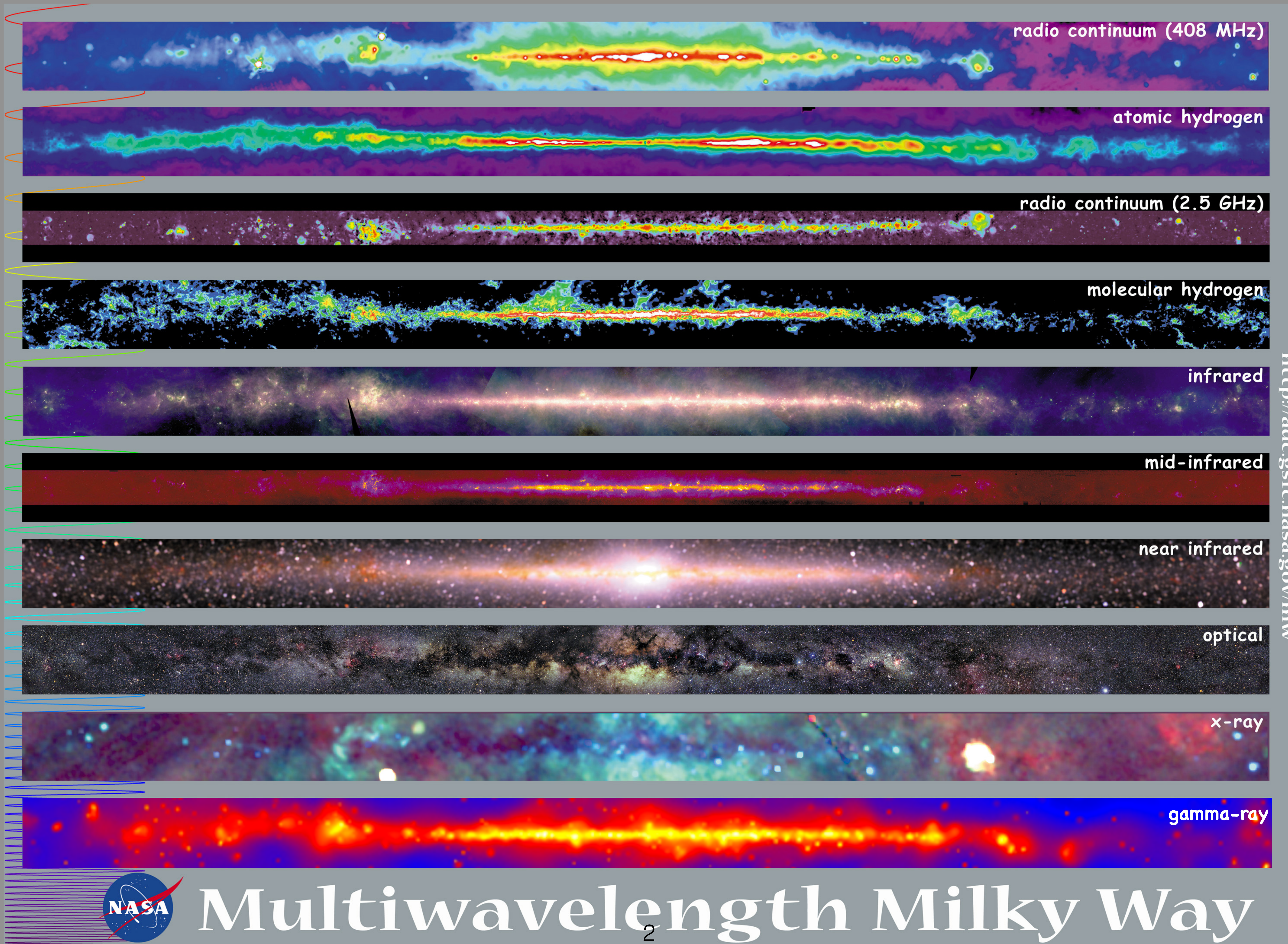
The GeV Excess: An Overview

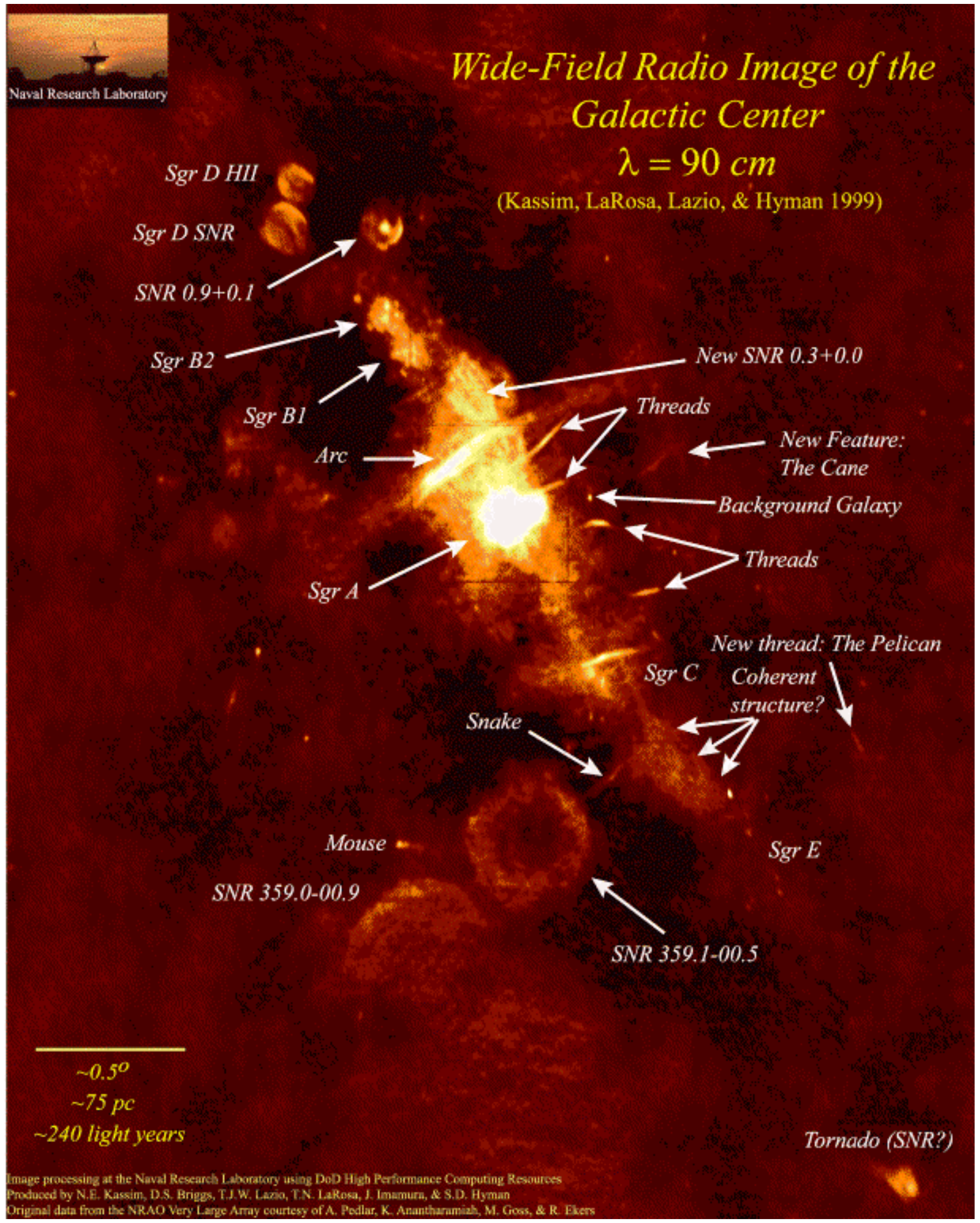
Francesca Calore

"Three Elephants in the gamma-ray sky"

Garmisch-Partenkirchen, 21/10/2017


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma-ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

The Galactic centre

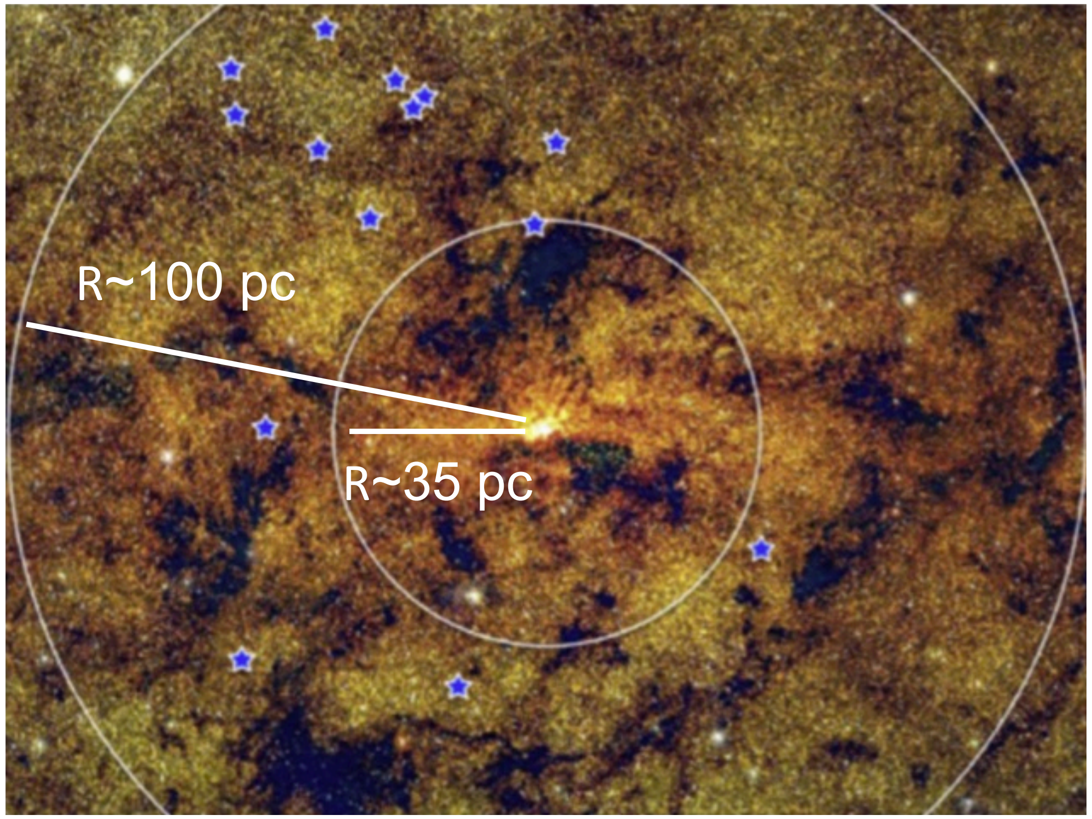


VLA image on the GC @ 90 cm — non-thermal and thermal radio filaments and SNRs —

In the central few parsecs of the Milky Way we find the Nuclear Gas Ring, the Nuclear Stellar Cluster, and the supermassive black hole Sagittarius A*

RRLyrae type ab star from the VVV near-infrared survey — Nuclear Stellar Cluster and Nuclear Bulge —

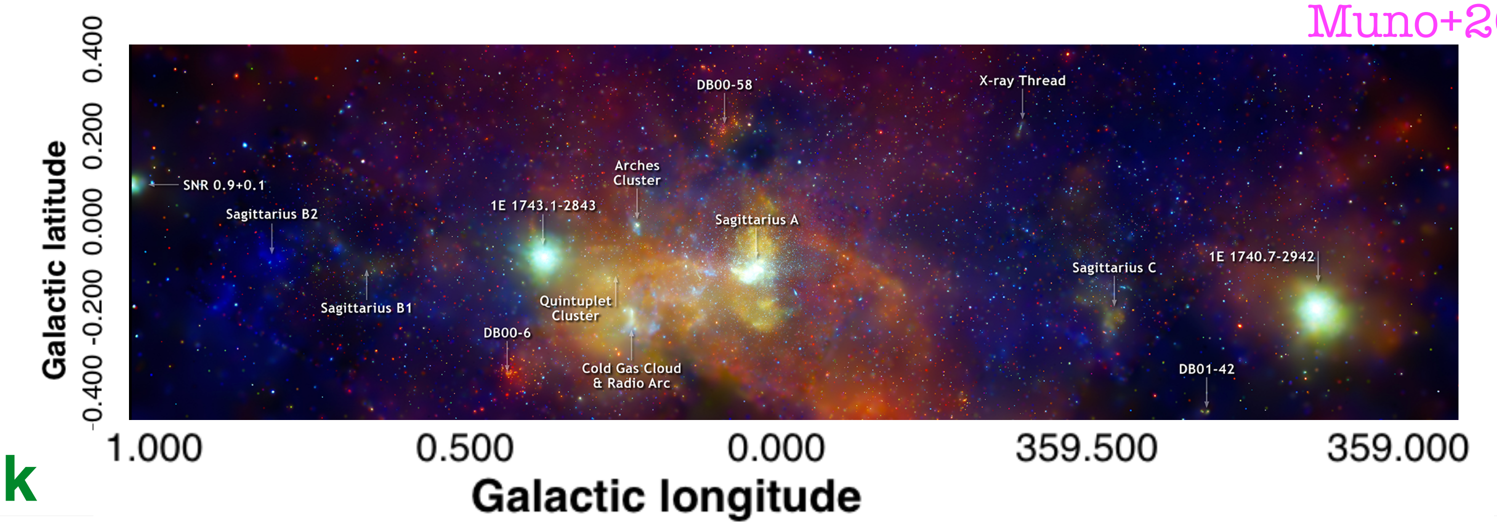
Minniti+2016



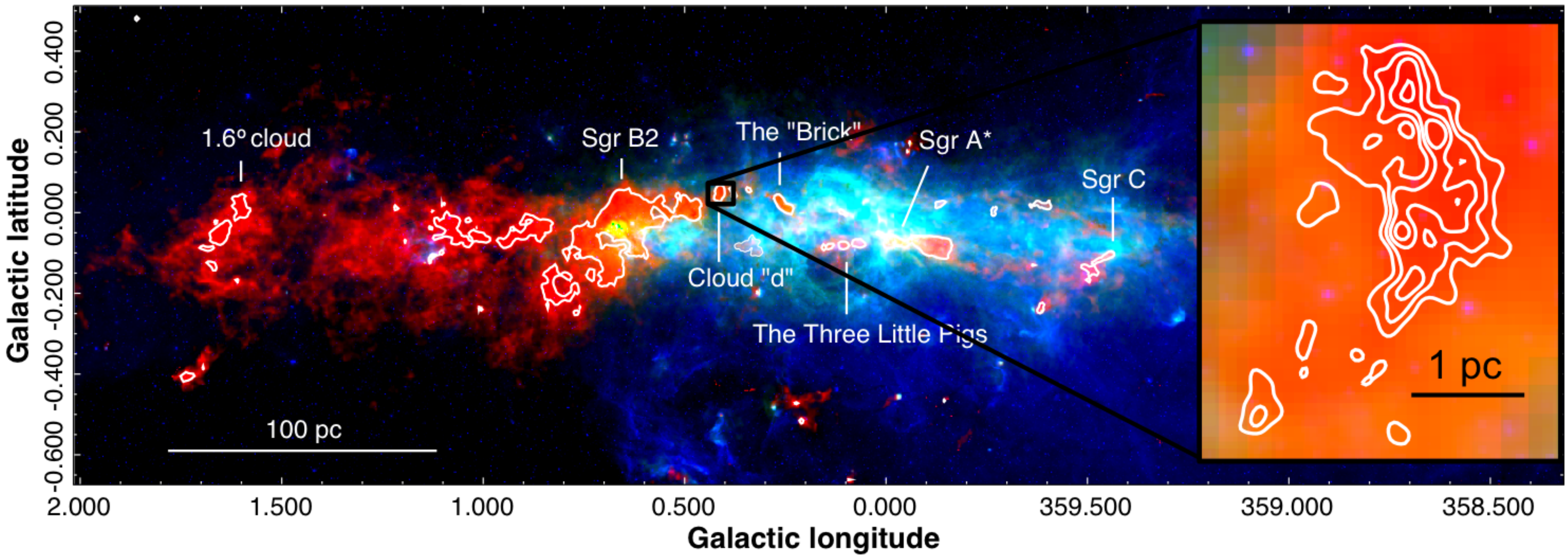
The Galactic centre

Chandra X-ray image of the GC: diffuse bkg, filaments, thousands of point-like sources

Muno+2006, Jonston+2006



S. Longmore's talk

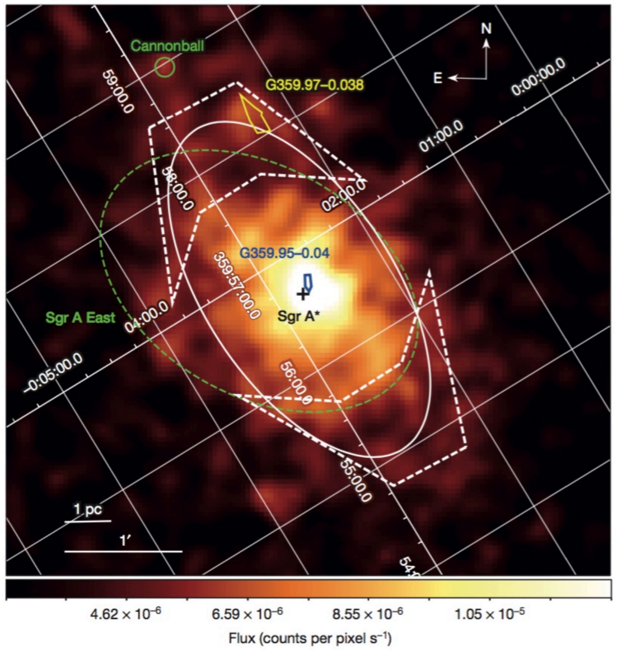


Infrared and multi-wavelength image of the **Central Molecular Zone**: dense gas, warm and cold dust, molecular clouds and massive starforming clusters

Battersby+

Some gamma-ray anomalies in the GC region

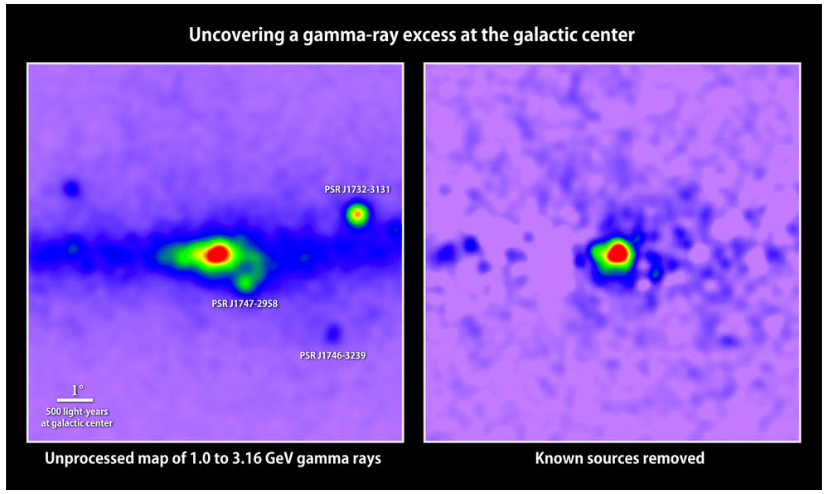
Perez+Nature'15



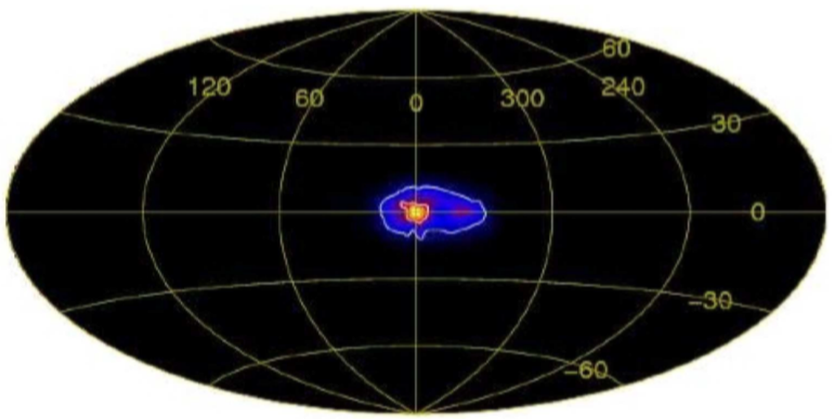
X-ray @ 20-40 keV
NuSTAR
hard diffuse excess emission

Gamma-ray @ few GeV
Fermi-LAT
Fermi GeV excess

Daylan+PRD'16



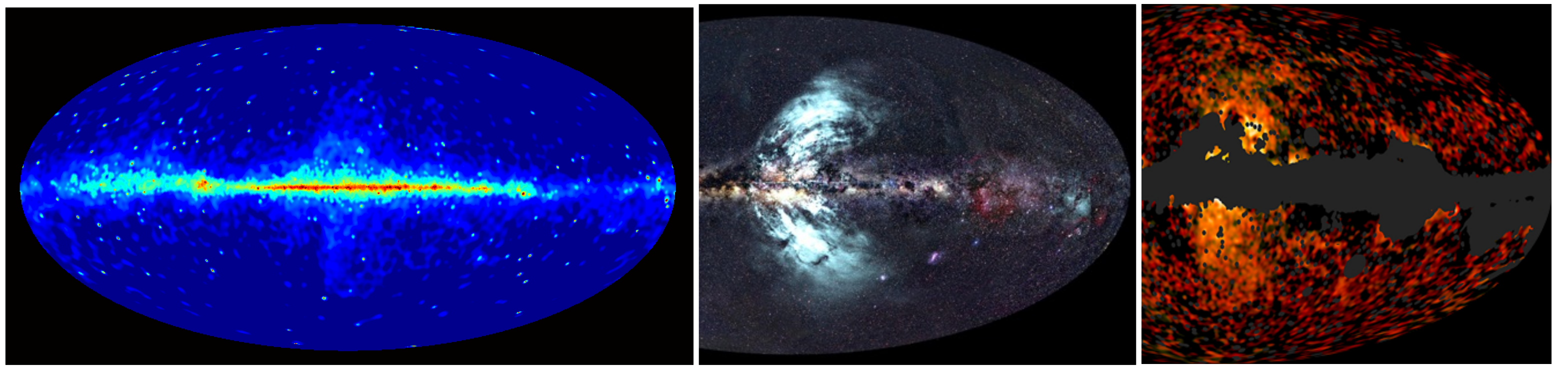
F. H. Panther's talk



Gamma-ray @ 511 keV
INTEGRAL/SPI
Positron annihilation line

Purcell+'93,'97; Knödlseder+'03,'05

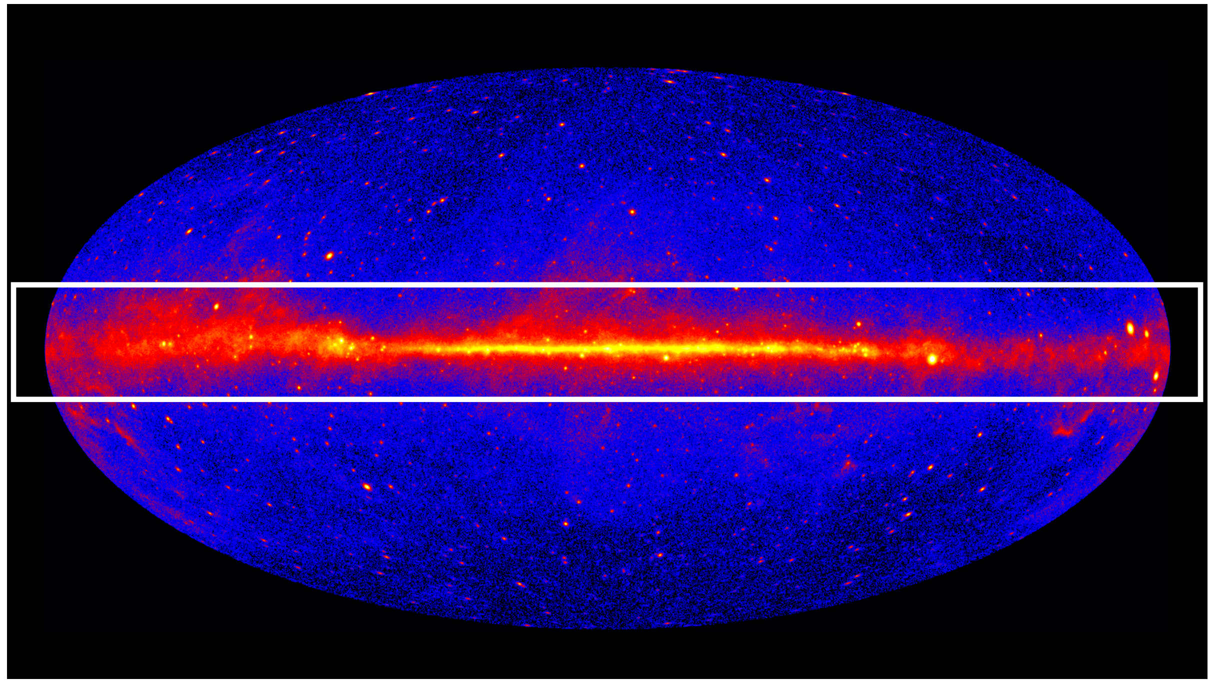
Su+'10; Fermi-LAT Collab'14; Carretti+'13; Planck Collab.'13



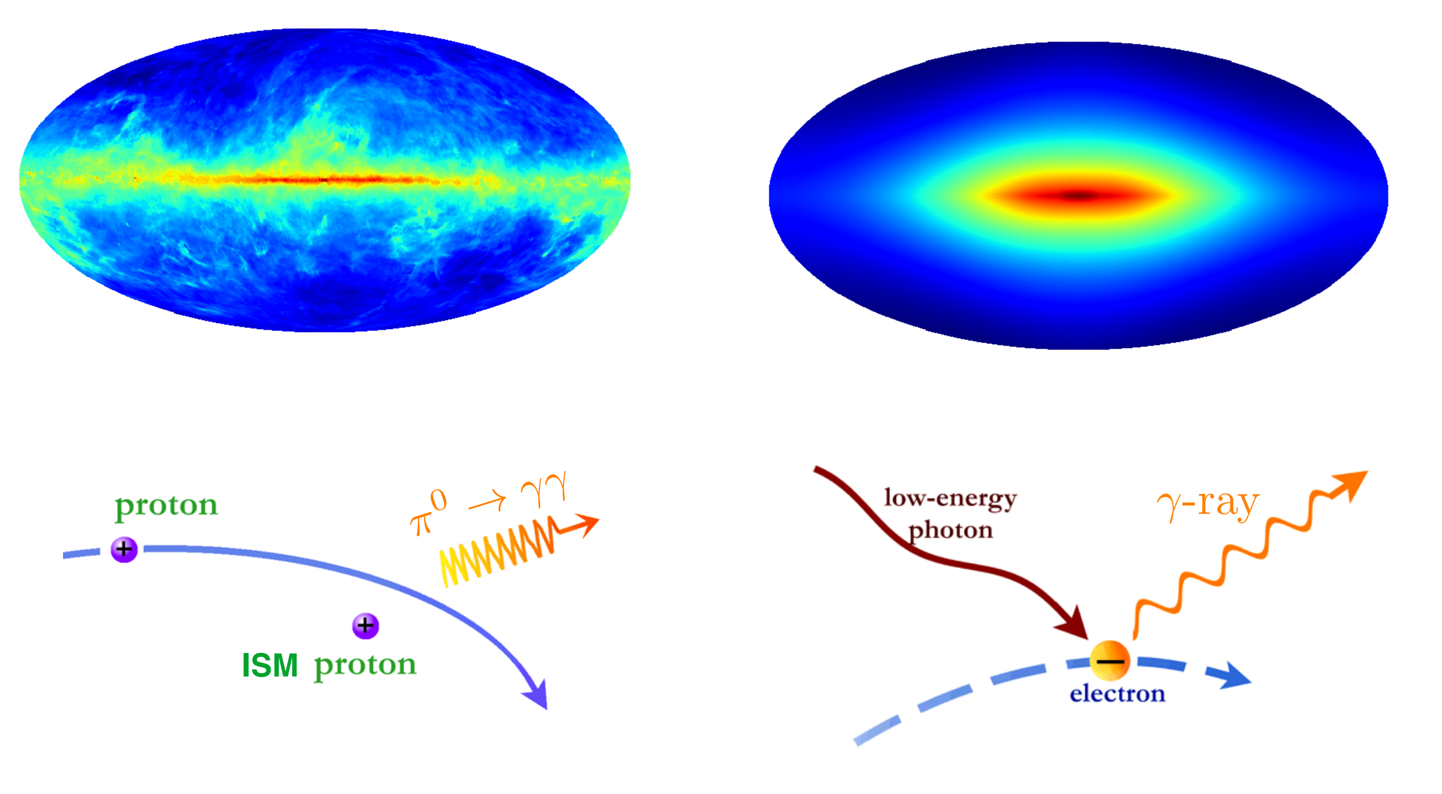
Gamma-ray @ hundreds GeV
Fermi-LAT
Fermi bubbles, and their **radio/ microwave** conterparts
T. Slatyers's talk

Excesses extended far beyond central CMZ and nuclear bulge
=> Relevance of propagation effects? Relantionship with GC accelerators?

