
SkyFACT: Building better models of the gamma-ray sky

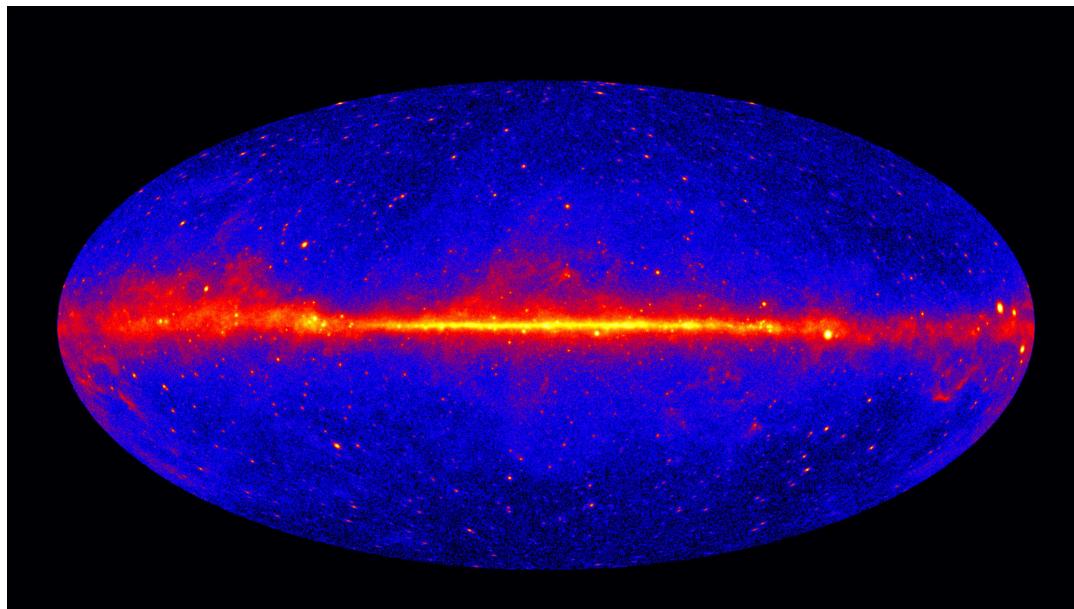
Emma Storm

In collaboration with:
Richard Bartels, Francesca Calore, Christoph Weniger

APLS | 12 October 2017

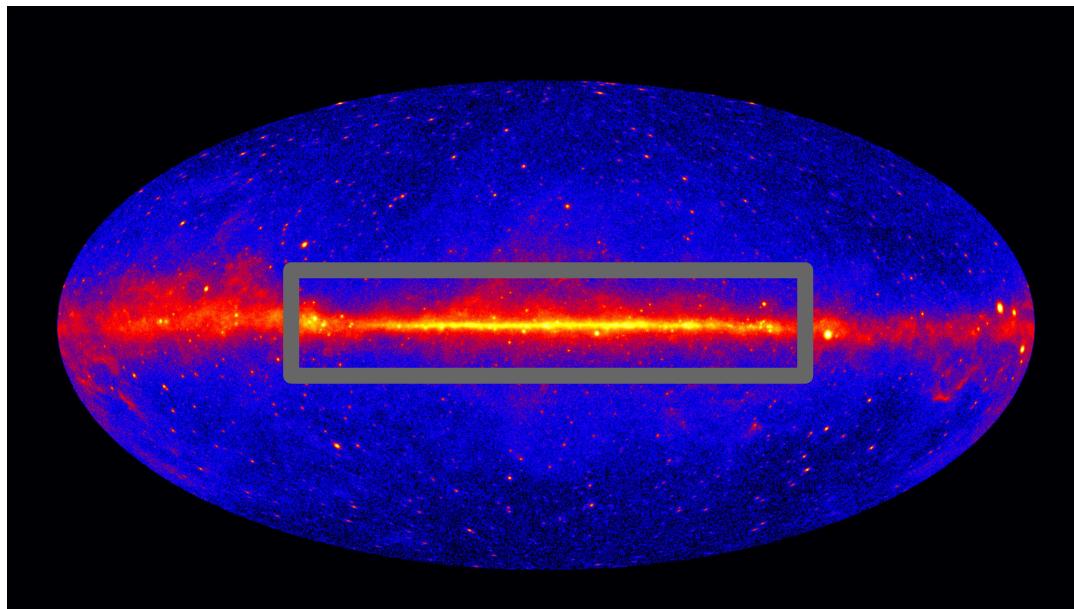
The gamma-ray sky

Fermi Gamma-ray
Space Telescope

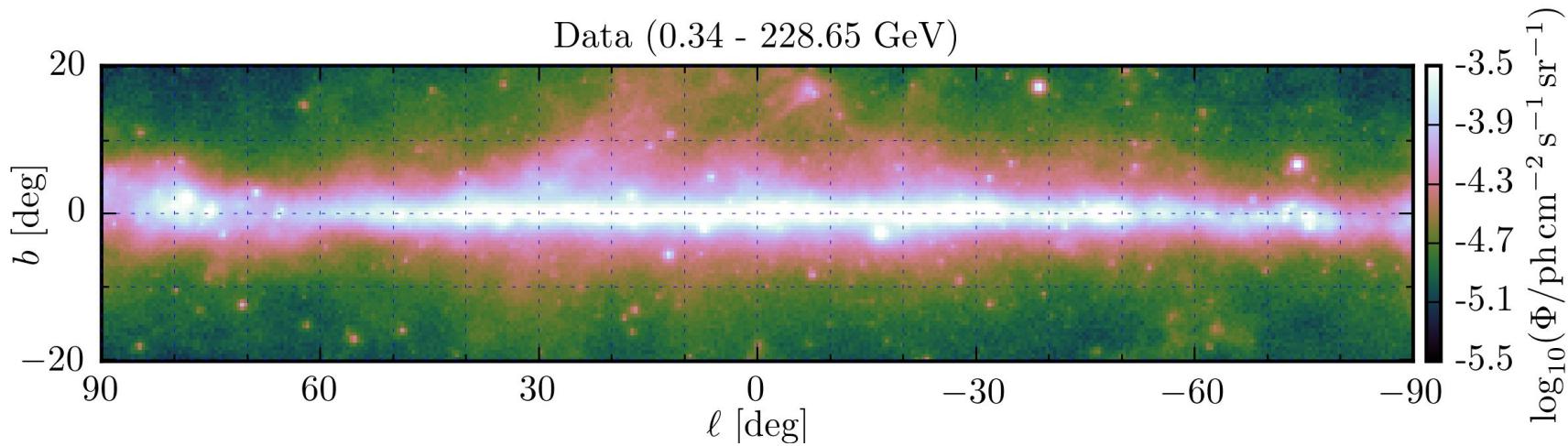


The gamma-ray sky

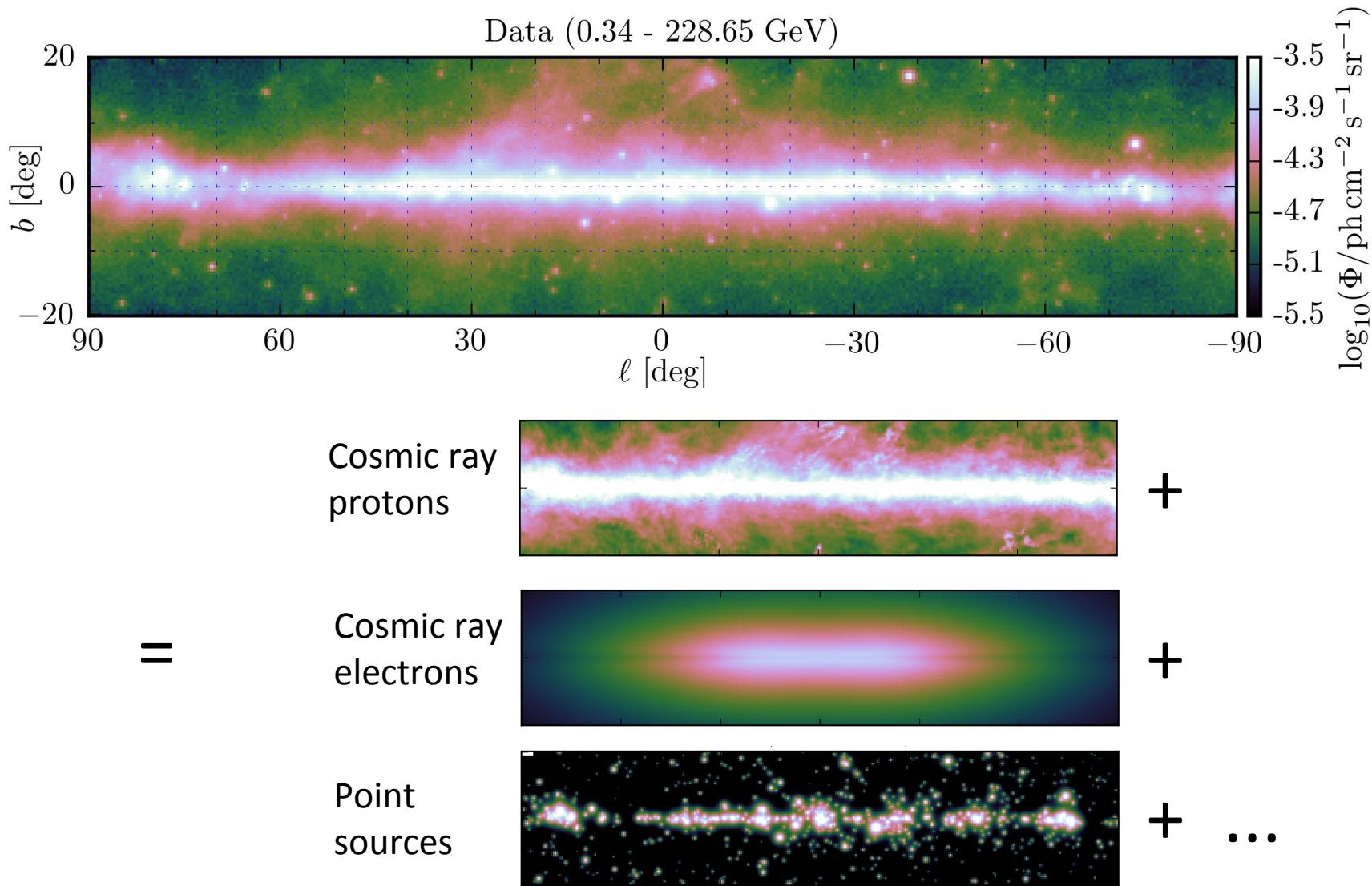
Fermi Gamma-ray
Space Telescope



The inner Galaxy in gamma rays



The inner Galaxy in gamma rays

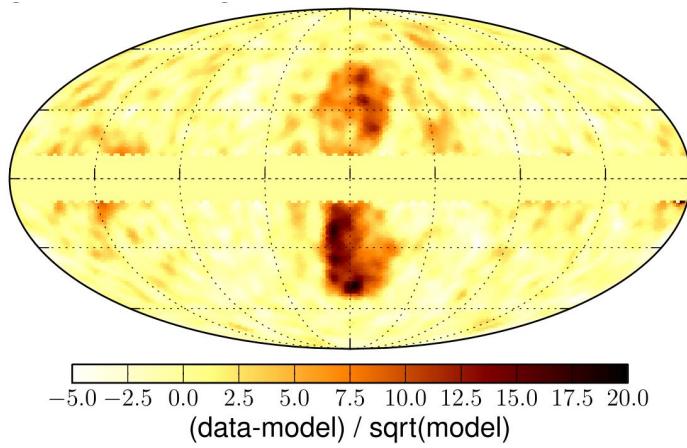


Template fitting: a primer

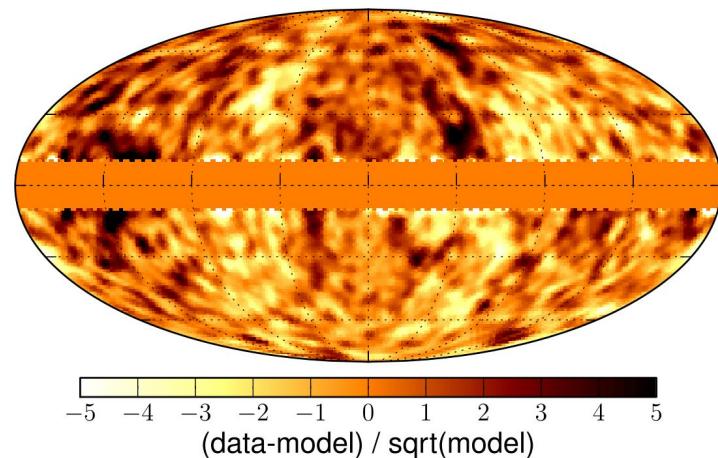
$$\text{Model} \sim \sum_k \text{Template}^{(k)}(E) \cdot \sigma^{(k)}(E)$$

Fixed
