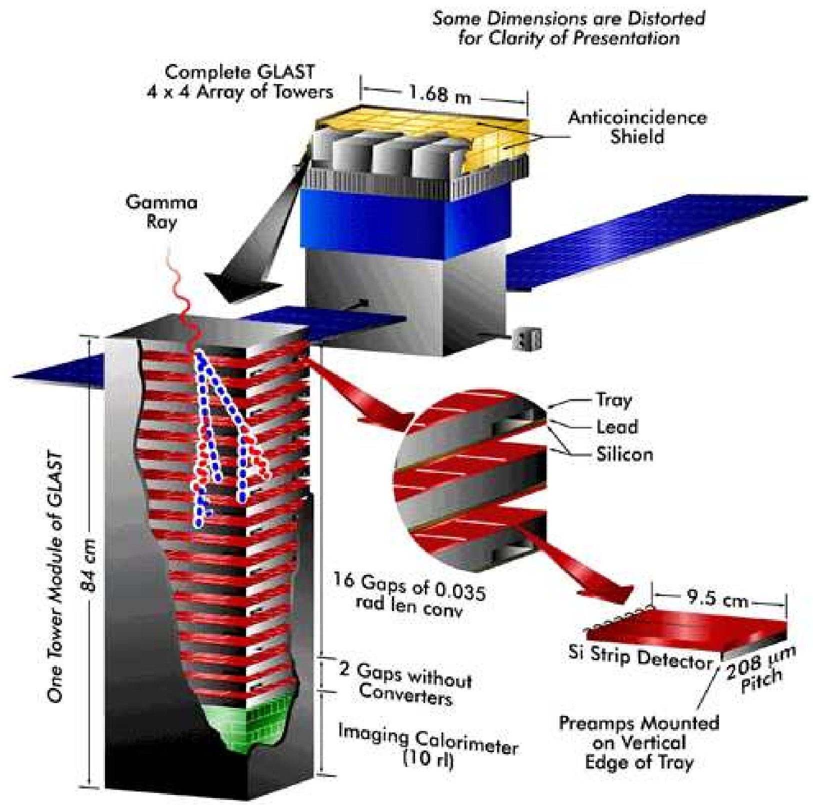
Imaging Using the GLAST Large-Area Telescope

