High-energy interactions at the Pierre Auger Observatory

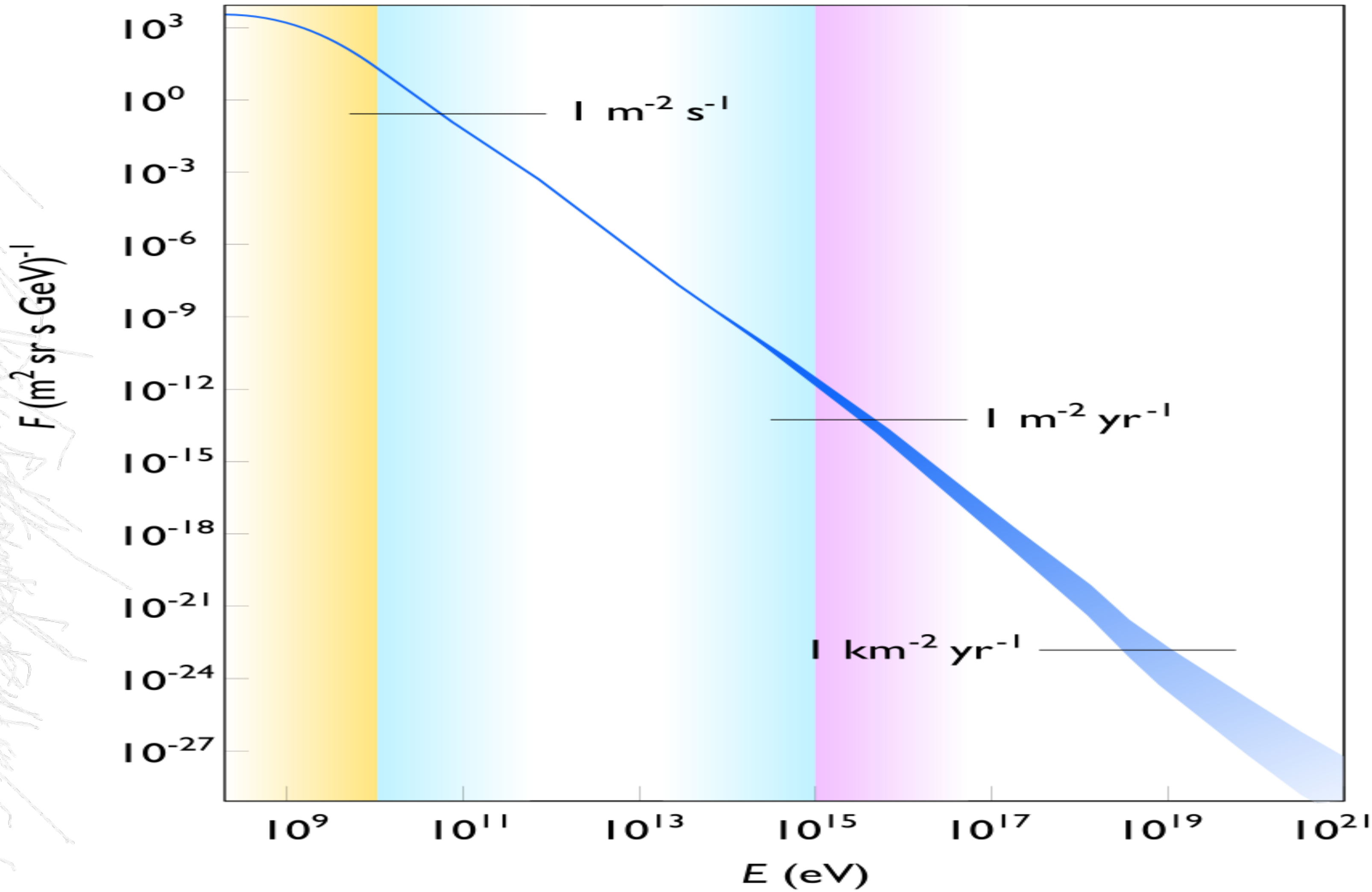
Ruben Conceição

for the Pierre Auger Collaboration

EPS – HEP2015, Vienna, July 23rd 2015

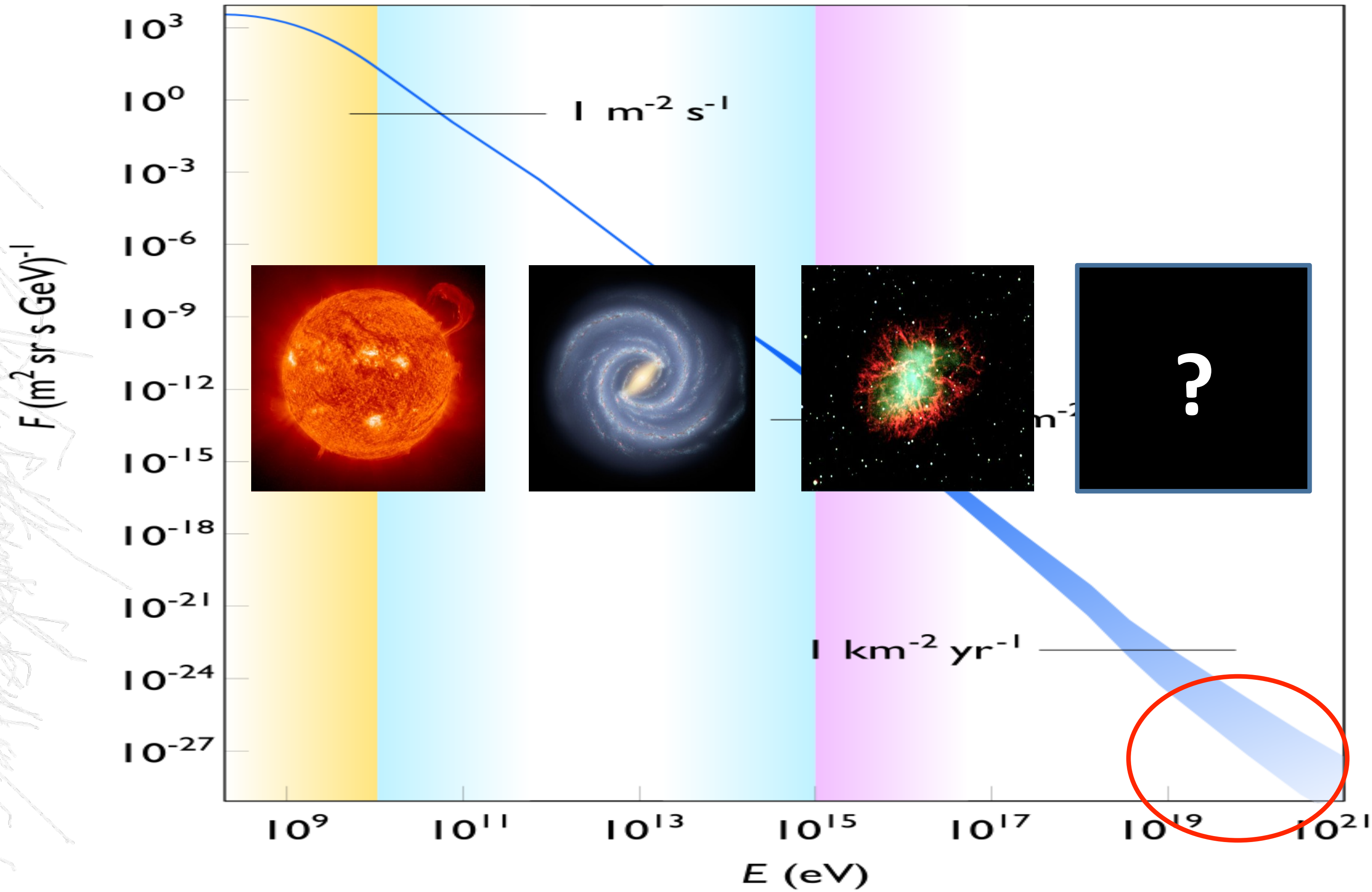
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum



