Highlights of GeV Gamma-ray Astronomy

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Outline

- Introduction - Gamma Rays and Cosmic Rays
- Distant GeV Gamma-ray Sources
  - Gamma-ray Bursts (GRB)
  - Active Galactic Nuclei (AGN)
  - Starburst galaxies
- Galactic GeV Gamma-ray Sources
  - Diffuse radiation
  - Pulsars and Pulsar Wind Nebulae
  - Binary sources
  - Supernova remnants
- The Future

Gamma Rays and Cosmic Rays

- **High-energy gamma rays are primarily produced by interactions of energetic particles.**
  - **Typical processes are inelastic nuclear collisions (pion production), inverse Compton scattering, curvature and synchrotron radiation.**

- **The Universe is mainly transparent to gamma rays with energies less than 20 GeV, so they can probe distant or obscured regions.**
  - **Potential to image regions of cosmic ray acceleration and interaction.**

A Milestone!

- **This week marks the beginning of the third year of science operations for the Fermi Gamma-ray Space Telescope**
- Planned mission of at least 5 years.
- The smaller AGILE gamma-ray satellite has been operating for over three years in space.

The Fermi Gamma-ray Space Telescope

An International Mission with Strong European Contributions

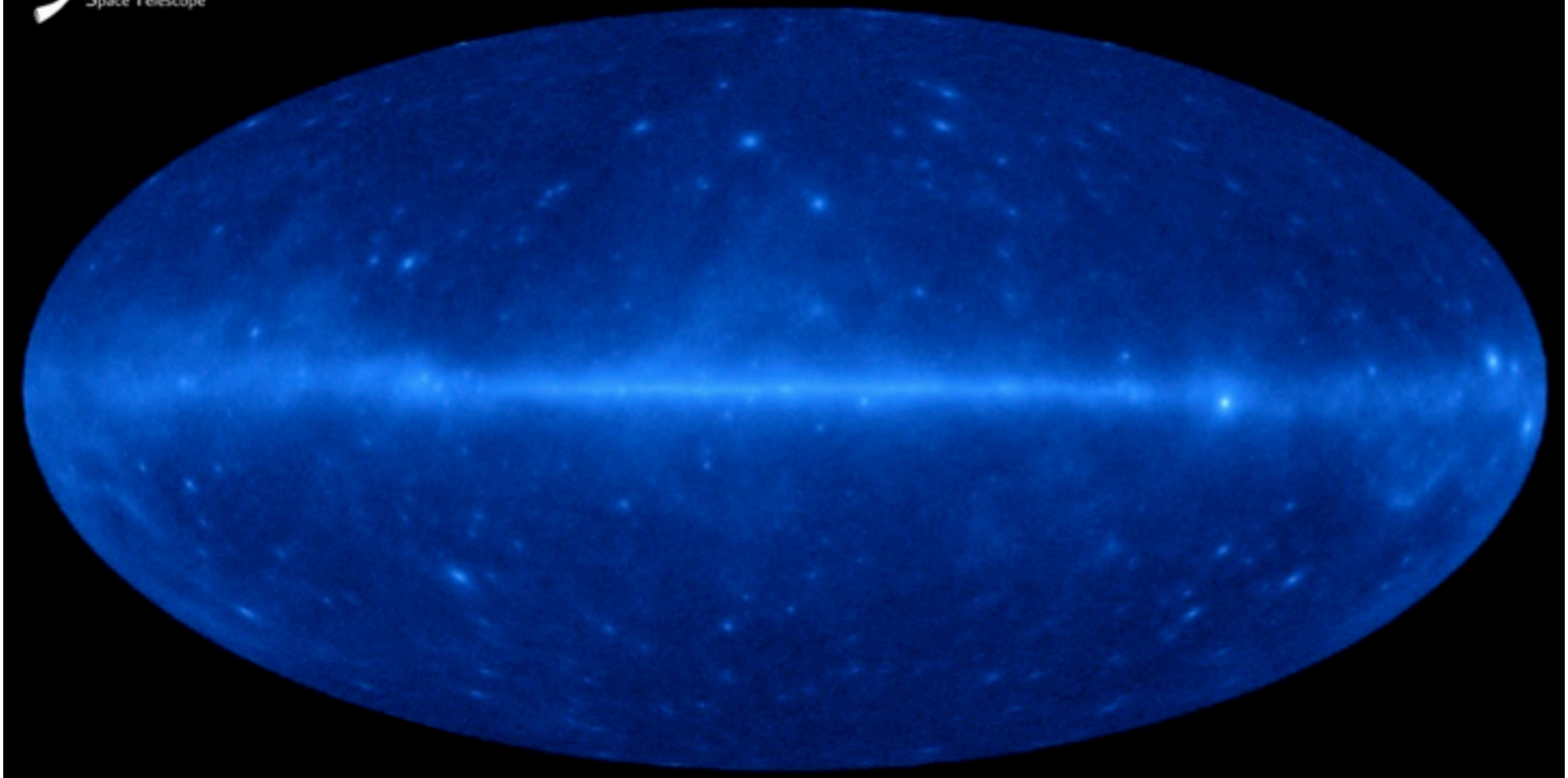
Large Area Telescope (LAT)

KEY FEATURES

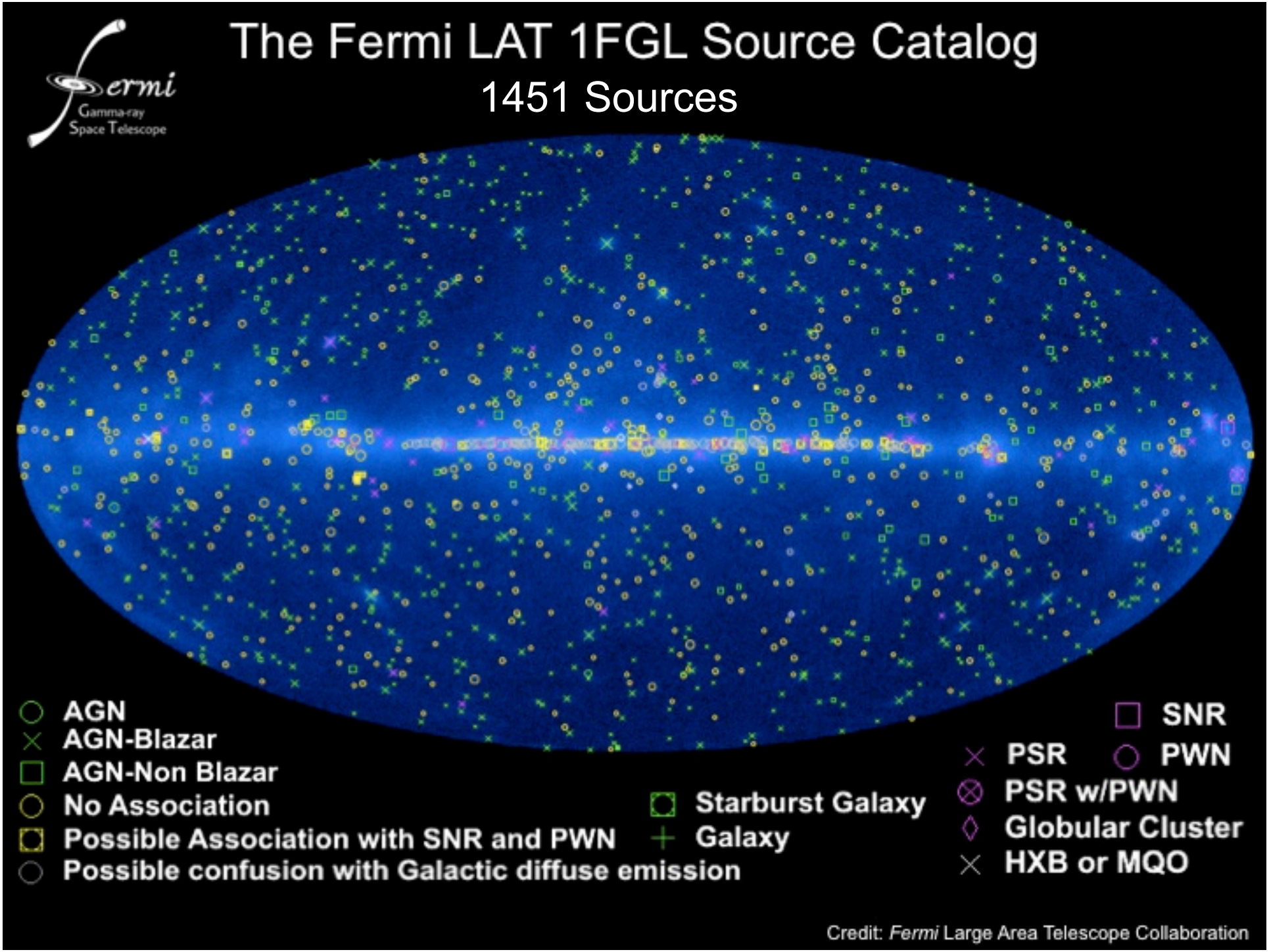
- 20 MeV -> >300 GeV
- 2.4 Steradian field of view
- Operated in scanning mode, so views the entire sky every 3 hours.
- Peak effective area ~8000 cm^2
- Single photon angular resolution 0.8° at 1 GeV, better at higher energies.
- Source location capability 1-10 arcmin.
- Energy resolution 10-20%

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

The Gamma-ray Sky Seen with Fermi LAT

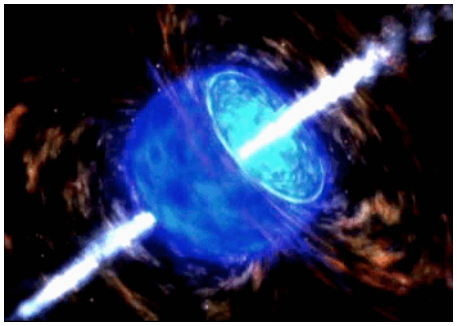


Sources are seen against a strong Galactic and extragalactic diffuse background. E > 1 GeV image.

