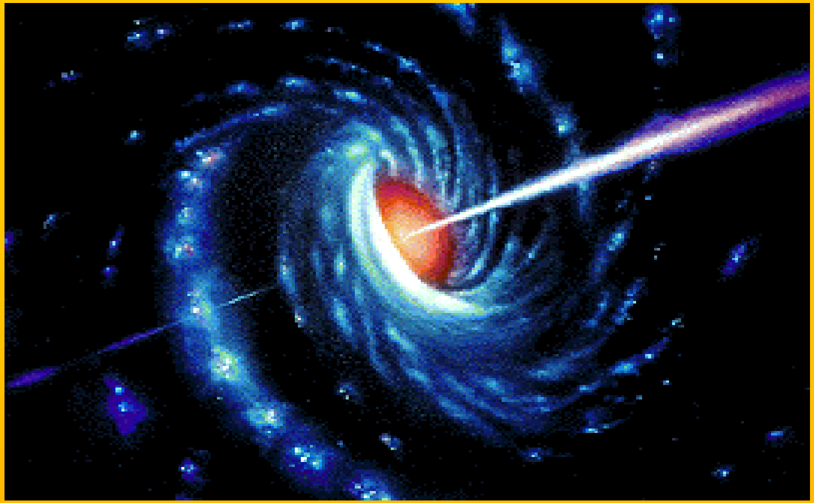
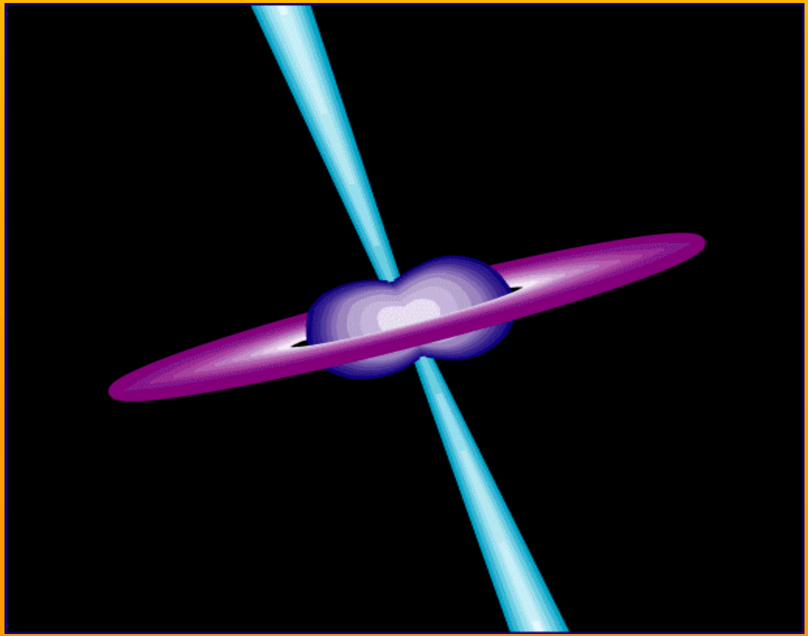
HAWC: A Next Generation All-Sky VHE Gamma-Ray Telescope

VHE Astrophysics

- Energy range 10 GeV – 10 TeV
- Non thermal processes in the universe
- Highly variable sources
- Particle acceleration
- Physics of extreme objects
  - Supernova remnants
  - Active galactic nuclei
  - Gamma ray bursts
- Fundamental Physics
  - Quantum gravity
  - Extragalactic background light
  - Dark Matter
- Poorly explored energy range
  - Discoveries likely
  - New types of sources revealed





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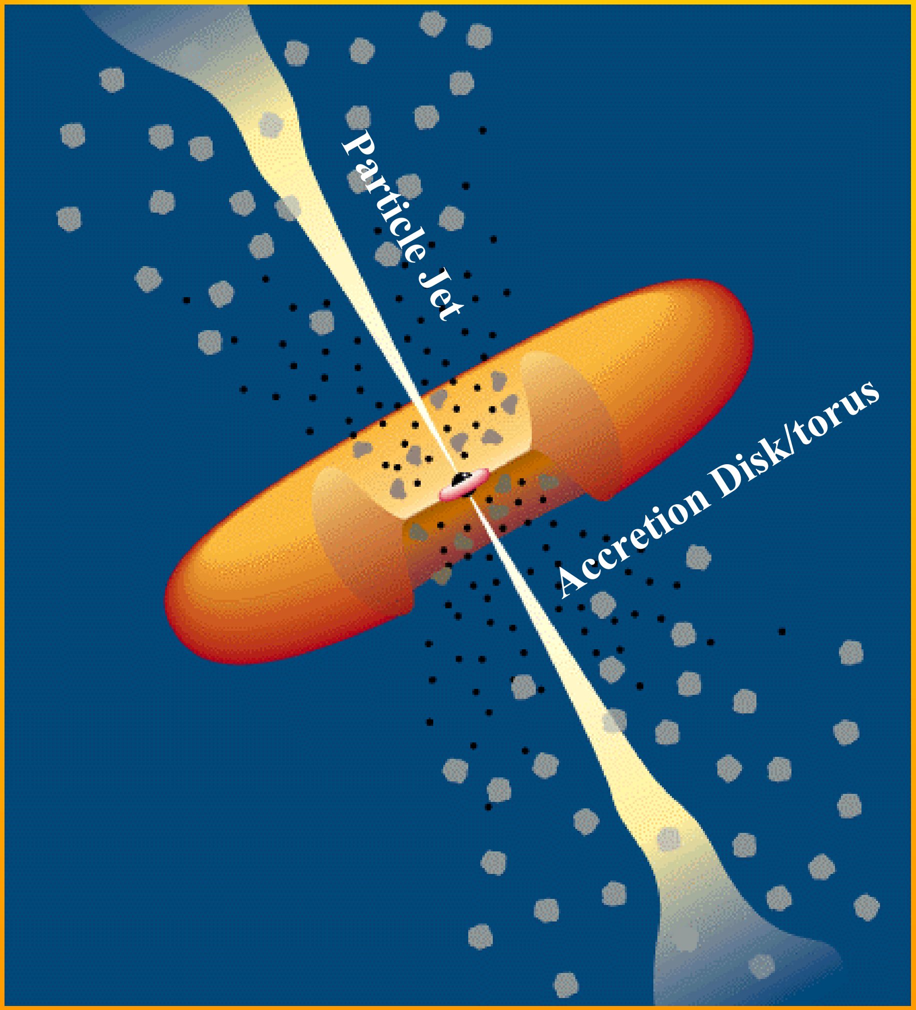
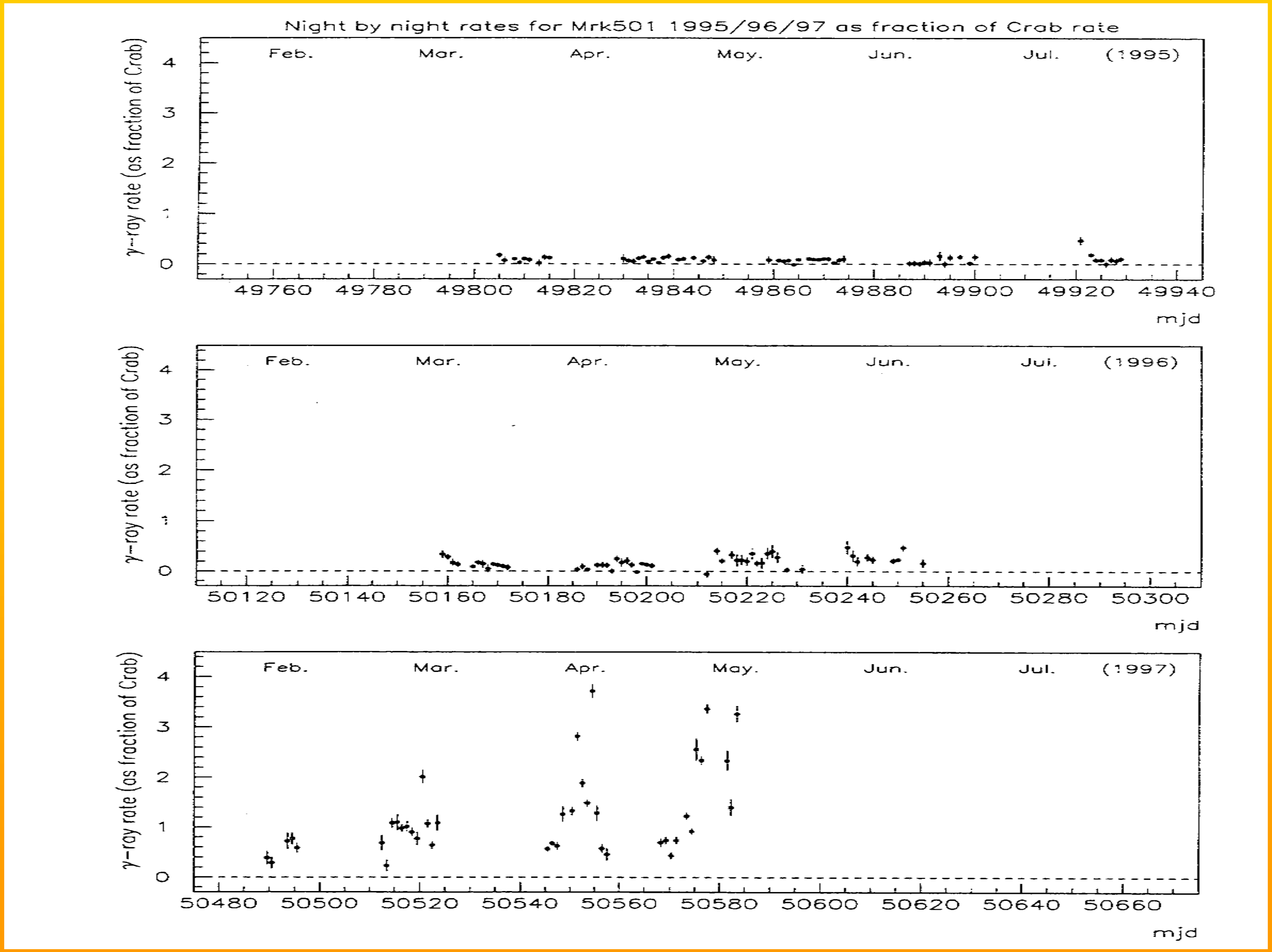
Active Galactic Nuclei



- Supermassive Black Hole
  $10^{8\text{-}10}\ M_{sun}$
- Rotating magnetic field converts rotational energy of hole into kinetic energy.
- Shocks propagate along jets and accelerate particles.
  $\Gamma\sim50$
- 10^{48} ergs/sec
- Highly variable in VHE band

Mrk 501 Longterm Variability



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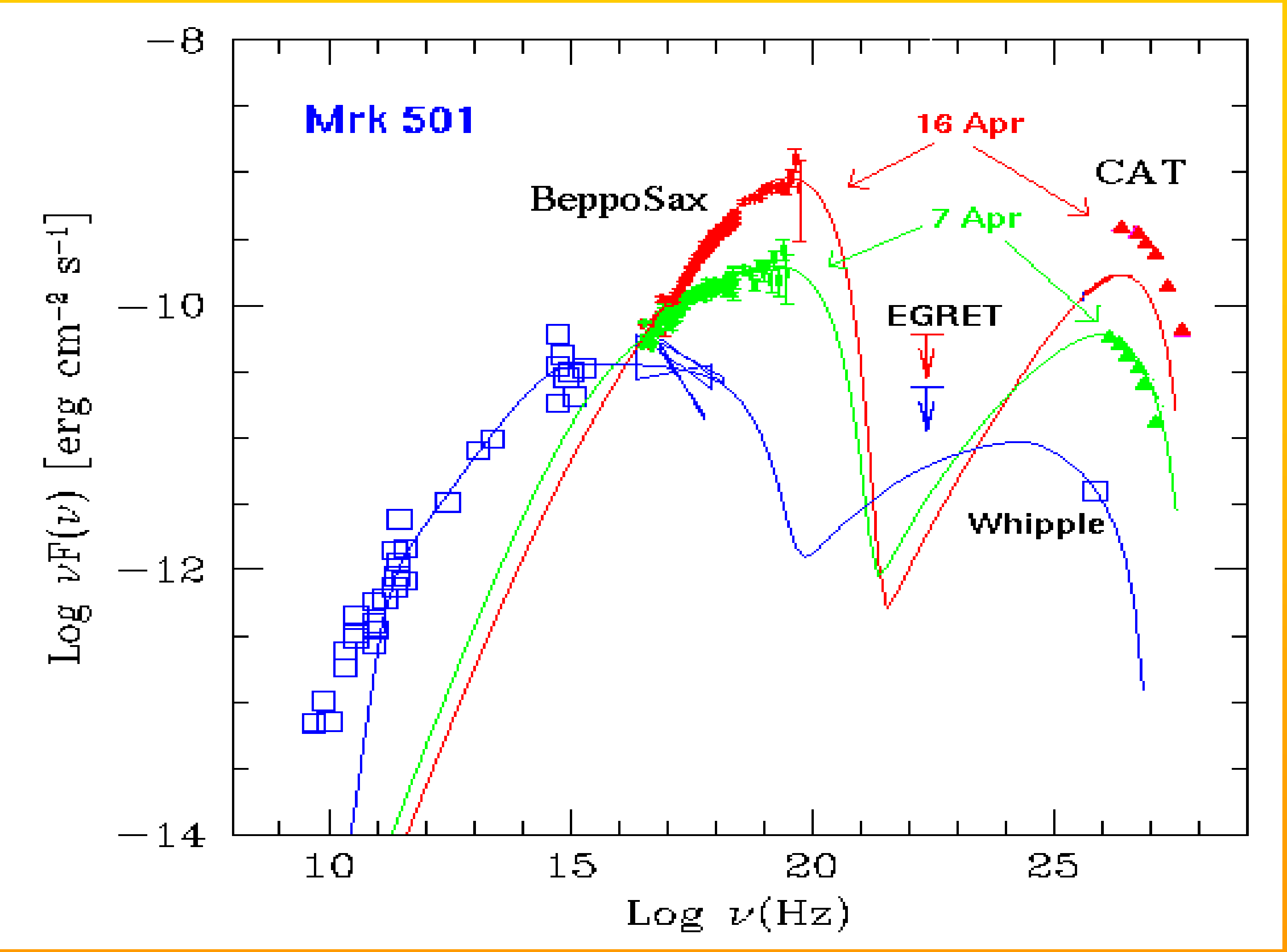
AGN Spectra



Mrk 501
16 Apr
7 Apr
CAT
BeppoSax
EGRET
Whipple
−8
−10
−12
−14
Log νF(ν) [erg cm⁻² s⁻¹]
10
15
20
25
Log ν(Hz)

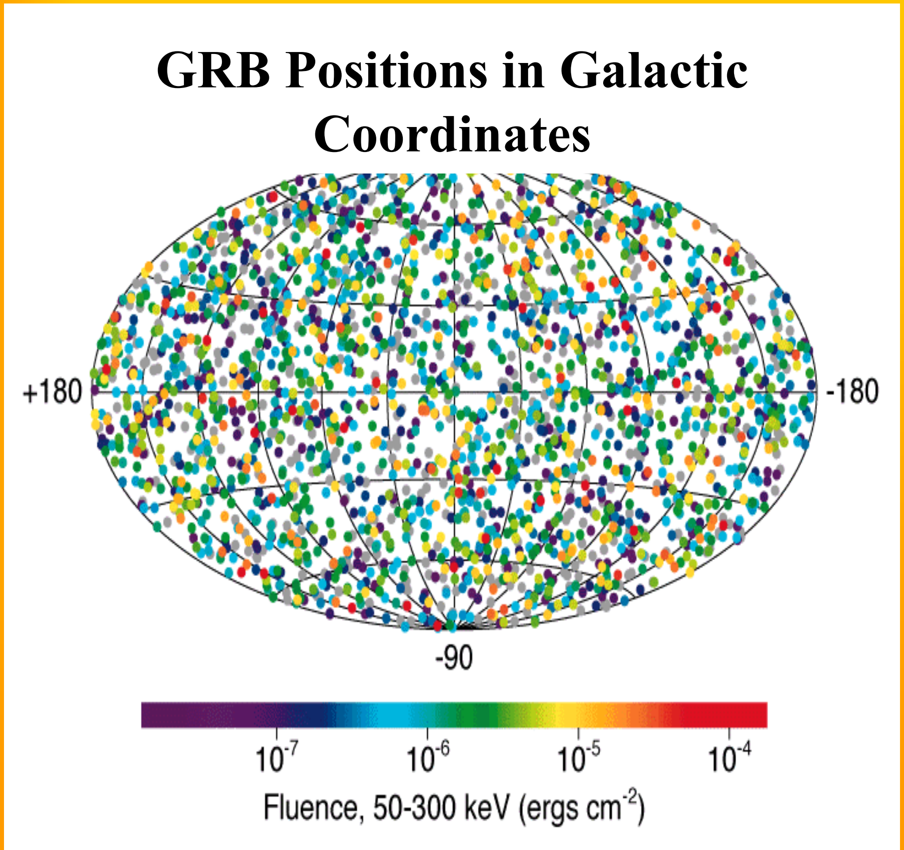
Gamma-Ray Bursts

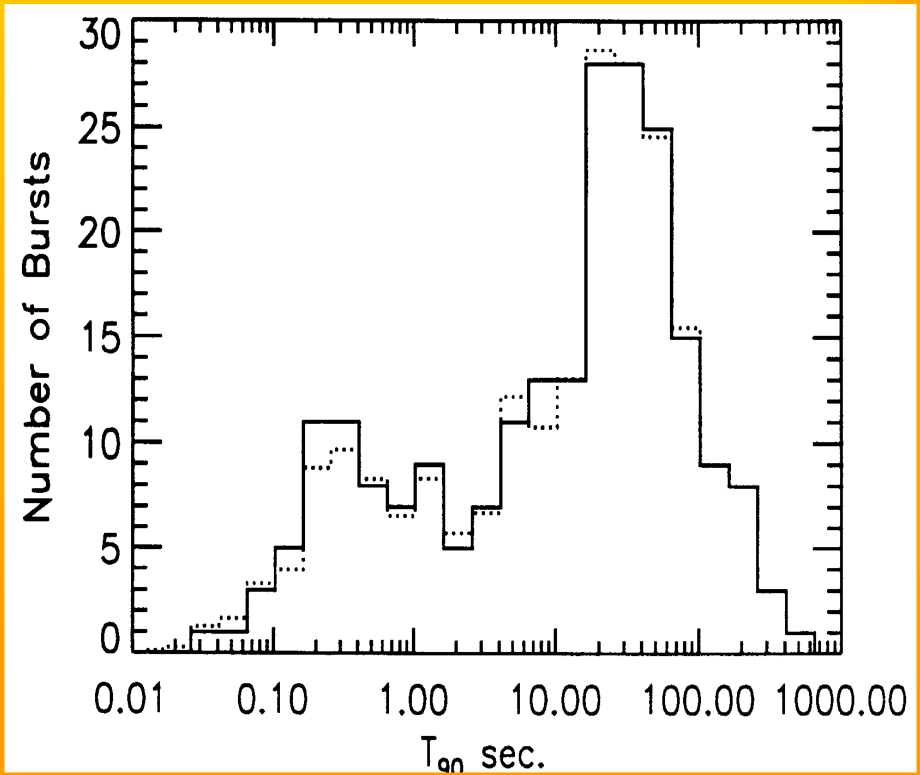
- Discovered in 1960's – VELA spy satellites at Los Alamos
- Intense bursts of γ-rays coming from seemingly random directions
- Last from milliseconds to 100's of seconds
- Over >2500 observed to date
- Cosmological origin
- Most energetic phenomena known - $10^{\sim 51}$ ergs
- Counterparts in other wavelengths (optical, radio, GeV, TeV?)

