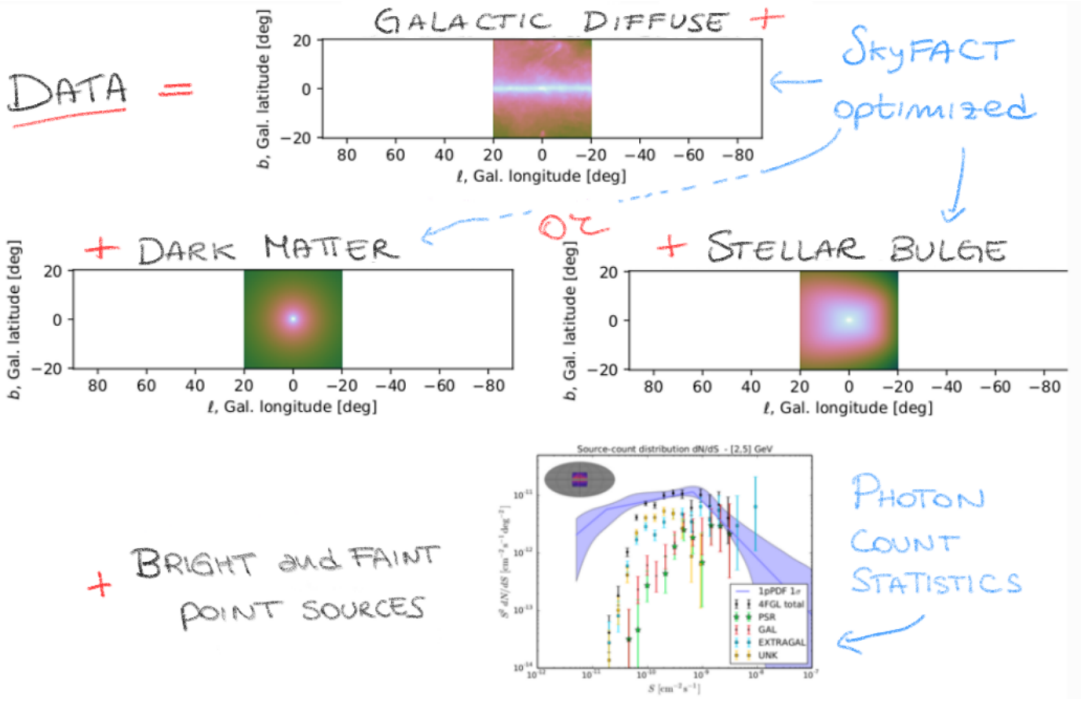
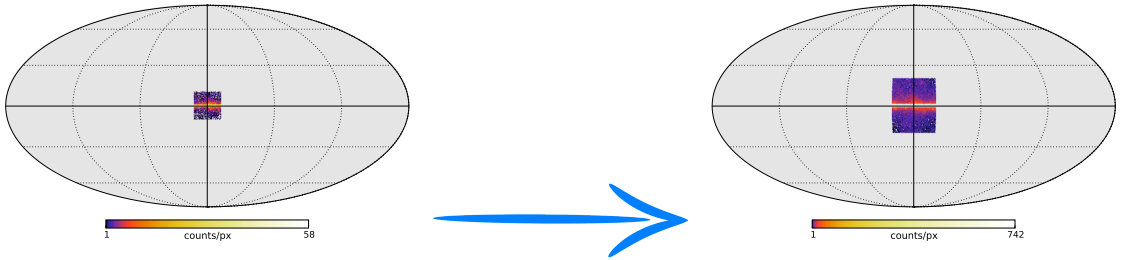
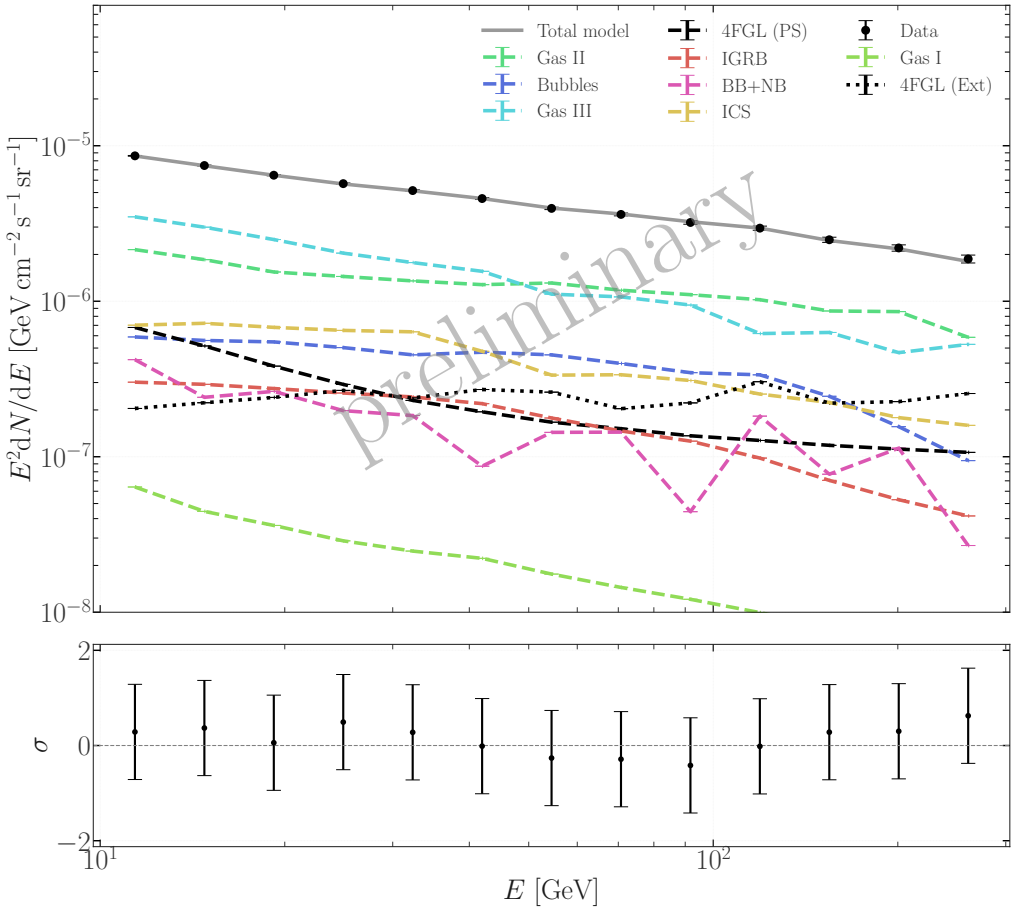


Extending inner Galaxy region of interest to 20x20 deg, cut plane at $b < |1|$ deg



SkyFACT results: inner Galaxy spectrum

GCE input spectrum: power law



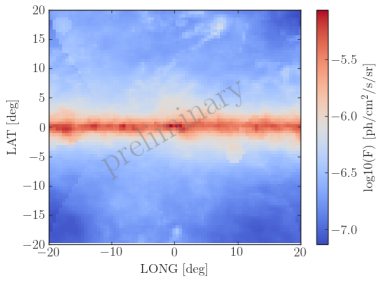
Model components compatible between
full energy (0.2-500 GeV) and high energy (> 10 GeV) fit

work in progress: MSP-like GCE input spectrum

Stellar bulge of dark matter?

SkyFACT fit, nested model comparison

no GCE



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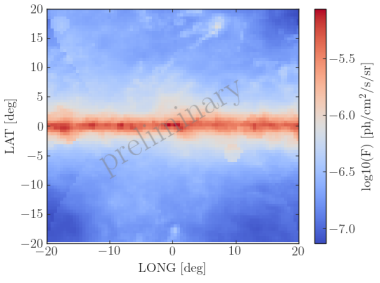
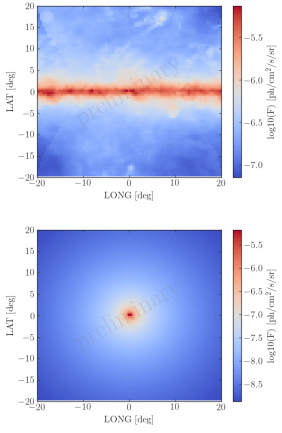


GCE: NFW ($\gamma = 1.26$)



Comparing to no GCE: 5.5σ

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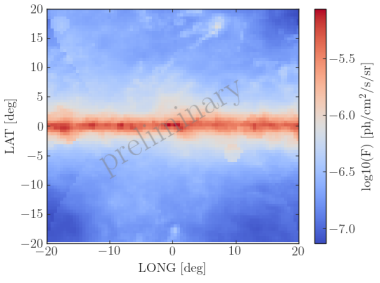

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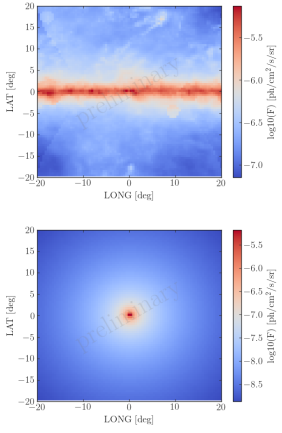

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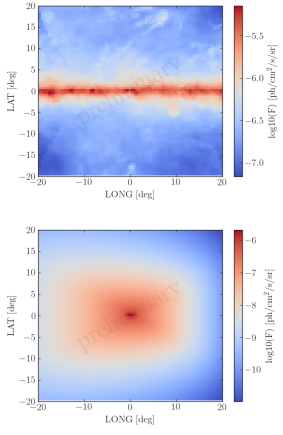
GCE: stellar + nuclear bulge



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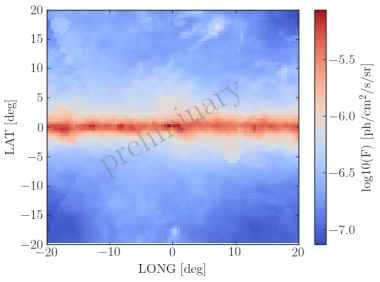

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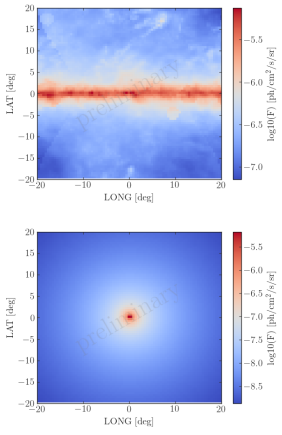