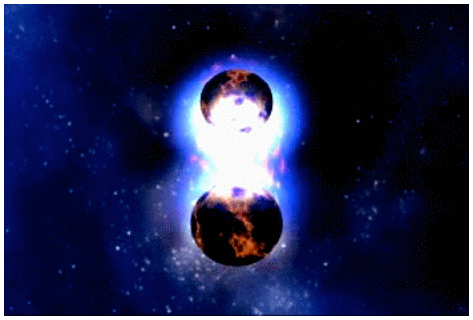

The Fermi LAT 1FGL Source Catalog
1451 Sources
Fermi
Gamma-ray
Space Telescope
AGN
AGN-Blazar
AGN-Non Blazar
No Association
Possible Association with SNR and PWN
Possible confusion with Galactic diffuse emission
Starburst Galaxy
Galaxy
SNR
PSR
PWN
PSR w/PWN
Globular Cluster
HXB or MQO
Credit: Fermi Large Area Telescope Collaboration

Extragalactic Gamma-ray Sources

Gamma-ray Bursts (GRBs) - the Brightest and Most Distant Sources Seen by Fermi



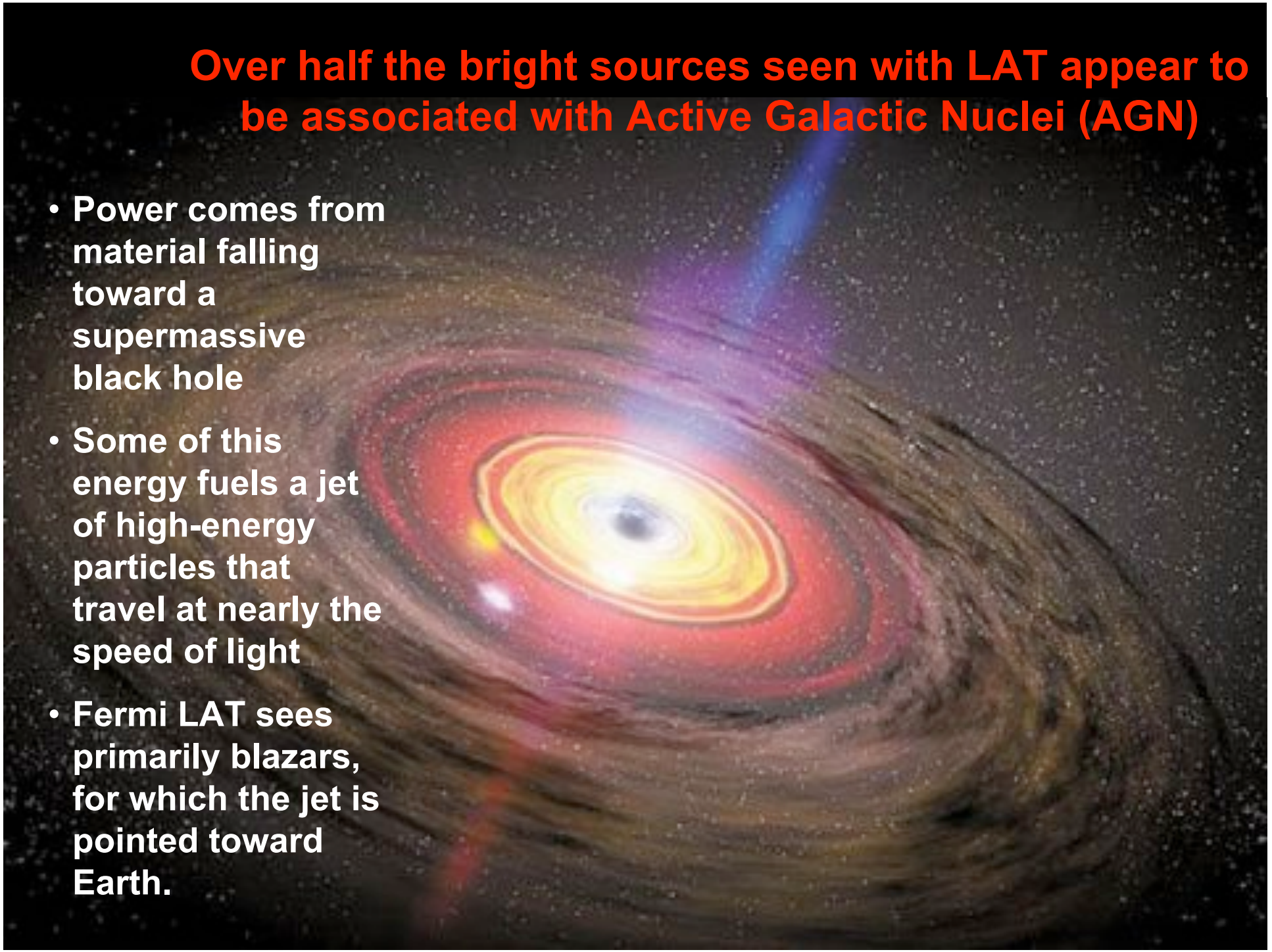
Collapsar: Rapidly spinning stellar core collapse supernova, with relativistic jets that can produce long GRBs



Compact Merger: Two neutron stars, or a neutron star and a black hole, merge, producing a jet that gives rise to a short GRB

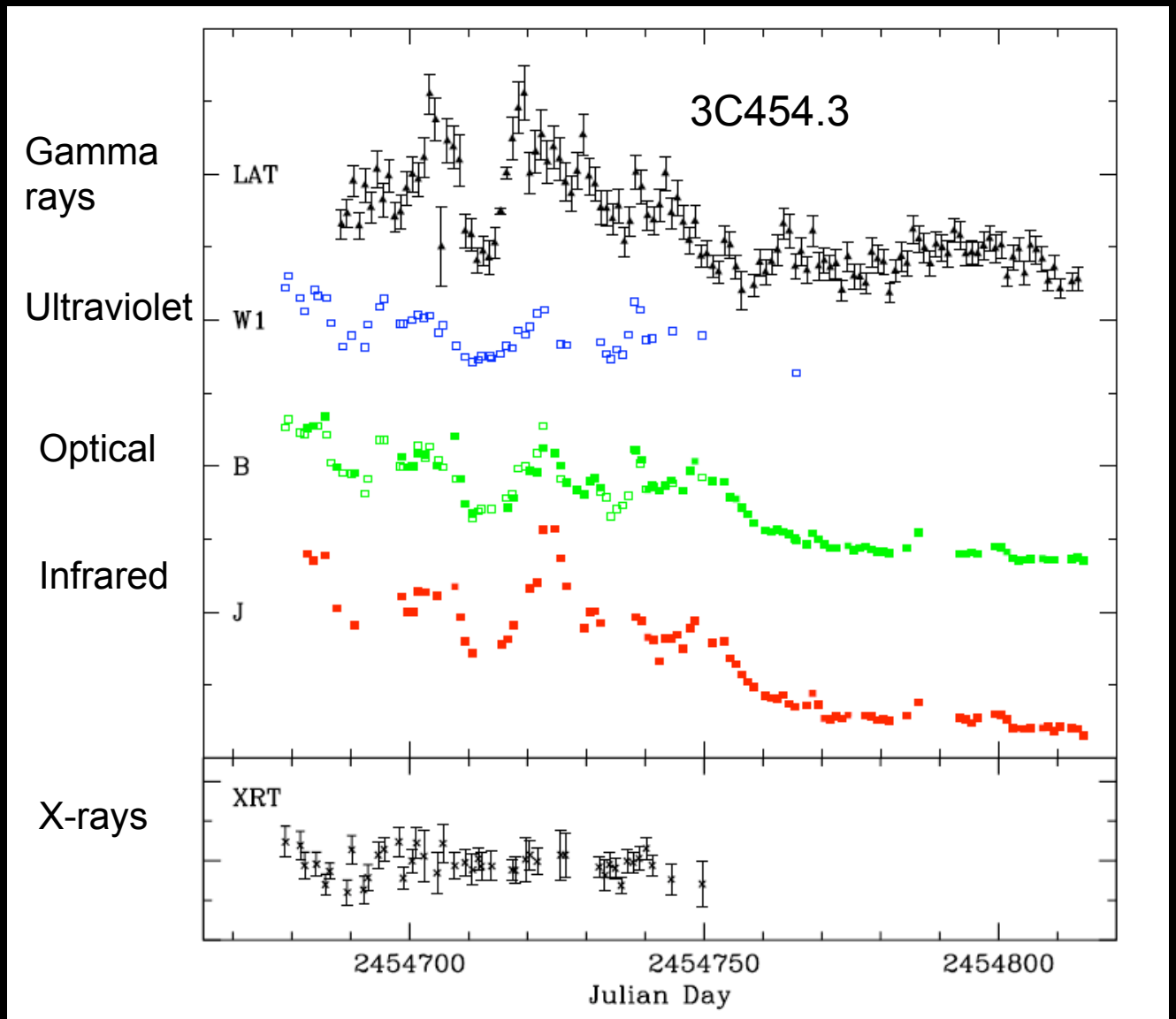
- Both long (>2 sec) and short (<2 sec) bursts have been seen
- Some bursts show high-energy emission afterglow
- Constraint: lower limit of bulk Lorentz factor: Γ_{min} ~1000
- Some bursts have an extra spectral component compared to the standard Band model.
- These short, bright flashes can be used as tools to probe basic physics, as in the example here.

Over half the bright sources seen with LAT appear to be associated with Active Galactic Nuclei (AGN)



- Power comes from material falling toward a supermassive black hole
- Some of this energy fuels a jet of high-energy particles that travel at nearly the speed of light
- Fermi LAT sees primarily blazars, for which the jet is pointed toward Earth.

