# The Milagro Observatory: Recent Results & Future Plans

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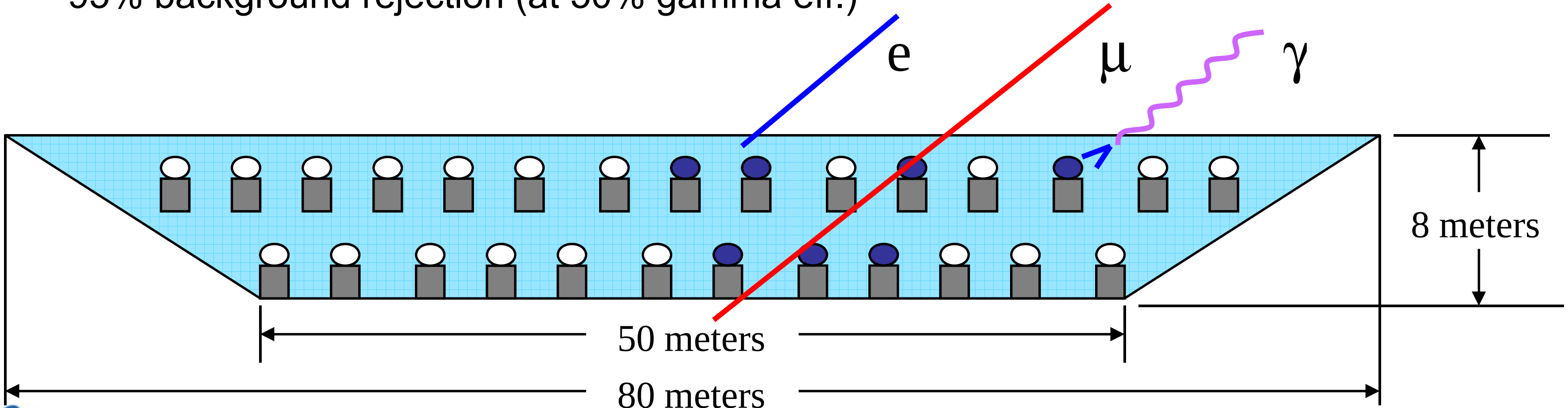
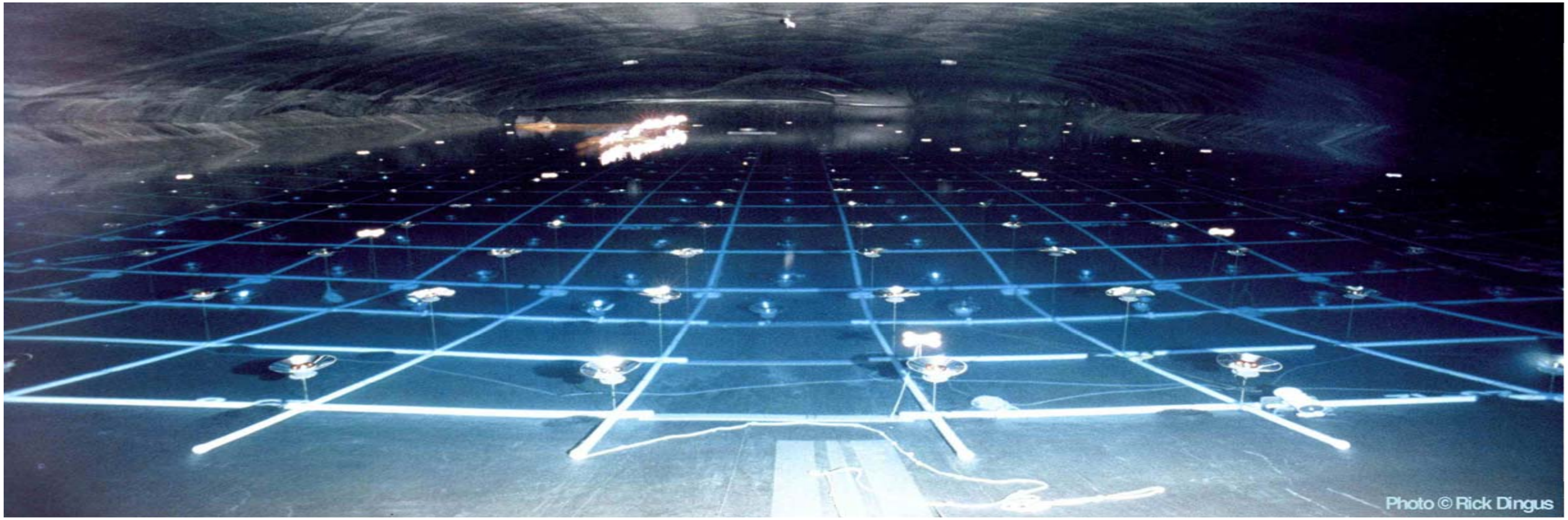
for the Milagro Collaboration

# Milagro

- Water Cherenkov Detector
- 2600m asl
- 898 detectors
  - 450(t)/273(b) in pond
  - 175 water tanks
- 4000 $m^2$ (pond) / $4.0\times10^4$ $m^2$ (phys. area)
- 2-12 TeV median energy (analysis dependent)
- 1700 Hz trigger rate
- $0.5^o$-$1.4^o$ resolution ($1.1^o$ average)
- 95% background rejection (at 50% gamma eff.)



# The Milagro Reservoir




7 years of operation: 2000 - 2007

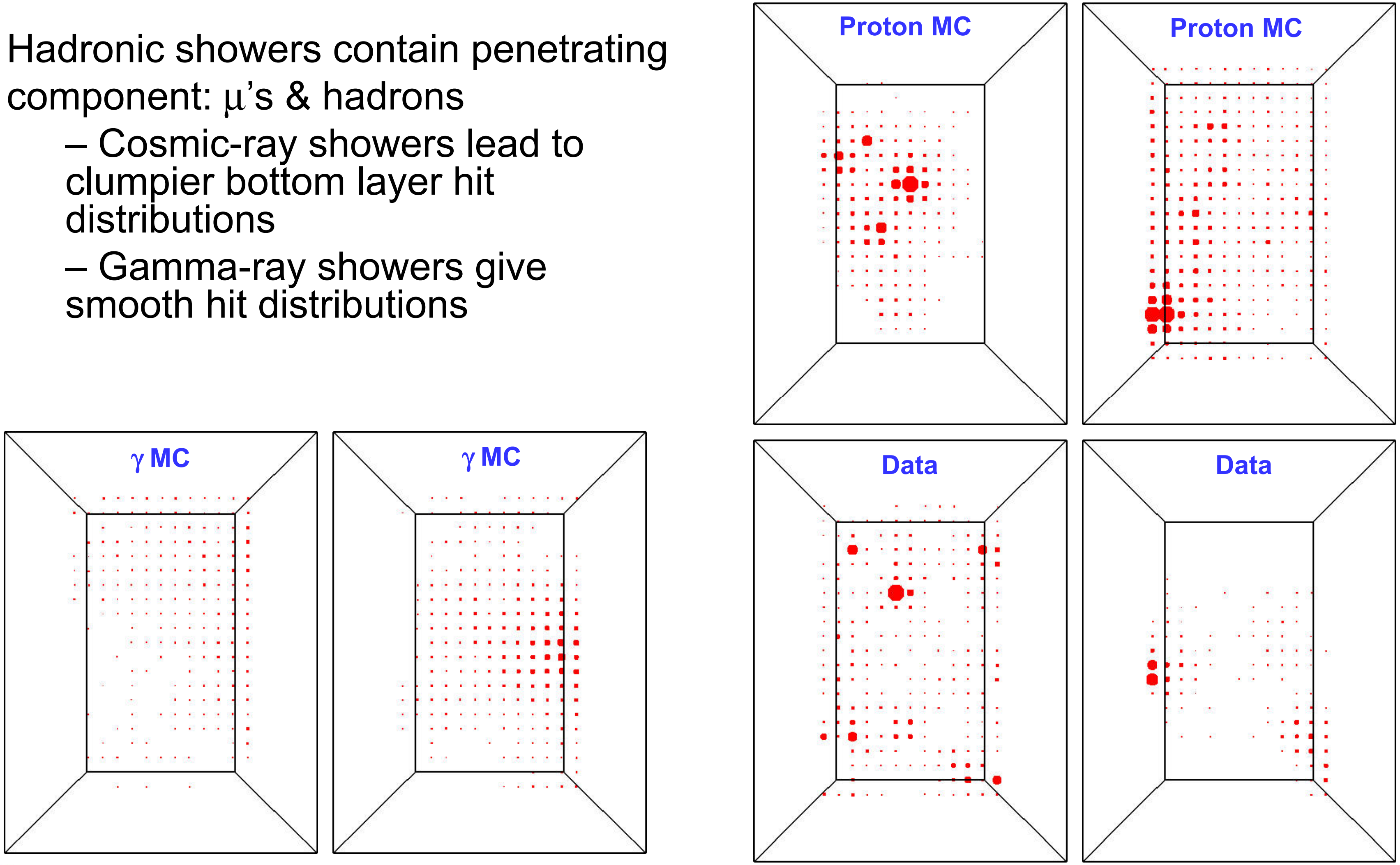
3 years with outrigger array

~320 billion events collected

# Background Rejection in Milagro

Hadronic showers contain penetrating component: μ’s & hadrons

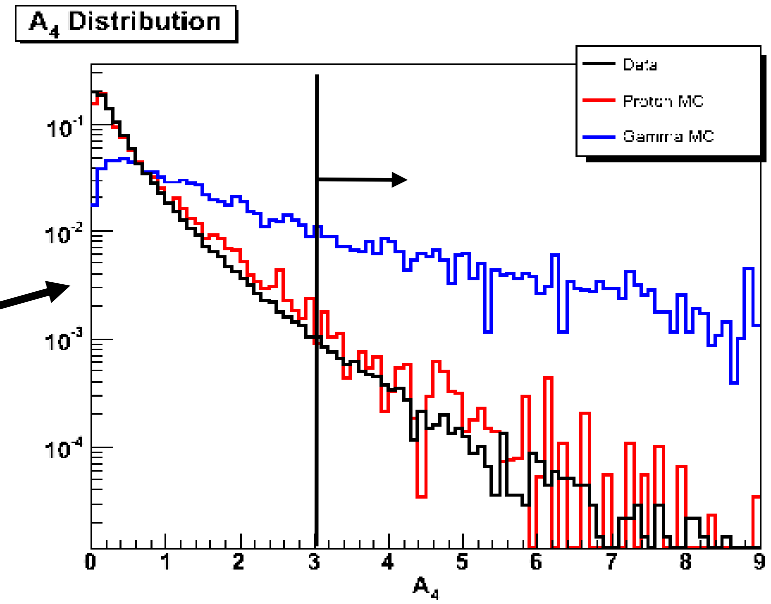
- Cosmic-ray showers lead to clumpier bottom layer hit distributions
- Gamma-ray showers give smooth hit distributions



