Ultra-High-Energy Cosmic Rays: A Tale of Two Observatories

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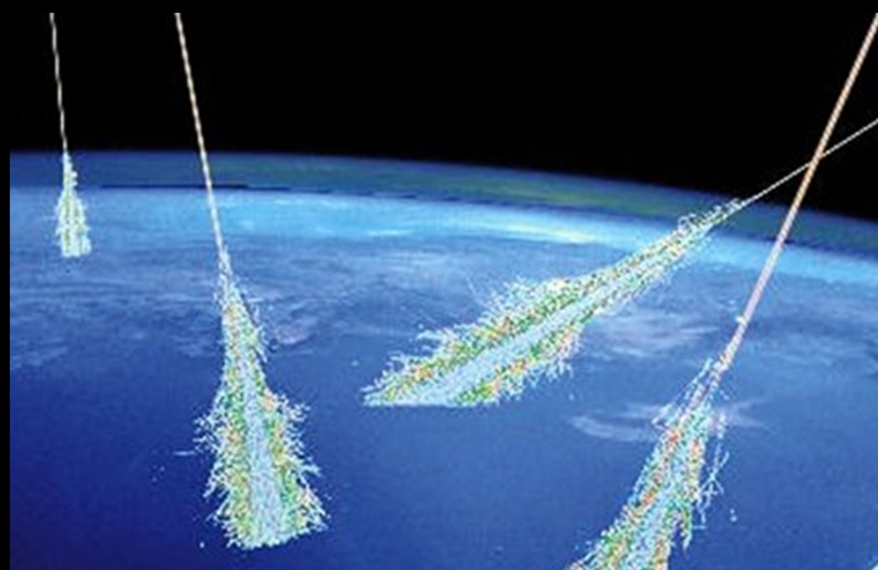
“Measurement of the Depth **of** Maximum **of** Extensive Air Showers above 10^{18} eV,"*Phys. Rev. Letters* **104** (2010) 091101
“Indications of Proton-Dominated Cosmic Ray Composition Above 1.6 EeV” *Phys.Rev.Lett*. **104** (2010) 161101

Outline

- Introduction: Basics of Extensive Air Showers
- Methods of detection
- Data reconstruction
- Findings, Interpretations, and Implications

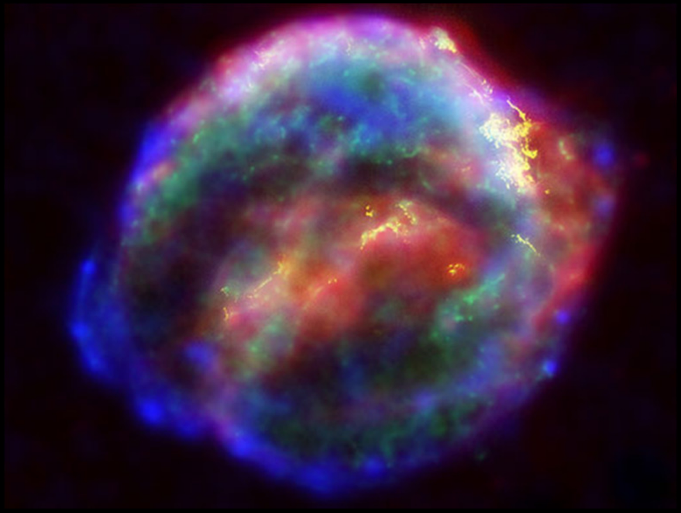
Cosmic Rays: Energetic Charged Particles

- Cosmic Rays are electrons, Protons, or Nuclei from Space
- They range in energy from 10^9 to over 10^{20} eV.
- The LHC only accelerates protons to about 10^{13} eV.



Cosmic rays and astrophysics

- Sources of ultra-high-energy cosmic rays largely unknown (Supernovae, Black Holes, Active Galactic Nuclei?)
- Composition of primary particle of ultra-high-energy cosmic rays unknown

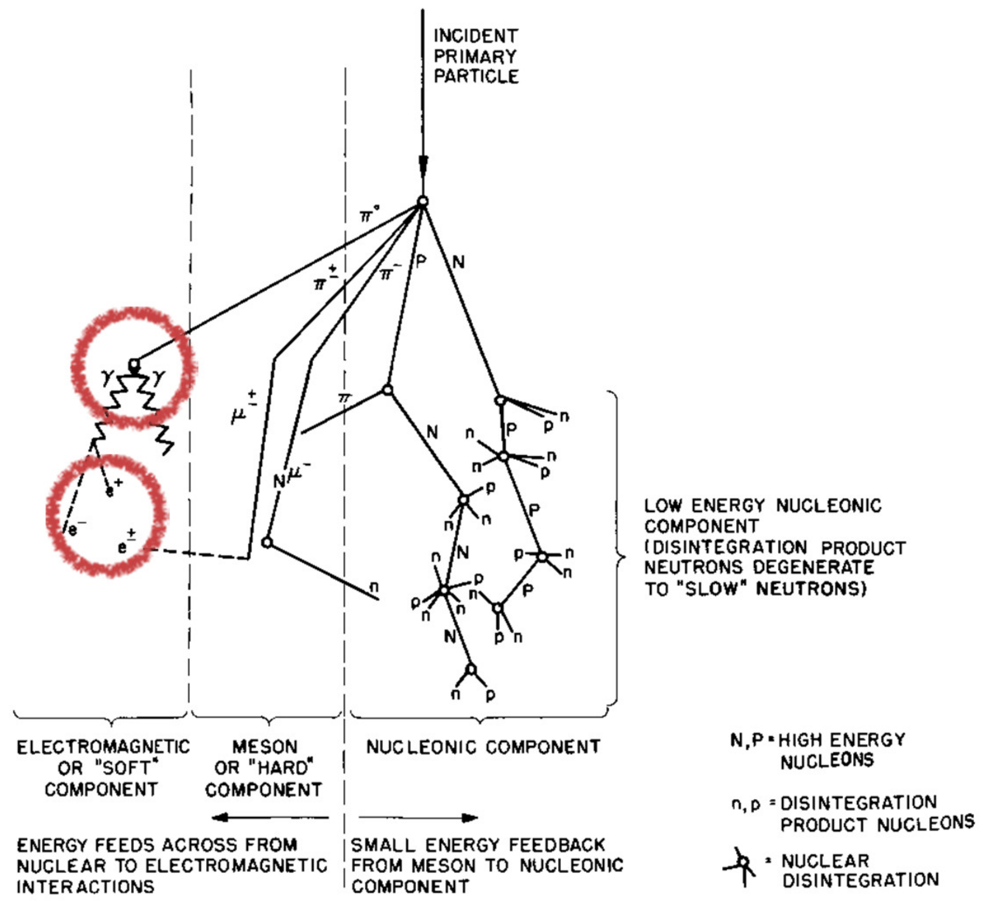


Shockwave and Supernova Remnant

Active Galactic Nucleus

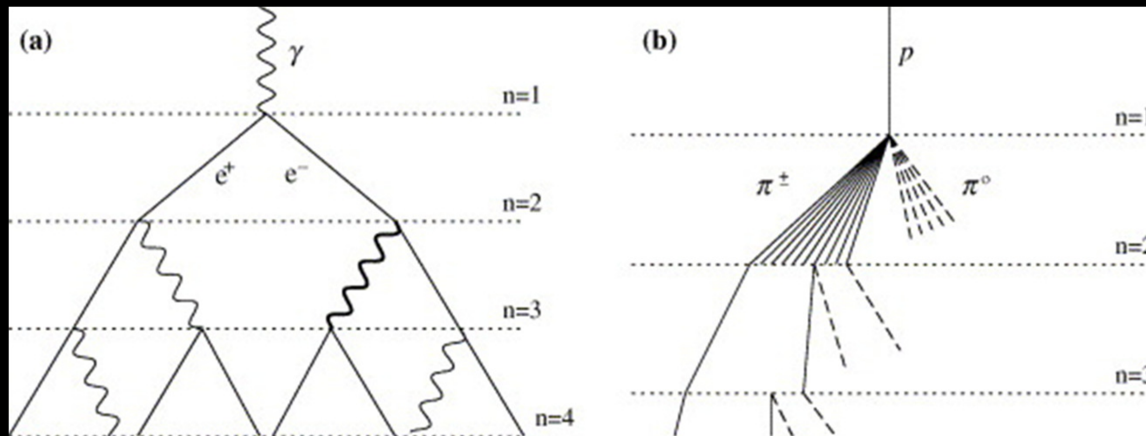
Cosmic Ray Air Shower

- A particle shower is initiated by CR - Atmosphere interaction. Particles and radiations are created during the period of shower development.
- Physicists detect a cosmic ray by detecting photons and electrons in its shower.
- The EM component carries 90% of shower energy.



