The Galactic center excess at the highest energies: morphology and photon-count statistics

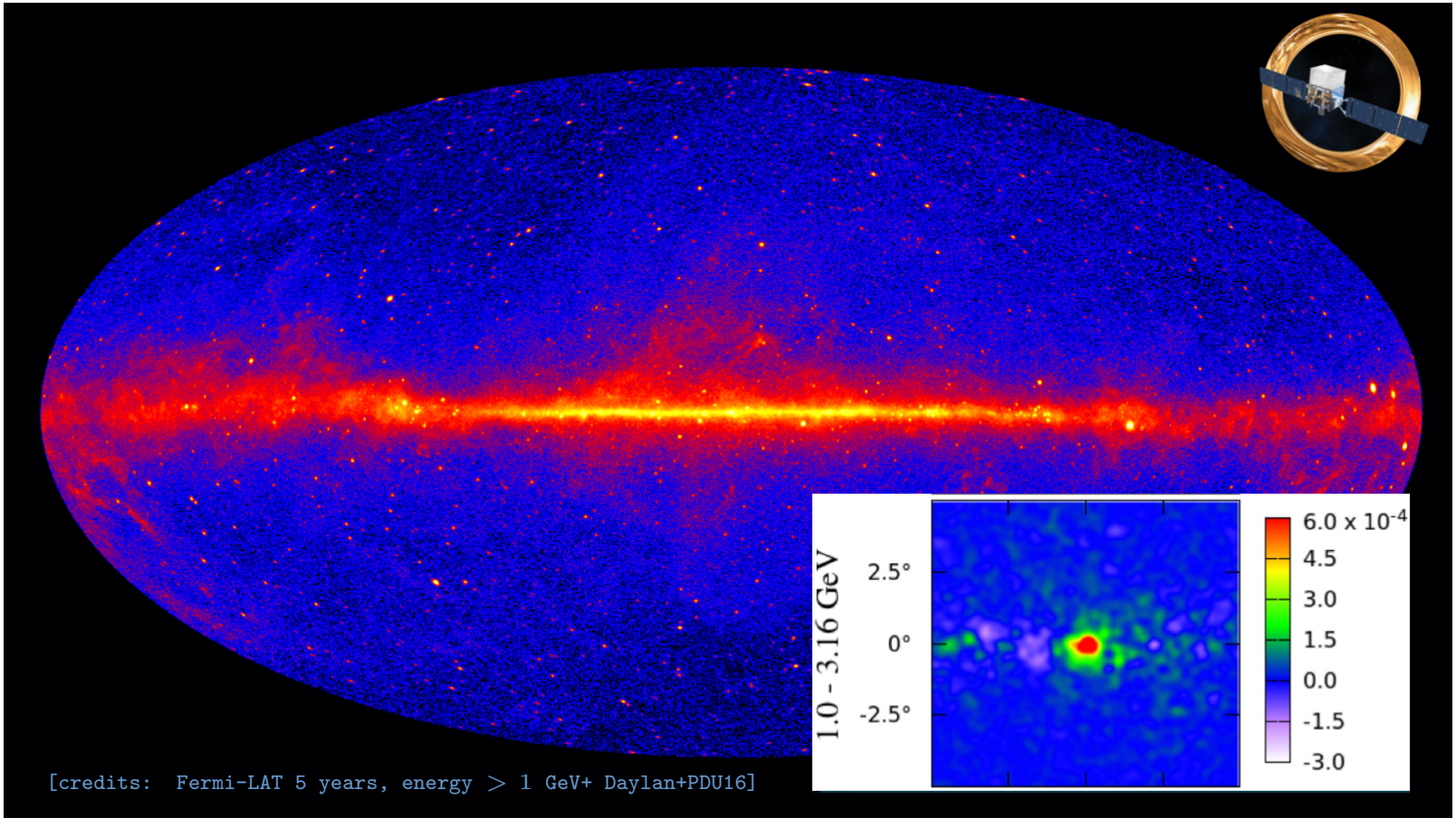
Silvia Manconi
Laboratoire d'Annecy-le-Vieux de Physique Theorique
CNRS (France)

September 11, 2024

11th Fermi Symposium, College Park, Maryland, USA
based on Manconi, Calore, Donato, PRD 2024 *arXiv:2402.04733*

The Galactic Center Excess

Since 2009 (first year of data)...



Statistically significant excess in Fermi-LAT data
few % of 2-20 GeV inner Galaxy flux, extended up to $\sim$ 10deg ($\sim$ 1.5kpc)

[Goodenough+'09,Vitale+'09,Abazajan+PRD'12,Hooper+PDU'13,Daylan+PDU'16, Calore+JCAP'15, Cholis+JCAP'15, Calore+PRD'15, Ajello+2015, Linden+PRD'16, Ackermann+ApJ'17,...500++papers]

The gamma ray Galactic Center Excess (GCE)

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

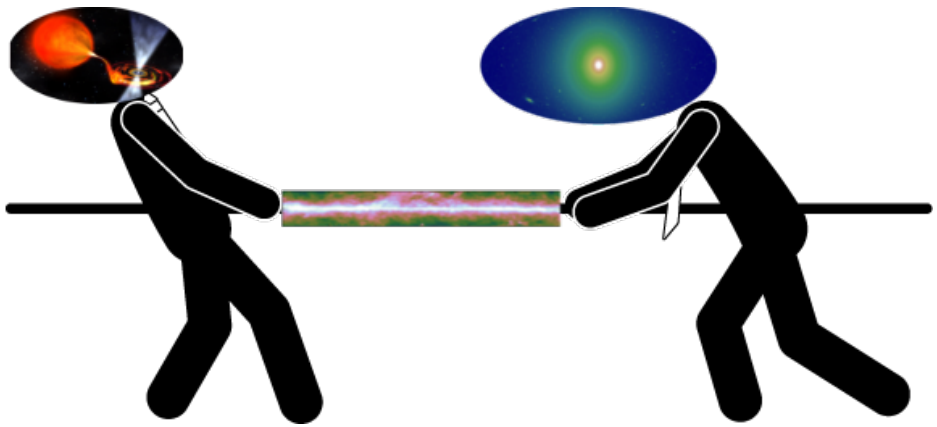
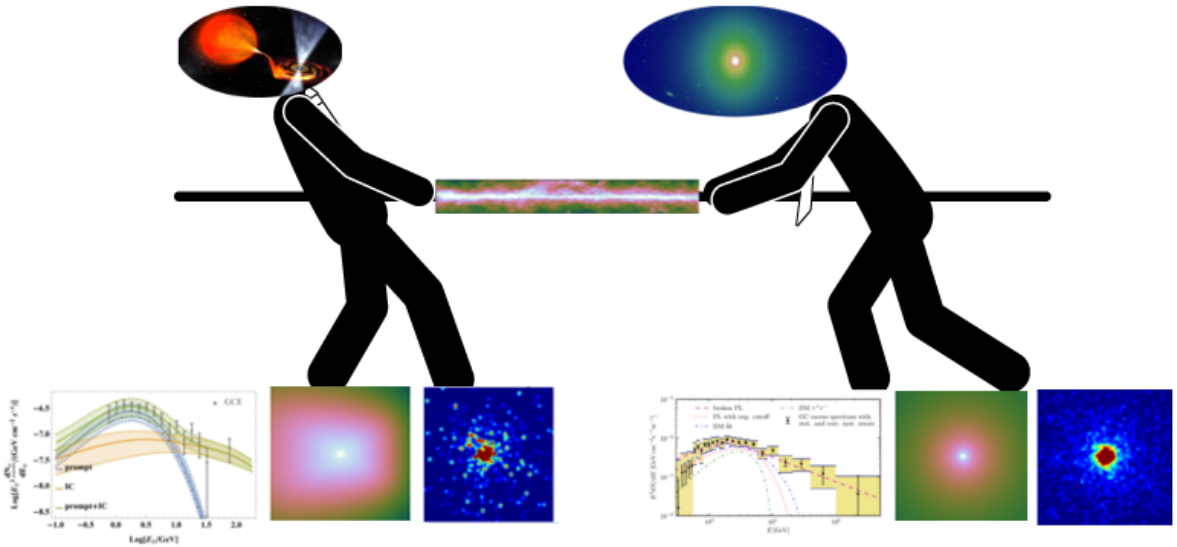


image credits: CLUMPY (J factor map), diffuse model [Storm+17], spectra [Gautam+21, Calore+14], morphology maps, [Storm+17], sim statistics [Lee+15]. *[Blame me for this collage]*

The gamma ray Galactic Center Excess (GCE)

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

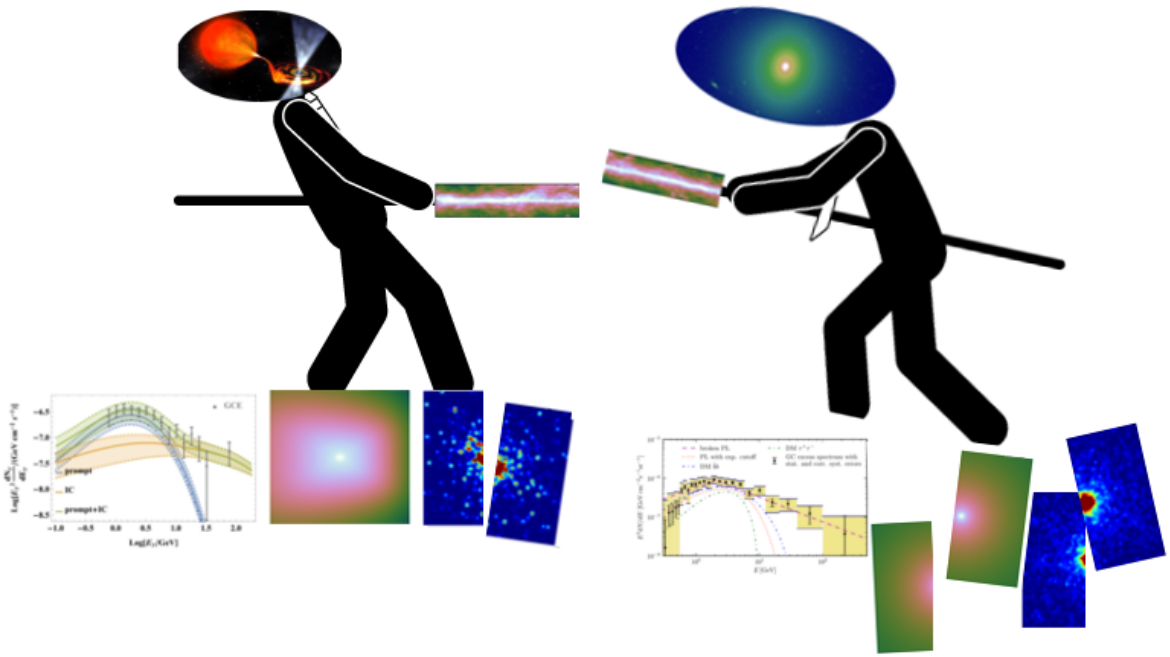


Characteristics: spectrum, morphology, photon statistics

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]*

The gamma ray Galactic Center Excess (GCE)

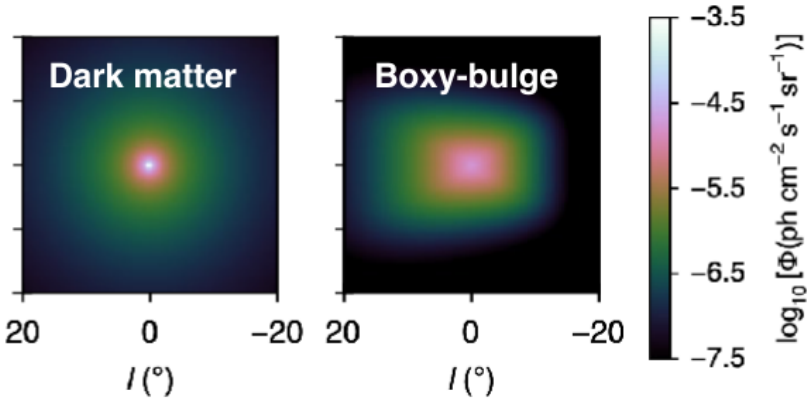
Debated nature:
Millisecond pulsar-like (MSP) in Galactic Bulge vs. Dark Matter (DM)



Interstellar diffuse emission mis-modeling

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]*

Morphology



Spherical symmetric (dark matter-like)

- Early works: spherical simmetric, contracted NFW profile $\gamma = 1.26$, but often *not testing* other morphologies
- Recent works: [DiMauro PRD'20,21, Cholis+PRD'22,McDermott+22], ... using astrophysical models and varying many parameters

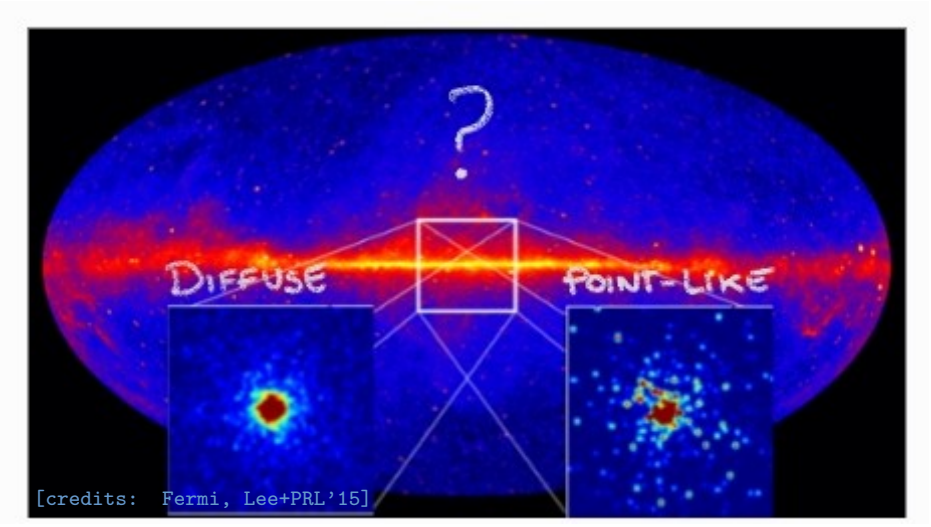
Stellar boxy-bulge (MSP-like)

- Stellar distribution of old MSP-like objects in Galactic bulge [Coleman+MNRAS20]
- First evidence: two independent groups [Bartels+NA'18,Macias+NA'18,JCAP'19]
- Subsequent works with even more significance: [Calore,SM PRL'21,Pohl+ApJ22]

Debate cleared by recent systematic comparisons in [Song+MNRAS'24]
see talk by D. Song, parallel 11B

