Observation of ultra-high energy cosmic rays

Status in middle of 2009

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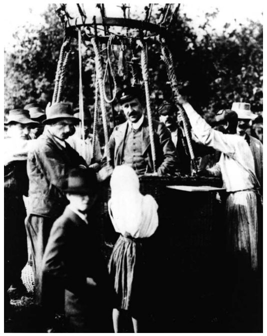
Outline

- History
- Spectrum
- Extensive Air Showers
- Experiments
- Results
- Plans for Future

ultra-high energy cosmic rays (UHECRs) $E > 10^{18}$ eV

Cosmic ray discoveries



1912: Victor Hess in a balloon at an altitude of 5 km discovered "penetrating radiation" coming from space.

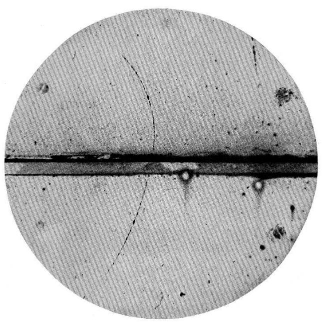
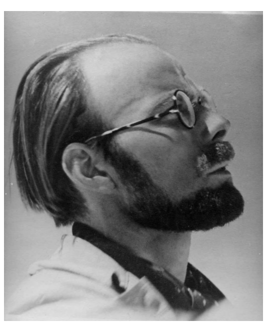


Fig. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

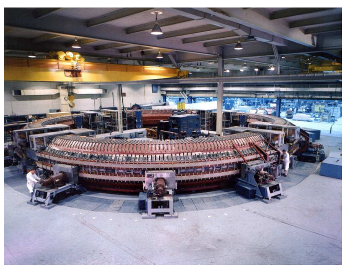
1932: Positron was discovered by Carl D. Anderson by passing cosmic rays through a cloud chamber and a lead plate surrounded by a magnet.



1938: Pierre Auger discovered "extensive air showers" of secondary particles caused by a collision of primaries with air molecules. He concluded that energies are 10^{15} eV – ten million times higher than any known before.

Cosmic ray discoveries

1946: Groups led by Bruno Rossi in USA and Georgi Zatsepin in Russia started experiments on the structure of Auger showers. These researchers constructed the first arrays of correlated detectors to detect air showers.

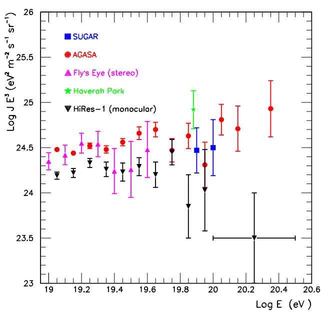


1953: Cosmotron in Brookhaven was the first accelerator to break the giga-electronvolt barrier, reaching energies as high as $3.3\ \mathrm{GeV}$. *We made cosmic rays!*

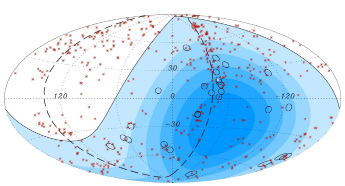
1962: John Linsley and collaborators discovered the first cosmic ray with an energy of about $10^{20}\ \mathrm{eV}$ in the Volcano Ranch array in New Mexico, USA.

CR discoveries – still continue

1991: Experiment Fly's Eye observed the most energetic particle ever recorded, its energy was 3.2×10^{20} eV.

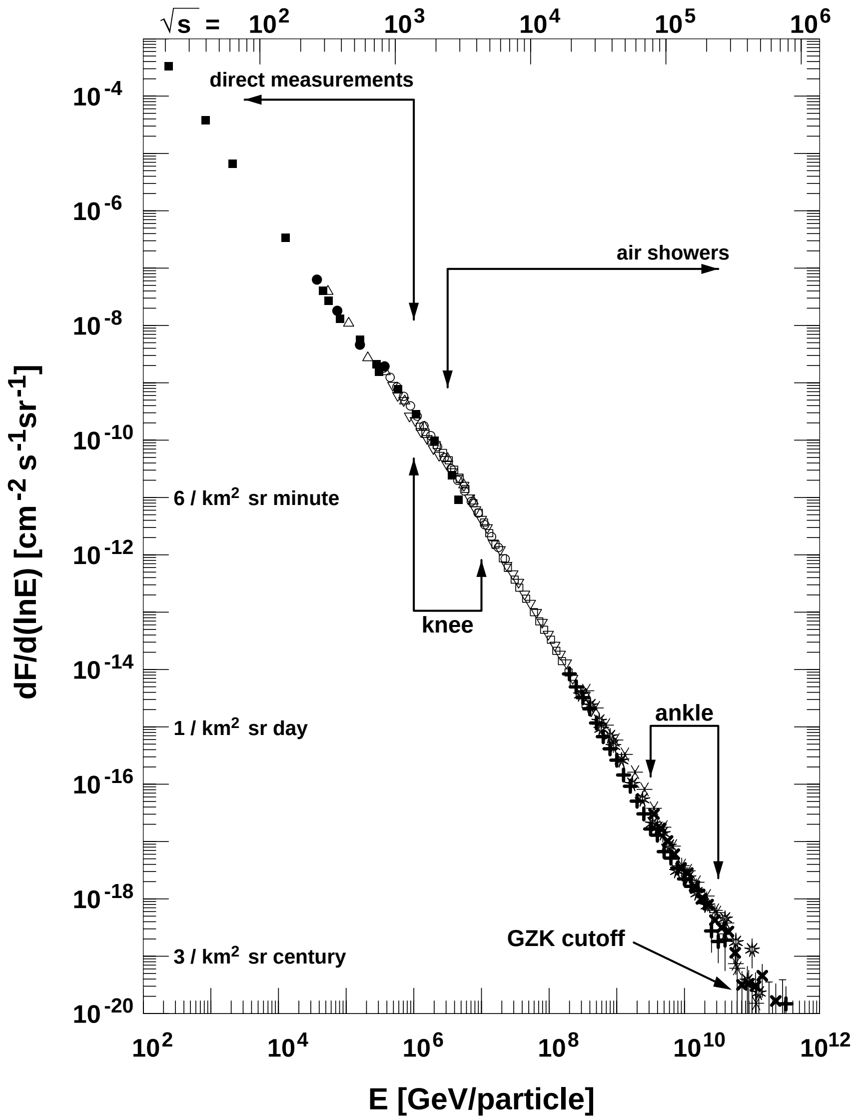


1998: Cosmic ray crisis – discrepancy in energy cosmic ray flux measured by different experiments at highest energies (AGASA vs. Fly's Eye & HiRes).



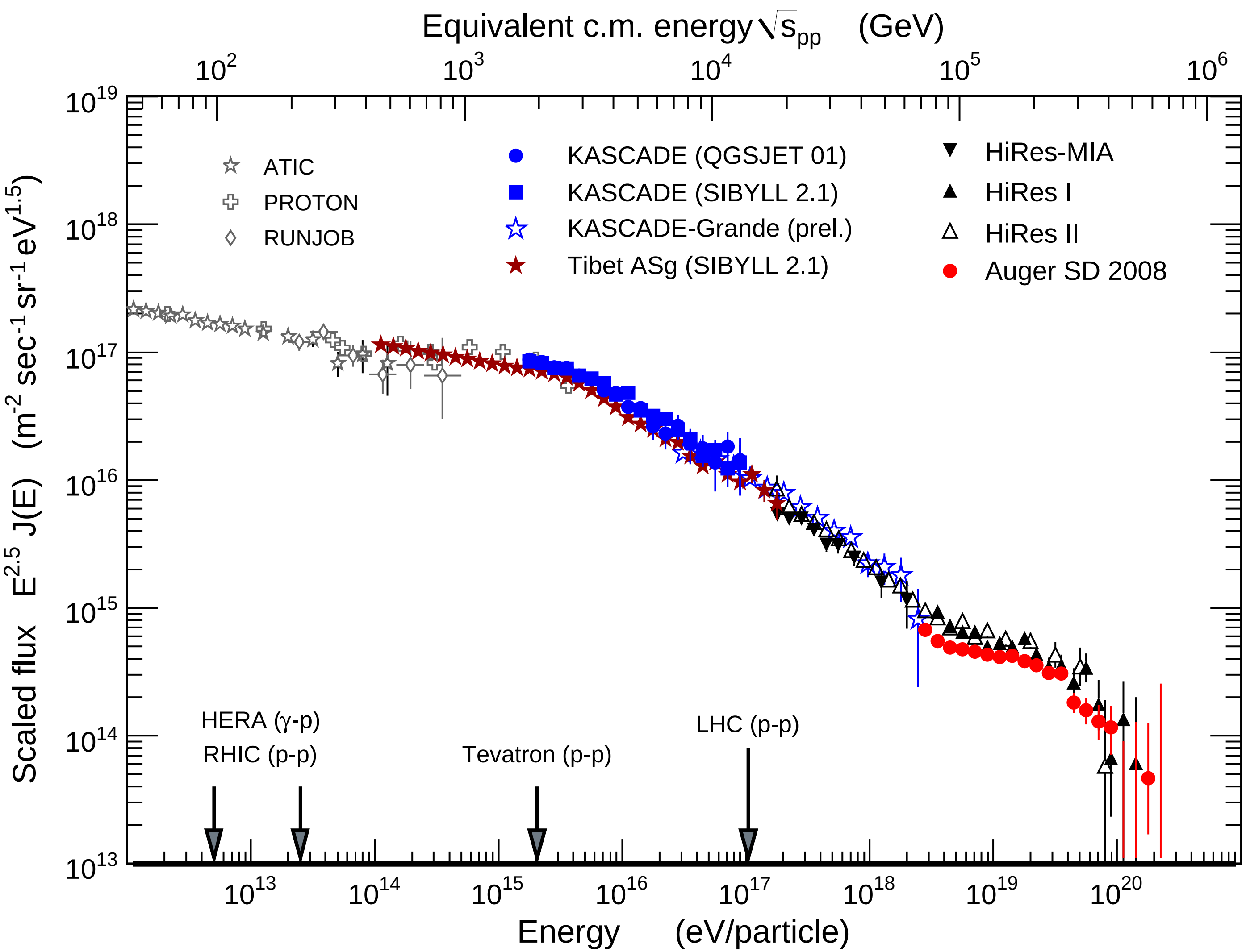
2007: Results from the Pierre Auger Observatory – suppression of cosmic ray flux and anisotropy of arrival directions at highest energies

Cosmic ray energy spectrum



- power-law flux over many orders of magnitude
- two features – knee and ankle
- end of spectrum?
- direct measurement only below 10^{14} eV
- measurement of air showers at higher energies

