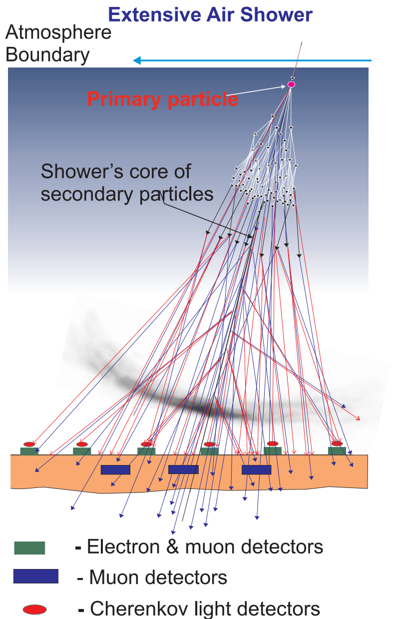
The Cosmic Ray Spectrum at Ultrahigh Energies

M.I. Pravdin

Yukutsk EAS Array

Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, 31 Lenin Ave., 678980 Yakutsk, Russia



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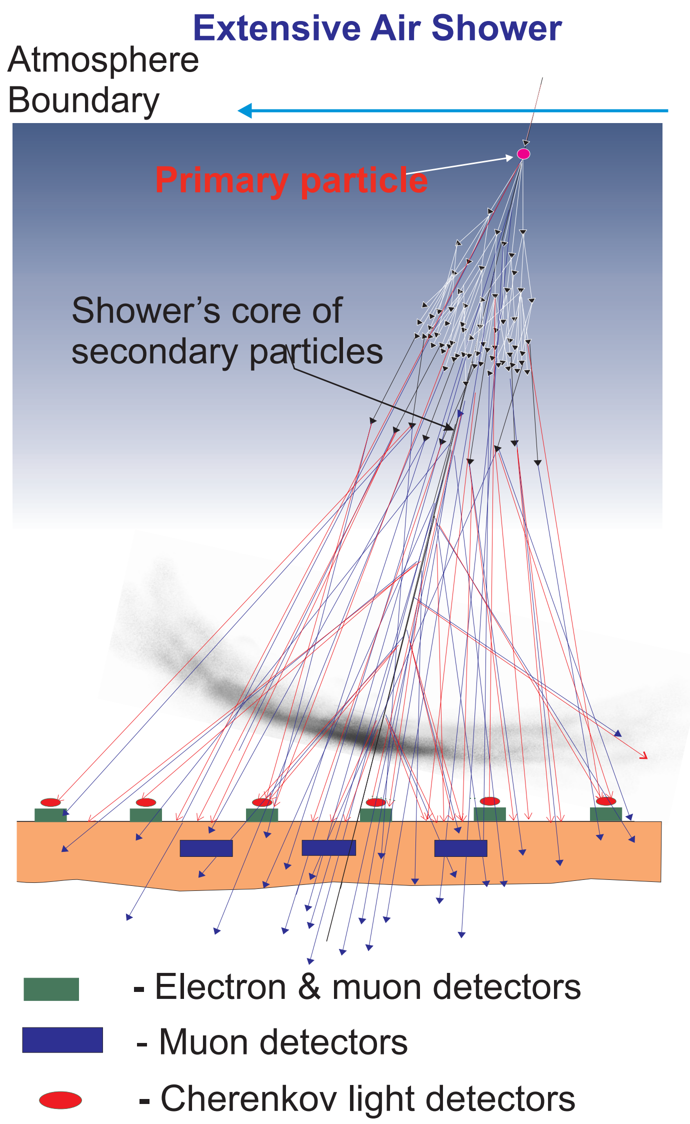
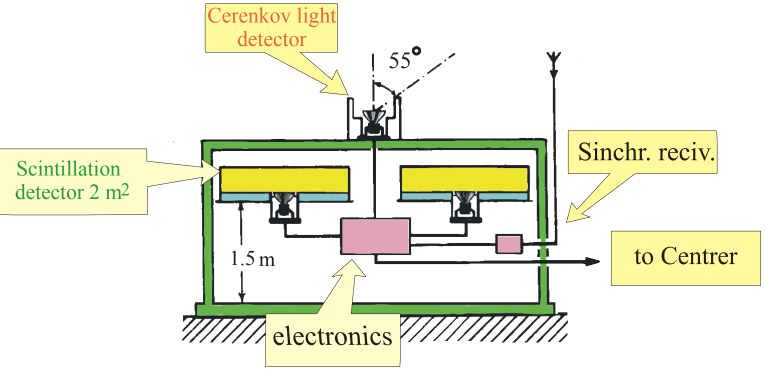
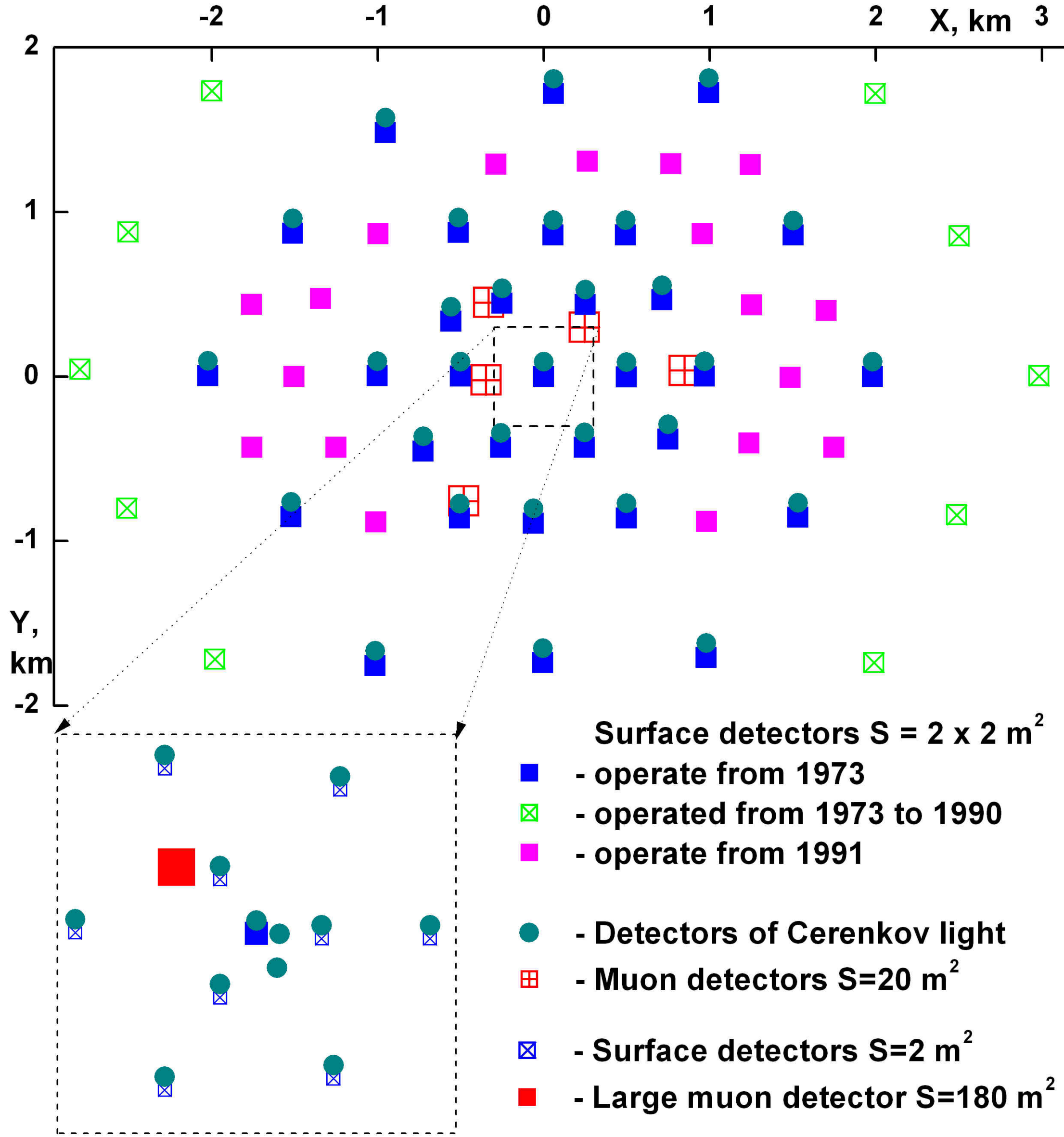
Outline

