

# Studies of UHECR: Results...

# “ To Be Announced ” ?

*14th International School on Particles and Cosmology,  
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# Extensive Air Showers

- Lateral distribution and timing (ground based detectors):

EM halo:

$e^{\pm}, \gamma$   
 $\mu^{\pm}$

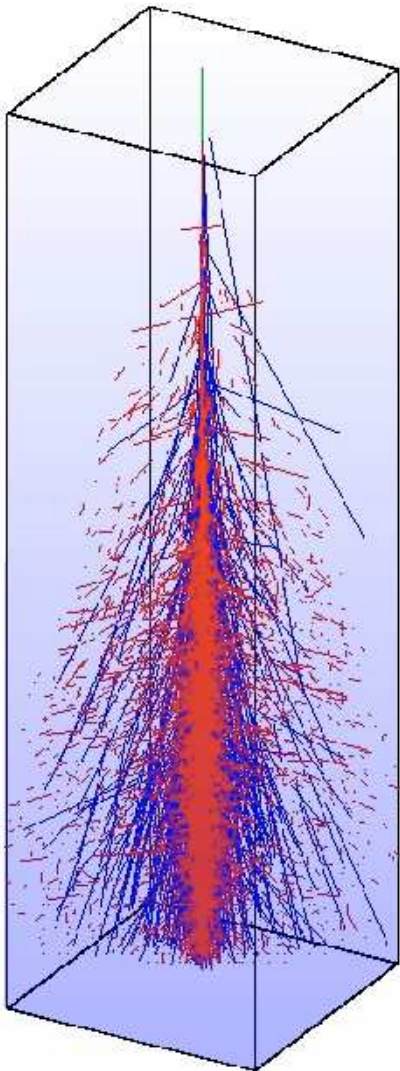
- Longitudinal profile and timing (ground or space based detectors):

EM core:

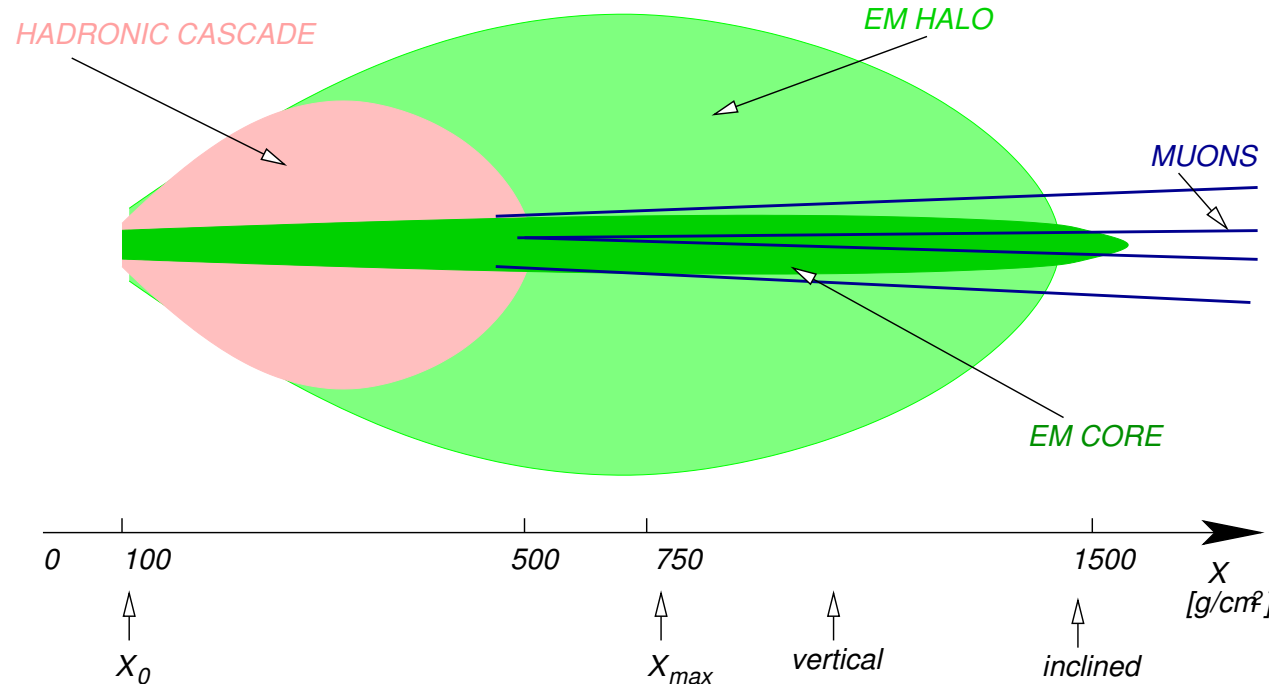
Cherenkov radiation,  
fluorescent light

EM halo:

radio signal?



D. Gorbunov



# Energy and arrival direction estimates by ground arrays

$$N_e = \text{const} \cdot E \left( \frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max} - X}{a}} \exp \left( \frac{X_{max} - X}{a} \right) \quad \text{Gaisser, Hillas}$$

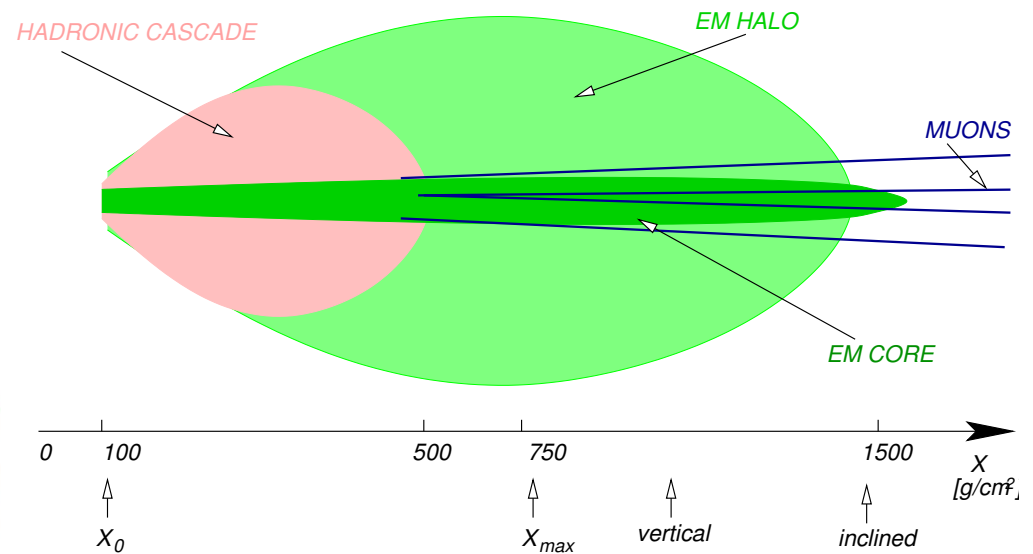
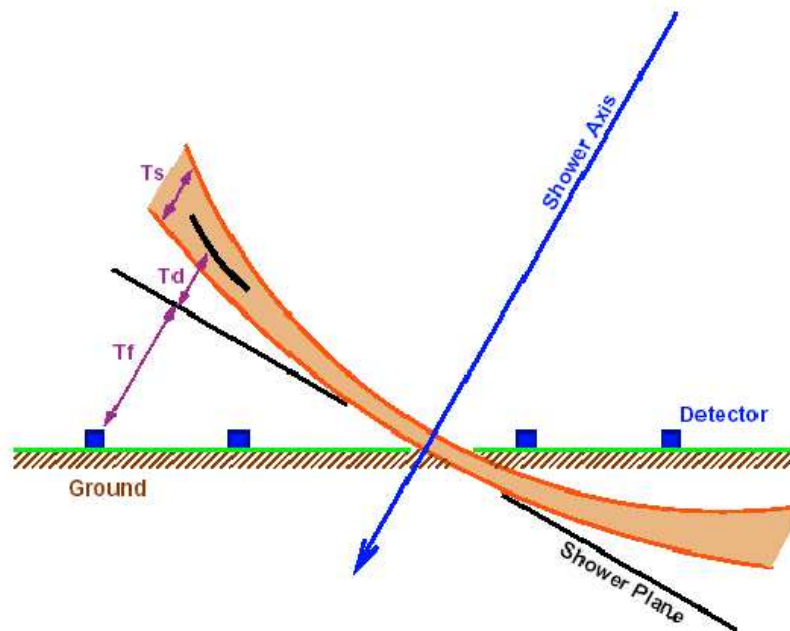
**const** — extrapolation from  $E \lesssim 10^{14}$  eV

$a = 70 \text{g/cm}^2$

$X_{max}$  depends on  $E$  logarithmically

$X$  depends on zenith angle

$N_e$  — from the most stable detector response (S=500-1000m)



# Energy estimate for inclined showers

$$N_e = \text{const} \cdot E \left( \frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max} - X}{a}} \exp \left( \frac{X_{max} - X}{a} \right)$$

**const** — extrapolation from  $E \lesssim 10^{14}$  eV

$a = 70 \text{g/cm}^2$

$X_{max}$  depends on  $E$  logarithmically

$X$  depends on zenith angle

$N_e$  — from the most stable detector response ( $S=500-1000\text{m}$ )