Gamma-Ray Burst Properties

Spatial Distribution

Duration Distribution





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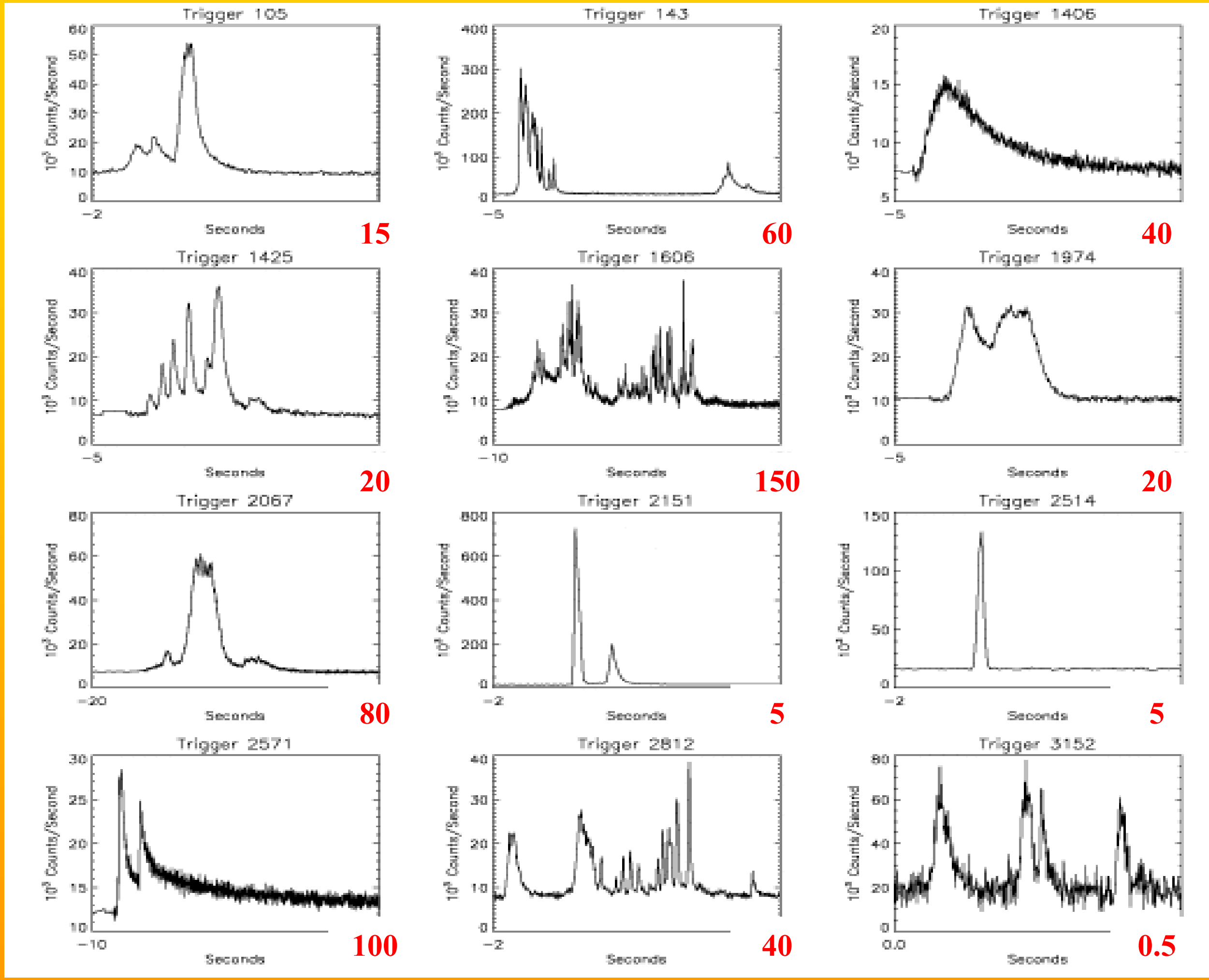
GRB Profiles

Counts/second



Seconds

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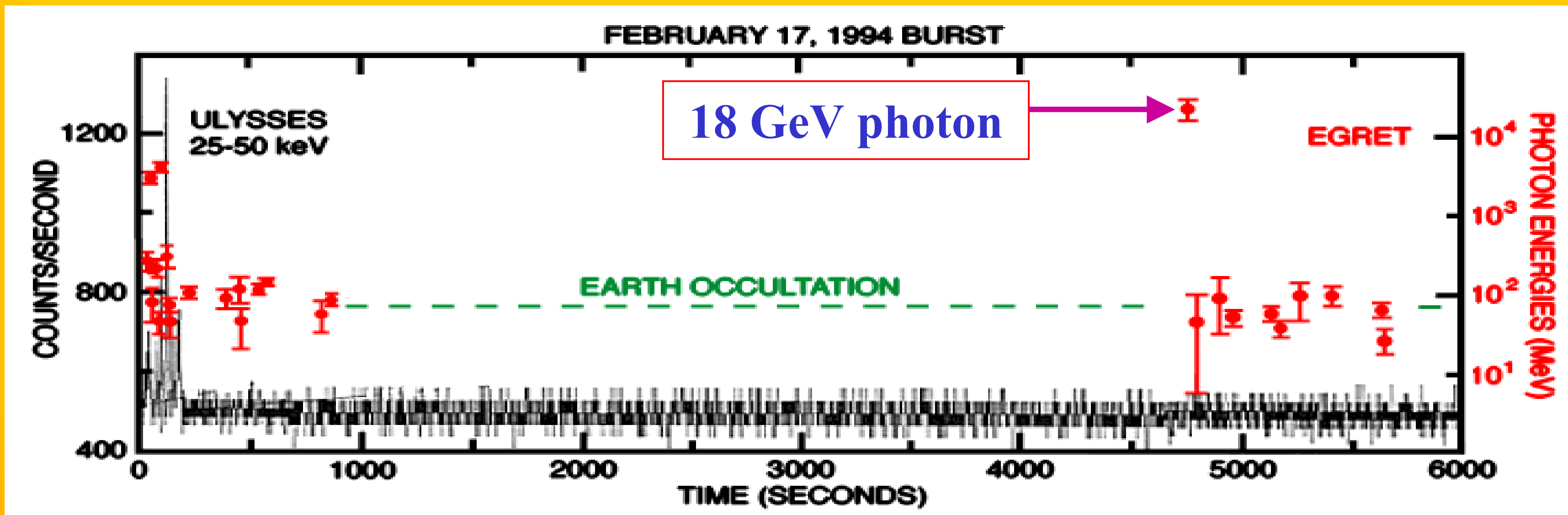
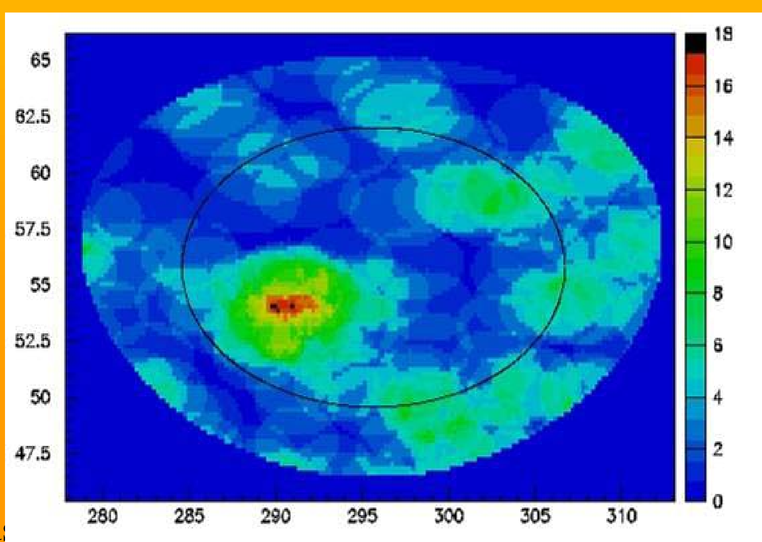
GRBs: High Energy Emission





GRB 970417a – Milagrito

10^{-3} chance probability

>650 GeV photons

GRB Models

Central Engine:

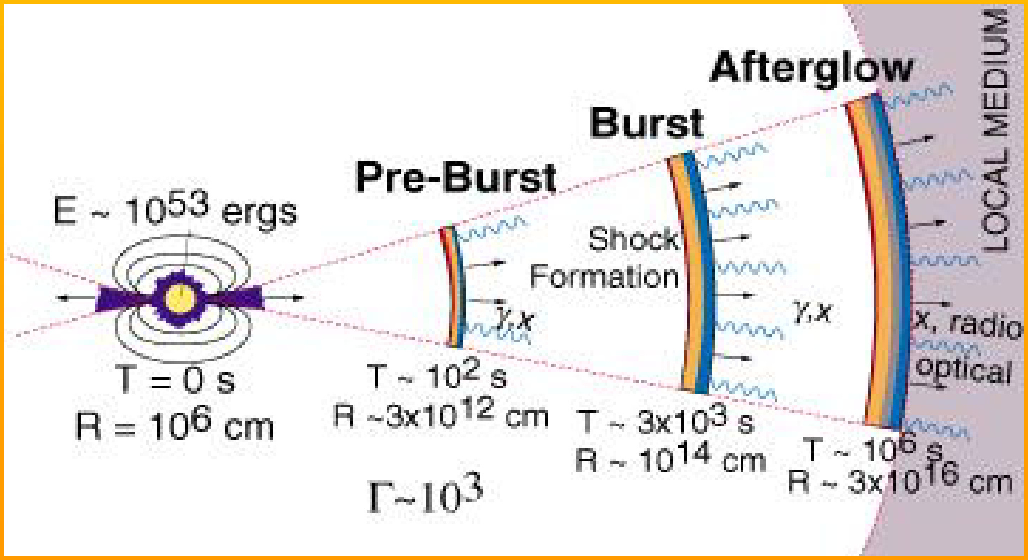
hypernovae (death of a very massive star)

neutron star - neutron star merger

black hole - neutron star mergers

Emission Spectra:

Fireball: internal or external shocks convert energy into electromagnetic radiation.



Quantum Gravity

- Quantum gravity may violate Lorentz invariance
- Most theories predict energy dependent speed of light
  - Interactions with Planck mass particles distort spacetime: yielding larger distances for HE gammas
  - Planck scale vacuum fluctuations probed by HE gammas
- Dynamics of the theory unknown
- Explore possible modifications to dispersion relation (Amelino-Camelia *et al*.)

$$m^2 \cong E^2 - p^2\left(1 - \eta \frac{E}{E_{QG}}\right)$$

For photons this leads to an energy dependent velocity

$$v \approx c\left(1 - \frac{\eta}{2}\frac{E}{E_{QG}}\right)$$

Quantum Gravity & GRBs

For E=1 TeV: $E/E_{QG} = 10^{-16}$

Distant sources of HE γ-rays can amplify this effect

$$\Delta t \approx \eta \frac{LE}{cE_{QG}} = 40\eta\, zE_{TeV} \text{ sec}$$

Figure of Merit: $$E_{probe} = 4\times 10^{17} \frac{zE_{GeV}}{\Delta t_{\text{sec}}}$$

A single detection allows one to set a compelling limit

To prove an effect from QG requires multiple GRBs at different redshifts

GLAST

- E = 30 GeV
- Δt = 1 sec
- z = 1
- E_{probe}= 1.2 E_{Planck}

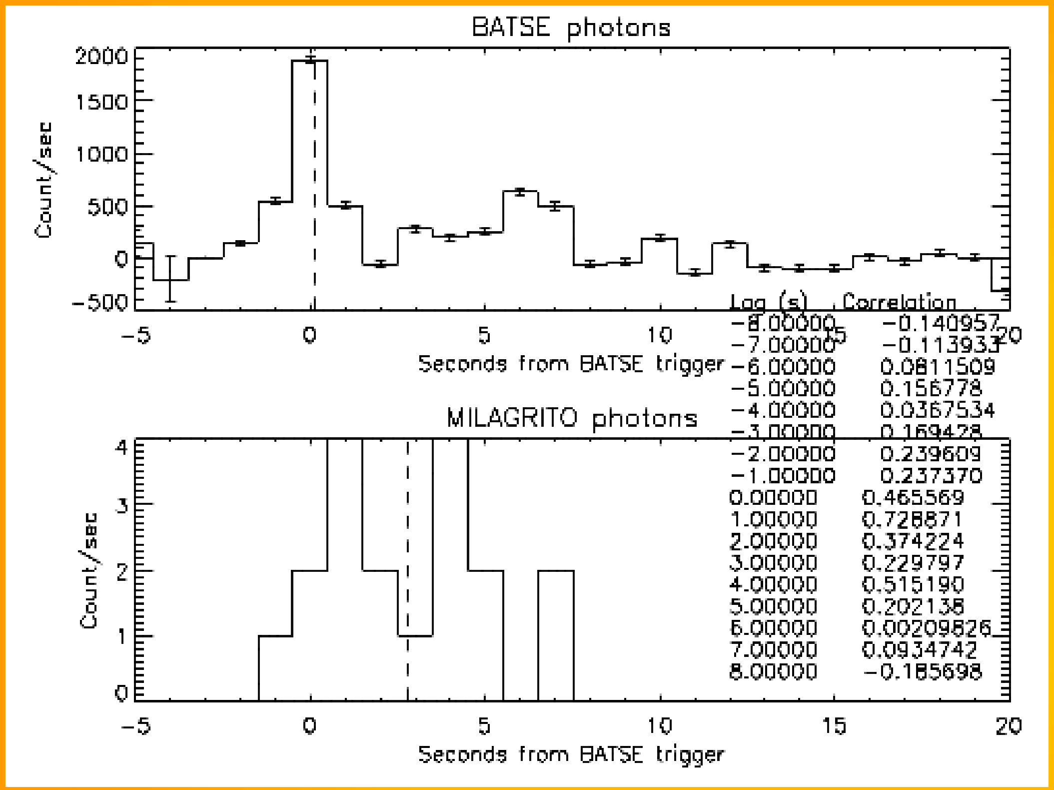
Milagro

- E = 300 GeV
- Δt = 1 sec
- z = 0.2
- E_{probe}= 2.5 E_{Planck}

HAWC

- E = 50 GeV
- Δt = 1 sec
- z = 1
- E_{probe}= 2 E_{Planck}

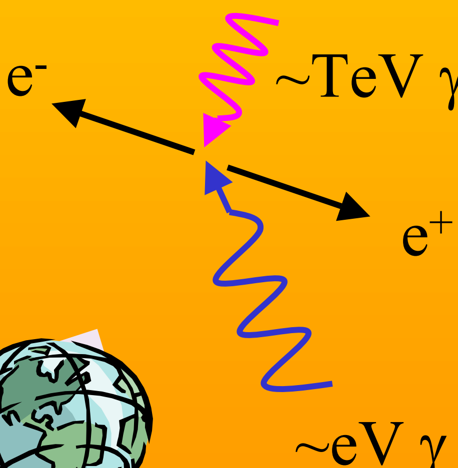
Milagrito Example

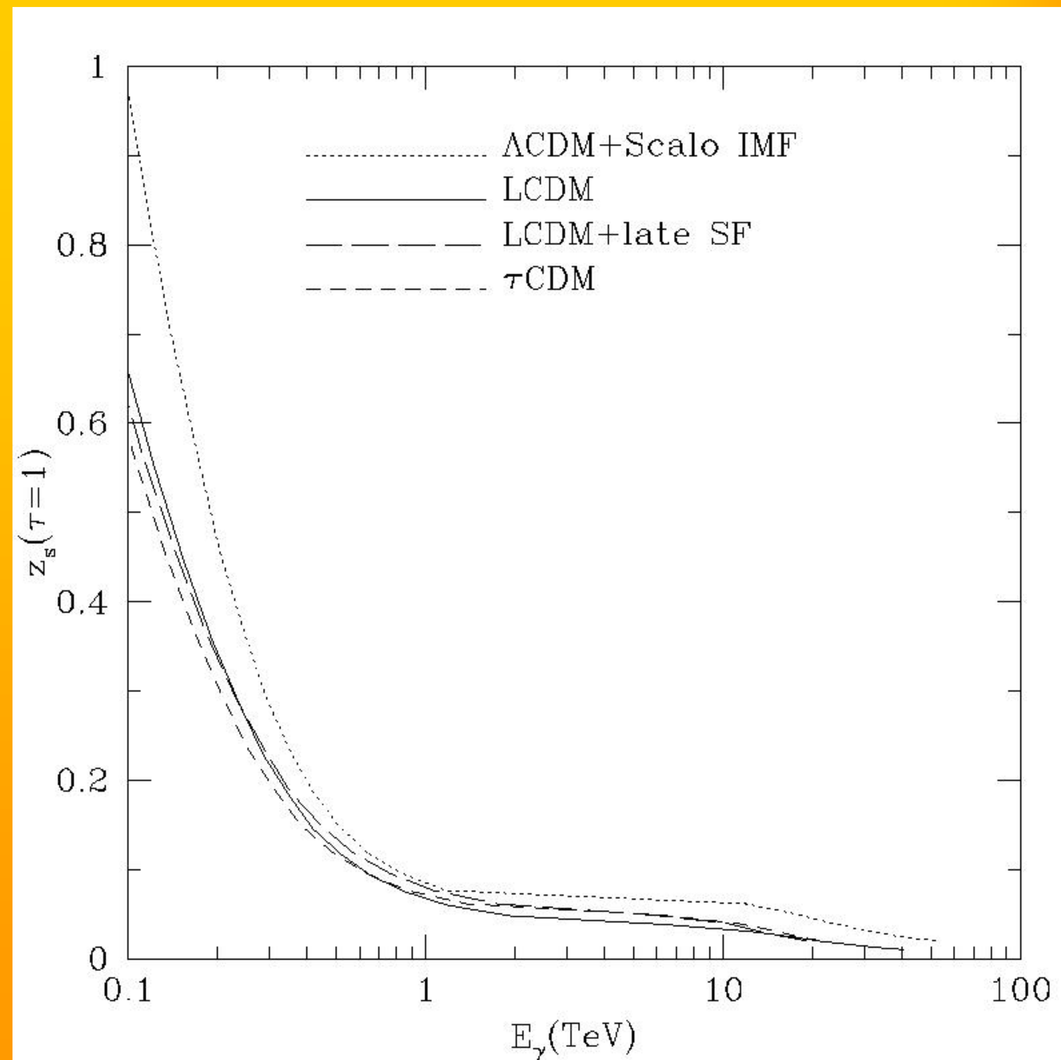


Cross correlation between TeV and sub-MeV lightcurves peaks at a lag of 1 s.

