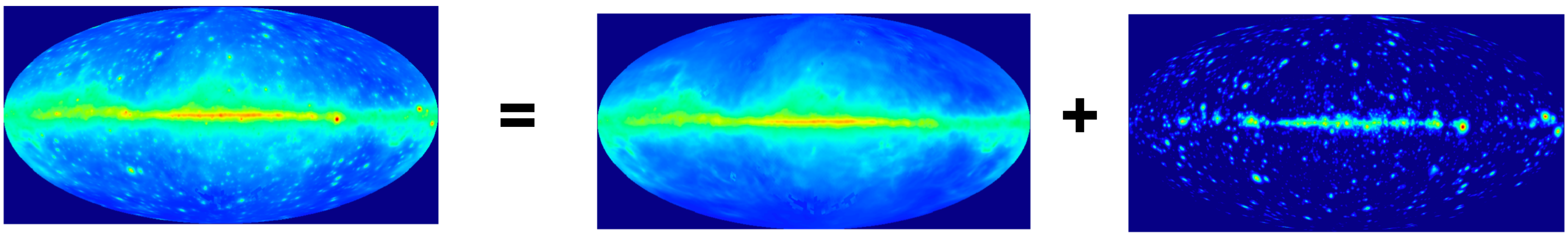
The Model of Diffuse Gamma-ray Emission for the LAT 4FGL Catalog

Seth Digel (KIPAC/SLAC) on behalf of the *Fermi* LAT Collaboration

2018 Fermi Symposium Baltimore

Introduction

- Gamma-ray astronomy at LAT energies has always been about distinguishing discrete sources from diffuse gamma-ray emission (of many potential origins)
- Concept:



(~65% + 25%) (~10%)

- The 3FGL catalog was supported by the development of the ‘4-year’ Pass 7-era diffuse emission model (led by J.-M. Casandjian; Acero et al. 2016)
- For 4FGL we have worked on a new model for deeper, Pass 8, 8-year data
  – The challenges of modeling the data have grown

Talk by B. Lott

Introduction 2

- Motivations for modeling the diffuse gamma-ray emission remain
  - The statistics are finite and the PSF has broad tails (and most of the sources are faint) – far from just picking out the sources like in a photo of the sky
  - Modeling the diffuse emission using information from other wavelengths brings more information to the problem
- Systematic uncertainties in the diffuse emission can be important relative to the gamma-ray statistics
  - Now the statistics require tighter tolerances
  - We need to reduce the systematic uncertainty, especially for softer/fainter sources at low latitudes

Introduction 3

- Why does modeling the diffuse gamma-ray emission work even approximately?

- Diffuse emission originates with cosmic-ray interactions with interstellar gas and soft photons
  - The (propagated) cosmic-ray distribution is fairly smooth
  - With radio-microwave surveys we know pretty well where the interstellar gas is, and the gas provides the small-scale structure
  - With infrared surveys and modeling we know fairly well what the radiation field is
- And the Galaxy is optically thin to gamma rays: they do not stop until they hit the LAT
  - So the model is linear in all of its components

Goals/Requirements for the Model

- An accurate model for the Galactic diffuse gamma-ray emission of the LAT Pass 8 gamma-ray sky
  - Quantitatively: Want fractional data-model discrepancies <3% on spatial scales 0.2–5 deg

- Over a broad energy range
  - 30 MeV to 1 TeV

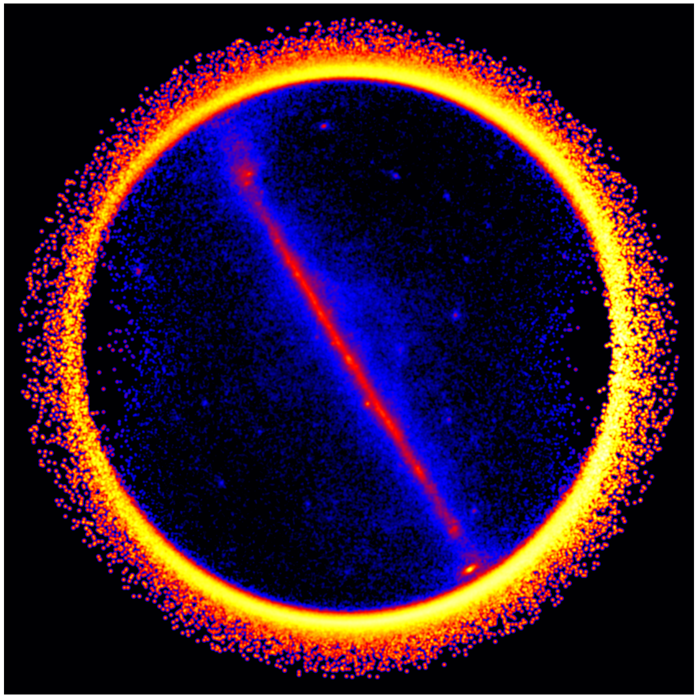
- Why do we think we can do better than the 4-year model?
  - Improved multiwavelength templates (tracers of the interstellar medium)
    - H I: HI4PI (16’), Dark gas: from Planck (6’)
  - And refined methods for assigning the gas to ‘rings’
    - Described at 2017 Fermi Symposium

