Development of the Galactic Diffuse Emission Model for the LAT 4FGL Catalog Analysis

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Role of the Galactic Diffuse Emission Model

- For source detection and characterization in gamma-ray data we want to model as accurately as possible everything other than the sources
- The Milky Way is rather bright in ~GeV gamma rays
  - ~65% of the celestial gamma rays detected by the LAT originate in diffuse processes in the Milky Way
  - ~25% is isotropic extragalactic background
  - ~10% is resolved into point and small extended sources
- Especially on the faint end of the source distribution (where most of the sources are), an accurate foreground model will result in a deeper, more accurate and reliable catalog

* Other diffuse components include residual charged-particle background, residual Earth limb emission, and the effectively diffuse emission from the moving quiet Sun and Moon. I will not say any more about these except that they have been updated

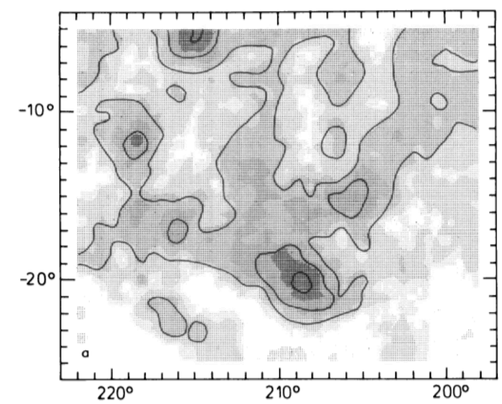
Motivations for a New Galactic Diffuse Emission Model

- **See talk by Jean Ballet this afternoon**
- **The model used for the 3FGL catalog (and current analyses) has known shortcomings that can be addressed with new multiwavelength data**
  - **Improving the accuracy (reducing systematic uncertainties) is possible**
- **The 3FGL-era model* was based on half of the current data set, and the event-level analysis has since been updated as well (Pass 8)**
  - **Effectively the model itself needs to be deeper now, continuing a trend**

*Acero et al. (2016, ApJS 223, 26)

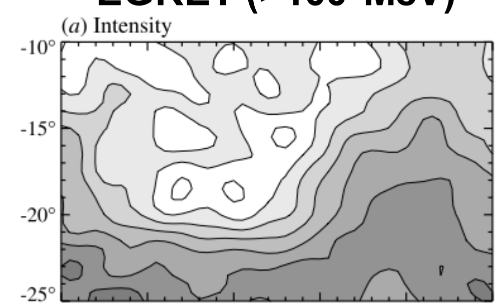
Gamma-ray Obs. of Orion

COS-B (>100 MeV)



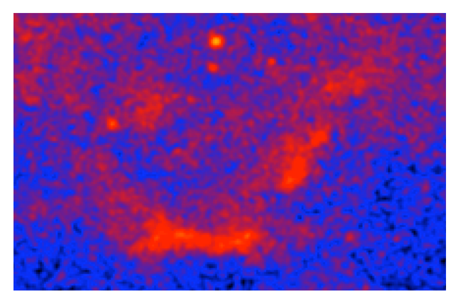
Bloemen et al. (1984)

EGRET (>100 MeV)



Digel et al. (1999)

LAT (8-year >1 GeV)