# Background Rejection (Cont'd)

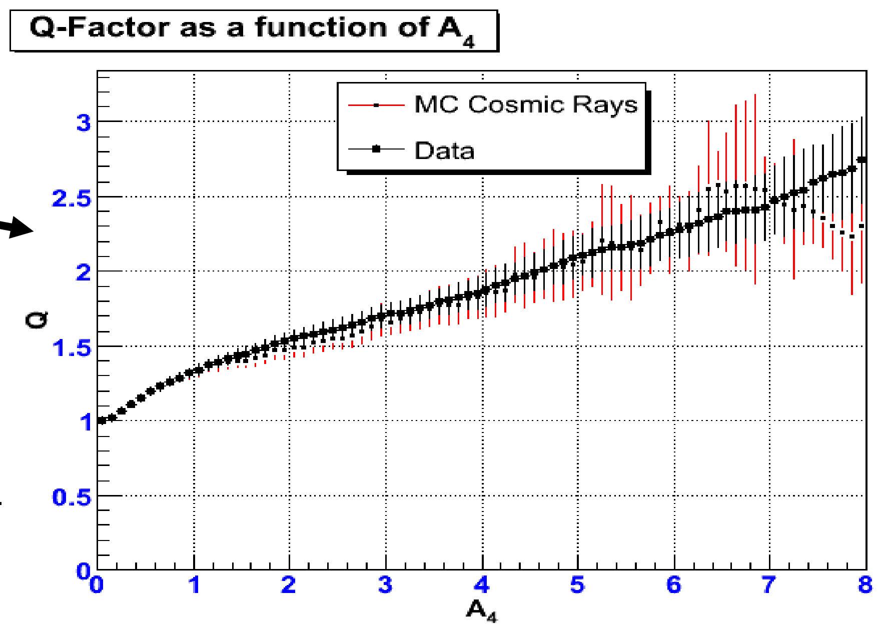
New Rejection Parameter: A4

$$A_4 = \frac{(fTop + fOut) * nFit}{mxPE}$$




Apply a cut on $A_4$ to reject hadrons:
$A_4 > 3$ rejects 99% of Hadrons
retains 18% of Gammas

S/B increases with increasing $A_4$




| | |
|---|---|
| mxPE: | maximum # PEs in bottom layer PMT |
| fTop: | fraction of hit PMTs in Top layer |
| fOut: | fraction of hit PMTs in Outriggers |
| nFit: | # PMTs used in the angle reconstruction |

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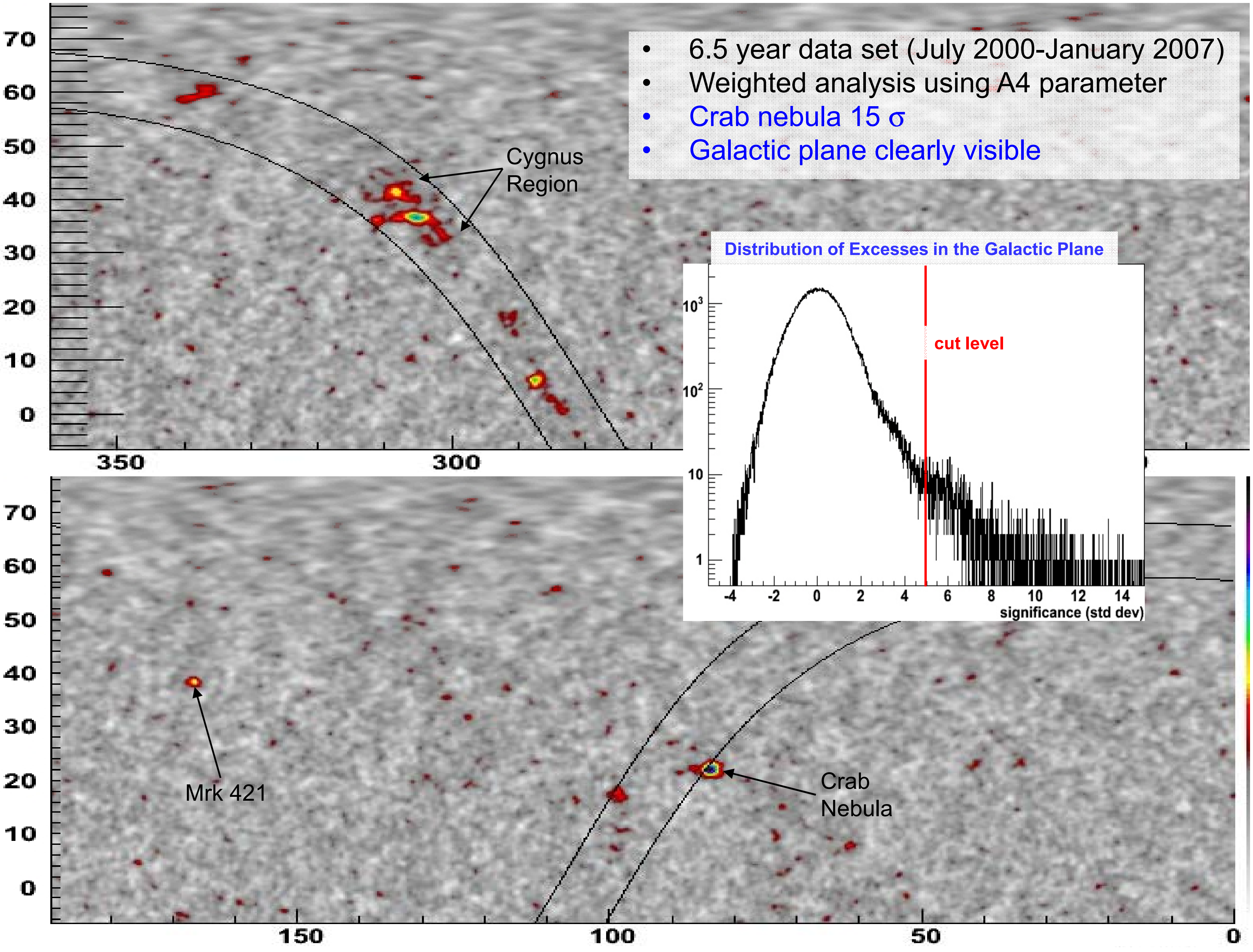
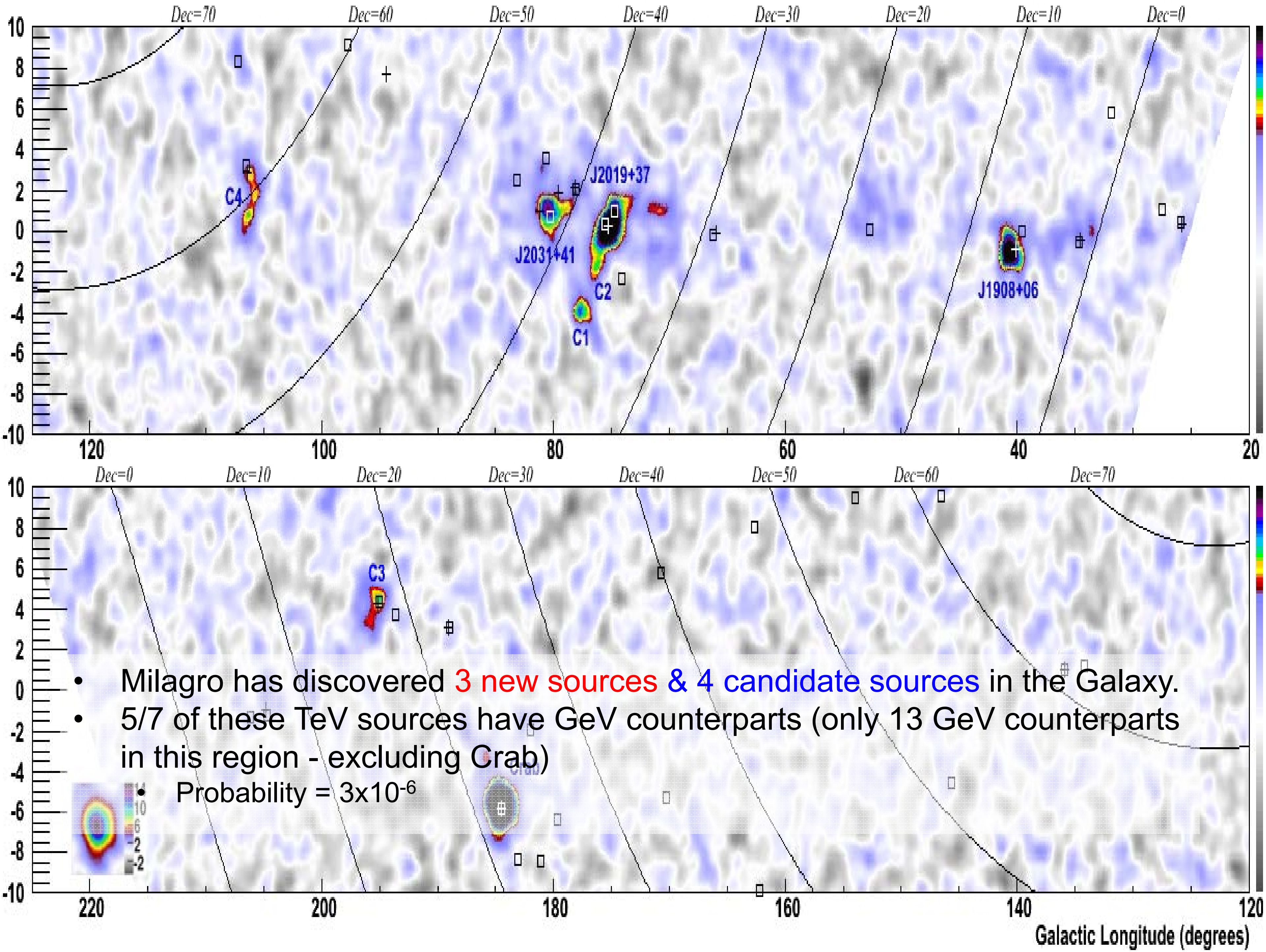
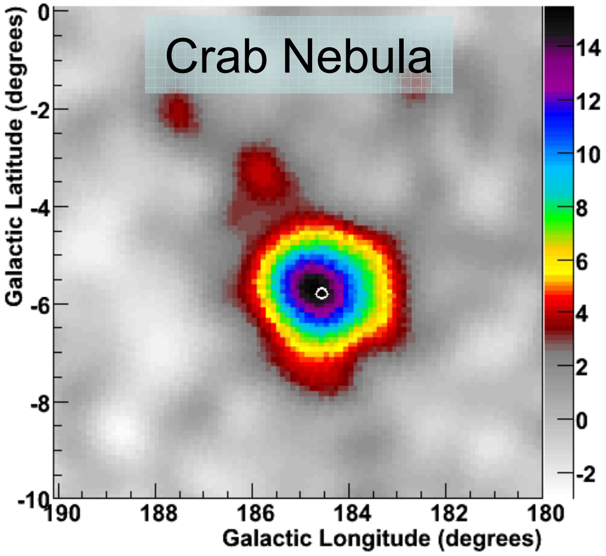


