Surveying the TeV Sky with Milagro

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University of Maryland
For the Milagro Collaboration

Outline

- Description of Milagro
- Background rejection technique
- TeV survey for point sources
- Detection of the galactic plane
- TeV survey for extended sources
- TeV emission from GRBs
- Future detector based on Milagro

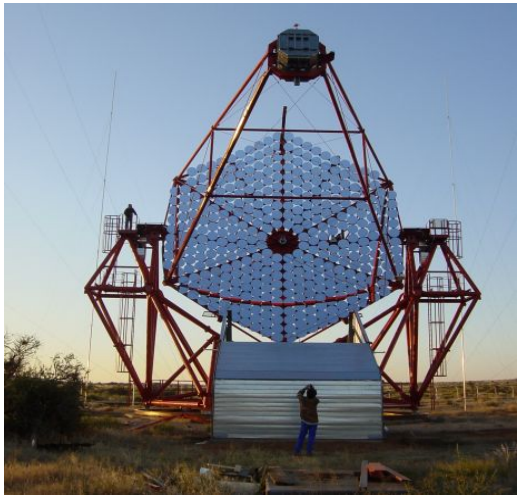
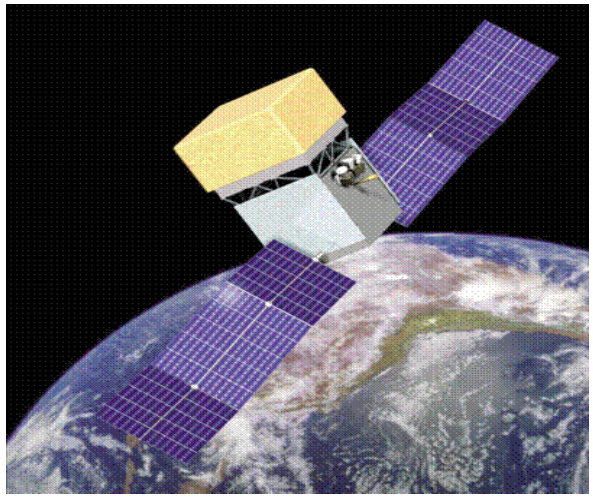
Current Milagro Collaboration -7/05

- Los Alamos – S. Casanova, B. Dingus, G. Sinnis, G. Walker
- Maryland – D. Berley, R. Ellsworth+, J. Goodman, C. Lansdell, J. McEnery*, D. Noyes, A. Smith, V. Vasileiou
- U.C. Santa Cruz – D. Coyne, P. Saz Parkinson, D. Williams, L. Yang
- U.C. Irvine – B. Allen, T. Shoup, G. Yodh
- NYU – B. Kolterman, A. Mincer, P. Nemethy
- Michigan State – A. Abdo, J. Linnemann
- U. New Hampshire – J. Ryan

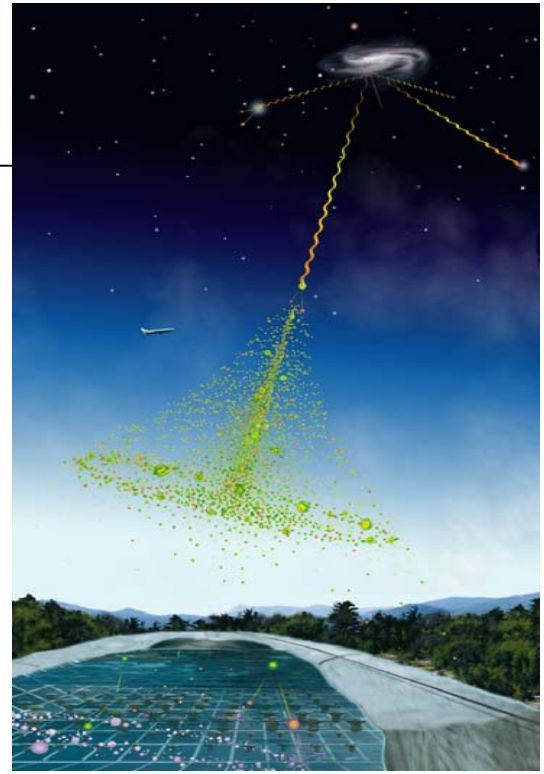
*at GSFC, +at George Mason University

10 (2) Faculty (Retired), 6 Students, 3 Research Scientists, 4 Post-docs

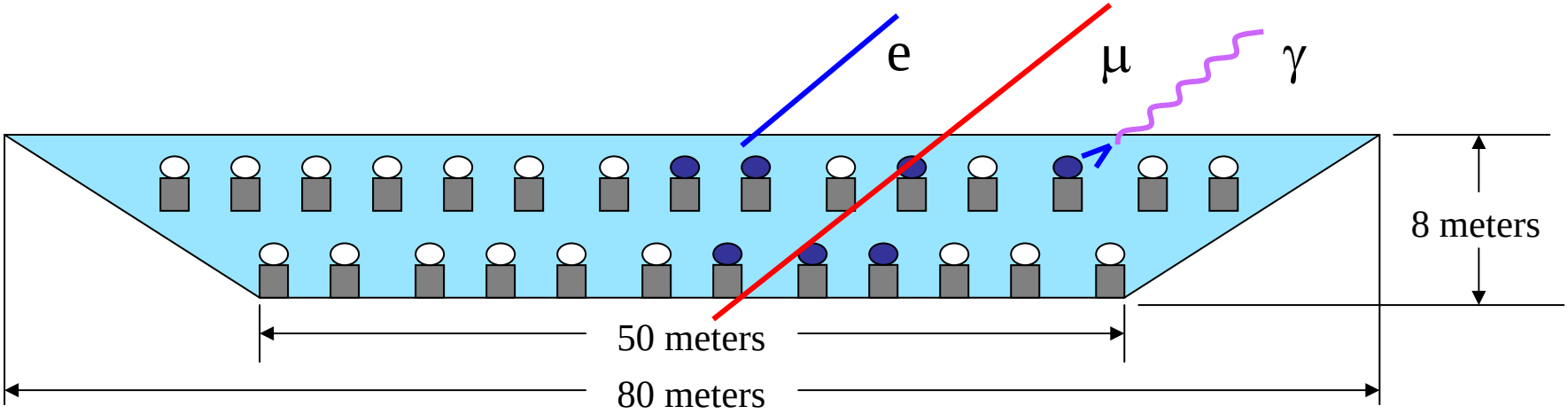
Detectors in Gamma-Ray Astrophysics

High Sensitivity HESS, MAGIC, CANGAROO, VERITAS	Low Energy Threshold EGRET/GLAST	Large Aperture/High Duty Cycle Milagro, Tibet, ARGO, HAWC?
		
Large Effective Area Excellent Background Rejection (>99%) Low Duty Cycle/Small Aperture	Space-based (small area) “Background Free” Large Duty Cycle/Large Aperture	Moderate Area/Large Area (HAWC) Good Background Rejection Large Duty Cycle/Large Aperture
High Resolution Energy Spectra Studies of known sources Surveys of limited regions of sky Point source sensitivity	Sky Survey (<10 GeV) AGN Physics Transients (GRBs) <100 GeV	Unbiased Sky Survey Extended sources Solar physics/space weather Transients (GRBs, AGNs)

How Does Milagro Work?

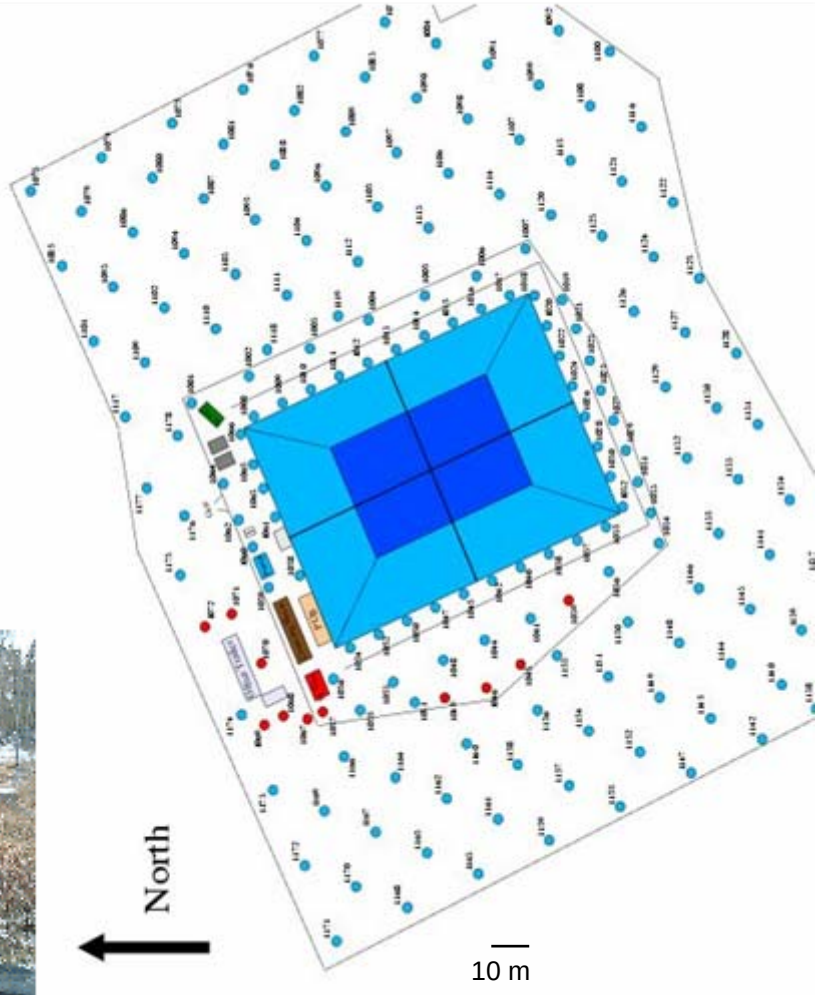


- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 6m pond containing filtered water
- Reconstruct shower direction to ~0.5˚ from the time different PMTs are hit
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Field of view is ~2 sr and the average duty factor is >90%



The Milagro Detector

- 2630m asl
- Water Cherenkov Detector
- 898 detectors
  - 450(t)/273(b) in pond
  - 175 water tanks
- 3.4×10^4 m^2 (phys. area)
- 1700 Hz trigger rate
- ~0.5˚ resolution
- > 90% proton rejection



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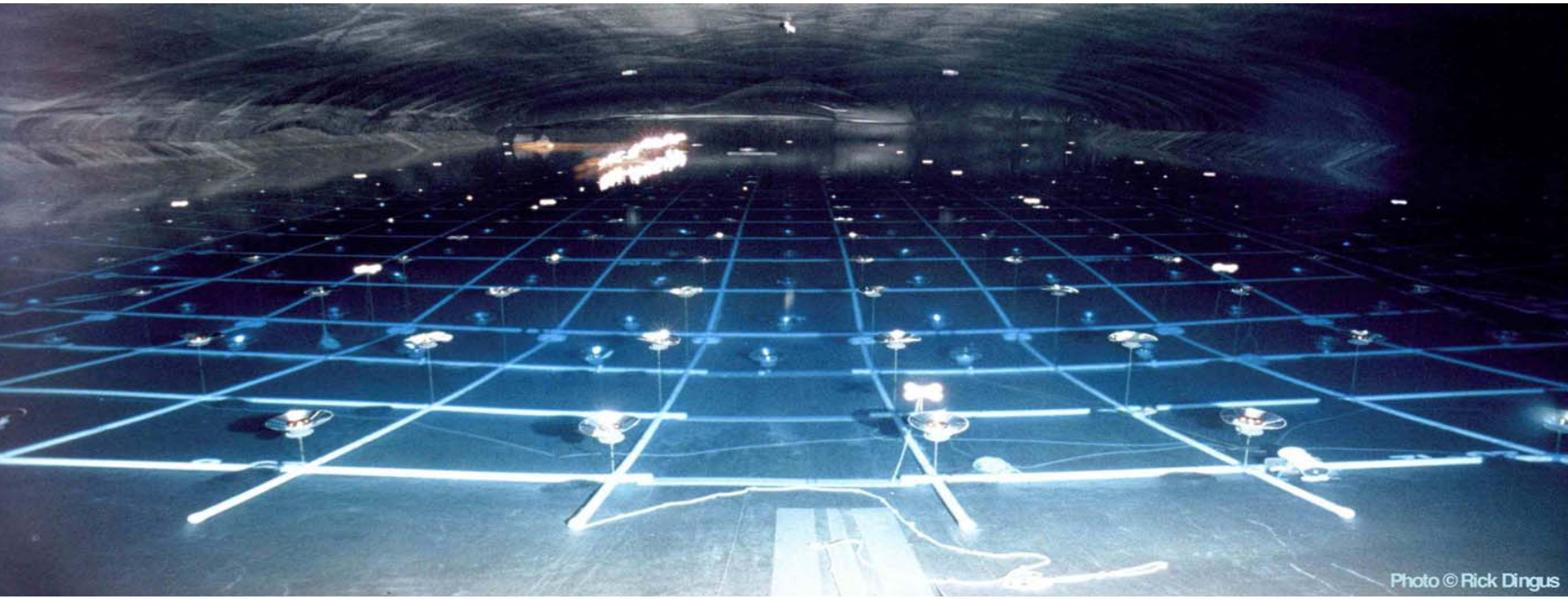
Under the Cover

