



# The Fermi Census: Challenge, discovery and innovation in the Fermi all-sky survey

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GSFC/UMCP/CRESST  
on behalf of the  
Fermi Large Area Telescope  
Collaboration

2012 Fermi Symposium  
Monterey, CA  
Oct. 28 – Nov. 2



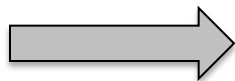
# Fermi is an All-sky explorer

- **Fermi has been operating for more than four years, primarily in all-sky survey mode**
- **Persistent gamma-ray sources:**
  - **List of bright LAT sources – 205 at  $>10\sigma$  in 3 months**
  - **Two LAT point source catalogs**
    - **1451 sources after 11 months, 1873 after 24 months**
  - **Two catalogs of LAT-detected AGN**
  - **Catalog of 43 LAT-detected pulsars**
  - **Catalog of GBM Earth-occultation sources**
- **Transient gamma-ray sources:**
  - **Two catalogs of GBM-detected GRBs**
  - **List of GBM-detected TGFs**



## Second Fermi-LAT Point Source Catalog

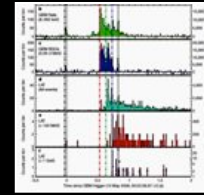
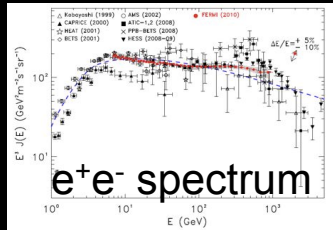
- Used two years of data, catalog of non-transient sources
- Improvements over 1FGL, included:
  - Revised Galactic diffuse model
    - Loop 1 structure
    - Excesses at spiral arm tangents
    - High-energy excess at high- $|b|$  (“Fermi Bubbles”)
  - Data-derived spatial template for residual Earth limb emission
  - Spatial templates for 12 known extended sources
  - Exponentially cutoff spectral models for pulsars
  - Curved spectral models for some sources



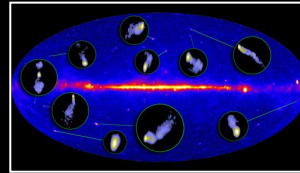
**1873 sources**

With measured source locations, spectra, light curves, and (for some) angular extent

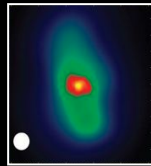
# Fermi Reveals the Very High Energy Universe



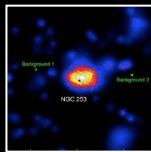
GRBs



Blazars

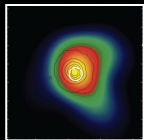
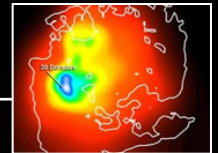


Radio Galaxies



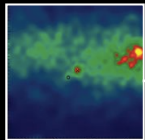
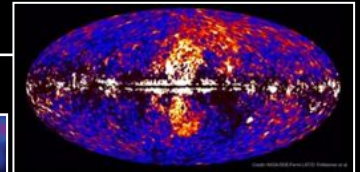
Starburst Galaxies