Jim Chiang
Stanford Linear Accelerator Center

The GLAST Large Area Telescope

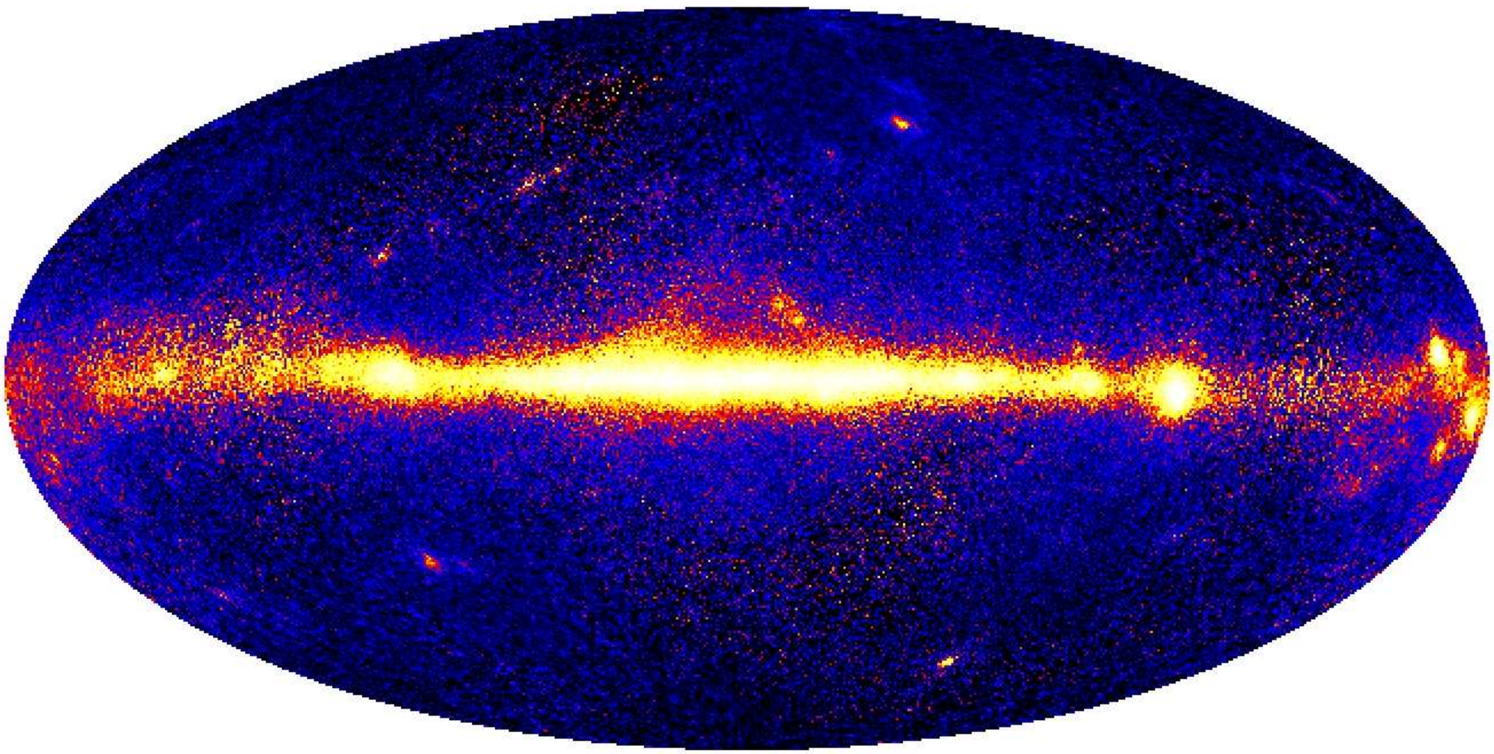


The Gamma-ray Large Area Space Telescope Mission

- Launch in early 2008 into low-Earth orbit (560 km altitude)
- Nominal 5 year mission, 10 years anticipated
- All-sky survey of the gamma-ray sky, with opportunities for pointed observations
- Astrophysical phenomena to be observed:
  - Cosmic-ray interactions with interstellar gas — Milky Way Galaxy, LMC, et al.
  - Pulsars — magnetospheres of rapidly spinning neutron stars
  - Active Galactic Nuclei (AGNs) — jets from accreting supermassive ($\gtrsim 10^8\, M_\odot$) black holes
  - Gamma-ray bursts — stellar explosions or compact object mergers
  - Supernova remnants — SN ejecta shocking on interstellar gas
  - Microquasars — jets from accreting $\sim 10\, M_\odot$ BHs
  - Dark/exotic matter — WIMP annihilation
  - New discoveries — ?

The Gamma-ray Sky

- Energetic Gamma-Ray Experiment Telescope (EGRET), data from 1991–2000:



GLAST Large Area Telescope (LAT) Properties

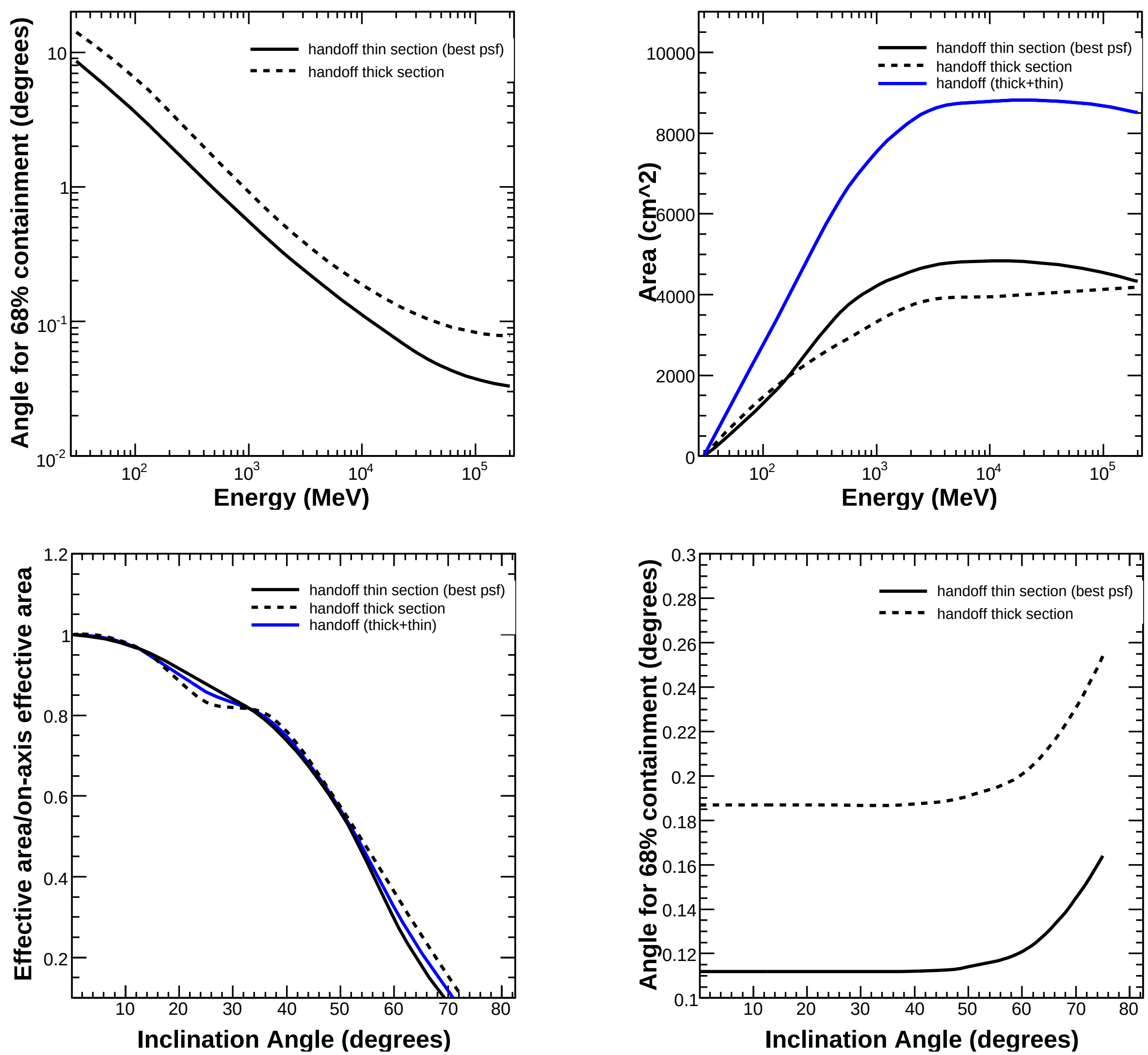
- ~ 2.4 sr field-of-view — 20% of the whole sky
- Energy coverage from 30 MeV to 300 GeV
- Energy resolution $\Delta E/E \sim 10\%$
- The point spread function (blurring) is strongly energy-dependent, $\sigma_{68} \sim E^{-1}$:

$$\begin{aligned} \sigma_{68} &\simeq 3\overset{\circ}{.}5 && \text{at 100 MeV} \\ &\simeq 0\overset{\circ}{.}15 && \text{at 10 GeV} \end{aligned}$$

- Effective area $\sim 10^4 \cos\theta\,\mathrm{cm}^2$ at 10 GeV
  - mean overall count rate $\sim$ 1–2 events s^{-1}
  - $\mathcal{O}(10^2)$ counts/day for strong sources
- Survey/scanning mode of operation:
  - 95 minute orbit
  - $\pm 35^\circ$ rocking of LAT z-axis about the orbital plane

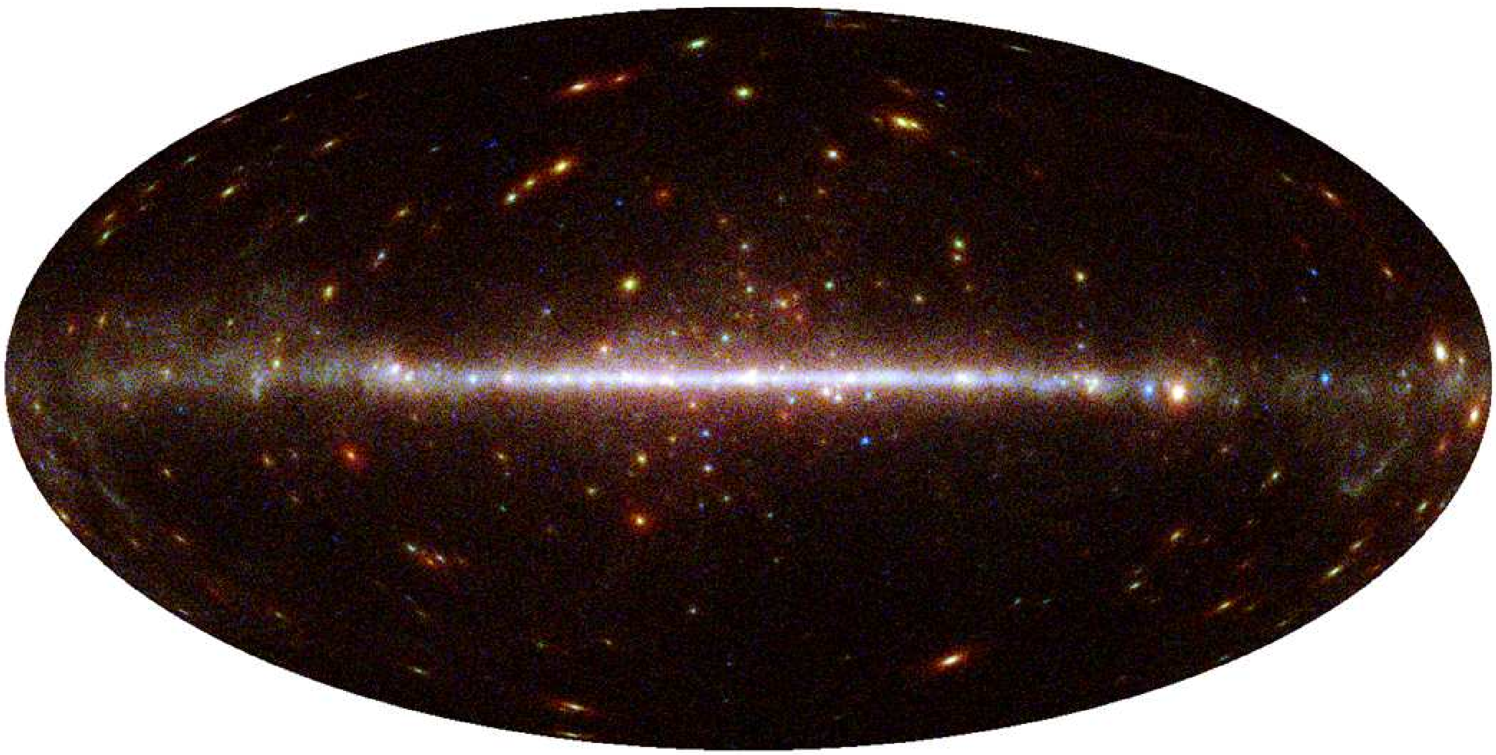
$\Rightarrow$ Continuous aspect changes of $\gtrsim 4^\circ$ per minute

