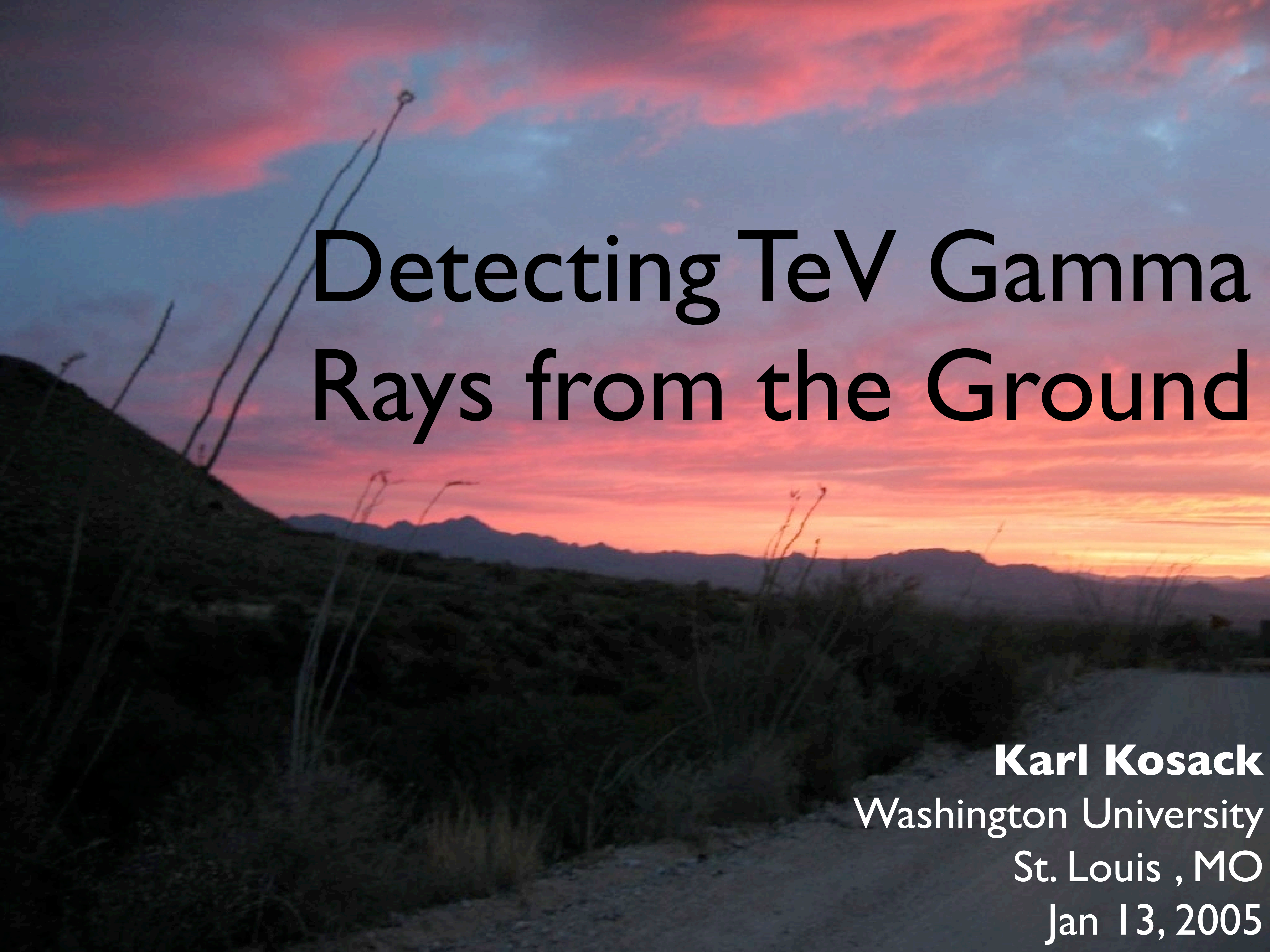


Detecting TeV Gamma Rays from the Ground

Karl Kosack
Washington University
St. Louis , MO
Jan 13, 2005

Collaborators

United States

Smithsonian Astrophysical Observatory
Purdue University
Iowa State University
Washington University in St. Louis
University of Chicago
University of Utah
University of California, Los Angeles
Associate members...

Ireland

National University of Ireland, Dublin
Galway-Mayo Institute of Technology
Cork Institute of Technology
Associate members...

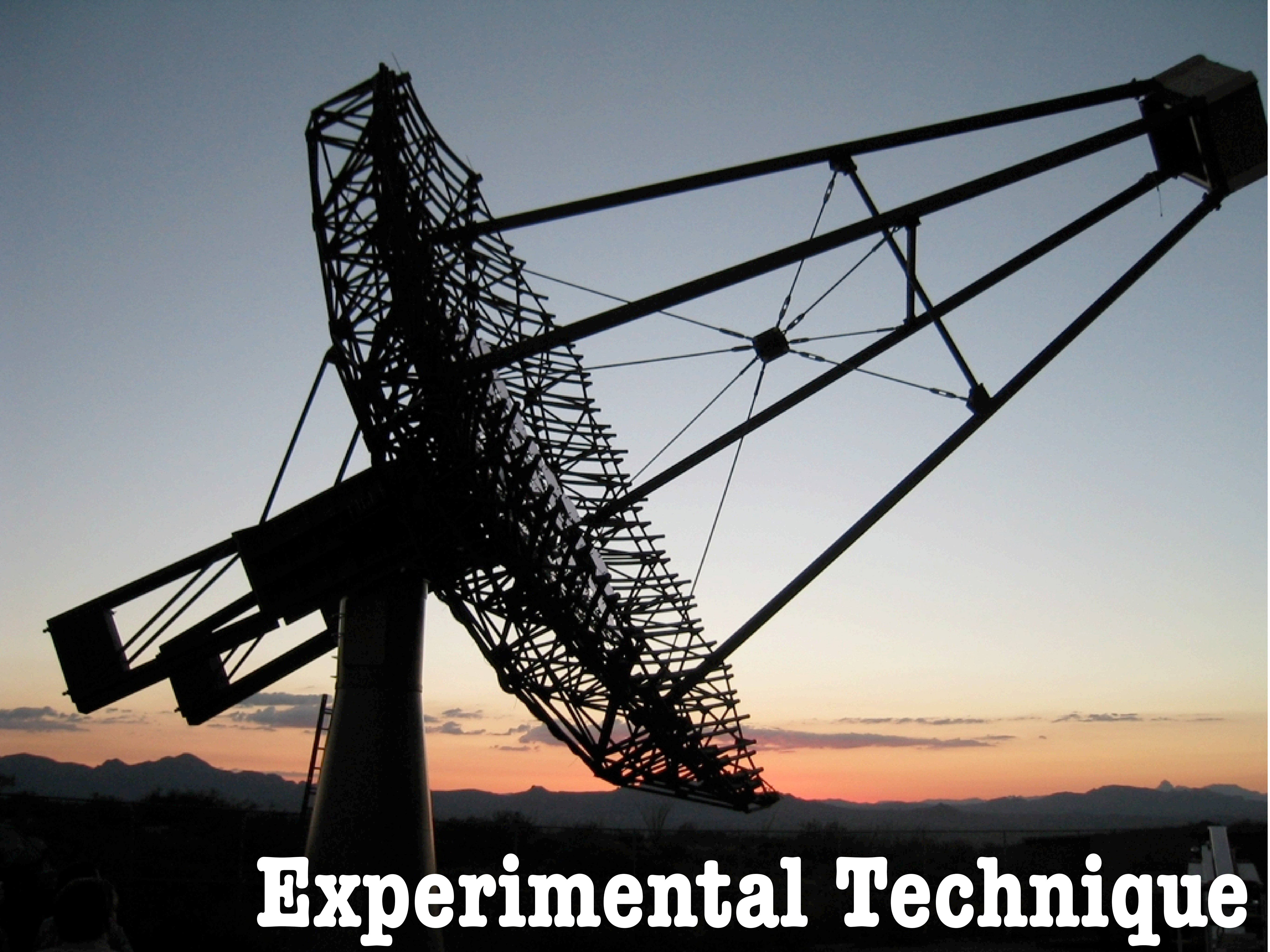
United Kingdom

University of Leeds
Associate Members

Canada

McGill University

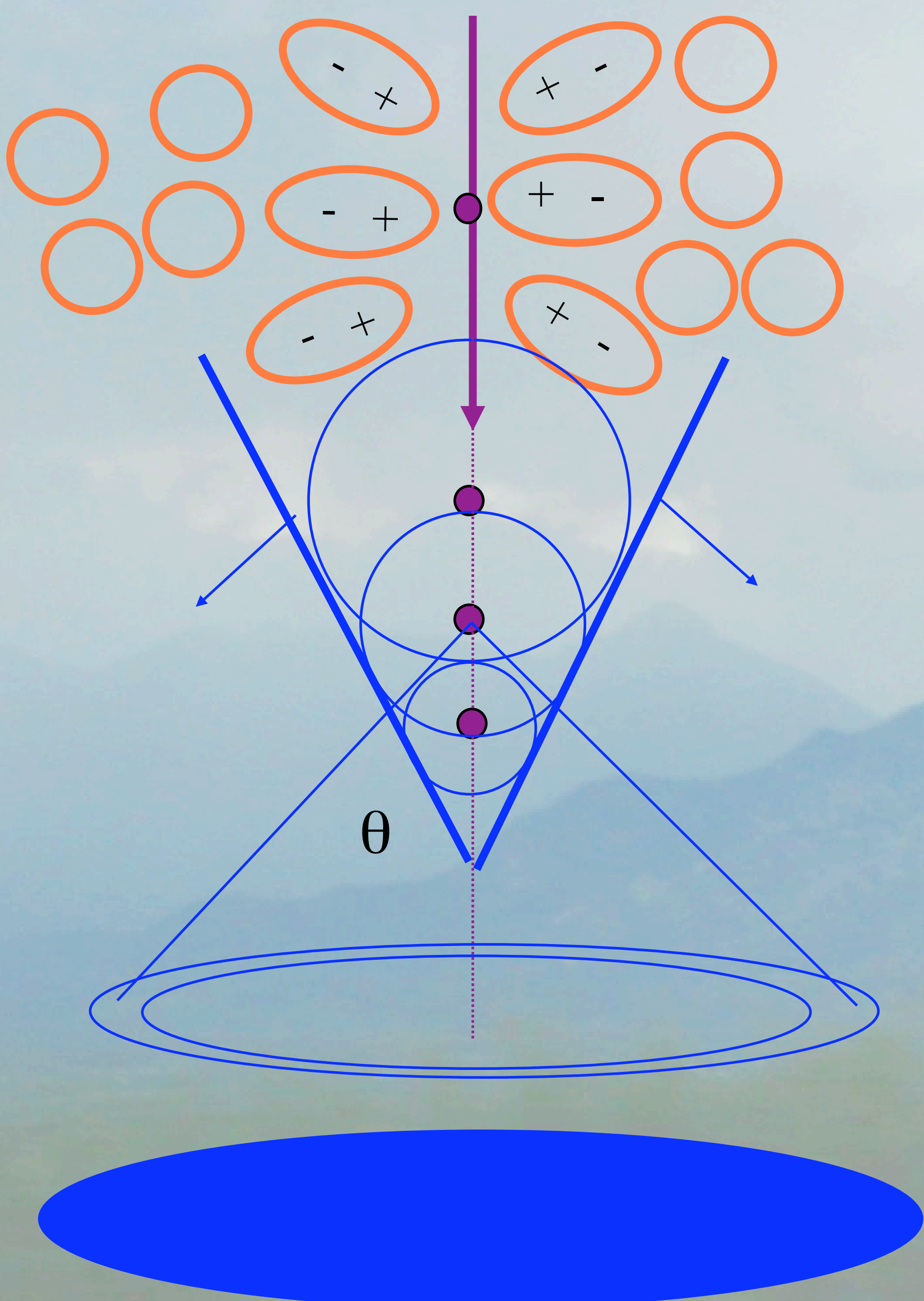
NSF, DOE, Smithsonian, NSERC (Canada), Science Foundation Ireland, PPARC (UK)


Experimental Technique

Q: Earth's Atmosphere is *opaque* to gamma rays - how can we detect them from the ground?

A: Use the entire atmosphere as *part* of the detector: an Atmospheric Cherenkov Telescope (ACT).

Čerenkov Radiation



A refresher from E&M class:

Charged particle traveling faster then speed of light in medium with I.O.R (n) polarizes the molecules

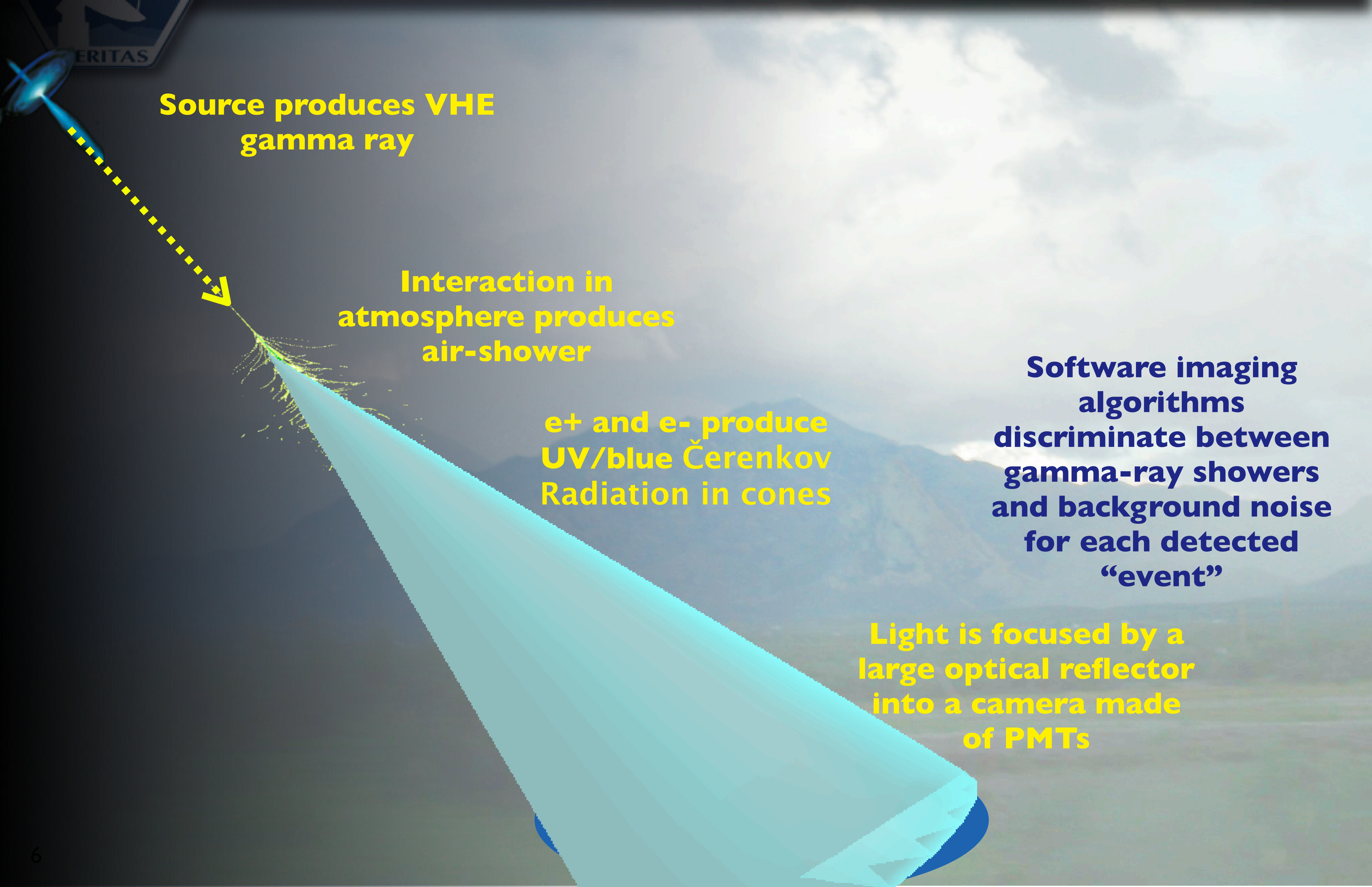
$$\sin(\theta) = \frac{1}{n\beta}$$

Conditions for radiation satisfied at the Čerenkov angle

Similar to a sonic boom, radiation is emitted in a forward cone when this condition is satisfied.

