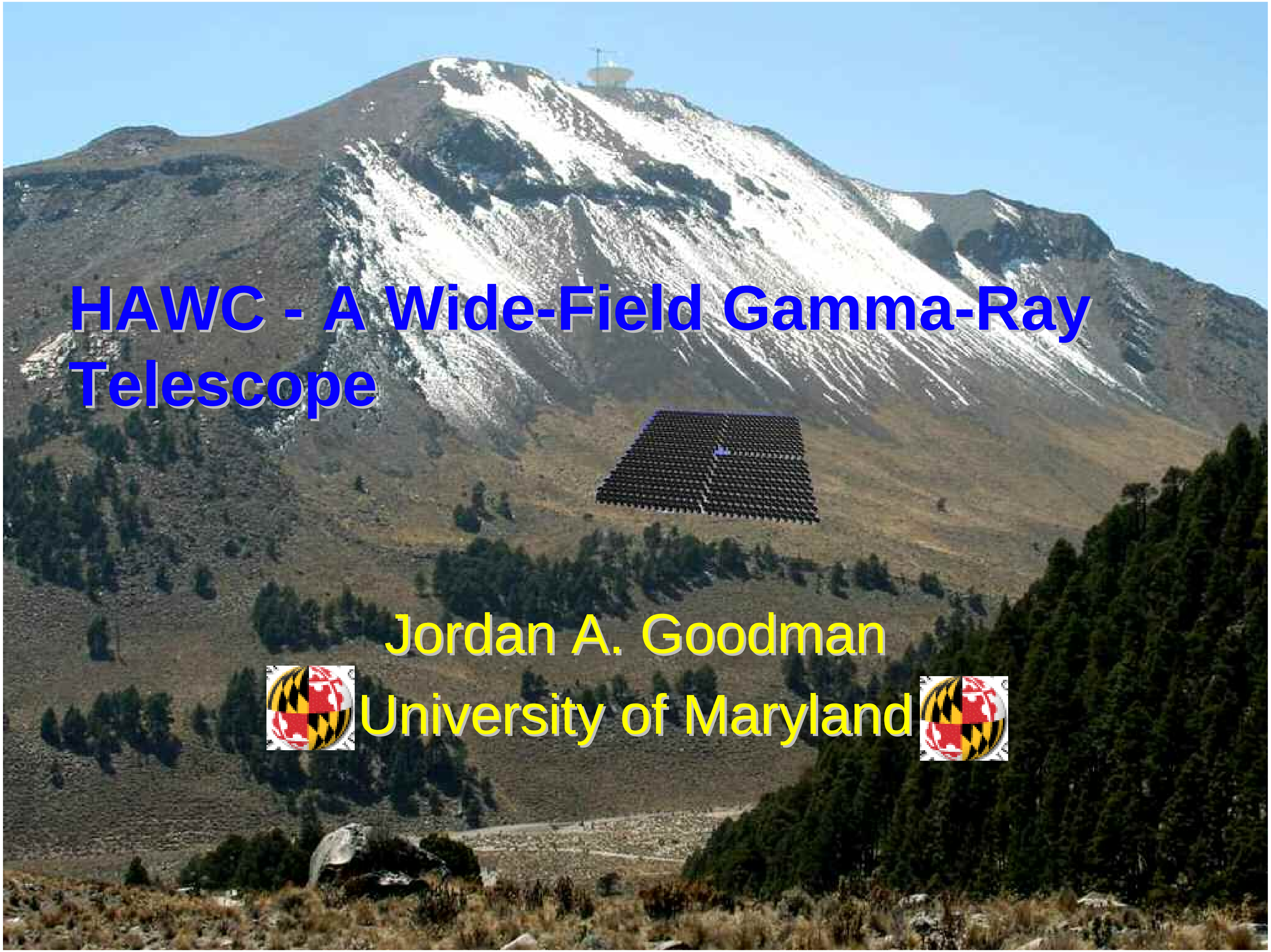


HAWC - A Wide-Field Gamma-Ray Telescope

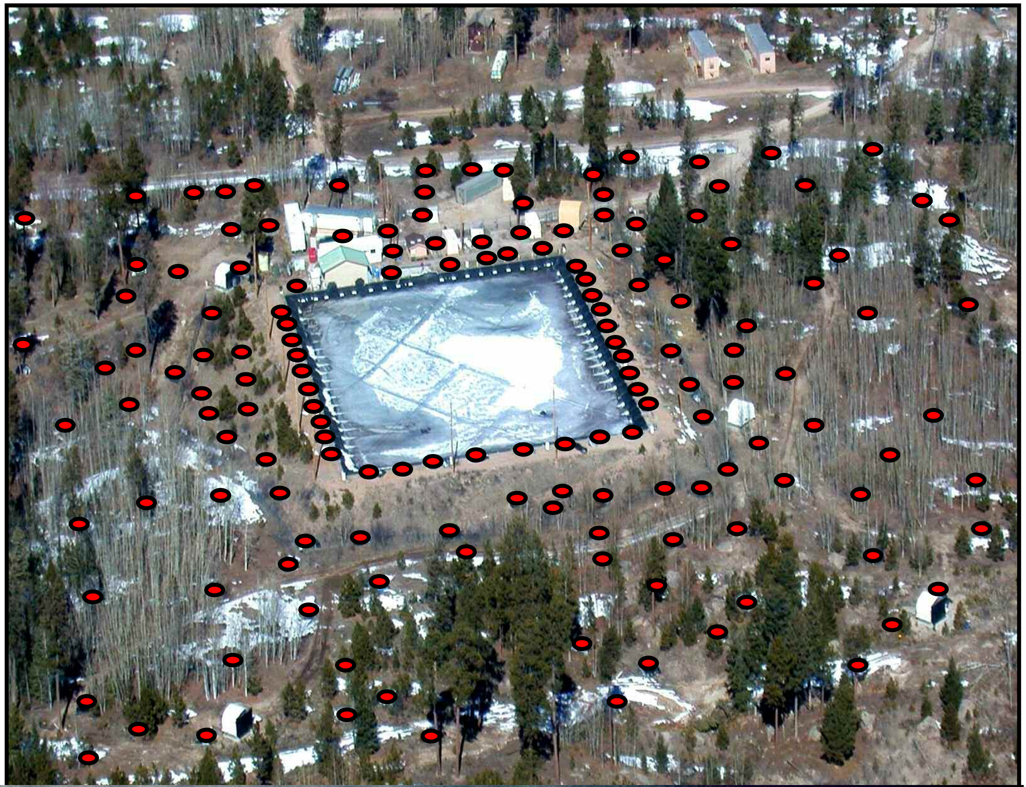
Jordan A. Goodman
University of Maryland

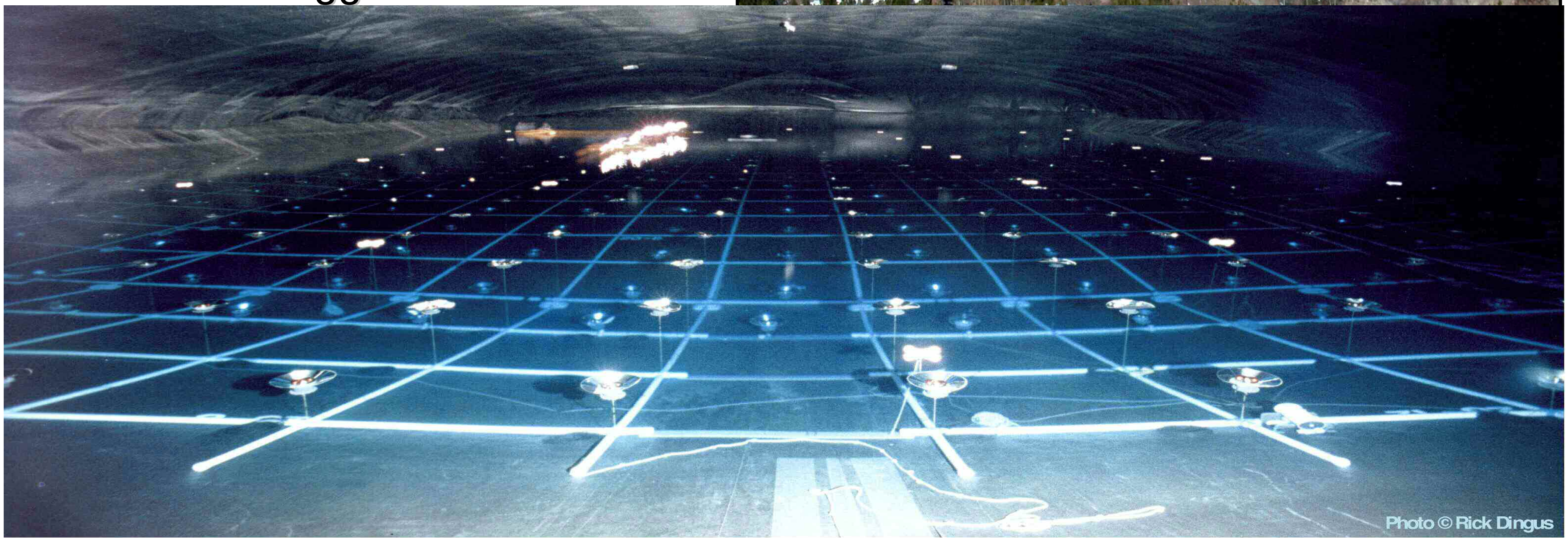
Complementarity of TeV Gamma-Ray Detectors

Imaging Air Cherenkov Telescopes	Extensive Air Shower Arrays
	
Energy Range .05-50 TeV	Energy Range 0.1-100 TeV
Area > 10^4 m^2	Area > 10^4 m^2
Background Rejection > 99%	**Background Rejection > 95%**
Angular Resolution 0.05°	**Angular Resolution 0.3° - 0.7°**
Energy Resolution ~15%	**Energy Resolution ~50%**
Aperture 0.003 sr	**Aperture > 2 sr**
Duty Cycle 10%	**Duty Cycle > 90%**
High Resolution Energy Spectra	Unbiased Complete Sky Survey
Precision Study of Known Sources	Extended Sources
Source Location & Morphology	Transient Objects (GRB's)
Deep Surveys of Limited Regions of Sky	Multi-Wavelength/Messenger Observations

Milagro

- Water Cherenkov Detector
- 2600m asl
- 898 detectors
  - 450(t)/273(b) in pond
  - 175 water tanks
- 4000 m^2 / 4.0×10^4 m^2
- 2-20 TeV median energy
- 1700 Hz trigger rate

