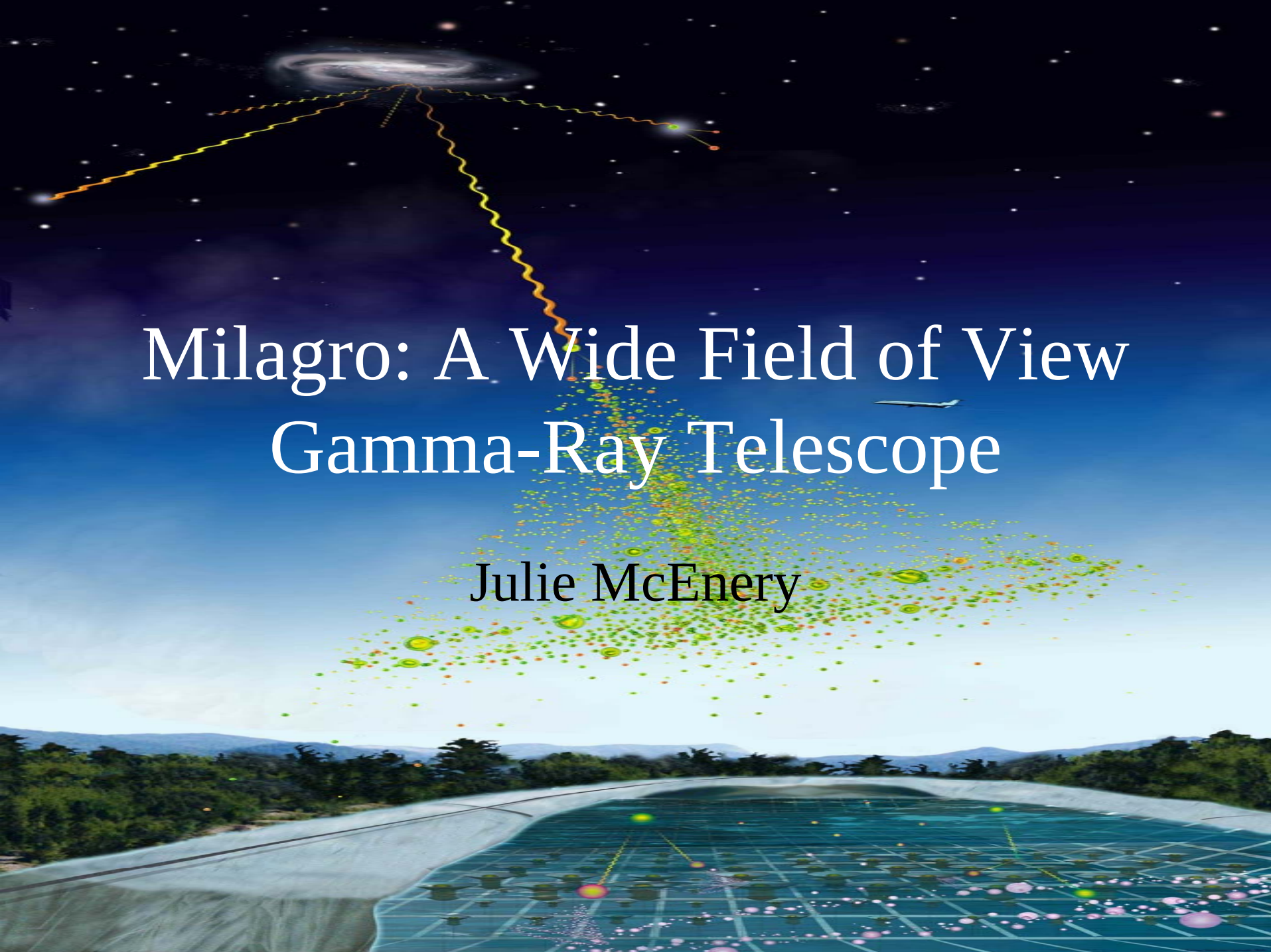


Milagro: A Wide Field of View Gamma-Ray Telescope

Julie McEnery

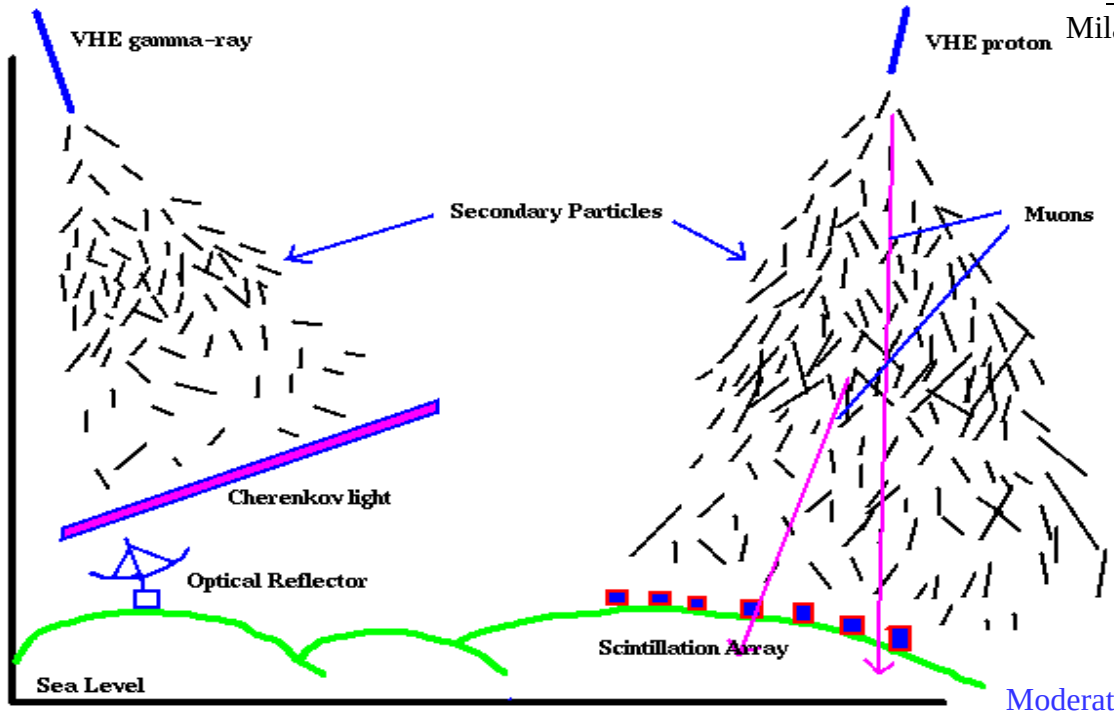
Outline

- Why is this talk relevant to GLAST?
  - Milagro detects air-shower particles at ground level
  - Milagro is a wide field of view Gamma-ray telescope which operates in scanning mode
- Ground-arrays as gamma-ray telescopes (technique)
- Some selected results
- Future directions? (if there is time)

Detectors in Gamma-Ray Astrophysics

ACTs-High Sensitivity
HESS, MAGIC, CANGAROO, VERITAS

Ground Arrays -Large Aperture/High Duty Cycle
Milagro, Tibet, ARGO, HAWC?



Large Effective Area
Excellent Background Rejection (>99%)
Low Duty Cycle/Small Aperture
High Resolution Energy Spectra
Studies of known sources
Surveys of limited regions of sky

Moderate Area/Large Area (HAWC)
Good Background Rejection
Large Duty Cycle/Large Aperture
Unbiased Sky Survey
Extended sources
Transients (GRB's)
Solar physics/space weather

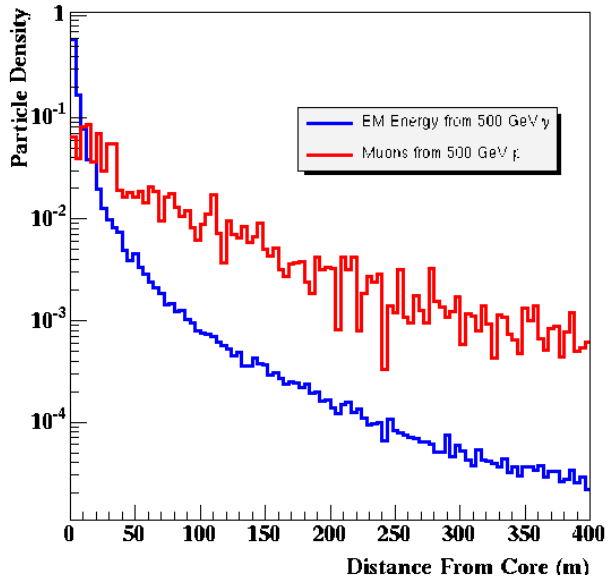
Extensive Air Showers at Ground-Level

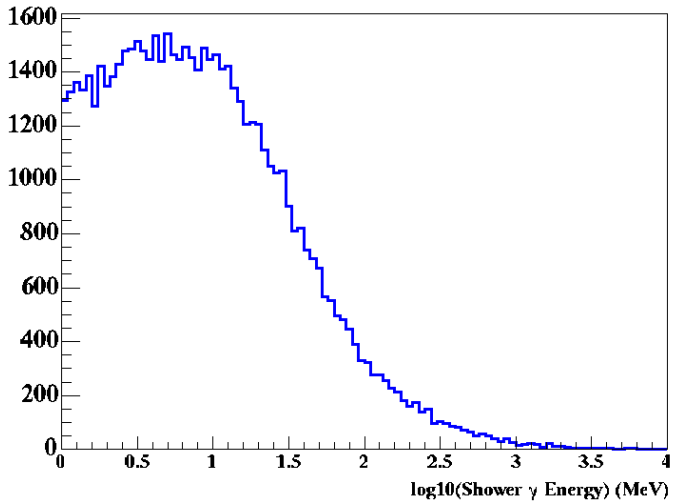
Most particles which reach ground-level are gamma-rays (outnumbering electrons by 5-10/1).

Median energy of these gamma-rays is ~10 MeV.

Hadron induced showers contain 5-20 times more energy in muons and hadrons, distributed over a wide lateral distribution.

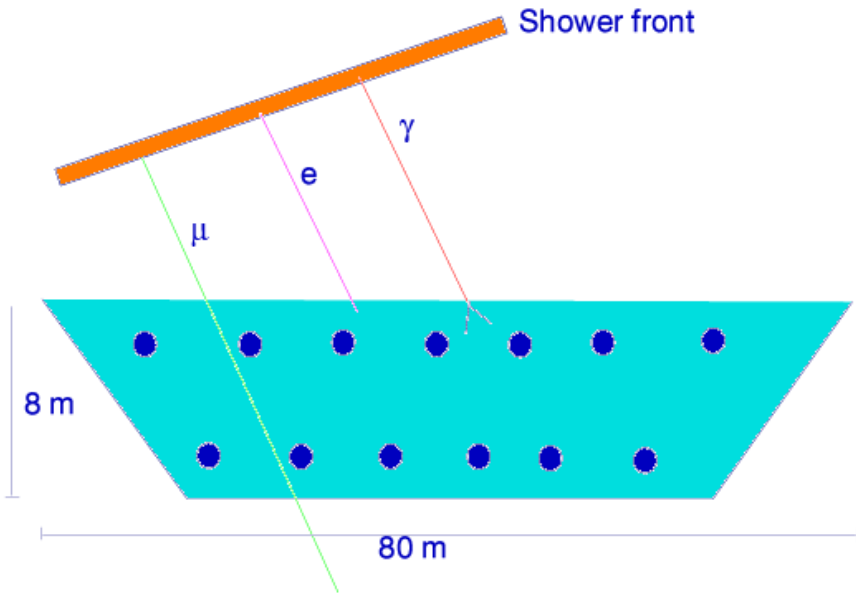
Number of EM particles reaching ground-level decreases rapidly with decreasing altitude.