Instrument Response Functions (IRFs)

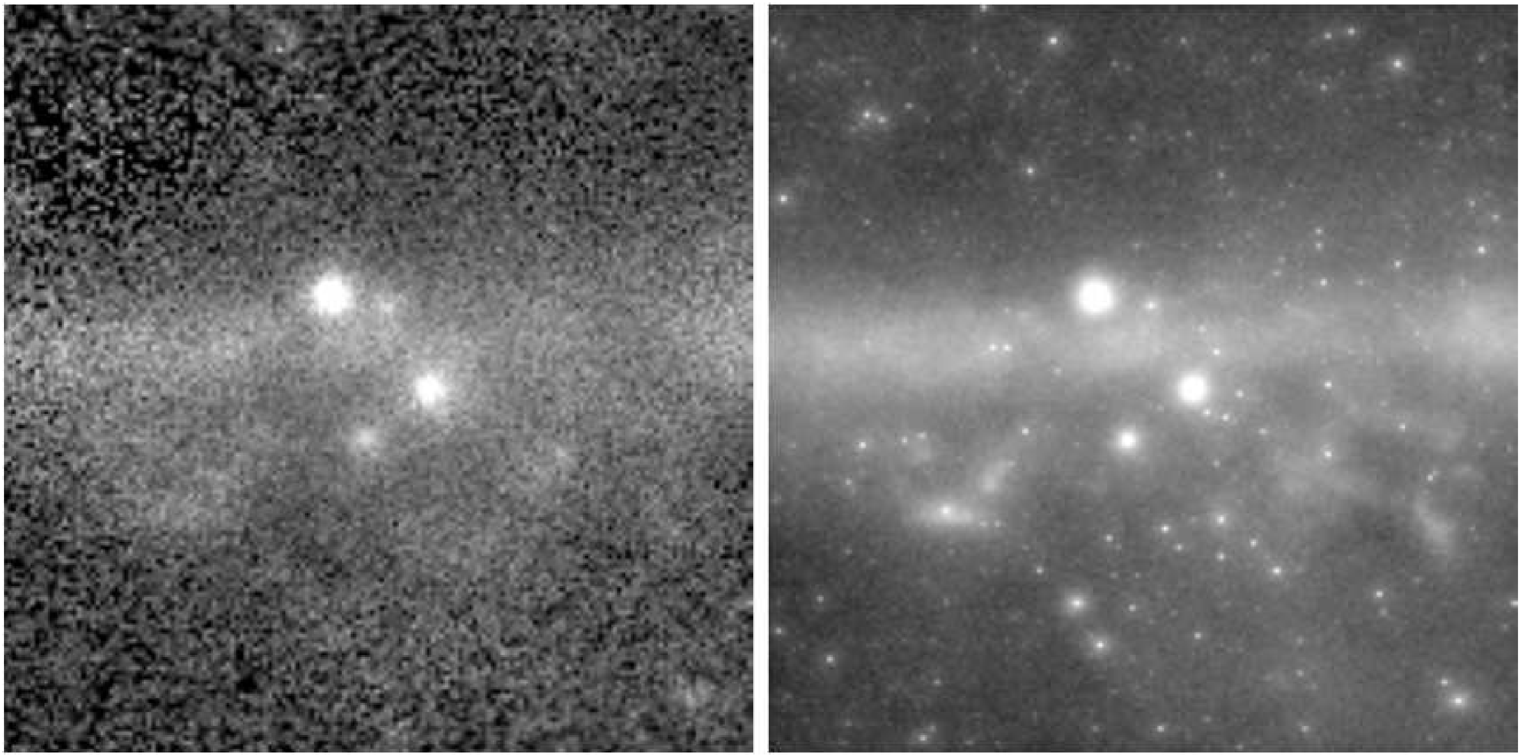


The Gamma-ray Sky

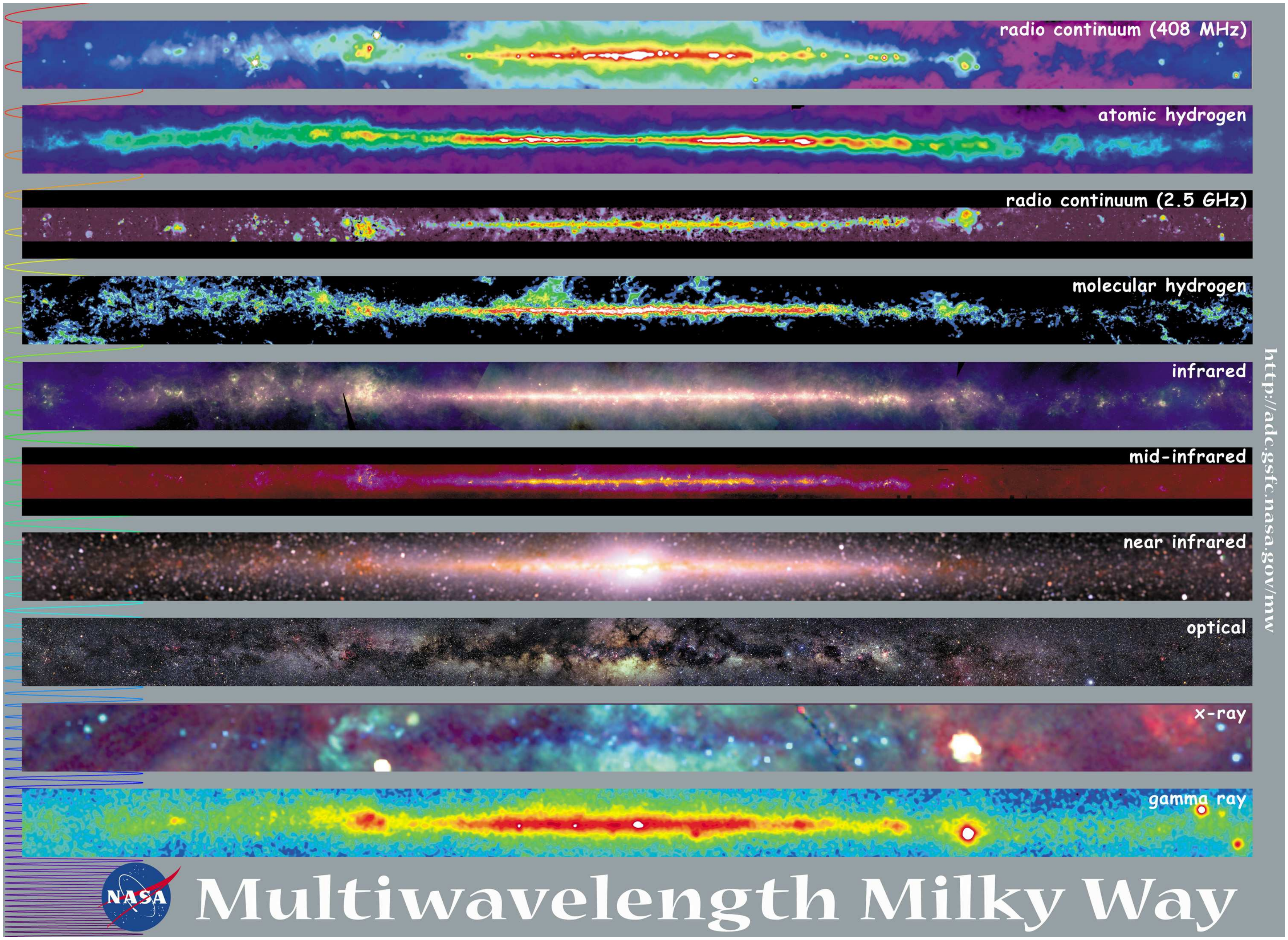
- GLAST/LAT, 55 day simulation:



Direct Comparison of EGRET vs GLAST/LAT



Left: Galactic anticenter region as seen by EGRET. Right: From a one-year simulation of LAT scanning mode data.


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
Multiwavelength Milky Way
http://adc.gsfc.nasa.gov/mw

Imaging Issues for GLAST/LAT data

General Questions:

- Point Sources:
  - Identifying and localizing point sources.
  - Determining the significance of a detection.
  - Distinguishing a collection of weak point sources from diffuse, extended emission.
- Diffuse Sources:
  - What is the underlying "shape" and significance of extended features in the presence of a structured and *uncertain* background?

Specifics:

- Galactic interstellar diffuse emission is the dominant "background" for all other sources, but it must be modeled and has its own set of uncertainties.
- Many interesting, potential extended sources, such as SNRs ($\lesssim 1^\circ$), lie on or near the Galactic plane, but they are a small perturbations to the interstellar component.
- Pulsars or other source populations could make a substantial contribution to the Galactic plane emission.
