SkyFACT: Building better models of the gamma-ray sky

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In collaboration with:

Richard Bartels, Francesca Calore, Christoph Weniger

The Three Elephants in the Gamma-ray Sky

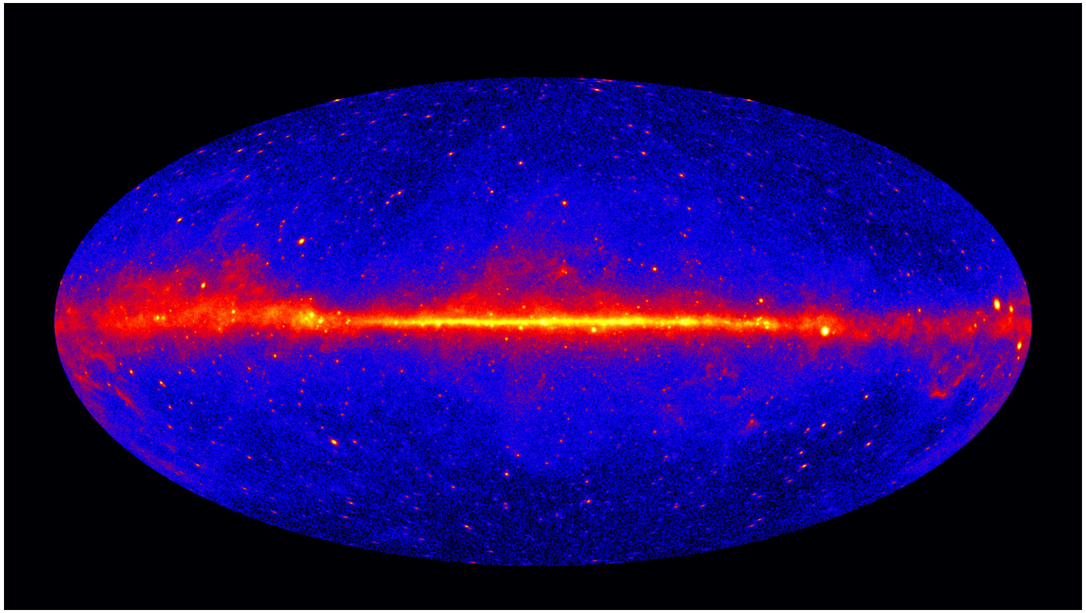
22 October 2017

GRAPPA
GRavitation AstroParticle Physics Amsterdam

University of Amsterdam

The gamma-ray sky

Fermi Gamma-ray
Space Telescope



The gamma-ray sky

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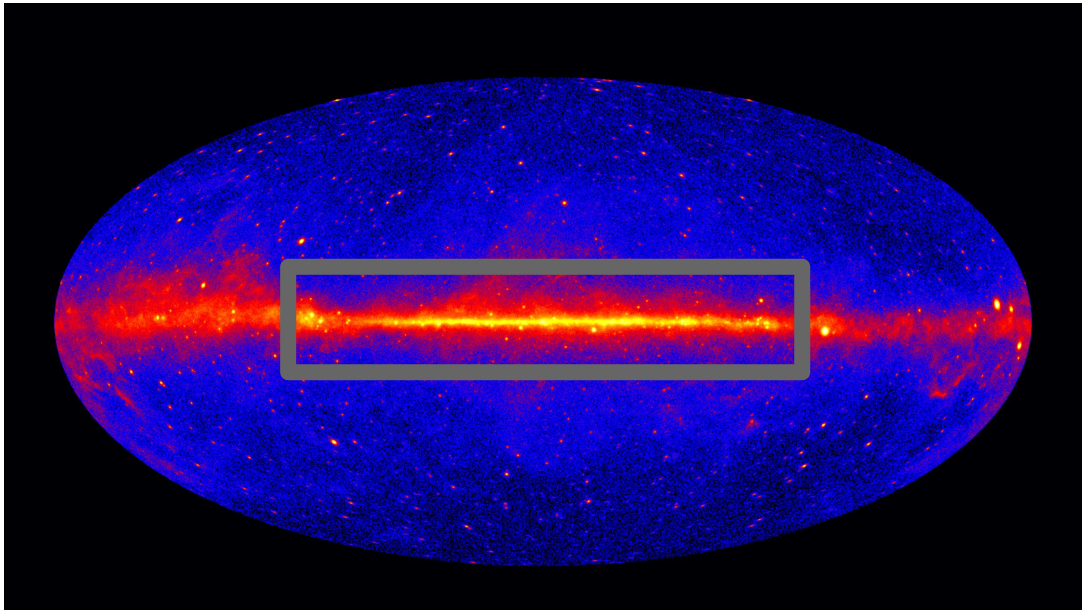
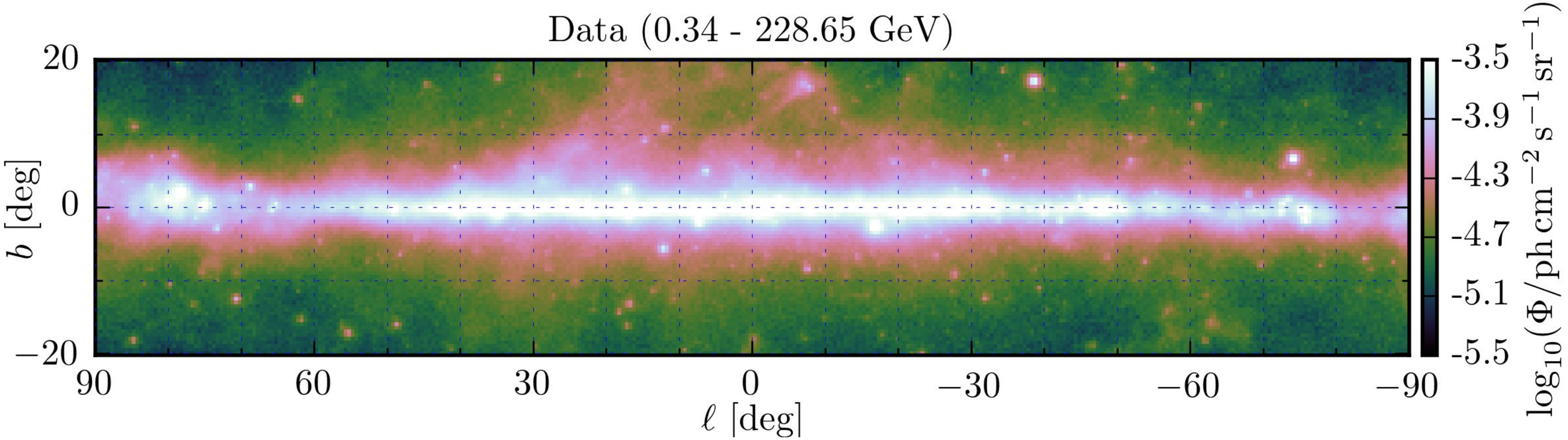
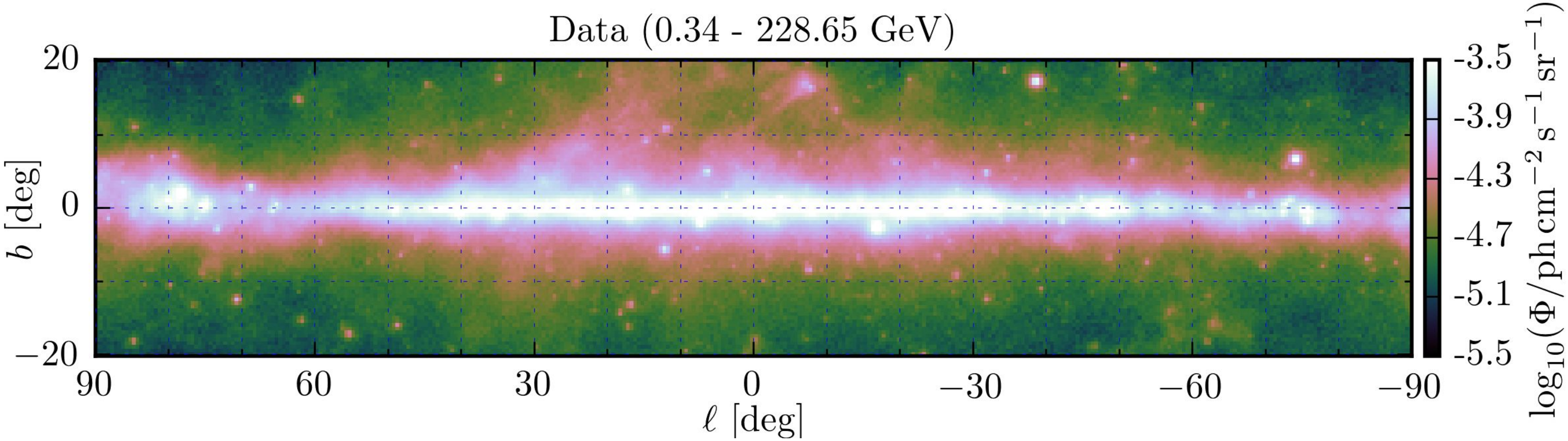


