XII International Conference on Calorimetry in High Energy Physics
Chicago, June 5 - 9, 2006

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

Bianca Keilhauer
for the Pierre Auger Collaboration

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Universität Karlsruhe (TH)
Forschungsuniversität · gegründet 1825

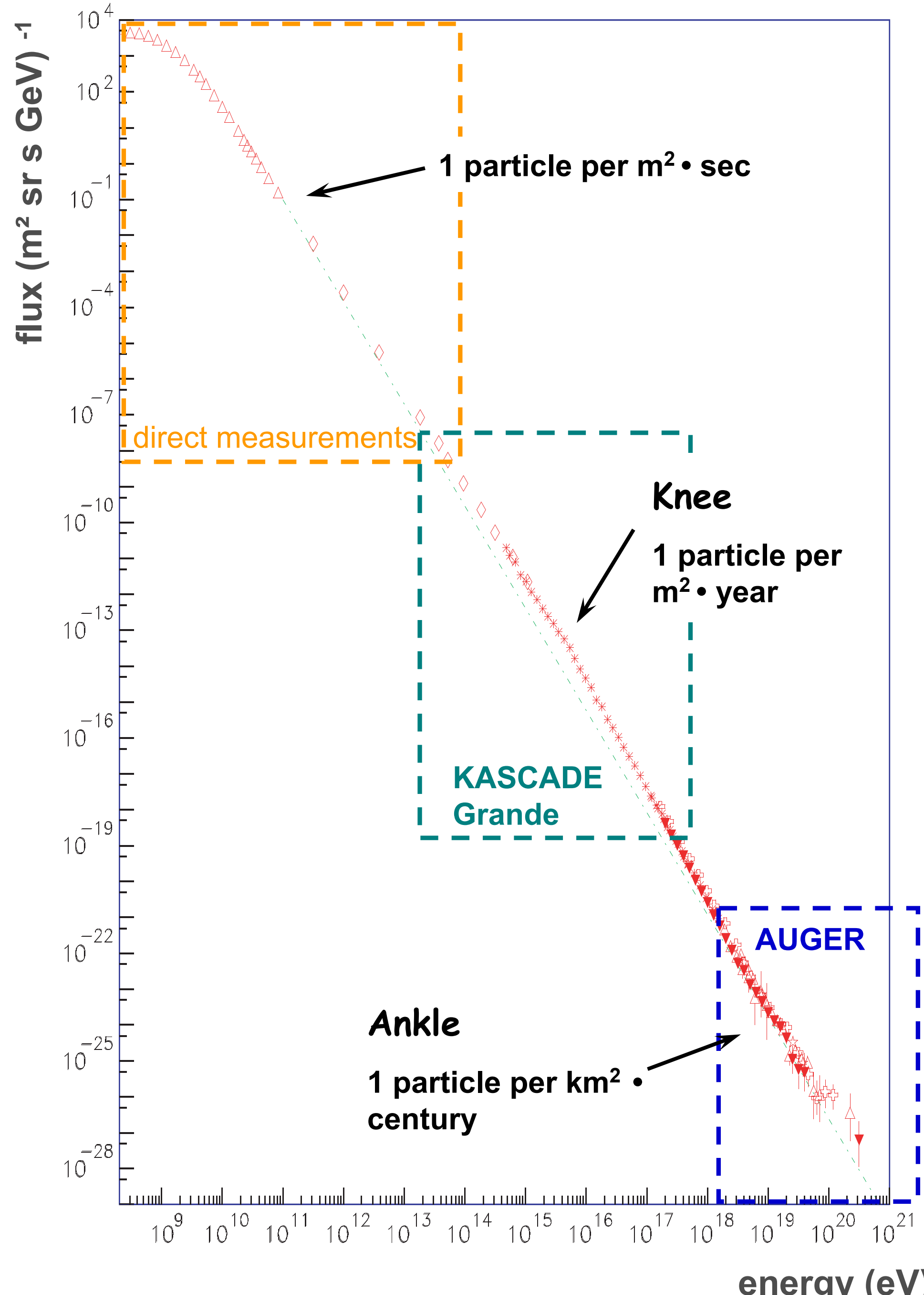
Deutsche
Forschungsgemeinschaft
DFG

Cosmic Ray (CR) Spectrum

- power law over more than 10 orders of magnitude in energy

$$\frac{dN}{dE} \propto E^{-\gamma}$$

- below **knee**:
  - particles from the Sun and supernova remnants
  - mainly protons and α-particles
- at **knee**:
  - γ changes from 2.65 to 3.1
  - transition to heavier composition
- at **ankle** and above:
  - CR of extra-galactic origin
  - again change of γ
  - sources, particle types, GZK-cut off ???

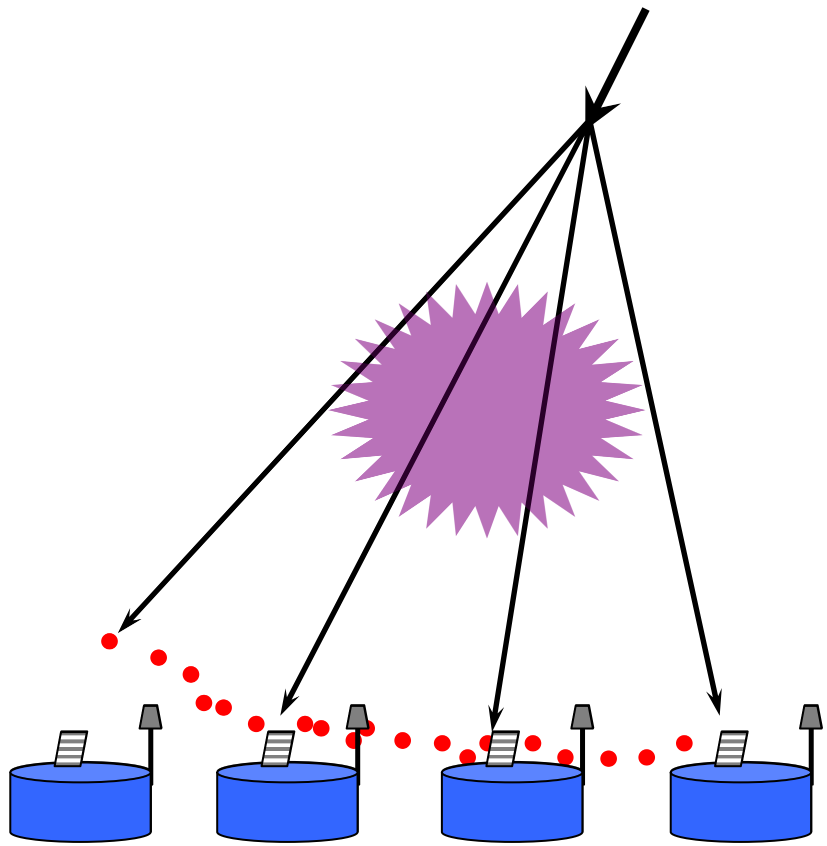


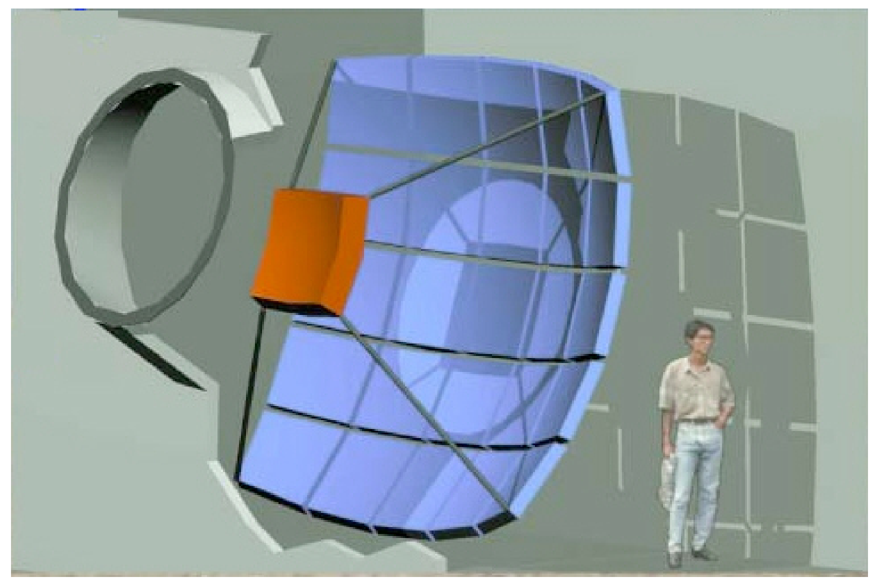
Scientific goals of the Pierre Auger Observatory

- detection of Extensive Air Showers induced by UHECRs
  - $E_0 > 5 \cdot 10^{18}$ eV
  - high statistics
  - good understanding of systematics
- disentangle energy, incoming direction, type of primary particle
- full sky coverage
- anisotropy
- neutrino detection
- limit on photon flux
- provide hybrid detection technique

Hybrid Detection Technique

- longitudinal shower profiles by fluorescence light in atmosphere
- lateral particle distribution at ground





Why Hybrid Detection Technique ?

Surface Detectors

- ⇧ 100 % duty cycle
- ⇧ acceptance = geometric
- ⇩ only last stage of shower development observed
- ⇩ energy scale model dependent

Fluorescence Detectors

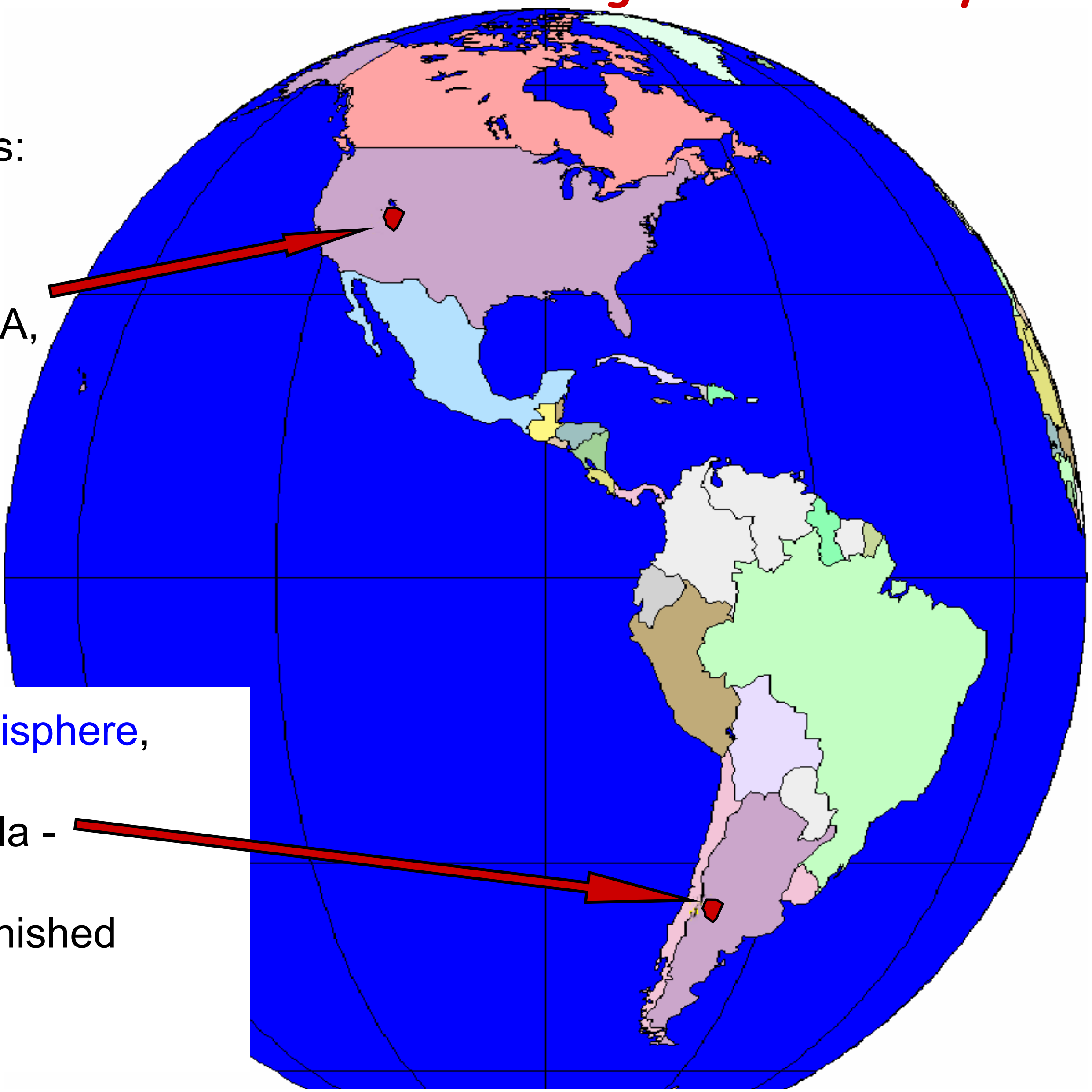
- ⇩ ≈ 15 % duty cycle
- ⇩ acceptance depends on distance and atmosphere
- ⇧ observation of longitudinal shower development
- ⇧ (almost) model independent

Location of the Pierre Auger Observatory

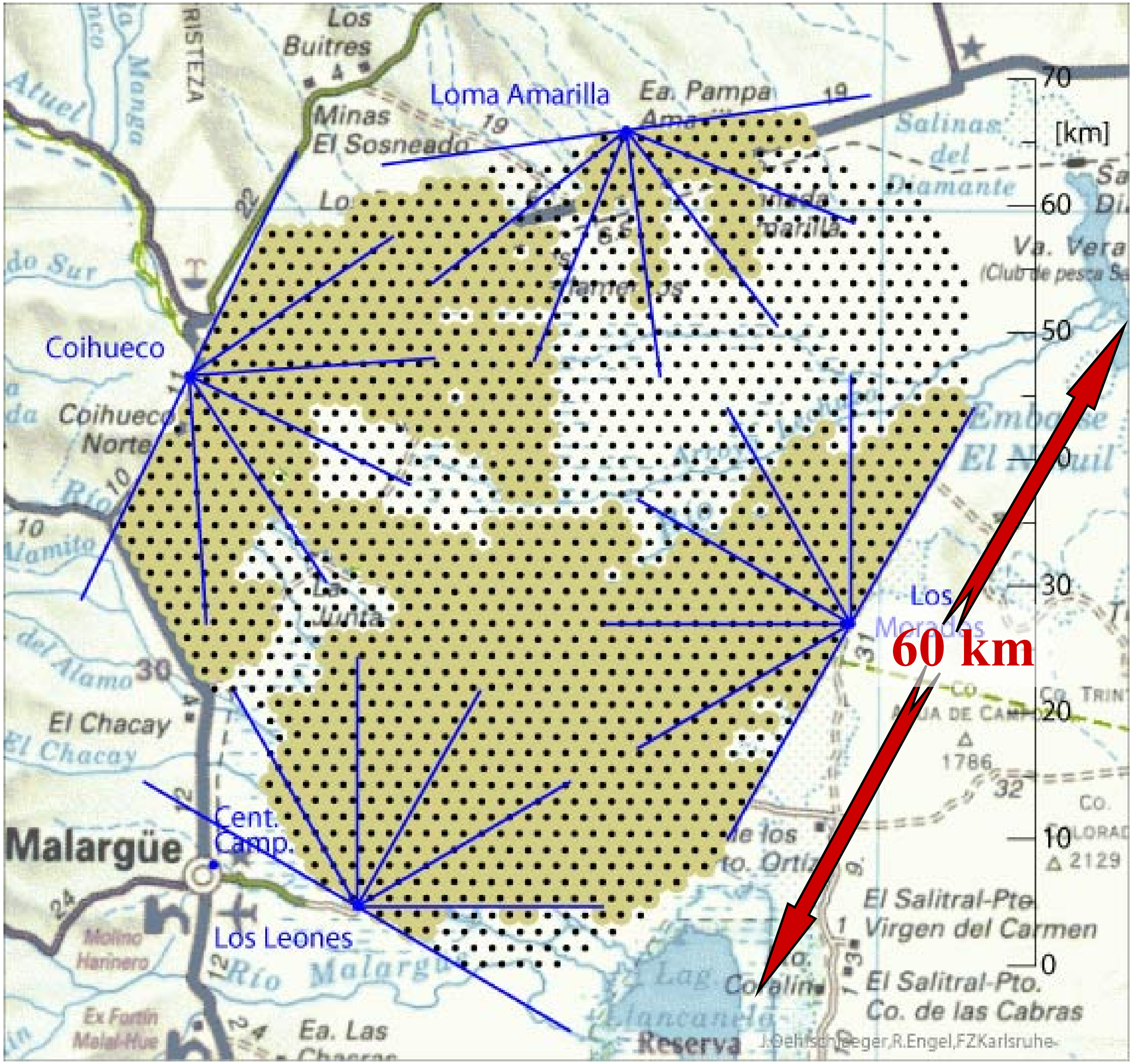
2 detection sites:

- Northern hemisphere, Colorado - USA, construction begin in 2009

- Southern hemisphere, Malargüe - Pampa Amarilla - Argentina, construction finished mid 2007



Layout of Southern Observatory

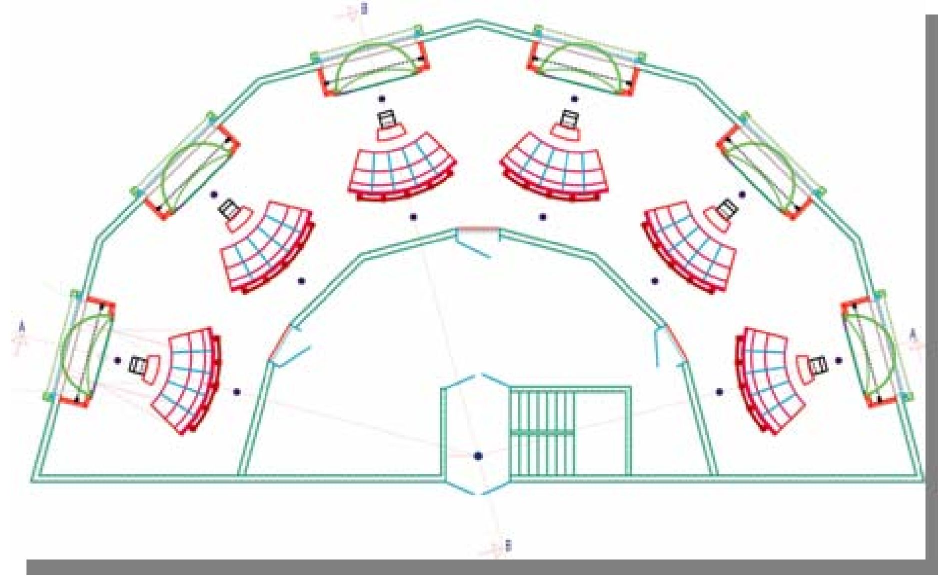


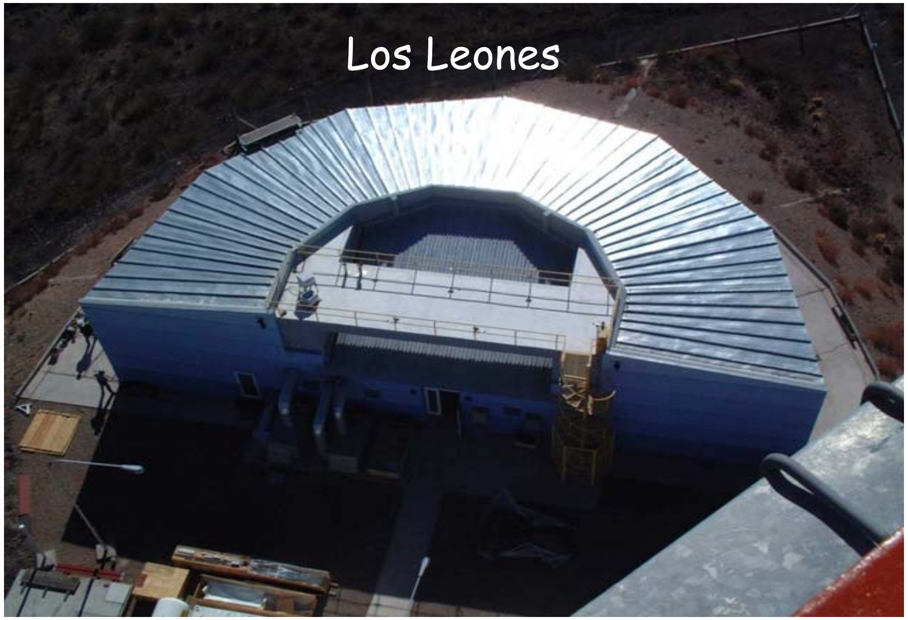
Auger Fluorescence Detectors

- 6 telescopes in a station

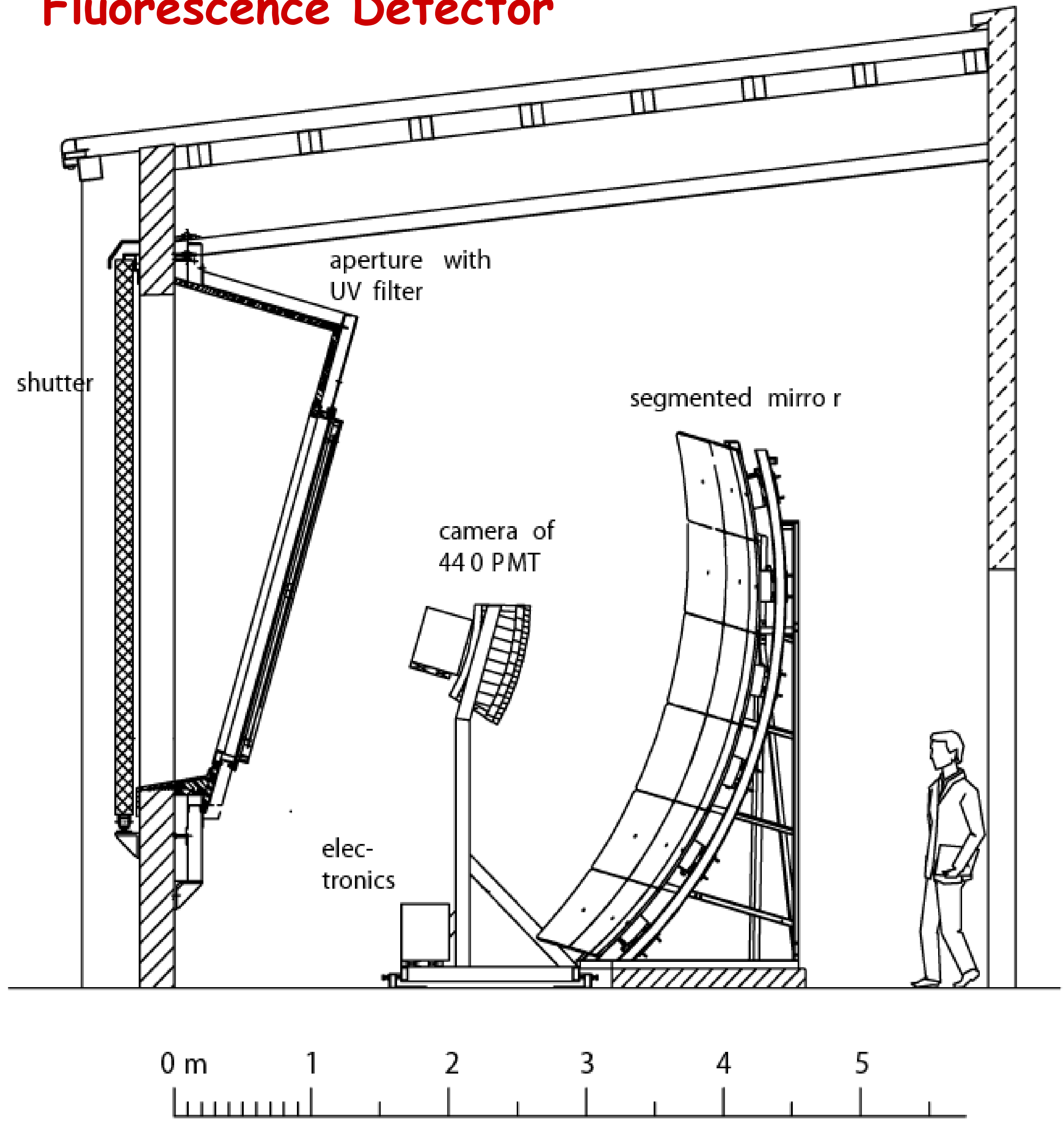
  6 x (30° x 28.6° field of view)

- 4 stations at the boundary of the array
- 3 stations ready, 4th under construction

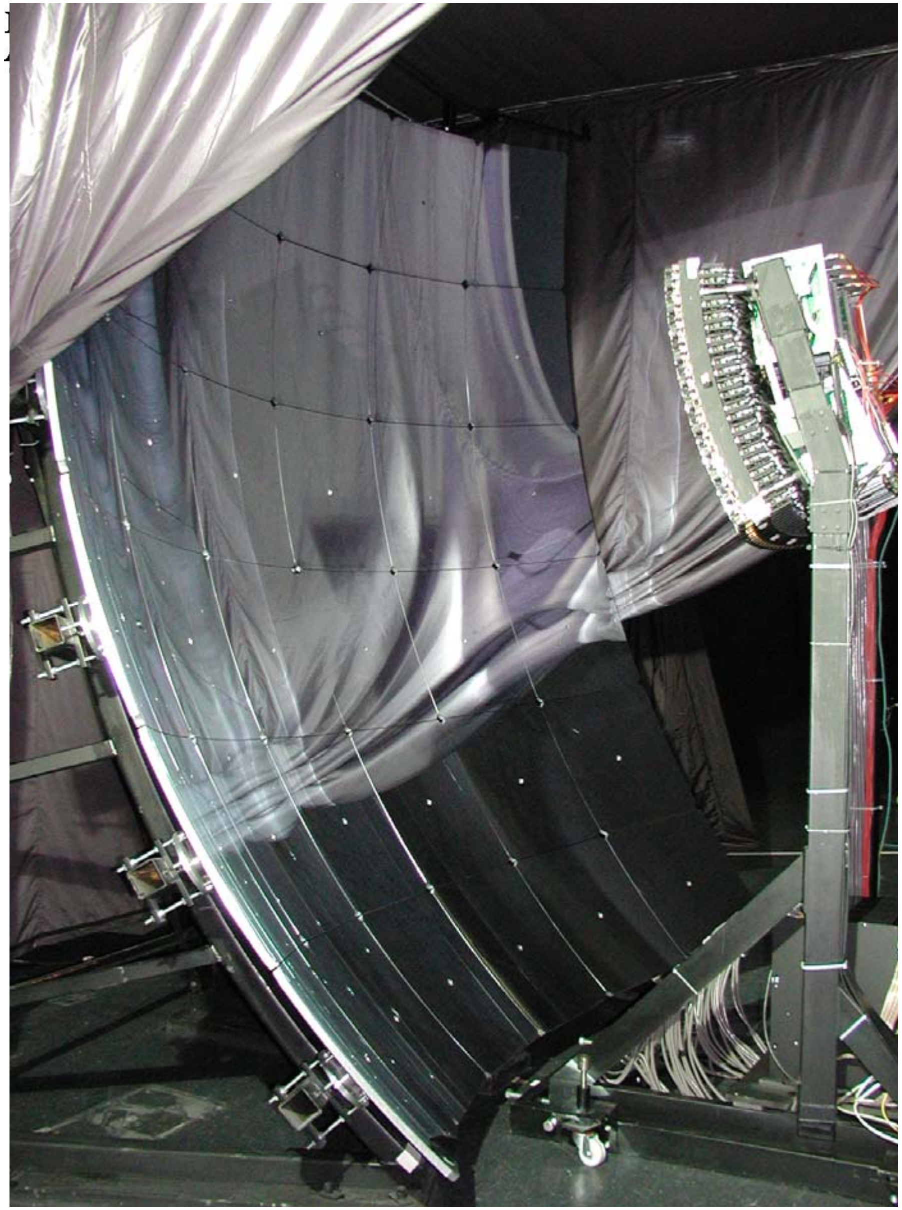


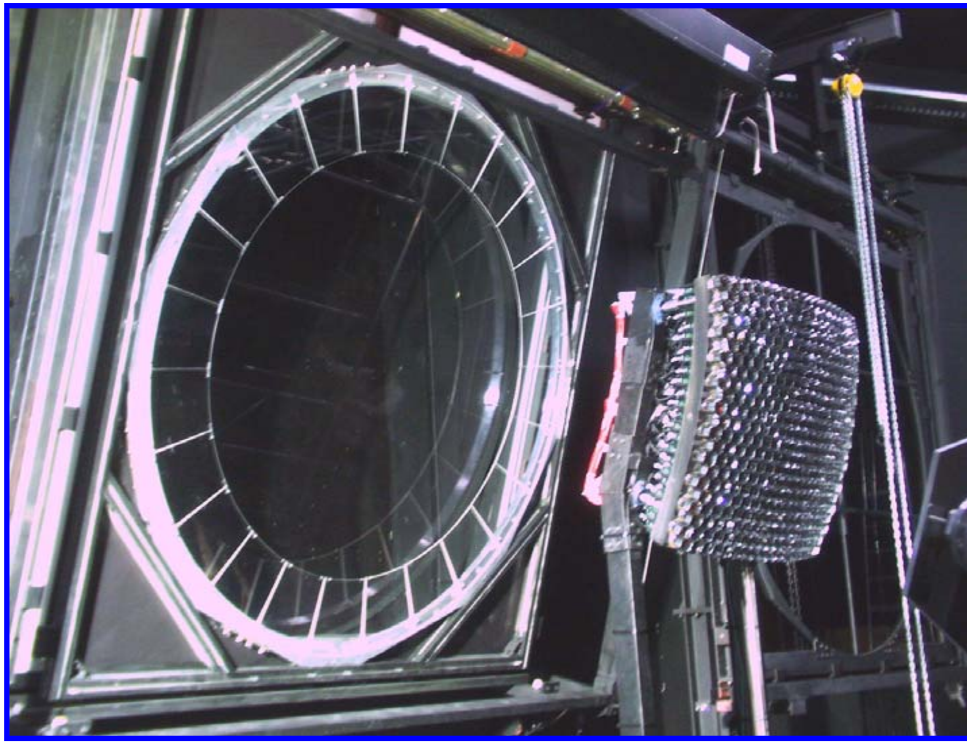


Fluorescence Detector



Fluorescence Detector





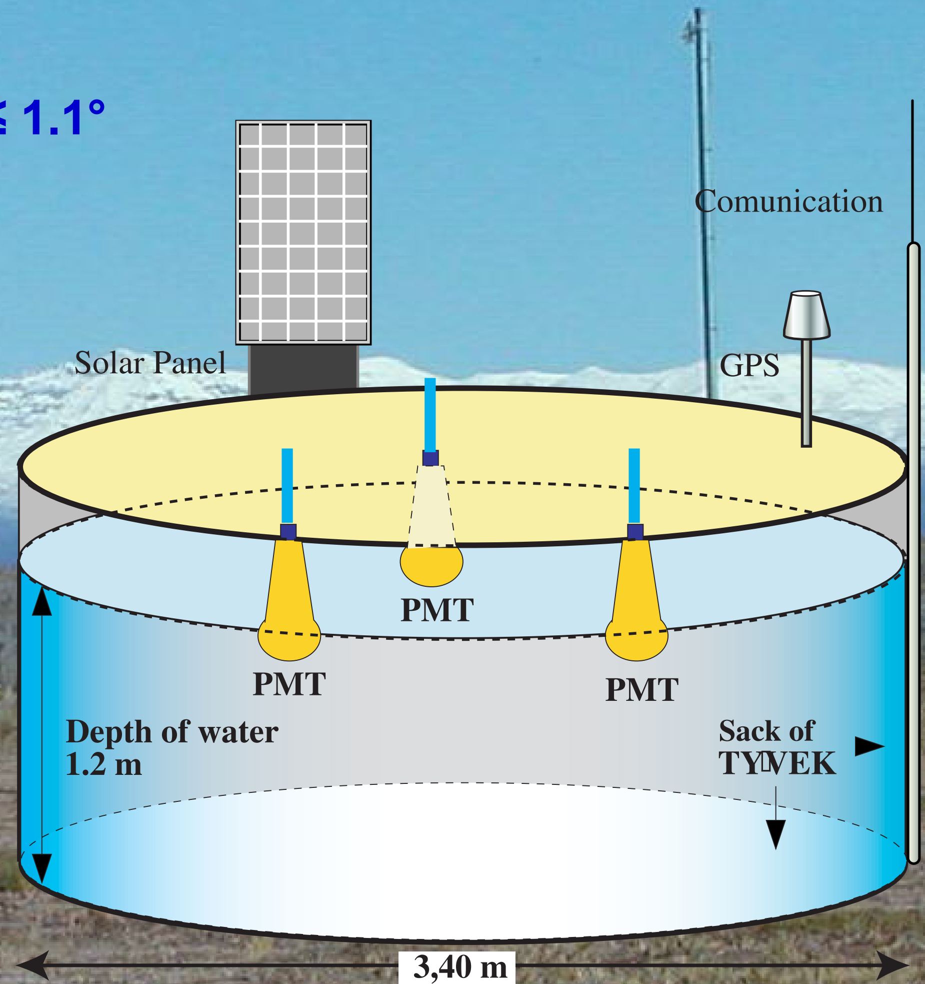
- 440 PMT per camera,
  each 1.5° → resolution better 1°
- 15% duty cycle
- 100 ns sampling intervals
- energy resolution ≤ 10%