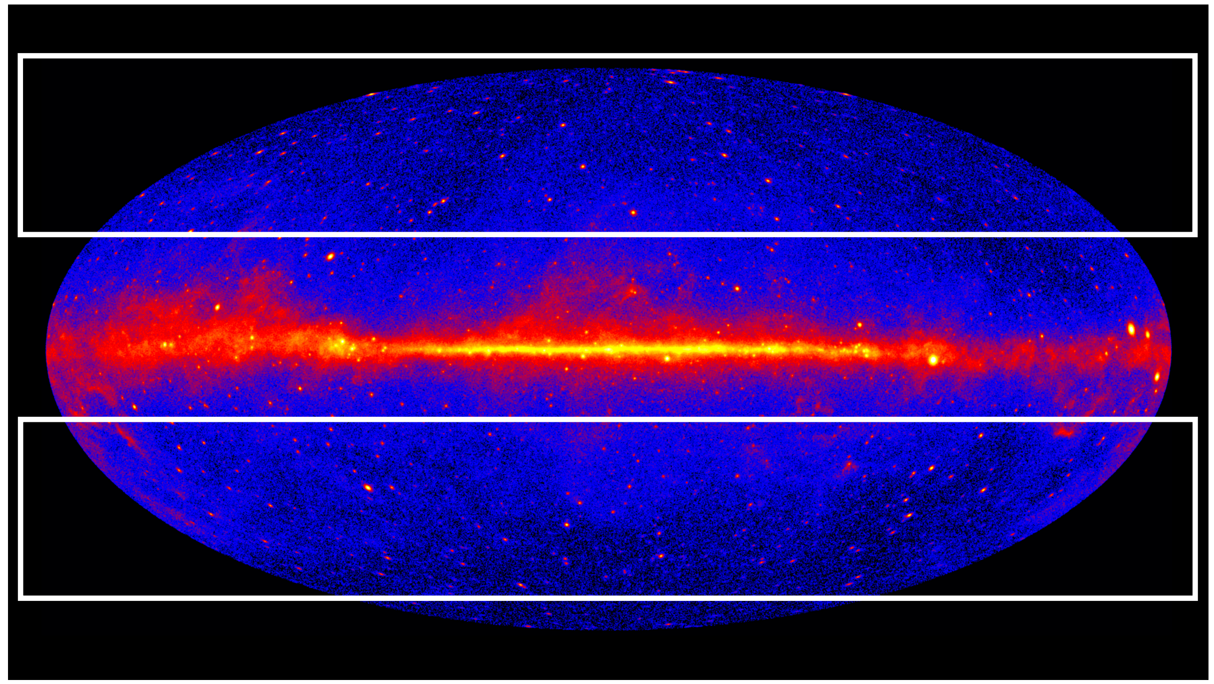
Modelling the gamma-ray sky



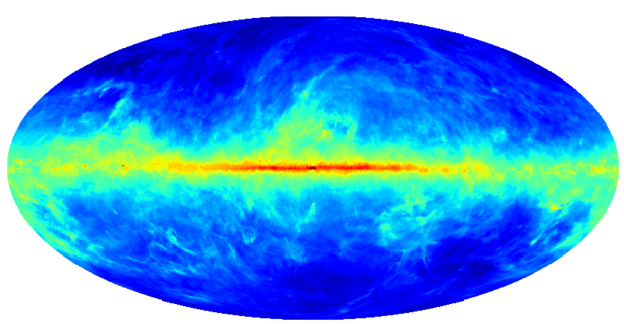
Galactic diffuse emission

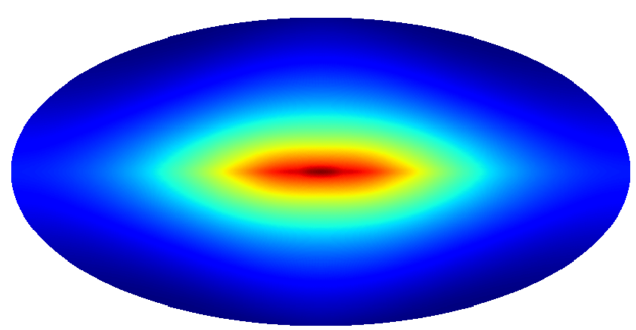


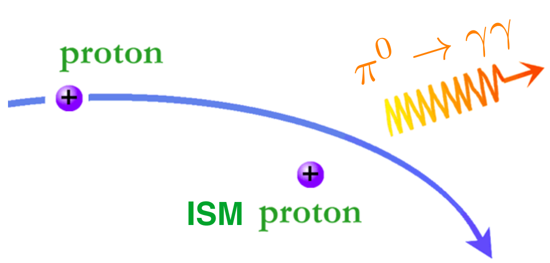
Modelling the gamma-ray sky

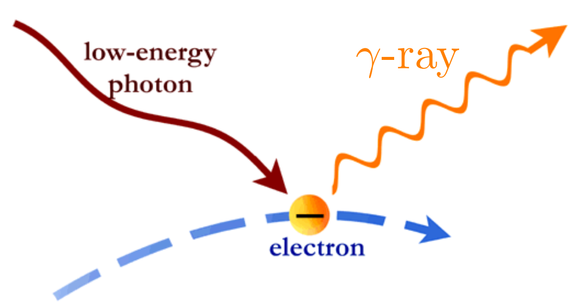


Galactic diffuse emission

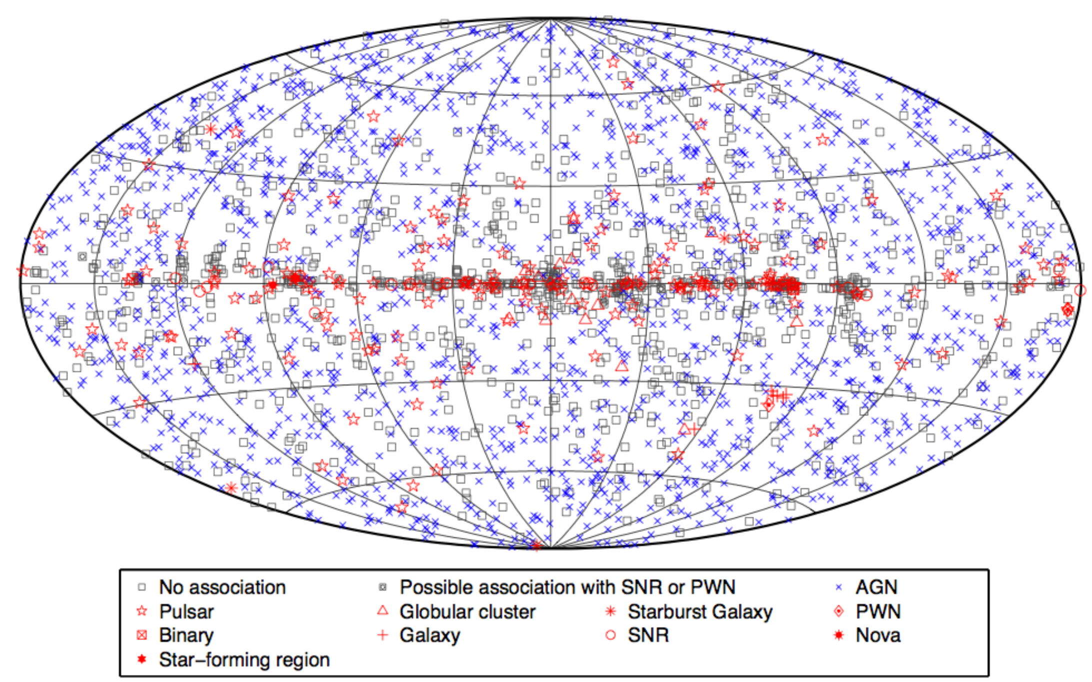


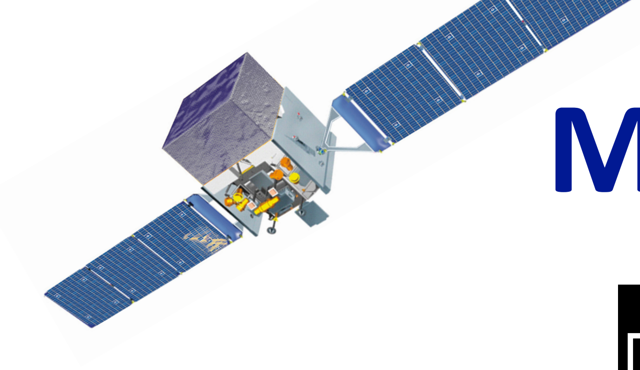




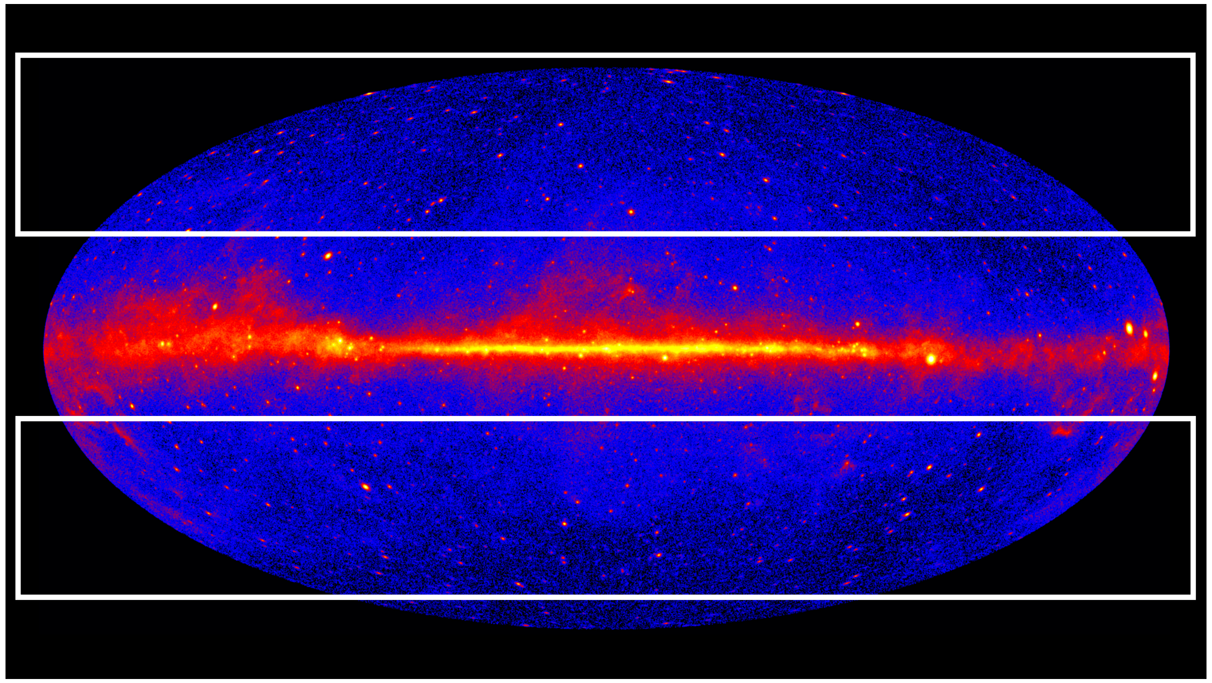


Detected point sources



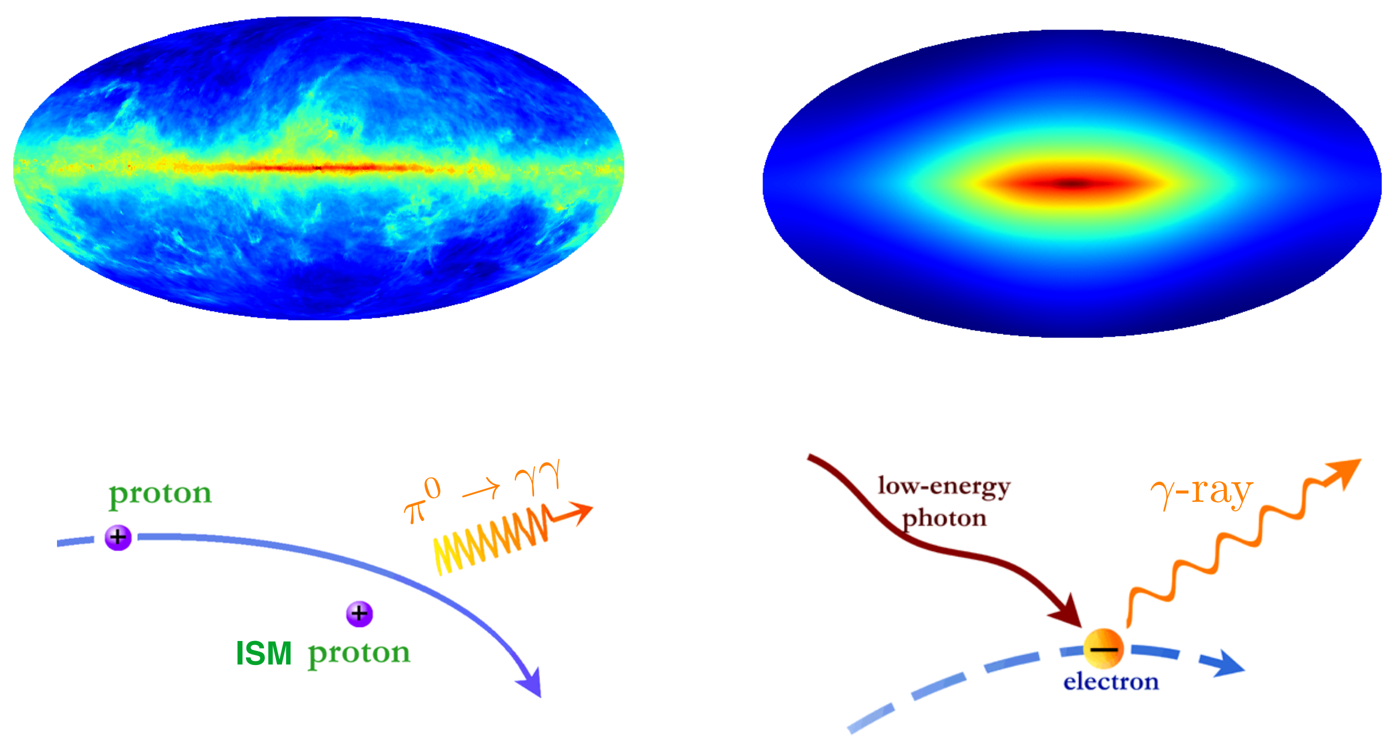


Modelling the gamma-ray sky

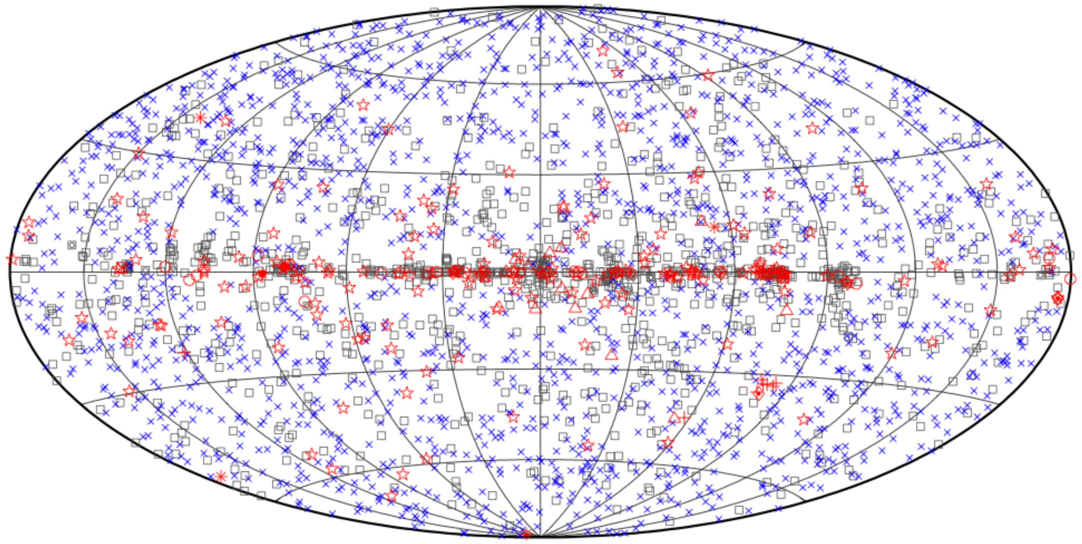
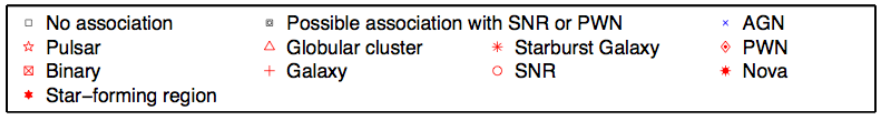