LMC & SMC



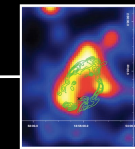
Globular Clusters

Fermi Bubbles

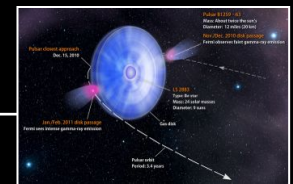


Nova

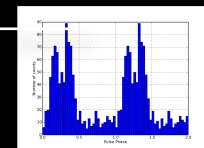
SNRs & PWN



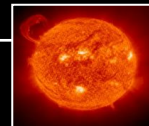
$\gamma$ -ray Binaries



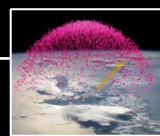
Pulsars: isolated, binaries, & MSPs



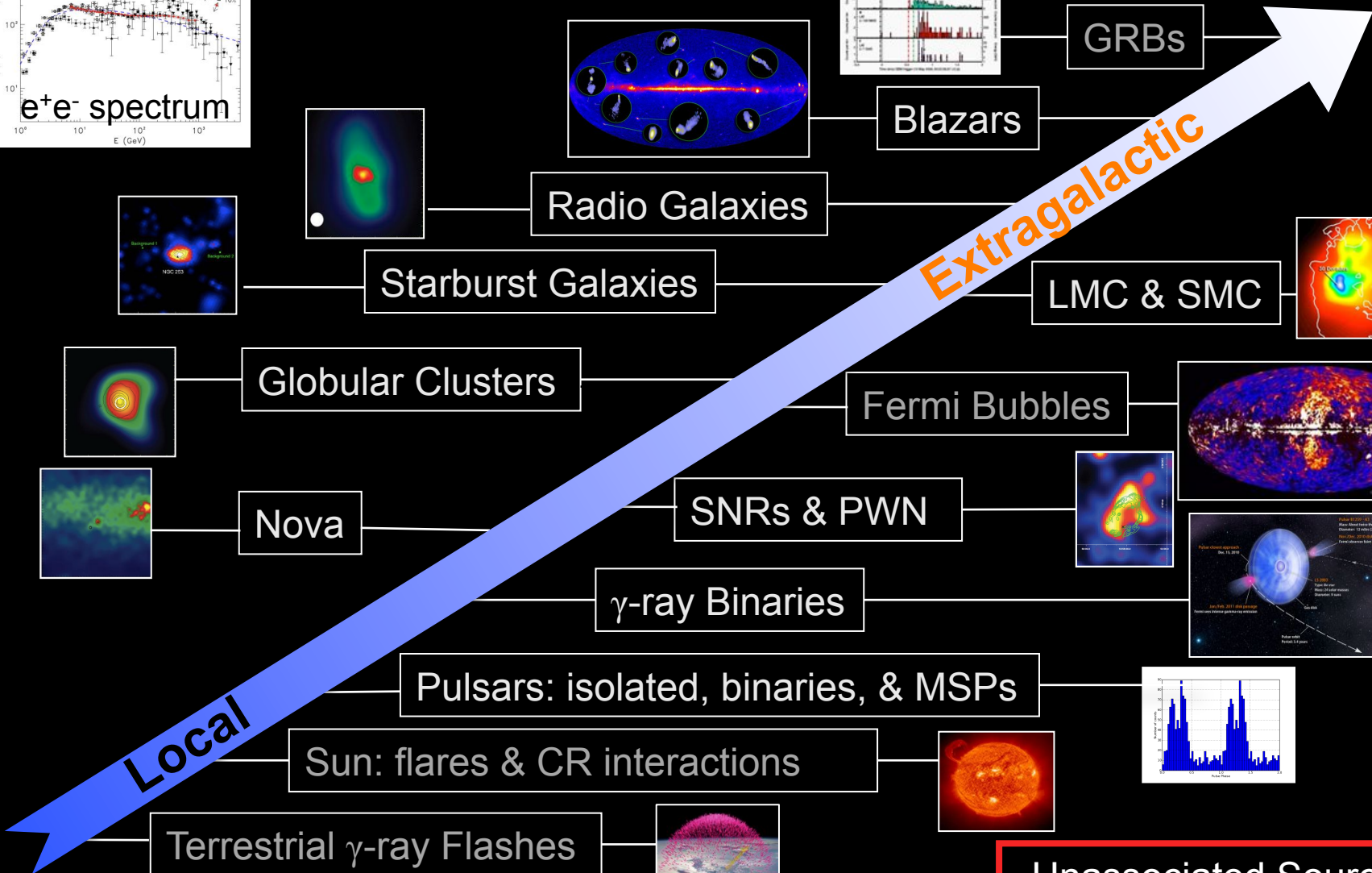
Sun: flares & CR interactions



Terrestrial  $\gamma$ -ray Flashes



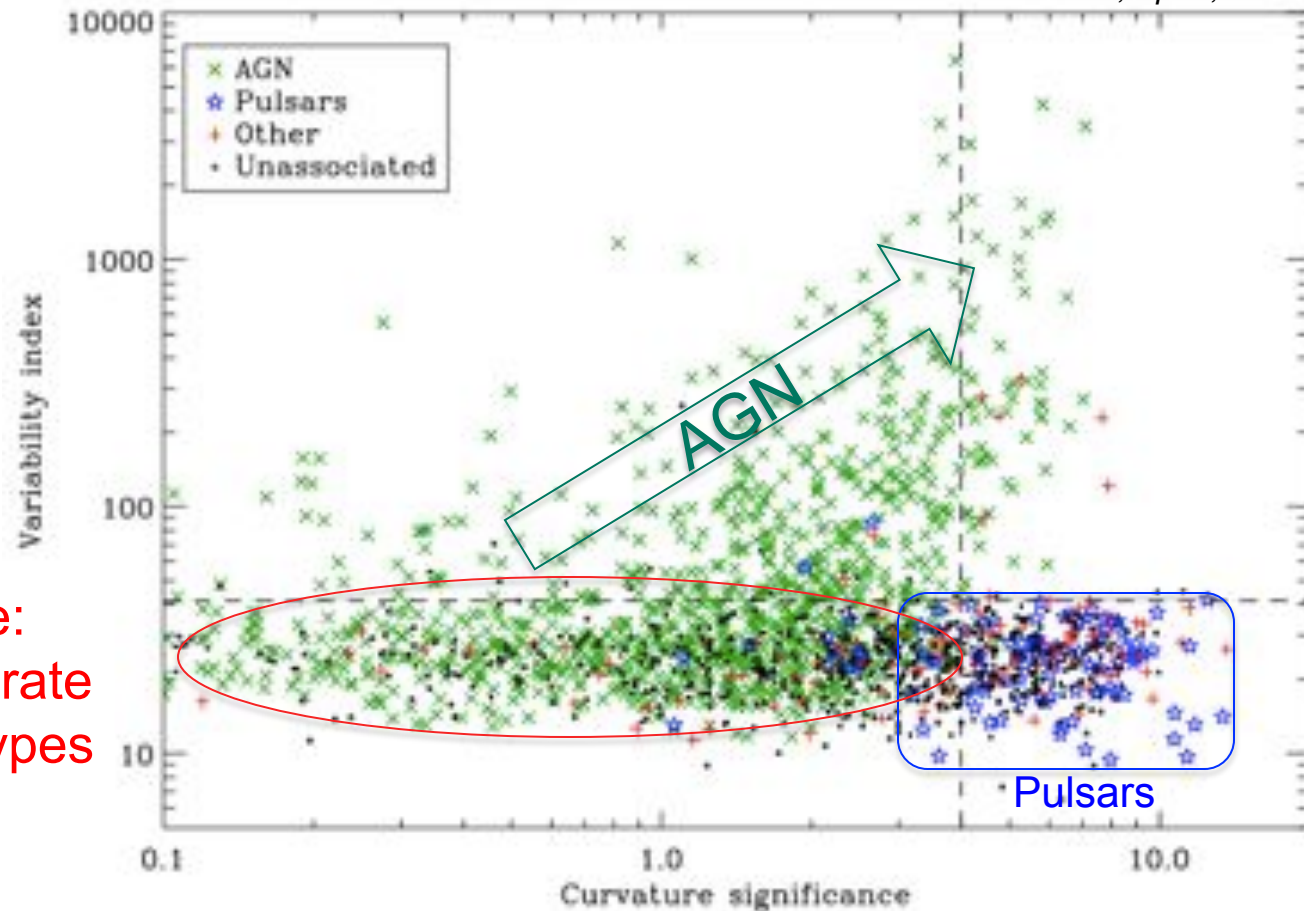
Unassociated Sources  
(577 of 1873)



# Investigating the Unassoccs

- Compare the gamma-ray unassociated sources with known gamma-ray classes
  - Only AGN and pulsars are numerous enough for statistical analyses

*Nolan et al, ApJS, 2012*



Challenge:  
How to separate  
the source types



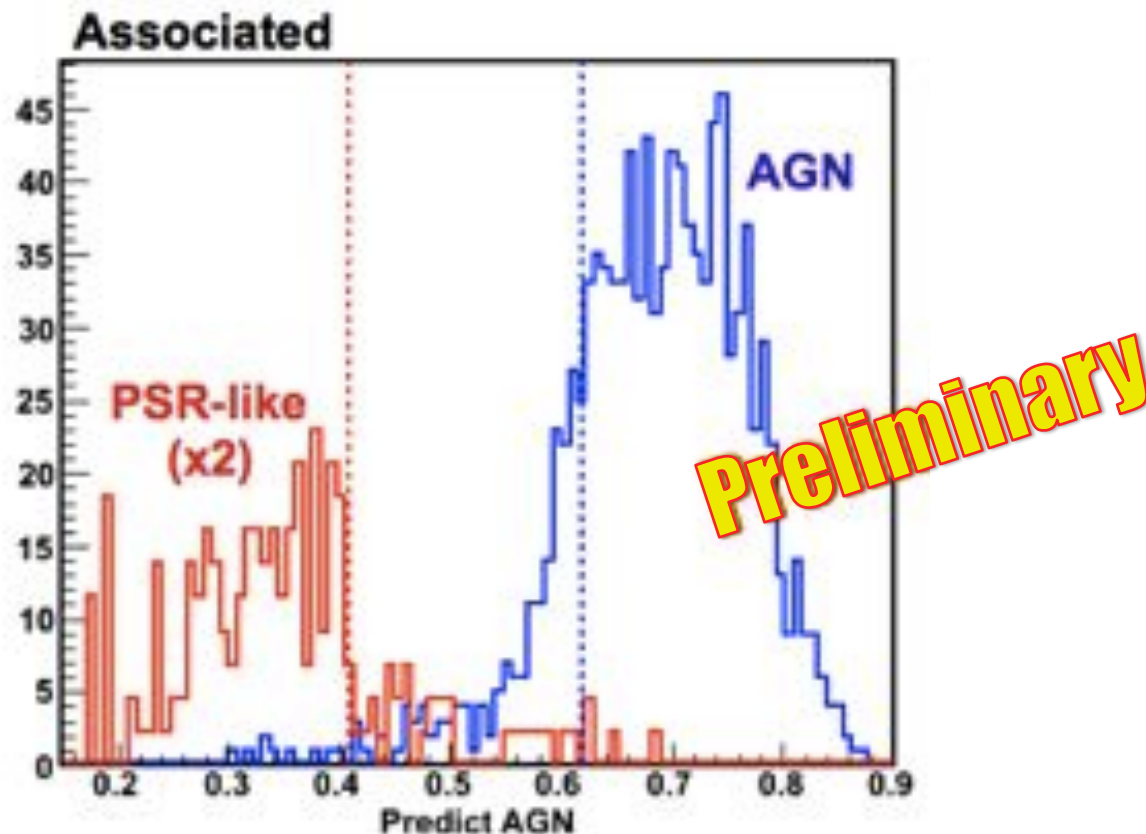
# Can We Classify Them?

- **Use statistical analysis to determine likely source classifications**
  - **1FGL parameters were tested for ability to distinguish between AGNs and pulsars (Ackermann et al. 2012)**
    - Classification Trees and Logistic Regression
  - **Most powerful predictors**
    - Variability index, Spectral index, Curvature significance, and Hardness Ratio between low and high energy bands
  - **Lower-level predictors**
    - Flux in lowest energy band, Hardness Ratio in intermediate energy bands, 4-band fluxes, 3-band curvature
  - **Galactic latitude was not used**
  - **2FGL Test sample:**
    - 1077 AGN and blazars
    - 180 pulsars and pulsar-like objects (SNRs, pulsar associations)
    - Other associated sources (39) were not used
      - **Globular clusters, HMXBs, radio galaxies, etc.**