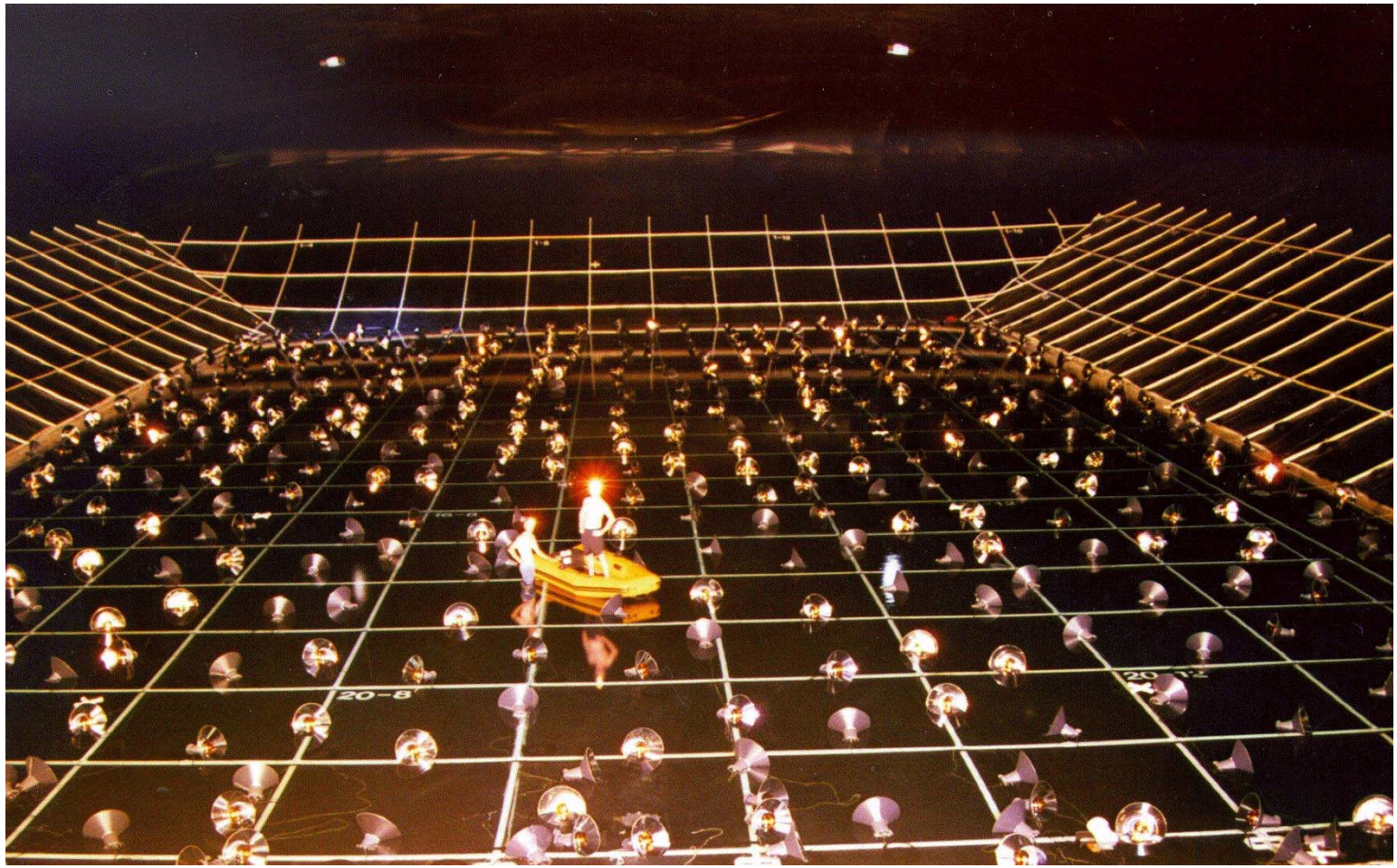
The Milagro Pond

- Shower front arrives at milagro as a ~plane of relativistic particles.
- Water as the detection medium.
  - Cheap
  - Secondary gammas produce relativistic electrons/positrons: no need for converter.
  - Cherenkov angle in water is 41 degrees => sparsely instrumented pond has high detection efficiency.
  - Over 50% of particles incident on the pond are detected.
- 2600m asl

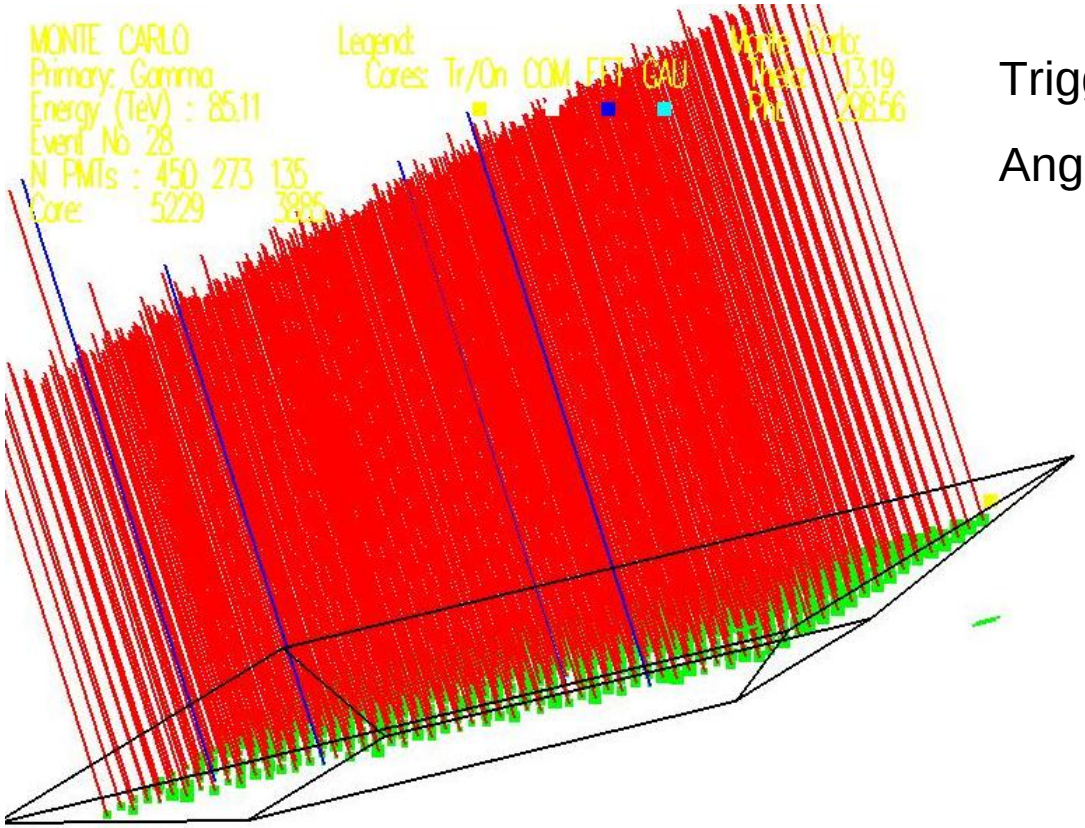


6 million gallon pond instrumented with two layers of PMTs. A top layer of 450 PMTs at 1.5 m and 273 PMTs at 6 m depth.

Inside the pond



Top Layer



Trigger

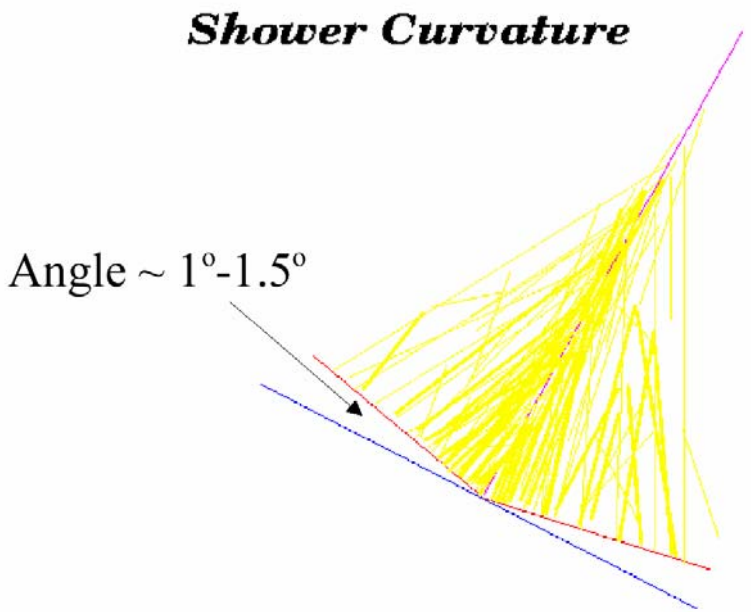
Angular reconstruction

Fit arrival time at the plane of PMTs to reconstruct the shower direction and time.

Angular resolution is ~0.5 degrees. (however there are systematic effects related to core location)

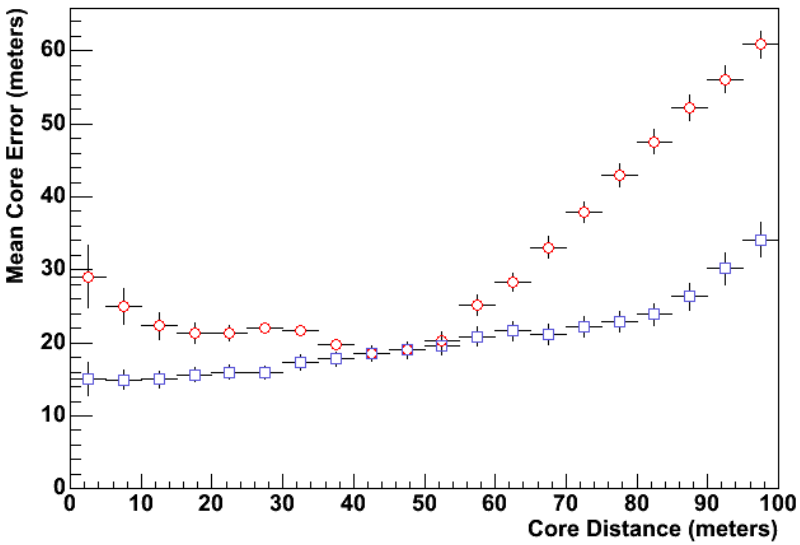
Curvature Correction

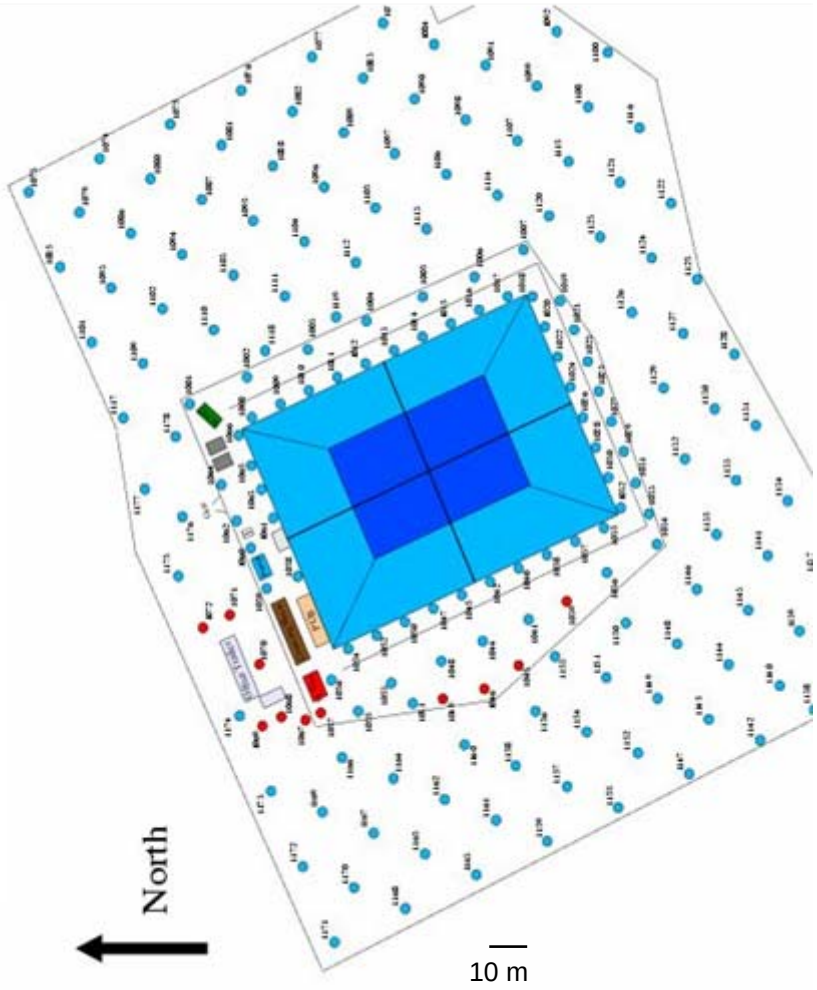
- Shower front is curved.
- To correct for this we need to determine the location of the shower core.
- Without knowledge of the core location this limits the angular resolution (and sensitivity) particularly at high energies.