- + Isotropic diffuse background
- + Fermi bubbles
- + Loop I

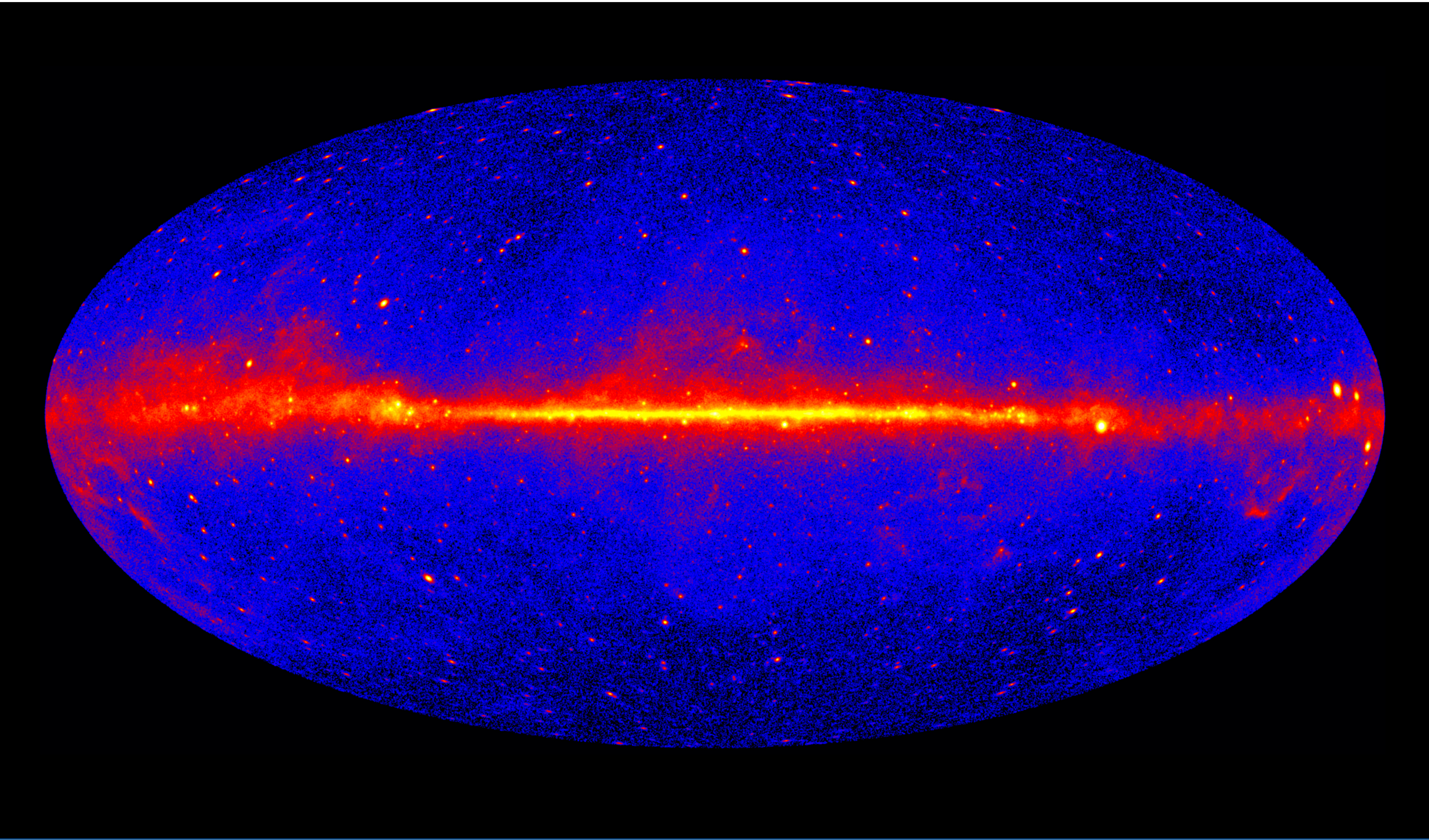
Galactic diffuse emission



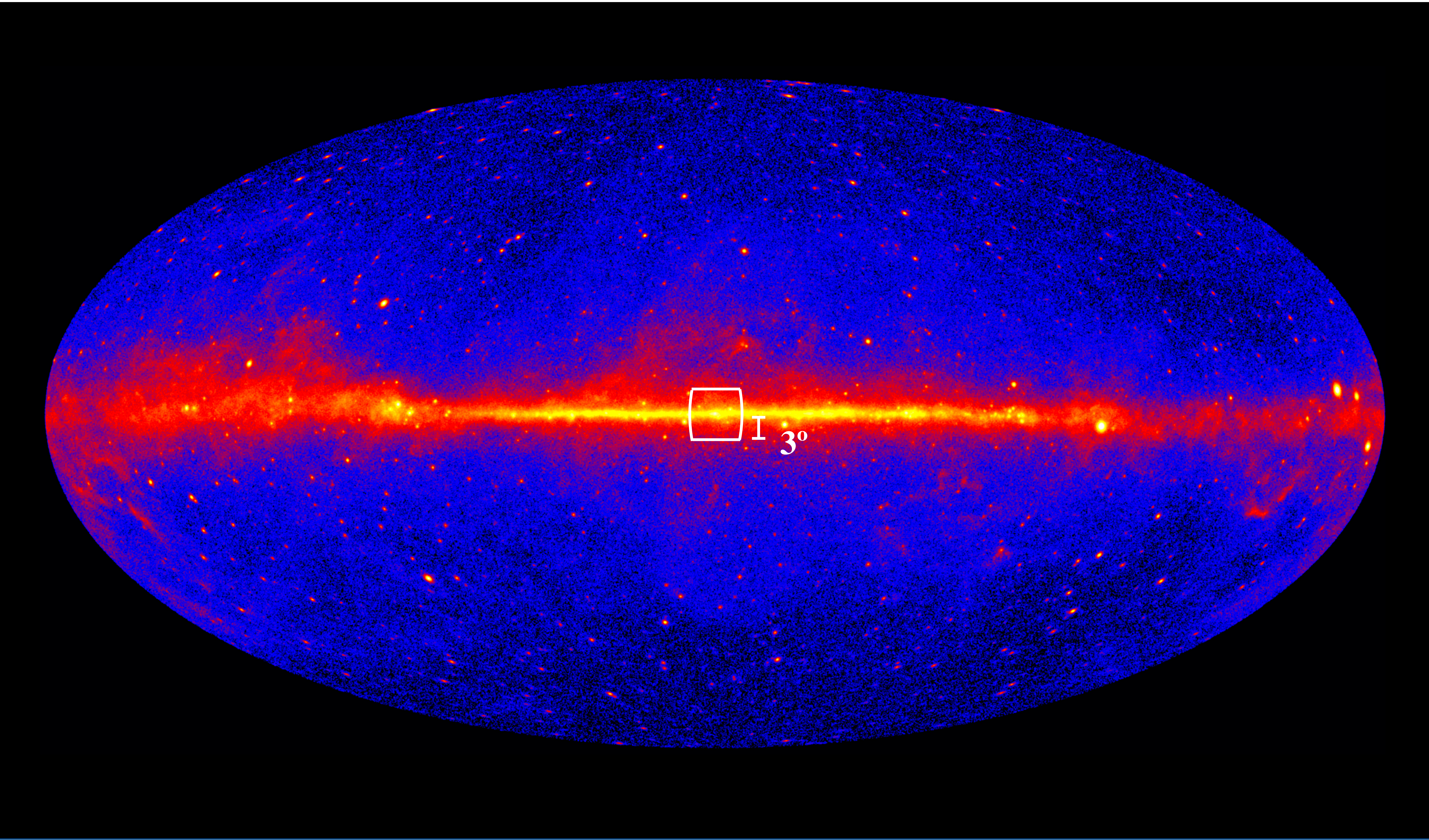
Detected point sources

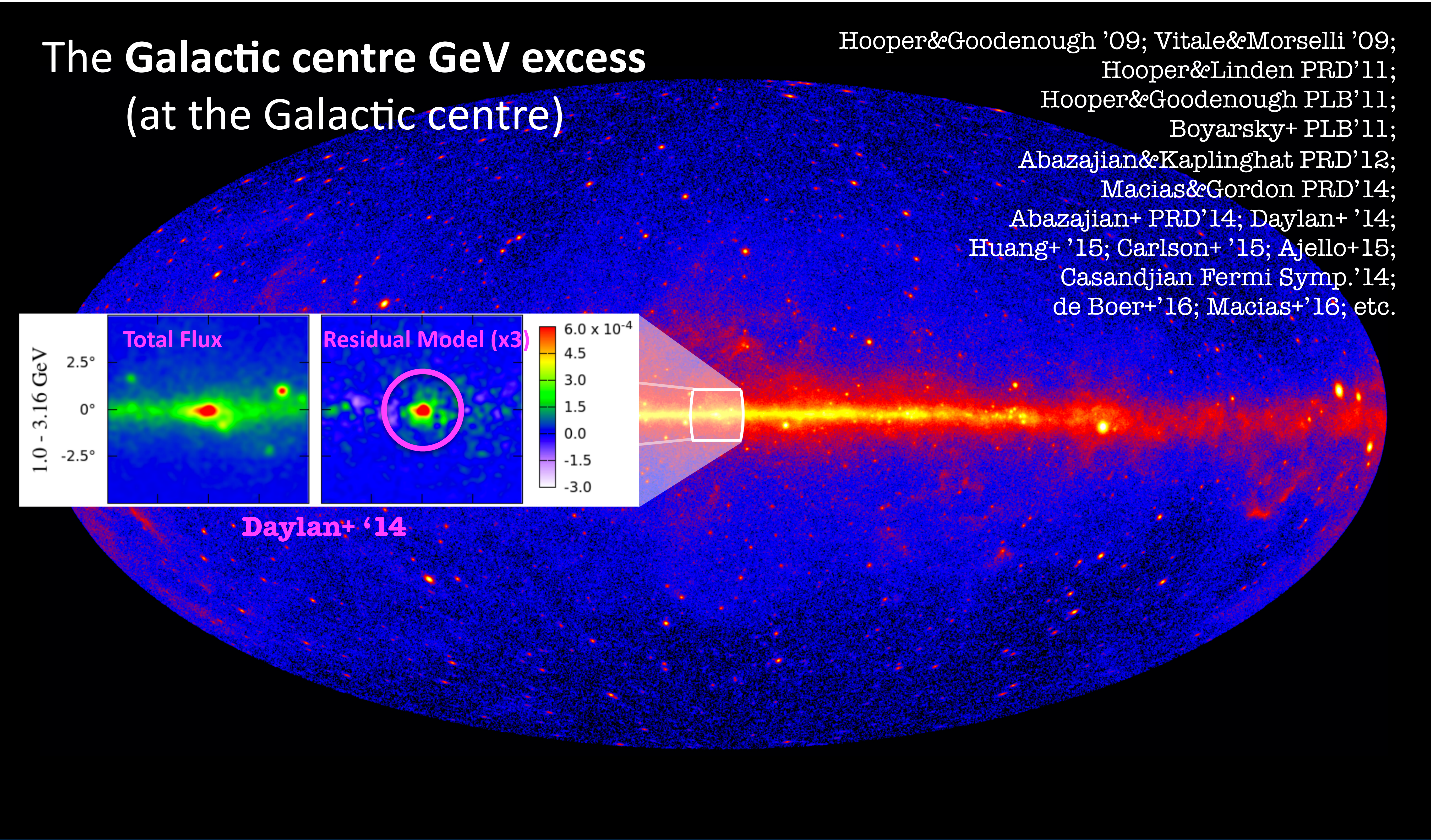
The Galactic centre GeV excess



The Galactic centre GeV excess

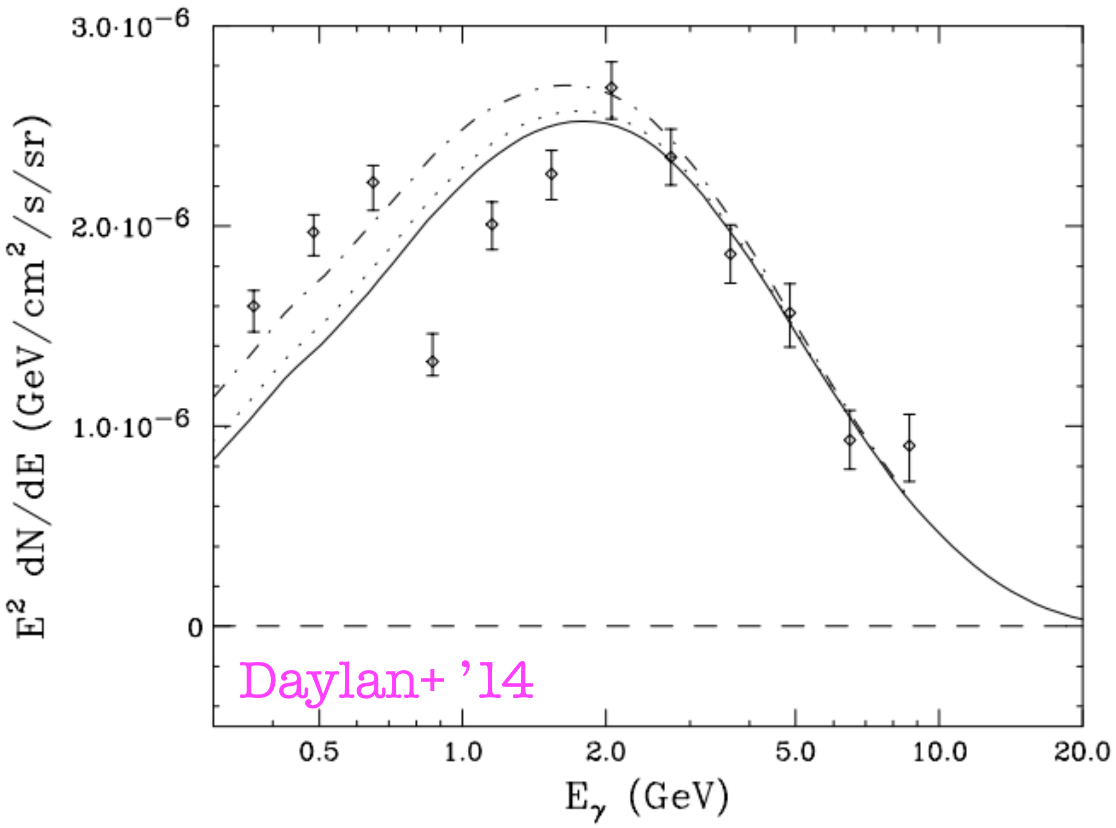


The Galactic centre GeV excess

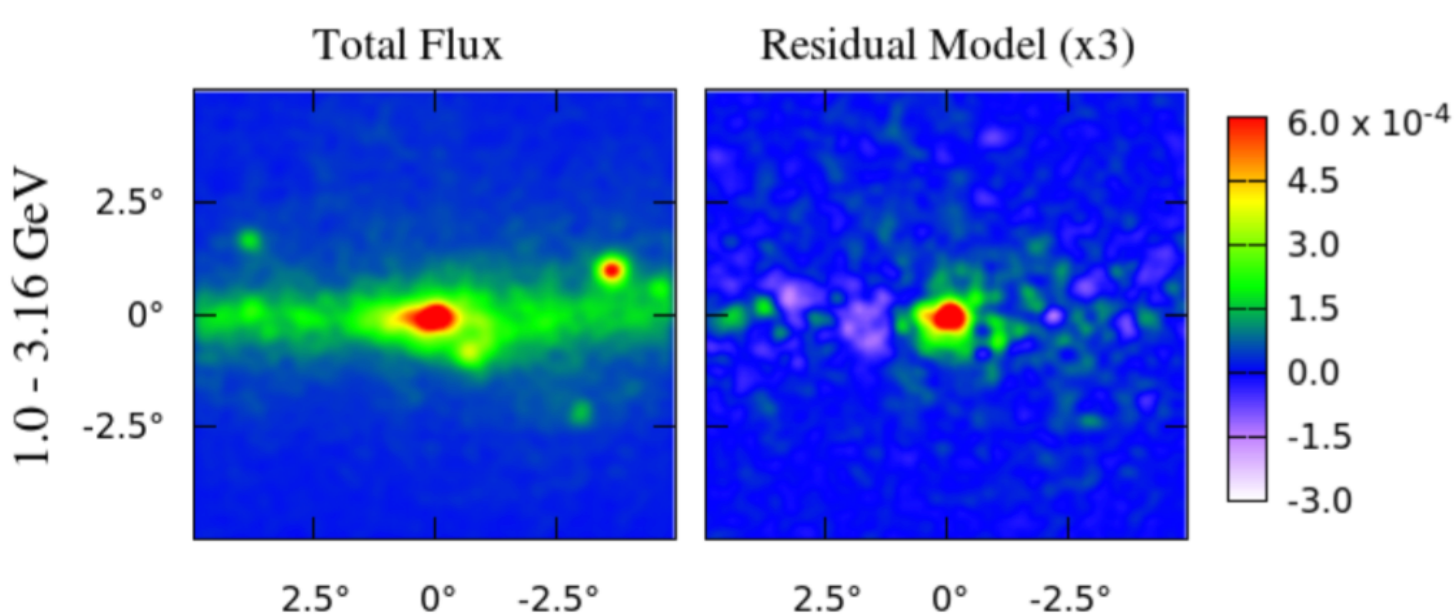


The GeV excess at the Galactic centre

Spectrum



Morphology



$$|\ell|, |b| \lesssim 2^\circ$$

- ✓ **Extended excess emission** above: model for diffuse emission, Sgr A* and other point sources.
- ✓ The **spectrum** might strongly suffer from **background modeling**.

Abazjian+ PRD'14

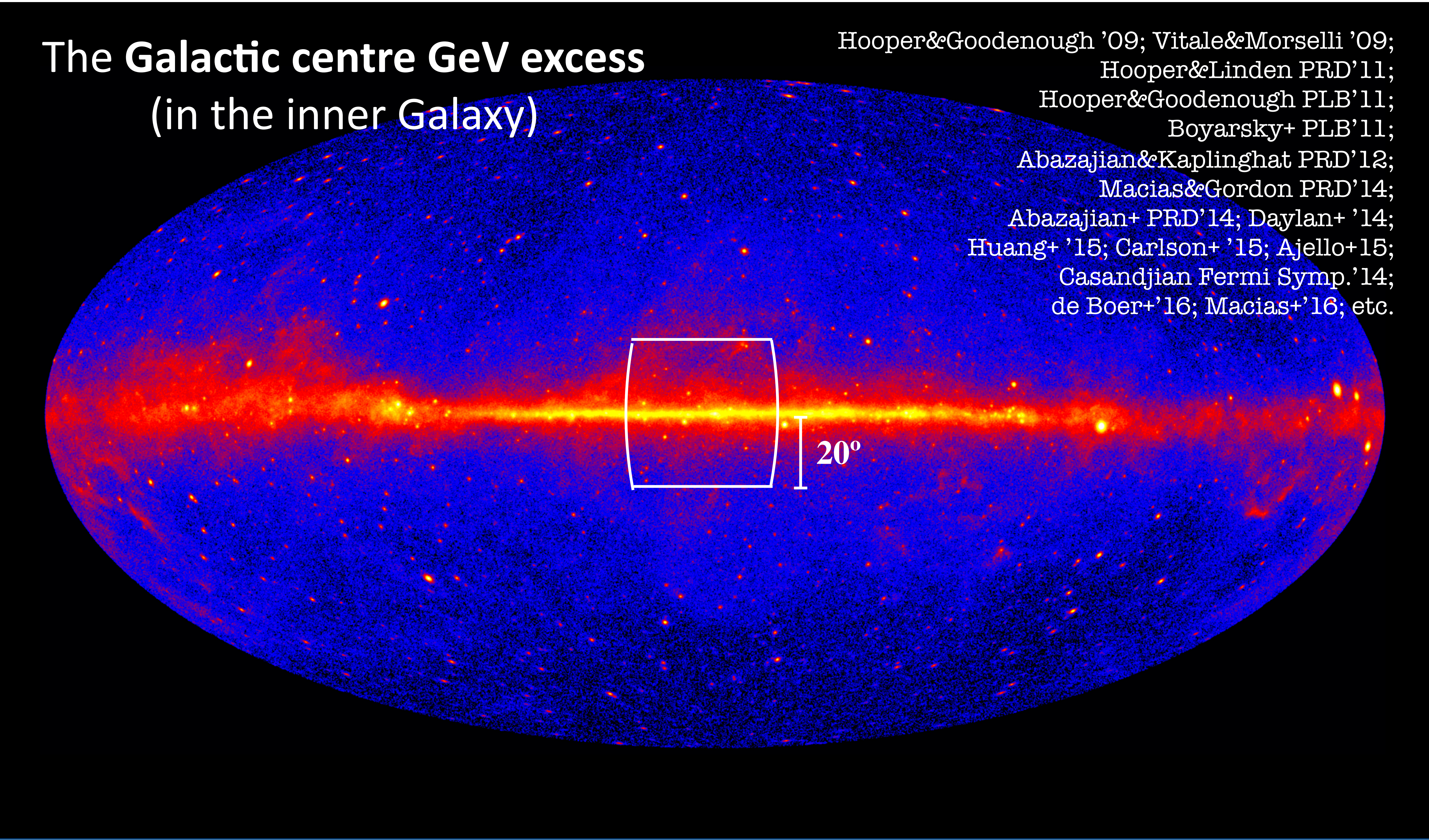
- ✓ Compatible to be **spherically symmetric** about the Galactic centre.
- ✓ Emission profile:

$$\frac{dn}{dV} \sim r^{-\Gamma} \qquad \Gamma \sim 2.6$$

- ✓ Connection with HESS TeV GC ridge.

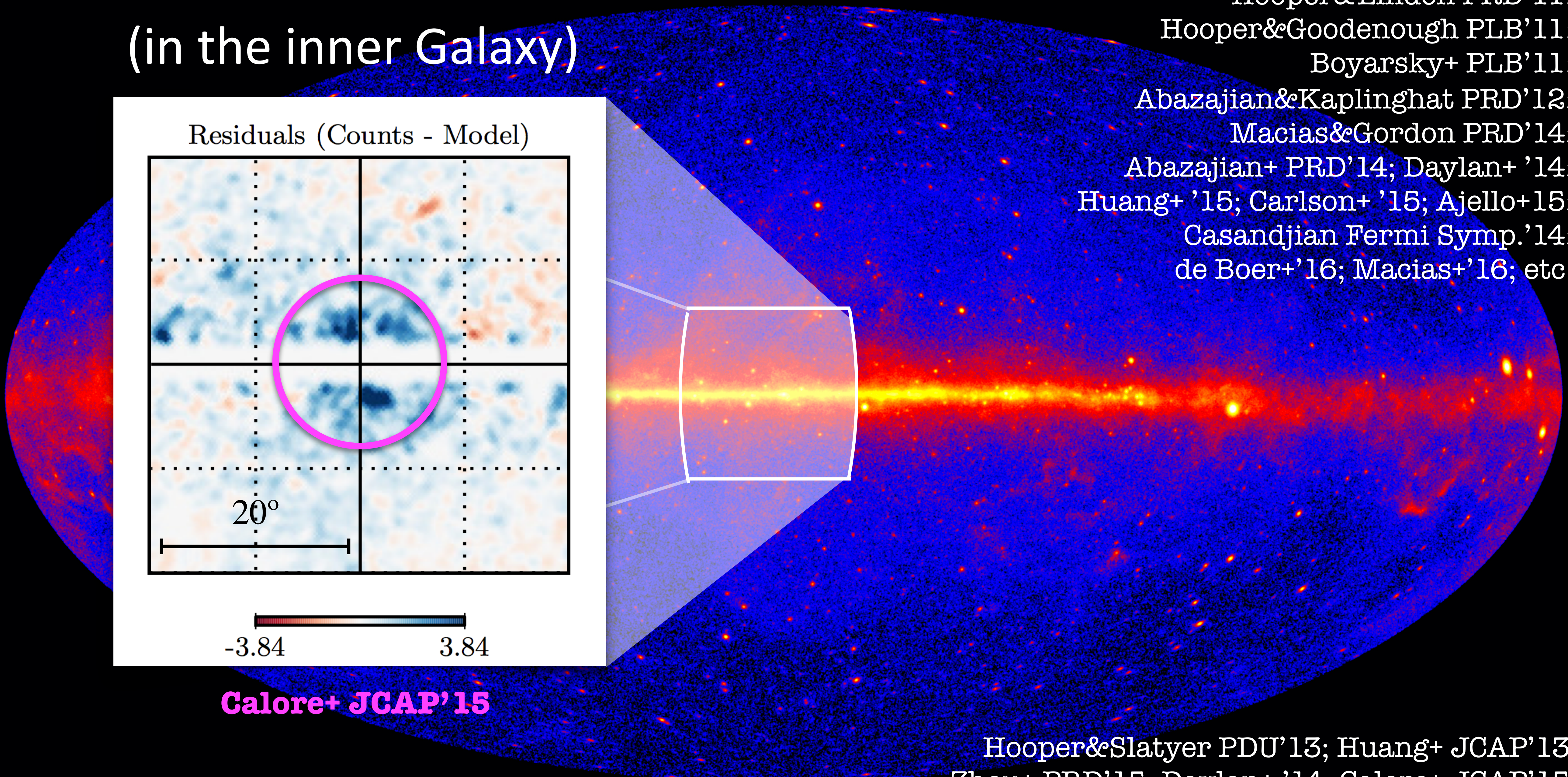
Macias&Gordon'14; Macias+'14

The Galactic centre GeV excess



The Galactic centre GeV excess

The **Galactic centre GeV excess**
(in the inner Galaxy)



Calore+ JCAP'15

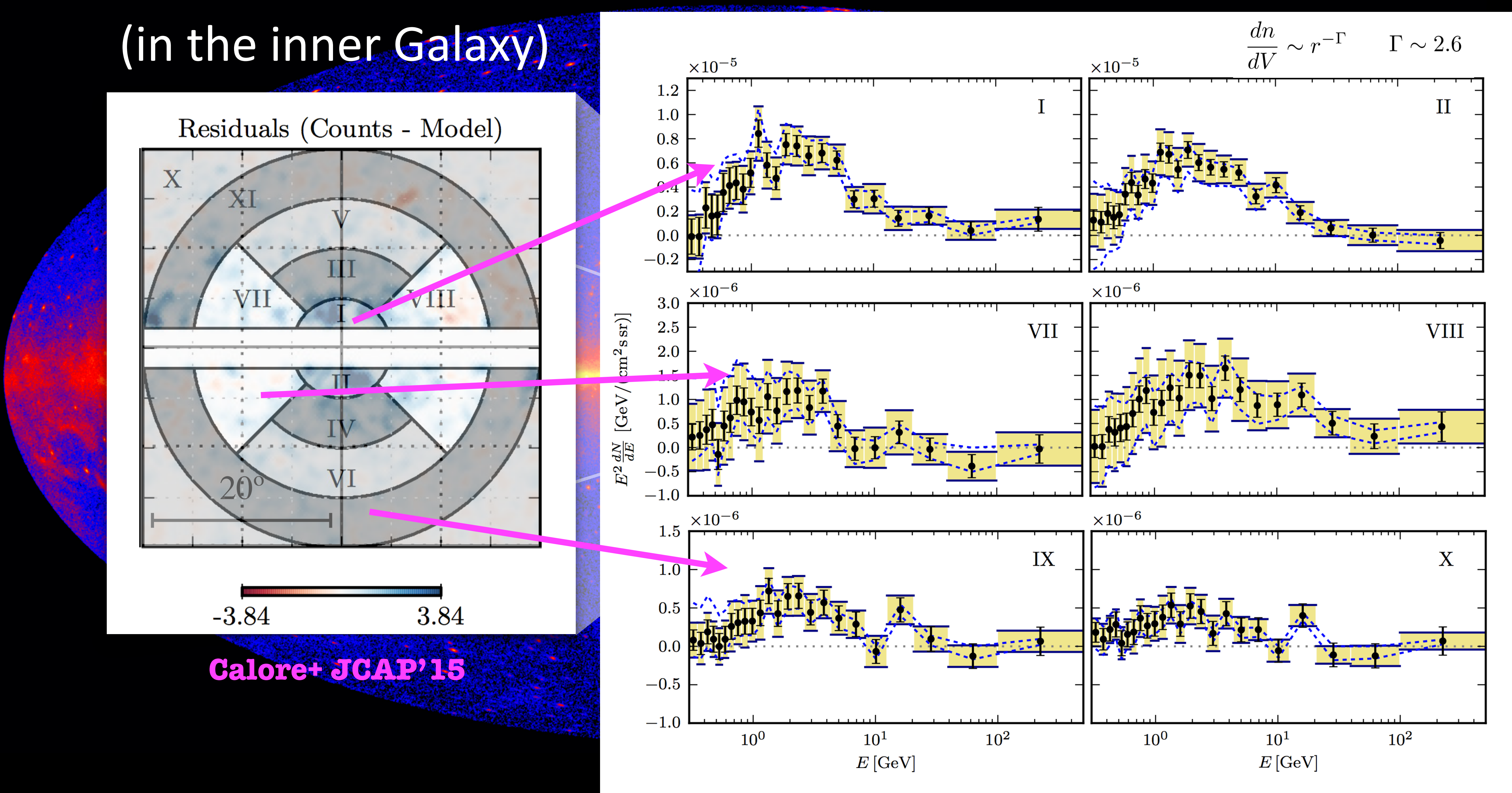
Hooper&Goodenough '09; Vitale&Morselli '09;
Hooper&Linden PRD'11;
Hooper&Goodenough PLB'11;
Boyarsky+ PLB'11;
Abazajian&Kaplinghat PRD'12;
Macias&Gordon PRD'14;
Abazajian+ PRD'14; Daylan+ '14;
Huang+ '15; Carlson+ '15; Ajello+15;
Casandjian Fermi Symp.'14;
de Boer+'16; Macias+'16; etc.

Hooper&Slatyer PDU'13; Huang+ JCAP'13;
Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15;
Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15
Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; etc.

