Gamma rays from the Galactic centre: an overview

Francesca Calore

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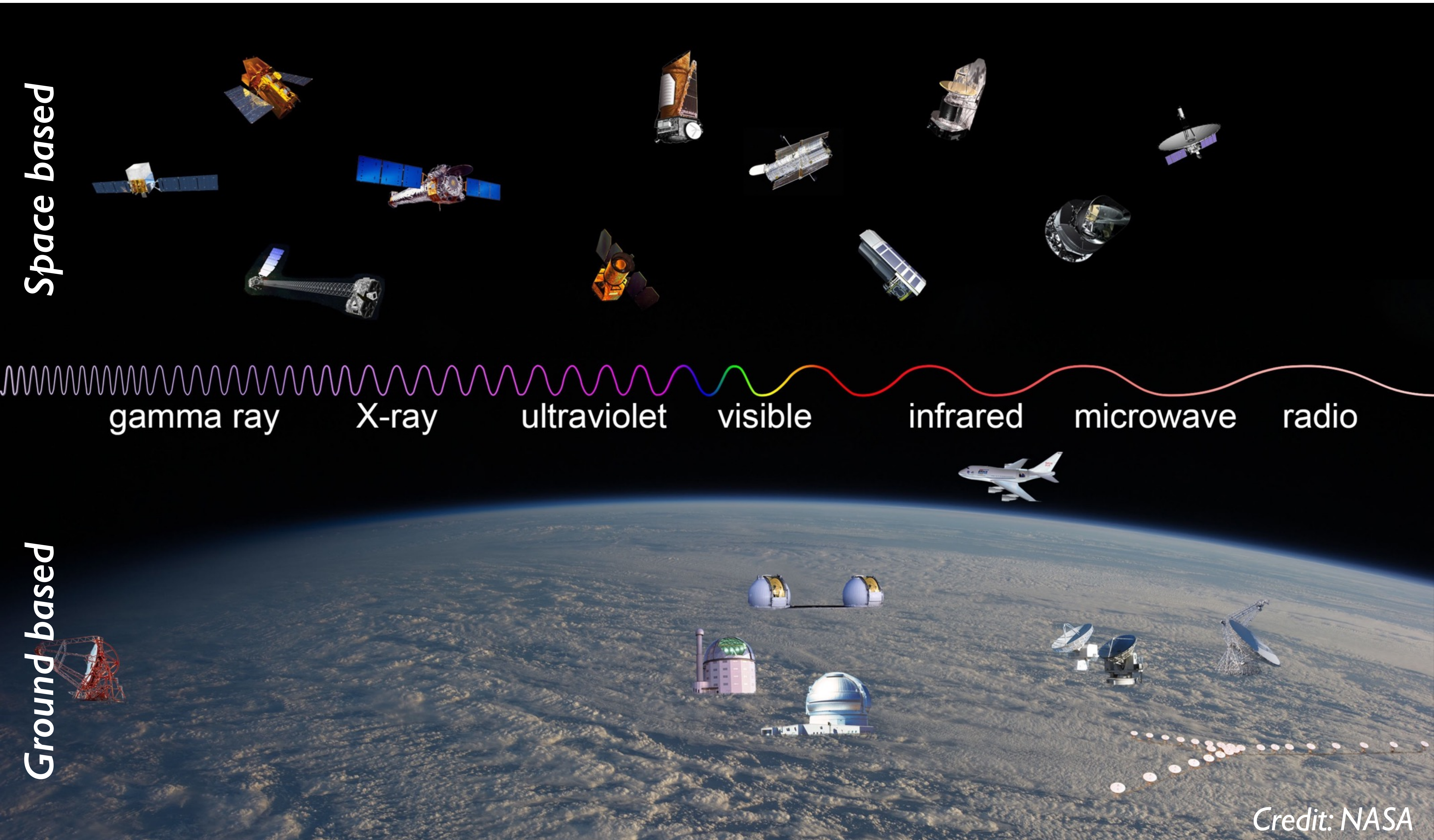
Laboratoire d'Annecy-le-Vieux de Physique Théorique

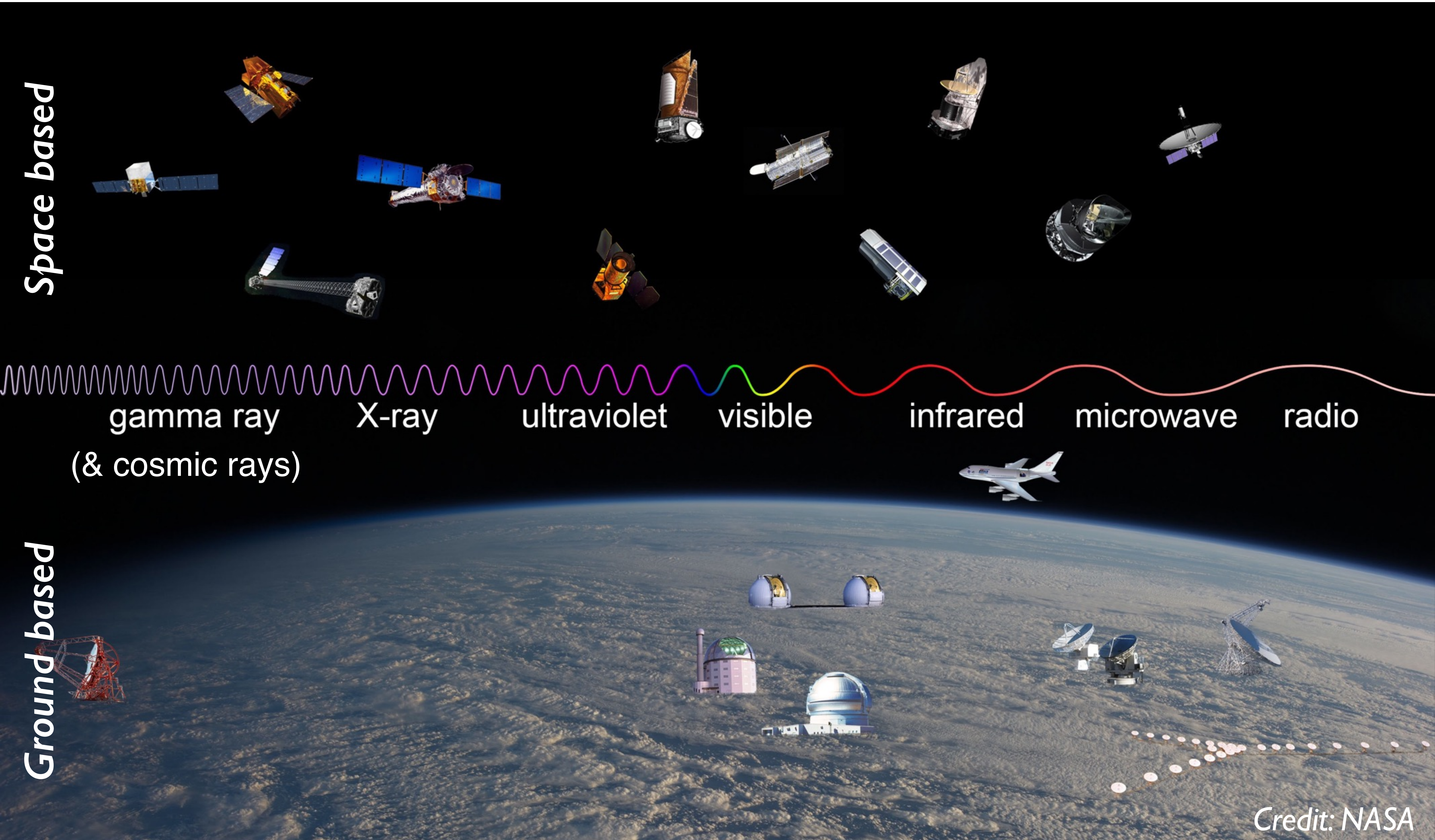
The astronomical data landscape

~TeV ~0.01 MeV



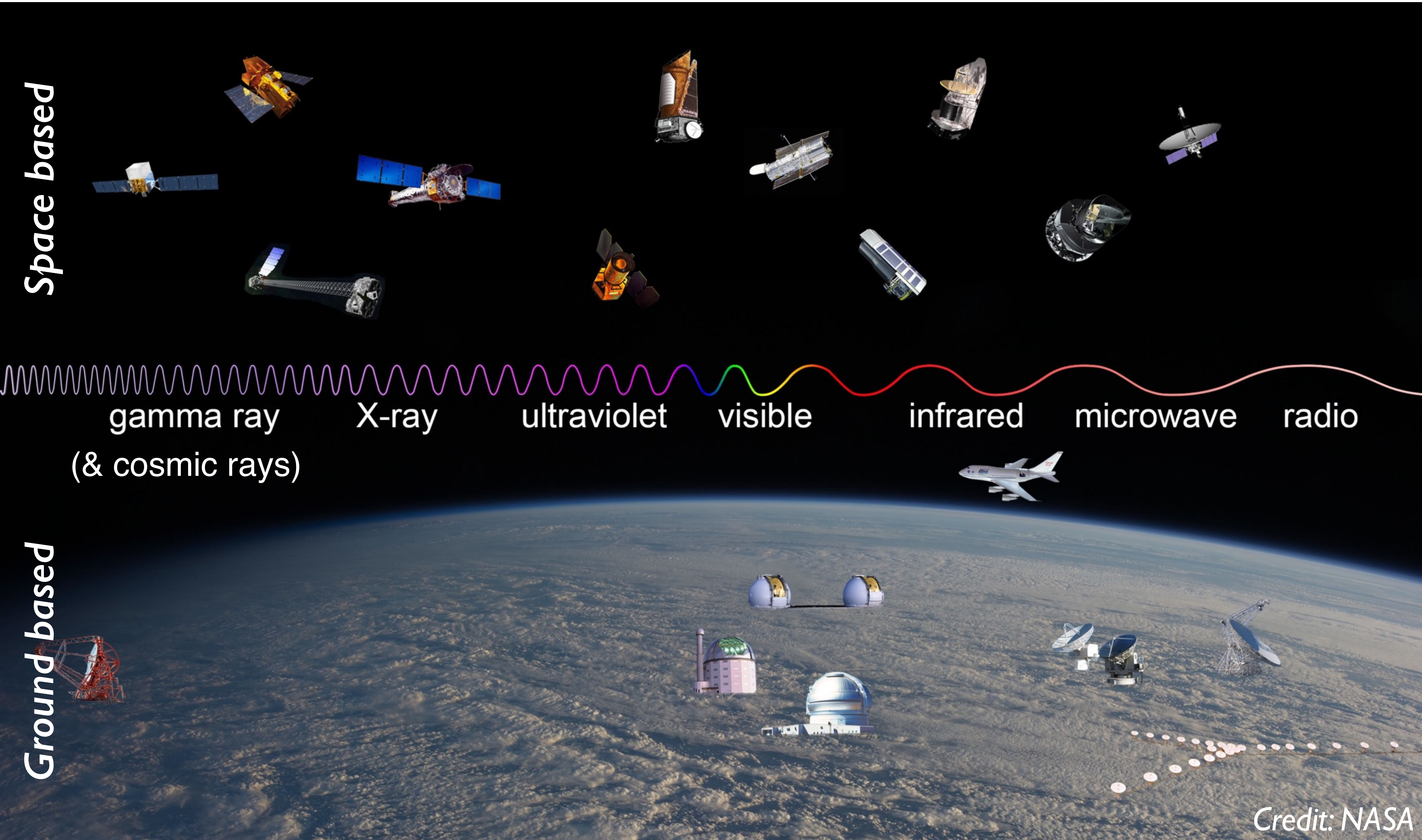
The astronomical data landscape

~10^{-43} GeV — dark matter mass — ~10^{67} GeV



The astronomical data landscape

~10^{-43} GeV | dark matter mass | ~ GeV/TeV | ~10^{67} GeV



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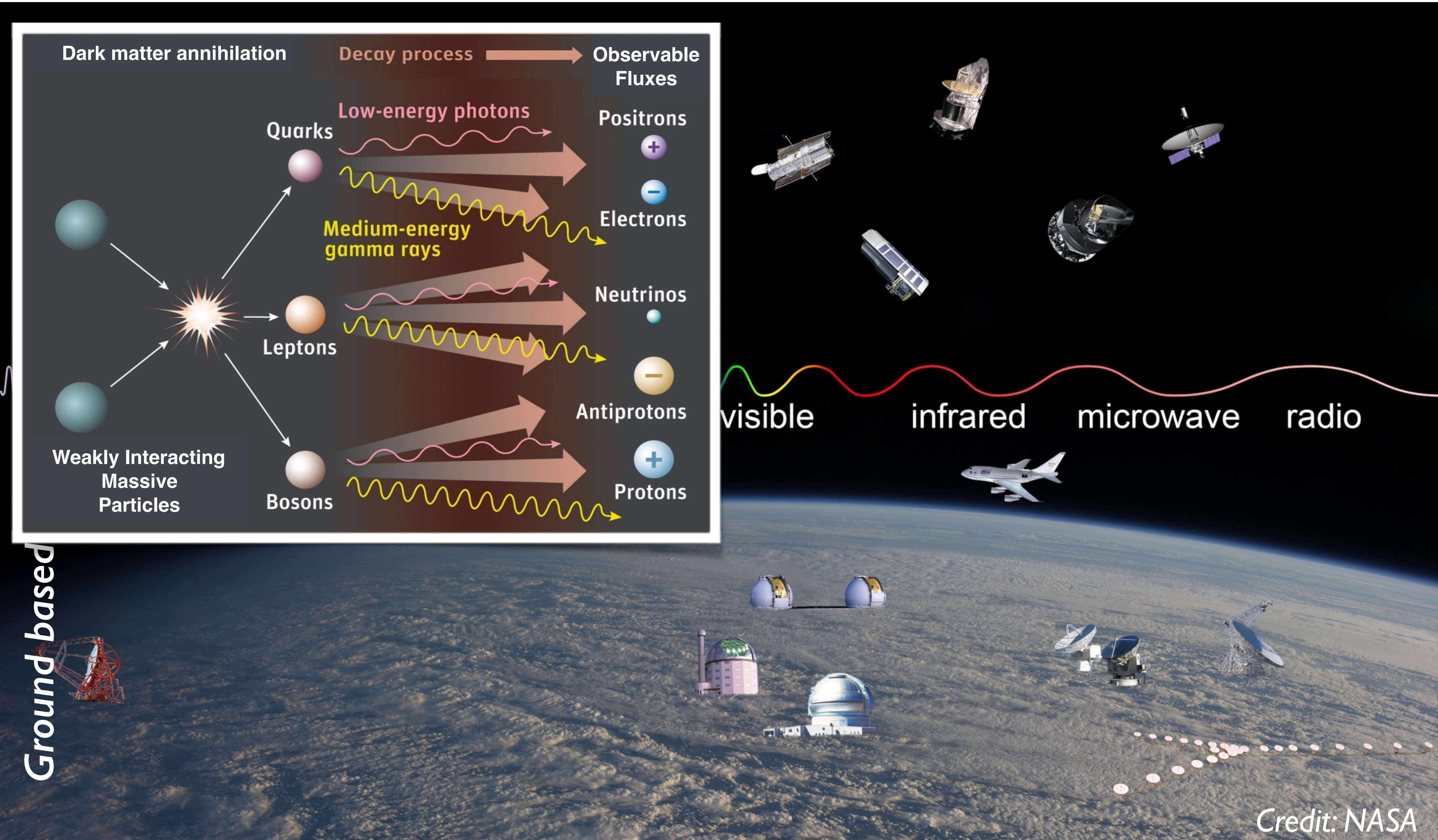
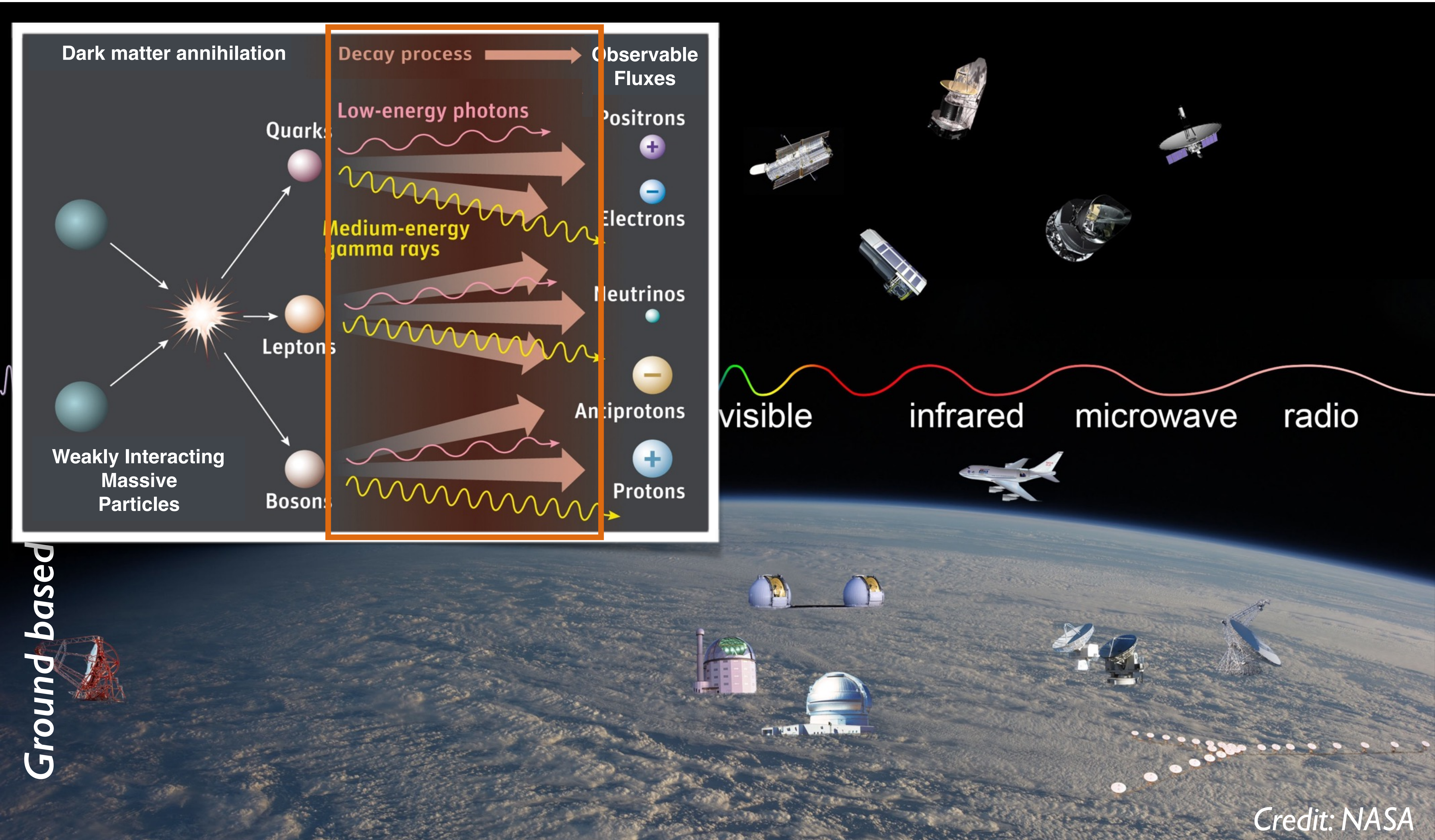