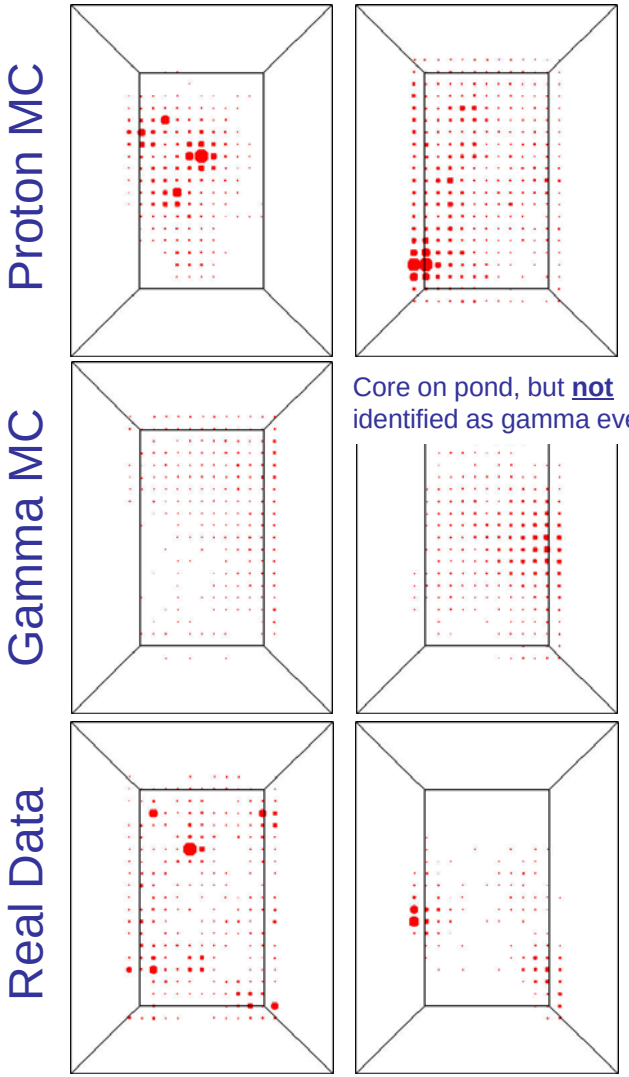


Timeline/Operation

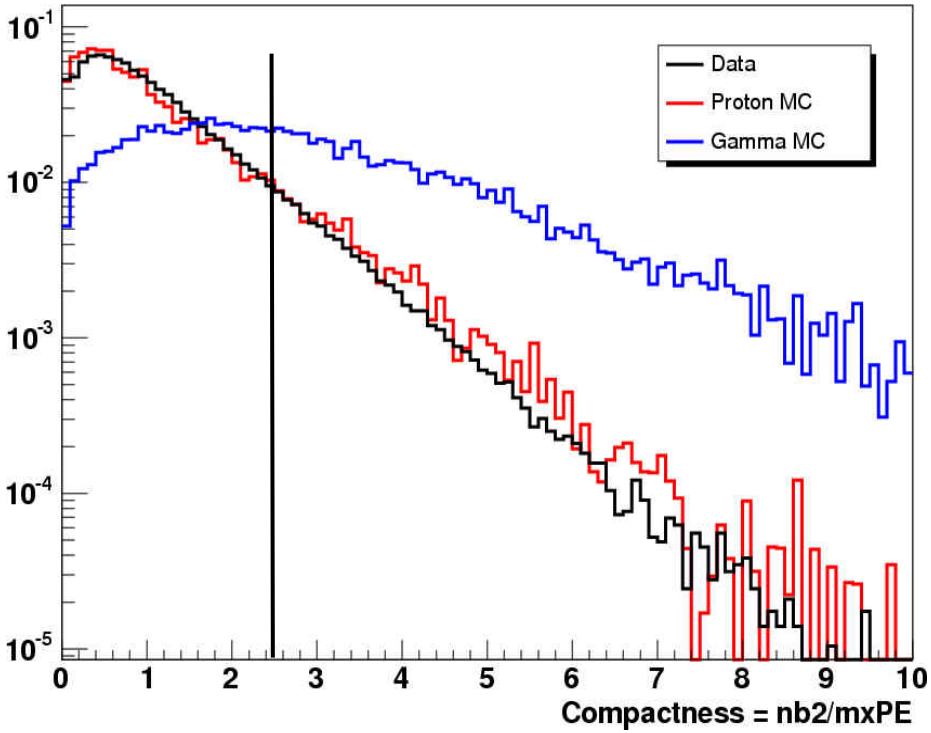
Fall 1999	- Installed PMTs
Summer 2000	- Began data taking, first “usable data”
January 2001	- Science data begins
Summer 2002	- Installed threshold lowering GRB trigger
	- Began construction of outrigger array
Spring 2003	- Completed outrigger array
Summer 2004	- Completed calibration system for outrigger array

- 6 MB/s DC data rate → ~100 TB of raw data/yr
- Use online reconstruction for sky surveys

γ/h Separation



Core on pond, but **not** identified as gamma event



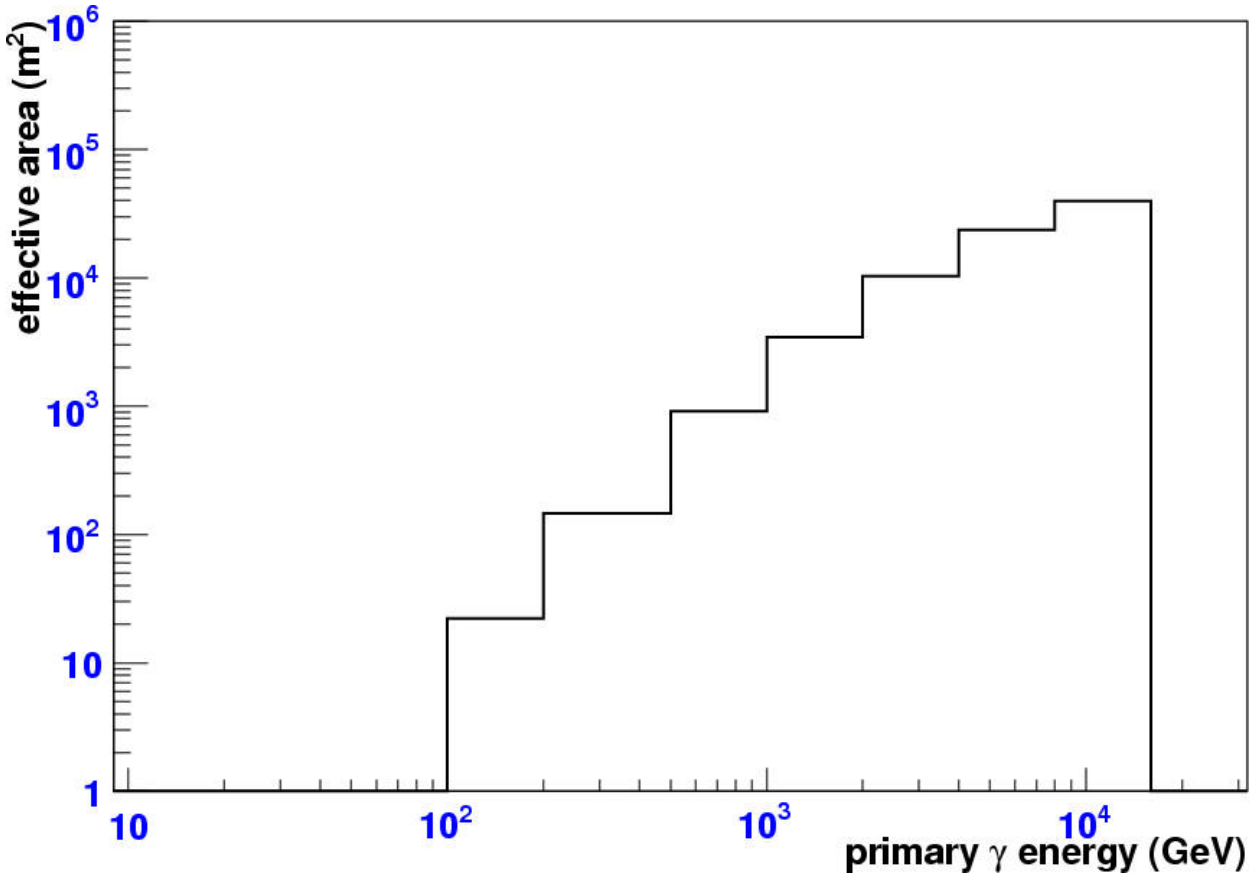
$$C = \frac{NBottom(>2PEs)}{PE_{\max}(Bottom)}$$

Retains 50% γs and 9% protons,

$$Q = \varepsilon_\gamma / \sqrt{\varepsilon_h} = 1.6$$

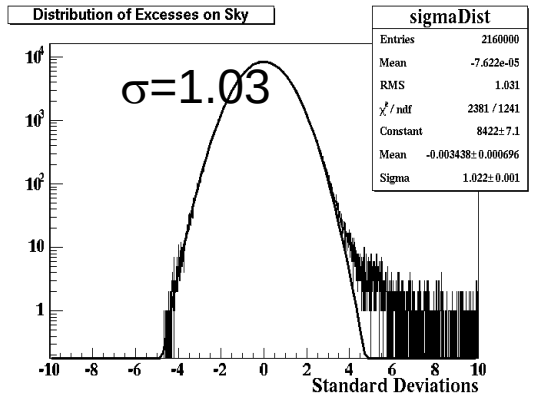
Effective Area

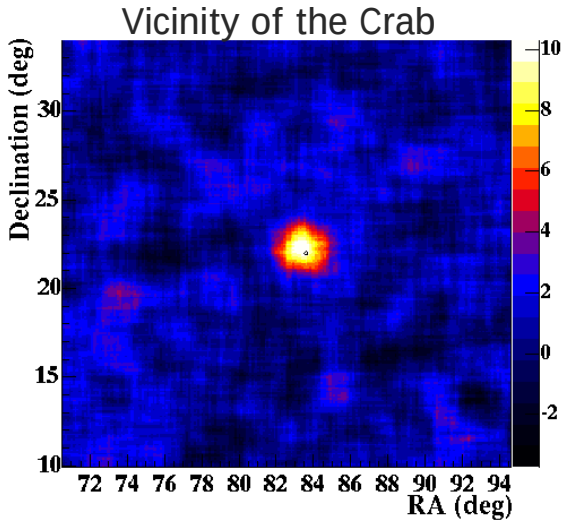
Median γ-ray energy assuming Crab spectrum is 3 TeV.

