Fermi Gamma-ray Space Telescope

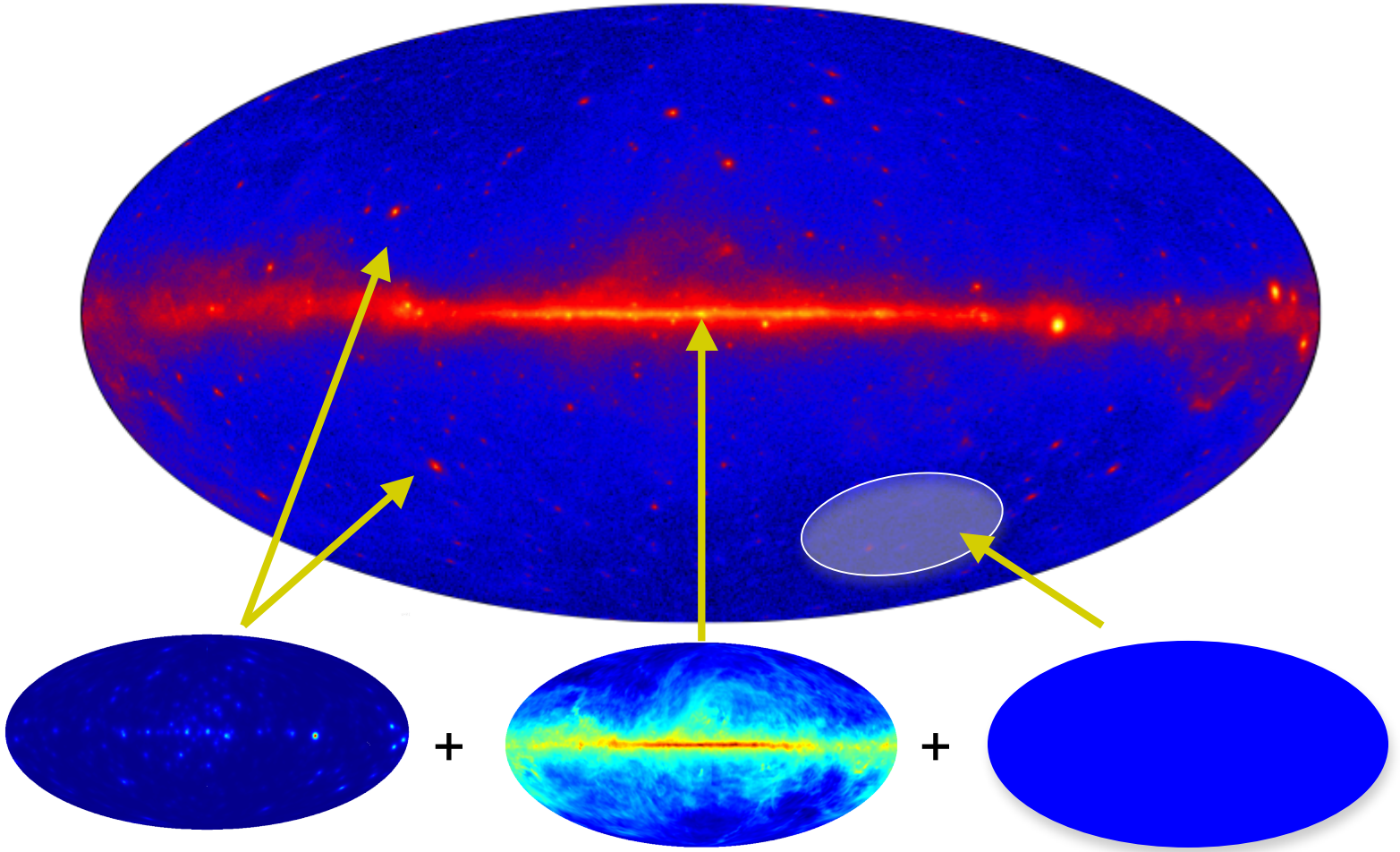
The variety of sources in LAT data

Elizabeth Ferrara
Fermi Science Support Center

2011 Fermi Summer School
May 31 - June 10

LAT Data Set

- **The LAT data consists of events from numerous different astrophysical sources + multiple sources of background**

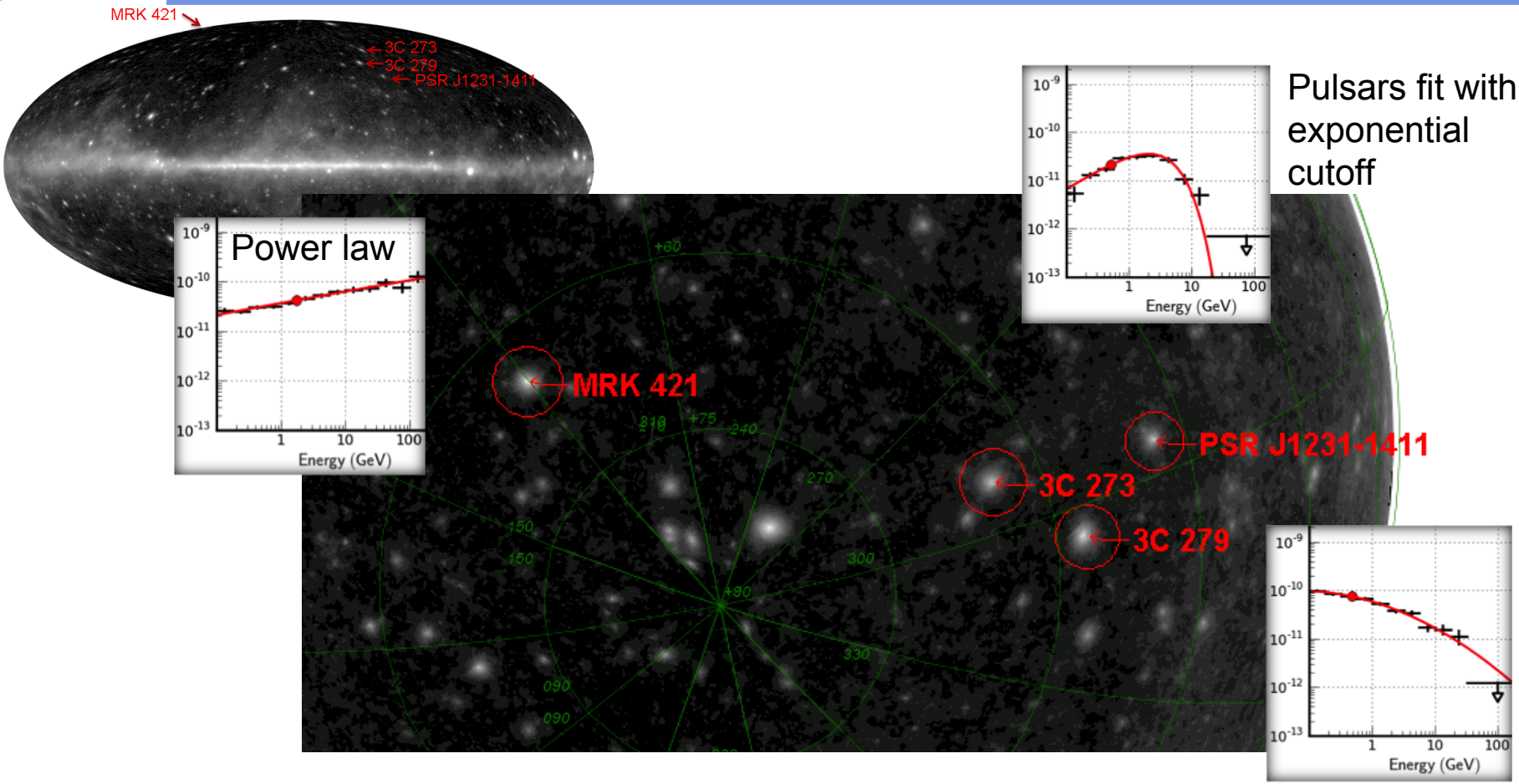


Detection and Analysis of Point Sources

- **Finding point sources in the LAT dataset is an iterative process**
  1. **Generate seed positions**
  2. **Simultaneously fit putative sources plus background**
  3. **Apply cut to remove sources that are not significant**
  4. **Look at residuals to find new candidate sources**
  5. **Iterate**

- **All-sky analysis is too computer-intensive**
  - **Requires sky be divided into "manageable" regions**
  - **Source extension or spectral shape can add to the complexity**

Spectral Shape



Pulsars fit with exponential cutoff

Spectral shape is a contributing factor in whether or not a source is significantly detected

Use log parabola or broken power law if it gives a better fit

Associations vs. Identifications

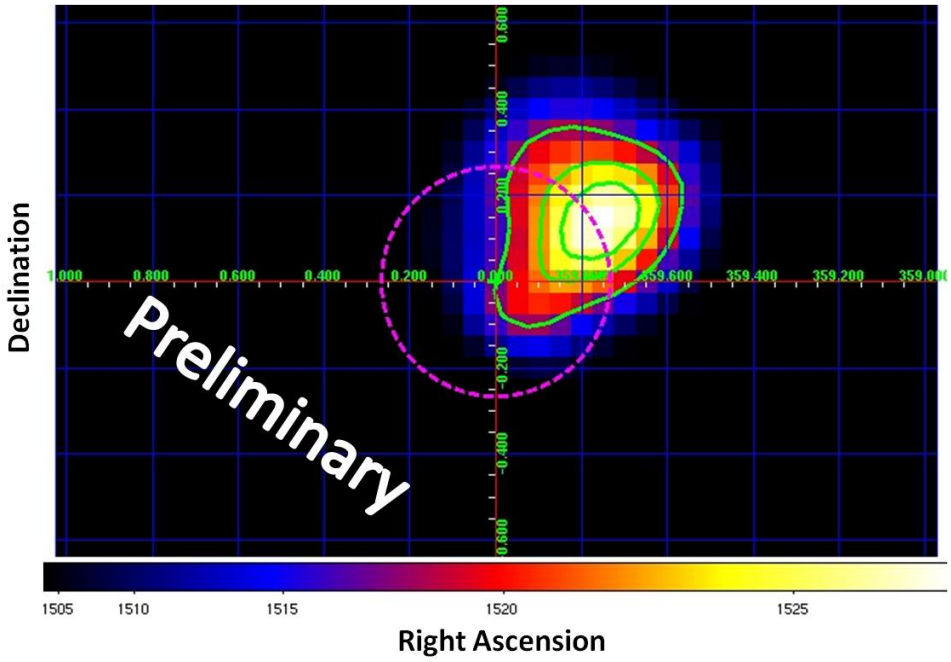
- **Sources are considered associated when their positions coincide with plausible gamma-ray-producing objects**
  - **Association technique is a Bayesian probability analysis based on the local density of sources from catalogs of likely objects**
  - **Average 95% uncertainty radius is about 7 arcmin**
  - **Too large in most cases to claim identification based on position**

- **Some LAT sources are firmly identified**
  - **Periodic signals, spatial morphology, or correlated variability with objects known at other wavelengths**

Unlocalized Events - 1

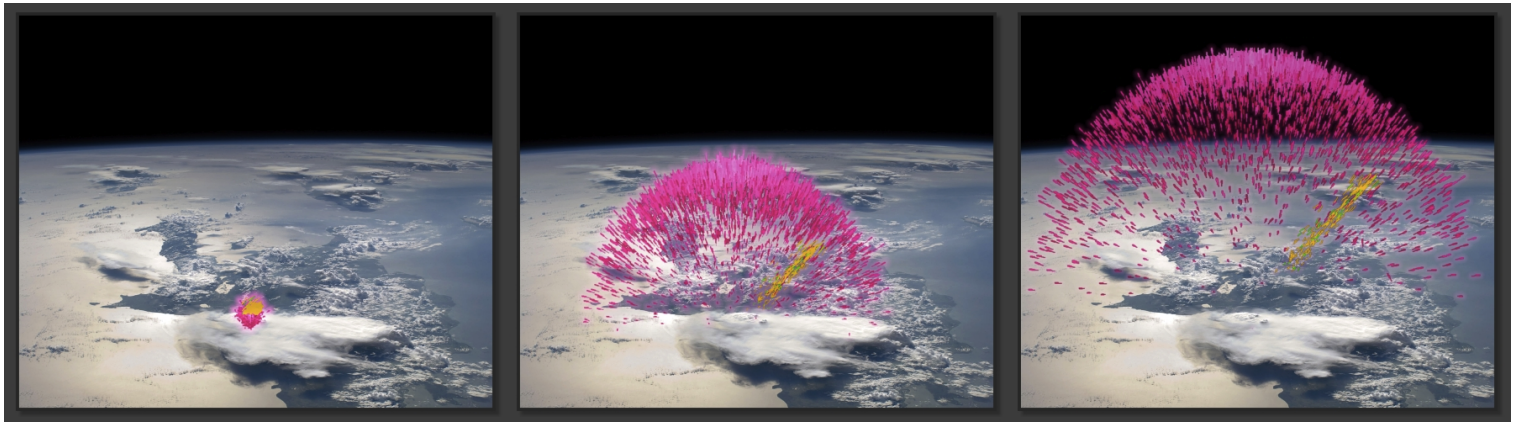
- **Some events affect the ability of the instrument to acquire data**
  - **In general, these events will be filtered out by the event classification process**
  - **Use the recommended data cuts to eliminate undesired effects**

- **Solar Flares**
  - **Seen by EGRET**
  - **Can last for many minutes to hours**
  - **Will become more prevalent as the solar cycle continues**
  - **As the Sun is a moving source, it can affect many other sources**

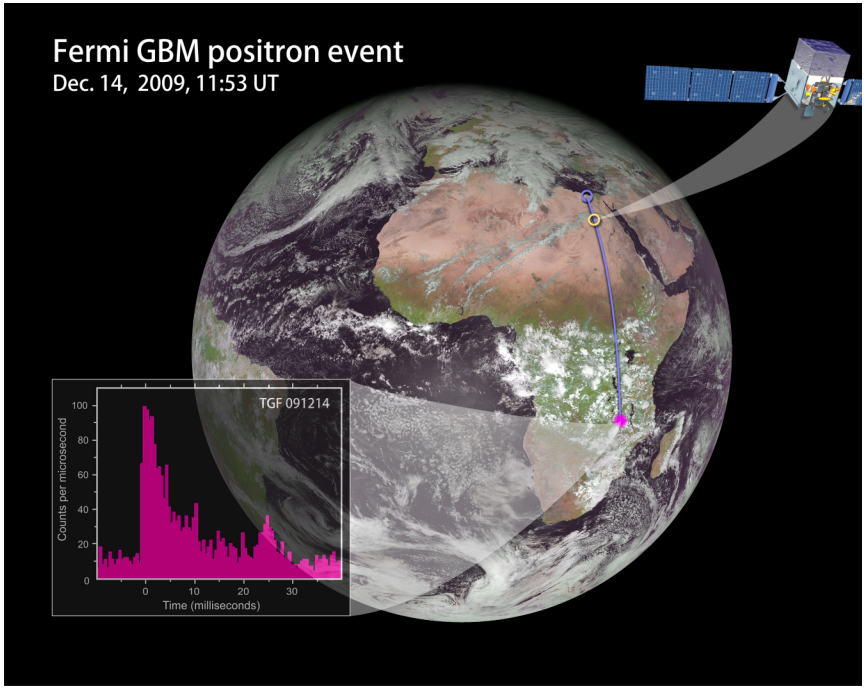


March 7, 2011 Solar Flare

Unlocalized Events - 2



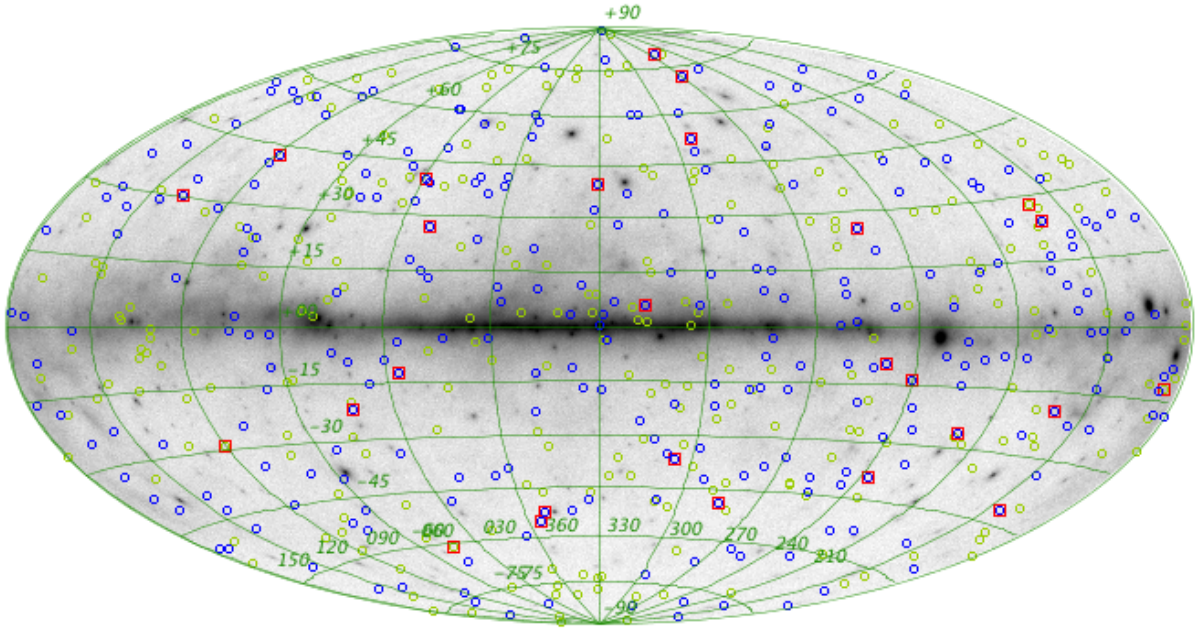
- **Terrestrial Gamma-Ray Flashes (TGFs)**
  - **Several-microsecond events associated with thunderstorms on the Earth**
  - **Two types seen by GBM**
  - **Not currently detected by the LAT**



