On the origin of gamma-rays from the Galactic center

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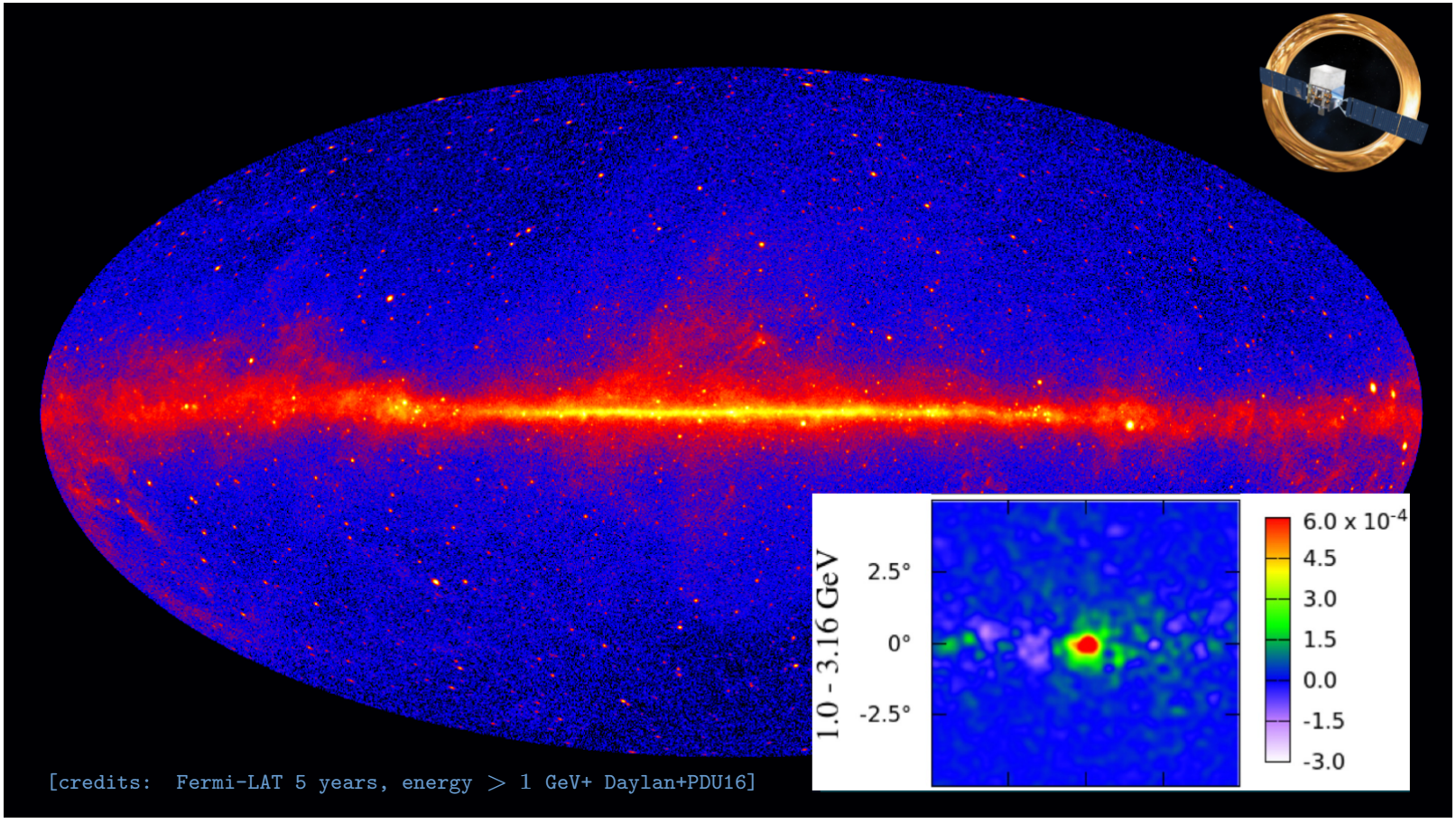
News from the Dark episode 9, OM vs. DM
Station Marine d'Endoume, Marseille (FR)

Outline

- *Introduction*: Galactic center in gamma rays, the excess, possible origins
- *State-of-the-art*: morphology, photon counts and spectrum properties discriminating excess's nature
- *What's next:* outlook and outstanding questions

The Galactic Center in gamma-rays: excess!

Since 2009 (first year of data)...



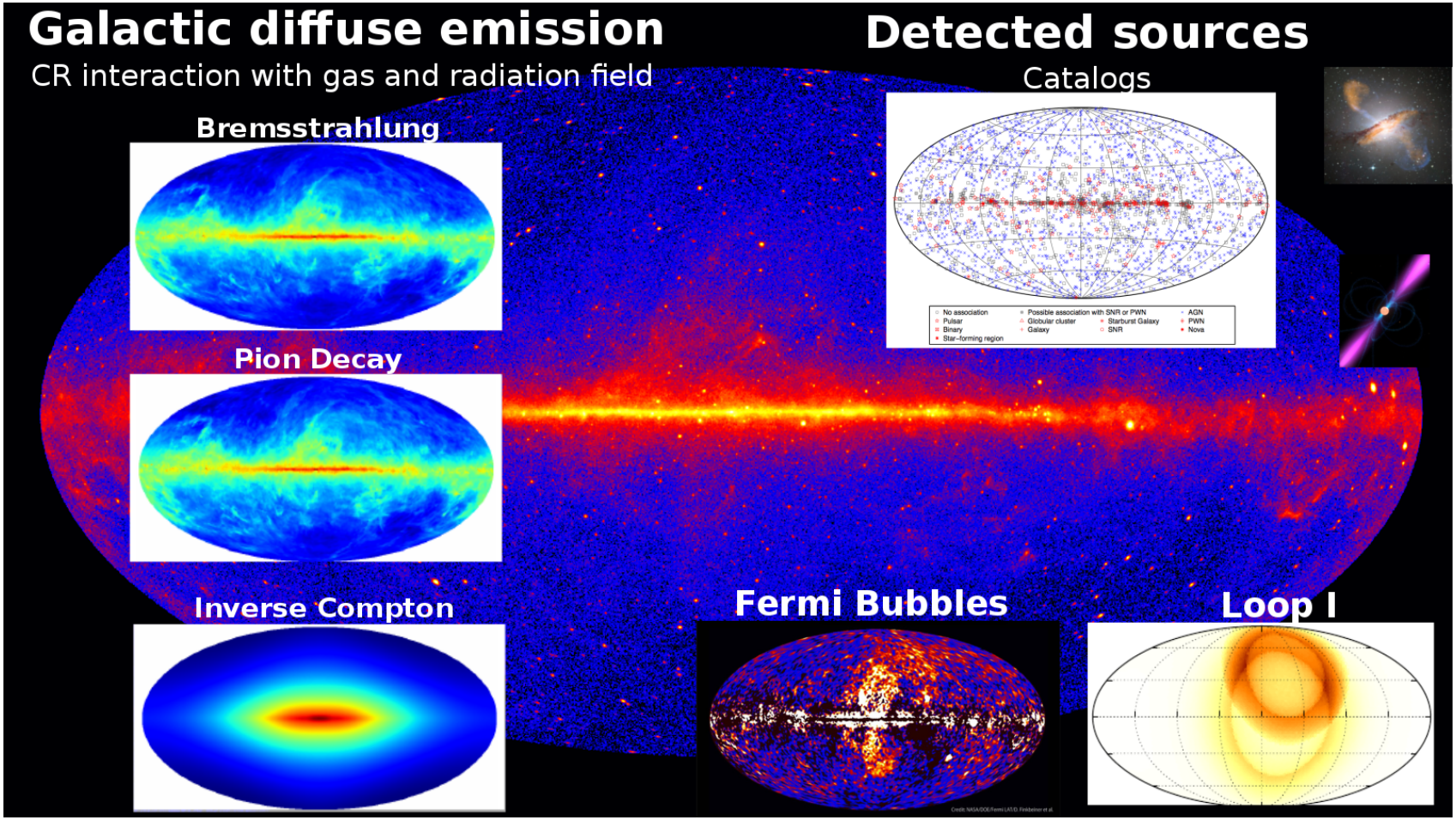
Statistically significant excess in Fermi-LAT data

few % of inner Galaxy flux [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]

Excess... with respect to what?

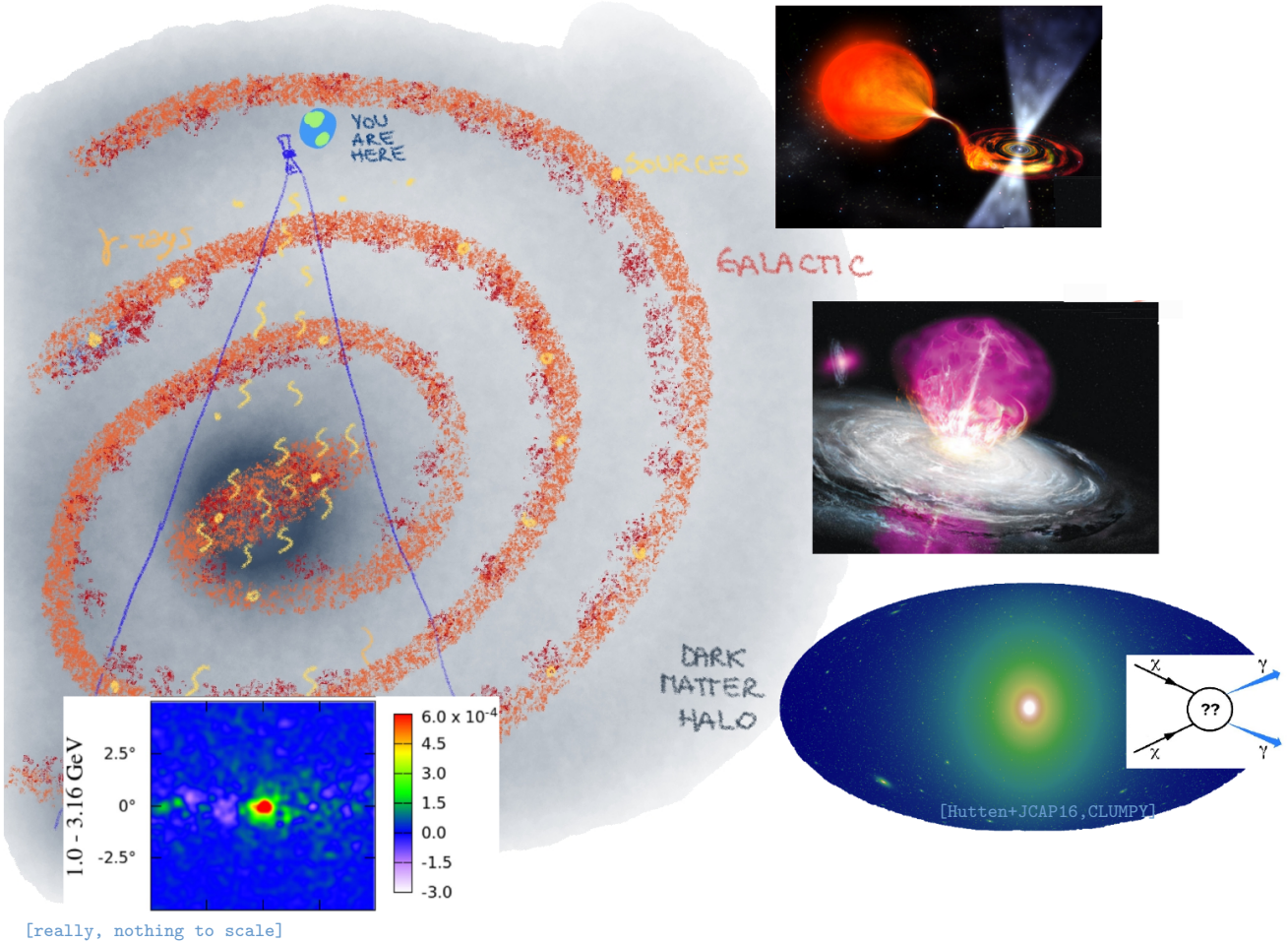
Diffuse emission* + resolved astrophysical sources**

