Supernova Remnants as Cosmic Ray Accelerants

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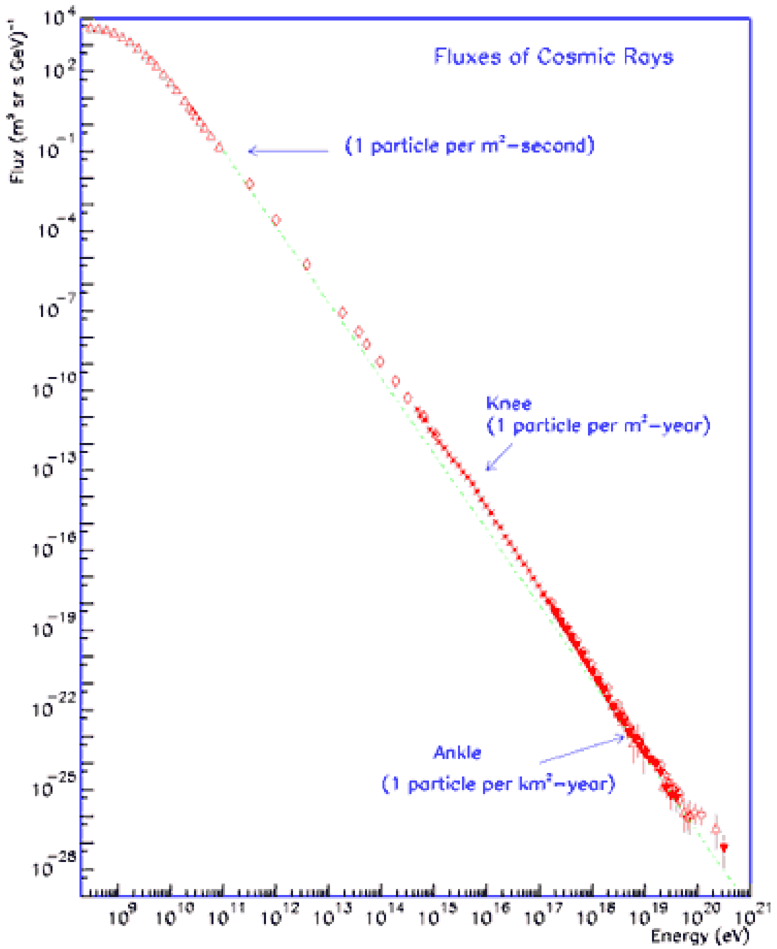
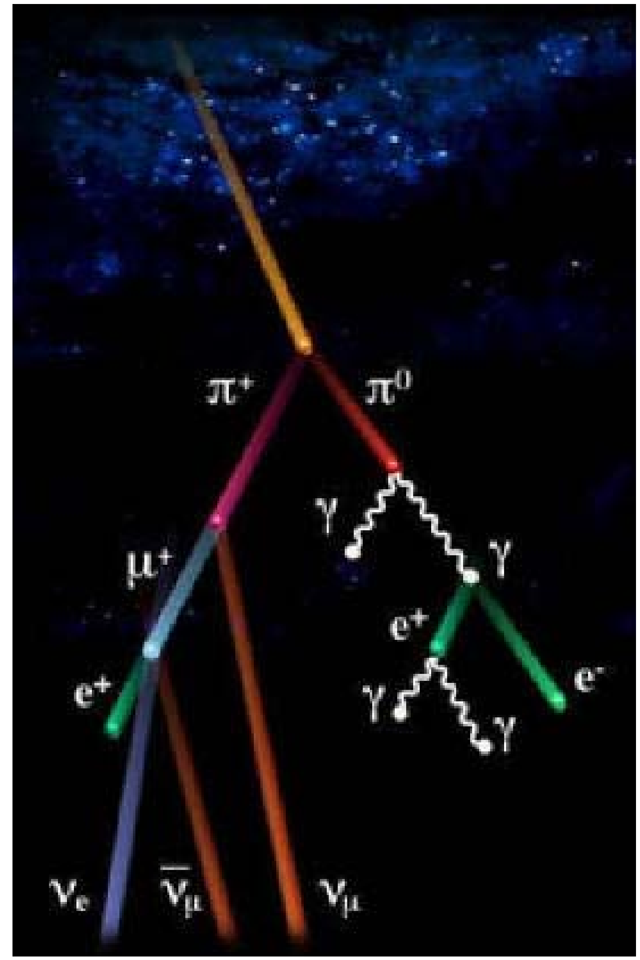
Cosmic Rays

