SkyFACT and the Galactic Center

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In collaboration with:

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BAM

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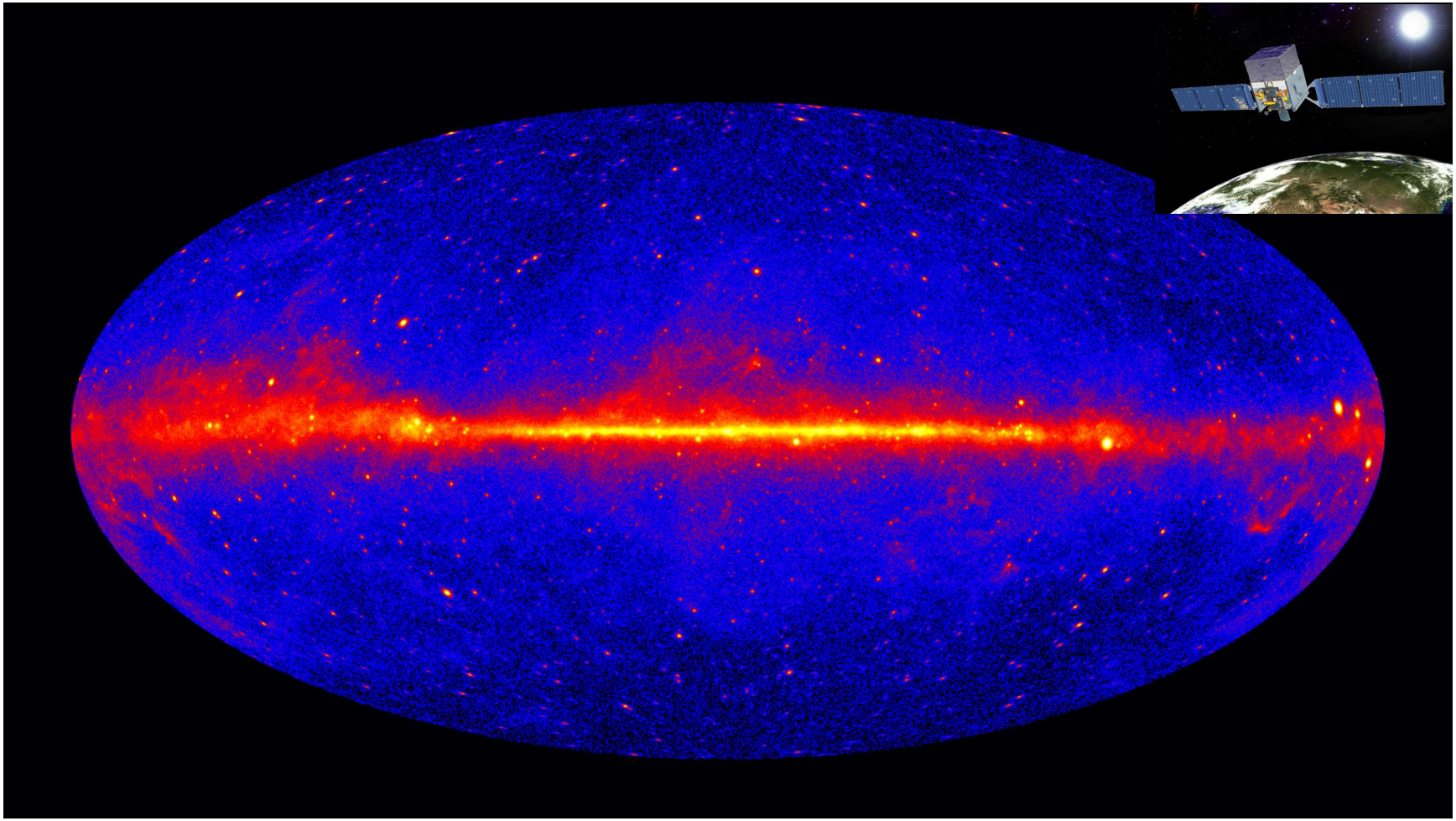
GRAPPA

GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

The gamma-ray sky



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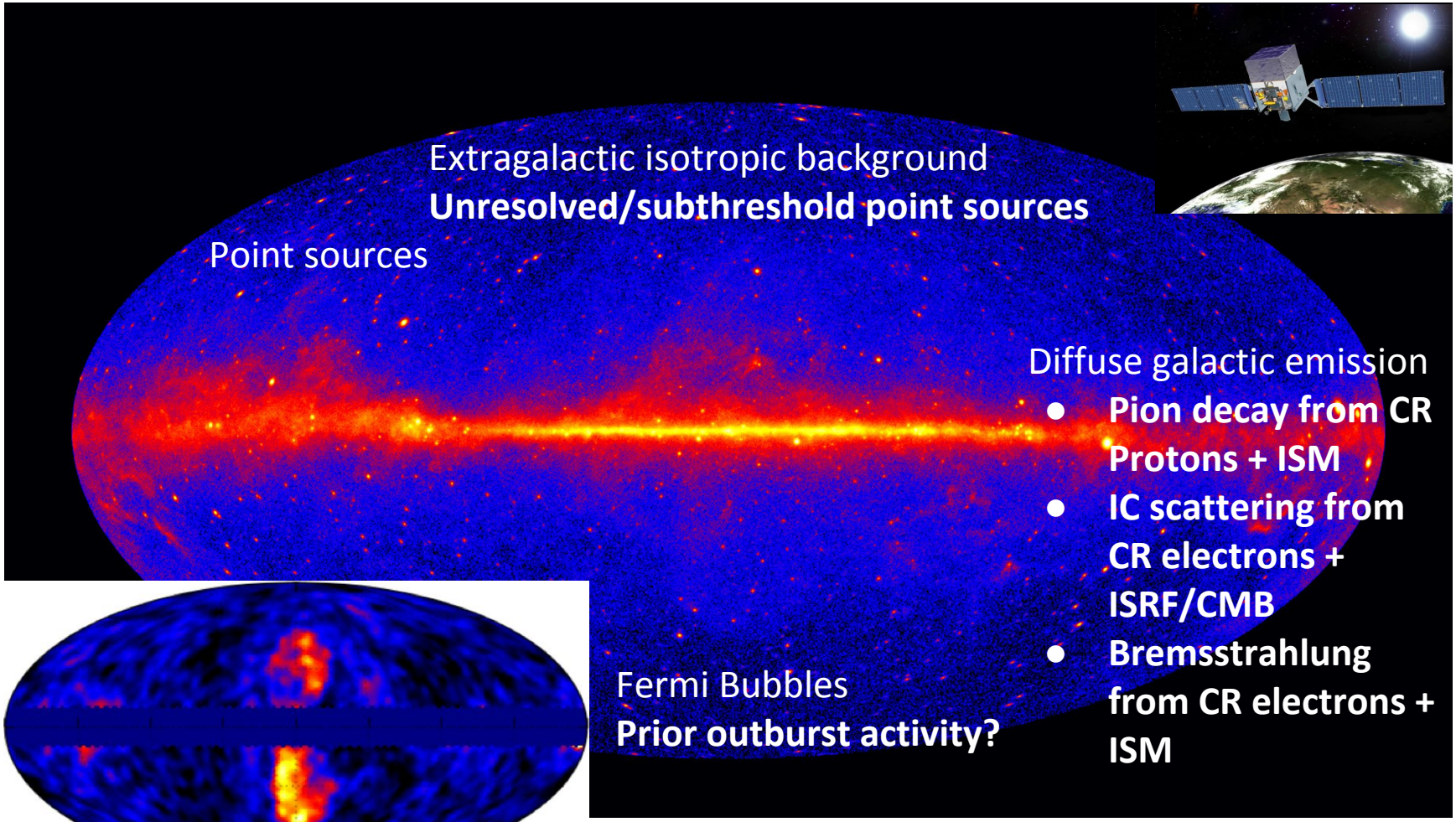

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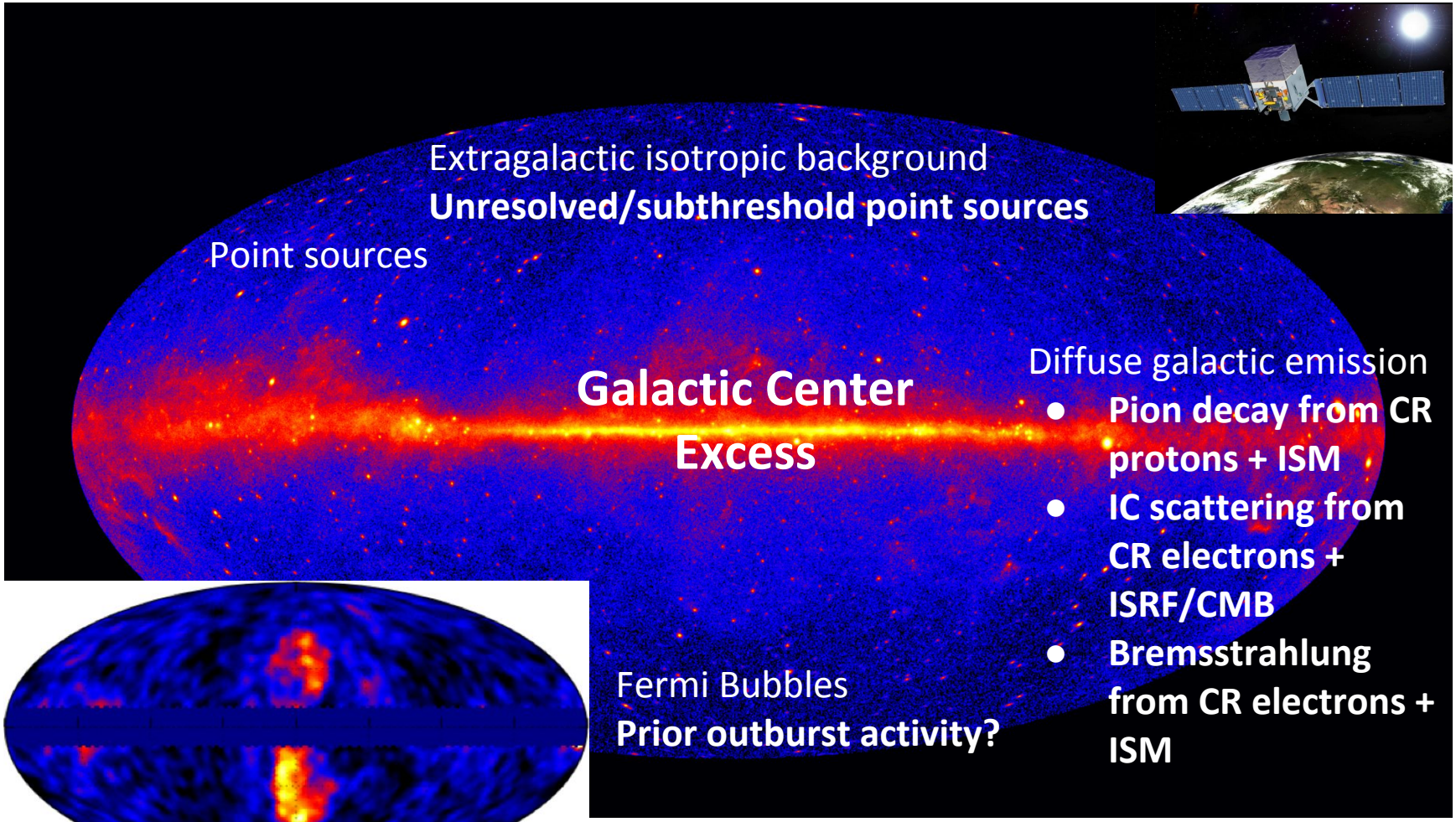
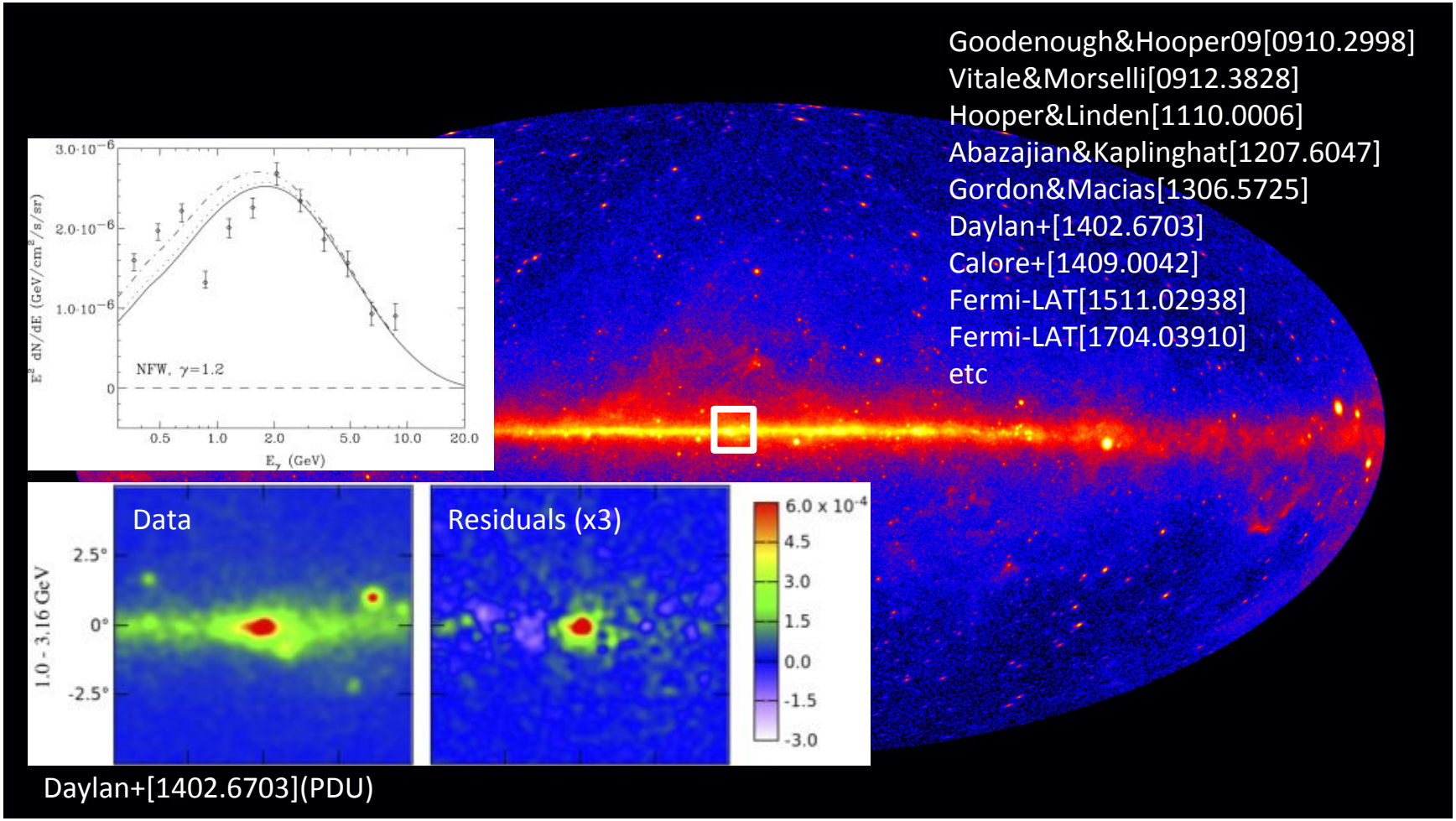
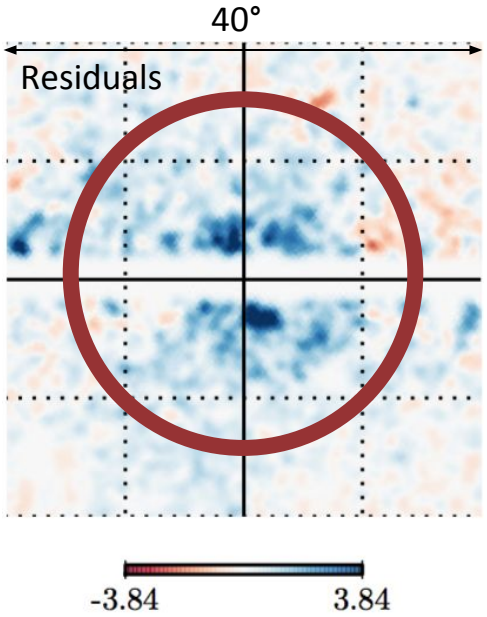