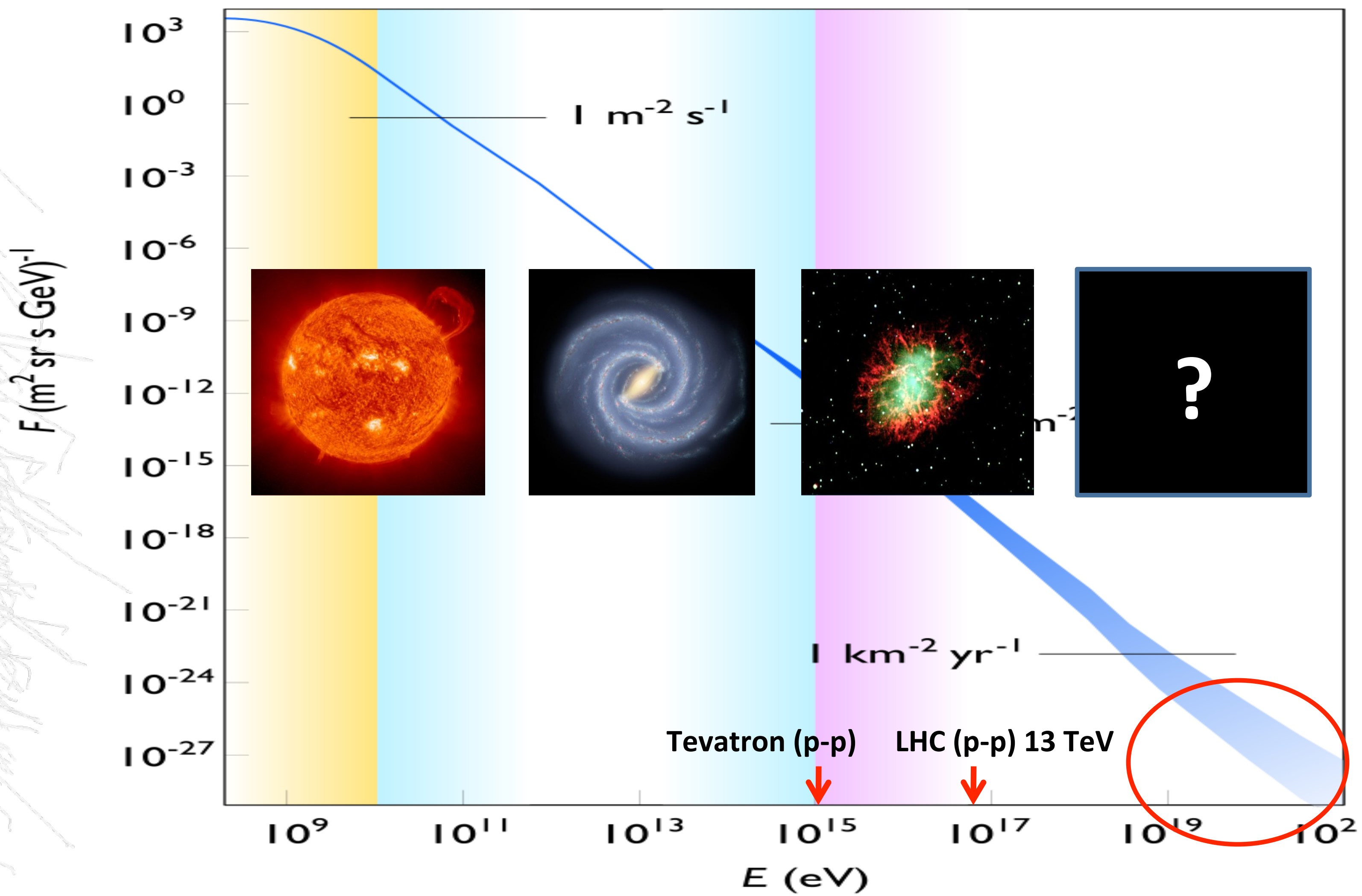
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum



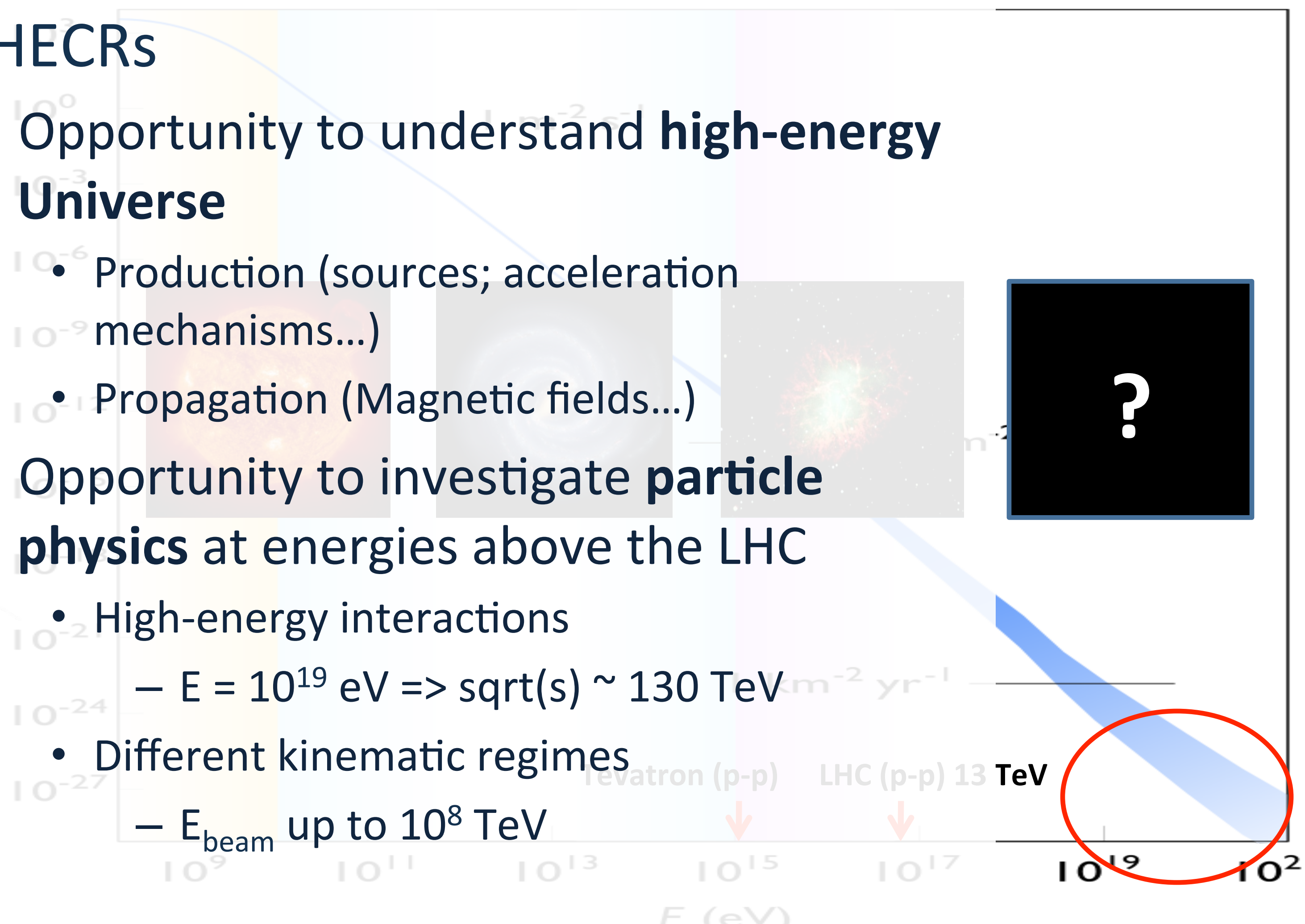
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum



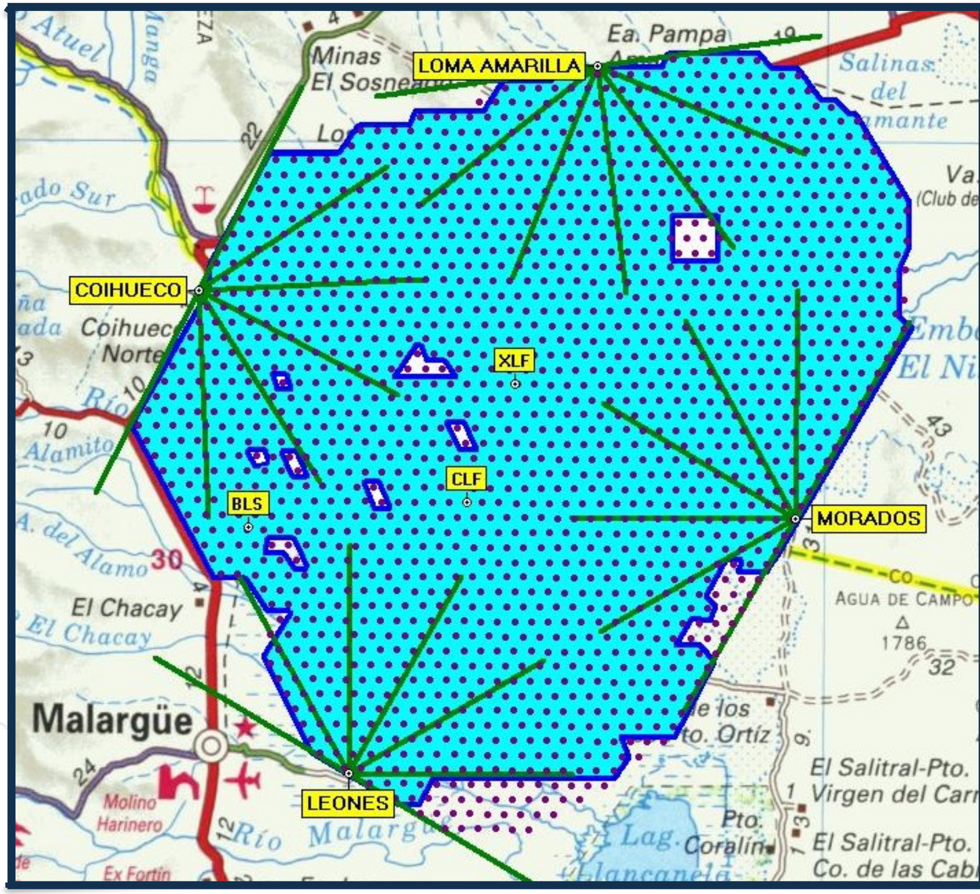
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum



- UHECRs
  - Opportunity to understand **high-energy Universe**
    - Production (sources; acceleration mechanisms…)
    - Propagation (Magnetic fields…)
  - Opportunity to investigate **particle physics** at energies above the LHC
    - High-energy interactions
      - $E = 10^{19}$ eV => sqrt(s) ~ 130 TeV
    - Different kinematic regimes
      - E_{beam} up to 10^{8} TeV