The astronomical data landscape

$\sim 10^{-43}$ GeV — dark matter mass — ~ GeV/TeV — $\sim 10^{67}$ GeV



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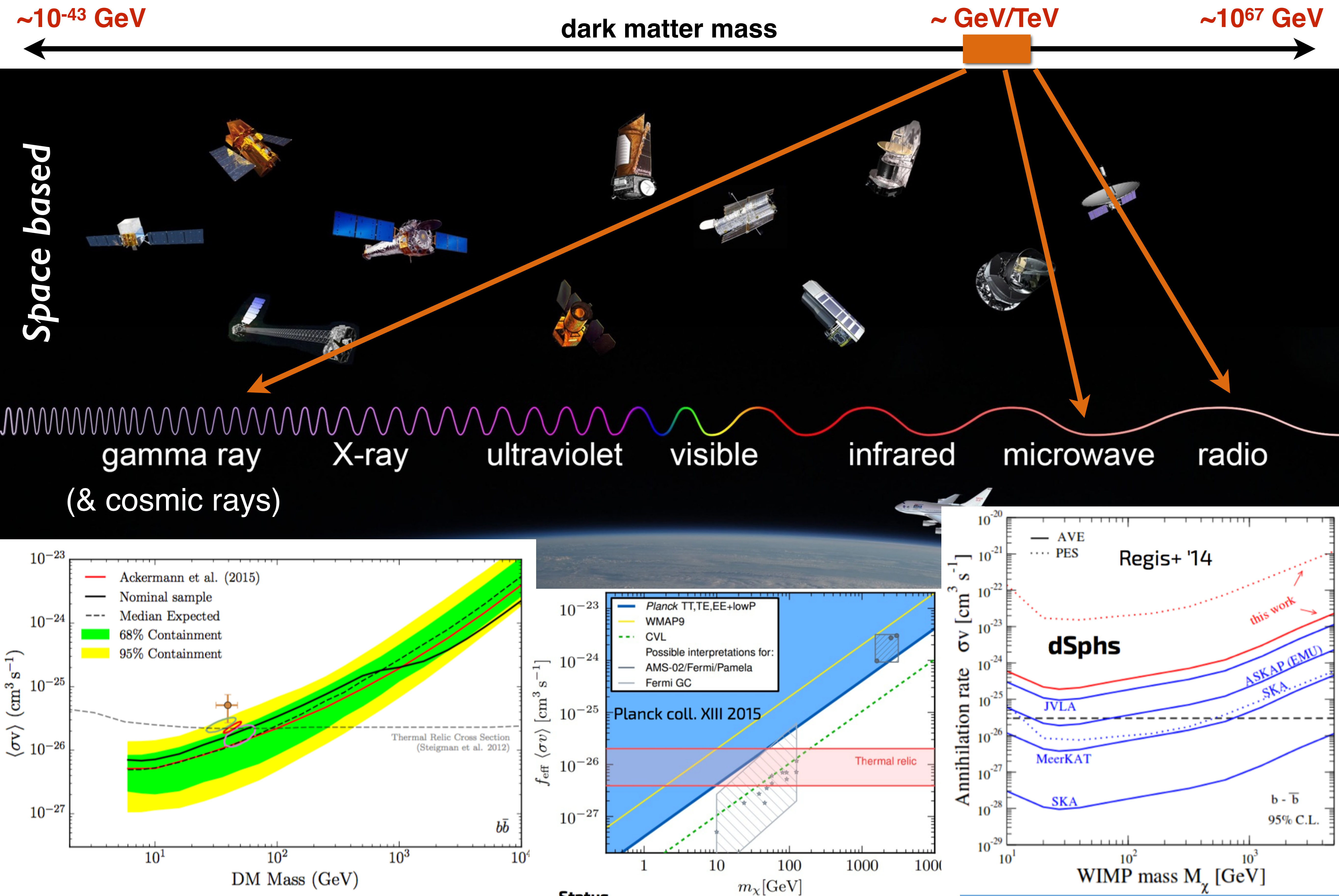
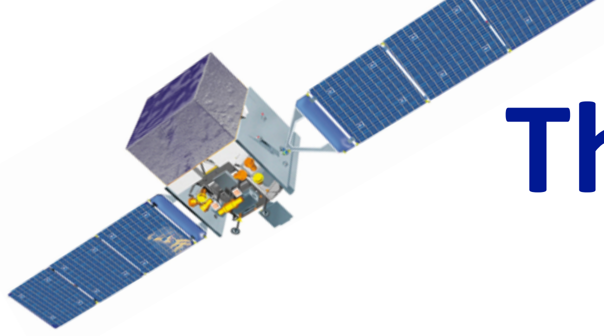
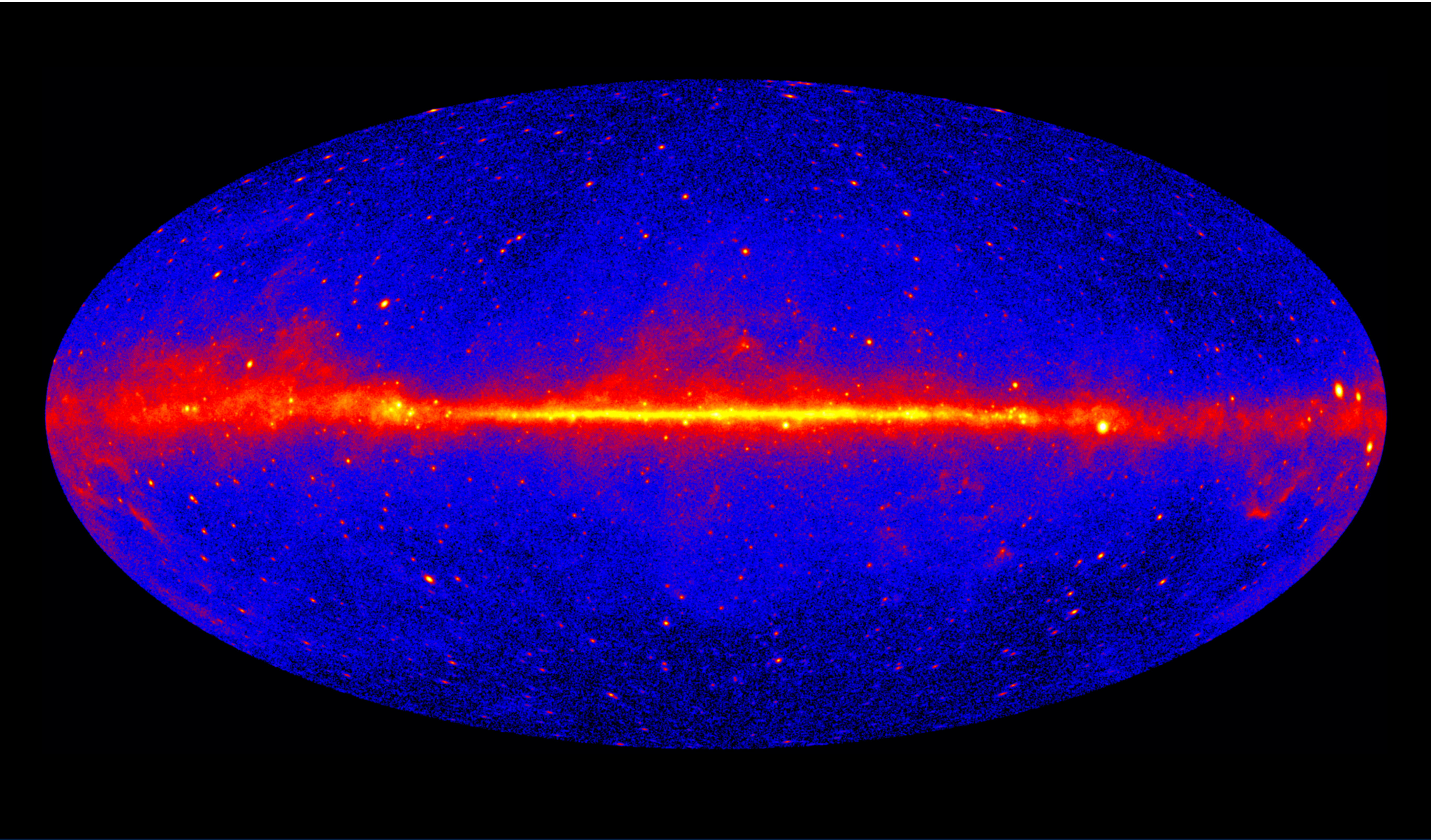
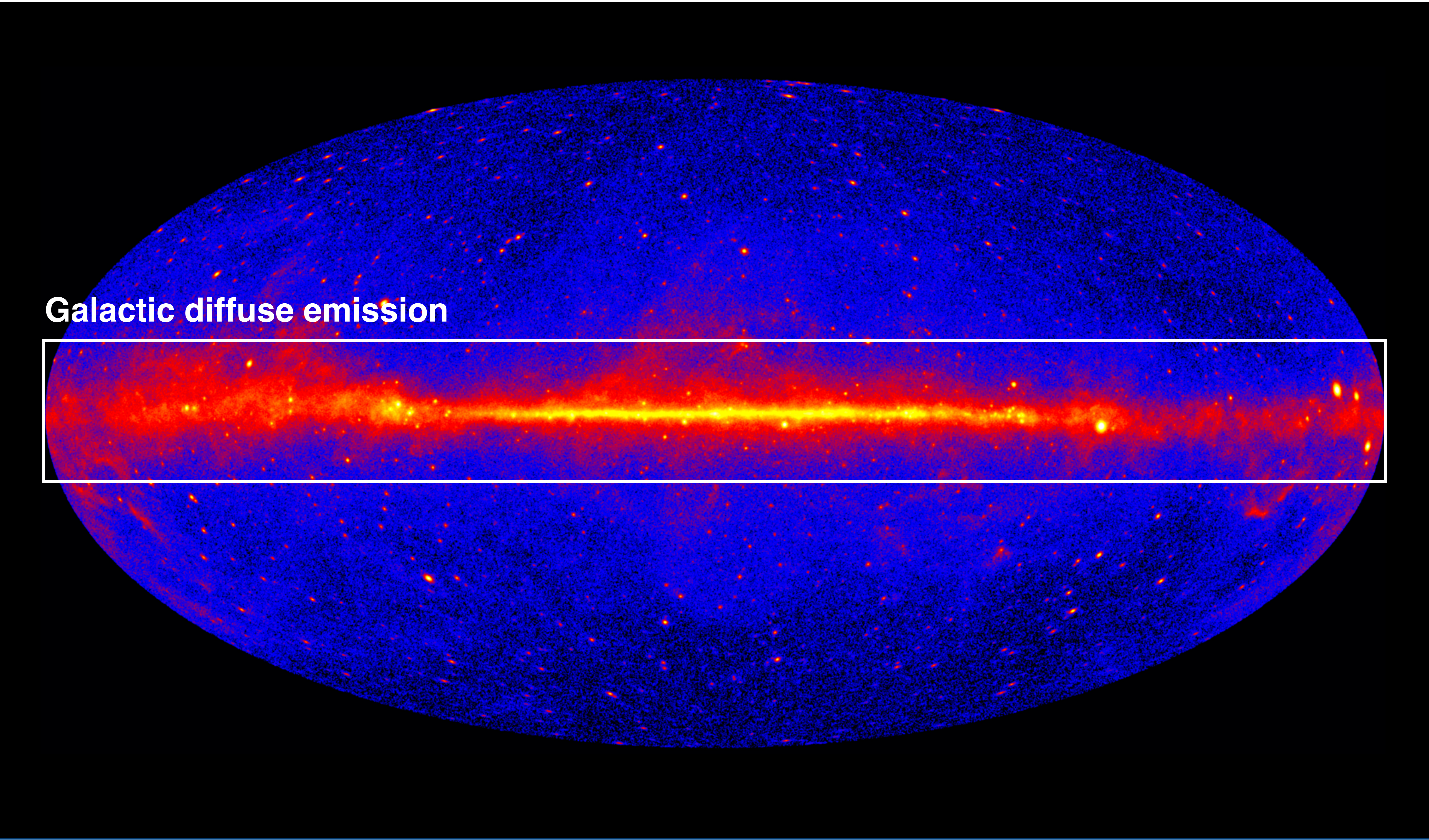




The Fermi-LAT gamma-ray sky



Astrophysical components



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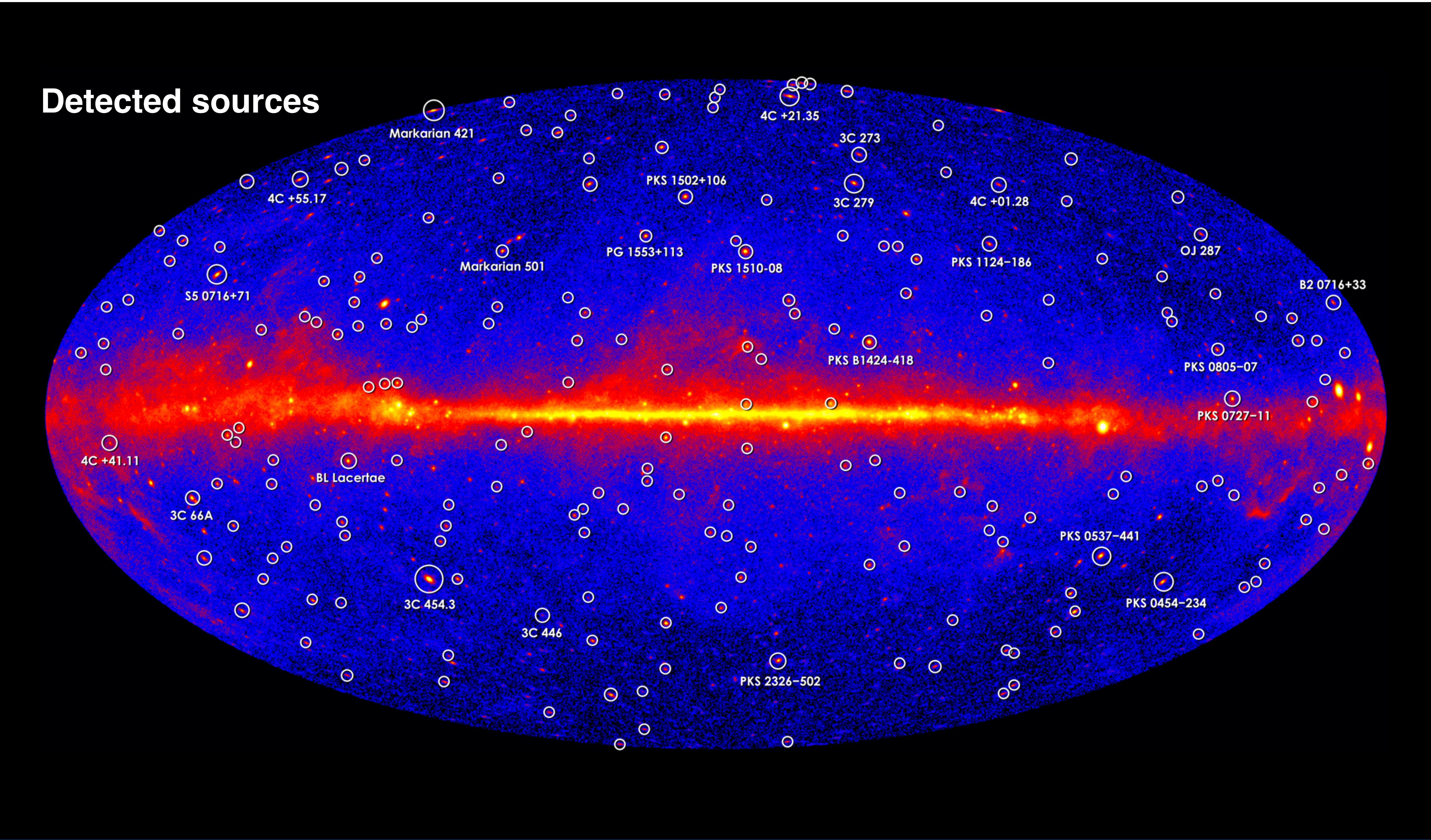
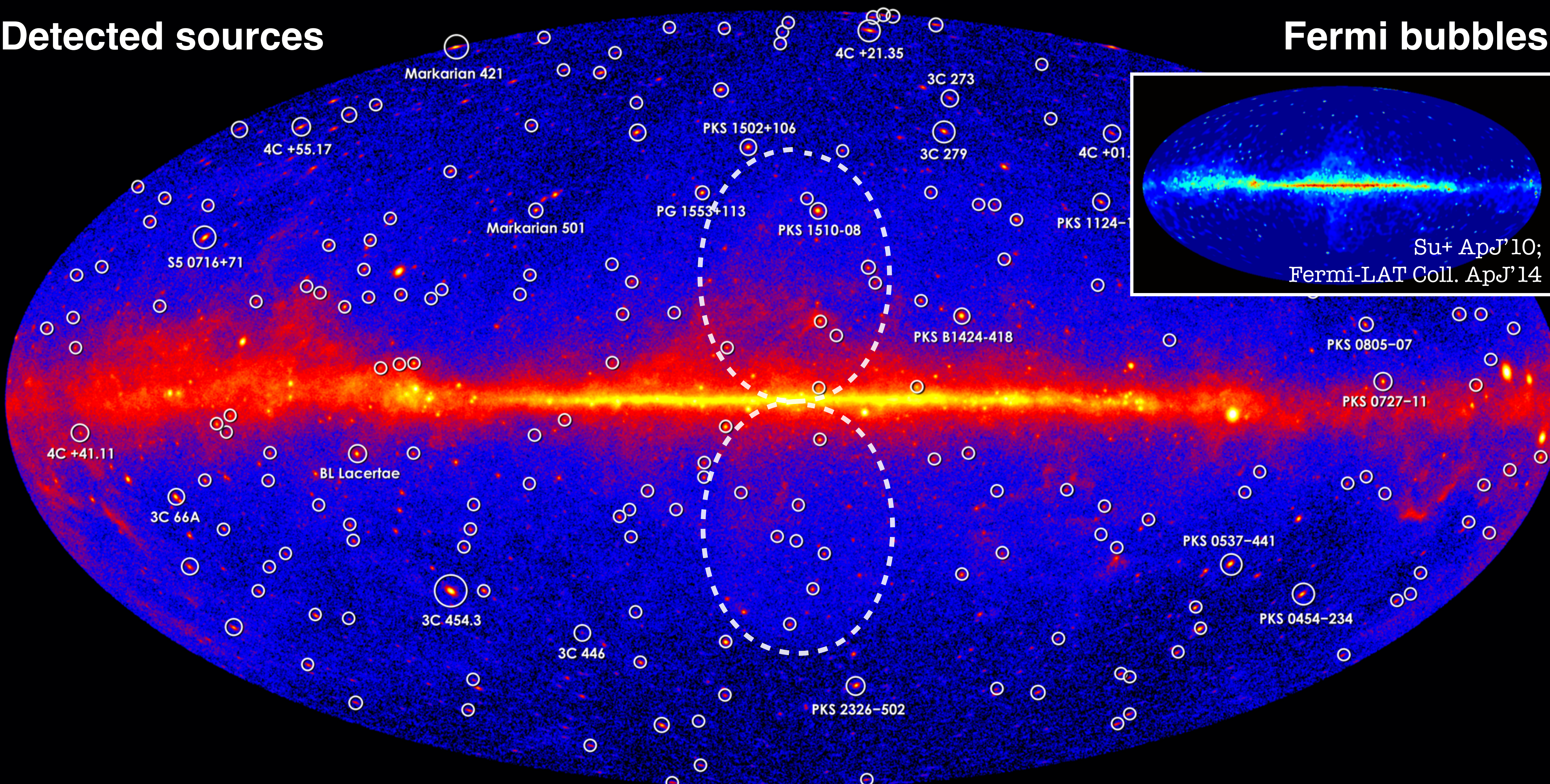