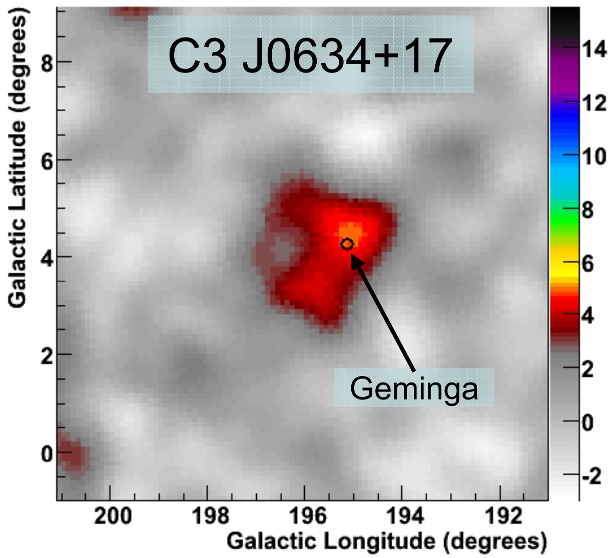
• 6.5 year data set (July 2000-January 2007)
• Weighted analysis using A4 parameter
• Crab nebula 15 σ
• Galactic plane clearly visible
Cygnus Region
Distribution of Excesses in the Galactic Plane
cut level
significance (std dev)
Mrk 421
Crab Nebula




- Milagro has discovered 3 new sources & 4 candidate sources in the Galaxy.
- 5/7 of these TeV sources have GeV counterparts (only 13 GeV counterparts in this region - excluding Crab)
  - Probability = $3 \times 10^{-6}$

# Crab Nebula & C3 J0634+17 (Geminga)

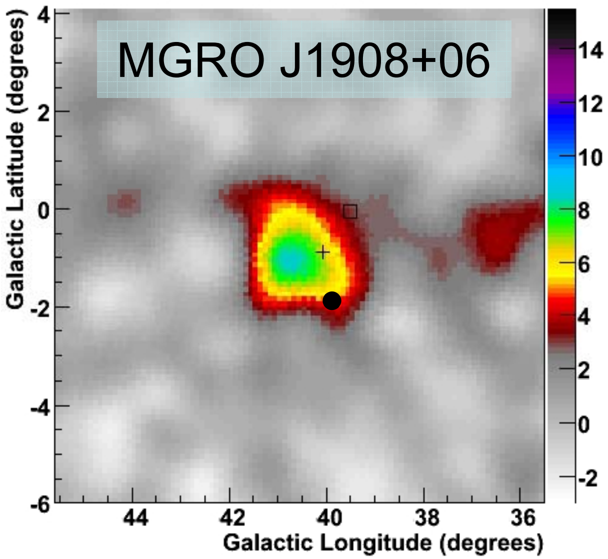


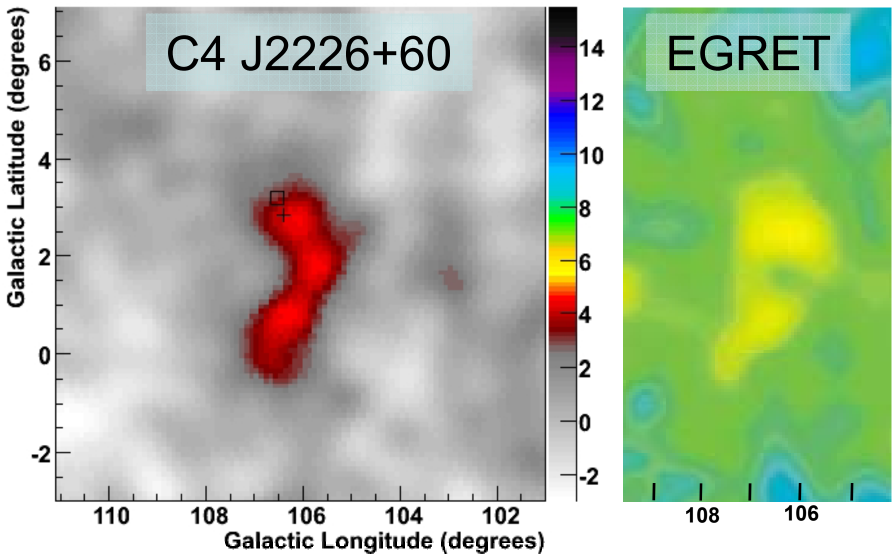




- Crab detected at 15.0 $\sigma$
- Fit position consistent with true position (within statistical error $0.1^o$)
- Fit width of $0.7^o$ consistent with Monte Carlo expectations of angular resolution (sigma of 2-D Gaussian)

- C3 J0634+17 position consistent with Geminga location
- 4.7 $\sigma$ at location of Geminga (5.1 $\sigma$ at peak)
- Diameter $2.8^o \pm 0.8^o$

# MGRO J1908+06 & C4 J2226+60



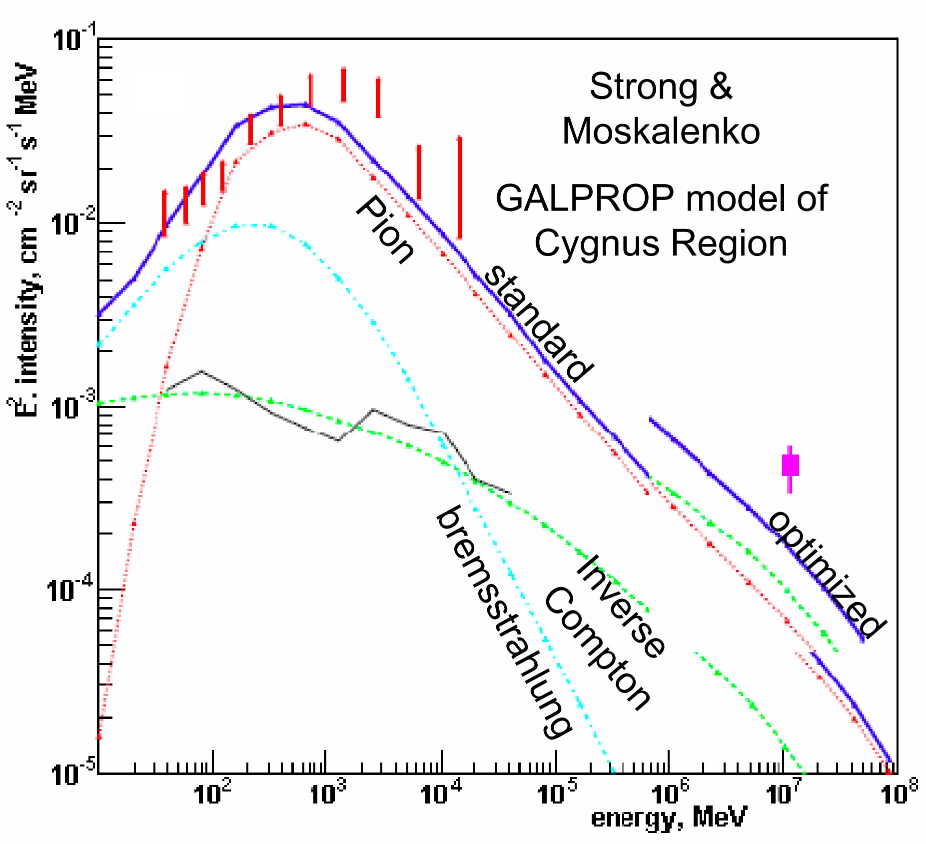

## MGRO J1908+06

- Statistical Sig. 8.3 σ
- Flux @ 20 TeV ~800 mCrab
- Diameter < 2.6$^o$
- Possible Counterparts
  - GeV J1907+0557
  - SNR G40.5-0.5
  - SS 433
  - Tibet Location of Interest (4.5σ)

## C4 J2226+60

- Statistical Sig. 5.0 σ pre-trial
  - 6.3σ in 3$^o$ x 3$^o$ bin
- Appears elongated
- Diameter: 3.4$^o$ $\pm$ 1.7$^o$
- Possible Counterparts
  - GeV J2227+6106, 3EG J2227+6122
  - SNR G106.6+2.9, Boomerang PWN

# The Cygnus Region




- MGRO J2019+37: 10.9σ (previously reported ApJ Lett v658 L33)
  - Extended source 1.1° ± 0.5° (top hat dia.)
  - Possible Counterparts
    - GeV J2020+3658, PWN G75.2+0.1
- MGRO J2031+41: 6.9σ (5.0σ post-trials)
  - Possible Counterparts:
    - 3EG J2033+4118, GEV J2035+4214
    - TEV J2032+413 (⅓ of Milagro flux)
  - 3.0° ± 0.9° (top hat dia.)
- C1 J2044+36: 5.5σ pre-trials
  - no counterparts
  - < 2.0°
- C2 J2031+33: 5.3σ pre-trials
  - no counterparts
  - possible extension of MGRO J2019+37
  - possible fluctuation of MGRO J2019 tail & diffuse emission & background
- TeV Diffuse emission ~3x predictions
  - Cosmic Ray sources?
  - Unresolved gamma-ray sources?