- Discovered by Victor Hess in 1911 during a balloon flight through Austria
- He used an electroscope to measure background radiation, which increased with increasing altitude even during a solar eclipse
- Cosmic rays reach us from many different sources
- 90 percent protons, 9 percent alpha particles, 1 percent electrons and heavier nuclei
- Accelerated to extremely high energies (≈10^{20} eV)



Detection Methods - Space

- In 1991, the Energetic Gamma Ray Experiment Telescope (EGRET) made the first complete survey of the sky in the gamma range
- Discovered many gamma sources, most of which are still unidentified
- Cosmic ray protons can sometimes collide with hydrogen in the interstellar medium
- When high-E protons collide with other protons, a shower of particles, including pions, are produced
- Neutral pions decay predictably into gamma radiation



Cosmic Ray Shower

Detection Methods - Fermi

- The Fermi Large Area Telescope (LAT) detects gamma radiation over a small area but with minimal background
- Collaboration by NASA, US Dept. of Energy, France, Germany, Italy, Japan, and Sweden
- Launched June 11, 2008 – has now been collecting data for two years
- Public data access
- Discovered less than 30% of gamma radiation from Active Galactic Nuclei
- Star-forming regions? Dark matter interactions?

An artist's rendition of Fermi

Detection Methods: Ground-Based

- Gamma rays entering Earth's atmosphere create self-propagating showers of particles (pions, muons, electrons, positrons, etc)
- Charged particles in the shower move faster than the speed of light in air, and give off an electromagnetic shockwave
- This is called Cherenkov radiation – has ≈1° spread, so when it reaches the ground it hits an area of several m^2

Detection Methods: VERITAS

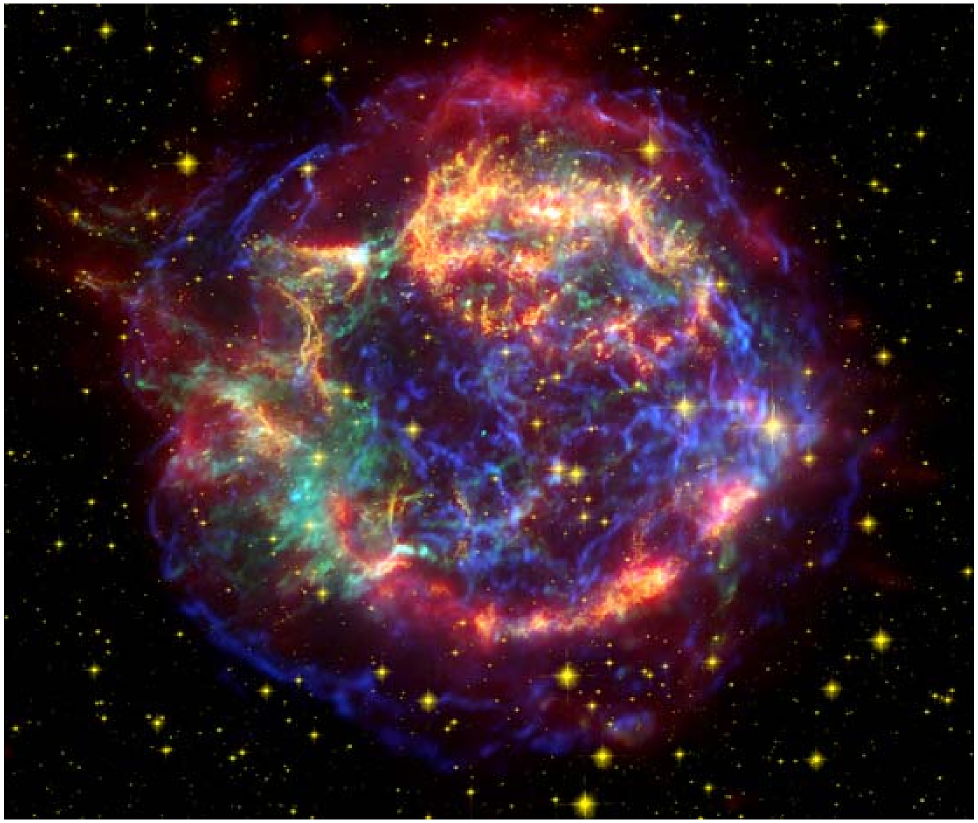
- Cherenkov radiation is detected by ground-based arrays like VERITAS (Very Energetic Radiation Imaging Telescope Array System)
- Radiation 'pools' are large enough that telescopes can be spread over a wide area to record many more events
- When multiple telescopes detect a particle shower, its point of origin can be calculated with great accuracy

