The Fermi GeV excess as a tracer of stellar mass: Results with SkyFACT

Emma Storm

In collaboration with:

Richard Bartels, Francesca Calore, Christoph Weniger

TeVPA

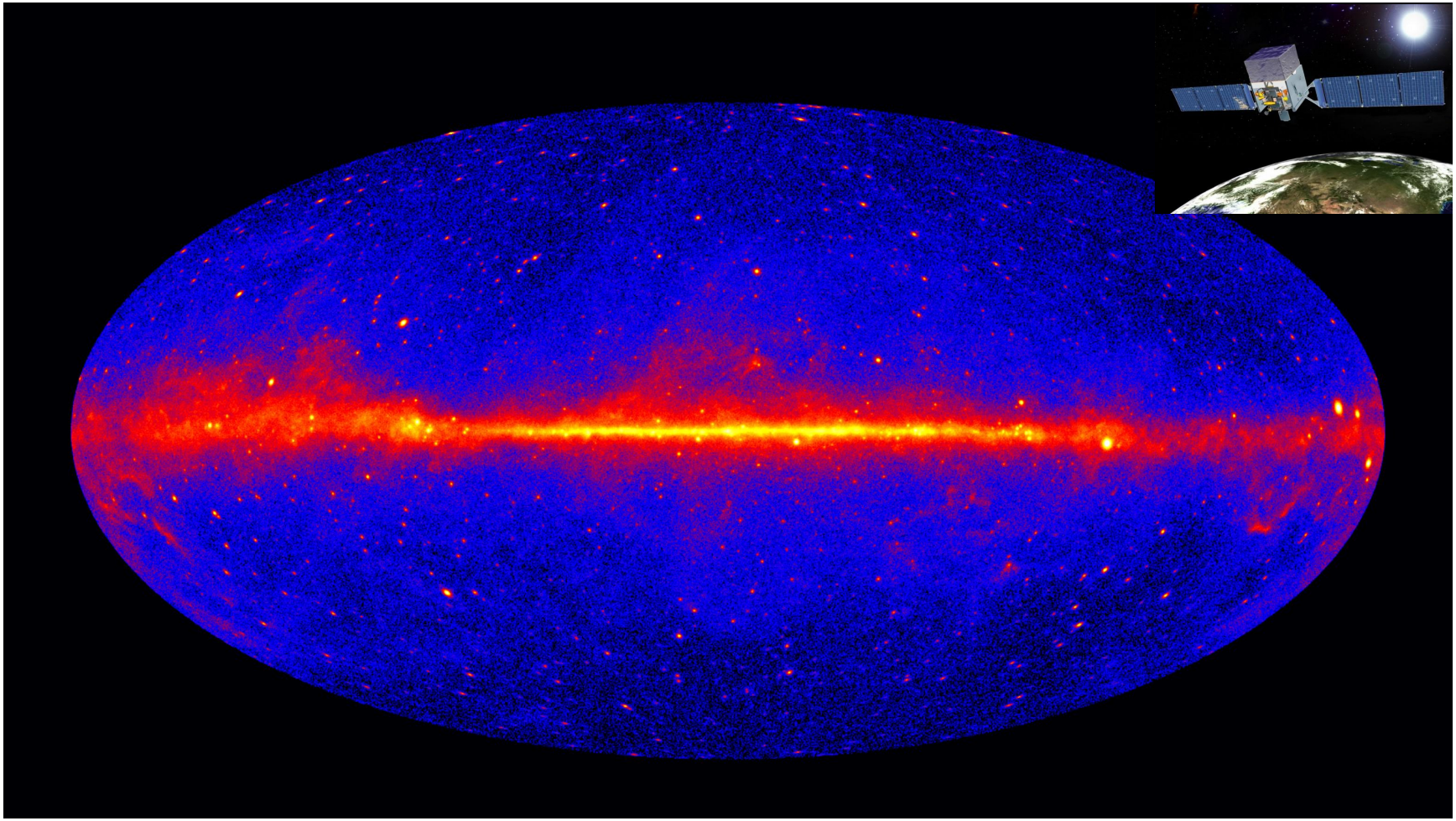
29 August 2018

GRAPPA

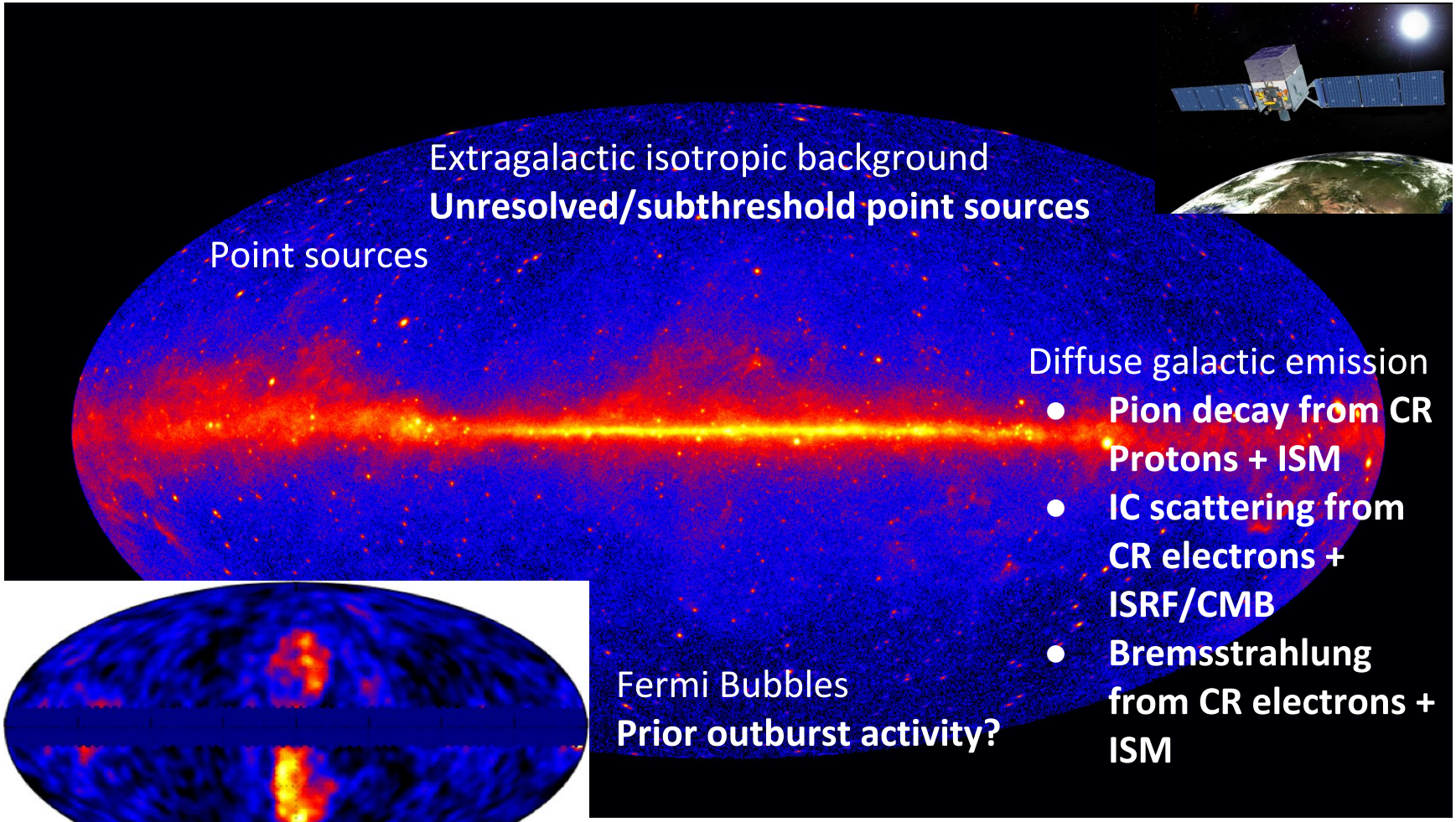
GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

