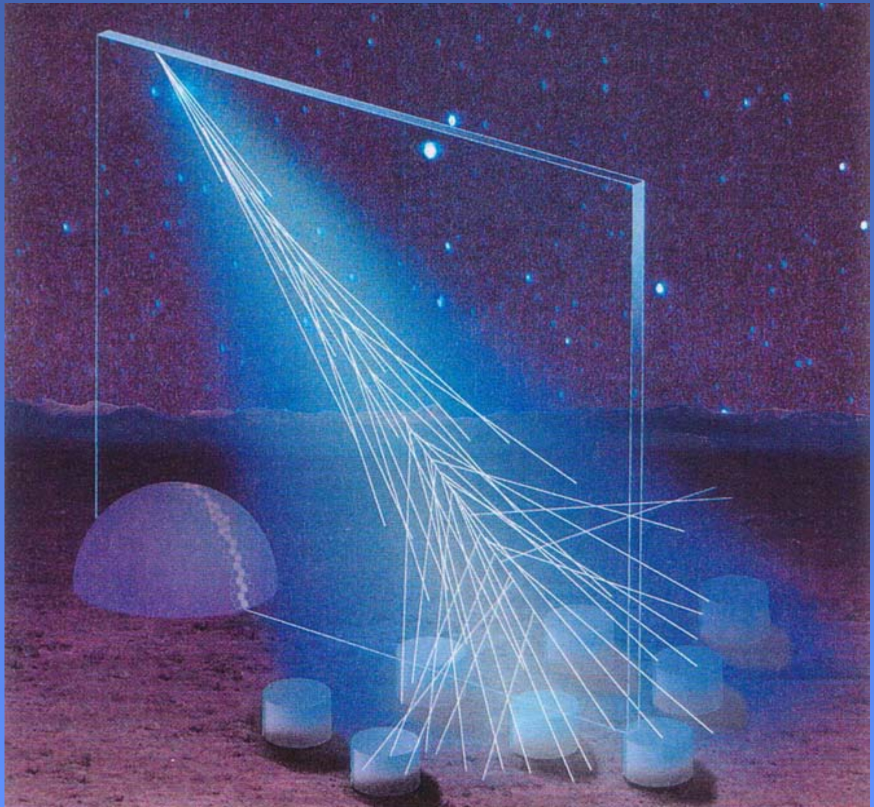
The First Energy Spectrum Results from the Pierre Auger Project

A new cosmic ray observatory designed for a high statistics study of the the Highest Energy Cosmic Rays.

Aaron S. Chou (FNAL)
Pierre Auger Collaboration



Mendoza, Argentina

The Auger Collaboration

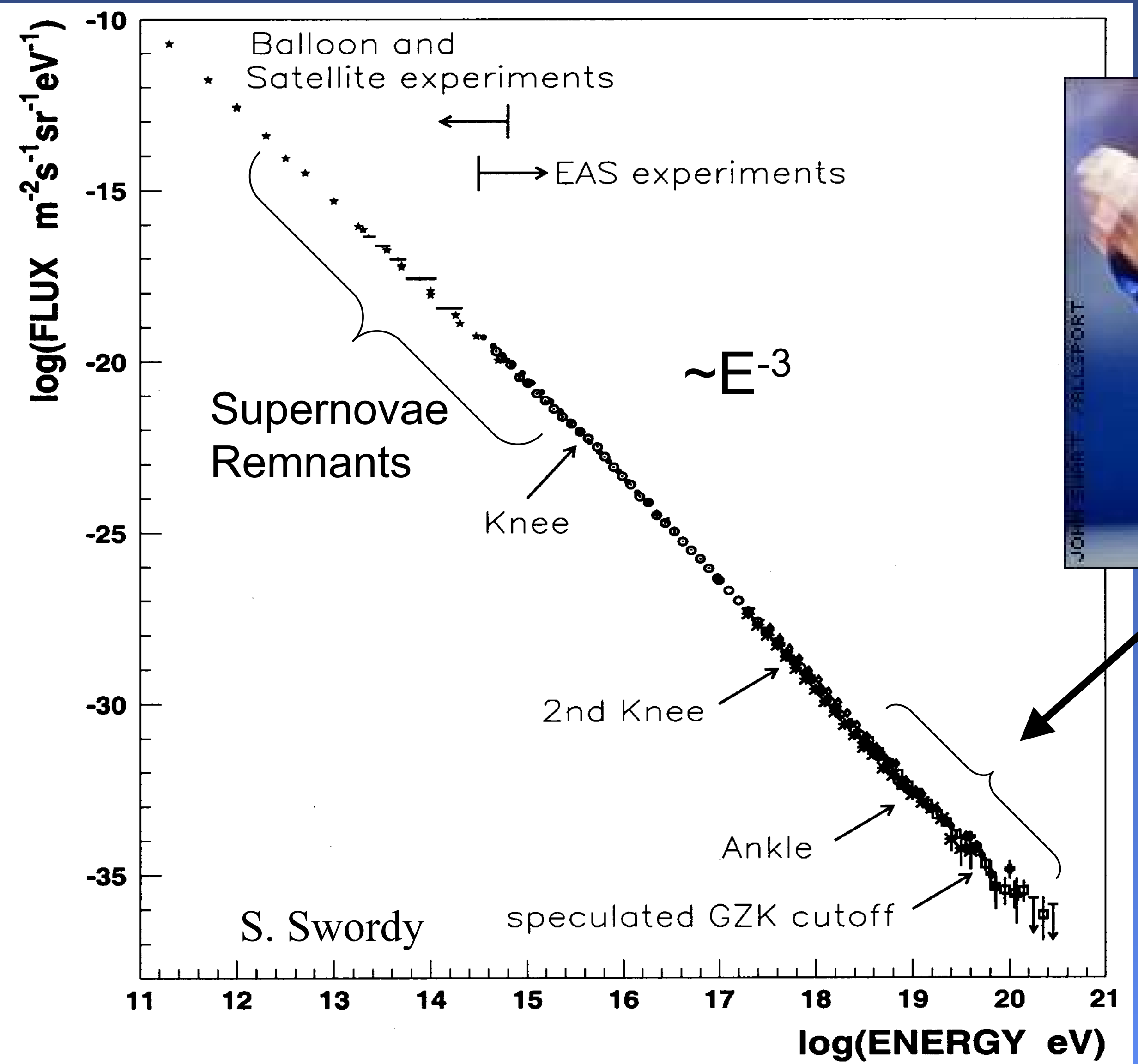
Participating Countries

- Argentina
- Australia
- Bolivia*
- Brazil
- Czech Republic
- France
- Germany
- Italy
- Mexico
- Netherlands
- Poland
- Slovenia
- Spain
- United Kingdom
- USA
- Vietnam*

**Associate*

18 Countries,
63 Institutions,
369 Collaborators

The measured cosmic ray energy spectrum



Lab frame energy ~ 10^{20} eV
= 100 EeV
~ 100mph-fastball.

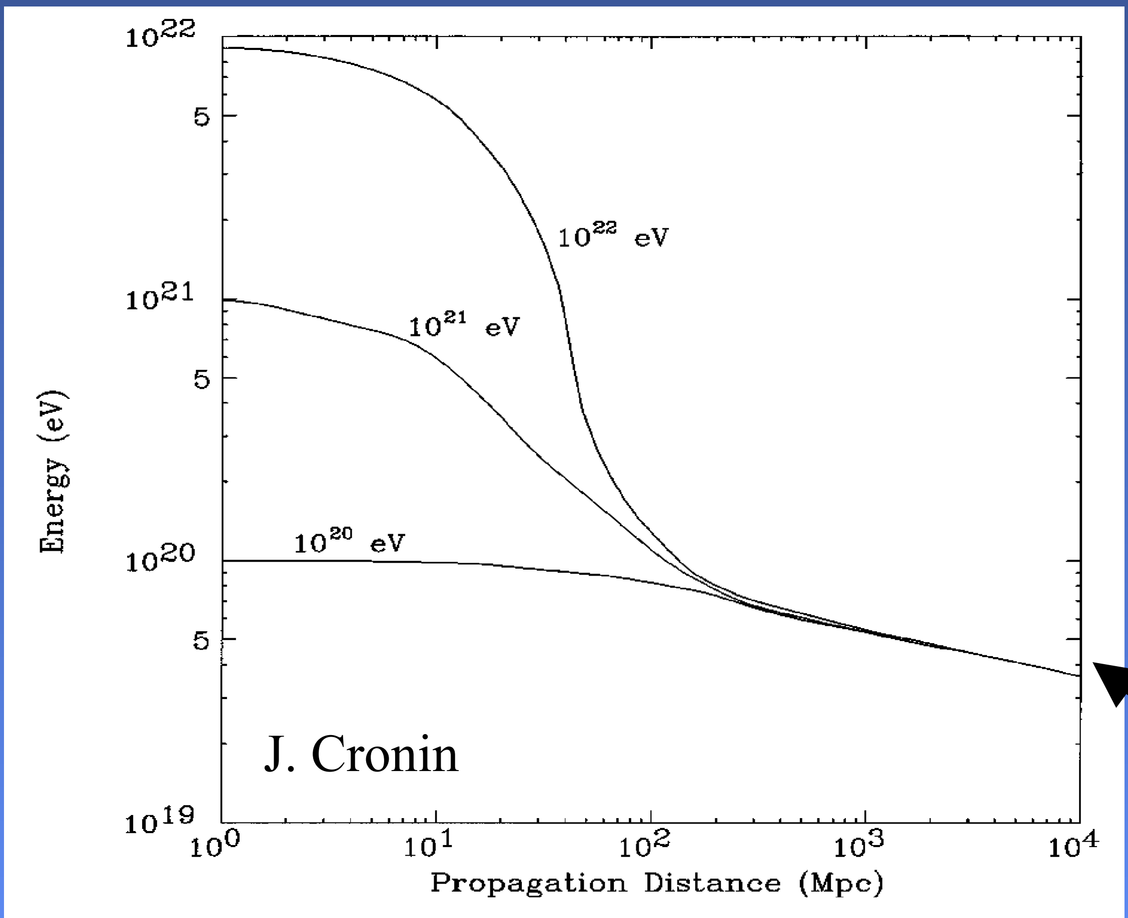
E_{cm} ~ 100TeV.

Composition?
Sources?
Extra-galactic origin?

Greisen-Zatsepin-Kuzmin (GZK): Interactions with the CMB

$$p+\gamma_{CMB} \rightarrow \Delta(1232) \rightarrow p+\pi^0 \rightarrow p\gamma\gamma$$

$$\rightarrow n+\pi^+ \rightarrow pe^-\bar{\nu}_e + e^+\nu_e\bar{\nu}_\mu\nu_\mu$$



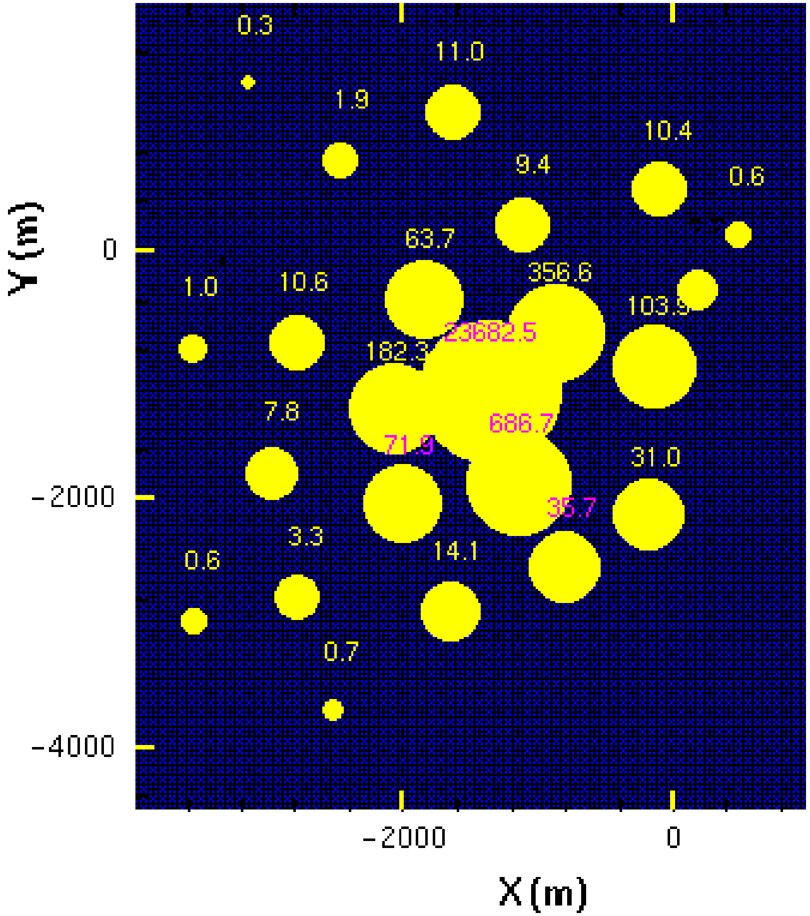
Possibilities:

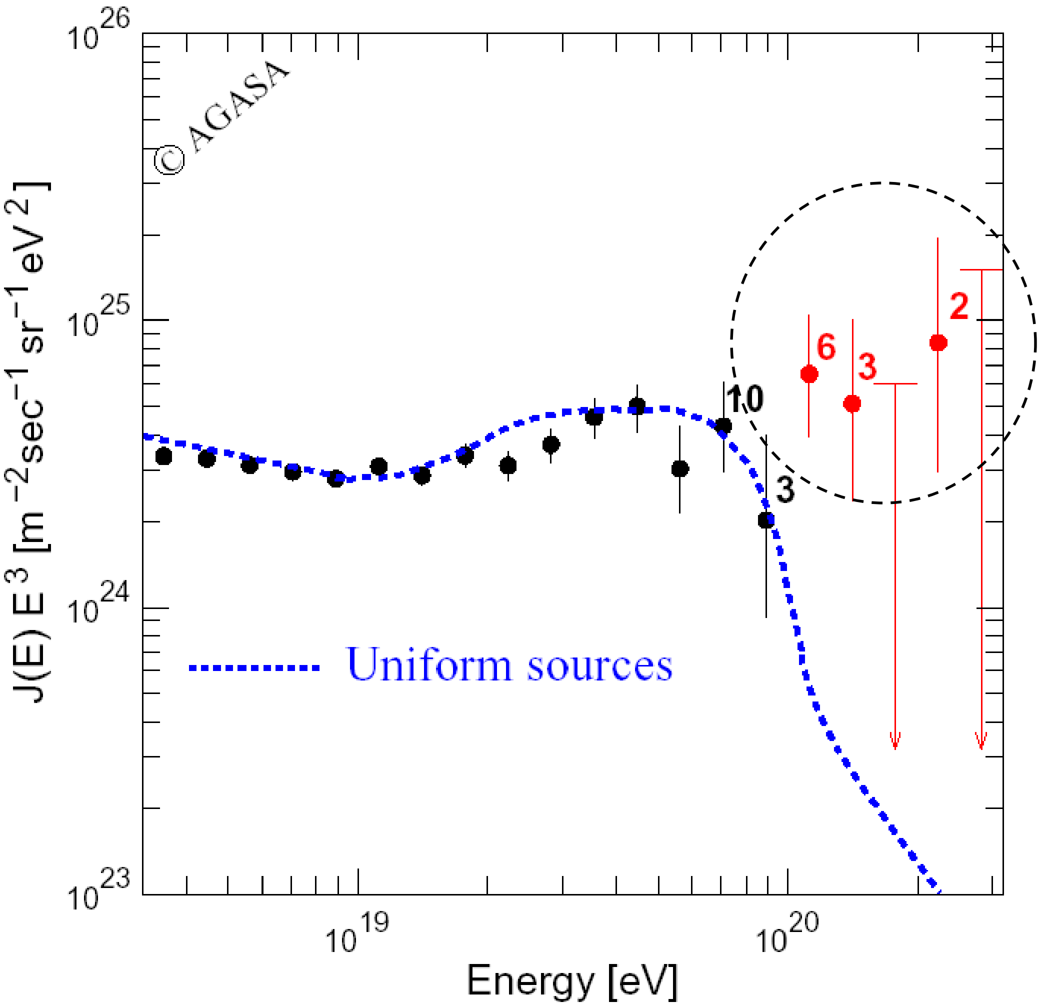
- The super-GZK sources are local (R<100Mpc)
- Lorentz invariance is broken such that the interaction is kinematically forbidden
- $\sigma_{CR\text{-}\gamma}$ is suppressed (nuclei, shadrons, neutrinos, etc.)