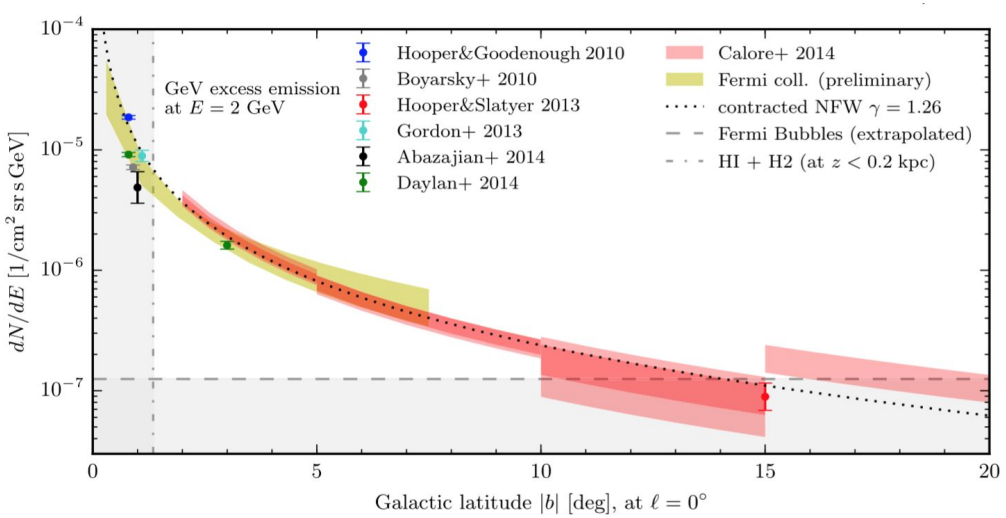
The Fermi Galactic Center Excess



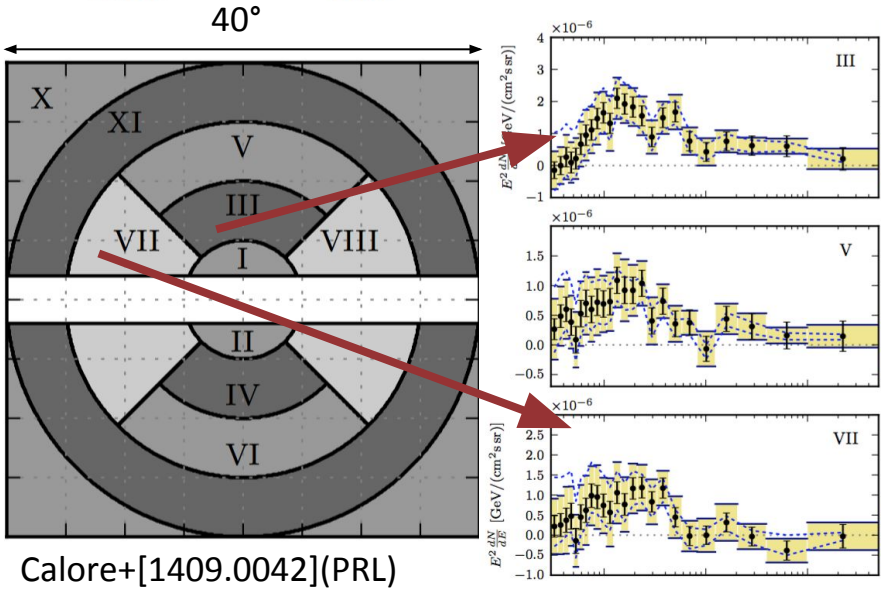
Daylan+[1402.6703](PDU)

The Fermi galactic center excess (GCE)





Calore+[1411.4647](PRD)



Calore+[1409.0042](PRL)

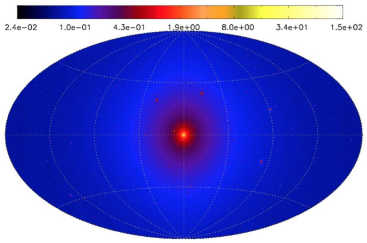
Characteristics:

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

Origins of the GCE

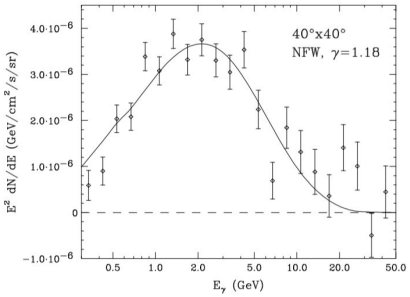
Dark Matter Interpretation

Expected ɣ-ray counts from DM annihilation

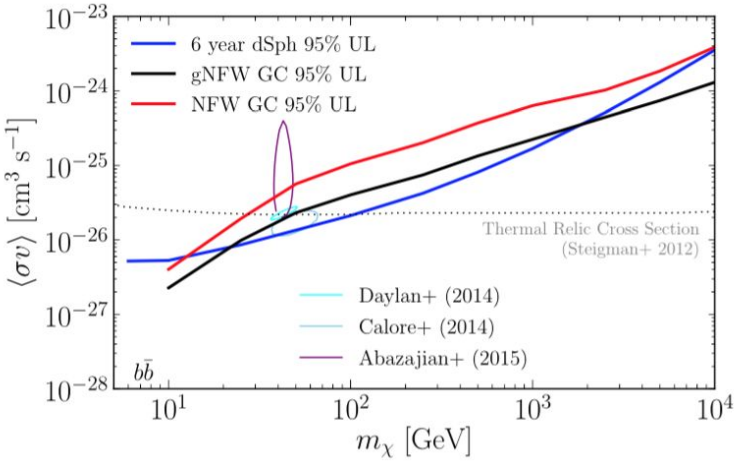


Pieri+[0908.0195](PRD)

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



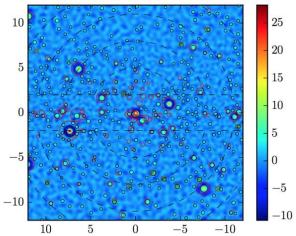
Daylan+[1402.6703](PDU)



Fermi-LAT+[1704.03910](ApJ)

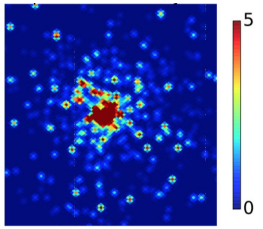
Astrophysics Interpretation: Unresolved Point Sources

Wavelet analysis



Bartels+[1506.05104](PRL)

Non-poissonian templates

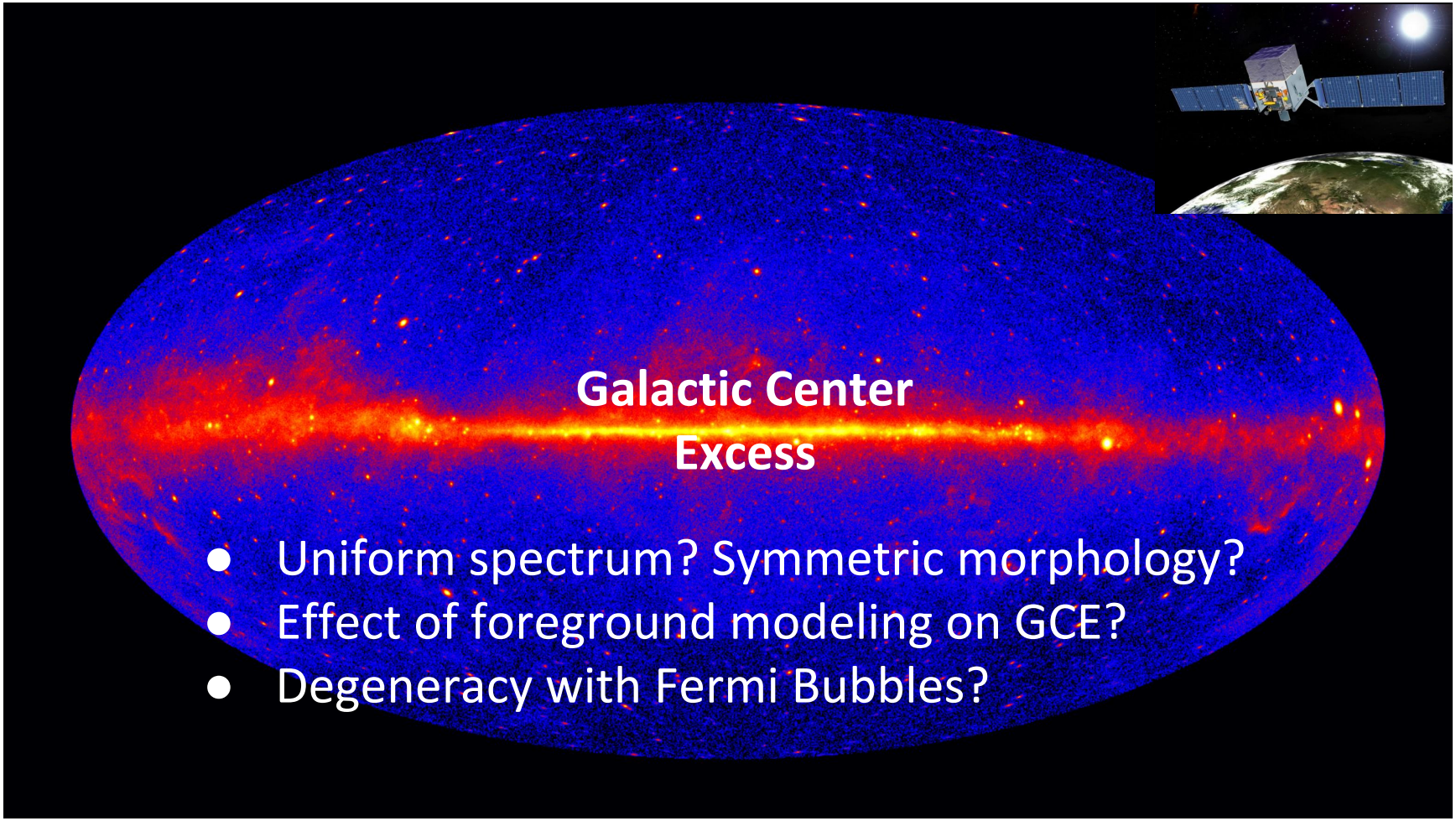


Lee+[1506.05124](PRL)

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

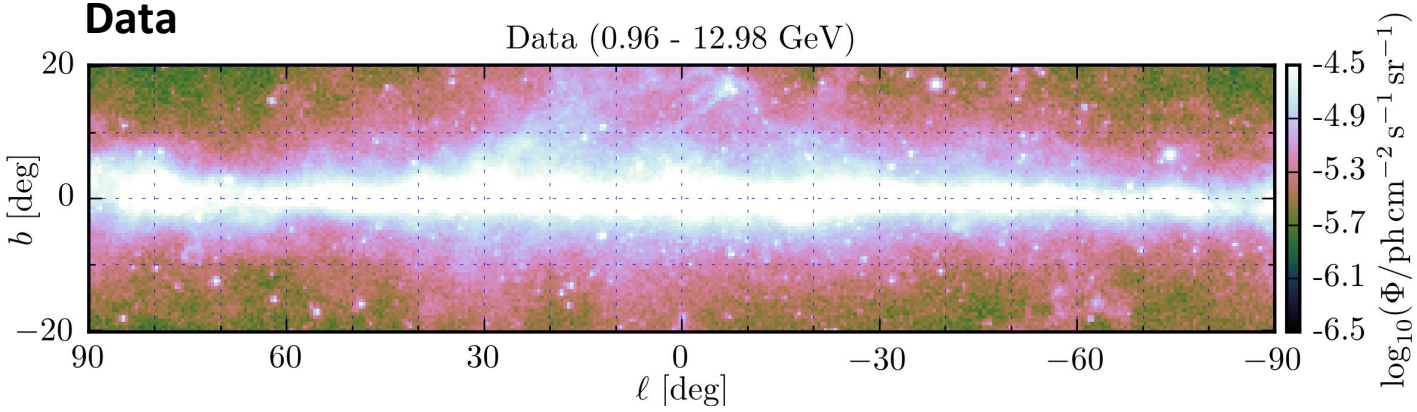
Other scenarios: Additional CR-induced emission, SF burst(s), steady increased SF in GC/CMZ, emission from molecular clouds …

Origins of the GCE



Standard template fitting

Data



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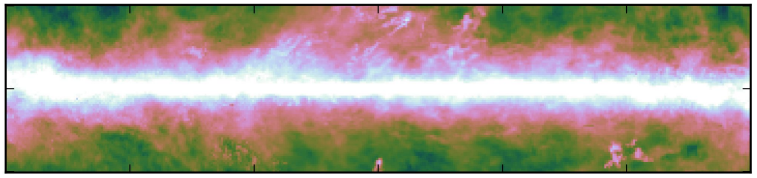
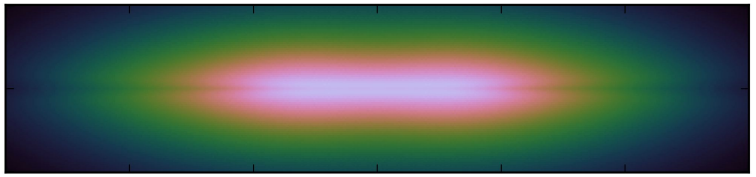
Models for γ-ray emission from:

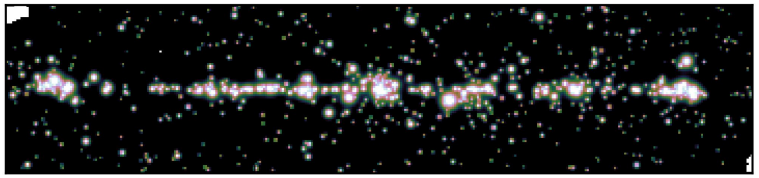
Cosmic ray protons



Cosmic ray electrons



Point sources



\+ Other extended + diffuse components...

