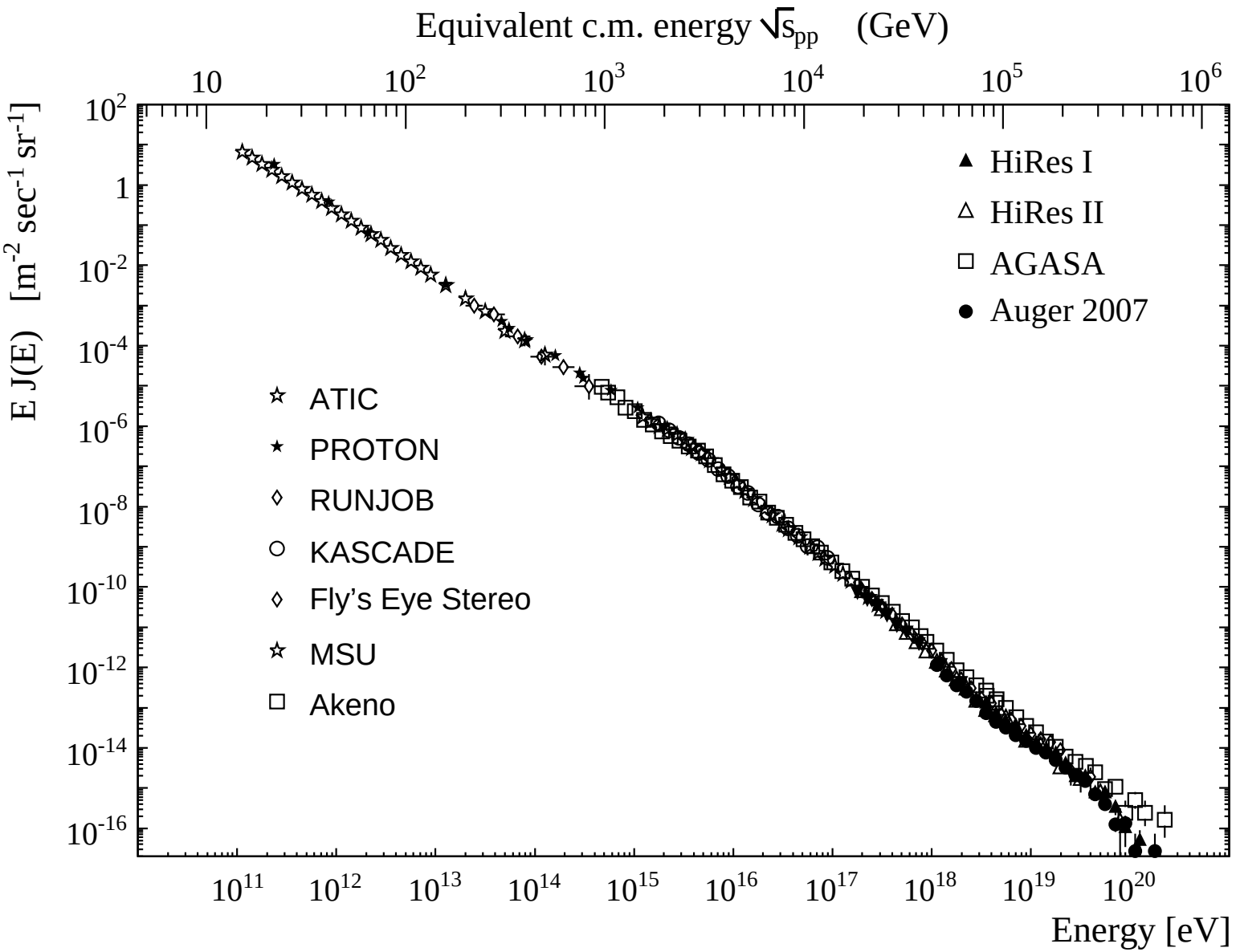
Measurement of the UHECRs flux and composition with Pierre Auger Observatory

Ioana C. Mariş for the Pierre Auger Collaboration

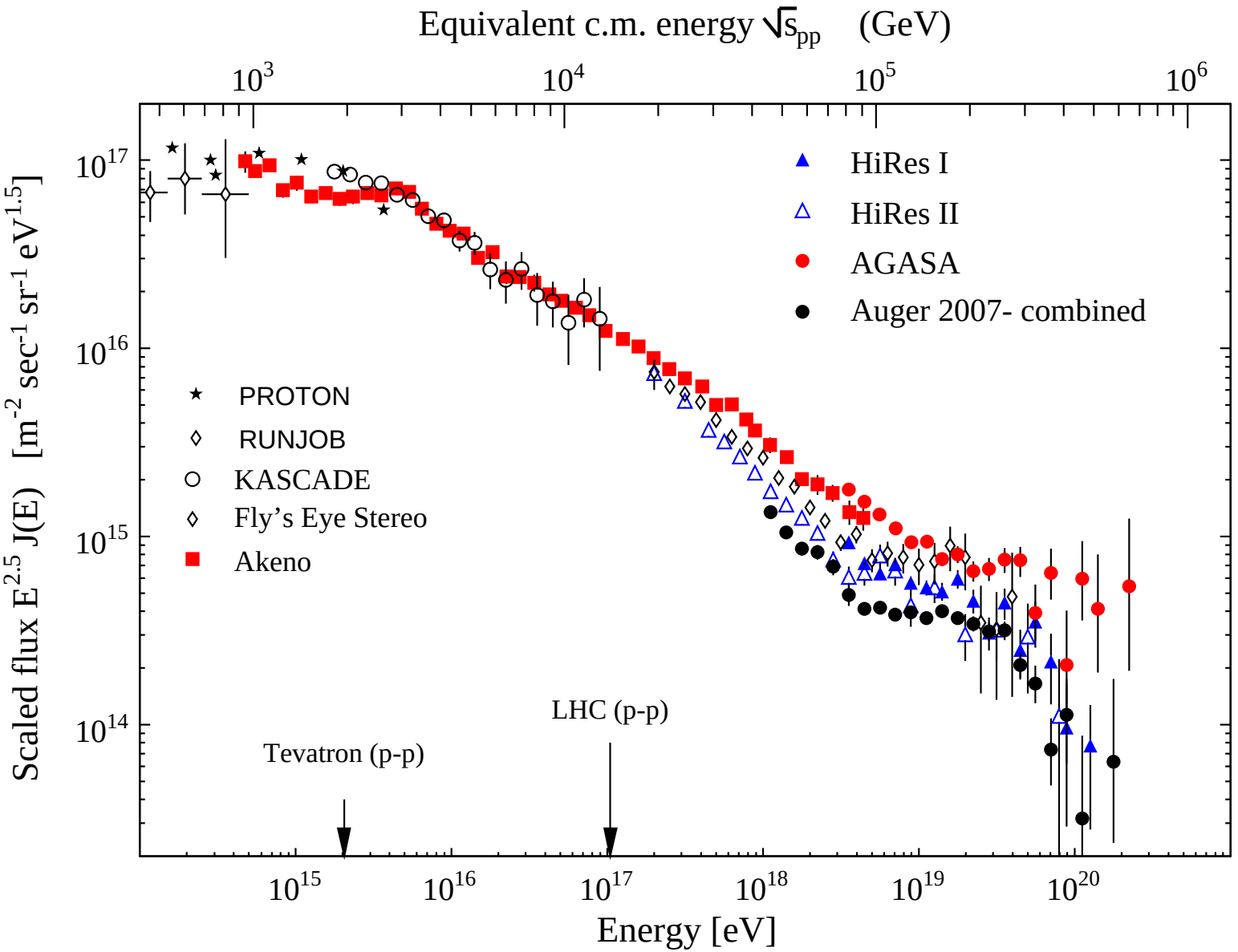
Outline

- Ultra high energy cosmic rays
- Pierre Auger Observatory
- Energy spectrum (calibration, combined spectrum)
- Composition

Introduction: Cosmic rays energy spectrum



Introduction: Cosmic rays energy spectrum



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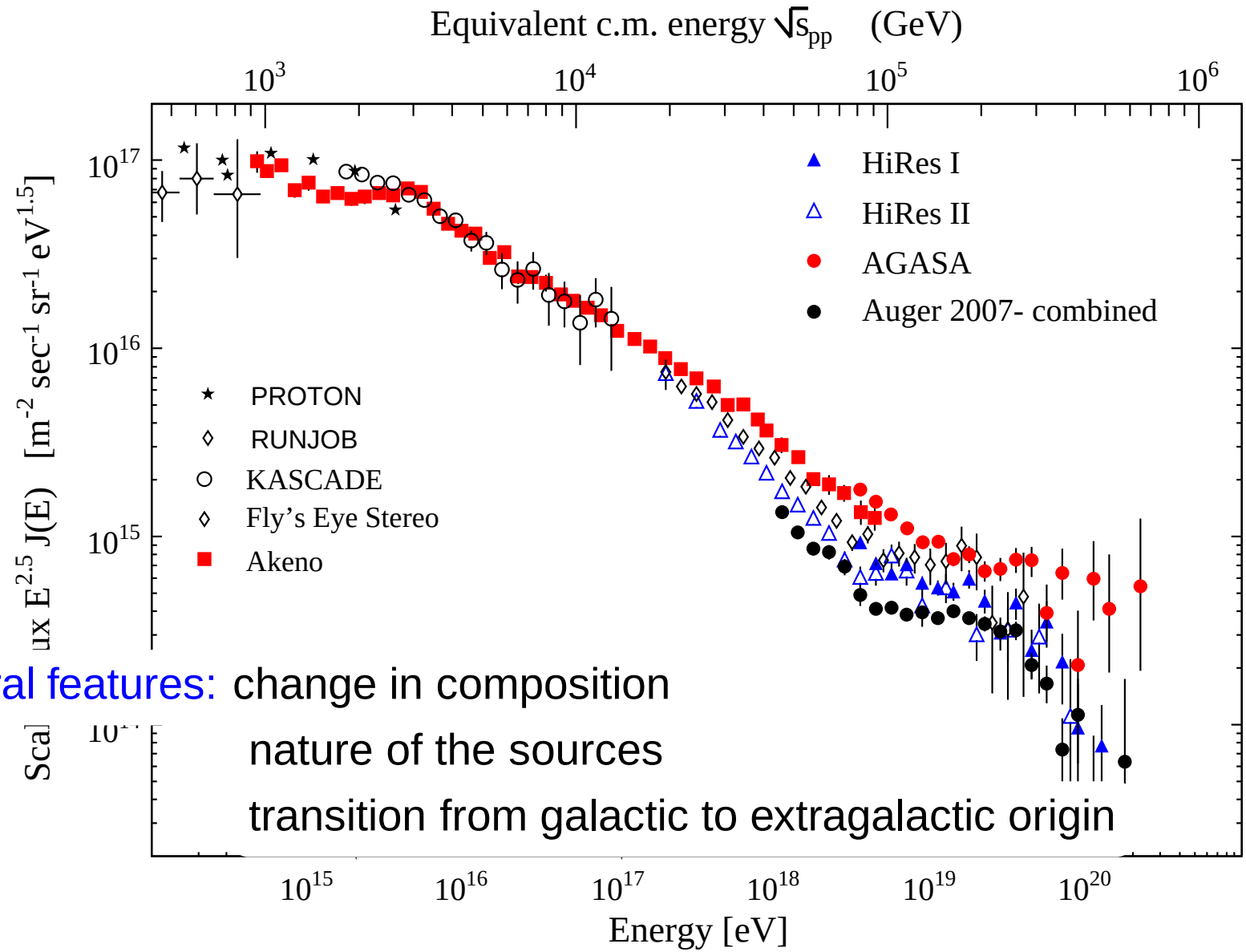
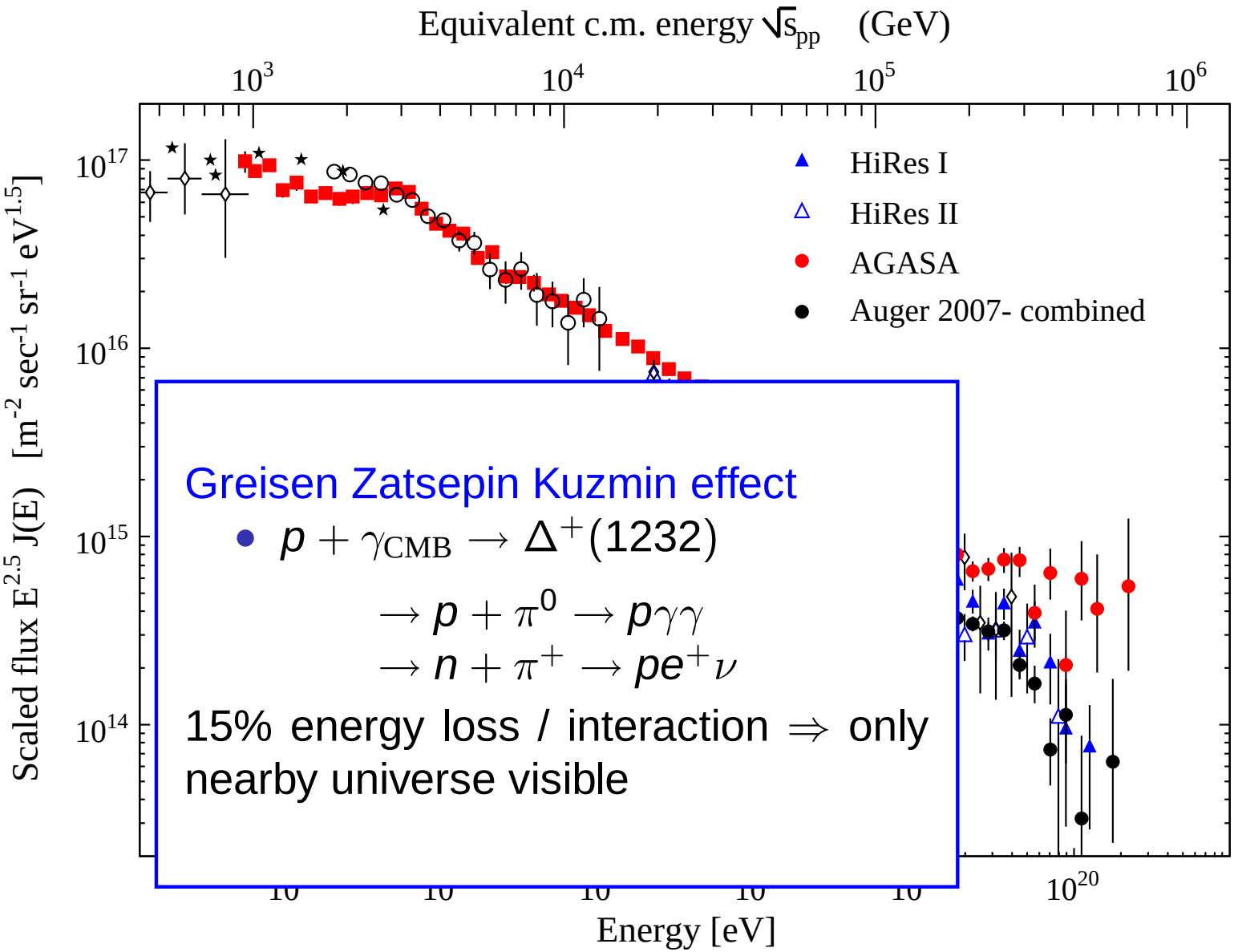


spectral features: change in composition

nature of the sources

transition from galactic to extragalactic origin

Introduction: Cosmic rays energy spectrum



Greisen Zatsepin Kuzmin effect

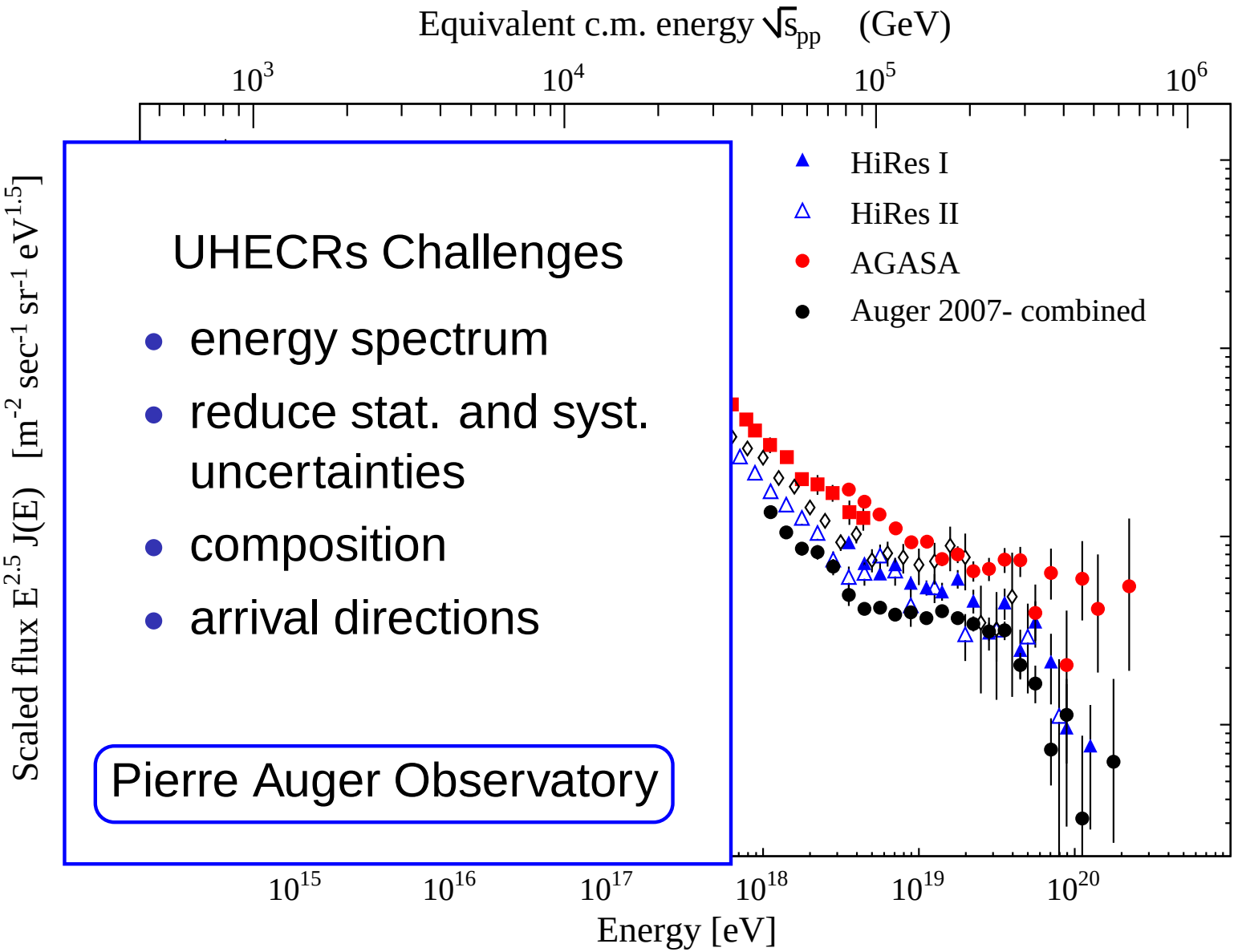
- $p + \gamma_{CMB} \rightarrow \Delta^+(1232)$