GZK maximum energy

AGASA (100 km² scintillator array) sees 11 events E>10^{20}eV

Measure via footprint on ground:
E = 2×10^{20}eV (AGASA,1993)



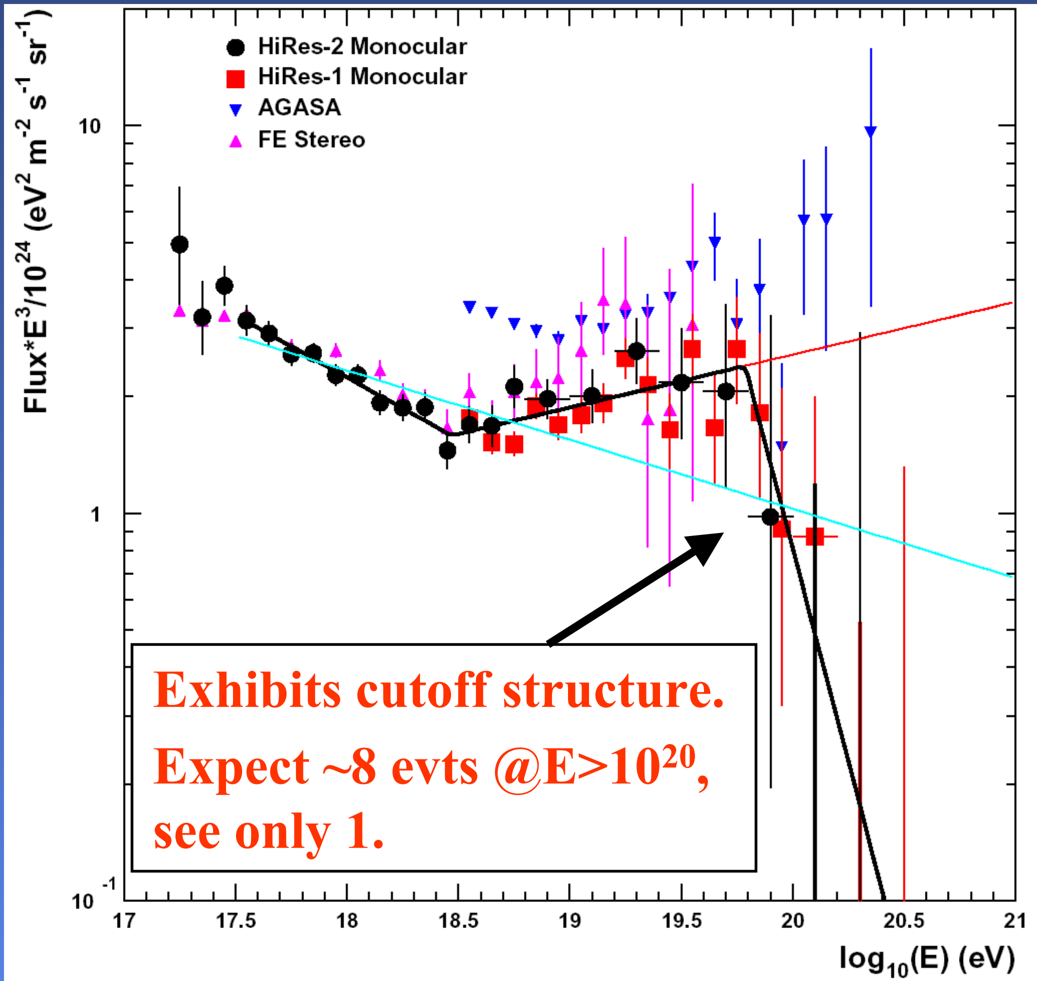


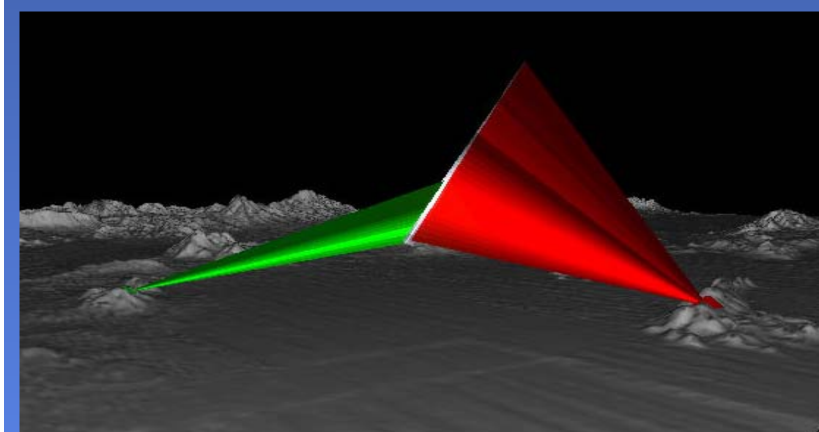
Surface Detector-alone Energy Measurement

- Con: The energy measurement technique relies on MC simulations of the expected signal level
  - Assumed hadronic interaction model requires extrapolations of collider data to higher energies and rapidities. Uncertainties are difficult (impossible) to estimate.

- Pros:
  - high duty cycle
  - Exposure is easily estimated
    - *The array trigger efficiency is 100% for large showers!*
  - self-calibration with atmospheric muons

HiRes Spectra



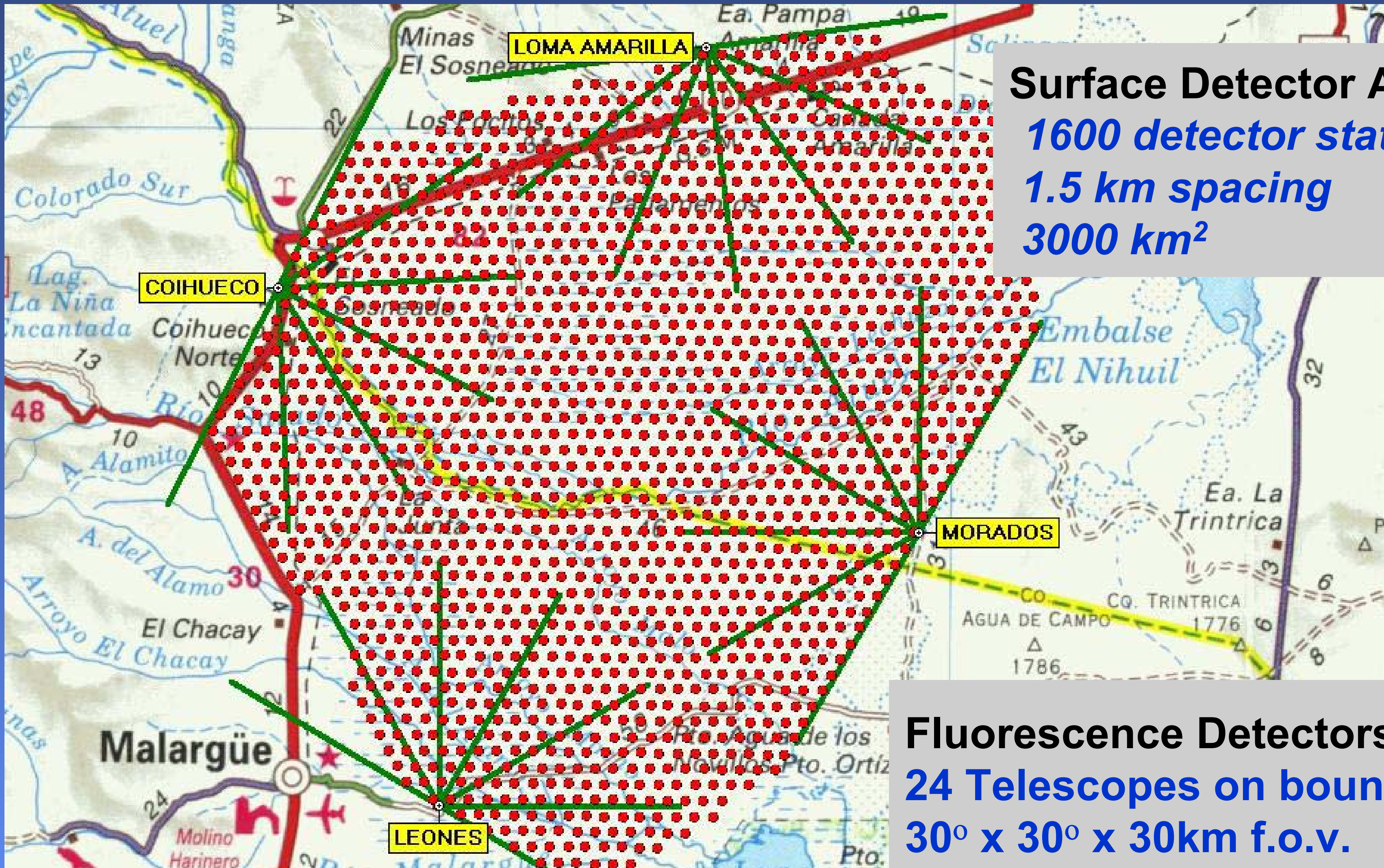


Measure longitudinal development by imaging with with UV telescopes.
N^2 fluorescence longitudinal profile → dE/dX profile.
Integrate the energy loss to get the initial energy.

Fluorescence Detector-alone Energy Measurement

- Pro: The energy measurement is calorimetric.
  - Energy~ionization loss~tracklength~fluorescence emission
- Cons:
  - Low duty cycle
  - The aperture is not easily determined. For example, if the atmosphere is dirtier than expected:
    - *Energy is underestimated.*
    - *Exposure (integrated trigger efficiency) is overestimated.*
  - Systematic errors from calibration, N_2 fluorescence yield

The Auger Observatory Plan: use both SD and FD



Surface Detector Array

1600 detector stations

1.5 km spacing

3000 km²

Fluorescence Detectors

24 Telescopes on boundary

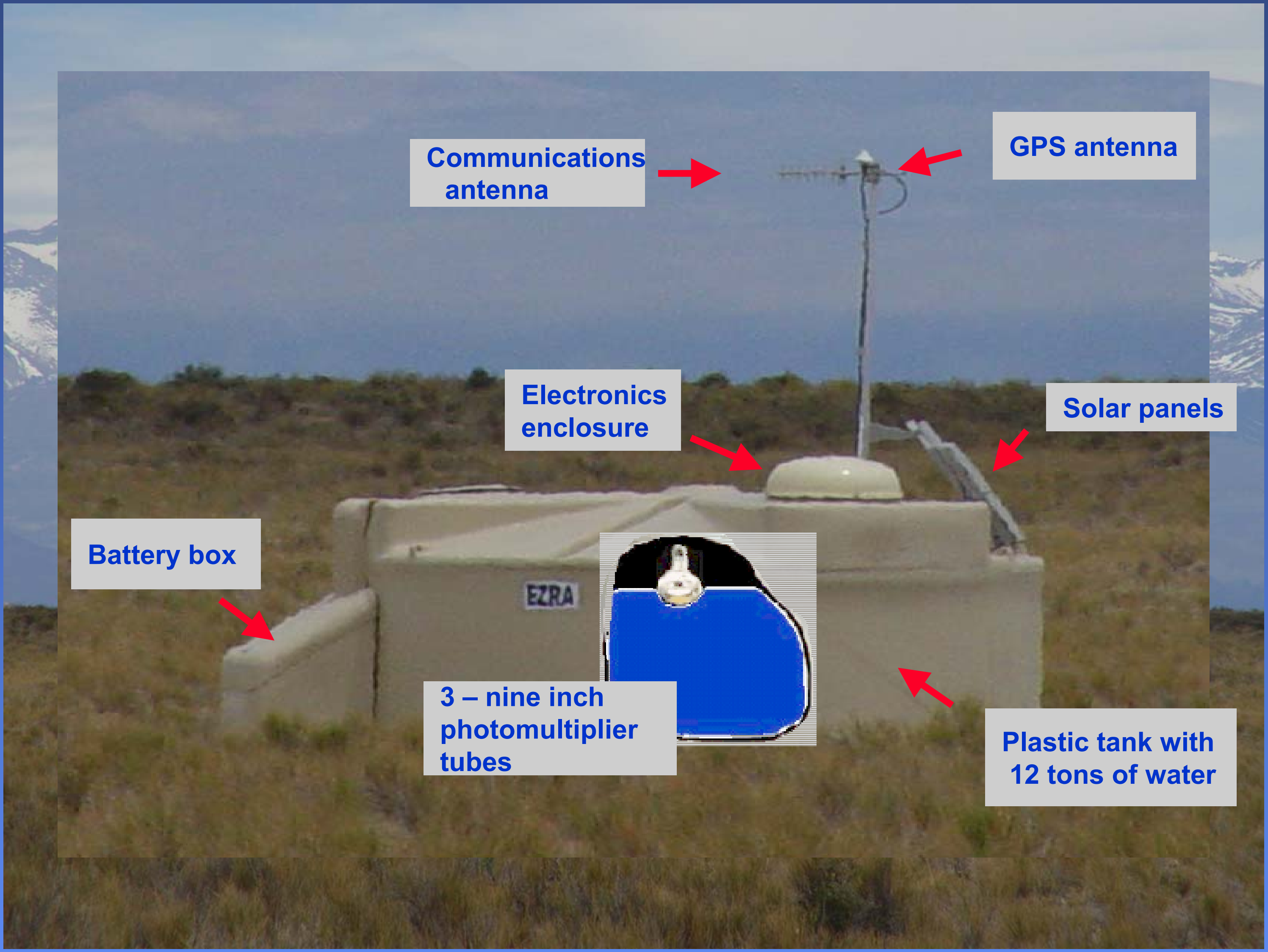
30^o x 30^o x 30km f.o.v.