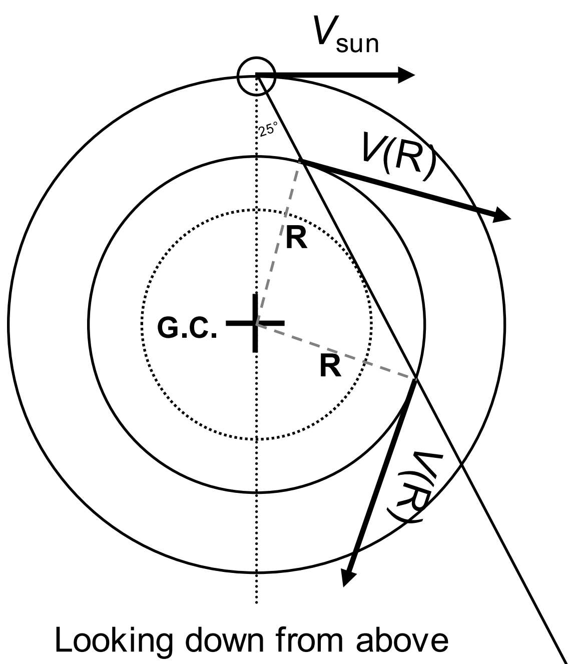
Modeling Diffuse Emission is Simple

- *In Concept*
  - The Milky Way produces cosmic rays and they diffuse around the Galaxy, largely confined
  - It also has an extensive interstellar medium (ISM, primarily atomic and molecular hydrogen) and stars and dust providing an interstellar radiation field
- The ISM is optically thin to cosmic rays and to gamma rays produced in cosmic ray interactions
  - Production processes: π^0 decay, Brems., IC scattering
- So the radiation transfer calculation is easy
  - Everything is linear
  - *All you need to know are the distributions of gas, interstellar radiation, and cosmic rays**

* With the LAT we learned from the the Fermi bubbles that the cosmic-ray intensity cannot always be considered a scale factor to be fit

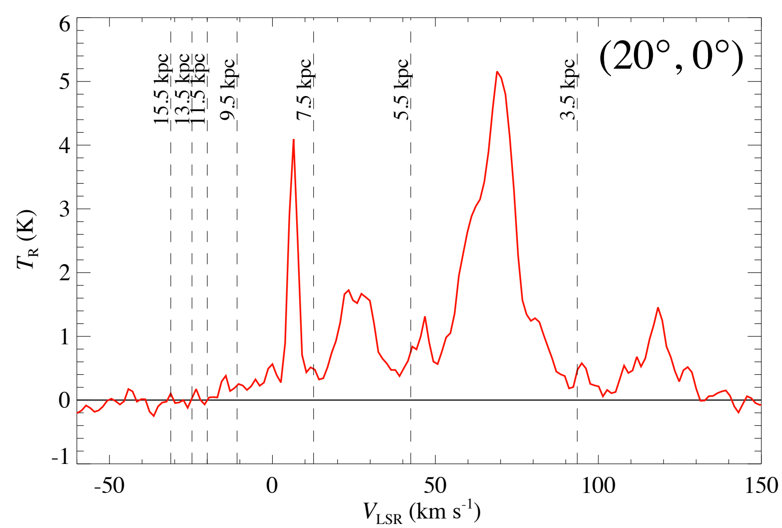
Updating the Model

- **The potential improvements are largely related to the gas and radiation field distributions**
- **Cosmic rays are assumed to be more smoothly distributed than the ISM and radiation field and their intensities can be fit as (energy-dependent) scale factors**
  - **Aside on Galactic rotation and ‘rings’**