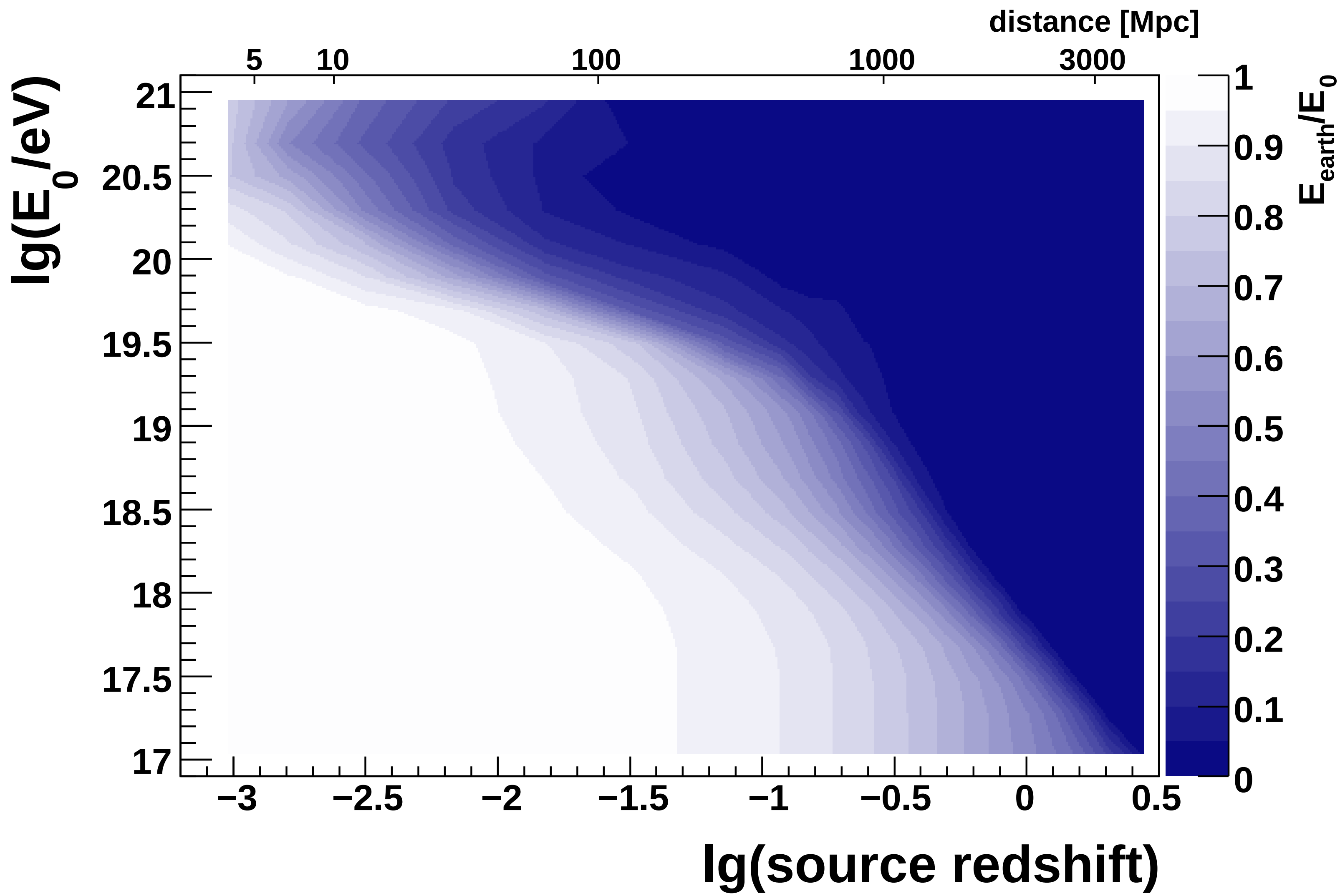
Scaled energy spectrum



GZK cut-off

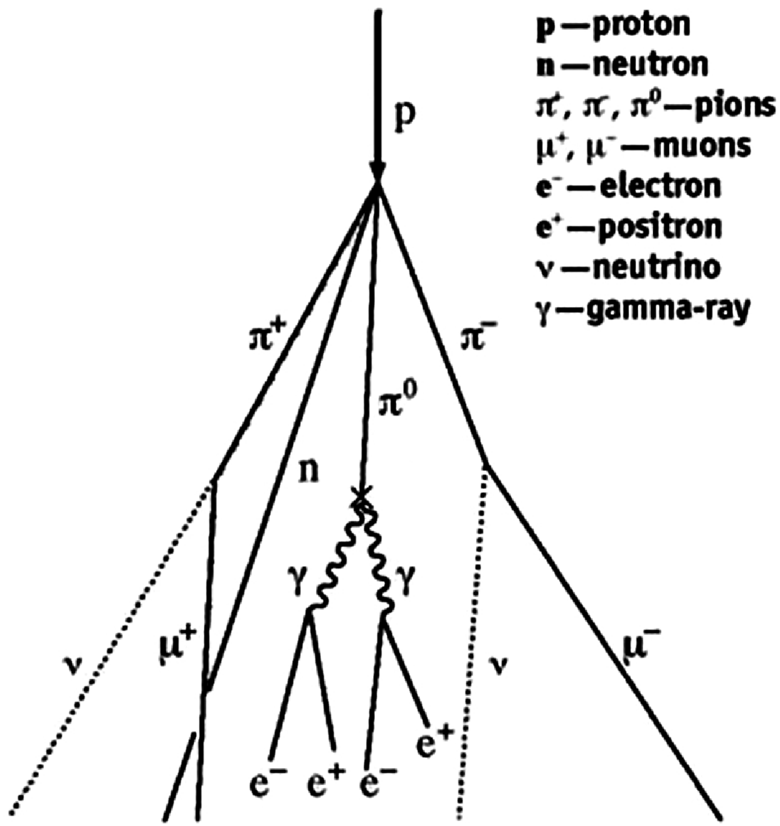
- cosmic microwave background (1965)
- Greisen-Zatsepin-Kuzmin (1966) – cosmic ray absorption in CMB
  $p + \gamma_{cmb} \longrightarrow \Delta(1232) \longrightarrow p + \pi^0 \quad \text{or} \quad n + \pi^+$
- photodisintegration of nuclei
  $Fe + \gamma_{cmb,ir} \longrightarrow nucleus + (1\ or\ 2)\ nucleons$
- suppression of cosmic ray flux above energy of 4×10^{19} eV (GZK cut-off)
- maximum source distance of $50 \div 100$ Mpc

Energy losses – source distance



M. Unger, ECRS (2008)

Extensive air shower

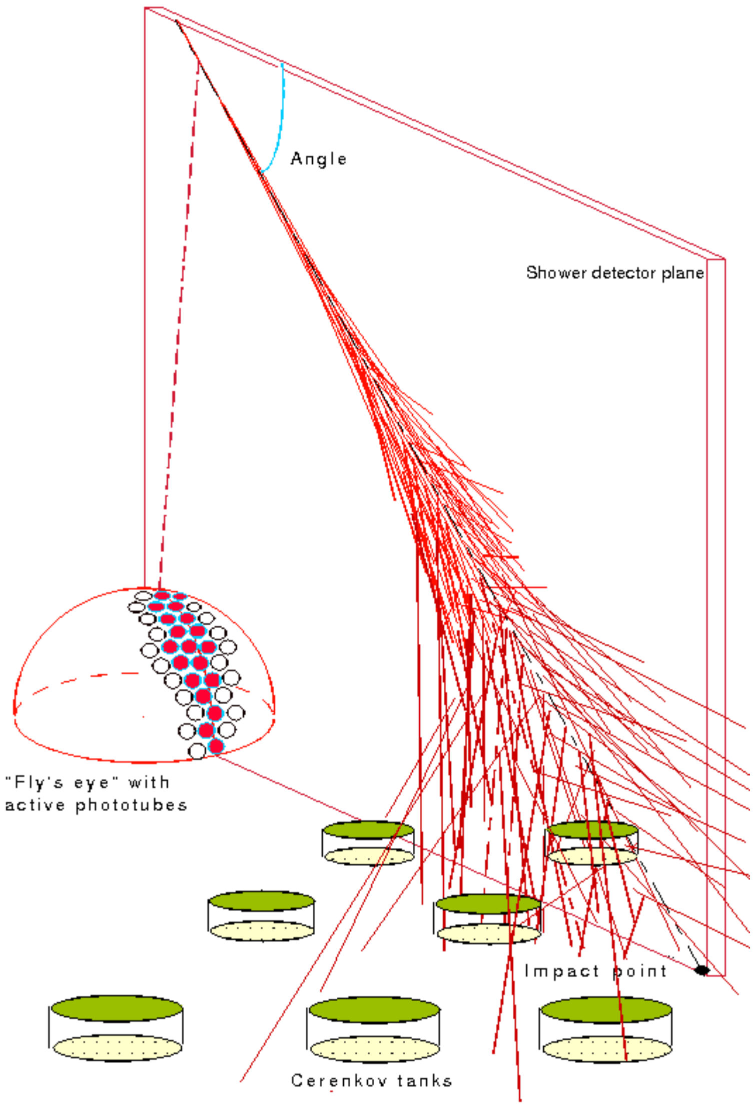


Collision of primary particle in air produce a shower of relativistic secondary particles.

