Why are we still studying cosmic rays?

Pierre Auger Observatory: past, present, future

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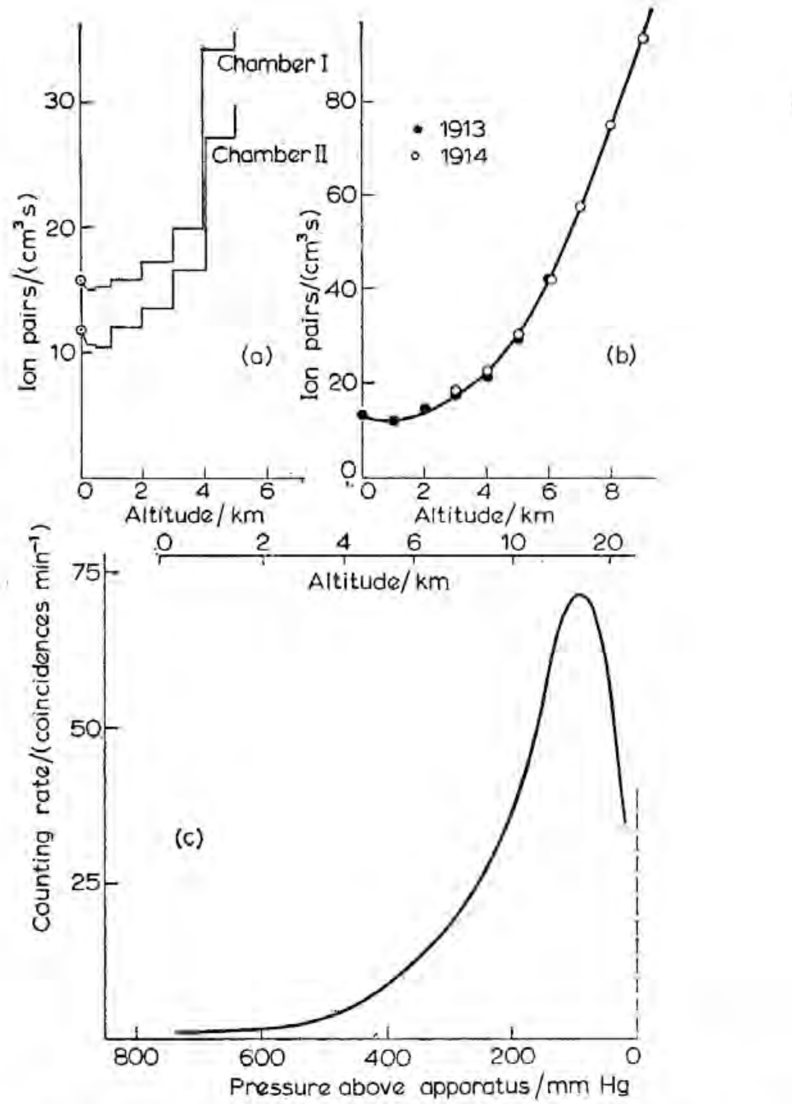
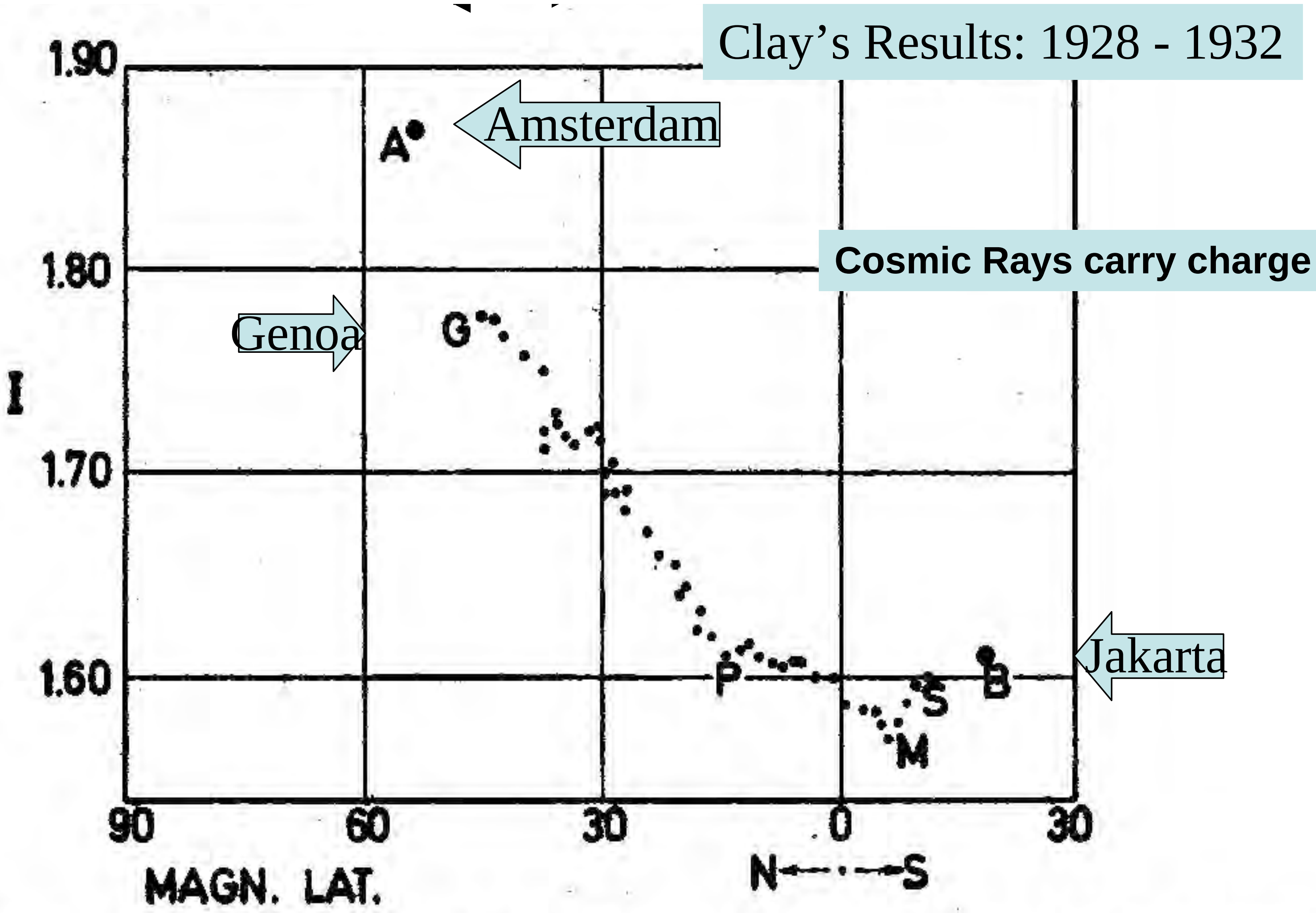
Adventures in Cosmic Ray Physics

Hess bei Ballonlandung (1912).



Altitude variation of ionisation detected by Hess and Kohlhoster (top) and Pfotzer (lower)



1. Variation of the intensity of the ultra-radiation with the Earth magnetic latitude.

Auger and LePrince-Ringuet sailed between Le Havre and Argentina in 1933

Why are we still searching for the origin of cosmic rays ~ 95 years after the discovery?

Magnetic Fields are the problem:

While gamma-rays and neutrinos are ‘blind’ to magnetic fields, cosmic rays are charged particles, the nuclei of atoms.

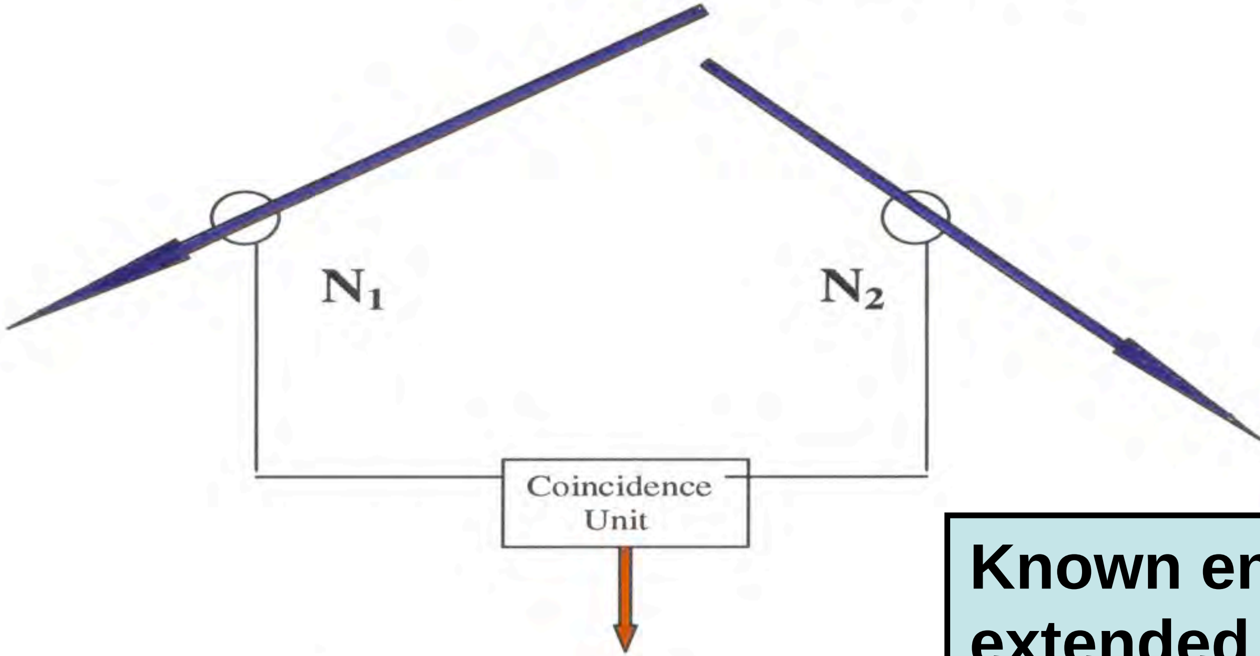
Like the drunken man’s walk!

BUT the highest energy particles are expected to be almost undeflected by the fields → cosmic ray astronomy.

But they are very rare:

~ 1 per square kilometre per century

Discovery of Extensive Air Showers: Pierre Auger (1938)



Chance Rate $= 2N_1N_2\tau$,

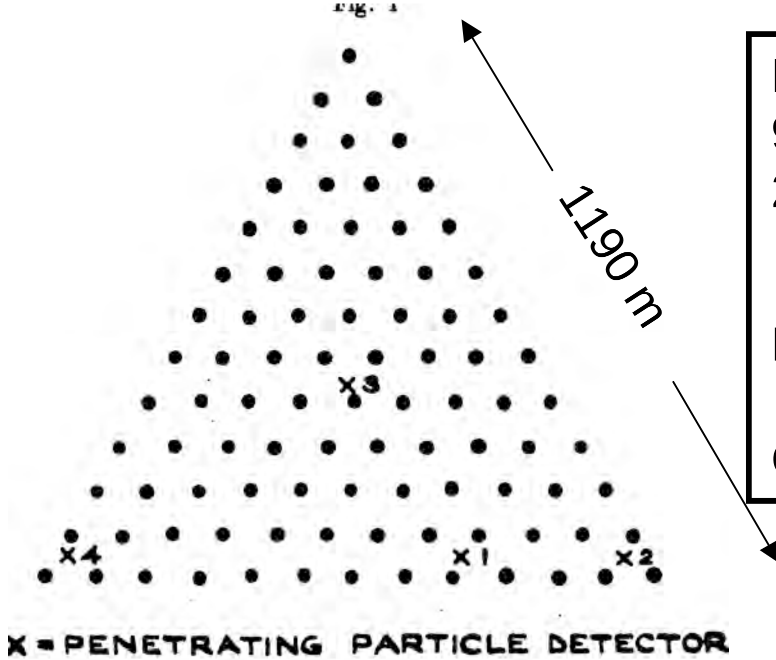
Known energy scale extended by ~10^6

Observed Rate was found to be much higher than the Calculated Chance Rate – even when the counters were as far as 300 m apart.

Large GM array at Harwell, UK in mid-1950s
91 stations
2 x 200 cm^2 and 1 x 15 cm^2

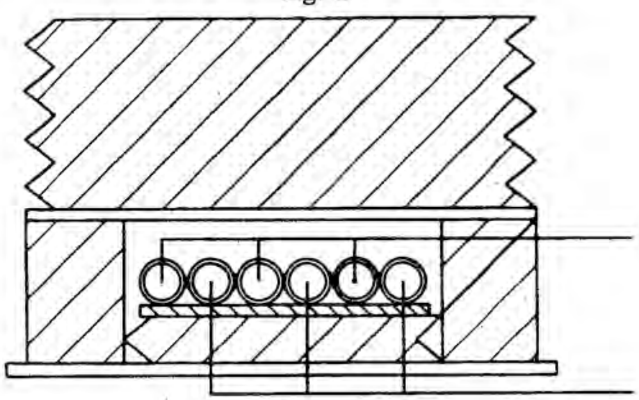
T E Cranshaw, W Galbraith, N A Porter, A M Hillas……..

Cherenkov light detection in 1953



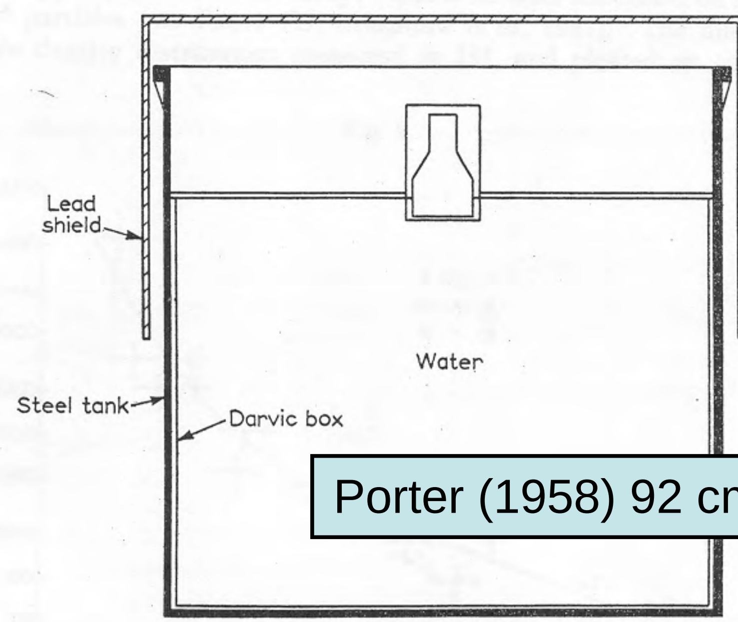
Position of shielded detectors on the array.

Fig. 2



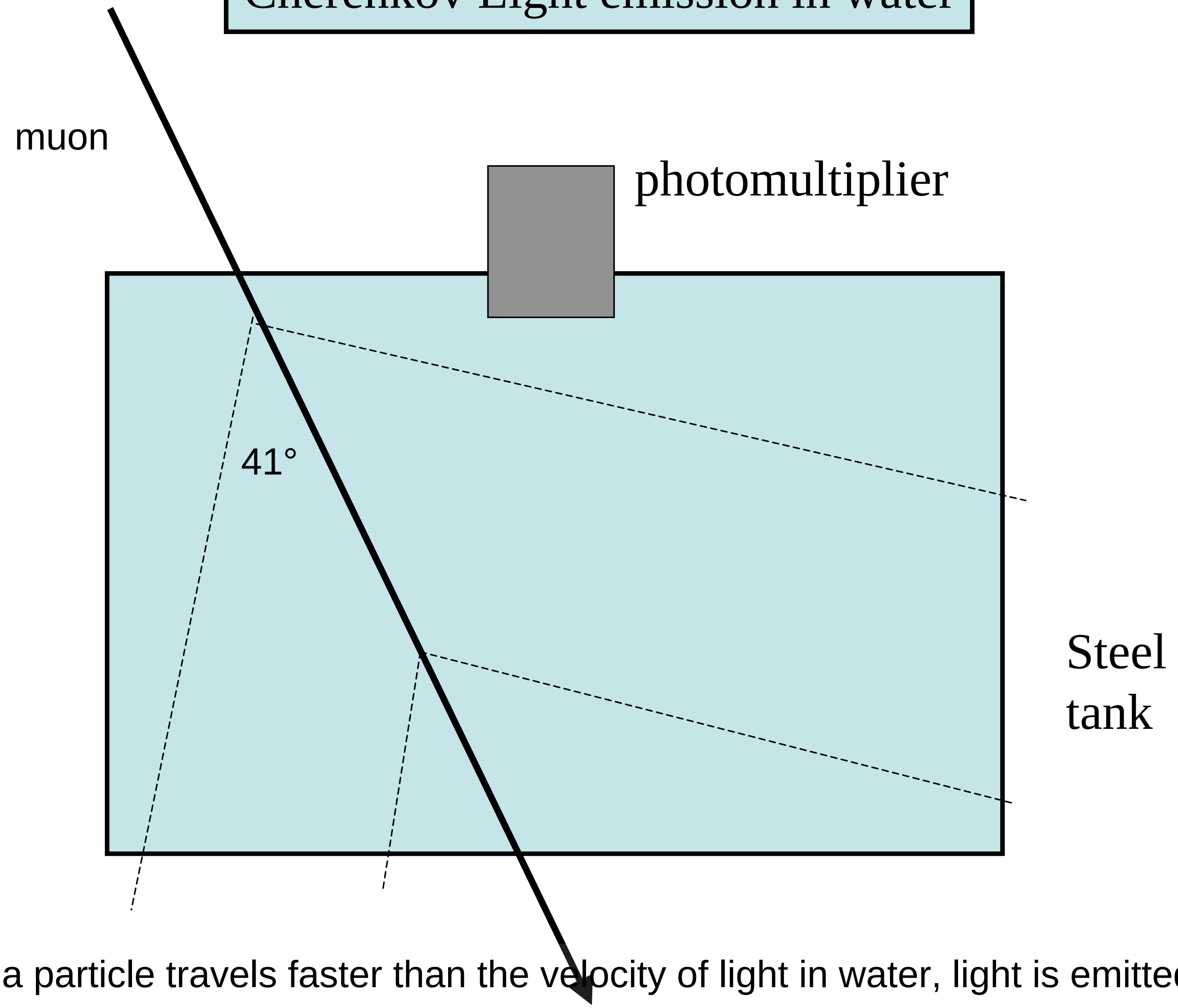
§ 2. Experimental Arrangement

Fig. 1



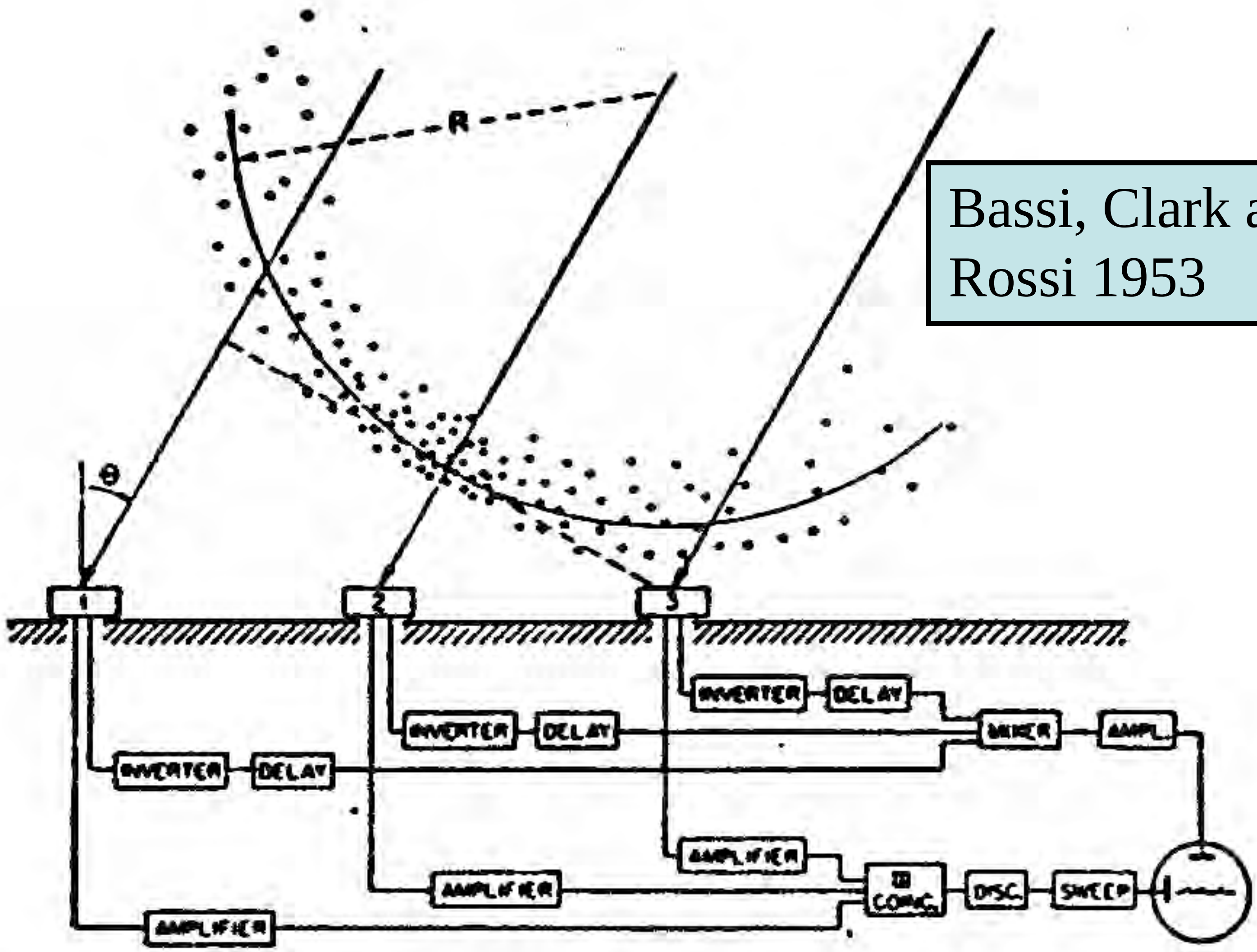
Porter (1958) 92 cm deep

Cherenkov Light emission in water



When a particle travels faster than the velocity of light in water, light is emitted