[Fermi-LAT 5 years, energy $>$ 1 GeV]



* systematic uncertainties, ** faint, unresolved sources

Excess interpretation: main hyphotesis

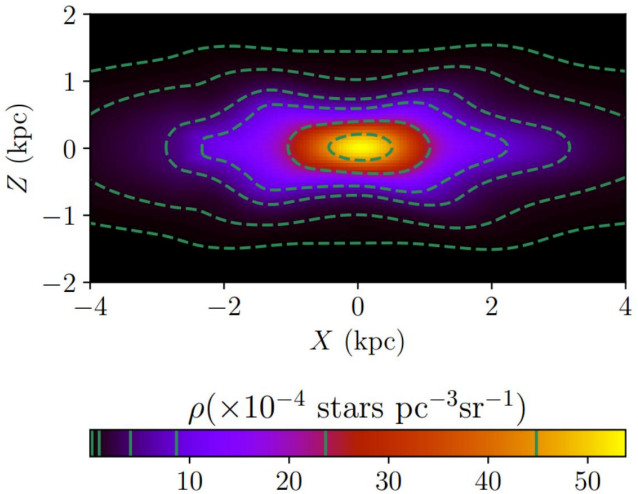


[really, nothing to scale]

+ **Stellar**: New population of (yet) unresolved faint sources, e.g. millisecond pulsar-like (MSP)
- **Cosmic rays**: $e^{\pm}$ diffuse emission: enhanced star formation/ leptonic bursts
+ **Dark Matter**: annihilation of thermal relics in Galactic halo

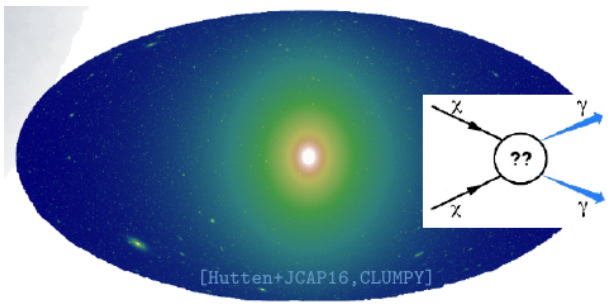
Stellar vs. Dark Matter

- New population of unresolved, faint sources: clumpy-like excess
- Old stars, millisecond-pulsar (MSP) like in the Galactic Bulge: elongated morphology (long)
- GeV-TeV γ rays produced in magnetosphere + possible inverse Compton of $e^{\pm}$
- Source number needed to match γ ray flux depends on luminosity function



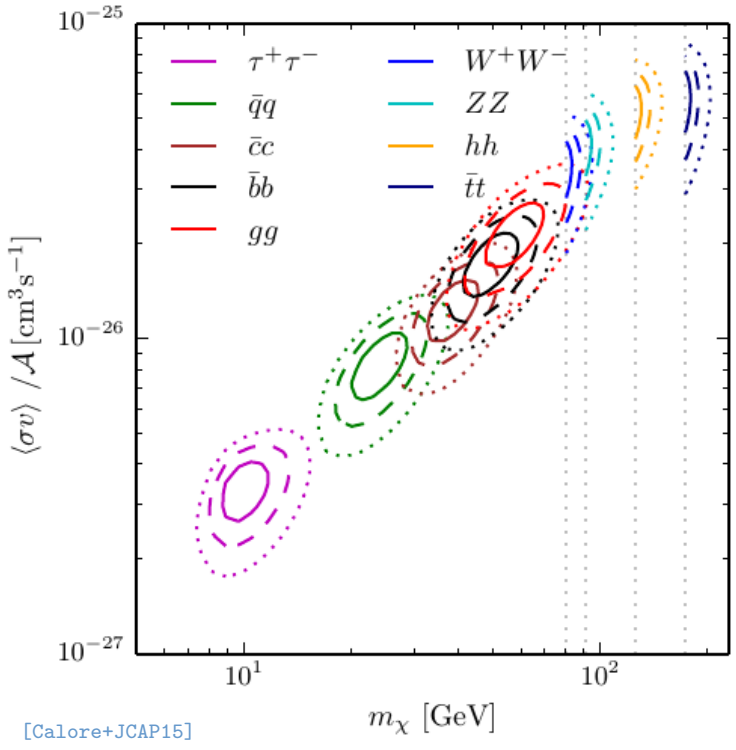
Density of Red clump stars [Coleman+MNRAS'20]

- Milky Way center: highest expected J factor (and background)
- Diffuse-like and spherically symmetric excess, following e.g. NFW profile
- Thermal relics, e.g. Weakly Interacting Massive Particle annihilation
- GeV-TeV γ rays produced by annihilation of GeV mass particles in hadronic channels $\chi\chi \to b\bar{b} \to ....\gamma$



Example J factor map (simulation)

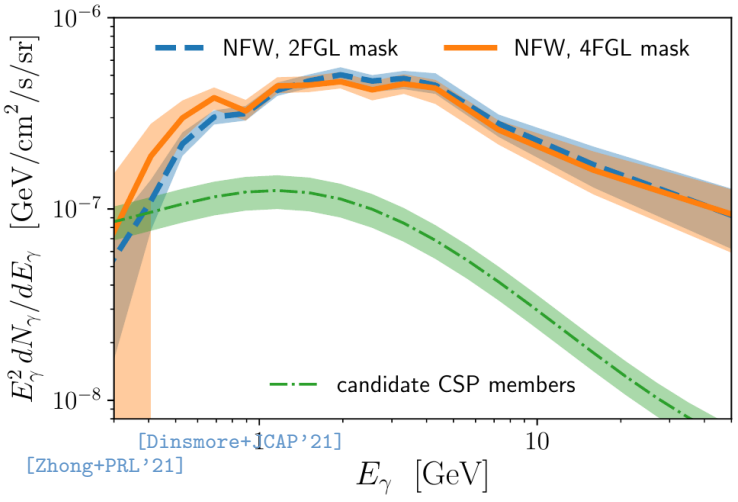
Intensity



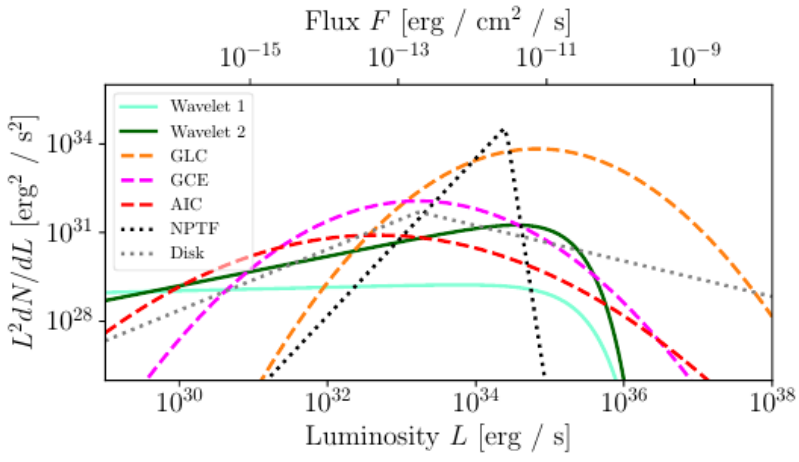
[Calore+JCAP15]

- Dark matter: cross section $\sim 10^{-26}\mathrm{cm}^3/s$, $m_{\mathrm{DM}} \sim 10 - 100$ GeV
- Many theoretical frameworks explored

Discriminate interpretation? Maybe

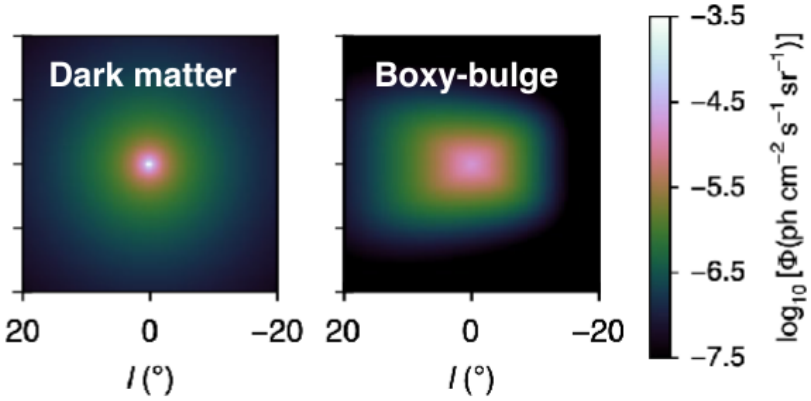


[Dinsmore+JCAP'21]
[Zhong+PRL'21]



- Observed MSP: not enough
  [Zhong+PRL'21]
- Population: modeling debated
  [Hooper+JCAP'16,24,Ploeg+JCAP20,Dinsmore+JCAP'21]

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

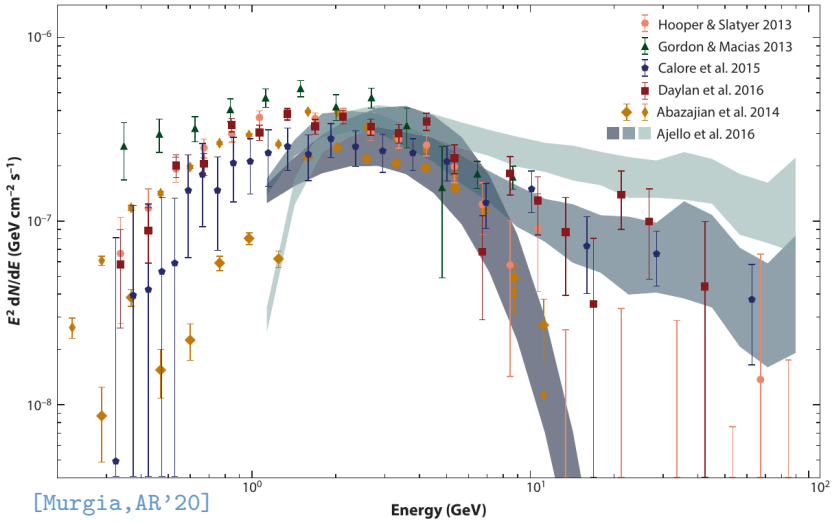
Stellar (MSP-like)

