Roma International Conference on AstroParticle Physics. RICAP-13

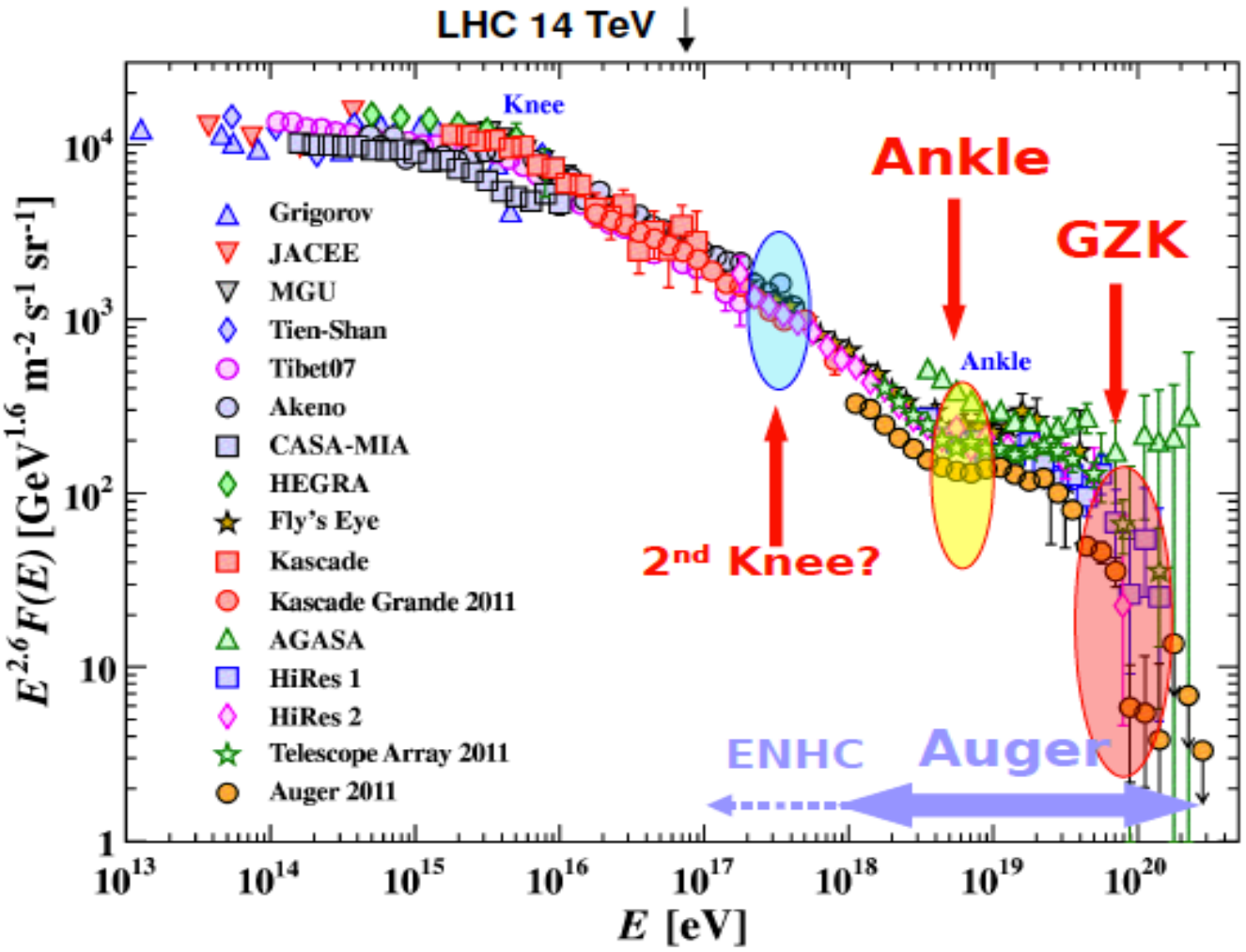
University "La Sapienza", Roma, Italy
May 22 – 24, 2013

Cosmic rays spectrum from the Pierre Auger Observatory

Gonzalo Rodriguez for the Pierre Auger Collaboration

INFN Roma Tor Vergata

Flux of Cosmic Rays



Pierre Auger Observatory Energy > 10^{18} eV

Pierre Auger Observatory research goals

Energy Spectrum of UHECR ($E > 10^{17}$ eV)

- Ankle region
- 2nd Knee region (with the lower energies extensions)
- End of the spectrum (GZK region)

Arrival Direction Distribution

- Search for departure from isotropy – point sources

Mass Composition

- Nuclei, photons, neutrinos, etc.

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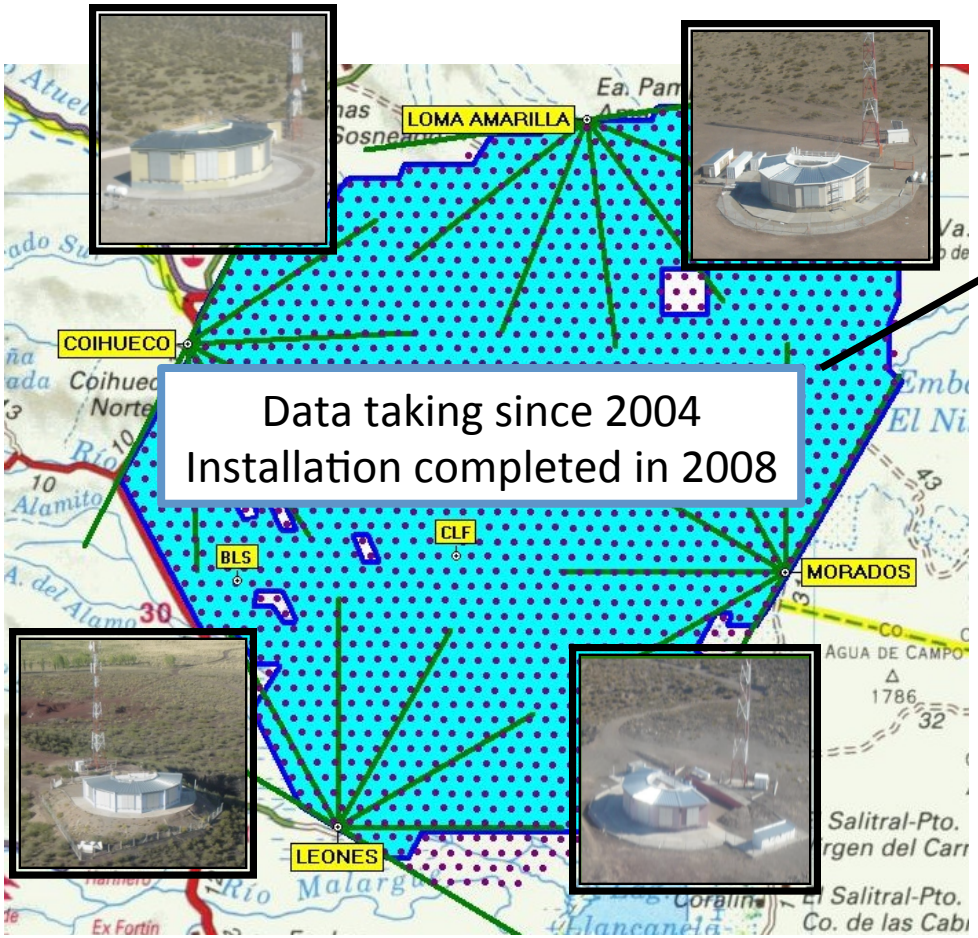
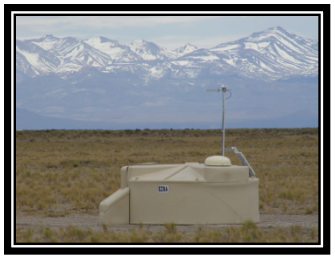
The Pierre Auger Experiment



~ 60 km

- 4 Fluorescence Detectors (FD)
- 6 x 4 Fluorescence Telescopes



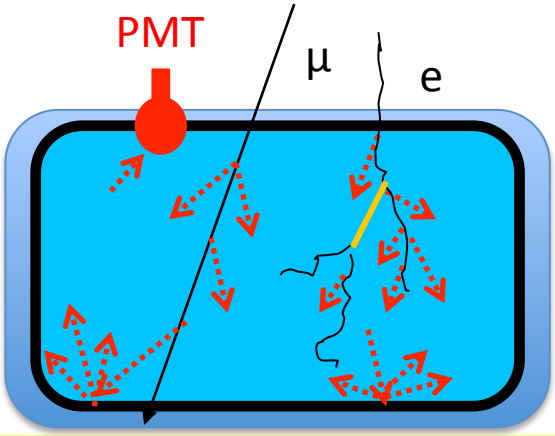
- ~ 1600 Surface Detector (SD) Stations
- 1.5 km spacing
- 3000 km^2