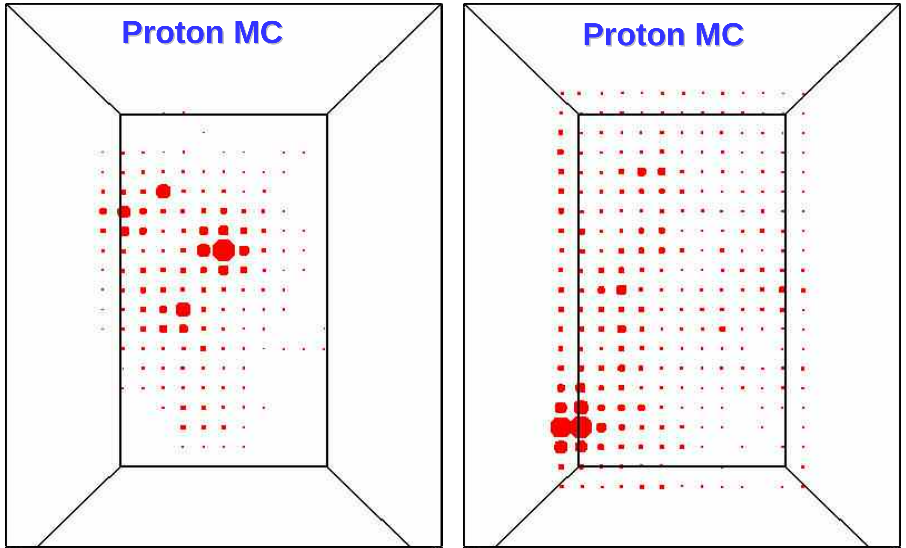


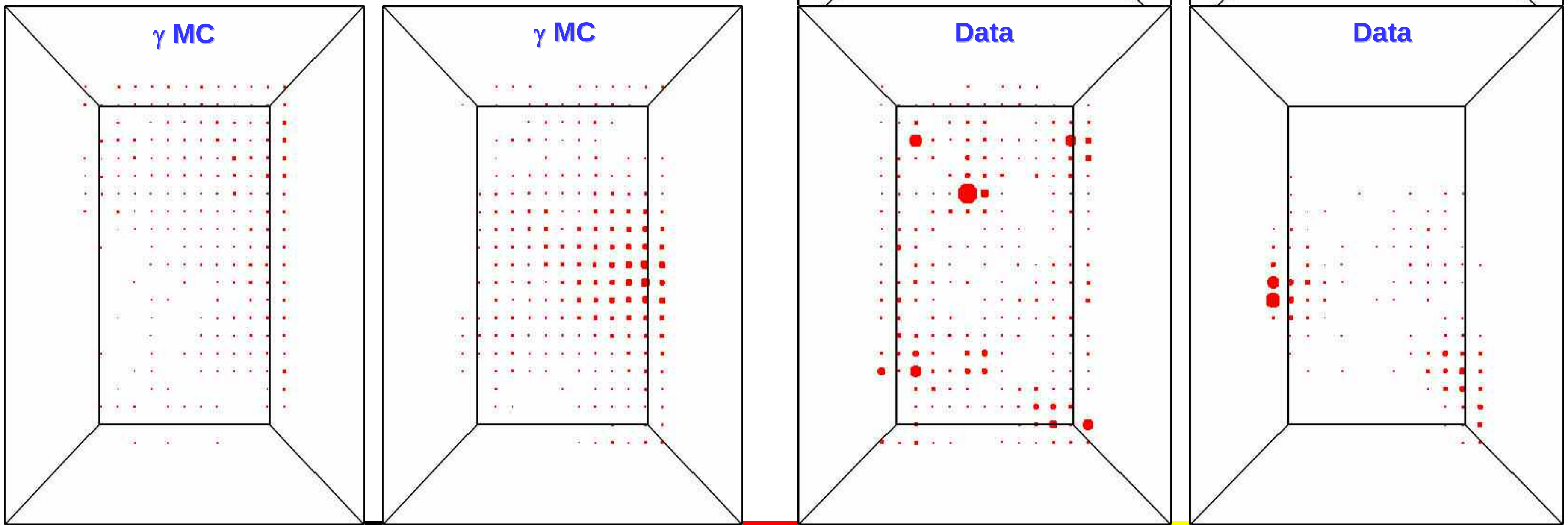


Background Rejection in Milagro

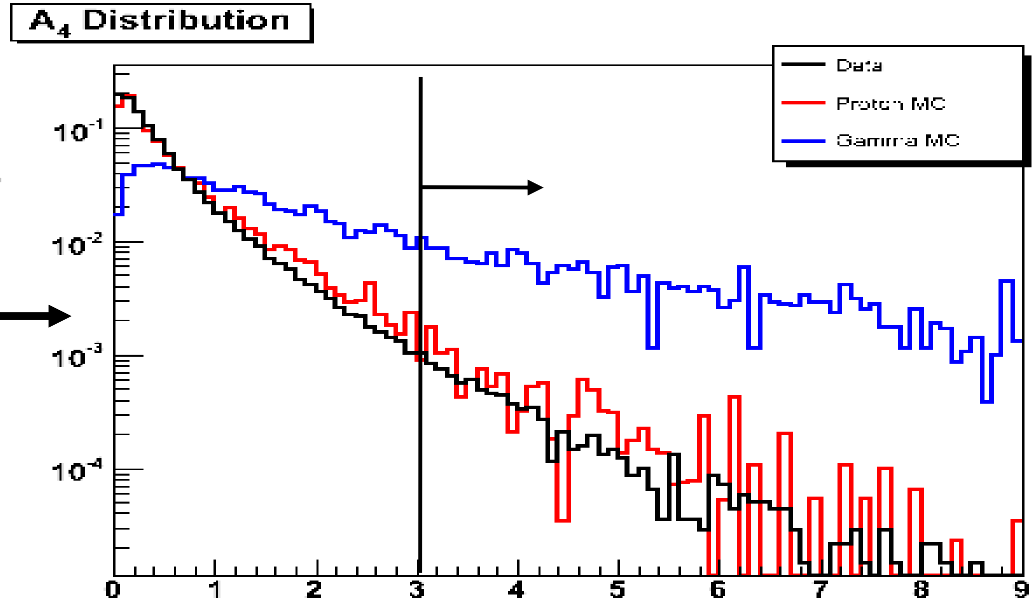
Hadronic showers contain penetrating component: μ's & hadrons

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





Background Rejection (Cont'd)



Background Rejection Parameter

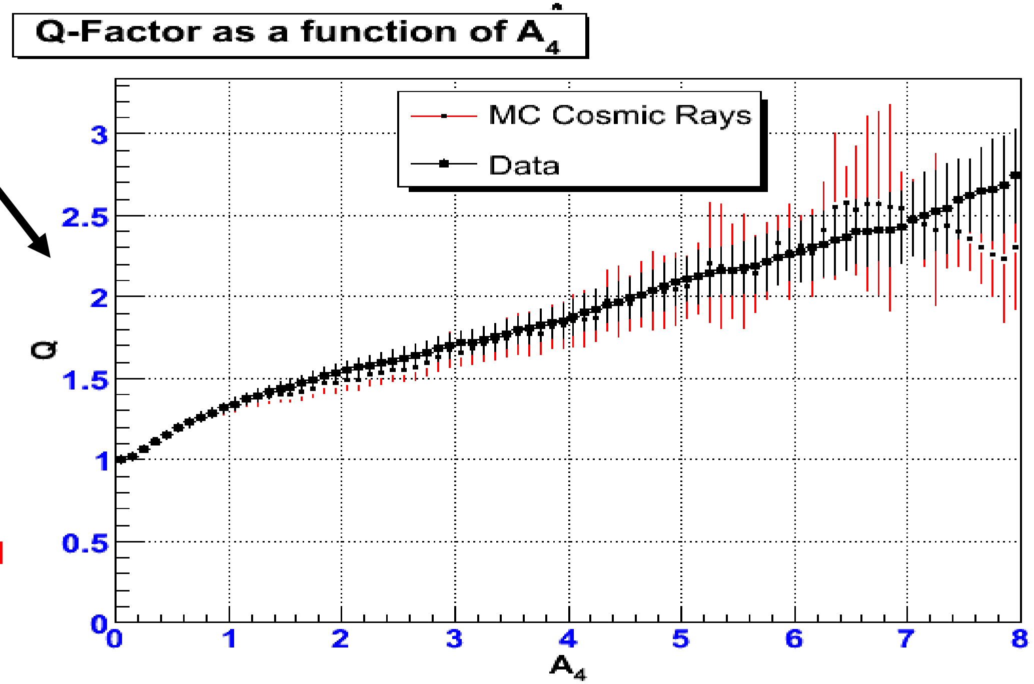
$$A_4 = \frac{(fTop + fOut) * nFit}{mxPE}$$

Apply a cut on A_4 to reject hadrons:

$A_4 > 3$ rejects 99% of Hadrons

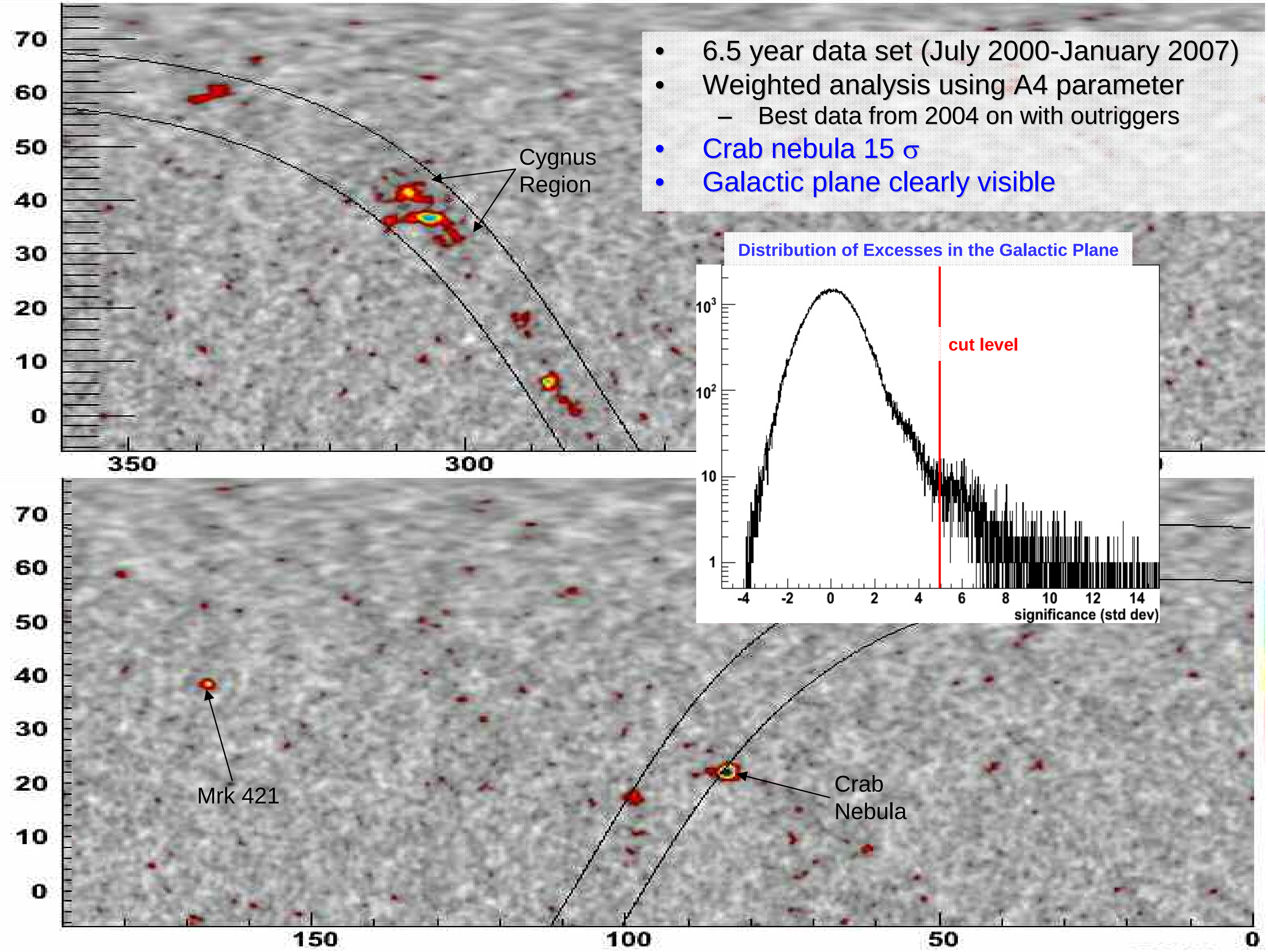
retains 18% of Gammas

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

- 6.5 year data set (July 2000-January 2007)
- Weighted analysis using A4 parameter
  - Best data from 2004 on with outriggers
- Crab nebula 15 σ
- Galactic plane clearly visible



