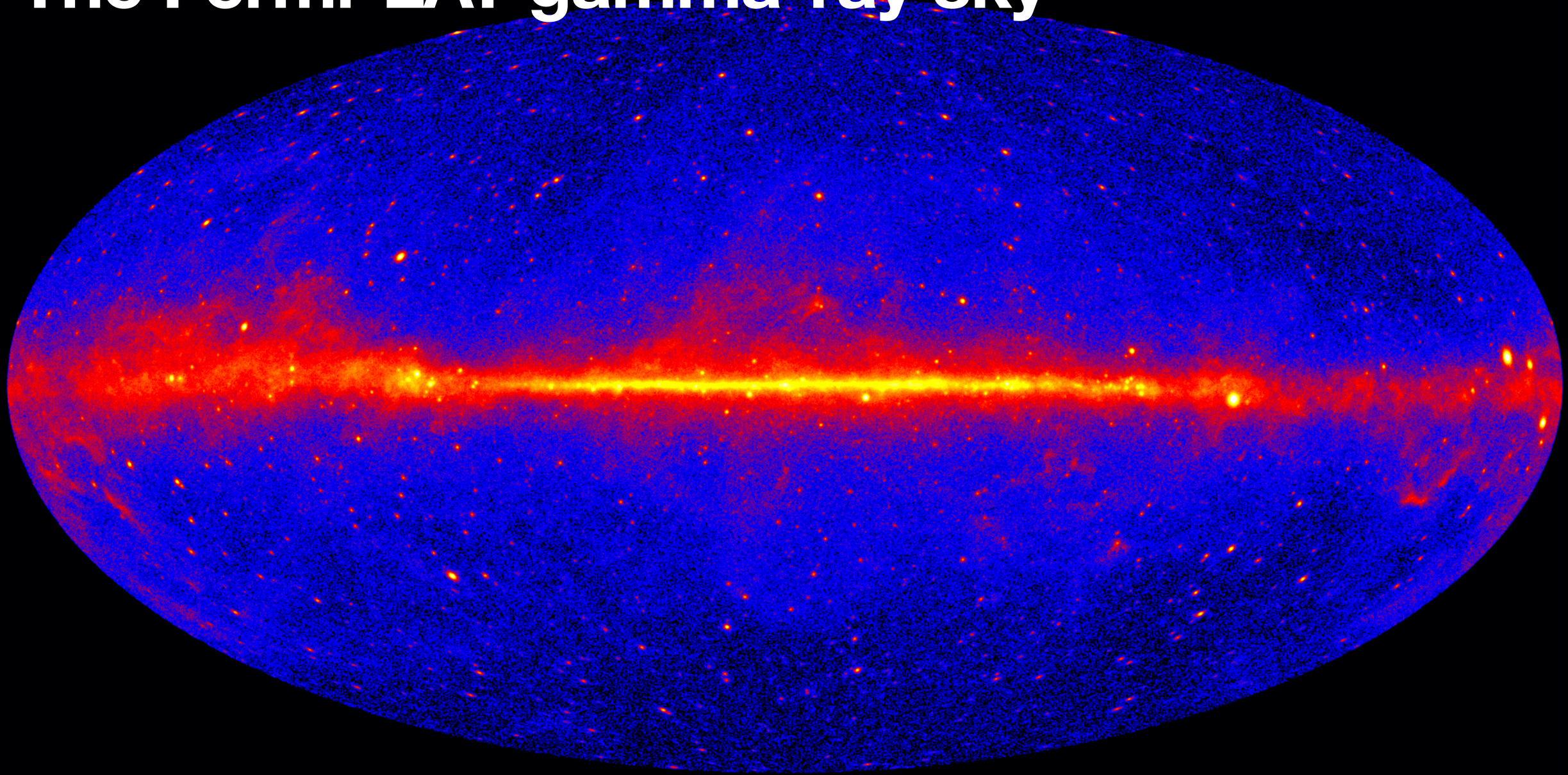
The Fermi-LAT GeV excess: from dark matter to point sources

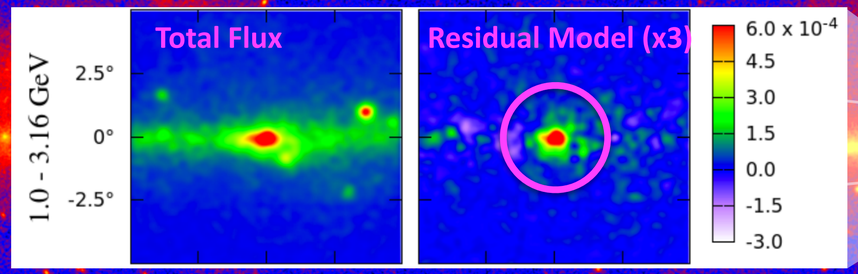
PANIC Conference 2021, Lisbon (online)
Francesca Calore (CNRS/LAPTh)

The Fermi-LAT gamma-ray sky



The Galactic centre GeV excess

The Galactic centre ROI



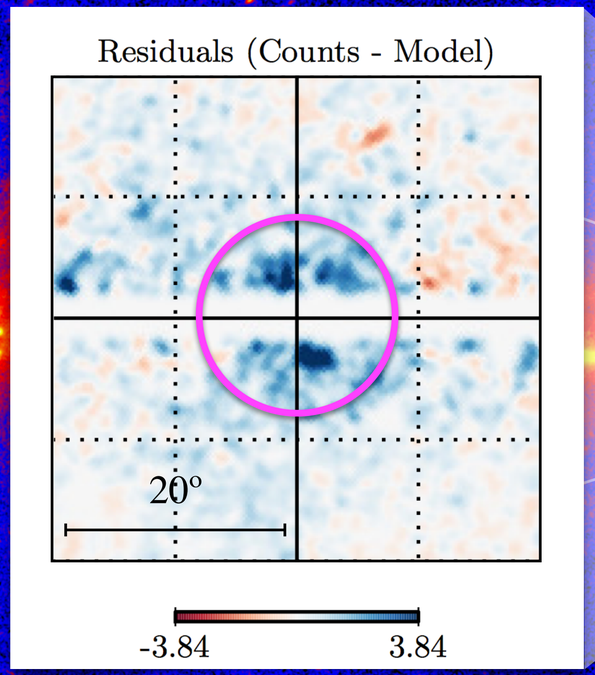
Daylan+ PDU'14

3°

Hooper&Goodenough '09; Vitale&Morselli '09;
Hooper&Linden PRD'11;
Hooper&Goodenough PLB'11;
Boyarsky+ PLB'11;
Abazajian&Kaplinghat PRD'12;
Macias&Gordon PRD'14;
Abazajian+ PRD'14; Daylan+ '14;
Huang+ '15; Carlson+ '15; Ajello+15;
Casandjian Fermi Symp.'14;
de Boer+'16; Macias+'16; etc.

The Galactic centre GeV excess

The inner Galaxy ROI



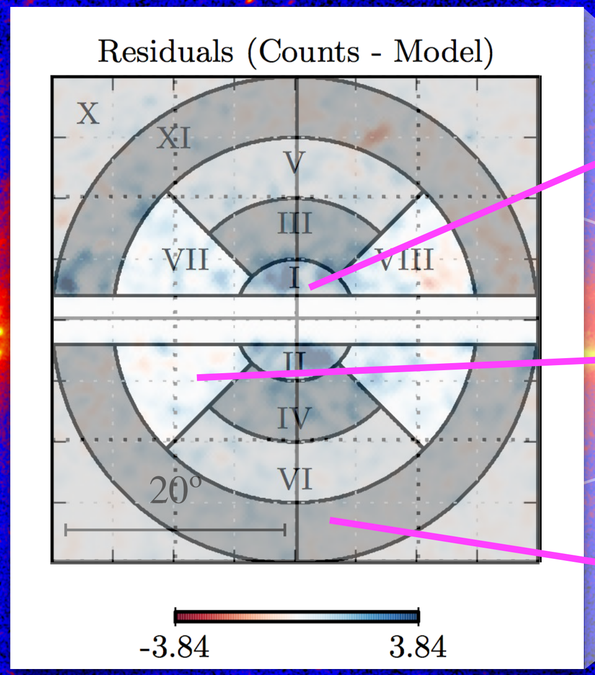
FC+ JCAP'15

20°

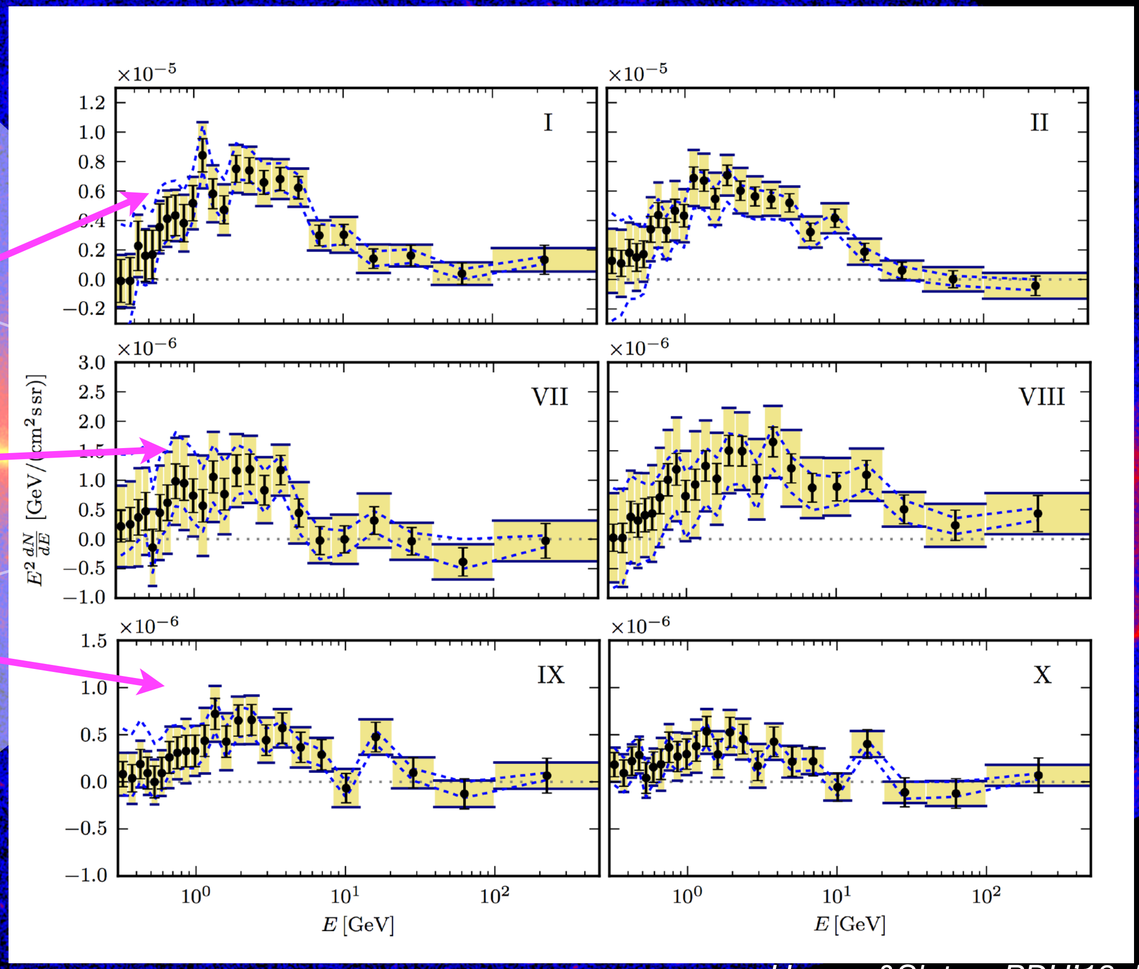
Hooper&Slatyer PDU'13; Huang+ JCAP'13;
Zhou+ PRD'15; Daylan+ PDU'14; FC+ JCAP'15;
Gaggero+ JCAP'15; Ajello+ 2015; Huang+JCAP '15
Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; Murgia ARNPS'20