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Comparing to boxy + nuclear bulge: no evidence

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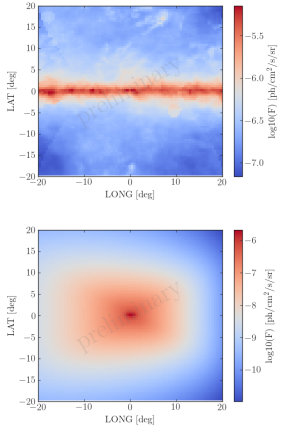

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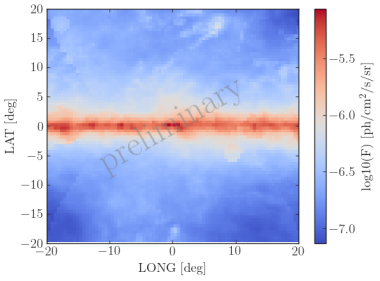

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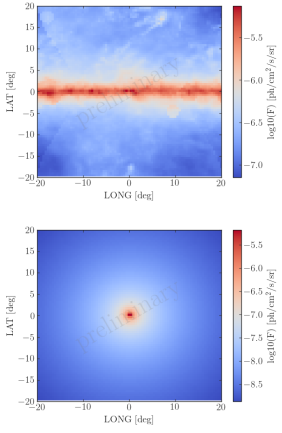

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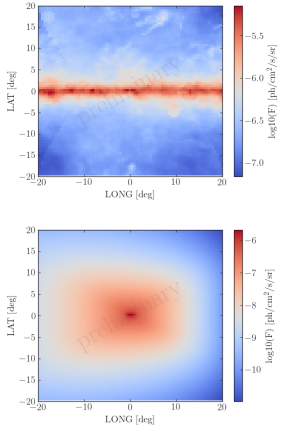

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Photon count statistics, Bayesian model comparison $B_{\rm ij} = \exp(\ln \mathcal{Z}_i - \ln \mathcal{Z}_j)$

no GCE

Stellar bulge of dark matter?

SkyFACT fit, nested model comparison

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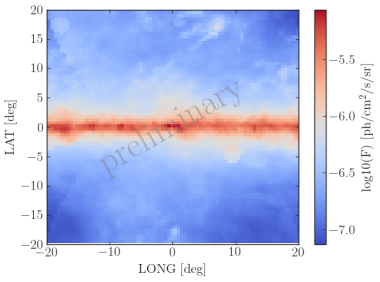

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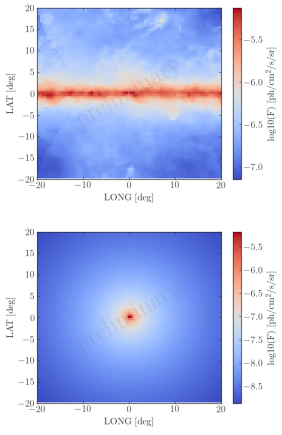

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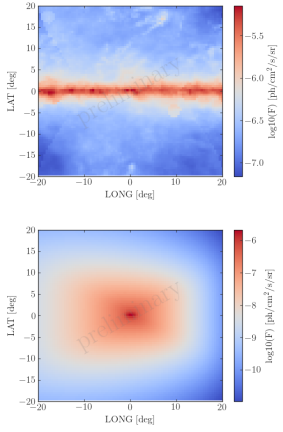

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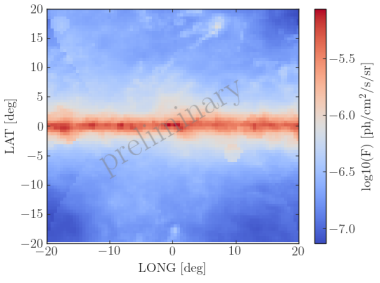
no GCE

Comparing to no GCE:
$\ln(B) = 17$

Stellar bulge of dark matter?

SkyFACT fit, nested model comparison

no GCE



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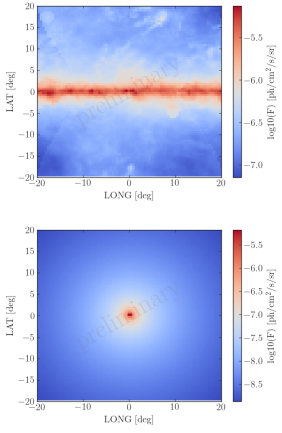

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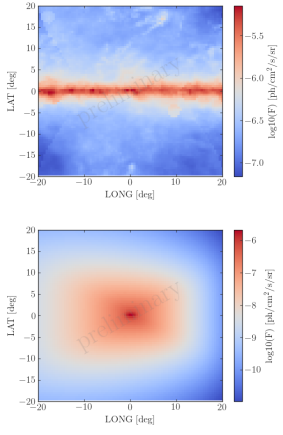

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Photon count statistics, Bayesian model comparison $B_{\rm ij} = \exp(\ln \mathcal{Z}_i - \ln \mathcal{Z}_j)$

no GCE

Comparing to no GCE:
$\ln(B) = 17$

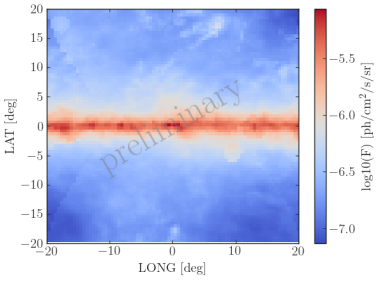
Comparing to no GCE:
lnB=37
Comparing to NFW: lnB=21

unresolved sources + norm of diffuse, GCE templates ~ 1

Stellar bulge of dark matter?

SkyFACT fit, nested model comparison

no GCE



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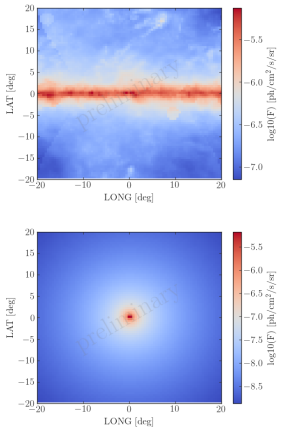

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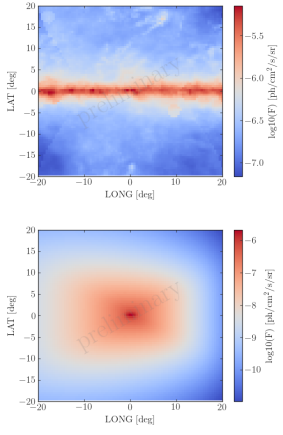
Comparing to boxy + nuclear bulge: no evidence

GCE: stellar + nuclear bulge



Comparing to no GCE: 9.7σ
Comparing to NFW: 7.9σ

Photon count statistics, Bayesian model comparison $B_{\rm ij} = \exp(\ln \mathcal{Z}_i - \ln \mathcal{Z}_j)$

no GCE

Comparing to no GCE:
$\ln(B) = 17$

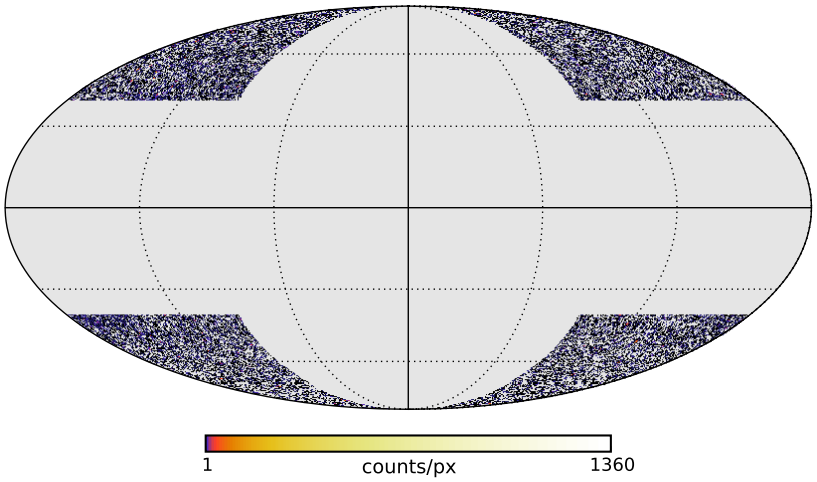
Comparing to no GCE:
lnB=37
Comparing to NFW: lnB=21

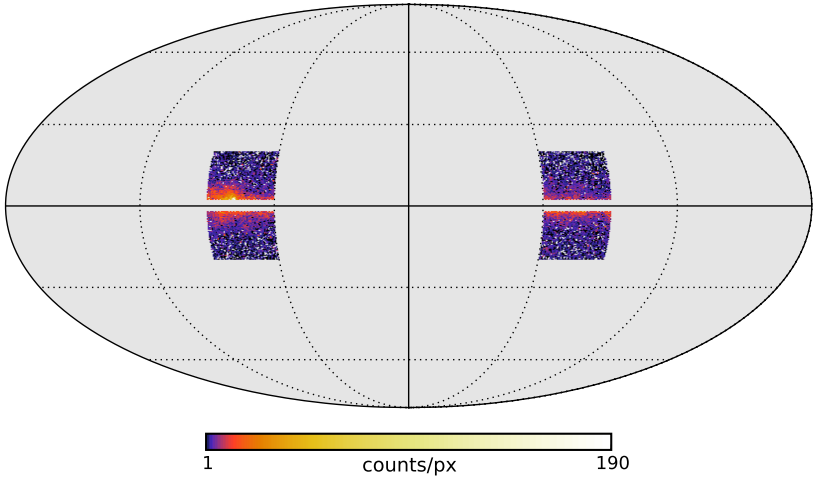
unresolved sources + norm of diffuse, GCE templates ~ 1

Evidence for a GCE at > 10 GeV
better described by a stellar bulge morphology

dN/dS results: control regions (10–300 GeV)

