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The Fluorescence Detector of the Pierre Auger Observatory - A Calorimeter for UHECR

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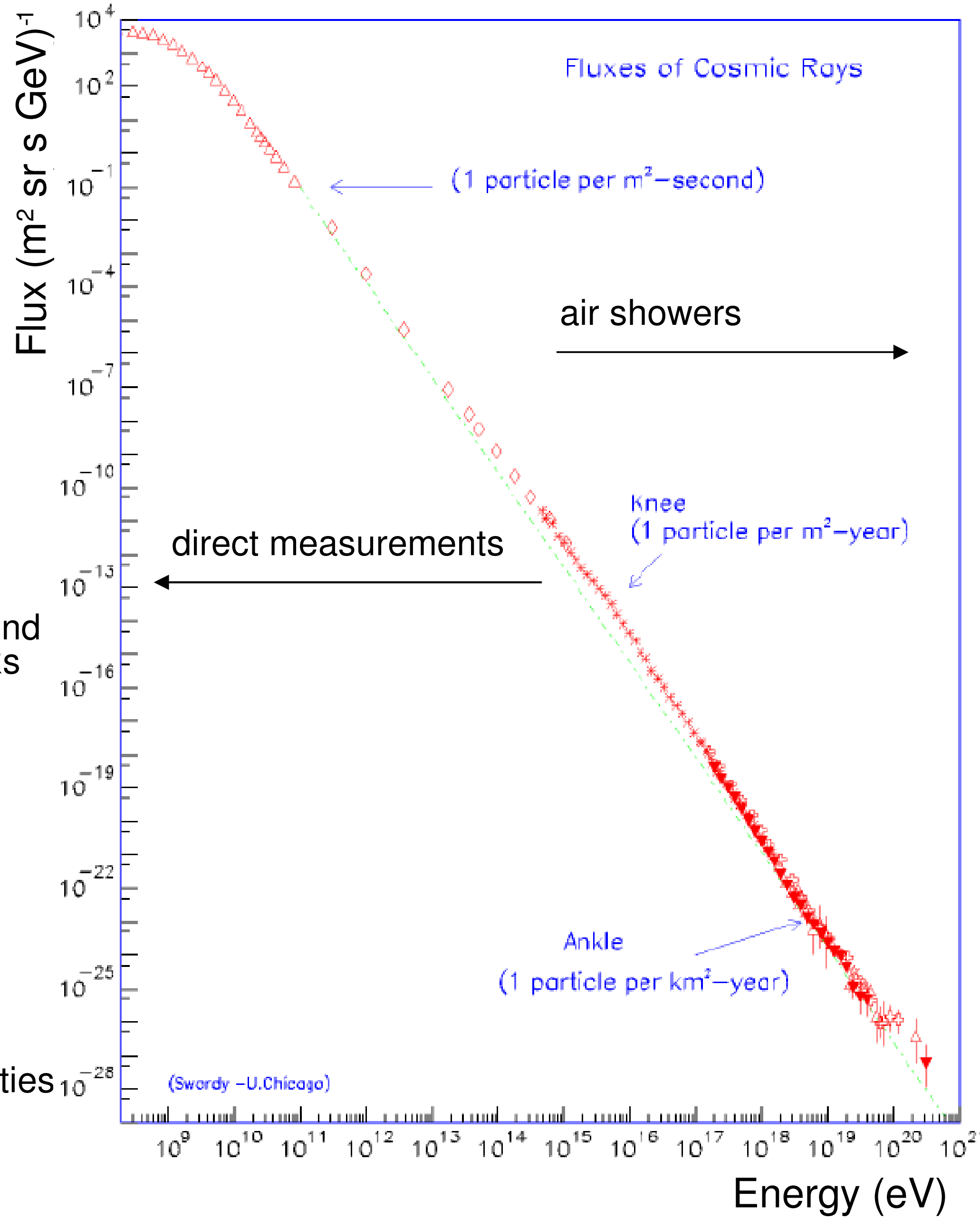
Outline

- Ultra – High Energy Cosmic Rays (UHECRs)
- UHECR detection
- Pierre Auger Observatory
  - Fluorescence detector and energy calibration
  - Uncertainties
  - Exposure
  - Selected results from hybrid detector

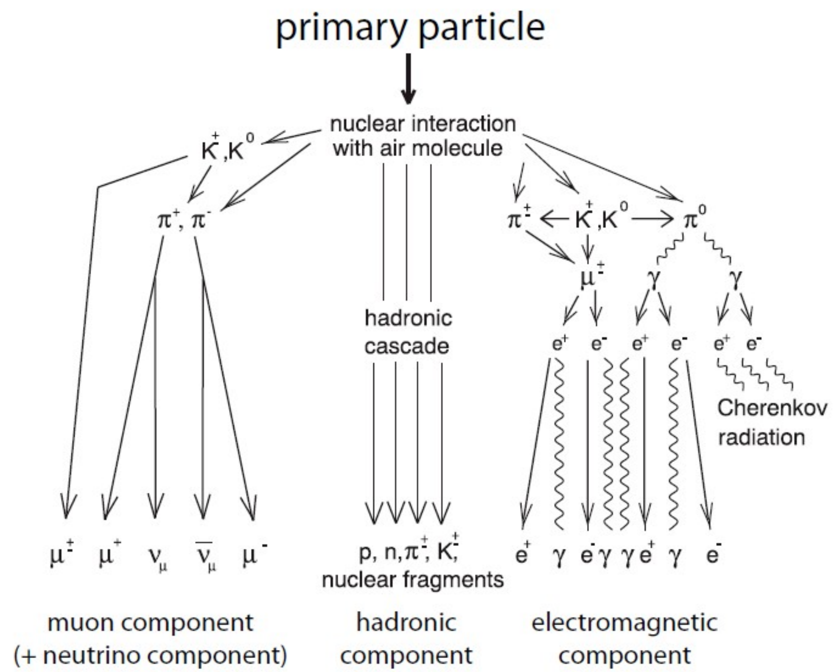
Ultra – High Energy Cosmic Rays (UHECRs)

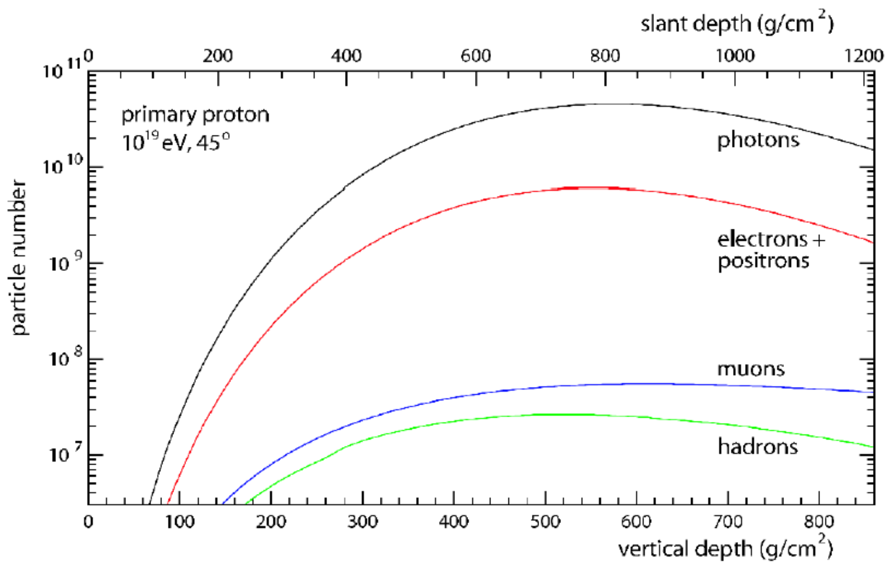
- Steeply falling flux
  - $\frac{dN}{dE} \propto E^{-\gamma}$
- Cosmic Rays (CR) below 'knee'
  - explained as from galactic sources
- CR at 'knee' (4×10^{15} eV)
  - γ changes from 2.7 to 3.2
  - one of theories explains knee as the end of energy spectrum from galactic SNRs
- CR at 'ankle' (3×10^{18} eV)
  - γ changes from 3.2 to 2.6
  - transition to extra-galactic particles
- CR above 'ankle'
  - another spectral index change
  - interaction with CMB,
  - GZK-cut off or end of sources capabilities



UHERC detection

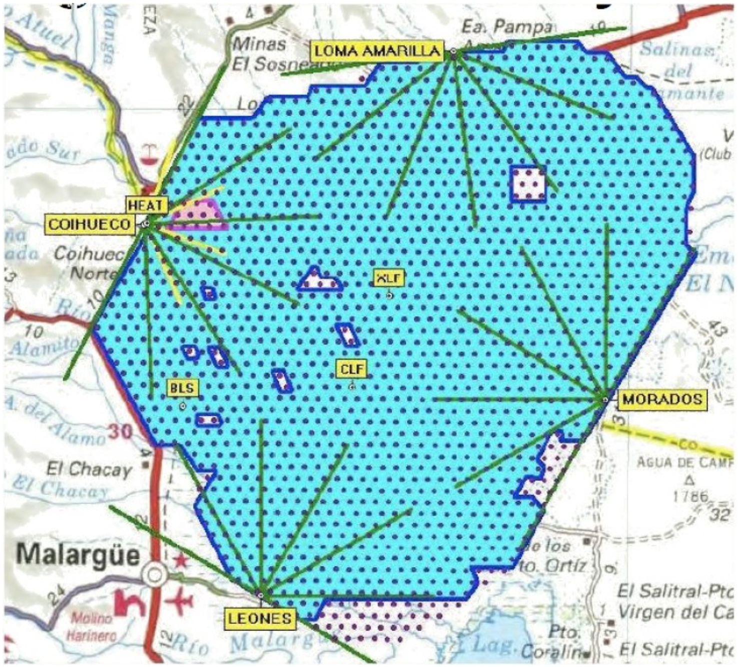
- Direct methods
  - satellites, balloons..
  - unable to measure at ‘higher’ energies due to small statistics
- Indirect methods - air showers
  - $E > 5 \cdot 10^{18}\, eV$
  - high statistics needed
  - understanding of systematics is essential
  - charged ground particles
    - array of Cherenkov detectors, scintillators, muon detectors
  - isotropic fluorescence light
    - fluorescence detectors
  - energy and direction reconstruction





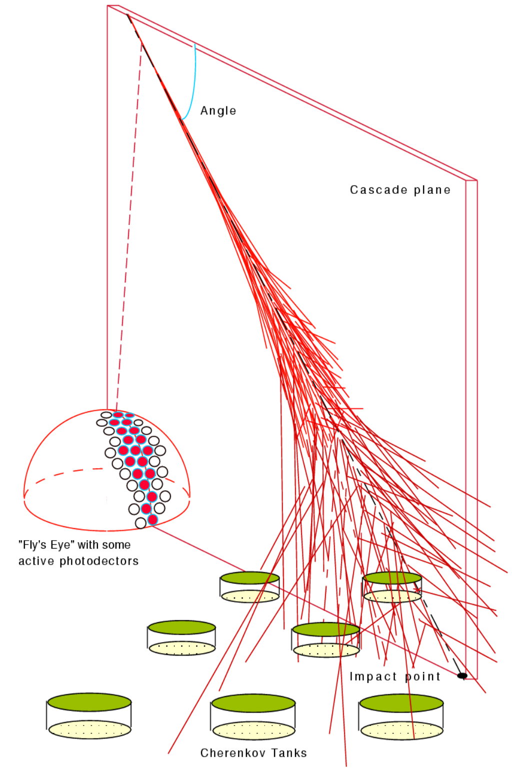
Pierre Auger Observatory (1)