Pierre Auger Observatory



~ 60 km

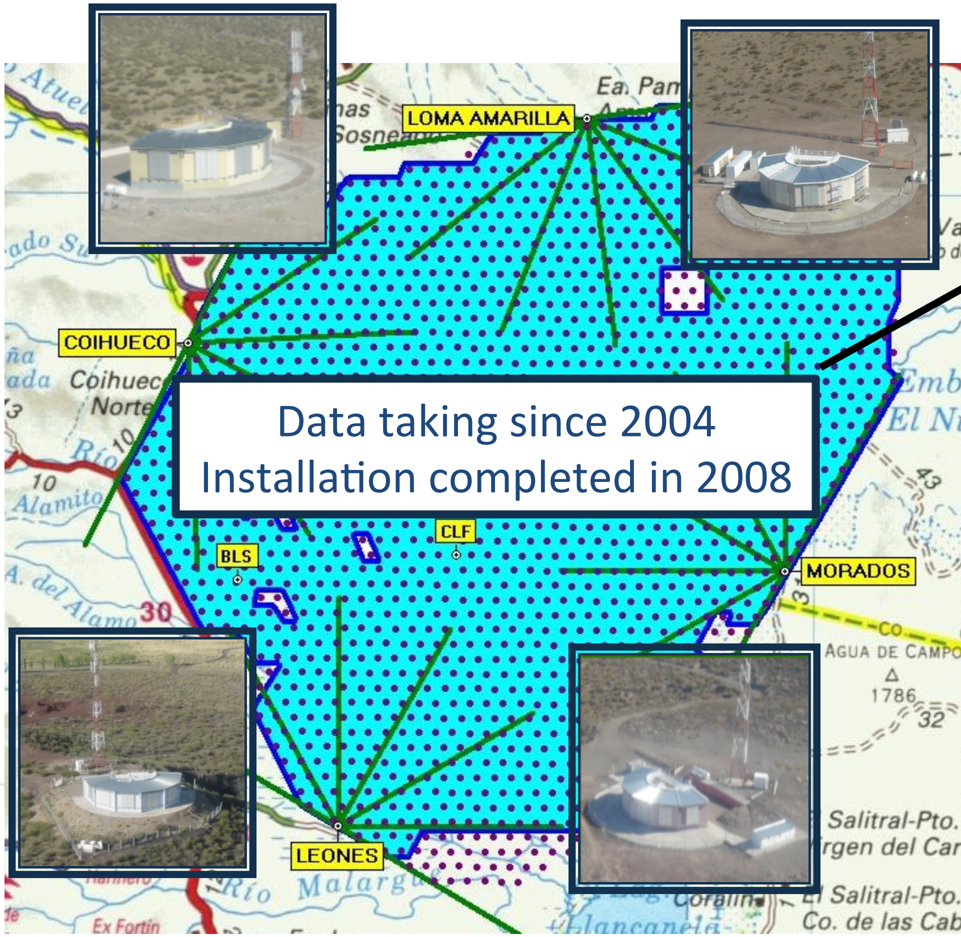
UHECR flux:

~ 1 km^-2 century^-1

Located in the Pampa Amarilla, Mendoza, Argentina

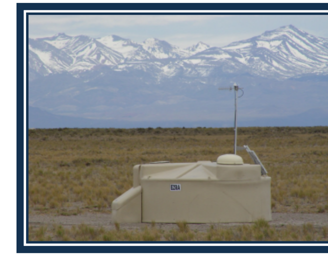
Altitude: 1400 m a.s.l.

Pierre Auger Observatory



~ 60 km

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



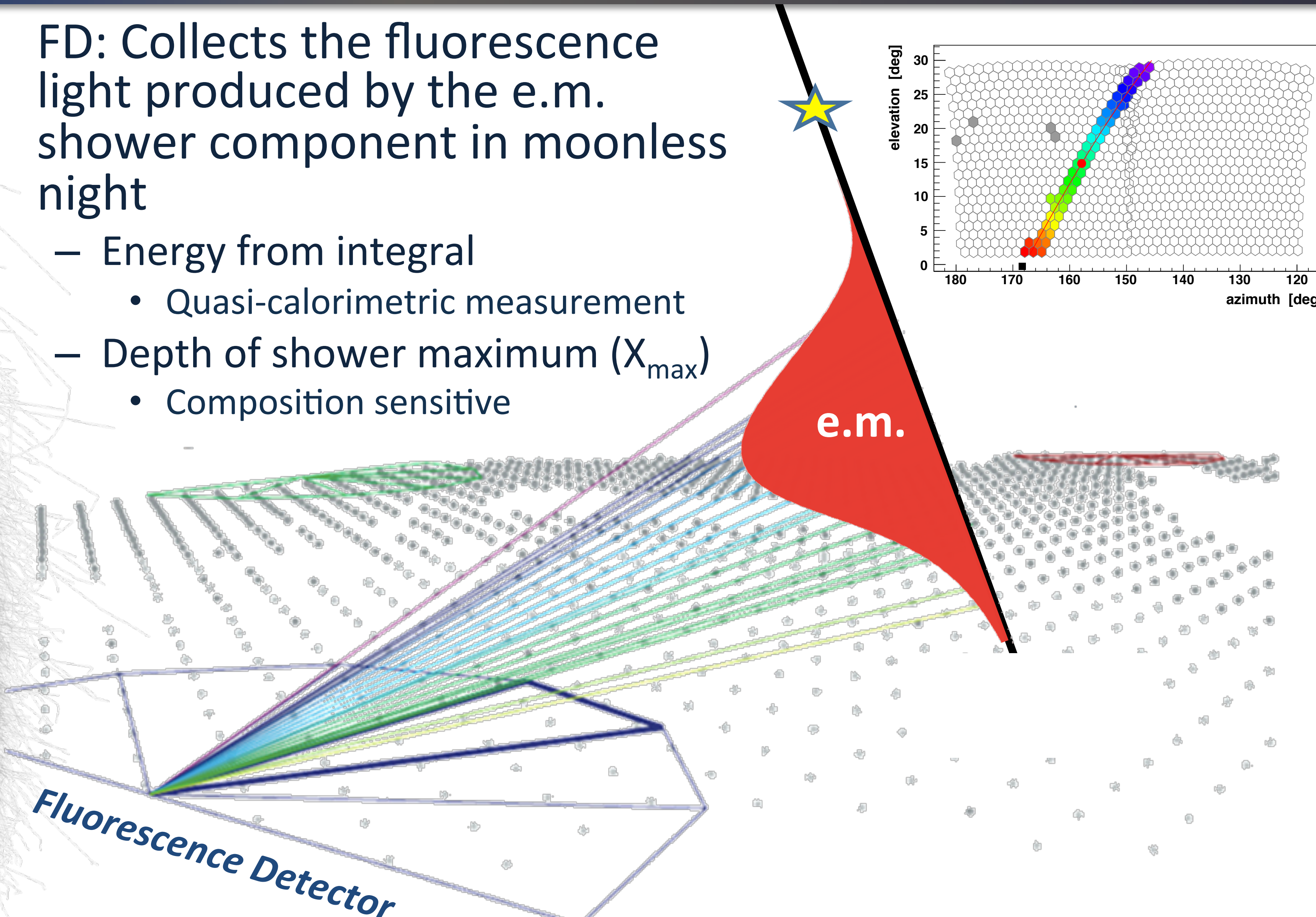
- ~ 1600 Surface Detector (SD) Stations
- 1.5 km spacing
- 3000 km^2

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

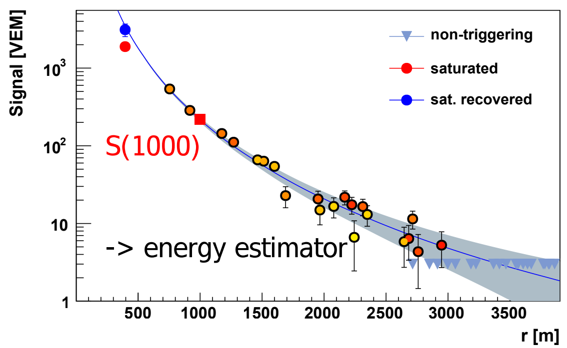
What is measured?