Fermi Acceleration

- How are these cosmic rays accelerated to such high energies?
- Enrico Fermi proposed the ‘Fermi Mechanism’ in 1949: collisions with magnetic shock waves from supernova remnants increase the particle energy
- If a particle undergoes many collisions, it can reach relativistic speeds
- How do we test Fermi acceleration? Observe gamma radiation from supernova remnants

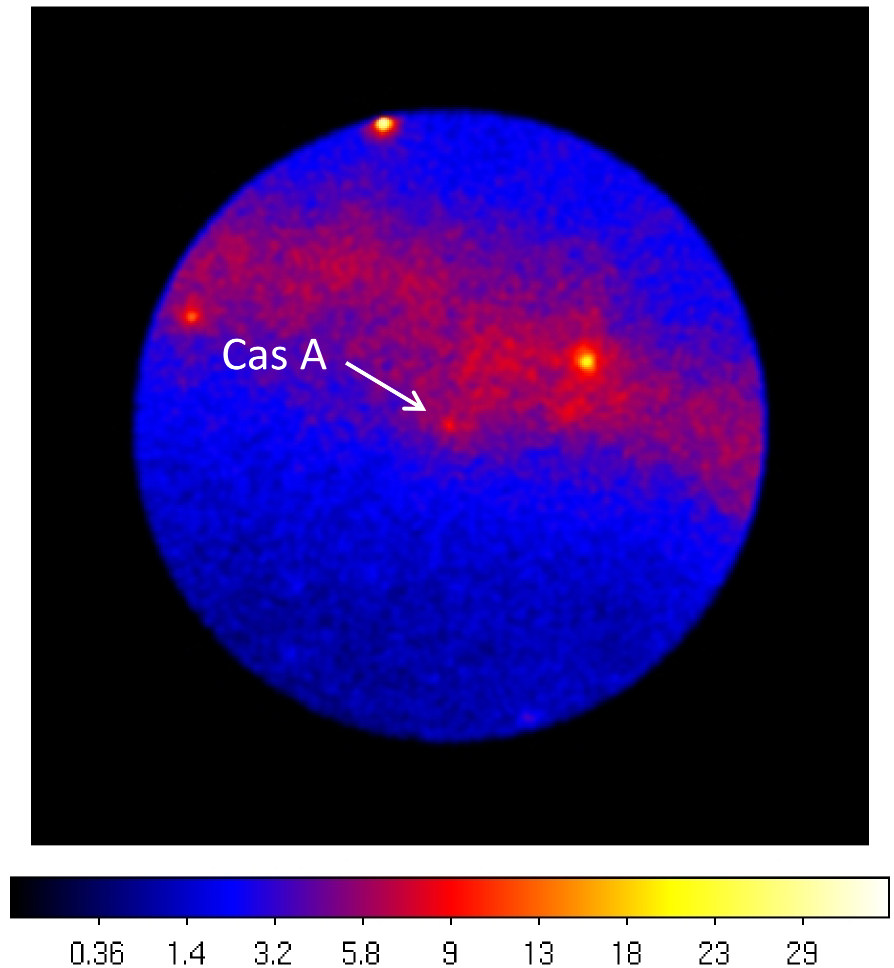
E0102 - Small Magellanic Cloud (Chandra)

