



# An overview of the Galactic Center Excess

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Silvia Manconi  
(LAPTh, Annecy, France)

January 10, 2023

19th Rencontres du Vietnam, Quy Nhon  
Theory meeting experiment: particle astrophysics and cosmology (TMEX 2023)

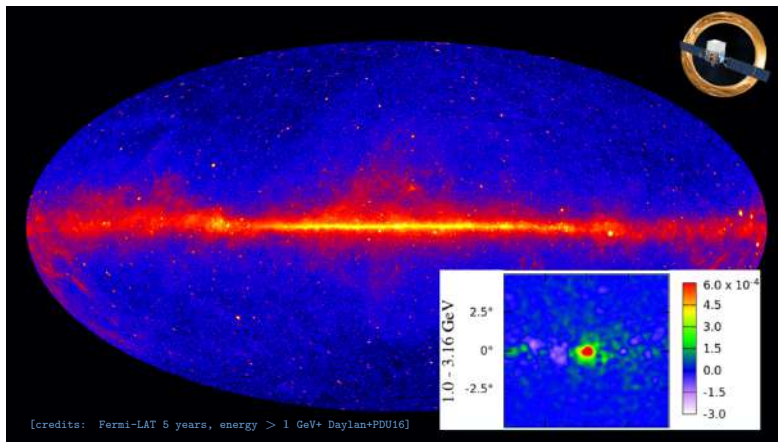
January 10, 2023

1. *The data* : **Fermi-LAT and the excess**
2. *The backgrounds*: **from our Galaxy and beyond**
3. *The origin of the excess*: **exotic or not?**
4. *How to discriminate?* **characteristics of the excess**
5. *Recent Progress*: **backgrounds, methods, source populations**
6. *What's next*: **Summary and Outlook**

*Additional slides + many references: what I do not have time to cover*

# The Galactic Center Excess

Since 2009 (first year of data)...



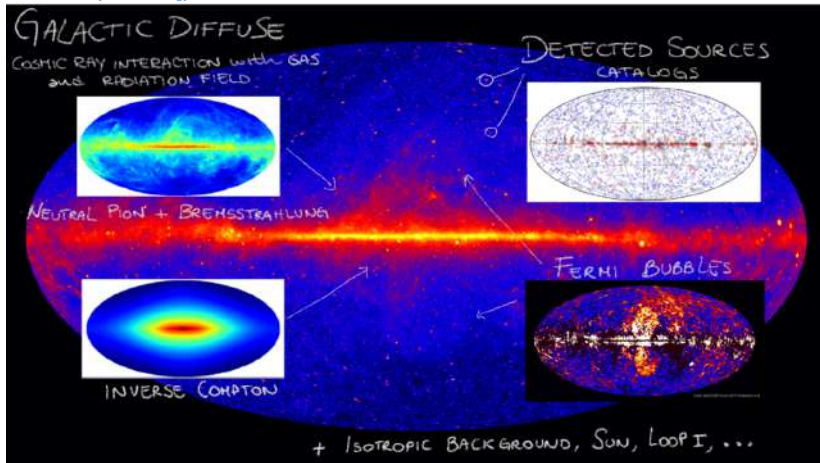
Statistically significant excess in Fermi-LAT data [talk by A.Morselli]  
few % of 2-20 GeV inner Galaxy flux

[Goodenough+'09, Vitale+'09, Abazajian+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]



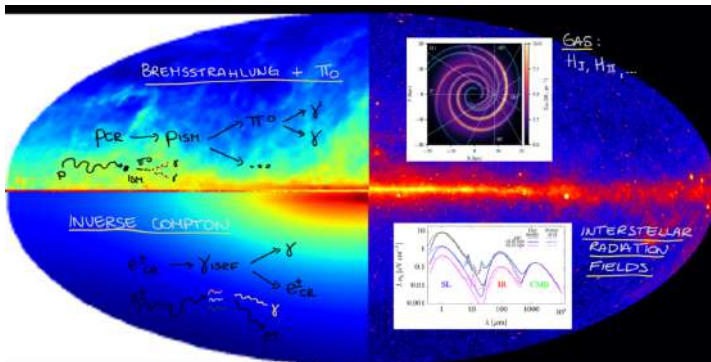
[talks by V.Gammaldi, R.Crocker]