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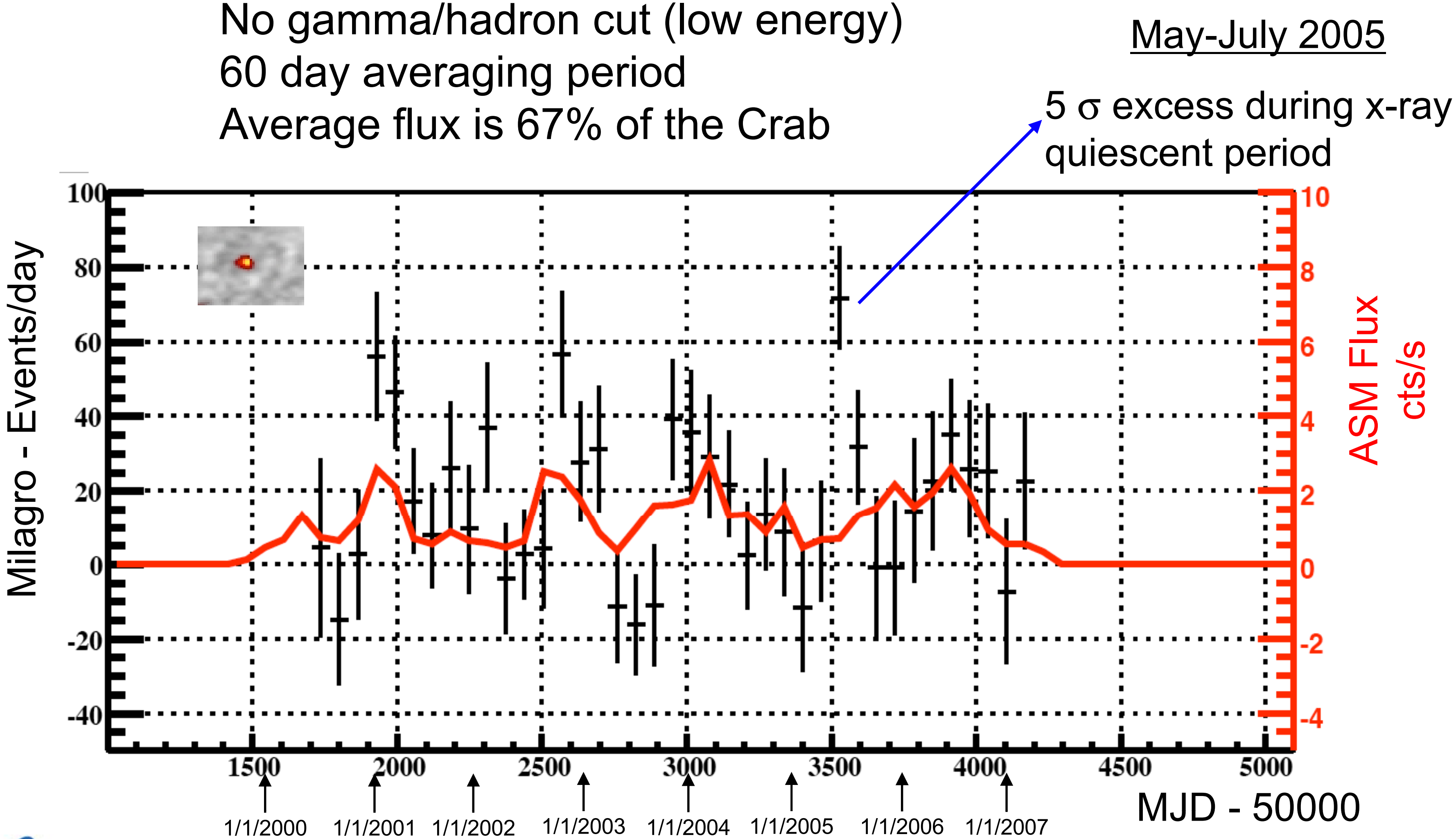
# Galactic Plane Survey Summary

>5σ post-trials

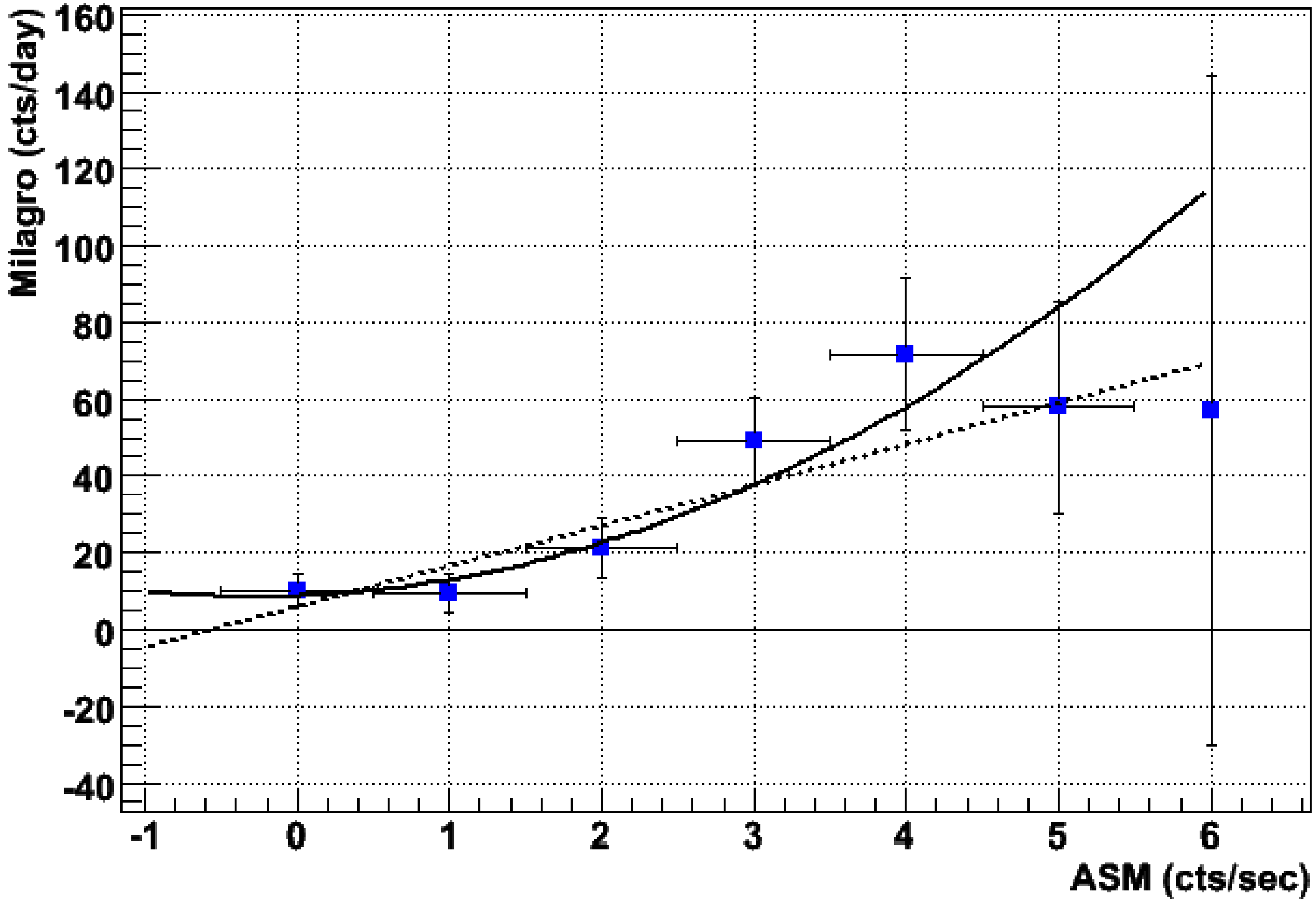
| Object | [2]Location (l, b) | Counterpart ? | Pre(Post)-Trial Significance | Flux @20 TeV (x$10^{-15}$) (/TeV/cm$^2$/s) |
|---|---|---|---|---|
| **Crab** | 184.5, -5.7 | | **15.0σ** (14.3σ) | $10.9 \pm 1.2_{stat}$ |
| **MGRO J2019+37** | 75.0, 0.2 | PWN G75.2+0.1<br>GeV J2020+3658 | **10.4σ** (9.3σ) | $8.7 \pm 1.4_{stat}$ |
| **MGRO J1908+06** | 40.4, -1.0 | GeV J1907+0557<br>SNR G40.5-0.5 | **8.3σ** (6.9σ) | $8.8 \pm 2.4_{stat}$ |
| **MGRO J2031+41** | 80.3, 1.1 | GeV J2035+4214 | 6.6σ (4.9σ) | $9.8 \pm 2.9_{stat}$ |
| **C1 J2044+36** | 77.5, -3.9 | ? | 5.8σ (3.9σ) | $2.8 \pm 0.6_{stat}$ |
| **C2 J2031+33** | 76.1, -1.7 | ? | 5.1σ (2.8σ) | $3.4 \pm 0.8_{stat}$ |
| **C3 J0634+17** | 195.7, 4.1 | Geminga | 5.1σ (2.8σ) | $6.5 \pm 1.5_{stat}$ |
| **C4 J2226+60** | 105.8, 2.0 | GeV J2227+6106<br>Boomerang PWN<br>SNR G106.6+2.9 | 5.0σ (2.7σ) | $3.5 \pm 1.2_{stat}$ |

# Mrk 421

7 year data set July 2000 - May 2007
No gamma/hadron cut (low energy)
60 day averaging period
Average flux is 67% of the Crab



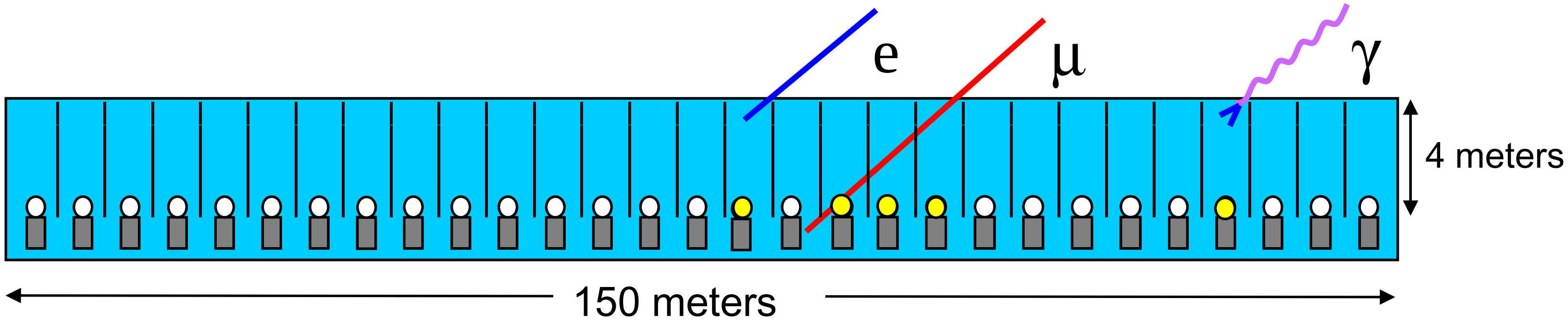
# Mrk 421 TeV/X-Ray Correlation




Both linear and quadratic fit well to data
(quadratic somewhat better)

# HAWC: High Altitude Water Cherenkov


- Build pond at extreme altitude (Tibet 4300m, Mexico 4100m)
- Incorporate new design
  - Optical isolation between PMTs
  - Larger PMT spacing
  - Single PMT layer (4m deep)
- Reuse Milagro PMTs and electronics
- 22,500 $m^2$ sensitive area