SNR Cassiopeia A

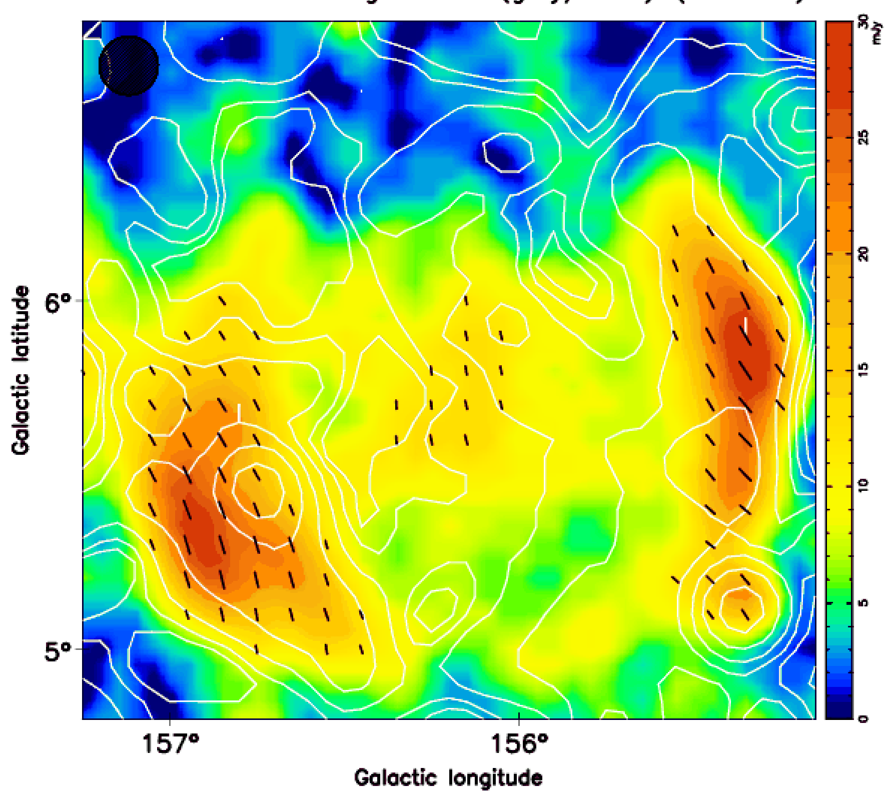


Cas A in the infrared (red), optical (yellow), and X-ray (blue)

Fermi Gamma ray counts map from Cas A (15 deg. rad.)