# Train, then Classify

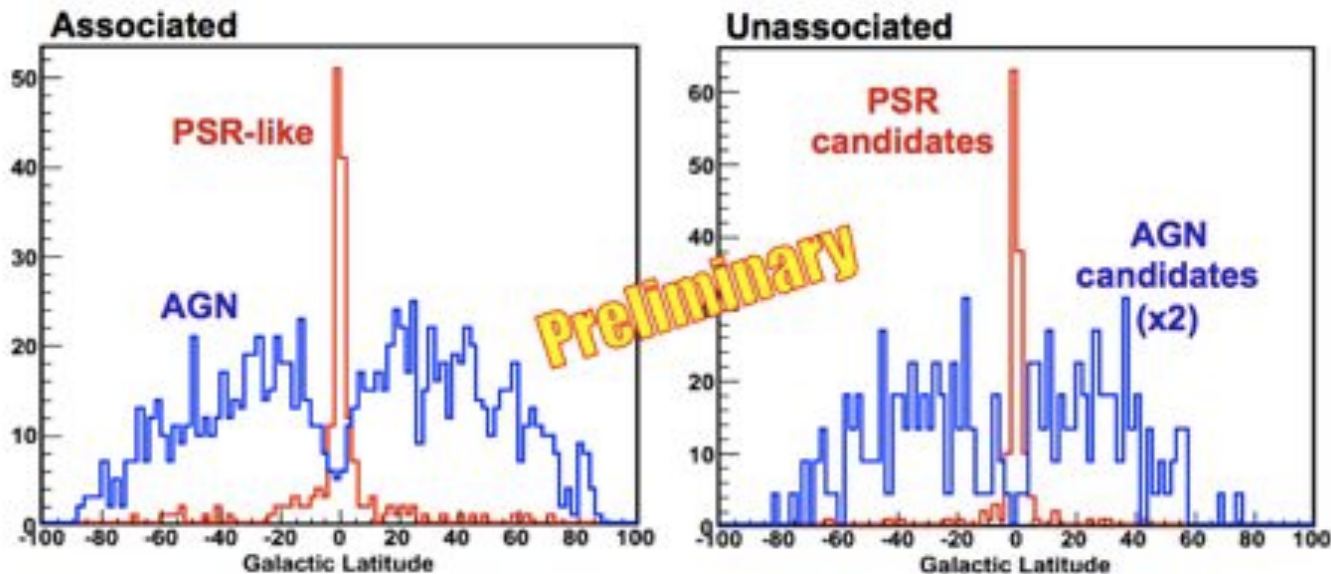
- Used Classification Tree method to combine weighted parameter values to calculate predictor value



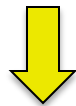
- Thresholds set for >80% efficiency and <5% contamination

# Check results

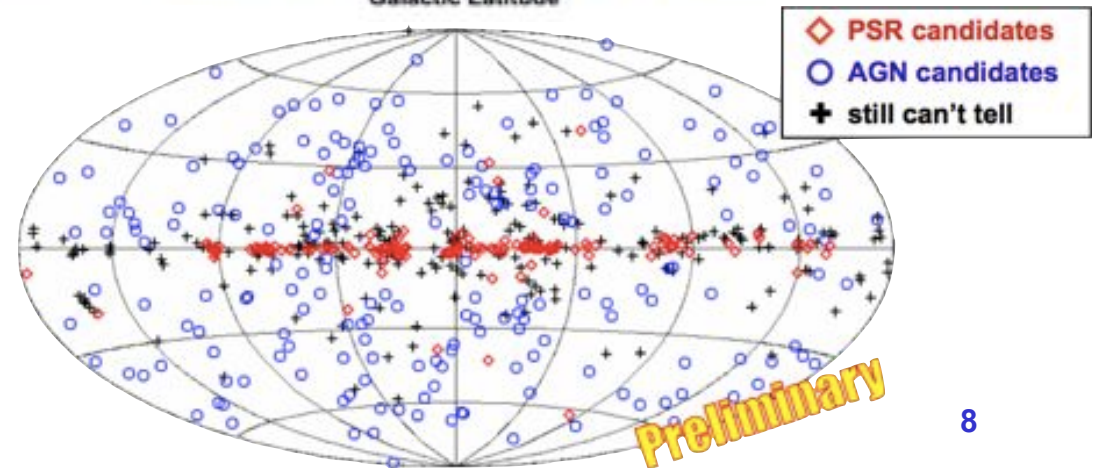
- Compare known AGN and pulsar-like populations to new pulsar and AGN candidates



577 unassociated sources



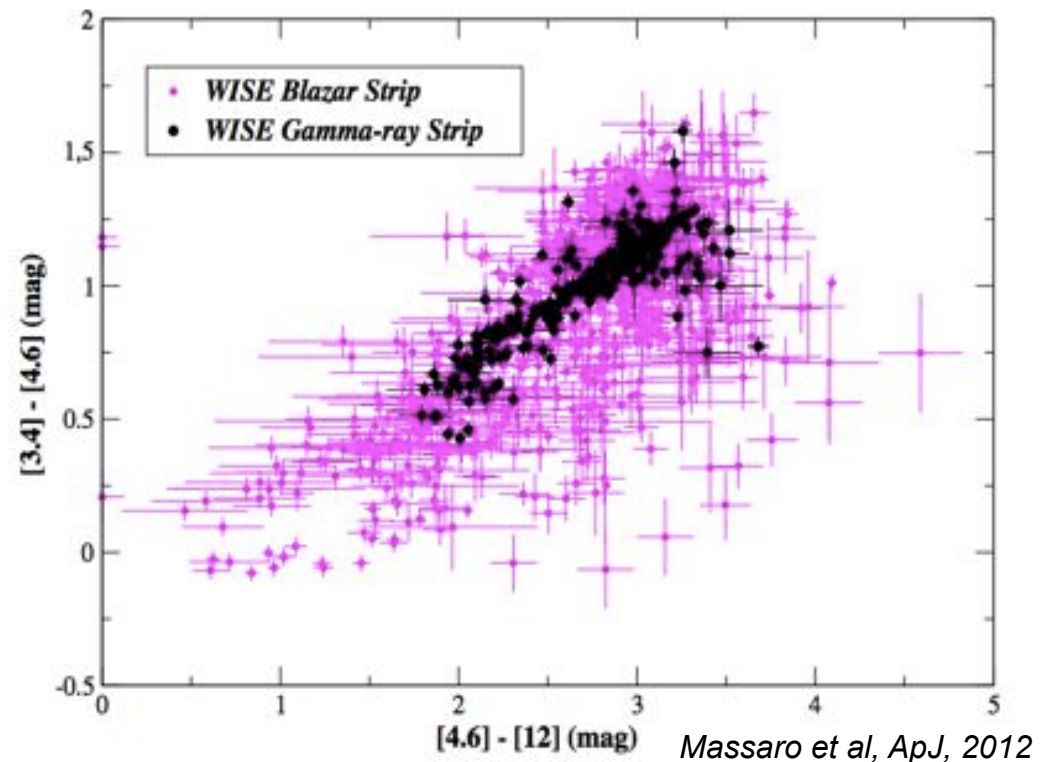
199 AGN candidates  
114 Pulsar candidates  
240 Unclassifiable





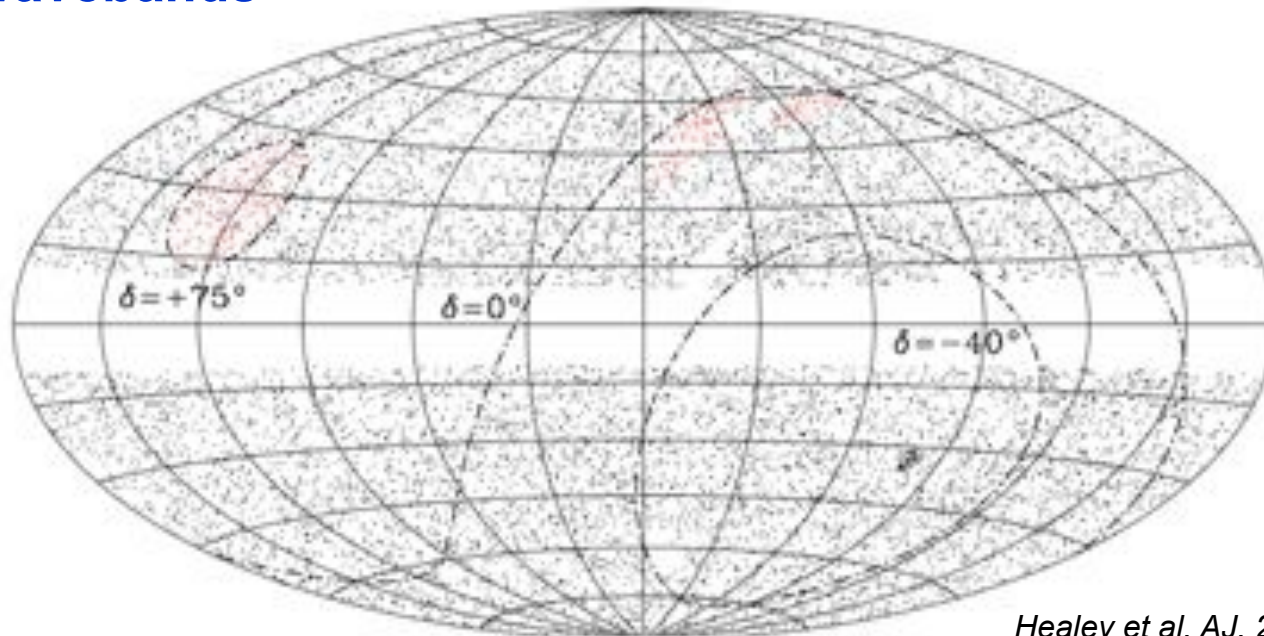
# Search Surveys & Archives

- 2FGL association process used existing catalogs of potential gamma-ray emitters
- Massaro et al. found a correlation for Fermi blazars while investigating their infrared properties with WISE
  - Of the 199 AGN candidates, 67 have counterparts in the WISE blazar strip
  - 17 pulsar-like sources also have potential WISE counterparts