Looking down from above the Milky Way

CO J=1-0 line spectrum



Doppler shifted velocity

H I Rings

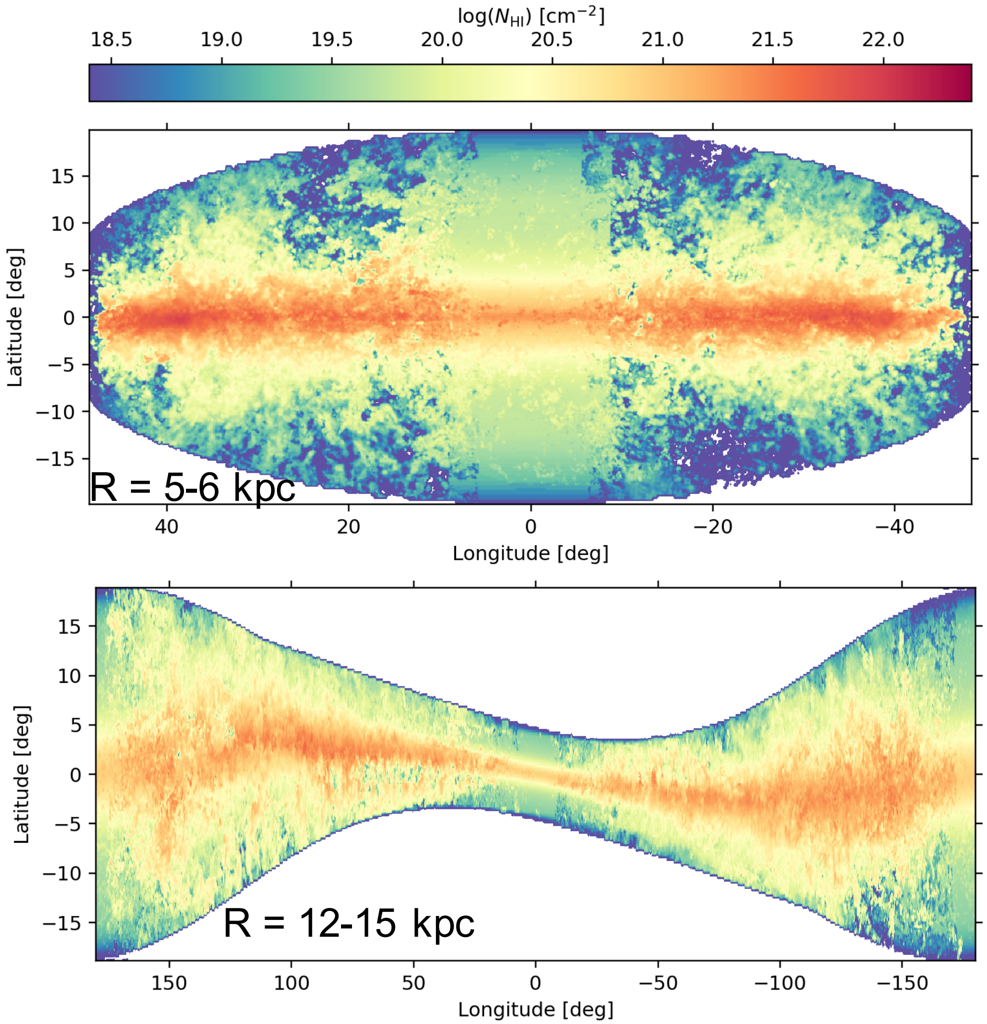
	4-year model (3FGL)	8-year model (4FGL)
H I Survey	LAB	HI4PI
Angular resolution	42’	16’
Rotation curve	Clemens (1985)	Sofue (2015)

- **Other important differences:**
  - **Line profiles are now fit to the spectra and the inferred column density for each profile is assigned entirely to the ring at the central velocity**
    - **Method extends closer to the GC and anticenter than the channel-by-channel approach**
  - **Interpolation across the center and anticenter is now based on models for the disk and halo components of gas density**
    - **Including warp and flare of the outer disk**
    - **Kalberla & Dedes (2008), Marasco & Fraternali (2010)**

H I Rings

- **Many other details including forbidden velocities, high-velocity clouds, & Local Group galaxies**
- **Issues: Optical depth correction is still for fixed T_{spin} = 150 K, and self absorption is not treated**
  - **Dark gas derivation can compensate the column density changes somewhat**

Example N(H I) rings

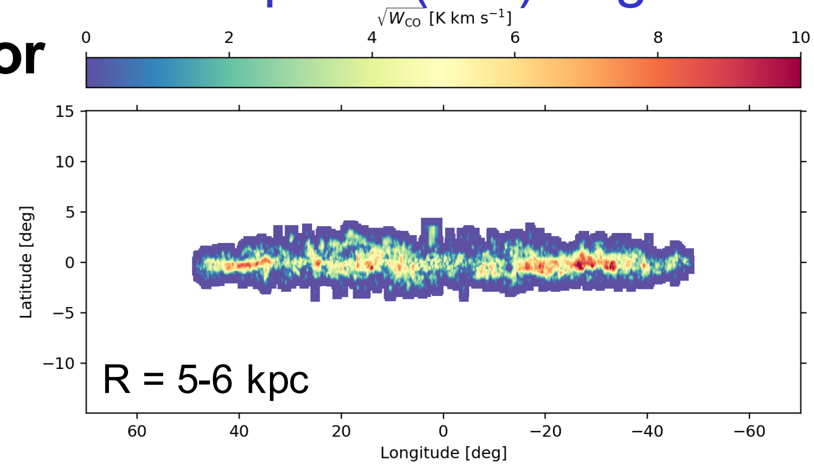


(N.B.: longitude ranges are different, and aspct ratios are not 1:1)