The inner Galaxy in gamma rays



The inner Galaxy in gamma rays



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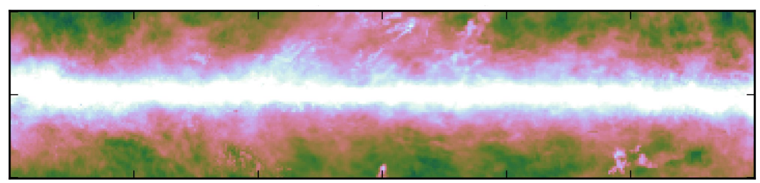
Cosmic ray protons



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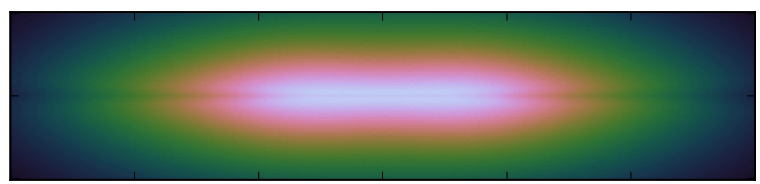
Cosmic ray electrons



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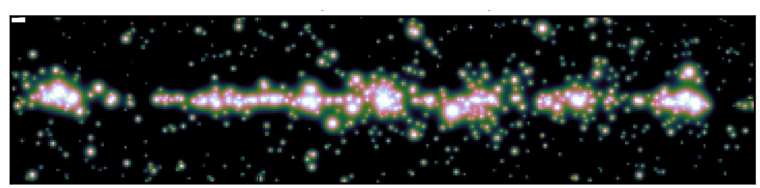
Point sources



+ …

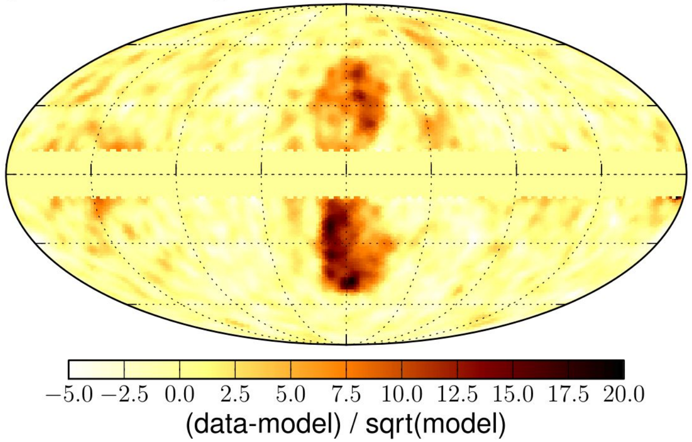
Template fitting: a primer

$$\text{Model} \sim \sum_k \text{Template}^{(k)}(E) \cdot \sigma^{(k)}(E)$$

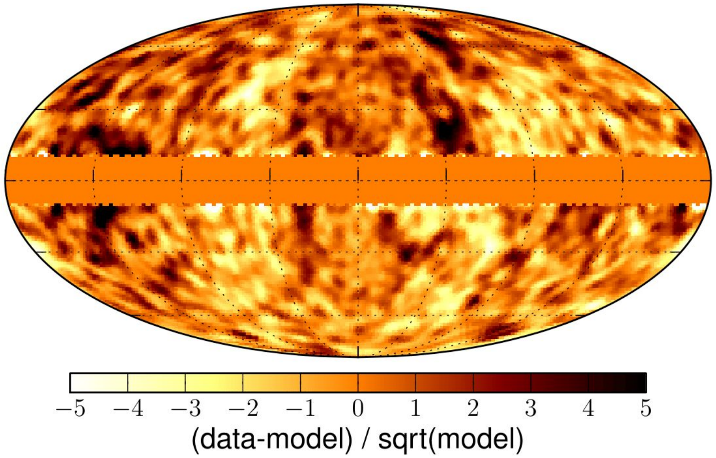
Fixed **spatial** templates

Free **spectral** templates

Discovery of new components:
Fermi Bubbles



However: quality of fits remains poor

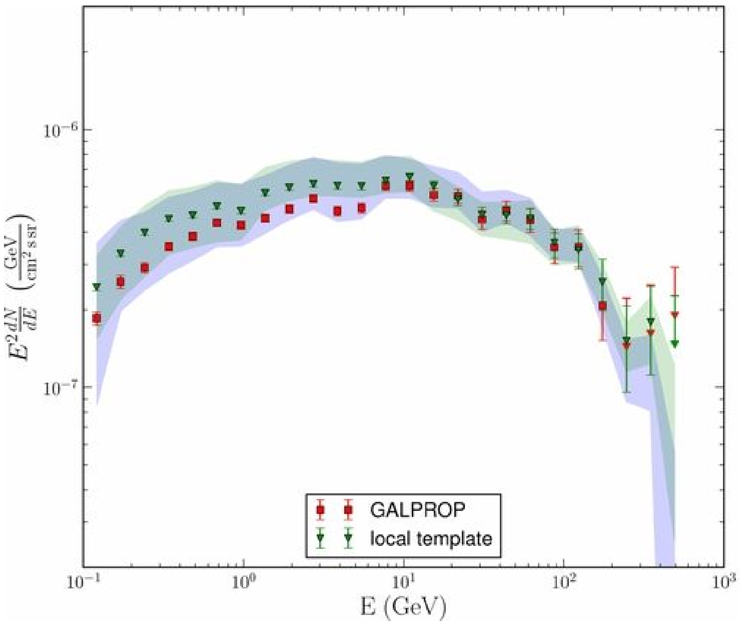


LAT Collaboration, 2014, ApJ 793:64

Template fitting: a primer

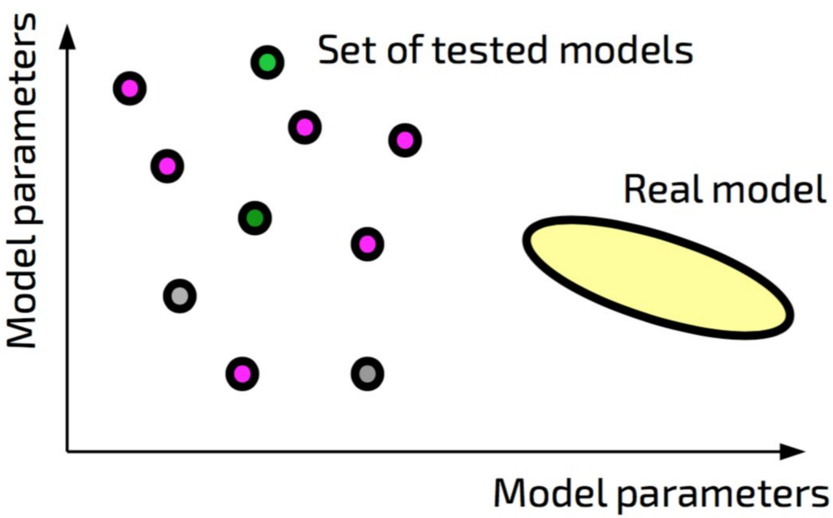
$$\text{Model} \sim \sum_k \text{Template}^{(k)}(E) \cdot \sigma^{(k)}(E)$$

Fermi Bubbles Spectrum



LAT Collaboration, 2014, ApJ 793:64

"Bracketing uncertainties"