In the atmosphere, the emitted wavelength is in the UV/Blue part of the spectrum.

Atmospheric Čerenkov Telescopes



ACTs vs Satellites

ADVANTAGES:

Much cheaper than launching something

Size is not a problem, hands-on work

Large collection area

Can detect very high (>10TeV) energies

High spatial resolution

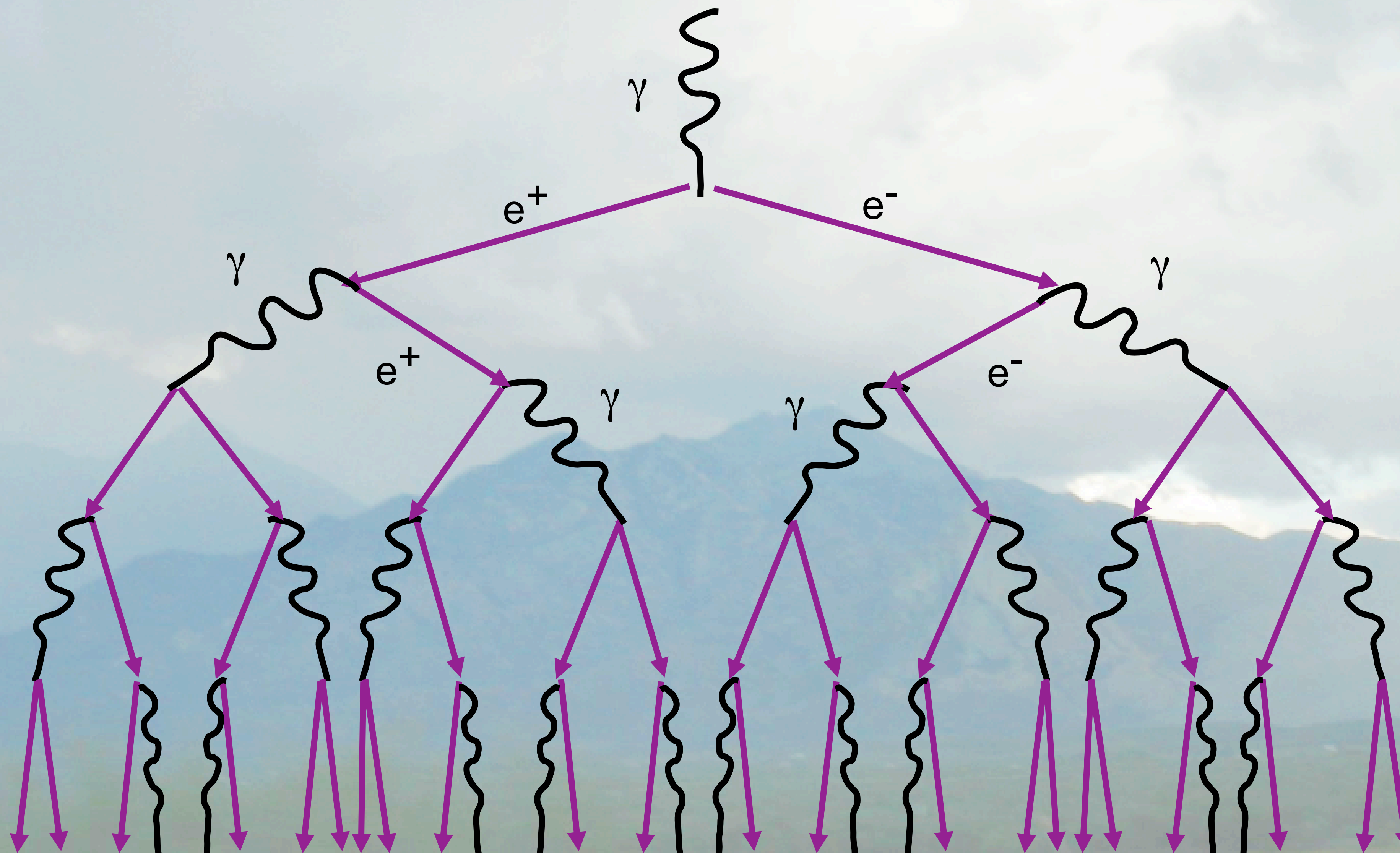
DISADVANTAGES:

Minimum energy = ~100GeV (for single telescope)

Pointed observations (3 deg FOV)

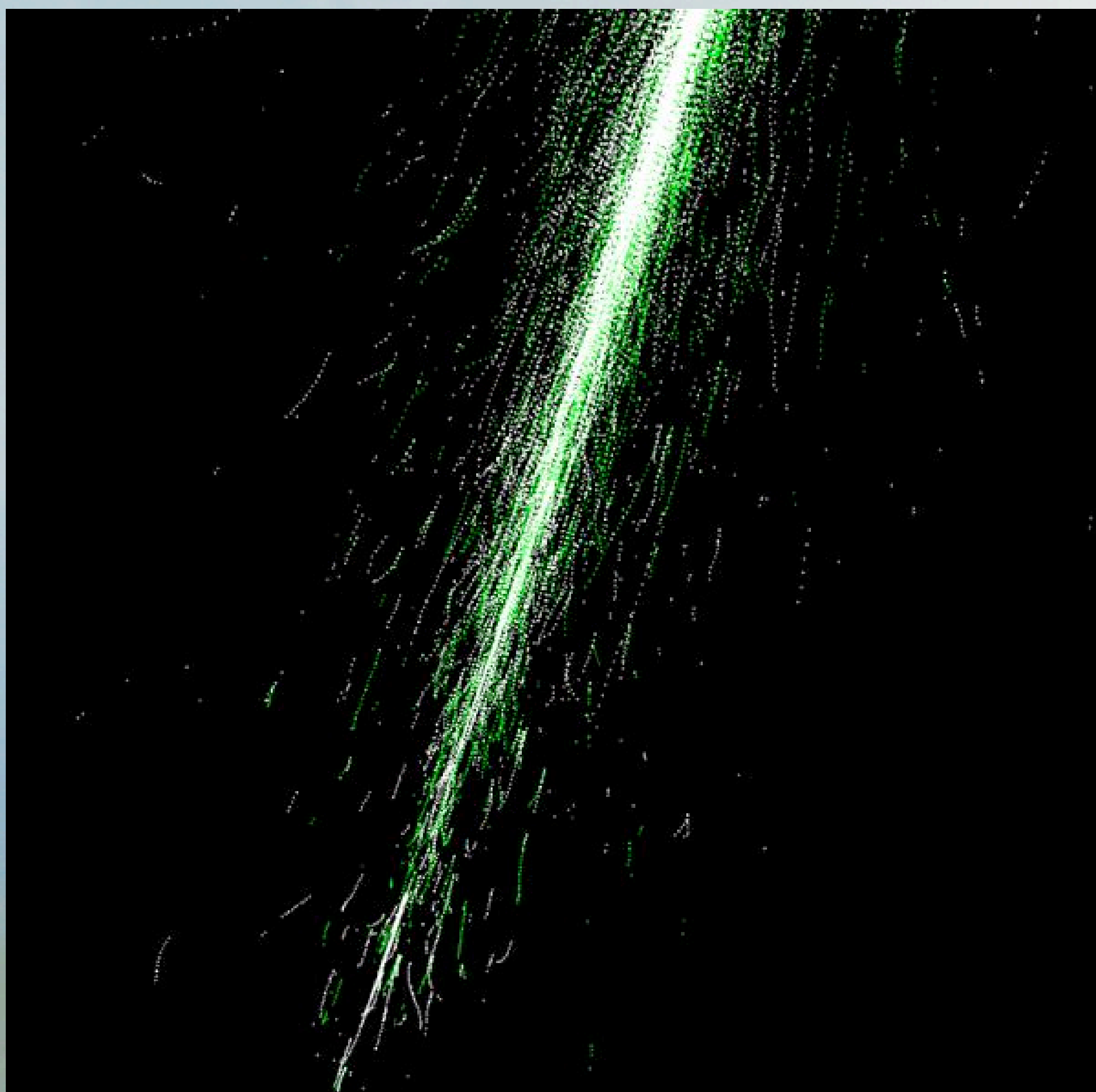
Can only observe in TOTAL DARKNESS (no moon, poor temporal coverage)