→ Compare source count distribution and density to inner Galaxy

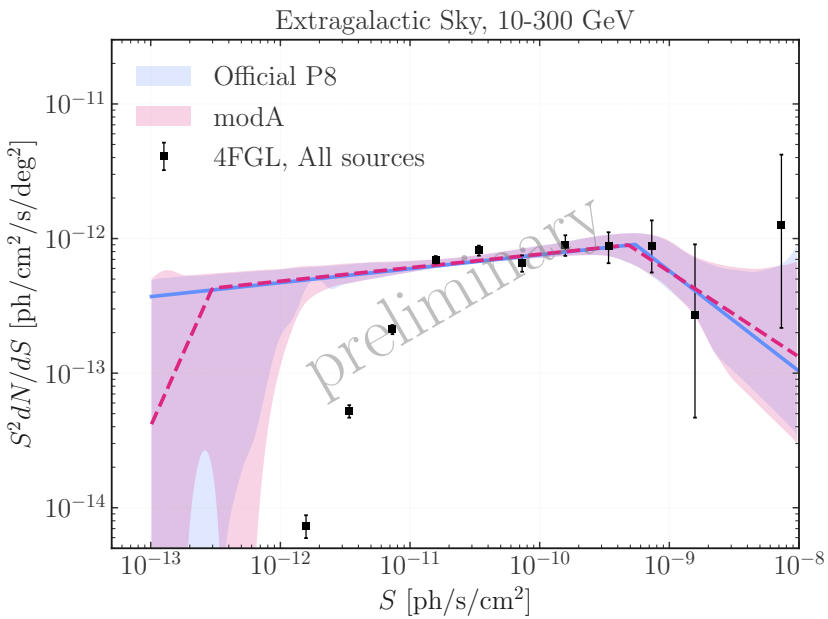


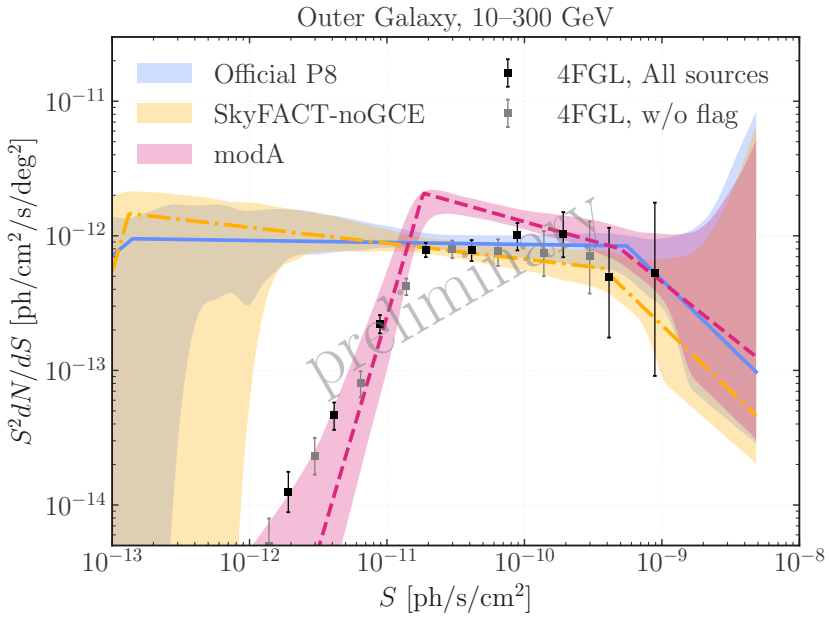


[2] GALPROP model from Fermi-LAT IGRB analysis [Ackermann+ApJ'15]

dN/dS results: control regions (10–300 GeV)

→ Compare source count distribution and density to inner Galaxy





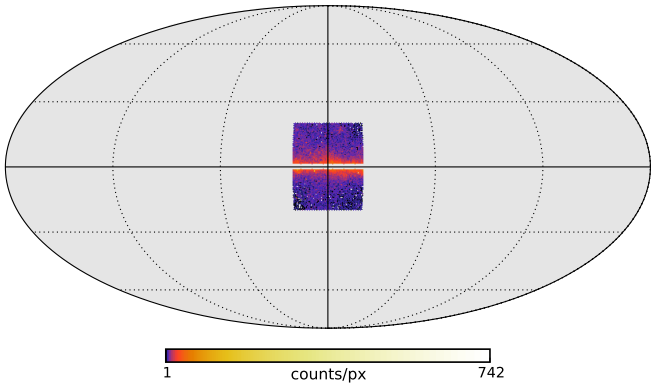
- High latitudes: stable and robust measurement, no matter diffuse model
- Low latitudes: large residuals with modA[2] drive spurious source reconstruction around catalog threshold
- Sources resolved at fluxes 1 order of magnitude lower with respect to catalog threshold, see e.g. 3FHL [DiMauro,SM+ApJ'18]

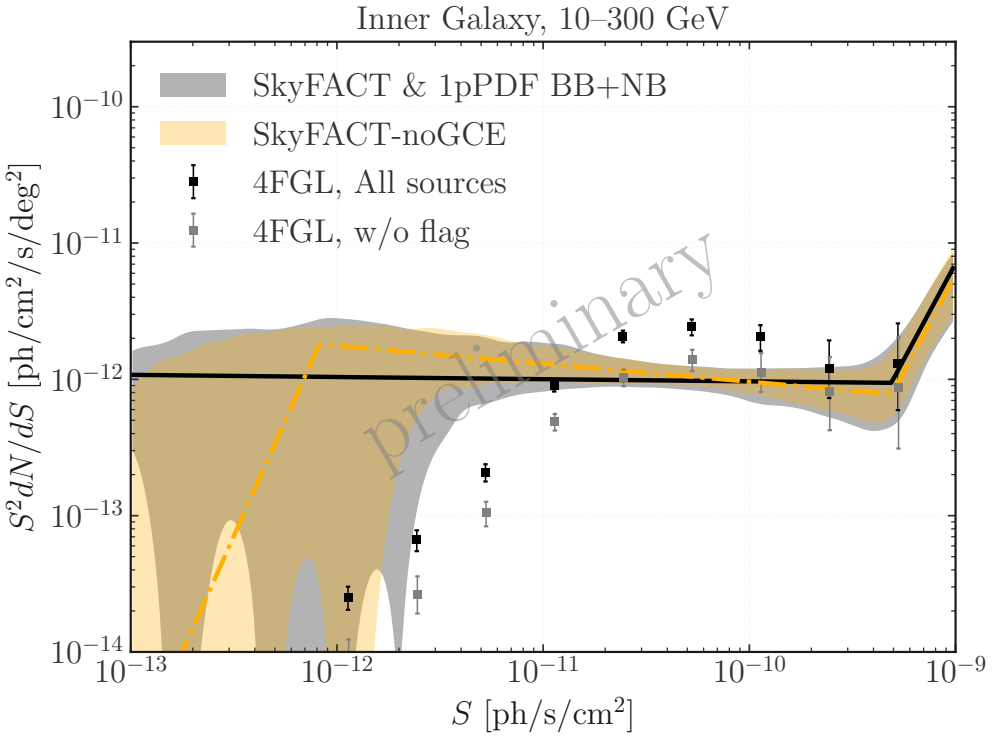
[2] GALPROP model from Fermi-LAT IGRB analysis [Ackermann+ApJ'15]

dN/dS results: inner Galaxy

Source-count distribution measured for 10–300 GeV:

20x20deg, cut plane at 1deg





- Gamma-ray point sources resolved down to $\sim 3 \cdot 10^{-12}$ ph cm^{-2} s^{-1}
- dNdS reconstruction robust against modification of diffuse emission model
- *work in progress*: spatial distribution

Summary & Outlook

Evidence for a stellar bulge-like Galactic Center Excess from $E > 10$ GeV Fermi-LAT data

- ✓ Addressing diffuse emissions mis-modeling with adaptive template fitting
- ✓ Measuring bright and faint point sources with photon count statistics

Summary & Outlook

Evidence for a stellar bulge-like Galactic Center Excess from $E > 10$ GeV Fermi-LAT data

✓ Addressing diffuse emissions mis-modeling with adaptive template fitting

✓ Measuring bright and faint point sources with photon count statistics

Work in progress:

- Spatial distribution of faint point sources in the inner Galaxy
- Consistency of results between energy bins
- Predictions for forthcoming surveys of high-energy gamma rays

Thank you for listening!

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I acknowledge the European Union's Horizon Europe research and innovation programme for support under the Marie Sklodowska-Curie Action PF2021, grant agreement No.10106280, project VerSi.