- Large scale structure ($\sim$ radians) in the extragalactic diffuse will be difficult to discern in the presence of exposure variations and may be confused with foreground Galactic contributions or with populations of point sources (e.g., AGNs).

Modeling GLAST/LAT data

- Source Model and Instrument Response

  The total source model is the sum of contributions from individual point-like and diffuse sources:

$$S(\varepsilon, \hat{p}) = \sum_i S_i(\varepsilon, \hat{p}), \tag{1}$$

where ε is the true energy of the photon and $\hat{p}$ is the true direction on the sky. For a point source i, the spatial and spectral part can be factored

$$S_i(\varepsilon, \hat{p}) = \tilde{S}_i(\varepsilon)\delta(\hat{p} - \hat{p}_i). \tag{2}$$

The instrument response is typically factored into three components:

$$R(\varepsilon', \hat{p}'; \varepsilon, \hat{p}) = A(\varepsilon, \hat{p})P(\hat{p}'; \varepsilon, \hat{p})D(\varepsilon'; \varepsilon, \hat{p}). \tag{3}$$

Here ε' and $\hat{p}'$ are the measured energy and direction of the photon, repectively. $P(\hat{p}'; \varepsilon, \hat{p})$ is the point spread function; and $D(\varepsilon'; \varepsilon, \hat{p})$ is the energy dispersion; both functions are pdfs. The effective area $A(\varepsilon, \hat{p})$ is the cross-section of the LAT for detecting an incident photon with $(\varepsilon, \hat{p})$.