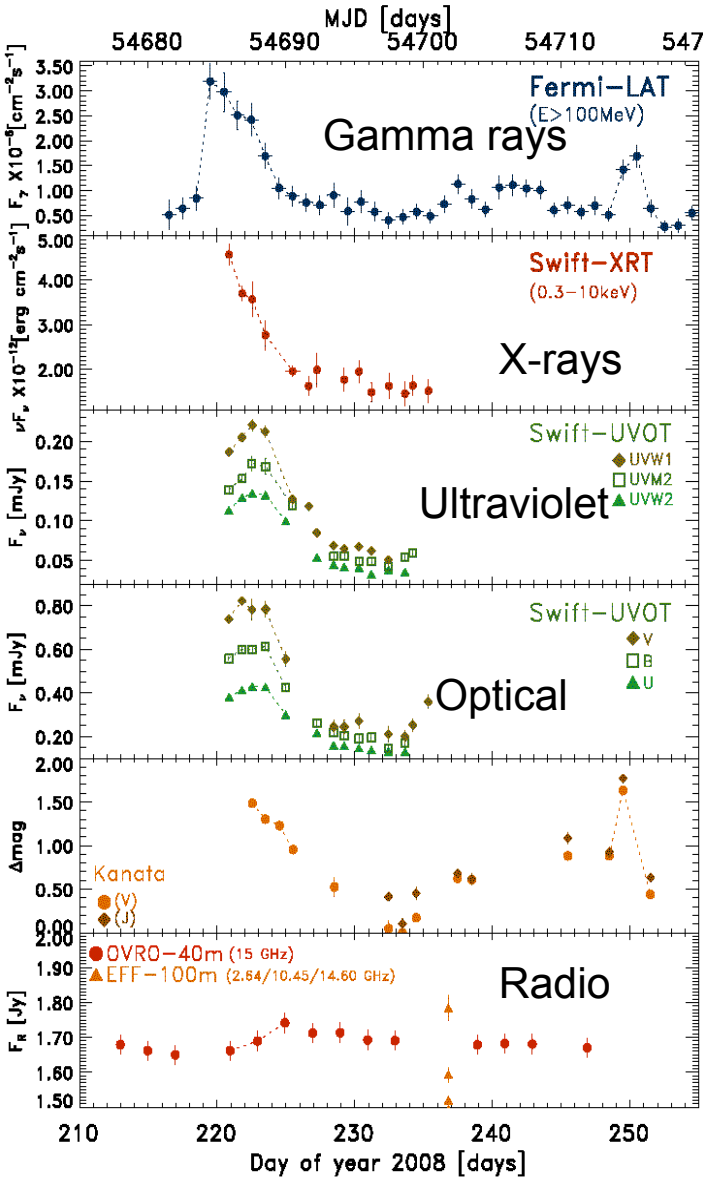
How to learn about jets? Variability

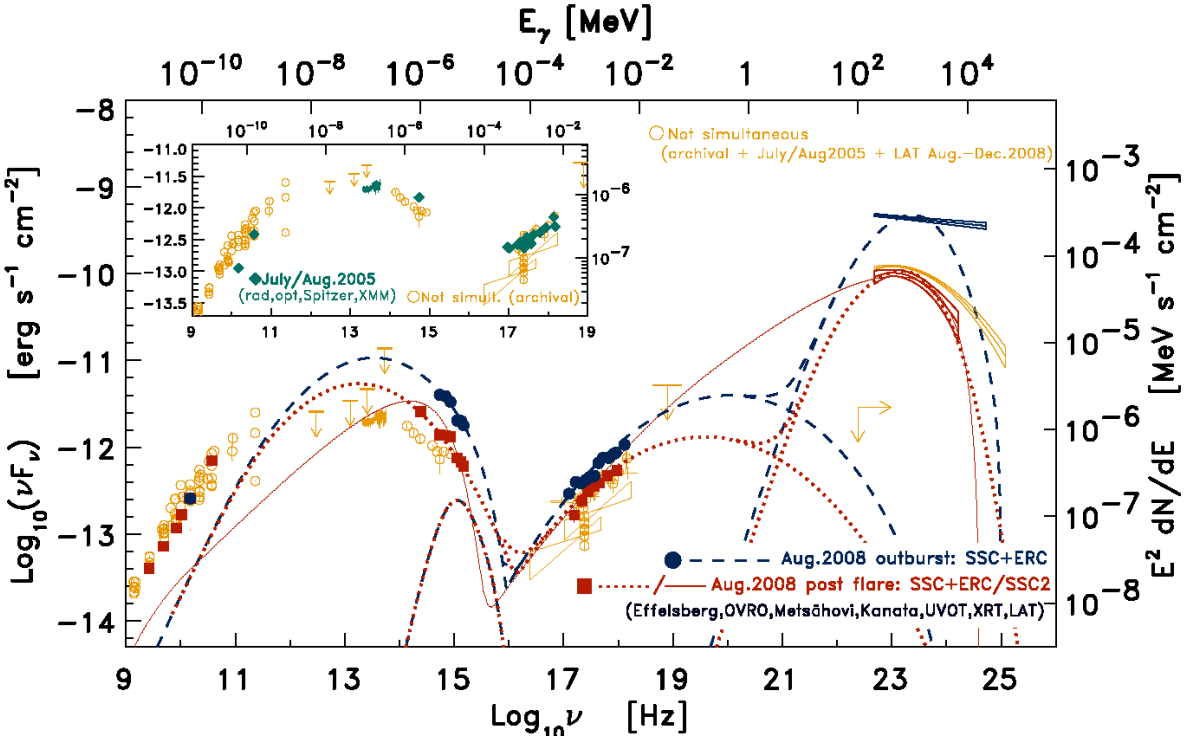


Bonning et al. 2008

Correlated variability helps us learn how jets work.

Blazar PKS 1502+106



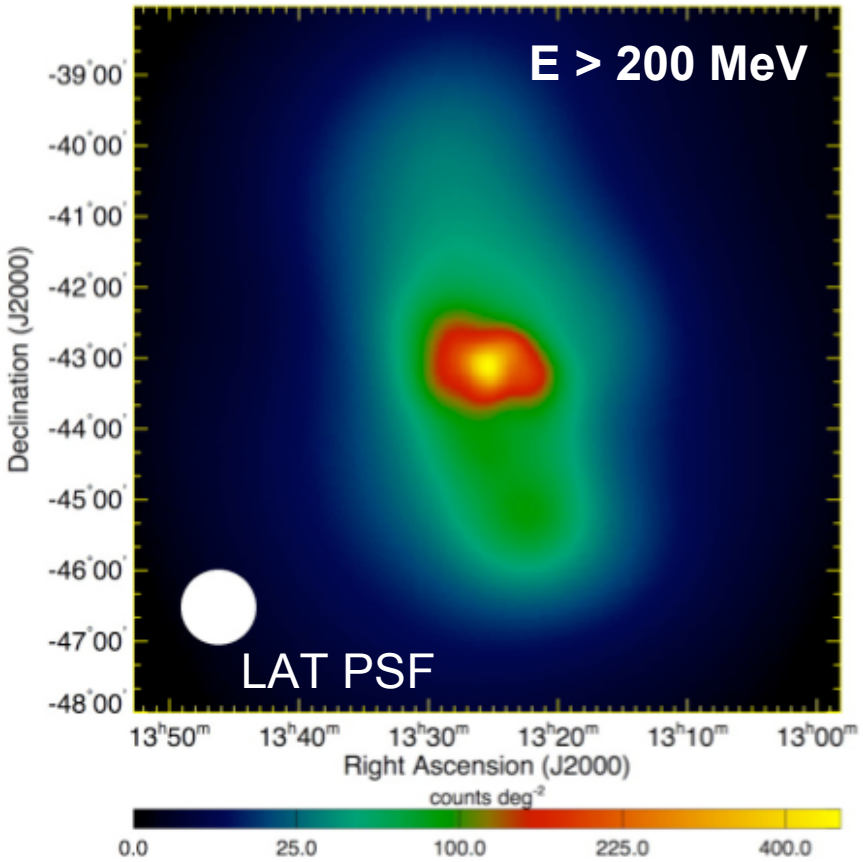


The spectral Energy Distribution (SED) of this blazar is complex, requiring multiple components that vary with time.

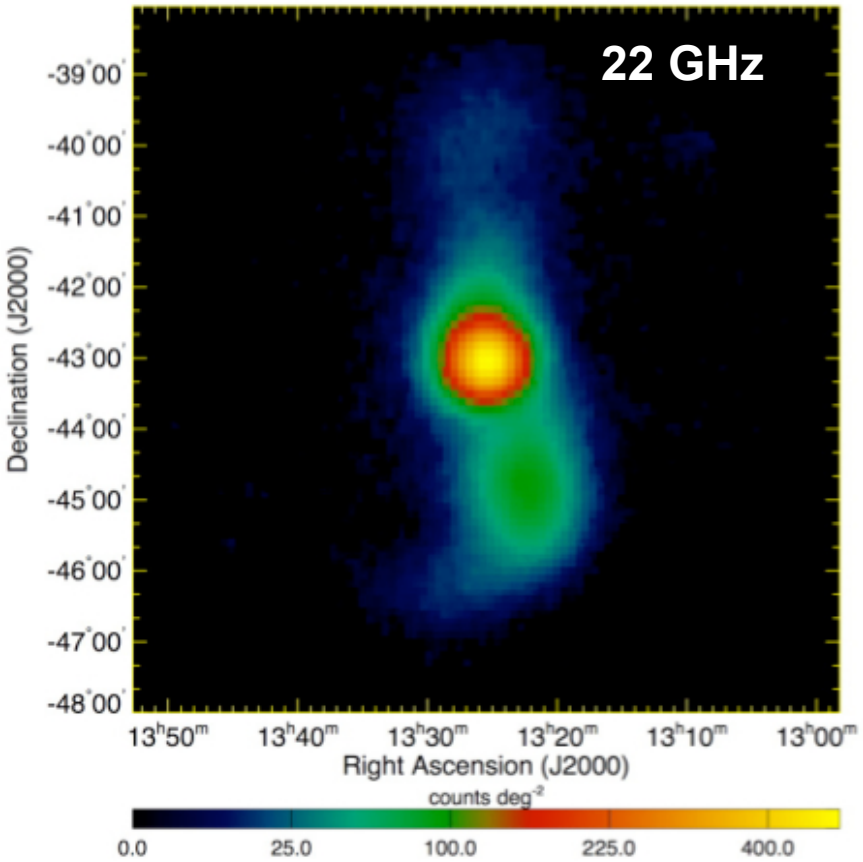
A key result for Fermi and multiwavelength studies: in most cases, simple models for blazars are inadequate.

Centaurus A - Radio Galaxy

Over ½ of the total >100 MeV observed LAT flux in the lobes



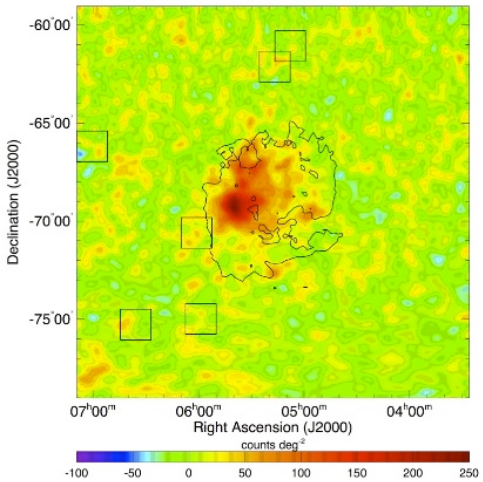
LAT counts map with background (isotropic and diffuse) and field point sources subtracted



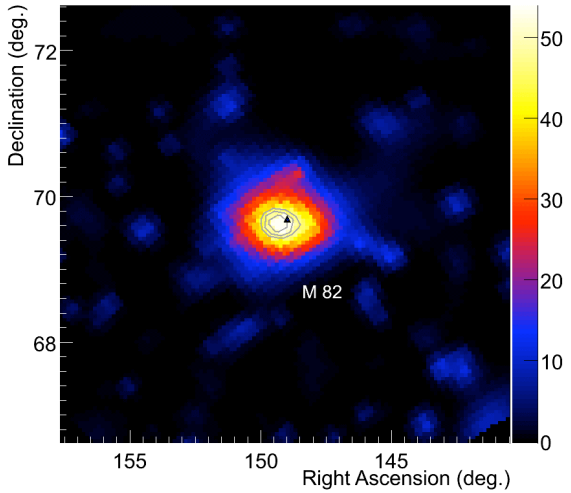
WMAP image provided by Nils Odegard (GSFC)

Requires 0.1-1 TeV electrons in giant 'relic' lobes: accelerated in-situ or efficient transport from center

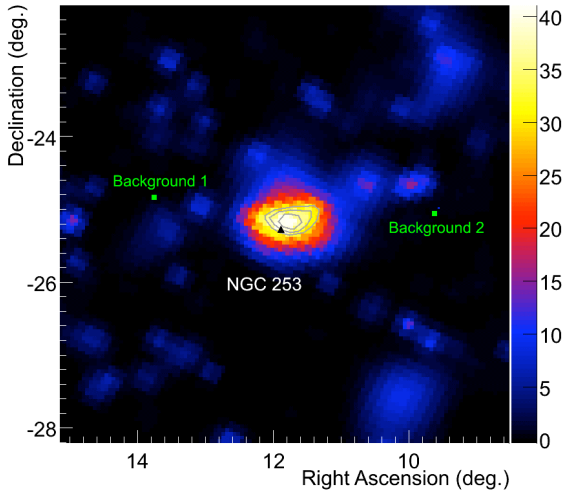
Galaxies Dominated by Cosmic-Ray Interactions