\* systematic uncertainties, \*\* faint, unresolved sources

# wrt: Galactic diffuse emission

Produced by **charged cosmic rays**:

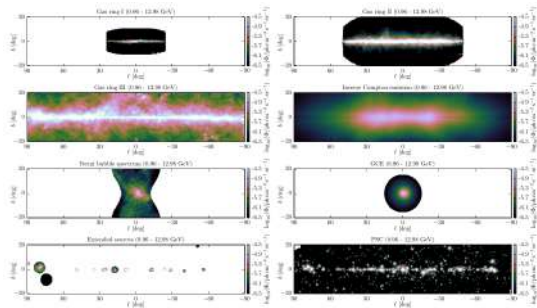
- Inject primary cosmic rays at source (p,  $e^\pm$ ) [talk by S.Celli]
- Propagate them in the Galaxy (code exists, GALPROP, DRAGON)
- **Interaction with gas and radiation fields**



Final model: spatial + spectral template

# Toolbox to investigate gamma rays from Inner Galaxy

*Templates: map-cube spectrum + morphology:*



[Storm+JCAP'17]

*then fitted to Fermi-LAT data:*

$\Sigma_{\text{pixels}}$  energy spectrum x spatial morphology

*Template-based:*

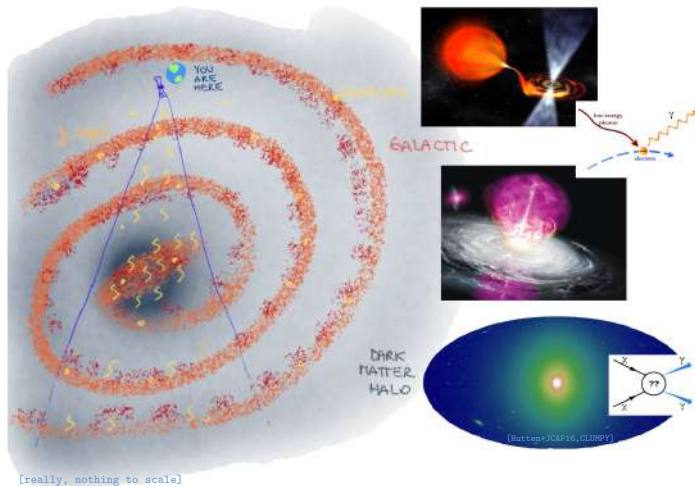
- Template fitting  
[e.g. Calore+JCAP'15]
- Adaptive template fitting (skyFACT [Storm+JCAP'17])
- Weighted likelihood [DiMauro PRD'21, Abdollahi+AJS20]
- Photon-count statistics 1pPDF [Calore, SM+PRL'21] NPTF [Lee+PRL'16]
- Machine learning  
[List+PRL20, Mishra-Sharma+PRD21, Caron+22]

*Others (no time to cover them):*

- 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**

# Interpretation: current hypothesis

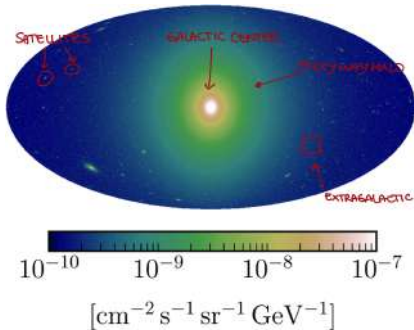


[really, nothing to scale]

- + **MSP**: New population of (yet) unresolved millisecond pulsar (MSP)-like sources
- **COSMIC RAYS**:  $e^\pm$  diffuse emission: enhanced star formation/ leptonic bursts
- + **DARK MATTER**: annihilation in Galactic halo [review](#): [S.Murgia ARNPS'20]