The Galactic centre GeV excess

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

The **Galactic centre GeV excess**
(in the inner Galaxy)



General: Fit to gamma-ray data

$$\mathsf{Model} = \sum_k \mathsf{Spectrum} \times \mathsf{Morphology}$$

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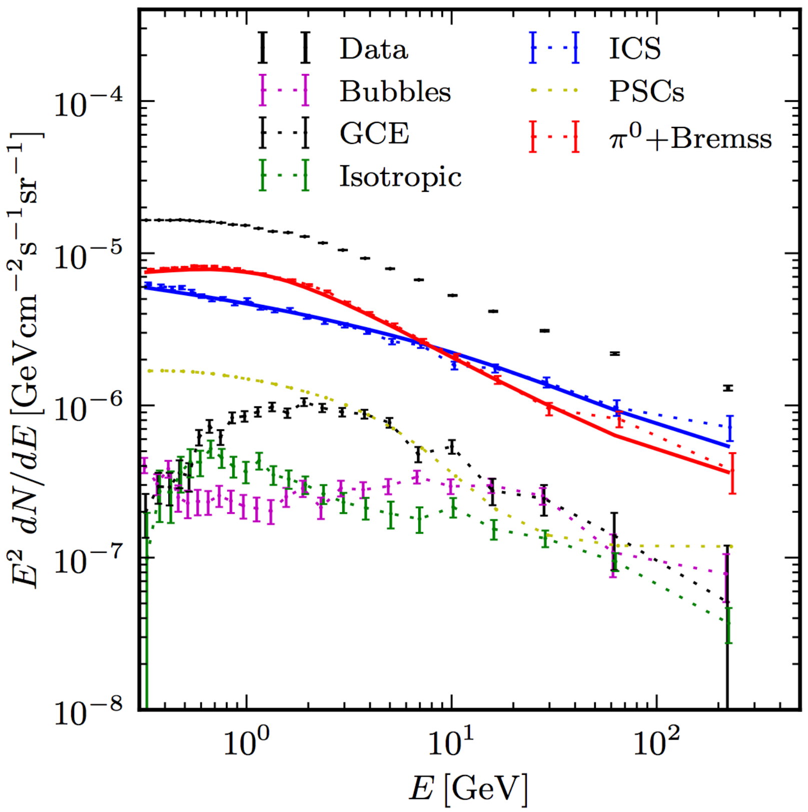
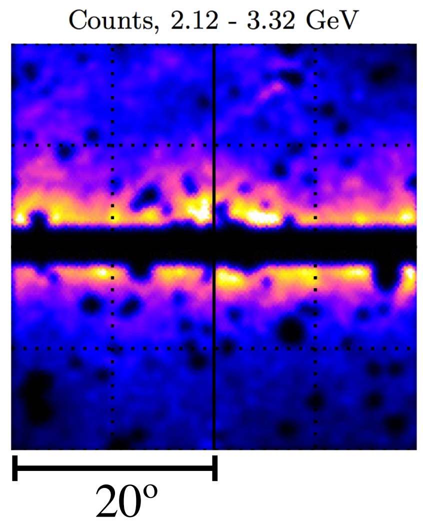


$$\phi_{pb} = \sum_k T_p^{(k)} \sigma_b^{(k)}$$

k: model component
p: spatial pixel
b: energy bin

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

Standard template fitting

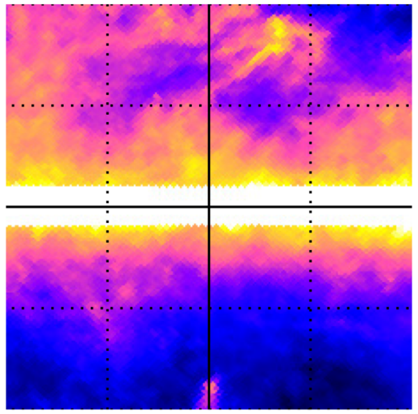


Data counts

$$k_{i,j}$$

Model counts

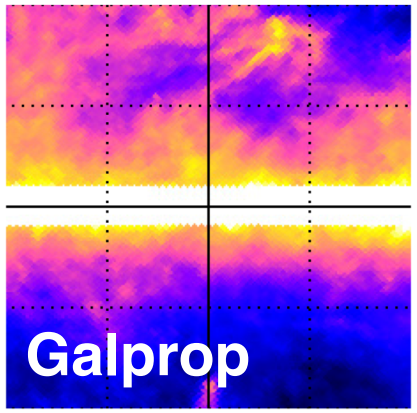
$$\mu_{i,j} = \sum_k \theta_{i,k}\mu_{i,j}^{(k)}$$



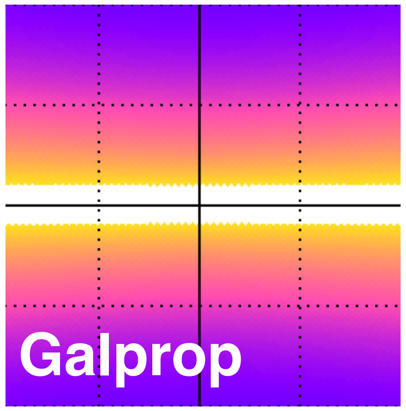
The (spatial) **template-fitting** method (maximum likelihood) → $\theta_{i,k}$

i^{th} energy

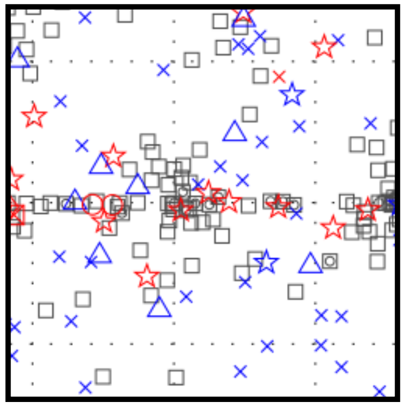
Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; Calore+ JCAP'15; Gaggero+ JCAP'15



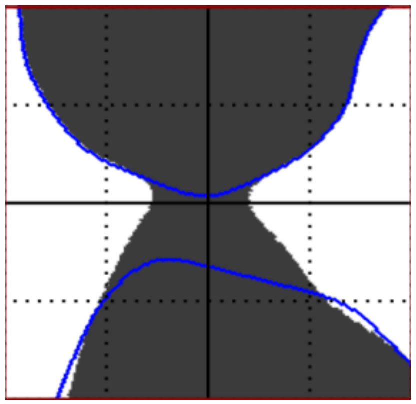
1. π^0 + Brems (free)



2. ICS (free)

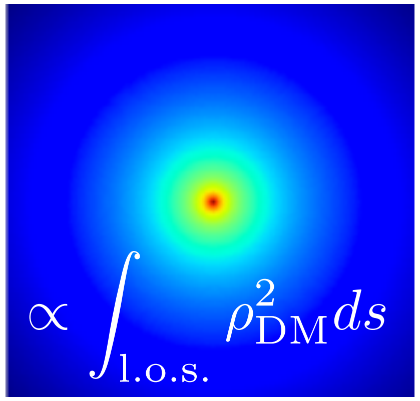


3. 2FGL (fixed)



4. Fermi bubbles (constrained)

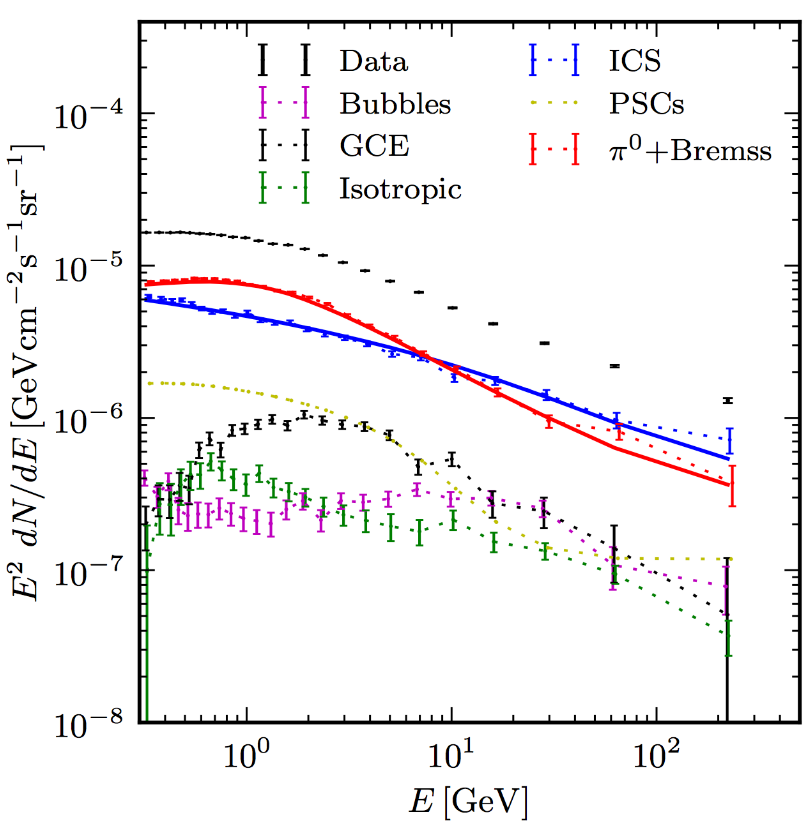
5. Isotropic diffuse bkg (constrained)



6. GeV excess template (free)

General: Fit to gamma-ray data

$$\text{Model} = \sum_k \text{Spectrum} \times \text{Morphology}$$



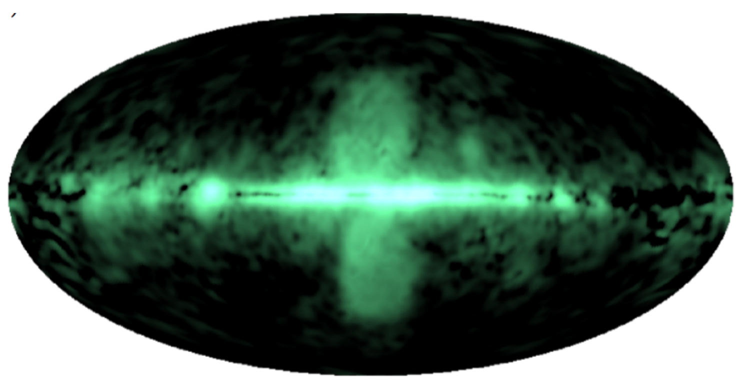
$$\phi_{pb} = \sum_k T_p^{(k)} \sigma_b^{(k)}$$

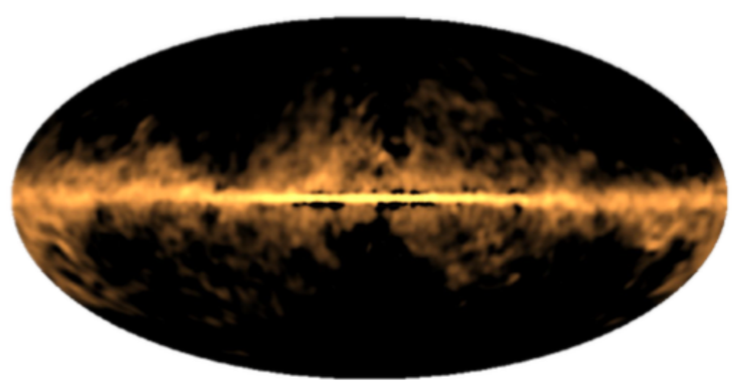
k: model component
p: spatial pixel
b: energy bin

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

$$\phi_{pb} = \sum_k S_b^{(k)} \tau_p^{(k)}$$

k: model component
p: spatial pixel
b: energy bin



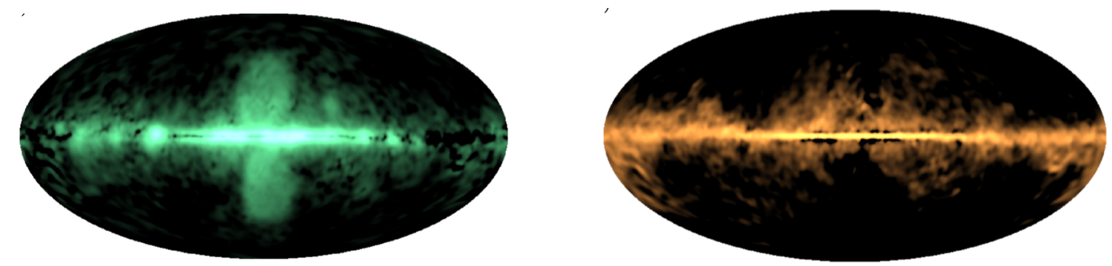


Selig+ A&A'14; Huang+ JCAP'16; de Boer+'16

Spectral decomposition

Talks by T. Ensslin, X. Huang, and I. Gebauer

- GDE phenomenologically constructed 2-component model: **bubble-like** & **cloud-like** (90% emission).
- Faint point-sources accounted for.



D3PO – Selig+ A&A'14

Pixel-wise maximum likelihood decomposition → $\theta_{i,k}$

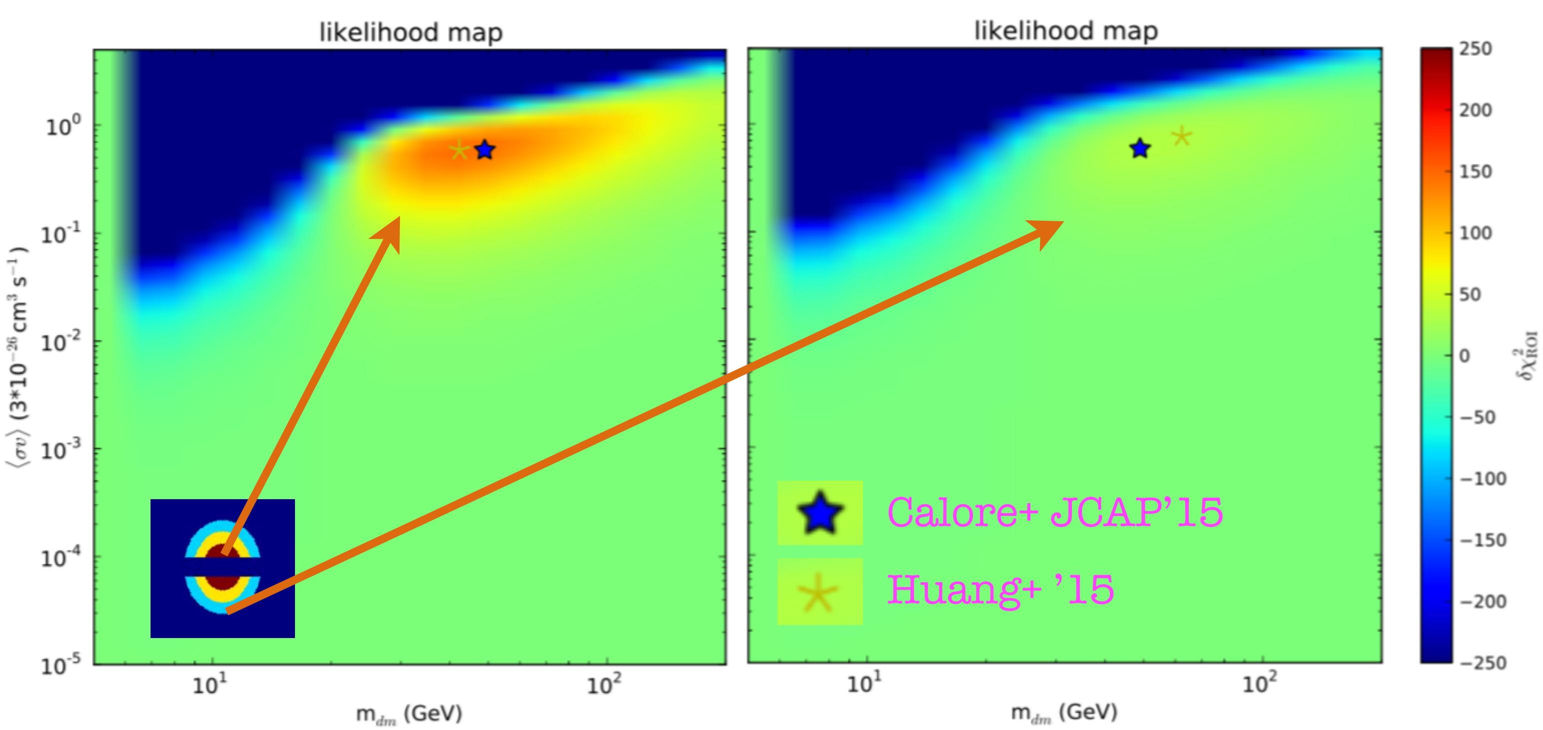
i[th] pixel

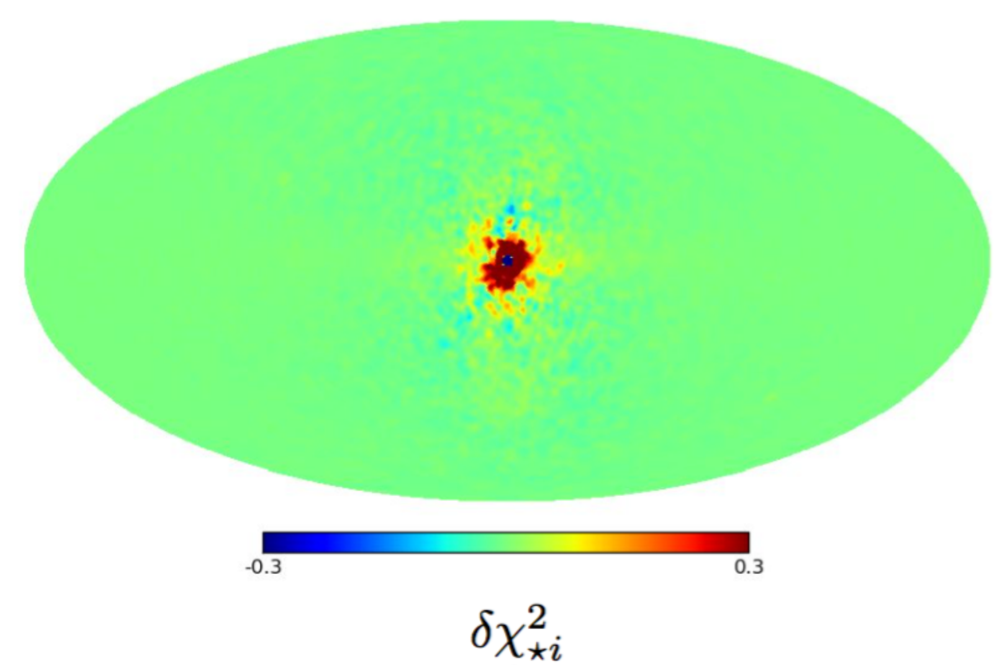
Huang+ '15

✓ Uniform and extended spectrum.

✓ Compatible with previous results.

✓ Spherically symmetric about the Galactic centre.





See also de Boer+'16

The Fermi-LAT Collaboration analysis

Ajello+ ApJ'15

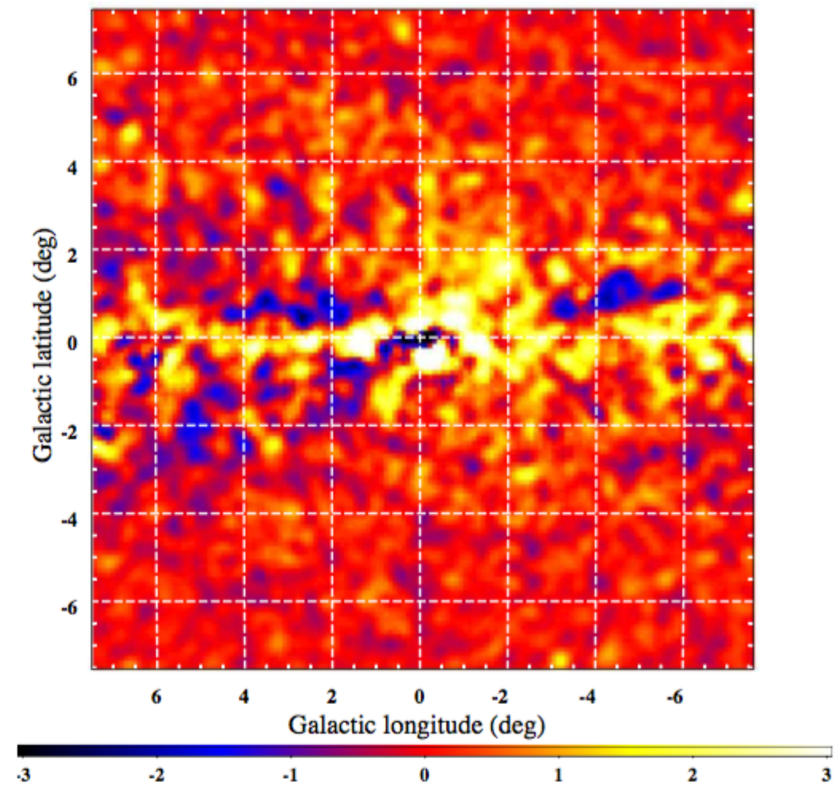
- 15° x 15° ROI; tuning of GDE outside → dedicated interstellar emission models.
- Wavelet transform for faint sources identification (1FIG catalog).

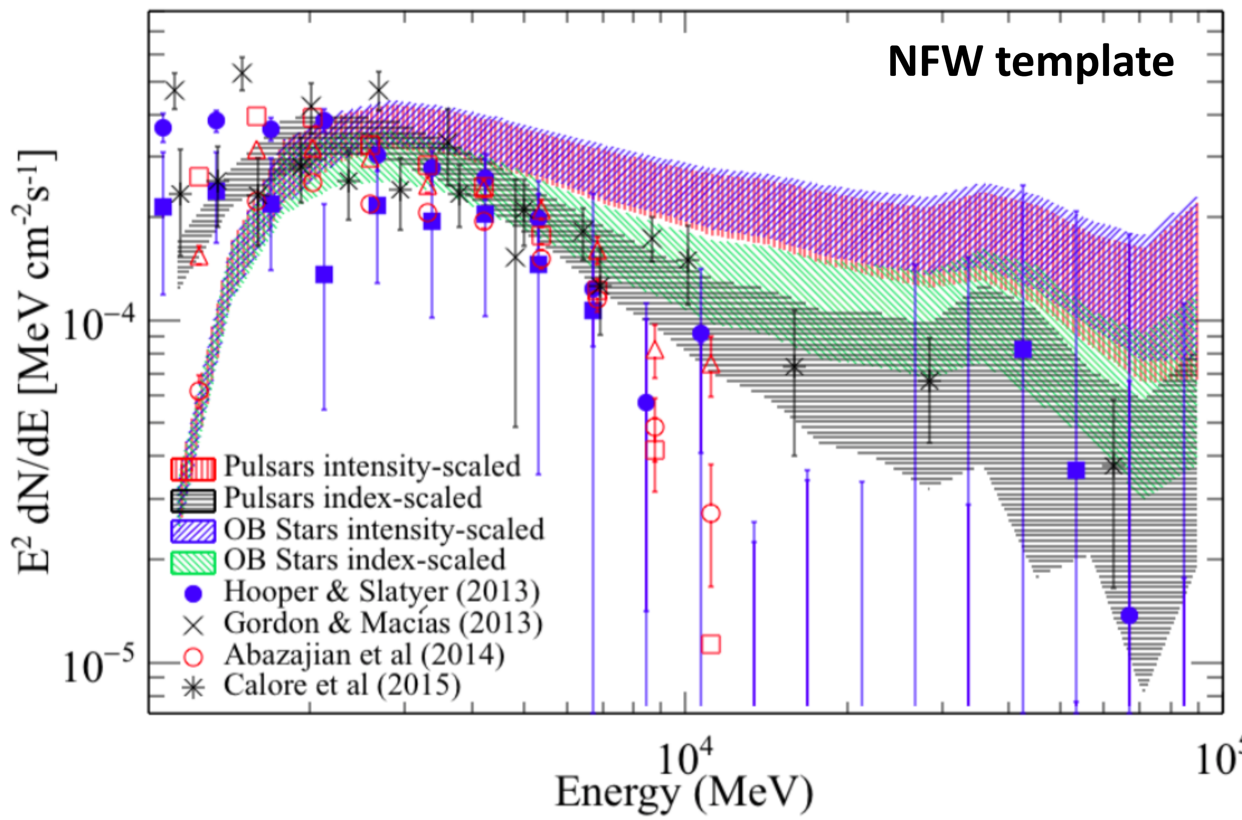
✓ **IC emission in inner 1 kpc enhanced** w.r.to baseline prediction (20% of the total GDE emission).

✓ Positive residuals are left and can be partially absorbed by an **additional centrally peaked spatial template**.

✓ **Not all positive residuals** are **accounted for** by such a model.

no NFW template





Talk by G. Johannesson (effect ISRF)

Some open questions and challenges

- ✓ Is the spectrum of the GeV excess truly uniform up to 10 degrees above and below the Galactic disc? Is it spherically symmetric or does it have some degree of elengation?

  Linden+ PRD'16, Macias+ 2016, Bartels, FC+17

- ✓ What is the effect of foreground model systematics on the GeV excess characterisation?

  Calore+ JCAP'15, Ackermann+ ApJ'17

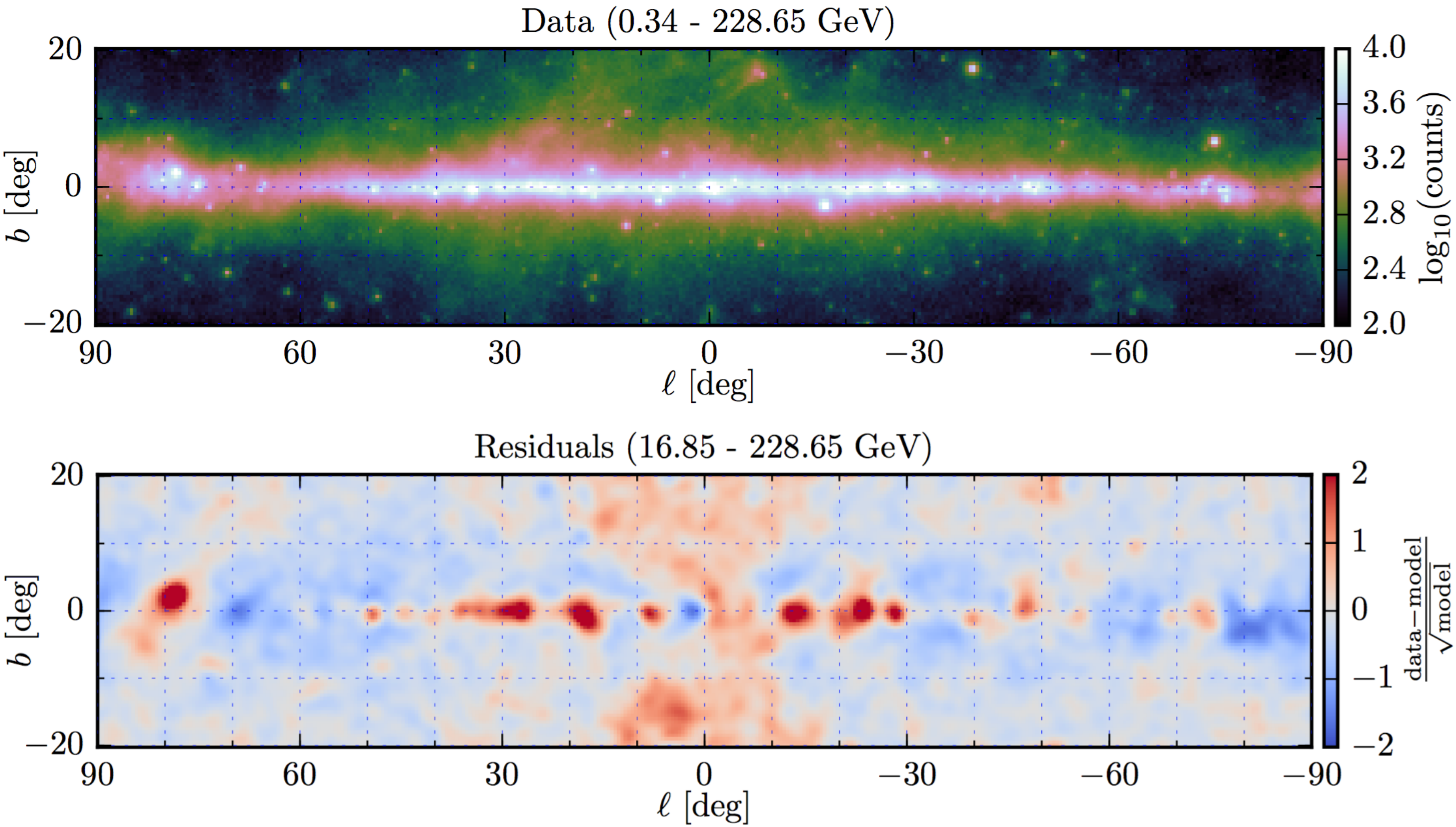
- ✓ How much is the GeV excess morphology degenerate with the Fermi bubbles? Can the GeV excess be part of the low-latitude bubbles?