Milagro Outriggers

- Array of 175 water tanks. Primary purpose is to locate the shower core.



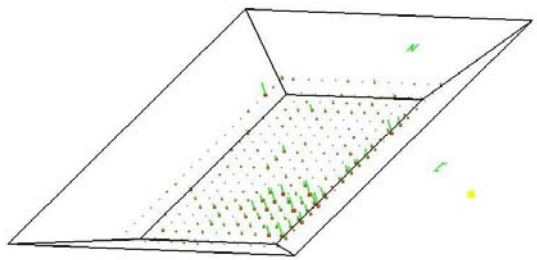


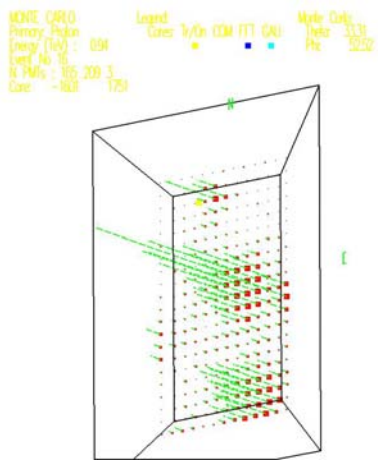
The Milagro Observatory

Outrigger: 4000 liter tank with a single 8” PMT

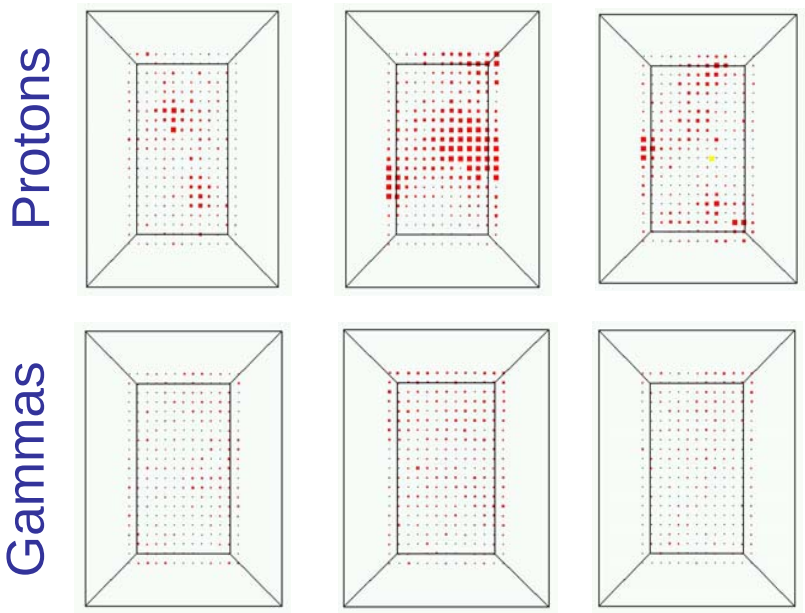
Bottom Layer

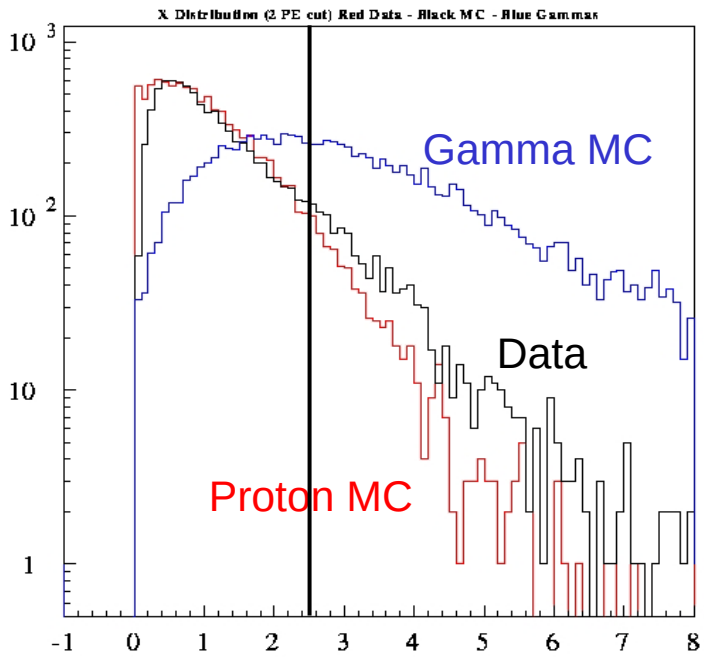
- Background rejection
- Measurement of energy
- Deep enough that contribution from electromagnetic component is smooth, muons/hadrons are sharply peaked.





Background Rejection in Milagro



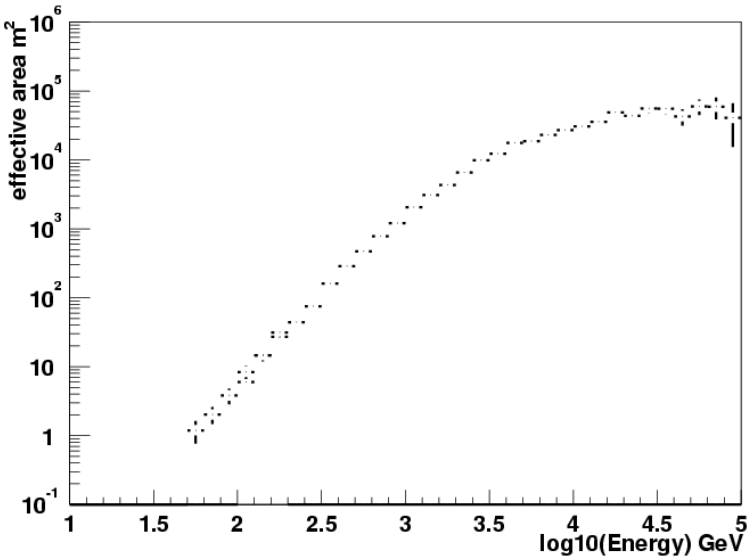


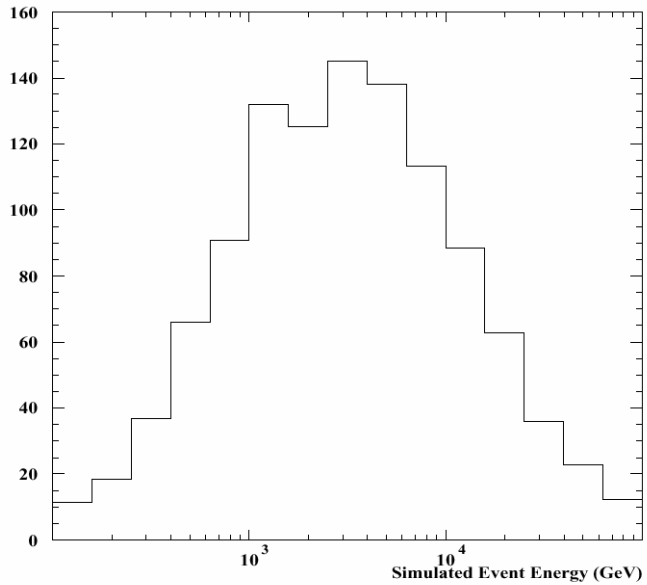
Retain 50% γ and 9% protons

(c.f. 48.9% g and 2.4% protons for HESS)

$$C = \frac{NBottom(>2Pes)}{PE_{Max}(Bottom)}$$

Energy Response

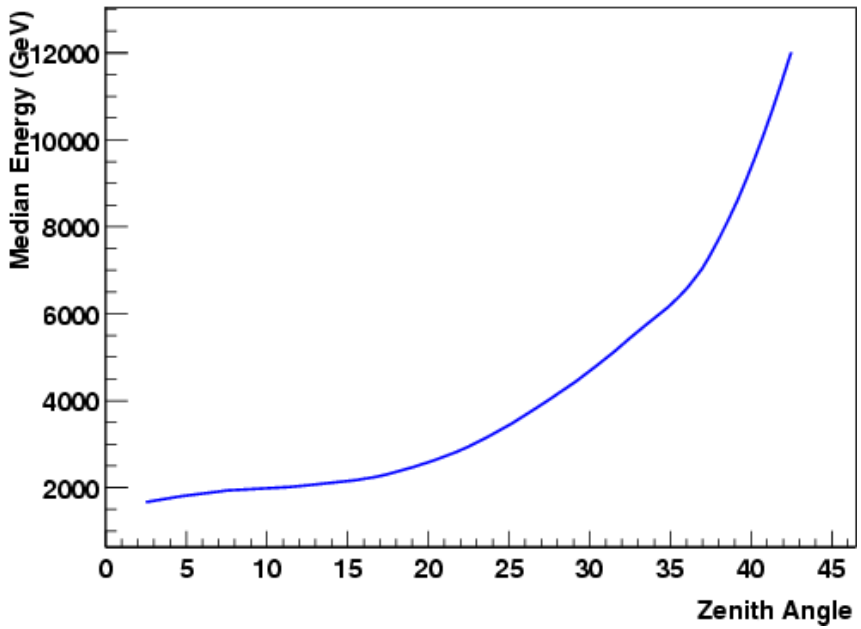


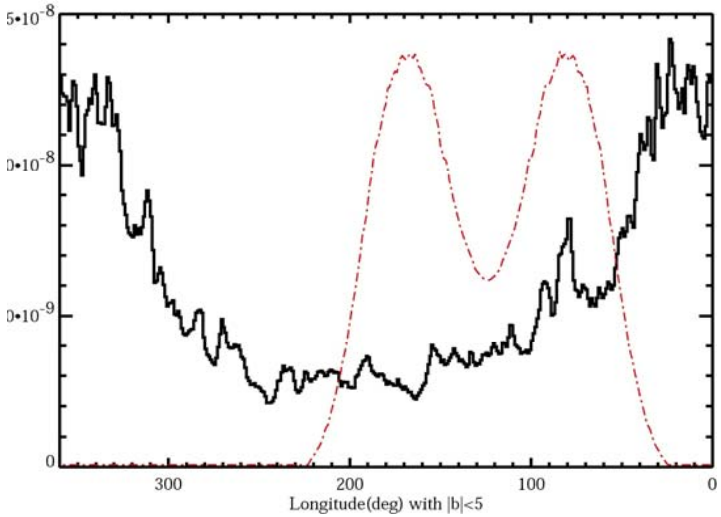


The effective area increases as ~E^2, flattening at high energies. Energy response is broad and not sharply peaked, it is not obvious how to define a threshold.

Field of view

- Energy threshold increases and sensitivity decreases with zenith angle.



