Ground based CR experiments

- EAS measurement with ground arrays
- Pierre Auger
- Hires
- LOFAR?

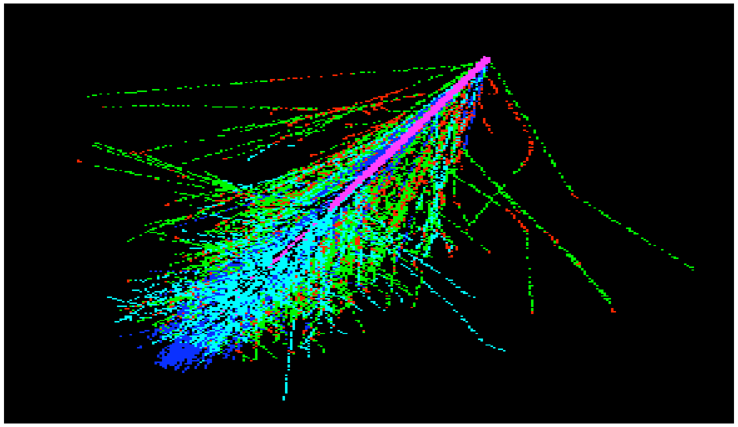
Units: 10^{18} eV = 1 EeV , 10^{21} eV = 1 ZeV = 160 Joules

For showers induced by primaries in 10^{14}-10^{15} eV range high altitudes are better because close to maximum shower size

For larger energies lower altitudes are better because there is no danger of observing showers before max

2 techniques are used and duty cycle of both is limited by moonless nights, clean and dry atmospheric conditions, no cloud coverage.

Less than 10%



Cosmic rays in the atmosphere

The atmosphere contains about 25 radiation lengths and 11 interaction lengths

$$\sigma_{p\ \mathrm{Air}}(E) \simeq 300\ \mathrm{mbarn}$$

$$\lambda_{\mathrm{int}}(E) = \frac{AM_N}{\sigma_{\mathrm{int}}(E)} \simeq 80\ \mathrm{g\ cm}^{-2}$$

$$X \sim \lambda_{\mathrm{int}} \sim 80\ \mathrm{g\ cm}^{-2}$$

$$X_{\mathrm{atm}} \simeq 1033\ \mathrm{g\ cm}^{-2}$$

$$\langle h \rangle \sim \frac{18\ \mathrm{Km}}{\cos\theta_{\mathrm{zenith}}}$$

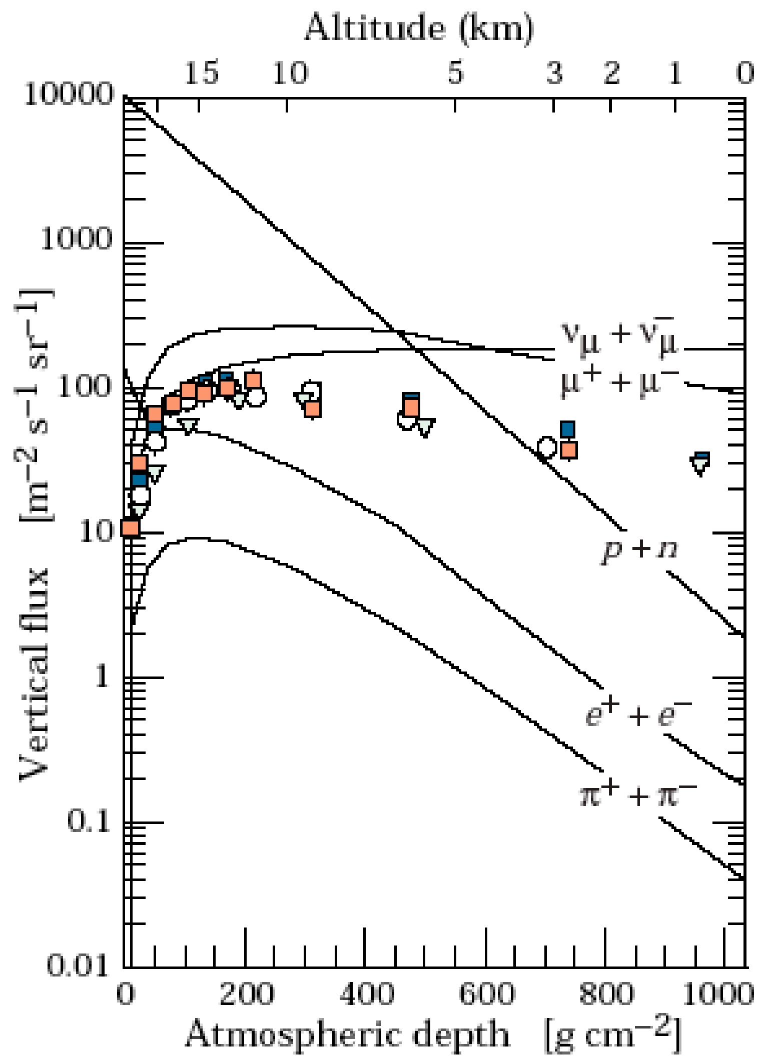
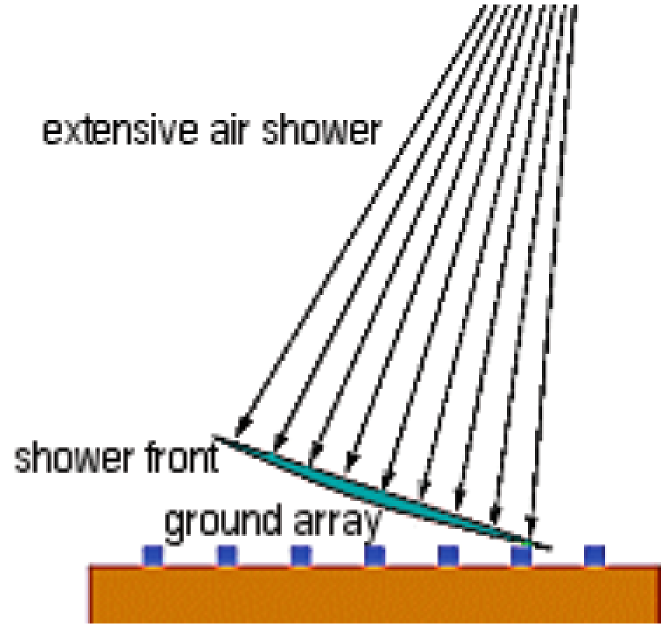


Figure 24.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (24.2). The points show measurements of negative muons with $E_\mu > 1$ GeV [4,19,20,21].

Two Techniques and 3 detectors

Surface detectors sampling particles
Cherenkov or fluorescence light detection
Measured quantities: $E_{primary}$ and X_{max} direction



Typical scintillator detectors of about 1 m^2 with plastic scintillators viewed by PMTs at each end
From ns timing the direction of the primary can be reconstructed

Shower array trigger if several detectors are hit within a short time interval Δt (that depends on the shower array size and on the daq system)
Once there is a trigger the particle densities and their arrival times in all detectors are recorded
An experiment of diameter d will be sensitive to a zenith angle θ given by $\Delta t = d\cos\theta/c$.

The lateral distribution of showers

In bremsstrahlung and pair production secondary particles are not emitted in the direction of the primary one. The average transverse momentum in these processes is ~electron mass + Coulomb scattering

The average angle deviation is given by $\langle \delta\theta^2 \rangle = \left(\frac{E_s}{E} \right) \delta X$

where $E_s = m_e c^2 \sqrt{\frac{4\pi}{\alpha}} \approx 21 MeV$

And X is the depth in radiation lengths

The Moliere length sets the scale for spread of showers in units of radiation length or in g/cm^2 $r_1 = \left(\frac{E_s}{E_c} \right) X$

Measured in m, r_1 is different for different materials and increases with decreasing density of air => showers developing at higher altitudes have bigger lateral dimensions

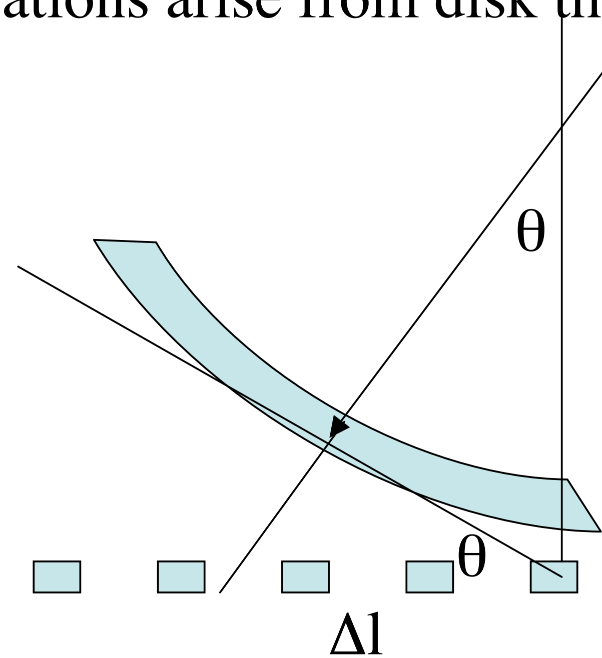
For Greisen parametrization of lateral distribution of charged particles in a shower (similar for NKG for em showers) is

$$\rho(r) = \frac{C_1(s) N_e}{2\pi r_1^2} \left(\frac{r}{r_1} \right)^{s-2} \left(1 + \left(\frac{r}{r_1} \right) \right)^{s-9/2} \left[1 + C_2 \left(\frac{r}{r_1} \right)^{\delta} \right]$$

s=1.25, δ=1 C_2 = 0.088 for $N_e = 10^6$ particle showers, $C_1(s)$ = normalization $\frac{2\pi}{N_e(X)} \int_0^\infty r\rho(r) dr = 1$

Reconstruction of showers

The position of the shower core must be determined. Particle densities are fit by Greisen parametrization. r is the distance in the plane normal to the shower axis that is determined fitting the arrival times of shower particles. The shower is a thin disk of particles that propagate at relativistic speed. The time delay between hits in different detectors provides the shower direction. For a perfect disc 3 detectors are needed, Complications arise from disk thickness which increase from shower axis

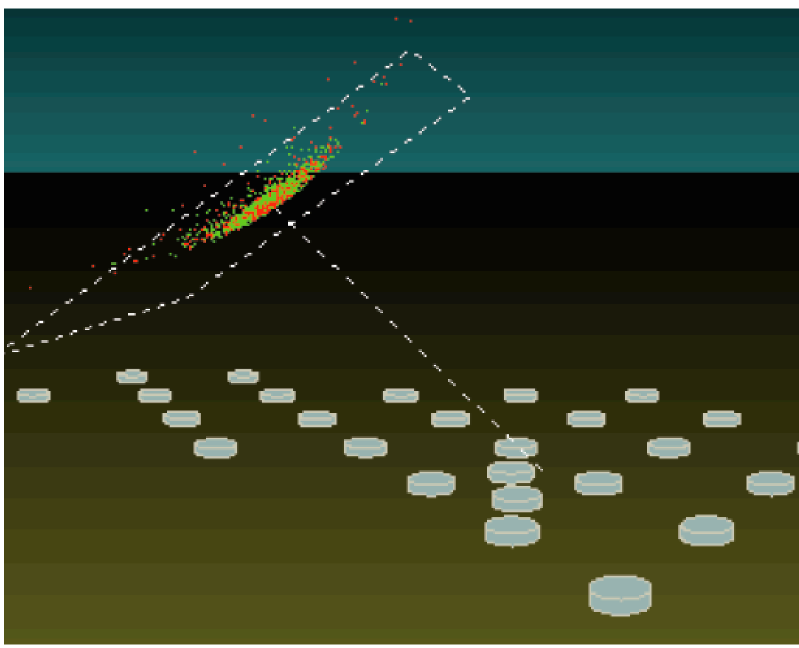


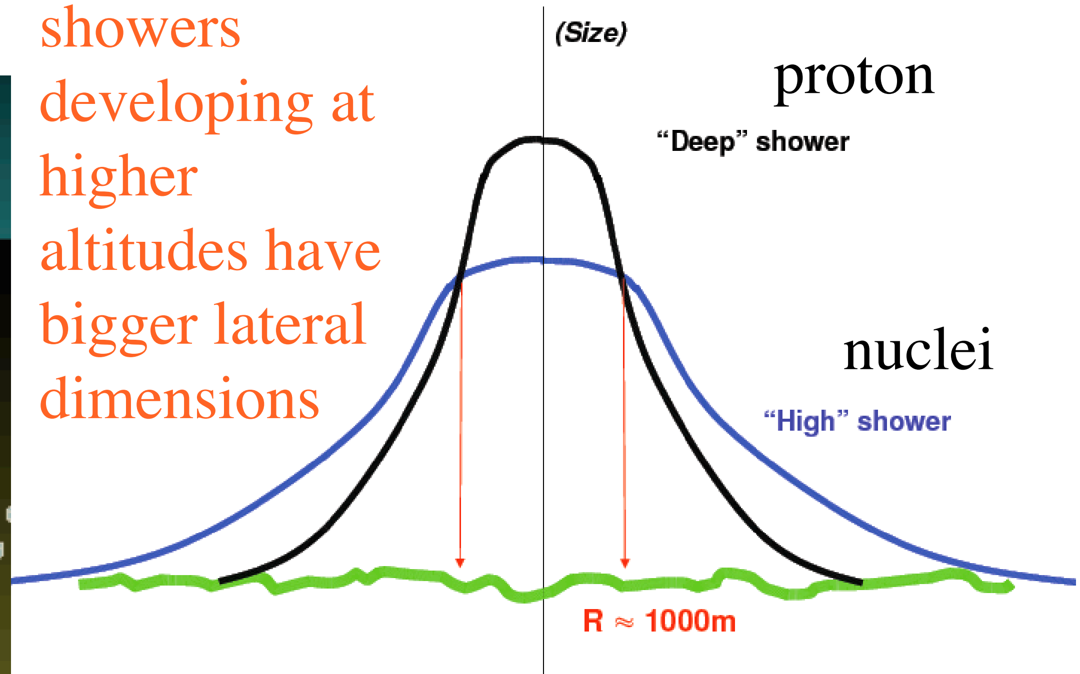
The time delay between 2 detectors at distance Δl is