Energy vs  $S(600)$  for vertical showers: AGASA

MC results by COSMOS+QCDJET

Dai *et al.*  
1988

$$E_0[\text{eV}] = 2.03 \cdot 10^{17} S_0(600), \quad S(600) = S_0(600)$$

For inclined showers: Empirical relationship

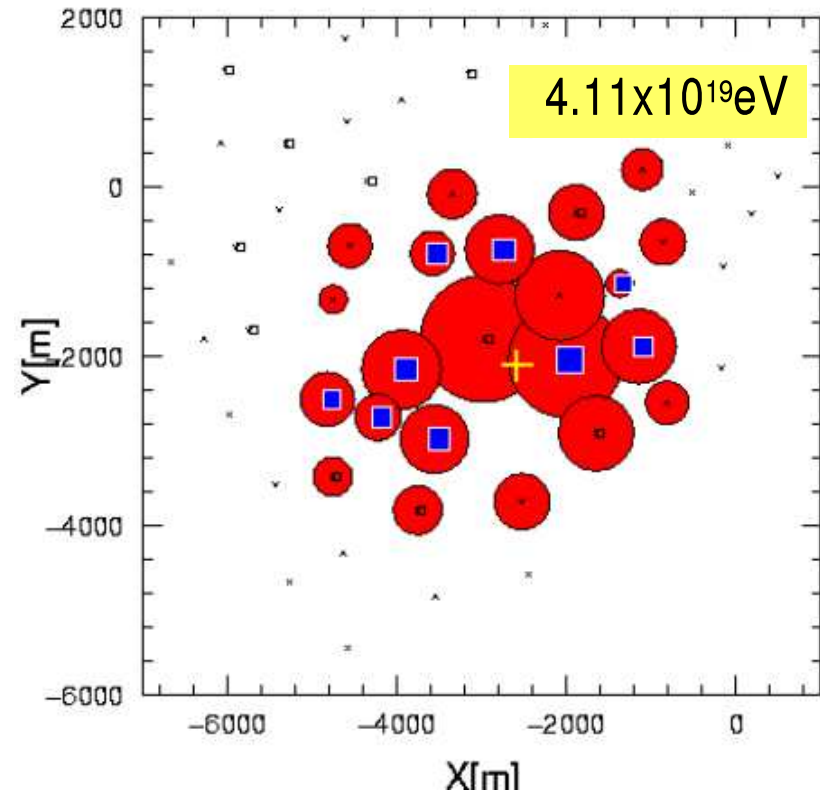
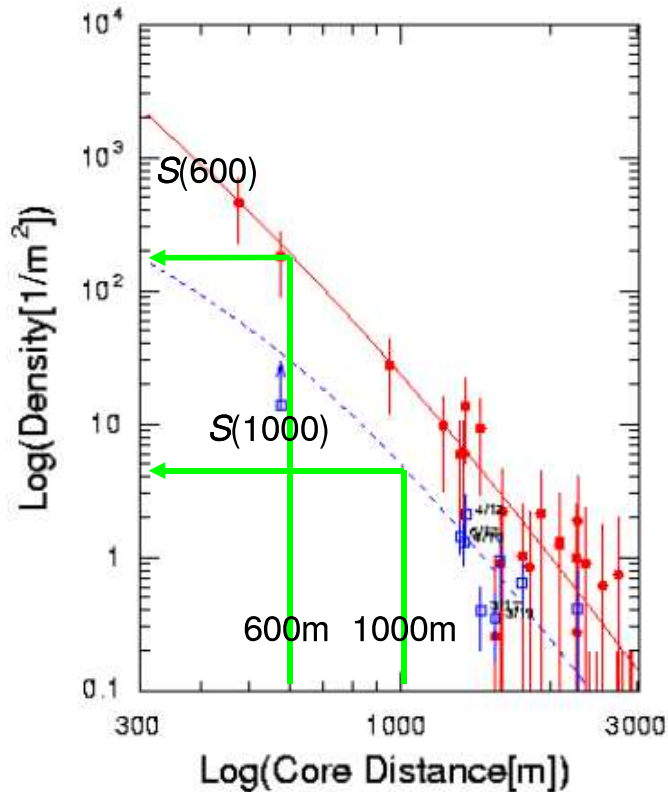
$$S(600) = S_0(600) \cdot \exp \left( -\frac{X_0}{\Lambda_1 (\sec \theta - 1)} - \frac{X_0}{\Lambda_2 (\sec \theta - 1)^2} \right)$$

$X_0$  — atmospheric depth ( $920 \text{g/cm}^2$  @ Akeno)

$\Lambda_1 = 500 \text{g/cm}^2$   $\Lambda_2 = 594 \text{g/cm}^2$



# Event sample & observables



- Energy estimator (charged particle density @600m):  $S(600)$ 
  - $S(600)$  attenuation modified by empirical function
- Primary mass estimator (muon density@1000m):  $S(1000)$

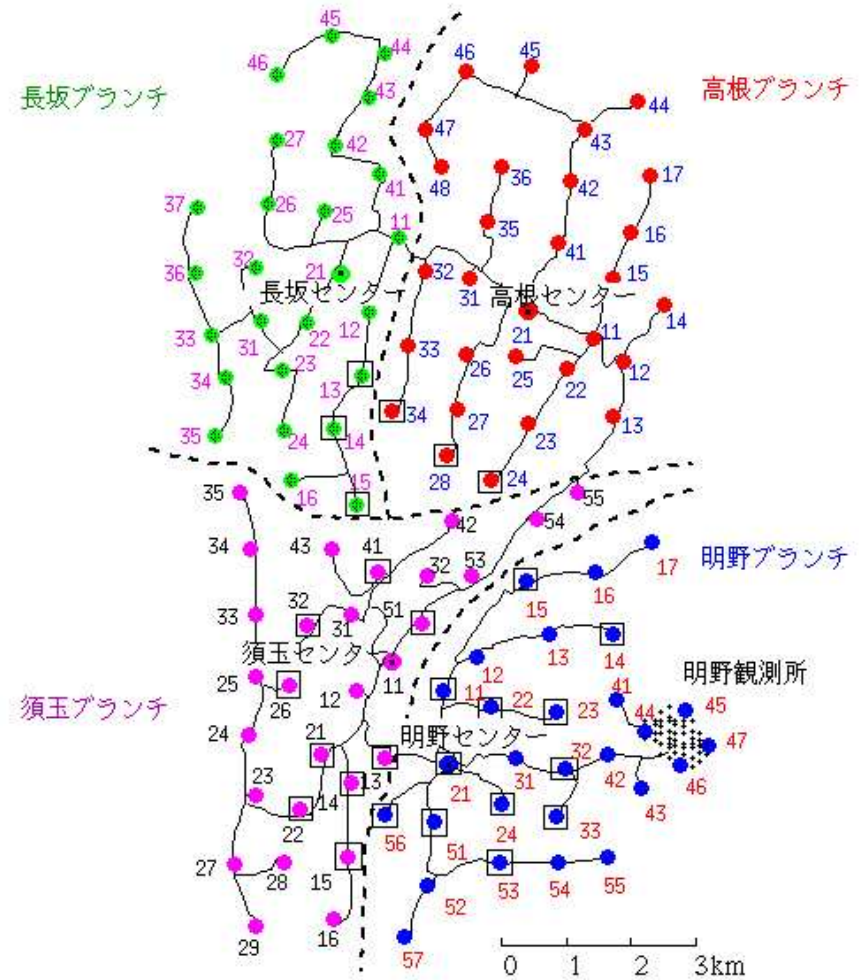
K.Shinozaki *et al.*  
QUARKS'04

# Experiments

- Volcano Ranch (1959-1963), USA:  
1962: first event with  $E > 10^{20}$  eV
- Haverah Park (1968-1987), UK:
- SUGAR (1968-1979), Australia
- Yakutsk (1974-...), Russia: plastic scintillators  
charged particles, muons, Cherenkov radiation
- AGASA (1990-2003), Japan: plastic scintillators  
charged particles, muons
- ground PAO (2003-...), Argentina: water tanks
- ground TA (2007-...), USA: plastic scintillators



# Ground array: AGASA

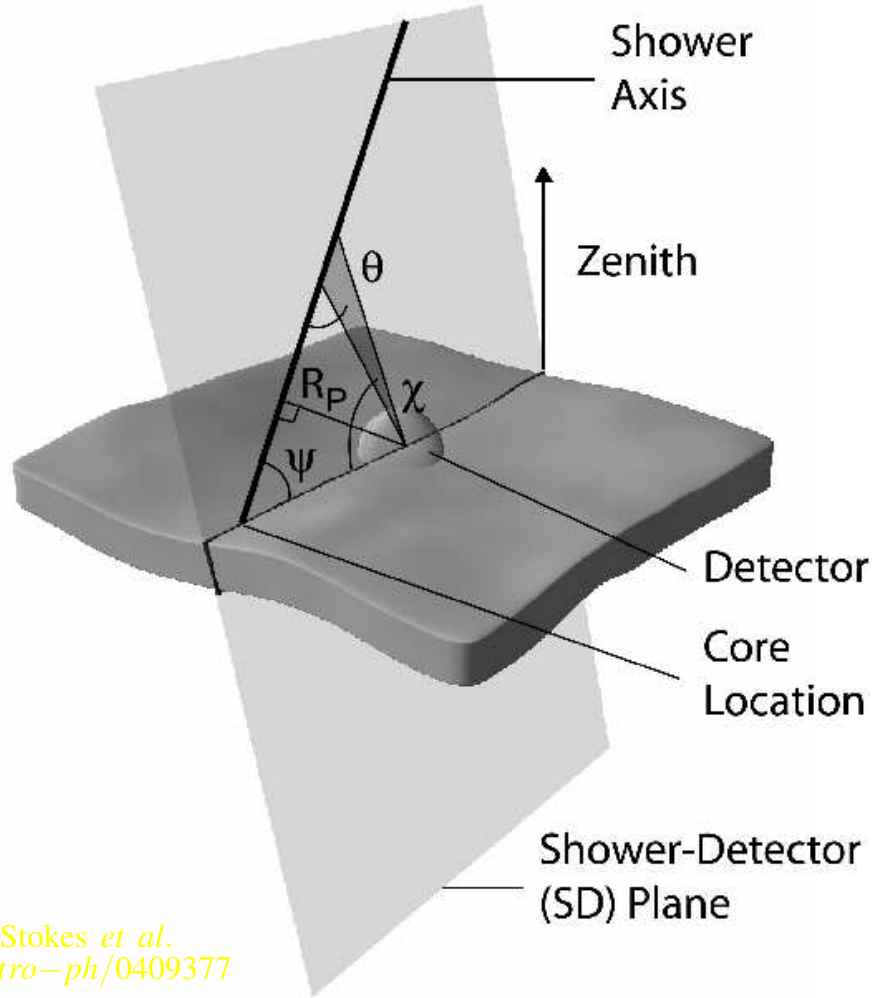


111 plastic scintillators & 27 muon detectors

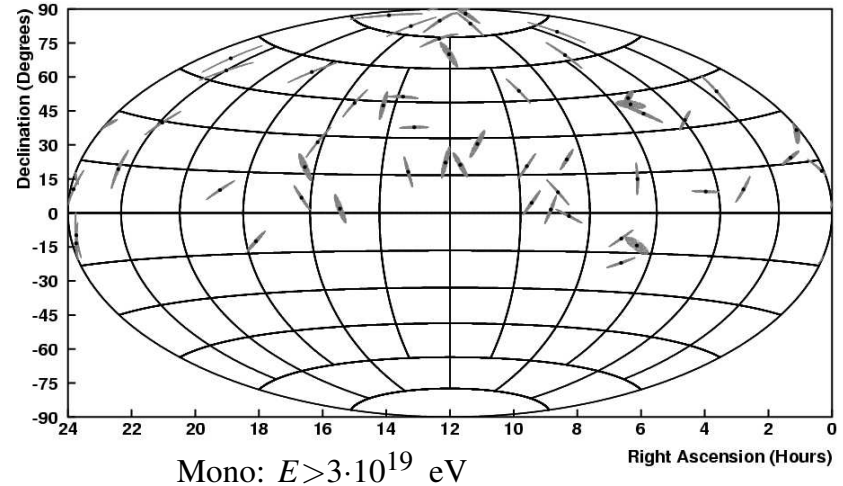
~ 100 km<sup>2</sup>

$$\Delta E/E \lesssim 20\%, \Delta\theta \lesssim 2^\circ$$

# Fluorescent detector: HiRes



B.Stokes *et al.*  
astro-ph/0409377

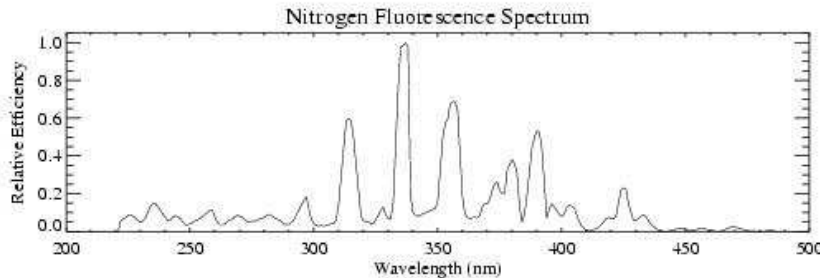


arrival **Mono:**  $\Delta\delta_{SD} \sim 1^\circ$ ,  $\Delta\psi \sim 5.5^\circ$