# Dark matter (WIMP) signal

**Galactic center: highest dark matter signal!** (but high background...)



Gamma-ray sky from dark matter only, obtained with CLUMPY code

**Flux** per unit energy and solid angle:

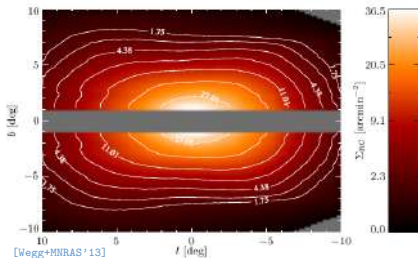
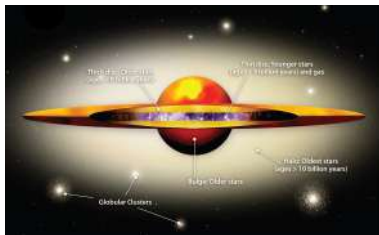
$$\frac{d\phi_{\text{DM}}}{dE d\Omega} = \frac{1}{4\pi} \frac{\langle\sigma v\rangle}{2} r_{\odot} \frac{\rho_{\odot}^2}{m_{\text{DM}}^2} \sum_f \left( \frac{dN_f}{dE} B_f \right) \mathcal{J}(\psi).$$



# MSP-like sources

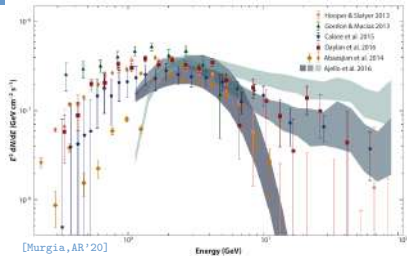
Known sources cannot explain excess: **new population of sources?**

MSP: rapidly rotating neutron stars, period decreased to ms by e.g. accretion from a companion object; bright for even  $10^9$ y

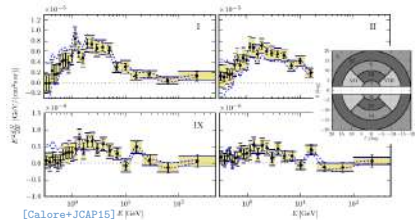
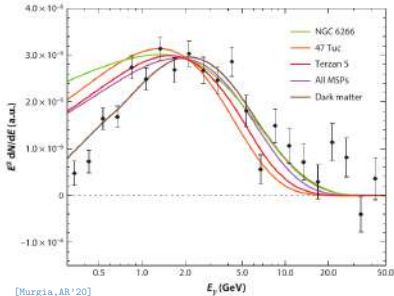


**Stellar distribution of old MSP-like objects in Galactic bulge?**

# Energy spectrum



Peaked at few (1-3) GeV

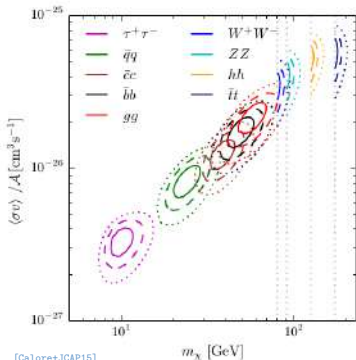


Consistent across inner Galaxy

- Dark matter: 20-70 GeV WIMP annihilation into gluons/ quarks
- MSP-like: similar spectrum
- Crucial: > 10 GeV tail

*Discriminate interpretation? Maybe*

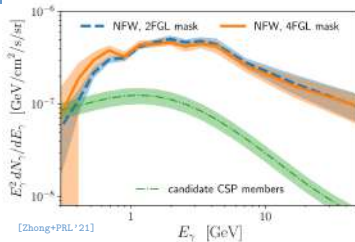
# Intensity



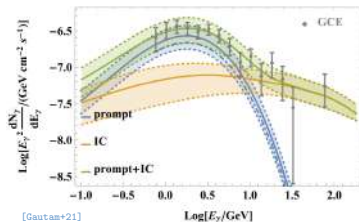
[Calore+JCAP15]

- Dark matter: cross section  $\sim 10^{-26} \text{cm}^3/\text{s}$ , thermal-relic WIMP
- Many theoretical frameworks explored [talk by J.Kumar]