Credit: C. Weniger

Template fitting: a primer

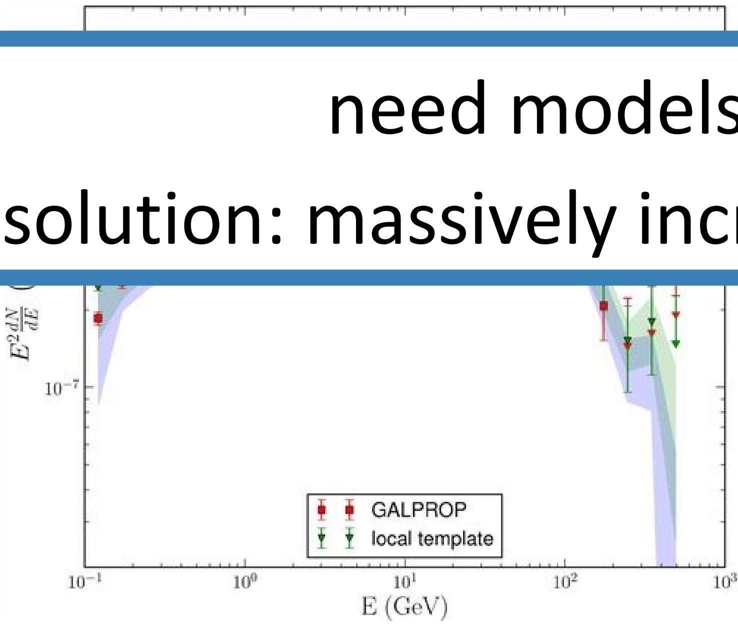
$$\text{Model} \sim \sum_k \text{Template}^{(k)}(E)\cdot\sigma^{(k)}(E)$$

Fermi Bubbles Spectrum

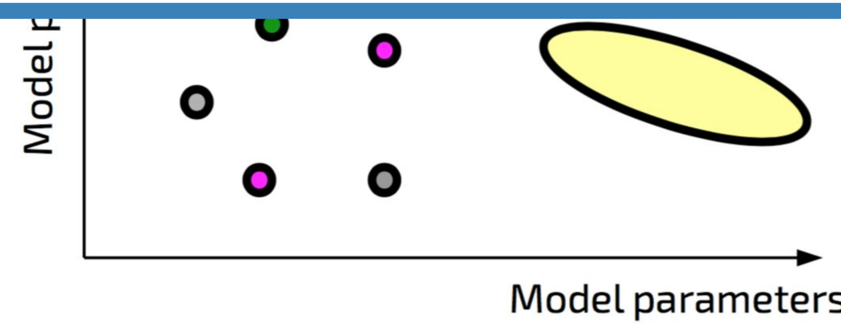
“Bracketing uncertainties”

need models that fit the data

solution: massively increase the parameter space



LAT Collaboration, 2014, ApJ 793:64



Credit: C. Weniger

A new approach: SkyFACT

Sky Factorization with Adaptive Constrained Templates

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

Storm, Calore, Weniger:
JCAP08 (2017) 022

A new approach: SkyFACT

Sky Factorization with Adaptive Constrained Templates

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

SkyFACT

Sky Factorization with Adaptive Constrained Templates

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

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

Spatial + spectral templates

Modulation parameters:
- Spatial
- Spectral
- overall

SkyFACT

Sky Factorization with Adaptive Constrained Templates

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p: spatial pixel
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Spatial + spectral templates

Normalizations per:
- pixel
- energy bin
- component

SkyFACT

Sky Factorization with Adaptive Constrained Templates

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

Normalizations per:

- pixel
- energy bin
- component

Number of free parameters~ number of pixels~**1e5**

- Need to prevent overfitting
- Borrow techniques from image reconstruction

SkyFACT

Sky Factorization with **Adaptive Constrained Templates**

Penalization terms in the likelihood:

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

Poisson term

Regularization of modulation parameters

$$\tau_p^{(k)}, \sigma_b^{(k)}, \nu^{(k)}$$

SkyFACT

Sky Factorization with **Adaptive Constrained Templates**

Penalization terms in the likelihood:

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

Regularization terms:

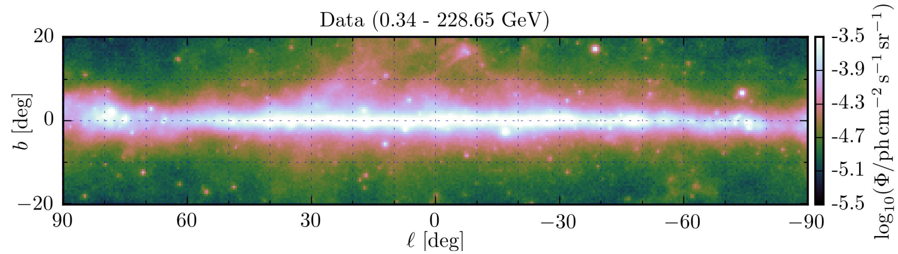
- Strength is controllable
- Typically, different for different components
- Regularization via MEM and smoothing

Regularization of modulation parameters

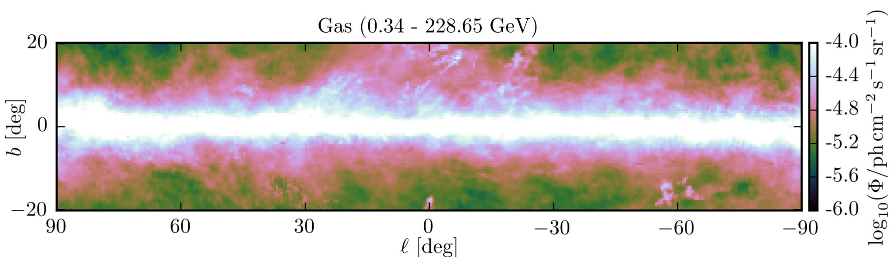
$$\tau_p^{(k)}, \sigma_b^{(k)}, \nu^{(k)}$$

Data and initial model

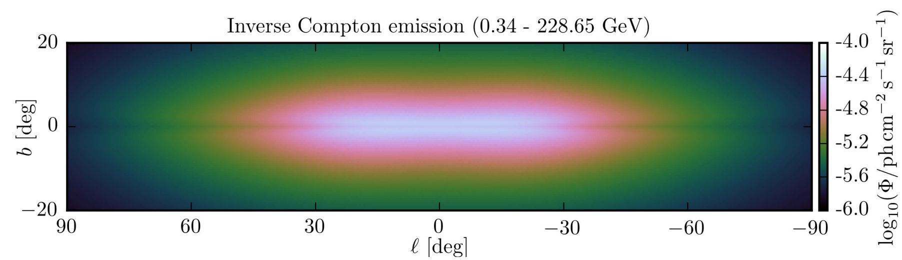
Data:



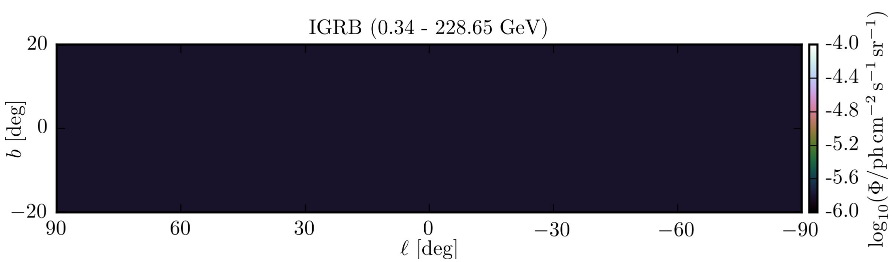
Model:



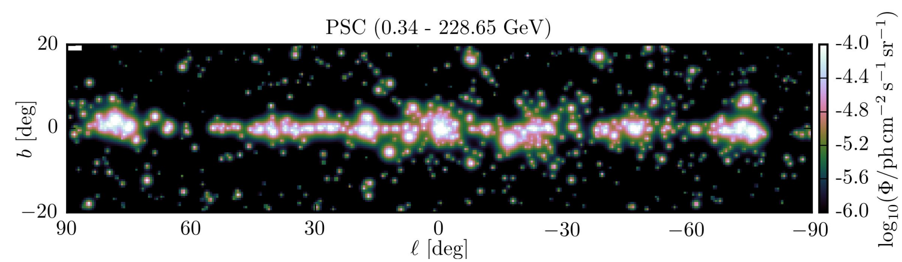
Template: sum of HI and H2 column densities from GALPROP; no dark gas correction
Spectrum: Fermi-LAT (2012) ApJ 750