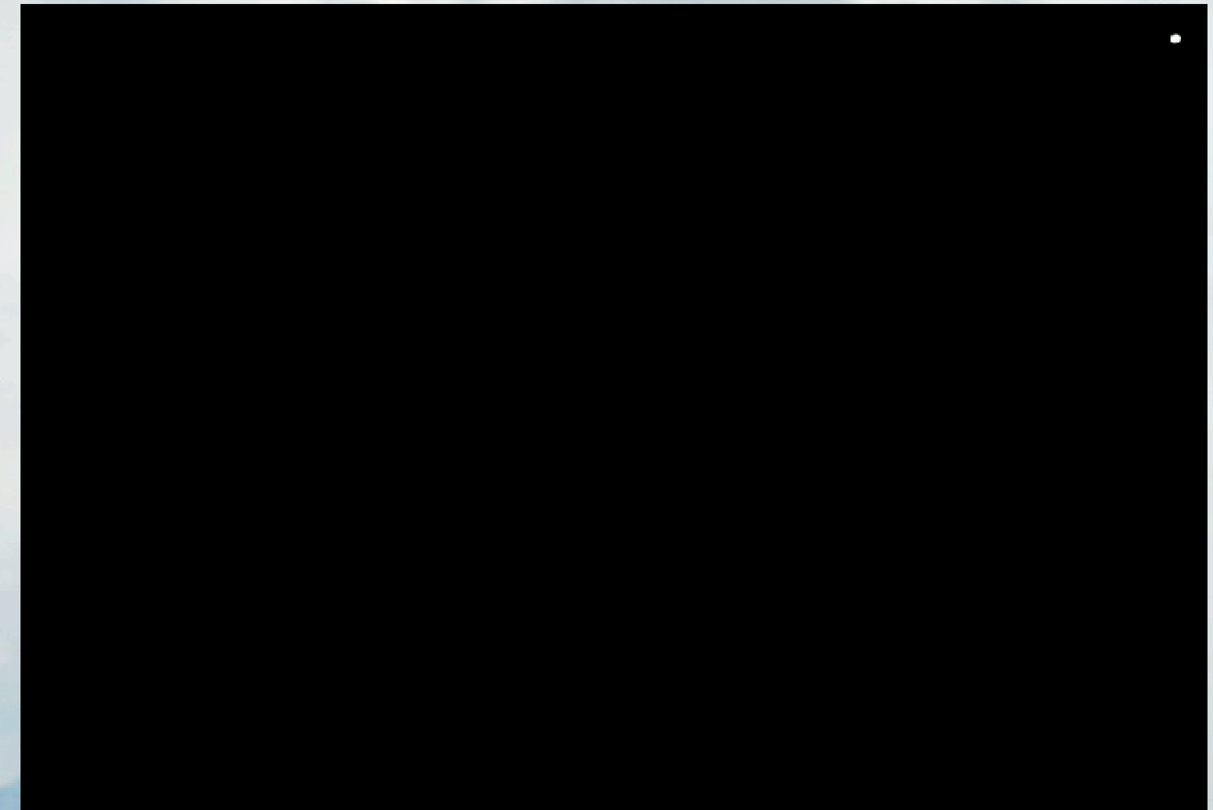
Gamma Ray Shower Model

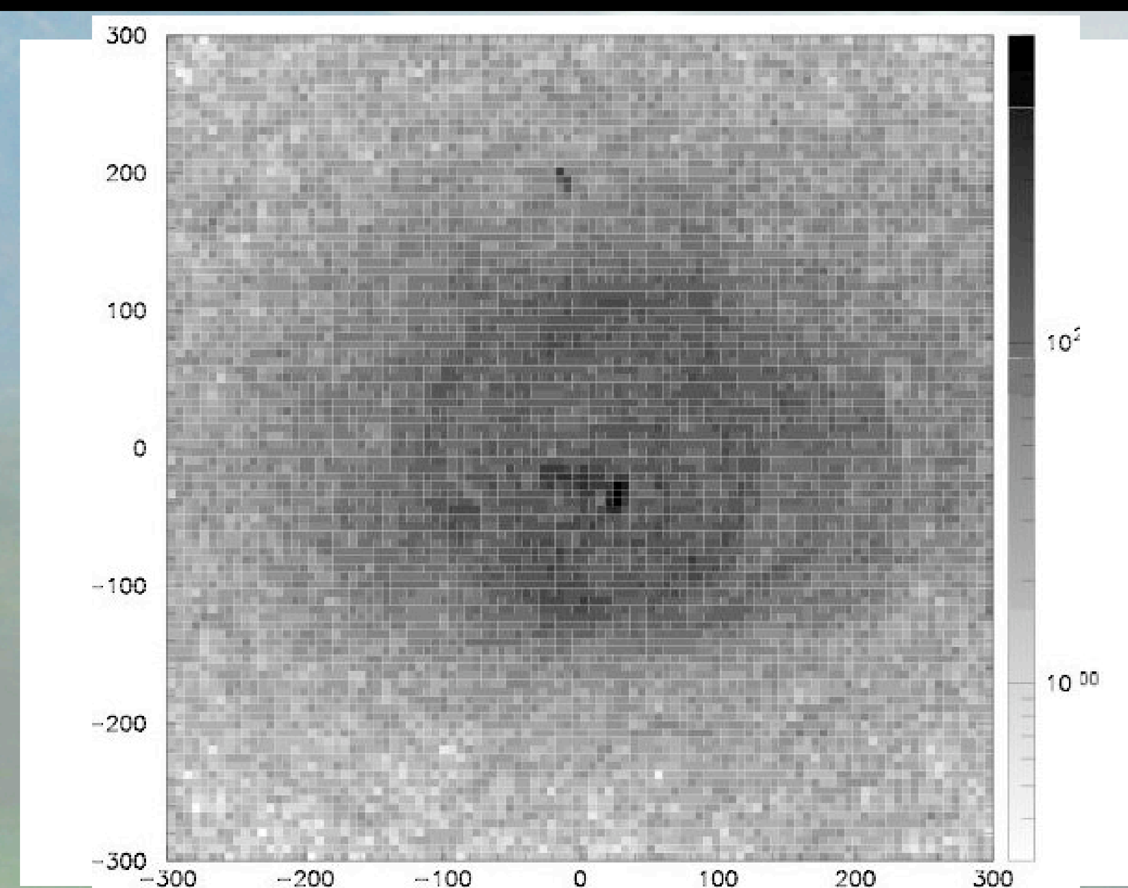


Eventually, $E<E_{pair}$ and the shower dies out

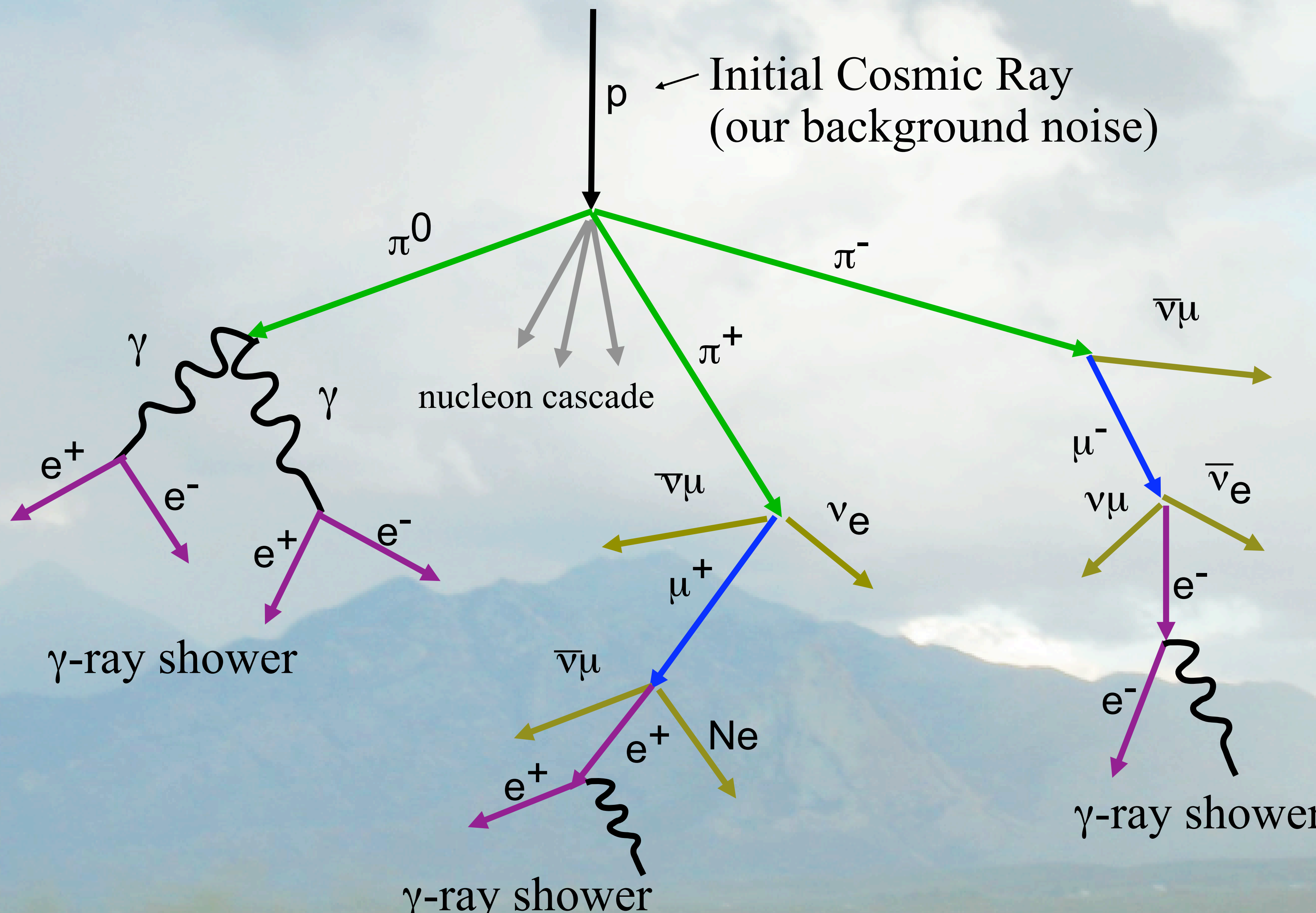
Gamma Ray Shower







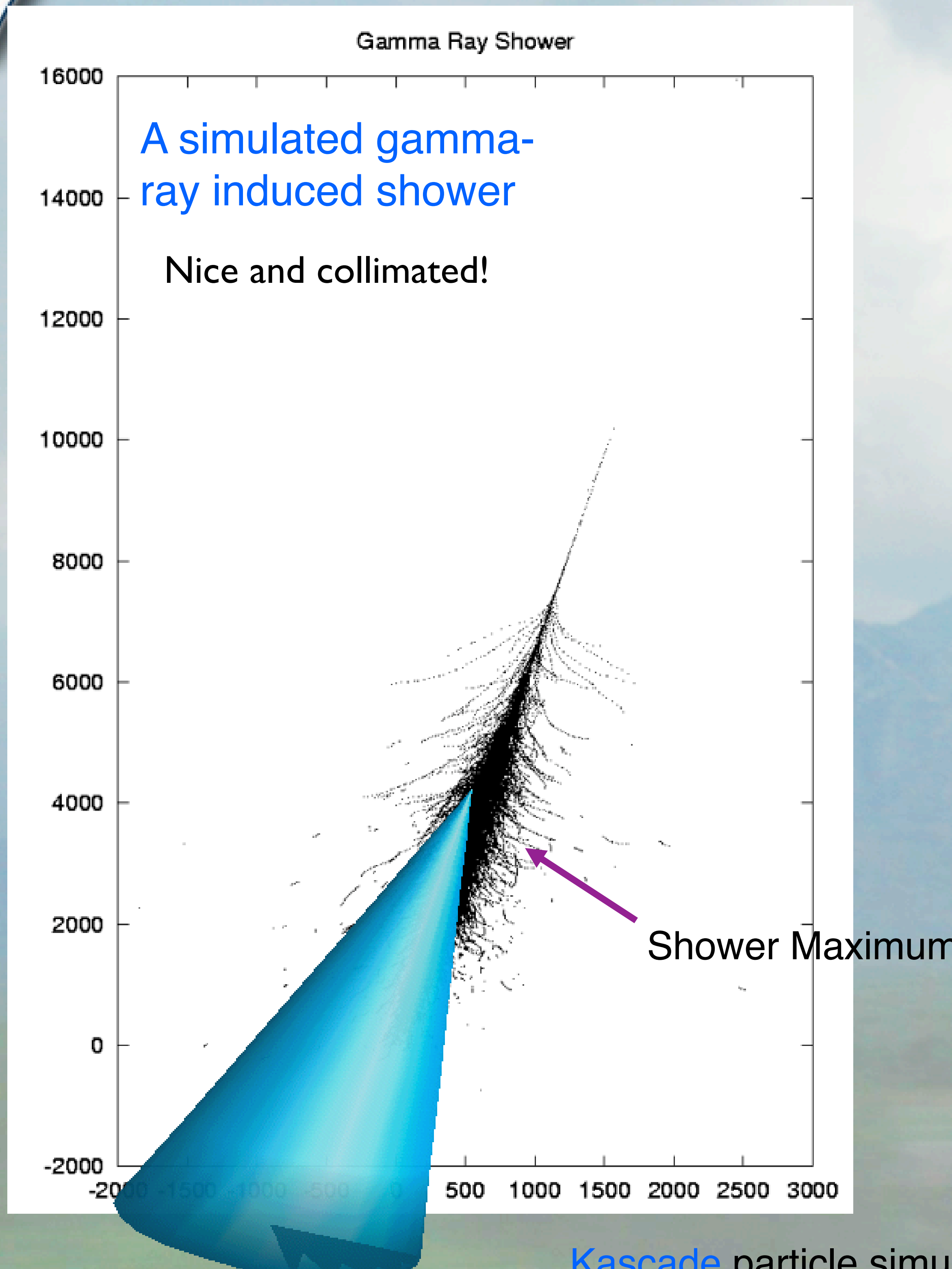
Proton Shower Model

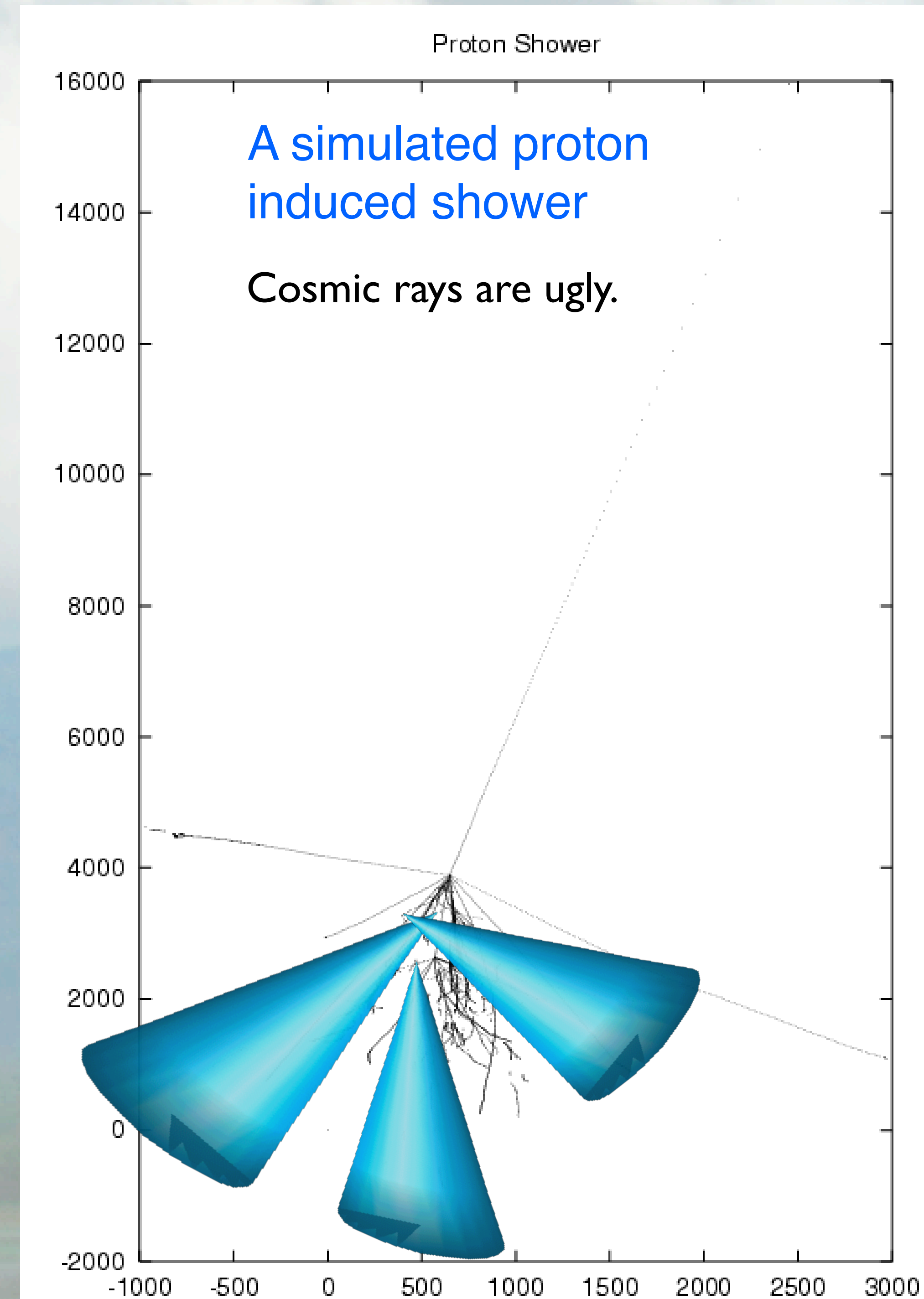


Way more background than signal!