Bassi, Clark and Rossi 1953

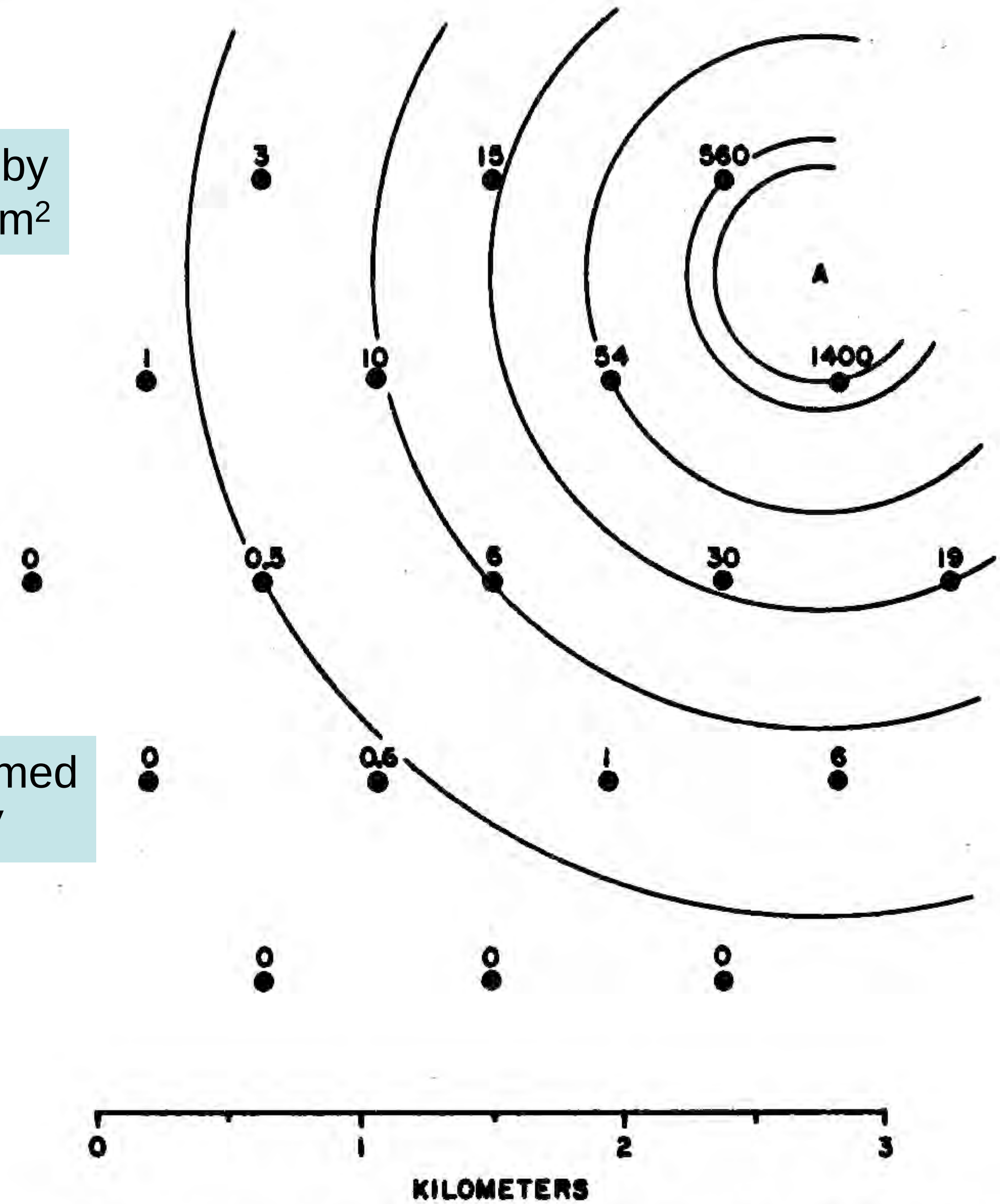


The shower particles travel in a disc – like a dinner plate – at the velocity of light: by timing when particles hit detectors, the direction can be found to about 2 degrees

The Volcano Ranch Array near Albuquerque, New Mexico

Area enclosed by detectors ~ 8 km^2

First event claimed to be > 10^{20} eV



The Volcano Ranch Detector and signals in the largest event of ~ 10^{20}

One of the early motivations for studying cosmic rays using extensive air showers was the expectation that anisotropies would be discovered

This led to the construction of larger and larger shower arrays

- **'large' meant a few square kilometres**

Volcano Ranch (US), Haverah Park (UK), SUGAR (Australia), Yakutsk (Siberia)………

1965: Discovery of 2.7 K cosmic microwave radiation

1966: Prediction of interaction of cosmic rays and CMR

Post 1966

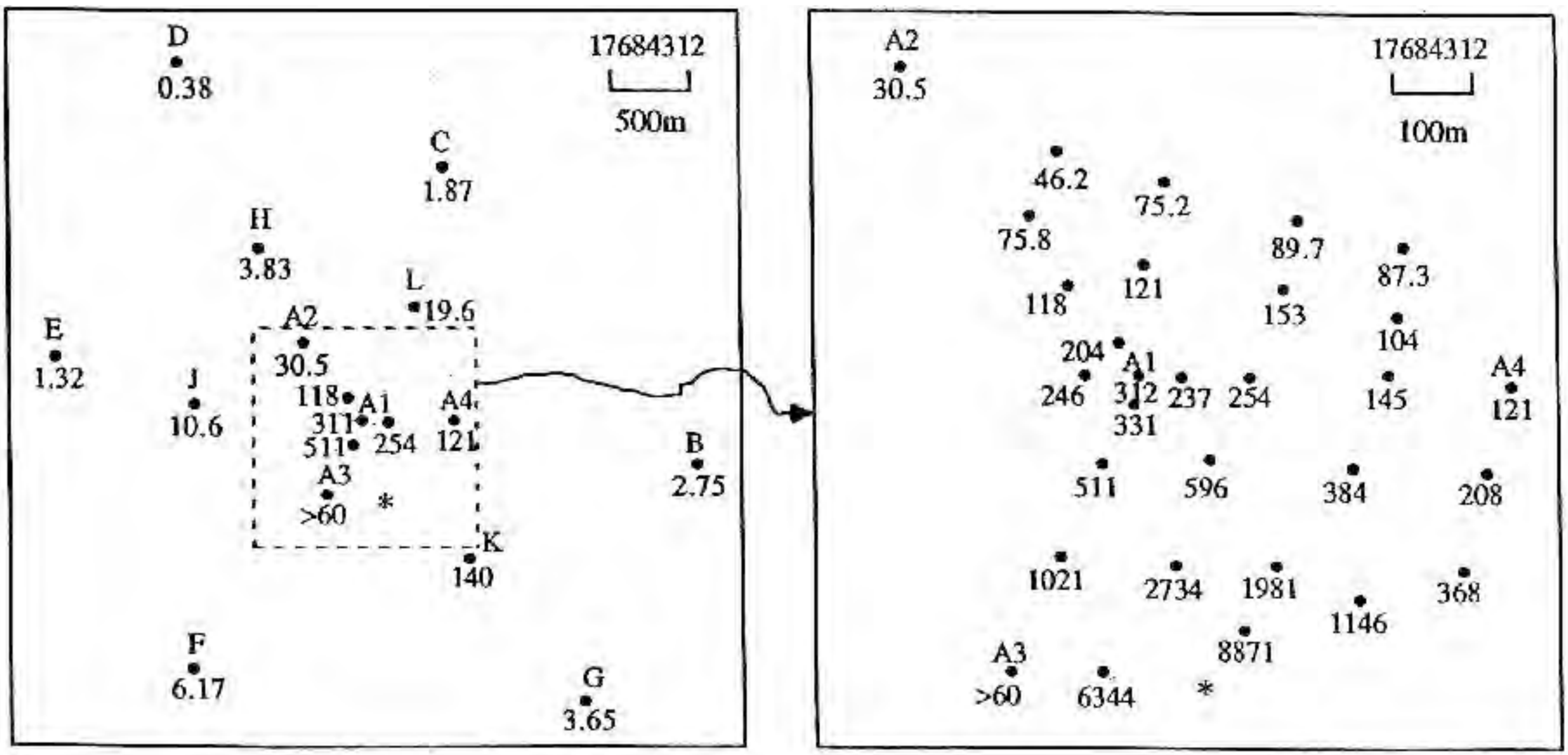
- **A primary interest became establishing the existence, or otherwise, of the Greisen-Zatsepin-Kuzmin (GZK) steepening**

$$p + \gamma_{2.7\,K} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \quad \text{or} \quad n + \pi^{+}$$

If particles are observed > 5 x 10^{19} eV, then they must be local (GZK cut-off) within ~ 100 Mpc, depending on energy

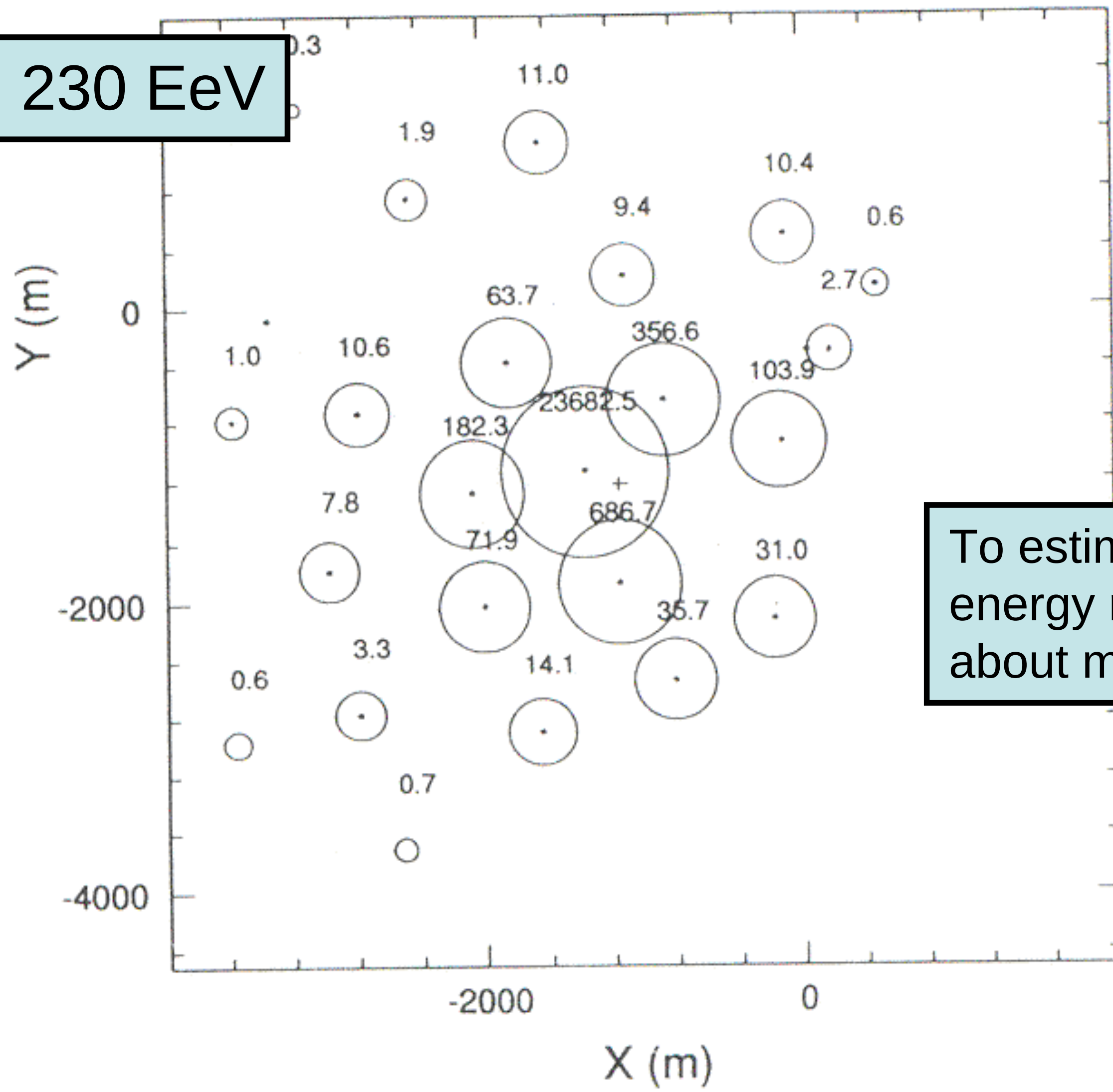
So **ANISOTROPIES** expected from **nearby sources**

Event with energy of ~ 8 x 10^{19} eV, well above GZK cut-off



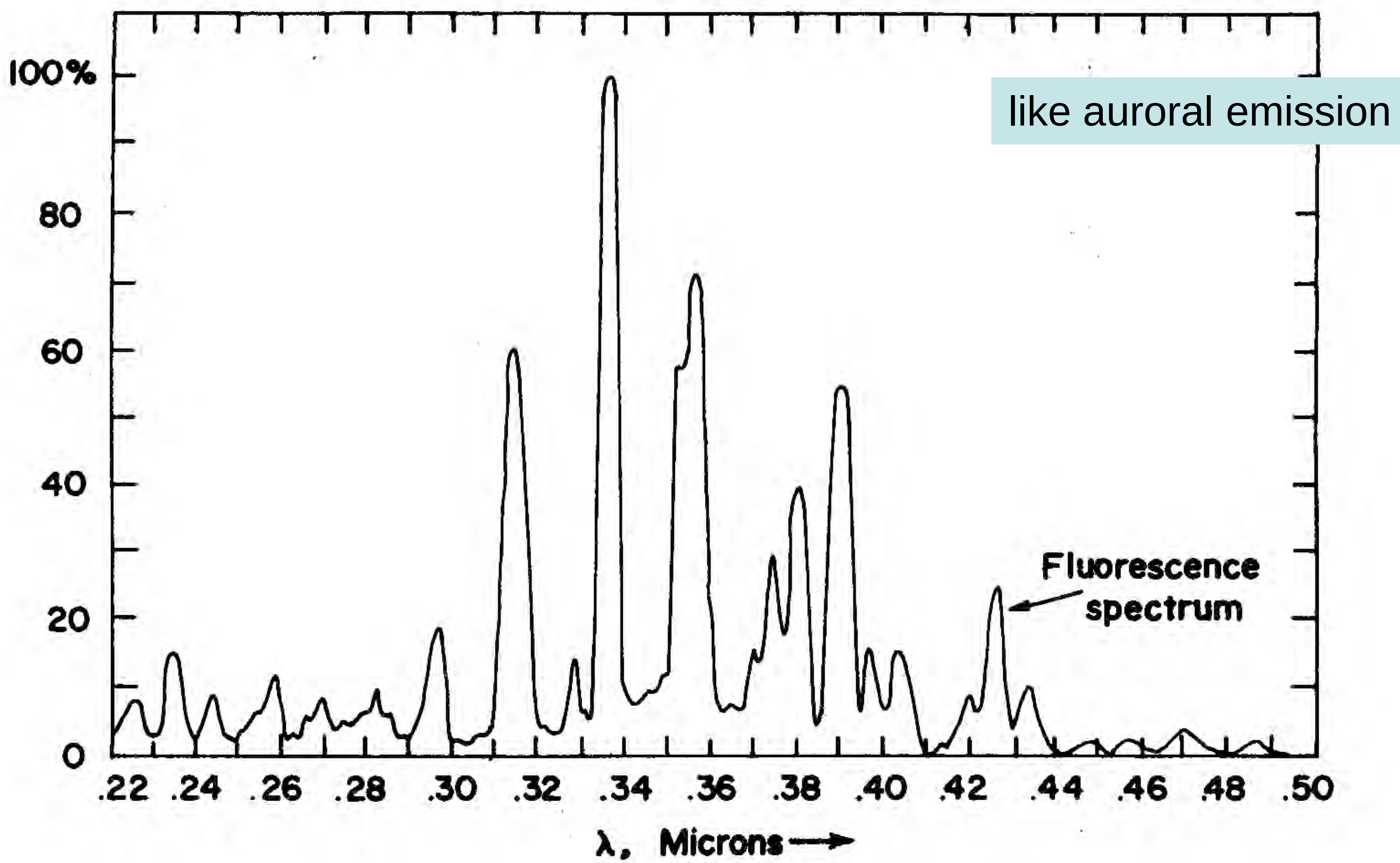
To Fly's Eye

AGASA: 230 EeV

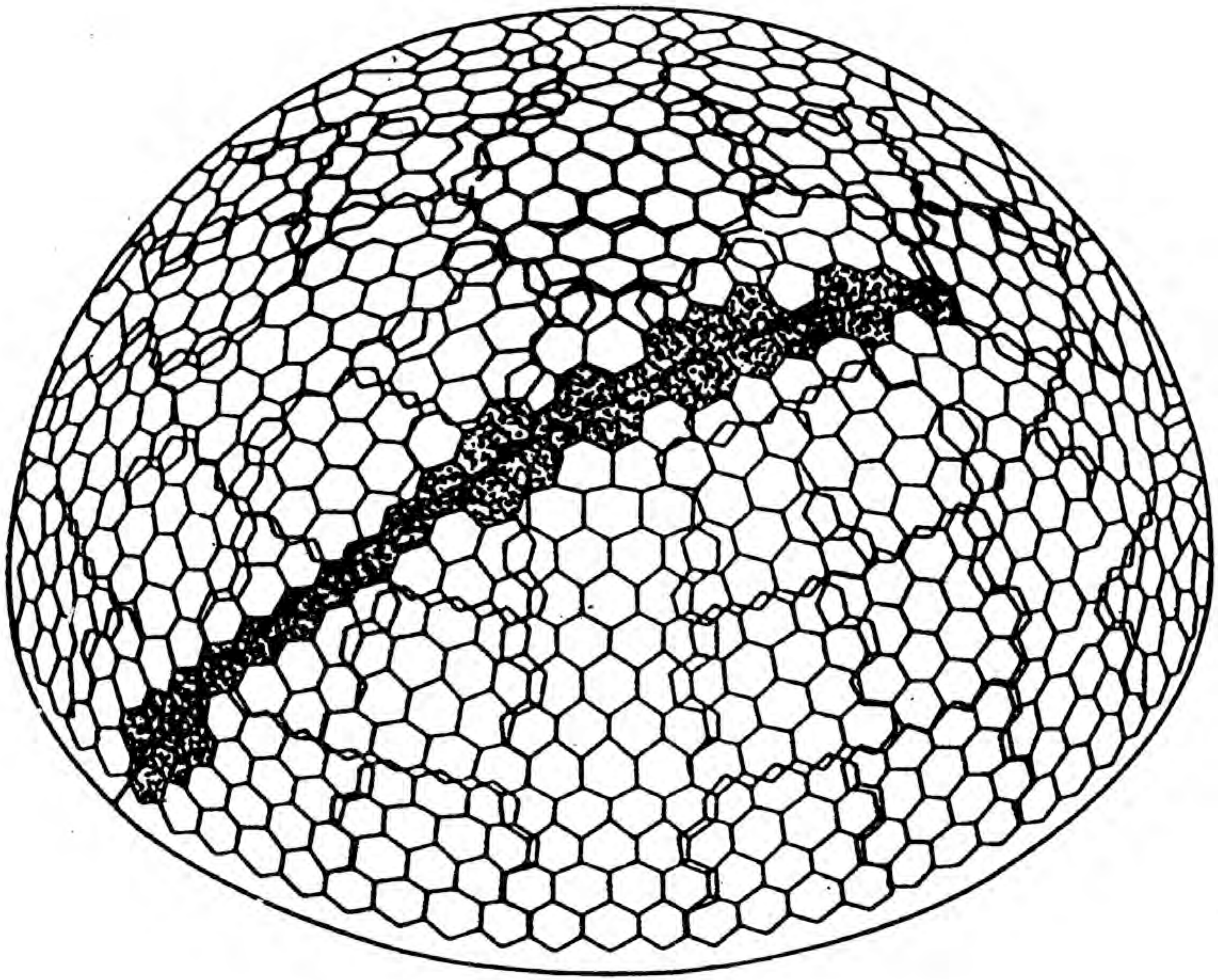


To estimate primary energy requires assumptions about models and mass

FIG. 1. Map of the density distribution of the giant EAS. The radius of each circle represents the logarithm of the density at each detector location. A cross shows the estimated position of the shower core.

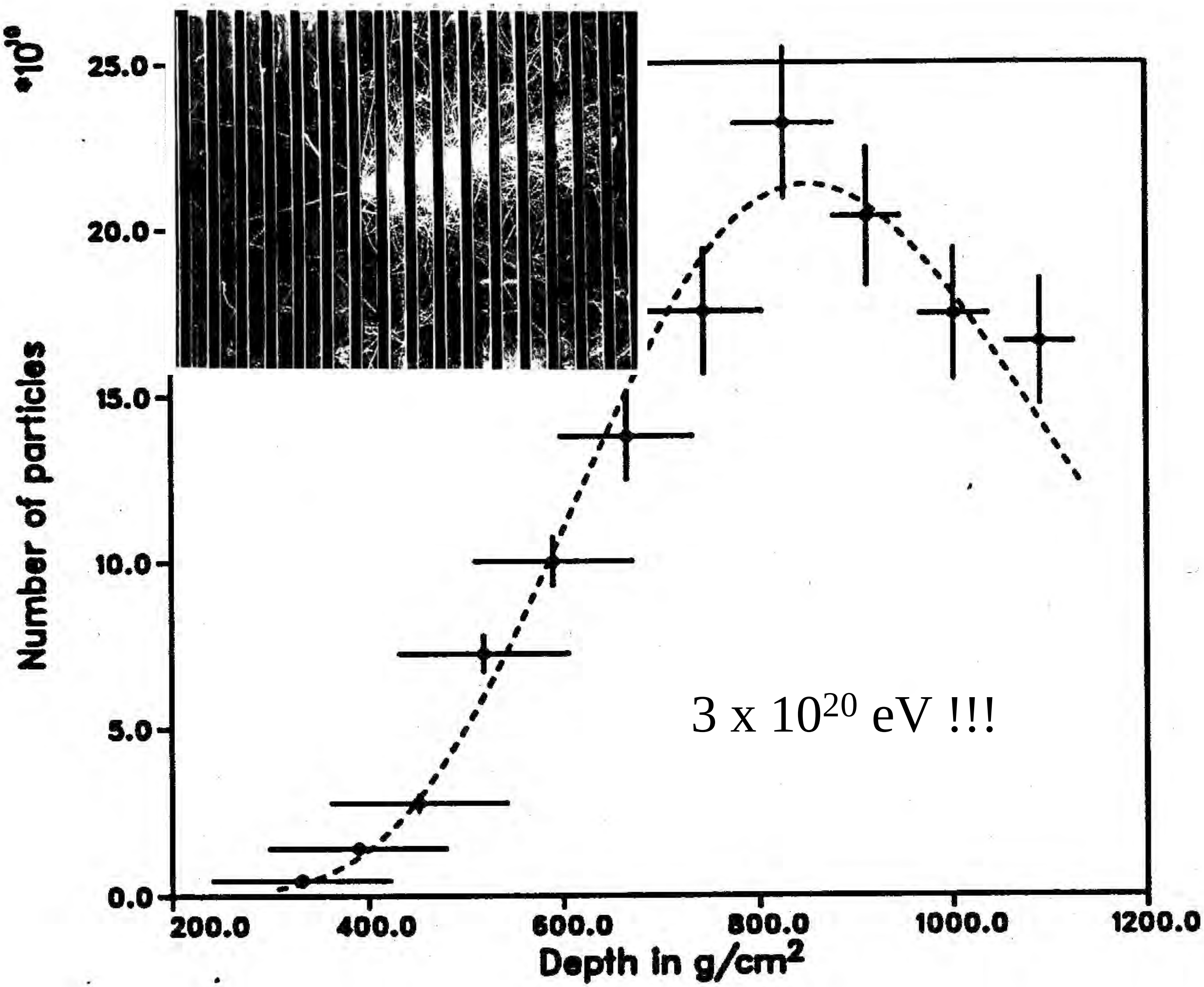


A different technique: detection of fluorescence light



Idea of Fly’s Eye Detector (University of Utah): 880 photomultipliers

$\times 10^{10}$



3×10^{20} eV !!!