- 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]

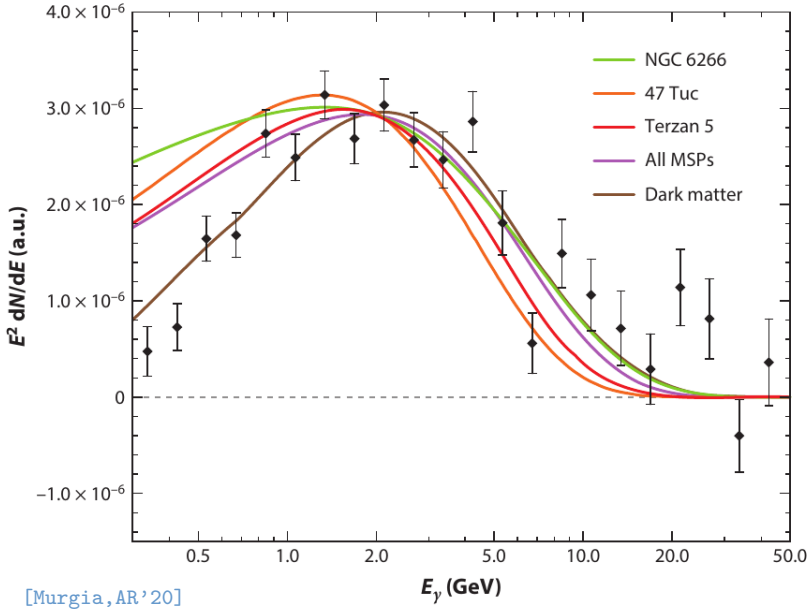
Crucial to discriminate interpretation

Energy spectrum



[Murgia,AR'20]

Peaked at few (1-3) GeV



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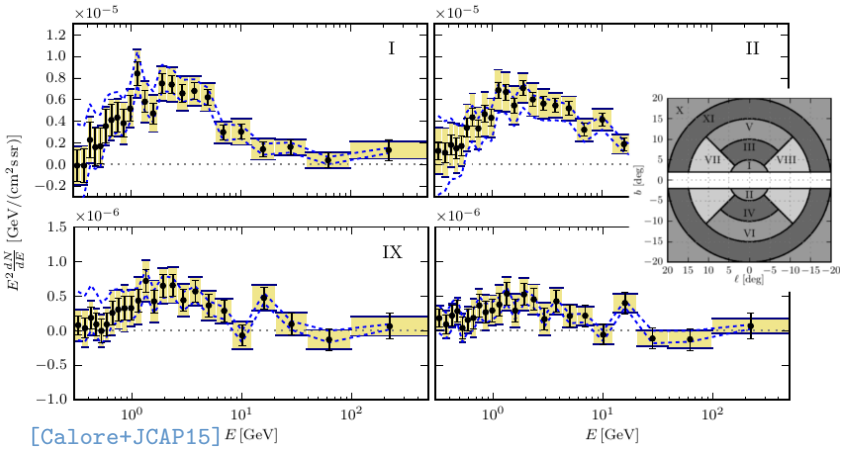


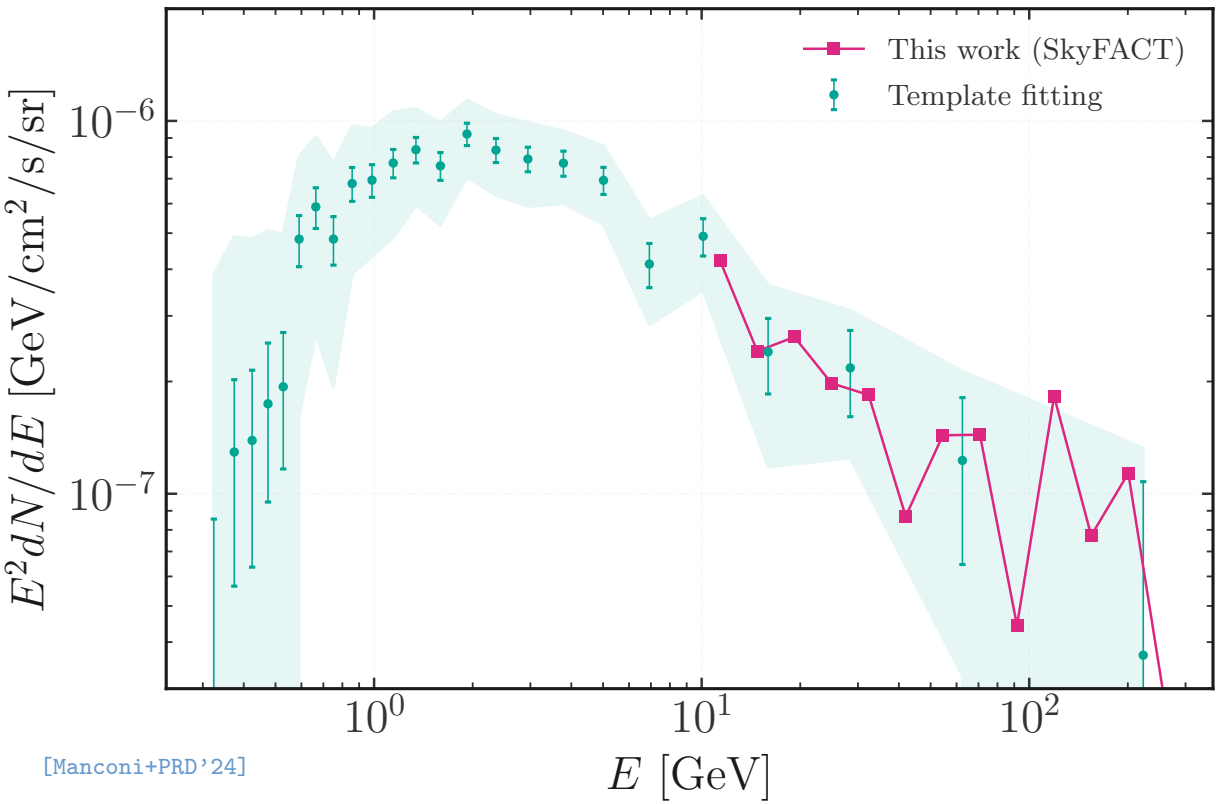
[Calore+JCAP15]

Consistent across inner Galaxy

- Dark matter: 20-70 GeV WIMP annihilation into gluons/ quarks
- MSP-like: similar spectrum

Discriminate interpretation? Maybe

Energy spectrum: the high energy tail



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

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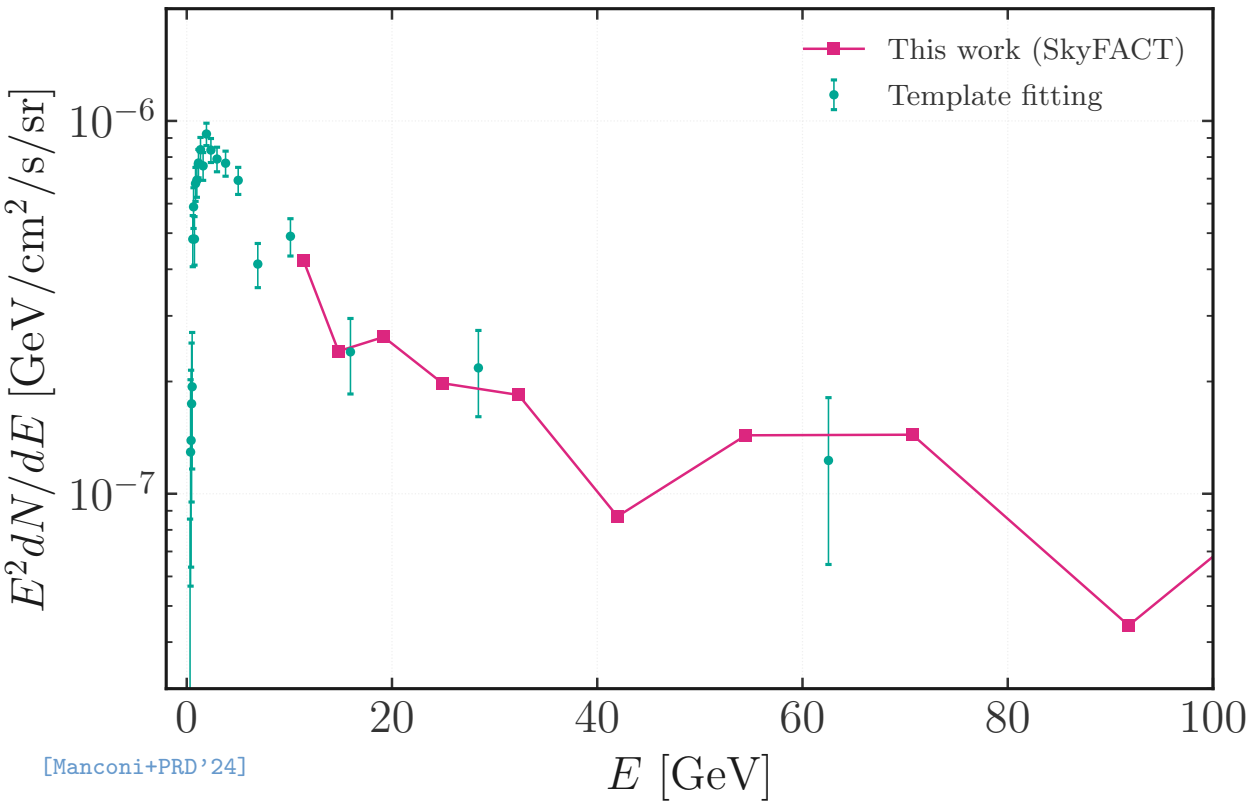