Large Magellanic Cloud

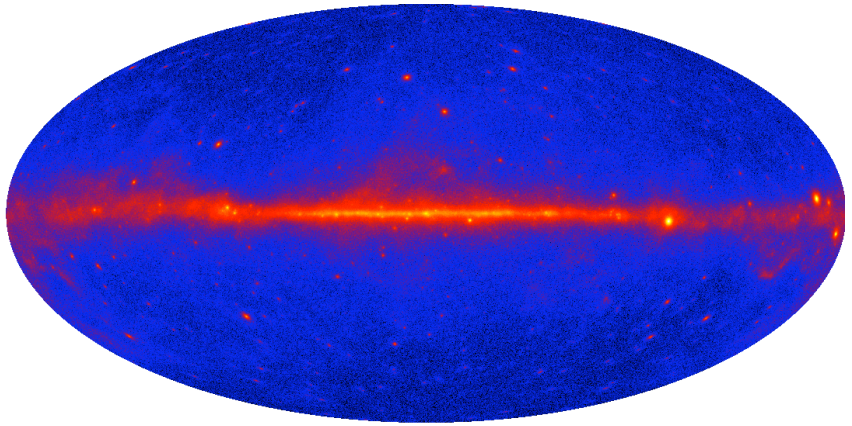


M82



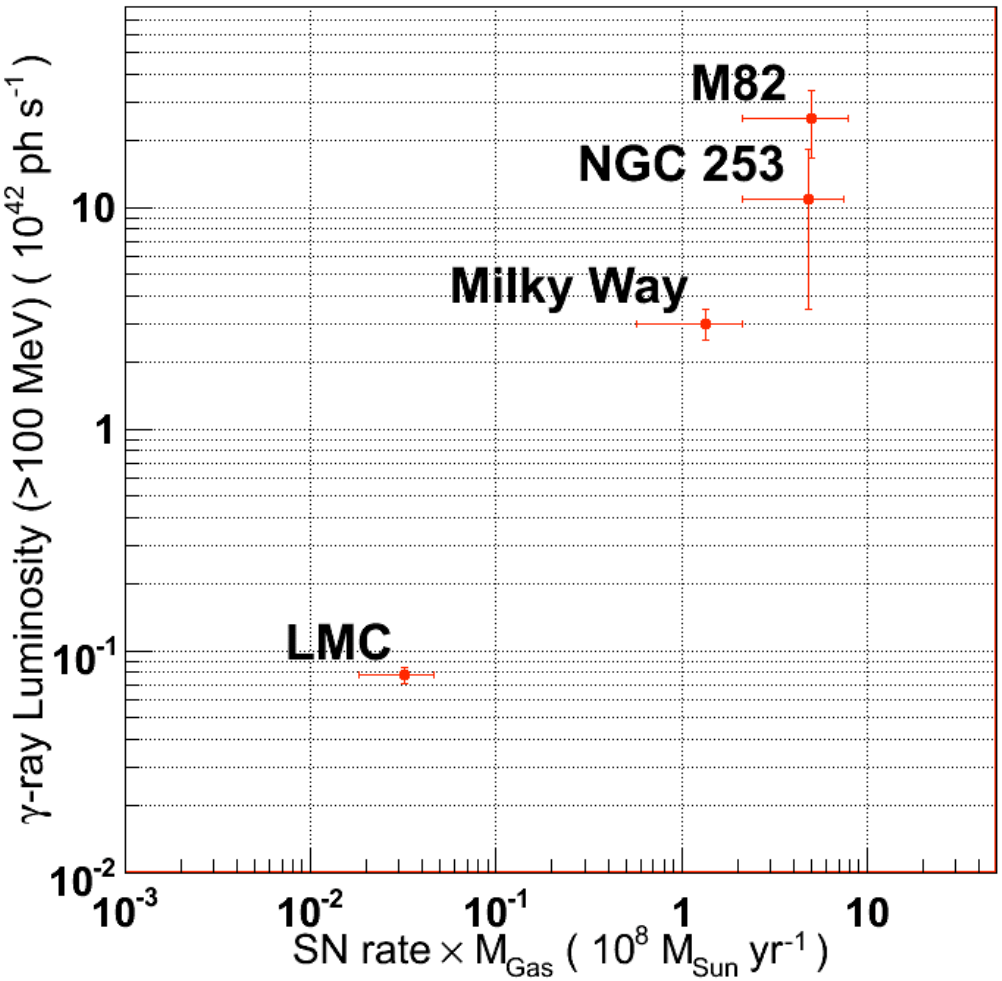
NGC253

Milky Way



GeV gamma rays in these galaxies come primarily from the interactions of cosmic ray hadrons and electrons with interstellar matter and photon fields.

Galaxies Dominated by Cosmic Ray Interactions

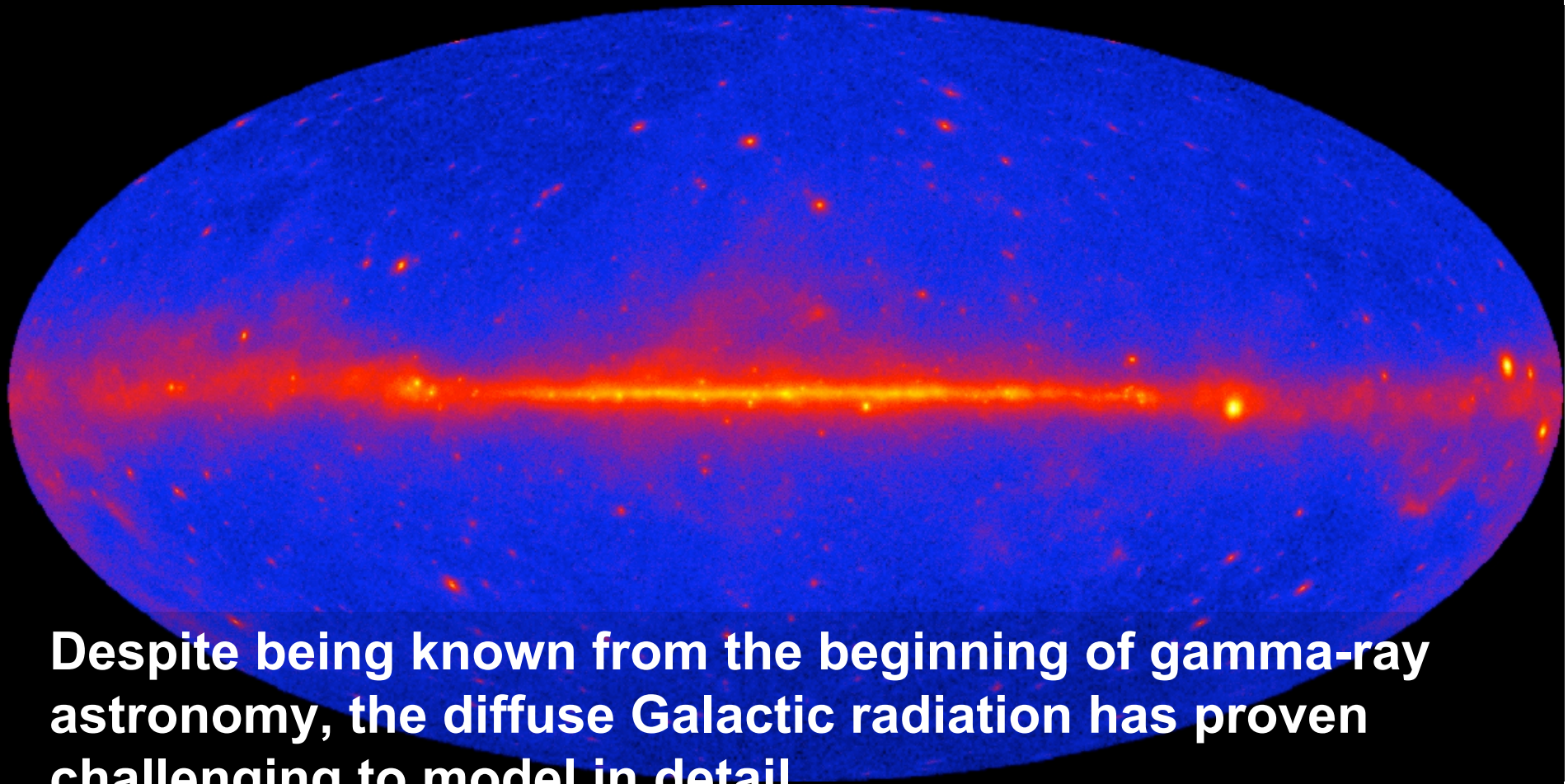


The product of the supernova rate and the total mass of gas in these galaxies appears to show a trend, supporting the long-held expectation that supernovae are the principal accelerators of cosmic rays (at least hadrons).

Note that there are large uncertainties in these calculations, so this result should be treated with some caution.

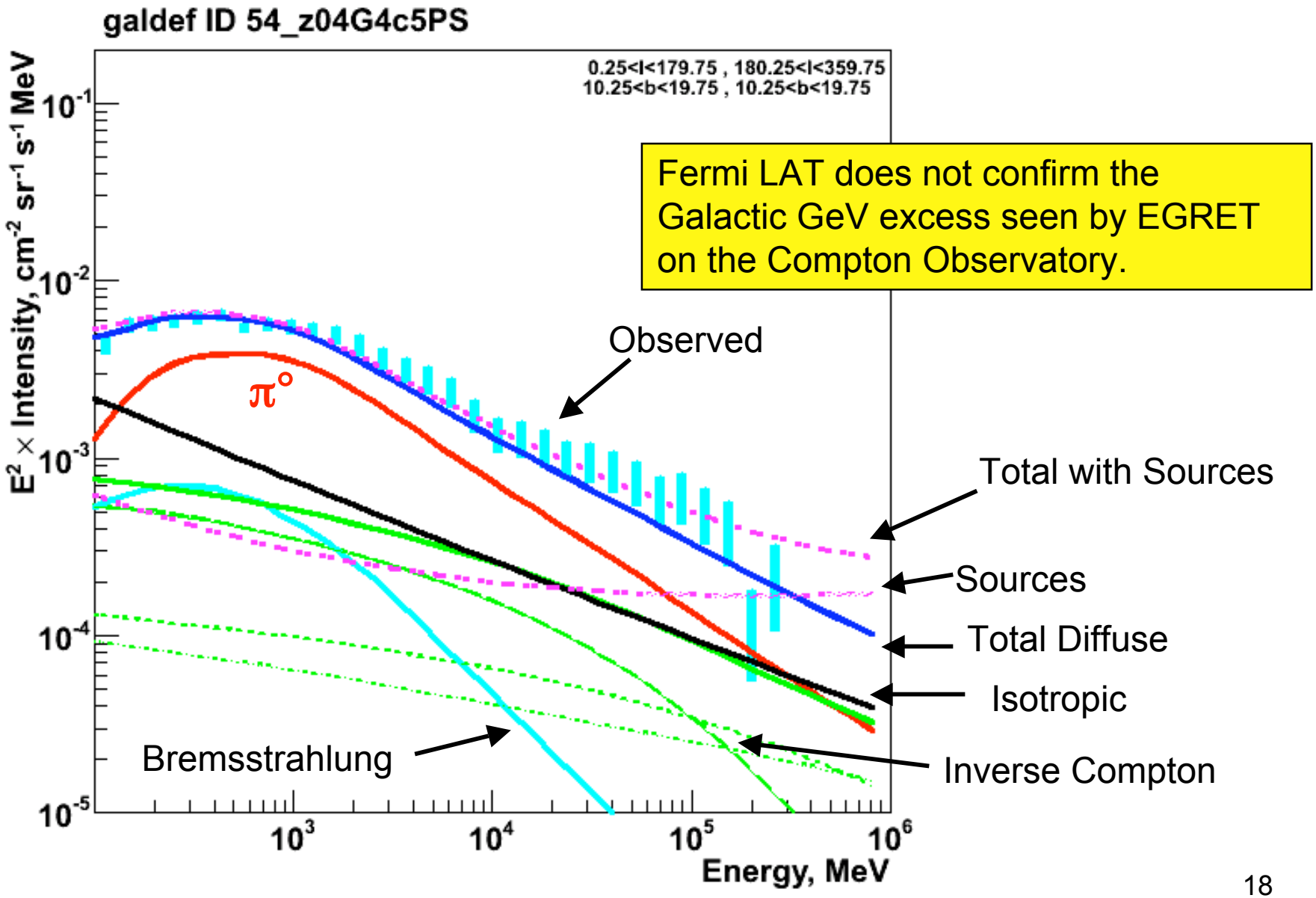
Galactic Gamma-ray Sources

Galactic gamma-radiation: largely diffuse emission from cosmic-ray interactions with the interstellar medium