per telescope

The Surface Detector Array

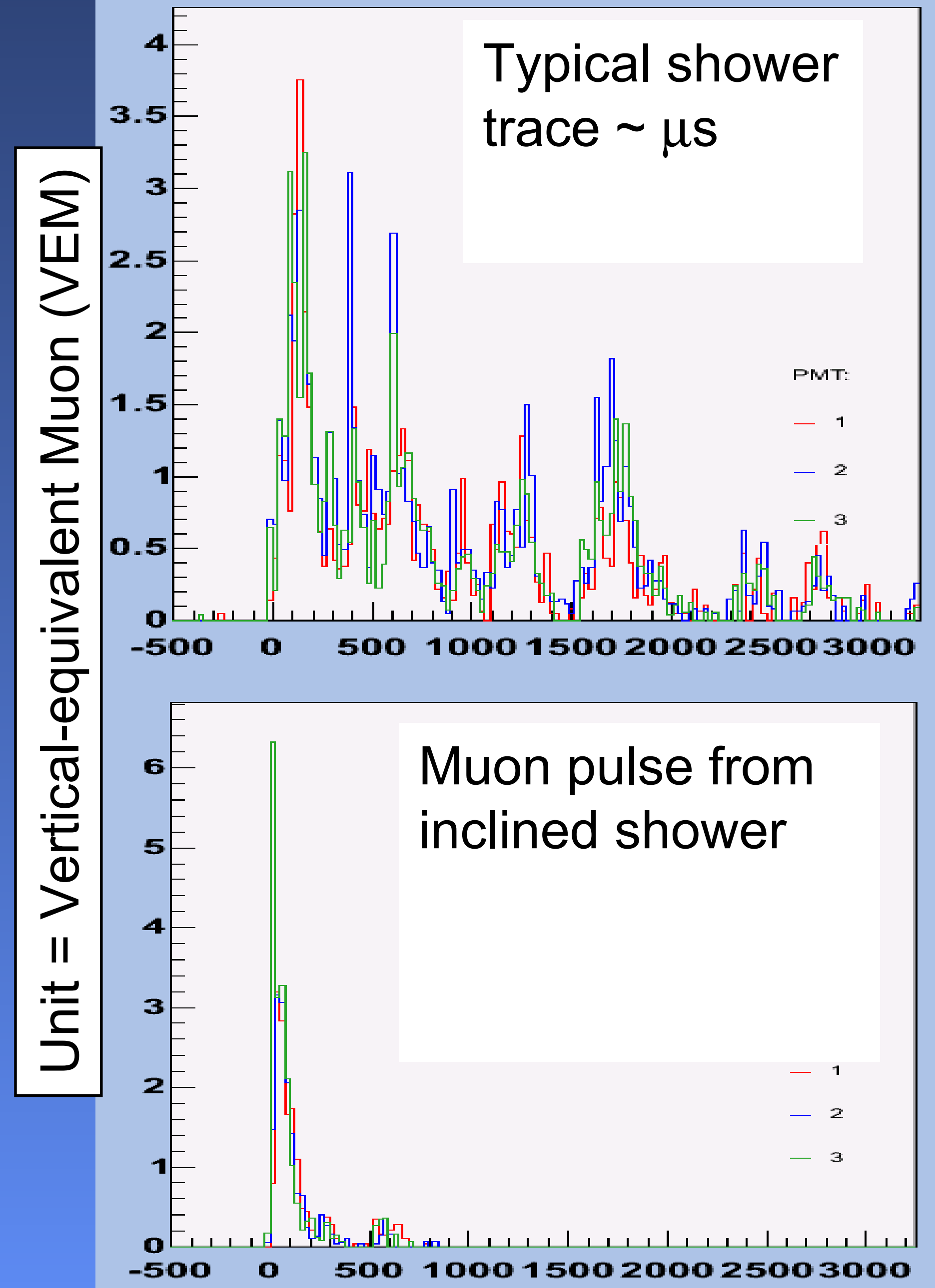
The Surface Detector Array

Water Cherenkov Detector Station

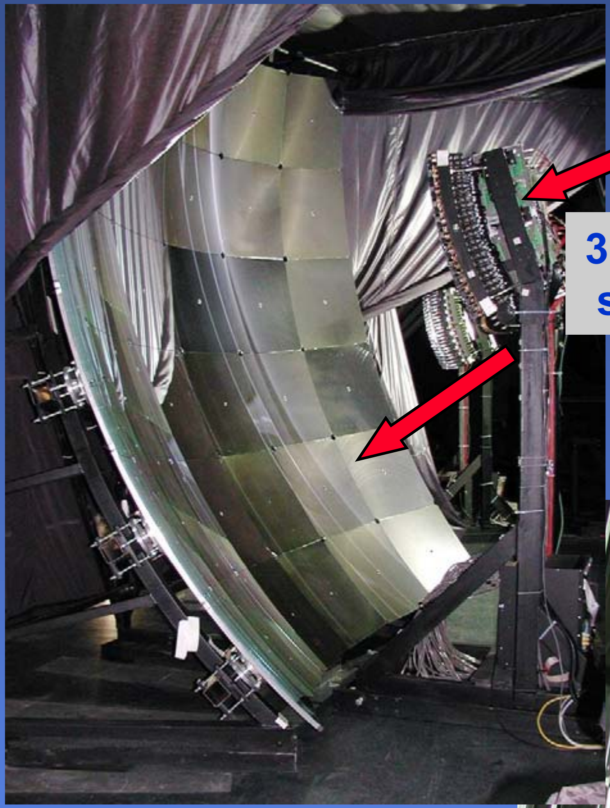


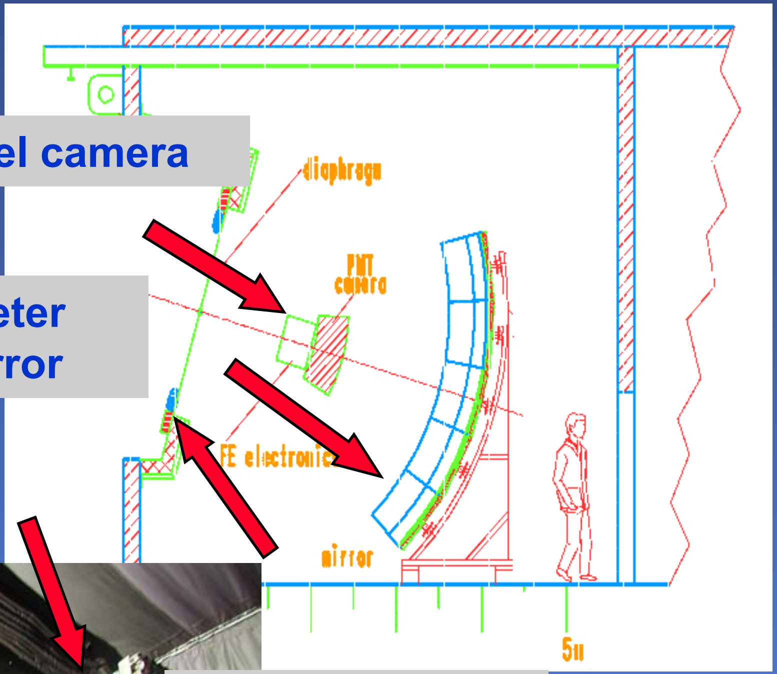
SD triggers

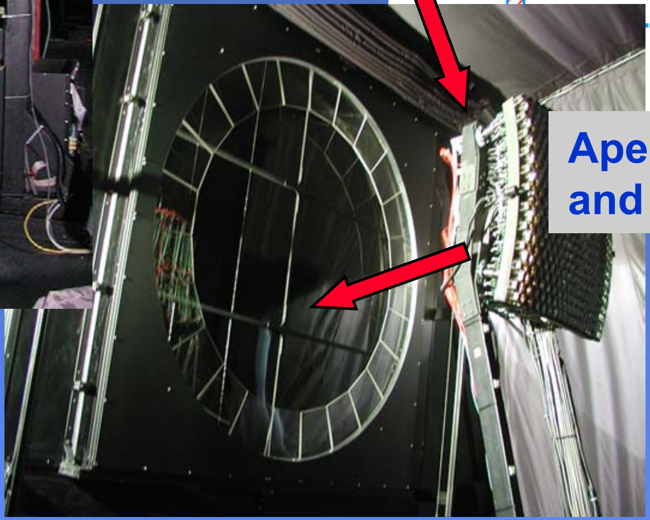
- Time-over-threshold (TOT) 1-5Hz
  - Long signals
- Single-bin Threshold 20Hz
  - Fast signals (inclined showers)
- Central trigger, rate~3000/day
  - look for topologically clustered triggered tanks
- Event selection (for current spectrum analysis)
  - look for at least 3 TOT triggers in a compact configuration
  - ~600/day (~0.9/tank/day)



The Fluorescence Detector







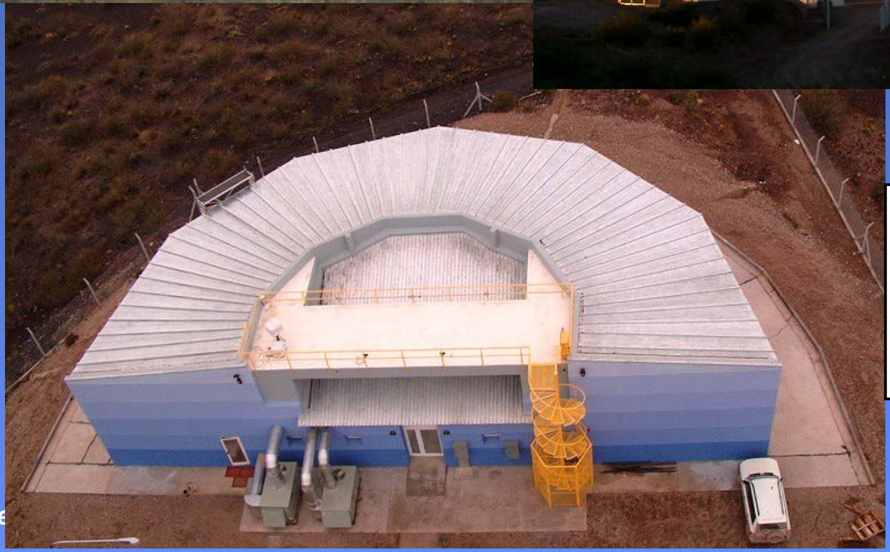
440 pixel camera

3.4 meter diameter segmented mirror

Aperture stop and optical filter

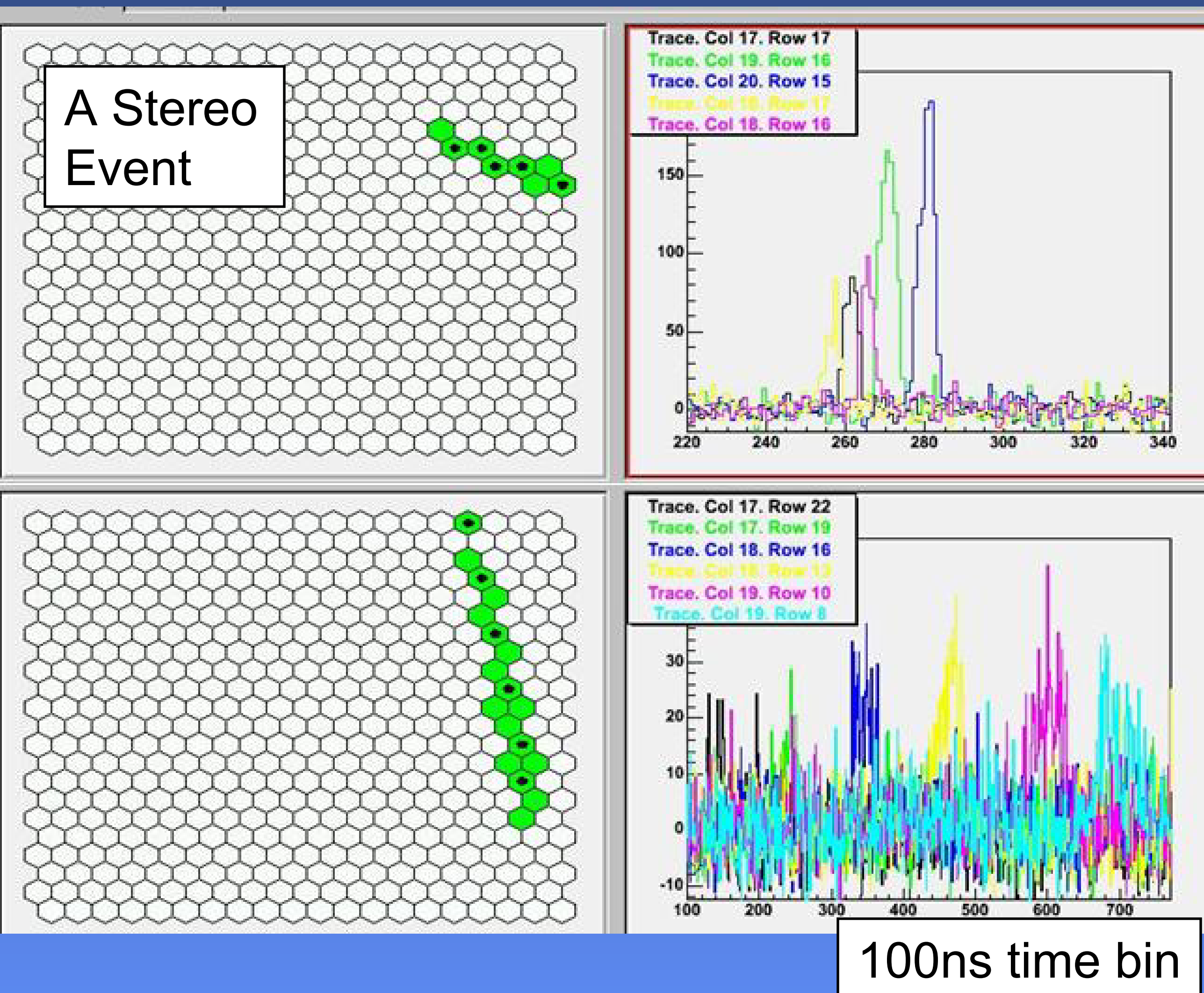
The Fluorescence Detector

Los Leones



Only operate on clear moonless nights
→ 10% duty cycle

FD Triggers



- 100 Hz Threshold trigger on individual pixels
- Look for “tracks”
  - 0.2 Hz /camera
- Geometry recon passed to central data acquisition system
  - Induces SD readout of tanks within range.
  - Obtain “Hybrid” events with both longitudinal and transverse shower information.

Lot's of toys: Atmospheric Monitoring and Fluorescence Detector Calibration

Atmospheric Monitoring

Central Laser Facility (laser optically linked to adjacent surface detector tank)

- **Atmospheric monitoring**
- **Calibration checks**
- **Timing checks**

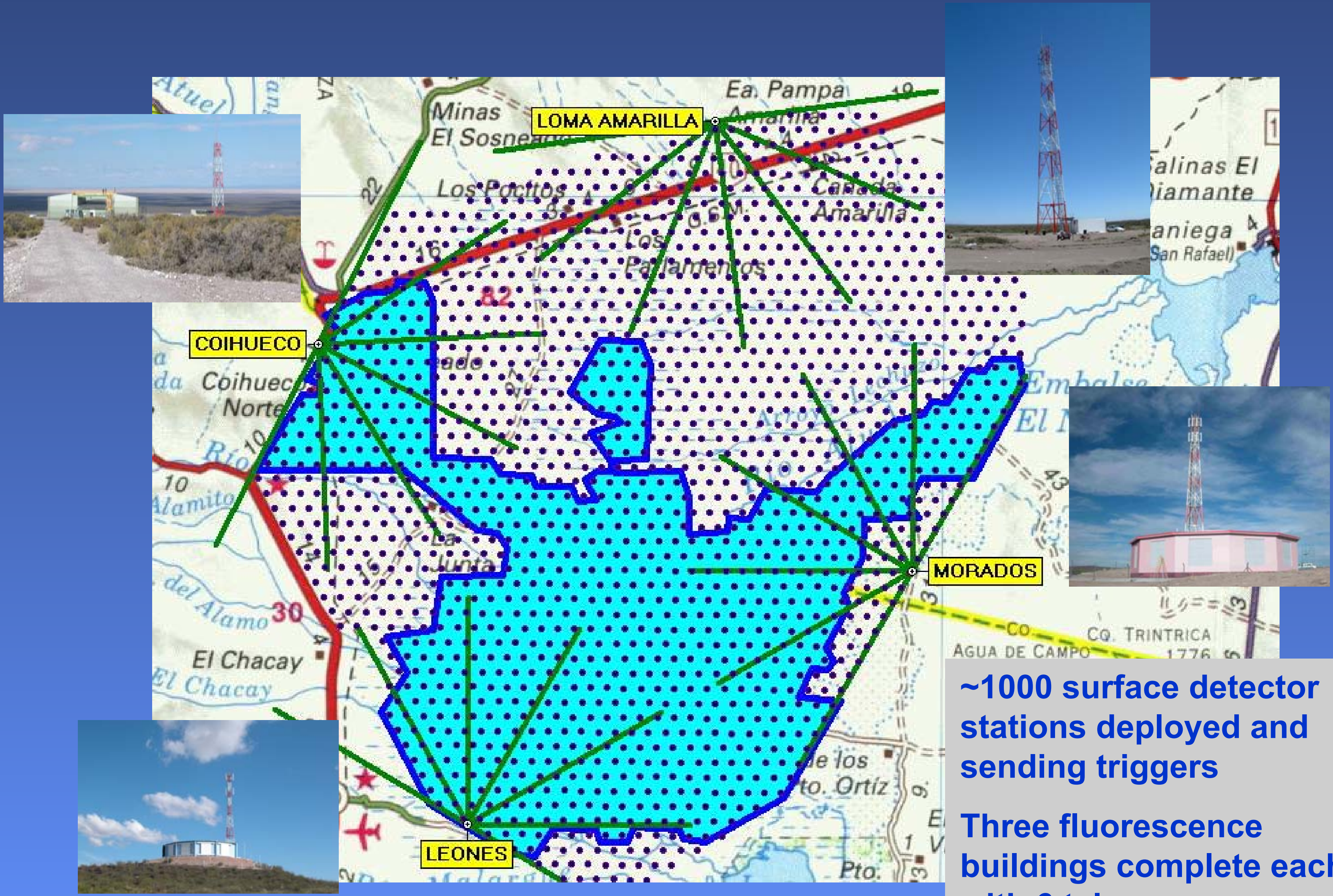
Radiosondes for atmos. profile

Lidar at each fluorescence eye for atmospheric profiling - "shooting the shower"