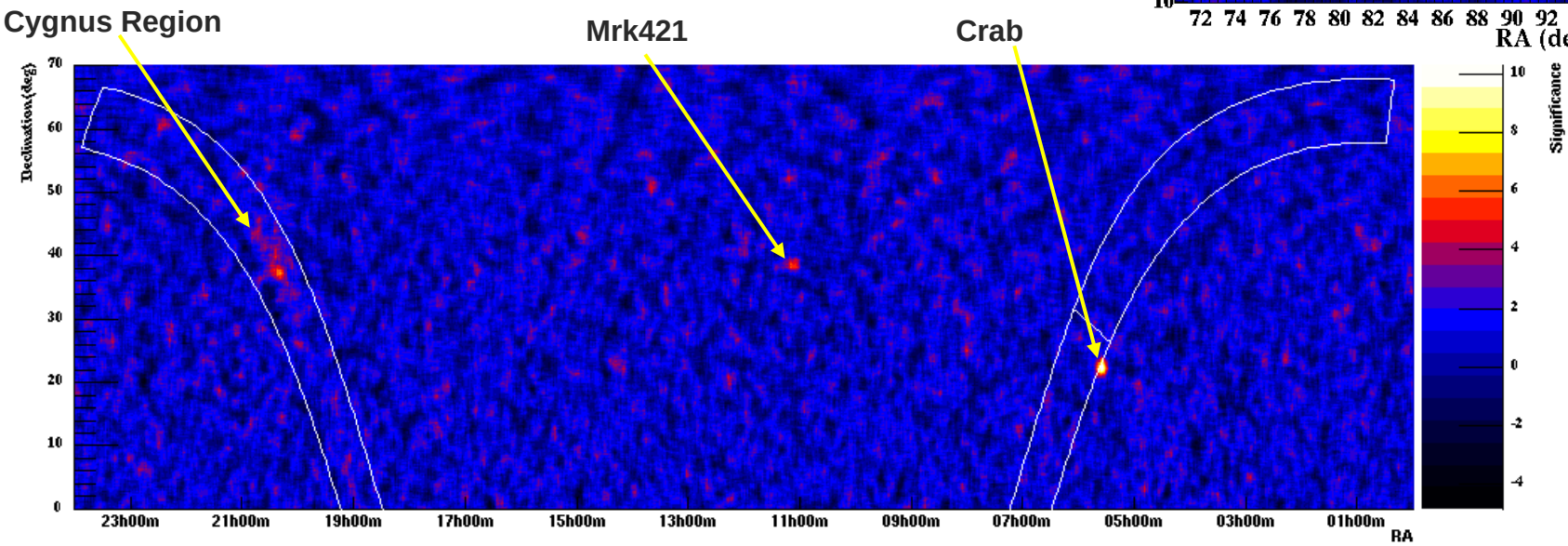


Point Source Search

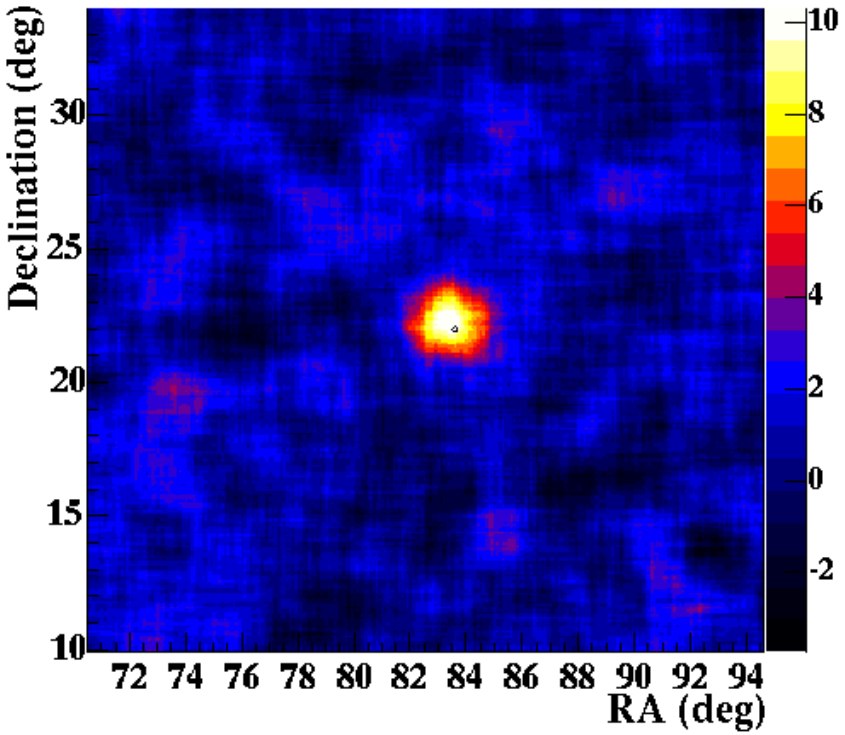
Bin Size = 2.1°
4.5 years of data
Crab significance 10.0σ
Mrk421 significance 5.4σ
Point in Cygnus Region at 5.9σ

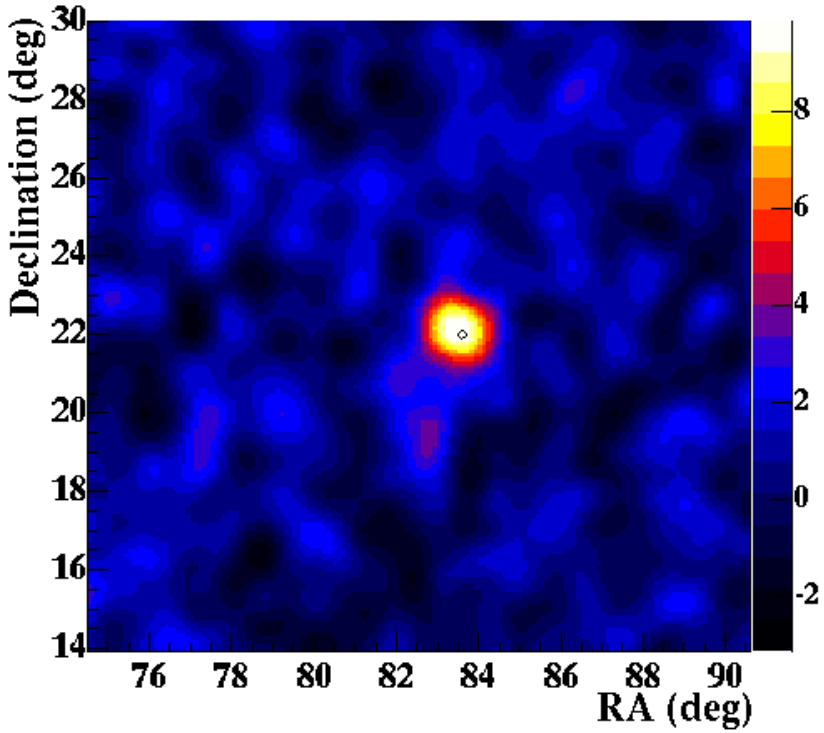






Sensitivity of Milagro to VHE Point Sources





Pre-Outrigger – data since 2000

- Optimized with MC simulations
- Published detection of the Crab (**ApJ** 595, **803** (2003))
- Sensitivity: ~4.7σ/yr on the Crab
- **10.0σ in 4.5 years**

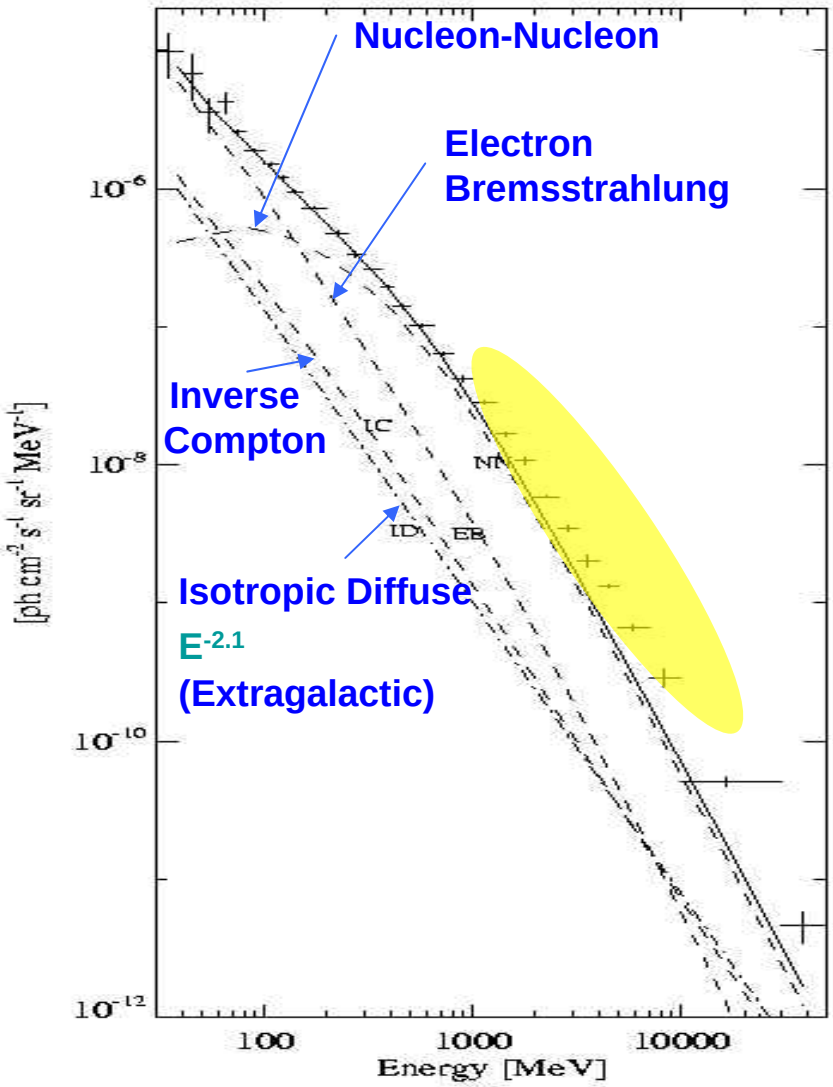
Post-Outrigger – data since 2003

- Good angular reconstruction on off-pond cores
- Sensitivity: ~8σ/yr on the Crab
- **9.7σ in <u>1.5 years</u>**