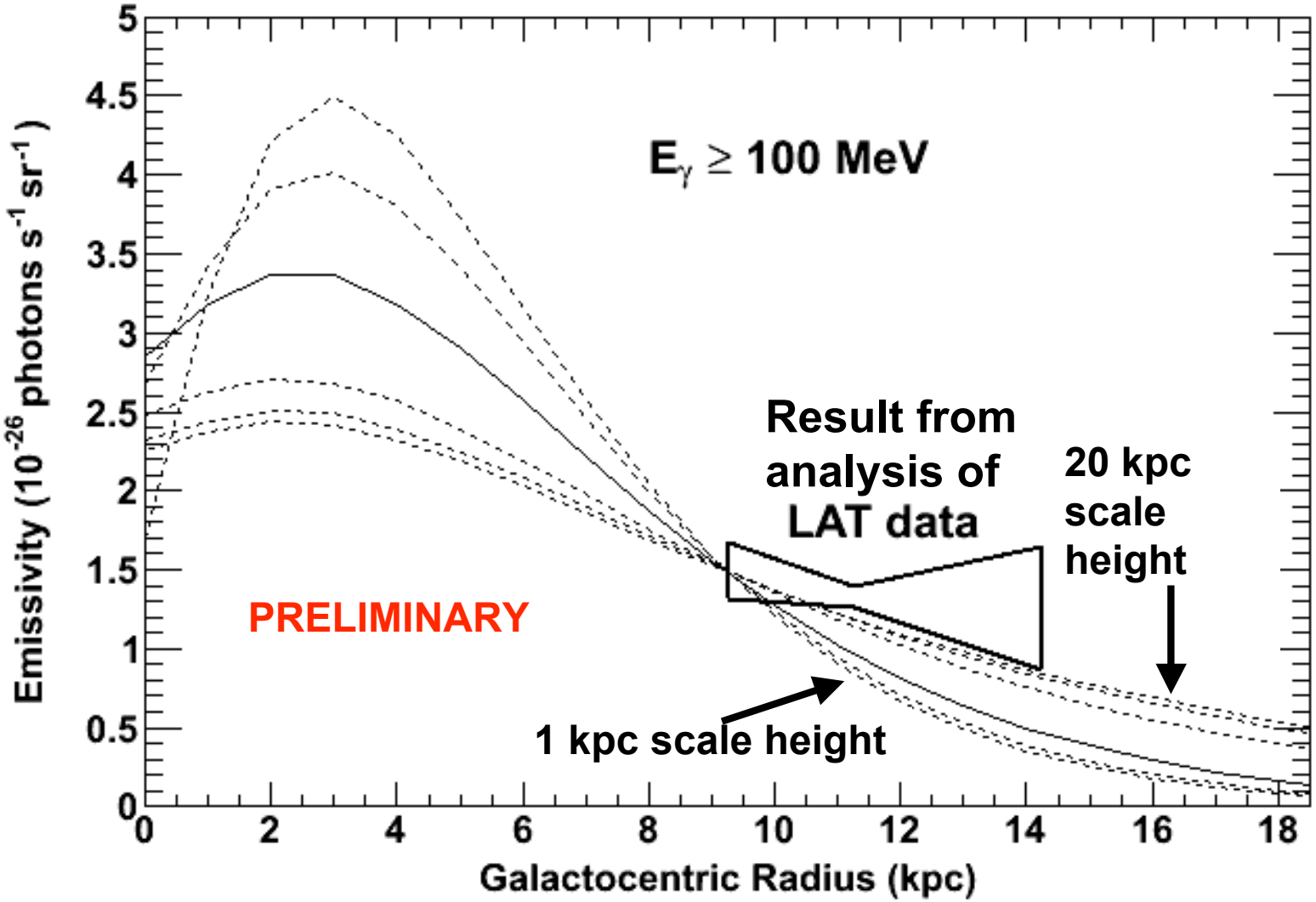
Despite being known from the beginning of gamma-ray astronomy, the diffuse Galactic radiation has proven challenging to model in detail.

Gamma-ray Spectrum at Intermediate Galactic Latitudes



Gamma-ray Indications of a Large Cosmic-ray Halo

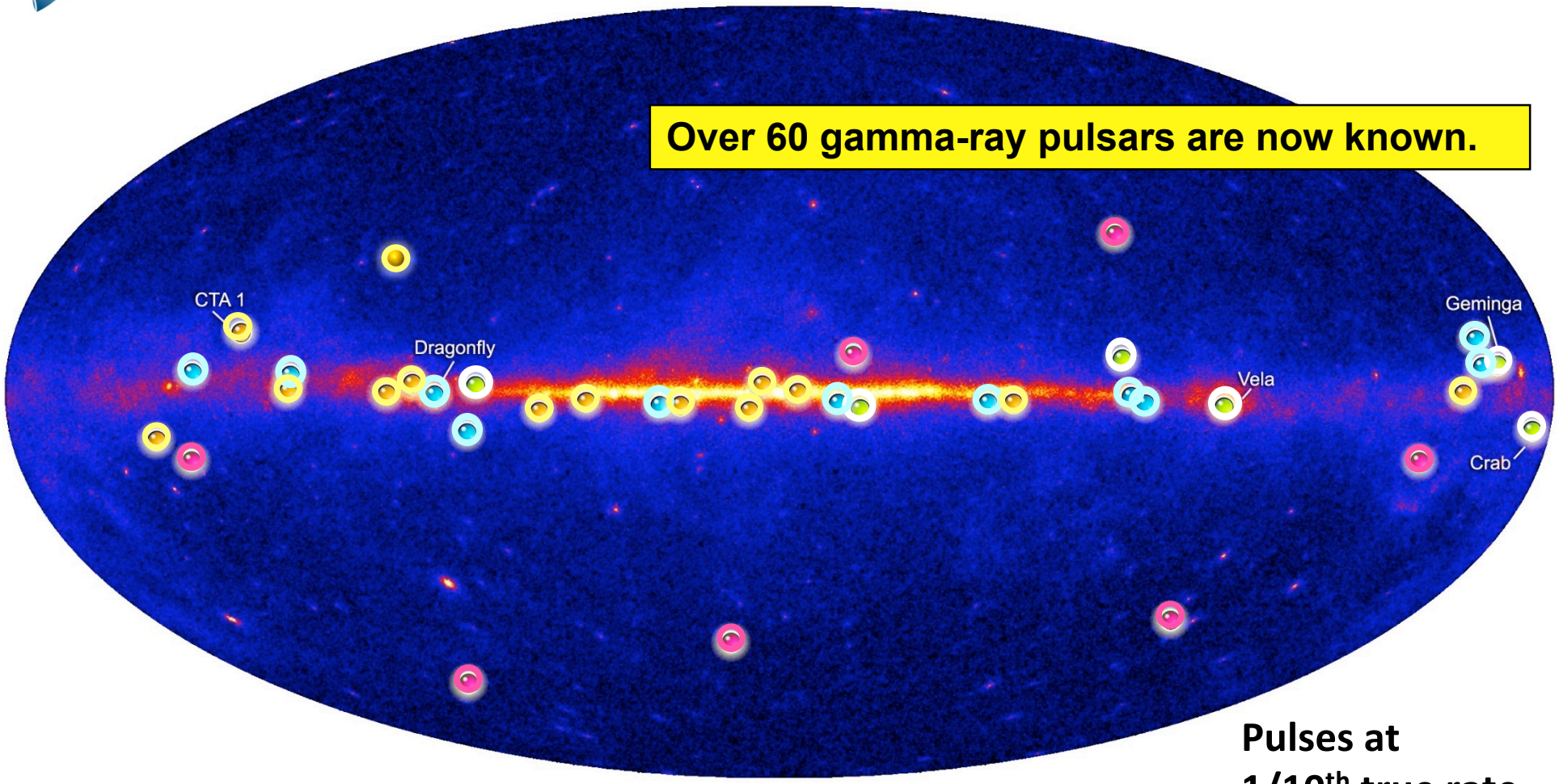
Model with standard cosmic ray source distribution but varying cosmic-ray halo scale heights. Analysis done for the third Galactic quadrant (210° < l < 250°)



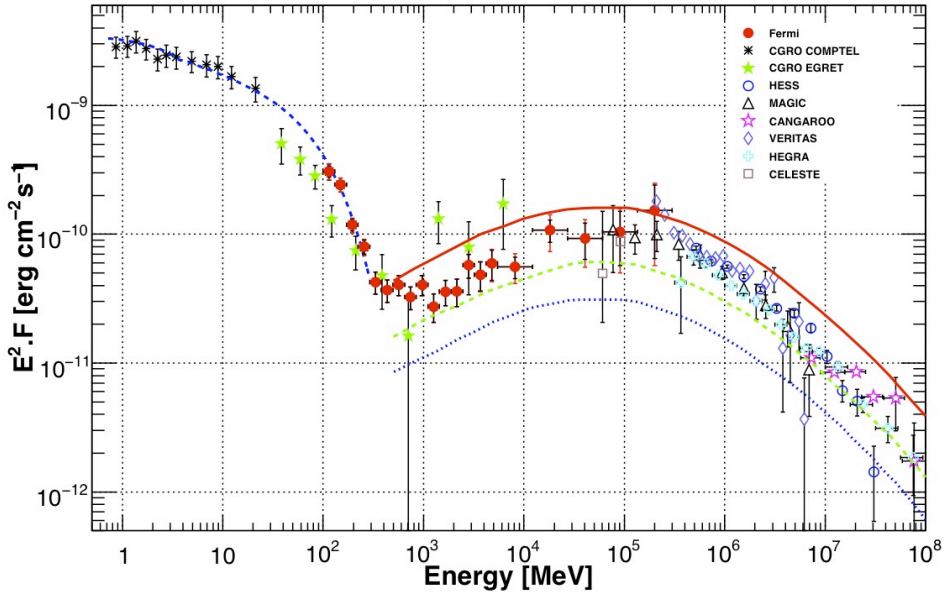
The Pulsing γ-ray Sky

Fermi Gamma-ray Space Telescope

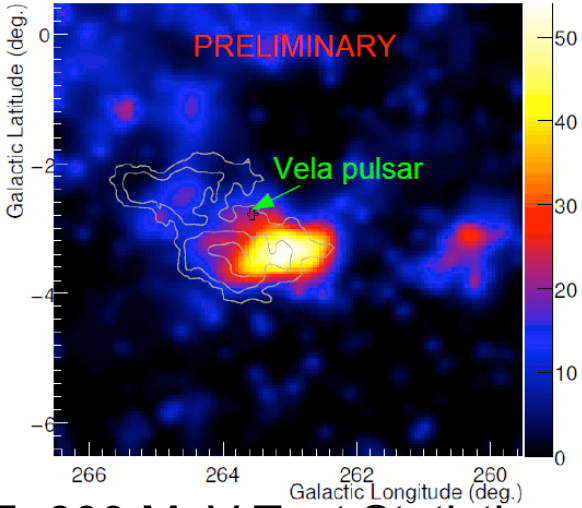
Good candidates for local sources of cosmic-ray electrons.