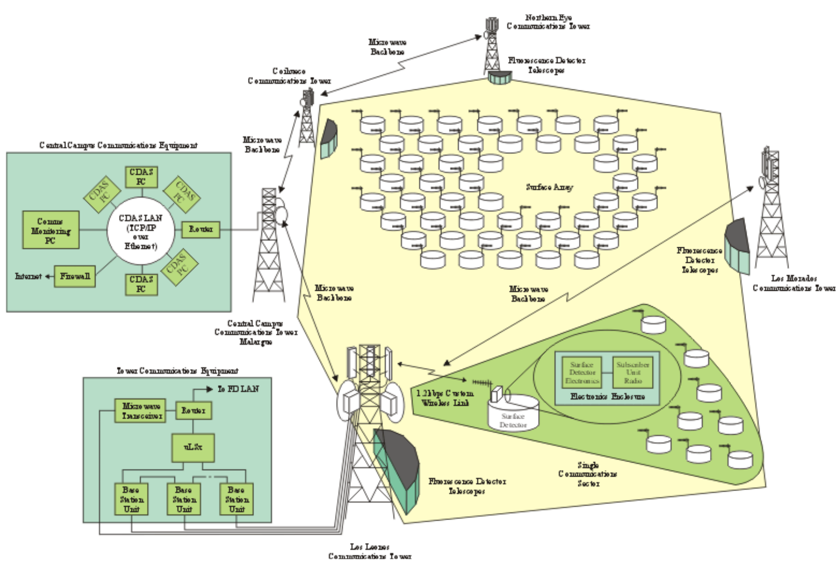
- 3000 km^2 experiment at high altitude (1500 m above see l.) in province Mendoza in Argentina
- 91 Institutions, 18 countries, 487 collaborators
- June 2008 – Southern site completed
- Activities started on the Northern site, Colorado USA

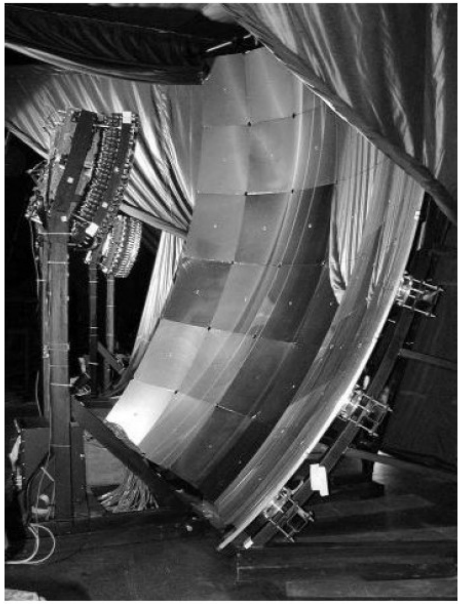


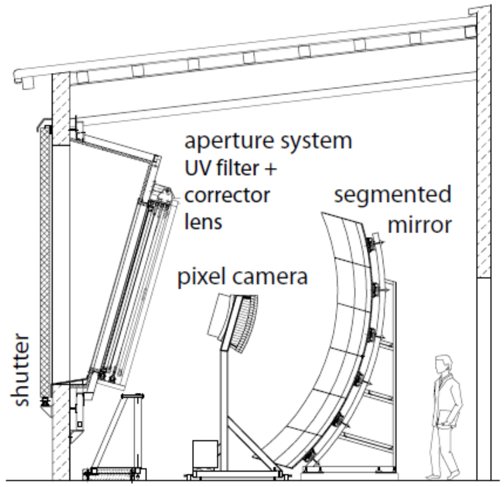
Pierre Auger Observatory (2)

- First experiment with hybrid detection technique
  - 4 fluorescence detectors with 6 telescopes each (30^0 x 28^0)
  - 1660 water Cherenkov tanks
    - 1,5 km triangular grid
    - 3 9” Photonis XP1805 PMTs per station
  - 12 % events with hybrid reconstruction
- Low energy extension infill & fluorescence telescopes (AMIGA + HEAT)
- Extensive program of atmospheric monitoring
- Wide area wireless radio system







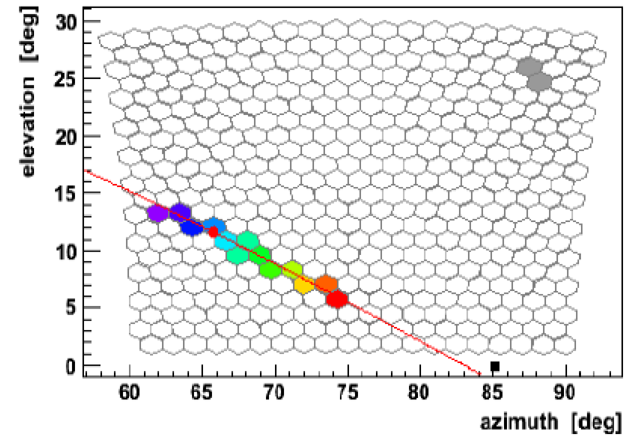


Fluorescence detector

Longitudinal profile from FD telescopes

- light from excited nitrogen molecules due to electromagnetic energy losses of charged particles
- ~ 20 photons per MeV emitted between 300 and 400 nm
- profile integral → 90 % of the primary particle energy at 10^{19} eV

=> atmosphere is an efficient calorimeter!



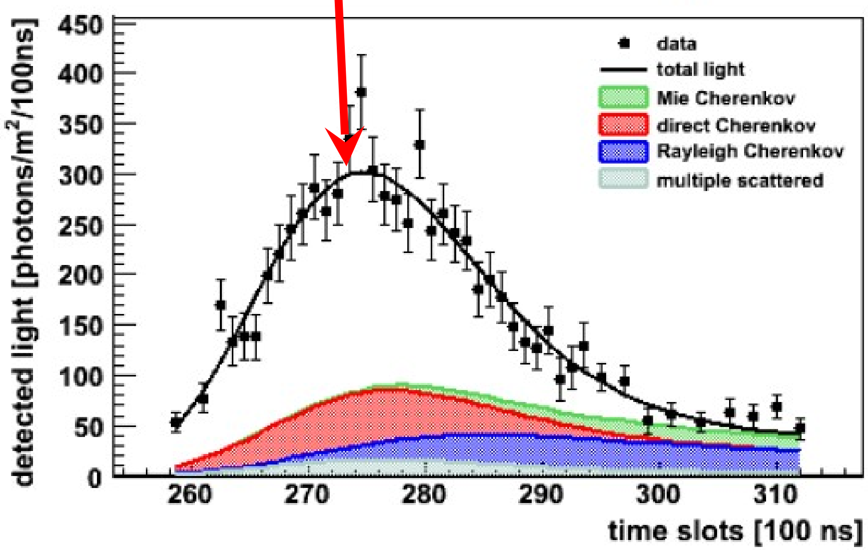
$$E_{\rm cal} = \int {\rm d}X \, \frac{{\rm d}E}{{\rm d}X}$$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 22\,\%$

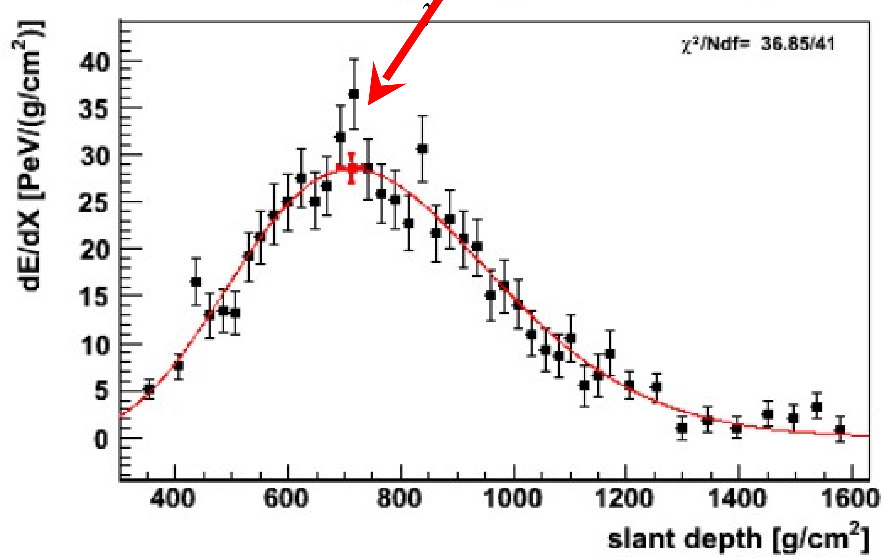
$\sigma_{X_{\rm max}} < 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \approx 15\,{\rm g/cm^2}$

$X_{\rm max}$

Fluorescence + Cherenkov photons



extract Xmax, shape and energy



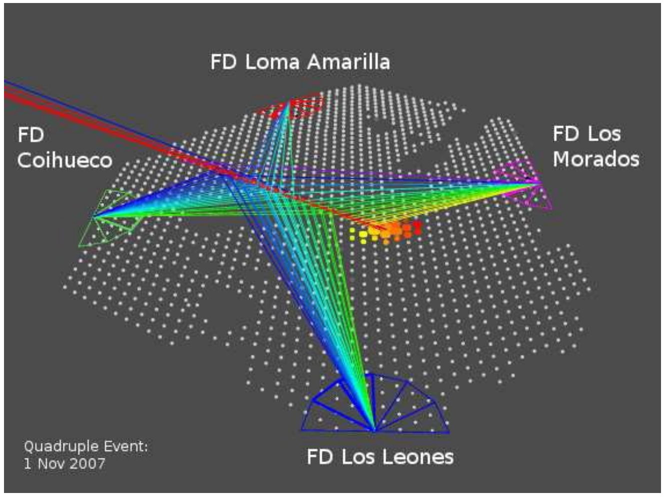
Hybrid detection technique (1)

Surface Detectors

- \+ 100 % duty cycle
- \+ geometric acceptance
- \- only last stage of shower development observed
- \- energy scale model dependent
- ● Angular resolution < 1 °
- ● Threshold at $10^{18.5}$ eV

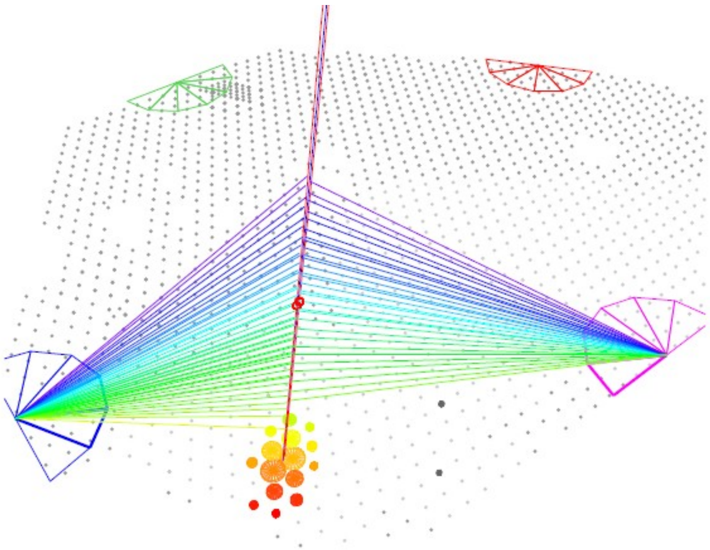
Fluorescence Detectors

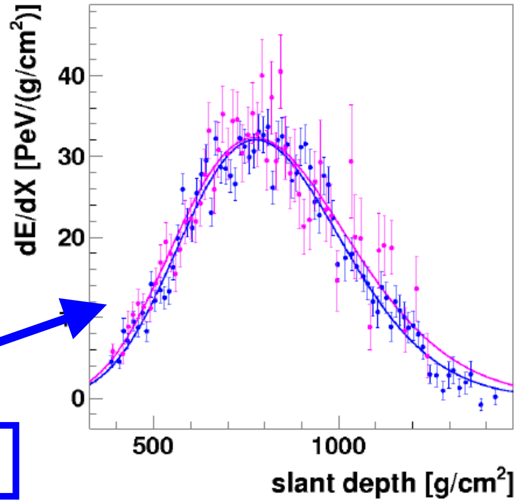
- \+ observation of longitudinal shower development
- \+ (almost) model independ. calorimetric E
- \- ≈ 12 % duty cycle
- \- acceptance depends on distance and atmosphere (model depend.)
- ● Angular resolution 0.6°
- ● Threshold ≈ $10^{18.0}$ eV