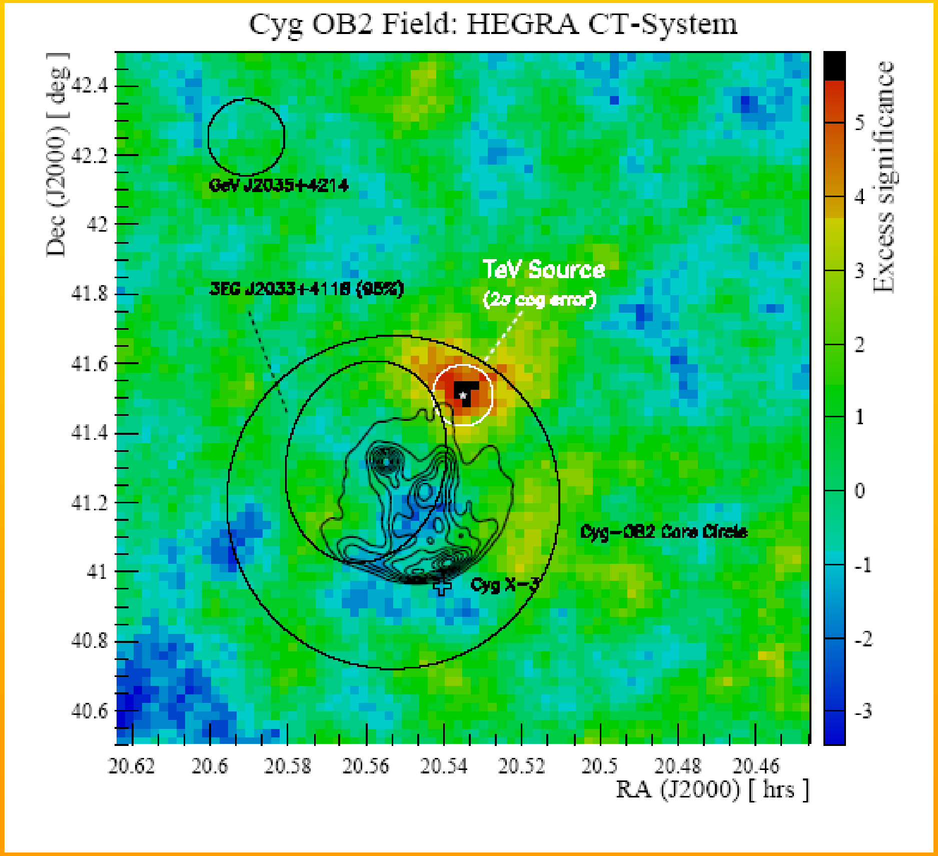
Assuming E_{obs} = 650 GeV, Δt = 4 s and z=0.1, we can obtain a constraint on E_{QG} which is a factor of ~70 better than previous limits (Biller 1999).

Absorption of TeV Photons





The First Unidentified TeV Source



HEGRA: Deep observation

113 hours of observation (3 years)

4.6σ significance

30 mCrab strength

Centered on Cygnus OB2 (dense region of young, massive stars)

Possibly an extended source

TeV Name	Source	Type	Date/Group	EGRET Catalog	Grade
TeV 0047−2518	NGC 253	Starburst	2003/Cangaroo	no	B
TeV 0219+4248	3C66A	Blazar	1998/Crimea	yes	C-
TeV 0535+2200	Crab Nebula	SNR	1989/Whipple	yes	A (Milagro)
TeV 0834−4500	Vela	SNR	1997/Cangaroo	no	C
TeV 1121−6037	Cen X-3	Binary	1999/Durham	yes	C
TeV 1104+3813	Mrk 421	Blazar	1992/Whipple	yes	A (Milagro)
TeV 1231+1224	M87	Radio Galaxy	2003/HEGRA	no	C
TeV 1429+4240	H1426+428	Blazar	2002/Whipple	no	A
TeV 1503−4157	SN1006	SNR	1997/Cangaroo	no	B
TeV 1654+3946	Mrk 501	Blazar	1995/Whipple	no	A (Milagro)
TeV 1710−4429	PSR 1706−44	SNR	1995/Cangaroo	no	A
TeV 1712−3932	RXJ1713.7−39	SNR	1999/Cangaroo	no	B+
TeV 2000+6509	1ES1959+650	Blazar	1999/TA	no	A
TeV 2032+4131	CygOB2	OB assoc.	2002/HEGRA	yes†	B
TeV 2159−3014	PKS2155−304	Blazar	1999/Durham	yes	A
TeV 2203+4217	BL Lacertae	Blazar	2001/Crimea	yes	C
TeV 2323+5849	Cas A	SNR	1999/HEGRA	no	B
TeV 2347+5142	1ES2344+514	Blazar	1997/Whipple	no	A
Galactic Plane	Milky Way	Diffuse	2004/Milagro	yes	B (Milagro)

† CygOB2 lies within the 95% error ellipse of the EGRET source 3EG J0233+4118
8 verified (A) sources, 5 B sources, 5 C sources
10 extragalactic source, 8 galactic

Horan & Weekes 2003

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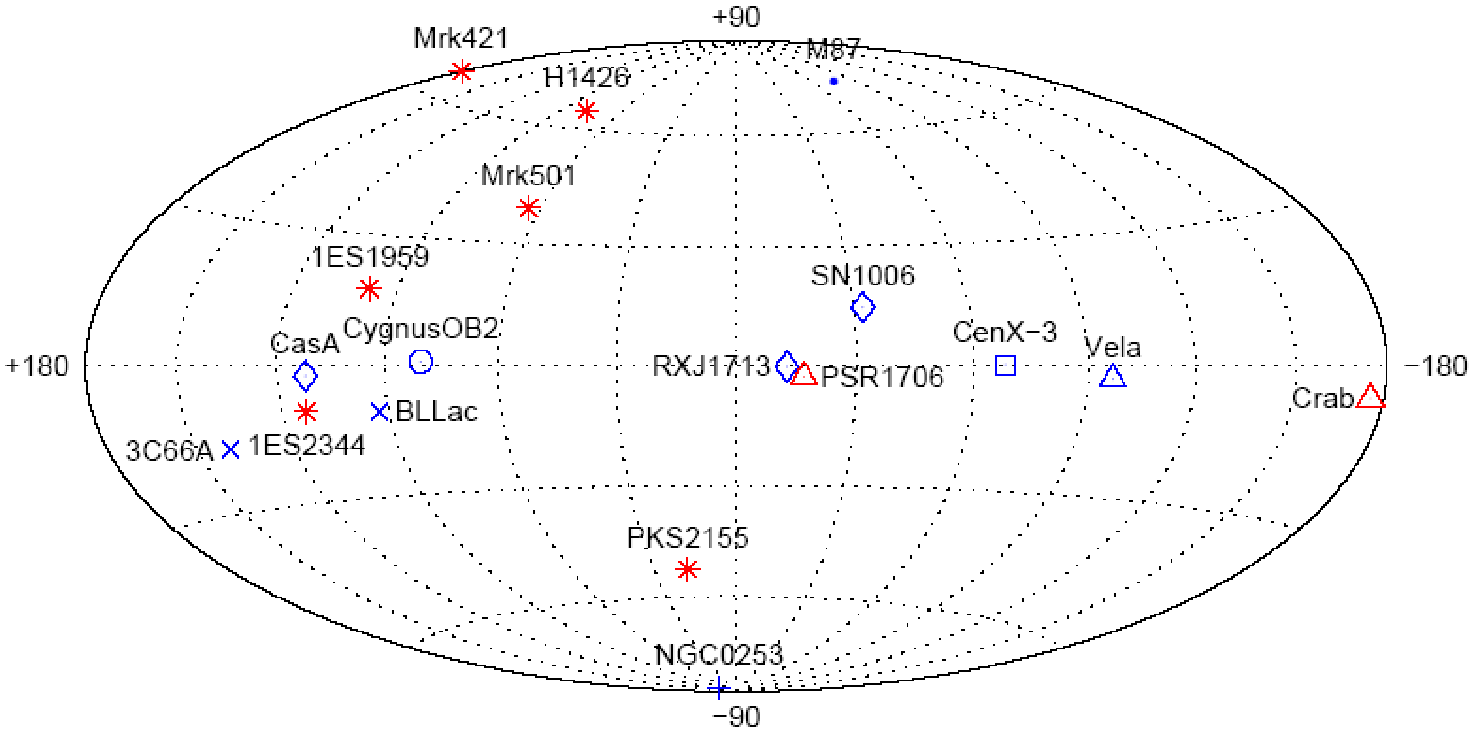
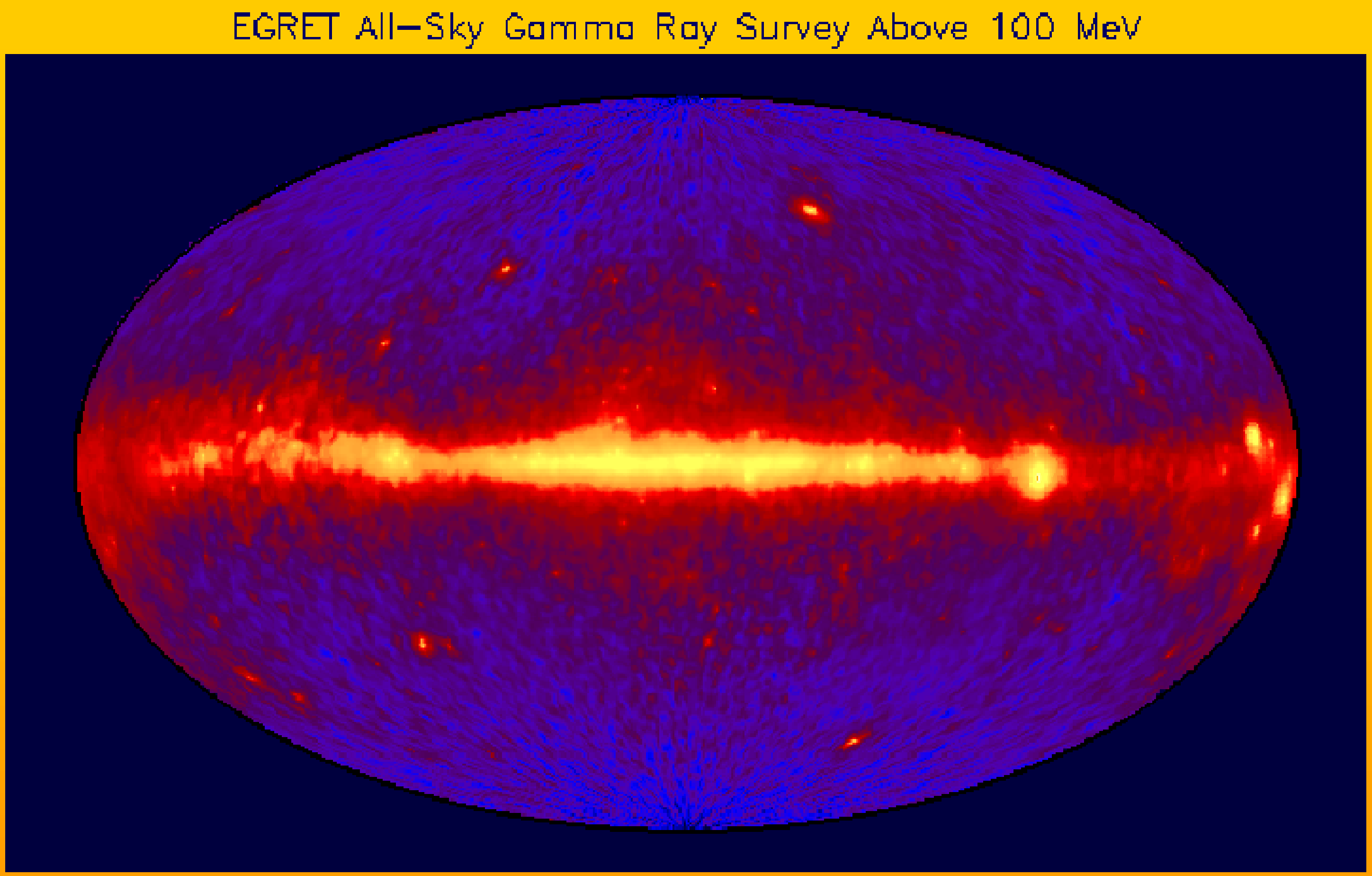
VHE Sky Map



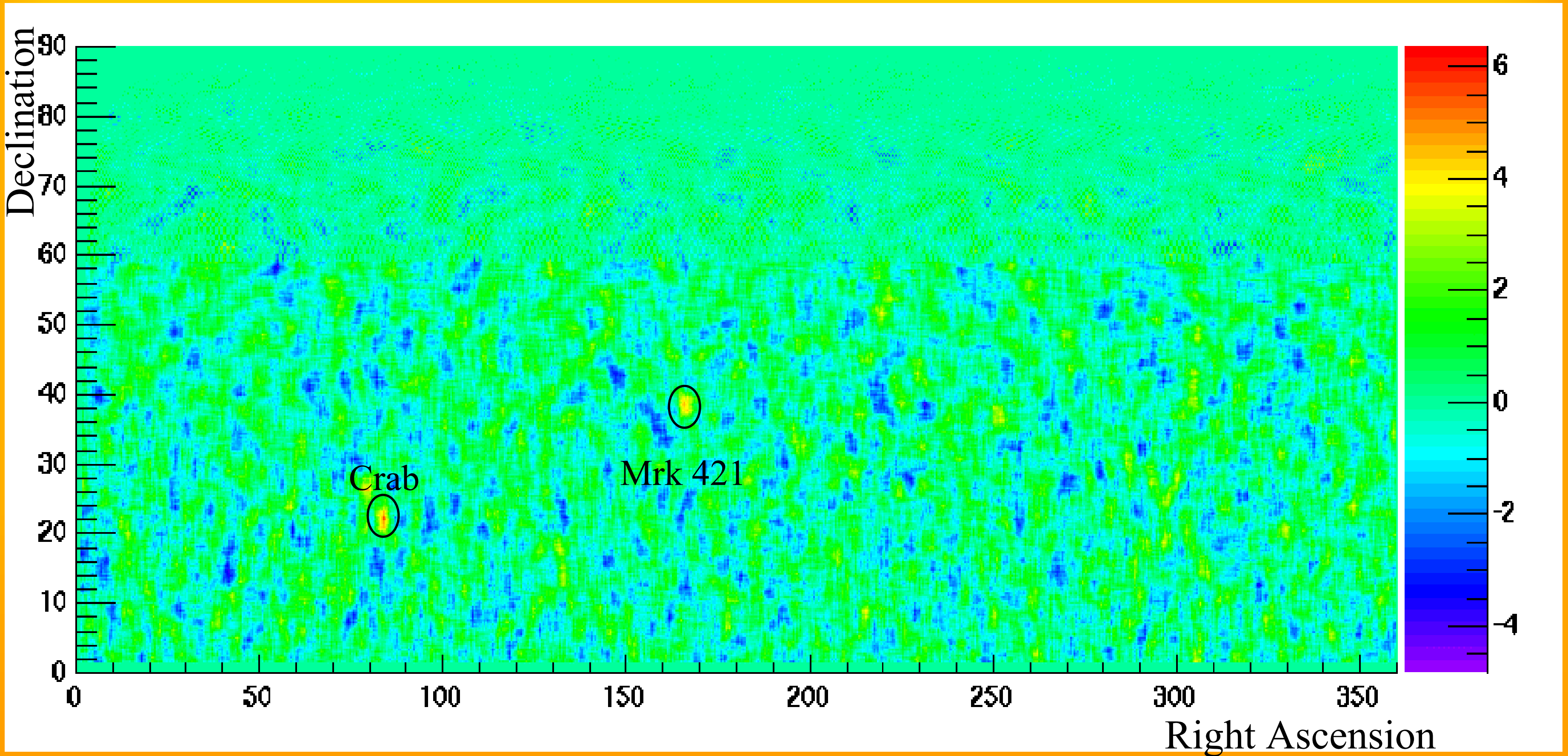
Horan & Weekes 2003

EGRET Sky Map



270 sources (150 unidentified)