The Galactic centre GeV excess

The inner Galaxy ROI



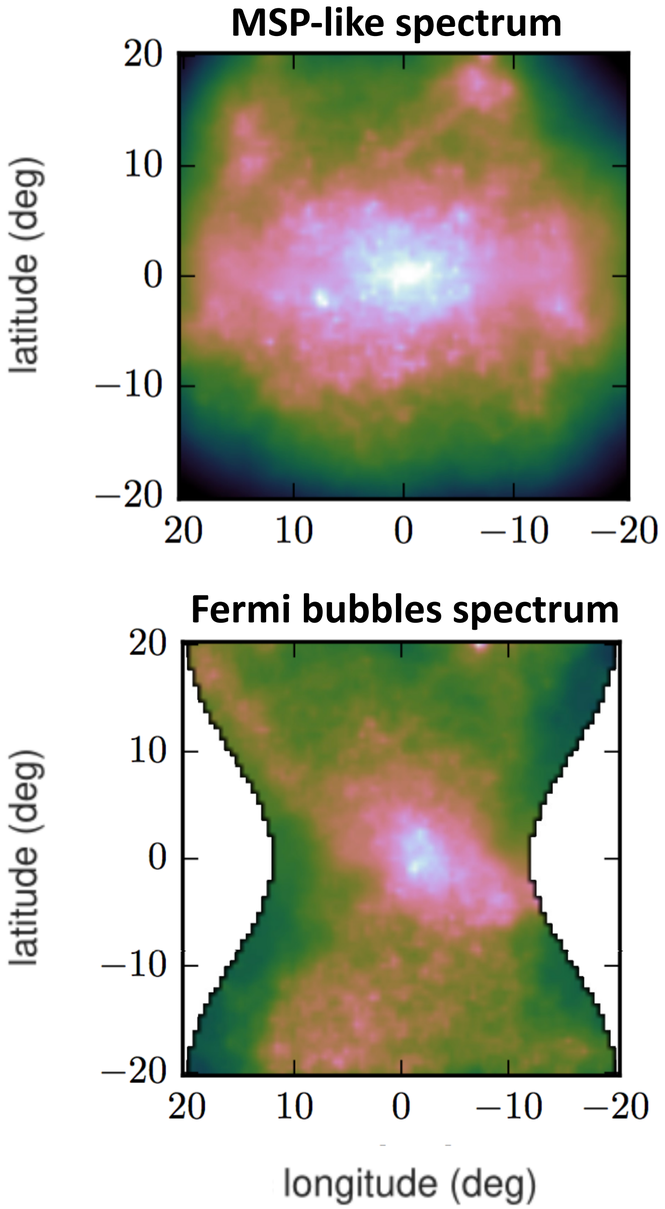
FC+ JCAP'15



1. Almost uniform spectrum peaked at ~2 GeV
2. Extended at least up to 10 degrees

Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ PDU'14; FC+ JCAP'15; Gaggero+ JCAP'15; Ajello+ 2015; Huang+JCAP '15 Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; Murgia ARNPS'20

The GeV excess emission



- Established evidence for an excess emission above **known** astrophysical backgrounds (diffuse emission + point-like sources)
- **Several independent techniques** find analogous results (template fitting, spectral decomposition, image reconstruction)

Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; FC+ JCAP'15; Ajello+ ApJ'15; Gaggero+ JCAP'15; etc

Selig+ A&A'14; Huang+ JCAP'16; de Boer+'16

Storm, Weniger & FC JCAP'17

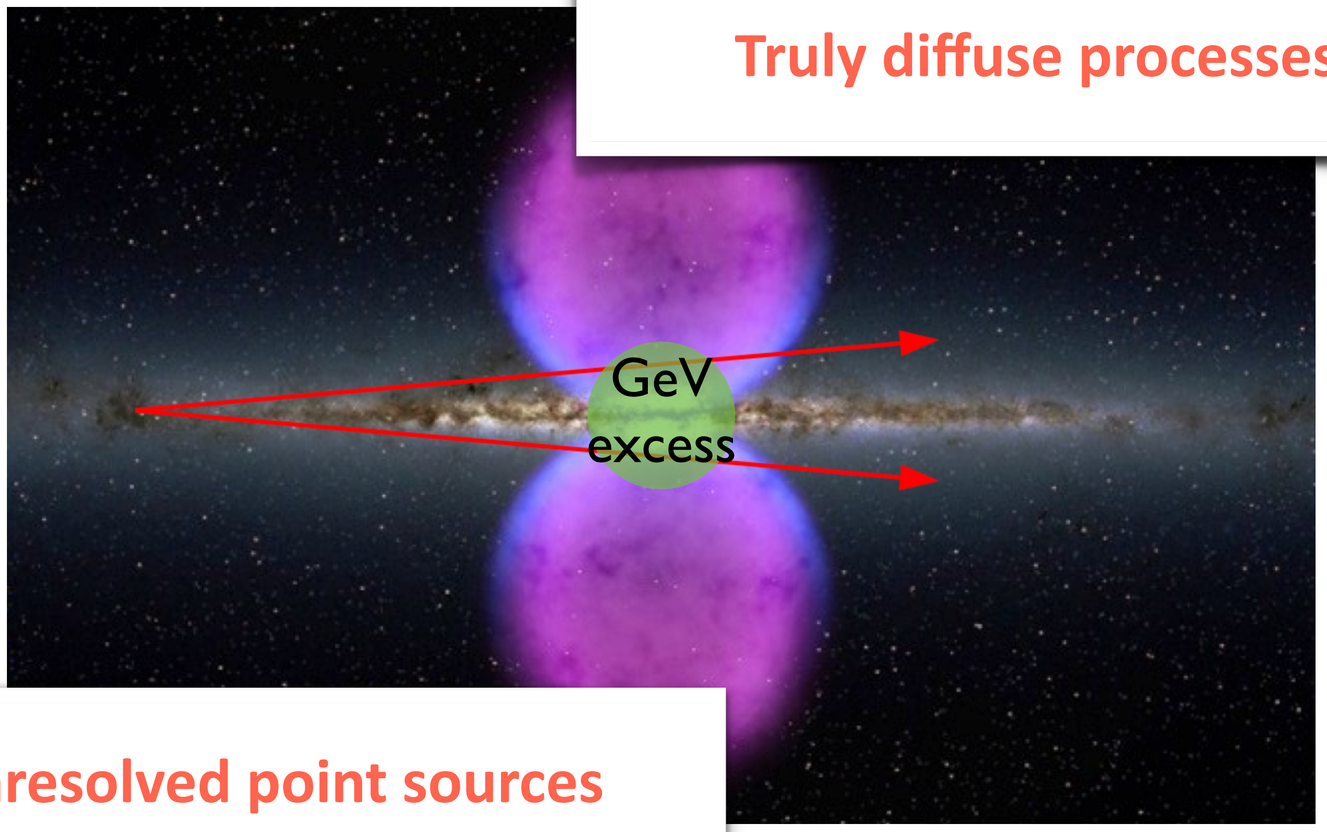
- **Template fitting - image reconstruction hybrid approach** (SKYFACT) has been proved very powerful in disentangling gamma-ray emission components

Storm, Weniger & FC JCAP'17

- **Residuals reduced significantly** when (realistic) nuisance parameters are included in the fit

What is the origin of the GeV excess?

Possible interpretations



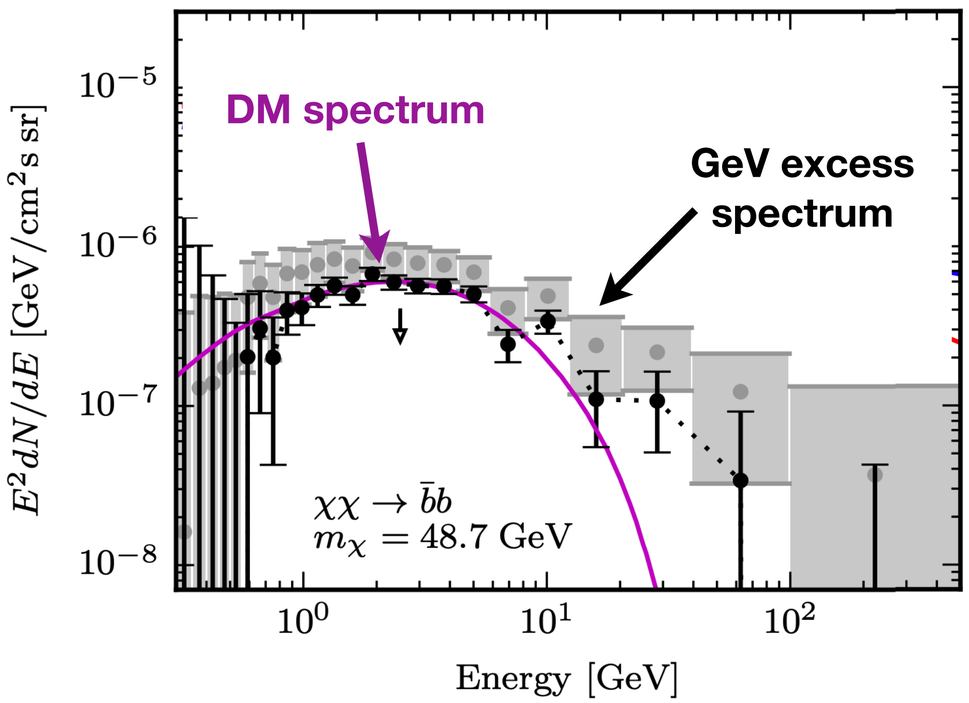
Constraints:

(a) Spectrum & Morphology of the excess? (b) Emission in other wavelengths?