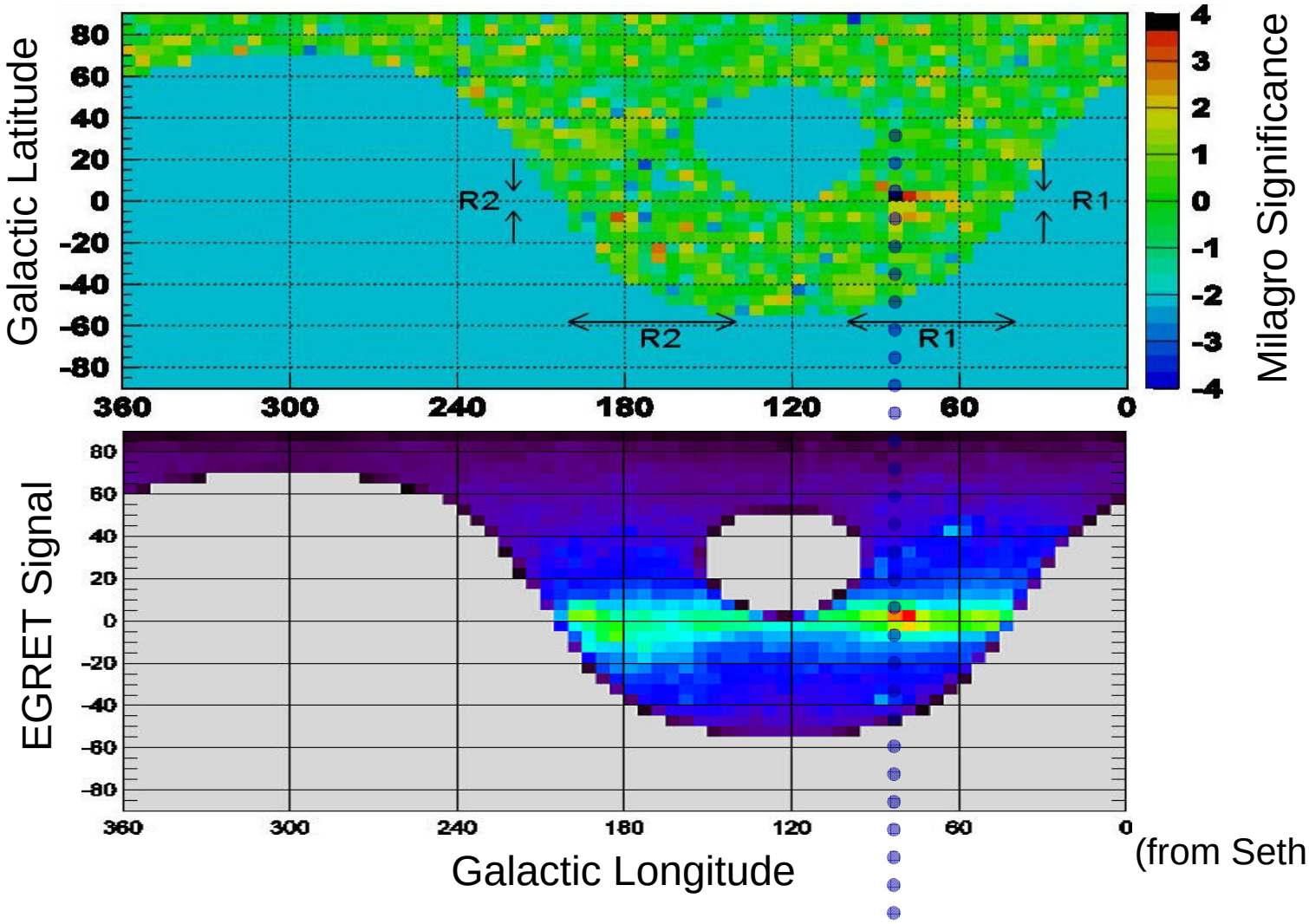
Galactic Plane Excess

- EGRET measured Galactic diffuse spectrum in |b|<10 and 300<l<60
- Still sees excess in flux >1 GeV
  - Softer $E^{-2.4}$ spectrum
- Is there an excess in TeV range?

Hunter, et al. ApJ **481**,205-240

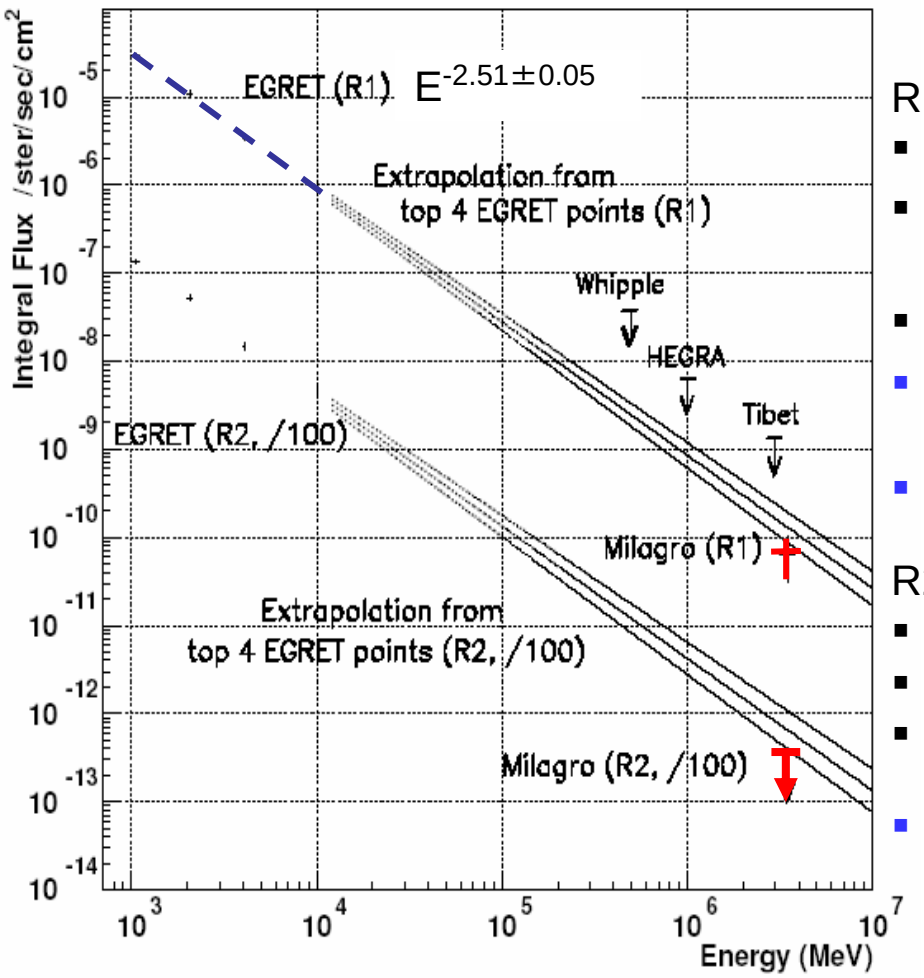


Milagro Results: 3 Year Exposure



(from Seth Digel)

Integral Flux: Milagro & EGRET



A priori cuts, based on 3yr of data, 4.5σ

R1

- Combined EGRET-Milagro fit
- Flux(>3.5 TeV) = $(6.8\pm1.5\pm2.2)\times10^{-11}$ /cm^2/s/sr
- Spectral Index = $-2.61\pm0.03\pm0.05$
- With outriggers we can measure the spectrum at TeV energies
- 2 more years of data needed for ±0.1 on spectral index at TeV energies

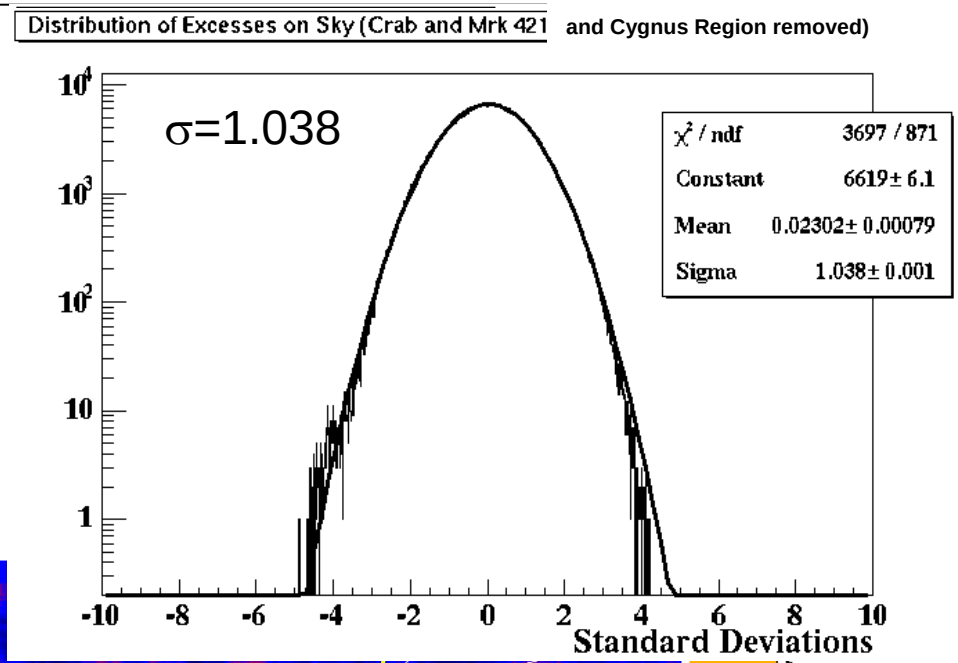
R2

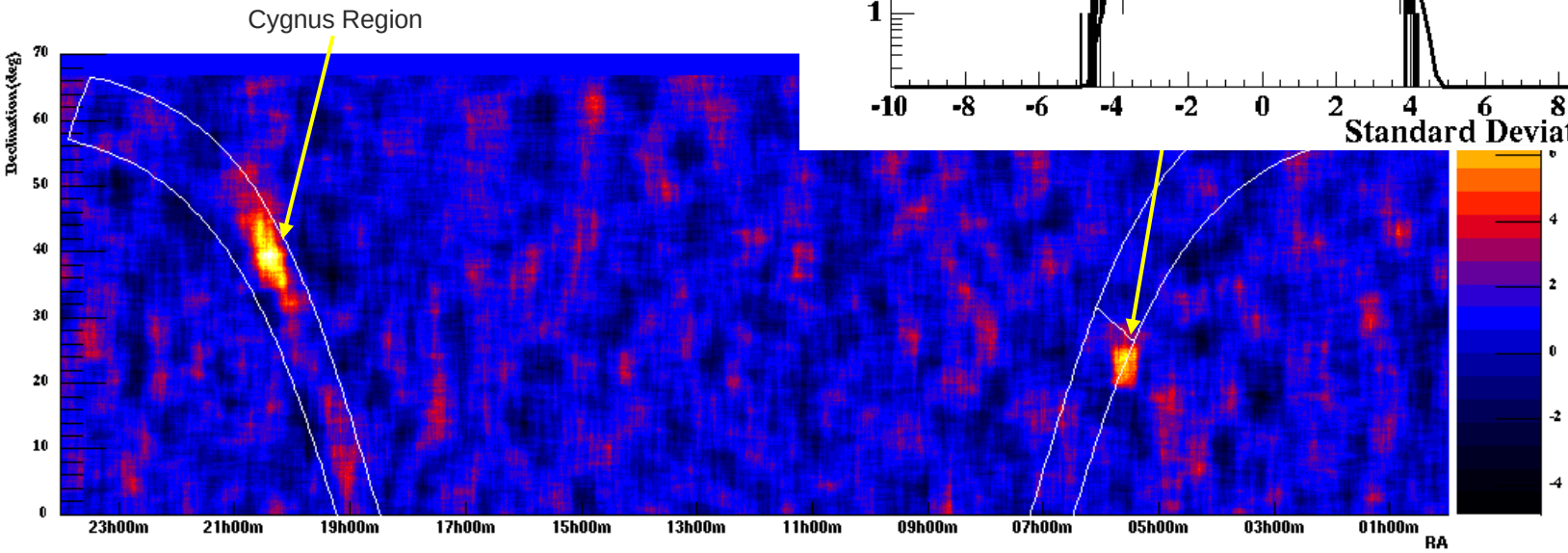
- Flux(>3.5 TeV) < 4×10^{-11} /cm^2/s/sr (99% CL)
- Spectral index < -2.66 (99% CL)
- Not yet a crisis but spectrum may be softer in outer Galaxy
- Additional data will tell

Extended Source Search

Bin Size = 5.9°
4.5 years of data
Cygnus Region Significance: 9.1σ
Post-trials probability: >7σ

Cygnus Region is the most luminous source of VHE γ-rays in the northern sky.