$\Delta t = \Delta l \cos\theta / c$

Thin scintillators measure only electrons and muons, while in thicker detectors photons convert in pairs increasing the total number of particles and change the lateral distribution and the shape of the shower front.
The particle density distribution is detector dependent.
Hillas noticed that at certain distances from the shower core the particle density could be related to the primary energy (eg ρ_{600}): at 600m from the shower axis the charged particle density does not depend on the mass of the primary CR nucleus. This distance may change at different elevations.
In P. Auger it is 1000 m

showers developing at higher altitudes have bigger lateral dimensions

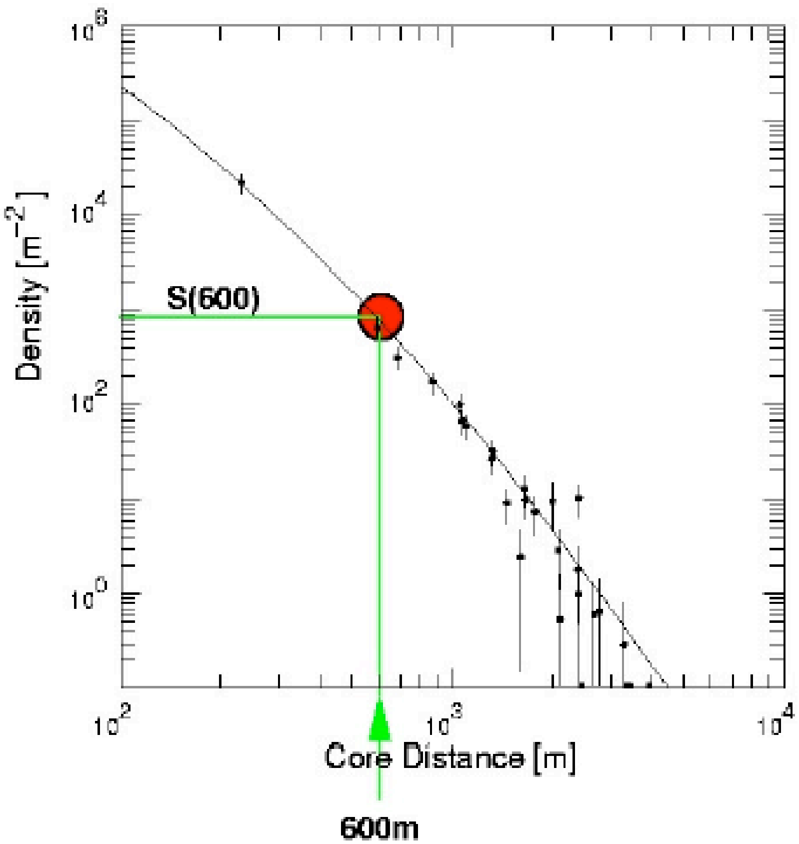


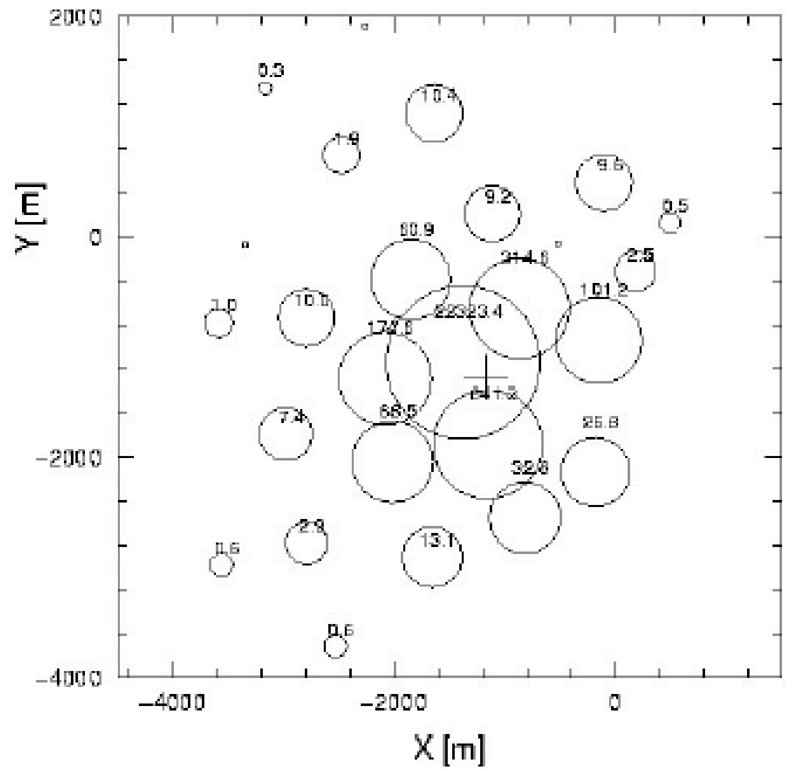


Energy determination by ground arrays (AGASA)

- Local density at 600m
  - Good energy estimator by M.Hillas

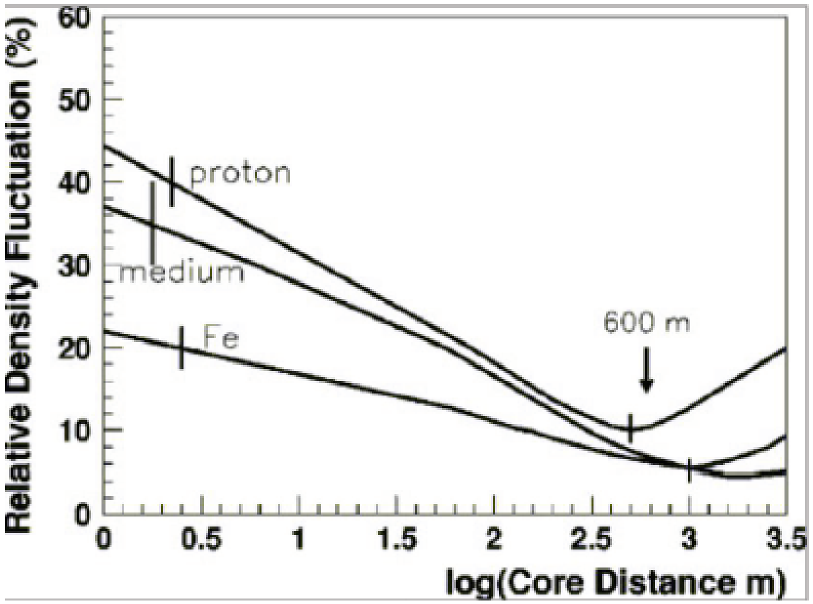
$E=2x10^{20}eV$, $E_{min} = 1.6x10^{20}eV$

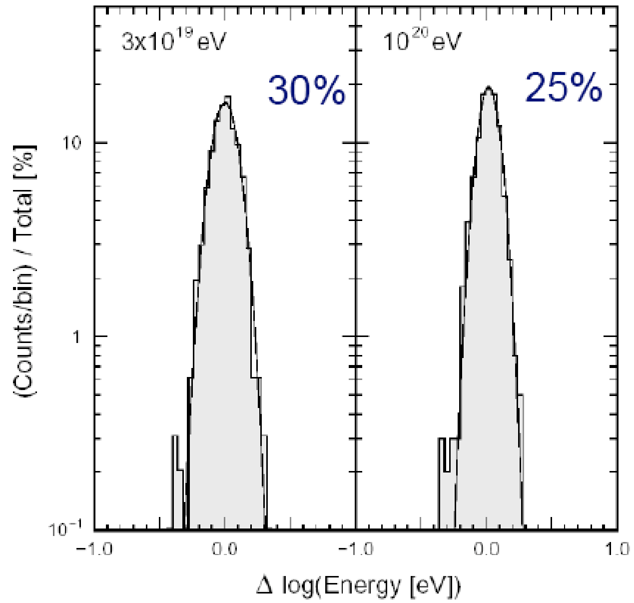


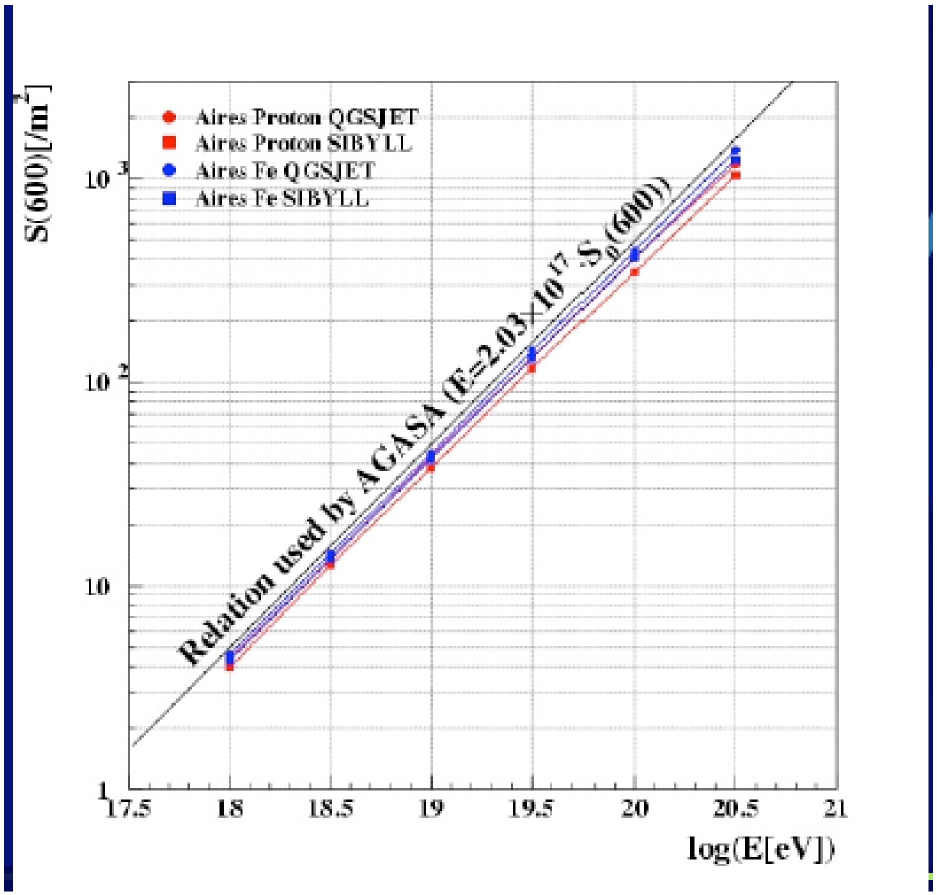


From S(600) to energy

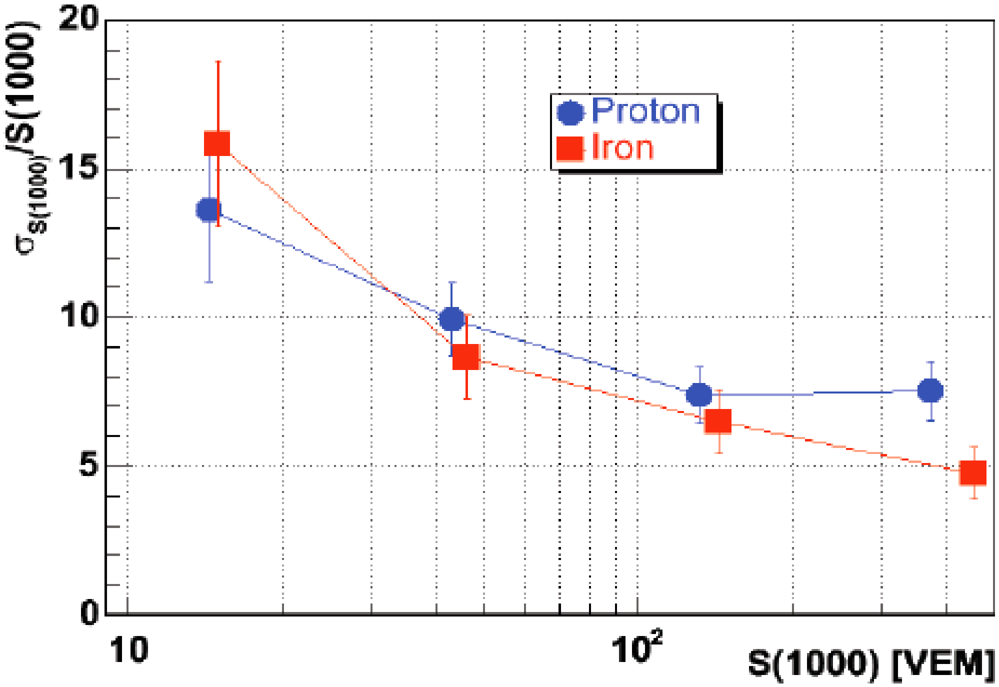
Corrections for energy lost in air
Bias: often same hadronic models







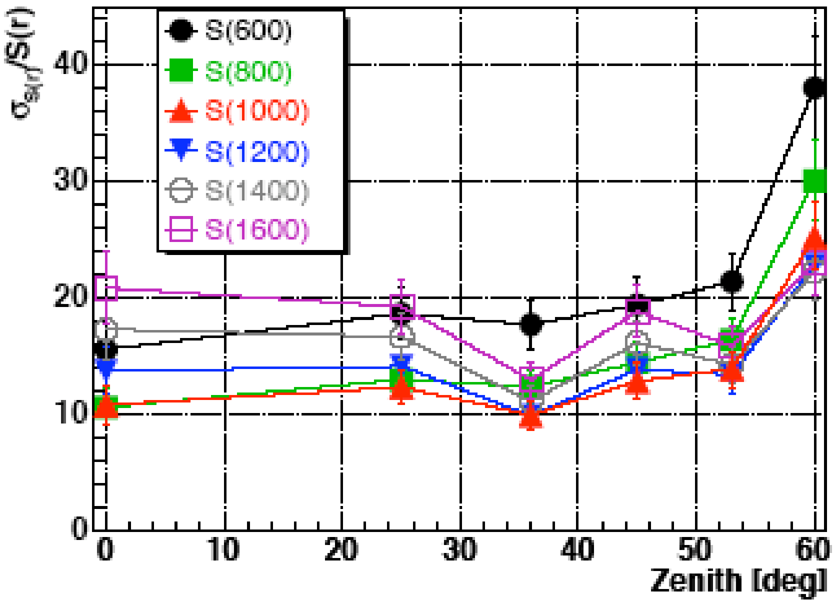
Energy determination in Pierre Auger: S(1000) indicator for the Surface Detector

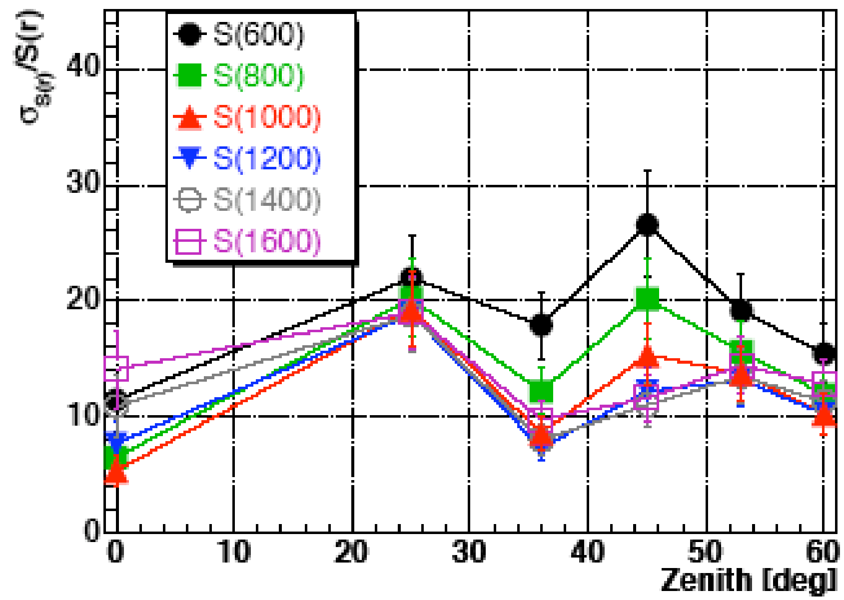


VEM= vertical equivalent muons

http://www.auger.org/icrc2005/icrc_2005_103.pdf

Reason to chose S(1000)

