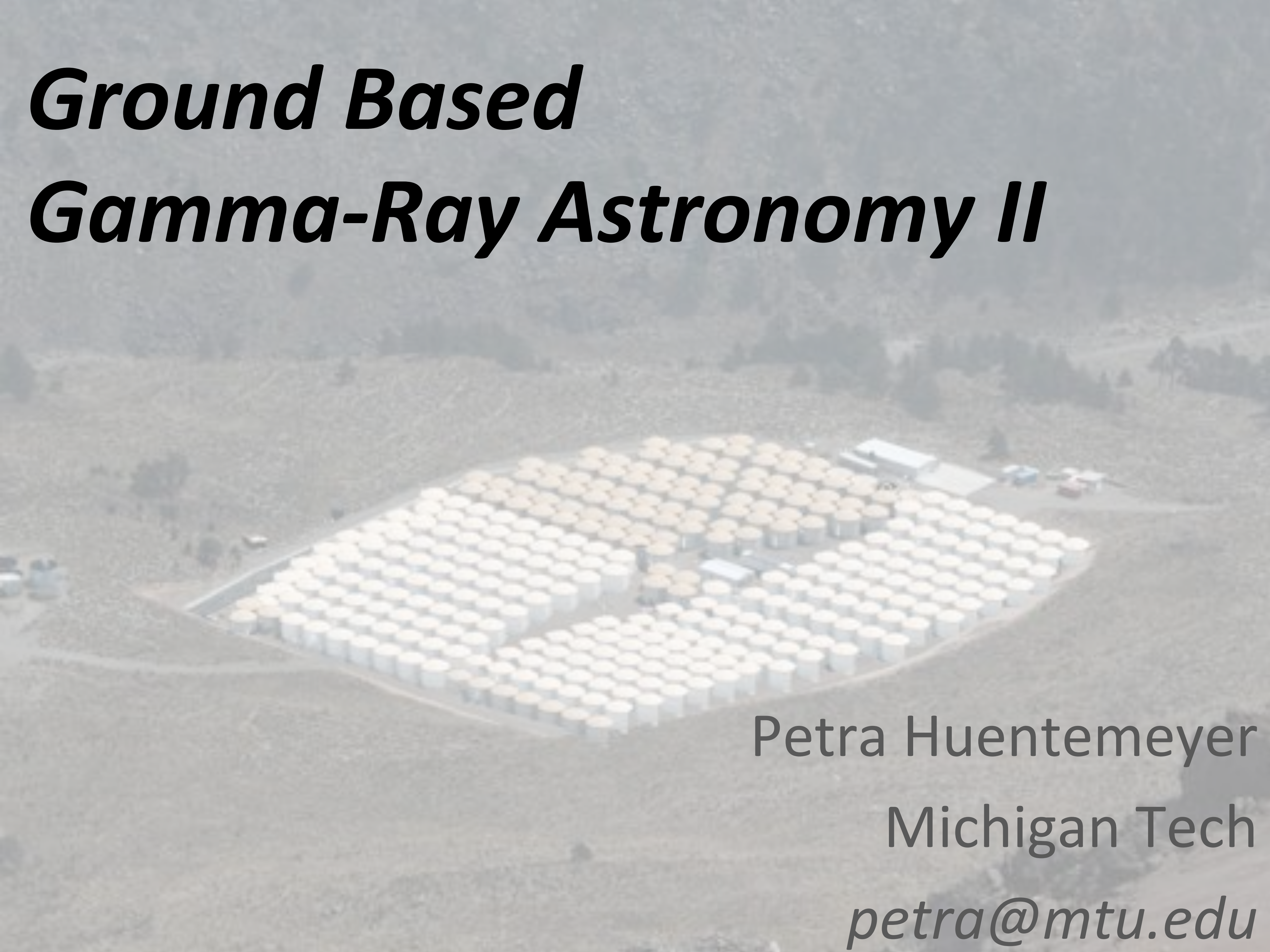
Ground Based Gamma-Ray Astronomy II



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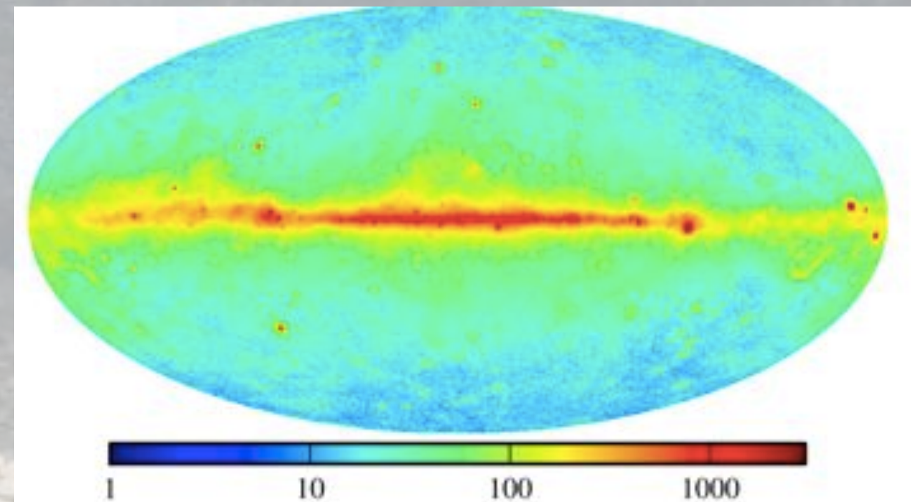
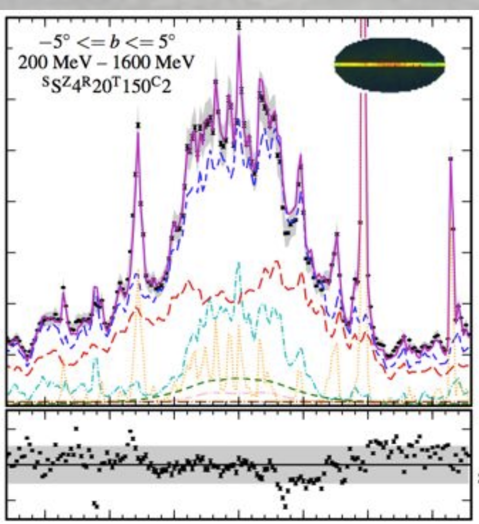
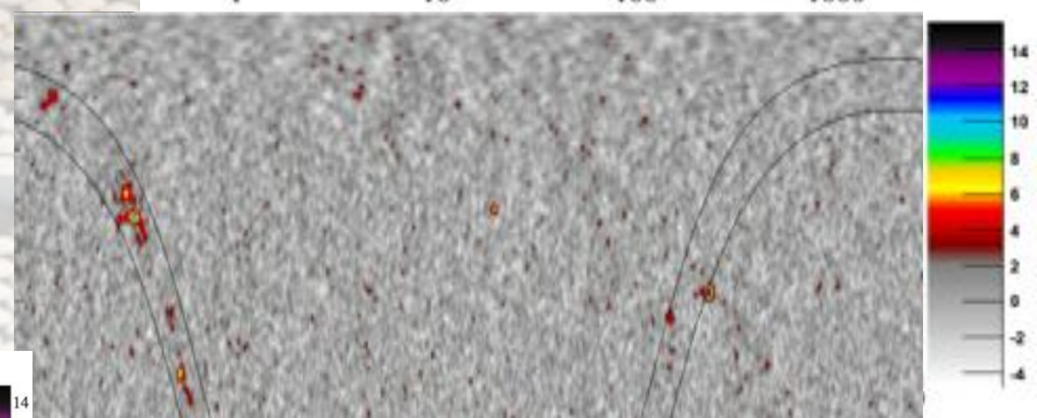
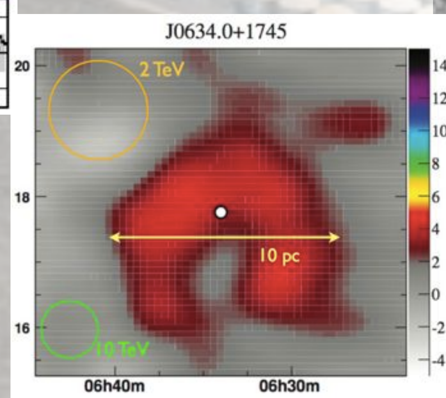
What are we trying to measure?

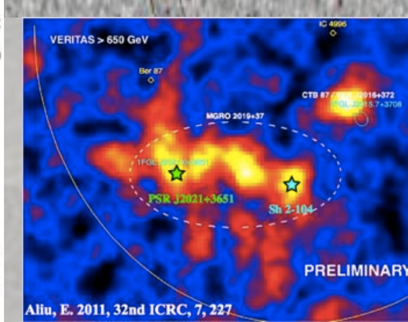
- **Directions**
  - Maps
  - Extensions
  - Spatial distribution

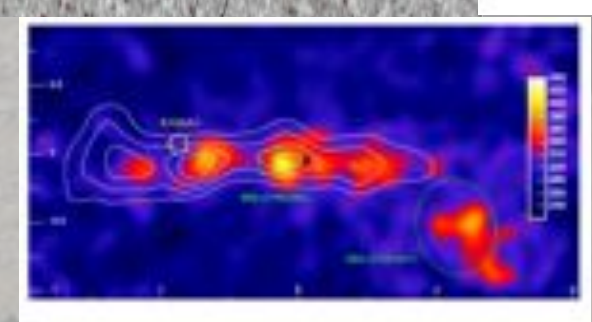






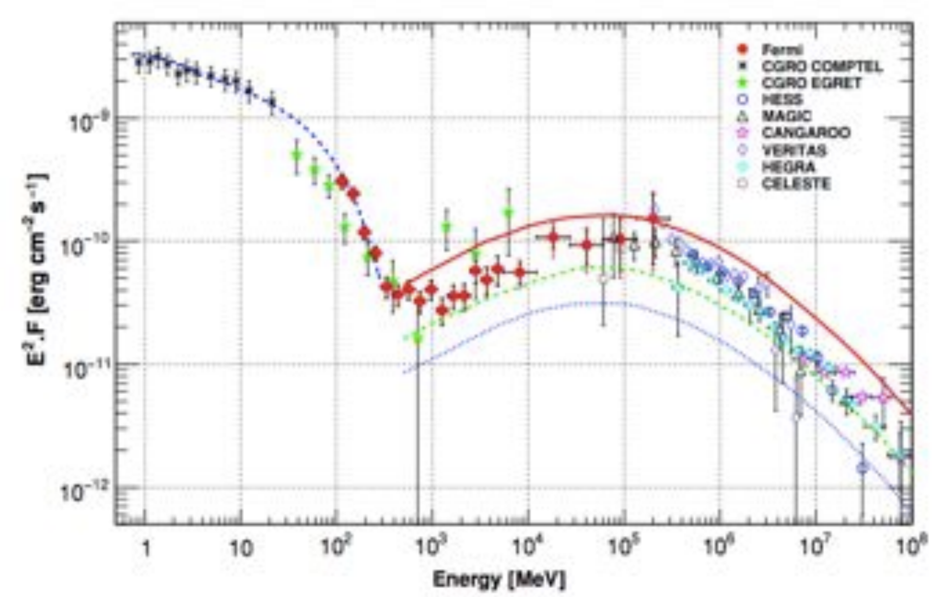


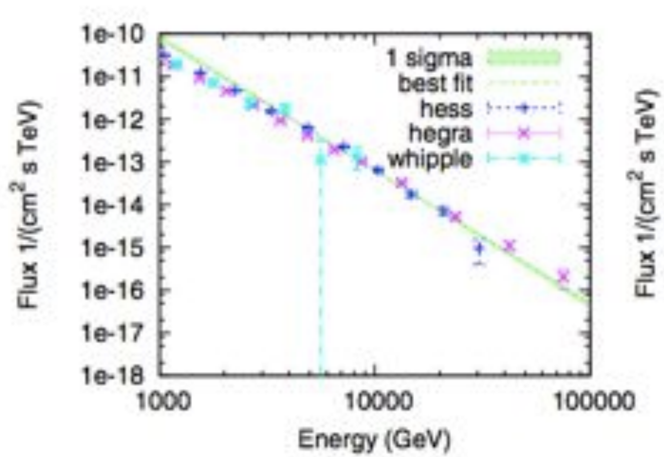


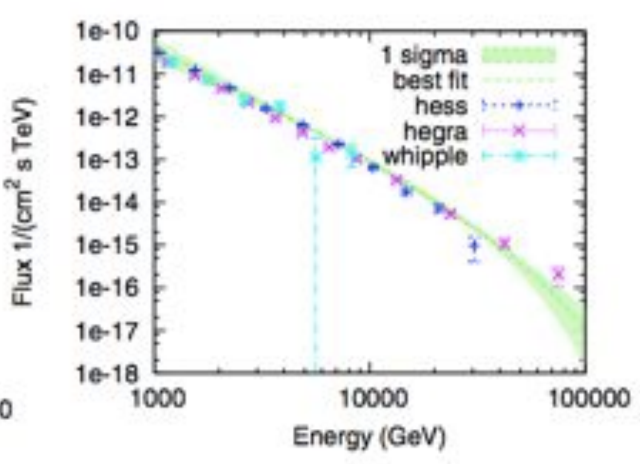


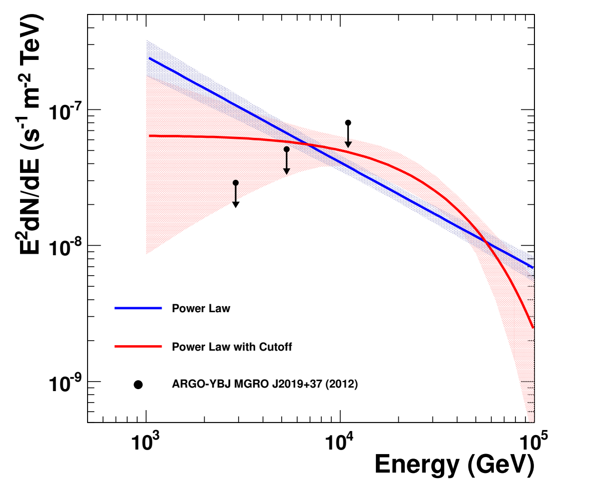
What are we trying to measure?