RESULTS SUGGESTED

There are events beyond the GZK cut-off at 5 x 10^{19} eV

BUT

ARRIVAL DIRECTION

SEEM TO BE VERY UNIFORM

but

NEED MORE DATA

The Pierre Auger Project

A new cosmic ray observatory designed for a high statistics study of the

The Highest Energy Cosmic Rays

Using

Two Large Air Shower Detectors

Colorado, USA
(in planning)

Mendoza, Argentina
(construction underway)

ICRC August 2005
Pierre Auger Collaboration

The Auger Collaboration

A True International Partnership
No country, region or institution dominates

A Model for International Science

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

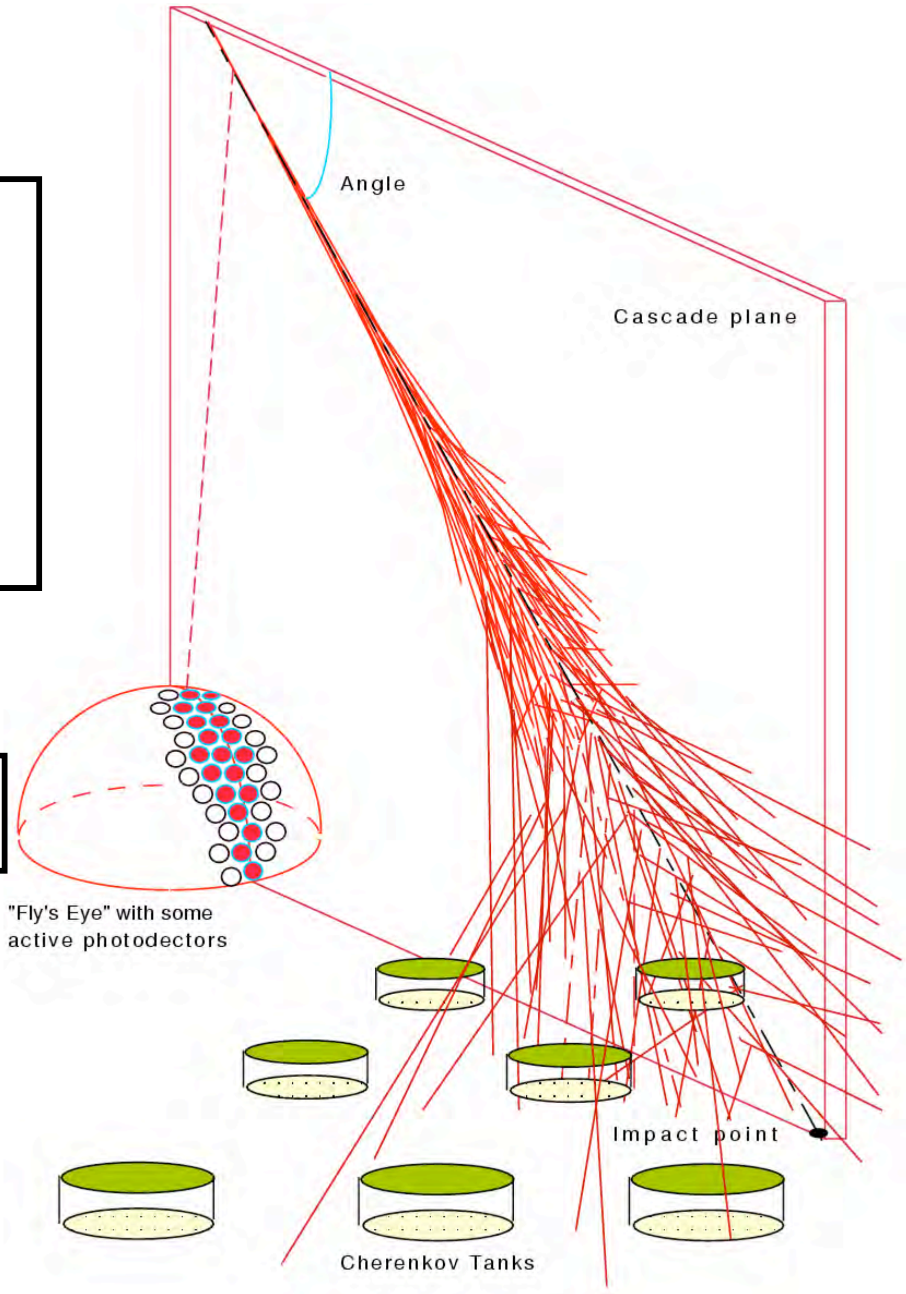
The Pierre Auger Observatory design marries two well-established techniques

The 'HYBRID' technique

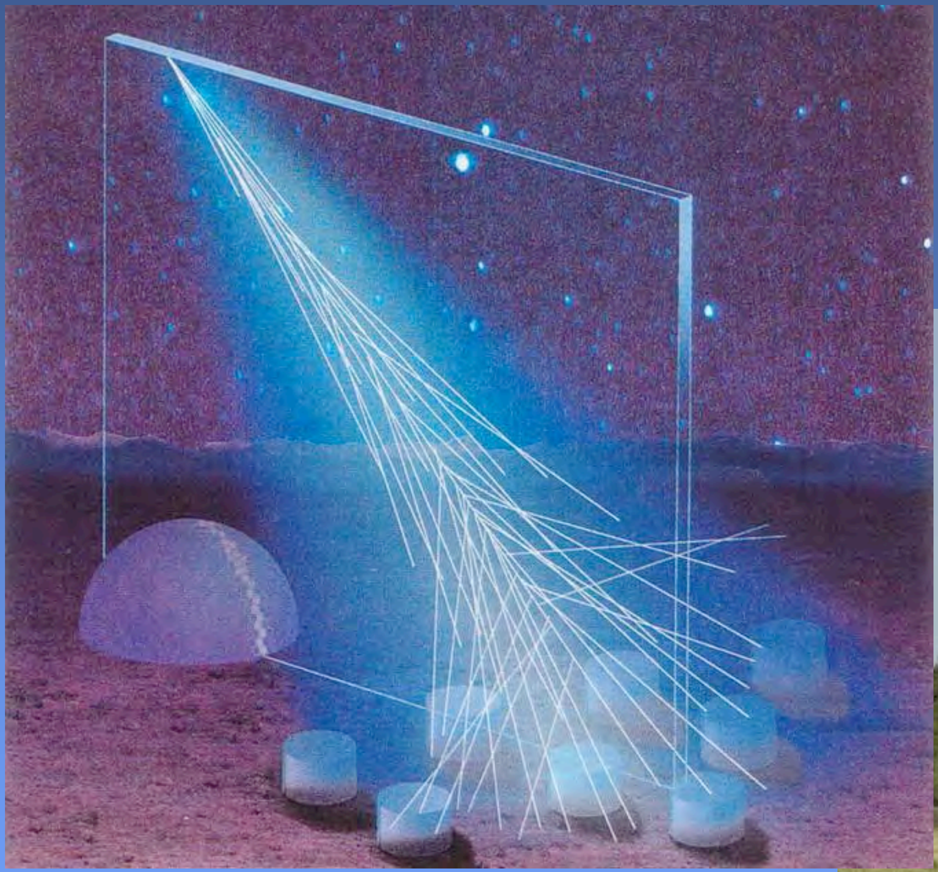
Fluorescence →

and

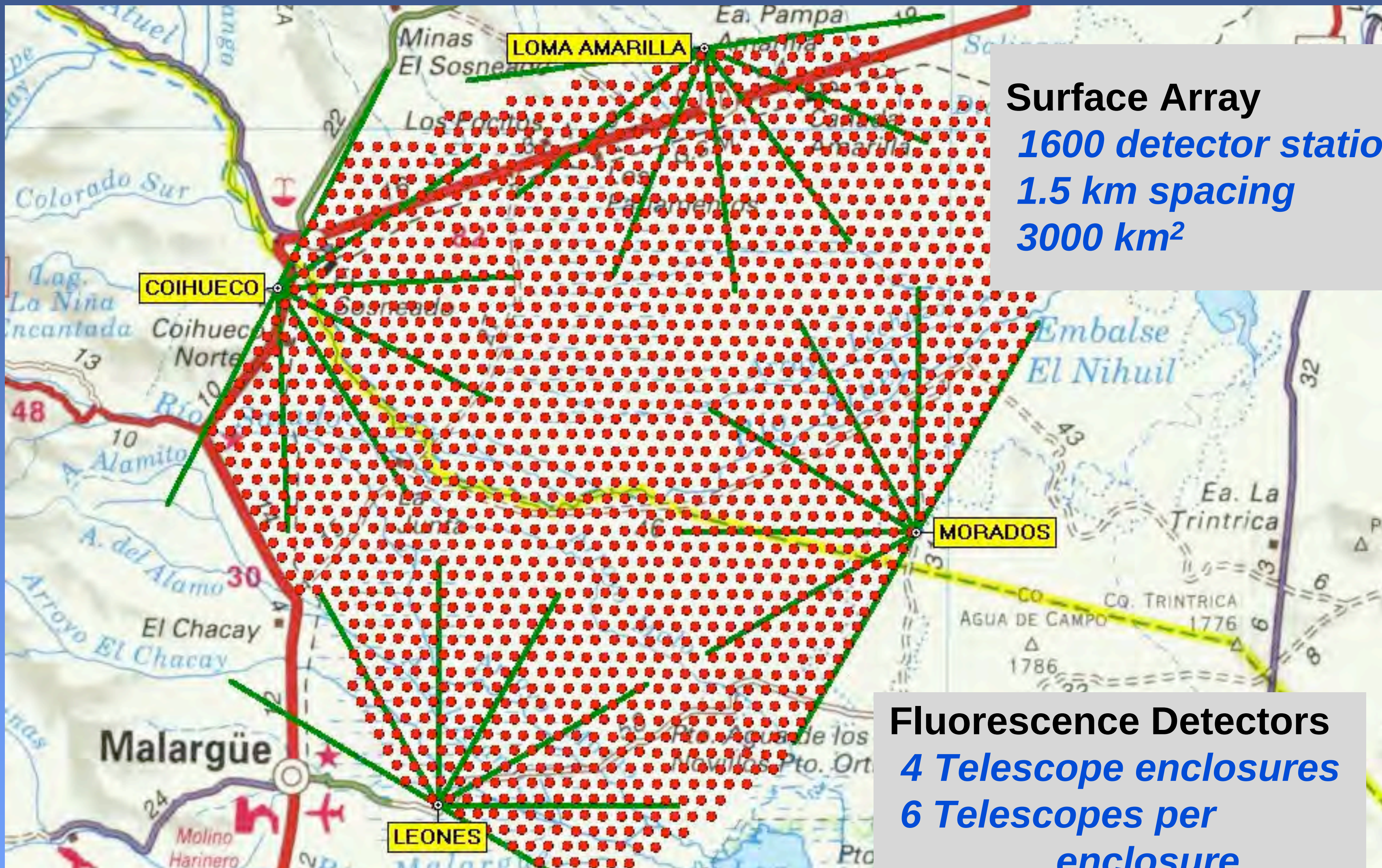
Array of water Cherenkov detectors →



The Design



The Observatory Plan



Surface Array

1600 detector stations

1.5 km spacing

3000 km²

Fluorescence Detectors

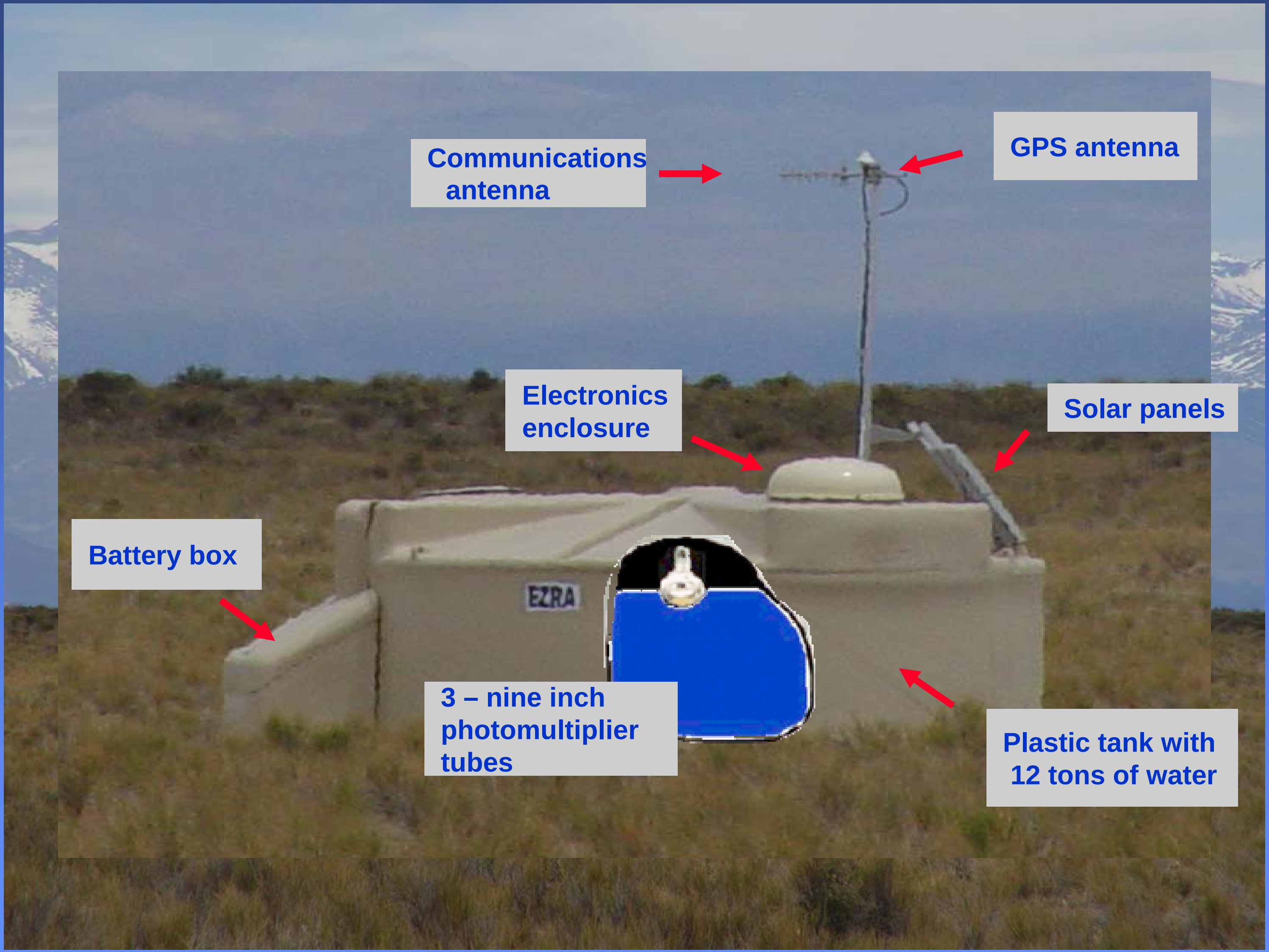
4 Telescope enclosures

6 Telescopes per enclosure

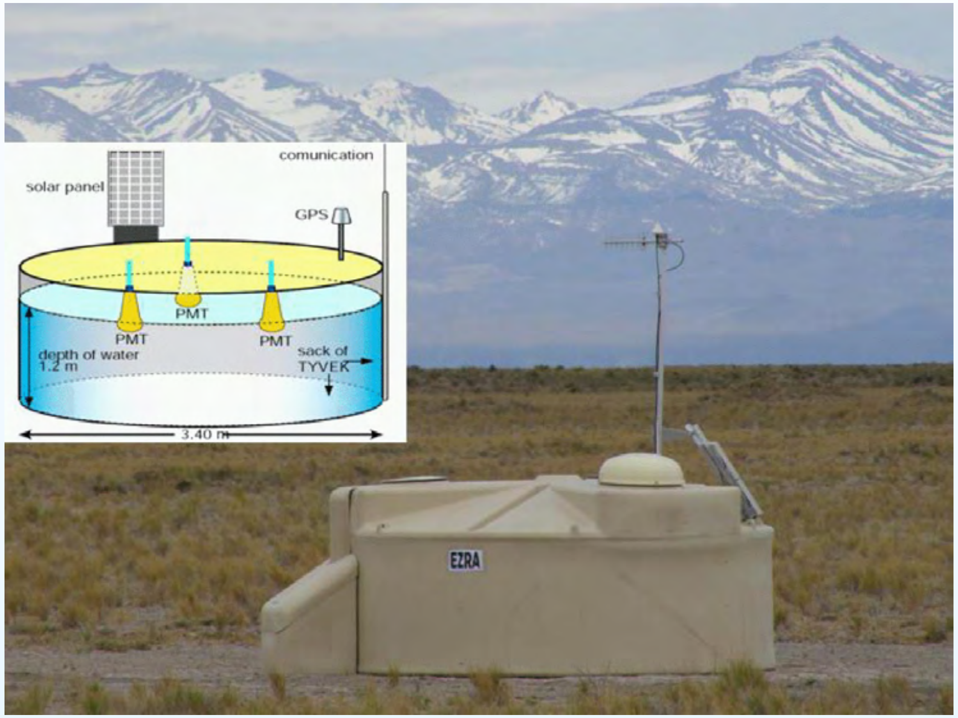
24 Telescopes total

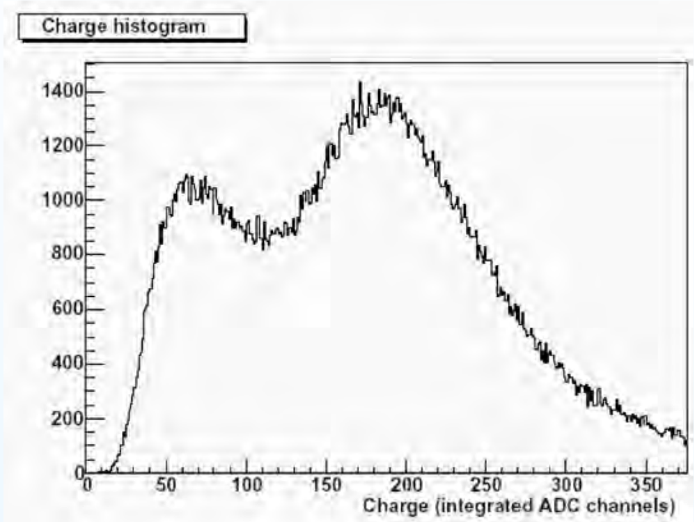
The Surface Array

Detector Station



Auger Surface Detectors (*aka SD*)





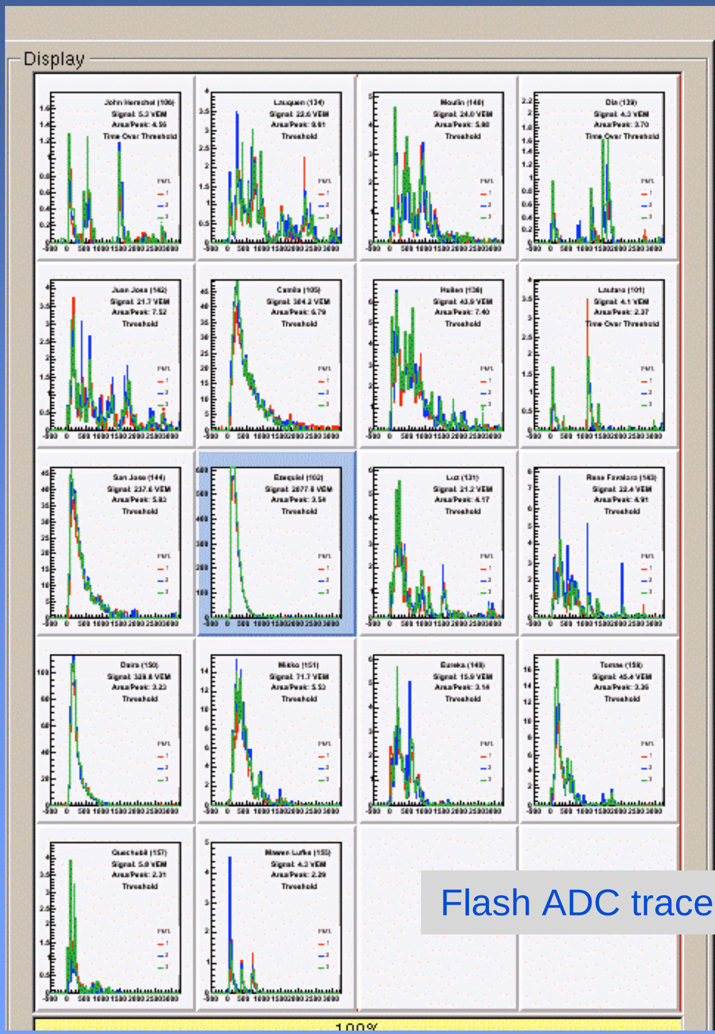
- **Left:** Photo of 1 of 1600 Auger (10m^2) surface detectors.
- **Right:** Through-going muons provide a *natural* calibration: Vertical Equivalent Muon (VEM).
- The Auger SD cosmic ray energy scale is obtained either: from the FD using hybrid events **OR** by Monte Carlo simulations (which may not model the physics at our shower energies!) For now we use the FD normalization.