Milagro TeV Sky Map



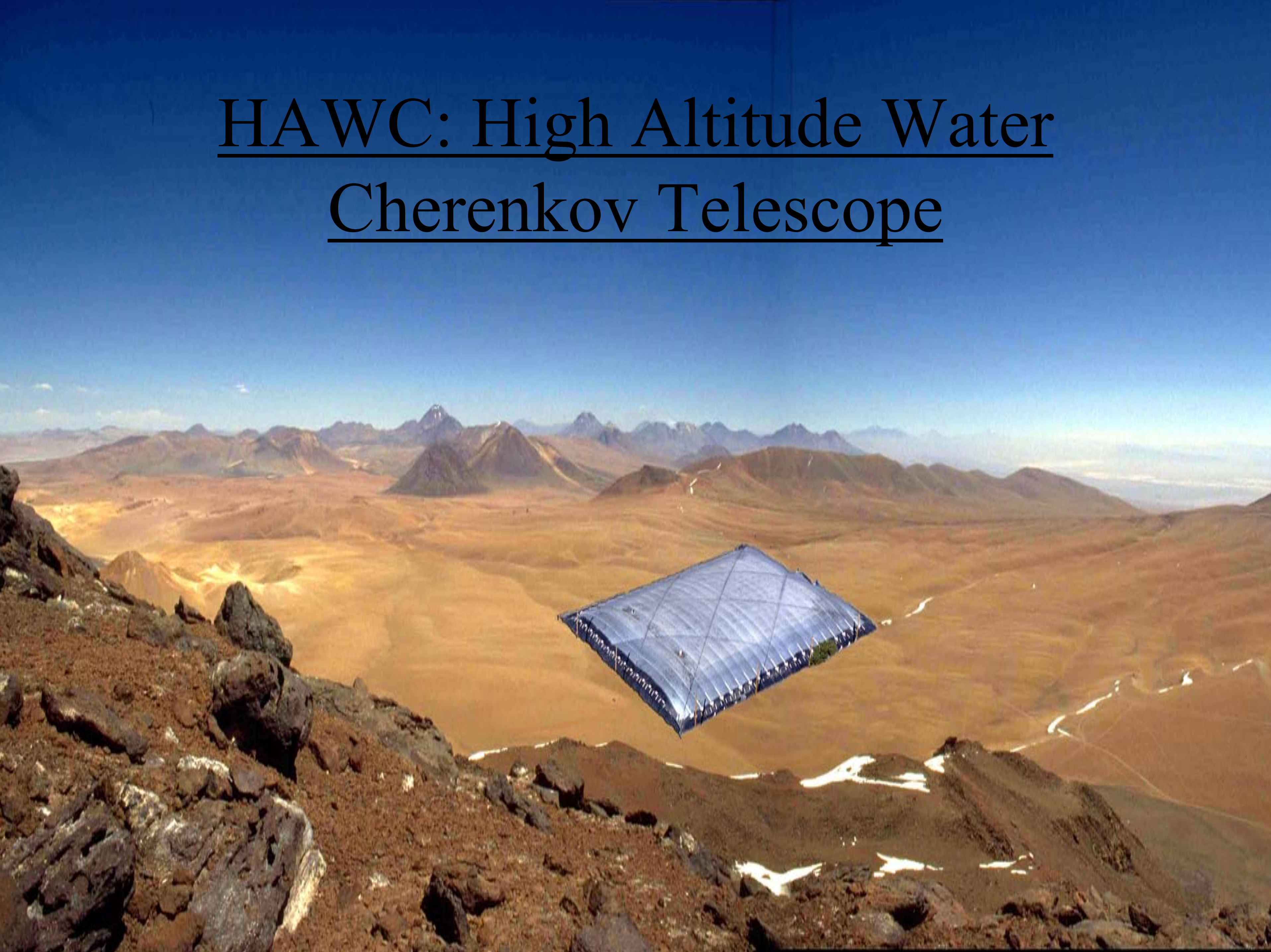
Current Status of VHE Astronomy

- Only 8 confirmed sources (89, 92, 2*x*95, 97, 2*x*99, 2002)
- Lack of sources due to:
  - Small field of view of ACTs
  - Low sensitivity of all-sky instruments
  - Transient nature of sources (GRBs and AGN)
- Small source counts lead to poor understanding of VHE sources
- VHE GRBs inconclusive (Milagrito)
- HAWC – high sensitivity over entire sky
  - Detect many sources
  - Monitor transient sources
  - Discover VHE emission from GRBs
  - Limit/Measure effects of quantum gravity

The Need for HAWC

- GLAST
  - Will discover 1000's of sources
  - Many variable
  - ACTs can monitor ~15/year at stated sensitivity
- GRBs
  - Detect highest energy photons in prompt phase
- AGNs
  - Detect/Monitor AGN at redshift < 0.3
  - Study AGN transients in VHE regime
  - Populations studies
- Fundamental Physics
  - Lorentz violation at high energies (quantum gravity?)
  - Dark matter
- VHE sky surveyed to 40% of Crab flux
  - Sensitive Sky Survey < 1% of Crab flux
- Time Domain Astrophysics in the VHE Regime
  - Extreme states of extreme systems

HAWC: High Altitude Water Cherenkov Telescope

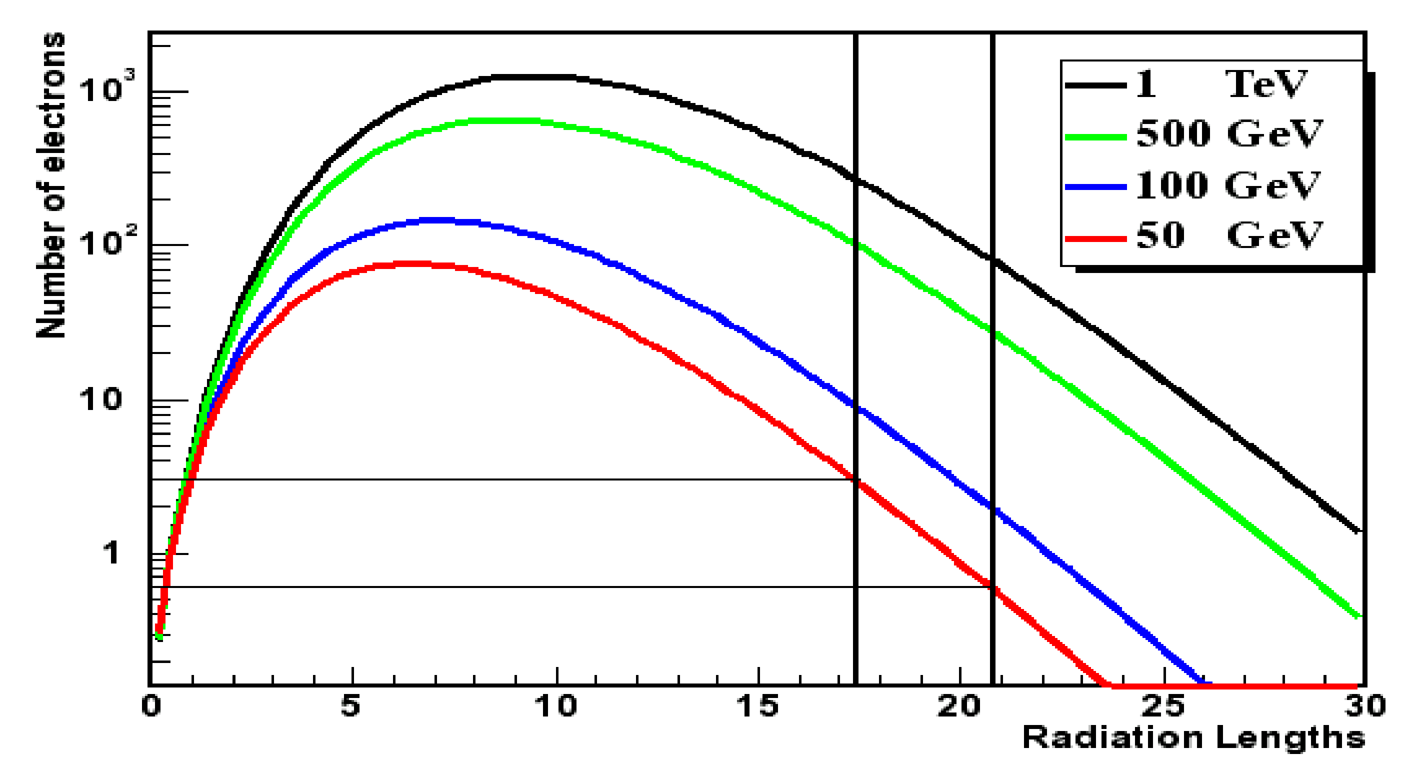


HAWC Performance Requirements

- Energy Threshold ~20 GeV
    - GRBs visible to redshift ~1
    - Near known GRB energy
    - AGN to redshift ~0.3
- Large fov (~2 sr) / High duty cycle (~100%)
    - GRBs prompt emission
    - AGN transients
    - Time domain astrophysics in VHE regime
- Large Area / Good Background Rejection
    - High signal rate
    - Ability to detect Crab Nebula in single transit
- Moderate Energy Resolution (~40%)
    - Measure GRB spectra
    - Measure AGN flaring spectra

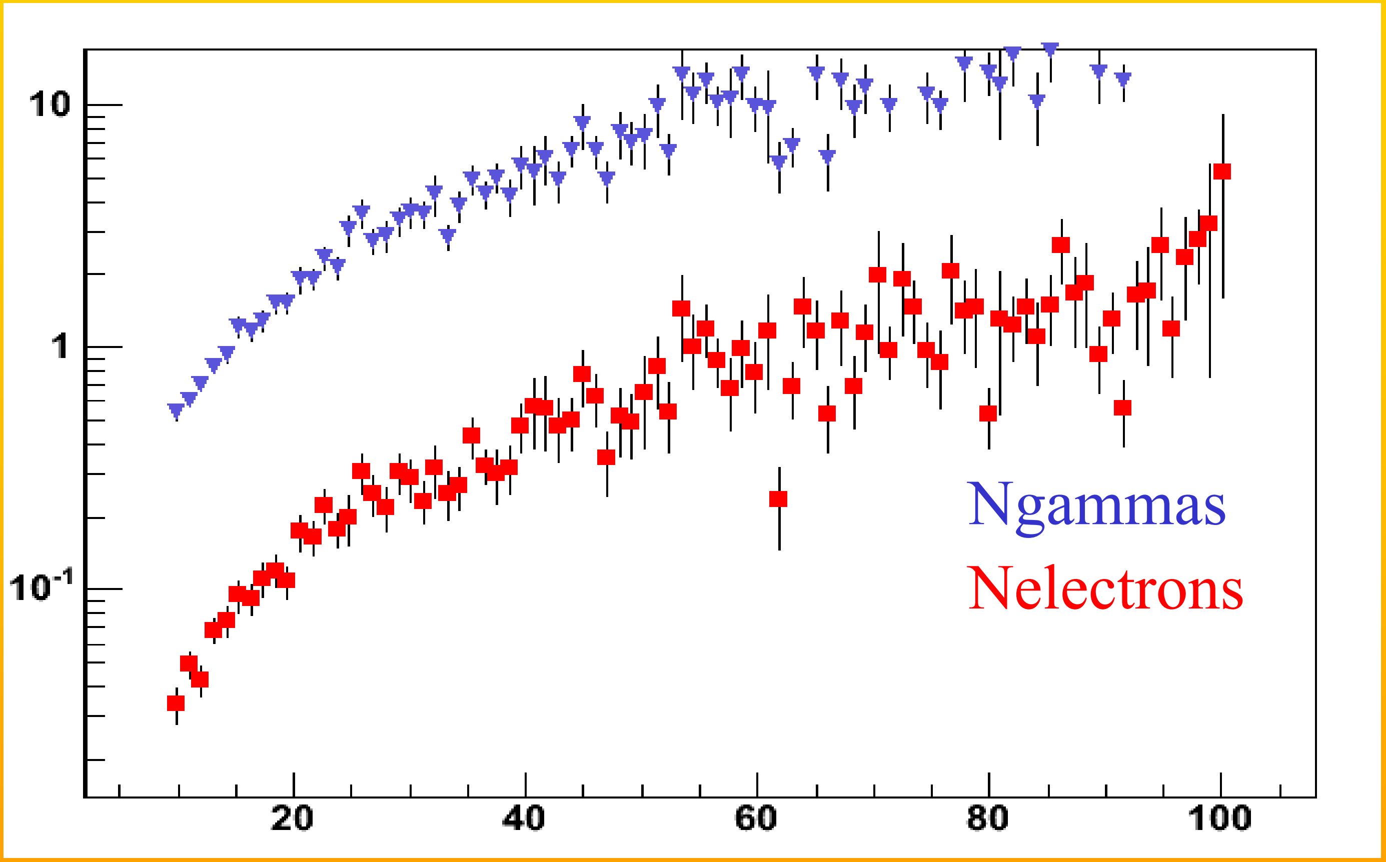
Effect of Altitude

Approximation B



Low Energy Threshold Requires High Altitude

EAS Particle Content

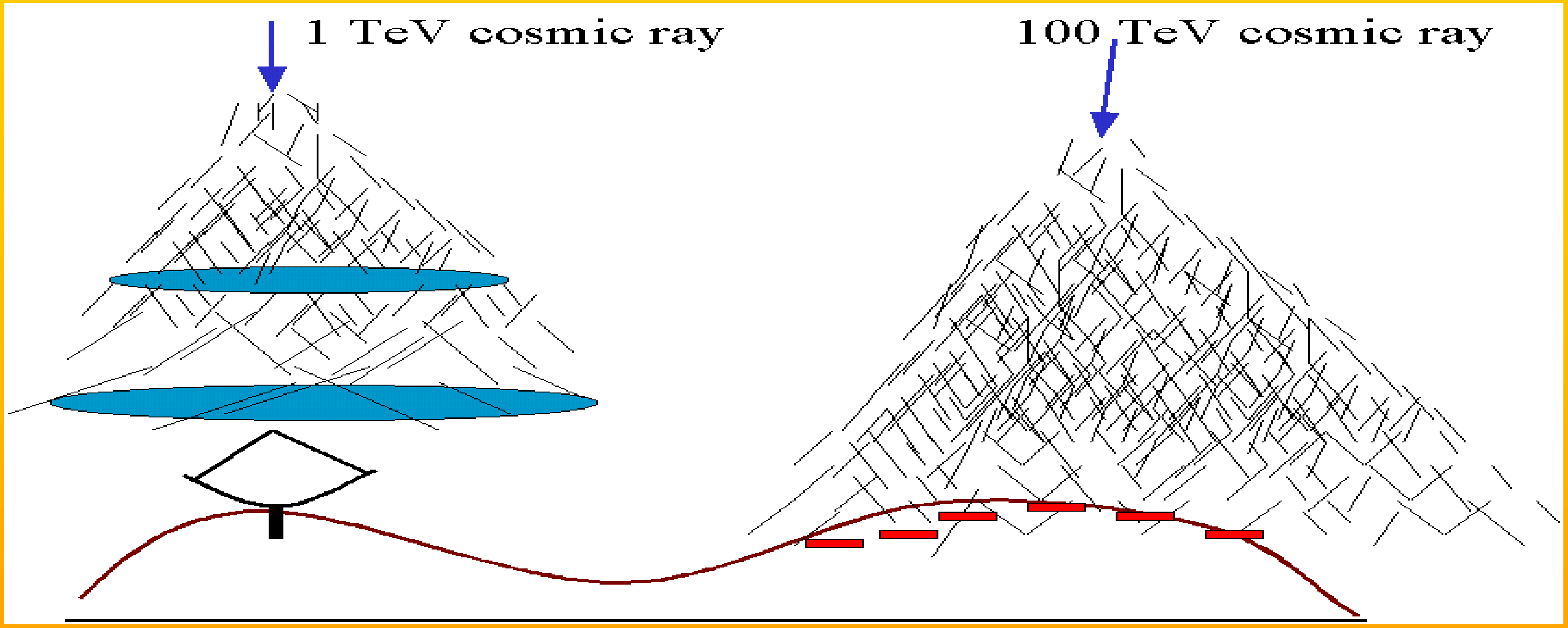


Primary Energy (GeV)