spatial
templates Free
spectral
templates

Discovery of new components:
Fermi Bubbles



However: quality of fits remains poor

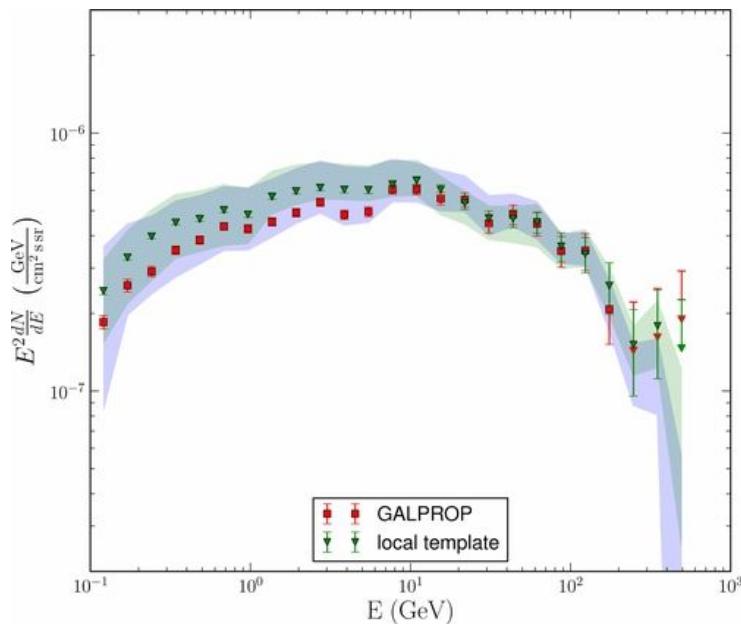


LAT Collaboration, 2014, ApJ 793:64

Template fitting: a primer

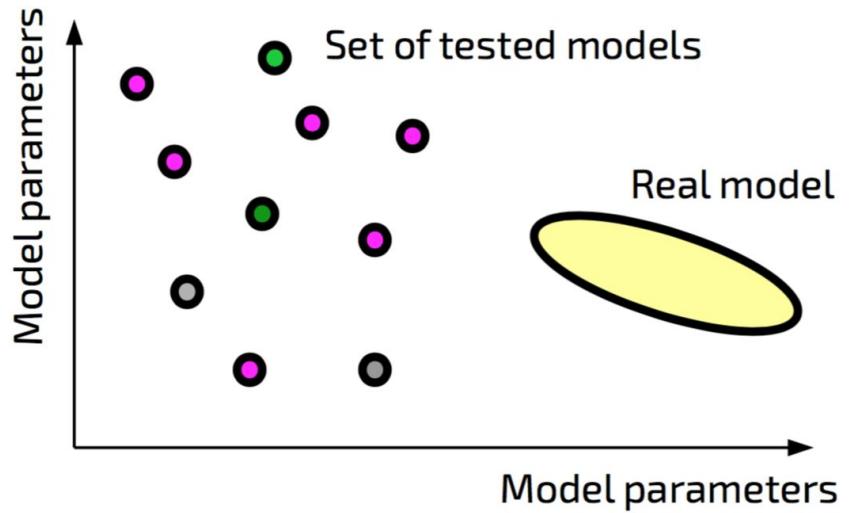
$$\text{Model} \sim \sum_k \text{Template}^{(k)}(E) \cdot \sigma^{(k)}(E)$$

Fermi Bubbles Spectrum



LAT Collaboration, 2014, ApJ 793:64

“Bracketing uncertainties”



Credit: C. Weniger

Template fitting: a primer

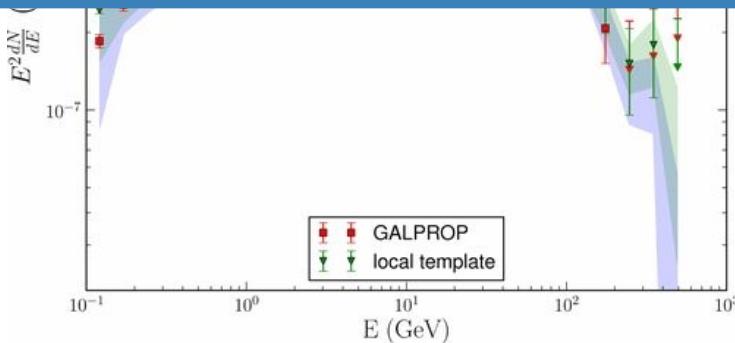
$$\text{Model} \sim \sum_k \text{Template}^{(k)}(E) \cdot \sigma^{(k)}(E)$$

Fermi Bubbles Spectrum

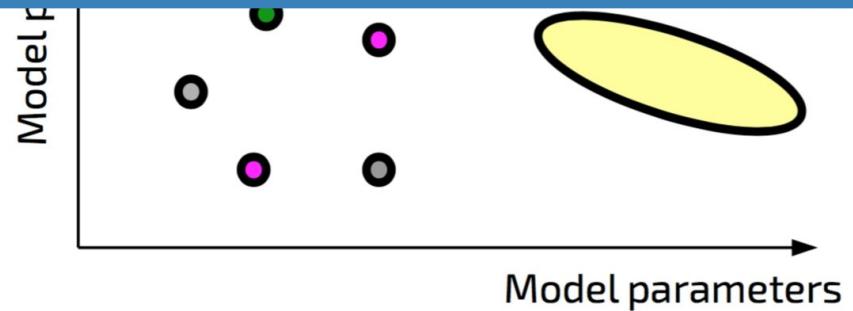
“Bracketing uncertainties”