LAT Data Set

- **Joint analysis over four γ-ray data sets**
  - **8-year data set matching 4FGL selection**
  - **Different combinations of PSF event types and zenith angle limits, cutting more severely at lower energies, so that residual Earth limb emission does not need to be modeled.**

Energy Range	Zen. max	Pass 8 Source PSF types
30–100 MeV	80º	3
100–300 MeV	90º	2, 3
300–1000 MeV	100º	1, 2, 3
1 GeV – 1 TeV	105º	0, 1, 2, 3

Earth + Sky (>300 MeV)

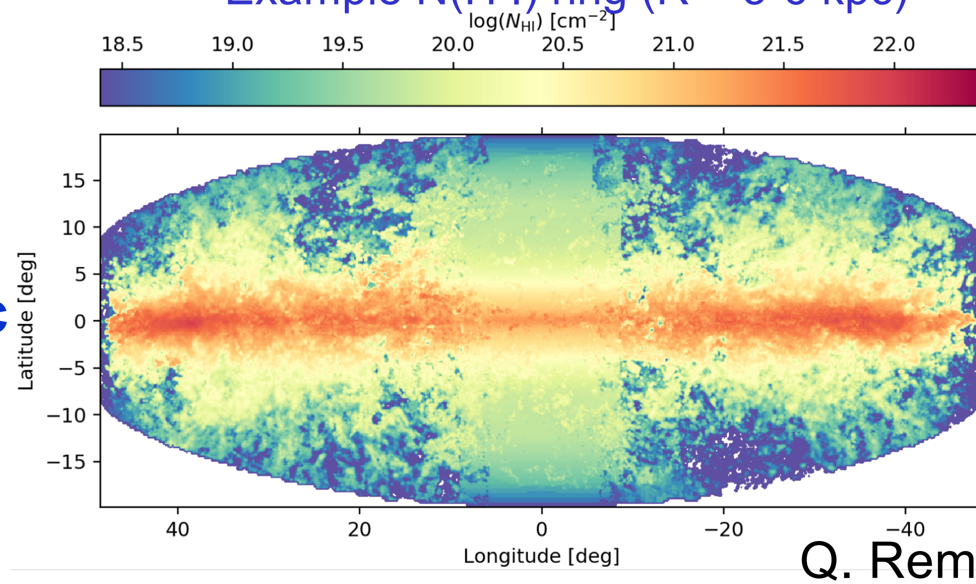


https://apod.nasa.gov/apod/ap131206.html

Diffuse Emission Model Components

- **Gas: We use H I and CO spectral line surveys to trace (most of) the interstellar gas**
  - **Doppler shifts are used to partition by Galactocentric distance (on kpc scales)**
  - **Line profiles are used to estimate column densities**

Example N(H I) ring (R = 5-6 kpc)



(N.B. aspect ratio not 1:1)