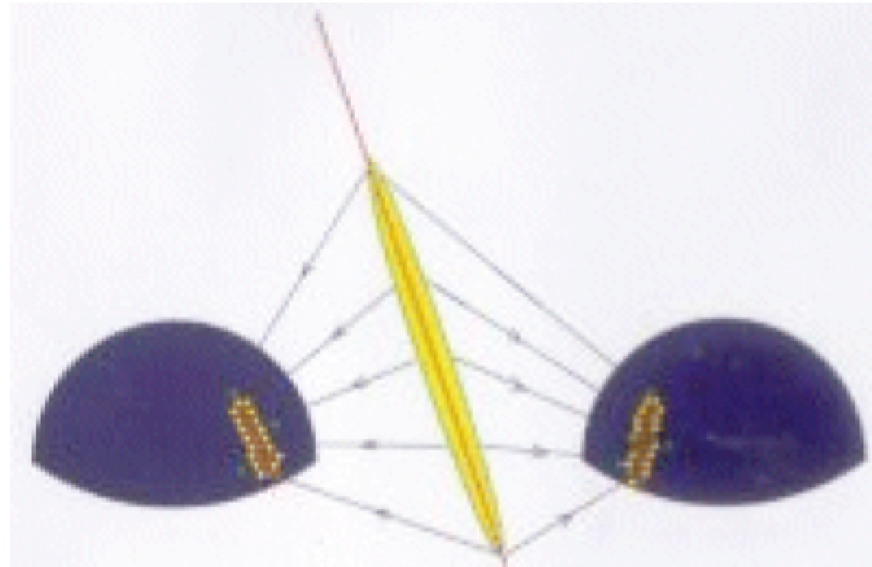




Figures 4 and 5 show the r.m.s. of the $S(r)$ distributions, at 10 EeV primary energy, as a function of the zenith angle, for r= 600÷1600 m, for primary protons and irons, respectively, and QGSJET as interaction model. These plots show that the shower-by-shower fluctuations are minimized for $S(1000)$, which is the main reason for choosing it as primary energy estimator.

The other technique: 2 kind of detectors

Observation of Cherenkov light emitted by shower electrons or fluorescent light emitted by the atmospheric nitrogen atoms excited by the shower passage



The 2 types of light are useful in different energy ranges: the Cherenkov cone is narrow and most of the light is emitted along the shower axis. So Even Cherenkov light from 1 TeV showers that are absorbed before reaching observation level is detectable.
Fluorescence is isotropic: each electron produces 4 photons/m and only very high energy showers produce detectable light above the night sky background

Cherenkov light detectors

Cherenkov air shower detectors measure the lateral distribution of the light emitted by the shower.

Since the opening angle of Cherenkov light is small all photons are almost emitted along shower axis.

At sea level the Cherenkov threshold for electrons is E_{min}=21 MeV and increases at higher altitudes.

At H_S =scale height of atmosphere =7.5km above sea level it is 35MeV

In the standard model of the atmosphere the density varies as $\exp(-H/H_S)$.

The change of E_{min} is due to the dependence on the spectral index with the index of refraction of the atmosphere:

$v = c/n(H)$.

Cherenkov light detectors

Since the atmospheric pressure varies with altitude

E_{min} = 0.511 MeV/sqrt(2δ) with δ = 1-n $\propto$ exp(-H/H_S).

Remember:

$$\beta_{th} = 1/n$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \text{ and E} = \text{m}\gamma$$

$$E_{\min} = \frac{mn}{\sqrt{n^2-1}} \approx \frac{nm}{\sqrt{2(n-1)}} = \frac{0.511}{\sqrt{2\delta}} \quad \text{MeV}$$

The Cherenkov angle is given by θ_{max} = acos(1/n) ~ 81$\delta^{1/2}$ degrees
At STP θ =1.3 deg .

The number of photons/m generated by a particle of energy E emitting Cherenkov light is

$$\frac{dN_\gamma}{dl} = 4\pi\alpha\left[1-\left(\frac{E_{\min}}{E}\right)^2\right]\int\frac{\delta}{\lambda^2}d\lambda \qquad \text{photons/m}$$

The $1/\lambda^2$ dependence means that much of the light is in the UV

A clear atmosphere has good transmittivity down to 290 nm at which point ozone absorption sets in.

The angular disribution is due to the angular spread of electrons due to MS and to the Cherenkov angle -> intense Cherenkov beam within about 6 deg of shower core (although Cherenkov light scattered by atmosphere can be detected up to 25 deg). The total Cherenkov light at surface is proportional to the total track length of electrons hence to Eprimary.

Cherenkov light generated from 20 km above sea level would fall within a ring 110-145 m ignoring electron MS.

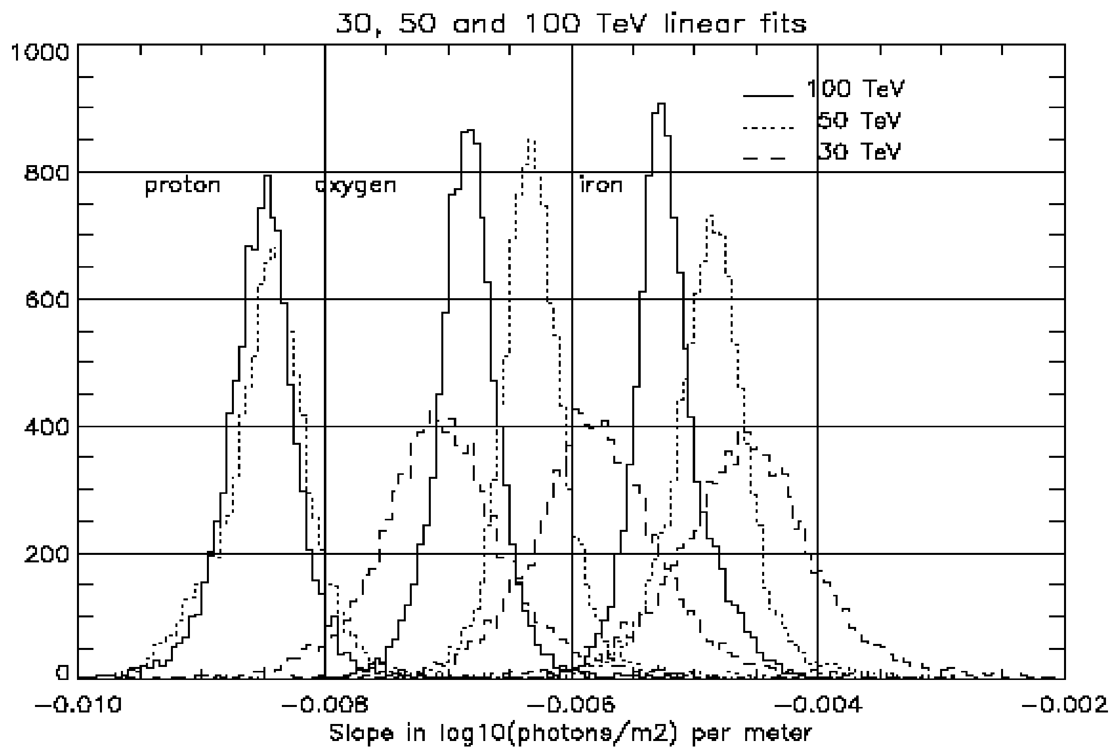
Mass determination

Cherenkov detectors determine the composition based on the sensitivity of the lateral distribution of Cherenkov light to the depth of shower max -remember that Fe interacts before than p in the atmosphere)

Most of the Cherenkov light is created at shower max. A flatter lateral distribution is expected for showers initiated by particles that interact higher in the atmosphere.

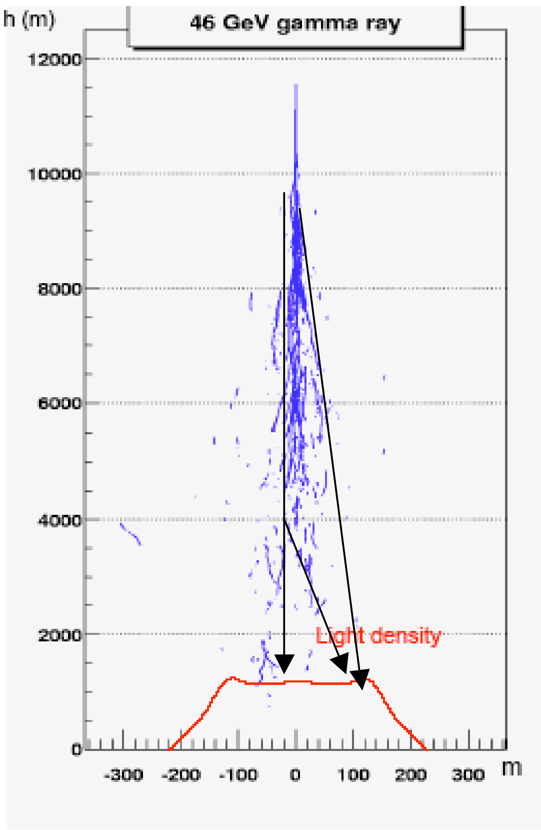
Later developing showers are steep.

Hence the shape of the lateral distribution inside about 150 m reflects the position of X_{max} The number of Cherenkov photons depends on the primary particle energy.

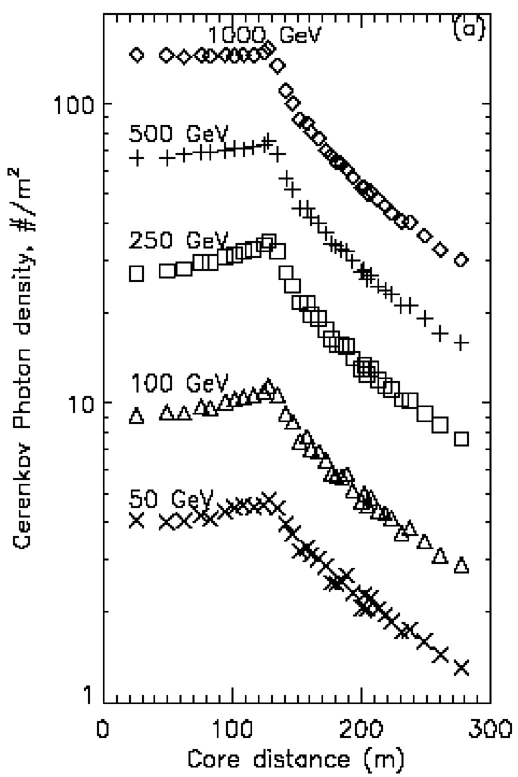


Milagro WACT Fit with a line in 50-200m the lat dr

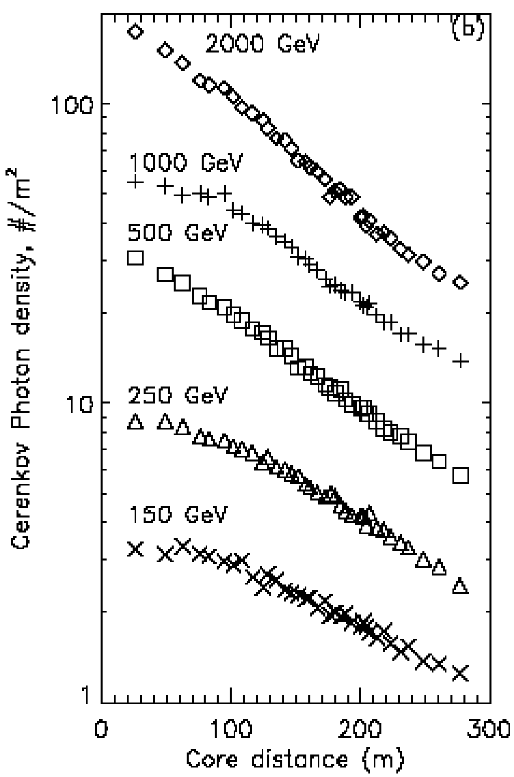
Gammas show a hump at about 135 m from the core for E up to 1 TeV
Due to the focussing of Cherenkov photons from a large range of heights
Where $\theta_C h$ = cost
For p, electrons are pair produced by gammas from π^0 decay.
Hence also the π^0 transverse momentum must be considered and the hump disappears because the threshold energy for electrons from protons is larger.



γ



p



Fluorescent detectors

Light emitted by excited N atoms by the shower
While the Cherenkov light is concentrated in the direction of the shower the flurescent light is isotropic (corrections for Cherenkov light must be applied)
Detectors trigger when many PMTs (FoV = 1 deg) are hit in coincidence and the shower looks like a luminous point moving through the sky at the speed of light.
The shower longitudinal profile and the primary CR energy can be measured after the shower trajectory is reconstructed.

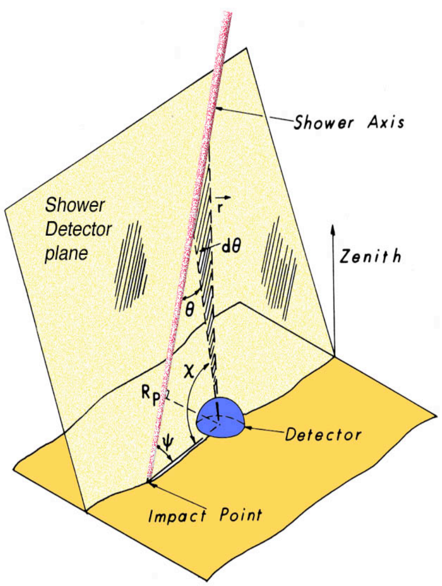
The triggered PMTs determine an arc in celestial coordinates that together with the position of the detector determine a plane.

Fluorescent detectors

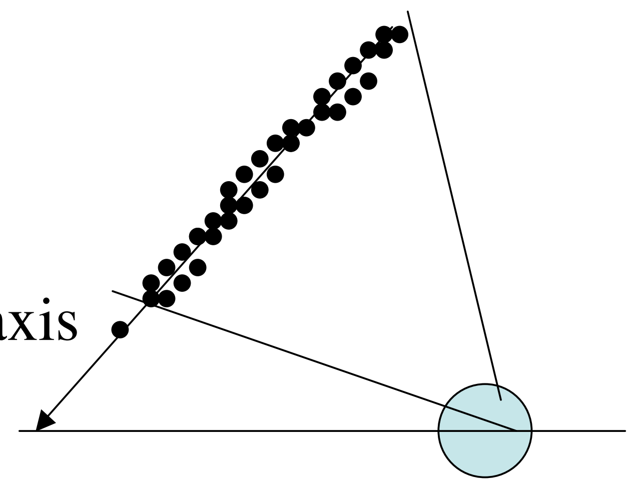
The triggered PMTs determine an arc in celestial coordinates that together with the position of the detector determine a plane.