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

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

A new approach: SkyFACT

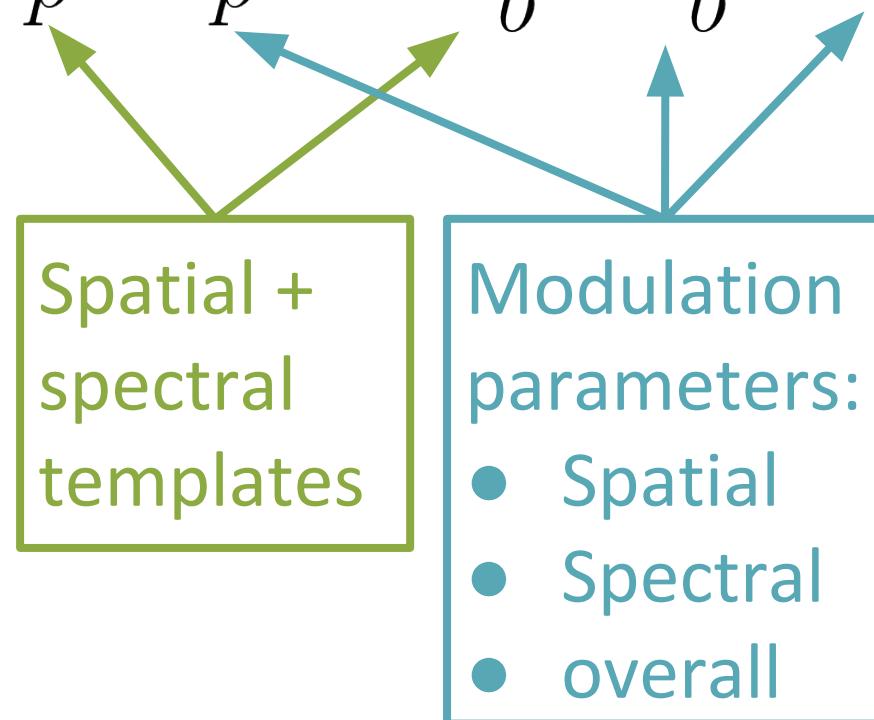
Sky Factorization with Adaptive Constrained Templates

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

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



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
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Spatial +
spectral
templates

Normalizations per:

- pixel
- energy bin
- component

Sky Factorization with Adaptive Constrained Templates

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

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

- Need to prevent overfitting
- Borrow techniques from
image reconstruction

Normalizations per:

- pixel
- energy bin
- component

Sky Factorization with Adaptive Constrained Templates

Penalization terms in the likelihood:

$$\ln \mathcal{L} = \ln \mathcal{L}_P + \ln \mathcal{L}_R$$

Poisson term

Regularization of modulation parameters

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

Sky Factorization with Adaptive Constrained Templates

Penalization terms in the likelihood:

$$\ln \mathcal{L} = \ln \mathcal{L}_P + \ln \mathcal{L}_R$$

Regularization terms:

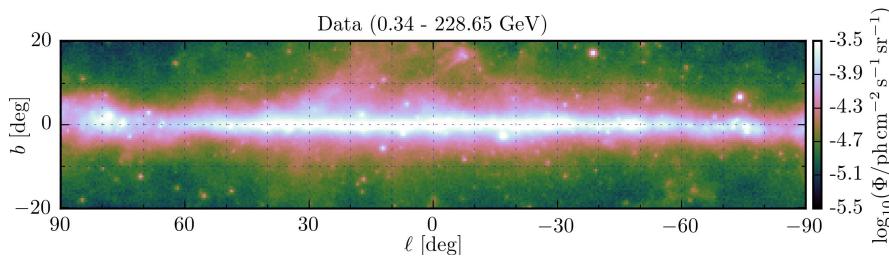
- Strength is controllable
- Typically, different for different components
- Regularization via MEM and smoothing

Regularization of modulation parameters

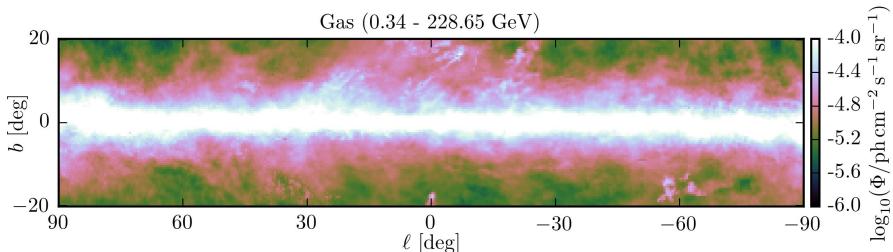
$$\tau_p^{(k)}, \sigma_b^{(k)}, \nu^{(k)}$$

Data and initial model

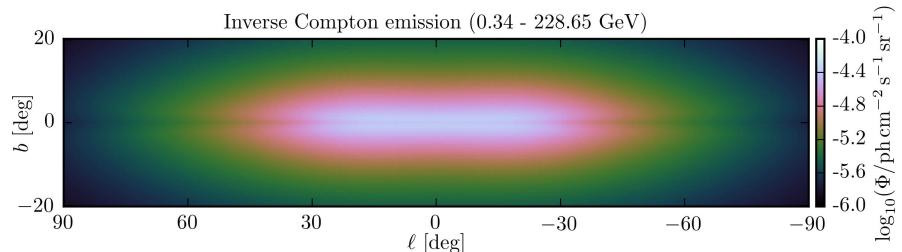
Data:



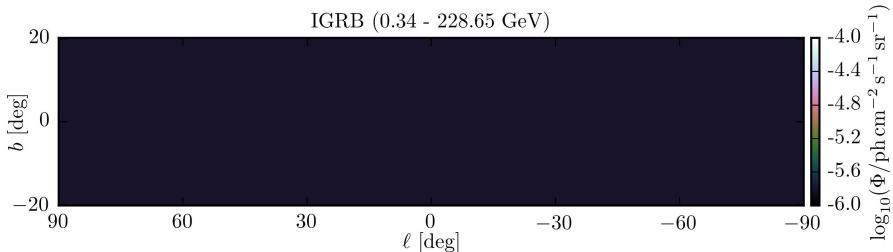
Model:



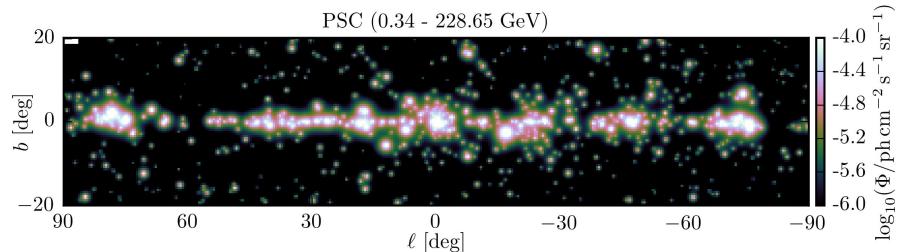
Template: sum of HI and H₂ column densities
from GALPROP; no dark gas correction
Spectrum: Fermi-LAT (2012) ApJ 750