directions **Stereo:**  $\Delta\delta \approx 0.6^\circ$

energy **Mono:**  $\Delta E/E < 25\%$  @  $E > 10^{18.5}$  eV

resolution **Stereo:**  $\Delta E/E < 15\%$  @  $E > 10^{18}$  eV



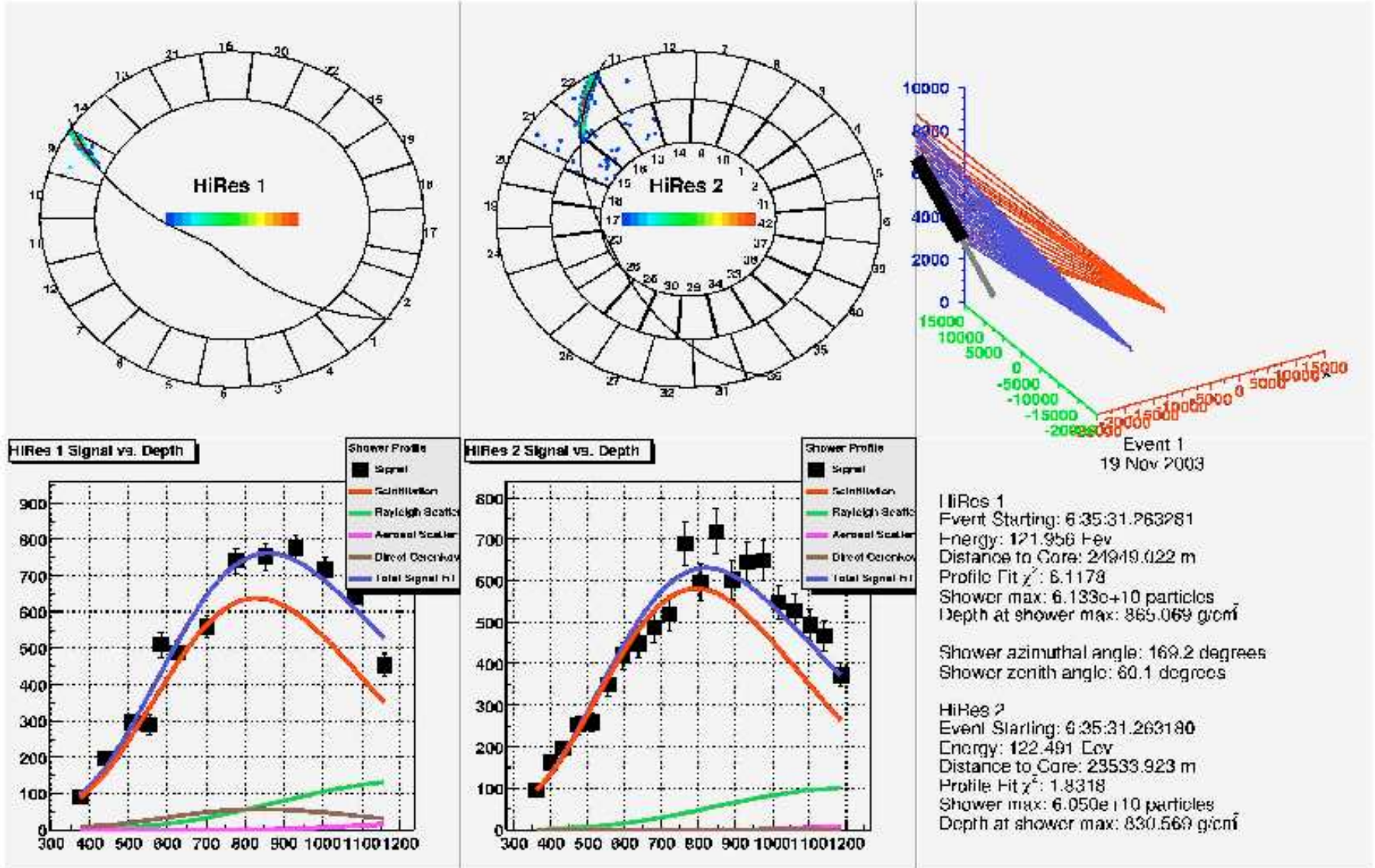
D. Gorbunov



# Direct measurement of $N_e$ @ $X_{max}$

$$N_e = \text{const} \cdot E$$

$$\times \left( \frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max} - X}{a}} \exp \left( \frac{X_{max} - X}{a} \right)$$



# Experiments: exposures

Exposure in  
 $10^{16} \text{ cm}^2 \text{ s sr}$



## ground arrays

|               |     |
|---------------|-----|
| Volcano Ranch | 0.2 |
| Haverah Park  | 0.9 |
| Yakutsk       | 1.8 |
| AGASA         | 5.3 |

## fluorescent detectors

|                 |     |
|-----------------|-----|
| Fly's Eye       | 2.6 |
| HiRes I,II Mono | 7.2 |
| HiRes Stereo    | 4.6 |

## hybrid detectors:

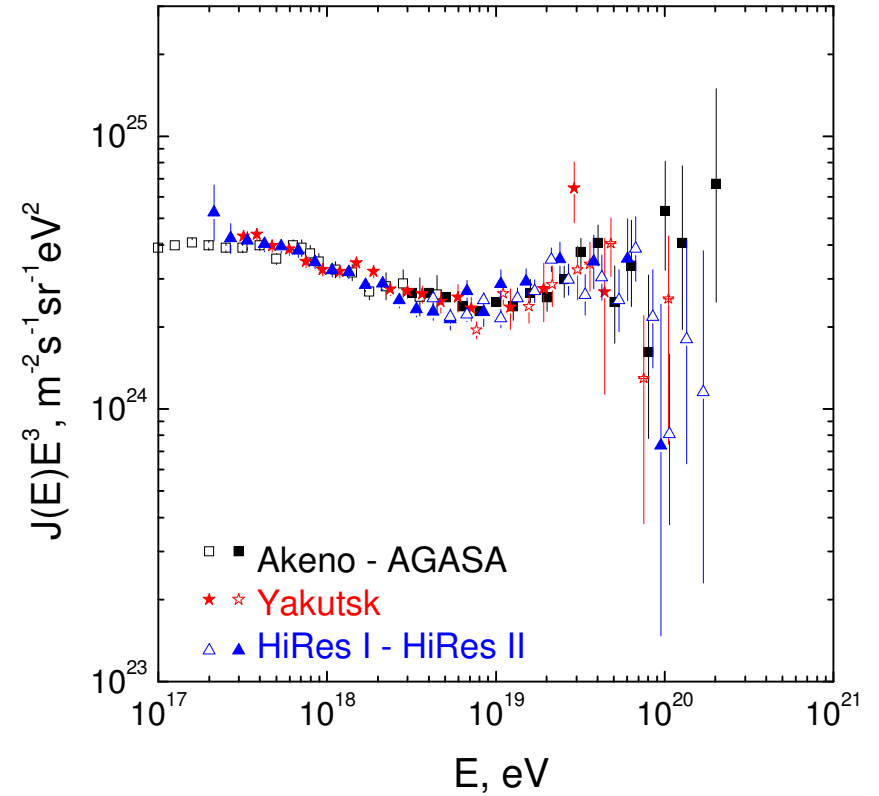
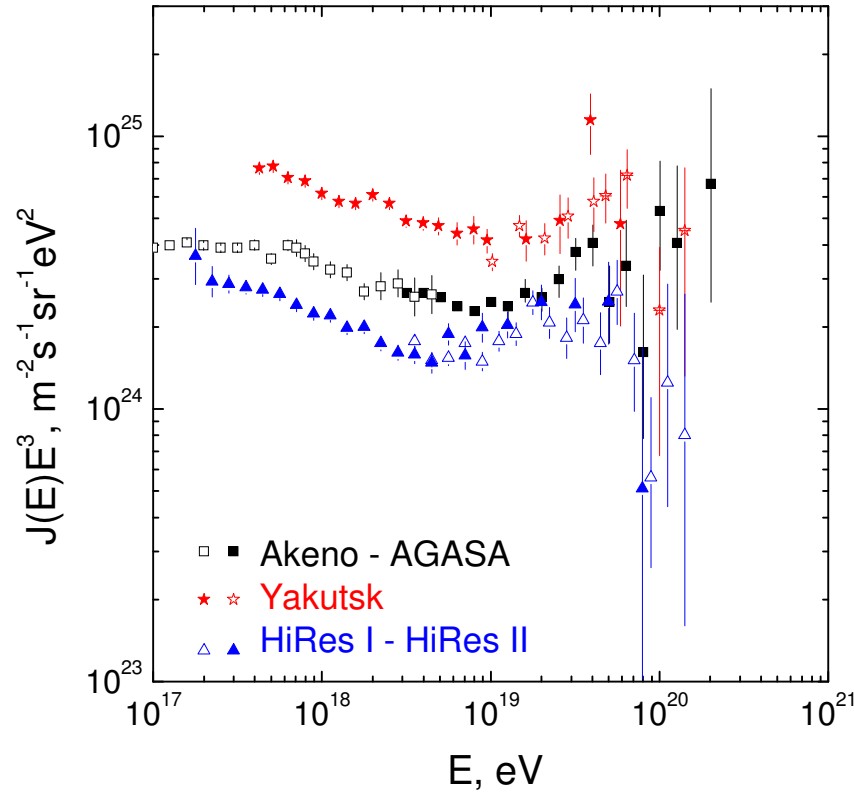
Pierre Auger (2005)