Components of shower:

- electromagnetic (e$^-$, e$^+$, γ)
- hadronic (p, n, π etc.)
- muons
- neutrinos

Air shower measurement



- surface detector (SD) – lateral distribution at the ground
- fluorescence detector (FD) – development of a shower in the atmosphere
- **hybrid detector** – better than than just sum of SD and FD

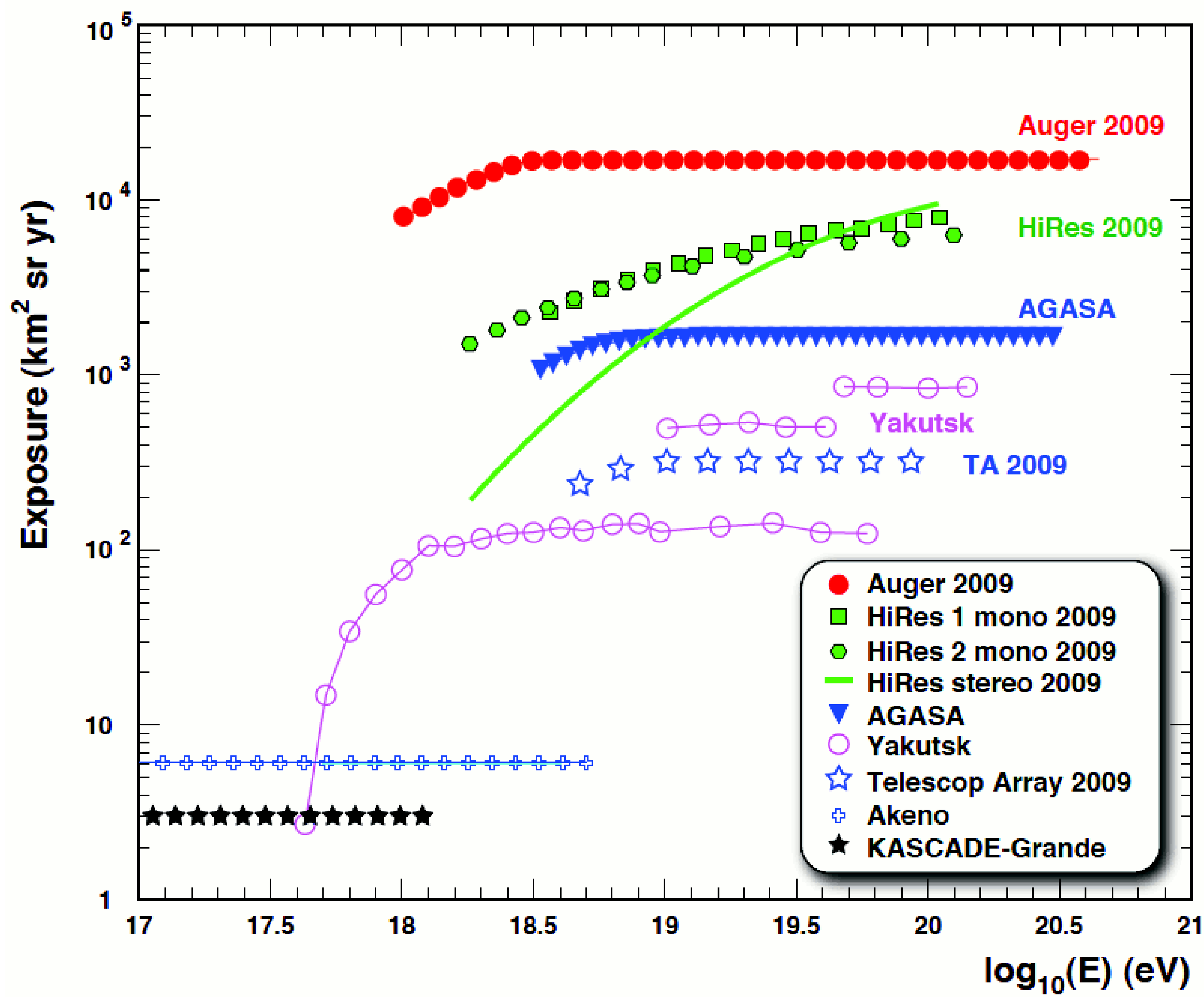
Hybrid detector

Surface detector:
+ high statistics (24h/day)
+ simple geometrical exposure
- energy calibration from EAS simulations

Fluorescence detector:
+ low energy threshold
+ calibration by laboratory experiments
- about 13% duty cycle
- complicated aperture

Hybrid:
+ well known calibration
+ well known aperture
+ excellent angular resolution ($\sim 0.2^{\circ}$)
+ low energy threshold

Experiments



K.H. Kampert, EPS-HEP (2009)

Pierre Auger Observatory

- planned to be on both hemispheres
- western Argentina, province Mendoza
- fully operated since June 2008
- $3\,000\ \mathrm{km}^2$
- 1 600 water Cherenkov tanks
- 1.5 km distance
- 4 sites with fluorescence telescopes
- lower energy extensions: HEAT and Amiga

Telescope Array

- Utah, northern hemisphere
- operated since March 2008
- $700\ \mathrm{km}^2$
- 507 plastic scintillators
- 1.2 km distance
- 3 sites with fluorescence telescopes
- lower energy ext.: TALE (5×10^{16} eV)
- No results yet published

FD supplemental measurements

- Absolute and relative calibration
- Atmospheric monitoring (lasers, lidars, cloud cameras, radiosondes, etc.)
- Fluorescence yield (e.g. AirFly)
- TA: Linac – "showers" by electron beam (40 MeV)

$\Rightarrow$ Aim of these measurements is precise estimation of air shower energy measured by FD!

UHECR science case

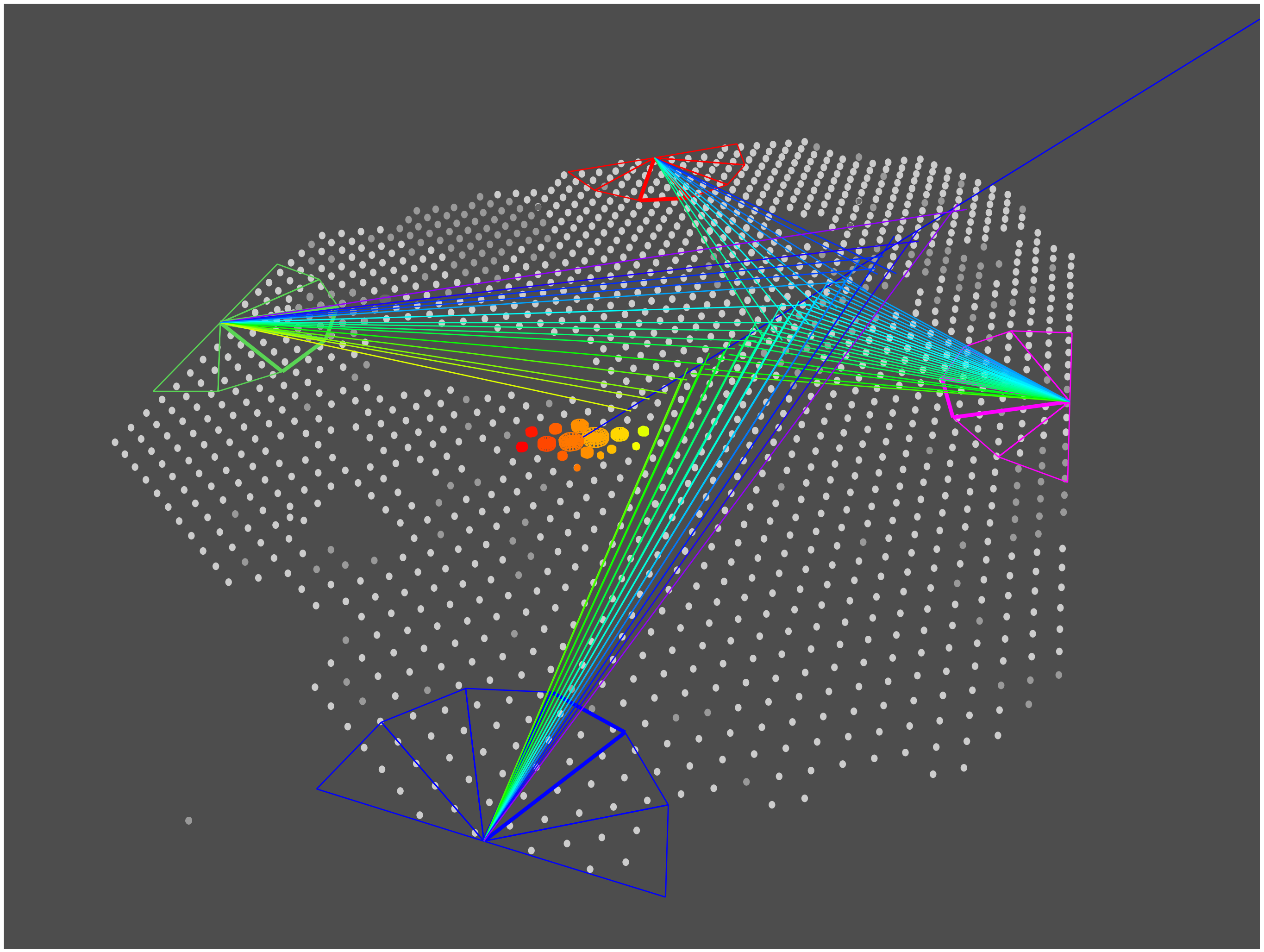
- Sources of most energetic CR need to be nearby.
- Deflections in magnetic fields may be weak.
- Need to measure: direction, energy, particle-type

$\Rightarrow$ Identification of sources by CR-astronomy

By-products:

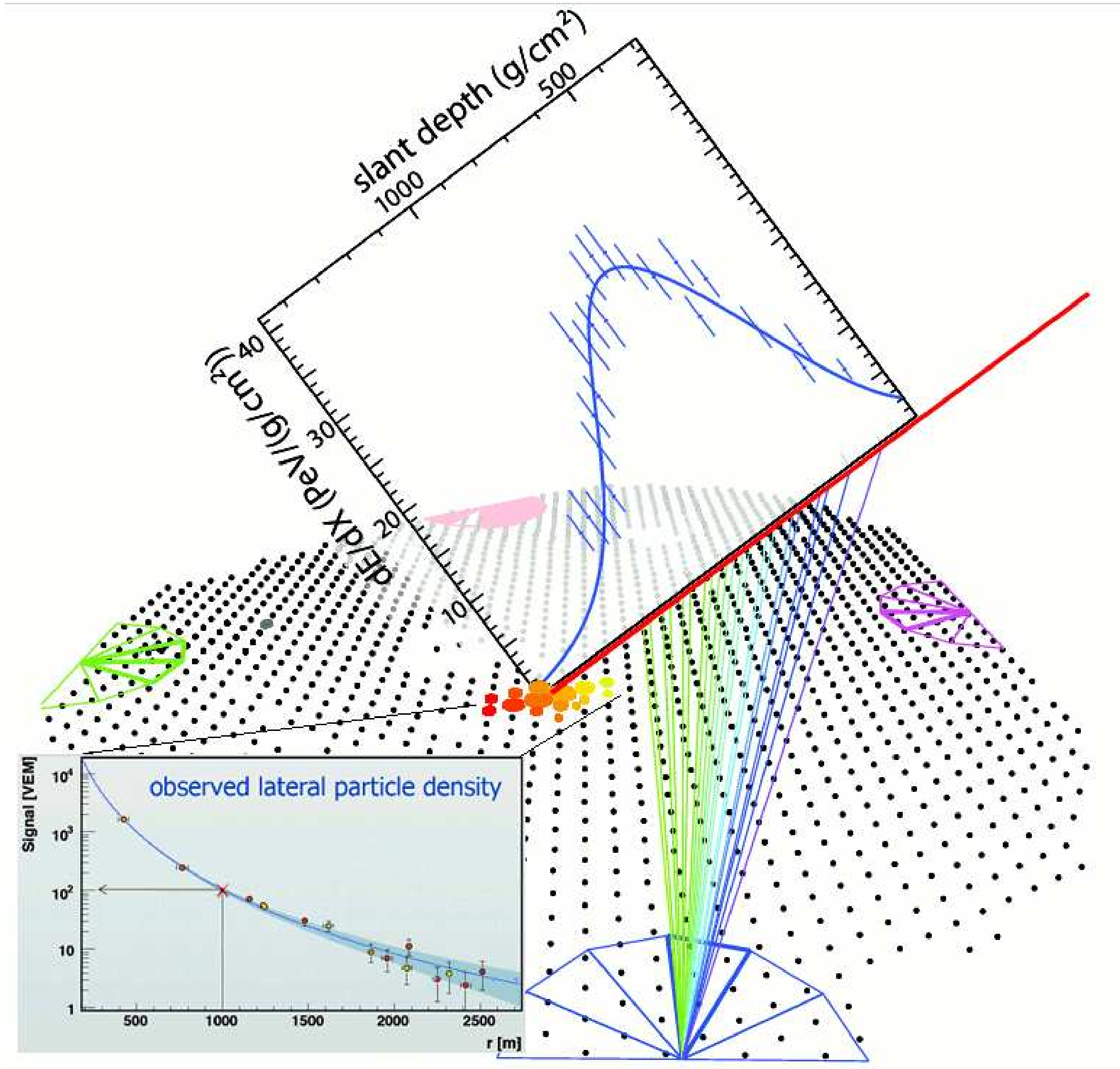
- Do particle physics (e.g. pA cross-sections)
- Probe fundamental physics (e.g. test of LIV)
- Learn about cosmic environment (e.g. B-fields)