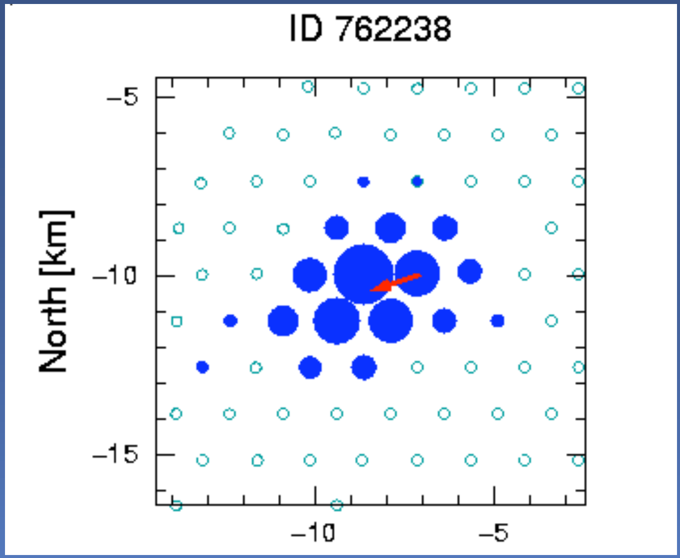
Surface Detector Progress

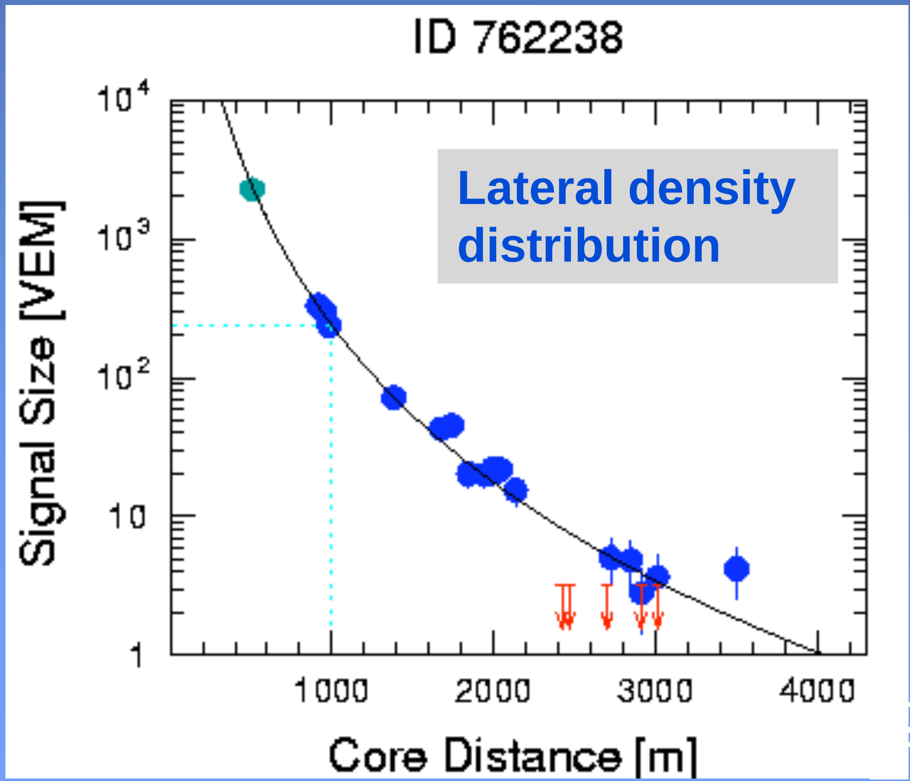
Deployment Status

Example Surface Array Event

Θ~ 48º, ~ 70 EeV

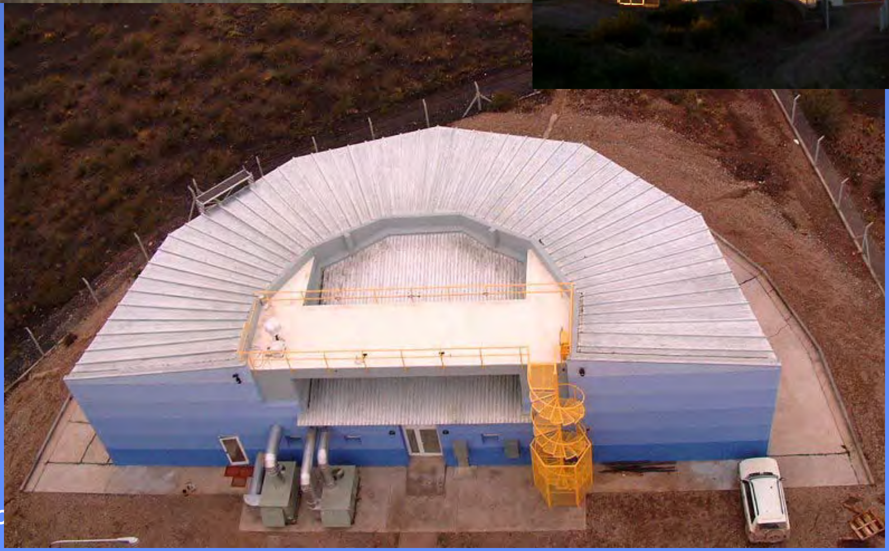




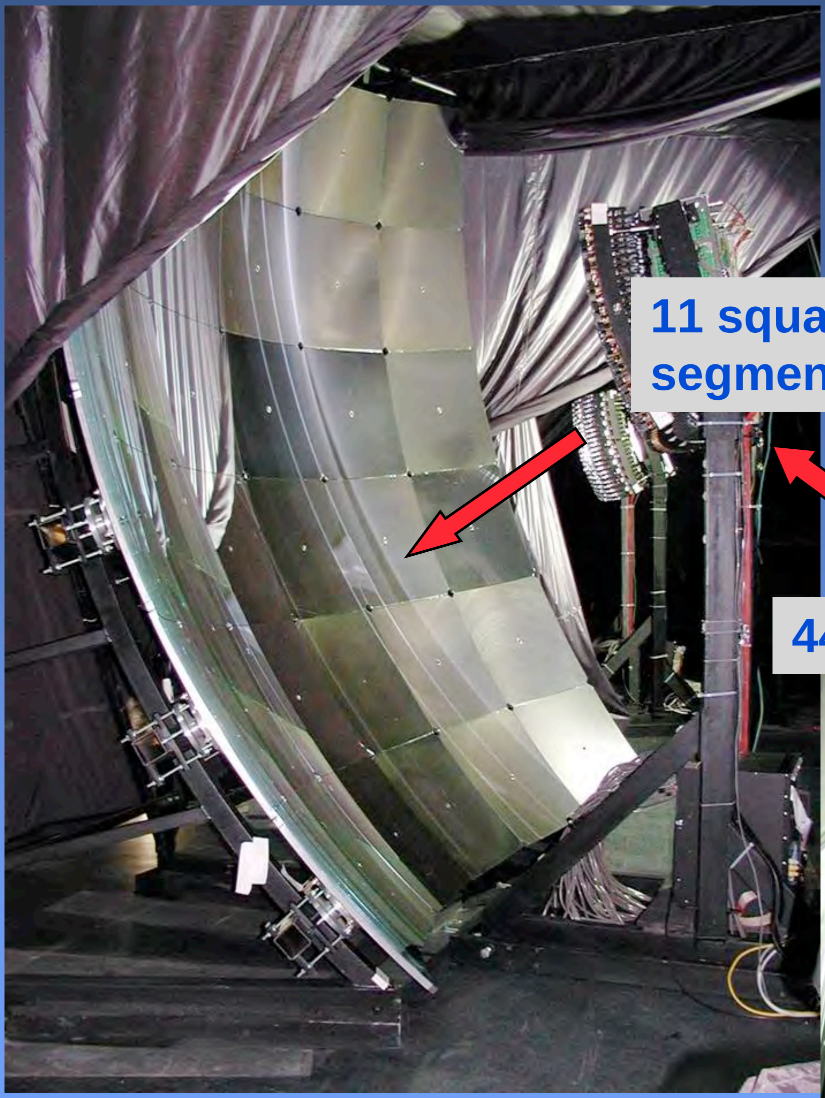


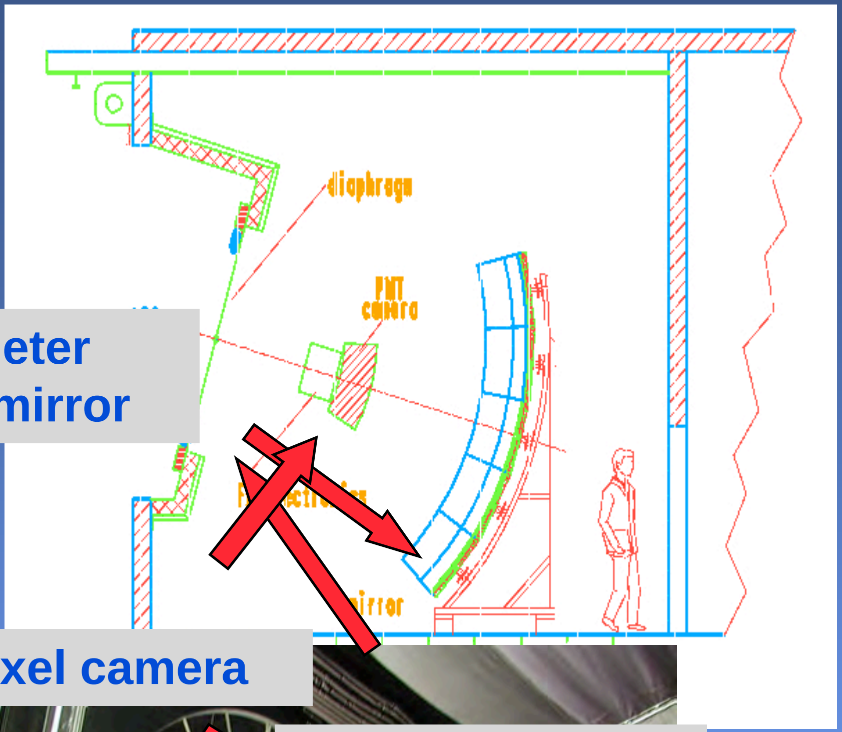
The Fluorescence Detector

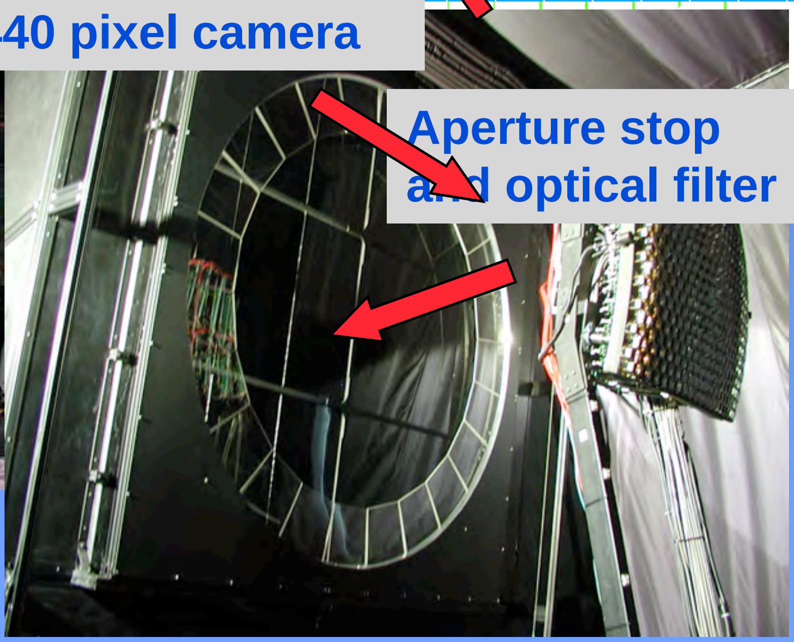
Los Leones



The Fluorescence Detector







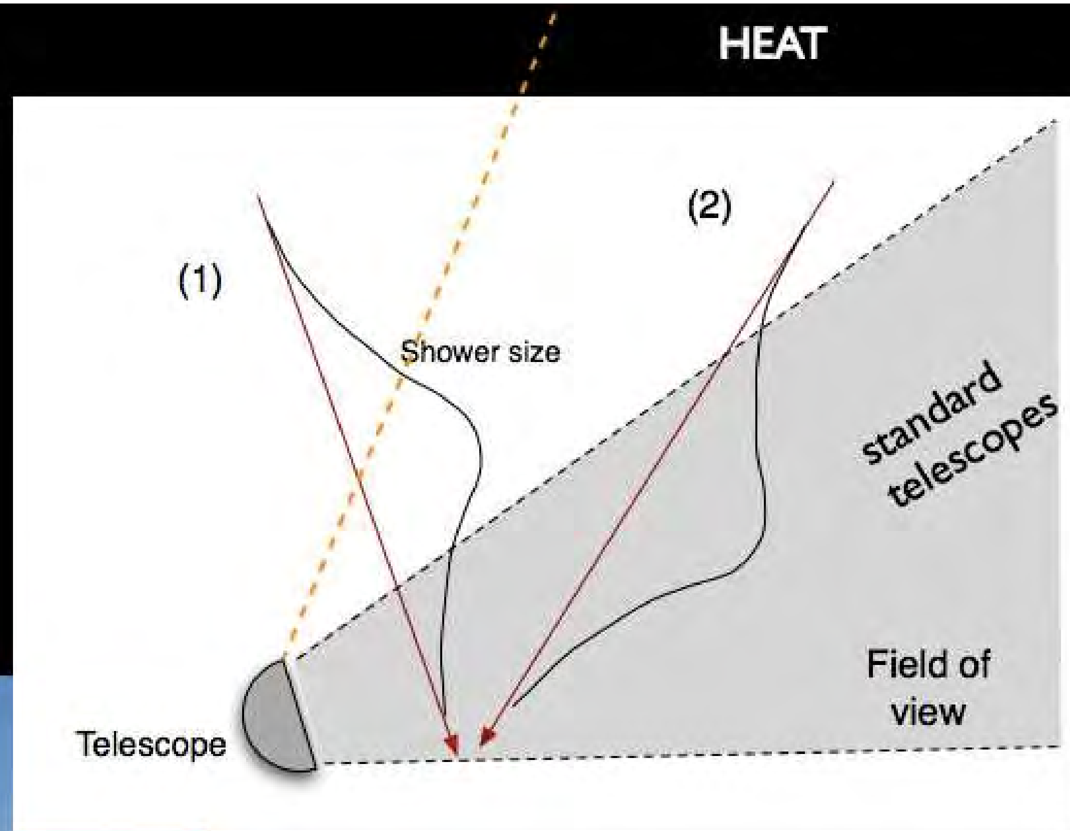
11 square meter segmented mirror

440 pixel camera

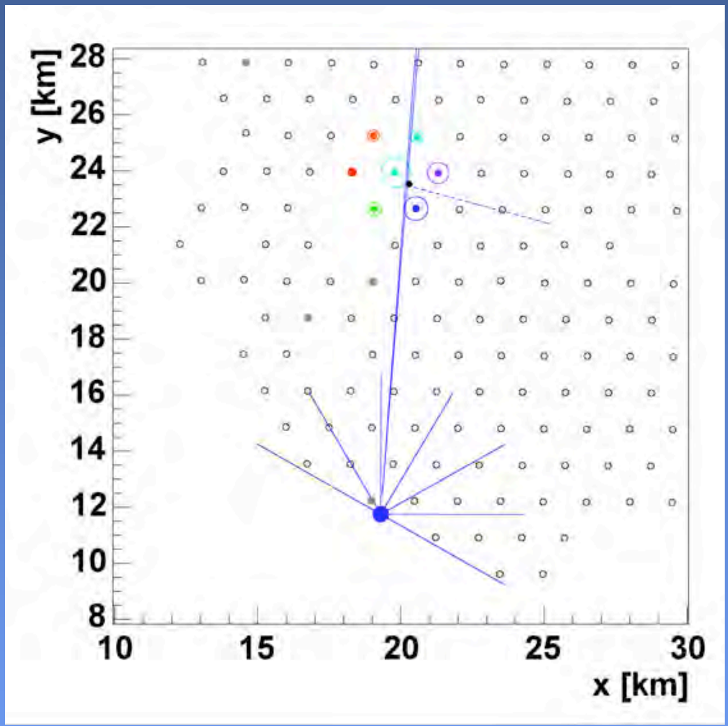
Aperture stop and optical filter

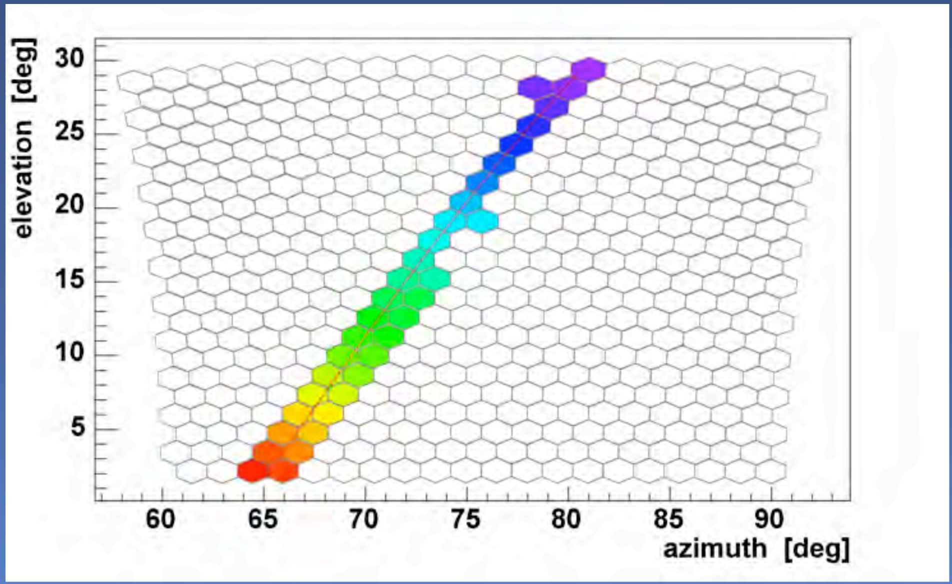
HEAT

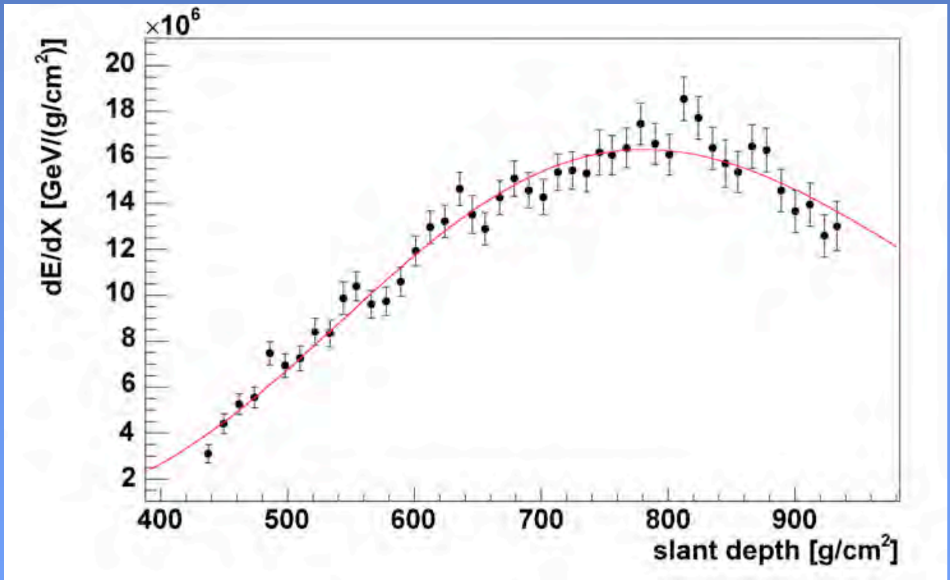
HEAT: High Elevation Auger Telescopes



Example Hybrid Event
Θ~ 30º, ~ 8 EeV



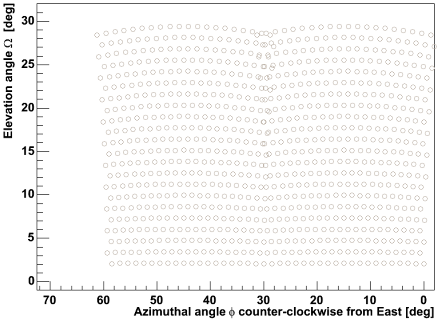




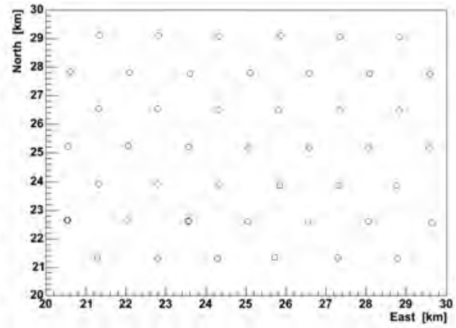
DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers



FD: Track in the sky



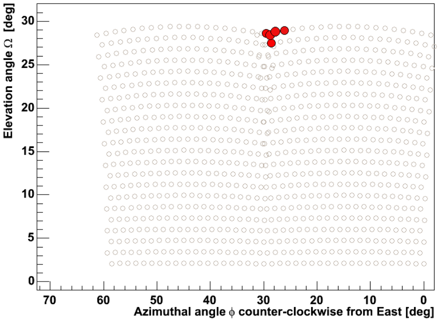
SD: Ground view

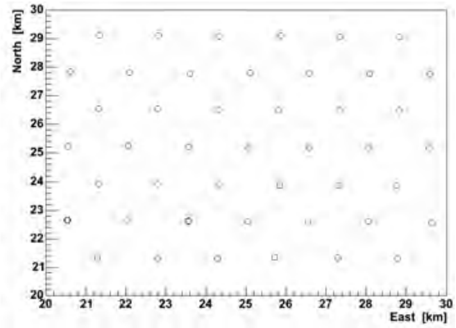
WHAT'S A "HYBRID" EVENT? (SLIDE 8)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





FD: Track in the sky

SD: Ground view

DEFINITION

`Simultaneous` detection in the sky **and** at ground

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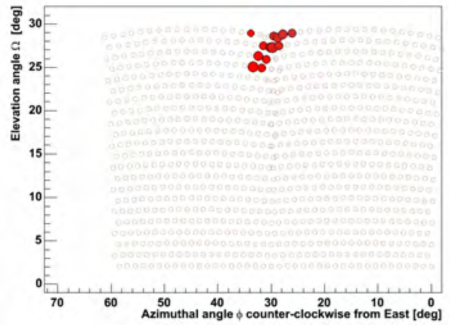
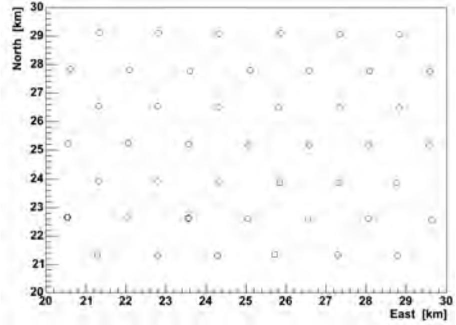


FD: Track in the sky



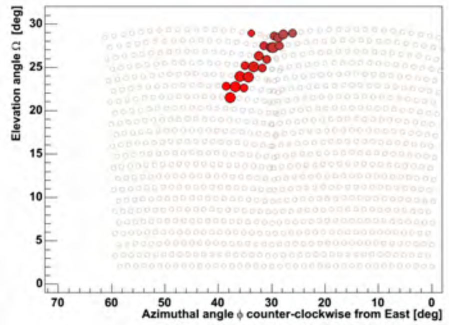
SD: Ground view

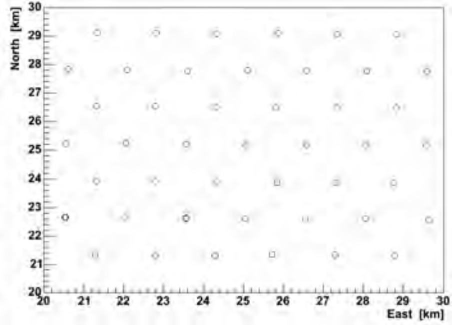
What's a "Hybrid" Event? (slide 10)

