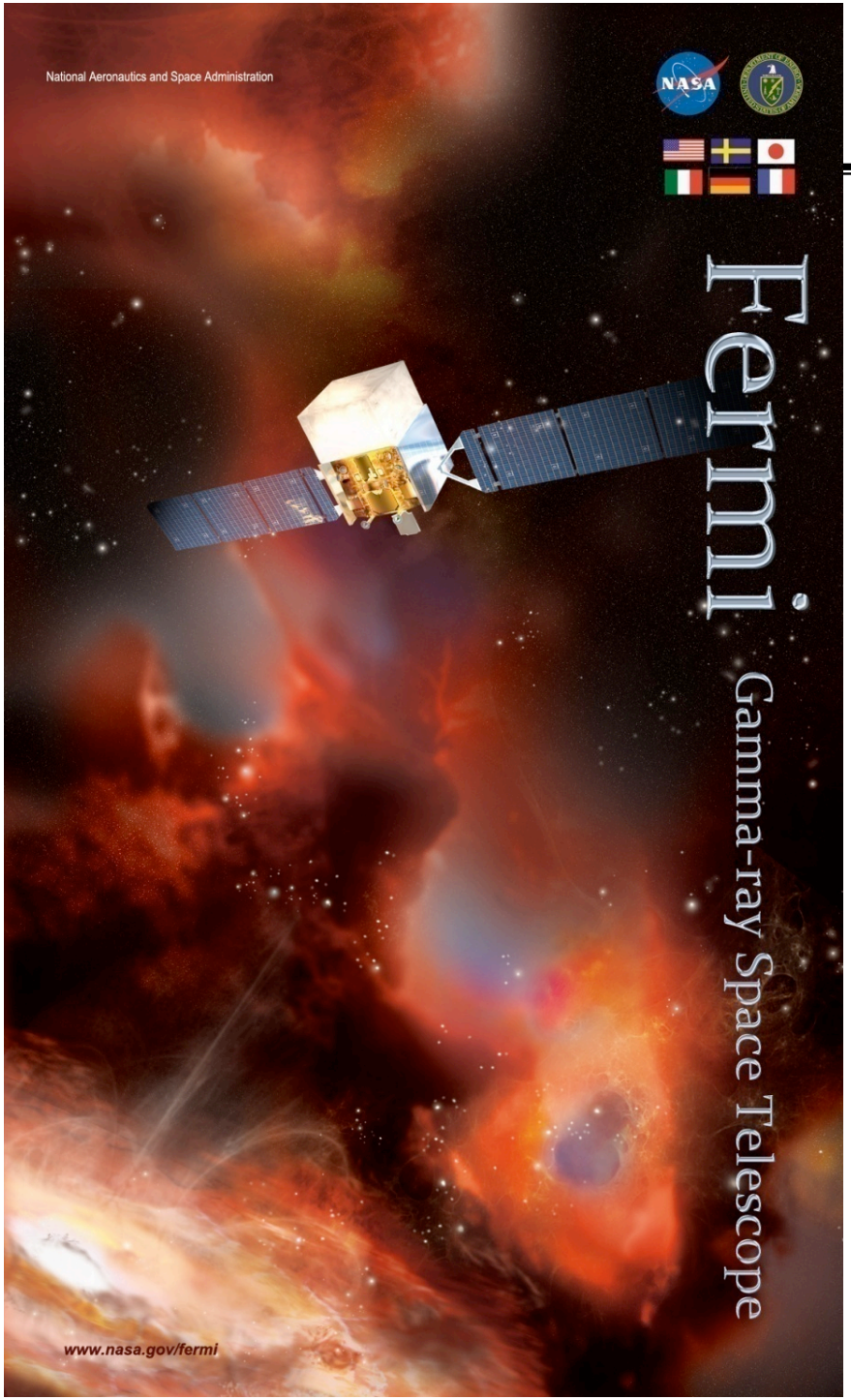


Fermi Gamma-ray Space Telescope

The Fermi LAT First Source Catalog & Using the Catalog for Analysis

Seth Digel
KIPAC/SLAC on behalf of the Fermi Large Area Telescope Collaboration

Catalog slides are from Jean Ballet's presentation at the 2009 Fermi Symposium

The First LAT Catalog (1FGL)

- 11 months of data 100 MeV to 100 GeV, 23.3 Ms livetime
- 10.6 M events over the whole sky (Pass 6 v3 Diffuse class)
- Improved diffuse model and calibration with respect to 0FGL
- Very uniform exposure (factor 1.25 between north and south)
- Detection based on integrated data (not on flares)
- Precise localization
- Characterization: spectral, variability
- Association with external catalogs

Contents of the LAT source catalog

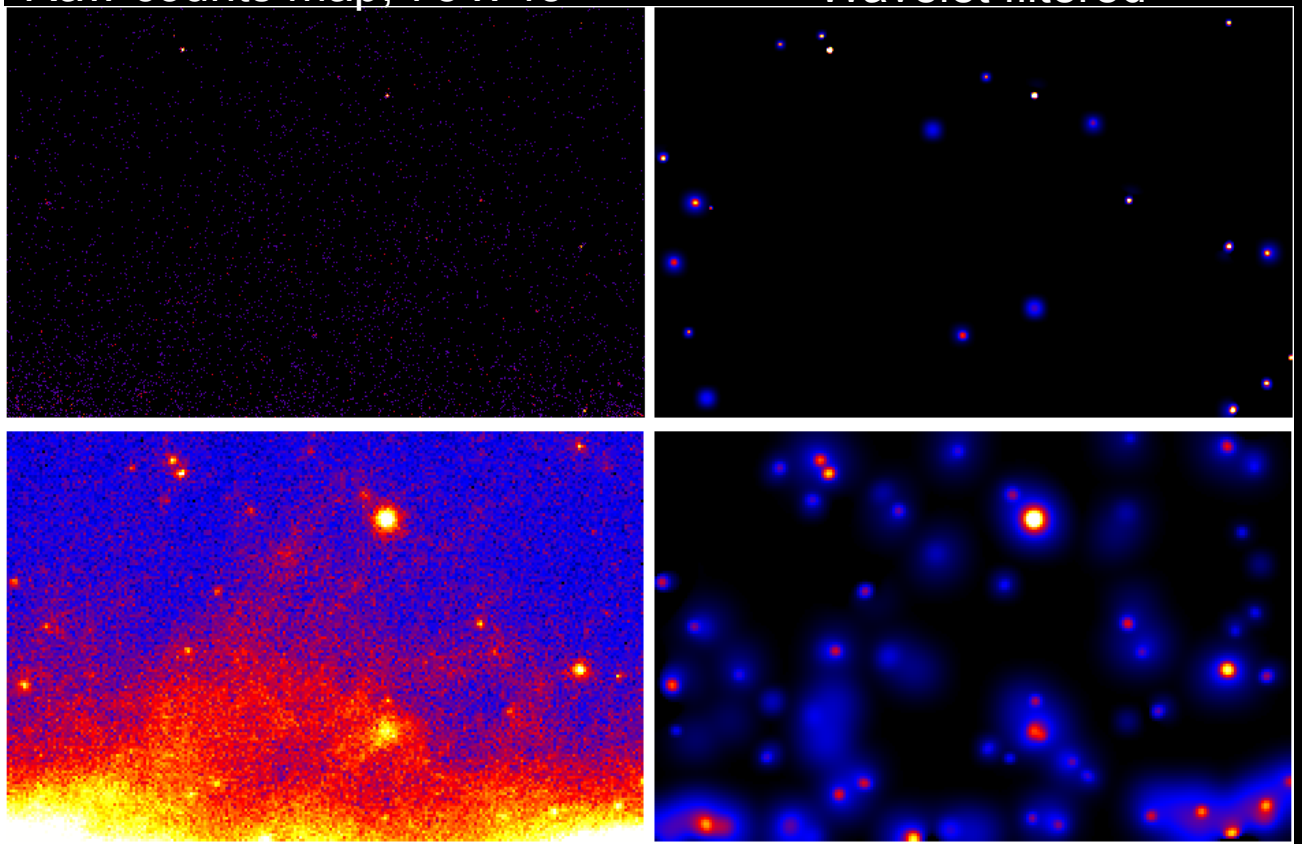
- Source coordinates and error ellipse at 95% confidence
- Source significance and overall spectral index
- Average flux in 5 energy bands 0.1 – 0.3 – 1 – 3 – 10 – 100 GeV, plus spectral index and flux for single power-law fit
- Flux per month, variability index
- Quality flags: sensitivity to diffuse model, confusion, error ellipse not well defined,etc.
- Associations with known sources