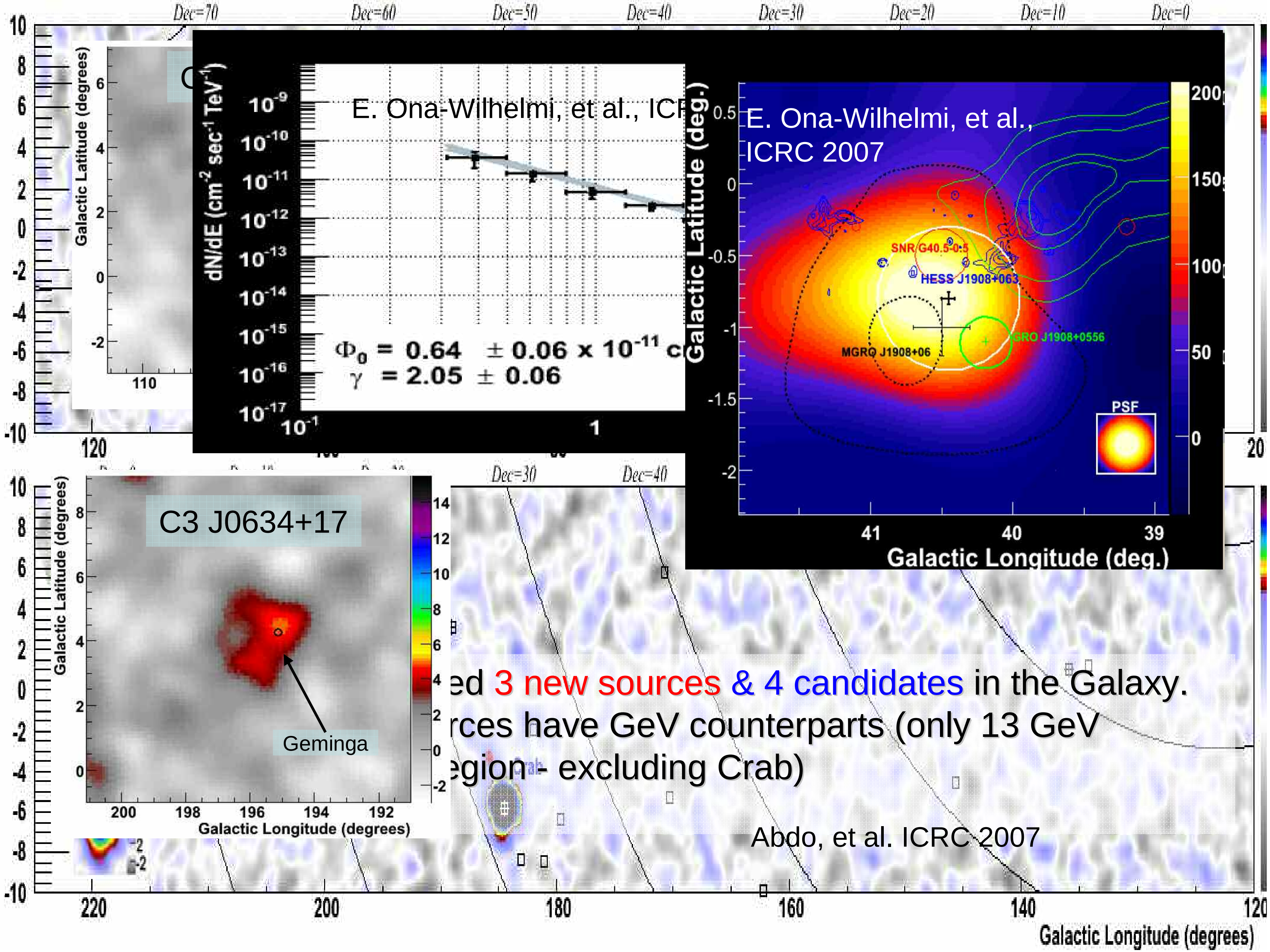
Galactic Plane Survey Summary

>4.5σ post-trials

>4.5σ pre-trials

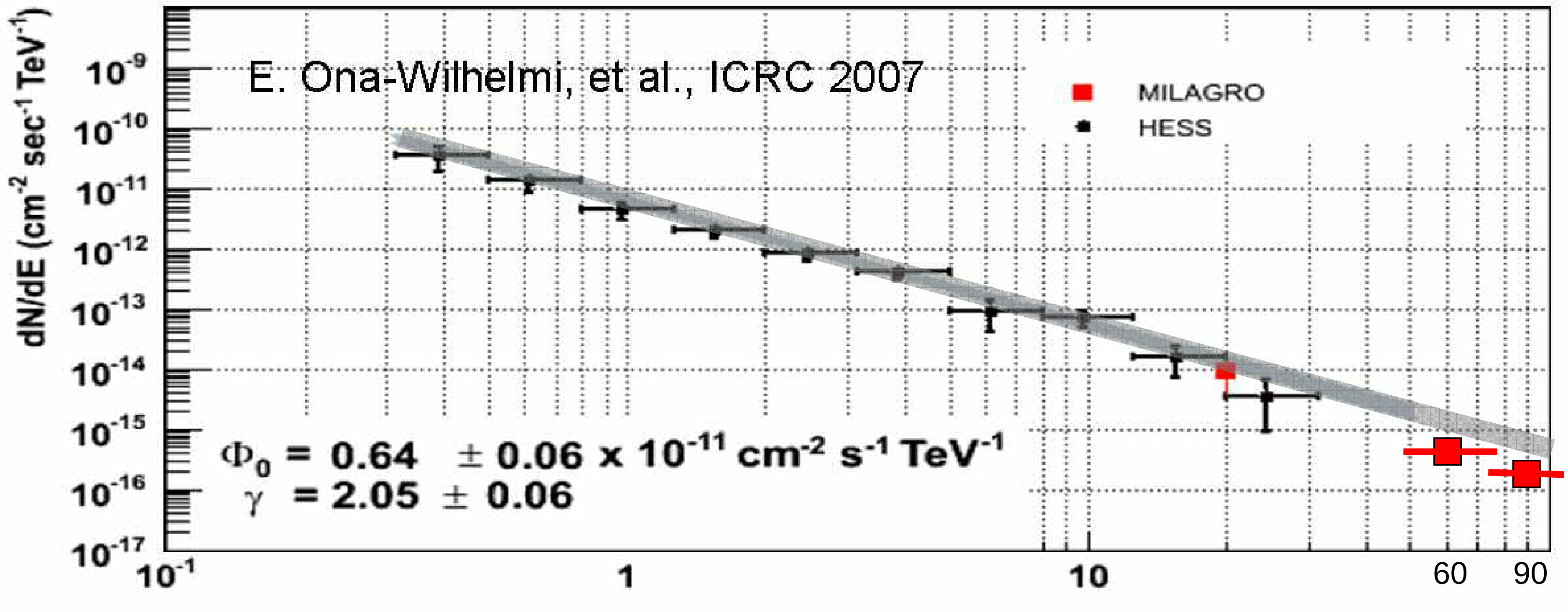
Object	[2]Location (l, b)	Counterpart ?	Pre(Post)-Trial Significance	Flux @20 TeV ($\times 10^{-15}$) ($/TeV/cm^2/s$)
Crab	184.5, -5.7		**15.0σ** (14.3σ)	$10.9 \pm 1.2_{stat}$
MGRO J2019+37	75.0, 0.2	PWN G75.2+0.1 GeV J2020+3658	**10.4σ** (9.3σ)	$8.7 \pm 1.4_{stat}$
MGRO J1908+06	40.4, -1.0	GeV J1907+0557 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 Boomerang PWN SNR G106.6+2.9	5.0σ (2.7σ)	$3.5 \pm 1.2_{stat}$

~100,000 trials taken for Galactic Survey

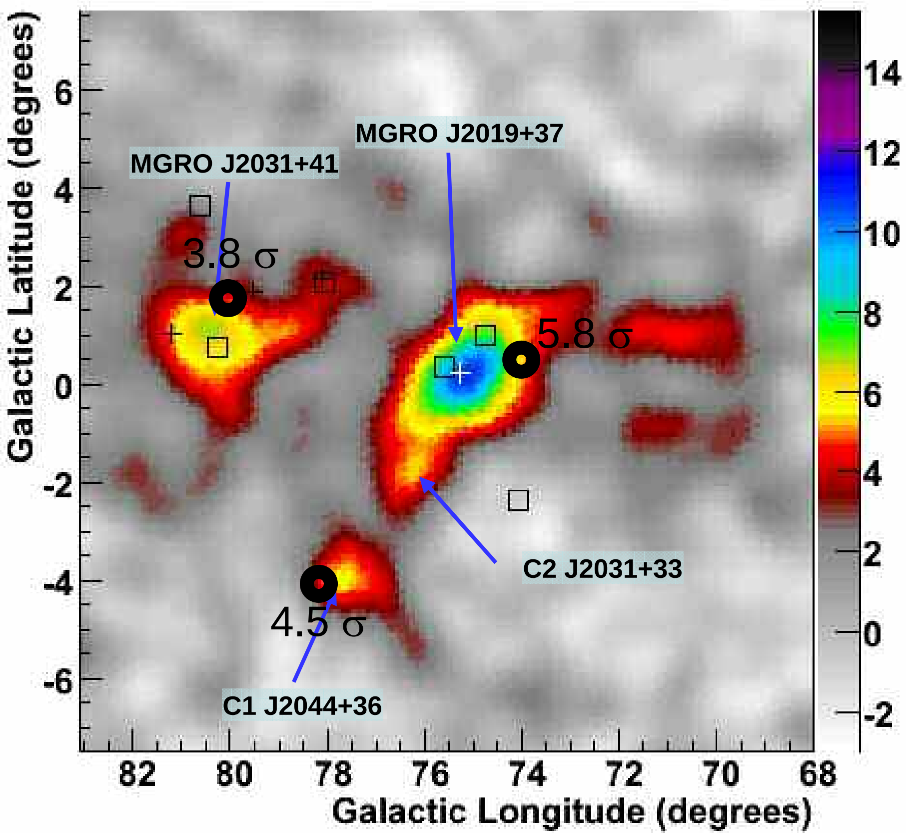

E. Ona-Wilhelmi, et al., ICR
Φ_0 = 0.64 ± 0.06 x 10^{-11} c
γ = 2.05 ± 0.06
dN/dE (cm^{-2} sec^{-1} TeV^{-1})
E. Ona-Wilhelmi, et al., ICRC 2007
SNR G40.5-0.5
HESS J1908+063
MGRO J1908+06
GRO J1908+0556
PSF
Galactic Latitude (deg.)
Galactic Longitude (deg.)
C3 J0634+17
Geminga
Galactic Latitude (degrees)
Galactic Longitude (degrees)
...ed 3 new sources & 4 candidates in the Galaxy.
...rces have GeV counterparts (only 13 GeV
...egion - excluding Crab)
Abdo, et al. ICRC 2007

More on 1908+06 - *Preliminary*

Median energy for this angle and α=-2.0 is 50 TeV
Cut on A4> 4 & 9 gives median E of 60 and 90 TeV