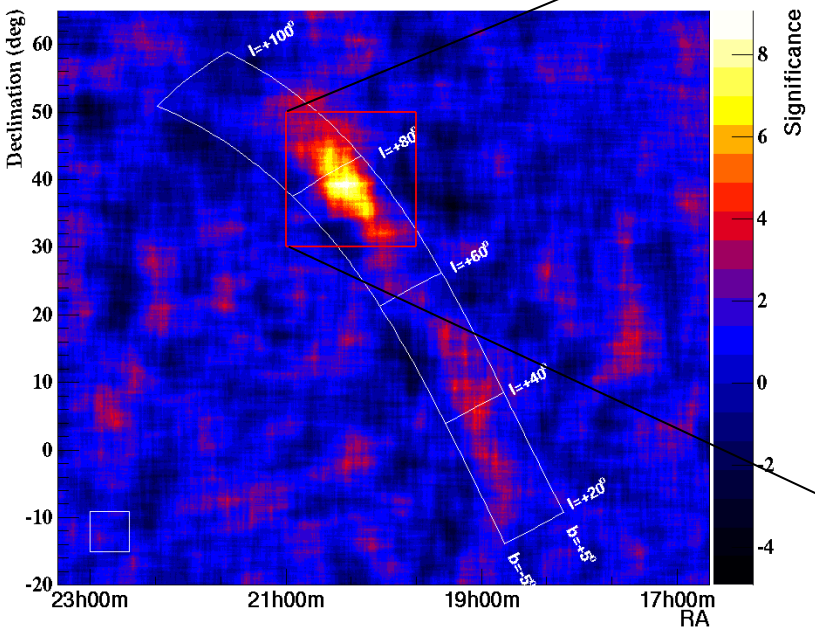


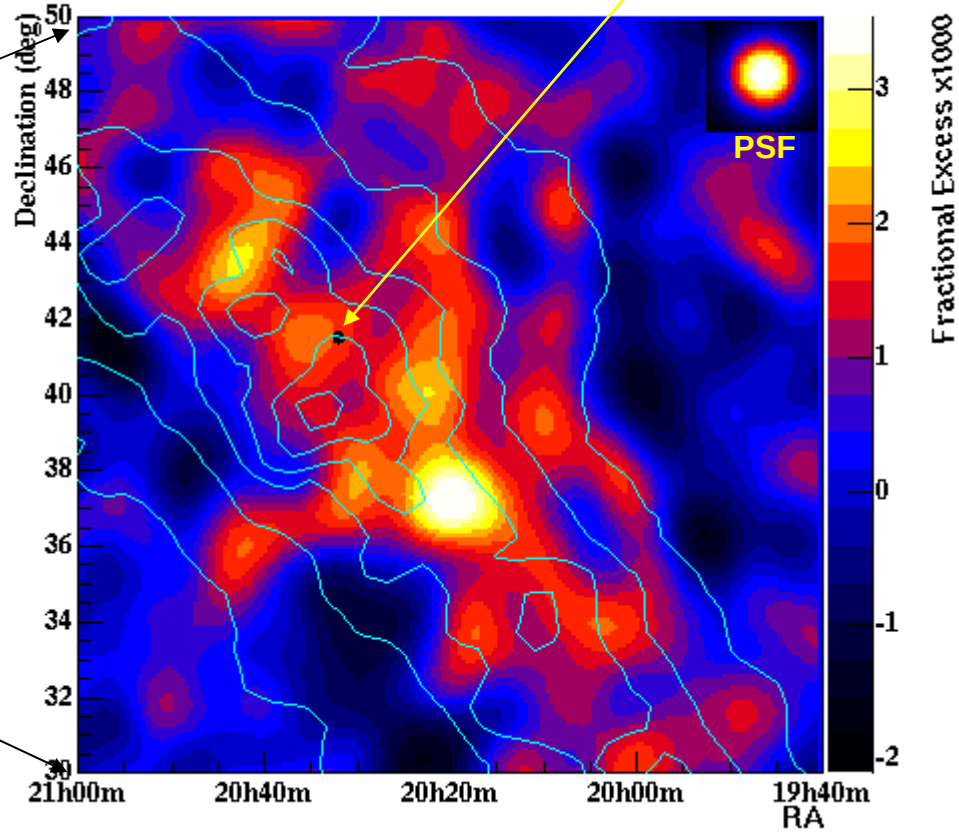
Cygnus Region Morphology

- Convolve Cygnus Region excess with Milagro PSF (0.75˚)
- Region shows resolvable structure

EGRET Diffuse Model

HEGRA detected TeV Source: TEV J2032_4130



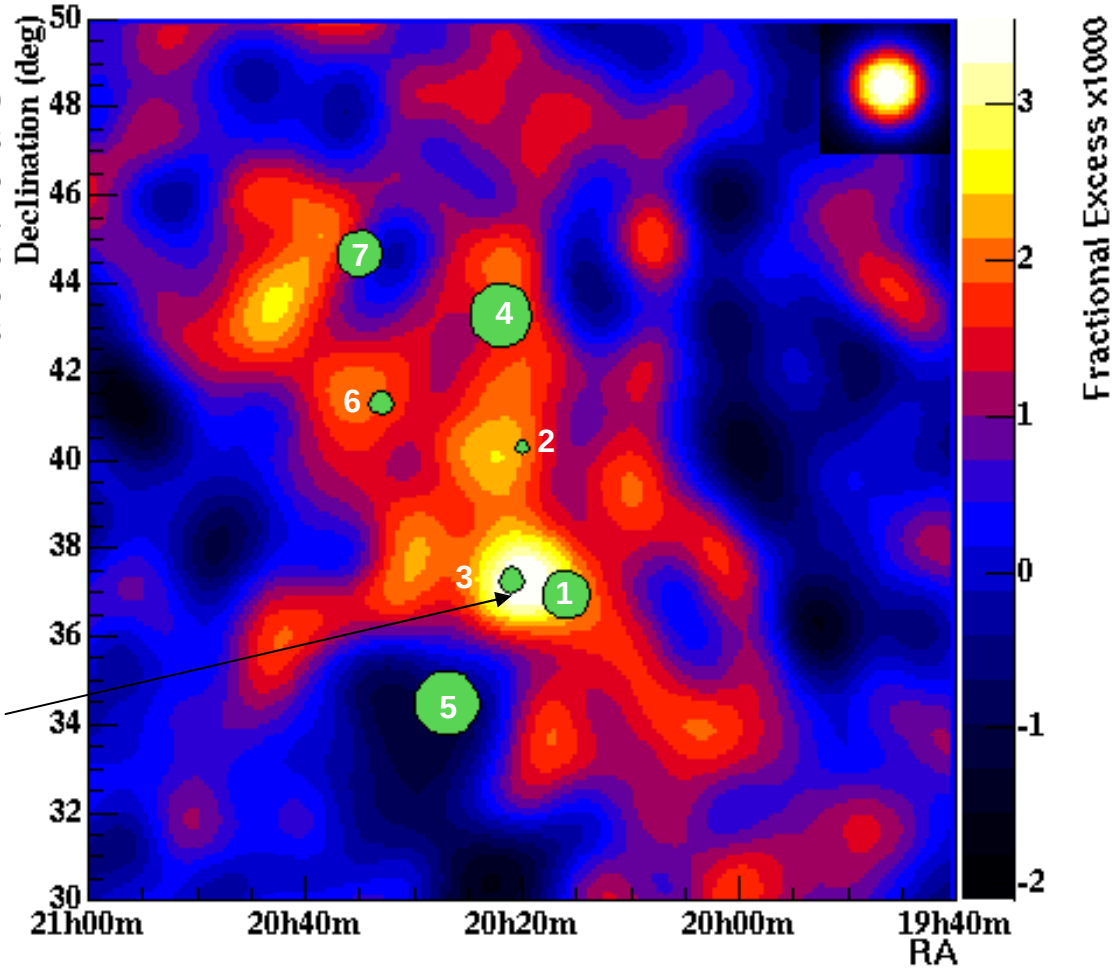


EGRET Unidentified Sources in the Cygnus Region

		$\Phi > 100$ MeV/cm^{2}s	γ
1	3EG J2016+3657	$(34.7 \pm 5.7) \times 10^{-8}$	2.09
2	3EG J2020+4017	$(123. \pm 6.7) \times 10^{-8}$	2.08
3	3EG J2021+3716	$(59.1 \pm 6.2) \times 10^{-8}$	1.86
4	3EG J2022+4317	$(24.7 \pm 5.2) \times 10^{-8}$	2.31
5	3EG J2027+3429	$(25.9 \pm 4.7) \times 10^{-8}$	2.28
6	3EG J2033+4118	$(73.0 \pm 6.7) \times 10^{-8}$	1.96
7	3EG J2035+4441	$(29.2 \pm 5.5) \times 10^{-8}$	2.08

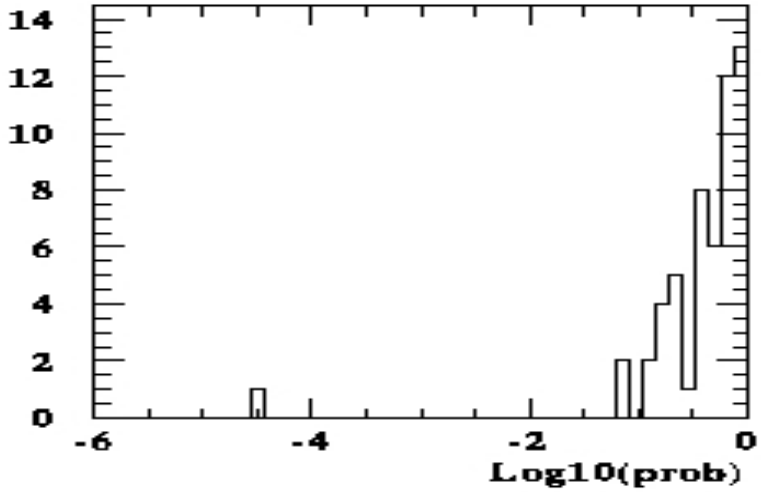
3rd EGRET Catalog sources shown with 95% position error circle.

Flux of maximum point: 500mCrab (May be extended)

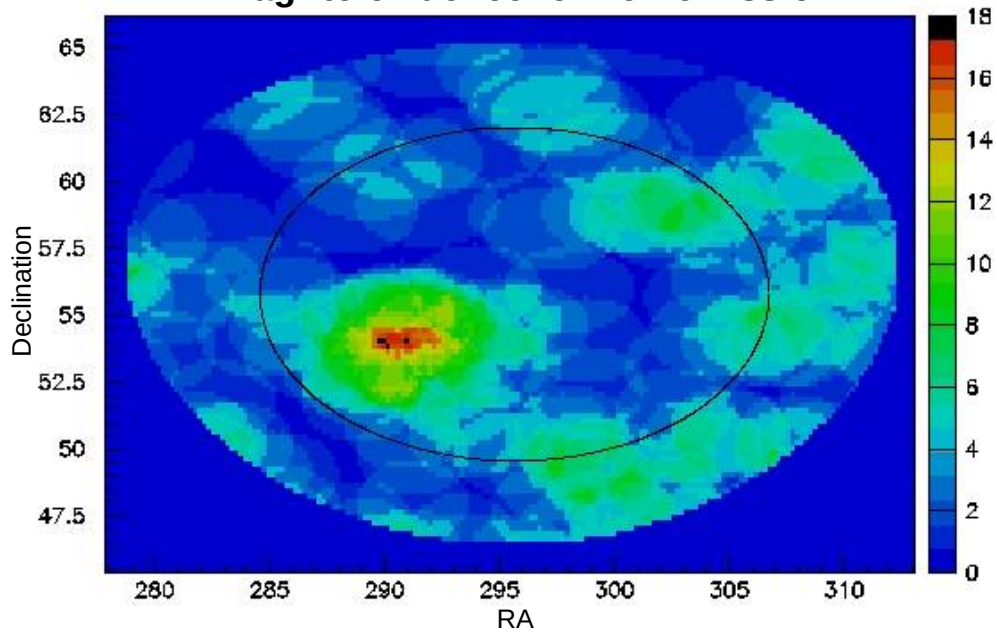


Satellite Detected GRBs in Milagro's FoV

- Milagrito: prototype ran from 1997-1998, detected 1 out of 54 GRBs



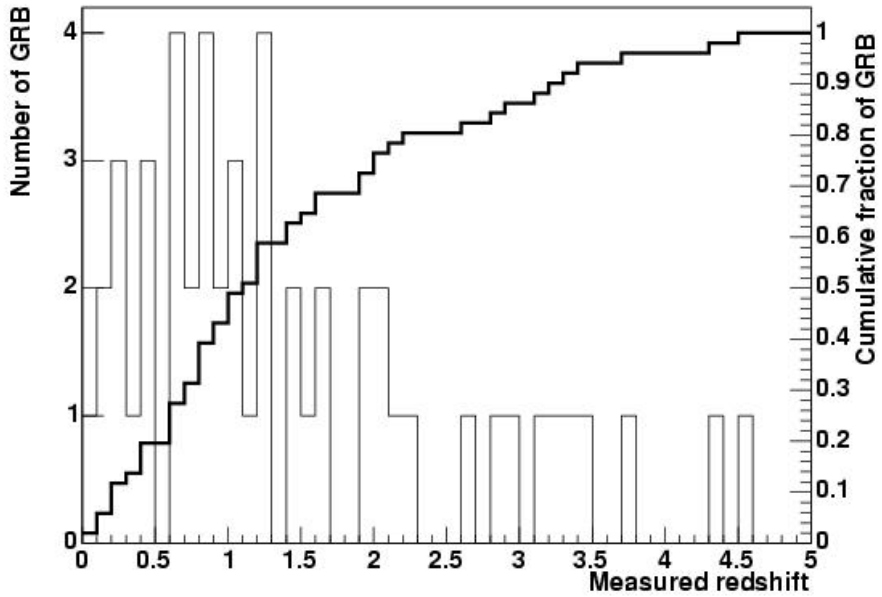
Milagrito evidence for TeV emission



1 of 54 BATSE bursts searched. The Milagro sample of bursts is still smaller than the sample Milagrito had. GRB 970417a had a post-trial probability of 1.5×10^{-3} (including the 54 bursts searched).