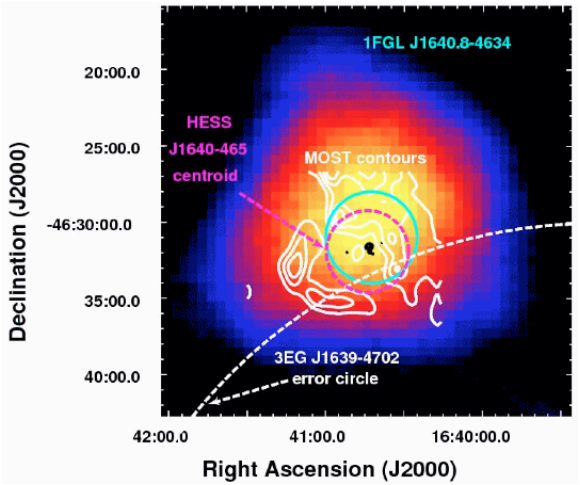
Pulsar Wind Nebulae - Powerful Particle Accelerators



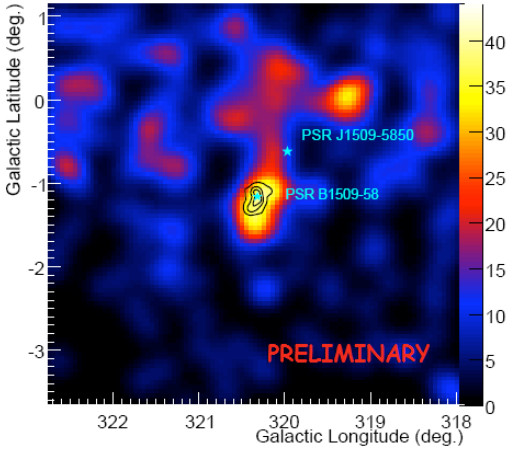
Crab Nebula Spectral Energy Distribution. Red points are Fermi LAT data, showing transition from synchrotron to Compton components.



E>800 MeV Test Statistic (significance) map. PWN Vela X

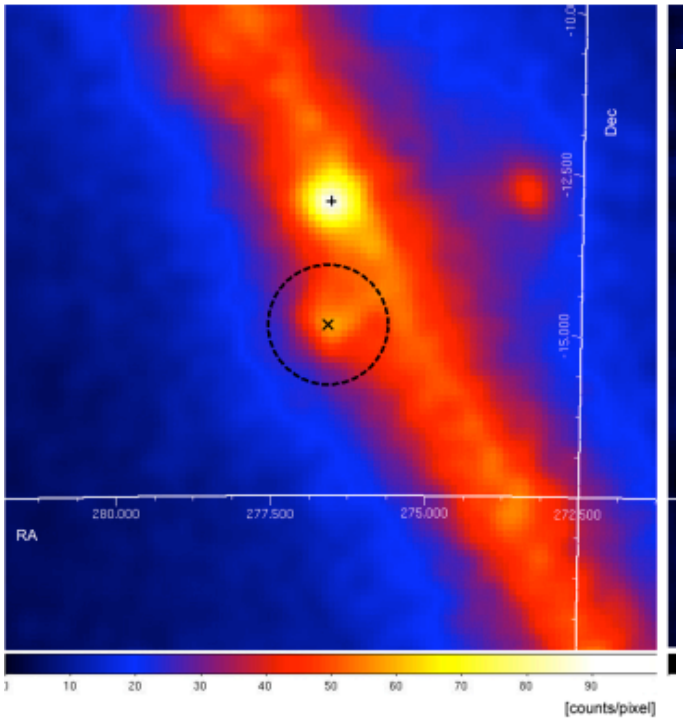


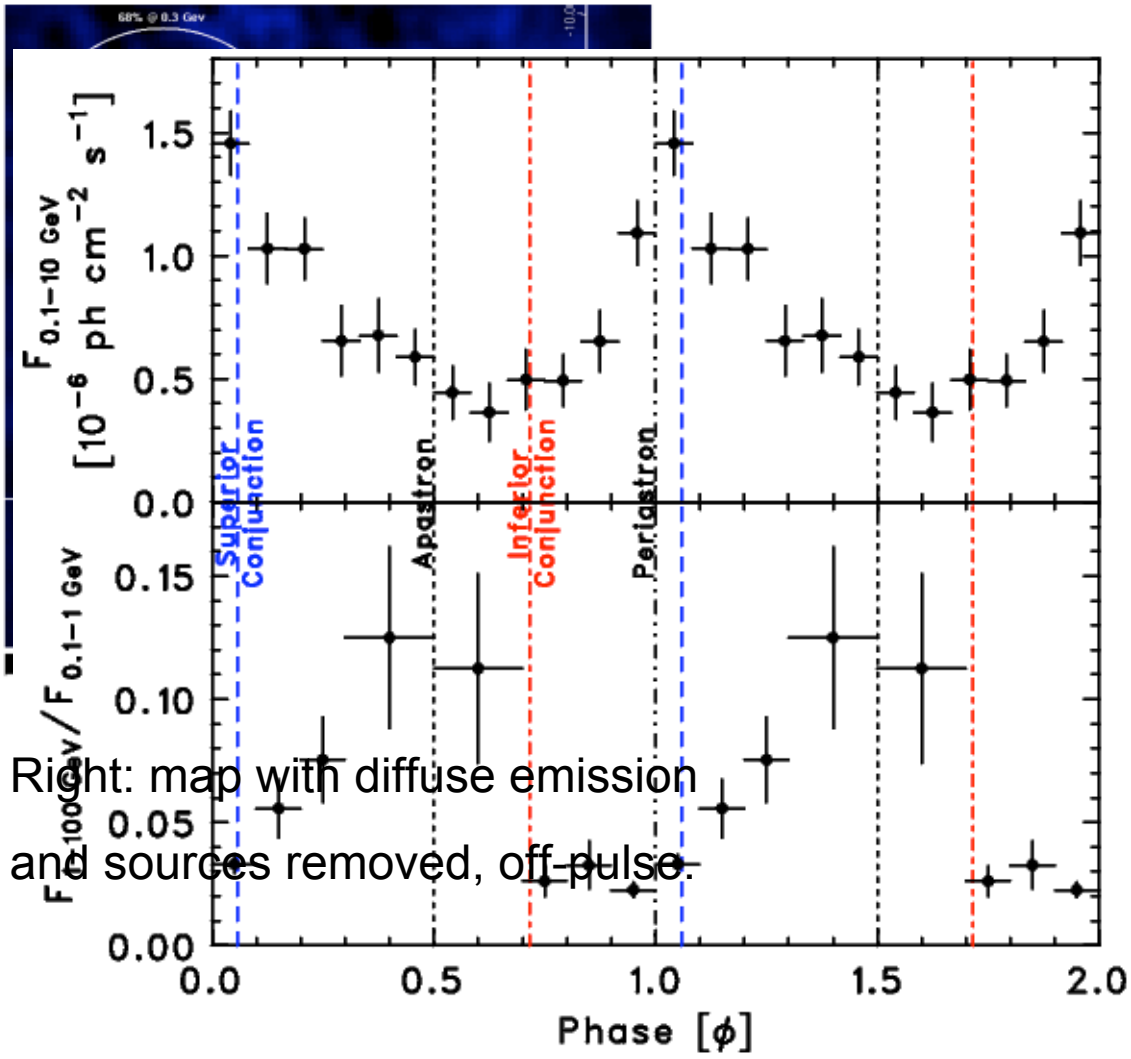
E>2 GeV counts map. PWN HESS J1640-465



E>10 GeV counts map. PWN MSH 15-52

LS5039 - High-Mass X-Ray Binary



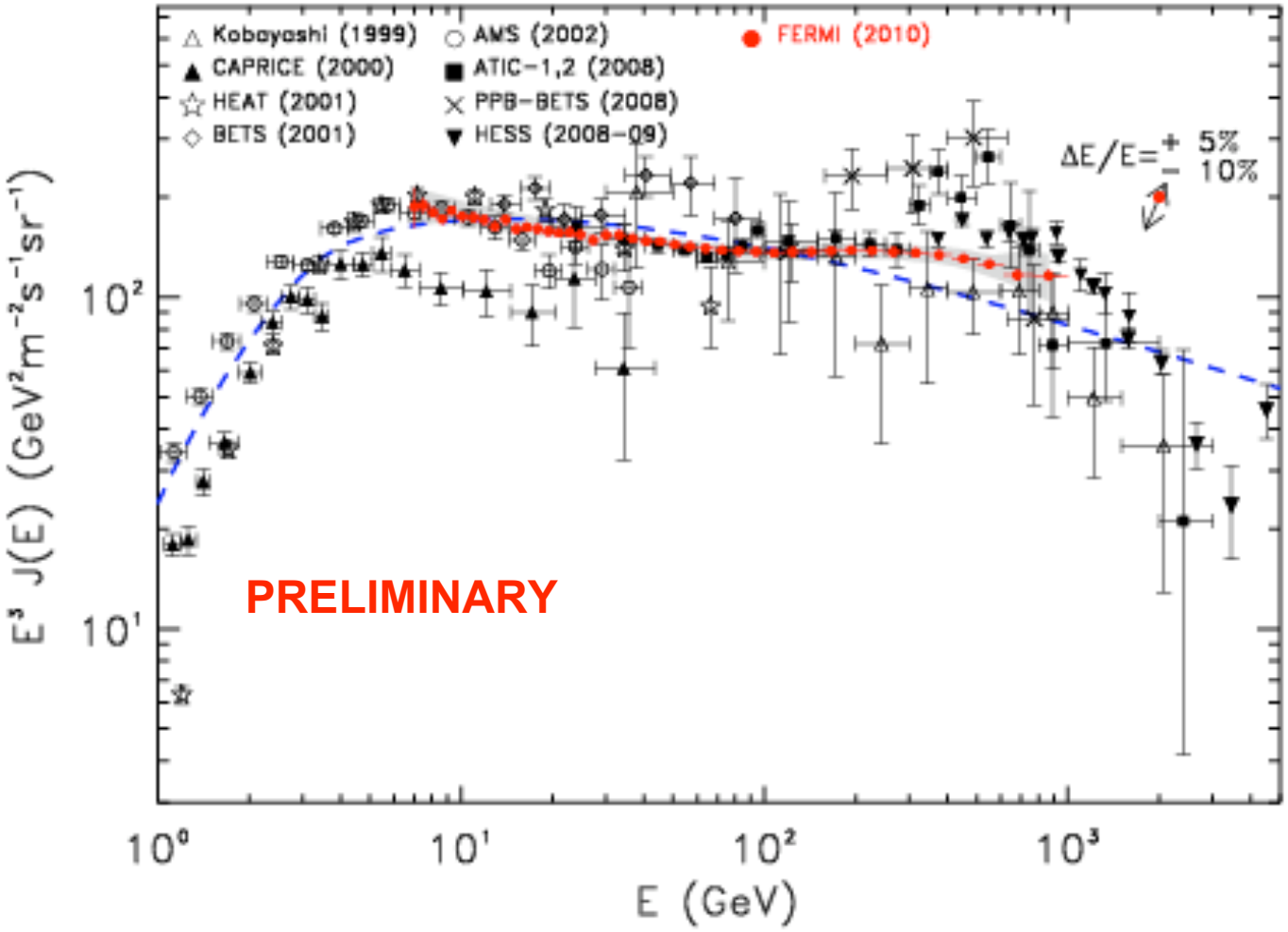


Left: LAT map of the LS5039 region E > 100 MeV

Right: map with diffuse emission and sources removed, off-pulse.