Definition

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers





FD: Track in the sky

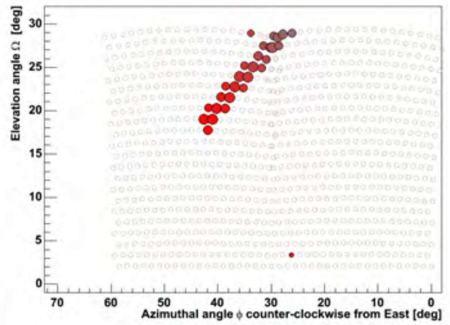
SD: Ground view

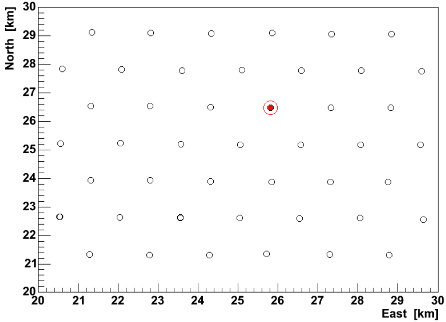
What's a "Hybrid" Event? (slide 11)

Definition

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers





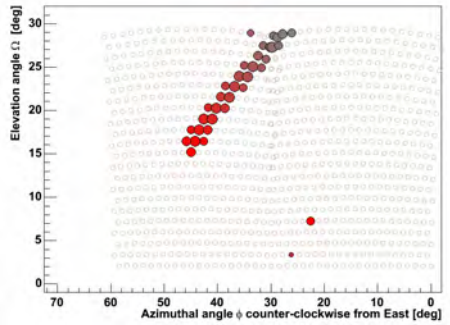
FD: Track in the sky

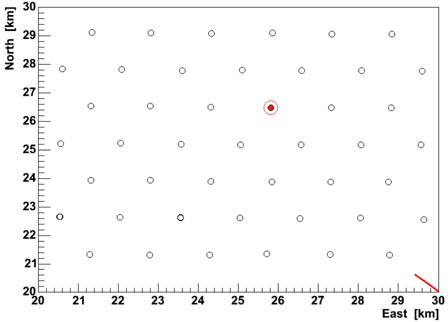
SD: Ground view

DEFINITION

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers





FD: Track in the sky

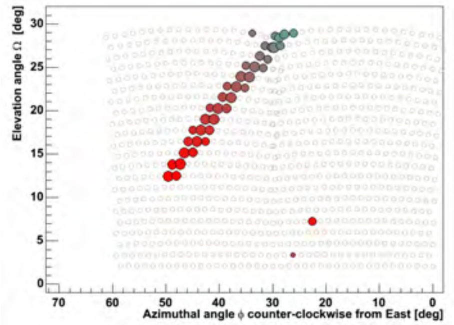
SD: Ground view

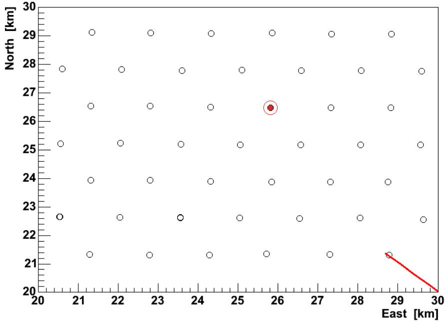
WHAT'S A "HYBRID" EVENT? (SLIDE 13)

DEFINITION

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers





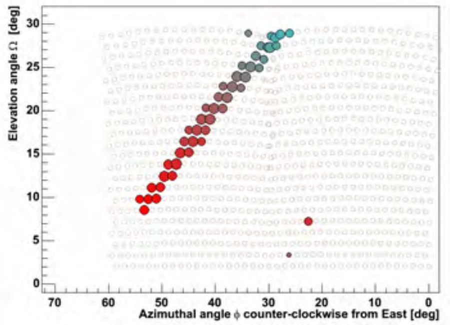
FD: Track in the sky

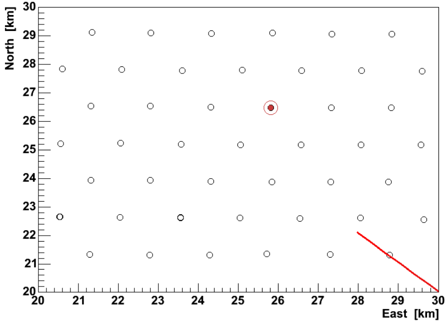
SD: Ground view

DEFINITION

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers





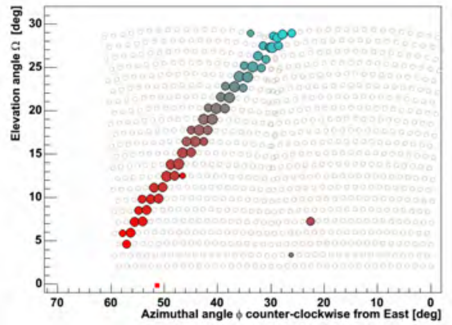
FD: Track in the sky

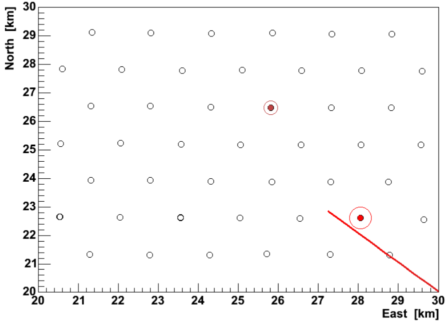
SD: Ground view

DEFINITION

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers





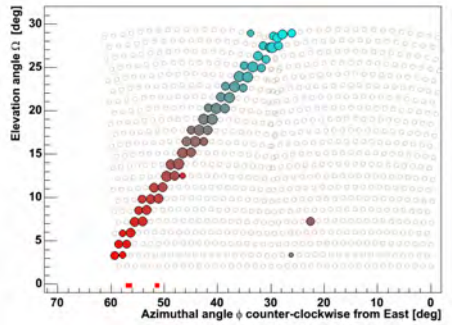
FD: Track in the sky

SD: Ground view

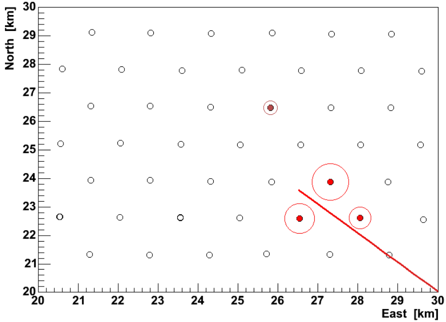
DEFINITION

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers



FD: Track in the sky



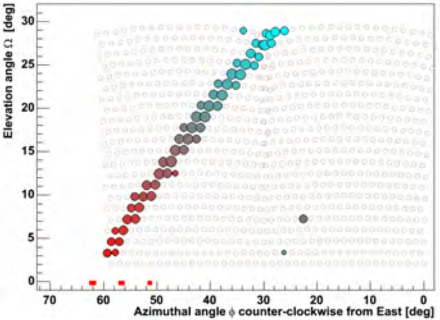
SD: Ground view

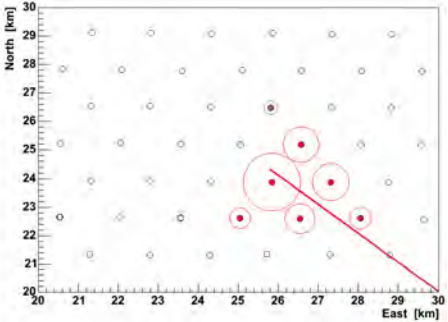
What's a "Hybrid" Event? (slide 17)

Definition

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers





FD: Track in the sky

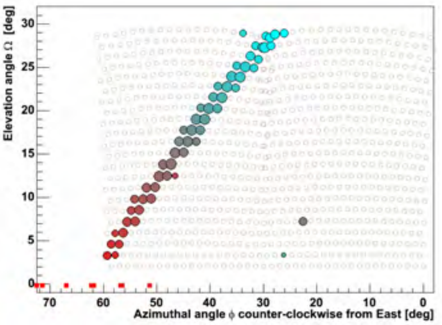
SD: Ground view

WHAT'S A "HYBRID" EVENT? (SLIDE 18)

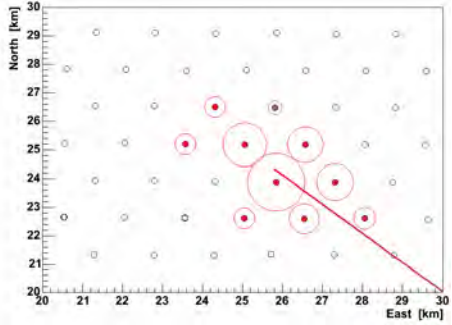
DEFINITION

Simultaneous detection in the sky **and** at ground

- Golden Events: independent triggers

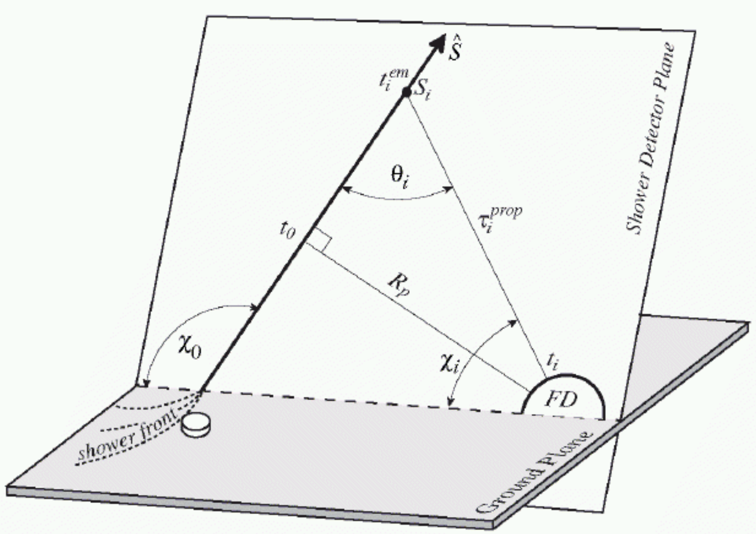


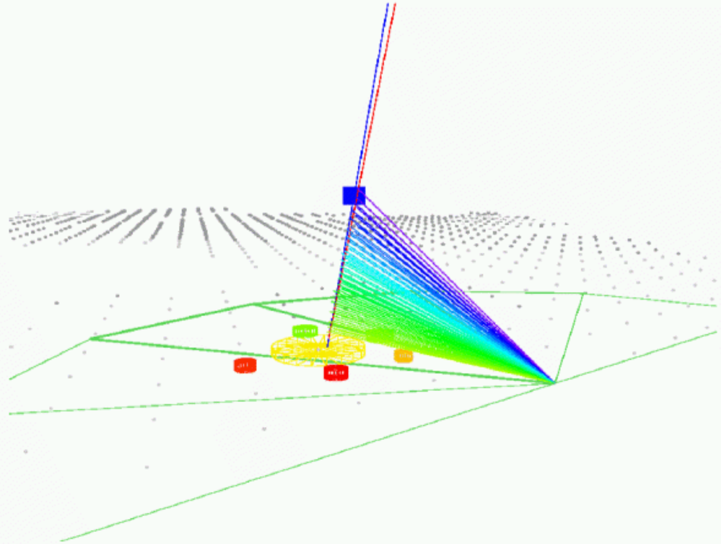
FD: Track in the sky

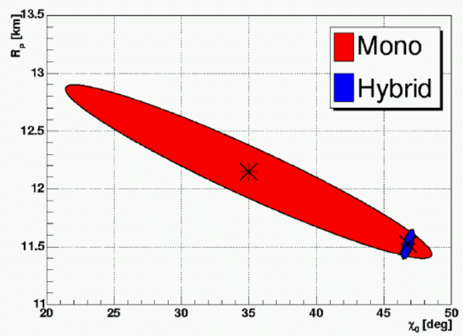


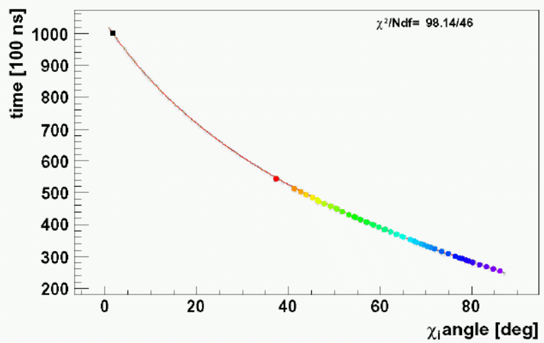
SD: Ground view

Why Hybrid?





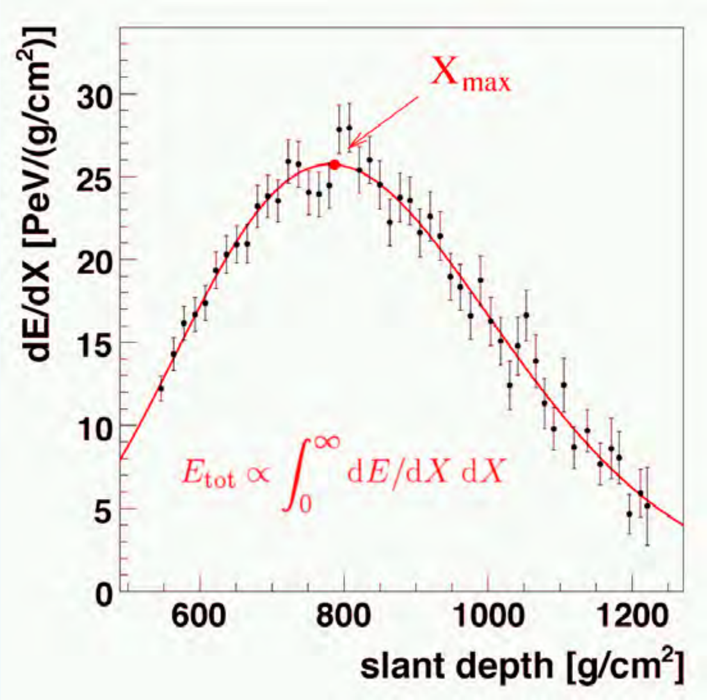




Adding SD timing to the FD reconstruction converts angular error *bananas* into *circles*

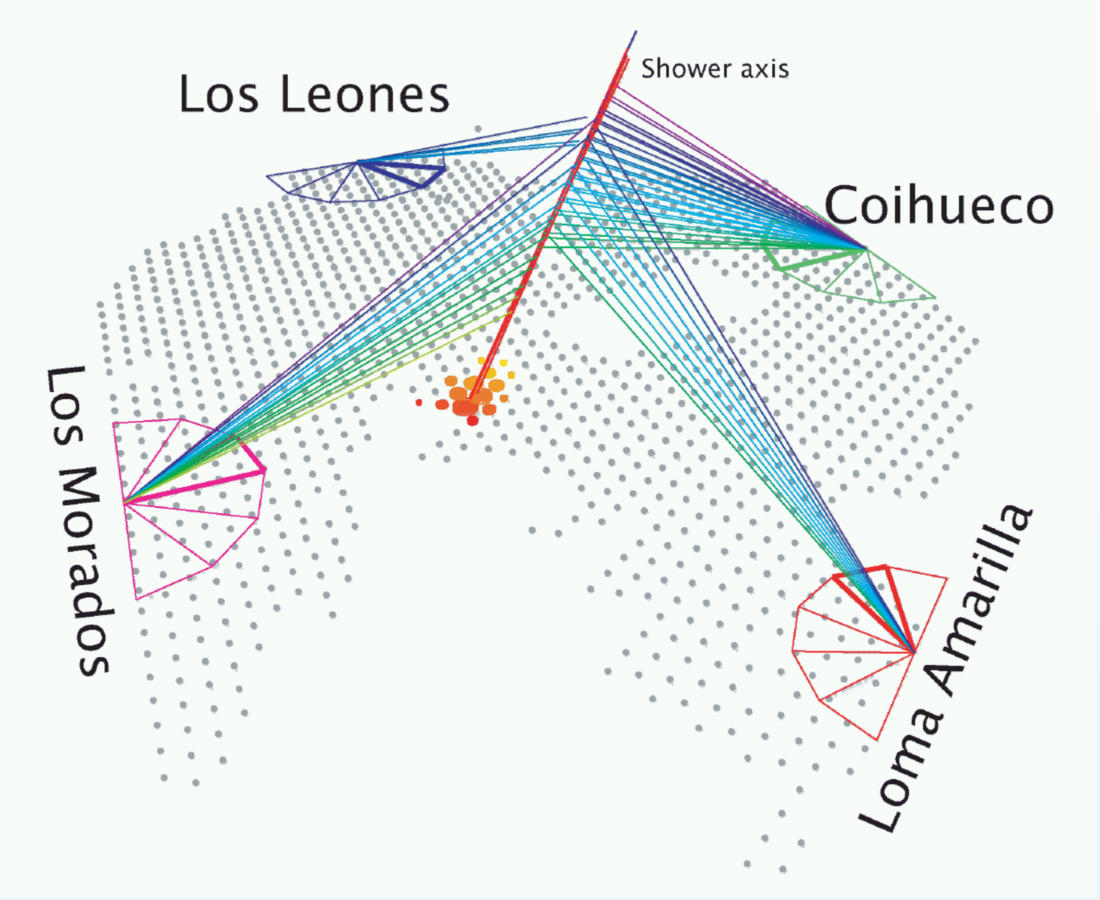
Hybrid events provide a high-precision data sample that **significantly extend the energy reach of Auger**

FD (hybrid) events



- FD events provide a colorimetric measurement of the shower energy and of the position of shower maximum, X_{max}
- However the FD has no *natural* calibration source ...
- Furthermore FD data depend on time varying atmospheric parameters
- **Thus in practice there are many details:** *e.g. fluorescence yield, absolute calibration and atmospheric monitoring*!

FD stereo-hybrid events



- **Event reconstruction (above):** First 4-fold stereo-hybrid event
- Hybrid, and stereo, events provide <u>essential cross-checks</u> with multiple measurements/event **and** 3-times the number of theses!

Atmospheric Monitoring and Fluorescence Detector Calibration

Atmospheric Monitoring

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

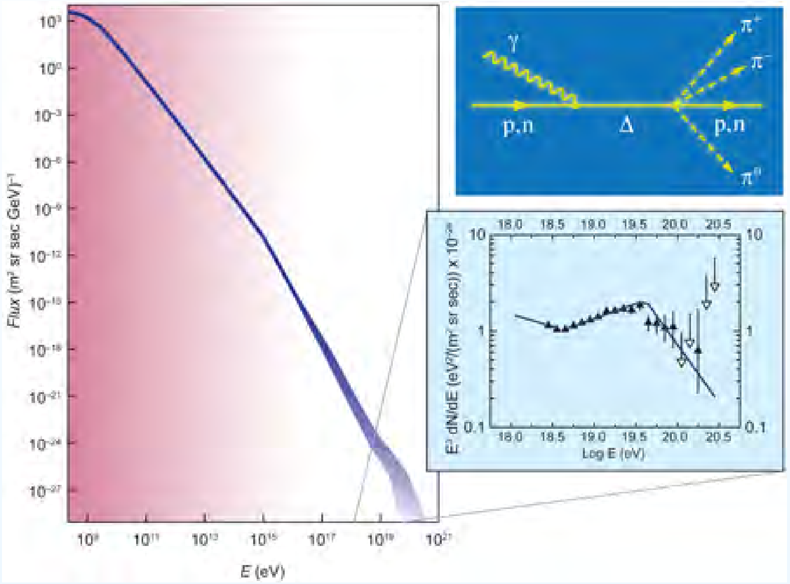
- Atmospheric monitoring
- Calibration checks
- Timing checks

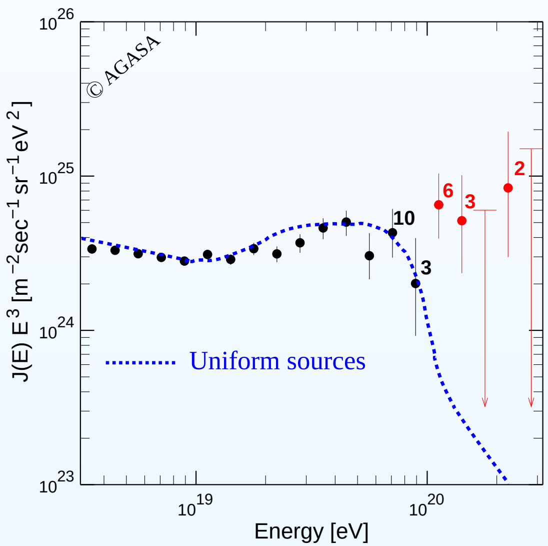
Lidar at each fluorescence eye for atmospheric profiling - “shooting the shower”

Absolute Calibration

Drum for uniform illumination of each fluorescence camera – part of end to end calibration .