*Discriminate interpretation? Maybe*



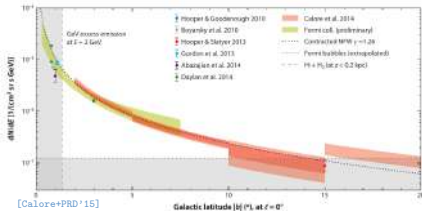
[Zhong+PRL'21]



[Gautam+21]

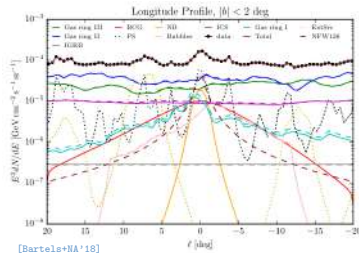
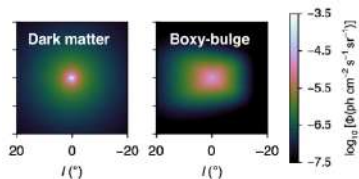
- observed MSP: not enough [Zhong+PRL'21]
- MSP-like population: modeling debated [Hooper+JCAP'16, Ploeg+JCAP20]

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



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

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

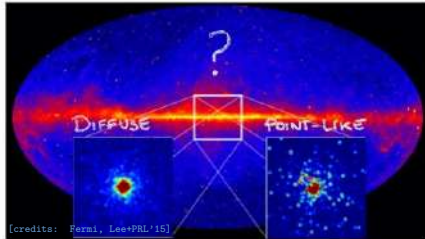


- Evidence for stellar bulge-like [Bartels+NA'18, Macias+NA'18, JCAP'19, Calore, SM+PRL'21]
- Longitudinal asymmetry at  $\sim 10$  deg

*Discriminate interpretation? Yes!*

# Diffuse or point-like?

**Truly diffuse emission:**  
*dark matter*



**Point-like:**  
Faint,  
unresolved  
sources:  
*millisecond  
pulsar*

## Difference in the statistics of photon counts

*Photon count statistics:* measure collective properties of faint sources

Two main implementations, based on seminal work [\[Malyshev&Hogg'11\]](#)

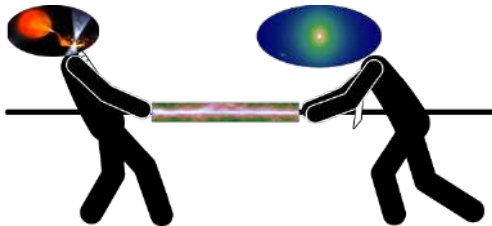
Non-Poissonian Template Fitting (NPTF), 1p-PDF

*Discriminate interpretation? Yes!*

*offline + backup for tech details on the methods*

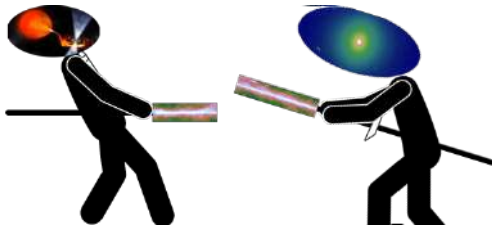
# A selection of *recent results*

1. Interpretation of photon count statistics analysis
2. Methodological advances: machine learning
3. Multiwavelength hints of the MSP population
4. Morphology: debate



# A selection of *diffuse modeling*

1. Interpretation of photon count statistics analysis & diffuse modeling
2. Methodological advances: machine learning & diffuse modeling
3. Multiwavelength hints of the MSP population
4. Morphology: debate & diffuse (mis)modeling



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

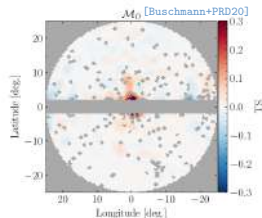
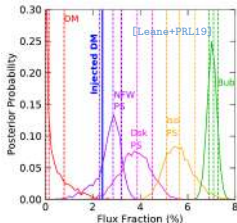
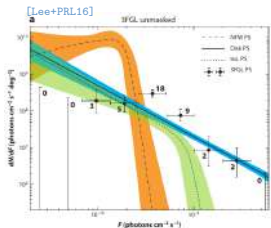
*Is the excess diffuse or point-like (sources spatially distributed as dark matter)?*

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 strikes 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]