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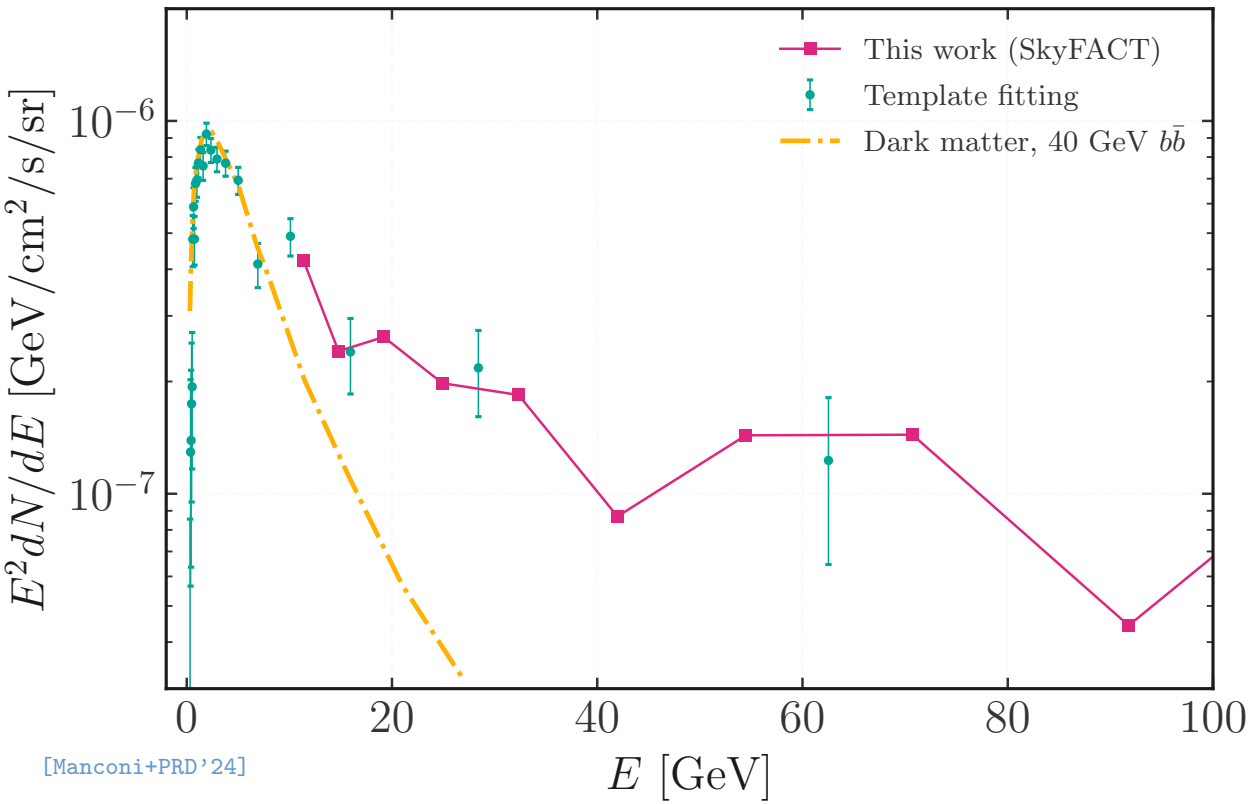

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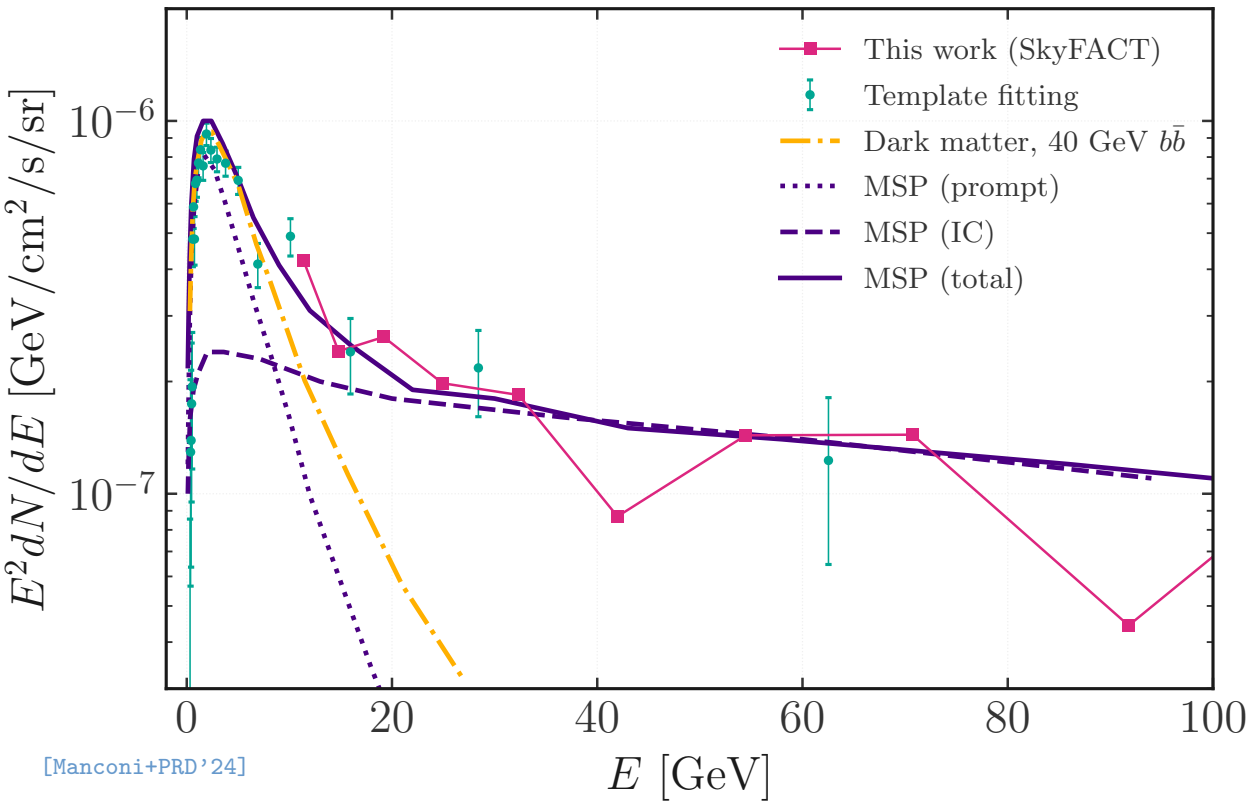

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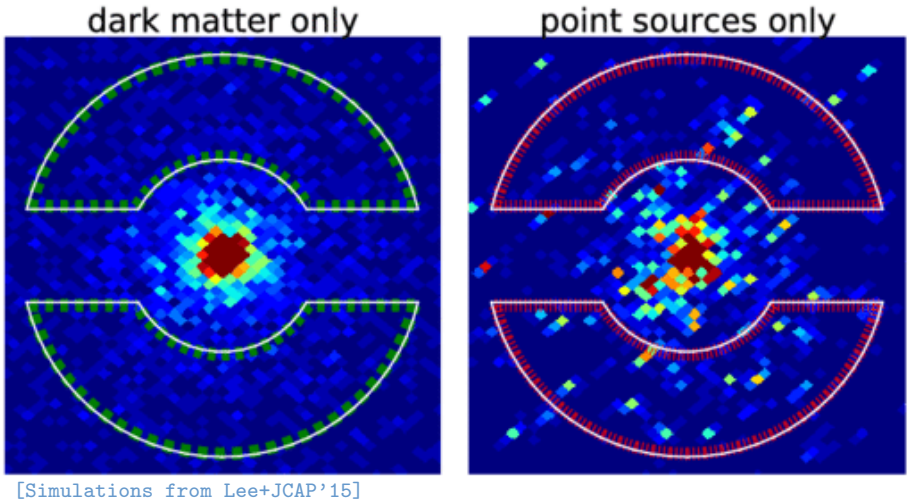
Diffuse or point-like?

Truly diffuse emission:
dark matter



[Simulations from Lee+JCAP'15]

Point-like:
Faint, unresolved sources,
e.g. MSPs

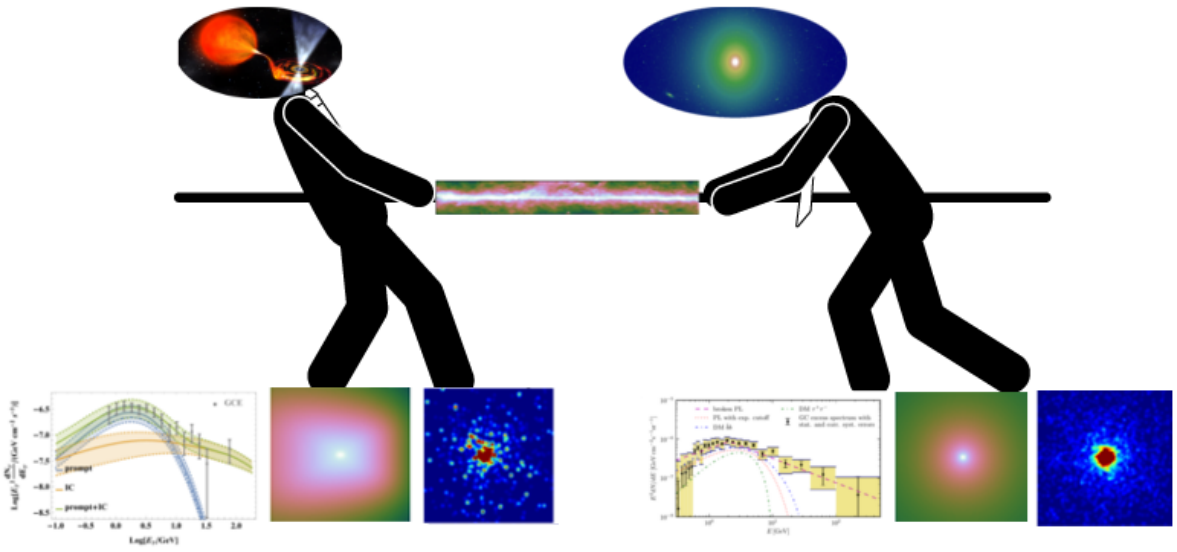
Difference in the statistics of photon counts