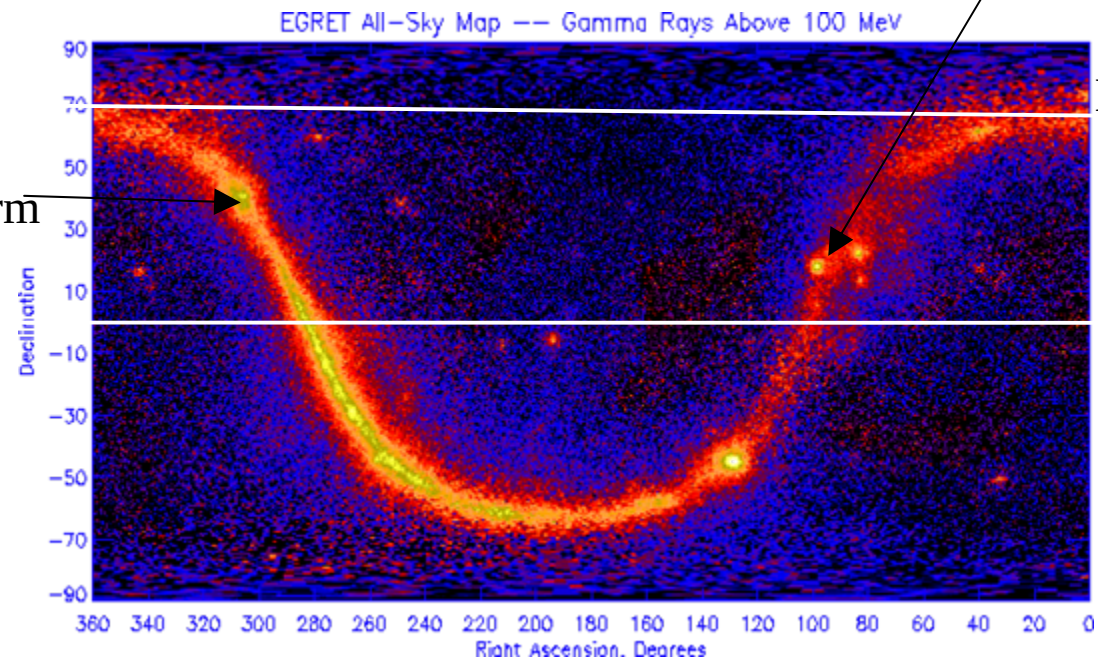


Milagro FoV

Crab

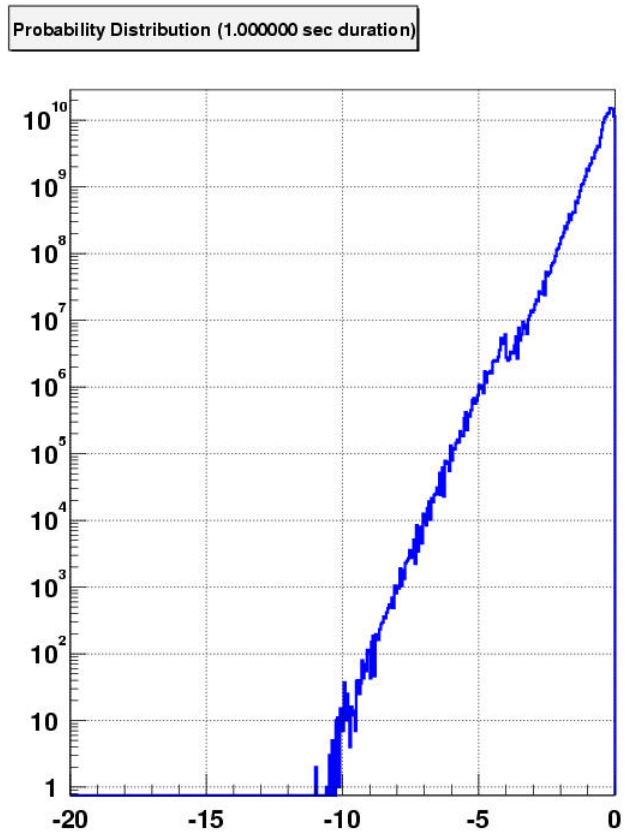
Milagro fov

Cygnus Arm



Operations

- 1500 - 2000 Hz Trigger rate, 5 Mb/s data rate.
- Remote operation.
- Calibrate and reconstruct the data online.
- Archive reconstructed events and a subset of the raw data.
- ~ Real time search for GRB on timescales of 1 ms to 2 hours. Produce and alert within few seconds of burst start.
- AGN flare search on timescales from 2 hours to 1 month.

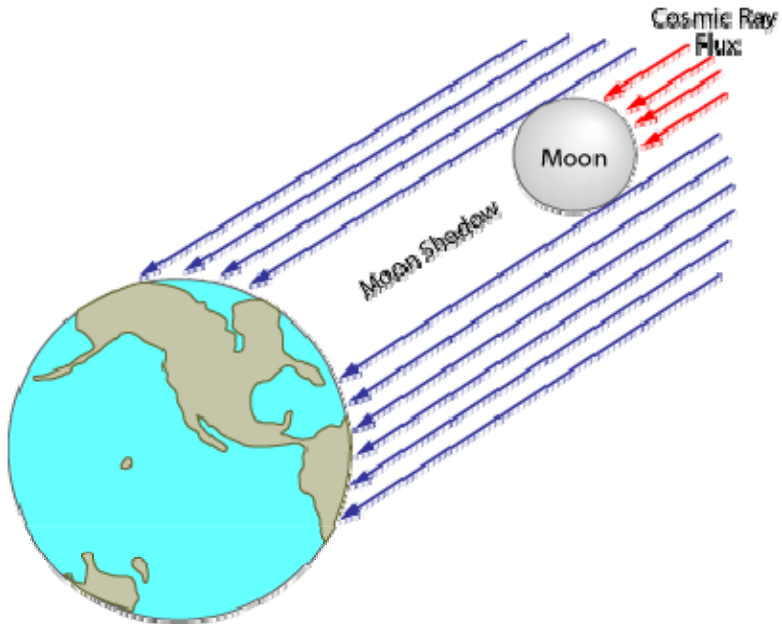


Moon Shadow

The moon is opaque to cosmic-rays and thus causes a deficit in cosmic-ray flux as observed on Earth.

The cosmic-rays are deflected by the Earths magnetic field so the shadow is shifted from the moon position.

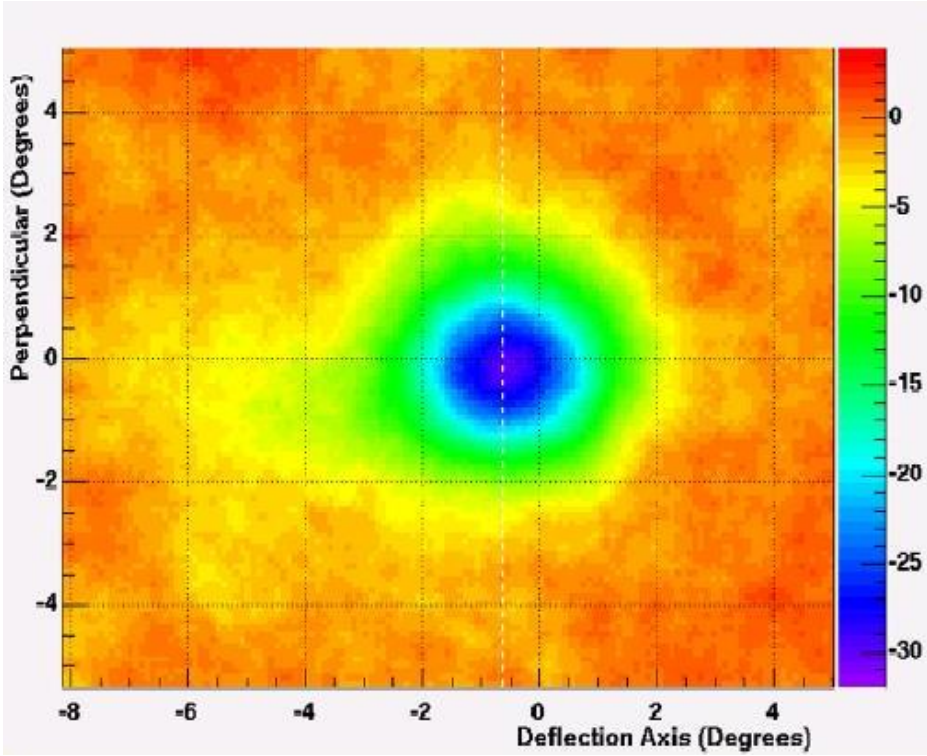
The magnitude of this shift is determined by the energy of the cosmic-rays. This can be used to verify our absolute energy scale.



Moon Shadow in Milagro

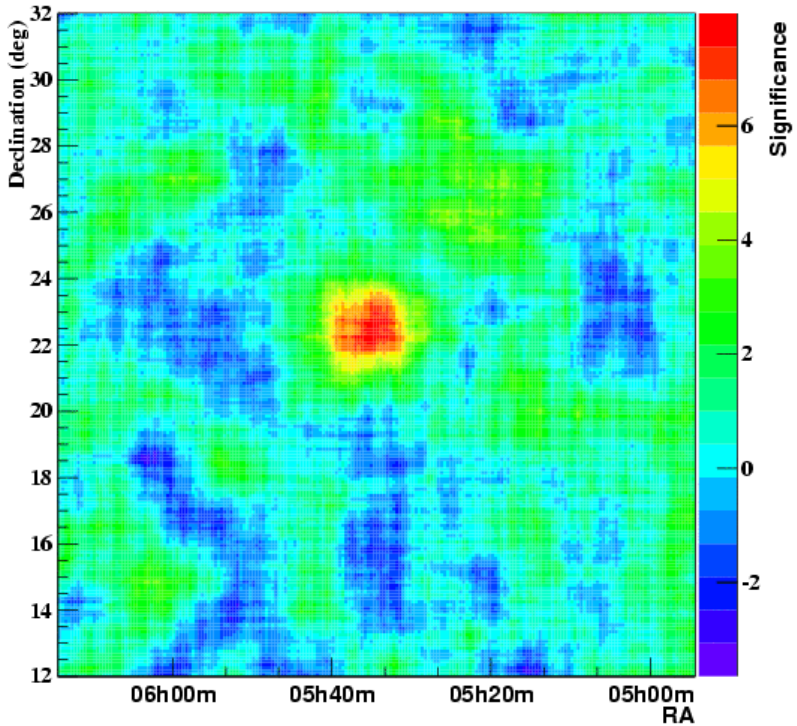
The shadow of the moon as observed by Milagro. The events have been rotated such that the x-axis is along the direction of magnetic deflection.

From the offset in the moon shadow we determine the median energy of proton triggers in Milagro to be 640±70 GeV, in agreement with MC simulations which predict a median energy of 690 GeV.

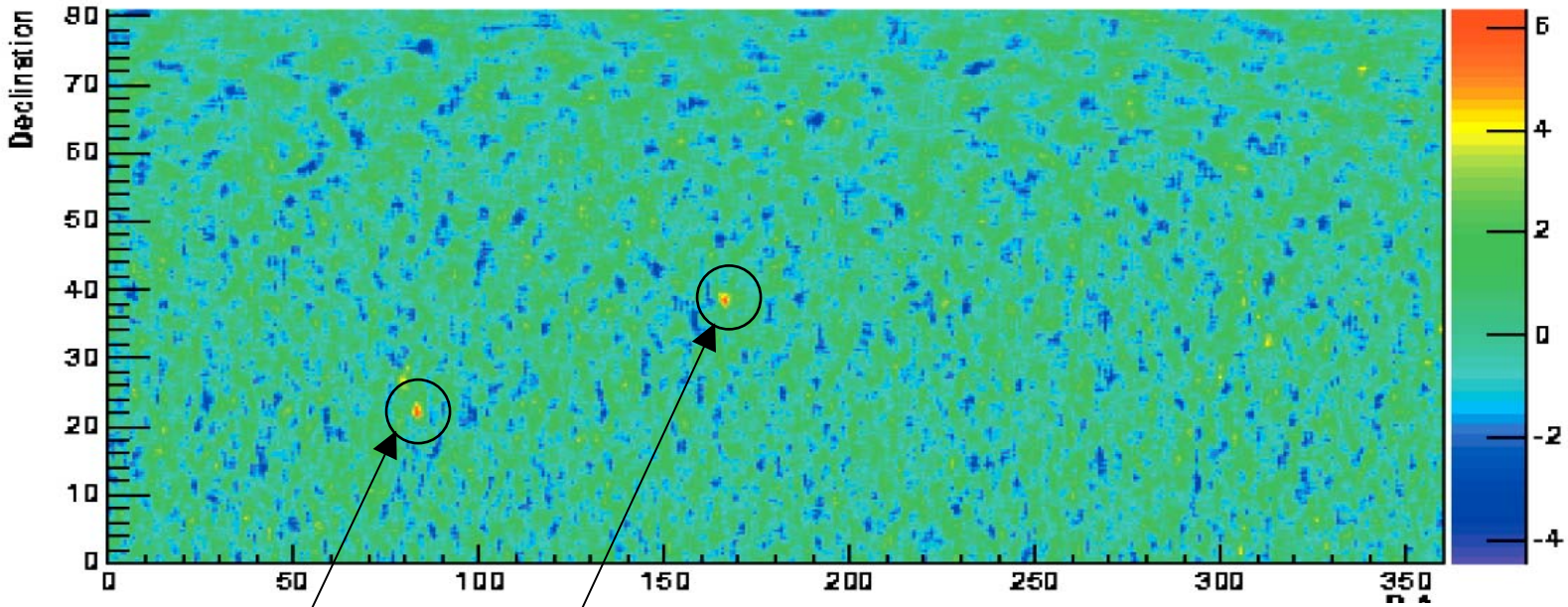


Crab Nebula

- Consistent with ACTs.
- Excess of 10 events/day (15,000 in total)