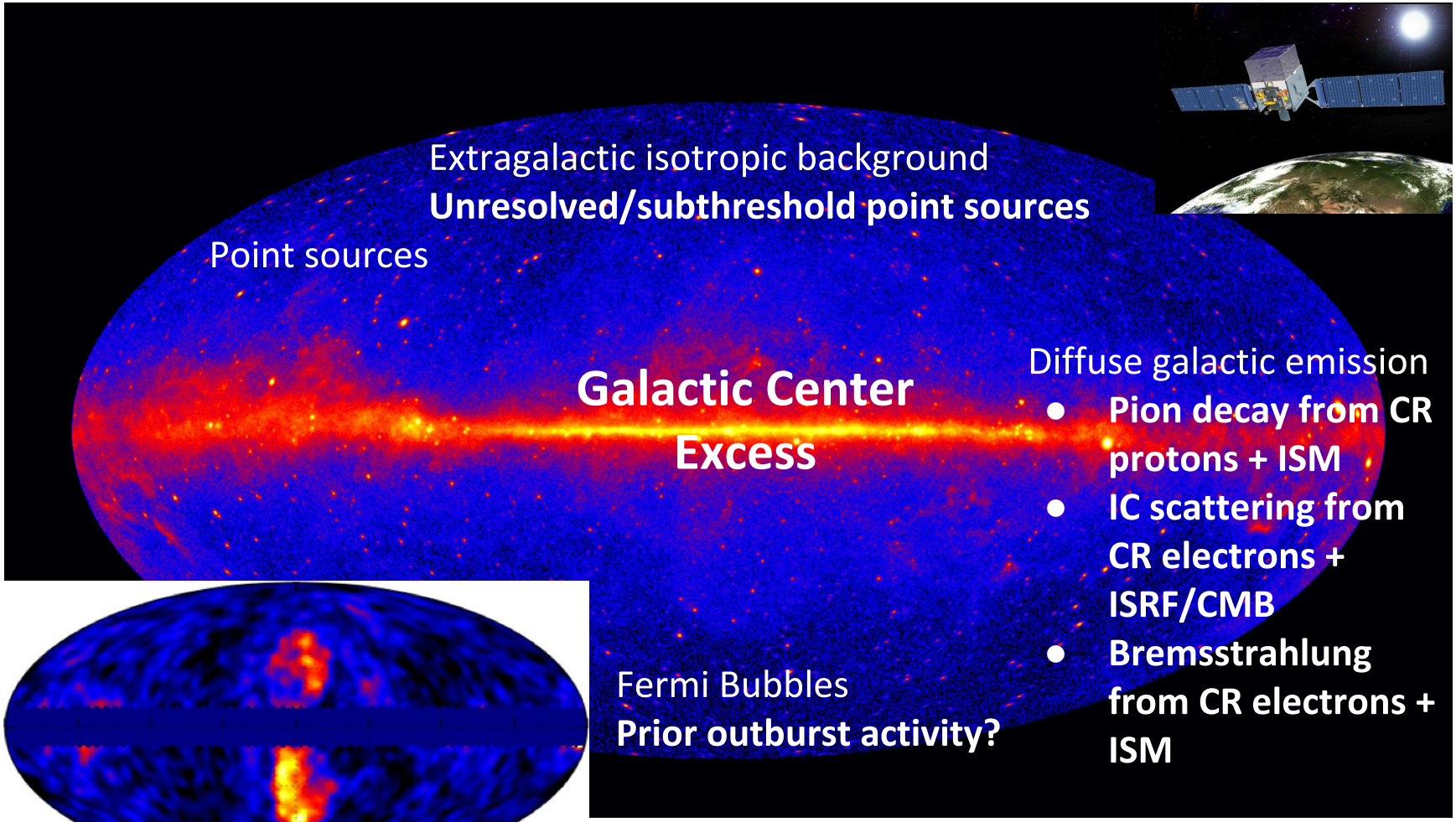
The gamma-ray sky



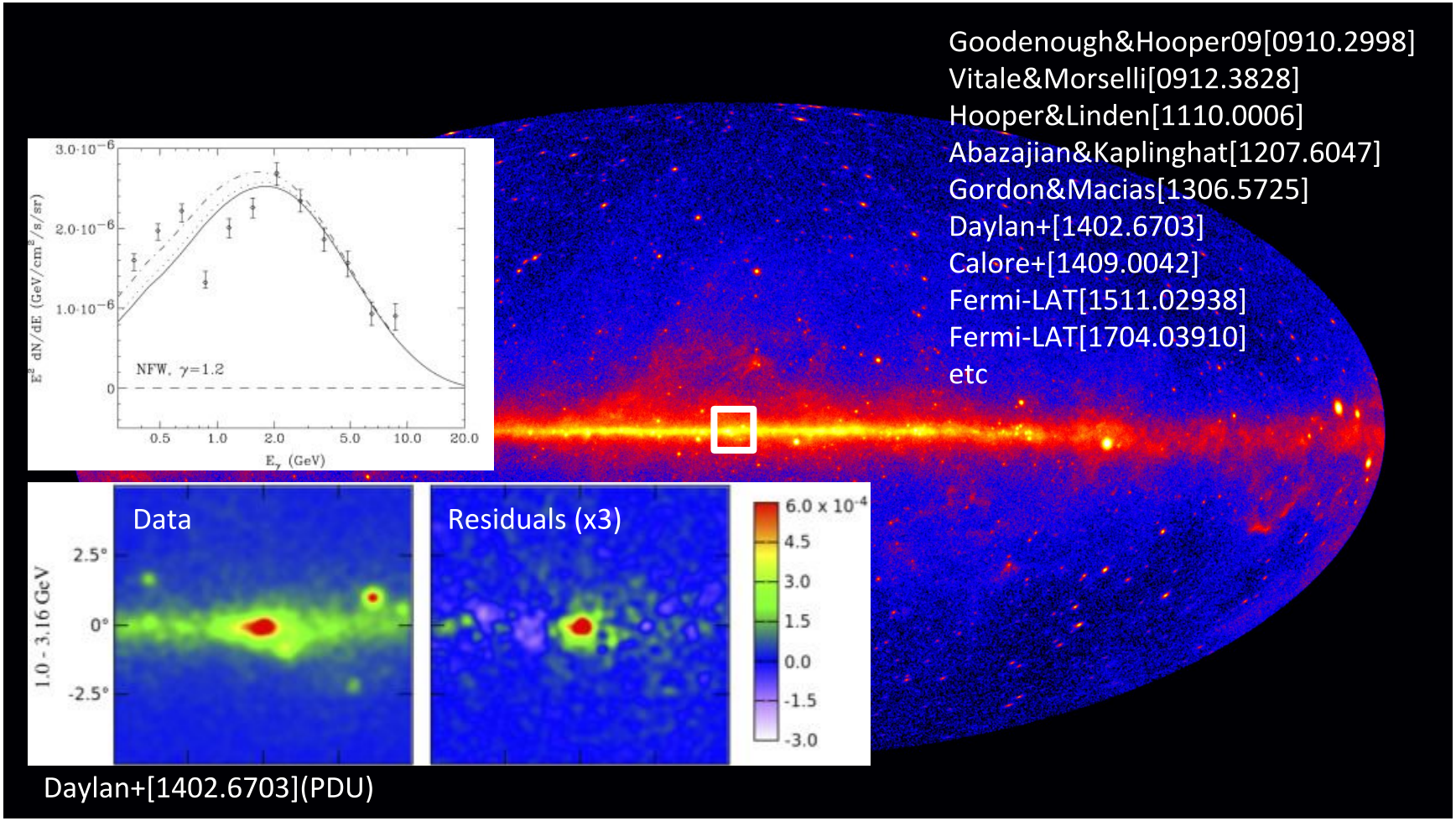
The gamma-ray sky



The gamma-ray sky

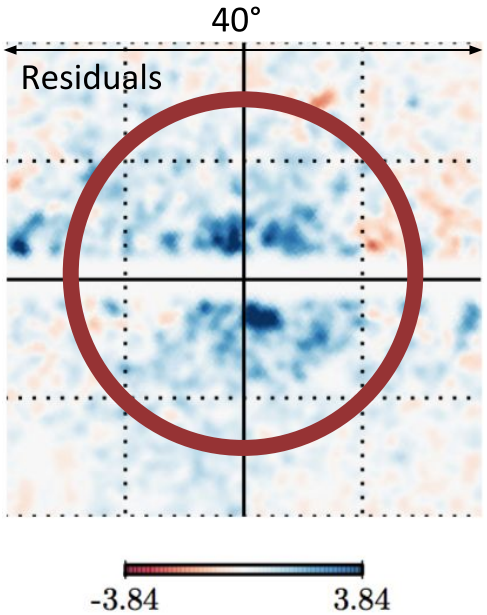


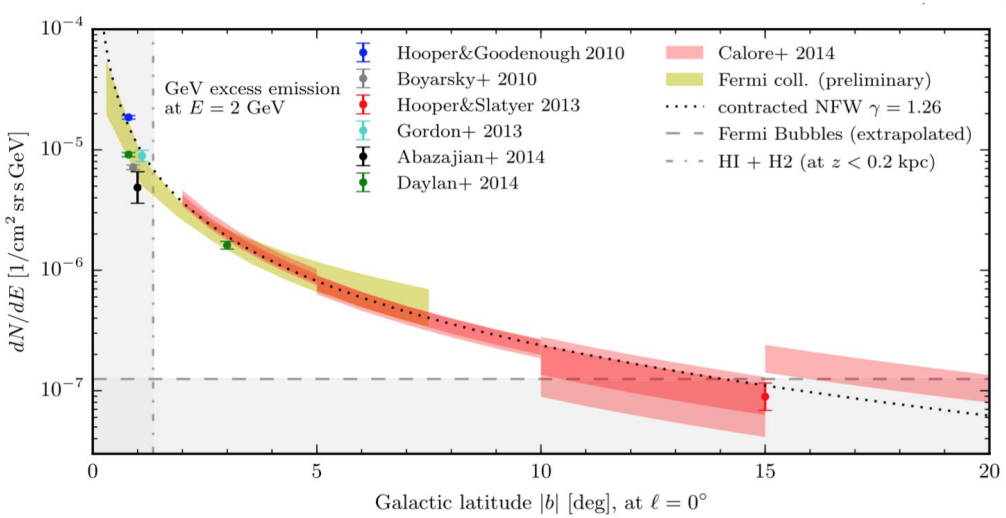
The Fermi Galactic Center Excess



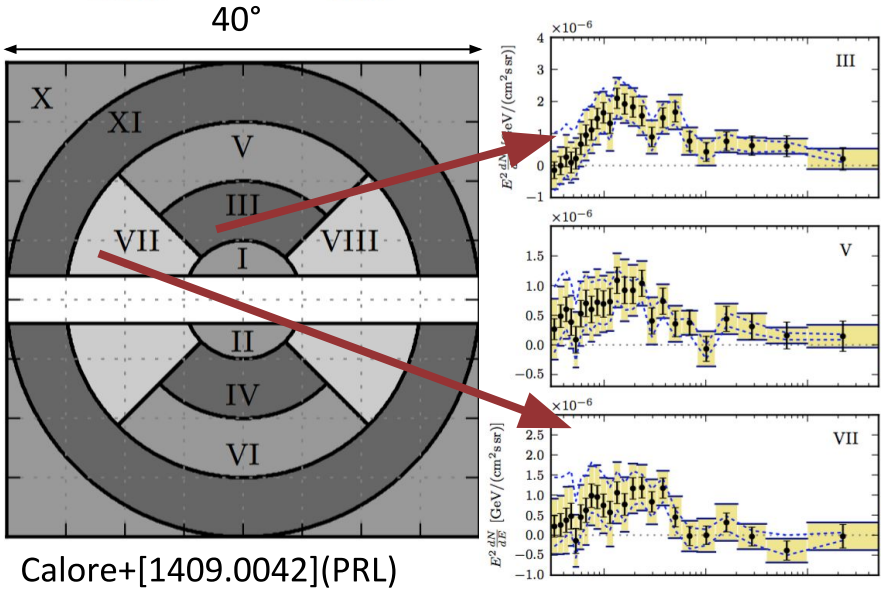
Daylan+[1402.6703](PDU)

The Fermi galactic center excess (GCE)





Calore+[1411.4647](PRD)



Calore+[1409.0042](PRL)

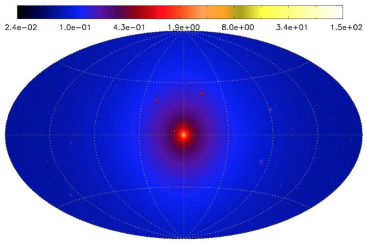
Characteristics:

- Located at Galactic Center
- 10° radius
- Symmetric morphology (?)
- Spectrum peaks at 2 GeV
- Uniform spectrum