Photon count statistics: measure collective properties of faint sources

Crucial to discriminate interpretation

Ordinary Matter vs. Dark Matter

Stellar population vs. Galactic Dark Matter halo



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]*

Ordinary Matter vs. Dark Matter

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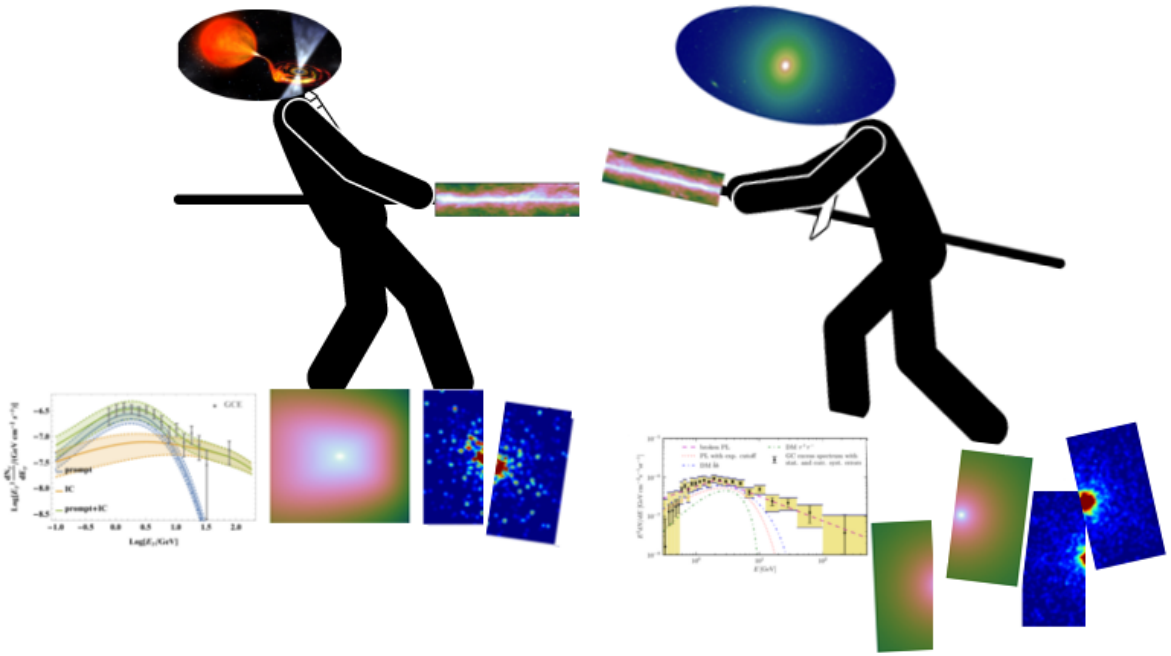
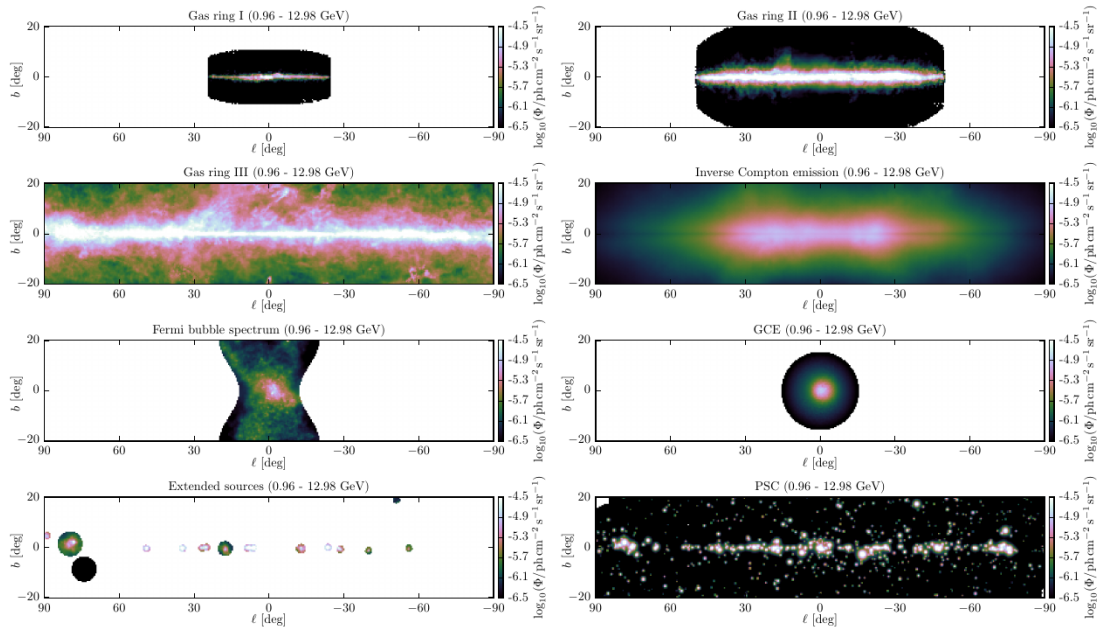


Interstellar diffuse emission mismodeling

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]*

Toolbox to investigate gamma rays from Galactic center

Templates: map-cube spectrum + morphology:



[Storm+JCAP'17]

then fitted to Fermi-LAT data:

Σ_{pixels} energy spectrum x spatial morphology

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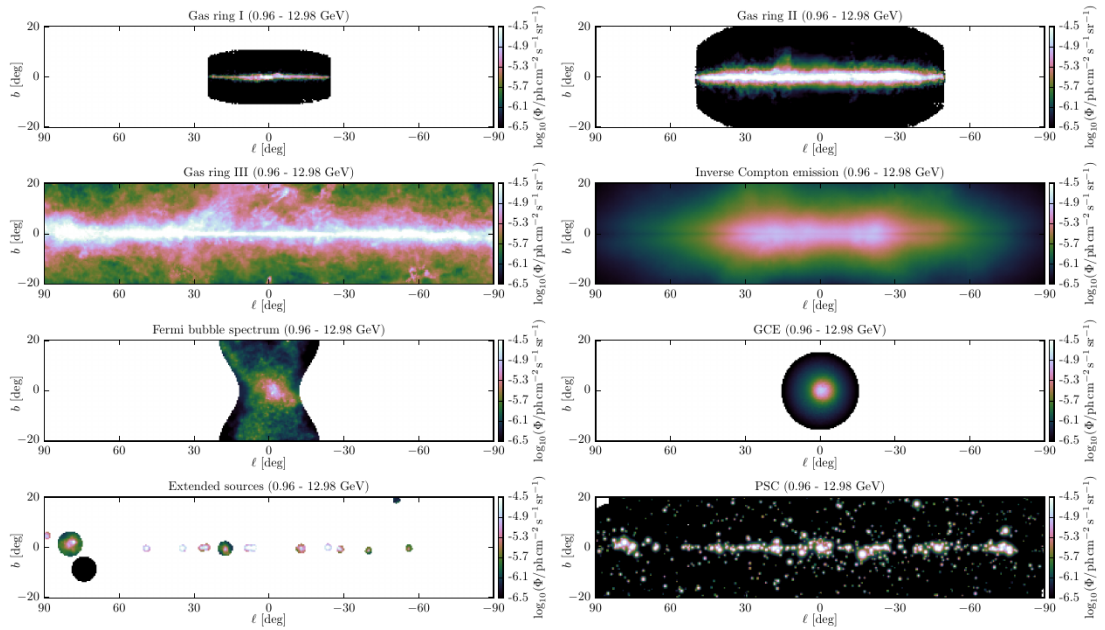


[Storm+JCAP'17]

then fitted to Fermi-LAT data:

Σ_{pixels} energy spectrum x spatial morphology

Template-based:

- Template fitting [e.g.Calore+JCAP'15]
- Adaptive template fitting (skyFACT [Storm+JCAP'17])
- Weigthed likelihood [DiMauro PRD'21, Abdollahi+AjS20]
- Photon-count statistics
  1pPDF [Calore,SM+PRL'21]
  NPTF [Lee+PRL'16]
- Machine learning [List+PRL20,Mishra-Sharma+PRD21,Caron+22]

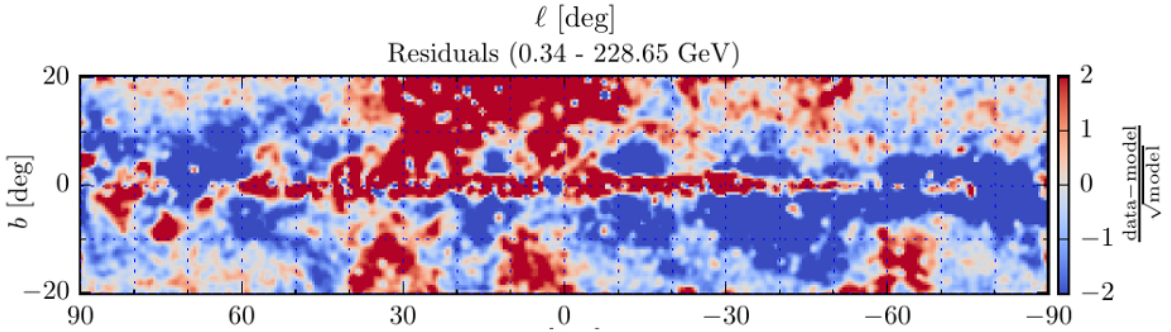
Others:

- Wavelet transform [Bartels+PRL'16,Zhong+PRL20]
- Spectral fits, D3P0 [Selig+A&A 15]

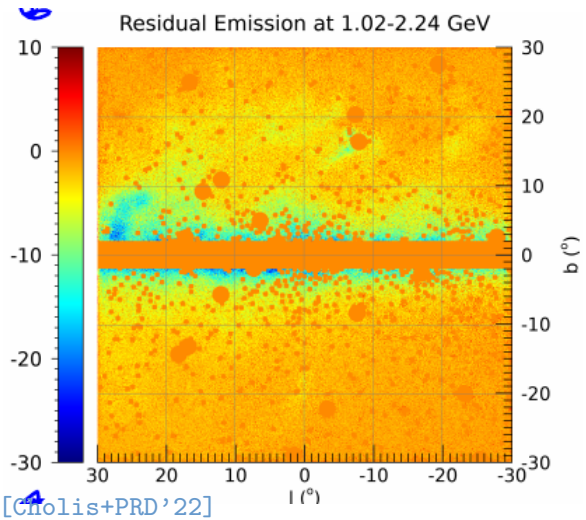
No matter the method, the Galactic Center excess is statistically significant

Galactic diffuse mismodeling: residuals

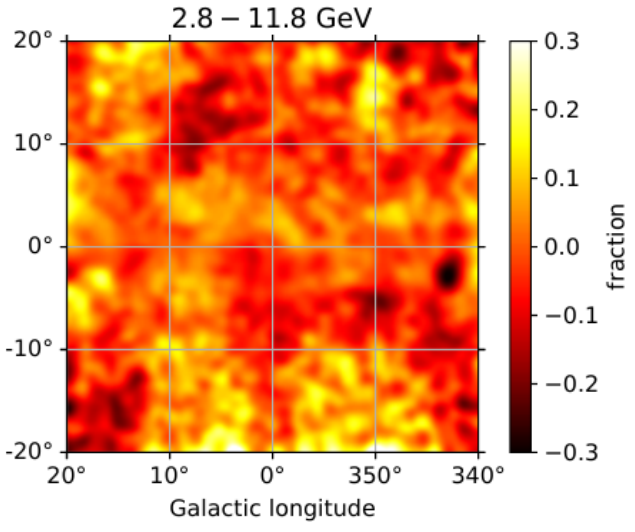
Model to fit Fermi-LAT data: Σ_{pixels} energy spectrum x spatial morphology



[Storm+JCAP'17]



[Cholis+PRD'22]



[Pohl+PRD'22]

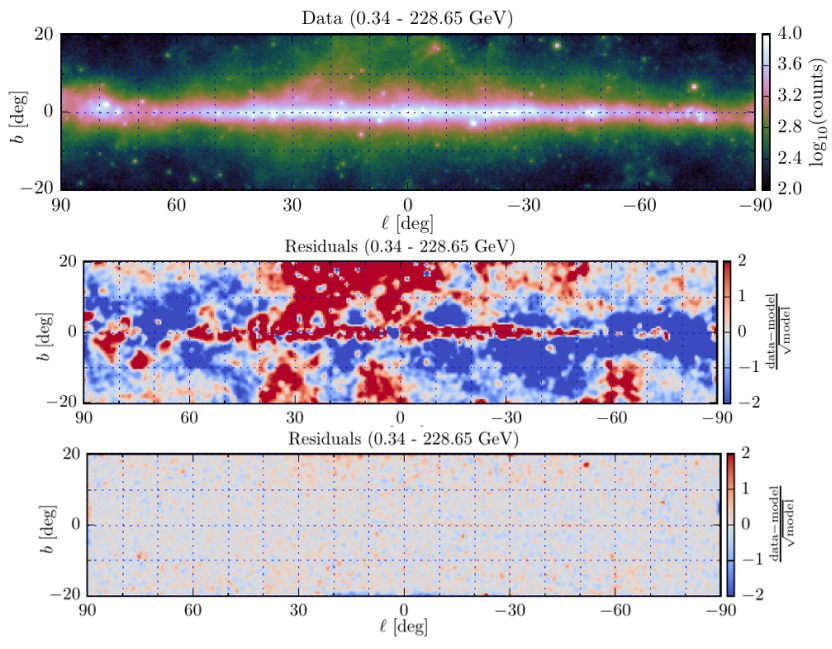
Template fitting: still up to 30% residuals

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?