Low energy extension

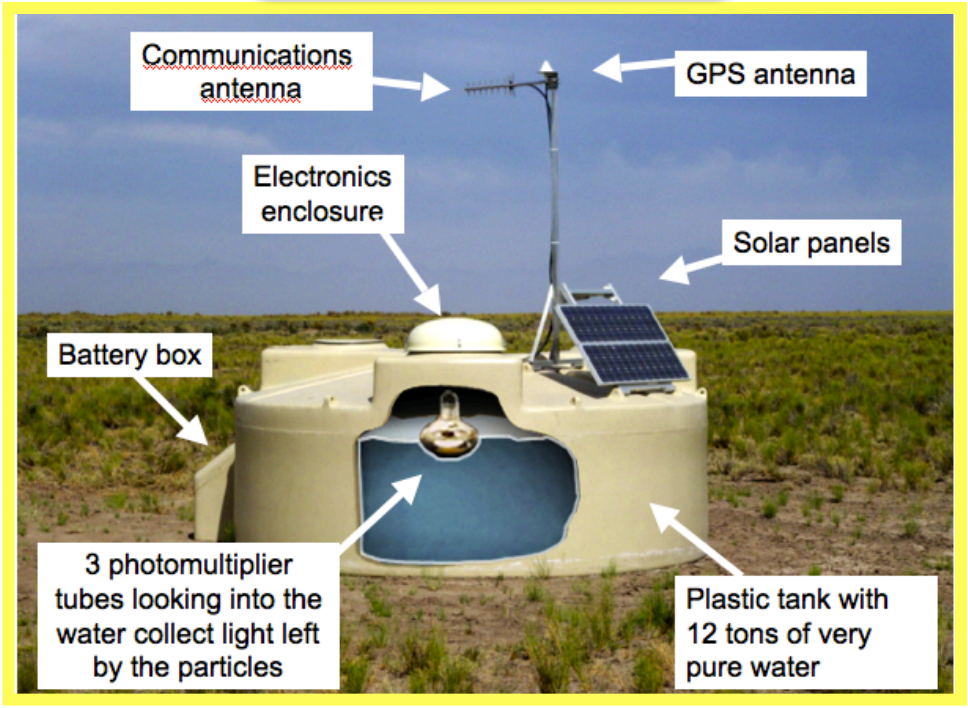
- Aim to E ≈ 10^{17} eV
- AMIGA
  - Denser array plus muon detectors
- HEAT
  - 3 additional FD telescopes with a high elevation FoV

Surface Detector Station

- Water Cherenkov Tank
  - Samples the density of secondaries at ground
  - Shower size -> Energy
  - Time -> direction
  - 100% Duty cycle

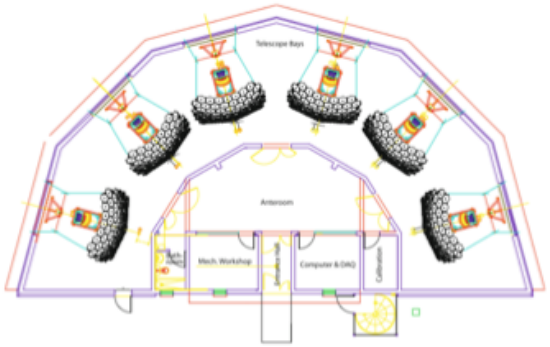


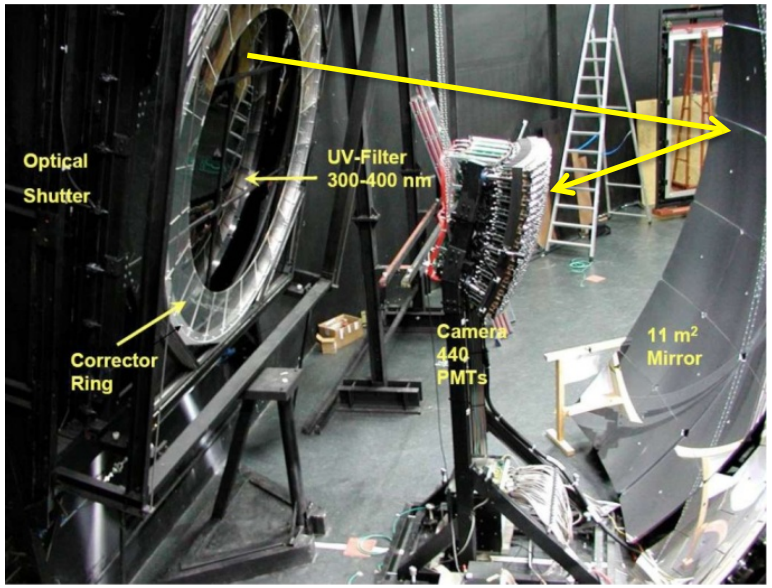
- SD station
  - Plastic Tank
  - Reflective tyvek liner
  - 12 m^3 purified water
  - 3 PMTs (9 inches)



Fluorescence Detector

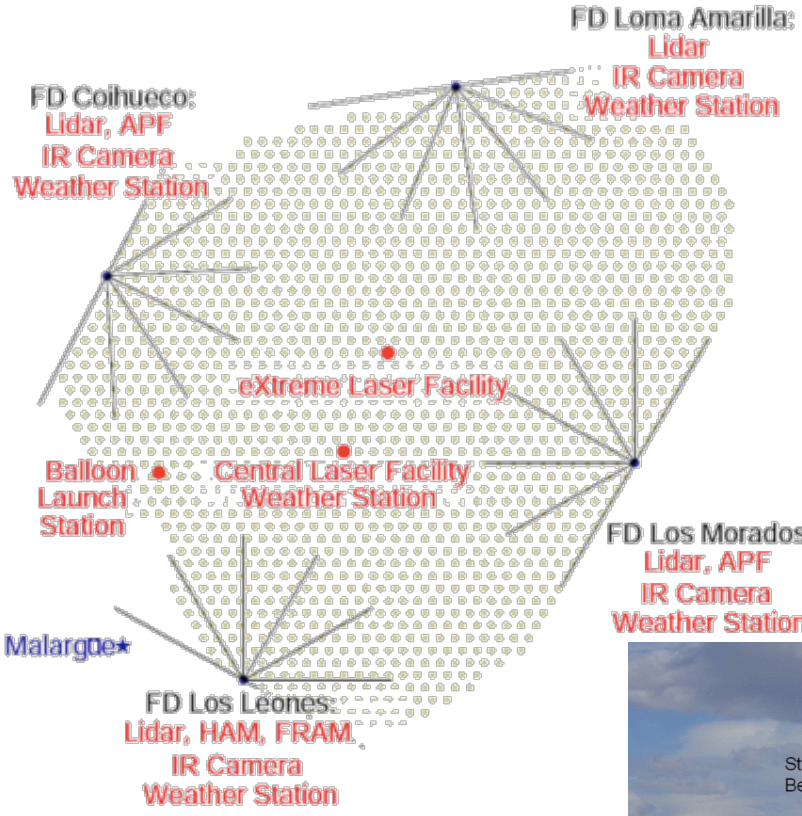
- Operates in moonless nights
  - Duty cycle ~13%
- Collects the fluorescence photons to reconstruct the energy deposit longitudinal profile
- 6 Telescopes each with 30° x 30° FoV
- Camera composed by 440 PMTs