- Directions
  - Map
  - Extensions
  - Spatial distribution
- **Energy**
  - Spectral Energy Distributions (SED)



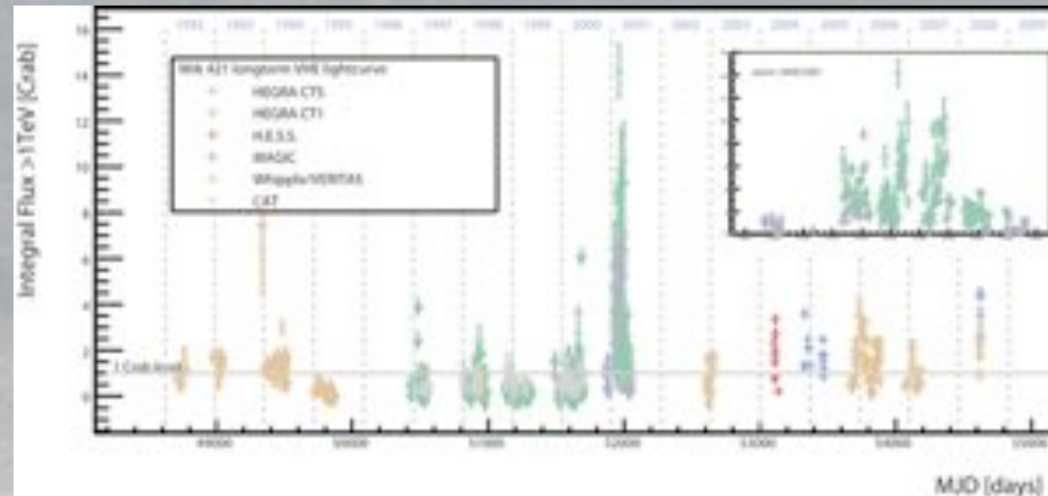


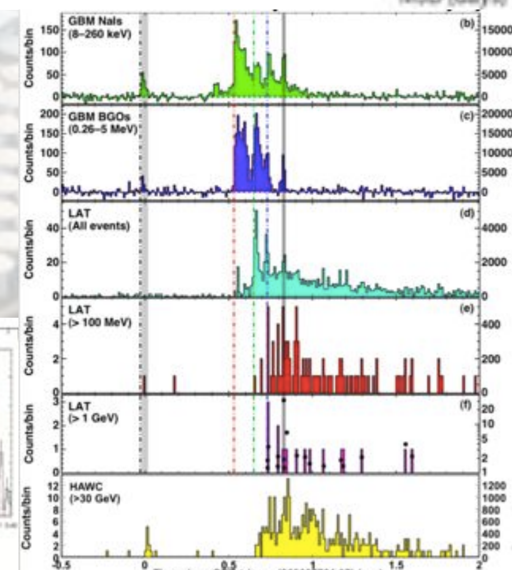


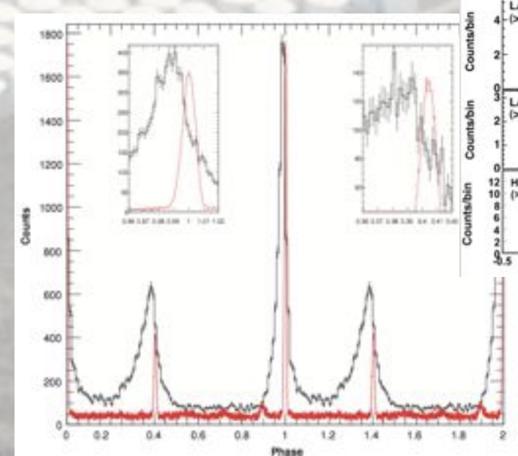


What are we trying to measure?

- Directions
  - Map
  - Extensions
  - Spatial distribution
- Energy
  - Spectral Energy Distributions (SED)
- **Time dependent behavior**
  - Periodic behavior
  - Temporary flux enhancements (e.g. flares etc.)







Ground-Based Technologies: 2 Classes

Atmospheric Cherenkov Telescopes (VERITAS/H.E.S.S./MAGIC)

50 GeV - 100 TeV
Large Area
Excellent background rejection
Good angular resolution
Small Aperture/Low Duty Cycle

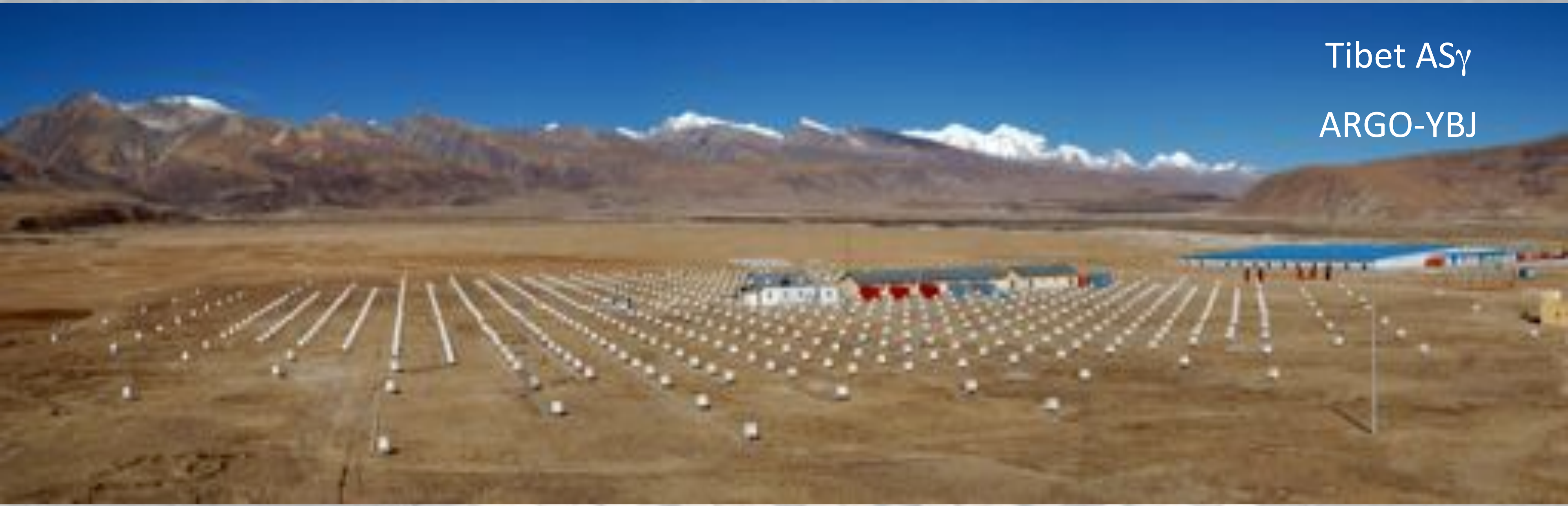
Study known sources
Deep surveys of limited regions
Source morphology (SNRs)
Fast transients (AGN flares)
High resolution spectra

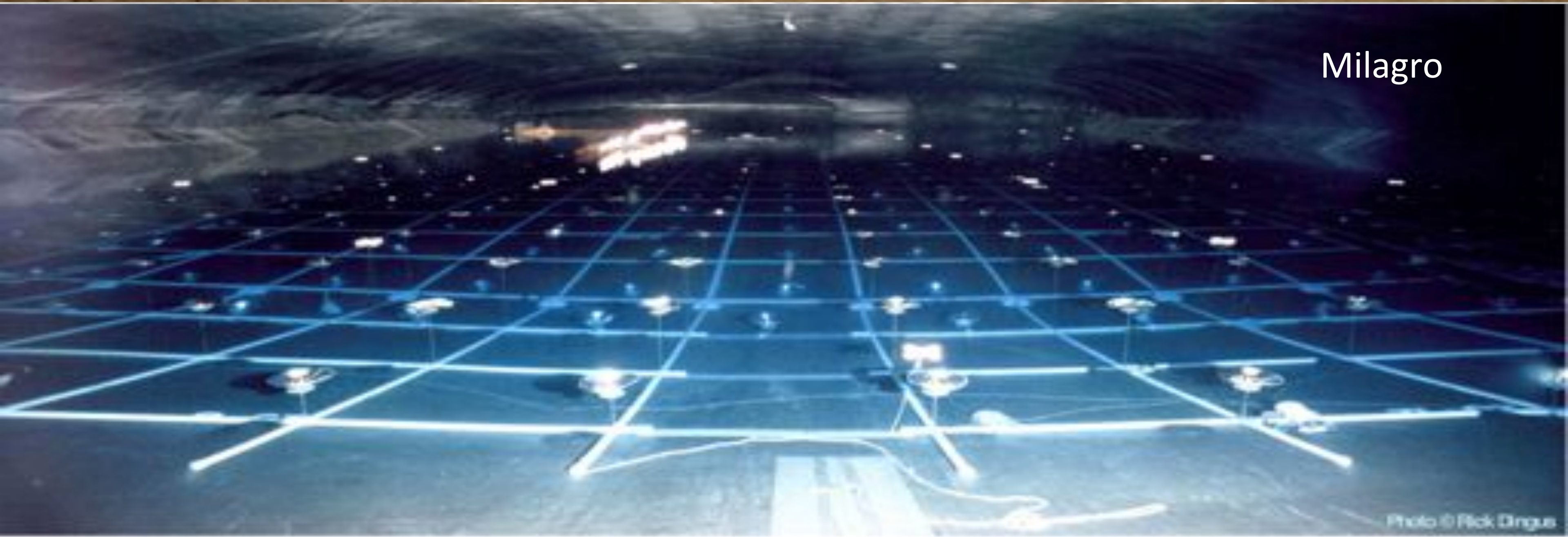
EAS Arrays Milagro/Tibet/ARGO/HAWC

100 GeV - 100 TeV
Large Area
Good background rejection
Improving angular resolution
Large Aperture & Duty Cycle

Partial sky survey & monitoring
Large scale diffuse emission and anisotropy
Extended Sources
Transients (GRBs, AGN flares)
Highest Energies (>10 TeV)