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



Spectrum: Fermi-LAT (2015) ApJ 799



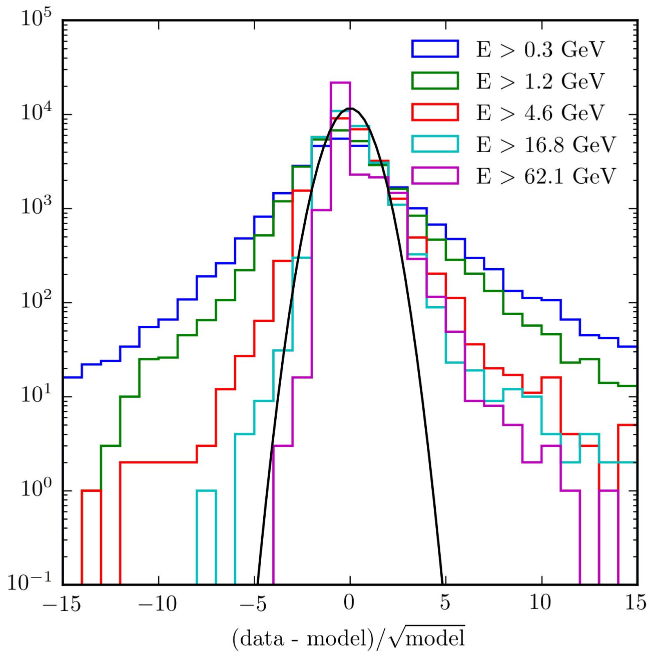
Locations and spectra: 3FGL catalog

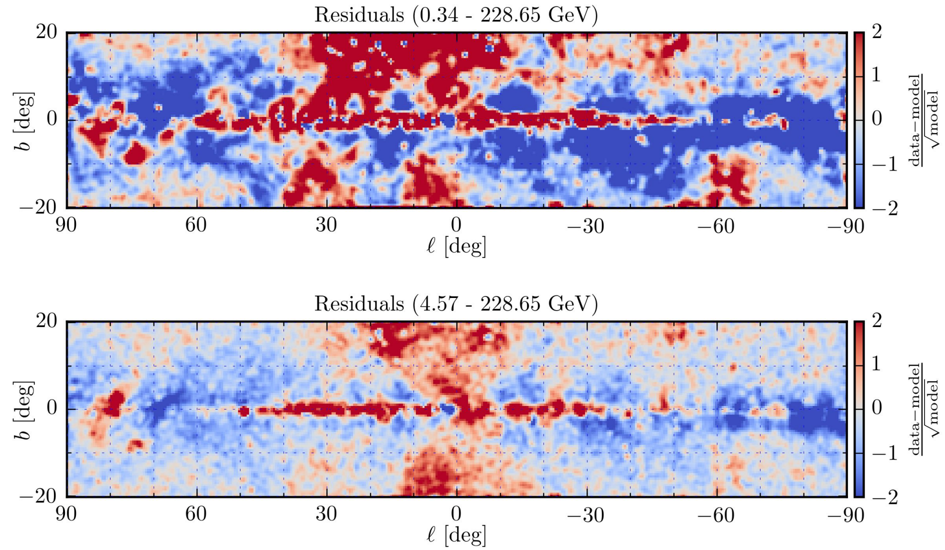
SkyFACT vs the traditional approach

Fixed templates + constrained spectra

No spatial modulation allowed

~25% variations allowed



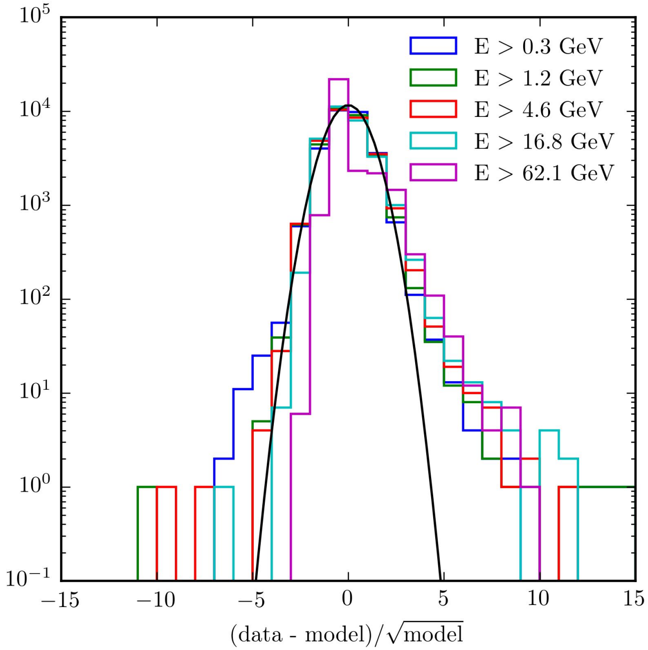


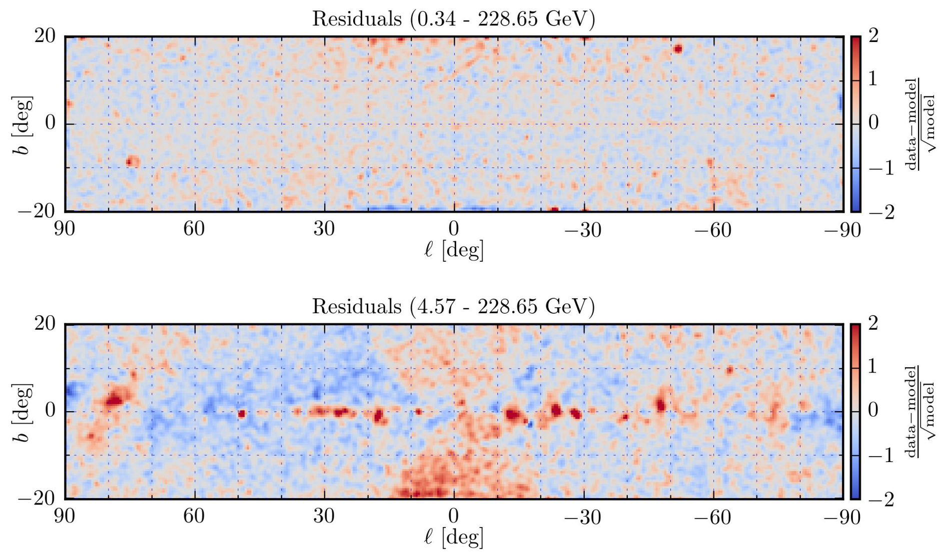
The traditional approach

SkyFACT vs the traditional approach

Constrained templates + spectra

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



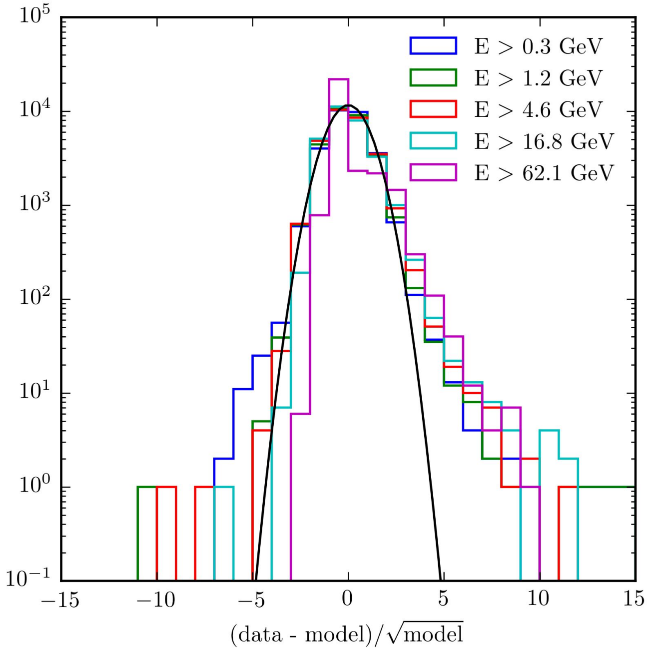


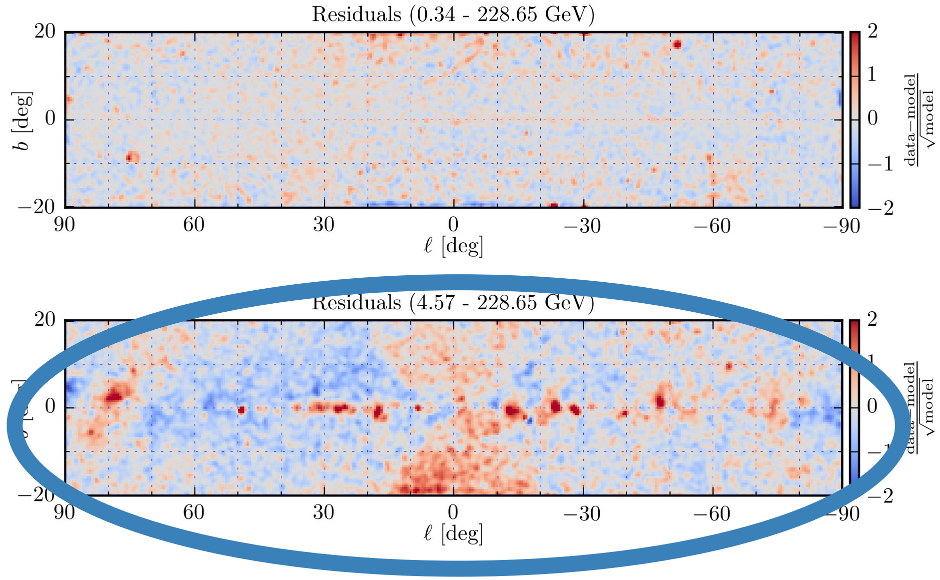
With adaptive template modulation

Additional necessary components

Constrained templates + spectra

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

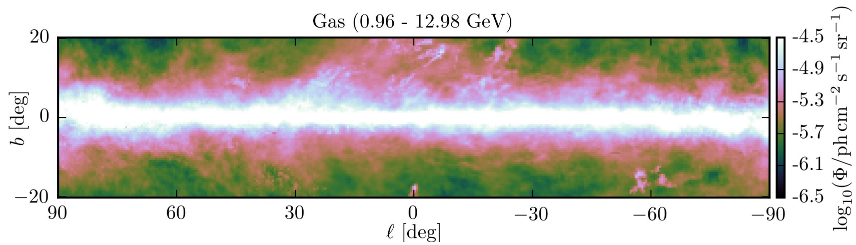




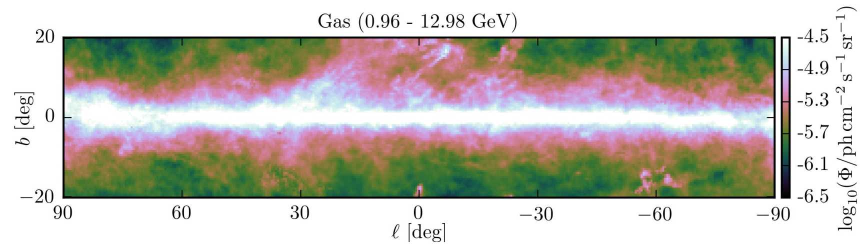
Irreducible residuals → add new components