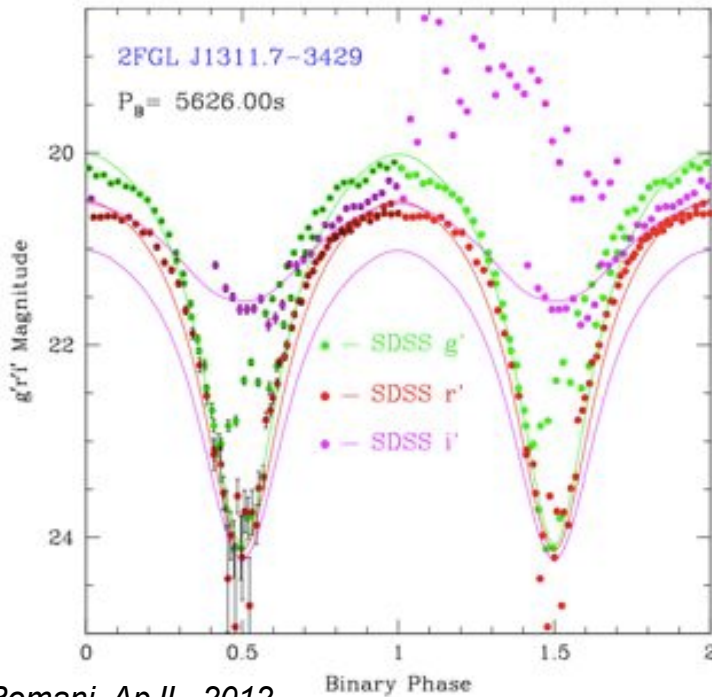
# Finding new AGN associations

- **Blazar candidates**
  - **Blazars are seen as flat spectrum sources in radio**
  - **Requires much better localization than typical Fermi errors (~8.5 arcmin for 2FGL unassociated sources)**
  - **Use survey data (radio, X-ray, IR) to find initial positions, then follow up with deeper radio measurements at several wavebands**

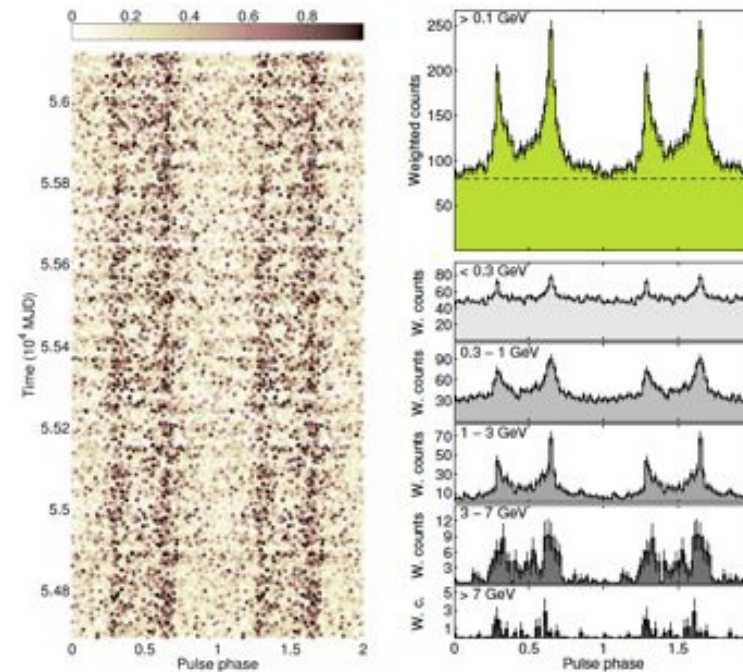


# Finding new Pulsars

- **Pulsar candidates**
  - If no obvious radio pulsar, must use blind search
  - X-ray positions (5-10'' accuracy) improve the chance of success by reducing the trials factor
  - For binary systems, an orbital solution is critical, requiring observations of optical or X-ray variability



Romani, ApJL, 2012



Pletsch et al., Science, 2012



# Request New Observations

- **Dedicated multiwavelength observations required**
  - **Partnerships developed with a number of different groups**
    - **Pulsar Search Consortium**
      - **GBT, Nançay, Effelsberg, Parkes, GMRT**
    - **TANAMI-CHI**
    - **Swift**
      - **Numerous TOO requests**
      - **Follow-up observations of 1FGL and 2FGL unassoc**
  - **Guest observer requests**
    - **VLA, VLBI, ATCA, XMM, Suzaku, Chandra, Swift, NOAO, NRAO, etc.**

# More ways to find sources?

- Look for high  $\dot{E}$  pulsars not seen as DC LAT sources
  - Huge effort by the Pulsar Timing Consortium

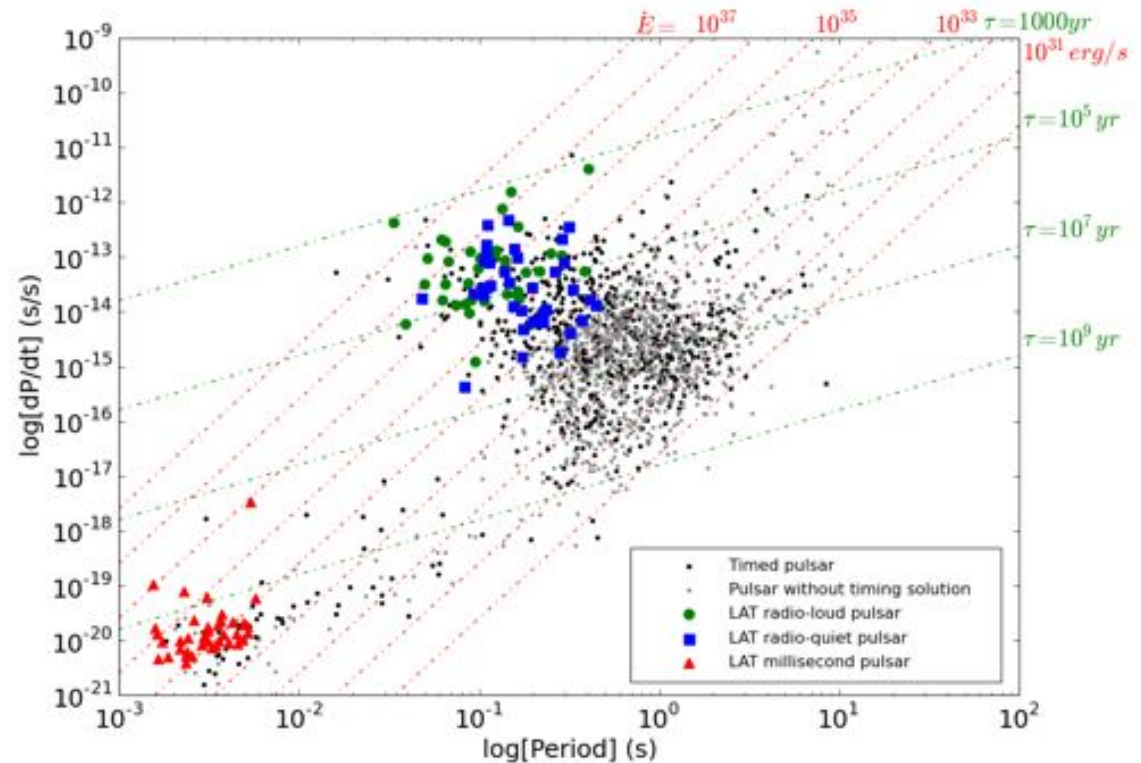
- Search for known SNRs and PWNe to find new gamma-ray detections

[T. Brandt, talk]

[R. Rousseau, talk]