When only 1 detector detects the shower the distance can be determined by the time differences between consequent triggered PMTs.

Showers far away from PMTs move more slowly than close ones since the fixed FoV of PMTs correspond to bigger distance along shower axis. Eg at 20 km a trajectory of length 2 deg is about 700m and the shower will take 2.3 μs to traverse it. At 10 km the time is 1/2 x 2.3 μs



Once the shower detector plane is determined, 2 variables need to be determined
R_p=impact parameter from detector to shower axis and Ψ



Stereoscopic fluorescent detectors

Stereoscopic observations: if 2 fluorescent detectors observe the shower development each of them determines a shower-detector plane and the shower trajectory is given by the intersection of the 2 planes.

The amount of light observed by each PMT is converted in pe vs atmospheric depth => direct observation of shower profile

Exercise 10 calculate photon intensity at the detector

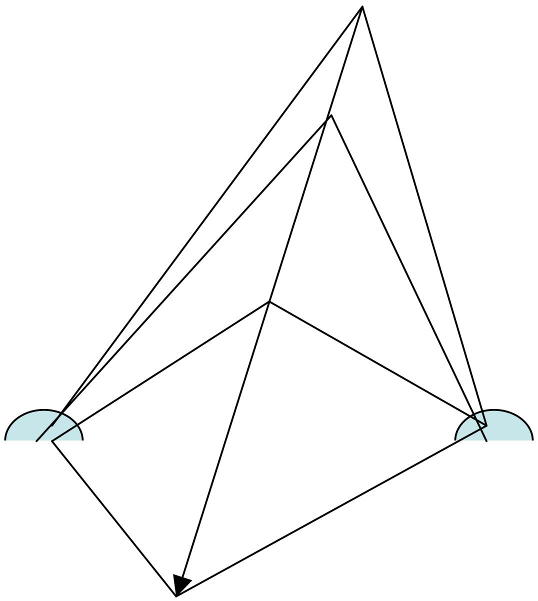
With such low numbers mirrors of large collection area are needed

Energy thresholds are around 10^{17}-10^{18} eV

The error of Hires on X_{max} is about ±20 g/cm^2 dominated by statistical fluctuations at each PMT

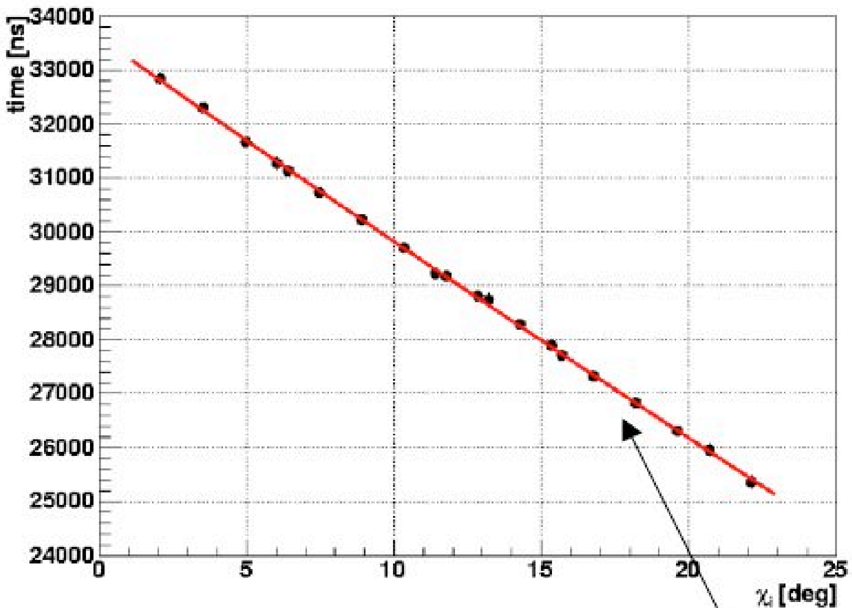
The shower energy is determined, given the shower profile, as

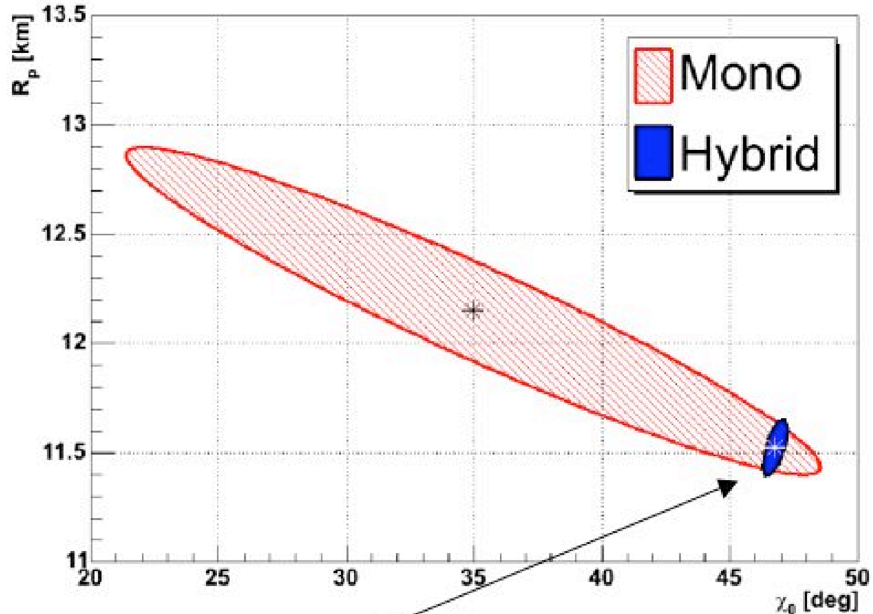
$$E_{em} = \alpha \int_0^\infty N_e(X)dX$$



Where a = average ionization E loss rate = 2.2 MeV/g/cm^2.

Hybrid vs Monocular





≈ line but

3 free parameters

T_0 from tank!

$$t(\chi) = T_0 + \frac{R_p}{c} \tan\left[\frac{(\chi_0 - \chi)}{2}\right]$$

Shower energy determination

The shower energy is determined, given the shower profile, as

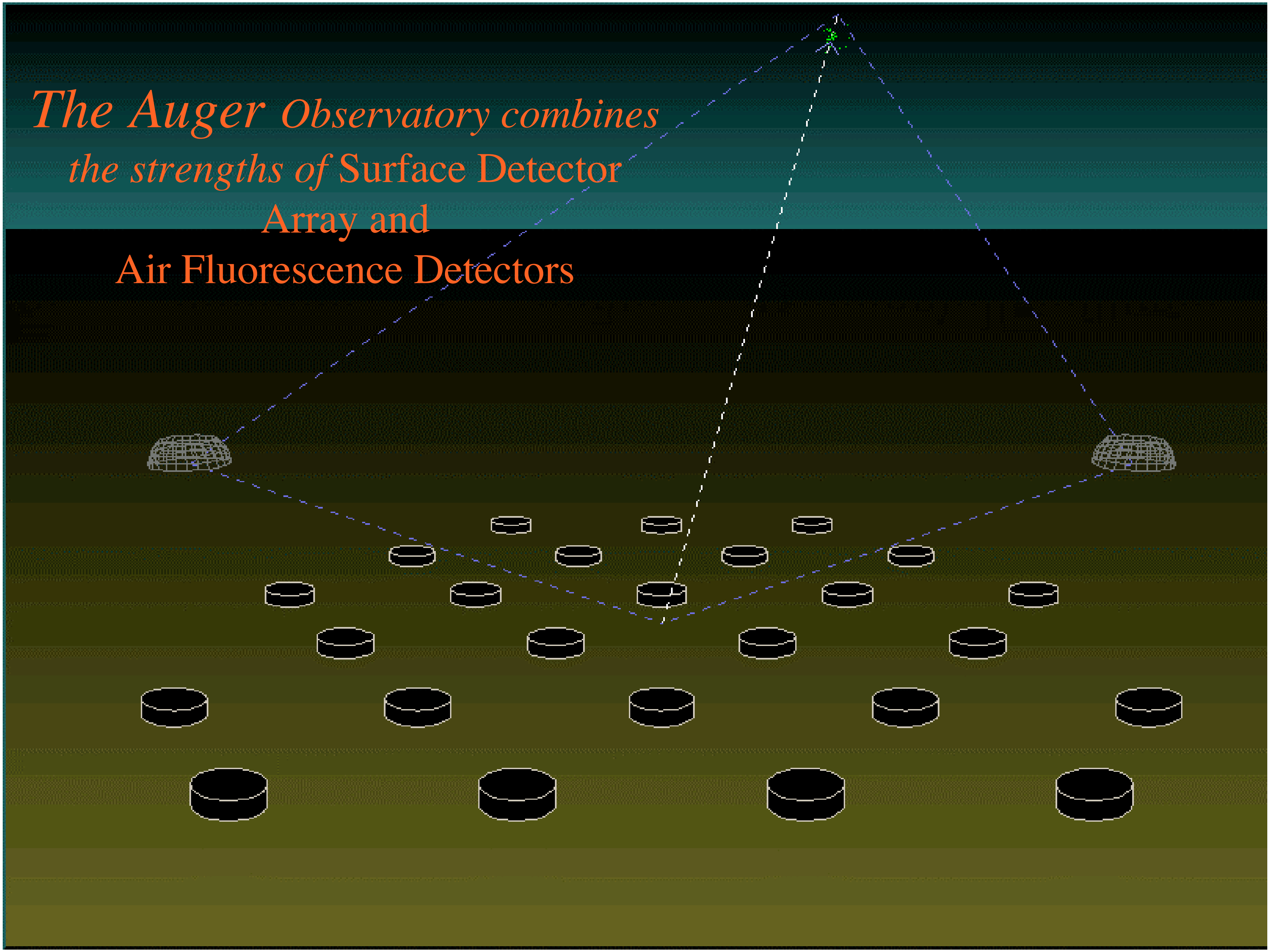
$$E_{em} = \alpha \int_0^\infty N_e(X)dX$$

Where α = average ionization E loss rate = 2.2 MeV/g/cm^2.

This must be corrected for the missing energy due to neutral particles that do not decay into charged ones (eg neutrinos), high energy muons that lose few energy in the atmosphere, nuclear excitation of nitrogen by hadrons that is not converted into scintillation light.

Corrections are approximately 30-40% at 10^{14} eV.

The Auger Observatory combines the strengths of Surface Detector Array and Air Fluorescence Detectors



Ground arrays

Oldest technique in the field: Rossi group at MIT in late 1940
Array at Harvard consisting of 12 0.9m^2 scintillators up to 1 EeV

1959: Vulcano Ranch in New Mexico 19 3.26 m^2 scintillators almost 1 km apart covering about 10 km up to 10 EeV

1962-87: Haverah Park (England) with water tanks that absorb the em component and produce Cherenkov light (a vertical muon on average produces 220 MeV (10 km^2)

Yakutsk: scintillators, Cherenkov light detectors and muon detectors (20 km^2) with smaller spacing

Akeno: 1979 20 km^2 -> Agasa 100 km^2

Sidney: 100 km2 array of muon counters of 6 m2 of liquid scintillator viewed by 1 PMT on a 1600 m square grid buried to have a muon threshold of 1 GeV

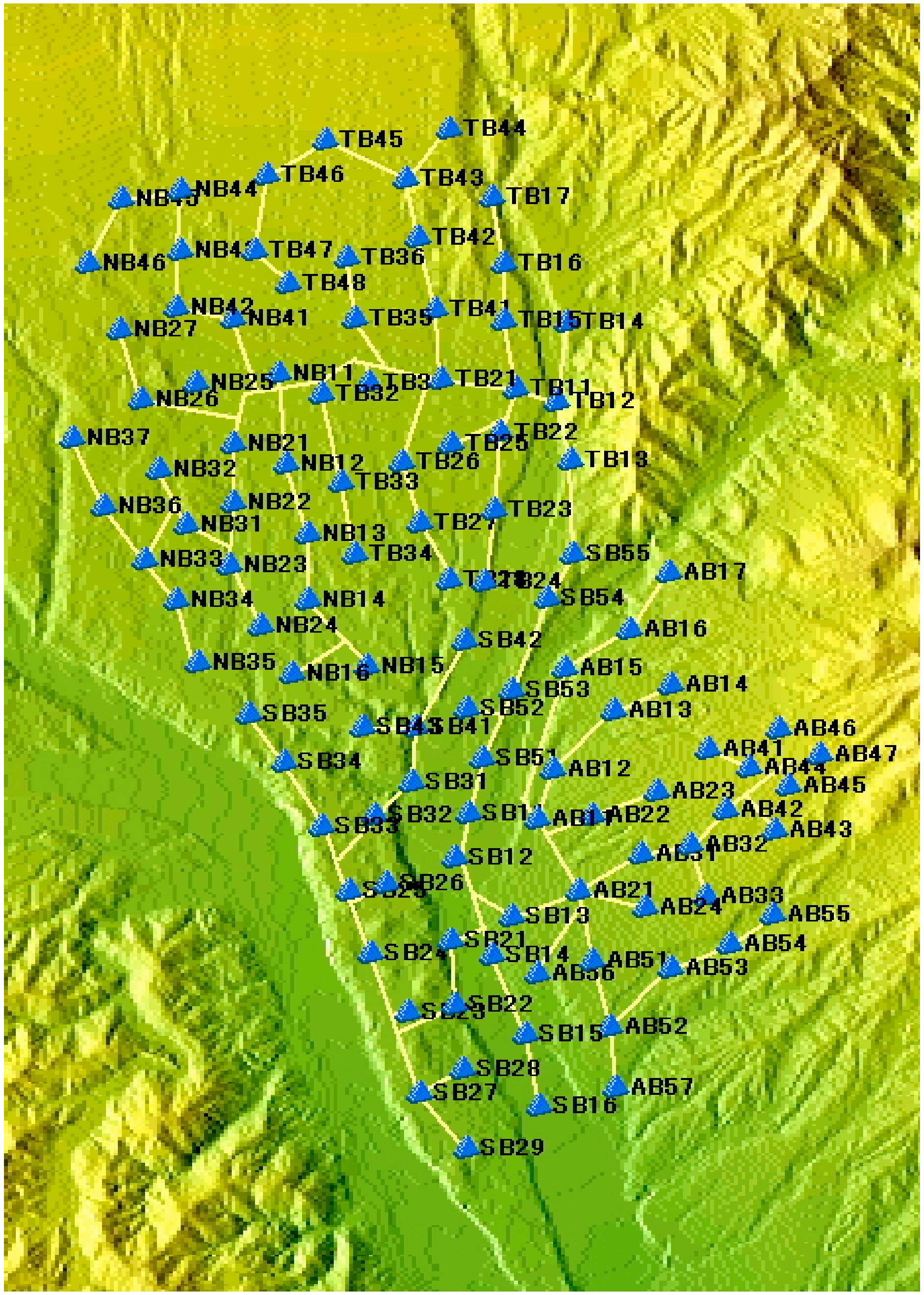
AGASA

Akeno Giant Air Shower Array

111 electron detectors of 2.2 m^2 separated by about 1 km covering About 100 km^2 connected by pairs of optical fibers