Standard template fitting

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

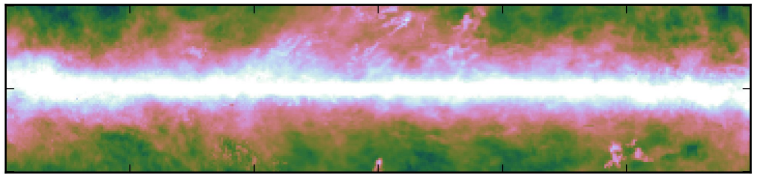
k: model component

Fixed, energy-dependent spatial templates

Derived from normalizations of spatial templates

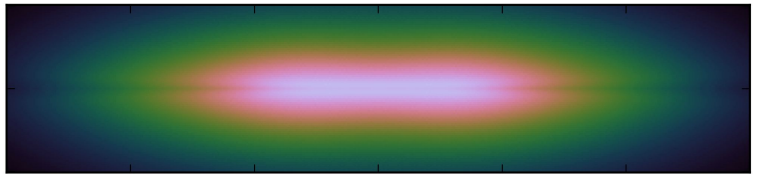
Models for γ-ray emission from: derived from CR prop codes like Galprop, Dragon

Cosmic ray protons



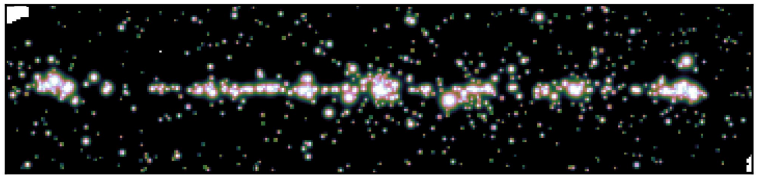
Uncertainties ≳ 30-50%

Cosmic ray electrons



Uncertainties ≳ factor of 2-3

Point sources



\+ Other extended + diffuse components...

A new approach: SkyFACT

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

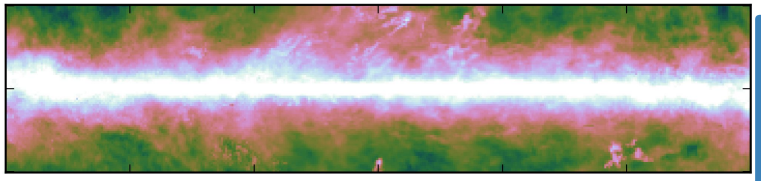
k: model component

Spatial templates that allow for uncertainties at the pixel level

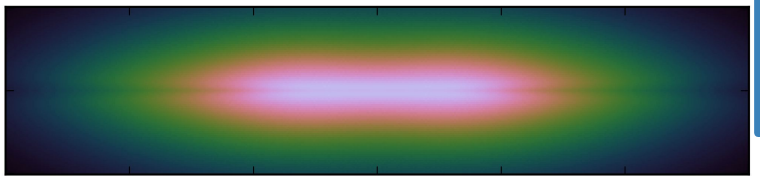
Spectral templates that allow for uncertainties in energy bins

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

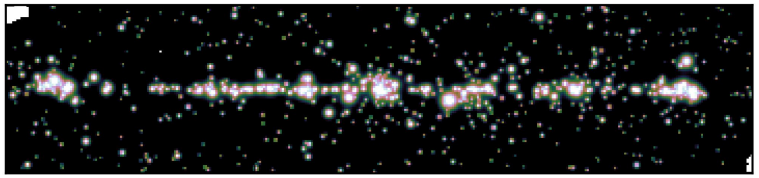
Cosmic ray protons



Cosmic ray electrons



Point sources

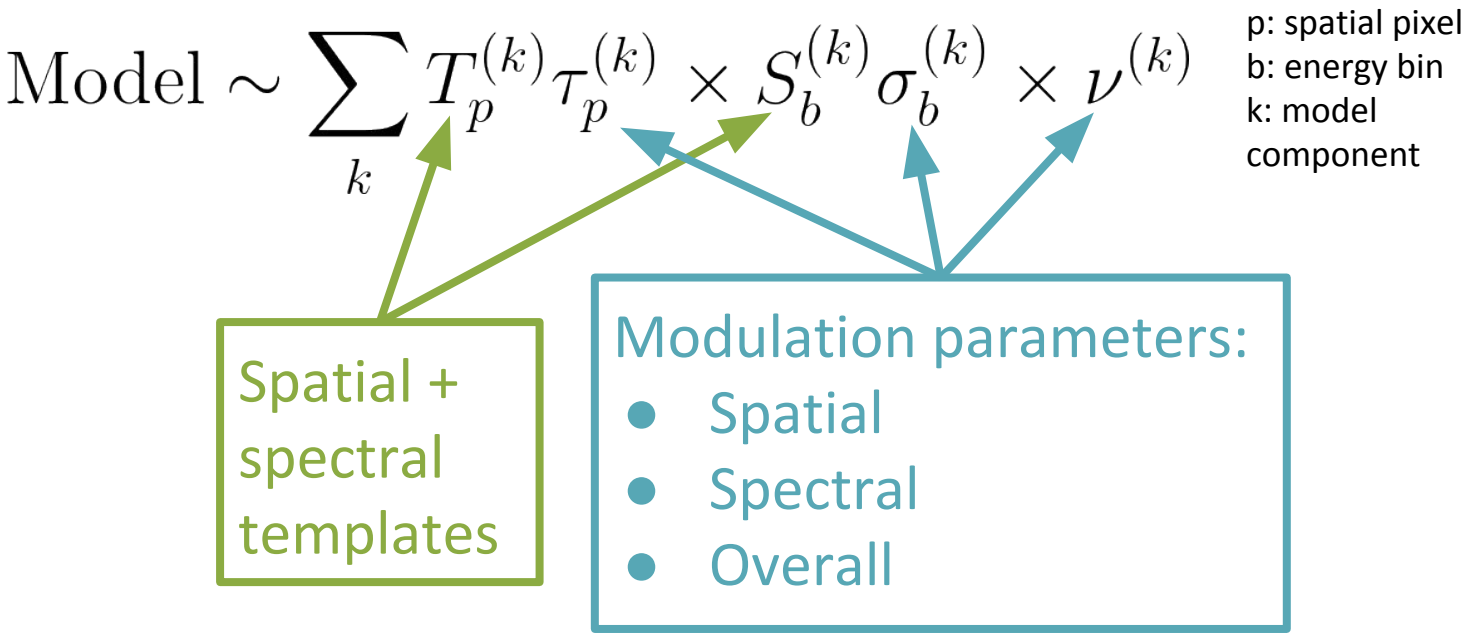


Uncertainties $\gtrsim$ 30-50%

Uncertainties $\gtrsim$ factor of 2-3

\+ Other extended + diffuse components...

A new approach: SkyFACT



Tuneable regularization on:

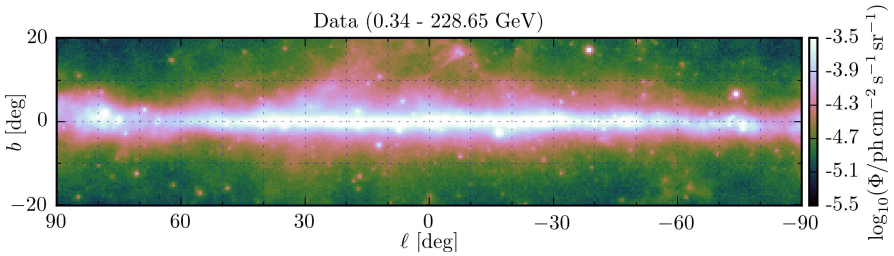
- Modulation: pixel, energy bin, overall normalizations (MEM)
- Smoothing: variation between pixels (L2-like)

Constraints (regularization) added to the likelihood:

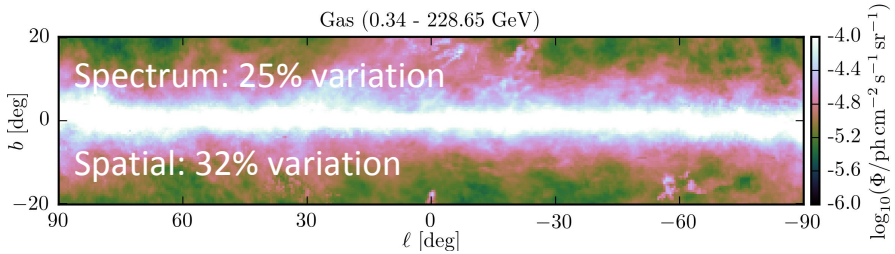
$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}$$

Example fit with SkyFACT

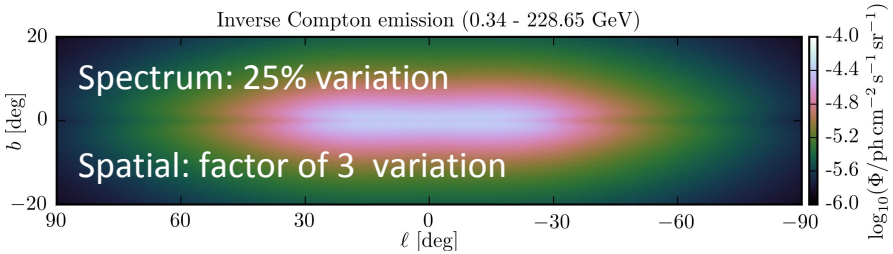
Data:



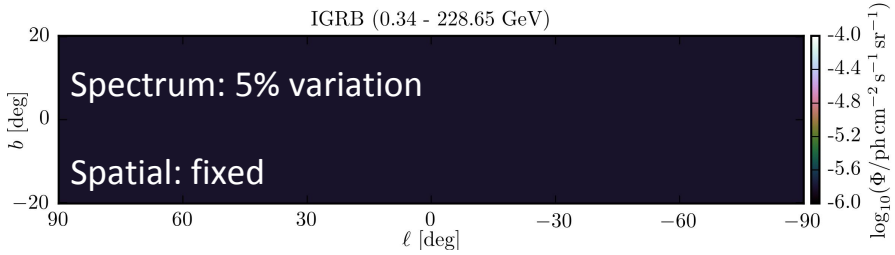
Initial model:



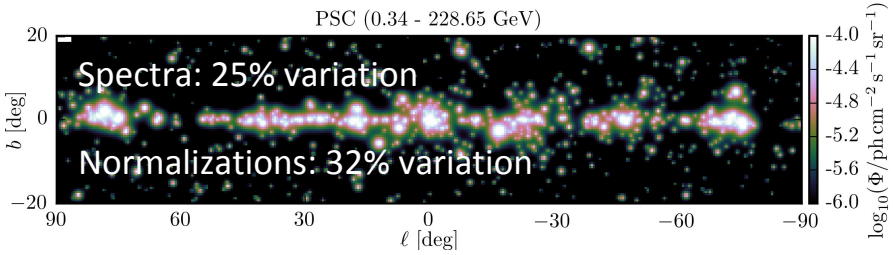
Template: sum of HI and H2 column densities from GALPROP; no dark gas correction
Spectrum: Fermi-LAT (2012) ApJ 750