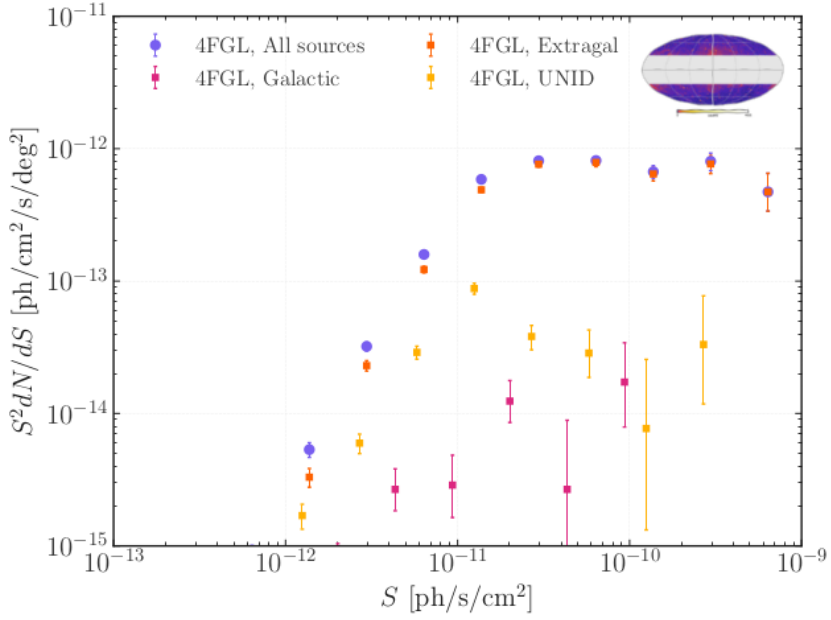
Backup

The dN/dS of gamma ray sources

Fermi-LAT source catalogs [3] $\rightarrow$ source count distribution dN/dS

Table Browser for 1: gll_psc_v27.fit

	Source_Name	DataR...	RAJ2000	DEJ2000	GLON	GLAT	Conf_68_S...	Conf_68_S...	Conf_68_Pc
1	4FGL J0000.3-7355	1	0.0983	-73.922	307.709	-42.7295	0.032378	0.031453	-62.7
2	4FGL J0000.5+0743	2	0.1375	7.7273	101.656	-53.0295	0.094544	0.069999	-10.22
3	4FGL J0001.2+4741	1	0.3126	47.6859	114.25	-14.3381	0.03688	0.03318	-45.9
4	4FGL J0001.2-0747	1	0.3151	-7.7971	89.0327	-67.305	0.01844	0.017577	64.1
5	4FGL J0001.5+2113	1	0.3815	21.2183	107.649	-40.1677	0.026026	0.023991	-60.52
6	4FGL J0001.6-4156	1	0.4165	-41.9425	334.226	-72.0285	0.042678	0.032378	44.09
7	4FGL J0002.1-6728	1	0.5378	-67.4746	310.085	-48.9635	0.021709	0.01918	52.51
8	4FGL J0002.1+6721c	1	0.5419	67.3578	118.203	4.93949	0.095593	0.068518	-82.1
9	4FGL J0002.3-0815	2	0.5937	-8.2652	89.0434	-67.8483	0.041752	0.033365	56.69
10	4FGL J0002.4-5156	2	0.6131	-51.9355	319.999	-63.539	0.096456	0.059823	15.
11	4FGL J0002.7+7220	2	0.6786	72.3479	119.209	9.82928	0.06858	0.049277	27.57
12	4FGL J0002.8+6217	1	0.7201	62.2905	117.32	-0.051036	0.021154	0.020229	3.84
13	4FGL J0003.1-5248	1	0.7817	-52.8071	318.99	-62.7889	0.020537	0.01881	-41.61
14	4FGL J0003.2+2207	1	0.8058	22.1302	108.439	-39.3808	0.060069	0.053285	-75.21
15	4FGL J0003.3+2511	1	0.8323	25.1912	109.382	-36.4115	0.062968	0.055567	63.58
16	4FGL J0003.3-1928	1	0.8465	-19.4676	65.1978	-76.581	0.043664	0.037867	-51.75
17	4FGL J0003.3-5905	1	0.8483	-59.0952	314.239	-56.9659	0.079619	0.047858	25.98
18	4FGL J0003.6+3059	1	0.9045	30.9898	111.004	-30.772	0.049955	0.044034	-83.55
19	4FGL J0003.9-1149	1	0.9986	-11.8251	84.5954	-71.0751	0.032317	0.030775	-31.93
20	4FGL J0004.0+5715	1	1.0017	57.2578	116.526	-5.02287	0.052545	0.041136	-8.21
21	4FGL J0004.0+0840	1	1.0073	8.6757	103.496	-52.3978	0.050263	0.038607	-56.38
22	4FGL J0004.3+4614	2	1.0757	46.2427	114.489	-15.8549	0.051805	0.048536	-56.83
23	4FGL J0004.4-4737	1	1.1091	-47.6233	323.986	-67.5378	0.027814	0.025286	-9.35
24	4FGL J0004.4-4001	1	1.1184	-40.0251	336.991	-73.8453	0.083752	0.054765	56.16
25	4FGL J0005.6+6746c	1	1.4155	67.7688	118.608	5.28213	0.116623	0.097196	19.83



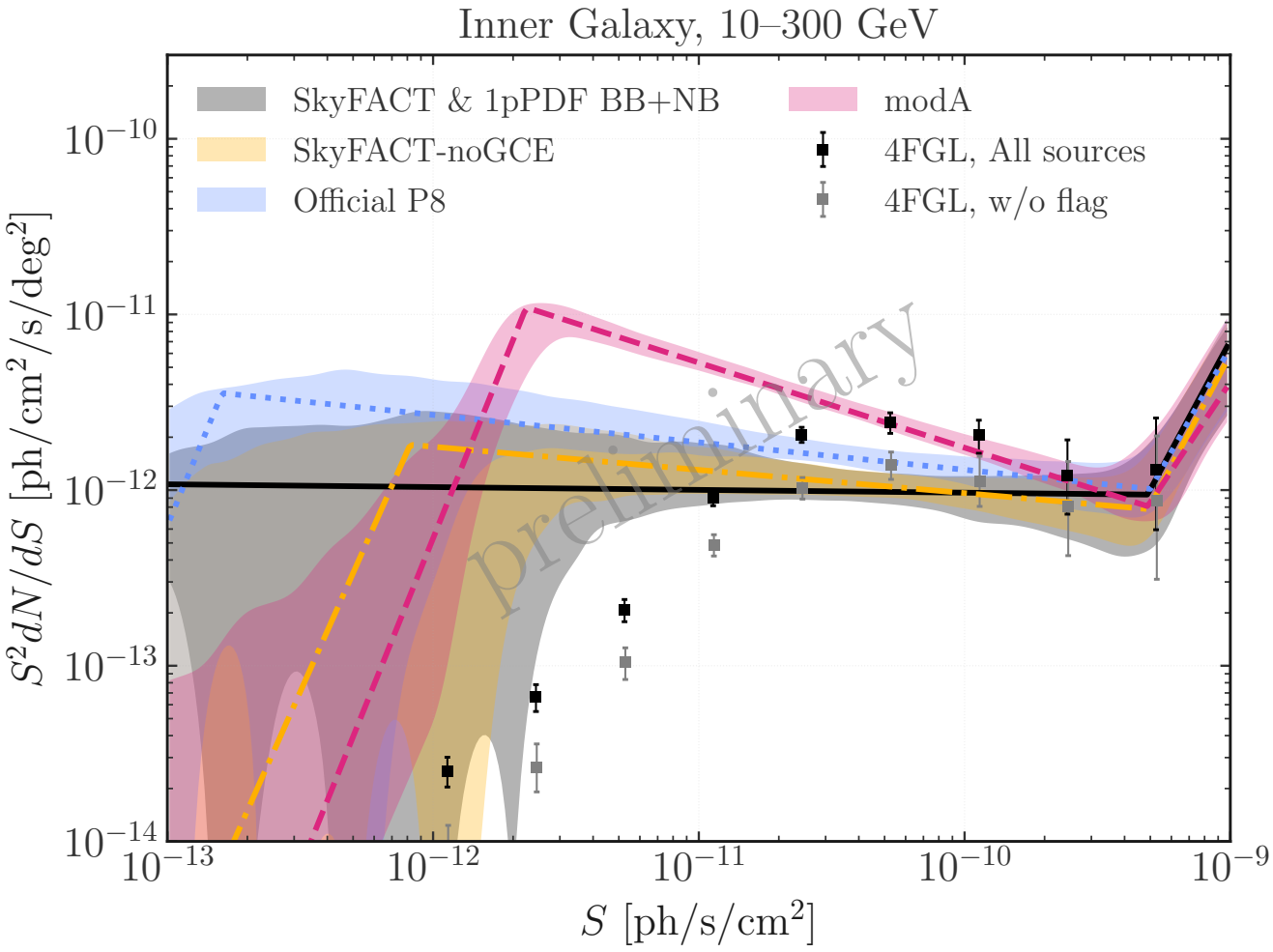
(# of sources N per $d\Omega$ with integral flux in $(S,\, S + dS)$)

Limited by detection threshold of given survey

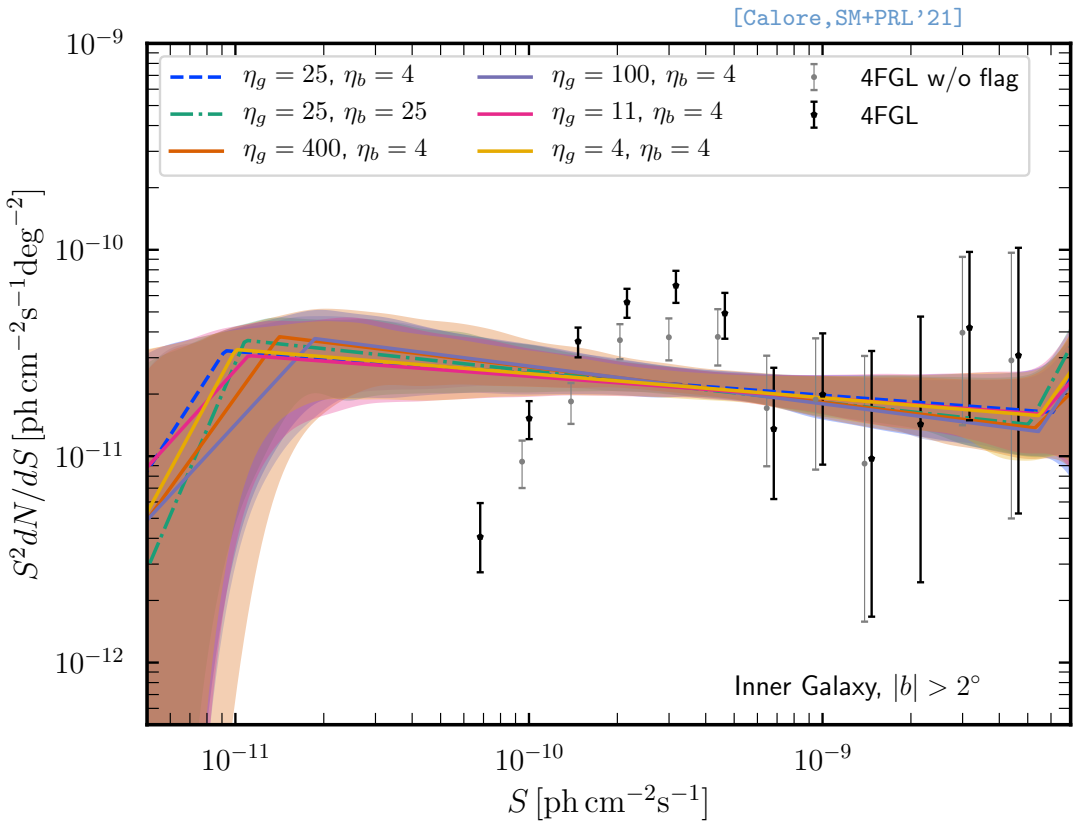
Characterizes gamma-ray sky composition and source populations