- Yakutsk EAS Array
- AGASA
- HiRes
- Auger
- Energy Spectrum
- Yakutsk Muon Data
- Conclusions



Yakutsk EAS array 10 km² (18 km² in 1973-1990)





49 surface detectors

S_{det}=2x2 m^2;

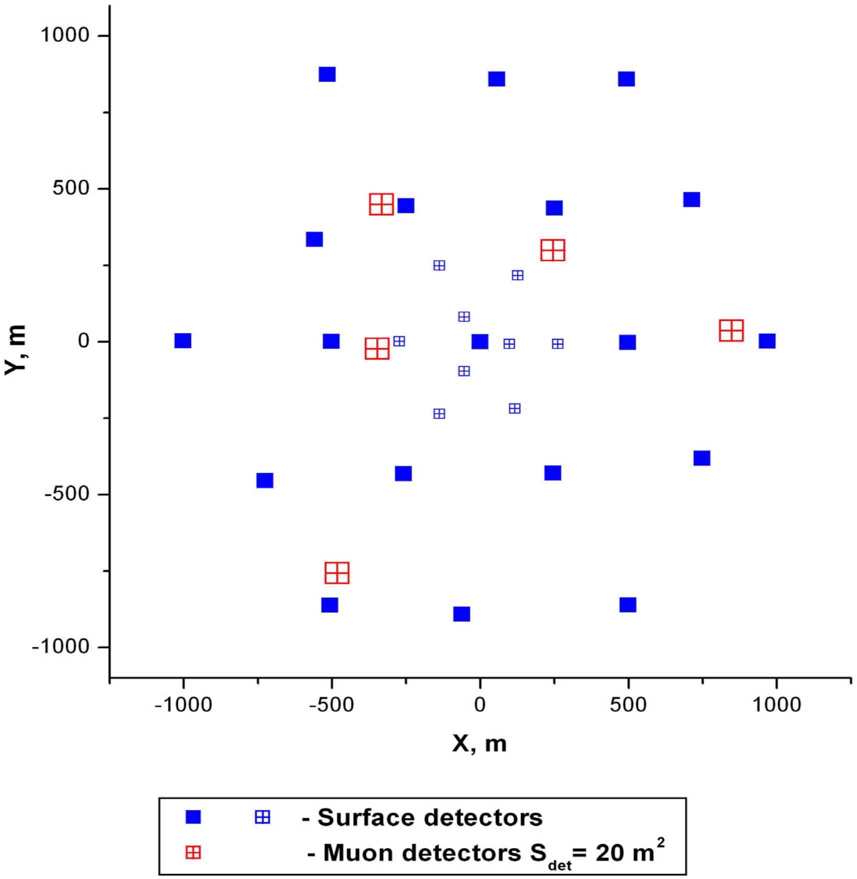
9 surface detectors

S_{det}=2 m2;

31 detectors of Cerenkov light

Distance between detectors – 500 m

Yakutsk EAS array 10 km^2 (18 km^2 in 1973-1990)



2 muons detectors S_{det}=20.25 m^2 and 3 ones S_{det}=20 m^2

Threshold energy of muons 1/ cos(θ) GeV

Estimation of shower energy E_0

Size parameter of EAS (energy estimator)

S600 - density at a distance of 600 m from the shower core

$S600(\theta)$. $S600(0^{\circ})$. E_0

The calorimetric formula

The relation between parameters S600(0˚) and primary particle energy E_0 for showers close to the vertical has been determined by the calorimetric method:

$$E_0 = E_i + E_{el} + E_{\mu} + E_{\mu i} + E_{\nu} + E_h$$

$E_i = k \cdot \Phi$ is the energy lost by a shower over the observation level. It is estimated by measurements of total Cerenkov light flux Φ

E_{el} - the energy of cascade below the array level

E_{μ} - the energy of the muon component.

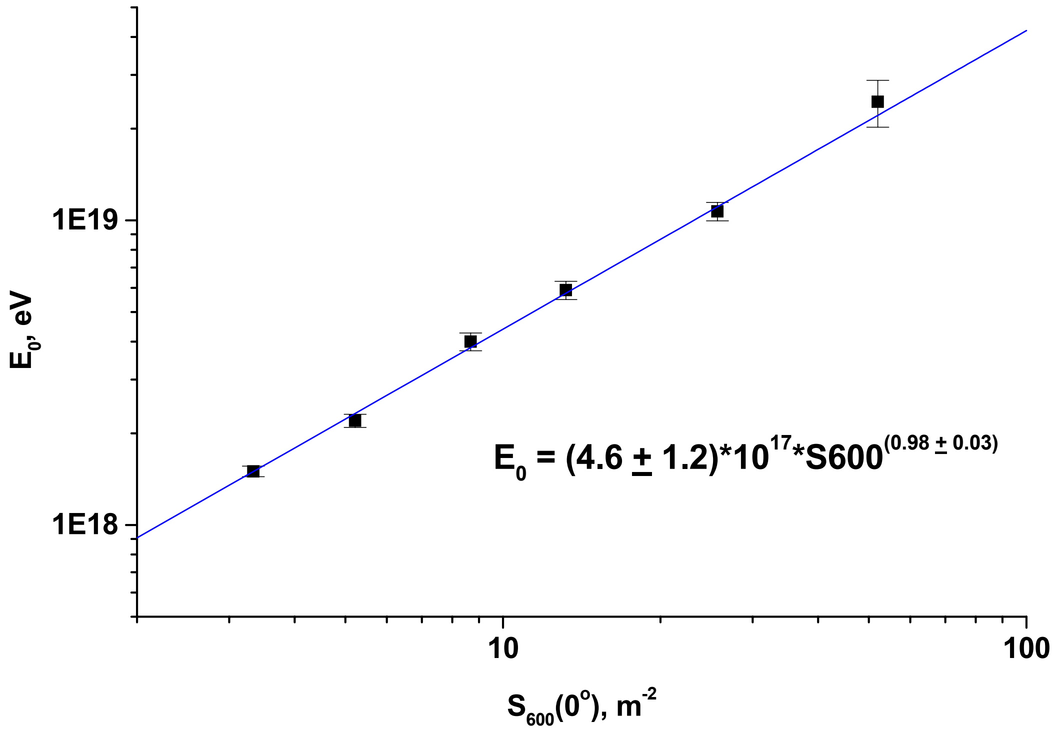
For $E_0 \cong 10^{19}$ eV :

$E_i / E_0 \cong 74\%;$

$(E_{\mu i} + E_{\nu} + E_h) / E0 \cong 7.4\%$ energy of muons losses on ionization, the neutrino and nuclear reactions