Transient Events - 1

More on Friday

- **Extragalactic Transients: Gamma-Ray Bursts (GRBs)**
  - **Rapid, very energetic events at extreme distances**
  - **Very short timescales (seconds to 100s of seconds)**
  - **Seen frequently by GBM (~550)**
  - **A subset of these are seen by the LAT (27)**
    - ***Must have a high-energy component***
    - ***Must be within the LAT field of view (FOV)***
  - **Can affect analysis if near the source of interest**



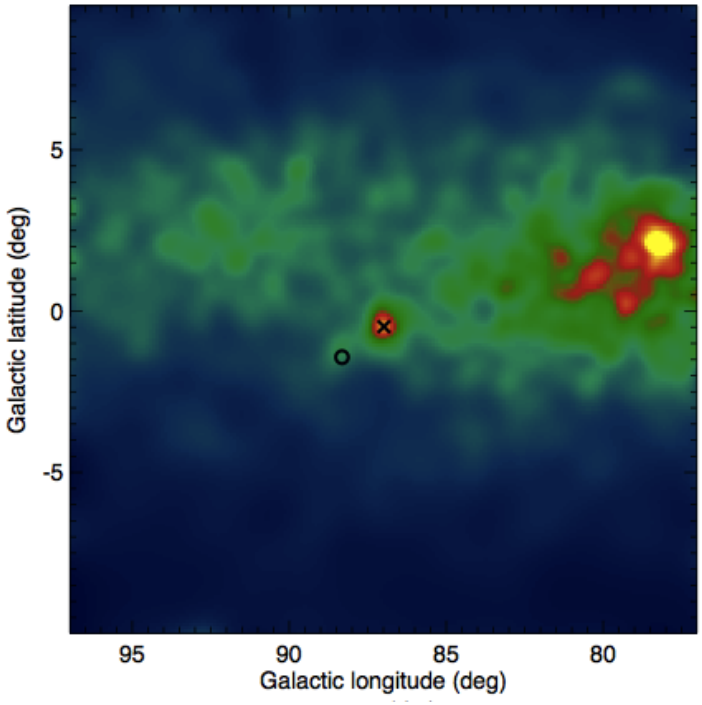
Circles:
In Field-of-view of LAT (<70˚): 275
Out of the FOV
Squares:
LAT detections

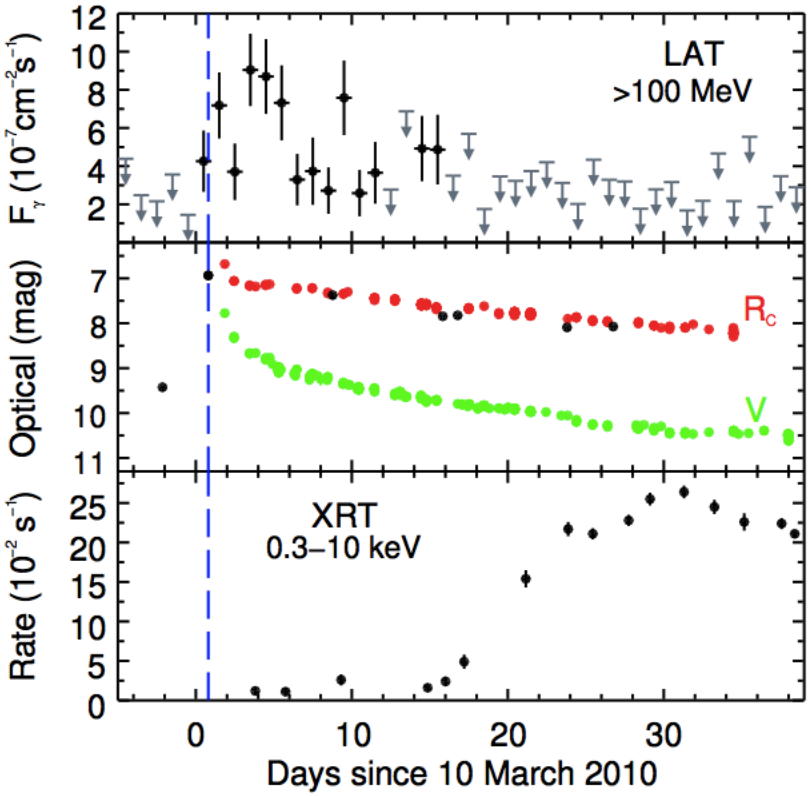
Transient Events - 2

More next Thursday

- **Galactic Transients:**
  - **Several Galactic transients have been seen by the LAT since Fermi started science operations**

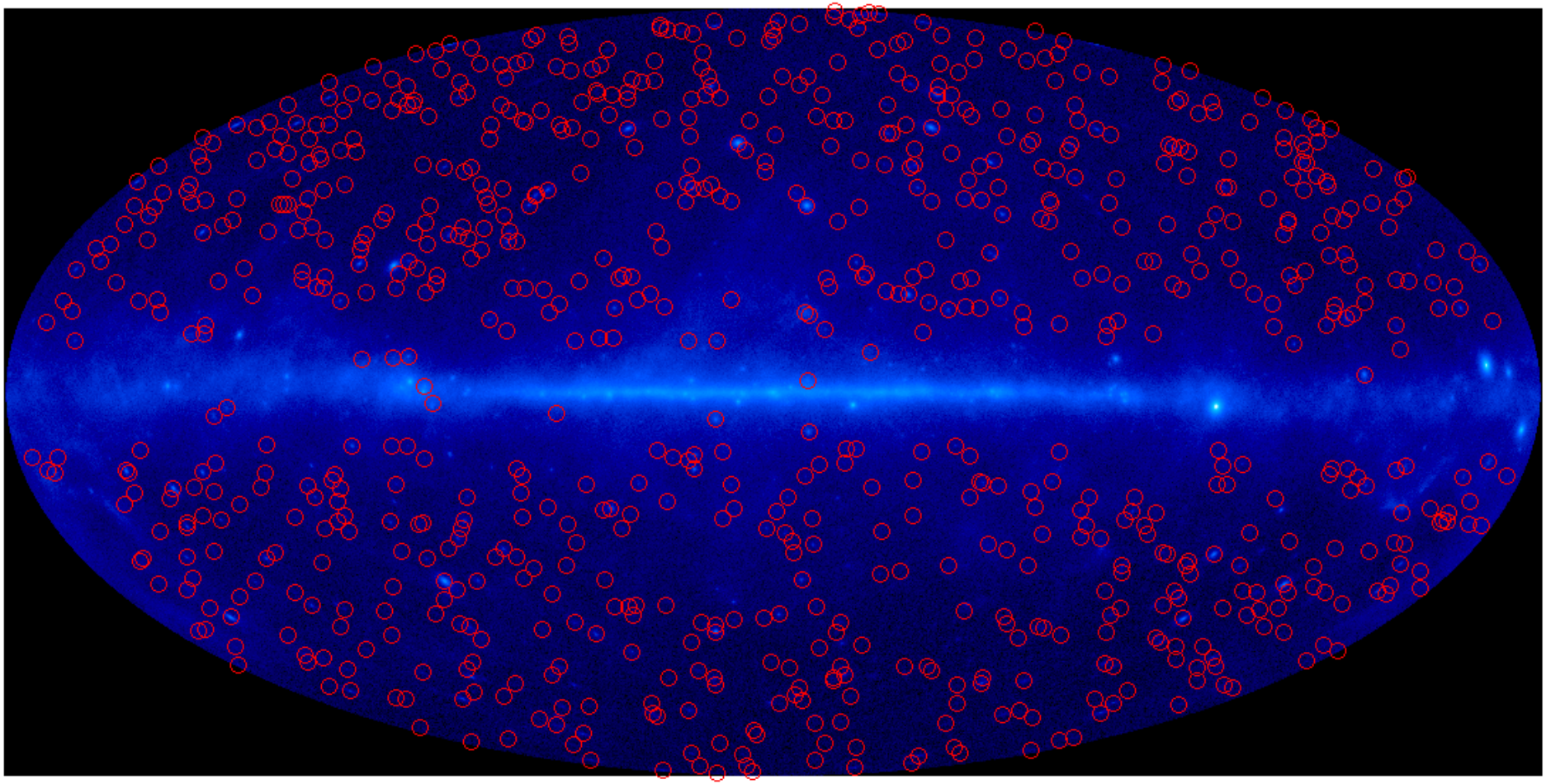
- **Nova V407 Cyg - symbiotic binary**
  - **Explosion into surrounding medium generated a shock front that generated gammas**





Blazars

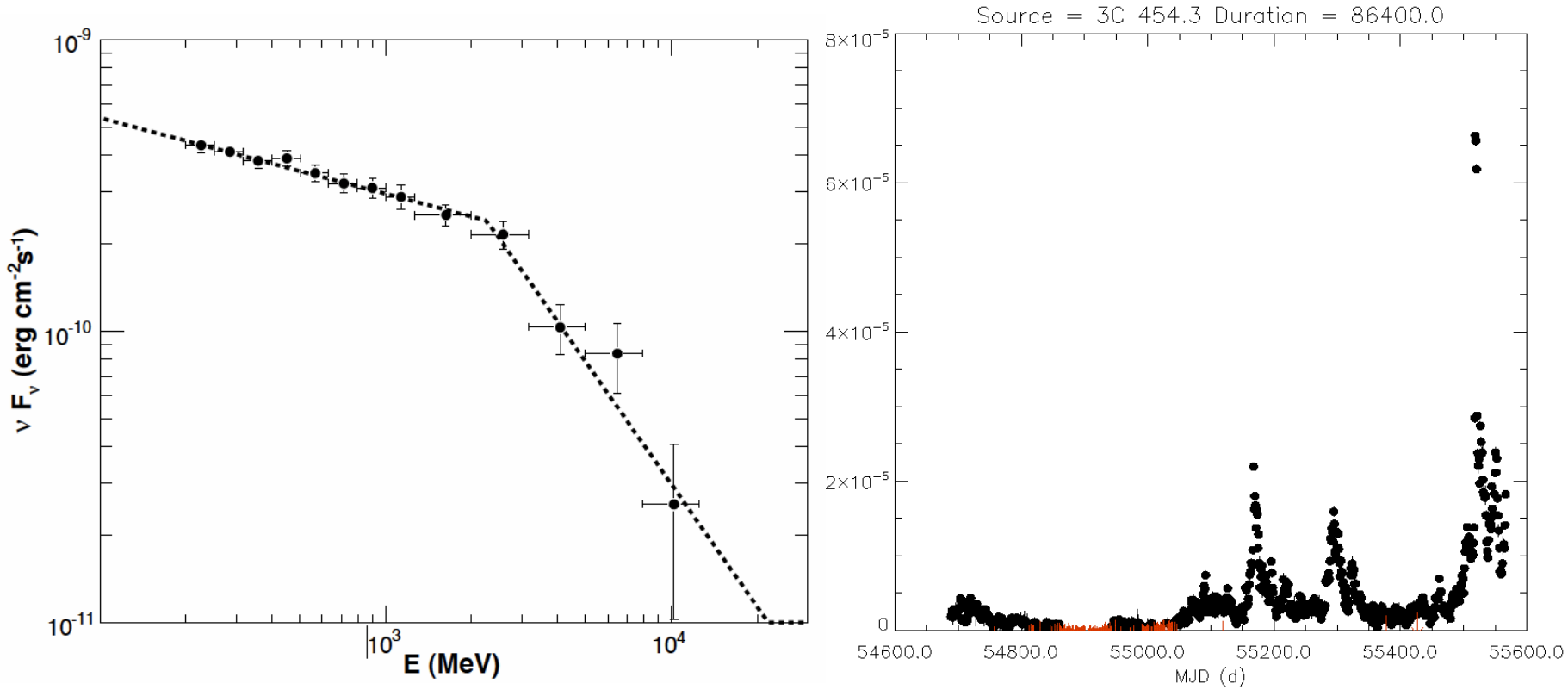
- **The most numerous class in the LAT data by far!**



Detecting LAT Blazars

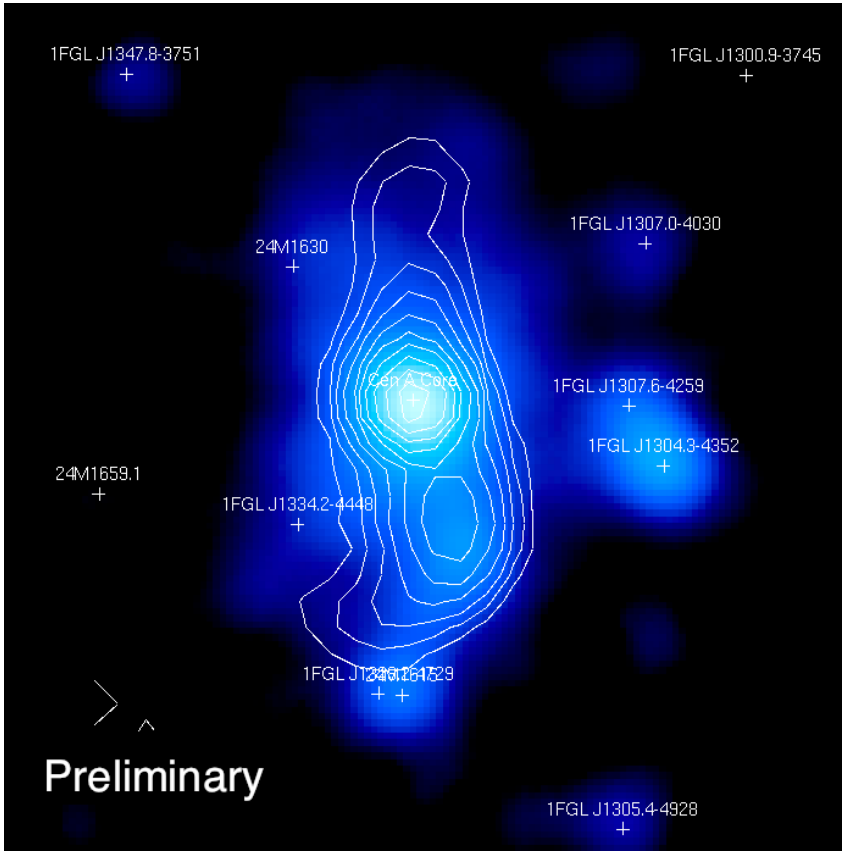
More tomorrow

- **Blazar detection is affected by both spectral and temporal characteristics**
  - **BL Lacs and FSRQs have spectral peaks in different energy ranges (spectral index varies widely)**
  - **Flux varies significantly with time**