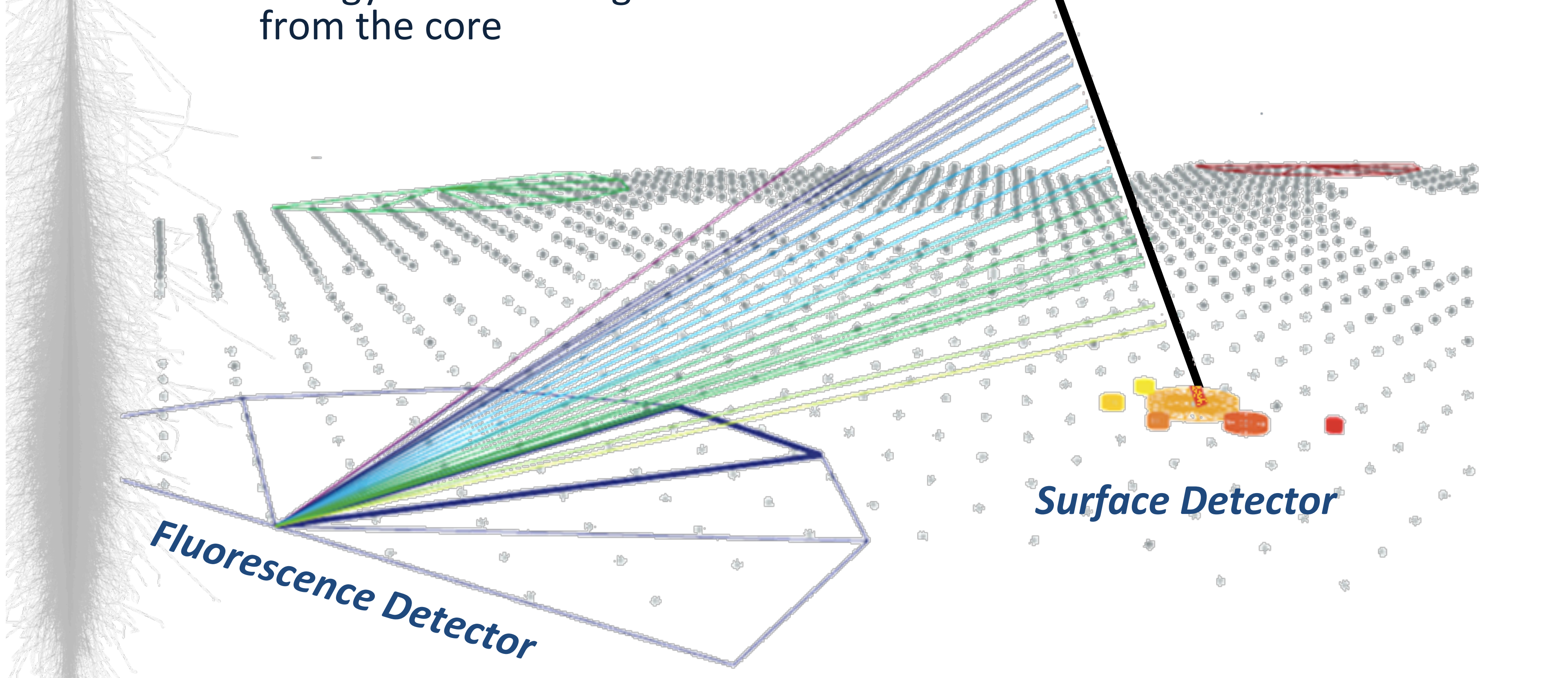
- FD: Collects the fluorescence light produced by the e.m. shower component in moonless night
  - Energy from integral
    - Quasi-calorimetric measurement
  - Depth of shower maximum (X_{max})
    - Composition sensitive



What is measured?

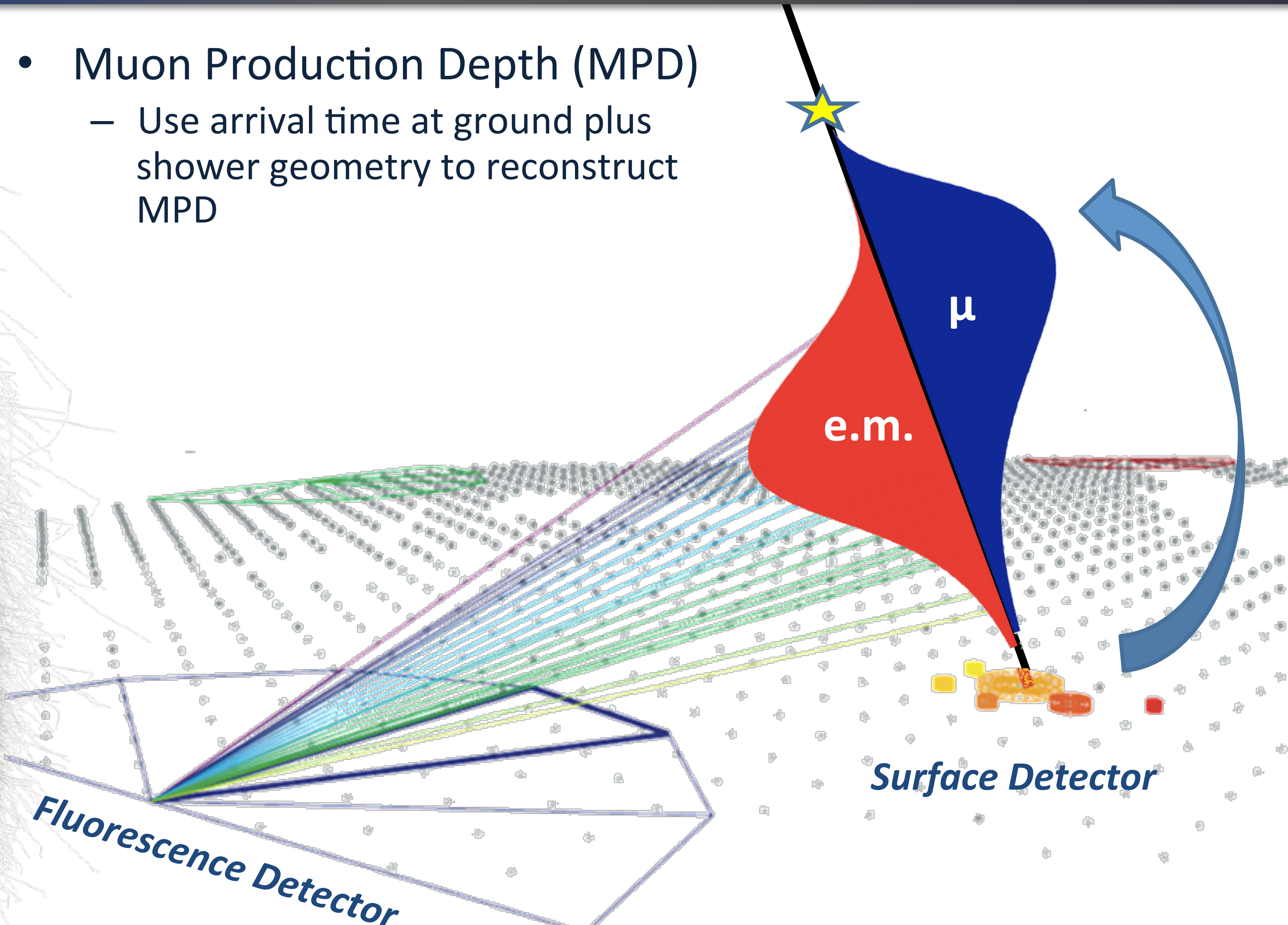
- SD: Sample the charged secondary particles that arrive at ground
  - 100% duty cycle
  - Shower direction: from arrival time
  - Energy estimator: signal at 1000 m from the core



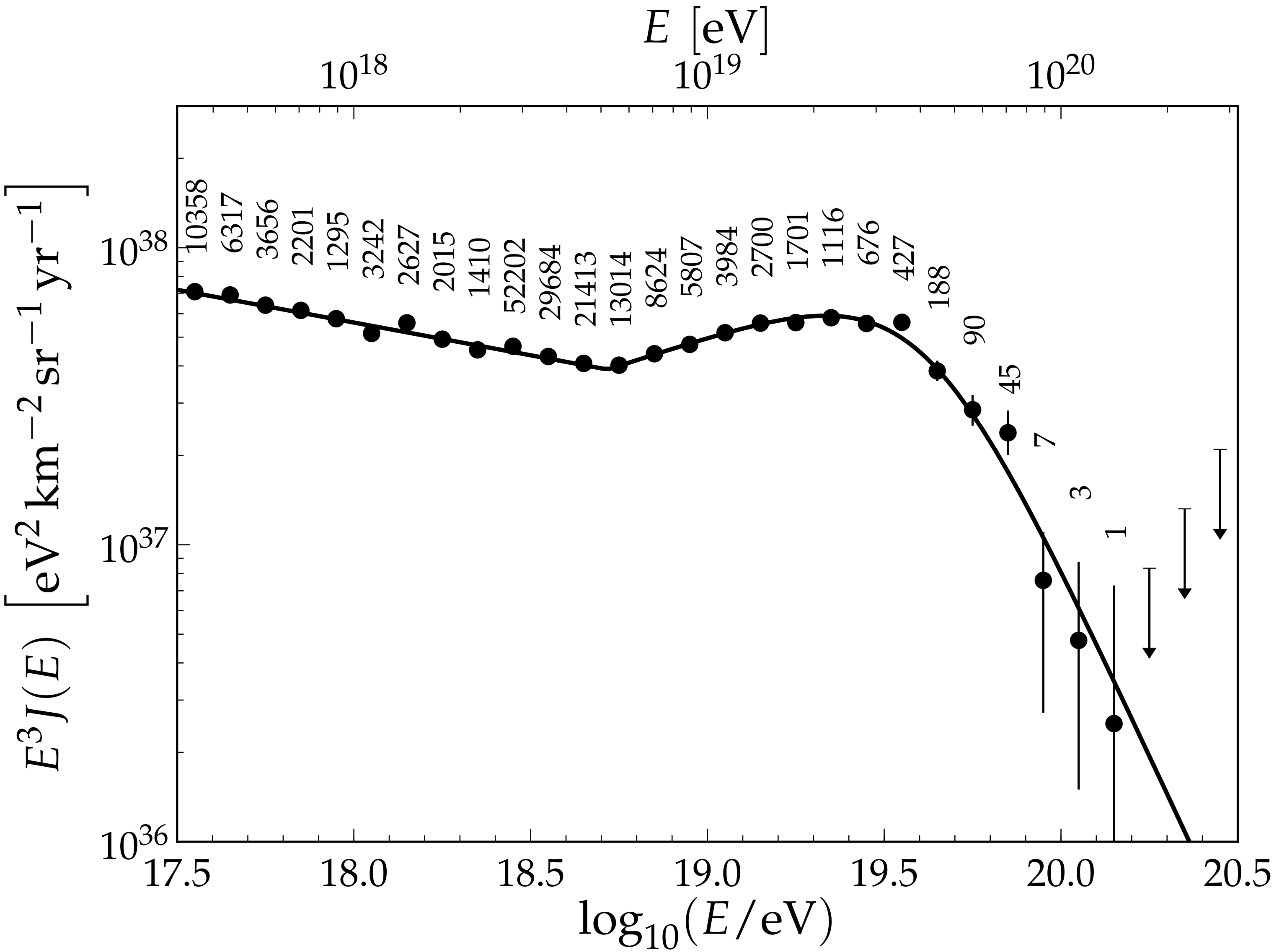


What is measured?