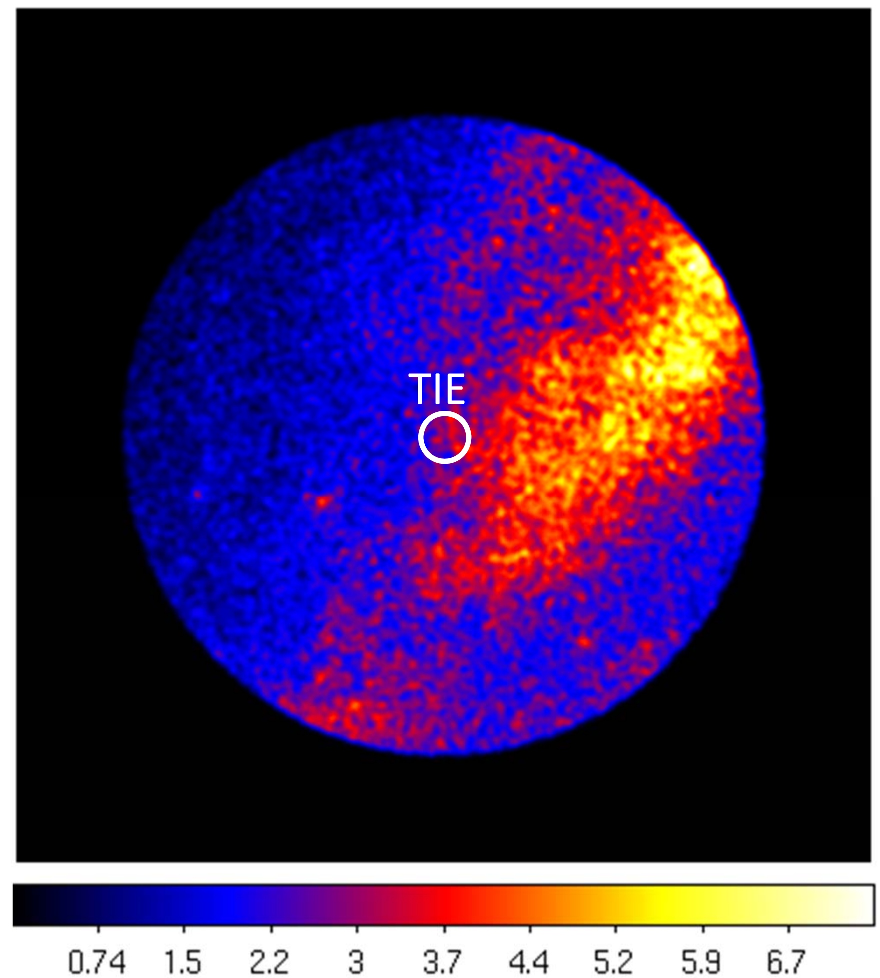


SNR G156.2+5.7



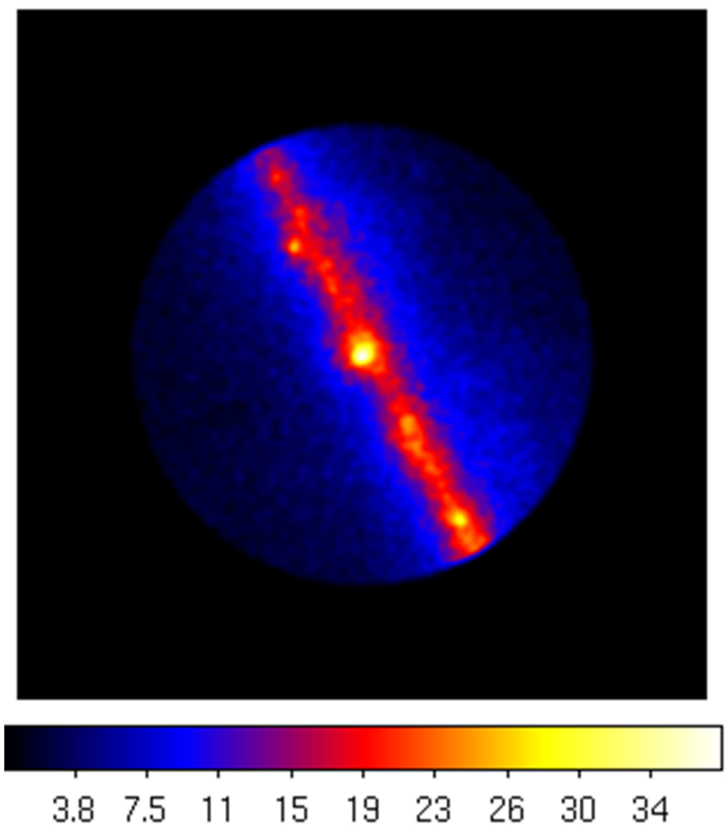
Spectral index map of G156.2+5.7 (nicknamed TIE)

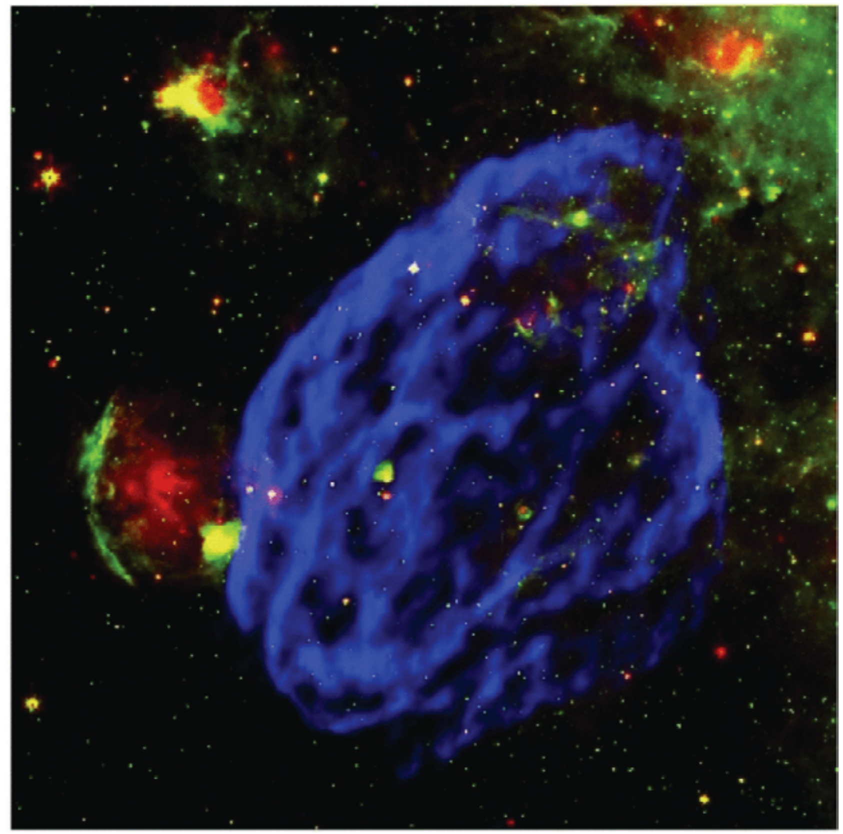
Fermi Gamma ray counts map from Cas A (15 deg. rad.)



SNR W44

Gamma ray counts map from W44 (10 deg. rad., 0.1 deg/pix.)