Source detection

- **Difficulty is that point spread function improves enormously from 5° at 100 MeV to nearly 0.1° above 10 GeV.**
- **No obvious optimal method to handle that in (α,δ,E) space**
- **Combine several energy bands, merge seeds from several detection methods.**

Raw counts map, 75 x 45°

Wavelet filtered

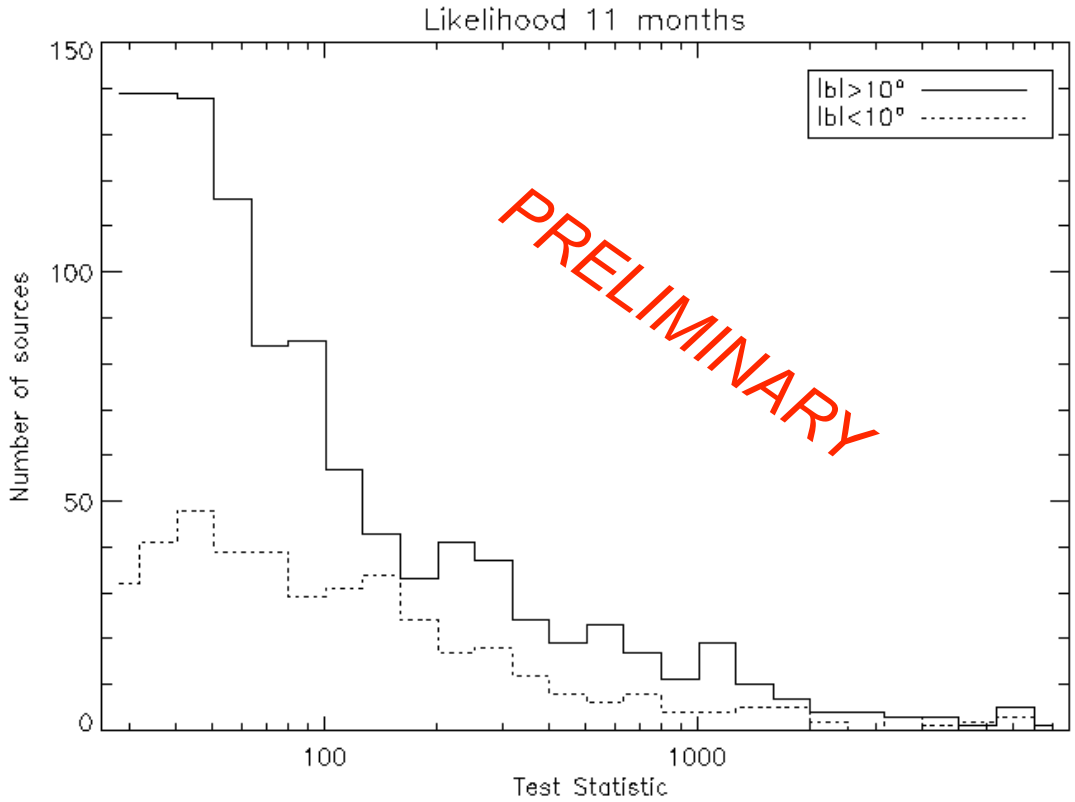


Front > 5 GeV
Back > 10 GeV
Very few events, very well localized

Front > 200 MeV
Back > 400 MeV
Many events, not so well localized

Source significance

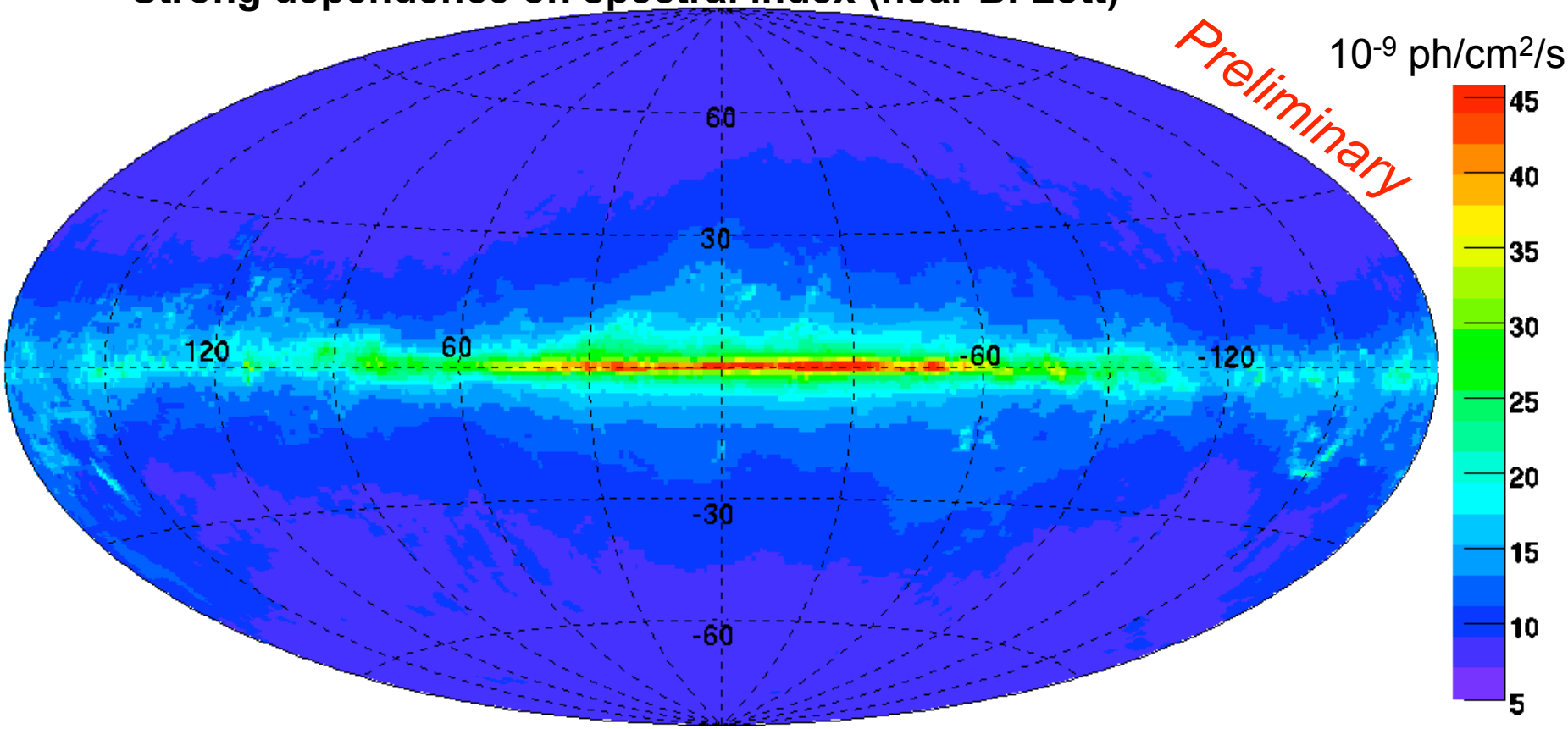
- **3D maximum likelihood analysis (position and energy) was used to determine source significance assuming power-law spectra on top of standard diffuse model**