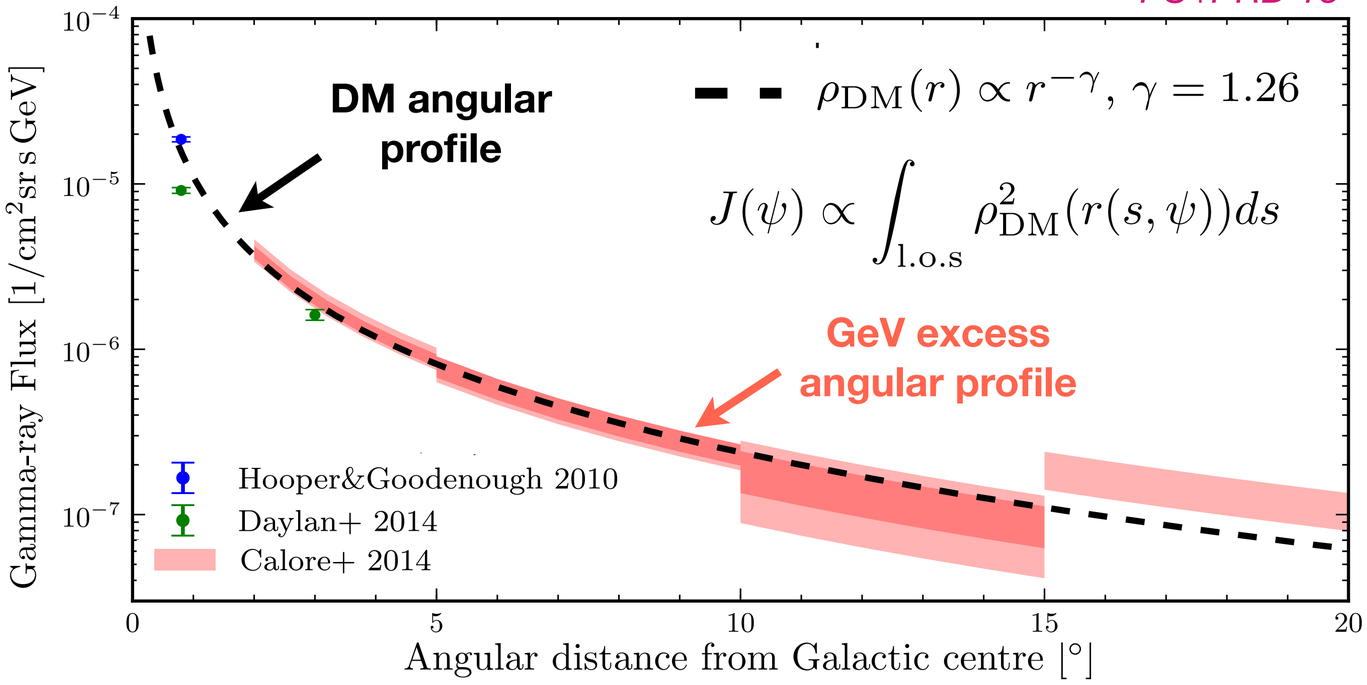
Diffuse processes I

Gamma rays from dark matter (DM) annihilation

- **Dark matter** dominant component (80%) of matter in the Universe
- In the standard paradigm, DM made by new particles beyond the std model of Particle Physics
- **Decay/Annihilation** of DM particles would lead to the production of **final gamma rays** with specific energy and spatial distribution



FC+PRD'15



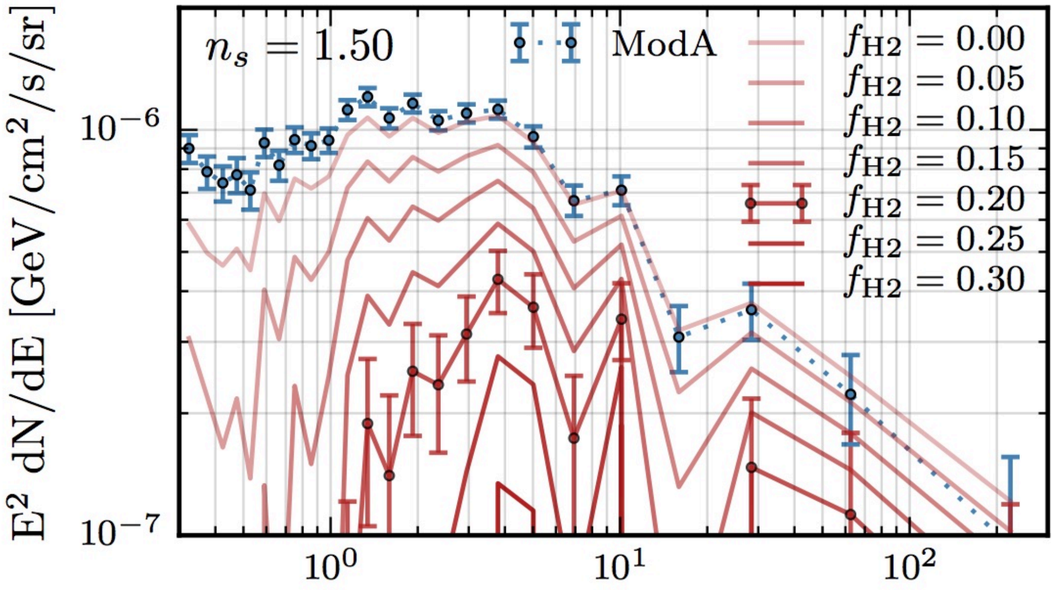
Agrawal+JCAP'15; Achterberg+JCAP'15; Bertone, FC+ JCAP'15; Liem, FC+ JCAP'16; O(>100) papers

Diffuse processes II

Cosmic rays in the GC

[See also talk by **M. Valli**]

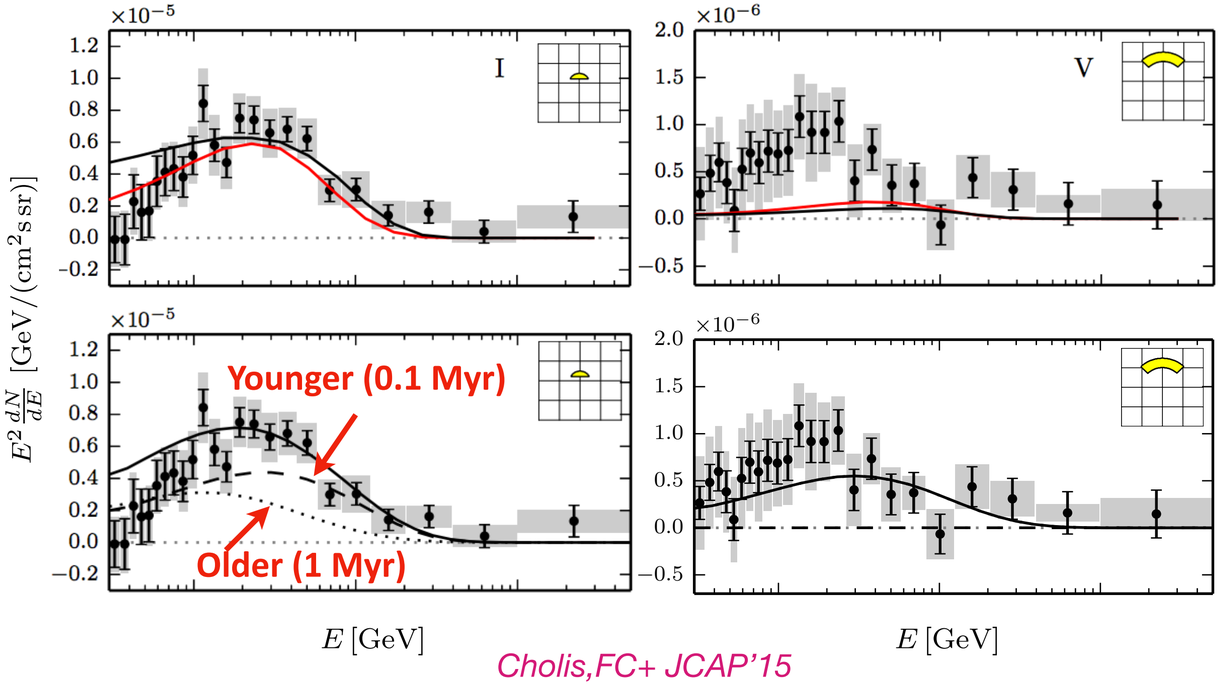
- **New population** of **cosmic rays** injected at the GC (electrons mostly)
- **Steady state** (from star formation in CMZ) and/or **time-dependent** (from outburst activity of the GC) source term



Carlson+ PRD'16

Additional CR injection at the GC, accounting for enhanced SFR traced by H2 regions (5-10% of total SFR)

Gaggero+JCAP'15; Carlson+ PRD'16, PRL'16
Petrovic+ JCAP'14; Cholis,FC+ JCAP'15

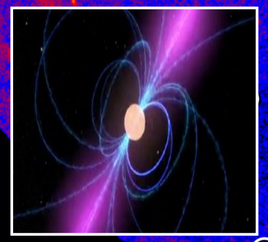


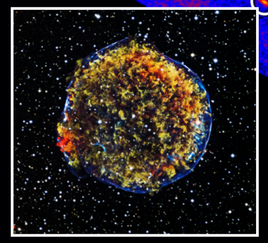
Cholis,FC+ JCAP'15

Time-dependent (burst) injection of leptons at the GC, and tuning of burst parameters (age, duration, injection spectrum, propagation parameters)