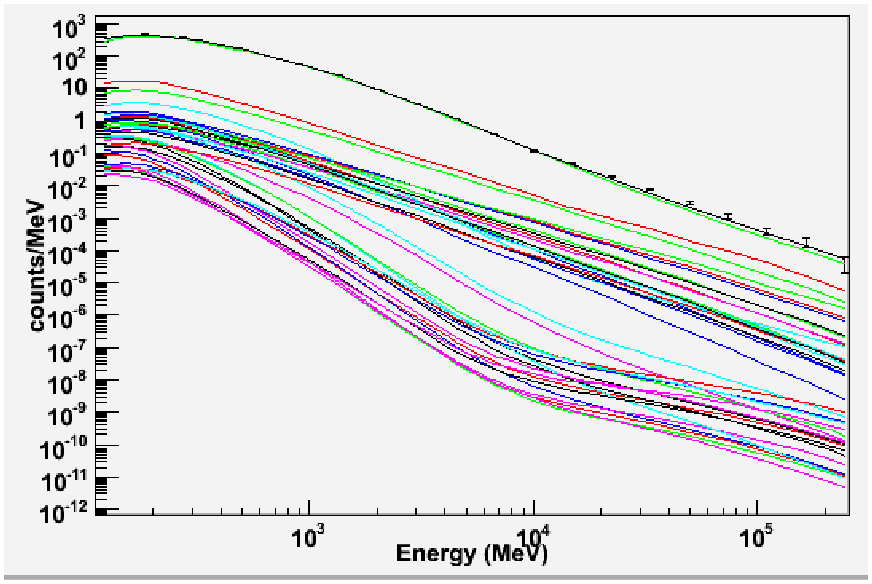


W44 in radio (Castelletti)

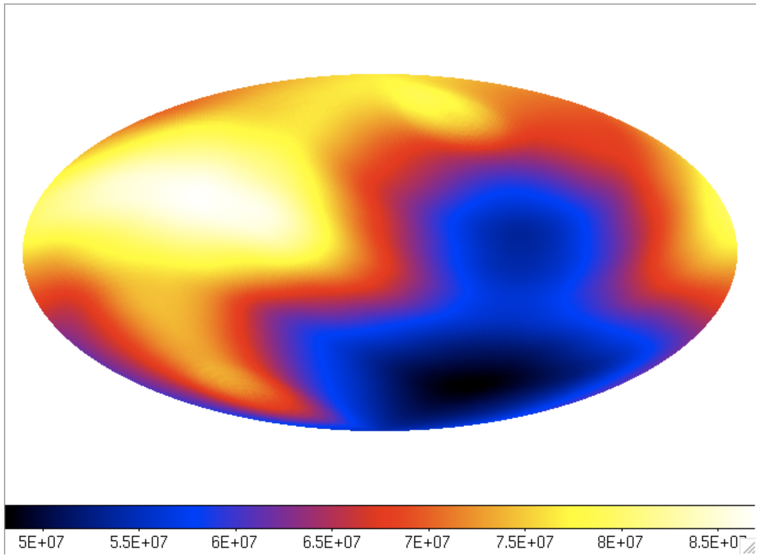
Likelihood Analysis

To analyze how significant a detected area is:

- Create an exposure map and livetime cube
- Make an xml file containing a model for local known sources
- Run a program called gtlike that fits the data to your model
- Determine the flux of the object