~$6M for complete detector

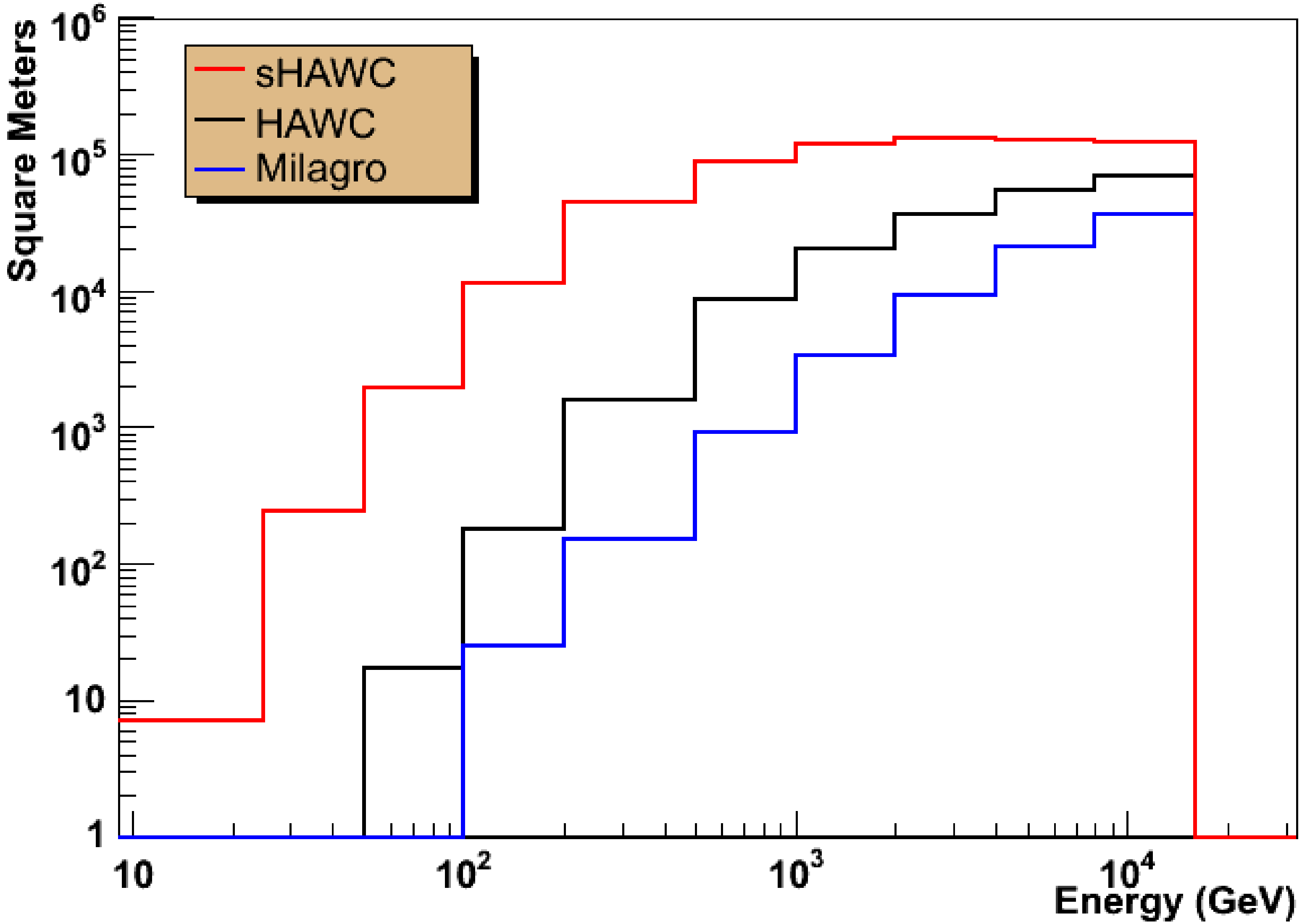
~10-15x sensitivity of Milagro

Crab Nebula in 1 day (4 hours) [Milagro 3-4 months]

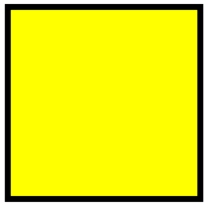
4x Crab flux in 15 minutes

GRBs to z < 0.8 (now 0.4)