Detected vs “unresolved” point-like sources

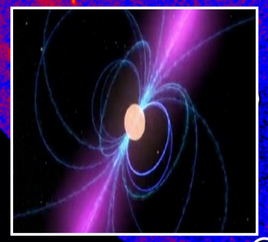
Detected sources

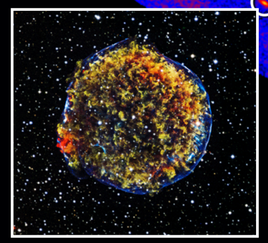




Detected vs “unresolved” point-like sources

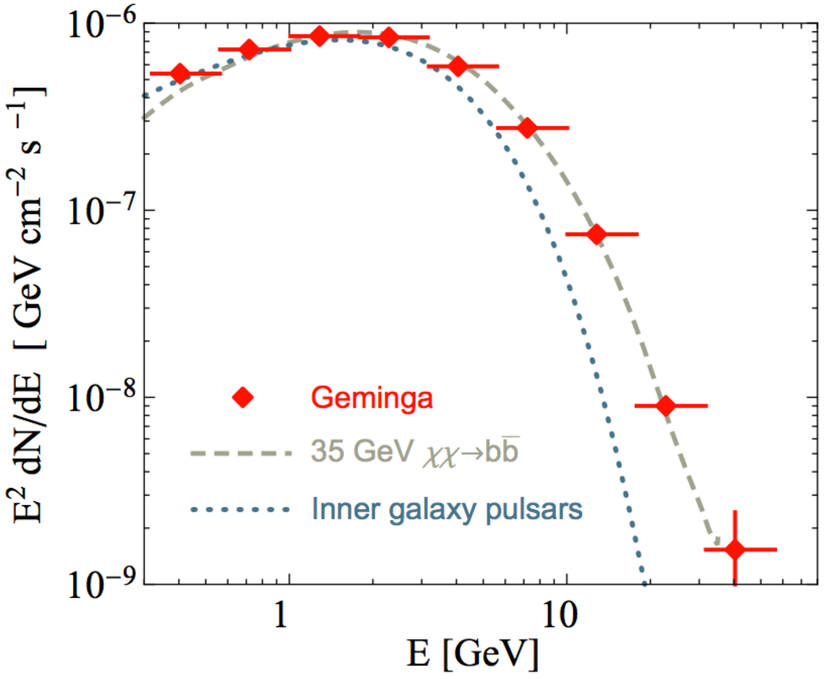
Detected sources





Unresolved sources: PSR and MSPs

Spectrum



✓ Excess spectrum compatible with observed **millisecond pulsars** (MSPs), and marginally **young pulsars**

Abazaijan&Kaplinghat'12

Morphology

$$\epsilon \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$

$$\Gamma = 2.5 \quad R_{\rm cut} = 3\,{\rm kpc}$$

✓ Proposed population of **MSPs in the bulge** (vs disc)

Hooper+PRD'14; Petrovic+ JCAP'15; Yuang+ MNRAS'14;

✓ **Young pulsars** from SF in the CMZ, but difficult to explain spatial extent and observed bright ones

O'Leary+ '15; Linden PRD'16

✓ **Bulge MSPs** from tidally disrupted globular clusters

Brandt&Kocsis ApJ'15; Abbate et al. 2017; Fragione et al. 2017; Arca-Sedda et al. 2017; Macias+JCAP'19

✓ Issues in luminosity function of observed MSP and LMXB-to-MSP ratio

Cholis+'14; Hooper+'15; Hooper&Linden JCAP'16; Haggard+ JCAP'17; Ploeg+ JCAP'17

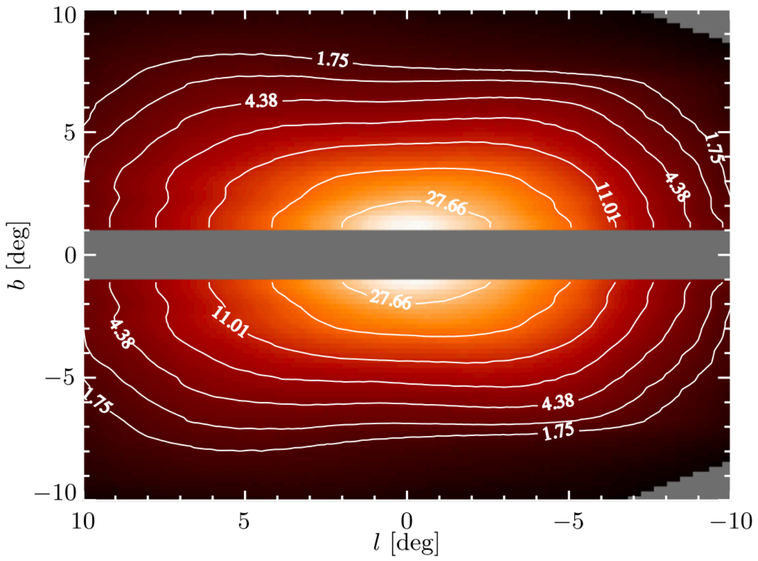
How to probe the GeV excess nature?

Going beyond dark matter templates

Stellar distribution in the bulge

Boxy bulge

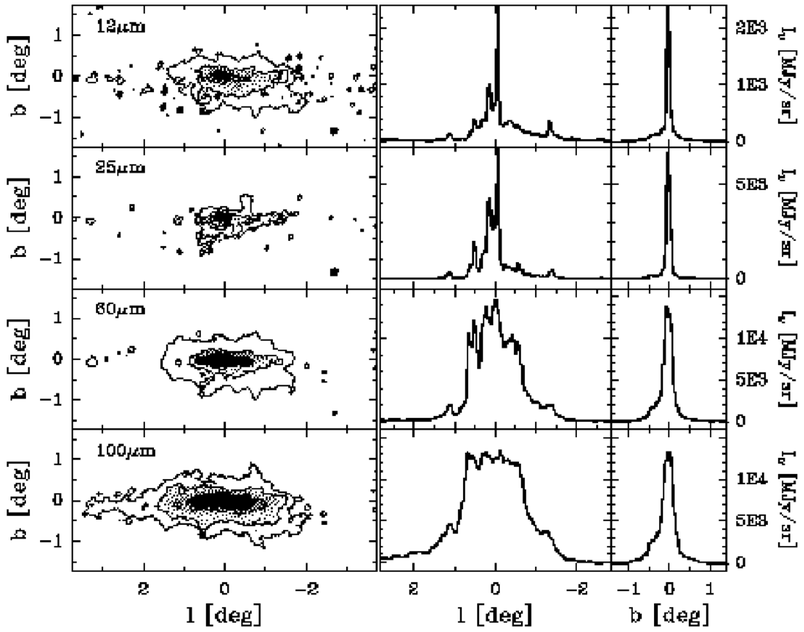
$0.9 \times 10^{10}\ M_\odot$



Wegg & Gerhard MNRAS'12

Nuclear bulge

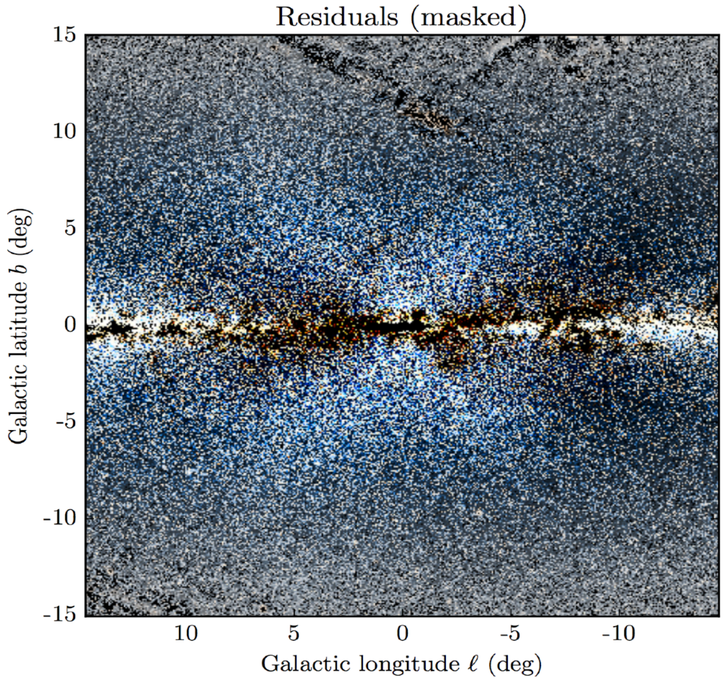
$1.4 \times 10^{9}\ M_\odot$



Launhardt+A&A'02

X-shaped bulge

~20% BB mass



Ness&Lang AJ'16

- **Red Clump stars** (near-IR) used to characterise the **three-dimensional density structure** of the BB
- Most recent non-parametrically deconvolved bulge model w/ VISTA Variables in the Via Lactea (VVV) data *Coleman+ MNRAS'20*
- X-shaped structure characteristic of boxy/peanut like morphology (extragalactic studies of barred galaxies and simulations)