CO Rings

- **Surrogate for H2. Same dataset as for the 4-year model (primarily CfA CO survey)**
- **Now with the updated ring decomposition and particular improvements in the inner Galaxy**
  - **The CMZ range is factored into separate rings, where the $N(H_2)/W(CO)$ relation is distinctly different**
  - **The 3 kpc arm (largely at forbidden velocities) is folded into the R = 2-3 kpc ring**

Example W(CO) ring



N.B.: Aspect ratio is not 1:1

- **HI and CO rings: Remy et al. in prep.**

Dark Gas

- **Atomic and molecular gas that is not properly traced by the above-mentioned surveys (optically-thick H I or CO-dark H_2)**

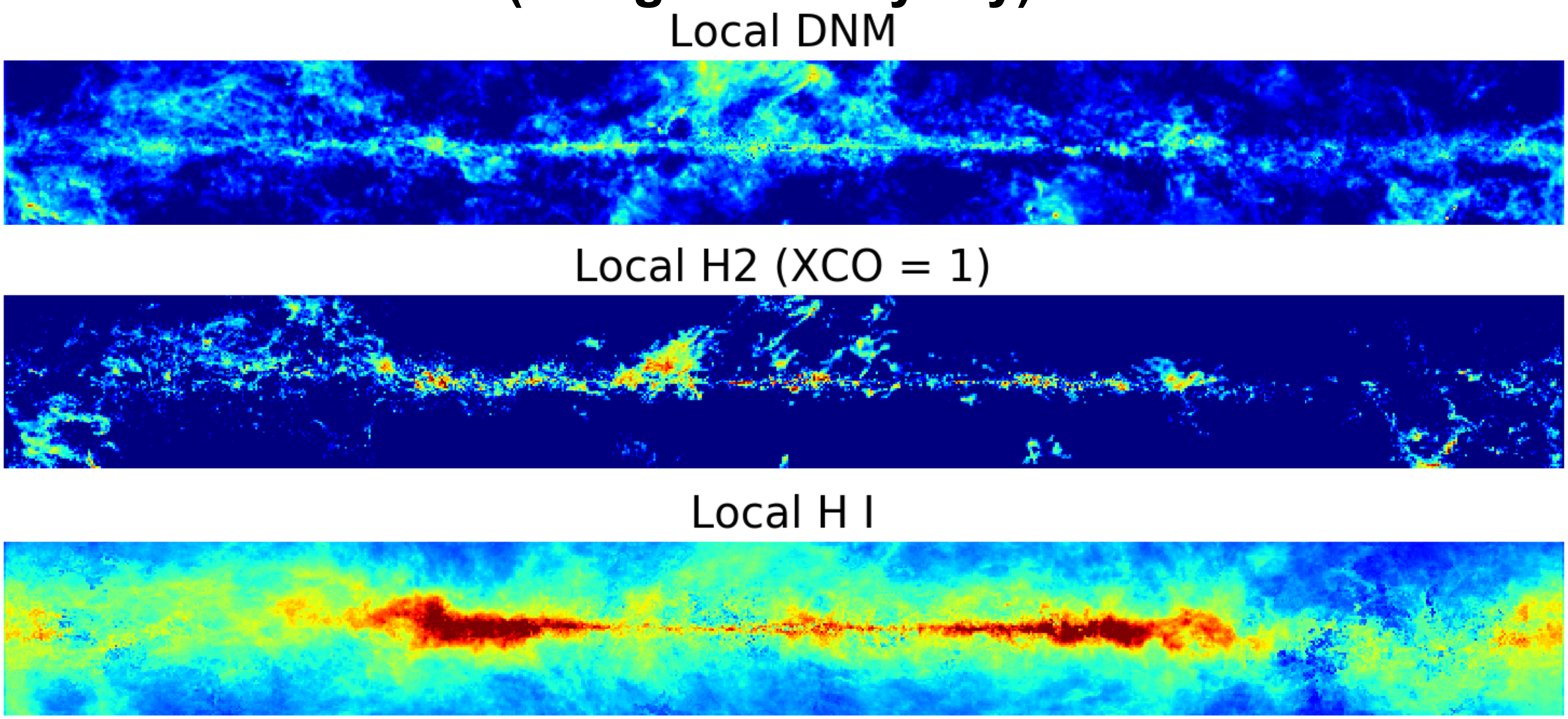
	4-year model (3FGL)	8-year model (4FGL)
Dust tracer	SFD E(B-V) (IRAS + COBE)	Planck τ_{353}
Angular resolution	~45' (DIRBE)	6’