Golden event

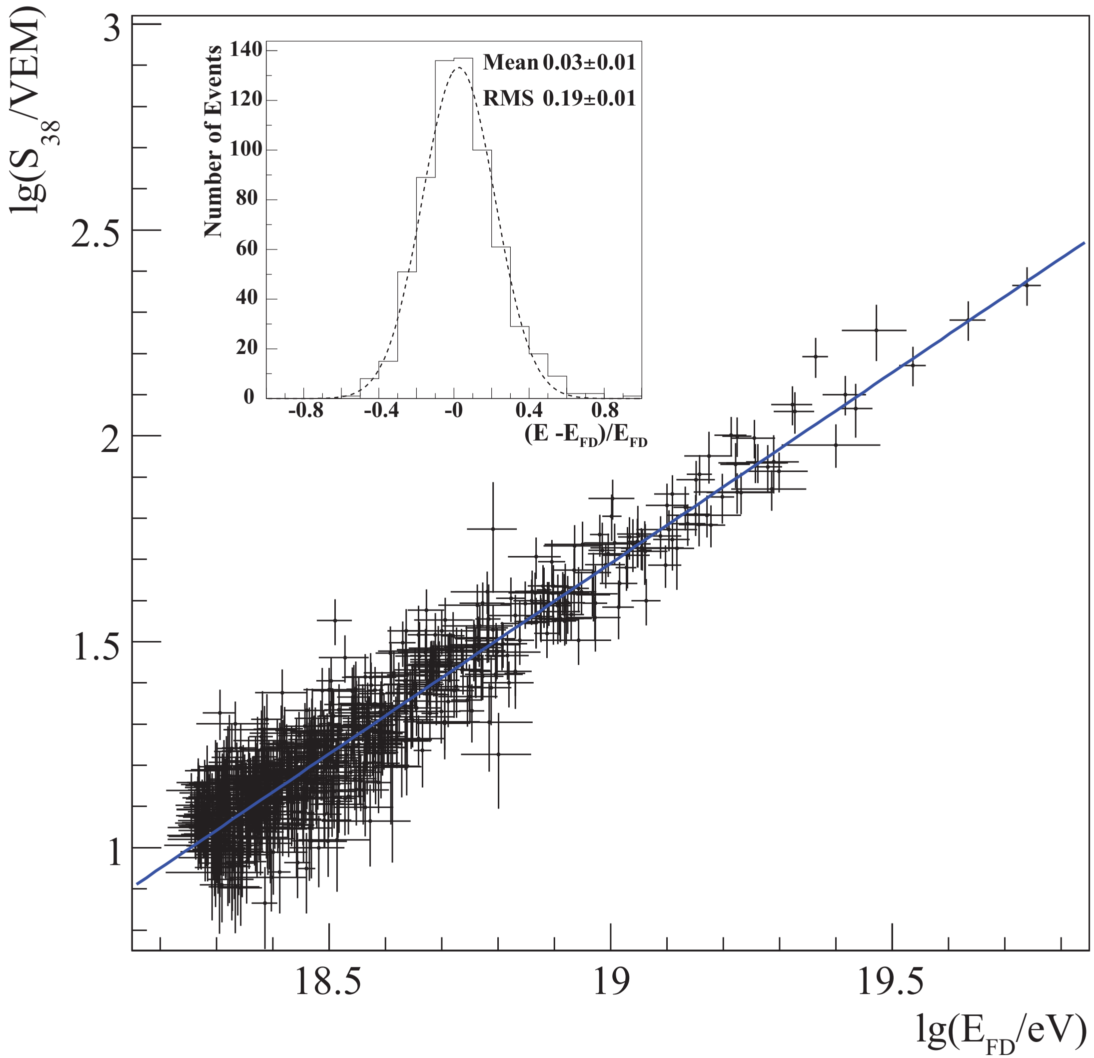


Victor Hess (Nobel Lecture, Dec 1936): "In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneosly and side-by-side."