Schematic Diagram of Cosmic Ray Shower

Basic Extensive Air Shower (EAS) Theory



Heitler Model

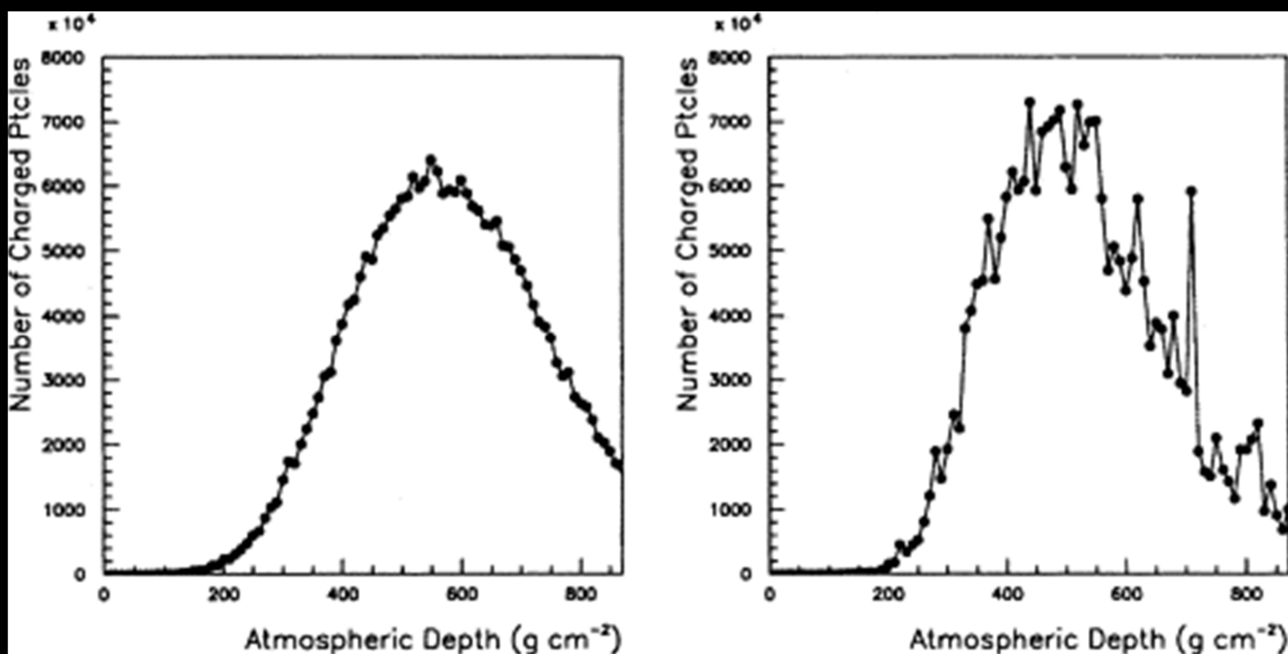
- Electromagnetic Component
- Photons decay into electrons and positrons, which in turn produce more photons
- Assumes decay happens at fixed lengths
- $X_{max} = \lambda_r \ln(\frac{E_0}{\xi_c^e})$
- $\Lambda \equiv \frac{dX_{max}}{dLog_{10}E_0}$

Hadronic Interactions

- Greater degree of complexity
- Computational Models and Monte Carlo Simulations
  - QGSJET01
  - QGSJET-II
  - SIBYLL

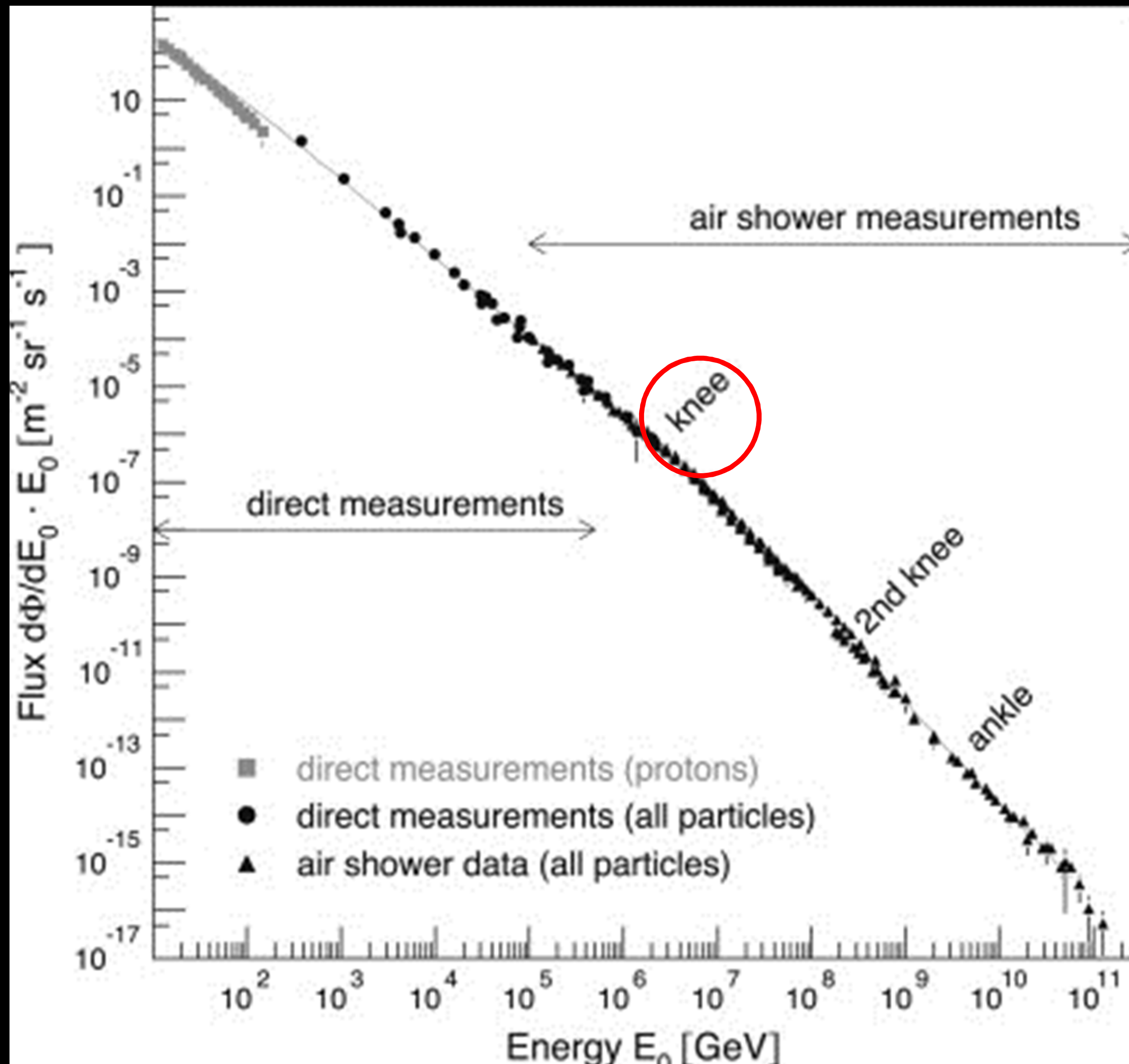
Important Quantities

- Depth of shower maximum (X_{max})
  - Can be used to determine primary energy
  - Can be used to determine primary mass
- Elongation Rate ($dX_{max}/dlogE$)