- **Other important developments since the 4-year model:**
  - **Availability of Planck microwave survey (R2.00)**
  - **Recognition of the nonlinearity of τ_{353}-N(H) relation***
  - **Incorporation of gradients of this relation across the Galaxy**

* See following talk by Q. Remy

Dark Gas

- **The dark gas is responsible for a lot of the small-scale structure in the ISM (and gamma-ray sky)**



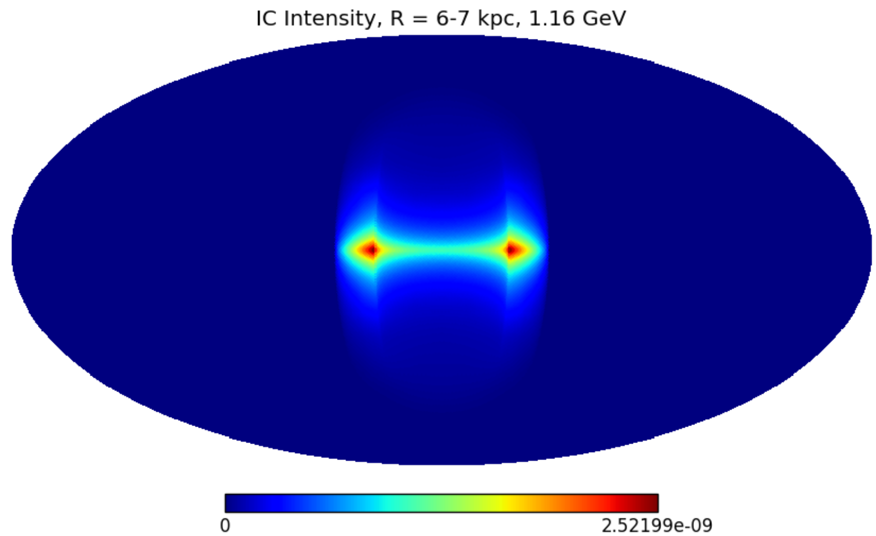
Maps for |b| < 20 deg, same (sqrt) scaling

- **With the new data and approach artificial structure around massive star-forming regions is also greatly improved**

Interstellar Radiation Field

- **The IC component is derived from a model of the ISRF based on stellar population models, dust distribution and properties, the CMB, a cosmic-ray electron distribution calculated in a GALPROP* cosmic-ray propagation model**
  - **The ISRF model is 2-dimensional spatially****
- **For the new model we factored the IC emission into Galactocentric rings (like the gas) and these are scaled independently**
  - **This approach and the particular model*** were applied in Ajello et al. (2016, ApJ, 819, 44)**