Origins of the GCE

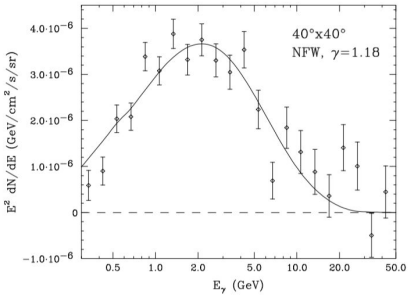
Dark Matter Interpretation

Expected ɣ-ray counts from DM annihilation

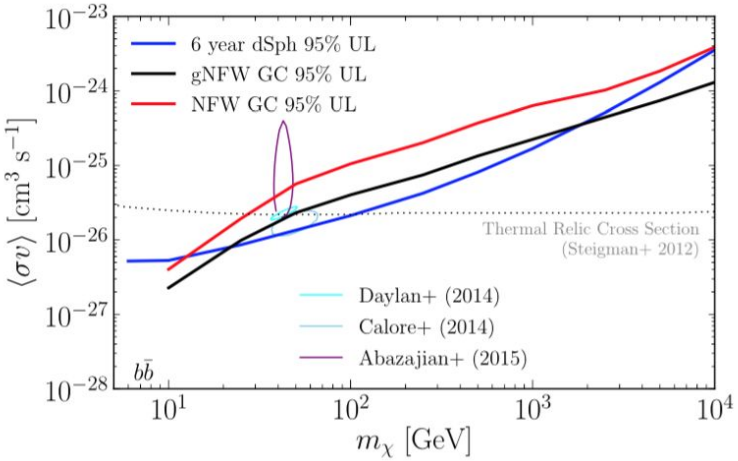


Pieri+[0908.0195](PRD)

DM → bbar, m=43GeV, $\sigma v = 2.25 \times 10^{-26}$ cm^{3}s^{-1}



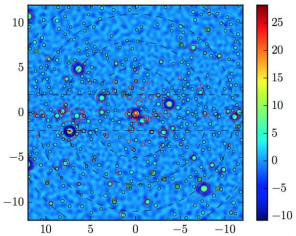
Daylan+[1402.6703](PDU)



Fermi-LAT+[1704.03910](ApJ)

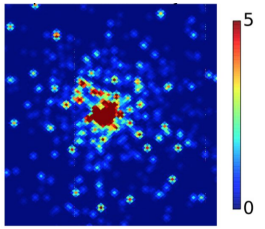
Astrophysics Interpretation: Unresolved Point Sources

Wavelet analysis



Bartels+[1506.05104](PRL)

Non-poissonian templates

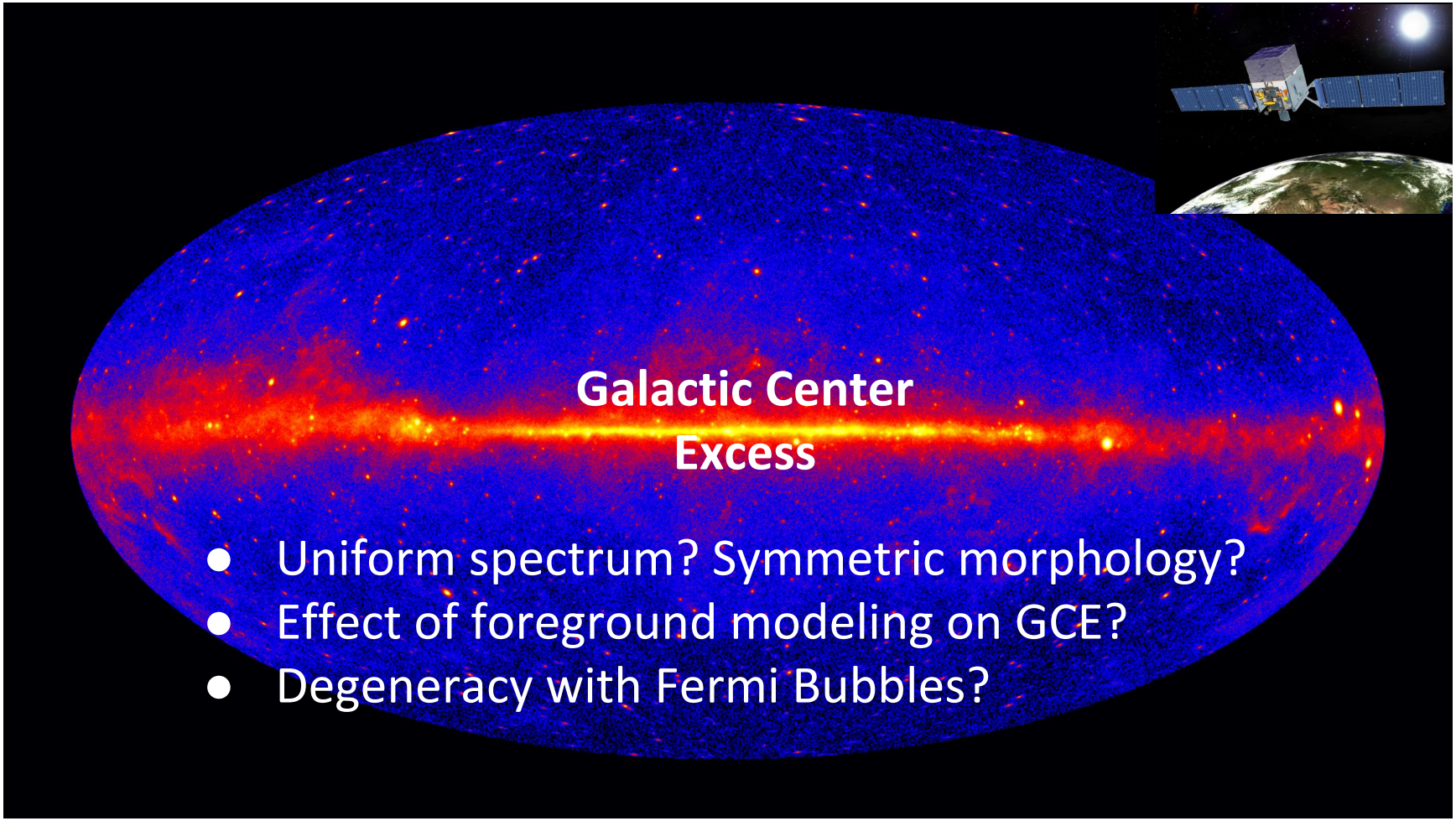


Lee+[1506.05124](PRL)

An as-yet unresolved population of **millisecond pulsars** are a good fit

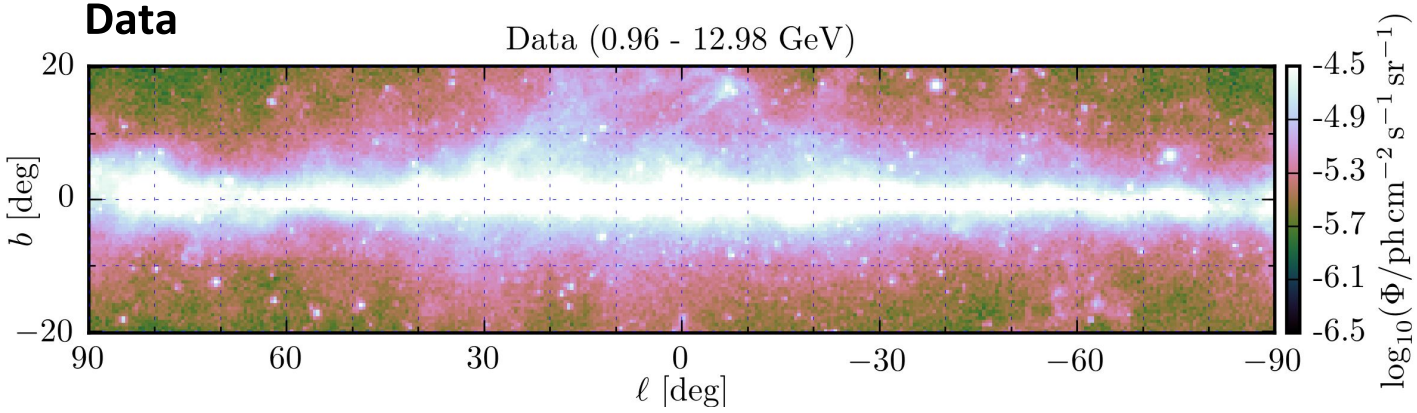
Other scenarios: Additional CR-induced emission, SF burst(s), steady increased SF in GC/CMZ, emission from molecular clouds …

Origins of the GCE



Standard template fitting

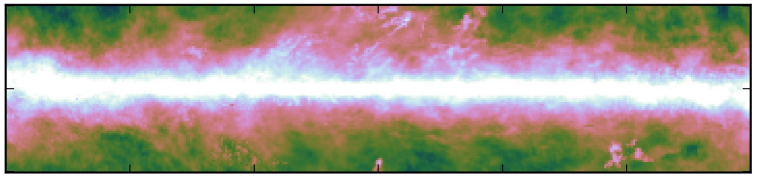
Data



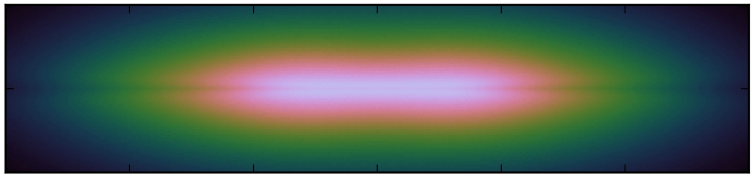
=

Models for γ-ray emission from:

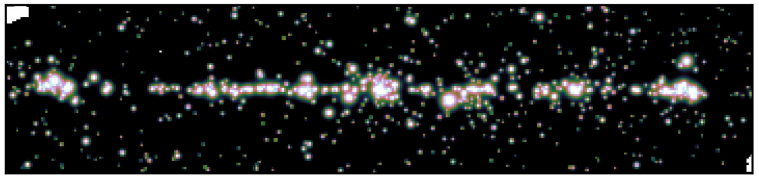
Cosmic ray protons



Cosmic ray electrons



Point sources



\+ Other extended + diffuse components...