Q. Remy

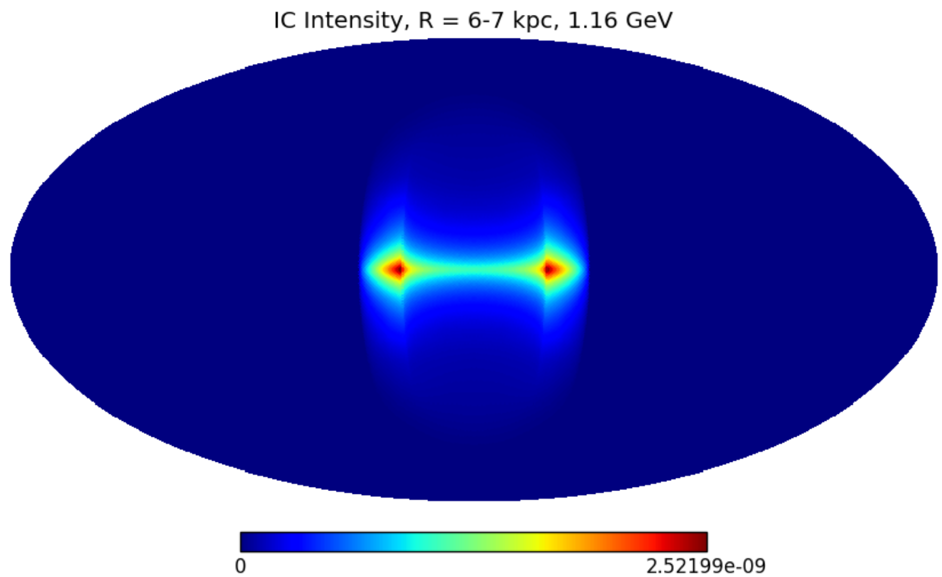
  - **Result is 'ring maps' for 10 ranges of Galactocentric distance**
  - **These maps are taken to be the targets for cosmic-ray electrons and protons (Bremsstrahlung and π^0 decay)**
- **'Dark Gas' – neutral interstellar gas not traced properly in H I or CO**
  - **Using new Planck dust optical depth maps (τ_{353})**
  - **Improved angular resolution and dynamic range relative to SFD E(B-V), fewer artifacts around massive star-forming regions**

Model Components 2

- **Photons: We use a model of the interstellar radiation (Porter et al.) converted to a model of Galactic IC emission in GALPROP***
  - **Divided into the same rings**
- **Non-template emission: Fermi bubbles, Loop I, etc. *More later***

Plus more components not part of the Galaxy (Sun, Moon, isotropic)

Example ring, Model IC Intensity, 1.16 GeV



R = 6-7 kpc

* LRYusifovXCO5z6R30_Ts150_mag2 (http://galprop.stanford.edu)

Model Fitting

- The gas maps are processed through GALPROP to generate ‘cubes’ of differential intensity maps
- Scaled by exposure and convolved with LAT IRFs to expect counts
- GaRDiAn* tool (G. Johannesson): Maximize the likelihood of the model given the data (photon counts maps for different energy bands)
  - Free parameters are scaling factors or functions of energy for the templates mentioned above (all run through GALPROP to make nominal gamma-ray intensity maps)
  - Depending on the importance of the template and the nature of the residuals, we use different functions: power laws or multiple broken power laws
  - Keeping in mind the challenges of multi-parameter optimizations

* Described in Ackermann et al. (2012, ApJ, 750, 30)