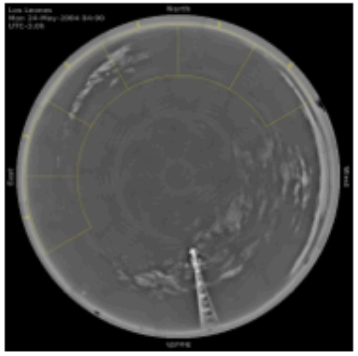
Atmospheric monitoring

balloons

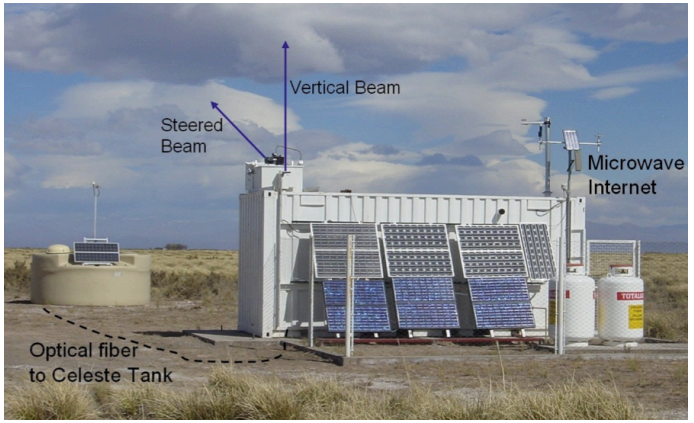


backscatter Lidar

IR cloud camera



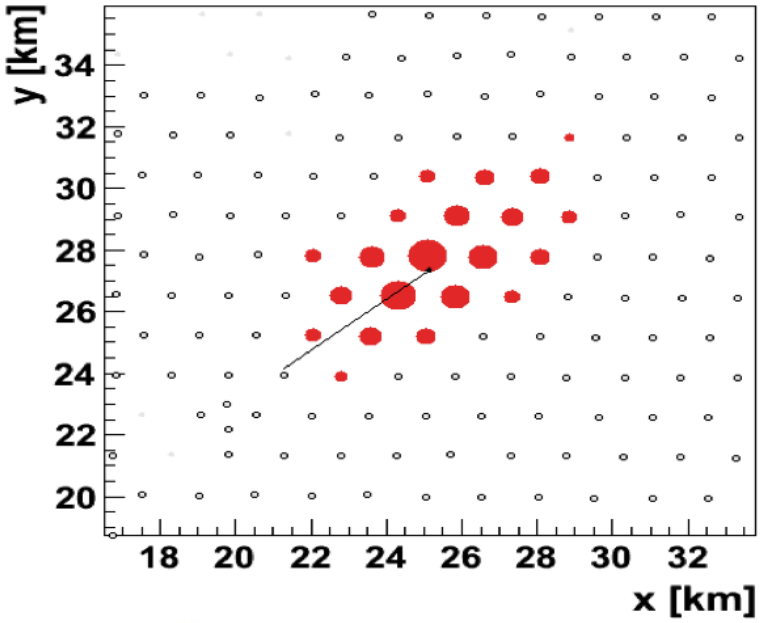
Central Laser Facility

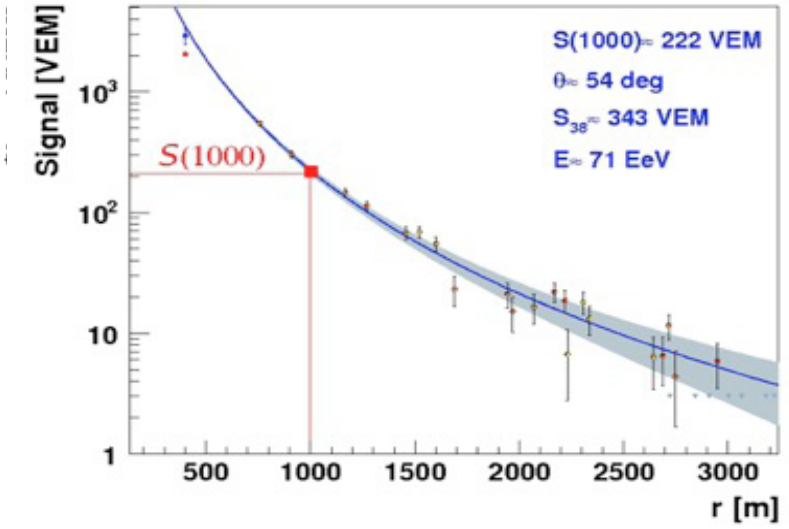


SD event reconstruction below 60^0

Reconstruction procedure:

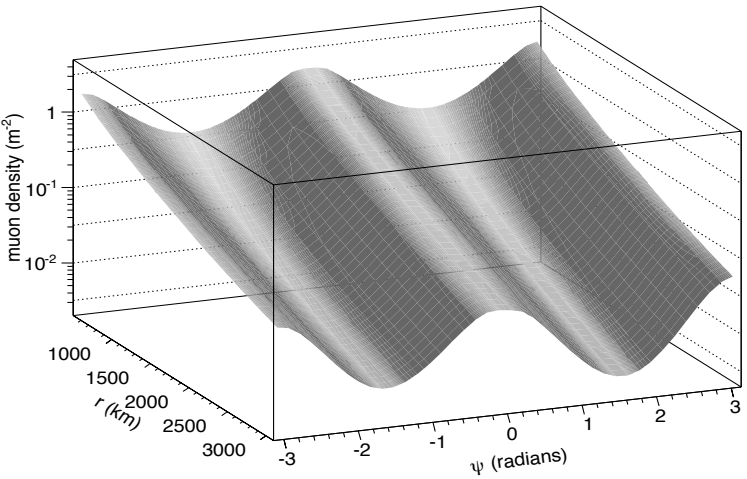
- Shower direction (θ,ϕ) using the time information of each time.
- Angular resolution is less than 1^0.
- Lateral Distribution Fit (LDF) from the recorded signals
- The signals near the core are dominated by the Electromagnetic component of the shower.
- Energy is obtained using the signal measured at 1000 meters from the shower core S(1000)

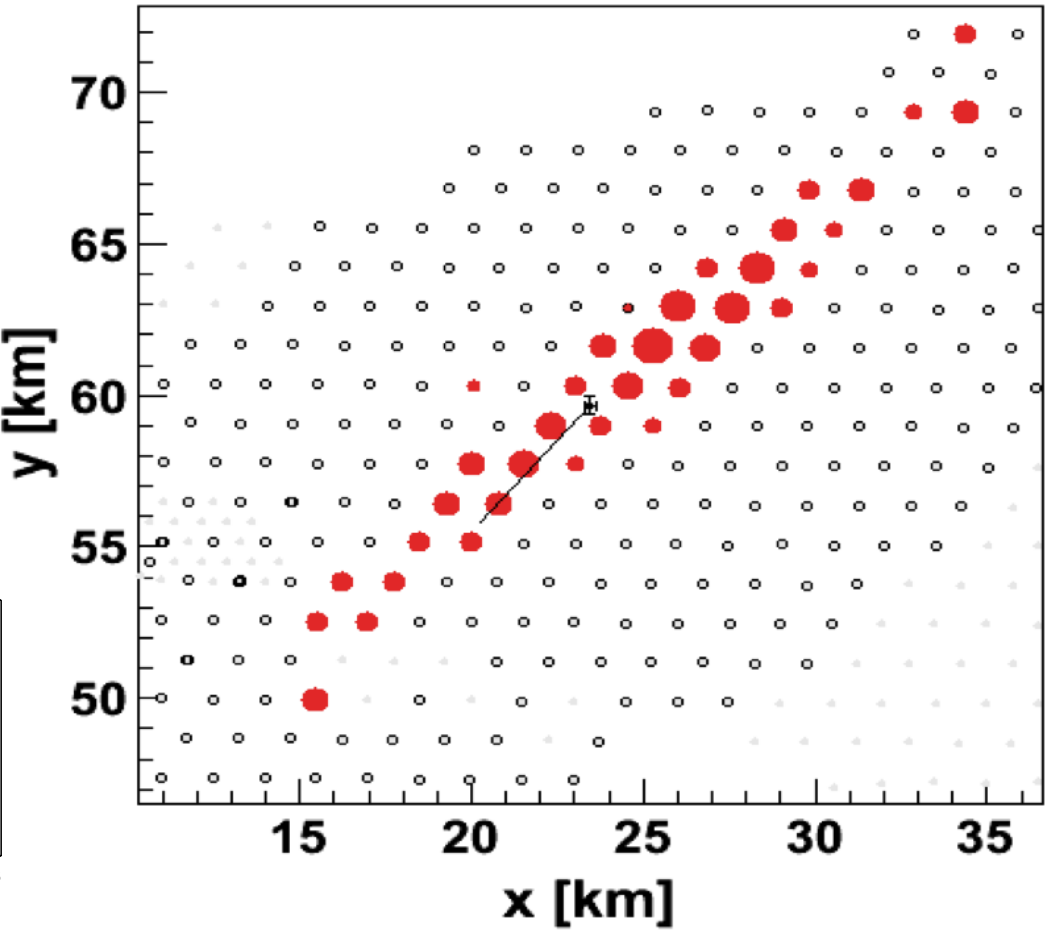




SD event reconstruction above 60^0

- EM component is absorbed in the atmosphere.
- Signals in the tanks are produced by muons
- Cylindrical symmetry is broken due to earth magnetic field
- Background for neutrino showers