SD calibration by FD

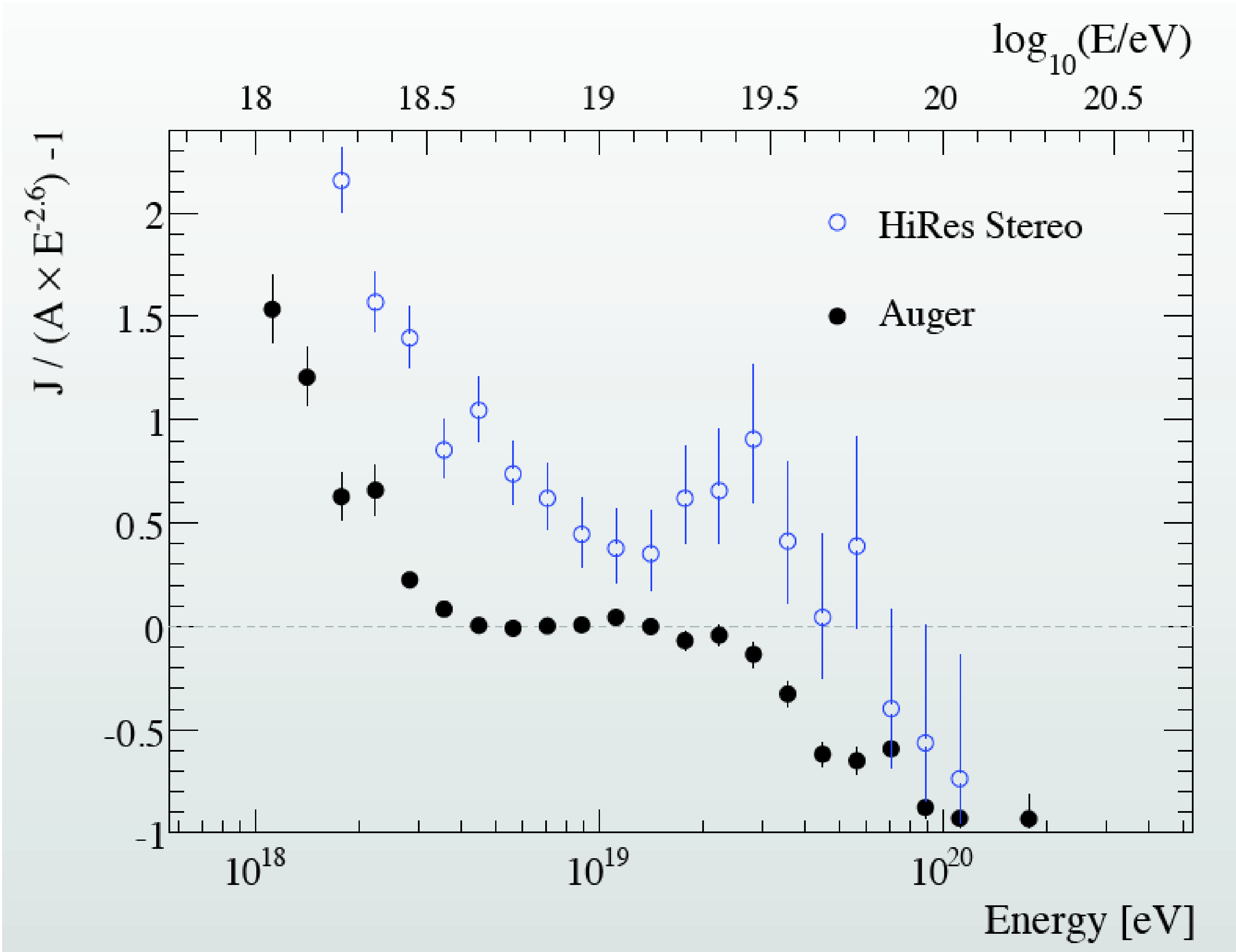


Correlation between S_{38} and E_{FD}

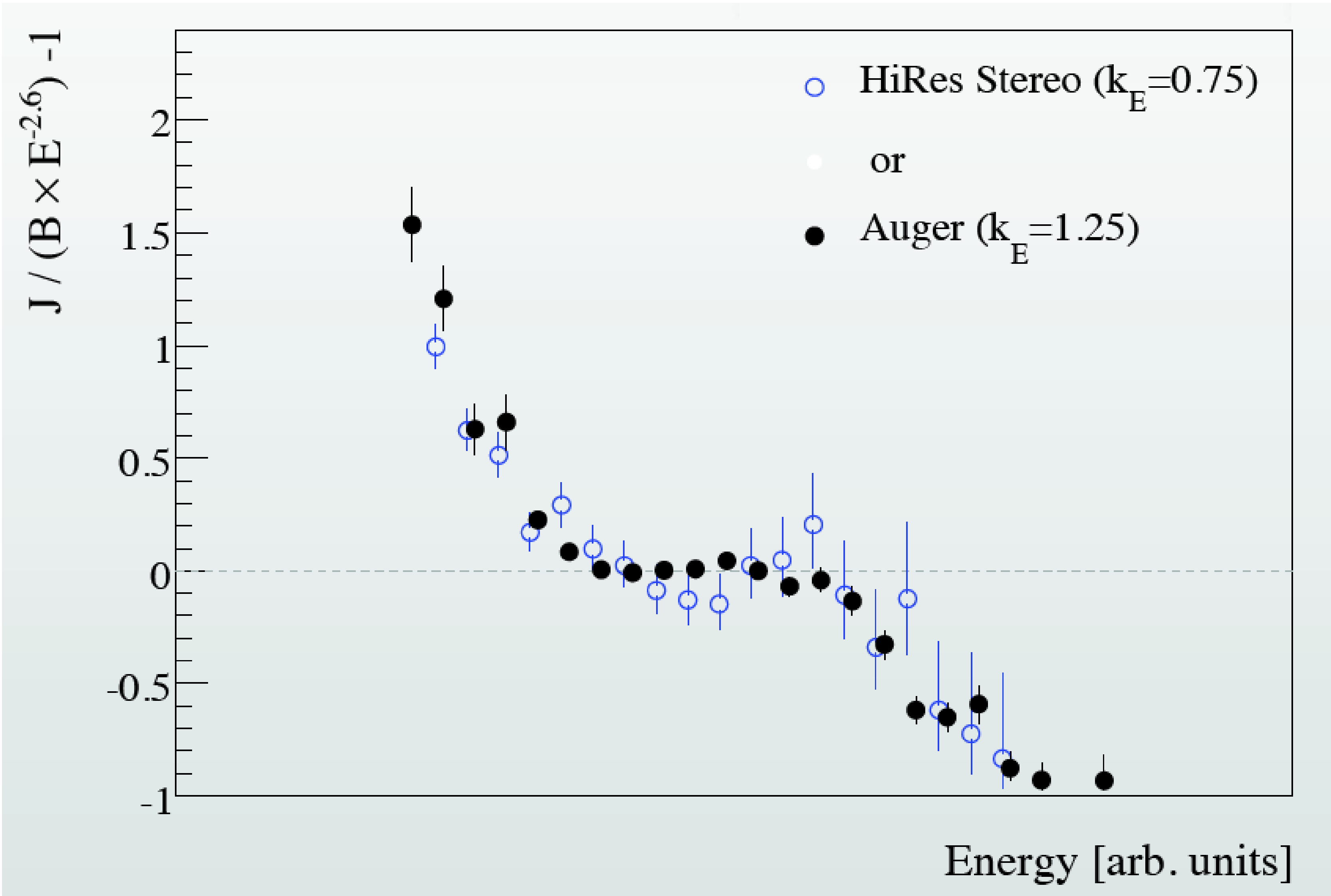


The Pierre Auger Collaboration, PRL 101 (2008)

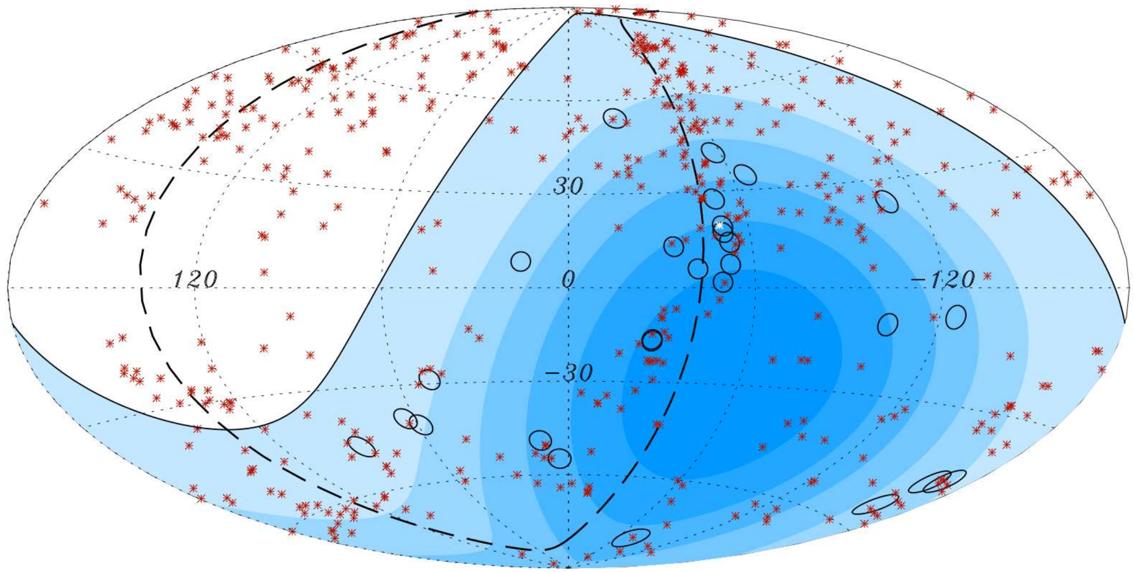
Suppression of CR spectrum



Rescaling of measured spectra

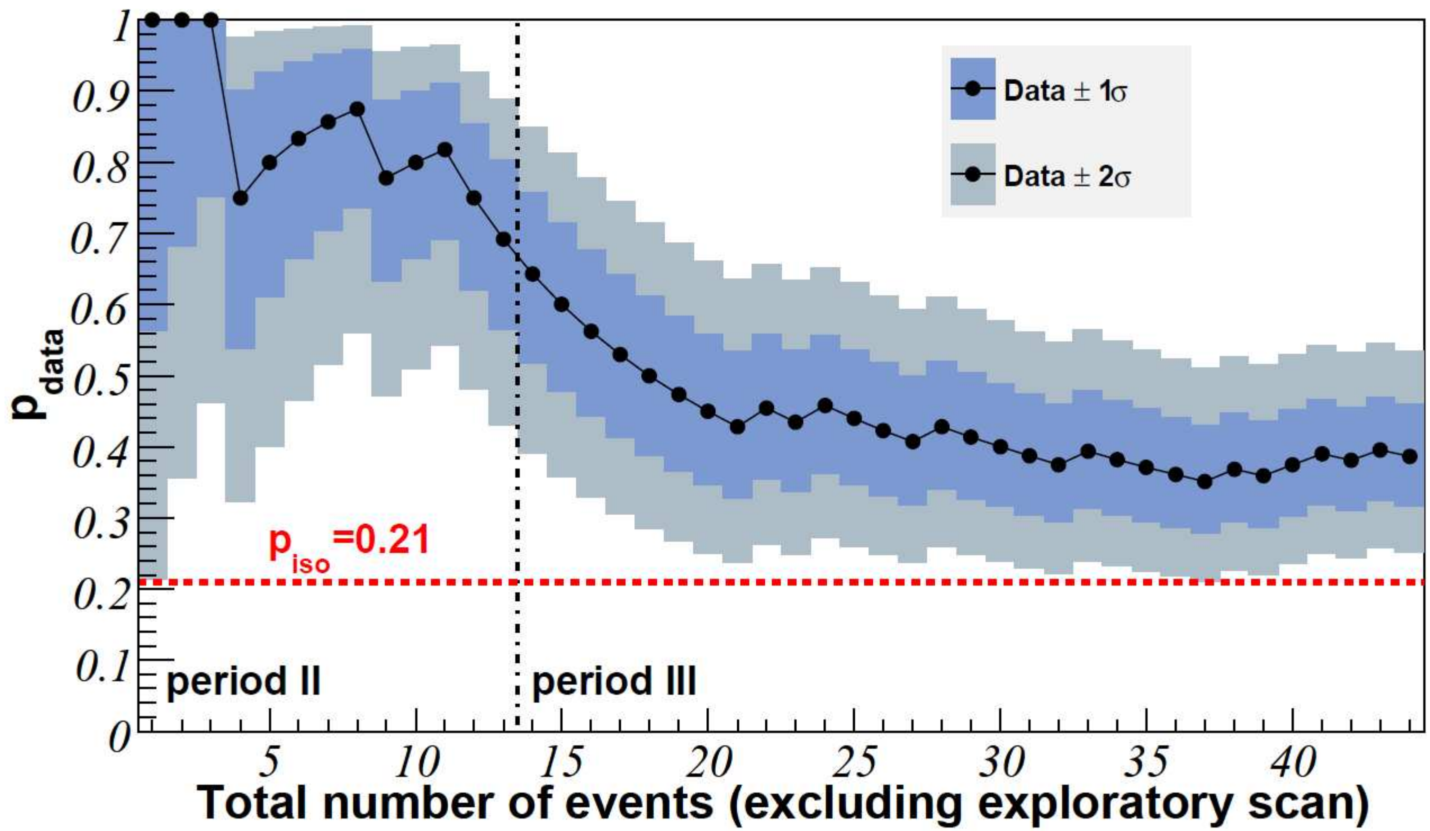


AUGER: UHECRs and AGN



- AGN with redshift < 0.018 (75 Mpc)
- AUGER data above 5.6×10^{19} eV
- 20 out of 27 correlate within 3.1°
- AUGER statement: anisotropy at > 99% CL