Absolute Calibration

Drum for uniform illumination of each fluorescence camera

Construction Progress



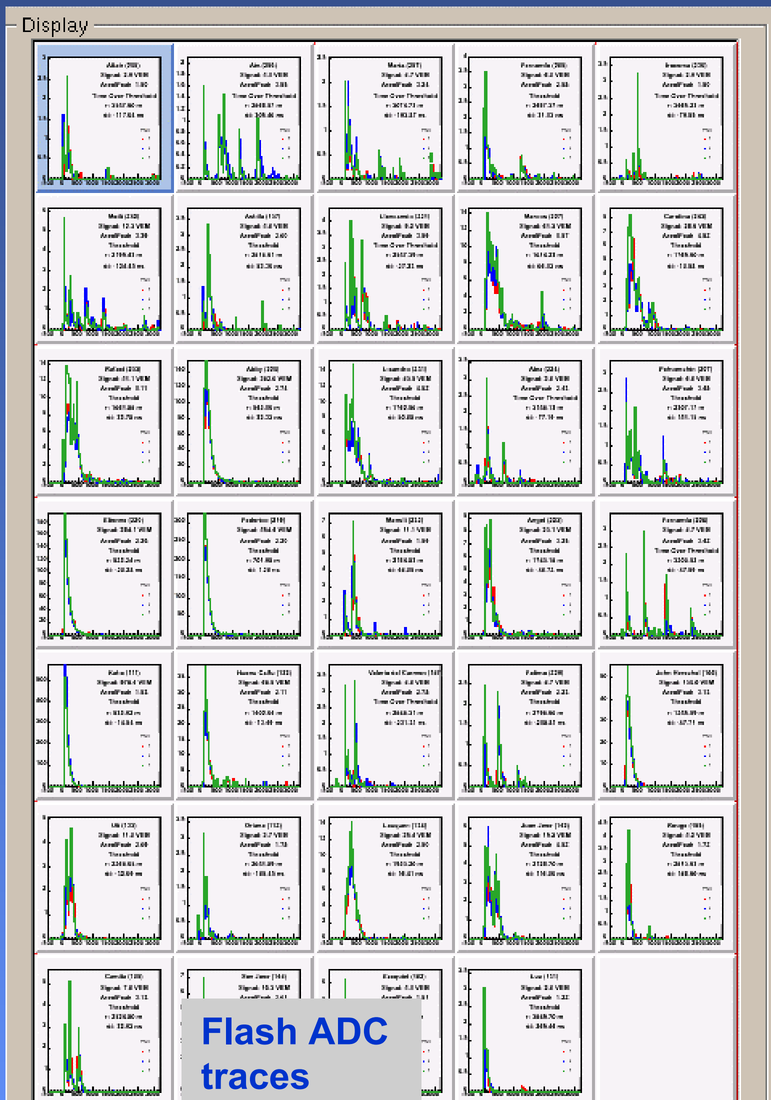
~1000 surface detector stations deployed and sending triggers

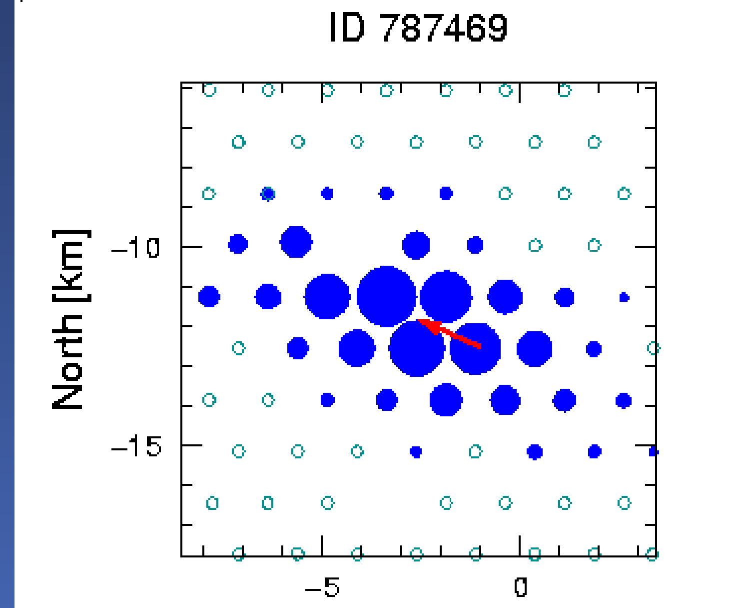
Three fluorescence buildings complete each with 6 telescopes

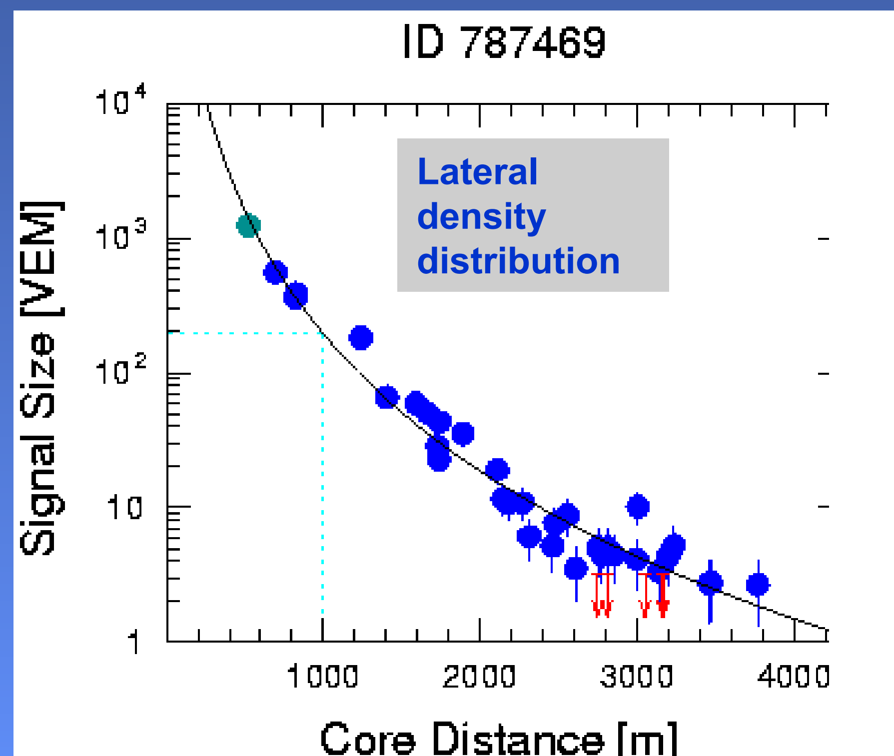
A “Typical” Event

An inclined event - 787469

Zenith angle ~ 60º, Energy ~ 86 EeV

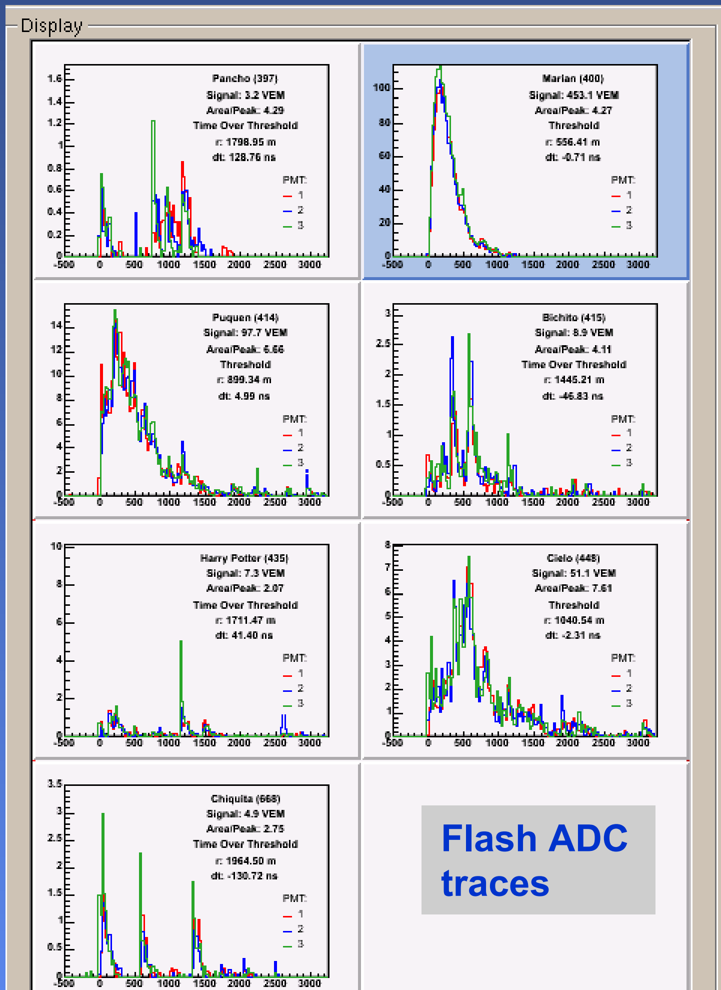


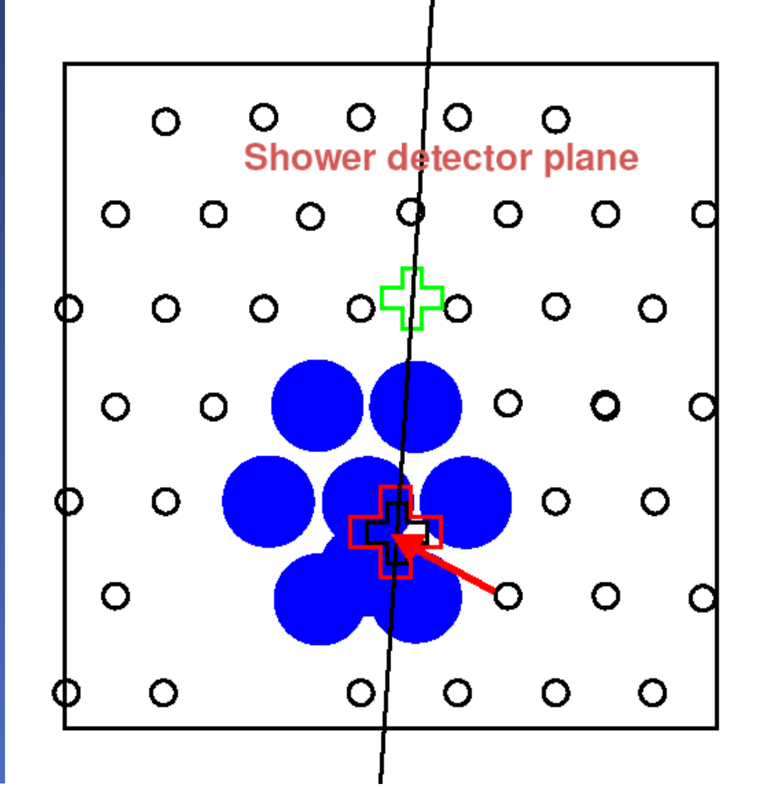


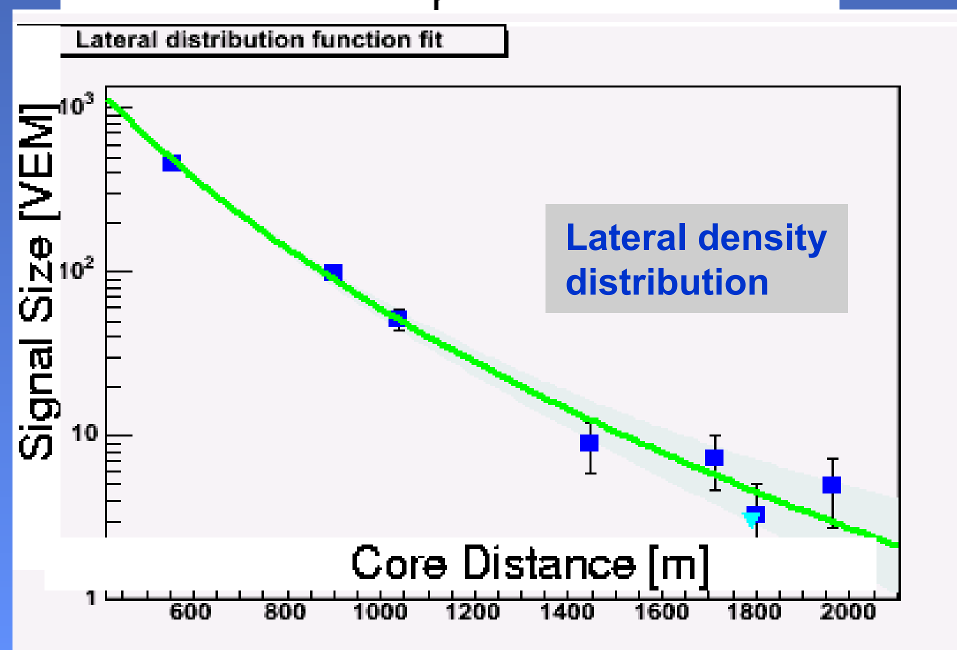


Hybrid Event (SD view)