- Search for off-pulse emission from known LAT pulsars to find pulsar wind nebulae

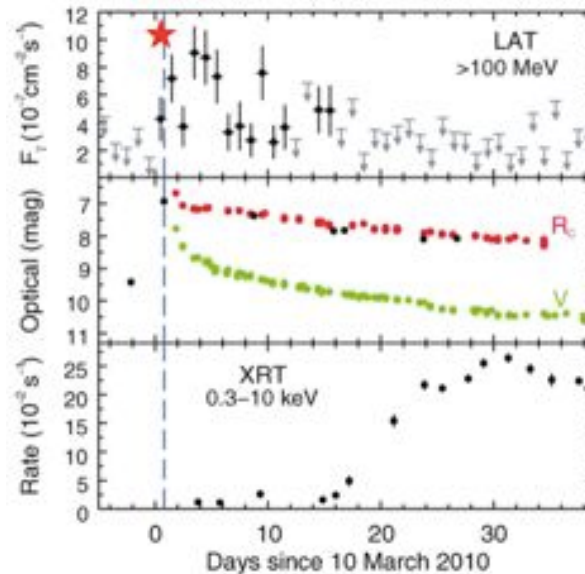
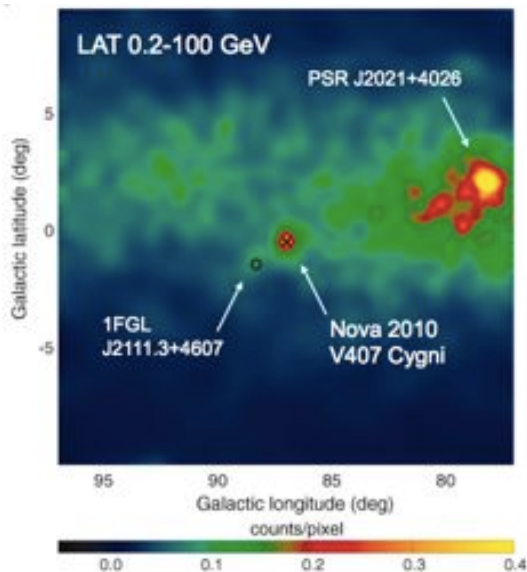
[J. Lande, poster]





# Refining the catalog

- Search for extension in LAT sources in or near the Galactic plane (see Lande et al., 2012)
  - Fitting extended sources with a point source model generates spurious sources in the catalog
- Keep watch for variable sources
  - Faint flaring AGN with low duty cycle
  - The occasionally variable Crab nebula
  - Stellar novae – correlated variability



Abdo et al.,  
Science, 2010

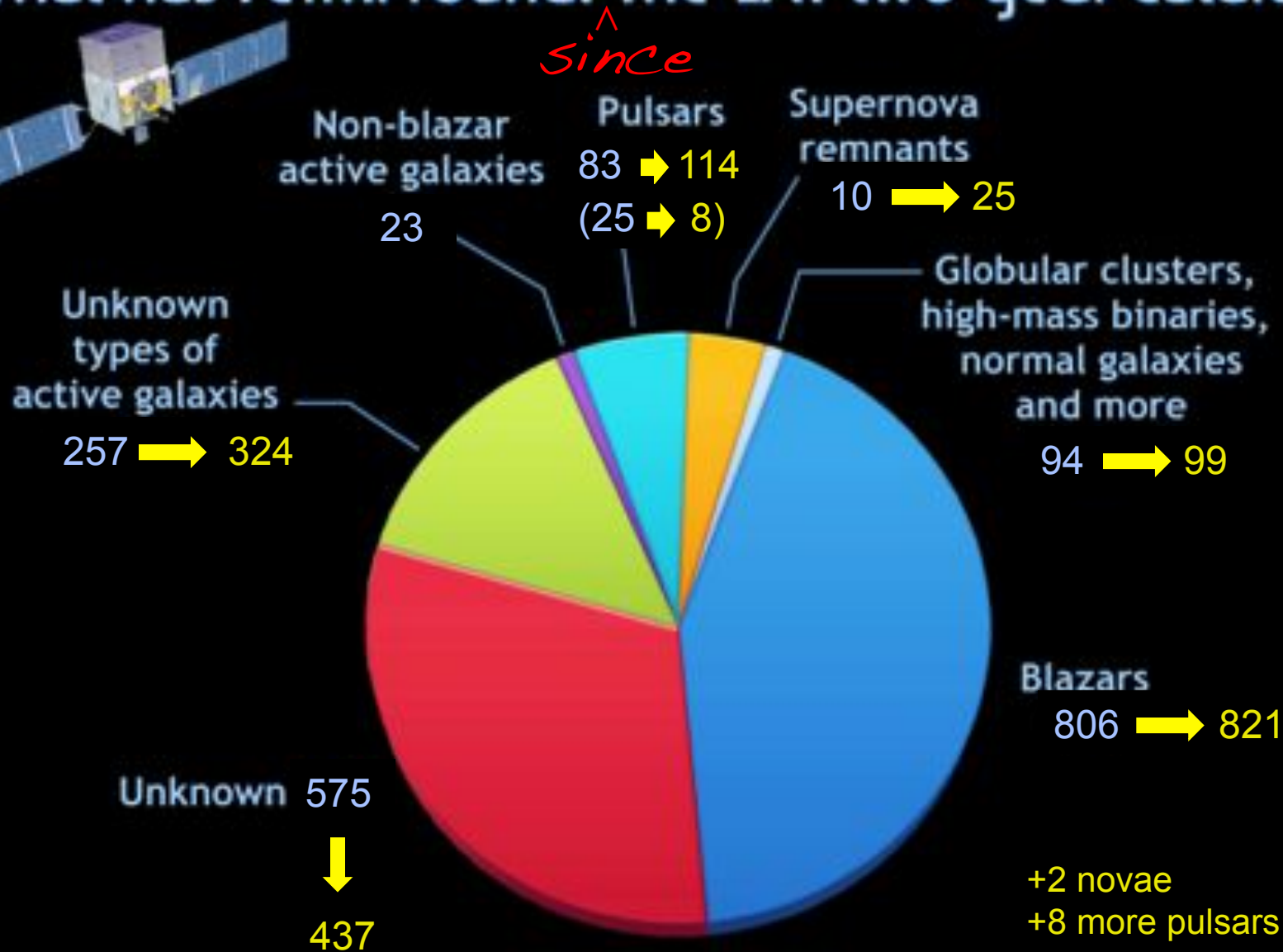
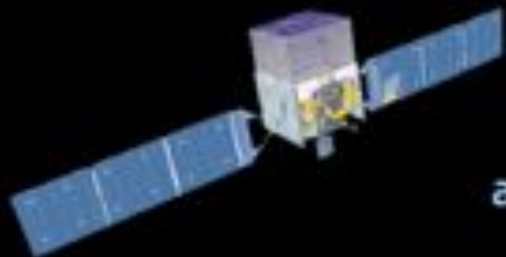


# Discovery!

- **Galactic**
  - **36 new pulsars discovered**
    - 22 more field MSPs (19 in binaries)
    - Double the number of Galactic black-widow binaries (4 → 8)
    - 14 more SNRs associated/identified
  - **6 new extended sources detected**
  - **13 spurious point sources removed**
  - **2 new stellar novae detected**
    - Nova Sco 2012, Nova Mon 2012
- **Extragalactic sources**
  - **67 new WISE blazar candidates**
  - **2 ATels with new AGN associations**
  - **Additional 13 new gamma-ray AGN without 2FGL detections**