  Yang&Aharonian A&A'16;
  Acero+ ApJS'16; Ackermann+ ApJ'17

The range of explored uncertainties, albeit larger than in any other study to date, is yet not a full representation of the uncertainties in the modeling, because residuals persist in all cases considered.

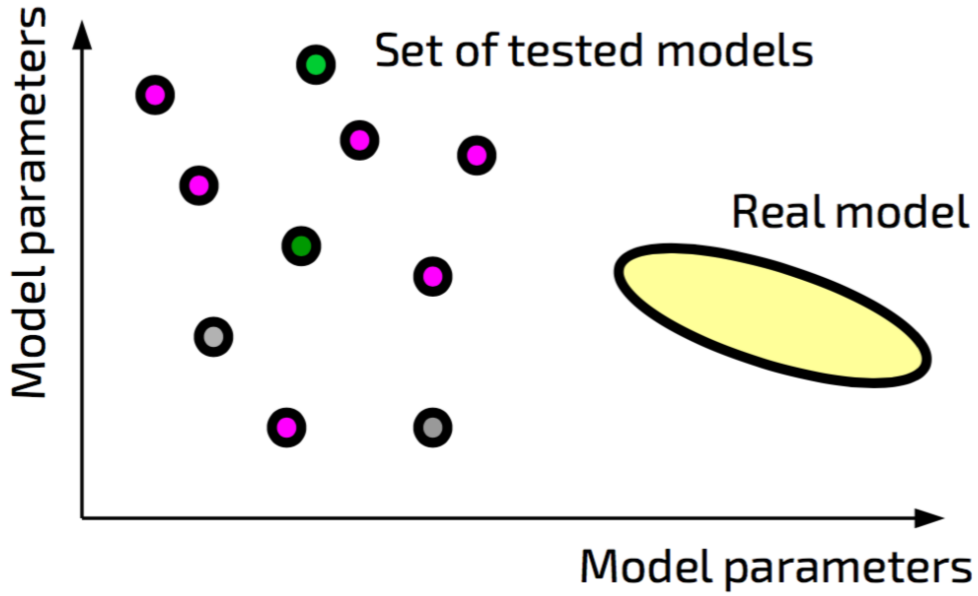
Ackermann+ ApJ'17

Fitting the gamma-ray sky



Large residuals (~30%) remain in the sky with this simple model, but clear structures emerge (extended sources, Fermi bubbles)

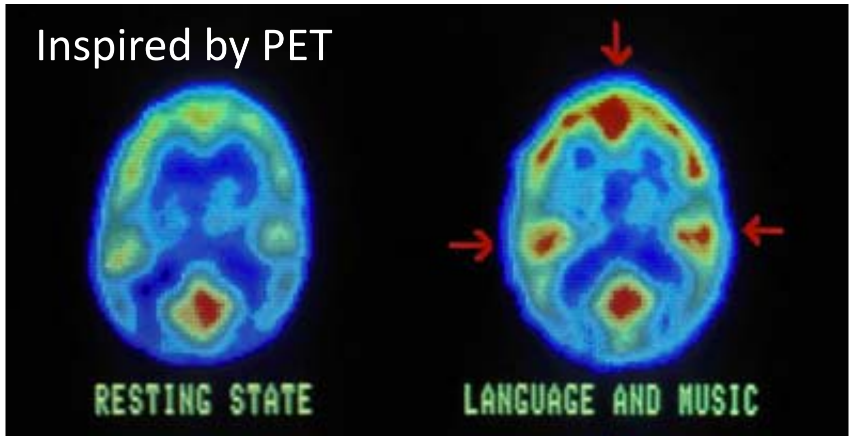
A way forward



Imperfect modelling might lead to severely **biased estimators**, above all for extended emission features.

Intrinsic uncertainties in spectral/spatial predictions must be fully taken into account by a very large number of nuisance parameters.

Penalised Poisson likelihood with regularisation conditions: **Sky F**actorisation with **A**daptive **C**onstraining **T**emplates (**SkyFACT**)



Storm, Weniger & Calore JCAP'17 [arXiv:1705.04065]

Talk by E. Storm

SkyFACT

$$\text{Model} = \sum_k \text{Spectrum} \times \text{Morphology}$$

Uncertain spectral modelling

Pixel-by-pixel correlated uncertainties

$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

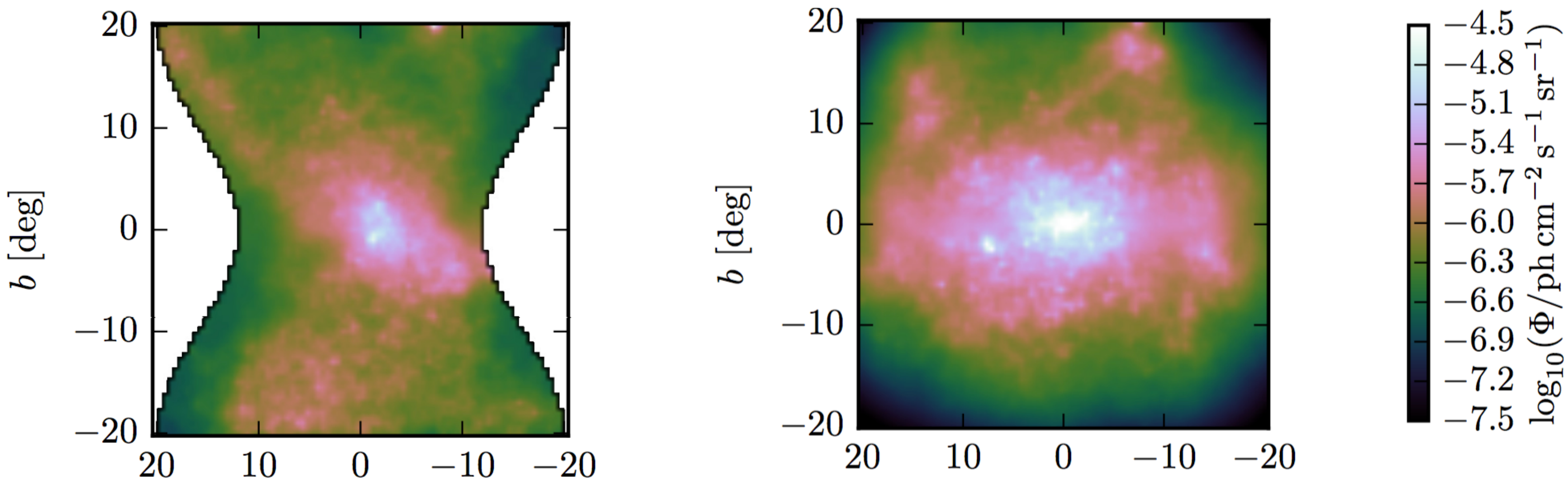
$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}(\lambda, \lambda', \lambda'', \eta, \eta')$$

Penalized Poisson likelihood with regularisation conditions

- ➡ Facilitate component separation in scenarios where only partial knowledge of the components is available.
- ➡ Sufficient number of nuisance parameters such that we can obtain formally good fits and perform model comparison.

Talk by L. Hendriks on NN

The bulge emission morphology



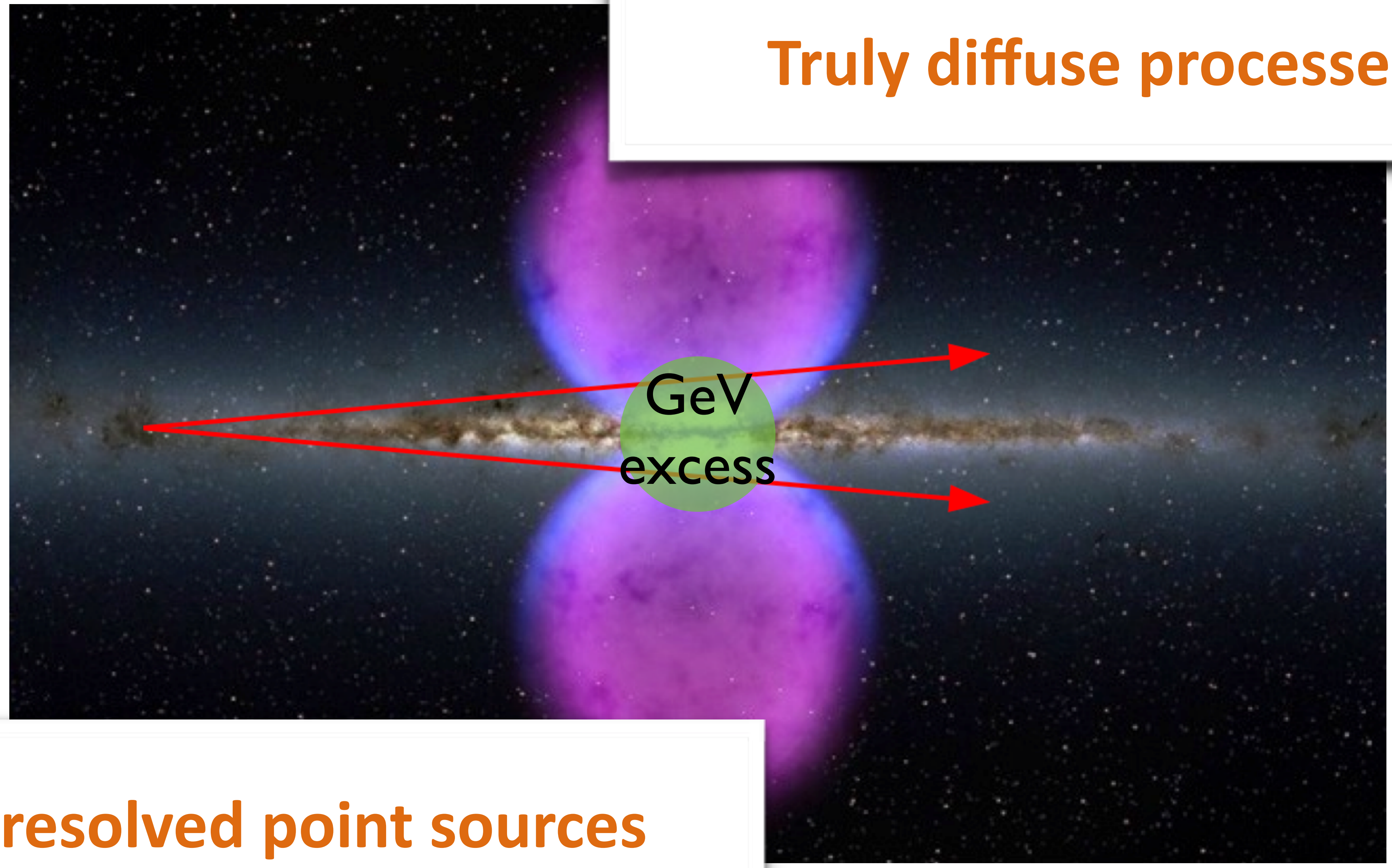
Fermi bubble spectrum
Free morphology

Fixed MSP-like spectrum McCann, ApJ'15
Reconstructed morphology
~12σ significance

- ✓ Strong degeneracy between Fermi bubbles and bulge emission (aka GeV excess)
- ✓ Residuals reduced significantly when (realistic) nuisance parameters are included in the fit.
- ✓ Once again, strong evidence for GeV excess (> 10σ significance), although more oblate morphology than previous studies.

Storm, Weniger & Calore JCAP'17 [arXiv:1705.04065]

Possible interpretations



Truly diffuse processes

Unresolved point sources

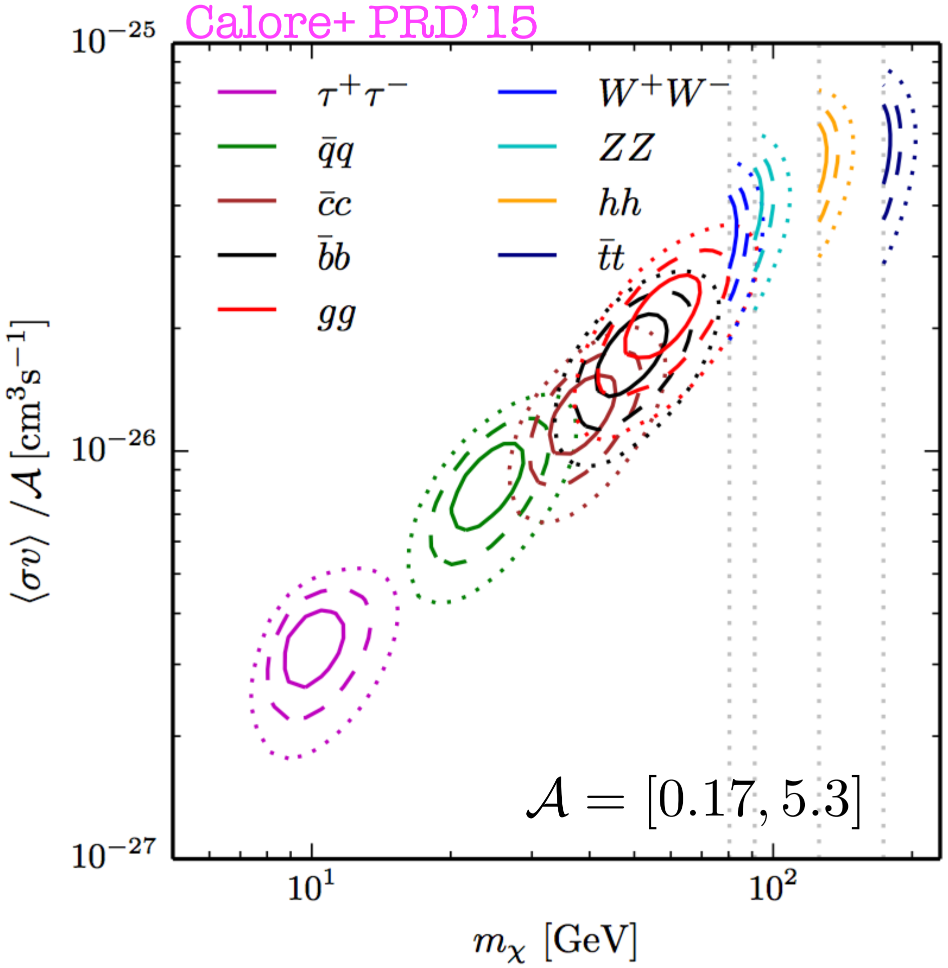
Constraints:

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

Dark matter annihilation

Spectrum

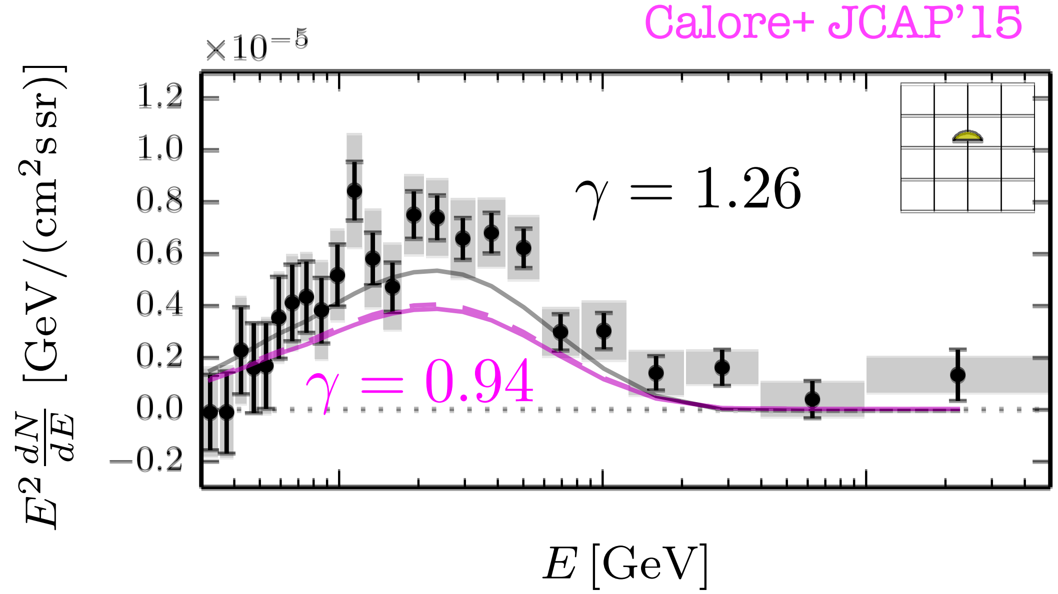
$$\frac{dN}{dE} = \sum_f \frac{\langle \sigma v \rangle_f}{8\pi\, m_\chi^2} \frac{dN_\gamma^f}{dE} \int_{\rm l.o.s} ds\, \rho^2(r(s,\psi))$$



Agrawal+JCAP'15; Achterberg+JCAP'15; Bertone, FC+ JCAP'15; Liem, FC+ JCAP'16; etc.

Morphology

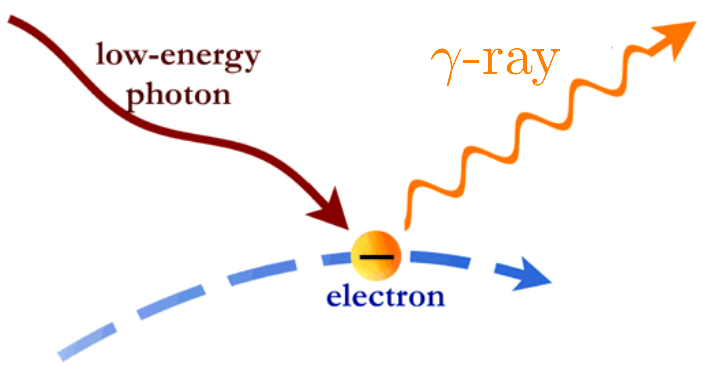
For EAGLE simulation: typically **shallower profiles** for Milky Way analogues, under conservative assumptions on resolution.



+ non-sphericity of the high-E excess? Linden+'16

+ disk component? Huang+JCAP'16, de Boer+'16

Inverse Compton scattering from GC CRs



Additional population of **leptonic cosmic rays** required at the Galactic centre:

a. Steady-state source term (from star forming CMZ)

Gaggero+JCAP'15; Carlson+ PRD'16, PRL'16

b. Time-dependent source term (from outburst event)

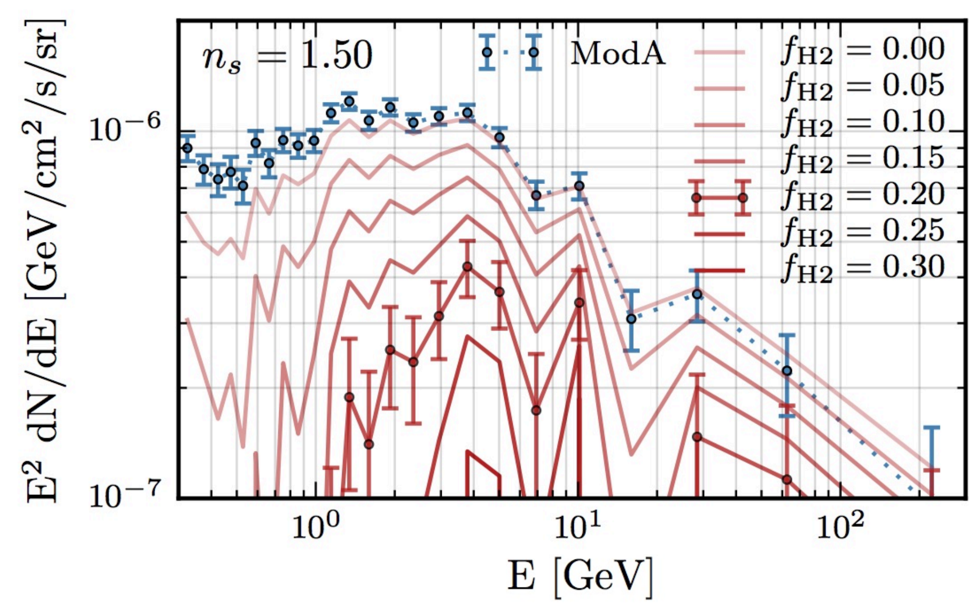
Petrovic+ JCAP'14; Cholis,FC+ JCAP'15

- Luminosity from SNe in the CMZ (with ~5% SF) enough to sustain energetics of Fermi GeV excess, ~3x10^{37} erg/s.

- Updated SN models for CR injection at the GC, accounting for enhaced SFR at the GC traced by H2 regions, 5-10% of total SFR.

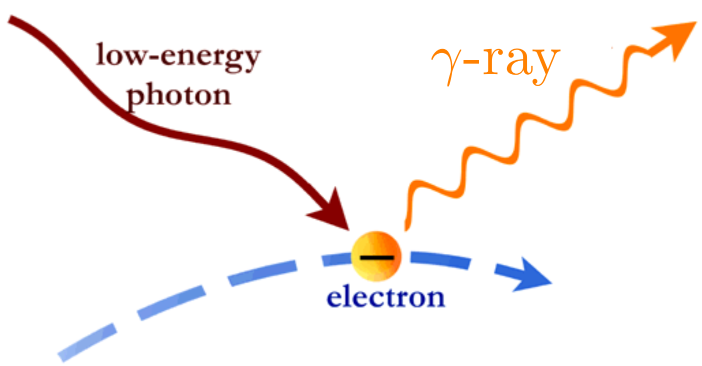
Carlson+ PRD'16

- Better fit to the data and reduced intensity of the excess but some over-subtraction at low energies —> Role of advective winds.



Talks by T. Linden, D. Gaggero

Inverse Compton scattering from GC CRs



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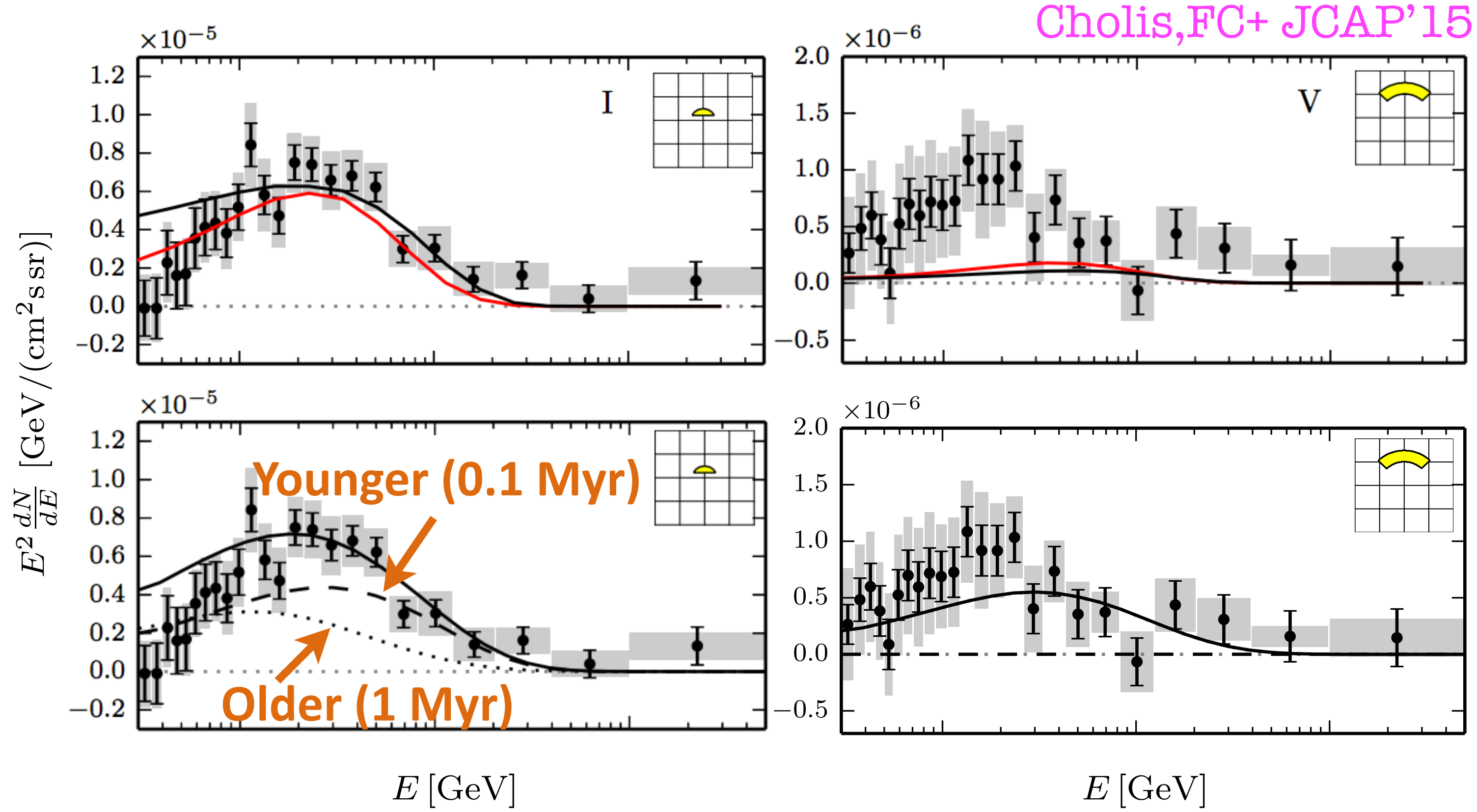
- Injection of high-energy CR in the past, at the GC (central black hole or starburst activity) ⟶ Tuning of burst(s) parameters.