Evidence for the stellar bulge GeV emission

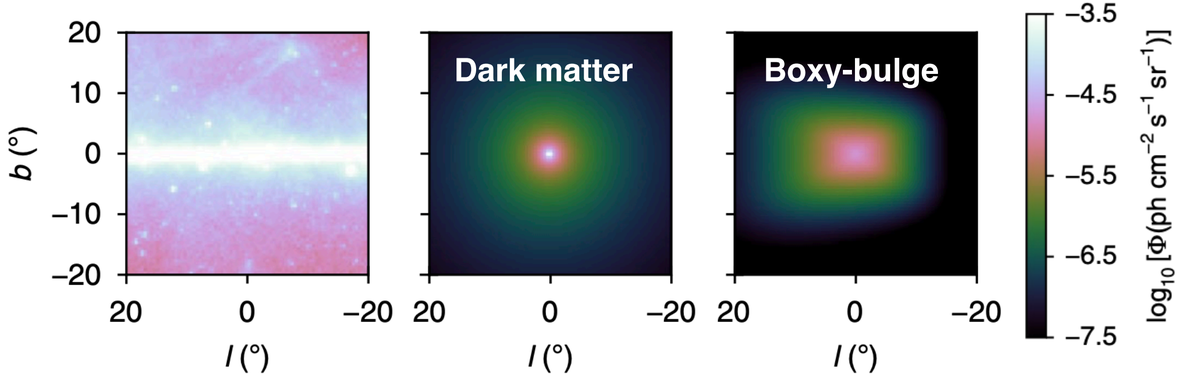
nature astronomy

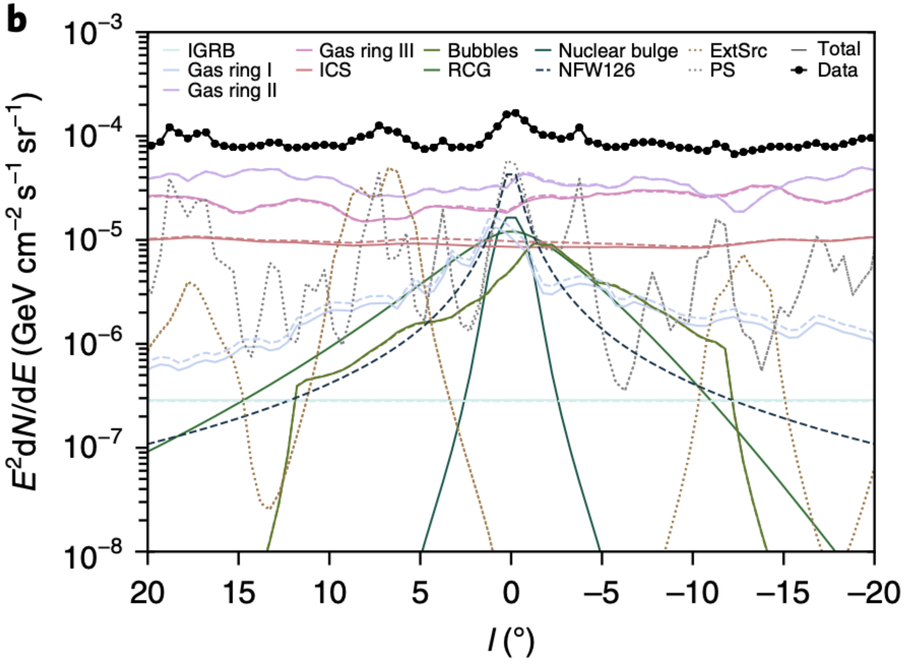
ARTICLES

https://doi.org/10.1038/s41550-018-0531-z

The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge

Richard Bartels[1]*, Emma Storm[1], Christoph Weniger[1] and Francesca Calore[2]





- ✓ **Stellar bulge model**: **Boxy bulge** as traced by red-clump giants + **nuclear bulge**

  Cao+MNRAS'13; Launhardt+ A&A'02

- ✓ Strong evidence for additional **stellar bulge model** (16σ); no evidence for additional **DM model** (< 3σ)

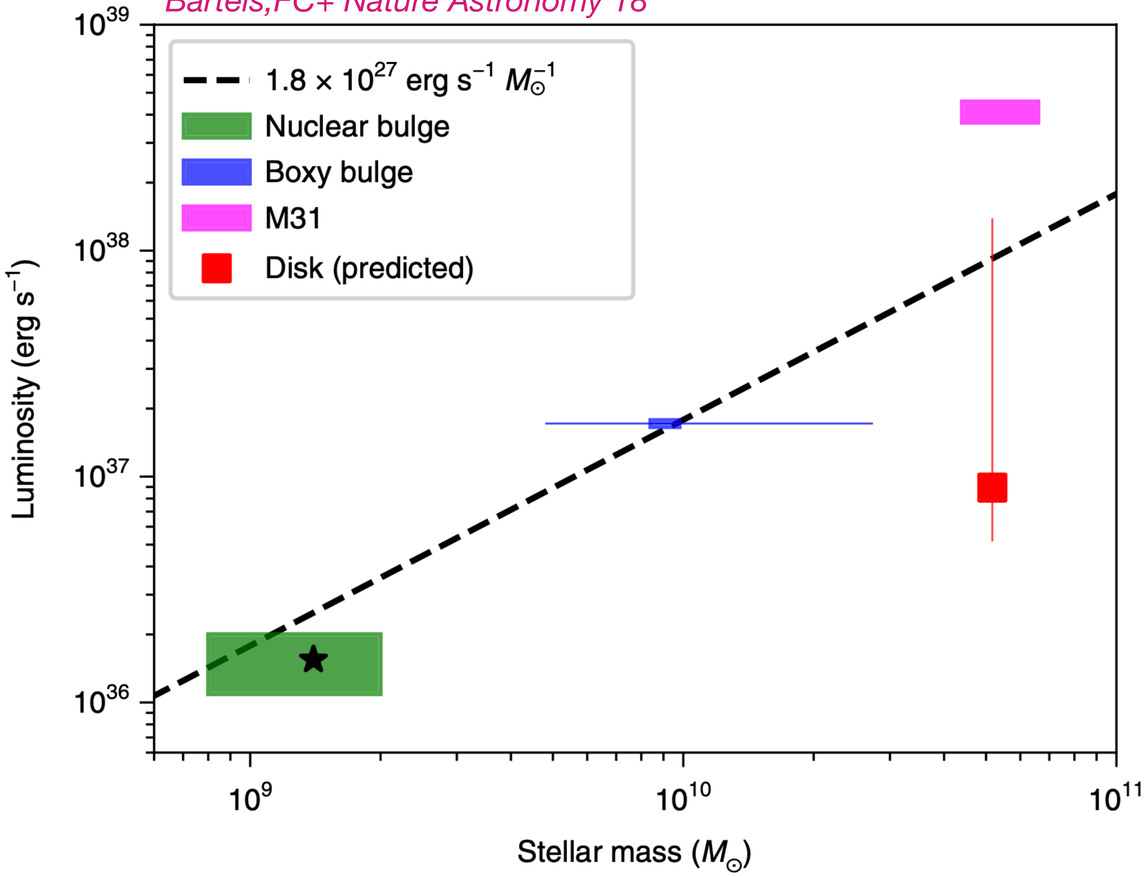
- ✓ Discriminating feature: Asymmetry at ~10 deg longitude => **Morphology** of the GCE **more oblate** than what found before

Macias+ Nature Astronomy'18; Macias+ JCAP'19

Gamma-ray luminosity vs stellar mass

A suggestive correlation

Bartels,FC+ Nature Astronomy'18



- ✓ **Gamma-ray luminosity** shows **correlation** with **stellar mass** in the Galactic bulge
- ✓ Emission from MSP requires bulge and disc components both consistent with the correlation

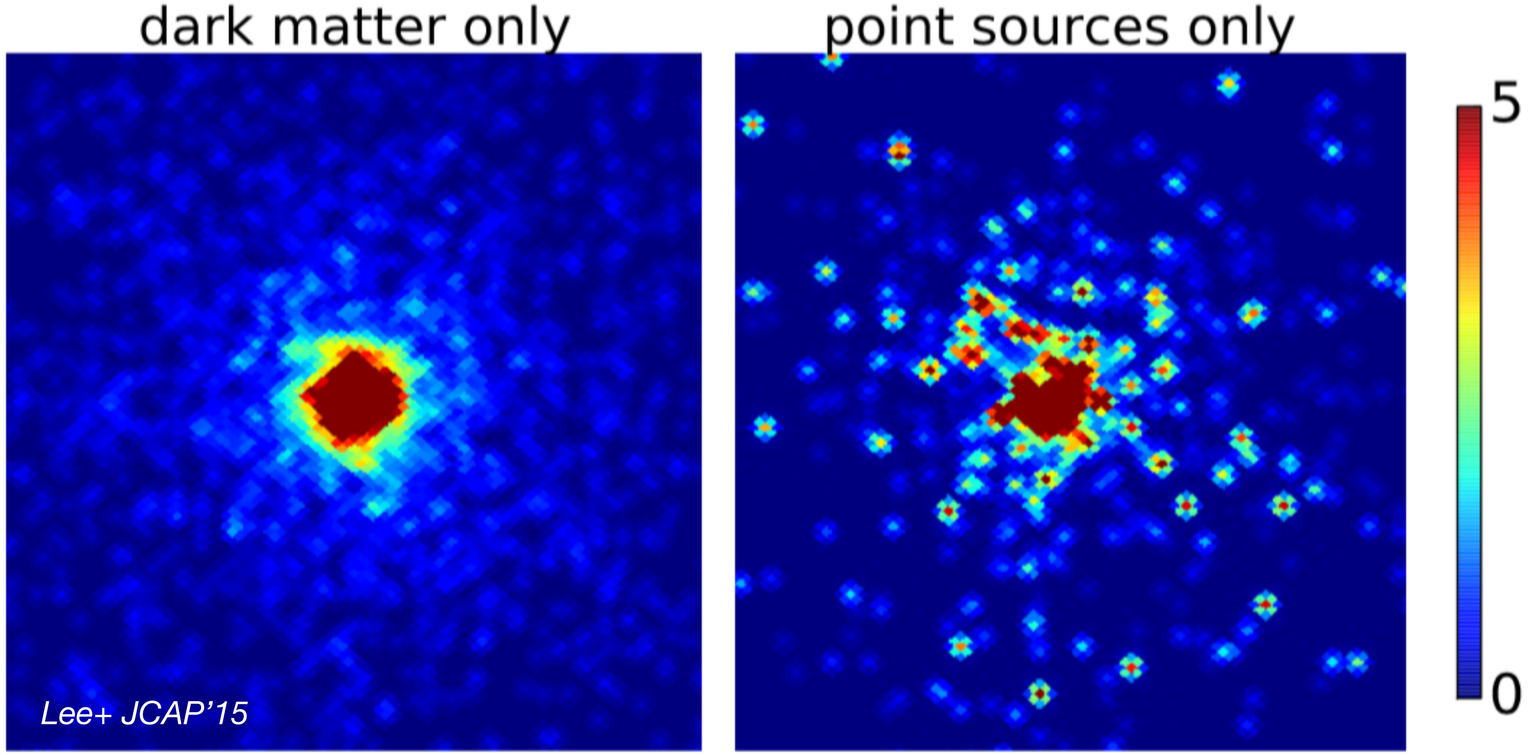
  Bartels+ MNRAS'18; Eckner+ ApJ'18; Ploeg+ 2008.10821
- ✓ **What is MSP formation scenario?** In-situ formation of MSP (+ dynamical formation) or from disrupted globular clusters?