A hybrid event – 1021302
Zenith angle ~ 30º, Energy ~ 10 EeV



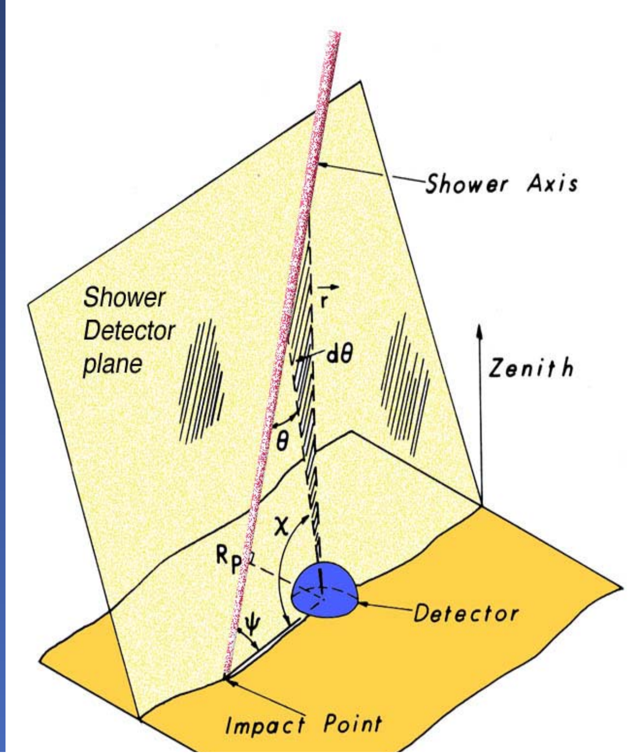


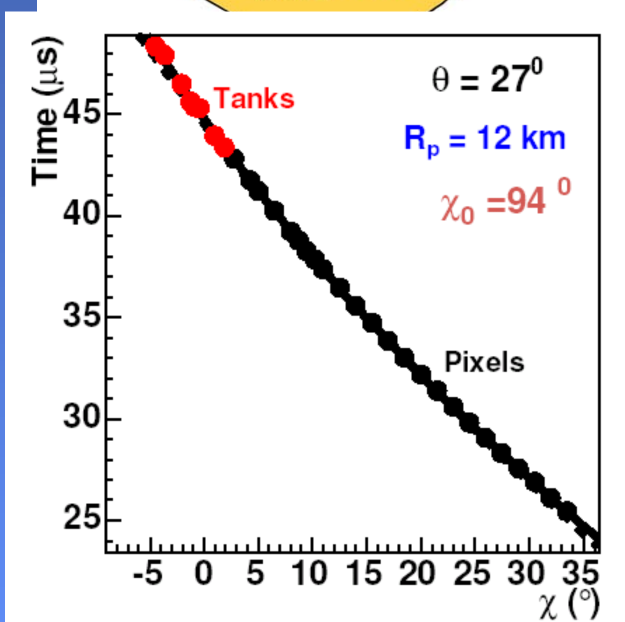


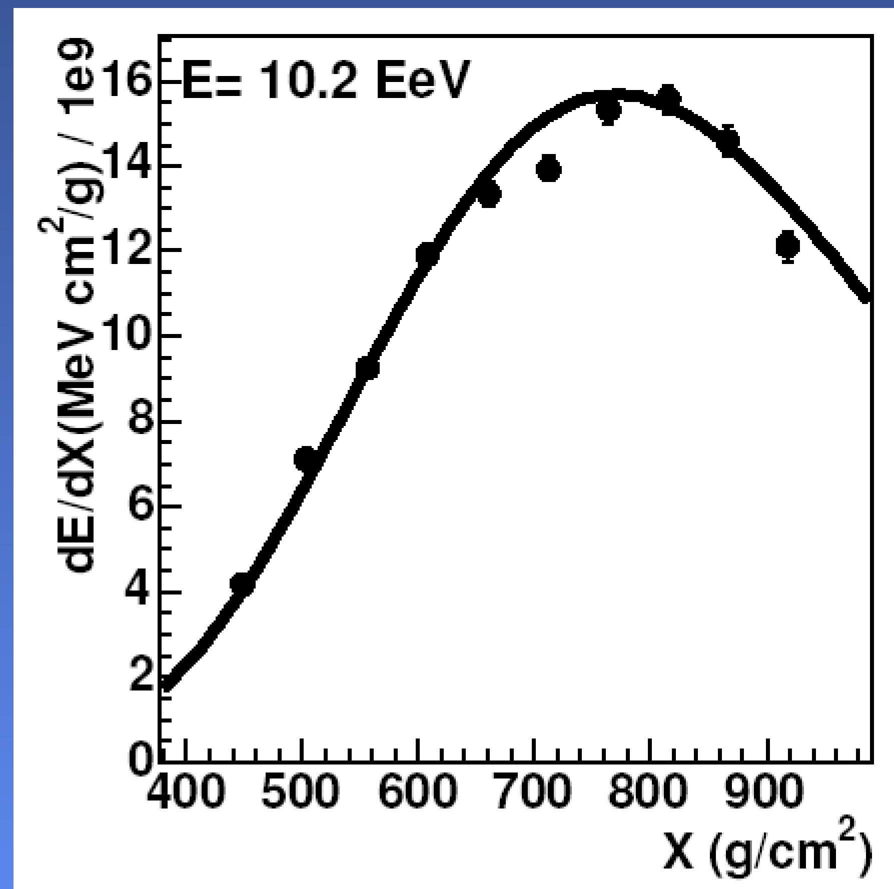
Hybrid Event (FD view)

A hybrid event – 1021302

Zenith angle ~ 30º, Energy ~ 10 EeV

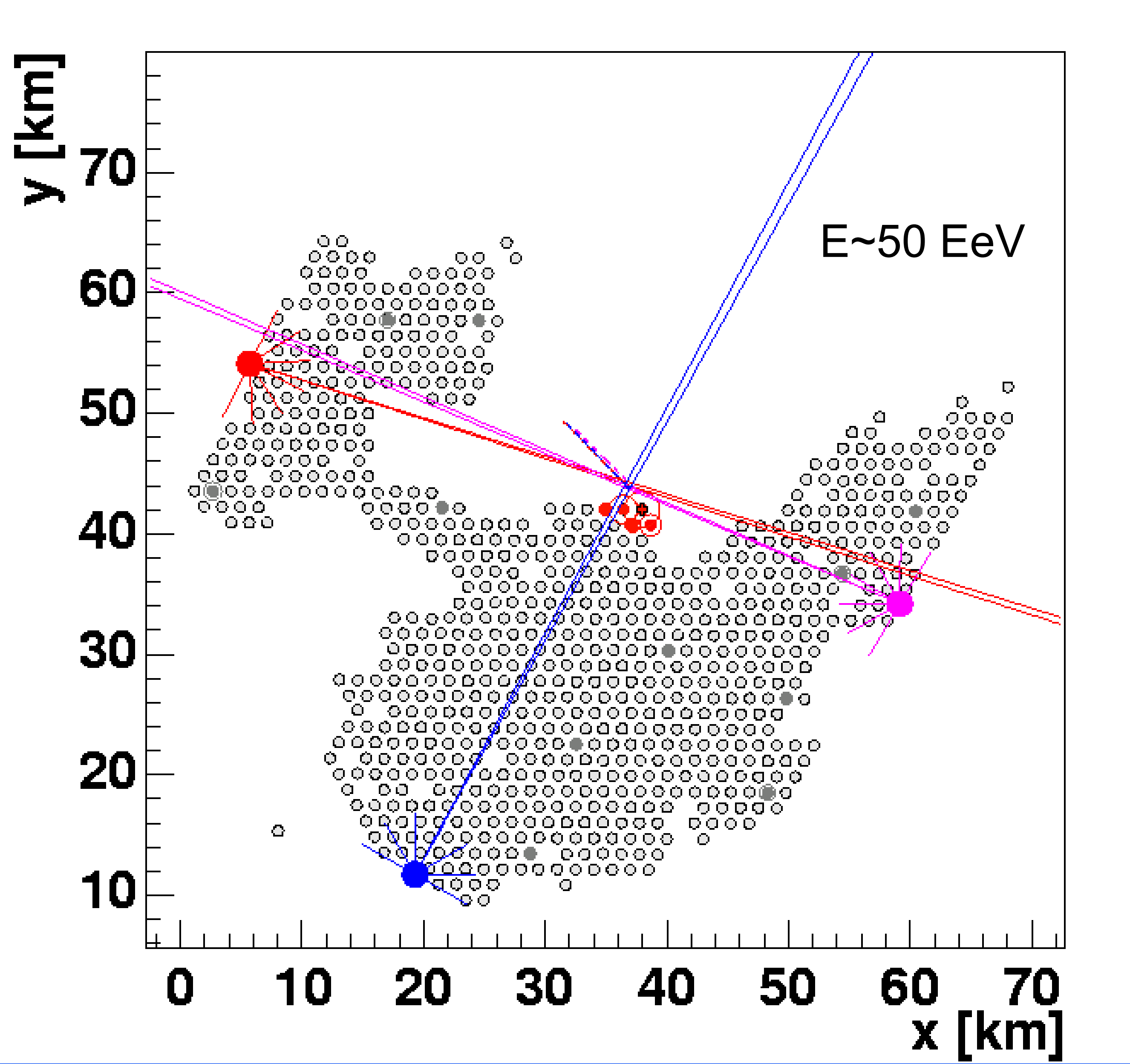




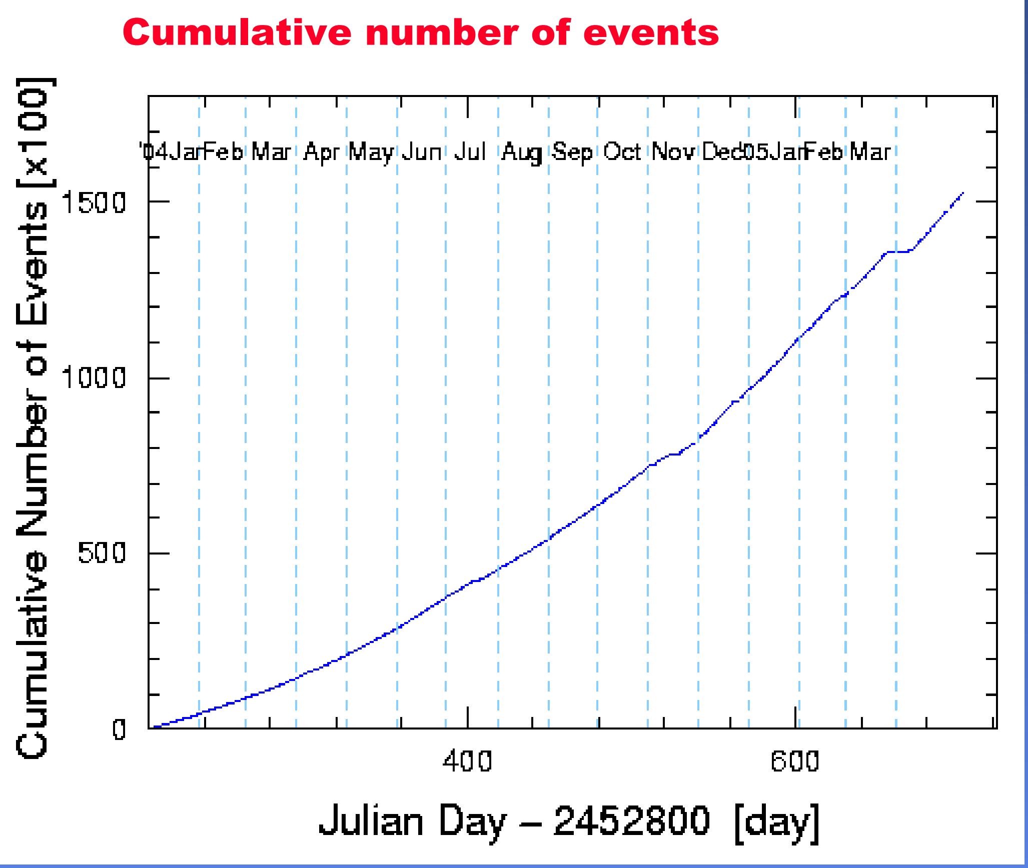


from Fly's Eye 1985

One of many frustrating events....



The First Data Set



Collection period – 1 Jan 2004 to 5 June 2005

Zenith angles - 0 - 60º

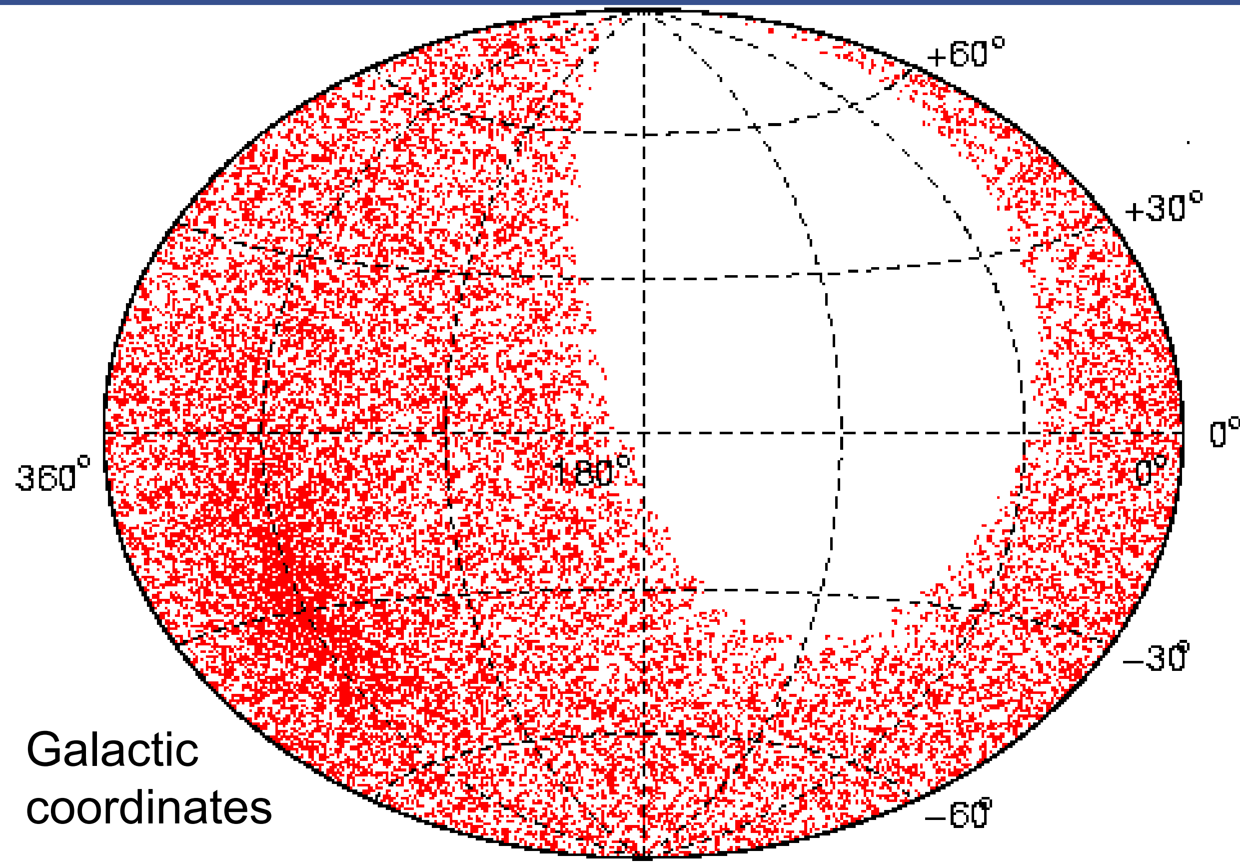
Total exposure – 1750km^2 sr yr (~ 1.07 * AGASA)

Surface array events (after quality cuts)

Current rate - 18,000 / month

Total - 150,000

Sky Map of Data set



Galactic coordinates

Auger latitude= -36.