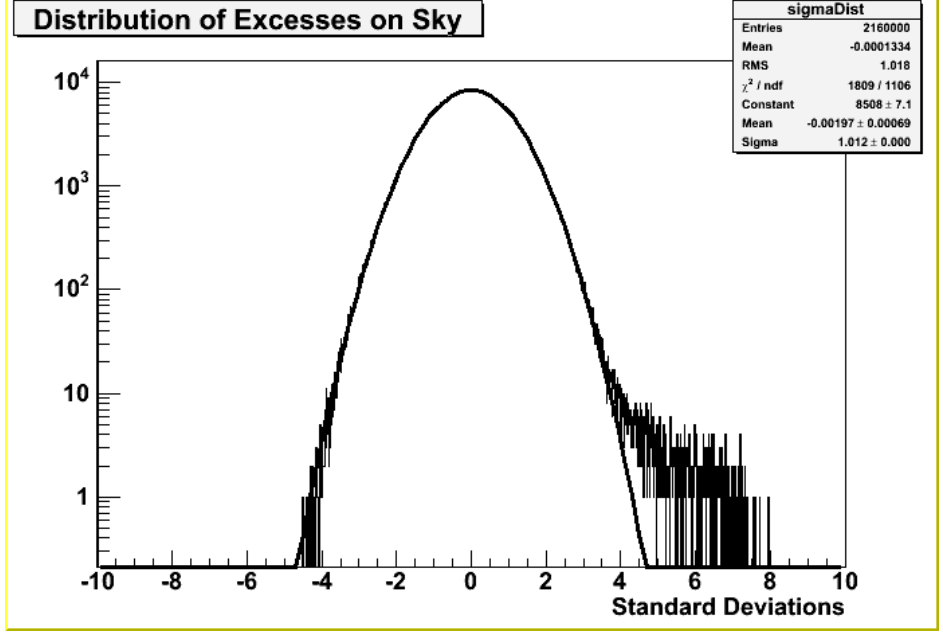
Sky Survey

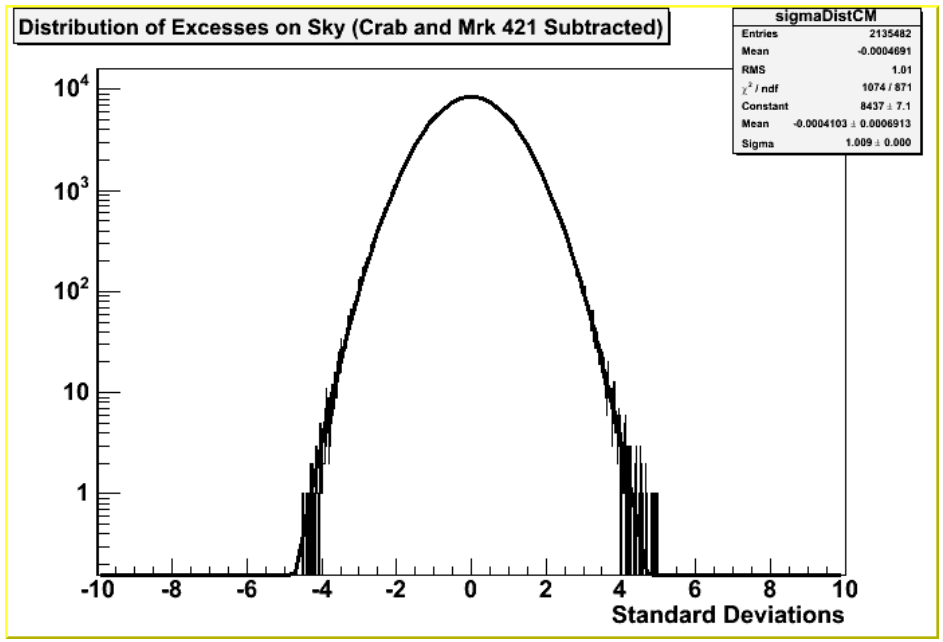


Sensitivity of ~0.5 crab.

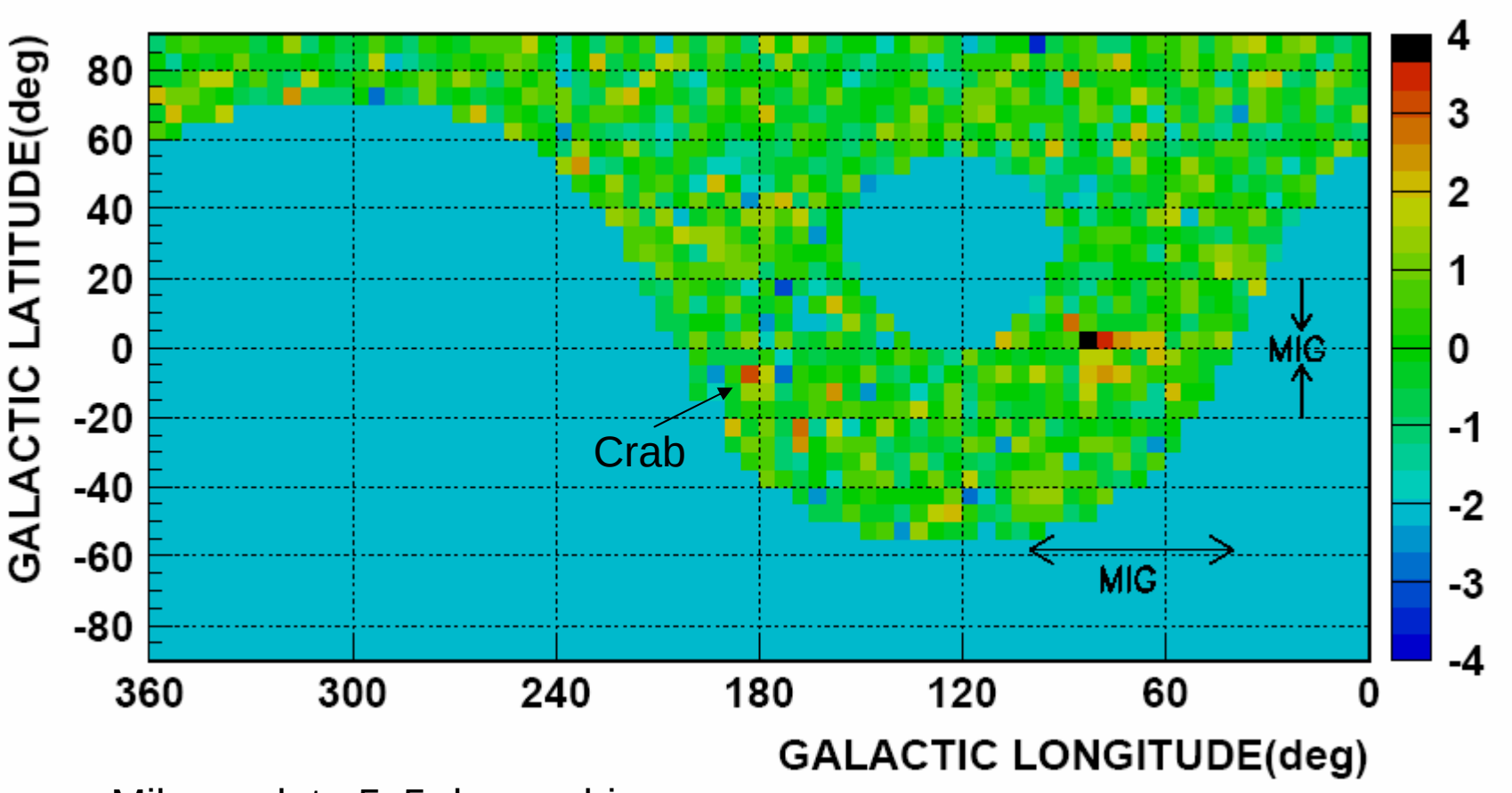
LOCATIONS OF ALL REGIONS WITH AN EXCESS GREATER THAN 4 σ

R.A.	Decl.	ON	OFF	Excess	σ	UL
0.3.....	34.3	3.12308e+06	3.11456e+06	8623	4.7	0.84
37.8.....	6.7	7.02166e+05	6.98667e+05	3498	4.0	1.8
43.6.....	4.8	5.85952e+05	5.82716e+05	3236	4.1	2.0
49.1.....	22.5	2.21431e+06	2.20813e+06	6175	4.0	0.87
79.9.....	26.8	2.57841e+06	2.57025e+06	8161	4.9	0.97
83.6[a].....	22.0	2.17188e+06	2.16222e+06	9665	6.3	NA
166.5[b].....	38.6	3.23552e+06	3.22467e+06	10850	5.8	NA
306.6.....	38.9	3.25329e+06	3.24531e+06	7983	4.2	0.78
313.0.....	32.2	3.08380e+06	3.07548e+06	8320	4.5	0.85
339.1.....	72.5	6.63534e+05	6.59727e+05	3807	4.2	3.02
356.4.....	29.5	2.98656e+06	2.97910e+06	7455	4.1	0.84


Distribution of Excesses on Sky
sigmaDist
Entries 2160000
Mean -0.0001334
RMS 1.018
χ² / ndf 1809 / 1106
Constant 8508 ± 7.1
Mean -0.00197 ± 0.00069
Sigma 1.012 ± 0.000
Standard Deviations

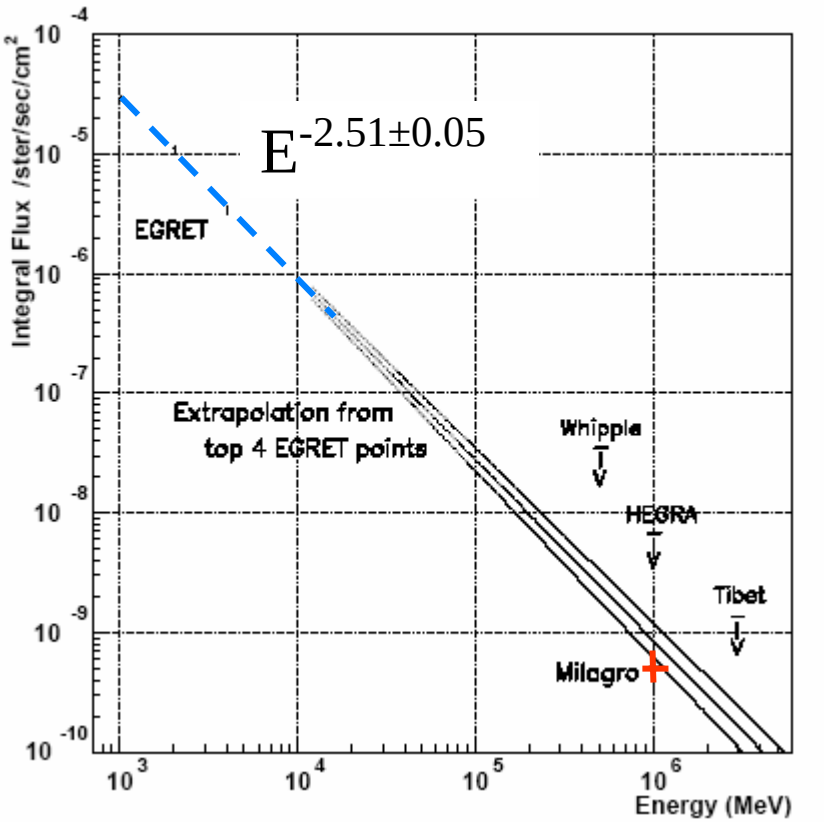

Distribution of Excesses on Sky (Crab and Mrk 421 Subtracted)
sigmaDistCM
Entries 2135482
Mean -0.0004691
RMS 1.01
χ² / ndf 1074 / 871
Constant 8437 ± 7.1
Mean -0.0004103 ± 0.0006913
Sigma 1.009 ± 0.000
Standard Deviations