  Fragione+1808.02497, MNRAS'18; Eckner+ ApJ'18
  Macias+ JCAP'19
- ✓ Test correlation with gamma-ray analysis of **M31** (Andromeda galaxy)

  Ackermann+ ApJ'17; Eckner+ ApJ'18; Armand & FC PRD'21

Statistics of photon counts

How to discriminate diffuse vs point-like emission



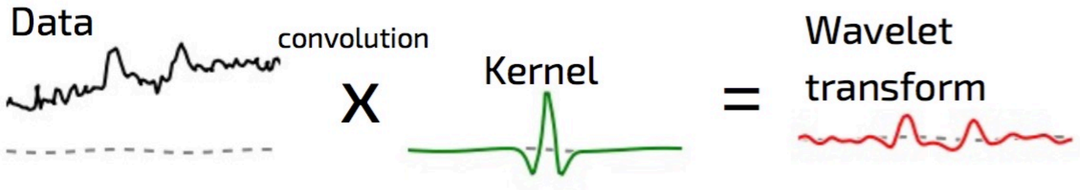
Differences in the **statistics of the photon counts** can be quantified and used for model comparison

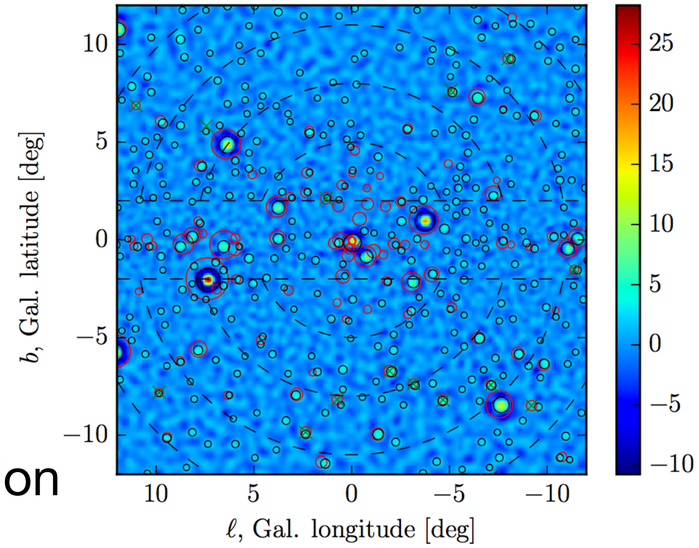
[See also talk by **N. Rodd**]

Support for unresolved point sources (PS)

Local maxima of normalised wavelet transform

Bartels+ PRL'16

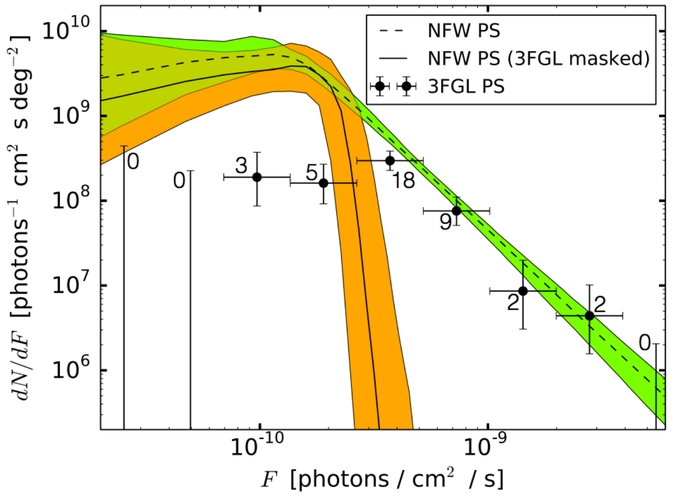


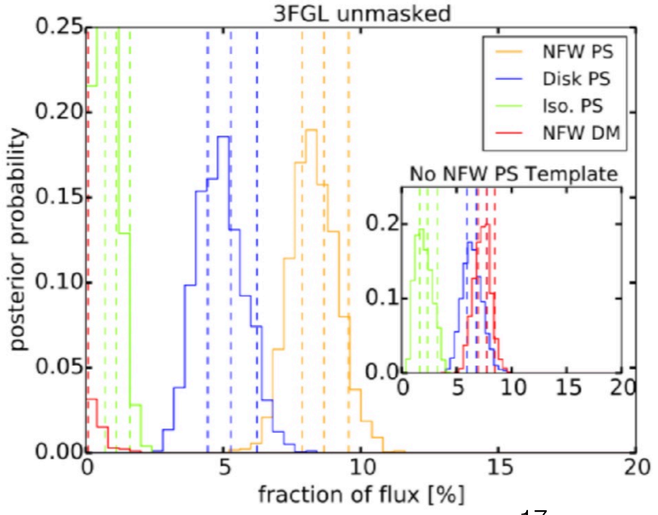


- Wavelet transform to look for **peaks** in data
- Enough peaks were found to explain the cumulative excess emission
- Evidence for unresolved PS population and constraints on luminosity function
- No modelling of diffuse emission required

Non-Poissonian template fitting

Lee+ PRL'16





- Exploits difference in photon statistics: smooth signal (DM) vs larger variance across pixels (PS)
- PS fluctuations follow non-Poissonian statistics
- Sensitivity to spatial distribution and luminosity function of PS
- Required modelling of diffuse emission

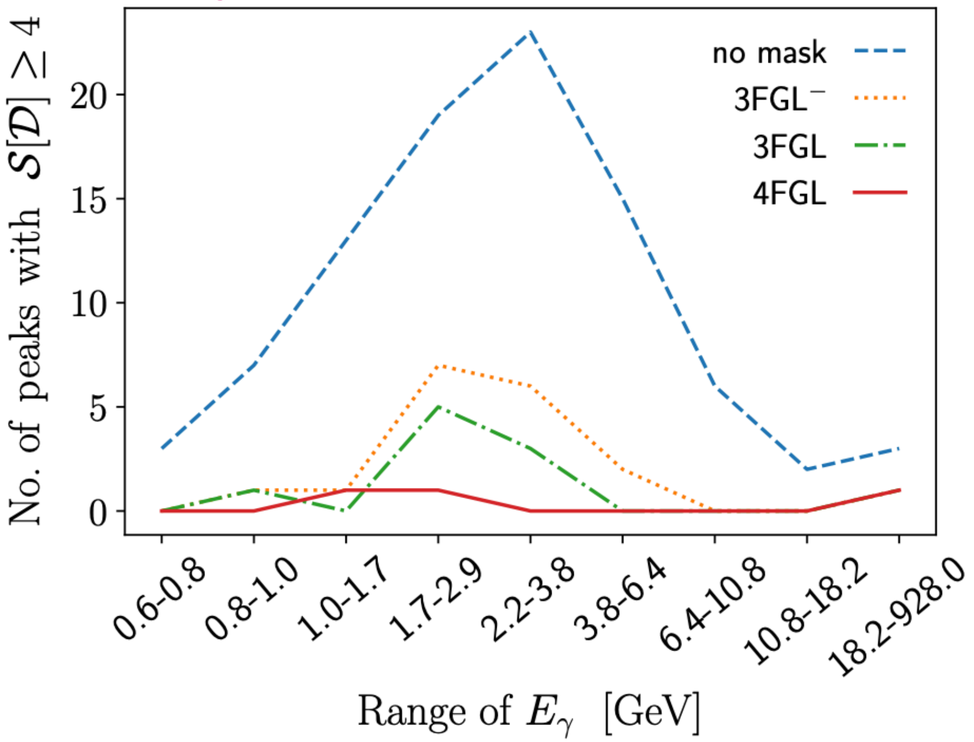
A yet to be solved debate

“Dark matter strikes back at the Galactic center?”

Measure of **power @ small scales**:

Real sources or residual structures from mis-modelling of diffuse components?

Zhong+PRL’19



Wavelets

- Analysis update with latest Fermi-LAT catalog (4FGL)
- Reduced number of wavelet peaks means more “just-below-threshold” resolved sources in new catalog
- The bulk of the excess disappears and non-resolved peaks cannot reproduce cumulative GCE emission

A yet to be solved debate

"Dark matter strikes back at the Galactic center?"

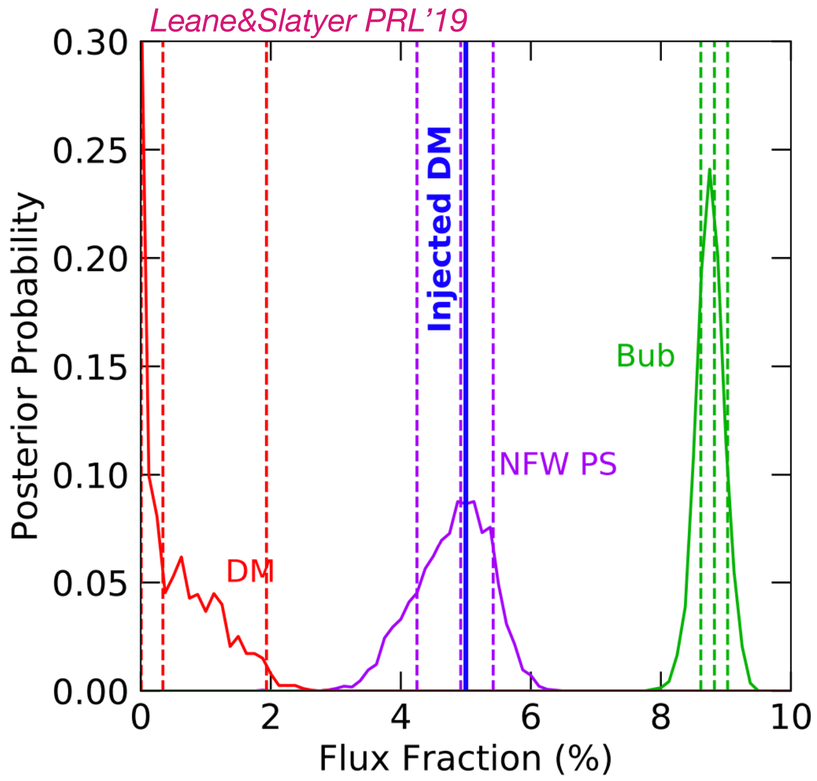
Measure of **power @ small scales**:

Real sources or residual structures from mis-modelling of diffuse components?