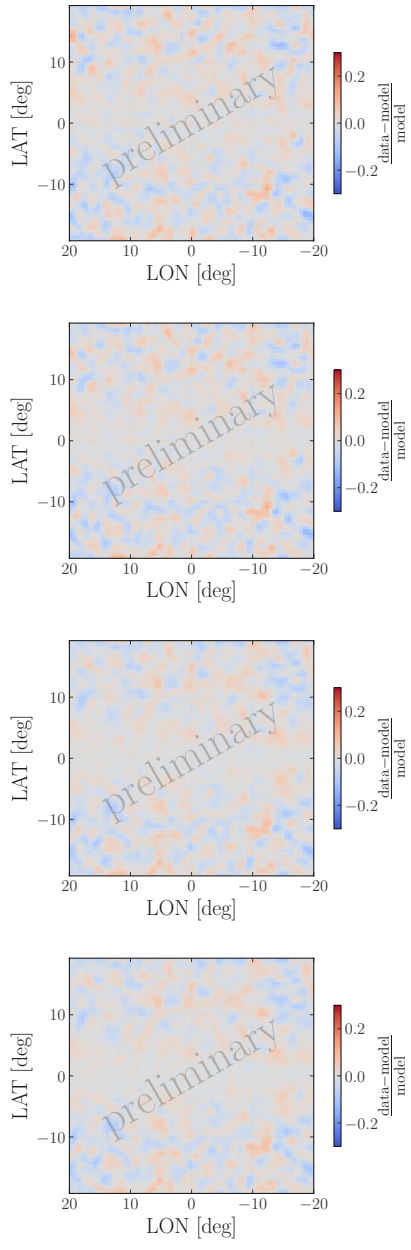
[3] 4FGL-DR3, 12 years [Fermi-LAT coll., ApJS'22]

More on dN/dS & diffuse mismodeling



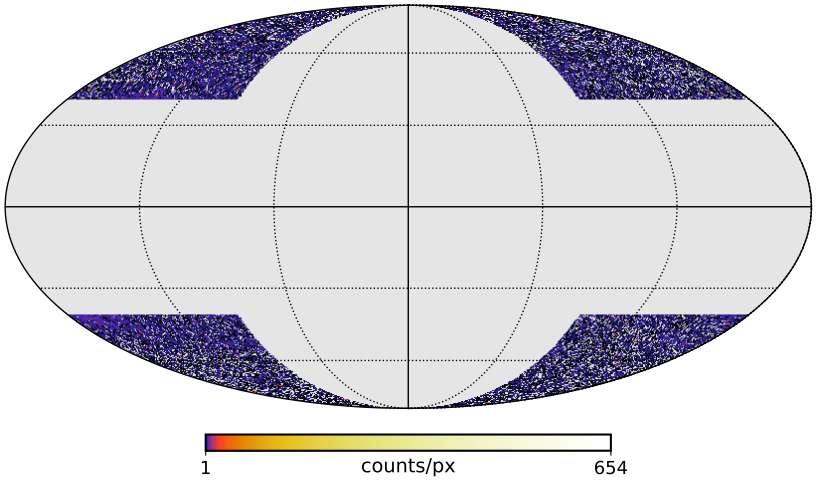
SkyFACT: gas smoothing scale

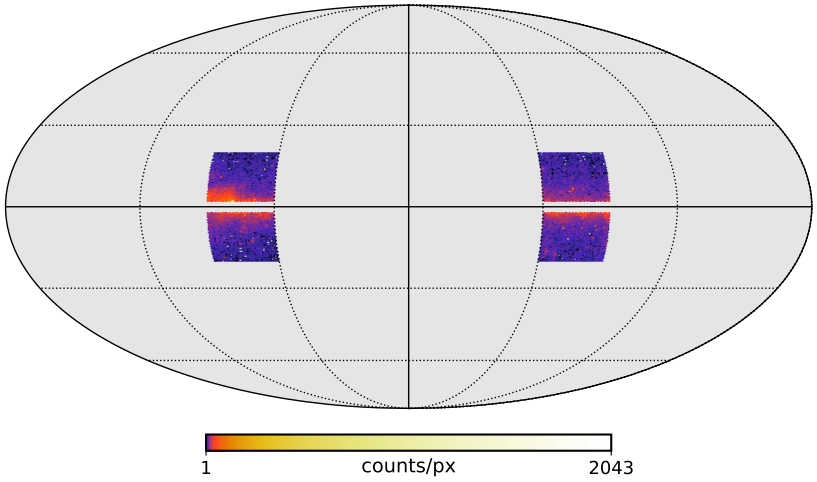


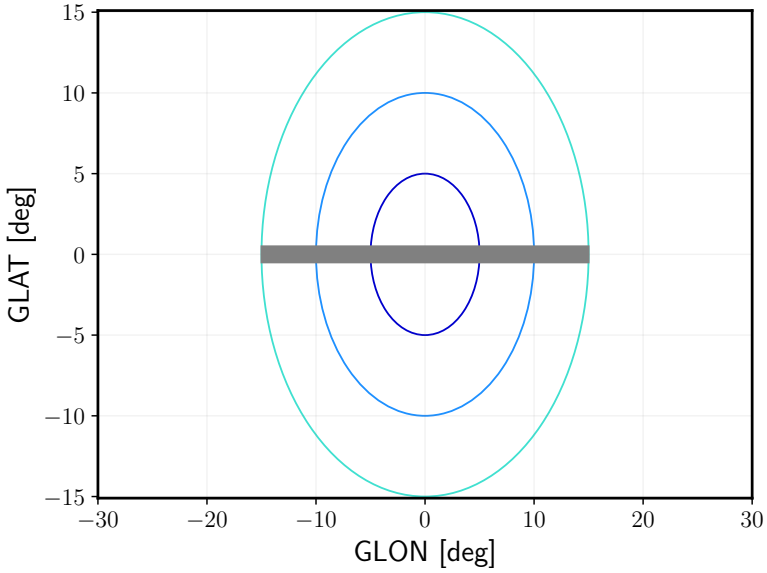


skyFACT: influence of smoothing scale of templates on dN/dS and residuals (2–5 GeV)

dNdS results: control regions (2–5 GeV)

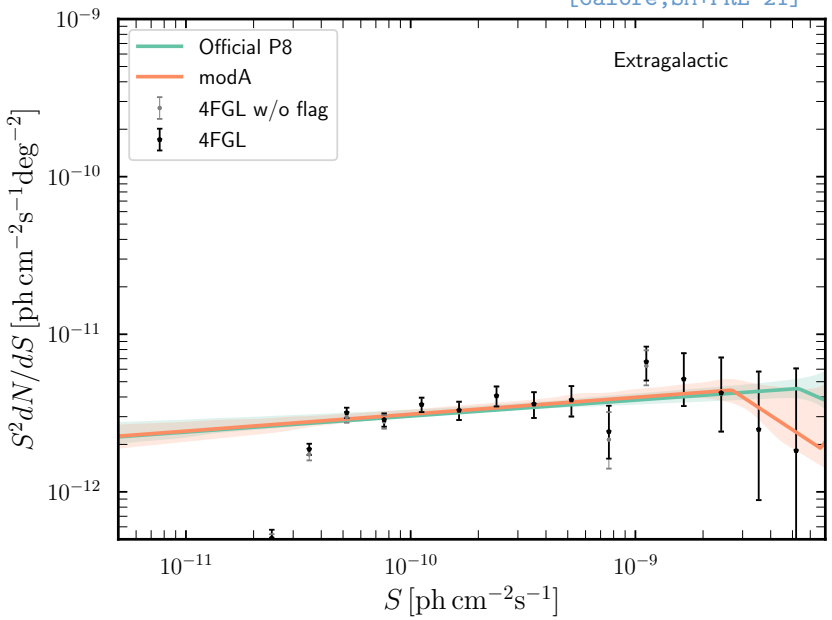




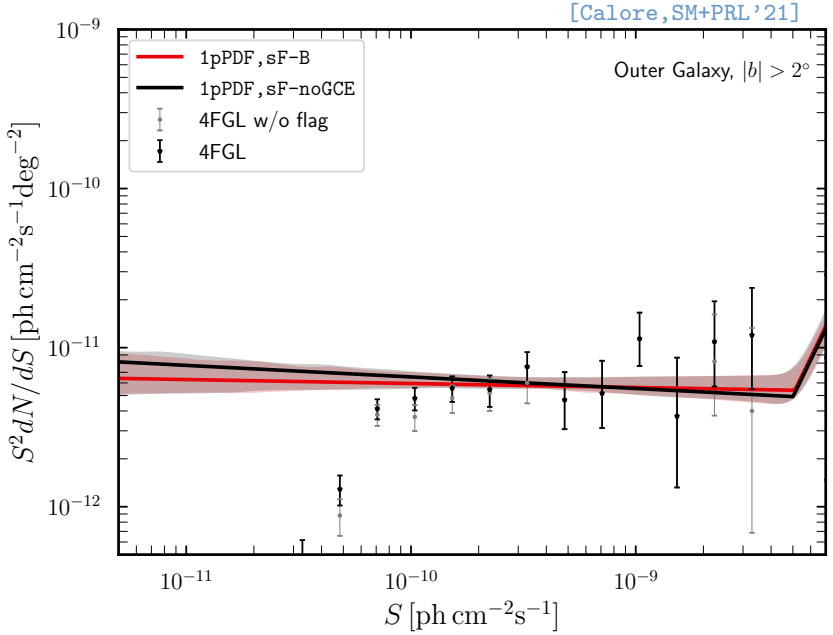


dNdS results: control regions (2–5 GeV)