3 major physics topics: **CR spectrum (details)**



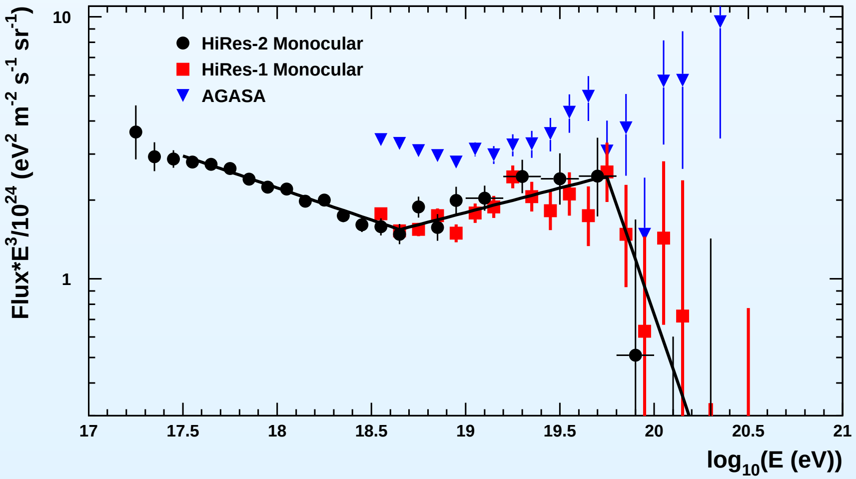


To enhance features in an E^{-n} spectrum, scale the spectrum by E^n:

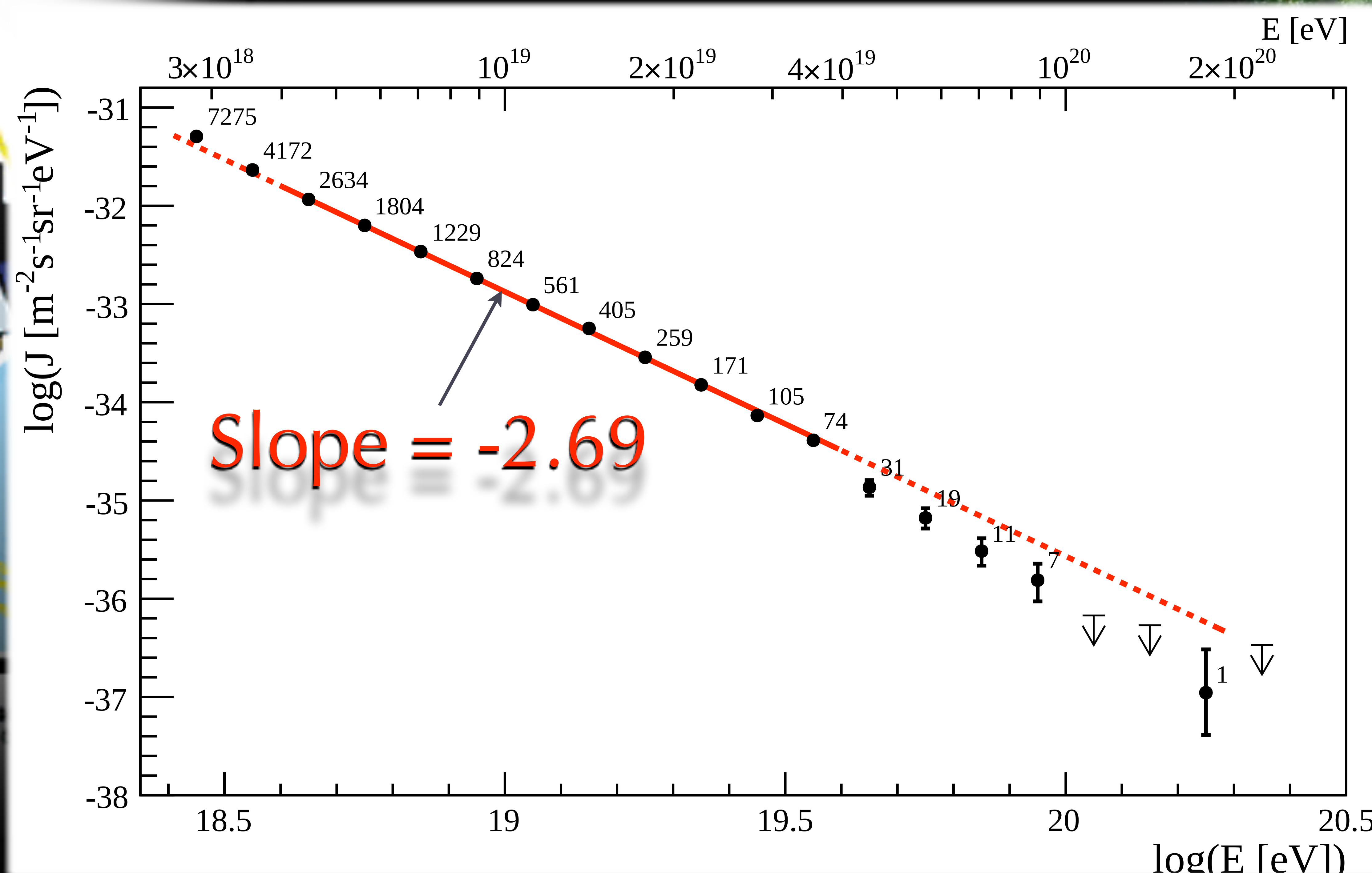
(Right top) AGASA spectrum

(Right bottom) HiRes spectrum, with:

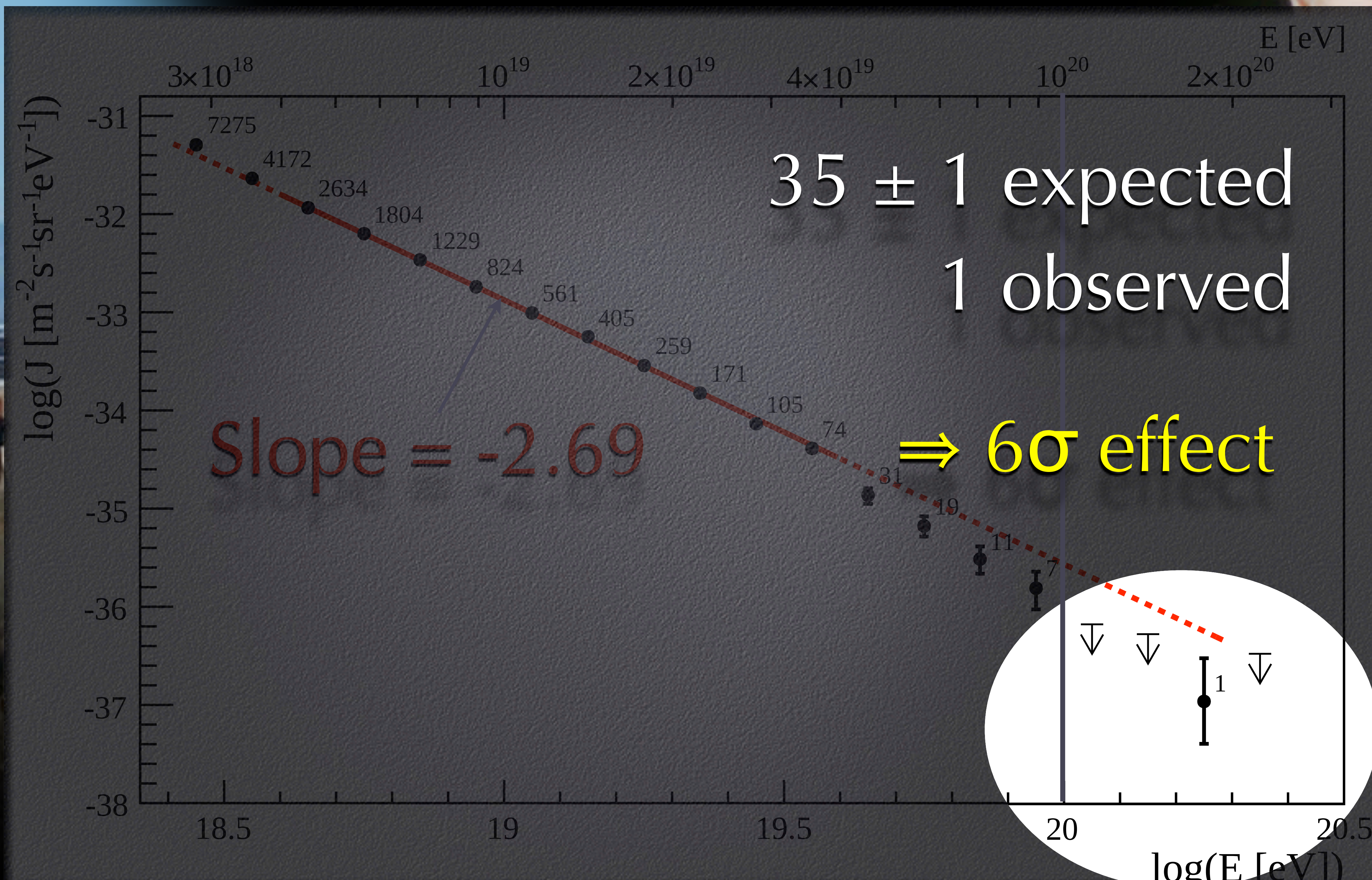
- **ankle** at 4.5×10^{18} eV ($\log_{10} E = 18.65$)
- **GZK-cutoff** above $10^{19.8}$ eV.



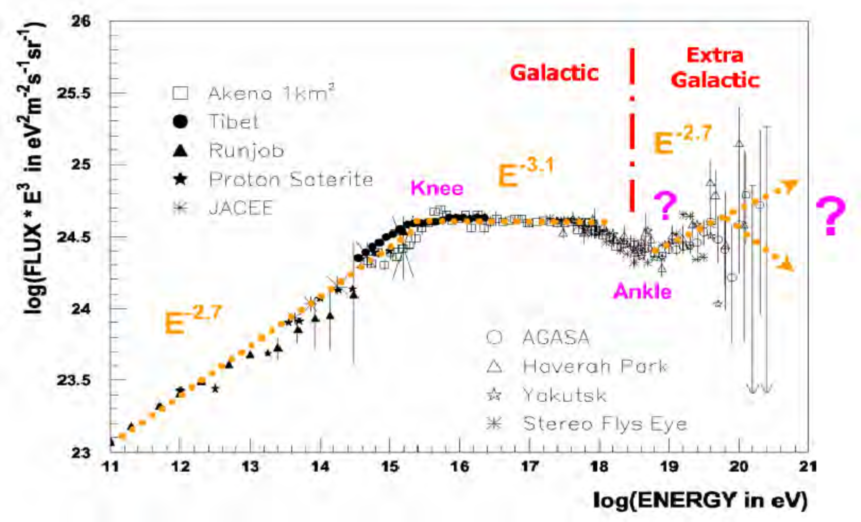
Energy Spectrum

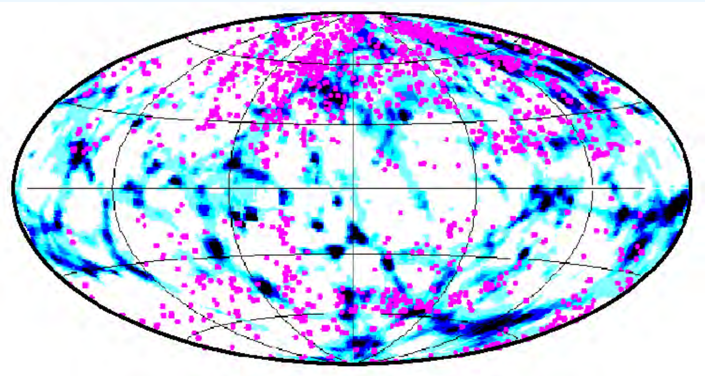


Energy Spectrum



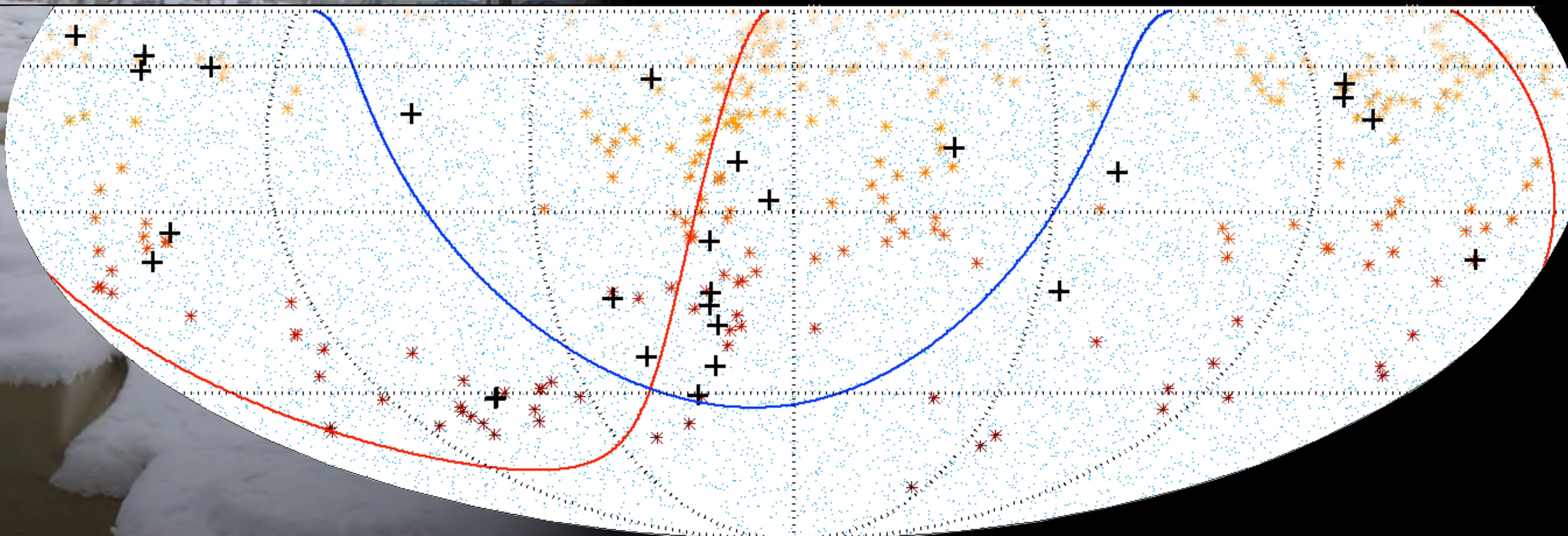
3 major physics topics: **CR sources (search strategy)**





- For several reasons, CRs with energies above *e.g. the ankle* are probably from extra-galactic sources ...
- If there is a GZK cutoff, then the very highest energy CRs must come from relatively nearby sources ...
- If the sources are **astrophysical**, the nearby ($9 < R < 93$ Mpc) universe is observed to be non-isotropic ...
- Thus, excluding magnetic field and/or composition surprises, the highest energy particles should not be isotropic!
- **And what is the best way to search for signal(s):** *clusters of CRs, CR correlations with astrophysical catalogs, non-isotropy in CR arrival directions,* **... ?**

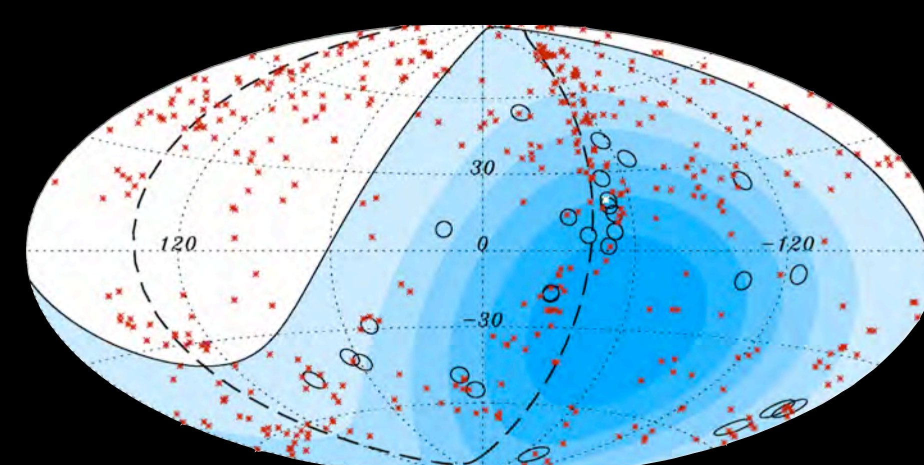
Iso-Exposure Map



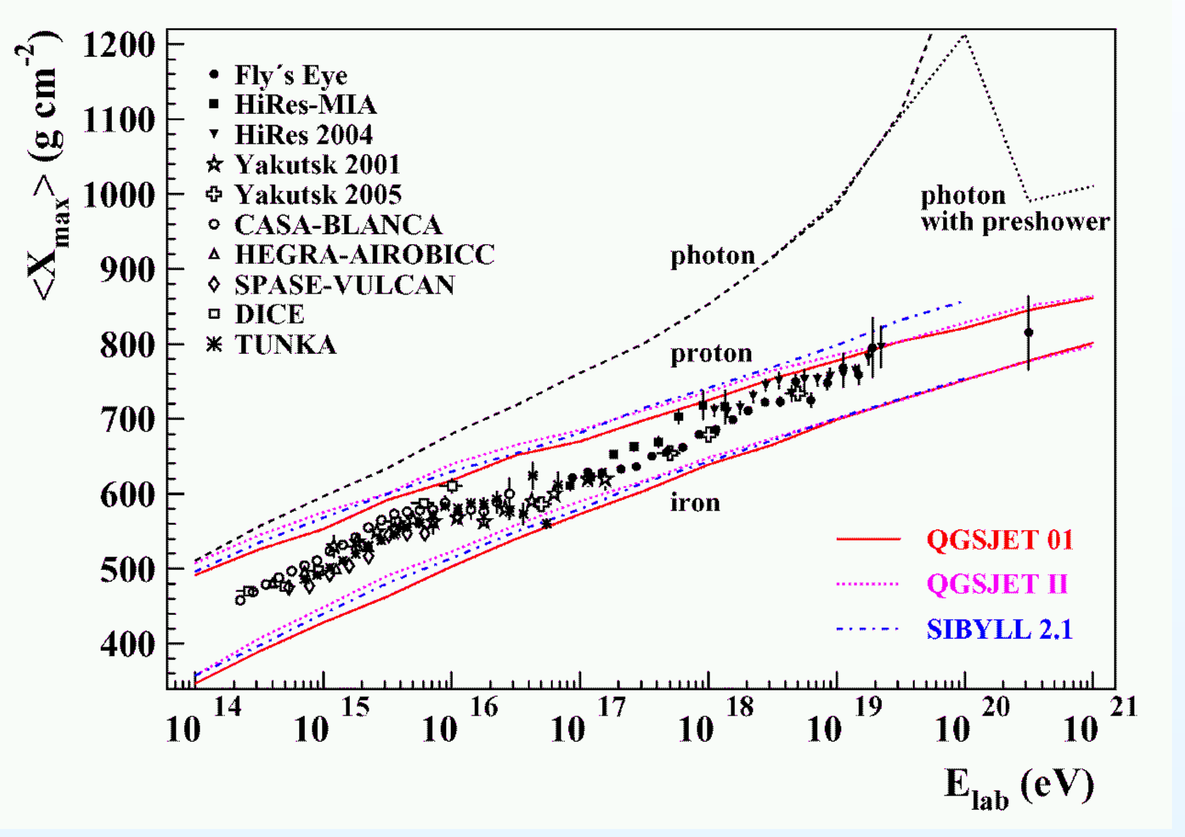
* *Nearby* AGNs

• Auger data above 3×10^{18} eV

+ 27 events above 5.7×10^{19} eV



3 major physics topics: **CR** *composition* **(Fe $\longrightarrow$ p ??)**



- Except for neutrinos, we infer the CR particle (type) from the depth of shower maximum, X_{max}, in the atmosphere ...
- Plot of the average depth of shower maximum $< X_{max} >$ vs shower energy E.
- Model predictions are given for CR primary: photons, protons and iron nuclei.

Auger's most direct *composition* measurements

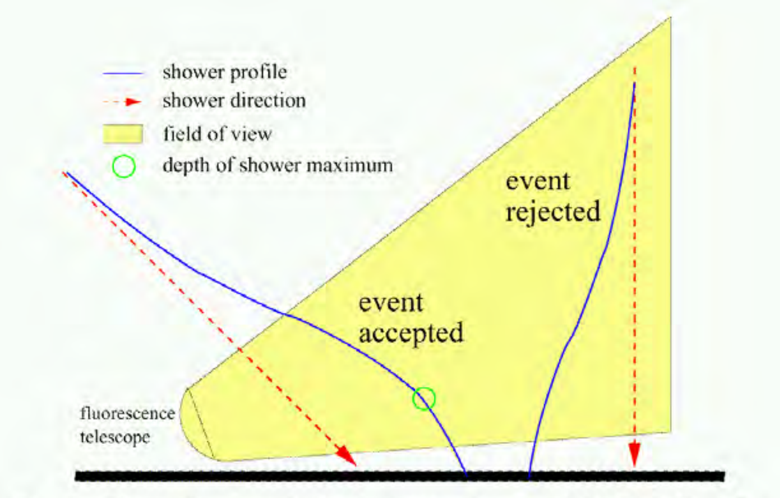
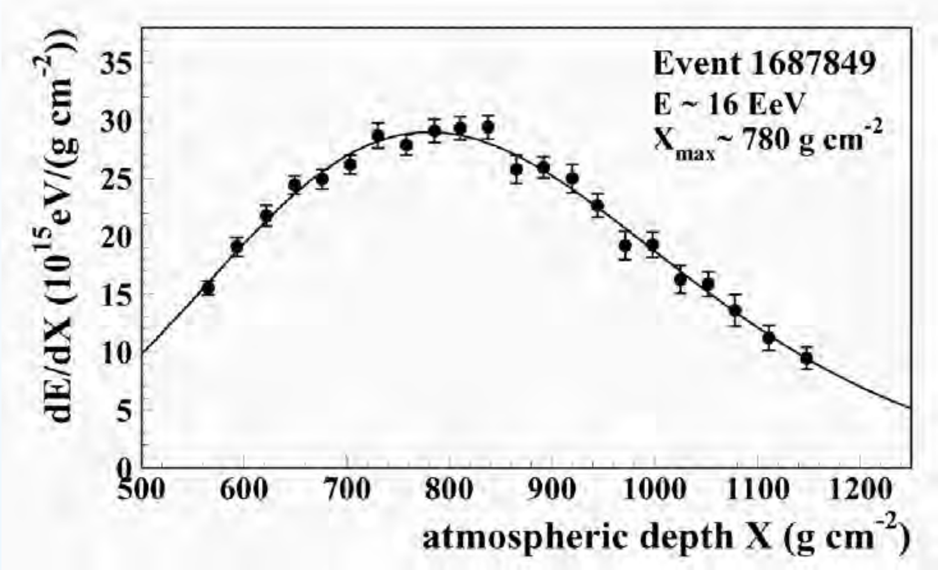
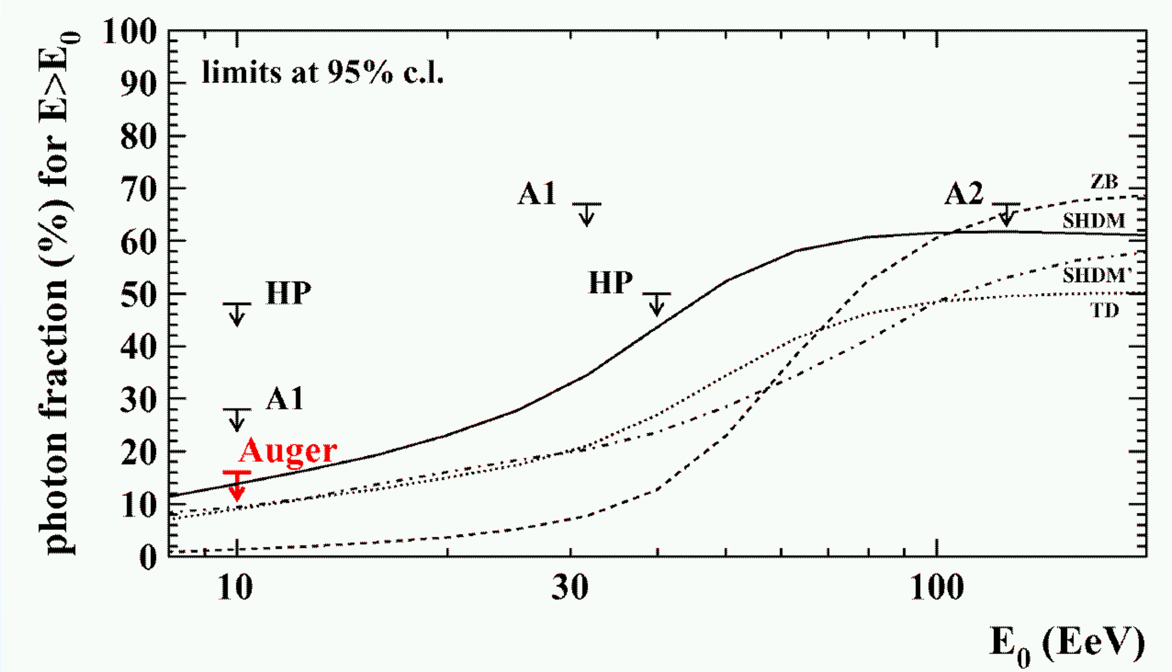


Fig. 4. Photon showers and the selection requirement of observing $X_{\max}$. For near-vertical photon showers, $X_{\max}$ is below the field of view of the telescopes; possibly the showers even reach ground before being fully developed as in the example shown. Such photon showers were rejected by the quality cuts. The situation changes when regarding more inclined photon events. The slant atmospheric depth that corresponds to the lower edge of the field of view increases with zenith. $X_{\max}$ can then be reached within the field of view, and the photon showers pass the $X_{\max}$ quality cut. Requiring a minimum zenith angle in the analysis, the reconstruction bias for photons is strongly reduced.