Example ring, Model IC Intensity, 1.16 GeV



R = 6-7 kpc

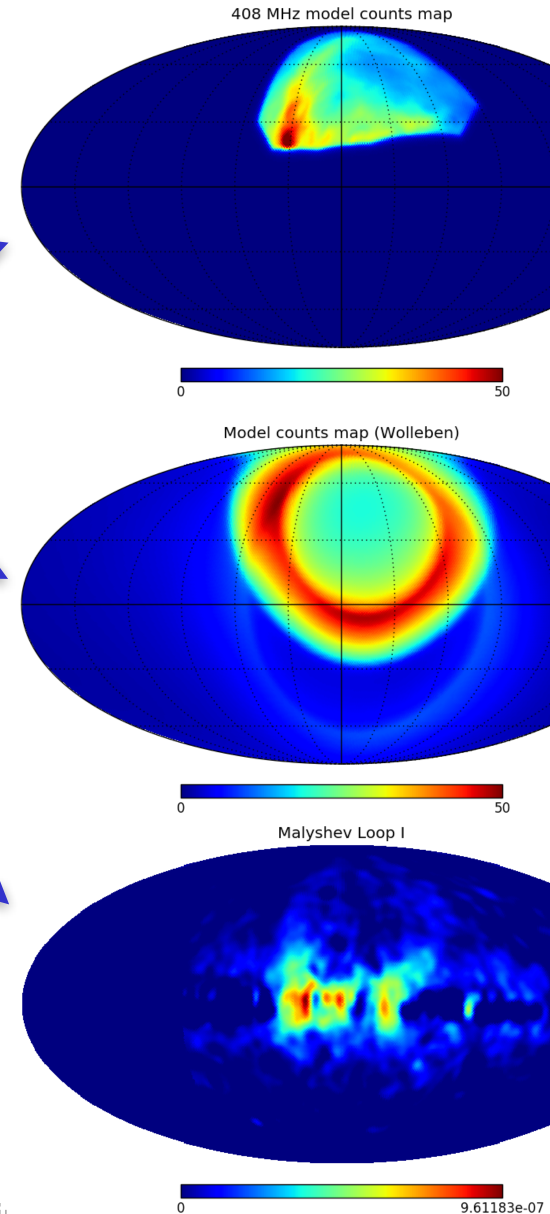
* http://galprop.stanford.edu. ** see talk by T. Porter for recent work on a 3-d ISRF model

*** LRYusifovXCO5z6R30_Ts150_mag2

Other Templates

- **Testing three models for Loop I - >100 deg diameter long known in non-thermal emission in the radio**
  - **Proportional to 408 MHz radio continuum**
  - **Analytical model of Wolleben et al. (2005)**
  - **Soft-spectrum gamma-ray component of Ackermann et al. (2017) [so a ‘non-template template’]**