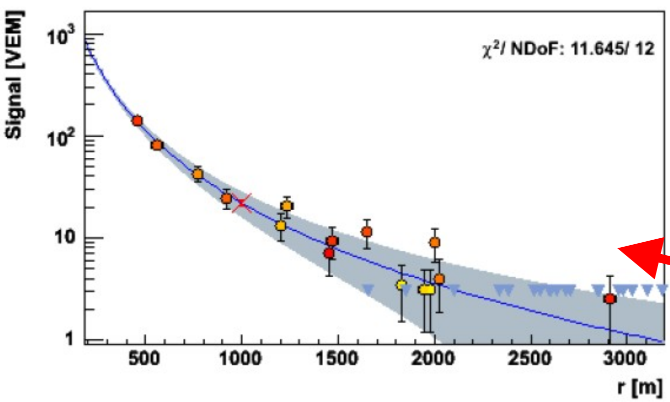
Hybrid detection technique and energy calibration (1)

- 4 x 6 FD telescopes with 440 PMTs each





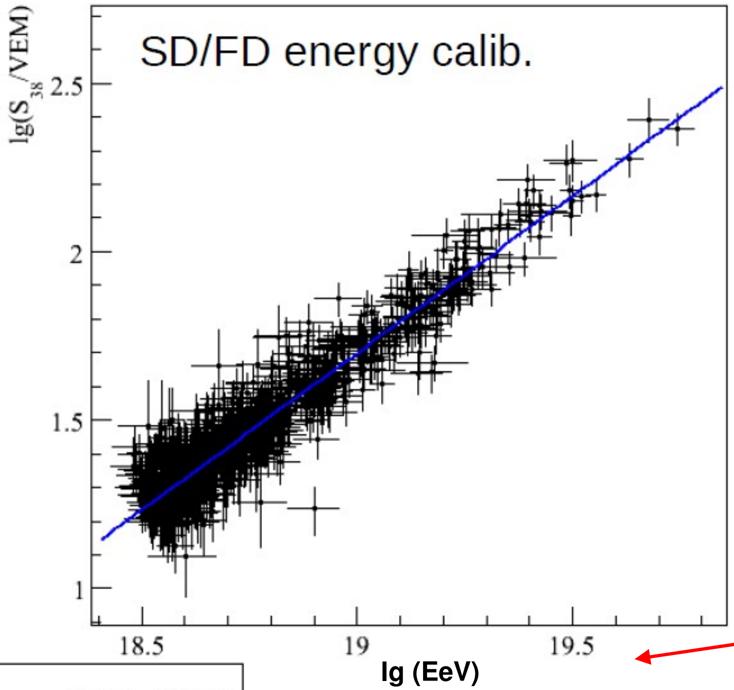
longitudinal profile from FDs

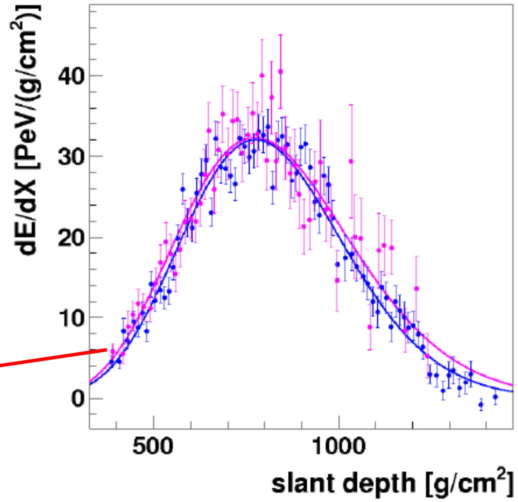


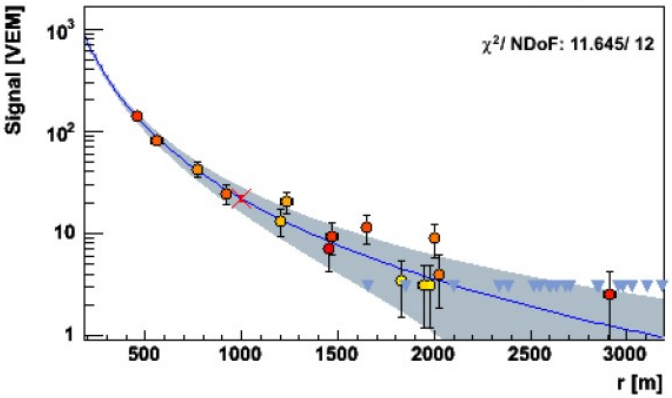
lateral distribution from SD array

Hybrid detection technique and energy calibration (2)

- 4 x 6 FD telescopes with 440 PMTs each







Energy CALIBRATION independent on simulation !

Uncertainties on the reconstructed energy from FD

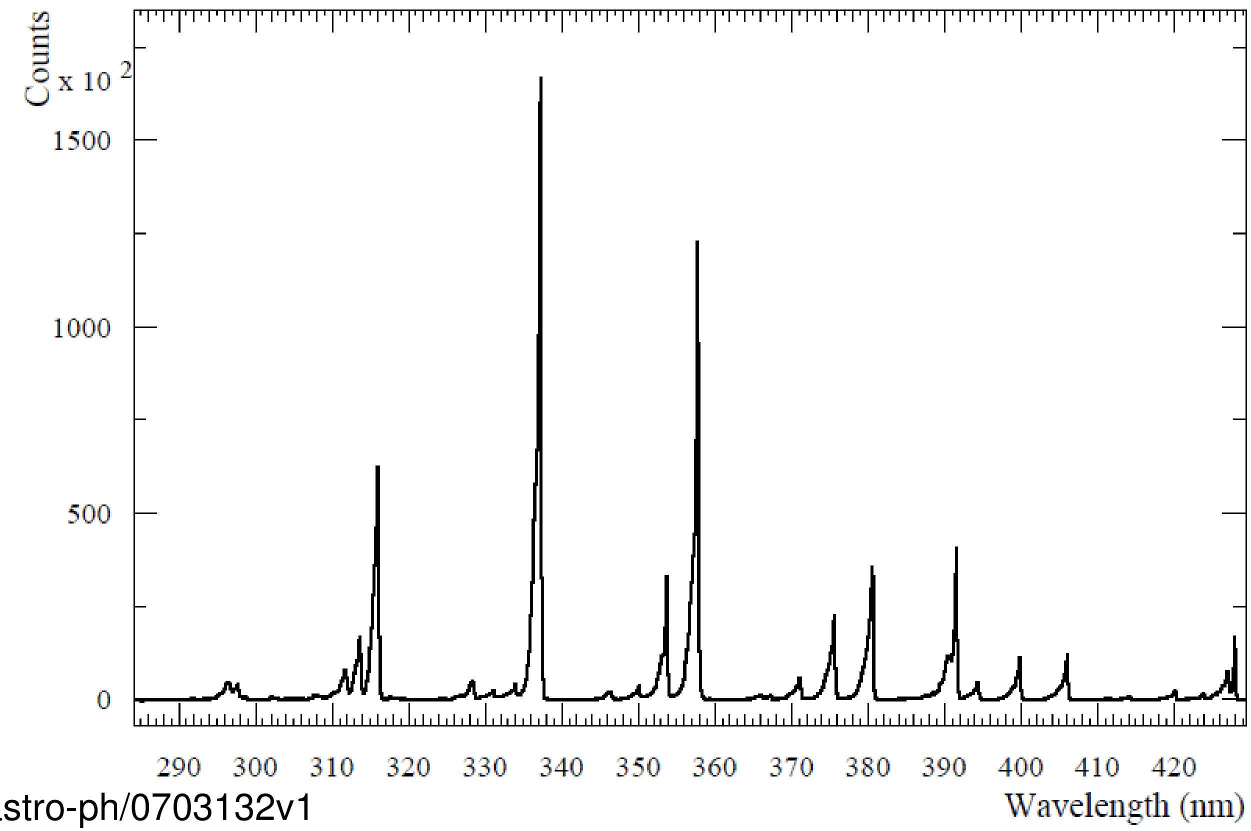
1. signal in the PMTs
   - telescope absolute calibration 9 %
2. photons at the FD
   - longitudinal shower profile reconstruction 10 %
3. fluorescence photons emitted at the shower axis
   - aerosol optical depth 7 %
   - molecular optical depth 1 %
   - fluorescence yield 14 %
4. energy deposit per slant depth
   - invisible energy correction 4 %

Systematics in total ≈ 22 %

Isotropic fluorescence light

- charged particles (mainly $e^{\pm}$) of EAS excites N_2 molecules in air
- several emission bands between 300 and 430 nm
- number of emitted photons is proportion to E deposited in the atmosphere
- FD measures longitudinal development profile $\frac{dE}{dX}(X)$ of the air shower

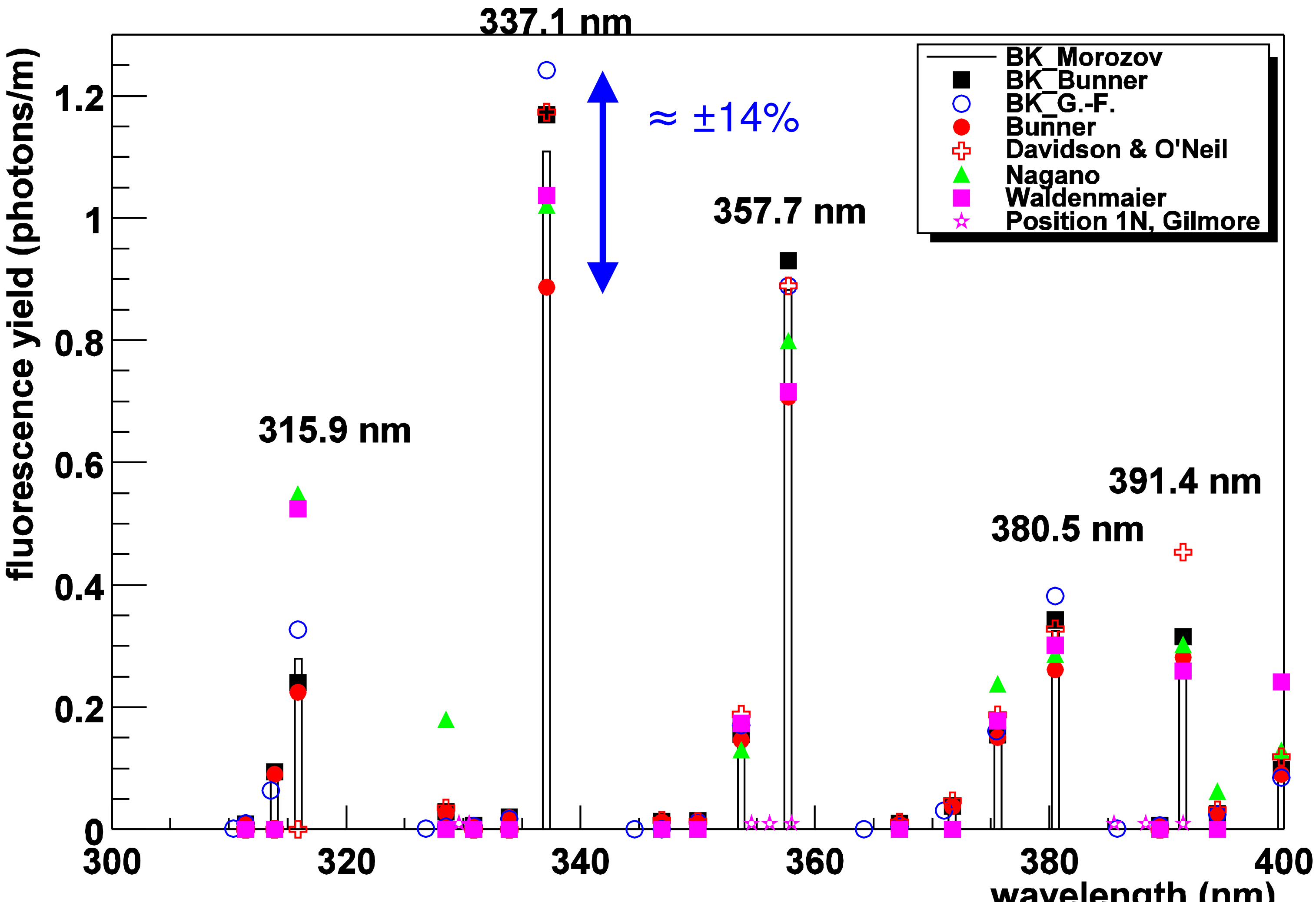
⇒ **Fluorescence yield (≈ 5 photons / MeV at 293 K and 1013 hPa from 337 nm band)**