Photon statistics

Truly diffuse emission:
dark matter

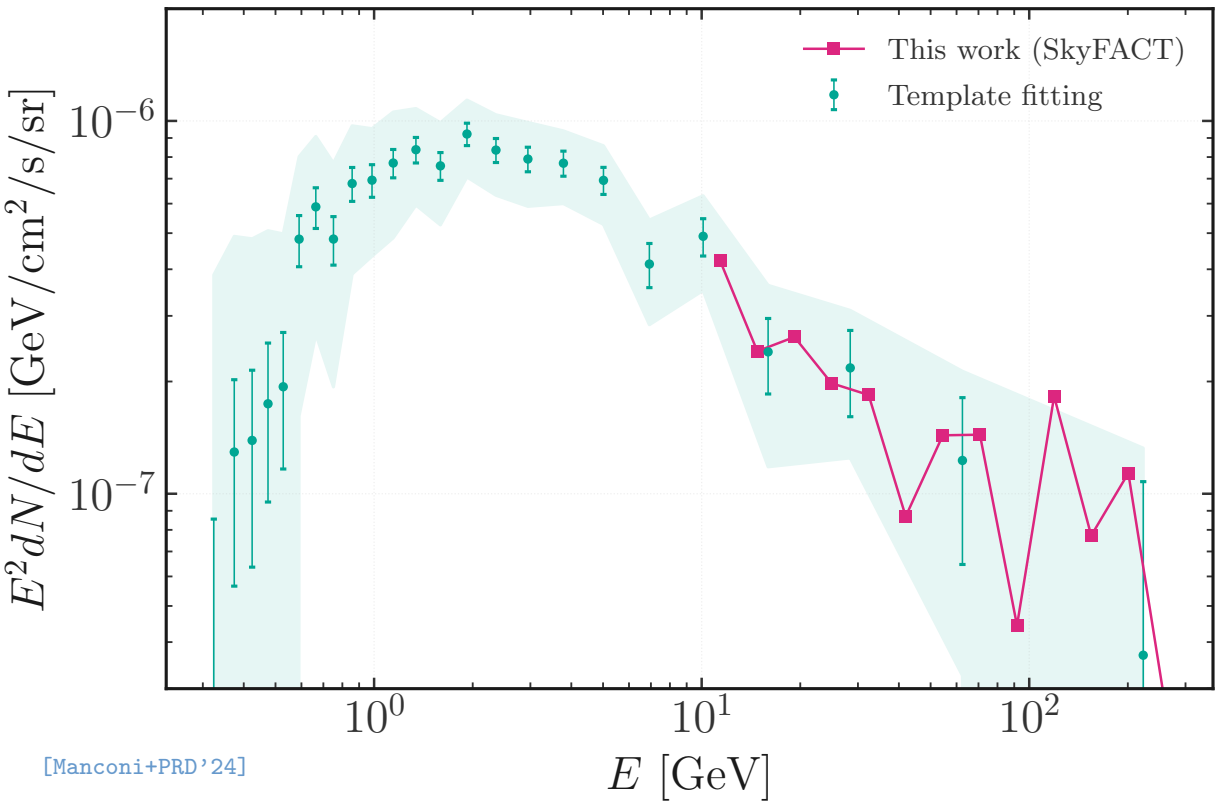


Point-like:
Faint, unresolved source population, e.g. MSPs

Difference in the statistics of photon counts

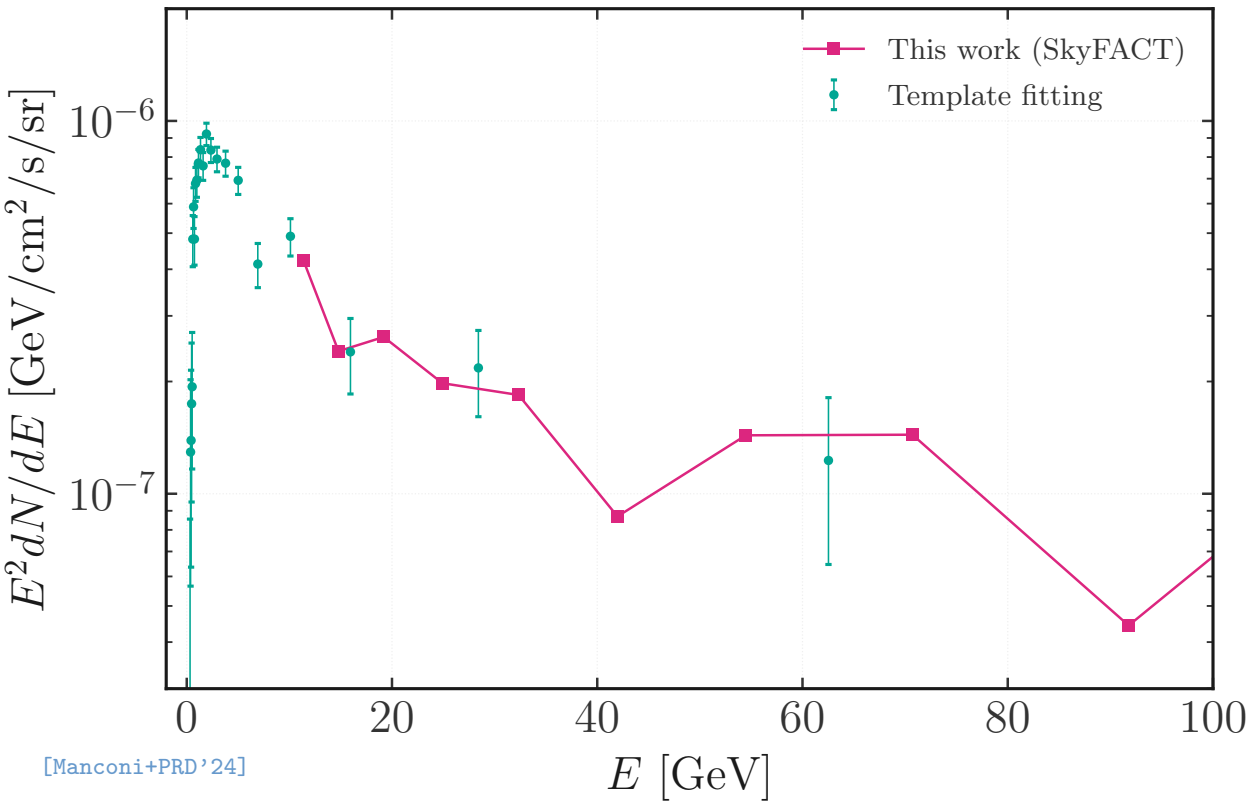
Small-scale residuals from diffuse mis-modeling could bias results
(see next + backup)

Spectrum: the high energy tail



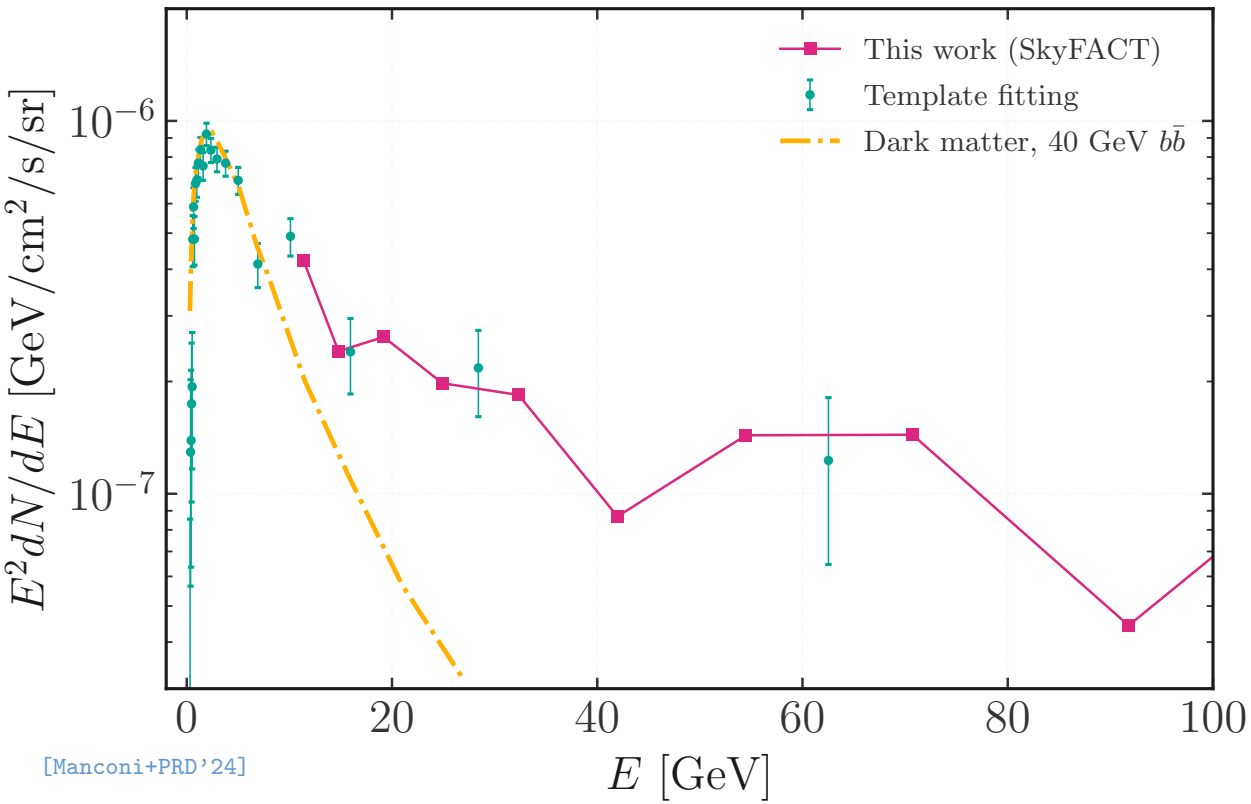
Crucial discrimination power: naturally explained by inverse Compton of $e^{\pm}$ in MSP, DM annihilation needs more tuning

Spectrum: the high energy tail



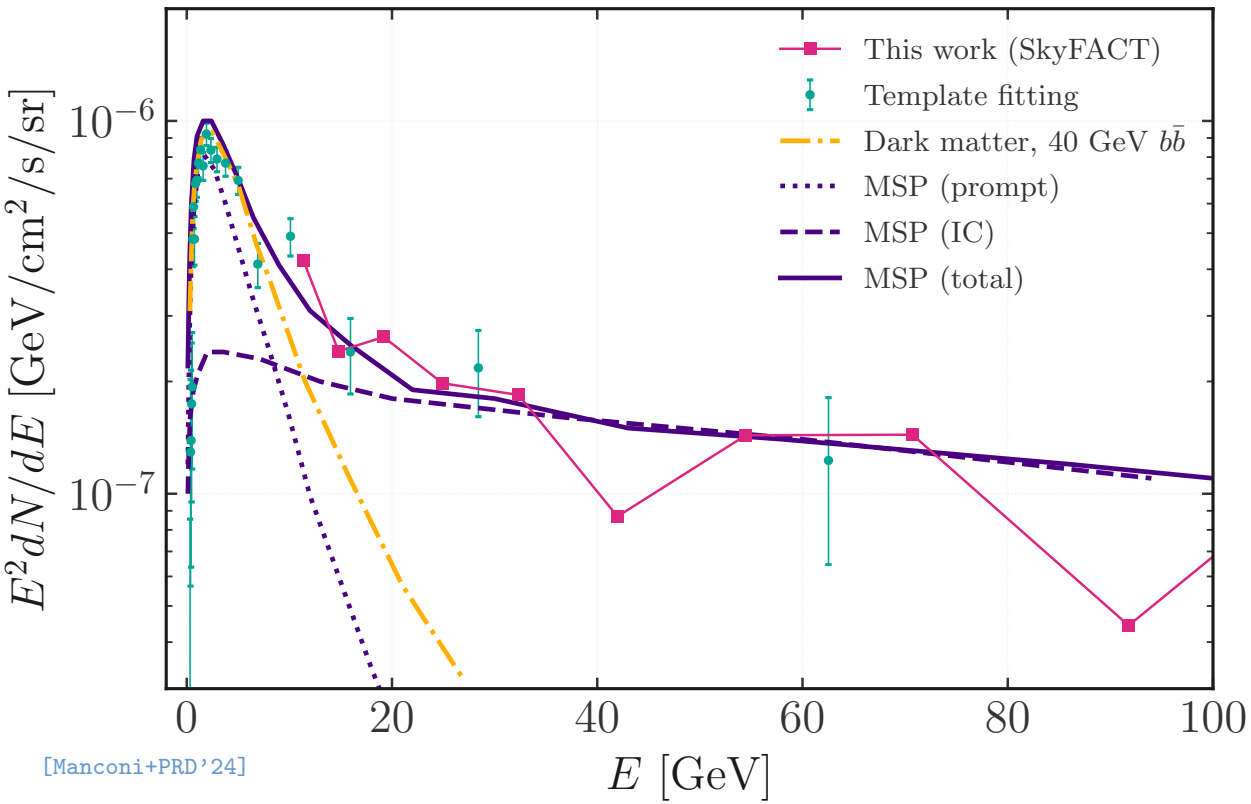
Crucial discrimination power: naturally explained by inverse Compton of $e^{\pm}$ in MSP, DM annihilation needs more tuning

Spectrum: the high energy tail



Crucial discrimination power: naturally explained by inverse Compton of $e^{\pm}$ in MSP, DM annihilation needs more tuning

Spectrum: the high energy tail



Crucial discrimination power: naturally explained by inverse Compton of $e^{\pm}$ in MSP, DM annihilation needs more tuning