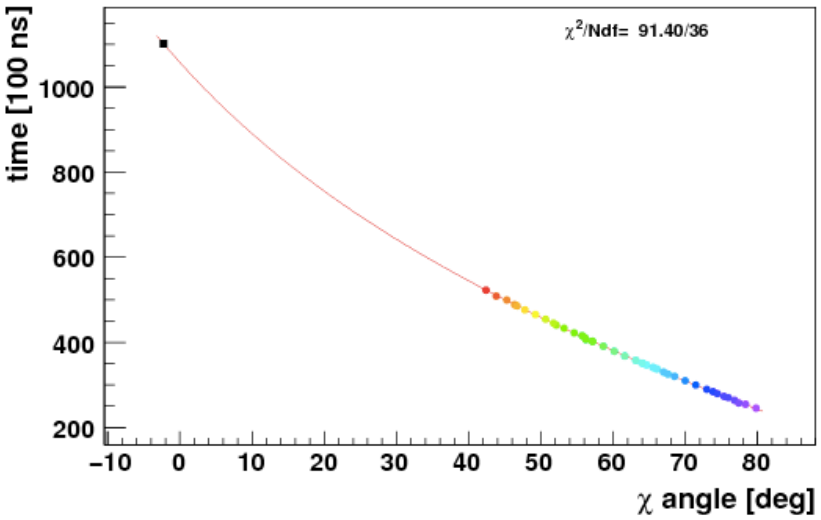


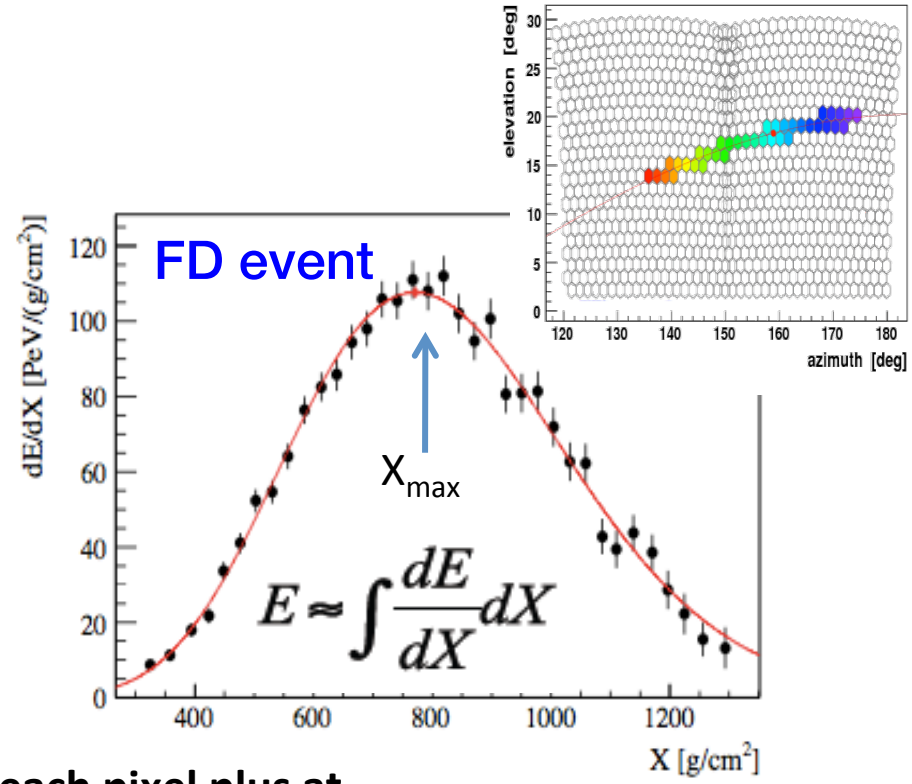


→ The core position and size parameter are obtained using 2D muon density profiles.

→ The size parameter is related with the number of muons at 10^{19} eV.

Fluorescence Reconstruction





- Reconstruct geometry from the time of each pixel plus at less one SD tank.

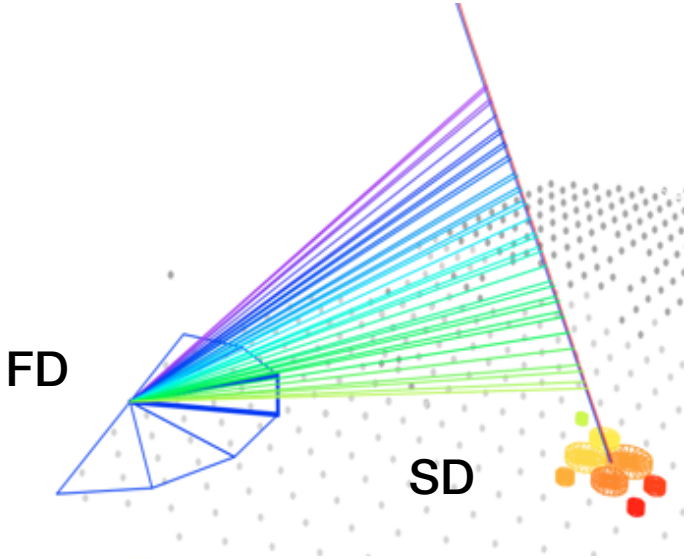
- Fit longitudinal shower profile.

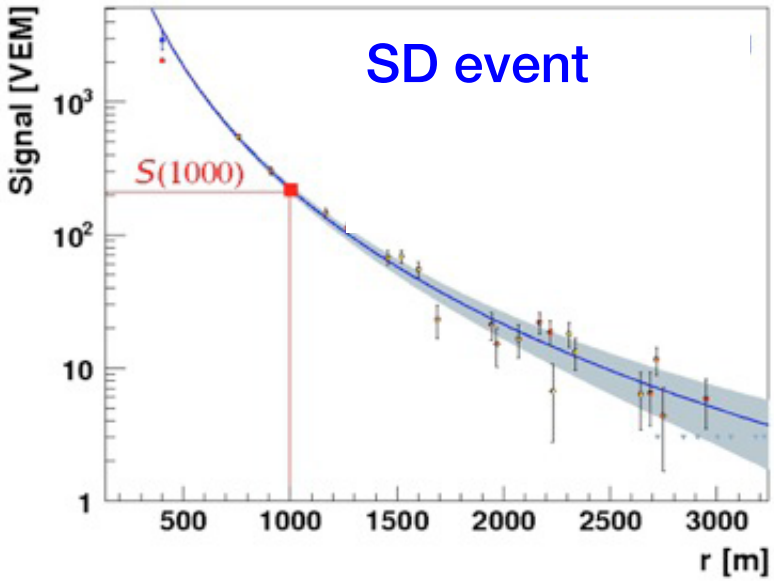
- Calorimetric measurement.

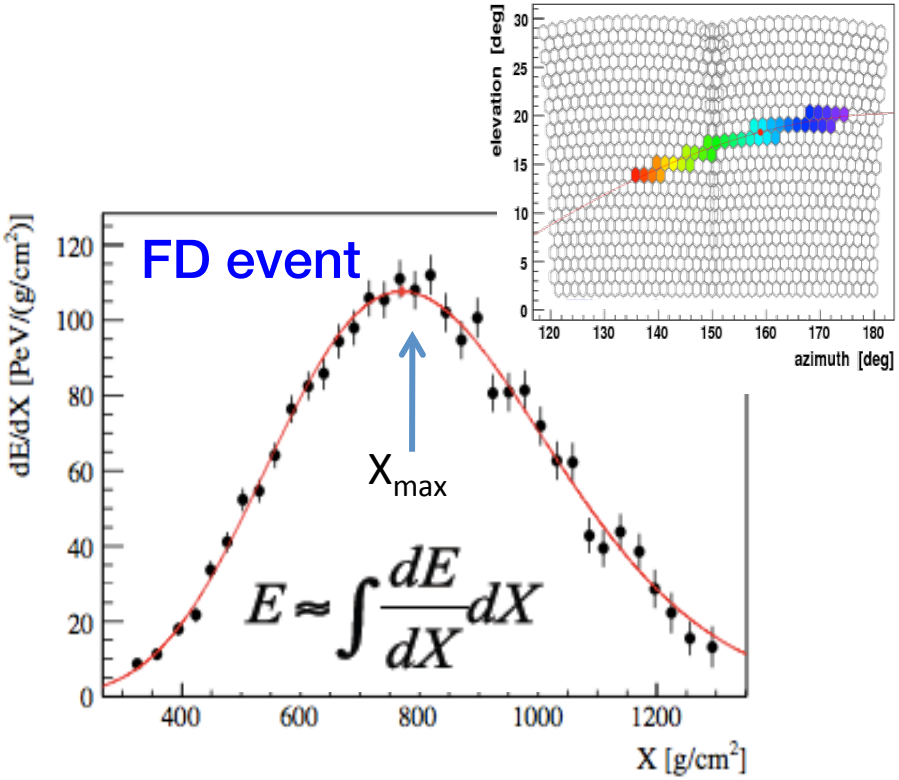
$$E_{FD} = f_{inv} \times E_{cal}$$

- Fluorescence energy is almost independent of MC model.