Fitted W44 area sources



Fermi all-sky exposure map

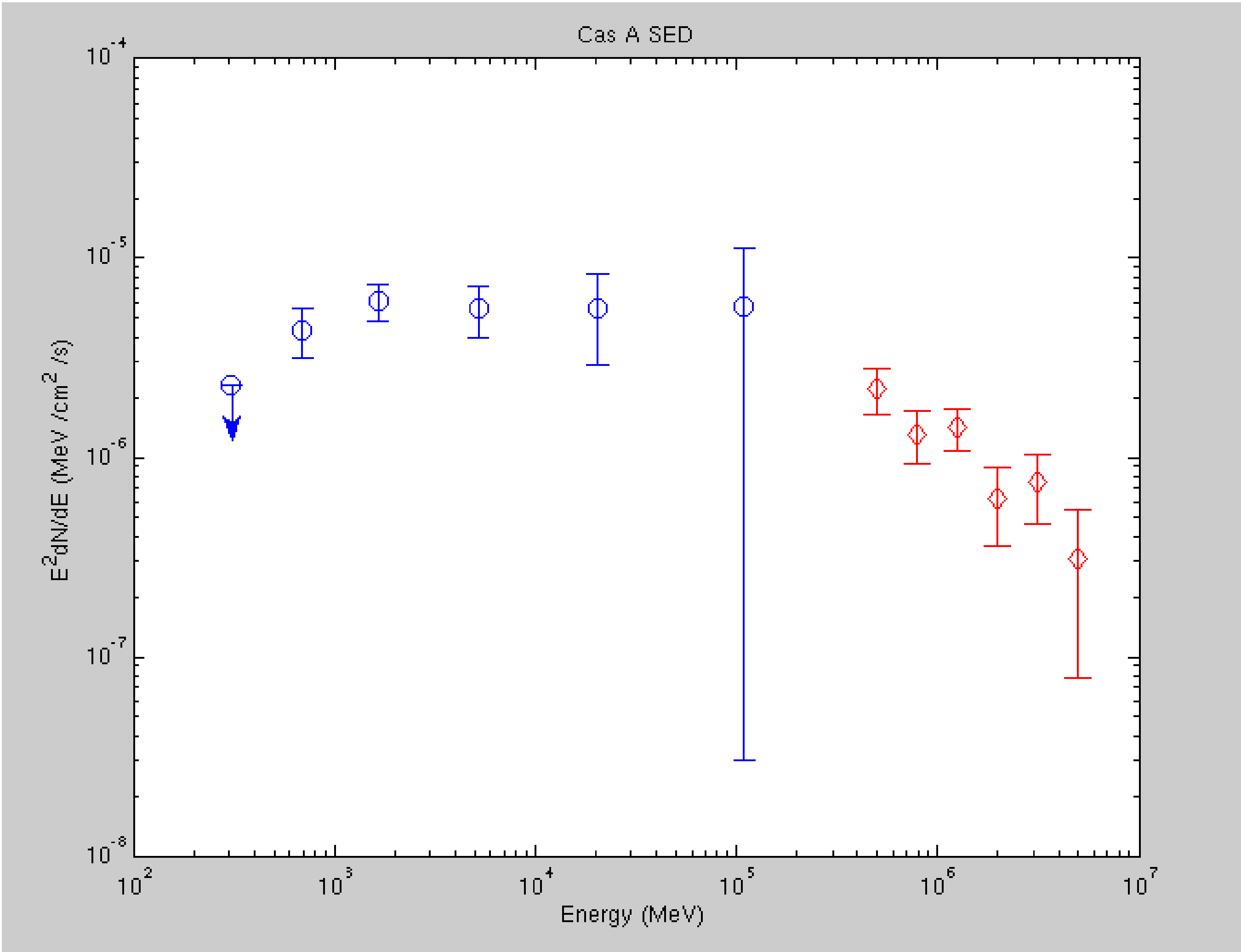
Sample Xml File (W44)


```xml
<?xml version="1.0" ?>
<source_library title="source library">

<!-- Point Sources -->

<!-- Sources between (0.0,3.0] degrees of ROI center -->
<source name="_1FGLJ1849.0-0055c" type="PointSource">
<spectrum type="PowerLaw2">
<!-- Source is 2.90175084498 degrees away from ROI center -->
<parameter free="1" max="1e4" min="1e-4" name="Integral" scale="1e-07"
value="0.0898092267221"/>
<parameter free="1" max="5.0" min="0.0" name="Index" scale="-1.0" value="2.16717"/>
<parameter free="0" max="5e5" min="30" name="LowerLimit" scale="1.0" value="100"/>
<parameter free="0" max="5e5" min="30" name="UpperLimit" scale="1.0" value="300000"/>
</spectrum>
<spatialModel type="SkyDirFunction">
<parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="282.271"/>
<parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="-0.9258"/>
</spatialModel>
</source>
<source name="_1FGLJ1856.1+0122" type="PointSource">
<spectrum type="PowerLaw2">
<!-- Source is 9.2990805649e-05 degrees away from ROI center -->
<parameter free="1" max="1e4" min="1e-4" name="Integral" scale="1e-07"
value="0.756455875717"/>
<parameter free="0" max="5.0" min="0.0" name="Index" scale="-1.0" value="2.275"/>
<parameter free="0" max="5e5" min="30" name="LowerLimit" scale="1.0" value="100"/>
<parameter free="0" max="5e5" min="30" name="UpperLimit" scale="1.0" value="300000"/>
</spectrum>
<spatialModel type="SkyDirFunction">
<parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="284.039"/>
<parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="1.3751"/>
</spatialModel>
</source>

...
```