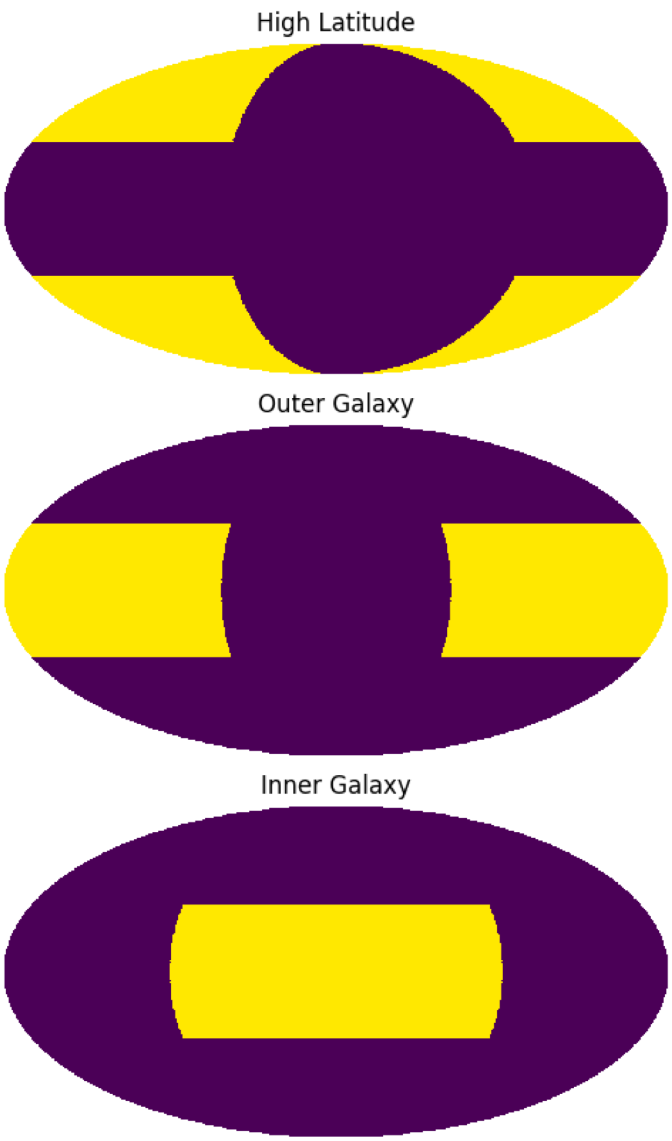
Model Fitting 2

- **The scaling in some cases has physical interpretations, e.g., in terms of CR intensity**
  - **For this work, we do not enforce consistency in CR spectra, e.g., between IC and gas-correlated components**

See posters by Orlando & Remy, Grenier, & Casandjian

- **Fitting approach**
  - **Sequence of regions of the sky fit: define 'all-sky' and outer Galaxy templates in regions not dominated by the inner Galaxy**
  - **Consideration of the degrees of freedom scaling the nominal 'cubes'**