Low Energy Threshold Requires Detection
of Gamma Rays in EAS

Detecting Extensive Air Showers

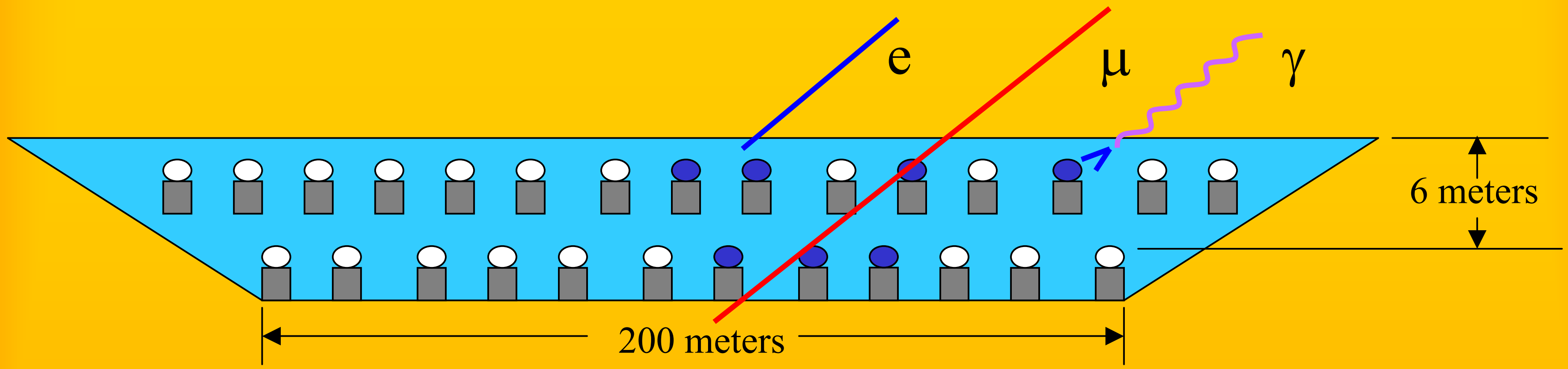
Air Cherenkov Telescope | **Extensive Air Shower Array**



Low energy threshold (300 GeV)
Good background rejection (99.7%)
Small field of view (2 msr)
Small duty cycle (< 10 %)

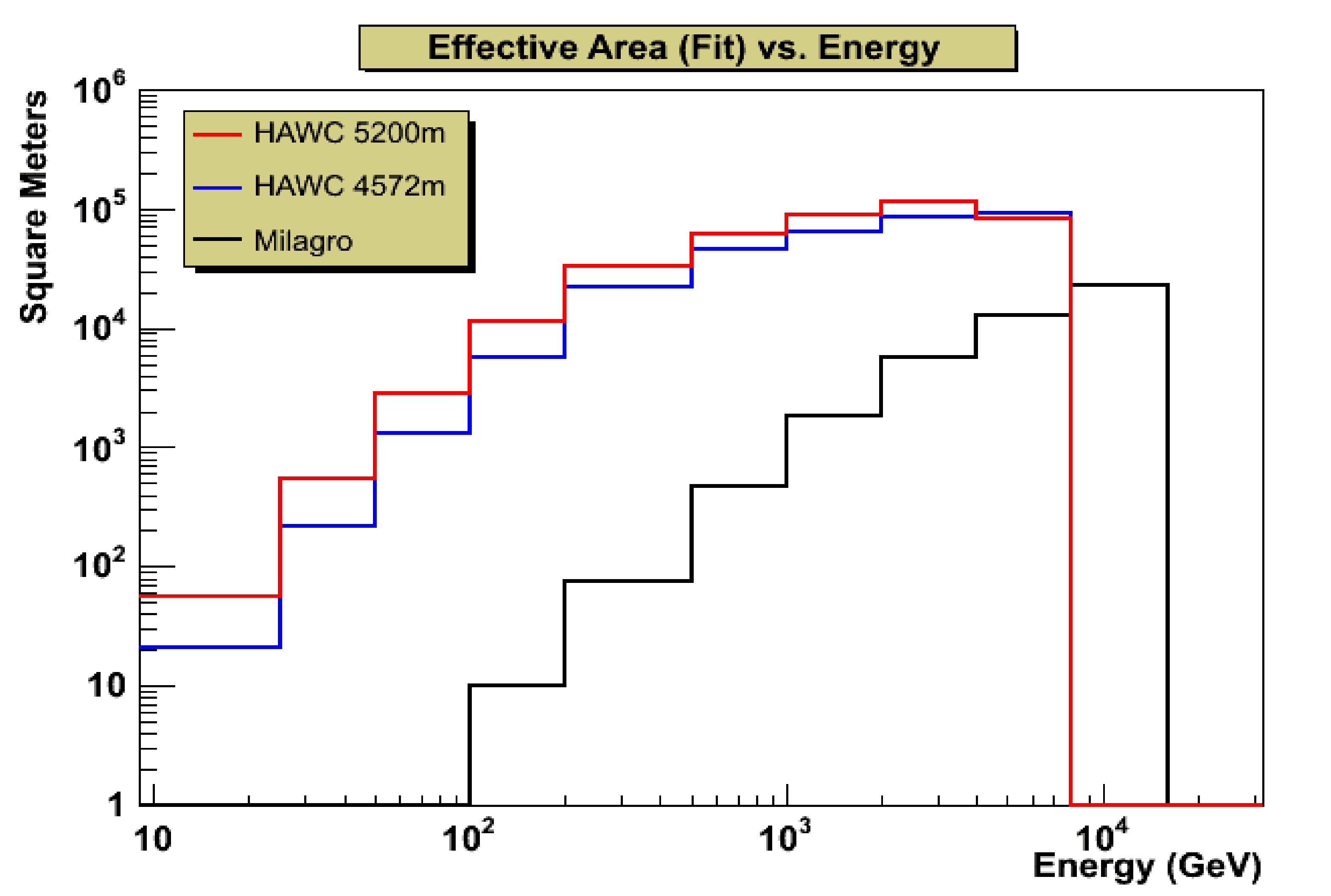
High energy threshold (100 TeV)
Moderate background rejection (50%)
Large field of view (~2 sr)
High duty cycle (>90%)

HAWC Strawman Design

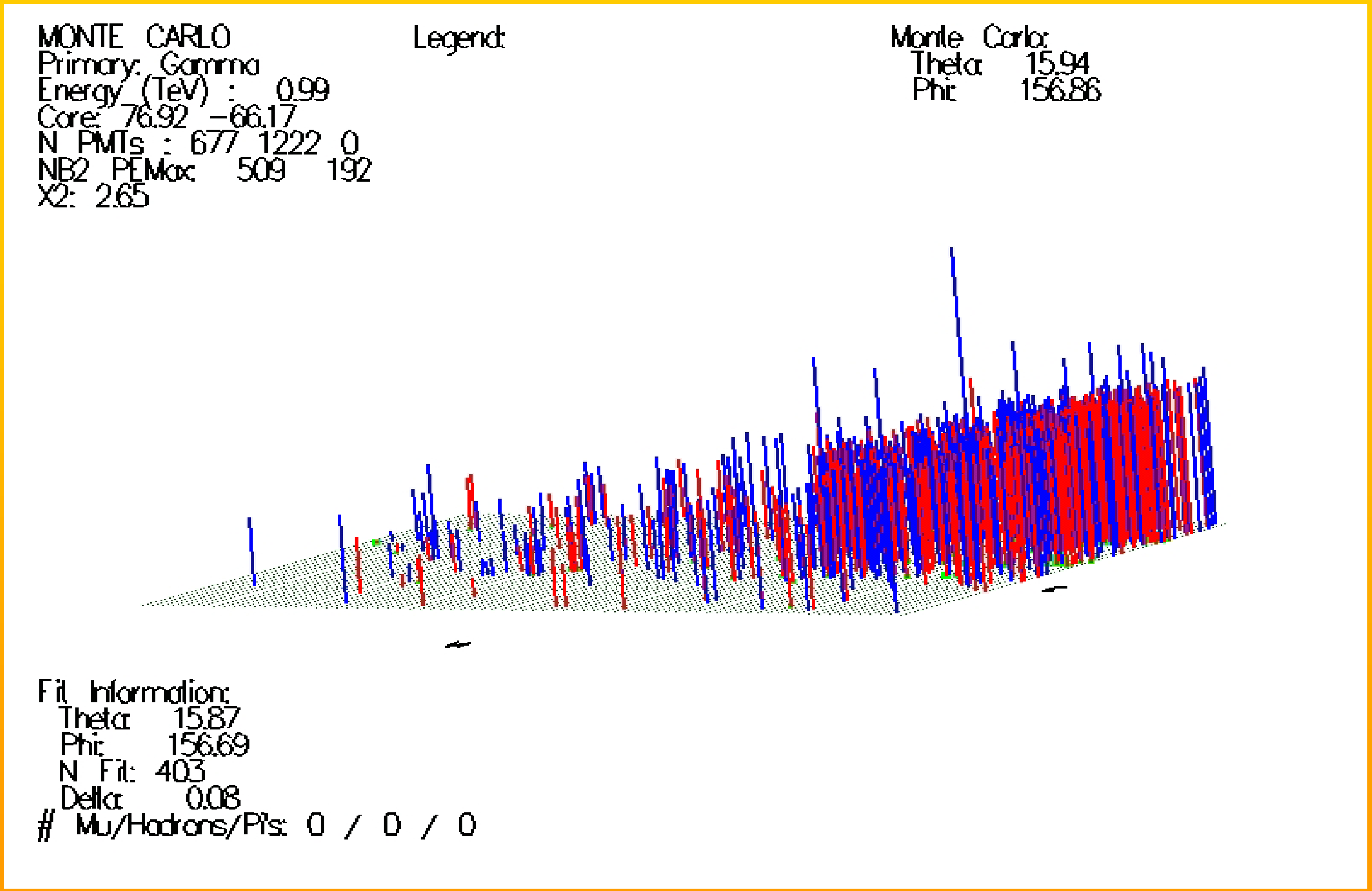


- 200m x 200m water Cherenkov detector
- Two layers of 8" PMTs on a 2.7 meter grid
  - Top layer under 1.5m water (trigger & angle)
  - Bottom layer under 6m water (energy & particle ID)
  - ~10,000 PMTs total (5,000 top and 5000 bottom)
  - Trigger: >50 PMTs in top layer
- Two altitudes investigated
  - 4500 m (~Tibet, China)
  - 5200 m (Atacama desert Chile)