The Cygnus Region

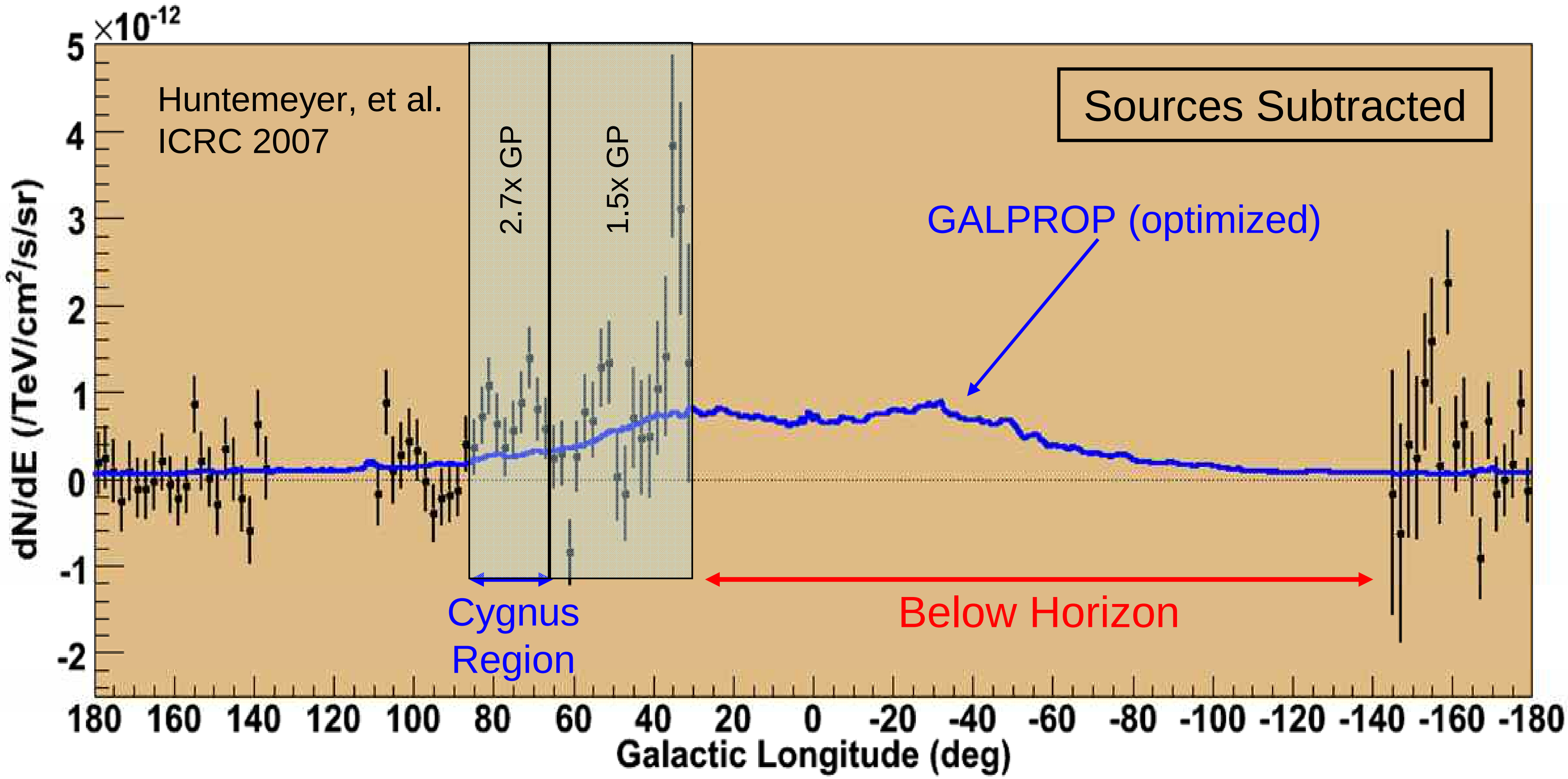


Abdo, et al. ICRC 2007

Wang, et al. ICRC 2007

- MGRO J2019+37: 10.9σ
  - 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
- Tibet ASγ preliminary detections of 3 sources

TeV Galactic Diffuse Emission

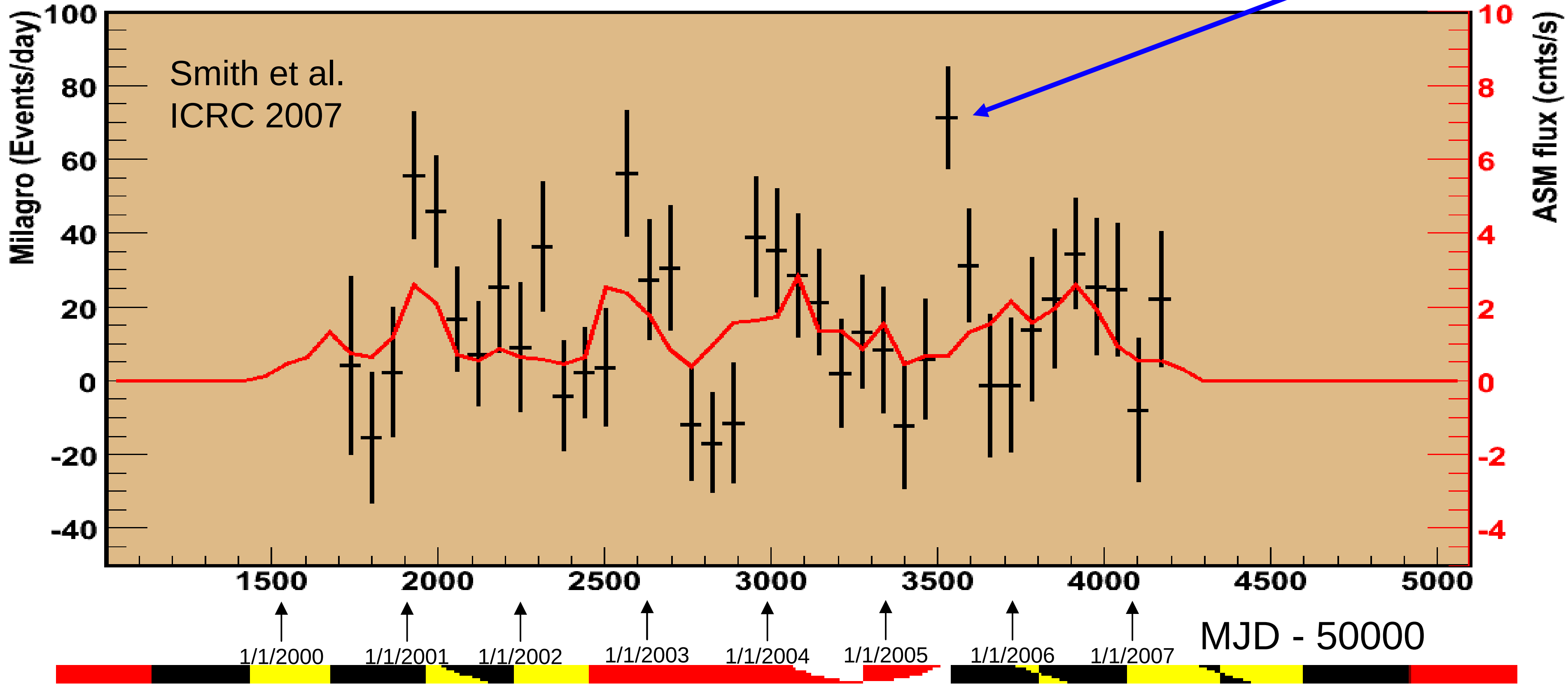


Mrk 421: 7 Year Multi-Wavelength Campaign

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

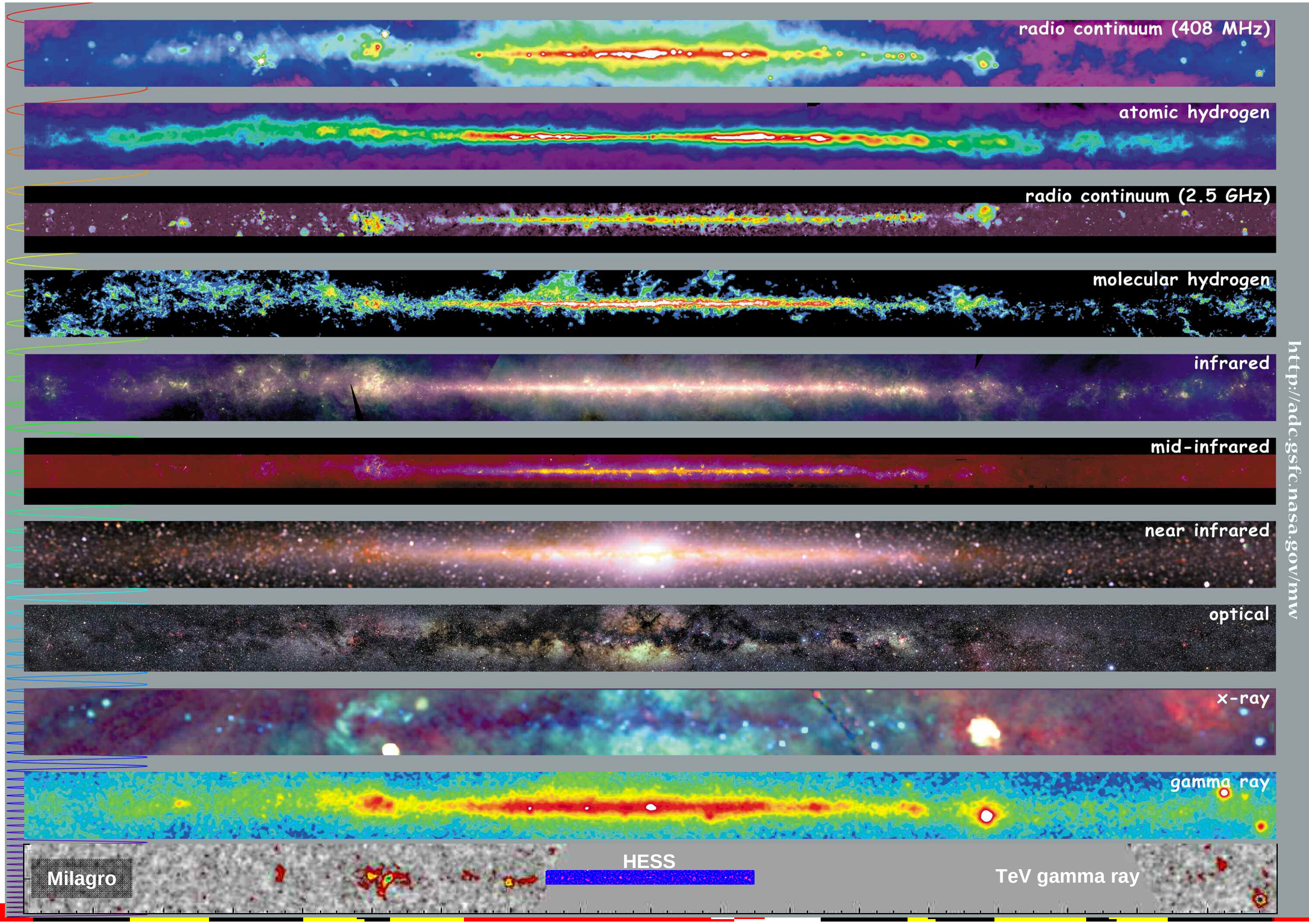
May-July 2005

5 σ excess during x-ray quiescent period



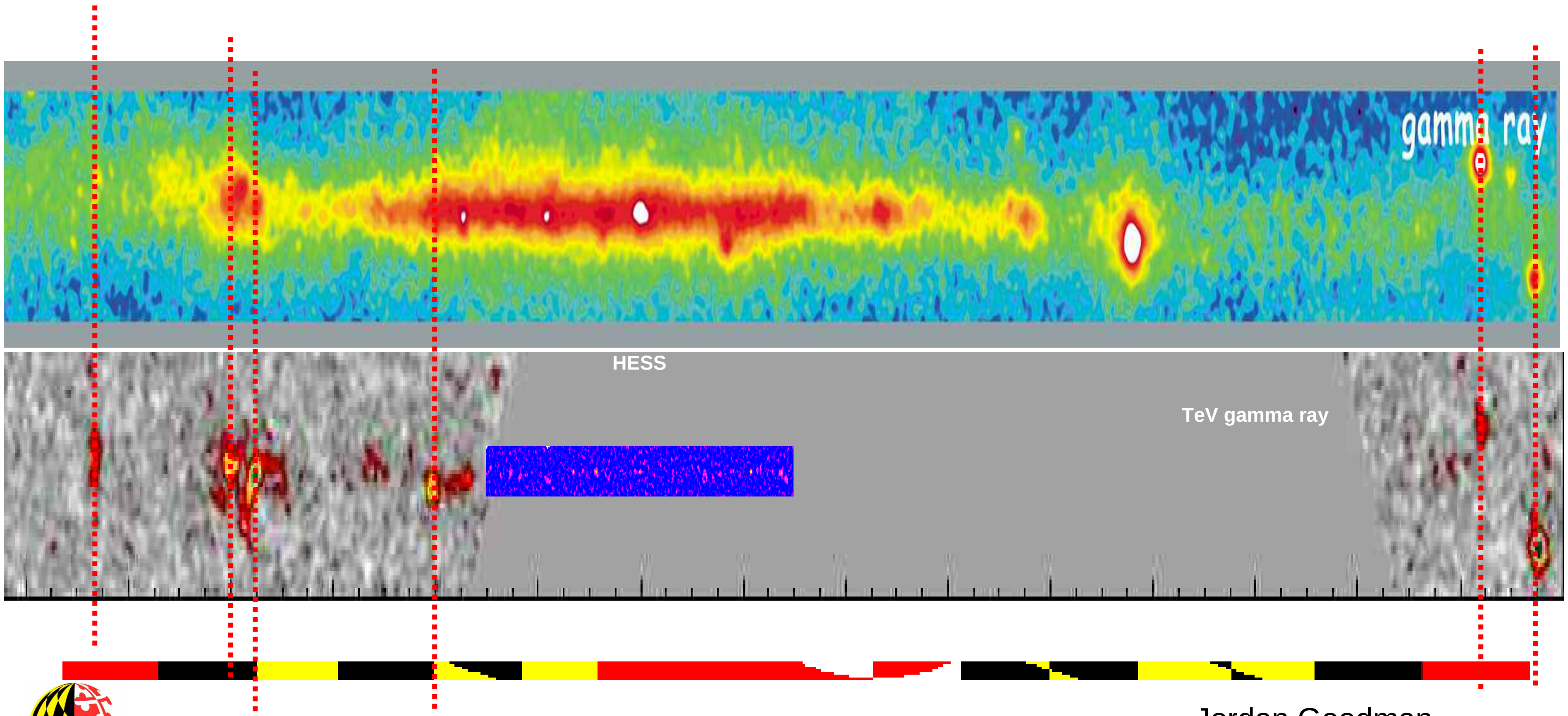
Jordan Goodman
TeV III Venice August 2007