- **Define TS = 2 Δlog(likelihood) comparing models with and without the source. Cut at TS = 25, corresponding to about 4 σ or 2.5E-5 probability (4 degrees of freedom including source position).**



Works well at high latitudes. Peak in TS distribution at threshold.
TS distribution flatter close to Galactic plane. Faint sources are not detected.

Sensitivity map

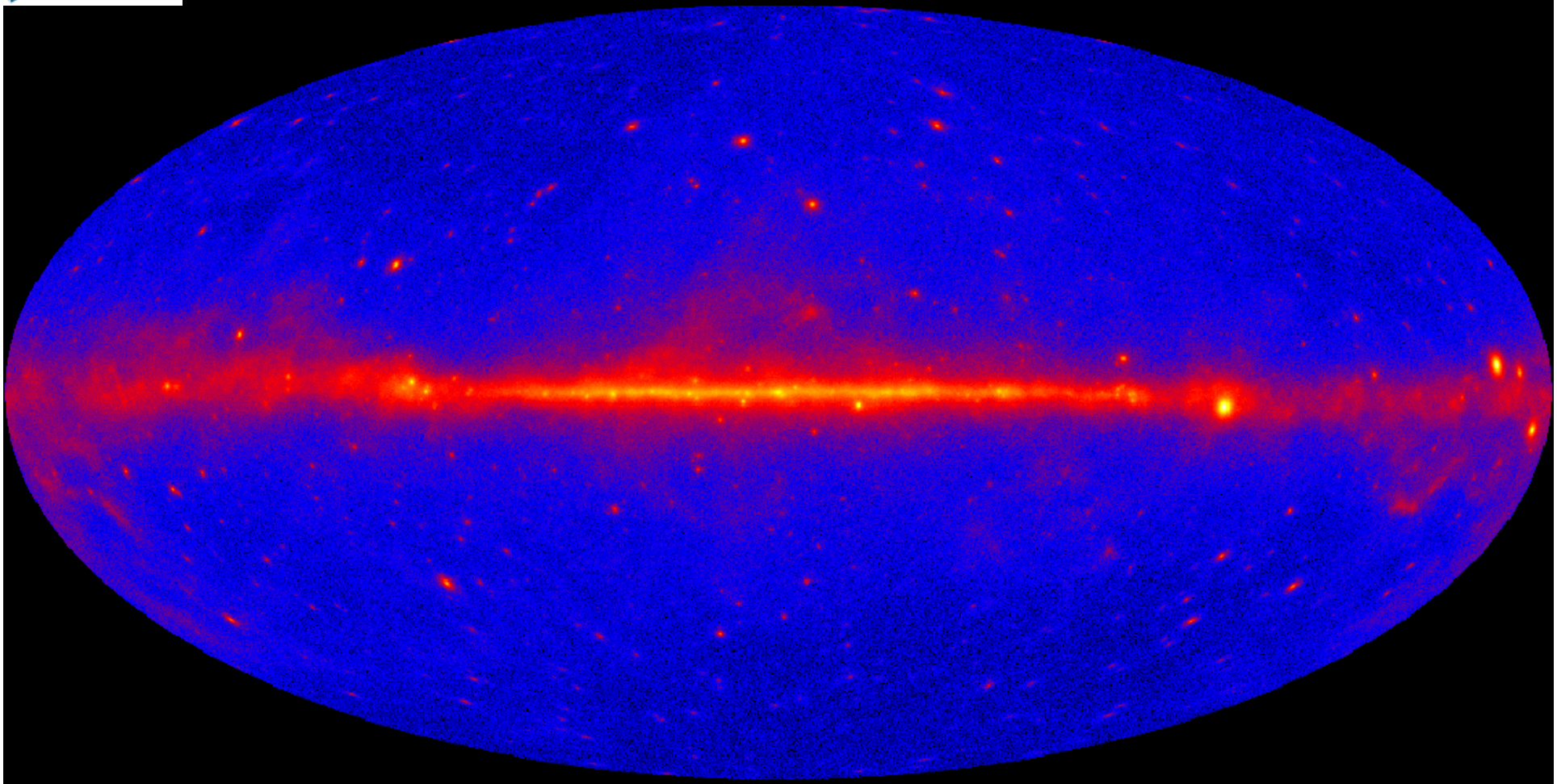
- **Structure is mostly that of the interstellar medium**
- **Below 10^{-8} ph/cm^2/s outside the Galaxy (|b| > 30°)**
- **Strong dependence on spectral index (hear B. Lott)**