The Galactic center excess at the highest energies

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

Manconi+PRD'24, arXiv:2402.04733

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

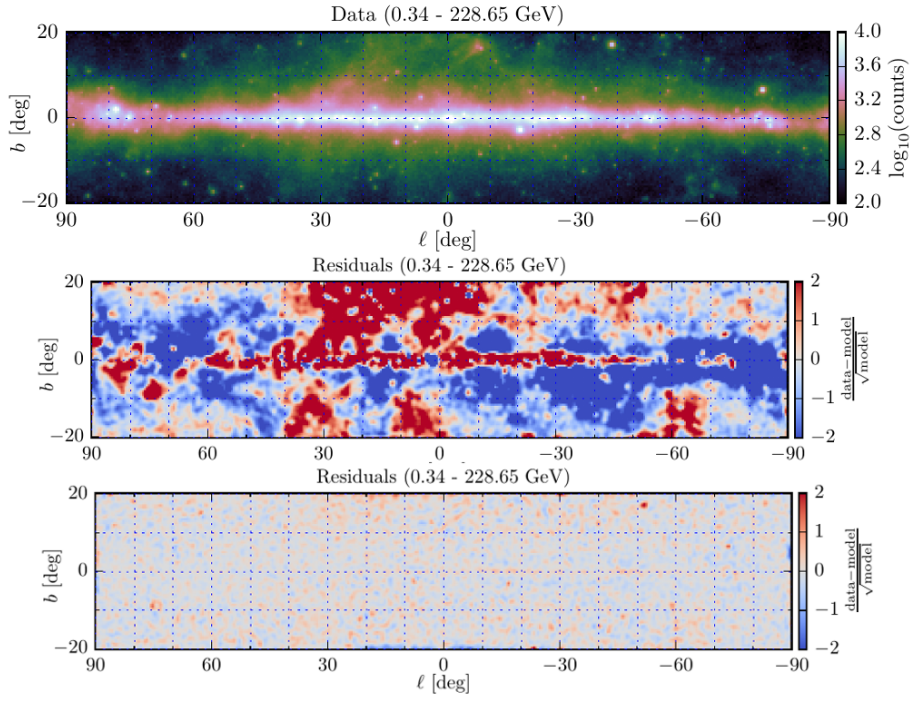
* *Adaptive template fitting* : Minimize/study diffuse emission model systematics, crucial for photon count statistics
* *Photon count statistics*: Measure faint point sources

Collaborators:

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

SkyFACT: overcoming diffuse emission mismodeling

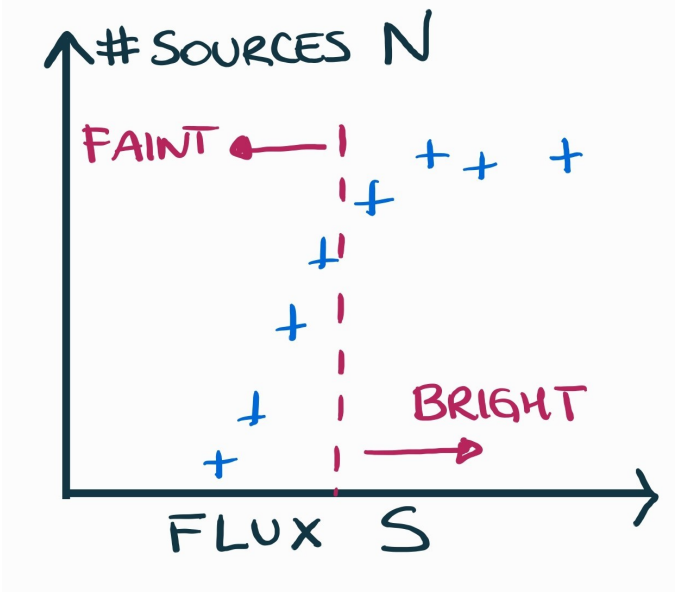
Model to fit Fermi-LAT data: Σ_{pixels} energy spectrum x spatial morphology



- 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]: data-driven account for intrinsic uncertainties in spectral/spatial predictions by introducing very large number of parameters w/ regularisation conditions for the likelihood

Photon count statistics of Fermi-LAT 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



Main application: isotropic, extragalactic sources

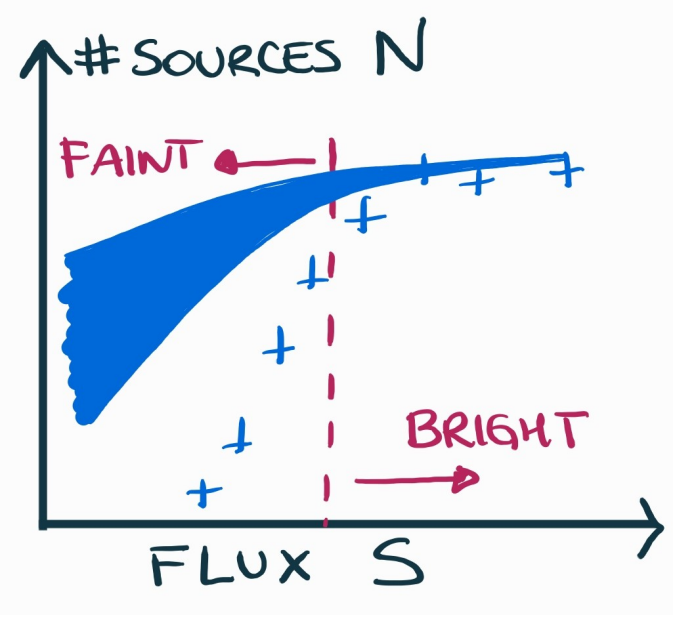
Bright diffuse backgrounds + mis-modeling could bias method at low latitudes

[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], ...

Photon count statistics of Fermi-LAT 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



Main application: isotropic, extragalactic sources

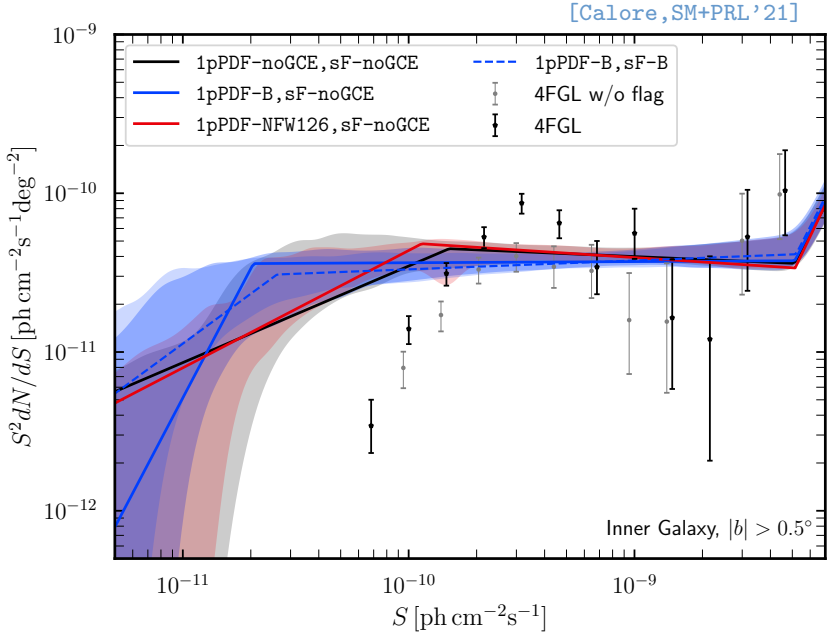
Bright diffuse backgrounds + mis-modeling could bias method at low latitudes

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

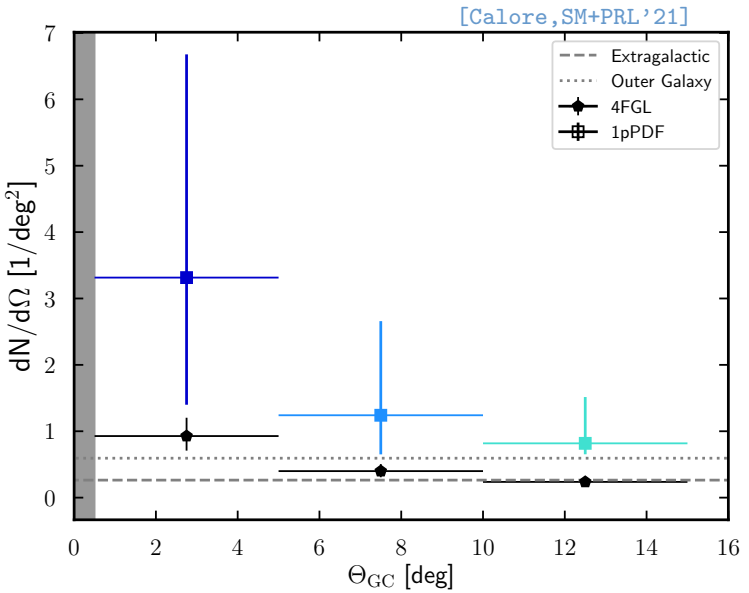
[1] Two main implementations: NPTF Lee+PRL16,Mishra-Sharma+AJ'17]; 1pPDF Zechlin+ApJS'16,+ApJL'16 based on formalism introduced in [Malyshev+ApJ2011]. Main applications include: extragalactic sources [Lisanti+Apj2016,DiMauro,SM+ApJ'18], blazar models [SM+PRD'20], DM halo, subhalo constraints [Zechlin,SM+PRD'18,Somalwar+ApJ'21],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

Inner Galaxy, energies 2–5 GeV: results recap

[Calore,SM+PRL'21]



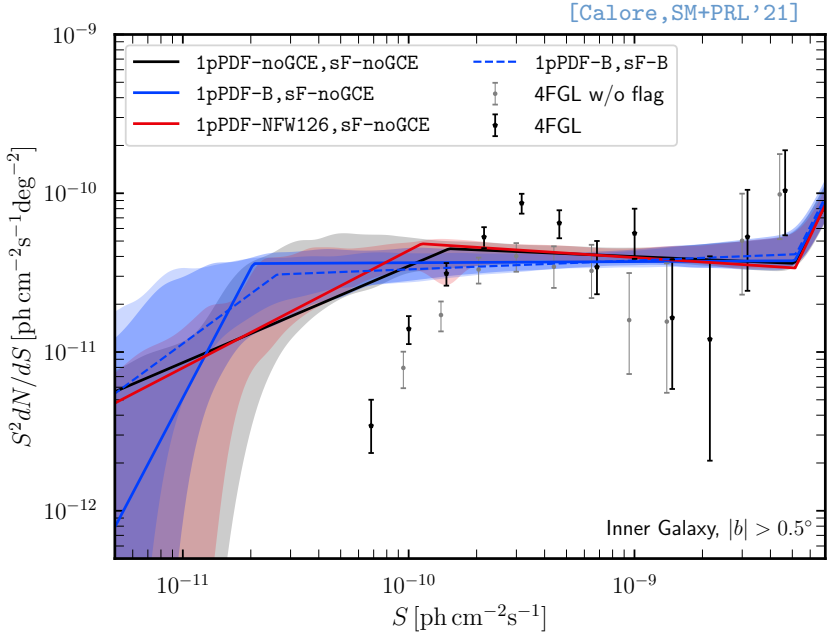
[Calore,SM+PRL'21]



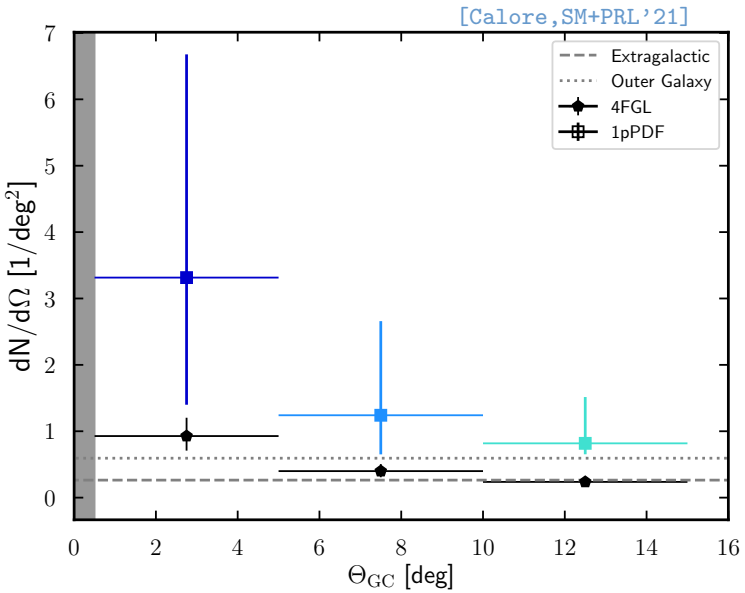
- Stellar-bulge morphology *preferred over dark matter*: SkyFACT only (10σ) and modeling faint sources (lnB$>$ 20), confirms [Bartels+NA'18,Macias+NA'18,JCAP'19]
- *Unresolved* point sources resolved down to $\sim 5 \cdot 10^{-11}$ ph cm^{-2} s^{-1}
- Diffuse mismodeling *strongly affects faint source reconstruction*
- Faint sources *not purely isotropic*, few % of total 2-5 GeV flux

Inner Galaxy, energies 2–5 GeV: results recap

[Calore,SM+PRL'21]



[Calore,SM+PRL'21]



- 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*
- Faint sources *not purely isotropic*, few % of total 2-5 GeV flux

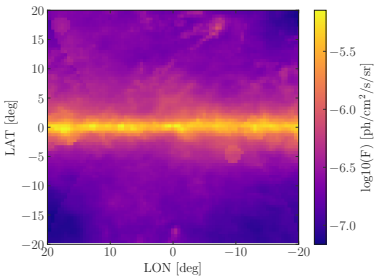
Corroborating a (at least) partial stellar origin of the Galactic center excess

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

Inner Galaxy at $10 - 300$ GeV: morphology

SkyFACT fit, nested model comparison

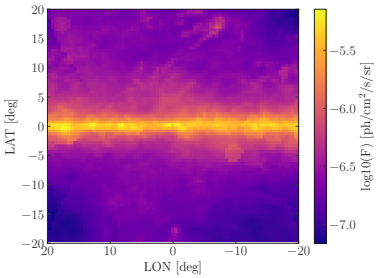
no GCE



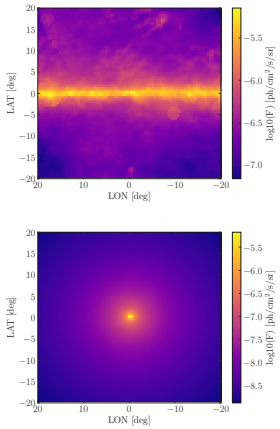
Inner Galaxy at $10 - 300$ GeV: morphology

SkyFACT fit, nested model comparison

no GCE



GCE: NFW ($\gamma = 1.26$)

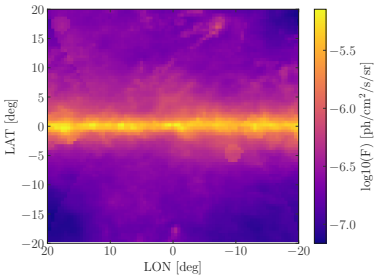


Comparing to no GCE: 5.6σ

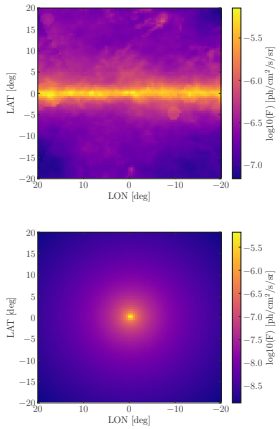
Inner Galaxy at $10 - 300$ GeV: morphology