Proton Shower

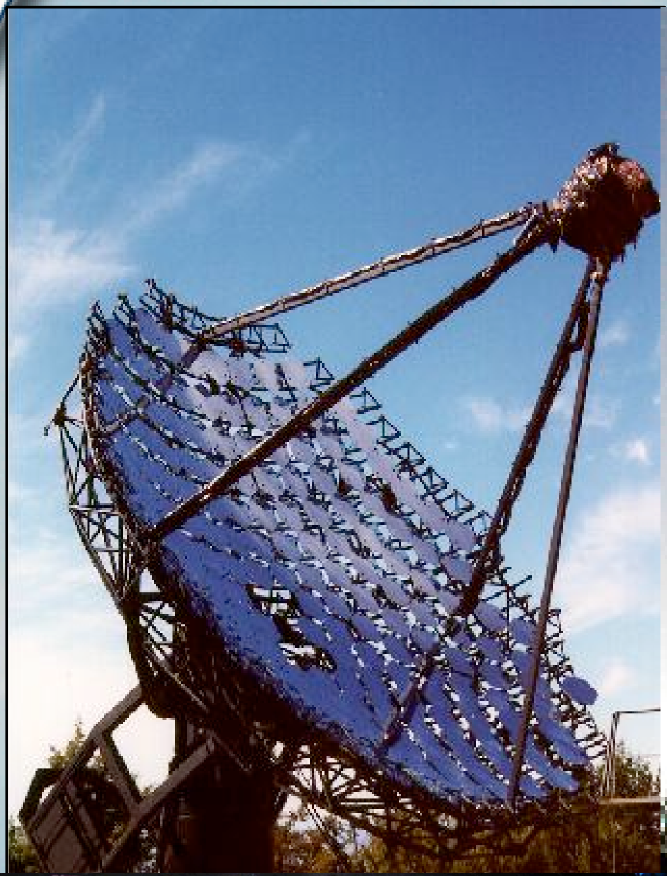
Simulated Showers

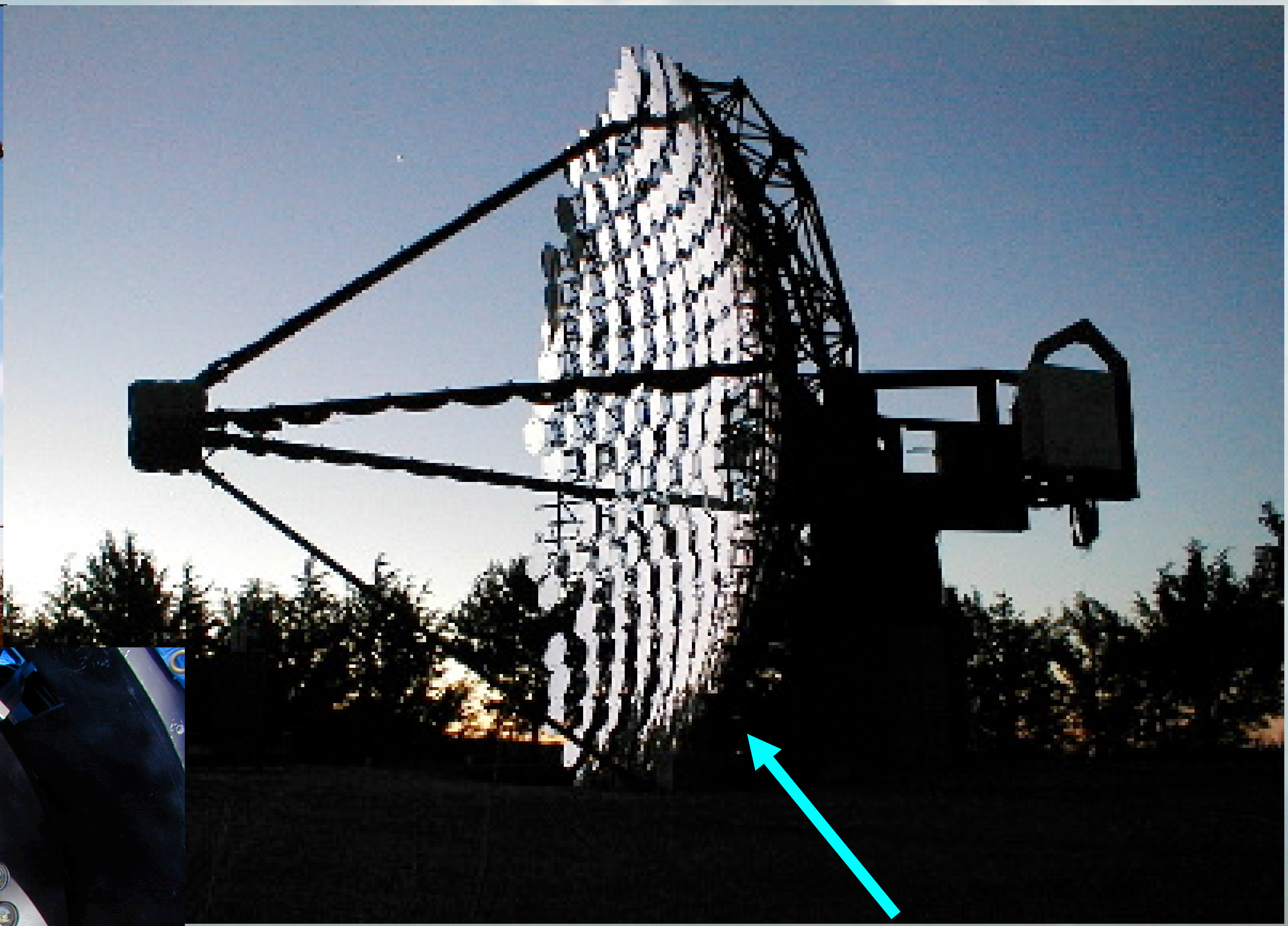




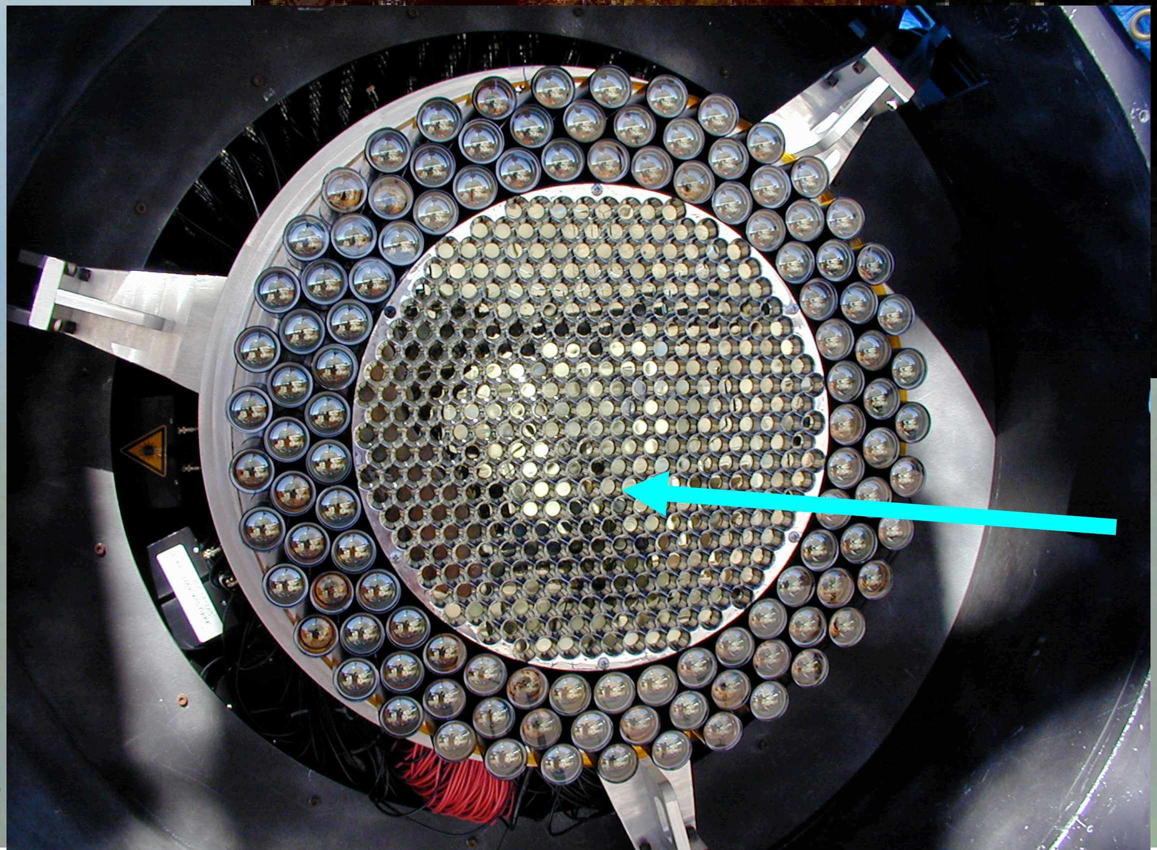
Kascade particle simulation package – Purdue/DePauw

Whipple 10M





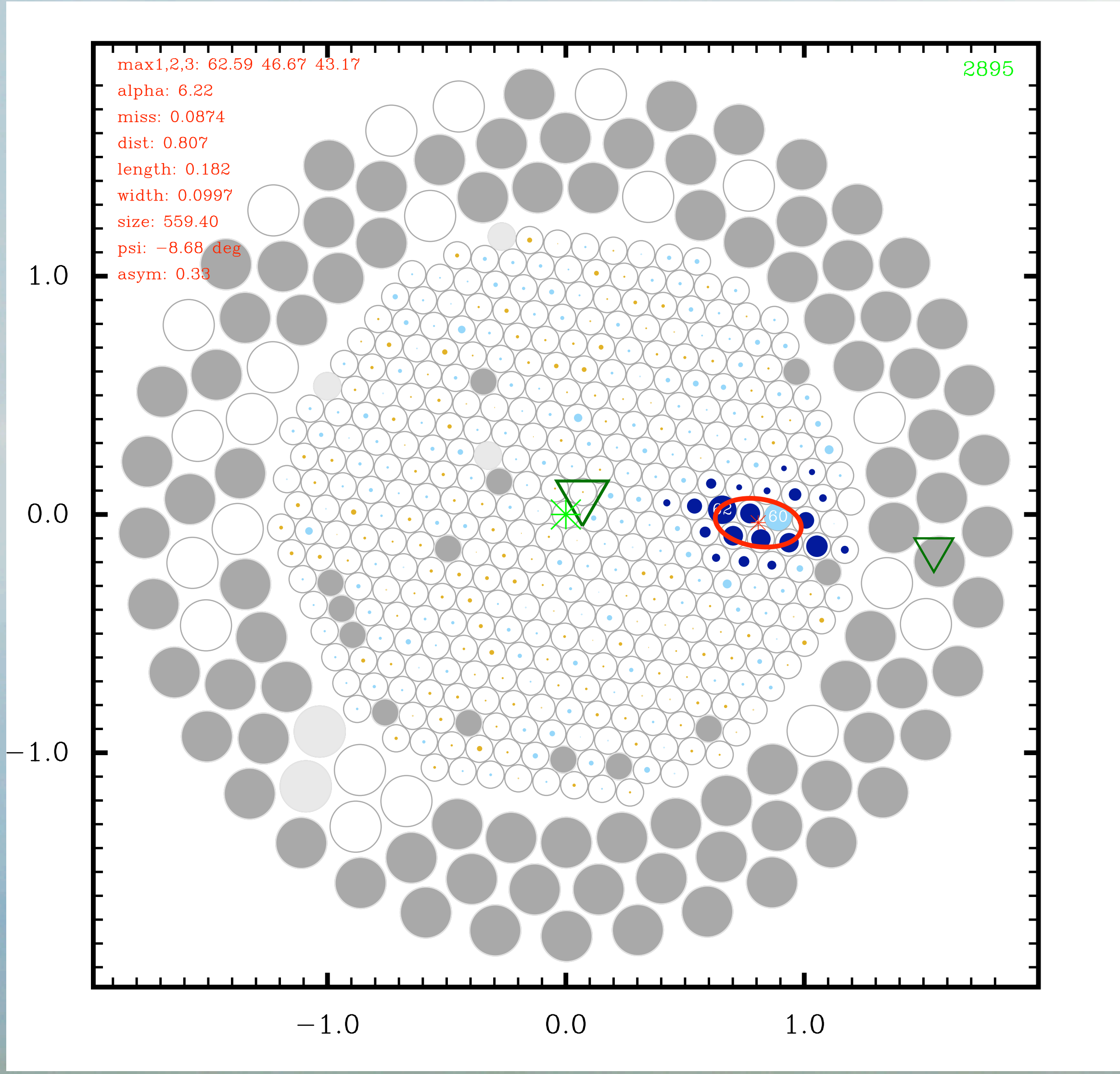
10m spherical mirror



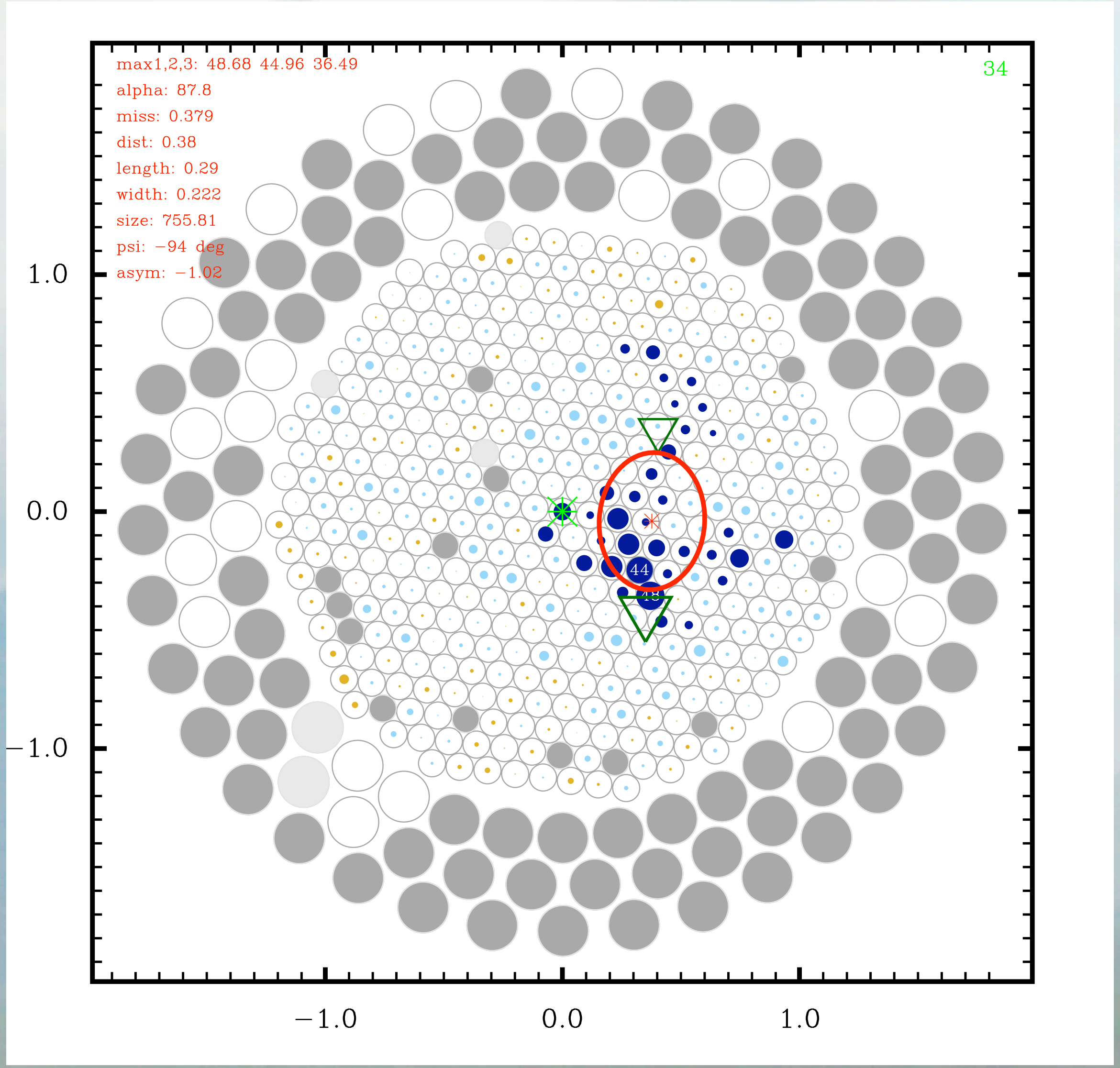
Each pixel is a photo-multiplier tube

Takes ~20ns exposures

Imaging Technique



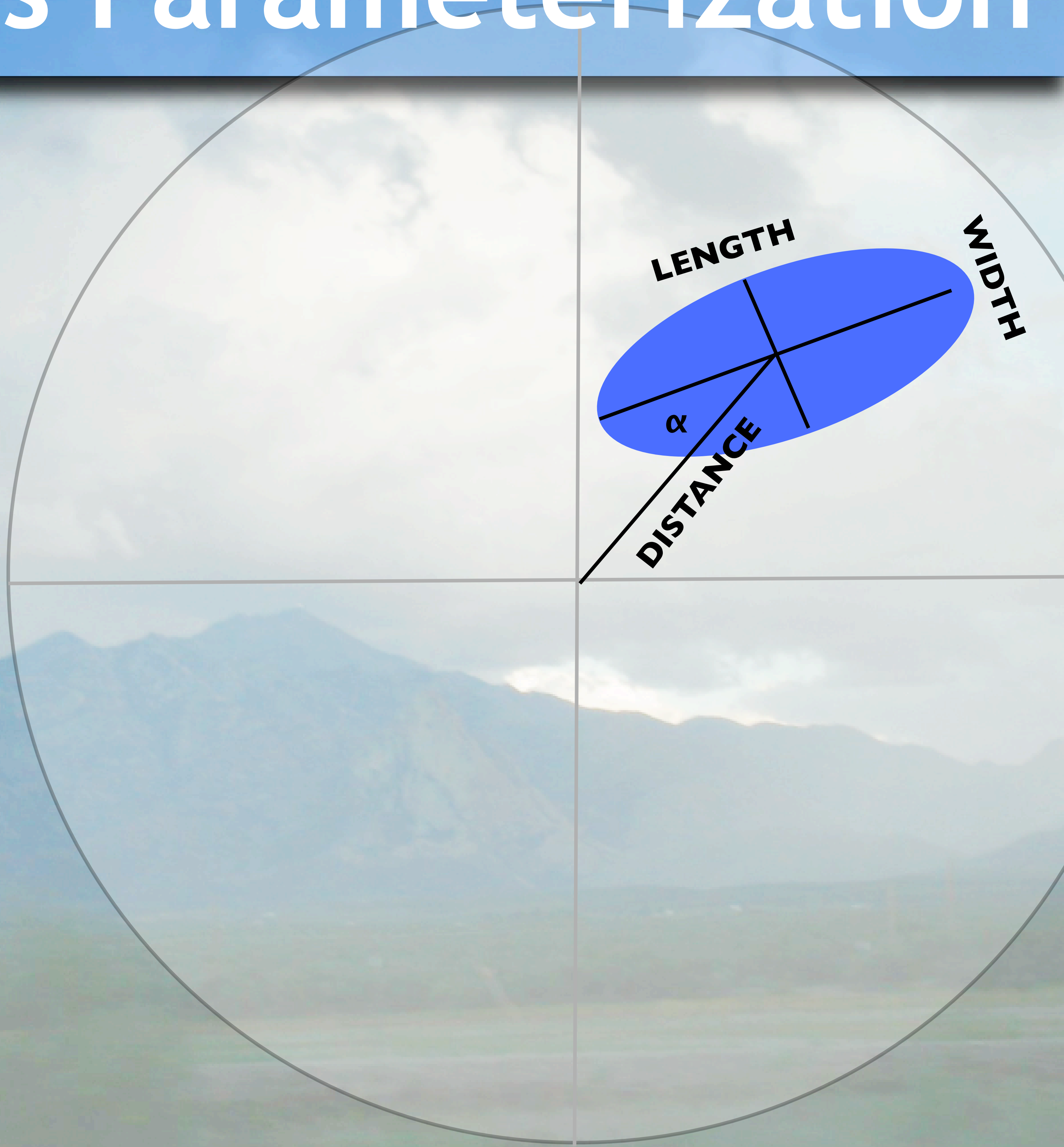
Gamma Ray
ACCEPT



Cosmic Ray (proton)
REJECT

Hillas Parameterization

- Subtract noise pedestals and apply gain corrections (flat fielding)
- Pad data with gaussian noise from pair run
- Clean the image
- Calculate the moments of the light distribution
    - 1st-order give centroid
    - 2nd order give LENGTH, WIDTH, alpha, psi
    - 3rd order give asymmetry (skewness)