**Since 2FGL**

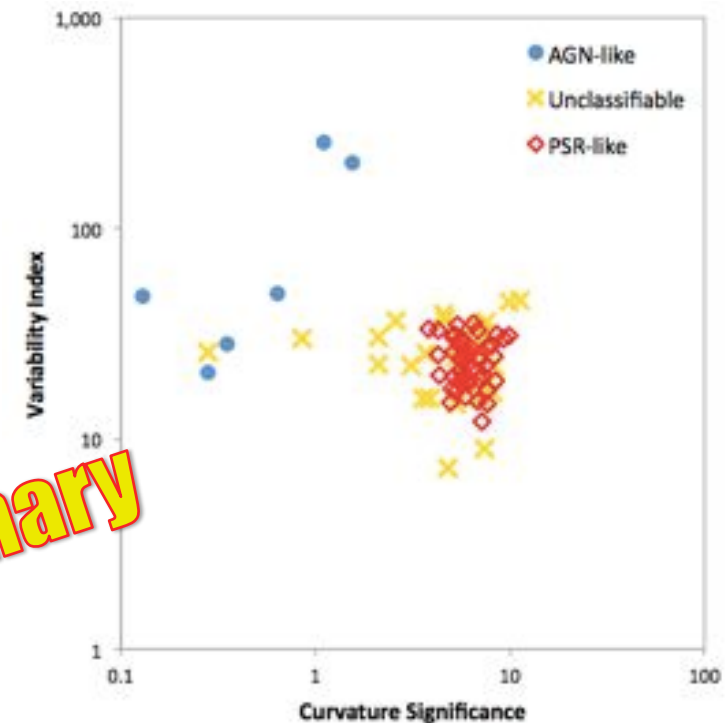
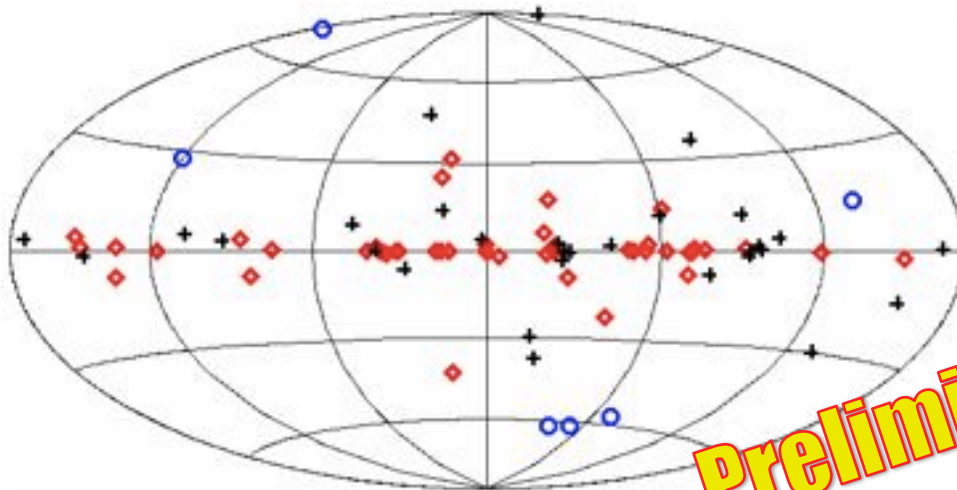
# What has Fermi found: The LAT two-year catalog?



Credit: NASA/Goddard Space Flight Center

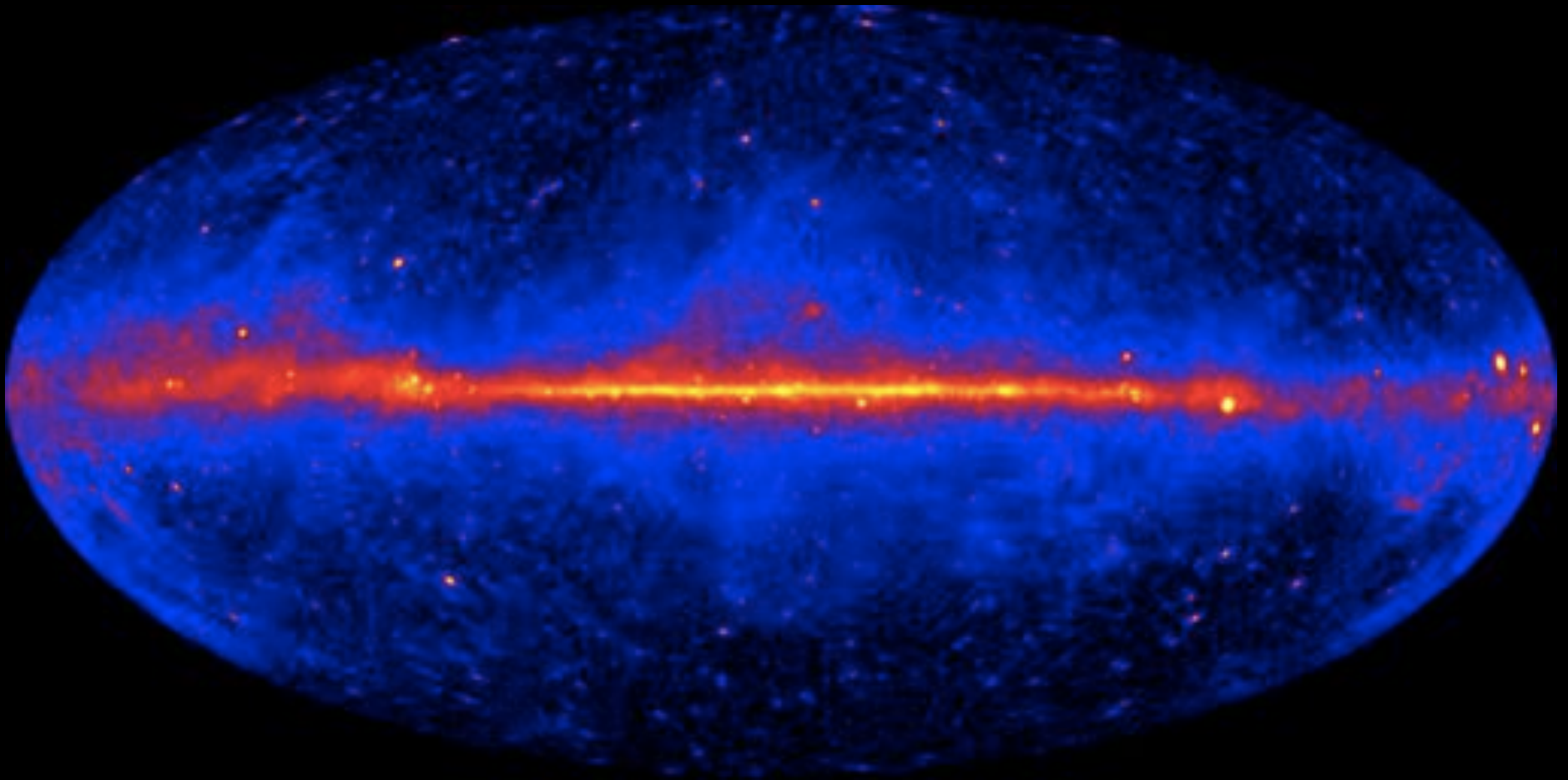
# What's left from 2FGL?

- 437 still-unassociated sources (~23%)
  - 5 BSL sources (1 at high= $|b|$ )
  - 84 have WISE candidates
  - 83 above  $10\sigma$  in 2FGL (31 above  $|b| = 5^\circ$ )
    - 6 AGN candidates, 47 pulsar candidates
    - 6 are variable (2 within  $5^\circ$  of the plane)
    - 14 are “c-sources”