TeV γ Rays: New Window for the Sky



Jordan Goodman
TeV III Venice August 2007

TeV γ Rays: New Window for the Sky



Jordan Goodman
TeV III Venice August 2007

HAWC: High Altitude Water Cherenkov

- Build detector at extreme altitude
  - Sierra Negra, Mexico 4100m
- Incorporate new design
  - PMTs in isolated tanks
  - 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

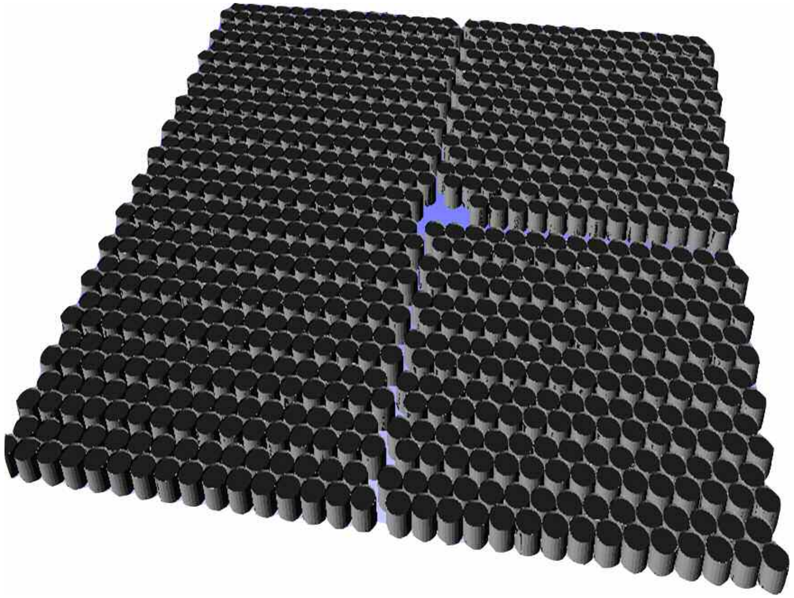
Crab Nebula in 1 day (4 hours) [Milagro 3-4 months]

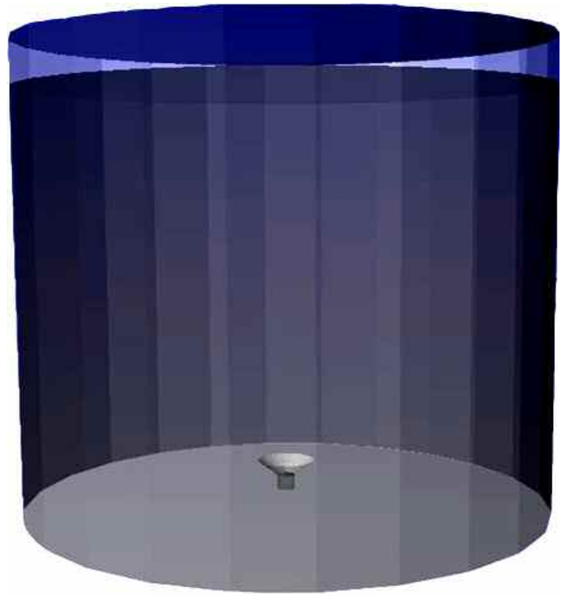
4x Crab flux in 15 minutes

GRBs to z < 0.8 (now 0.4)

From Milagro to HAWC

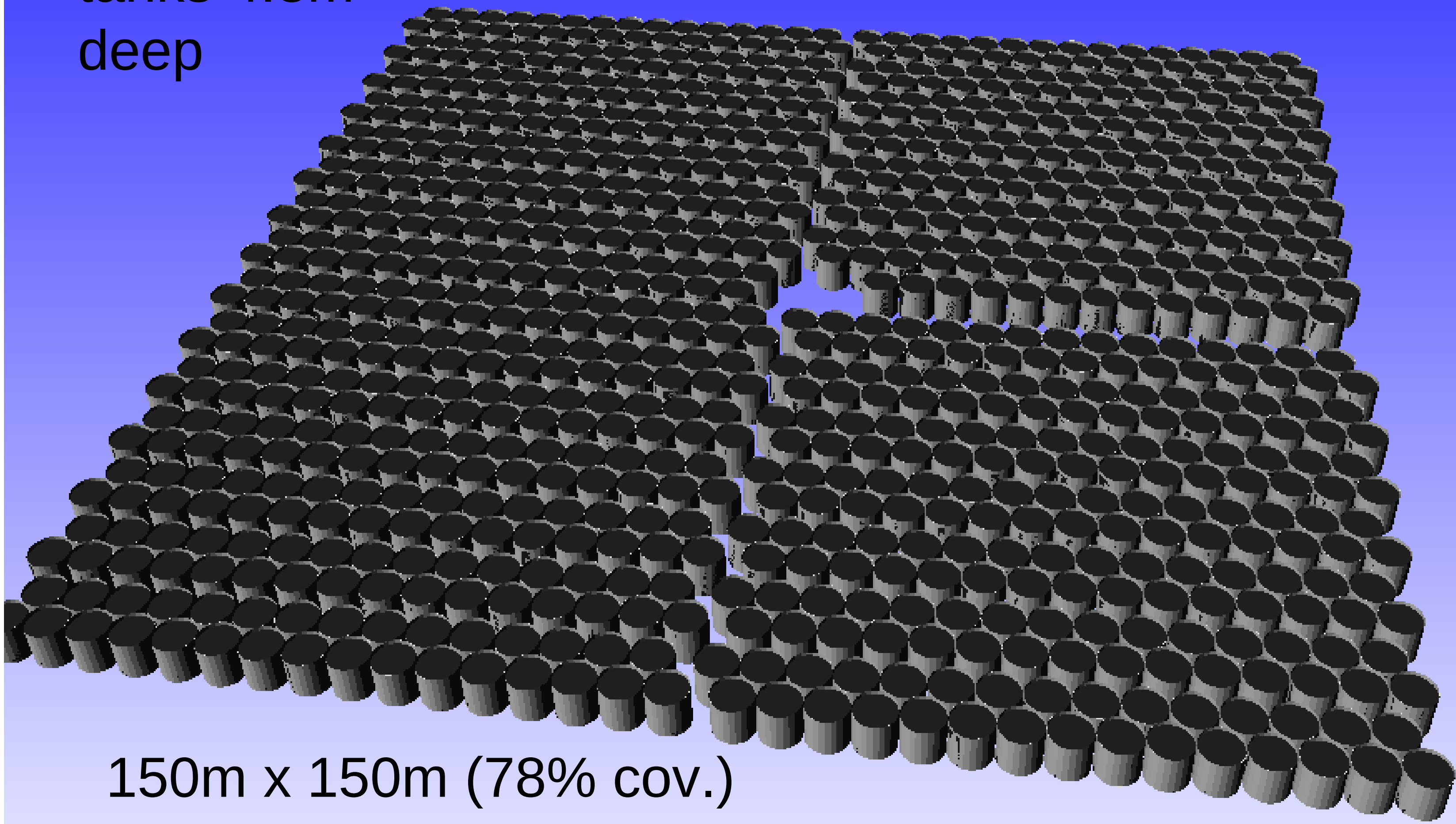
- Increase Altitude to 4100 m from 2650 m
- Increase Area to 22,000 m^2 from 4,000 m^2 (2,200m^2)
- Reuse Milagro PMTs and front end electronics - upgrade later?
- HAWC ~10x-15x Sensitivity of Milagro:
  - HAWC: Detect Crab in ~ 1 day (5σ)
  - Milagro: Detects Crab in 3 mo
- Better Sensitivity at Low Energy
  - ~100m^2 at 100-200 GeV





900 5m dia. tanks 4.3m deep

Reuse Milagro PMTs & FE elec.

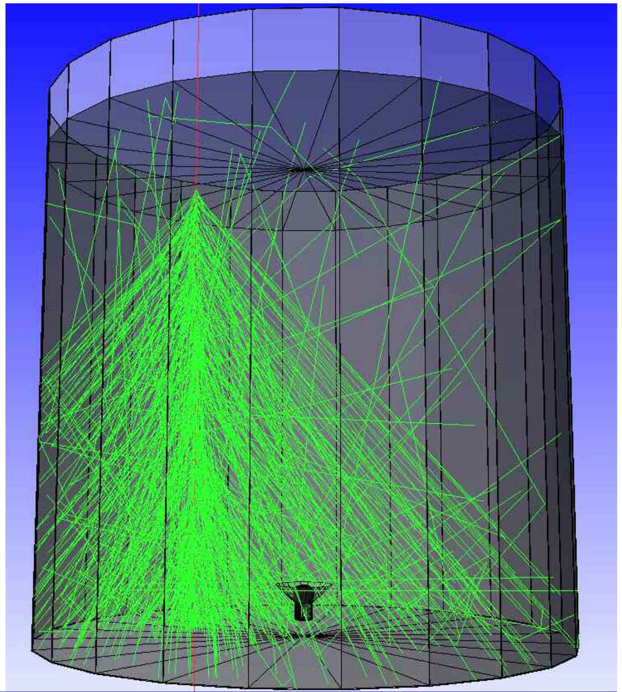


150m x 150m (78% cov.)