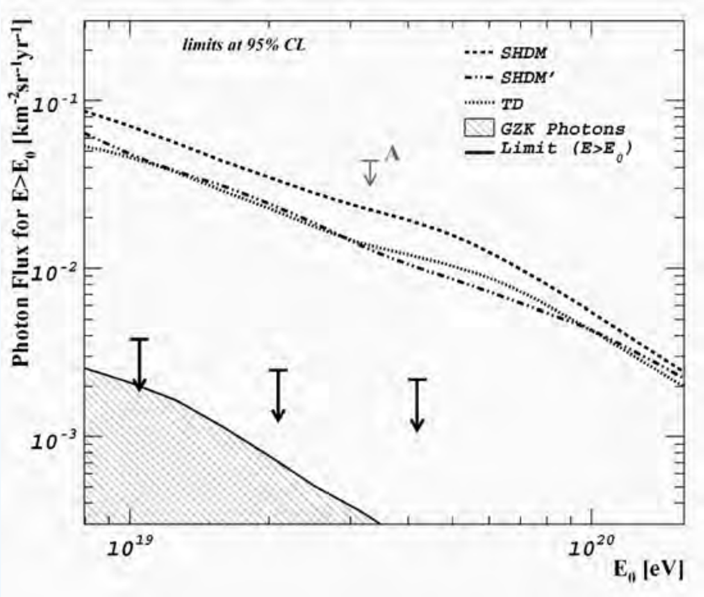
- The fluorescence detectors image the shower development and thus directly measure X_{max}, with typical reconstruction uncertainties ~ 20 g cm^{-2}.
- However, Auger hybrid events have potential biases:
  - At the lowest energies, shower X_{max} may not enter the telescope field of view
  - At the highest energies, shower X_{max} may extend past the telescope field of view; atmospheric depth for vertical showers is ~ 860 g cm^{-2}.

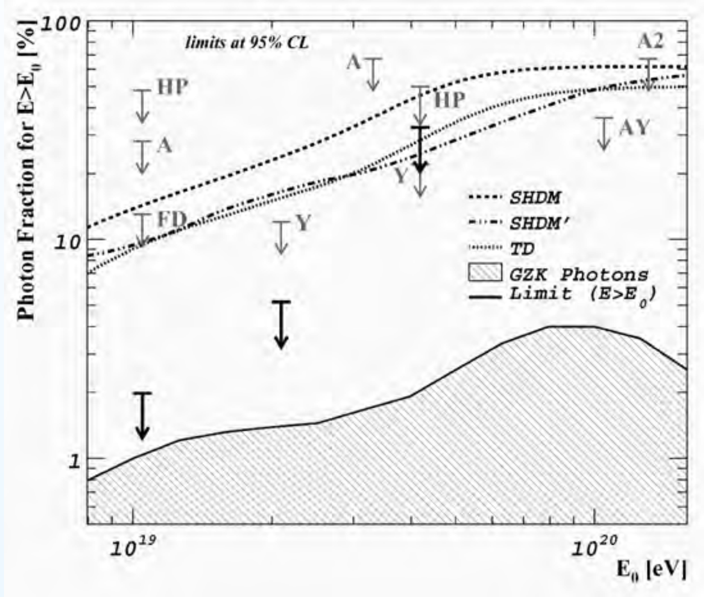
Upper-limit on CR γ-Fraction (FD)



- Plot of 95% c.l. upper limits on the (integrated) CR γ-fraction above the energy plotted
- Plot also shows previous upper limits from: Haverah Park (HP), and AGASA (A)
- Representative theory predictions include: Z-burst (ZB), Topological Defects (TD) and Super Heavy Dark Matter particles (SHDM)
- **Auger** FD-hybrid result, Astropart. Phys. **27** 155 (2007), close to restricting models ...

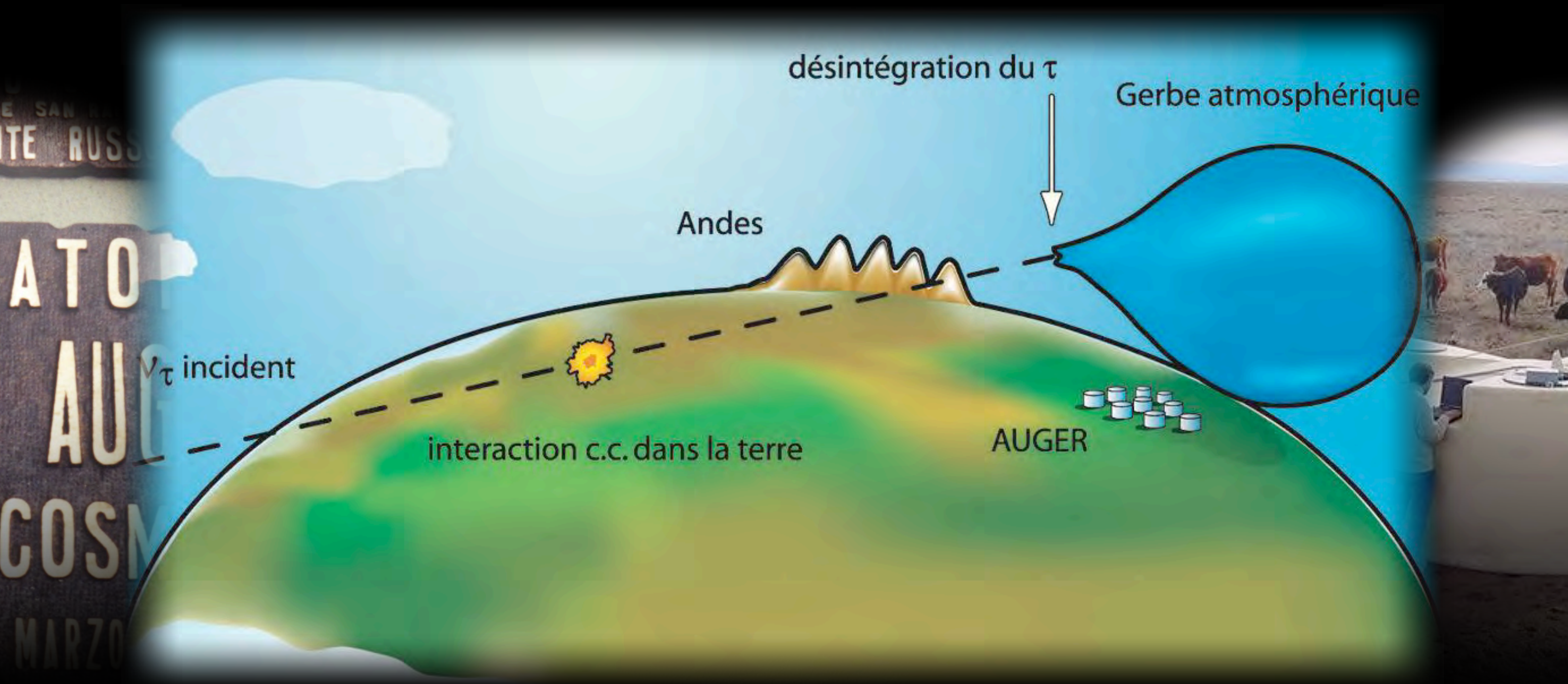
Upper-limit on CR γ-Fraction (SD)



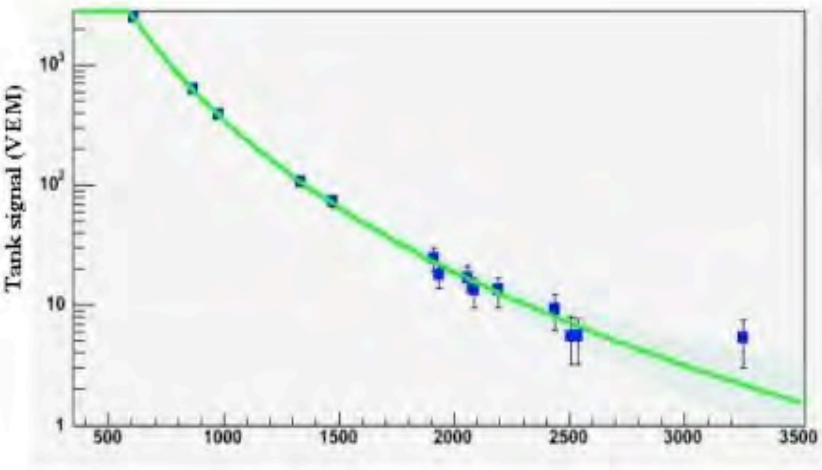


- 95% c.l. upper limits on the (integrated) CR γ-flux (**Left**) and γ-fraction (**Right**) above the energy plotted
- Plot(s) include upper limits from AGASA (A), Haverah Park (HP) and Yakutsk (Y)
- Representative theory predictions include: Topological Defects (TD), Super Heavy Dark Matter particles (SHDM), and GZK-photons
- **Auger** SD result, arXiv:0712.1147, are now restricting models ... and approaching observing GZK-photons!
- One caveat is that the SD results rely on Monte Carlo shower simulations ...

A Neutrino Detector



PIERRE AUGER OBSERVATORY



Mon Dec 29 09:23:45 2003
Easting = 470343 ± 21 m
Northing = 6095432 ± 25 m
dt = 126.8 ns

Theta = 34.4 ± 0.3 deg
Phi = 140.1 ± 0.3/sin(Theta) deg

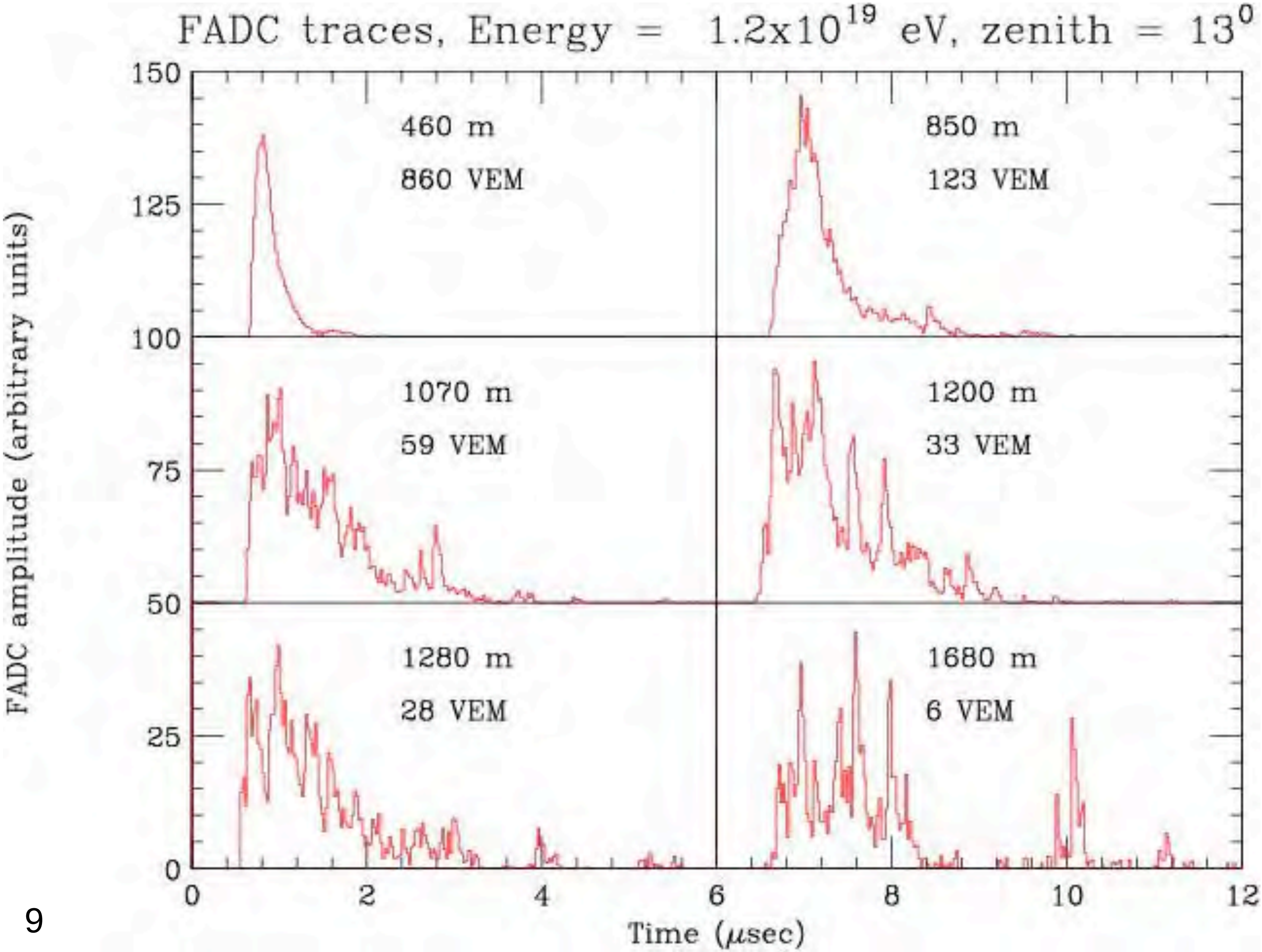
R = 12.5 ± 0.8 km

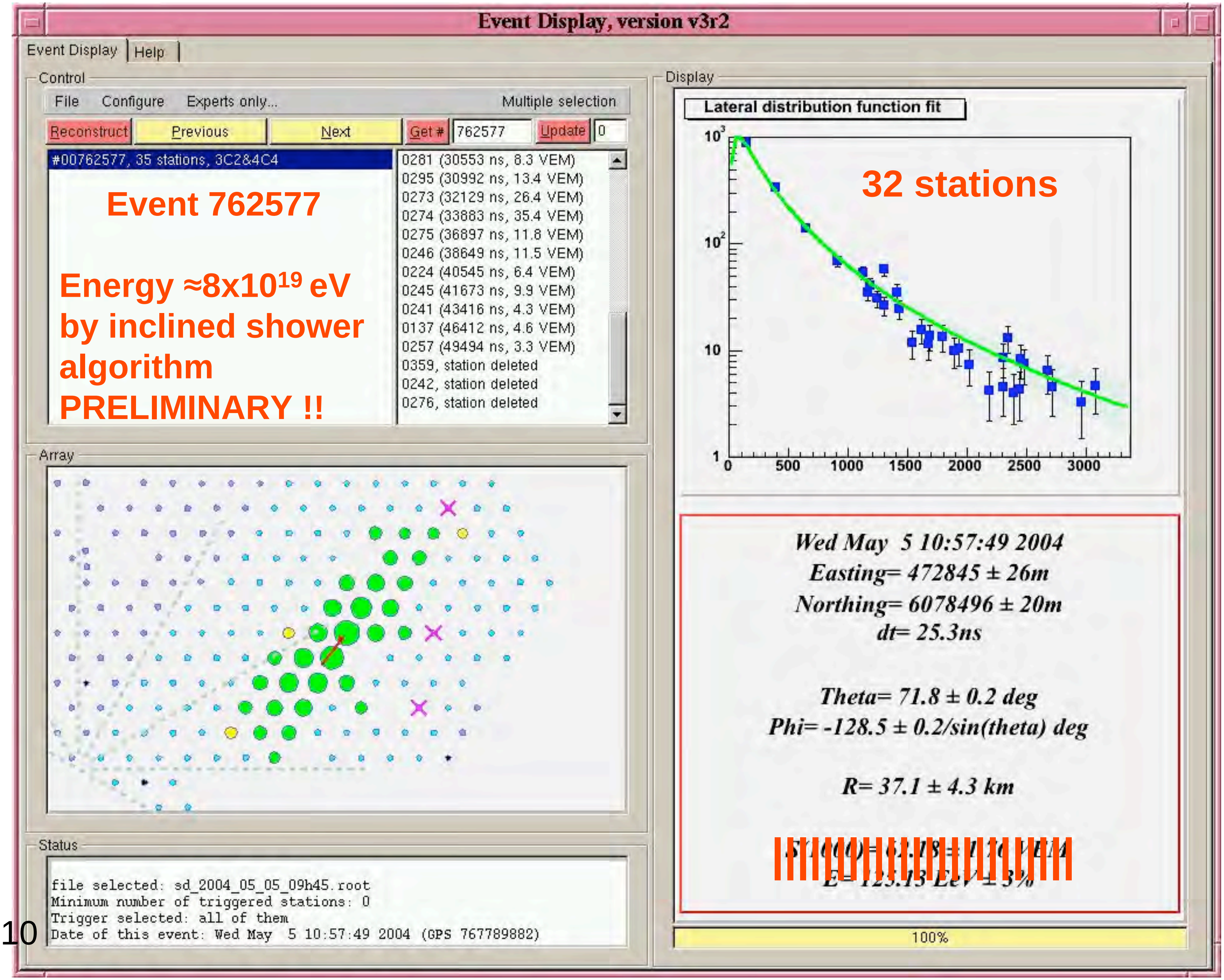
S(1000) = 347.8 ± 8.43 VEM
E = 75.2 EeV ± 3%
(stat. error only)
PRELIMINARY

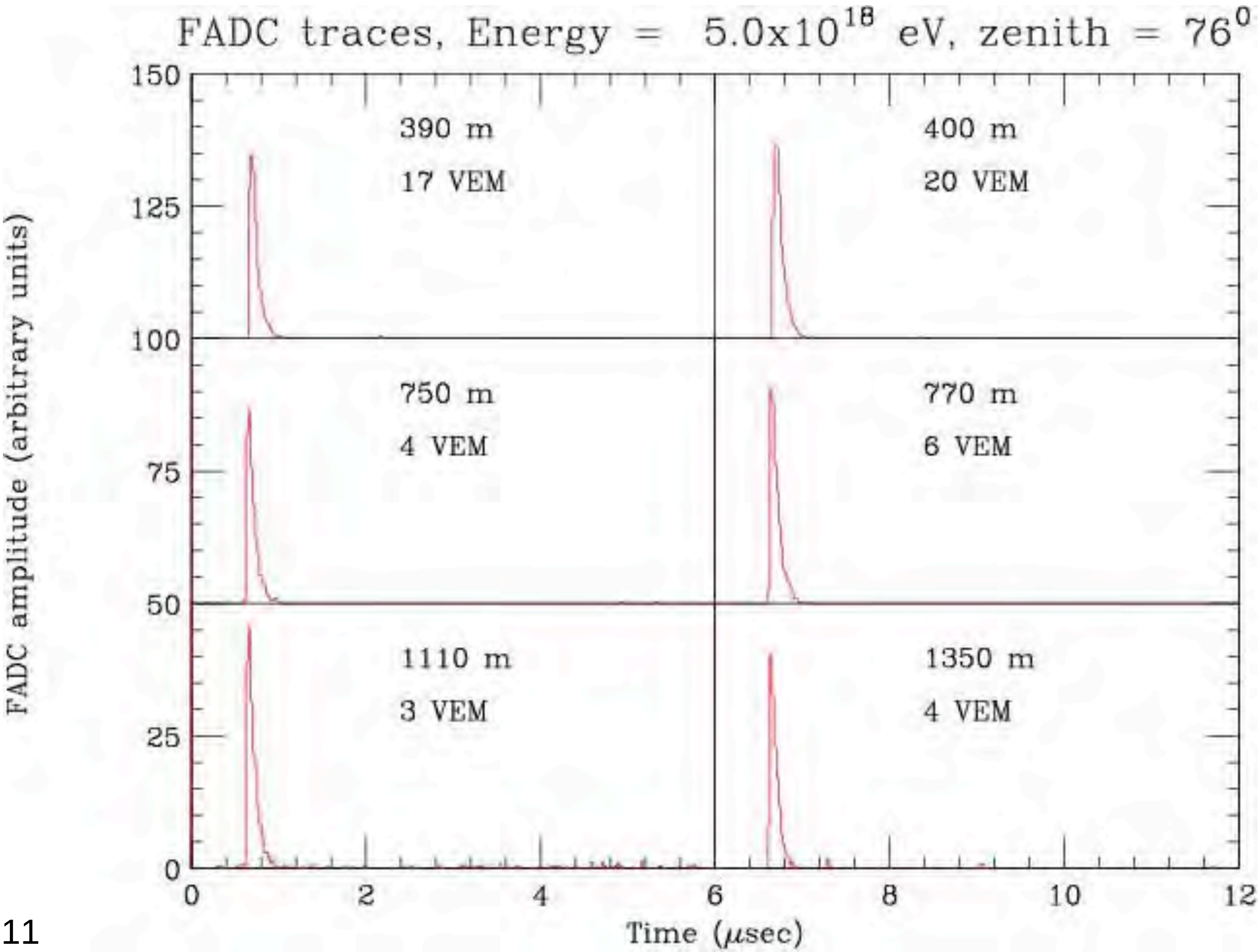
Lateral Distribution Function Fit

Surface Array view

A young shower (vertical)