7\* HiRes' aperture

Telescope Array



# Results... spectrum



Energy rescaling

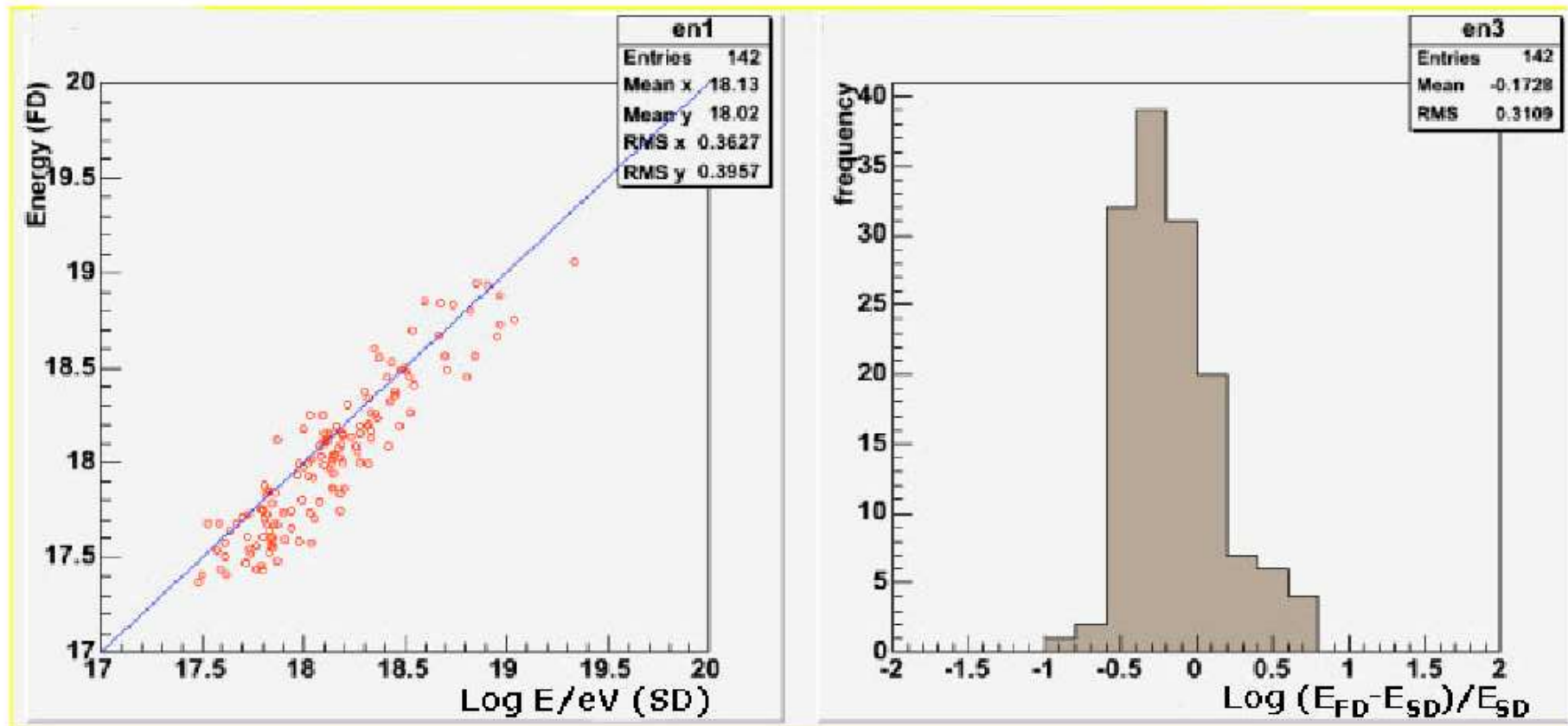
$$\lambda_{AGASA} = 0.9$$
$$\lambda_{Yakutsk} = 0.75$$
$$\lambda_{HiRes} = 1.2$$



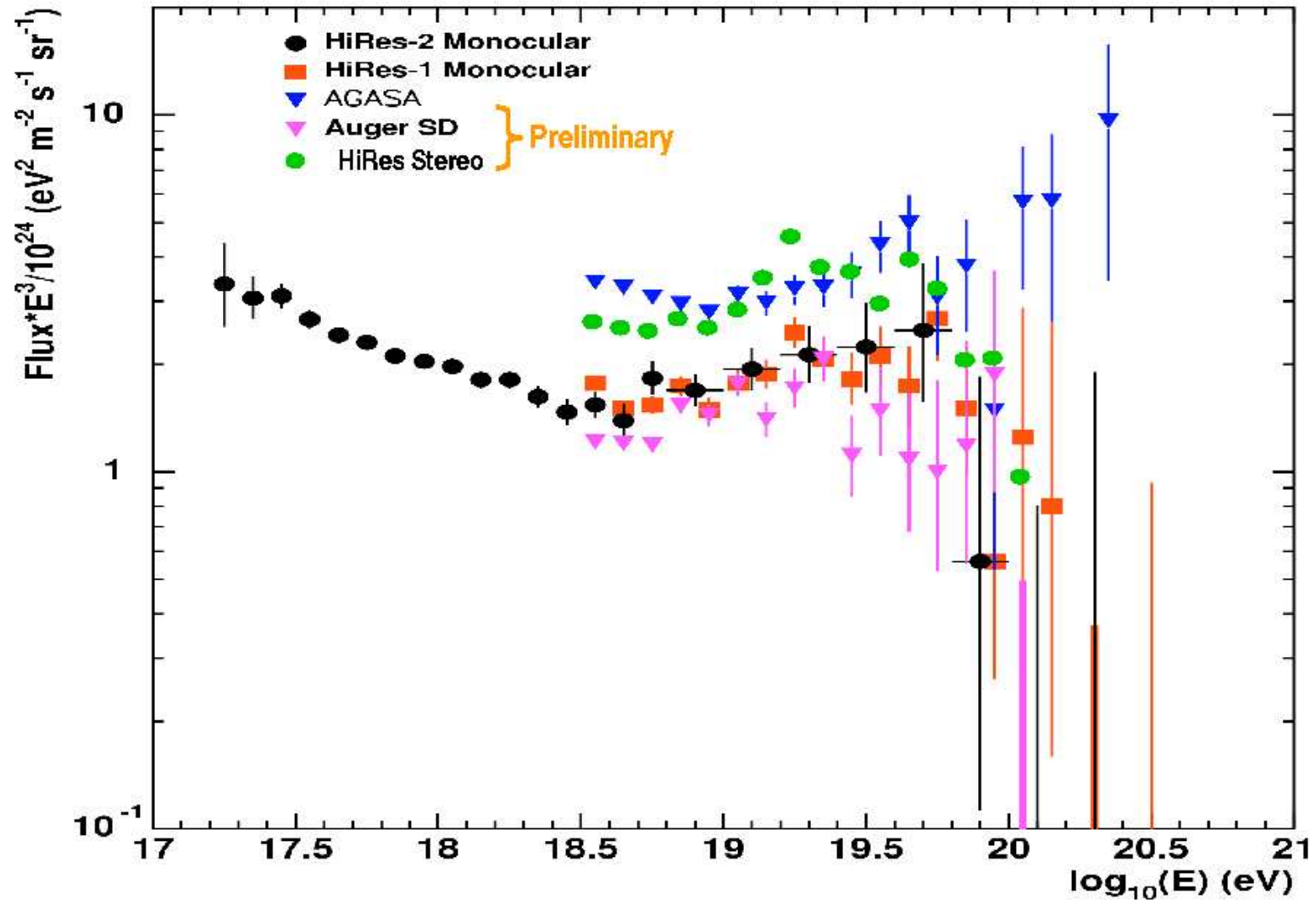
# PRESENT

Pierre Auger Observatory – Hybrid method reveals **systematic difference between SD and FD energy estimates**  
SD is calibrated by FD energy estimates:

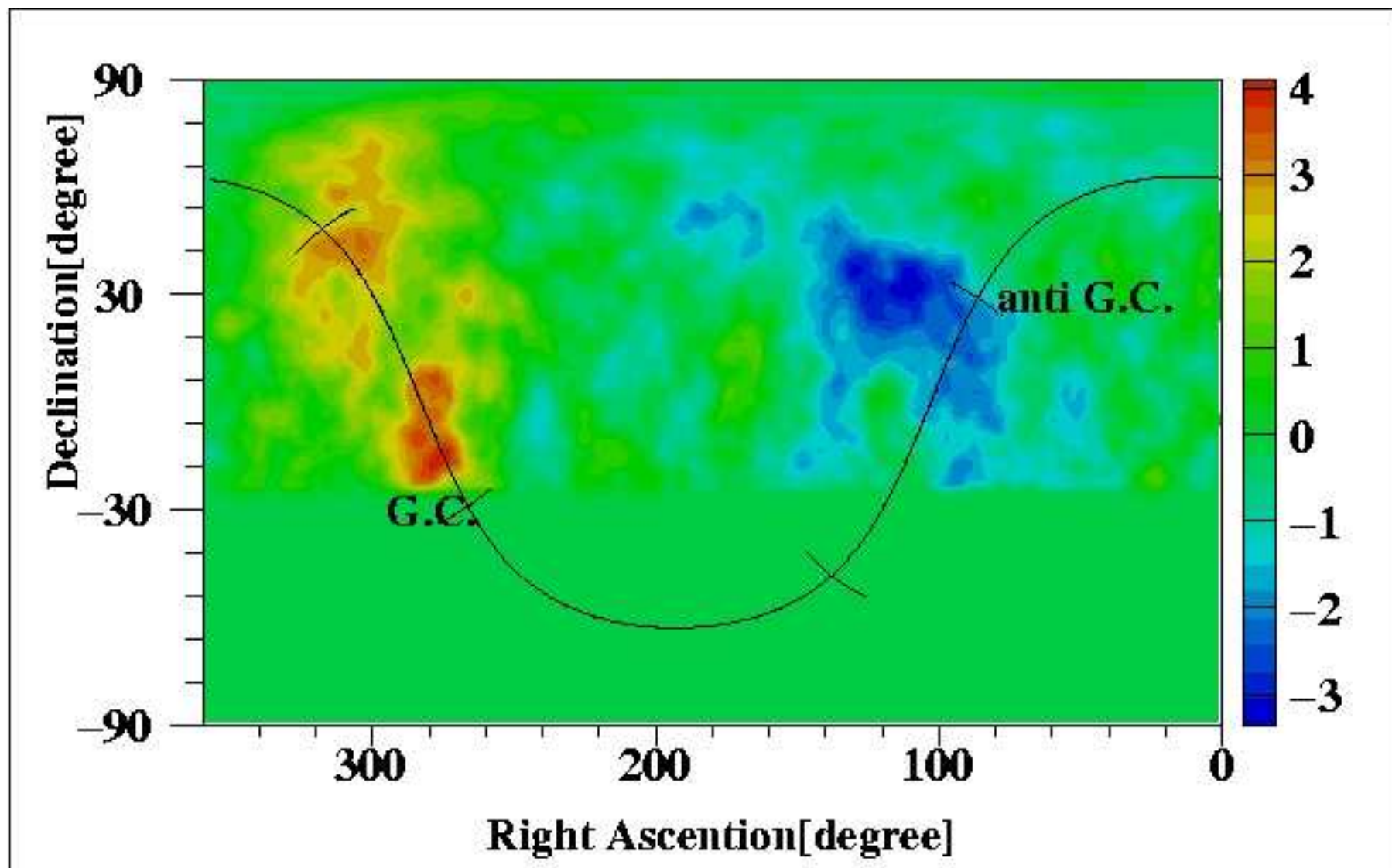
$$N_e = \text{const} \cdot E \left( \frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max} - X}{a}} \exp \left( \frac{X_{max} - X}{a} \right)$$



# PAO spectrum



# Results.. arrival directions



Akeno+AGASA (11 years): 4% dipole @  $E \sim 10^{18}$  eV

N.Hayashida *et al.*  
astro-ph/9807045

# Yakutsk vs AGASA

Harmonic analysis. Interval about  $10^{17}$  eV

The inhomogeneity of the sky survey is essential to the Yakutsk EAS array. Its account considerably decreases amplitudes of anisotropy vectors

Taking account distorting factor, the statistical significant anisotropy of the first and second harmonics is not observed:  
By sidereal time