SkyFACT: modulation parameters

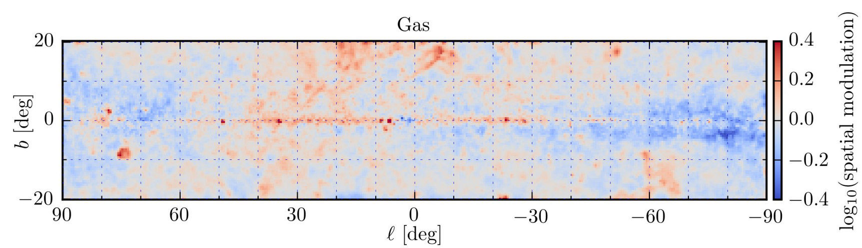
Original Template

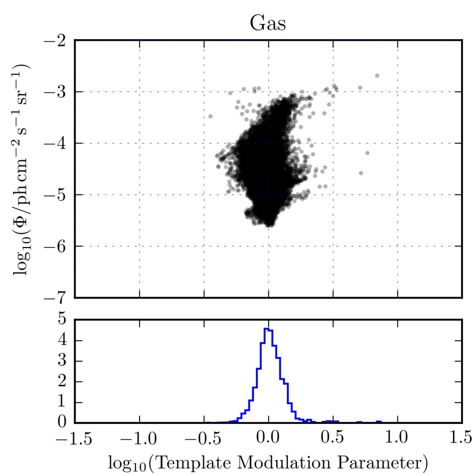


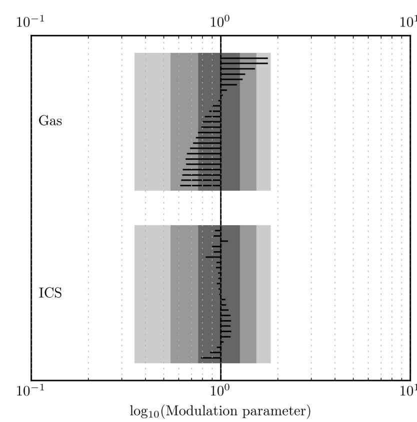
Best-fit Template



Template and Spectra Modulation

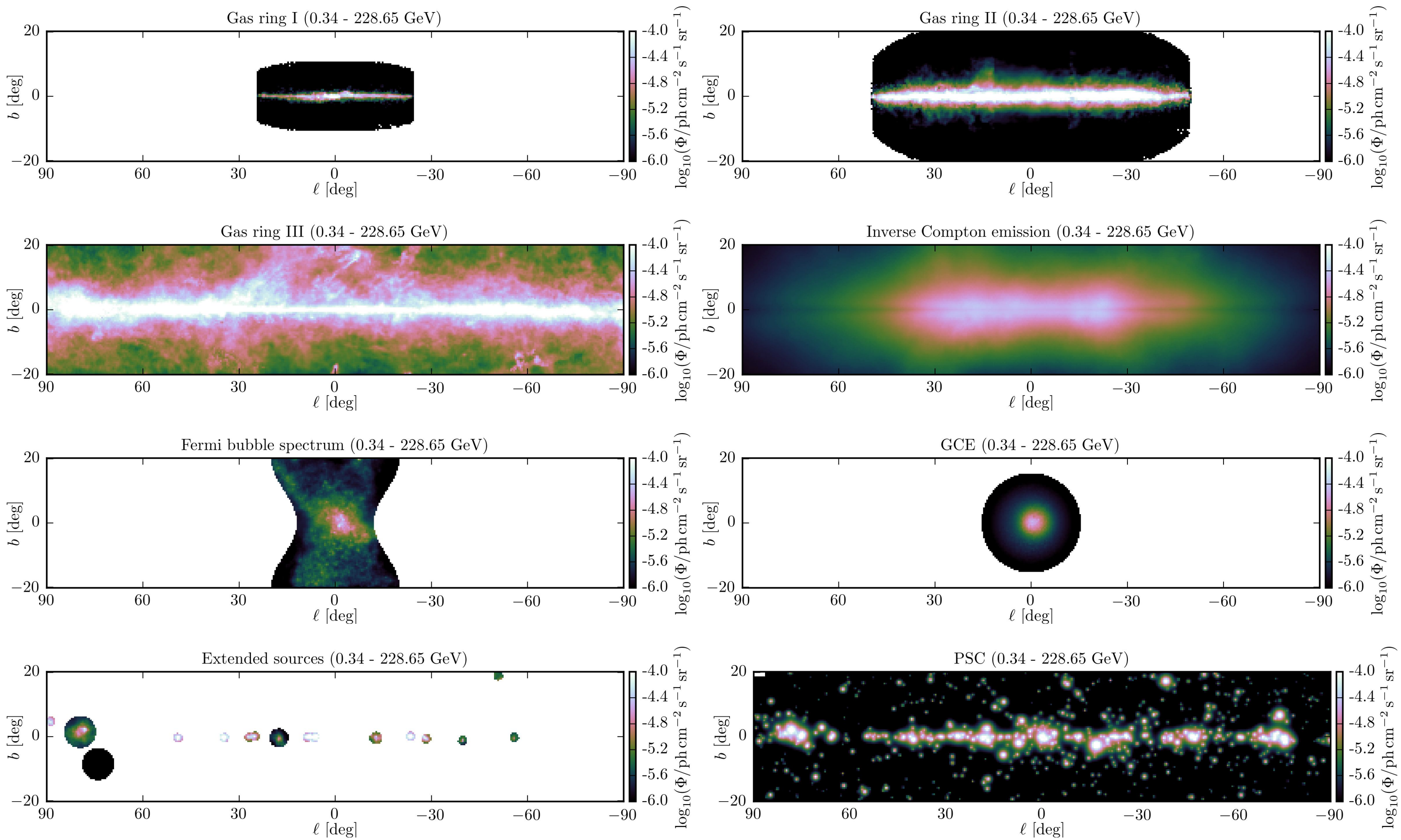






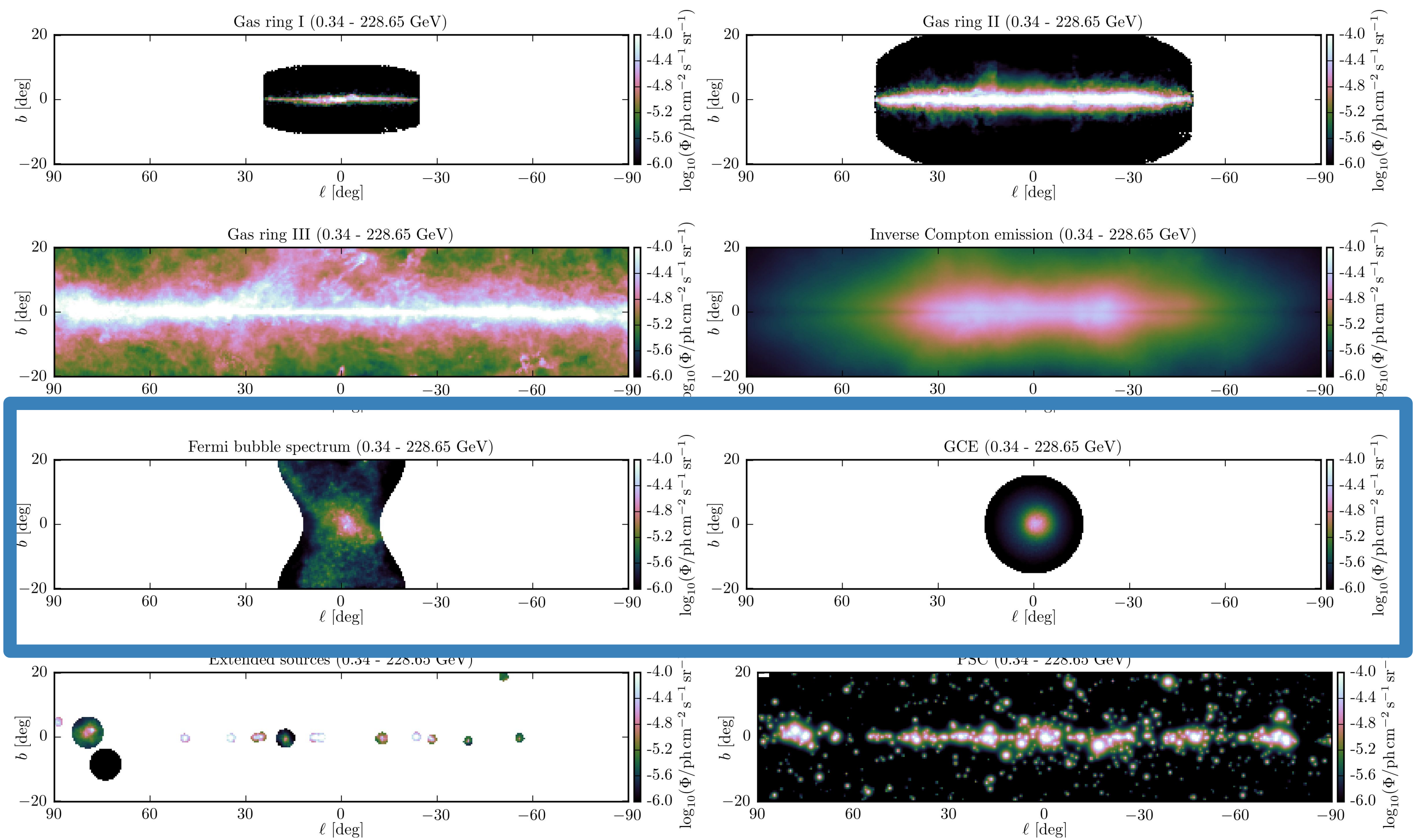
Reference model

Best-fit model components for reference model:

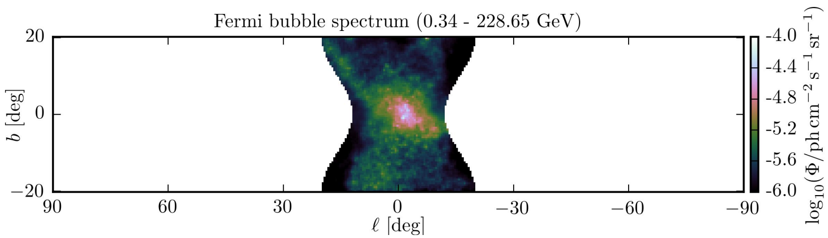


Application: bulge emission

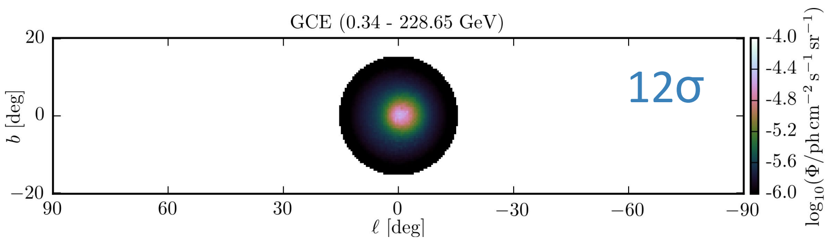
Best-fit model components for reference model:



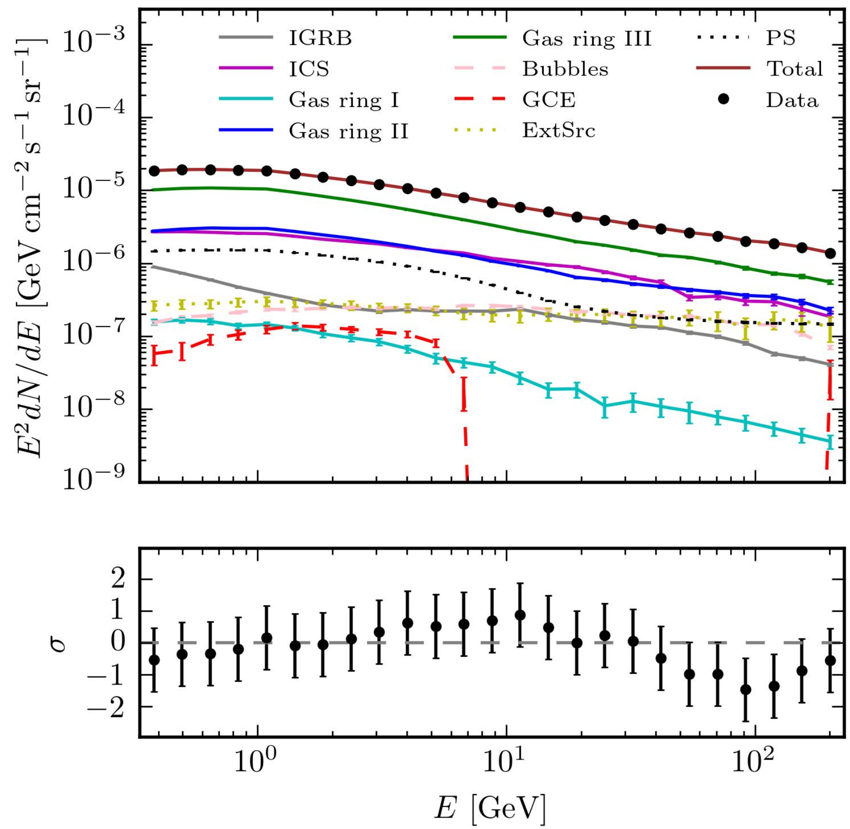
Application: bulge emission



Spectrum: fixed to Fermi-LAT (2014) ApJ 793, 5% variation
Template: free



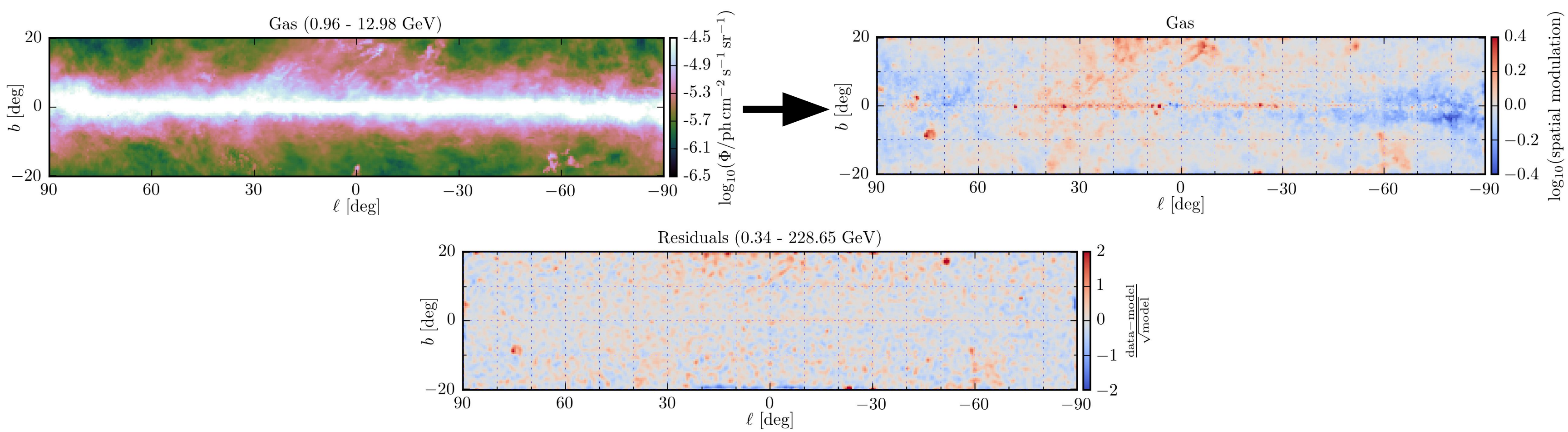
Spectrum: free
Template: fixed to 511 keV emission, 20% variation