Standard template fitting

$$\text{Model} \sim \sum_k \text{Template}^{(k)} \times \text{Spectrum}^{(k)}$$

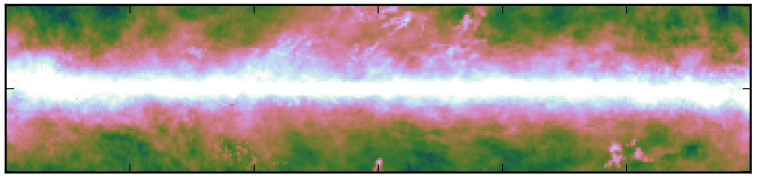
k: model component

Fixed, energy-dependent spatial templates

Derived from normalizations of spatial templates

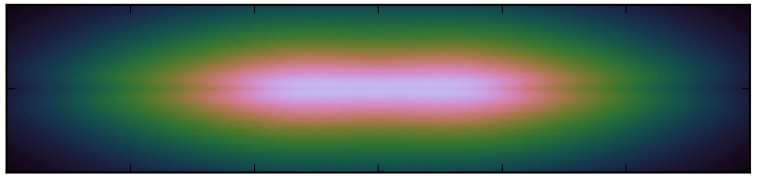
Models for γ-ray emission from: derived from CR prop codes like Galprop, Dragon

Cosmic ray protons



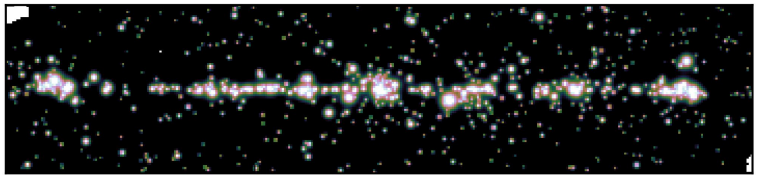
Uncertainties ≳ 30-50%

Cosmic ray electrons



Uncertainties ≳ factor of 2-3

Point sources



\+ Other extended + diffuse components...

A new approach: SkyFACT

$$\text{Model} \sim \sum_k \text{Template}^{(k)} \times \text{Spectrum}^{(k)}$$

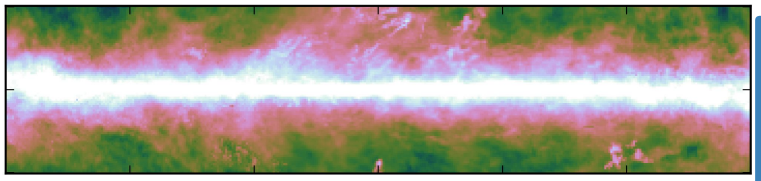
k: model component

Spatial templates that allow for uncertainties at the pixel level

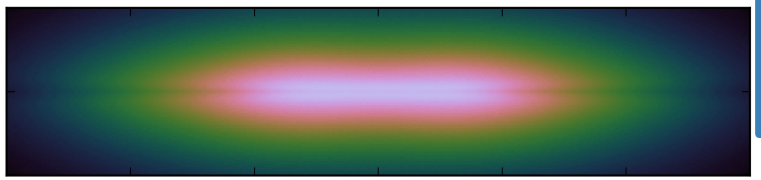
Spectral templates that allow for uncertainties in energy bins

Models for γ-ray emission from: derived from CR prop codes like Galprop, Dragon

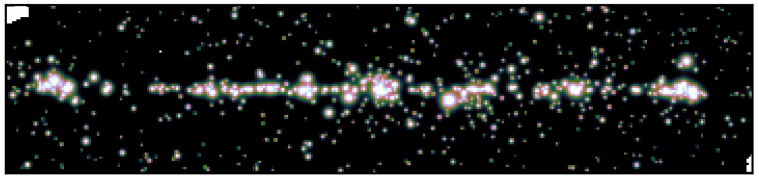
Cosmic ray protons



Cosmic ray electrons



Point sources

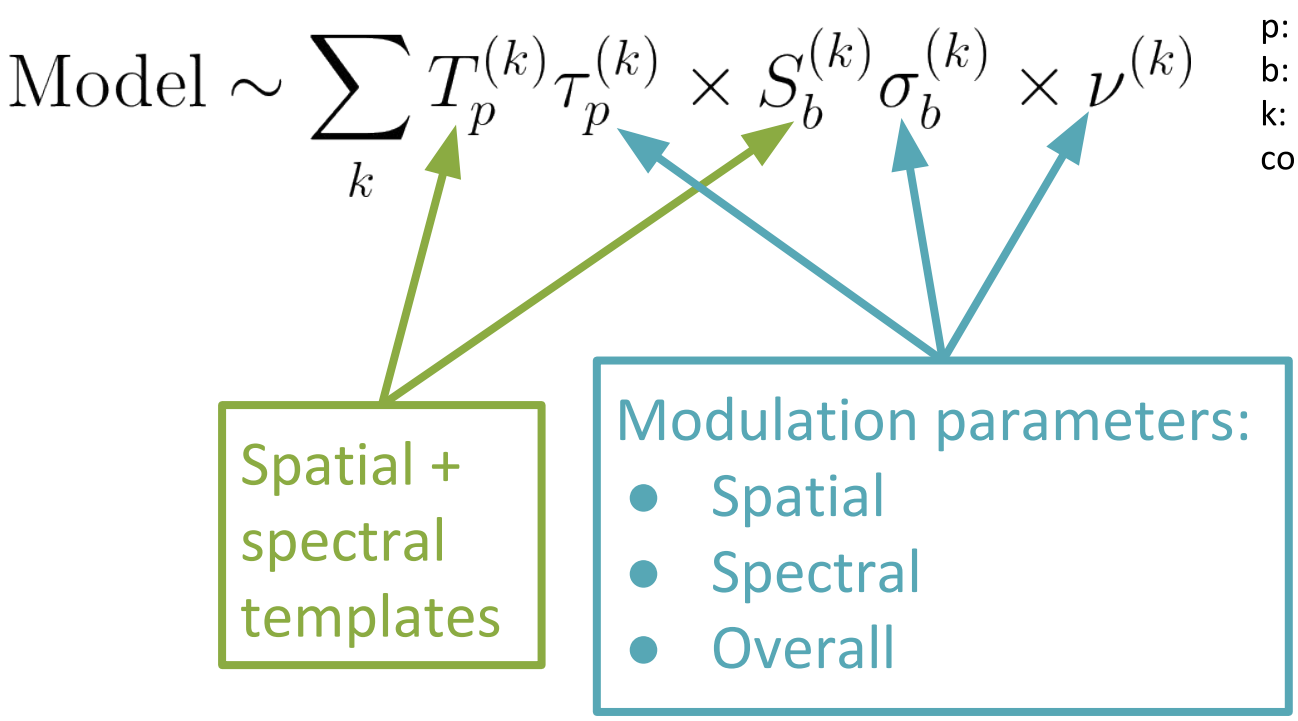


Uncertainties $\gtrsim$ 30-50%

Uncertainties $\gtrsim$ factor of 2-3

\+ Other extended + diffuse components...

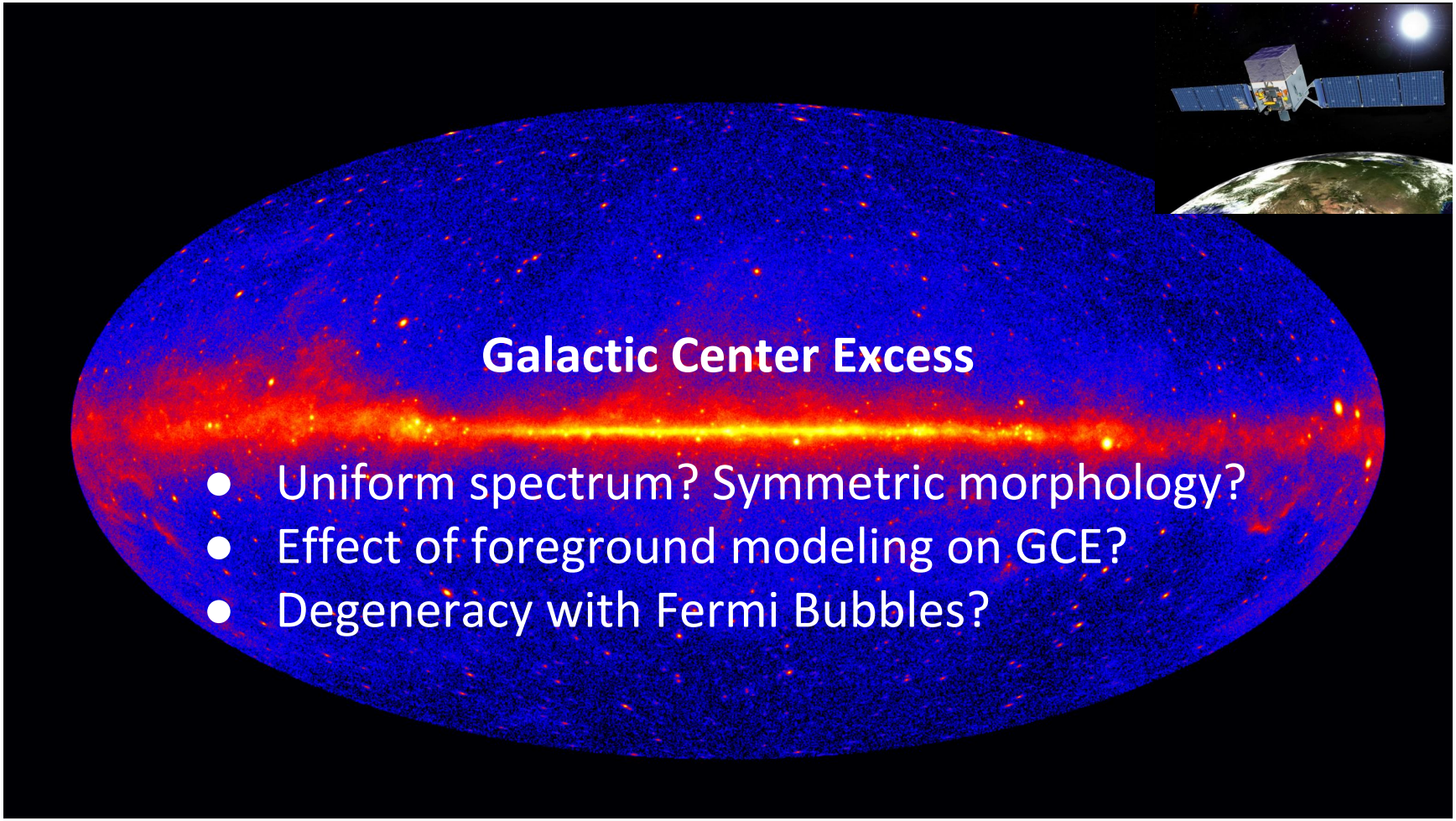
A new approach: SkyFACT



Constraint (or regularization) terms in the likelihood control how much variation is allowed