Yakutsk EAS array

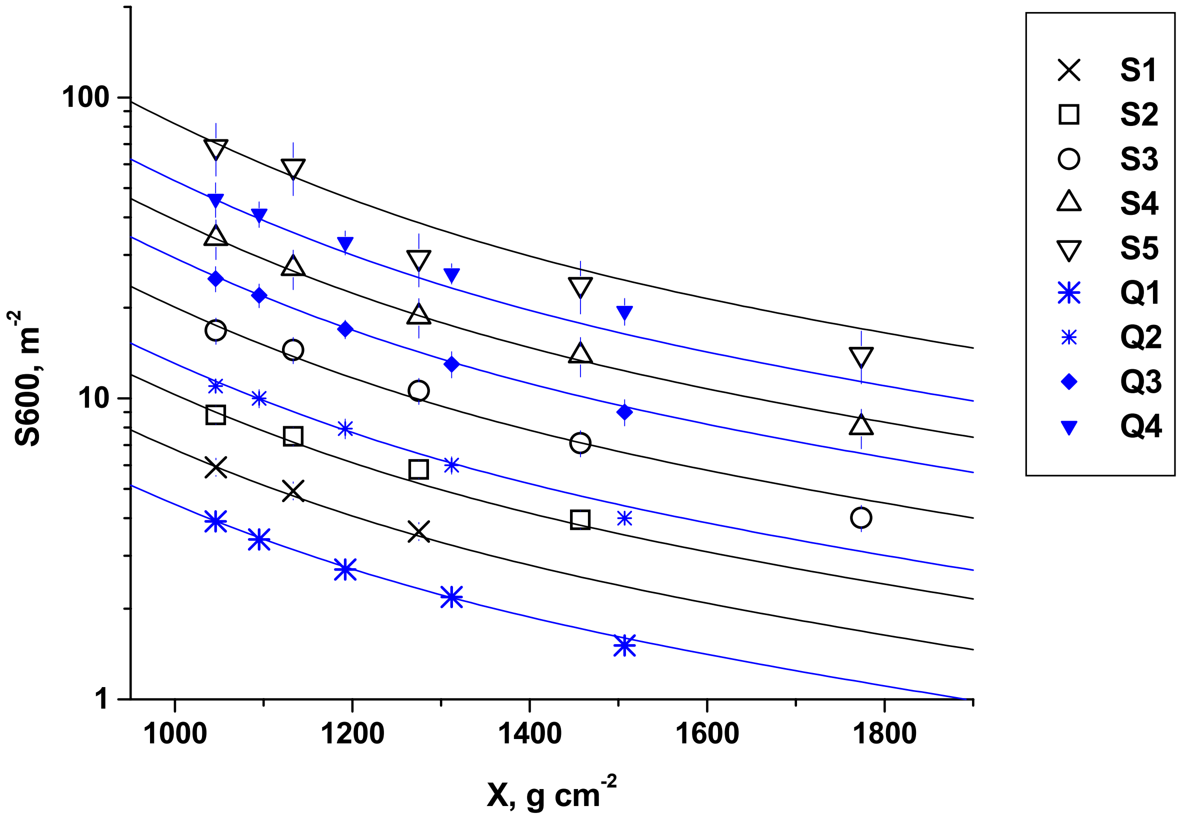
Estimation of shower energy E_0



Ratio between shower energy E_0 and $S_{600}(0^o)$ determined by the calorimetric method

$$E_O = (4.6 \pm 1.2) \cdot 10^{17} \cdot S_{600}(0^o)^{0.98 \pm 0.03}$$

Estimation of shower energy E_0



Zenith angle dependence S600

S_{600} versus the atmospheric depth X for different energies.

Akeno Giant Air Shower Array AGASA

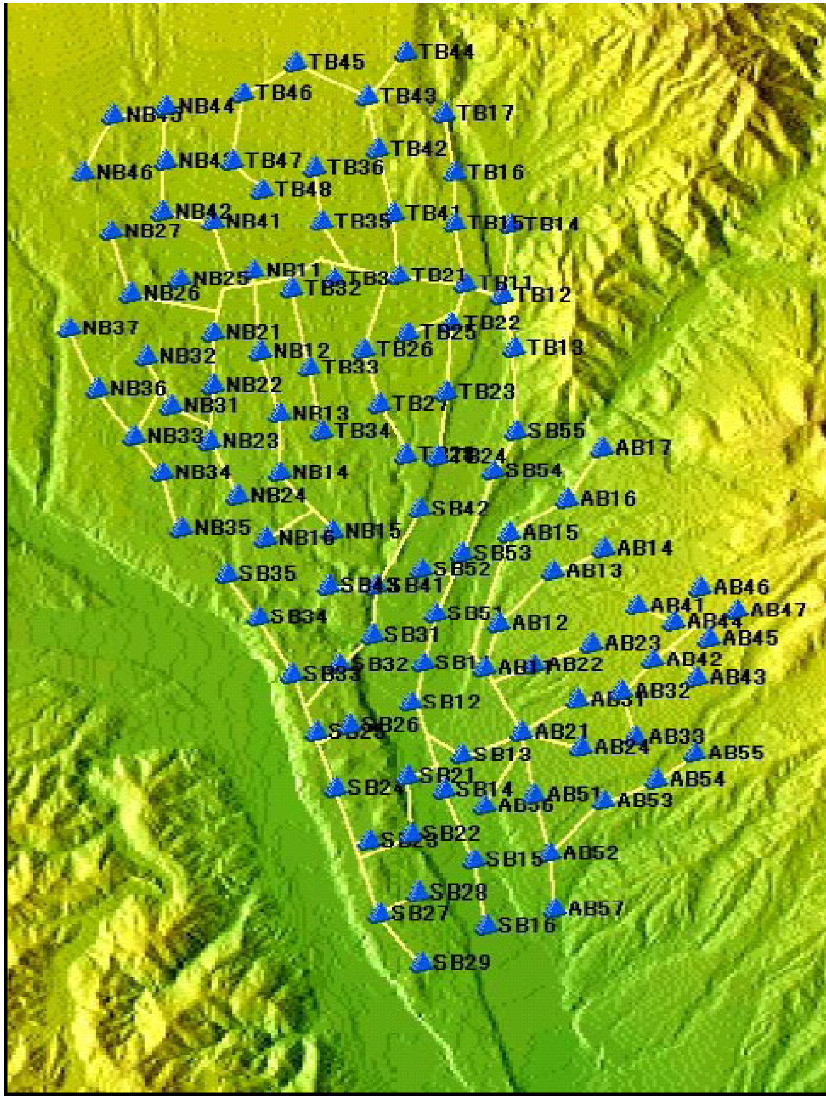
Area – 100 km^2
Distance between detectors – ≈1000 m

Energy estimator – S600
S600(θ) . S600(0.) . E0

Zenith angle dependence S600 – from experiment

Energy formula from model simulations

11 events > 10^{20} eV (2003)



111 scintillators + 27 muon det.