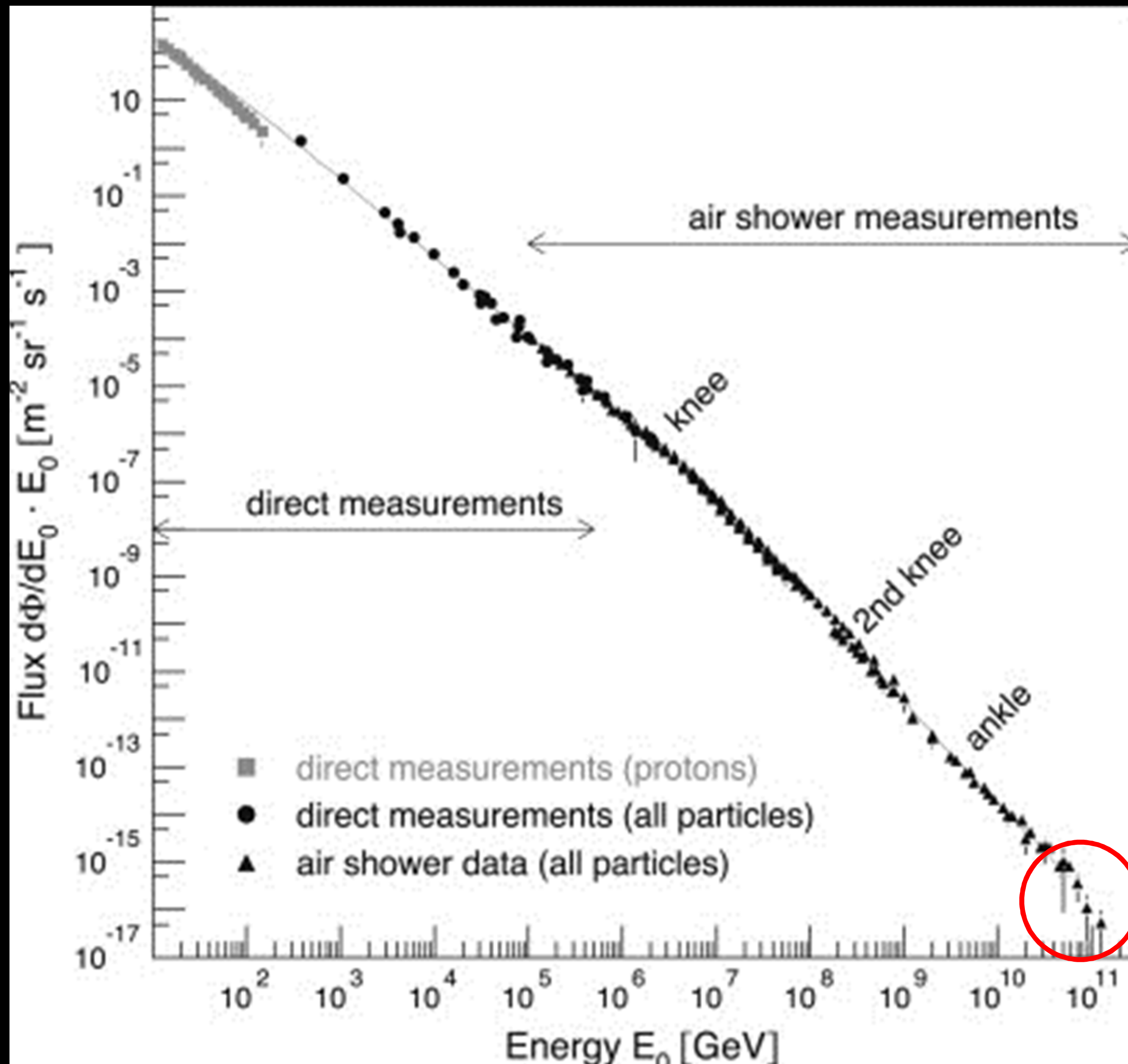
Flux vs. Energy Spectrum

- "Knee" in spectrum



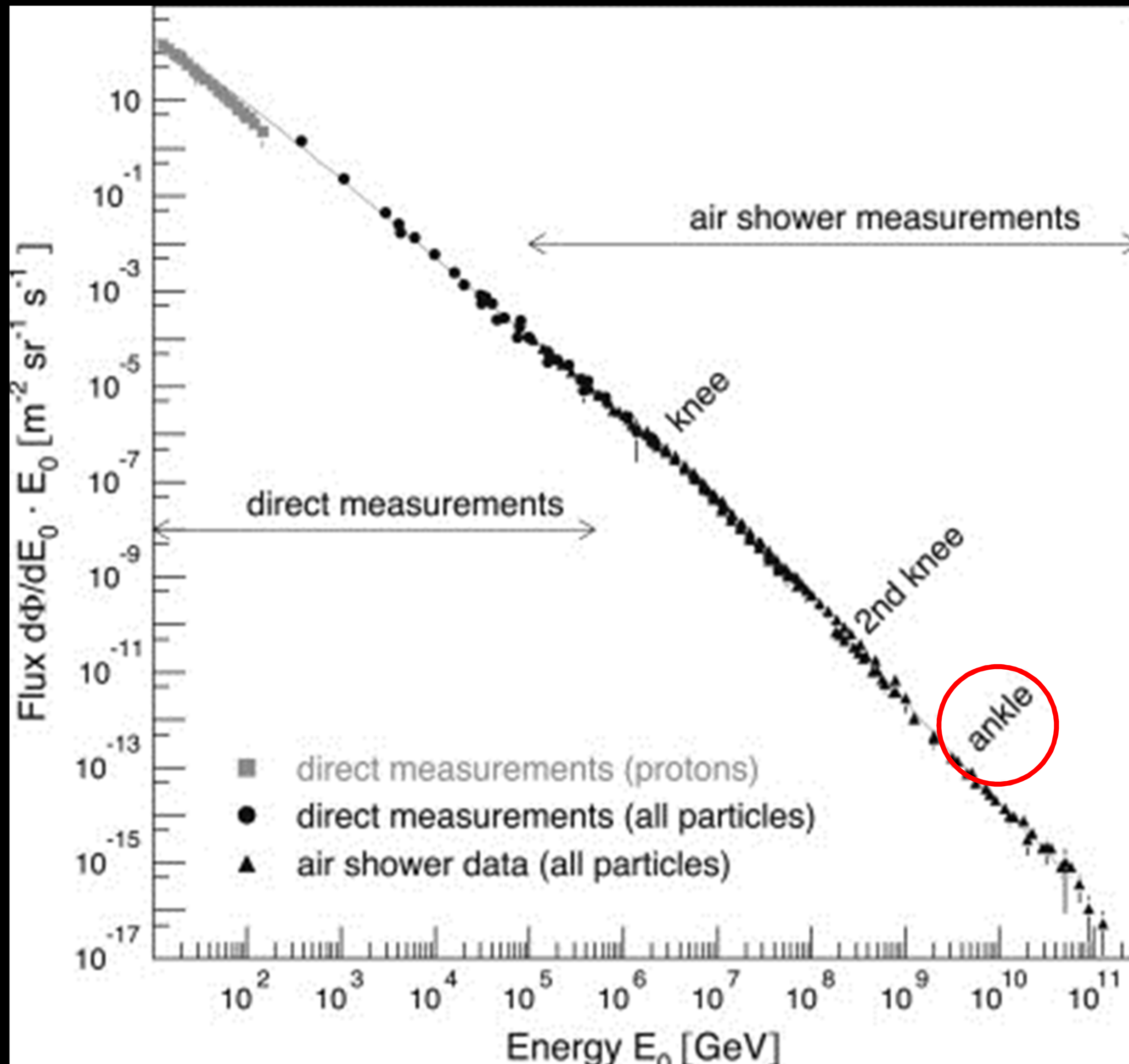
Flux vs. Energy Spectrum

- "Knee" in spectrum
- GZK Cutoff



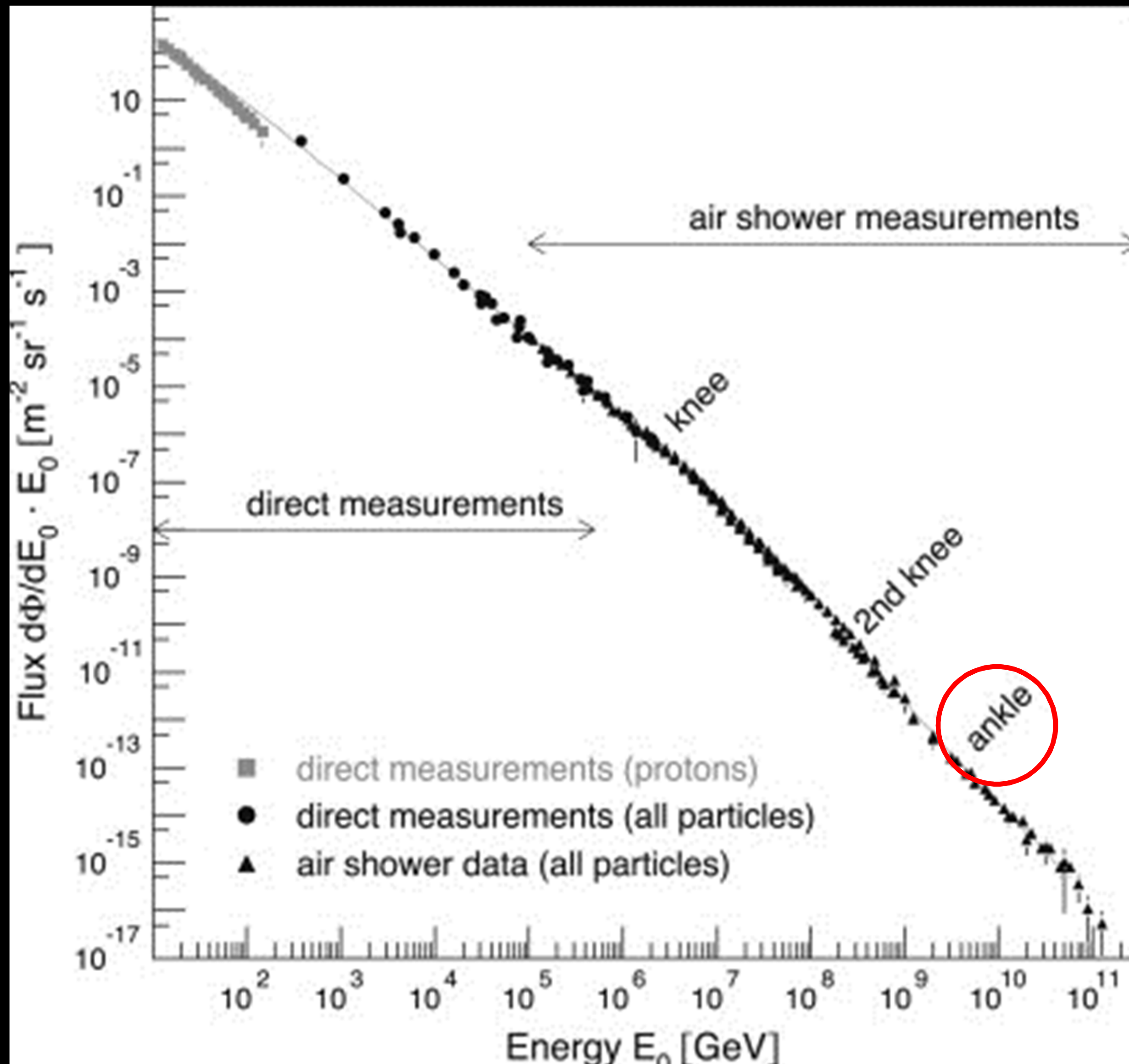
Flux vs. Energy Spectrum

- “Knee” in spectrum
- GZK Cutoff
- “Ankle” in spectrum



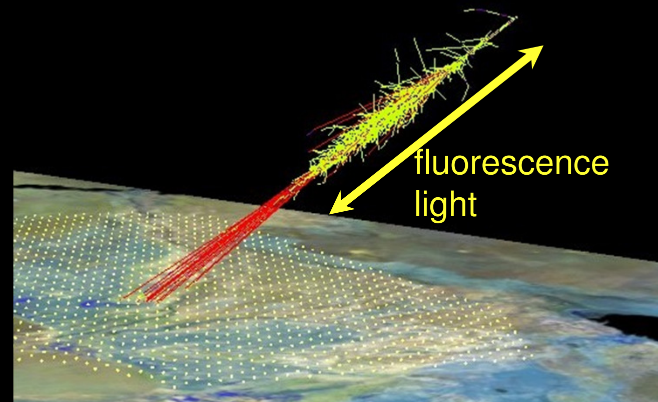
Flux vs. Energy Spectrum

- “Knee” in spectrum
- GZK Cutoff
- “Ankle” in spectrum
  - Extragalactic protons losing energy due to pair production?
  - Transition from galactic to extragalactic spectrum?