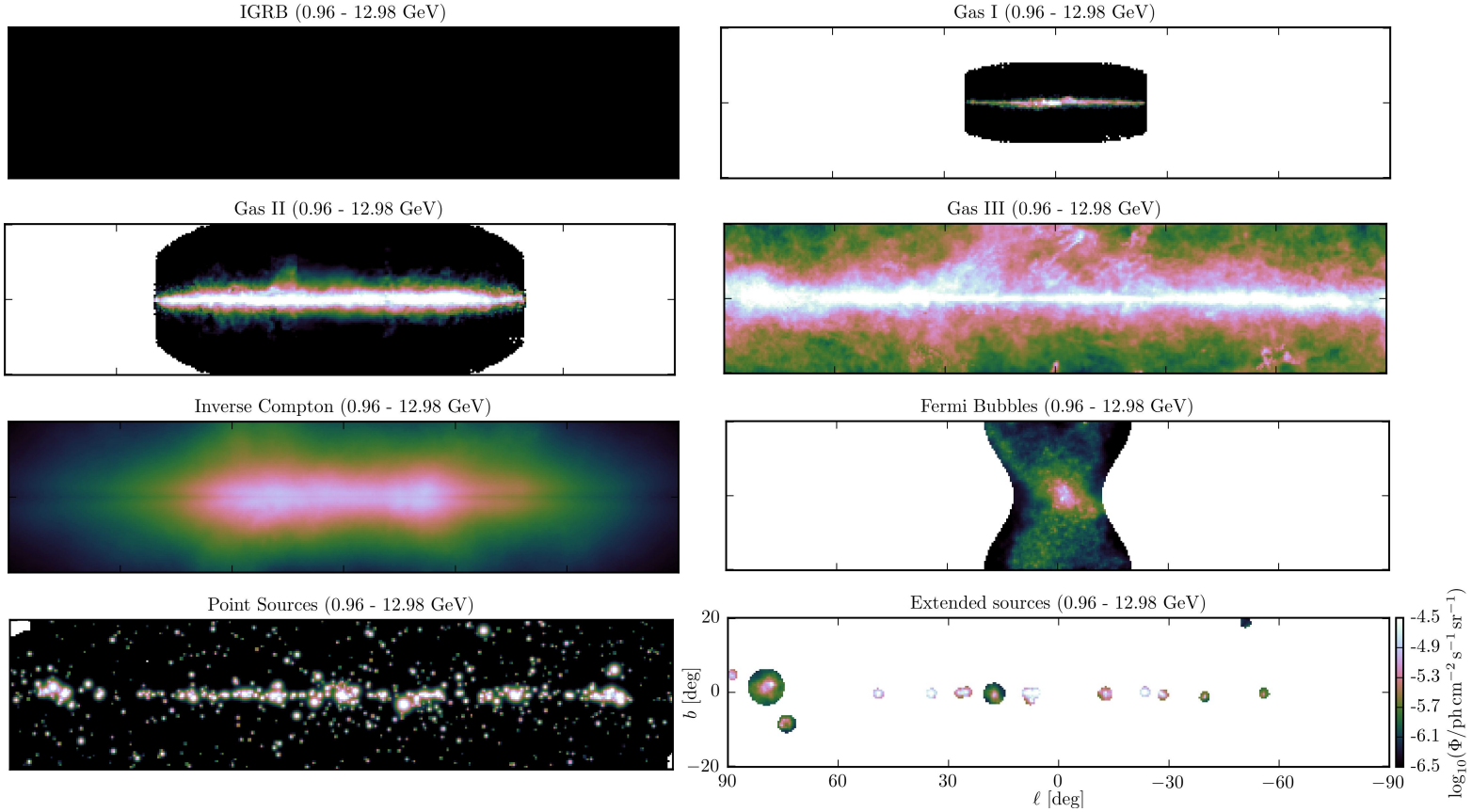
$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}$$

Analyzing the GCE with SkyFACT



Foreground model

Best-fit models

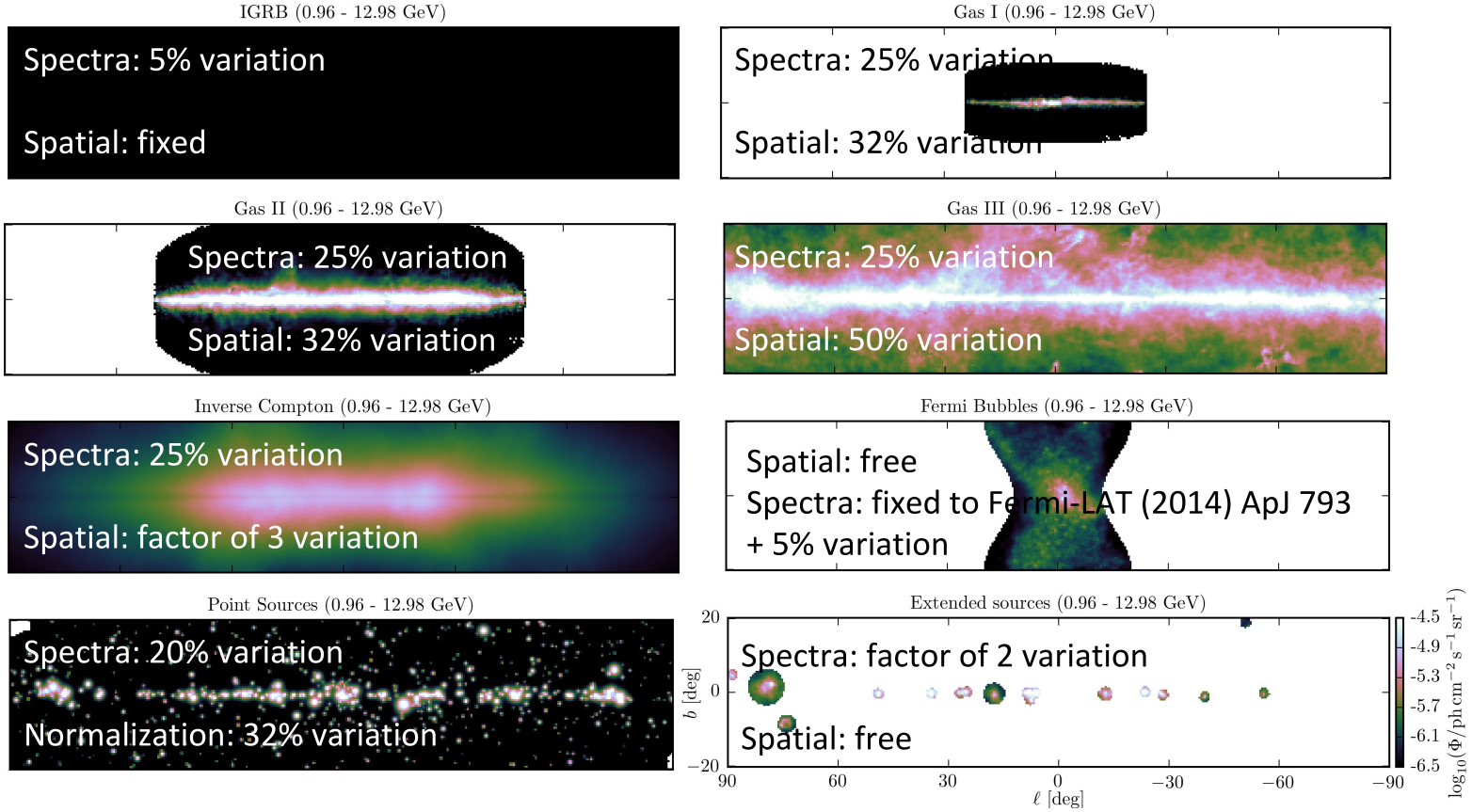


\+ Various spatial templates for GCE with free spectra and fixed morphology

*Foreground modulation similar to run5 in SkyFACT paper Storm+[1705.04065](JCAP)

Foreground model and constraints

Best-fit models



\+ Various spatial templates for GCE with free spectra and fixed morphology

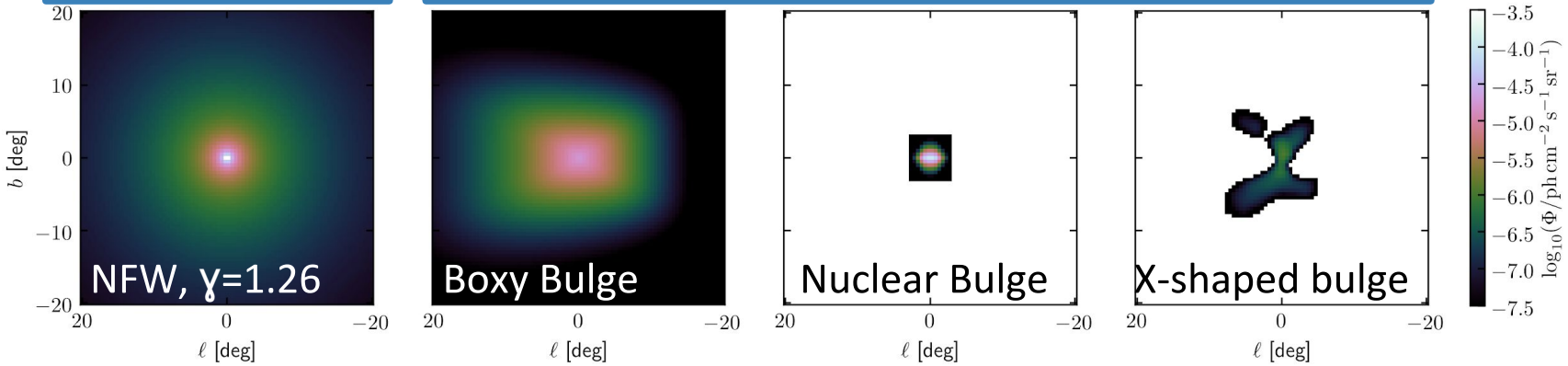
*Foreground modulation similar to run5 in SkyFACT paper Storm+[1705.04065](JCAP)

GCE spatial templates

Best-fit models

Dark Matter

Stellar Distributions



Correlation between GCE and X-shaped bulge: Macias+[1611.06644] (Nat Astro)