Galactic Plane



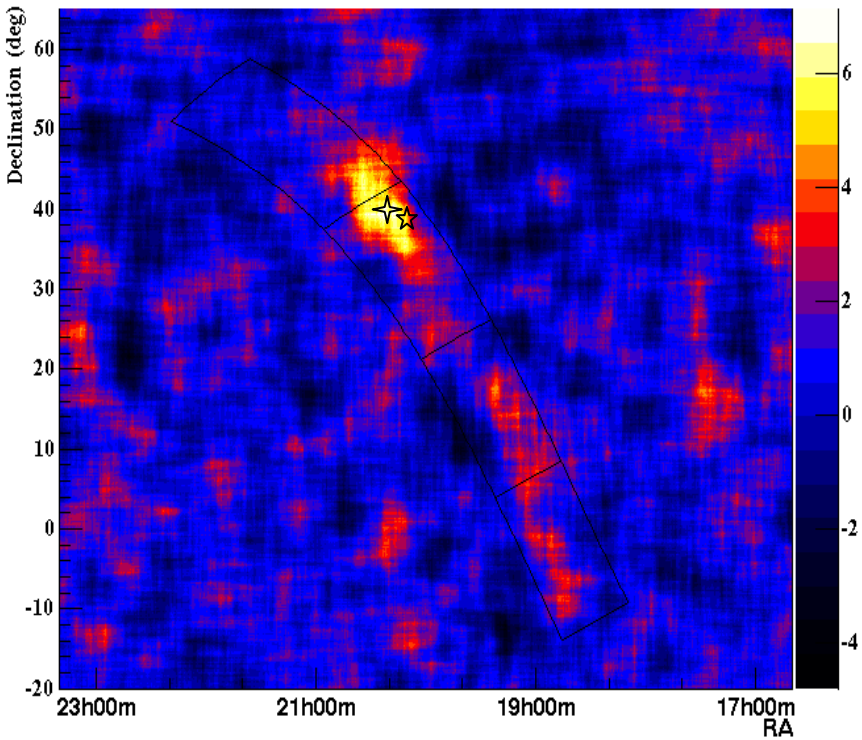
Milagro data 5x5 degree bins

Galactic Plane



- Demonstrates the strength of EAS in finding diffuse and extended sources
  - Due to good “inherent” background rejection
  - Angular resolution unimportant
  - Large observation time
  - Large field of view
- Milagro flux measurement is ~1/10 of previous upper limits

Extended Sources

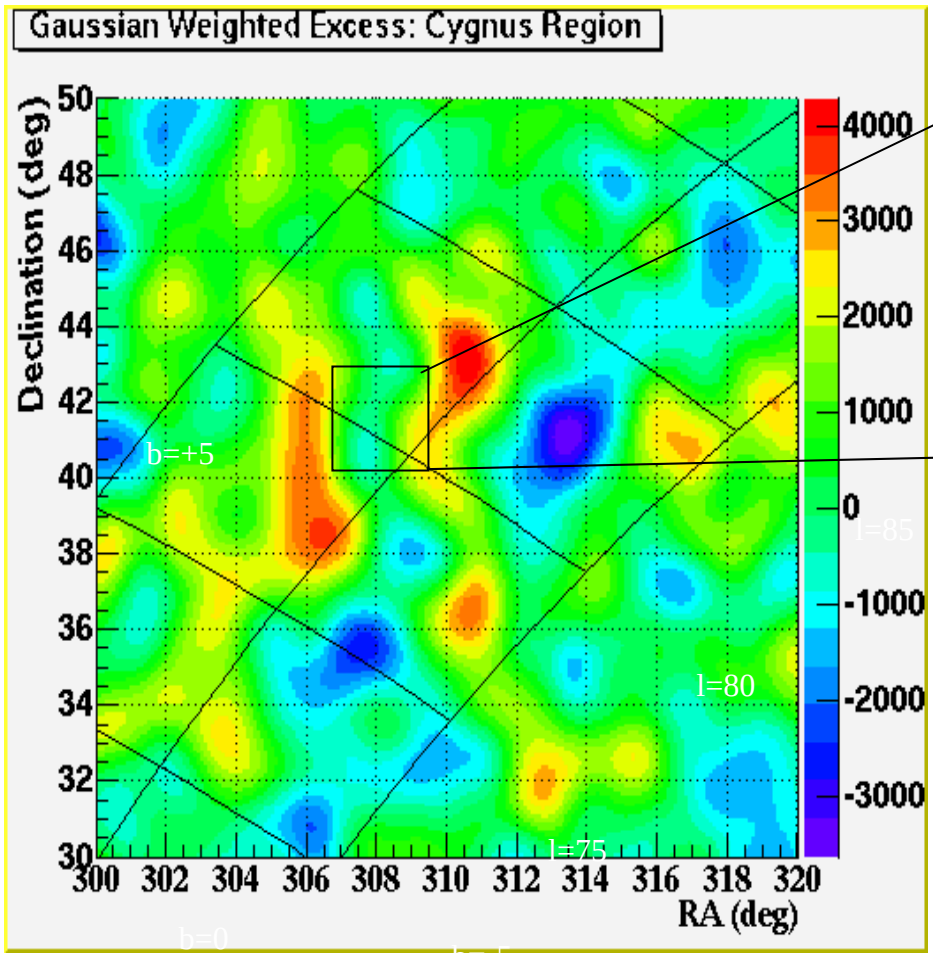


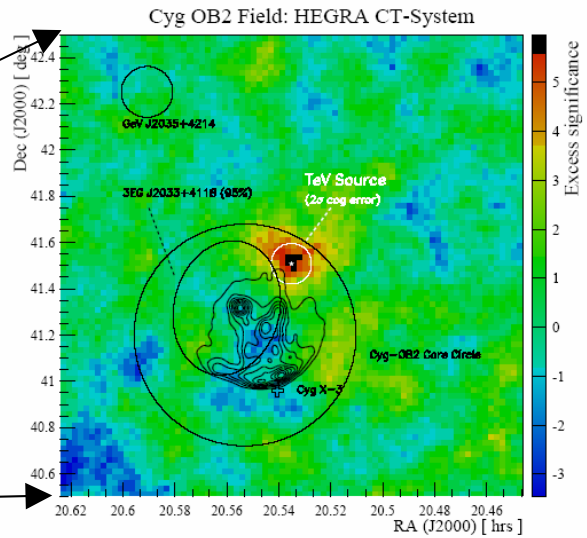
- ✧ Tibet hotspot
- ☆ Milagro point source hotspot

- Search northern sky for large sources
- ~6 degree source in Cygnus arm of Galaxy
  - EGRET observed as brightest region in Northern hemisphere
- 6.7 sigma excess
- Prob. of seeing an excess of this magnitude at any position in the sky and in any of the spatial scales considered in the search is 1 e-5 (determined by MC).
- Emission extends to 10 TeV and the flux is ~1.5 crab.

Cygnus Region and the HEGRA OB2 detection.

Cyg OB2 field

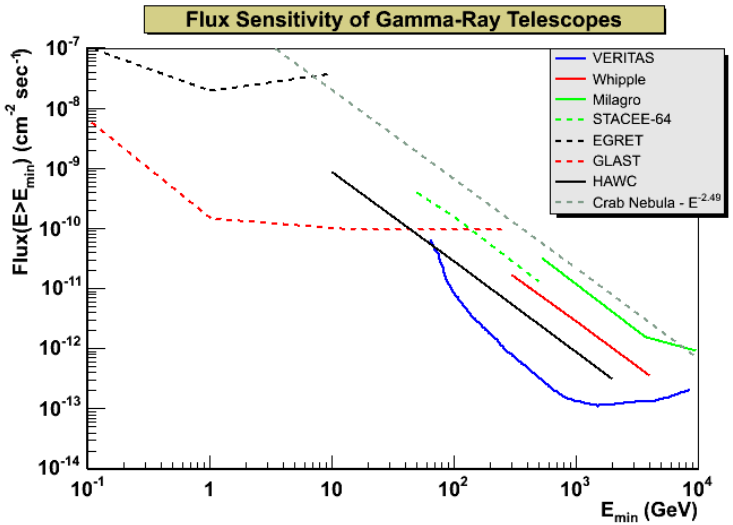




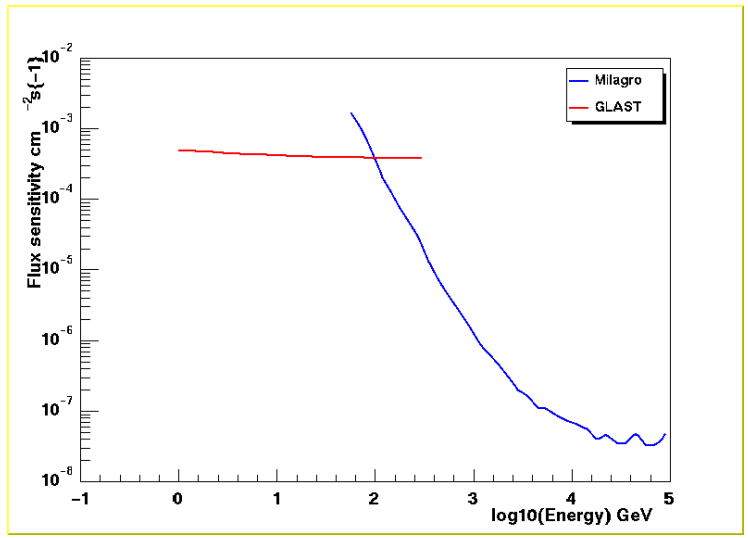
HEGRA bin size ~1000x Milagro bin size (.2x.2 vs 6x6).

Milagro observation should appear as a ~2mCrab floor shift.