27 muon detectors

In the SE corner there is the Akeno 1 km^2 array (since 1979) between $10^{14.5}$-$10^{18.5}$ eV

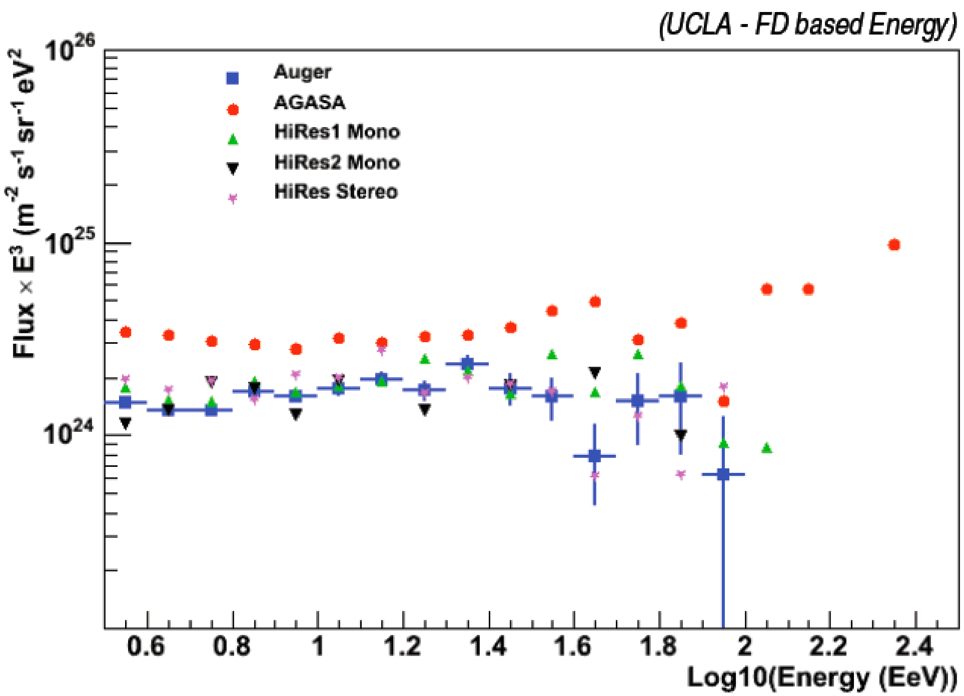


AGASA E spectrum

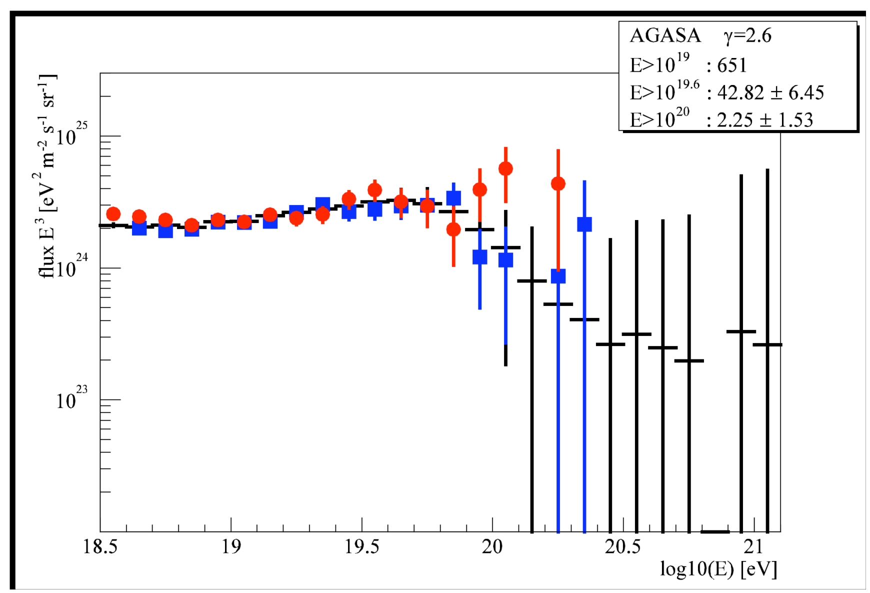
11 events with E > 10^{20} eV

M. Takeda et al. ICRC03

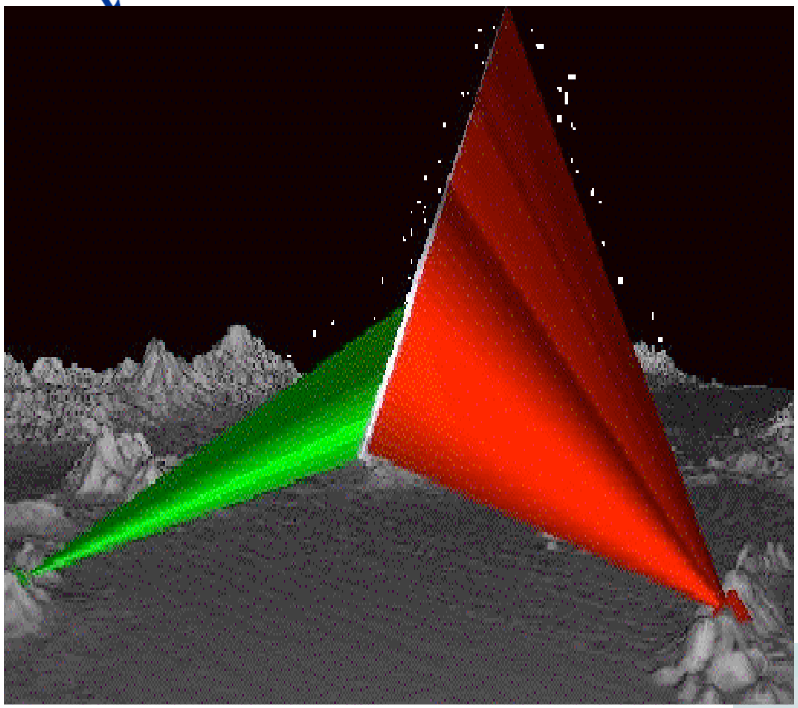
AGASA systematic errors ~ 18%

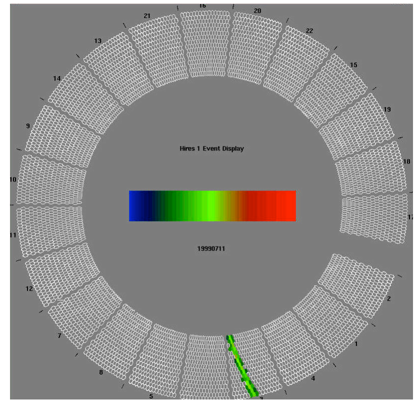


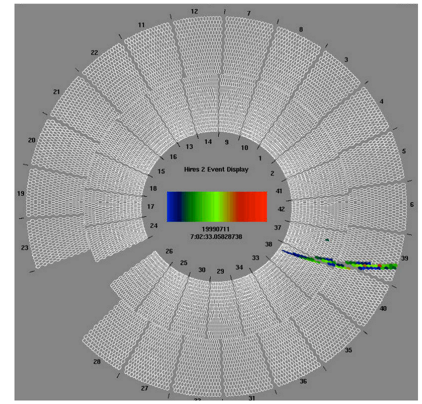
AGASA -15%



The *High Resolution* Fly's Eye







HiRes 1 **HiRes 2**

- **Air fluorescence detectors**
- **HiRes 1 - 21 mirrors**
- **HiRes 2 - 42 mirrors**
- **Dugway (Utah)**
- **start '97HR1 '99HR2**

Possible systematics in HiRes

Most of them are energy dependent

Air Fluorescence yield

- Total yield is known with 10~20% accuracy
- Yields of individual lines are not known well
  - Rayleigh Scattering effect ($\propto 1/\lambda^4$)

Light transmission in air

- Mie Scattering
  - Horizontal attenuation, Scale Height, Wind velocity, Temperature → single model represents whole data
  - Horizontal 12km (1999) → 25km (2001)

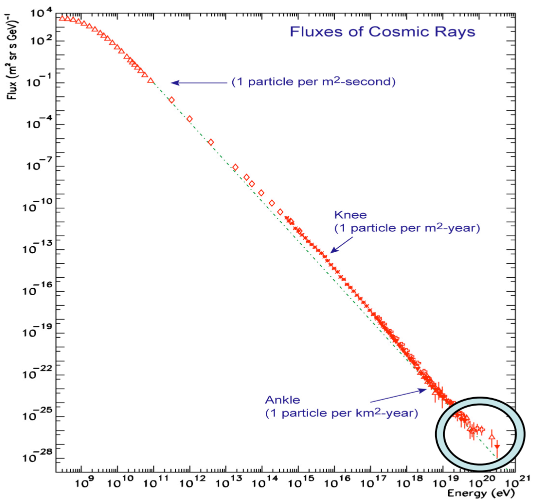
Cherenkov light subtraction

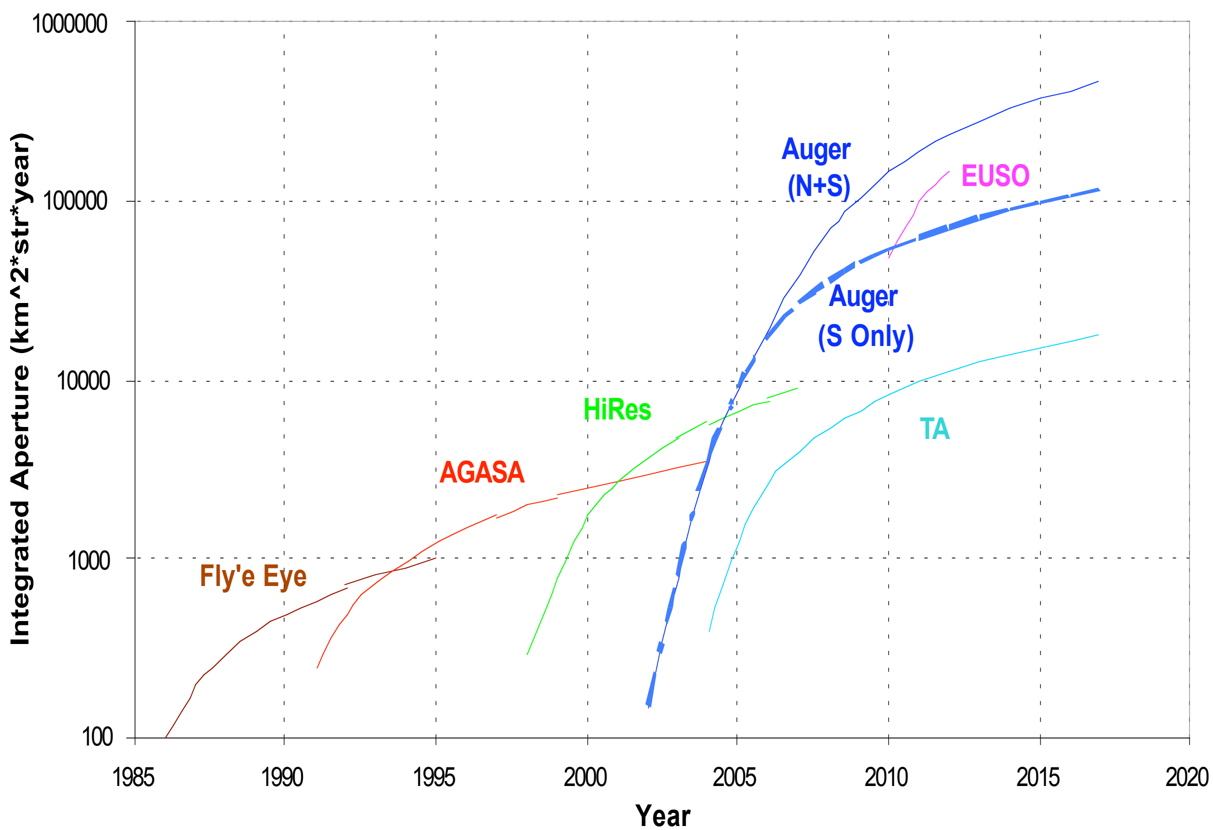
Bias by Narrow FOV in elevation

Errors in Mono analysis

- Aperture estimation (Narrow F.O.V.)
  - Chemical composition / Interaction dependent

Exposures at ICRC2003





Pierre Auger

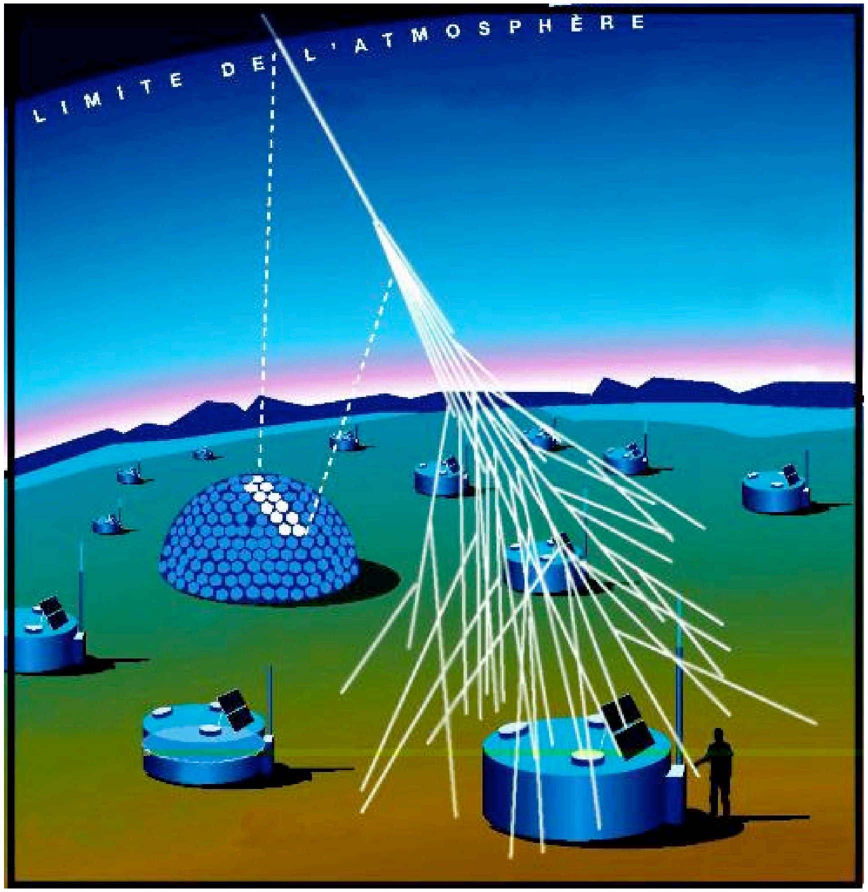
- 2 Giant Ground Arrays (30 x AGASA) with Fluorescent detectors (HYBRID detector)
- independent techniques allow control of systematics