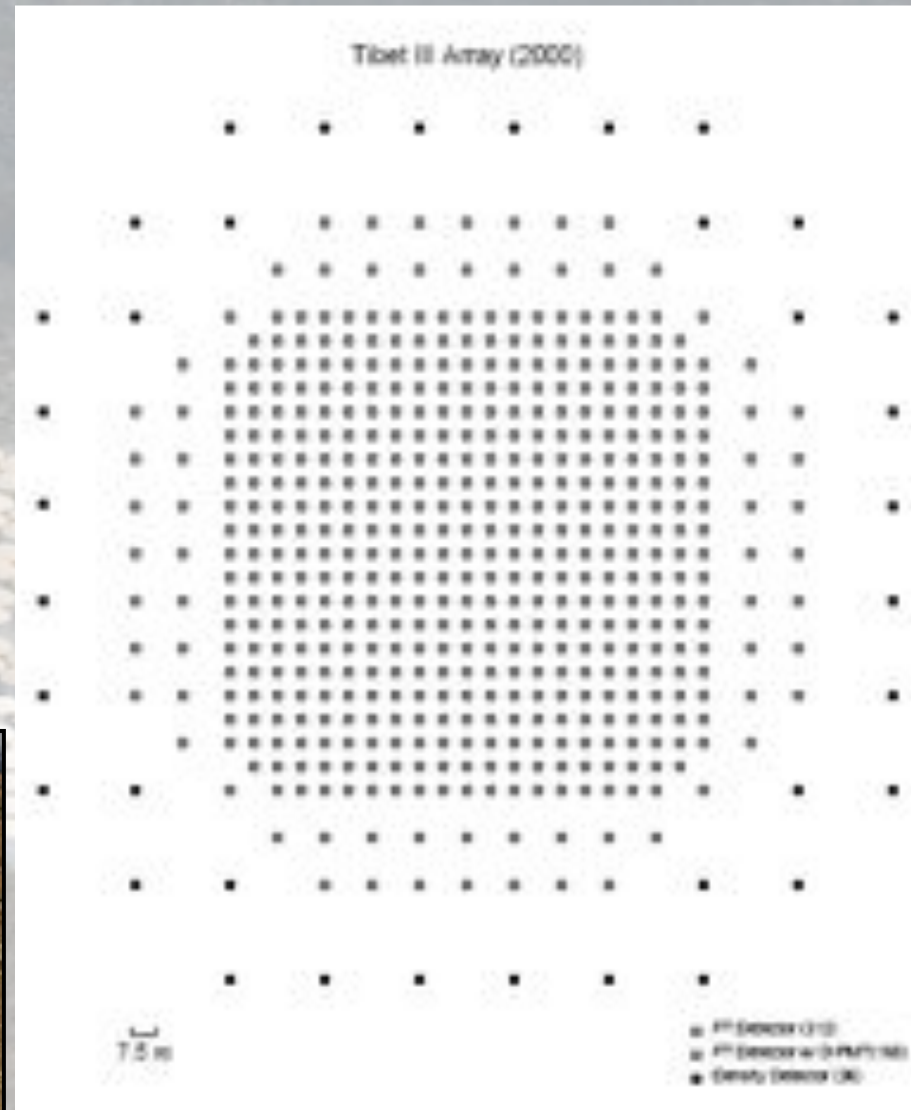
Different Types of Ground Array Detectors





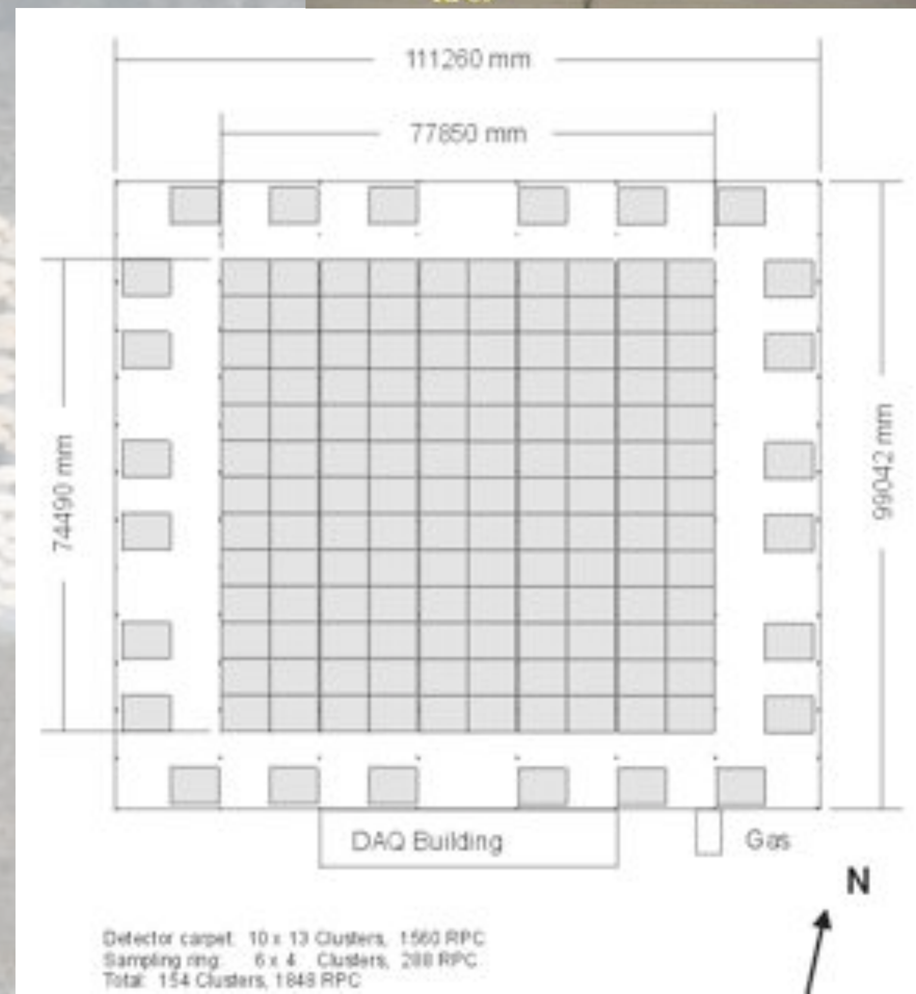
Tibet Air Shower Array (>1990)

- 4300m asl
- Scintillator array
- 497 detectors
  - $0.5m^2$ each
  - 5mm lead on each
- $5.3x10^4$ m^2 (phys. area)
- 3 TeV median energy
- 680 Hz trigger rate
- 0.9^o resolution



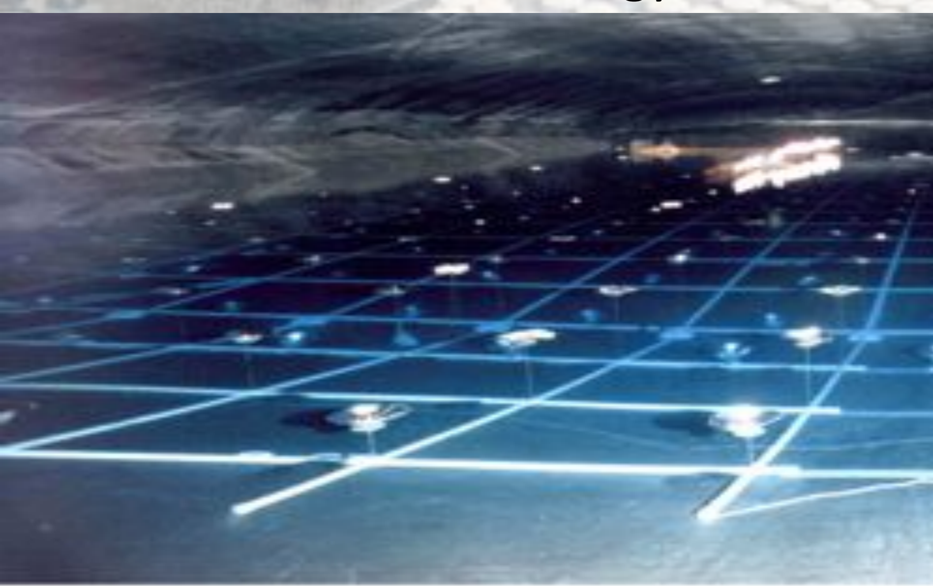
Argo-YBJ (>2000)

- 4300m asl
- Single layer of RPCs (Resistive Plate Counters)
- 154 detectors
- 6500 m^2 (phys. area)
- Energies:
  - Gamma rays > 100 GeV,
  - GRB >10 Gev
  - CR-p 10-200 TeV
  - p/anti-p ratio 300 GeV-1 TeV
- Tens of Hz trigger rate
- 0.1°-1° resolution

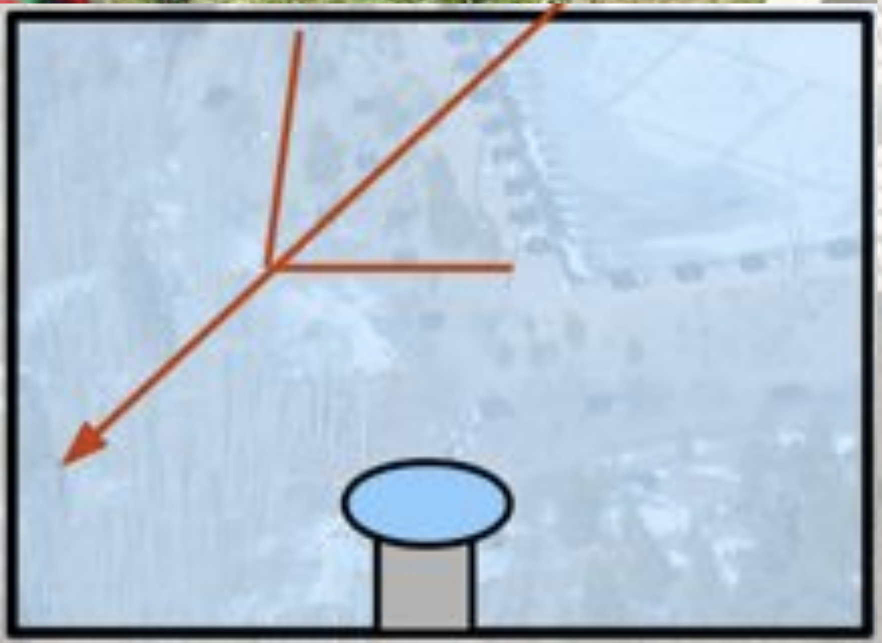


Milagro (2000-2008)

- 2600m asl (NM, USA)
- Water cherenkov detector
- 898 PMTs
  - 450 top/273 bottom
  - 175 outriggers
- 40,000m^2 area
- 1700 hz trigger rate
- 0.4^o-0.9^o resolution
- 2-40 TeV median energy



The Water Cherenkov Technique

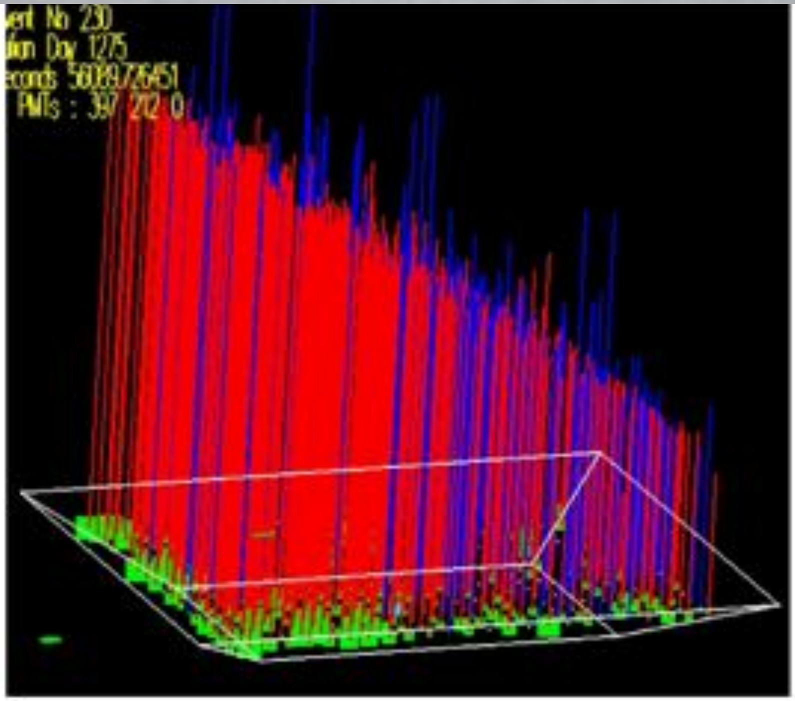


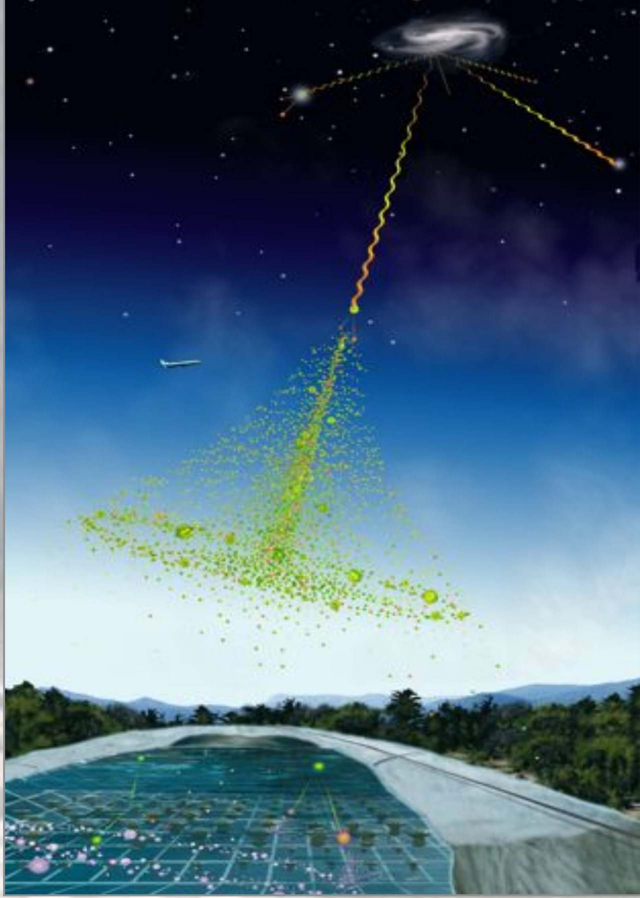
- Instrument a volume of water with Photo-Multiplier Tubes
- Detect Cherenkov light from high- energy particle passage through the water.
- Technique used by Super Kamiokande, IceCube, SNO
- Why Water?
  - Clear Cherenkov medium
  - Inexpensive and abundant.
- Instrument a large flat area to see air showers.
- Reconstruct primary particle direction from PMT timing