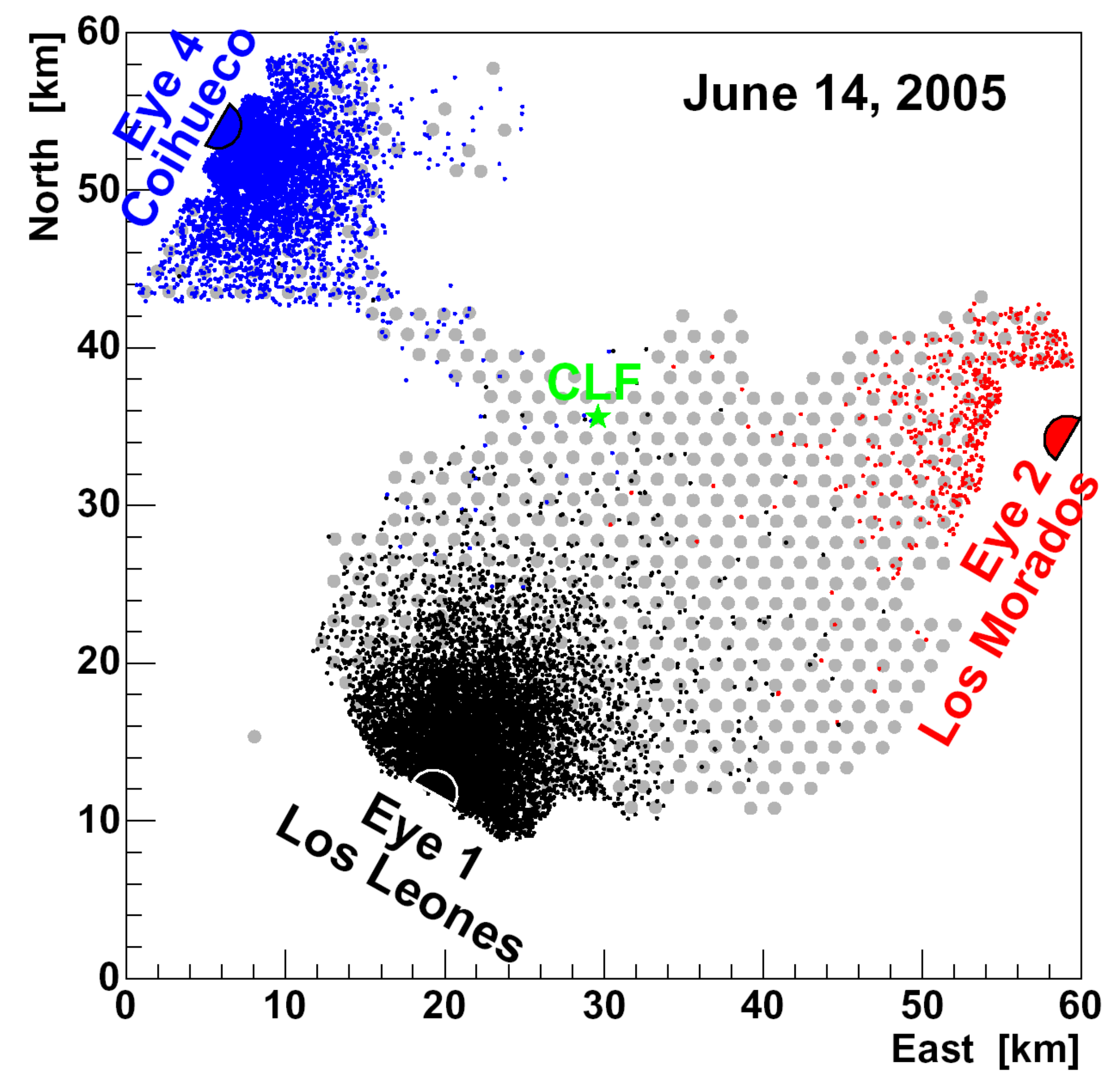
Always looking towards South.

Limited coverage in Northern region.

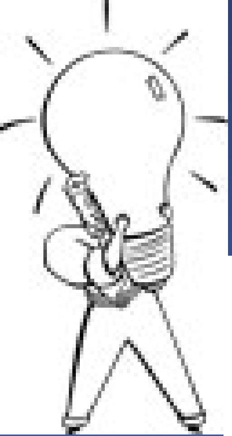
We mainly measure properties of the Southern sky flux!

If superGZK events come from a finite set of local sources in the North, we could miss them….

Hybrid Events



- Reconstructed
  - 1800/month
  - Total = 10,000
  - Mostly at low energies near eyes
  - ~2000 events at >1 EeV



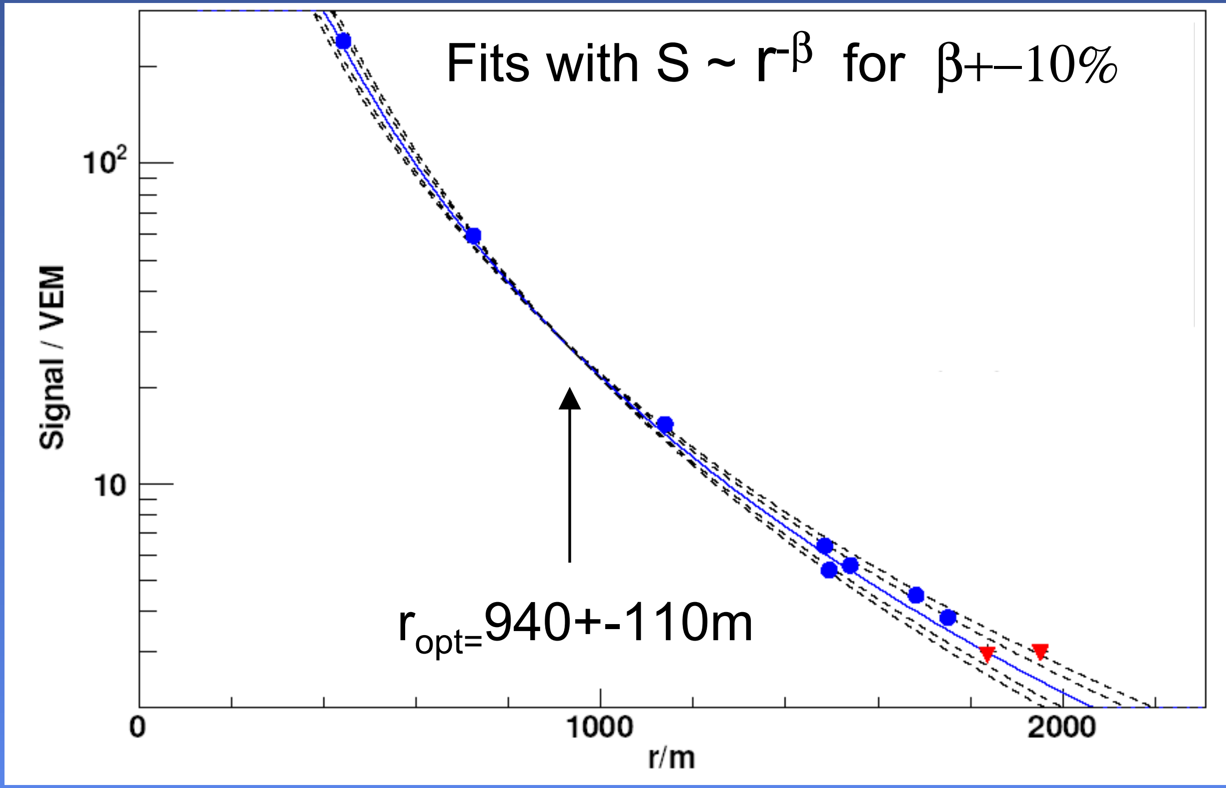
The Auger Empirical Approach to Measuring the Spectrum

Use the strengths from each technique:
FD(Hybrid) energy, SD statistics, SD aperture.

- **From SD data, reconstruct a stable ground parameter S(1000) (SD signal at 1000m) which is correlated with shower energy**
- **Empirically determine the S(1000)→Energy conversion**
  - **Measure the zenith angle dependence of S(1000)**
  - **Use Hybrid data to:**
    - ***Normalize the converter assuming the FD (hybrid) energy scale***
    - ***Determine the energy dependence of the converter***
- **Divide the SD energy histogram by the SD exposure to obtain the measured spectrum.**

Energy is proportional to S(1000), the signal at 1000m core distance.

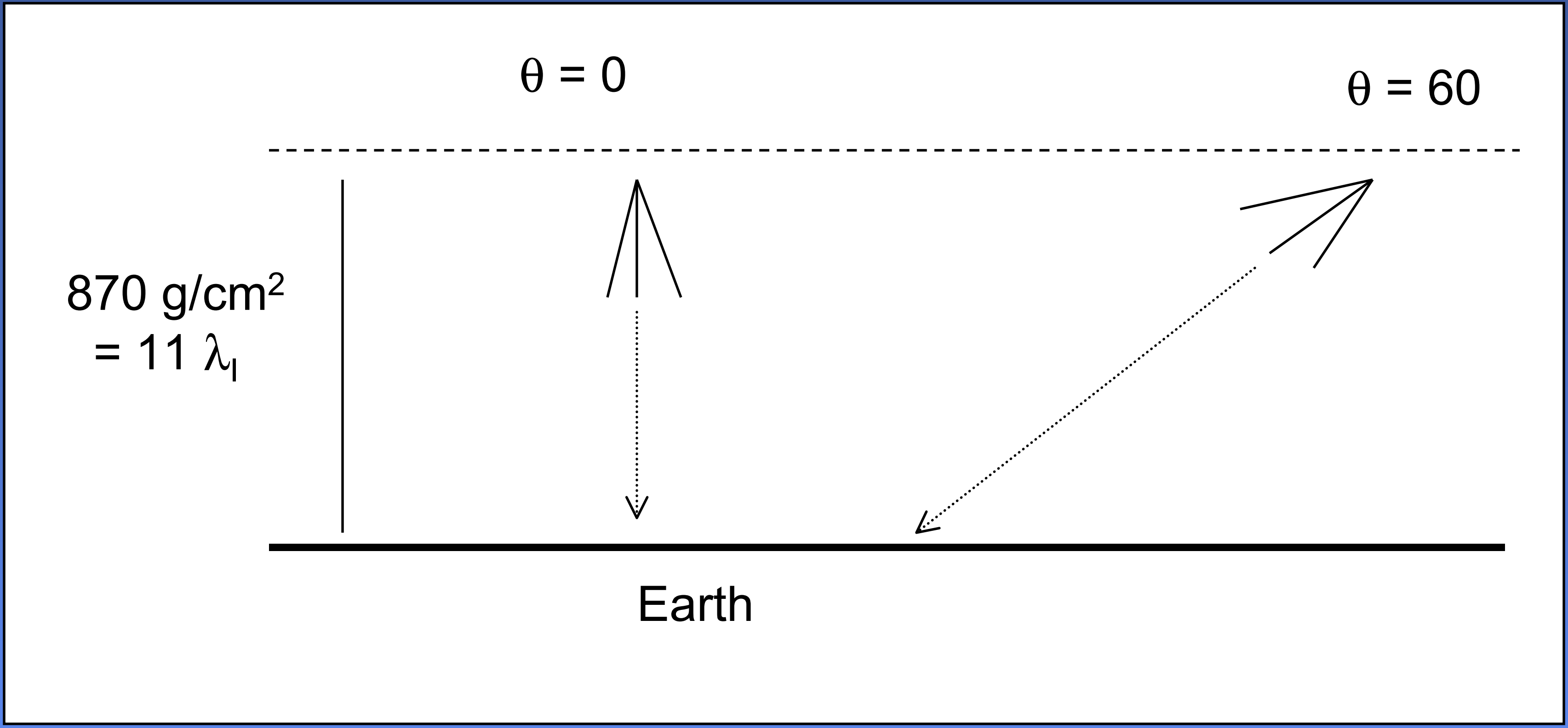
- To determine the shower energy, a single ground parameter S(1000) is traditionally chosen to minimize the effects of reconstruction uncertainties, and shower-to-shower fluctuations



$S(r_{opt})$ is a stable ground parameter. (Effects of changing β are minimized)
→ σ_S ~ 10%, ΔS ~ 4%

Zenith Angle Dependence:

Showers coming from different zenith angles give very different signals due to flux attenuation in the atmosphere

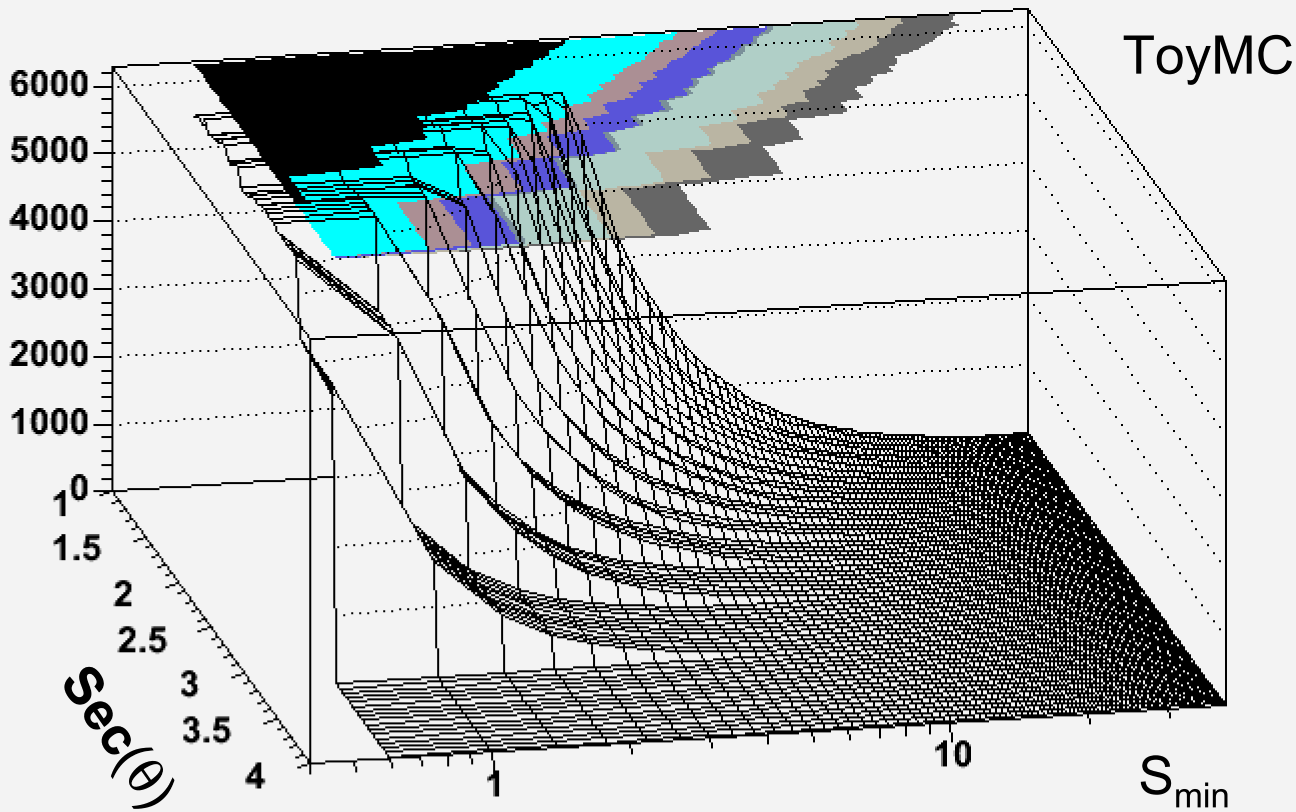


The "slant depth" is $870 g/cm^2 * \sec(\theta)$

Measure the θ Dependence directly from the data (Constant Intensity Cut Method)

$$\varepsilon^{-1} \int_{S_{min}}^{\infty} \frac{dN}{dS \cdot d\Omega} dS$$

Geometric efficiency correction



- The power-law flux dN/dS can in principle be measured independently in each zenith angle bin.
- Because the CR flux is isotropic to a good approximation, bins at different θ but with the same measured flux intensity must correspond to cosmic rays of the same energy!
  - **Therefore, contours of constant intensity give the θ-dependence of S.**

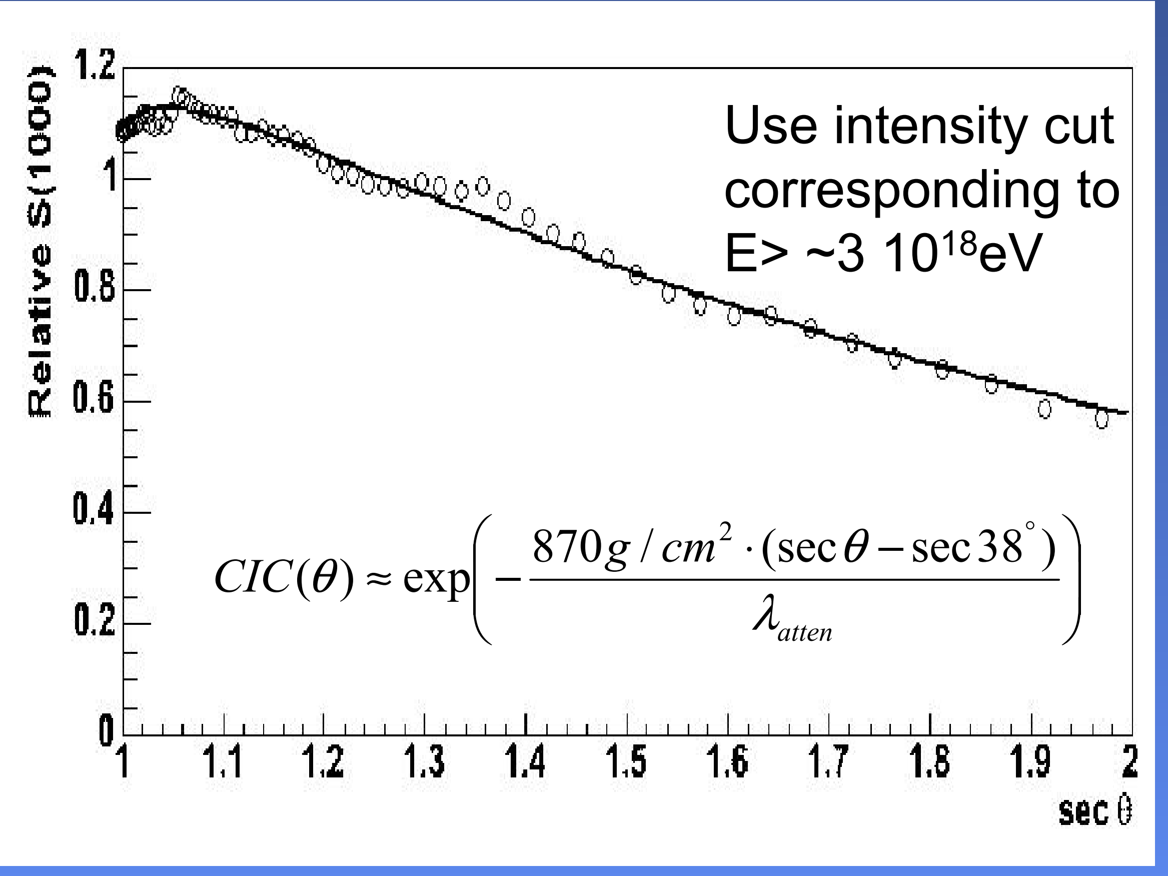
The measured θ-dependence

- Shape is scanned in θ using bins of $\Delta\sin^2(\theta)=0.1$
- Normalize at the median zenith angle of 38 degrees.