SkyFACT fit, nested model comparison

no GCE

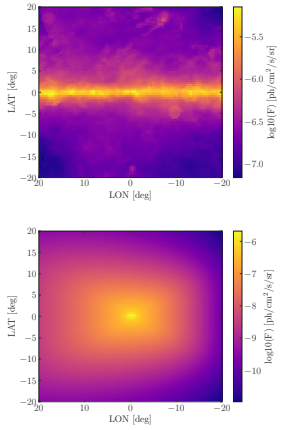


GCE: NFW ($\gamma = 1.26$)



Comparing to no GCE: 5.6σ

GCE: stellar + nuclear bulge

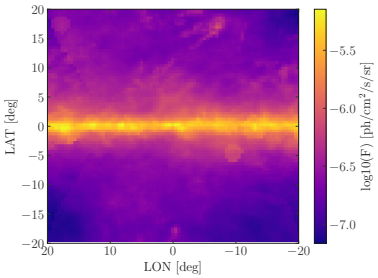


Comparing to no GCE: 8.1σ

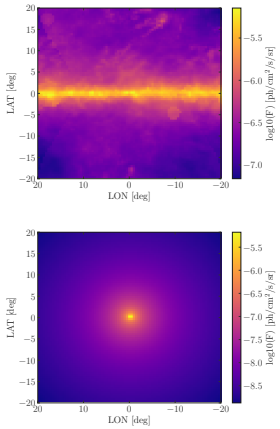
Inner Galaxy at $10 - 300$ GeV: morphology

SkyFACT fit, nested model comparison

no GCE



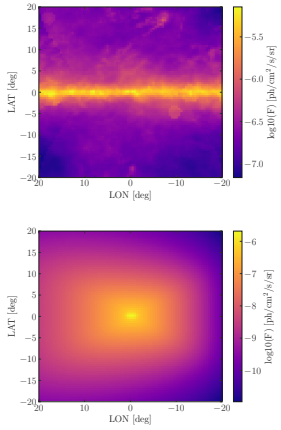
GCE: NFW ($\gamma = 1.26$)



Comparing to no GCE: 5.6σ

Comparing to boxy + nuclear bulge: no evidence

GCE: stellar + nuclear bulge



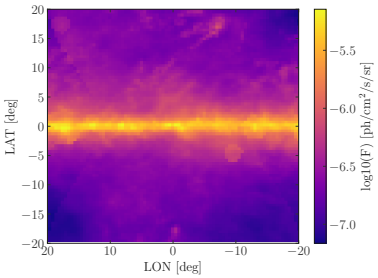
Comparing to no GCE: 8.1σ

Comparing to NFW: 5.5σ

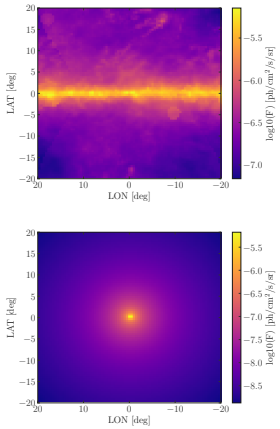
Inner Galaxy at $10 - 300$ GeV: morphology

SkyFACT fit, nested model comparison

no GCE



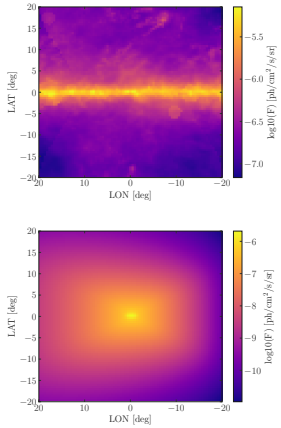
GCE: NFW ($\gamma = 1.26$)



Comparing to no GCE: 5.6σ

Comparing to boxy + nuclear bulge: no evidence

GCE: stellar + nuclear bulge



Comparing to no GCE: 8.1σ

Comparing to NFW: 5.5σ

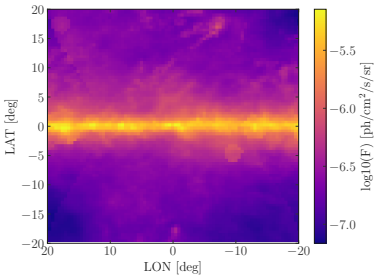
Photon count statistics, Bayesian model comparison $B_{\rm ij} = \exp(\ln \mathcal{Z}_i - \ln \mathcal{Z}_j)$

no GCE

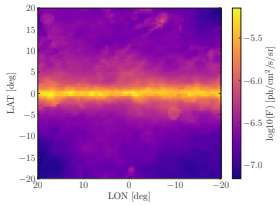
Inner Galaxy at $10 - 300$ GeV: morphology

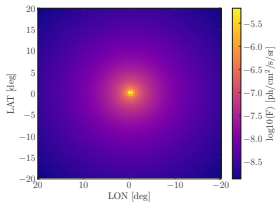
SkyFACT fit, nested model comparison

no GCE



GCE: NFW ($\gamma = 1.26$)

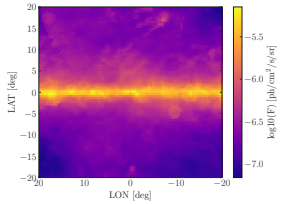


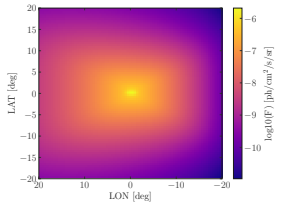


Comparing to no GCE: 5.6σ

Comparing to boxy + nuclear bulge: no evidence

GCE: stellar + nuclear bulge





Comparing to no GCE: 8.1σ

Comparing to NFW: 5.5σ

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

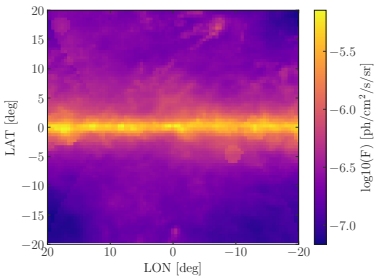
no GCE

Comparing to no GCE:
$\ln(B) = 13$

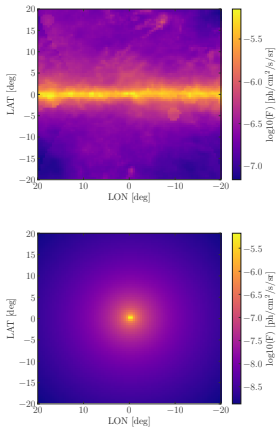
Inner Galaxy at $10 - 300$ GeV: morphology

SkyFACT fit, nested model comparison

no GCE

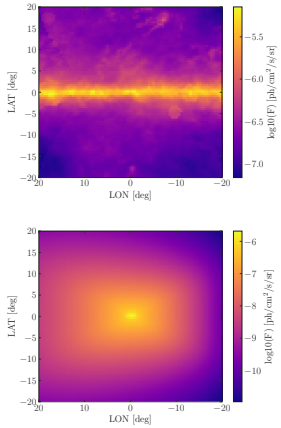


GCE: NFW ($\gamma = 1.26$)



Comparing to no GCE: 5.6σ
Comparing to boxy + nuclear bulge: no evidence

GCE: stellar + nuclear bulge



Comparing to no GCE: 8.1σ
Comparing to NFW: 5.5σ

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

no GCE

Comparing to no GCE:
$\ln(B) = 13$

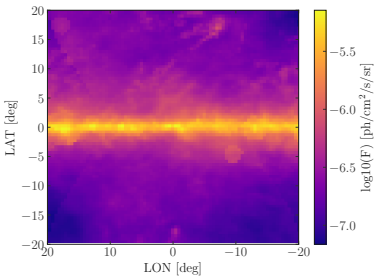
Comparing to no GCE:
$\ln B \gtrsim 30$
Comparing to NFW: lnB=18

unresolved sources + norm of diffuse, GCE templates ~ 1

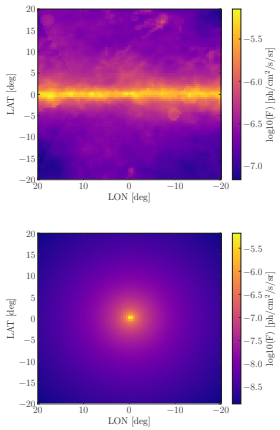
Inner Galaxy at $10 - 300$ GeV: morphology

SkyFACT fit, nested model comparison

no GCE

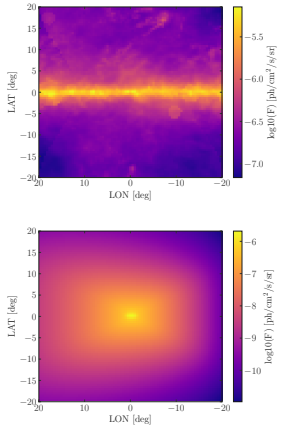


GCE: NFW ($\gamma = 1.26$)



Comparing to no GCE: 5.6σ
Comparing to boxy + nuclear bulge: no evidence

GCE: stellar + nuclear bulge



Comparing to no GCE: 8.1σ
Comparing to NFW: 5.5σ

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

no GCE

Comparing to no GCE:
$\ln(B) = 13$

Comparing to no GCE:
lnB$\gtrsim$30
Comparing to NFW: lnB=18

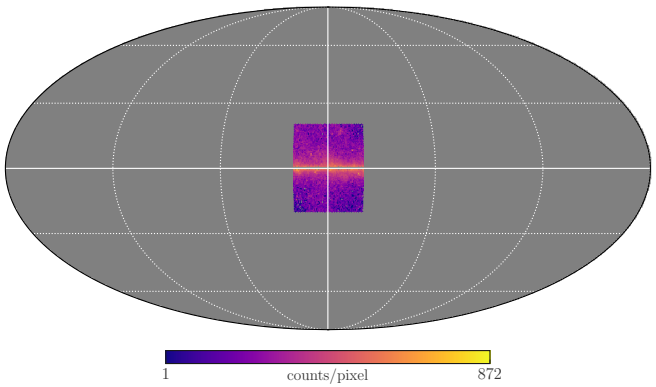
unresolved sources + norm of diffuse, GCE templates ~ 1

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

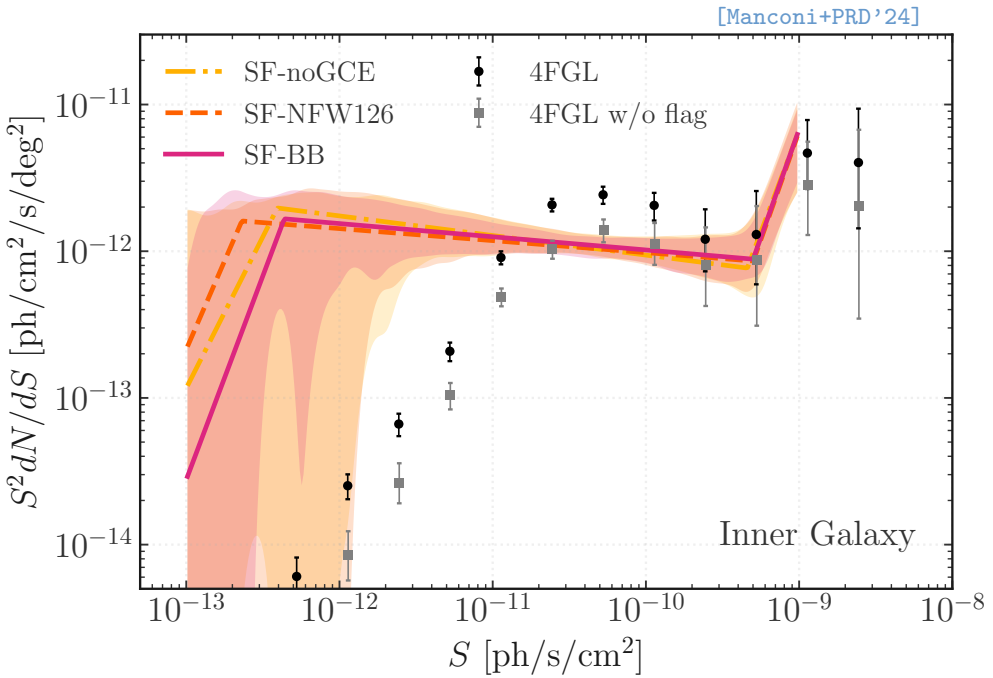
Inner Galaxy at 10–300 GeV: dN/dS

Cumulative source-count distribution:

20x20deg, cut plane at 1deg



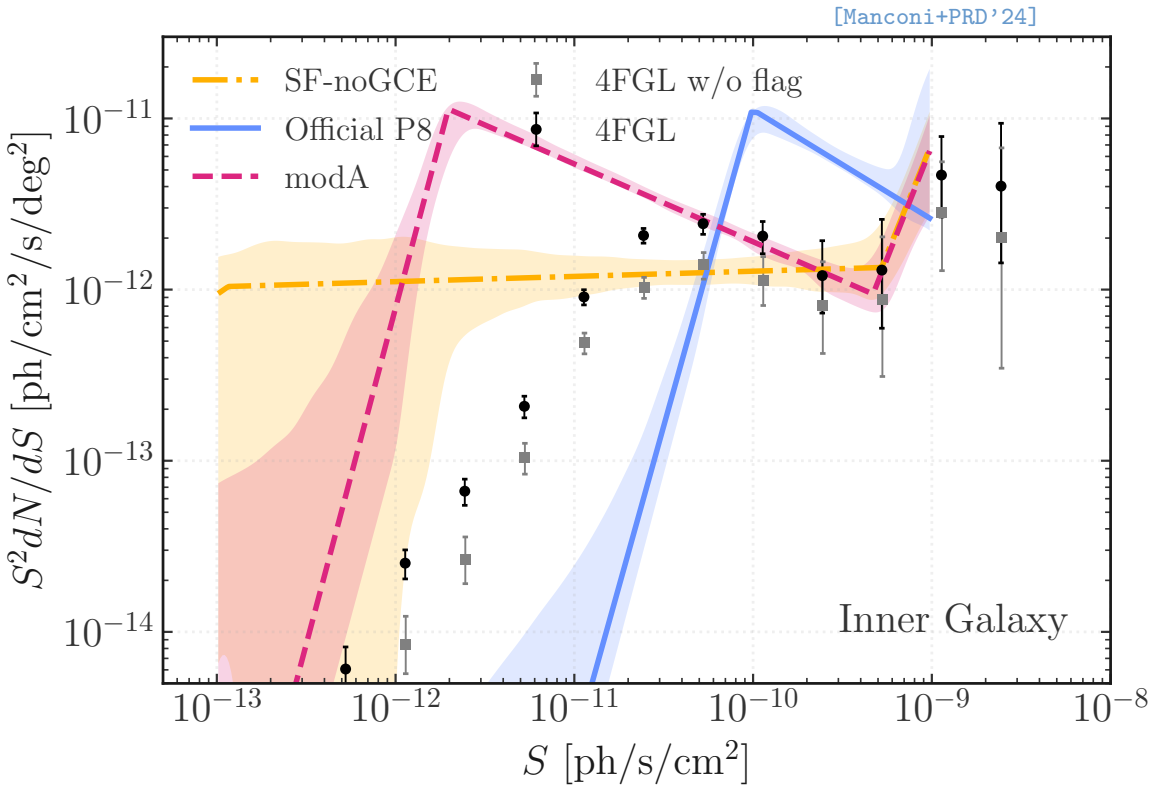
[Manconi+PRD'24]