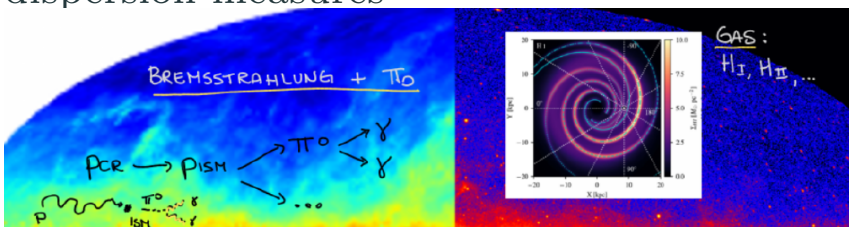
Data-driven:

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



Improve models:

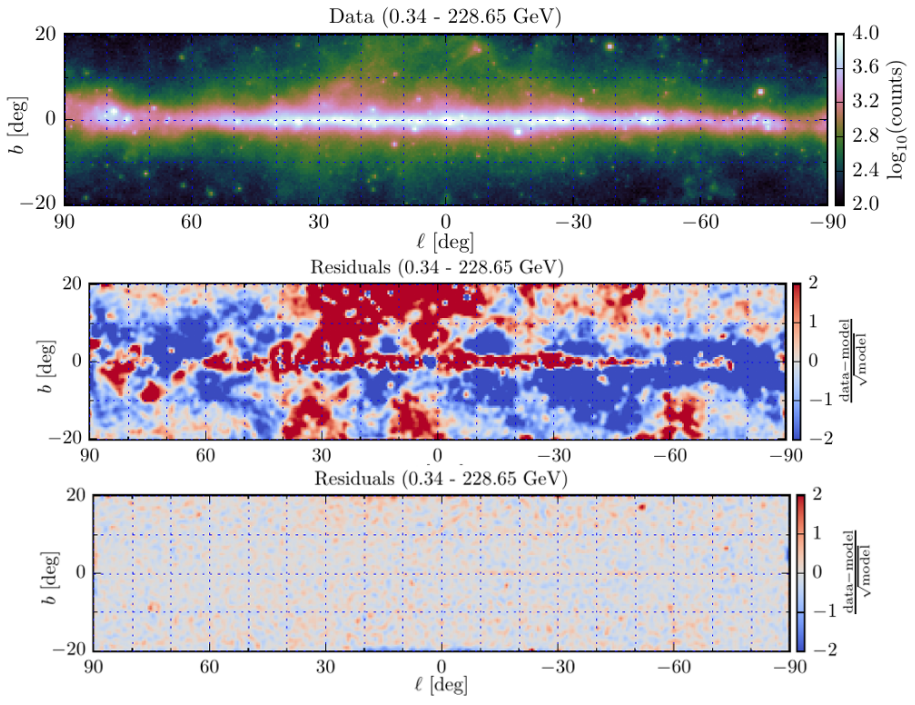
Better estimates of target H_I, H_2, H_{II} gas column density, inferred by line spectra, dispersion measures



- 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]

SkyFACT: overcoming diffuse emission mismodeling

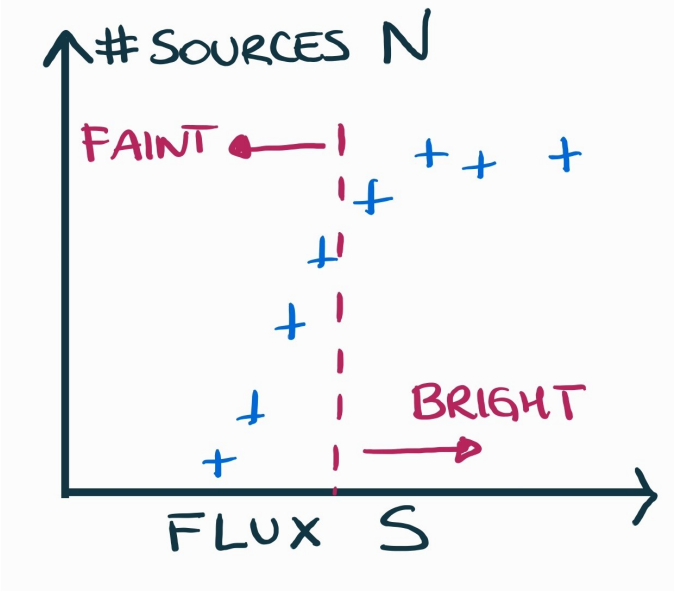
Model to fit Fermi-LAT data: Σ_{pixels} energy spectrum x spatial morphology



- 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

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



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], ...

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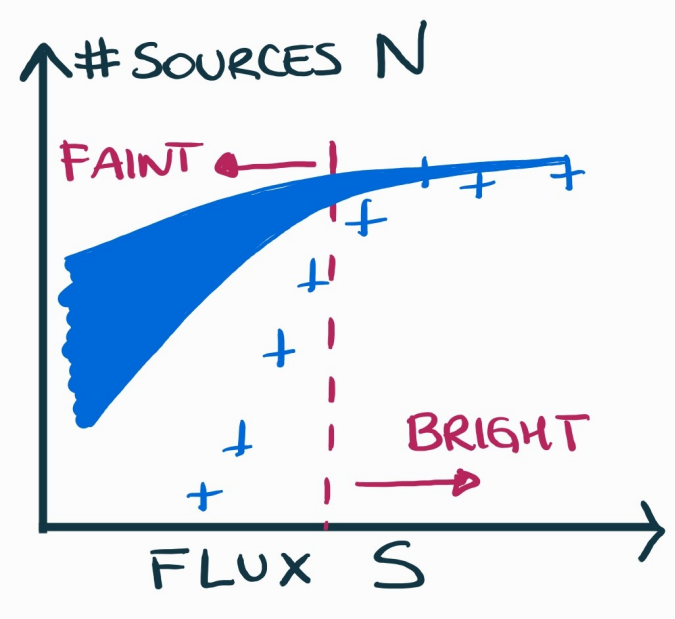

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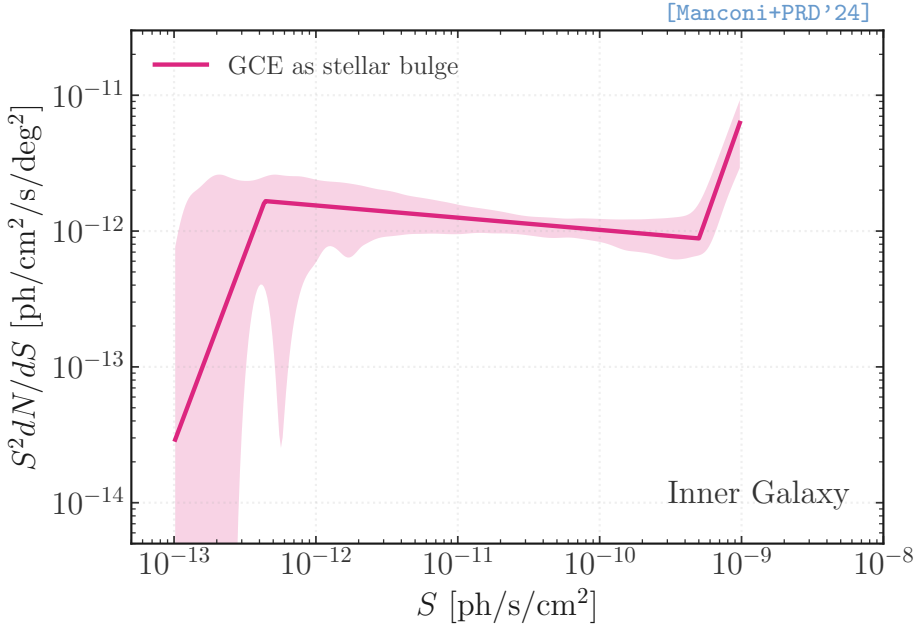
[Manconi+PRD'24]



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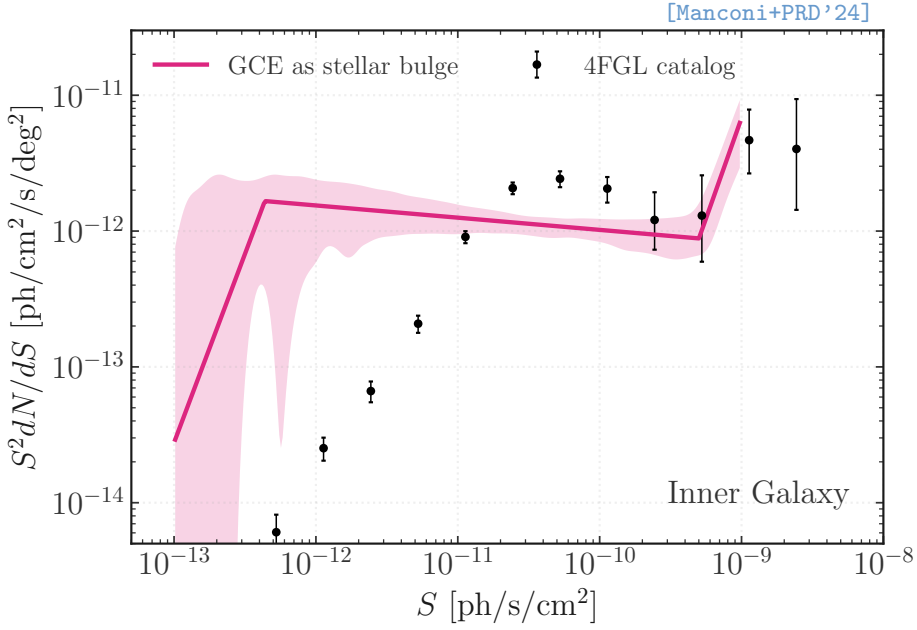