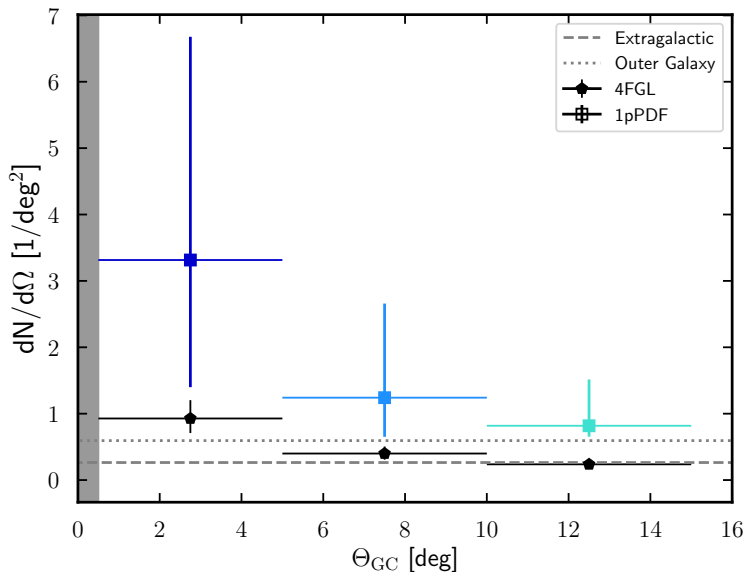
[Calore,SM+PRL'21]



[Calore,SM+PRL'21]



[Calore,SM+PRL'21]

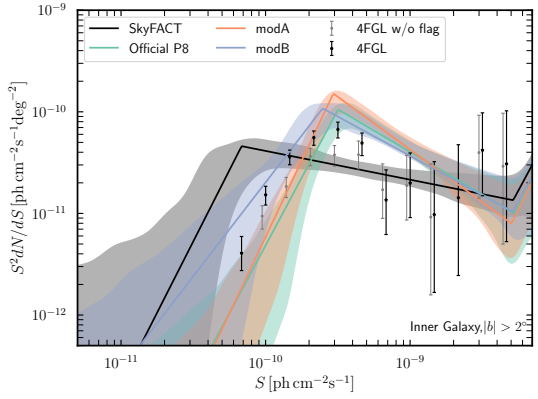


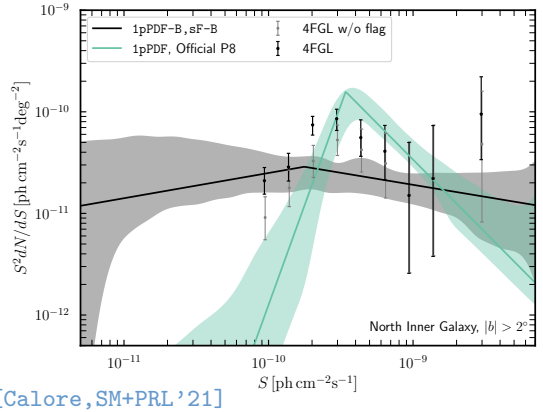
Source count distribution 2–5 GeV: systematics

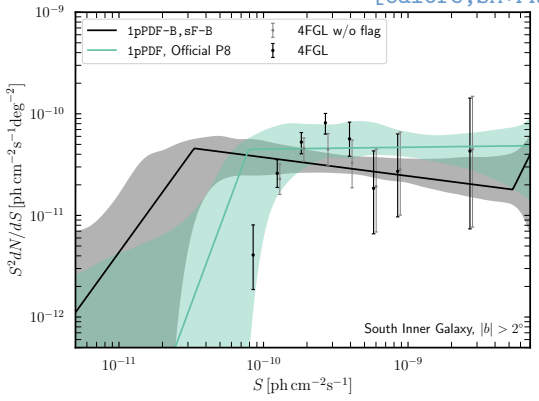
Stability of results tested against many systematics, see supplementary [Calore, SM+PRL'21]

Diffuse emission mismodeling

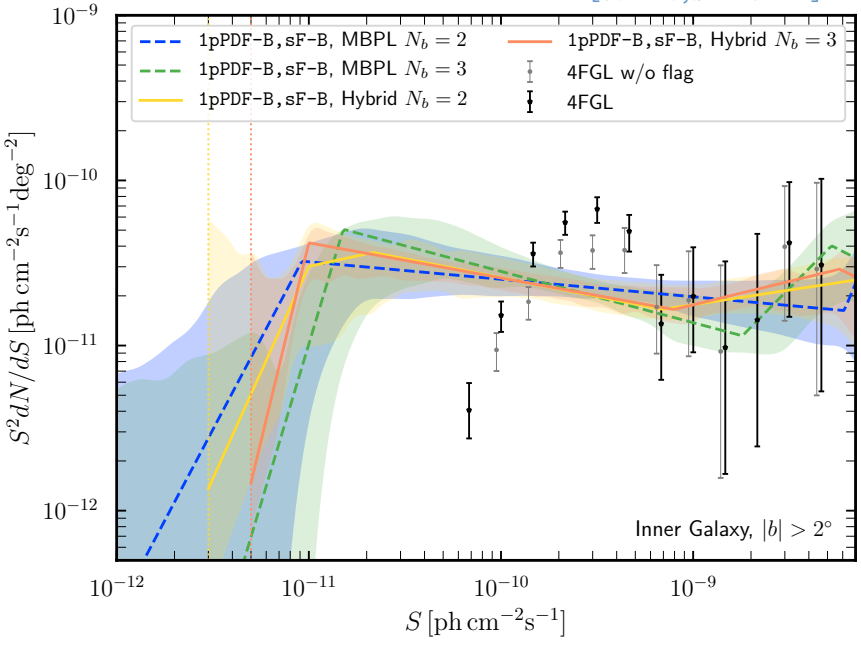
[Calore,SM+PRL'21]







[Calore,SM+PRL'21]

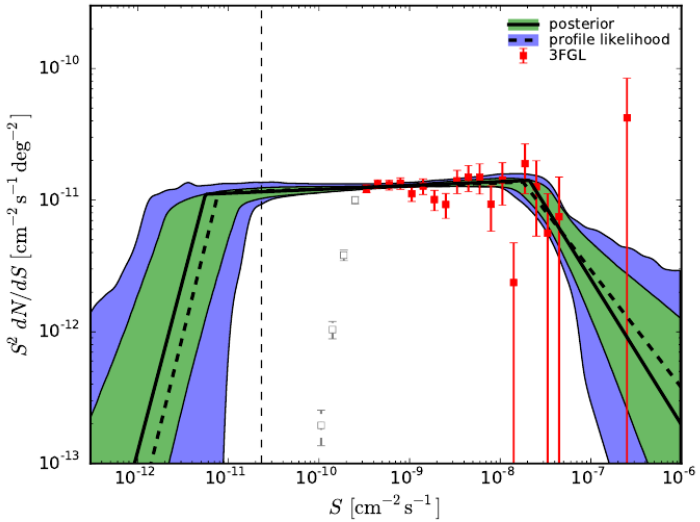


1pDPF modeling: flux cuts, dNdS breaks

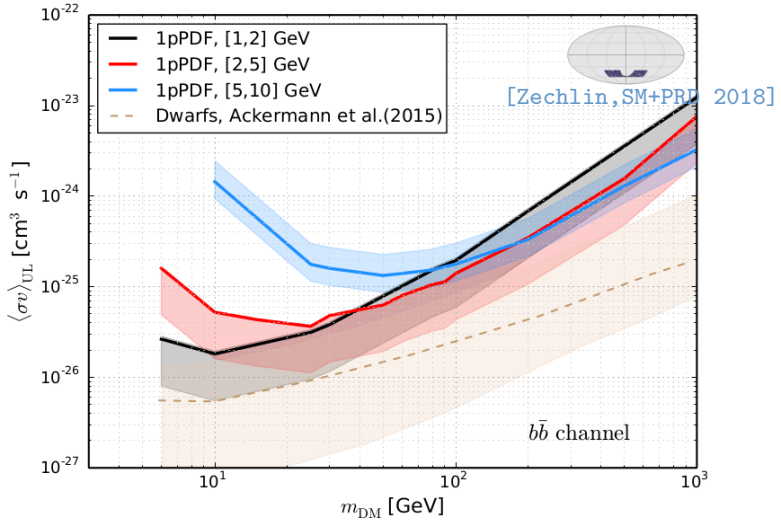
Test of 1pPDF method with Fermi-LAT data

In 1-10 GeV

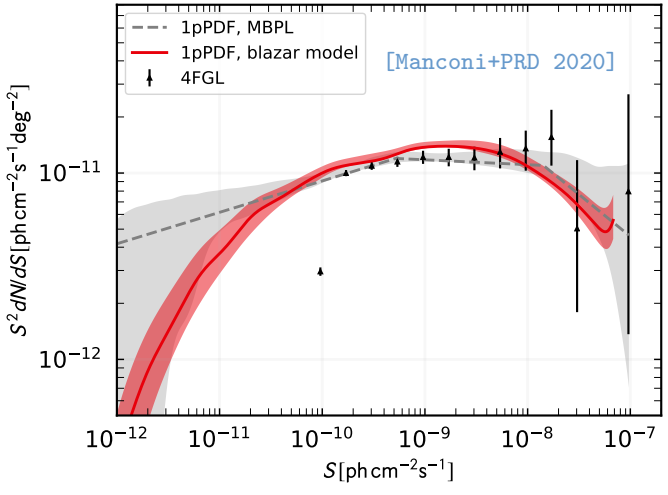
[Zechlin+ApjS 2016]



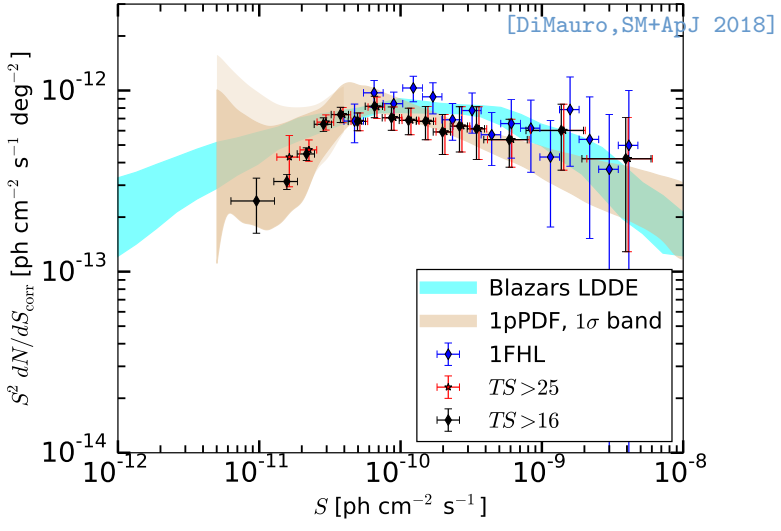
Adding a galactic dark matter template



To constrain blazar models



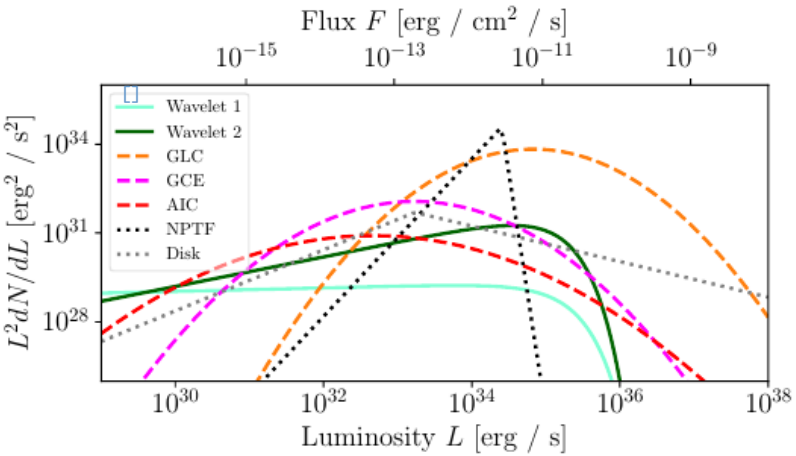
In $>$ 10 GeV, with efficiency corrections