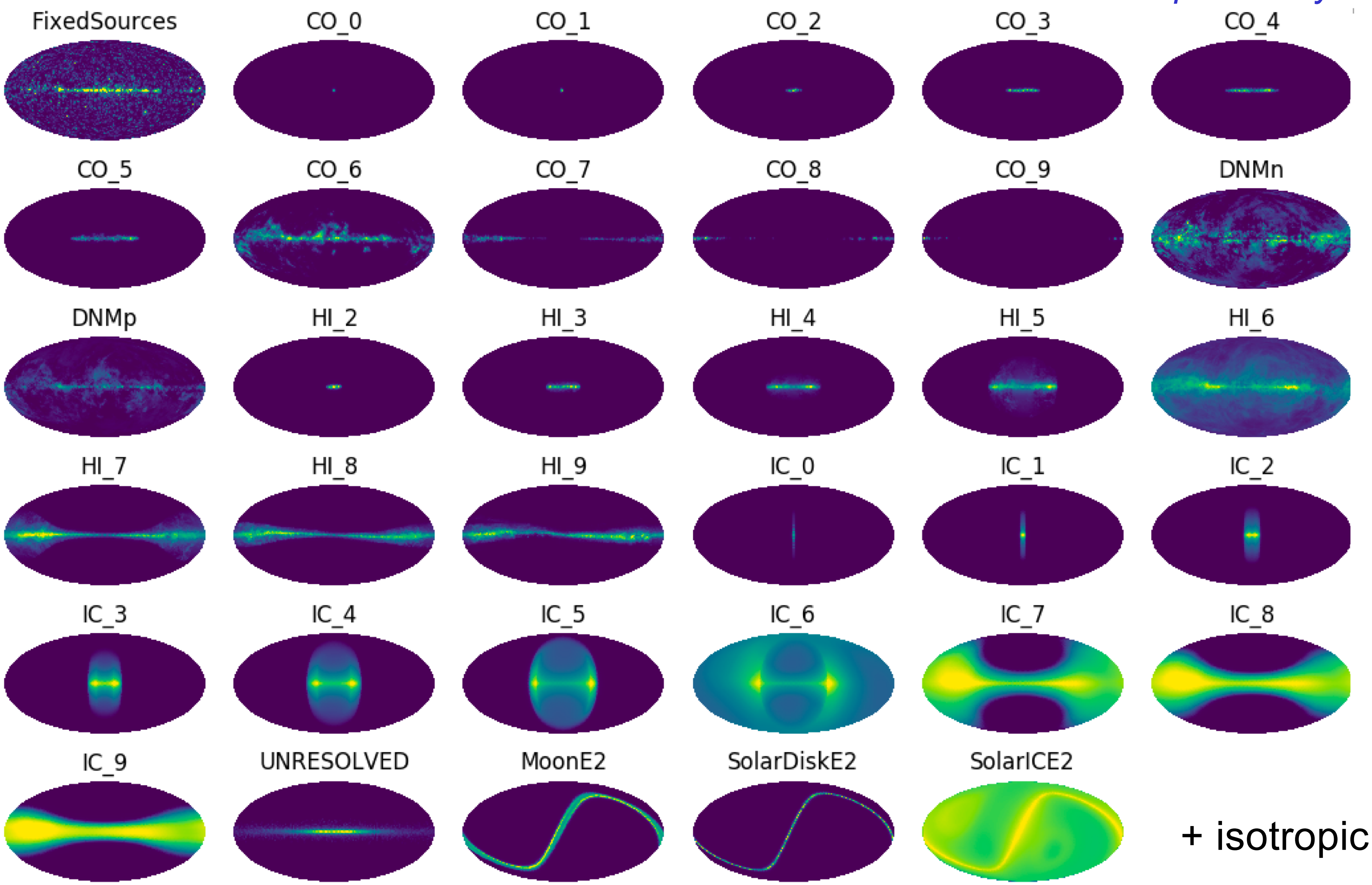
Example Sequence



Example Templates (one energy band)

- **These have been processed into predicted counts maps**

independently scaled



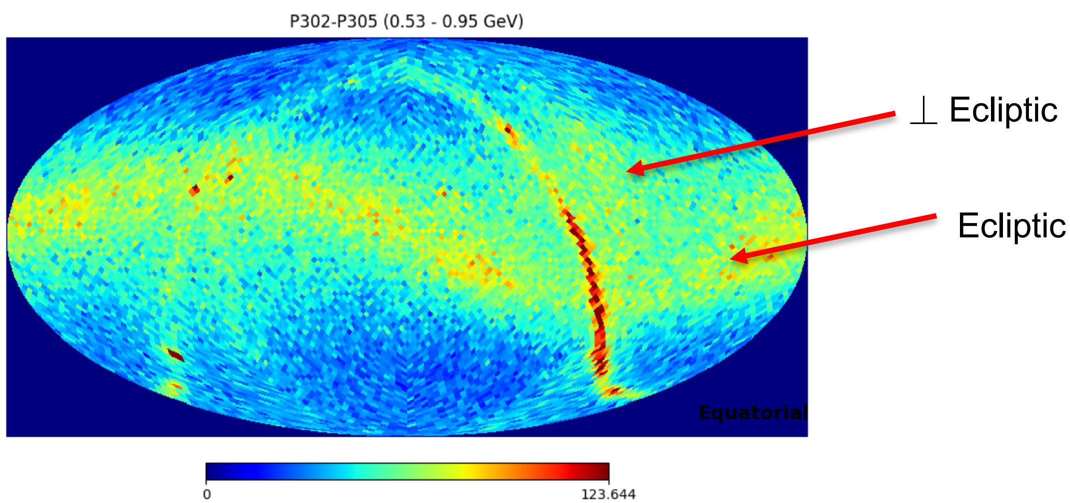
Some Things We Have Learned

Residual cosmic rays in P302

- **P302 has structured residual CR background: The isotropic intensity in Pass 8 P302 [NOT the EGB] was not particularly isotropic – a component of the residual charged particle background was correlated with the ecliptic (and perpendicular to the ecliptic)**
  - **The origin is now understood in detail and resulted in the P305 event selections.**
  - **P305 has ~6 M fewer gamma rays but acceptance is very similar to P302, and we can again model the residual background as part of the isotropic component**

Poster by Bruel et al.