  $\rightarrow p + \pi^0 \rightarrow p\gamma\gamma$

  $\rightarrow n + \pi^+ \rightarrow pe^+\nu$

15% energy loss / interaction $\Rightarrow$ only nearby universe visible

Introduction: Cosmic rays energy spectrum

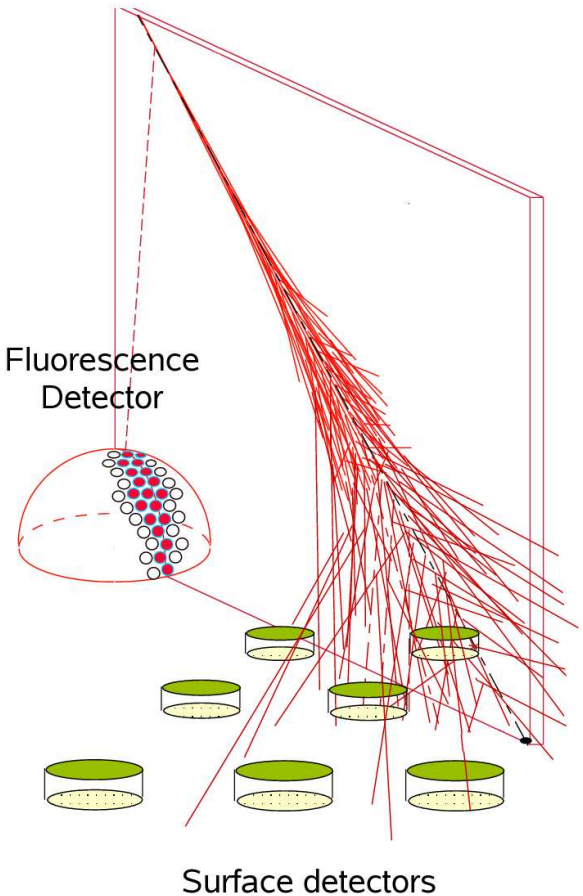


UHECRs Challenges

- energy spectrum
- reduce stat. and syst. uncertainties
- composition
- arrival directions

Pierre Auger Observatory

Introduction: Measurement Techniques



Surface detector(SD)

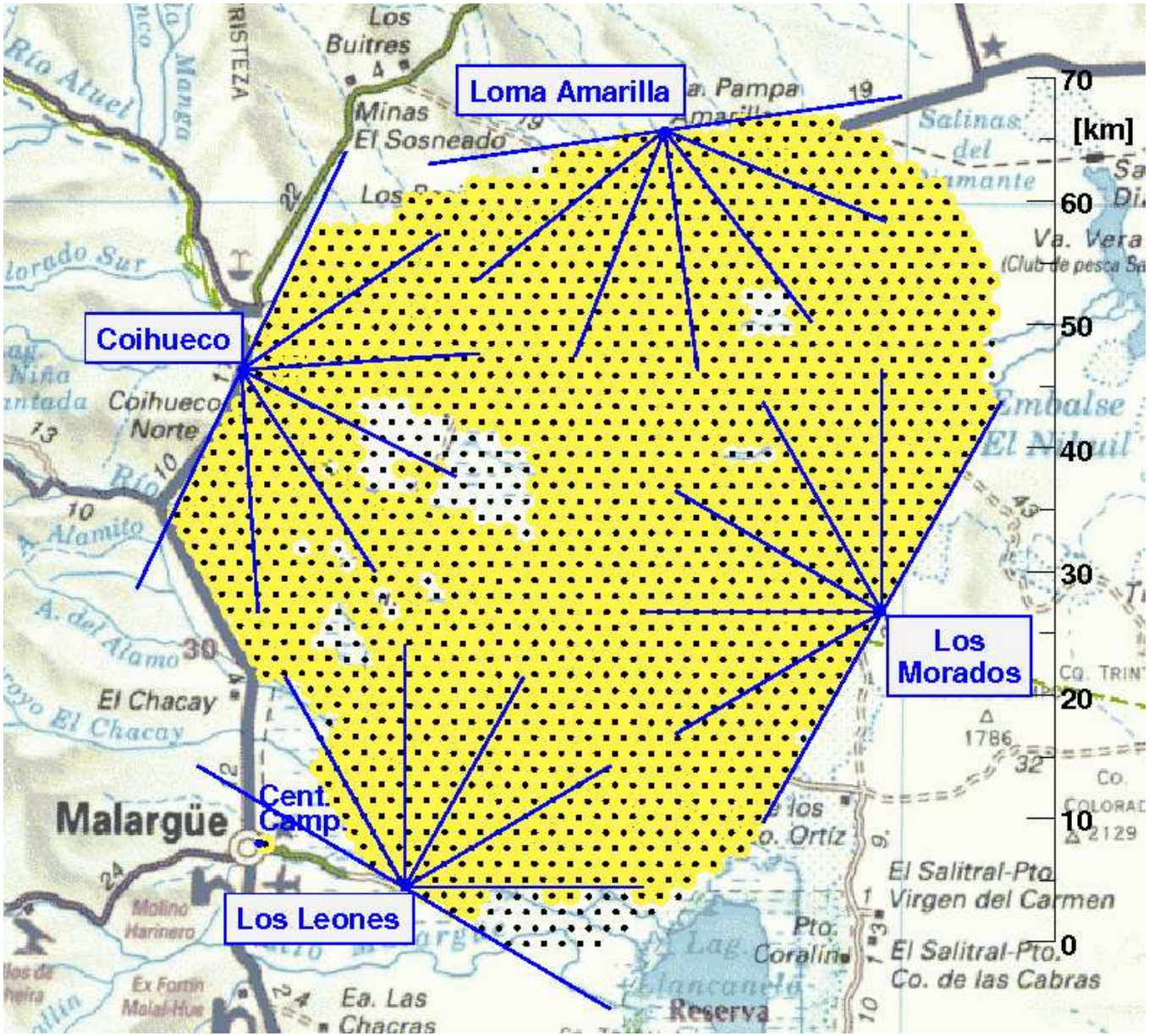
- acceptance geometric
- energy scale from air shower simulations
- duty cycle $\approx$ 100%

Fluorescence detector(FD)

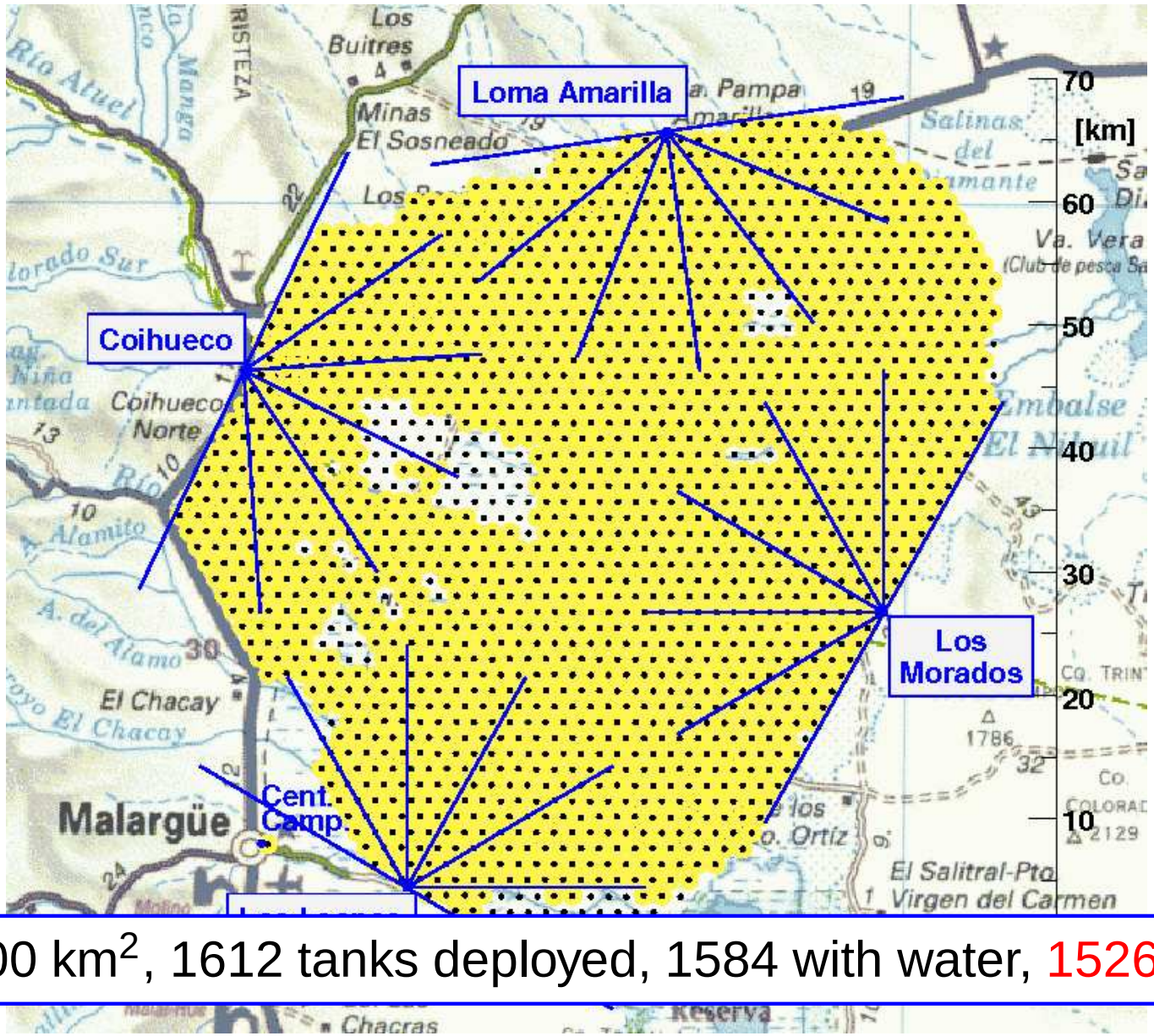
- energies from longitudinal energy deposit, nearly calorimetric
- acceptance from detector and atmosphere simulation
- duty cycle $\approx$ 10%

Pierre Auger Observatory: acceptance and energy from data !

Pierre Auger Observatory: hybrid detector

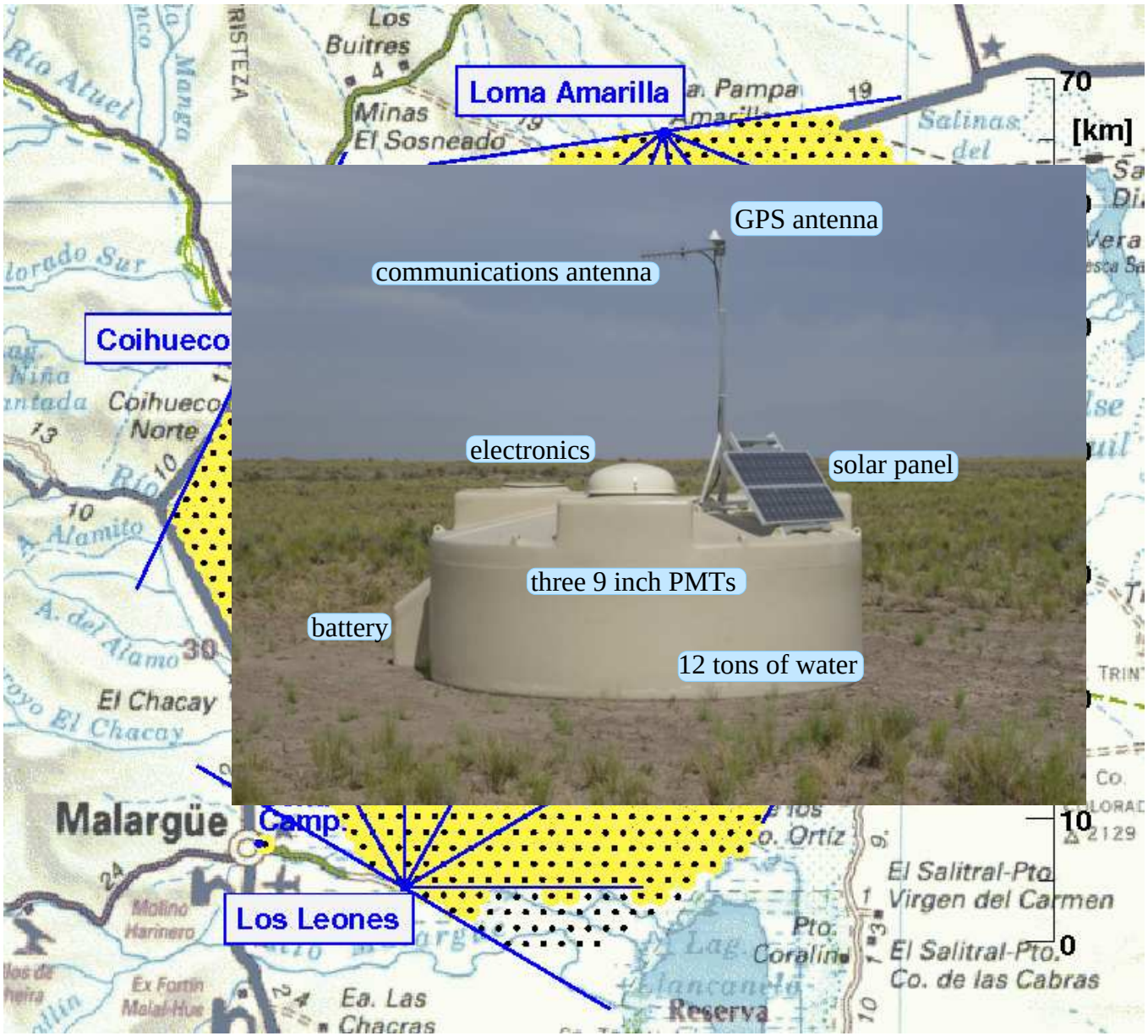


Surface detector (SD)

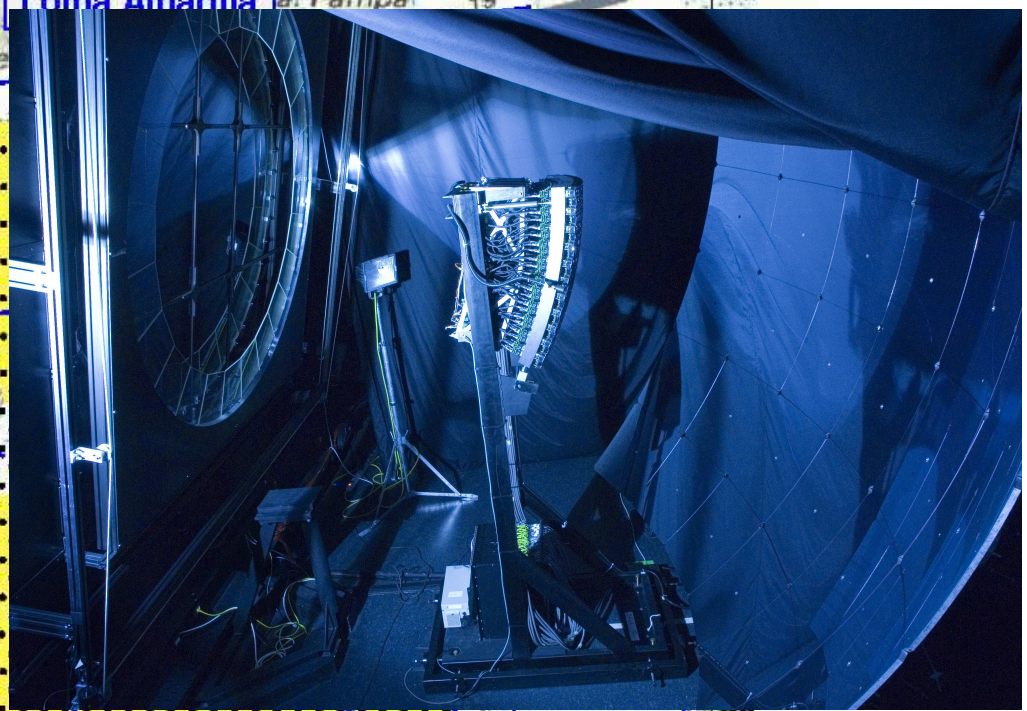


3000 km^2, 1612 tanks deployed, 1584 with water, 1526 working

Surface detector (SD)