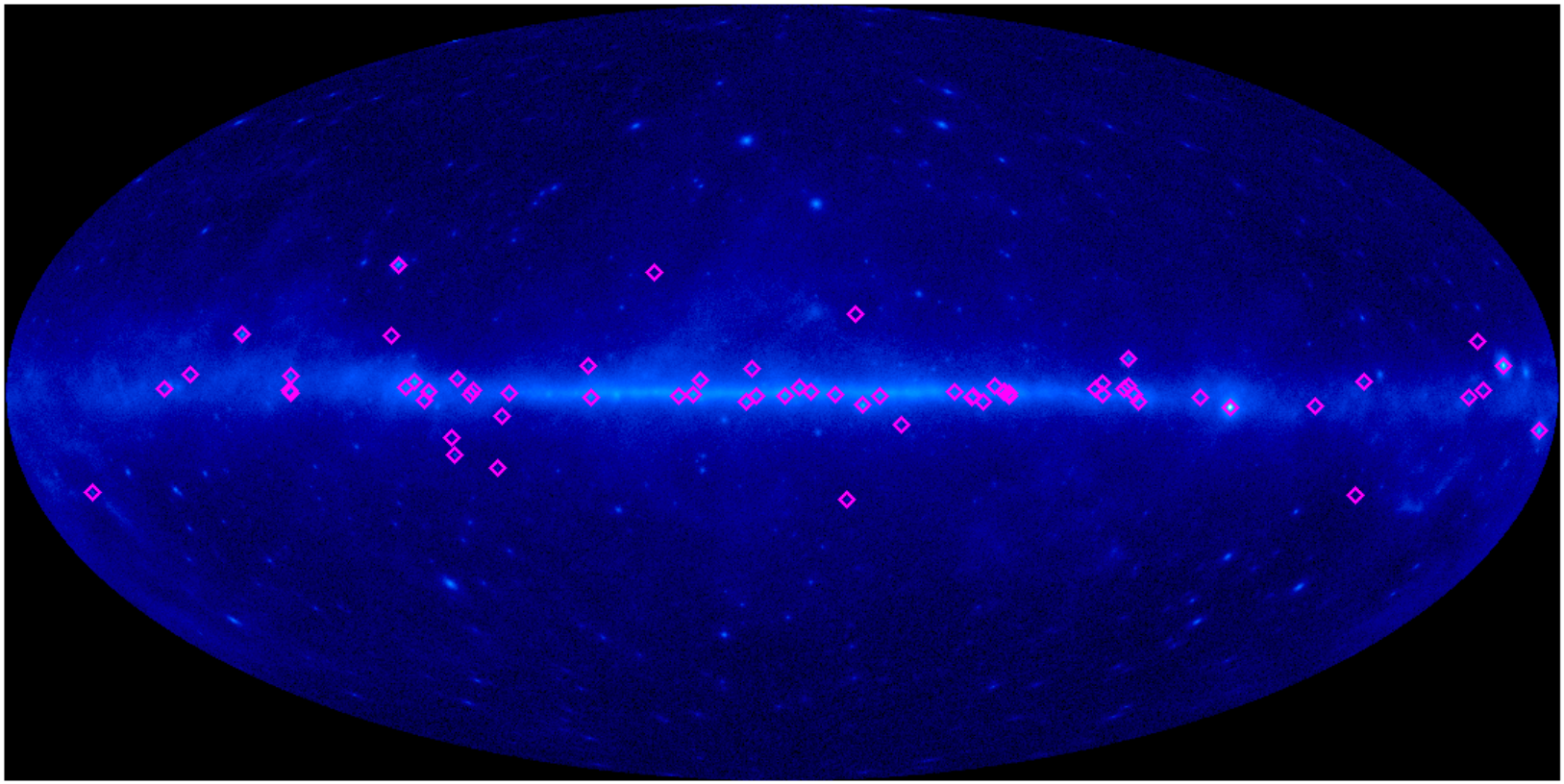
Other AGN

- **Blazar Candidates**
  - **Blazar associations use a 'figure of merit'**
  - **Candidate sources have radio detections that look like blazars**
  - **But require additional follow-up to be able to calculate the FOM**
- **Narrow-Line Seyfert 1s**
  - **Three of these sources show LAT emission**
- **Radio Galaxies**
  - **Currently 4 of these sources are showing LAT emission**
  - **Centaurus A radio lobes are fully resolved by the LAT**



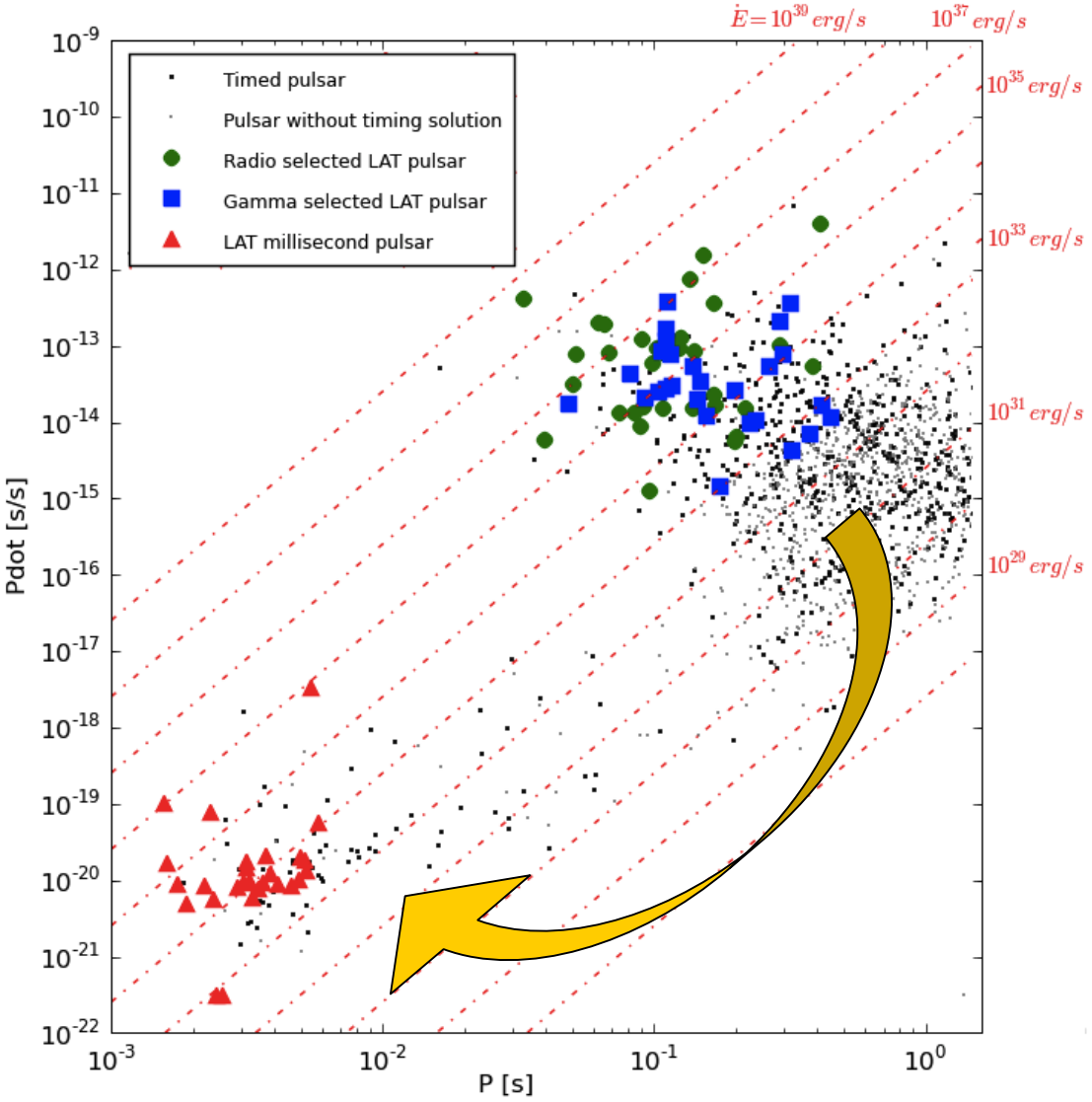
Young Pulsars

- **Highly energetic pulsars have long been known to be gamma-ray emitters**
  - **Typically discovered by applying known radio ephemerides to the gamma rays**
  - **Can also be discovered in the gamma-ray data (26 with LAT)**



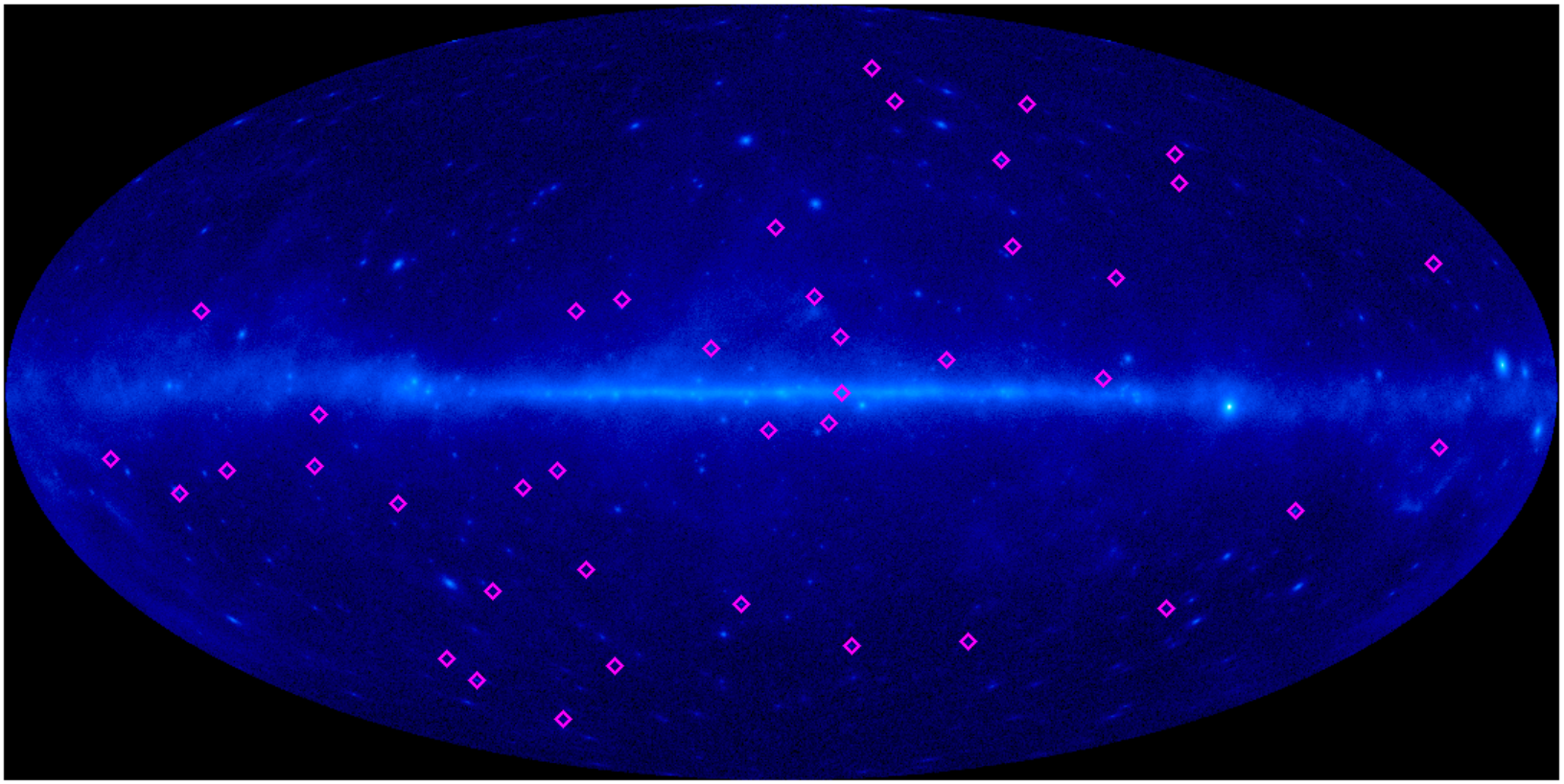
Recycled Pulsars

- Over time young energetic pulsars slow down
  - Power for pulsations comes from rotation
  - Once energetics are no longer favorable, pulsations cease
- Pulsars in binaries can get a second life through mass transfer
  - Increase in angular momentum produces millisecond periods and high energetics



Millisecond Pulsars

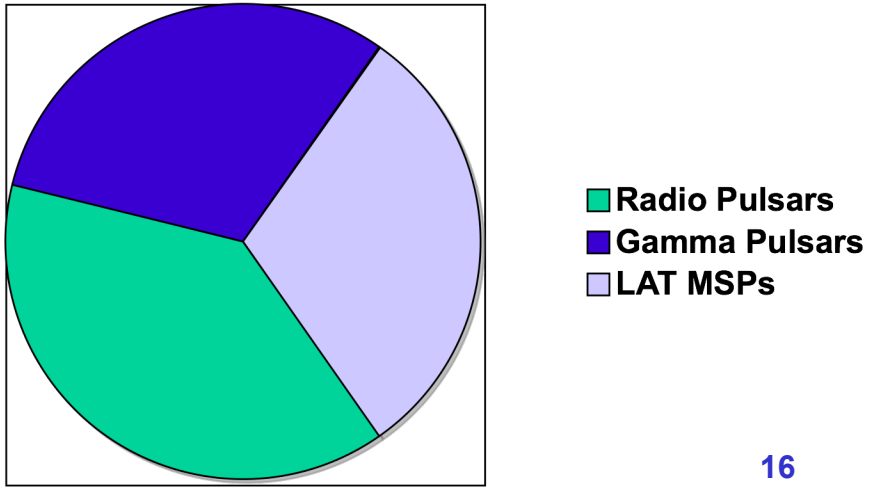
- **Indeed a number of new millisecond pulsars have been found in the LAT data**
  - **Discovered by radio searches in LAT sources that lack counterparts**
  - **Significant increase in Galactic MSPs known (~60 +33 new)**



Pulsar Populations

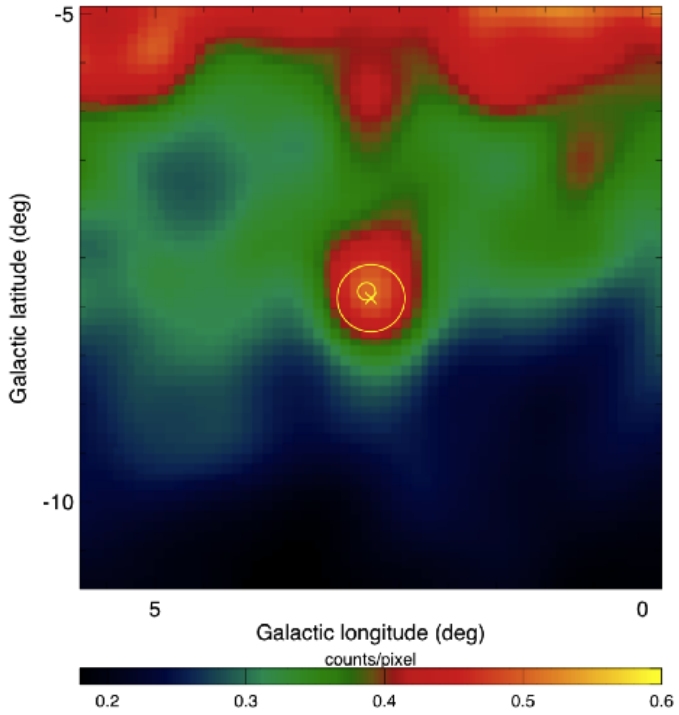
More next Monday

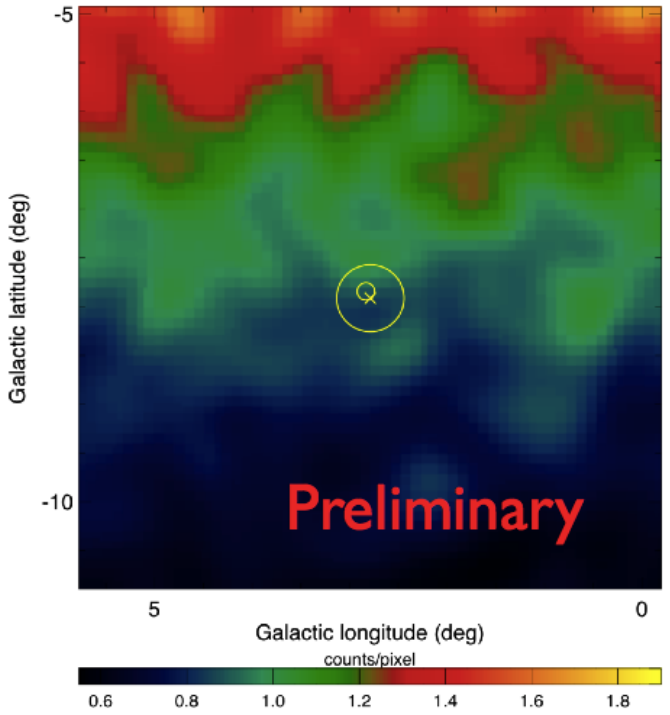
- The LAT-detected pulsars are typically referred to by their discovery method
  - Radio-selected used known radio ephemerides to find the LAT pulsations
  - Gamma-selected were discovered by folding the gamma-ray data (blind searches), and are usually radio-quiet (or very radio-faint)
  - LAT MSPs were all found using radio ephemerides
    - *Current blind search techniques are not sensitive to millisecond periods*
- Also 23 'radio-only' MSPs
  - Discovered in the radio by looking at LAT sources
  - Takes 6 months to a year to get a good timing solution
  - May soon be LAT pulsars