Orbital period 3.9 days

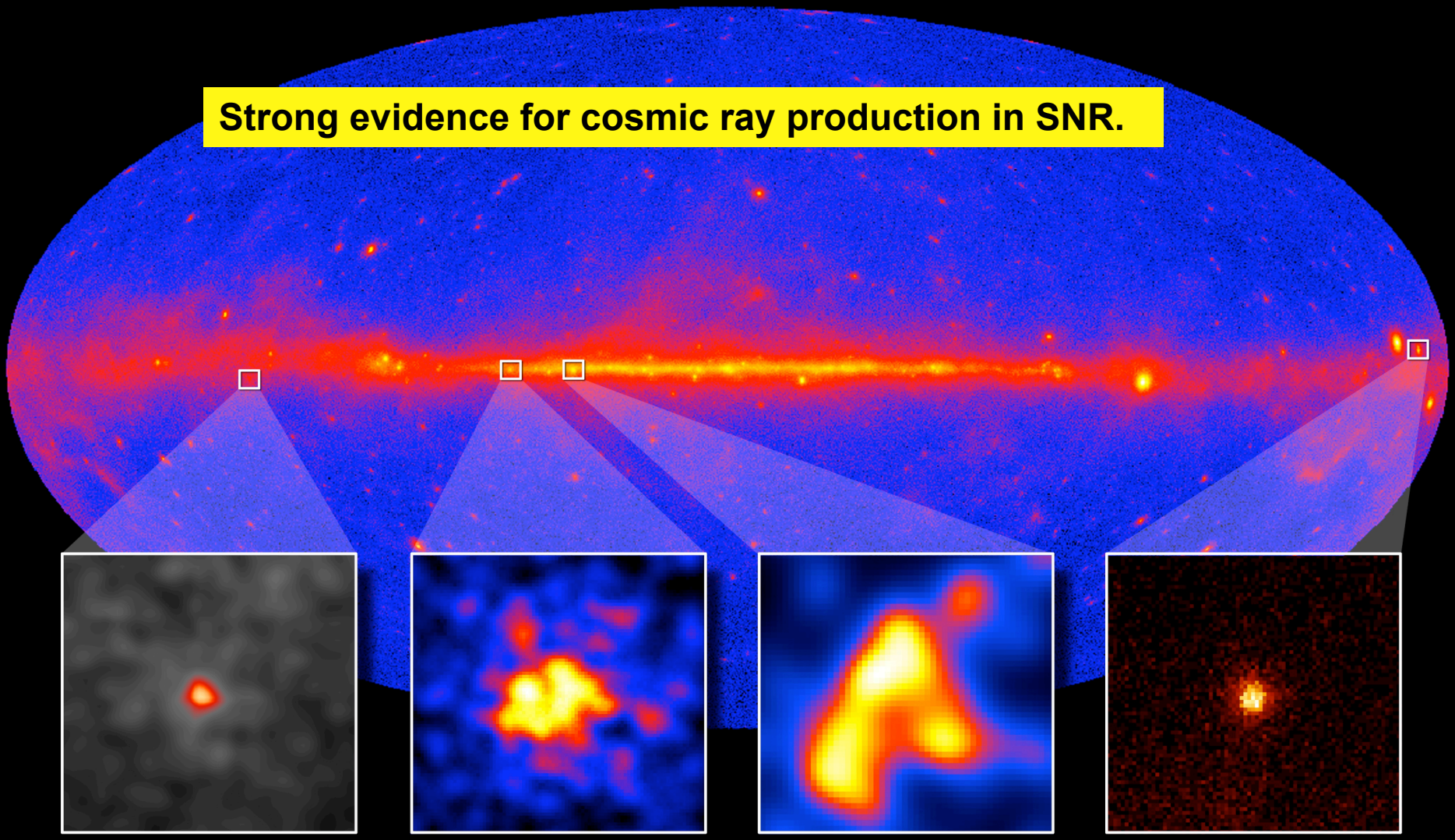
Cosmic-Ray Electron Spectrum



Sources such as pulsars, pulsar wind nebulae, and binaries may all contribute to the electron spectrum. Recent results presented by L. Baldini at this meeting.

Supernova Remnants - Spatially Resolved

Strong evidence for cosmic ray production in SNR.



Note: LAT does not resolve Cas A

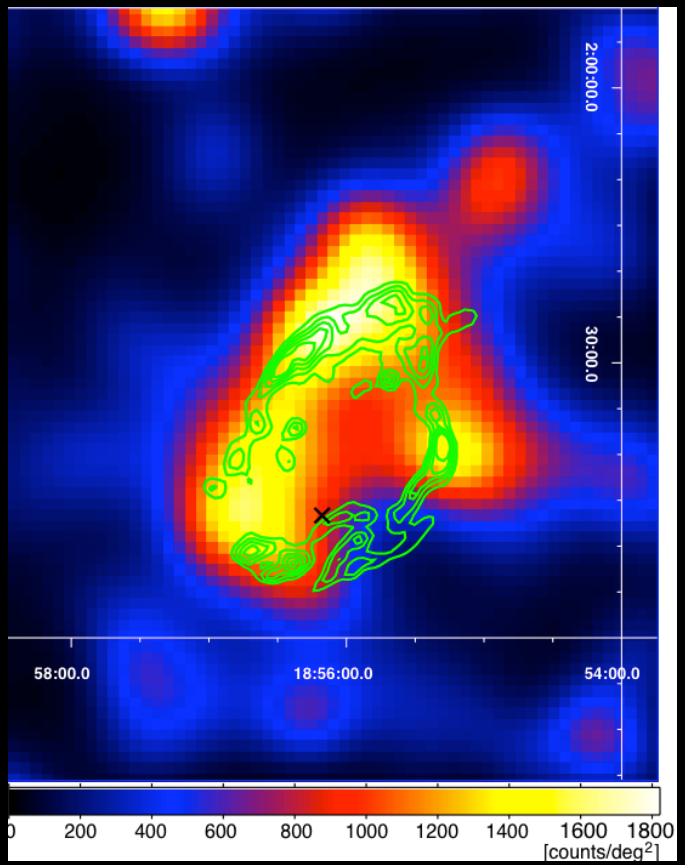
W51C

W44

IC 443

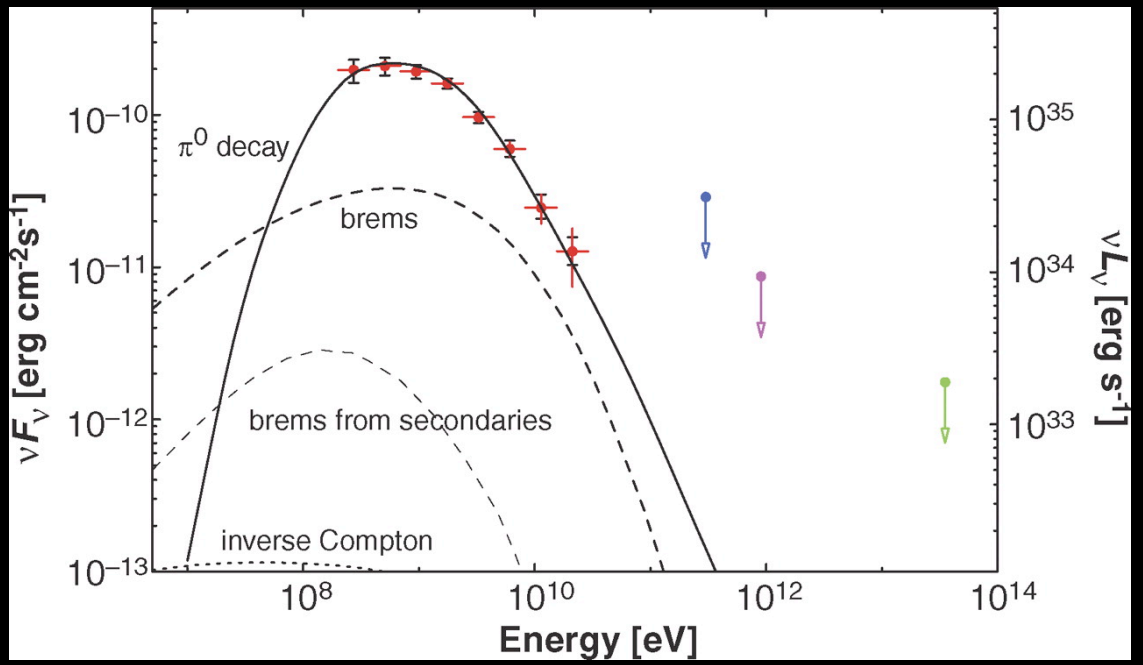
Fermi Observations of SNR

- **Supernova remnant W44 - spatially resolved. 2-10 GeV front-converting events, deconvolved image.**



Green contours are from Spitzer IRAC, shocked H_2

Black cross is PSR B1853+01, not seen as a pulsed source.



Note: leptonic models are not excluded.

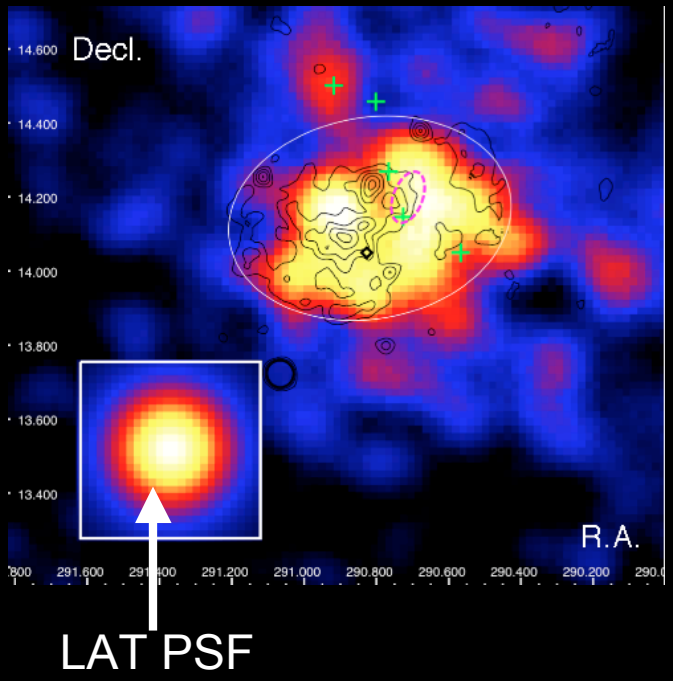
Fermi Observations of SNR

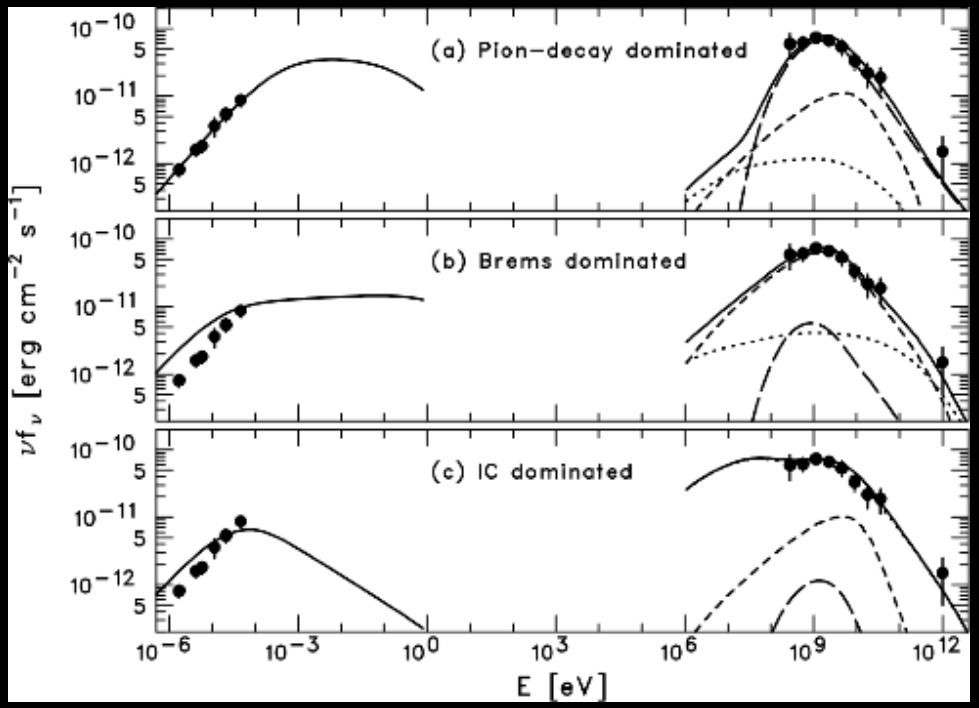
- **Supernova remnant W51C - spatially resolved. 2-10 GeV front-converting events, deconvolved image.**

Magenta contours are region of shocked CO

Black diamond is possible PWN CXO J192318.5+143035

White ellipse is the outer boundary of W51.