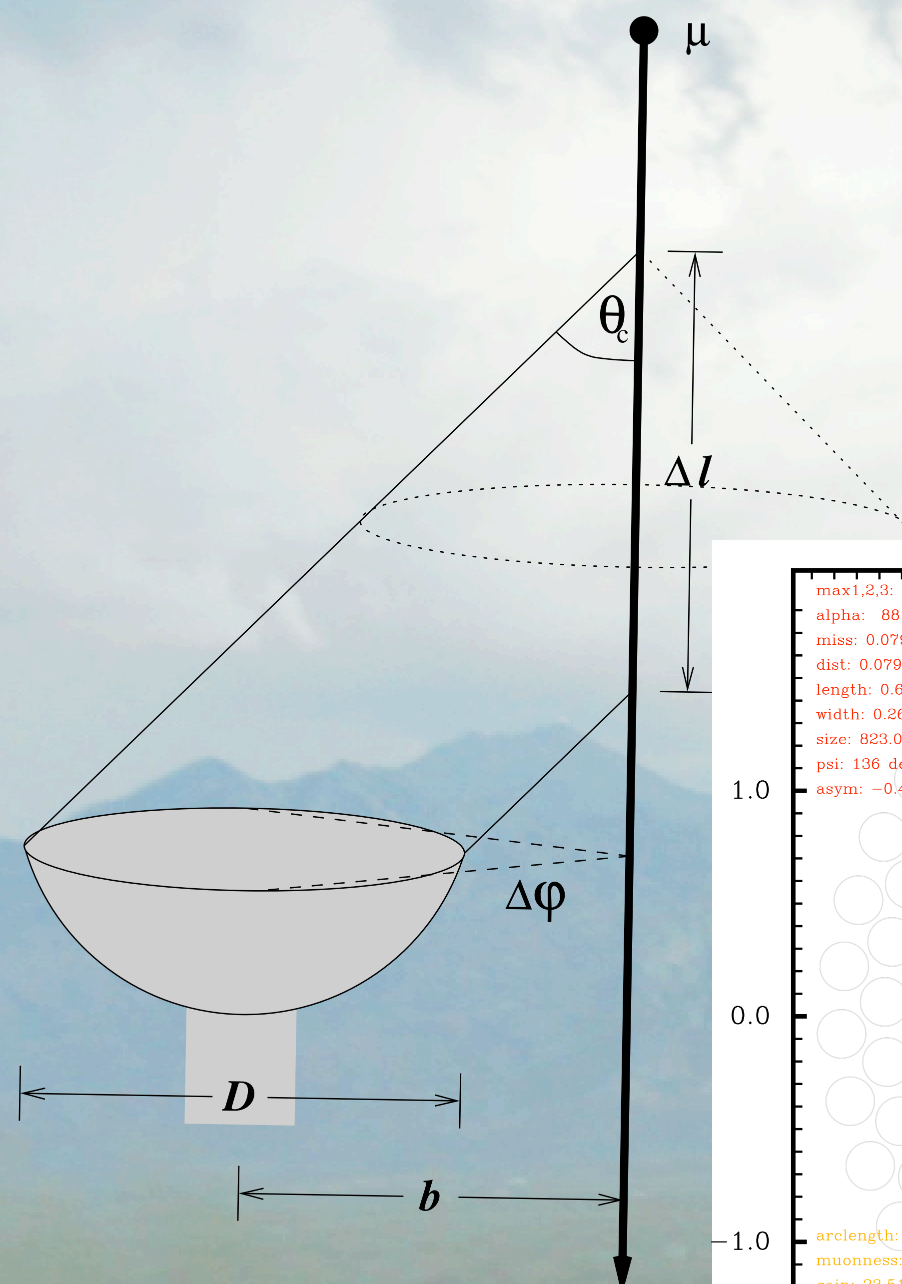
Stop here for 1D (ALPHA) analysis

Gain Calibration

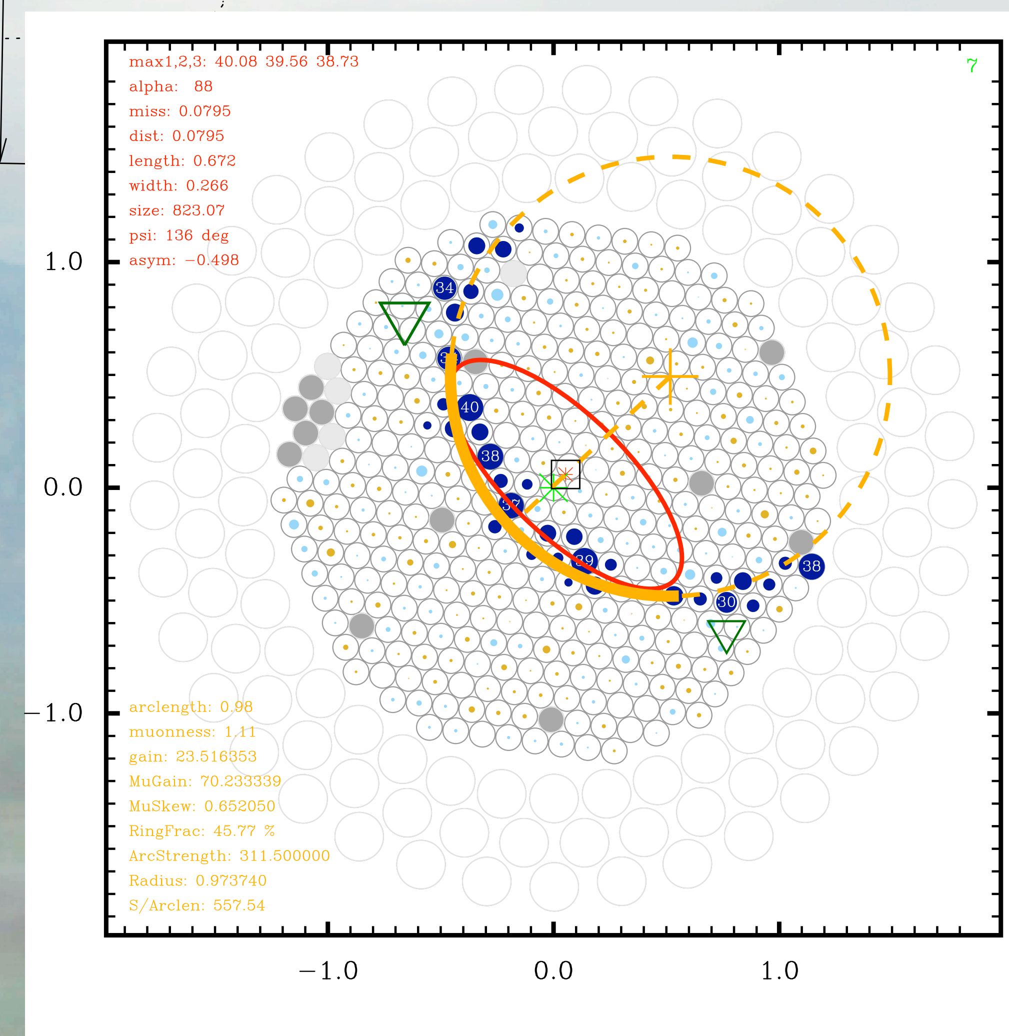
- Muons show up as rings due to low Coulomb scattering angle

- The light-per-arclength is *constant* and can be used for absolute calibration

- Produce histogram of muon Signal/Arclength for each season and correct PMT gains accordingly

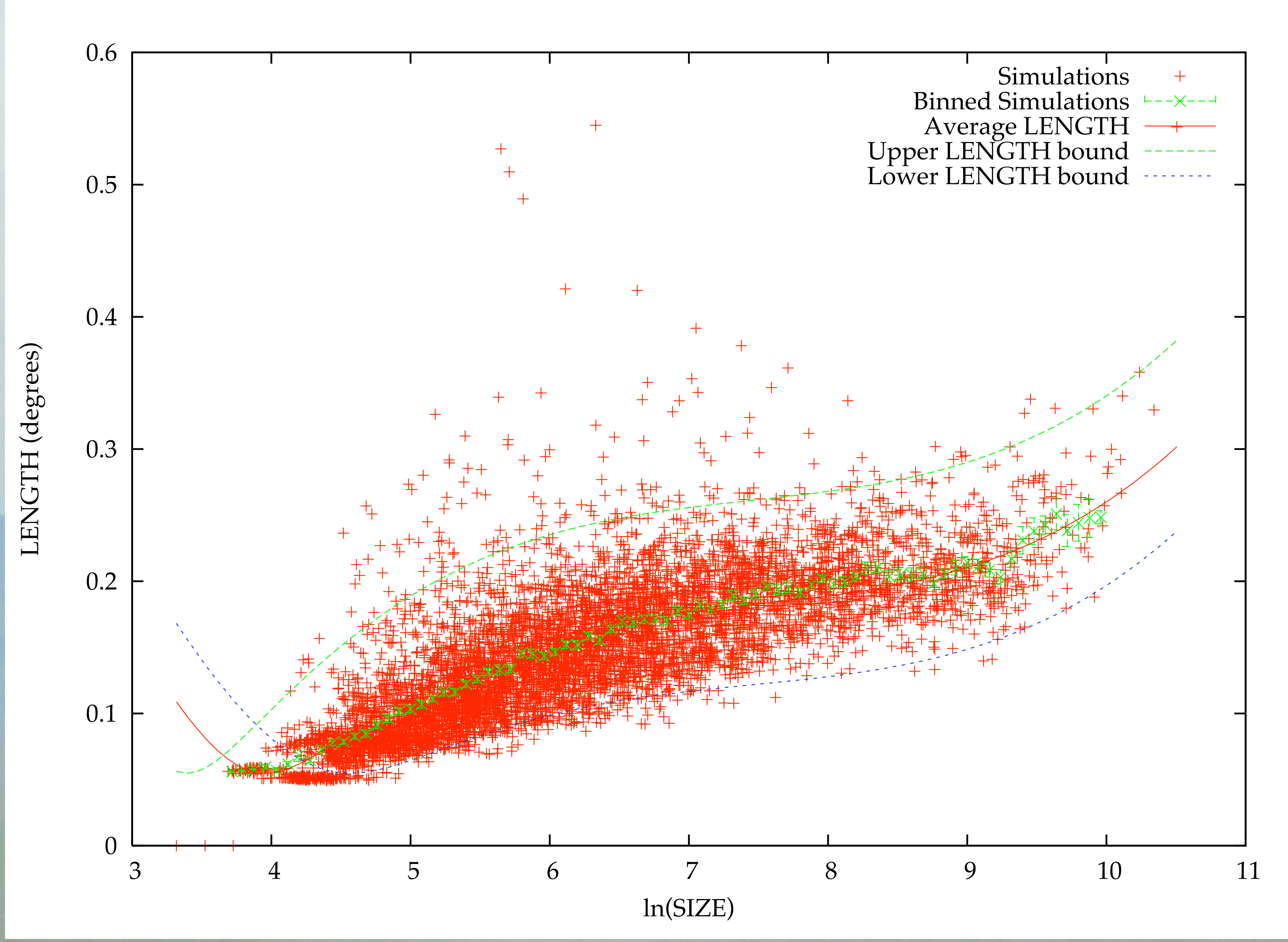


Ring-shaped image from a muon, selected from the data with an arc-detection algorithm:

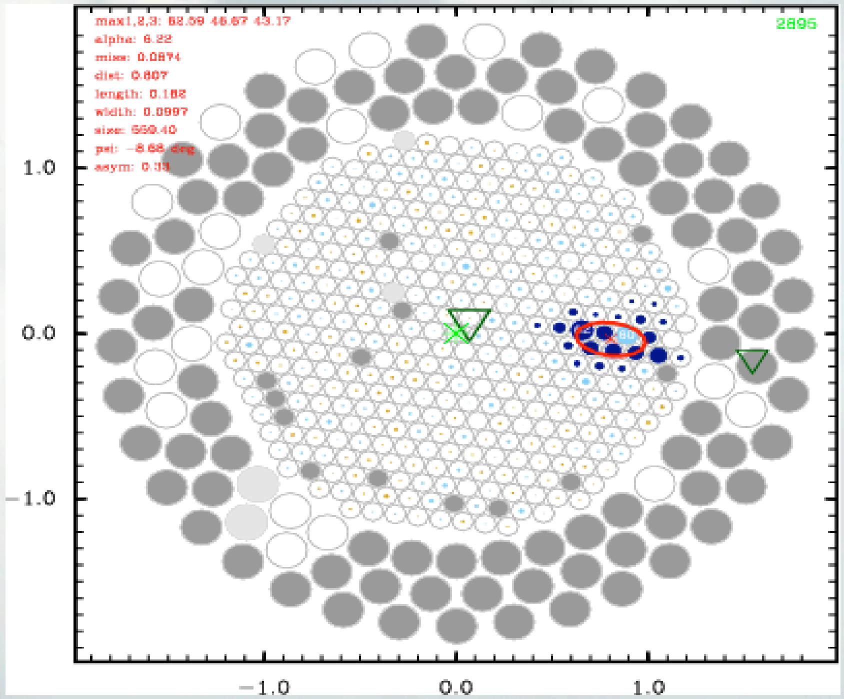


Gamma-Hadron separation

- Cut data on each Hillas parameter. Cuts are developed to pick out gamma rays
- Cuts are optimized on real data (from the Crab) to maximize significance (and sometimes excess)
- Advanced technique: *data selection criteria* which scale with zenith angle and energy using detailed simulations + real data