Globular Clusters

- **Some globular clusters have long been known to contain numerous MSPs**
  - **LAT detects 11 sources coincident with globular clusters**
  - **In one instance (J1823-3021A) a single luminous gamma-ray pulsar has been found to be responsible for the entire LAT-detected emission from the cluster**

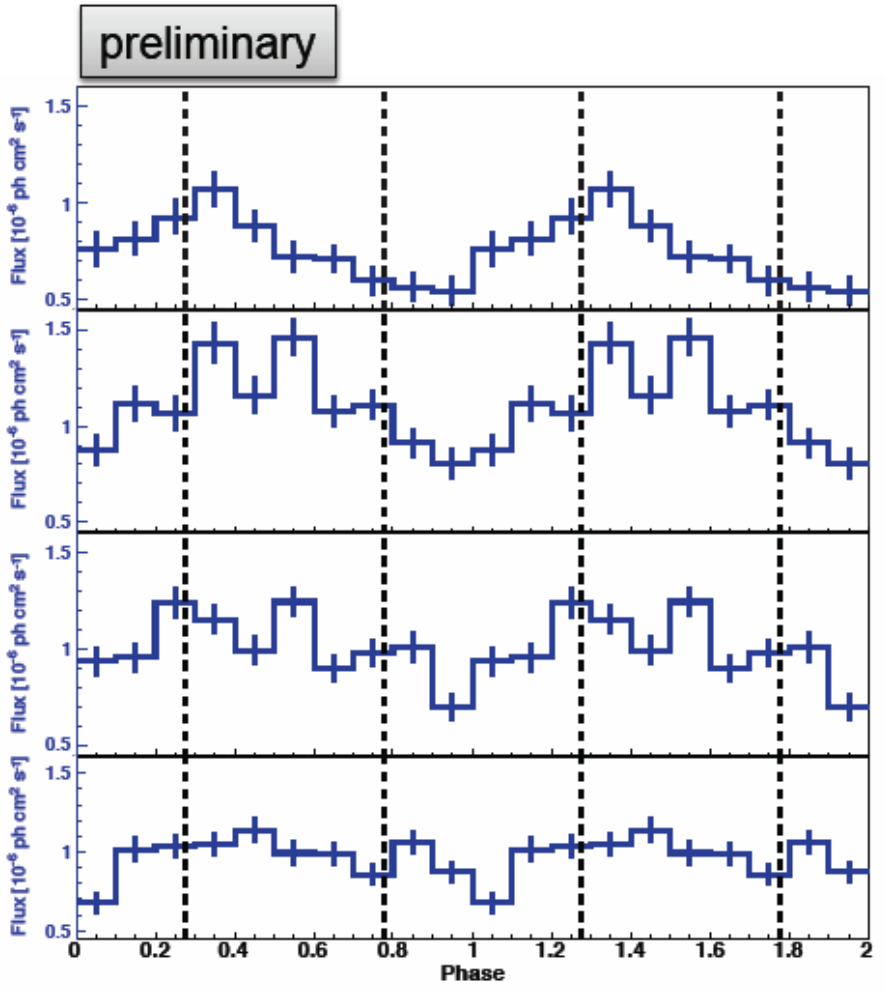




High-Mass X-ray Binaries

More next Tuesday

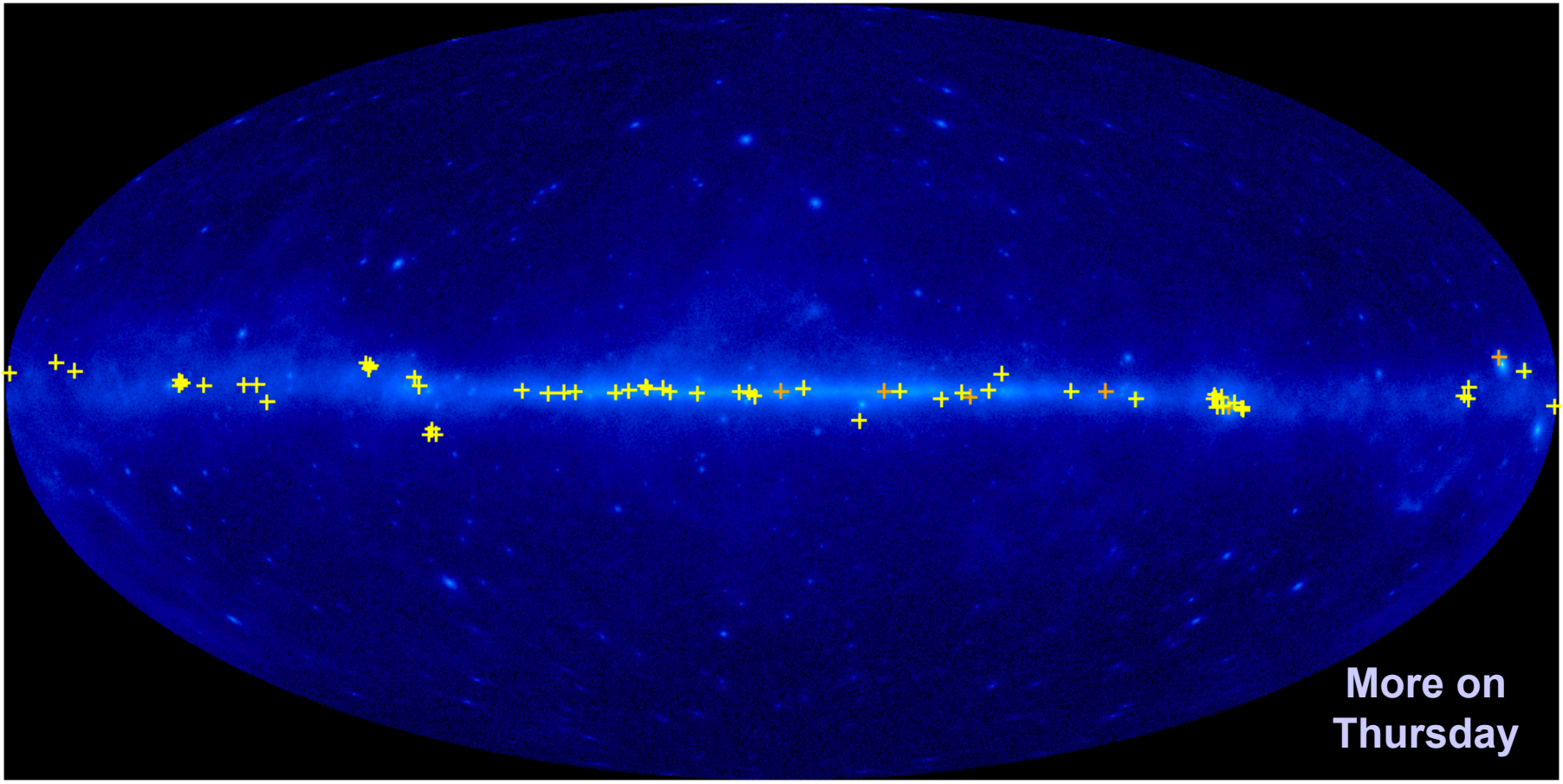
- The LAT detects periodic signals from four HMXBs:
  - Cyg X-3
  - LS 5039
  - LSI +61 303
  - 1FGL 1018.6-5856 (new discovery!)
- LSI +61 303 orbital signal appears to have slowly disappeared since the beginning of science operations



Folded light curve in 6-month intervals

Supernova Remnants / Pulsar Wind Nebulae

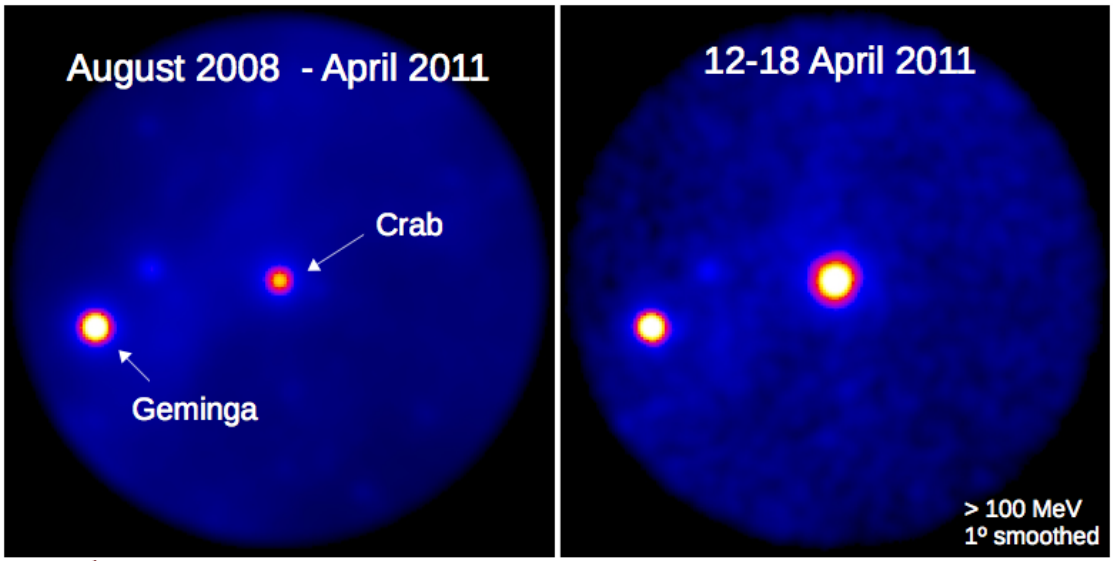
- **Third most numerous class behind blazars and pulsars**
  - **60 SNRs/PWNe in a very narrow distribution**
  - **Some positively identified by matching their extension to other wavelengths**

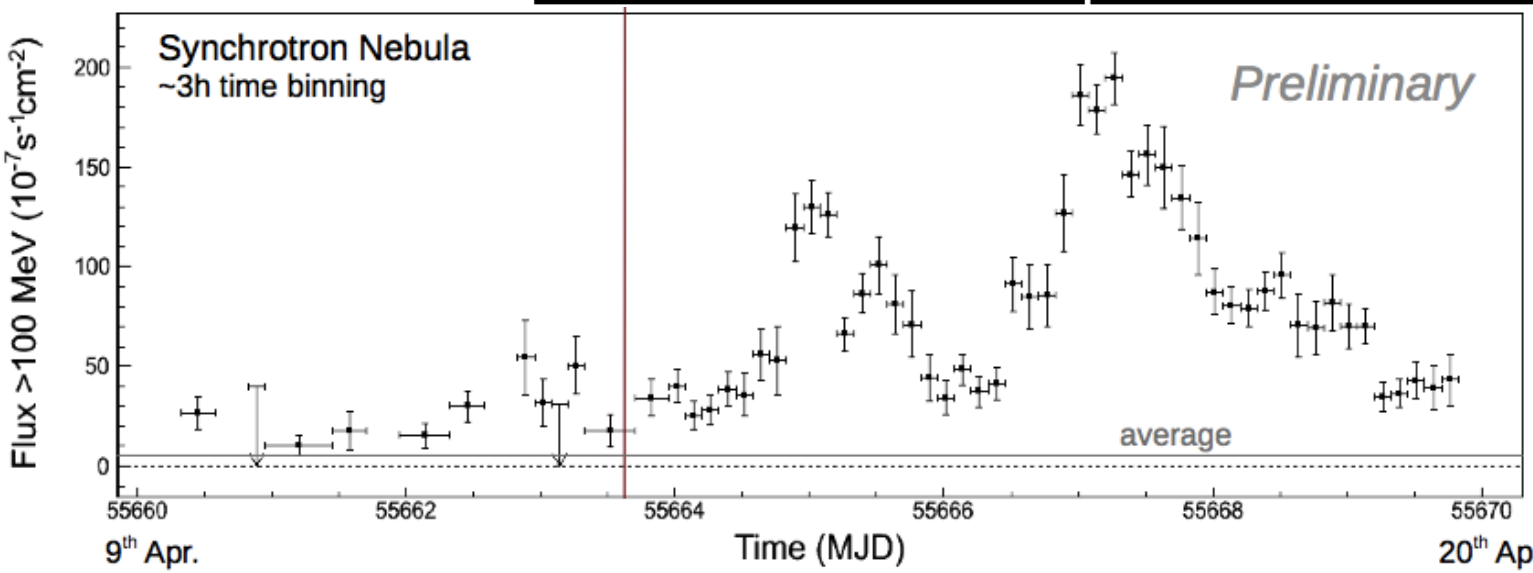


The Variable Crab?

- **The Crab pulsar + SNR is used as a calibration source in high-energy astronomy**

Recent variability from this source was quite a surprise!