**amplitude of the first harmonic is smaller than 0.6% with the probability 0.95 and for second harmonic it is 0.65%;**

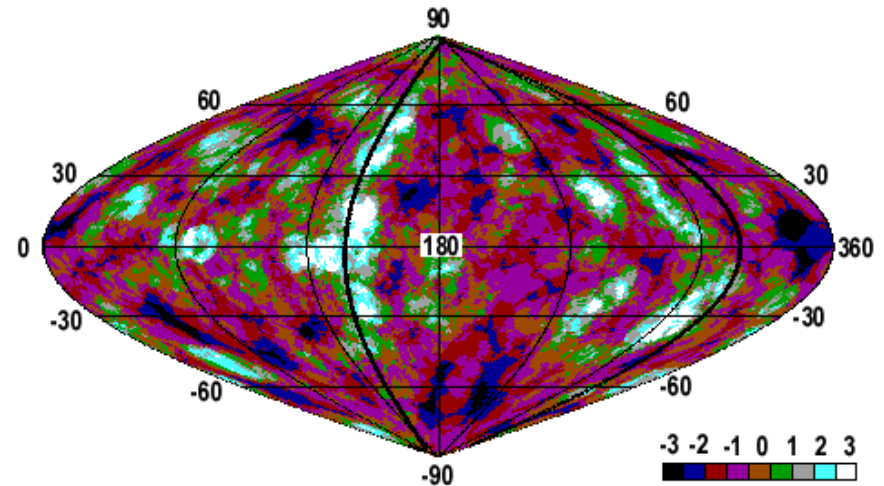
In the analysis samples of previous work (1997) the amplitude of the first harmonic with respect to the RA with regard to the perturbing factors is  **$(0.45 \pm 0.55)\%$** . (Instead of 1.35)

Harmonic analysis. Interval about  $10^{18}$  eV

A  $18.0 < \text{Log}(E_0) < 18.5$ , Events: 27301,  **$r_1 = (0.7 \pm 0.9)\%$**

at  $10^{18}$  eV the statistically significant anisotropy is not observed.

our results do not confirm given AGASA. The Yakutsk array cannot observe the center of the Galaxy.



Map of distribution on arrival directions of cosmic rays with  $E_0 > 8 \cdot 10^{18}$  eV in galactic coordinates on Yakutsk data and SUGAR. Intensity - in terms of a standard deviation of a difference of observable number and expected average for an isotropic flux. A bold line - a plane of the Supergalaxy

Events with  $E_0 > 10^{19}$  eV

Harmonic analysis RA:  $19.0 < \text{Log}(E_0) < 19.5$ , events 312,

**$r_1 = (26.4 \pm 8.0)$ ,  $r_2 = (2.3 \pm 1.2)$  h,  $P = 0.004$**

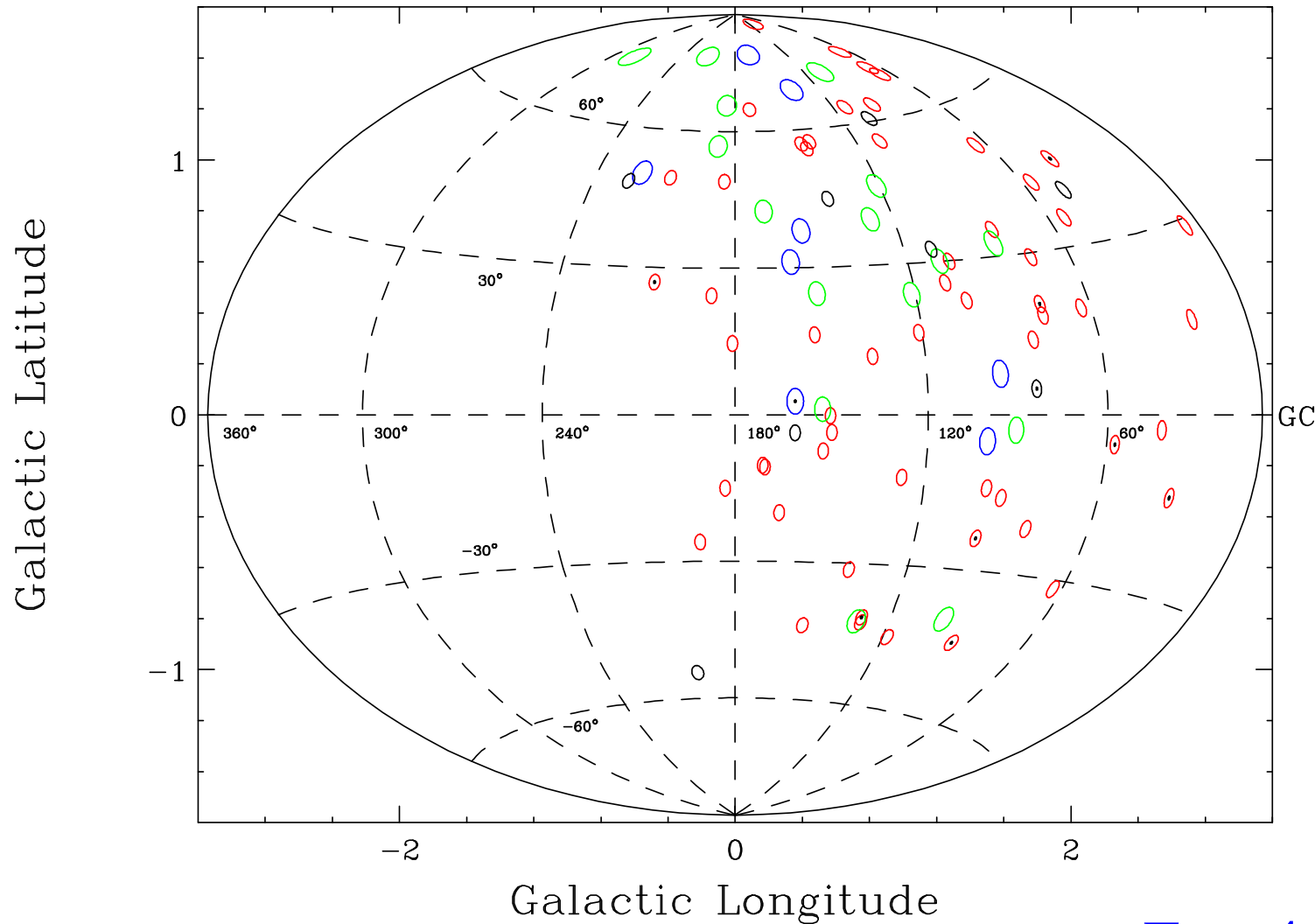
This result specifies existence anisotropic components of cosmic rays in the given interval of energy

**HiRes(?) and PAO are consistent with isotropy**

# Higher energies: extragalactic isotropy

89 events,  $E > 4 \times 10^{19}$  eV AGASA(red),Haverah(green),Yakutsk(blue),Volcano(black)