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



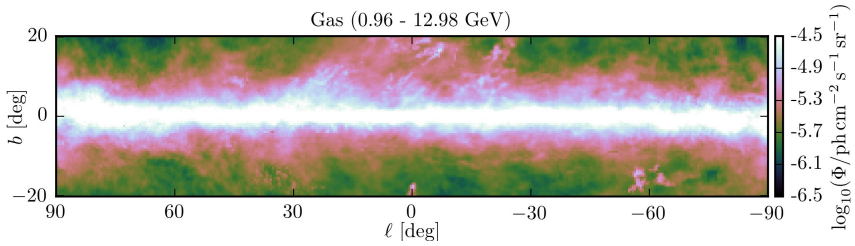
Spectrum: Fermi-LAT (2015) ApJ 799



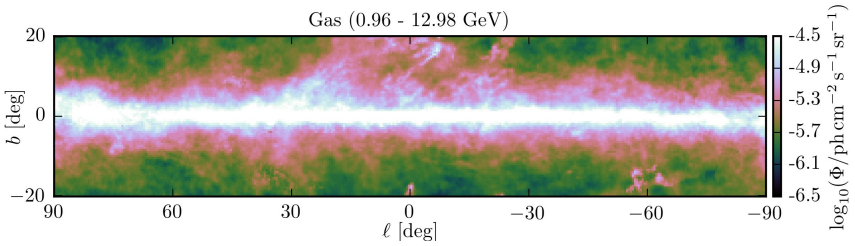
Locations and spectra: 3FGL catalog

Example fit with SkyFACT: modulation

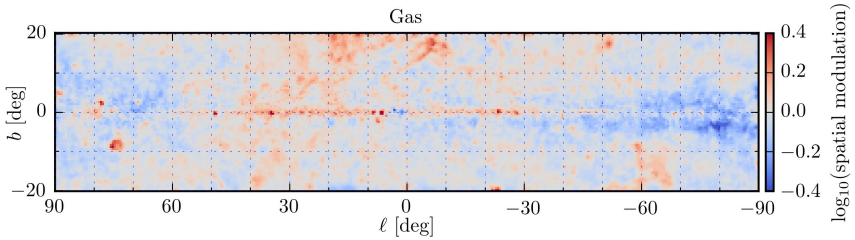
Original Template

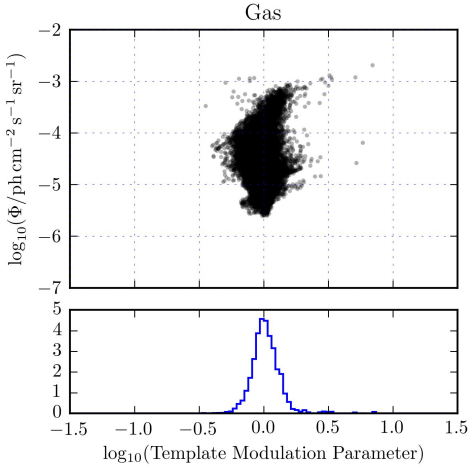


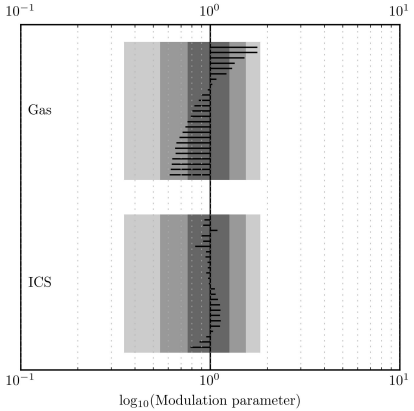
Best-fit Template



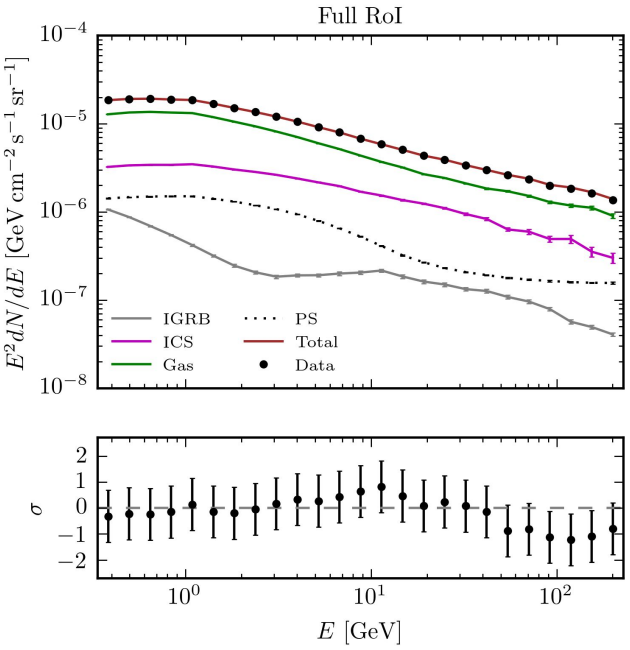
Template and Spectra Modulation

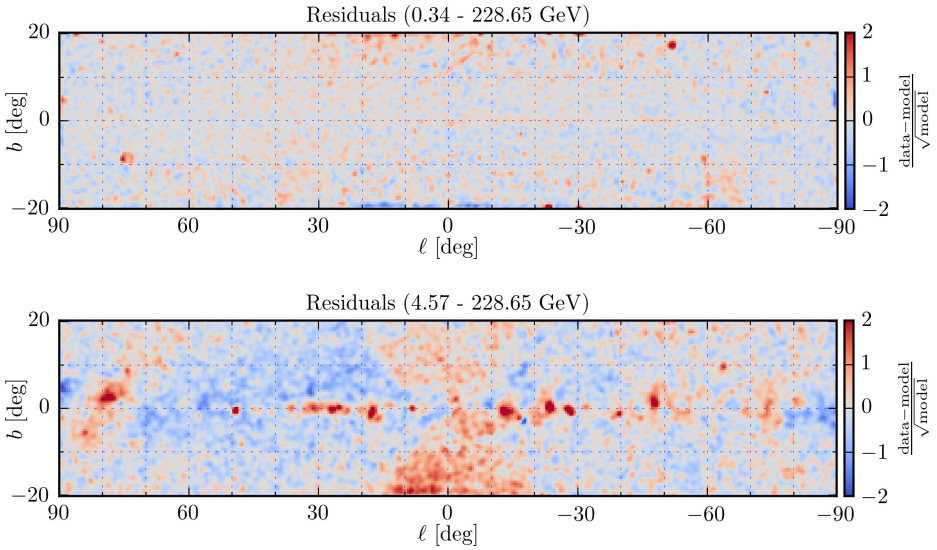






Example fit with SkyFACT: results

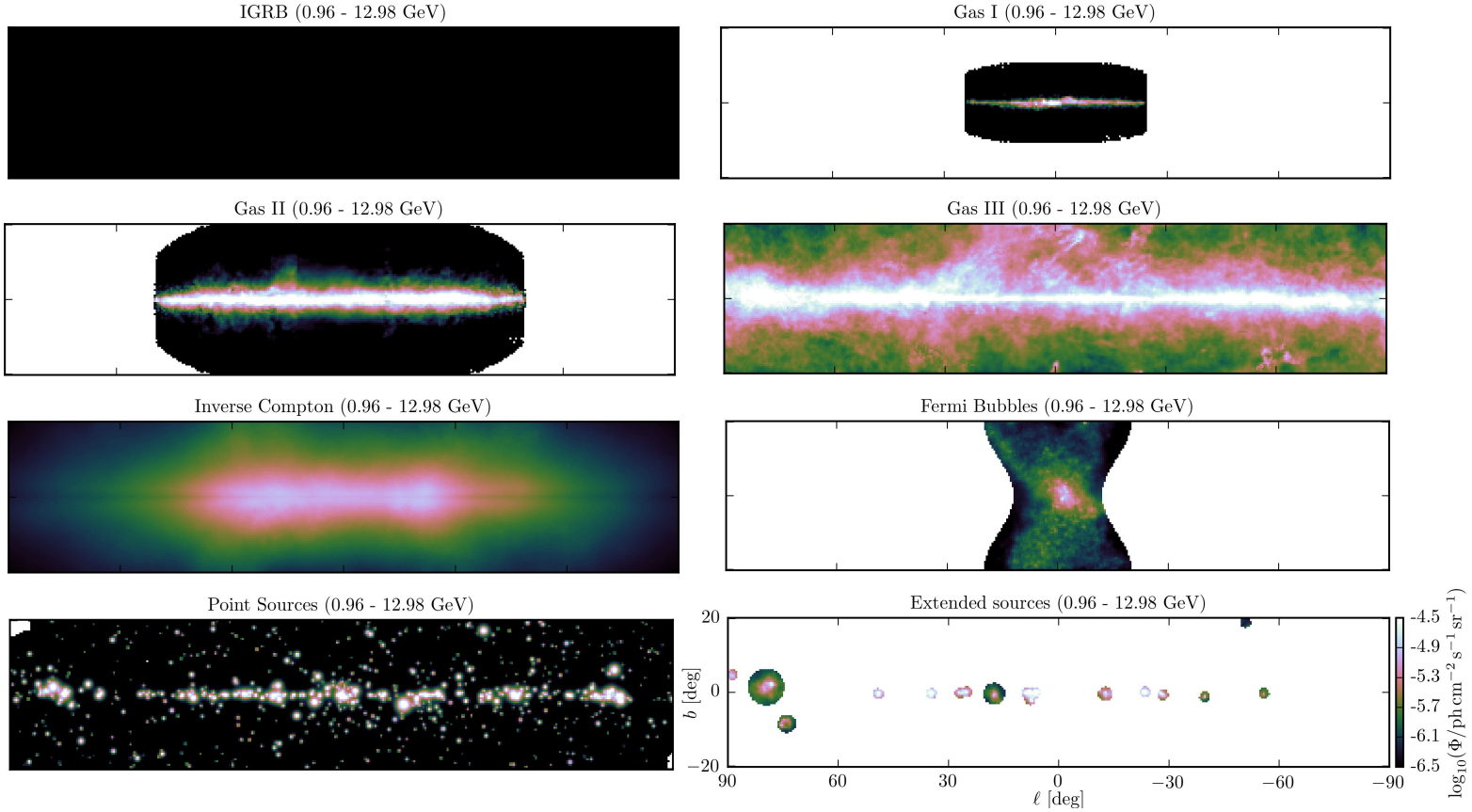




Irreducible residuals ⟶ add new components

Foreground model

Best-fit models

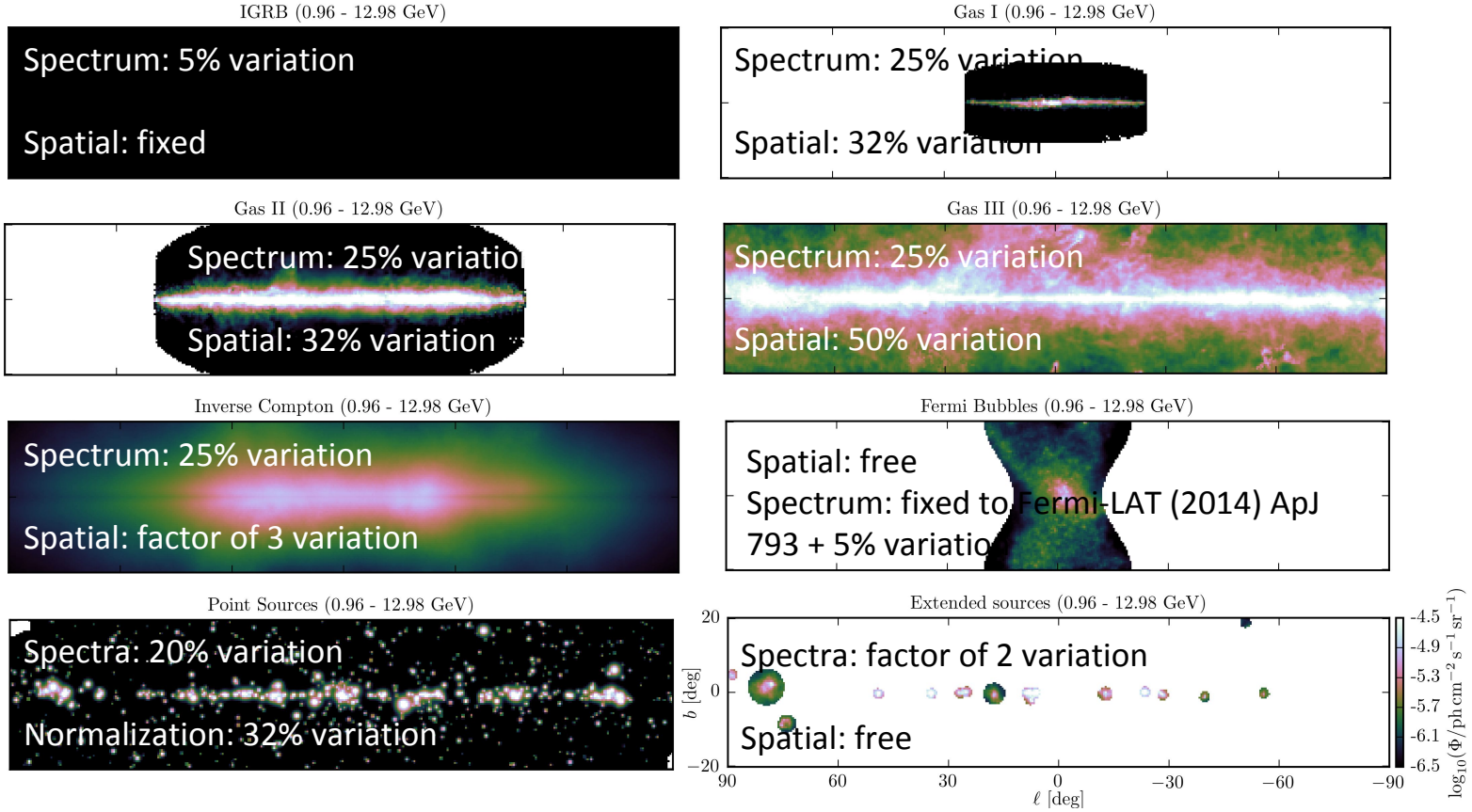


\+ Various spatial templates for GCE with free spectra and fixed morphology

*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

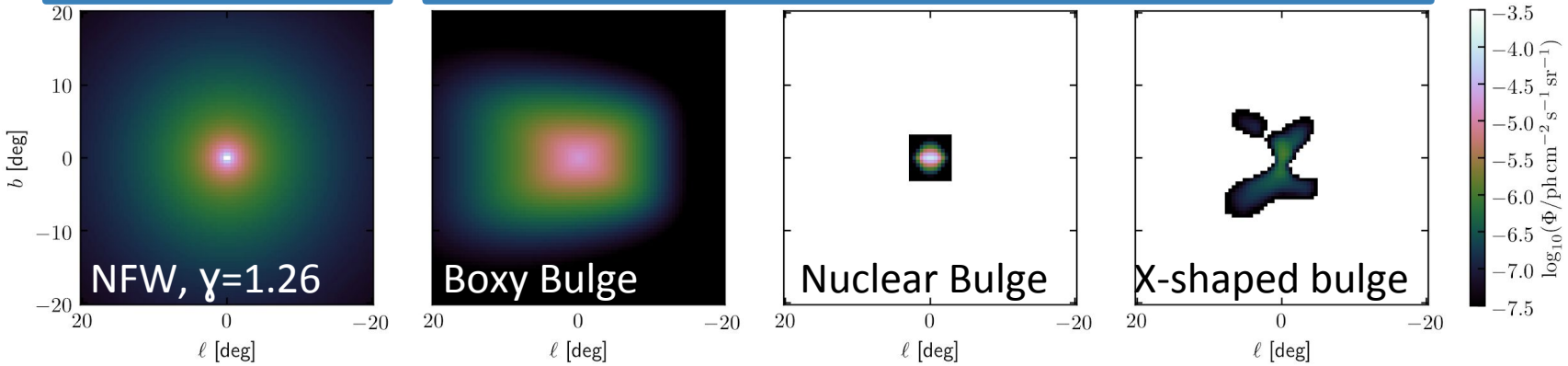
*Foreground modulation similar to run5 in SkyFACT paper Storm+[1705.04065](JCAP)

GCE spatial templates

Best-fit models

Dark Matter

Stellar Distributions



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

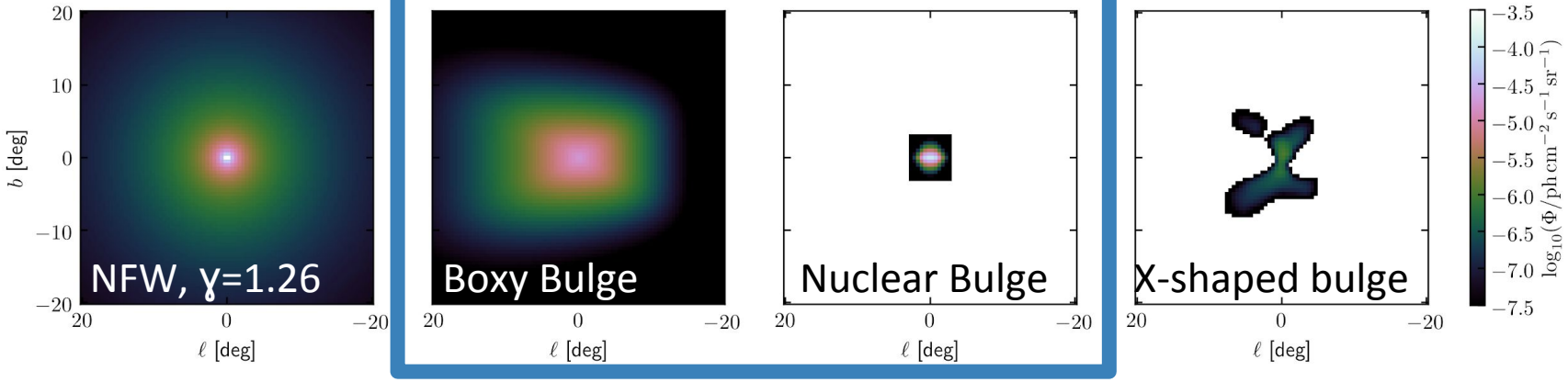
Other templates tested:

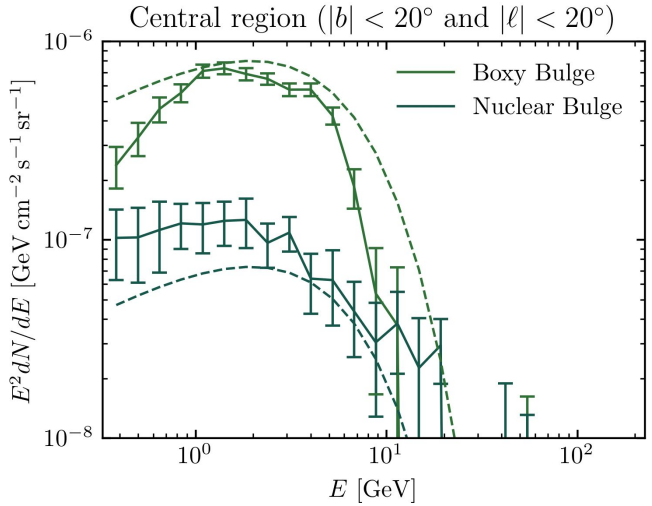
- NFW, γ=1
- Einasto
- 511 keV emission
- Combinations

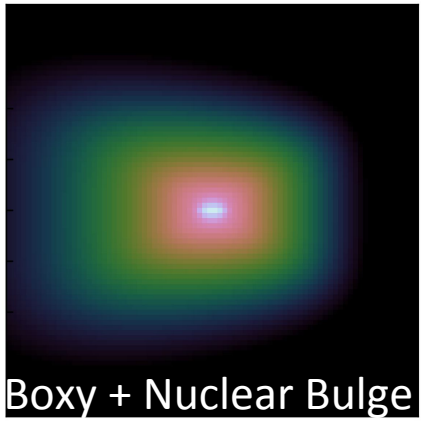
Bartels+[1711.04778](Nat Astro)

GCE spatial templates

Best-fit combination
Preferred over DM at 16σ

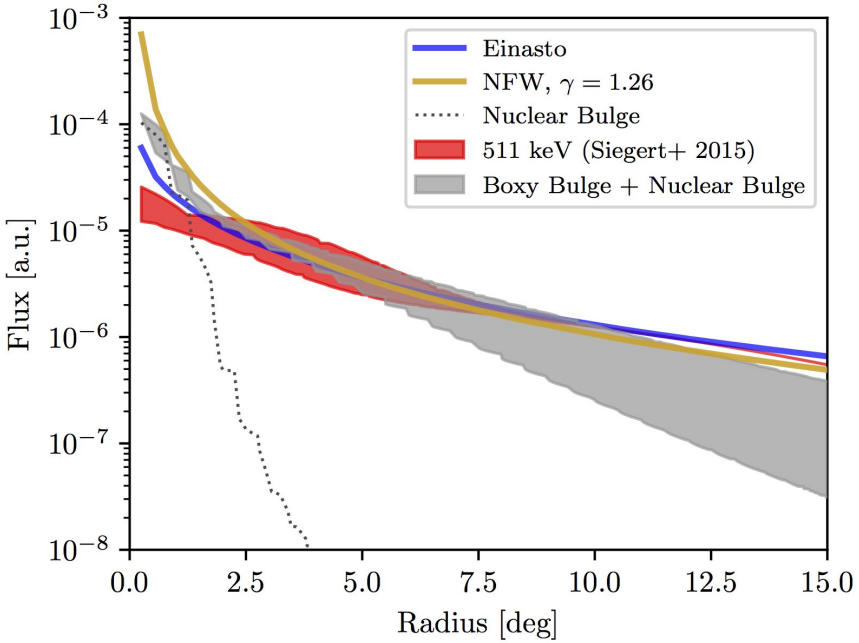


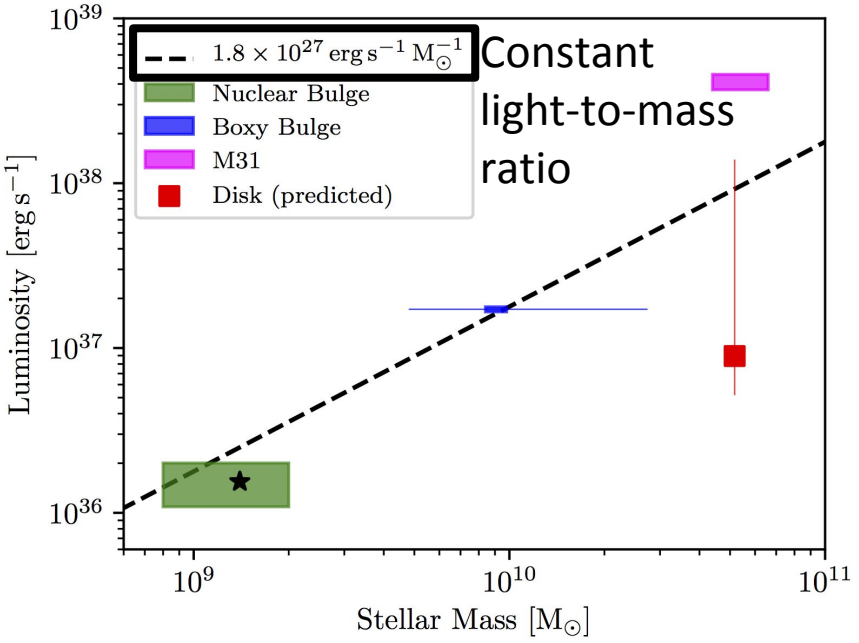




Bartels+[1711.04778](Nat Astro)

The GCE as a tracer for stellar mass



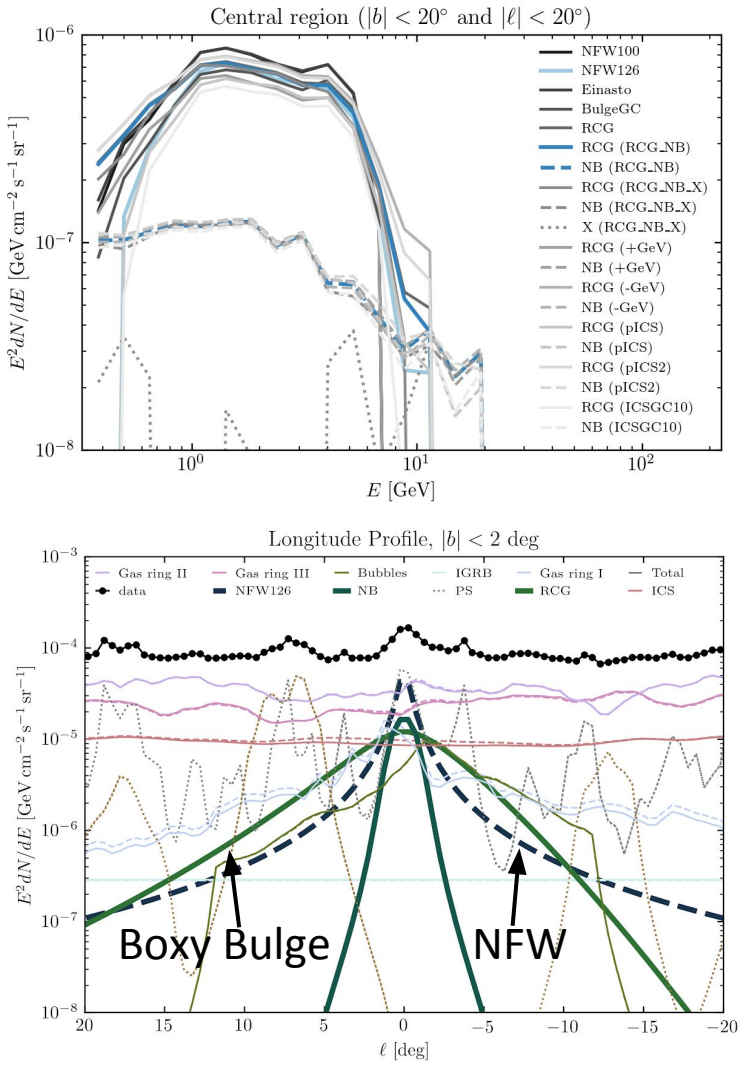


Morphology of the GCE is more oblate

The GCE luminosity scales with stellar mass

Bartels+[1711.04778](Nat Astro)

Systematic checks



Bartels+[1711.04778](Nat Astro)

Results robust to:

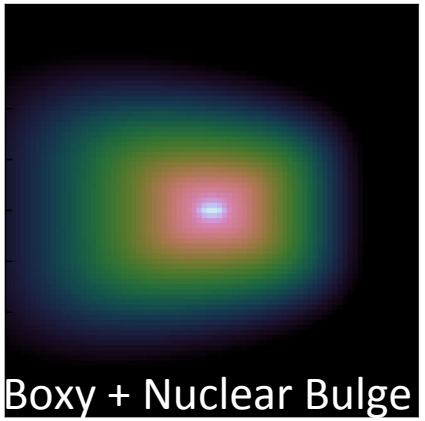
- Inclusion of more point sources (from the 2FIG catalog)
- Changes to the Fermi bubbles spectrum and template
- Additional templates for the CMZ, ICS emission from a central source
- Splitting gas rings into separate HI and CO templates
- Varying the modulation on foreground components

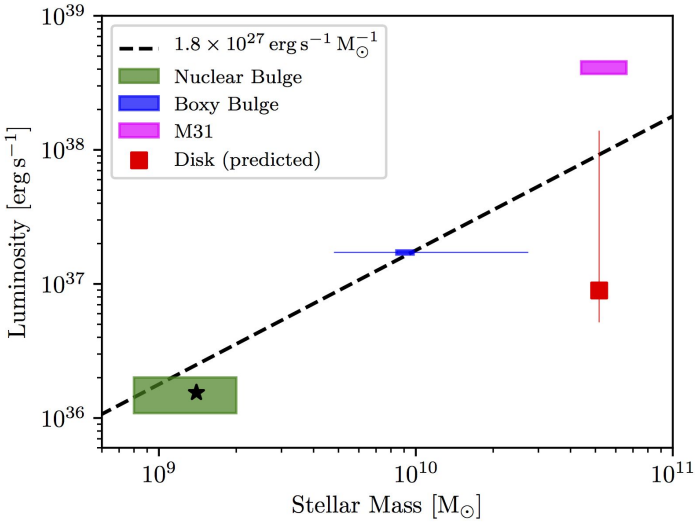
Stable results require:

- 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

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

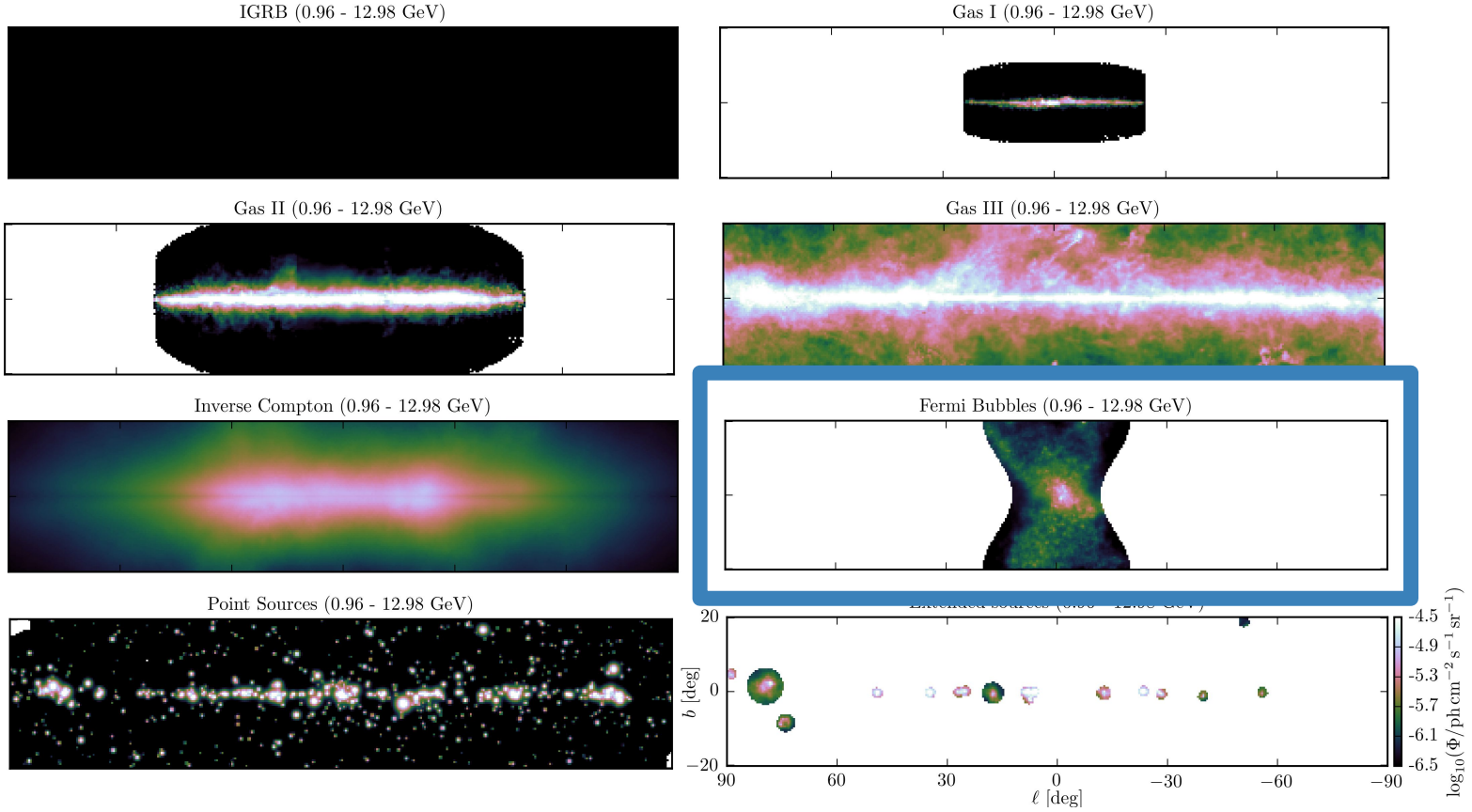




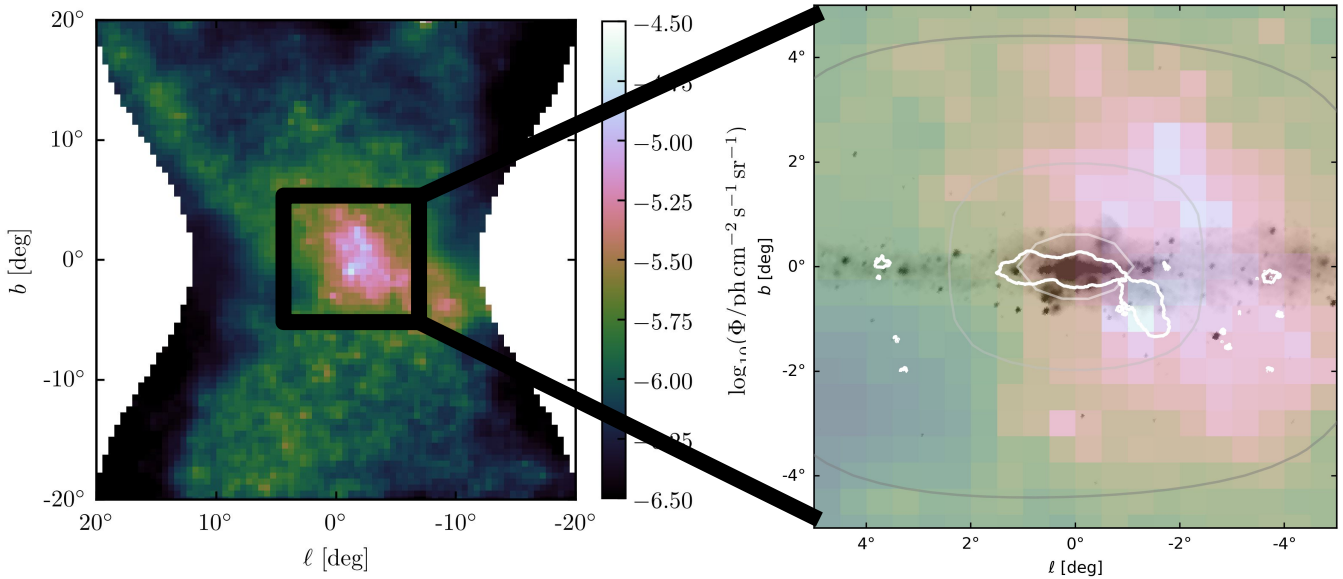
Bartels+[1711.04778](Nat Astro)

The Fermi Bubbles

Best-fit models



The Fermi Bubbles



Color: Bubbles
Gray contours: Boxy + nuclear bulge
White contours: HESS Galactic ridge emission
Black: IRAS 25μm

Observations:

- Persistent excess in Fermi Bubbles template
  - Implies this excess has a hard spectrum
- Offset from GC by ~2° towards negative longitudes

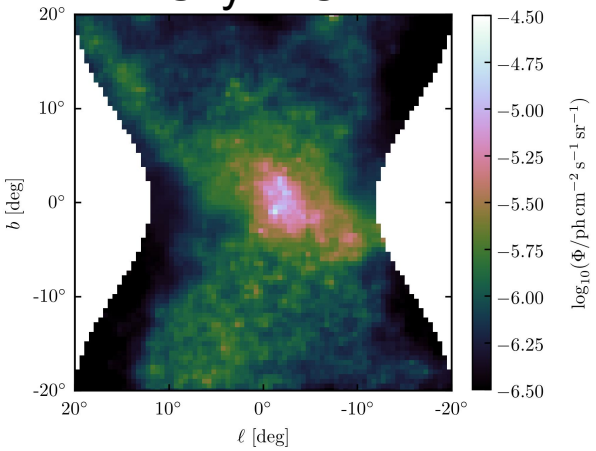
Questions:

- Is the spectrum actually uniform across the whole region?
- Why is the emission offset towards negative longitudes?

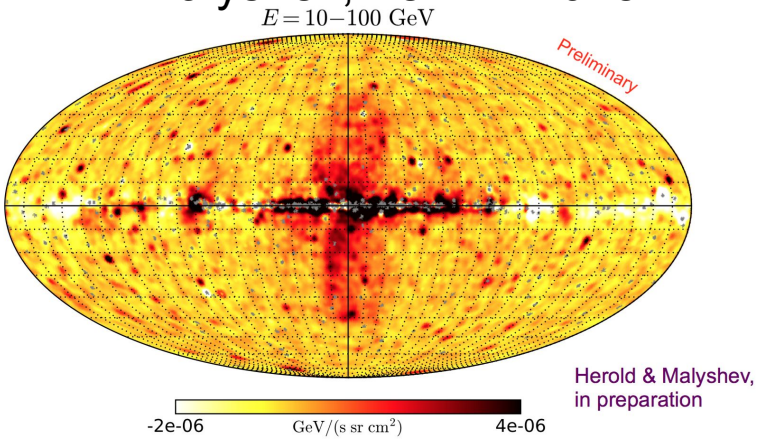
*preliminary

The Fermi Bubbles: low latitude behavior

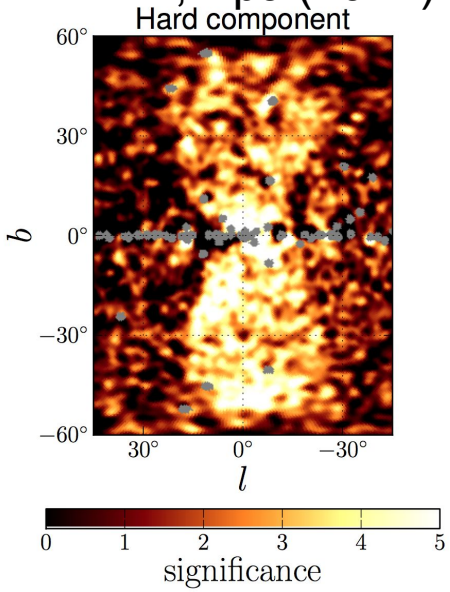
SkyFACT



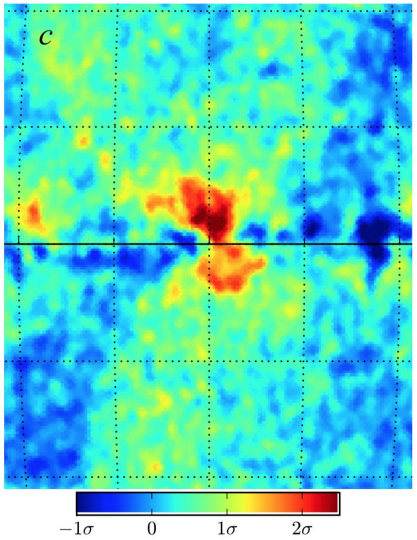
D. Malyshev, TeVPA 2018



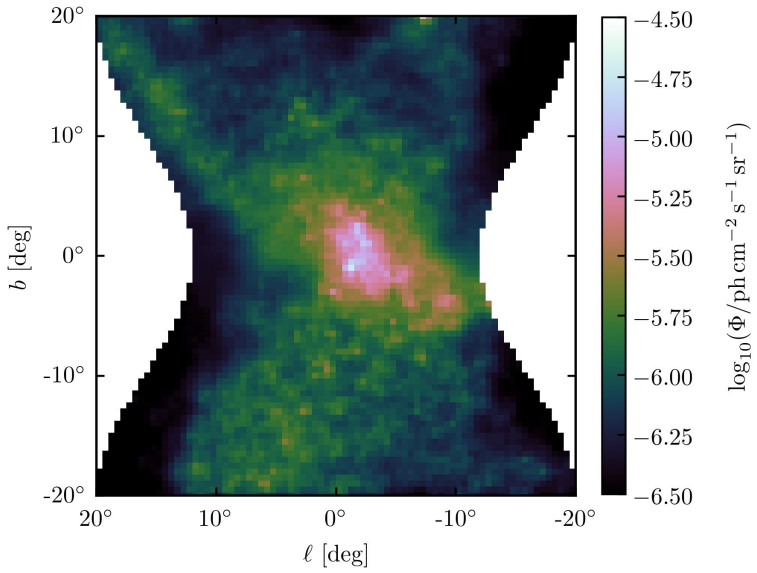
Fermi LAT, ApJ (2017) 840



Fermi LAT, ApJS (2016) 223



The Fermi Bubbles: image reconstruction



Modulation for this template:

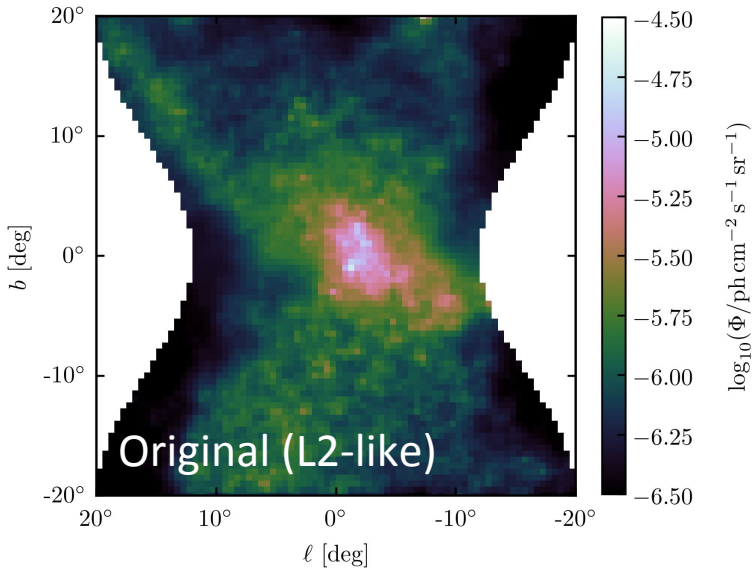
- Spectrum is set to Fermi-LAT (2014) ApJ 793 + 5% variation
- Spatial modulation on pixel normalization is left free
- Smoothing on adjacent pixel values is applied

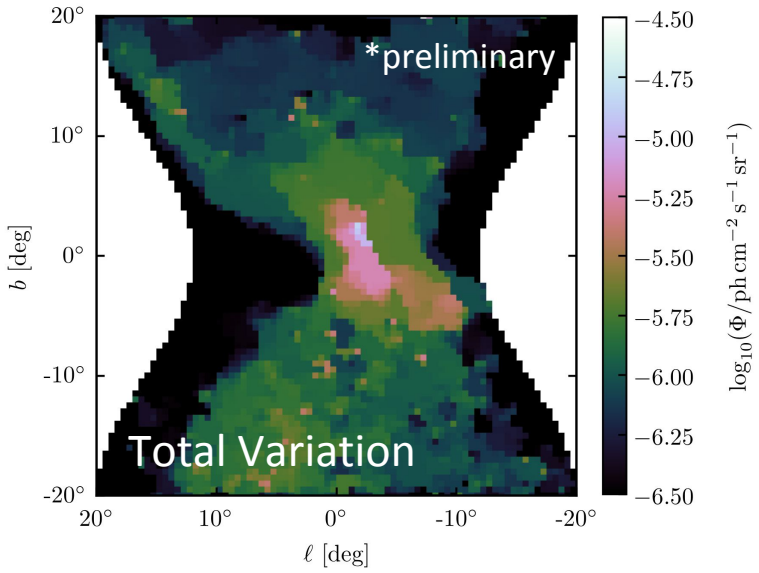
An image reconstruction problem:

- Pixel smoothing makes interpretation difficult
- Smoothing regularization (L2-like) destroys edges

*preliminary

The Fermi Bubbles: image reconstruction





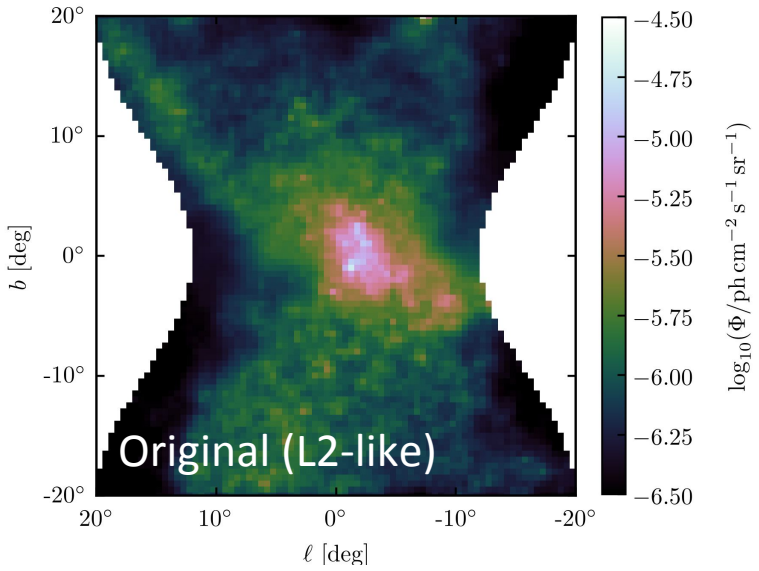
An image reconstruction problem:

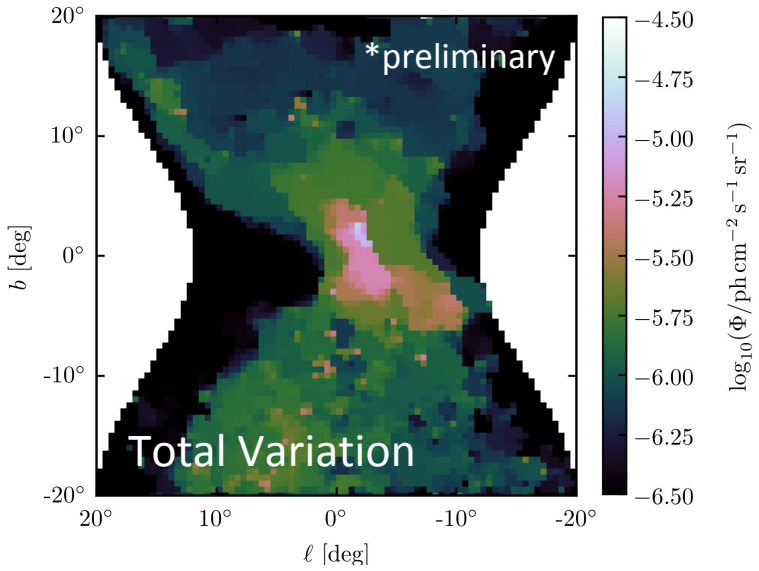
- Pixel smoothing makes interpretation difficult
- Smoothing regularization (L2-like) destroys edges