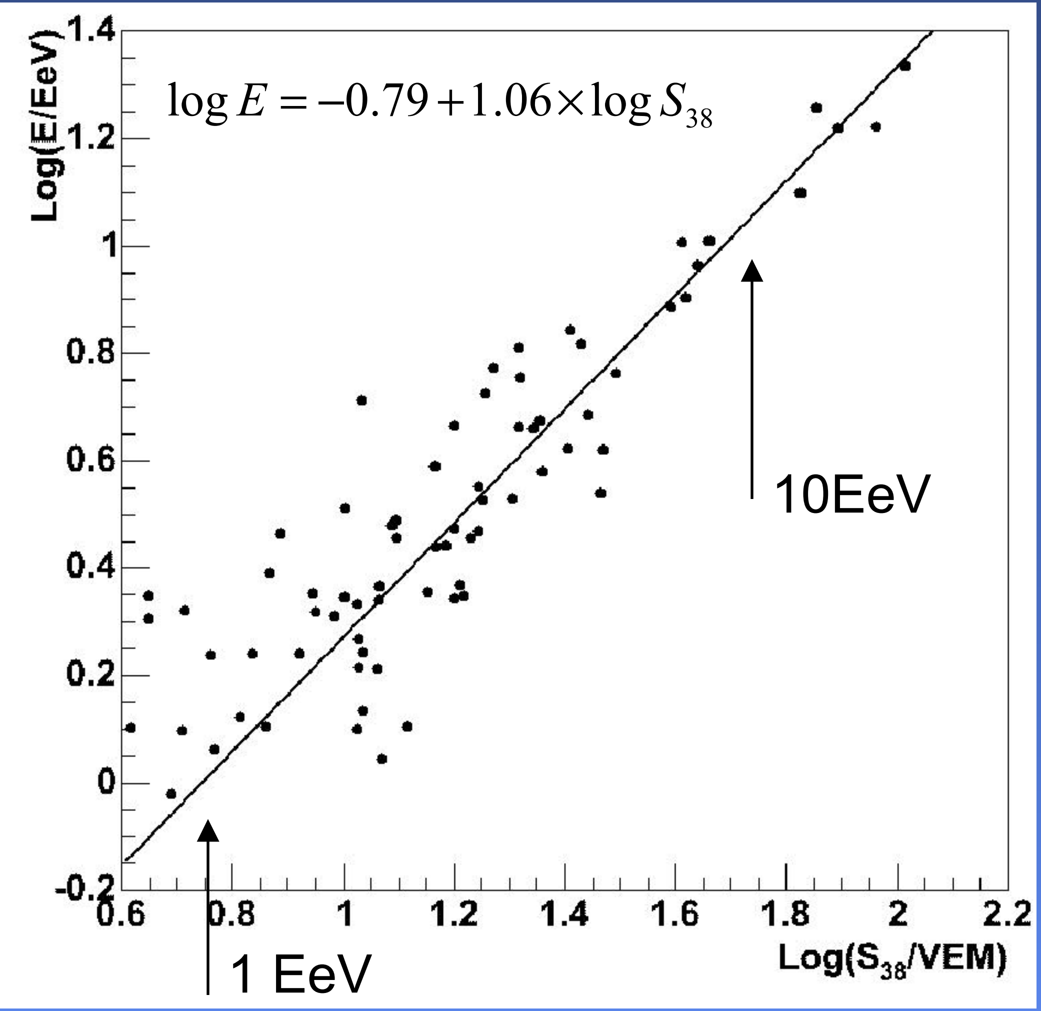
$$S(1000)_\theta = S_{38}(E) \times CIC(\theta)$$

- **Assume for now that CIC(θ) is independent of energy.**

Note: bins are correlated!



Obtain the S38→Energy Correlation with Fluorescence energies from hybrid events

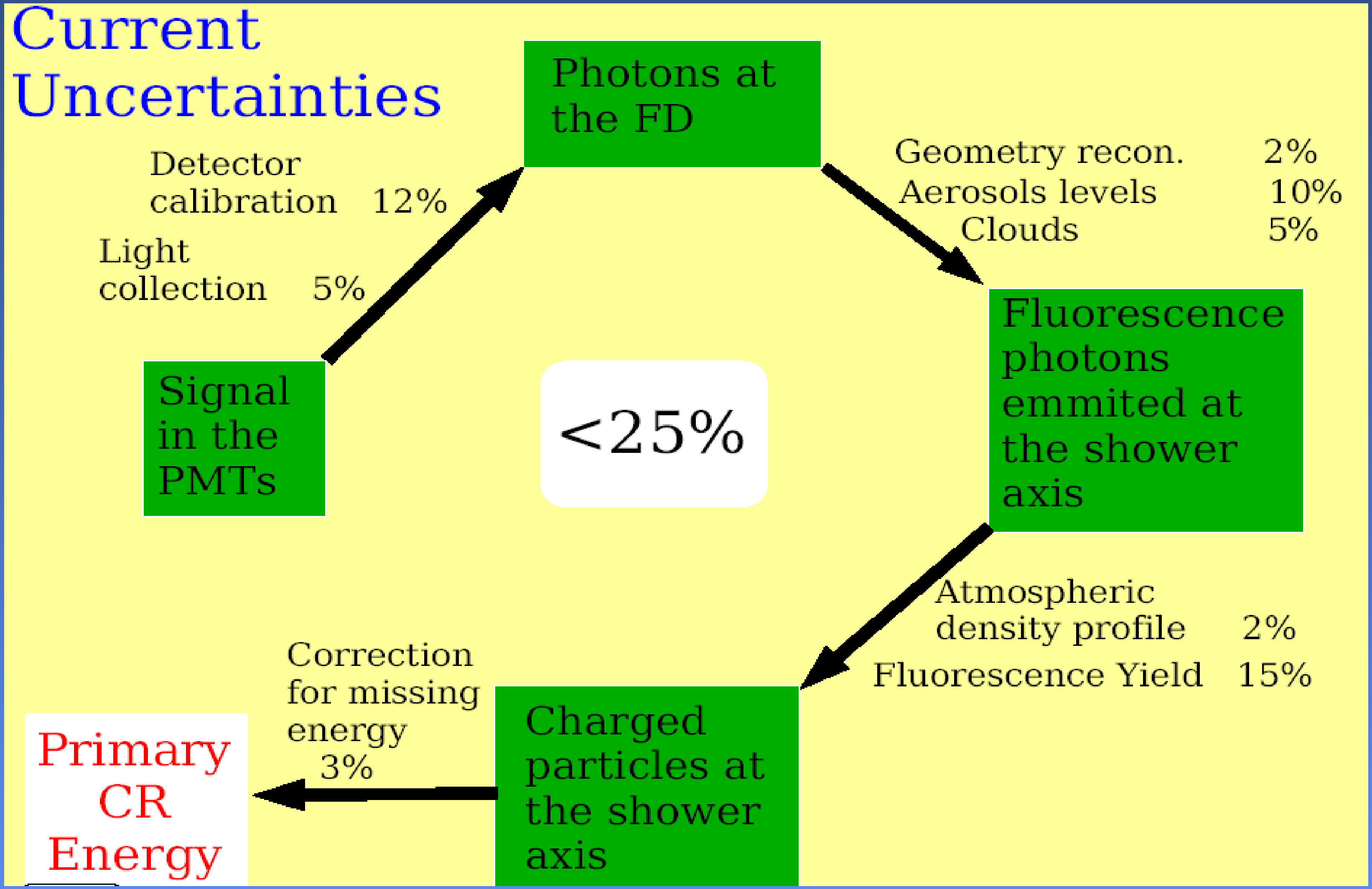


- Strict event selection:
  - tracklength >350g/cm^2
  - Cherenkov contamination<10%
- Obtain converter:

$$E / EeV = 0.16 \times \left(\frac{S(1000)/VEM}{CIC(\theta)} \right)^{1.06}$$

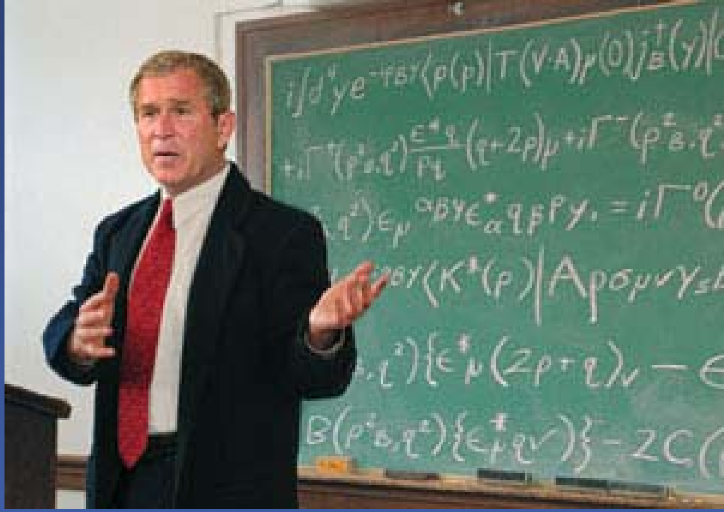
- **Note: systematic error grows when extrapolating this rule to 100 EeV!**

Systematic Errors in the FD(Hybrid) Energy Normalization



Auger E is highly correlated with HiRes E!

Summary of procedure

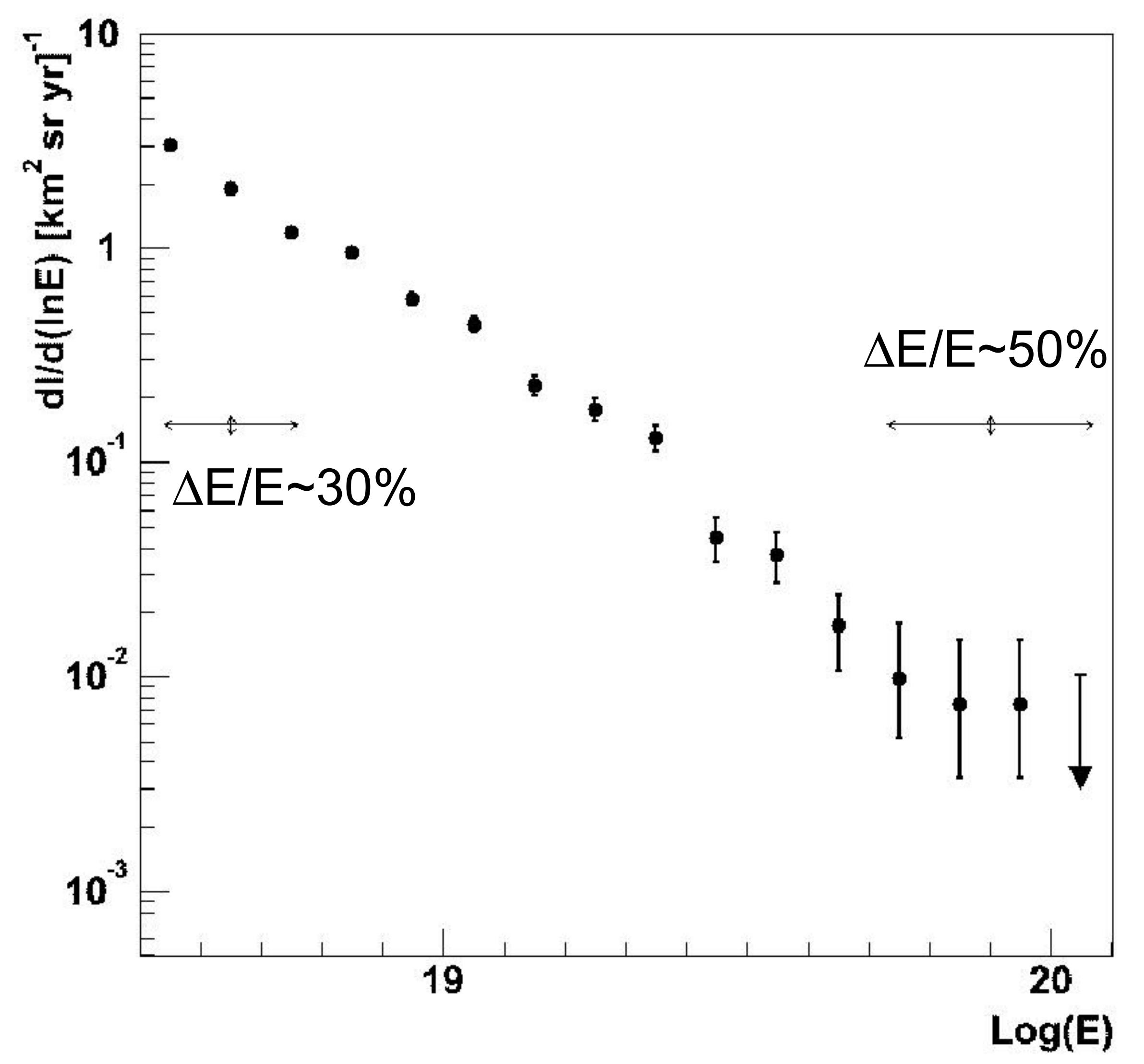


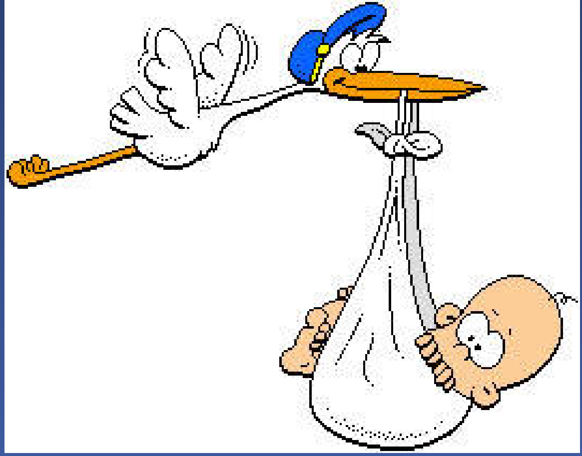
- **Reconstruct the ground parameter S(1000)**
- **Correct for the zenith angle dependence by converting S(1000) to S38 using the measured CIC curve.**
- **Convert S38 to Energy using the correlation determined with hybrid data**

Tank signals → S(1000) → S38 → Energy

Each step is empirically determined!