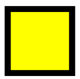
# HAWC Effective Area v. Energy



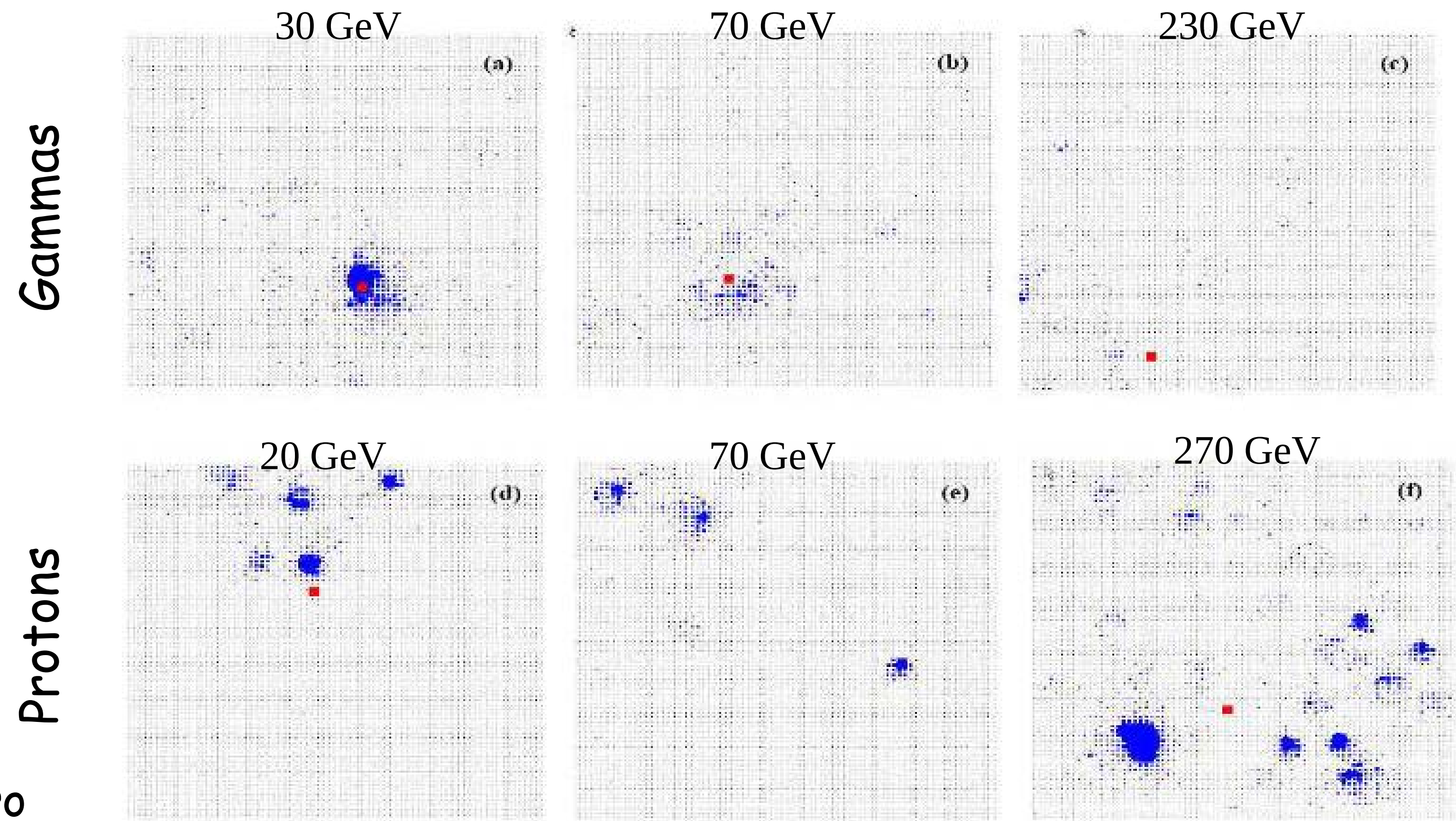
# Gamma/Hadron Separation



Size of HAWC

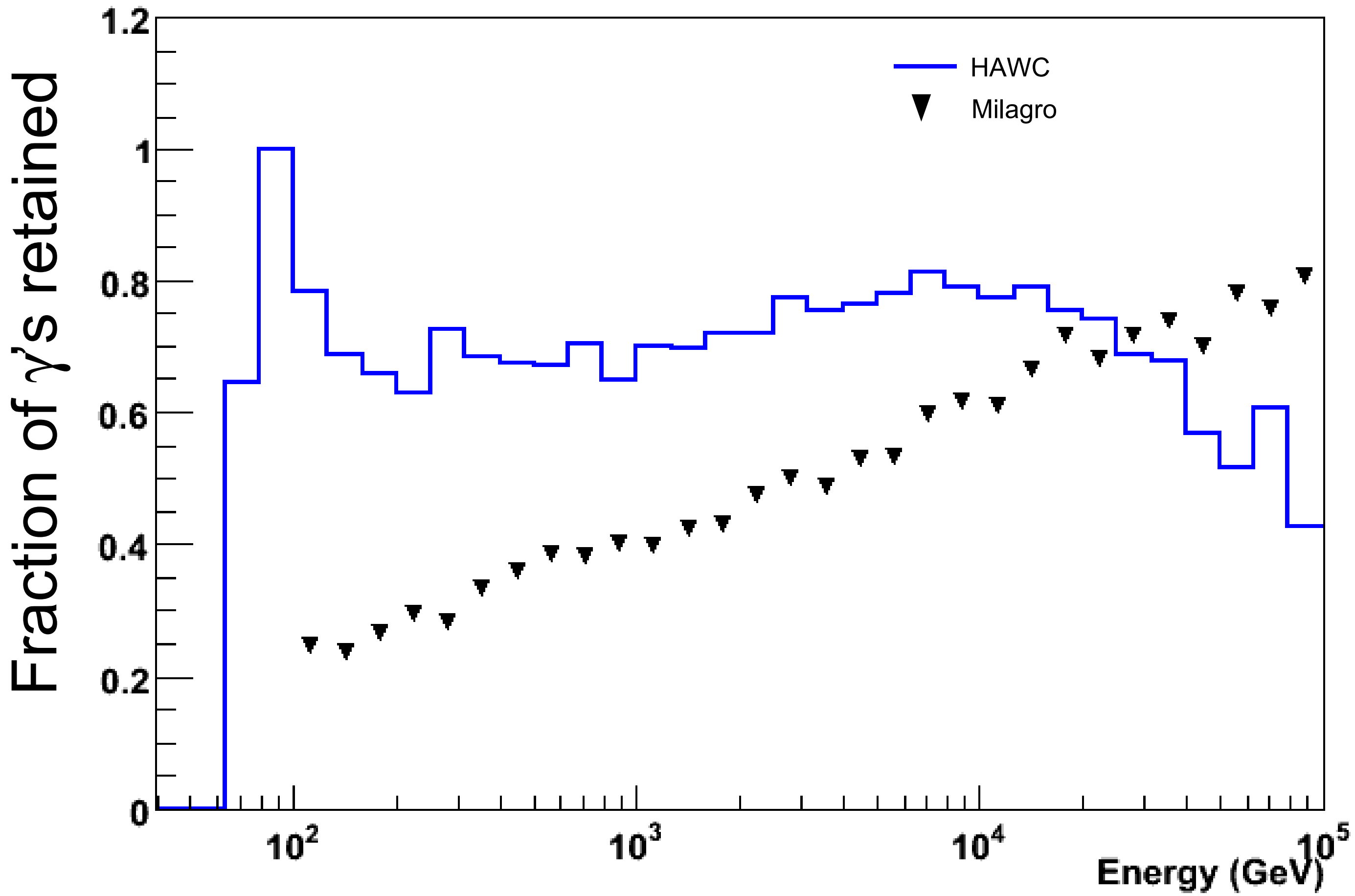


Size of Milagro deep layer



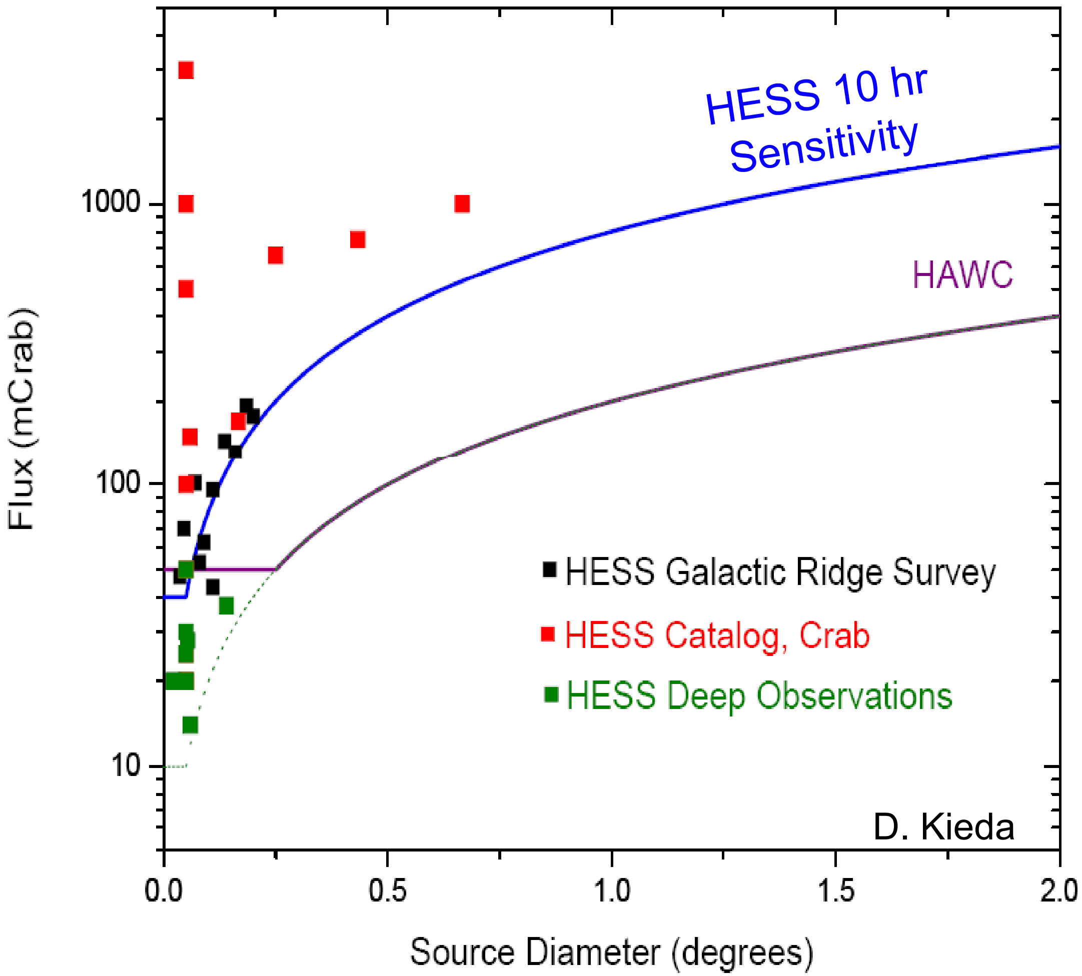

Energy Distribution at ground level

# Background Rejection in HAWC




By excluding region near core (30m) HAWC can retain low energy gamma events

# Sensitivity vs. Source Size




Large, low surface brightness sources require large fov and large observation time to detect.

$$S_{\text{extended}} \approx S_{\text{point}} \frac{\sigma_{\text{source}}}{\sigma_{\text{detector}}}$$

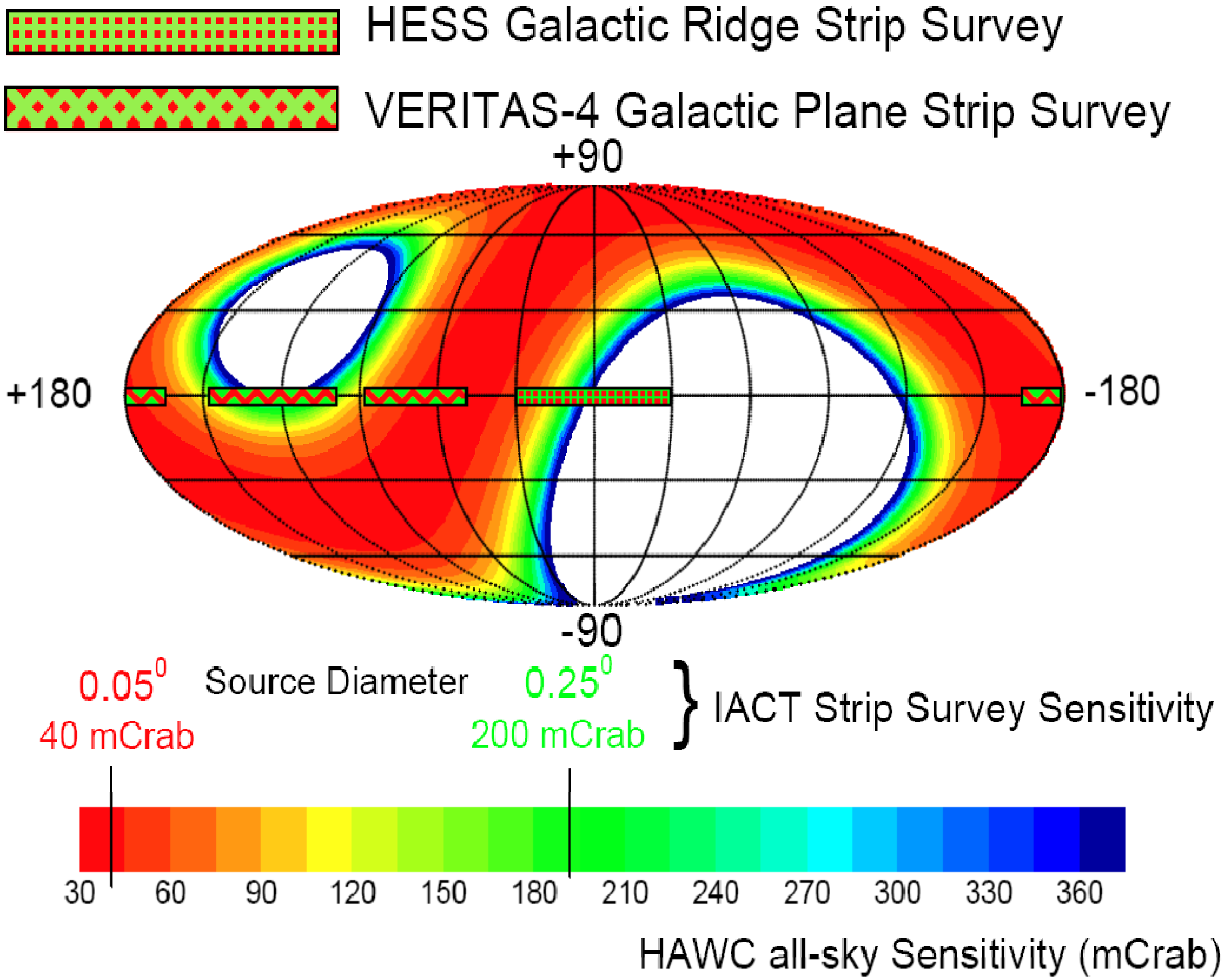
EAS arrays obtain >1000 hrs/yr observation for every source.

Large fov (2 sr):