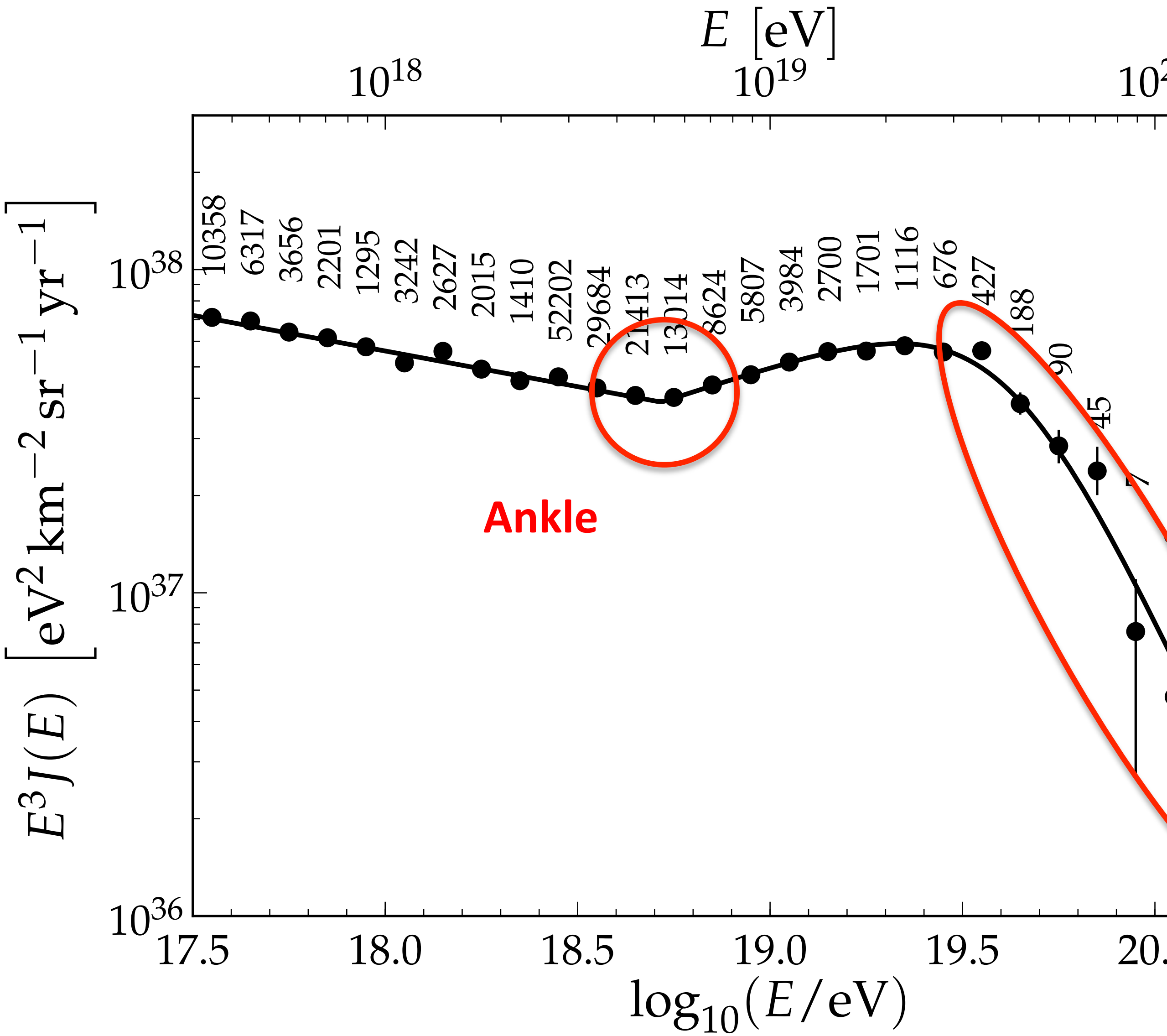
- Muon Production Depth (MPD)
  - Use arrival time at ground plus shower geometry to reconstruct MPD



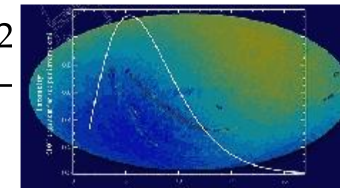
UHECRs Energy Spectrum

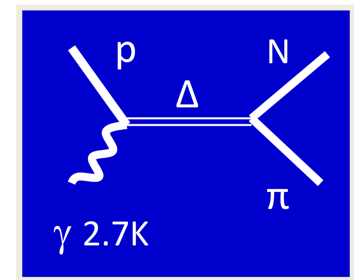


UHECRs Energy Spectrum



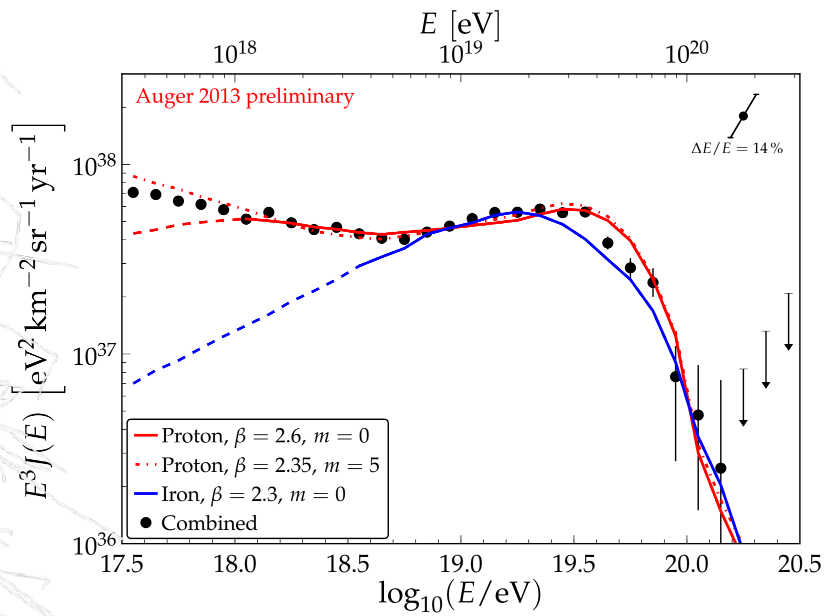
GZK effect





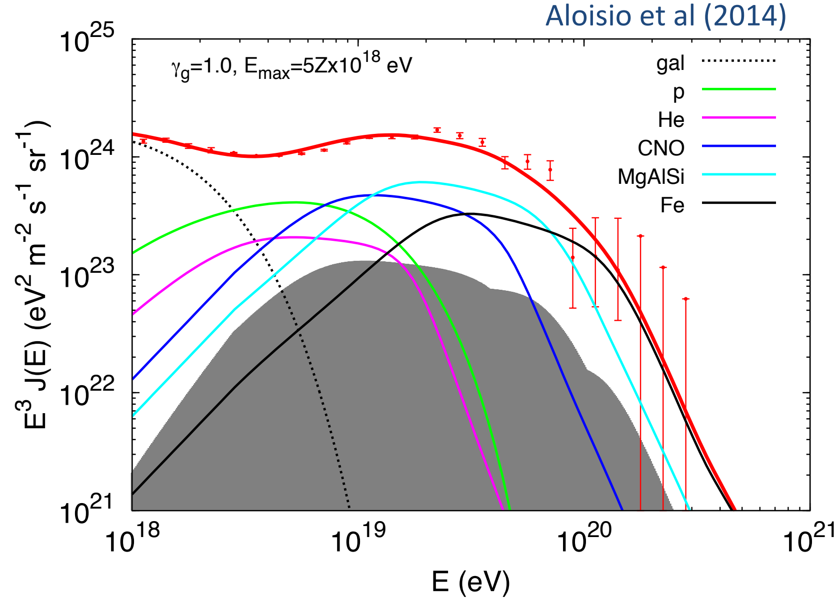
UHECRs Energy Spectrum

Pure proton or Fe nuclei at source
Cutoff caused by **GZK or photo-disintegration**