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



Spectrum: Fermi-LAT (2015) ApJ 799

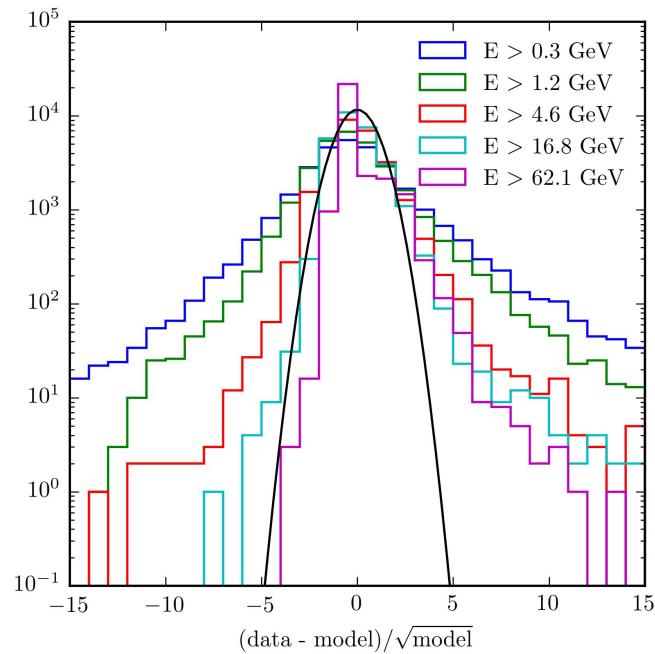


Locations and spectra: 3FGL catalog

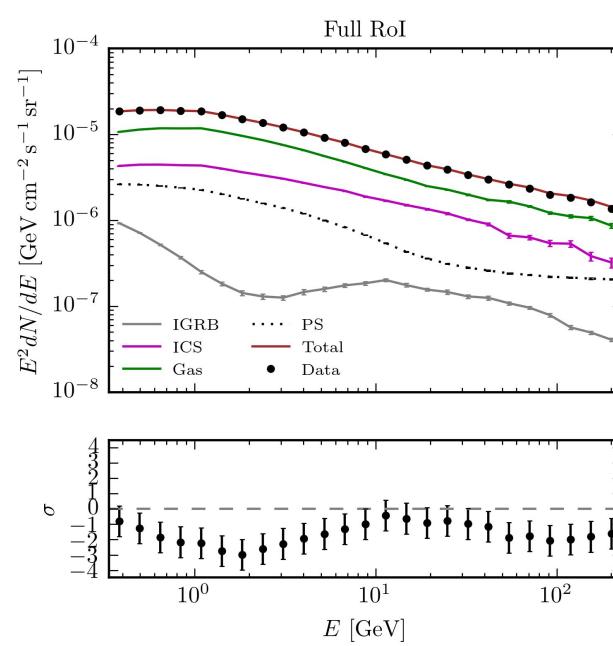
SkyFACT vs the traditional approach

Fixed templates + constrained spectra

No spatial modulation allowed



~25% variations allowed

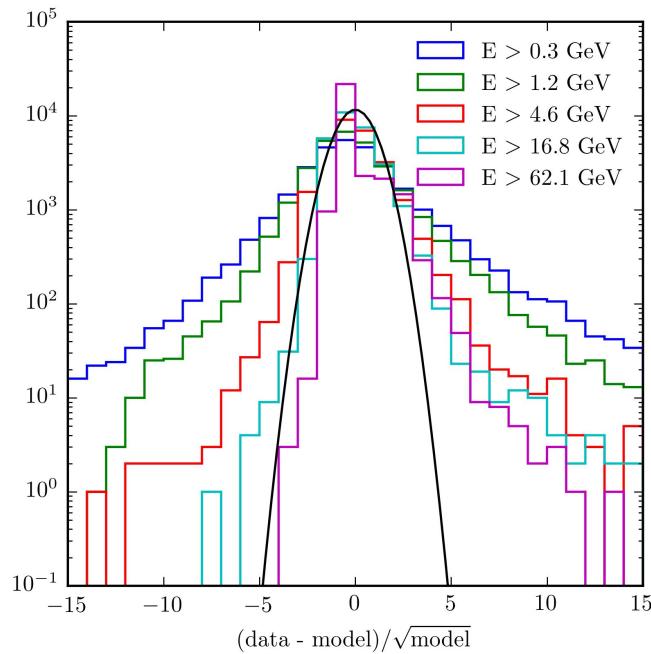


The traditional approach

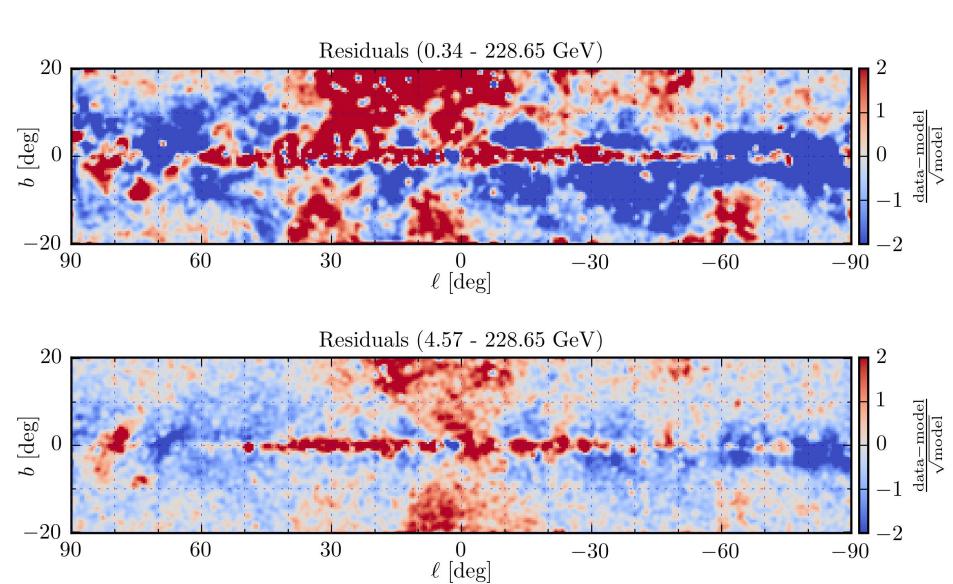
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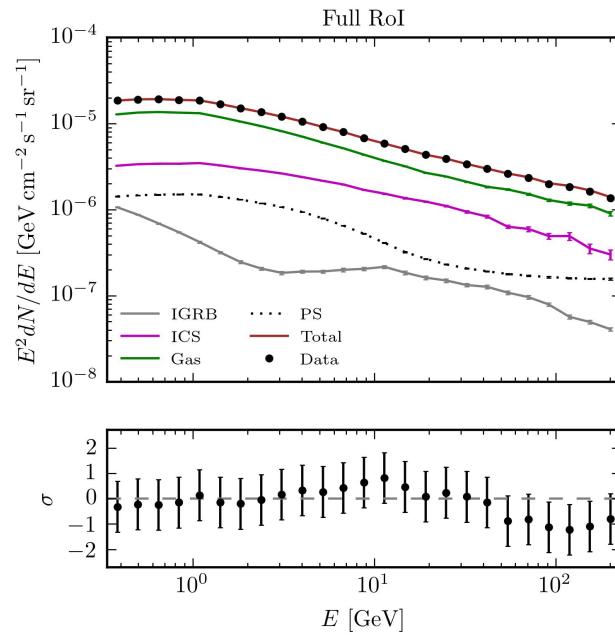
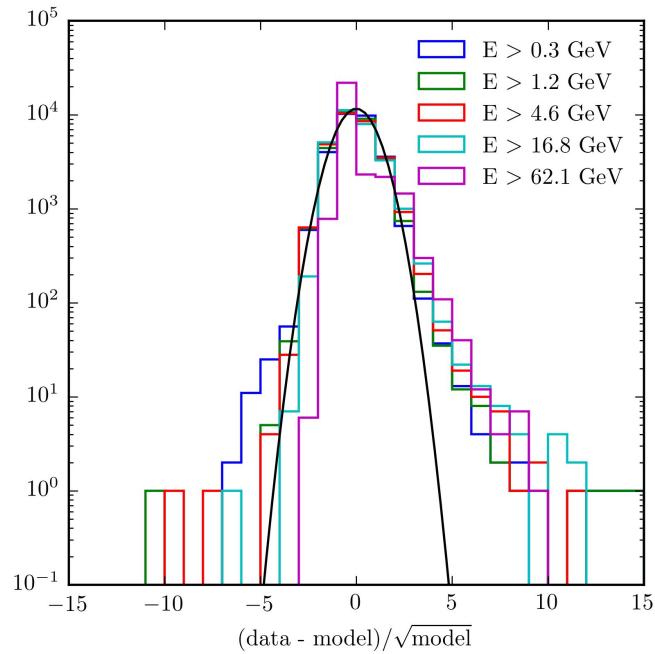
The traditional approach

SkyFACT vs the traditional approach

Constrained templates + spectra

Spatial modulation: 25% for gas, x2 for ICS

Spectral modulation: 20-25%



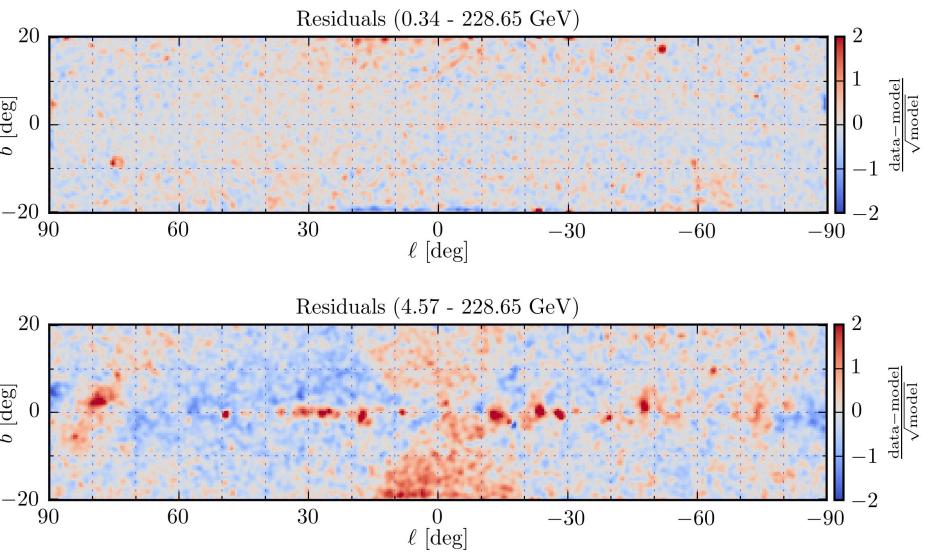
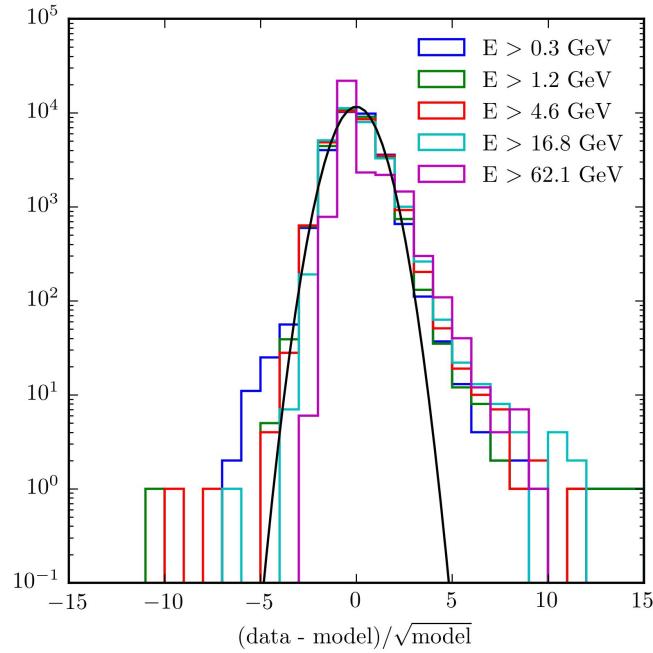
With adaptive template modulation