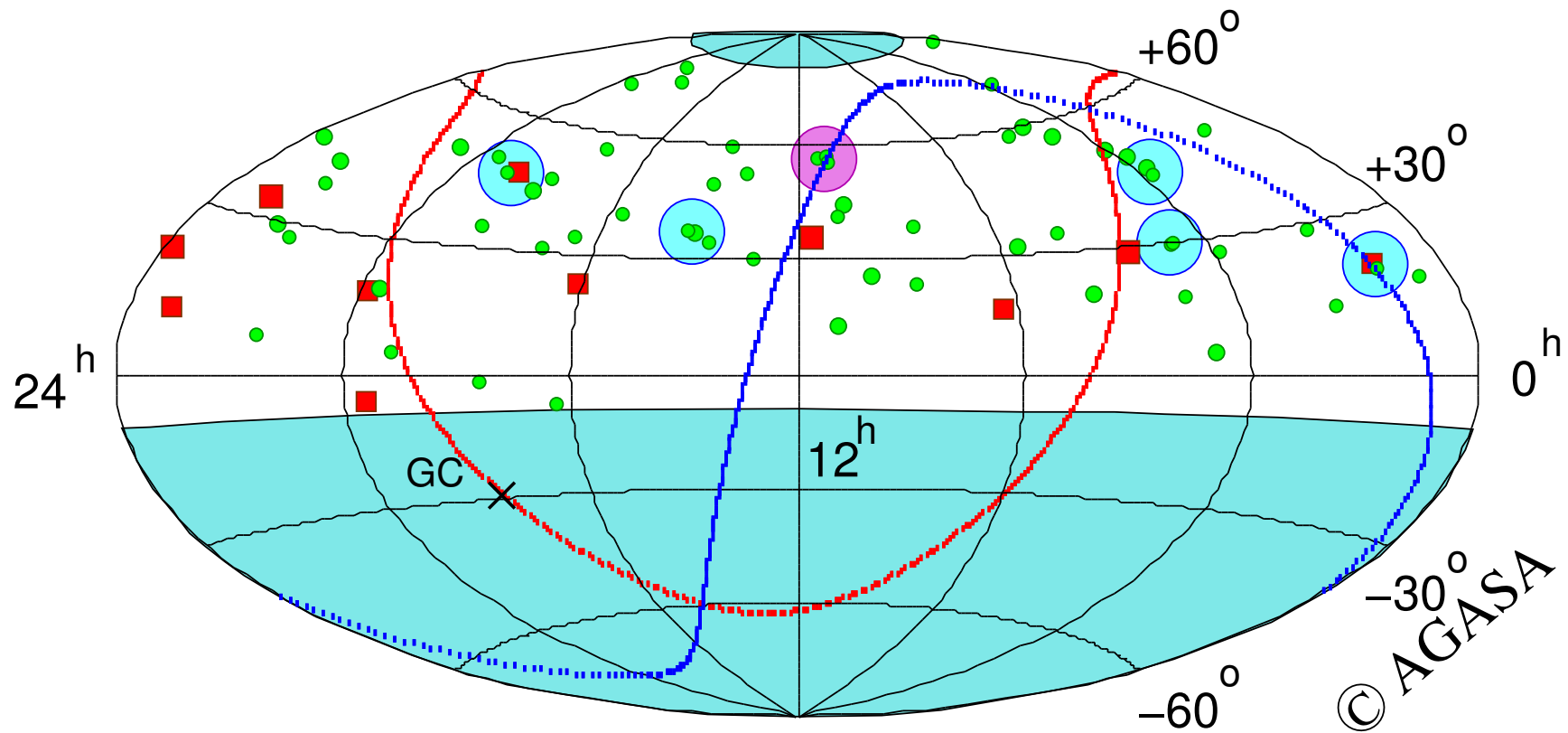
J.Cronin  
astro-ph/0402487



$E > 4 \cdot 10^{19}$  eV



# AGASA: small scale anisotropy



P.Tinyakov, I.Tkachev  
astro-ph/0102101

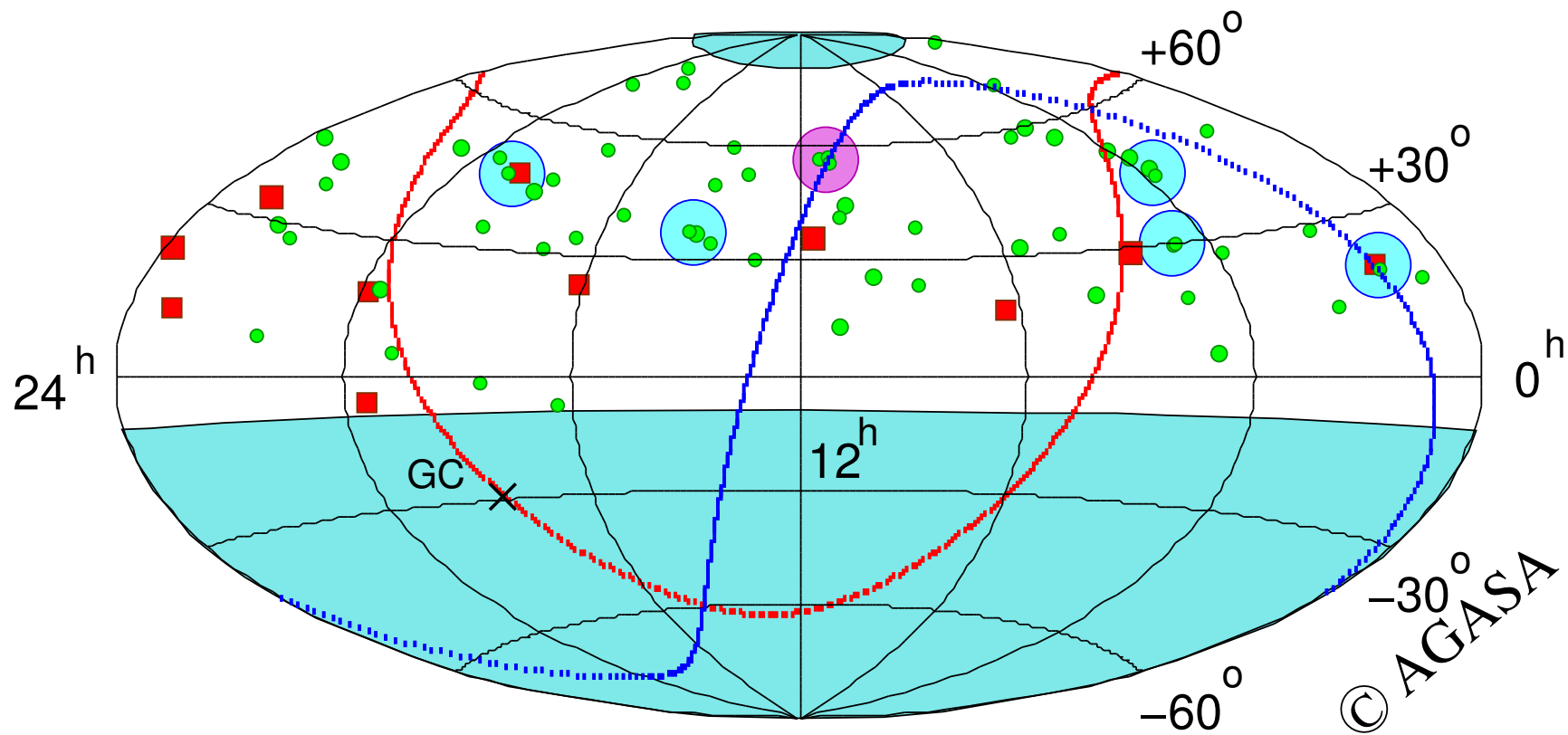
AGASA:  $E > 4 \cdot 10^{19}$  eV @  $2.5^\circ$ : 5 doublets & 1 triplet  $P_{autcr} < 10^{-3}$

Yakutsk:  $E > 2.4 \cdot 10^{19}$  eV @  $4^\circ$ : 5 doublets & 1 triplet  $P_{autcr} \sim 10^{-3}$

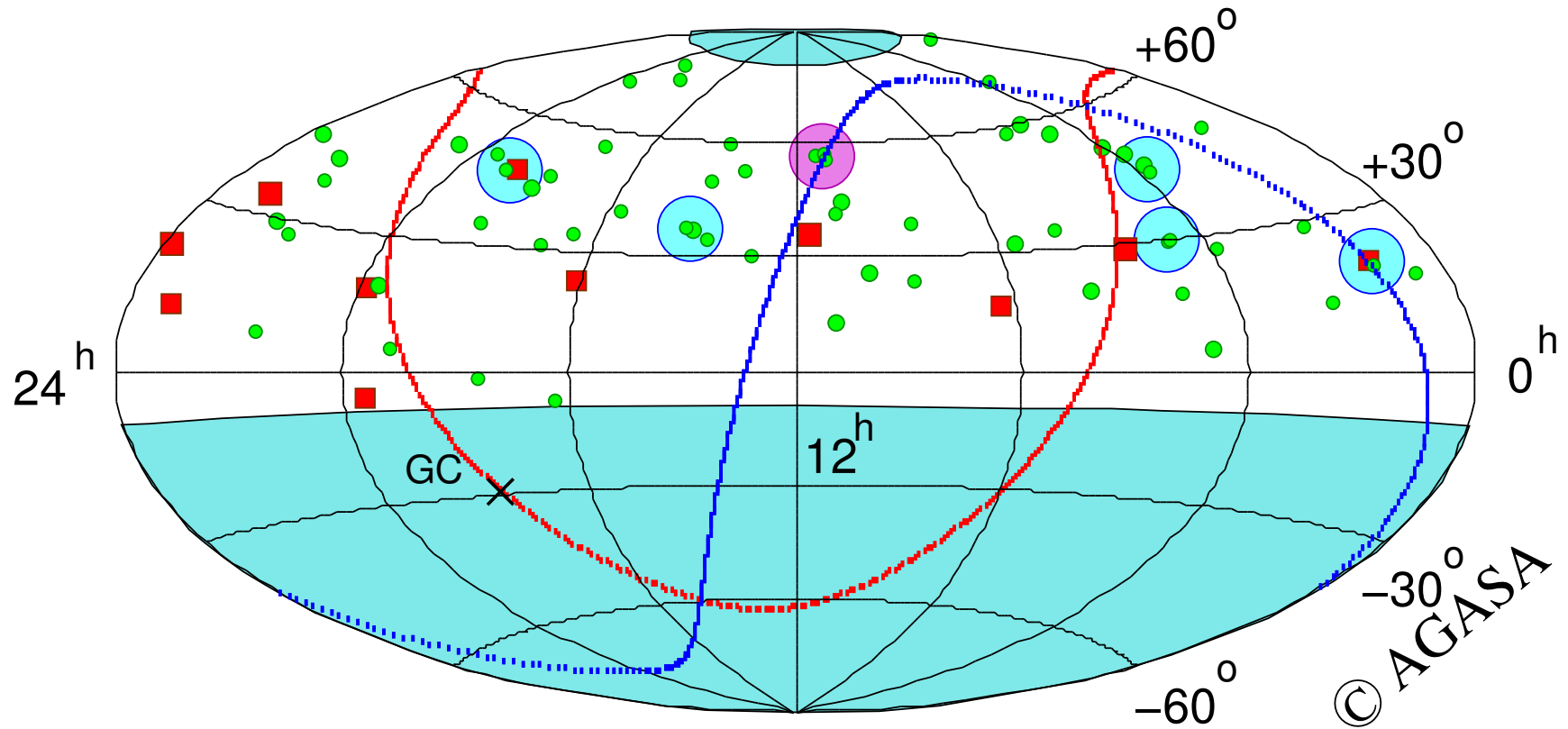
More multiplets in (AGASA+Yakutsk+HP+VR)  $P \sim 10^{-3}$

Y.Uchihori et al.  
astro-ph/9908193

# No global anisotropy



# Global anisotropy @ $E \gtrsim 10^{20}$ eV ?



All other experiments exhibit the same anisotropy,  $P \sim 10^{-2}$

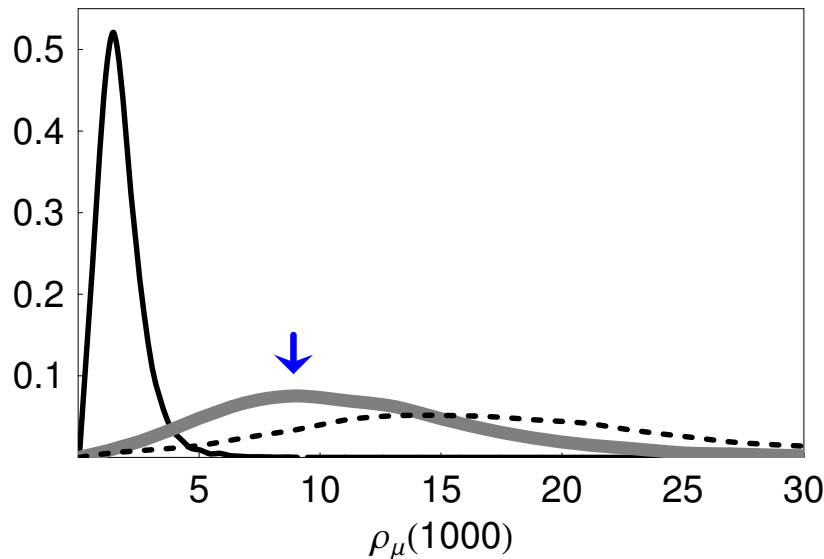
D.G., S.Troitsky  
*astro-ph/0306145*

All UHECRs with  $E > 10^{20}$  eV (about 15 events in total) come from  $\theta < 45^\circ$