The High Resolution Fly's Eye - HiRes

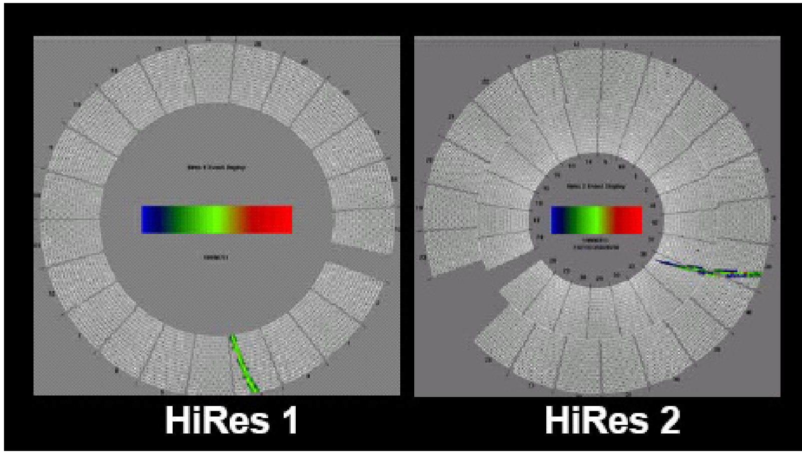
Fluorescence Technique

HiRes 1 – 21 mirrors

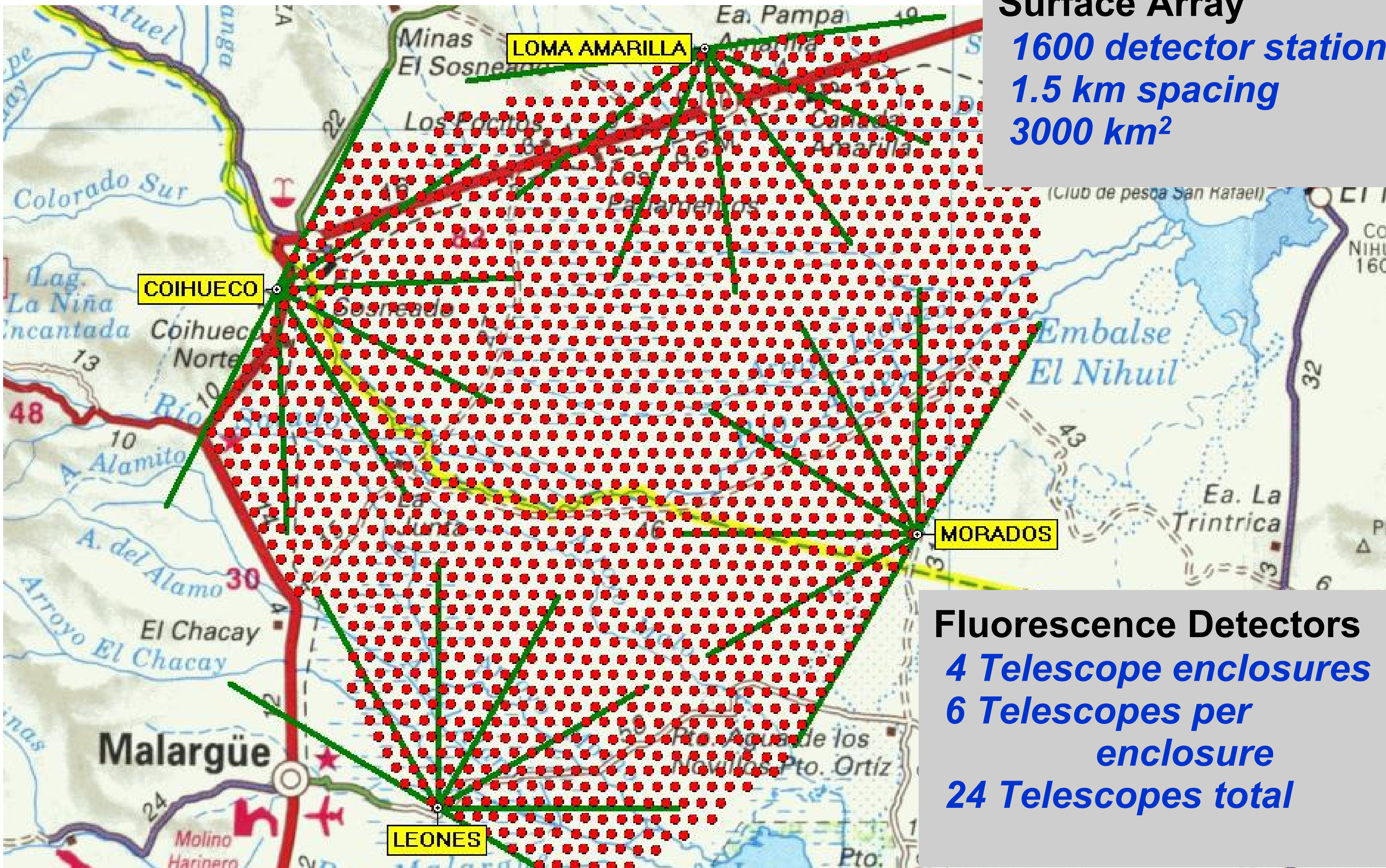
HiRes 2 – 42 mirrors

Xmax, Nmax from EAS profile

Nmax → E0



Pierre Auger Observatory



Surface Array

1600 detector stations

1.5 km spacing

3000 km^2

Fluorescence Detectors

4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

Pierre Auger Observatory

Energy estimator – ρ1000

ρ1000(θ) . ρ1000(38.) . E0

Zenith angle dependence **ρ**1000 – from experiment