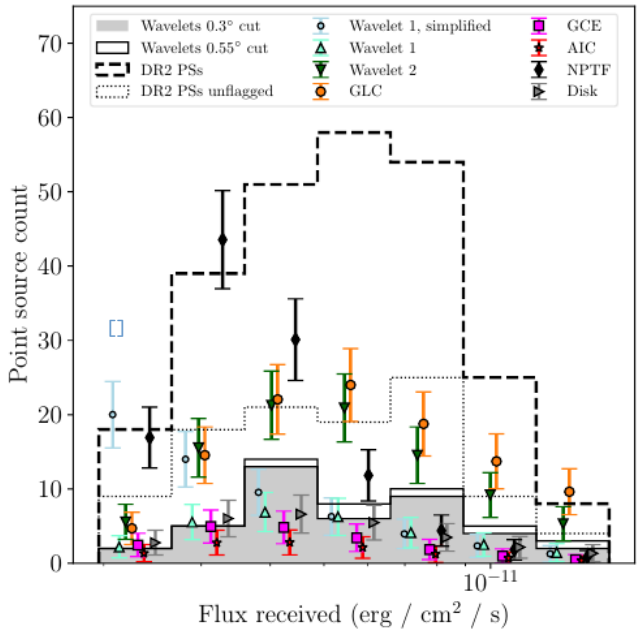
Luminosity functions of MSP explaining the excess

[Dinsmore&Slatyer'JCAP'22]: Comparing 7 models for MSP properties explaining the excess:

sources detectable? # overall to explain excess? viable luminosity functions?



Number of detectable MSP highly depends on luminosity function model, which is uncertain



Models can produce 100-10^6 MSP w/o overproducting 4FGL sources

Factor 5-20 sensitivity: 30% of the excess would give detectable MSP in Fermi-LAT

Photon count statistics: timeline [until 2020, using NPTF]

Is the excess diffuse or point-like (sources spatially distribuited as dark matter)?

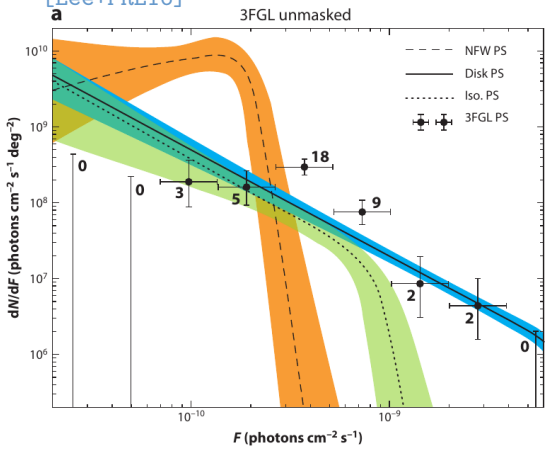
2016 : Excess entirely due to unresolved **point-sources** [Lee+PRL'16]

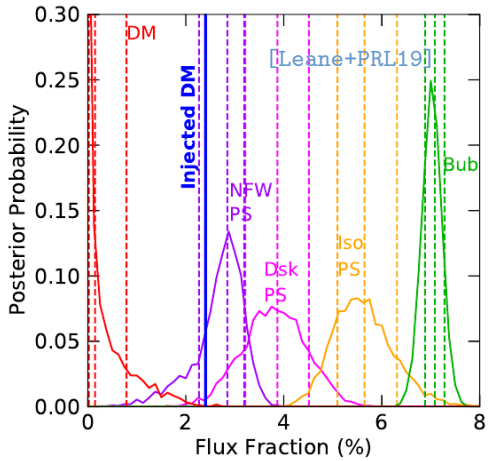
2019 : Earlier results not robust: smooth dark matter not reconstructed even if injected **dark matter** *strickes back?* [Leane+PRL'19]

2019/2020 : Explain why injection test failed: background mismodeling! excess still consistent with being **partially point sources** with updated diffuse models [Chang+PRD'20, Buschmann+PRD'20]

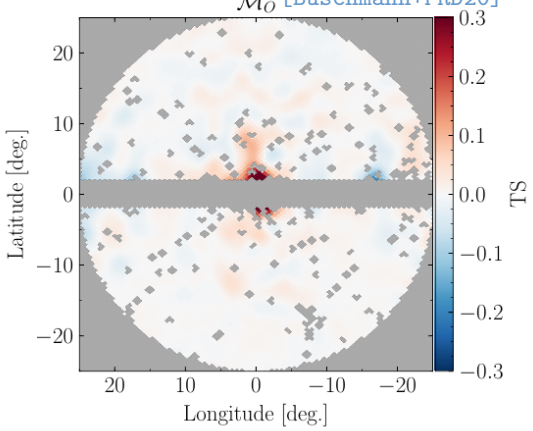
2020 : Preference for point sources influenced by spurios sources/ excess north-south asymmetry, robustness further casted into doubt [Leane+PRL,PRD'20]

[Lee+PRL16]





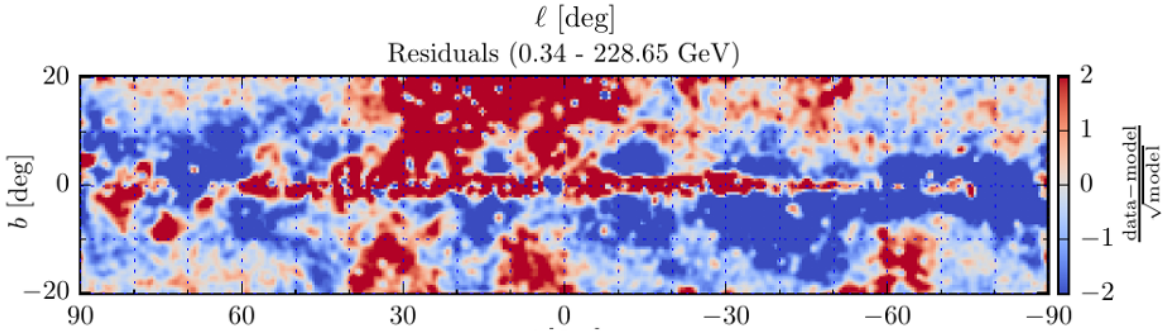
$\mathcal{M}_O$ [Buschmann+PRD20]



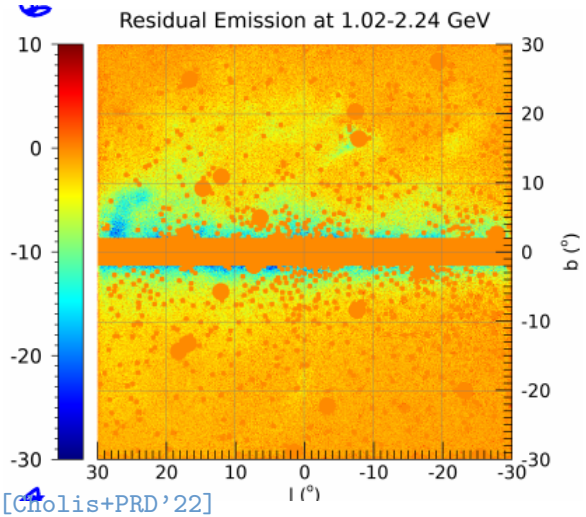
Robustness of results highly dependent on serious systematics from Galactic diffuse emission mismodeling

Galactic diffuse mismodeling: residuals

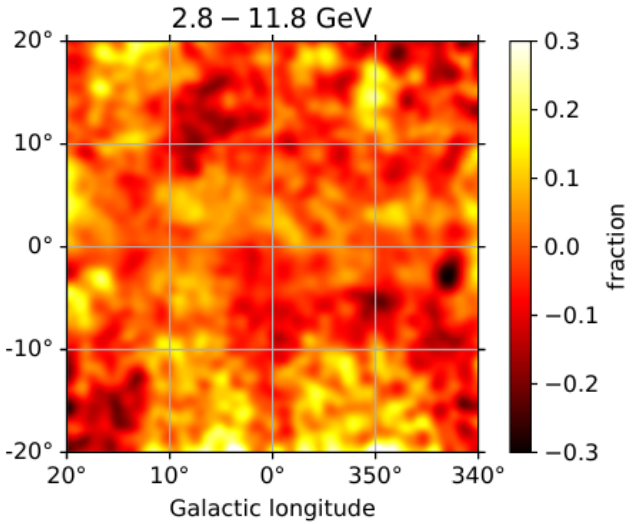
Model to fit Fermi-LAT data: Σ_{pixels} energy spectrum x spatial morphology



[Storm+JCAP'17]



[Cholis+PRD'22]



[Pohl+PRD'22]