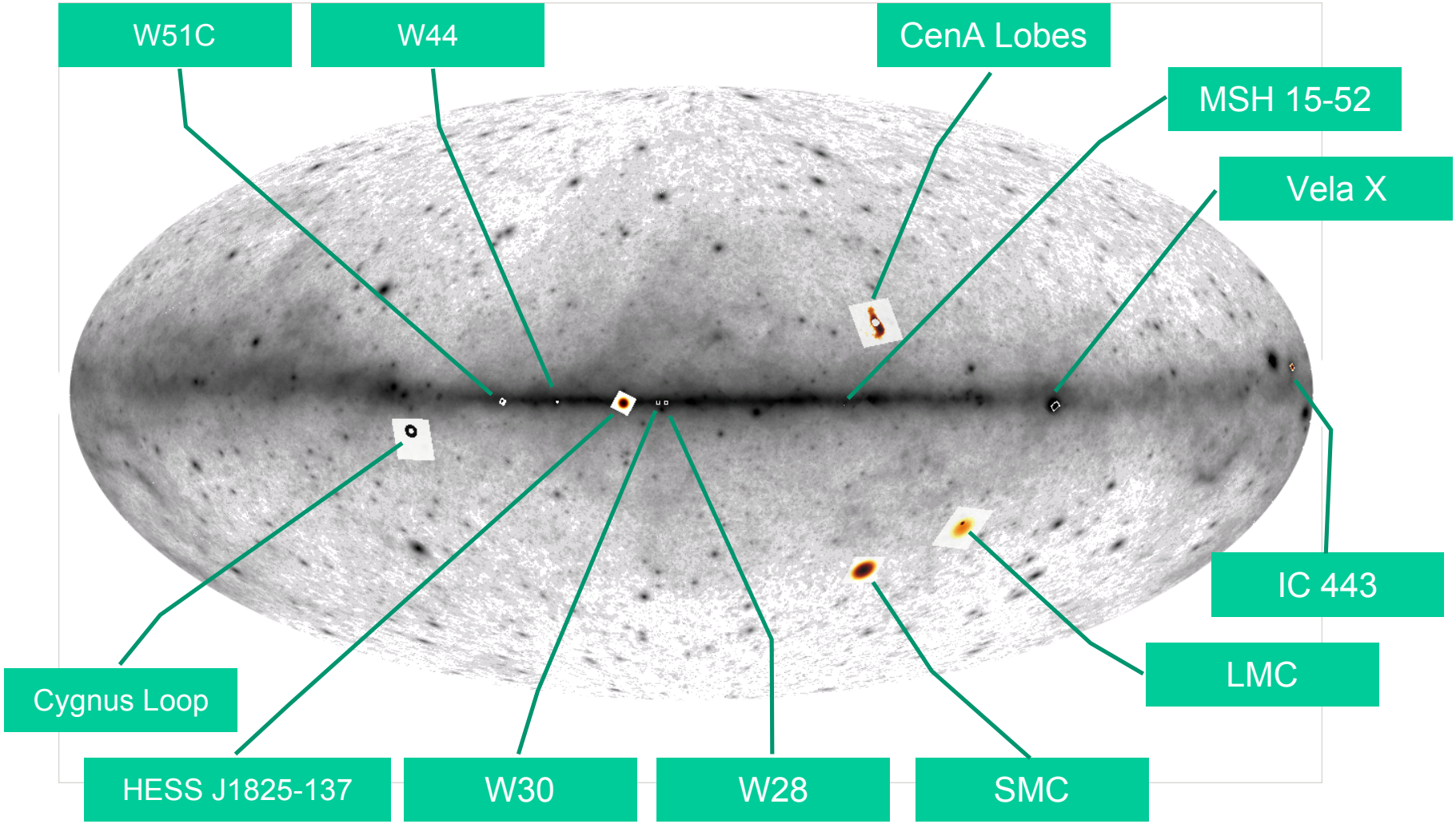




Spatially Extended Sources

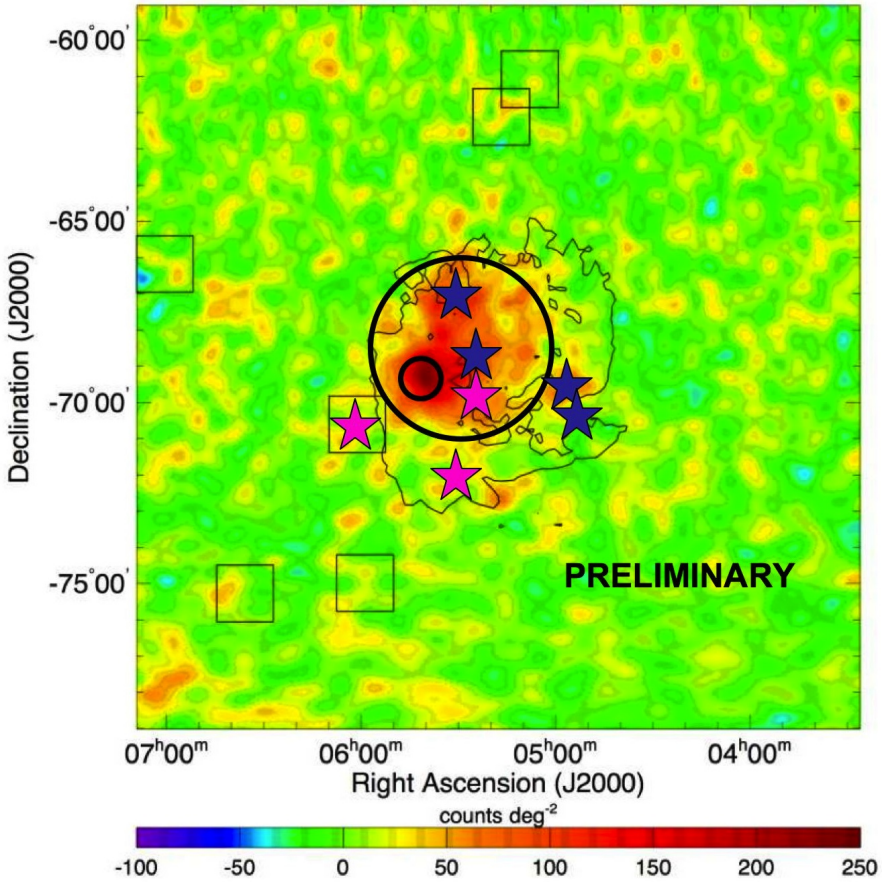
Extended Source	Spatial Form	Spectral Form
SMC	2D Gaussian	Exp Cutoff PL
LMC	2D Gaussian[a]	Exp Cutoff PL
IC 443	2D Gaussian	Log Parabola
Vela X	Disk	Power Law
Centaurus A (lobes)	Contour Map	Power Law
MSH 15−52	Disk	Power Law
W28	Disk	Log Parabola
W30	Disk	Log Parabola
HESS J1825−137	2D Gaussian	Power Law
W44	Ring	Log Parabola
W51C	Disk	Log Parabola
Cygnus Loop	Ring	Exp Cutoff PL

Extended Source Templates



Extended Source Uncertainties

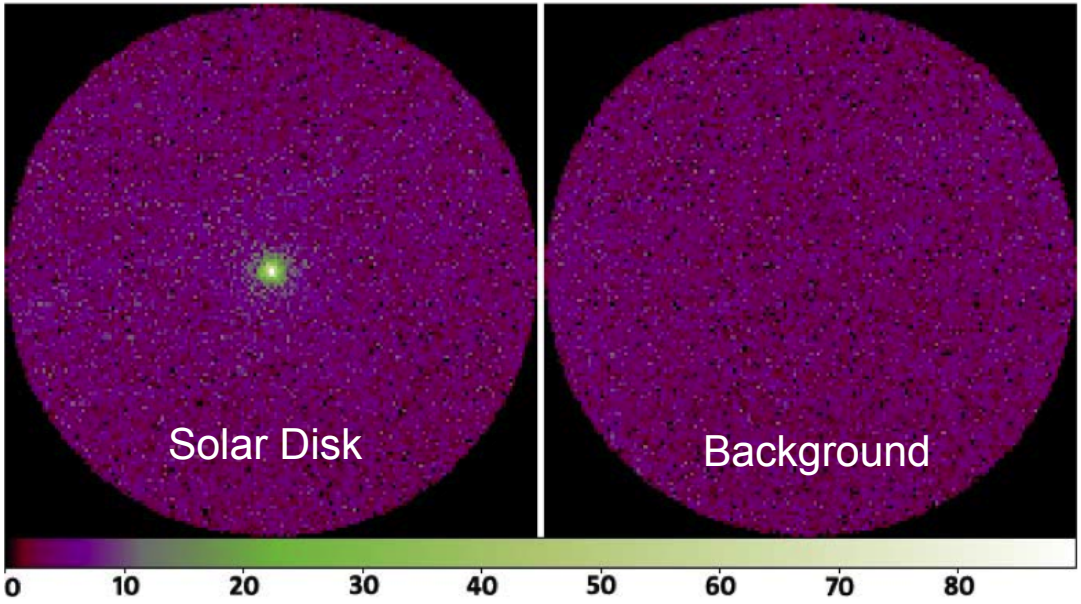
- **The templates for the 12 sources that are spatially extended are approximations based on our best current knowledge**
  - **Analysis of regions around such sources can leave residuals that look like point sources (and in some cases may be)**
  - **For example, there are 7 point sources in the vicinity of the Large Magellanic Cloud. 3 of these have blazar/radio source associations, but 4 do not and could be artifacts.**



LAT LMC map with overlay showing 2 component template and nearby sources

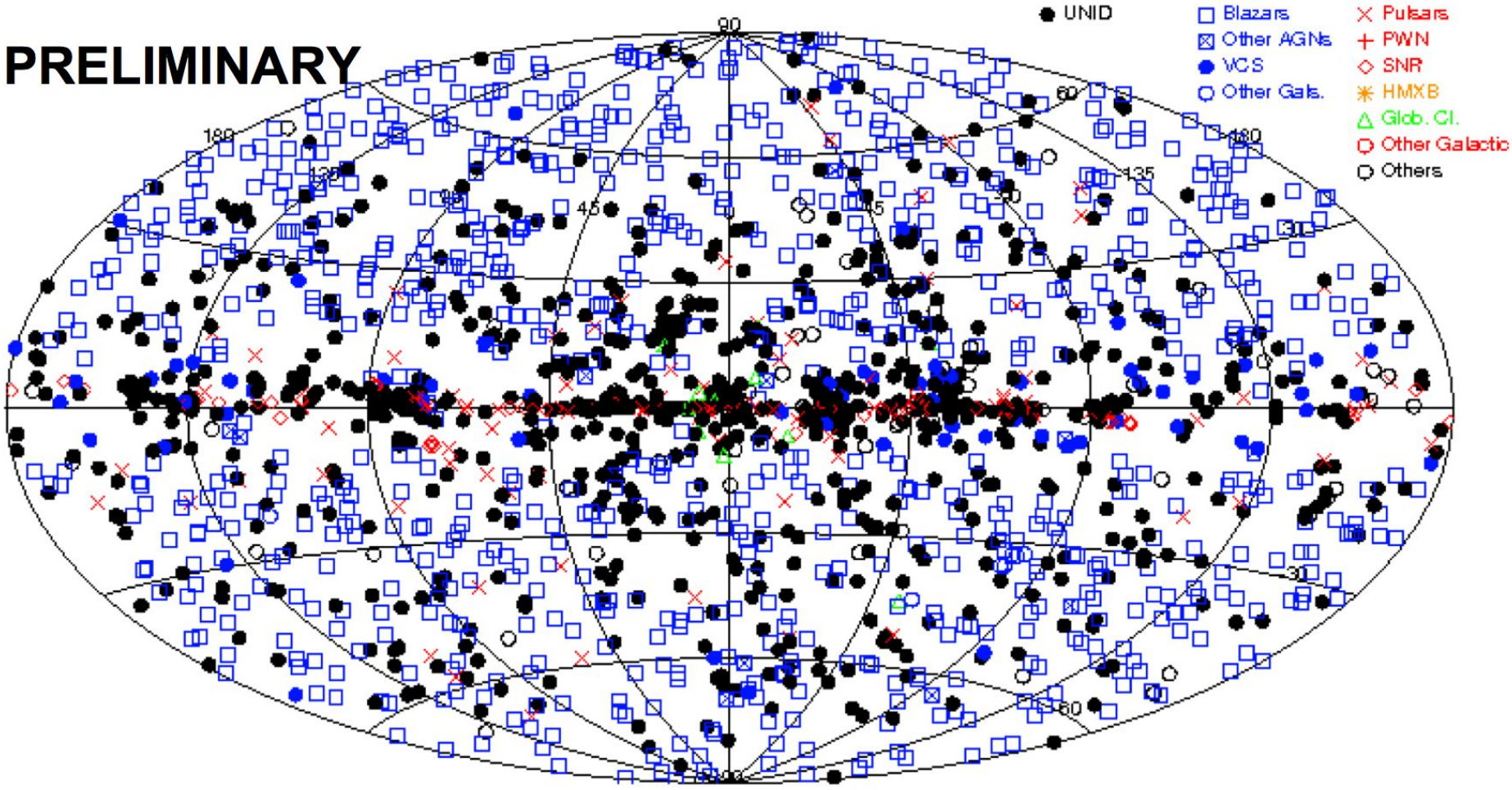
Other Source Types...

- **Eta Carina (colliding wind binary)**
- **Starburst Galaxies**
- **Solar System bodies - Moon and quiescent Sun**



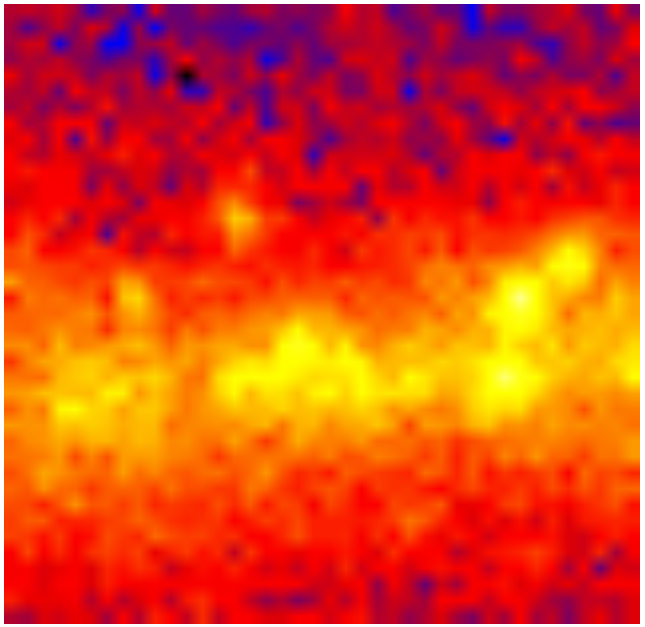
- **That's a lot of different types of sources!!**

Classifications - 2FGL

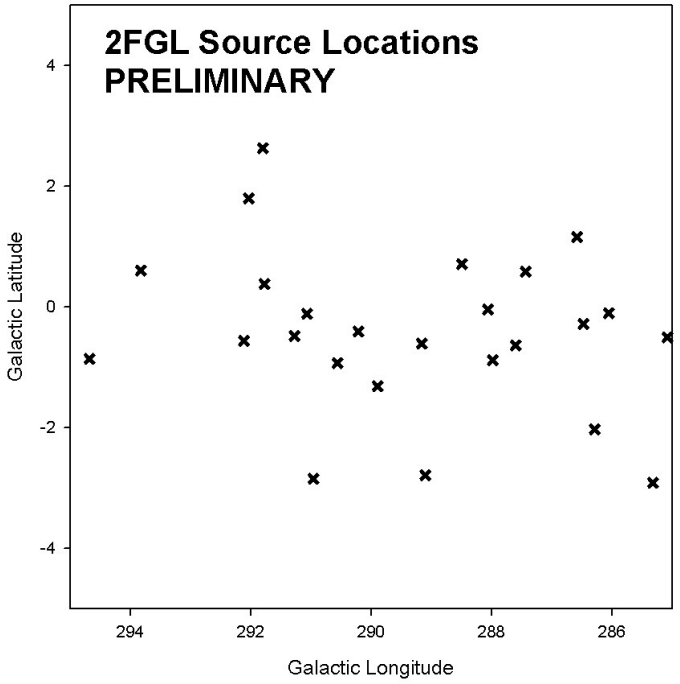


Source Confusion

- There is a concentration of sources at low Galactic latitudes toward the inner Galaxy
  - Results in sources close enough to each other that their Point Spread Functions (PSFs) overlap
  - Particularly significant at lower energies, so affects soft sources more
- Parts of the sky away from the Galactic Plane show little impact



Counts map E > 1 GeV



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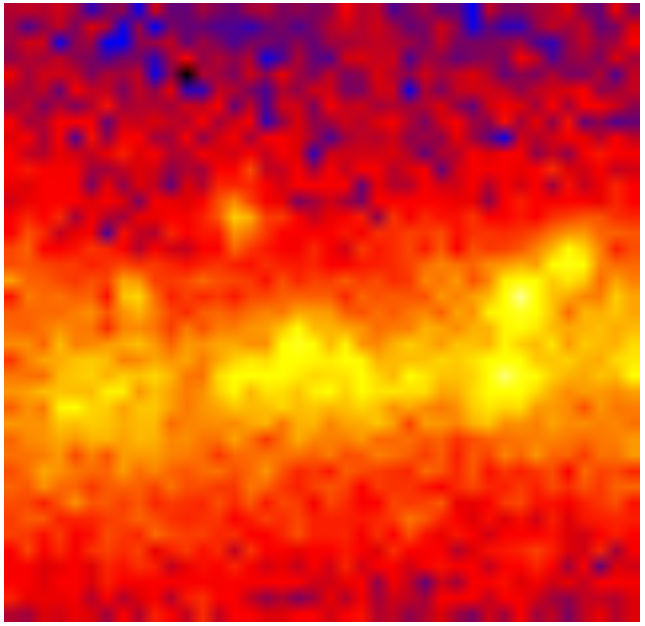