For future study:

- Low latitude behavior of Fermi Bubbles
- Robust characterization of GCE **-- see Richard's talk!**

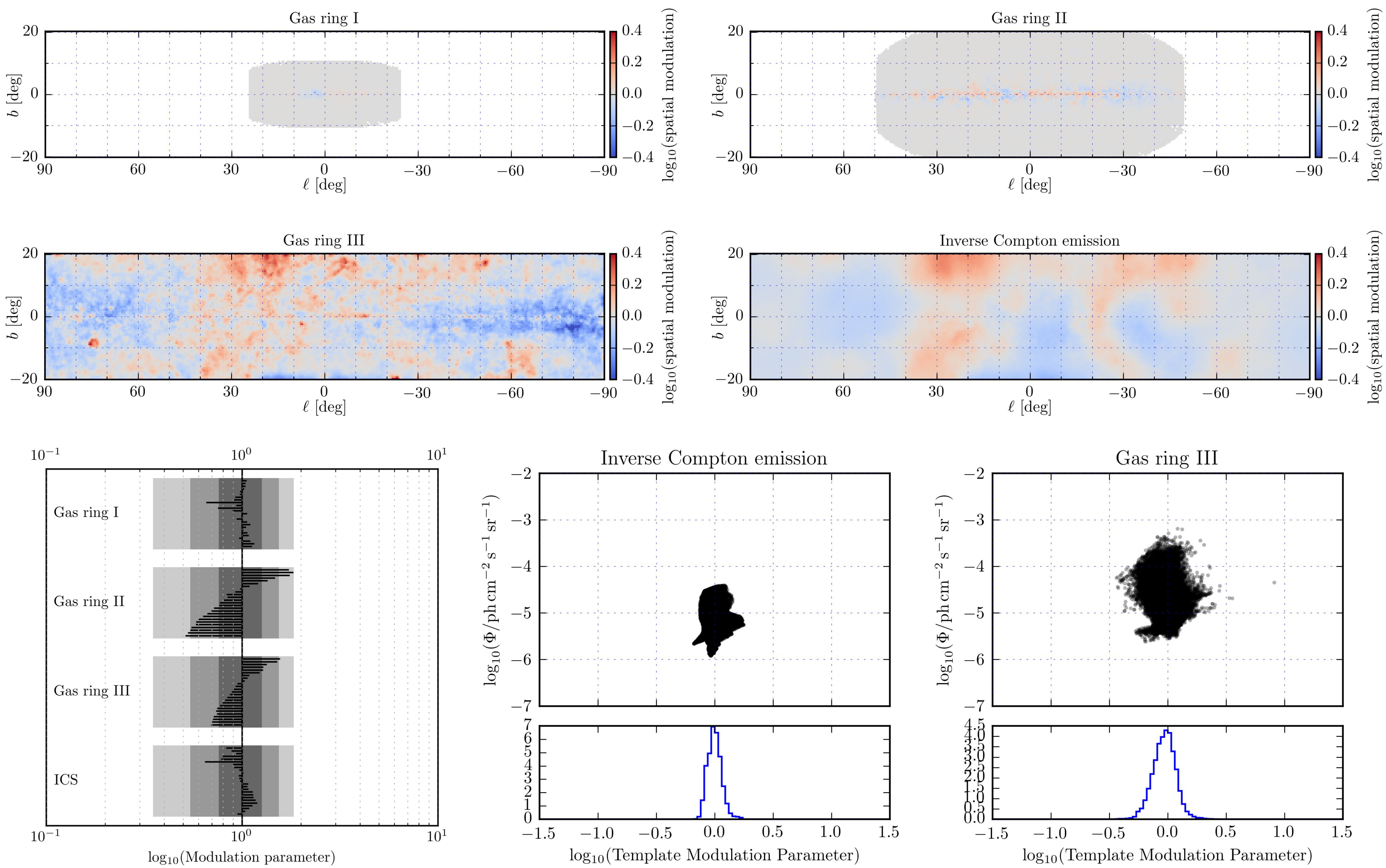
SkyFACT: summary



- Introducing nuisance parameters into template fits dramatically improves fit quality
- Modulation can account for intrinsic uncertainties in diffuse templates
- GCE spectrum recovered from input spatial template **-- see Richard's talk tomorrow!**