Astrophysical components

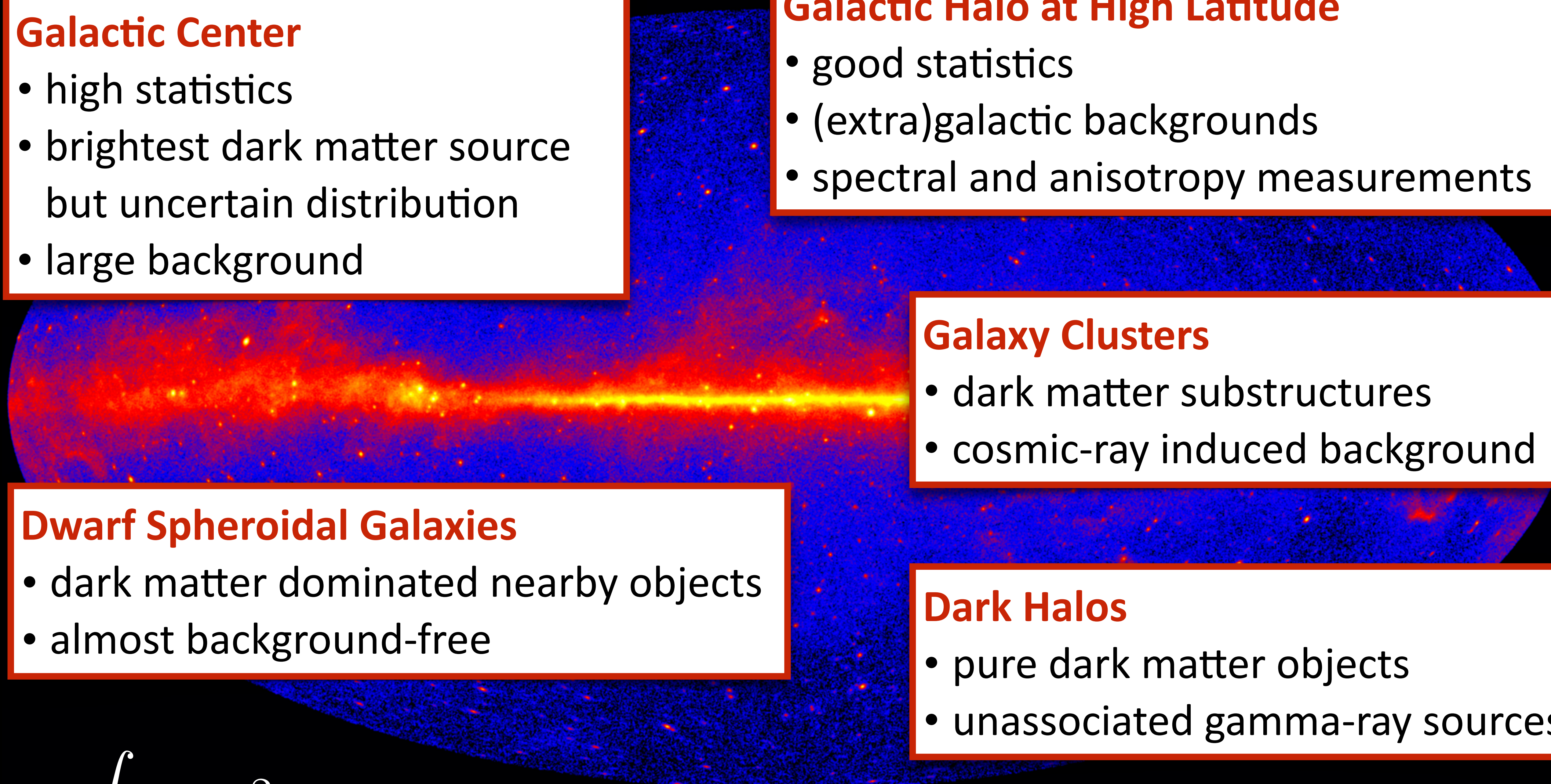
Detected sources

Fermi bubbles



Targets for dark matter searches

M. Fornasa, M. Sanchez-Conde talks



Galactic Center
- high statistics
- brightest dark matter source but uncertain distribution
- large background

Galactic Halo at High Latitude
- good statistics
- (extra)galactic backgrounds
- spectral and anisotropy measurements

Galaxy Clusters
- dark matter substructures
- cosmic-ray induced background

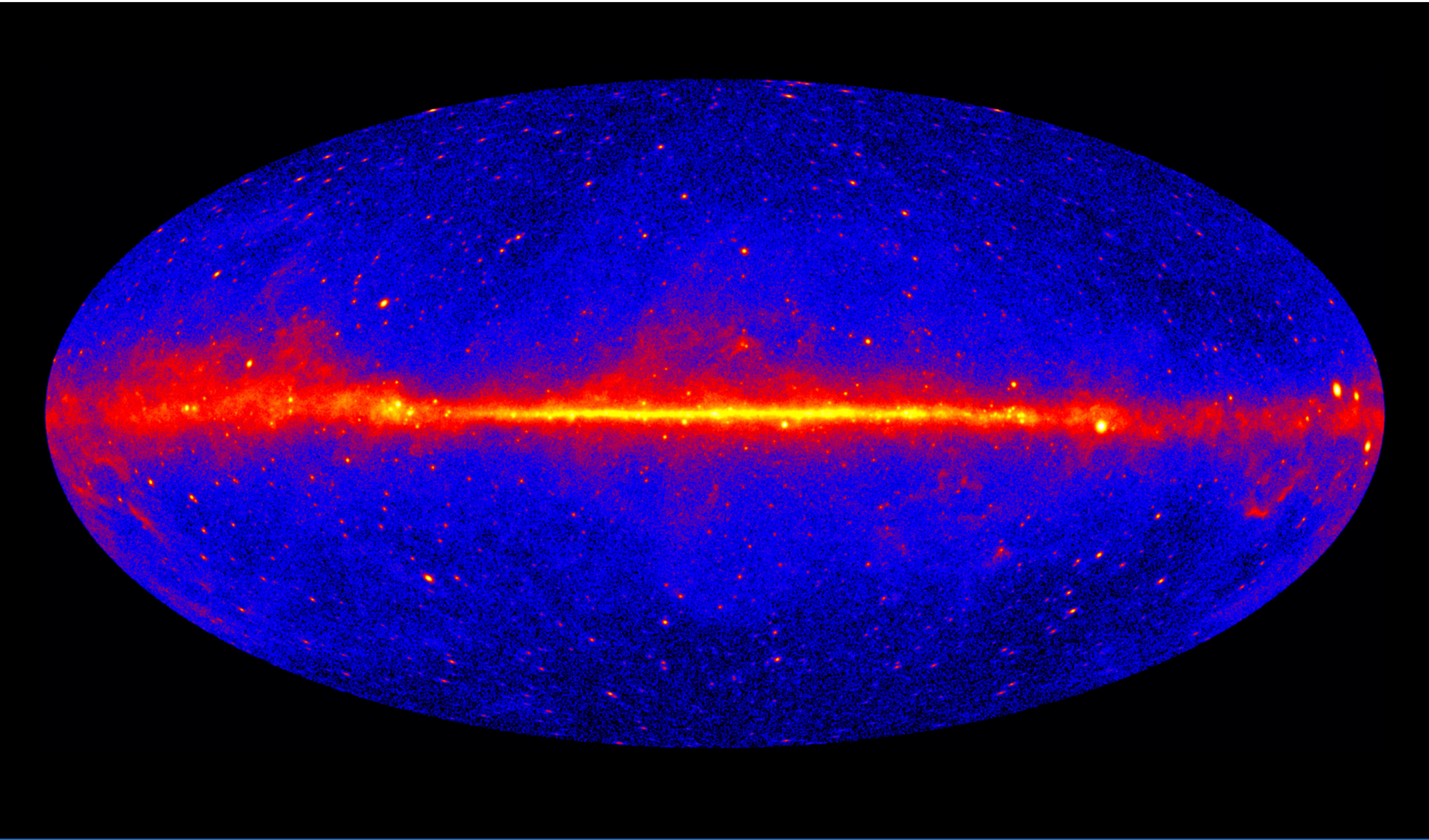
Dwarf Spheroidal Galaxies
- dark matter dominated nearby objects
- almost background-free

Dark Halos
- pure dark matter objects
- unassociated gamma-ray sources

$$\propto \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2 ds$$

+ dedicated searches for gamma-ray lines

The Galactic centre GeV excess



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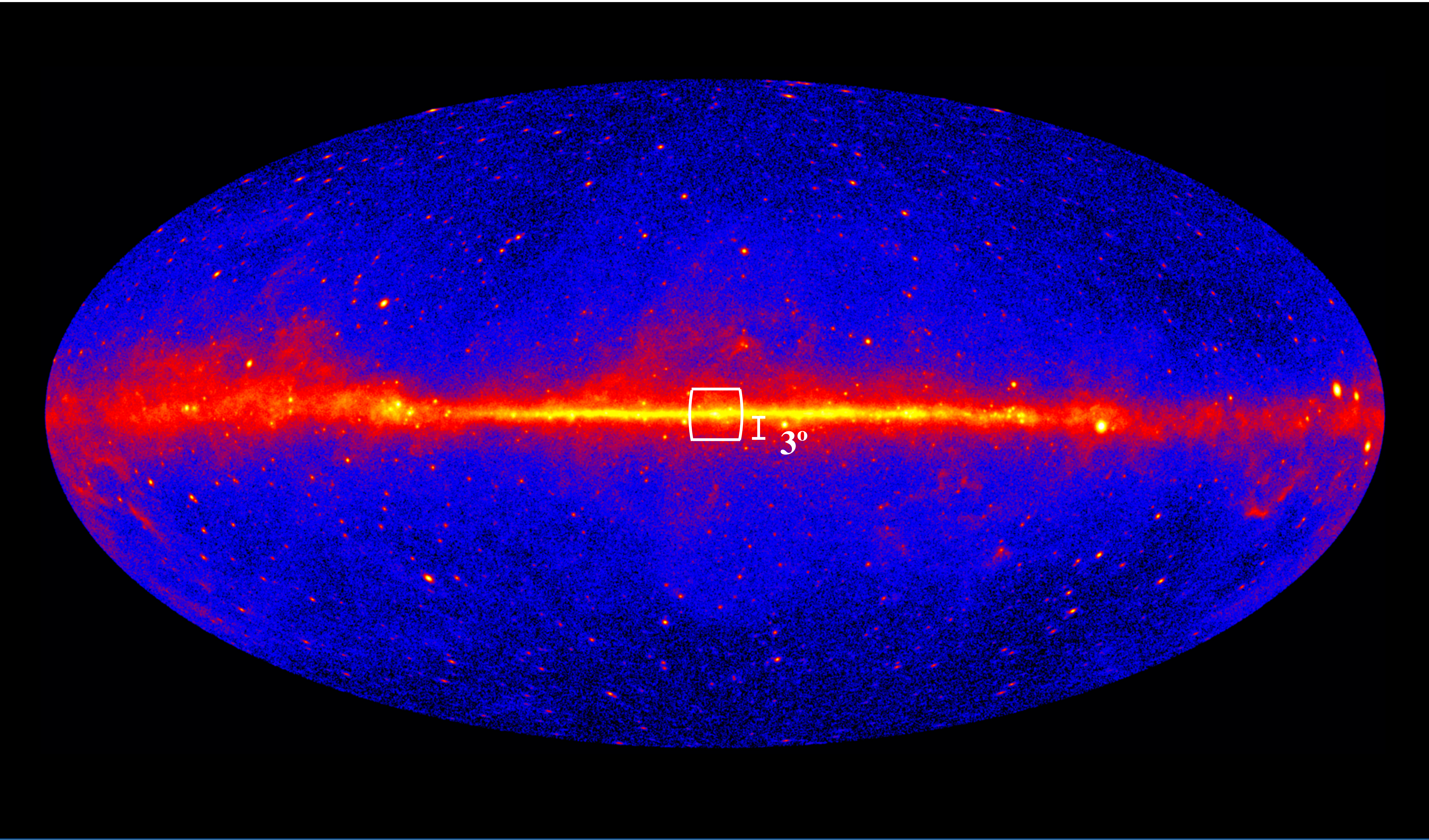

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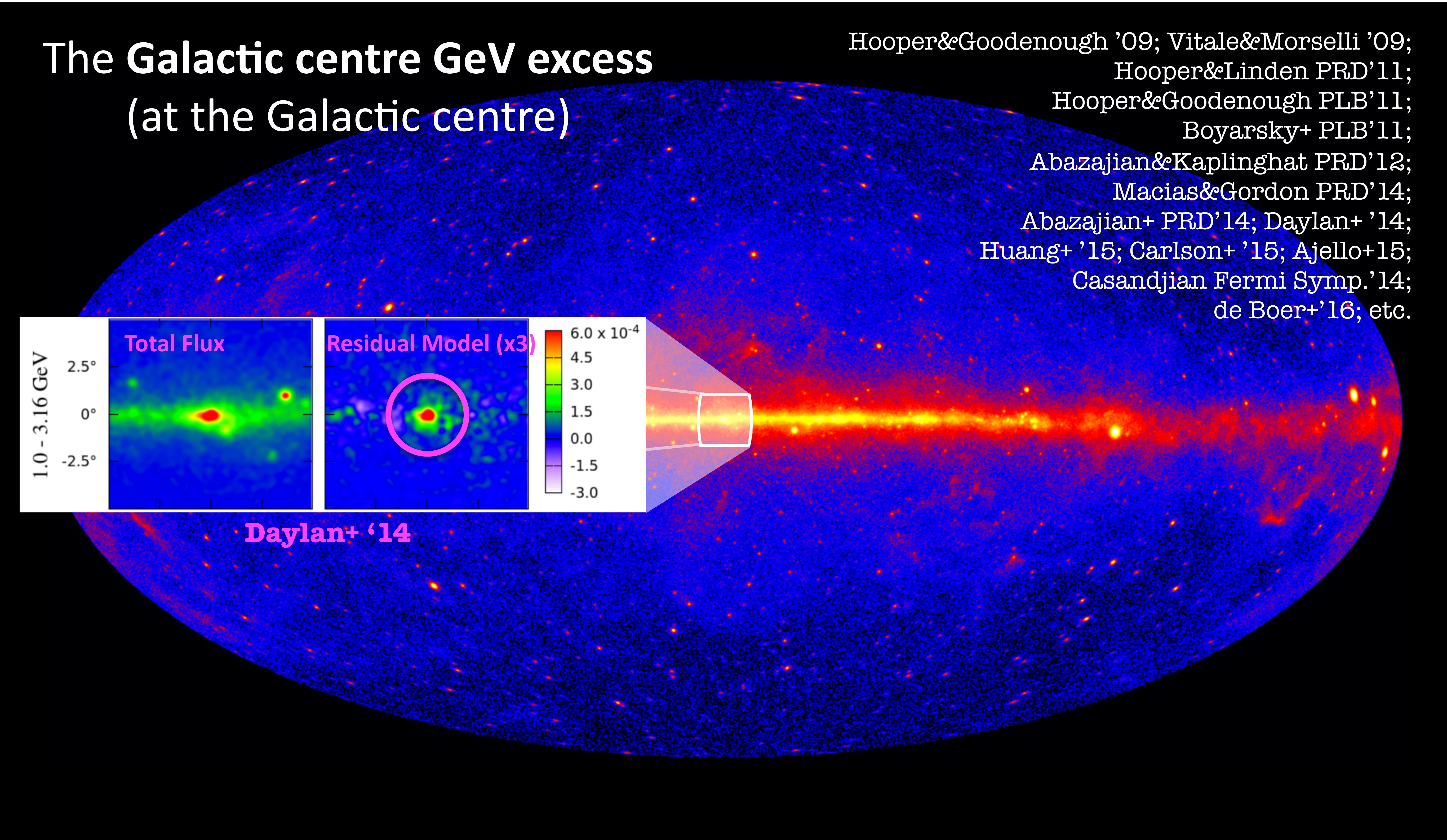
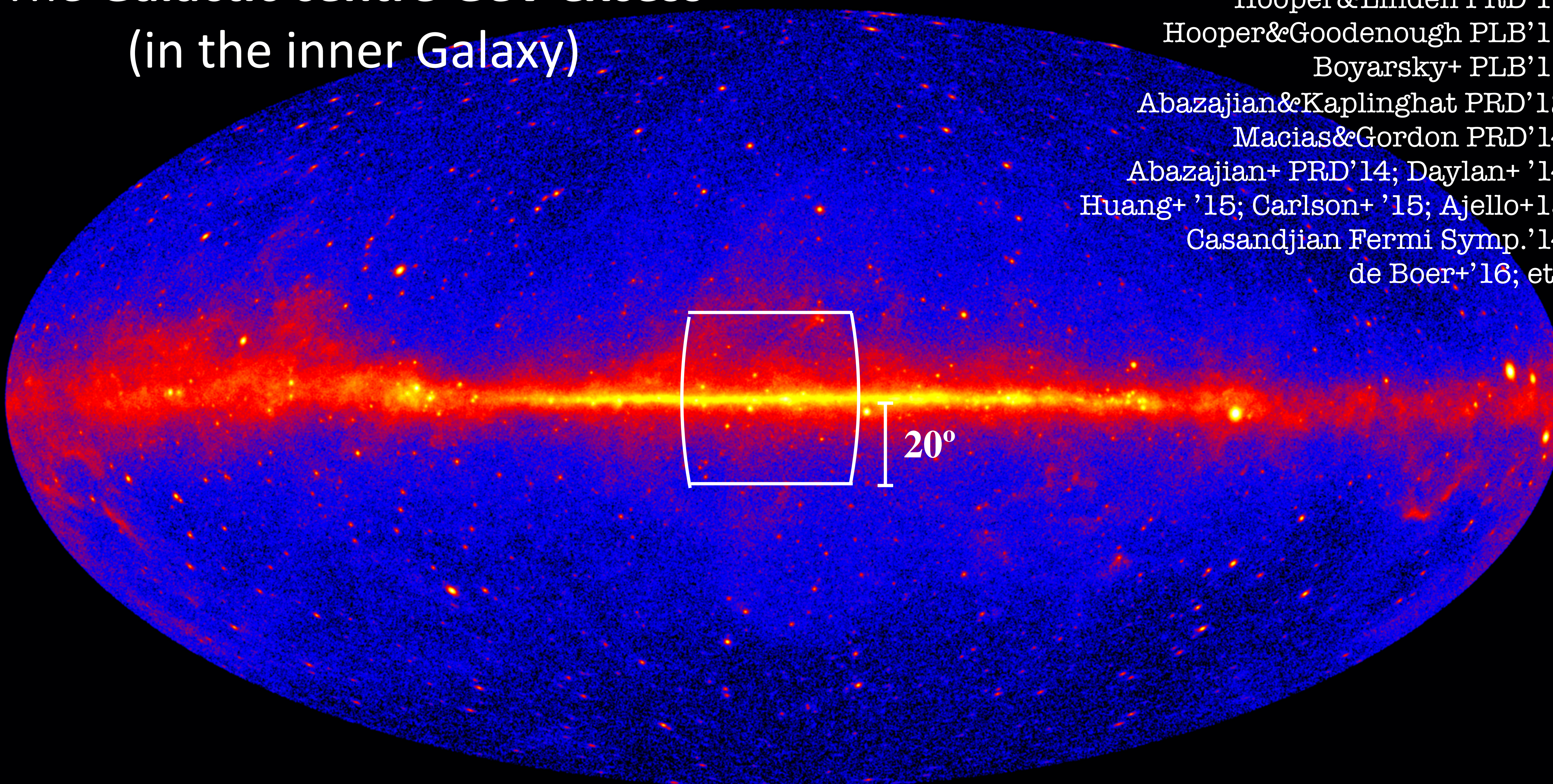


The Galactic centre GeV excess

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

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; etc.