Anisotropy above $\sim 6 \times 10^{19}$ eV

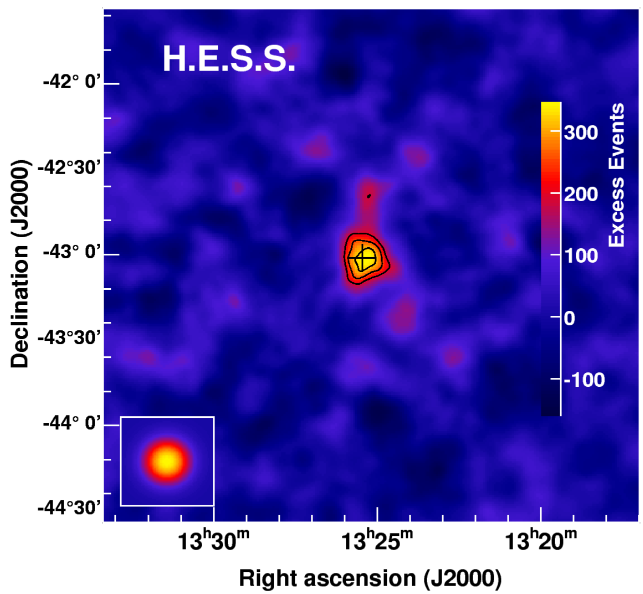


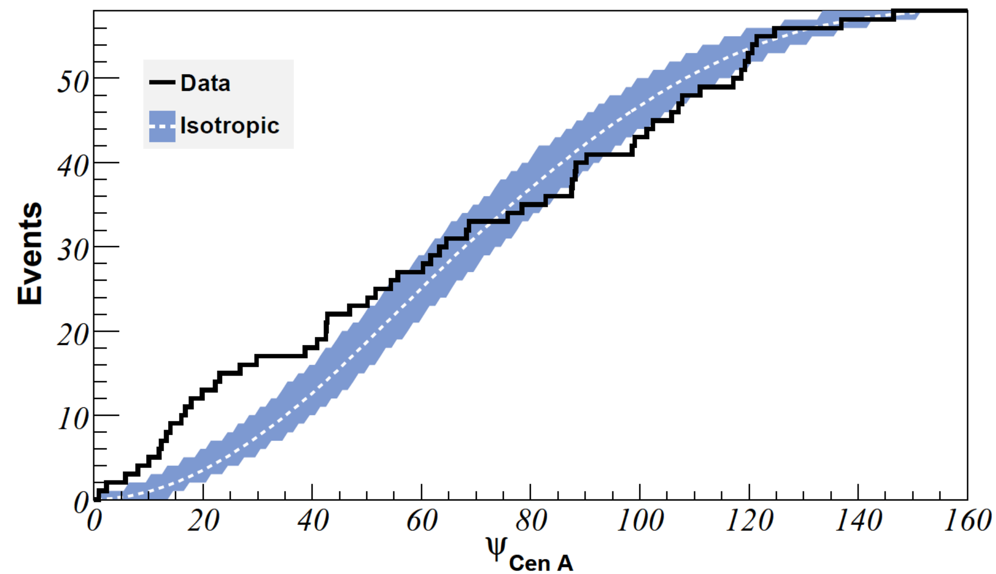
- AUGER correlation strength with AGN positions dropped from 70% to 40%, but the isotropy of arrival directions is still excluded.

Local luminous matter

- correlation of AUGER highest-energy cosmic rays with nearby luminous matter

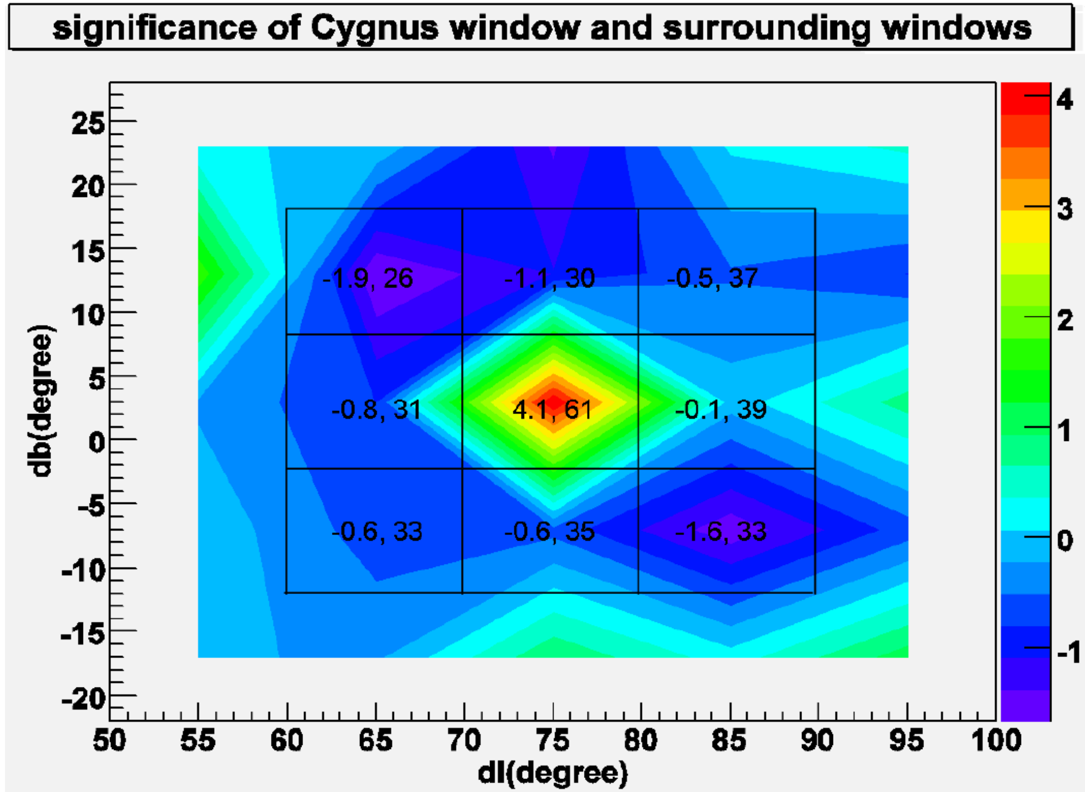
Centaurus A (NGC 5128)





- the closest AGN (~ 4 Mpc)
- photons – radio, X-ray, γ-ray, up to TeV
- AUGER: excess of UHECRs within separation angle $\sim 20° \div 30°$

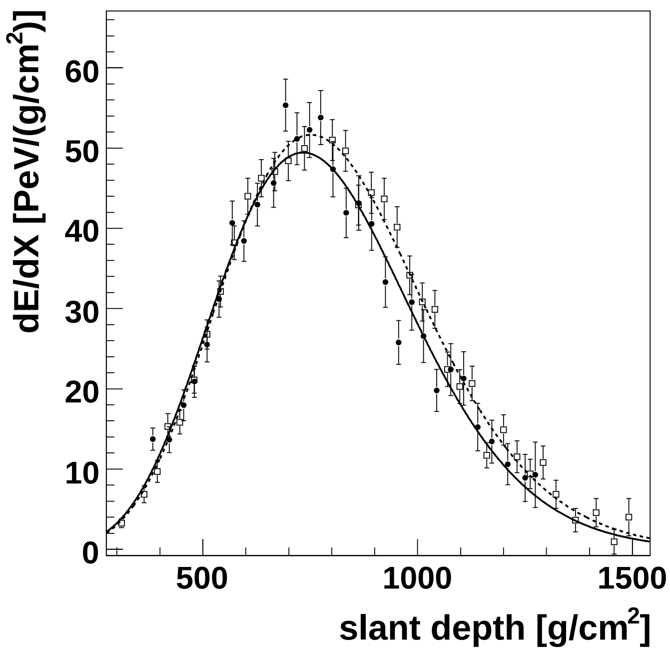
HiRes: Cygnus region

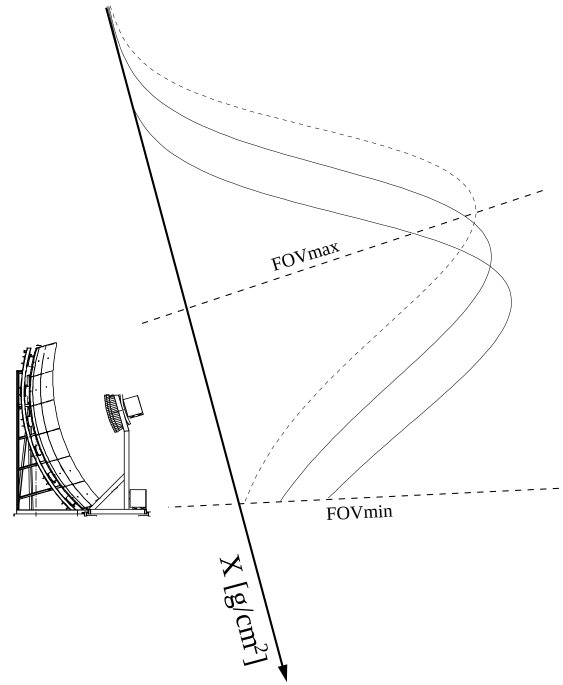


- many massive stellar associations and SNRs
- ~ 1.7 kpc, $(294° < R.A. < 314°, 34° < \delta < 44°)$

H. He, ICRC (2009)

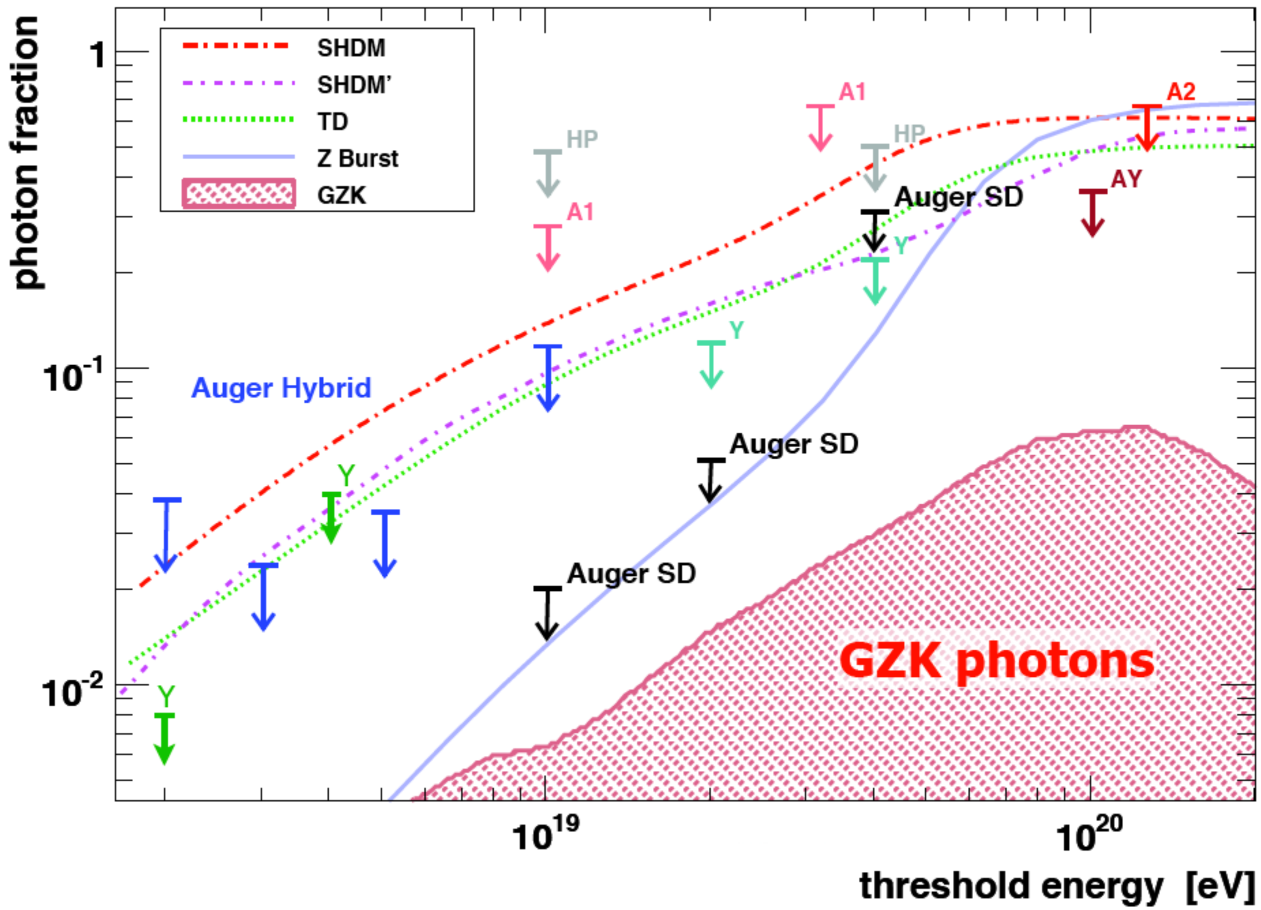
Composition study





- longitudinal profile – "clever" cuts
- shower maximum X_{max}
- photons deeper than nuclei
- mass sensitive parameters also for SD