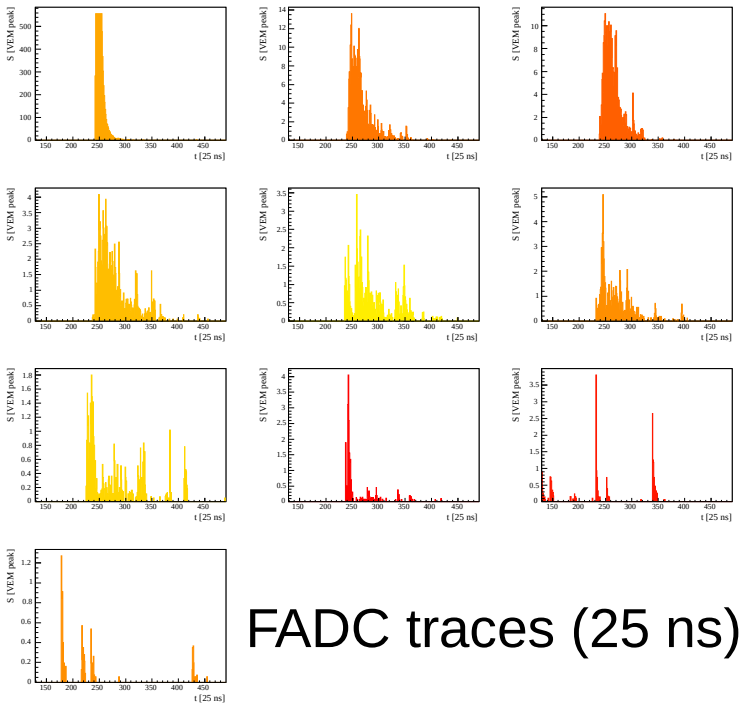
Fluorescence detector (FD)



Atmosphere monitoring

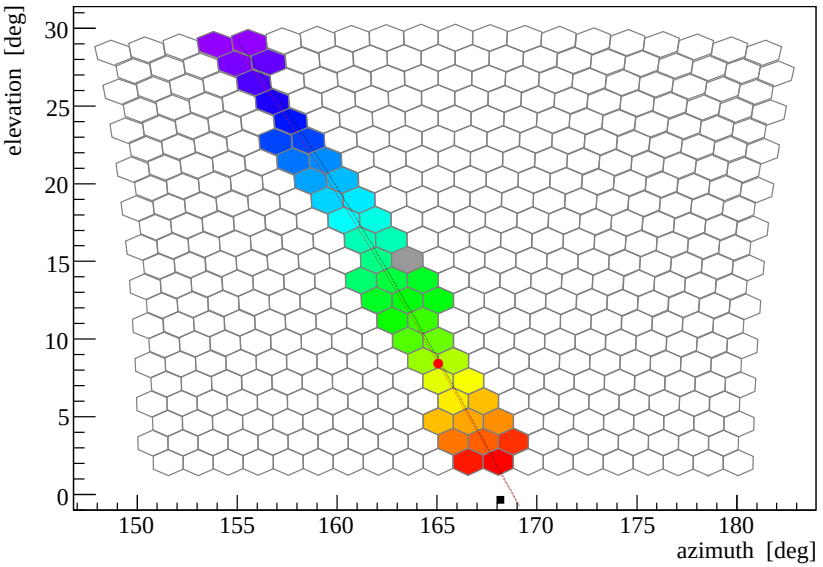
- radio soundings (h, T, P), LED for end to end calibration, LASER shots, horizontal attenuation, IR cloud cameras, star light monitor

Pierre Auger Observatory: event example

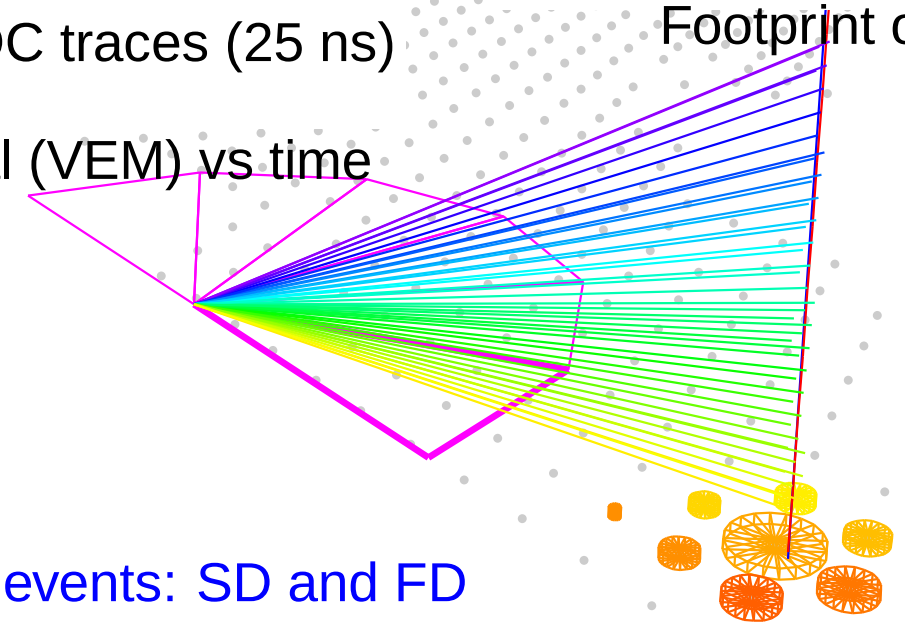


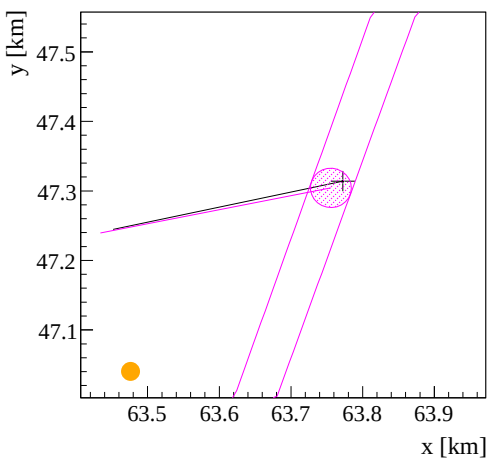
FADC traces (25 ns)

Detector signal (VEM) vs time



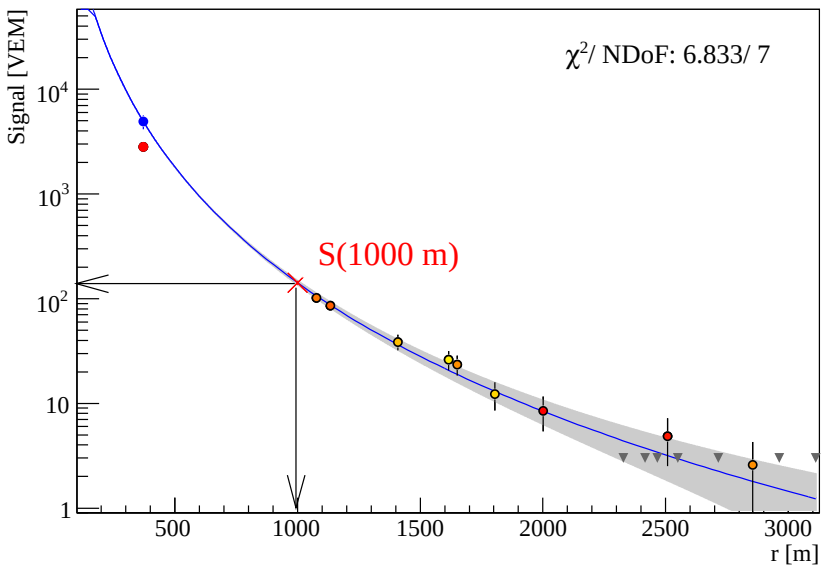
Footprint on the camera

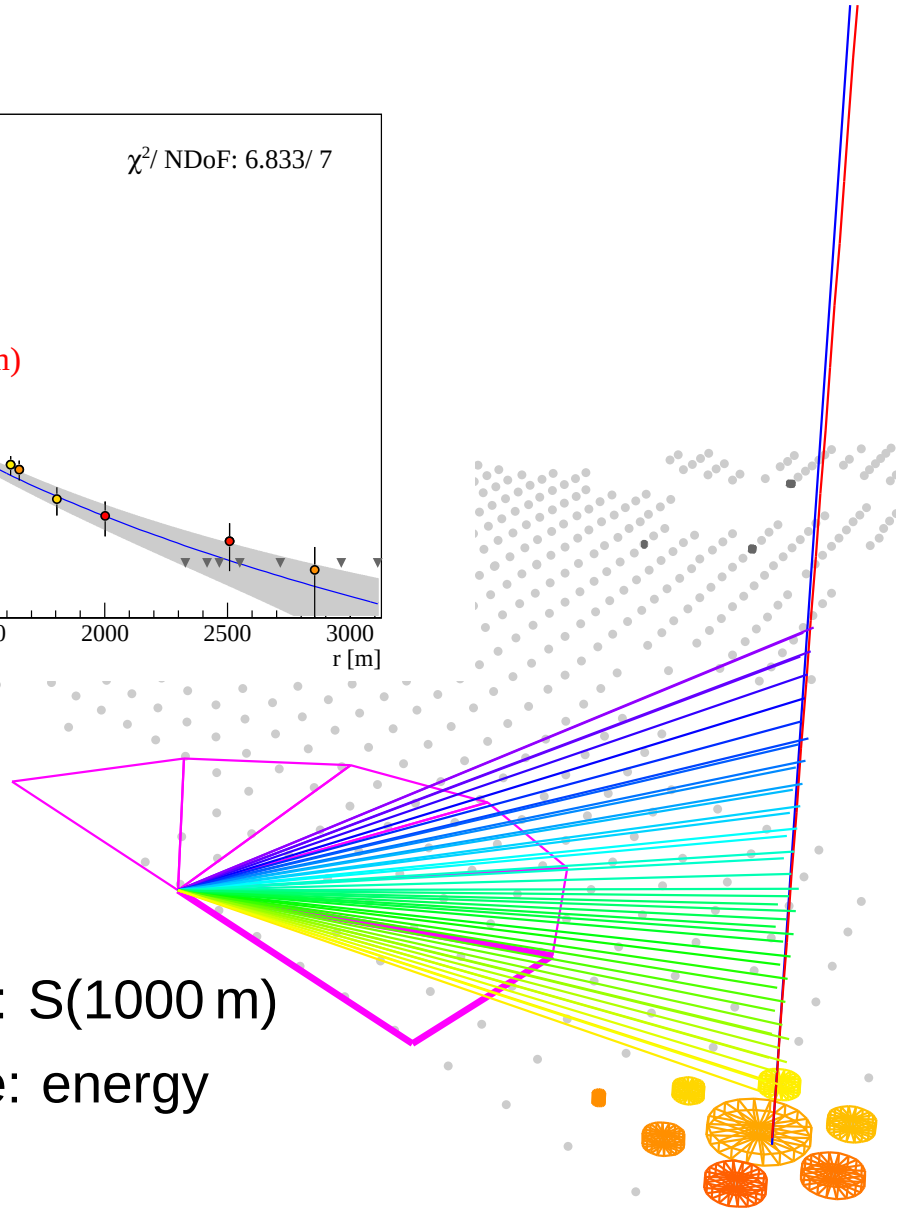


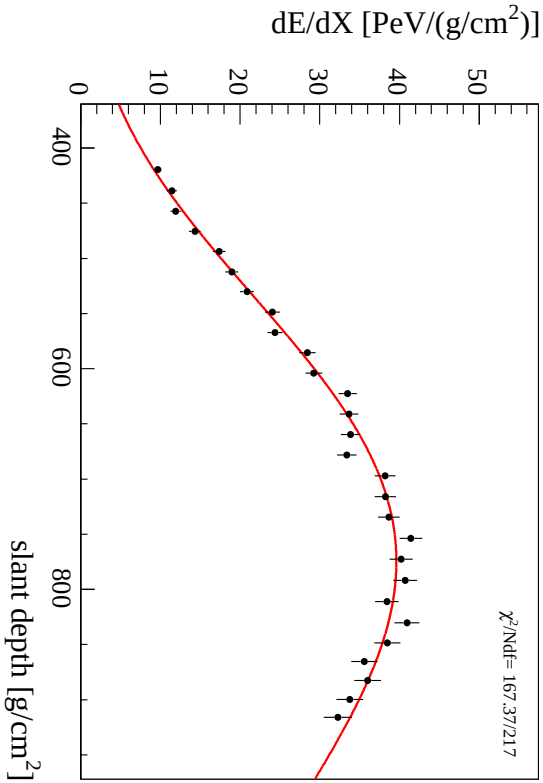


Golden hybrid events: SD and FD

Pierre Auger Observatory: event example







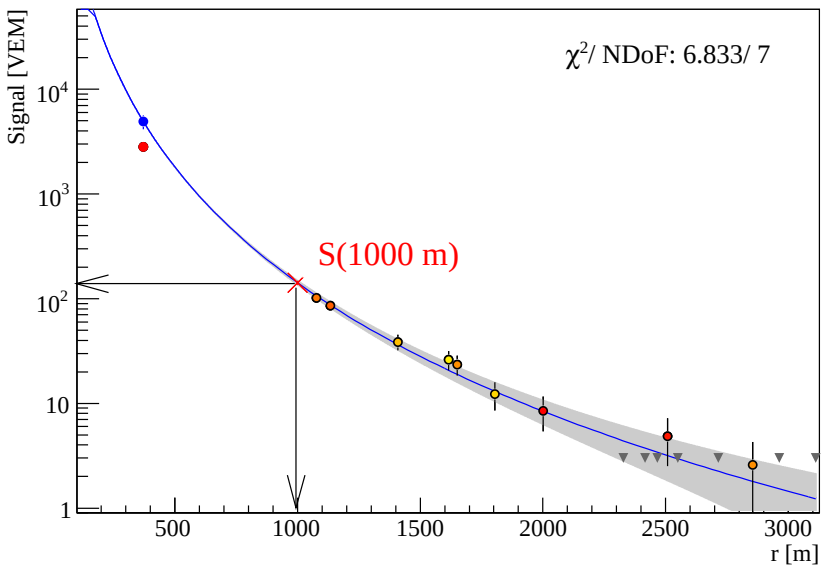
Lateral distribution: S(1000 m)

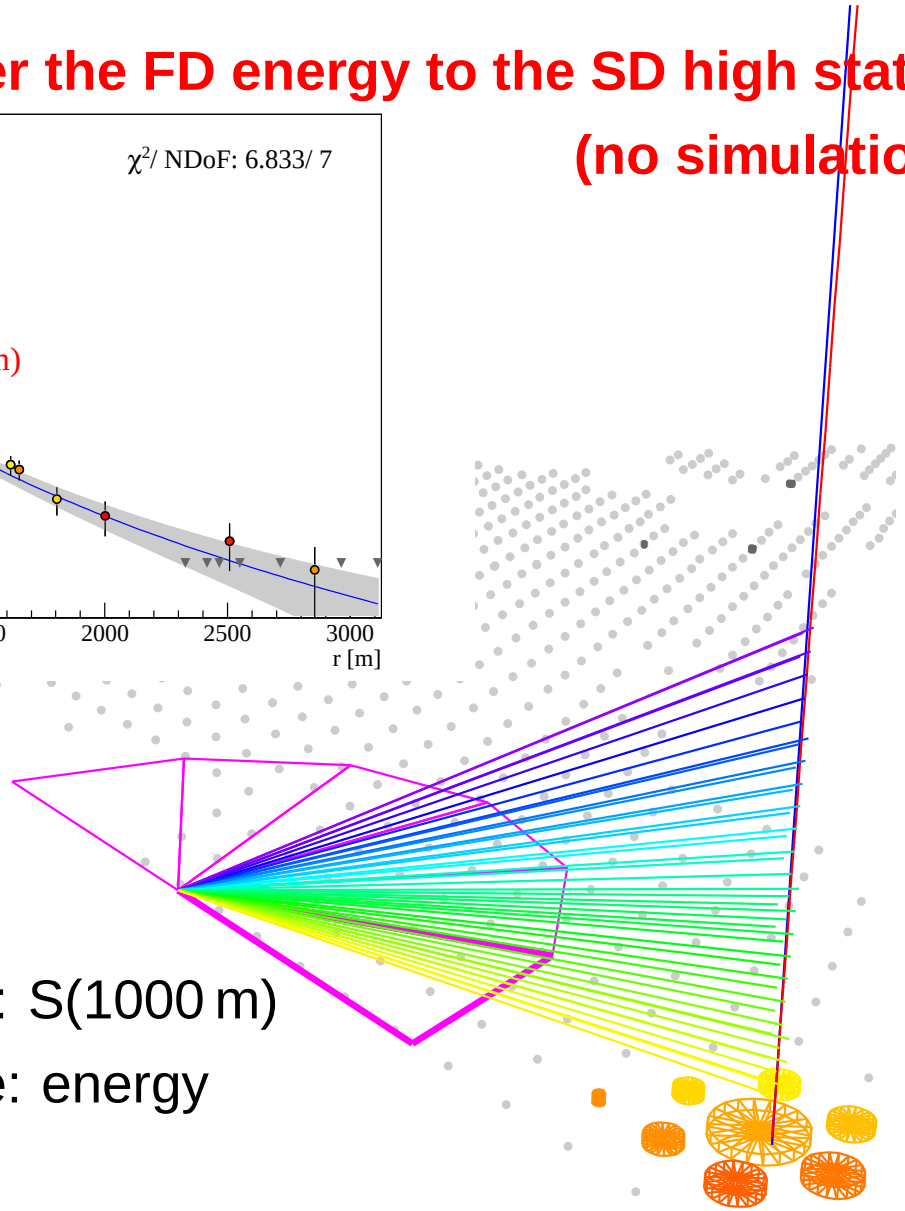
Longitudinal profile: energy

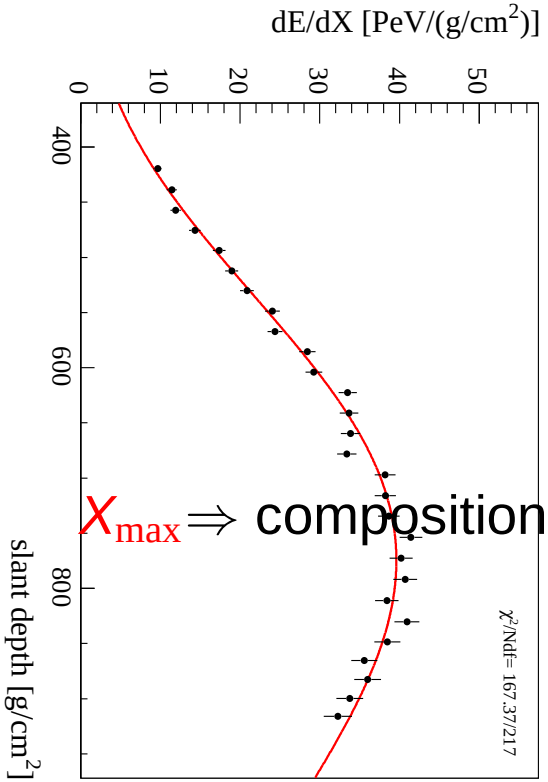
Pierre Auger Observatory: event example

Transfer the FD energy to the SD high statistics data!