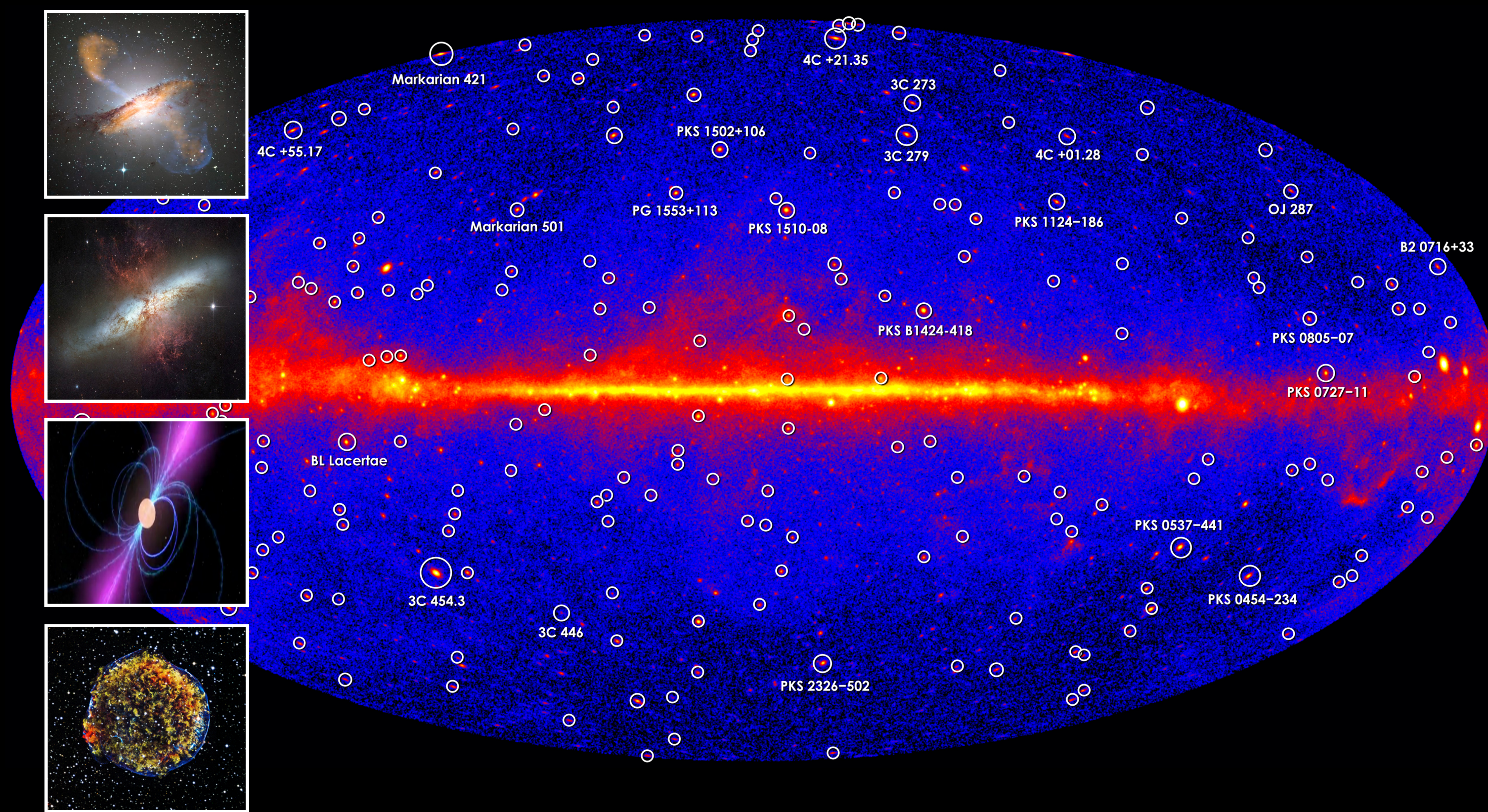
- At least two bursts are required to fit the and extended highly uniform spectrum, with somewhat hard injection indices (<2).

Cholis,FC+ JCAP'15



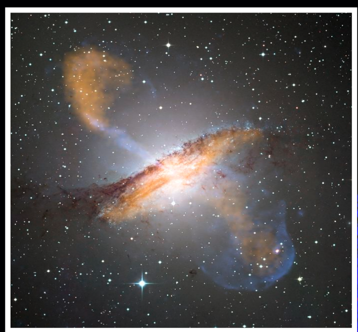
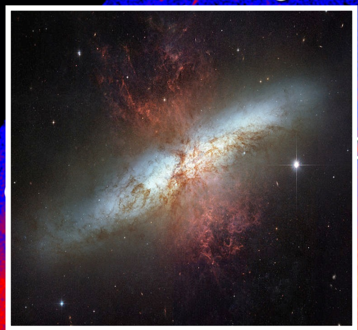
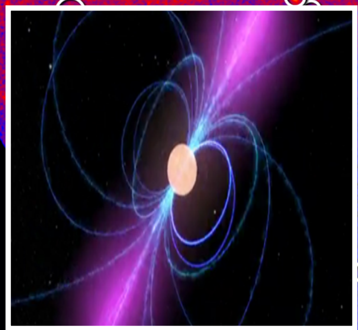
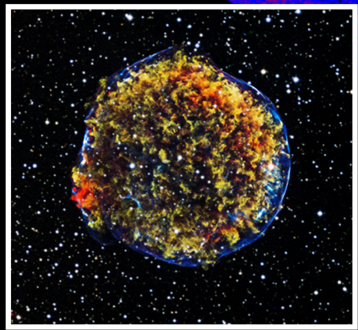
Detected vs unresolved point-like sources

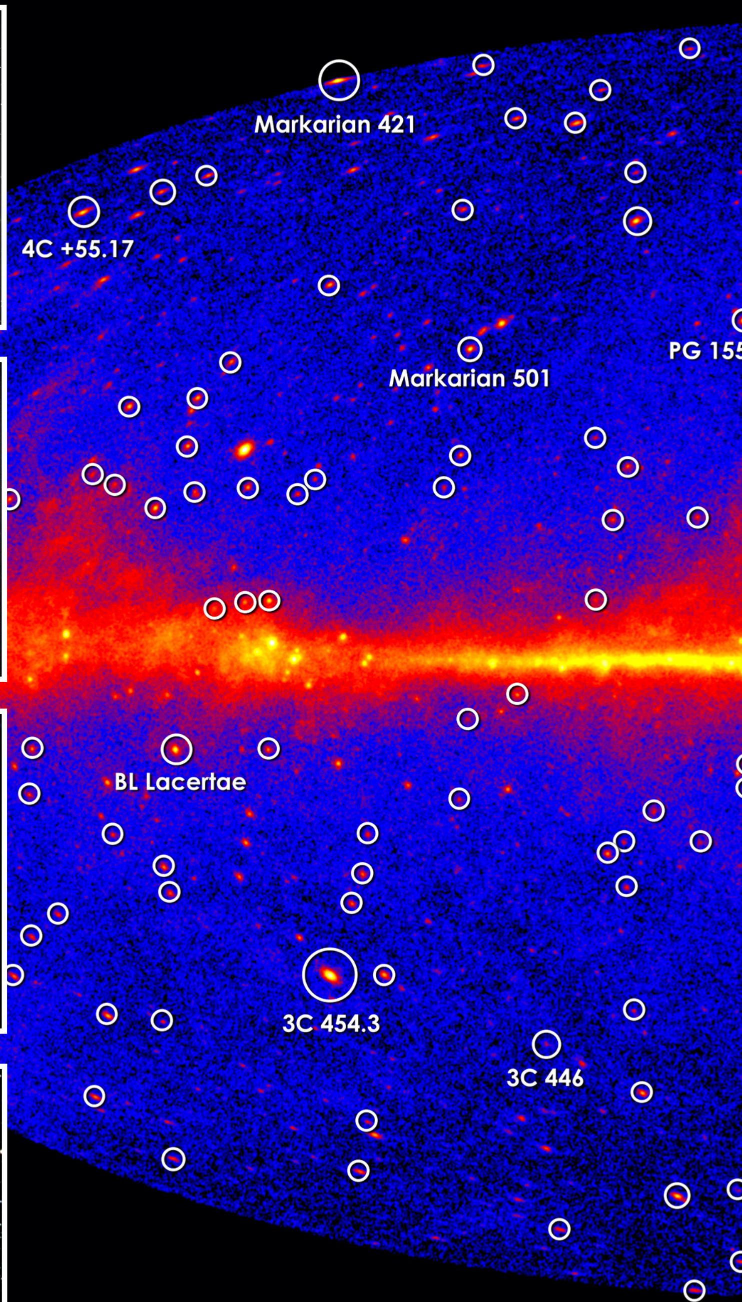
Detected sources

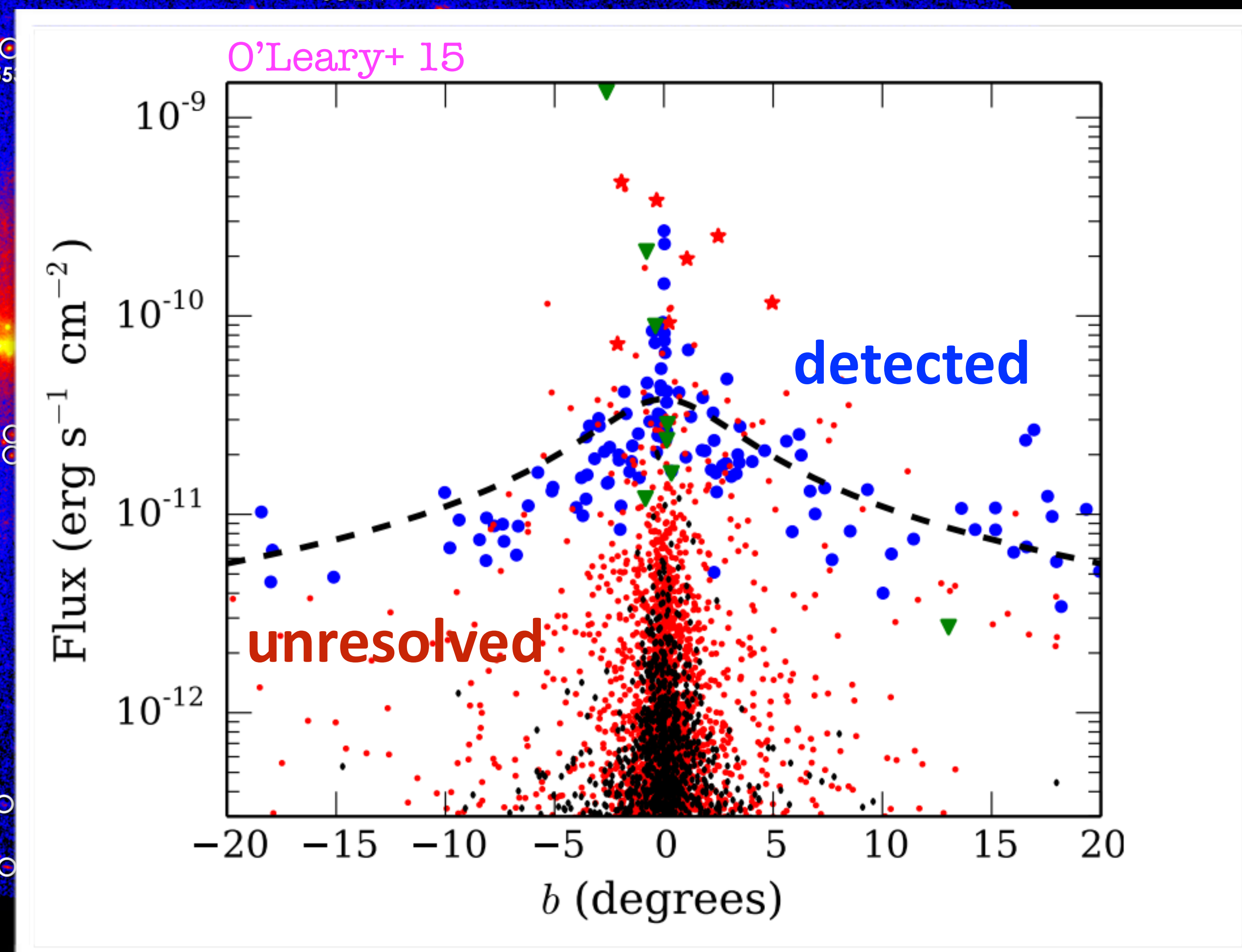


Detected vs unresolved point-like sources

Detected sources

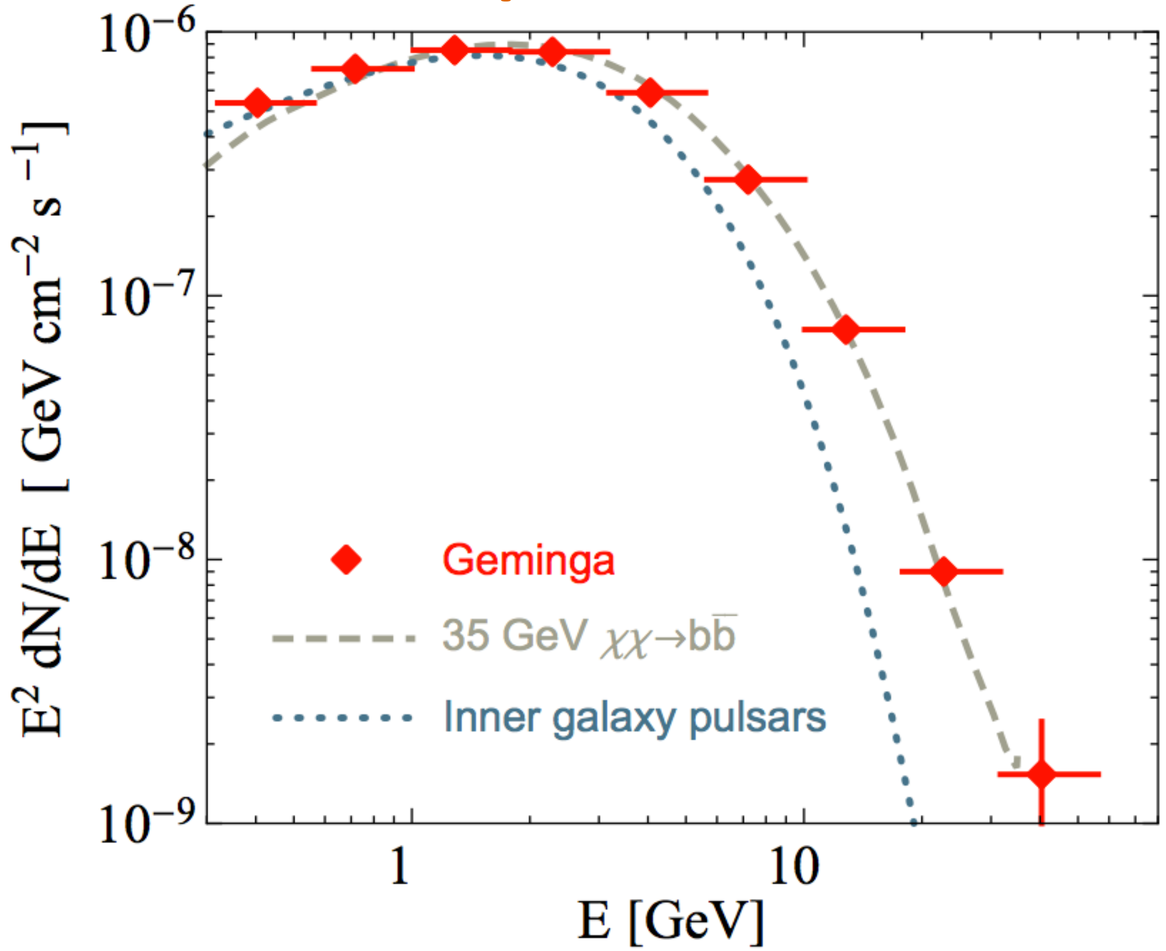









Unresolved pulsars and millisecond pulsars

Spectrum



- ✓ Spectrum compatible with Fermi-LAT 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 disk).

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

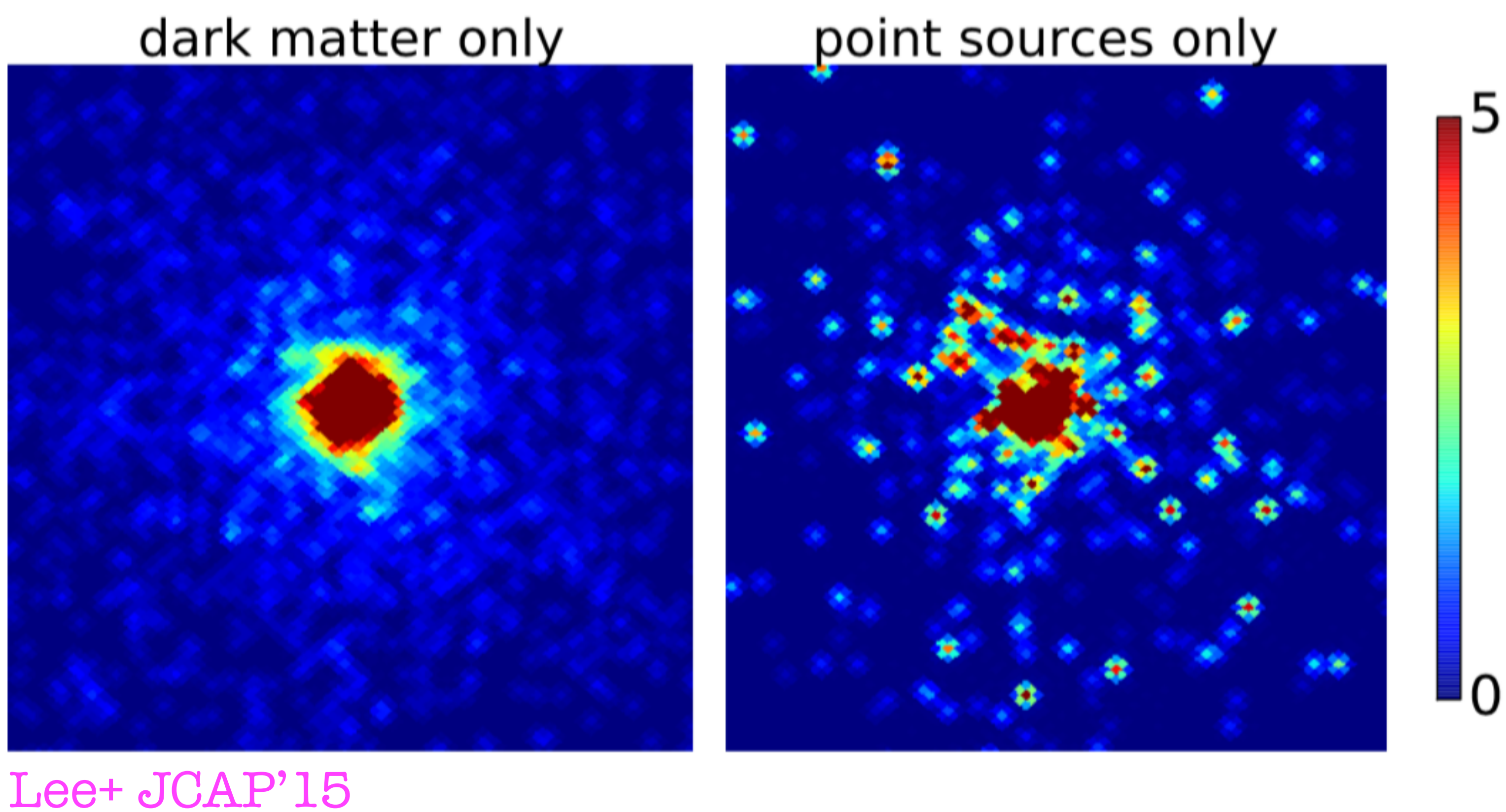
- ✓ Bulge MSPs: from tidally disrupted globular clusters.

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

- ✓ 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 discriminate point sources from diffuse emission?

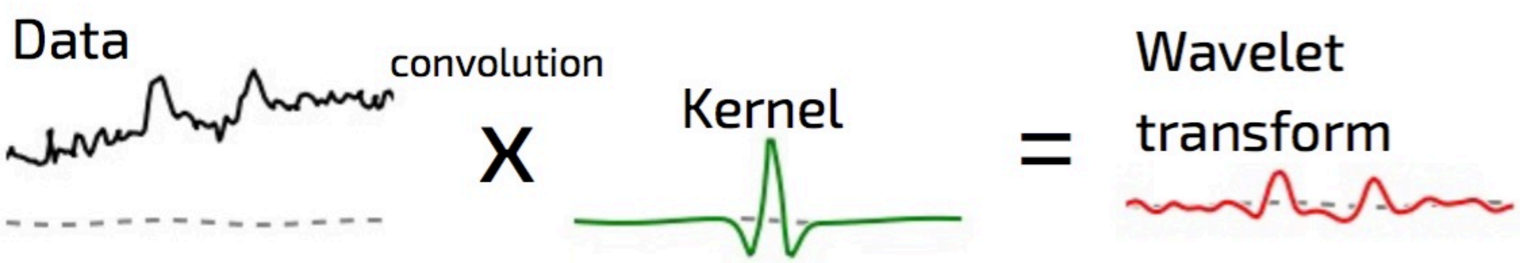


Differences in the statistics of the photon counts can be quantified and used for model comparison.

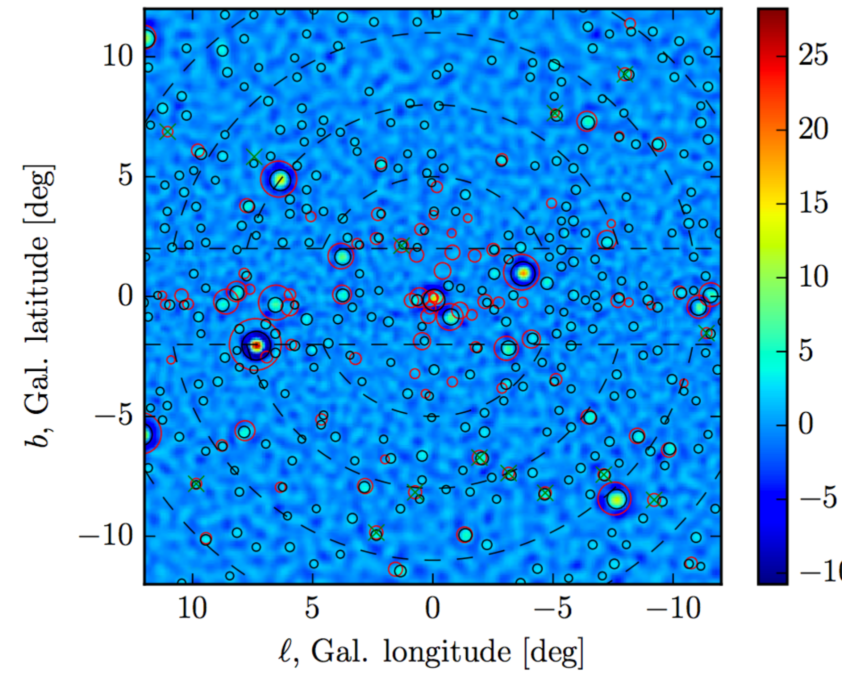
Caveat: Contamination from Galactic diffuse emission.