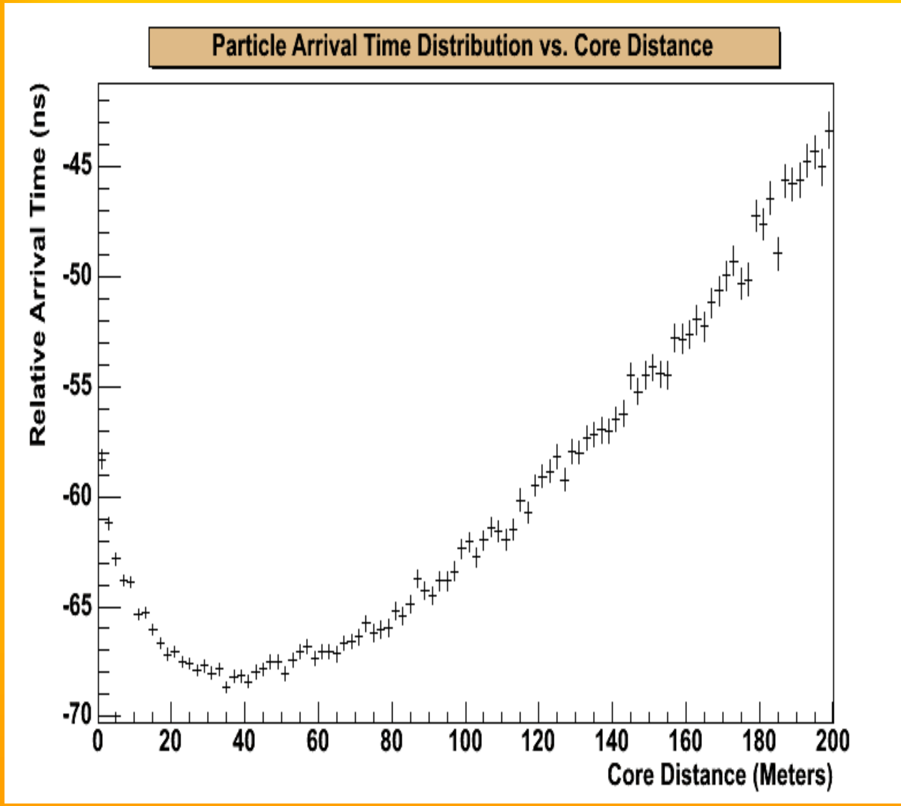
Effective Area vs. Energy

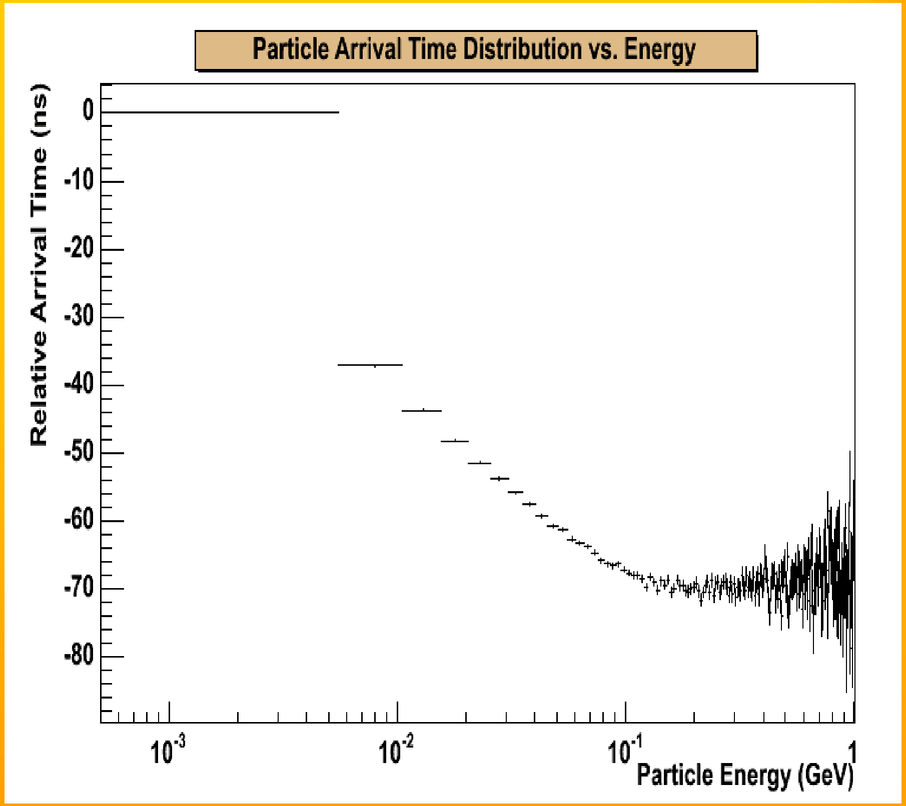


Event Reconstruction

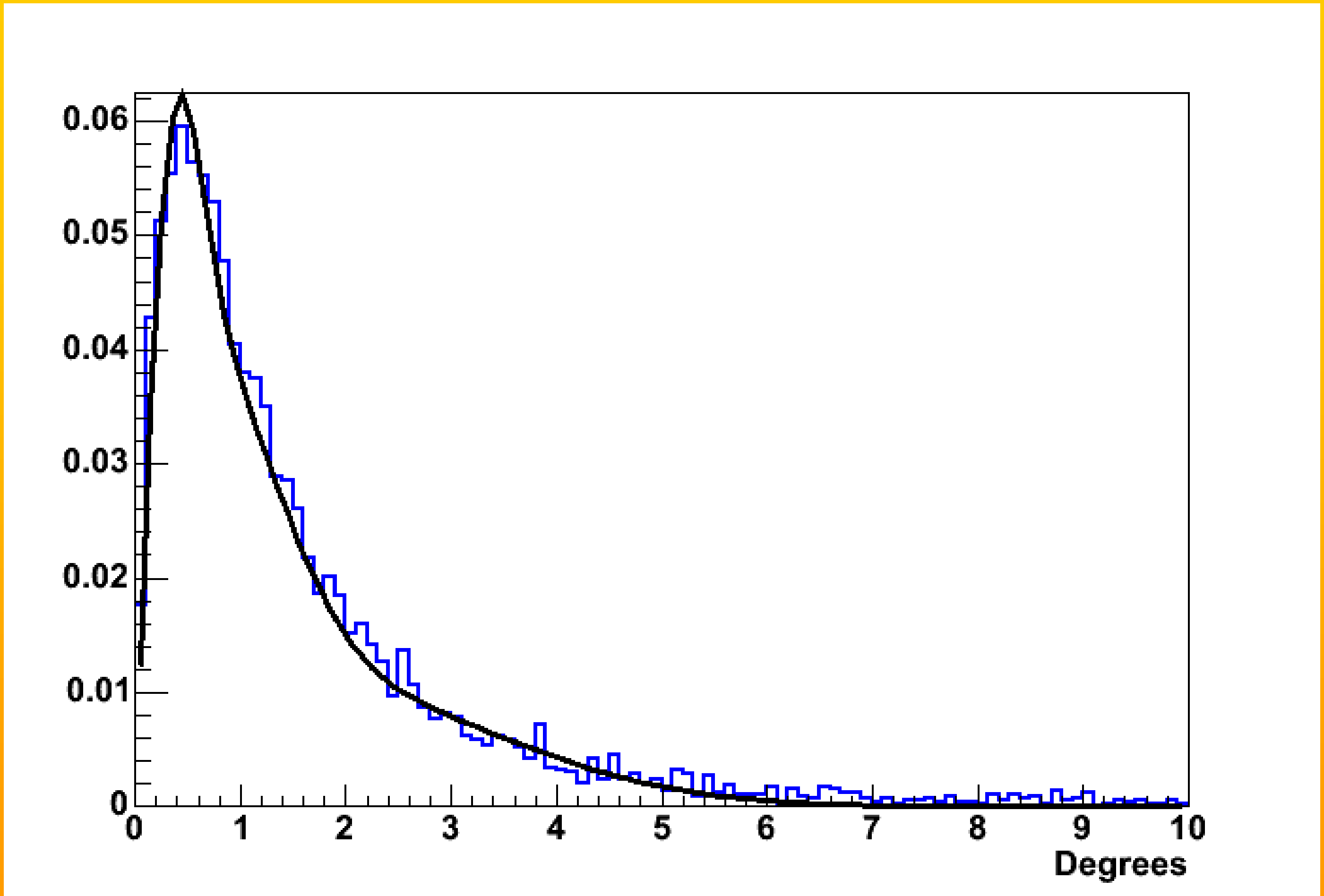


Event Reconstruction

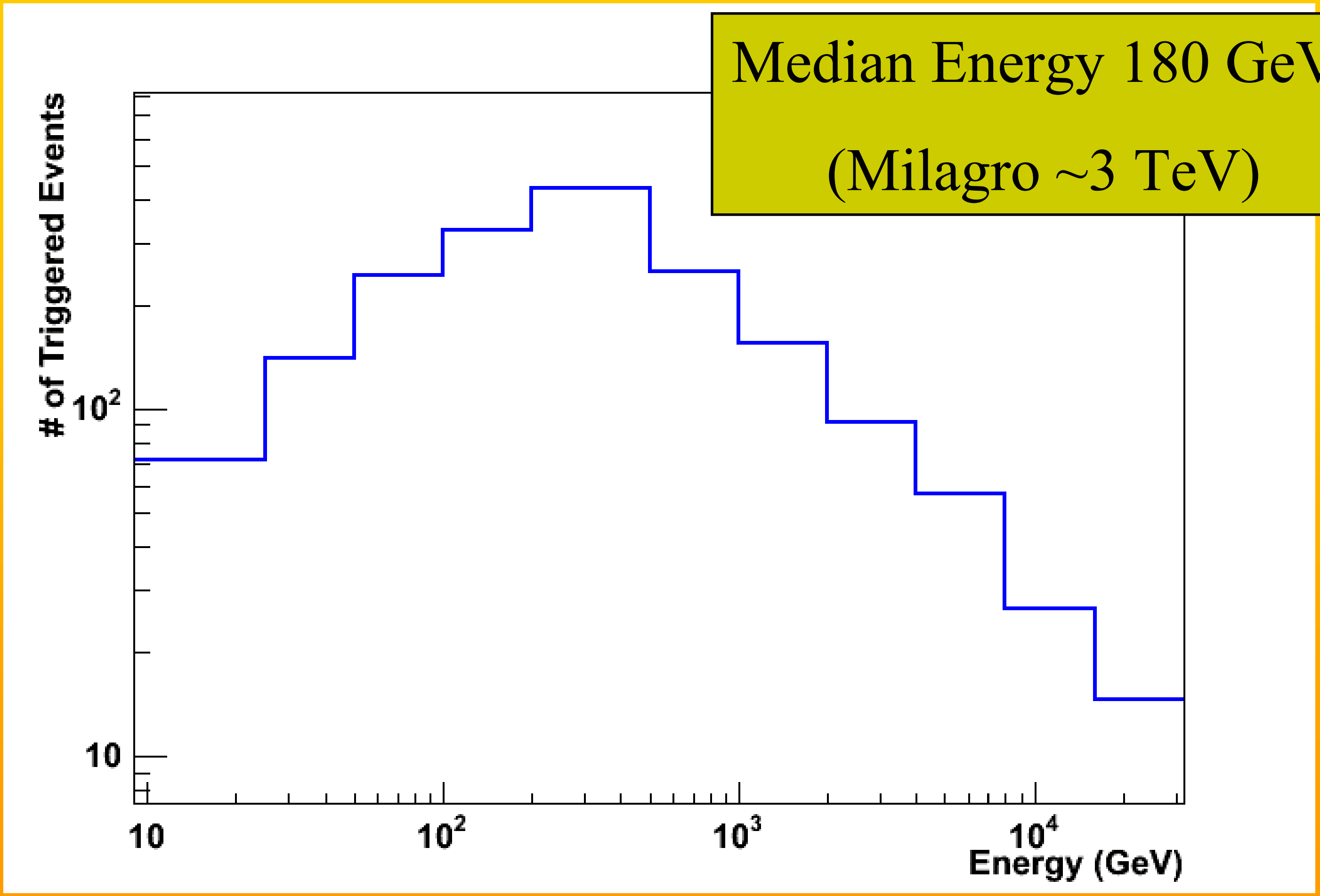




Angular Resolution



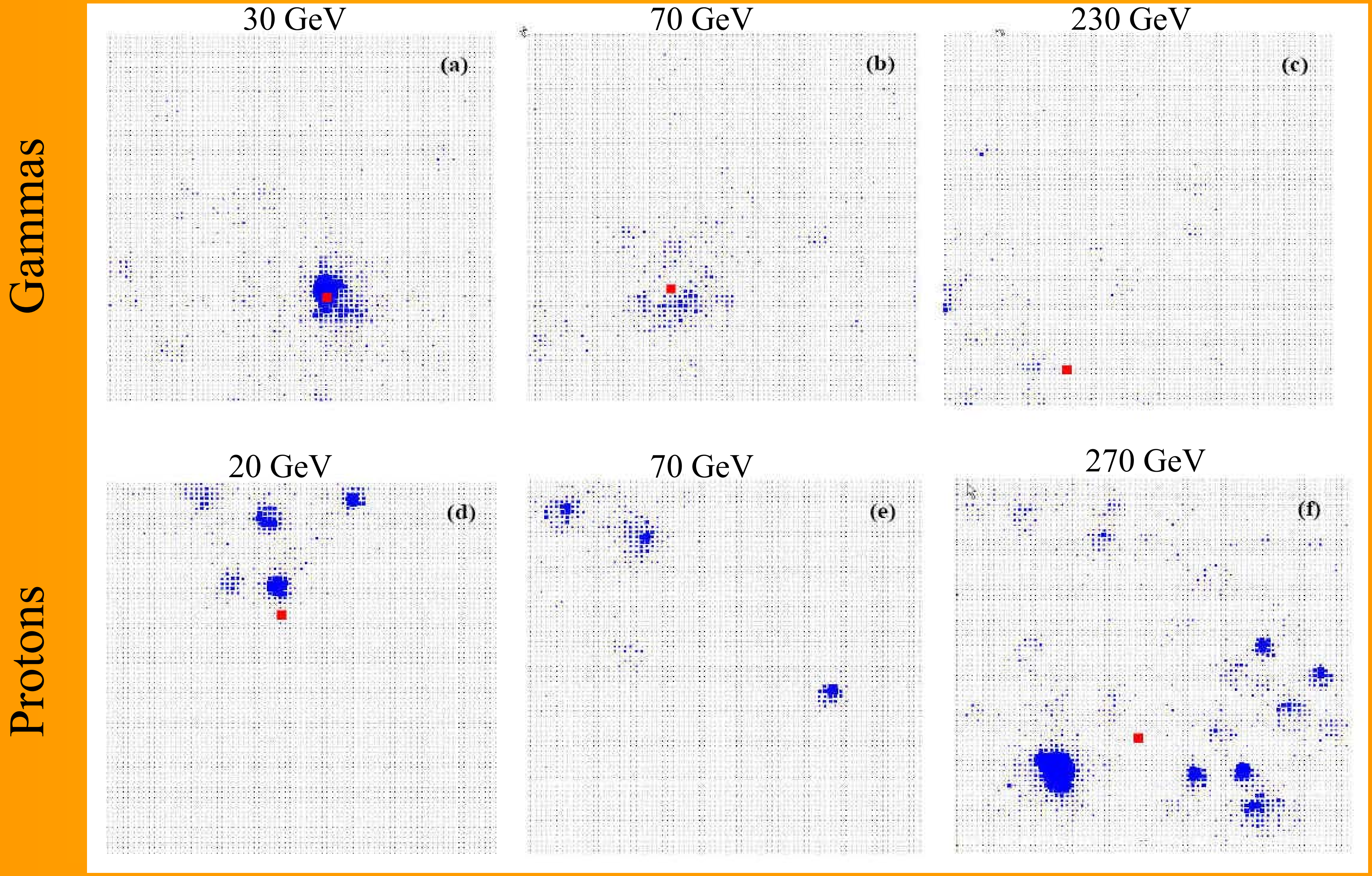
Energy Distribution of Fit Events



Median Energy 180 GeV

(Milagro ~3 TeV)

Background Rejection Bottom Layer



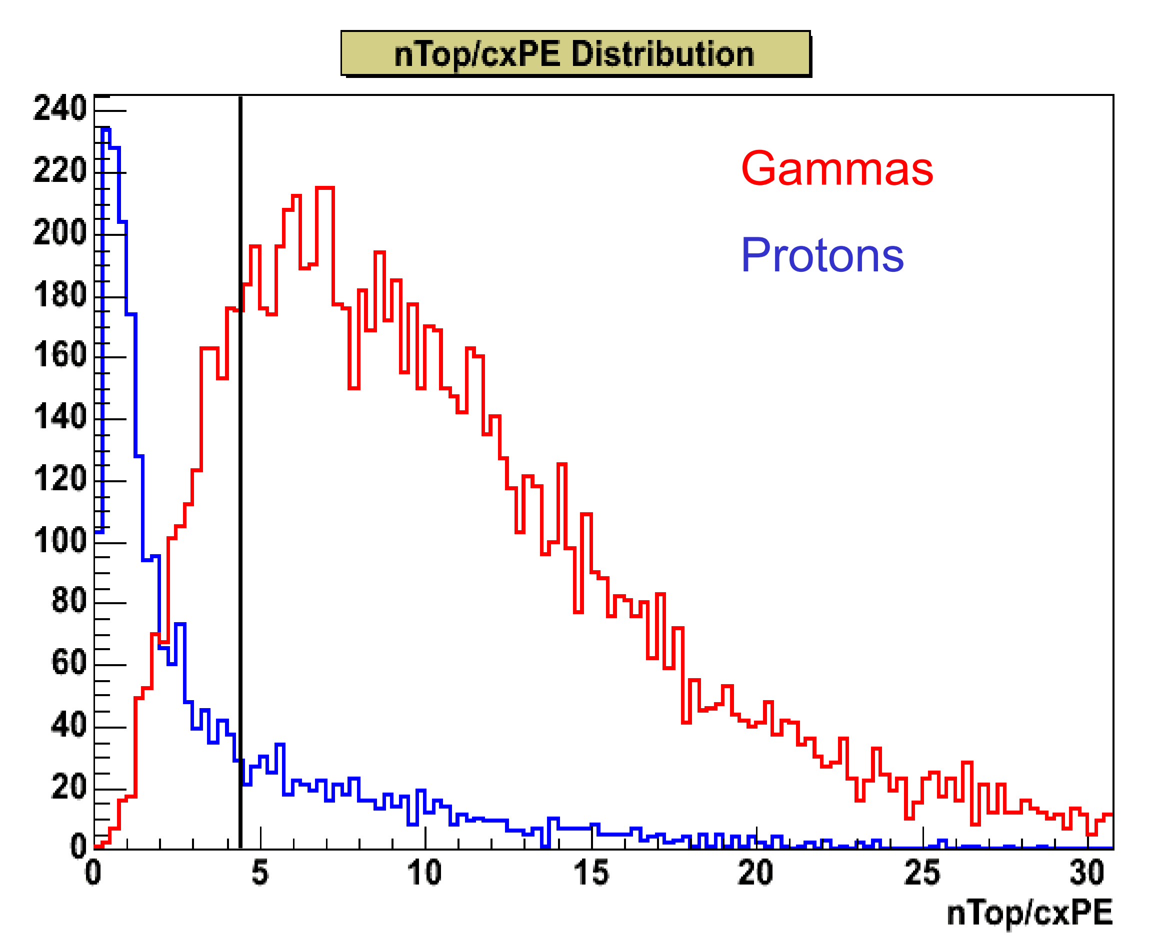
Background Rejection

Uniformity Parameter
nTop/cxPE > 4.3

Reject 70% of protons

Accept 87% of gammas

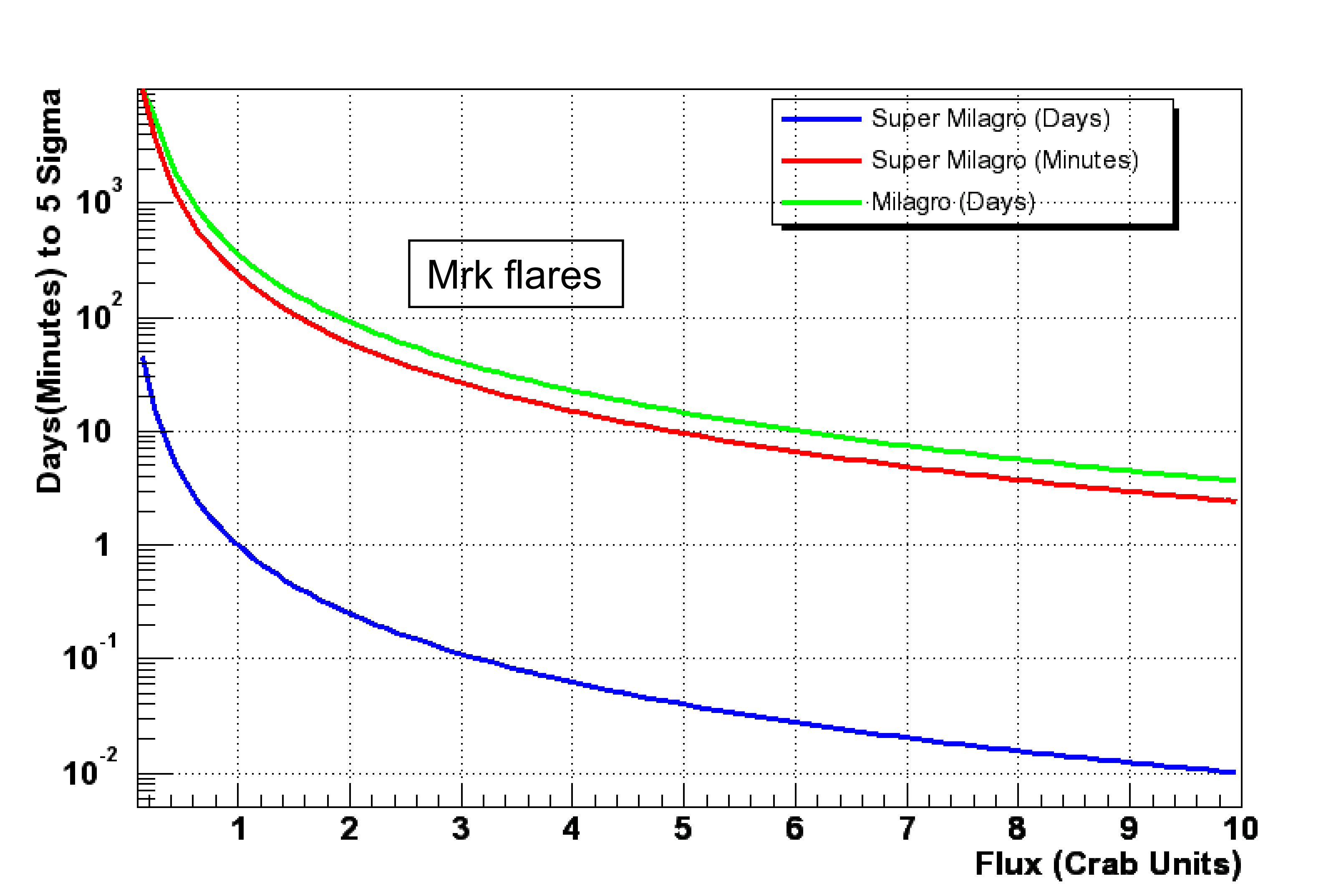
1.6*x* improvement in sensitivity



D.C. Sensitivity: Galactic Sources

- Crab Spectrum: $dN/dE = 3.2x10^{-7} E^{-2.49}$
  - Milagro 0.002 (0.001) Hz raw (cut) rate
  - HAWC 0.220 (0.19) Hz raw (cut) rate
  - Whipple 0.025 Hz
  - Veritas 0.5 (.12) Hz raw (cut) rate
- Background rate 80 (24) Hz raw (cut)
- 4 σ/sqrt(day) raw data
- 6 σ/sqrt(day) cut data
  - 120 σ/sqrt(year)
- 40 mCrab sensitivity (all sky) in one year
  - Whipple: 140 mCrab per source
  - VERITAS: 7 mCrab per source (15 sources/year)