Entire source & background simultaneously observable

Background well characterized

# HAWC Sky Survey

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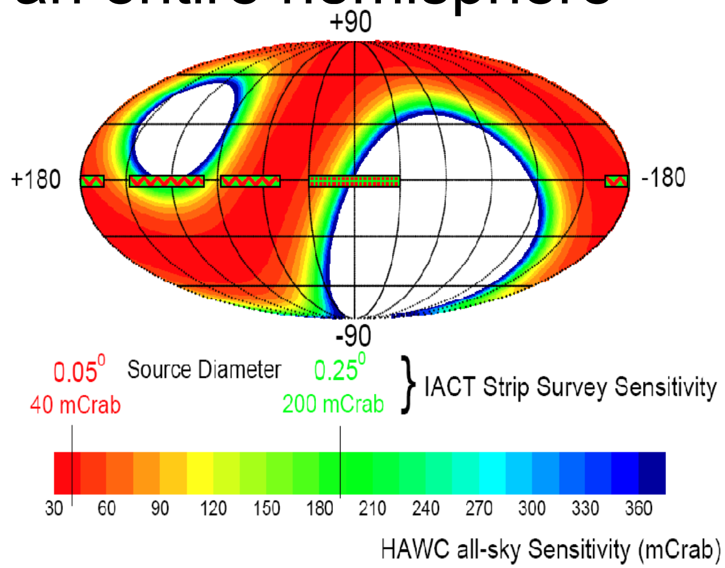
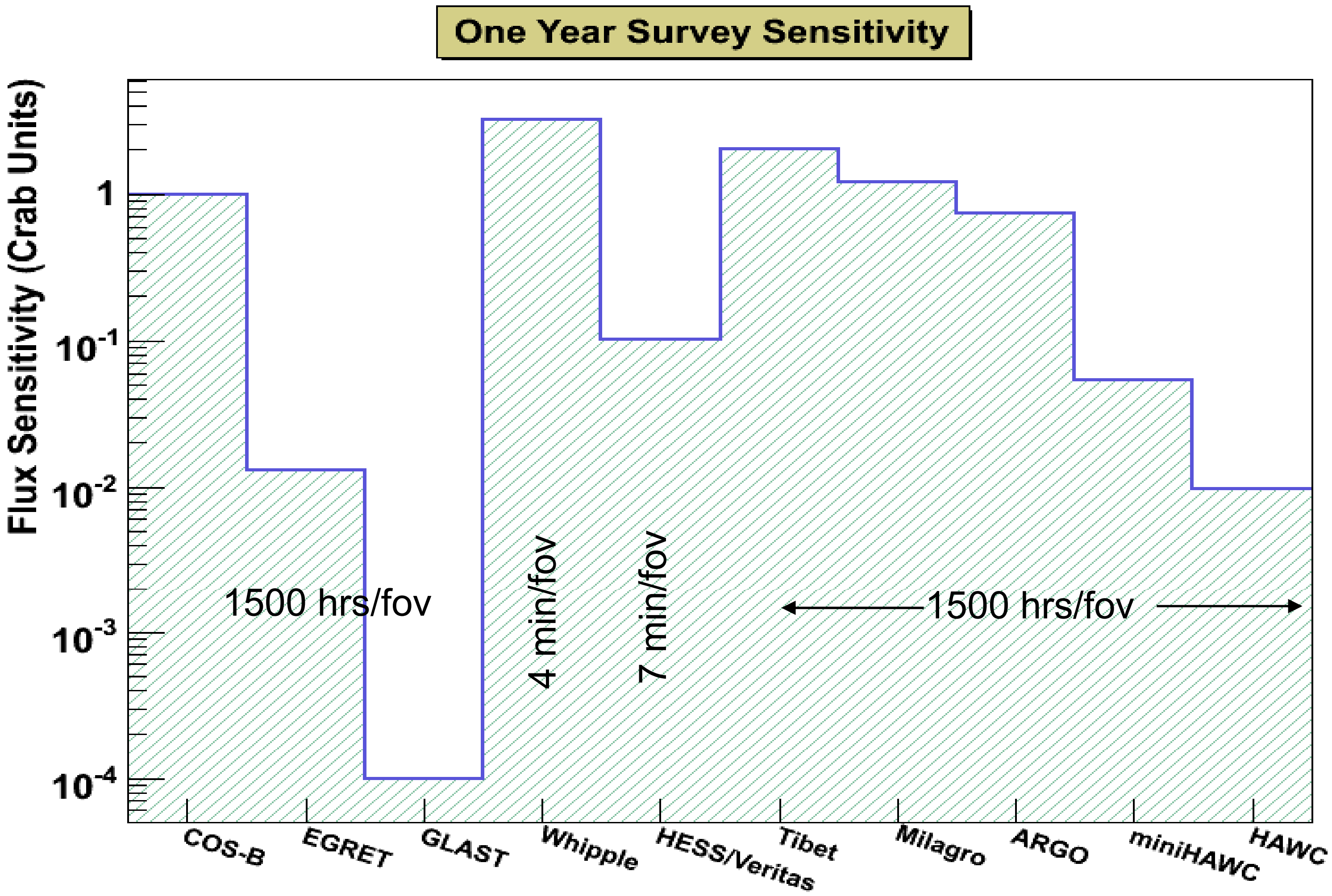
# Conclusion

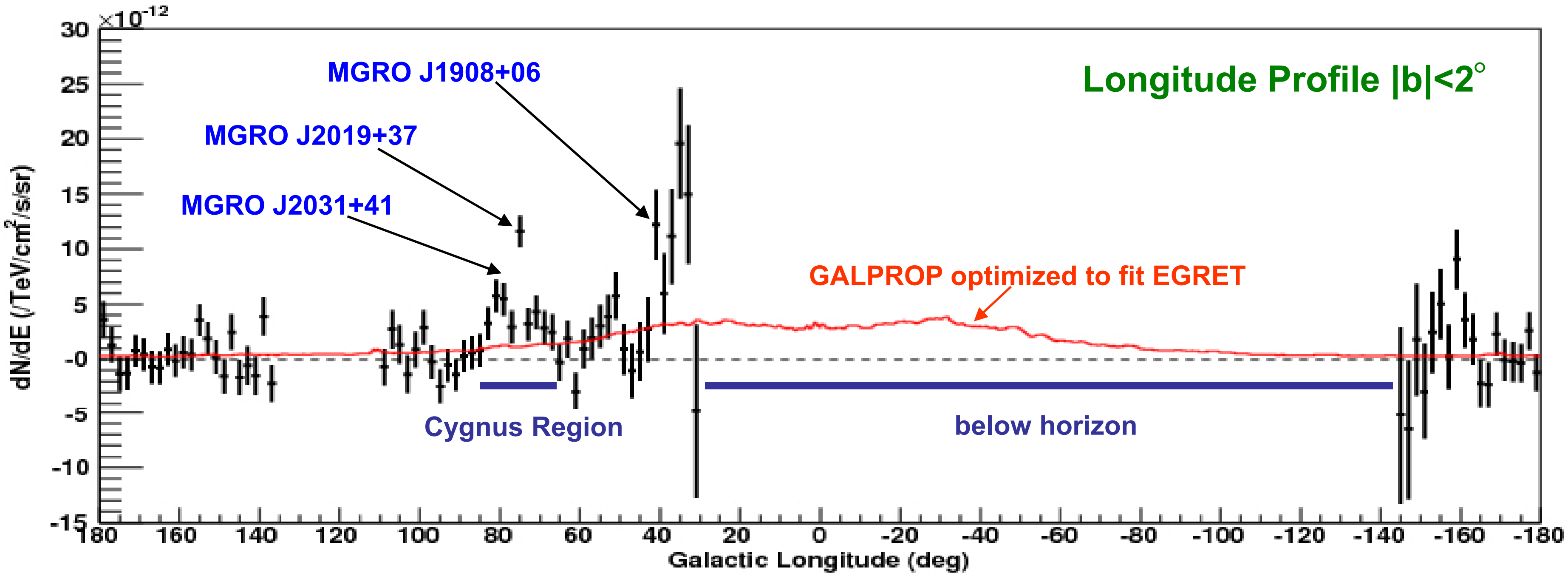
- Enormous progress has been made in the past decade in TeV survey technology
  - Discovery of diffuse TeV gamma rays from the Galactic plane
  - Discovery of diffuse TeV gamma rays from the Cygnus region
  - Discovery of 3 Galactic TeV sources
  - Likely detection of Geminga at 10-20 TeV
  - Strong correlation between TeV sources and GeV catalog (and PWN)
- HAWC can attain high sensitivity over an entire hemisphere
  - ~15 times the sensitivity of Milagro
  - ~5 sigma/√day on the Crab
  - 30 mCrab sensitivity over hemisphere
  - Unsurpassed sensitivity to extended sources
  - Study Galactic diffuse emission
  - Unique TeV transient detector
    - (4*x* Crab in 15 minutes)



# Survey Sensitivity

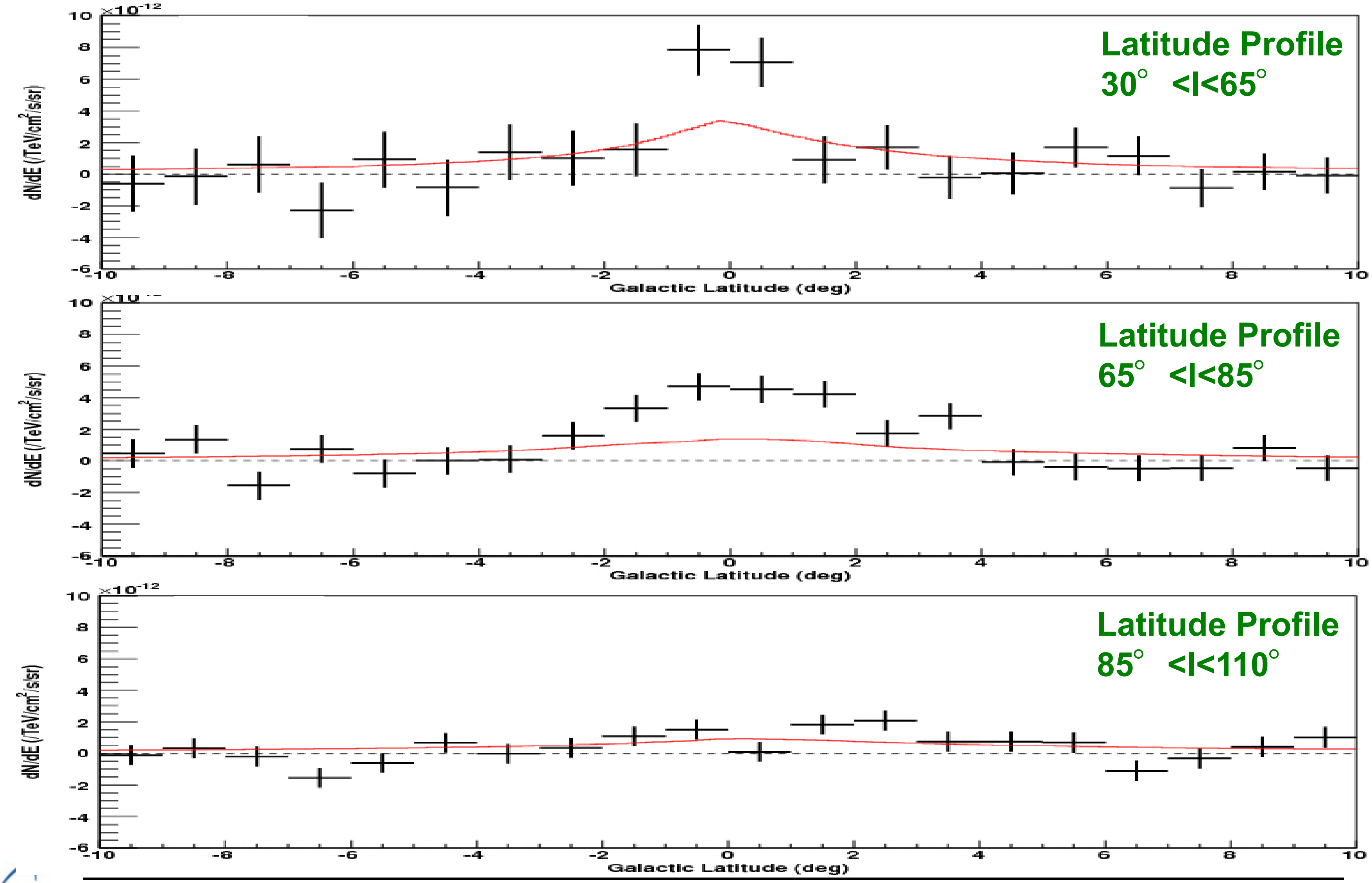


# Galactic Longitude Flux Profile




- Flux calculations assume a Crab spectrum (-2.62)
- Milagro measurements at 12 TeV (first detection above 20 GeV)
- There is an excess of diffuse TeV gamma rays from the Galactic plane
  - Additional unresolved sources?
  - Cosmic-ray acceleration sites?