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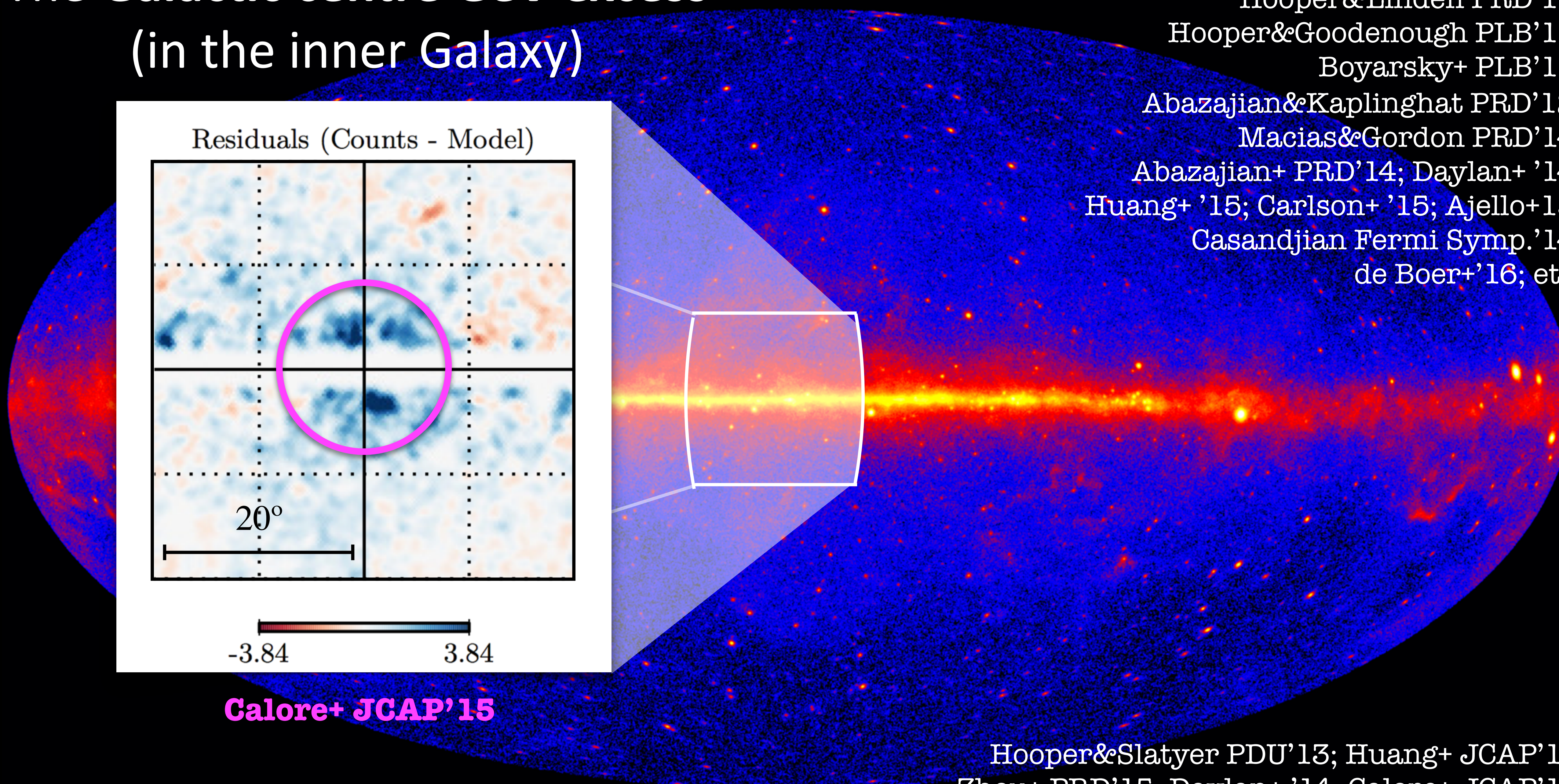


Calore+ JCAP'15

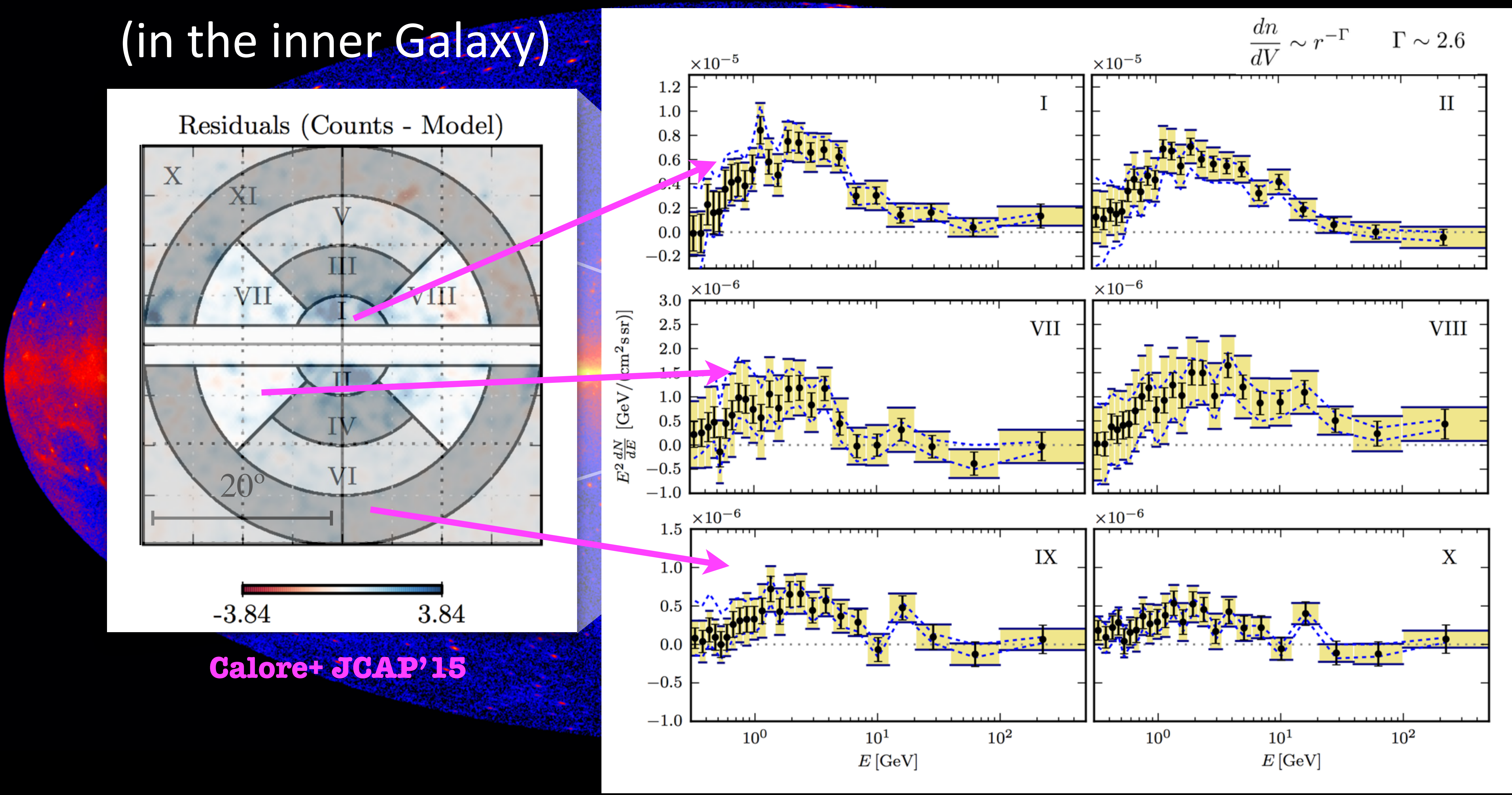
Hooper&Slatyer PDU'13; Huang+ JCAP'13;
Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15;
Gaggero+ 2015; Ajello+ 2015; Huang+ '15
Linden+'16; Horiuchi+'16; etc.

The Galactic centre GeV excess

1.Uniform spectrum peaked at ~2 GeV

2.Extended *at least* up to 10 degrees

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



Calore+ JCAP'15

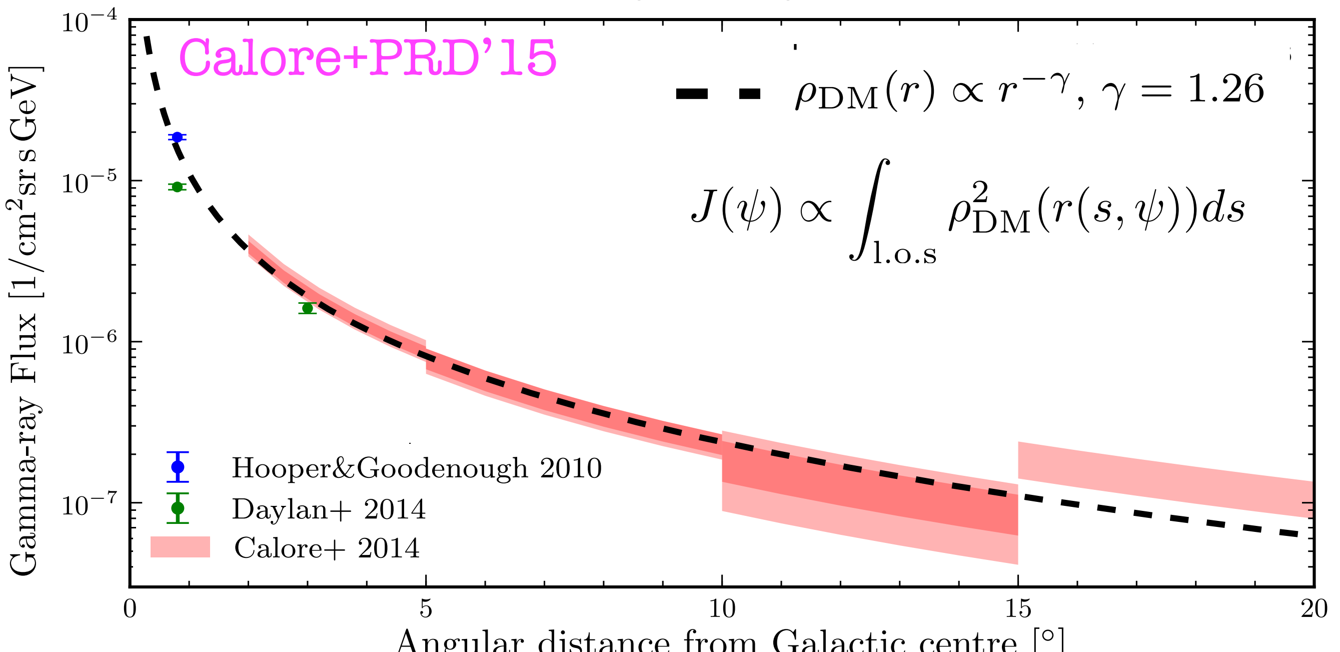
Possible interpretations

Unresolved sources

- ✓ Spectrum compatible with Fermi-LAT observed **millisecond pulsars** (MSPs), and marginally **young pulsars**.
- ✓ Plausible population of young pulsars in the CMZ and/or bulge MSPs from tidally disrupted globular clusters.
  O'Leary+ '15; Brandt&Kocsis'15
- ✓ Strong support for population of discrete faint sources from wavelet decomposition and non-poissonian noise.
  Bartels+PRL'16; Lee+PRL'16
- ✓ Future dedicated radio observations can allow us to **discover the bulge point source population**.
  Calore+ApJ'16

Truly diffuse processes

- ✓ Steady-state star formation at the Galactic centre and continuous injection of cosmic rays.
  Gaggero+ JCAP'15; Carlson+'15
- ✓ Past activity of the central black hole and series of leptonic outbursts — some fine tuning required.
  Petrovic+ JCAP'14; Cholis+JCAP'15
- ✓ Annihilation of DM particles in the halo of the Milky Way. > O(100) papers

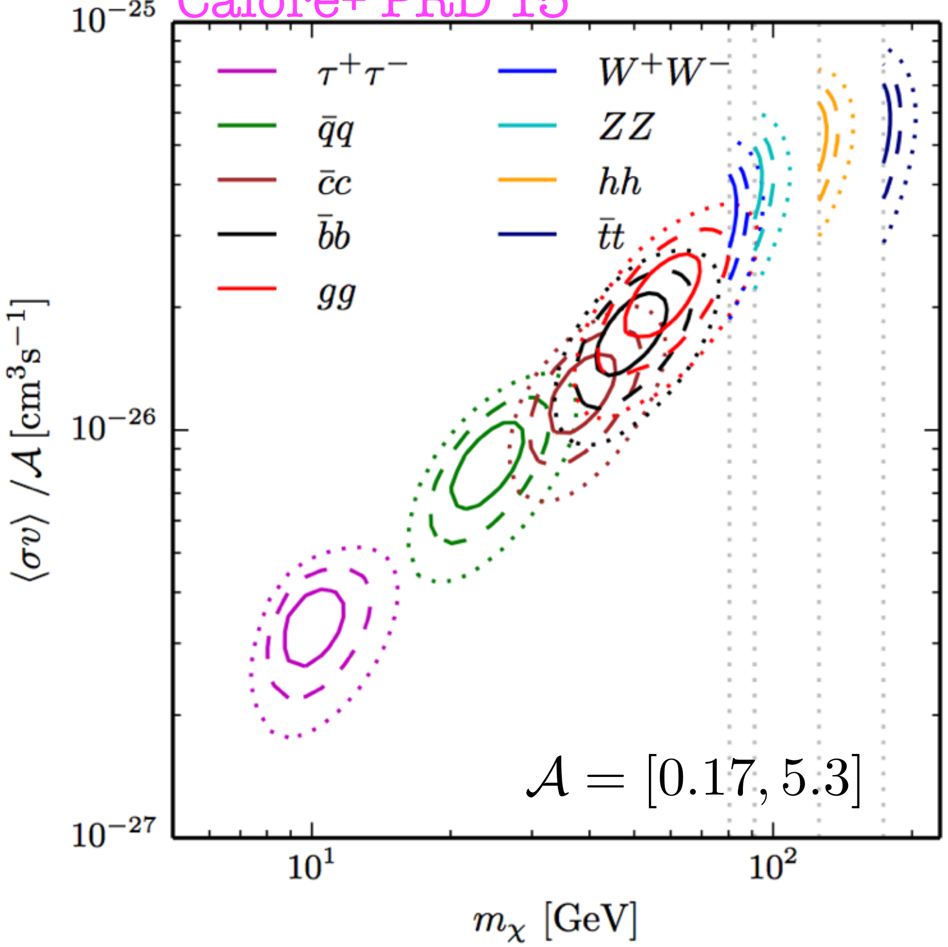


Dark matter annihilation

Spectrum

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

Calore+ PRD'15



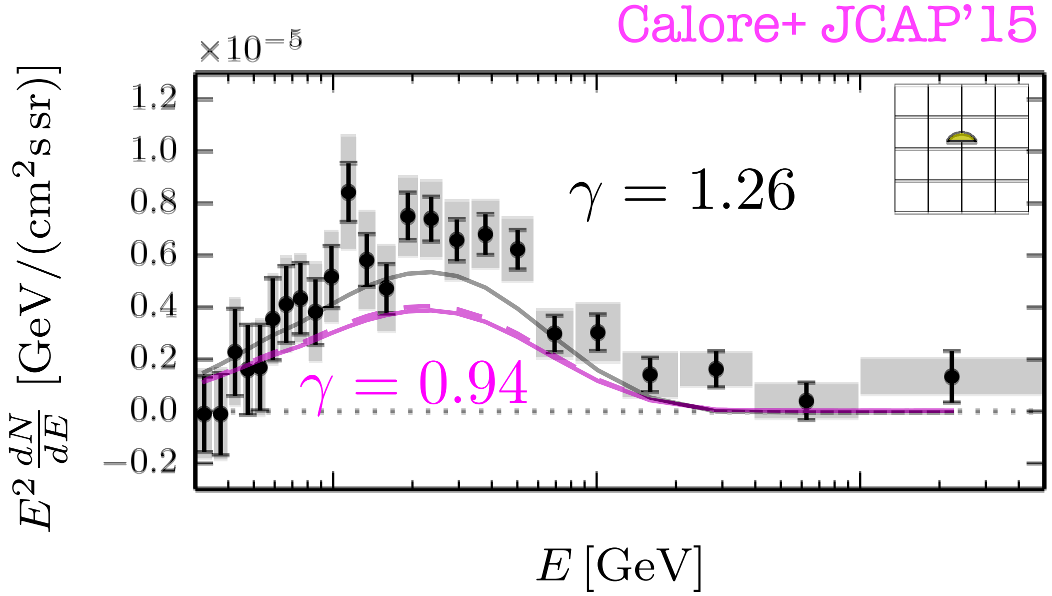
Agrawal+JCAP'15; Achterberg +JCAP'15; Bertone+ JCAP'15; Liem+ JCAP'16; etc.

Morphology

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

N. Bozorgnia's talk

Calore+ JCAP'15



+ non-sphericity of the high-E excess?

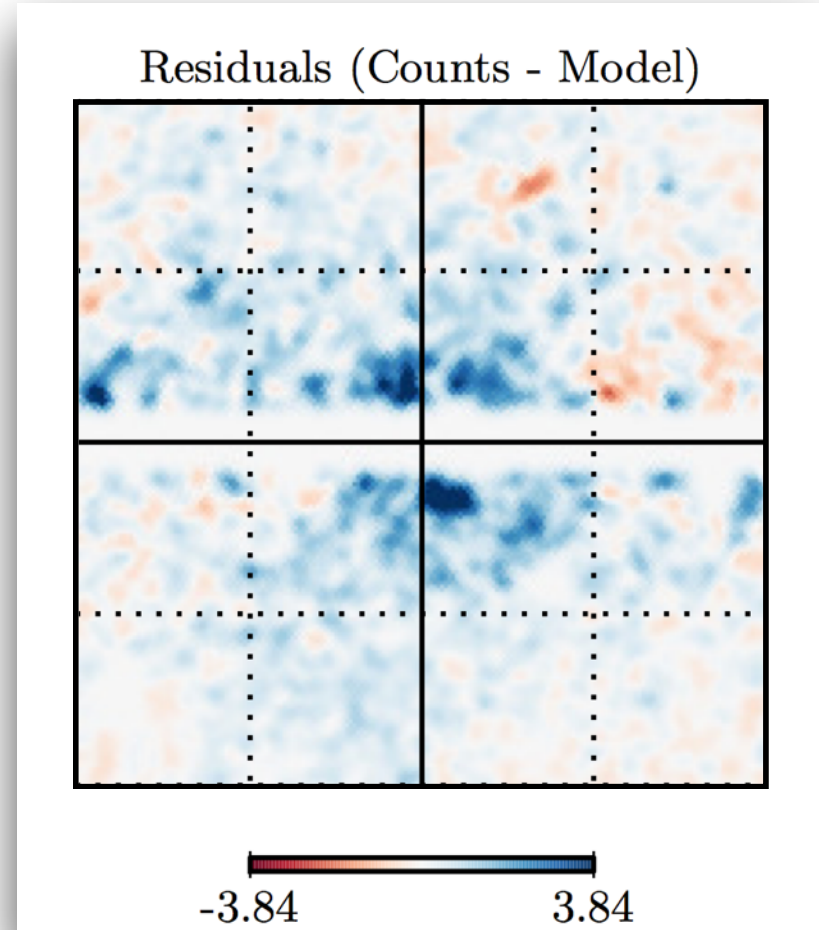
Linden+'16

+ disk component?