- 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
- Source density higher than extragalactic and outer Galaxy
- Hints of an asymmetry among negative and positive longitudes

Corroborating a (at least) partial stellar origin of the Galactic center excess, now from > 10 GeV only

Inner Galaxy dN/dS & diffuse mismodeling



Using non-optimized Galactic diffuse emission models, 1pPDF looses sensitivity/finds spurious peaks

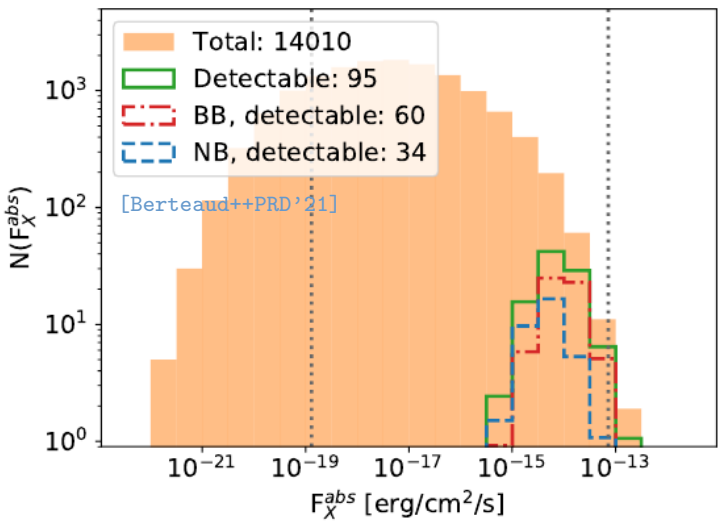
Testing MSP hyphothesis: X-rays & radio

Searches for the Bulge MSP contributing to GeV excess are ongoing

→ **talk by J.Berteaud**, Plenary 10

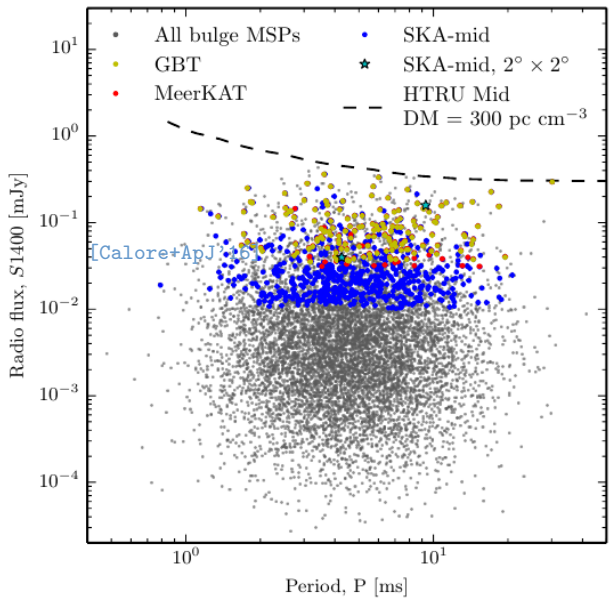
Unresolved in gamma rays but could be seen at other energies!

X-ray searches



- MSP population explaining the excess **consistent with Chandra data**
- Set of promising candidates only seen in X-rays so far

Radio searches



- Current radio telescopes: not sensitive to MSP in Galactic bulge
- Future SKA, MeerKAT: can discover this population, $O(100)$h observation

Summary & Outlook

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

Manconi+PRD'24, arXiv:2402.04733

- ✓ Addressing diffuse emissions mis-modeling with adaptive template fitting
- ✓ Measuring bright and faint point sources with photon count statistics
- ✓ Characterizing source density of faint point sources in the inner Galaxy

Summary & Outlook

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

Manconi+PRD'24, arXiv:2402.04733

- ✓ Addressing diffuse emissions mis-modeling with adaptive template fitting
- ✓ Measuring bright and faint point sources with photon count statistics
- ✓ Characterizing source density of faint point sources in the inner Galaxy

Work in progress:

- Consistency of results between energy bins and interpretation
- Predictions for forthcoming surveys of high-energy gamma rays

Thank you for listening!




Dr. Silvia Manconi

silvia.manconi@lapth.cnrs.fr

Marie Sklodowska-Curie fellow

Laboratoire d'Annecy-le-Vieux de Physique Theorique

CNRS (France)

https://silviamanconi.wordpress.com/

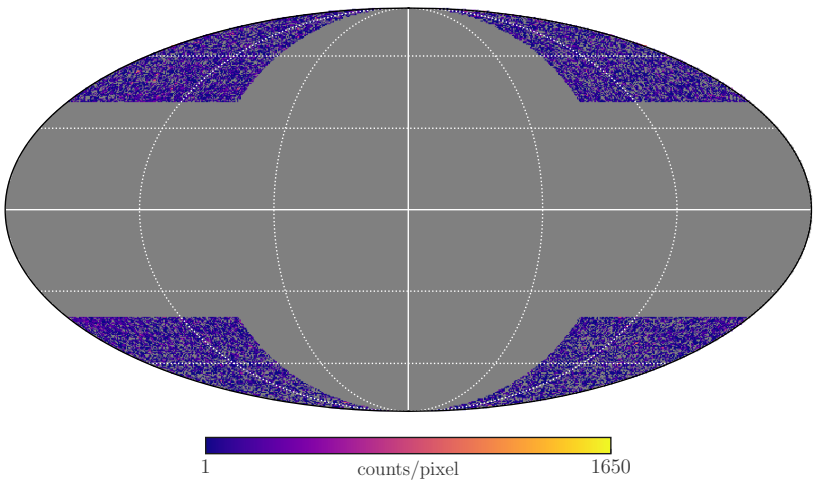
I acknowledge the European Union's Horizon Europe research and innovation programme for support under the Marie Sklodowska-Curie Action PF2021, grant agreement No.10106280, project VerSi.

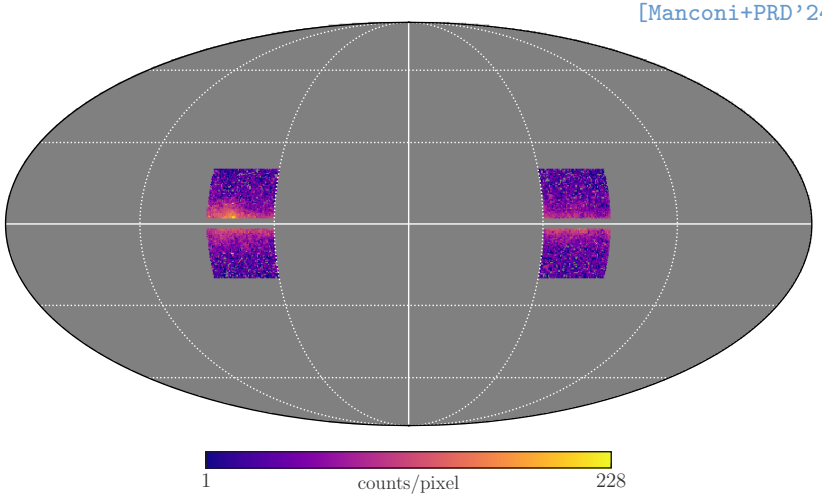
Backup

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

→ Compare source count distribution and density to inner Galaxy

[Manconi+PRD'24]

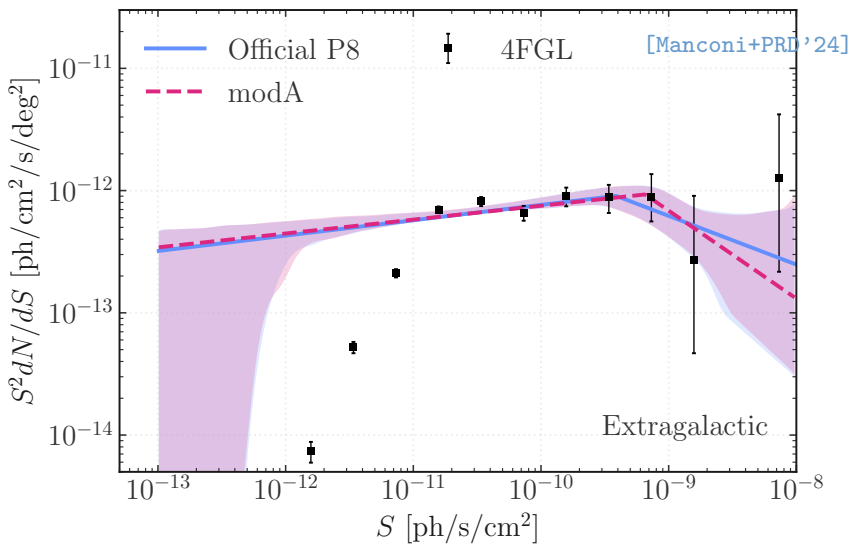


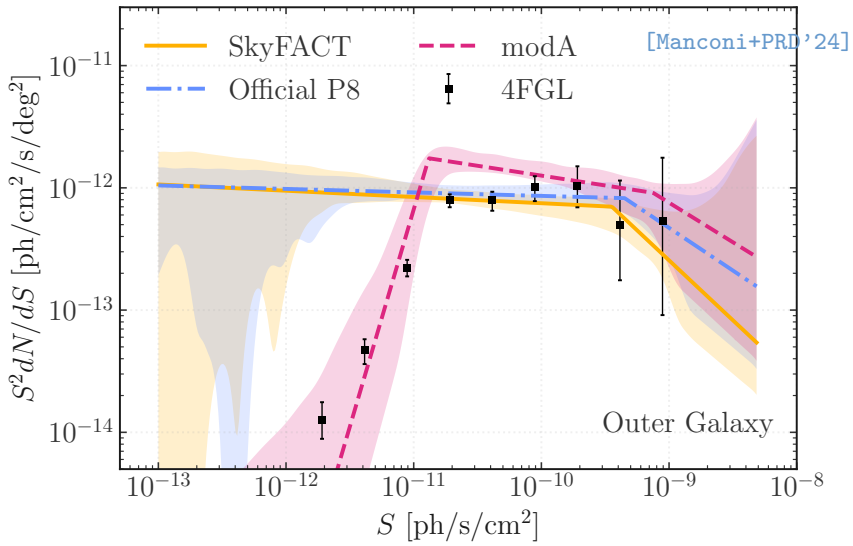


[2] GALPROP model from Fermi-LAT IGRB analysis [Ackermann+ApJ'15]

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

→ Compare source count distribution and density to inner Galaxy

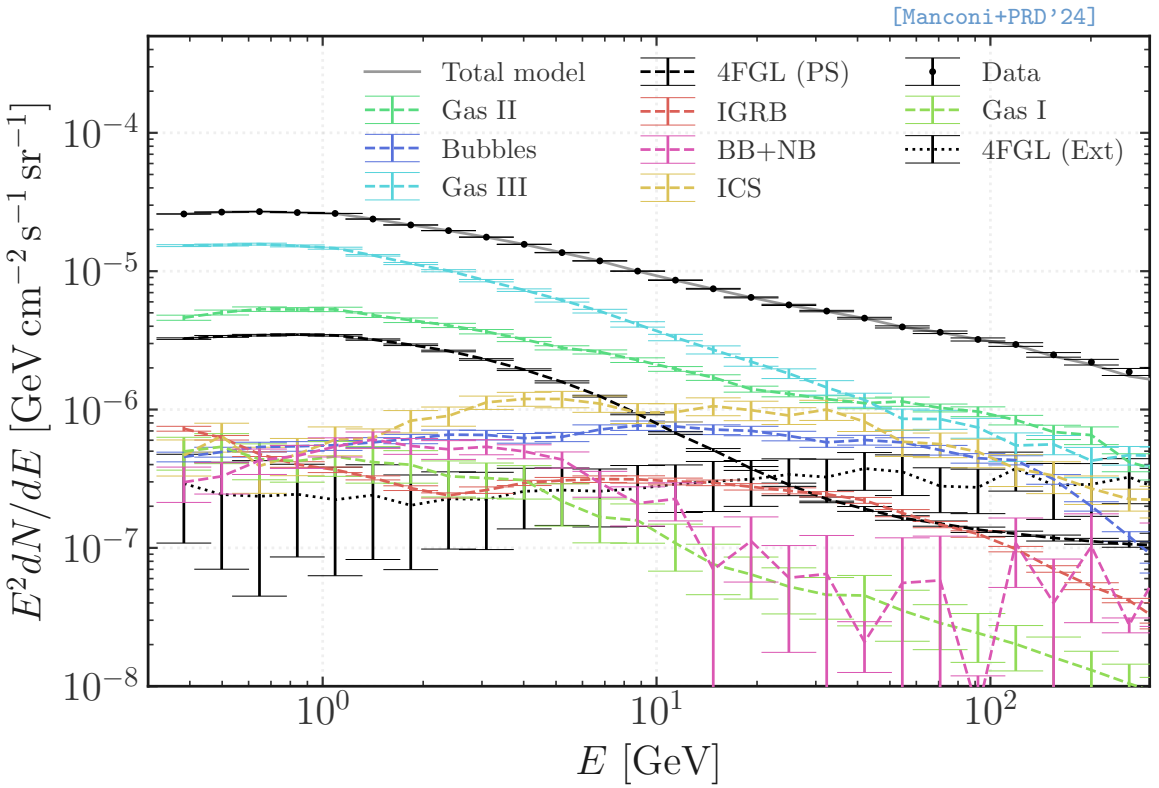




- High latitudes: stable and robust measurement, no matter diffuse model
- Low latitudes: large residuals with modA[2], drives spurious source reconstruction around catalog threshold
- Sources resolved at fluxes 1 order of magnitude lower with respect to catalog threshold, see e.g. 3FHL [DiMauro,SM+ApJ'18]

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

SkyFACT results: inner Galaxy spectrum

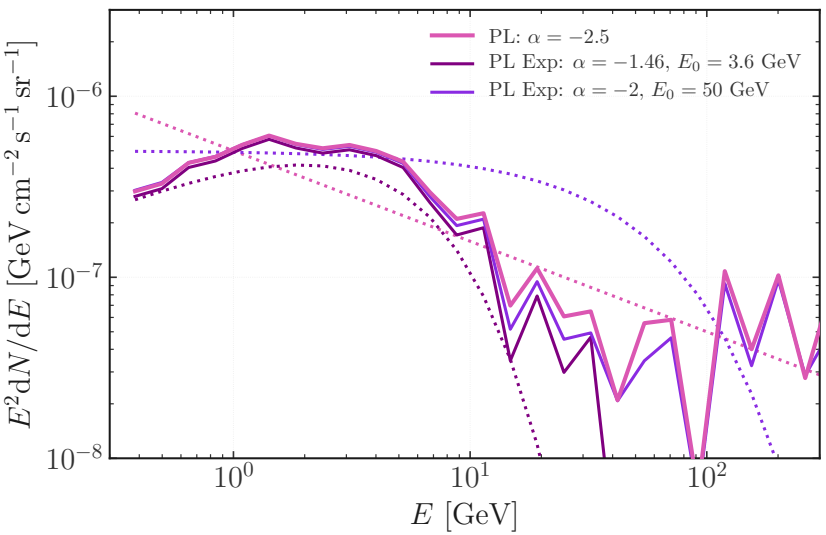


- Significant GCE high energy tail at $E > 10$ GeV (BB+NB)
- Model components compatible between full energy (0.2-500 GeV) and high energy (> 10 GeV) fit
- Optimized diffuse templates $E > 10$ GeV used for 1pPDF

Systematic tests (backup): input spectrum, Fermi Bubbles, ...