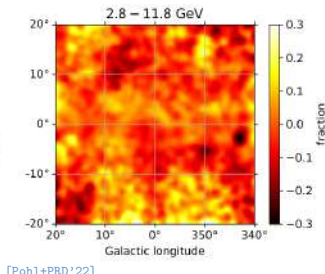
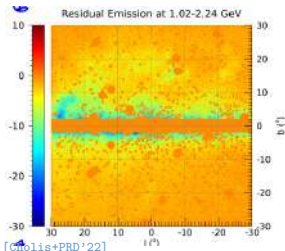
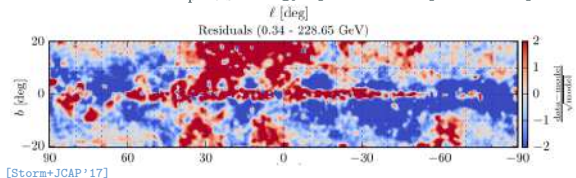
2020 : Preference for point sources influenced by spurious sources/ excess north-south asymmetry, robustness further casted into doubt [Leane+PRL,PRD'20]





# Galactic diffuse mismodeling: residuals

Model to fit Fermi-LAT data:  $\Sigma_{\text{pixels}}$  energy spectrum x spatial morphology



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]

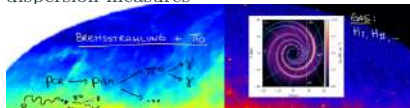
# How do we reduce residuals?

## Data-driven:

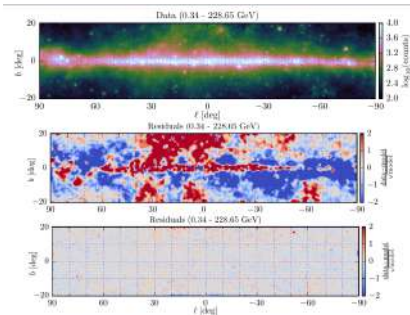
- Spherical harmonic marginalization  
[Buschmann+PRD20]
- Gaussian Processes  
[Mishra-Sharma,Cranmer,'22]
- SkyFACT: sky factorisation with adaptive constraining templates  
[Storm+JCAP'17]

## Improve models:

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

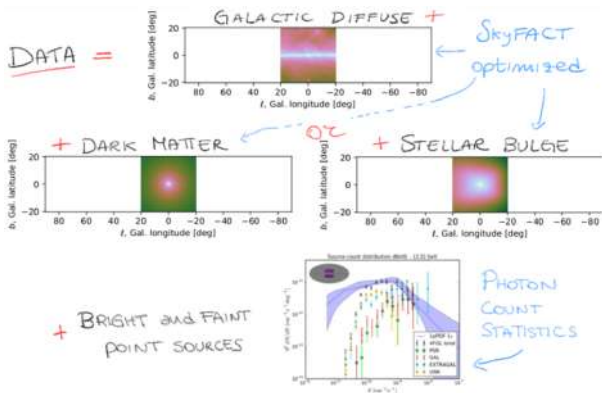


- new atomic HI reconstr, with radiation model of emission + absorption [Shmakov+22]
- convolutional neural nets to fill gaps in molecular  $H_2$  tracers like CO [Shmakov+22, Karwin+22]
- bayesian inference of 3D CO maps [Mertsch&Vittino'20]



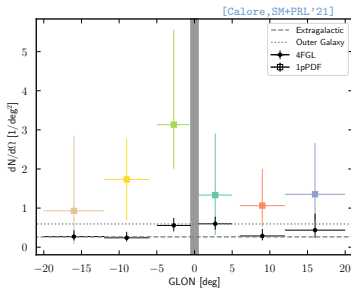
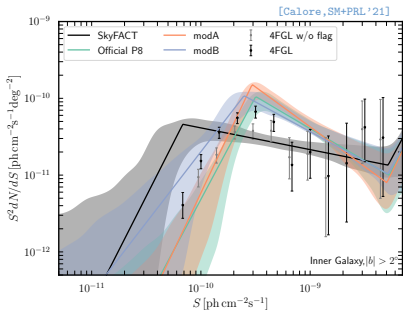
# Combining skyFACT and photon count statistics