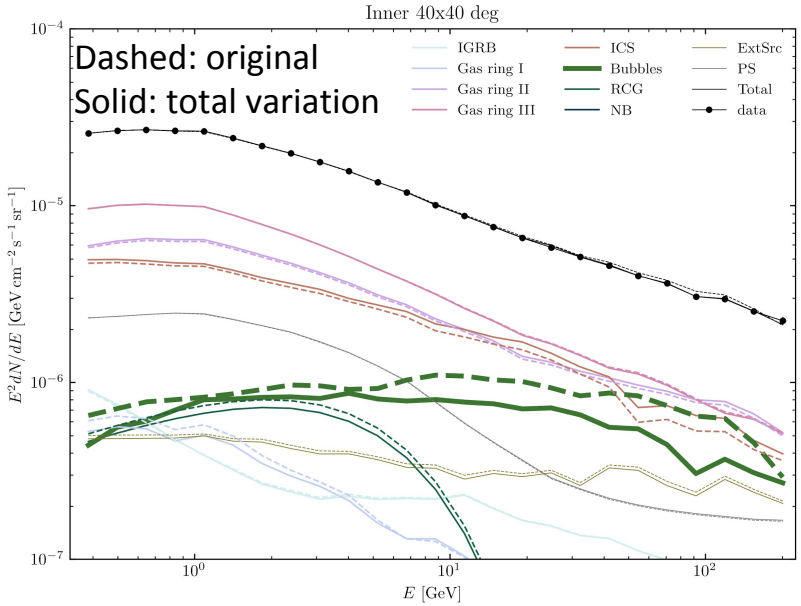
→ use total variation regularization:

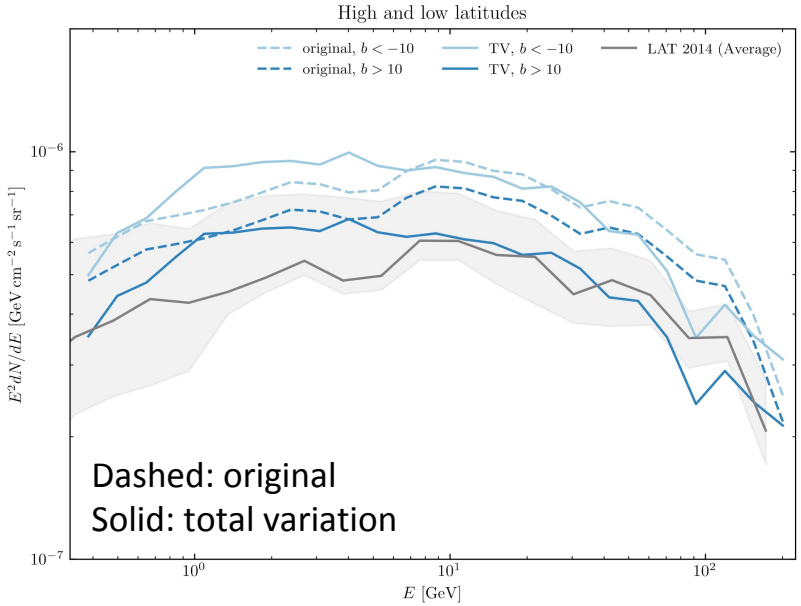
- Good at reconstructing noisy, sparse images, edge-preserving
- However, very sensitive to regularization strength

The Fermi Bubbles: spectral analysis

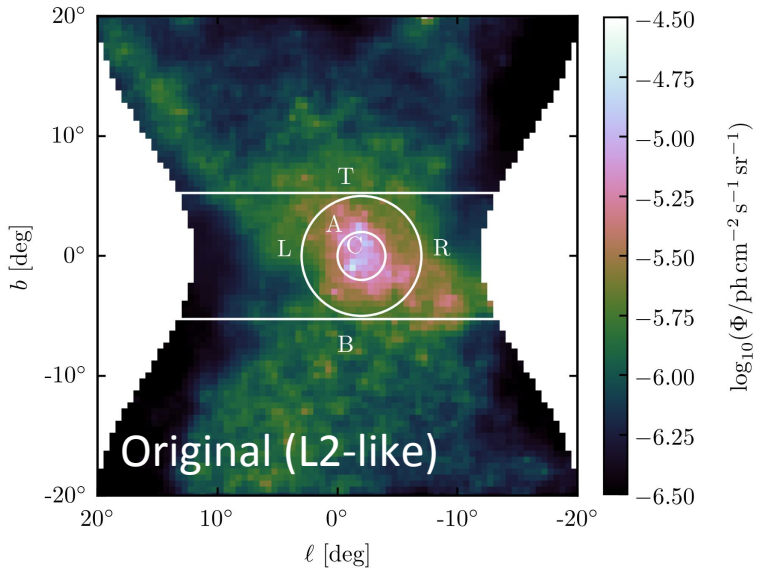


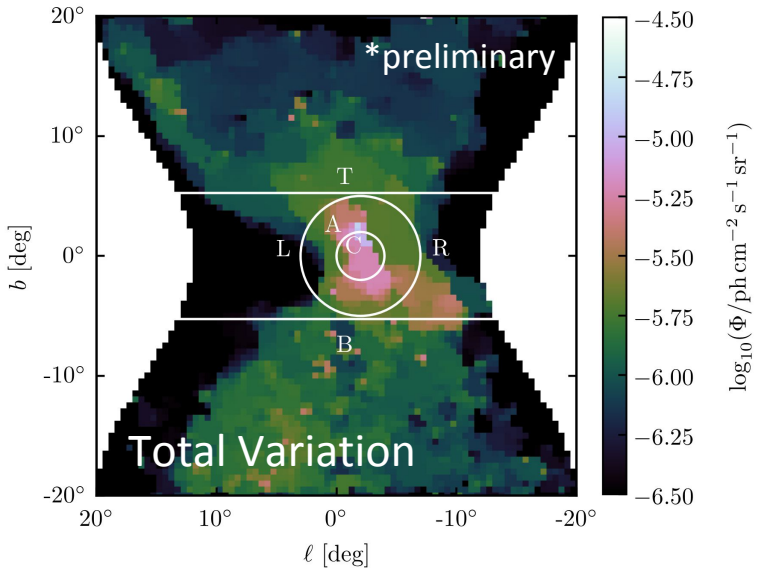


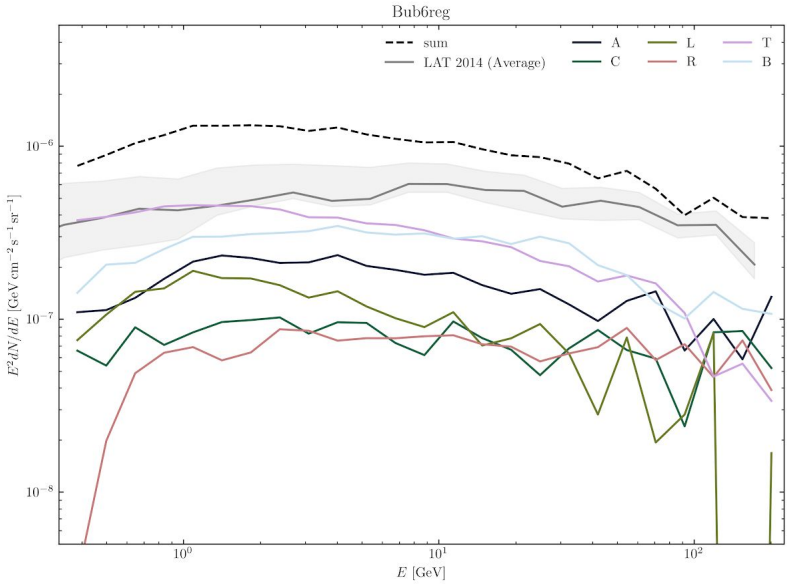


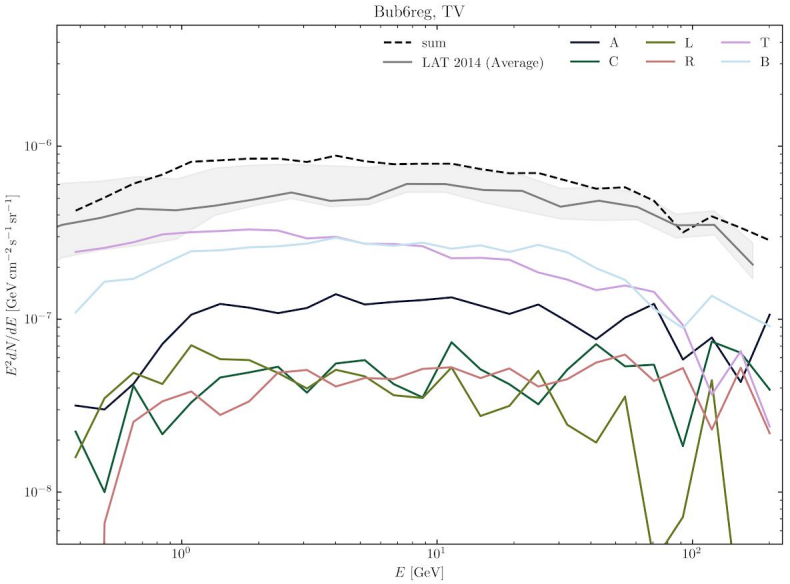


The Fermi Bubbles: spectral analysis

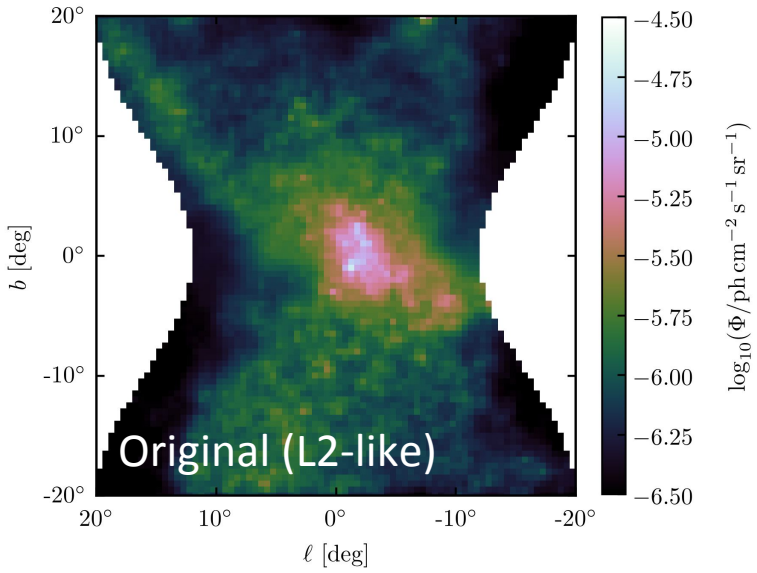


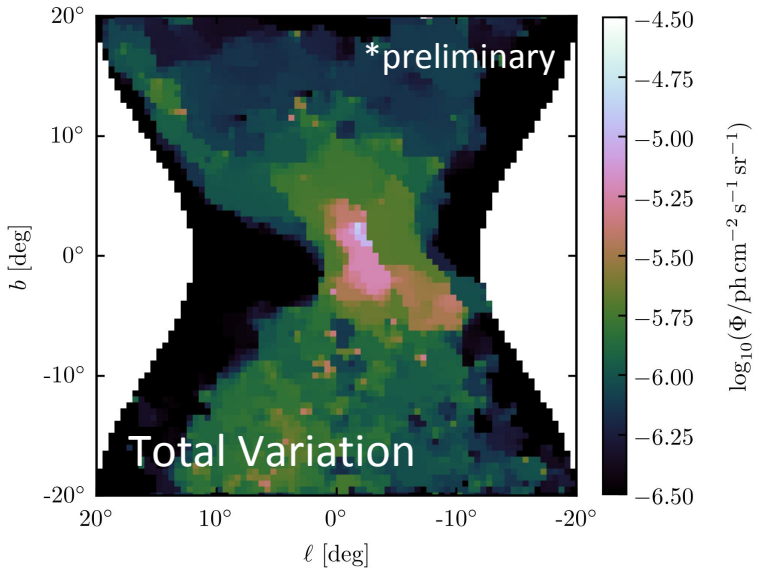






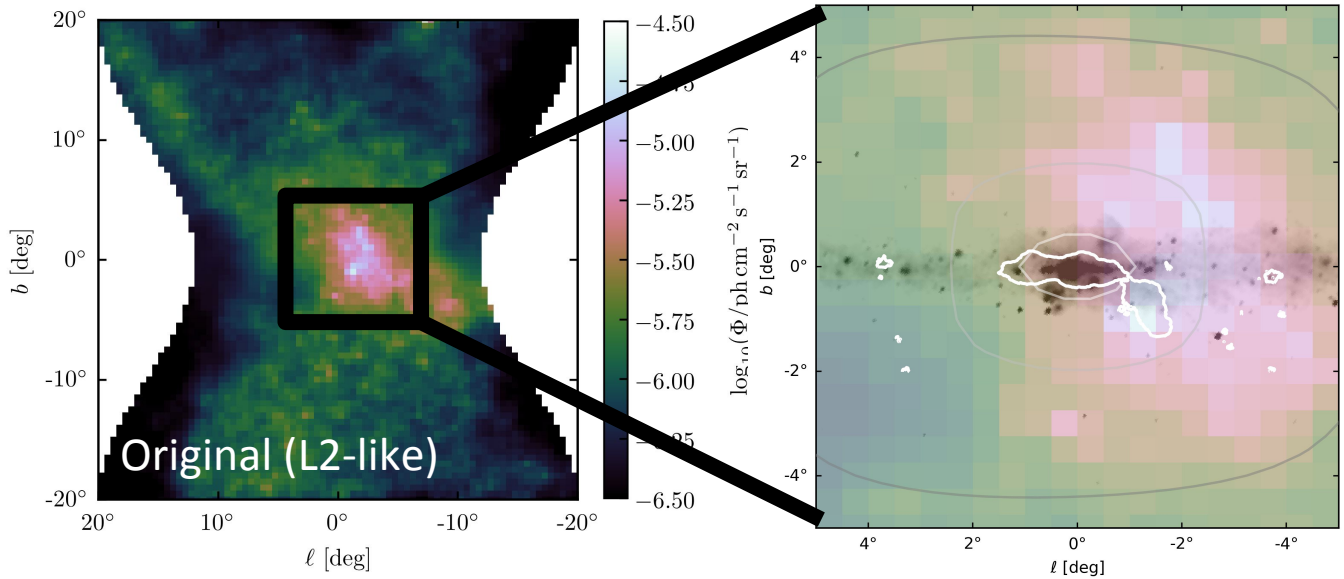
The Fermi Bubbles: systematic checks



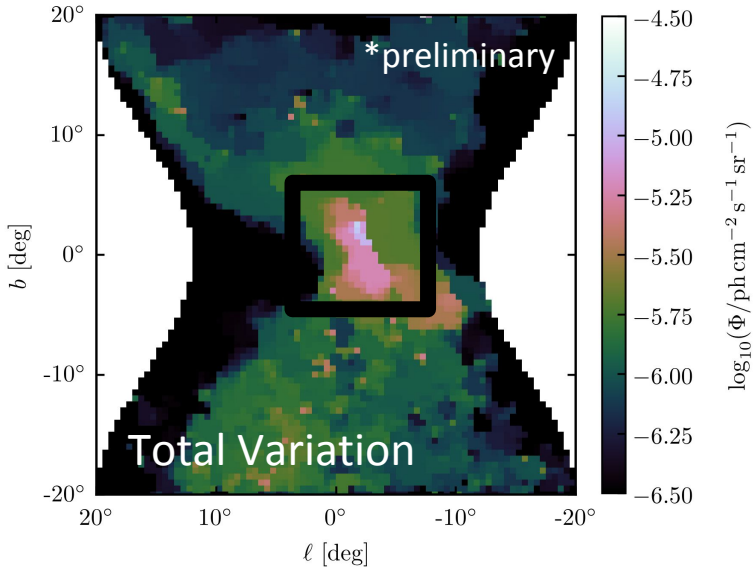


- Mock data tests for total variation performance: ok
- Modifications of point sources: ok
- Presence (or not) of a GCE component: ok
- Changes to foreground templates + modulation?
  - Especially ICS emission?