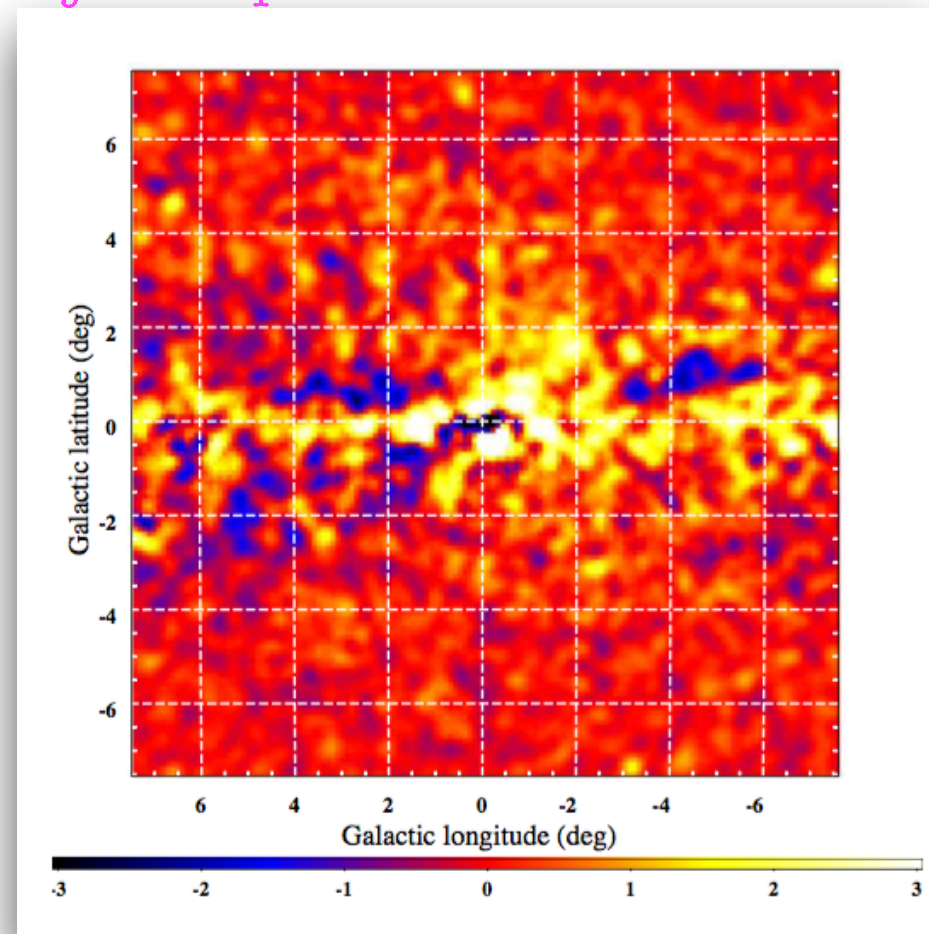
Huang+JCAP'16, de Boer+'16

Diffuse emission and residuals

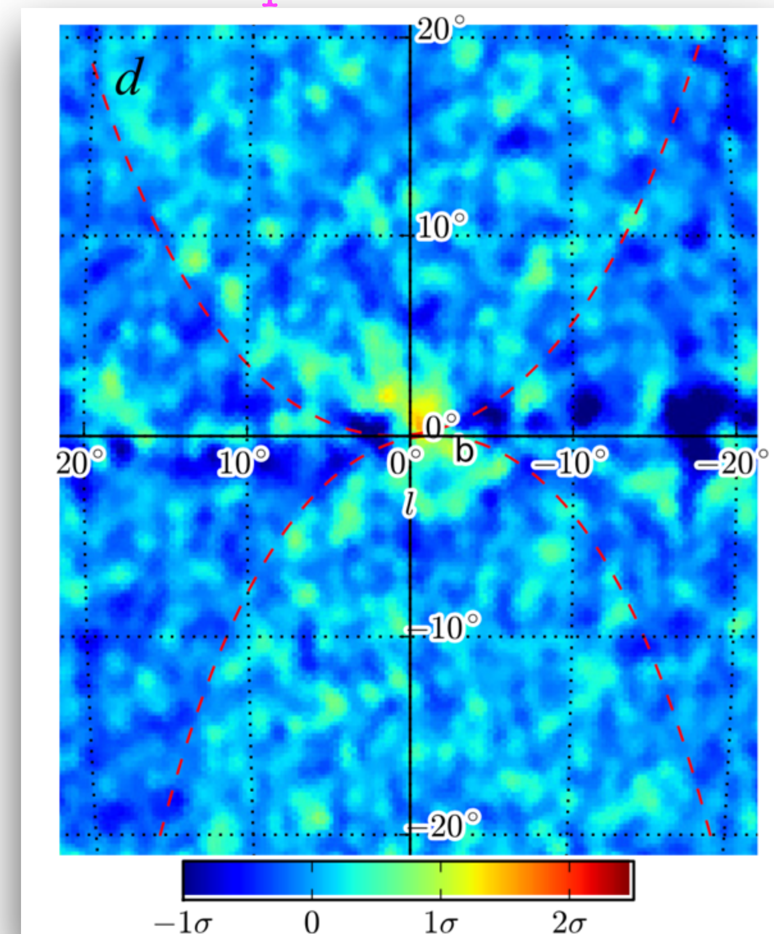
Calore+ JCAP'15



Ajello+ ApJ'15



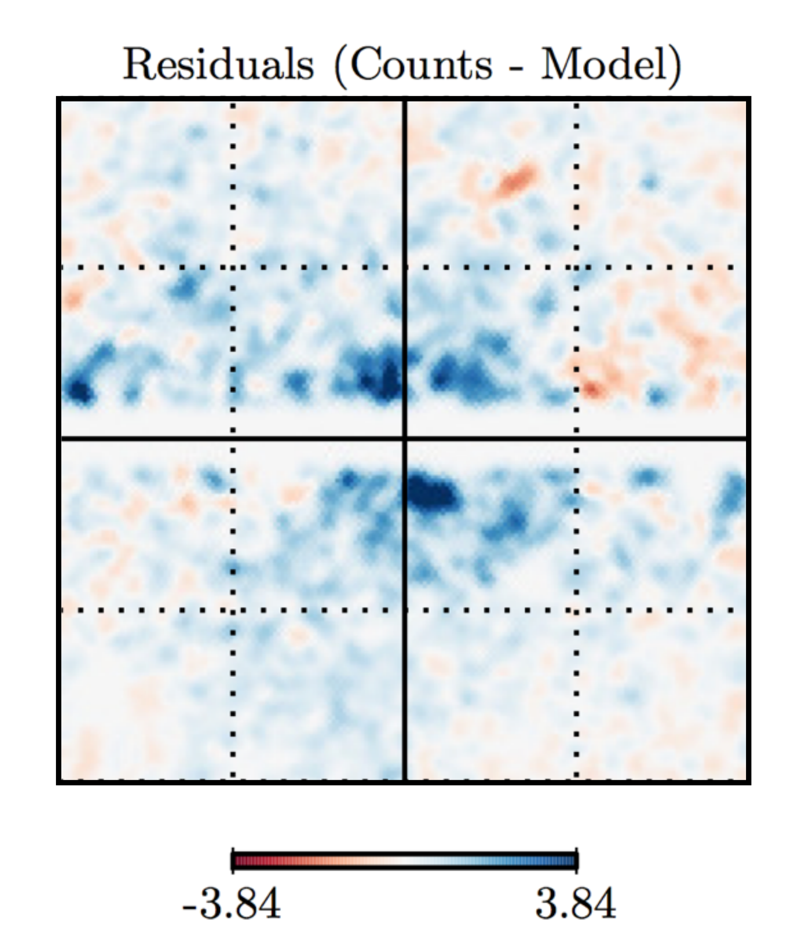
Acero+ ApJS'16



- None of the diffuse emission models gives reasonable fit to the data.
- Models excluded by many sigmas when performing goodness of fit.
- There are other excesses along the disk that are not understood, but that can be explained by background modelling uncertainties!

Diffuse emission and residuals

Calore+ JCAP'15



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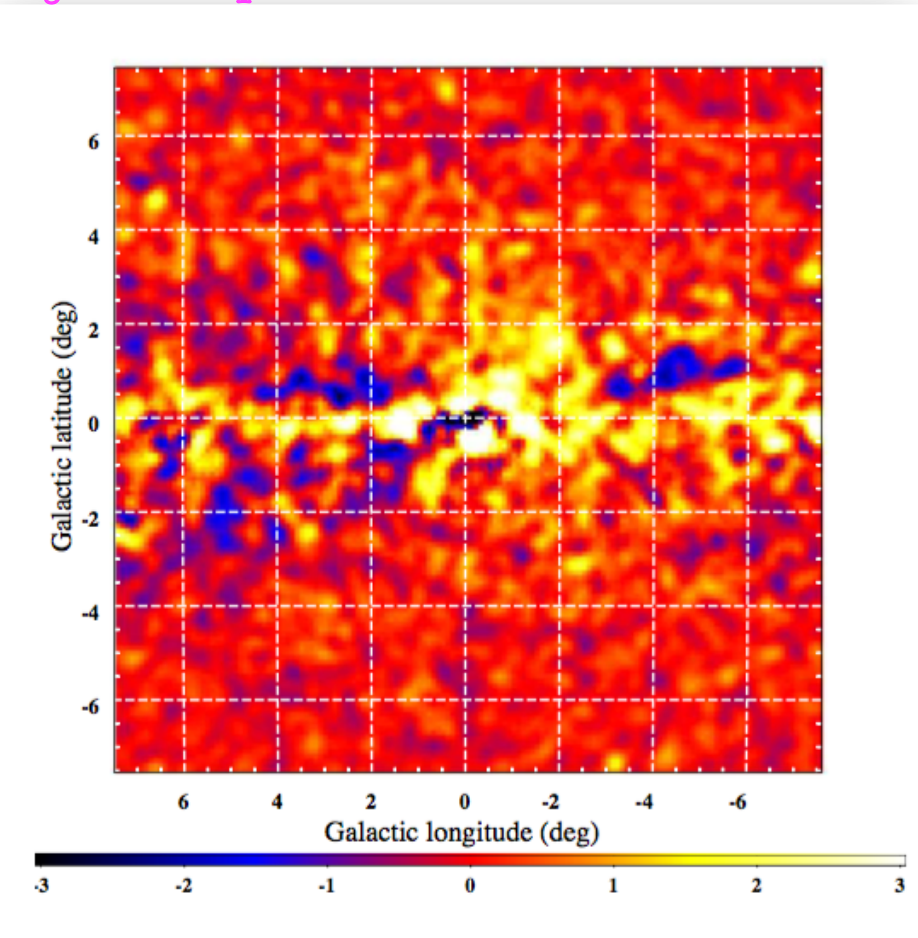

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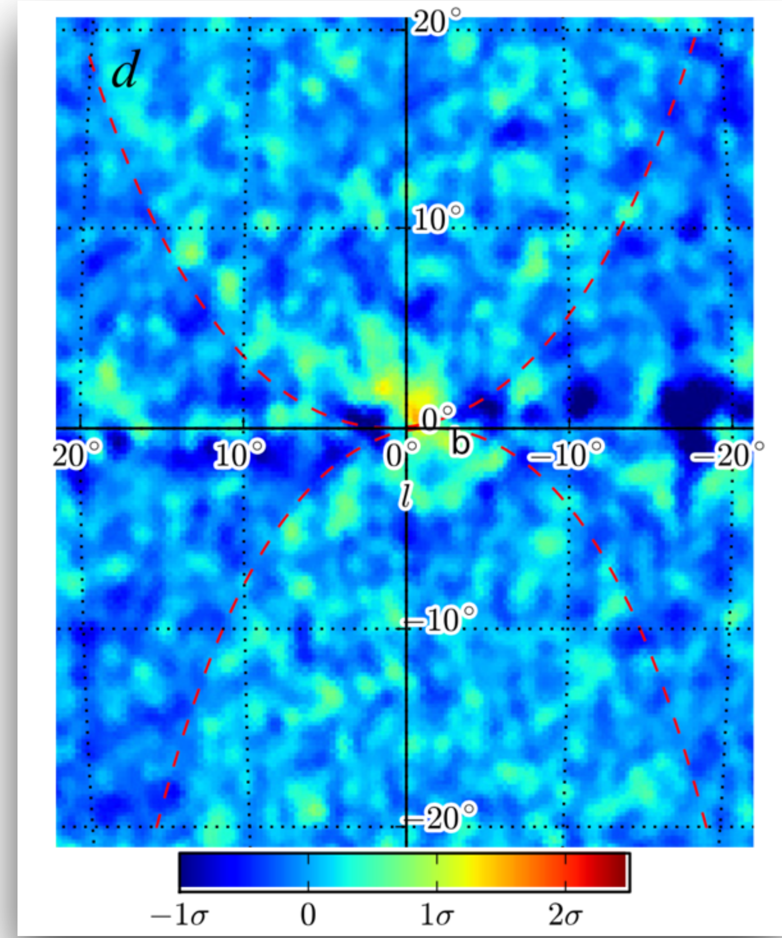

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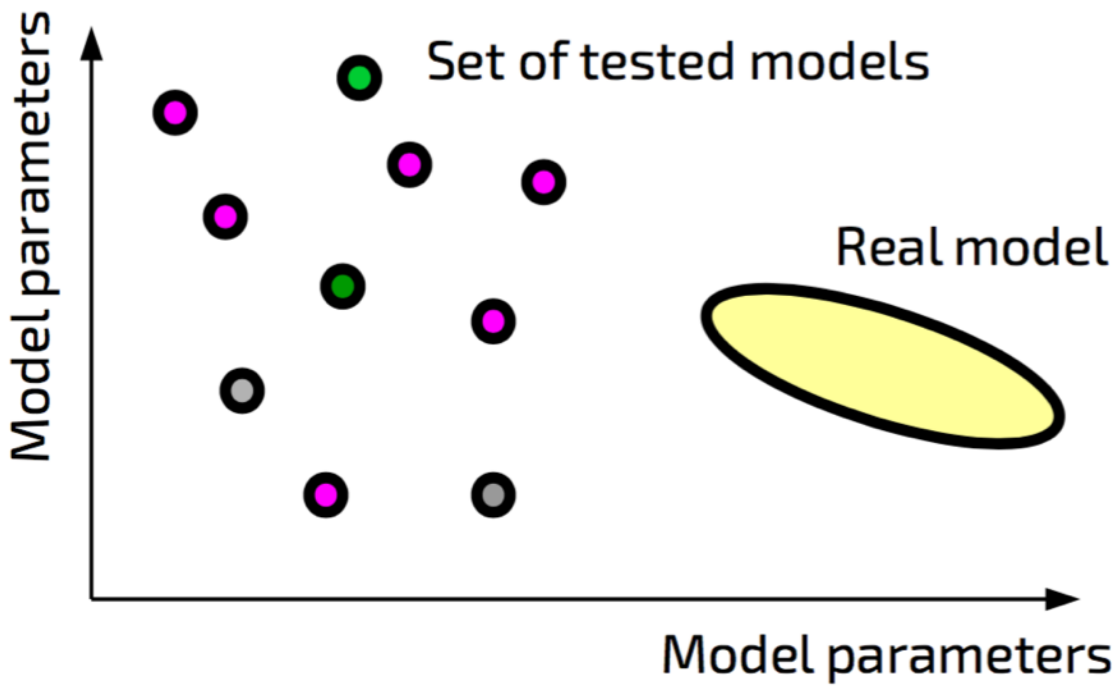
How can we trust the characterisation of large scale residual emissions?

First, we need to achieve good fits



Among the tested models, even the best-fit one leaves large residuals.

Bracketing uncertainties with models that are largely excluded leads to **biased results**.

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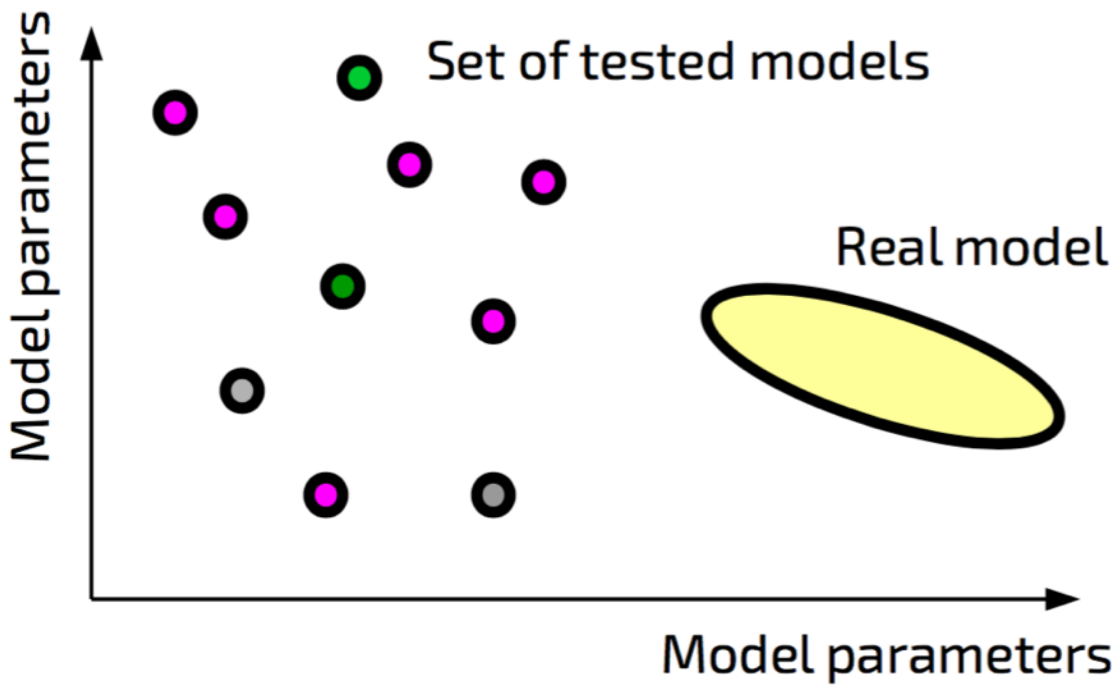

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HOW TO PROGRESS?

- Better theoretical predictions, e.g. 3D ISRF, gas maps, etc.
- A way to fit the data taking into account uncertainties on those predictions.

➡ Those uncertainties are there, we need to parameterise them!

➡ We need to increase the number of free parameters!

General: Fit to gamma-ray data

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

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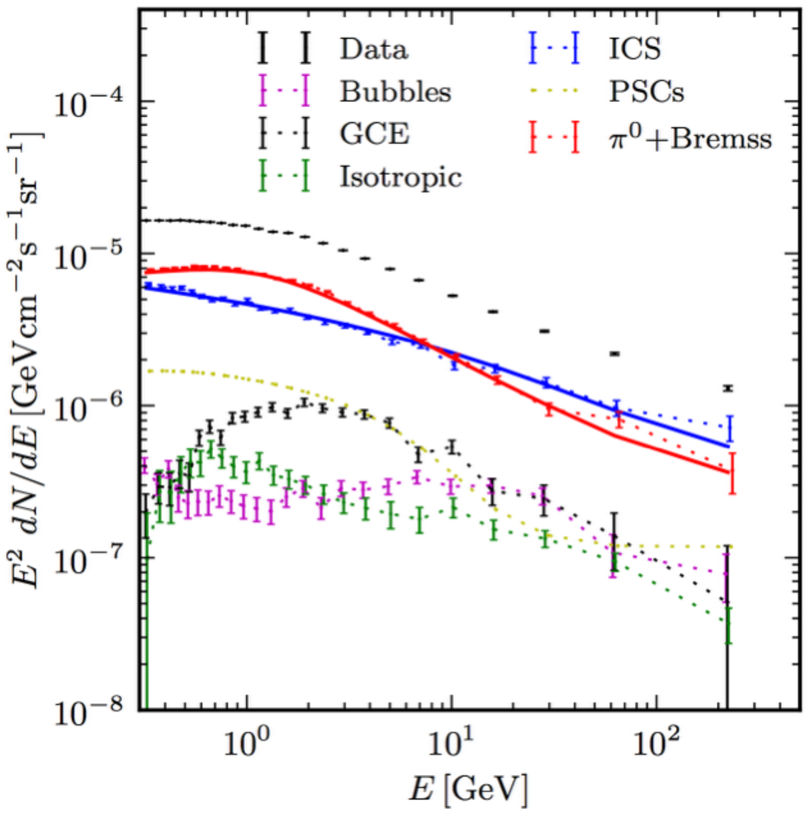

$$\mu_{ij} = \sum_k \mathrm{T}_i^{(k)} \theta_j^{(k)}$$

i: spatial pixel
j: energy bin
k: model component

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

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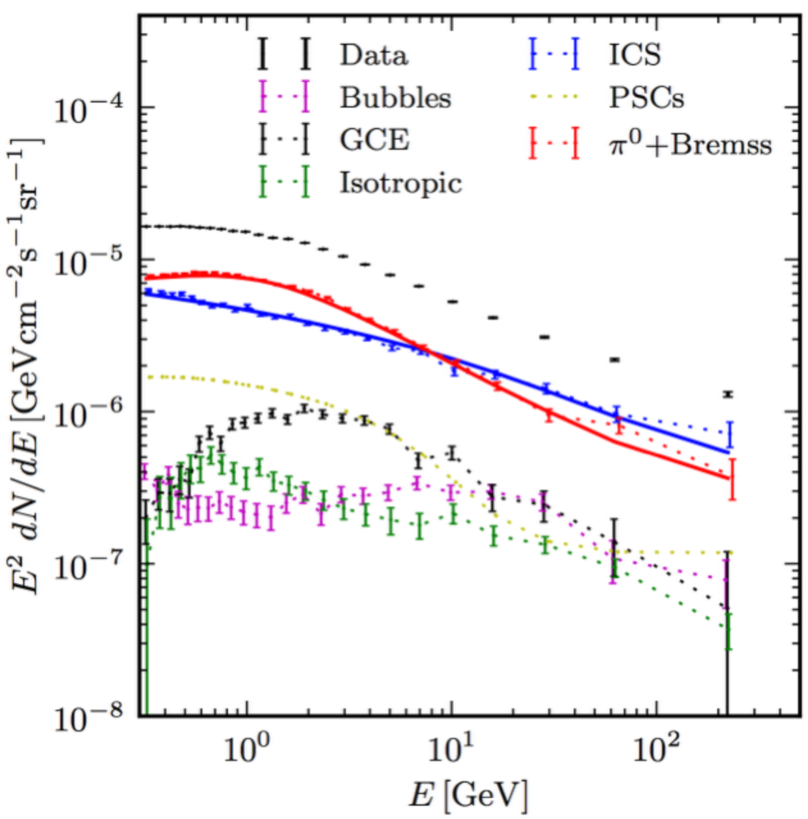