- Model Fitting

  For data binned in $(\varepsilon', \hat{p}')$, the likelihood is

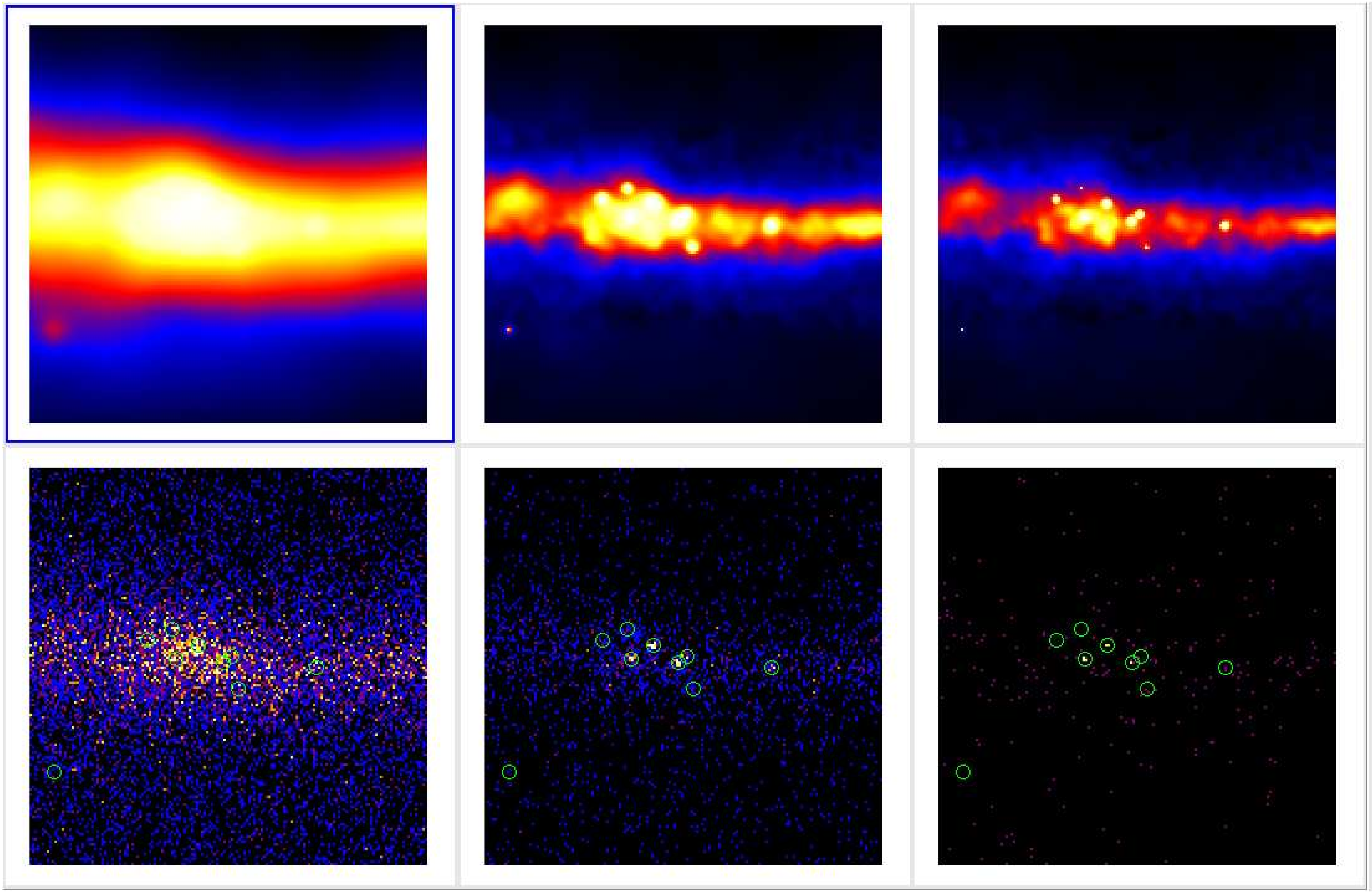
$$\mathcal{L} = \prod_j \frac{\theta_j^{n_j} e^{-\theta_j}}{n_j!}, \tag{4}$$

where n_j is the number of events in bin j, and θ_j is the predicted number of events lying in that bin given the model:

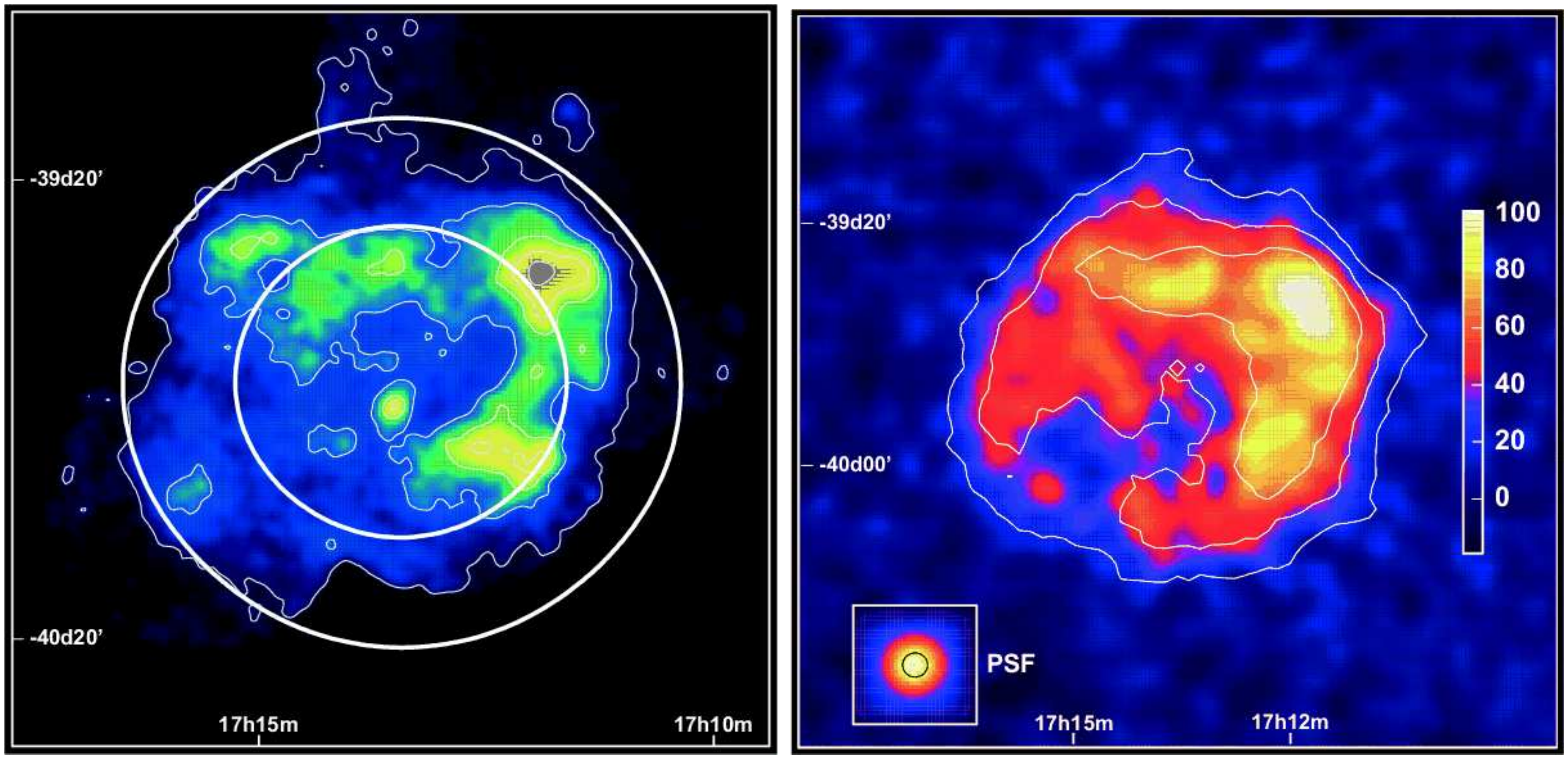
$$\theta_j = \int_j d\varepsilon' d\hat{p}' \int d\varepsilon\, d\hat{p}\, R(\varepsilon', \hat{p}'; \varepsilon, \hat{p})\, S(\varepsilon, \hat{p}) \tag{5}$$

Here $\int_j d\varepsilon' d\hat{p}'$ indicates the integral over the jth bin, and $\int d\varepsilon d\hat{p}$ is the integral over the whole sky and all energies.

Energy-dependent Blurring in Poisson Limit



Using Lower Wavelength Data to Constrain γ-ray Reconstructions



X-ray (ASCA, left) vs TeV γ-ray (H.E.S.S., right) observations of the SNR RX J1713.7−3946

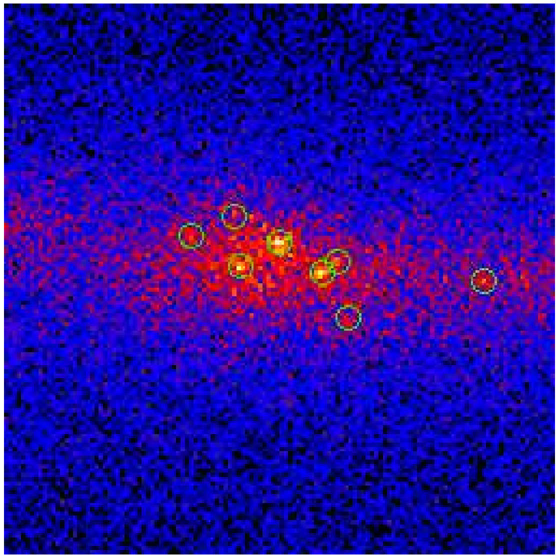
Image Reconstruction for γ-ray Data: Past Efforts