Water Cherenkov Tanks

- ≈ 1100 of 1600 tanks deployed
- distance 1.5 km to each other
- 12 m³ ultrapure water

Water Cherenkov Tanks

- duty cycle: 100%
- angular resolution ≲ 1.1°
- energy resolution ≈ order (10%)



PMT signals:

- shape and
- time information
- 25 ns intervals

Electromagnetic Shower

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

Heitler model:

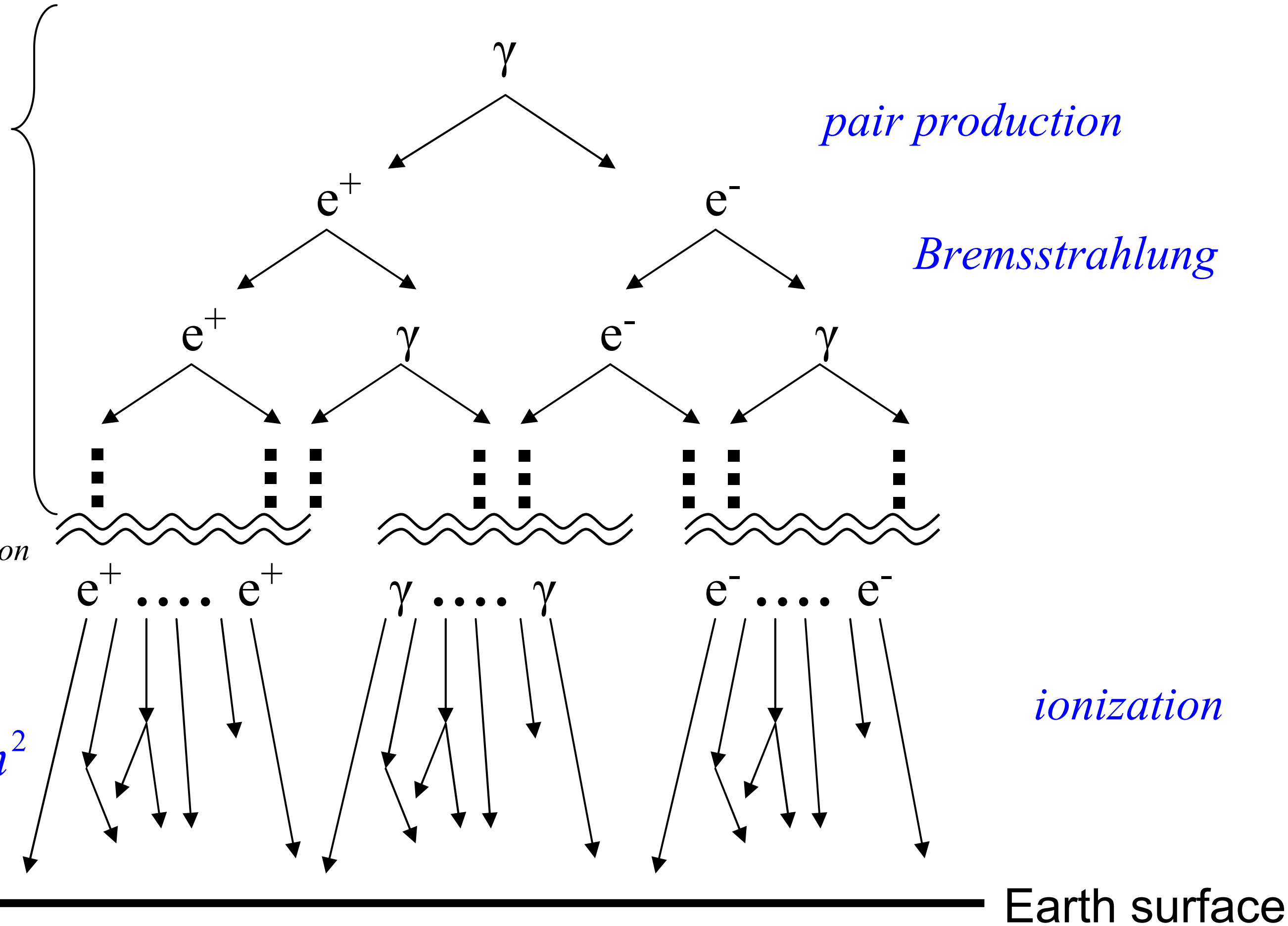
$$\overline{E}_{particle} > E_{critical}$$

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

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

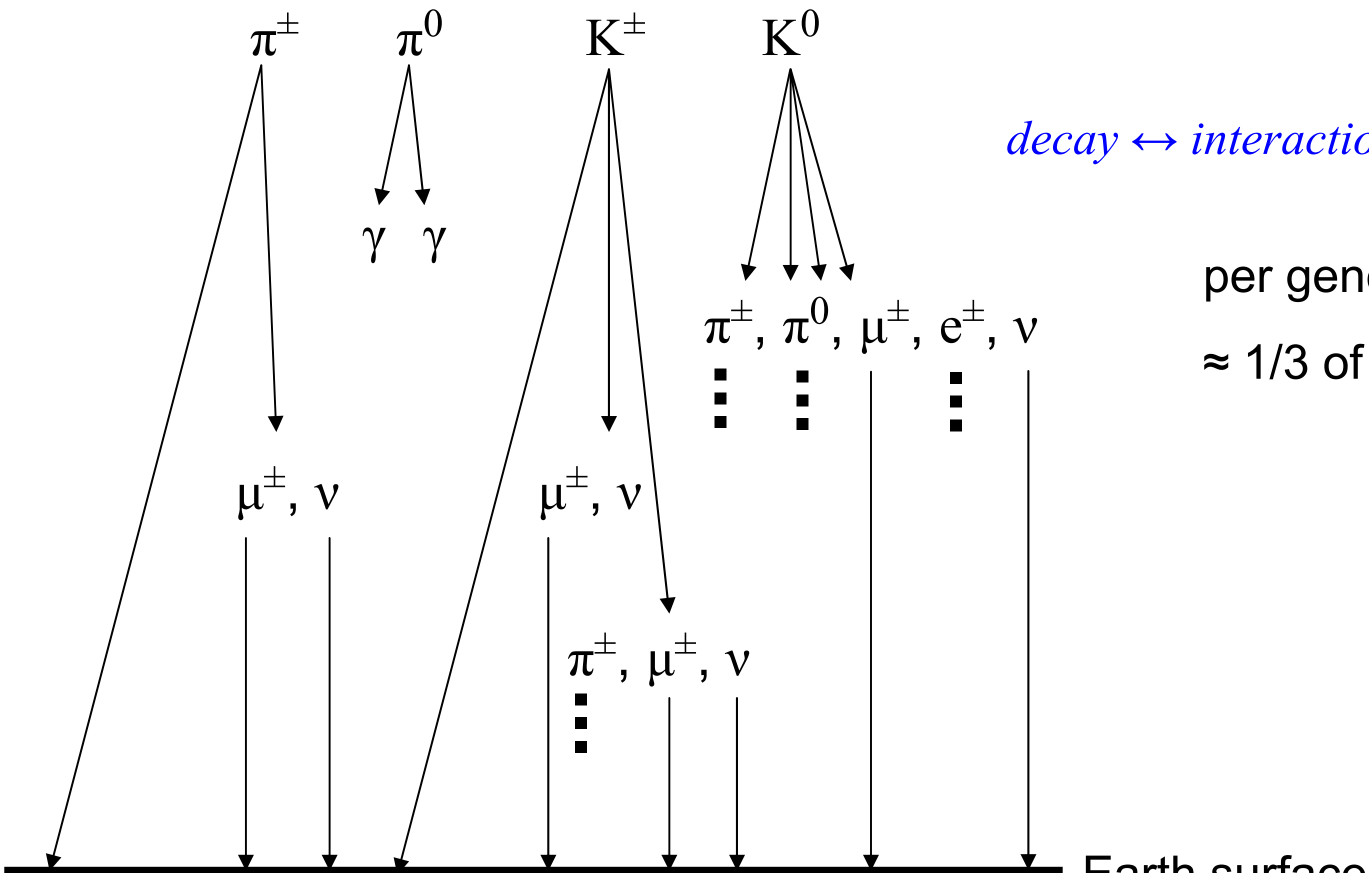
$$\Rightarrow E_{critical} \approx 81\, MeV$$

$$E^{loss}_{ionization} \approx 2.2\, MeV \big/ g/cm^2$$



Hadronic Shower

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



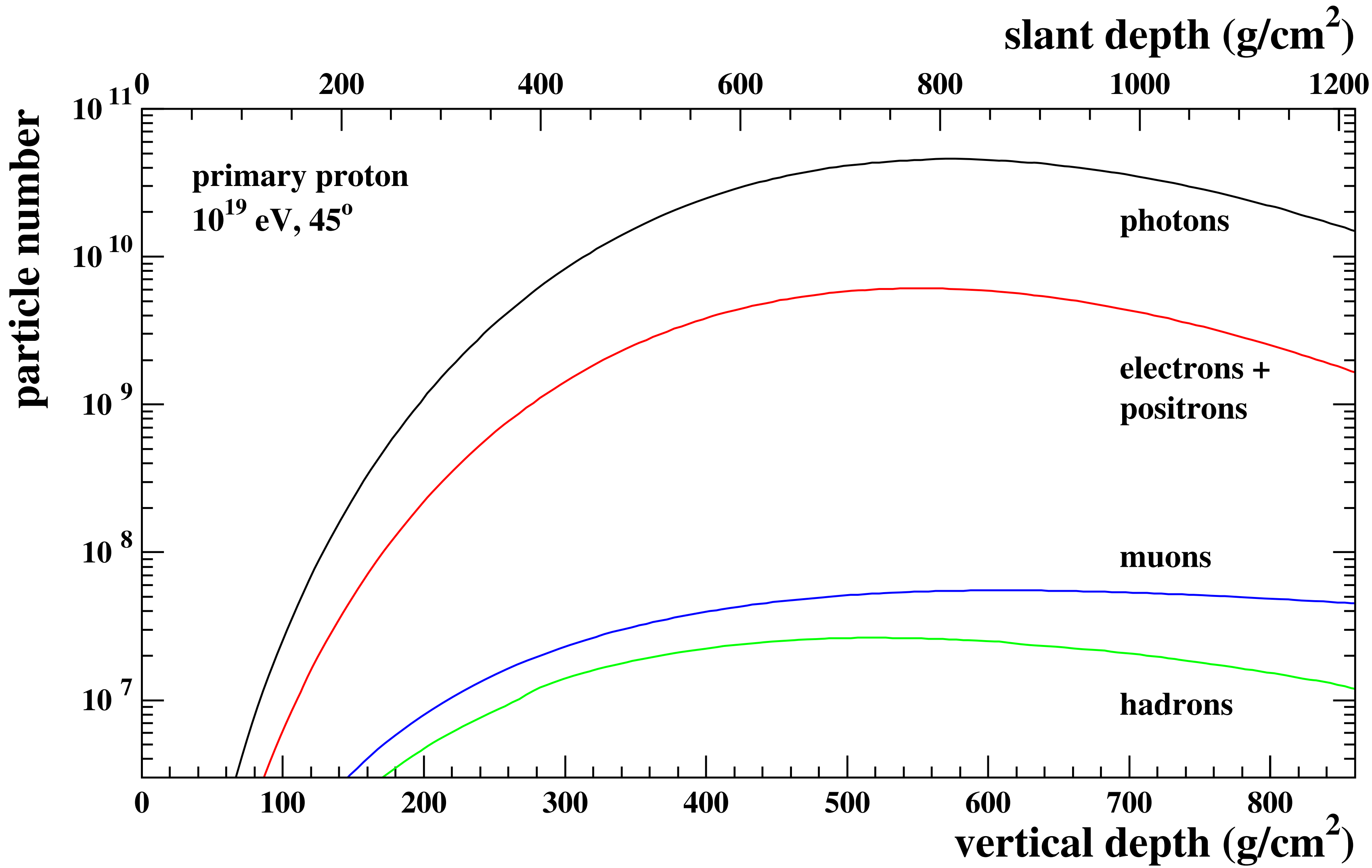
decay ↔ interaction

per generation:

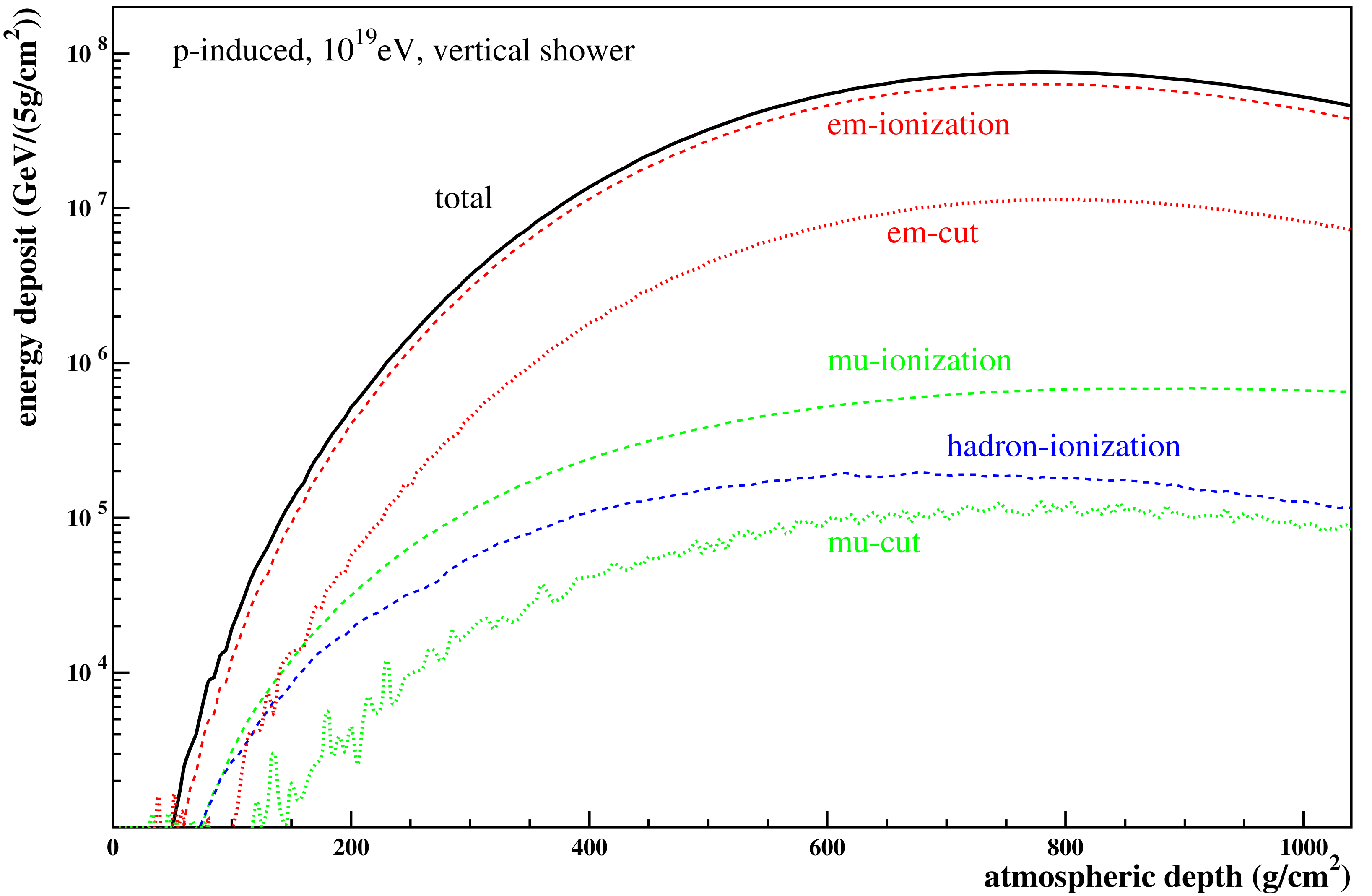
≈ 1/3 of E in em. cascade

< 10 % of E_0 in hadr. cascade

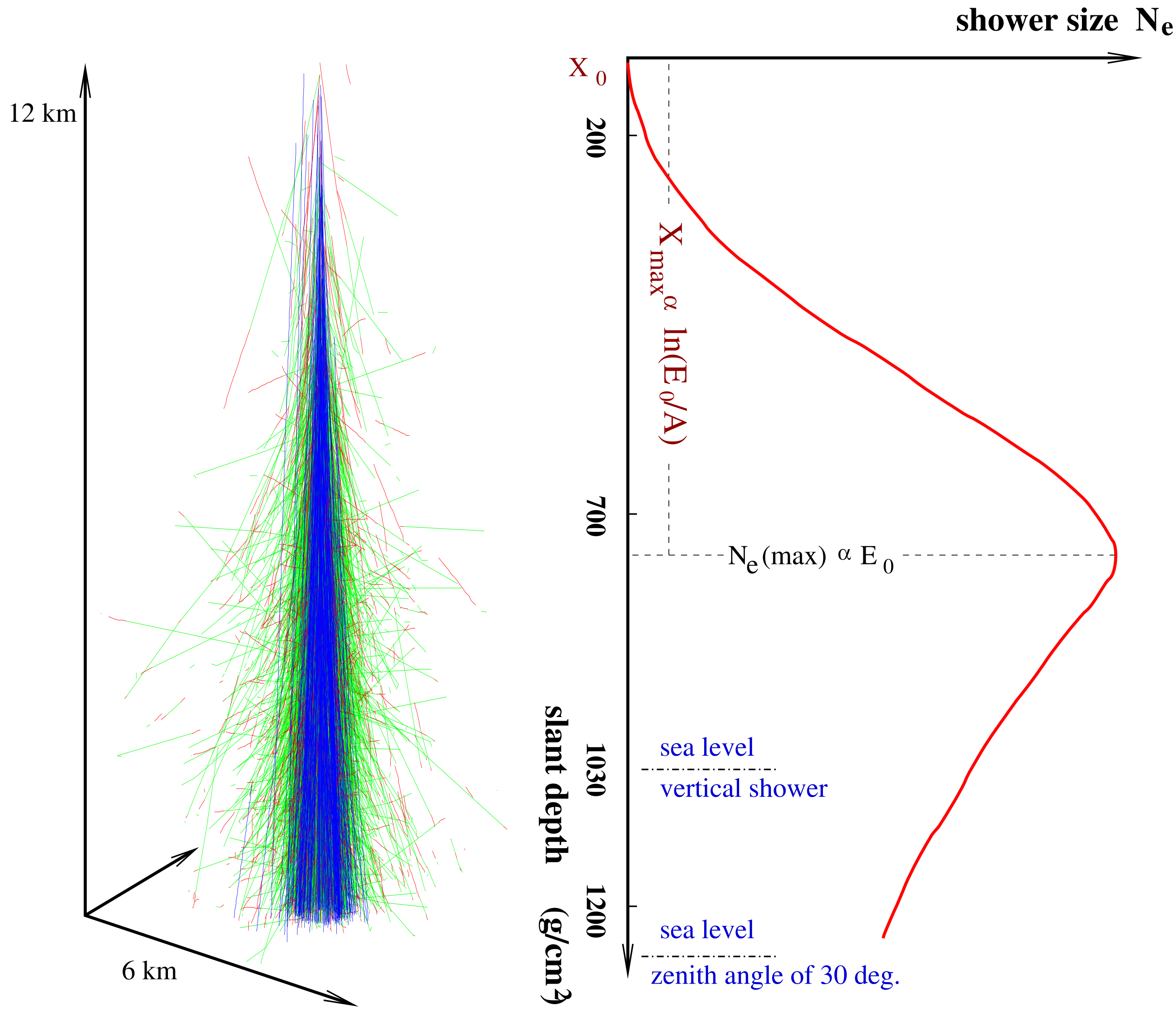
Particle Numbers in EAS



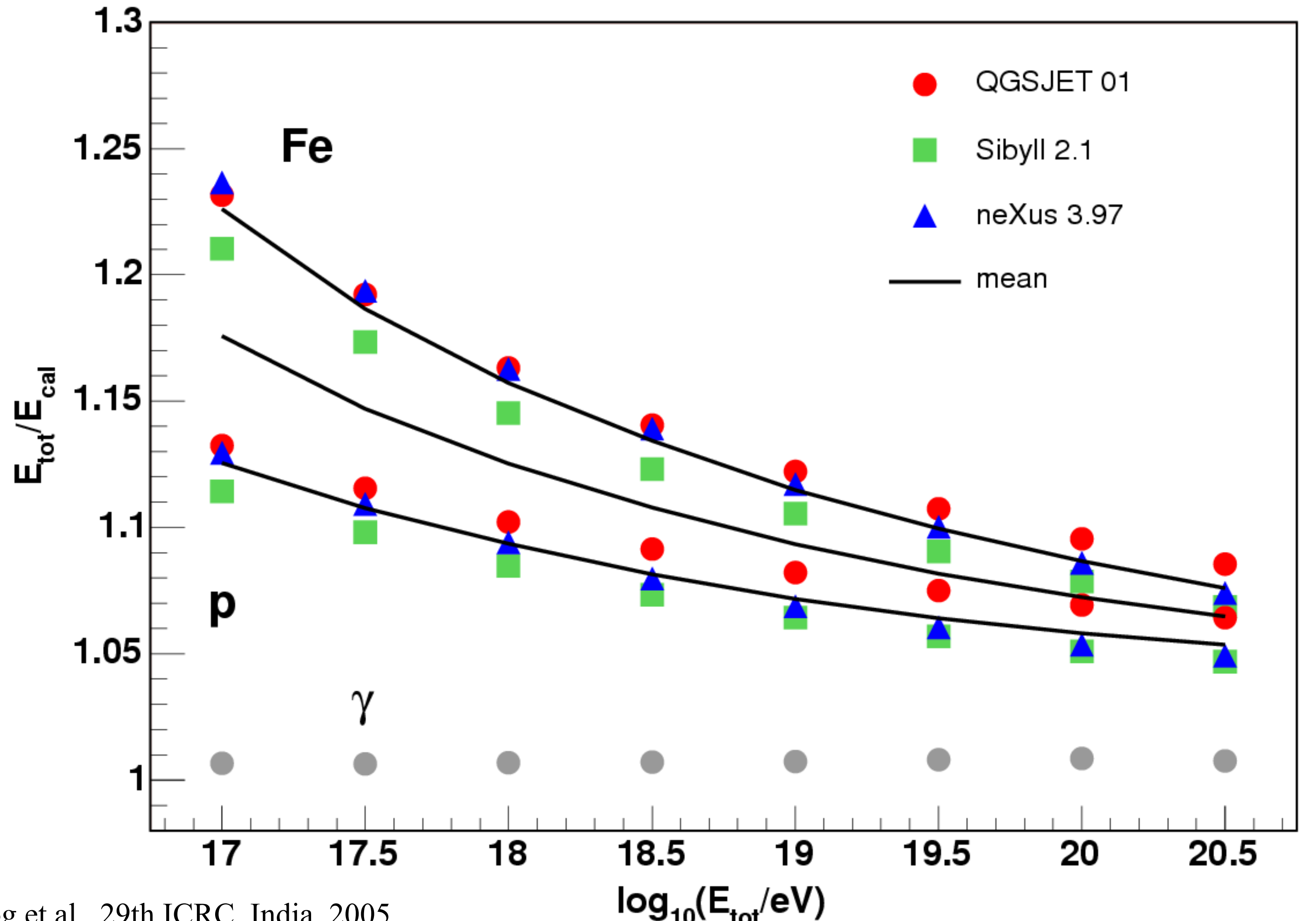
Energy Deposit of EAS in the Atmosphere



Shower Maximum

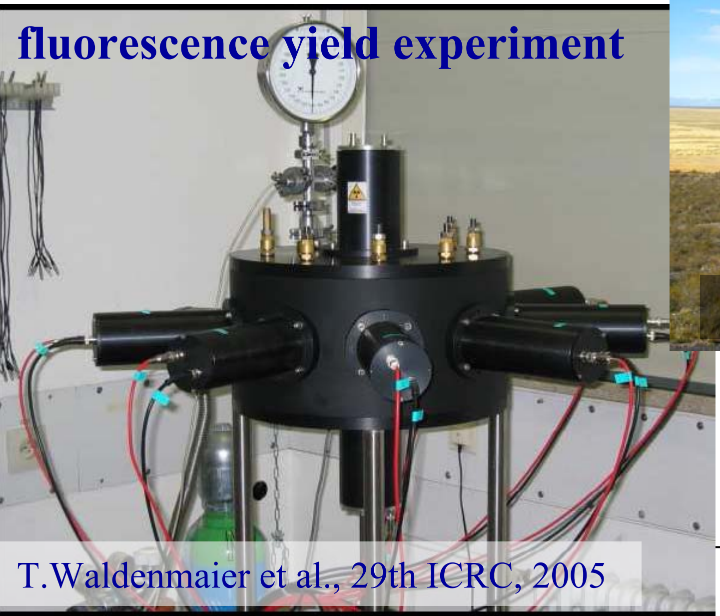


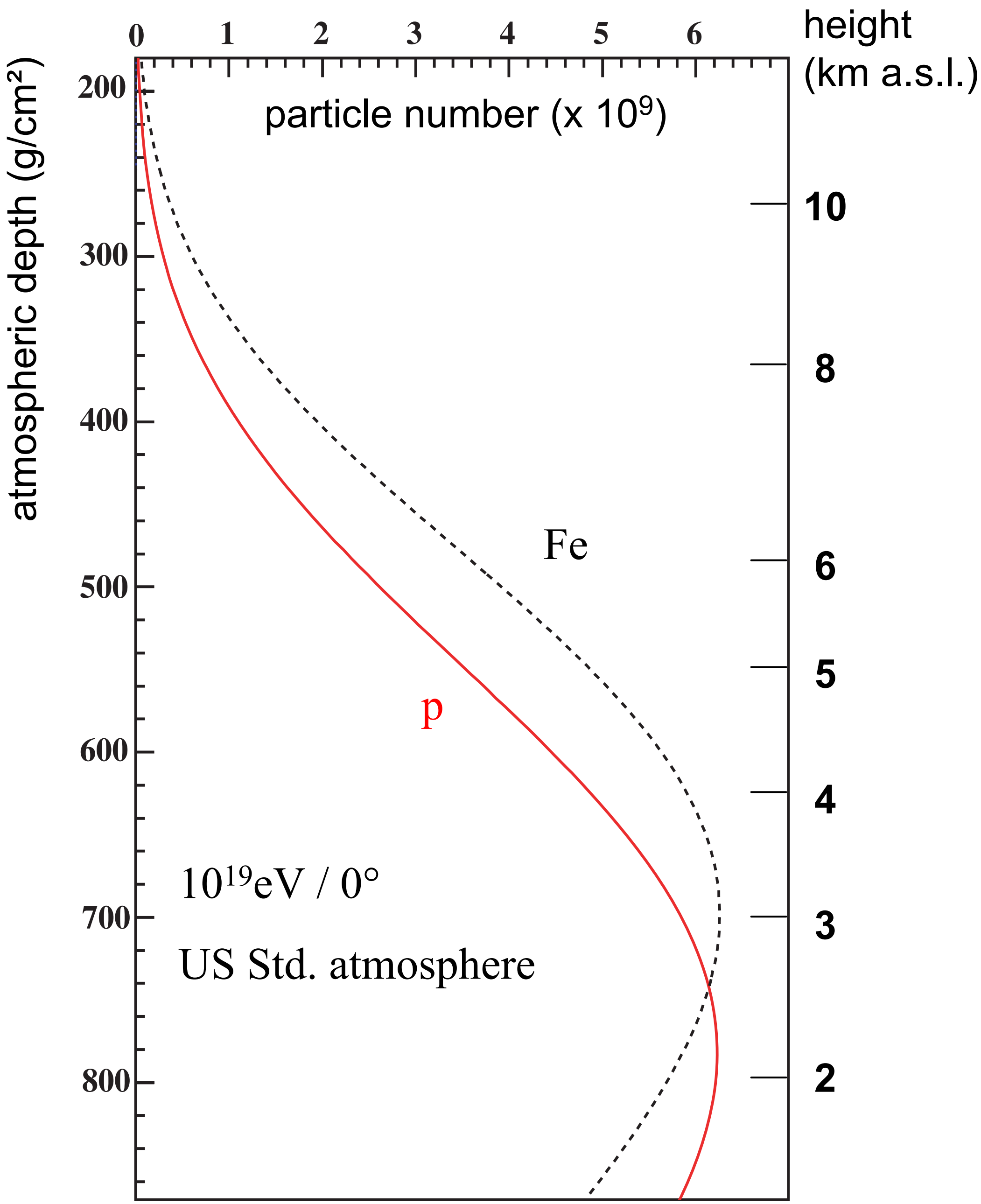
Correction Factor for „Missing Energy“



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

Efforts on reduction of uncertainties





Geometrical Effect

atmospheric depth:

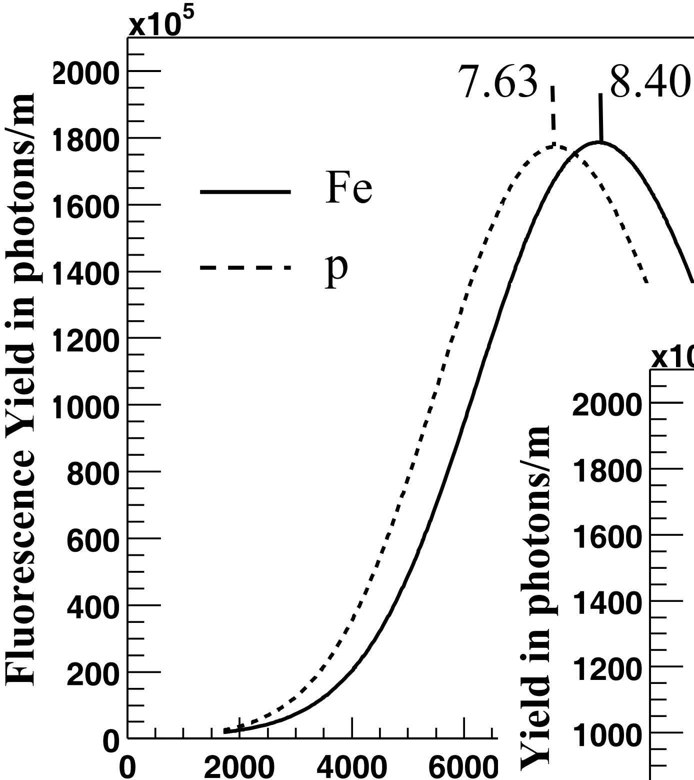
$$X = \int_h^\infty \rho(z)\,dz$$

air density:

$$\rho(z) = \frac{p(z) \cdot M_m}{R \cdot T(z)}$$

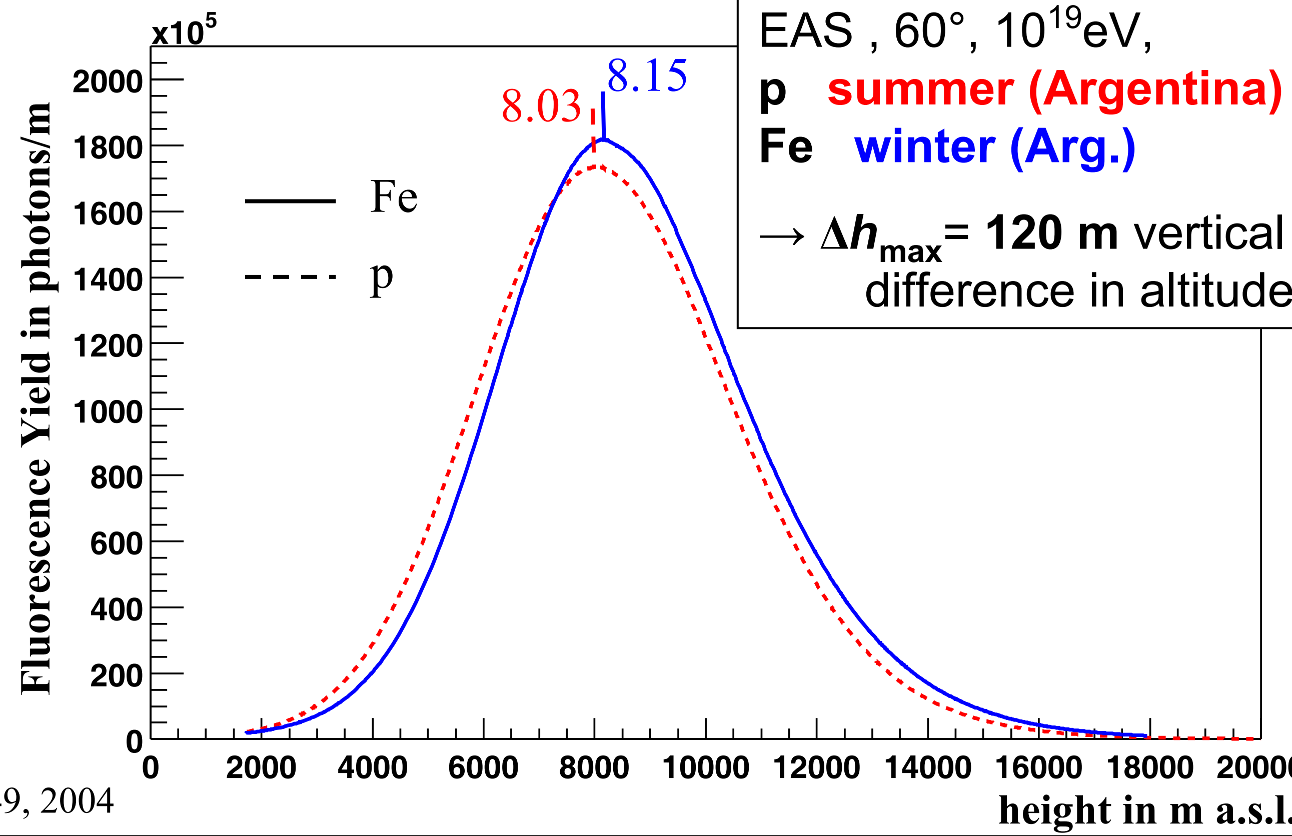
⇒ altitude and time dependent

Position of Shower Maximum



both EAS in **US-Std**, 60°, 10^{19}eV:

→ Δh_{max}= **770 m** vertical difference in altitude



EAS , 60°, 10^{19}eV,
p summer (Argentina)
Fe winter (Arg.)

→ Δh_{max}= **120 m** vertical difference in altitude

B. K. et al., Astropart.Phys.22, 249, 2004

Fluorescence Light

- mainly $e^{\pm}$ of EAS excites N_2 molecules in air
- 18 strong emission bands in 2P system between 300 and 400 nm
- 1 strong emission band in 1N system between 300 and 400 nm

⇒ **Fluorescence Yield**

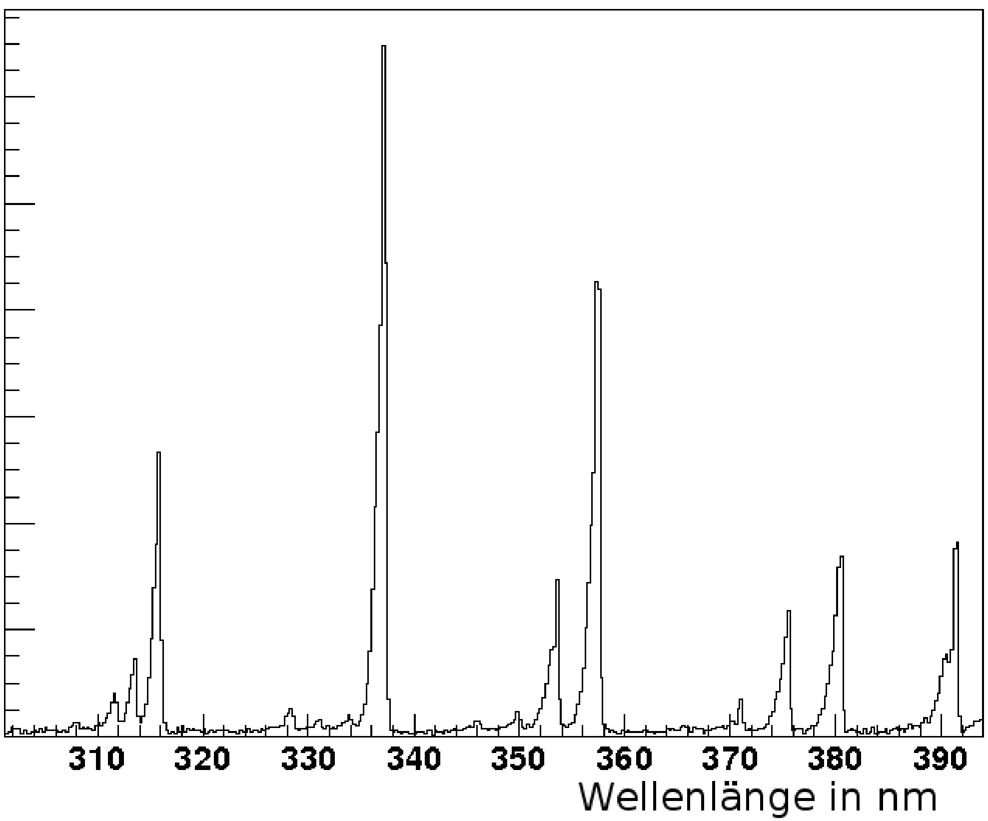
$$FY_\lambda = \varepsilon_\lambda(p,T) \cdot \frac{\lambda}{hc} \cdot \frac{dE}{dX} \cdot \rho_{\mathrm{air}} \quad \left[\frac{\mathrm{photons}}{\mathrm{m}}\right]$$

with assumption $FY_\lambda \propto {dE}/{dX}$

Fluorescence Light

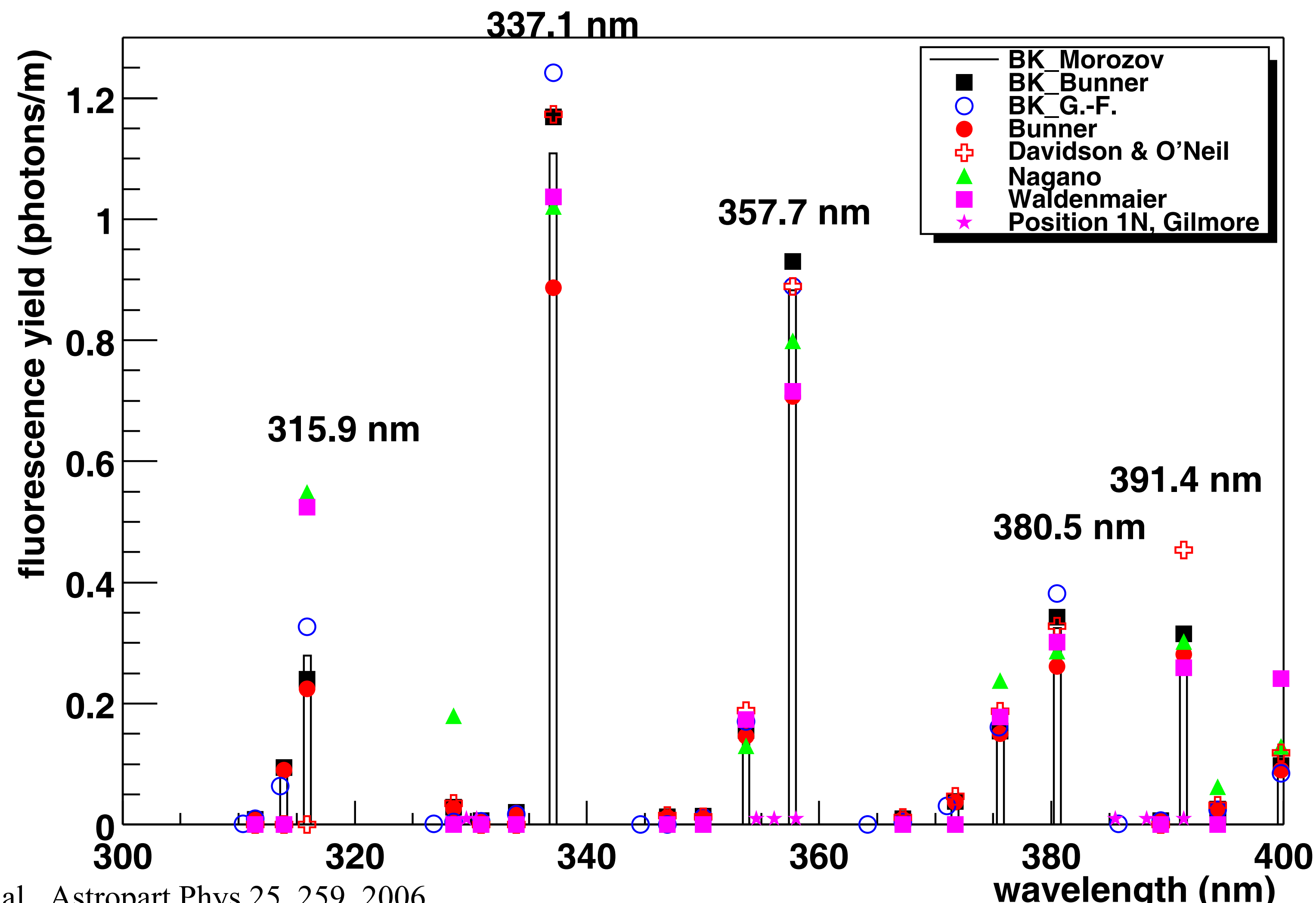
- mainly $e^{\pm}$ of EAS excites N_2 molecules in air
- 18 strong emission bands in 2P system between 300 and 400 nm
- 1 strong emission band in 1N system between 300 and 400 nm