Gamma-Ray Analysis Overview



Raw Event Data
(anything that triggers telescope)

↓

Gain Calibration and Flat-Fielding
(N2 Pulser for relative gain, Muon rings for absolute gain)

→

Pedestal subtraction, flat-fielding, padding, cleaning

↓

Shower Image Parameterization

↓

Gamma Ray candidate selection

←

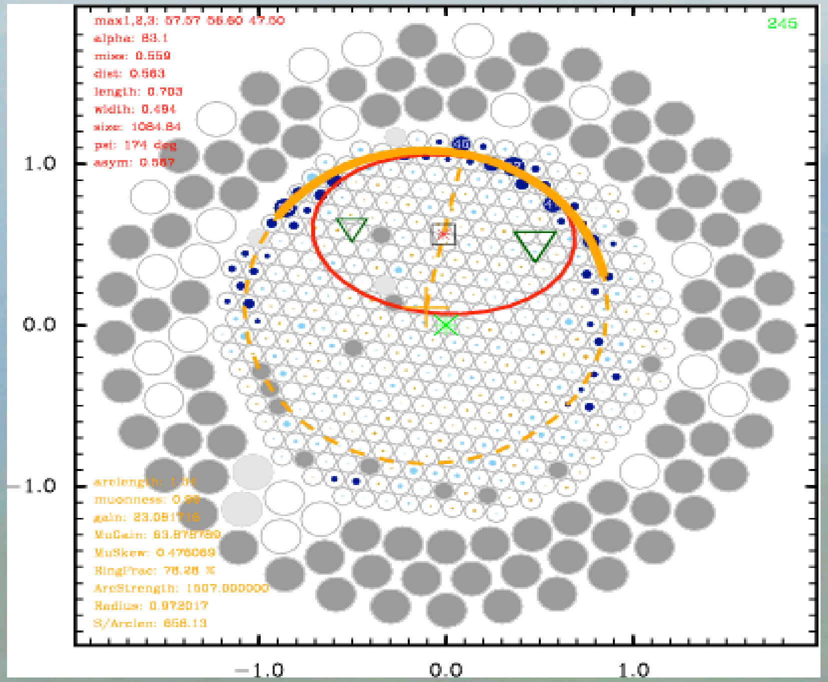
Cut Optimization Data
(simulated and real)

↓

Background Subtraction and Statistical Analysis

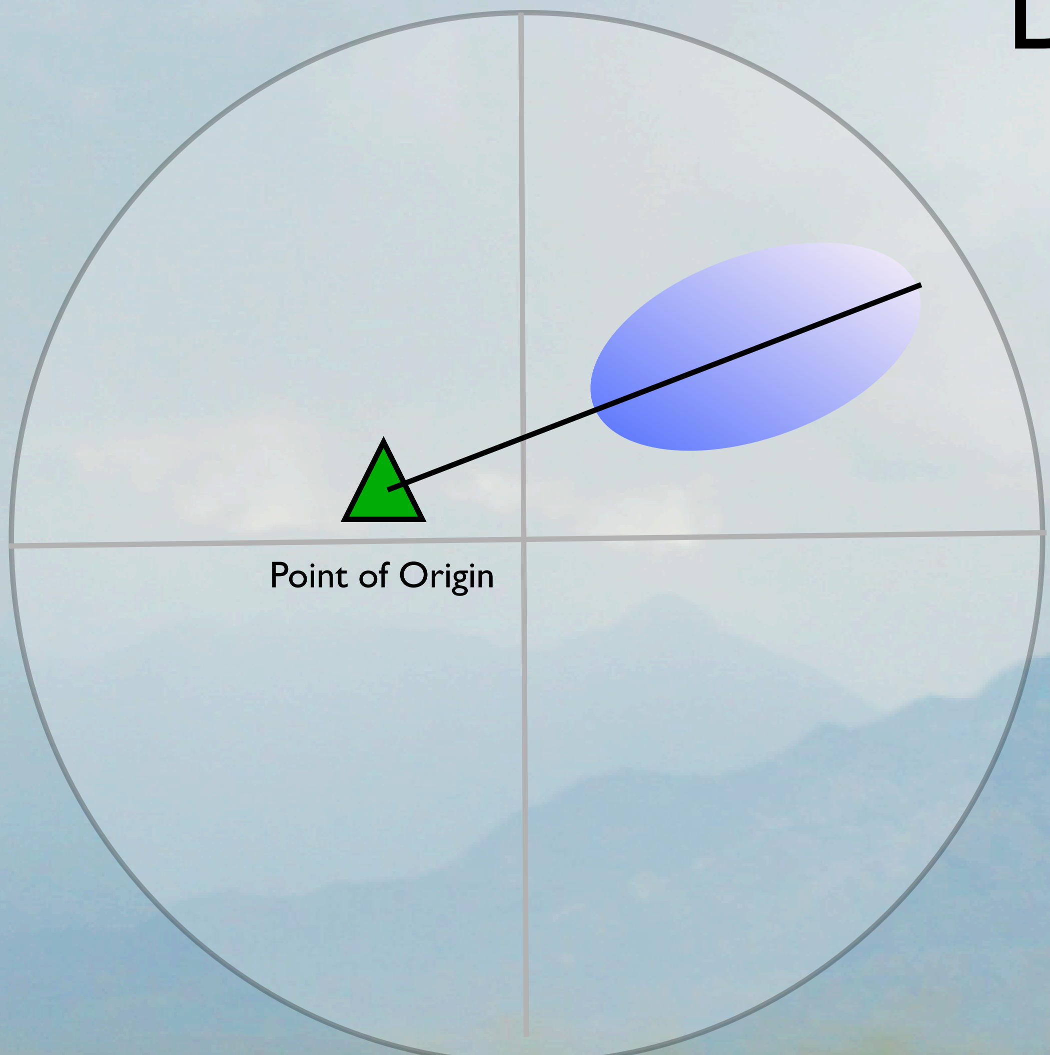
←

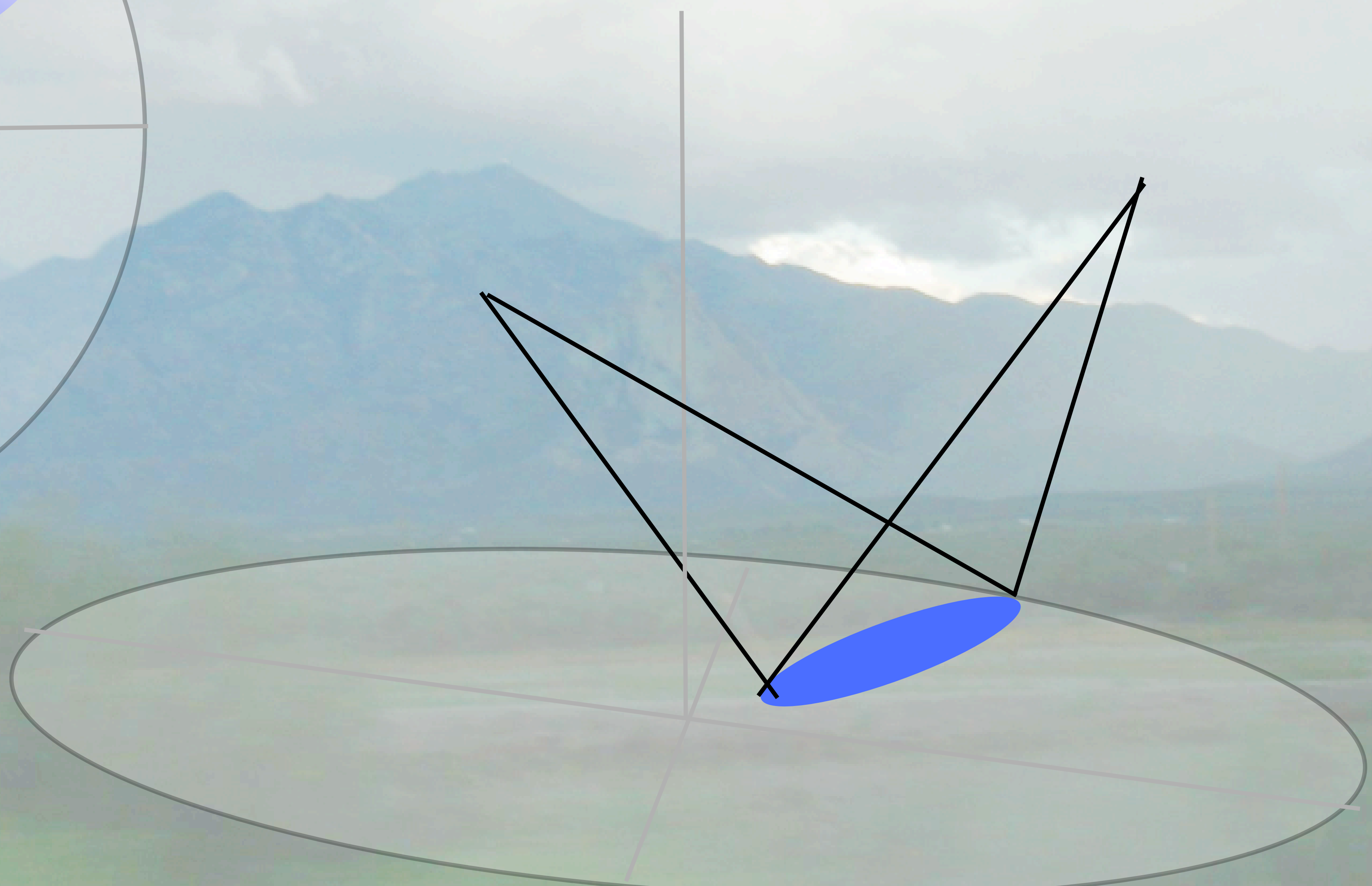
OFF-source gamma ray candidates
(processed in same manner)



Point of Origin: 2D

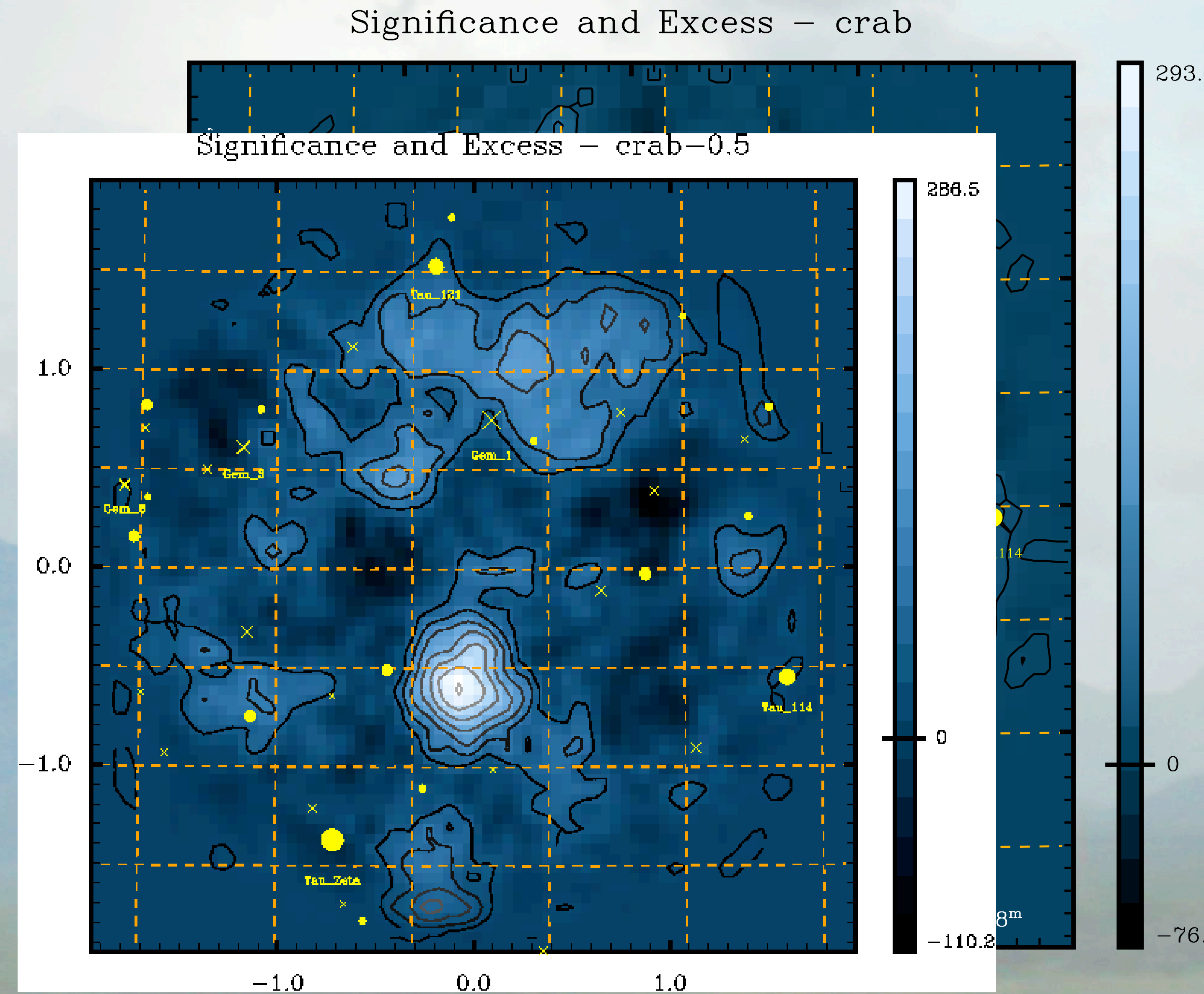
$$\text{Displacement} = \epsilon(S) \cdot [1 - W/L]$$