Upper limit on flux of photons



HP: Ave et al. '00 & '02
A1: Shinozaki et al. '02
A2: Risse et al. '05
AY: Rubtsov et al. '06
Y: Glushkov et al. '07

SHDM, TD, Z Burst: Gelmini et al. '05

SHDM': Ellis et al. '06

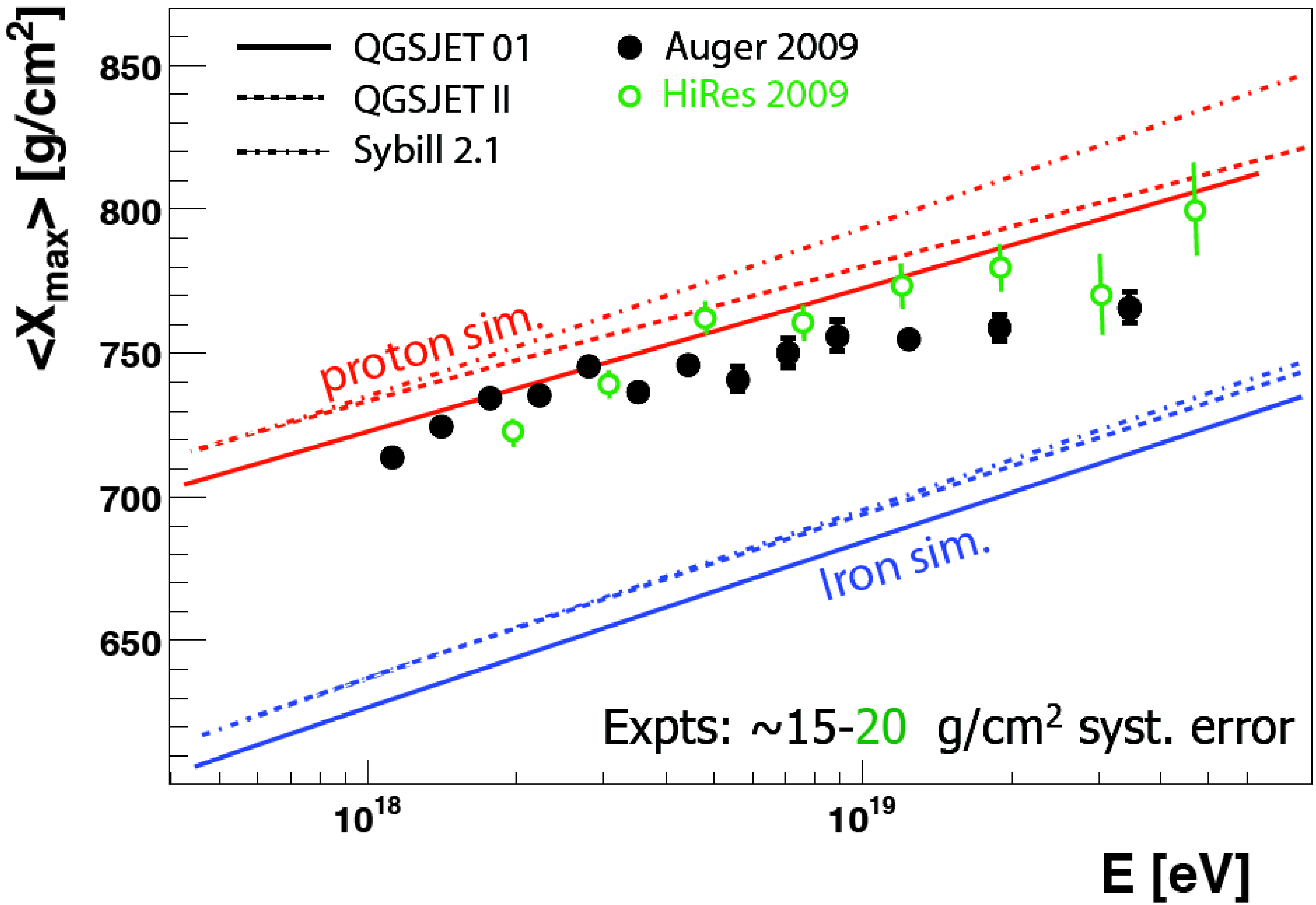
GZK: Gelmini et al. '07

Auger 09

Yakutsk 09

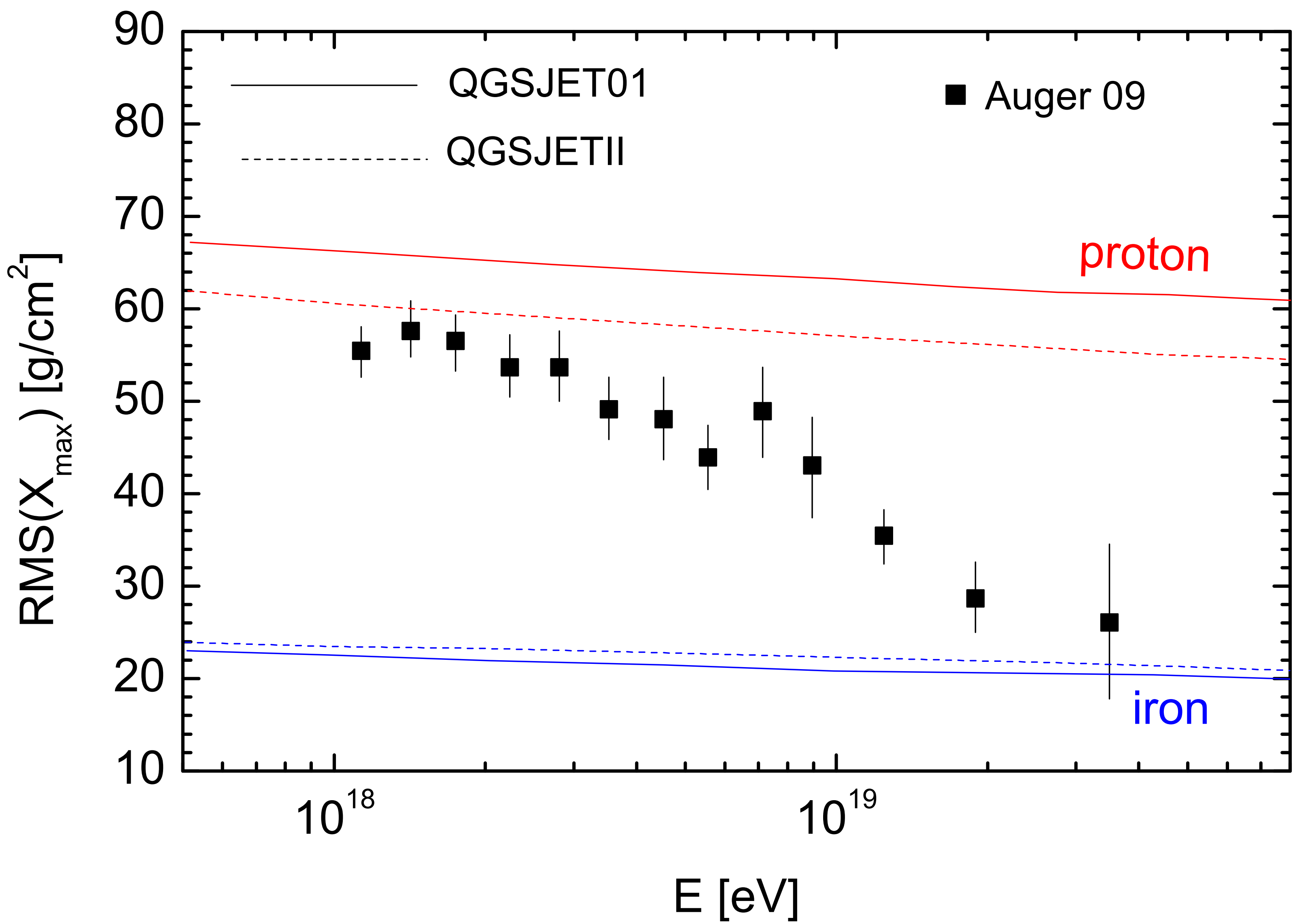
- Top-down models largely ruled out.
- Waiting for GZK photons.