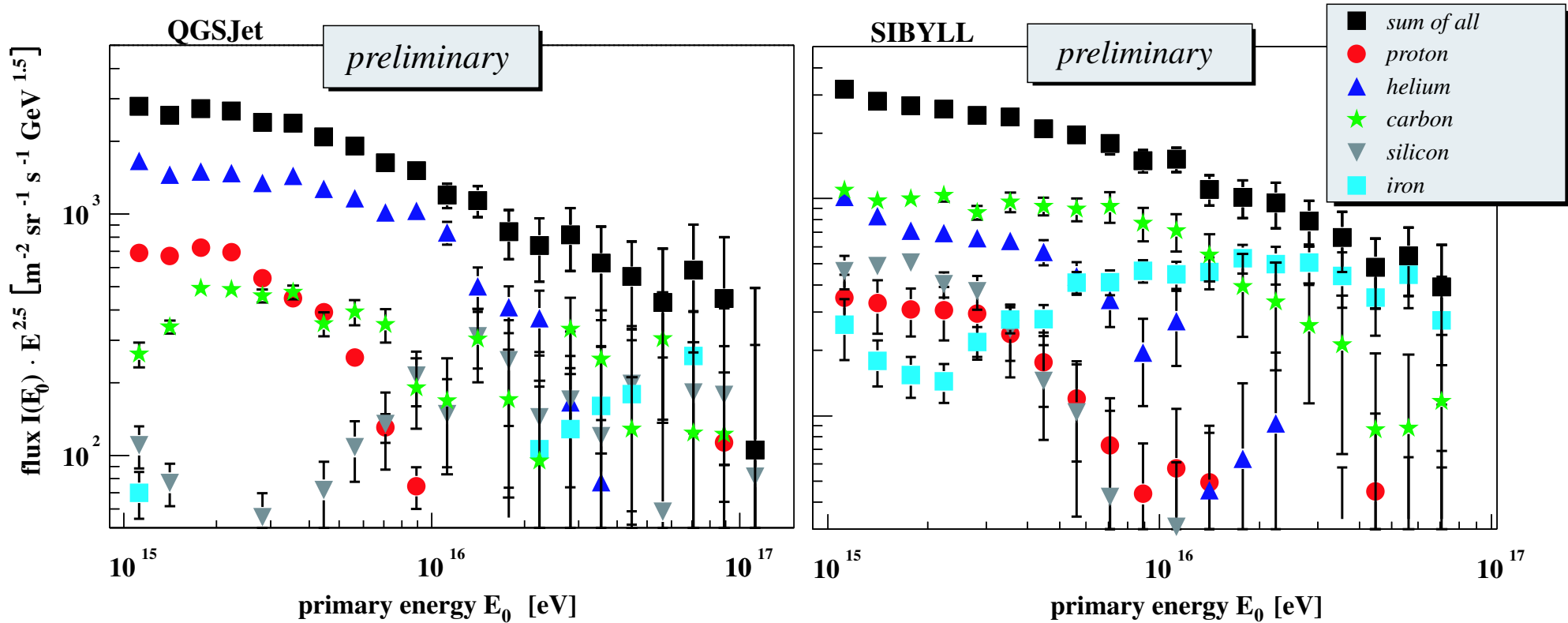
# Results... chemical composition

- muon component : ground arrays
- inclined showers : both
- horizontal showers : both
- $X_{max}$  : fluorescent
- structure of a shower front : ground arrays

Note, that energy estimate depends on primary type...  
results are generator-dependent ...



# Results... chemical composition



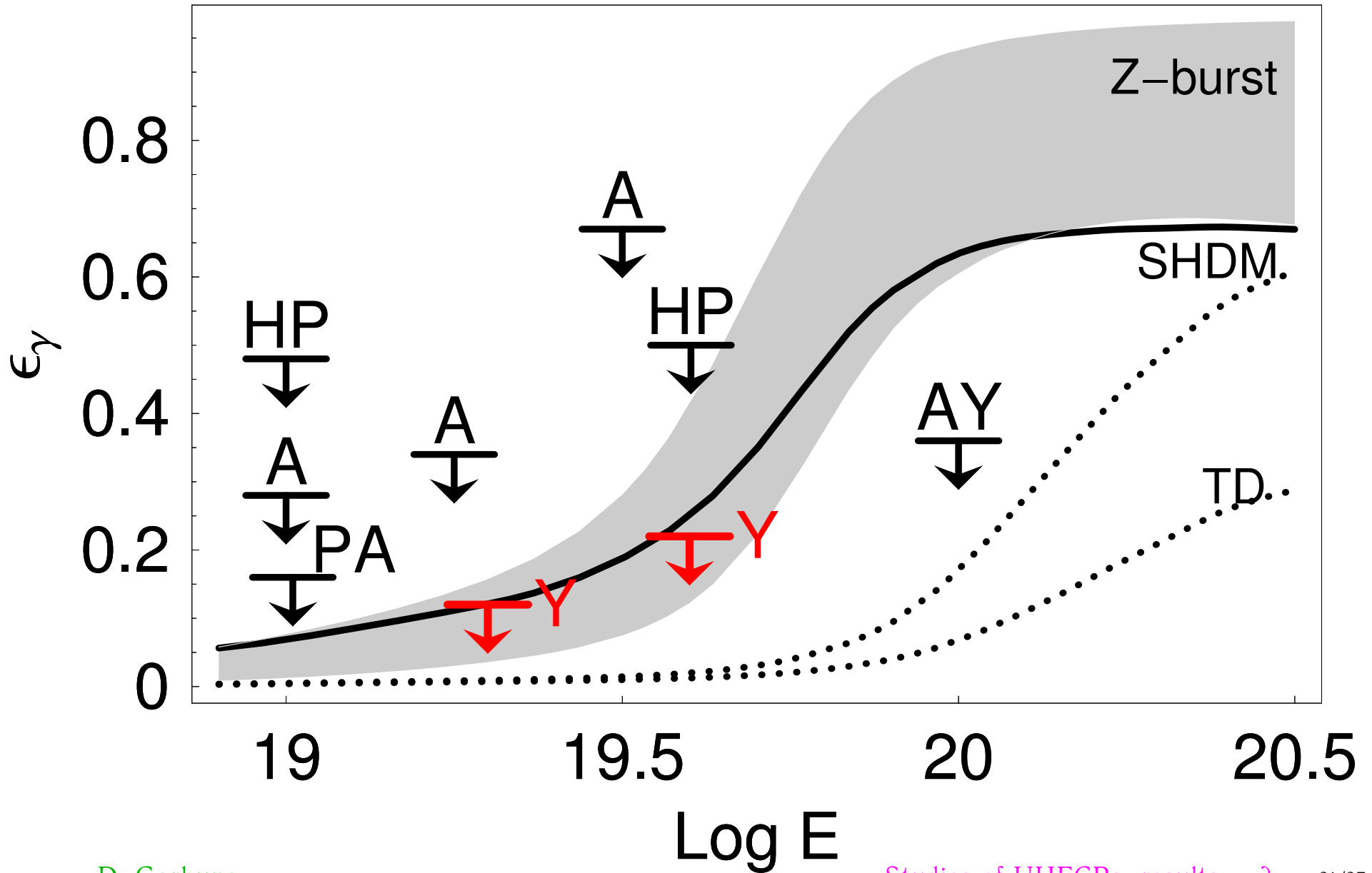
K.-H.Kampert *et al.*  
astro-ph/0406078

$$\frac{Z}{M_A} :$$

Rigidity-dependent acceleration and propagation  
without energy loss



# Chemical composition: no $\gamma$ , $\nu$



# What can we learn from UHECR-studies?

What are sources of UHECRs? (BL Lac's, SHDM, Cosmic strings, ...?)

What are primaries of UHECRs? ( $p$ , Fe,  $\gamma$ ,  $\nu$ , axions, ...?)

## Astrophysics

sources:

acceleration mechanism,  
local backgrounds

space:

$\gamma$ -background,  
magnetic fields

cosmology?

**UHE astronomy**

## Particle physics

interactions at  $E_{cm} \gtrsim 300$  TeV:

cross section,

inelasticity,

multiplicity,

$P_T$ -distribution,

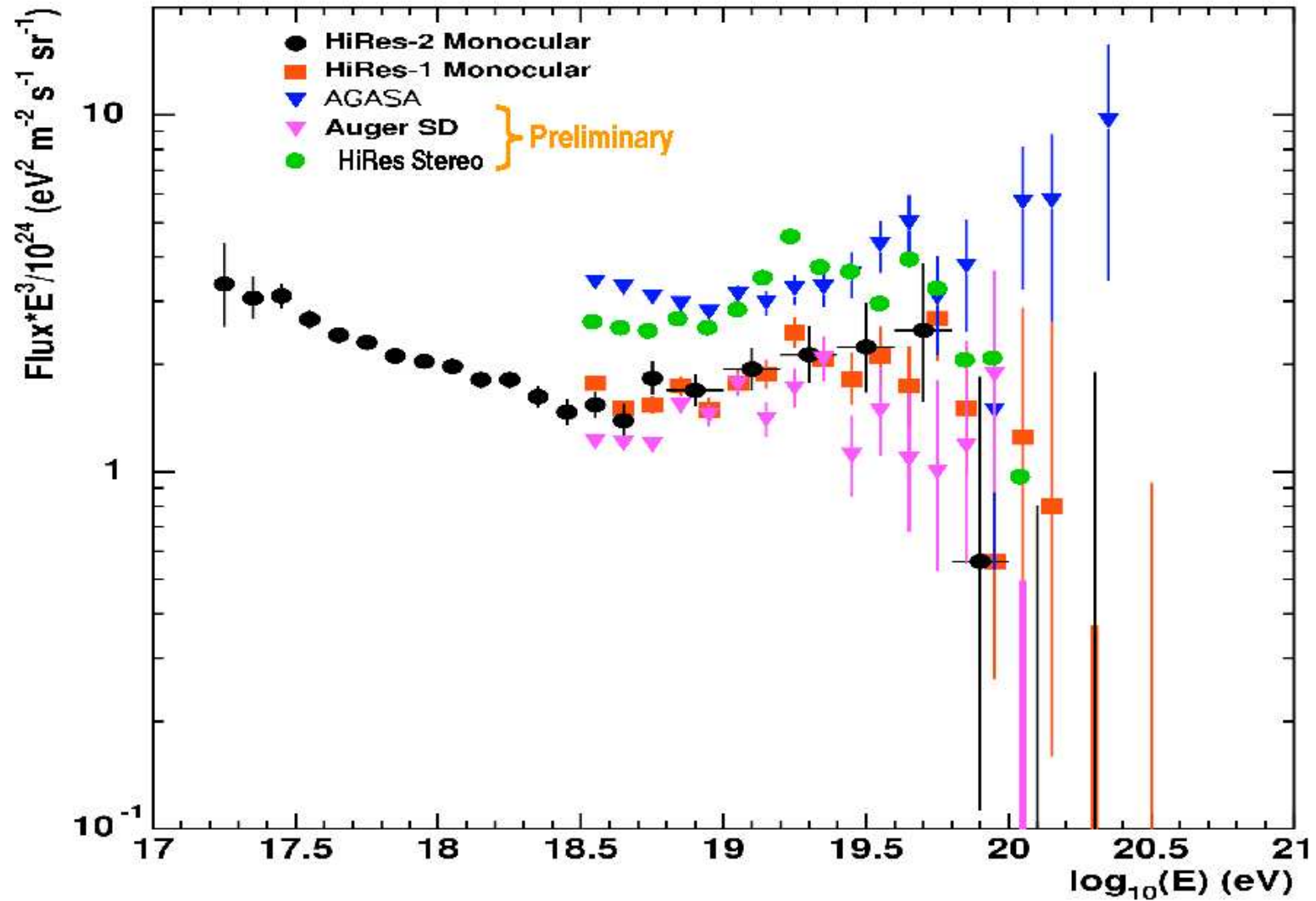
...

new physics phenomena?