Flux > 100 MeV required to reach TS=25 for average $E^{-2.2}$ spectrum

Galactic coordinates, Aitoff projection

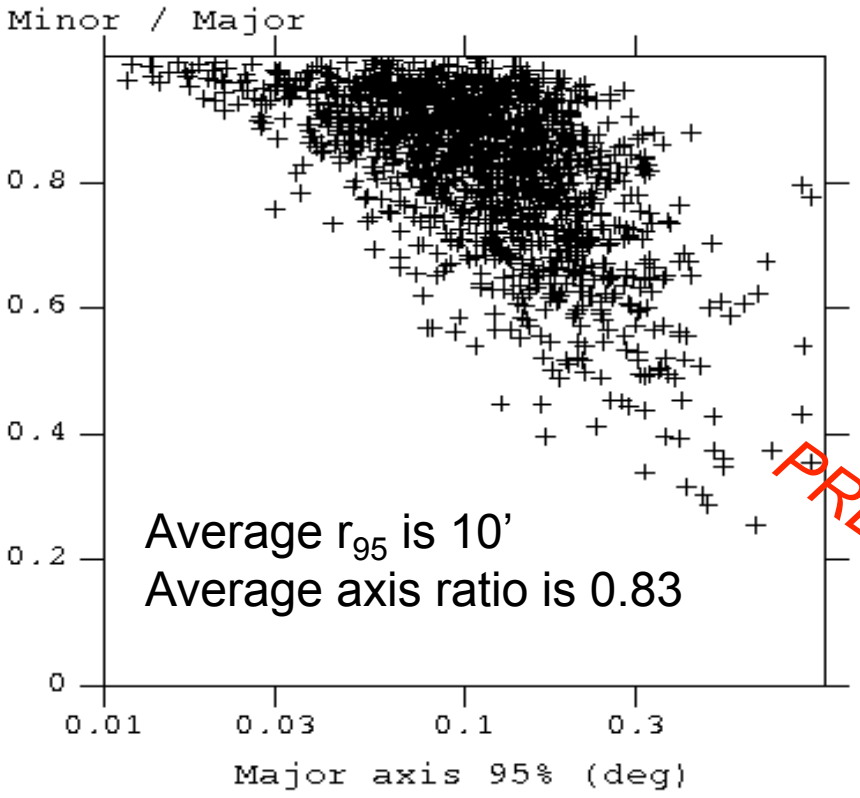
> 1000 LAT sources



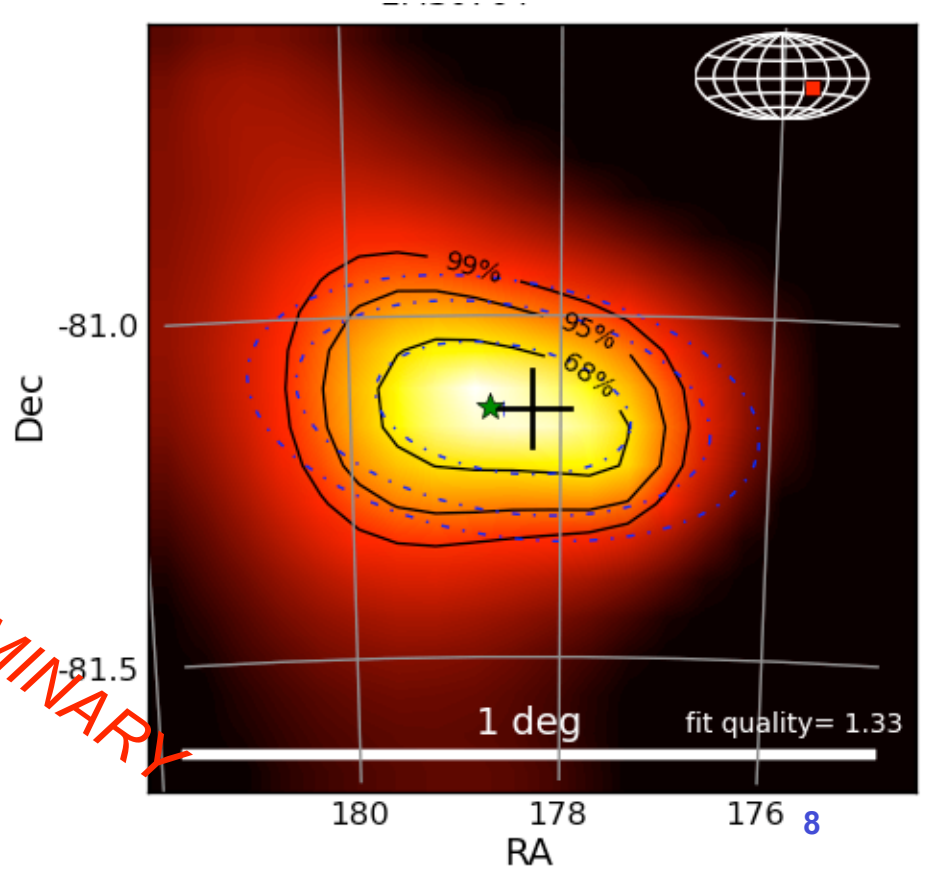
- Front > 200 MeV, Back > 400 MeV, log color scale
- Galactic coordinates, Aitoff projection

Source localization

- **Conservative error radii adjusted on known associations**
- **Conservative 0.012° absolute limit based on bright pulsars**
- **Elliptical parameters whenever can be extracted, mostly round.**



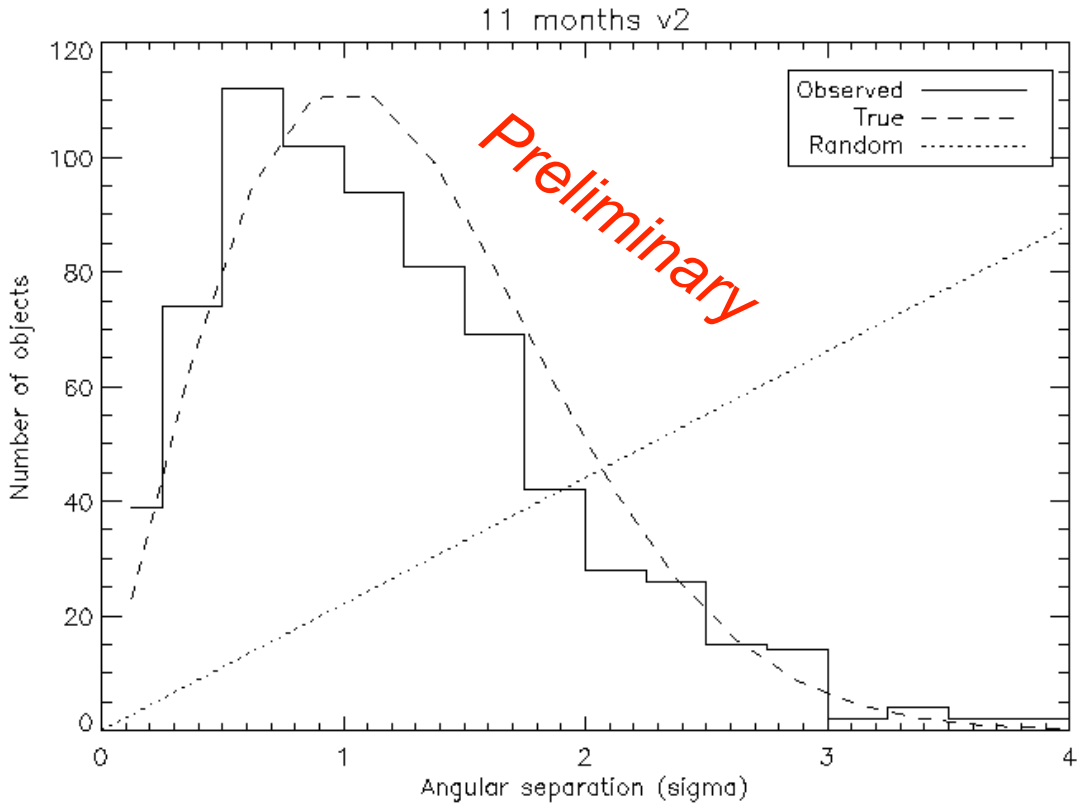
- **A difficult example is below. Cross is 1σ 1D error from other localization method for comparison**