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Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; Calore+ JCAP'15; Ajello+ ApJ'15; Gaggero+ JCAP'15

$$\mu_{ij} = \sum_k \mathsf{S}_j^{(k)} \theta_i^{(k)}$$

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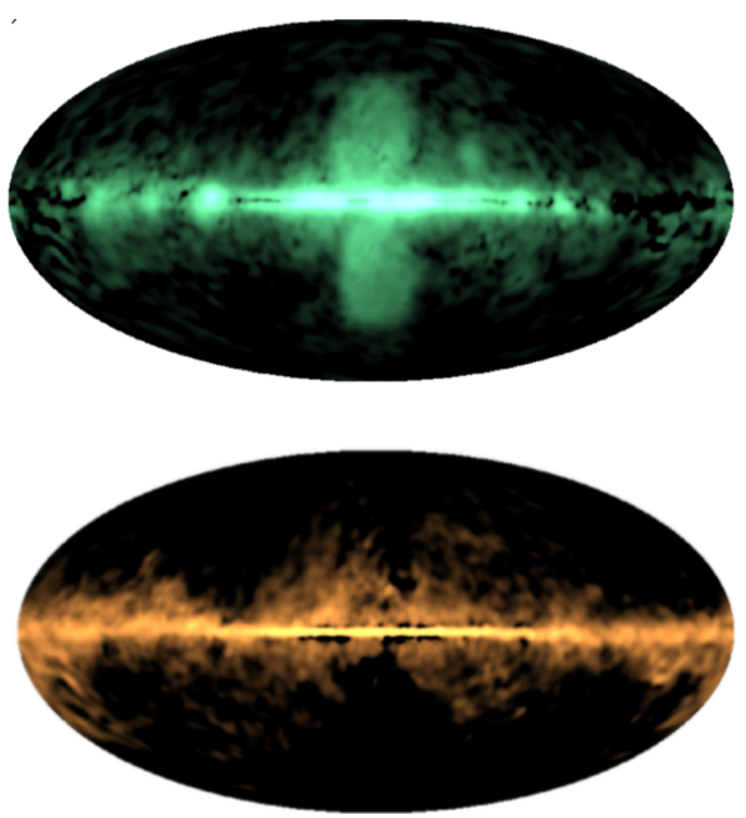
j: energy bin
k: model component



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

A new approach

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

Spectra parameterisation from physical models is uncertain

Pixel-by-pixel variations. To account for them a large number of **additional free parameters** is required!

$$\mu_{ij} = \sum_k \mathrm{T}_i^{(k)} \mathrm{S}_j^{(k)} \theta_i^{(k)} \theta_j^{(k)} \theta^{(k)} \longrightarrow$$

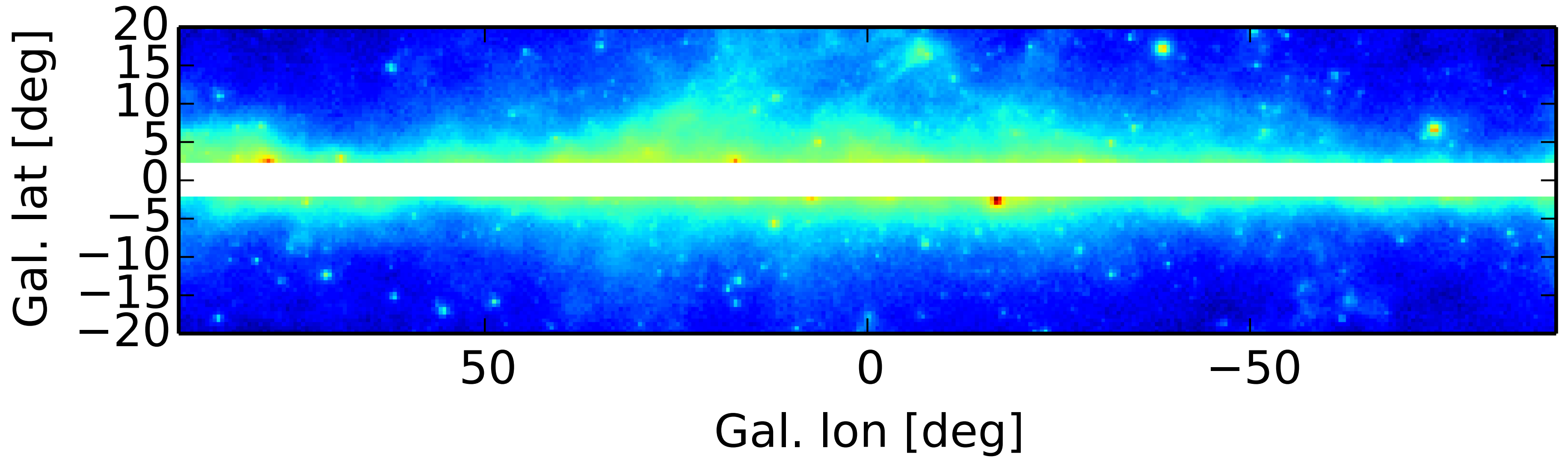
Likelihood fit
$O(10^5)$ free parameters

Adaptive template fitting: SkyFACT
(Sky Factorisation with adaptive constraining templates)

Collaboration with **Emma Storm** and **Christoph Weniger** (GRAPPA, University of Amsterdam)

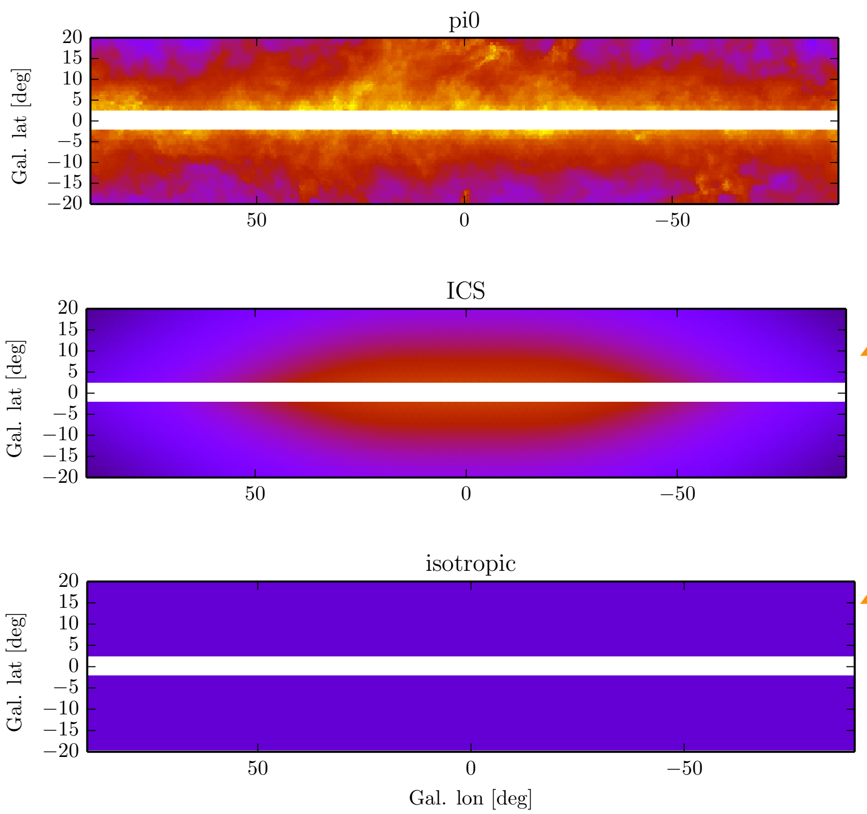
Unveiling the Bulge emission

DATA



- Pass8 ULTRACLEAN
- ca. 8 yr data
- 180x40 deg^2
- 0.3 — 200 GeV
- 0.5 deg resolution

MODEL COMPONENTS



π^0 (2 gas rings) and ICS (Dragon)
free spectra & templates

+

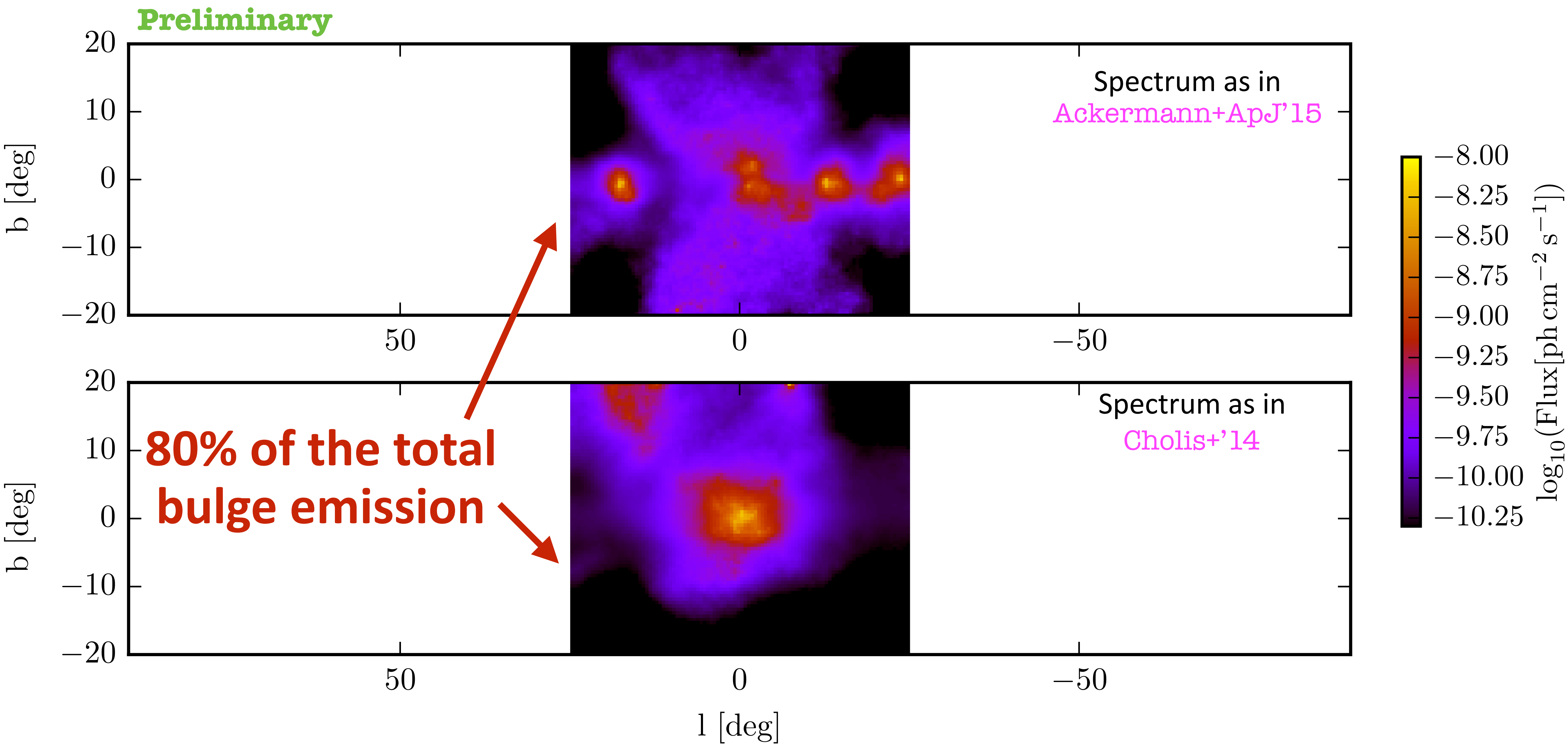
Isotropic emission
fixed spectrum & template

Ackermann+ApJ'15

+

<u>All</u> 3FGL sources spectra from catalog & **free normalisation**

Bulge emission components



We put in **fixed spectra** and **isotropic free templates…**

…and we get out these morphologies!

The 511 keV line emission

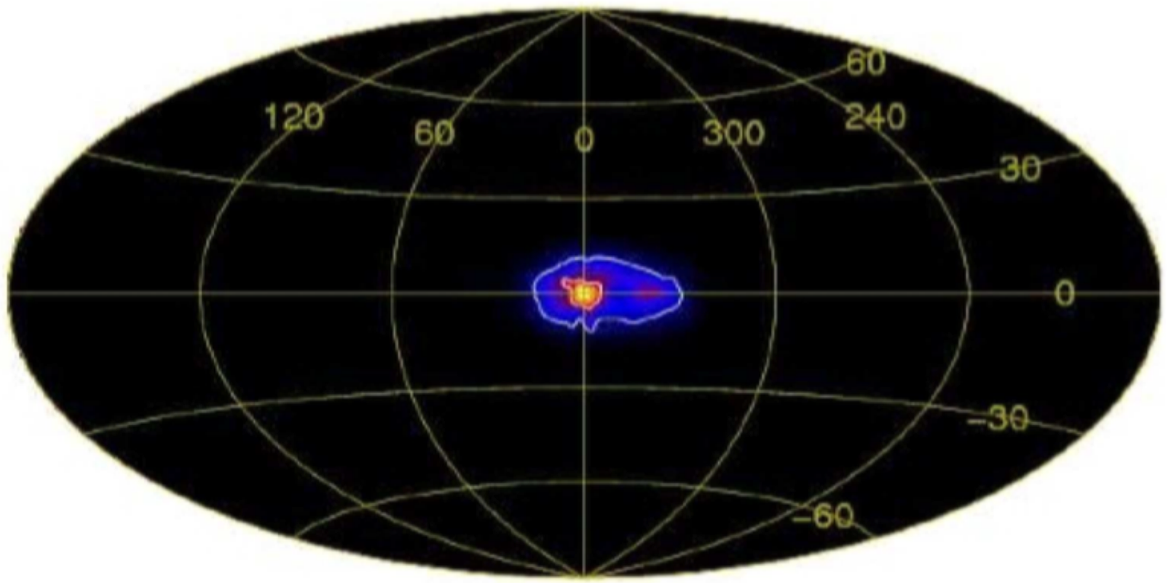


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

Purcell+'93,'97; Knödlseder+'03,'05; Siegert+16

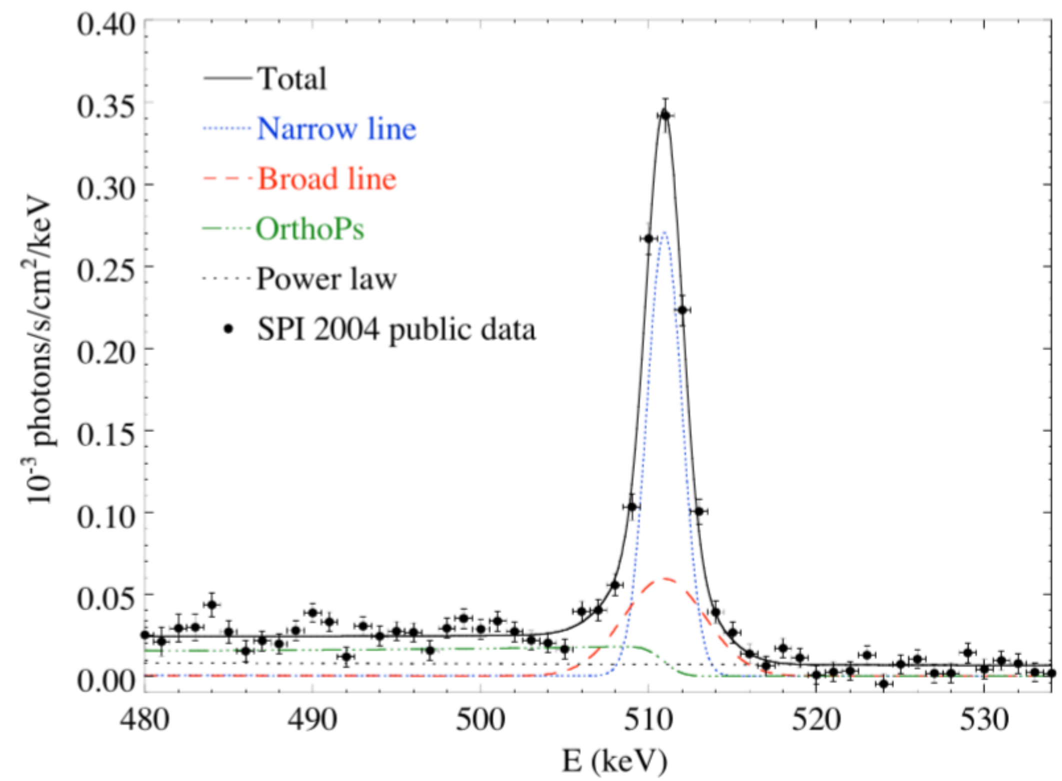


FIG. 5 Fit of the spectrum of the annihilation emission measured by SPI with narrow and broad Gaussian lines and an ortho-positronium continuum. The power-law account for the Galactic diffuse continuum emission (Jean *et al.*, 2006).

Intensity: Total Galactic line intensity ~ 2.8 x 10^{-3} ph/cm^2/s Siegert+16

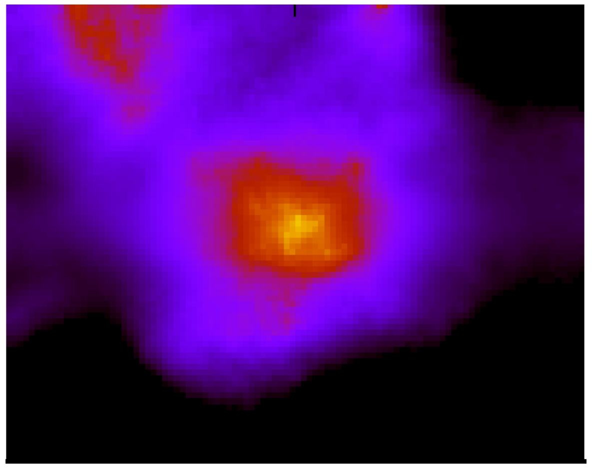
Morphology: 2D Gaussians for disk, bulge (N and B), GC source. **B/D ~ 0.6**

Spectroscopy: Line-to-continuum ratio constrains the medium.

Interpretation: radioactive decay of unstable nuclei, micro quasars, dark matter, etc. e.g. Martin+'12; Guessoum='06; Boehm+'04; etc

A correlation with the 511 keV line?