SkyFACT vs the traditional approach

Constrained templates + spectra

Spatial modulation: 25% for gas, x2 for ICS

Spectral modulation: 20-25%



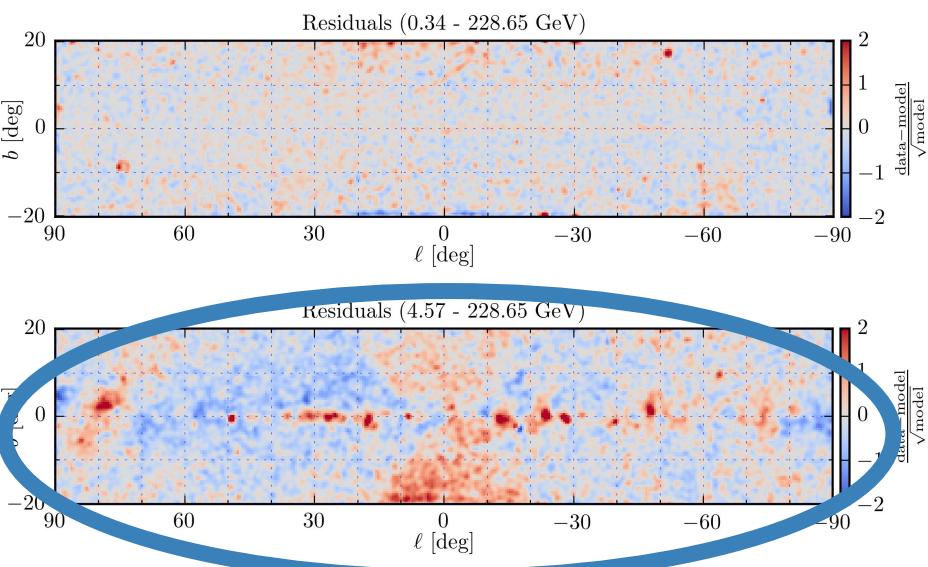
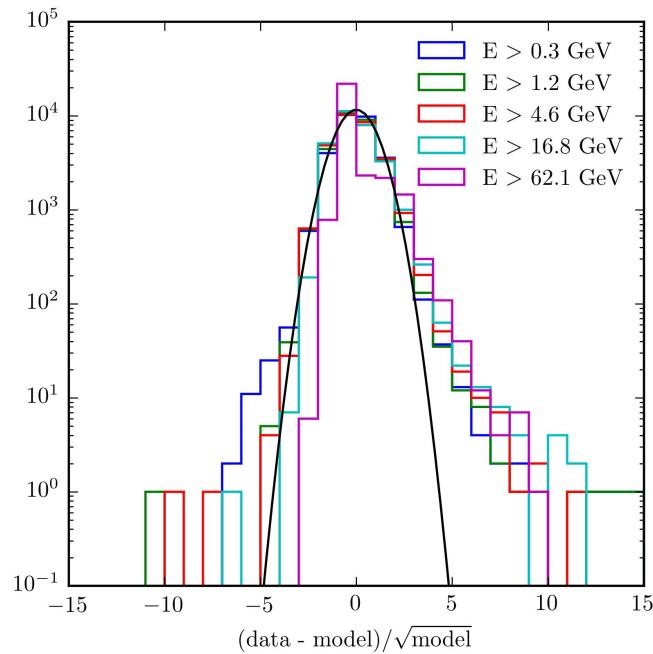
With adaptive template modulation

Additional necessary components

Constrained templates + spectra

Spatial modulation: 25% for gas, x2 for ICS

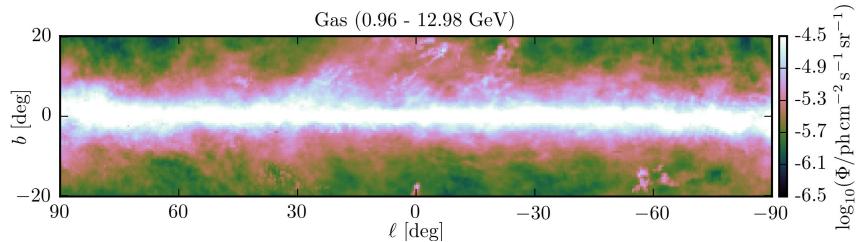
Spectral modulation: 20-25%



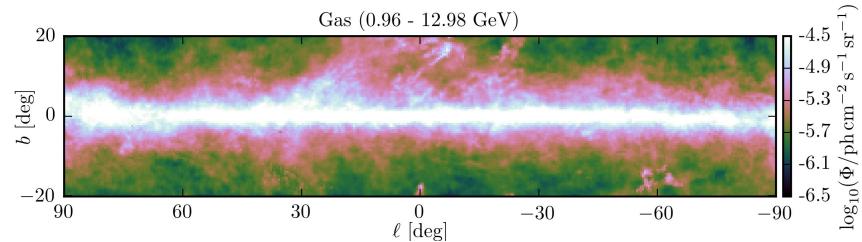
Irreducible residuals → add new components