Mixed composition at source
Cutoff caused by **source energy exhaustion**

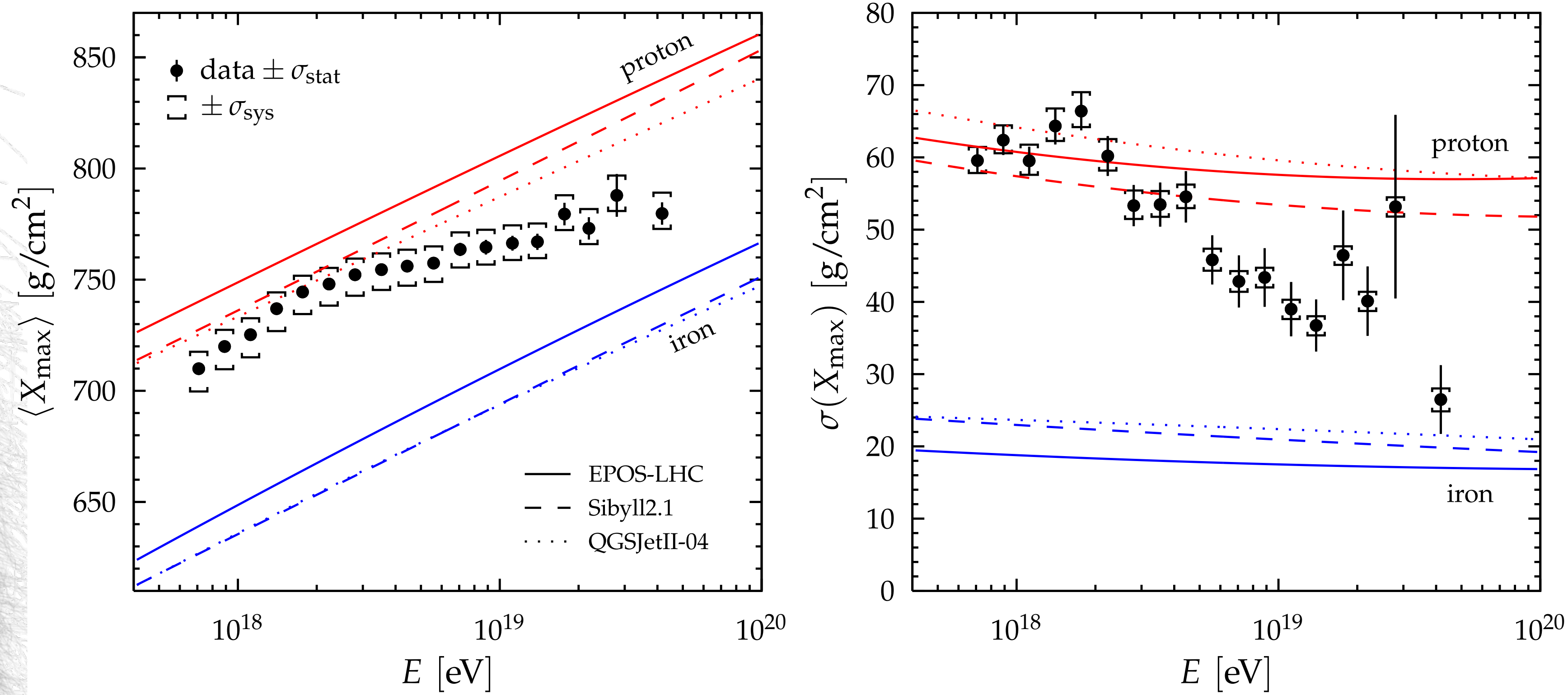
Aloisio et al (2014)



The UHECR composition is the key to understand the spectrum features cause

Depth of Shower Maximum (X_{max})

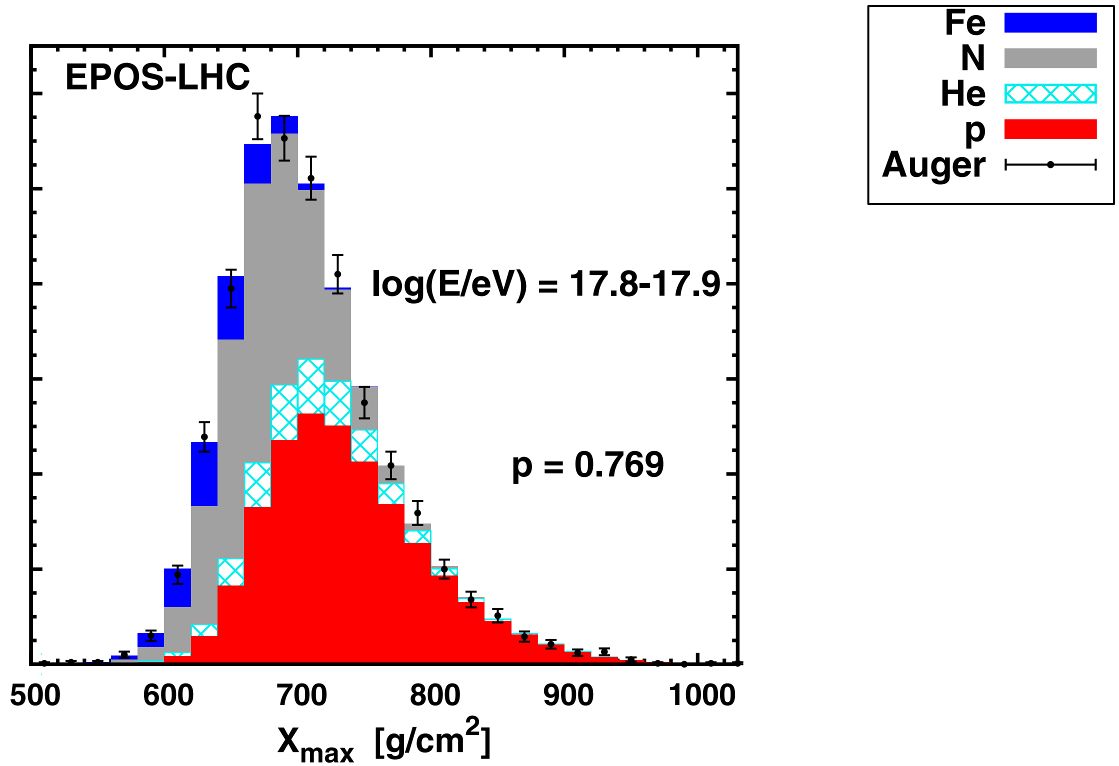
Phys.Rev. D90 (2014) 12, 122005



- Average X_{max} and its RMS consistent with a lighter(heavier) composition at lower(higher) energies
- Change on elongation rate around log(E/eV) = 18.2

Mass composition interpretation

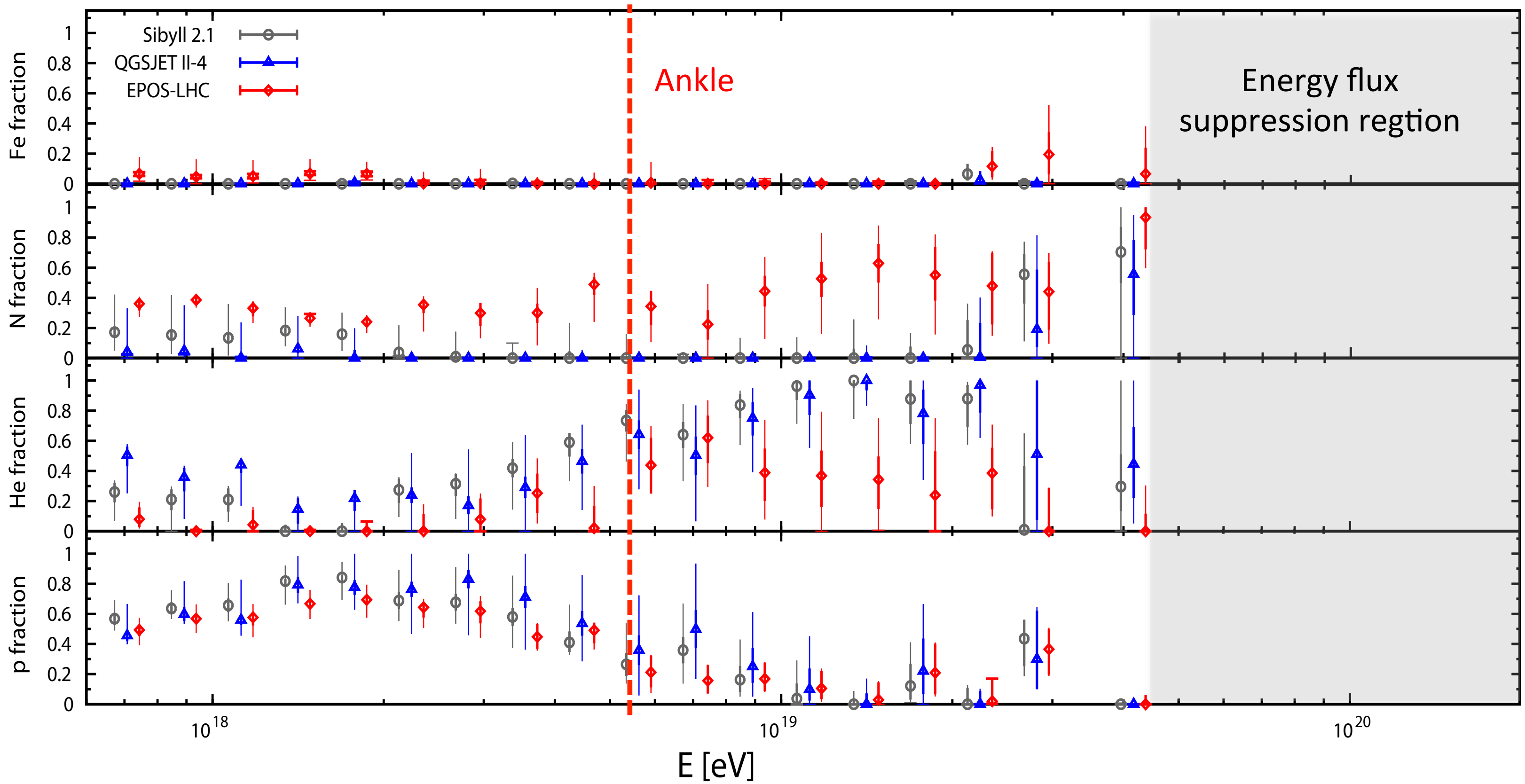
Phys.Rev. D90 (2014) 12, 122006



- Interpretation of the X_{max} distribution in terms of mass composition
  - Depends on the performance of hadronic interaction models