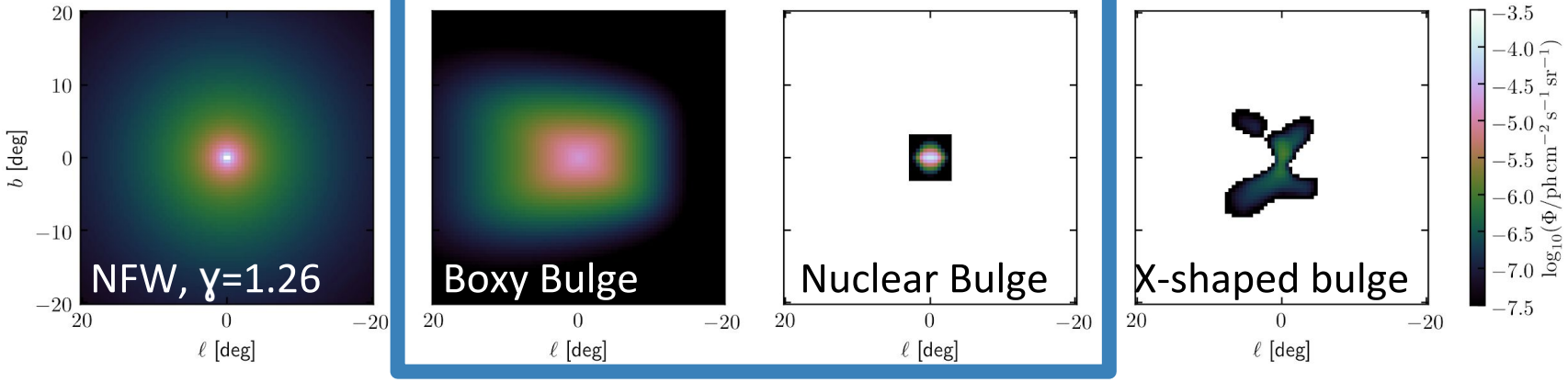
Other templates tested:

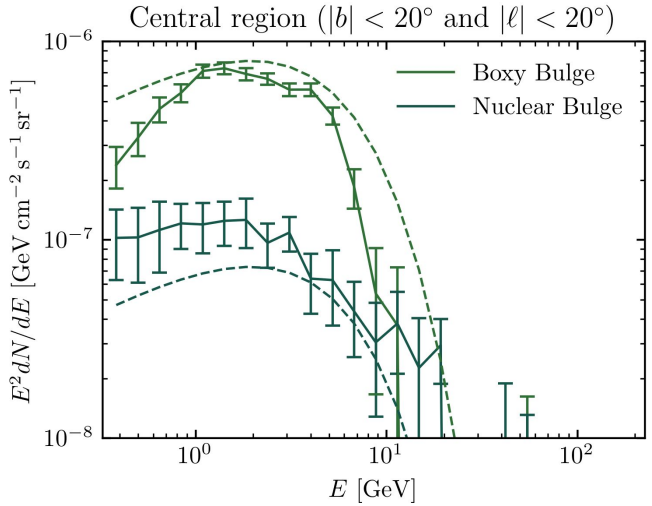
- NFW, γ=1
- Einasto
- 511 keV emission
- Combinations

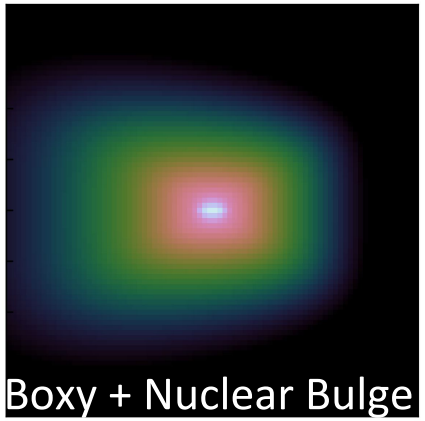
Bartels+[1711.04778](Nat Astro)

GCE spatial templates

Best-fit combination
Preferred over DM at 16σ

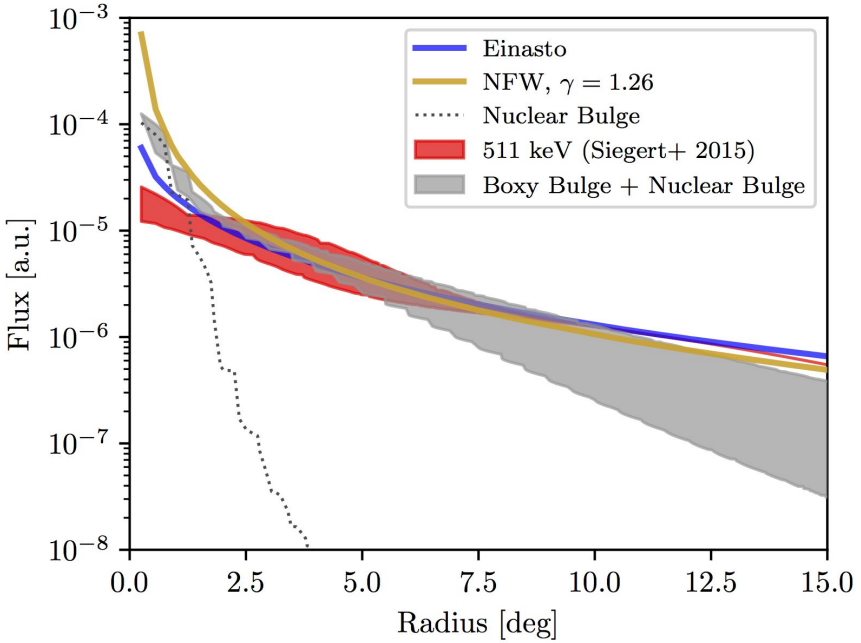


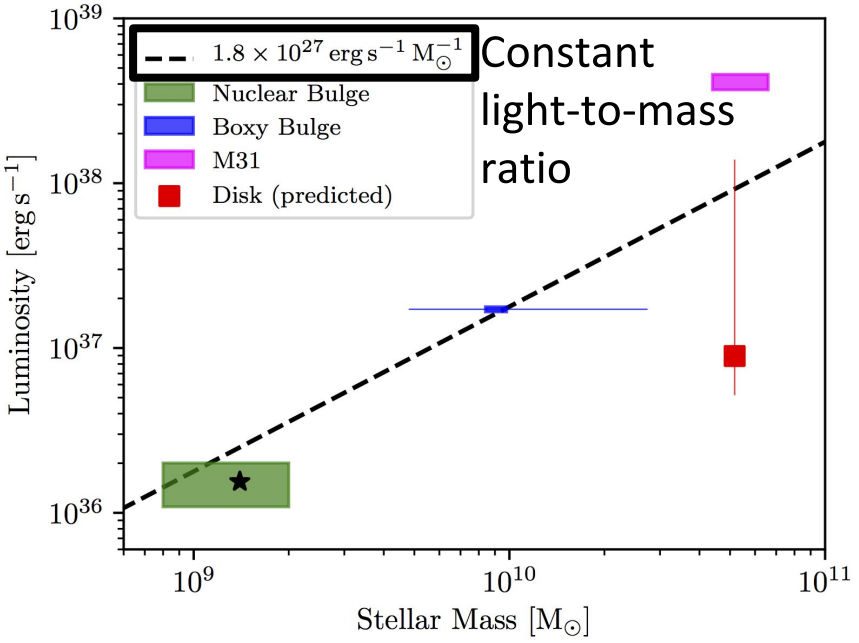




Bartels+[1711.04778](Nat Astro)

The GCE as a tracer for stellar mass



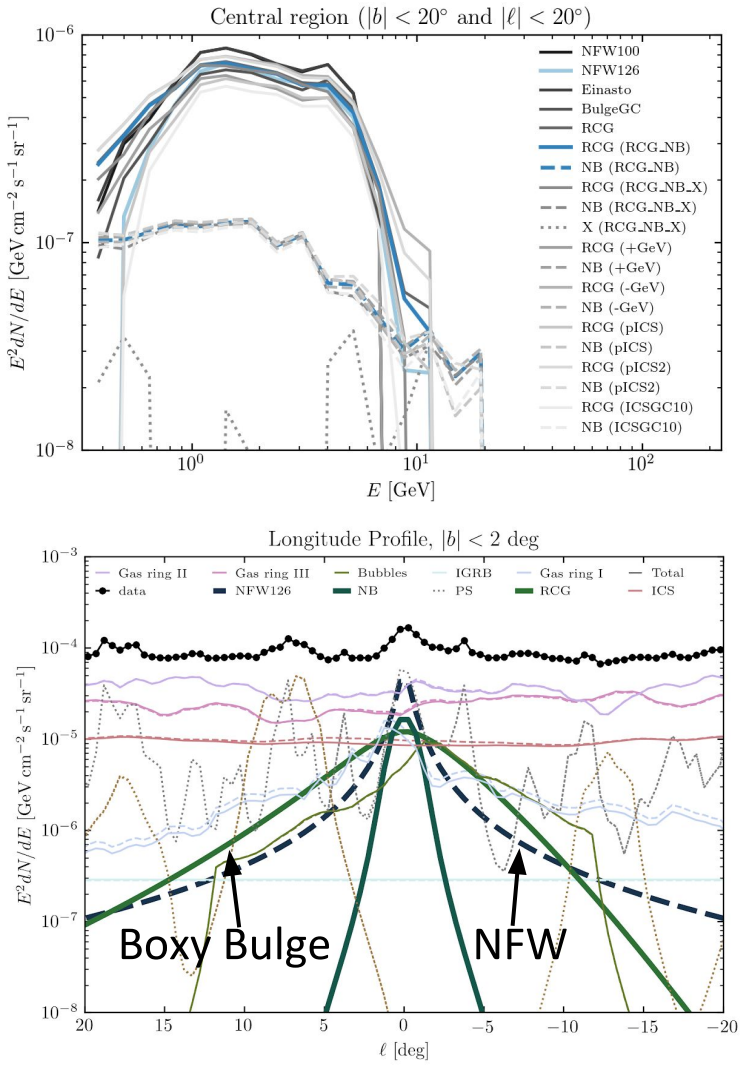


Morphology of the GCE is more oblate

The GCE luminosity scales with stellar mass

Bartels+[1711.04778](Nat Astro)

Systematic checks



Bartels+[1711.04778](Nat Astro)

Results robust to:

- Inclusion of more point sources (from the 2FIG catalog)
- Changes to the Fermi bubbles spectrum and template
- Additional templates for the CMZ, ICS emission from a central source
- Splitting gas rings into separate HI and CO templates
- Varying the modulation on foreground components

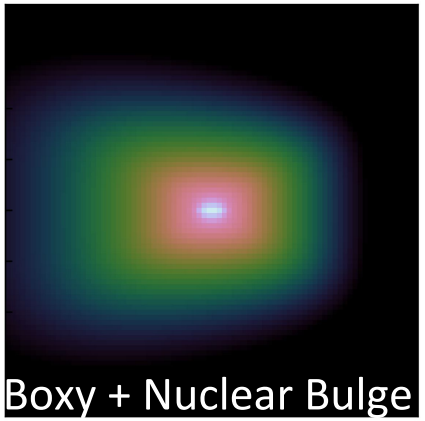
Stable results require:

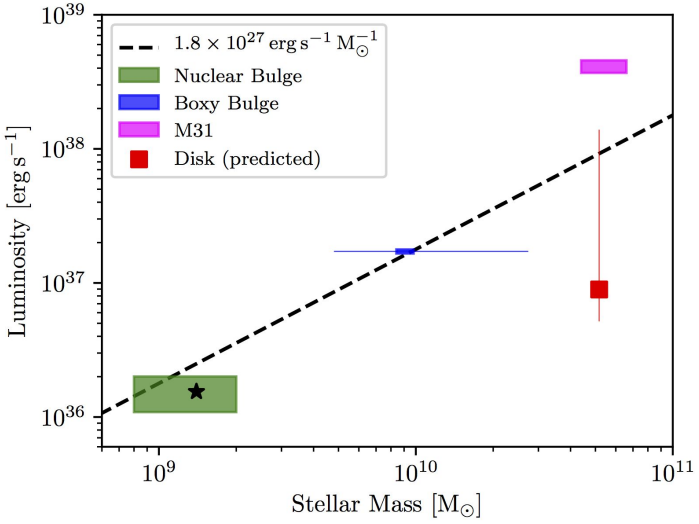
- Large enough ROI to discriminate foreground components
- Sufficient spatial modulation to account for intrinsic uncertainty in foreground models

The GCE as a tracer of stellar mass

- SkyFACT allows for incorporation of intrinsic uncertainties through adjustable modulation parameters

- GCE traces stellar mass in the Galactic bulge
- Provides further support for point source origin of the GCE
- Future radio/MW surveys will conclusively test this scenario

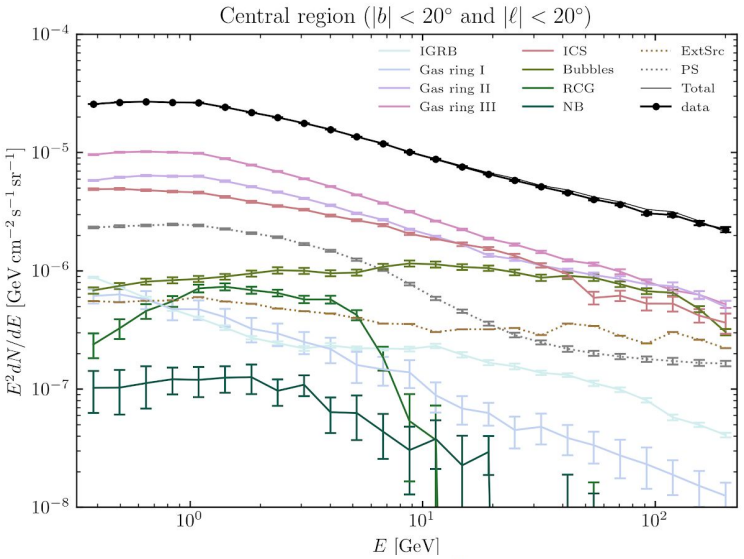


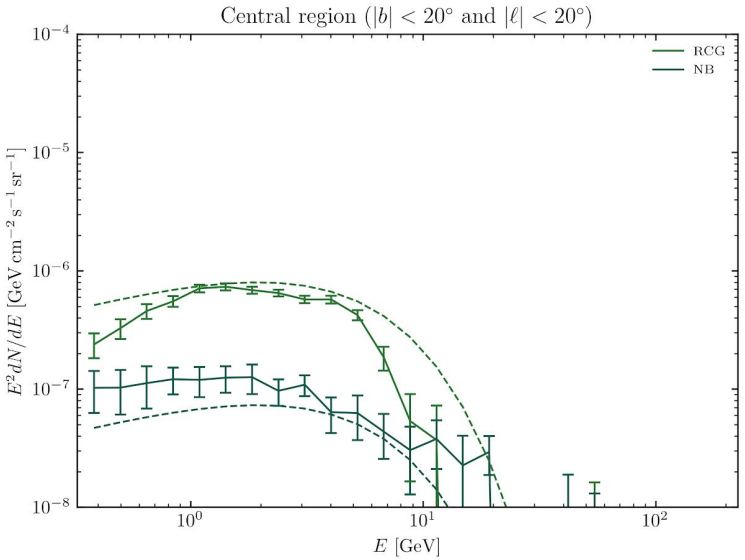


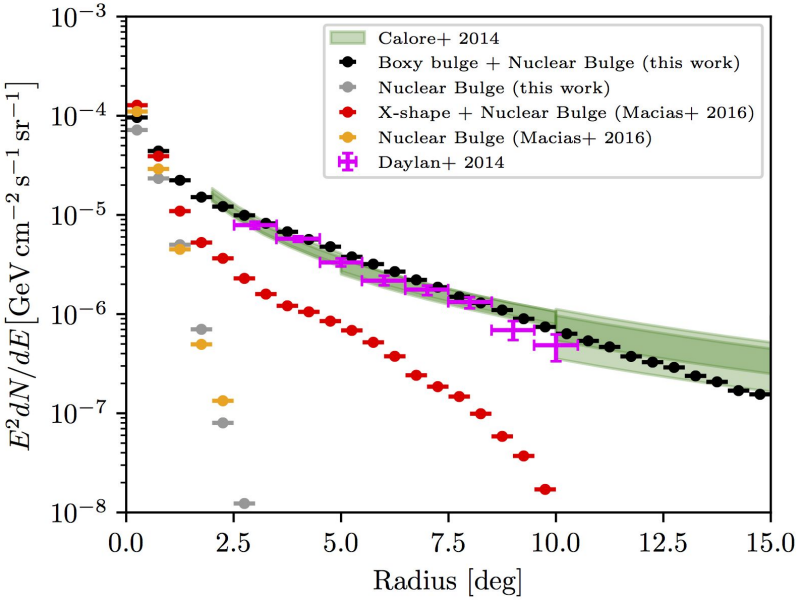
Bartels+[1711.04778](Nat Astro)

Backup Slides

Spectra + profile comparison for GCE







Bartels+[1711.04778](Nat Astro)

SkyFACT: likelihood + regularization

Poisson Likelihood: $\ln \mathcal{L}_{\rm P} = \sum_{pb} c_{pb} - \mu_{pb} + c_{pb} \ln \frac{\mu_{pb}}{c_{pb}}$

Regularization Likelihood Terms:

$$-2 \ln \mathcal{L}_R = \sum_k \lambda_k \mathcal{R}_X(\tau^{(k)}) + \lambda'_k \mathcal{R}_X(\sigma^{(k)}) + \lambda''_k \mathcal{R}_X(\nu^{(k)}) + \eta_k \mathcal{S}_1(\tau^{(k)}) + \eta'_k \mathcal{S}_2(\sigma^{(k)})$$
$$+ \sum_s \lambda'_s \mathcal{R}_X(\sigma^{(s)}) + \lambda''_s \mathcal{R}_X(\nu^{(s)}) + \eta'_s \mathcal{S}_2(\sigma^{(s)})$$

Regularization Definitions

$$\lambda \mathcal{R}_{MEM}(x) = 2\lambda \sum_i 1 - x_i + x_i \ln x_i$$

$$\eta \mathcal{S}_1(x) = \eta \sum_{(p,p') \in \mathcal{N}} (\ln x_p - \ln x_{p'})^2 \qquad \eta \mathcal{S}_2(x) = \eta \sum_b (\ln x_{b-1} - 2 \ln x_b + \ln x_{b+1})^2$$

SkyFACT: model

Model Definition

$$\theta \equiv (\tau^{(k)}, \sigma^{(k)}, \nu^{(k)}, \sigma^{(s)}, \nu^{(s)})^T \qquad \phi^D \equiv (\phi_{bp})$$

$$(\phi^D)_i = (A^{(1)}\theta)_i (A^{(2)}\theta)_i (A^{(3)}\theta)$$

A1,A2,A3 = spatial, spectral, normalization

Expected counts

$$\mu^D = \sum_j P_{ij} (\phi^D)_j (E)_j$$

SkyFACT: statistics definitions

Naively:

$$N_{\mathrm{data}} = N_{\mathrm{pix}} \times N_{\mathrm{ebin}} = 360 \times 81 \times 25 = 729000$$

$$N_{\mathrm{DOF}} = N_{\mathrm{data}} - N_{\mathrm{param}}$$

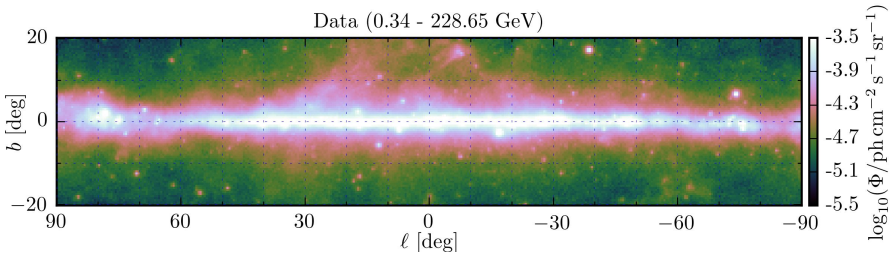
But: non-gaussianity, regularization constraints, parameter degeneracies:

$$N_{\mathrm{data}}^{\mathrm{eff}} \equiv \langle -2 \ln \mathcal{L}_P(\theta) \rangle_{\mathcal{D}(\theta)}$$

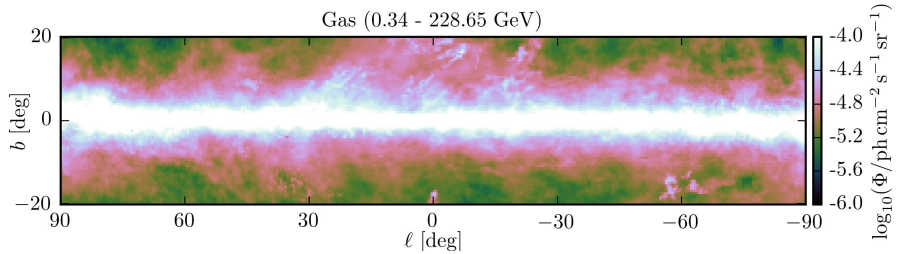
$$N_{\mathrm{DOF}}^{\mathrm{eff}} \sim \langle -2 \ln \mathcal{L}_P \rangle_{\mathrm{mock}}$$