Hadronic composition



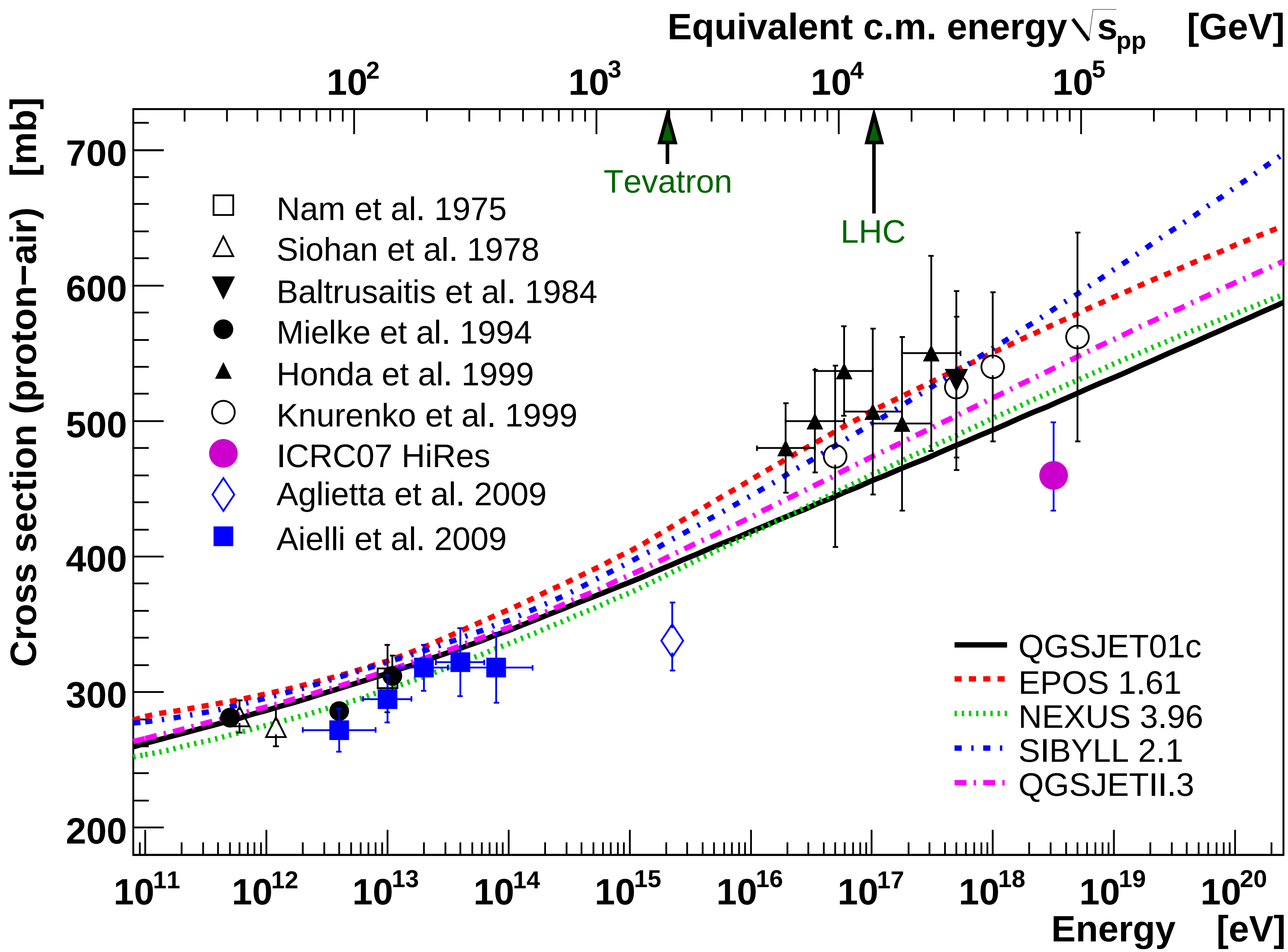
K.H. Kampert, EPS-HEP (2009)

Fluctuation of X_{max}



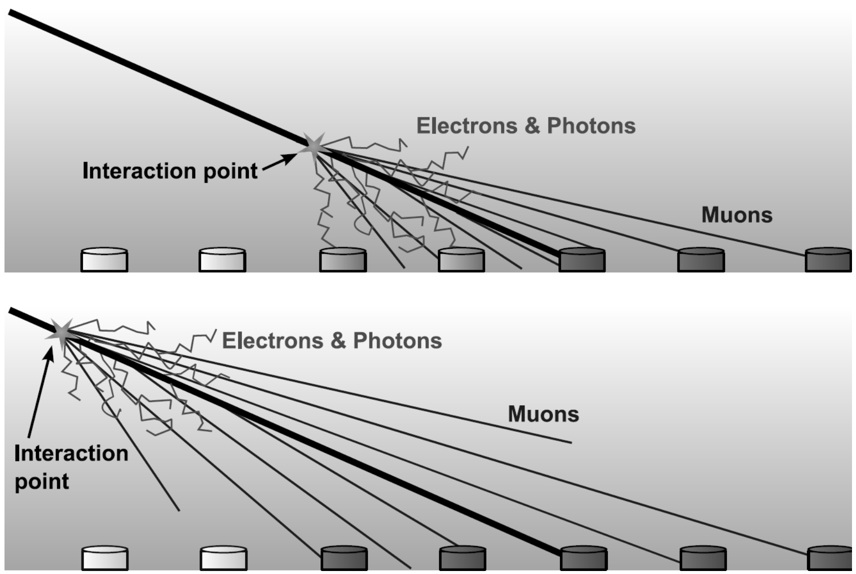
The Pierre Auger Collaboration, ICRC (2009)

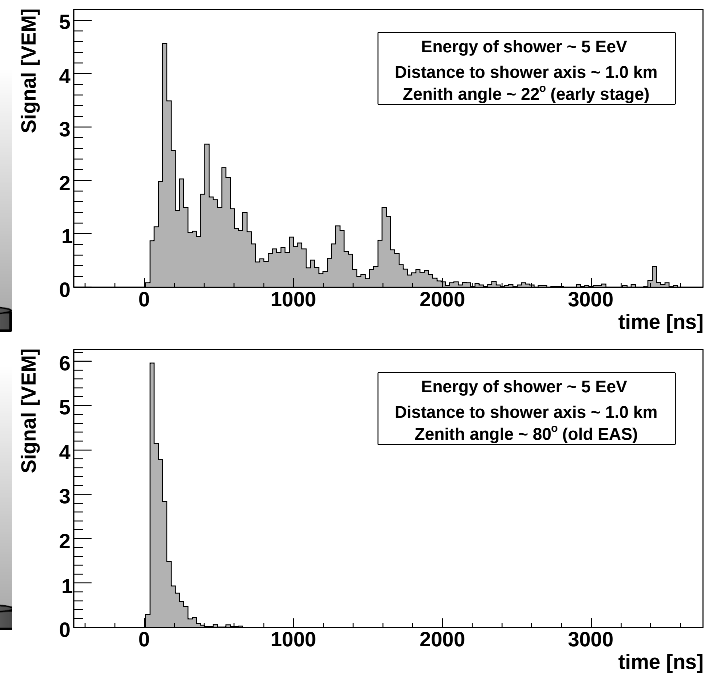
Proton-air cross section



R. Ulrich, New J. Phys. 11 (2009)

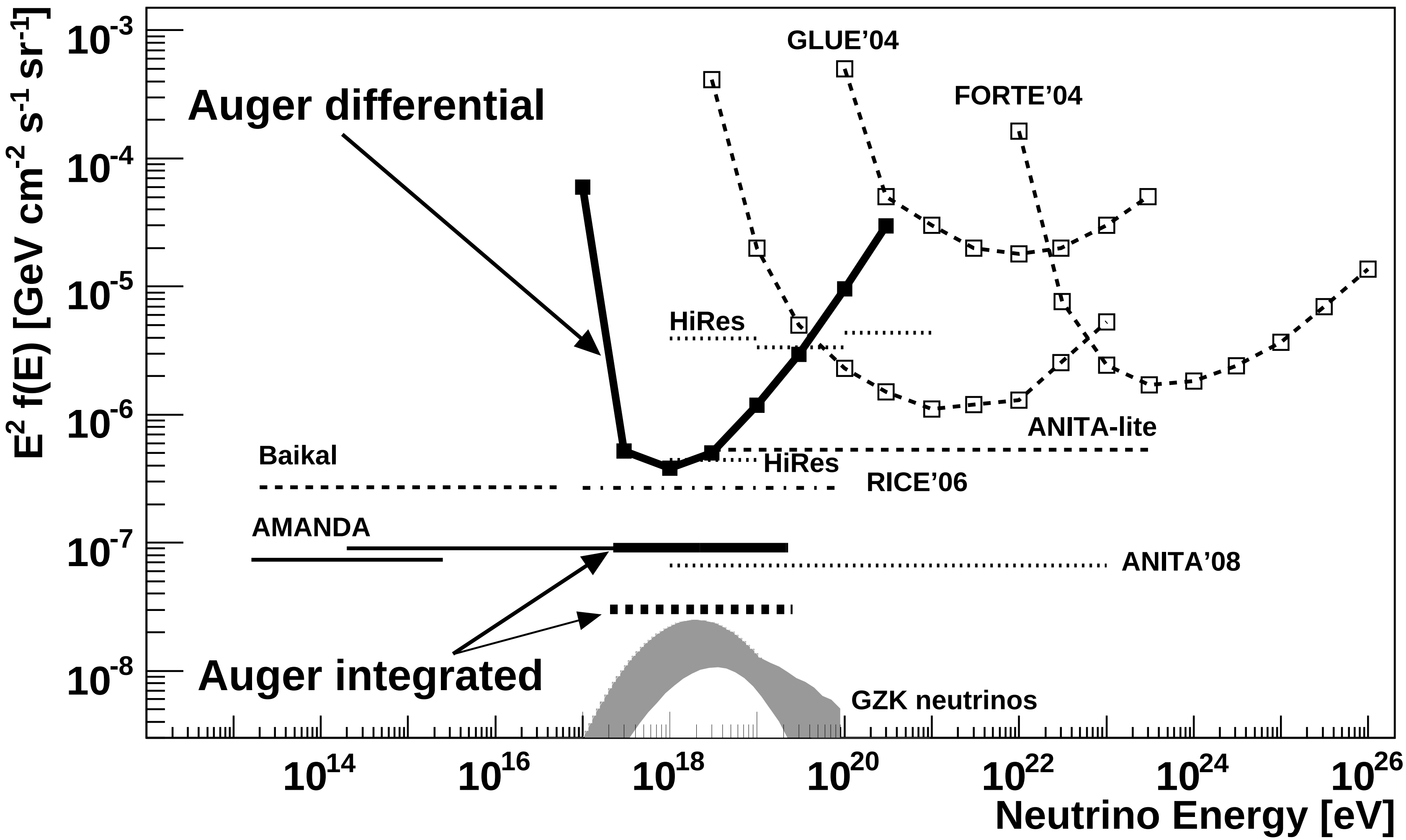
Upper limit on flux of neutrinos





- decay of charged pions produced in CR interactions within sources or during their propagation
- top-down models

Upper limit on flux of neutrinos



The Pierre Auger Collaboration, Phys. Rev. D 79 (2009)

Plans for future

- Fluorescence yield from laboratory measurements
- Error in energy reconstruction $\sim 15\%$
- Radio detection – currently under development
- Pierre Auger Observatory on northern hemisphere ($20\ 000\ \mathrm{km}^2$ in Colorado)
- JEM-EUSO (on ISS)
- Goals: chemical composition, finding sources, detection of GZK photons and neutrinos, proton-proton cross section

Conclusions

- Existence of ultra-high energy cosmic rays
- Current experiments: Pierre Auger Observatory, Telescope Array (and Yakutsk)
- Suppression of CR flux above 4×10^{19} eV
- Anisotropy above $\sim 6 \times 10^{19}$ eV
- Still unknown chemical composition
- Photons and neutrinos expected very soon
- More results in the close future

UHECR observatories