PRELIMINARY

Source association

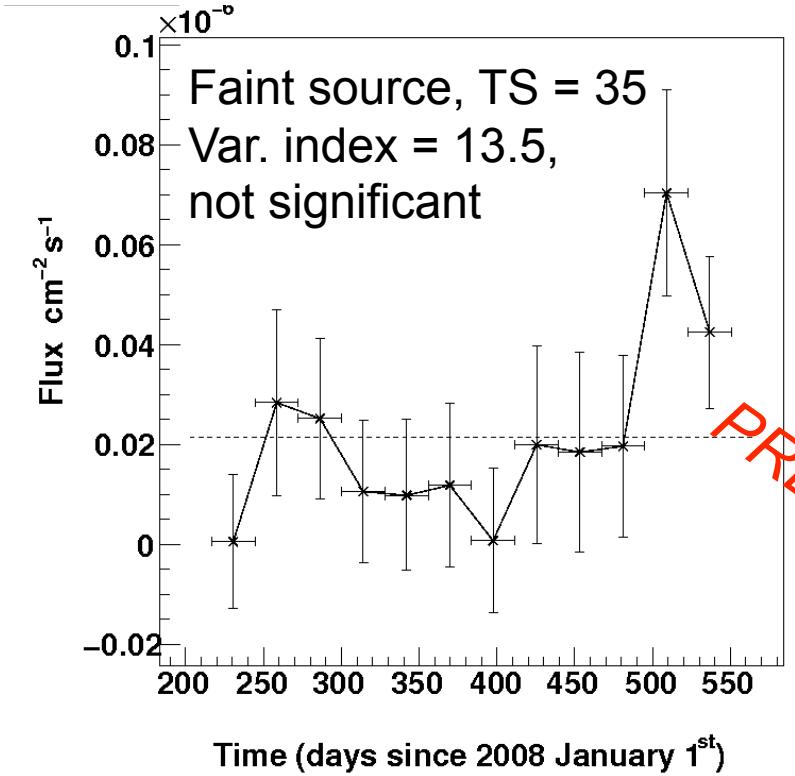
- **Likelihood ratio between true association (gaussian distribution with width defined from r_{95}) and random association (flat at counterpart density)**
- **Typically one half of the sources are associated to a plausible counterpart (radio blazar, pulsar, PWN, SNR, XRB), down from 2/3 at 0FGL (brighter)**

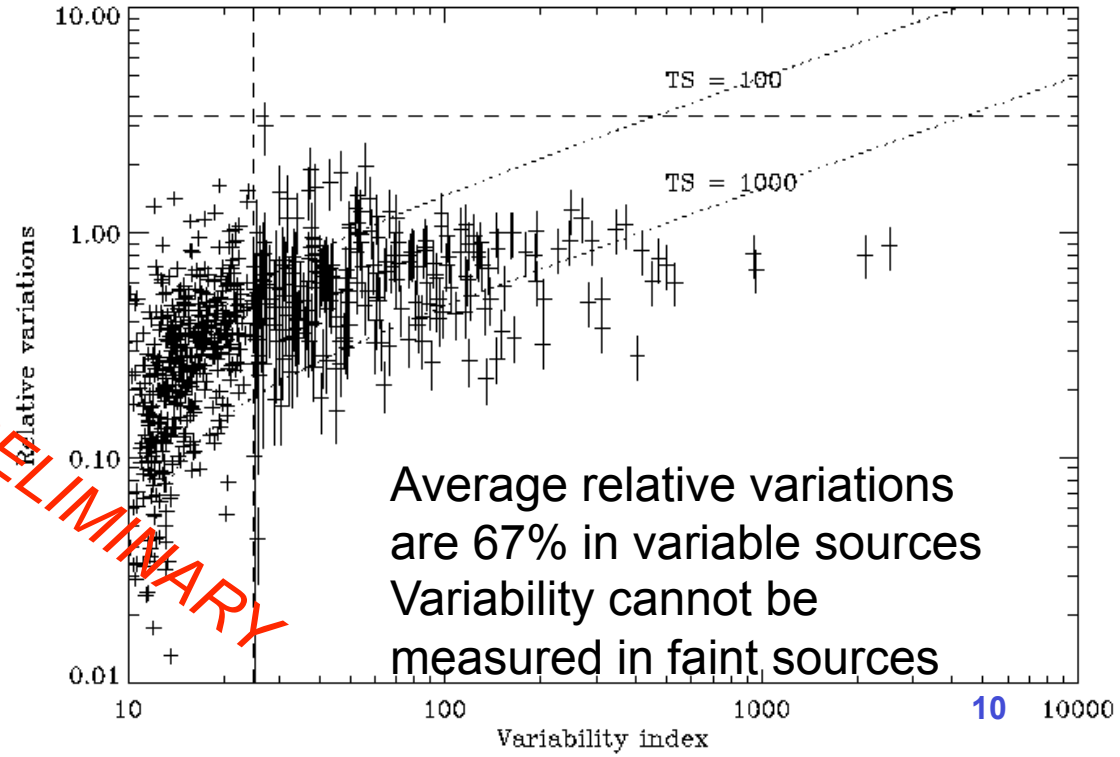


Point sources only
No doubt that most of these associations are true.
r_{95} was multiplied by 1.2 to cover the tail.
The distance distribution may be more complex than a simple gaussian