# Galactic Latitude Flux Profiles

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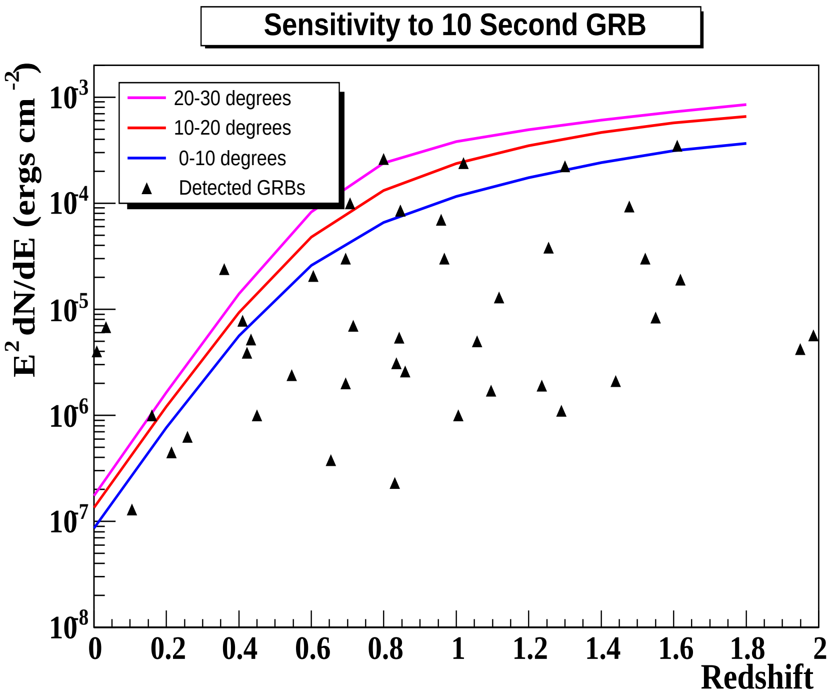
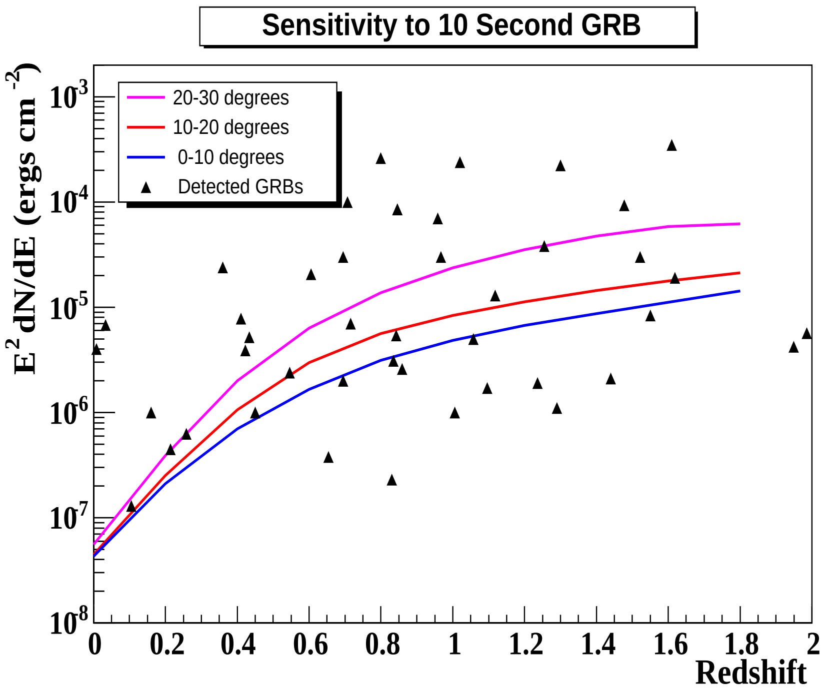
RICAP, Rome June 2007

# GRB Sensitivity

Milagro




HAWC

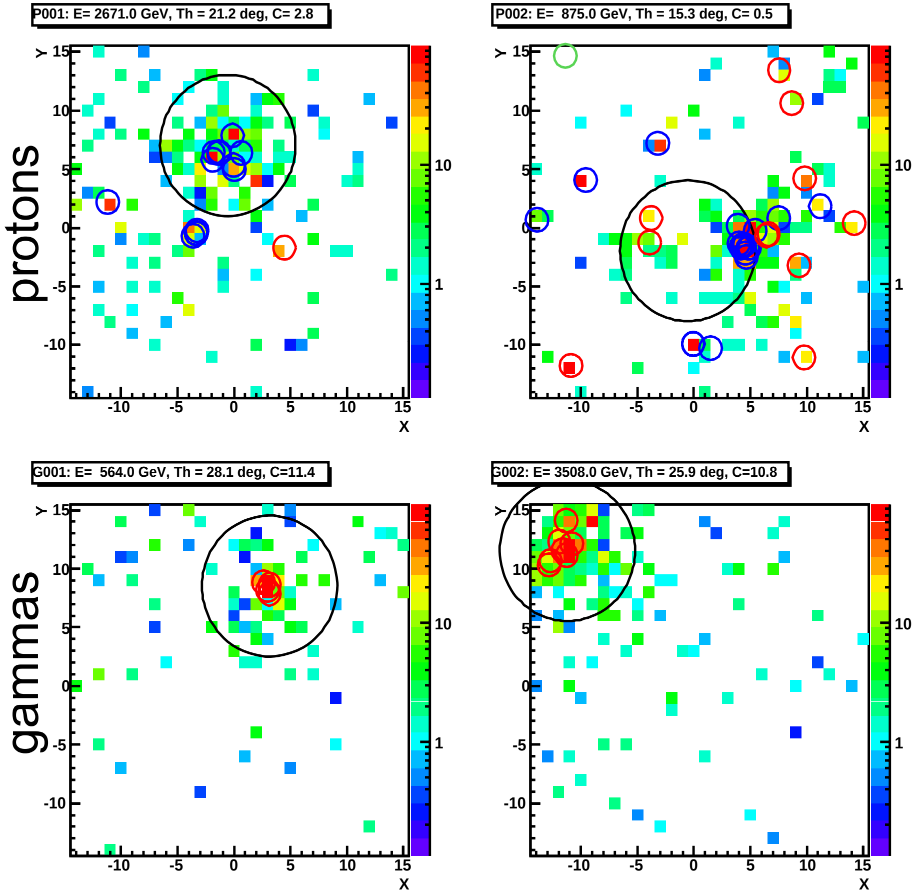


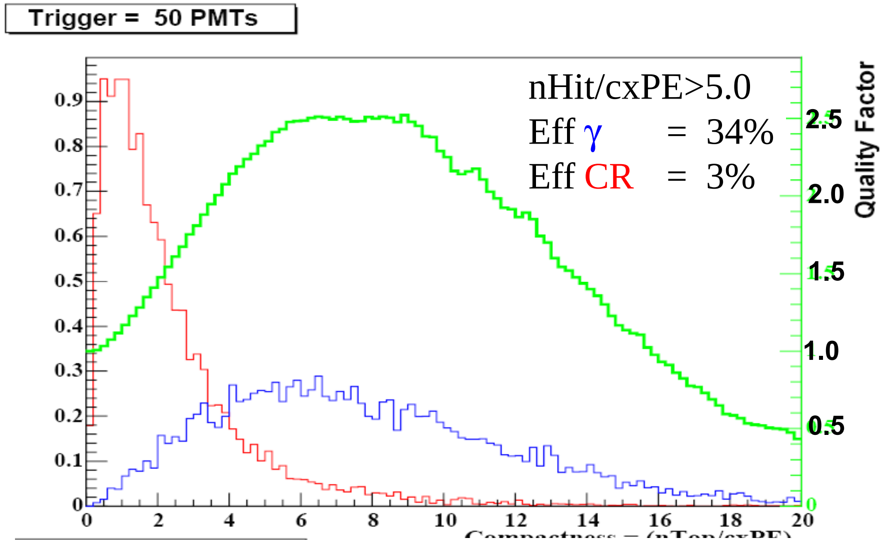

Fluence Sensitivity to 10s GRB.

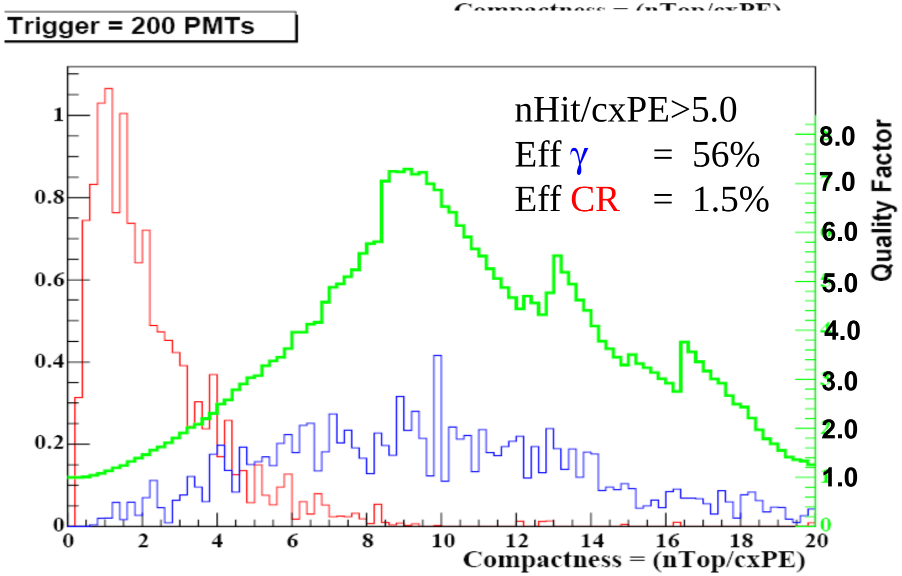
Both Milagro and HAWC can "self trigger" and generate alerts in real time.

GRB rate in FOV ~100 GRB/year (BATSE rate)

# Background Rejection




Circles are EM particles > 1 GeV

Circles are μ's & hadrons > 1 GeV

Circles are 30m radius (~area of Milagro μ layer)

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