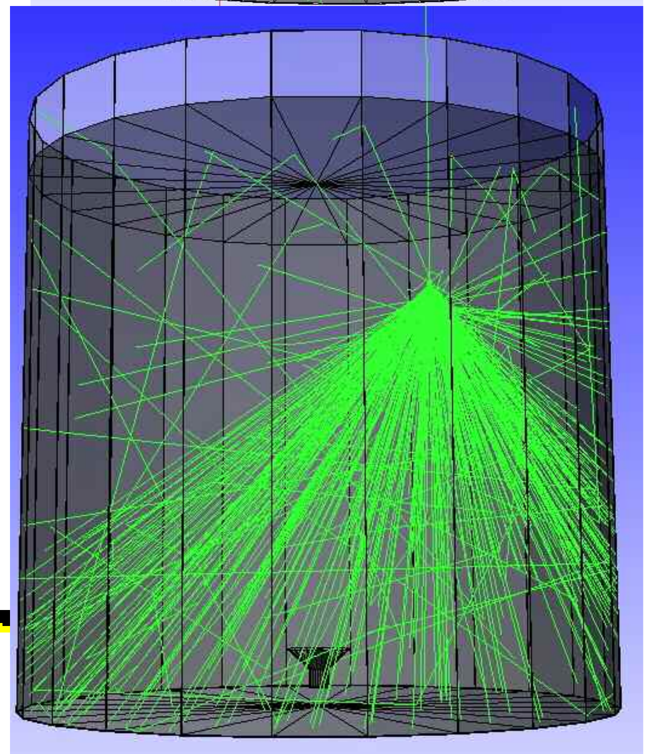
Tanks vs Pond

- Less expensive
- Build incrementally
  - Develop & debug as we are building
  - Water can be done incrementally as well
- Within 2 yrs it will be more sensitive than Milagro
- Expandable & upgradeable

Muon
thinned 1/50

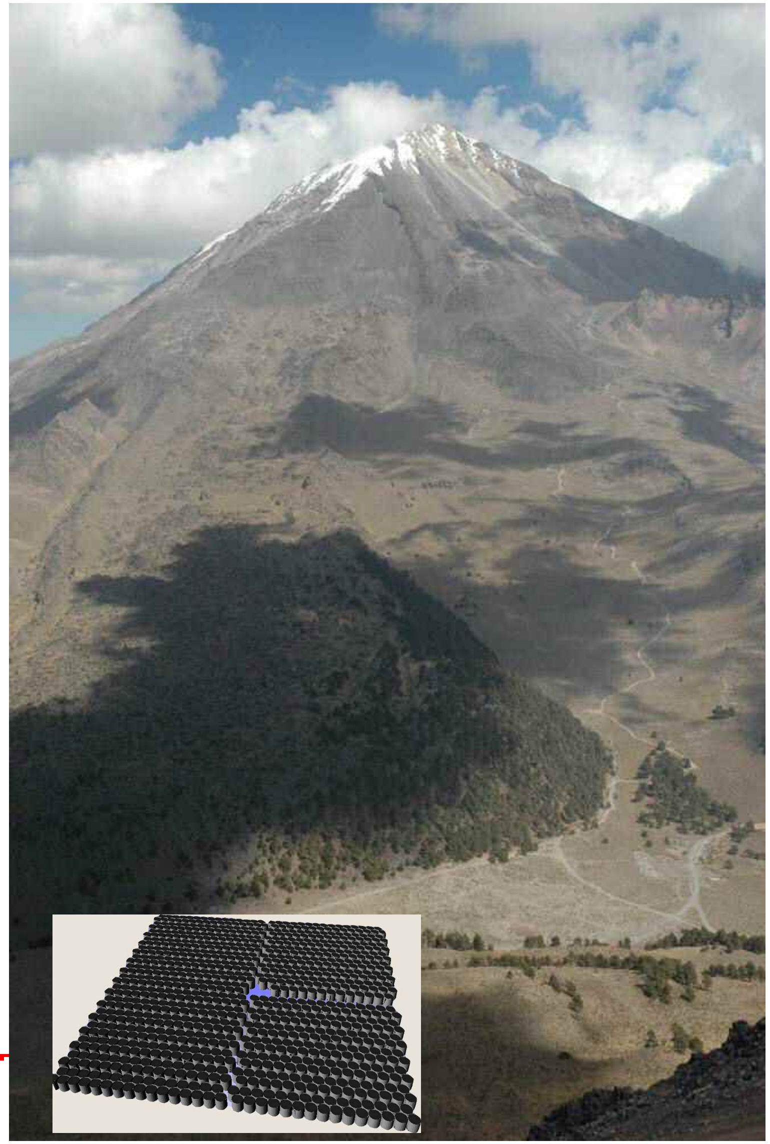


100 MeV γ
thinned 1/200



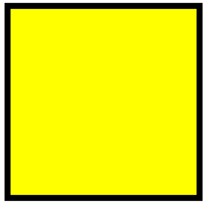
Site Location is Sierra Negra, Mexico

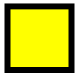
- 4100 m above sea level
- Easy Access
  - 2 hr drive from Puebla
  - 4 hr drive from Mexico City
- Existing Infrastructure
  - Few km from the US/Mexico Large Millimeter Telescope
  - Power, Internet, Roads
  - Sierra Negra Scientific Consortium of ~7 projects
- Excellent Mexican Collaborators
  - ~15 Faculty at 7 institutions have submitted proposal to CONACYT for HAWC
  - Experience in HEP, Auger, and astrophysics (including TeV)