(no simulations needed)







$X_{max} \Rightarrow$ composition

Lateral distribution: S(1000 m)

Longitudinal profile: energy

S(1000 m) to Energy

From ’Golden Hybrids’ (FD+SD)

lateral particle distribution

↓

$S(1000\text{m})$

↓

zenith angle correction (constant intensity cut method)

↓

S_{38}

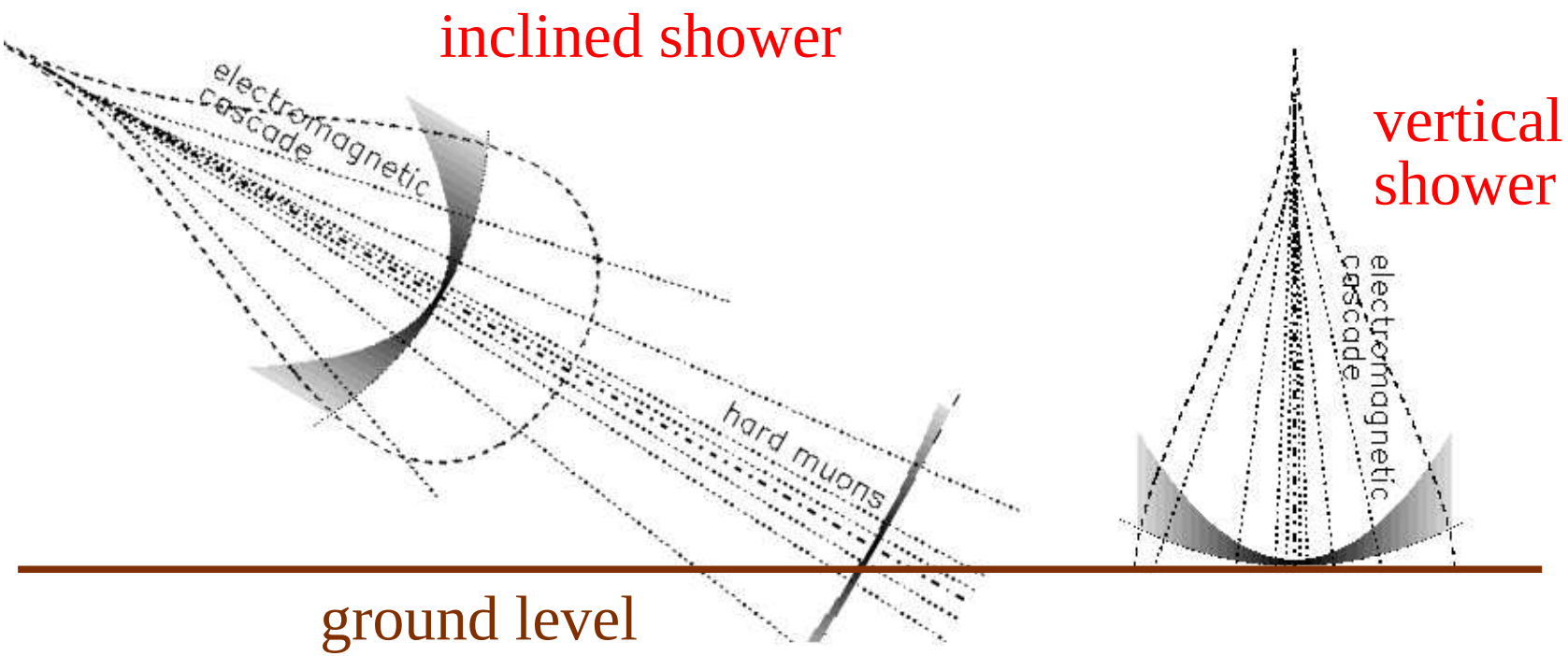
↓

FD energy

↓

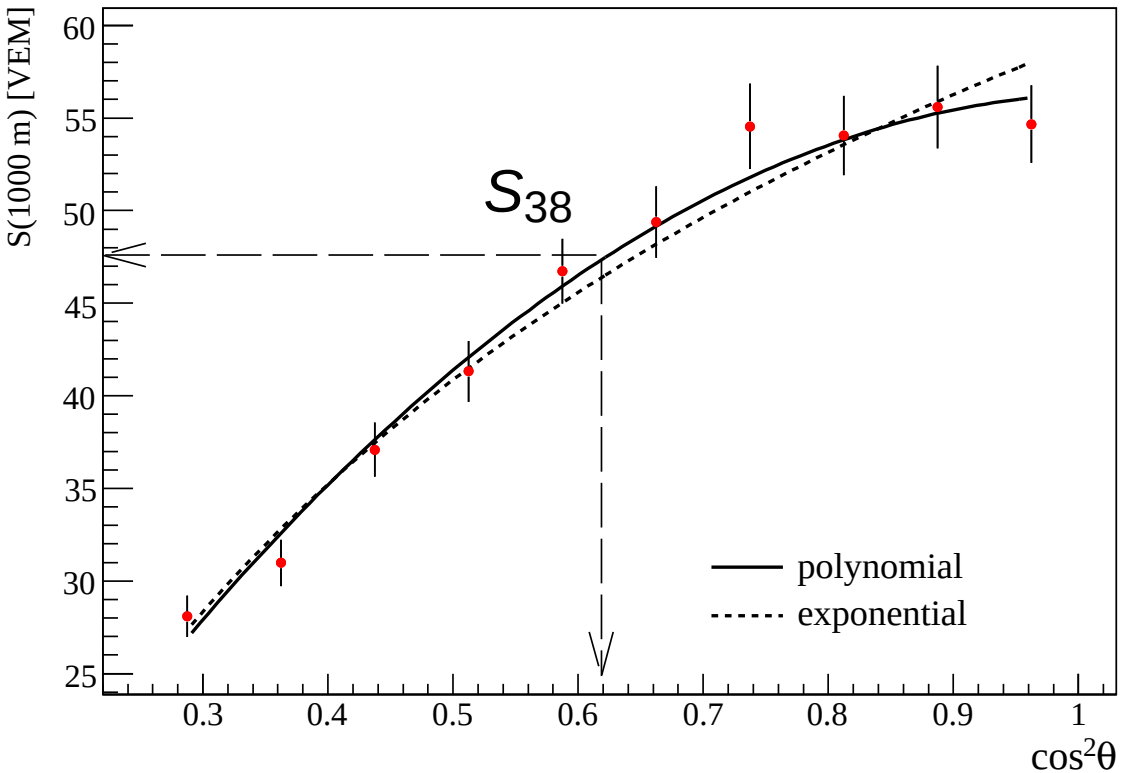
E_{SD}

S(1000 m)- Attenuation in the atmosphere



inclined S(1000m) $<$ vertical S(1000m)

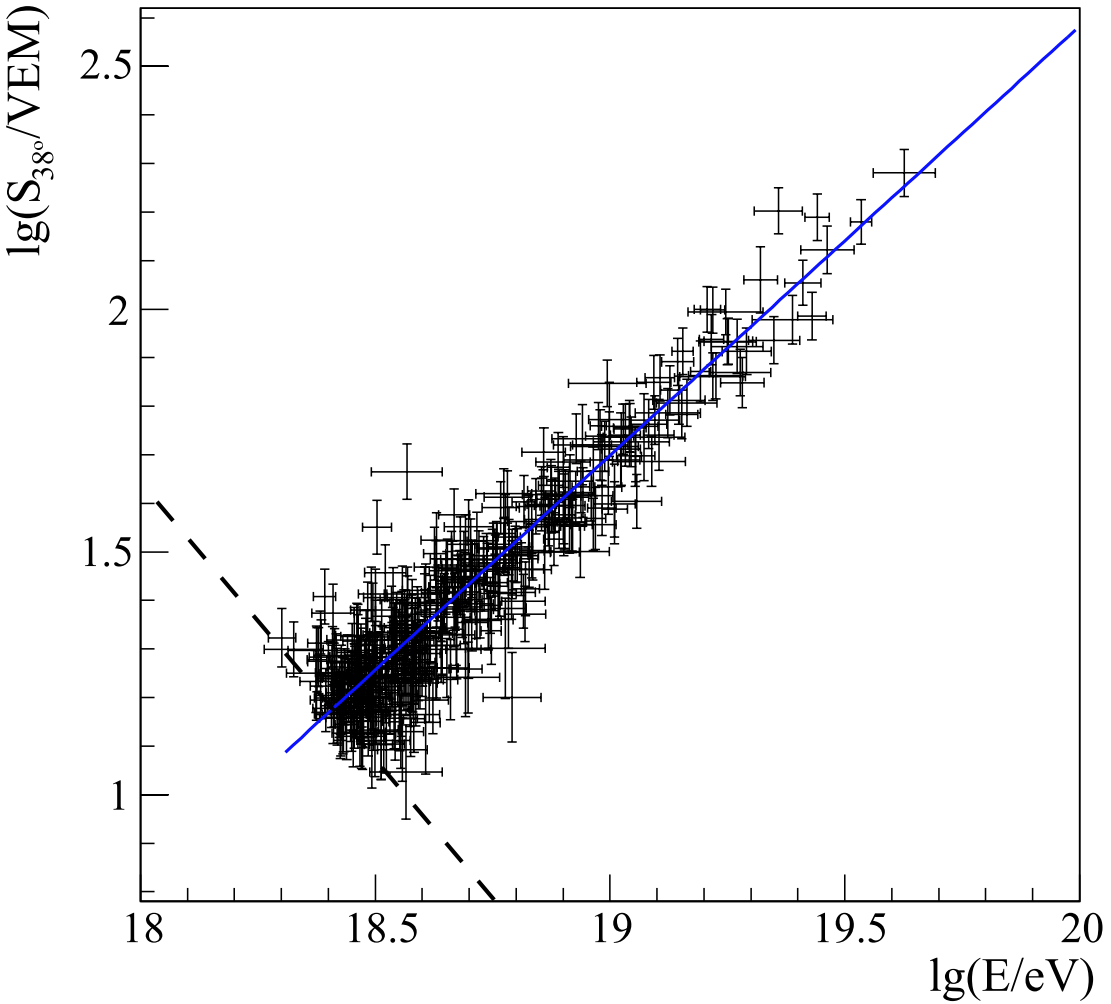
Zenith angle correction: S(1000m) $\Rightarrow S_{38}$



$$S_{38}(1000\,\mathrm{m}) = S(1000\,\mathrm{m})/f(\theta)$$
$$f(\theta) = 1 + a \cdot x + b \cdot x^2 \;, x = \cos^2\theta - \cos^2 38^\circ$$

- *correct* all shower sizes to the same angle 38°

Energy Calibration



Stat. uncertainties:
S_{38° ($\approx 16\%$)

- shower to shower fluctuations
- reconstruction

E_{FD}($\approx 8\%$)

- reconstruction
- atmosphere

$$E = A \cdot S_{38^\circ}^{B}$$

Energy Scale Systematics

Absolute Fluorescence Yield 14%
Pressure dependence of Fluorescence Yield 1%
Humidity dependence of Fluorescence Yield 1%
Temperature dependence of Fluorescence Yield 5%

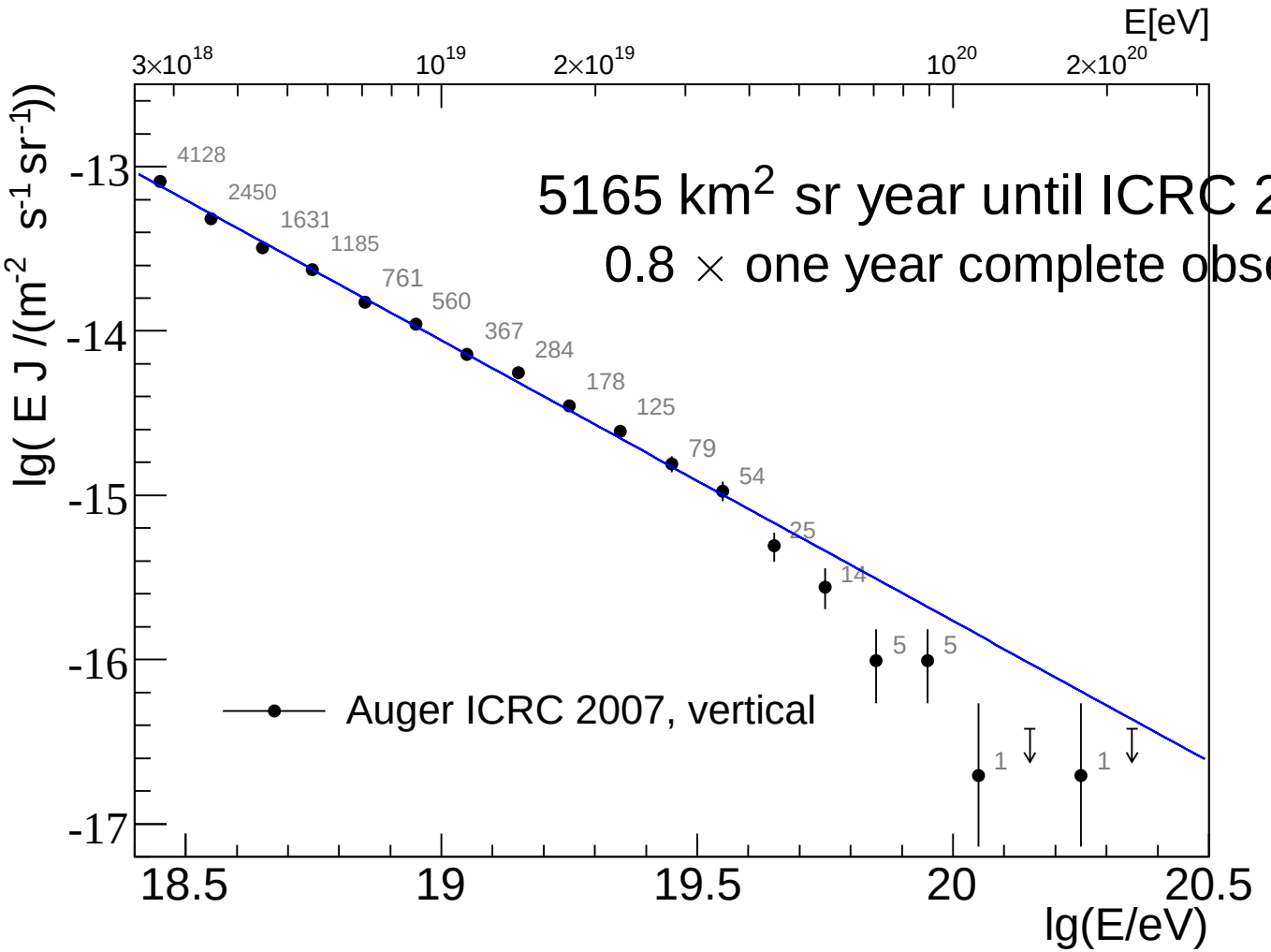
FD absolute calibration 11%
FD wavelength dependence response 3%
Rayleigh scattering in atmosphere 1%
Wavelength dependence of aerosol scattering 1%