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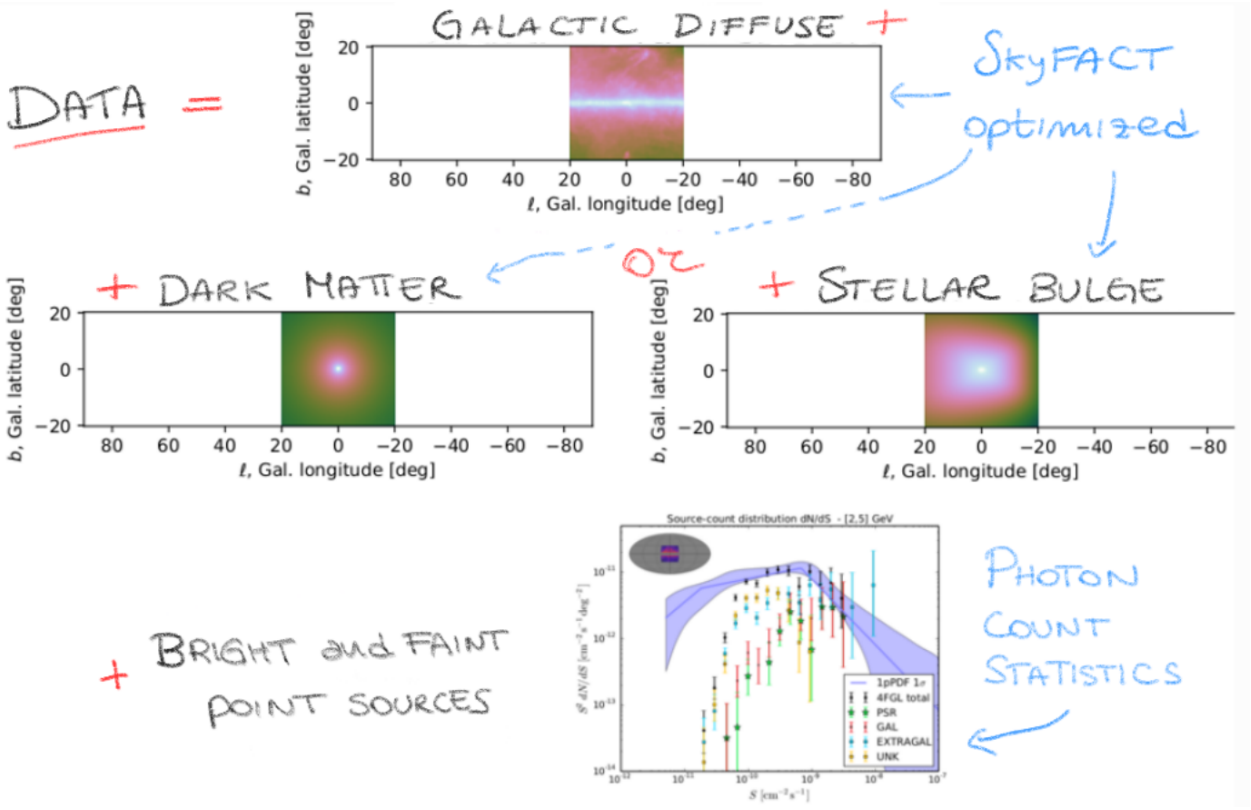
Combining photon count statistics and SkyFACT

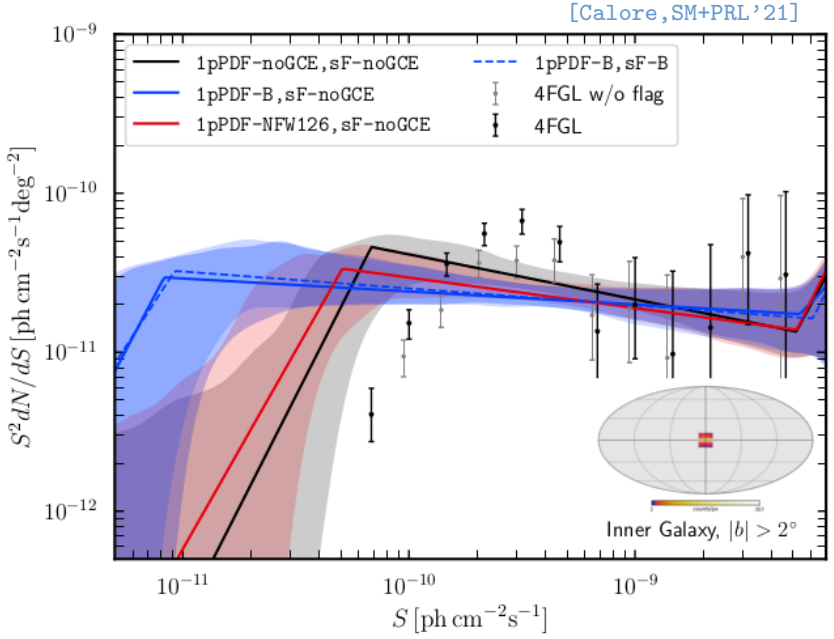


- SkyFACT: *reduce diffuse mis-modeling*
- Photon-count statistic: model faint sources *after reducing residuals*

First application to inner Galaxy at energies 2-5 GeV [Calore,SM+PRL21]
https://arxiv.org/abs/arXiv:2102.12497,
extended to > 10 GeV in https://arxiv.org/abs/2402.04733

Inner Galaxy, energies 2–5 GeV: results recap

[Calore,SM+PRL'21]



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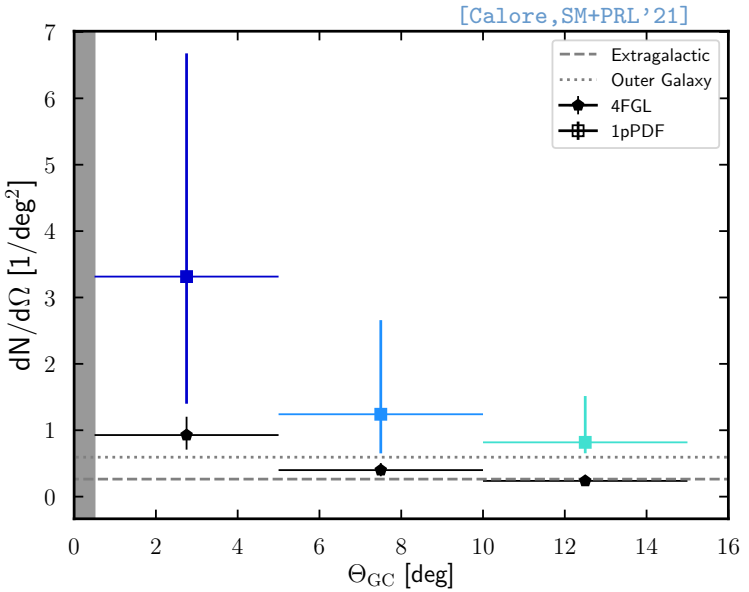
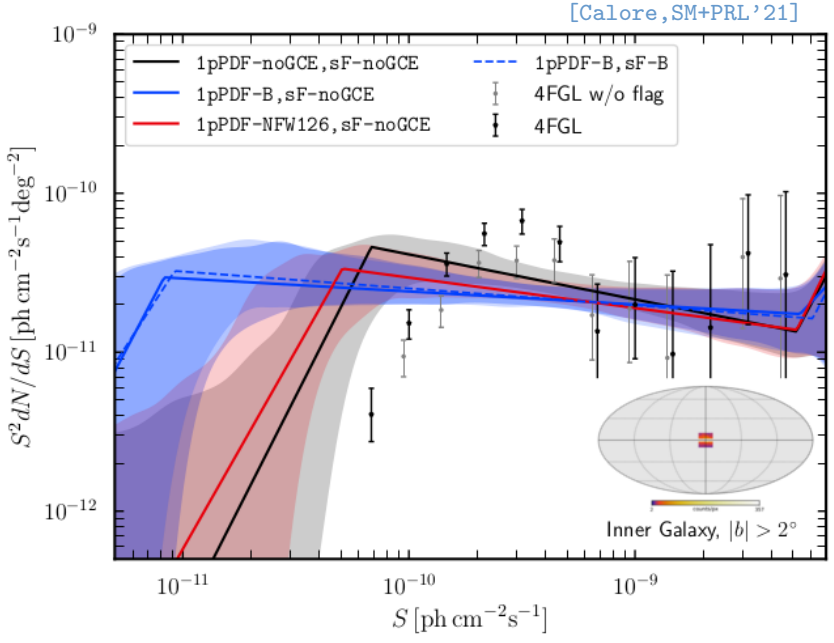


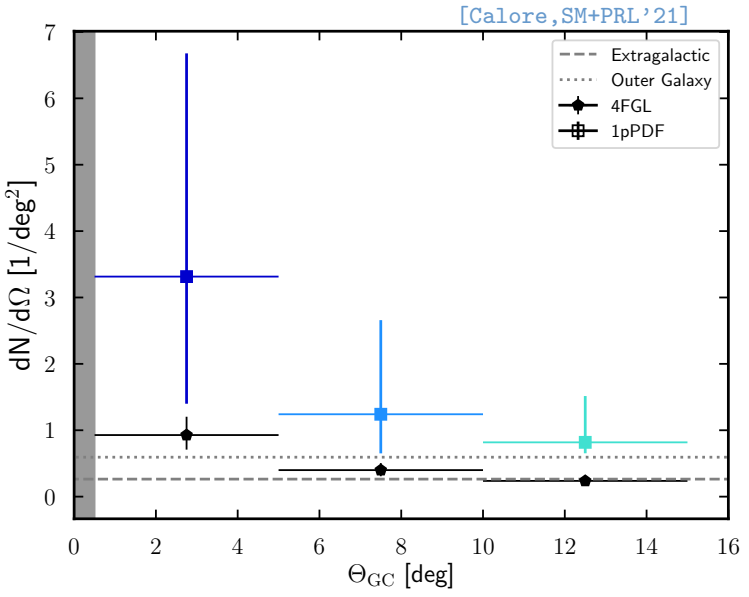
- Stellar-bulge morphology *preferred over dark matter*: SkyFACT only (10σ) and modeling faint sources (lnB$>$ 20), confirms [Bartels+NA'18,Macias+NA'18,JCAP'19]
- *Unresolved* point sources resolved down to $\sim 5 \cdot 10^{-11}$ ph cm^{-2} s^{-1}
- Diffuse mismodeling *strongly affects faint source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

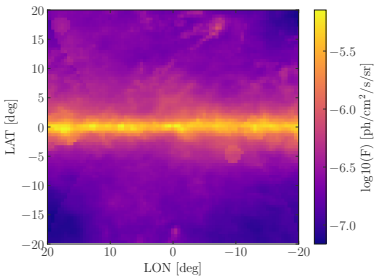
Corroborating a (at least) partial stellar origin of the Galactic center excess

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

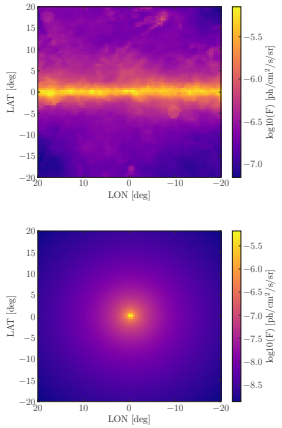
Morphology: stellar or dark matter?