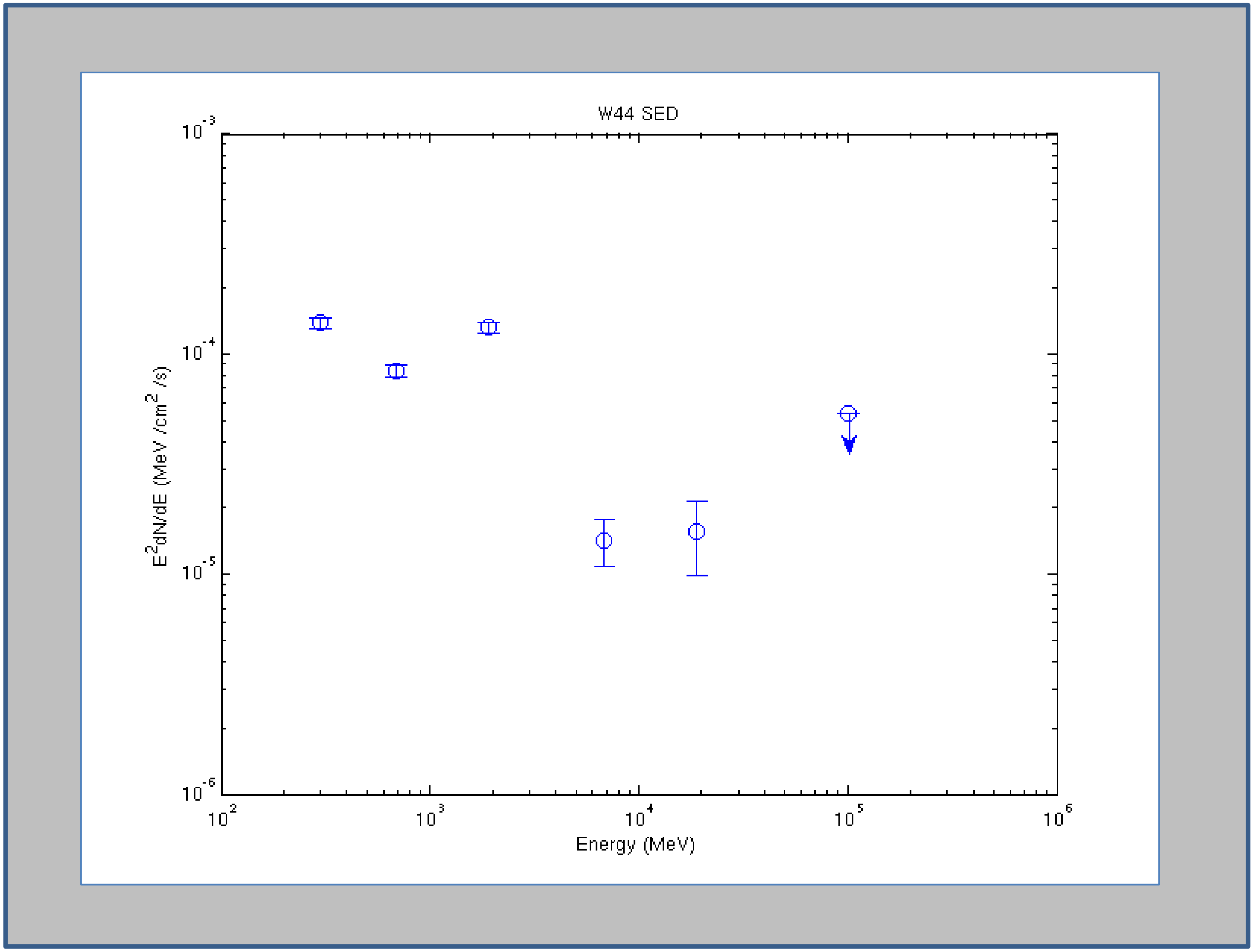
Spectra Analysis

- To observe how energy flux changes over a gamma-band energy range, separate photon data into smaller energy bins
- Typically use bins from 200-500 MeV, 500-1000, 1000-5000, 5000-10000, 10000-50000, 50000-300000 MeV
- Run gtlike and a likelihood analysis using Python
- If the TS value (statistical significance) of the energy flux is too low, calculate an upper limit for those energies
- Energy spectra from the Fermi LAT (detects photons in the 20 MeV to 300 GeV range) and VERITAS (100 GeV to 10 TeV) can be combined for a more complete spectrum

Spectra Analysis



Spectra Analysis



Future Goals

- This information can help determine the sensitivity of the LAT
- Energy spectrum data can be used to refine models for particle interaction
- Hopefully, the spectra I obtain can be combined with other Fermi and VERITAS data for a better understanding of Fermi acceleration and cosmic rays

- Nobel Prize !?!