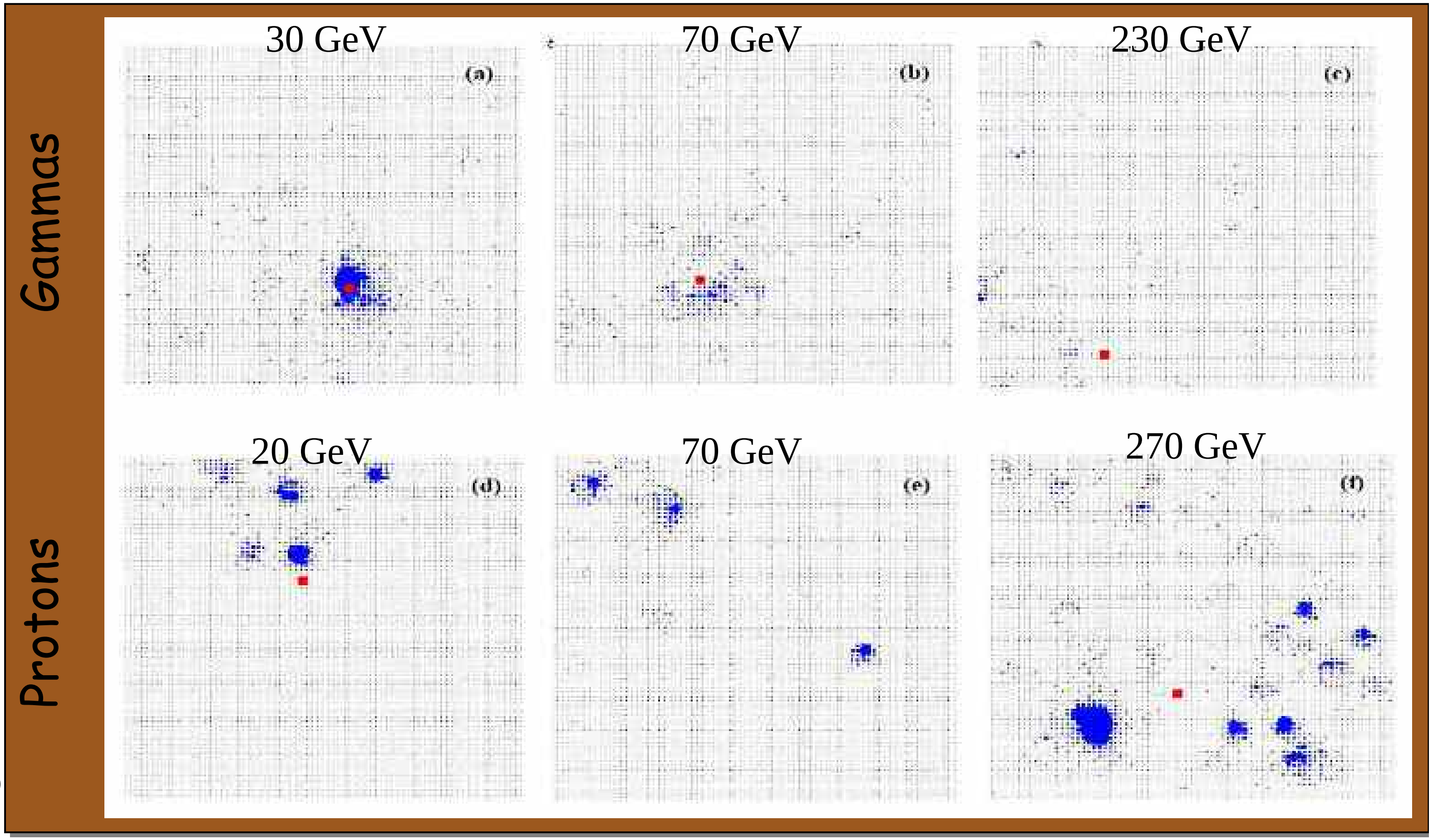


Gamma/Hadron Separation

Rejection factor ~ $e^{-<\mu>}$

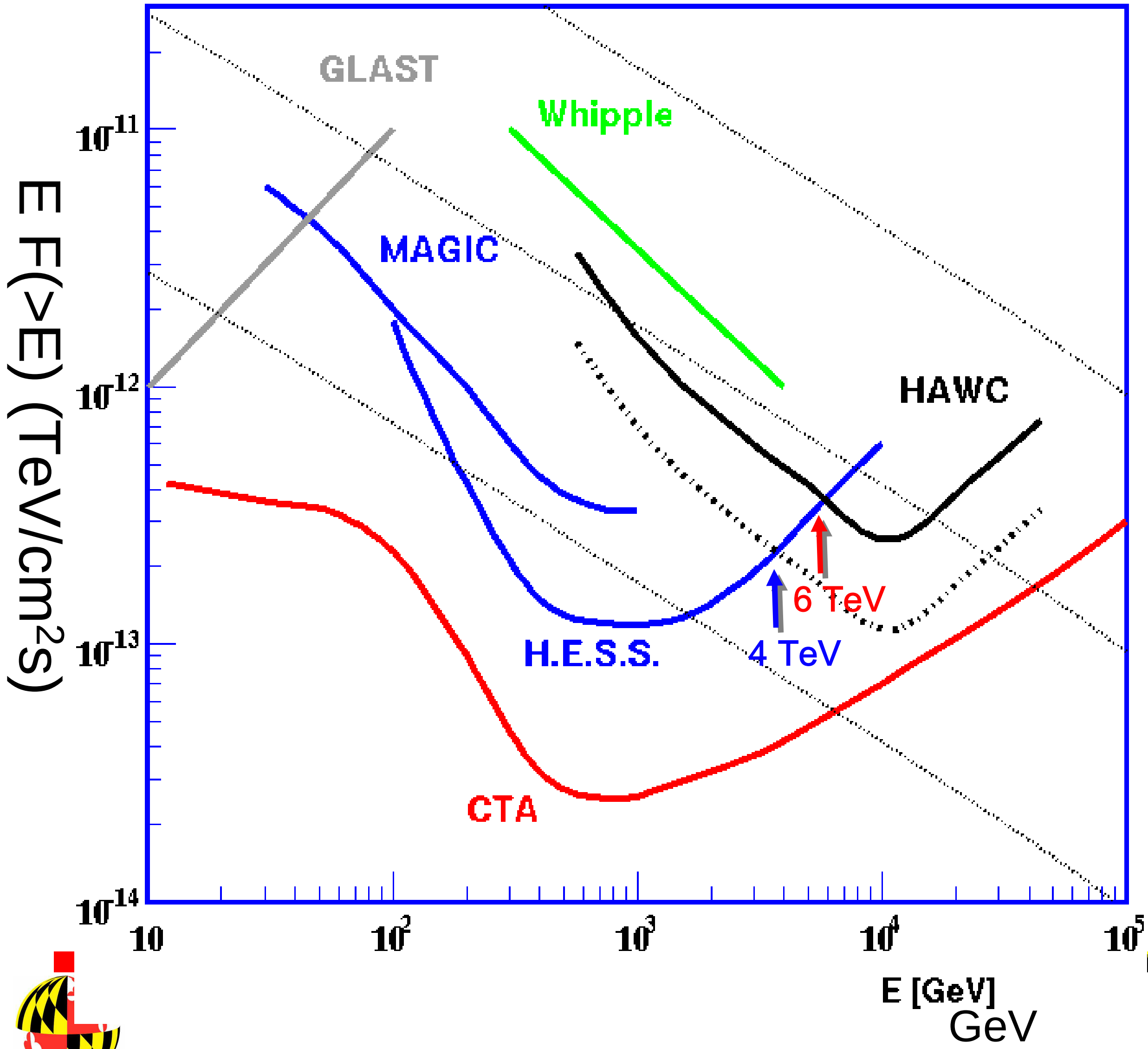






Energy Distribution at ground level

Gamma-Ray Sensitivity to Crab-like Point Source

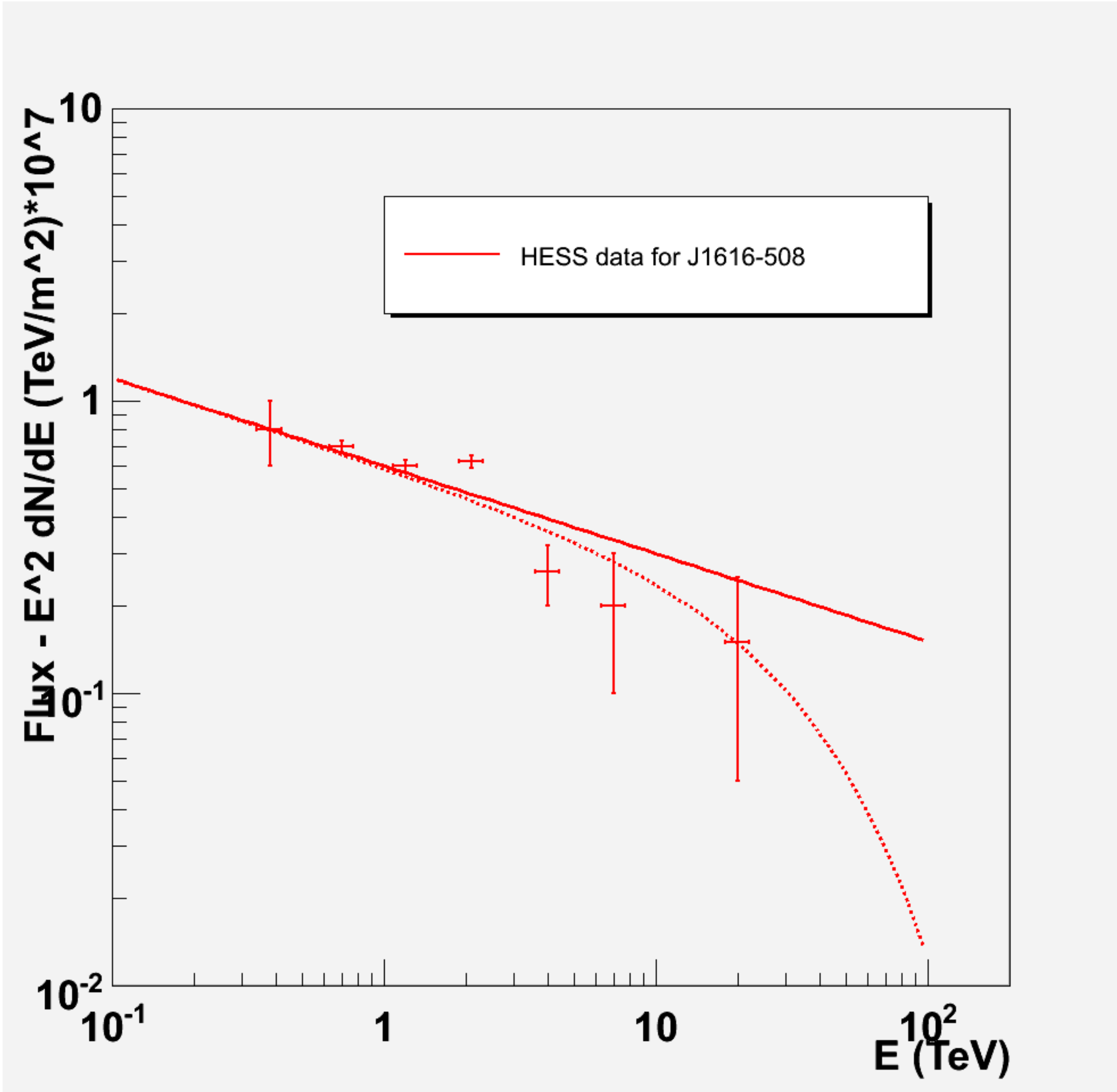


- **HESS/VERITAS, MAGIC, Whipple, CTA** sensitivity in 50 hours, (~0.2 sr/year)
- **GLAST** sensitivity in 1 year (4π sr)
- **HAWC, Milagro**, sensitivity in 1(5) year 2π sr
- HAWC will do better for hard & diffuse sources