- Richardson-Lucy (Expectation Maximization)
  + Guaranteed to converge.
  + Includes deconvolution.
  + Photometric, i.e., # counts preserved, so allows flux estimates from reconstructed image
  + Very fast and easy to implement
  – Amplifies Poisson fluctuations at low counts ⇒ must to stop iterations short of convergence
- Wavelet thresholding (e.g., TIPSH translation invariant Poisson smoothing using Haar wavelets)
  + Multiscale: "Natural objects and distributions are often seen to have localized structure on many size scales." (Kolaczyk & Dixon 2000).
  + Fast.
  + Principled thresholding scheme, including "background" model specification.
  – Often not photometric (TIPSH a notable exception).
  – No deconvolution.
  – Hypothesis testing applies to wavelet coefficients, i.e., no feature-based significance.

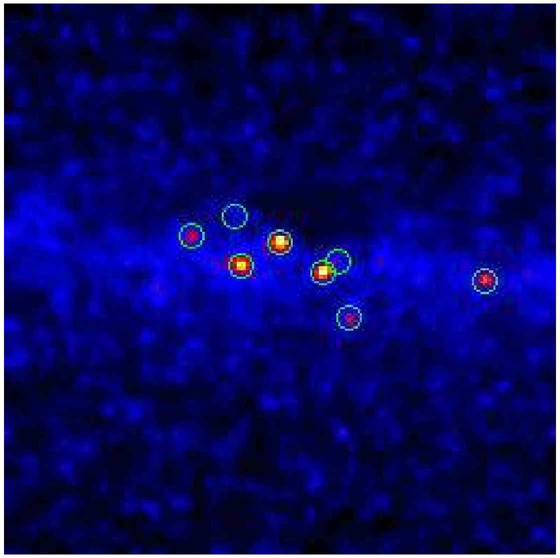
- "NK" (Nowak & Kolaczyk 2000)
  + Multiscale with dyadic Haar-wavelet like partitioning, but non-negative.
  + Explicitly photometric – "splits" reassign counts at next higher level of resolution
  + Bayesian framework for smoothing priors allows for MAP estimate of reconstructed image.
  + Combines EM deconvoution step with multiscale regularization.
  − No background model
  − Feature significance and/or uncertainties not available.
- EMC2 (Expectation through Markov Chain Monte Carlo; Esch et al. 2004, Connors & van Dyk 2006):
  All of the benefits of NK, plus
  + Can specify a background model.
  + Feature significance and uncertainties are available.
  − Some extra computational cost because of MCMC steps.

  See DvD's talk.

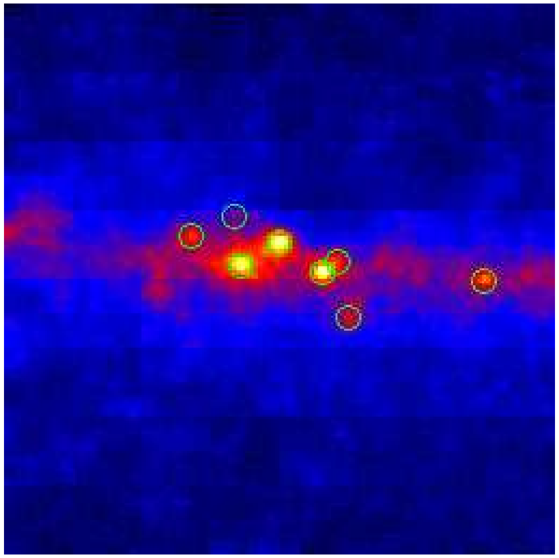
Image Reconstruction Examples



Simulated counts map



Richardson-Lucy (EM)



Multiscale Poisson
(Nowak & Kolaczyk 2000)

Imaging Reconstruction Wish List for GLAST/LAT Data

- Identifying and localizing point sources.
- Determining the significance of a detection.
- Distinguishing a collection of weak point sources from diffuse, extended emission.
- What is the underlying "shape" and significance of extended features in the presence of a structured and uncertain background?
- Can we use higher resolution data from radio, optical, and X-ray observations to guide, but not bias, the gamma-ray reconstructions?
- For large scale images, covering $>$ several degres, projection effects from the Celestial sphere causes severe distortions near coordinate system poles. On sphere, global dyadic partitioning is difficult. Can we generalize the methods that operate on Euclidean spaces to work on a sphere?
- The energy dependence of the LAT psf provides more resolving power at higher energies, but at the cost of lower statistics. How can we better use this information?

Backup Slides

The Interstellar Diffuse Emission Model

- Gamma-rays are produced by cosmic-ray interactions with interstellar gas.
- Gas distributions are inferred from high resolution radio observations of lines from H, CO (H_2), but these data are integrated along lines-of-sight, so there is distance ambiguity for radial distribution of gas.
- The origin of cosmic rays are likely SNRs, but the distribution in space and time of SNs is not well known.
- Cosmic rays propagation must be modeled and depends on uncertain Galactic magnetic fields, etc.
- Inverse Compton scattering by relativistic electrons in the Galaxy also contribute, but these electrons cannot be observed directly at other wavebands.