Challenge: to reach

$> 10^4 - 10^5$ km^2 sr yr

Present experiments

$\sim 10^3$ km^2 sr yr



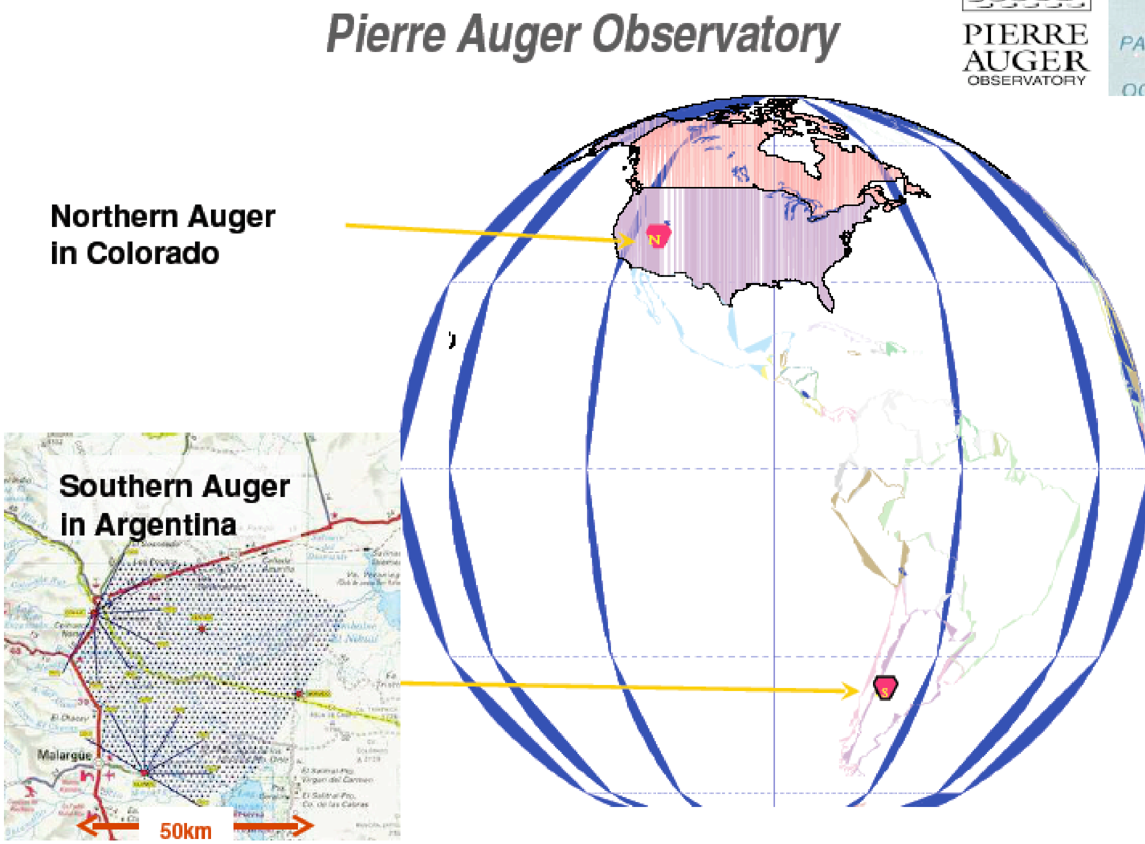
PIERRE AUGER Observatory (South)

3,000 km^2 array + 4 Fluorescence Telescopes

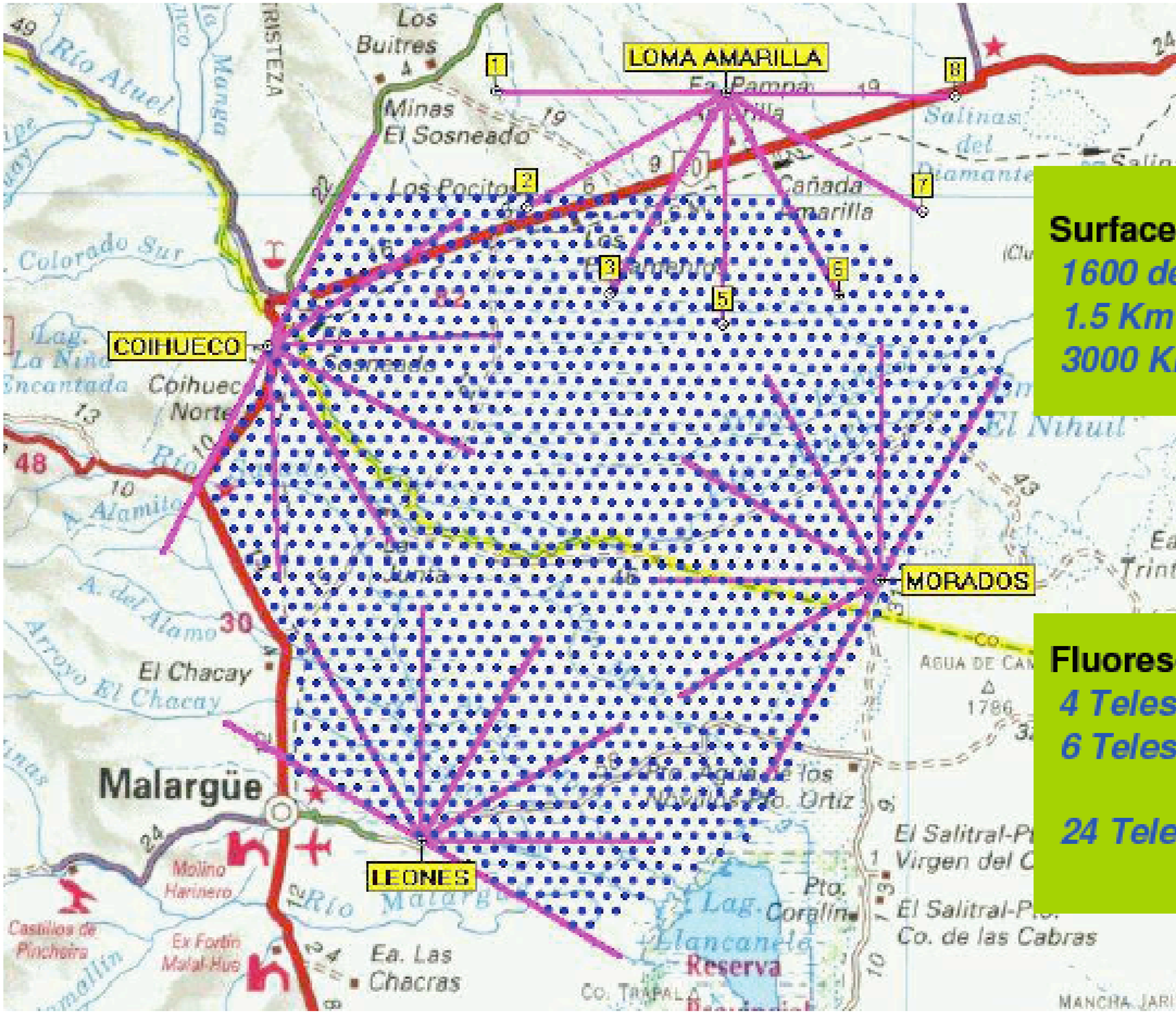
Aperture 6,600 km^2 sr - reach $> 10^4$ in 2 years

The observatory

PIERRE AUGER OBSERVATORY



The plan



Surface Array

1600 detector stations

1.5 Km spacing

3000 Km²

Fluorescence Detectors

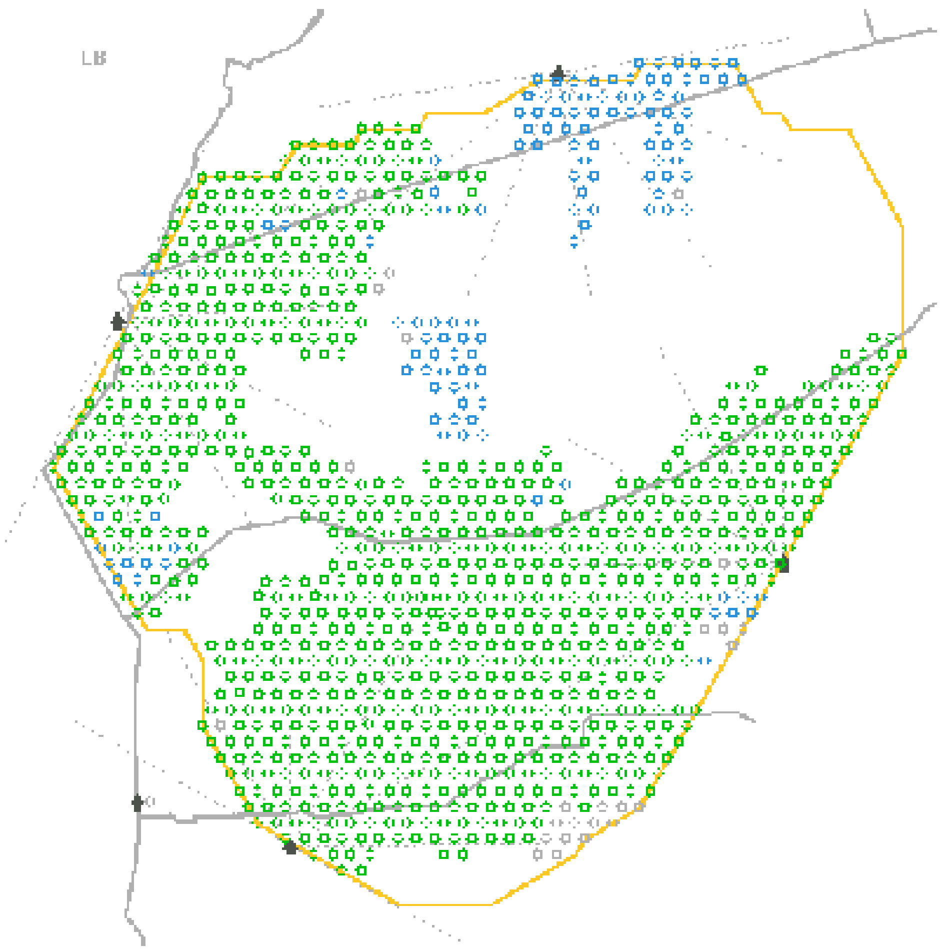
4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