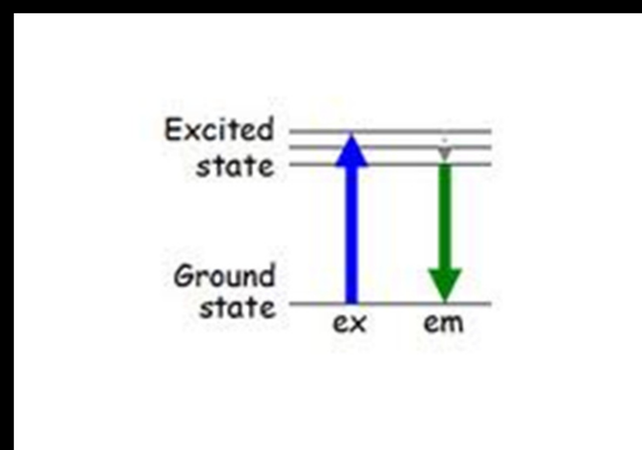


Detecting the Photon Component

The passage of charged particles through the atmosphere results in the ionization and excitation of the gas molecules (mostly nitrogen).

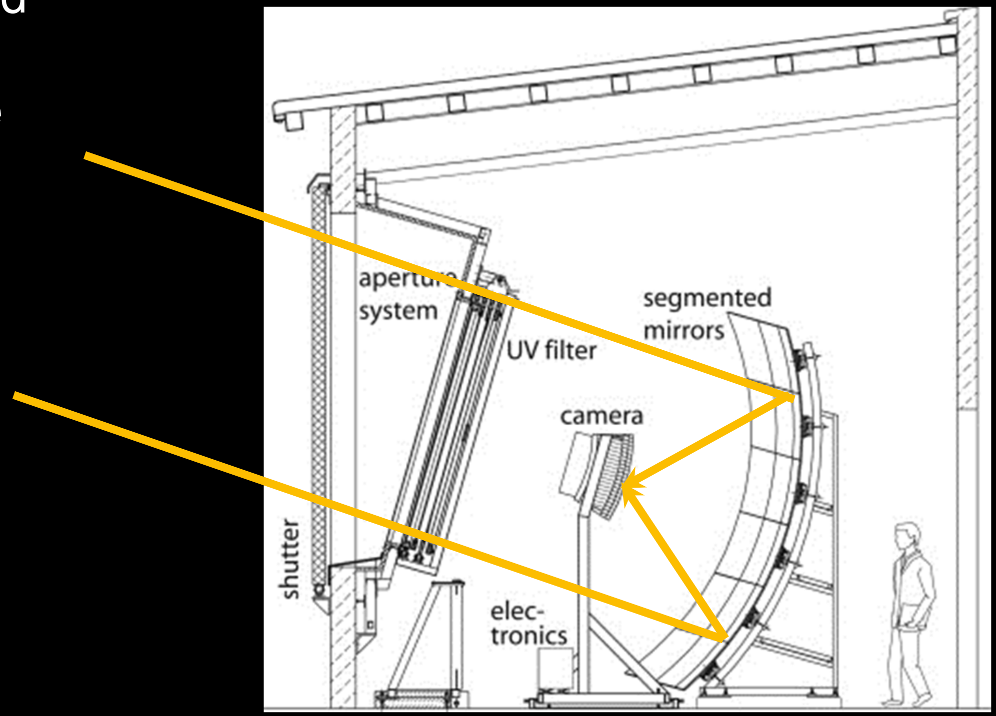


Some of this excitation energy is emitted in the form of visible and UV radiation.



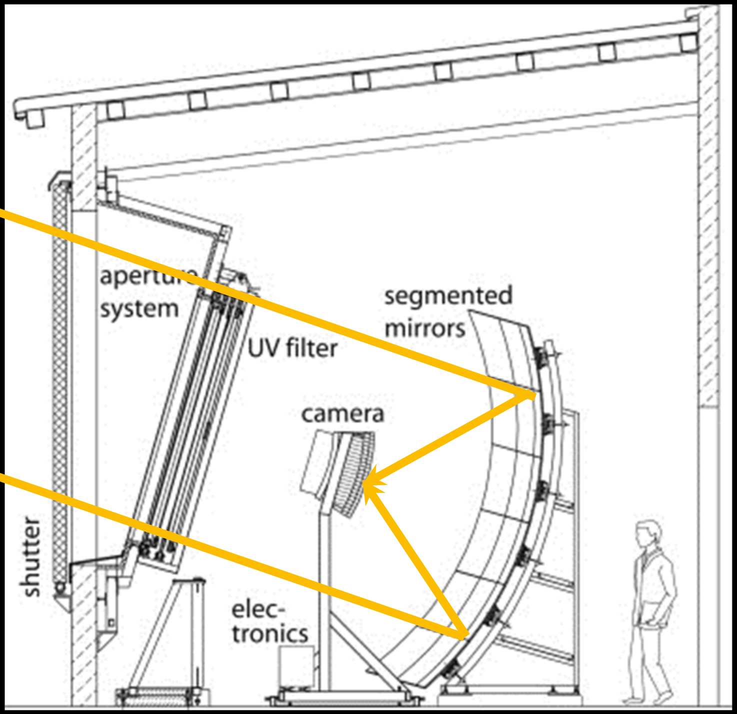
Detecting the Photon Component

The fluorescence light is collected by mirrors and reflected onto a camera. The camera records the image of the cosmic ray shower.



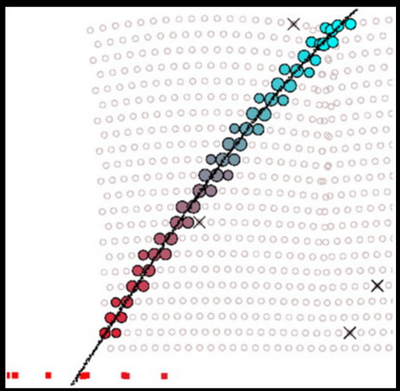
Detecting the Photon Component

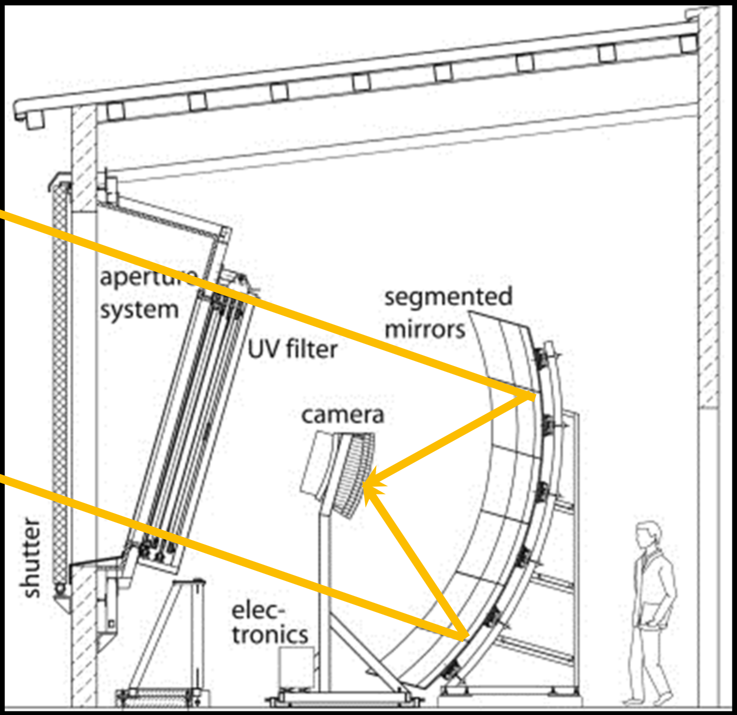
The camera is an array of photomultipliers (PMT). Each pixel of PMT can record the intensity and the timing information of the incoming fluorescence light.



Detecting the Photon Component

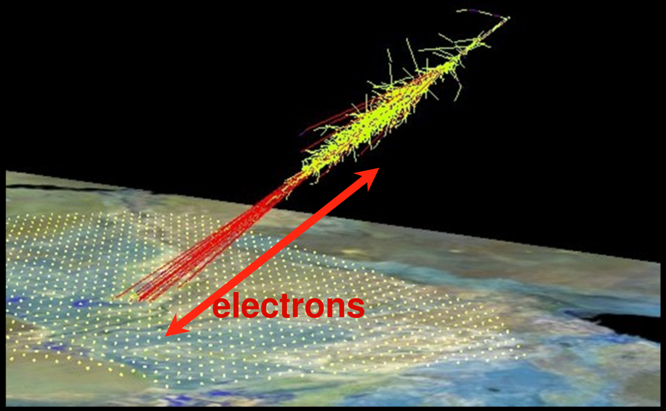
This picture demonstrates a simulated shower event. The triggered pixels have the colors that shows the time when the triggering occurs.



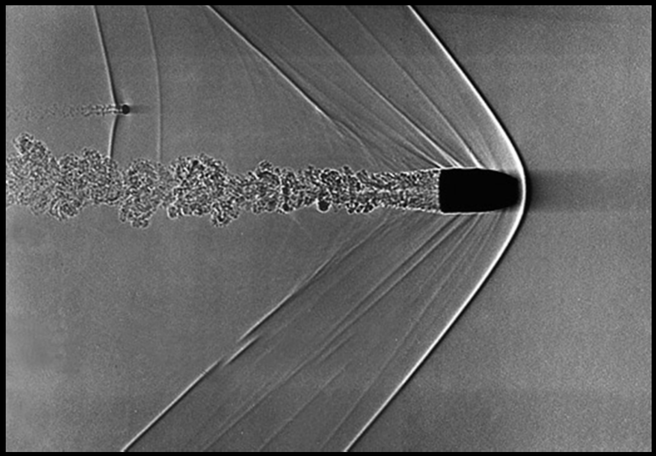


Detecting the Electron Component

Cosmic ray shower also consists of a large amount of electrons.