Backup slides

Reference model rescaling

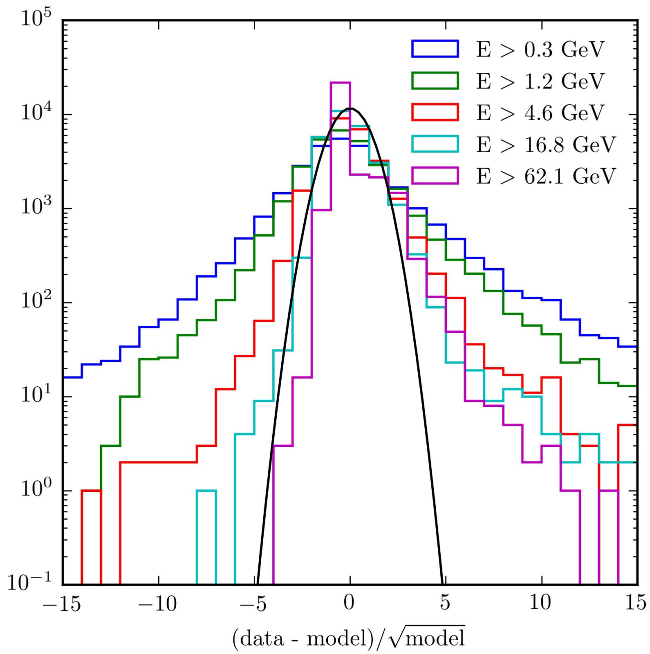


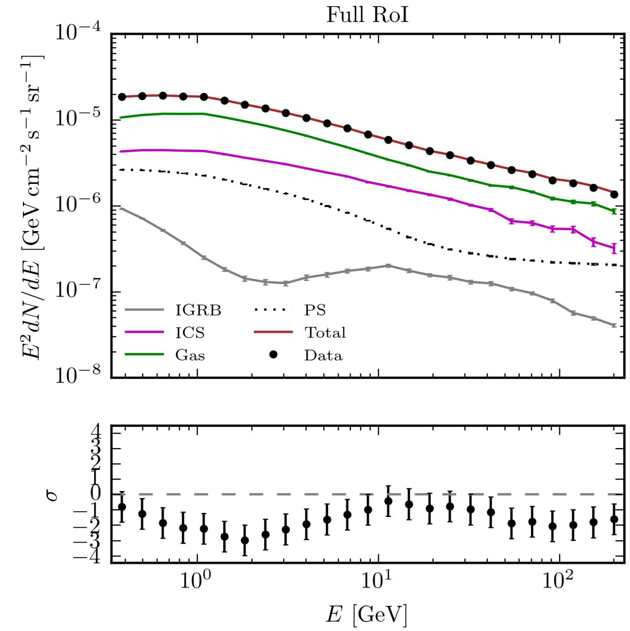
SkyFACT vs the traditional approach

Fixed templates + constrained spectra

No spatial modulation allowed

~25% variations allowed



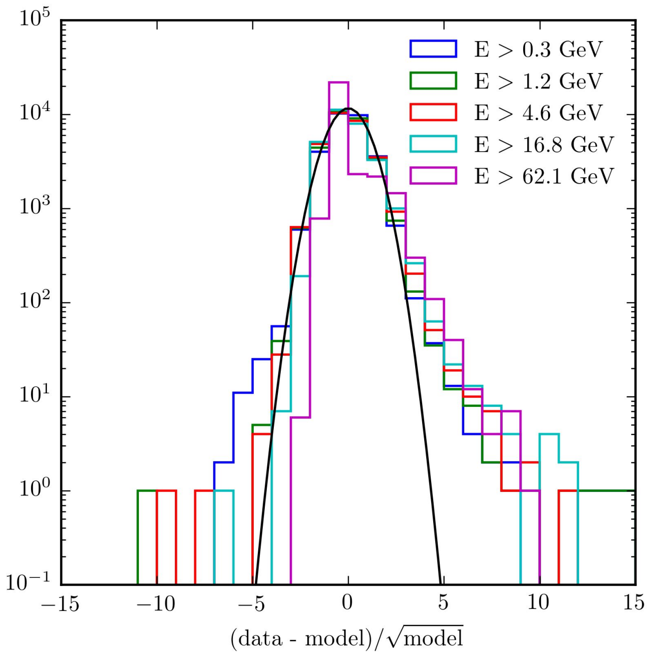


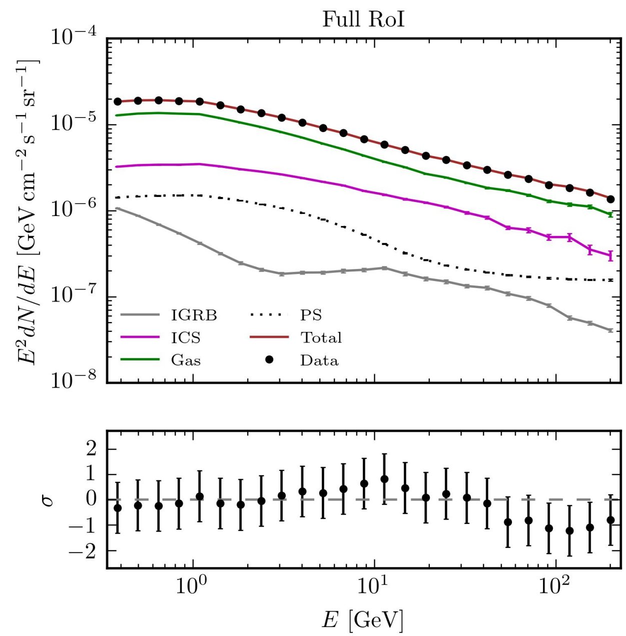
The traditional approach

SkyFACT vs the traditional approach

Constrained templates + spectra

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

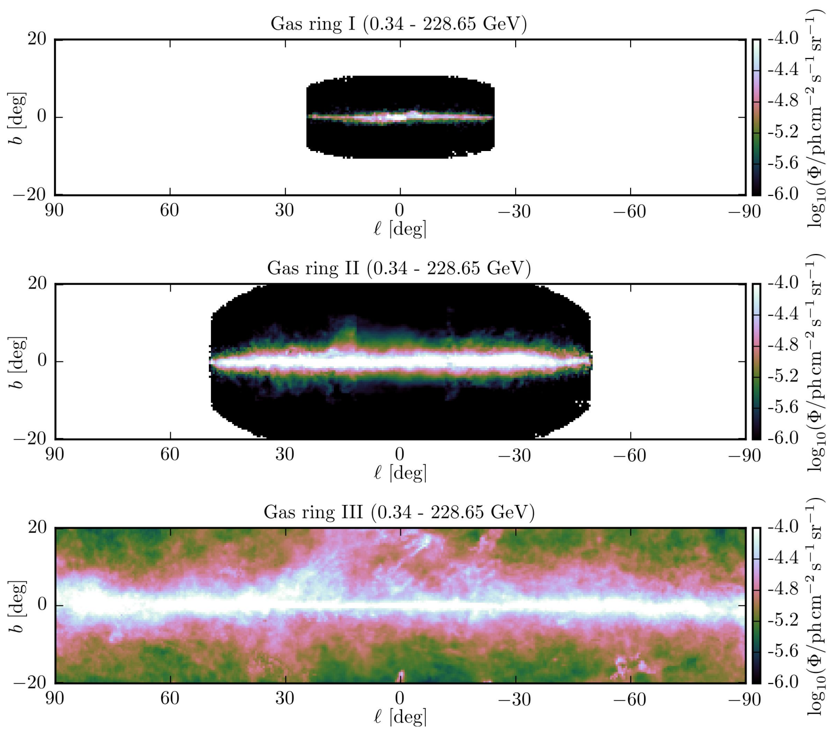


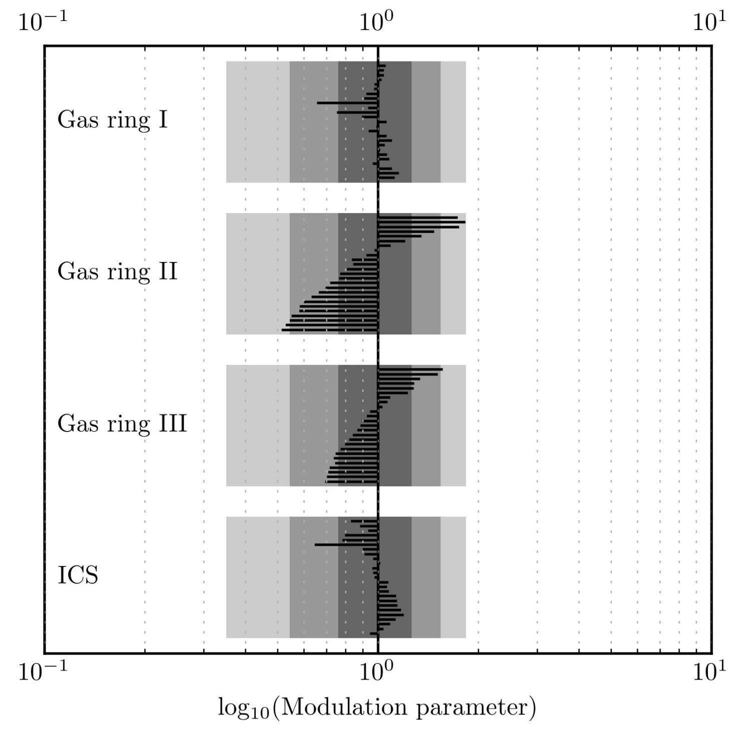


With adaptive template modulation

Application: CR proton gradient

Does the cosmic ray proton spectrum get harder closer to the Galactic Center?





With: Mart Pothast, Daniele Gaggero

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

Big sparse matrices

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:

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

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

SkyFACT: statistics table

Components	RUN1	RUN2	RUN3	RUN4	RUN5
Regularization hyper-parameters: $\begin{bmatrix} \lambda & \lambda' & \lambda'' \\ \eta & \eta' & \cdot \end{bmatrix}$					
IGRB	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$
3FGL PSC	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$
Gas (0–19 kpc)	$\begin{bmatrix} \infty & 16 & 0 \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	—	—	—
Gas ring I (0–3.5 kpc)	—	—	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$
Gas ring II (3.5–6.5 kpc)	—	—	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$
Gas ring III (6.5–19 kpc)	—	—	$\begin{bmatrix} 4 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 4 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 4 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$
Extended sources	—	—	—	$\begin{bmatrix} 0 & 1 & \infty \\ 4 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & \infty \\ 4 & 0 & \cdot \end{bmatrix}$
Inverse Compton	$\begin{bmatrix} \infty & 16 & 0 \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 1 & 16 & 0 \\ 100 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 1 & 16 & 0 \\ 100 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 1 & 16 & 0 \\ 100 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 1 & 16 & 0 \\ 100 & 0 & \cdot \end{bmatrix}$
Fermi bubbles	—	—	—	$\begin{bmatrix} 0 & 400 & \infty \\ 4 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 0 & 400 & \infty \\ 4 & 0 & \cdot \end{bmatrix}$
511 keV template	—	—	—	—	$\begin{bmatrix} 25 & 0 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$
Naive model parameters, N_{param}	20253	78573	97838	104596	107639
Naive DOF	708747	650427	631162	624404	621361
Eff. model parameters, $N^{\mathrm{eff}}_{\mathrm{param}}$	1900	11800	10200	12700	12800
Eff. data bins, $N^{\mathrm{eff}}_{\mathrm{data}}$	624700	622700	620200	618800	619000
Eff. DOF, k	622800	610900	610000	606100	606200
$-2\ln\mathcal{L}_P$	1016041	637742	633334	627206	626998
$-2\ln\mathcal{L}_R$	14152	24652	23709	21640	20988
Model fidelity, $\mathcal{F}$	627	164	153	145	144