**Preliminary**

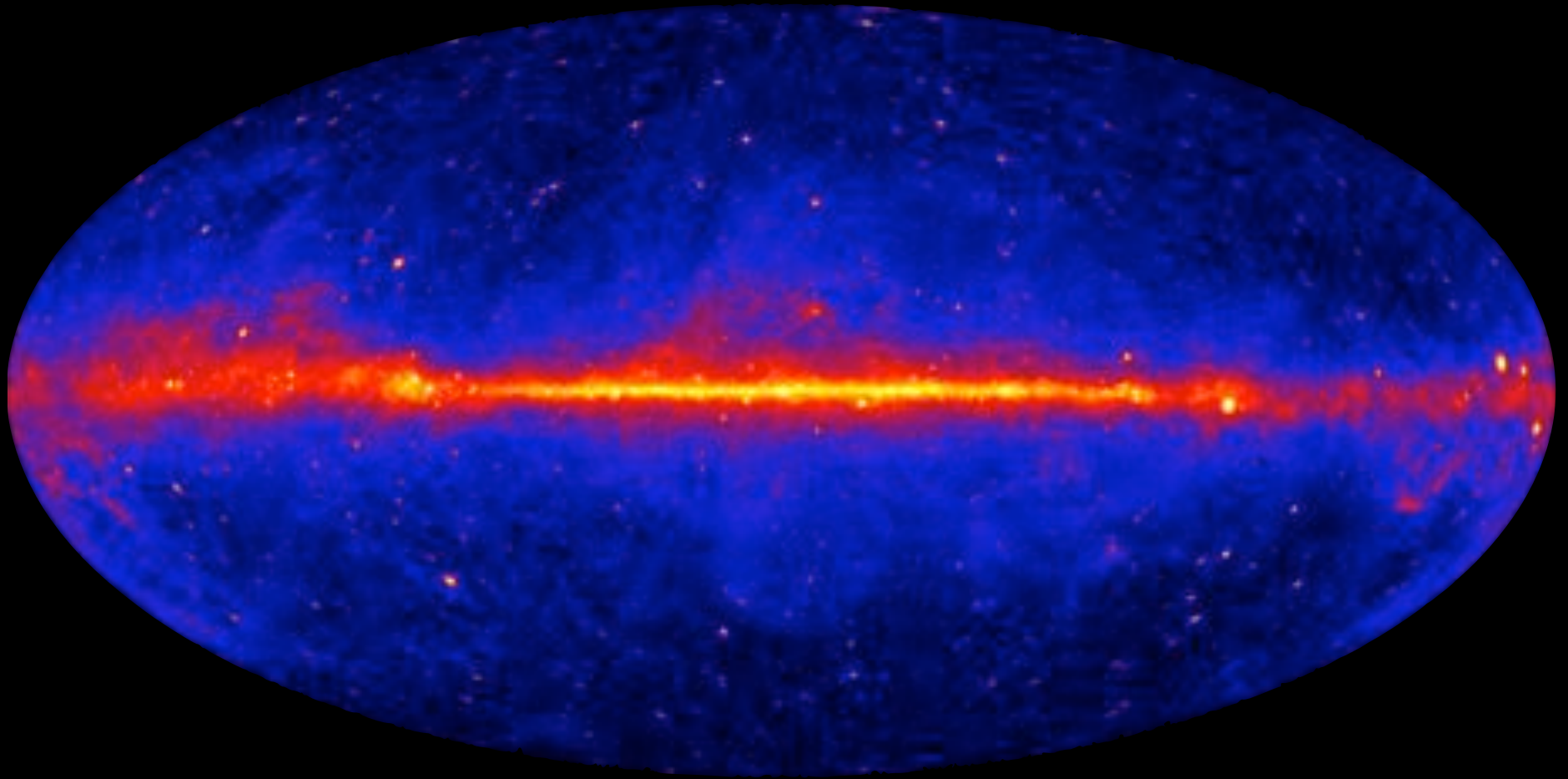
# LAT 2-year Sky Map



>1 GeV for the interval ending August 2010

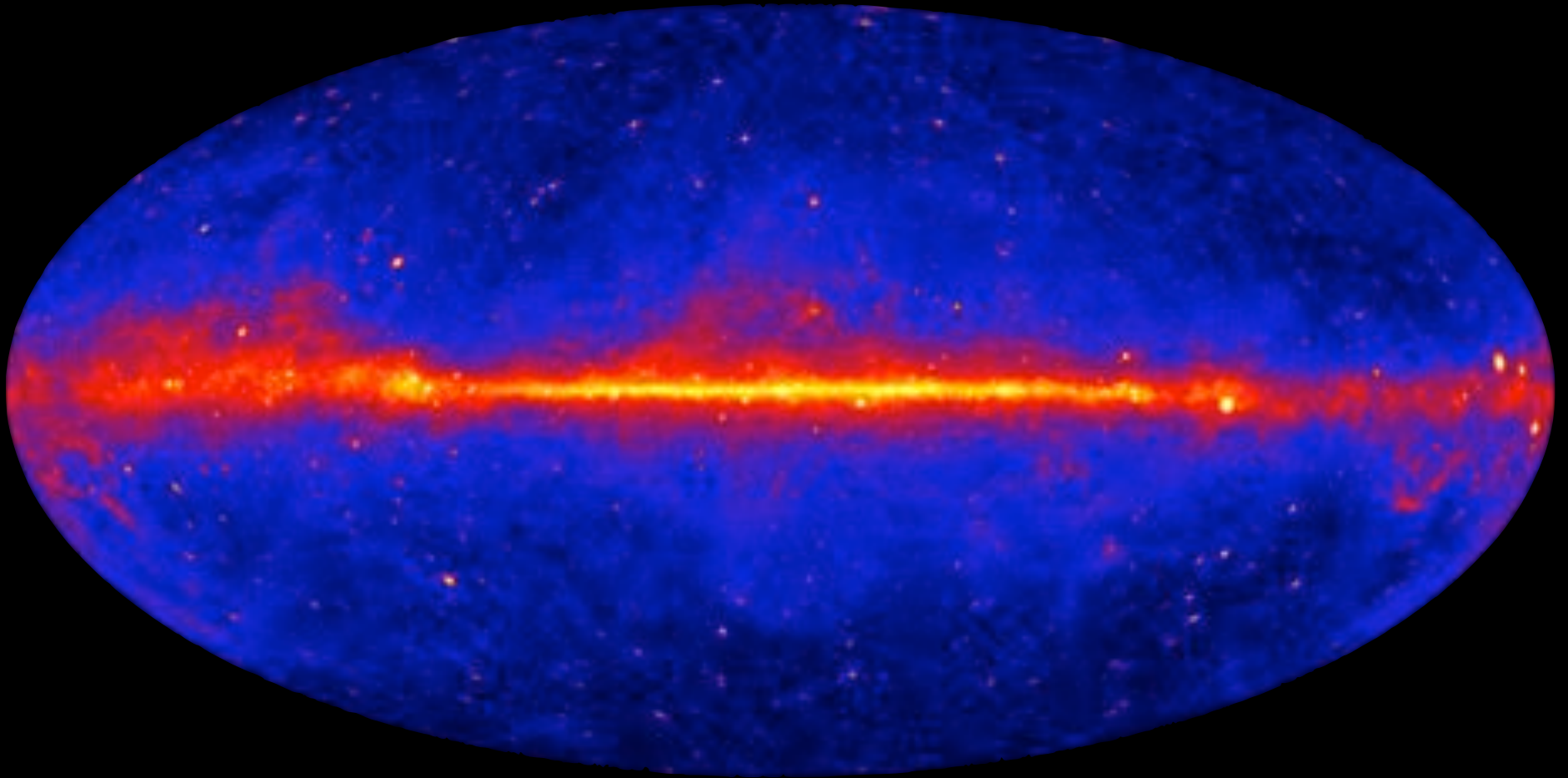


# LAT 3-year Sky Map



>1 GeV for the interval ending August 2011

# LAT 4-year Sky Map



>1 GeV for the interval ending August 2012

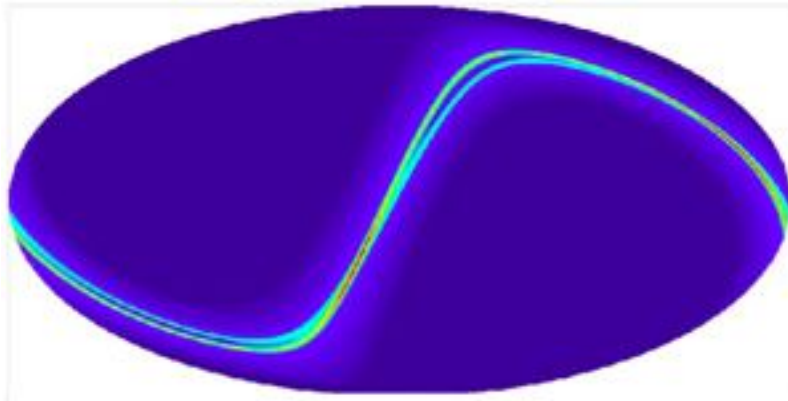


# Lots more to do!

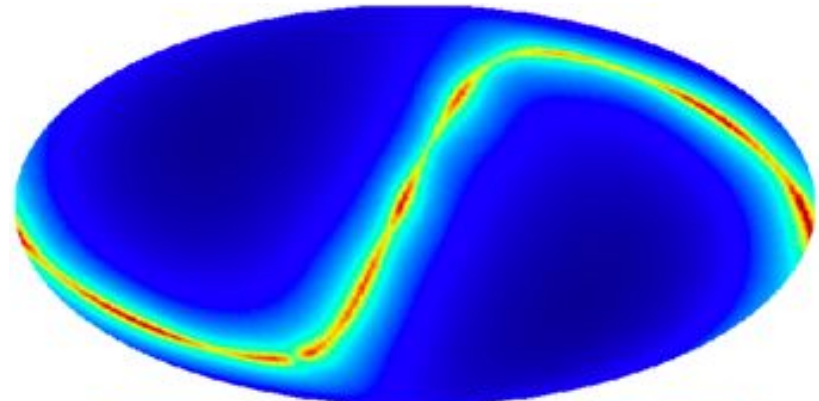
- **Near-term upcoming results**
  - **Second LAT pulsar catalog** [P. Ray, Monday]
  - **Catalog of LAT-detected SNR** [T. Brandt, Tuesday]
  - **Catalog of LAT sources at >10 GeV** [D. Paneque, next]
  - **Catalog of Flaring LAT sources** [A. Allafort, just after]
  - **List of LAT-detected TGFs** [J. Grove, Wednesday]
  - **List of LAT-detected solar flares** [N. Omodei, Monday]
  - **Catalog of LAT-detected GRBs**
  - **Extension of both GBM GRB catalogs for years 3 & 4**  
[A. von Kienlin, after that]
  - **Catalog of joint Fermi-Interplanetary Network GRBs**
  - **Update to GBM-detected TGFs** [V. Connaughton, Monday]
  - **Type-1 X-ray bursts in GBM**
  - **5-year catalog of LAT point sources**