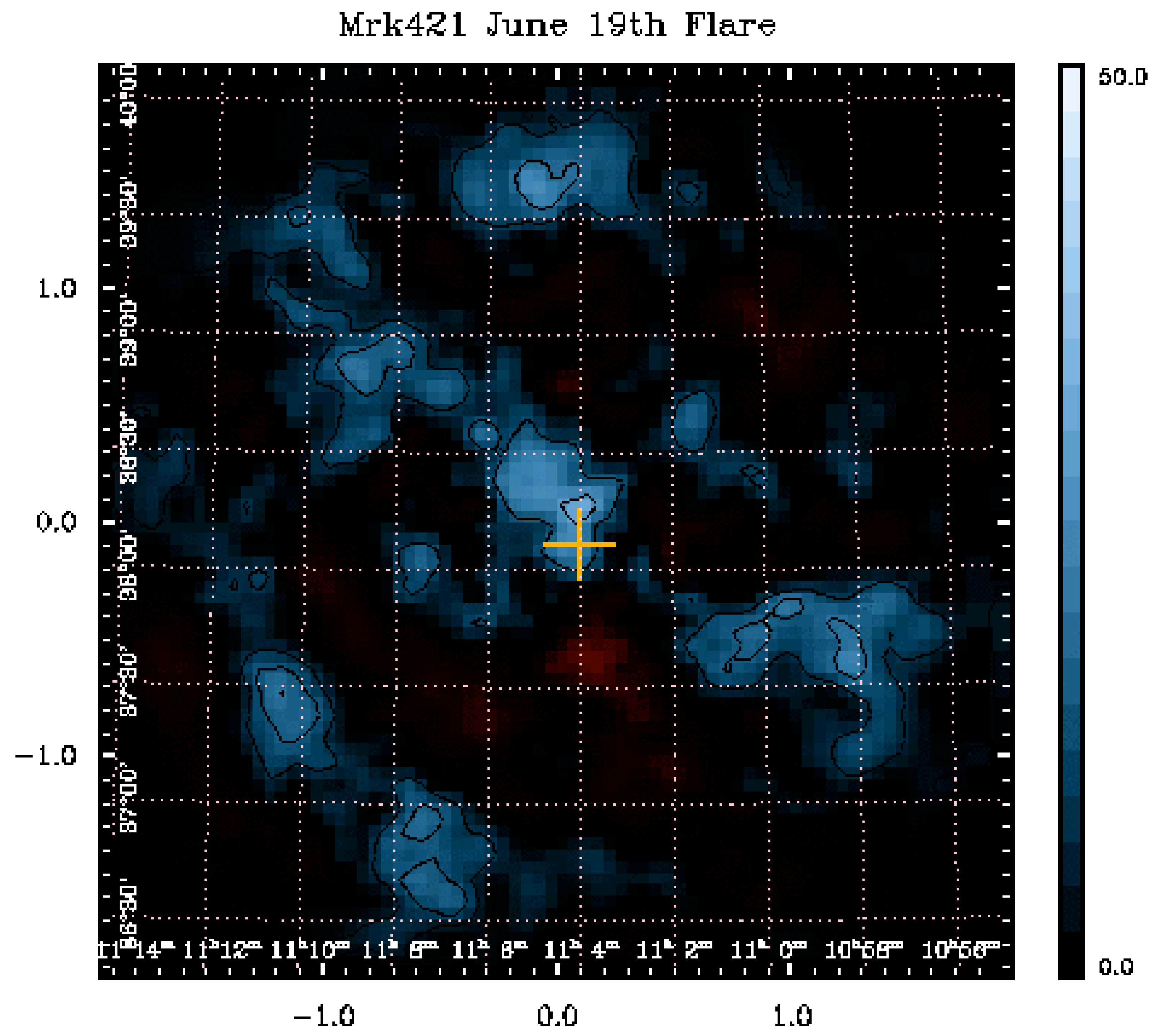
Imaging Technique: 2D

- For ON and OFF source observations:
  - Pick out gamma-ray showers
  - Calculate points-of-origin
  - Accumulate in 2D histogram
- Subtract OFF from ON, calculate statistical significance at each gridpoint.

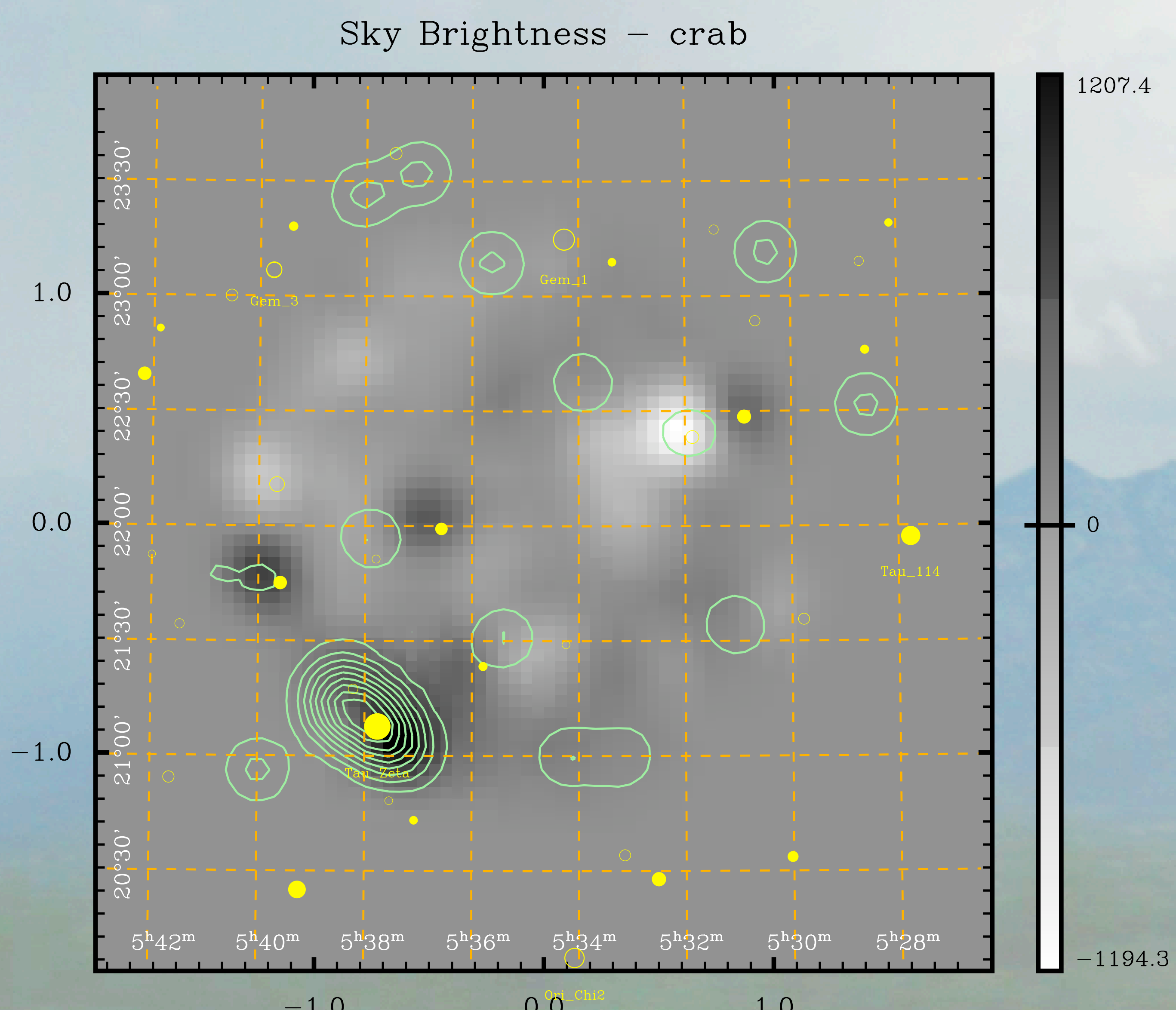


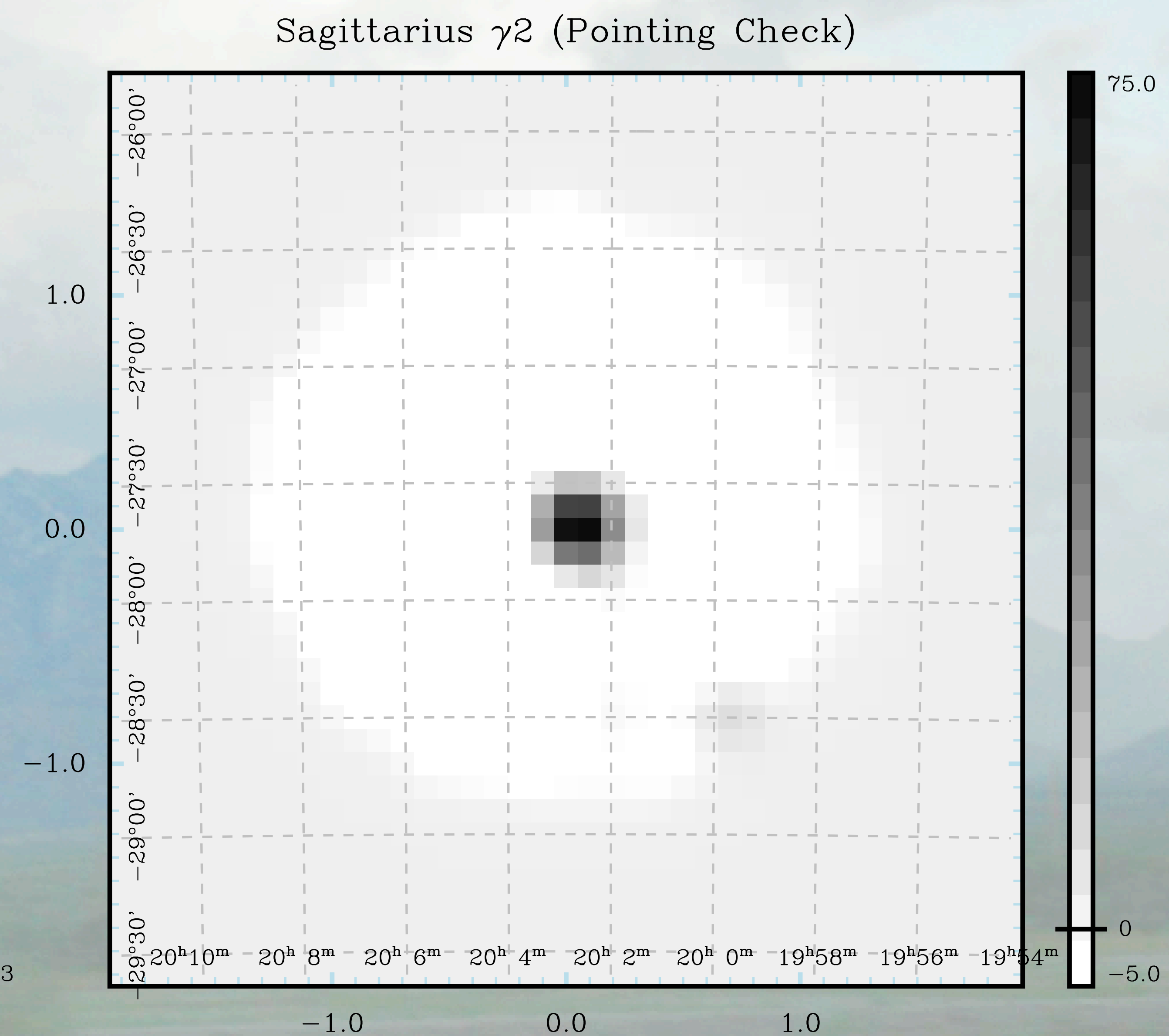
Crab Nebula at low elevation

Example: Markarian 421



Optical Sky Brightness





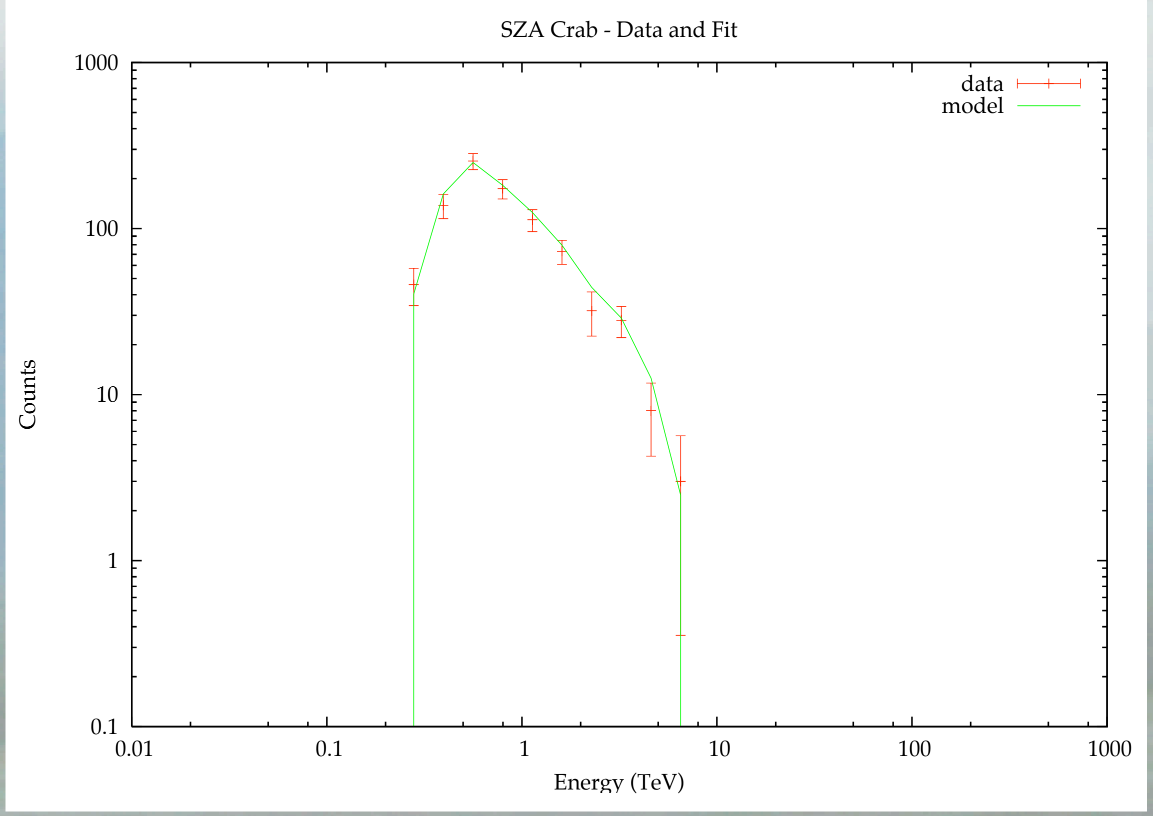
Spectral Analysis

$$F(E) = N_0 E^{-\gamma}$$

- Derive energy estimator function from detailed simulations

$$E = f(S, d)$$

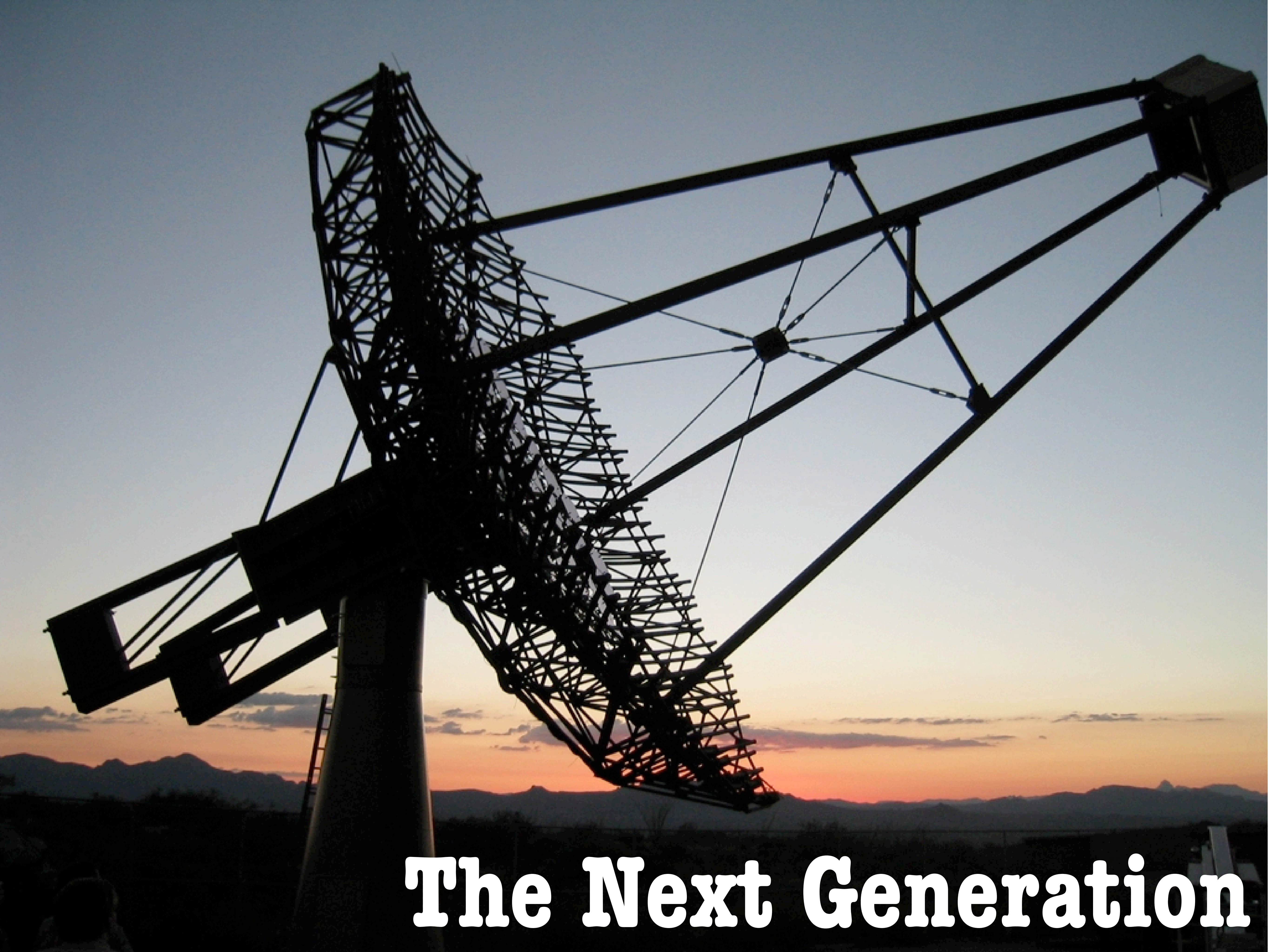
- Forward-fold real data with simulations, searching through grid of spectral indices (γ) and Flux factors (N_0).