A Surprise - A Gamma-ray Nova

- **In early March, the LAT skywatchers found a new, flaring gamma-ray source in the Cygnus region.**

Electronic Telegram No. 2199

Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION

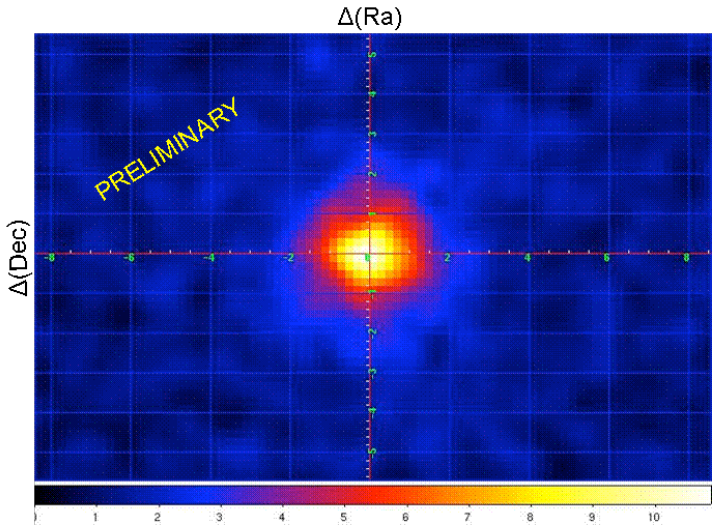
Follow-up observations showed X-ray and radio emission. In order to produce the gamma rays, this nova had to be accelerating particles to cosmic-ray energies.

Details in an article to appear in Science on August 13, 2010.

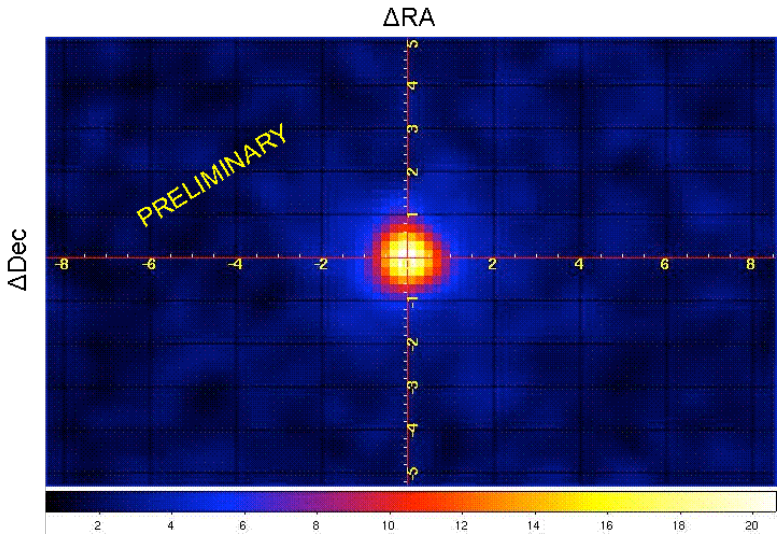
discovery by Koichi Nishiyama (Fukuoka, J , Japan) of an apparent unusually bright ou ic star V407 Cyg on an unfiltered CCD image 105-mm camera lens (+ SBIG STL6303E camer confirmed the outburst on two unfiltered (at mag 6.8) and 10.814 (mag 6.9) using a 0.4

The amateur astronomers who discovered the optical flare.

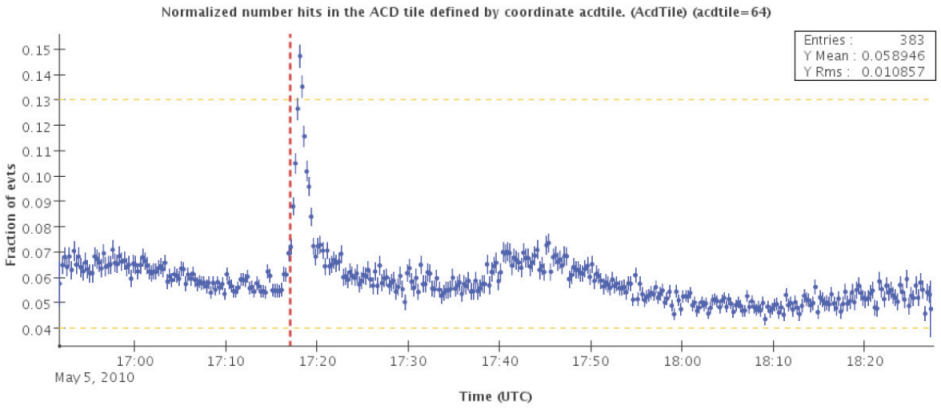
Solar System Gamma-ray Sources



The Moon - gamma rays from cosmic-ray interactions with the lunar surface.



The Sun - gamma rays from cosmic-ray interactions with solar matter and photons.



A small solar flare. As solar activity increases, more flares are likely.

The Future:
Short-term and Long-term Prospects

In the Short-term

The Fermi spacecraft and the LAT are working well.

The LAT gamma-ray data are public, released as soon as the basic processing is done. The LAT team encourages use of the data. The Fermi Science Support Center, at http://fermi.gsfc.nasa.gov/ssc/ is the access center for these data.

Improvements in the LAT diffuse model and the analysis procedures are constantly being tested and will be made public as soon as the LAT team has confidence in them. Goals of an upcoming release are better sensitivity at energies below 100 MeV and lower instrumental background at all energies.

As statistics accumulate, the LAT view of the GeV sky will become clearer.

In the Long-term

As with any space mission, there is always a possibility of a failure. The Fermi spacecraft and the LAT have many redundant systems and no expendables, but something could go wrong. Fermi is not designed to be serviceable in space.

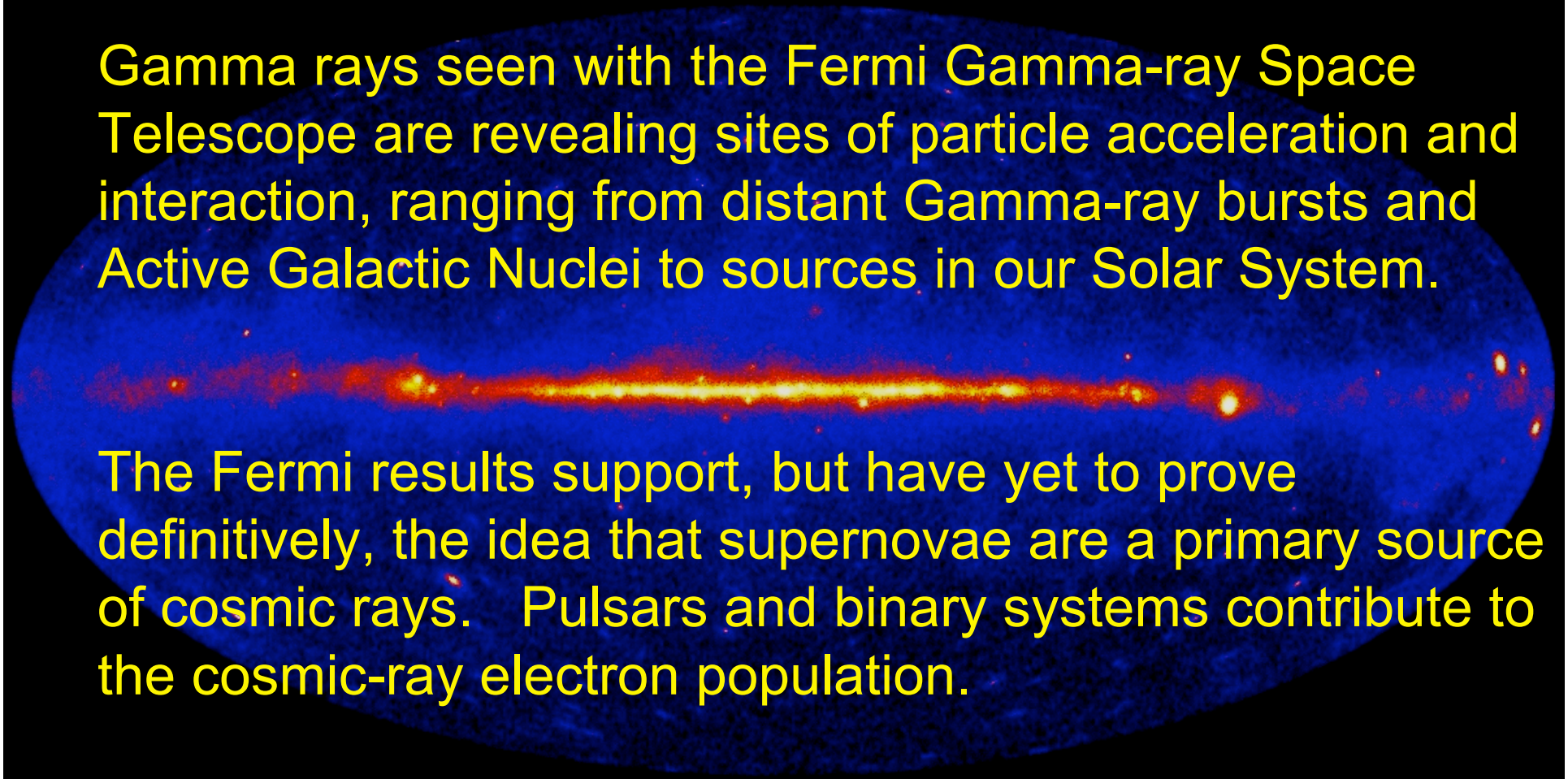
In 2012, Fermi goes into NASA's "Senior Review" for an evaluation of its scientific productivity. Continued funding depends on a successful review (i.e. many good scientific papers). This process repeats every 2 years.

What Next for Fermi?

- **We have only scratched the surface of what the Fermi Gamma-ray Space Telescope can do.**
  - **The gamma-ray sky is changing every day, so there is always something new to learn about the extreme Universe.**
- **Beyond pulsars, blazars, X-ray binaries, SNR, starburst galaxies and gamma-ray bursts, other sources remain mysteries. Nearly 40% of the sources in the First LAT Catalog do not seem to have obvious counterparts at other wavelengths.**
  - **Multiwavelength/multimessenger studies will be critical for learning the nature of such sources.**

Summary

Gamma rays seen with the Fermi Gamma-ray Space Telescope are revealing sites of particle acceleration and interaction, ranging from distant Gamma-ray bursts and Active Galactic Nuclei to sources in our Solar System.



The Fermi results support, but have yet to prove definitively, the idea that supernovae are a primary source of cosmic rays. Pulsars and binary systems contribute to the cosmic-ray electron population.

All the Fermi gamma-ray data are public. Join the fun!