⇒ **Fluorescence Yield**



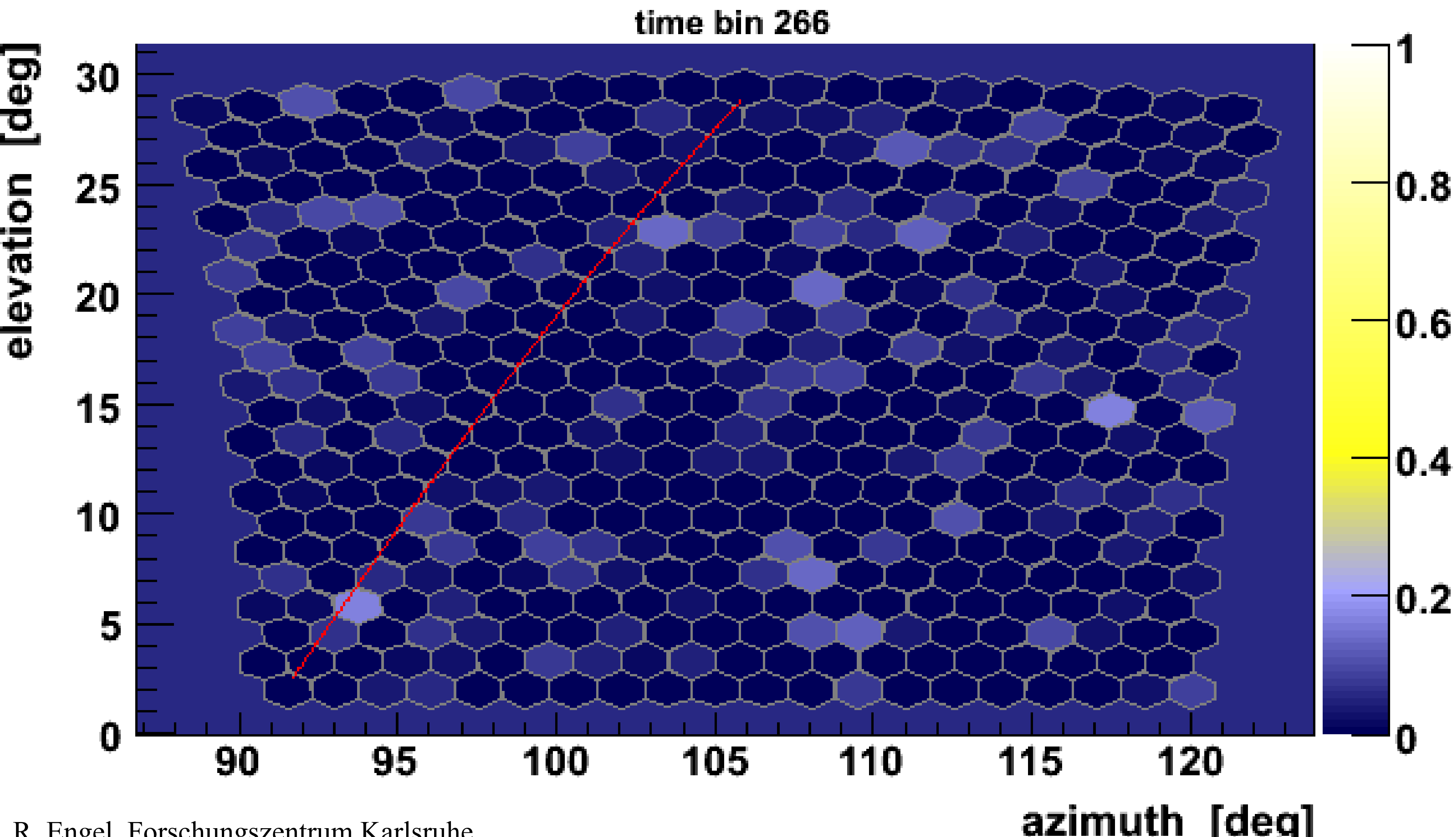
Fluorescence Yield at sea level

for a 0.85 MeV electron in US Std. Atmosphere



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

Real EAS Event from Auger



R. Engel, Forschungszentrum Karlsruhe

Energy determination from hybrid events

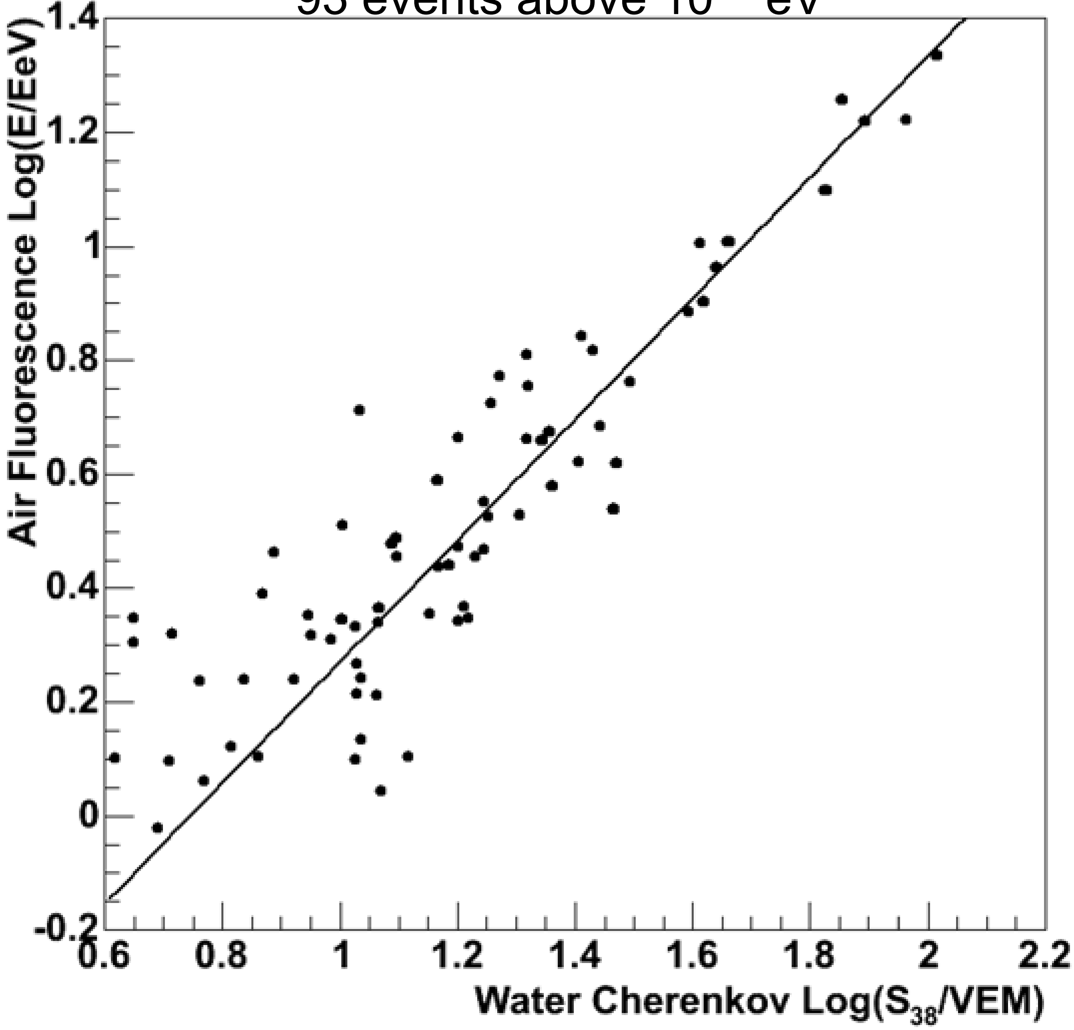
- take S_{38} value from SD vs. energy from FD
- fit line through data
  Log (E) = -0.79 + 1.06 Log(S_{38})
- energy conversion factor

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

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

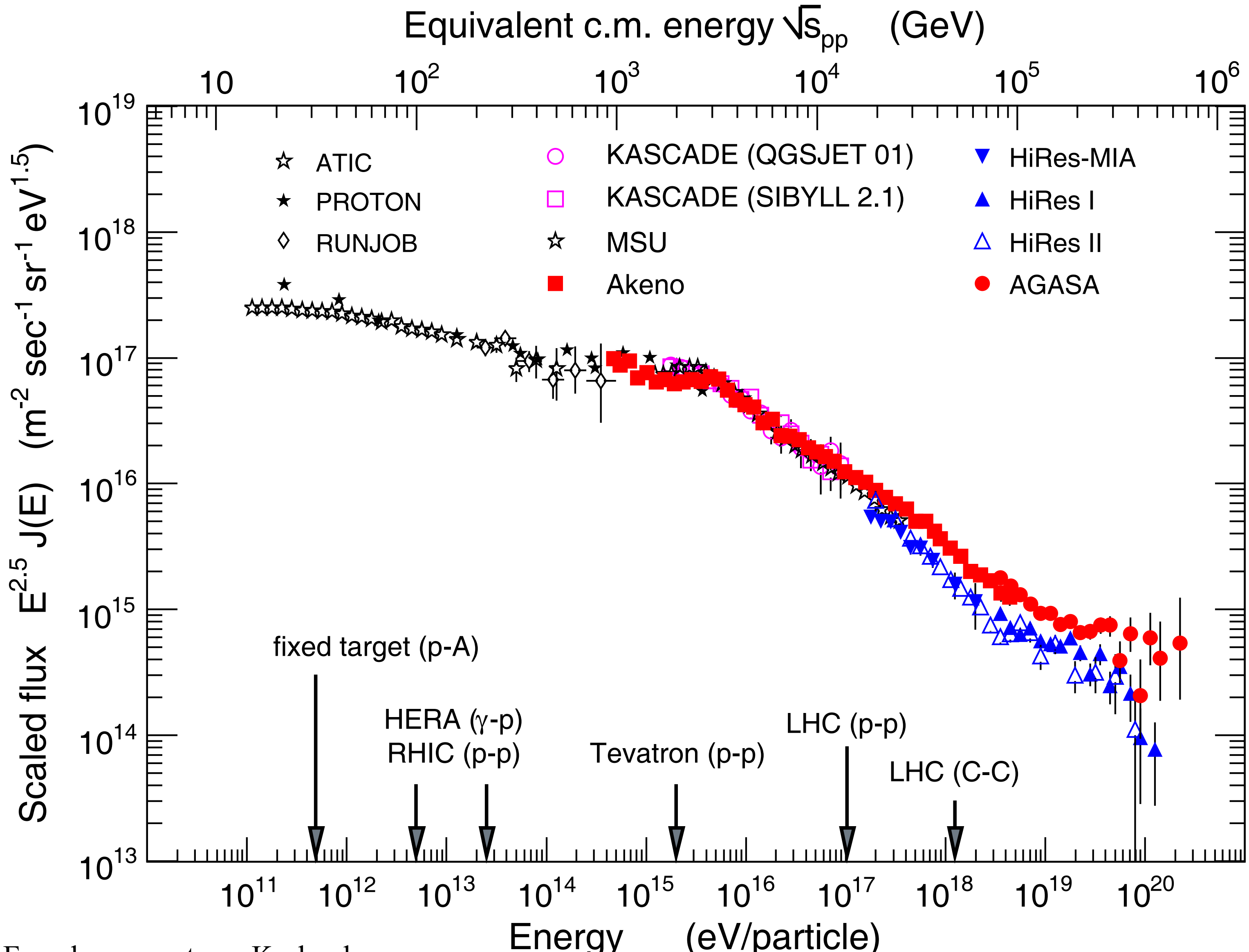
Uncertainty:
15% at 3 EeV
40% at 100 EeV

93 events above 10^{18} eV



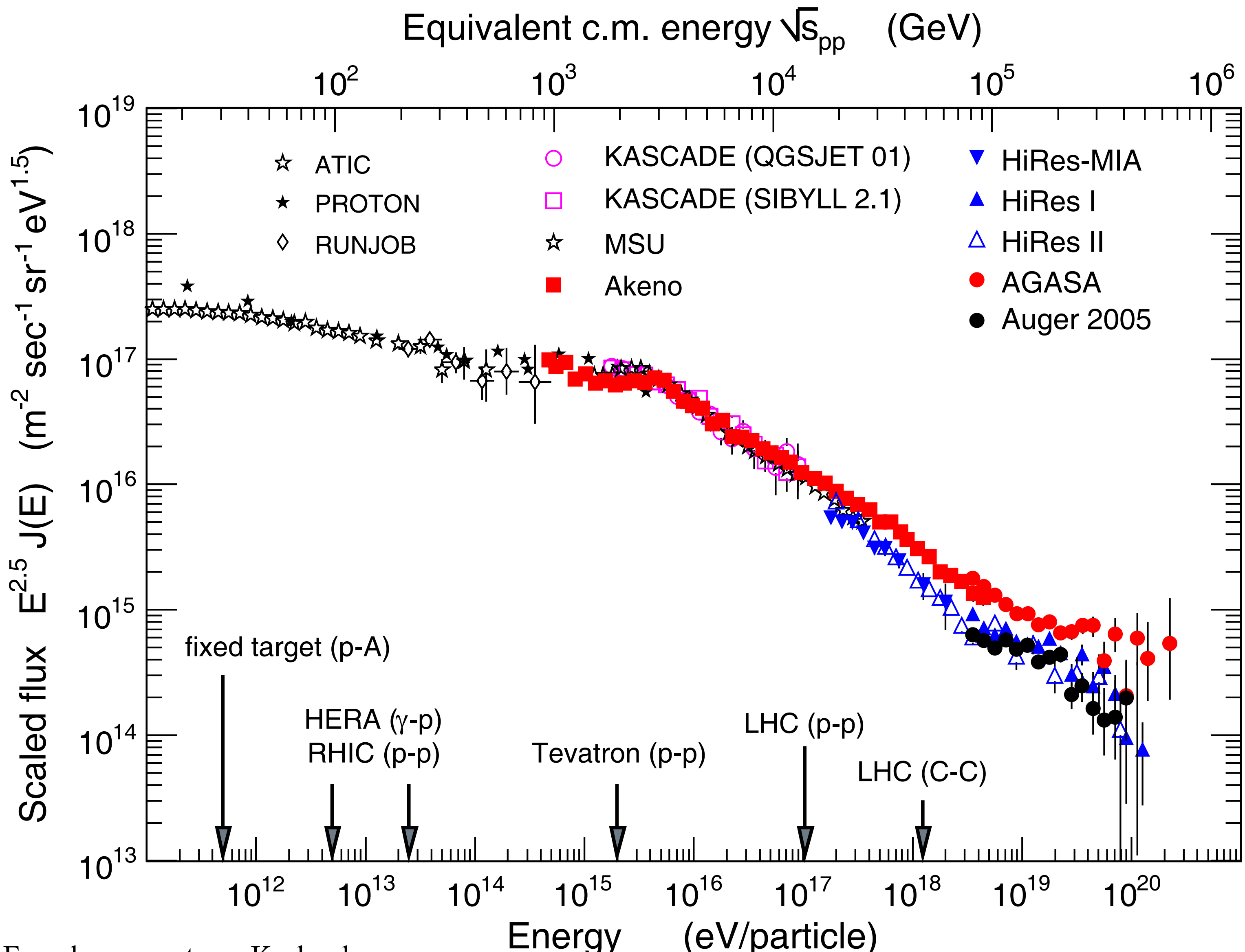
P. Sommers, Auger Collab. 29th ICRC, 2005

Cosmic Ray Spectrum „before Auger“



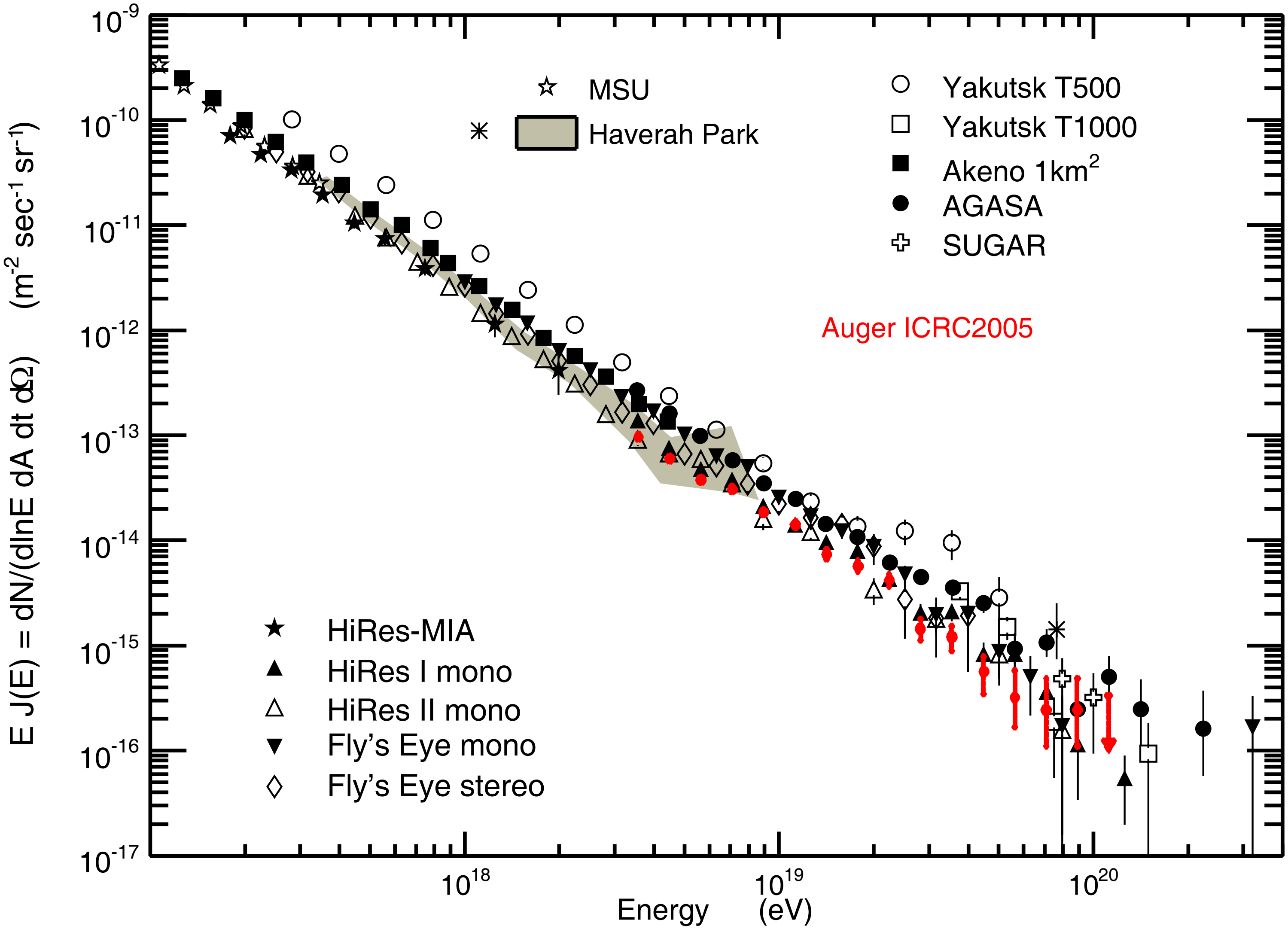
R. Engel, Forschungszentrum Karlsruhe

Cosmic Ray Spectrum with estimated „Auger Flux"



