Understanding Uncertainties in Modeling the Galactic Diffuse Gamma-ray Emission

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with Francesca Calore, Christoph Weniger

TeVPA
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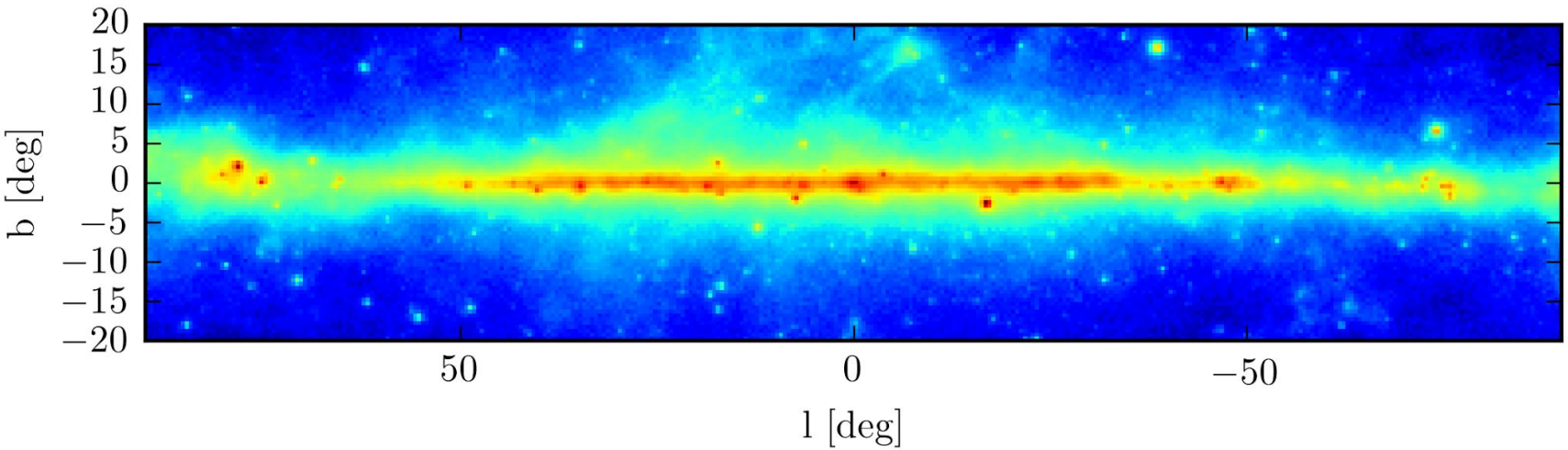
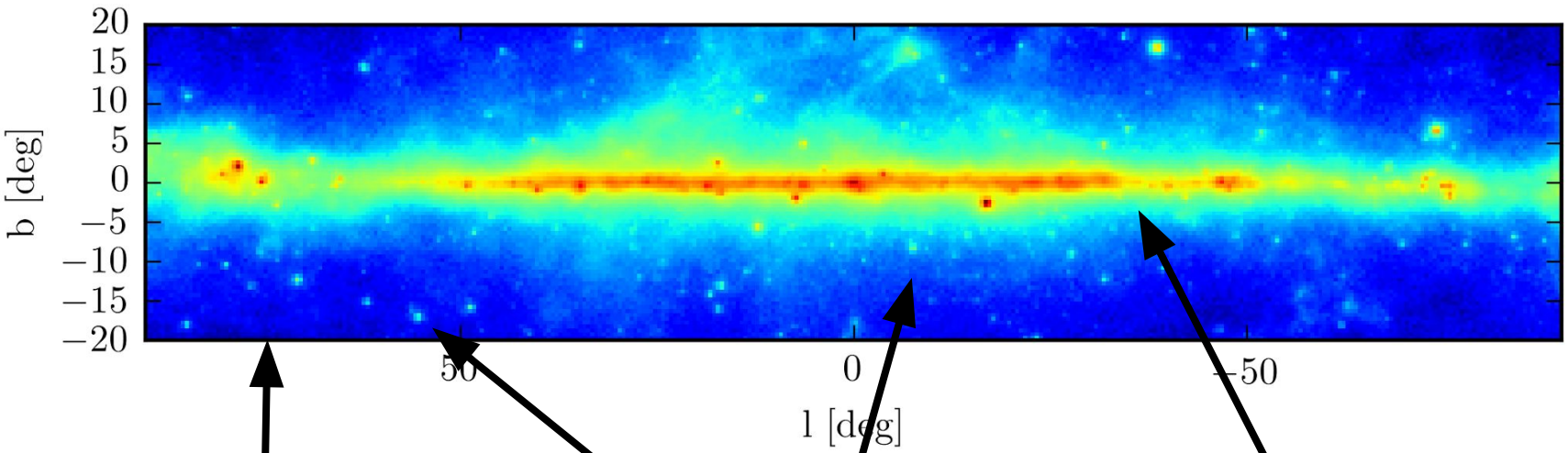
University of Amsterdam
GRAPPA
GRavitation AstroParticle Physics Amsterdam