AGASA spectrum >> 100 events/yr above 10^{20} eV

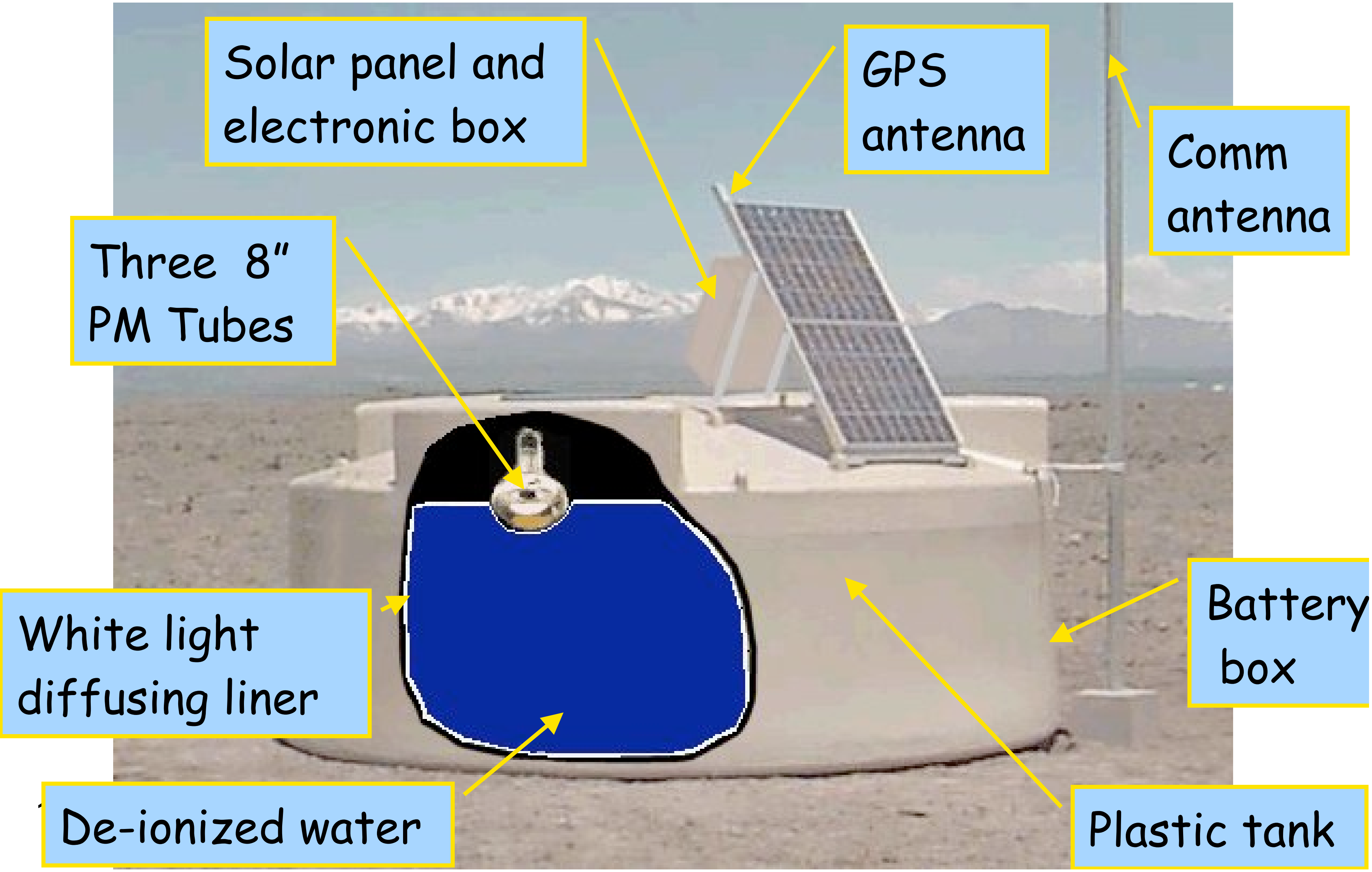
Status



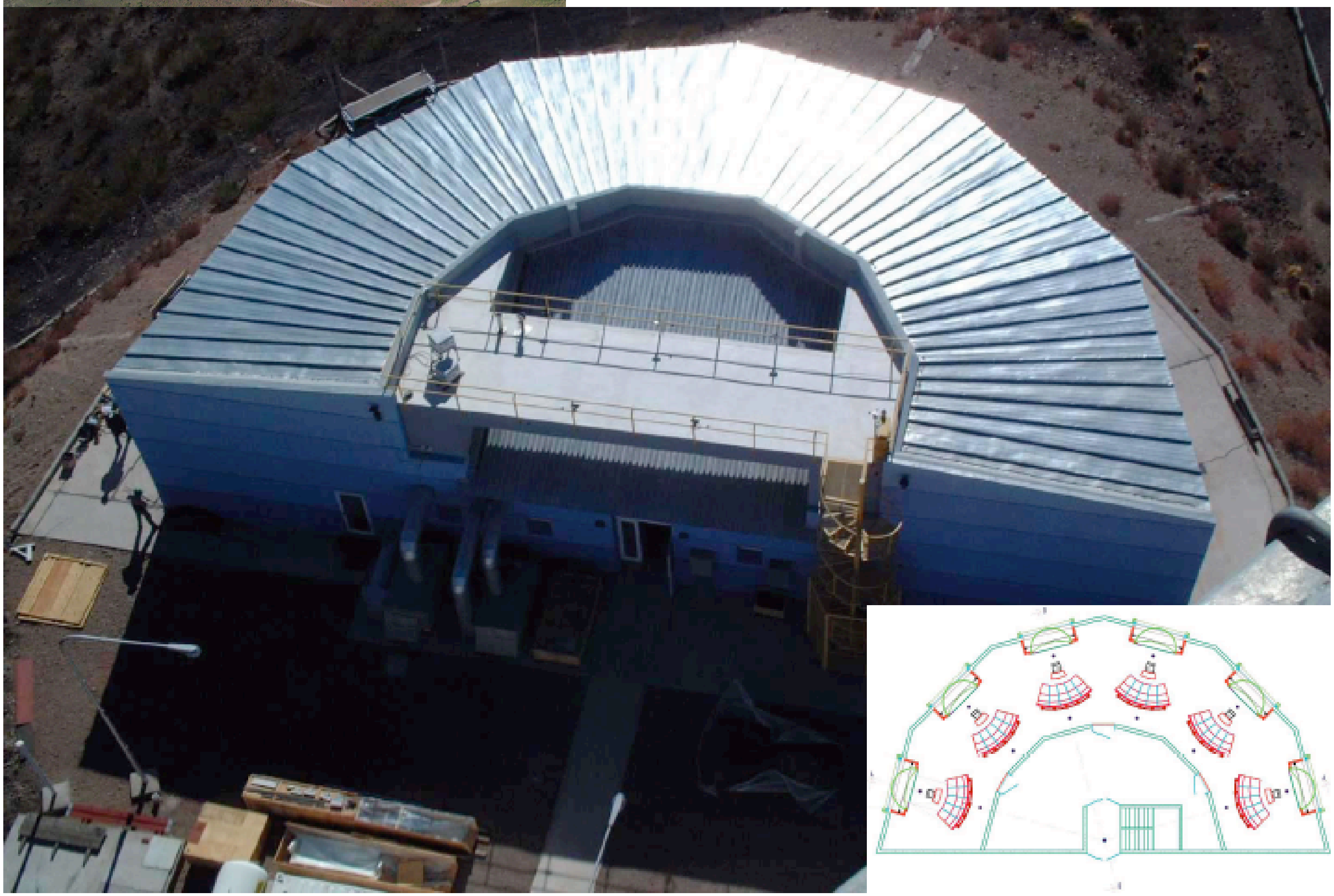
15 February 2006

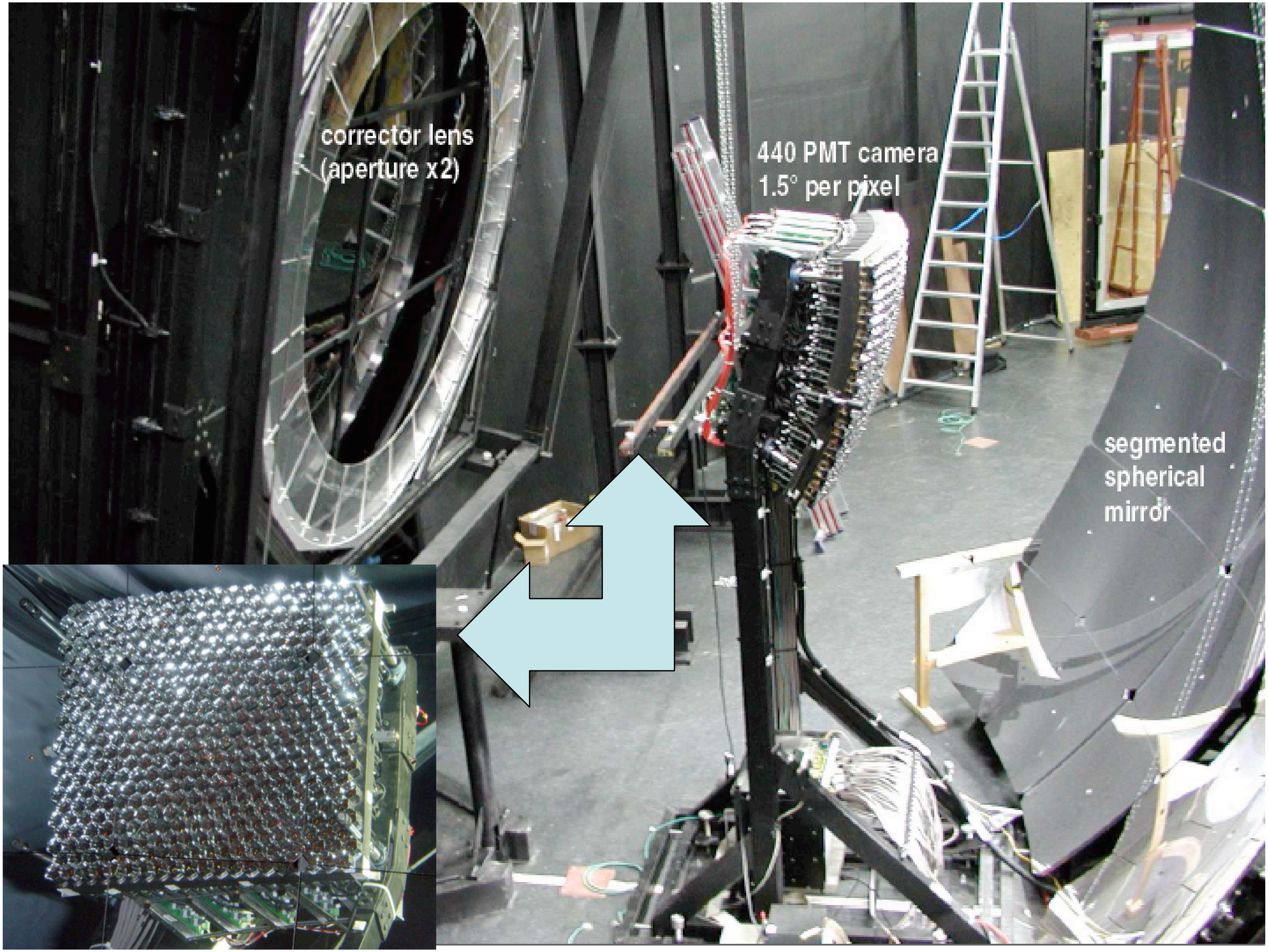
There are 1115 tanks deployed, 1043 with water and 919 with electronics

Surface Detectors

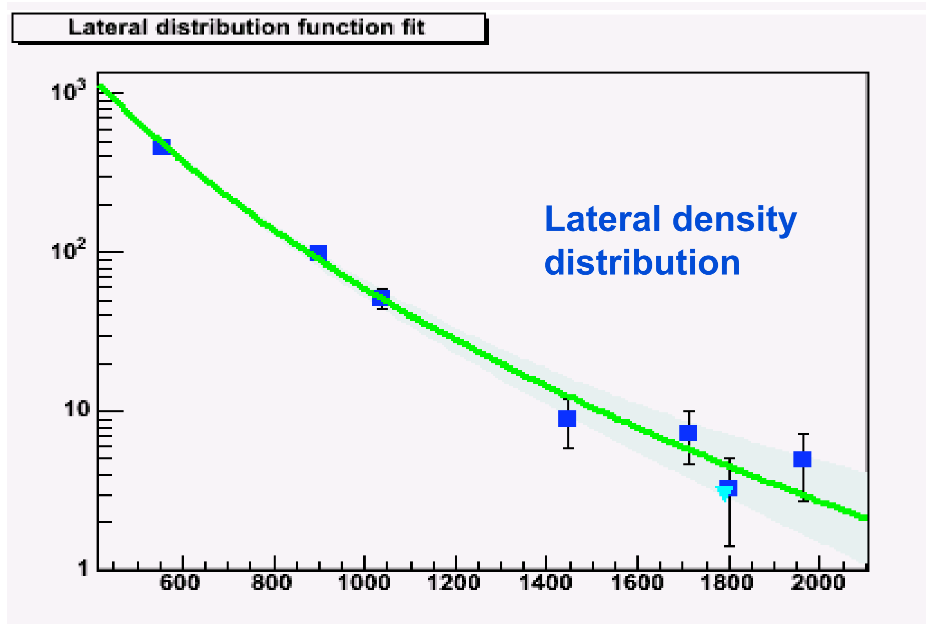


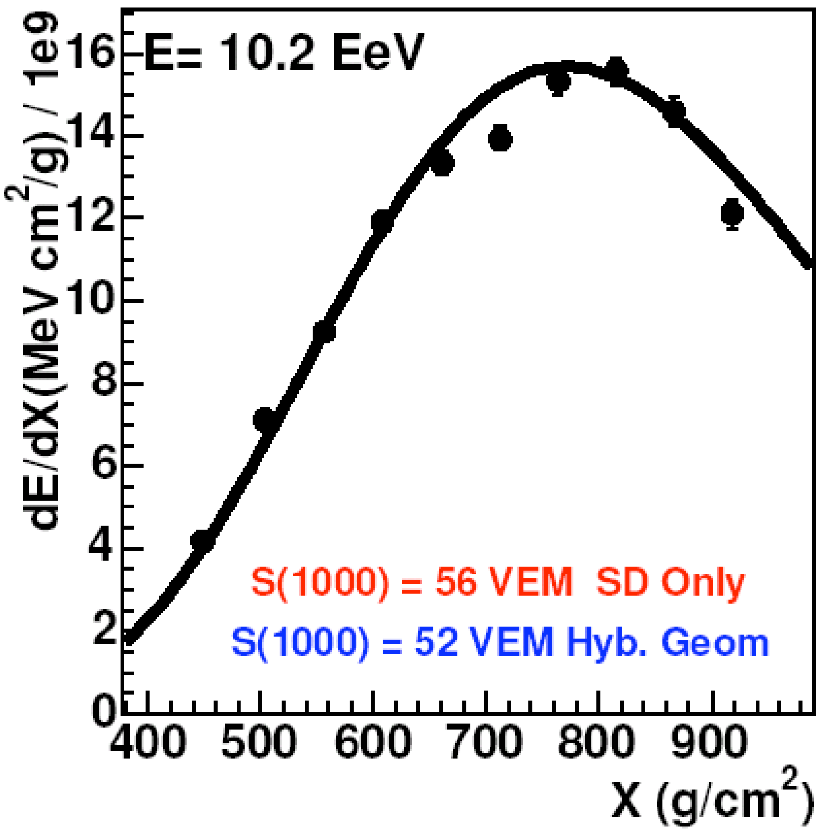
Fluorescent detectors

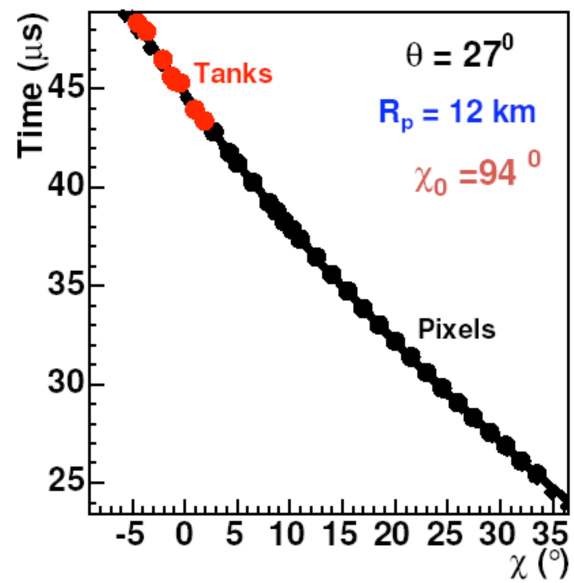


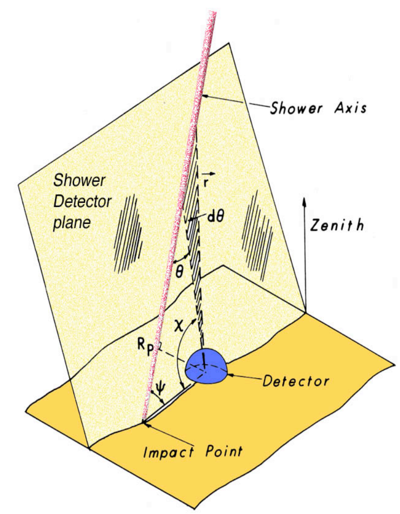

corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segmented
spherical
mirror

Zenith angle ~ 30º, Energy ~ 10 EeV FD (hybrid events) have both traverse and longitudinal shower information