Example fit with SkyFACT

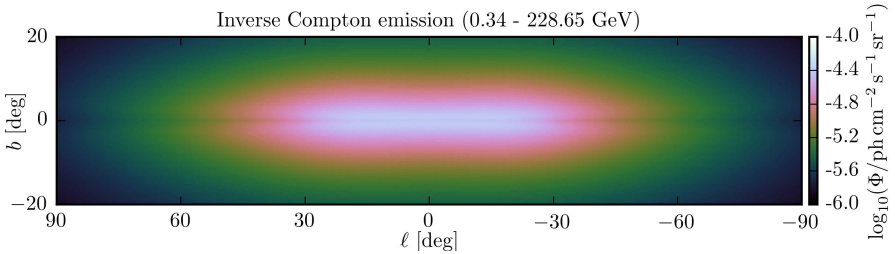
Data:



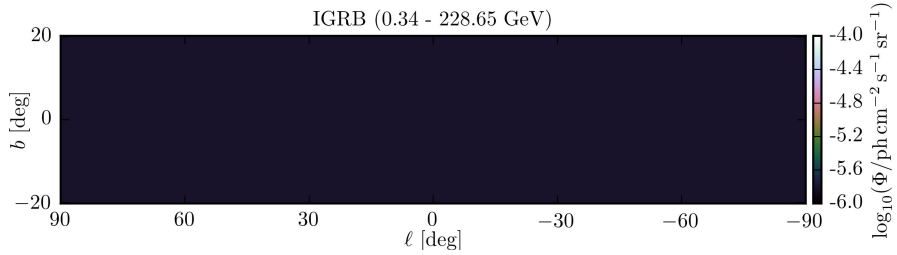
Model:



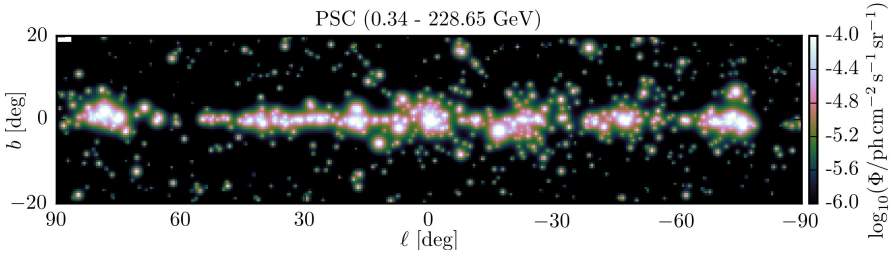
Template: sum of HI and H2 column densities from GALPROP; no dark gas correction
Spectrum: Fermi-LAT (2012) ApJ 750



Template: ISRF from GALPROP, propagation with DRAGON
Spectrum: Fermi-LAT (2012) ApJ 750



Spectrum: Fermi-LAT (2015) ApJ 799



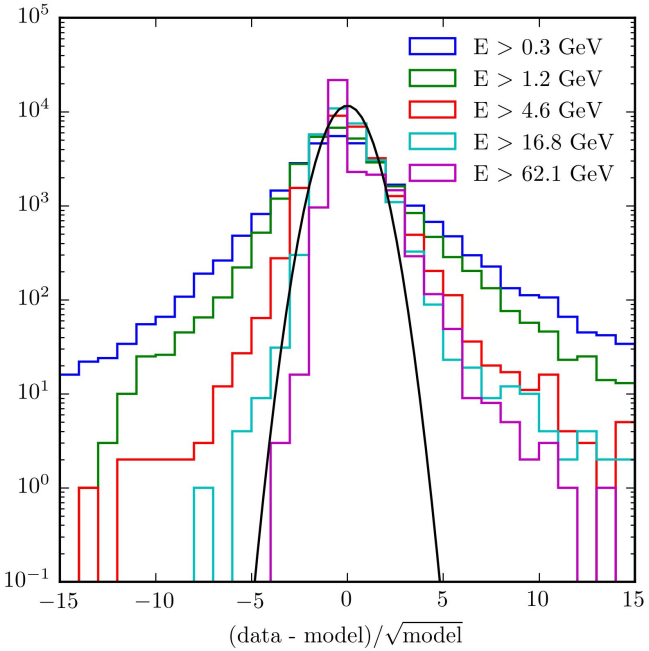
Locations and spectra: 3FGL catalog

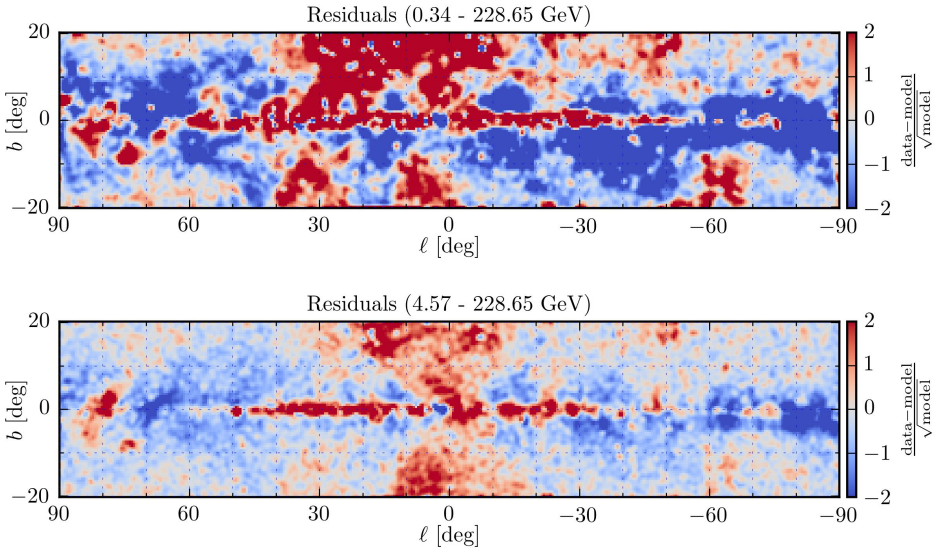
SkyFACT vs the traditional approach

Fixed templates + constrained spectra

No spatial modulation allowed

~25% variations allowed



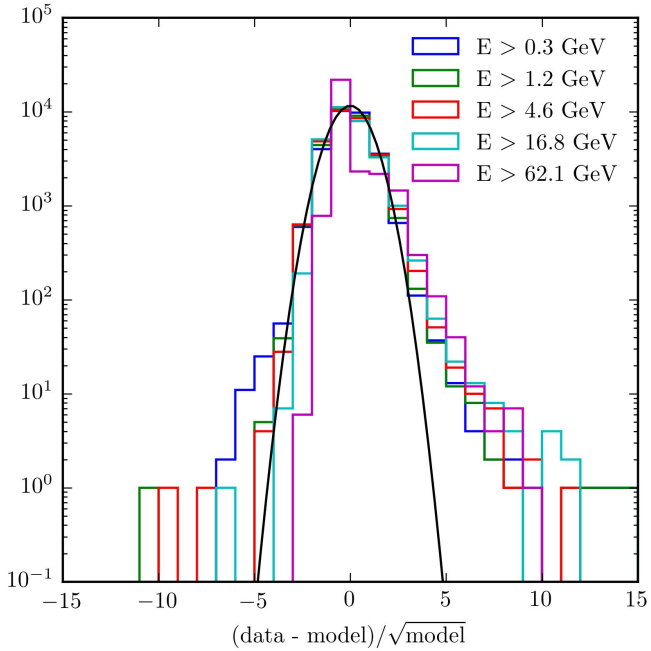


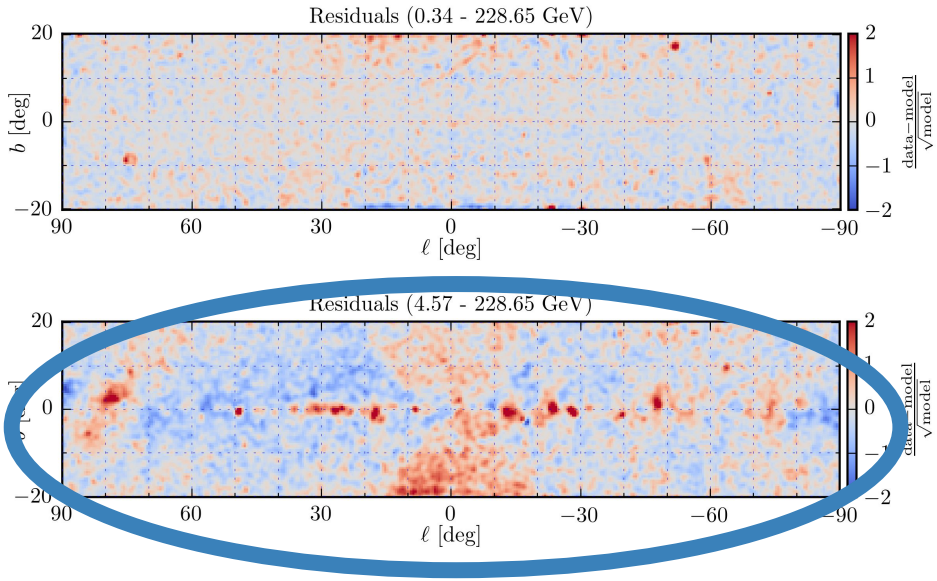
The traditional approach

Additional necessary components

Constrained templates + spectra

Spatial modulation: 25% for gas, x2 for ICS
Spectral modulation: 20-25%

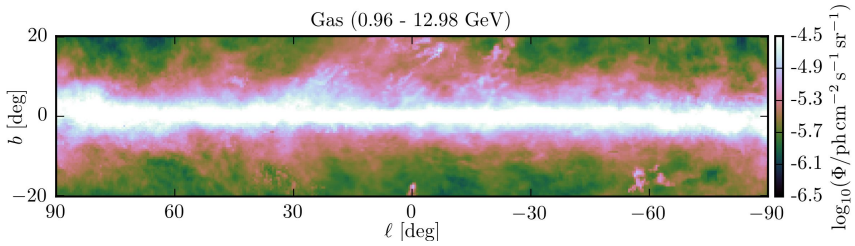




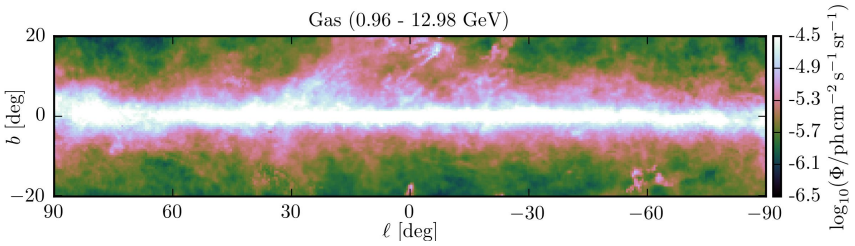
Irreducible residuals ⟶ add new components

SkyFACT: modulation parameters

Original Template



Best-fit Template



Template and Spectra Modulation