Non-Poissonian template fitting

- Strong effects of yet unexplored systematics
  Leane&Slatyer PRL'19; Chang+ PRD'20
- Mis-modelling of background templates
  => Mitigation of diffuse mis-modelling
  => Evidence for PS population decreased to 3σ
  Buschmann+ PRD'20

- Mis-modelling of smooth and/or PS signal
  => Increased pixel-to-pixel variance
  => Appearance of spurious PS population
  Leane&Slatyer PRL, PRD'20



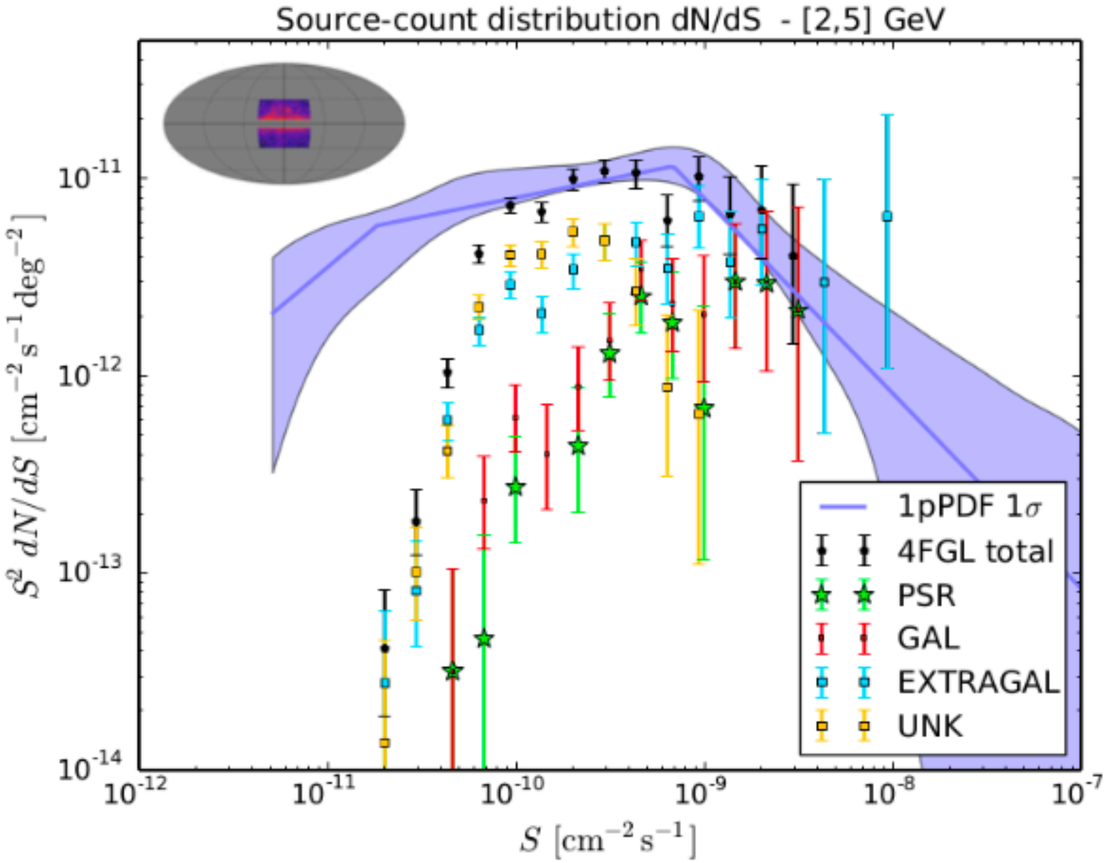
[For alternative methods see: *Caron+JCAP'18* (Deep learning); *List+ 2006.12504, 2107.09070* (CNN)]

1-point probability distribution function (1p-PDF)

Statistical analysis of photon counts to decompose the gamma-ray sky and measure the source count distribution (dN/dS)

Zechlin+ApJS'16,+ApJL'16, Zechlin+PRD'18

- *Measures* the source count distribution dN/dS as a function of the gamma-ray flux
- *Extends* the sensitivity for dN/dS below the nominal Fermi-LAT catalog flux threshold
- *Decomposes* the gamma-ray sky into: point sources + Galactic diffuse emission + isotropic diffuse background + additional components (e.g. DM)



Method thoroughly tested on Fermi-LAT data

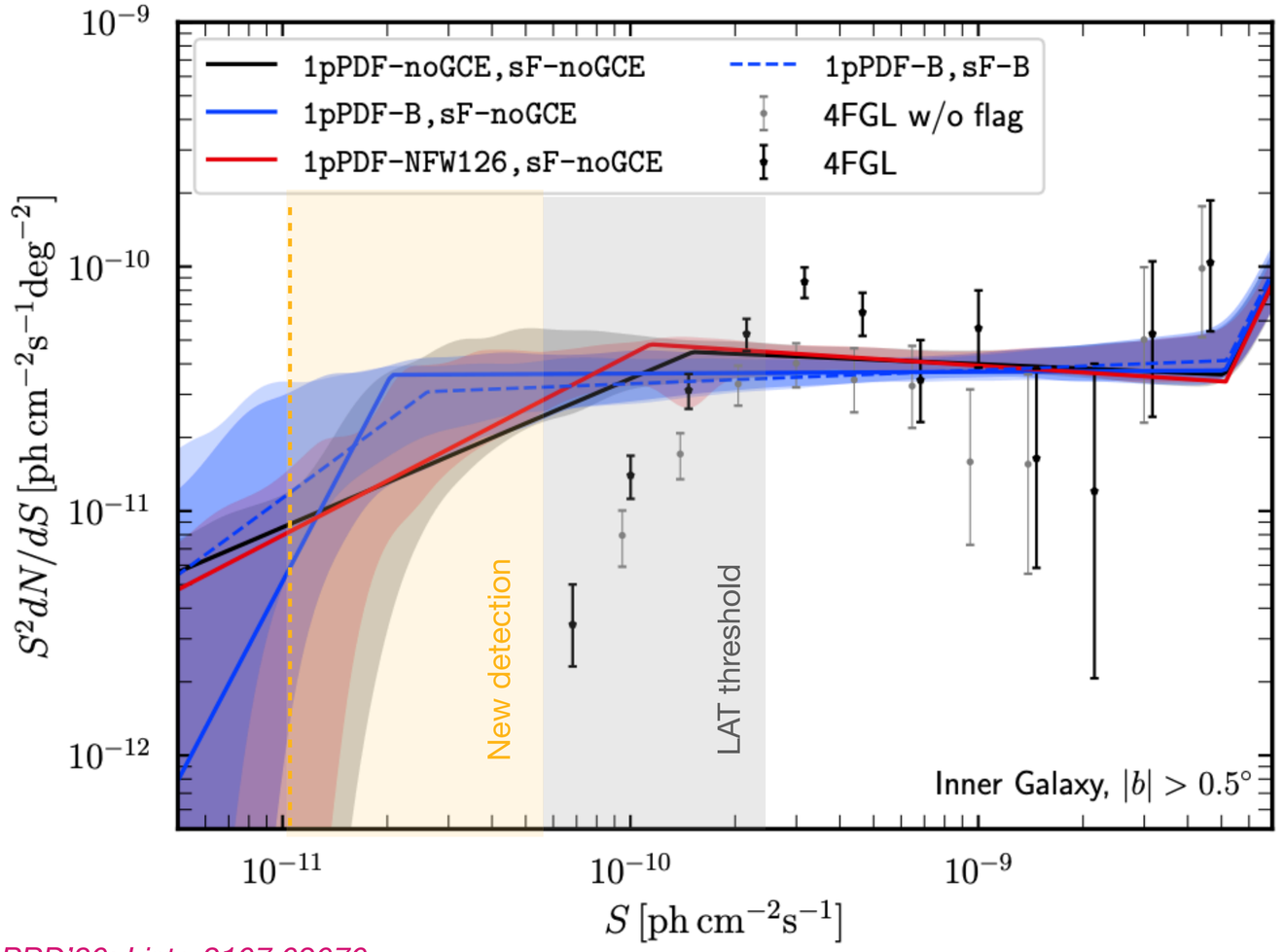
Zechlin+ApJS'16,+ApJL'16, Zechlin+PRD'18, Manconi+PRD'20, DiMauro+ApJ'18

Evidence for unresolved PS

Characterise the source count distribution of faint PS

Measure of dN/dS *below catalog flux threshold*:

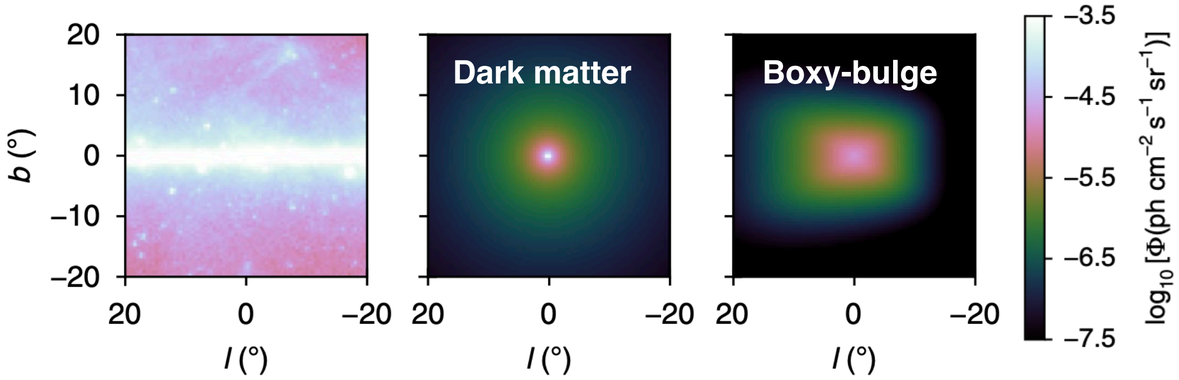
- Optimised Galactic diffuse emission: dNdS results stable w.r.to all tested systematics
- **Unresolved point sources** in the inner Galaxy *resolved* down to ~ $5 \cdot 10^{-11}$ ph cm^{-2} s^{-1}



Buschmann+PRD'20; List+ 2107.09070

Morphology of the Fermi excess

Dark matter vs stellar bulge-like distribution



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

- *Without unresolved sources*: stellar bulge preferred over DM at 11σ!