Sky map of 'gamma rays' removed in **P305** selection for 500-950 MeV

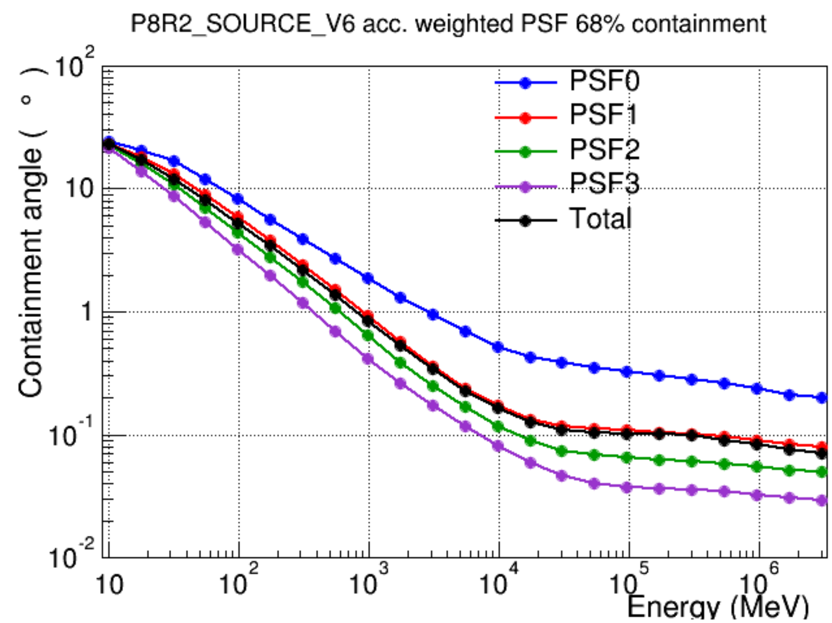


N.B. **Celestial coordinates**

More Things Learned

Accurately accounting for LAT response

- **Combining PSF types must be done carefully in an all-sky analysis. Pass 8 PSF event types each have 25% of the acceptance, but they do not have the same profile of effective area with off-axis angle.**



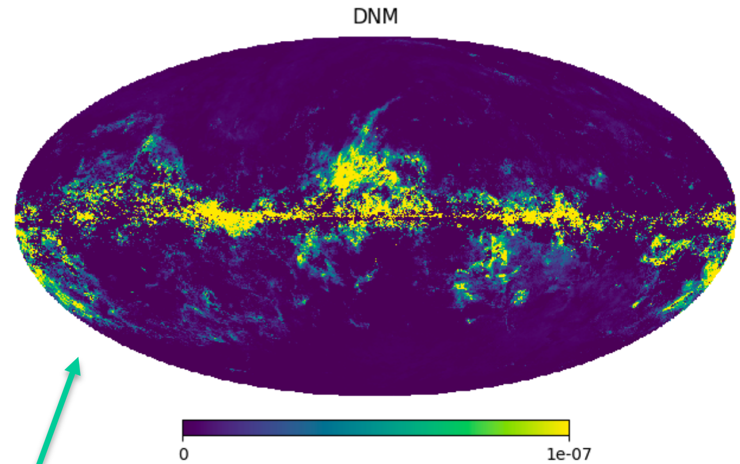
- **Distribution of live time with inclination depends on declination -> combining counts and exposure for different event types resulted in declination-dependent misestimates of effective PSFs**
  - **We now handle the PSF event types and exposures individually and derive more accurate effective PSFs**

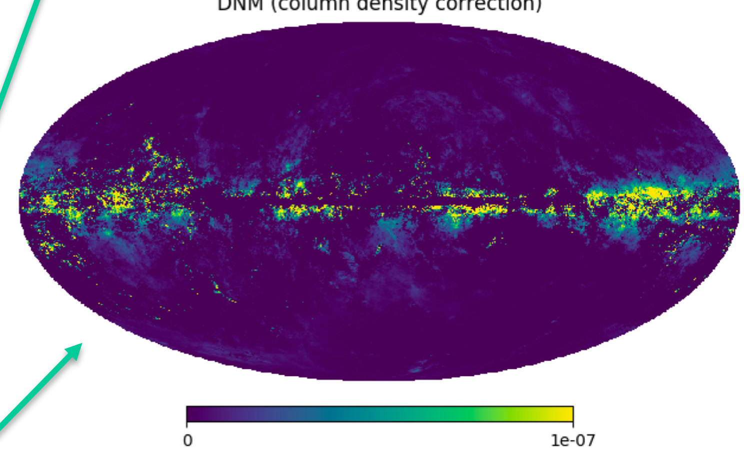
More Things Learned

Dark gas residuals

- **Dark gas (or Dark Neutral Medium) modeling – We tried a new, direct approach in which a non-linear relation between dust optical depth and N(H) was adopted**
  - **Dark gas column densities were derived directly rather than as a component orthogonal to HI and CO**
  - **For reasons we think we understand, this approach resulted in over-predictions of γ-ray intensity around molecular clouds**
  - **We are now using the 2-component approach of the 4-year model: DNM + column density correction map**

Example Dark Gas Model Intensity (190 MeV)