Pierre Auger as a Hybrid detector



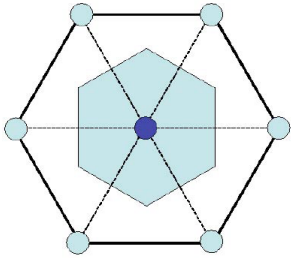


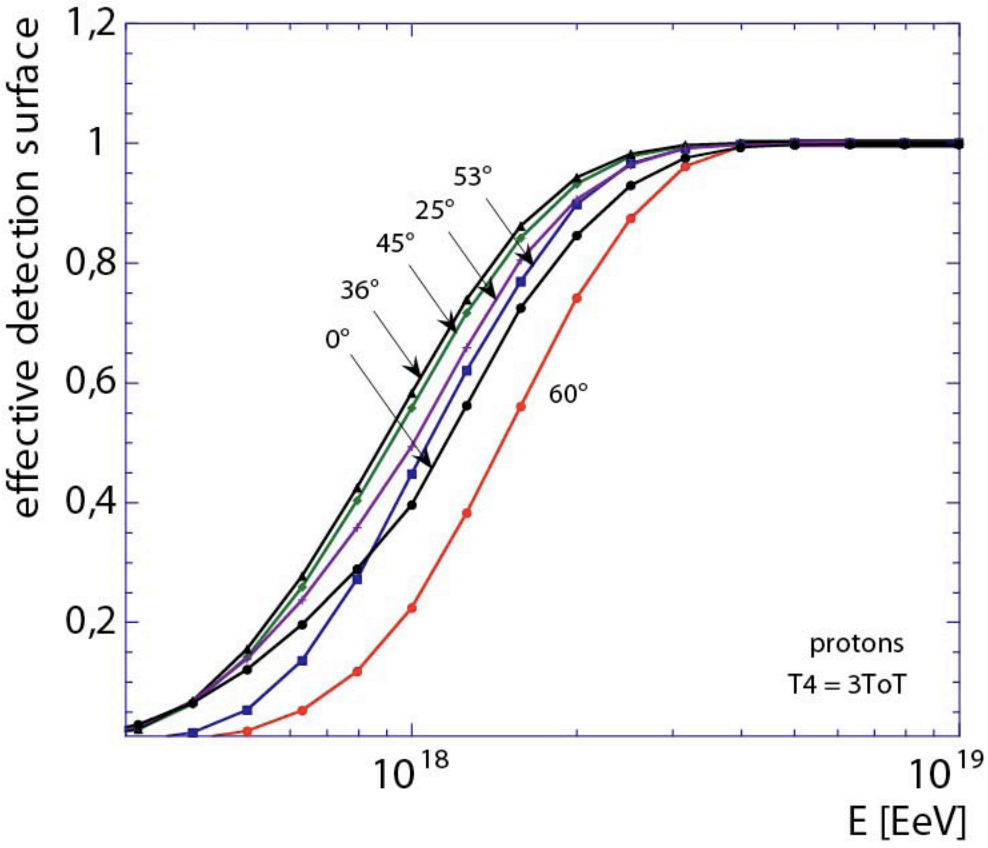


- Same event recorded with SD & FD
- Shower size from SD can be calibrated using the FD energy.
- SD Energy estimation is independent of MC

SD Event selection and acceptance

- Physics trigger T4: 3ToT
- Quality trigger T5:
  Tank with maximum signal surrounded by 6 active stations.
- Full efficiency:
  Energy > 3×10^{18} eV
- Zenith angle range:
  $[0,60]^0$ and $[62,80]^0$
- Data period:
  Jan 2004 to Sept 2010
- Exposure:
  20905 km^2 yr sr, uncertainty 3%





FD Event quality cuts

→ Xmax in the FoV

→ Δ E/E < 20%

→ Cherenkov Fraction < 50%

→ $\chi^2_{linear} - \chi^2_{GH} > 4$

→ hole in the profile < 20%

→ maxVOAD 0.1

→ LidarCloudRemoval 25

→ MinCloudDepthDistance -50 50

→ MaxCloudThickness 100

→ reject bad Pixels

→ skip Saturated pixels

→ nAxisPixels 5

→ Δ Xmax < 40 $gr.cm^{-2}$

→ $Chi^2_{GH}/ndf < 2.5$

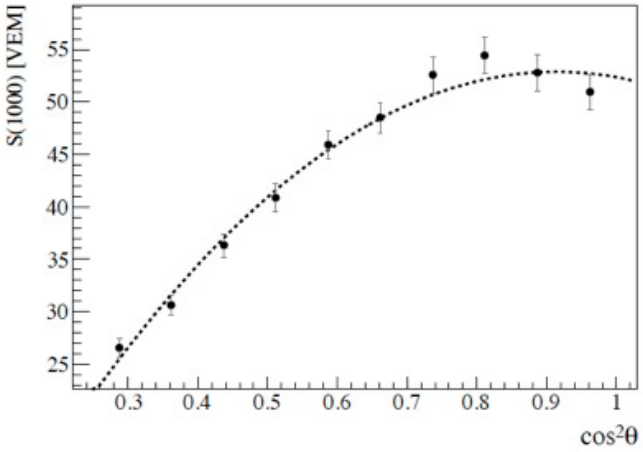
→ Distance to core < 750m

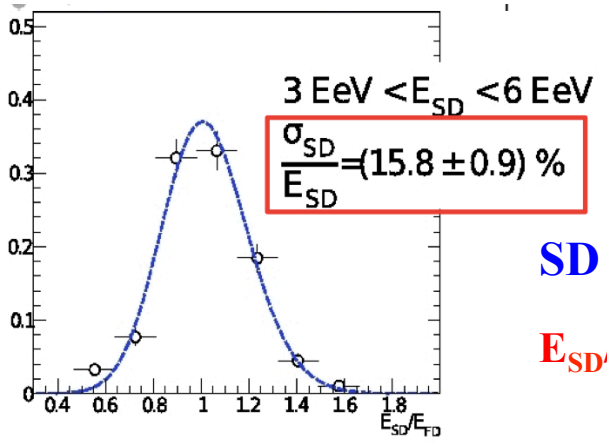
→ Delta T < 300 ns

→ Fiducial volume cuts

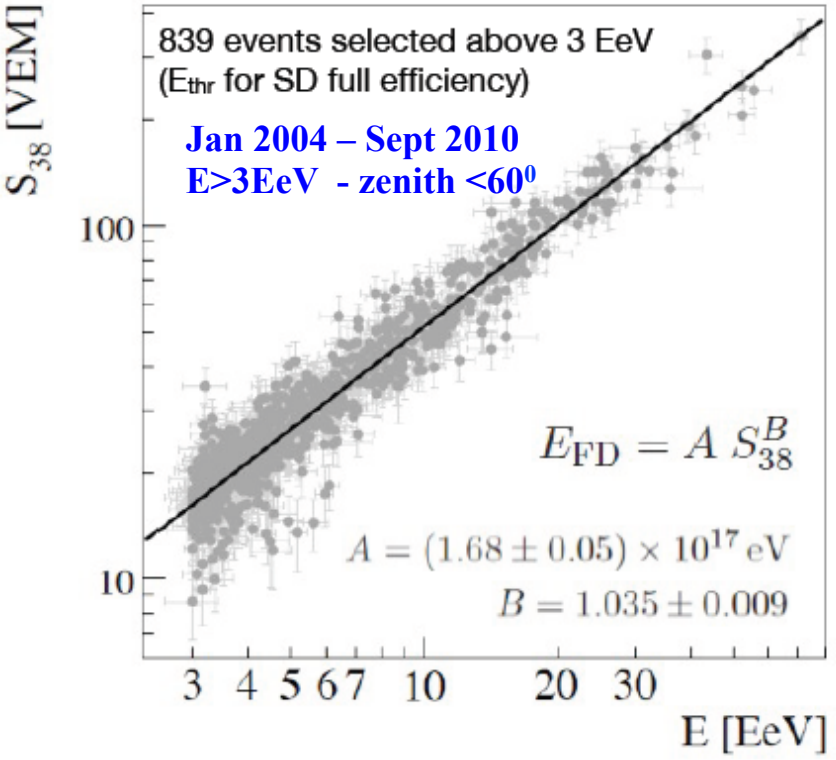
Energy Calibration of the SD

S38: is the equivalent signal of S(1000) of a shower with θ=38°





R. Pesce, ICRC2011



SD Energy Resolution:

E_{SD}/E_{FD} ~ 15%

Calibration Systematic Uncertainties:

- **7% at 10 EeV**
- **15% at 100 EeV**

Systematic uncertainties in the FD energy measurement

Source	Systematic uncertainty
- Fluorescence yield	14%
- P,T and humidity effecs on yield	7%
- Calibration	9.5%
- Atmosphere	4%
- Reconstruction	10%
- Invisible energy	4%
TOTAL	22%

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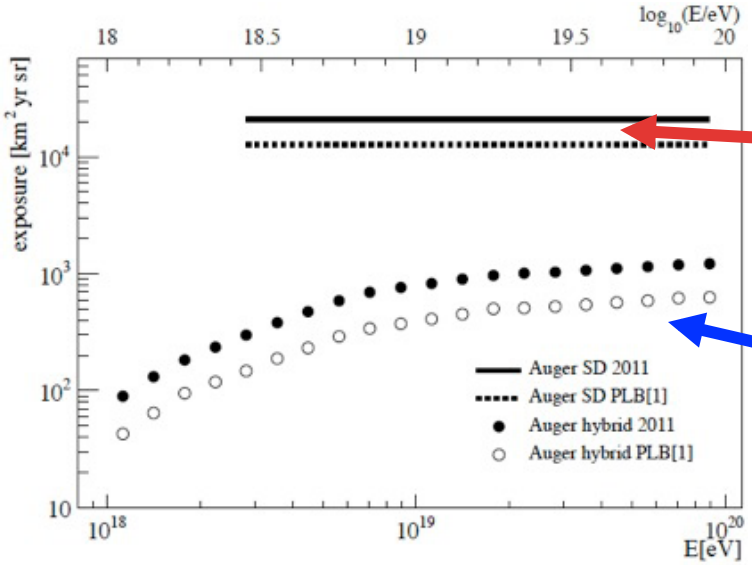
The energy scale and the systematics uncertainties will be update in the ICRC 2013

Energy Spectrum: SD & FD Hybrid



SD Exposure (01/2004-12/2010)