FD reconstruction method 10%
Invisible energy 5%

Total: 22%

experimental uncertainties to be improved

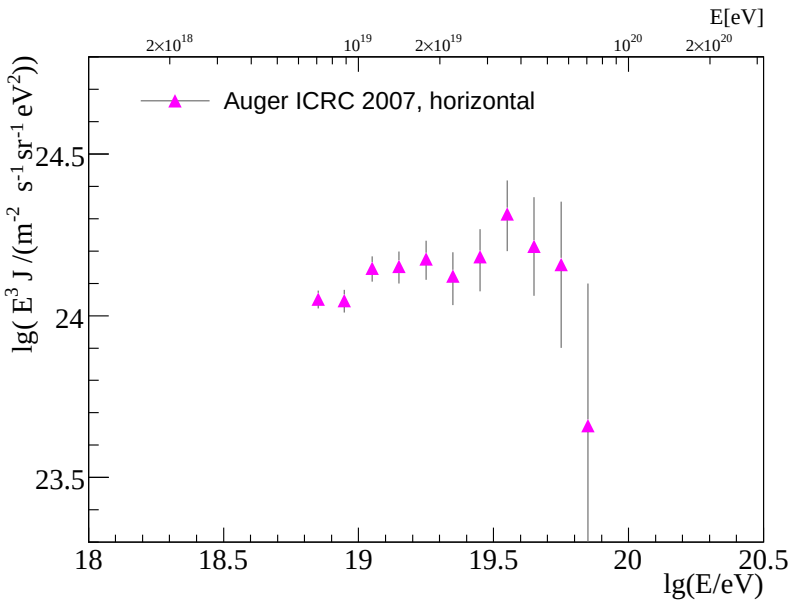
Vertical Energy Spectrum

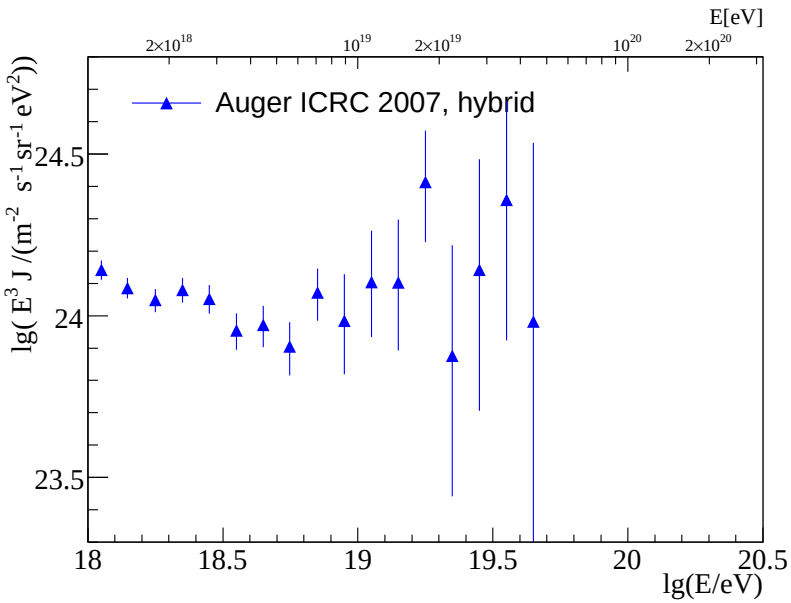


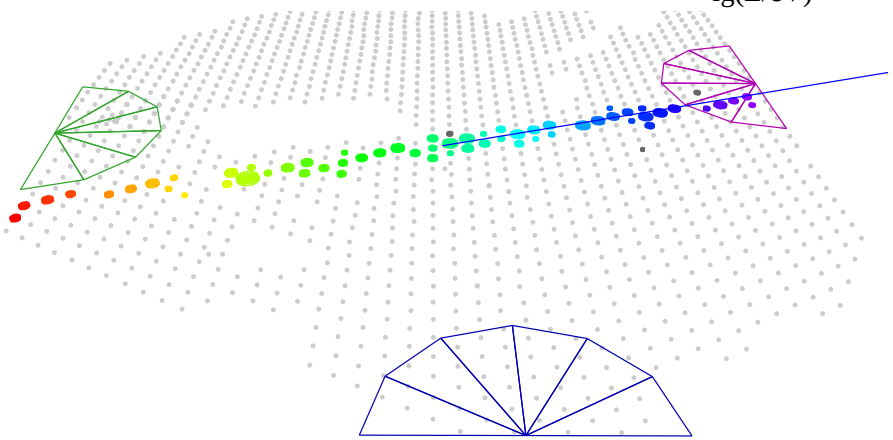
Events (observed/expected) above $4 \cdot 10^{19}$ eV: $51/(132 \pm 9)$

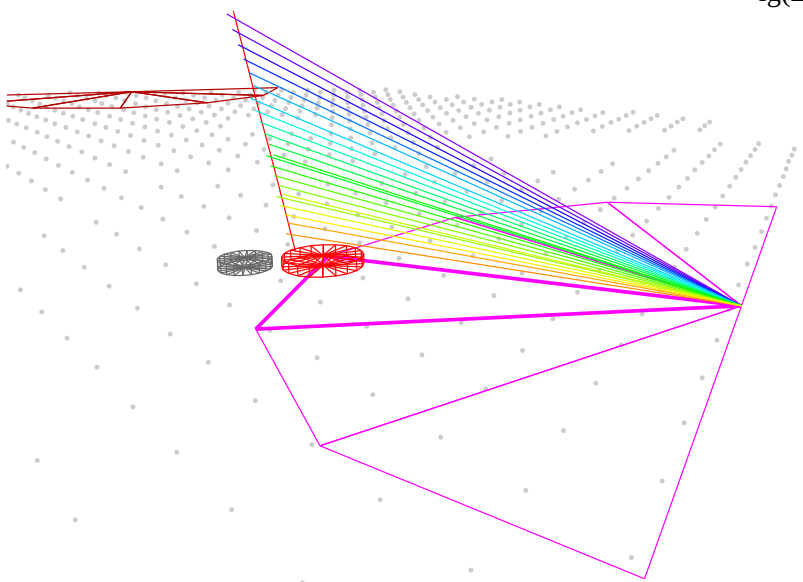
above 10^{20} eV: $2/(30 \pm 2.5)$

Horizontal and Hybrid Energy Spectra

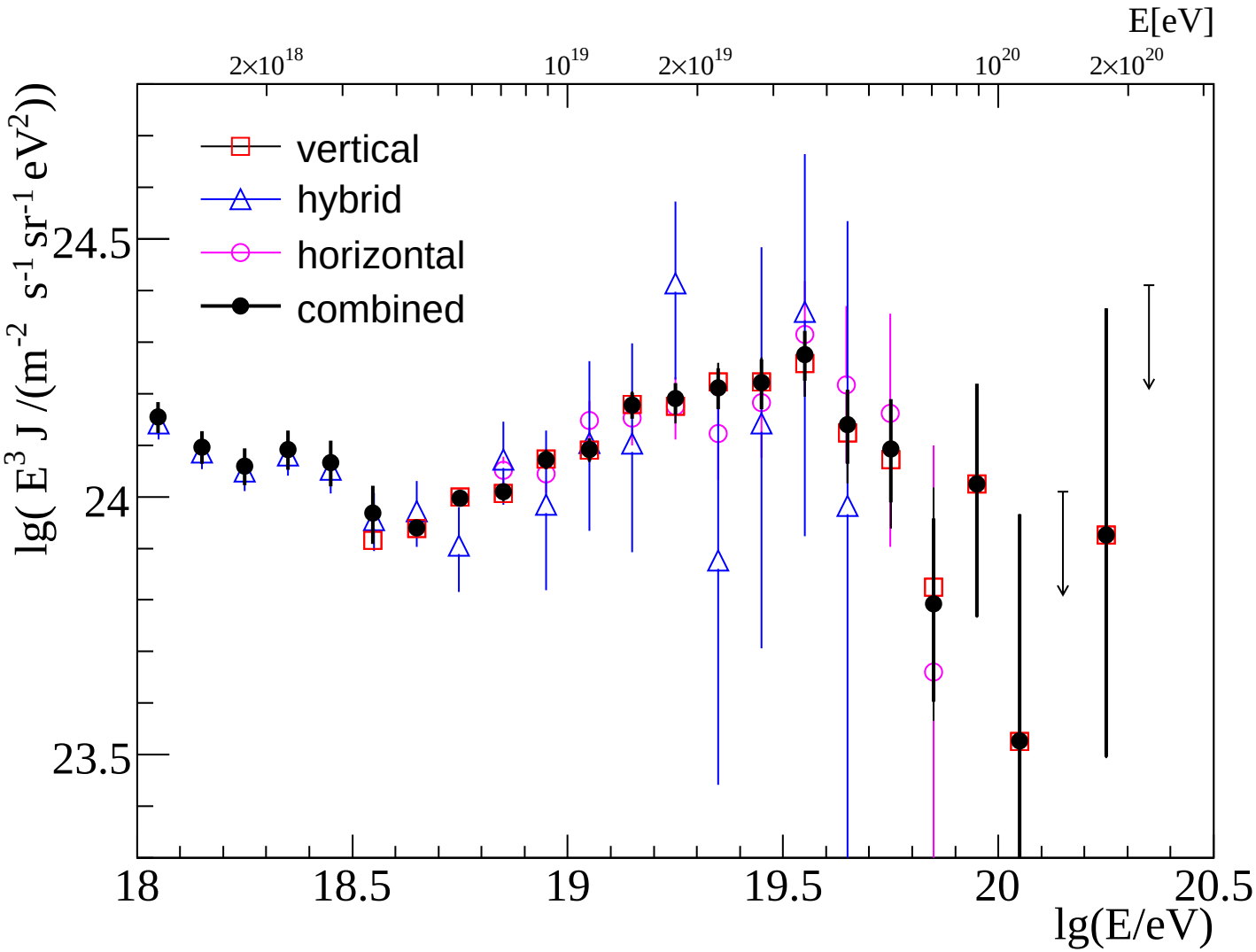






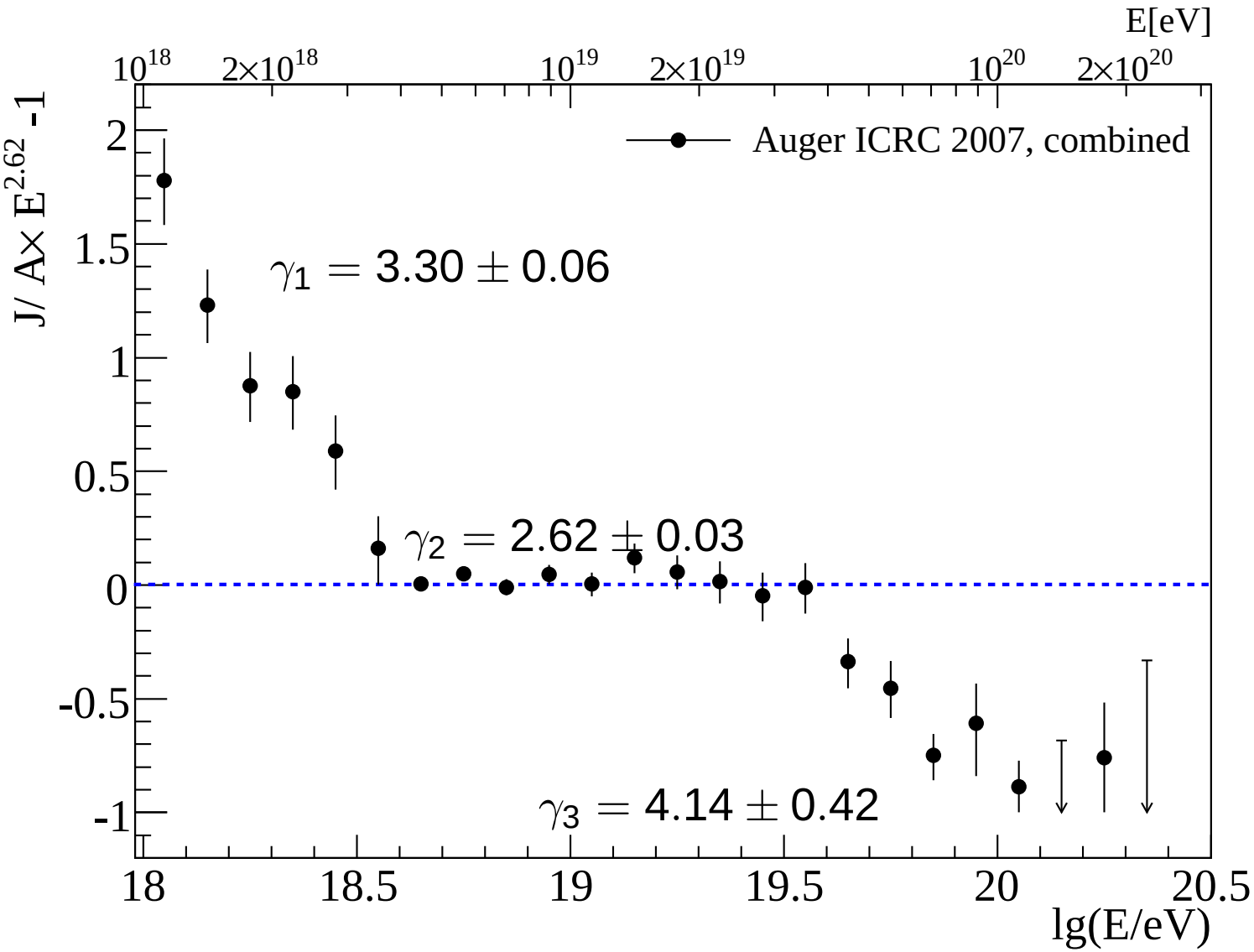


Auger Energy Spectrum

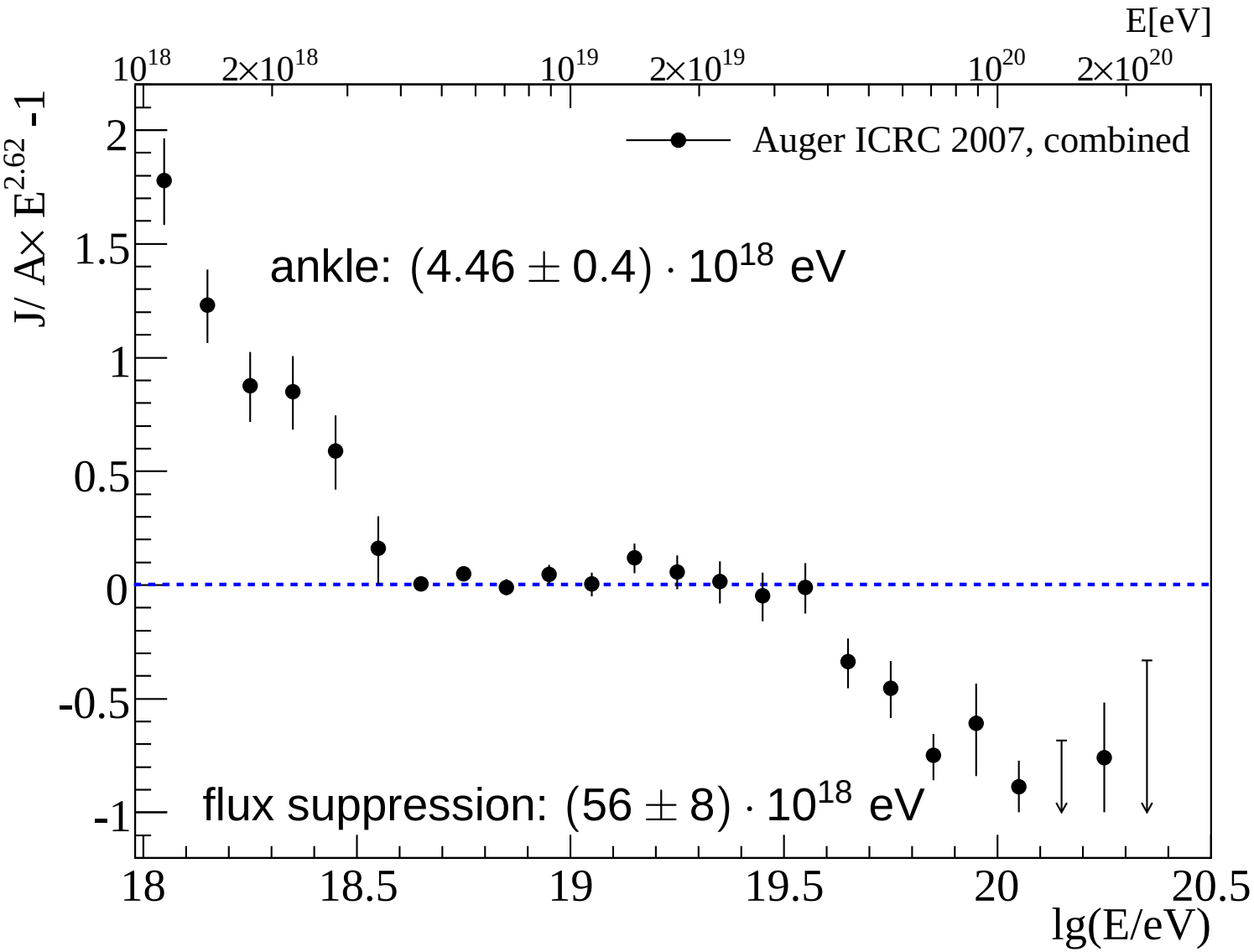


Very good agreement between the three spectra ($< 3\%$)