M. Ave, arXiv: astro-ph/0703132v1

Fluorescence Yield at sea level

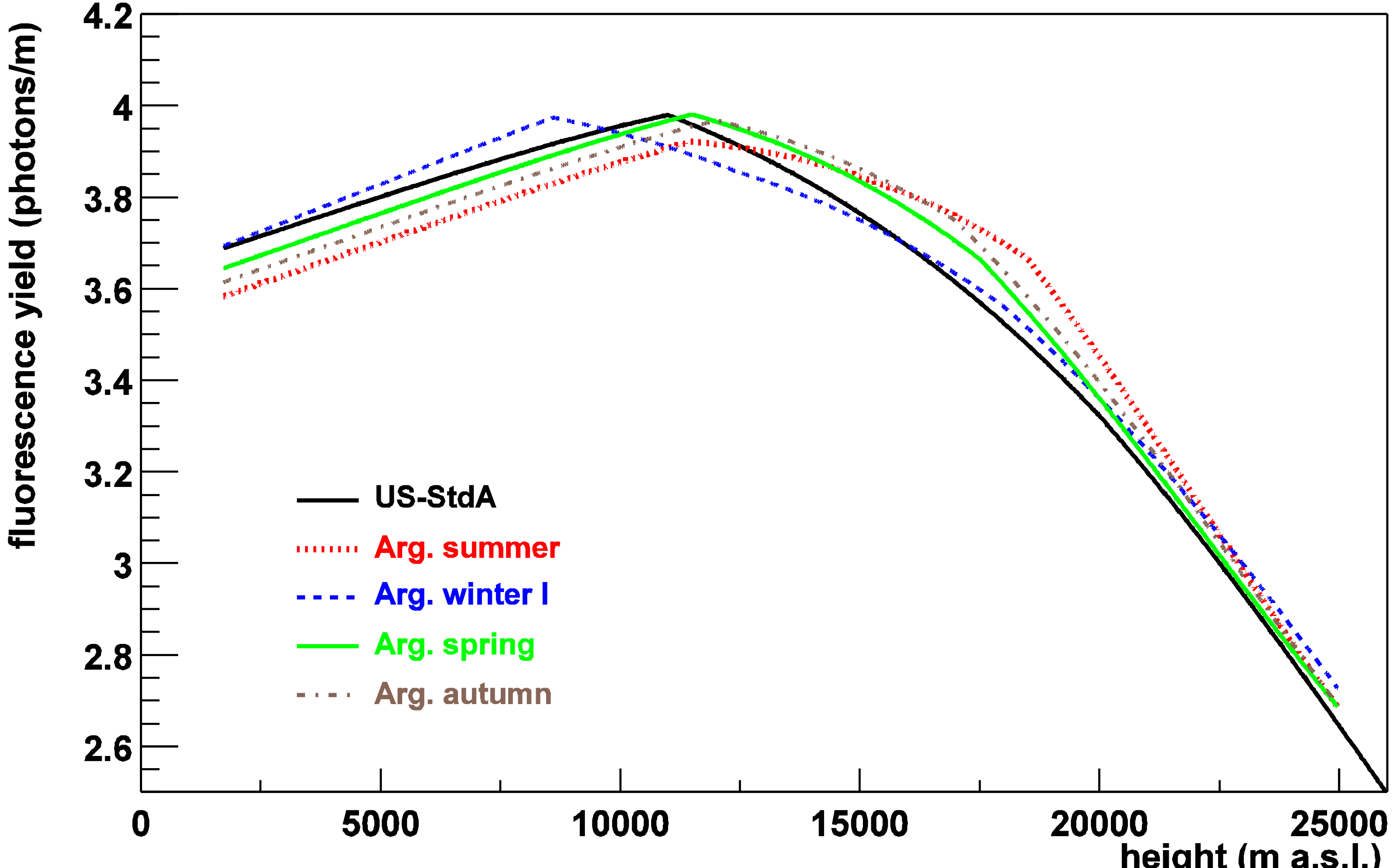
- Comparison of absolute fluor. yield for 0.85 MeV electron in US Std. atmosphere



B. K. et al., Astropart.Phys.25, 259, 2006

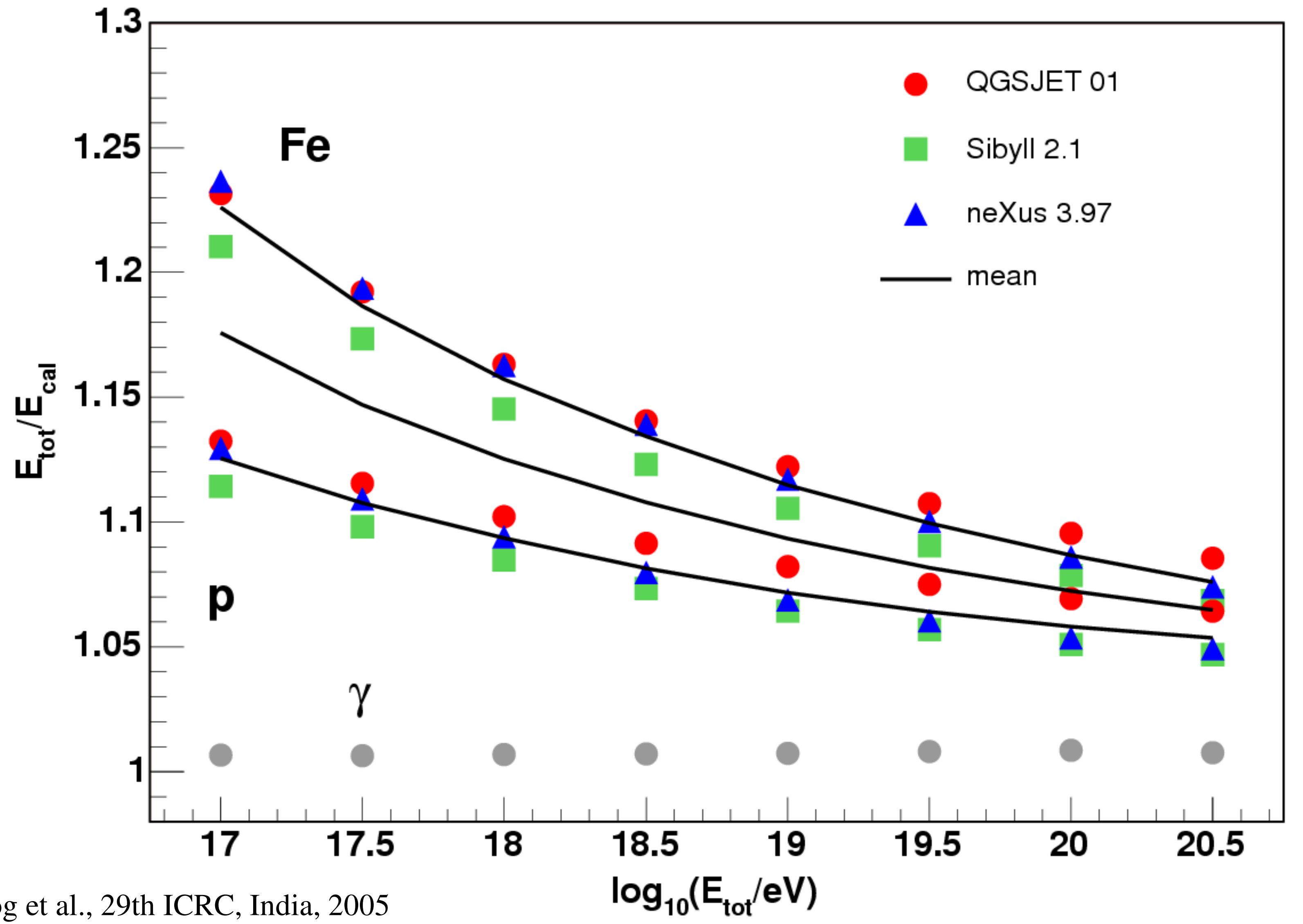
Seasonal and Altitude dependence for Auger

for a 0.85 MeV electron



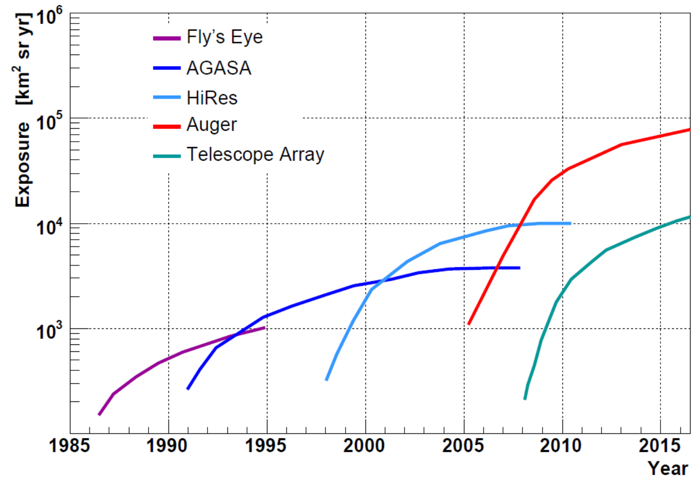
B. K. et al., Astropart.Phys.25, 259, 2006

Correction Factor for „Missing Energy“



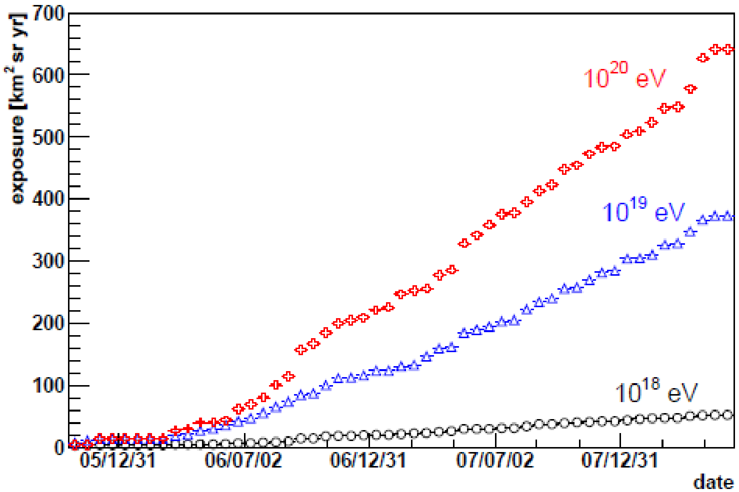
T. Pierog et al., 29th ICRC, India, 2005