Mass composition interpretation

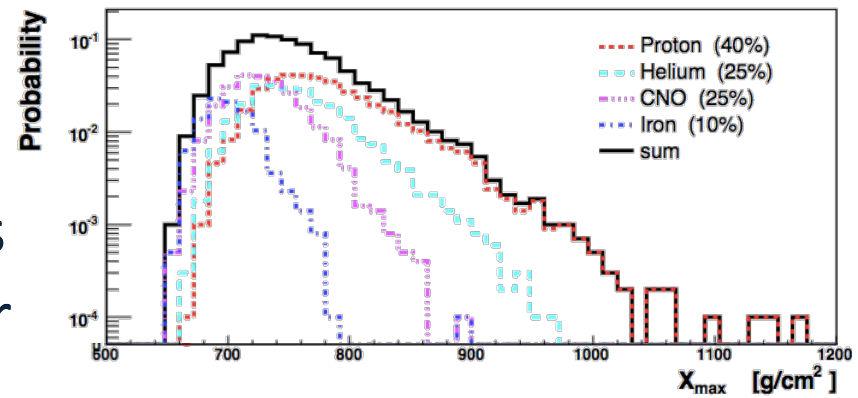
Phys.Rev. D90 (2014) 12, 122006

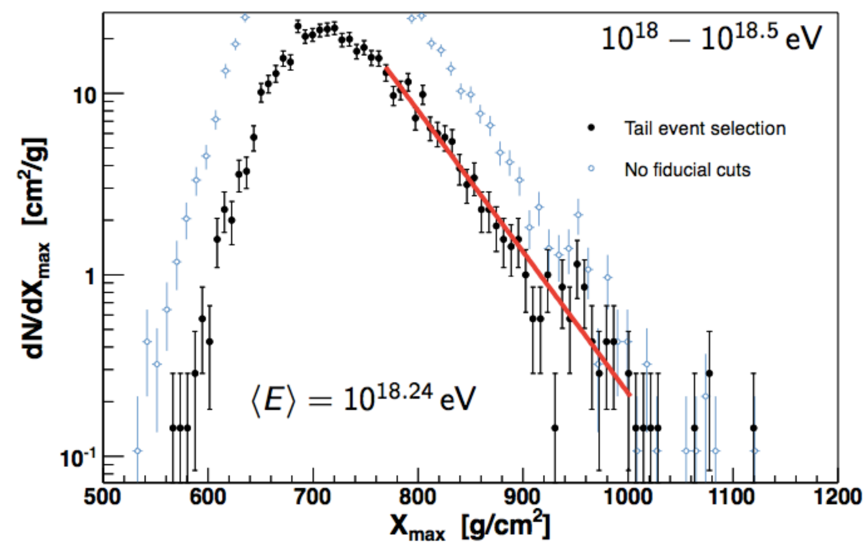


- Interpretation of the X_{max} distribution in terms of mass composition
  - Depends on the performance of hadronic interaction models
    - Mostly proton at low energies
    - Intermediate mass states at the highest available energies
    - Nearly no iron

Proton-air Cross-section ($\sqrt{s}$=57 TeV)

- X_{max} distribution tail is sensitive to the primary cross-section
- If there is enough proton it is possible to measure the p-air cross-section at very high energies

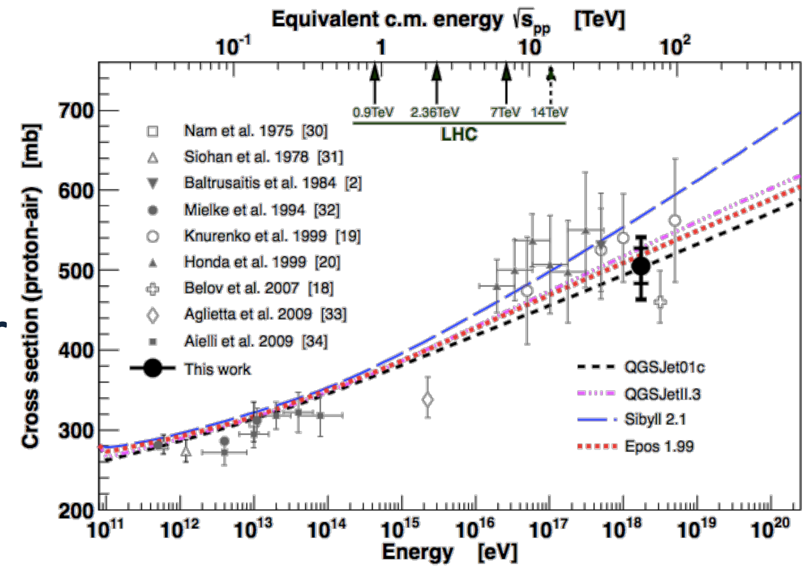


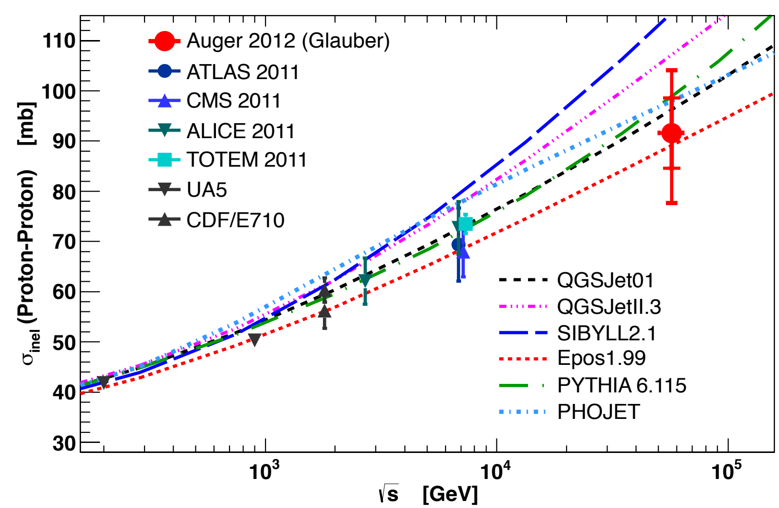


Proton-air Cross-section

- X_{max} distribution tail is sensitive to the primary cross-section
- If there is enough proton it is possible to measure the p-air cross-section at very high energies
- Measurement performed at:
  - E = $10^{18.25}$ eV
  - $\sqrt{s}$ = 57 TeV
- Using Glauber theory is possible to translate this result into p-p cross-section

Phys. Rev. Lett. 109, 062002 (2012)

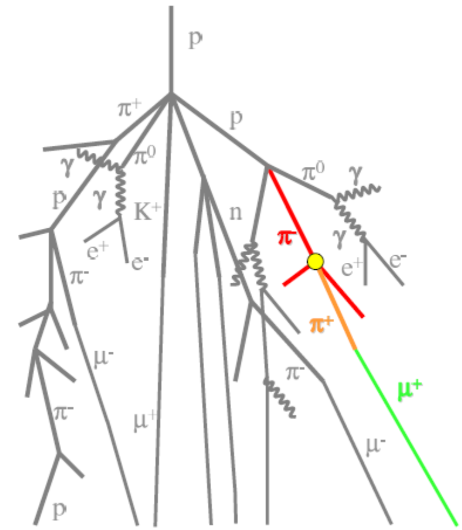


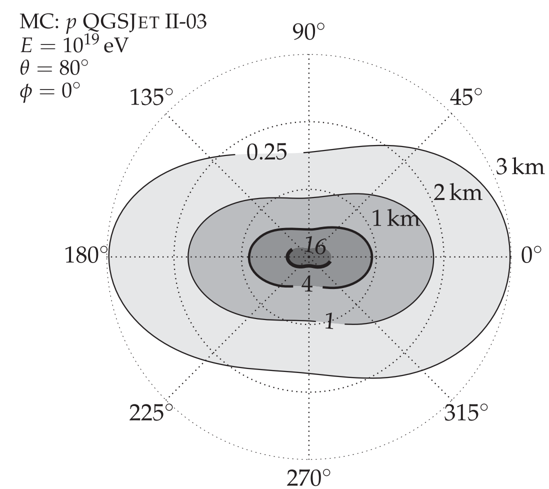


Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component
- Through inclined showers is possible to measure directly the muon content (R_μ) in the SD
  - Electromagnetic shower component gets attenuated