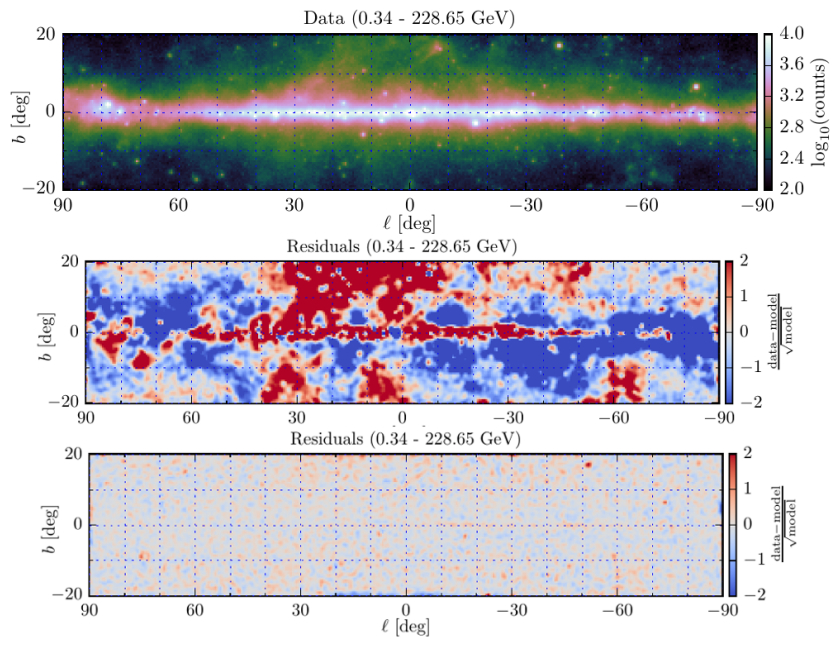
Template fitting: still up to 30% residuals

Mismodeling at low angular scales, north-south: *spurious evidence* for new components such as point sources [Leane&Slatyer PRD'20, Karwin+22]

How do we reduce residuals?

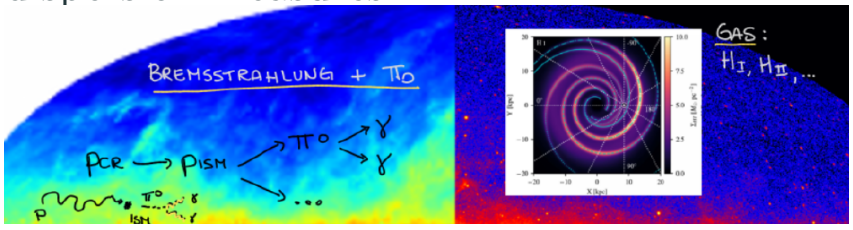
Data-driven:

- Spherical harmonic marginalization [Buschmann+PRD20]
- Gaussian Processes [Mishra-Sharma,Cranmer,'22]
- SkyFACT: sky factorisation with adaptive constraining templates [Storm+JCAP'17]



Improve models:

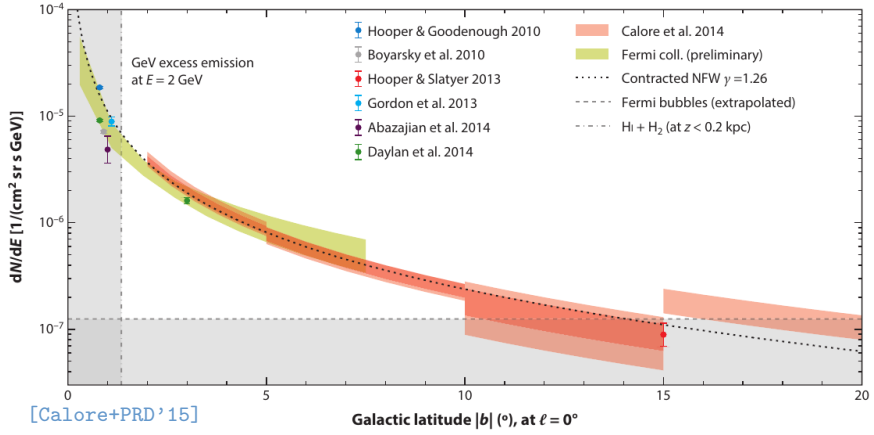
Better estimates of target H_I, H_2, H_{II} gas column density, inferred by line spectra, dispersion measures



- new atomic HI reconstr, with radiation model of emission +absorption [Shmakov+22]
- convolutional neural nets to fill gaps in molecular H_2 tracers like CO [Shmakov+22,Karwin+22]
- bayesian inference of 3D CO maps [Mertsch&Vittino'20]

Morphology

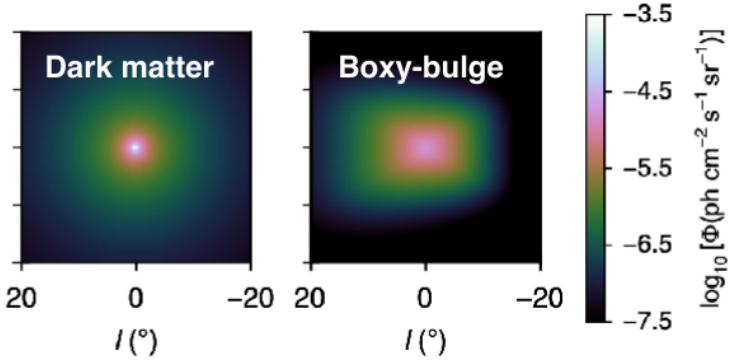
Extended up to $\sim$ 10deg ($\sim$ 1.5kpc)

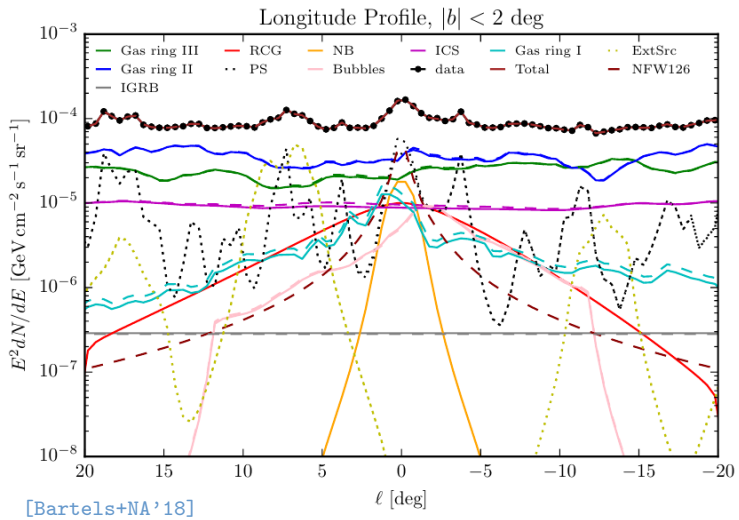


[Calore+PRD'15]

Early works: spherical simmetric around GC, contracted NFW profile $\gamma = 1.26$

Recent debate: [DiMauro PRD'20,21, Pohl+ApJ'22, McDermott+22], ...





[Bartels+NA'18]

- Evidence for stellar bulge-like
  [Bartels+NA'18,Macias+NA'18,JCAP'19,Calore,SM+PRL'21]
- Longitudinal asimmetry at $\sim$ 10 deg

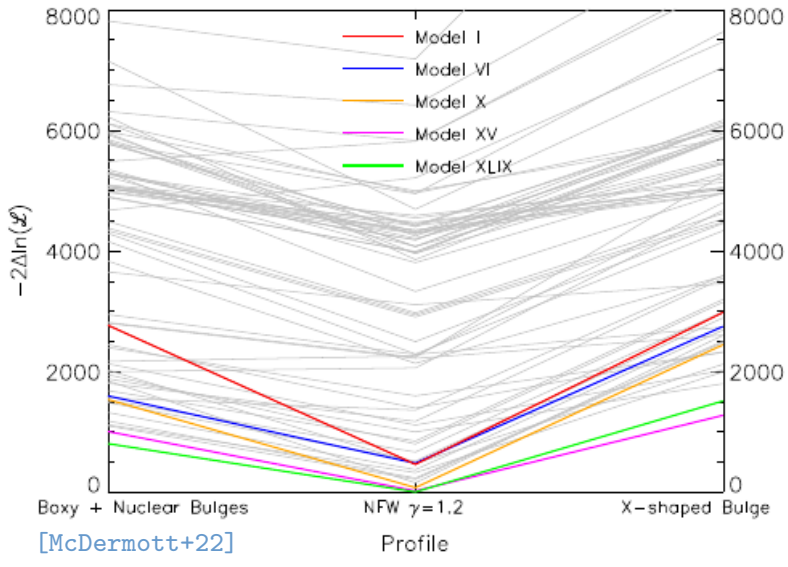
Discriminate interpretation? Yes!

Morphology: still debated

Independent groups find different results for the morphology of the excess

Spherical symmetric (dark matter-like)

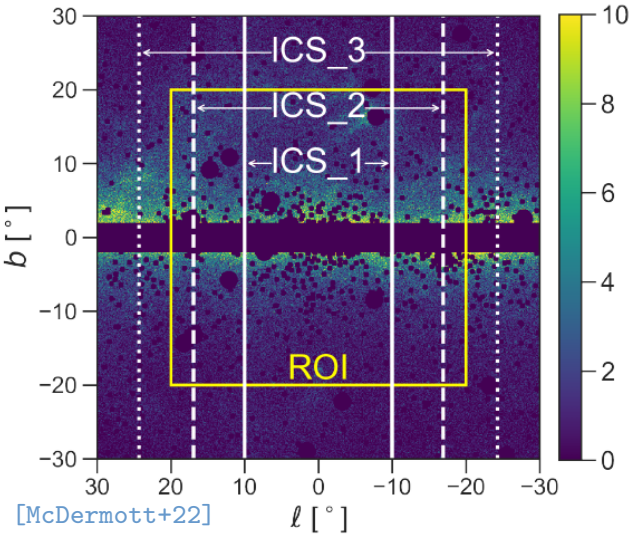
- Early works often *not testing* other morphologies
- Recent works: [DiMauro PRD'20,21, Cholis+PRD'22,McDermott+22], ... using astrophysical models and varying many parameters



[McDermott+22]

Stellar bulge (MSP-like)

- Two independent groups in 2018 [Bartels+NA'18,Macias+NA'18,JCAP'19]
- Subsequent works with even more significance: [Calore,SM PRL'21,Pohl+ApJ22] (ring based, skyfact based)



[McDermott+22]

Difficult to close this debate using only template fitting: current residuals too high