Support for unresolved PS interpretation

Local maxima of normalised wavelet transform



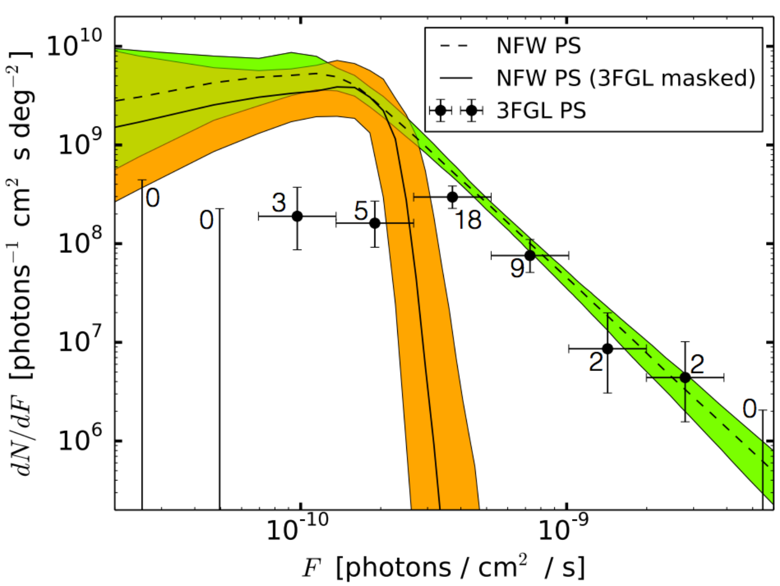
Bartels+ PRL'16

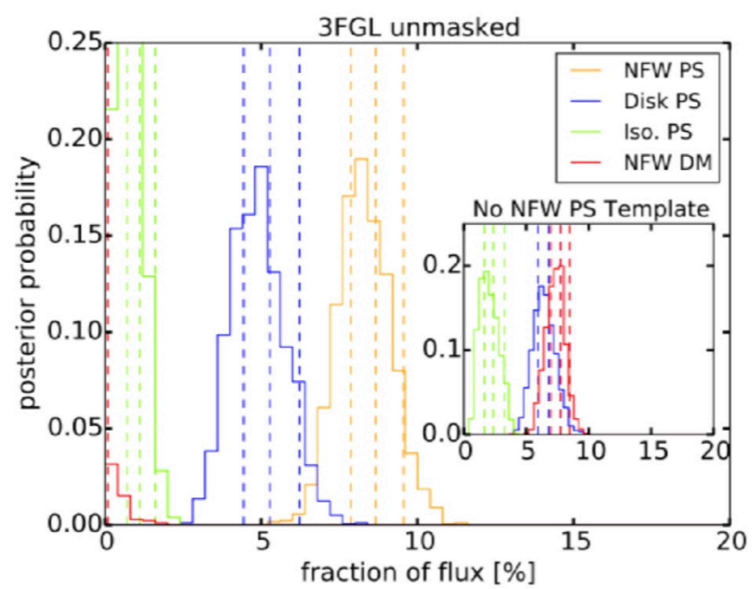


- No background modelling
- Evidence for MSP-like population in the bulge
- Constraints on luminosity function

Non-Poissonian template fitting

Lee+ PRL'16

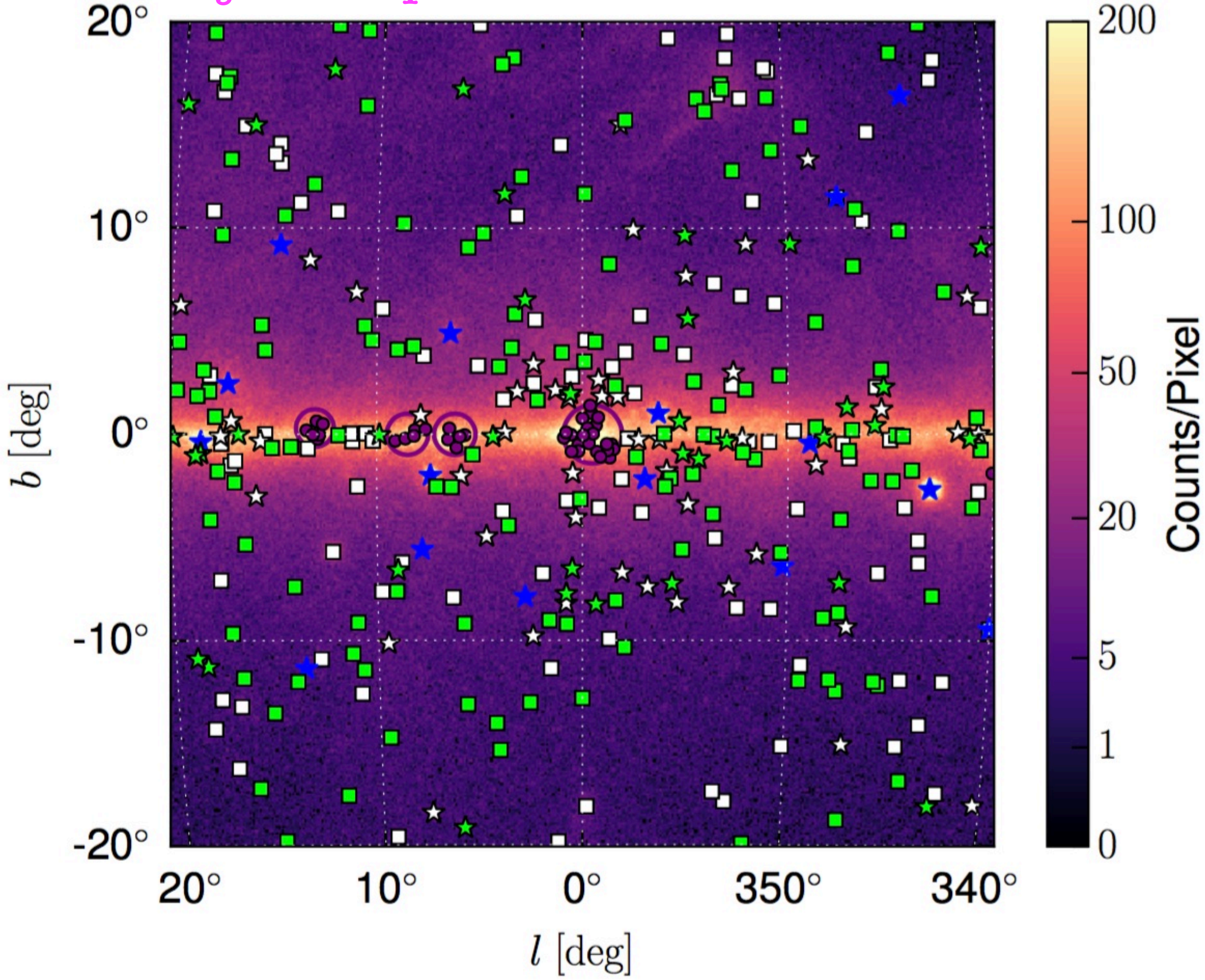


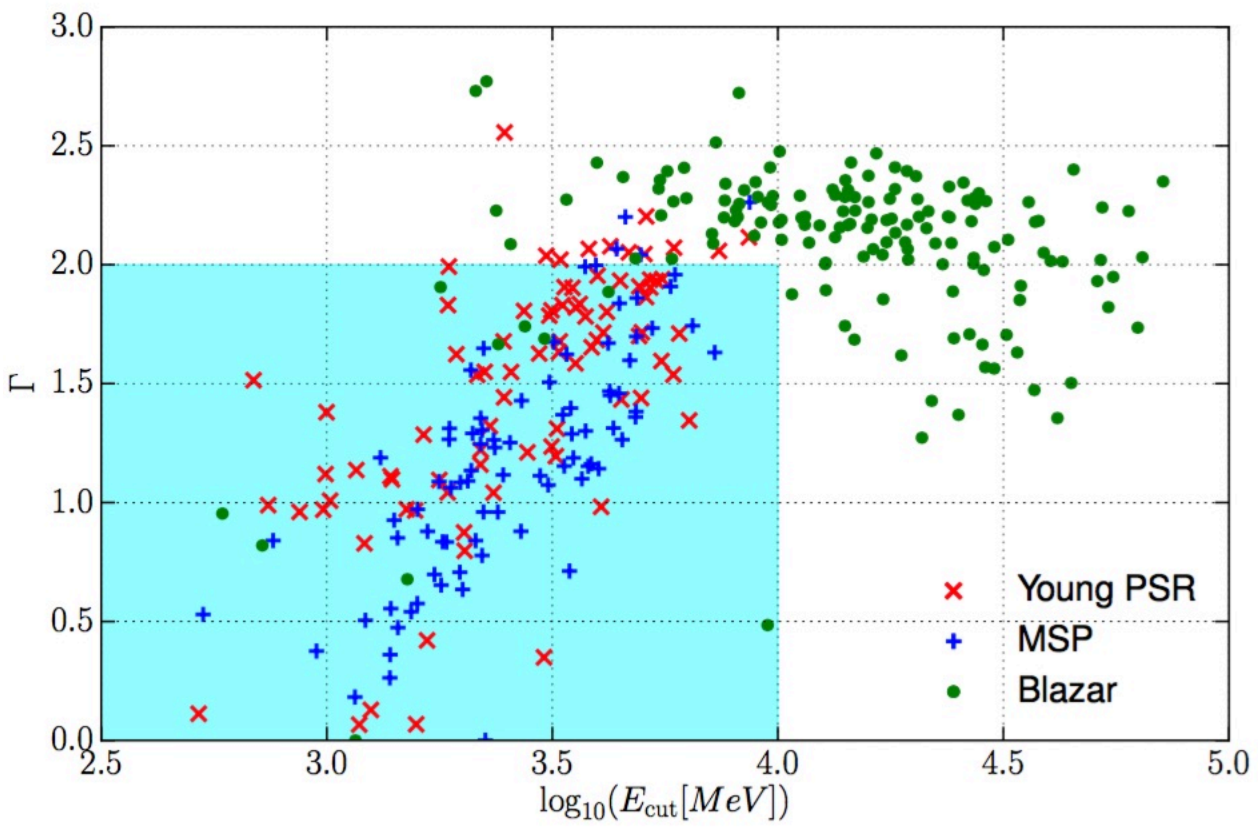


- The statistics of PS is non-Poissonian
- PS NPT NFW distribution absorbs the most of the excess
- A priori, it suffers more form contamination of background modelling

Gamma-ray faint PS in the inner Galaxy

Ajello+ ApJ'17



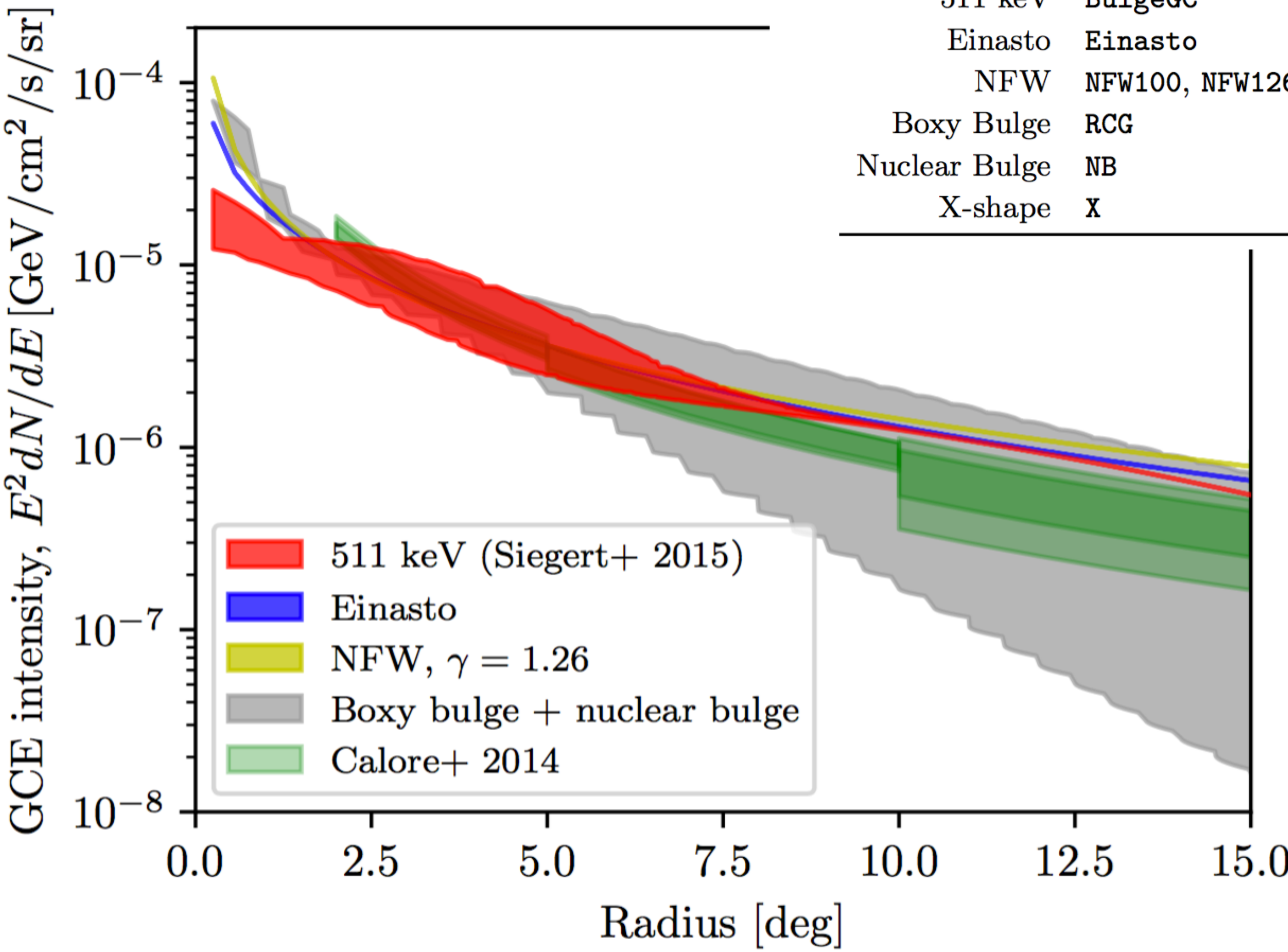


- Search for low-significance gamma-ray sources and spectral classification
- 2FIG catalogue: 7.5 years of data; ~400 sources; 66 PSR candidates
- Preference for bulge + disk distribution of inner Galaxy PSR/MSP candidates
- Preference for very hard luminosity function so that most of the emission comes from brightest sources

Talk by E. Charles

Going beyond DM-motivated templates

Template	ID	Reference
511 keV	BulgeGC	Siegert et al. (2016)
Einasto	Einasto	Vincent et al. (2012)
NFW	NFW100, NFW126	Navarro et al. (1997)
Boxy Bulge	RCG	Cao et al. (2013)
Nuclear Bulge	NB	Launhardt et al. (2002)
X-shape	X	Ness & Lang (2016)



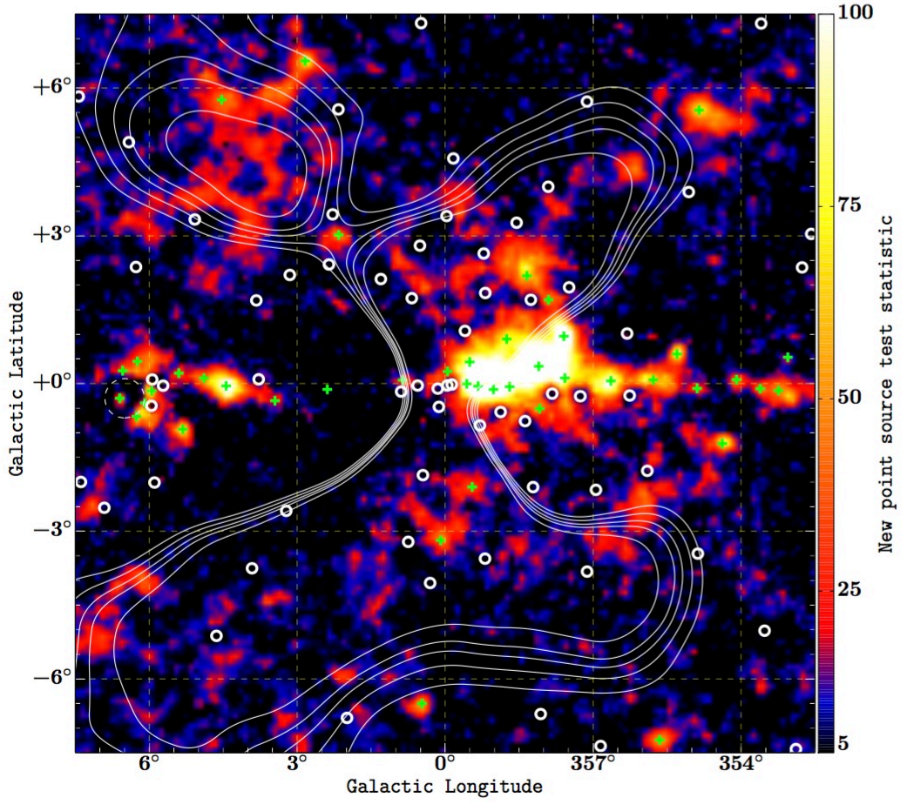
Correlation with (old) stellar populations?

Correlation with X-shaped bulge?

- Positive correlation with WISE infrared X-shaped template
- Better gas maps from hydro simulations
- Significant contribution from nuclear bulge, while low significance for additional DM template

Talk by R. Crocker

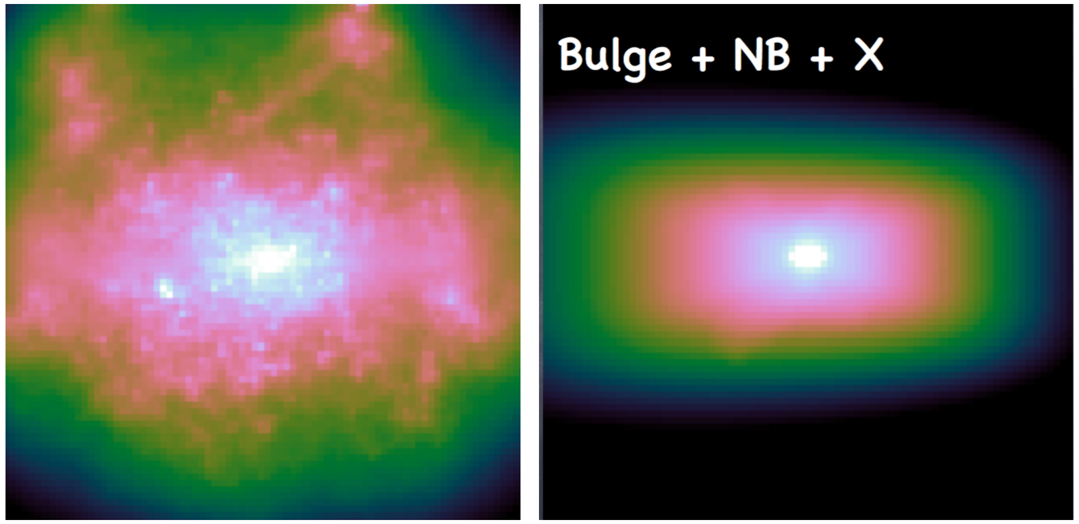
Macias+'16



Correlation with boxy bulge and nuclear bulge?

Talk by R. Bartels

Bartels, Storm, Weniger, Calore, In prep.



- GeV excess component more oblate than previously found
- GeV excess seems to trace stellar mass in the inner Galaxy
- Significant contribution from bar/boxy bulge
- Negligible contribution from X-shaped bulge

A unified scenario: 511 keV line and GCE

Some common features: Spatial extension, origin possibly related to binary compact objects

Scenario:

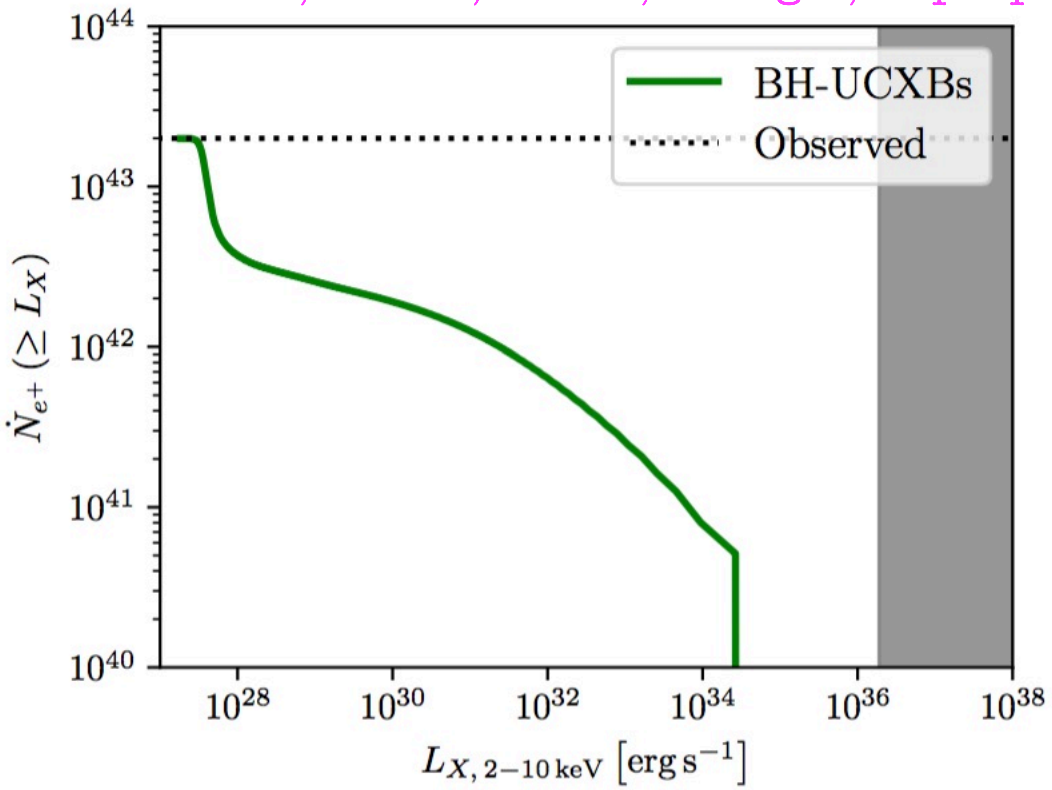
- Population synthesis of ultra-compact X-ray binaries predicts about **2×10^5 NS-UCXB in the bulge**, which leads also to **~1×10^4 MSPs**

van Haaften+ A&A'13,'15

- NS-UCXB progenitors of MSPs accounting for the GeV excess
- Companion BH-UCXB population —> Positron annihilation line from accreting BHs cold jets

Guessoum+ A&A'06; Bandyopadhyay+ MNRAS'09; Siegert+ A&A'16

Bartels, Calore, Storm, Weniger, In prep.



Results:

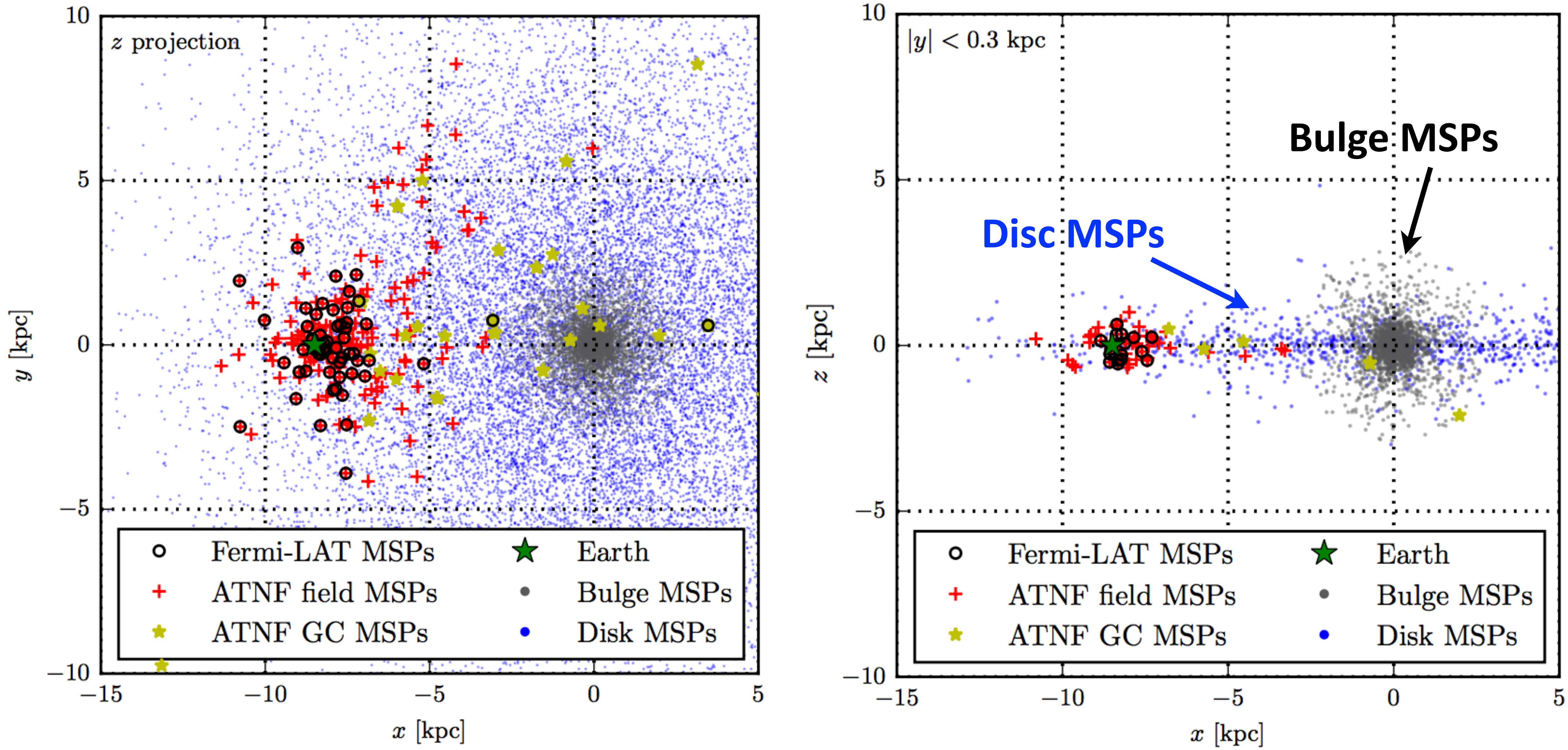
✓ Can supply the required positron/electron yield

✓ Can be tested with future observations of Milky Way globular clusters

Talks by R. Bartels, F. H. Panther

How to test conclusively PS interpretation of the GeV excess?