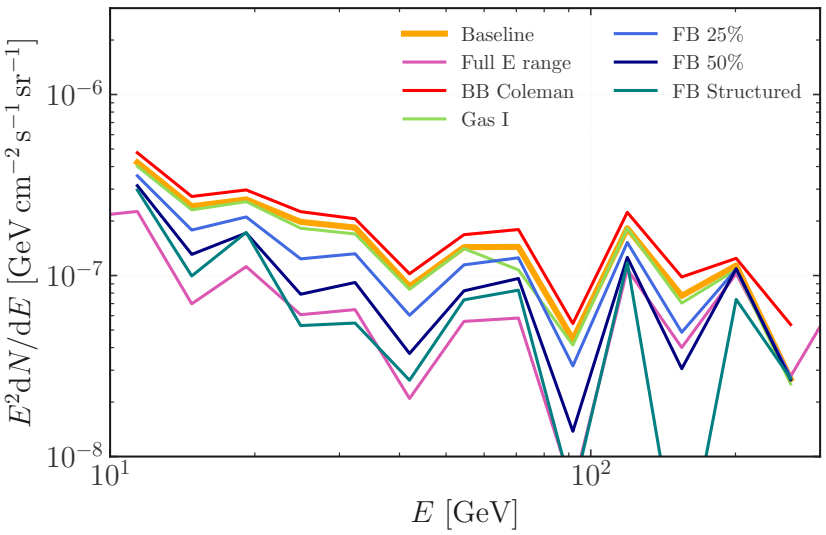
SkyFACT: systematics on GCE spectrum

[Manconi+PRD'24]



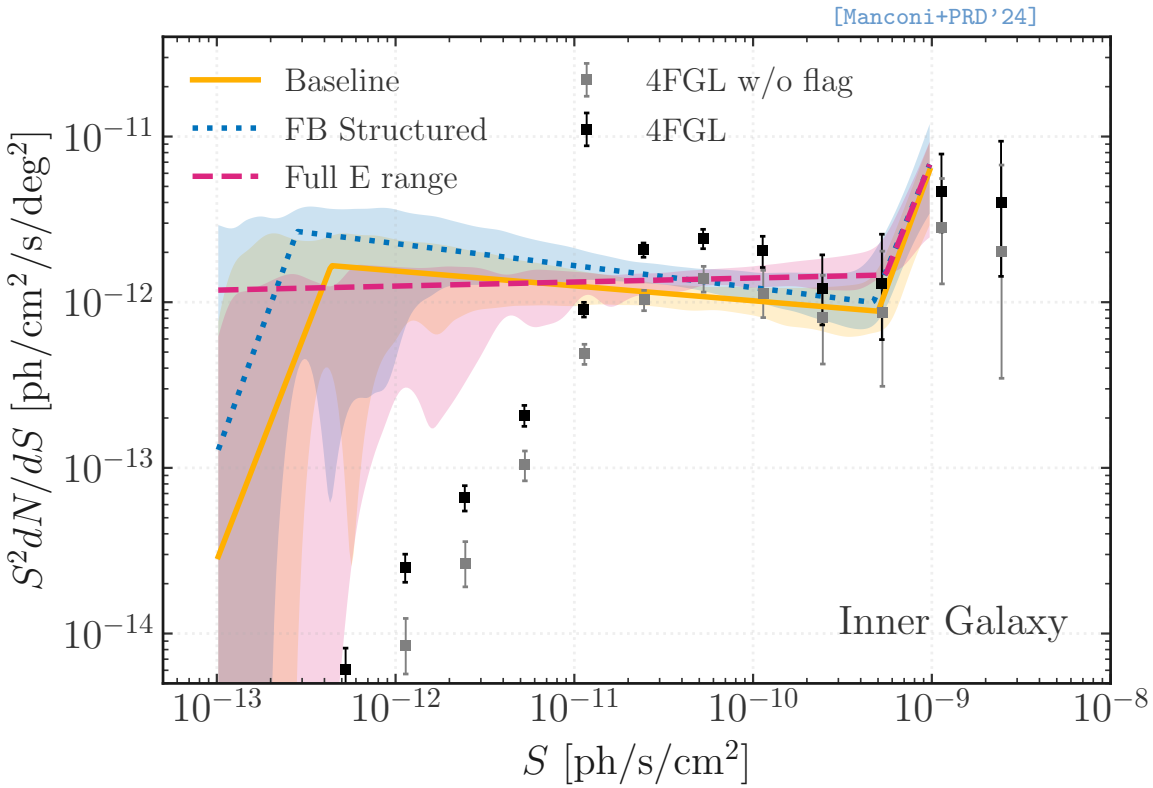
A power law input spectrum is needed to possibly reconstruct HE tail

[Manconi+PRD'24]



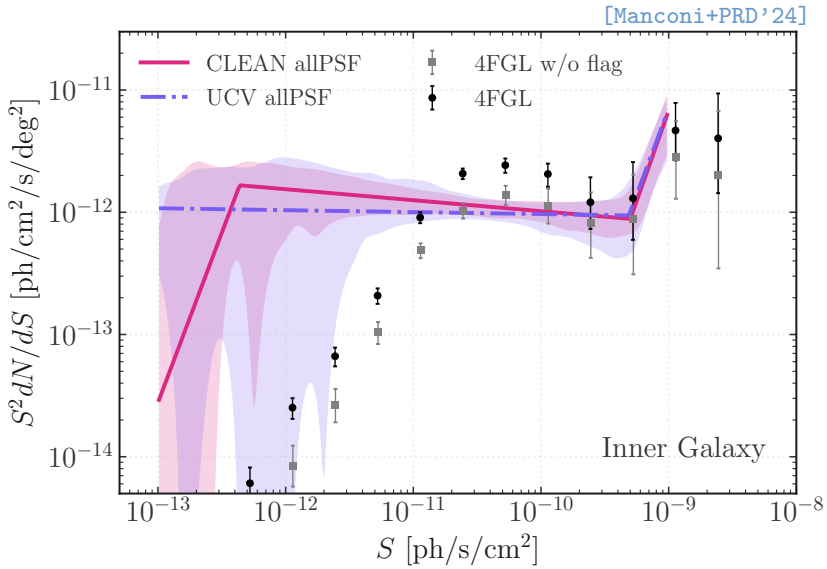
GCE spectra reconstructed testing uncertainties: results stable, factor ~ 2 normalization

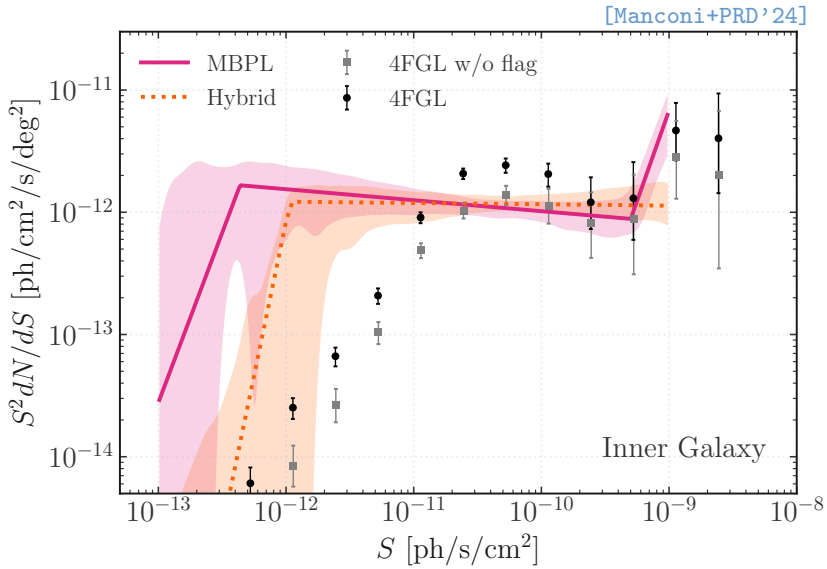
1pPDF: systematics (I)



Fermi Bubbles template, and energy interval in which the skyFACT template is optimized, leave 1pPDF results for the dN/dS consistent

1pPDF: systematics (II)

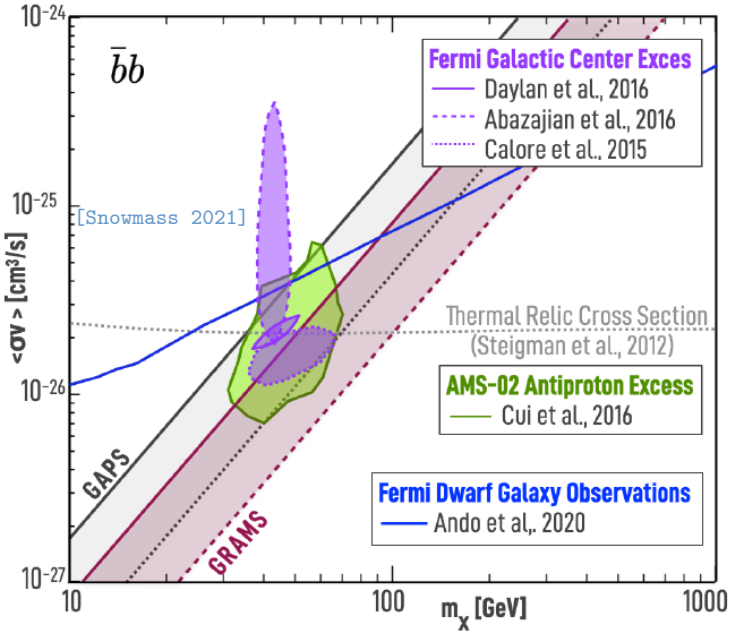




Variations of Fermi-LAT data event selection (left) and treatment of faint sources (right) give consistent results

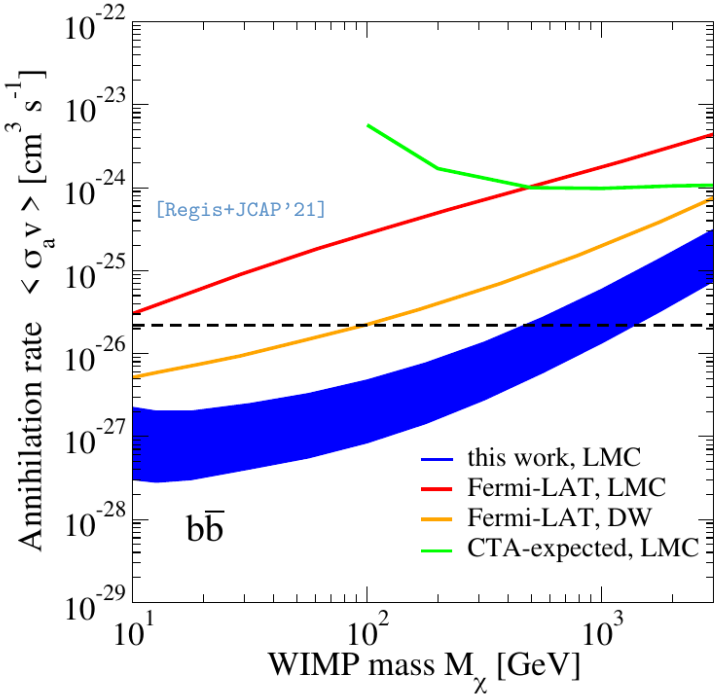
Testing dark matter hyp.: Multi target + cosmic rays

If dark matter: we want consistent signal elsewhere: dwarfs, $\bar{p}$, e^+, $\bar{d}$, ...
not only WIMPs, e.g. hidden sectors [Hooper+JHEP'20]



- Still no signal in **dwarfs**, excess region not excluded [DiMauro+PRD'21, Ando+'20]
- $\bar{p}$ **excess**: debated! if not there, tension with constraints [DiMauro+PRD'21,Heisig+PRR'20,Boudaud+PRR'20, Cholis+PRD'19, ...]

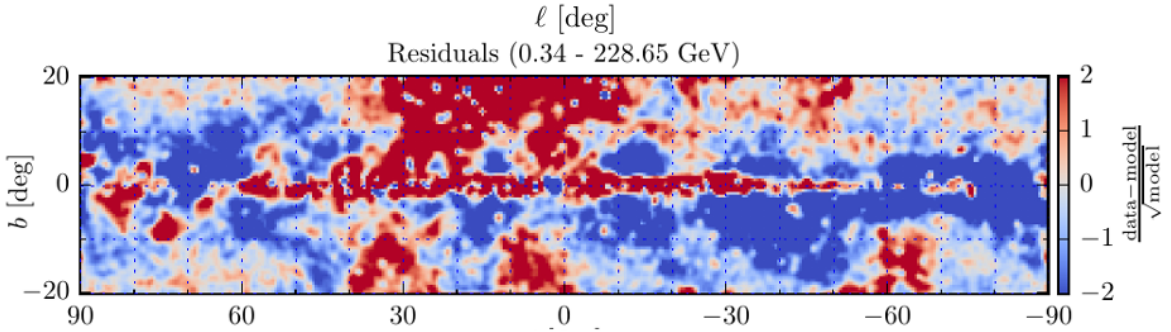
- Large Magellanic Cloud: larger J factor after Galactic center!