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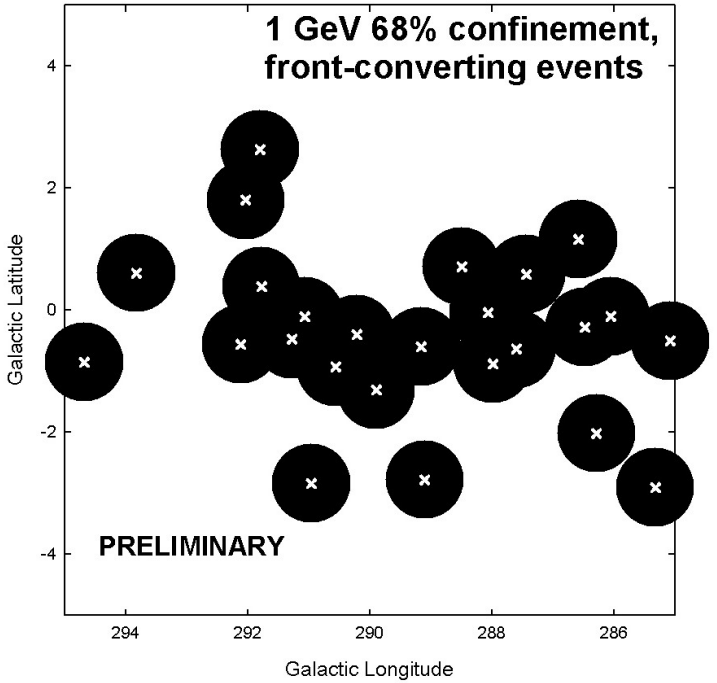
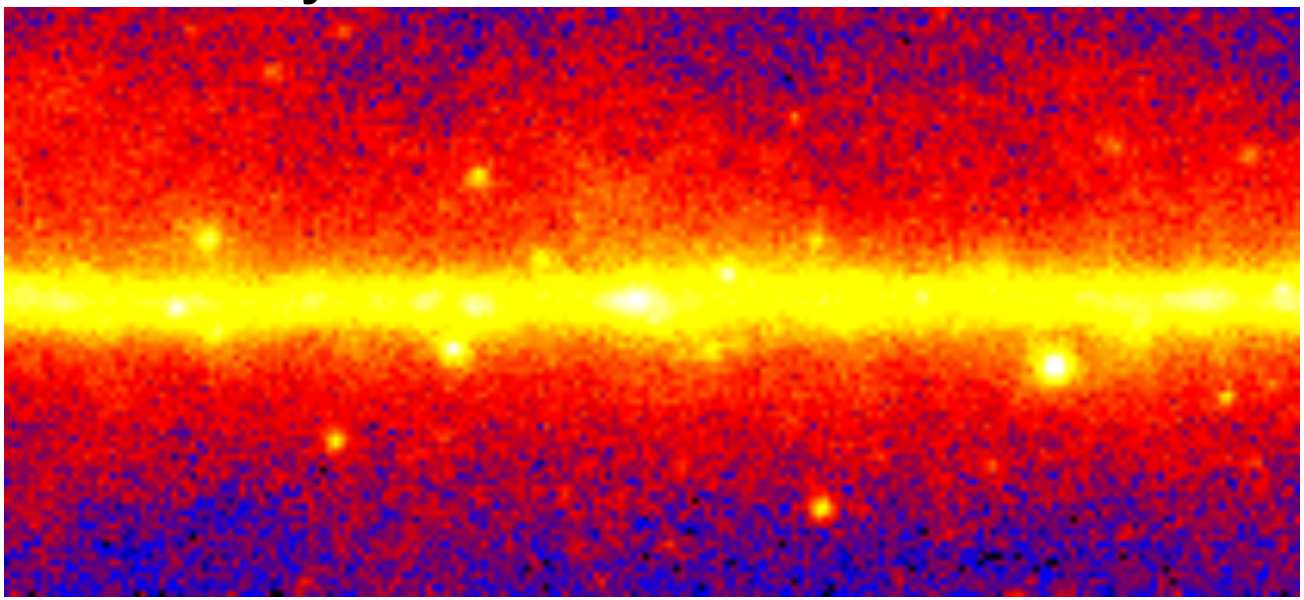


Source Confusion

- There are many sources in the Galactic Center region
  - Many overlapping PSFs
  - Lots of soft-spectrum sources
  - The diffuse model shows some residuals compared to the large-scale diffuse emission observed in this region
- LAT catalog results for the region around the Galactic Center should be considered a good first approximation rather than a comprehensive analysis.

50° x 25°

E>1GeV



32-months of LAT Sources

~ Movie ~

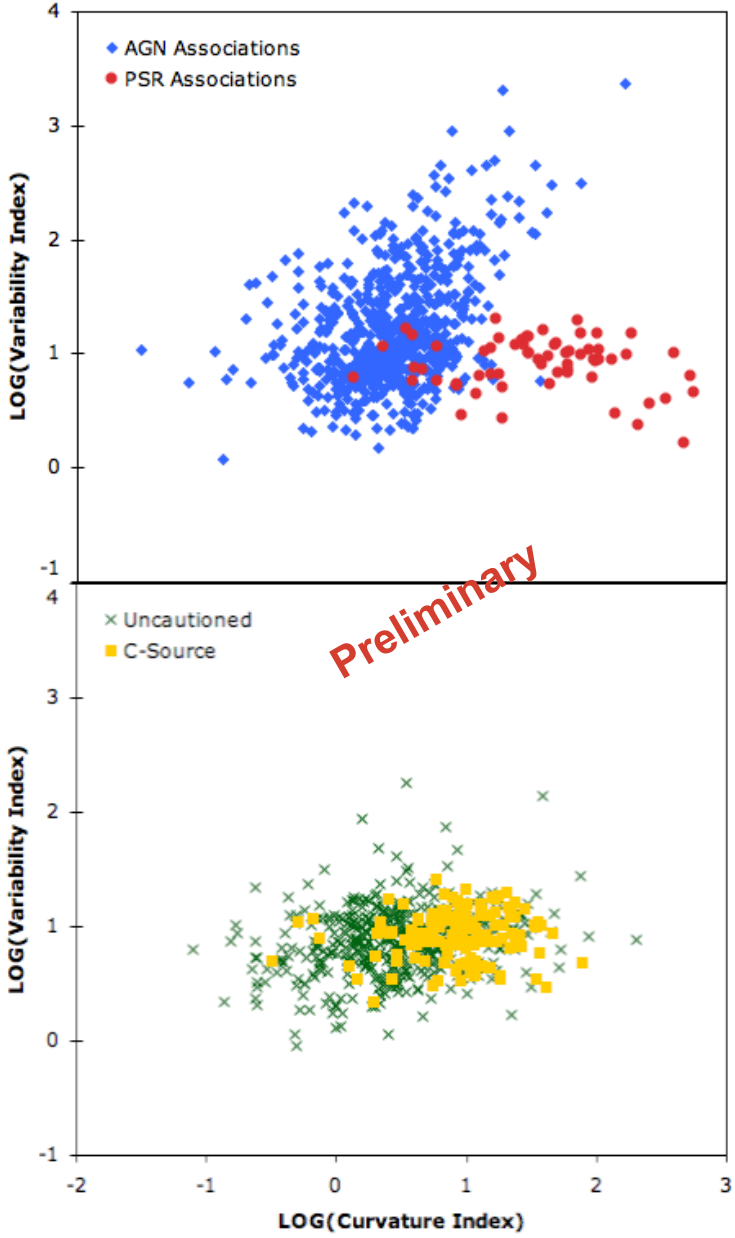
What Else Could There Be?

- **The Upcoming 2FGL catalog has 1888 sources:**
  - **Extragalactic Sources**
    - *44% are AGN (832)*
    - *14% are 'Candidate AGN' (268)*
    - *<1% are 'Other Galaxies' (7)*
  - **Galactic Sources**
    - *6% are Pulsars (114)*
    - *3% are SNRs/PWNe (60)*
    - *<1% are Globular Clusters (11)*
    - *<1% are Binary Systems (4)*
  - **Total = 1296 sources**

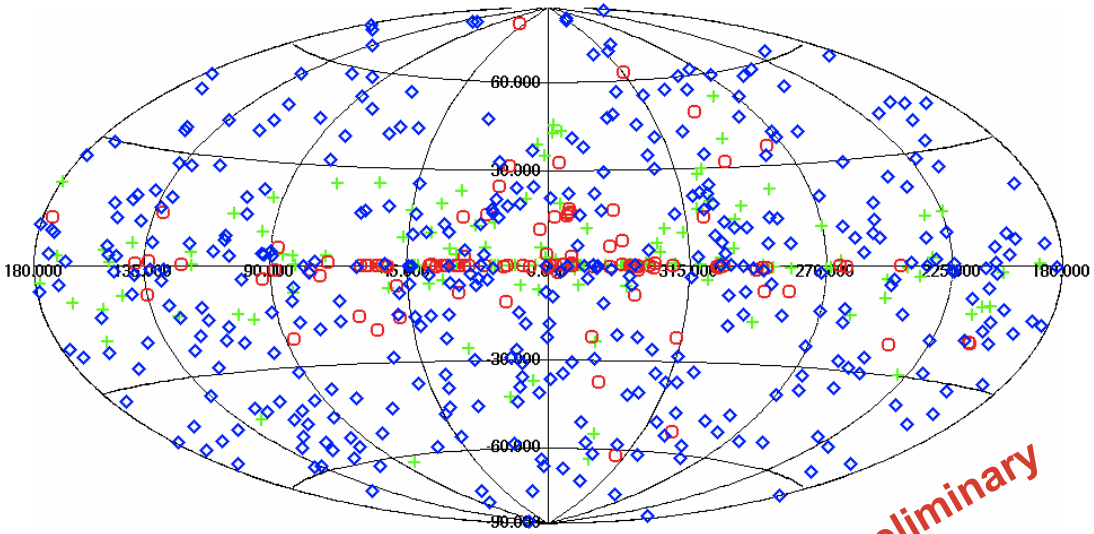
All numbers still preliminary!

- **The remaining 592 sources are still not associated!!**

Classifying Unassociated Sources



- **Can attempt to use the gamma-ray spectral and temporal properties to determine likely source class for these 592 sources**

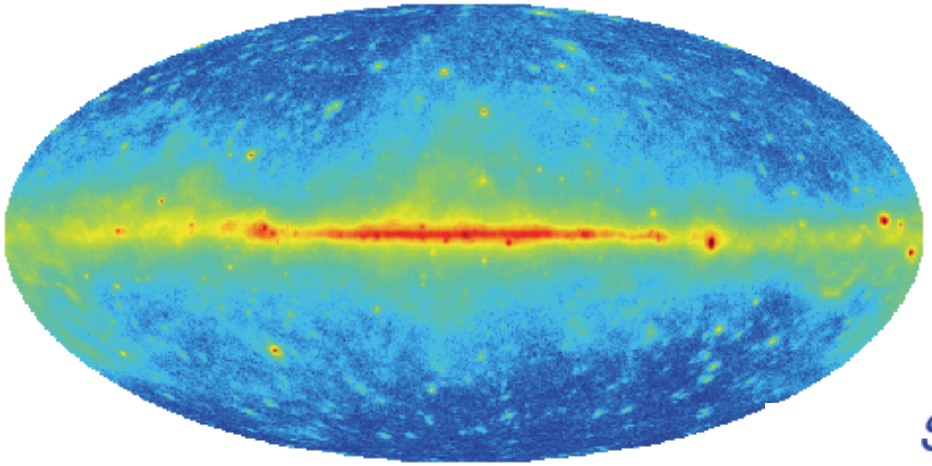


- AGN-like sources
- Pulsar-like sources
- Unclassifiable

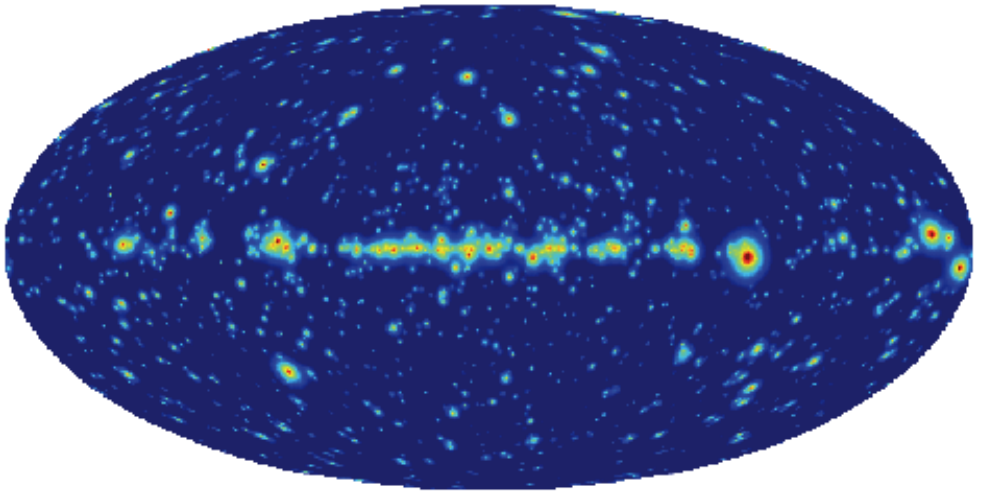
Is that all we see?