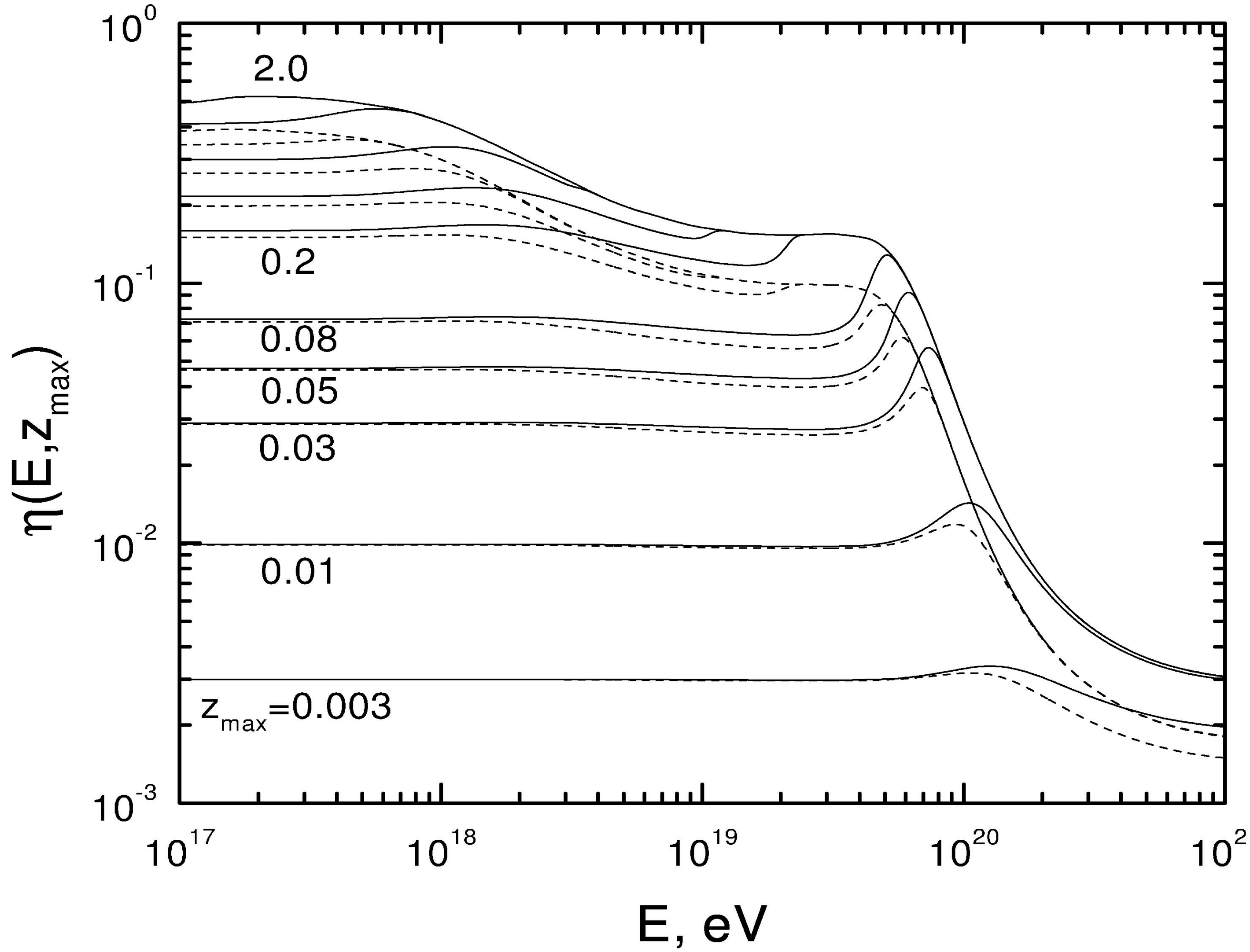






Energy Losses of protons

Berezinsky et al. 03

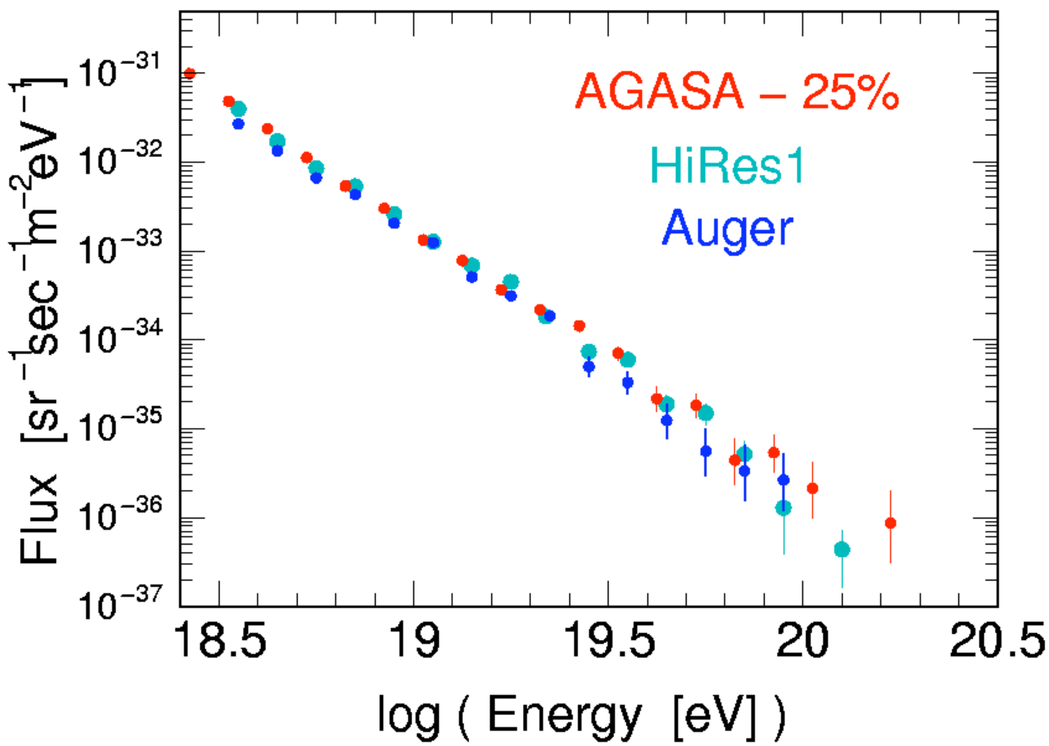


modification factor: $J_{obs}(E,z) = \eta(E,z) \times J_{injec}(E)$

Energy spectrum in Auger

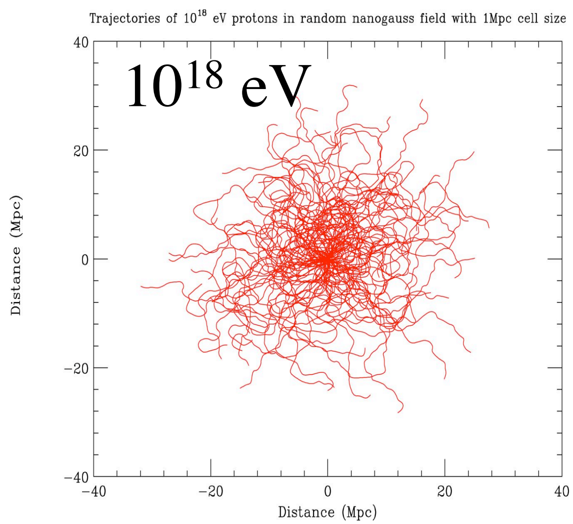
- SD data → ground parameter S(1000) = SD signal at 1000m
- Determine the S(1000)→ Energy & Zenith Angle conversion
  - Zenith Angle dependence: SD and Hybrid data
  - Fluorescence Detector energy scale Normalization via Hybrids (error < 25%)
- + SD exposure

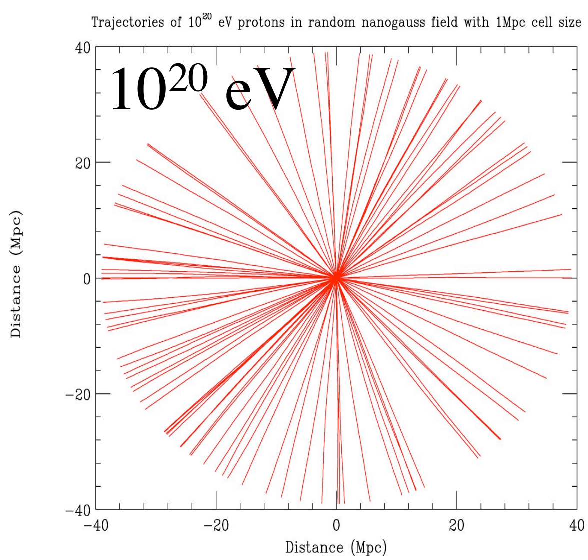
→ measured spectrum.



Anisotropies

Astronomy with p is possible at Energies above ~ 10^{19} - 10^{20} eV

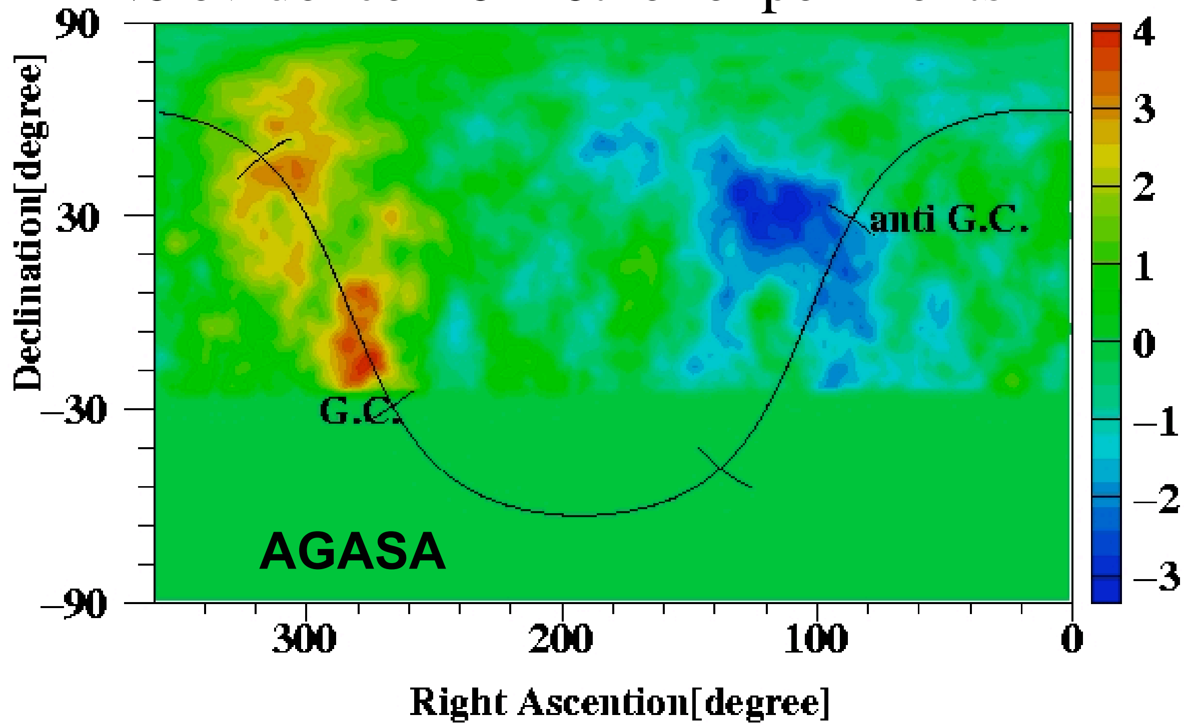




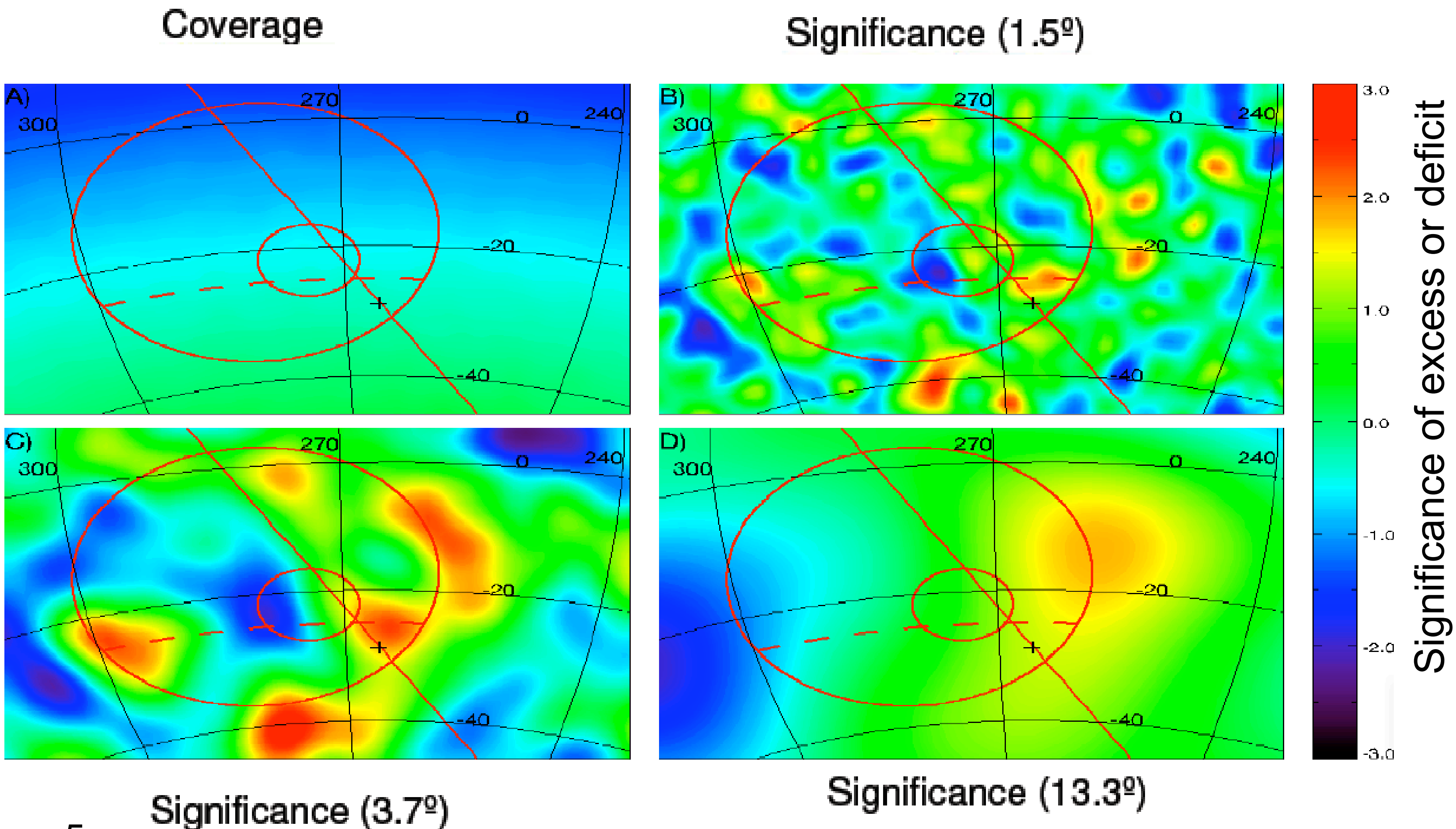
- AGASA: excess 4.5σ 20 deg window near the GC with E=1-2.5EeV.

http://arxiv.org/pdf/astro-ph/9906056

- SUGAR 2.9σ excess with 5.5 degree window near the GC with E=0.8-3.2EeV.
- No evidence from other experiments



Auger sees nothing (ICRC2005)!



Suggested readings

P. Sokolsky Introduction to Ultrahigh Energy Cosmic Ray Physics
Addison-Wesley 1989

Stanev High Energy Cosmic rays Springer 2004

T.K. Gaisser Cosmic Rays and Particle Physics
Cambridge University Press, 1990.

M. Lemoine & G. Sigl, Physics and Astrophysics of Ultra-High-Energy Cosmic Rays

http://pdg.lbl.gov/2005/reviews/cosmicrayrpp.pdf