Sensitivity to Transients



1 year integration



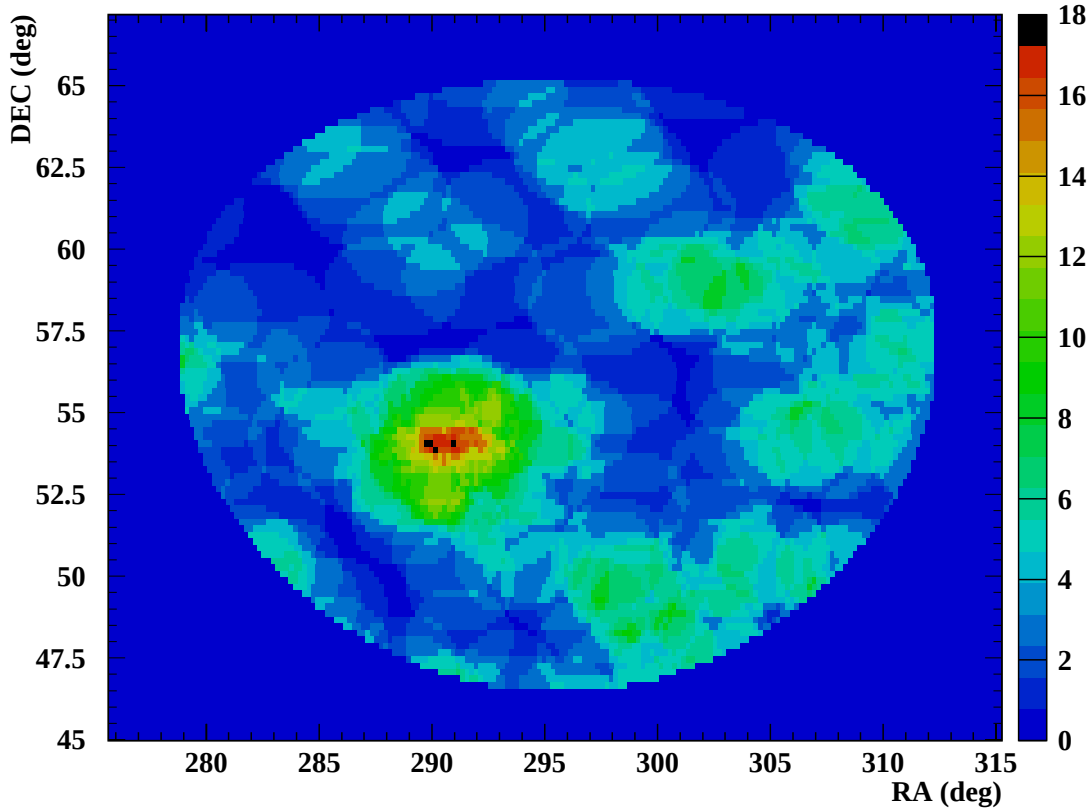
1 second observation

- For observations of rapid, transient events field of view is more important than sensitivity.

GRB 970417

Evidence for TeV emission from a GRB was seen by Milagrito (a smaller prototype of Milagro). The excess was coincident in space and time with the prompt emission seen by BATSE.

Implies that the emission extended up to at least 650 GeV, the highest energy photons ever observed from a GRB

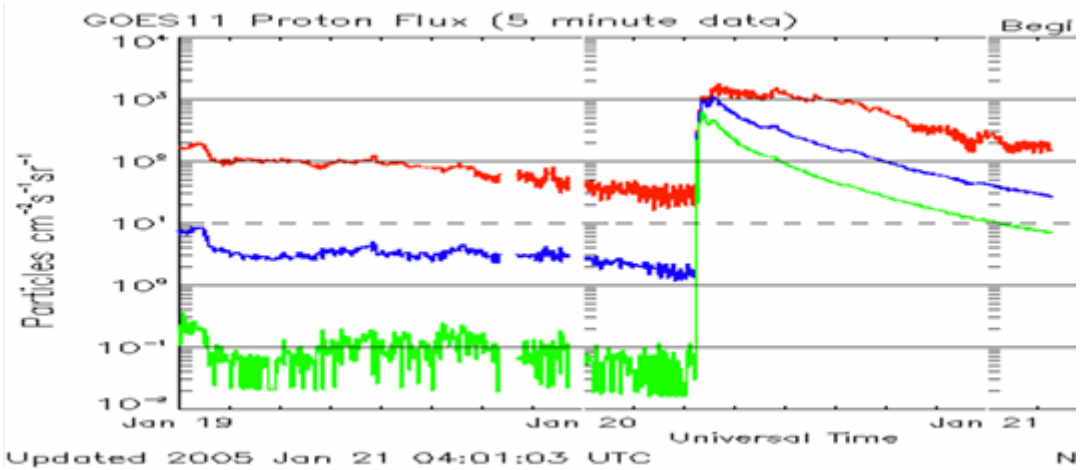


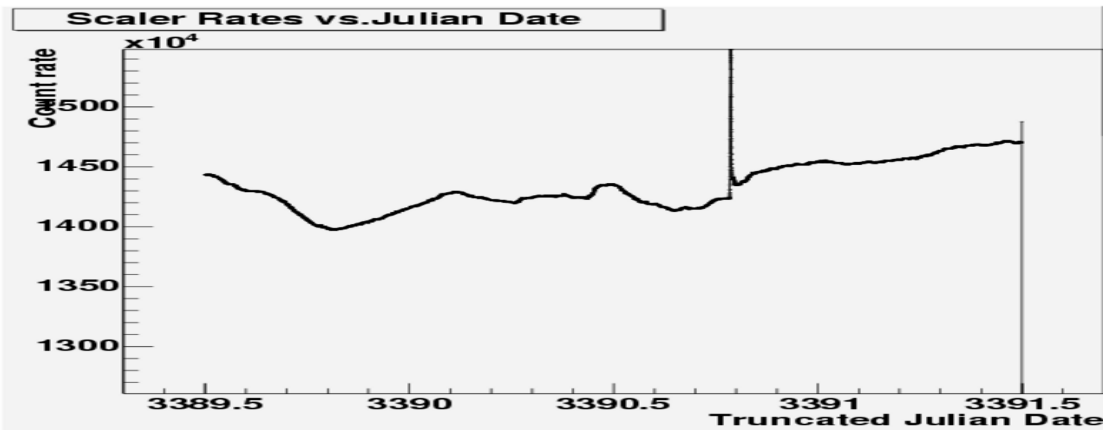
18 events observed with an expected background of 3.46 -> Poisson prob 2.9e-8

Prob after correcting for size of search region is 2.8e-5.

Chance prob of seeing such an excess from any of the 54 GRB in Milagrito is 54*2.8e-5 = 1.5e-3

X7-Class flare Jan. 20, 2005





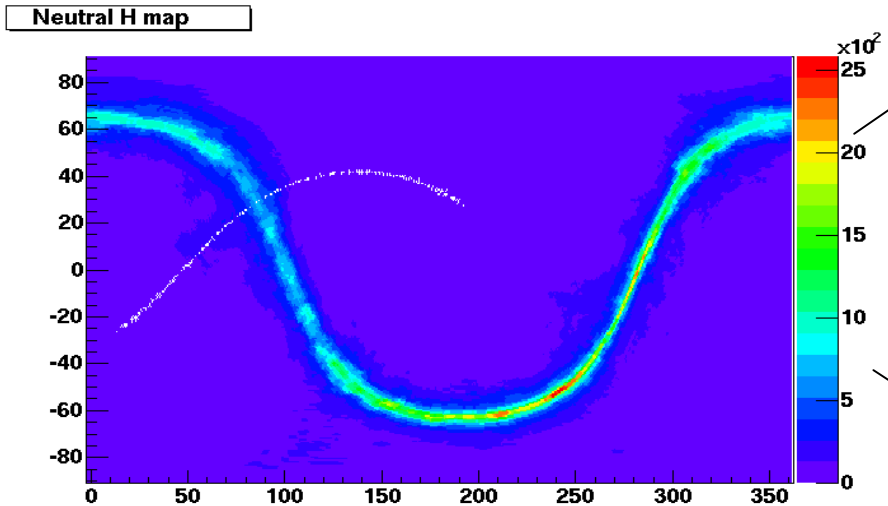
- GOES proton data
  - >10 MeV
  - >50 MeV
  - >100 MeV

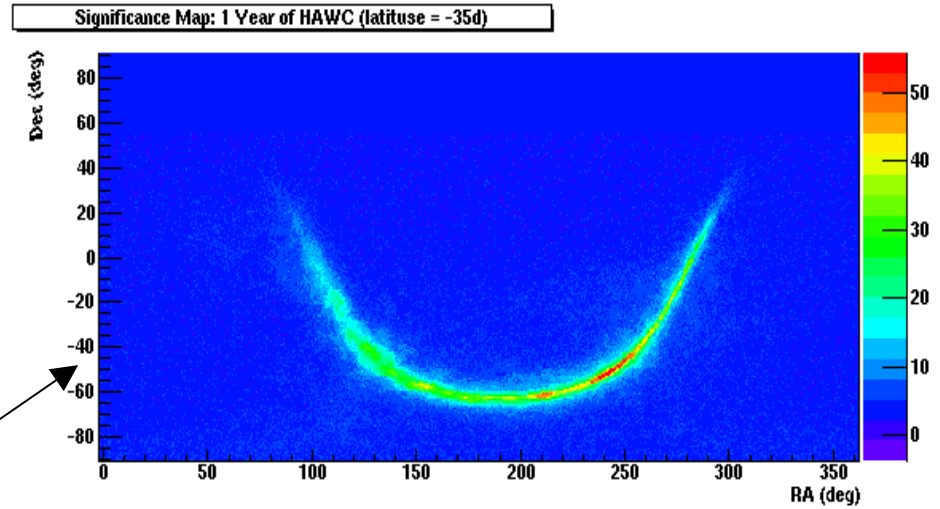
- Milagro scaler data
  - > 10 GeV protons
  - ~1 min rise-time
  - ~5 min duration

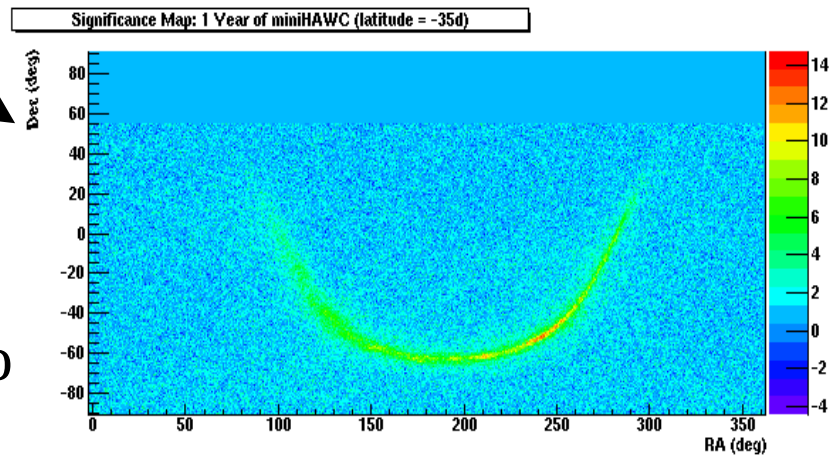
Conclusions

- EAS Arrays have achieved sufficient sensitivity to detect the brightest TeV sources
- At the level of 0.5 Crab there are only 2 known sources in the northern hemisphere
- EAS arrays excel at detecting extended sources
  - Diffuse γ-ray emission from the Galactic plane
  - Large source in Cygnus region
  - Possible source coincident with EGRET unidentified object
- Solar physics results to study particle acceleration in well known environment
- Still no solid evidence of VHE emission from GRBs
- We are still understanding the performance of EAS arrays
  - large improvements seem feasible.

The Diffuse Galactic Plane in miniHAWC and HAWC



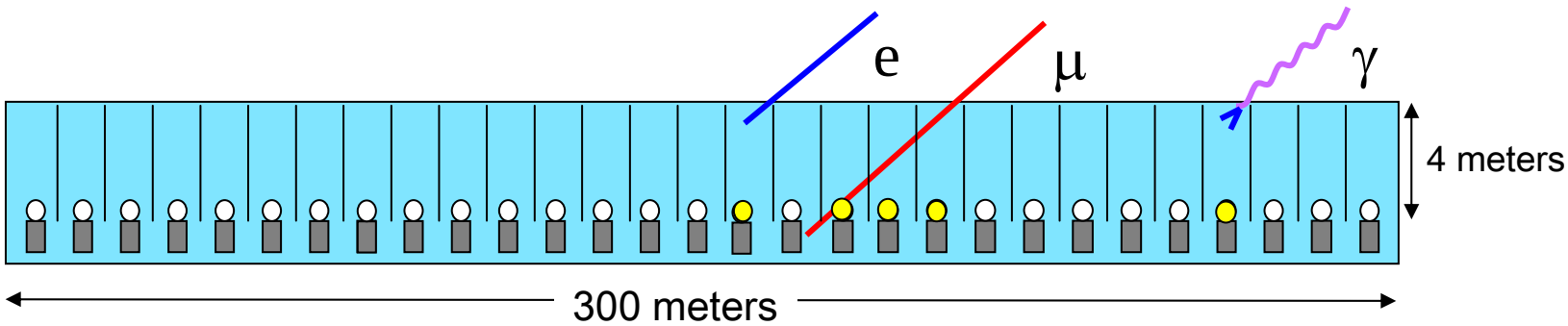




Use Neutral H map to trace out VHE Gamma-Ray flux. Normalize to Milagro observed TeV diffuse Galactic plane.