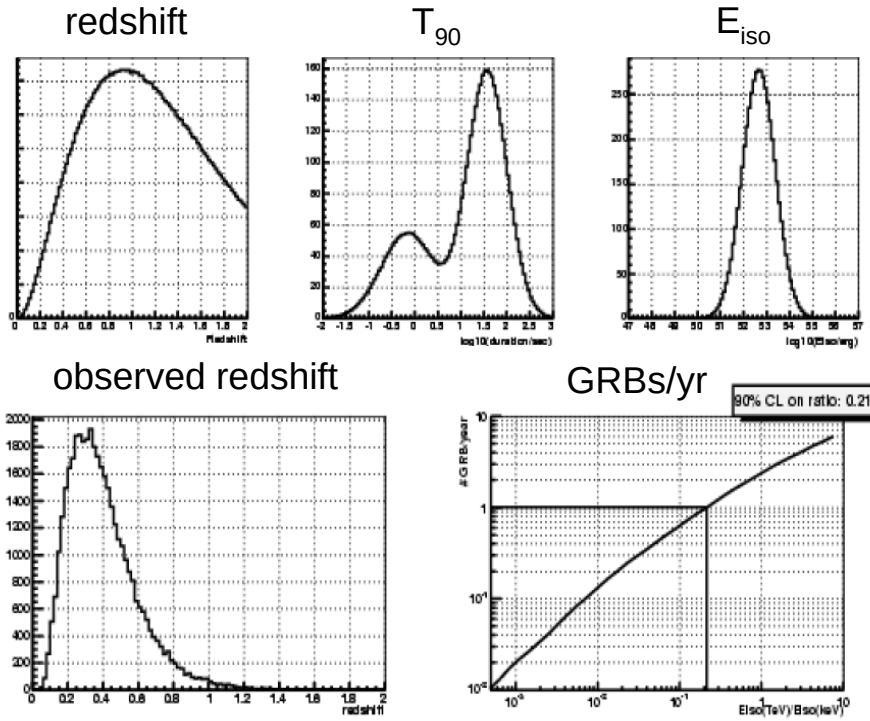
GRBs in Milagro

- Have not had such a burst during Milagro running
  - Searched 52 GRBs for TeV emission
  - 10 GRBs with known redshifts and 1 with redshift<0.5
- New SWIFT data should increase the rate to ~20 GRBs/yr (from ~4/yr) in Milagro FoV
- Most bursts are at high redshift
- $\gamma_{TeV} + \gamma_{IR} \rightarrow e^{+} + e^{-}$,
  so TeV gamma-rays are absorbed at high redshift
  - Difficult to see most GRBs, want redshift<0.5 and in Milagro's FoV
- Searching 3 years of Milagro data for short duration transients constrains VHE emission from GRBs, but is model dependent



Constraining GRB models

- Redshift dependence
- EBL model dependence
- Fluence dependence

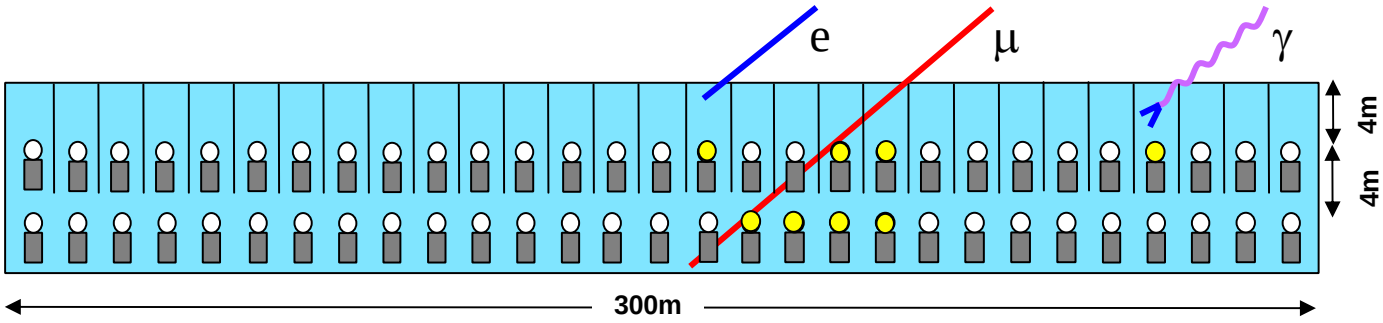


Conclusion: Milagro can set model-dependent upper limits on the VHE emission from GRBs.

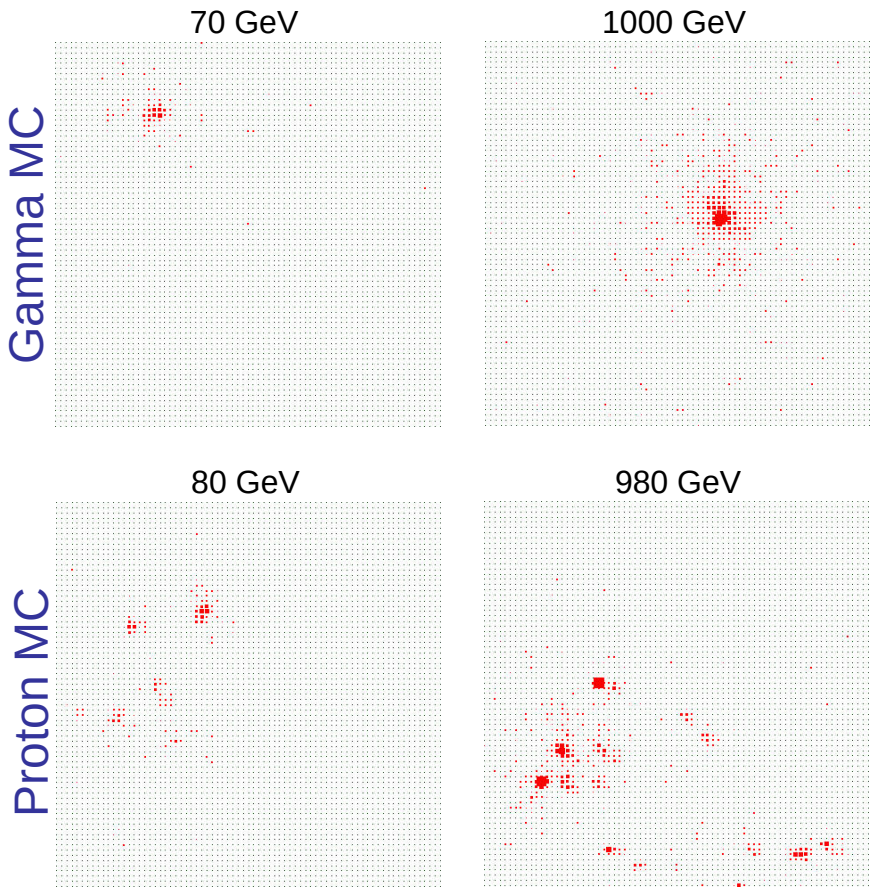
HIGH ALTITUDE WATER CHERENKOV experiment

Increase Altitude → Lower threshold
Increase Area → Better fitting (lever arm)
→ Better γ/h separation
Optical Isolation → Containment of Muon light - Triggering