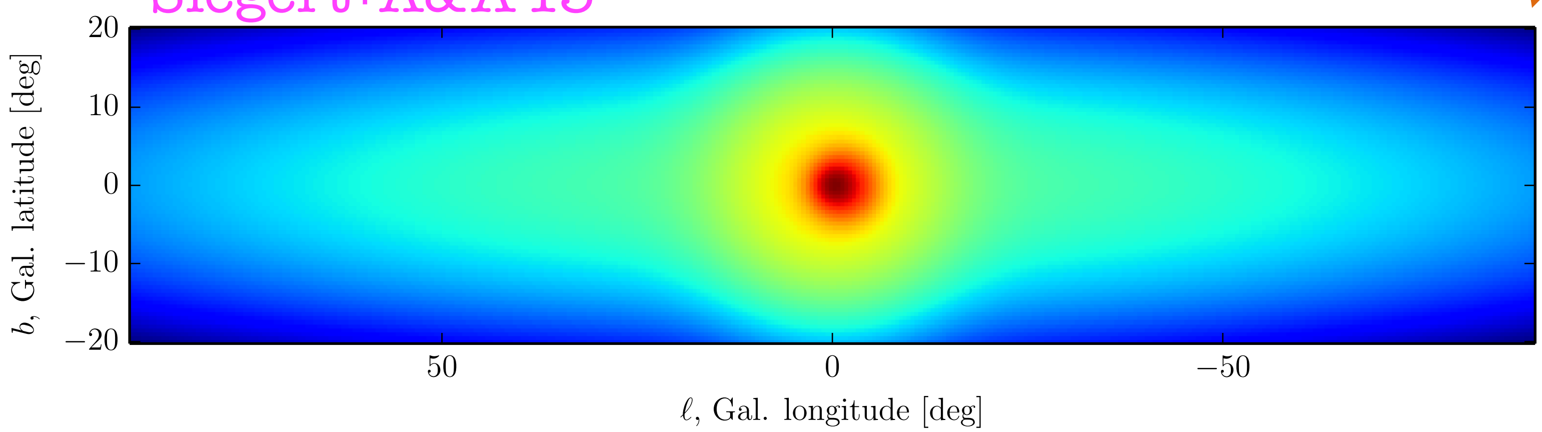
Bartels, Storm, Weniger & Calore, In preparation



Gamma-ray bulge emission template

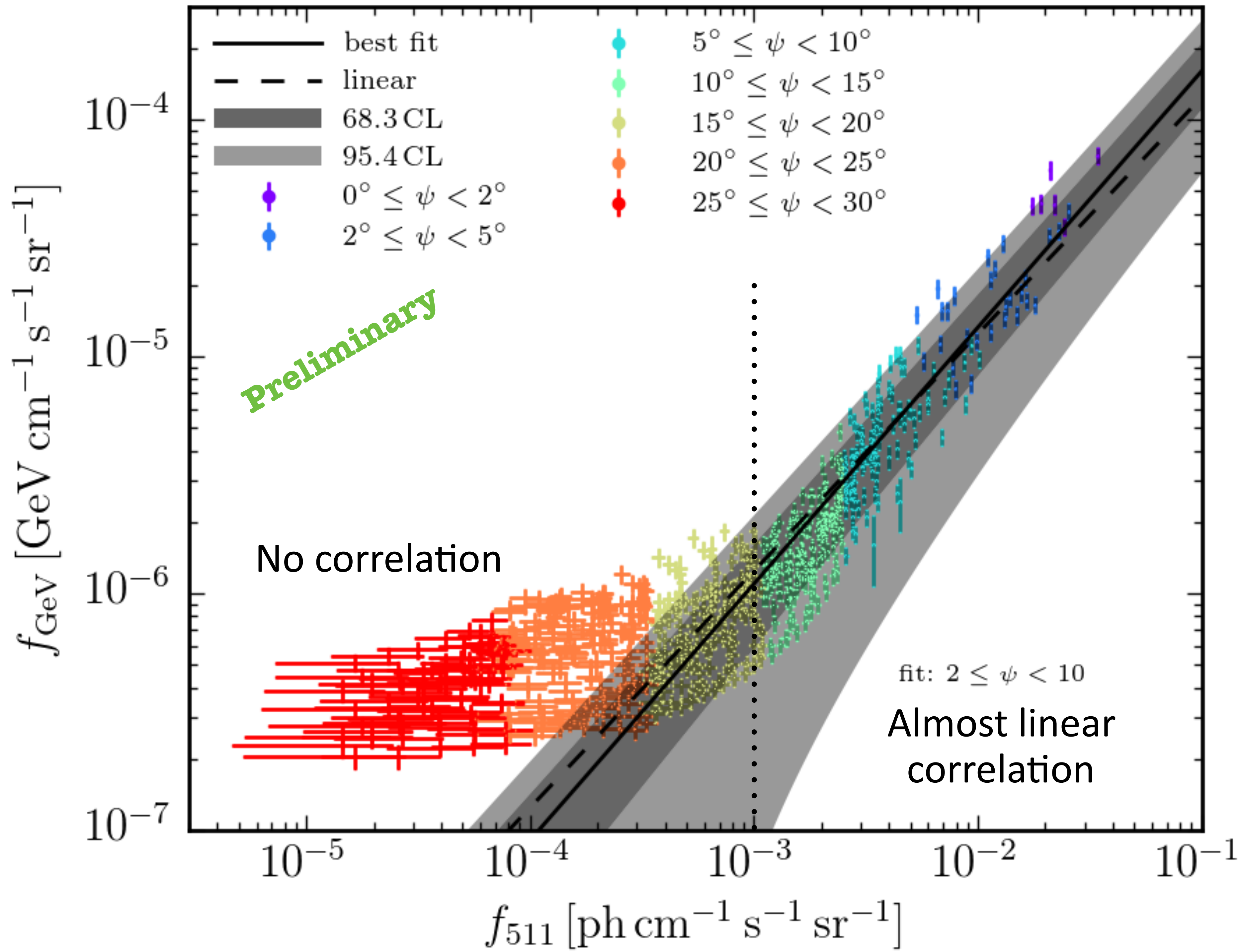
$$F_{\rm GCE}\,[\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}] \;=\; aF^{b}_{511}\,[\mathrm{ph\,cm^{-2}\,s^{-1}\,sr^{-1}}]$$

Siegert+A&A'15



GC + narrow bulge + broad bulge best-fit model

A correlation with the 511 keV line



F_{GeV} [GeV/cm^2/s/sr] = 1.24 x 10^{-03} F_{511} [ph/cm^2/s/sr]

Challenges and open questions

- The 511 keV line is seen in the disk as well. Is there a GeV excess emission along the disk? Is this consistent with the 511 keV line B/D ratio?
- What is the spatial extent of the correlation and what is the common radial profile?
- How likely is that a random dark matter profile would just look like that?
- What are possible astrophysical scenarios that can lead to a correlated emission? Crocker+'16
- What is the effect of the bubbles, if any?

Correlation does not imply causation.
It is nevertheless suggestive of a common origin of the two anomalies and quantifies it for the very first time.

Backup slides

The Fermi-LAT Collaboration analysis

Ajello+ '15

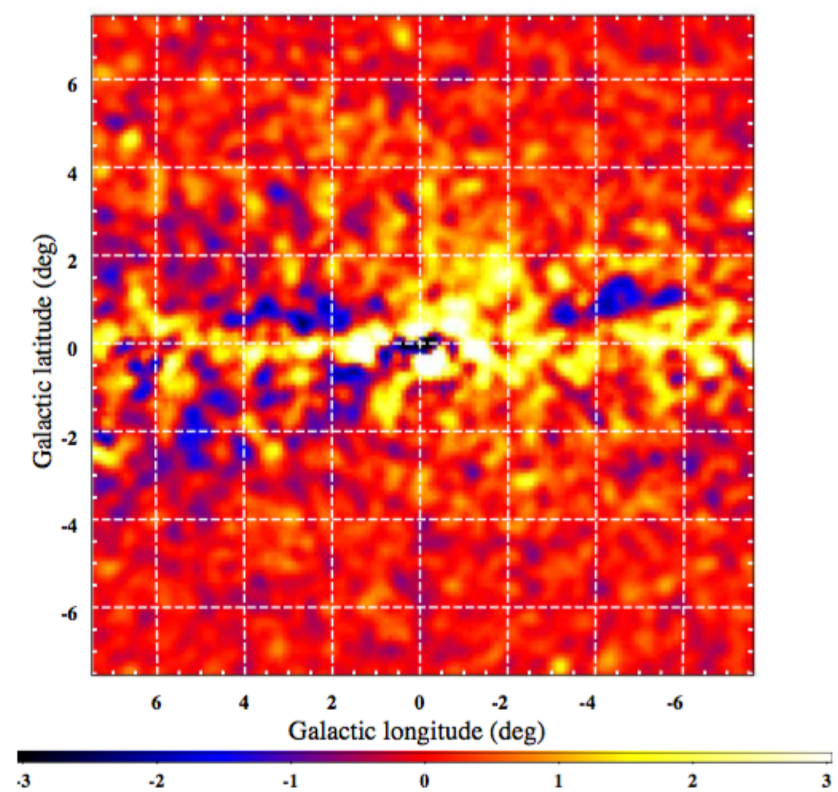
- 15º x 15º ROI; tuning of GDE outside → specialised interstellar emission models.
- Wavelet transform for source identification (1FIG catalog).

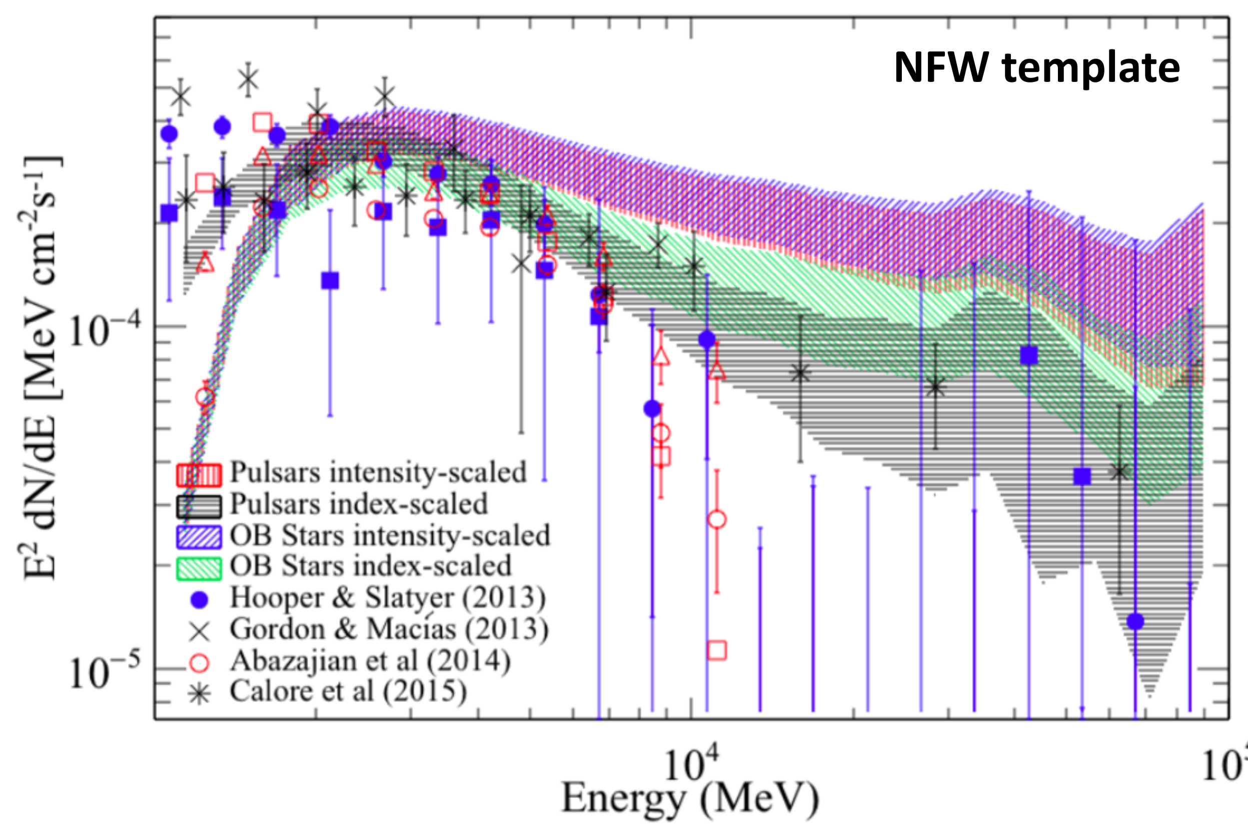
✓ **IC emission in inner 1 kpc enhanced** w.r.to baseline prediction (20% of the total GDE emission).

✓ 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.

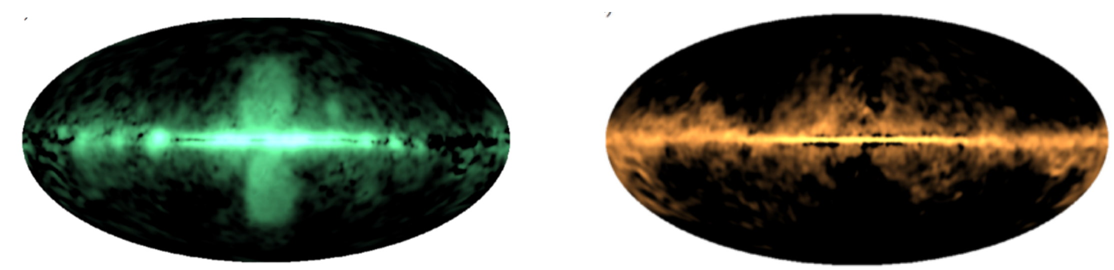
no NFW template





An alternative method: the D^{3}PO algorithm

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



Selig+ A&A'14

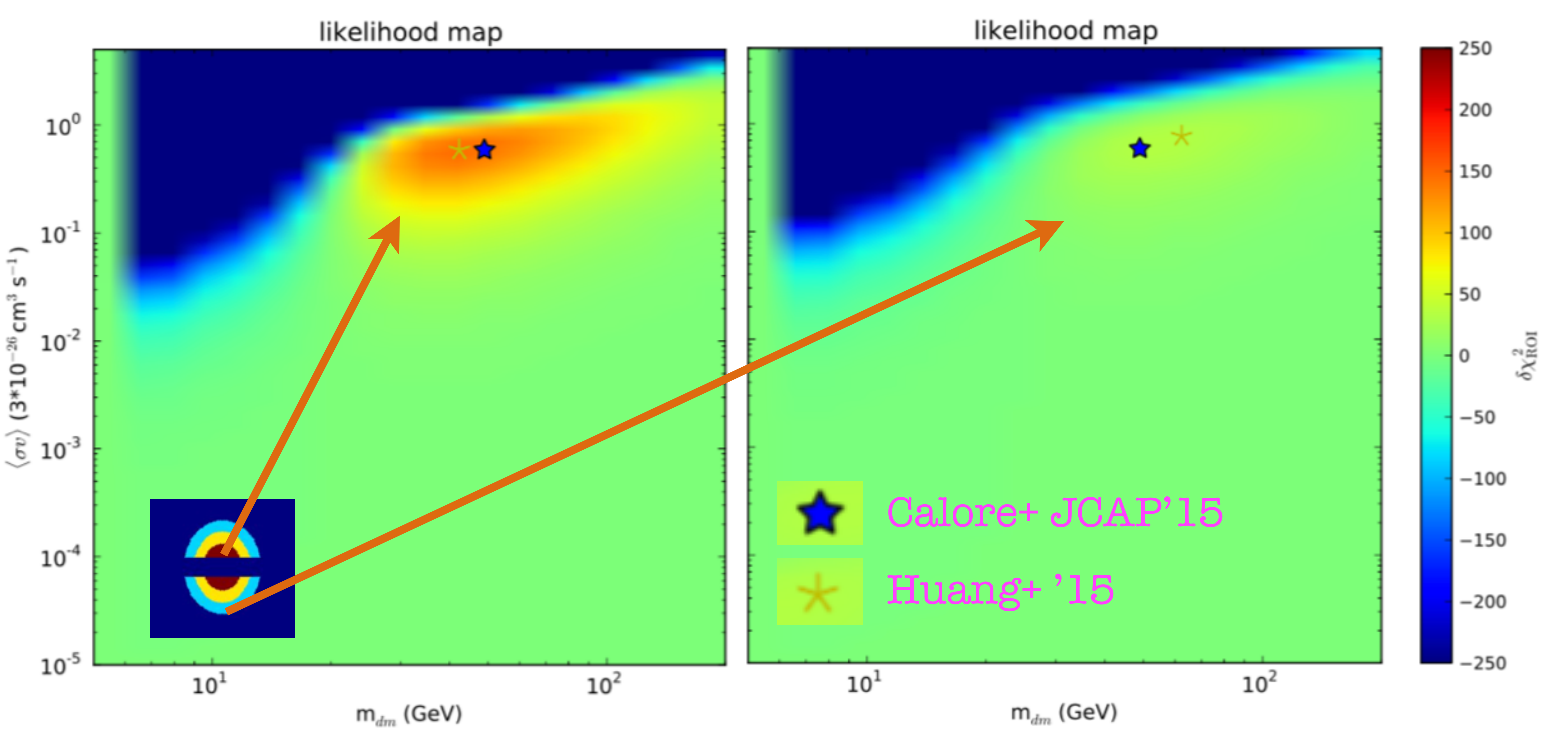
Pixel-wise maximum likelihood decomposition → $\theta_{i,k}$

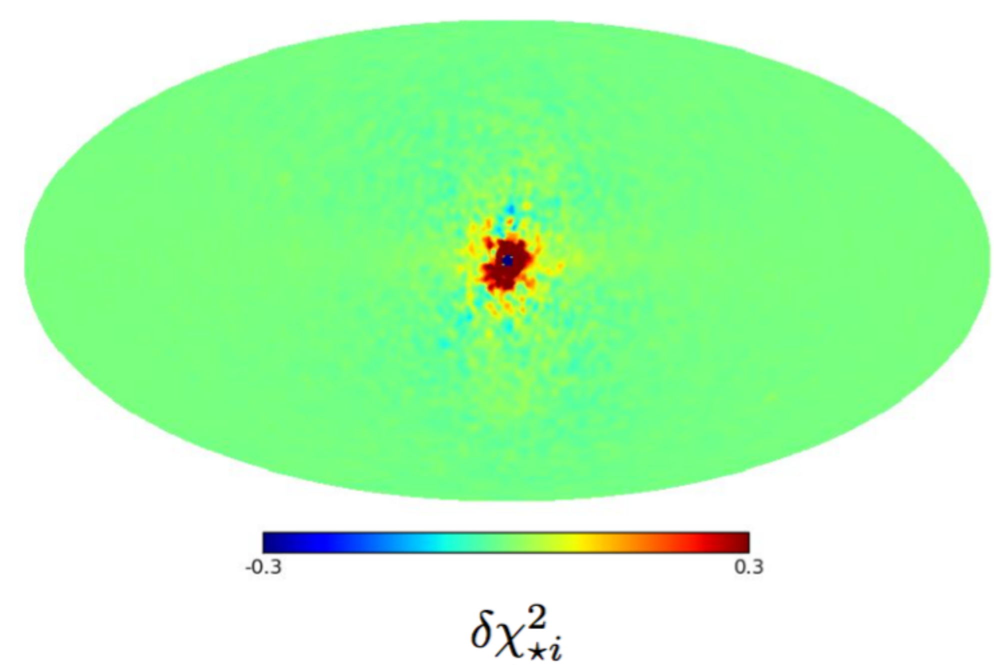
i$^{\text{th}}$ pixel

Huang+ '15

✓ Uniform and extended spectrum.
✓ Compatible with previous results.

✓ Spherically symmetric about the Galactic centre.