Transient Sensitivity



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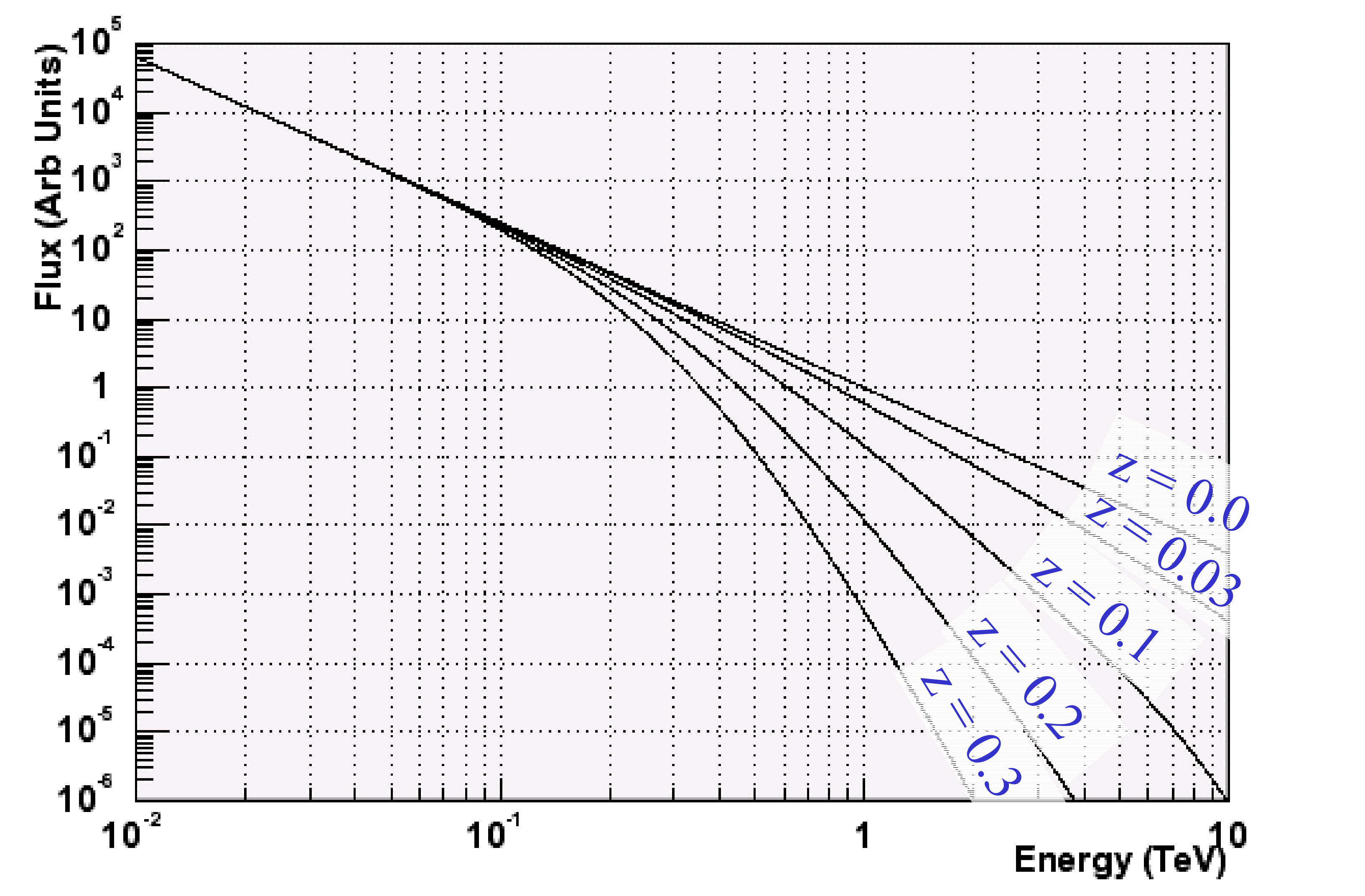
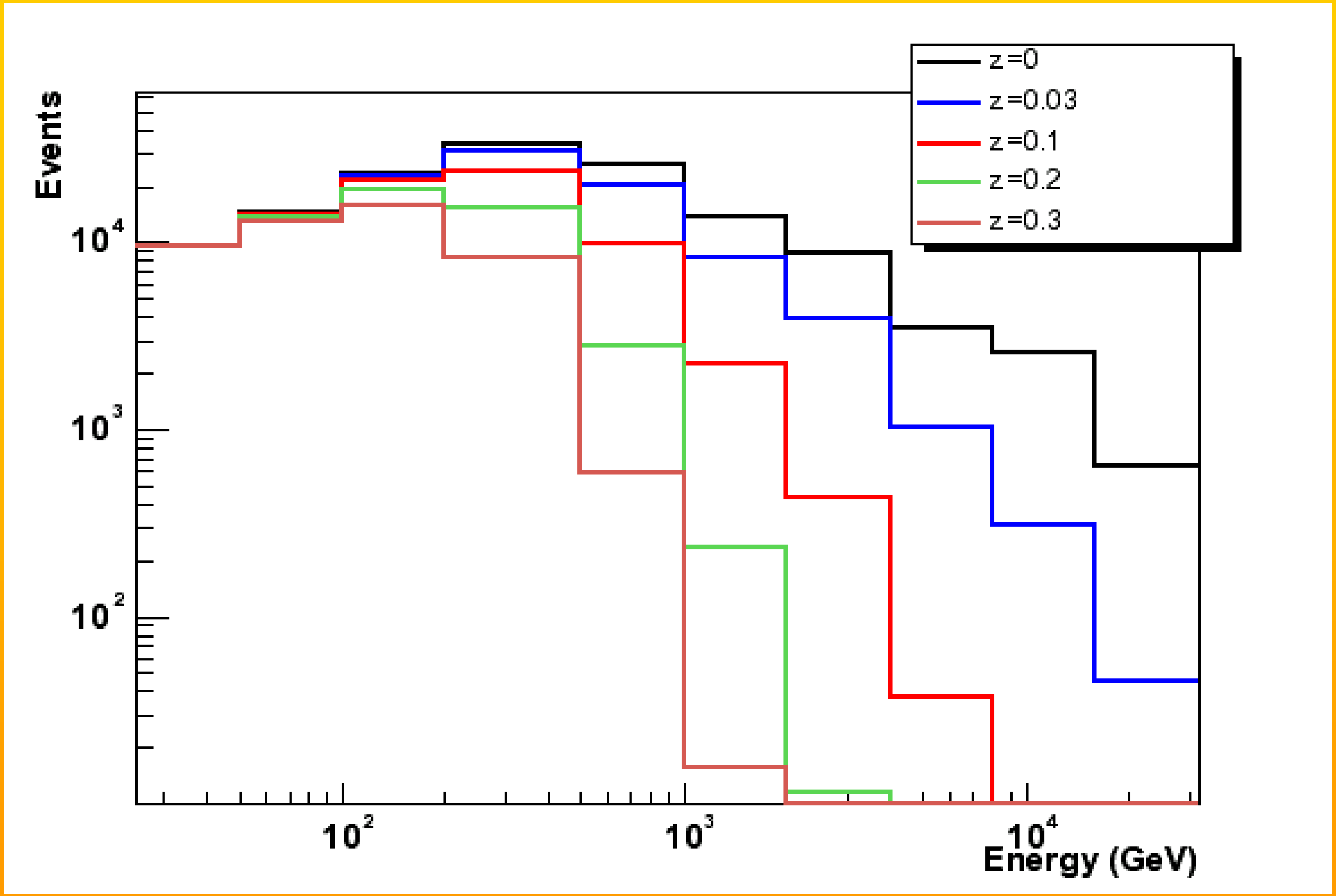
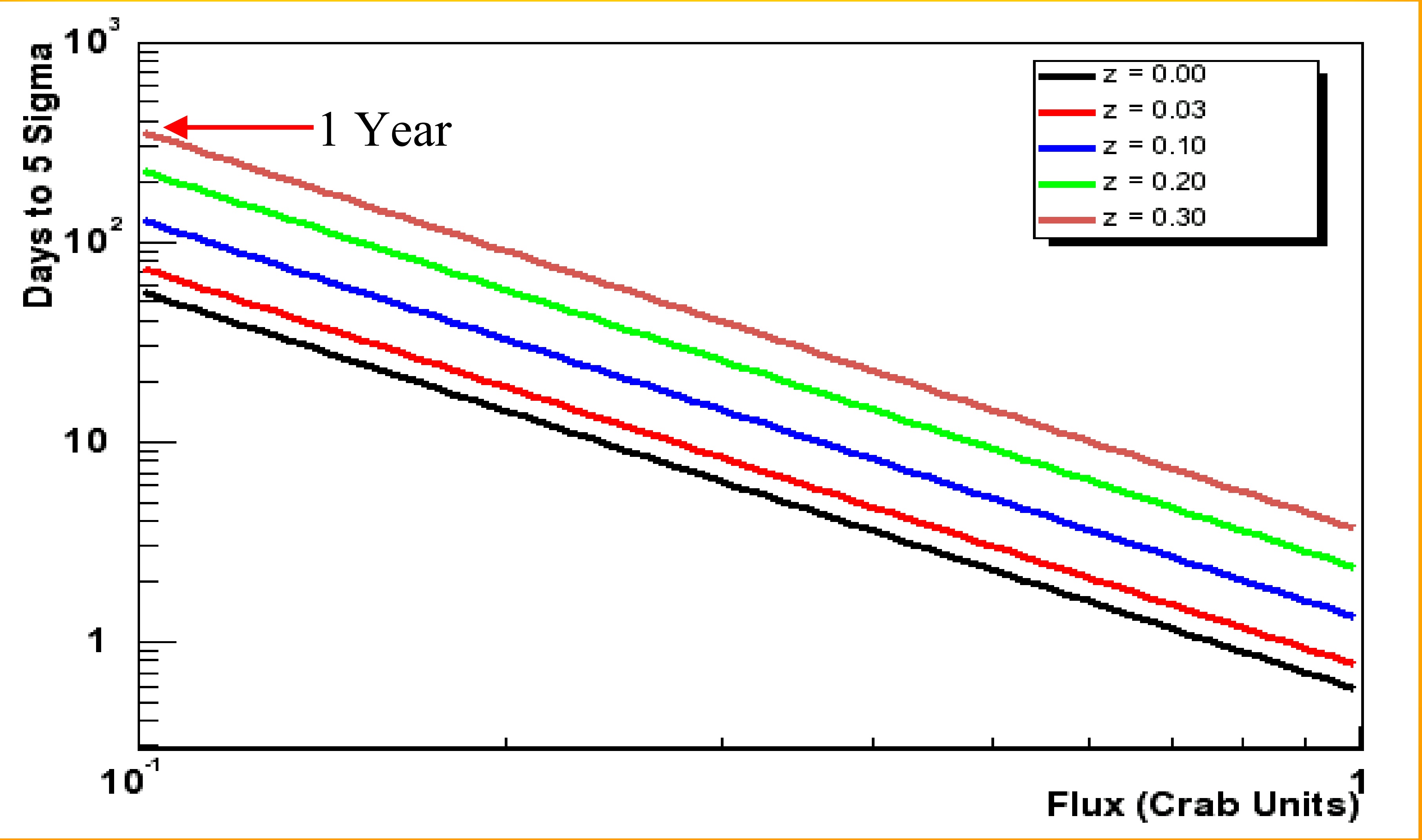
Effect of EBL on Distant Sources



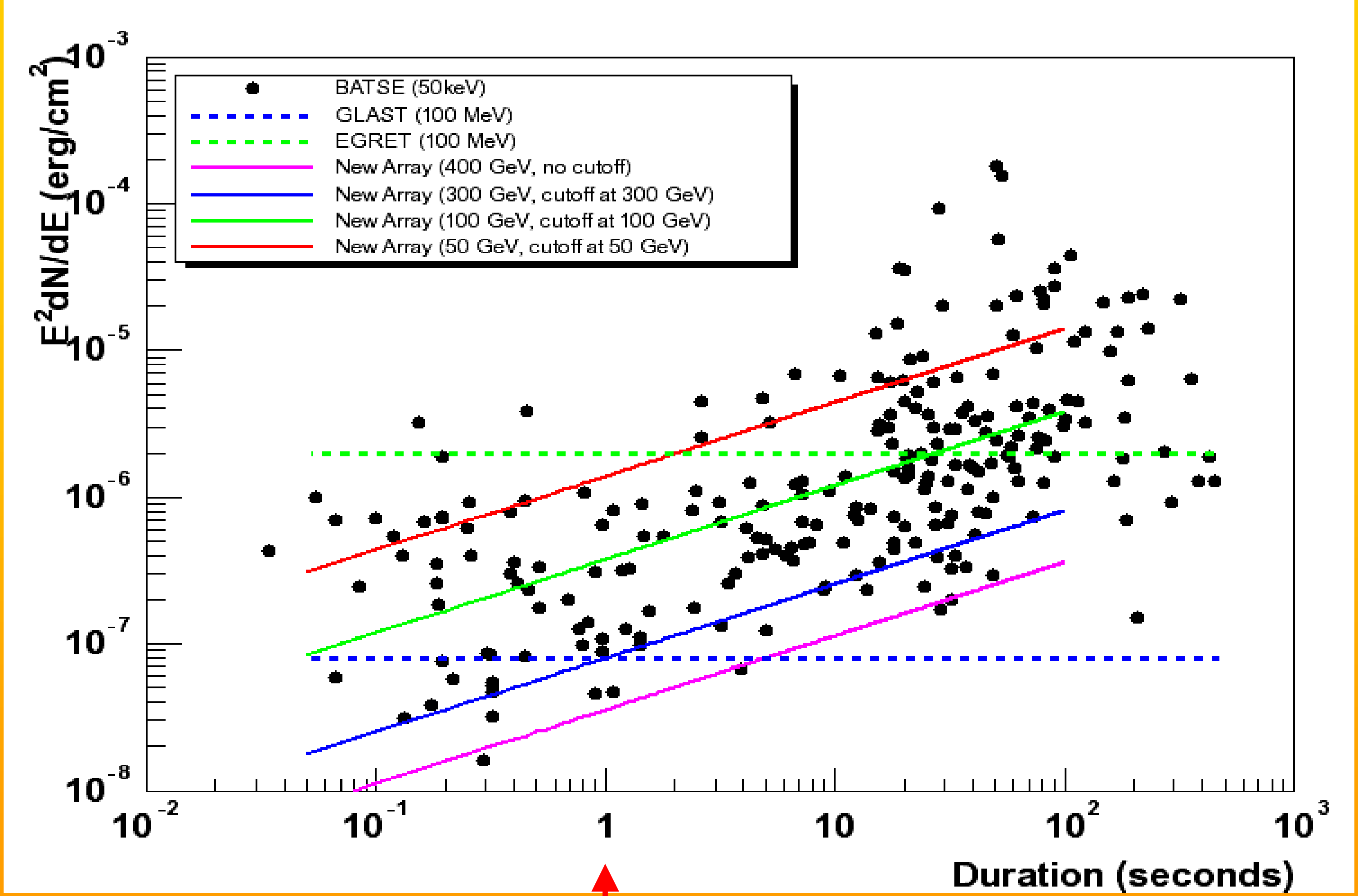
Energy Distribution After EBL



AGN Sensitivity



Gamma Ray Burst Sensitivity



50 events

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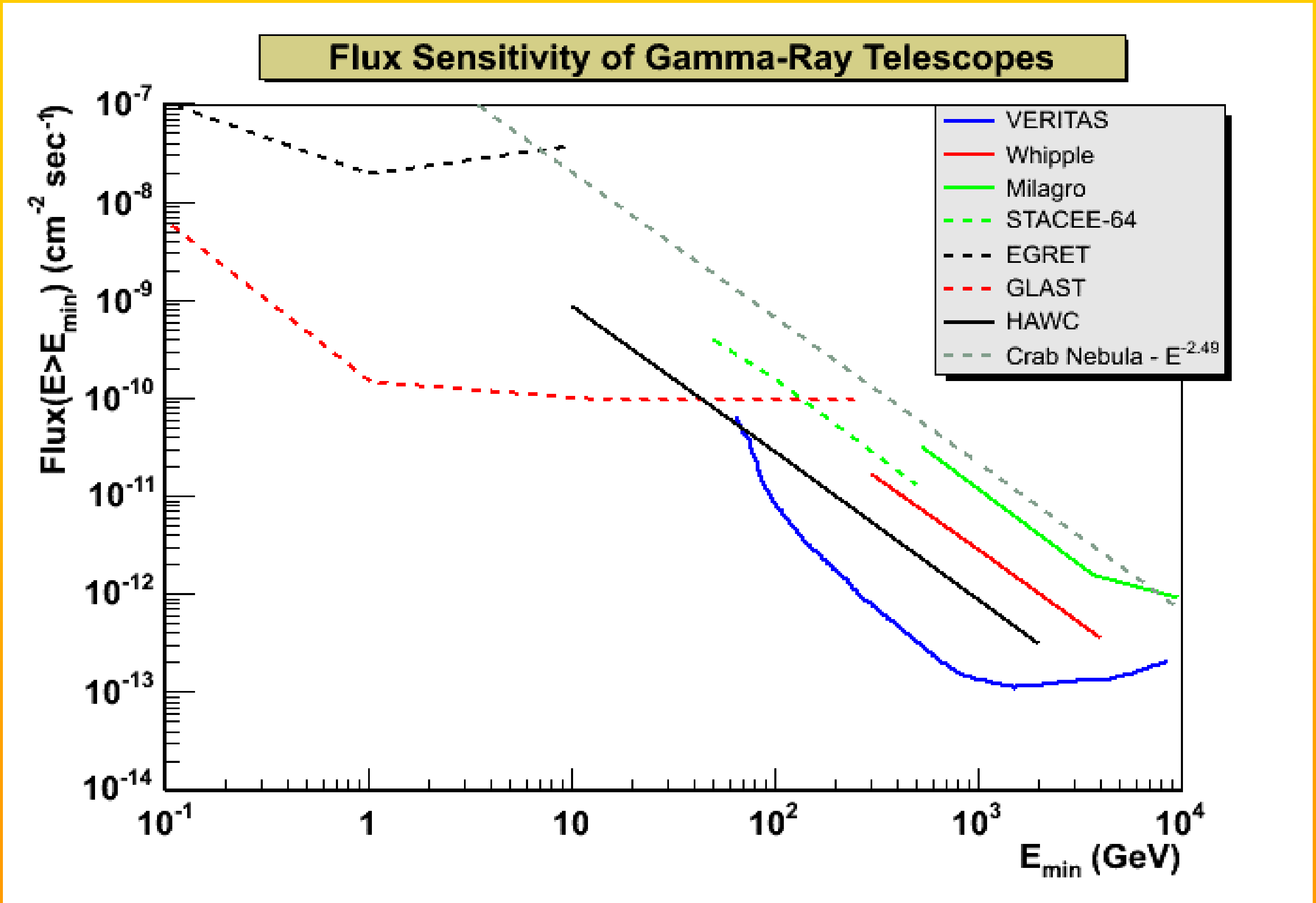
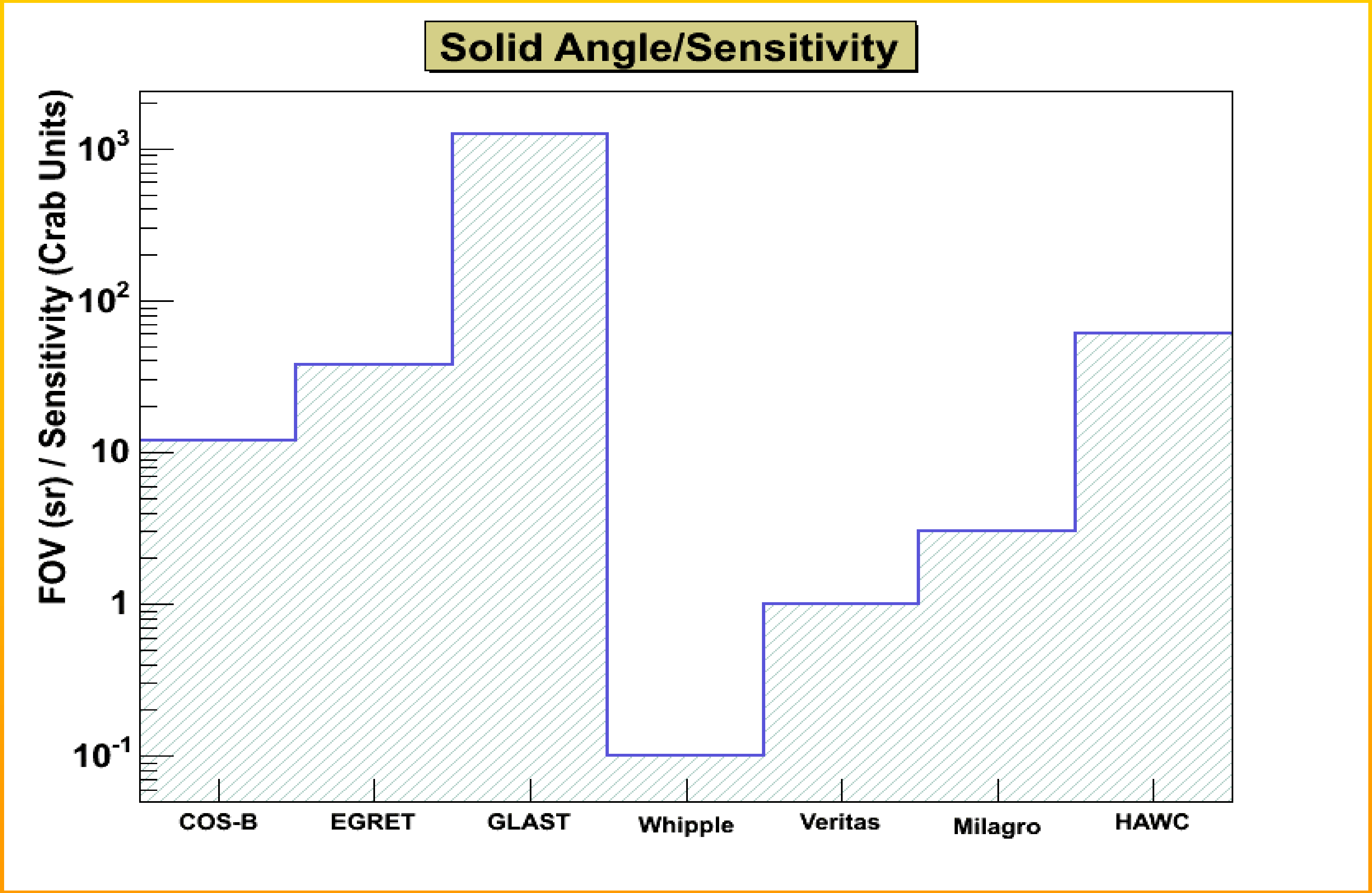
Point Source Sensitivity