Source variability

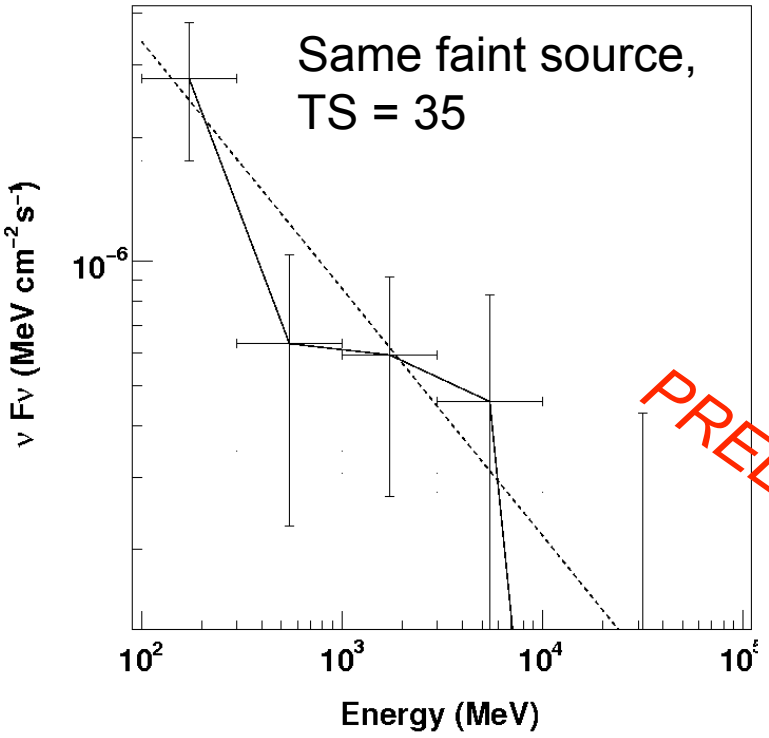
- **Build light curves of all sources on one-month time scale**
- **Pulsars are stable within 3%**
- **Bright blazars are very clearly variable**
- **Variability index: χ2 against constant hypothesis. 250 variable sources**
- **Relative variations: ΔF/F where ΔF^2 = measured variance minus Poisson variance**



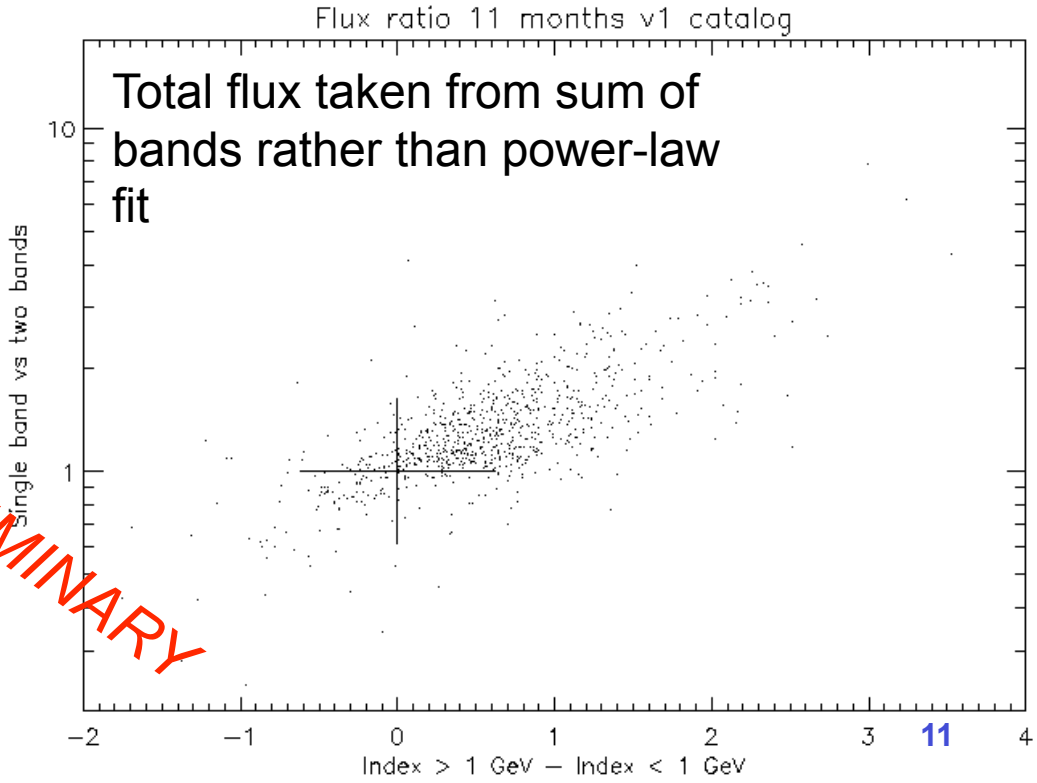


Source spectra

- **Extract flux of all sources in 5 bands from 100 MeV to 100 GeV**
- **Upper limit in bands in which sources are not significant**
- **Average spectrum is broken, power-law estimate is too high**
- **Sources not significant in all bands, total flux not well measured (strong detection does not imply well measured $F_{>100\ MeV}$)**