  Macias+ Nature Astronomy'18; Macias+ JCAP'19

- *Stellar bulge* + *unresolved sources* (> 3% of total ROI emission) significantly preferred

- *Stellar bulge morphology preferred over DM* also when modelling faint point sources!

An (at least) partial **stellar origin of the GeV excess** seems to be confirmed

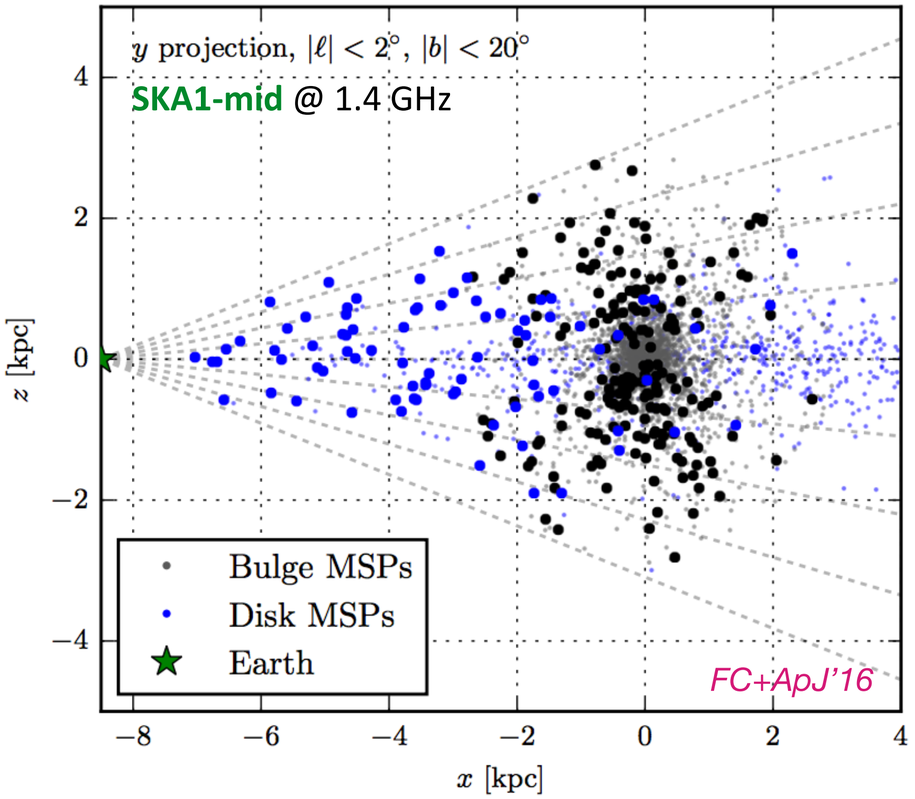
If there is a **population of unresolved MSPs in the Galactic bulge**, this should be **abundant in number**, right **below** detection **threshold in gamma rays**, **emit in other wavelengths**

What are the **multi-messenger probes** of the **GeV excess point-like source nature?**

FC+ApJ'16; FC+PRL'19; Berteaud, FC+ PRD'21
Macias+ MNRAS'21

Multi-messenger tests of the GeV excess

Radio telescopes: MeerKAT, Square Kilometre Array



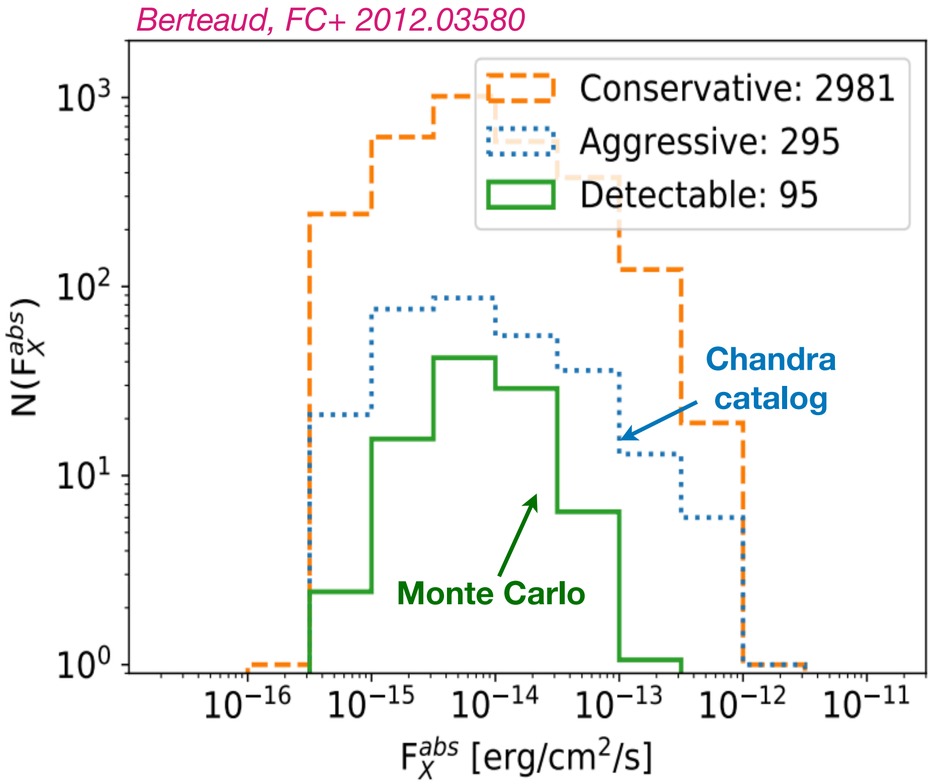
- ✓ **Current radio telescopes** are simply **not sensitive** to an MSPs population in the Galactic bulge
- ✓ **Future radio telescopes can discover** this population with a few hundreds hours of observations
- ✓ MeerKAT mid-lat survey ~300h: ~30 bulge MSPs

Searches on-going with MeerKAT

Multi-messenger tests of the GeV excess

X-ray telescopes: Chandra

Berteaud, FC+ 2012.03580



- ✓ About 100 MSPs from the bulge can be **detectable** in the Chandra CSC 2.0 catalog
- ✓ Selections of Chandra sources based on spectral constraints and optical (GAIA) counterparts
- ✓ Sample of about **300 sources** matching synthetic MSPs properties

MW follow-up of promising sources

Conclusions & Outlook

- ✓ 10 years of Fermi-LAT data lead to a better comprehension of **point-like source populations** (catalogs and diffuse emission) and **large-scale diffuse emissions**
- ✓ Discovery of **unexpected and exciting gamma-ray features anomalies**: Fermi bubbles and GeV excess
- ✓ Improved characterisation the **GeV excess** (spectrum and morphology) which seems to confirm its (at least partial) **stellar origin**, but no conclusive determination of its nature from gamma-ray only observations
- ✓ Evidence for unresolved point source population hypothesis may come from **multi-messenger and multi-wavelength searches** (from radio to GW), and complementary constraints on its dark matter interpretation will be set by **dwarf galaxies** and **antiproton** fluxes

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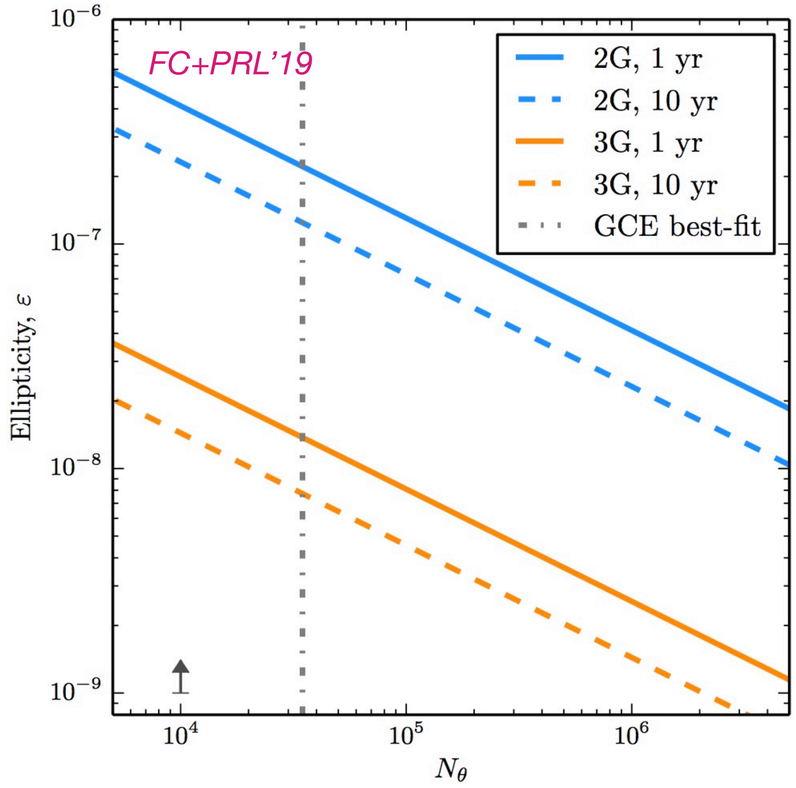
- ✓ Discovery of **unexpected and exciting gamma-ray features anomalies**: Fermi bubbles and GeV excess
- ✓ Improved characterisation the **GeV excess** (spectrum and morphology) which seems to confirm its (at least partial) **stellar origin**, but no conclusive determination of its nature from gamma-ray only observations
- ✓ Evidence for unresolved point source population hypothesis may come from **multi-messenger and multi-wavelength searches** (from radio to GW), and complementary constraints on its dark matter interpretation will be set by **dwarf galaxies** and **antiproton** fluxes

Thank you for the attention

Multi-messenger tests of the GeV excess

Gravitational waves: 3rd generation (Einstein telescope)



- ✓ Neutron stars high rotation velocities make any irregularity (ellipticity) in their shape a **quadrupolar source of GWs**
- ✓ A **population of MSPs in the bulge** represents the **dominant contribution to the stochastic GW background** in the LIGO/Virgo sensitivity range
- ✓ This search can provide **crucial diagnostics for the GeV excess nature**