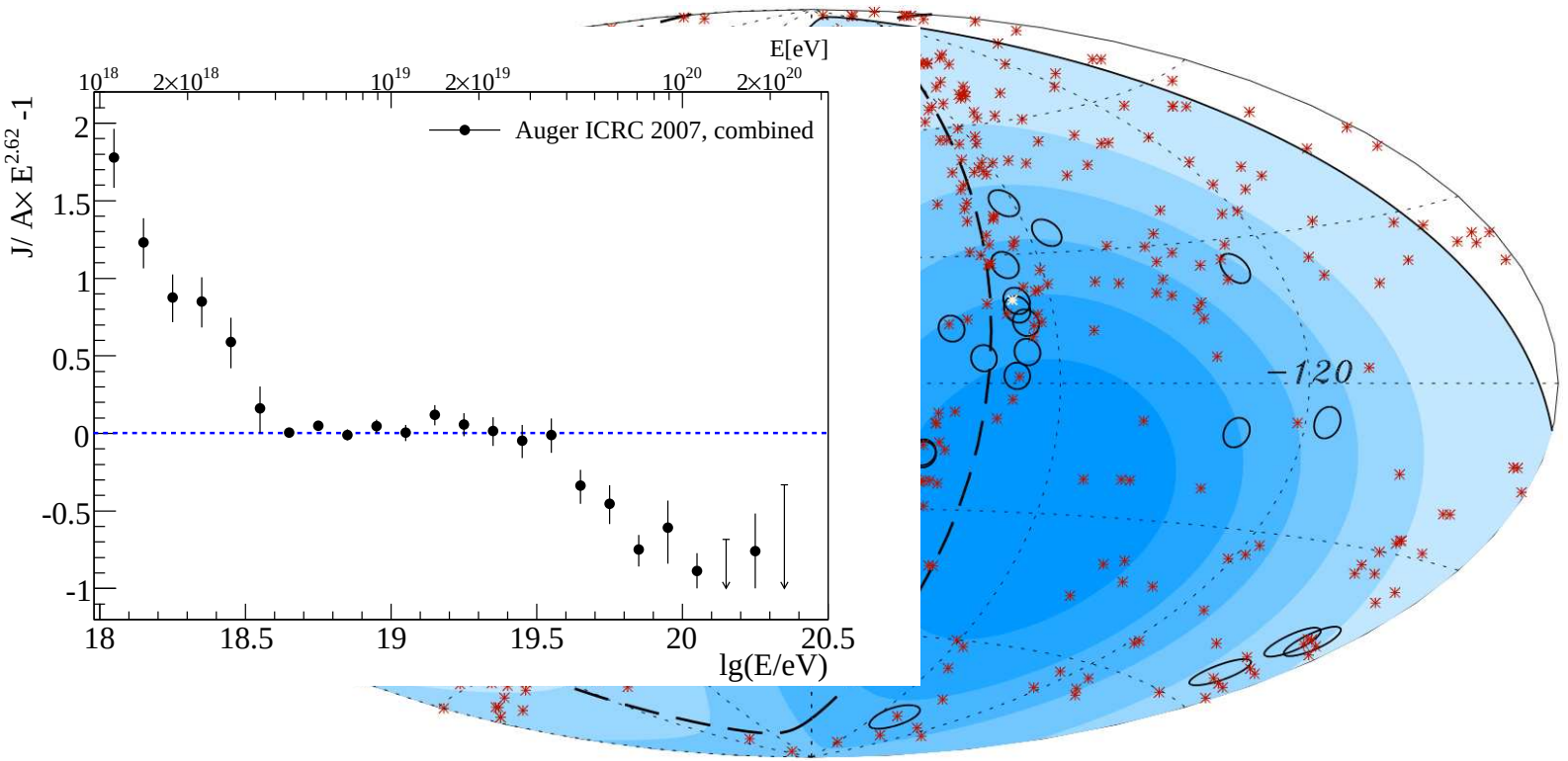
Auger Energy Spectrum: Spectral features



Auger Energy Spectrum: Spectral features

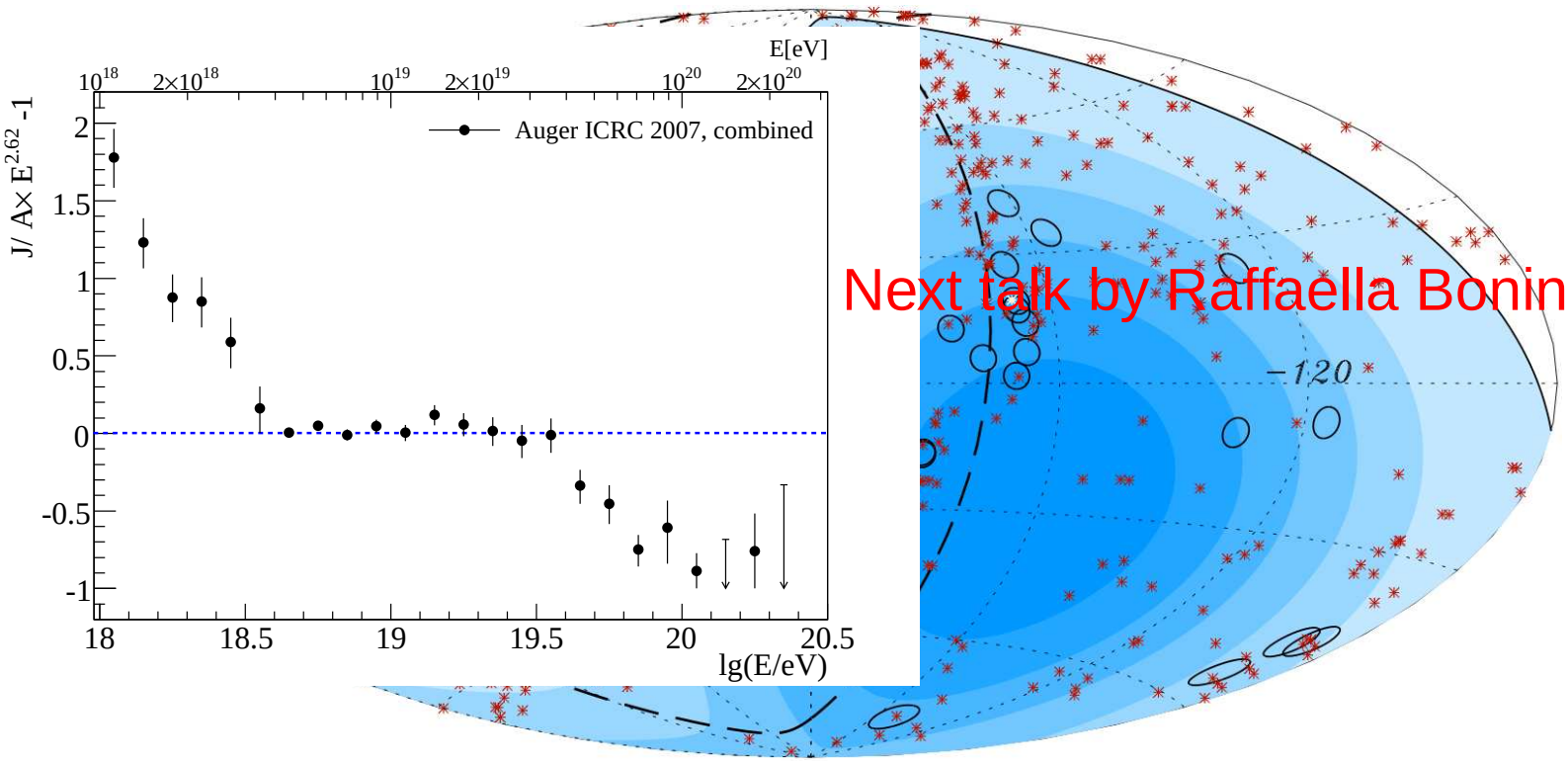


Anisotropies- energy spectrum



- the energy and redshift that maximise the signal are compatible with the GZK horizon

Anisotropies- energy spectrum



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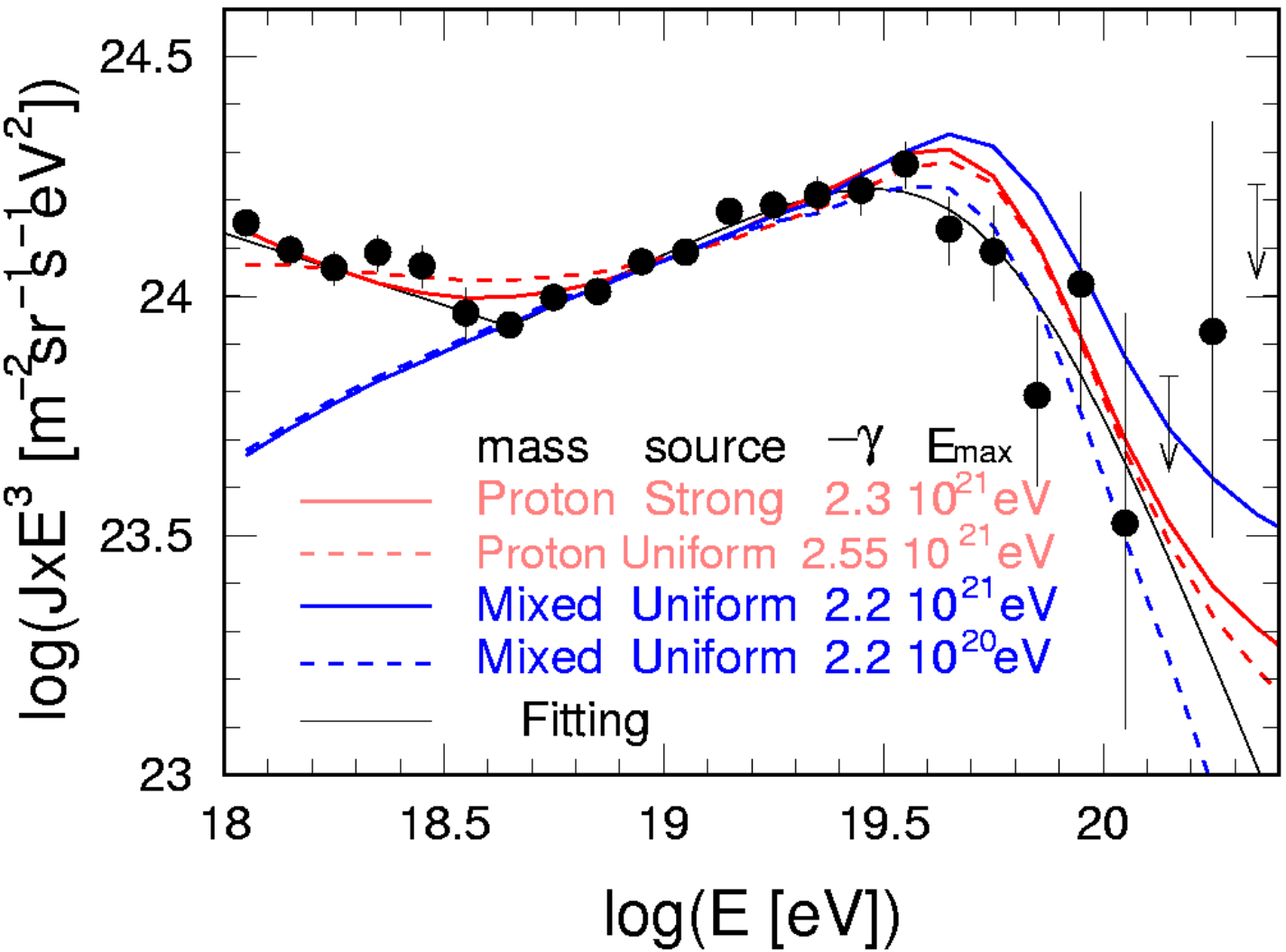
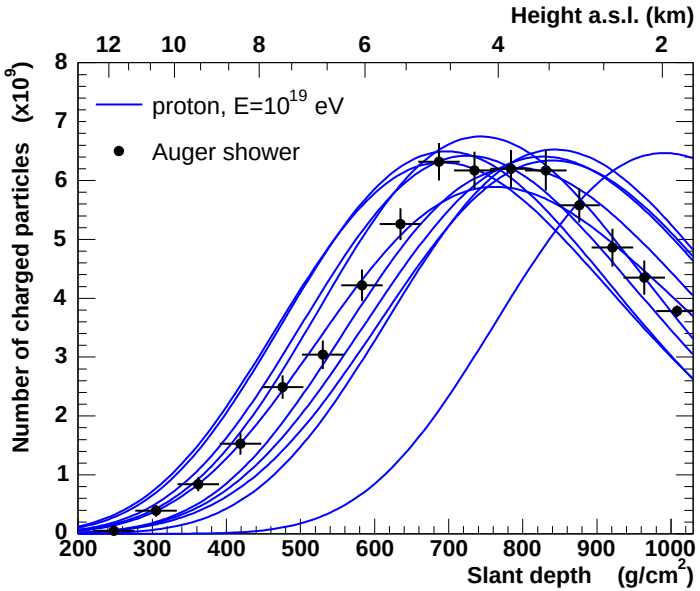
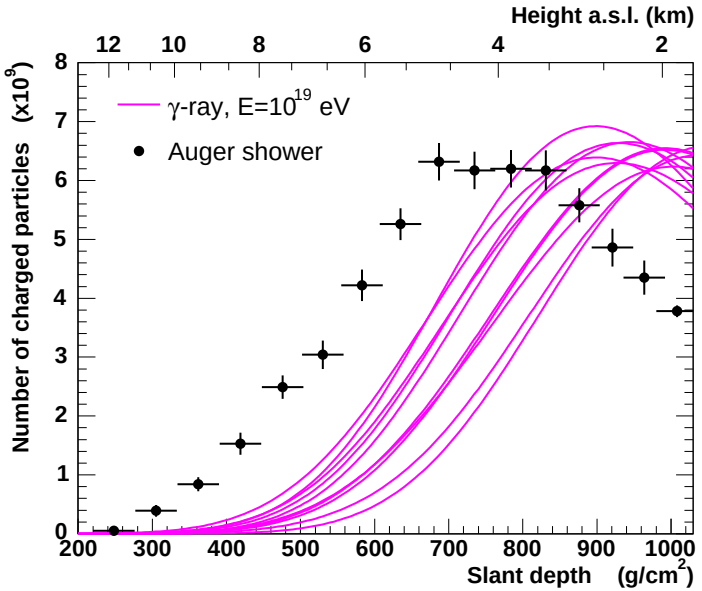
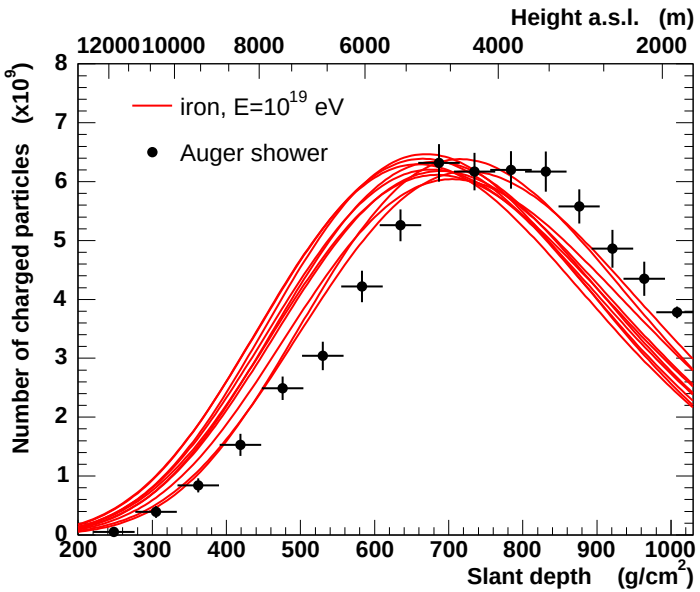
Mass composition- energy spectrum