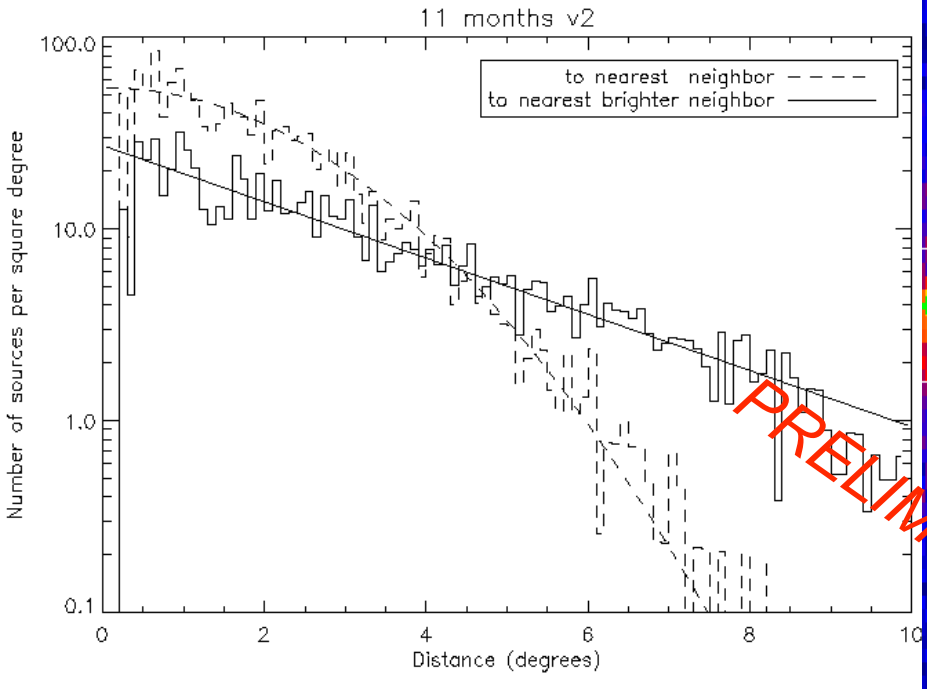


PRELIMINARY

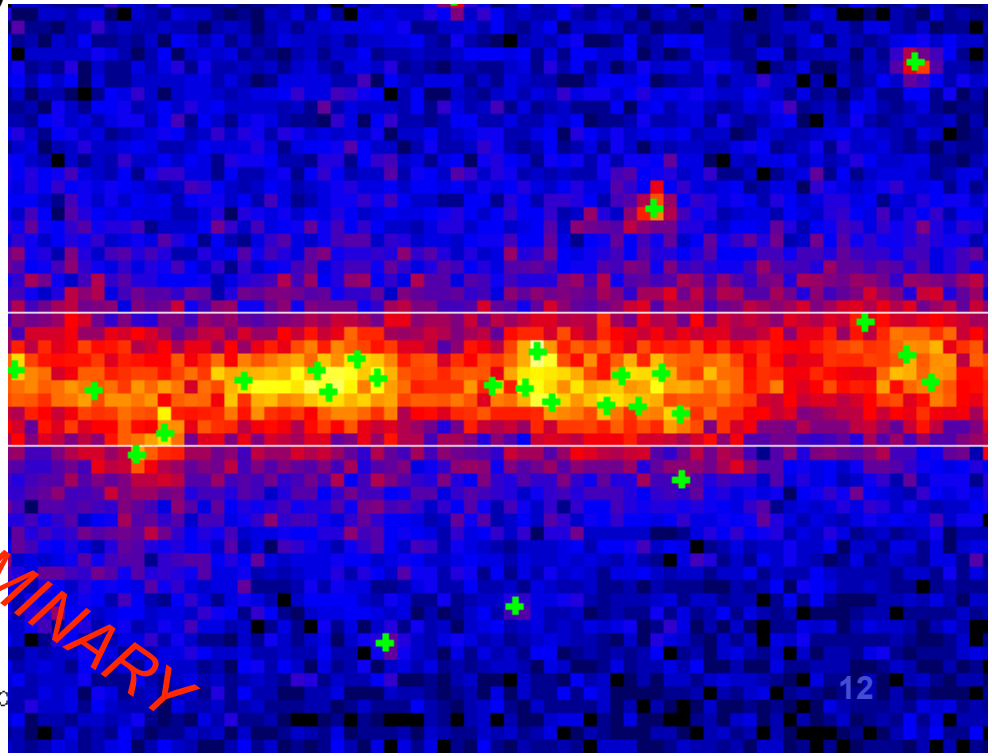


Source confusion

- Average distance between sources outside the plane is about 3°
- Much more than r_{68} at typical detection energy (0.8° at 1 GeV)
- Extrapolation to 0 distance indicates that only 6 sources or so are confused outside the plane
- Introduces additional bias against very soft sources ($\Gamma \geq 3$)



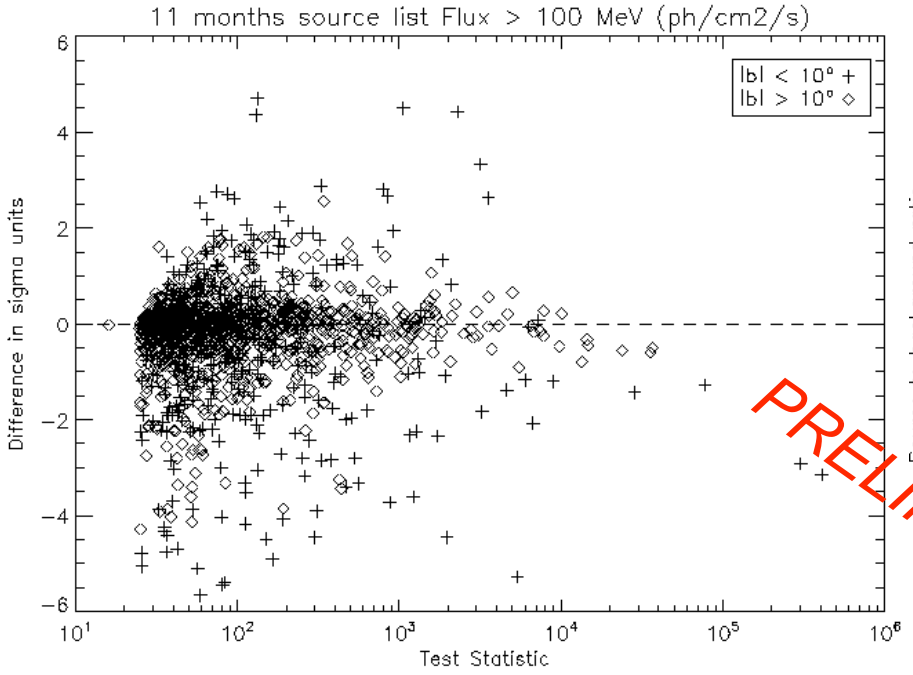
- **15° region of the Galactic ridge above 1 GeV**
- **Crosses are sources, pixel is 0.2°**
- **Sources not clearly separated**
- **Could be unmodeled diffuse emission**

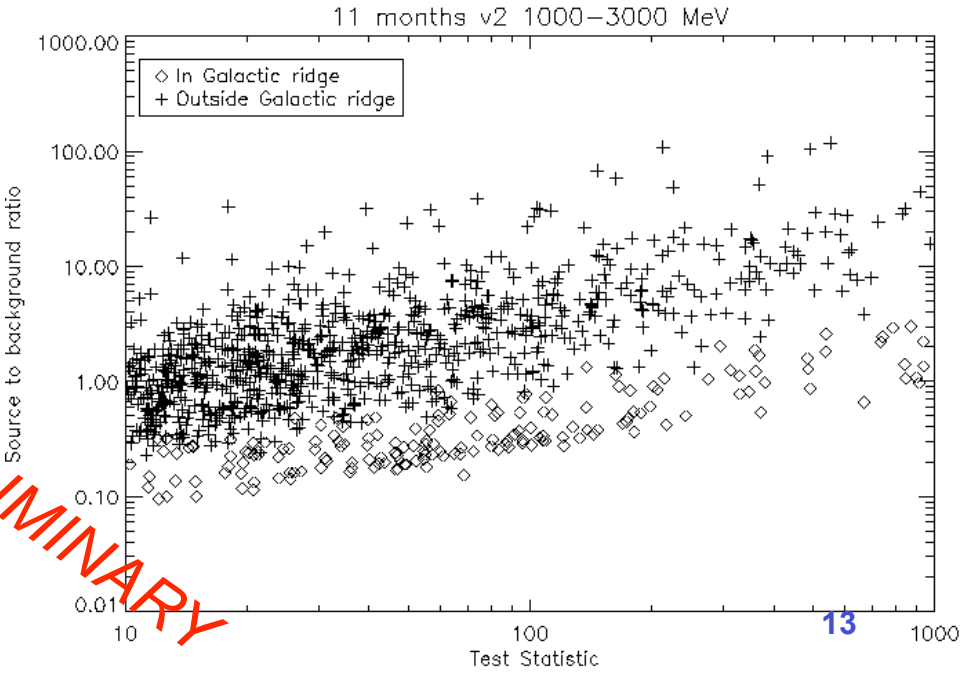


Diffuse emission uncertainties

- Use two different diffuse models to assess sensitivity of sources
- With good statistics, 10% of the background can be significant
- Inside Galactic plane, dispersion due to diffuse model is 1.8 sigma
- Outside plane, dispersion is 0.7 sigma