Exposure



- SD exposure
- 10 times the AGASA exposure

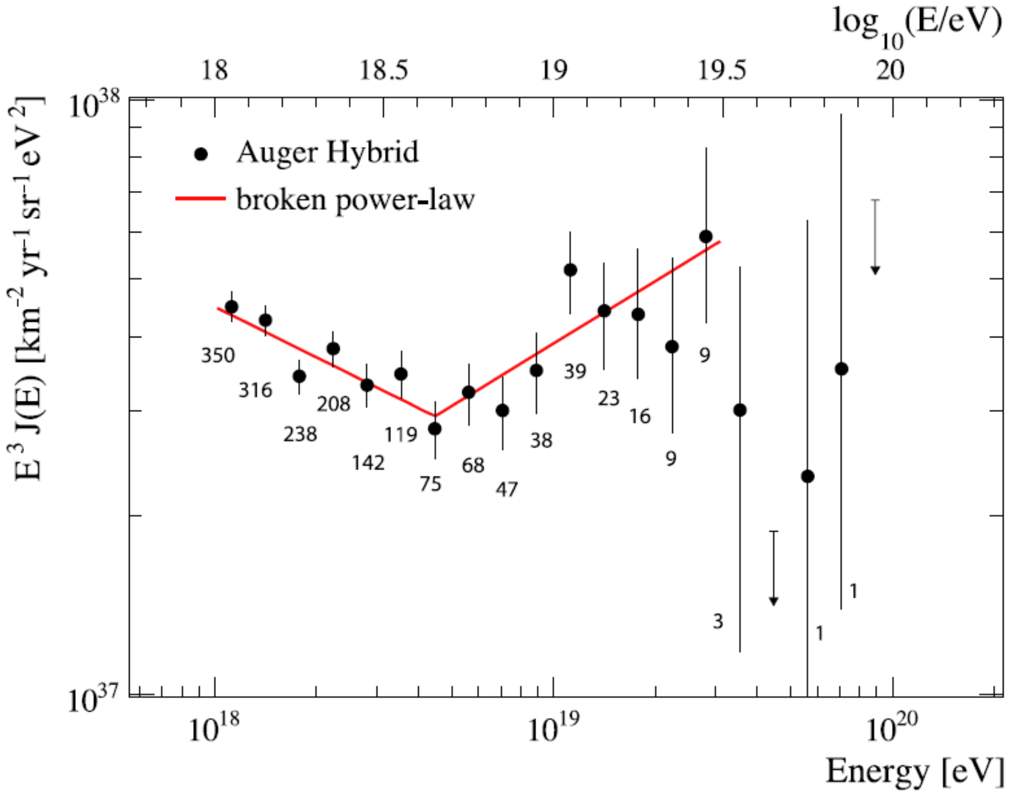
- Hybrid exposure
- Growth of the hybrid exposure from November 2005 up to May 2008:



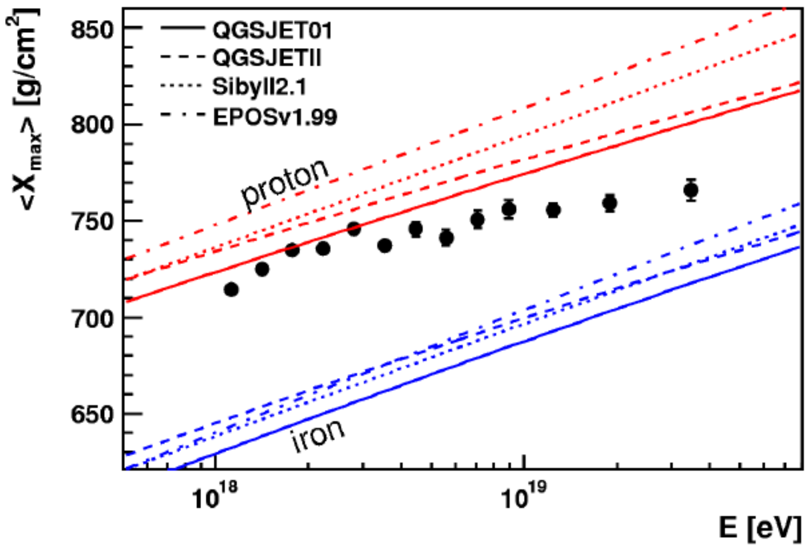
- atmospheric conditions (aerosols, background light,..)
- detector configuration
- primary energy (higher E → more light → larger exposure)
- time dependent detector MC
  - reproduce actual data taking conditions

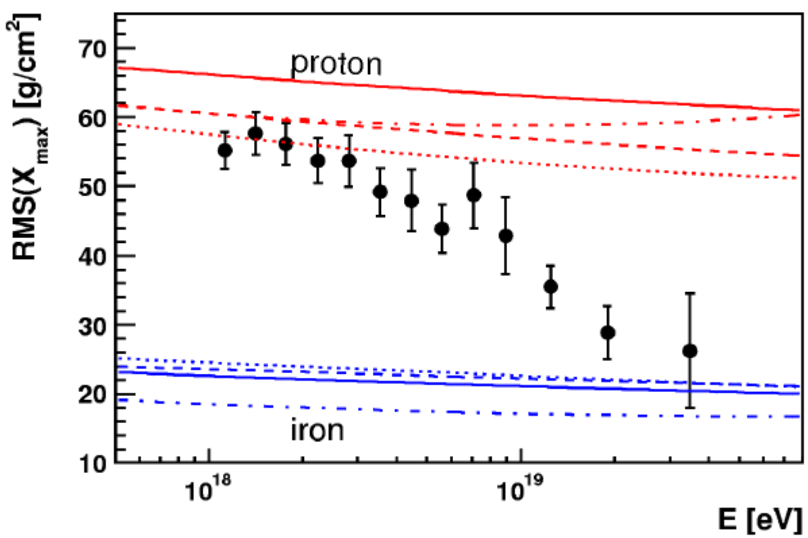
Selected results from hybrid detector (1) –spectrum

- Hybrid spectrum of ultra-high energy CR:
  - evidence for ankle and investigation of its position



Selected results from hybrid detector (2) - composition





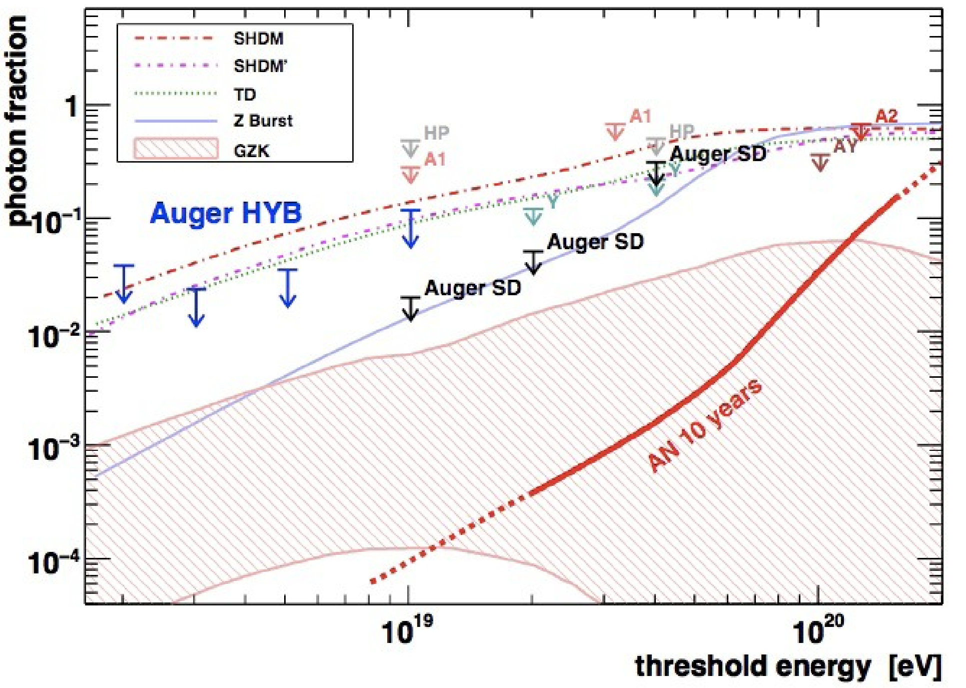
- $\langle X_{max} \rangle$ Auger data suggest mixed composition

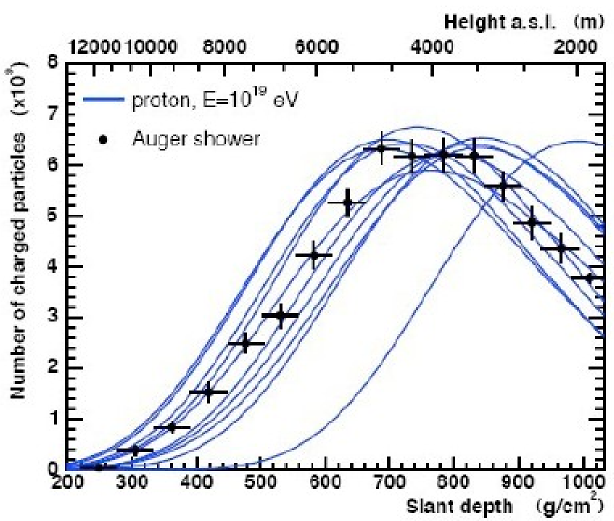
- RMS(X_{max}) shows strong trend to small X_{max} fluctuations (large mass of primary particle) at high energy

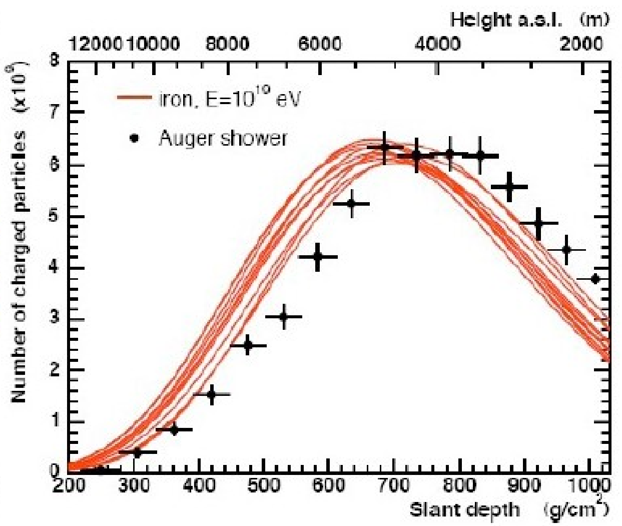
Selected results from hybrid detector (3) - photon limits

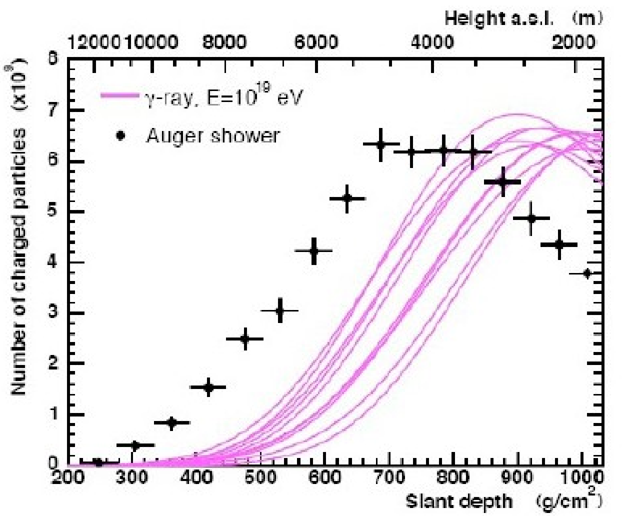
- GZK photons
- 'Top-down' scenarios (e.g. SHDM decay)

- Photon showers have large X_{max}, with Auger FD possible to set first photon limits bellow 10 EeV ever









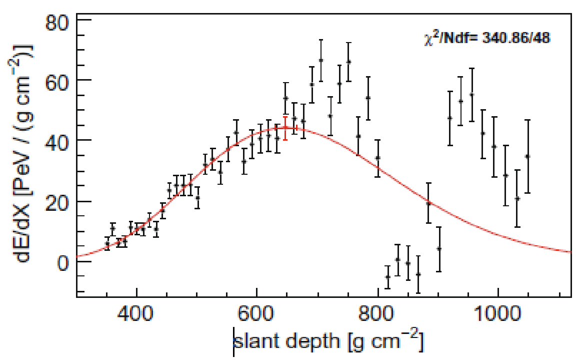
Summary

- Pierre Auger Observatory steadily operates in full design size!
  - first CR detector with hybrid technique
  - atmosphere is an efficient calorimeter!
  - energy spectrum
  - arrival directions
  - shower profiles and X_{max}

- Scientific results and prospects
  - CR mass composition
  - Studies of hadronic interactions at ultra-high energies
  - Identification and studies of the sources
  - Auger North

Systematic uncertainties in the hybrid rec. due to atm.