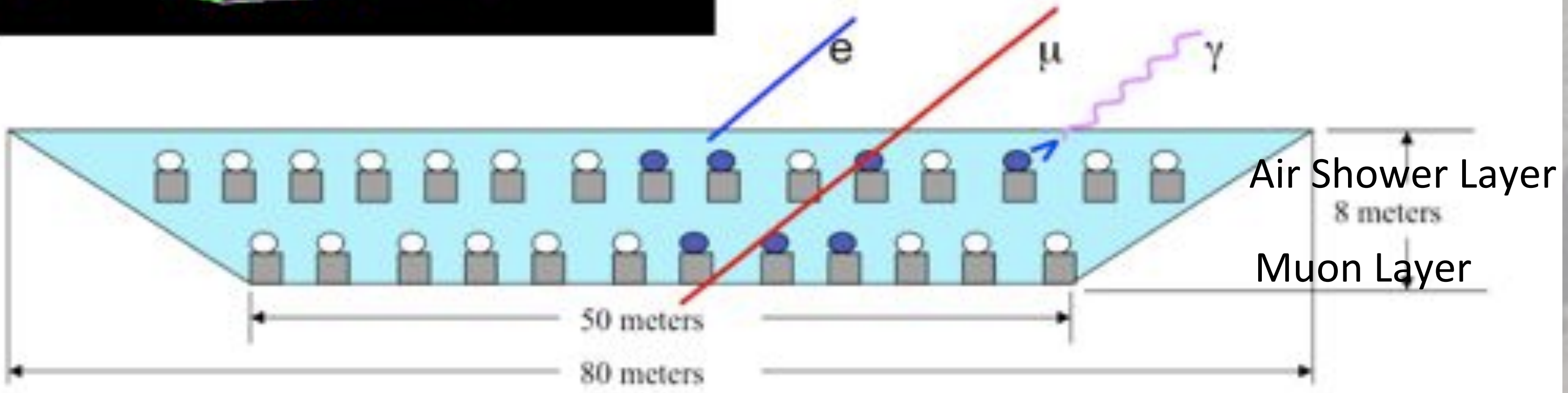
The Photodetector

8” Hamamatsu R5912, 12 stage, 10^7 gain, QE ~25%

The Water Cherenkov Technique





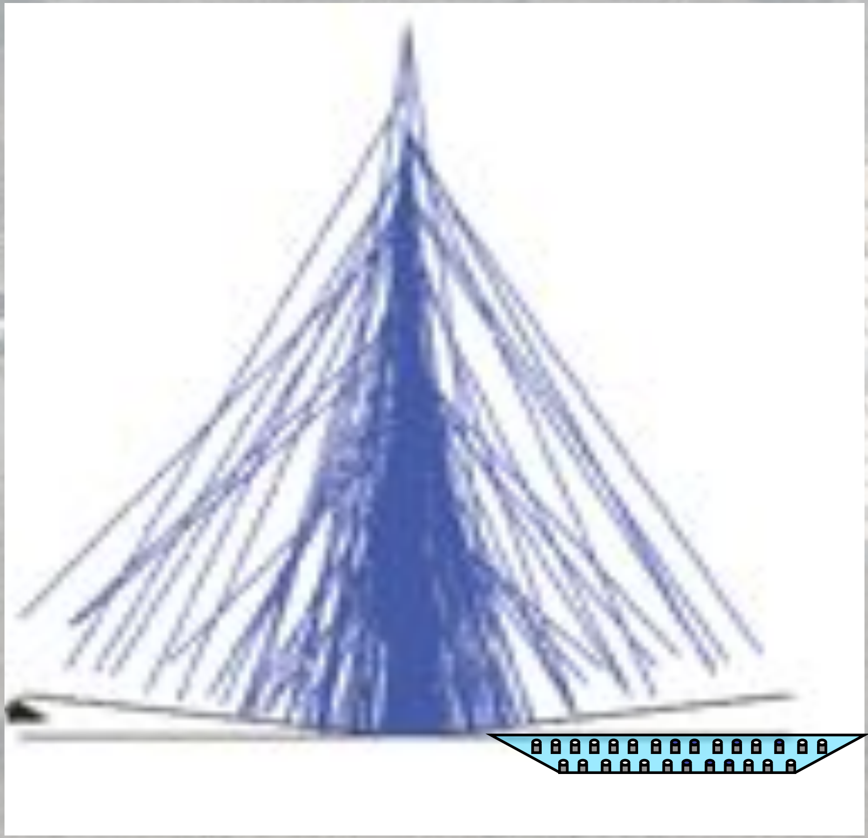


EAS Reconstruction

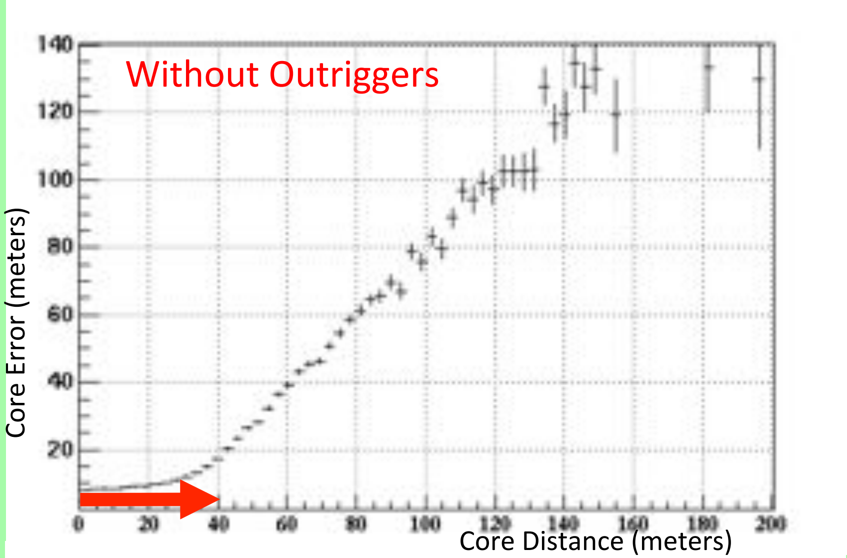
- Identify an ‘event’ through trigger conditions, e.g. require a minimum number of significant signals in your array, or a minimum charge etc.
- Reconstruct the core of the shower through a gaussian fit to the signal strengths in each of your PMTs

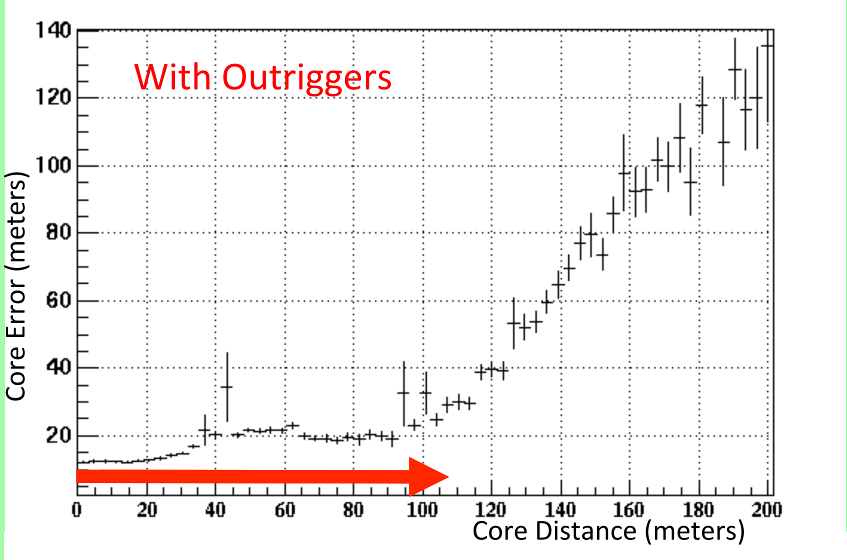
Curvature Correction

- The shower front is not a plane, but is curved about the shower core
- Times of individual PMTs are adjusted based on the distance to the shower core



Core Location Error vs
True Core Distance from Center of Pond





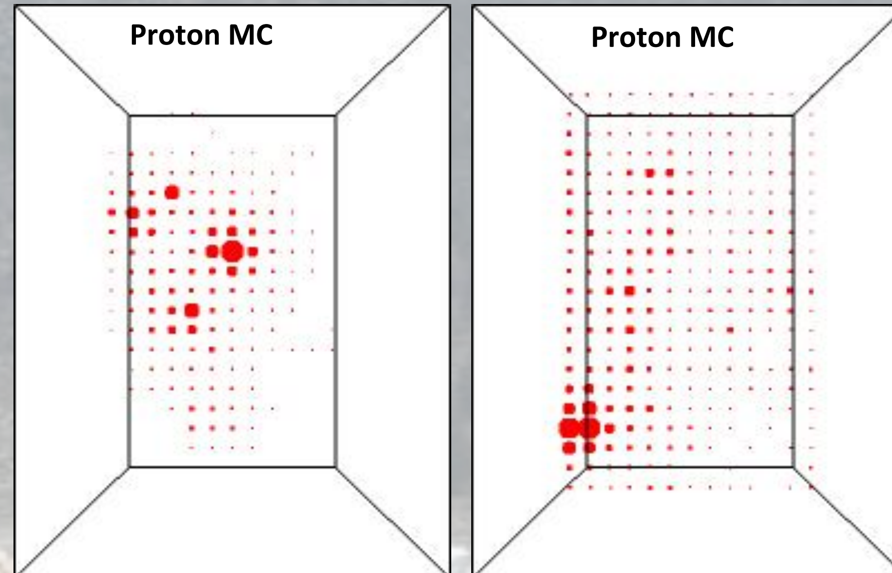
Two Types of Background

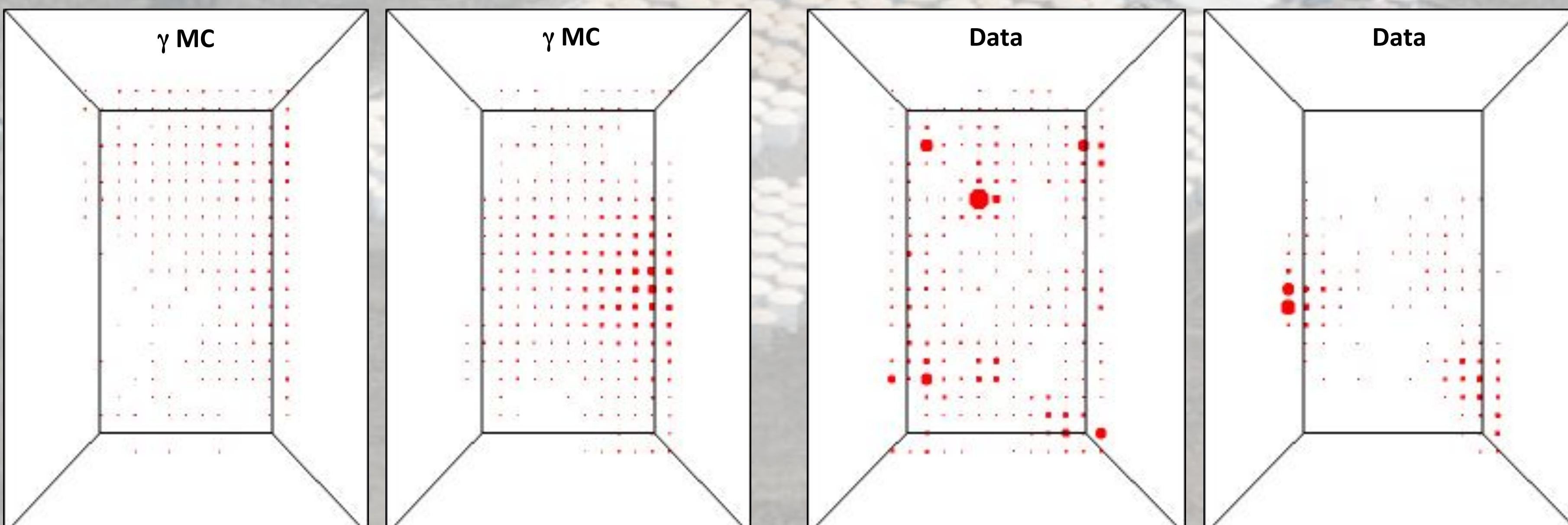
1. Cosmic Rays (A_4)
2. Any isotropic background (direct integration)