Mass composition- energy spectrum

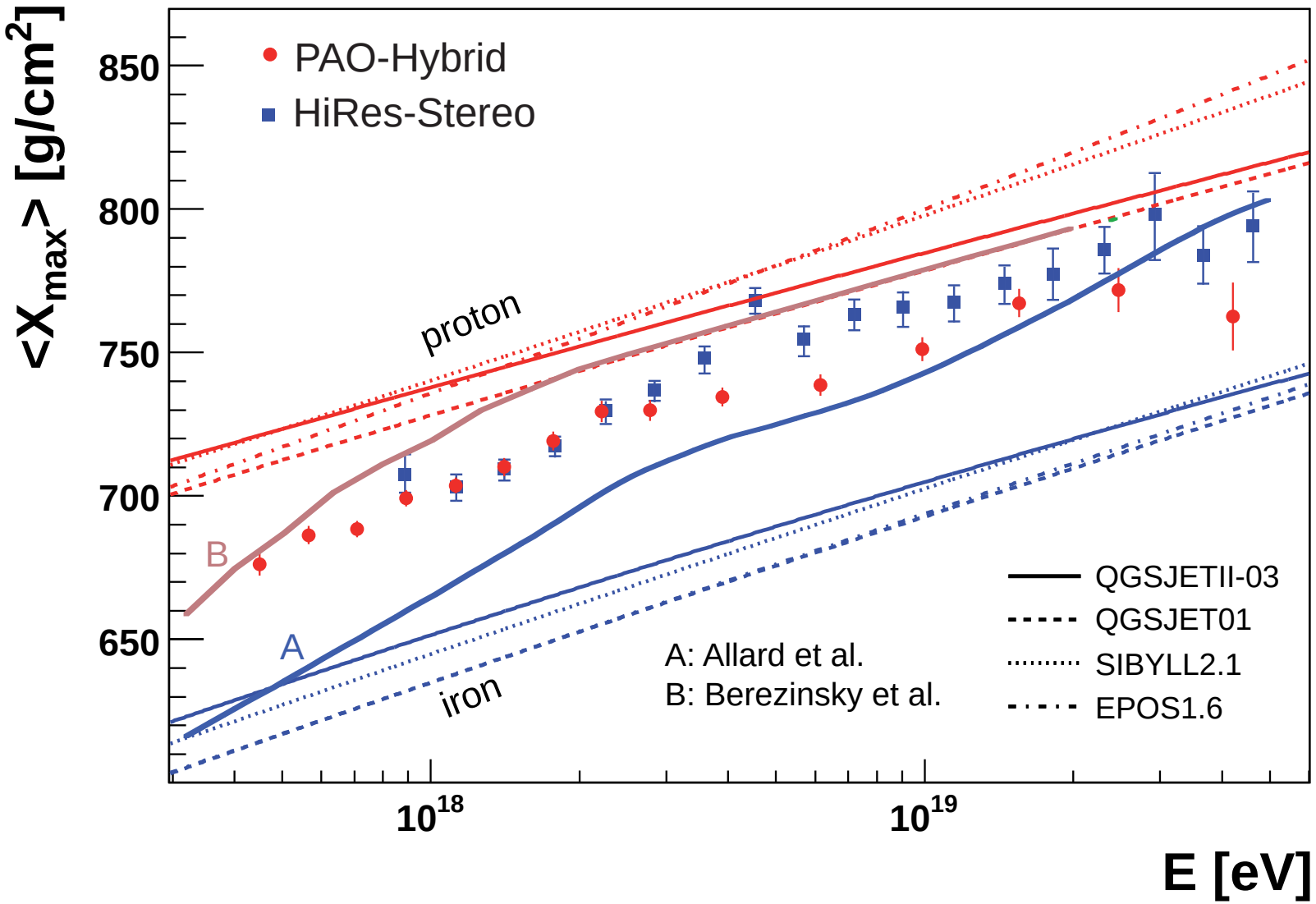






- $X_{\max}$
  $\Rightarrow$ FD composition
- shower front properties
  $\Rightarrow$ SD composition

Mass composition- energy spectrum



Conclusions

Auger energy spectrum

- vertical SD spectrum acceptance: 5165 km^2 sr year (02.2007)
- good agreement between the three energy spectra
- 6σ evidence for flux suppression at high energies
- combined with the anisotropies studies $\Rightarrow$ GZK effect

Composition

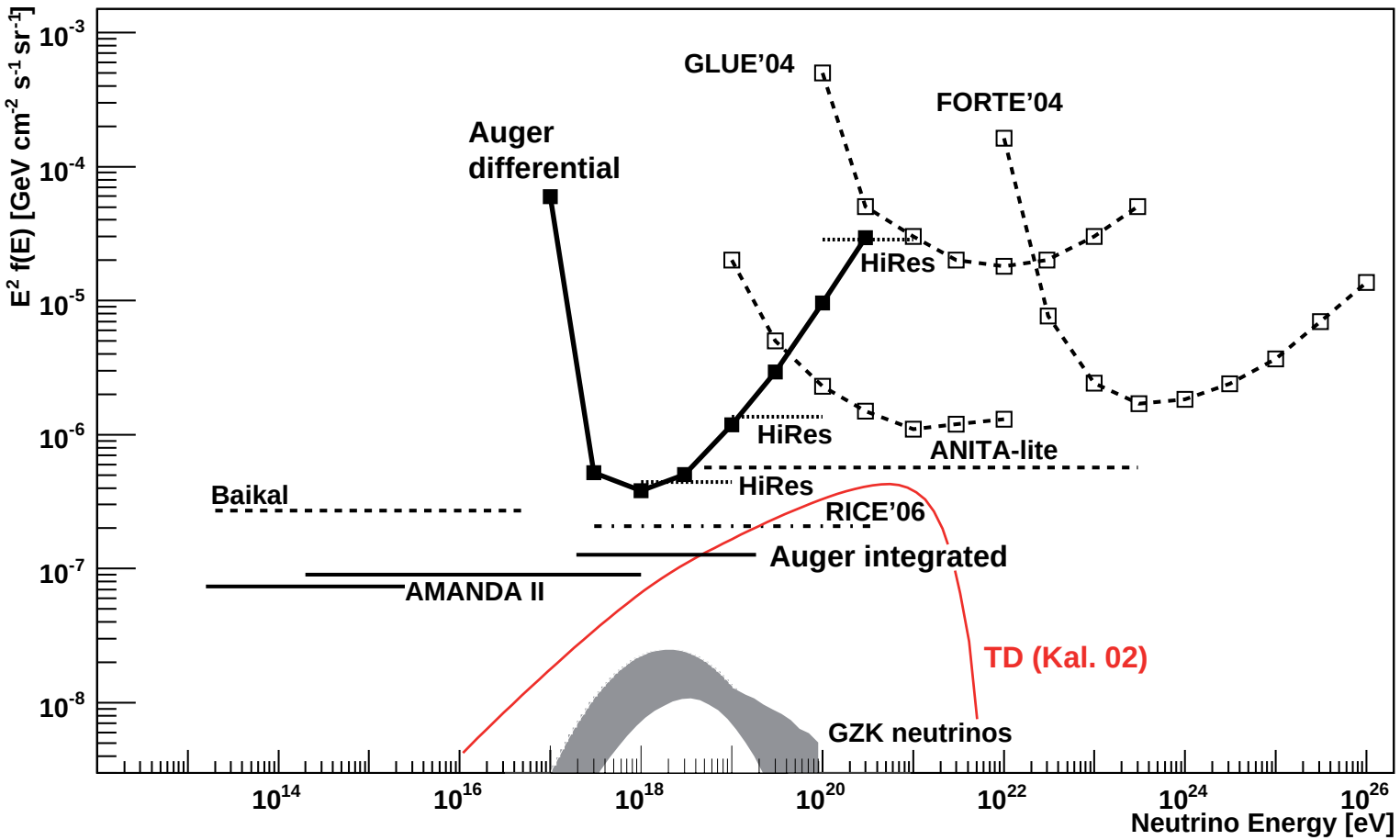
- mean $X_{\rm max}$ $\Rightarrow$ mixed composition
- (strong photon limits from SD+ independent FD: TD & SHDM excluded)
- (neutrino limits)
- ....

Outlook

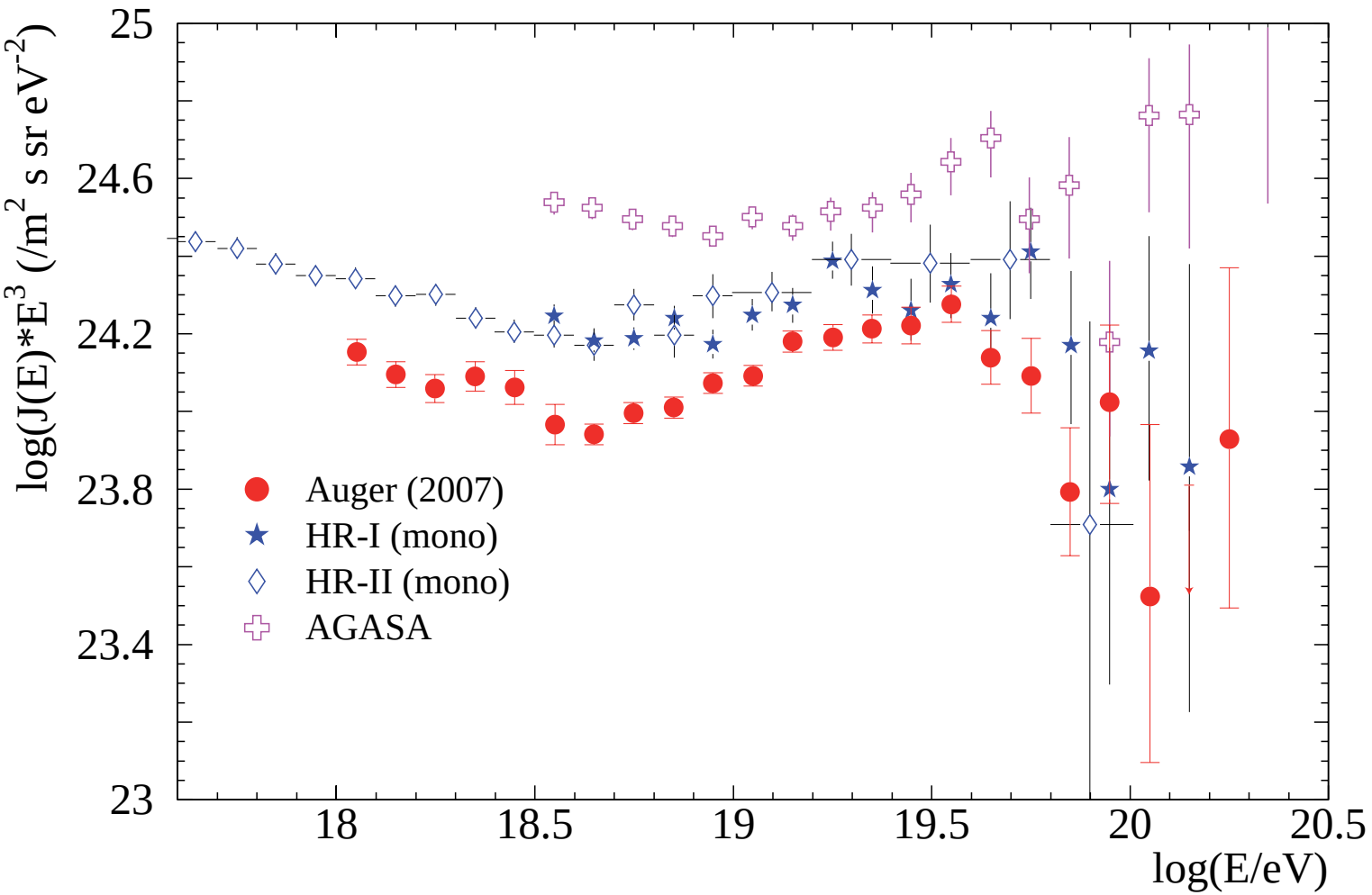
- (soon) updated energy spectrum: 8000 km^2 sr year
- high statistics above $10^{19.8}$ eV needed to constrain models $\Rightarrow$ Auger North

Extra slides

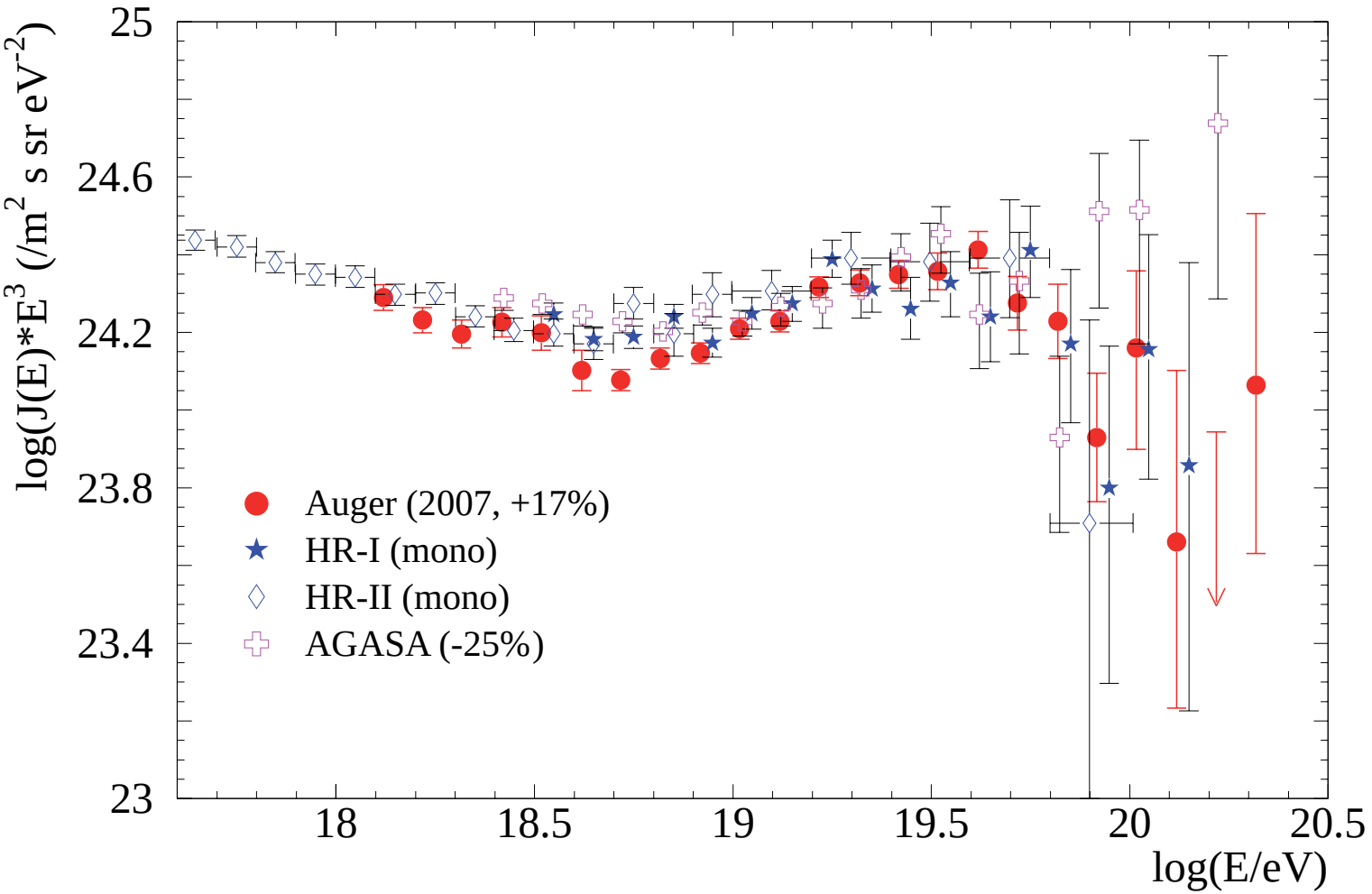
Neutrino limit



Auger Energy Spectrum: Extra slide 1



Auger Energy Spectrum: Extra slide 1



Method of Constant Intensity

Hypothesis:

cosmic ray flux is isotropic
(at least in local coordinates)

$$\Phi = \frac{dN}{d\Omega dE\, dA_{eff} dt}$$

SD data:
projection on flat array geometry

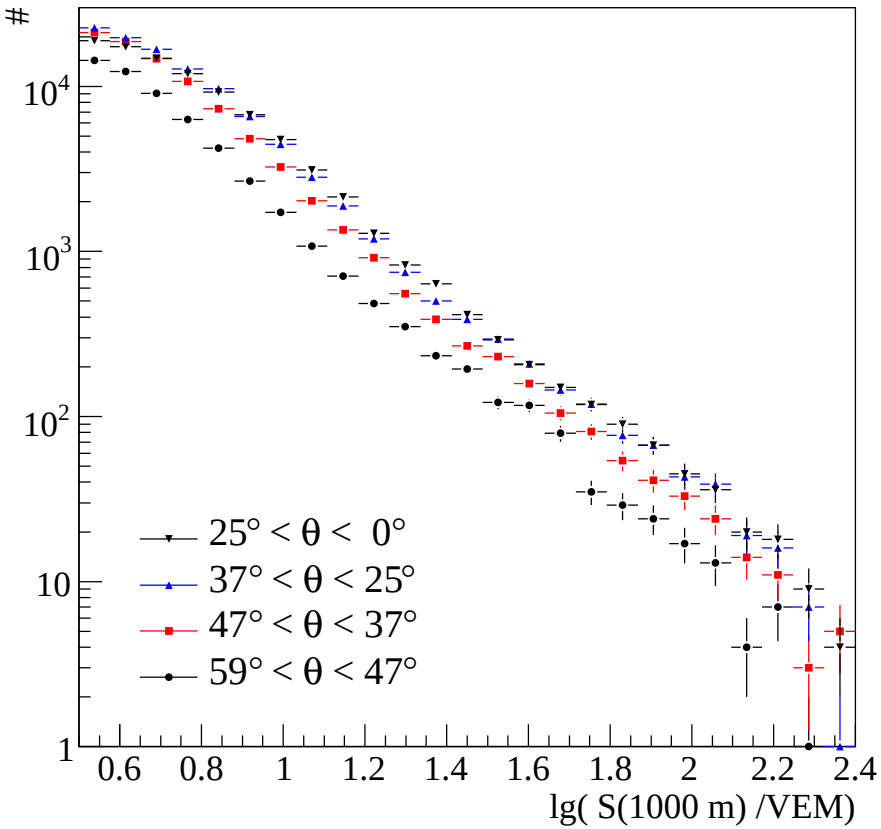
$$A_{eff} = A \cdot \cos\theta$$

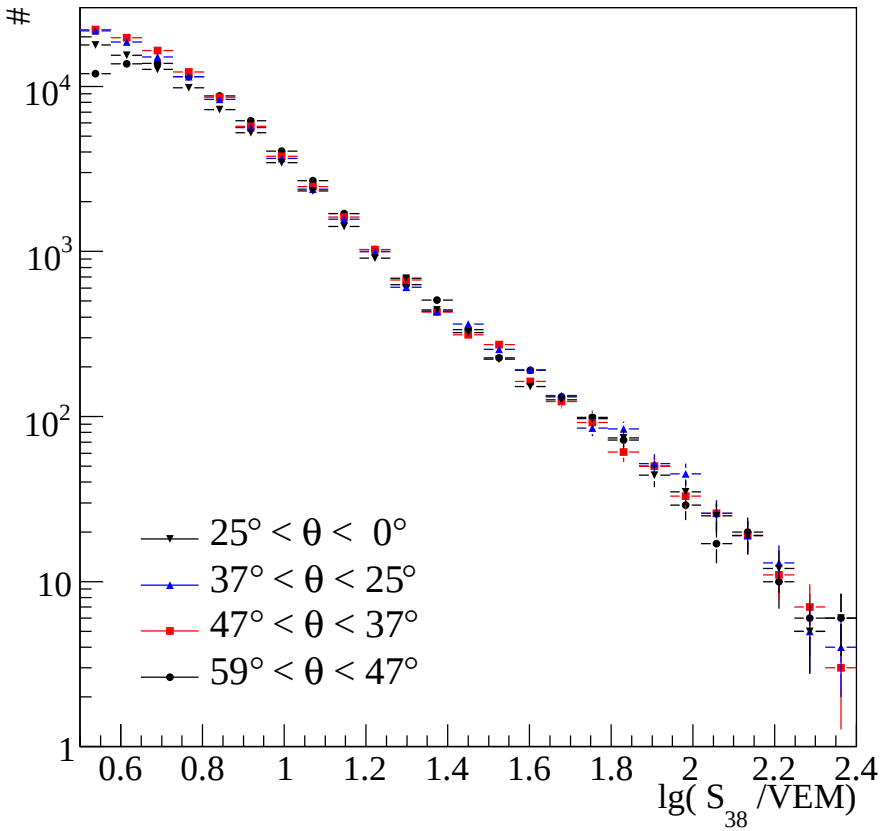
intensity: events above a certain energy

$$\frac{dI}{d\cos^2\theta} = \text{const}$$

Method of Constant Intensity

aim: find $S(\theta)$ from $I = \text{const}$, $\Delta \cos^2\theta = \text{const}$