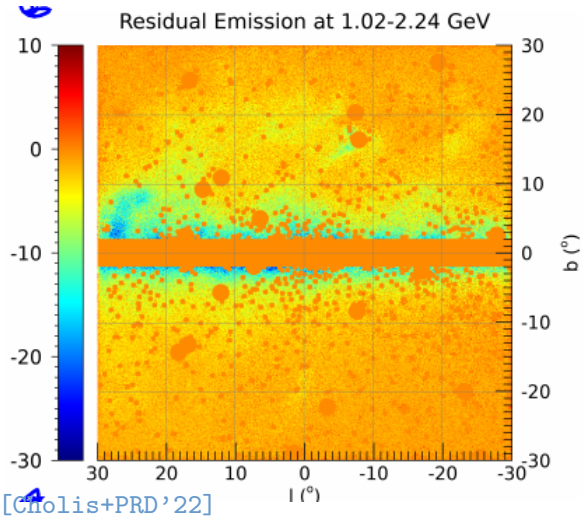
Troubles for sub-TeV WIMPs?

Galactic diffuse mismodeling: residuals

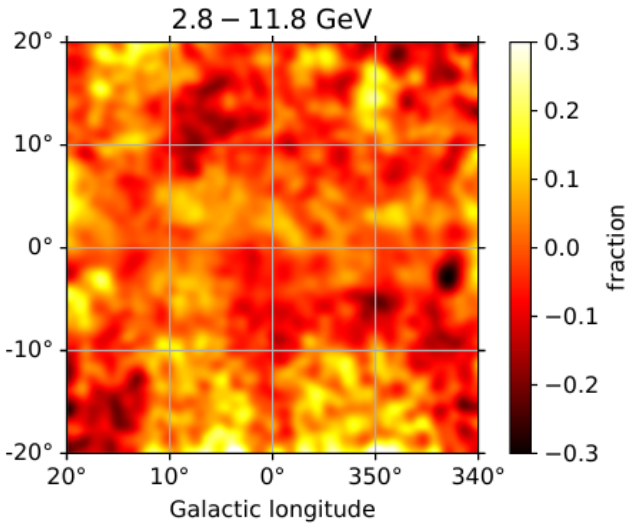
Model to fit Fermi-LAT data: Σ_{pixels} energy spectrum x spatial morphology



[Storm+JCAP'17]



[Cholis+PRD'22]



[Pohl+PRD'22]

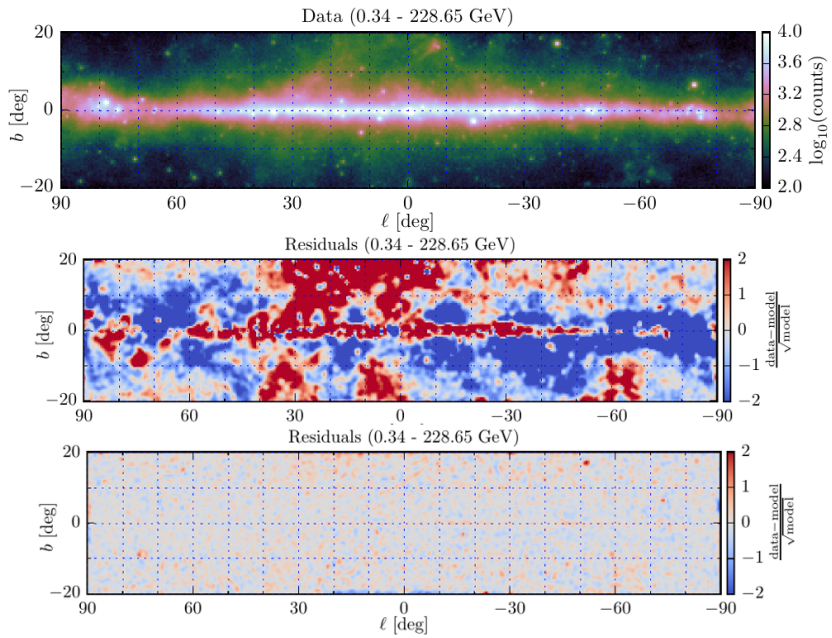
Template fitting: still up to 30% residuals

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?

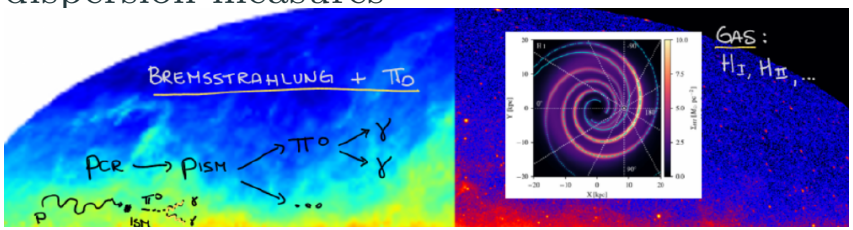
Data-driven:

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



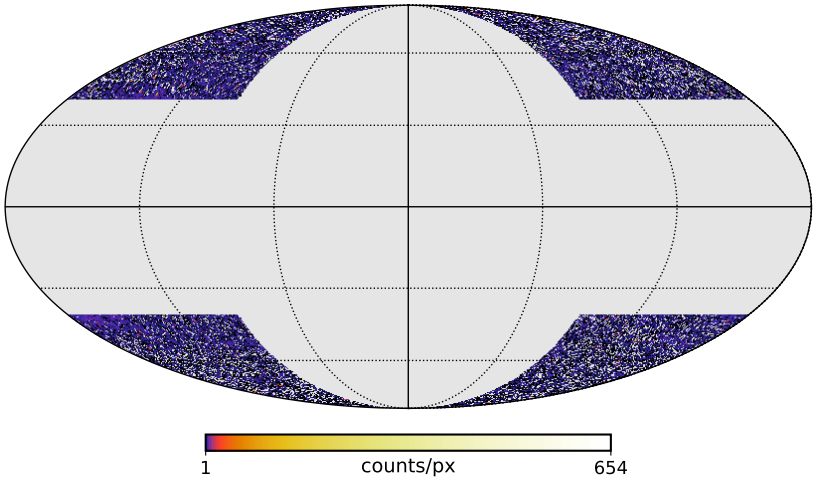
Improve models:

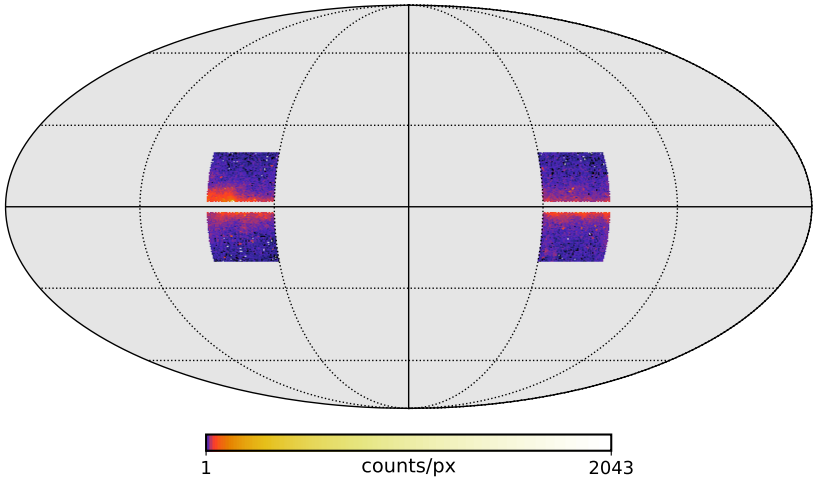
Better estimates of target H_I, H_2, H_{II} gas column density, inferred by line spectra, dispersion measures

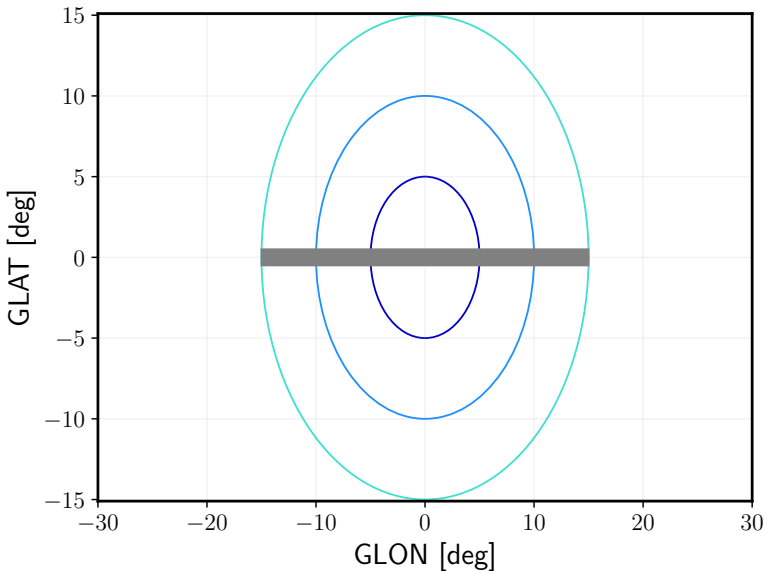


- new atomic HI reconstr, with radiation model of emission +absorption [Shmakov+22]
- convolutional neural nets to fill gaps in molecular H_2 tracers like CO
  [Shmakov+22,Karwin+22]
- bayesian inference of 3D CO maps
  [Mertsch&Vittino'20]

dNdS results: control regions (2–5 GeV)

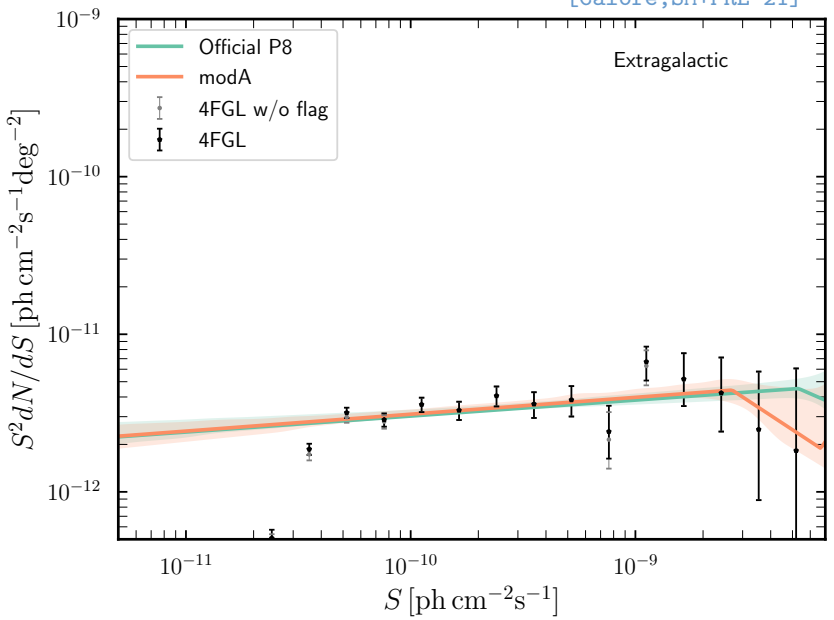




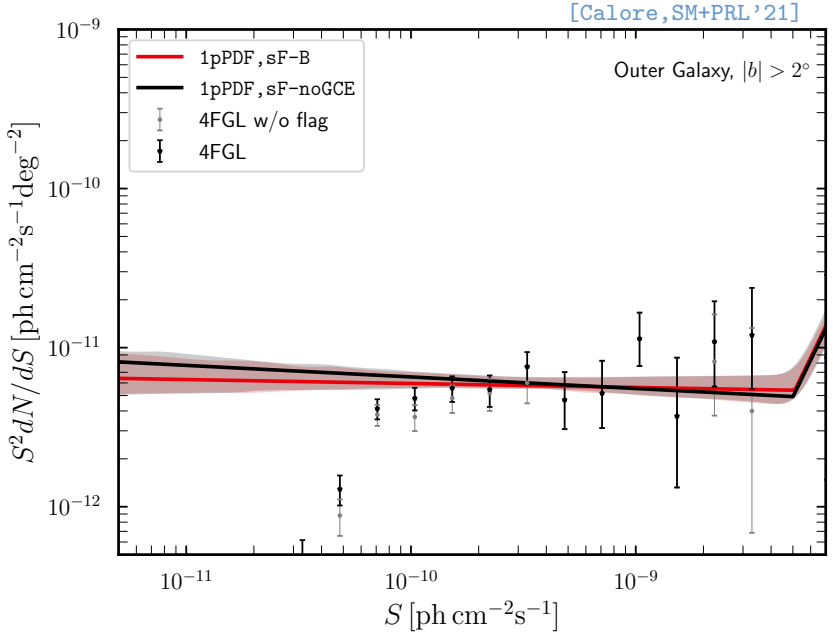


dNdS results: control regions (2–5 GeV)

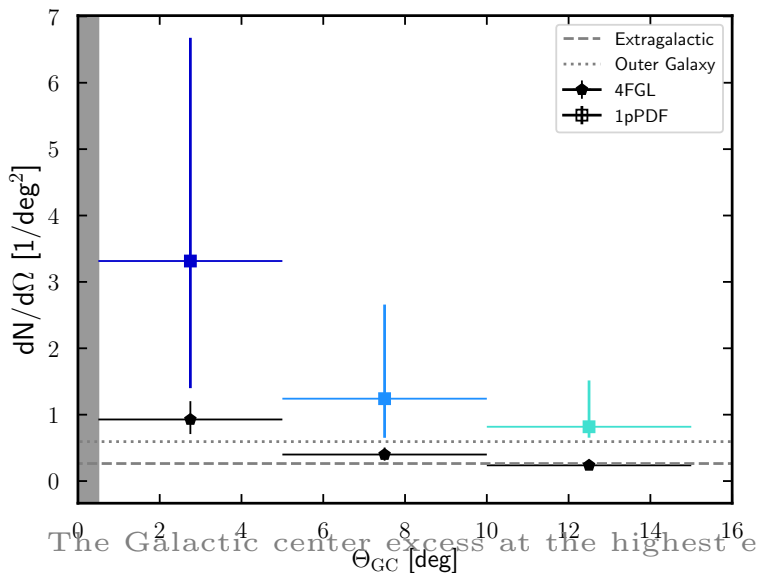
[Calore,SM+PRL'21]



[Calore,SM+PRL'21]



[Calore,SM+PRL'21]