Phys.Rev. D91 (2015) 3, 032003

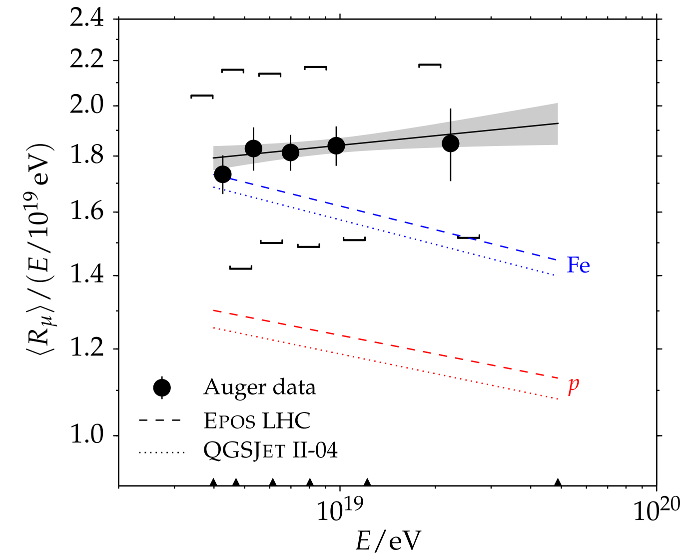


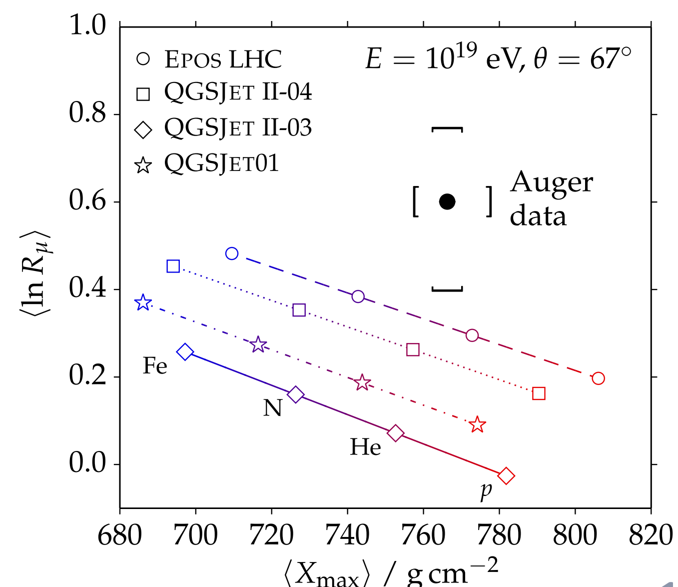


Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component
- Through inclined showers is possible to measure directly the muon content (R_μ) in the SD
  - Electromagnetic shower component gets attenuated
- Mean muon number compatible with iron showers within systematic uncertainties
- Combination of the R_μ with X_{max} shows tension between data and all hadronic interaction models

Phys.Rev. D91 (2015) 3, 032003

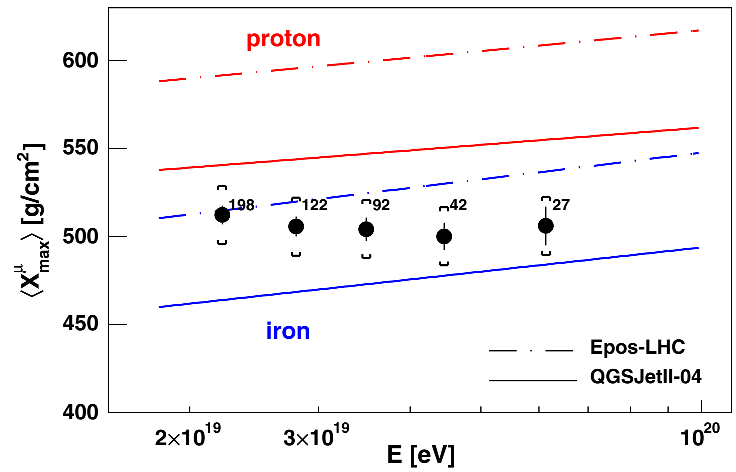


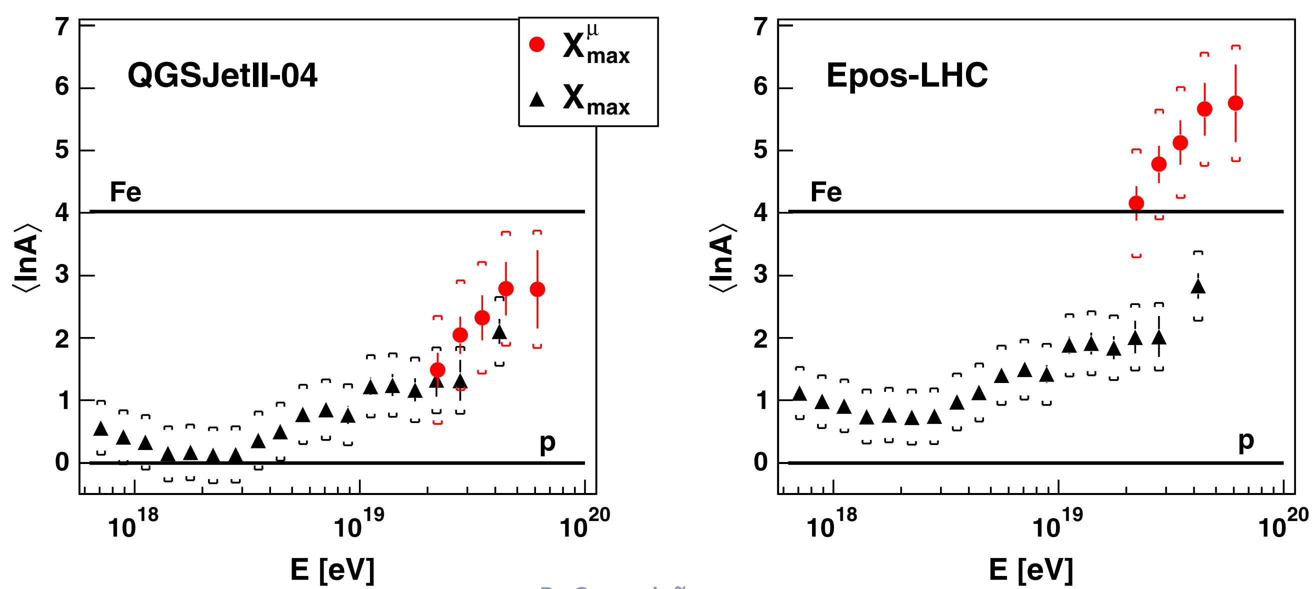


Shower consistency

- Muon Production Depth
  - Sensitive to composition
- Mean X_{max} and X^{μ}_{max} should give the same average mass composition
  - EPOS-LHC fails to provide a consistent solution

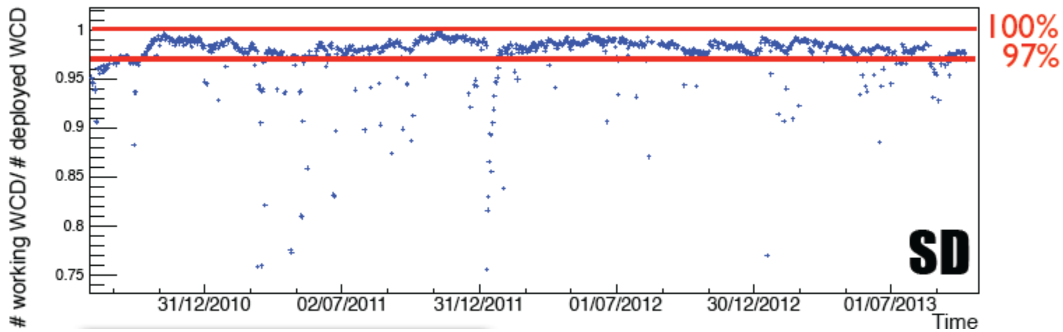
Phys.Rev. D90 (2014) 1, 012012

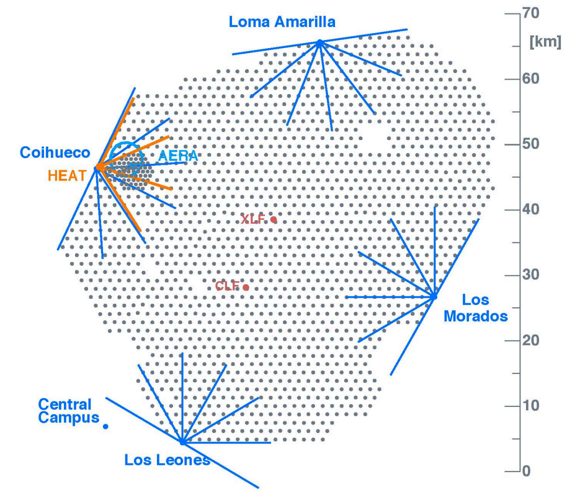




Auger upgrade

Fraction of Cherenkov tanks in operation





- Auger PRIME – "Primary cosmic Ray Identification through Muons and Electrons"
  - Scintillator on top of the tank to measure directly e.m. shower component
  - WCD measures e.m. + muons
  - Upgrade to:
    - Enhance primary identification
    - Improve shower description
    - Reduce systematic uncertainties

Summary

- UHECRs measured at Pierre Auger Observatory
  - Opportunity to study the high-energy Universe and Particle Physics at the highest energies
- Pierre Auger Observatory has delivered many important results
  - GZK-like suppression established
  - Unexpected primary mass composition scenarios
  - Current hadronic interaction models not able to describe consistently the air shower observables
- Upgrade: Auger PRIME
  - Measure independently the e.m. and muonic component at ground

Acknowledgments

FCT
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COMPETE
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BACKUP SLIDES

Mass composition interpretation

Phys.Rev. D90 (2014) 12, 122006