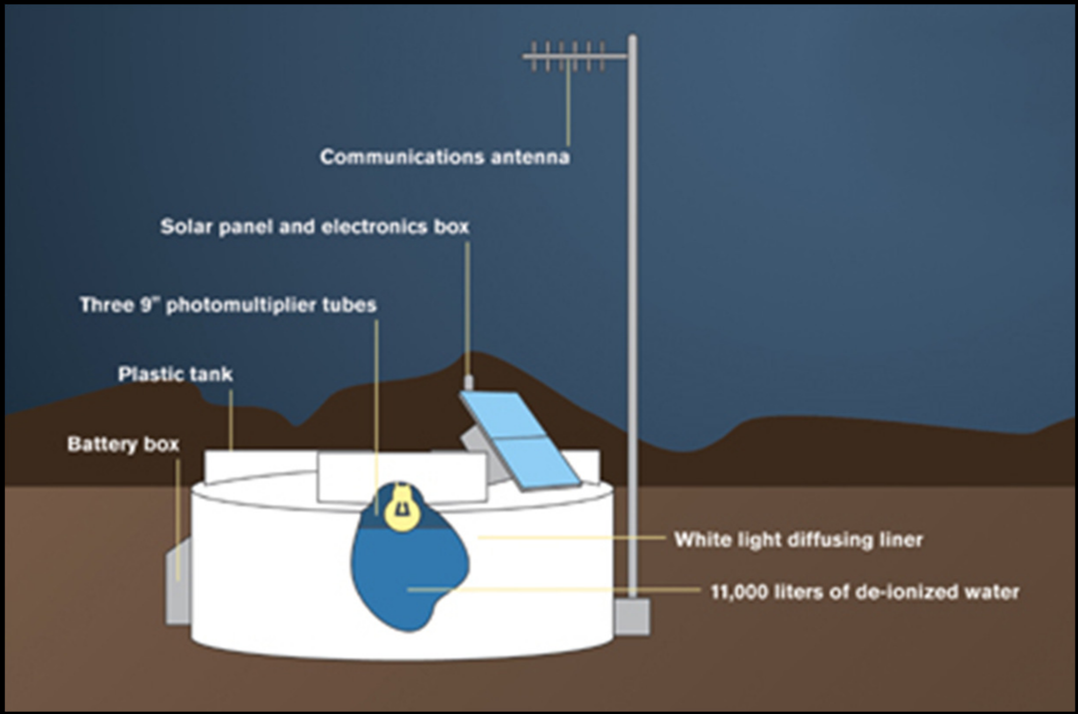


Experimentalists build water tanks to detect electrons. When the electrons pass through water, they produce Cherenkov light.



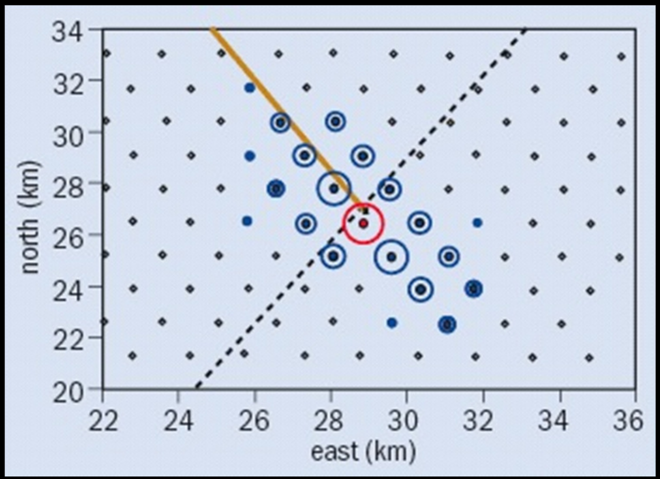
Detecting the Electron Component

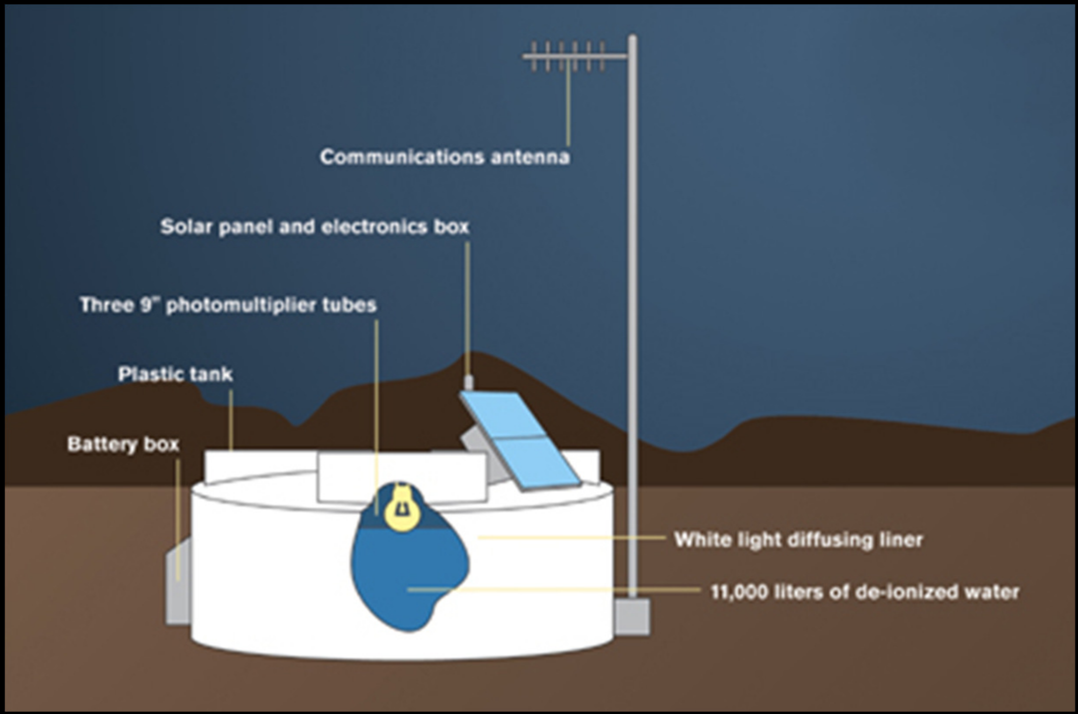
The detection of cosmic ray is achieved by using PMTs to detect the Cherenkov radiation when secondary electrons passing through the water tank.



Detecting the Electron Component

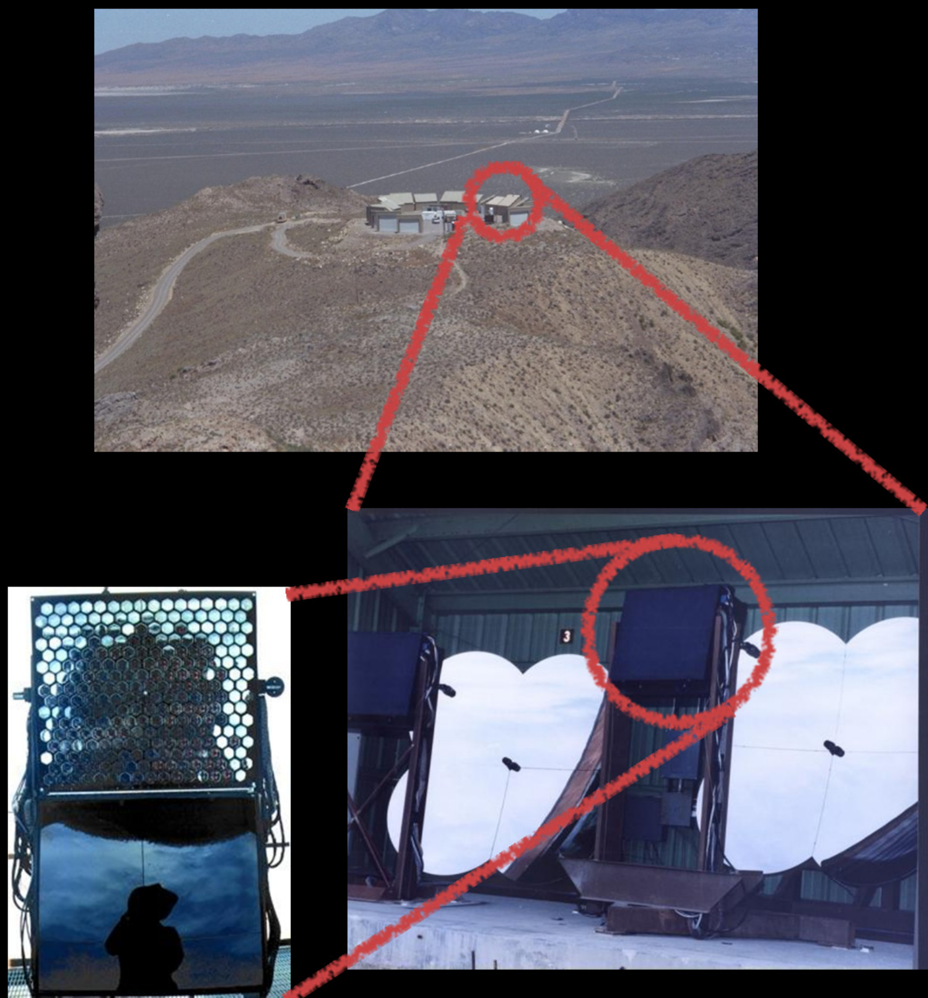
A single water tank provides very little information about showers. However, with a huge ground array of water tanks, we can see the patterns of the cosmic ray showers.