SkyFACT: modulation parameters

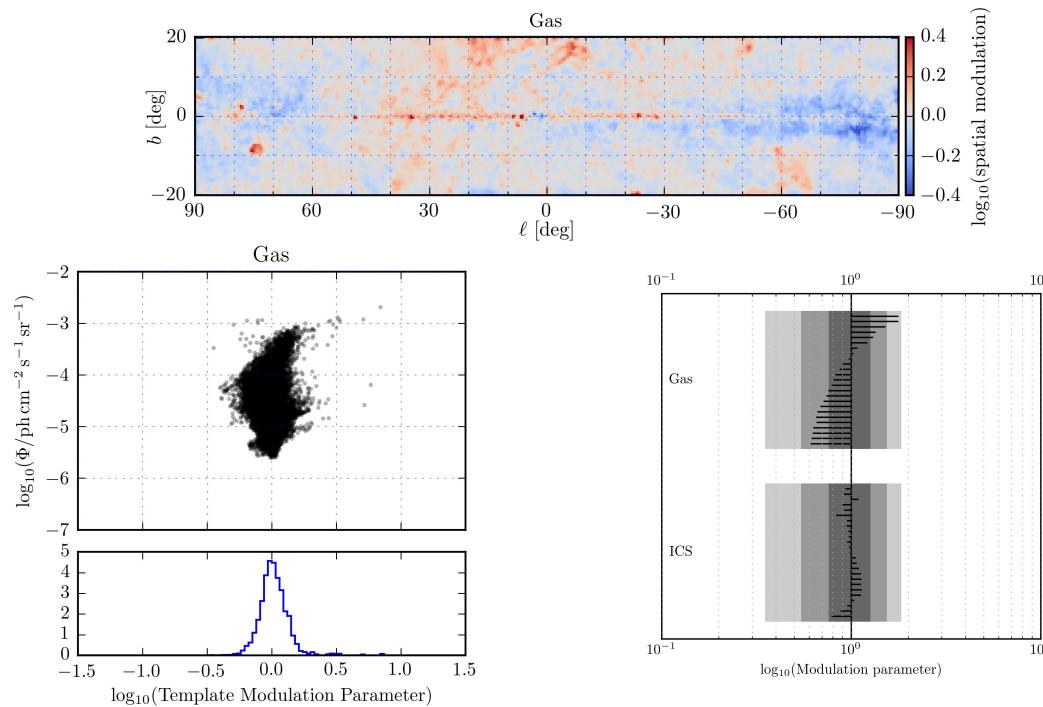
Original Template



Best-fit Template

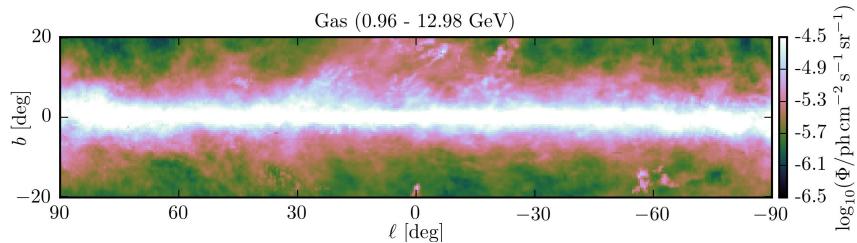


Template and Spectra Modulation

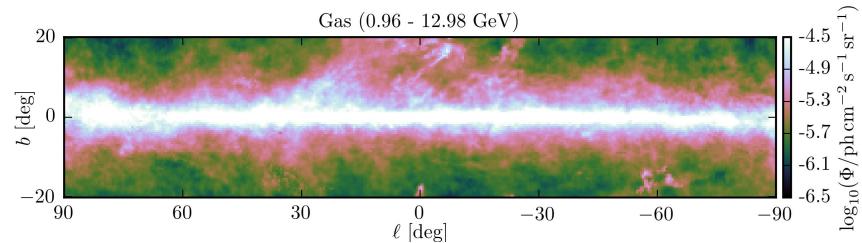


SkyFACT: modulation parameters

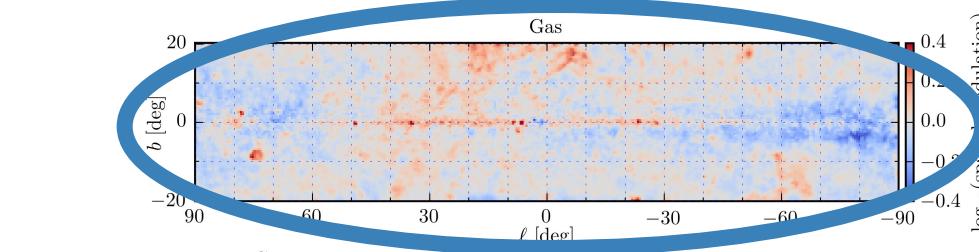
Original Template



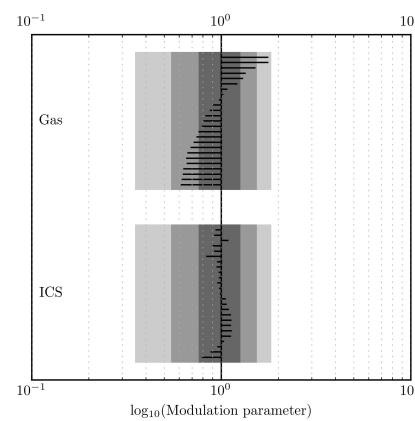
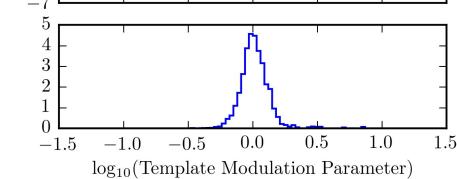
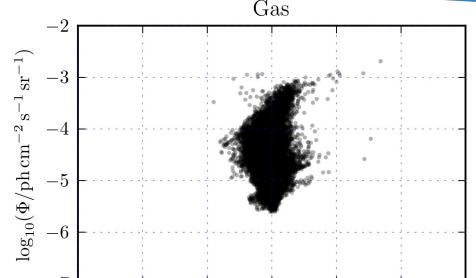
Best-fit Template