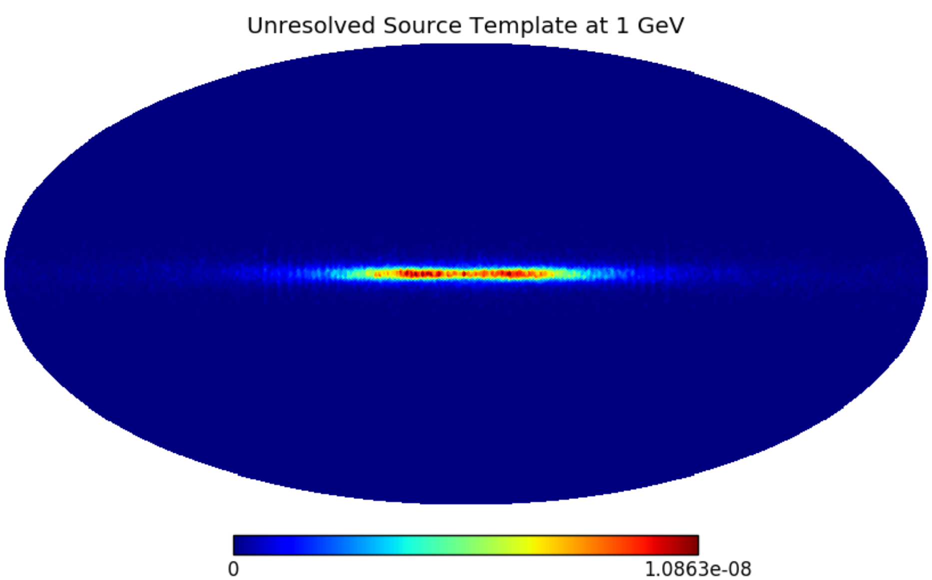
Loop I Models



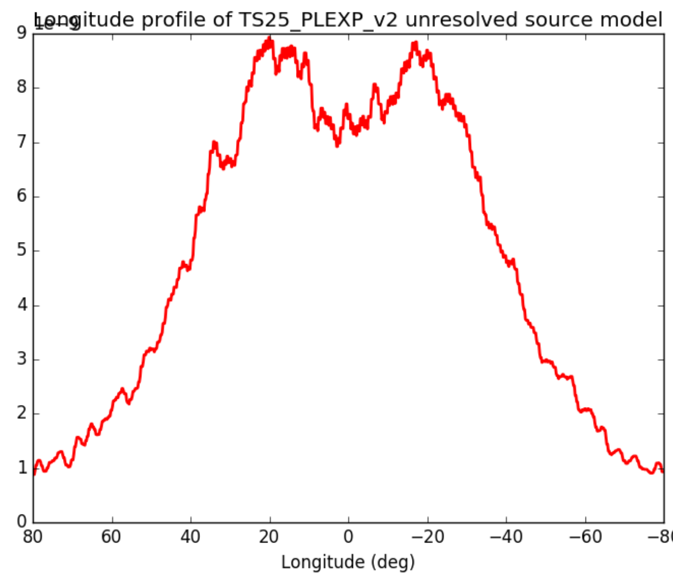
Other Templates: Unresolved Sources

- **Combining a population model* with 8-year sensitivity map to make a template out of sub-threshold sources**
- **At low latitudes the spatial distribution is strongly modified by the sensitivity map**

One Unresolved Source Template



Longitude profile at b = 0



* Luminosity function + assumed Galactic disk spatial distribution; see Appendix of 3FGL paper (Acero et al. 2015, ApJS, 218, 23)

Fitting Approach

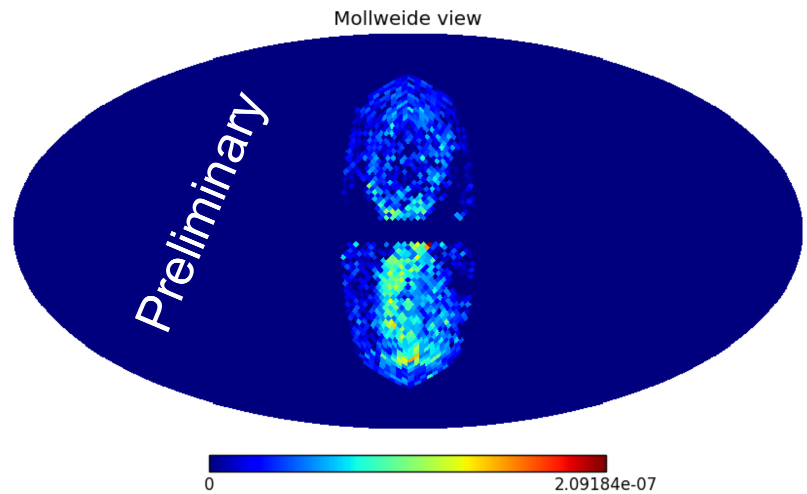
- **Maximum likelihood analysis optimized for all-sky studies: Gardian*, developed by G. Johannesson**
  - **Actually a summed likelihood analysis because the PSF event type and zenith angle limits depend on energy in the 4FGL data set**
- **We run it with the interim 8-year source list converted to a ‘template’ with fixed scaling**
- **The templates are all effectively three dimensional, i.e., spatial maps of intensity in planes for different energies**
  - **Gardian optimizes the parameters of scaling functions for each template (from proportionality to logParabola)**
- **Maximizing likelihood is a *many* parameter optimization**
  - **We fit in sequence: high latitude, outer Galaxy, inner Galaxy**
  - **Monitoring parameter covariance can help diagnose correspondences between templates**