Background Rejection in Milagro

Hadronic showers contain penetrating component: μ's & hadrons

- Cosmic-ray showers lead to clumpier bottom layer hit distributions
- Gamma-ray showers give smooth hit distributions

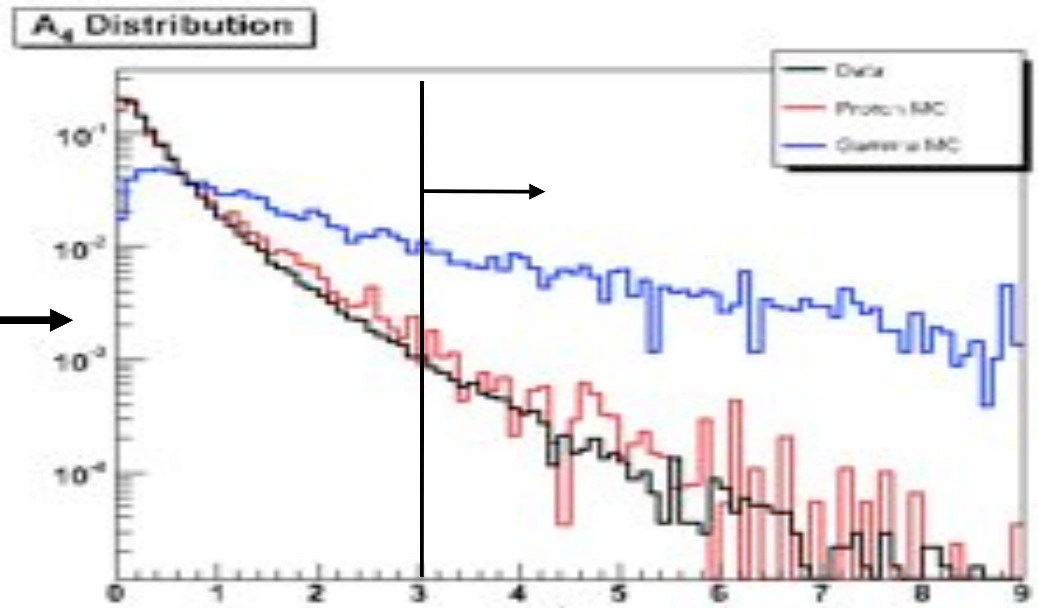




Milagro Background Rejection (Cont'd)

Background Rejection Parameter

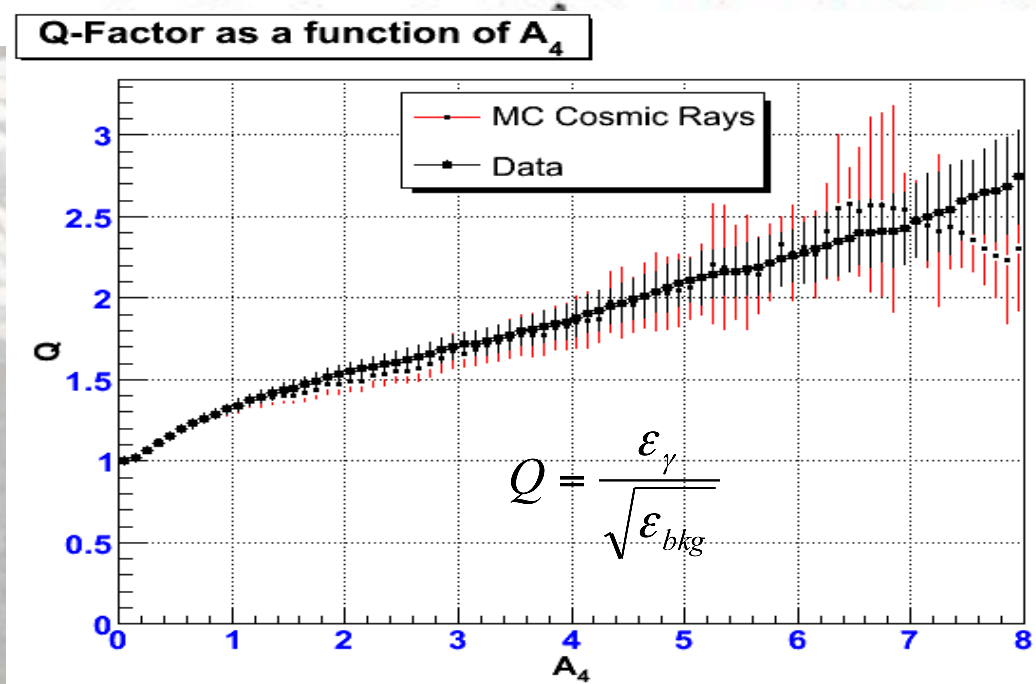
$$A_4 = \frac{\left(f_{Top} + f_{Out}\right) * n_{Fit}}{mxPE}$$



- mxPE: maximum # PEs in bottom layer PMT
- f_{Top} : fraction of hit PMTs in Top layer
- f_{Out} : fraction of hit PMTs in Outriggers
- n_{Fit} : # PMTs used in the angle reconstruction

S/B increases with increasing A_4 so analysis weights events by S/B as determined by the A_4 value of the event

Improves sensitivity by ~2x



Background estimation

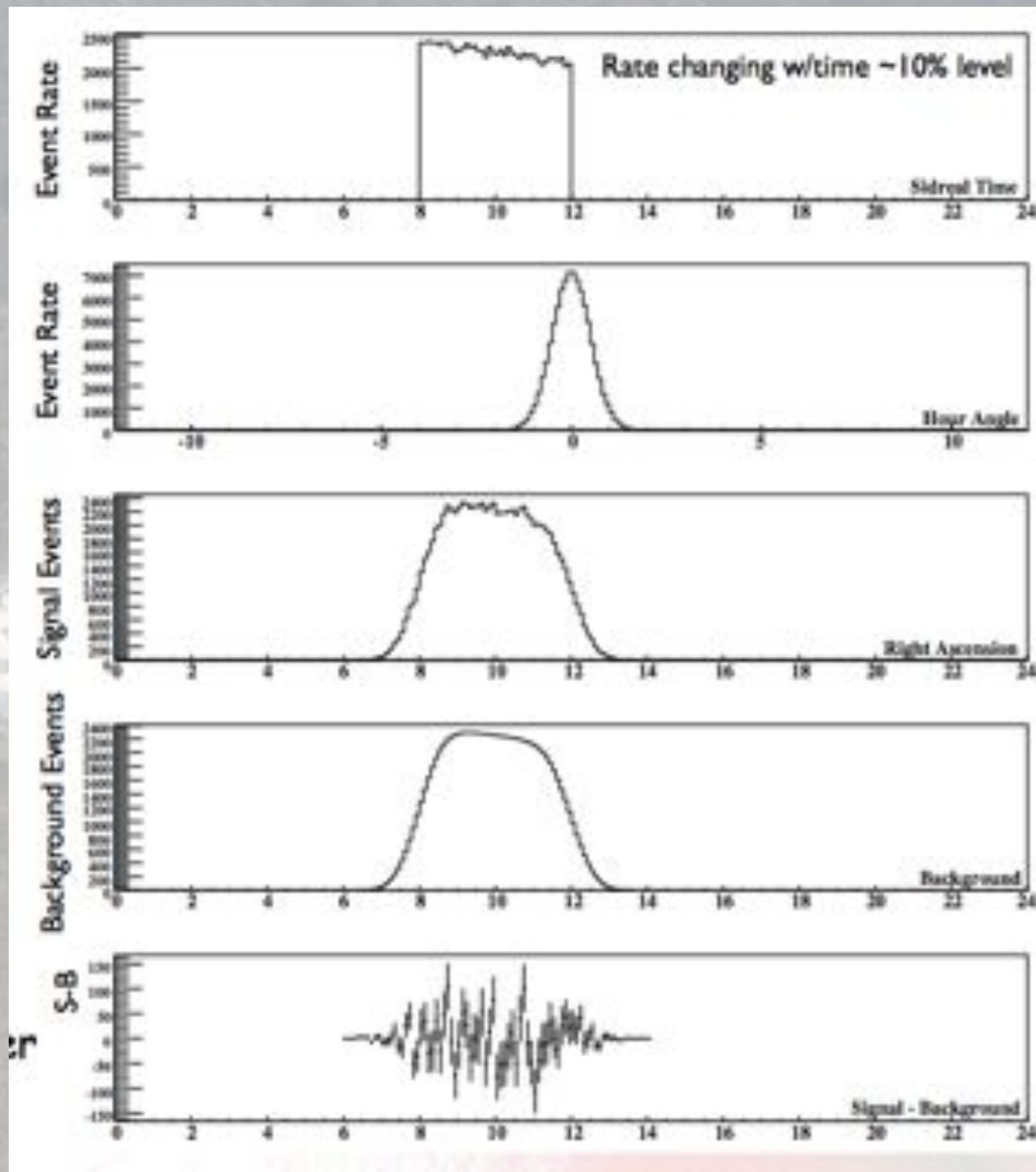
"Direct Integration"

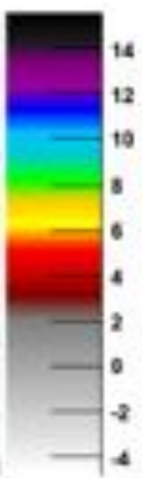
- 2 hr integration time: method assumes that the detector acceptance in local coordinates is independent of the trigger rate over this time
- No. of expected background events:

$$N_{\text{exp}}[\text{R.A.}, \delta] = \int\int E(\text{ha}, \delta)\, R(t)\, \epsilon(\text{ha}, \text{R.A.}, t)\, dt\, d\Omega$$

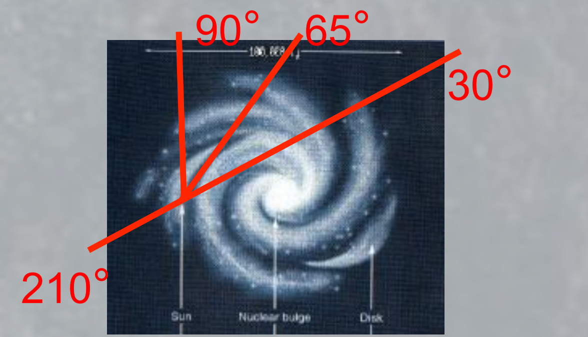
- Li & Ma prescription used for significance calculation
- R.O.I. around the crab nebula (+/-2 deg) and Galactic Plane (+/- 2.5 deg)