The Gamma-ray Sky



The Gamma-ray Sky



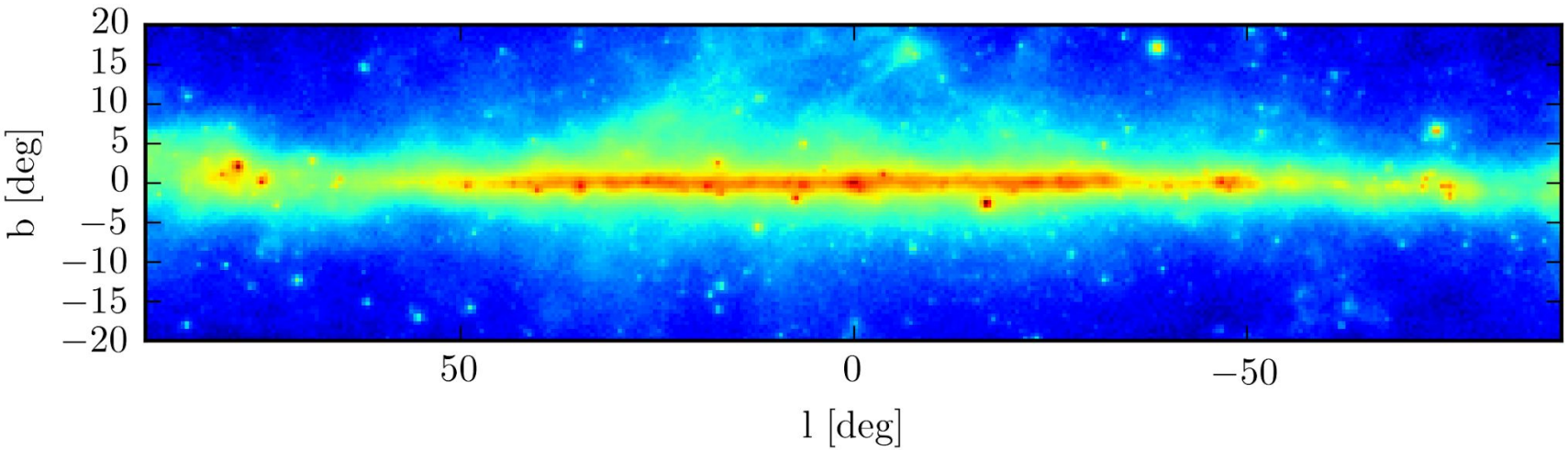
extragalactic

point sources

galactic

+ others…

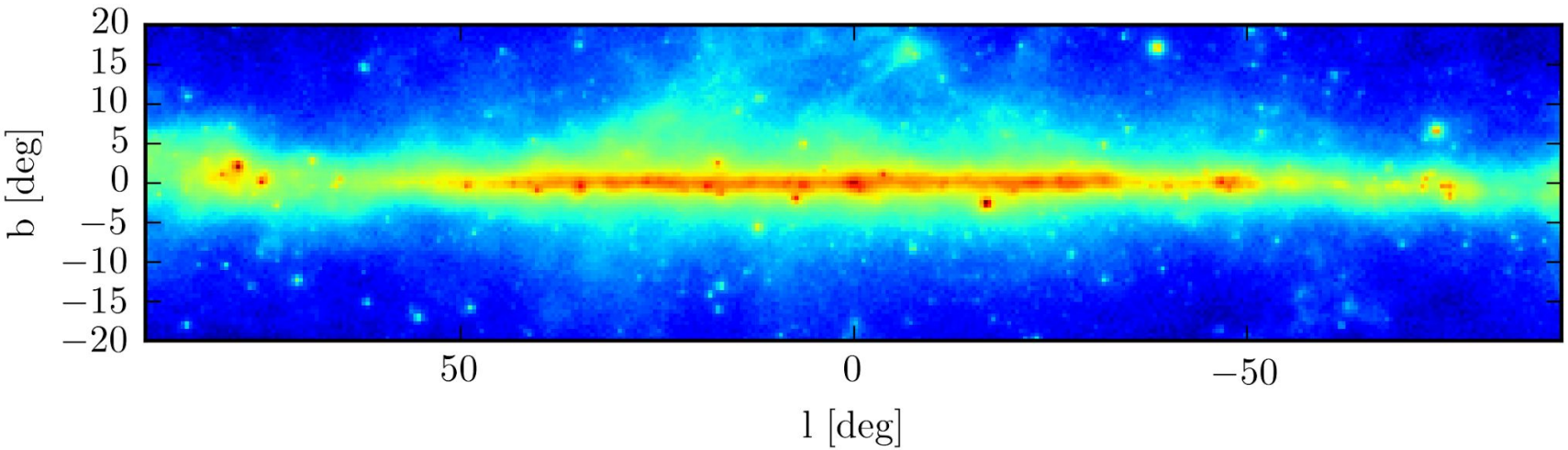
Template Fitting: The Standard Approach



=

sum of modeled components

Template Fitting: The Standard Approach



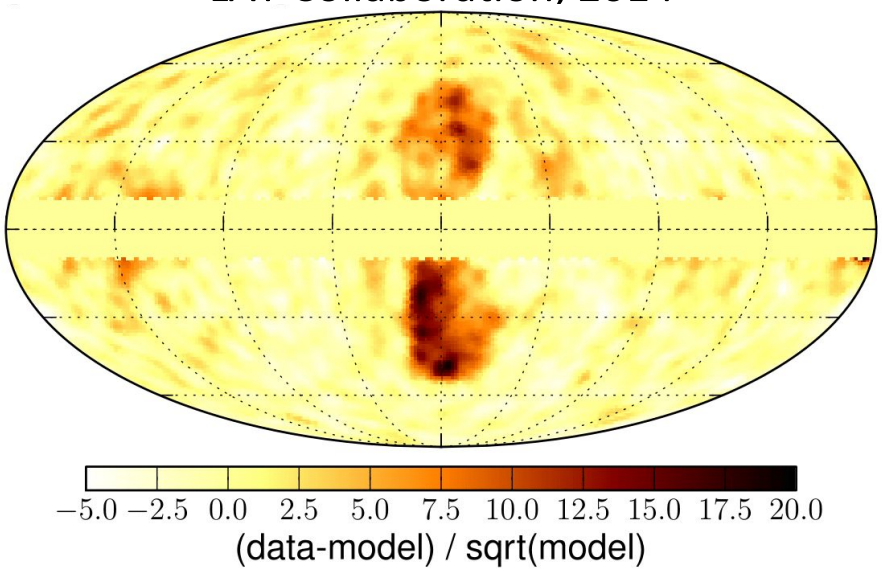
=

sum of modeled components

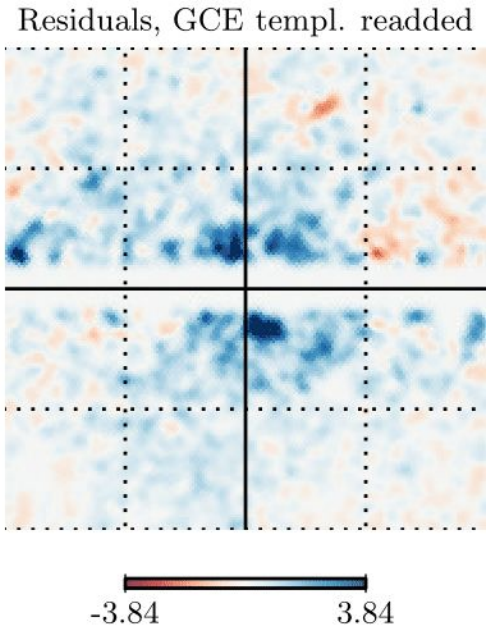
→ examine residuals

Template Fitting: The Standard Approach

Fermi Bubbles
LAT Collaboration, 2014



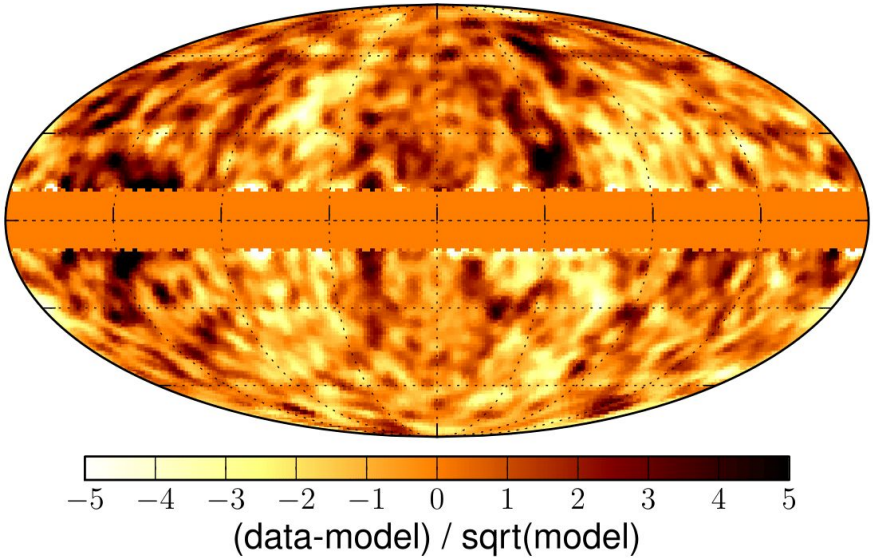
GeV Excess
Calore+2015



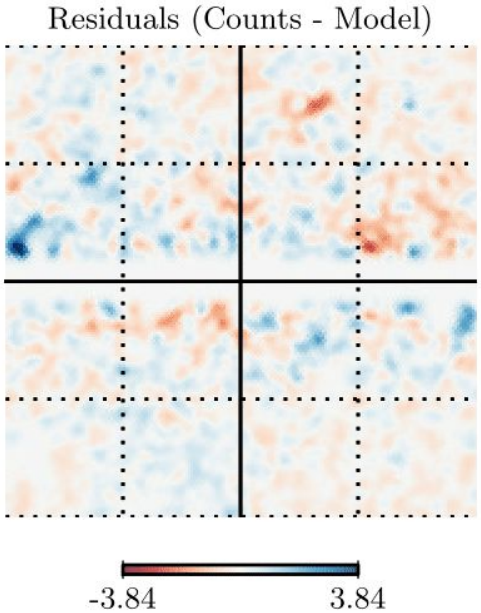
Fruitful approach, so far

Template Fitting: The Standard Approach

LAT Collaboration, 2014



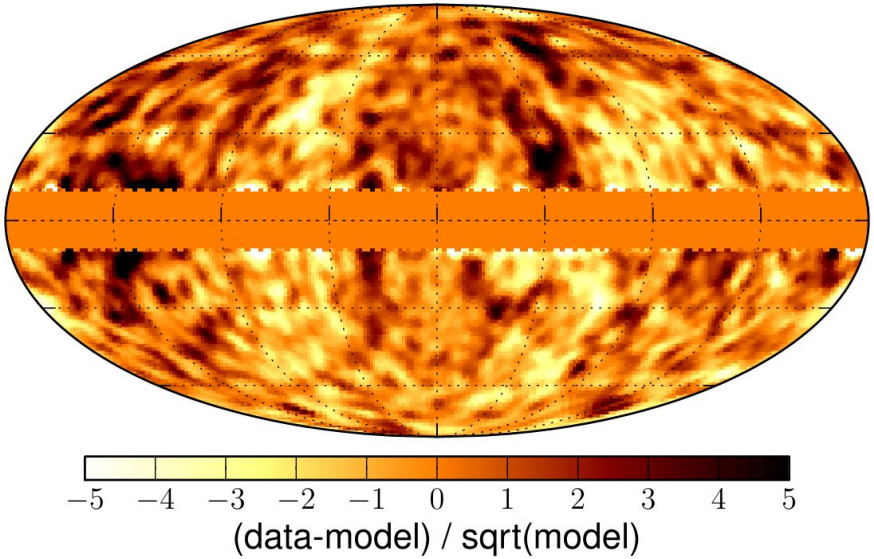
Calore+2015



Always present: other residuals

Template Fitting: The Standard Approach

LAT Collaboration, 2014



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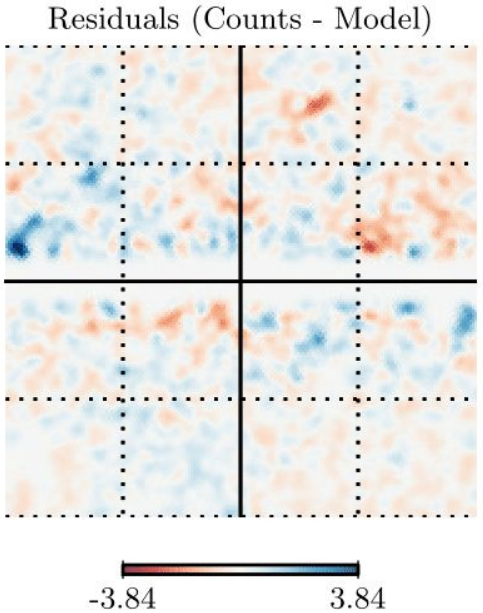
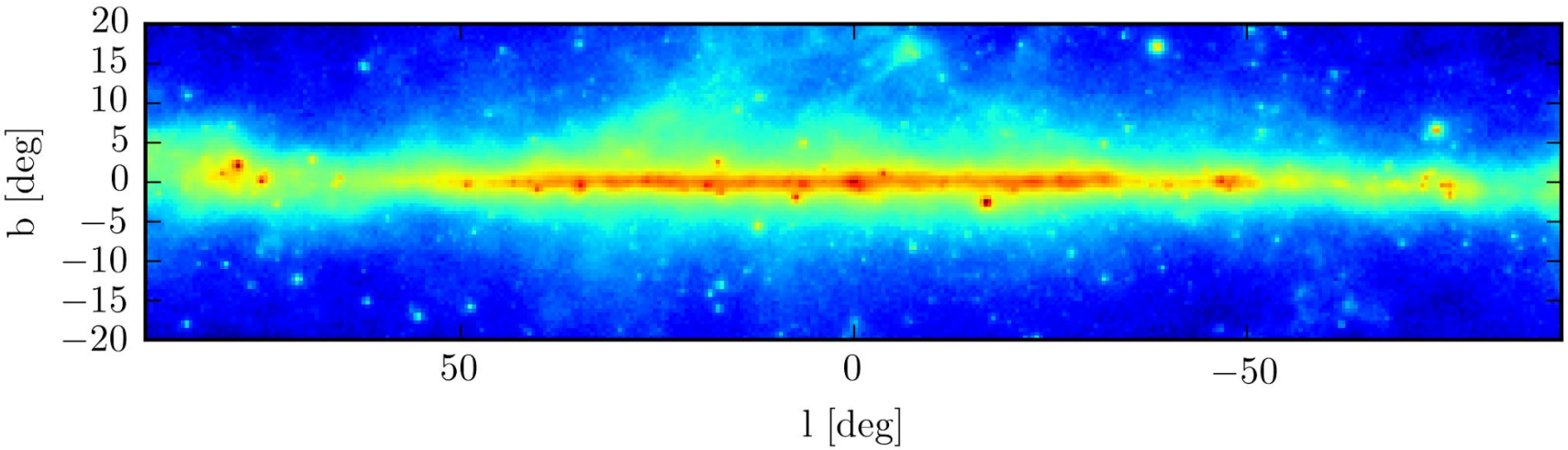


Residuals: missing components? Mis-modeling?
Consistent with uncertainties in data/model?

Template Fitting: The Standard Approach



What can we do?