Template and Spectra Modulation

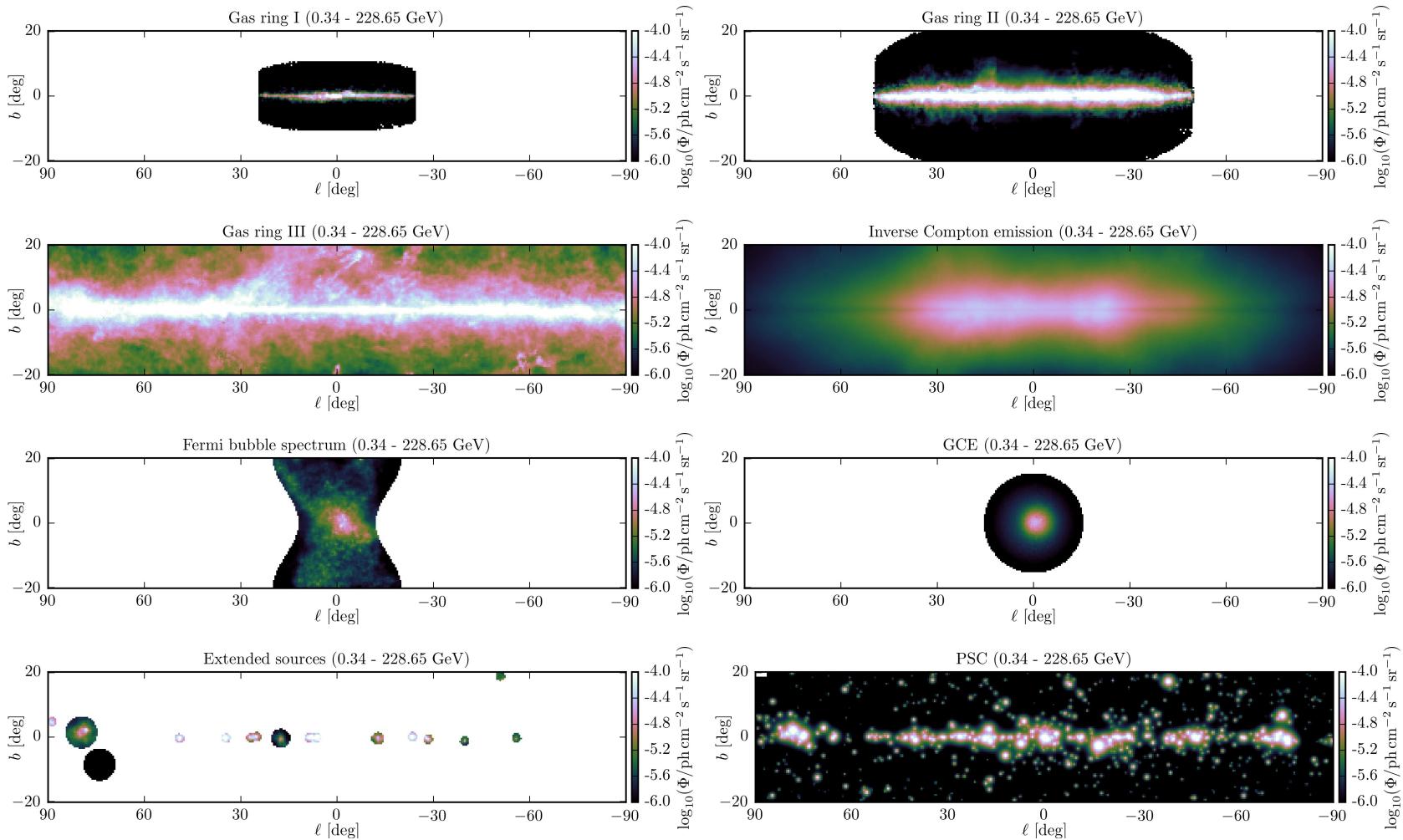


Dark gas



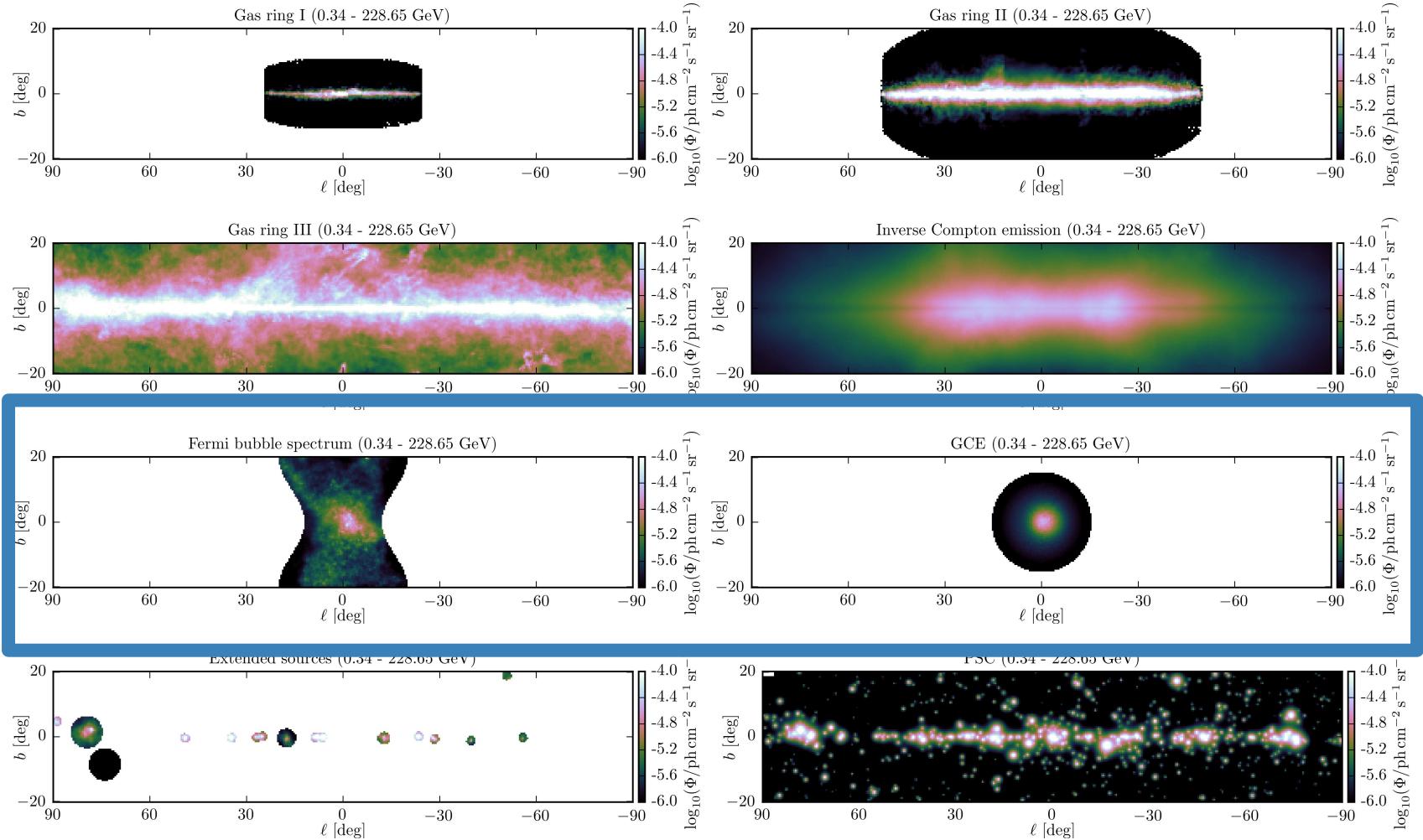
Reference model

Best-fit model components for reference model:

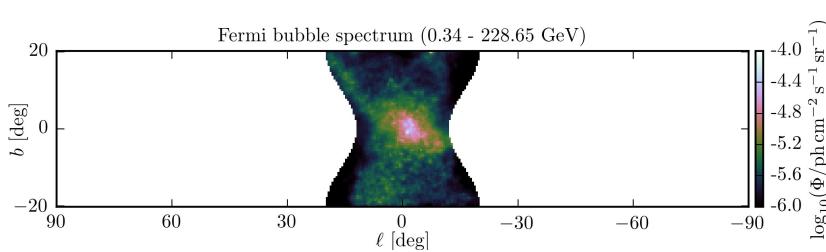


Application: bulge emission

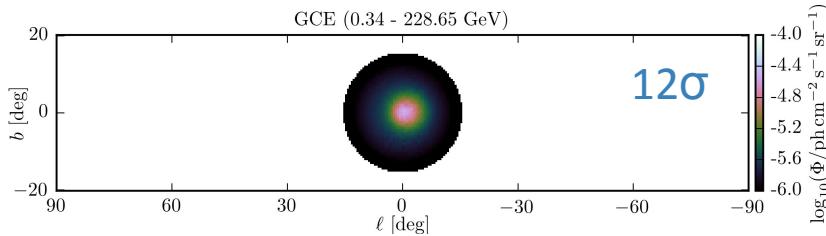
Best-fit model components for reference model:



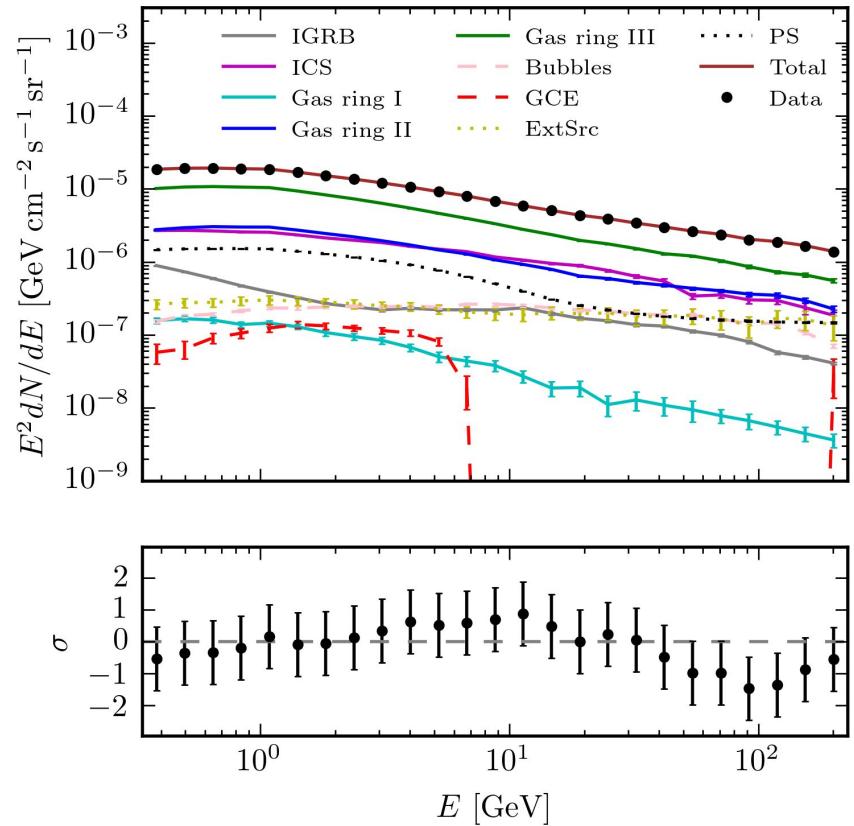
Application: bulge emission



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



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

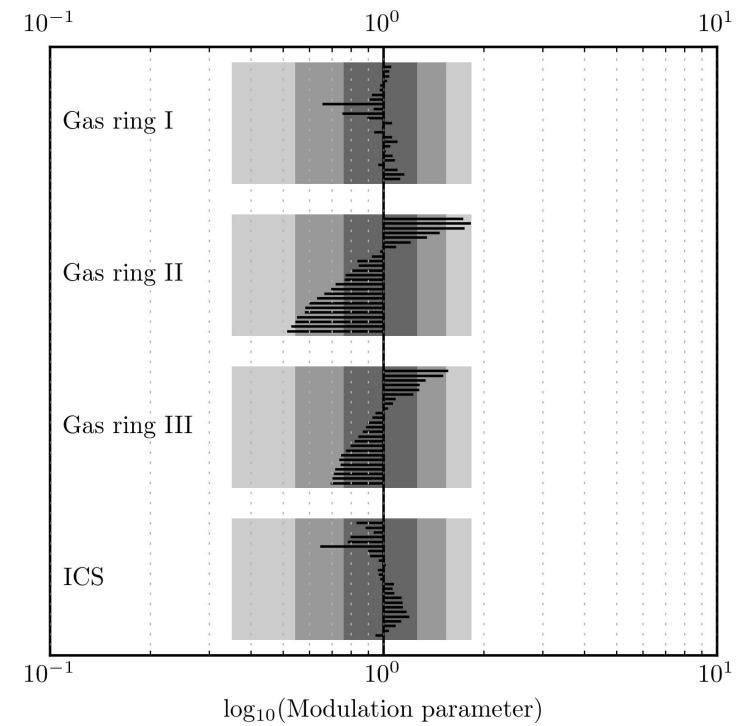
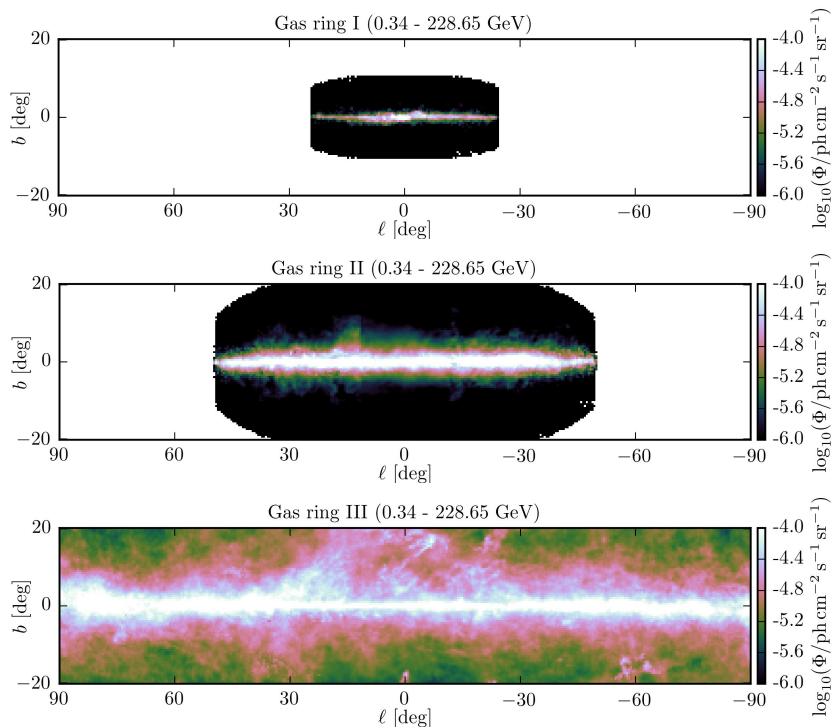


For future study:

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

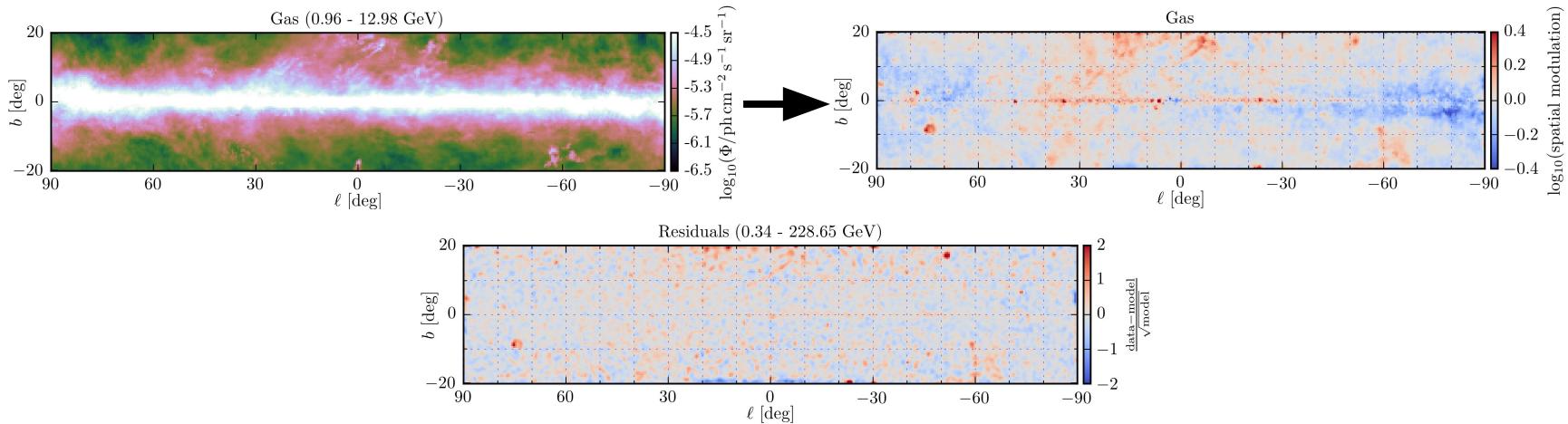
Application: CR proton gradient

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



With: Mart Pothast, Daniele Gaggero

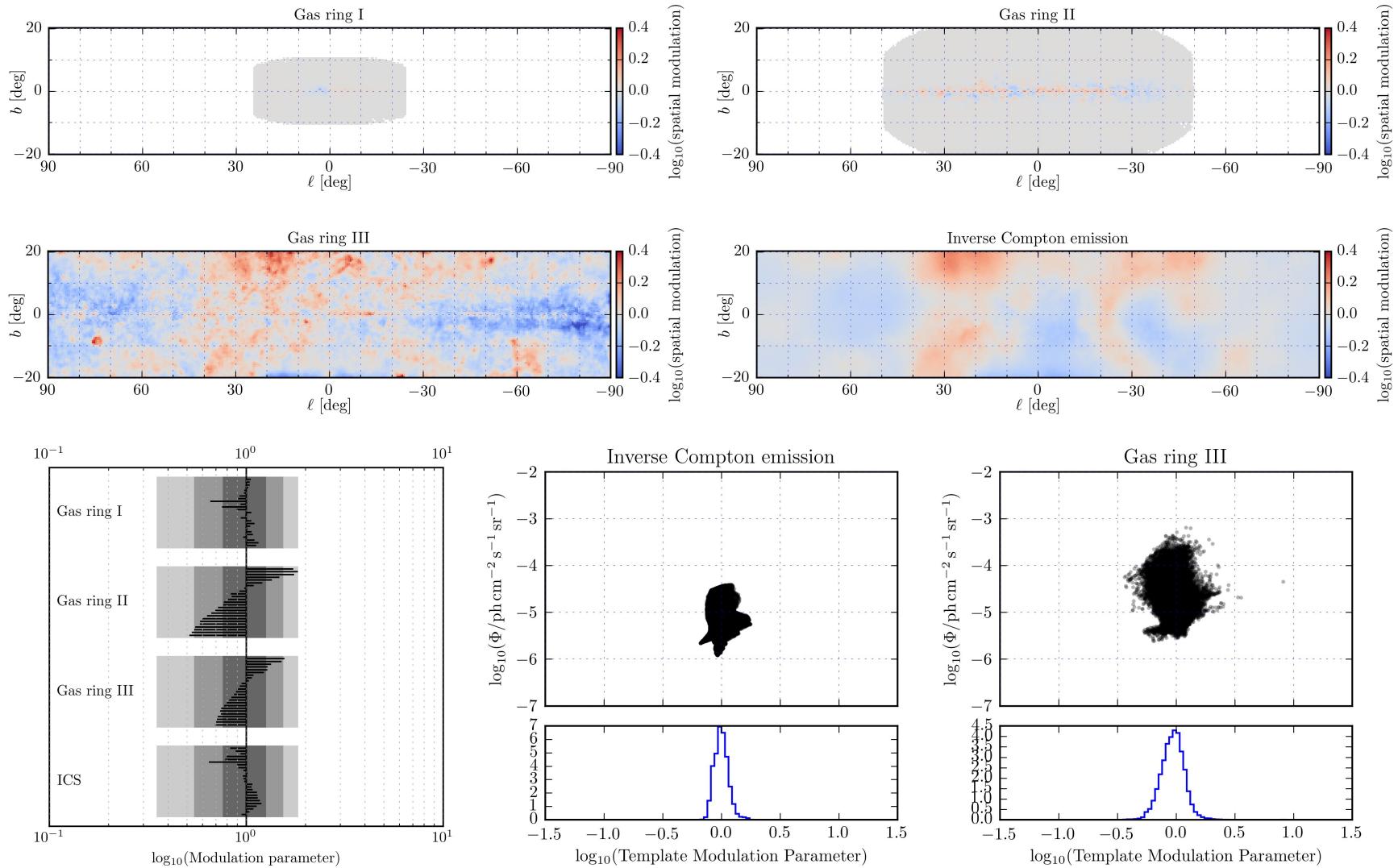
SkyFACT: summary



- Introducing nuisance parameters into template fits dramatically improves fit quality
- Dominant components (gas, ICS) are recovered within 30-40%
- GCE spectrum recovered from input spatial template -- see Richard's talk tomorrow!

Backup slides

Reference model rescaling



SkyFACT: likelihood + regularization

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

Regularization Likelihood Terms:

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

Regularization Definitions

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

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

SkyFACT: model

Model Definition

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

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

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:

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

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

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

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

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

SkyFACT: statistics table

Components	RUN1	RUN2	RUN3	RUN4	RUN5
	Regularization hyper-parameters: $\begin{bmatrix} \lambda & \lambda' & \lambda'' \\ \eta & \eta' & \cdot \end{bmatrix}$				
IGRB	$[\infty \ 16 \ \infty]$	$[\infty \ 16 \ \infty]$	$[\infty \ 16 \ \infty]$	$[\infty \ 16 \ \infty]$	$[\infty \ 16 \ \infty]$
3FGL PSC	$[: 25 \ 0]$	$[: 25 \ 0]$	$[: 25 \ 0]$	$[: 25 \ 0]$	$[: 25 \ 0]$
Gas (0–19 kpc)	$[\infty \ 16 \ 0]$	$[\frac{10}{25} \ 16 \ 0]$	—	—	—
Gas ring I (0–3.5 kpc)	—	—	$[\frac{10}{25} \ 16 \ 0]$	$[\frac{10}{25} \ 16 \ 0]$	$[\frac{10}{25} \ 16 \ 0]$
Gas ring II (3.5–6.5 kpc)	—	—	$[\frac{10}{25} \ 16 \ 0]$	$[\frac{10}{25} \ 16 \ 0]$	$[\frac{10}{25} \ 16 \ 0]$
Gas ring III (6.5–19 kpc)	—	—	$[\frac{4}{25} \ 16 \ 0]$	$[\frac{4}{25} \ 16 \ 0]$	$[\frac{4}{25} \ 16 \ 0]$
Extended sources	—	—	—	$[\frac{0}{4} \ 1 \ \infty]$	$[\frac{0}{4} \ 1 \ \infty]$
Inverse Compton	$[\infty \ 16 \ 0]$	$[\frac{1}{100} \ 16 \ 0]$	$[\frac{1}{100} \ 16 \ 0]$	$[\frac{1}{100} \ 16 \ 0]$	$[\frac{1}{100} \ 16 \ 0]$
<i>Fermi</i> bubbles	—	—	—	$[\frac{0}{4} \ 400 \ \infty]$	$[\frac{0}{4} \ 400 \ \infty]$
511 keV template	—	—	—	—	$[\frac{25}{0} \ 0 \ \infty]$
Naive model parameters, N_{param}	20253	78573	97838	104596	107639
Naive DOF	708747	650427	631162	624404	621361
Eff. model parameters, $N_{\text{param}}^{\text{eff}}$	1900	11800	10200	12700	12800
Eff. data bins, $N_{\text{data}}^{\text{eff}}$	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