- **The point sources comprise only a subset of the data**

LAT counts above 300 MeV

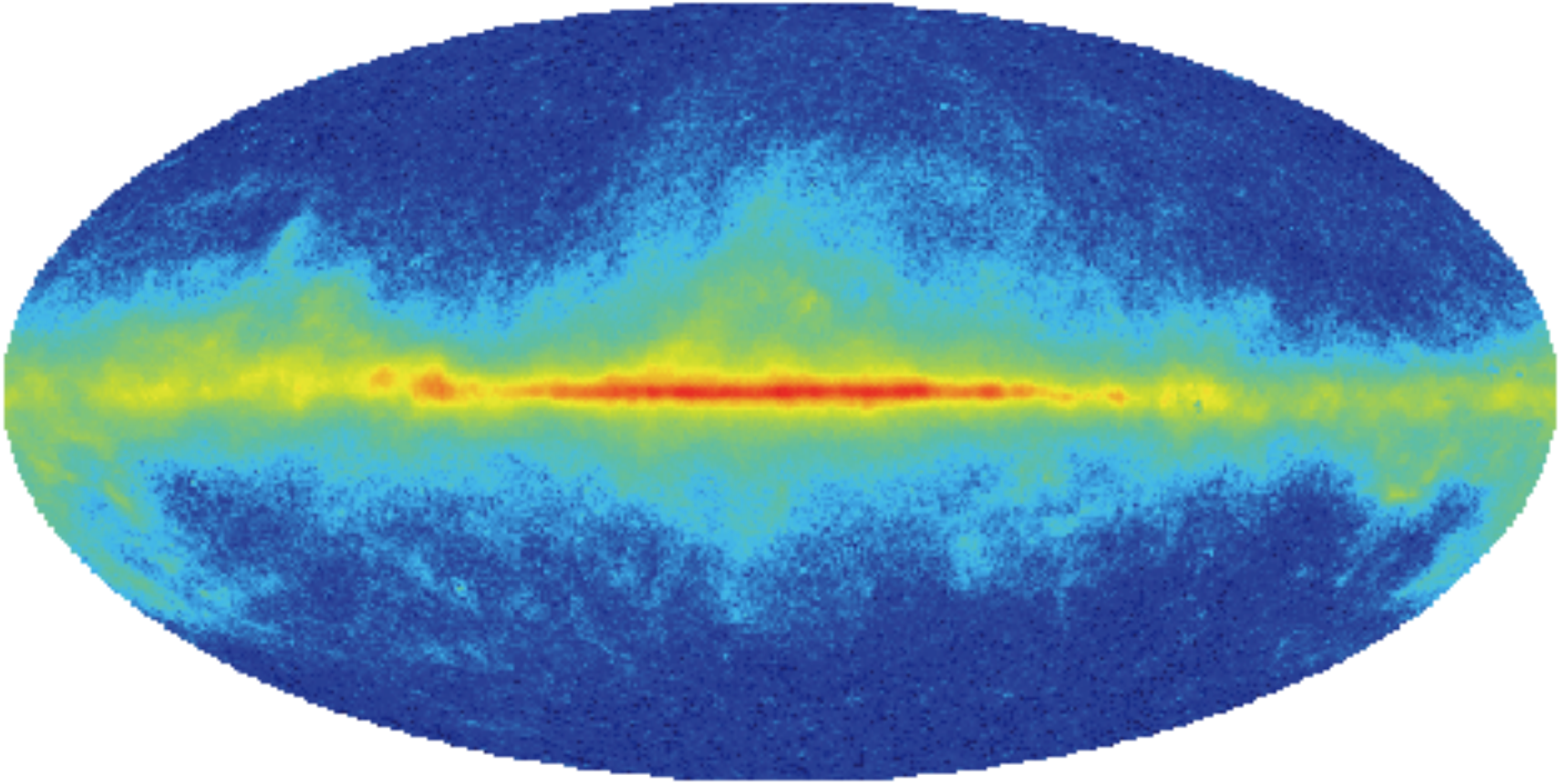


Sources, 2FGL early version



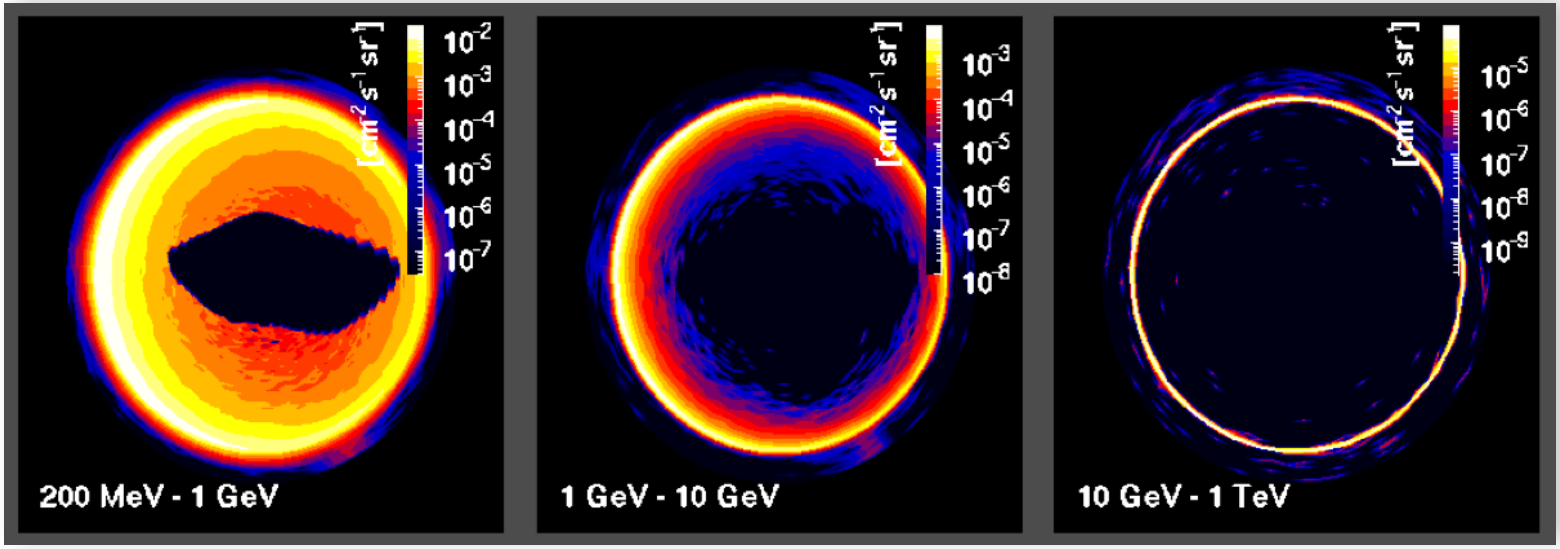
What remains is ‘Background’

LAT counts minus sources



Atmospheric gamma rays

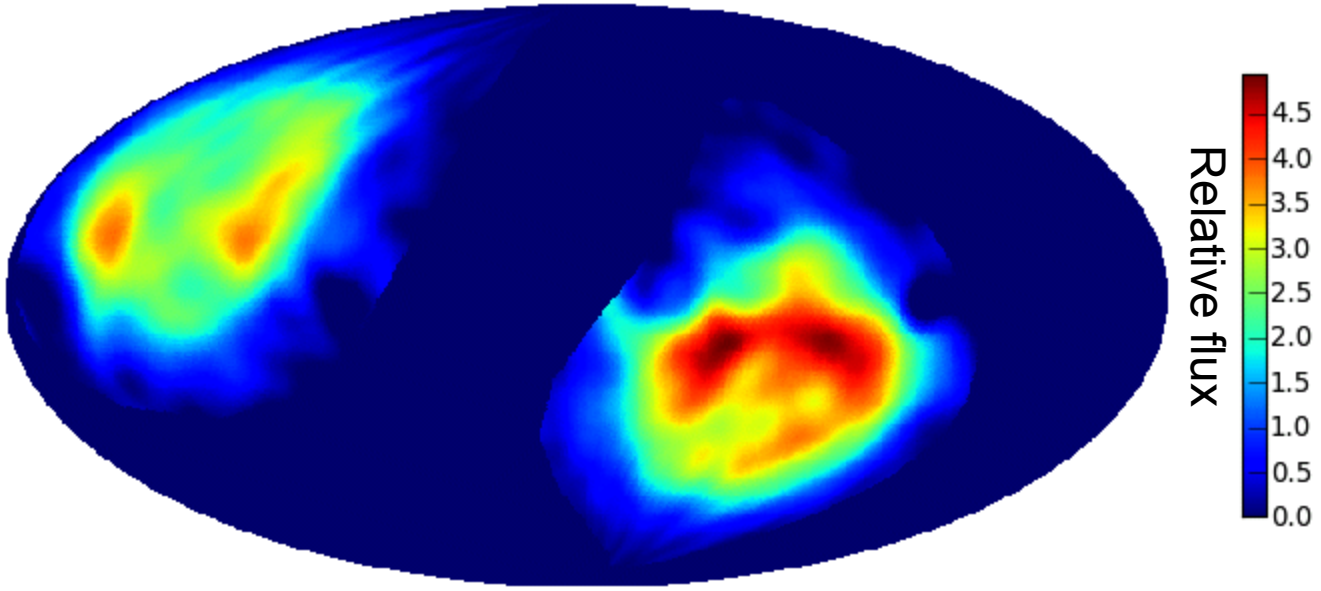
- **The Earth's limb is *bright* in gamma-rays!**
  - **Secondary gamma rays from cosmic ray interactions in the Earth's atmosphere**
    - ***At Fermi's altitude, the limb is ~113 deg from zenith***
  - **Far brighter than celestial sources**
    - ***Need to remove limb gammas from analysis of celestial sources***
    - ***Do geometry cut (standard recommendation)***
      - **e.g. cut on zenith angle**



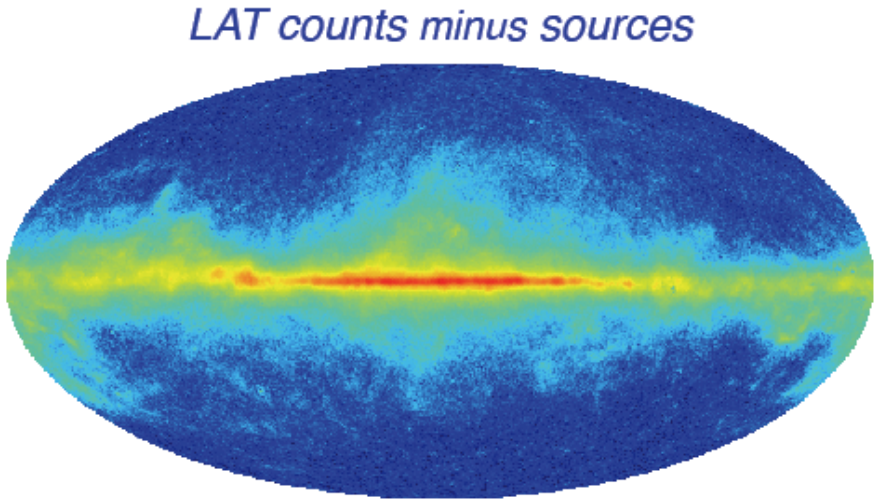
Abdo et al. 2009, Phys Rev D, 80, 122004

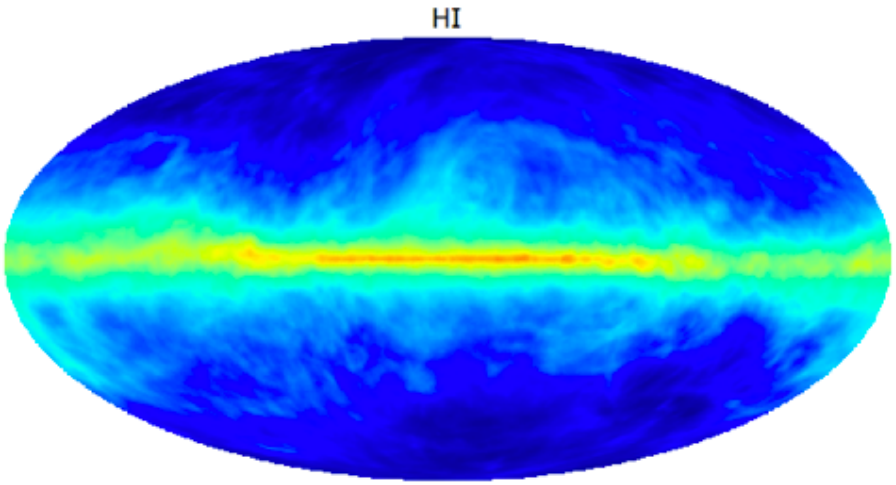
Contribution from the Earth's limb

- **Some leakage can happen even after excluding events close to the limb**
  - **Residual limb photons can be seen at the celestial poles at low energies (low energy = large PSF)**
  - **Can be fitted as a separate background template**
  - **Time-variable contribution, so average contribution may not be appropriate for time-series analysis**

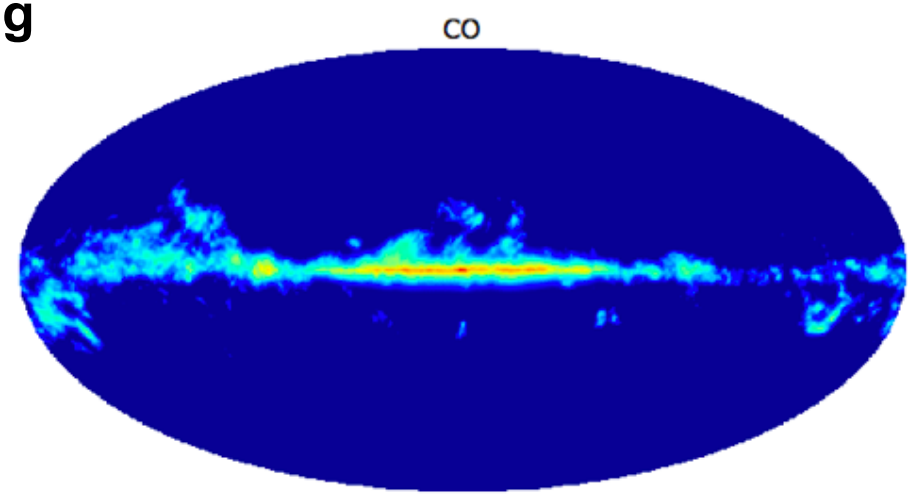


Galactic Diffuse Component(s)





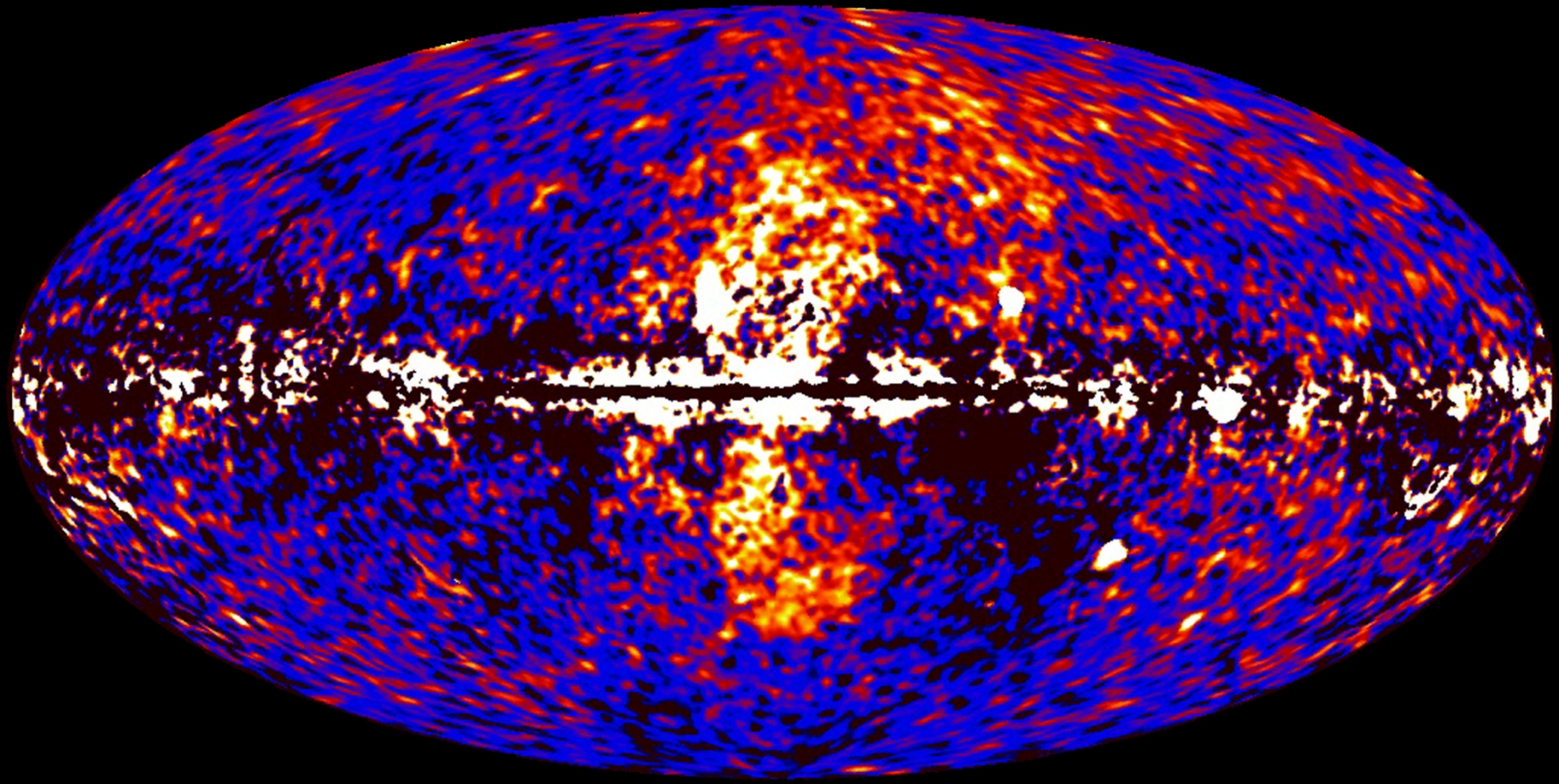
- **Still a lot of detail in the remaining emission**
- **Need to account for large-scale structure**
  - **Requires modeling to remove**
  - **HI tracks ionized Hydrogen**
  - **CO is a tracer for neutral H_2**



Deconstructing the Diffuse

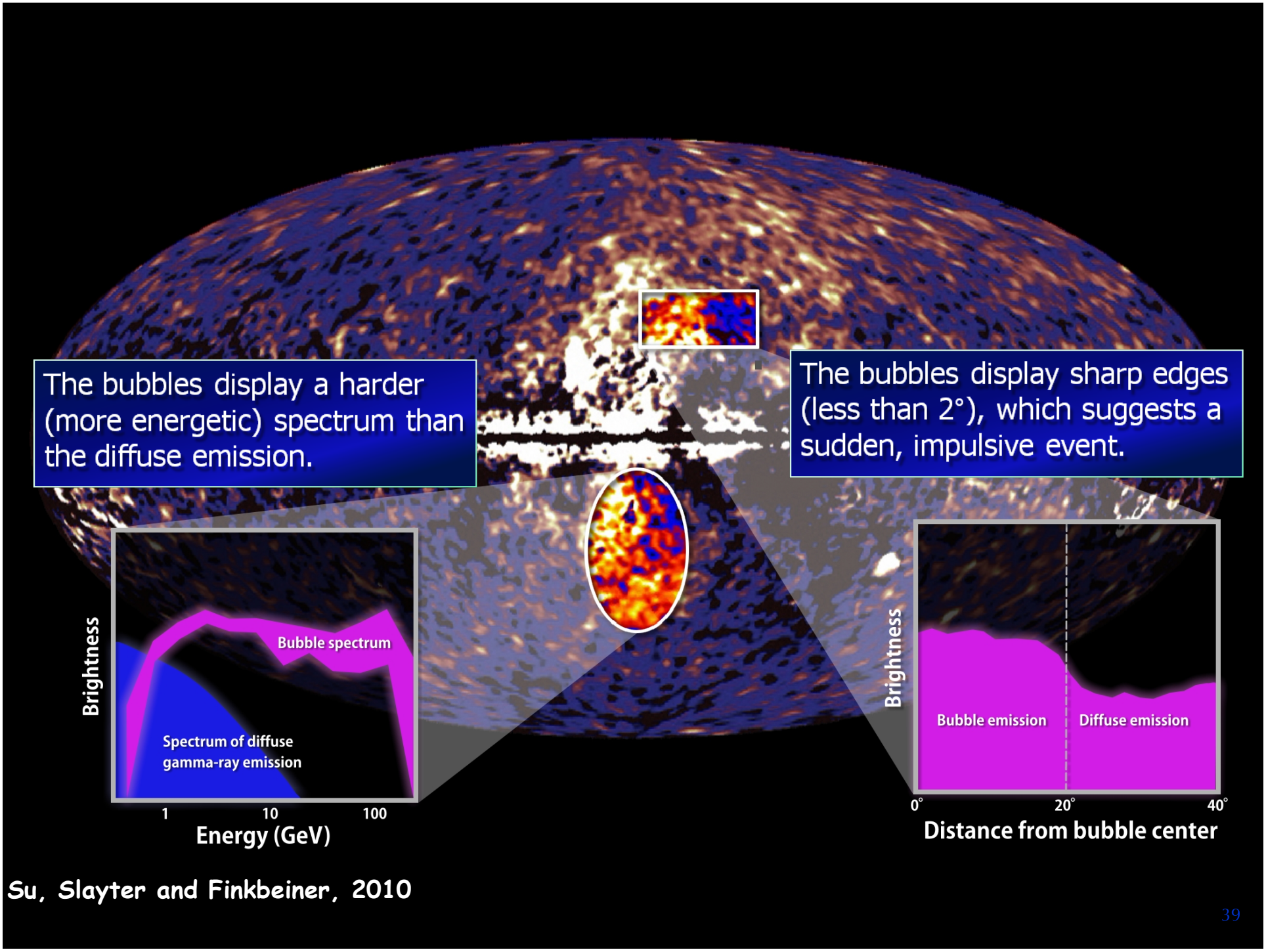
~ Movie ~

What's Hiding in the Data



The new structure consists of enormous bubbles extending about 50° north and south of the galactic center.