- Develop better data analysis techniques
- Develop better theoretical predictions
- Parameterize uncertainties in models

Template Fitting: A Primer

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

The Traditional Approach

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The Traditional Approach

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

Spectra free to vary in energy bin by bin

Templates fixed to (data-driven) model predictions

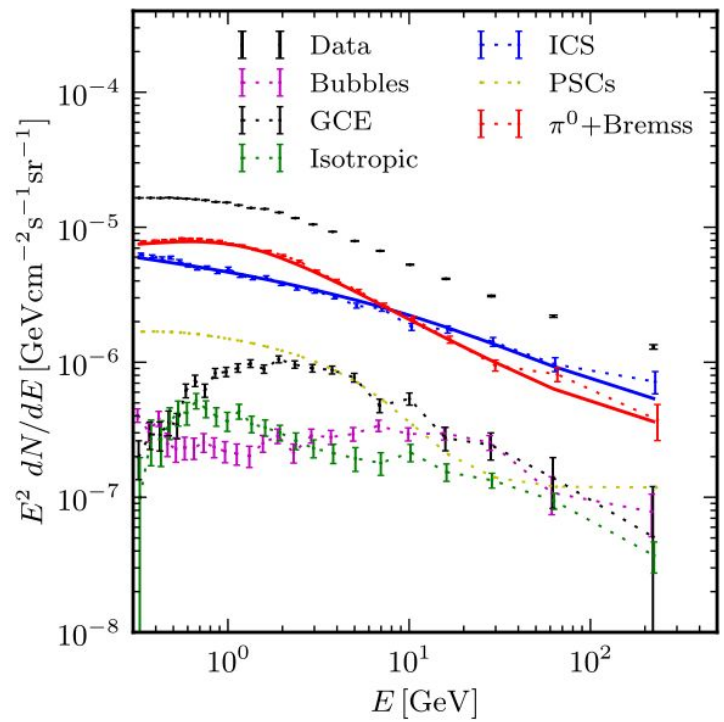
The Traditional Approach

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

fixed free

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

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



Calore+2015

Spectral Decomposition

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

Spectral Decomposition

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

Spectra fixed to (data-driven) model predictions

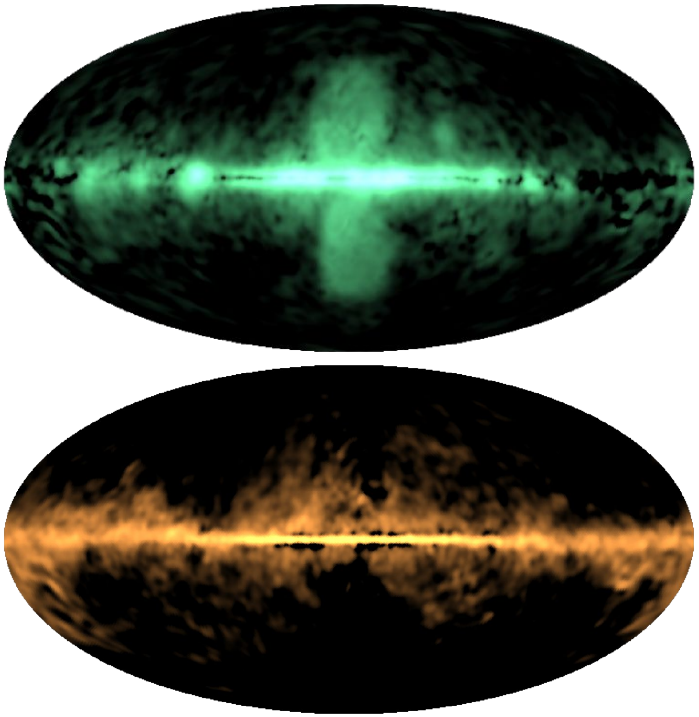
Spatial templates free to vary

Spectral Decomposition

$$\text{Model} = \sum_k \underbrace{\boxed{\text{Spectrum}}}_{\text{fixed}} \times \underbrace{\boxed{\text{Morphology}}}_{\text{free}}$$

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

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



Selig+2015, Huang+2016

A New Approach

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

A New Approach

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Spectra free to vary in energy bin by bin

Templates free to vary spatially pixel by pixel

A New Approach

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

Spectra free to vary in energy bin by bin

Templates free to vary spatially pixel by pixel

SkyFACT

SkyFACT

Sky Factorization with Adaptive Constrained Templates

SkyFACT

Sky Factorization with Adaptive Constrained Templates

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

SkyFACT

Sky Factorization with Adaptive Constrained Templates

$$\mu_{ij} = \sum_k \underbrace{\mathsf{T}_i^{(k)} \mathsf{S}_j^{(k)}}_{\text{Spatial + spectral templates}} \underbrace{\theta_i^{(k)} \theta_j^{(k)} \theta^{(k)}}_{\text{Scaling parameters:}}$$

Spatial + spectral templates

Scaling parameters:

- Spatial
- Spectral
- overall

SkyFACT

Sky Factorization with Adaptive Constrained Templates

$$\mu_{ij} = \sum_k \underbrace{\mathsf{T}_i^{(k)} \mathsf{S}_j^{(k)}}_{\text{Spatial + spectral templates}} \underbrace{\theta_i^{(k)} \theta_j^{(k)} \theta^{(k)}}_{\text{Will be around } \mathbf{1} \text{ for reasonable templates!}}$$

SkyFACT

Sky Factorization with Adaptive Constrained Templates

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

+ Constraints on parameters
+ Spatial and spectral smoothing
+ Point sources

SkyFACT

Sky Factorization with Adaptive Constrained Templates

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+ Constraints on parameters
+ Spatial and spectral smoothing
+ Point sources

Model $\longrightarrow$ Likelihood Fit

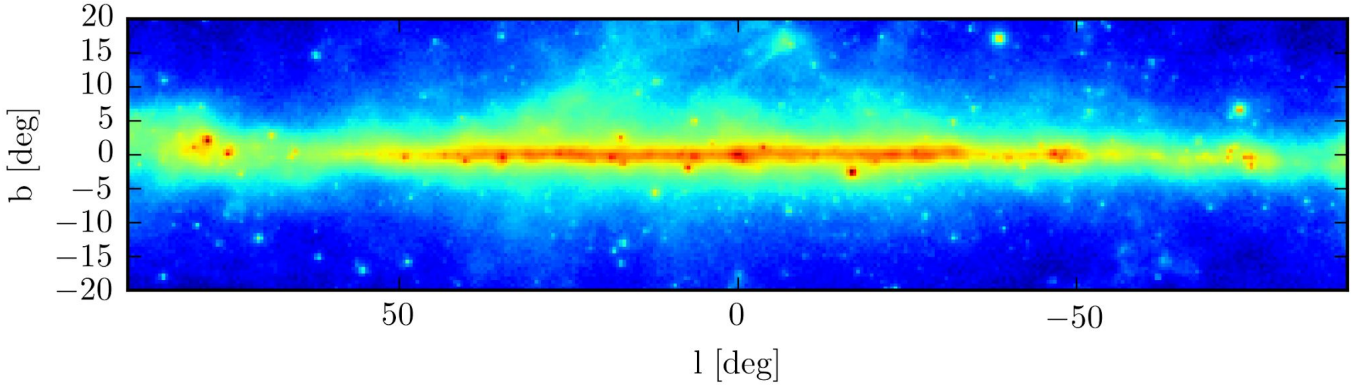
SkyFACT

Sky Factorization with Adaptive Constrained Templates

Preliminary Science

SkyFACT vs the Traditional Approach

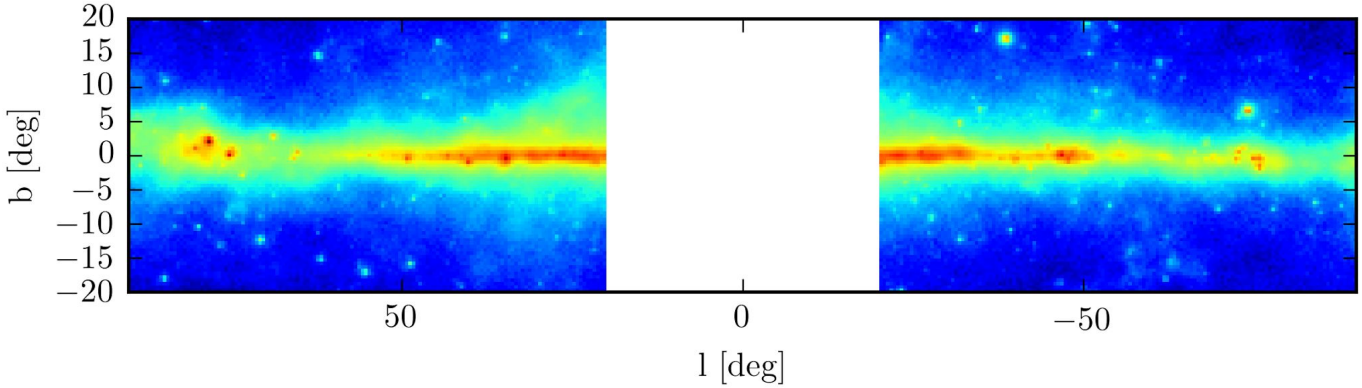
Data:



Pass 8, 8 years, 0.3-200 GeV, 180x40°

SkyFACT vs the Traditional Approach

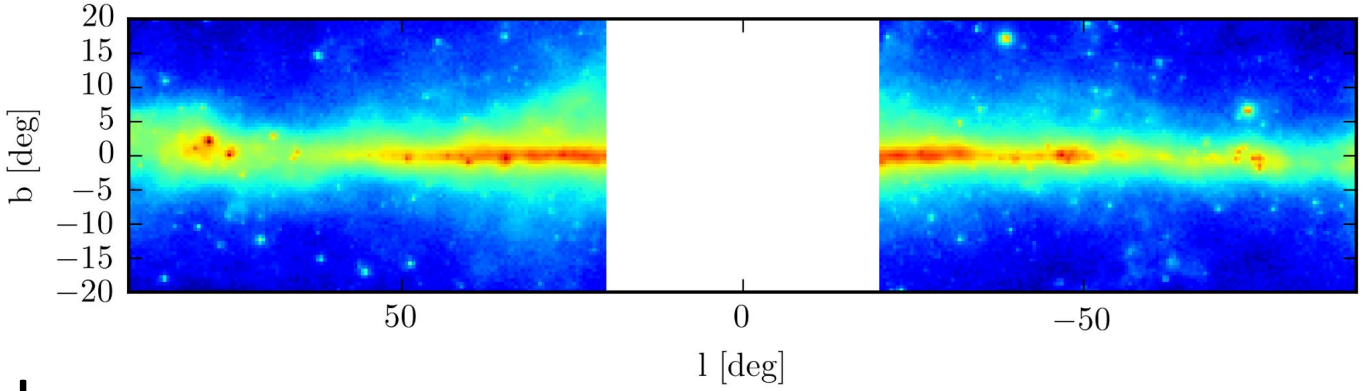
Data:



Mask inner galaxy (for now)

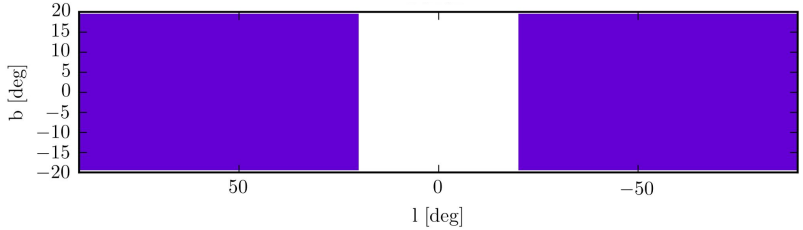
SkyFACT vs the Traditional Approach

Data:

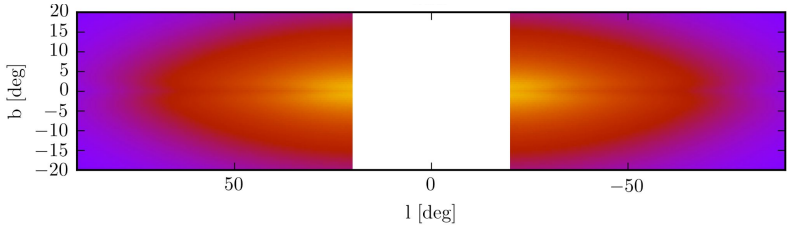


Model:

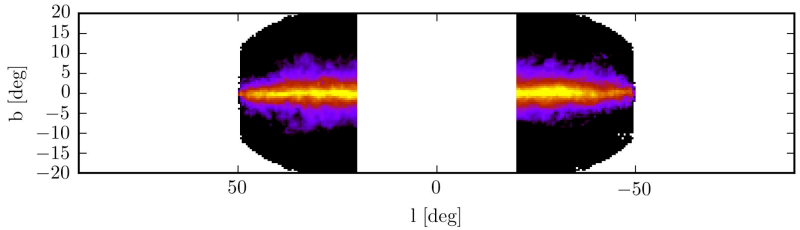
IGRB



ICS



Gas (r < 5.5 kpc)



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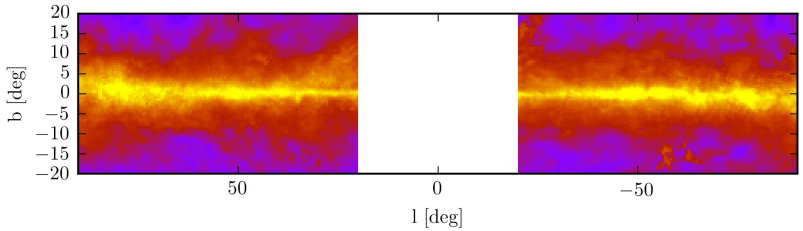
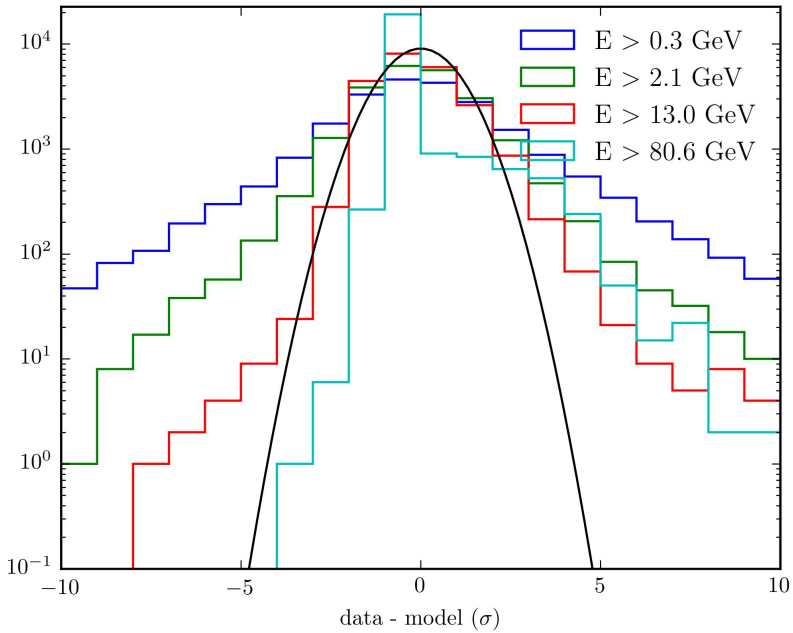
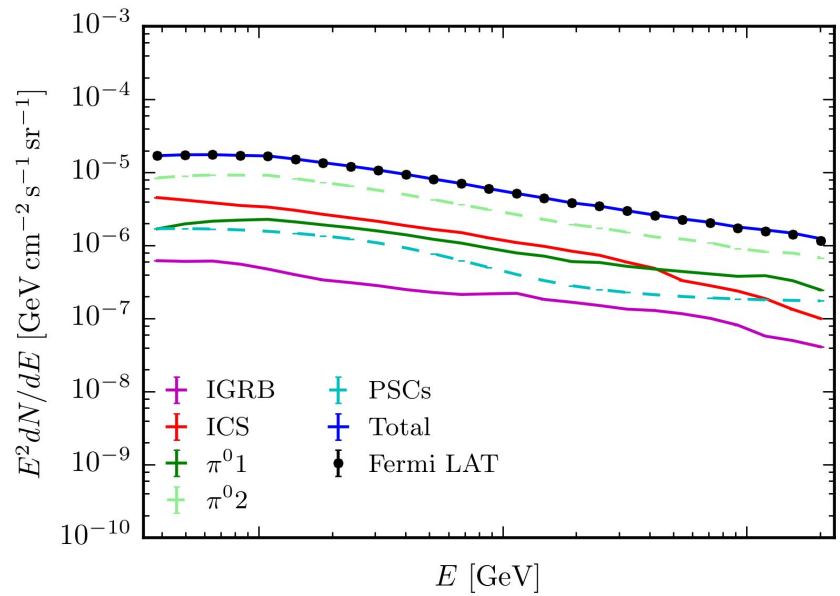