Background estimation



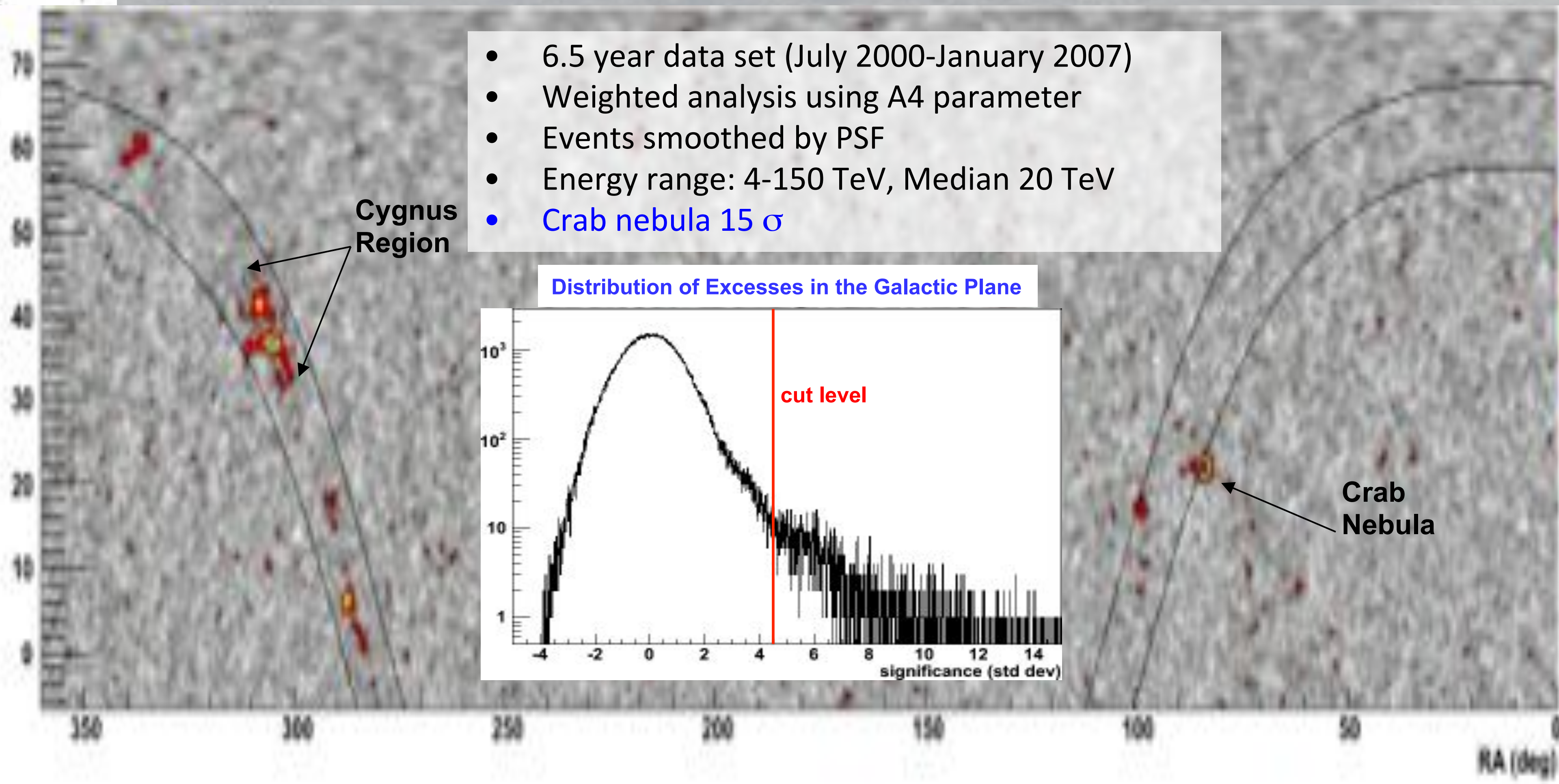


Milagro Survey

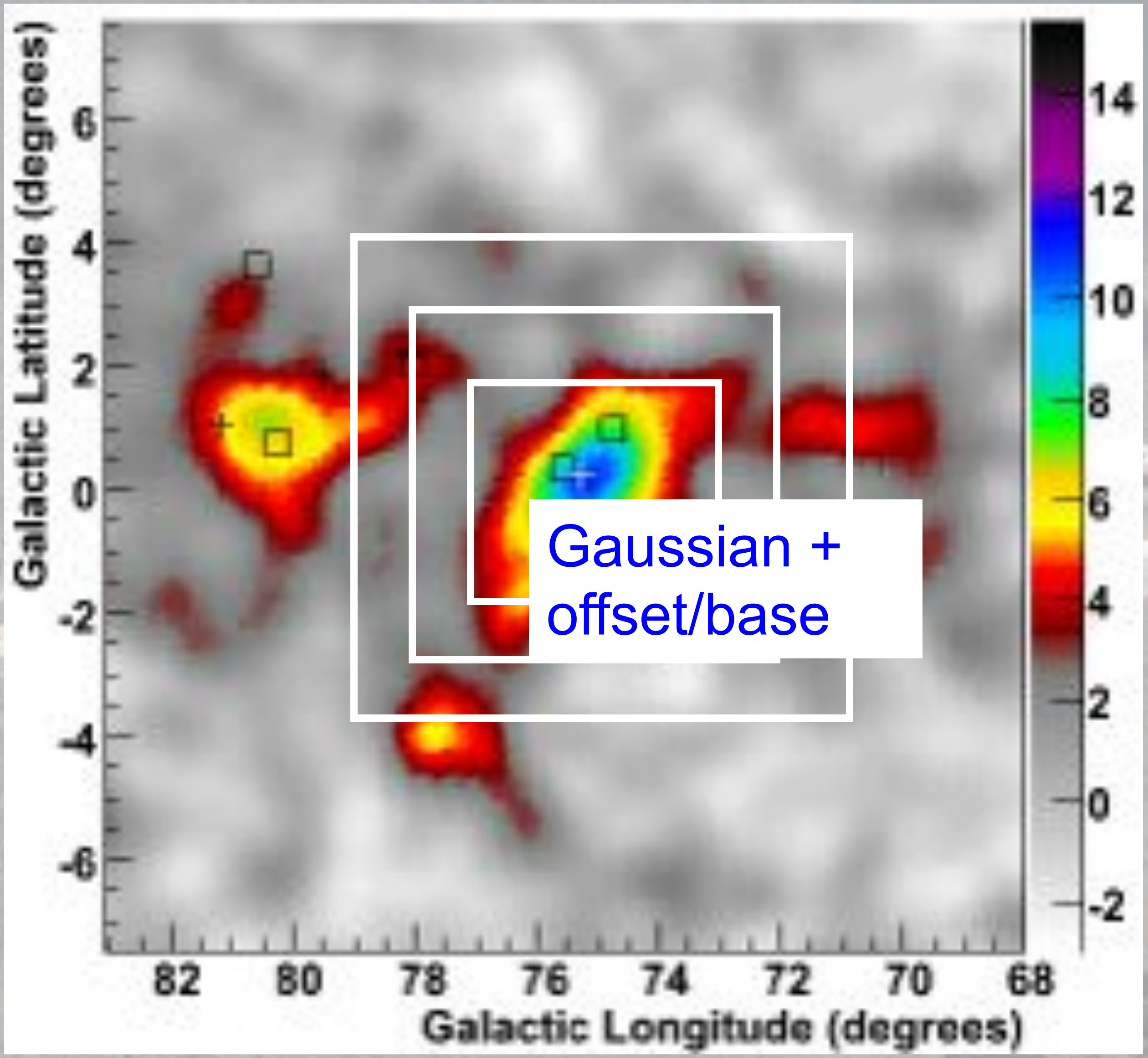


Milagro sees the Galactic plane from longitude ~30° to ~220°

- 6.5 year data set (July 2000-January 2007)
- Weighted analysis using A4 parameter
- Events smoothed by PSF
- Energy range: 4-150 TeV, Median 20 TeV
- Crab nebula 15 σ

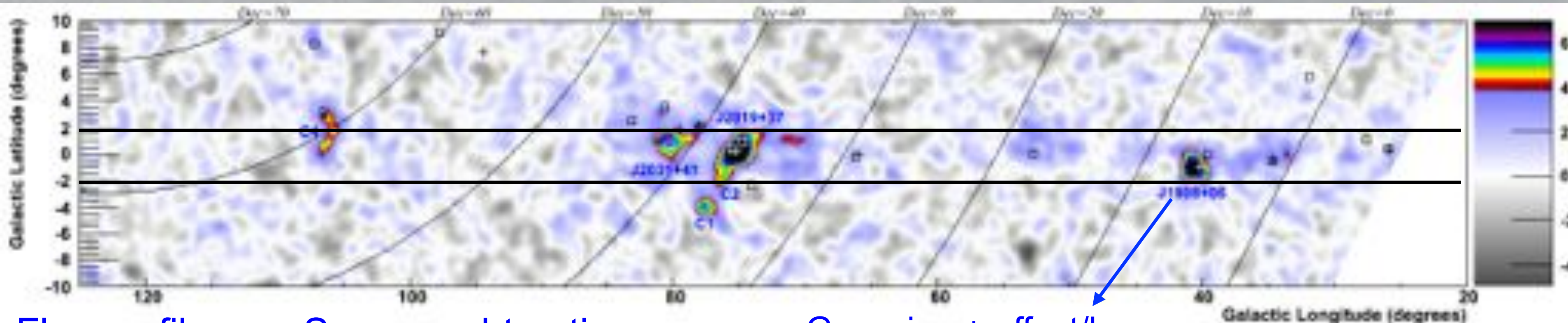


Remarks about source fitting

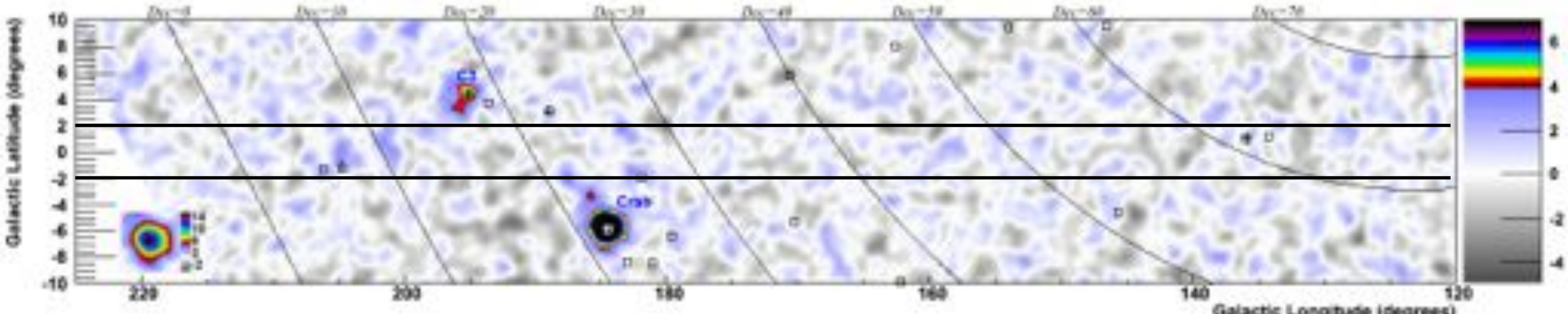


Diffuse Emission

A4 –weighted significance map



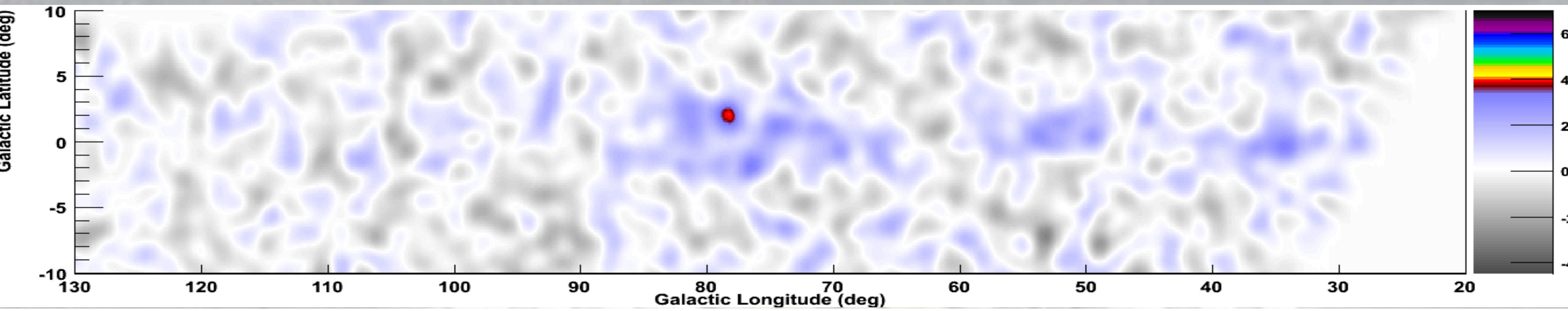
Flux profiles ⟵ Source subtraction ⟵ Gaussian + offset/base