- **Source to background ratio within r_{68} is not very large in the Galactic plane even above 1 GeV.**
- **Has to go above 3 GeV to be above 50%**

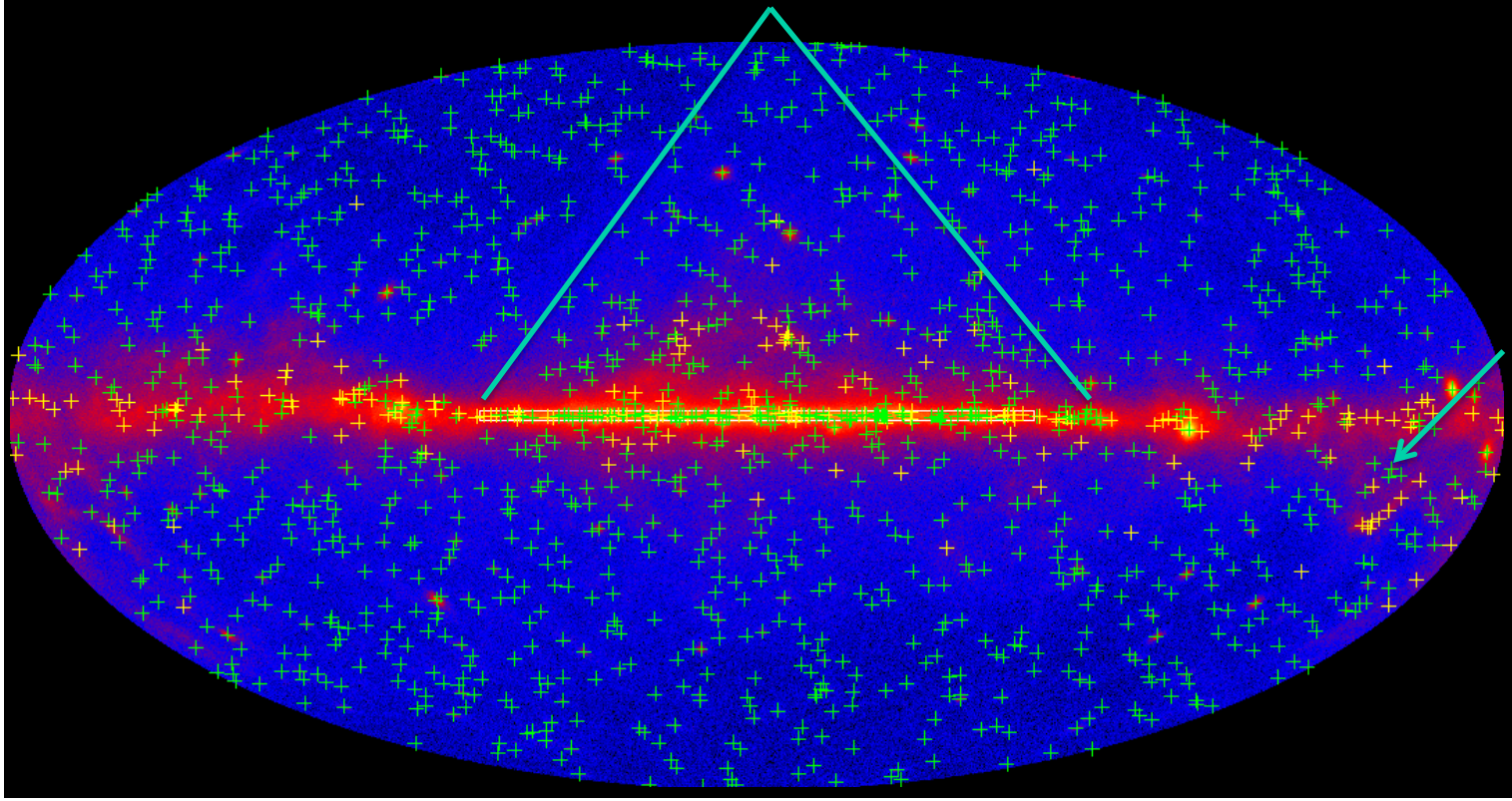




PRELIMINARY

First LAT source catalog: Difficulties

- The Galactic ridge (|lat| < 1°, |lon| < 60°) has serious difficulties: sources are close to each other, are not high above the background below 3 GeV, and the Galactic diffuse model is very uncertain there. This even affects sources statistically very significant (TS > 100).
- We plan to set Galactic ridge sources apart entirely (some 120 sources), and warn against using them without detailed analysis. Of course there are still many true sources in there, including pulsars and SNRs.



yellow flagged
green not flagged

Orion and ρ Oph clouds visible
Sources outside the Gal. ridge can be handled individually

On using the Catalog for Analysis

- As for the Bright Source List, the 1FGL Catalog will be distributed via the FSSC
  - As a FITS table, an XML input file for gtlike/ModelEditor, and as an ds9 region file
- The 1FGL Catalog will be useful for selecting specific sources for further study (e.g., with more or less data or with different spectral models or different model for diffuse emission)
- And for any likelihood analysis it will be useful for defining an initial guess at the point-source component for any ROI
  - N.B. The gamma-ray sky (blazars in particular) are highly variable and the flux and spectrum information in the 1FGL are only time averages for the 11 months of the data set
- For studies of diffuse emission at low latitudes and toward prominent local clouds, be aware that some 1FGL sources may be unresolved diffuse emission – whether they should be in the source model is a case-by-case decision

First LAT Source Catalog Conclusions

- Extends 0FGL to much fainter sources
- Typical 95% error radius is 10 arcmin. Absolute accuracy is better than 1'
- About 250 sources show evidence of variability
- About half the sources are associated positionally, mostly with blazars and pulsars
- Other classes of sources exist in small numbers (XRB, PWN, SNR, starbursts, globular clusters, radio galaxies, narrow-line Seyferts)
- Uncertainties due to the diffuse model, particularly in the Galactic ridge, should be kept in mind for low-latitude and local cloud studies
- The Catalog is an analysis product but also a useful input for many other studies with LAT data

Backup Slides

Other LAT catalogs

- The AGN catalog, drawn from sources above 10° latitude, excluding known non AGN. Goes with the full source catalog, which adopts the AGN associations. Similar to LBAS (ApJ 700, 597) vs BSL (ApJS 183, 46)
- The pulsar catalog, drawn from all pulsed detections of both radio and γ-ray pulsars. First version (6 months of data) submitted to ApJ (arXiv:0910.1608)
- The gamma-ray burst catalog, drawn from all GRB detections. Completely separate (bright GRBs are actually excluded for the LAT source catalog). Available in quasi real time at Fermi SSC