What are the Highest Energy Cosmic Rays Telling Us?

-OR-

Why are we still studying Cosmic Rays?

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Abstract/Background:

In November 2007 the Pierre Auger experiment (Auger) in Mendoza province Argentina published evidence for Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects potentially opening the door for cosmic ray astronomy. In February 2010 the Auger experiment published evidence for a significant fraction of the highest energy cosmic rays not being protons. As cosmic rays are bent by magnetic fields in the universe, the increased angular deflection of non-proton cosmic rays meant that there was(is) a mild to significant tension between these two results.

Since then the Telescope Array experiment (TA) in Millard County Utah has results in the same energy range as the Auger experiment. Furthermore the air shower simulation programs, used to interpret the composition of the cosmic rays, have been significantly revised to reflect the latest collider data.

Thus it is timely to ask: what are the highest energy cosmic rays telling us?

Why are we still searching for the origin of cosmic rays ~ 95 years after the discovery?

Magnetic Fields are the problem:

While gamma-rays and neutrinos are ‘blind’ to magnetic fields, cosmic rays are charged particles, the nuclei of atoms.

Like the drunken man’s walk!

BUT the highest energy particles are expected to be almost undeflected by the fields → cosmic ray astronomy.

But they are very rare:

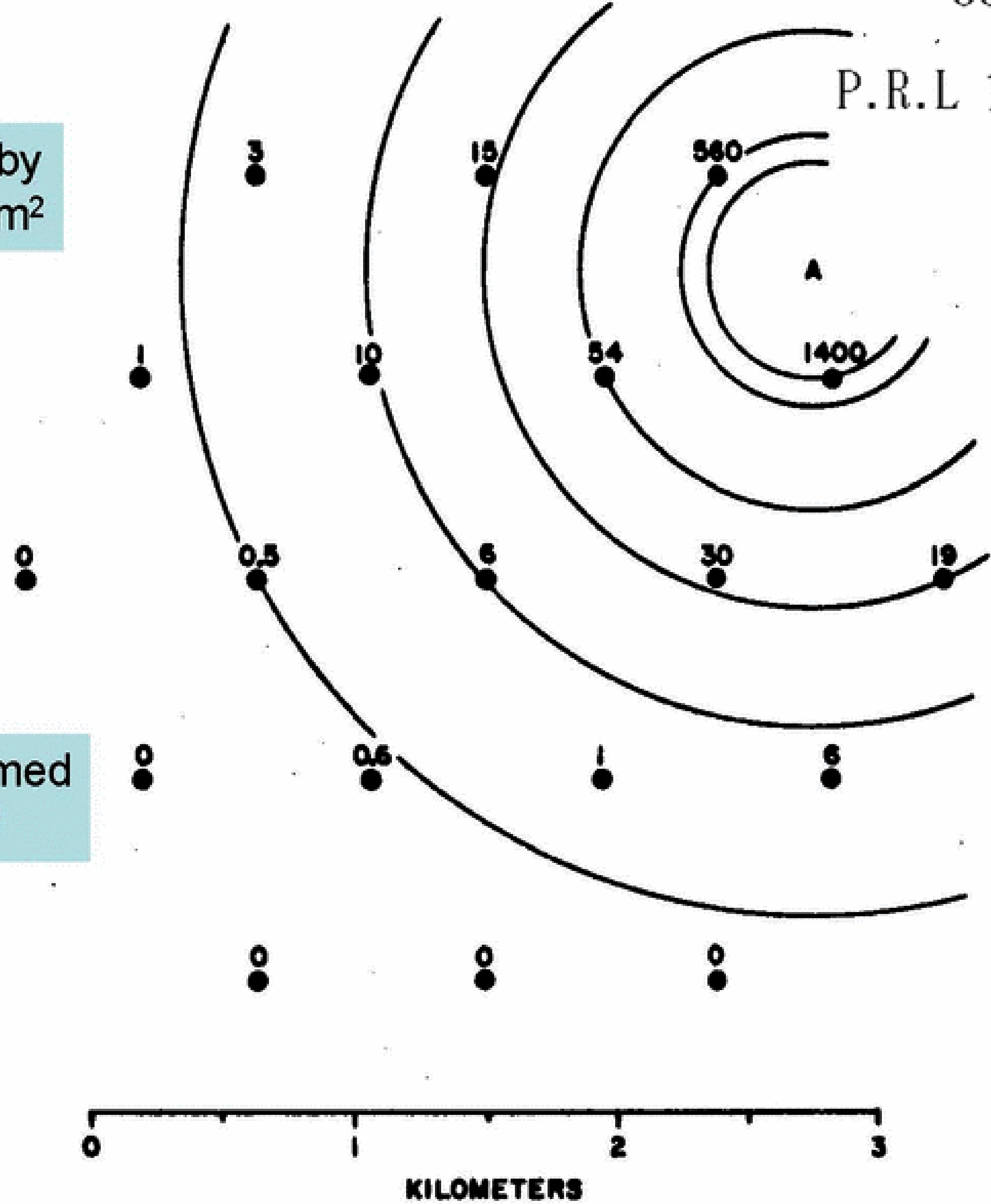
~ 1 per square kilometre per century

John Linsley

P.R.L 10, 146 (1963)