The Roots of the Fermi Bubbles



Color: Bubbles
Gray contours: Boxy + nuclear bulge
White contours: HESS Galactic ridge emission
Black: IRAS 25μm



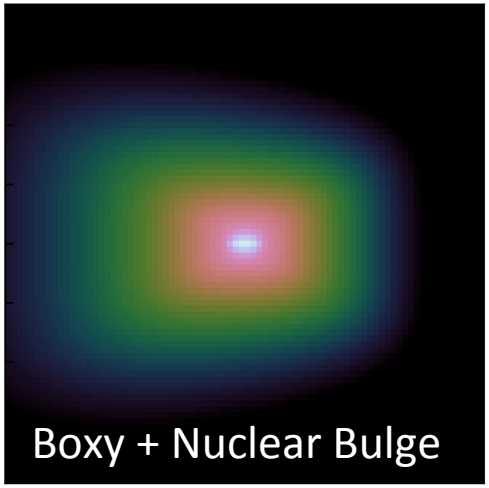
- Persistent, bright emission region with a hard spectrum present near bulge
- Possibly connected to star formation at the galactic center

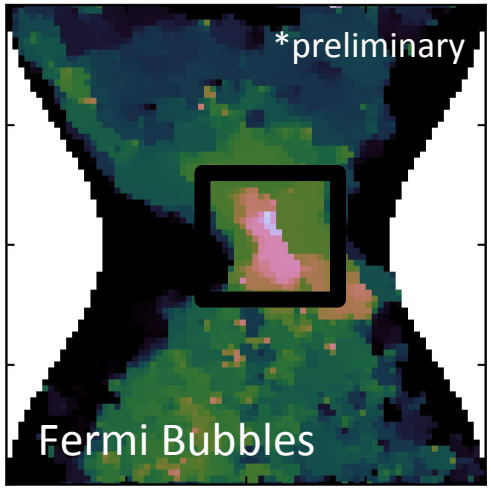
*preliminary

Summary

Skyfact

- Allows for incorporation of realistic spatial and spectral uncertainties into template fitting via adjustable modulation





The Galactic Center Excess

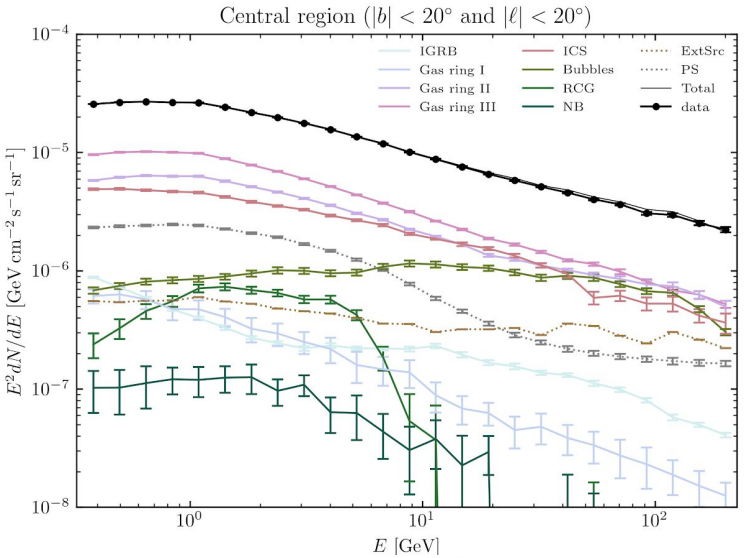
- Traces stellar mass
- Likely point-source origin

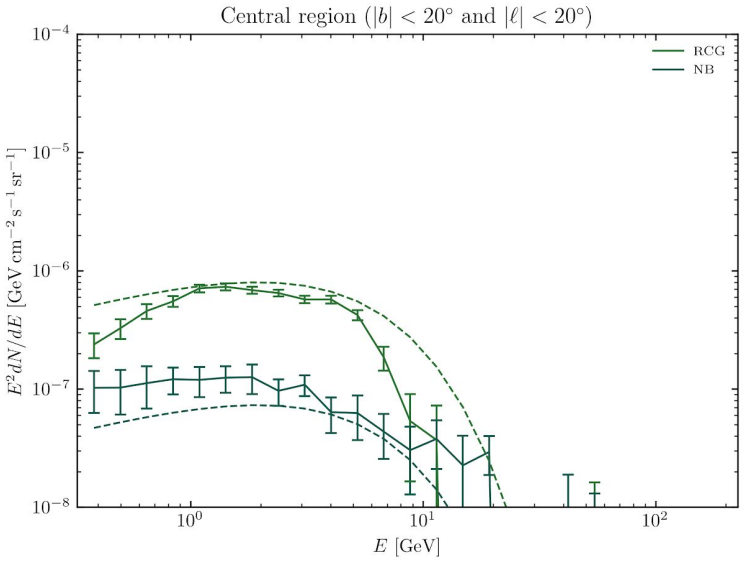
The roots of the Fermi Bubbles

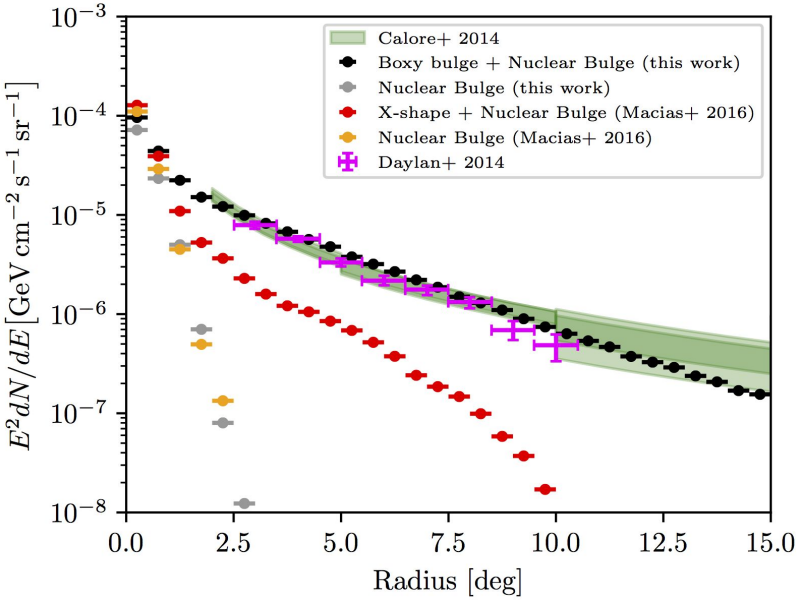
- Persistent excess at GC
- Connection to star formation?

Backup Slides

Spectra + profile comparison for GCE

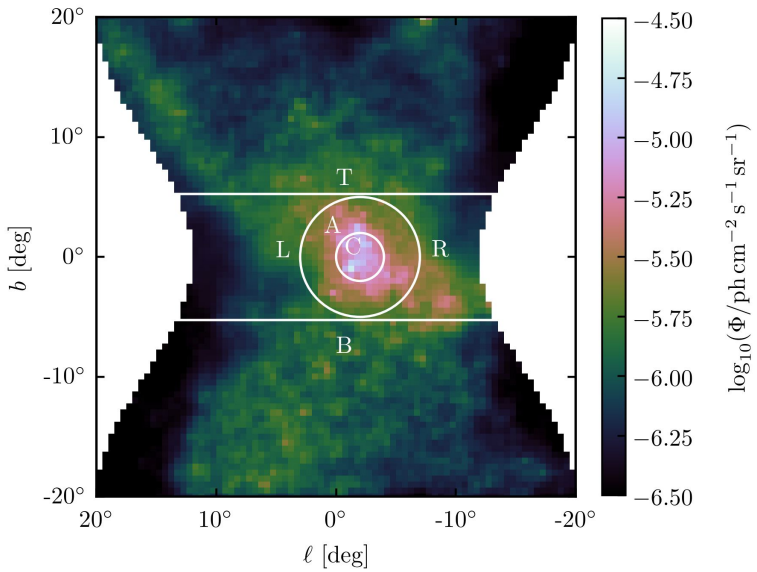






Bartels+[1711.04778](Nat Astro)

The Fermi Bubbles: spectral analysis



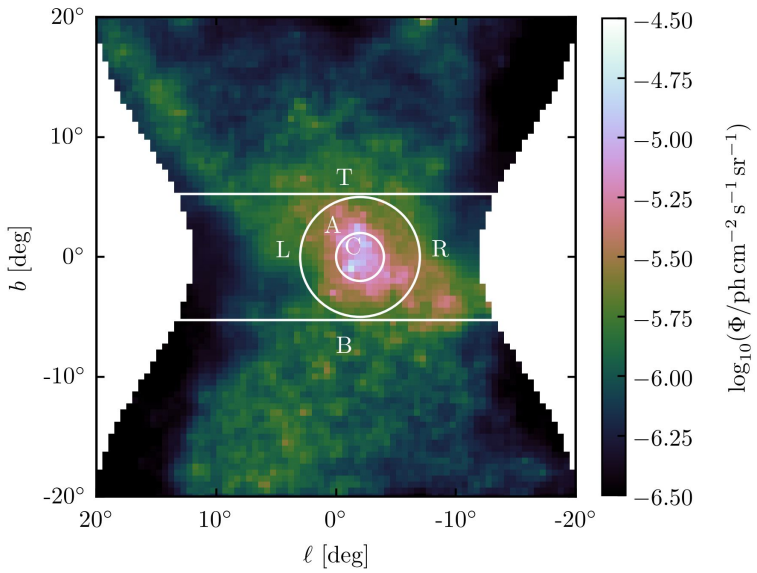
Circle: r < 2, origin: (-2,0)
Annulus: 2 < r < 5, origin: (-2,0)
Left: abs(b) < 5 & outside A
Right: abs(b) < 5 & outside A
Top: b > 5
Bottom: b < -5

Iterative procedure:

1. Fit spatial template with fixed spectrum
2. Break up spatial template
3. Fit spectra in various regions with fixed spatial templates

*preliminary

The Fermi Bubbles: spectral analysis



Circle: r < 2, origin: (-2,0)
Annulus: 2 < r < 5, origin: (-2,0)
Left: abs(b) < 5 & outside A
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Top: b > 5
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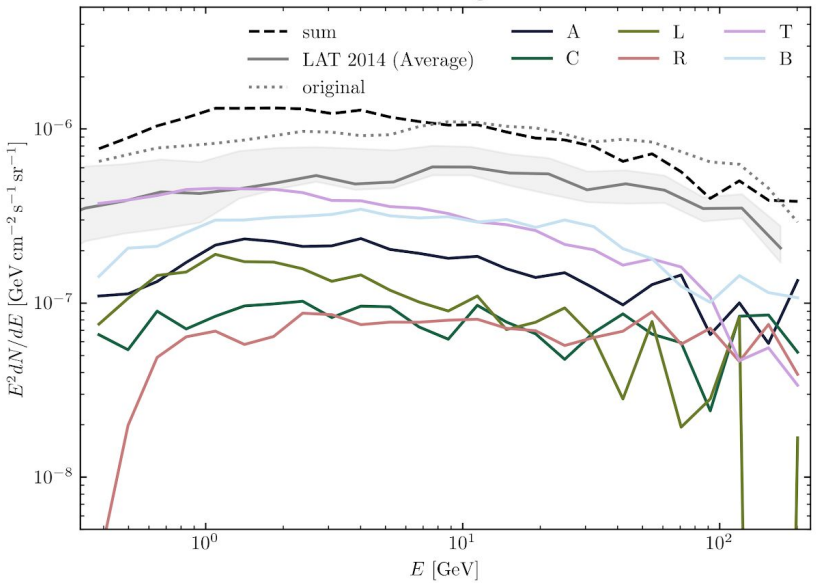


Spectra in bright central region **harder** than high/low latitude emission

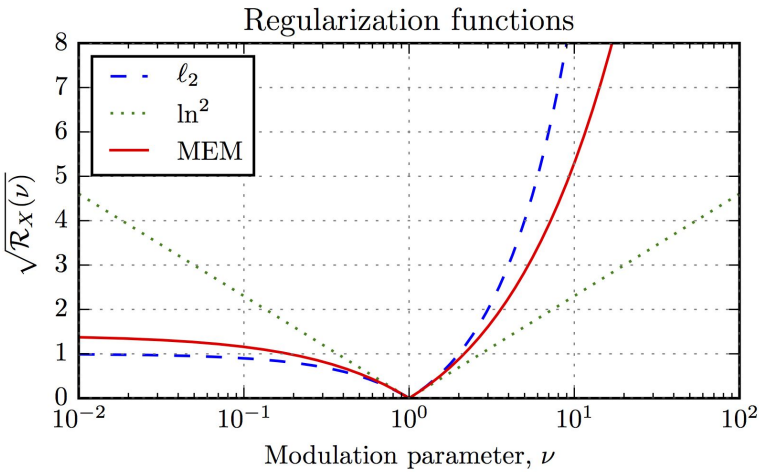
*preliminary

SkyFACT: likelihood + regularization

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

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:

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

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

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

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

$$N^{\rm eff}_{\rm DOF} \sim \langle -2 \ln \mathcal{L}_P \rangle_{\rm mock}$$