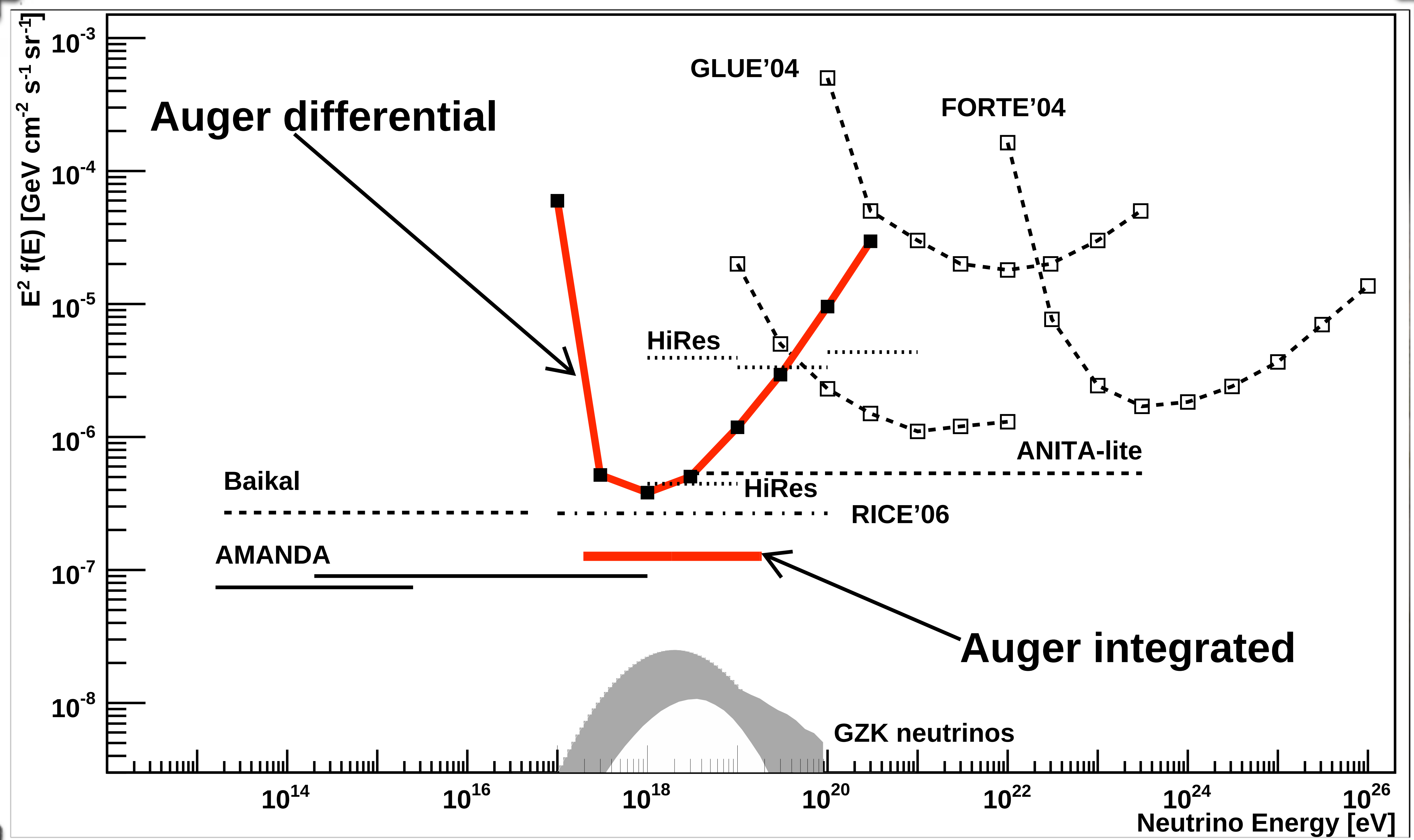

FADC traces, Energy = 1.2x10^19 eV, zenith = 13^0
FADC amplitude (arbitrary units)
Time (μsec)
460 m
860 VEM
850 m
123 VEM
1070 m
59 VEM
1200 m
33 VEM
1280 m
28 VEM
1680 m
6 VEM
150
125
100
75
50
25
0
0
2
4
6
8
10
12


Event Display, version v3r2
Event Display
Help
Control
File
Configure
Experts only...
Multiple selection
Reconstruct
Previous
Next
Get #
762577
Update
0
#00762577, 35 stations, 3C2&4C4
Event 762577
Energy ≈8x10^19 eV
by inclined shower
algorithm
PRELIMINARY !!
0281 (30553 ns, 8.3 VEM)
0295 (30992 ns, 13.4 VEM)
0273 (32129 ns, 26.4 VEM)
0274 (33883 ns, 35.4 VEM)
0275 (36897 ns, 11.8 VEM)
0246 (38649 ns, 11.5 VEM)
0224 (40545 ns, 6.4 VEM)
0245 (41673 ns, 9.9 VEM)
0241 (43416 ns, 4.3 VEM)
0137 (46412 ns, 4.6 VEM)
0257 (49494 ns, 3.3 VEM)
0359, station deleted
0242, station deleted
0276, station deleted
Array
Status
file selected: sd_2004_05_05_09h45.root
Minimum number of triggered stations: 0
Trigger selected: all of them
Date of this event: Wed May 5 10:57:49 2004 (GPS 767789882)
Display
Lateral distribution function fit
32 stations
10^3
10^2
10
1
0
500
1000
1500
2000
2500
3000
Wed May 5 10:57:49 2004
Easting= 472845 ± 26m
Northing= 6078496 ± 20m
dt= 25.3ns
Theta= 71.8 ± 0.2 deg
Phi= -128.5 ± 0.2/sin(theta) deg
R= 37.1 ± 4.3 km
100%



FADC traces, Energy = 5.0x10^18 eV, zenith = 76^0
390 m
17 VEM
400 m
20 VEM
750 m
4 VEM
770 m
6 VEM
1110 m
3 VEM
1350 m
4 VEM
FADC amplitude (arbitrary units)
Time (μsec)
0
25
50
75
100
125
150
0
2
4
6
8
10
12

Neutrino Limits



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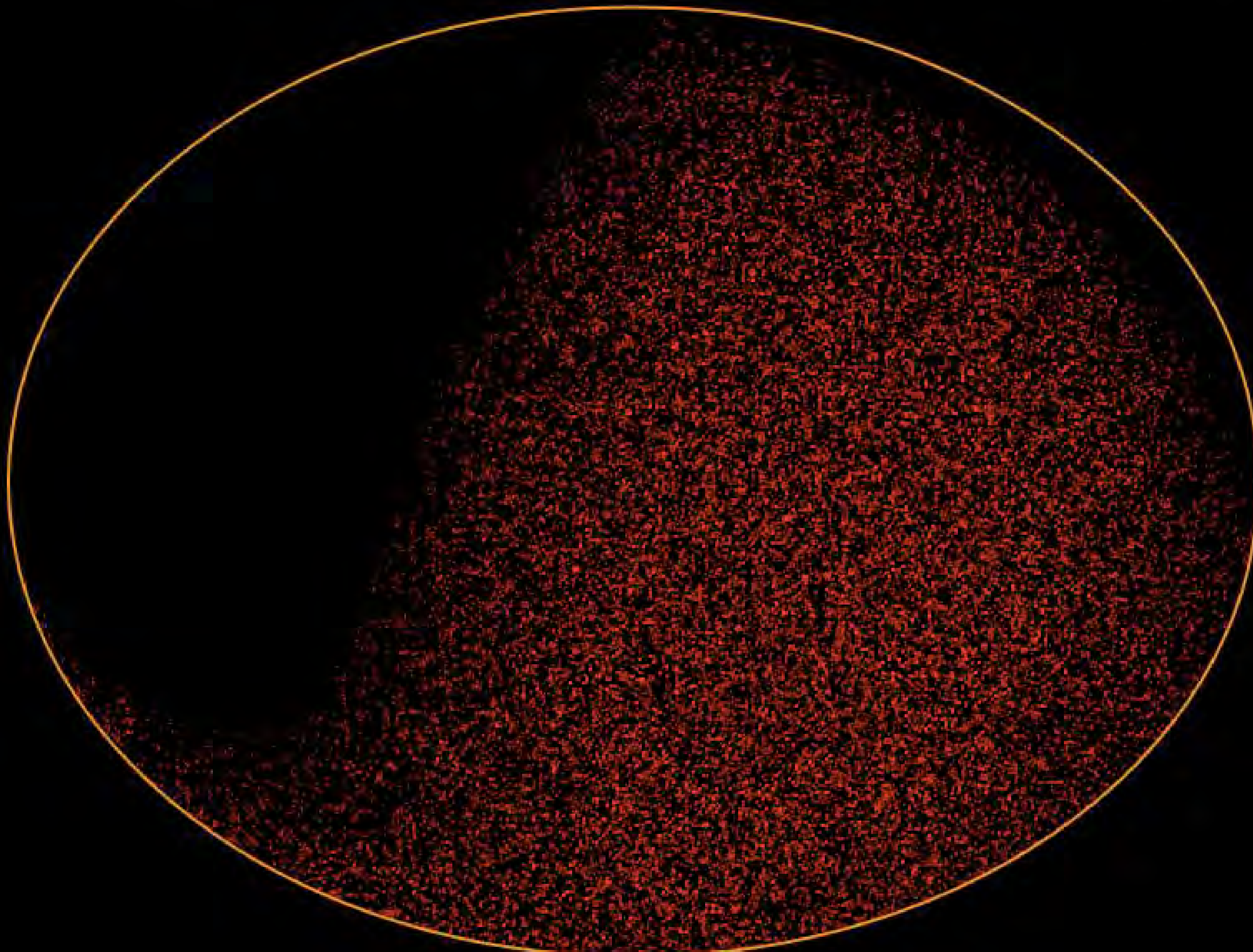
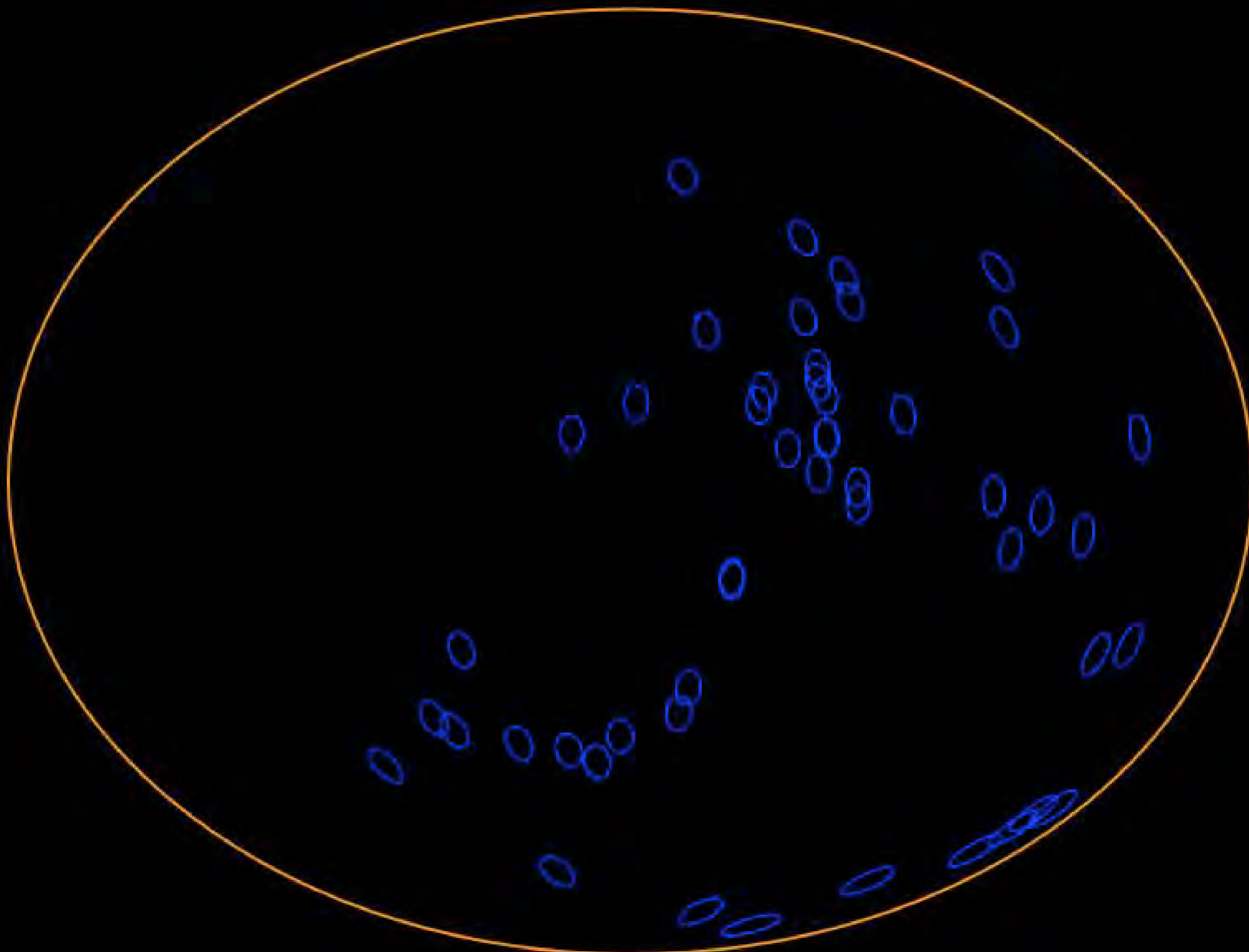
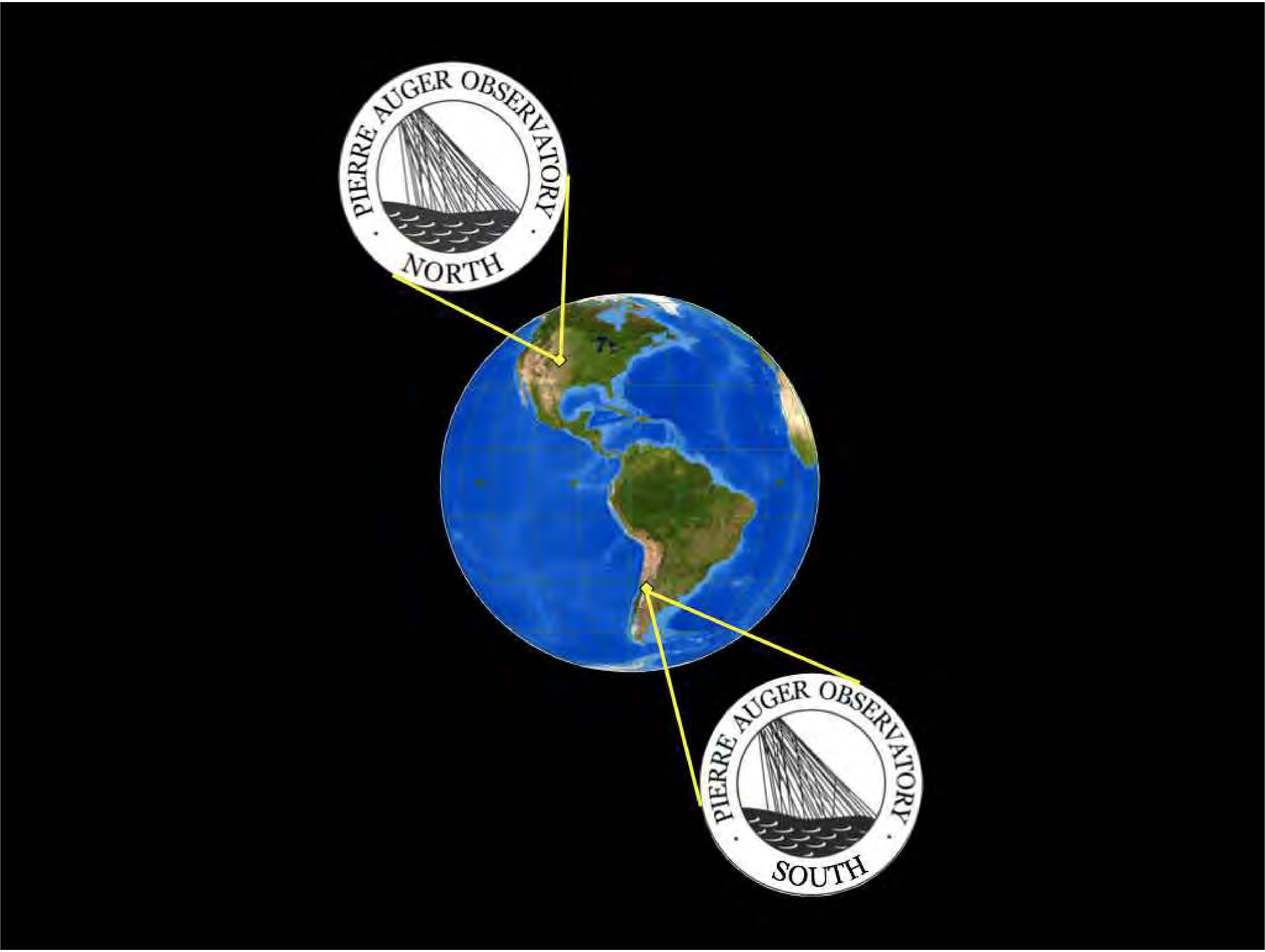
the sky view with high-energy cosmic rays



the sky view with the most energetic cosmic rays




PIERRE AUGER OBSERVATORY
NORTH
PIERRE AUGER OBSERVATORY
SOUTH


WYOMING
NEBRASKA
UTAH
KANSAS
ARIZONA
OKLAHOMA
NEW MEXICO
TEXAS
COLORADO
0
50 mi
41° N
40° N
39° N
38° N
37° N
36° N
109° W
108° W
107° W
106° W
105° W
104° W
103° W
102° W
Walden
Wellington
Fort Collins
Windsor
Sterling
Holyoke
Julesburg
Craig
Hayden
Steamboat Springs
Estes Park
Loveland
Greeley
Rocky Mountain National Park
Berthoud
Ft. Morgan
Brush
Longmont
Rangely
Meeker
L. Granby
Granby
Yuma
Wray
Kremmling
Boulder
Fort Lupton
Broomfield
Brighton
Winter Park
Arvada
Golden
Denver
Bennett
Aurora
Eagle
Vail
Lakewood
Edwards
Silverthorne
Littleton
E-470
Rifle
Glenwood Springs
Parker
Basalt
Breckenridge
Carbondale
Castle Rock
Burlington
Limon
Leadville
Fruita
Aspen
Fairplay
Monument
Grand Junction
Clifton
Black Forest
Woodland Park
Cheyenne Wells
Paonia
Crested Butte
Colorado Springs
Manitou Springs
Security-Widefield
Buena Vista
Delta
Black Canyon of the Gunnison Nat. Park
Cripple Creek
Fountain
Gunnison
Salida
Montrose
Blue Mesa Res.
Penrose
Canon City
Pueblo West
Naturita
Pueblo
Las Animas
Holly
Saguache
Lamar
Ouray
Rocky Ford
La Junta
John Martin Res.
Telluride
Colorado City
Dove Creek
Creede
Great Sand Dunes Nat. Pk.
Silverton
Del Norte
Walsenburg
Monte Vista
Alamosa
Springfield
Cortez
Mancos
Durango
Mesa Verde National Park
Bayfield
Pagosa Springs
San Luis
Manassa
Trinidad
Navajo Res.

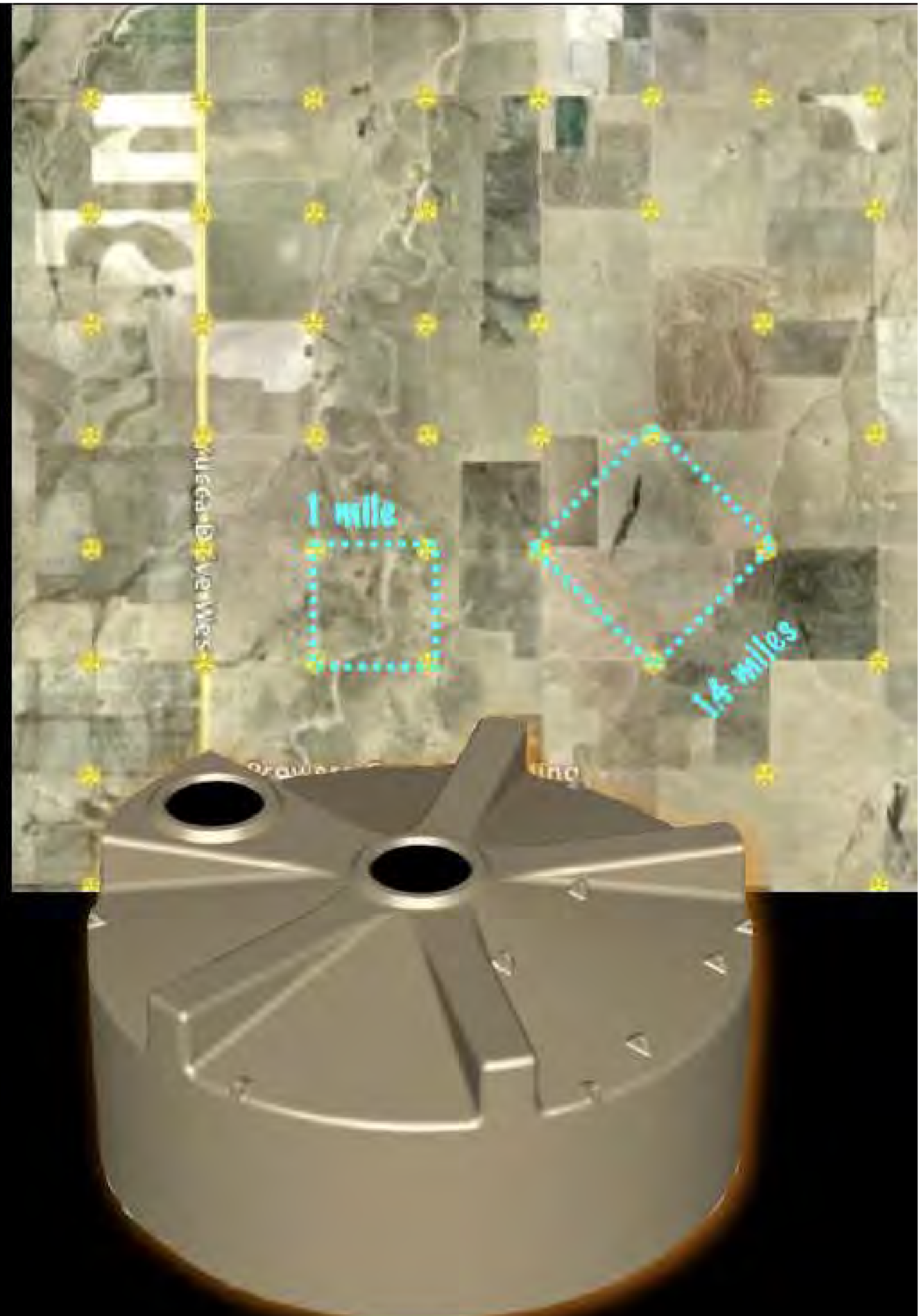
Auger-North Configuration

4,000 tanks at 2.3 km spacing

- fill the space available!
- 8,000 mi^2 = 20,000 km^2
- efficiency 50% at 10^{19} eV
- 400 SDs
  - 10% area infilled sqmi-sub-grid
  - efficiency 100% at 10^{19} eV

39 telescopes in 5 stations

- particle physics!
- 40 km viewing distance
- cover infilled area
- calibration



Summary

- First anisotropy result above GZK energies
- Photon and neutrino limits
- Most precise measurement of the flux suppression

And at the end of a hard day: *asado time*!

Brought to you by an amazing local team:

- Bernie Becker
- Michael Gold
- John (Doug) Hague
- William Miller