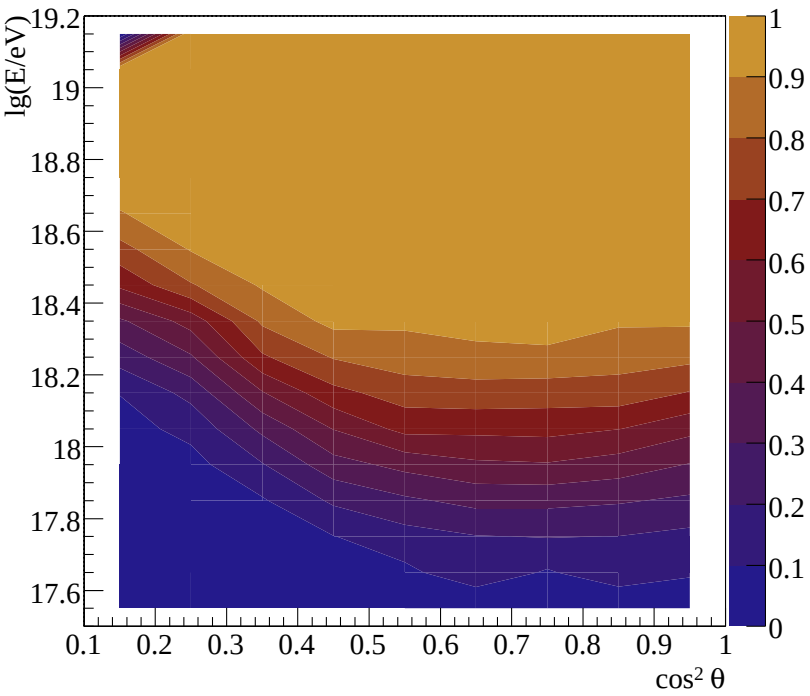




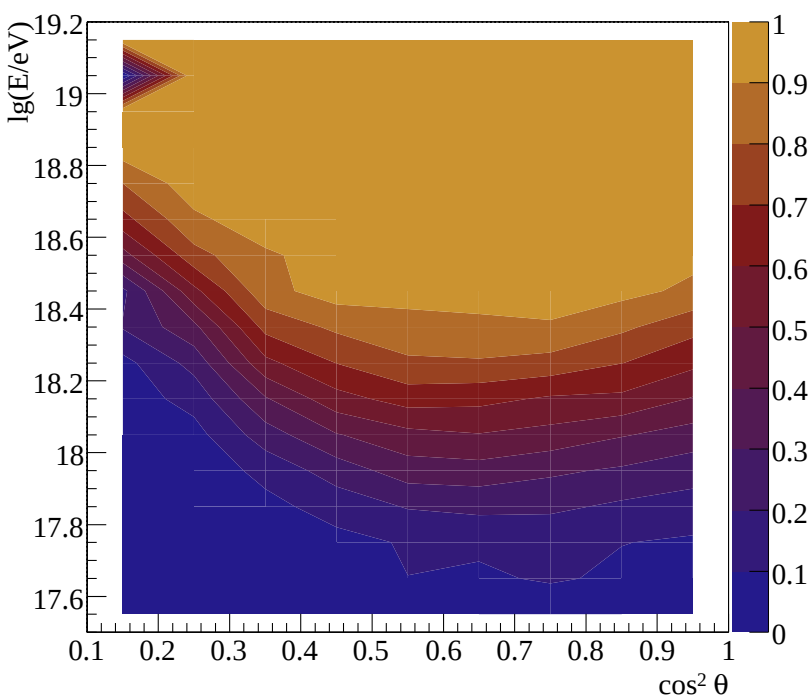
- 'correct' all shower sizes to same zenith angle 38°

Acceptance

iron

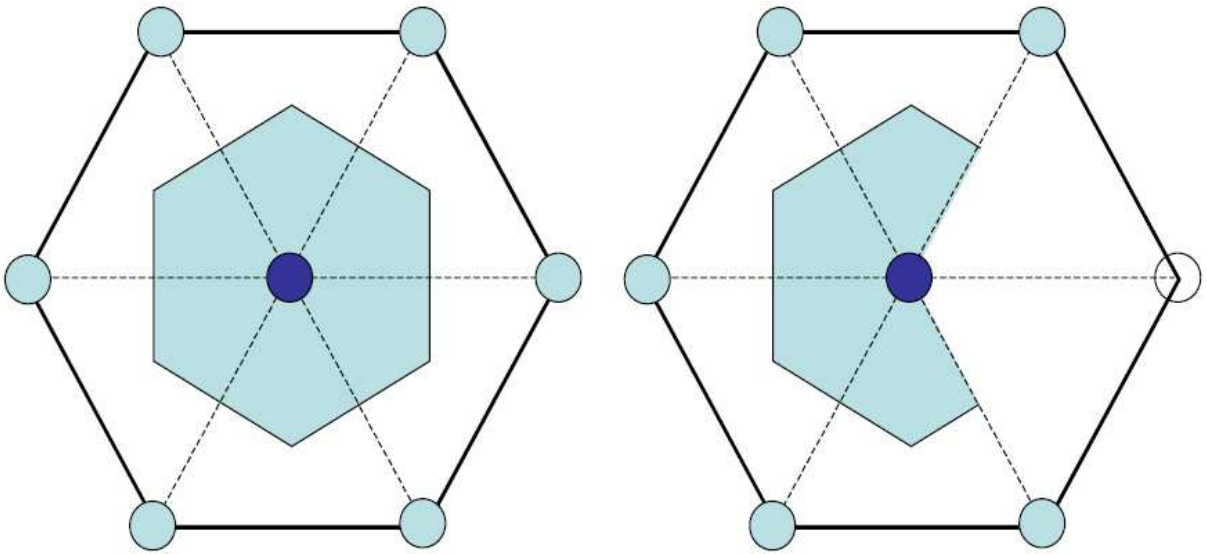


proton



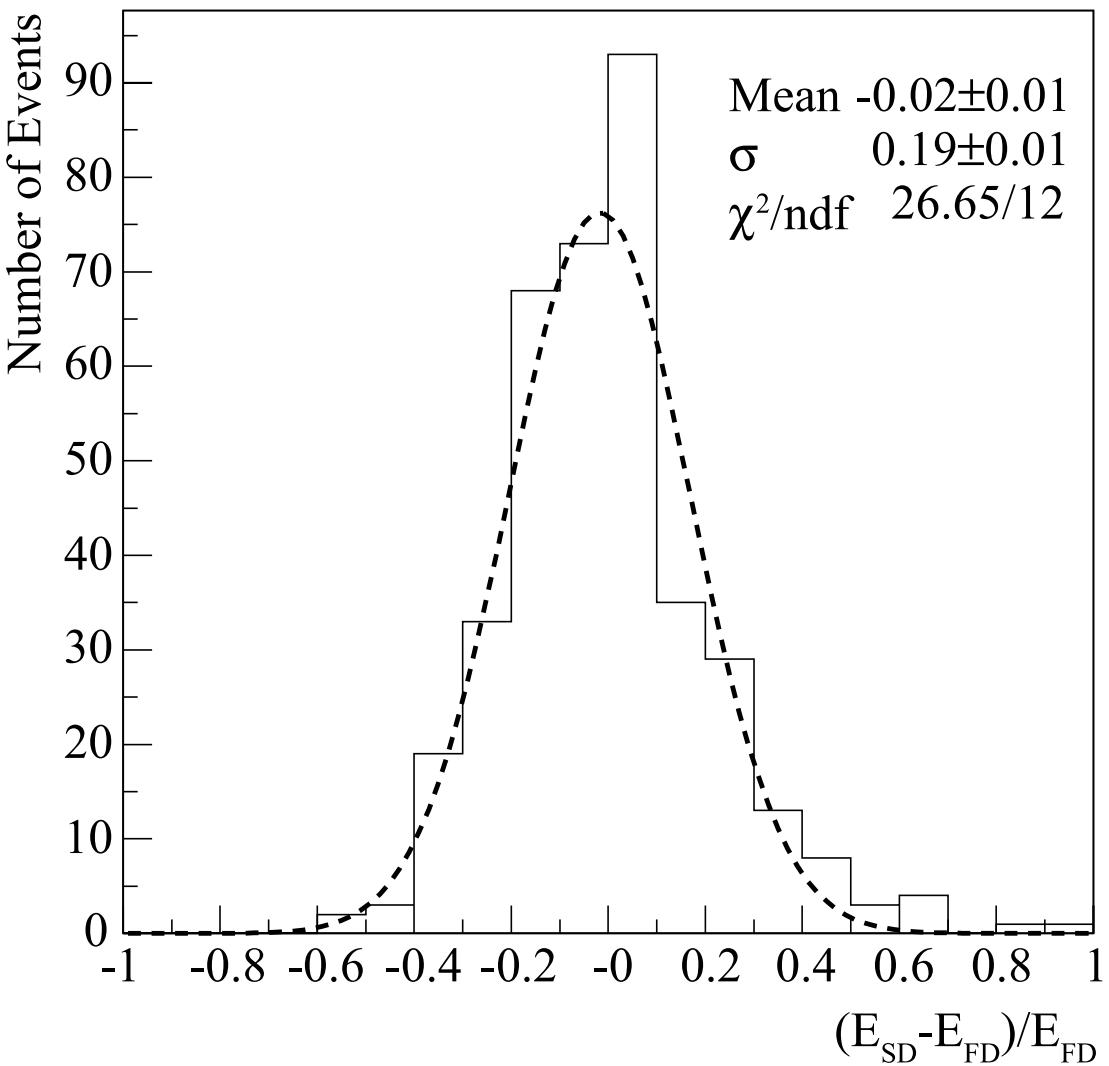
- trigger efficiency= 1 for E>4 EeV
  (independent of primary mass, core position , etc)
- cross-checked with hybrid events!
- reconstruct any T5 event
- maximization of elementary hexagons

Acceptance



- trigger efficiency= 1 for E$>$4 EeV
  (independent of primary mass, core position , etc)
- cross-checked with hybrid events!
- reconstruct any T5 event
- aperture is sum of elementary hexagons

Energy Calibration



Stat. uncertainties:
S_{38° ($\approx$ 16%)

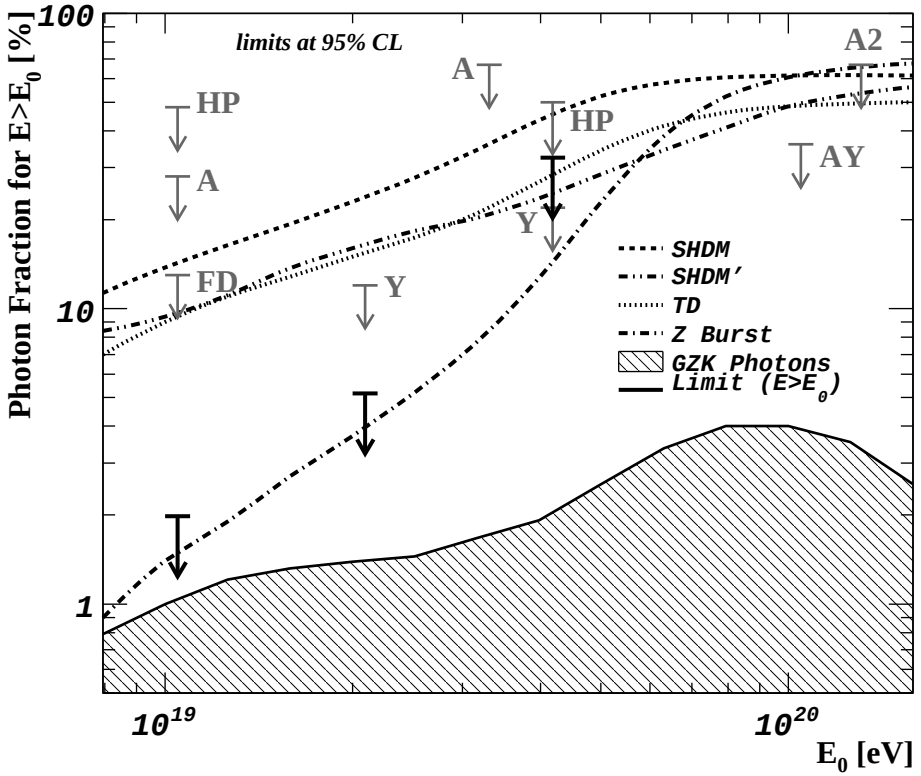
- shower to shower fluctuations
- reconstruction

E_{FD}($\approx$ 8%)

- reconstruction
- atmosphere

$$E = A \cdot S_{38^\circ}^{B}$$

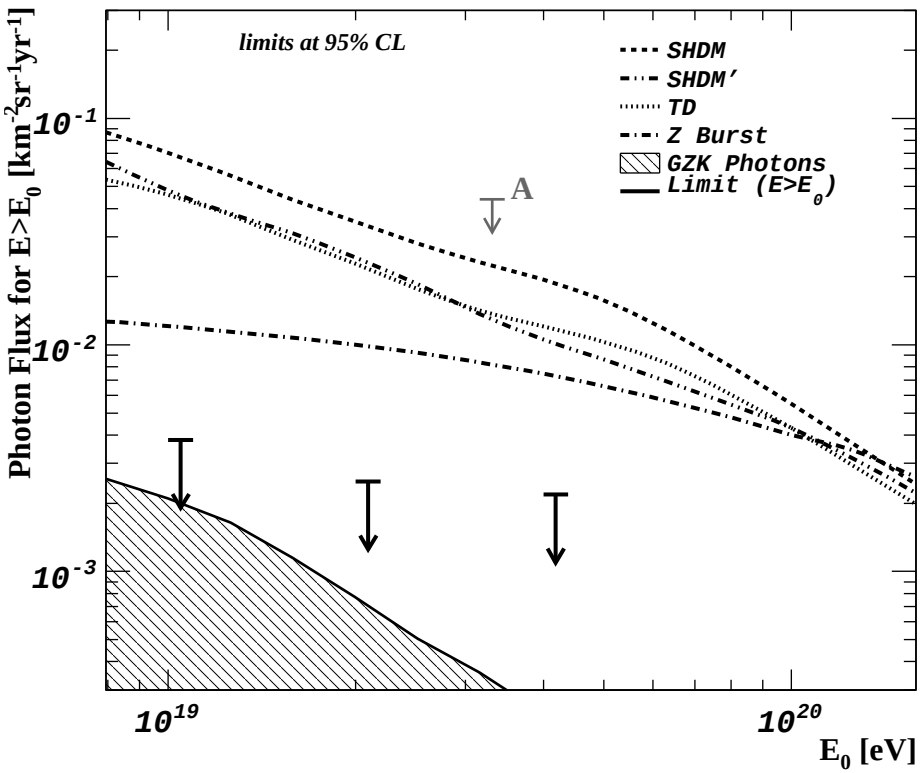
Photon limit



SHDM & TD: astro-ph/0506128

SHDM': C.T. Hill Nucl.Phys. B224, 469(1983), T.W.B.Kibble, Rep. Prog.Phys. 58, 477(1995)

Photon limit



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