R. Engel, Forschungszentrum Karlsruhe

Estimated Spectrum



R. Engel, Forschungszentrum Karlsruhe

Uncertainties on the reconstructed energy from FD

1. signal in the PMTs
   - light collection 5 %
   - detector calibration 12 %
2. photons at the FD
   - geometry reconstruction (hybrid) 2 %
   - aerosol levels 10 %
3. fluorescence photons emitted at the shower axis
   - atmospheric density profile 2 %
   - fluorescence yield 15 %
4. energy deposit per slant depth
   - correction for missing energy 3 %
5. **primary cosmic ray energy < 25 %**

Inprovements in the near future

J. Bellido, Auger Collab. 29th ICRC, 2005

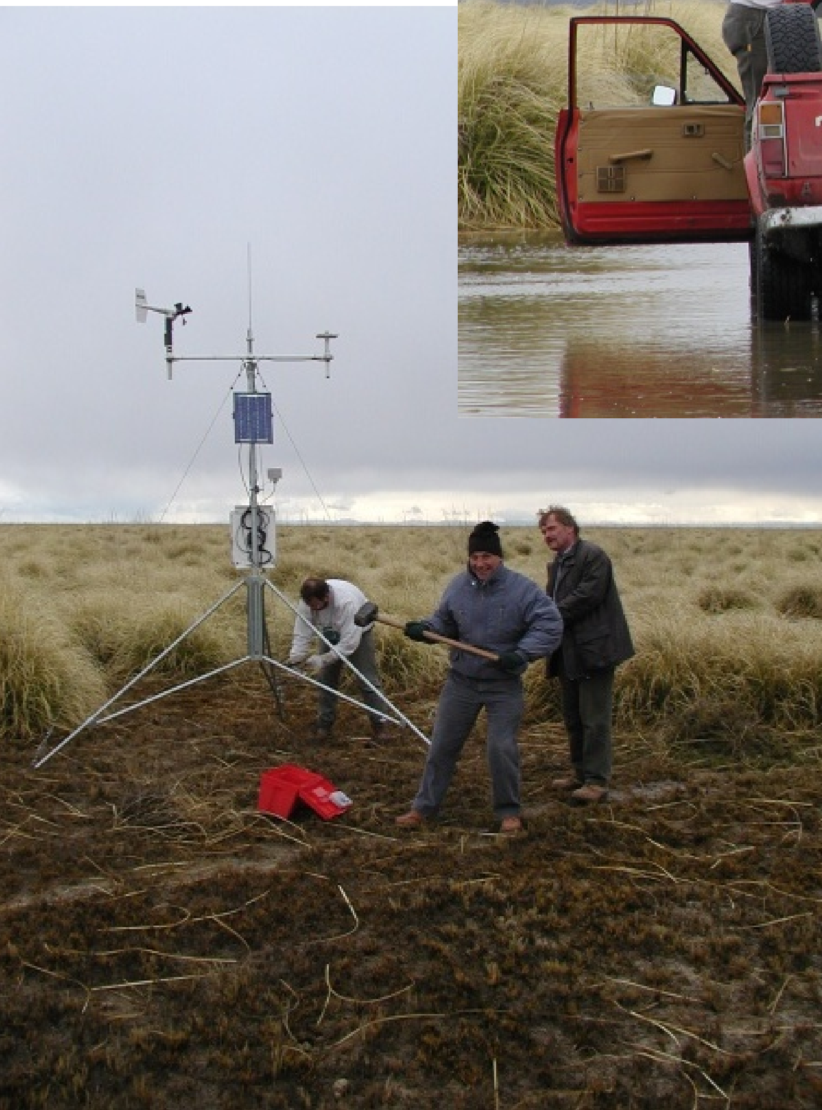
Summary

- Southern detector near completion
- First cosmic ray spectrum
- Multiple efforts on atmospheric monitoring and calibration
- 36 presentation and 1 highlight talk at the 29th International Cosmic Ray Conference, Pune, India, 2005

⇒ *just brief overview about science results presented*

PIERRE
AUGER
OBSERVATORY

That's also working for Auger



First estimate of the cosmic ray spectrum

- data set from January 1st 2004 - June 5th 2005
- all events with zenith angle between 0° and 60°
- time average area = 660 km² (22 % of final size)
- Quality cuts:
  - core surrounded by equilateral triangle of working stations
  - station with highest signal has ≥ 5 working nearest neighbours
- full efficiency above 3 EeV
- 3525 SD events above $10^{18.5}$ eV

Procedure

1. calculate energy from SD signal → time-integrated water Cherenkov signal S(1000)
2. zenith angle correction - *Constant Intensity Cut* method
3. use hybrid events for conversion of SD value to energy
4. calculate exposure of the growing array

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

Estimated Spectrum

$$\frac{dI}{d\ln(E)} \equiv E\frac{dI}{dE}$$

vs.

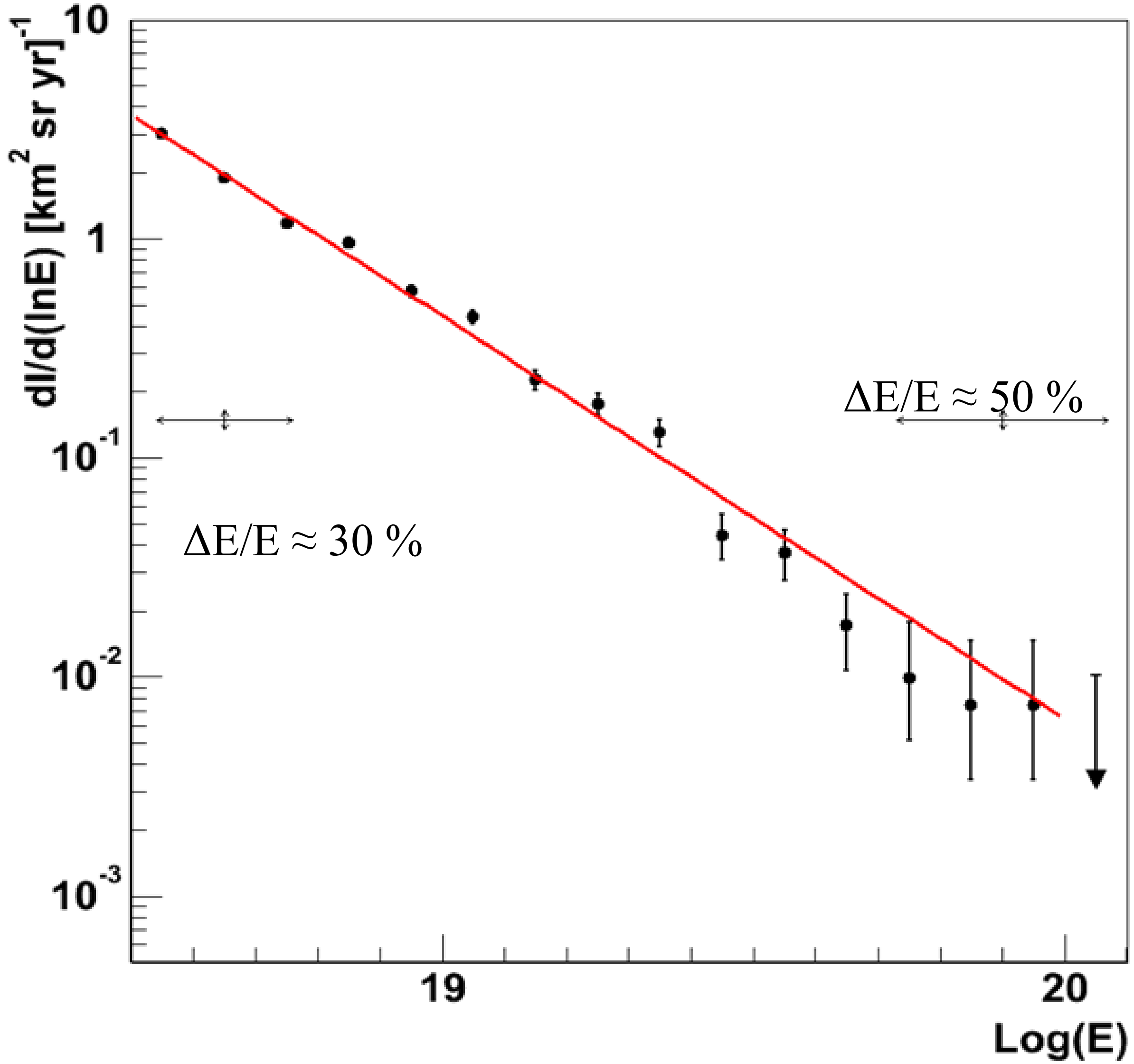
Log(E)

Error bars on points indicate Poisson statistical uncertainty (or 95% CL upper limit) based on the number of events.

Systematic uncertainty is indicated by double arrows at two different energies.

Horizontal: Systematic ΔE

Vertical: Exposure uncertainty

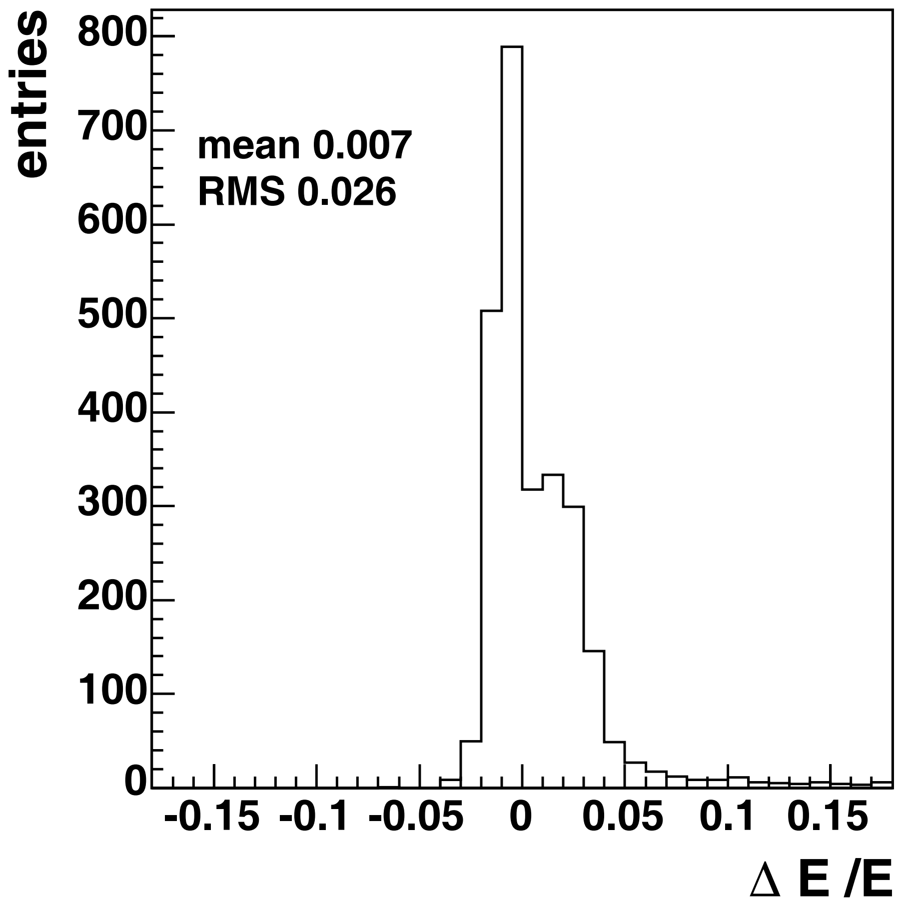


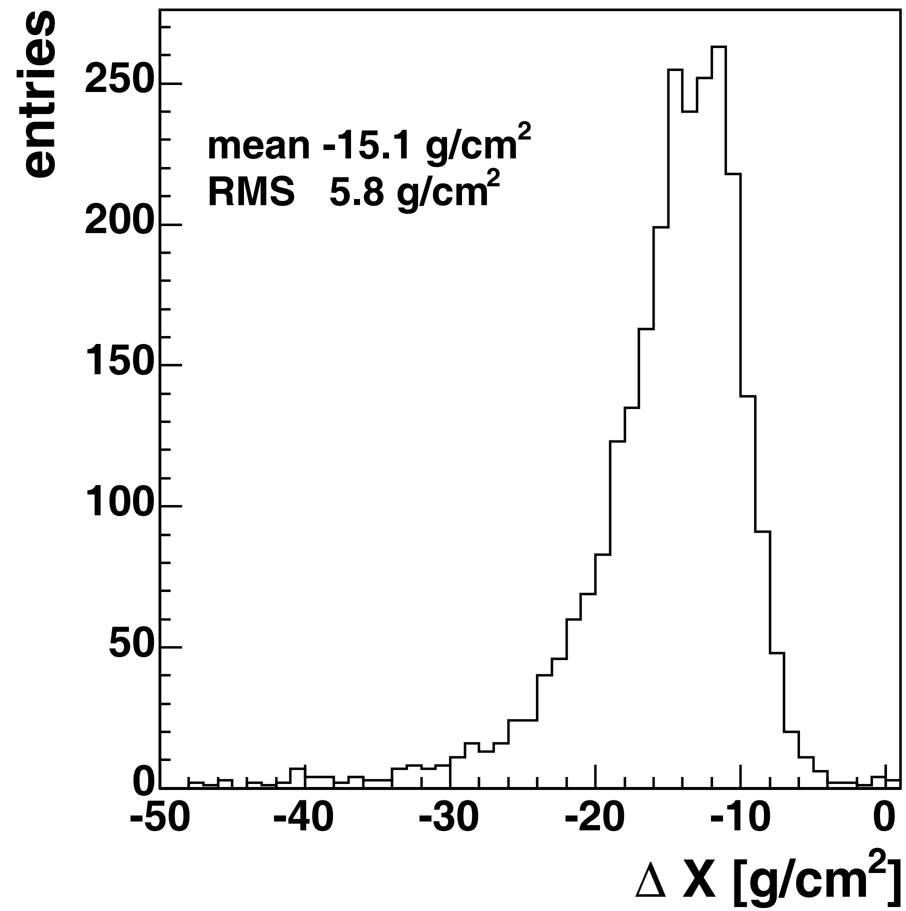
P. Sommers, Auger Collab. 29th ICRC, 2005