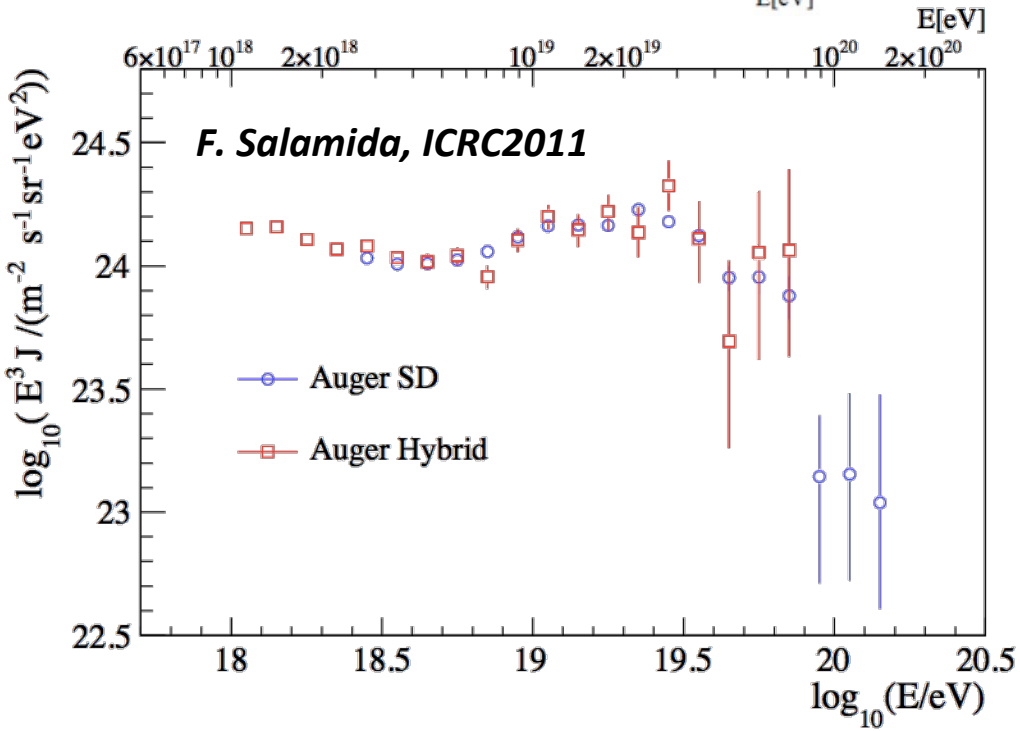
-geometrical calculation (~20905 km^2 yr sr)

syst. uncertainties: ~ 3%

Hybrid Exposure (11/2005-09/2010)

- time-dependent Monte Carlo simulations

- syst. uncertainties ~10% (6%) at 10^{18} eV (10^{19} eV)



- SD has a higher exposure allowing to reach higher energies
- Energy resolution is around 15%
  - Unfolding method to correct for bin-to-bin migration
- FD (Hybrid) can reach lower energies but exposure is MC based
- Good agreement between FD and SD

Spectrum with inclined events

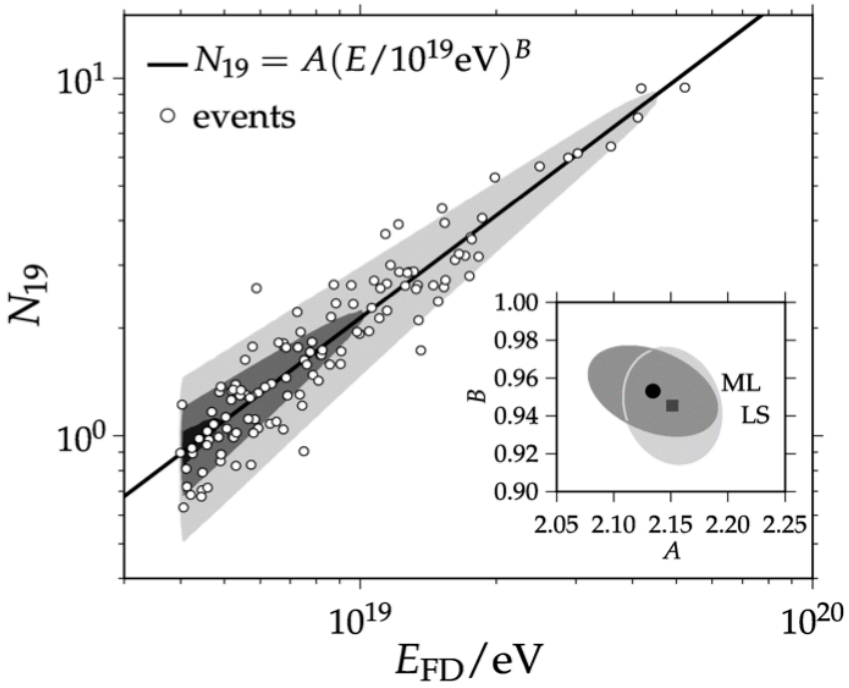
Energy Calibration with FD energy

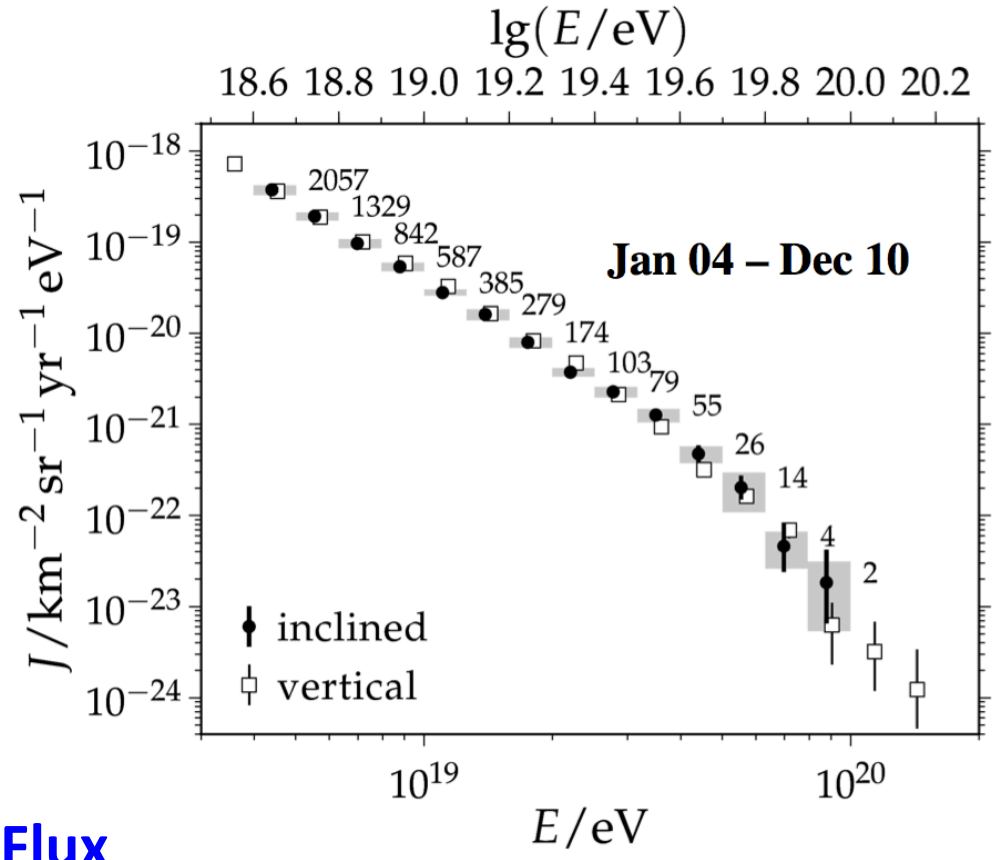
N_{19} is the shower size -> related to the total number of muons

Direct measurement of the hadronic shower component.