High-Resolution Fly's Eye

-Fluorescence Detector



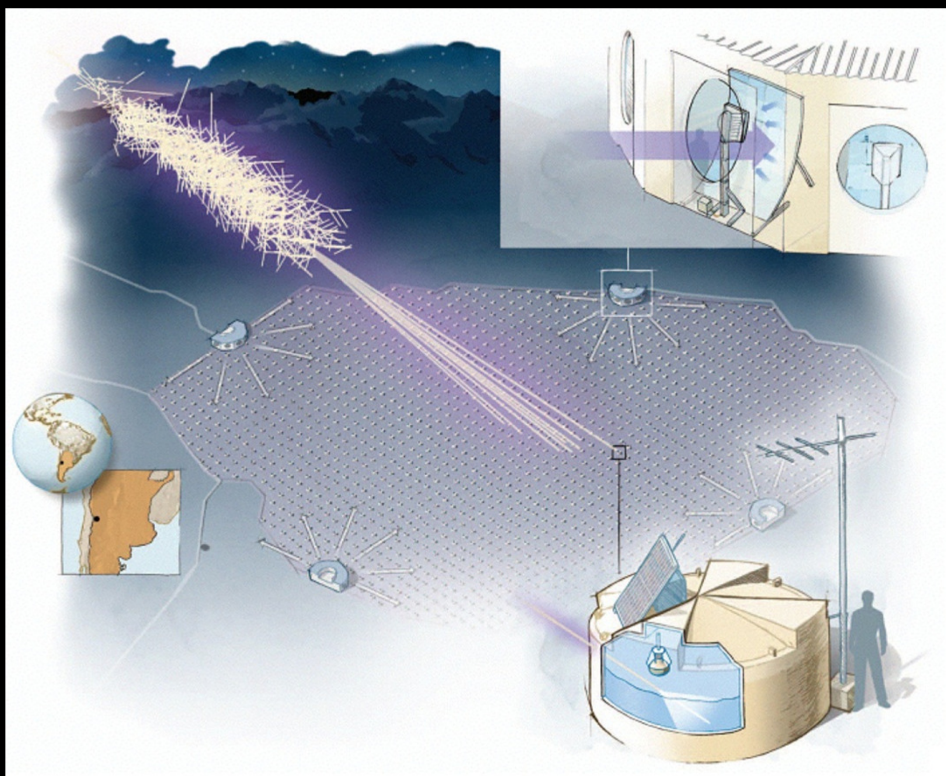
HiRes consists of 2 sites of fluorescence detectors separated by 12.6 km.

Site1: 22 mirrors; each viewing 16 degree in azimuth, 14 degree in elevation.

Site2: 42 mirrors in 2 rings; each viewing 16 degree in azimuth. Ring1 views from 3-17 degree in elevation, ring2 views from 17-31 degree.

Pierre Auger Observatory

-Fluorescence & water Cherenkov Detector



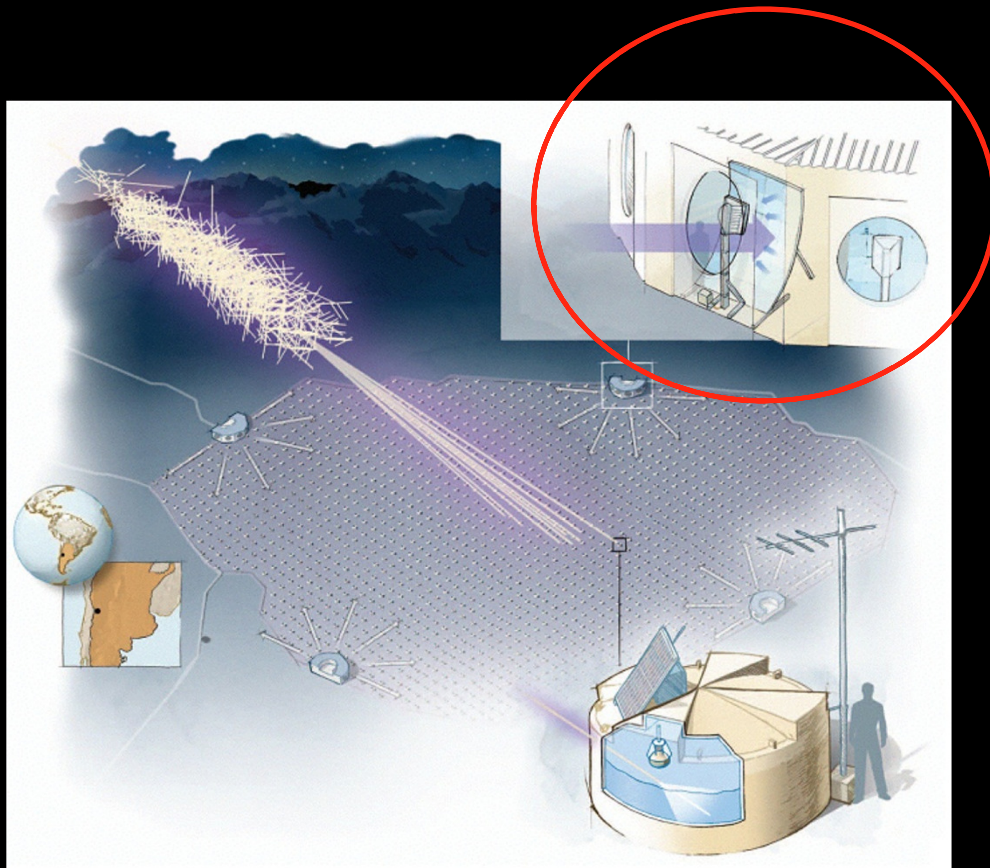
Auger consists of two types of detectors:

- The fluorescence detector consists of 24 telescopes that cover 1.5 to 30 degree in elevation.

- The surface detector array consists of 1600 water Cherenkov detectors that cover an area of 3000 km^2.

Pierre Auger Observatory

-Fluorescence & water Cherenkov Detector



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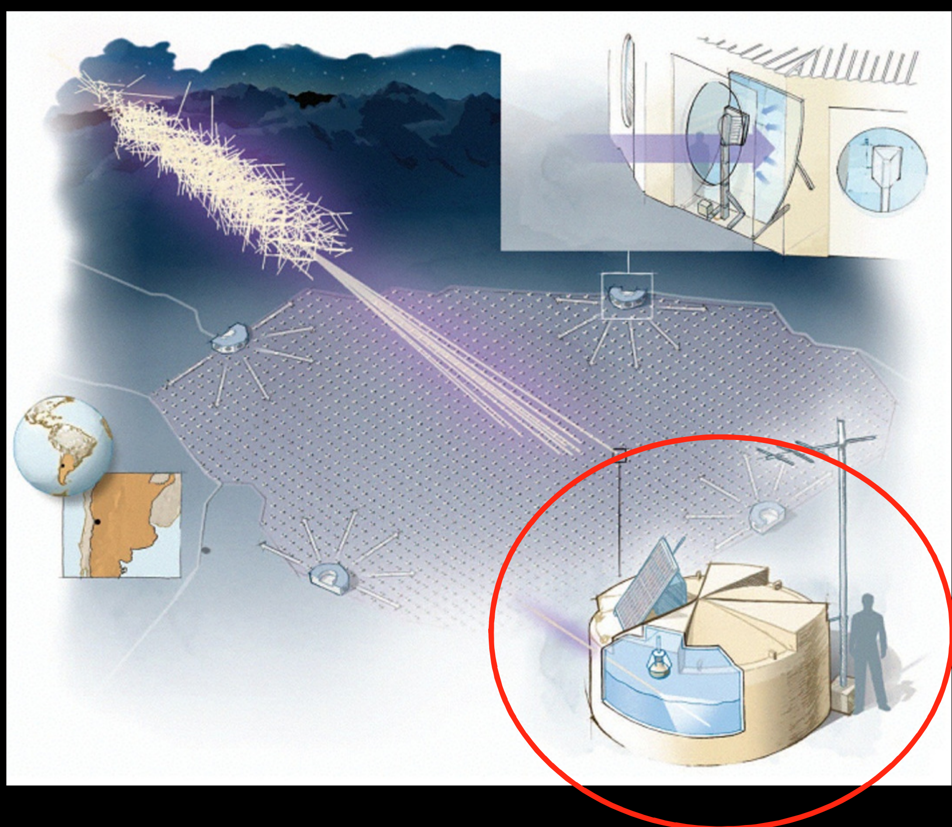

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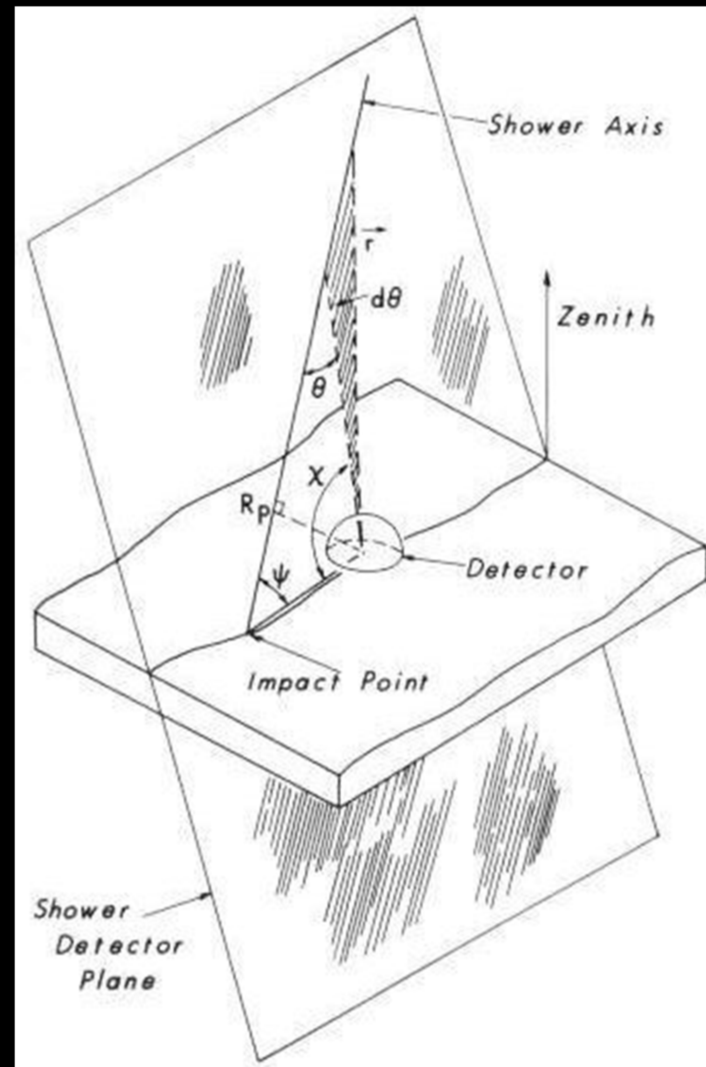
Measuring a Shower

- Determine the Shower Plane
- Determine the shower axis using timing information
- Longitudinal profile determines X_{max} and E



Measuring a Shower (cont.)