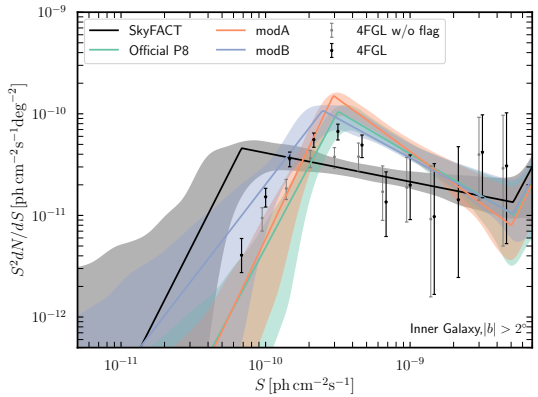


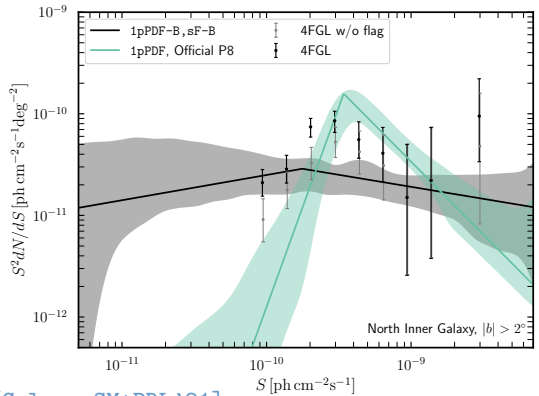
Source count distribution 2–5 GeV: systematics

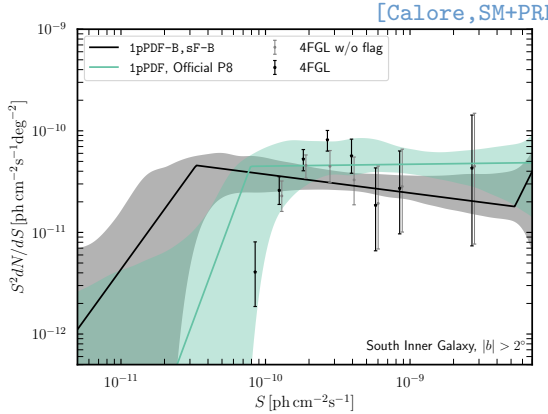
Stability of results tested against many systematics, see supplementary [Calore, SM+PRL'21]

Diffuse emission mismodeling

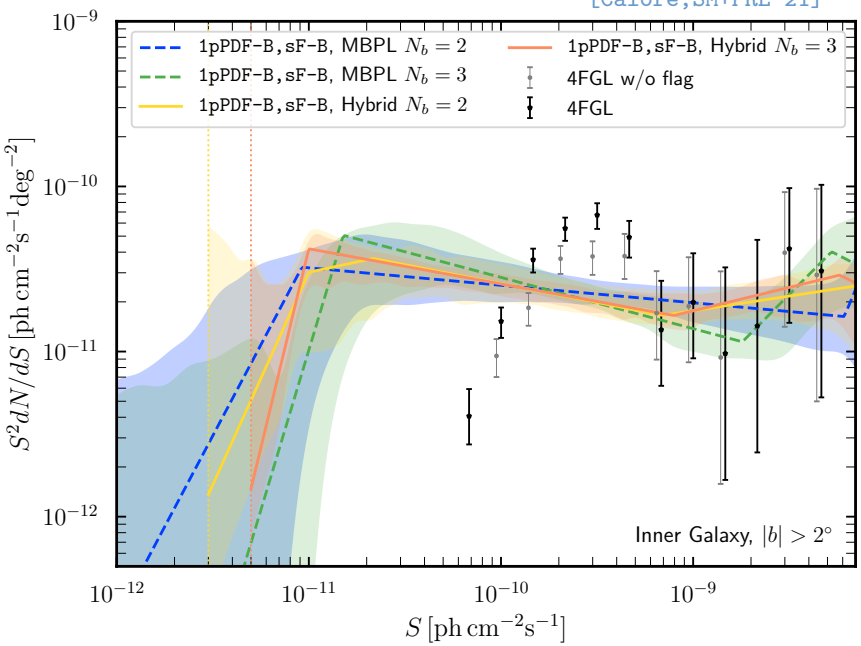
[Calore,SM+PRL'21]







[Calore,SM+PRL'21]

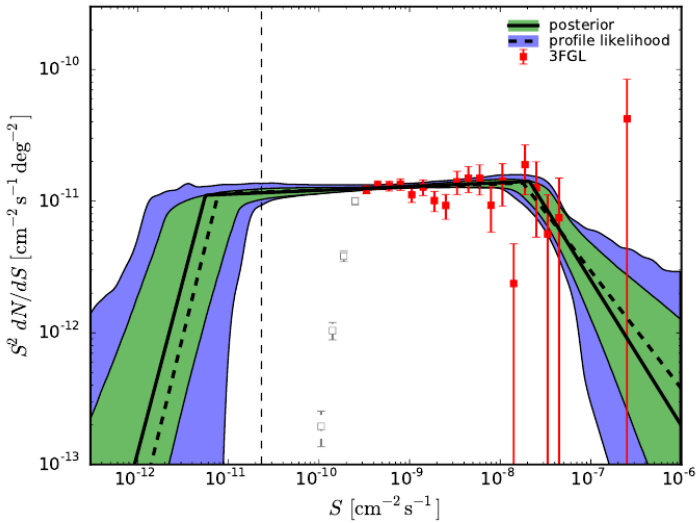


1pDPF modeling: flux cuts, dNdS breaks

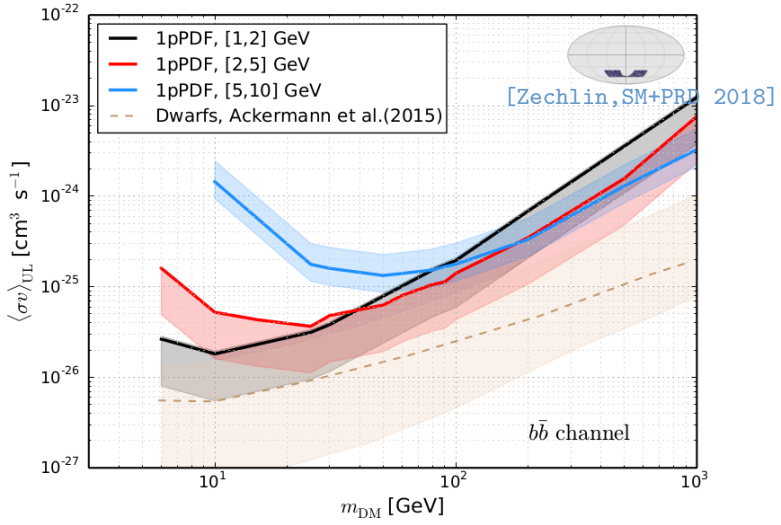
Test of 1pPDF method with Fermi-LAT data

In 1-10 GeV

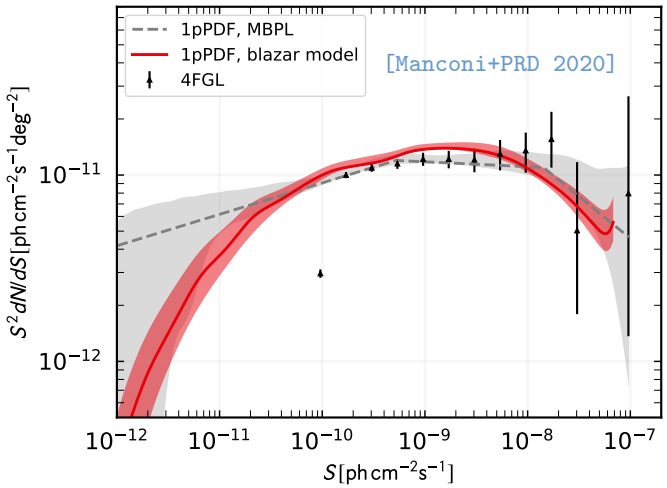
[Zechlin+ApjS 2016]



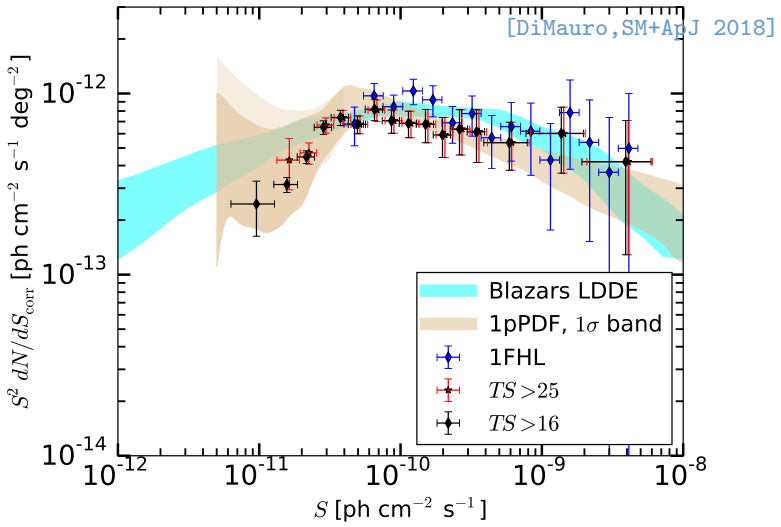
Adding a galactic dark matter template



To constrain blazar models



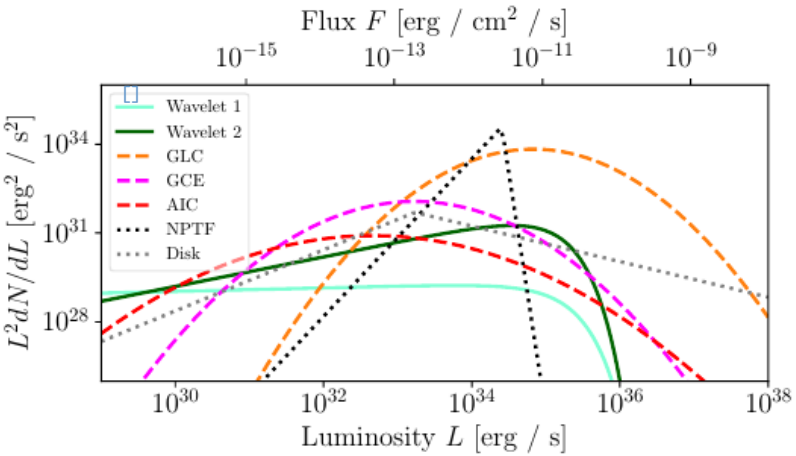
In $>$ 10 GeV, with efficiency corrections



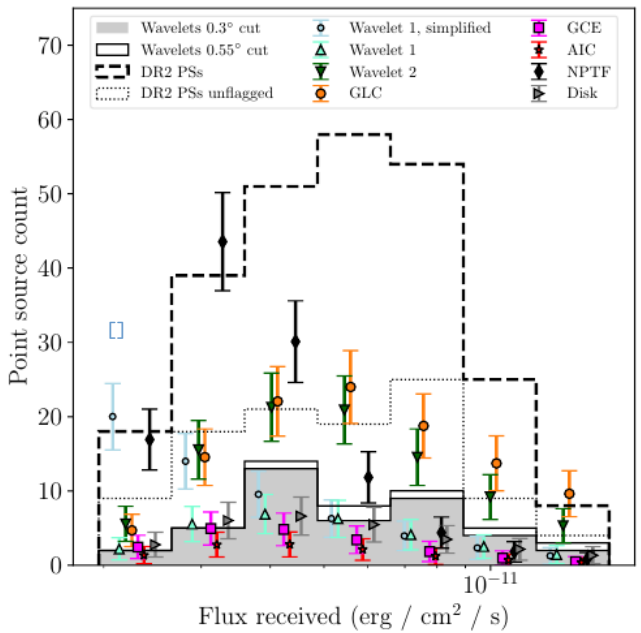
Luminosity functions of MSP explaining the excess

[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)?

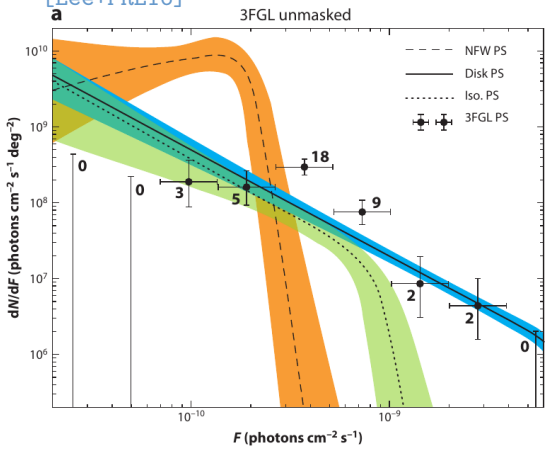
2016 : Excess entirely due to unresolved **point-sources** [Lee+PRL'16]

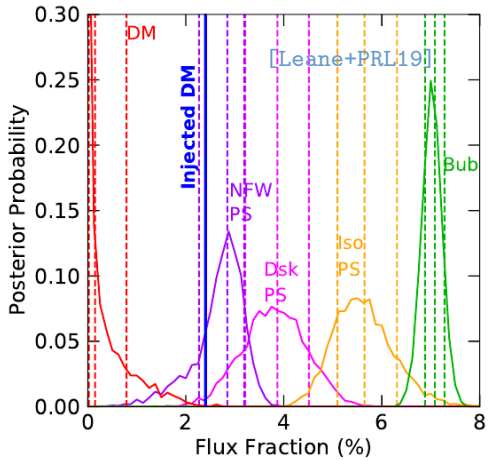
2019 : Earlier results not robust: smooth dark matter not reconstructed even if injected **dark matter** *strickes back?* [Leane+PRL'19]

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]

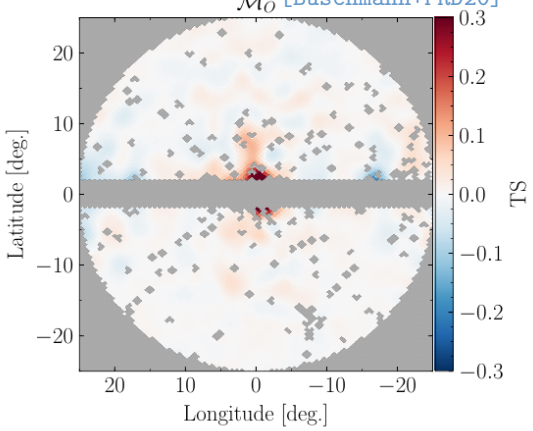
2020 : Preference for point sources influenced by spurios sources/ excess north-south asymmetry, robustness further casted into doubt [Leane+PRL,PRD'20]

[Lee+PRL16]





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



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