Ground Based
Gamma-Ray Astronomy II

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What are we trying to measure?

- Directions
  - Maps
  - Extensions
  - Spatial distribution
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- Energy
  - Spectral Energy Distributions (SED)
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- Directions
  - Map
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- 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 ASγ
ARGO-YBJ
Milagro
Tibet Air Shower Array (>1990)

- 4300m asl
- Scintillator array
- 497 detectors
  - 0.5m² each
  - 5mm lead on each
- $5.3 \times 10^4$ m² (phys. area)
- 3 TeV median energy
- 680 Hz trigger rate
- 0.9° resolution
Argo-YBJ (>2000)

- 4300m asl
- Single layer of RPCs (Resistive Plate Counters)
- 154 detectors
- 6500 m² (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
- 40,000m² area
- 1700 Hz trigger rate
- 0.4°-0.9° 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

Air Shower Layer
Muon Layer
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
Two Types of Background

1. Cosmic Rays (A₄)
2. Any isotropic background (direct integration)
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
Background Rejection Parameter

\[ A_4 = \frac{(f_{\text{Top}} + f_{\text{Out}}) \times n_{\text{Fit}}}{\text{mxPE}} \]

mxPE: maximum # PEs in bottom layer PMT

\( f_{\text{Top}} \): fraction of hit PMTs in Top layer

\( f_{\text{Out}} \): fraction of hit PMTs in Outriggers

\( n_{\text{Fit}} \): # 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

- 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 \( \sigma \)

Milagro sees the Galactic plane from longitude \( \sim 30^\circ \) to \( \sim 220^\circ \)
Remarks about source fitting

Gaussian + offset/base
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

\[
\text{FrASOR} = \frac{N_{\text{hit}}^{\text{AS}}}{N_{\text{live}}^{\text{AS}}} + \frac{N_{\text{hit}}^{\text{OR}}}{N_{\text{live}}^{\text{OR}}}
\]

Parameter Range: 0.2-2. in 9 bins
Energy Dependence of FrASOR

0.2-0.4
1.0-1.2
1.8-2.0
Energy Dependence of FrASOR
The Cygnus Region: MGRO J2019+37
The Cygnus Region: MGRO J2031+41
The Cygnus Region is complicated