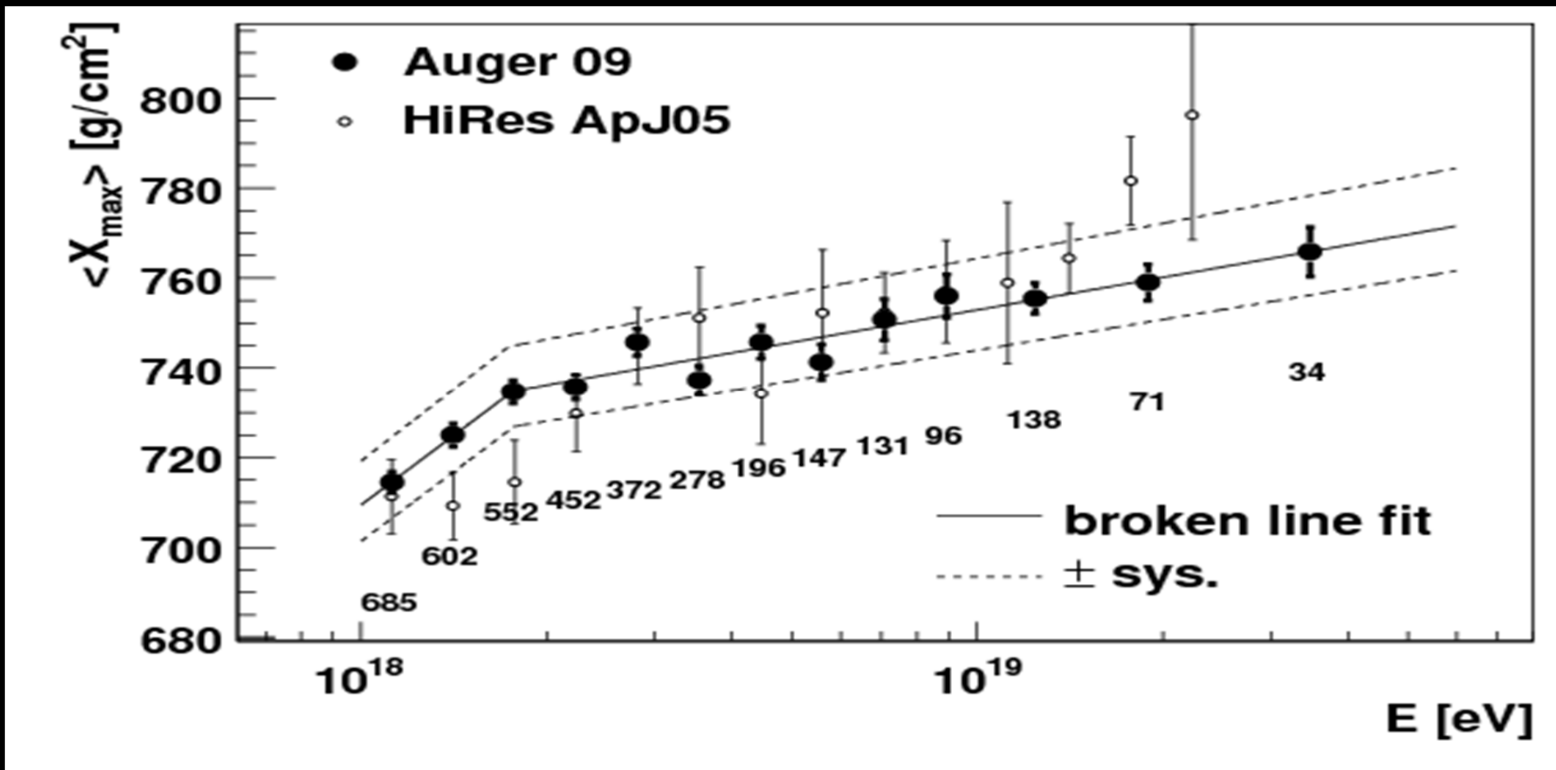
- Using multiple detectors improves accuracy
  - Auger: water Cherenkov tanks help determine the shower's time of arrival and lateral profile.
  - HiRes: two fluorescence telescopes allow for a stereo image of the shower.
- An uncertainty in the measured shower parameters is determined along with the fit

Discarding Low Quality Data

- Showers with too much uncertainty in the measured parameters are removed from the data set.
- Showers where X_{max} is not in the view of the telescopes are removed from the data set.
- Showers which do not trigger any water Cherenkov tank are removed from the data set (Auger).

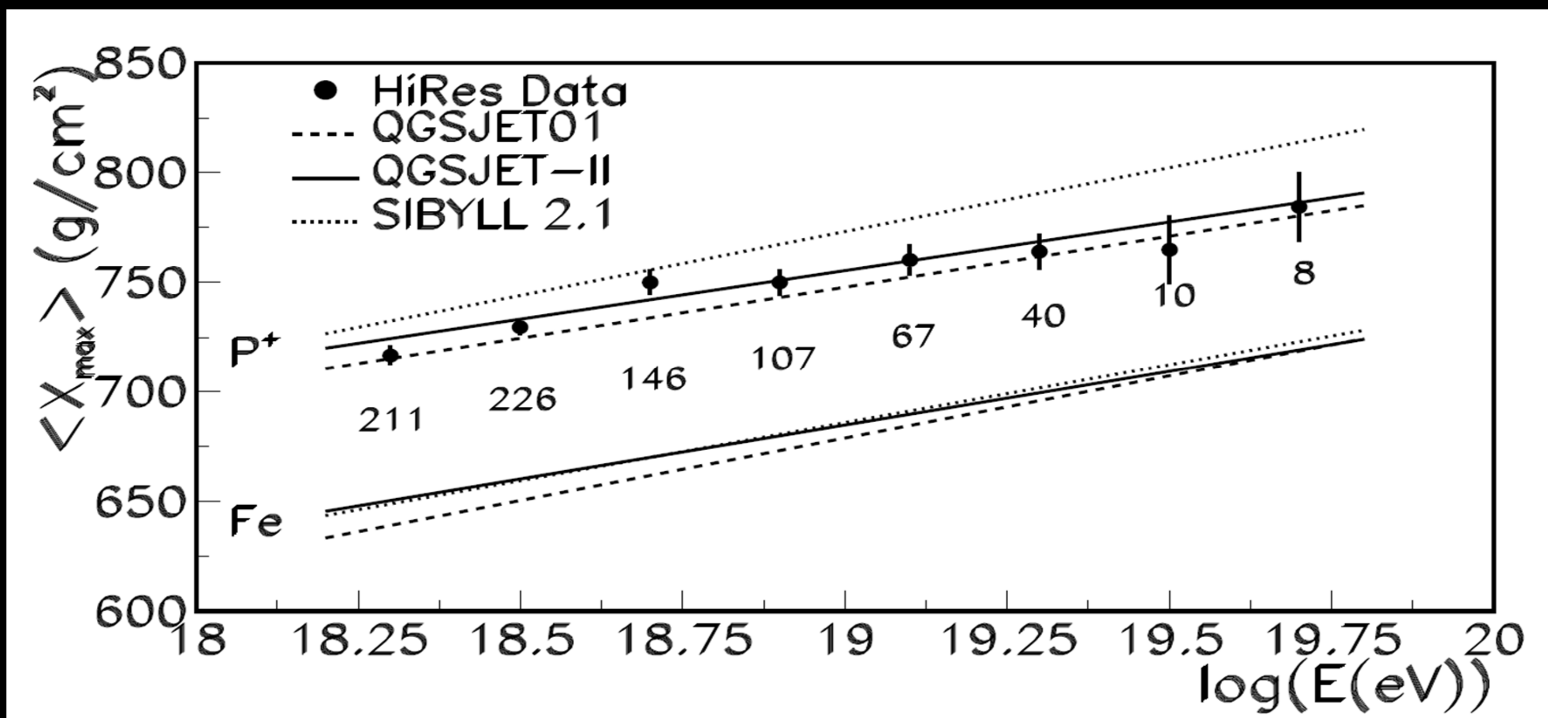
Plotting X_{max} vs. E

- Showers of similar energy are grouped together in a bin.
- The uncertainty of X_{max} is due to the variation in X_{max} between showers in that energy bin.