Systematic uncertainties					
Source	log (E/eV)	$\Delta E/E$ (%)	RMS($\Delta E/E$) (%)	ΔX_{max} (g cm^{-2})	RMS(X_{max}) (g cm^{-2})
Molecular light transmission and production					
Horiz. uniformity	17.7–20.0	1	1	1	2
Quenching effects	17.7–20.0	+5.5	1.5–3.0	−2.0	7.2–8.4
p, T, u Variability	17.7–20.0	−0.5		+2.0	
Aerosol light transmission					
Optical depth	<18.0	+3.6, −3.0	1.6 ± 1.6	+3.3, −1.3	3.0 ± 3.0
	18.0–19.0	+5.1, −4.4	1.8 ± 1.8	+4.9, −2.8	3.7 ± 3.7
	19.0–20.0	+7.9, −7.0	2.5 ± 2.5	+7.3, −4.8	4.7 ± 4.7
λ-Dependence	17.7–20.0	0.5	2.0	0.5	2.0
Phase function	17.7–20.0	1.0	2.0	2.0	2.5
Horiz. uniformity	<18.0	0.3	3.6	0.1	5.7
	18.0–19.0	0.4	5.4	0.1	7.0
	19.0–20.0	0.2	7.4	0.4	7.6
Scattering corrections					
Mult. scattering	<18.0	0.4	0.6	1.0	0.8
	18.0–19.0	0.5	0.7	1.0	0.9
	19.0–20.0	1.0	0.8	1.2	1.1



- Shower light profile with a large gap due to the presence of an intervening cloud
- Uncertainties from combined all atmospheric measurements:

$$RMS\left(\frac{\Delta E}{E}\right) \approx 5 \pm 1\%$$

$$RMS\left(X_{\max}\right) \approx 11 \pm 1\ g.cm^{-2}$$

PIERRE AUGER OBSERVATORY

Electromagnetic Shower

- Primary particle is electron or positron
- Hadronic interaction yields in $\pi^0 \rightarrow$ decay into 2 γ

Heitler model:

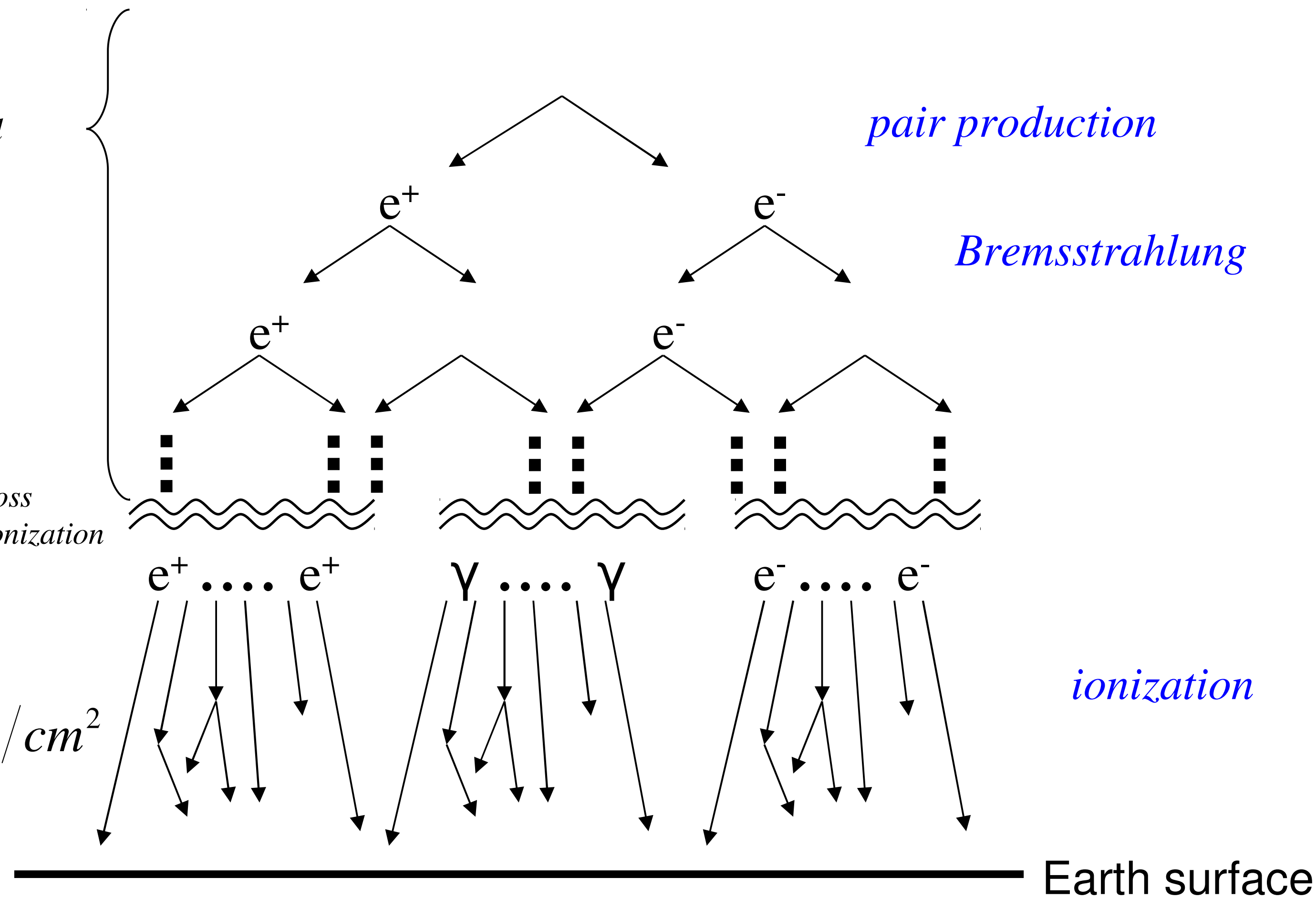
$$\overline{E}_{particle} > E_{critical}$$

$$X_0^{air} \approx 37\, g/cm^2$$

$$E_{critical} : E_{radiation}^{loss} = E_{ionization}^{loss}$$

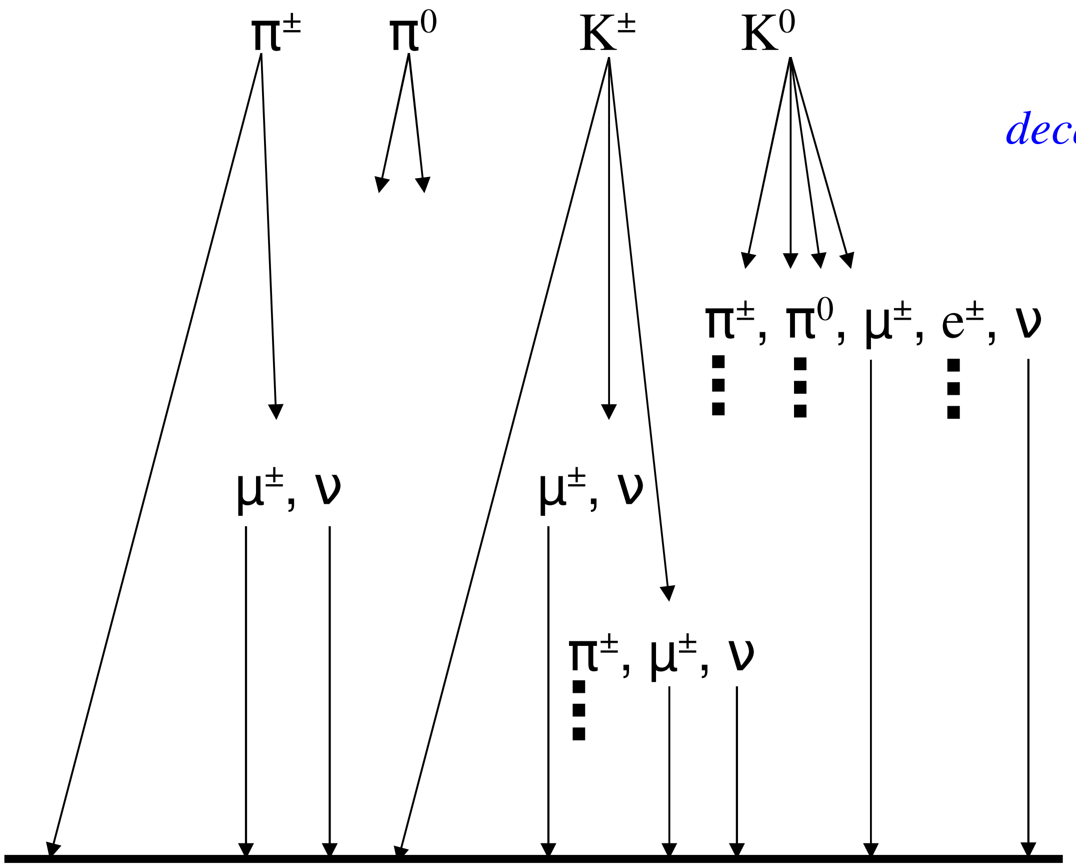
$$\Rightarrow E_{critical} \approx 81\, MeV$$

$$E_{ionization}^{loss} \approx 2.2\, MeV / g/cm^2$$



Hadronic Shower

- primary particle is nucleus
- for heavier nuclei - superposition of A proton showers