The radio MSP bulge population



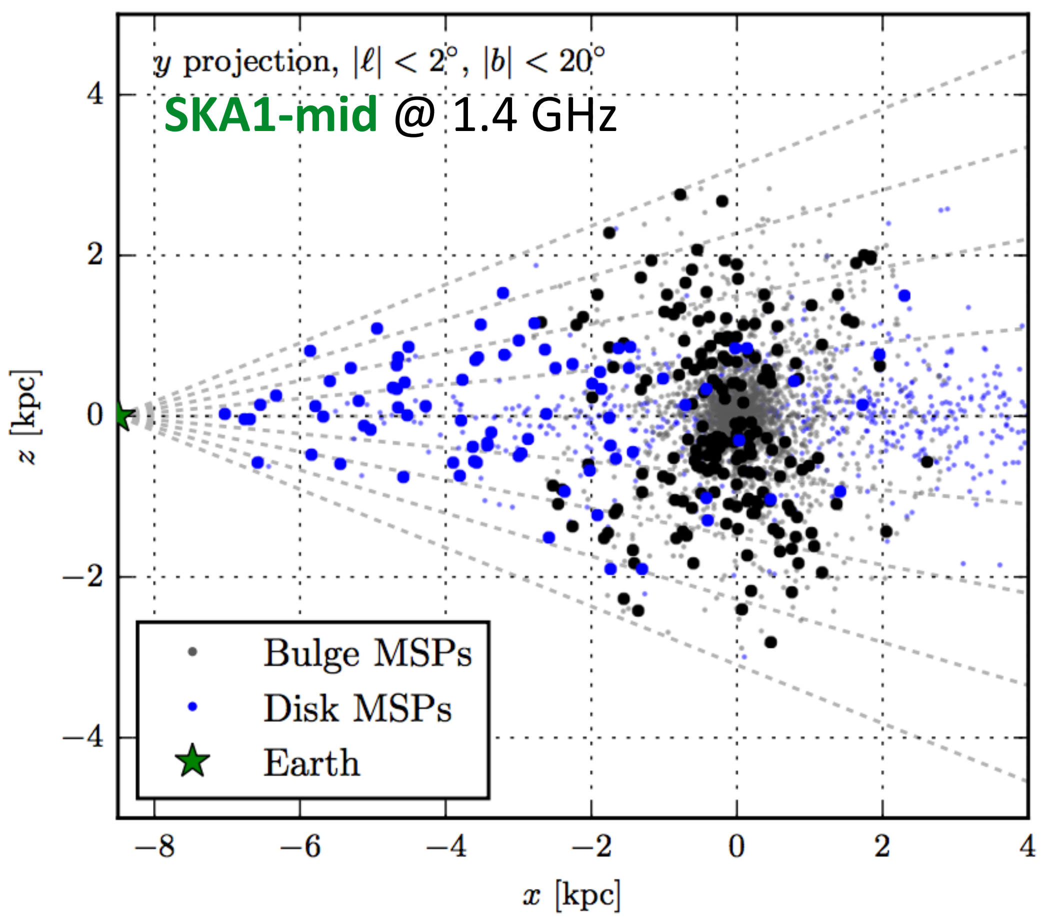
+ Model for luminosity function (from radio globular clusters)

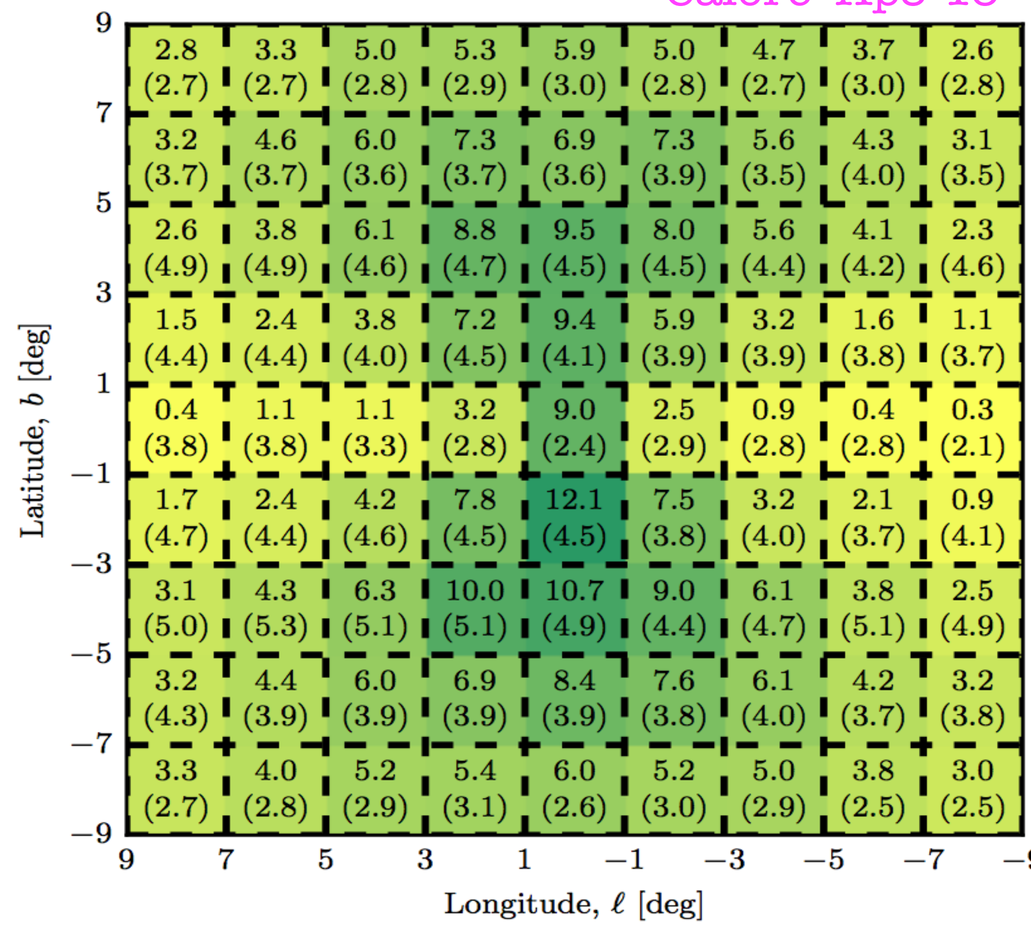
+ Radio telescopes sensitivity:

$$S_{\nu,\mathrm{rms}} = \frac{T_{\mathrm{sys}}}{G\sqrt{t_{\mathrm{obs}}\,\Delta\nu\,n_p}}\left(\frac{W_{\mathrm{obs}}}{P - W_{\mathrm{obs}}}\right)^{1/2}$$

Discovering radio MSPs in the inner Galaxy

Calore+ApJ'16





Bulge population is just below sensitivity of Parkes HTRU mid-latitude survey.

- GBT targeted searches ~100h: ~3 bulge MSPs
- MeerKAT (and SKA) mid-lat survey ~300h: ~30 bulge MSPs

➡ With future dedicated observations we can **discover this MSP bulge population**.

➡ We need observation time (Fermi GI Proposals, TRAPUM project, etc.)

Talk by J. Deneva

Open issues and future perspectives

✓ Many questions have been answered thanks to the development of new advanced statistical tools for data analysis.

✓ Improved characterisation the GeV excess (spectrum and morphology) but not conclusive determination of its origin.

✓ Better study of the degeneracy with the Fermi bubbles is needed as well as input from models for bubbles formation, to understand their low-latitude behaviour.

➡ Can we find sub-threshold PS in the Galactic bulge in radio and X-rays?

➡ What, if any, is the space left for truly diffuse emission at the GC? What is the role of SF, winds and molecular clouds?

➡ Can we use what we know about the GeV excess to cross check models/observations from other galaxies, e.g. Andromeda?

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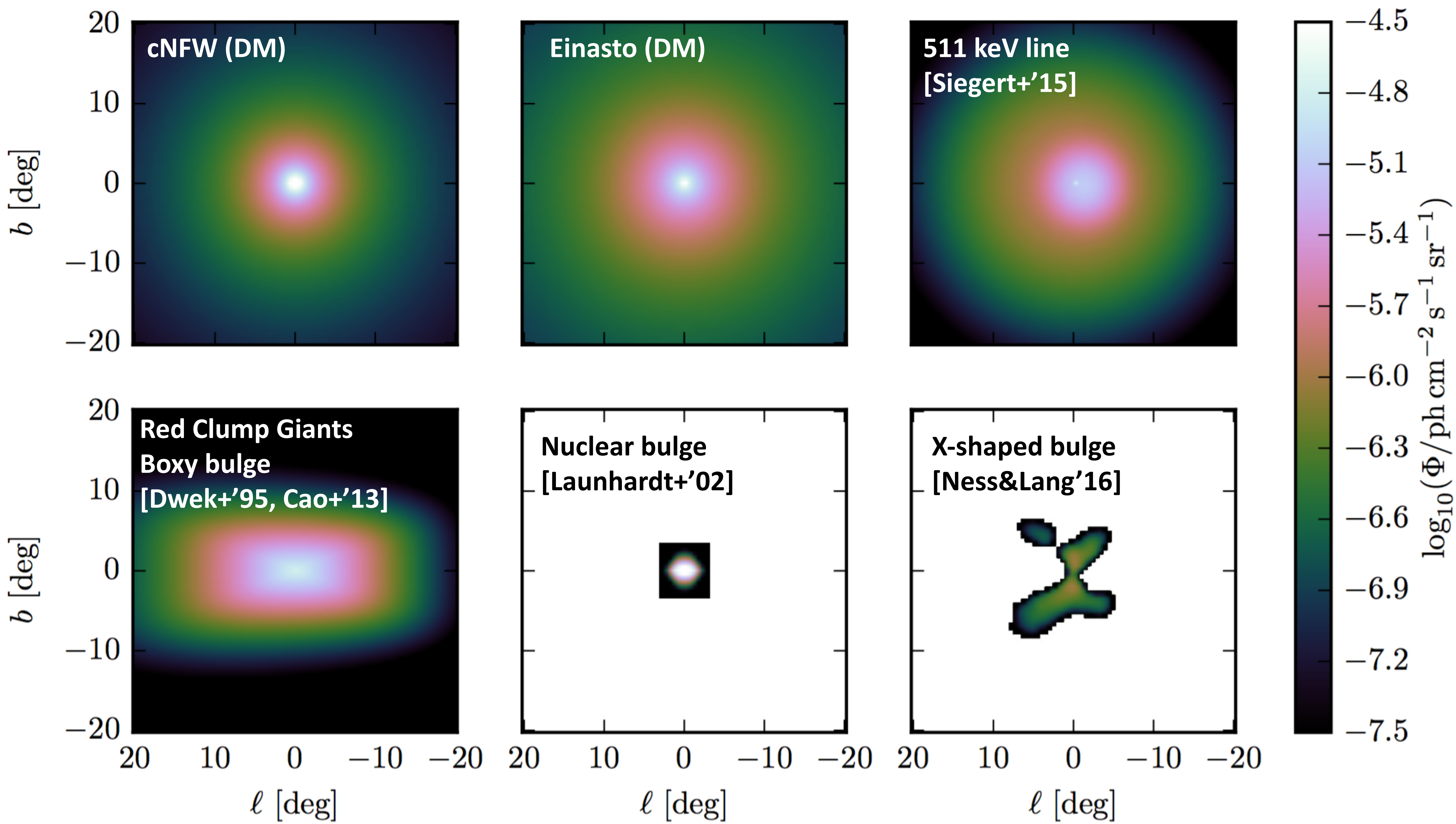
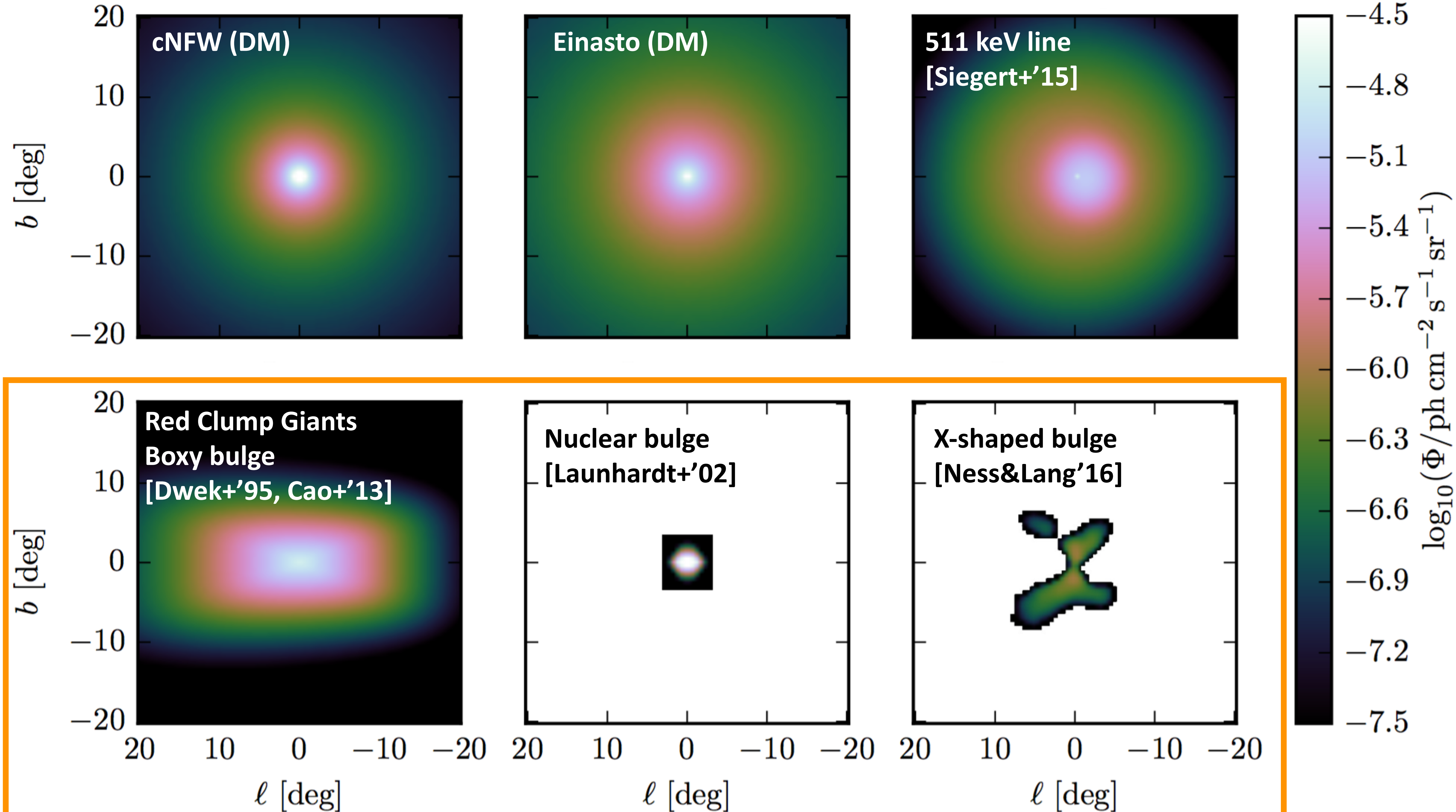
Thanks for the attention

Backup slides

Models for the bulge emission

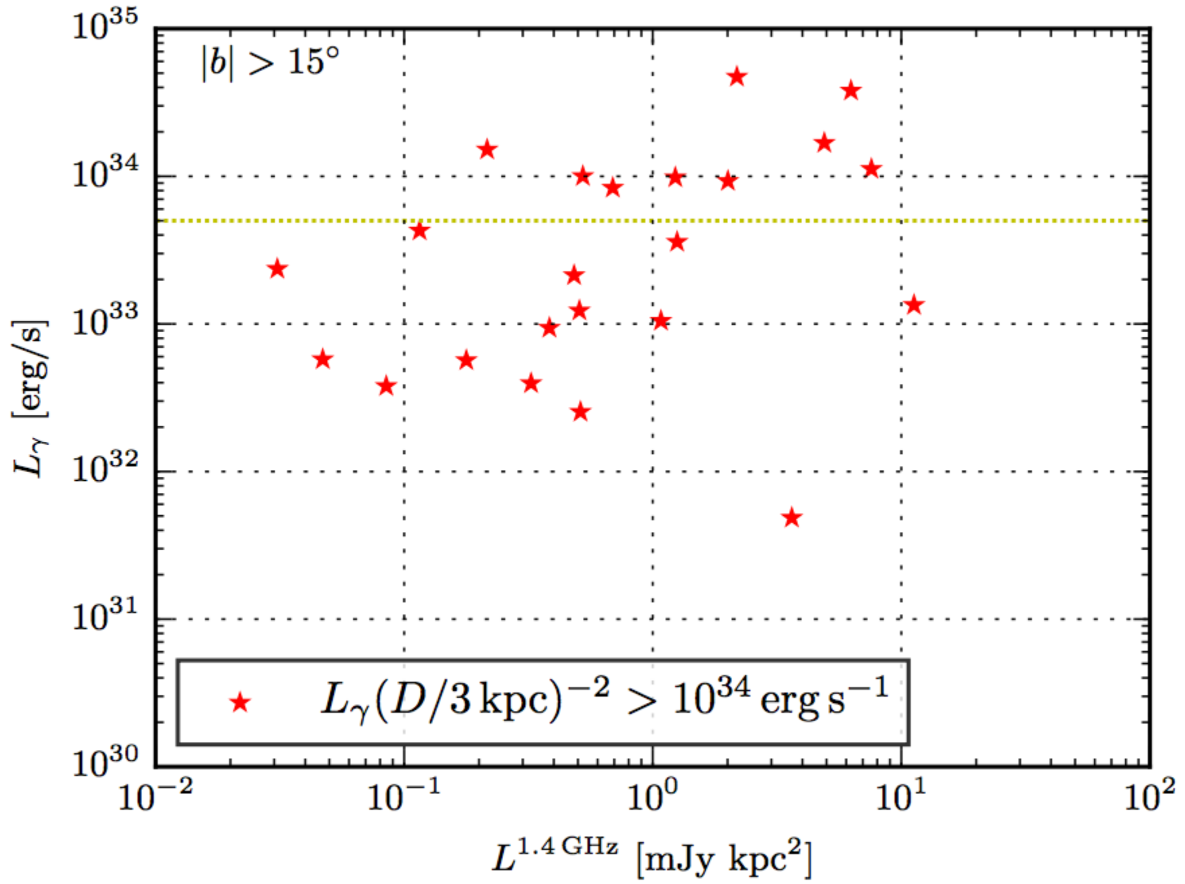


Models for the bulge emission



Superposition of these, weighted by their relative mass

Strategy A: Targeted searches (short-term)



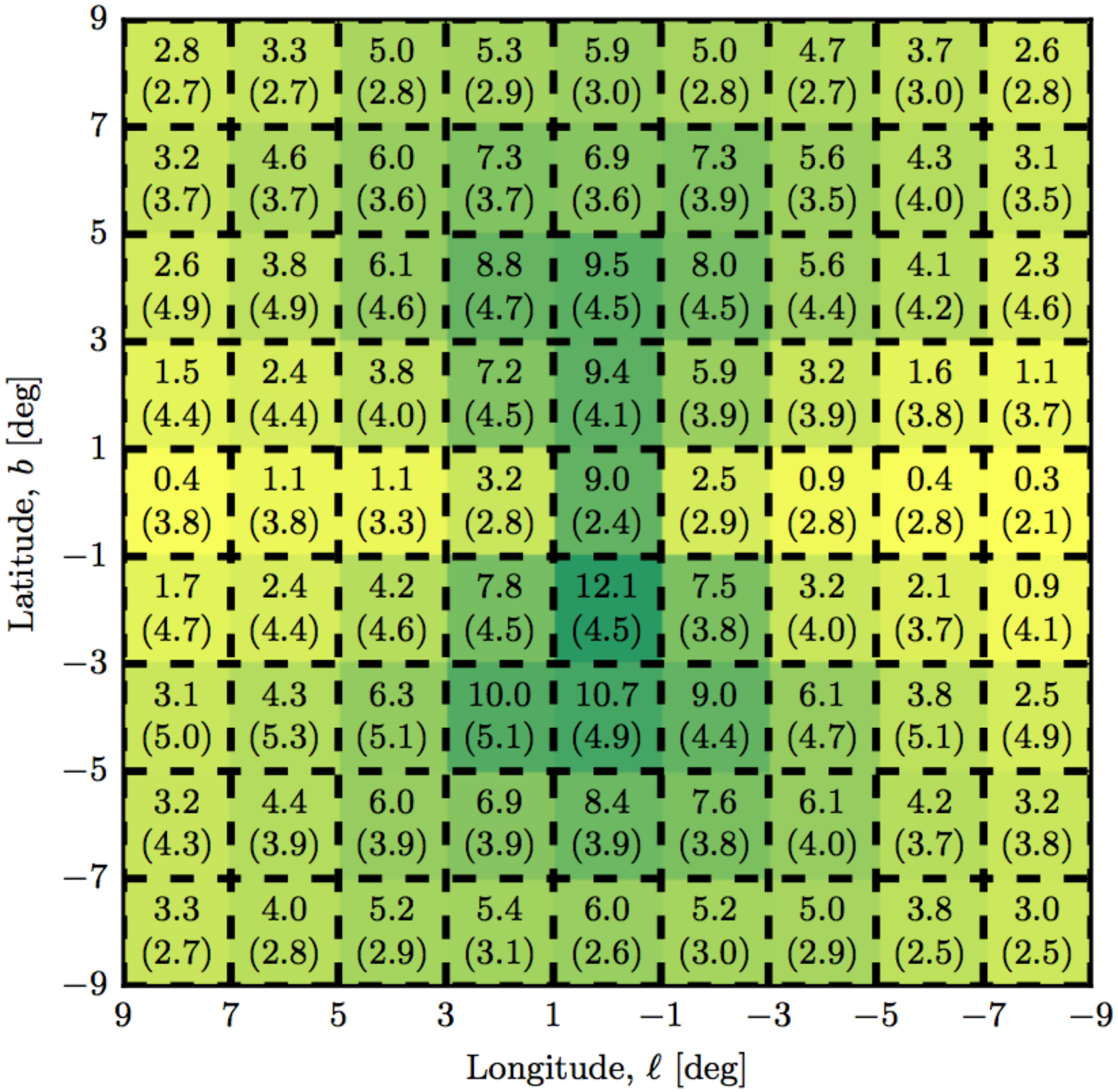
- ✓ Depends on details of gamma-ray / radio correlation and beaming.
- ✓ Empirical relation + 30% completeness correction (from 3FGL unassociated sources).

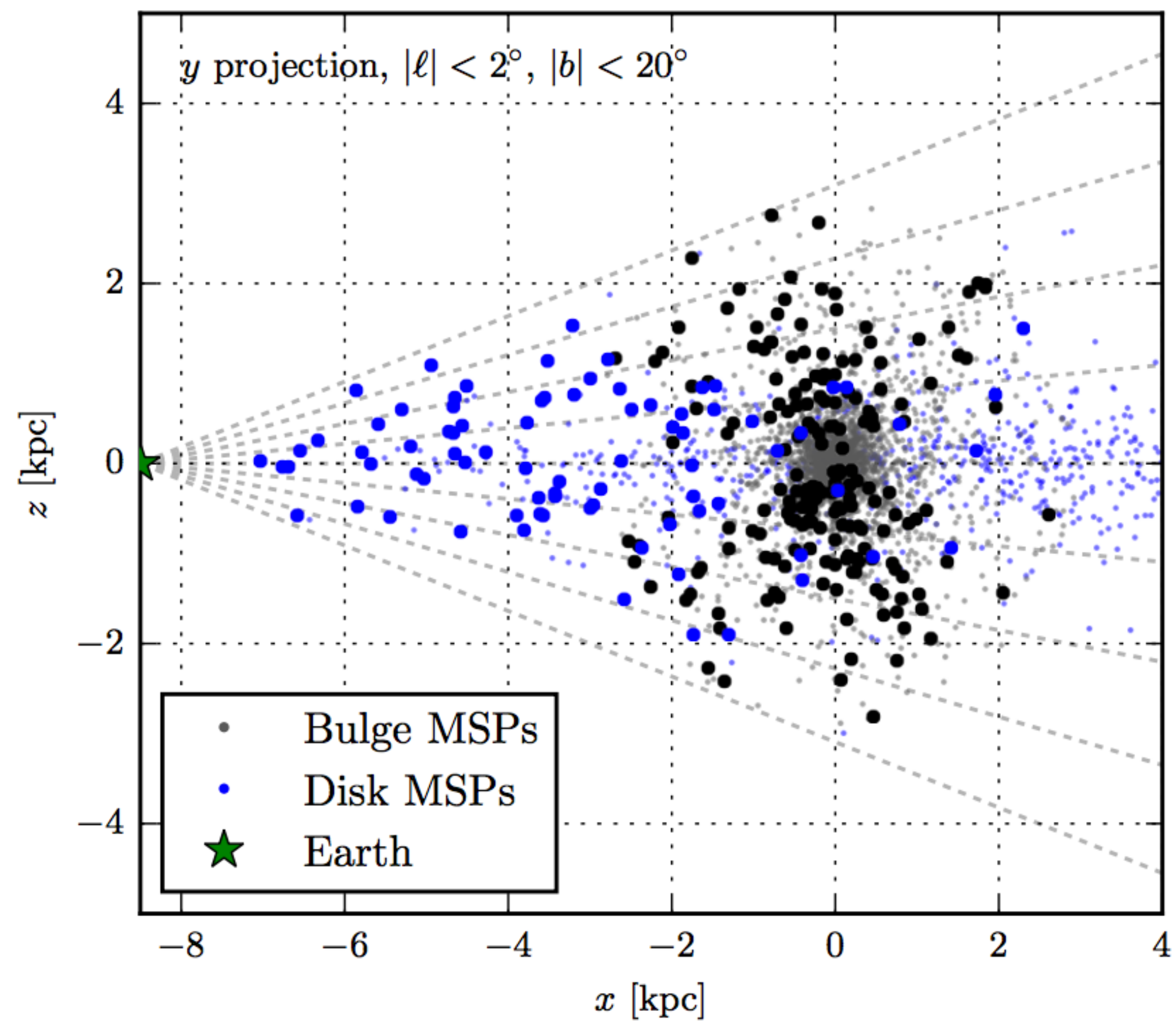
Instrument	t_{obs} total	Detection of MSP candidates Probability	Number (20 total)
GBT	20 h	18.4%	3.7
MeerKAT	20 h	20.5%	4.1
SKA-mid	20 h	40.8%	8.2

- ✓ Deep (1 hour/target) **follow-up observations** of gamma-ray "**hot spots**" (wavelet peaks +unassociated Fermi sources).
- ✓ Most promising strategy for the GBT.

Strategy B: Radio surveys (long-term)

SKA1-mid @ 1.4 GHz (T_{4deg2} = 3.5 hr)





- ✓ Deep (100 hrs) **surveys** of deg^2 regions in the inner Galaxy with O(100) detections.
- ✓ Most promising strategy for future radio telescopes, like MeerKAT and SKA.
- ✓ Not feasible with GBT or VLA.