Energy formula from fluorescence detector data

Fluorescence Technique

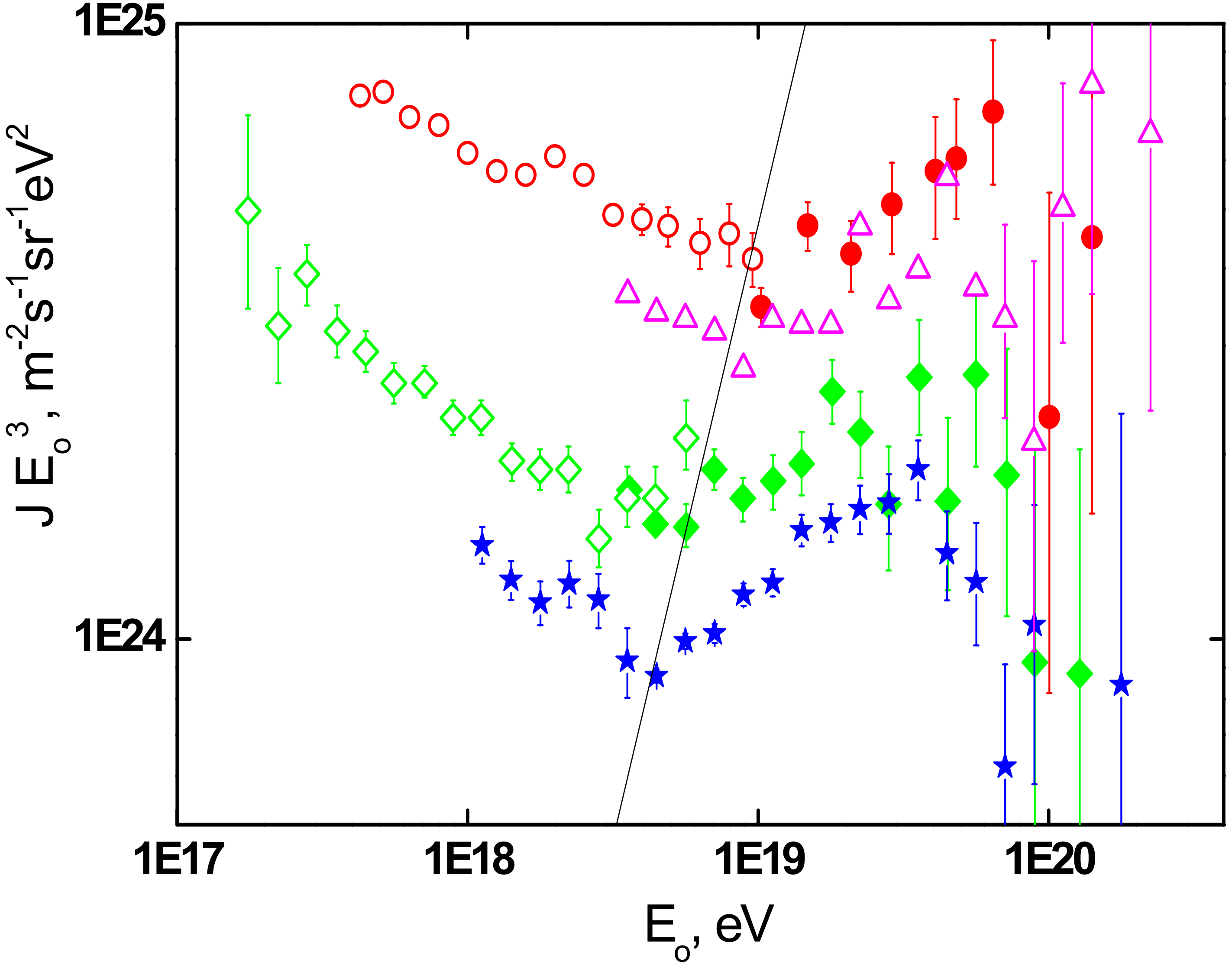
Xmax, Nmax from EAS profile

Nmax → E0

Differential energy spectrum:

Yakutsk – circles, AGASA – triangles,

Auger – asterisks, HiRes – diamondsn



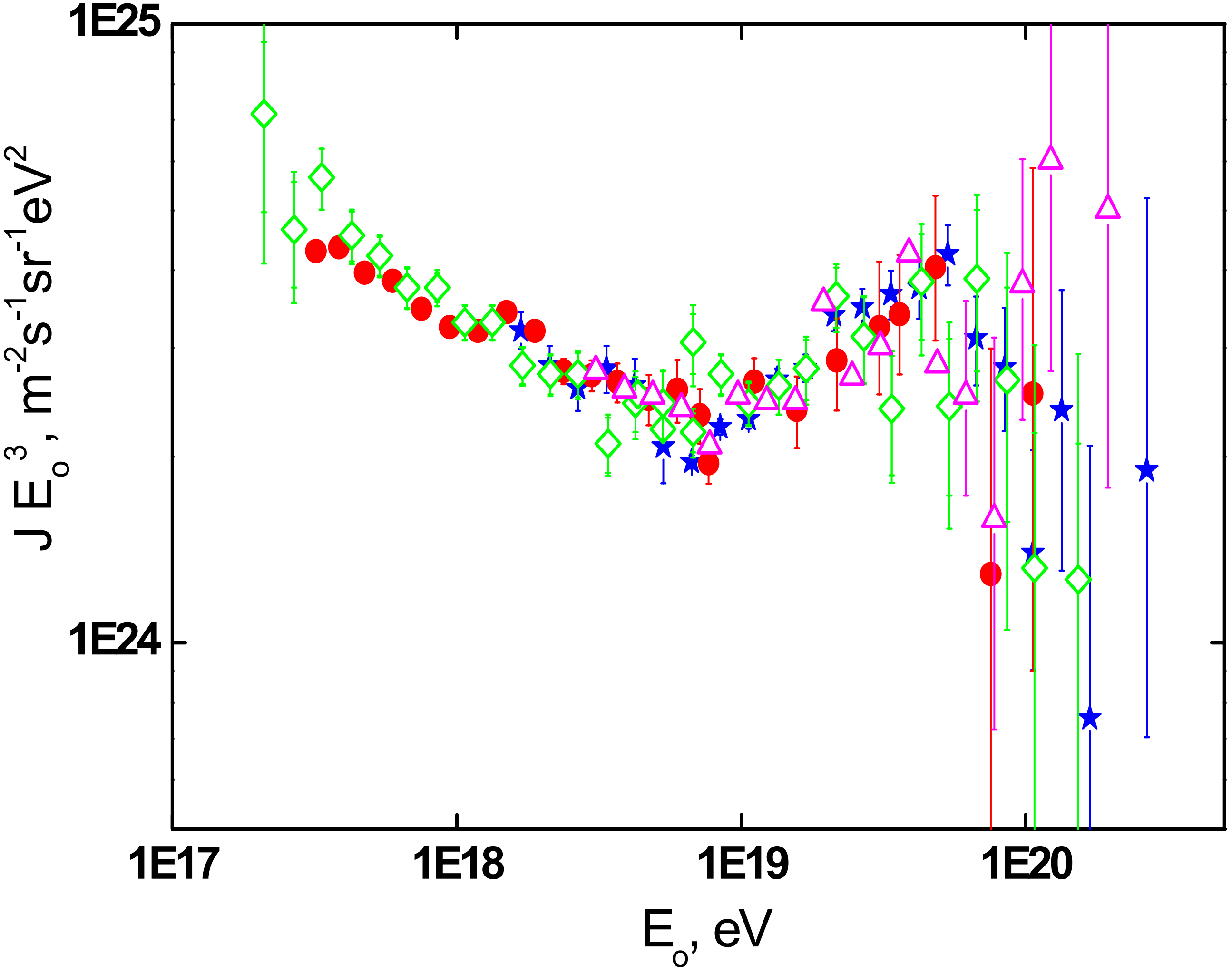
Systematic errors E_0

- Yakutsk - $\theta \approx 0^\circ$ 25-26%. $\theta \approx 60^\circ$ 30%.
- AGASA – 18%
- HiRes – 15%
- Auger – 22%

Energy spectrum after the energy correction: $E_C = K \cdot E_0$:

Yakutsk – K = 0.75, AGASA – K =0.87,

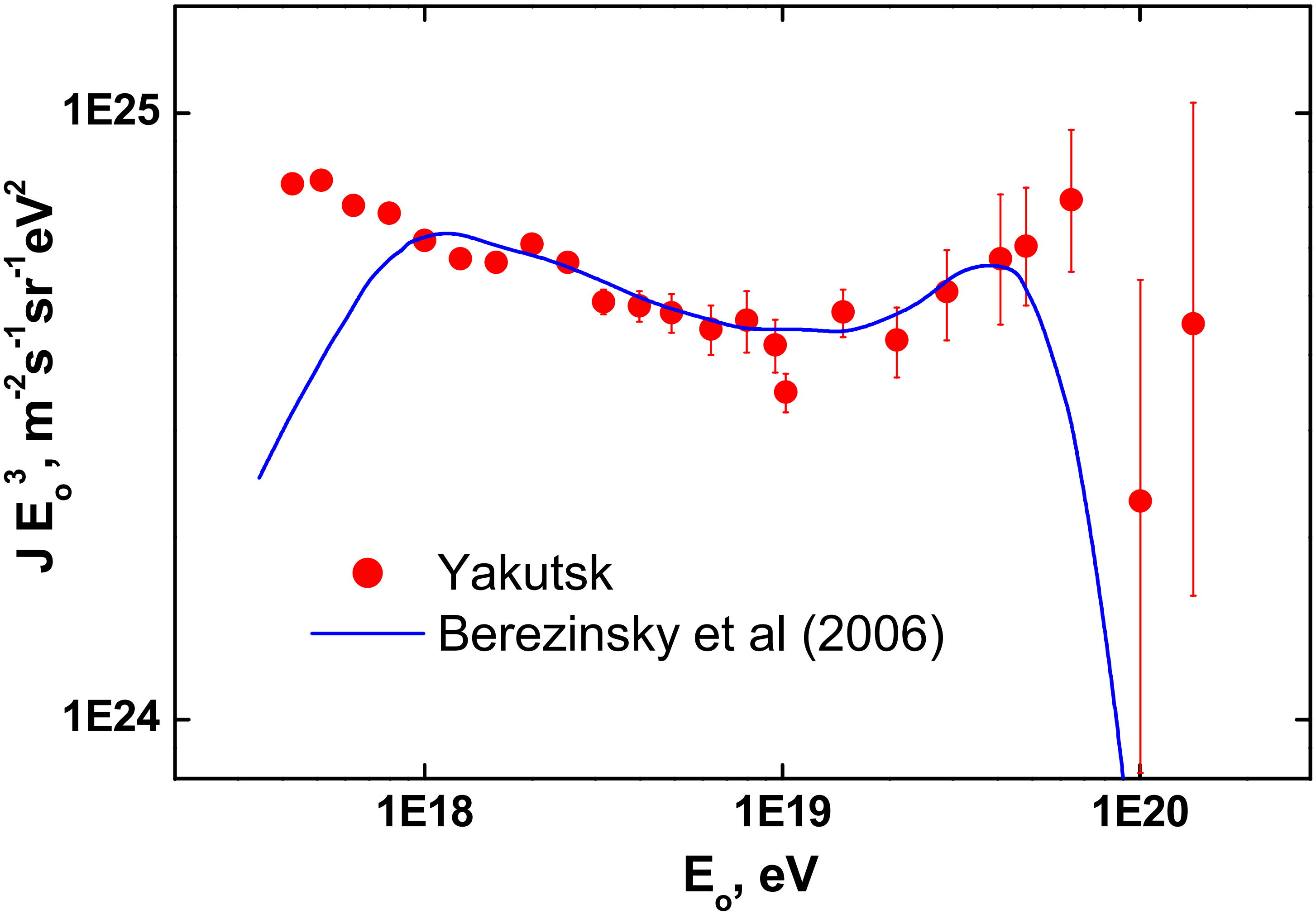
Auger – K =1.5, HiRes – K =1.2.

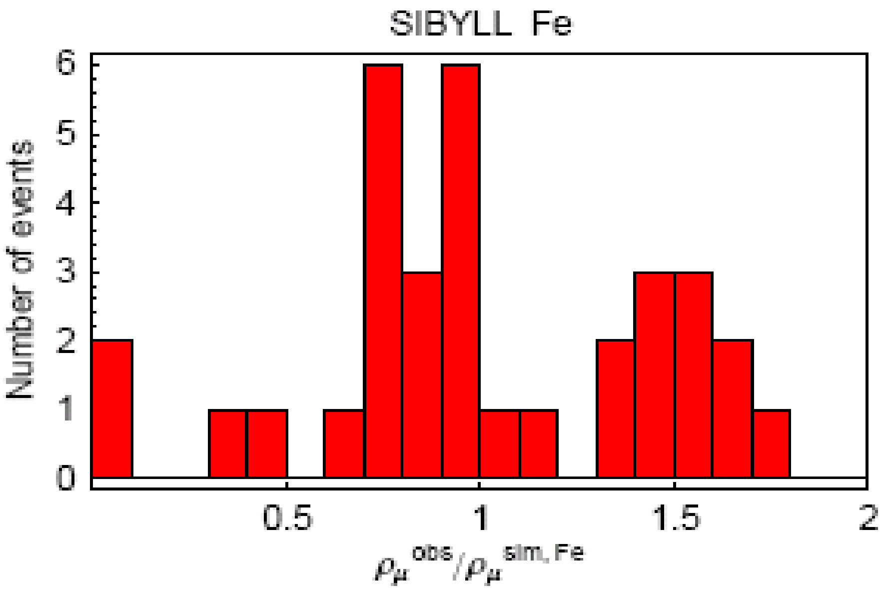


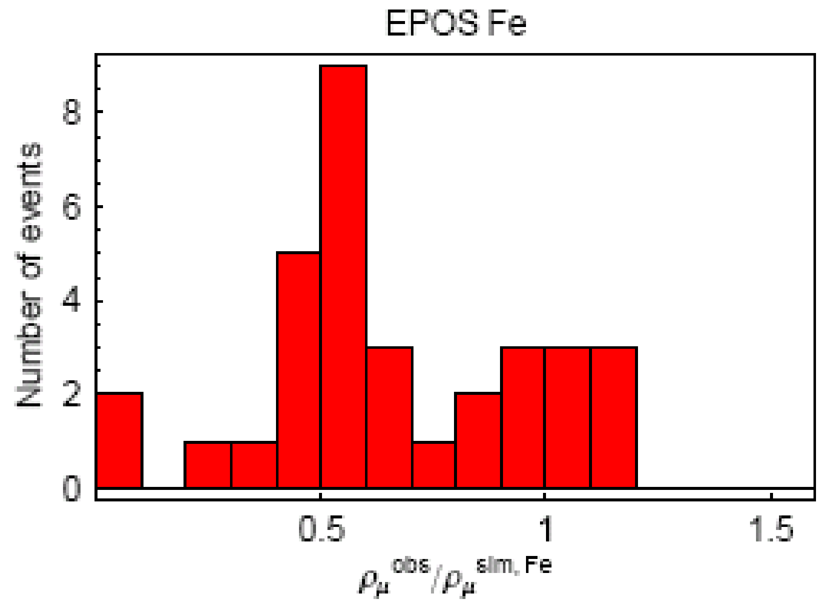
Calorimetric methods of energy estimation

Yakutsk – Cherenkov light detectors
Auger – Fluorescence telescopes.
$E_{Yakutsk} / E_{Auger} \approx 2$

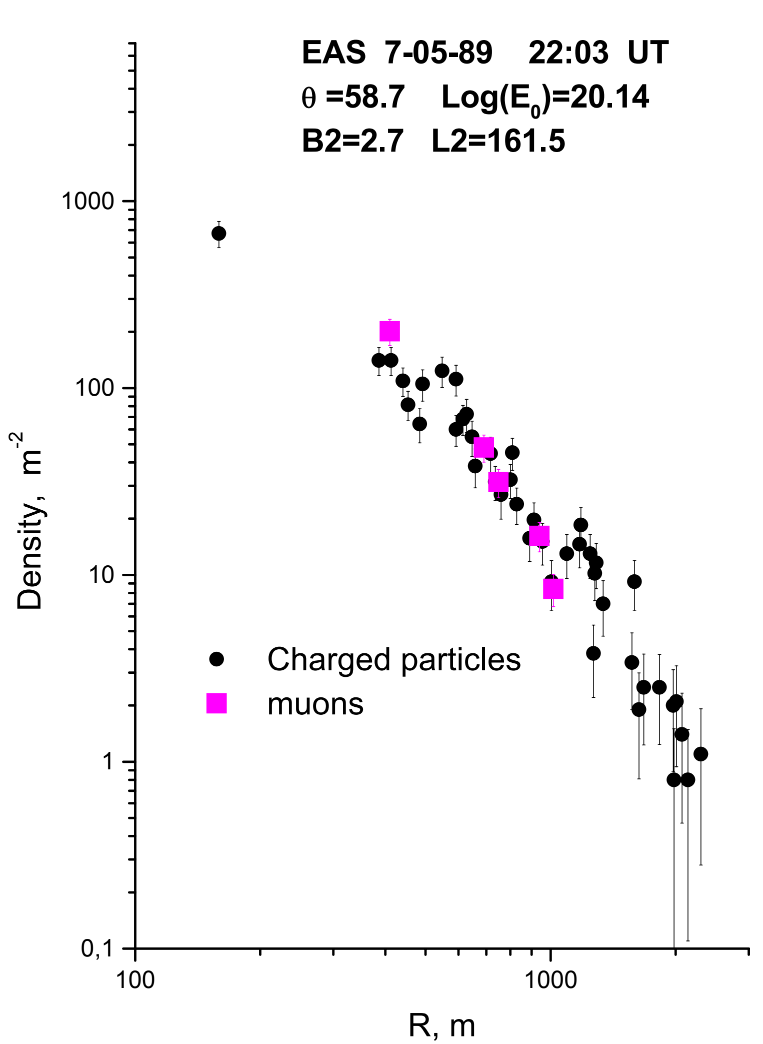
Comparison of the Yakutsk array Spectrum with accounts from AGN