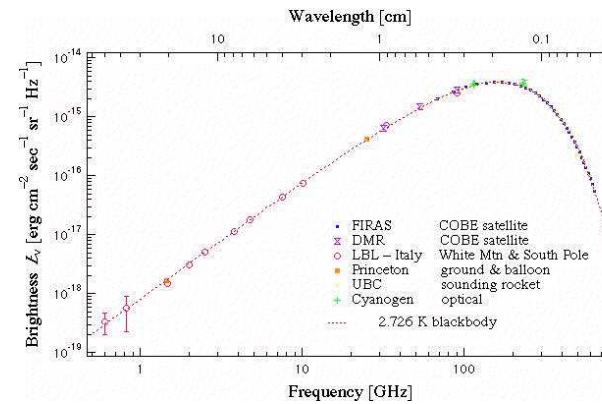
**physics at the smallest distance**



# PAO spectrum



# about 40 years ago...

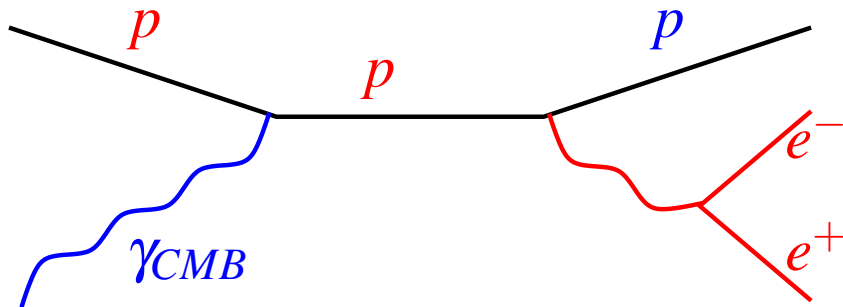


1965 — discovery of CMB

1966 — K. Greisen, **PRL 16, 748**

G. Zatsepin, V. Kuzmin, **JETP Lett 4, 78**

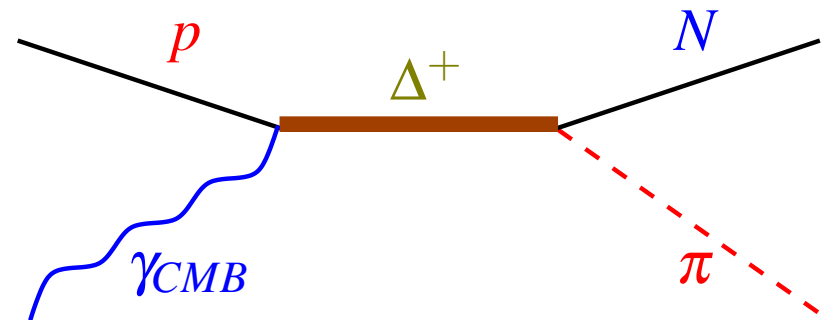
$$E_p \lesssim 5 \cdot 10^{19} \text{ eV}$$



$$L_{p\gamma_{\text{CMB}} \rightarrow pe^+e^-}^{m.f.p.} \sim 1 \text{ Mpc}$$

$$\Delta E_p / E_p \sim 10^{-3}$$

$$E_p \gtrsim 5 \cdot 10^{19} \text{ eV}$$

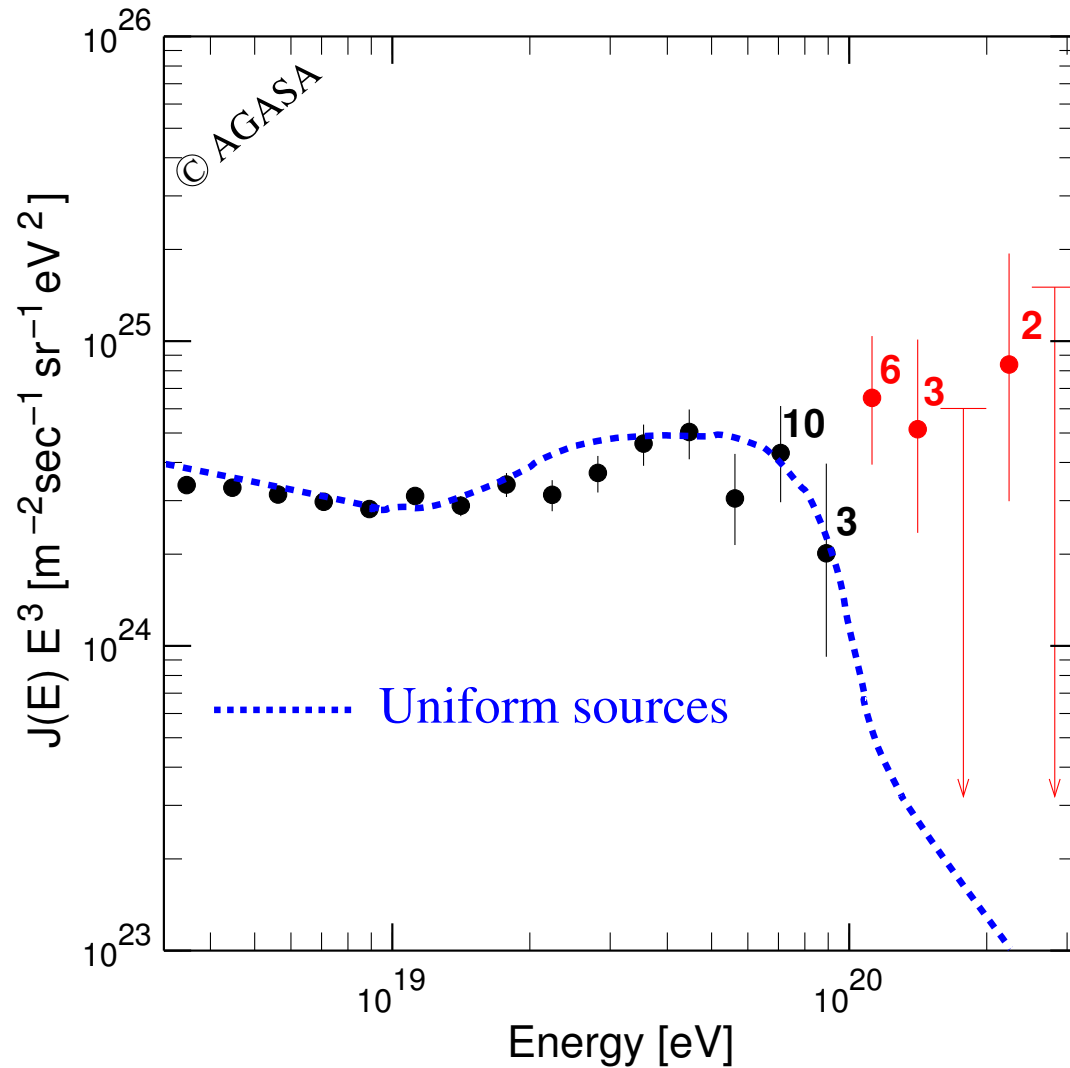


$$L_{p\gamma_{\text{CMB}} \rightarrow N\pi}^{m.f.p.} \sim 10 \text{ Mpc}$$

$$\Delta E_p / E_p \sim 20\%$$



# AGASA: energy spectrum ( $z < 45^\circ$ )



fit:

$$dN/dE = F_0 \cdot E^{-\gamma}$$

$F_0, \gamma$  — low  $E$

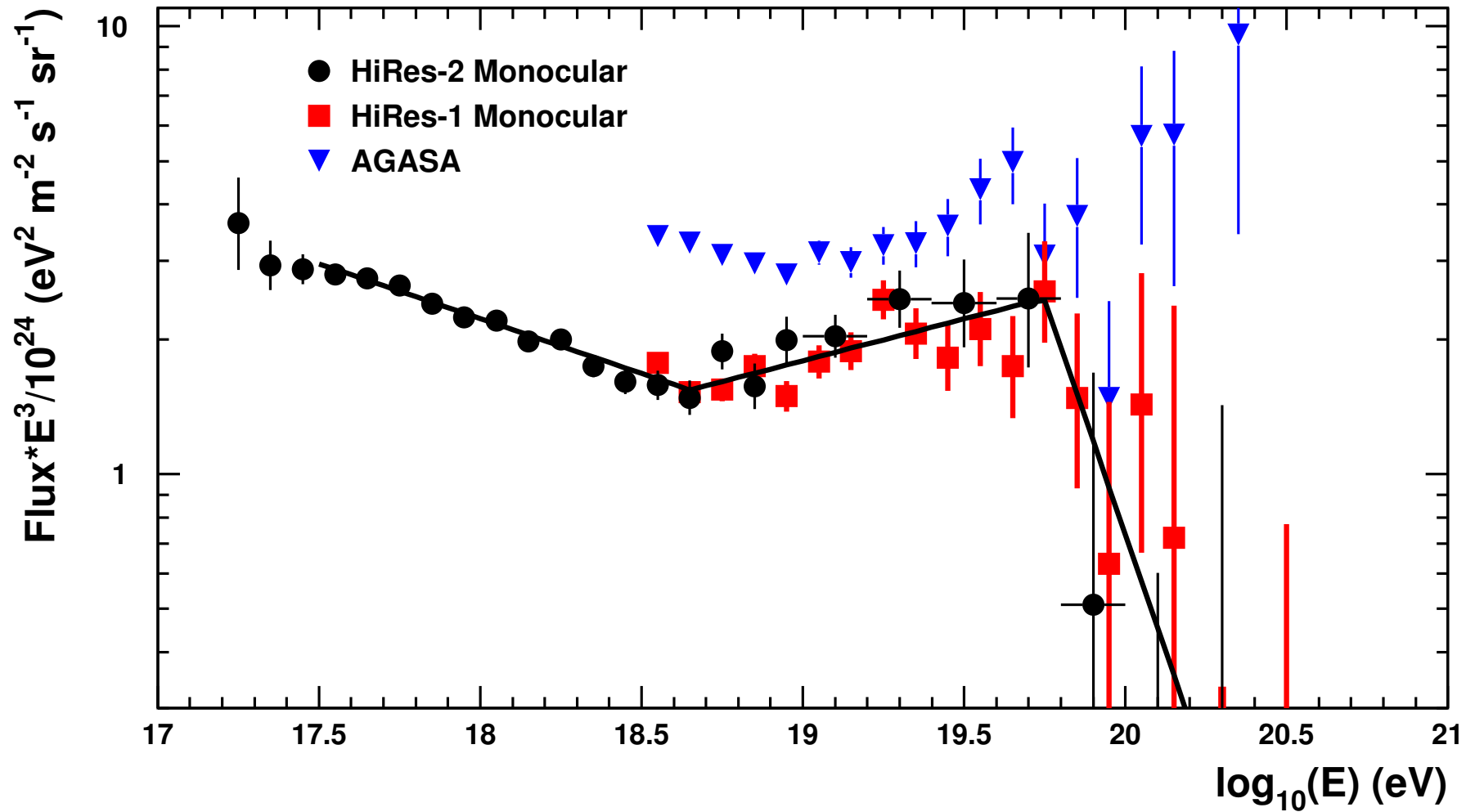
1.9 events  
expected

11 events  
observed

4.4 $\sigma$   
deviation



# HiRes claim



absence of the second feature is excluded at 5 $\sigma$



# FUTURE: experiments

AGASA — final results, catalog of all events... ???

HiRes — final results, catalog of all events

Yakutsk — detailed analysis of rich data

Pierre Auger Observatory (PAO) — FD vs SD ... ?

Telescope Array (TA) — “small PAO” in northern hemisphere

$\Delta E/E \sim 20\%$ ,  $\Delta\theta \sim 0.6^\circ$  (hybrid)

array of 576 detectors; this year it starts to collect statistics

TA Low energy Extension (TALE) —  $0.1^\circ$  (hybrid stereo)

TUS/KLYPVE project — RosCosmos, satellite “Photon” launching in 2009

Japanees EUSO project — 201x ?