- Minimize ChiSqr between the real and simulated energy estimator distributions.

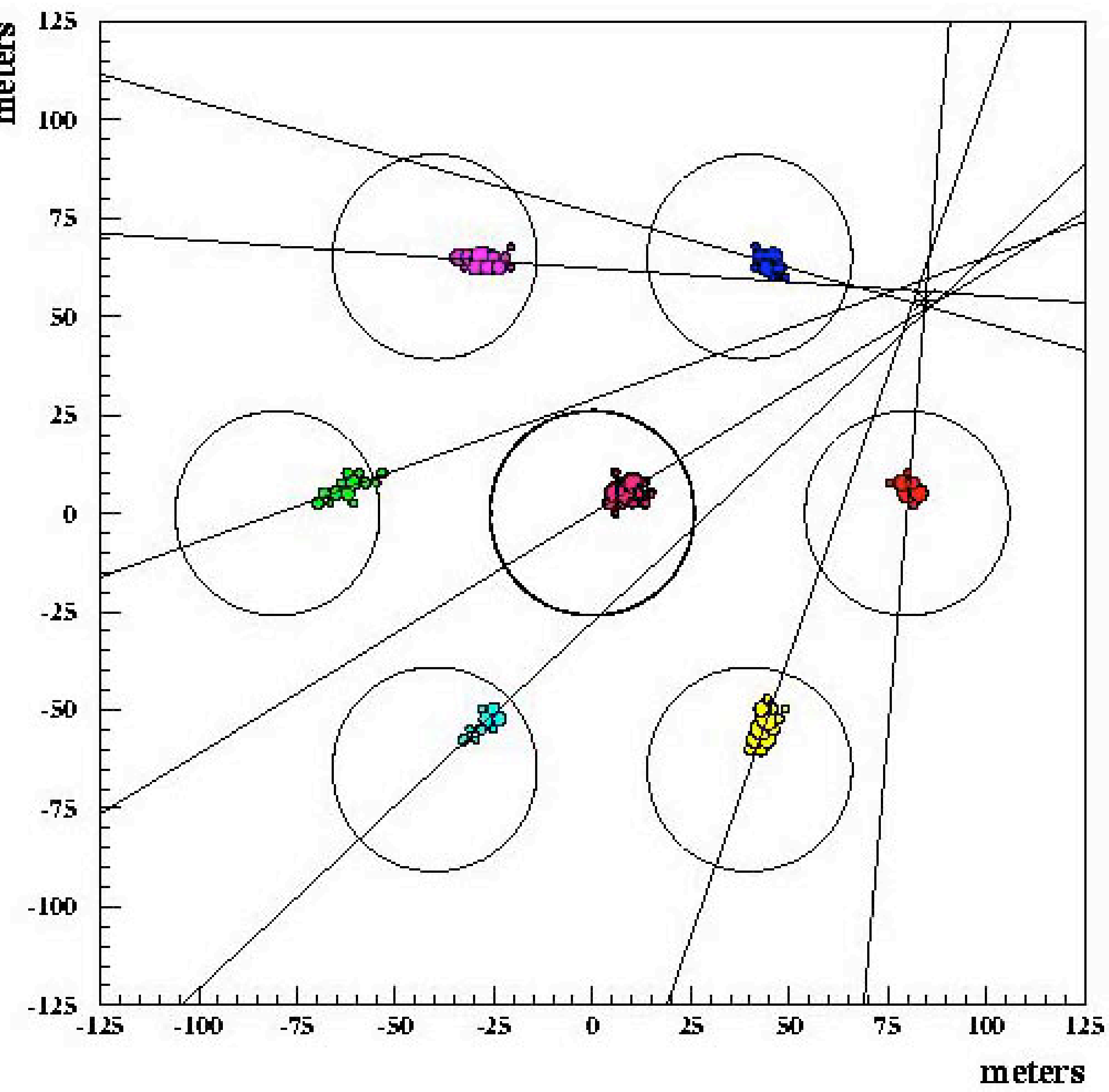
Simulations

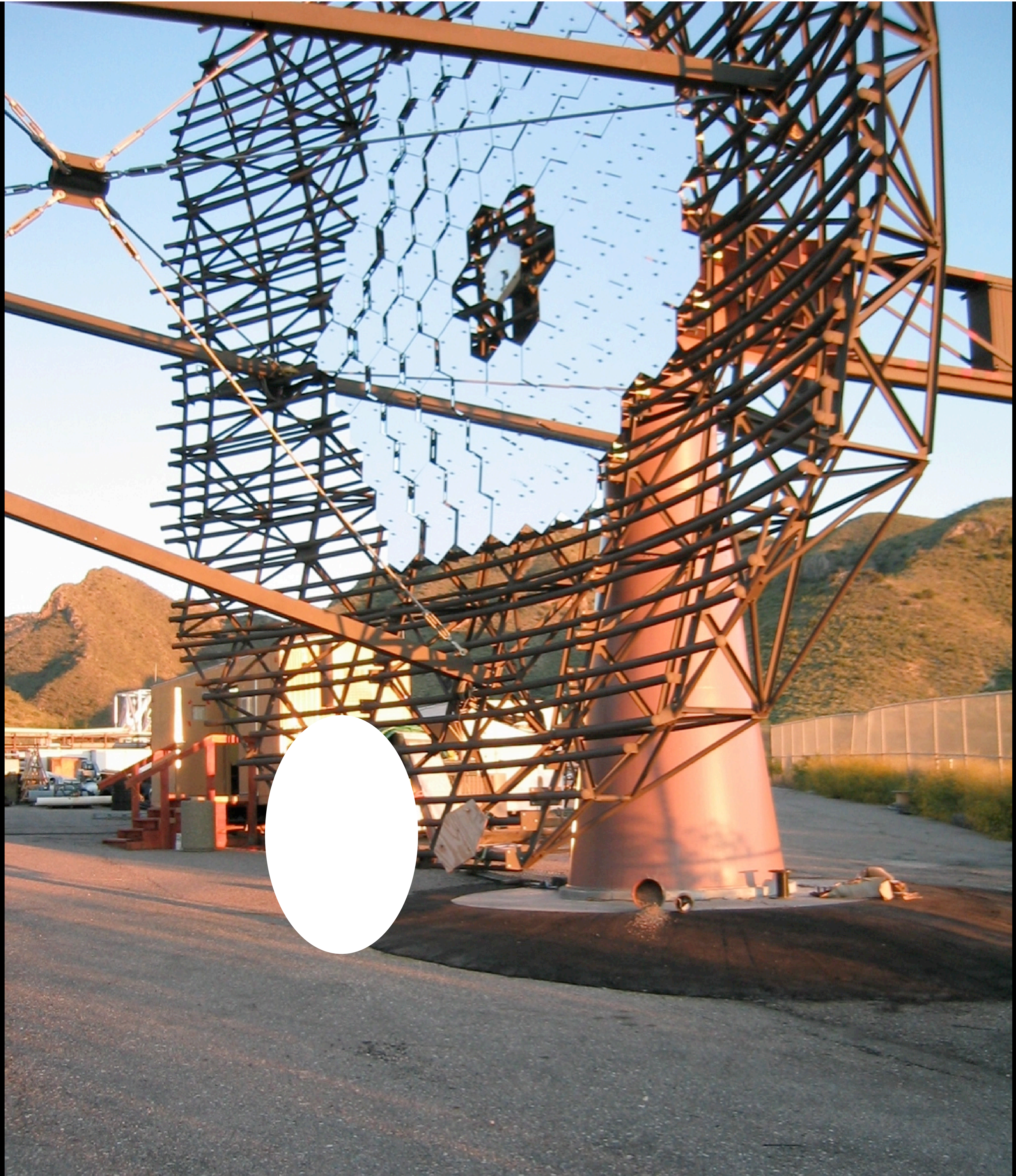
- **Air Shower simulations (KASCADE)**
  - particles + interactions
  - nuclear and particle physics
  - Atmosphere model
- **Cerenkov Simulations**
  - Atmosphere model
- **Instrument Simulation**
  - Ray tracing of Cerenkov photons
  - Mirror reflectivities
  - PMT characteristics
  - Electronics response


The Next Generation

VERITAS

The **V**ery **E**nergetic **R**adiation **I**maging **T**elescope **A**rray **S**ystem





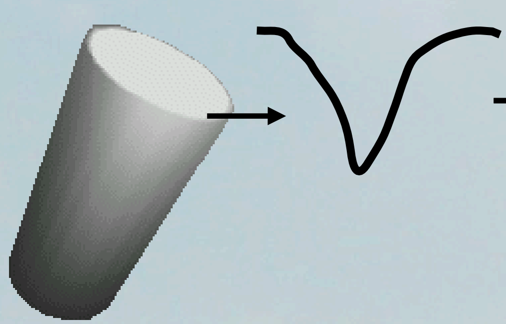
VERITAS Specs

- 4 telescopes (7 planned) located on Kitt Peak in AZ
- 12 m reflectors
- nanosecond time resolution
- Sub-arcminute spatial resolution

	VERITAS 4 telescopes	VERITAS 7 telescopes
Peak Energy (GeV)	110	90
Crab Rate ($\gamma\ min^{-1}$)	35	50
Effective Area at 10 TeV ($10^8 cm^2$)	30	36
Effective Area at 100 GeV ($10^8 cm^2$)	3.3	6.3
Flux Sensitivity at 10 TeV* ($10^{-11} erg\ cm^{-2} s^{-1}$)	0.37	0.36
Flux Sensitivity at 100 GeV† ($10^{-11} erg\ cm^{-2} s^{-1}$)	1.4	1.0

* 50 hours, 5σ
† 50 hours, 5σ

FlashADC Data Acquisition



Camera PMT

Trigger System
Determines what is called an "event"

- **Channel-level constant-fraction discriminator**
- **Telescope pattern trigger**
- **Array trigger**

When trigger system detects an event, it signals the FADC

FADC channel
Continuously digitizes the input waveform

The FADC "looks back" to the time when the trigger actually occurred, and reads out the data

Entire pulse read out in electronic form for analysis

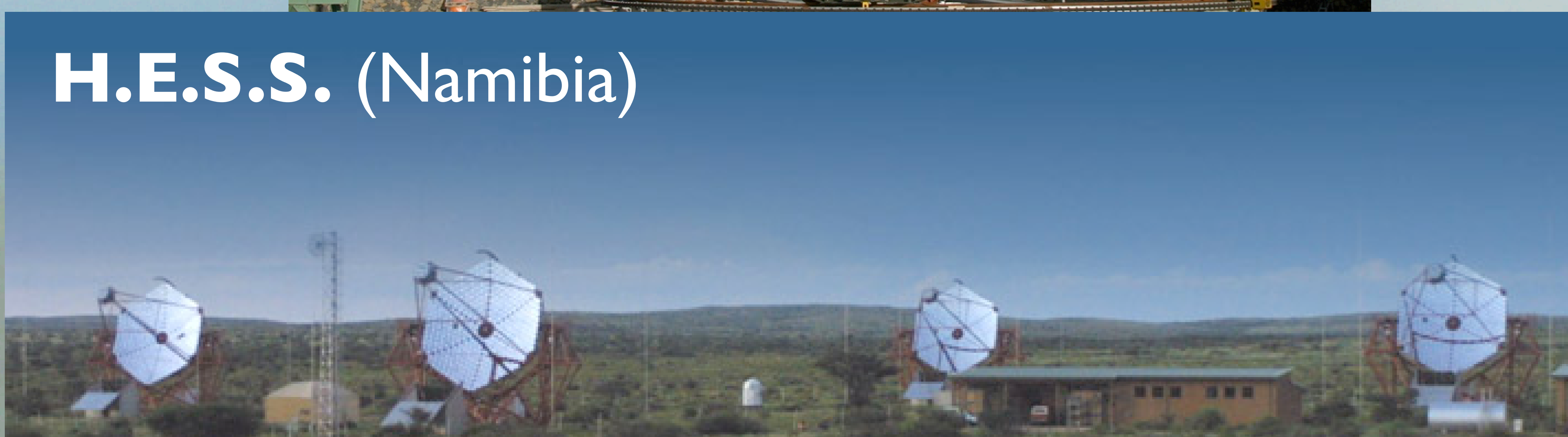
Similar to a high-speed electronic oscilloscope, but a LOT cheaper! (Each board can digitize 10 waveforms)

Events occur at up to 1Khz, so data-rate is VERY HIGH – requires reflective memory, high-speed fiber optic links, clusters of analysis computers, etc. Timing must be EXACT between all telescopes!

Other Next-Gen ACTs

MAGIC (Canary Islands)

H.E.S.S. (Namibia)



VERITAS Summary

Lower E_{thresh} (<100Gev, significant sensitivity at 50GeV)

Better energy resolution: DE/E < 0.1 (for E>300GeV)

Increased sensitivity to dim sources (50 hrs for 0.5% Crab)

Higher angular resolution (<0.05°)

Will be able to understand current sources better than before (spectra and variability)

Will detect many NEW sources, that have yet to be seen (EGRET unidentified sources?)

Will provide excellent complement to new satellite-based gamma-ray observatories