And More

Coupling of catalog and diffuse model

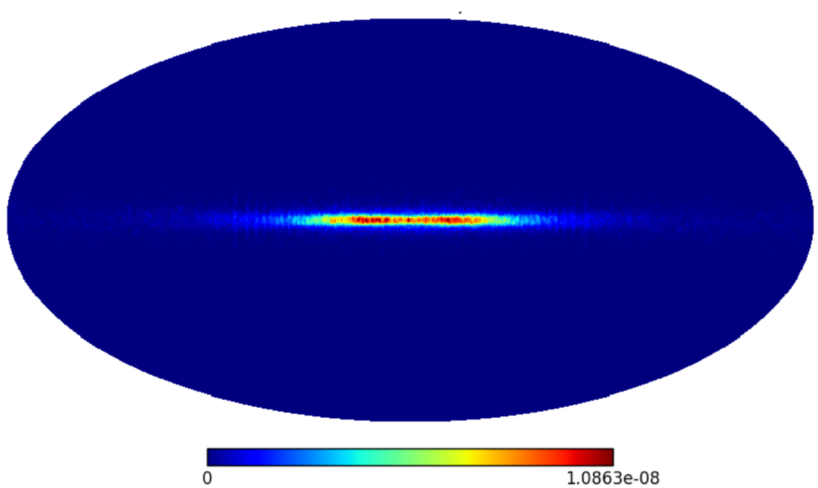
- Also, the diffuse emission model of course is not independent of the source catalog
  - Influences can be direct – e.g., less flux in diffuse emission – and indirect – e.g., via biases caused by slight mismodelling of the brightest gamma-ray sources
  - Partially mitigating by freeing normalizations of the brightest sources
- A related issue: Extending the source catalog spectra below the 100 MeV FL8Y limit was not particularly accurate
  - Going to <100 MeV is difficult because of the uncertainty of their spectra (typically modeled as power laws)
  - Mitigating the influence of the spectral uncertainty, e.g., using an FL8Y-like list derived for >50 MeV, and modeling spectra as curved (log parabola)

And More

Unresolved Galactic sources

- **We tested a template representing a population of Galactic sources below the 8-year flux limit. It necessarily depends on the luminosity function, source spectra, spatial distribution, and the depth of the observations.**
- **It also tends to be quite closely correlated with gas rings in the inner Galaxy**
  - **We have left it in the model as a subdominant component with fixed normalization**

Unresolved Source Template (1 GeV)



Appendix of 3FGL paper
(Acero et al. 2015, ApJS, 218, 23)