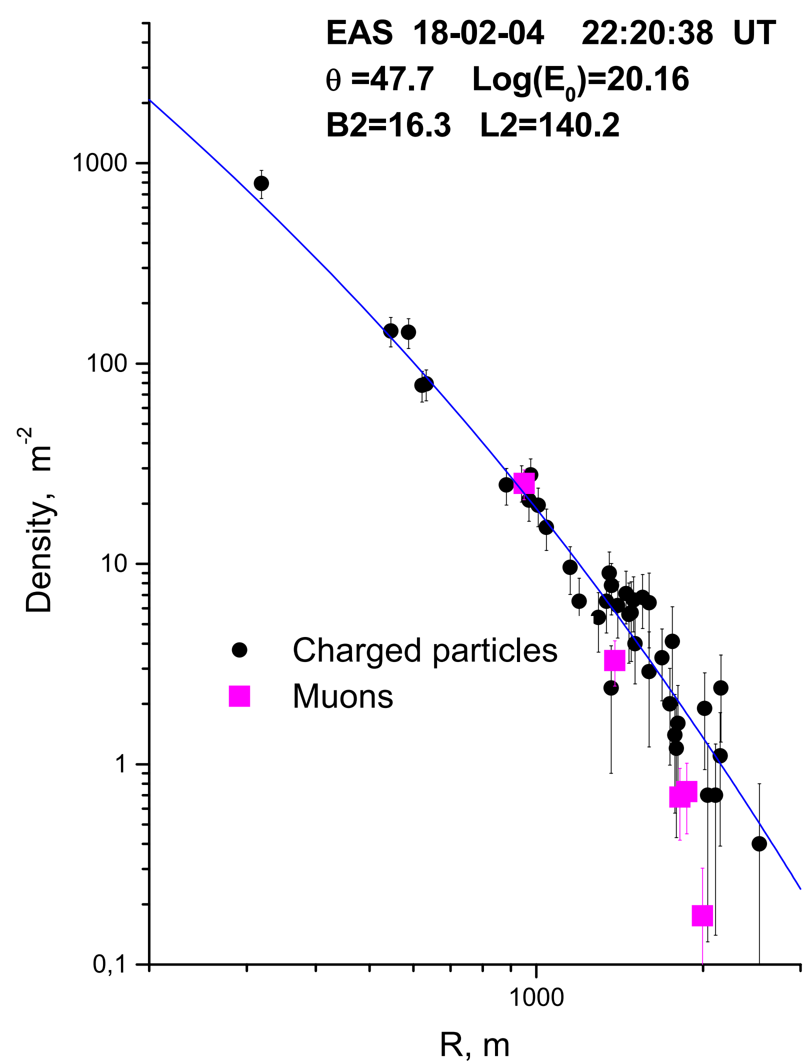






Distribution of ratios of observed and simulated muon densities at 1000 m from the shower core for iron on models SYBILL and EPOS. $E_0 > 10^{19}$ eV, $\theta < 45^\circ$
For EPOS fraction of iron from 95 % probability is an interval 29 - 68 % (average value of 48 %)


EAS 7-05-89 22:03 UT
θ =58.7 Log(E0)=20.14
B2=2.7 L2=161.5
Density, m-2
R, m
Charged particles
muons
1000
100
10
1
0,1
100
1000


EAS 18-02-04 22:20:38 UT
θ =47.7 Log(E0)=20.16
B2=16.3 L2=140.2
Density, m-2
R, m
Charged particles
Muons
1000
100
10
1
0,1
1000

The method: event-by-event analysis

D.S. Gorbunov, G.I. Rubtsov and S.V. Troitsky, Astropart. Phys. **28** (2007) 28

The idea of the method is the event-by-event comparison of observed muon densities in air showers with those in simulated gamma-ray induced showers which have the same scintillator energy deposit (S_{600}) and the same arrival direction as the observed ones.

The advantage of the method is its independence both on the energy reconstruction procedure used by experiment and on the Monte-Carlo simulation of hadronic air showers: we use simulated gamma-induced showers and we select the simulated showers by the observable scintillator signal.

S600 – energy estimator (E – observable)

$\rho_\mu(300)$ – the muon density at 300 m from the shower axis – composition estimator (C – observable)

The method: **event by event analysis**

D.S. Gorbunov, G.I. Rubtsov and S.V. Troitsky, Astropart. Phys. **28** (2007) 28

We use the sample of events satisfying the following criteria:

- the event passed the selection cuts for the spectrum reconstruction;

- the reconstructed core location is inside the array boundary;

- the zenith angle $\theta < 45^{\circ}$;

- the reconstructed energy $E_{rec} > 10^{18}$ eV;

- the reconstructed shower axis is within 300 m from an operating muon detector.