Farther Future:HAWC

- Build pond at extreme altitude (Tibet 4300m or Chile 5200m)
- Incorporate new design
  - Optical isolation between PMTs
  - Larger PMT spacing
  - Deeper PMT depth (in top layer)



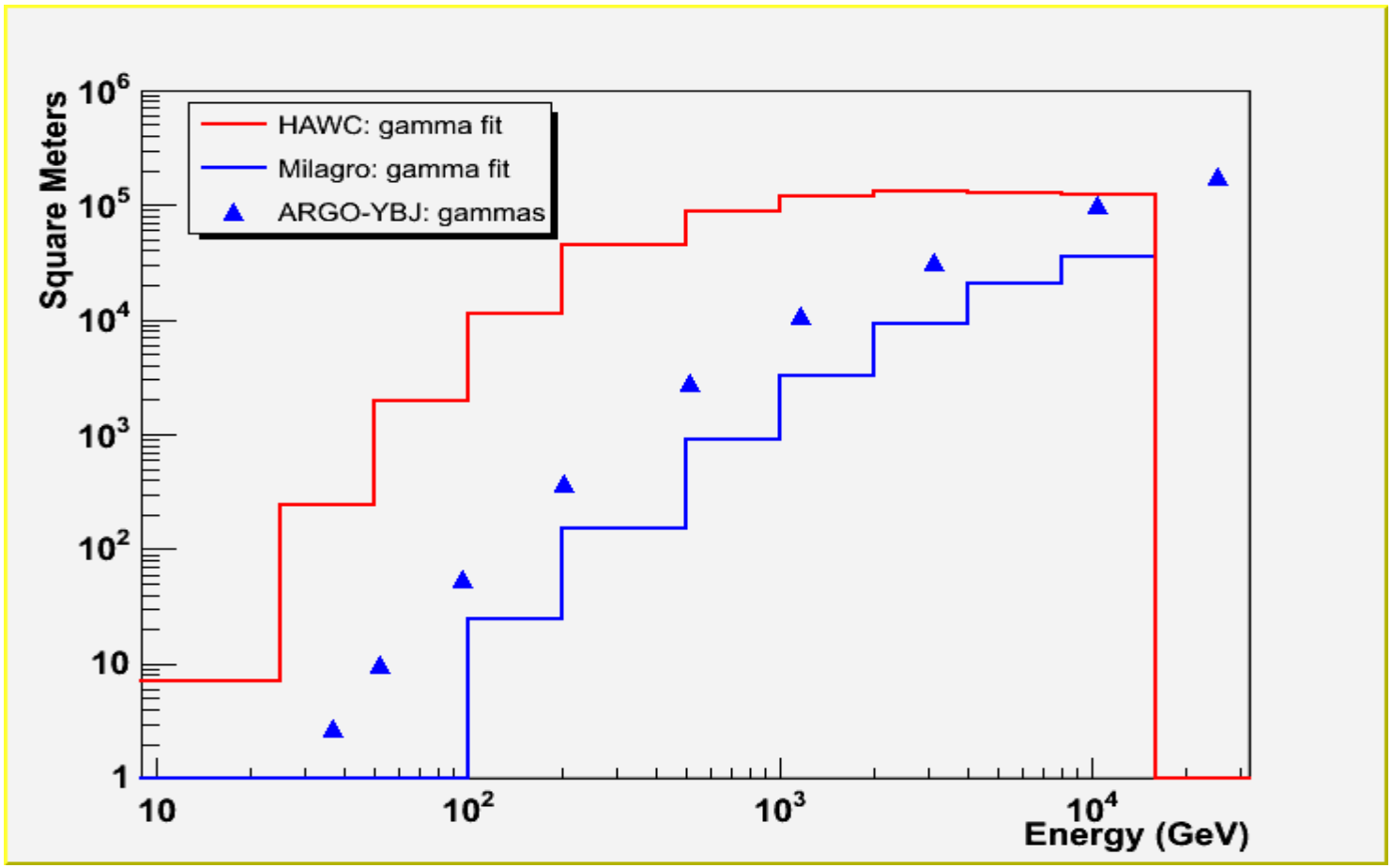
~$20M for complete detector

~60x sensitivity of Milagro – instantaneous sensitivity of Whipple over 2 sr

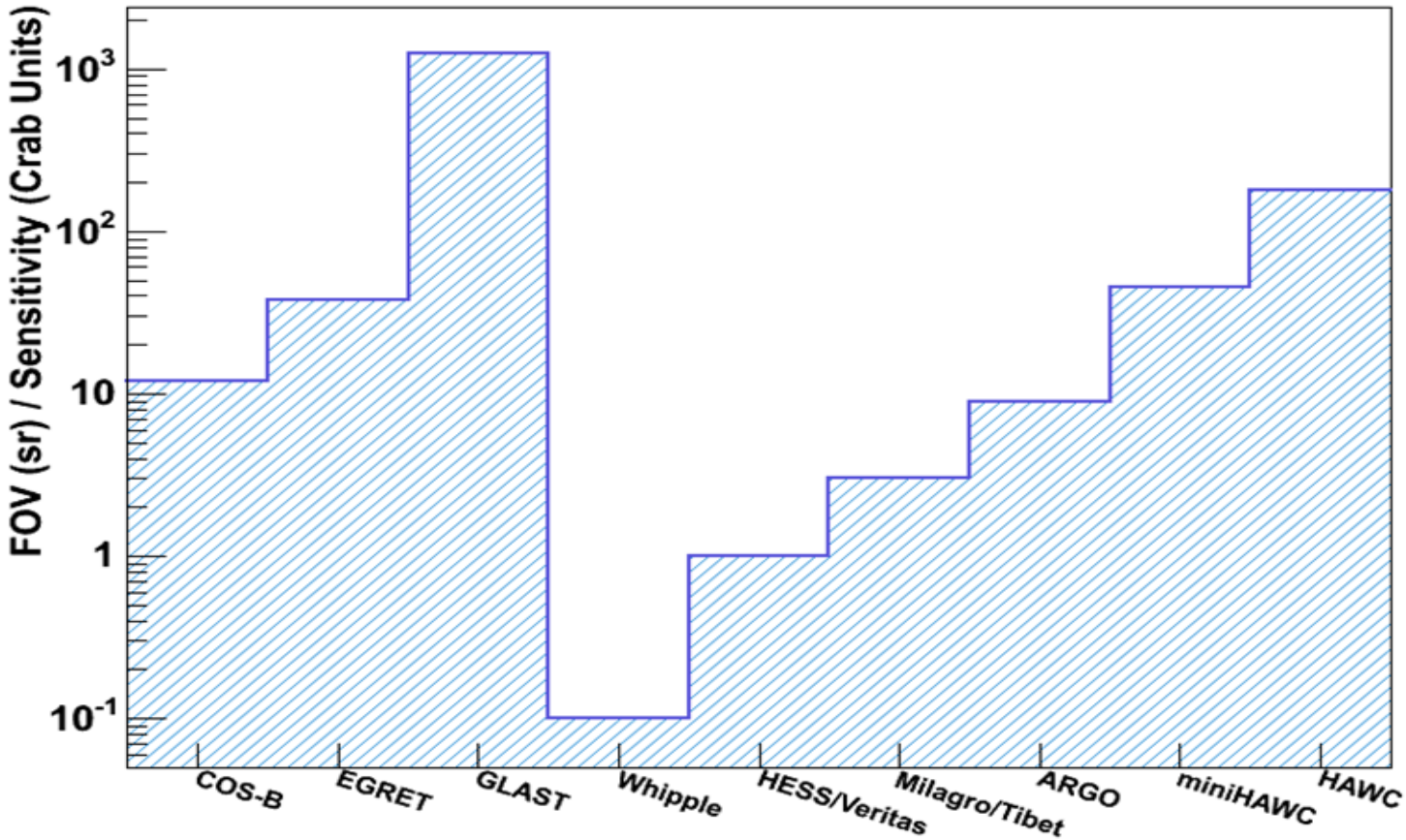
Crab Nebula in 30 minutes (now 1 year)

GRBs to redshift of >1 (now 0.4)

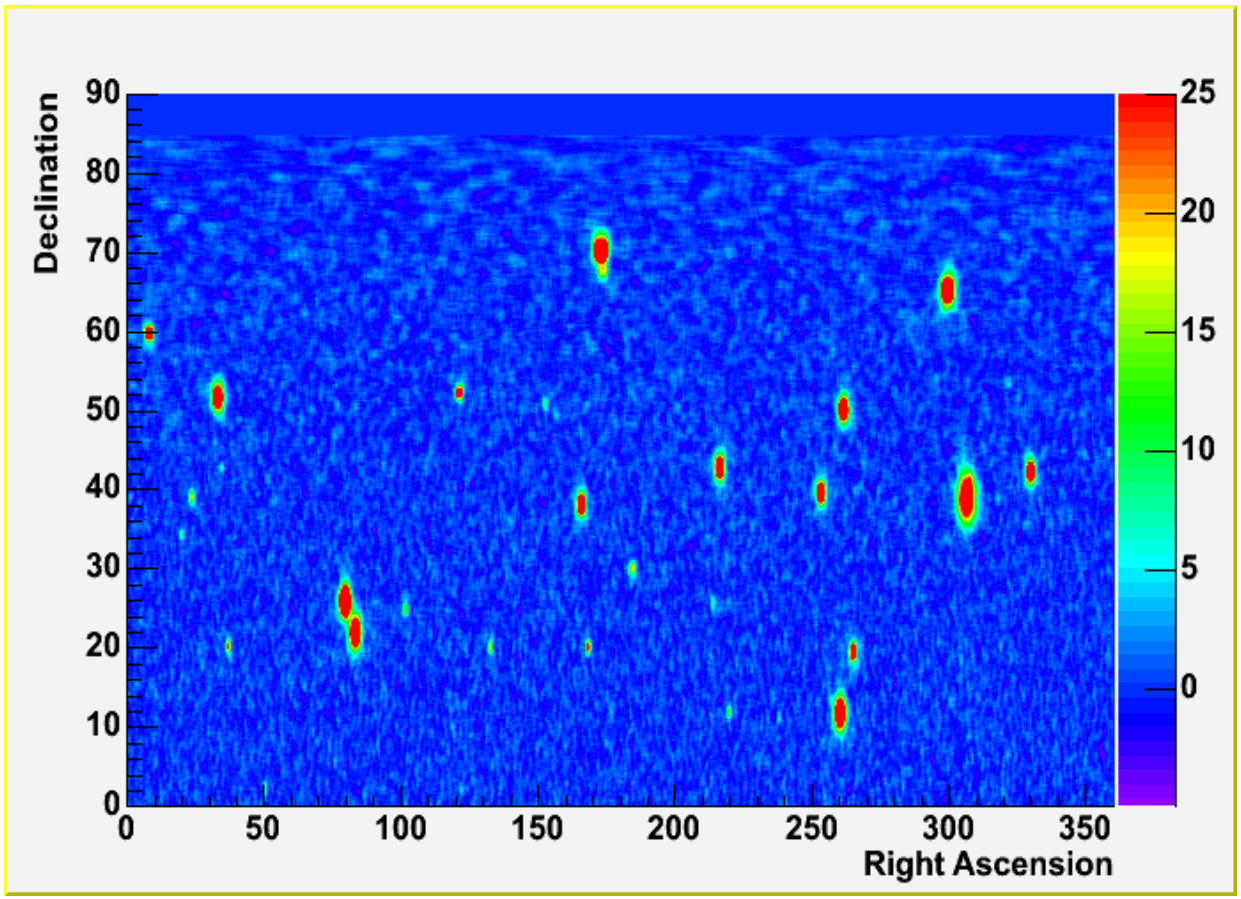
Effective Areas: Future Detectors



Survey Sensitivity



HAWC: Simulated Sky Map



- C&G AGN
- Hartmann IR model
- known TeV sources
- Milagro extended sources
- 1-year observation