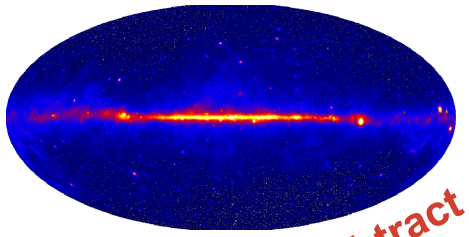
Su, Slayter and Finkbeiner, 2010



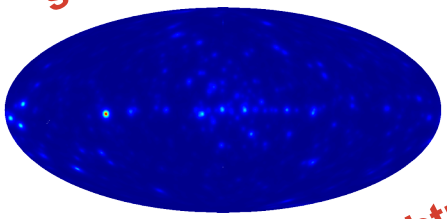
Su, Slayter and Finkbeiner, 2010

Deriving the extragalactic diffuse spectrum

LAT Sky

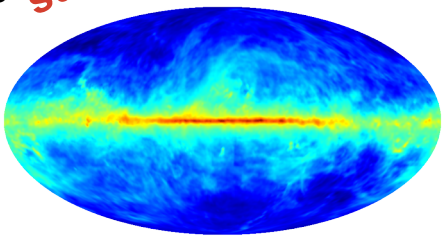


subtract



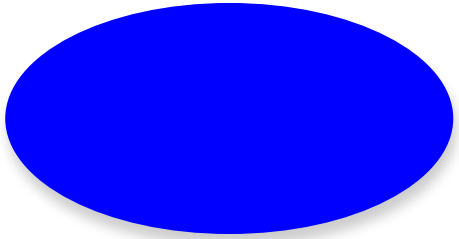
Point Sources

subtract



Galactic Diffuse Components

leaves →



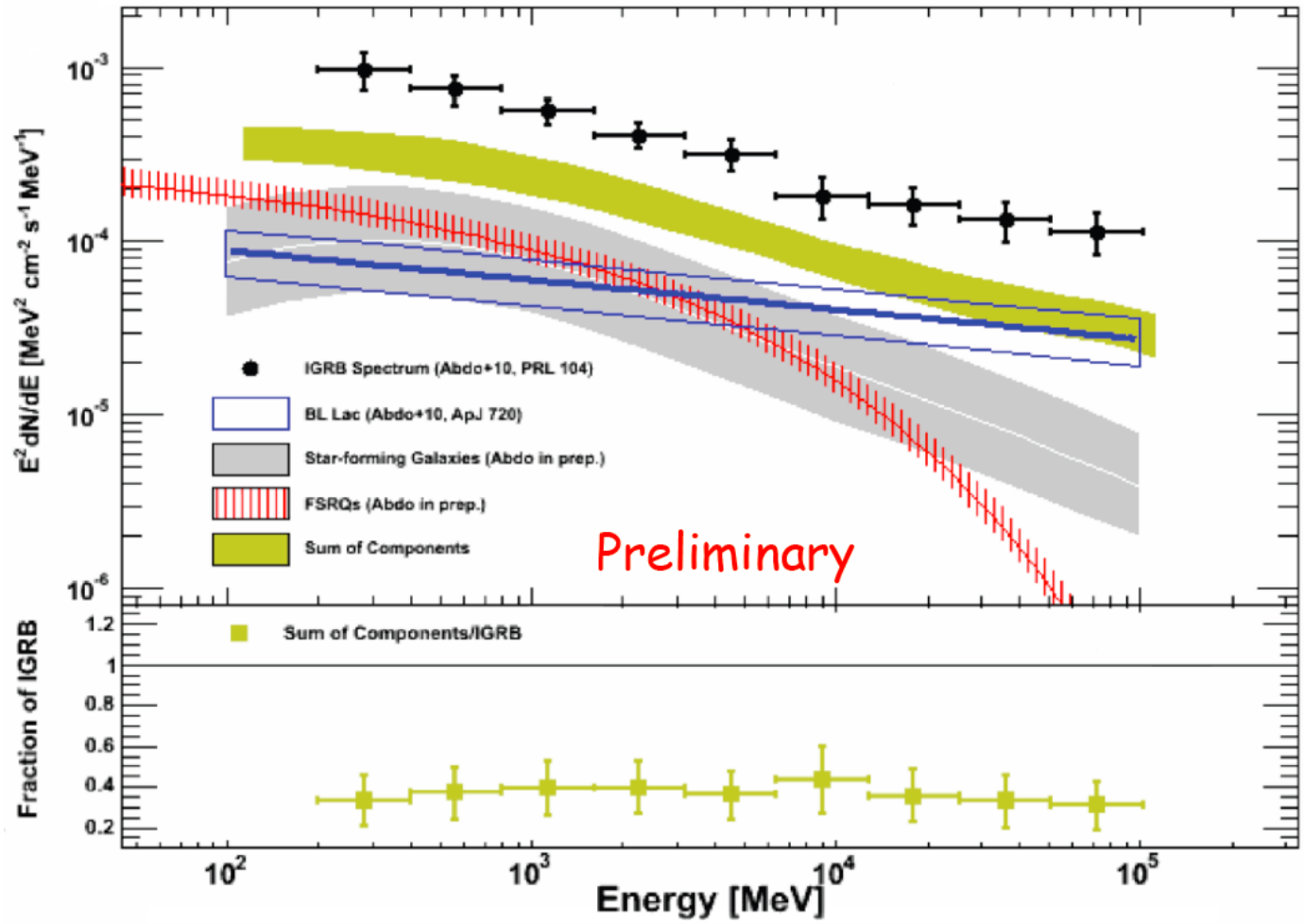
Isotropic Diffuse Emission

- **Isotropic diffuse spectrum is a combination of:**
  - ***Emission from unresolved extragalactic sources***
  - ***Residual charged-particle background***
  - ***Other signal?***
- **Model the charged particles background to remove that signal**

Isotropic Gamma-ray Background

More on Saturday

- **Much, but not all, of the IGRB is accounted for**
  - **May provide cosmological clues**



What Doesn't the LAT See?

- **Seyfert Galaxies**
  - **They're AGN, why aren't they seen?**
- **Galaxy Clusters**
  - **Filled with great targets for cosmic rays, why aren't they seen?**
- **Accreting X-ray Pulsars, Magnetars**
  - **Seen by GBM, extreme physics, why aren't they seen?**

Dark matter searches: Nothing Yet

Satellites

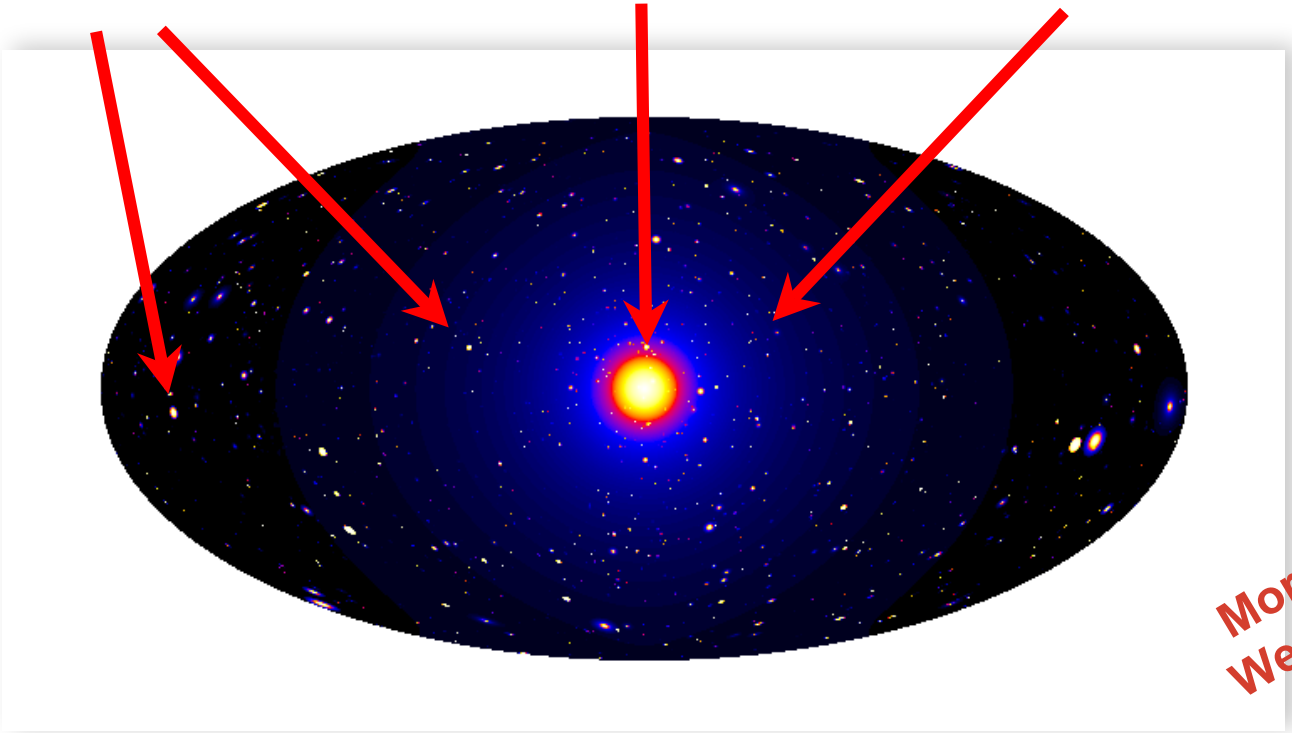
Low Galactic background and good source ID, but low statistics

Galactic Center

Good statistics, but source confusion and high Galactic diffuse background

Milky Way Halo

Large statistics, but significant diffuse Galactic and extragalactic background



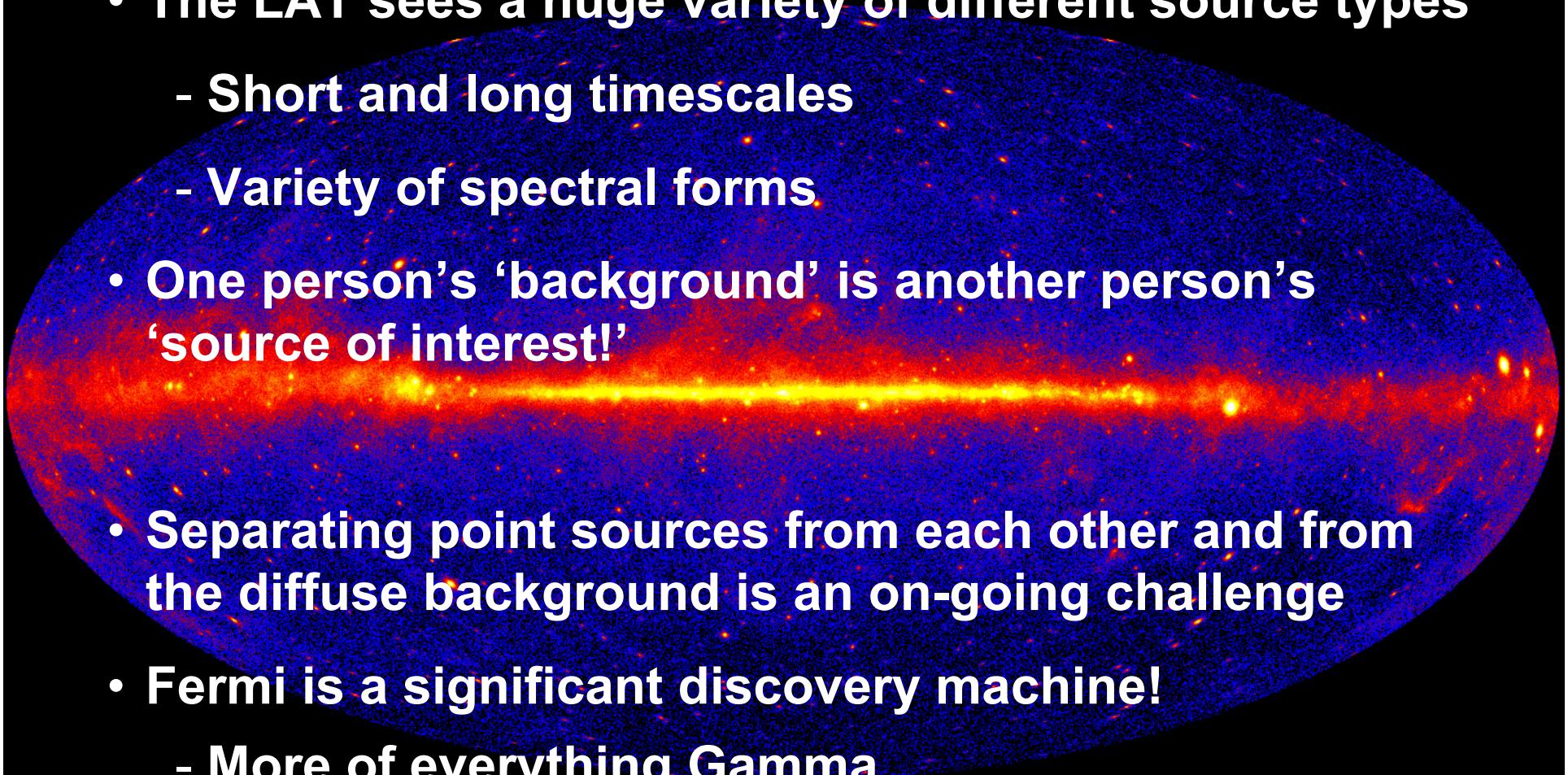
All-sky map of simulated gamma ray signal from DM annihilation (Pieri et al. arXiv:0908.0195)

More next Wednesday

Photon statistics just beginning to reach the levels where predictions indicate DM may be detectable

Pre-launch estimates of sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

Summary



- The LAT sees a huge variety of different source types
  - Short and long timescales
  - Variety of spectral forms
- One person's 'background' is another person's 'source of interest!'
- Separating point sources from each other and from the diffuse background is an on-going challenge
- Fermi is a significant discovery machine!
  - More of everything Gamma

    New Galactic Structures

    Many new source types