SkyFACT fit, nested model comparison

no GCE

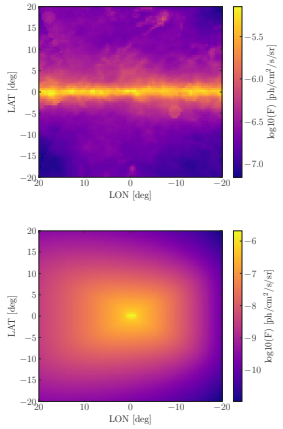


GCE: NFW ($\gamma = 1.26$)



Comparing to no GCE: 5.6σ
Comparing to stellar: no evidence

GCE: stellar bulge



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

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

no GCE

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

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

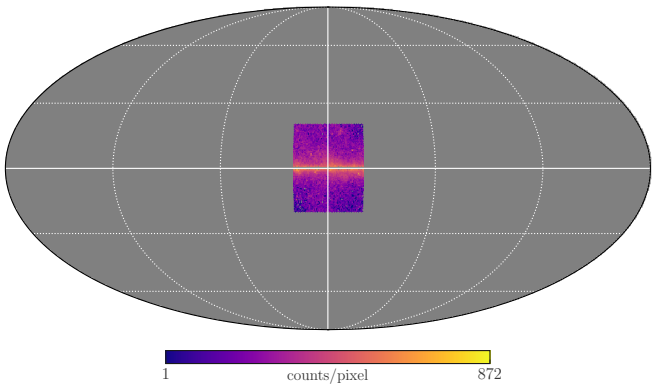
unresolved sources + norm of diffuse, GCE templates ~ 1

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

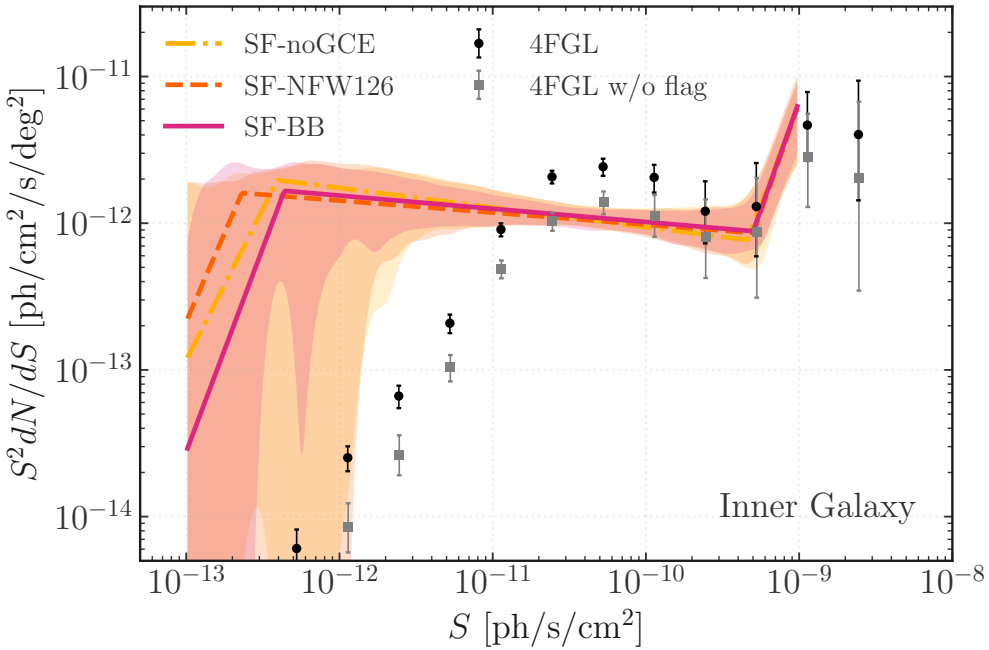
Inner Galaxy at 10–300 GeV: dN/dS

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

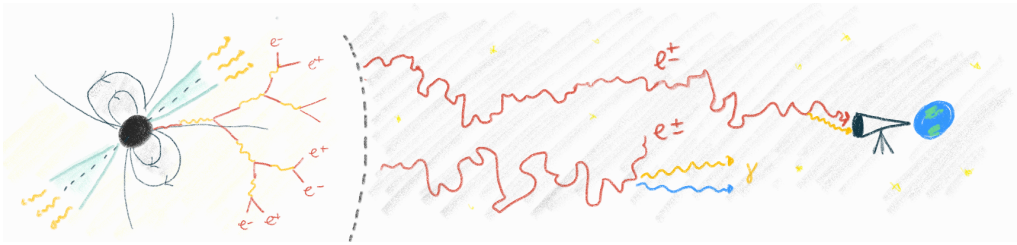
Corroborating a (at least) partial stellar origin of the Galactic center excess, now from > 10 GeV only

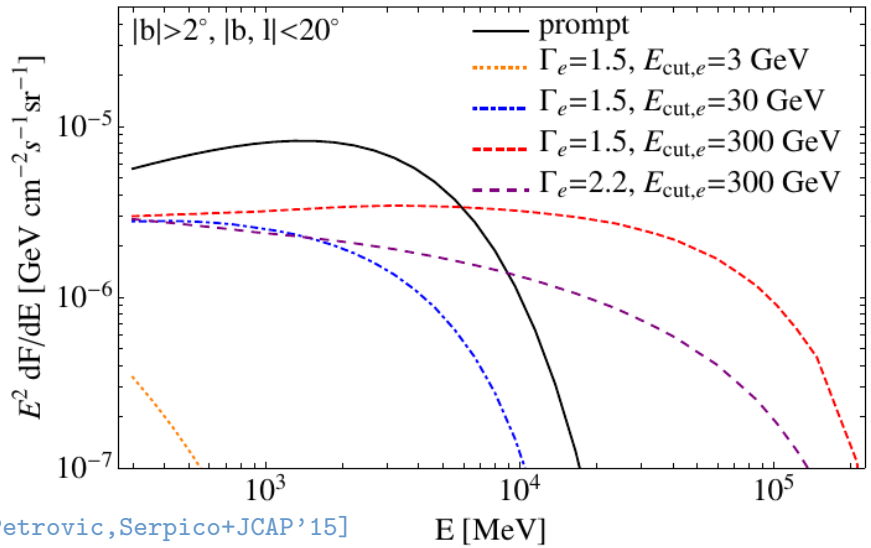
Interpreting high energy tail: $e^{\pm}$ by MSP?

$e^{\pm}$ in MSP: prompt magnetosphere γ rays + inverse Compton of emitted $e^{\pm}$?

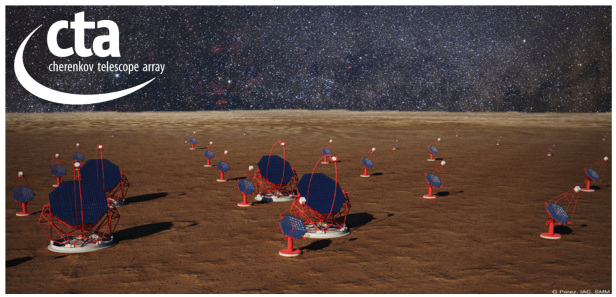
[Petrovic+JCAP'15,Horiuchi+JCAP'16, Linden+PRD'16,Macias+MNRAS'22]

$\rightarrow$ similar hints in globular clusters [Song+MNRAS'21]





[Petrovic,Serpico+JCAP'15]

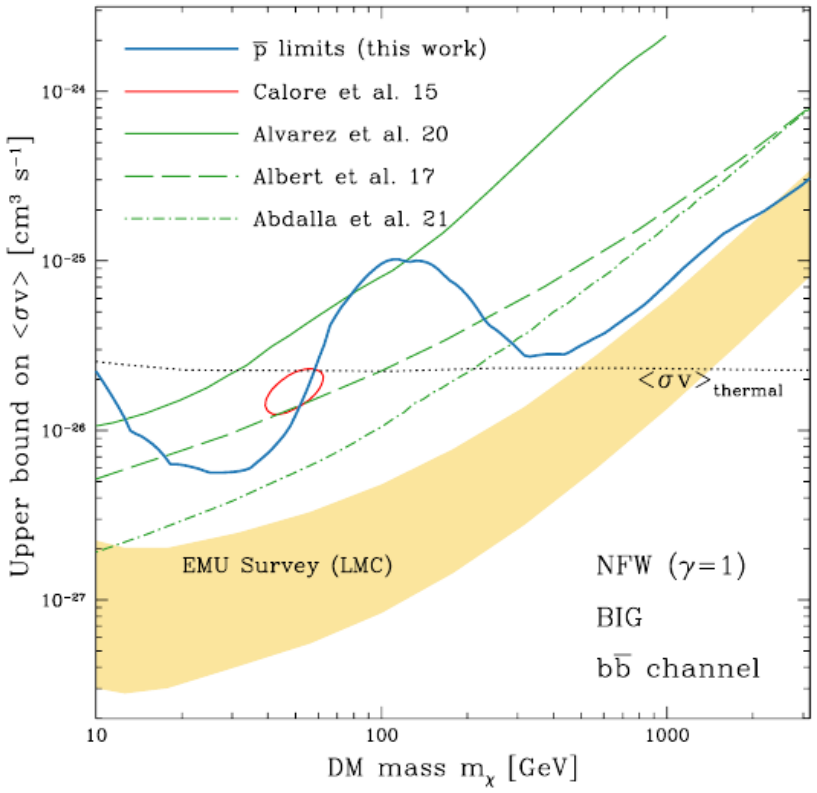


Forthcoming **Cherenkov Telescope Array** could detect this signature and discover this new stellar population

depends on luminosity function + spectral properties

Complementary of indirect dark matter constraints

If dark matter: consistent signal elsewhere: $\bar{p}$, gamma rays, ...



[Calore+SciPost'22]

- Still no gamma-ray signal in **dwarfs**, testing excess region
  [Fermil-LAT legacy: MCDaniel+23]
- Cosmic ray $\bar{p}$: start to be in tension with constraints
  [DiMauro+PRD'21,Heisig+PRR'20,Boudaud+PRR'20, Cholis+PRD'19, Balan,SM+23]
- **Large Magellanic Cloud** (LMC): larger J factor after Galactic center: no signal in radio, tight constraints [Regis+JCAP'21]

Summary

After more than 10 years:
nature of Galactic Center excess still to be uncover,
but triggered significant advances in understanding
of Galactic processes & analysis techniques

- ⋆ Suggestive case for **dark matter annihilation** signal
- ⋆ Many astrophysical processes could explain the signal, e.g. a population of **MSP-like sources in the stellar bulge**
- ⋆ Crucial to explain **spectrum, intensity and morphology** of the excess
- ⋆ State-of-the-art analysis suggest the **stellar origin is preferred**, based on observed morphology, energy spectrum and photon count statistics

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