Energy > 4×10^{18} eV

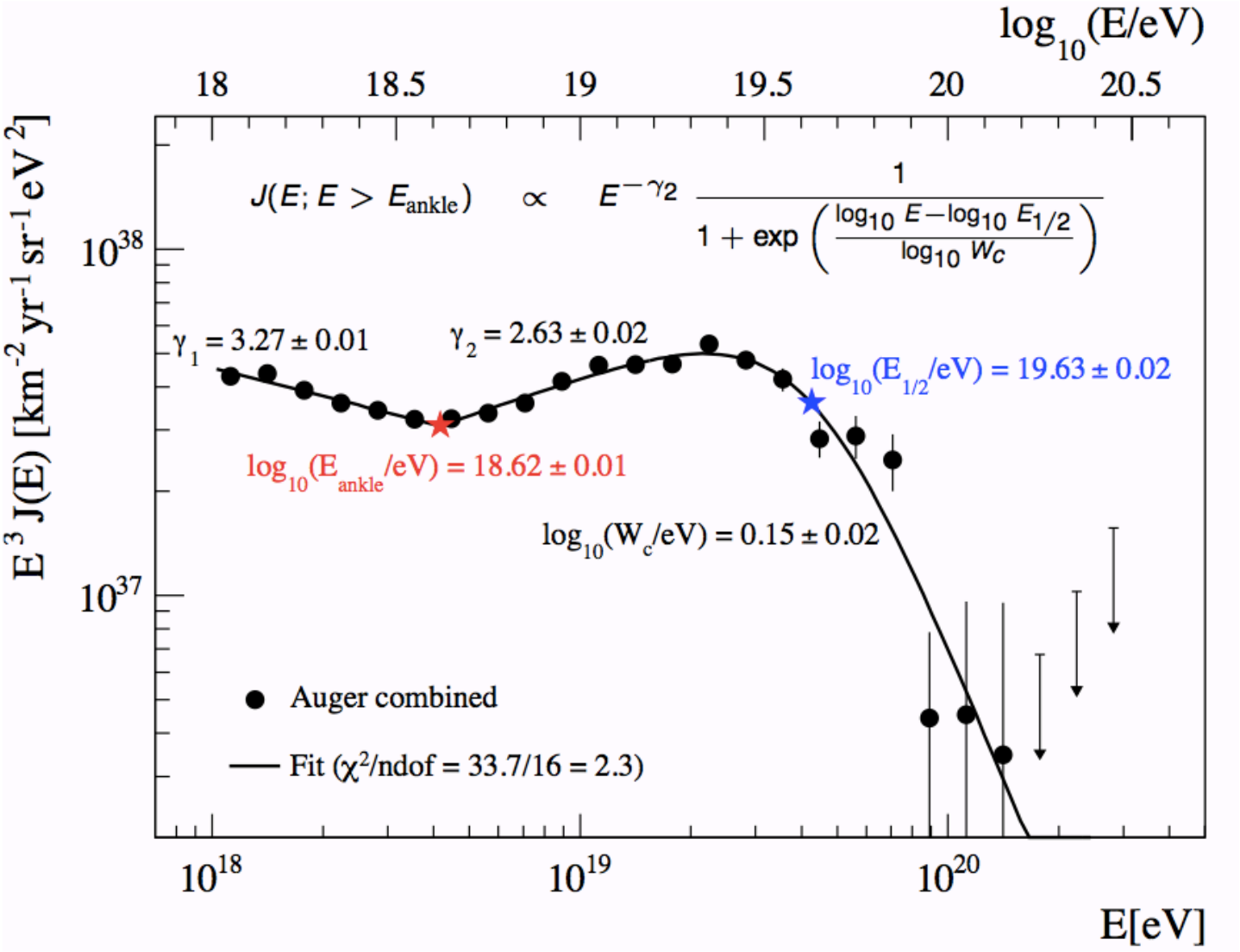
62^0 > zenith < 80^0





Full agreement with the vertical Flux

Combined Auger Spectrum (FD+SD)



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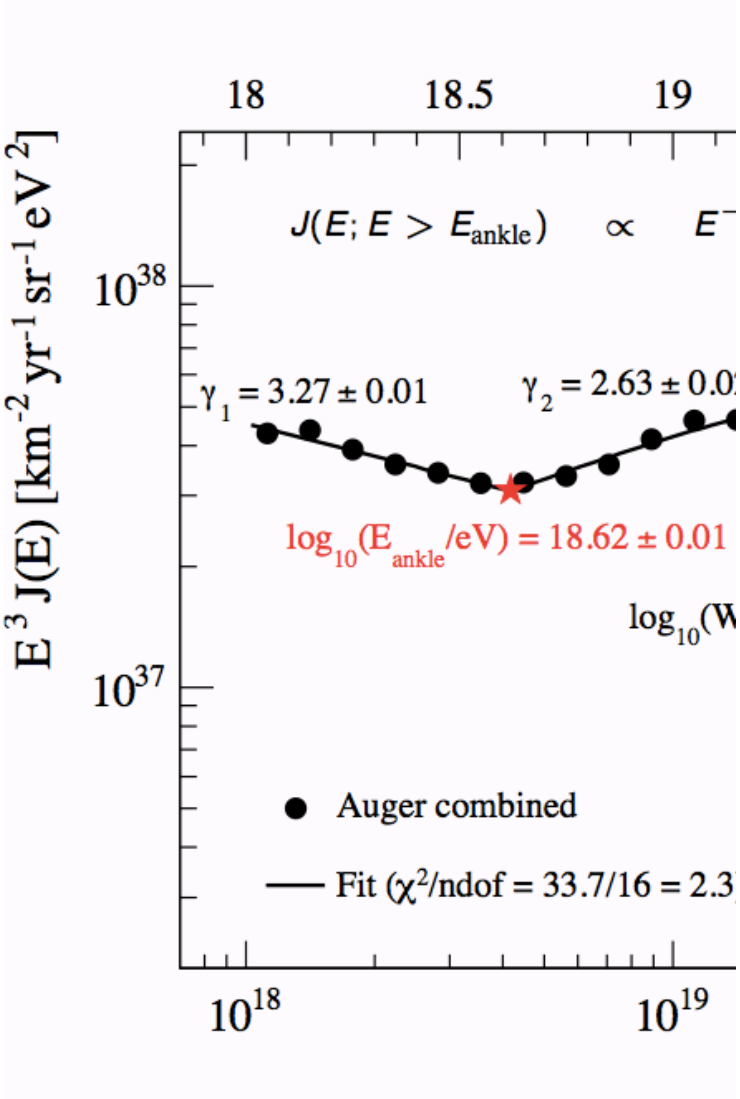


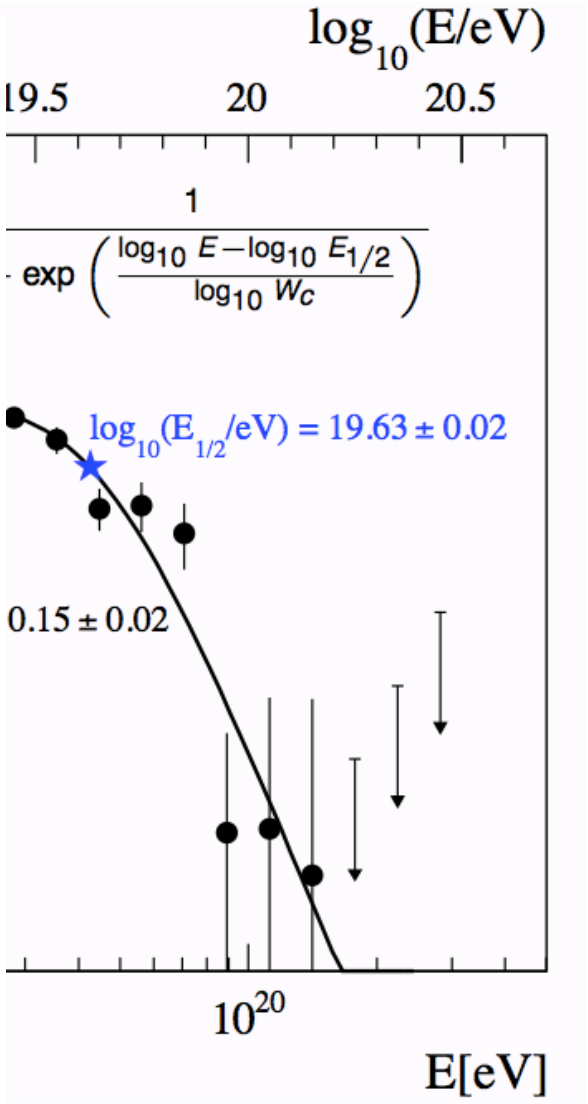
- Ankle region clearly observed
- Galatic to extragalatic transition?
- Astrophysical interpretation depends:
  - Primary composition
  - Sources distribution
  - ...

M. Unger, arXiv:0812.2763[astro-ph]

Combined Auger Spectrum (FD+SD)

- Auger data shows a flux suppression at the highest energies
  - Cutoff significance > 20 σ

- This feature is compatible with:
  - GZK cuttoff
    - Greisen, Zatsepin, Kuz'min (1966)
    - Cosmic ray interaction with CMB
  - Sources running out of power