\+ 3FGL point sources

SkyFACT vs the Traditional Approach

Fixed templates, free spectra

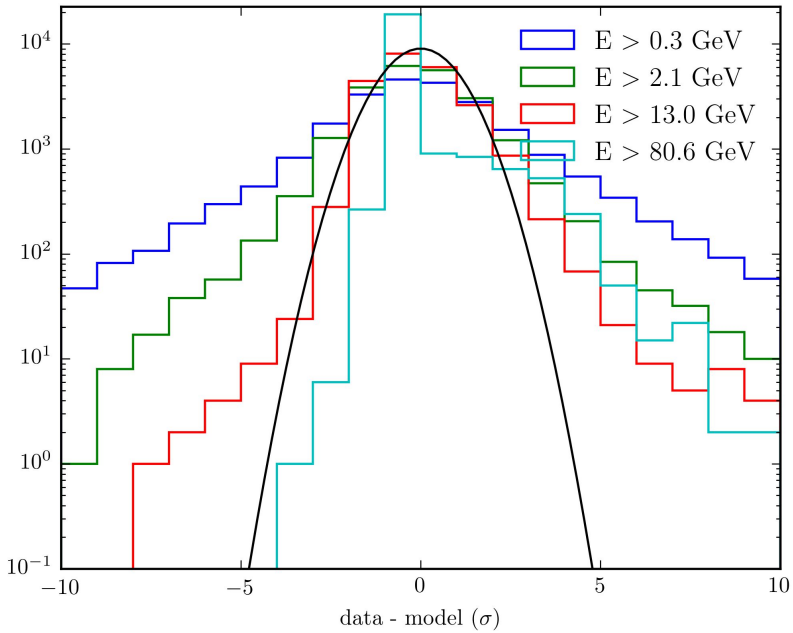


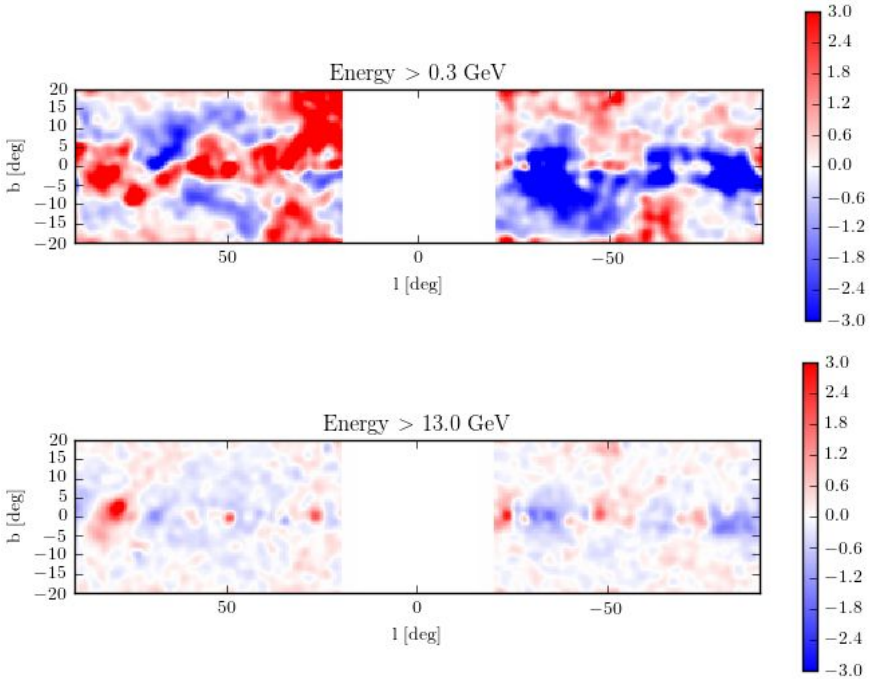


The traditional approach

SkyFACT vs the Traditional Approach

Fixed templates, free spectra

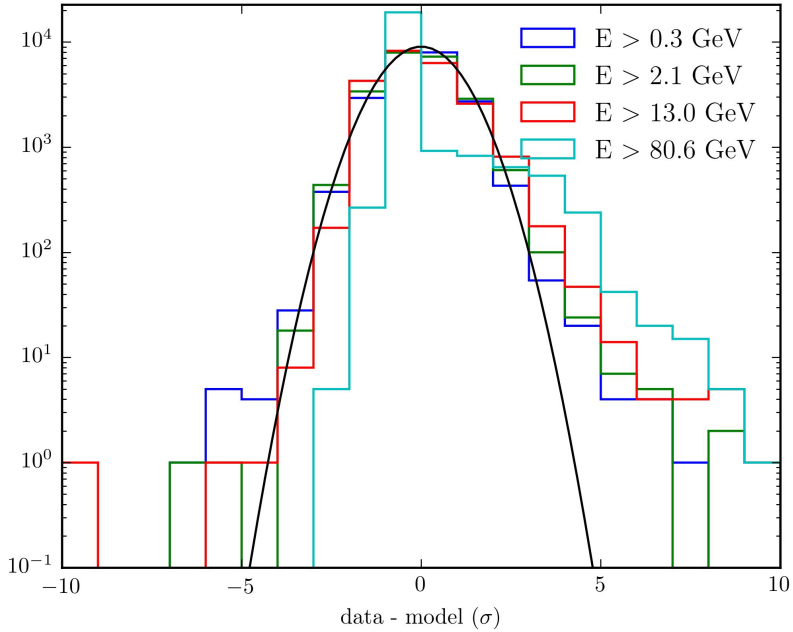


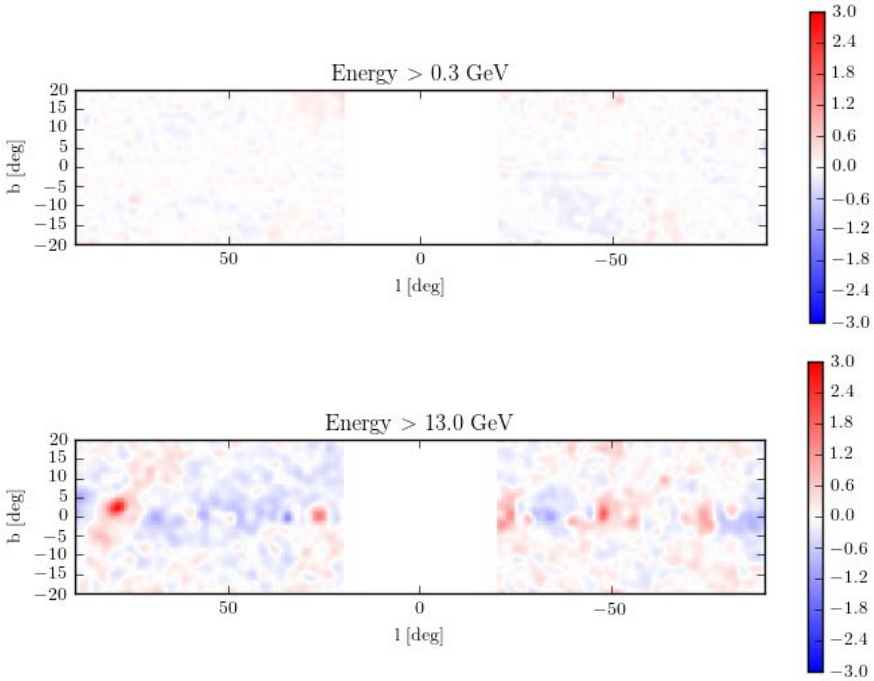


The traditional approach

SkyFACT vs the Traditional Approach

Constrained templates, free spectra

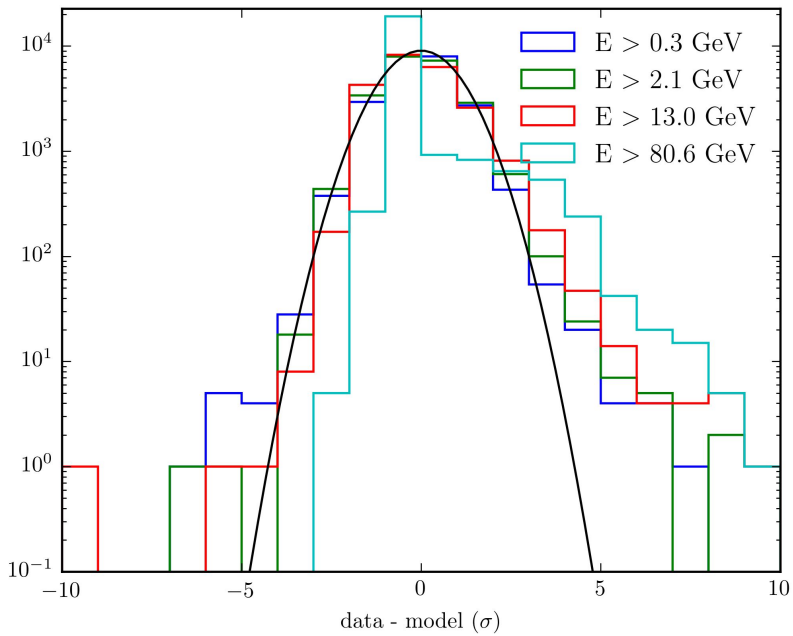


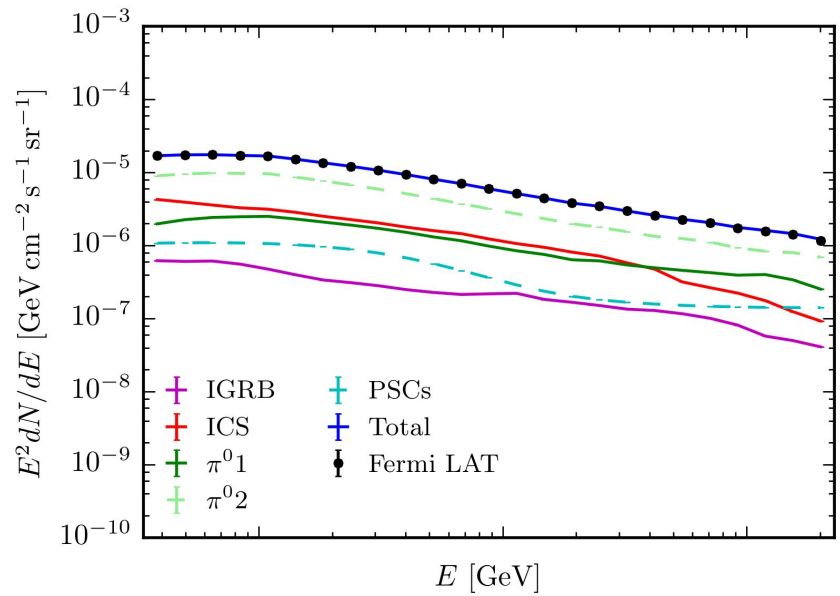


With adaptive template fitting

SkyFACT

Constrained templates, free spectra



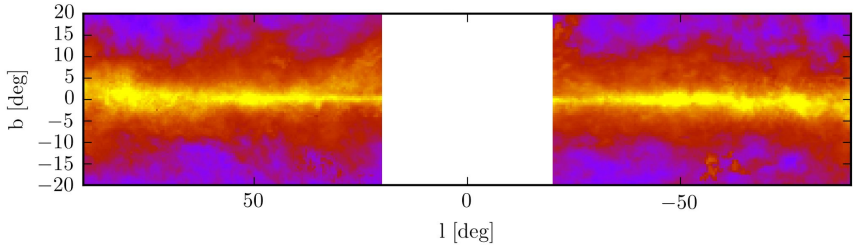


With adaptive template fitting

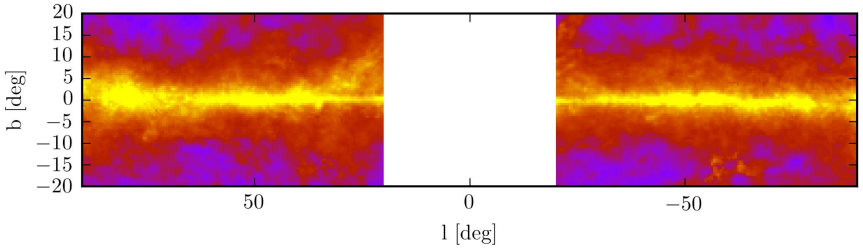
SkyFACT

Adaptive Template Rescaling

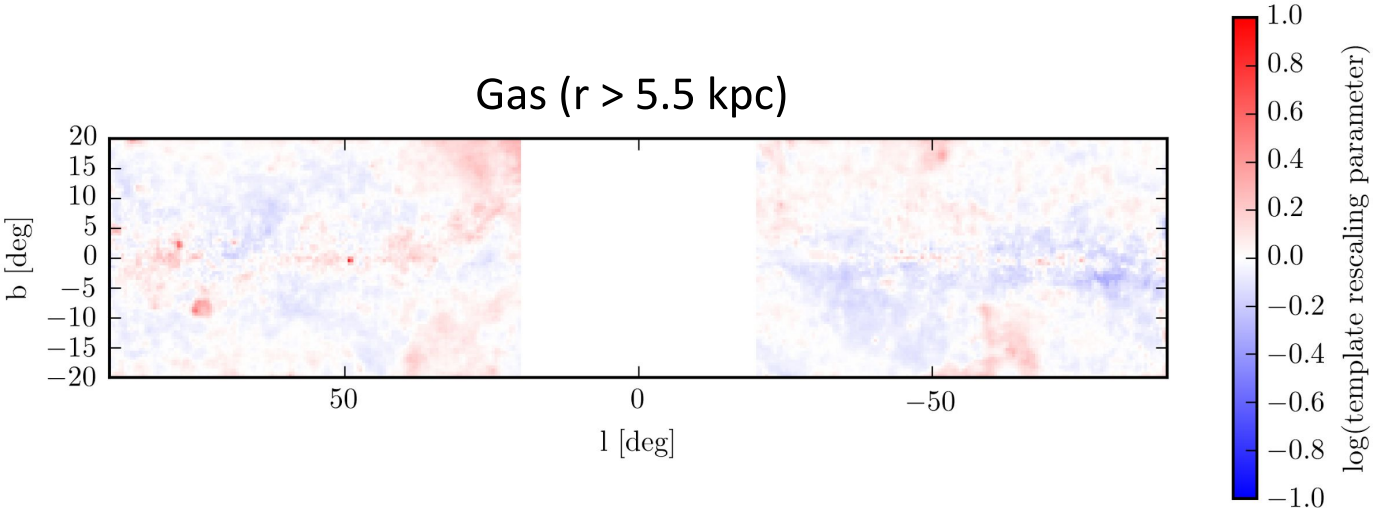
Original Template



Template After Adaptive Fitting



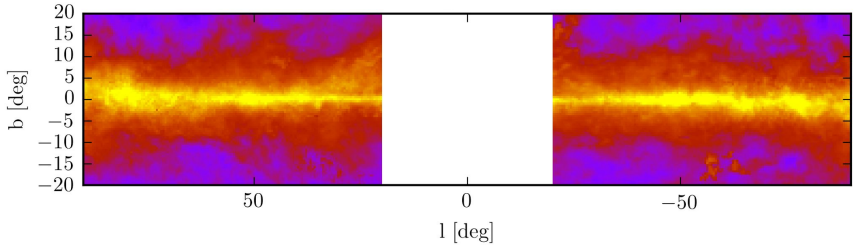
Gas (r > 5.5 kpc)