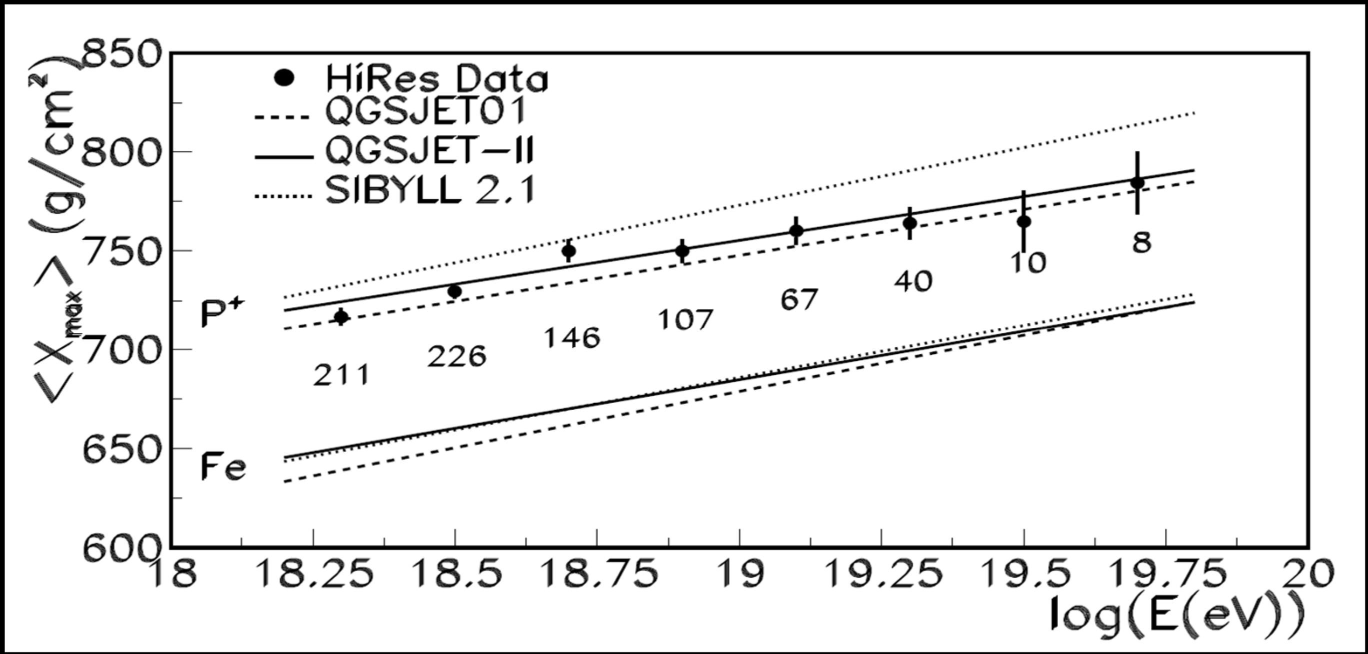
Plotting X_{max} vs. E (cont).

- If shower composition is constant the slope of X_{max} vs. ln(E) will be linear.
- The best fit is determind by a χ^2 test.



The HiRes Data Interpretation

- Is consistent with a constant elongation rate
- Is consistent with a predominantly protonic composition of cosmic rays
- Constrains models in which the galactic-to extragalactic transition causes the “ankle”
- Suggests that cosmic rays above 1 EeV are protons of extragalactic origin

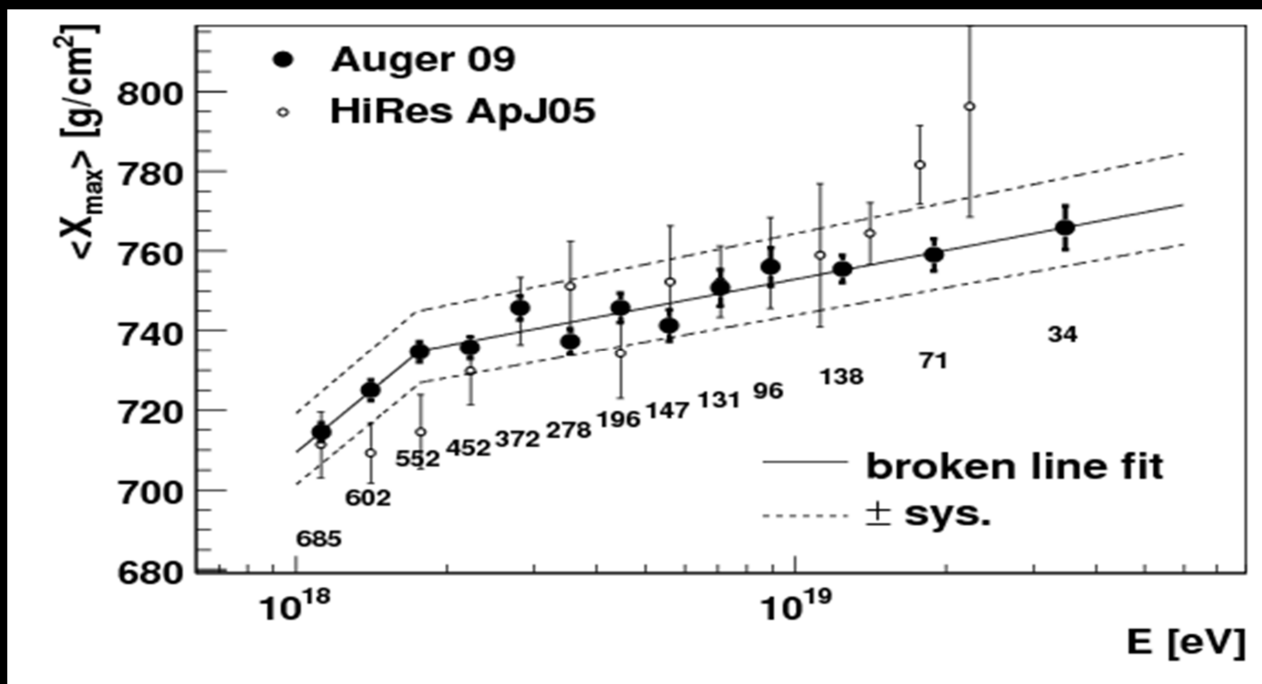


The Auger Data Interpretation

- Change of elongation rate

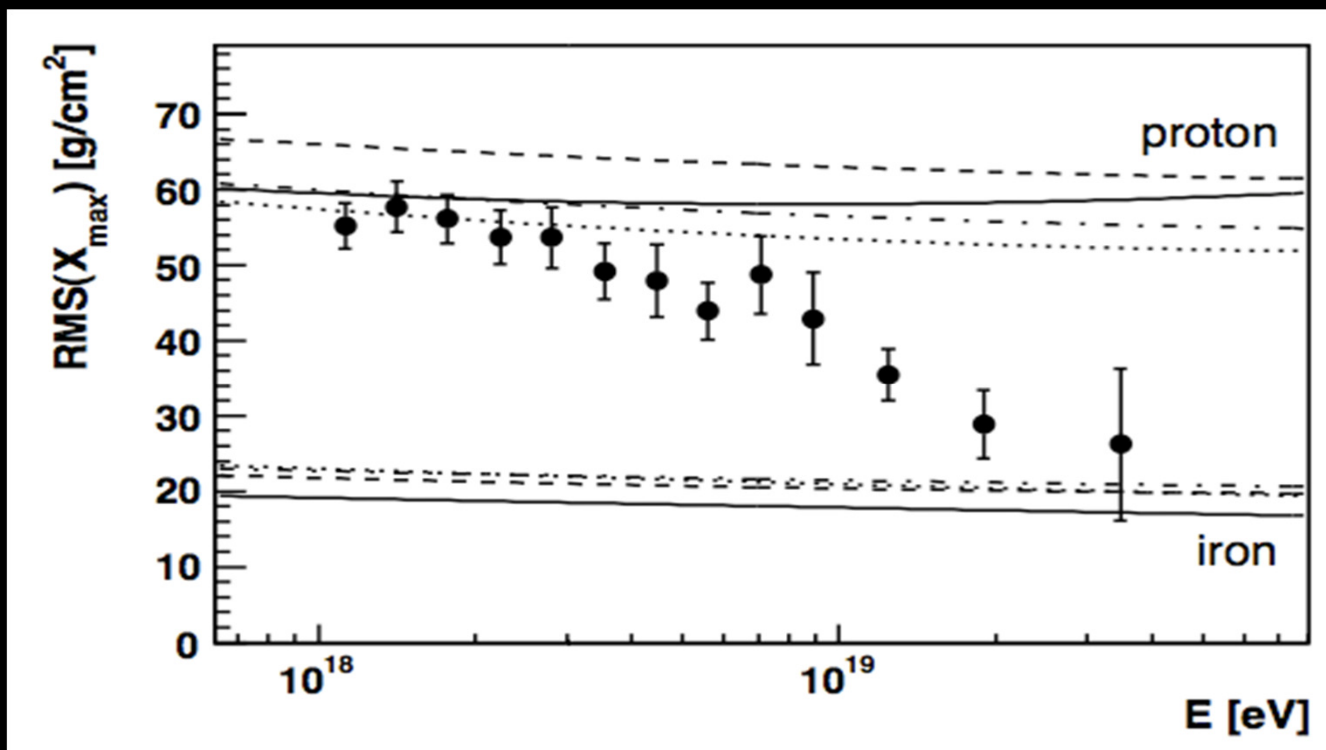
  → a change in the energy dependence of the composition around the "ankle"

  → support the hypothesis of a transition from galactic to extragalactic cosmic rays



RMS(X_{max}) vs. E

- Decreasing shower-to-shower fluctuations with increasing energy → an increasing average mass of the primary particles



Conflicting Conclusions

The HiRes data

- Constant elongation rate for 1.6~63 EeV
- Proton-dominated mass composition
- Cosmic rays above 1 EeV are of extragalactic origin

The Auger data support:

- Change of elongation rate at 1.74 EeV
- Progressively heavier nuclei composition
- galactic-to-extragalactic transition around the ankle (1~10 EeV)

Our Criticisms

- Auger's piecewise line fit depends upon only two data points.
- Single best fit line for Auger data looks like it would be close to HiRes data.
- Binning data may destroy information.