1647 events Exposure of $\mathbf{7.4 \cdot 10^{14}\ m^2 \cdot s \cdot sr}$

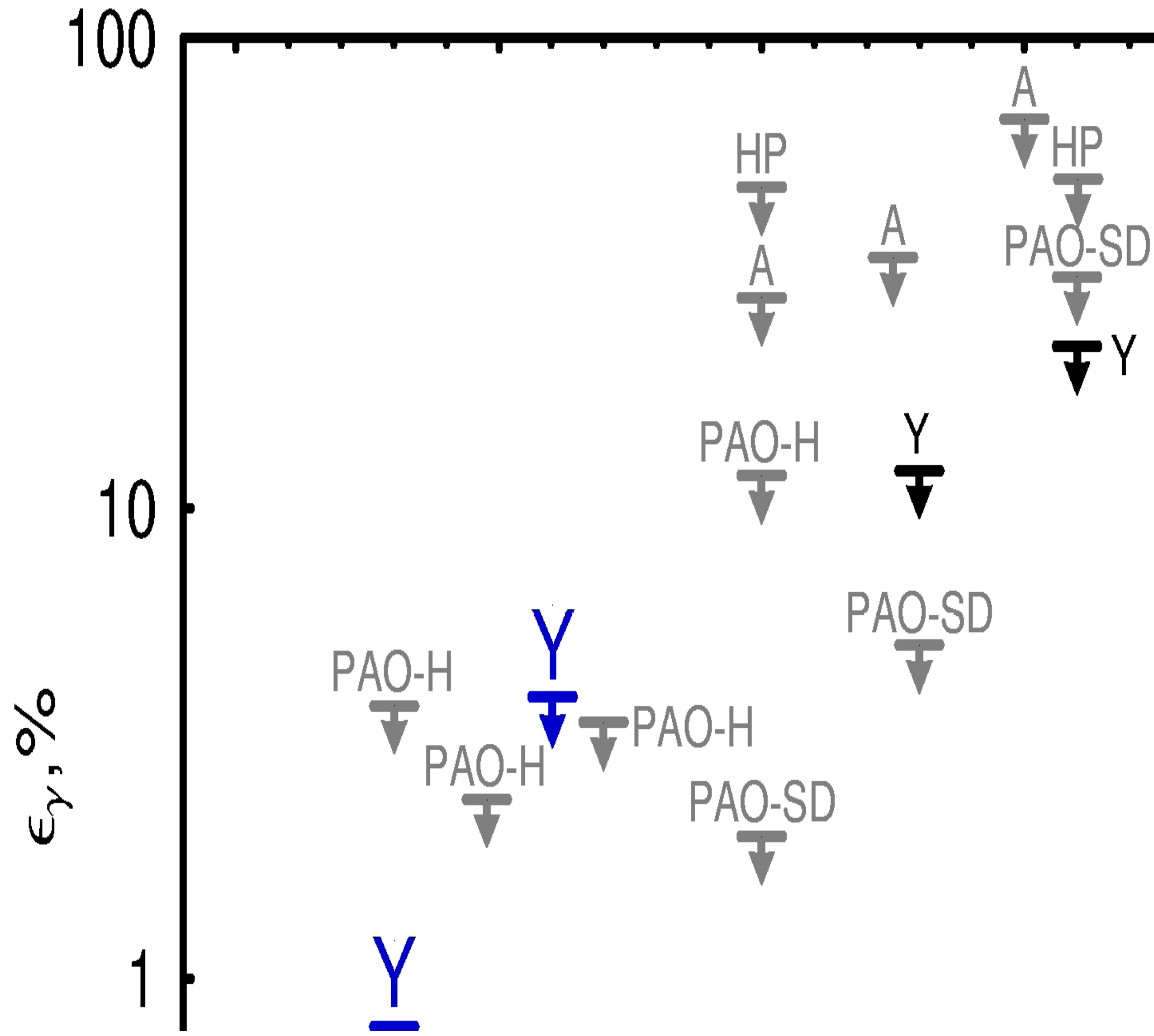
Limits (95% CL) of photons

Fraction:

***E* > 10^{18} eV: ε_γ < 0.4%**

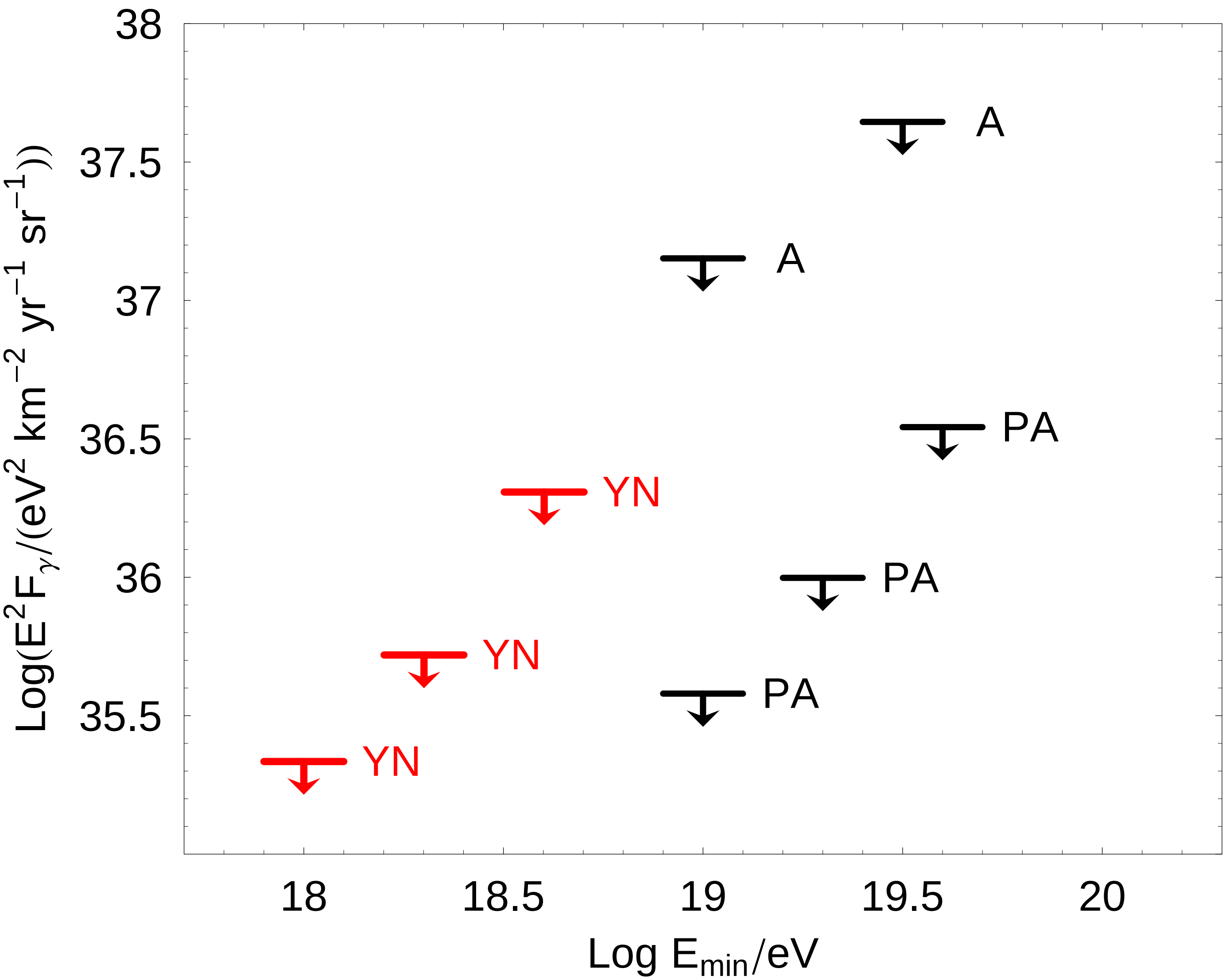
***E* > $2 \cdot 10^{18}$ eV: ε_γ < 0.8%**

***E* > $4 \cdot 10^{18}$ eV: ε_γ < 4%**



Limits (95% CL) of photons

Flux



Conclusions

- The discrepancy in the intensities of the energy spectra obtained in different experiments can be explained by the presence of systematic errors in the estimated shower energies.
- Calorimetric estimations two experiments Yakutsk and Auger different: $E_{Yakutsk} / E_{Auger} \approx 2$
- The HiRes and Auger data indicate the GZK - cutoff of the CR spectrum
- At energy >2 $\cdot$ 10^{19} eV the muon fraction is great (the Yakutsk data). Fraction of iron from 95 % probability is an interval 29 - 68 % (using EPOS model)
-

Conclusions

- **In the most inclined showers at $E_0 > 2 \cdot 10^{19}$ eV, the responses of the muon the same as surface detectors in a wide range of distances. These results may indicate the occurrence of new processes upon interactions of particles with such energies. If this is true, the estimated energy of the most intense showers may be incorrect for all arrays.**
- **The analysis of the Yakutsk muon data allowed to place the strongest (up to now) upper limits on photon fraction at $E > 10^{18}$ eV and $E > 2 \cdot 10^{18}$ eV**