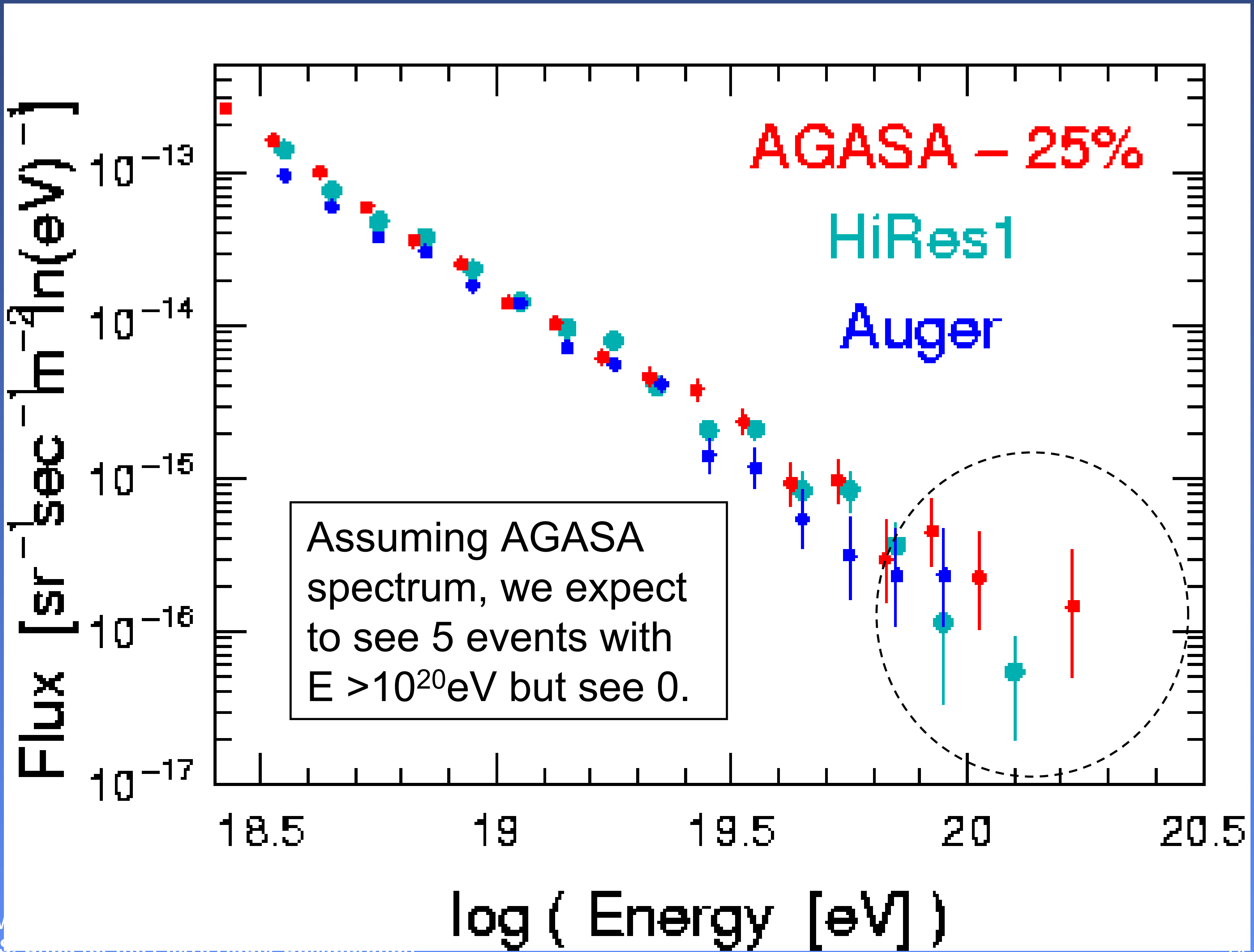
The Auger Southern Sky Energy Spectrum (SD data)





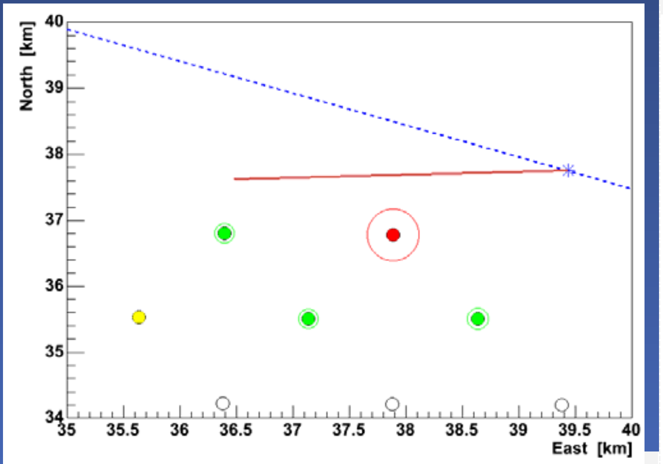
- dN/d(lnE) = E*dN/dE
- Errors on points are Statistical only
- Systematic errors are estimated at two energy regions
  - Energy measurement (horizontal)
  - Exposure determination (vertical)

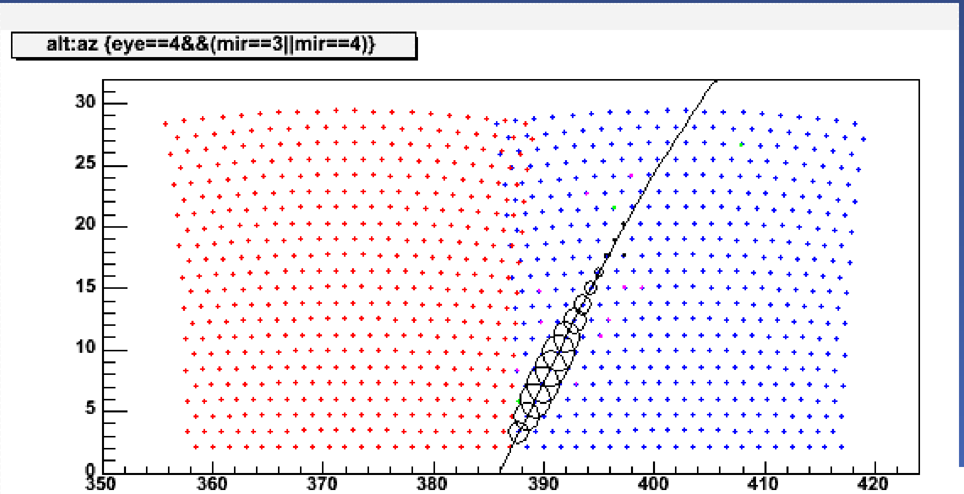
Comparison with HiRes1 Mono, AGASA (E-25%)

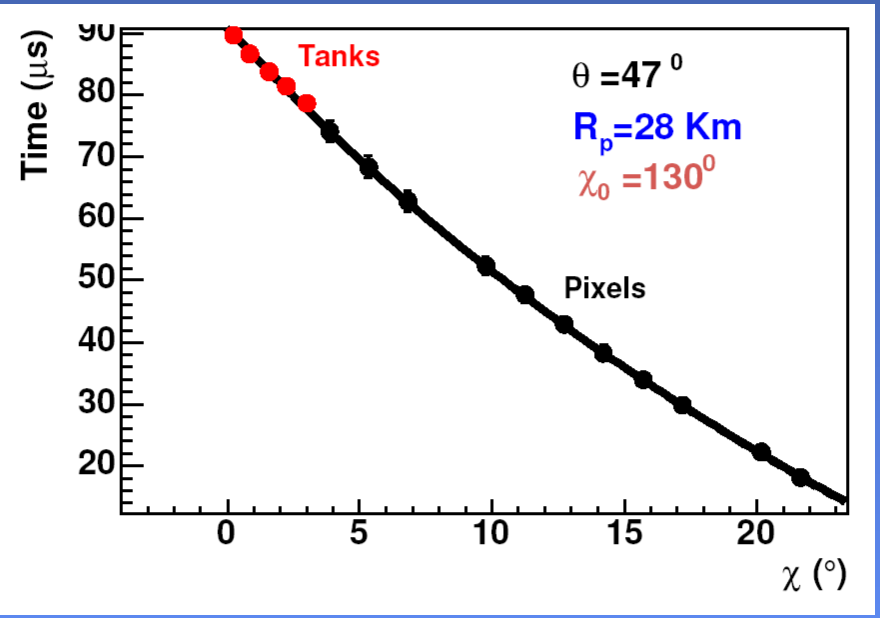


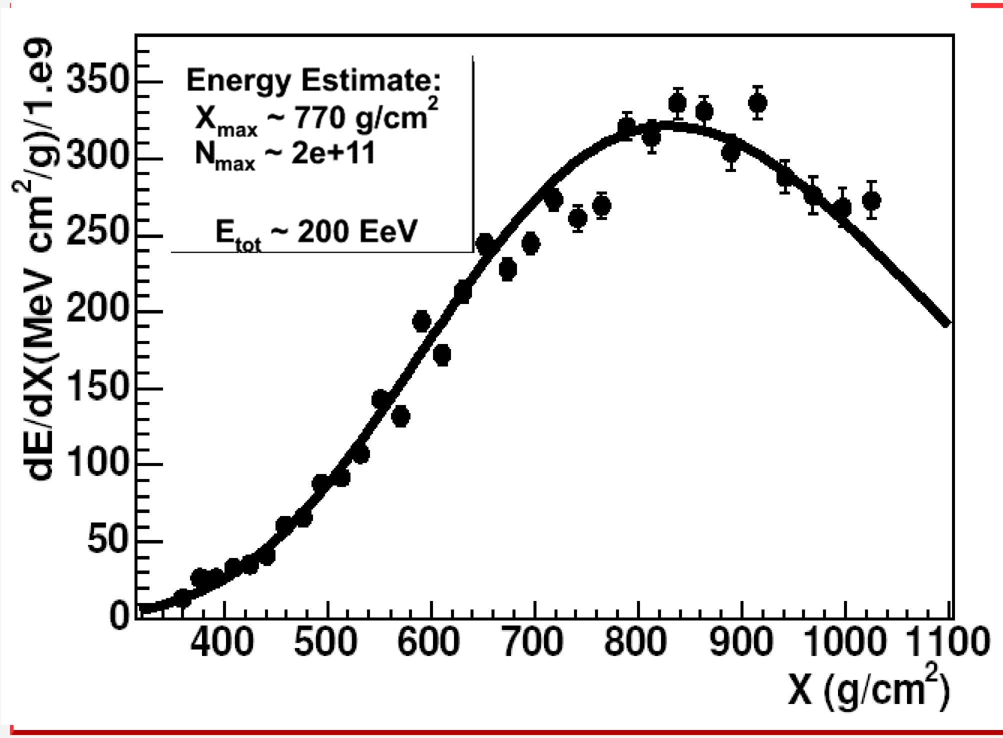
Our Highest Energy Event E_{FD}~2 10^{20}eV

Landed just outside the array, so not used in SD spectrum!

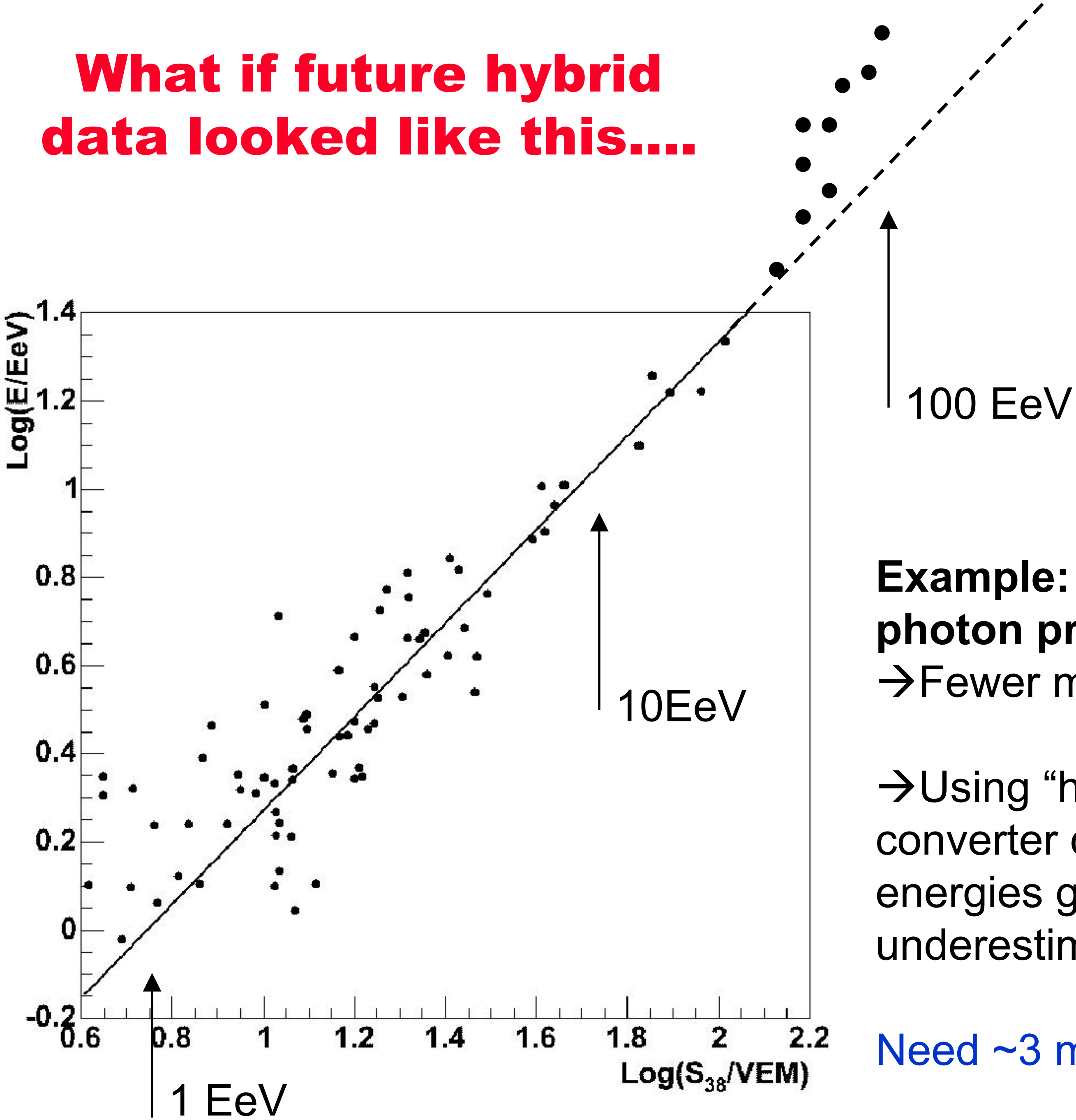








What if future hybrid data looked like this....



Example: transition to photon primaries at high E
→Fewer muons in the shower.

→Using "hadronic" energy converter derived from lower energies gives a 50% underestimate of the energy

Need ~3 more years of data…

Summary and Future Plans

- **With only 25% of a full Auger-year exposure, we have already defined our empirical spectrum analysis strategy and produced our first "model-independent" spectrum**

- **The energy converter is based on the average "hadronic" composition of cosmic rays at lower energies**
  - **Need more hybrid events to study composition**
    - ***(3 years with full observatory)***

- **To do:**
  - ***Get high statistics transGZK spectrum***
  - ***Measure UHE photon flux to test models of top-down production***
  - ***Investigate changes of mass composition with energy.***
  - ***Explore feasibility of CR astronomy with 2x sensitivity***
    - ***Clustering, BL Lac correlations (3 evts from Mrk501), GRB correlations…***
  - ***Look for UHE neutrinos in earth-skimming events***