HESS J1616-508

0.2 Crab @ 1 TeV
α=-2.3

Highest energy
~20 TeV

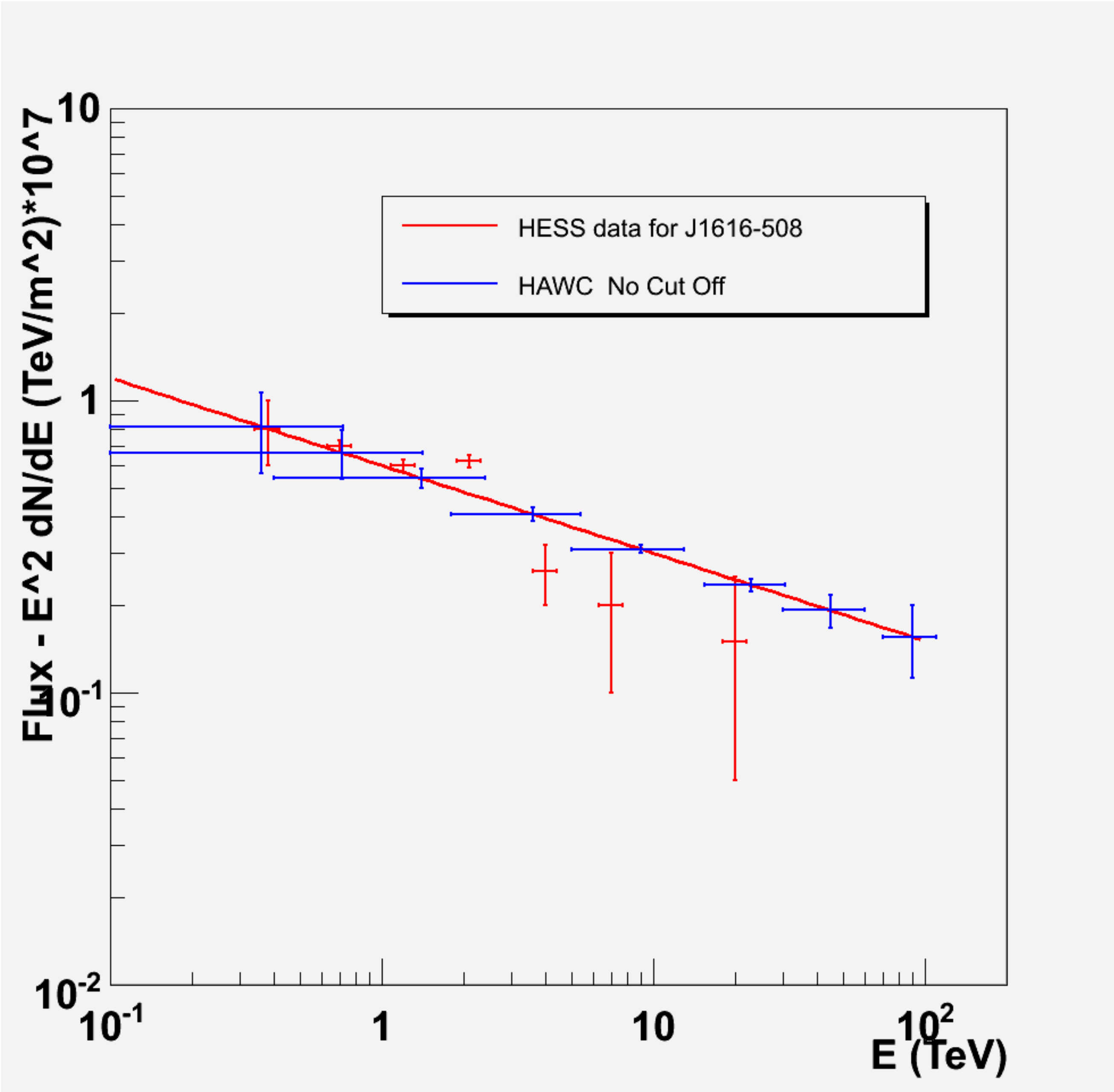


HESS J1616-508

0.2 Crab @ 1 TeV
α=-2.3

Highest energy
~20 TeV

Simulated HAWC data for 1 year with no cutoff

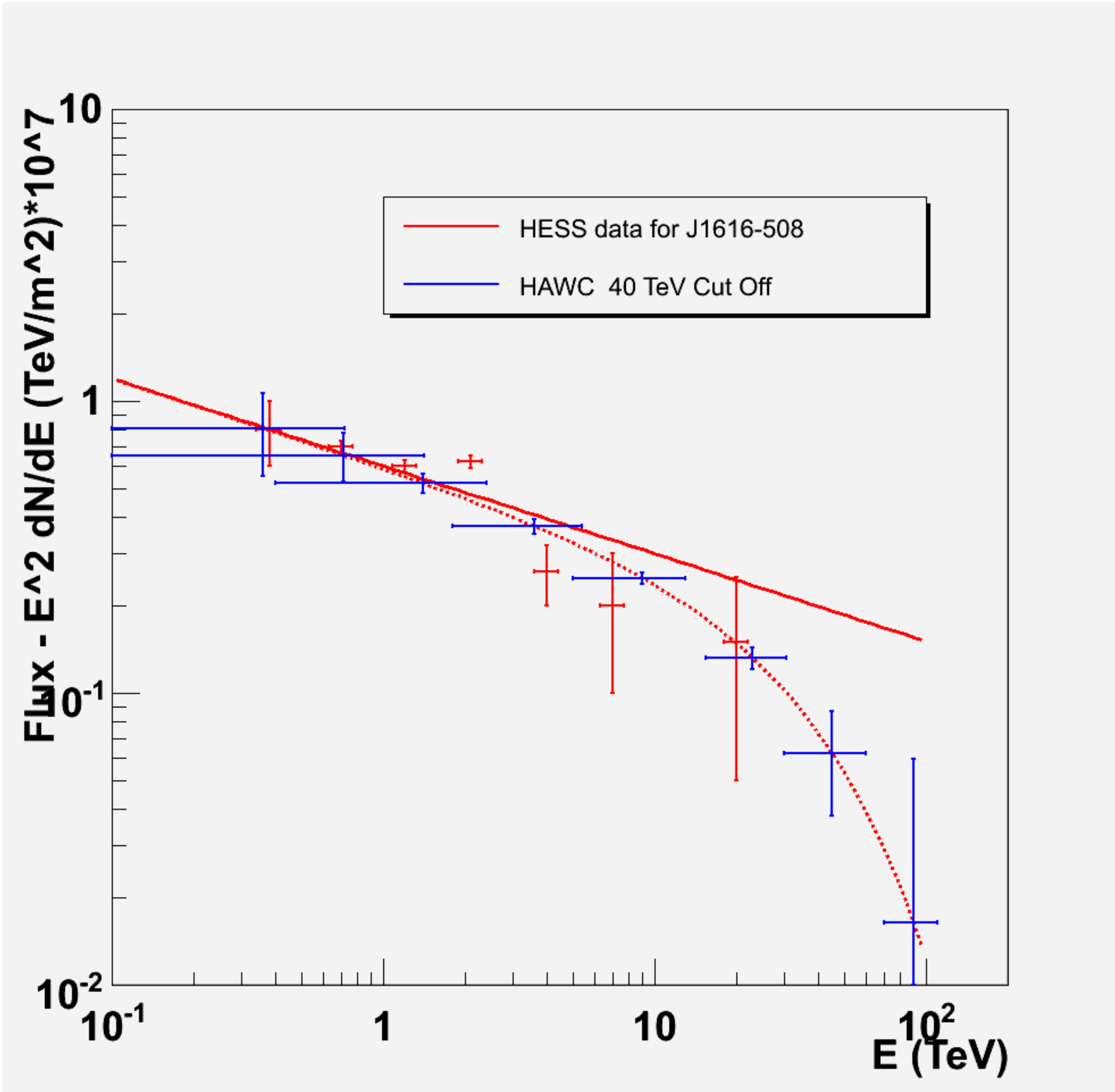


HESS J1616-508

0.2 Crab @ 1 TeV
α=-2.3

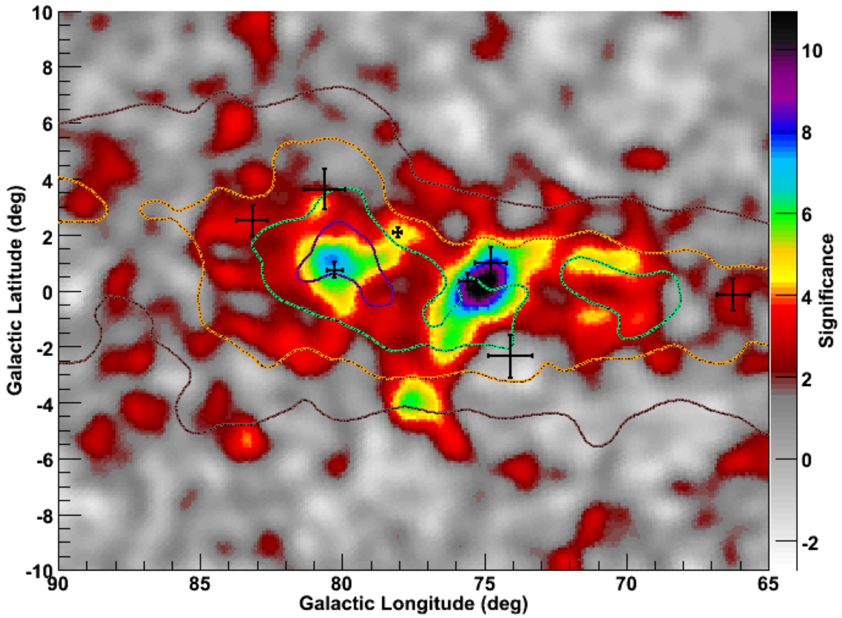
Highest energy
~20 TeV

Simulated HAWC data for 1 year with 40 TeV exponential cutoff

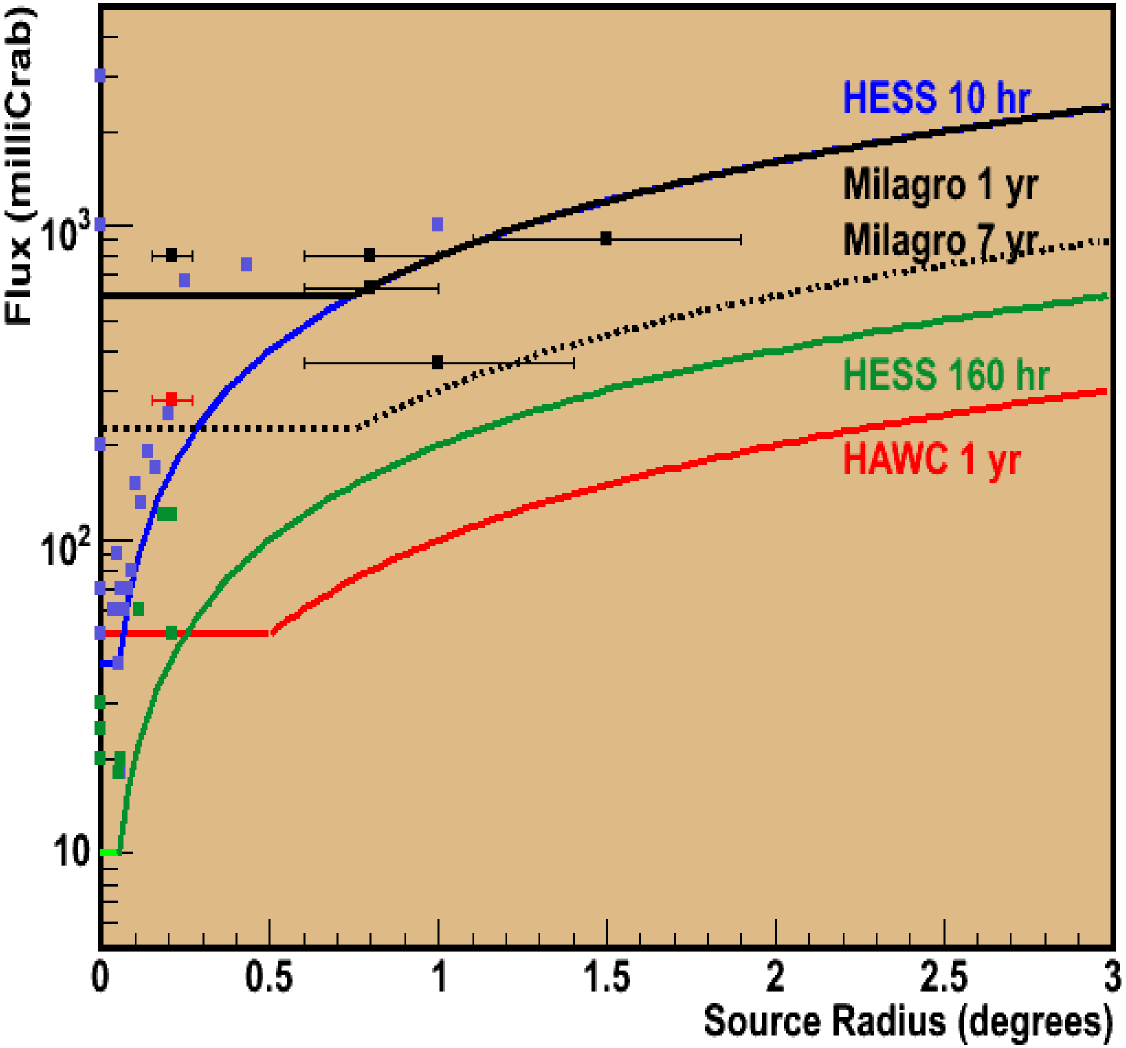


Why are High Energies Important?

- Do spectra continue or break at high energies?
  - Hard to accelerate electrons beyond 50-100 TeV
- Photons from hadronic interactions probe the knee region (~10x higher E)
- Need a high energy picture of the Galaxy



Sensitivity vs. Source Size



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

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

σ_{EAS} ~0.5° σ_{IACT} ~0.1°

EAS arrays obtain ~1500 hrs/yr observation for every source.

Large fov (2 sr):

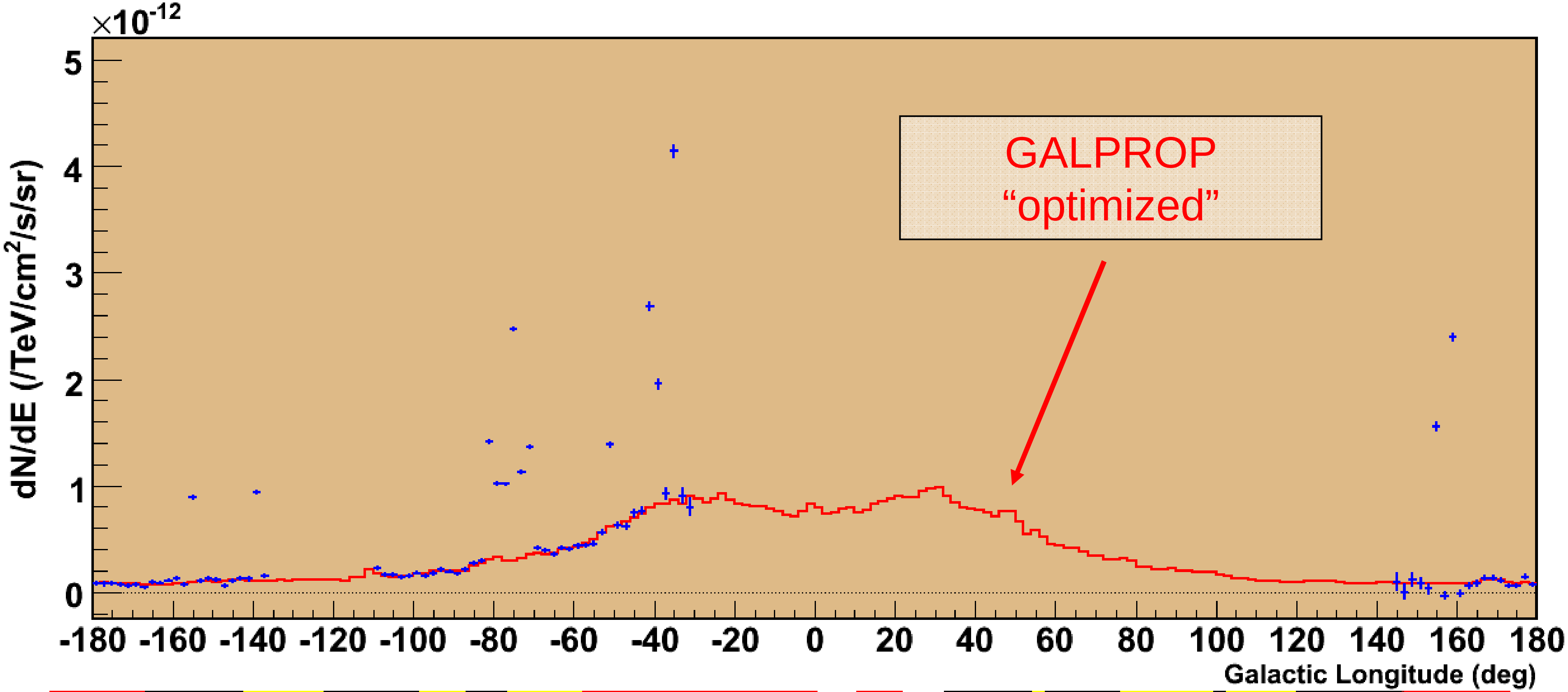
Entire source & background simultaneously observable

Background well characterized

HAWC: Galactic Diffuse Emission

Diffuse model: GALPROP + Milagro (if Milagro >1.5σ above GALPROP use Milagro measurement)

HAWC can map TeV diffuse emission with 2° longitude resolution.



Conclusions

- Milagro technique works:
  - Discovery of diffuse TeV gamma rays from Galactic plane & Cygnus region
  - Discovery of at least 3 new Galactic TeV sources
  - Demonstration of long-term multi-wavelength AGN monitoring
  - Cosmic-ray anisotropy observed
- With HAWC Large improvements are possible
  - 10-15 times the sensitivity of Milagro in near term
  - ~5 $\sigma/\sqrt{}$day on the Crab
  - 3% of Crab flux sensitivity over entire hemisphere (after 5 year operation)
  - HAWC will cost ~$6M and can be built within several years and is expandable and upgradeable
- Scientific goals
  - Highest energies (>5 TeV)
  - Extended sources
  - Galactic diffuse emission
  - Unique TeV transient detector (GRBs and AGN flares)
    - 4x Crab in 15 minutes


Grazie to the organizers for inviting us to
Venice

HAWC sensitivity calculation

- Milagro MC is used to calculate HAWC sensitivity increase of 10-15x
- B.O.T.E.C. (back of the envelope calculation) is similar
  - Energy Threshold 3x lower than Milagro (Approx. B gives 6x more particles, but density of PMTs is less)
    - Sensitivity increase depends on spectrum, but is ~2x
  - Area for Triggering is 5x larger than Milagro
    - Sensitivity increase is ~2x
  - Angular resolution improves because of increased lever arm, better core location, …
    - Sensitivity increase is 1.5-2x
  - Gamma/hadron rejection improves due to increased probability of detecting muon away from the core - don't reject gammas
    - Sensitivity increase is >1.5x

~4

~7

~12

HAWC Effective Area v. Energy