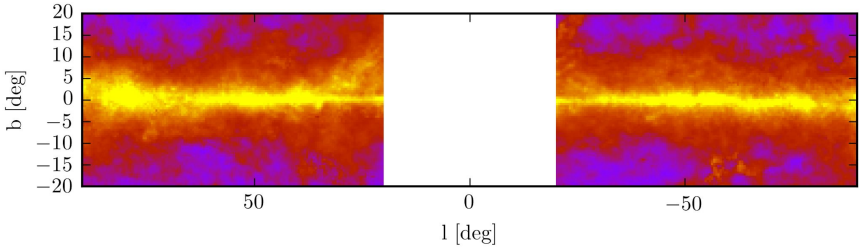
SkyFACT

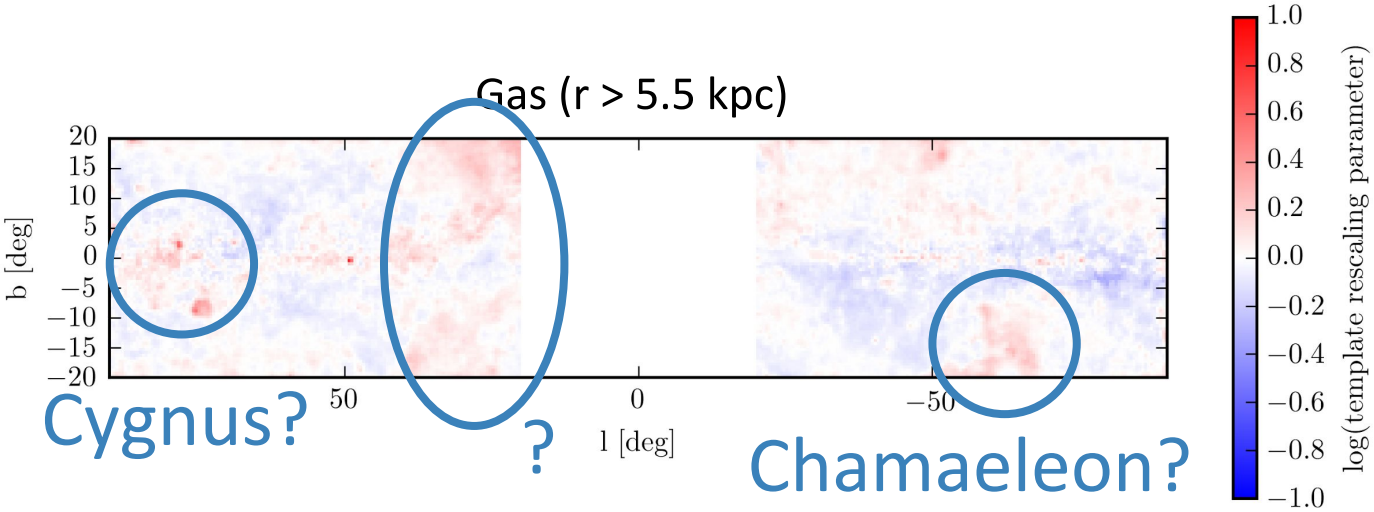
Adaptive Template Rescaling

Original Template



Template After Adaptive Fitting





SkyFACT

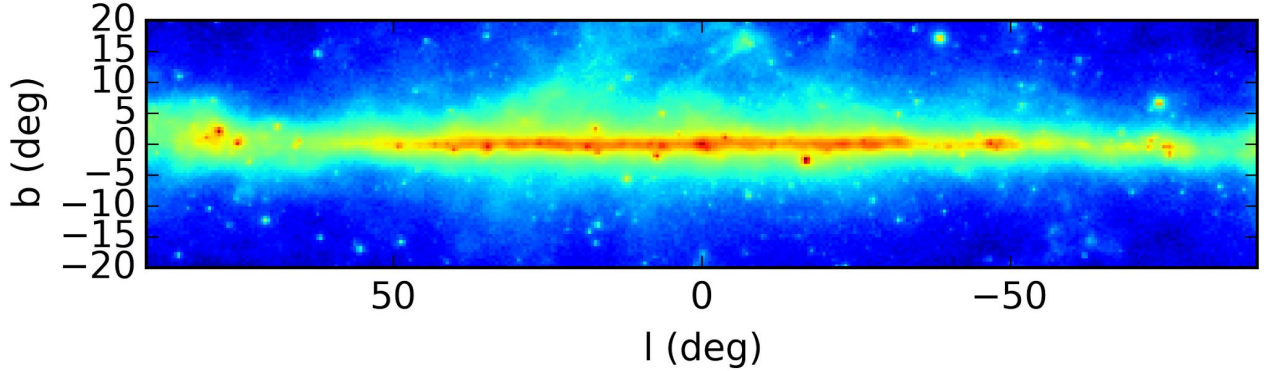
Sky Factorization with Adaptive Constrained Templates

The Galactic Bulge Emission

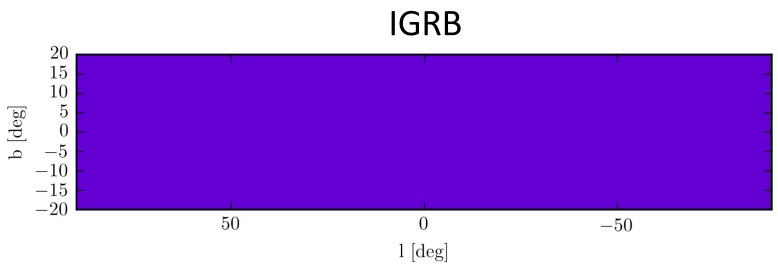
*See also talk by C. Weniger (Wed)

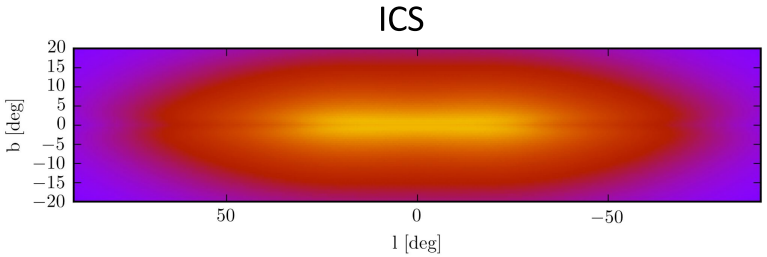
SkyFACT: The Galactic Bulge

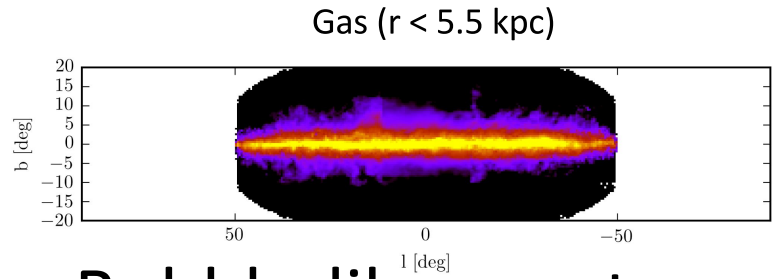
Data:

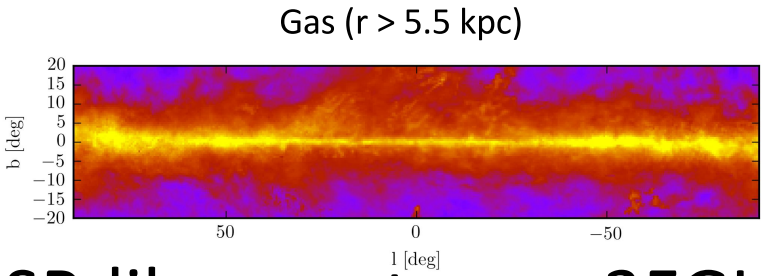


Model:





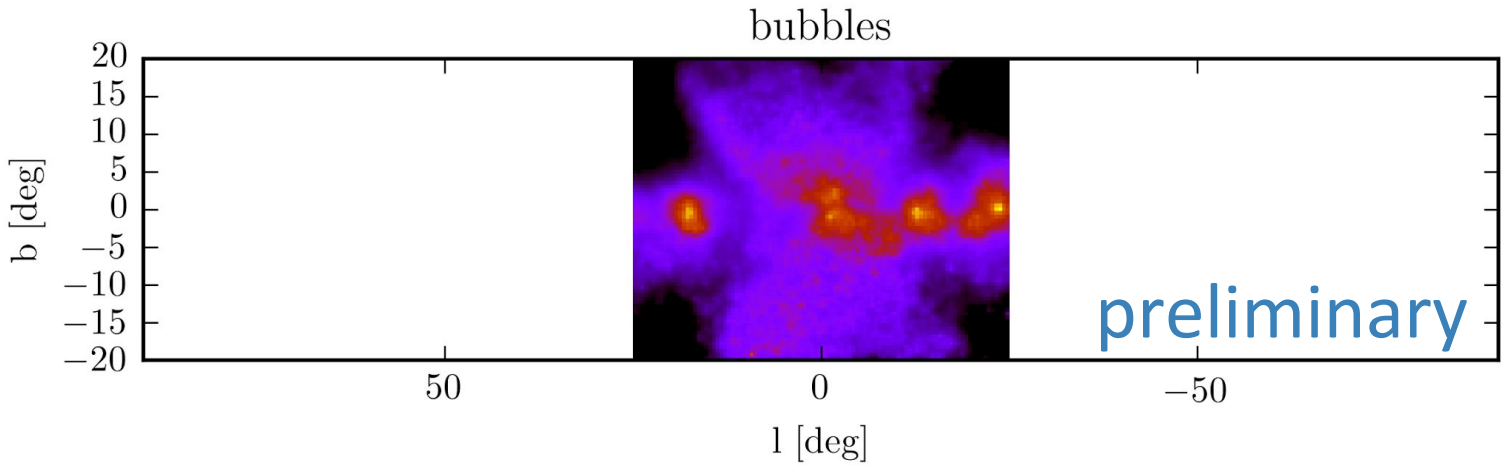


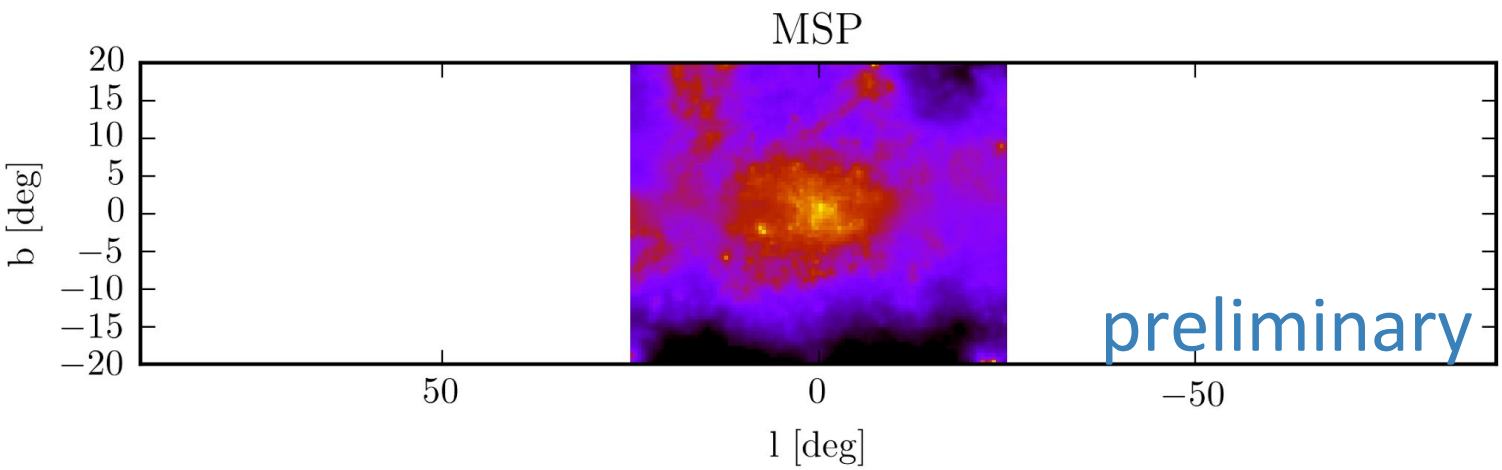


+ Bubble-like spectrum + MSP-like spectrum +3FGL point sources

SkyFACT: The Galactic Bulge

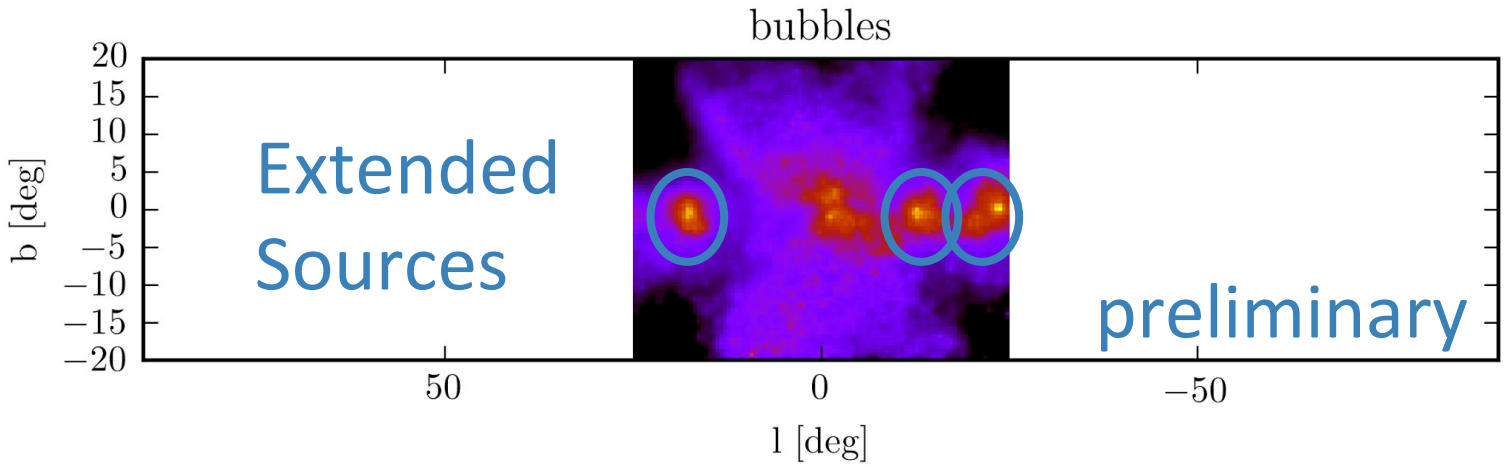
Fixed Bubble + MSP spectra
(Completely) Free templates

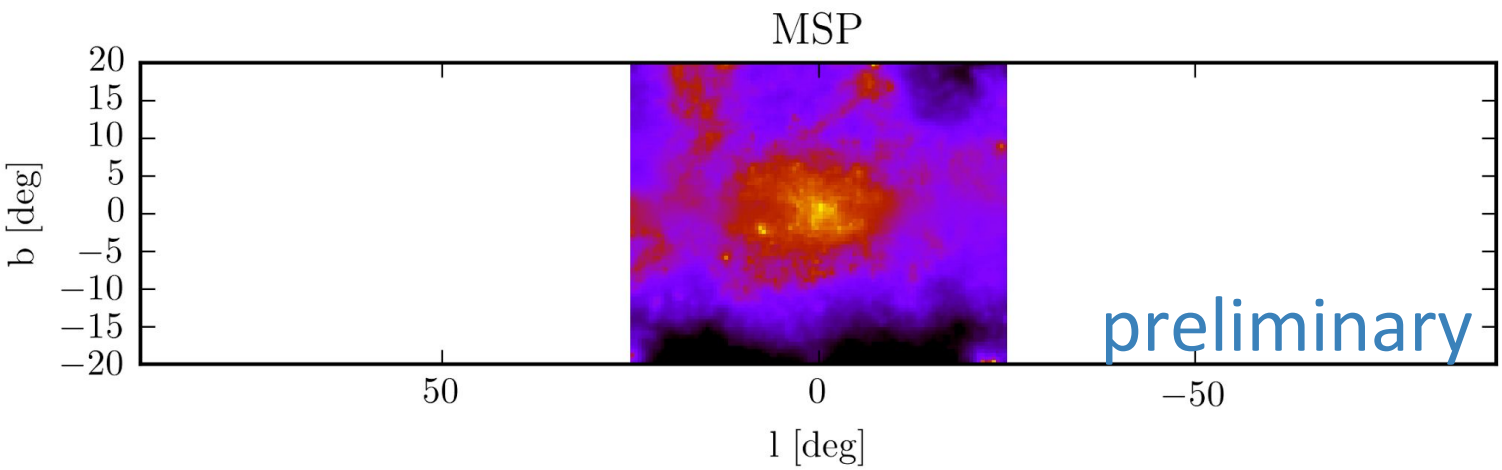




SkyFACT: The Galactic Bulge

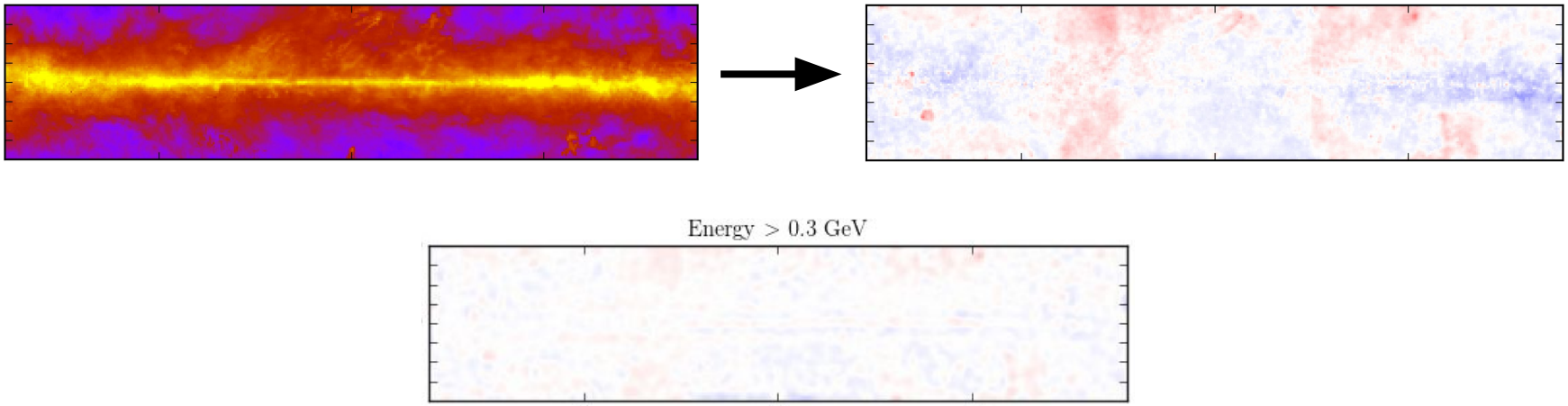
Fixed Bubble + MSP spectra
(Completely) Free templates





Summary and future plans

SkyFACT: Adaptive Template Fitting



Future plans:

- Robust understanding of the bulge emission
- Degeneracies between model/data components
- Physical interpretation of rescaling parameters

Backup Slides

SkyFACT

Log Likelihood:

$$\ln\mathcal{L} = \ln\mathcal{L}_d + \ln\mathcal{L}_c + \ln_s\mathcal{L}$$

Poisson Likelihood:

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

Constraints:

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

Smoothing:

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

SkyFACT

Numerical Details:

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

$$\vec{\mu} = (\mathsf{D}_1\vec{\theta})\cdot(\mathsf{D}_2\vec{\theta})\cdot(\mathsf{D}_3\vec{\theta}) + (\mathsf{P}_1\vec{\theta})\cdot(\mathsf{P}_1\vec{\theta})$$

$$\vec{\theta} = (\nu^1, \sigma_j^1, \tau_i^1, \ldots)$$

SkyFACT

Numerical Details:

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

$$\vec{\mu} = \underbrace{(\mathrm{D}_1\vec{\theta})\cdot(\mathrm{D}_2\vec{\theta})\cdot(\mathrm{D}_3\vec{\theta})}_{\text{diffuse}} + \underbrace{(\mathrm{P}_1\vec{\theta})\cdot(\mathrm{P}_1\vec{\theta})}_{\text{point sources}}$$

$$\underbrace{\vec{\theta} = (\nu^1, \sigma_j^1, \tau_i^1, \ldots)}_{\text{parameter vector}}$$

SkyFACT

Sky Factorization with Adaptive Constrained Templates

Traditional Approach:

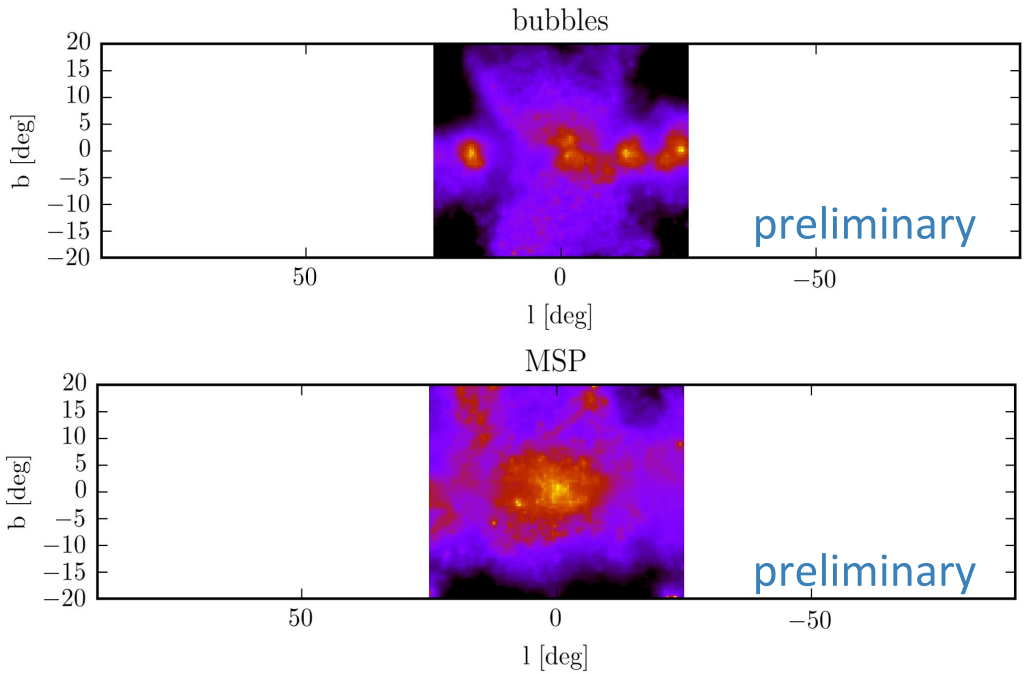
- 10s of free parameters
- Slow fitting (e.g. Minuit)
- Rigid spatial templates not accurate enough for data
- Large residuals that are difficult to interpret

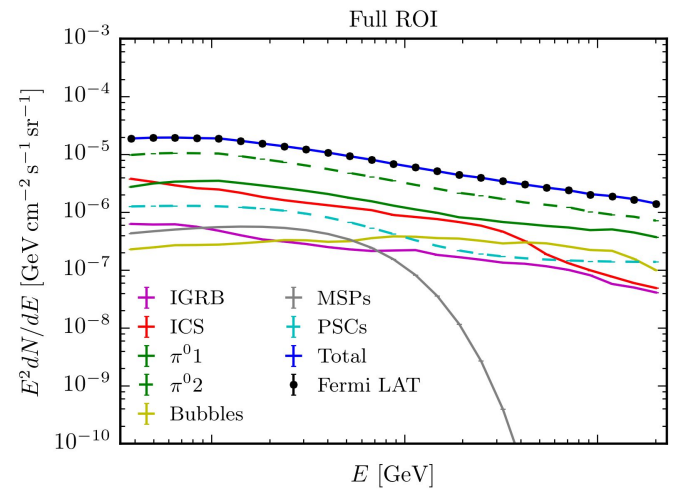
SkyFACT:

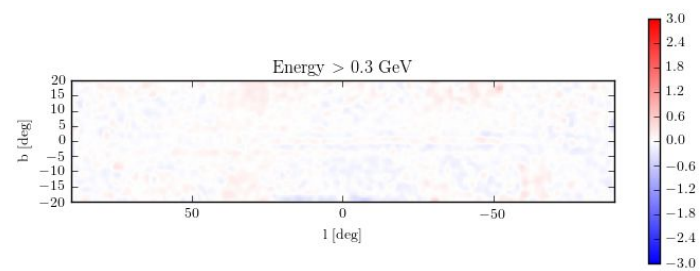
- ~100,000 free parameters
- Super fast fitting algorithm
- Realistic model uncertainties built in
- Flexible physically motivated templates

SkyFACT: The Galactic Bulge

Fixed Bubble + MSP spectra
(Completely) Free templates

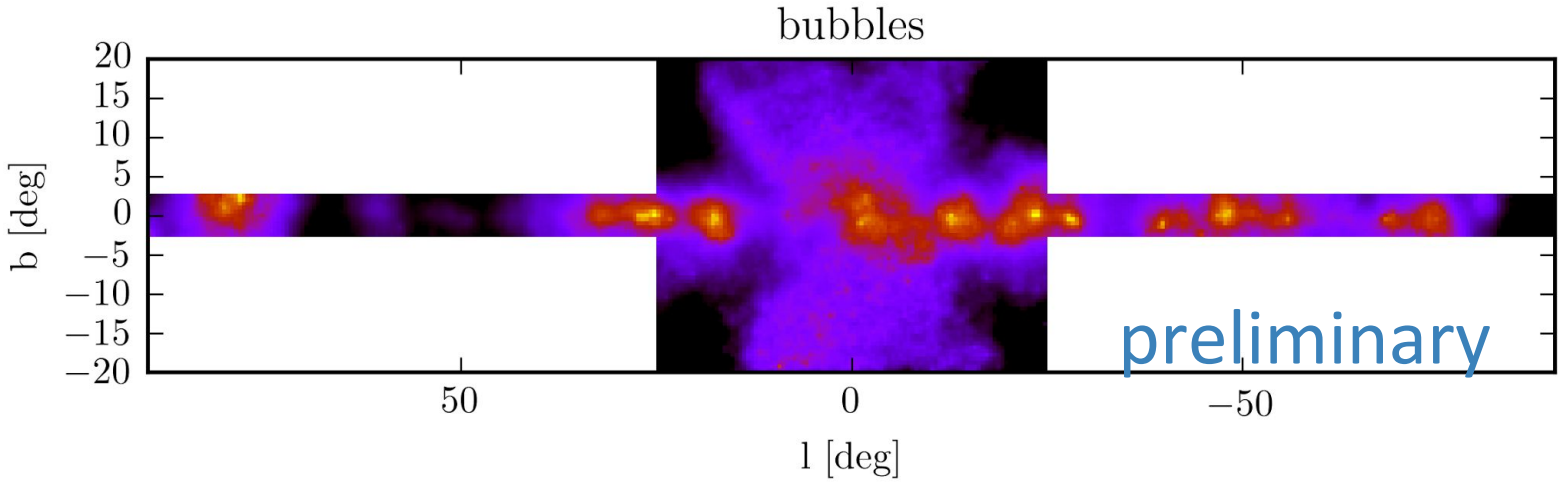


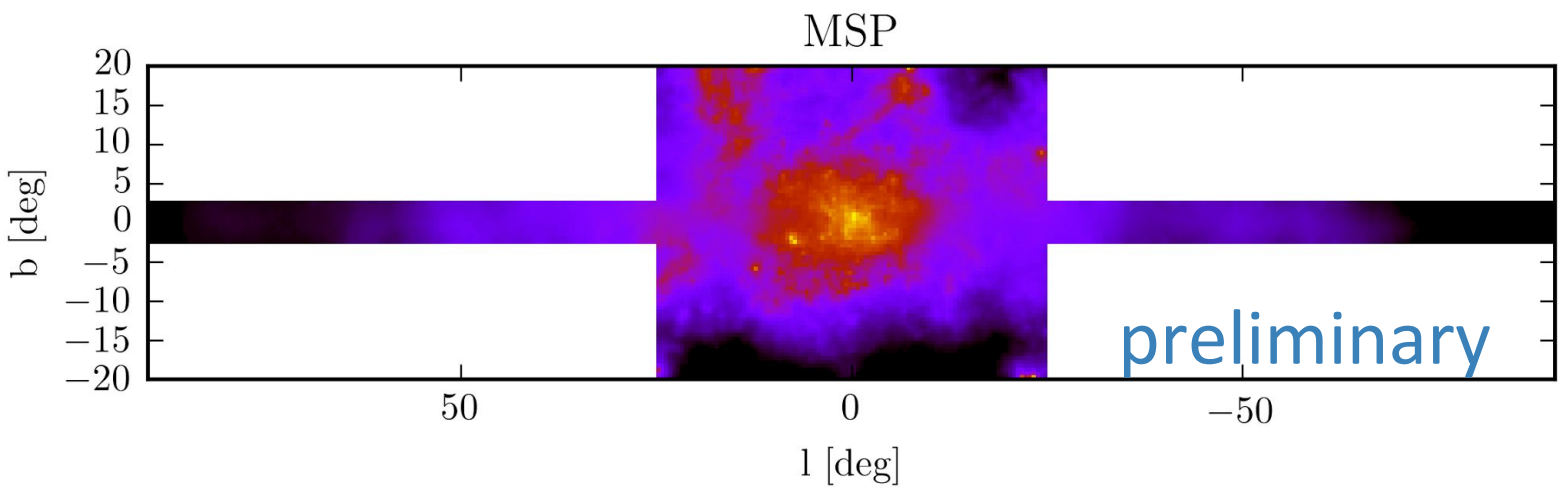




SkyFACT: The Galactic Bulge + Disk

Fixed Bubble + MSP spectra
(Completely) Free templates





SkyFACT: ISRFx10 for r<3kpc

Fixed Bubble + MSP spectra
(Completely) Free templates