- 11250 PMTs
- Median energy ~300 GeV



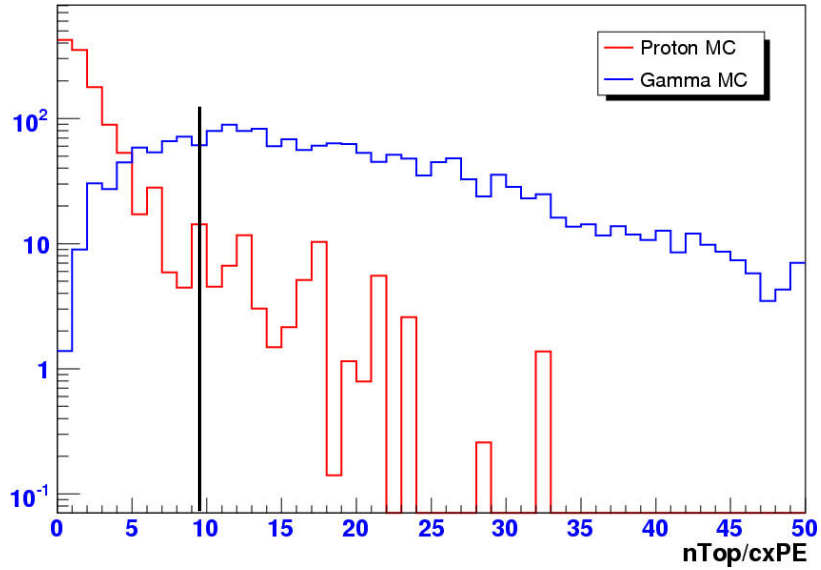
γ/h Separation with HAWC



Redefine Compactness:
Exclude large hits near the shower core

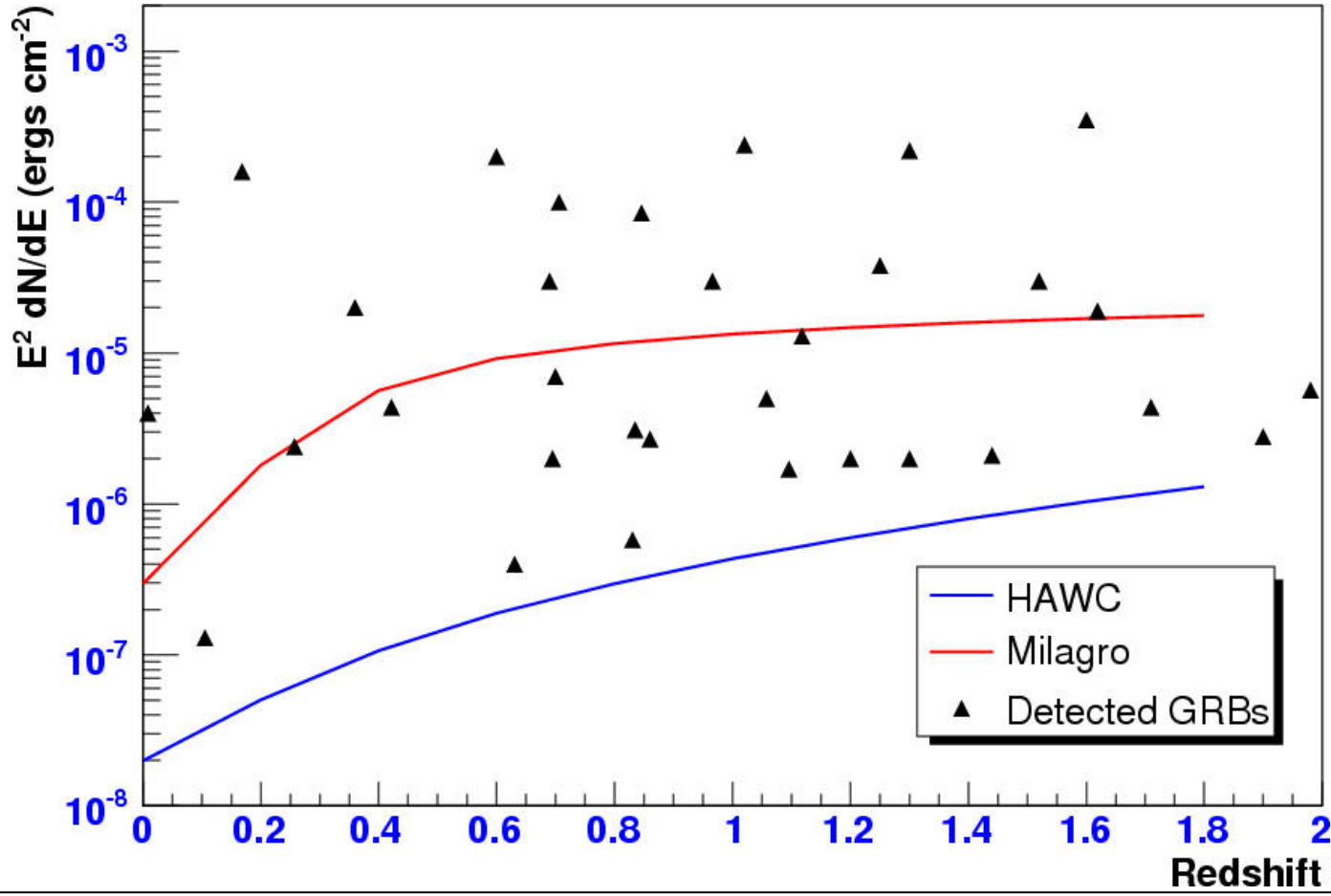
C>9.6:
Reject 95% of hadrons, retain 78% γs
Q=3.5

Median energy ~300 GeV

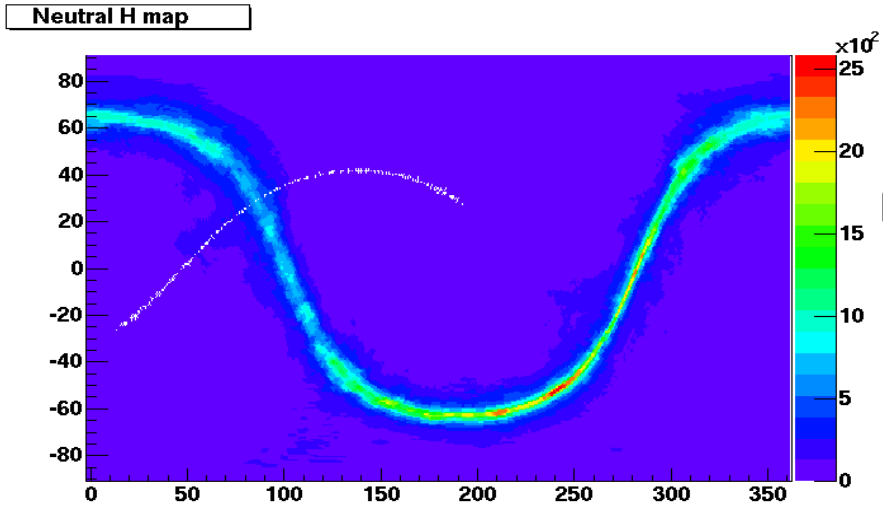


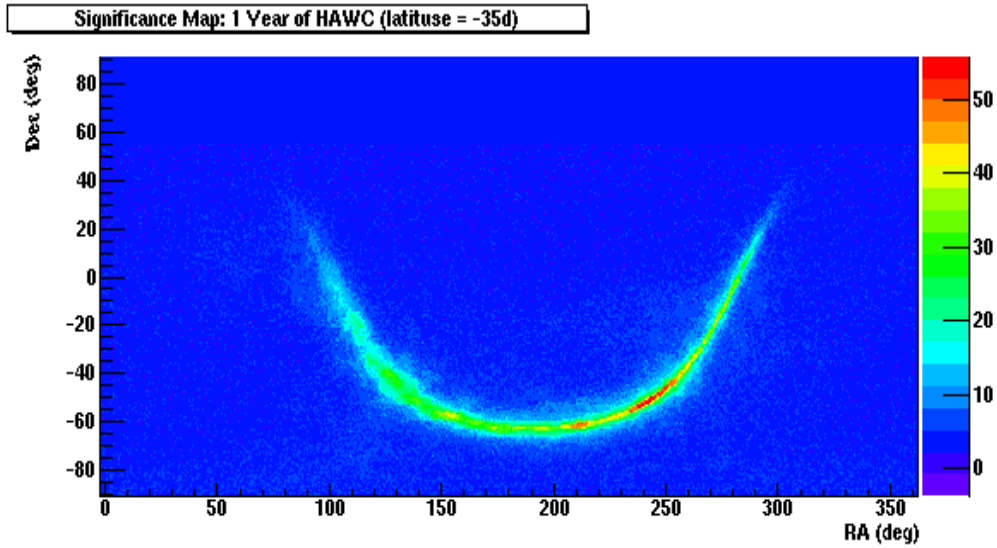
100sec GRB Sensitivity vs Redshift

Sensitivity lines are for GRBs assumed to fall within 20° of zenith.
Comparing lines to data, assume GRBs have same fluence at TeV energies as at keV-MeV.



Diffuse Galactic Plane in HAWC





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

HAWC sees galactic plane at **~55σ in 1 year**.

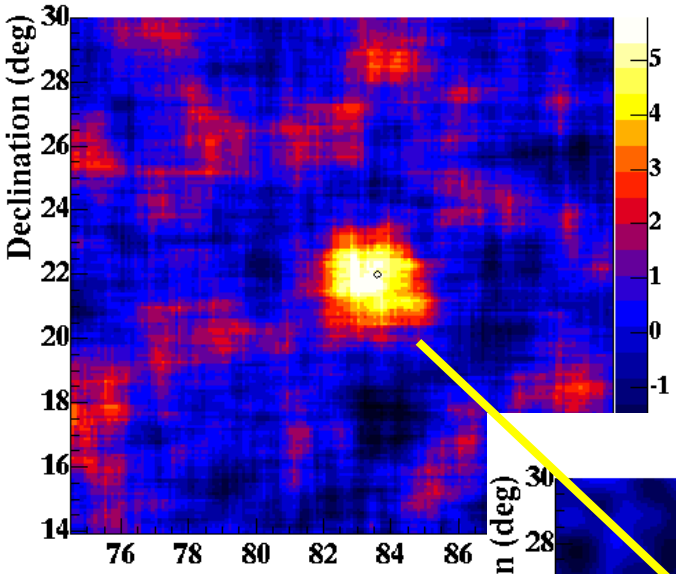
Conclusions

- Water Cherenkov method has not yet been fully exploited
  - Design improvements (Size, Altitude, …) lead to much better than sqrt(N) sensitivity improvements
  - HAWC ~60x Milagro sensitivity
- Milagro TeV Survey
  - Crab Nebula at 8σ/yr
  - Galactic Plane at 7.5σ in 4.5 years
  - Cygnus Region at 9.1σ in 4.5 years
  - Able to constrain VHE emission from GRBs
- Milagro's Future
  - Get energy spectrum of Galactic Plane to $\pm$0.1
  - Resolve hot spots in the Cygnus Region
  - Search for VHE GRB emission for ~20 SWIFT GRB/yr

Extra Slides

Crab in Milagro: Signal significance almost independent of cut level

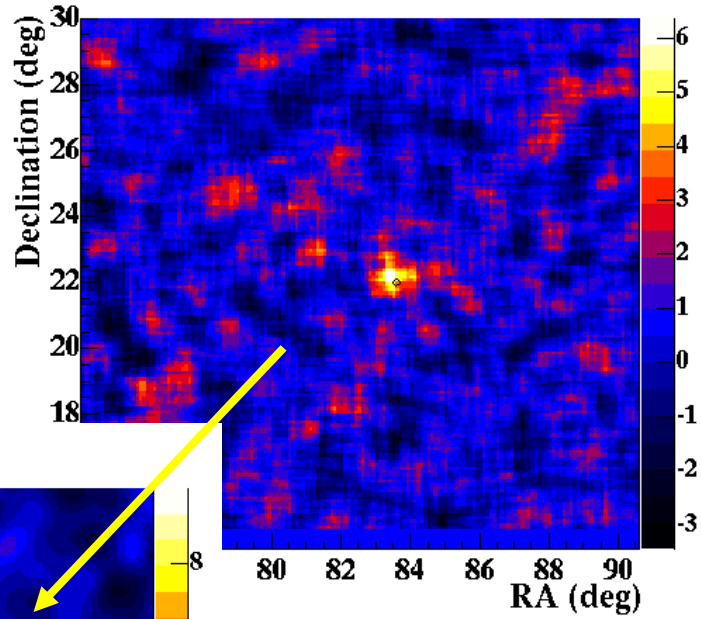
Std Cuts: nFit≥20,C>2.5



Excess = 5410, Off = 1218288,

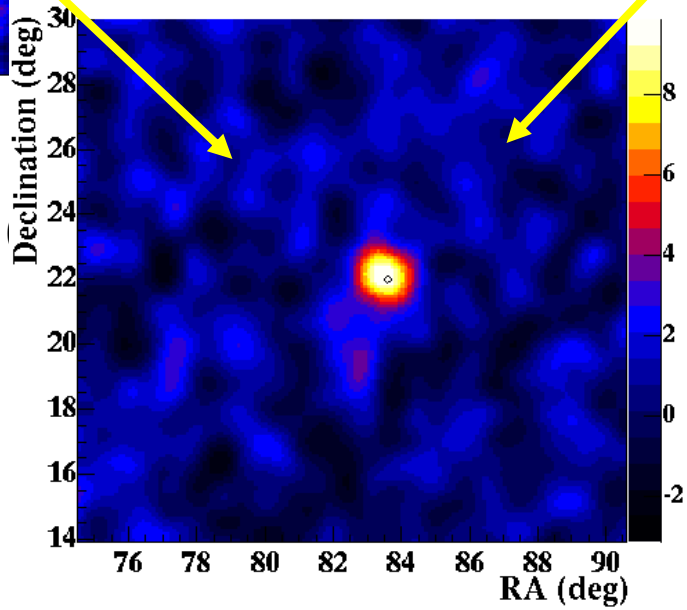
$\varepsilon_{\text{hadron background}} \approx$