[Calore, SM+PRL21, arXiv:2102.12497]



- **SkyFACT**: (more) robust diffuse modeling
- **Photon-count statistic**: (1pPDF) to model faint sources after reducing residuals

# Results



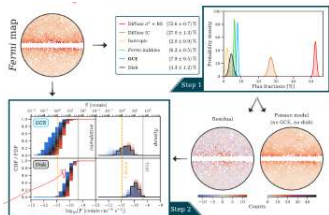
- Diffuse mismodeling strongly affects faint source reconstruction
- Stellar-bulge morphology preferred over dark matter  
(point sources, diffuse, stellar bulge) make (13,77,10) % of 2-5 GeV flux
- unresolved point sources resolved down to  $\sim 5 \cdot 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}$
- faint sources *not purely isotropic*

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

# Machine learning methods

[List+PRL'20, List+'21]

Convolutional neural-network + histogram regression



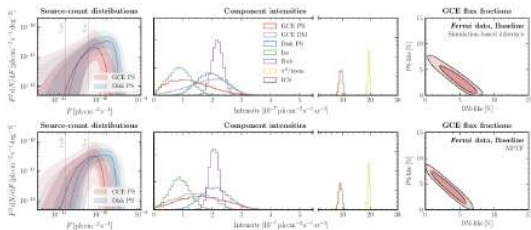
Smooth fraction of the excess  
is  $< 66\%$   
faint sources  
peaked  $\sim 4 \cdot 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}$

Note: *bulge-like excess not tested*

diffuse and point sources have same dark matter-like spatial distribution

[Mishra-Sharma&Cranmer'21]

Convolutional neural-network + simulation based inference



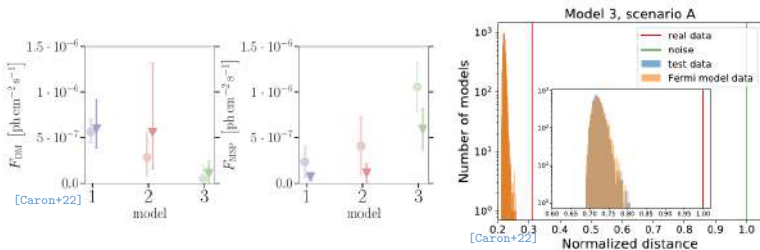
At least  $\sim 40\%$  of excess attributed to faint sources

Smaller (but large overlap) fraction wrt NPTF + improve diffuse modeling using Gaussian Processes

# Mind the gap!

Very recent update: [\[Caron+2211.09761\]](#)

Simulations used to train the machine learning algorithms can influence their conclusions, i.e. flux reconstructed to be dark matter or MSP

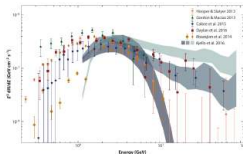


**Sizeable 'gap to reality' found in all simulated models**

We should further reduce the *distance* between data and background model

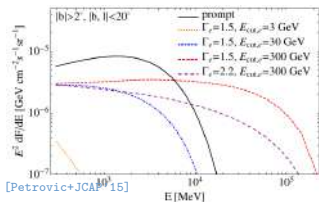
# The high energy tail

Excess spectrum at  $> 30$  GeV:

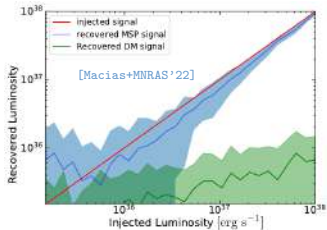


$e^\pm$  in MSP: prompt gamma rays + inverse Compton on ambient photons

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



[Petrovic+JCAP'15]



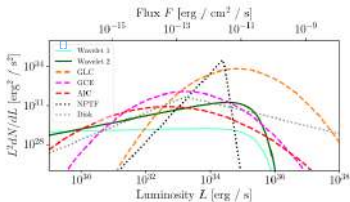
[Macias+MNRAS'22]

CTA could potentially detect this signature and discover the GCE MSP  
depends on luminosity function + spectral index