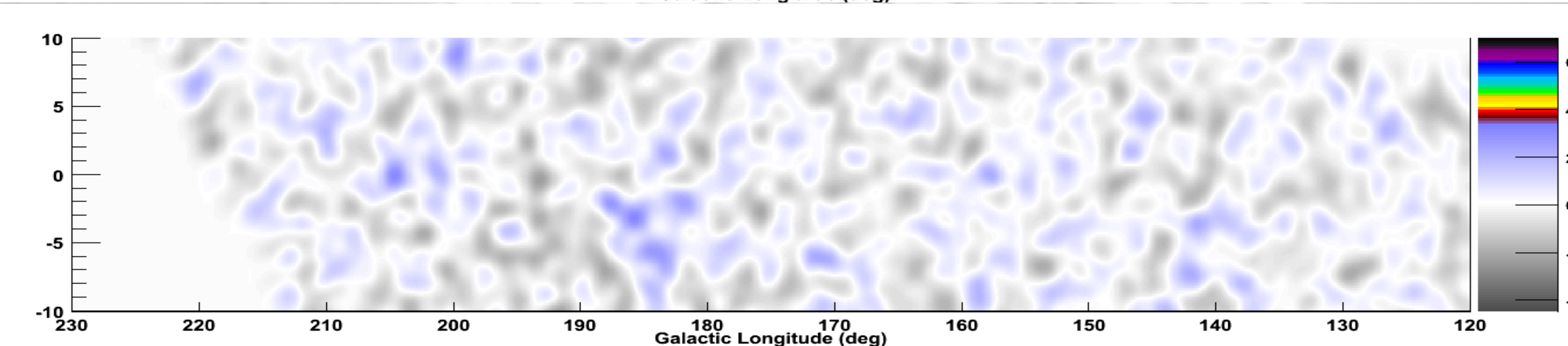


Diffuse Emission

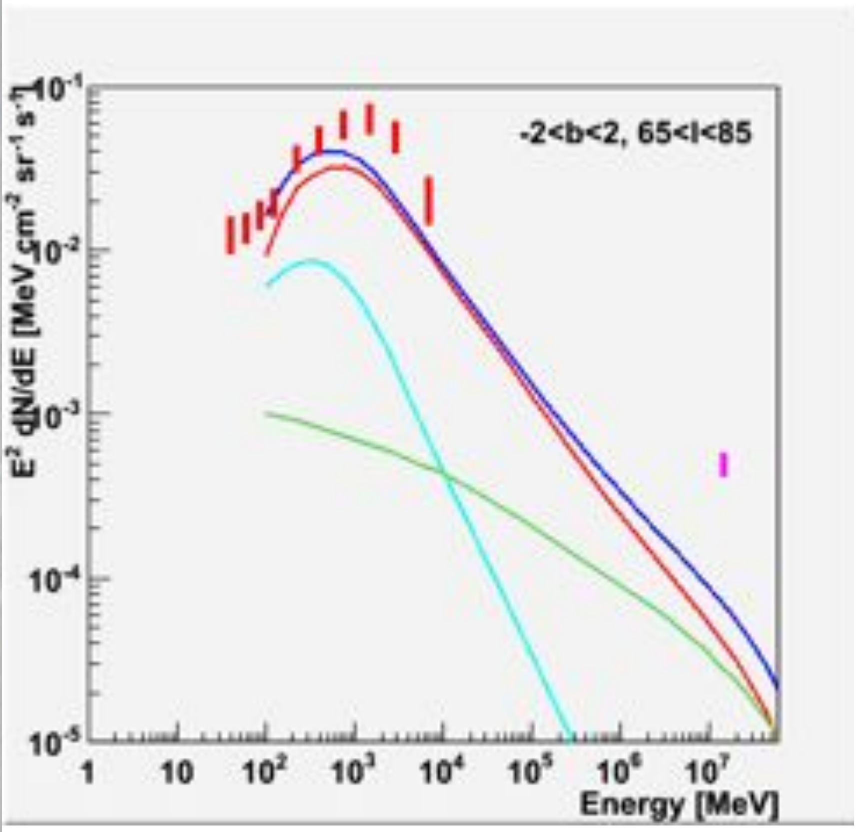
The Diffuse Galactic Plane

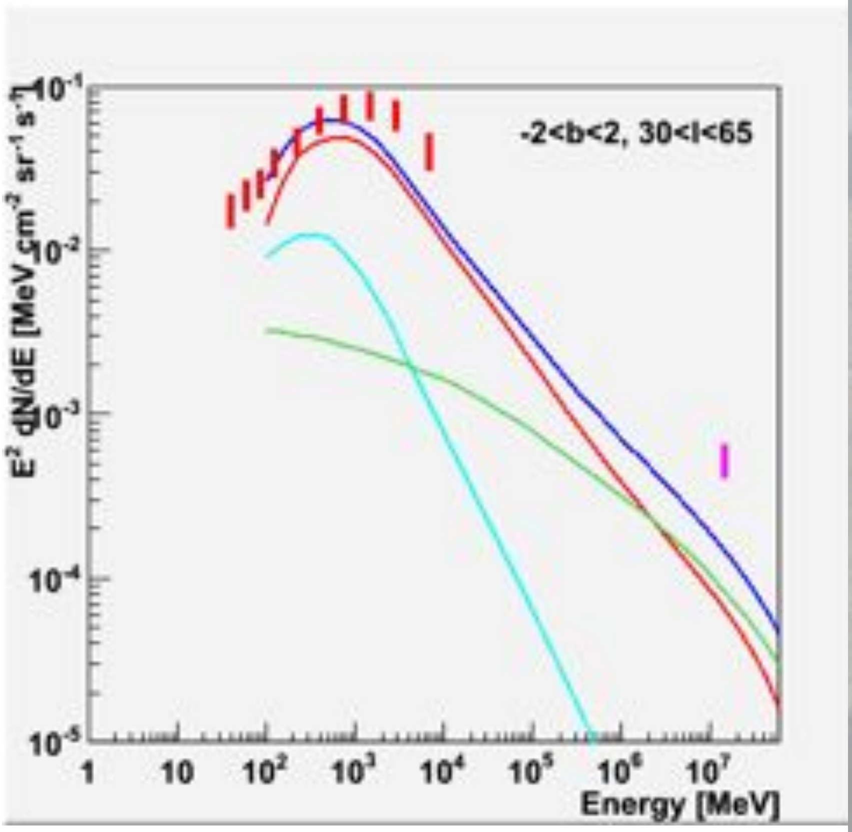
Cygnus region





The Diffuse Flux Measured by Milagro

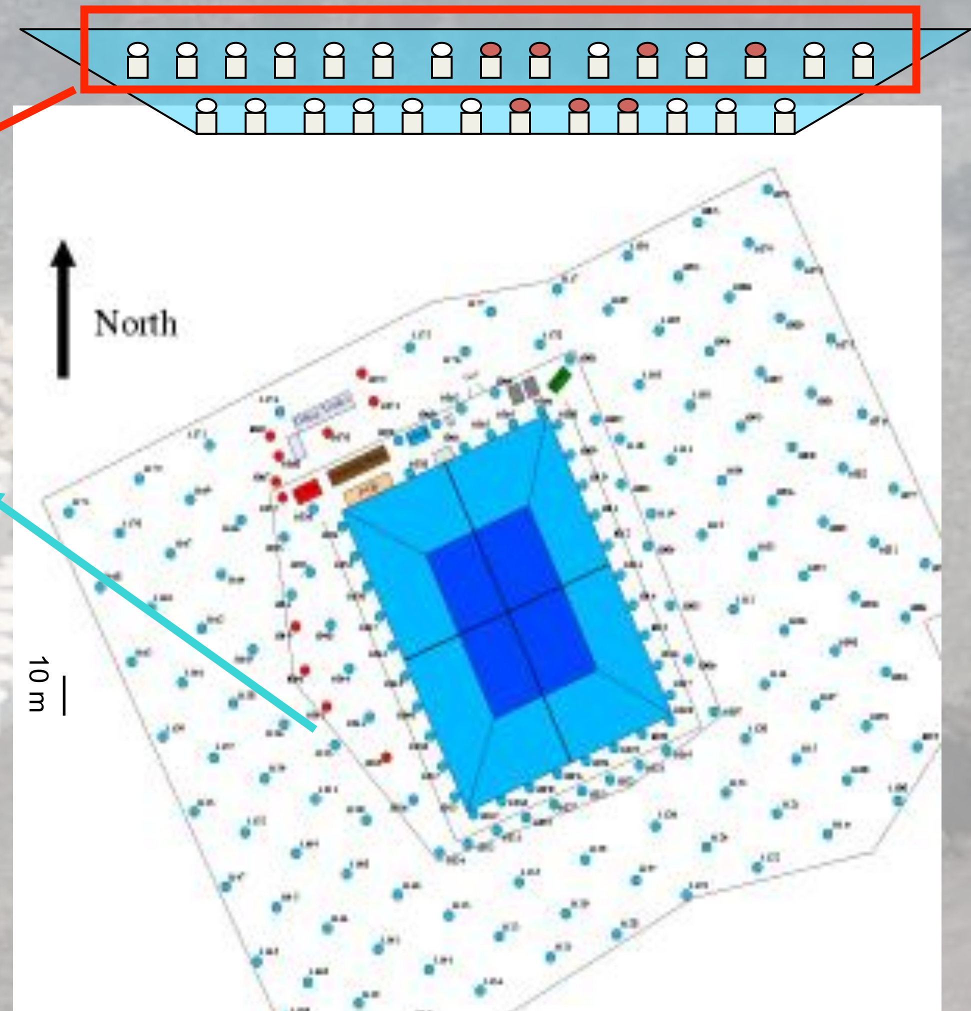




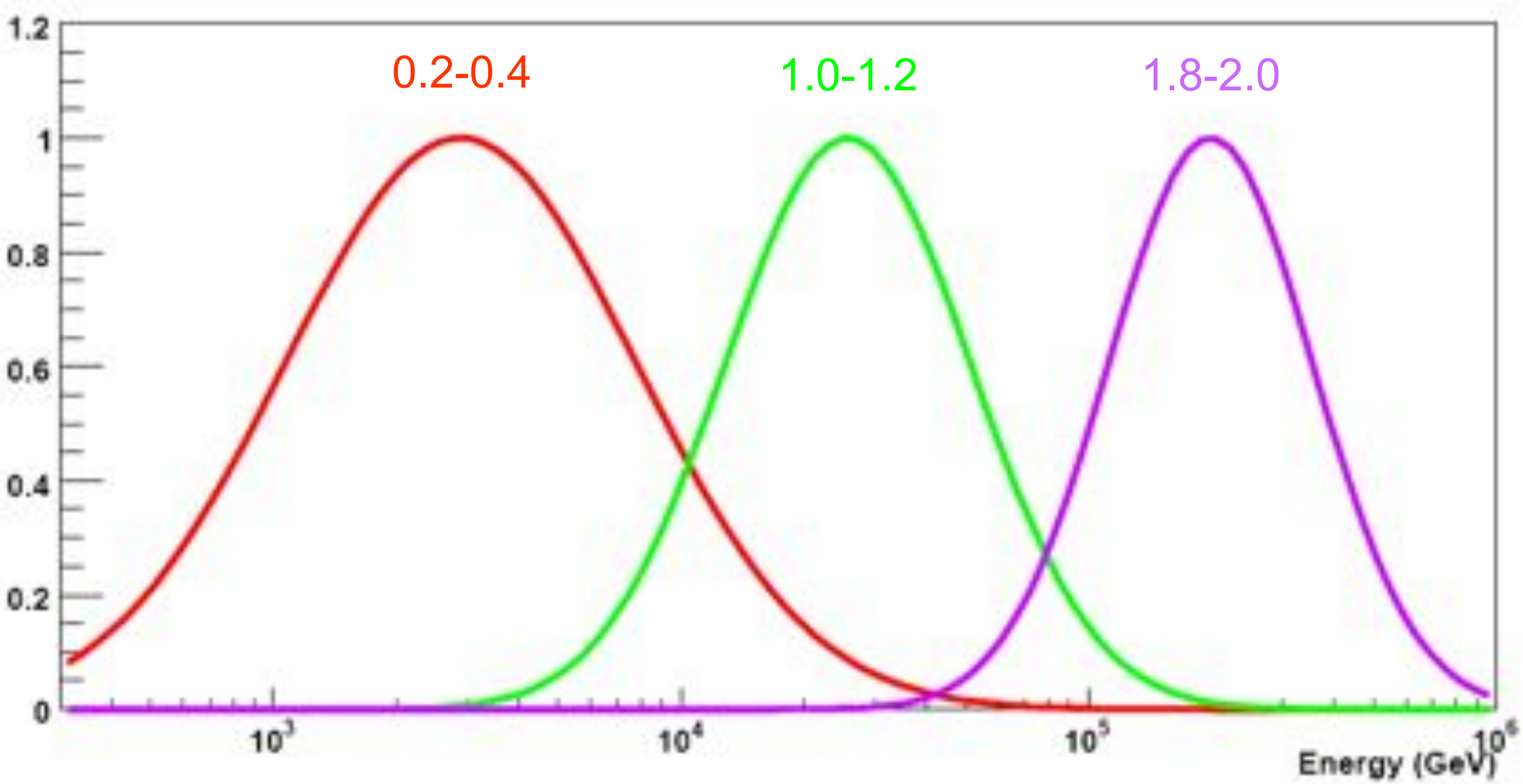
Energy Spectrum: Introduction of Energy Parameter

$$\mathrm{FrASOR} = \frac{N_{AS}^{hit}}{N_{AS}^{live}} + \frac{N_{OR}^{hit}}{N_{OR}^{live}}$$