Hard Cuts: nFit≥200,C>6.0



60, Off = 140, S:B = 1:2.3

on background $\approx 1\text{x}10^{-5}$



Weight events by Expected S:B

1.5yr of data with outriggers

Extended Source Sensitivity

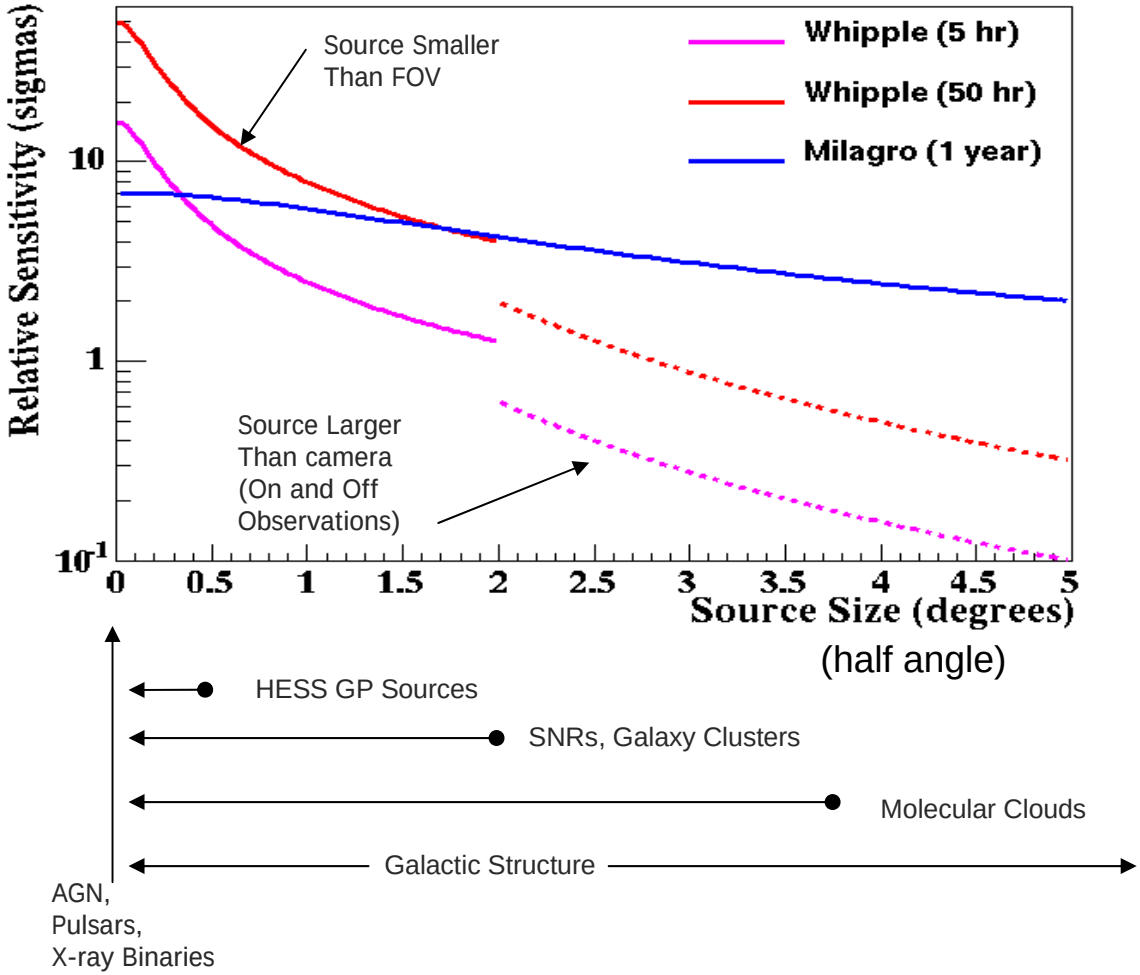
ACT's rely on angular resolution for excellent background rejection.

When the source size is large compared to PSF, sensitivity is reduced by a factor of

$$\sim \sigma_{detector} / \sigma_{source}$$

When the source size is large compared to the FOV, sensitivity is reduced by

$$\sim \sigma_{detector} / \sigma_{source}$$



Galactic Plane Excess

-2° <b<2°

Consider Region l = 20° -100°

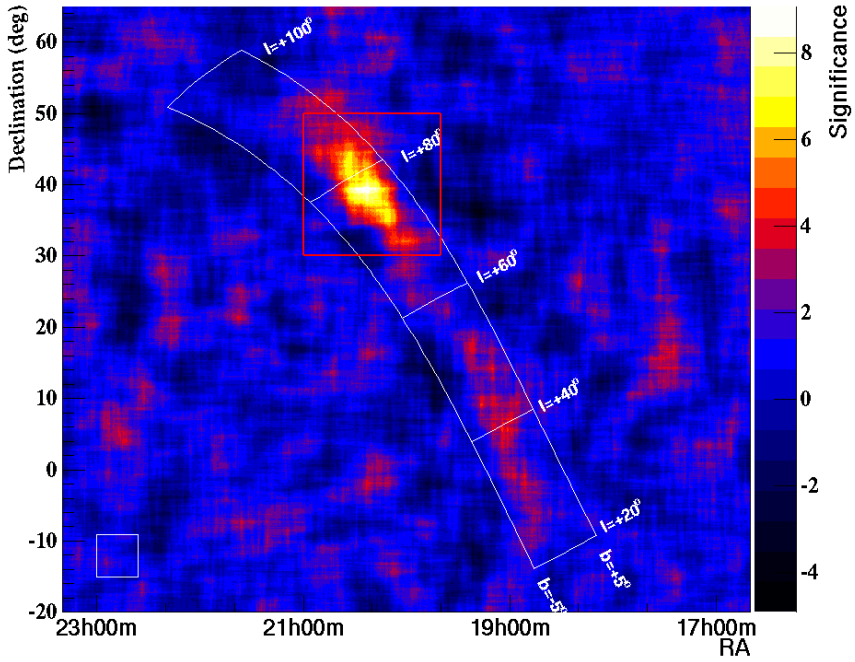
Std Map: 5.0σ

Weighted Map: 7.5σ

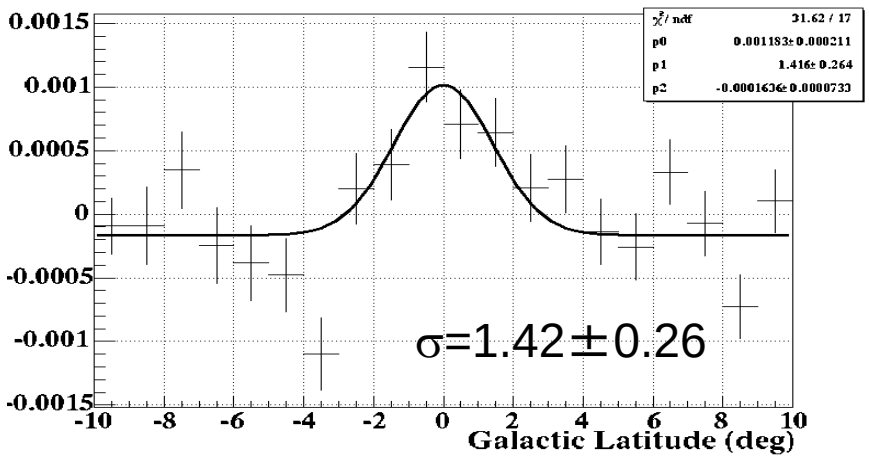
Exclude the Cygnus Region: l=20° -75°

Std Map: 4.2σ

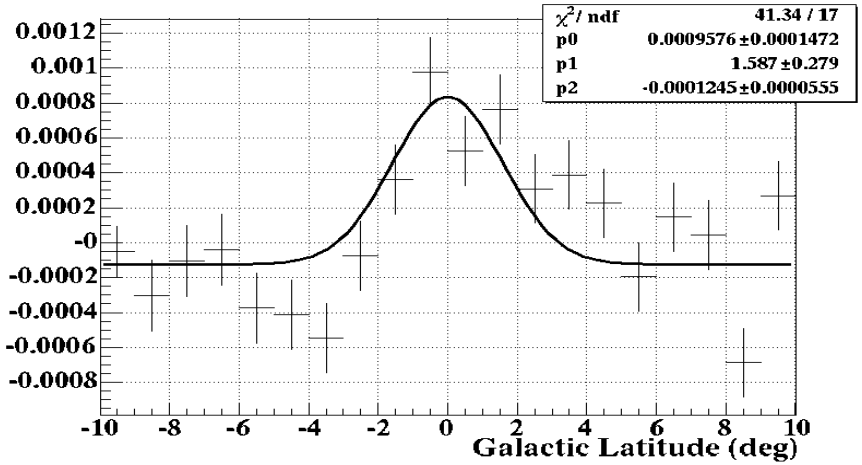
Weighted Map: 5.8σ



Galactic longitude 20-75 excludes Cygnus region



Galactic longitude 20-100 includes Cygnus region



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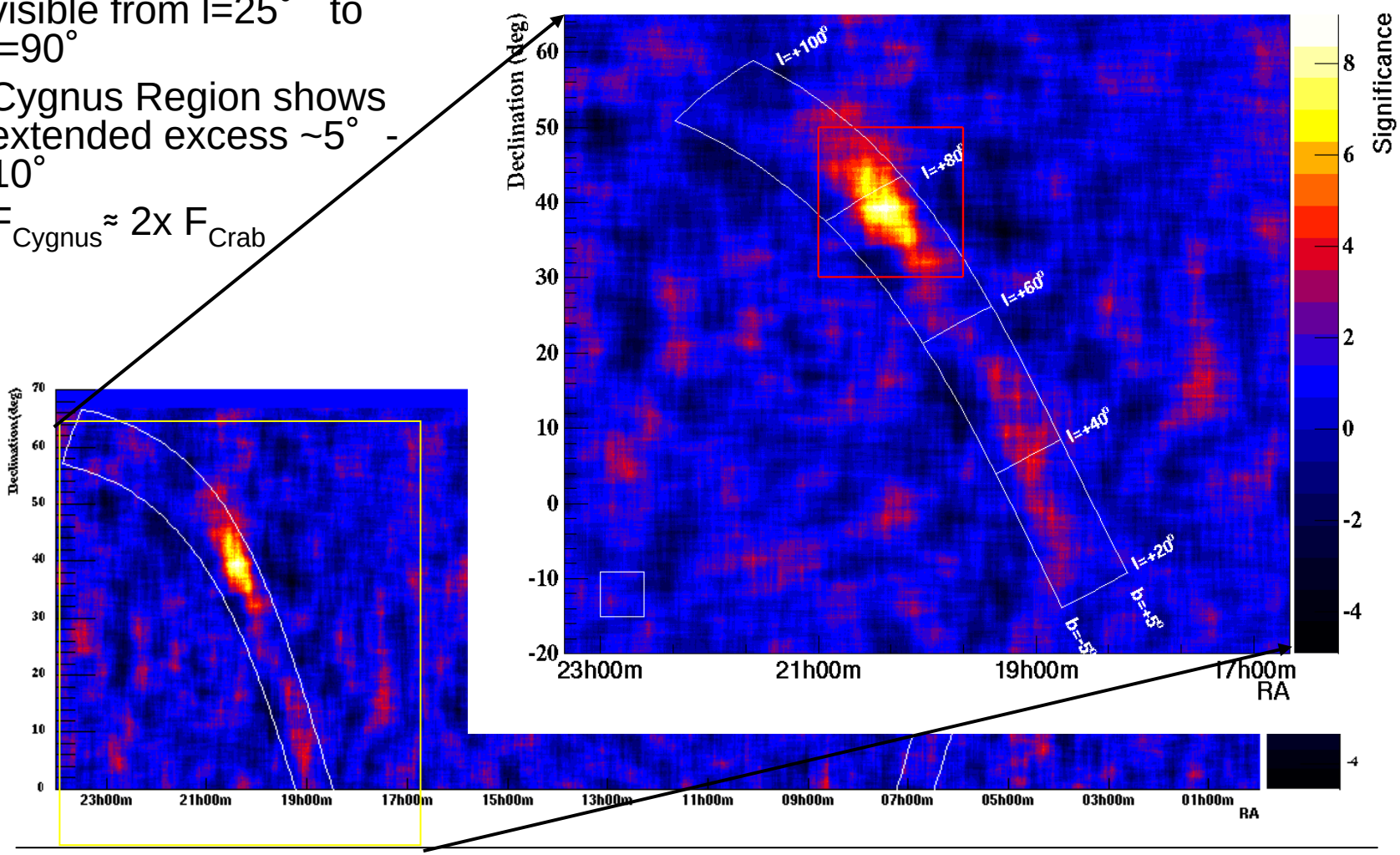
A Closer Look at the Galactic Plane

- GP diffuse excess clearly visible from l=25° to l=90°
- Cygnus Region shows extended excess ~5° - 10°
- $F_{Cygnus} \approx 2x\ F_{Crab}$



Curtis Lansdell
PANIC 2005

HEGRA Unidentified TeV Point Source: TEV J2032+4130

- HEGRA detected a 30 mCrab source in the Cygnus region
  - Milagro's point source sensitivity is insufficient to detect
  - The diffuse excess contributes a floor shift of ~1-2 mCrab to the HEGRA background
- Cygnus region is the most luminous TeV source in the northern sky, but a hard target for ACTs