Earth surface

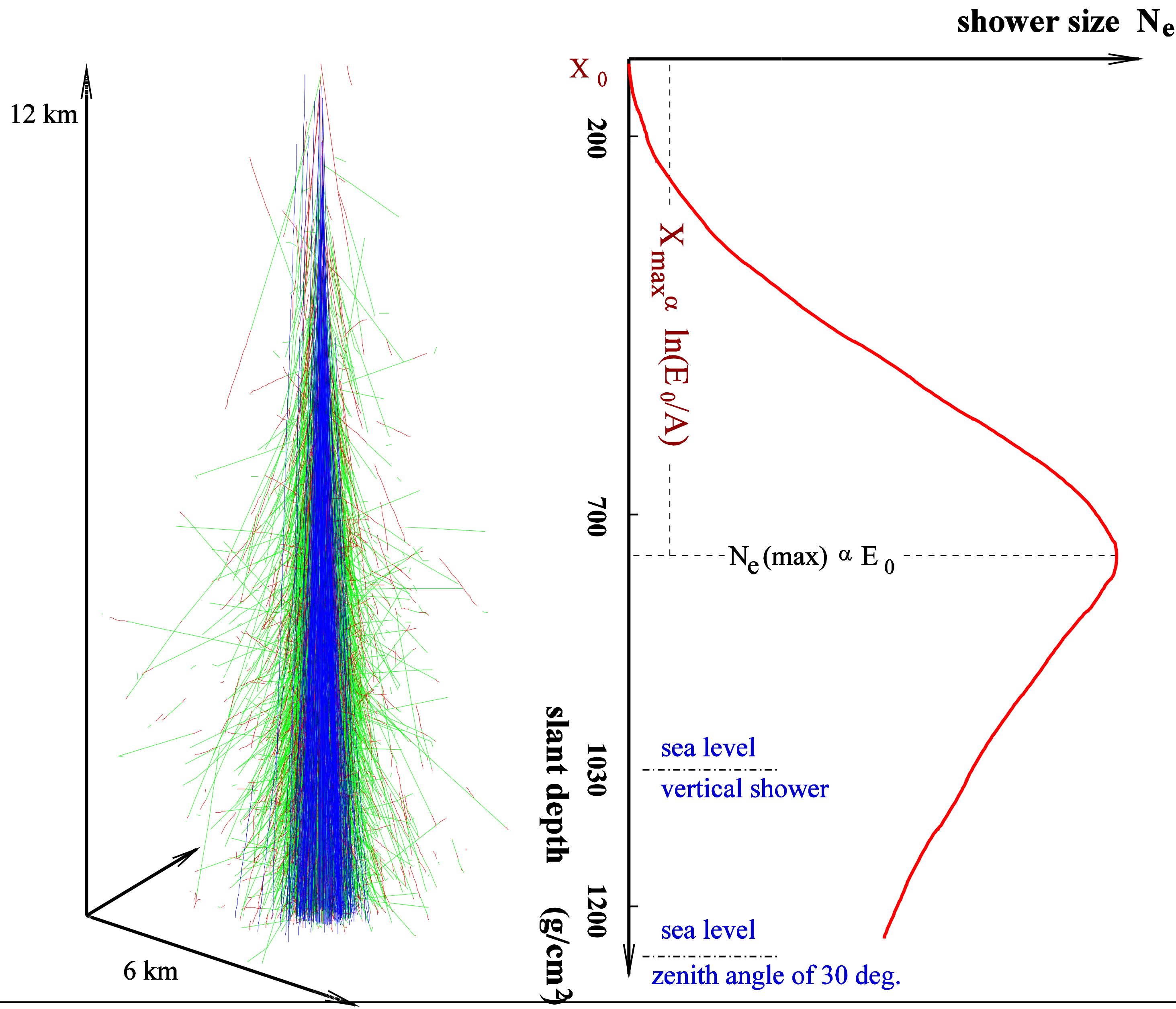
decay ↔ interaction

per generation:

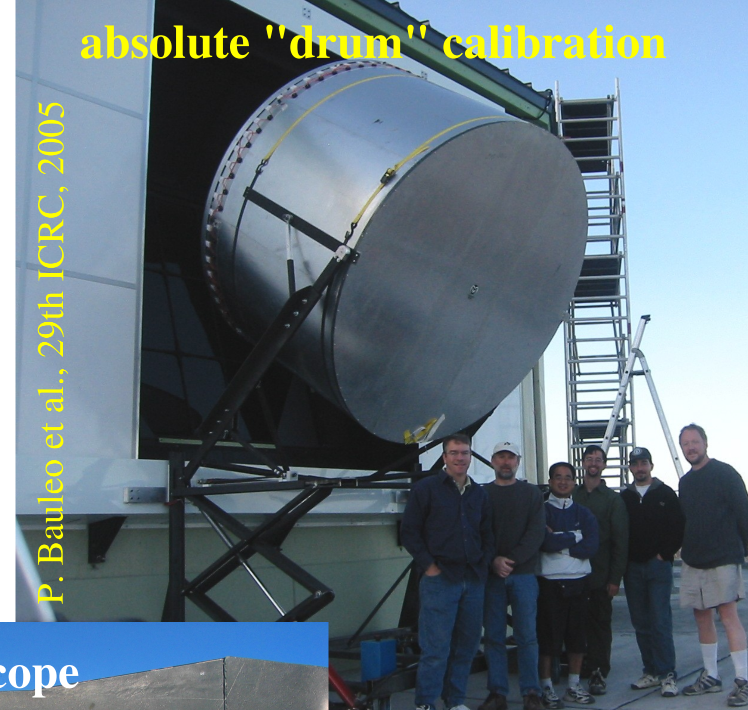
$\approx$ 1/3 of E in em. cascade

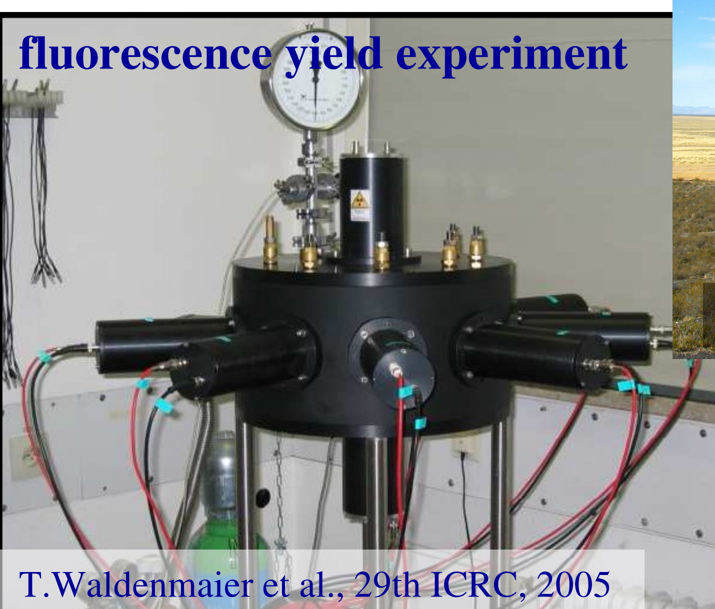
$<$ 10 % of E_0 in hadr. cascade

Shower Maximum

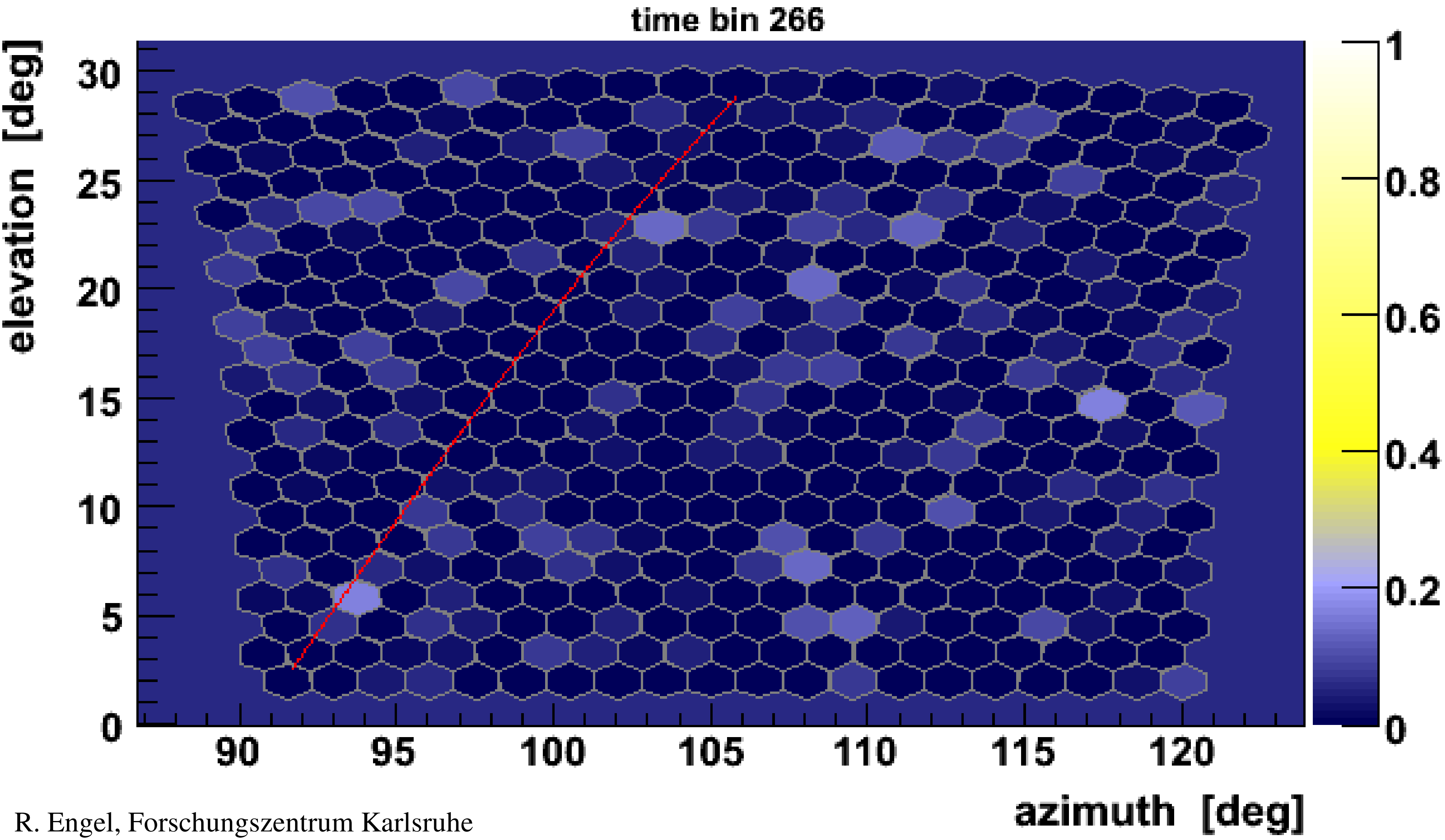


Efforts on reduction of uncertainties





Real EAS Event from Auger



R. Engel, Forschungszentrum Karlsruhe

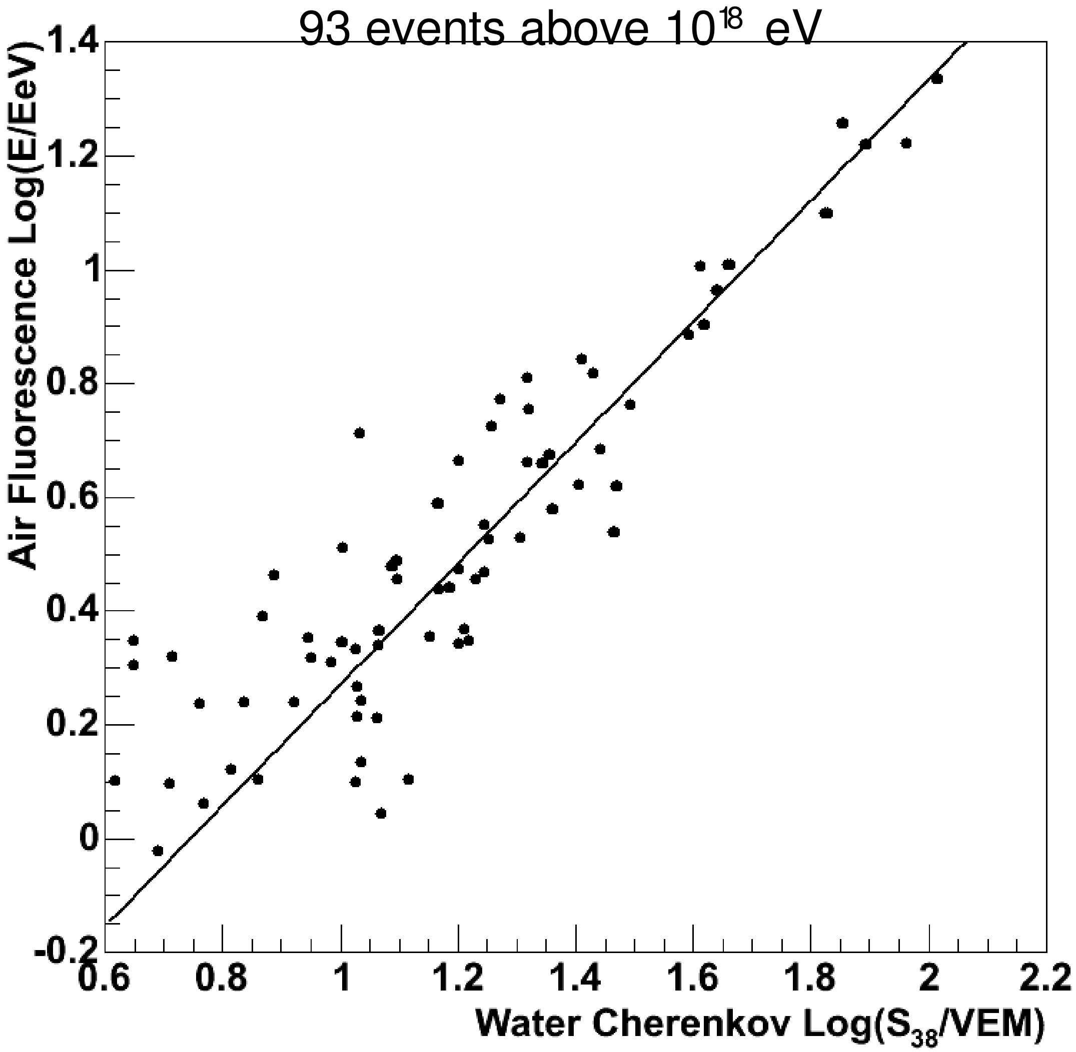
Energy determination from hybrid events

- take S_{38} value from SD vs. energy from FD
- fit line through data
  $\mathrm{Log}(E) = -0.79 + 1.06\ \mathrm{Log}(S_{38})$
- energy conversion factor

  $E = 0.16\ S_{38}^{1.06}$

  (E in EeV, S_{38} in VEM)

Uncertainty:
15% at 3 EeV
40% at 100 EeV



P. Sommers, Auger Collab. 29th ICRC, 2005

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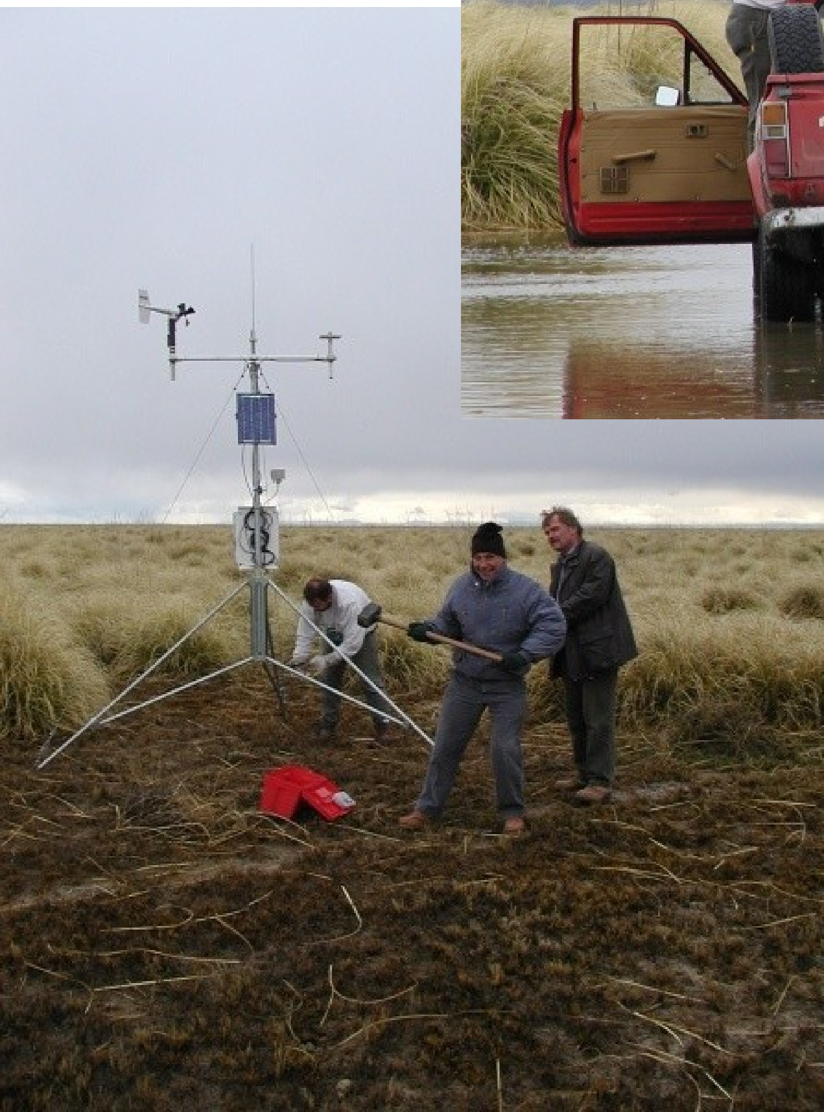
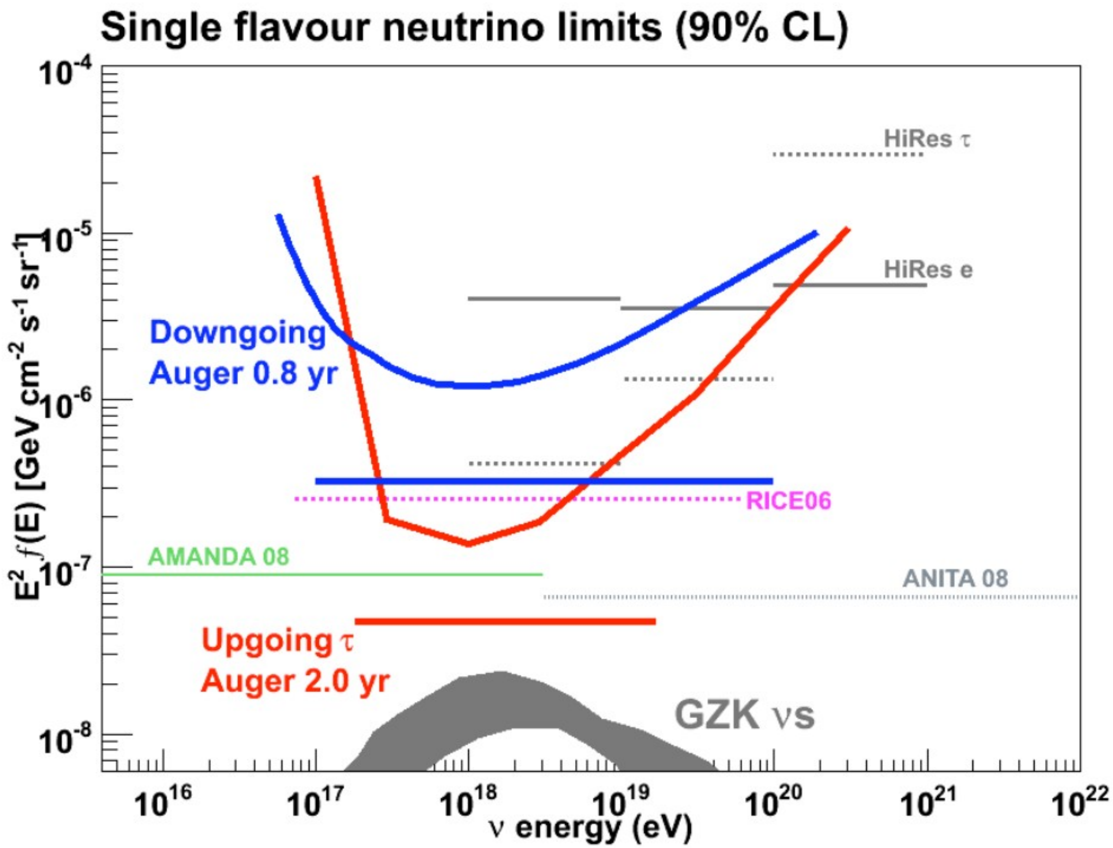
That‘s also working for Auger



Neutrino limit



- Data from SD
- Earth-skimming (upgoing) τ neutrino
- No neutrino discovery, but approaching GZK neutrino limits

ICRC09, arXiv: 0906.2319

Combined energy spectrum

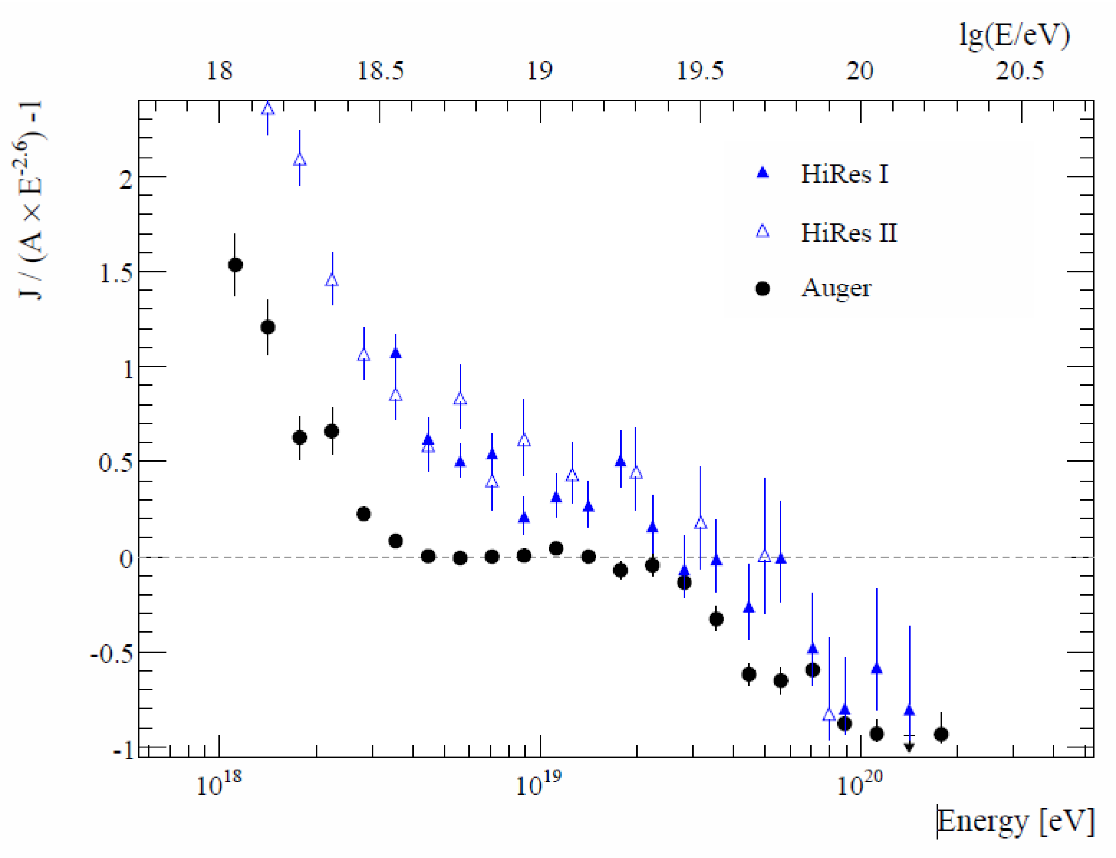


Fig. 4. The fractional difference between the combined energy spectrum of the Pierre Auger Observatory and a spectrum with an index of 2.6. Data from the HiRes instrument [3], [21] are shown for comparison.