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

Non-template Templates

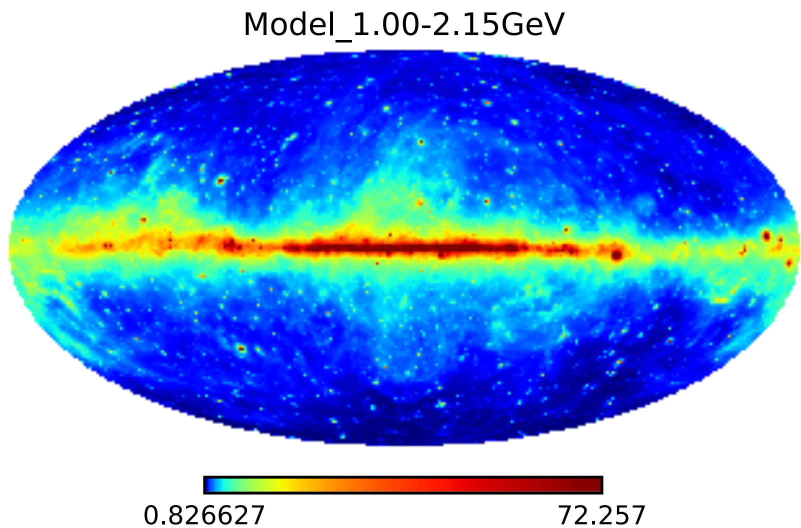
- The Fermi bubbles are the primary example
  – Fermi bubbles are still there…
- For the 4-year (3FGL model) additional, softer-spectrum residuals were found over a larger area
  – These were filtered (for sources), folded back in to the model fitting as templates (to un-bias the fits of the other components) and re-fit
- We are still assessing the required level of these additional, non-template components

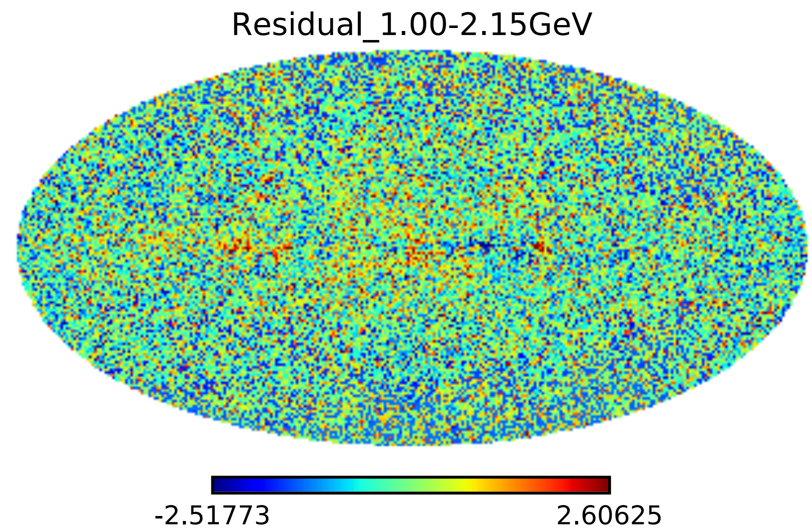
1st Iteration Fermi Bubbles Template (from 10-100 GeV residuals)



Example Assembled Galactic Diffuse Emission Model

- **This model included the Wolleben et al. Loop I template, the first version of the Fermi bubbles template, and tested the unresolved source template (which was not detected)**





log scale

linear scale

counts per ~0.2 deg pixel

- **The residuals do not look flat yet at all energies, and some improvements in the procedure (e.g., for dealing with correlated templates and the brightest point sources) are underway**

Conclusions

- **The size and quality of the LAT data set require an updated model for Galactic diffuse gamma-ray emission**
- **The recent availability of improved tracers of the interstellar medium and advances in our approaches to using them is yielding a Galactic diffuse emission model for the 4FGL catalog analysis**
  - **In cases where viable alternative templates exist (e.g., Loop I), we are exploring to find the best performing**