Time Domain Sensitivity



Conclusions

- A large area, high altitude all-sky VHE detector will:
  - Detect the Crab in a single transit
  - Detect AGN to z = 0.3
  - Observe 15 minute flaring from AGN
  - Detect GRB emission at ~50 GeV / redshift ~1
  - Detect 6-10 GRBs/year (EGRET 6 in 9 years)
  - Monitor GLAST sources at VHE energies
  - Begin field of VHE time-domain astrophyscis

Conclusions

- Continuing work
  - Improve background rejection & event reconstruction
    - Increase sensitivity by ~50% - 100%?
    - Develop energy estimator
  - Detailed detector design (electronics, DAQ, infrastructure)
  - Reliable cost estimate needed (~$30M???)
  - Site selection (Chile, Tibet, White Mountain)
- Time Line
  - 2004 R&D proposal to NSF
  - 2006 full proposal to NSF
  - 2007-2010 construction

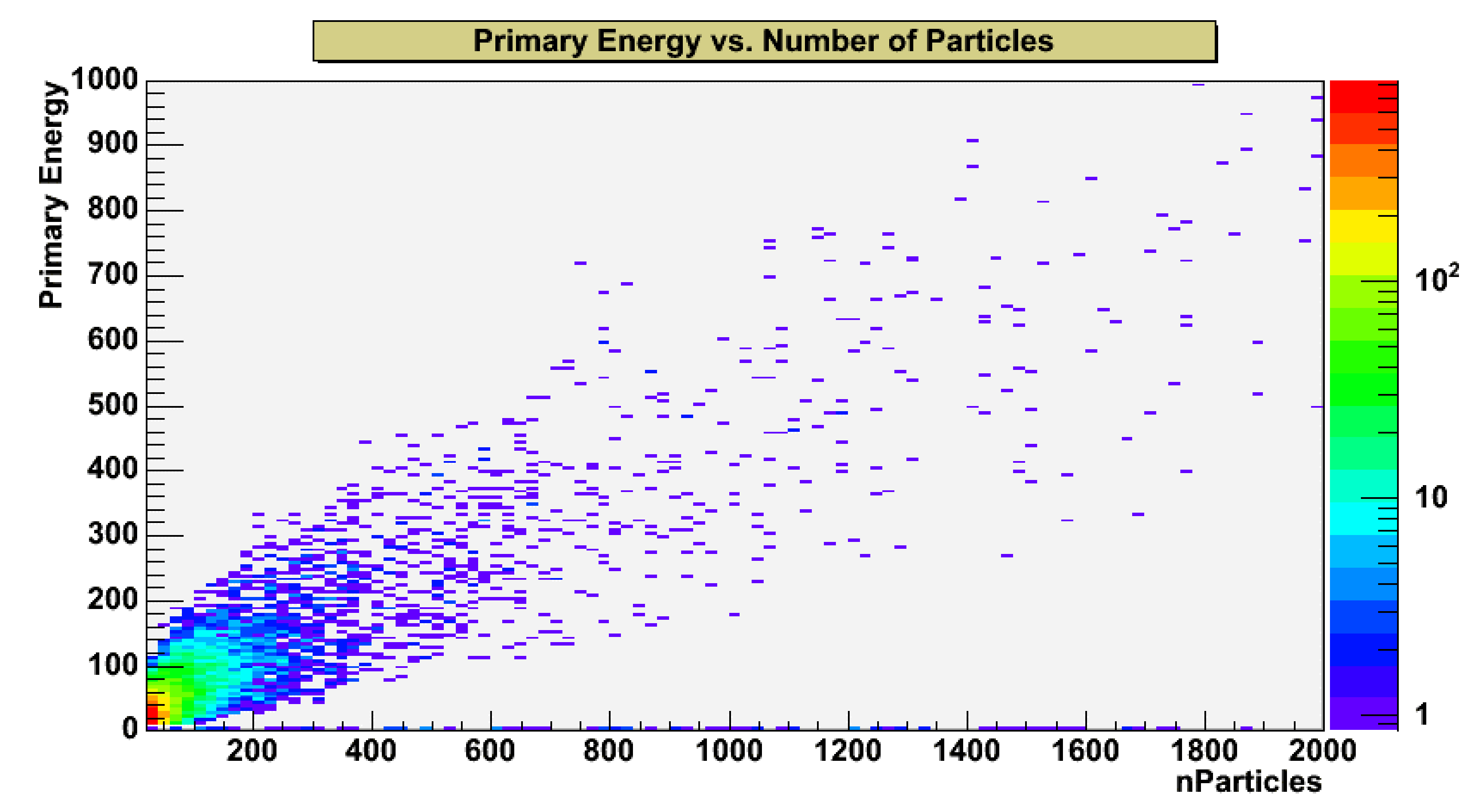
Site Visit: YBG 4/1-6

- Excellent location
  - Land available
    - many km^2 available at 4300m
    - Room at ~4800m
  - Power available (3 MWatts generated in YBJ)
  - Water available
  - Dormitories (“Western rooms”)
- Existing gamma ray detectors
  - ASγ array
  - ARGO detector

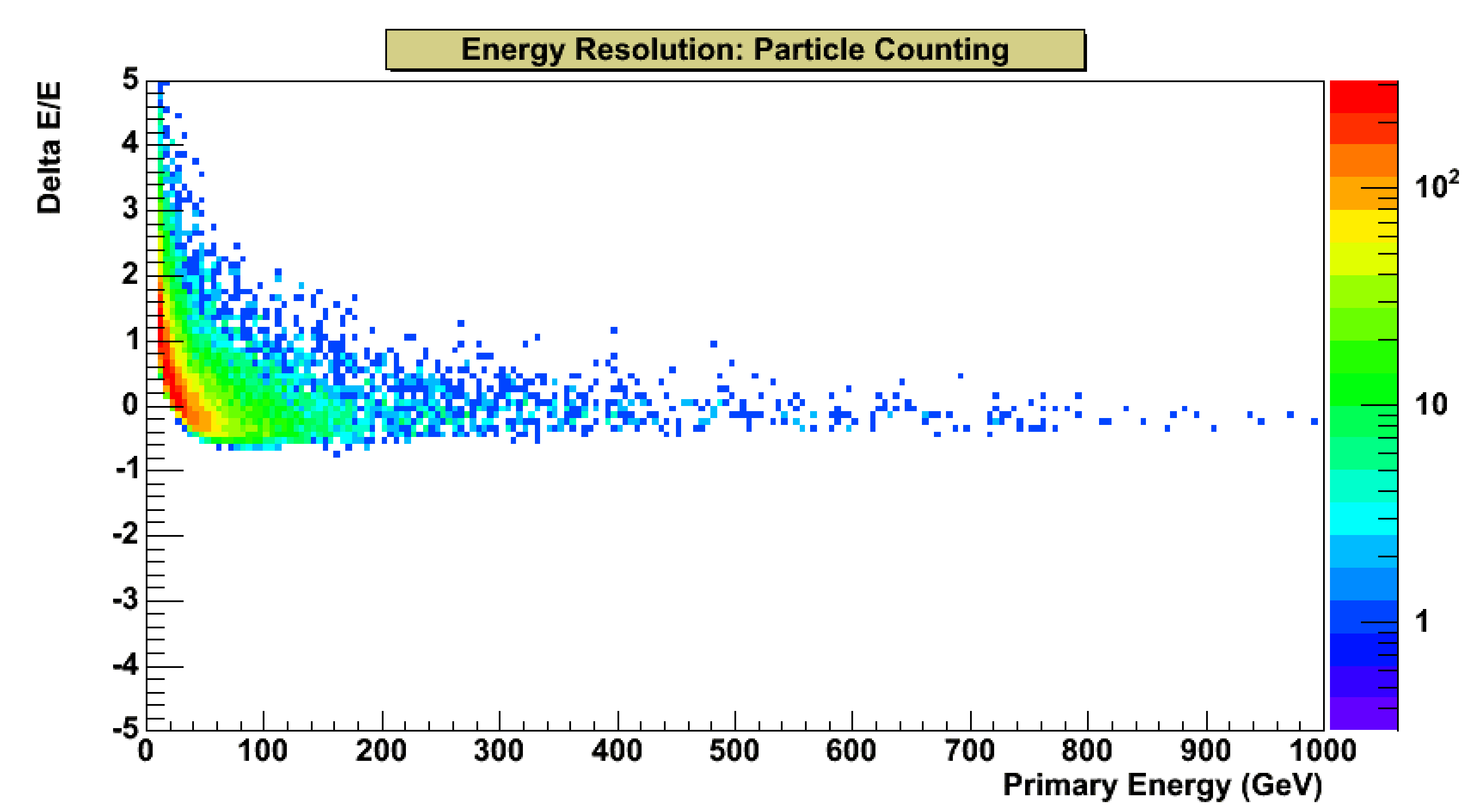
Site Visit: IHEP Beijing

- Scientists excited by project (IHEP and Tibet University)
  - Would like full-scale collaboration
  - Have experience with ASγ and ARGO
- IHEP Director Hesheng Chen enthusiastic about project
  - Committed to provide land, power, water, and people
    - Will provide letter to NSF on request
  - Funds for infrastructure (building, etc) can not be promised at this time
    - They paid ~$2M for ARGO building/infrastructure

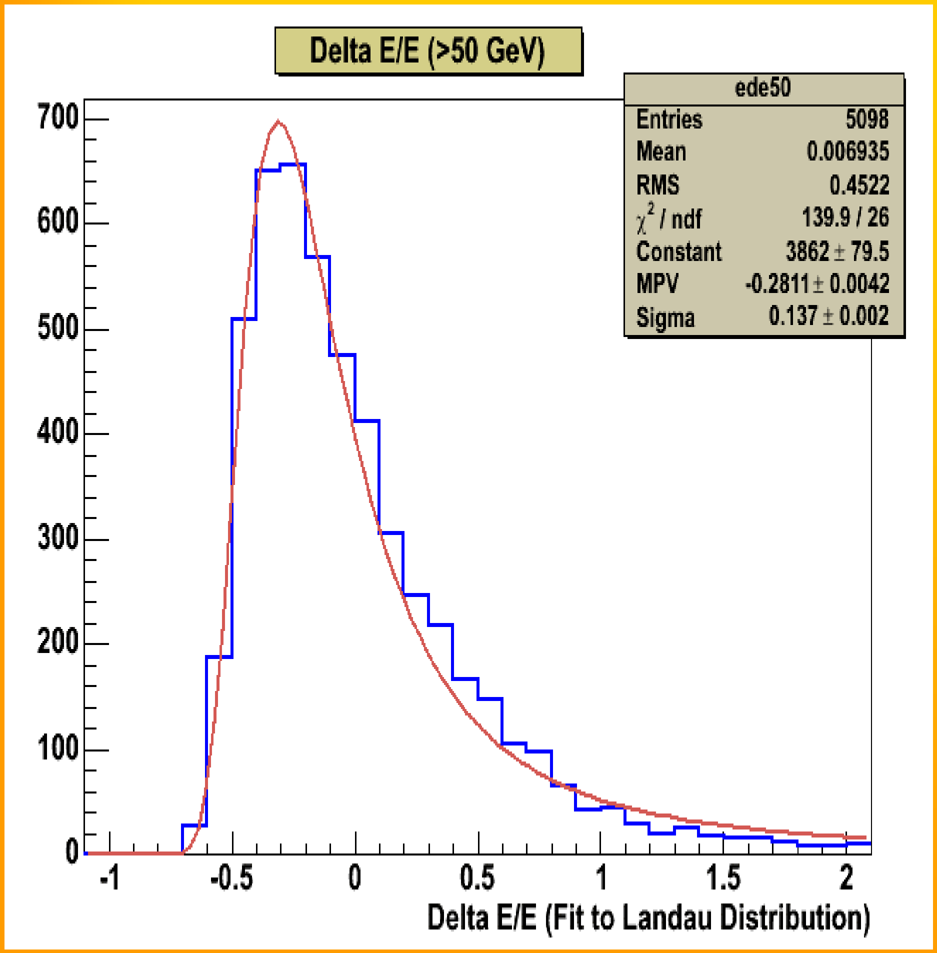
CORSIKA: Energy Resolution

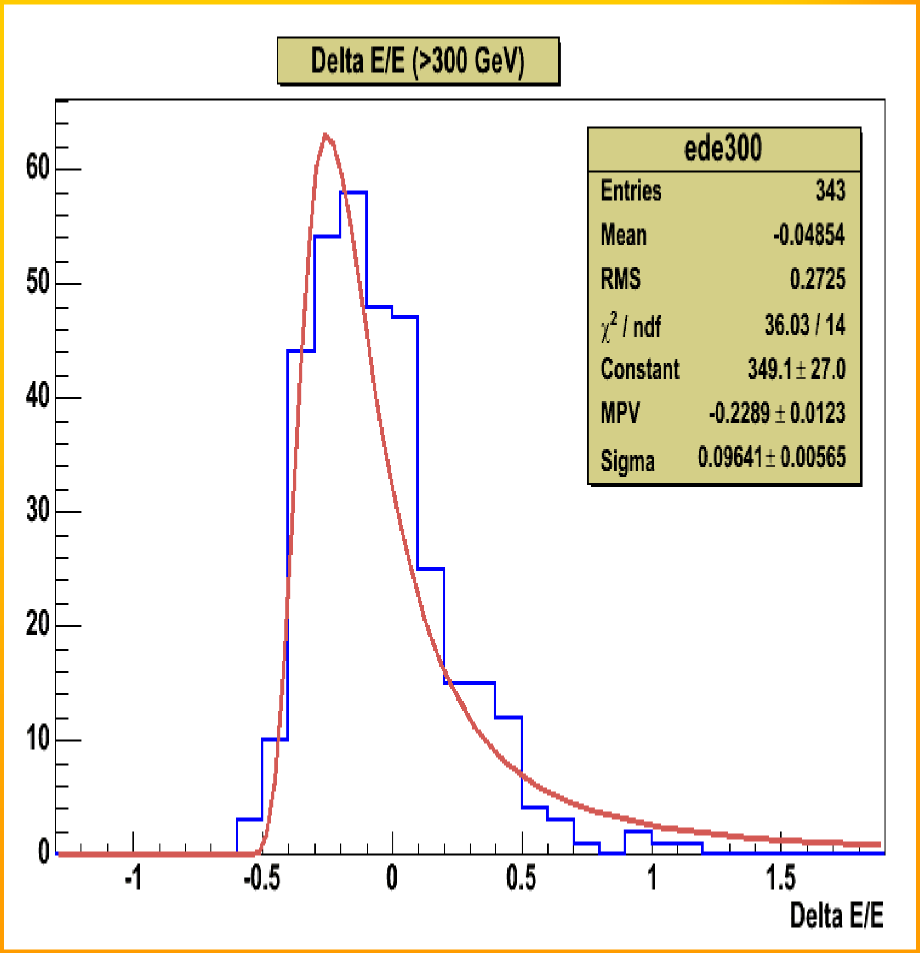


CORSIKA: Energy Resolution



CORSIKA: Energy Resolution





Background Rejection