# Development for 5-year catalog

- **Both quiescent Sun and Moon can be seen in the 4-year integrated data set**
  - **Developing tools to calculate exposure-corrected templates using measured spectra**
  - **Sun and Moon templates will be included as an all-sky source in 5-year catalog analysis**



Example template with both sun and moon, using 1-year average exposure

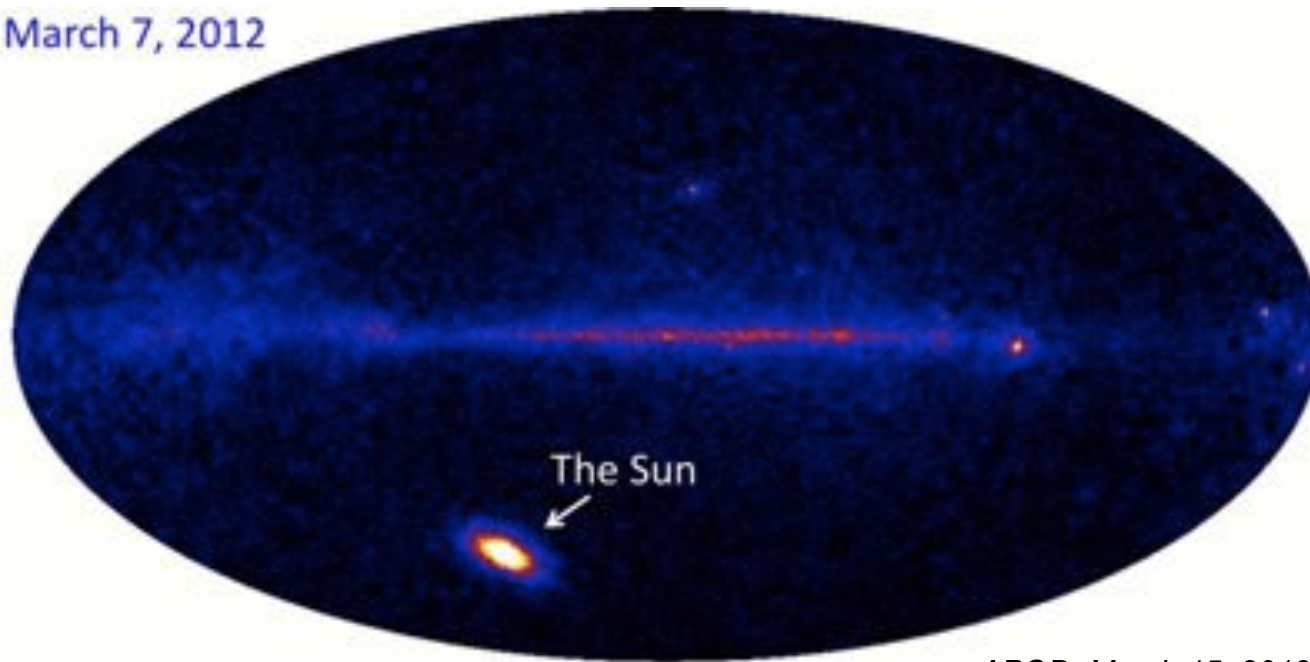


Example template of sun using one year of actual exposure

# Development for 5-year catalog

- **Bright solar flares affect the instrument response (X-rays pile up)**
    - Data is flagged as “bad” during these periods
    - Sun bright in the data for much longer than is flagged
    - Detected solar flare times are cut from dataset
- ~ 54 hours to date

March 7, 2012

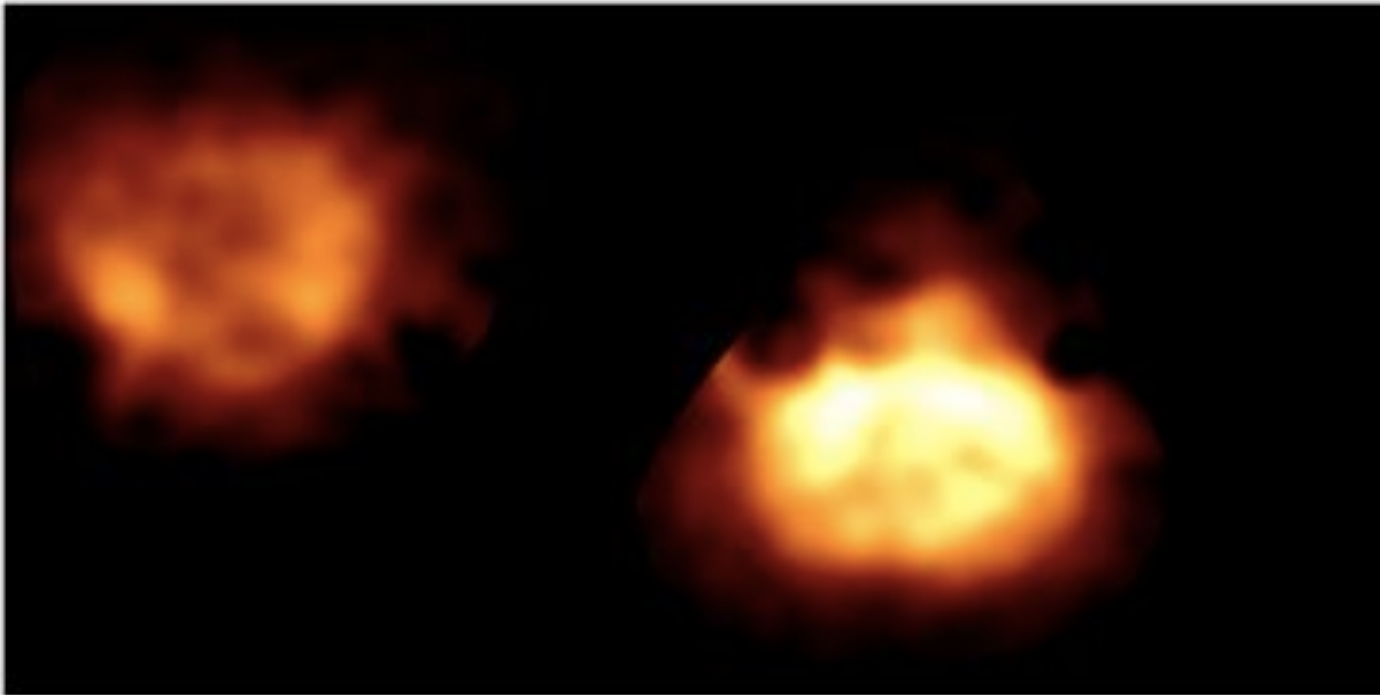


APOD, March 15, 2012



# Development for 5-year catalog

- **Phenomenological Earth Limb model**
  - Some residual earth limb emission present after zenith cut
  - 2FGL limb photon template was derived from data
  - Developing new tools to generate limb template using actual exposure and measured spectrum



# 5-year projection

- **Extrapolating...**
  - **More than 1500 blazars**
    - Association process finds these
  - **More than 200 pulsars**
    - Current count 122 and climbing quickly
  - **~30 SNRs**
    - Current count 25
  - **(~800 sources > 10 GeV)**  
...next talk...
  - **Add in other sources and assume unassociated fraction of 25% to 30%**

➔ **~2800 sources**