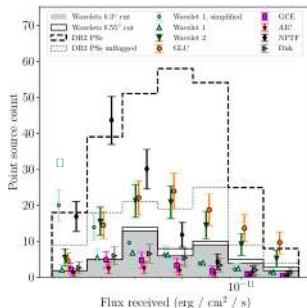
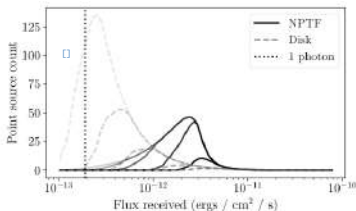
# Luminosity functions of MSP explaining the excess

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

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



Low-flux tails of luminosity functions to distinguish models



Models can produce 100-10<sup>6</sup> MSP w/o overproducing 4FGL sources

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



# Morphology: still debated

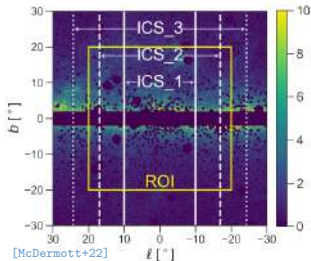
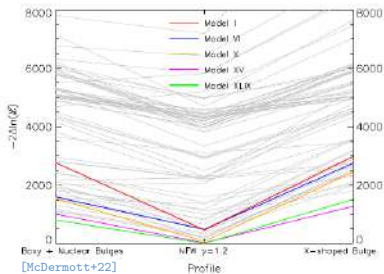
Independent groups find different results for the morphology of the excess

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

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)



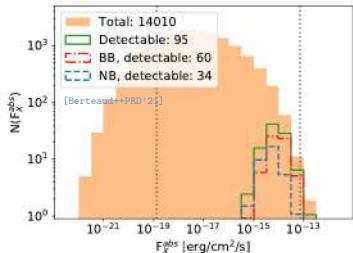
my take: difficult to close this debate using only template fitting:  
current residuals too high

# Testing MSP hypothesis: X-rays & radio

## Searching for the Bulge MSP contributing to GeV excess

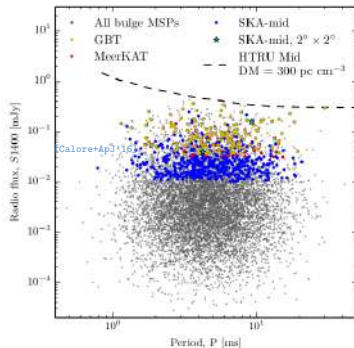
Unresolved in  $\gamma$ -rays *but* could be seen at other energies!

X-ray searches:



- MSP population explaining the excess **consistent with Chandra data**
- Set of promising candidates only seen in X-rays so far
- relation MSP X-ray - radio luminosity to tailor observations to detect pulsation

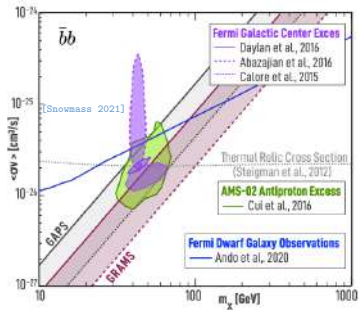
Radio searches:



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

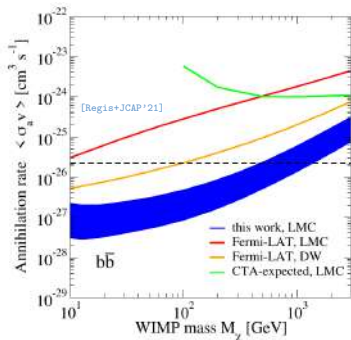
# Testing dark matter hyp.: Multi target + cosmic rays

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?

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

### *Recent progress:*

- ★ Photon count statistics + adaptive template fitting and machine learning results corroborate **partial stellar/point -like origin of the excess**
- ★ Many multi-wavelength/messenger/target avenues **to test dark matter and MSP interpretation**

**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

## *Moving forward:*

- ★ Galactic diffuse emission modeling: cosmic rays, 3D gas/radiation maps
- ★ Search for new source populations: radio (SKA), X-ray, refine models
- ★ Dark matter: multi-target evidence/constraints

