Understanding Uncertainties in Modeling the Galactic Diffuse Gamma-ray Emission

Emma Storm
with Francesca Calore, Christoph Weniger

TeVPA
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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
Residuals, GCE templ. readded

Fruitful approach, so far
Template Fitting: The Standard Approach

LAT Collaboration, 2014

Always present: other residuals

Calore+2015
Residuals (Counts - Model)
Template Fitting: The Standard Approach

LAT Collaboration, 2014

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
Model = \sum_{k}^{\text{Spectrum}} \times \text{Morphology}
The Traditional Approach

\[
\text{Model} = \sum_{k} \text{Spectrum} \times \text{Morphology}
\]
The Traditional Approach

\[ \text{Model} = \sum_{k} \text{Spectrum} \times \text{Morphology} \]

- Spectra free to vary in energy bin by bin
- Templates fixed to (data-driven) model predictions
The Traditional Approach

Model = \sum_{k} \text{Spectrum} \times \text{Morphology}^{\text{fixed}} \times \text{Morphology}^{\text{free}}

\mu_{ij} = \sum_{k} T_{i}^{(k)} \theta_{j}^{(k)}

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

Model = \sum_{k} \text{Spectrum} \times \text{Morphology}
Spectral Decomposition

\[ \text{Model} = \sum_{k} \text{Spectrum} \times \text{Morphology} \]

Spectra fixed to (data-driven) model predictions

Spatial templates free to vary
Spectral Decomposition

Model = \sum_{k} \textbf{Spectrum} \times \textbf{Morphology}

k \quad \text{fixed} \quad \text{free}

\mu_{ij} = \sum_{k} S_{j}^{(k)} \theta_{i}^{(k)}

i: \text{spatial pixel} \\
j: \text{energy bin} \\
k: \text{model component}

Selig+2015, Huang+2016
A New Approach

Model = \sum_{k} \text{Spectrum} \times \text{Morphology}
A New Approach

Model = \sum_{k} \text{Spectrum} \times \text{Morphology}

- Spectra free to vary in energy bin by bin
- Templates free to vary spatially pixel by pixel
A New Approach

\[ \text{Model} = \sum_{k} \text{Spectrum} \times \text{Morphology} \]

- Spectra free to vary in energy bin by bin
- Templates free to vary spatially pixel by pixel

SkyFACT
Sky FACT

Sky Factorization with Adaptive Constrained Templates
SkyFACT

Sky Factorization with Adaptive Constrained Templates

\[ \mu_{ij} = \sum_{k} T_{i}^{(k)} S_{j}^{(k)} \theta_{i}^{(k)} \theta_{j}^{(k)} \theta^{(k)} \]
SkyFACT

Sky Factorization with Adaptive Constrained Templates

\[ \mu_{ij} = \sum_k T_i^{(k)} S_j^{(k)} \theta_i^{(k)} \theta_j^{(k)} \theta^{(k)} \]

- **Spatial + spectral templates**
- **Scaling parameters:**
  - Spatial
  - Spectral
  - Overall
Sky FACT

Sky Factorization with Adaptive Constrained Templates

\[ \mu_{ij} = \sum_k T_i^{(k)} T_j^{(k)} \theta_i^{(k)} \theta_j^{(k)} \theta(k) \]

Spatial + spectral templates

Will be around 1 for reasonable templates!
Sky FACT

Sky Factorization with Adaptive Constrained Templates

\[ \mu_{ij} = \sum_{k} T_i^{(k)} S_j^{(k)} \theta_i^{(k)} \theta_j^{(k)} \theta^{(k)} \]

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

Sky Factorization with Adaptive Constrained Templates

\[ \mu_{ij} = \sum_{k} T^{(k)}_{i} S^{(k)}_{j} \theta^{(k)}_{i} \theta^{(k)}_{j} \theta^{(k)} \]

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

Model \rightarrow 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:

+ 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

Gas (r > 5.5 kpc)

Cygnus?  ?  Chamaeleon?
Sky FACT

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

Extended Sources

preliminary

MSP

preliminary
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:

\[ -2 \ln \mathcal{L}_s = \sum_{k=1}^{n_{comp}} \left( \sum_{(i,i')_nn} \left( \frac{\ln \tau_{i}^k - \ln \tau_{i'}^k}{\Xi^k_\tau} \right)^2 + \sum_{j=1}^{n_{bins}-1} \left( \frac{\ln \sigma_j^k - \ln \sigma_{j+1}^k}{\Xi^k_\sigma} \right)^2 \right) \]
SkyFACT

Numerical Details:

\[ \mu_{ij} = \mu_{ij}^{\text{diff}} + \mu_{ij}^{\text{psc}} \]

\[
\vec{\mu} = (D_1 \vec{\theta}) \cdot (D_2 \vec{\theta}) \cdot (D_3 \vec{\theta}) + (P_1 \vec{\theta}) \cdot (P_1 \vec{\theta})
\]

\[ \vec{\theta} = (\nu^1, \sigma_1^1, \tau_1^1, \ldots) \]
SkyFACT

Numerical Details:

\[ \mu_{ij} = \mu^\text{diff}_{ij} + \mu^\text{psc}_{ij} \]

\[ \vec{\mu} = (D_1 \vec{\theta}) \cdot (D_2 \vec{\theta}) \cdot (D_3 \vec{\theta}) + (P_1 \vec{\theta}) \cdot (P_1 \vec{\theta}) \]

- \( \vec{\theta} = (\nu^1, \sigma^1_j, \tau^1_i, \ldots) \)
- diffuse
- point sources
- parameter vector
<table>
<thead>
<tr>
<th>Traditional Approach:</th>
<th>SkyFACT:</th>
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<tbody>
<tr>
<td>10s of free parameters</td>
<td>~100,000 free parameters</td>
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<tr>
<td>Slow fitting (e.g. Minuit)</td>
<td>Super fast fitting algorithm</td>
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<td>Rigid spatial templates not accurate enough for data</td>
<td>Realistic model uncertainties built in</td>
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<td>Large residuals that are difficult to interpret</td>
<td>Flexible physically motivated templates</td>
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SkyFACT: The Galactic Bulge

Fixed Bubble + MSP spectra
(Completely) Free templates

[Graphs and images related to Galactic Bulge and spectrum analysis]
SkyFACT: The Galactic Bulge + Disk

Fixed Bubble + MSP spectra
(Completely) Free templates

preliminary

preliminary
SkyFACT: ISRFx10 for r<3kpc

Fixed Bubble + MSP spectra
(Completely) Free templates