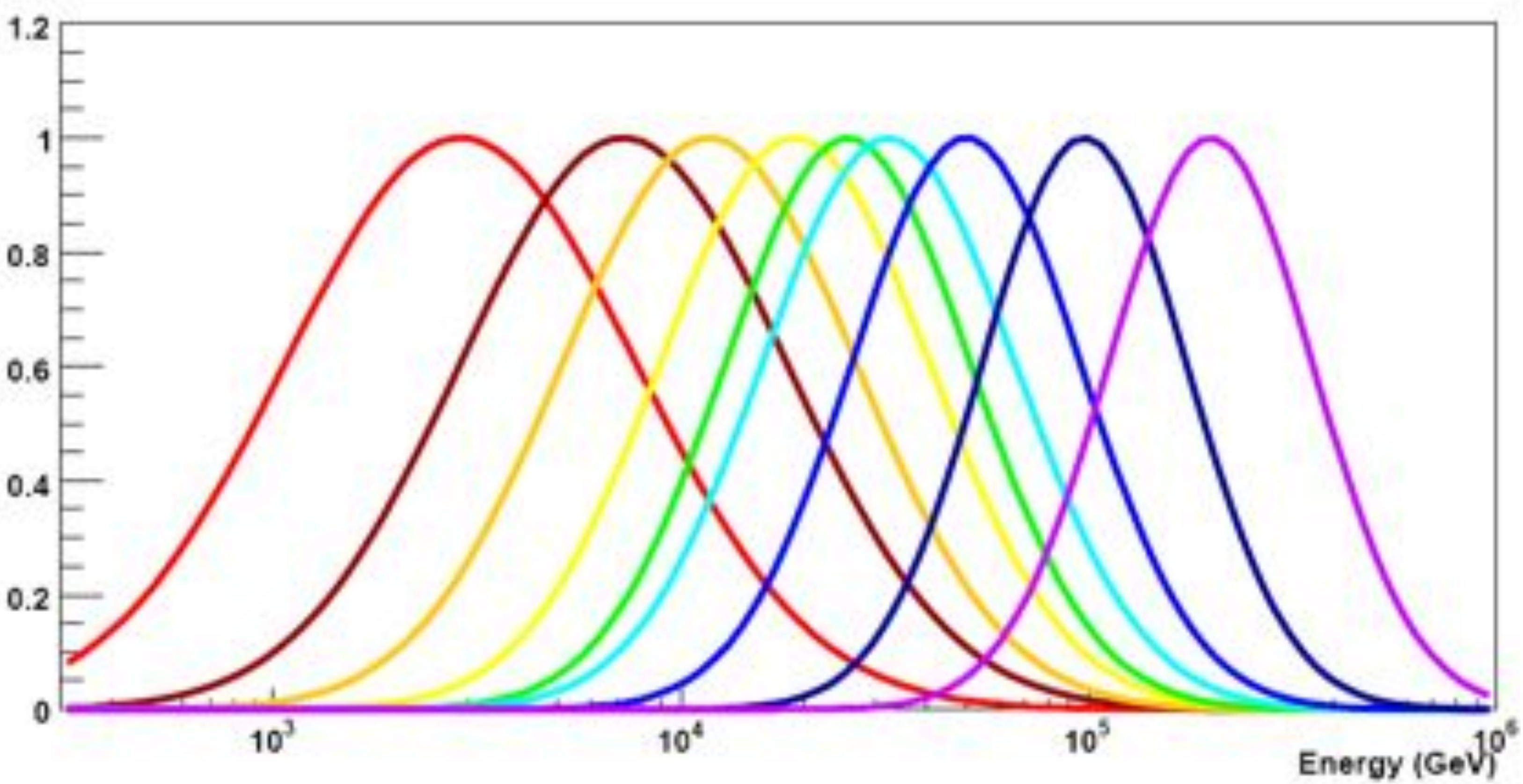
Parameter Range: 0.2-2. in 9 bins



Energy Dependence of FrASOR

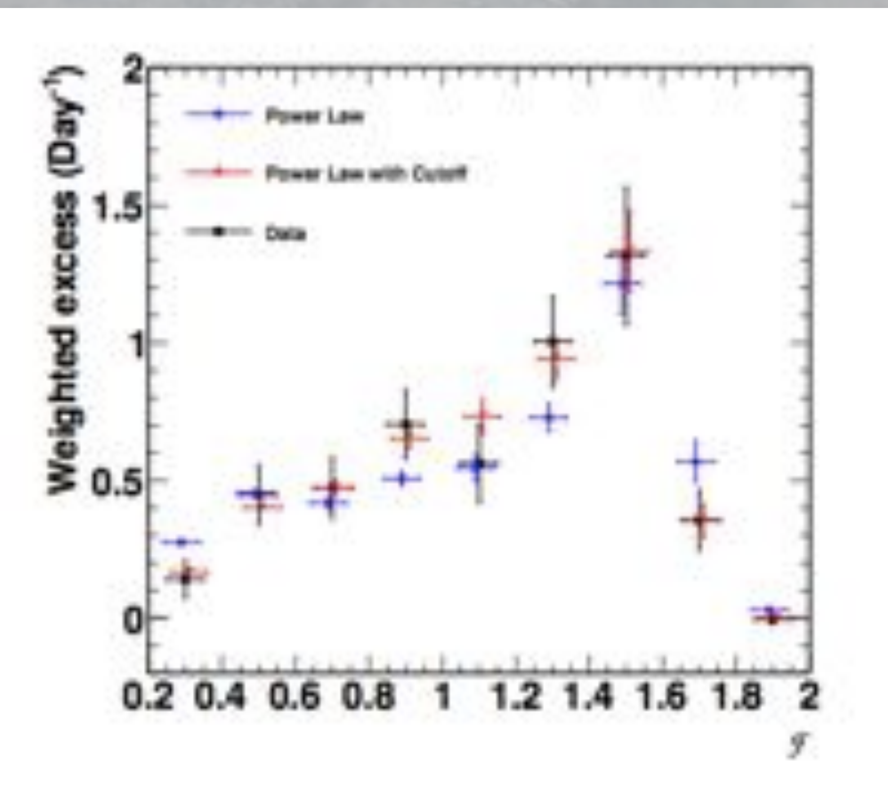


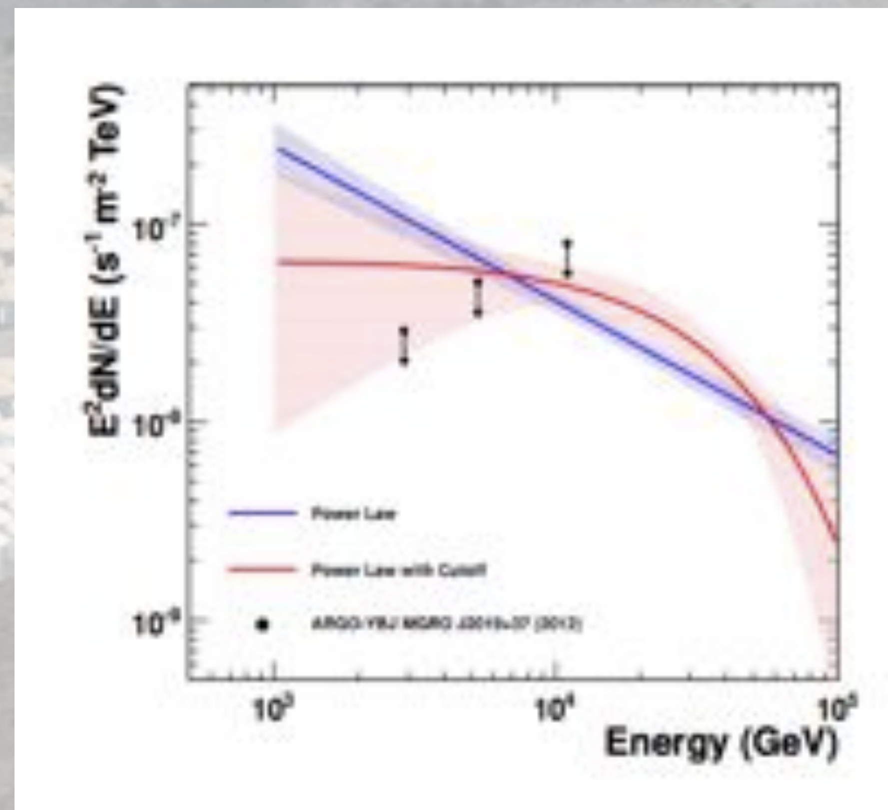
Energy Dependence of FrASOR



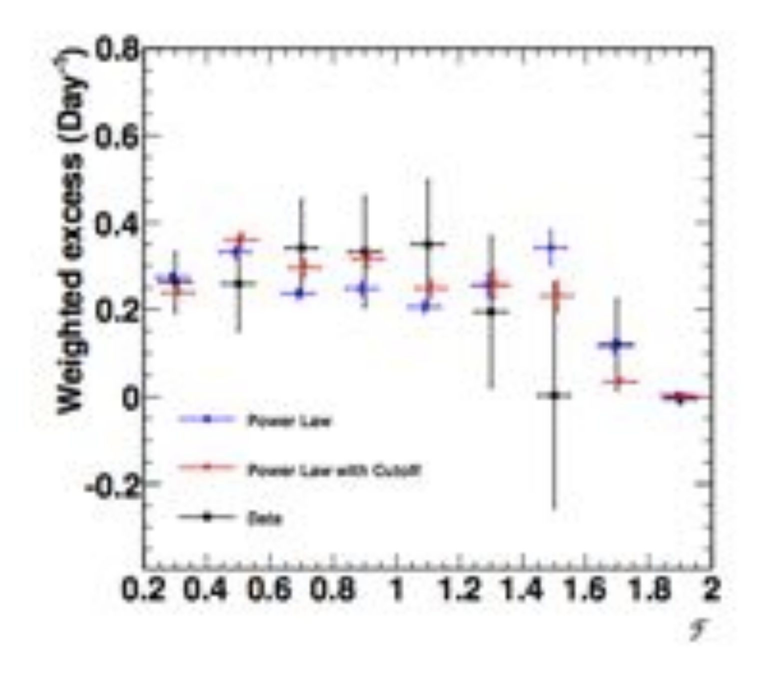
Forward folding

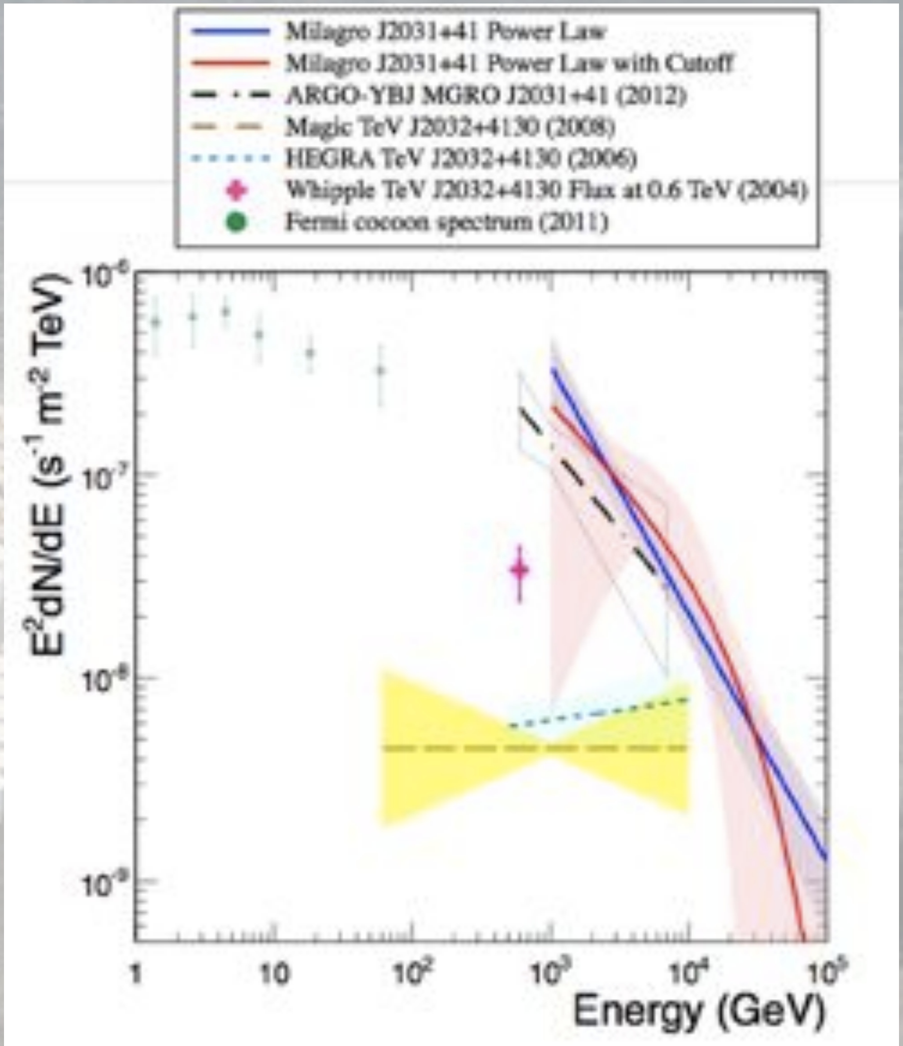
The Cygnus Region: MGRO J2019+37





The Cygnus Region: MGRO J2031+41





The Cygnus Region is complicated