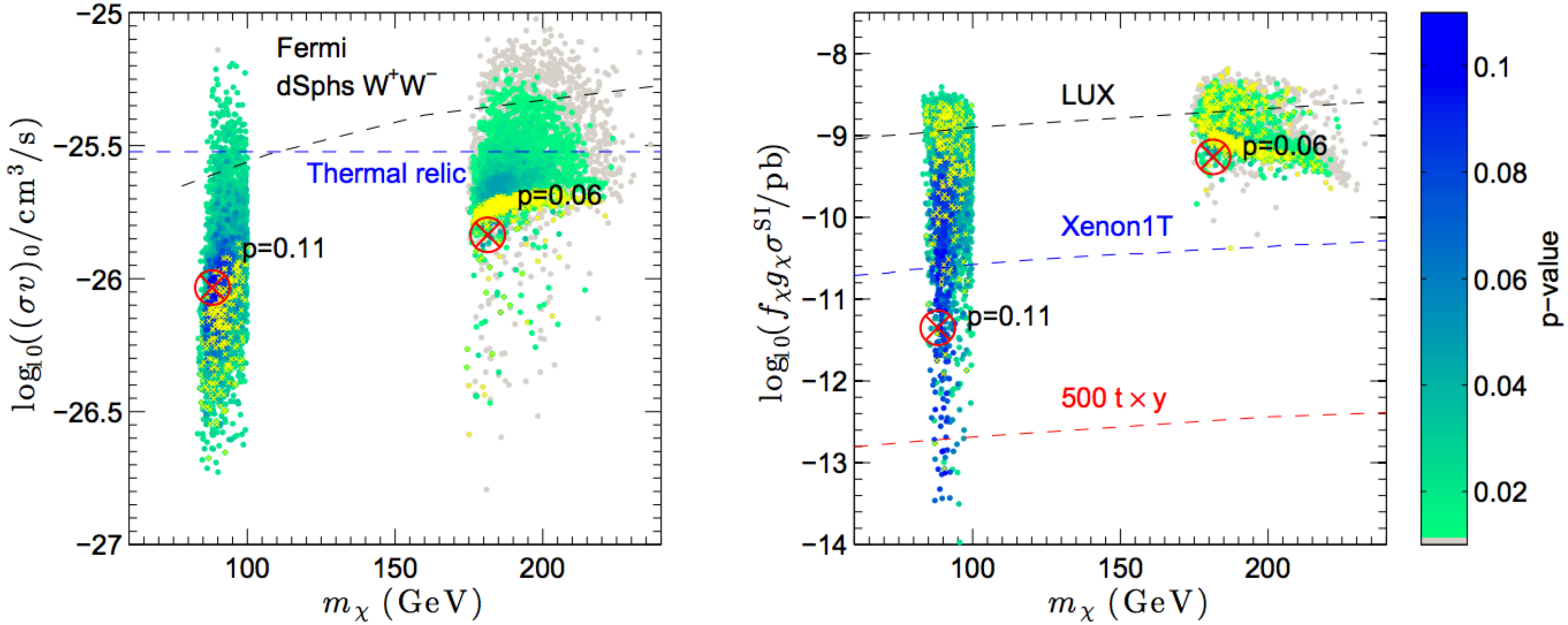




… but also the disk prefers a DM-like spectral component!

pMSSM solutions to the GeV excess

$$\ln \mathcal{L}_{\rm Joint} = \ln \mathcal{L}_{\rm GCE} + \ln \mathcal{L}_{\rm EW} + \ln \mathcal{L}_{\rm B(D)} + \ln \mathcal{L}_{\Omega_\chi h^2} + \ln \mathcal{L}_{\rm LUX} + \ln \mathcal{L}_{\rm IC} + \ln \mathcal{L}_{\rm Higgs} + \ln \mathcal{L}_{\rm SUSY},$$



Solutions:

1) 80-100 GeV, 95% WW, bino (90%) - higgsino/wino (10%) or higgsino dominant (Planck)
2) 180-200 GeV, 87% tt, bino (90%) - higgsino (10%), through heavy stops (1 TeV)

Most sensitive searches for LHC run II: (1) light squarks (< 2 TeV 70% points) and smuons (< 400 GeV 60% points); (2) heavy Higgs decay searches; (3) chargino/neutralino (compressed)

Bertone+ JCAP'16

The model

$$\text{Model} = \sum_{k} \text{Spectrum}_k \times \text{Morphology}_k$$

$$\phi_{ij} = \sum_{k}^{n_{comp}} \mathsf{T}_i^k \mathsf{S}_j^k \tau_i^k \sigma_j^k \nu^k$$

$$\mu_{ij}^{diff} = \phi_{ij} \times \text{PSF} \times \text{Exposure}$$

$$\mu_{ij} = \mu_{ij}^{diff} + \mu_{ij}^{psc}$$

The likelihood

$$\ln \mathcal{L} = \ln \mathcal{L}_{\rm d} + \ln \mathcal{L}_{\rm c} + \ln \mathcal{L}_{\rm s}$$

Poisson likelihood

$$-2\ln \mathcal{L}_{\rm d} = 2 \sum_{i=1}^{n_{\rm pix}} \sum_{j=1}^{n_{\rm bins}} \left(\mu_{ij} - c_{ij} + c_{ij} \ln \frac{c_{ij}}{\mu_{ij}} \right)$$

Scale (close to one) $\sigma_j^k, \tau_i^k, \nu^k \sim 1$

$$-2\ln \mathcal{L}_c = \sum_{k=1}^{n_{\rm comp}} \left(\sum_{j=1}^{n_{\rm bins}} \left(\frac{\ln \sigma_j^k}{\Delta \sigma^k} \right)^2 + \sum_{i=1}^{n_{\rm pix}} \left(\frac{\ln \tau_i^k}{\Delta \tau^k} \right)^2 + \left(\frac{\ln \nu^k}{\Delta^k} \right)^2 \right)$$

Smoothness

$$-2\ln \mathcal{L}_s = \sum_{k=1}^{n_{\rm comp}} \left(\sum_{j=1}^{n_{\rm bins}-1} \left(\frac{\ln \sigma_j^k - \ln \sigma_{j+1}^k}{\Xi_\sigma^k} \right)^2 + \sum_{(i,i')_{nn}} \left(\frac{\ln \tau_i^k - \ln \tau_{i'}^k}{\Xi_\tau^k} \right)^2 \right)$$

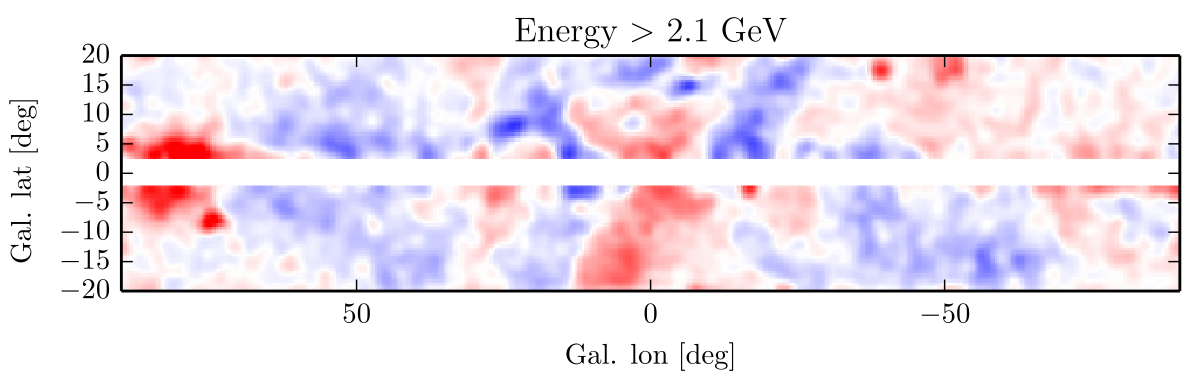
No overfitting:

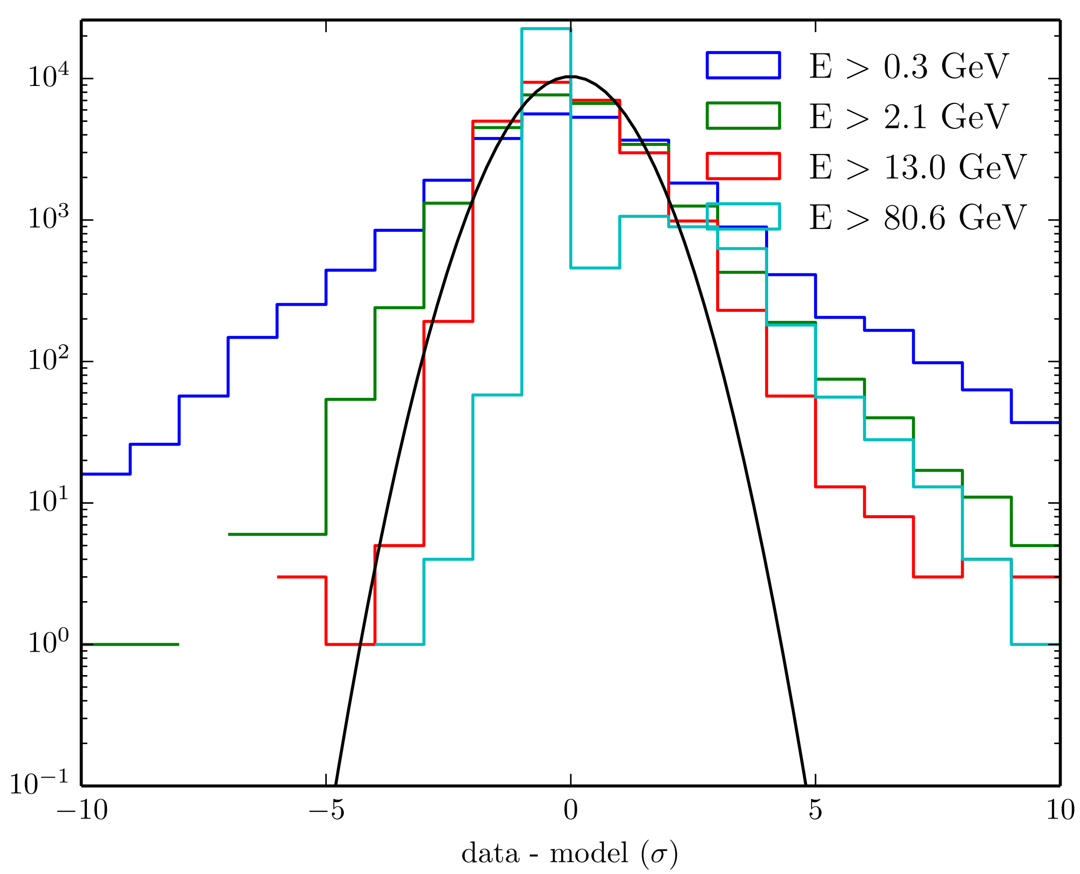
$N_{\rm data} = N_{\rm pixels} \times N_{\rm en} \times N_{\rm comp}$

$N_{\rm params} = N_{\rm comp} \times (N_{\rm pixels} + N_{\rm en})$

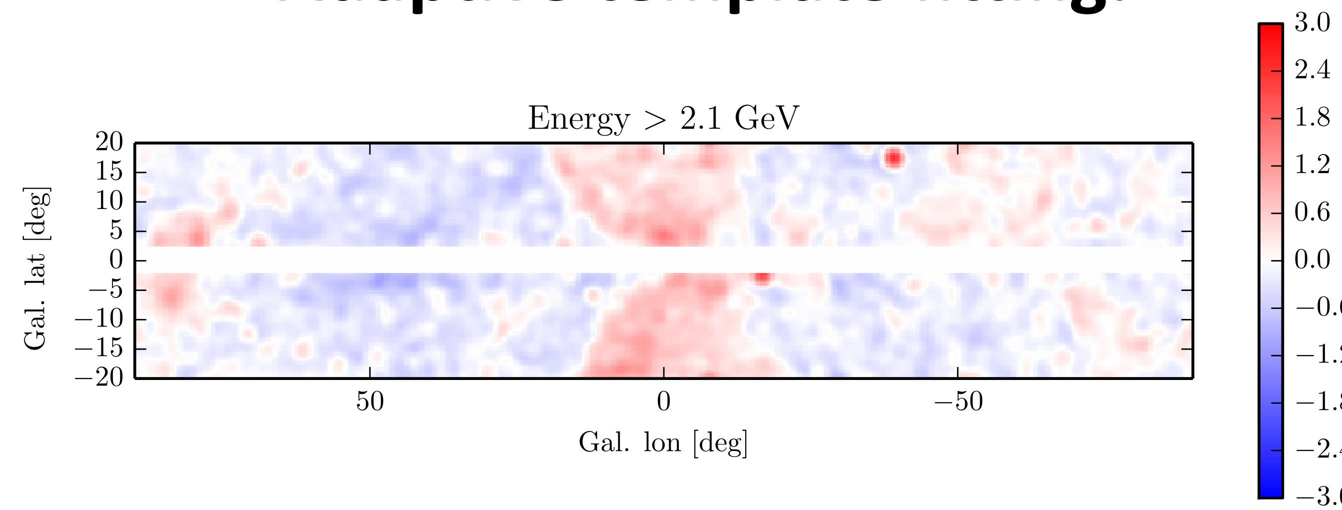
Towards Poissonian residuals

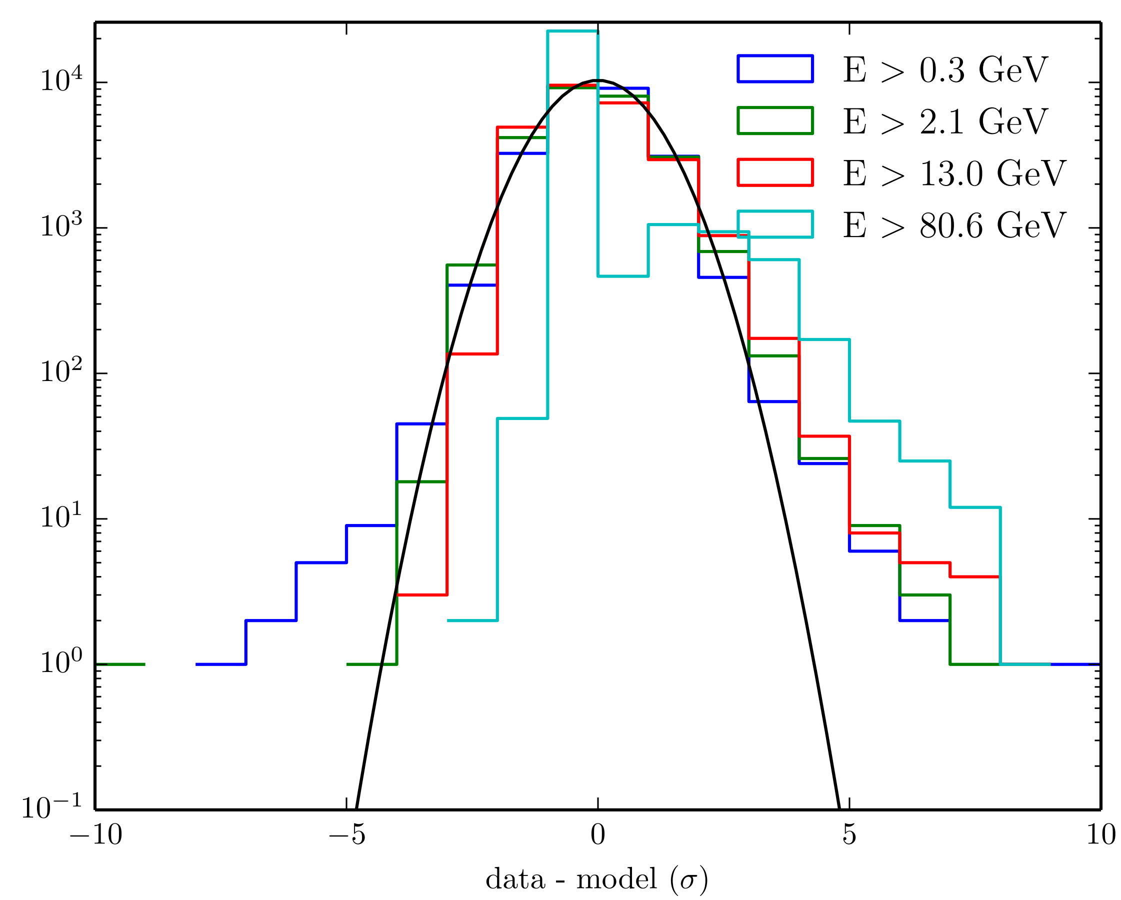
Standard template fitting:





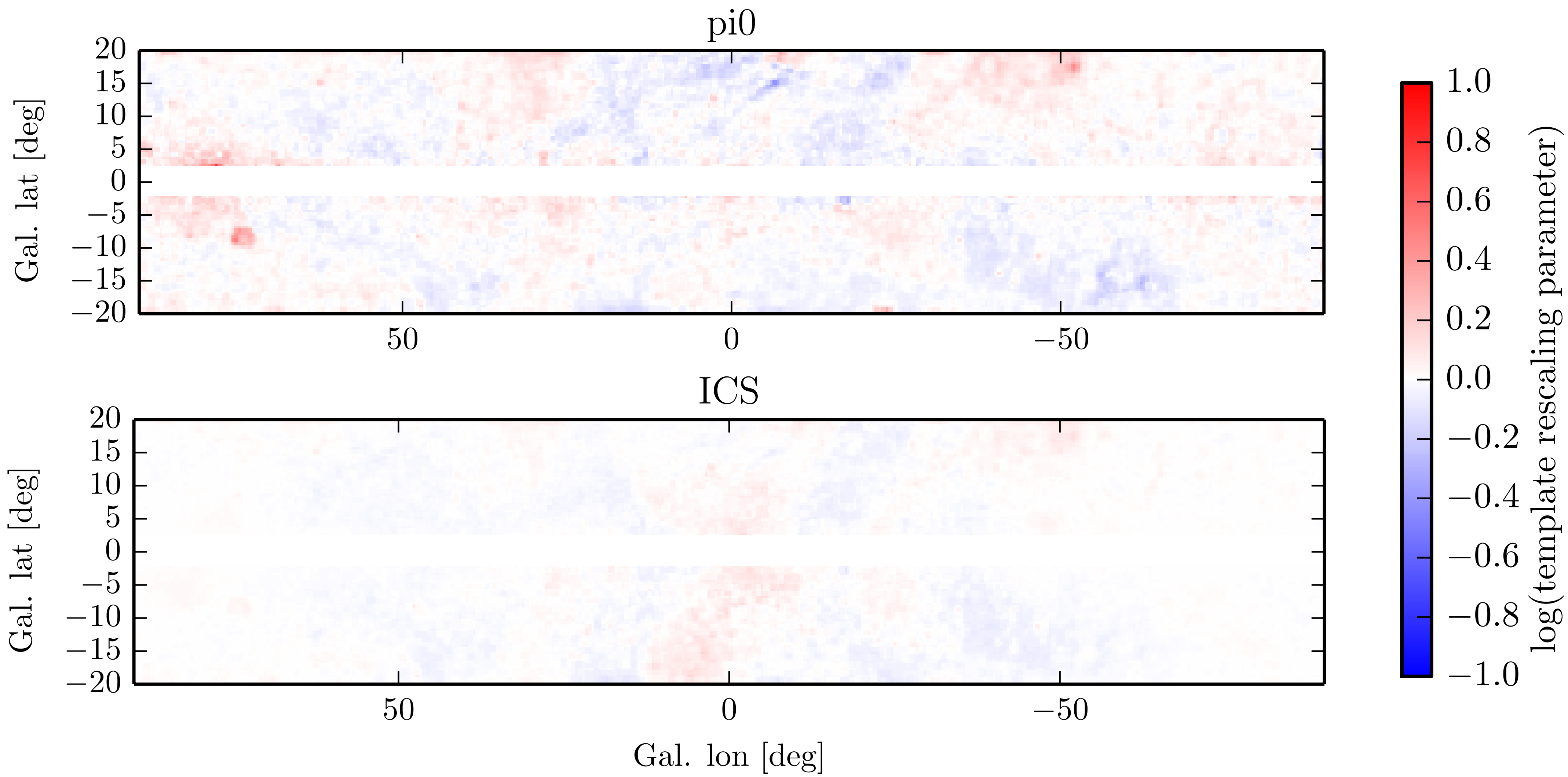
Adaptive template fitting:





Rescaling parameters

$$\mu_{ij} = \sum T_i^{(k)} S_j^{(k)} \theta_j^{(k)} \theta_i'^{(k)} \theta^{(k)}$$



What is the physical meaning of the rescaling parameters?

- Uncertainties in gas tracers, CR density, etc. (NO overfitting!)
- Large-scale additional components: Fermi bubbles and bulge emission.