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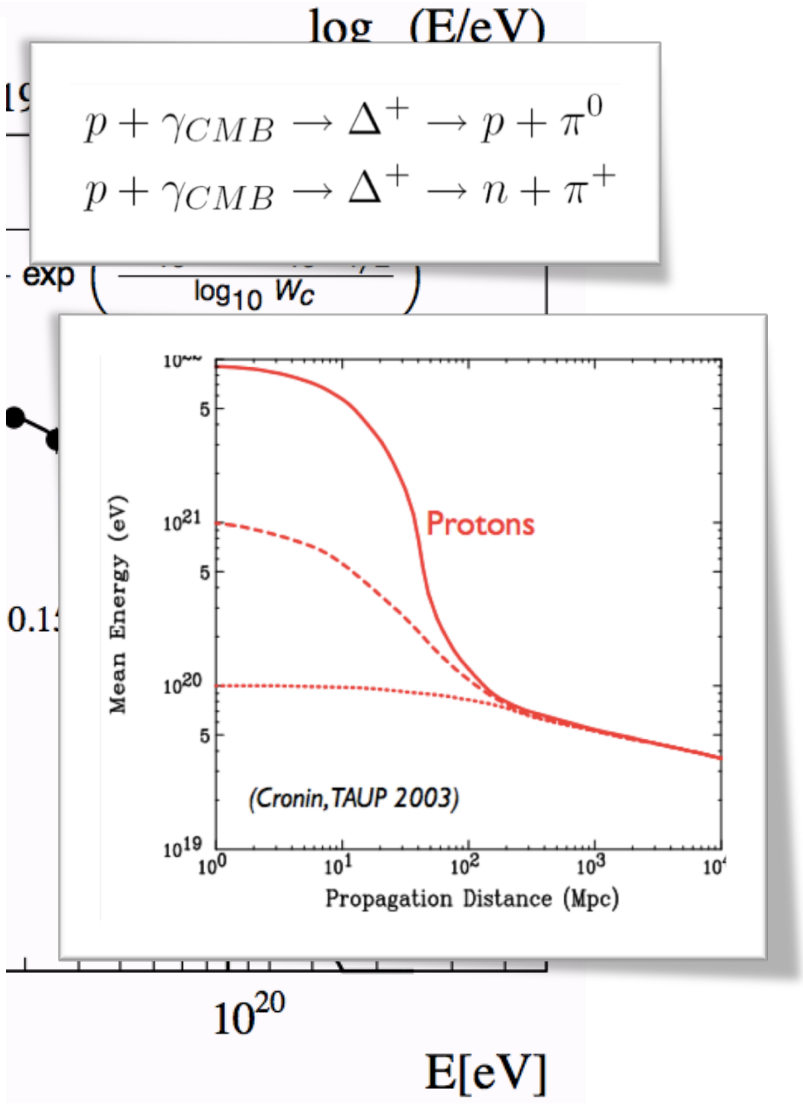

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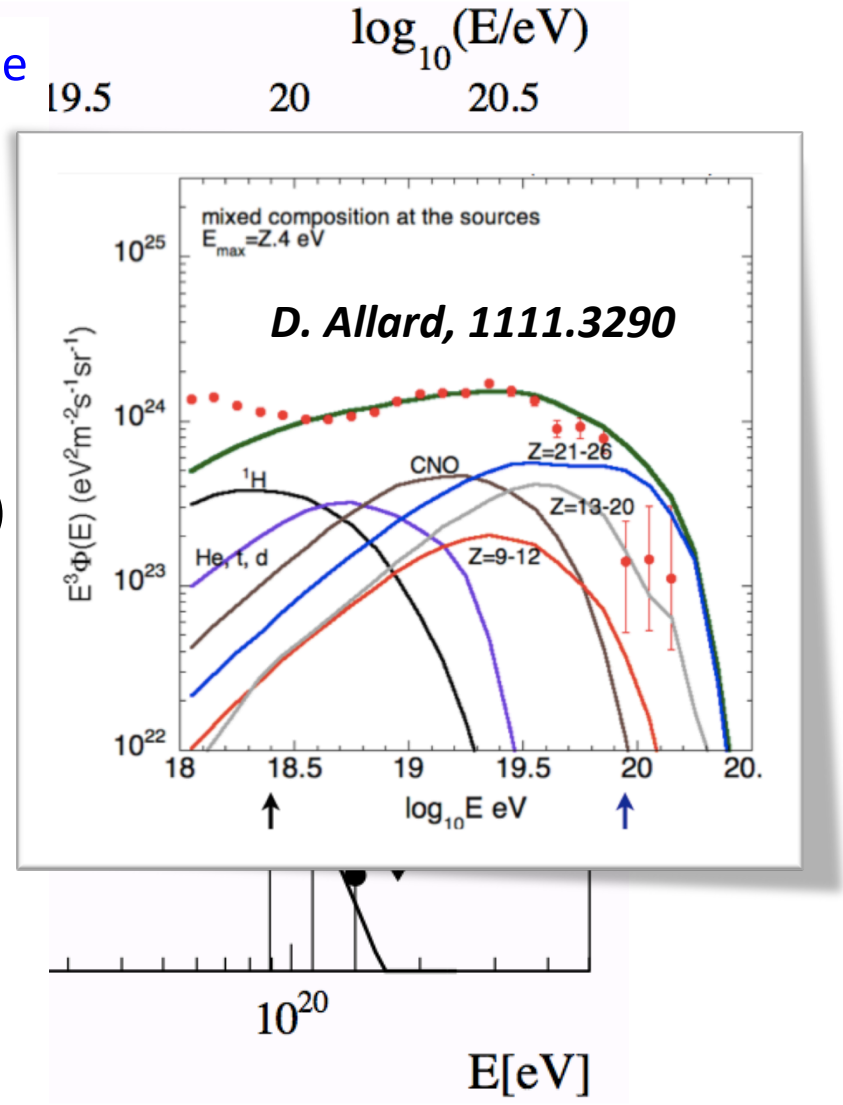
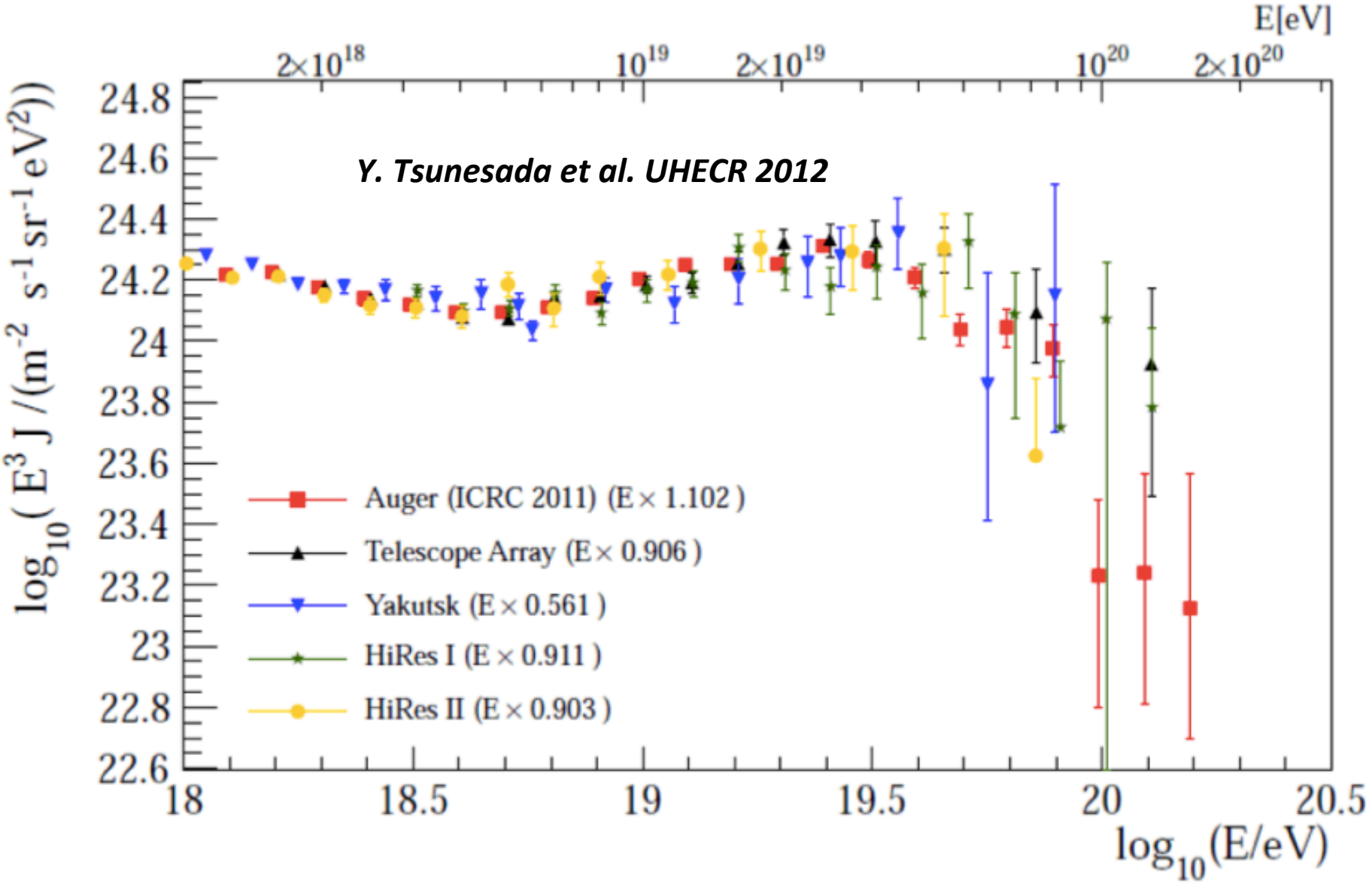


Energy Spectrum comparison



Auger/HiRes /TA compatible within their energy scale systematic uncertainties

Summary of the results

We measure the CR energy spectra using:

- **SD vertical events, zenith < 60^0**
- **SD inclined events 62^0 > zenith < 80^0**
- **FD hybrid events**
  - **Full agreement within the uncertainties.**
  - **Combined spectrum -> Energy > 10^{18} eV**

Two features are observed in the Energy spectrum.

- **Ankle clearly observed around (E ~ 4.2 X 10^{18} eV)**
- **Flux suppression established at (E > 4.3 X 10^{19} eV)**

The shape and energy scale of the spectrum are compatible with others CR experiments within the systematics uncertanties.