Non-Template Emission

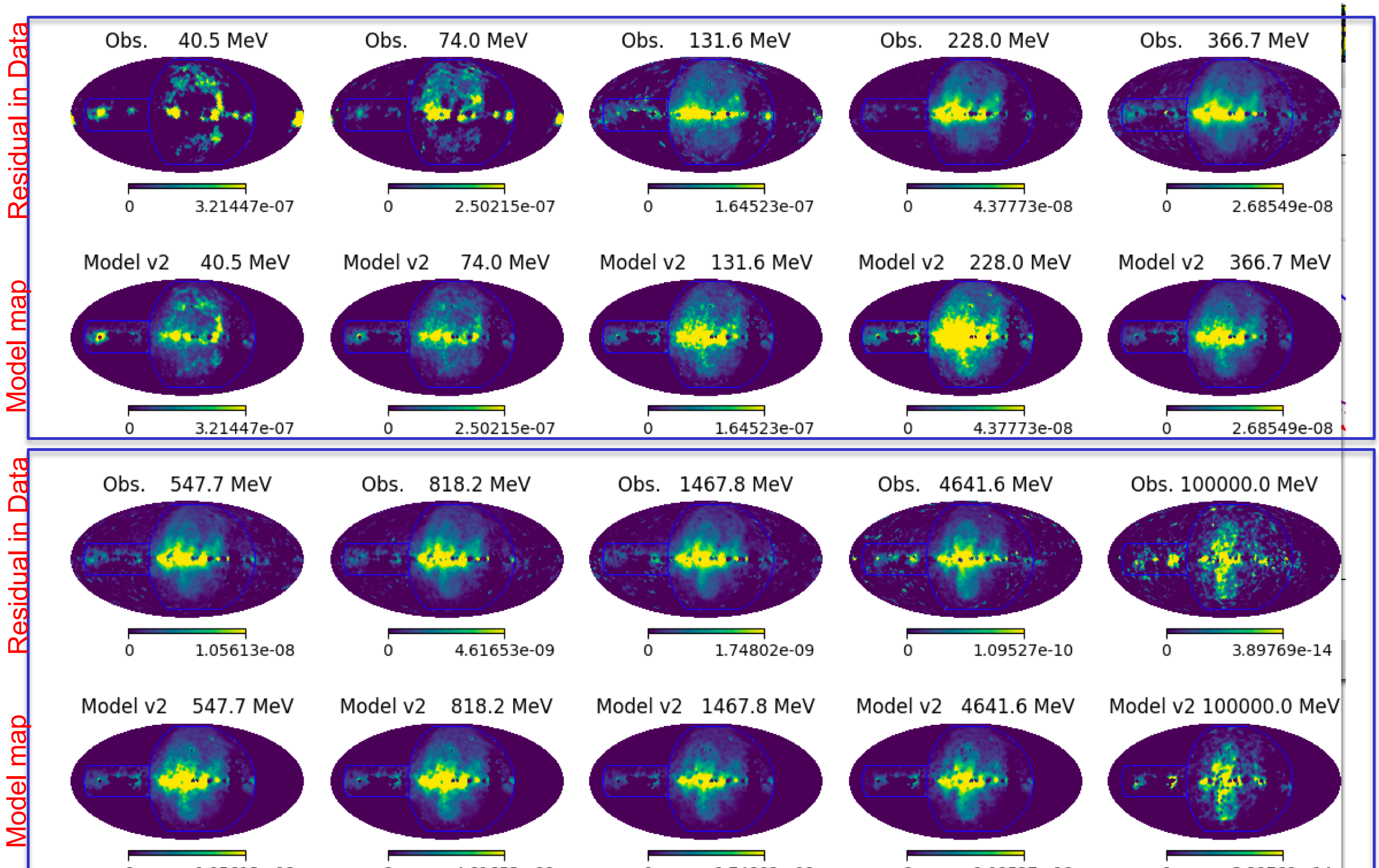
- Some large-scale features have no template at other wavelengths: Fermi bubbles
- Others have no ‘good’ (proportionate) tracer: Loop I [we tried]
- Others are regions at low latitudes where for some reason the current tracers are not adequate

- Care is needed to define a component based on a residual
  – To unbias the fitting of other components of the diffuse emission model and to not absorb discrete sources
  – Also to enforce spectral smoothness – whatever physical phenomenon is involved is not likely to have sharp spectral features
  – And spatial smoothness – to not cancel discrete sources

Non-template Component

Not final

- **Comparison with data minus the rest of the model**



Spectrum is strongly spatially dependent

Diffuse Emission Model Status

- We have implemented the improvements noted in templates and methodology. Final stages:
  1. Tuning/iterating the non-template template;
  2. Checking against an iteration of source detection for the Catalog analysis
- We anticipate finalizing the model in time to support release of the 4FGL source list by the end of the year

Future Prospects for Galactic Diffuse Modeling

- **We expect the 4FGL model to have a fairly long shelf life**
- **Prospects for templates**
  - **Survey data for templates: No big advances are on the horizon (until the FAST H I survey); large-area optical surveys are yielding ~3-d maps of interstellar dust, but only up to ~few kpc distances**
  - **Dark gas: Potential improvement from the 'direct' approach**
  - **Unresolved sources: Challenges with correlation with inner Galaxy gas 'rings'**
- **Releasing the components of the model individually? [*Maybe* – yes, if it is useful, e.g., for estimating systematics for a particular region]**
- **3-d CR density fitting? [*I doubt it*]**
- **Galactic center region will likely remain quite challenging**

Backup slides

Diffuse Emission Modeling Improvements for 4FGL

- **On large scales:**
  - **Refined decomposition of CO (H_2 tracer) and H I into 'rings' of Galactocentric distance**
  - **Decomposition of inverse Compton model into 'rings'**
  - **P305 event selection (Bruel et al. poster) removes structure in residual charged particle background**
  - **Re-evaluated 'non-template' gamma rays (Fermi bubbles + Loop I + etc.)**
- **On finer scales:**
  - **Factored the CMZ from the innermost ring**
  - **Better angular resolution for H I with the new HI4PI survey (16')**
  - **Better angular resolution (6') and linearity for Dark gas (Planck data)**
  - **Used 8-year source list derived for >50 MeV**