Reconstruction of measured EAS profiles

PIERRE AUGER OBSERVATORY

Malargüe Monthly Models vs. US standard atmosphere



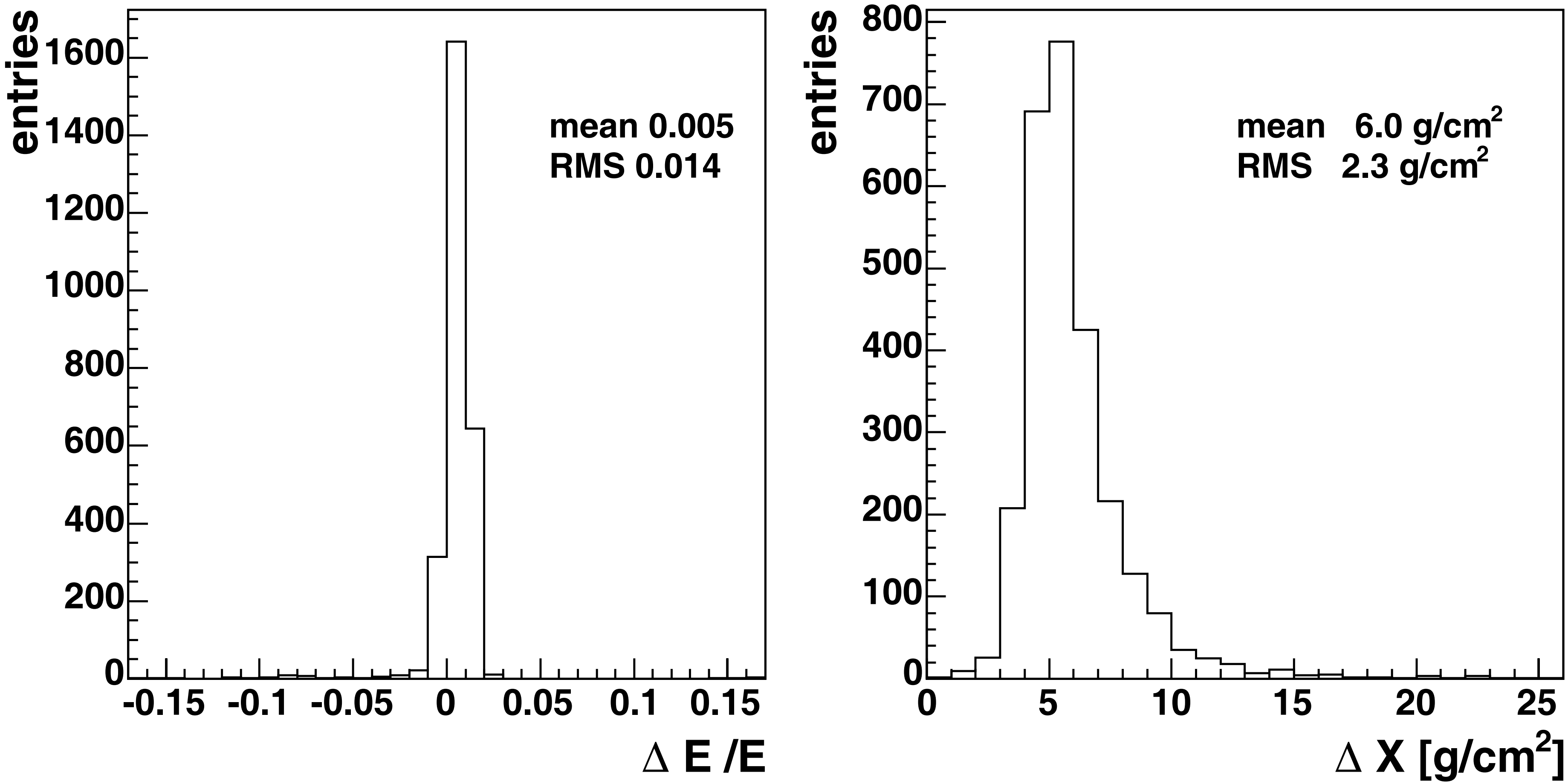


Änderung der **rekonstruierten Primärenergie < 1%**

Verschiebung der **Position des Schauermaximums ≈ -15 g/cm²**

B.K. et al., Auger Collab. 29th ICRC, 2005

Remaining Uncertainties within monthly models

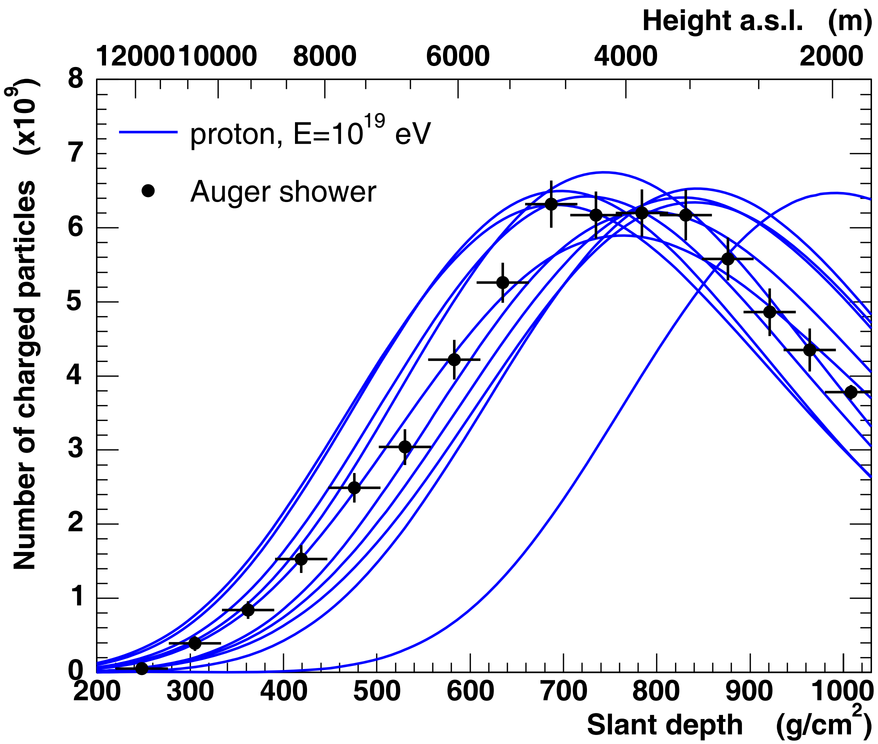


- Malargüe Monthly Models modified by **applying an 1σ error** (day-to-day variations)
- uncertainty of **depth of maximum ≈ 6 g/cm²**
- uncertainty of **primary energy ≈ 0.5 %**

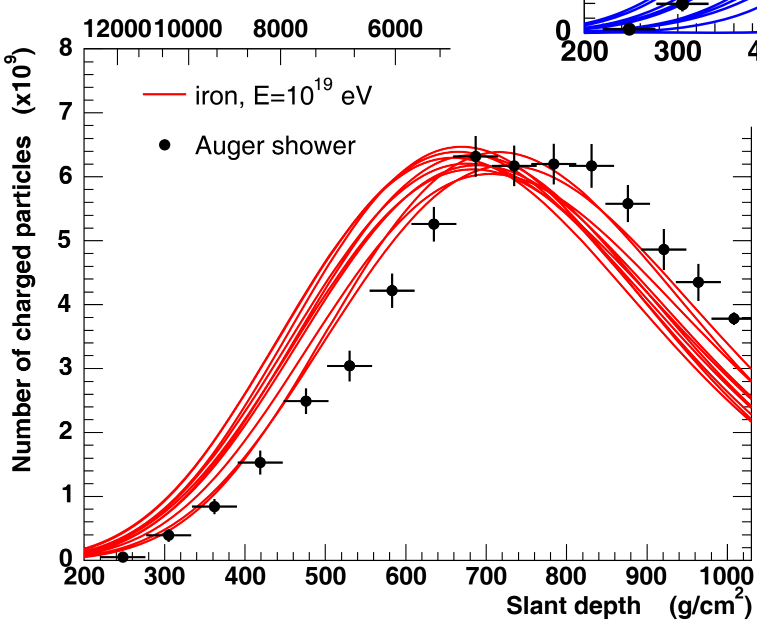
B.K. et al., Auger Collab. 29th ICRC, 2005

Auger Shower Profiles

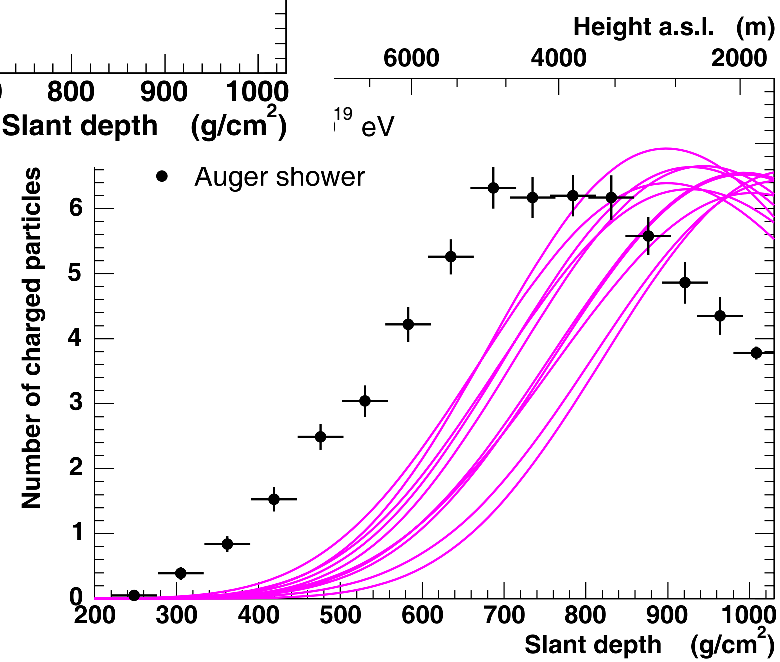
proton



iron



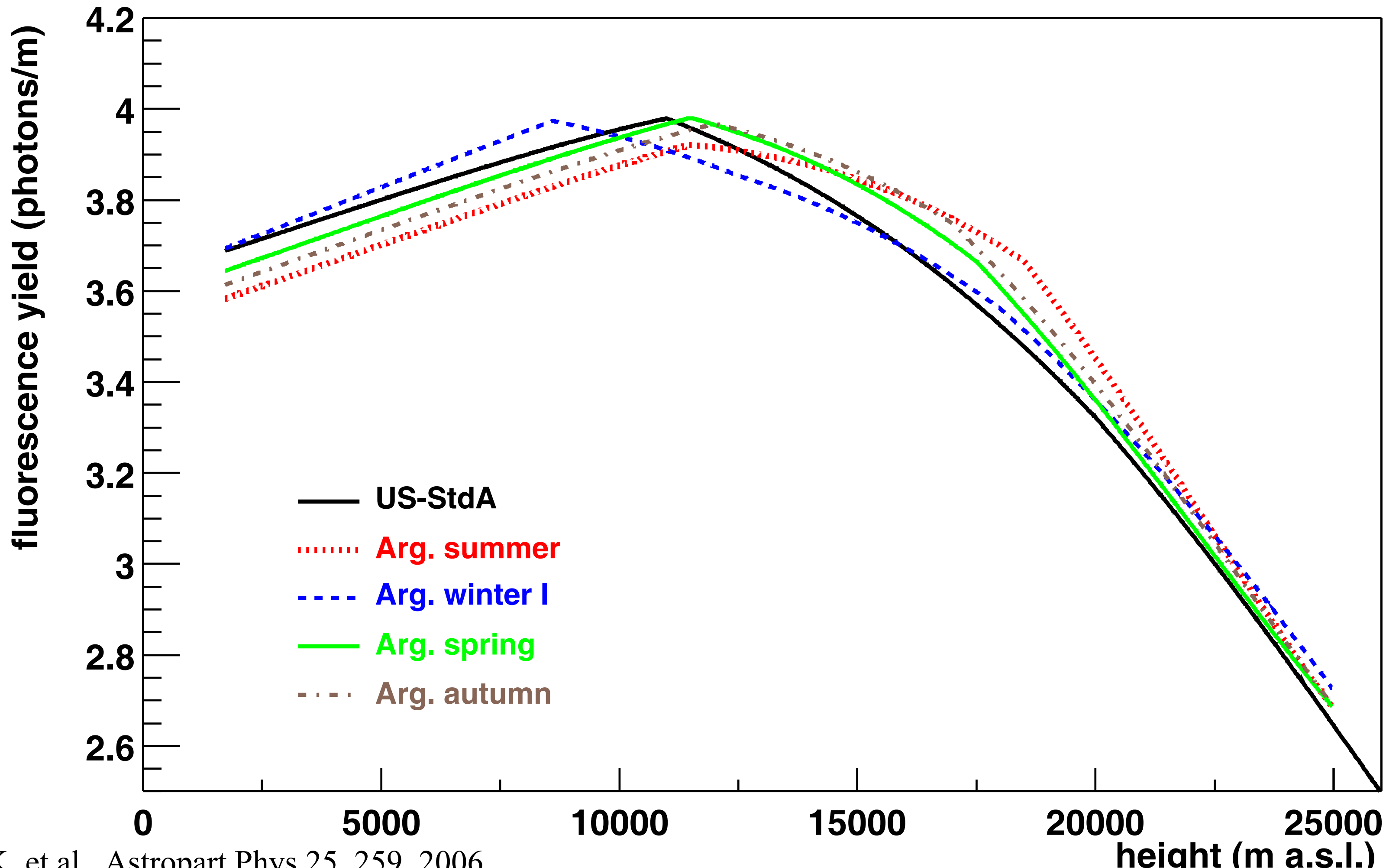
photons



M. Risse, astro-ph/0512434, 2005

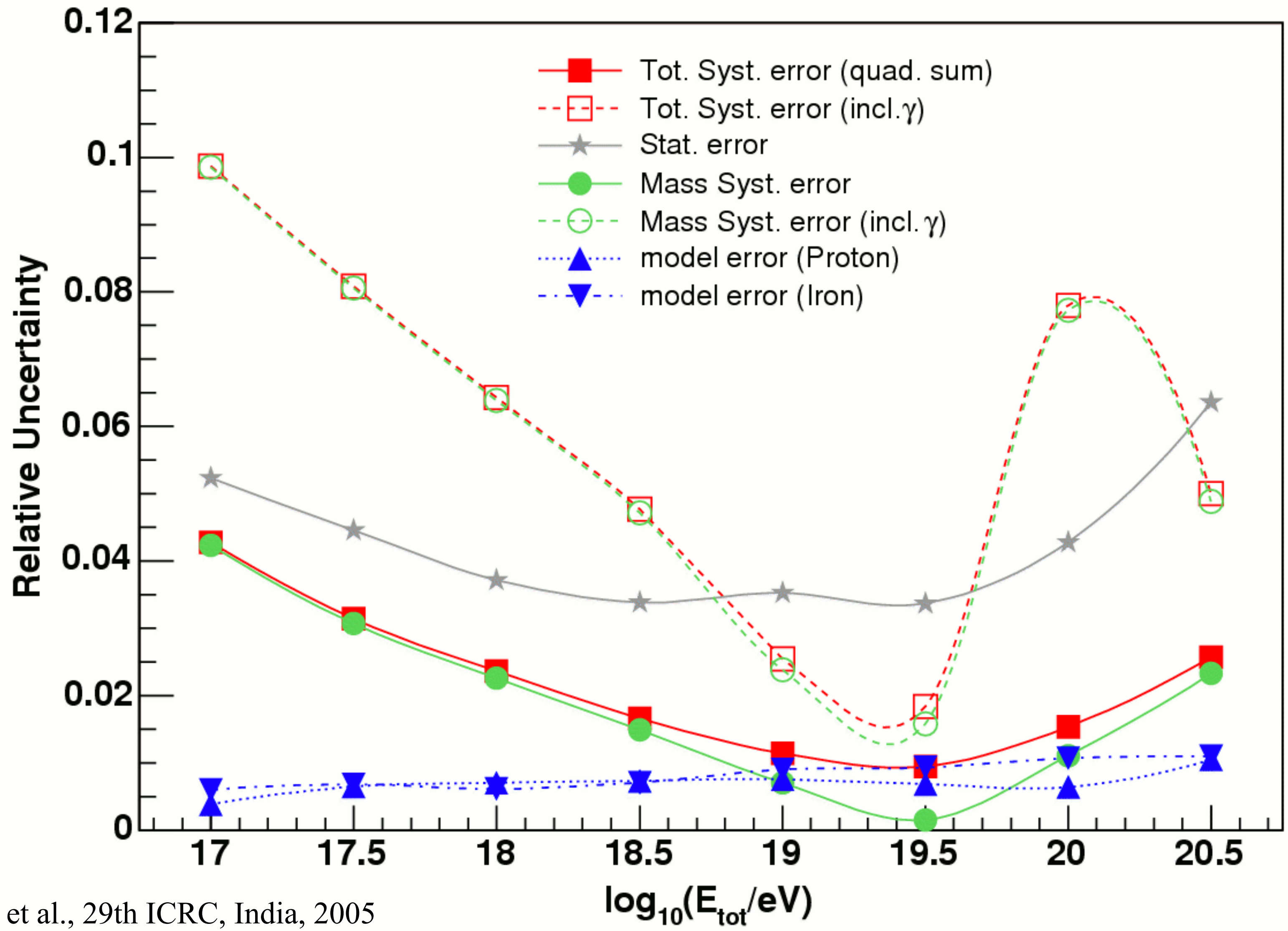
Seasonal and Altitude dependence for Auger

for a 0.85 MeV electron



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

Energy Resolution of the Atmosphere
- Energy Deposit at Shower Maximum -



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