Area enclosed by detectors ~ 8 km^2

First event claimed to be > 10^{20} eV



The Volcano Ranch Detector and signals in the largest event of ~ 10^{20} eV

Scintillation detector, Volcano Ranch
Albuquerque West Mesa

Post 1966

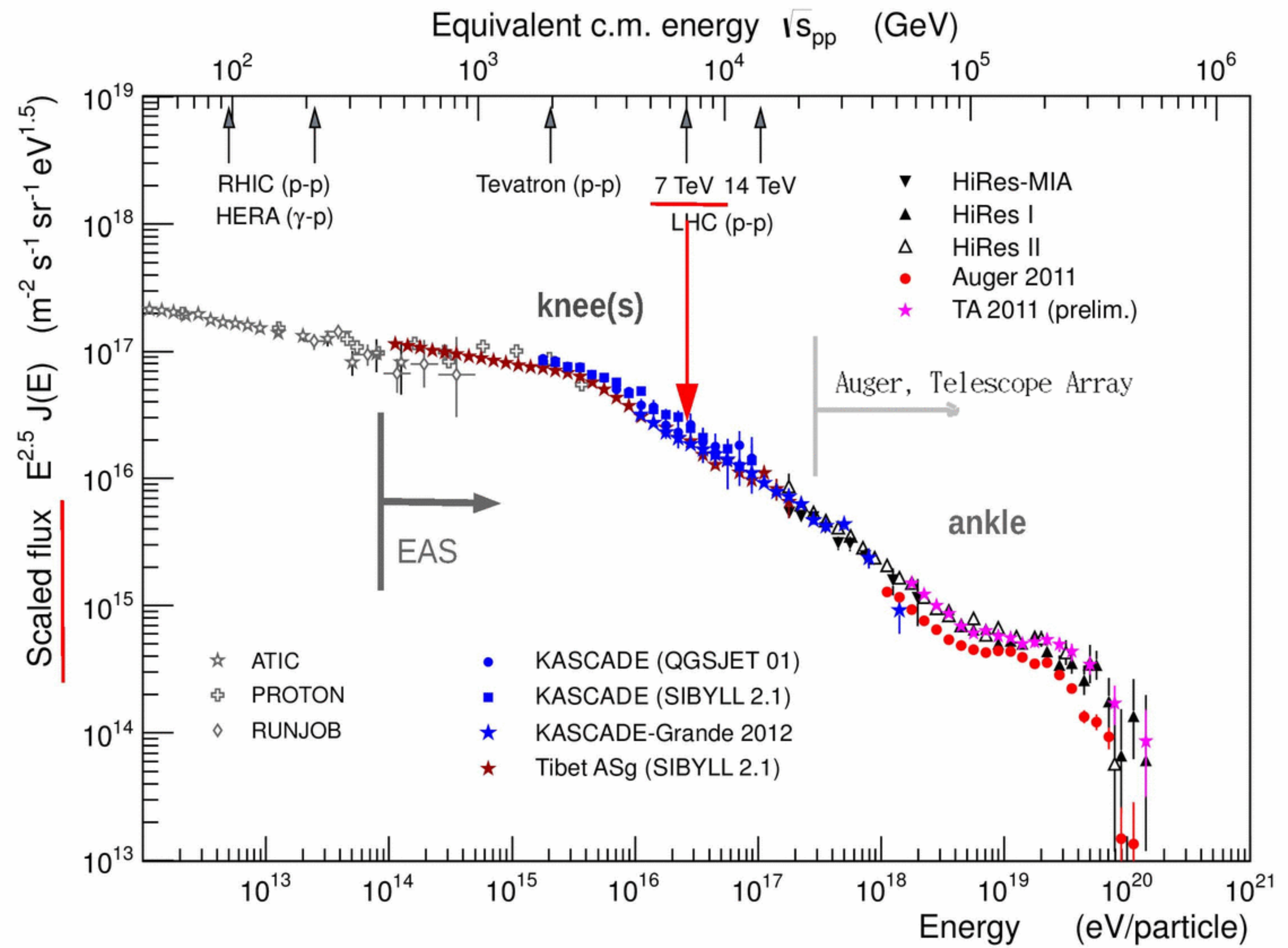
• **A primary interest became establishing the existence, or otherwise, of the Greisen-Zatsepin-Kuzmin (GZK) steepening**

$$p + \gamma_{2.7\,K} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \quad \text{or} \quad n + \pi^{+}$$

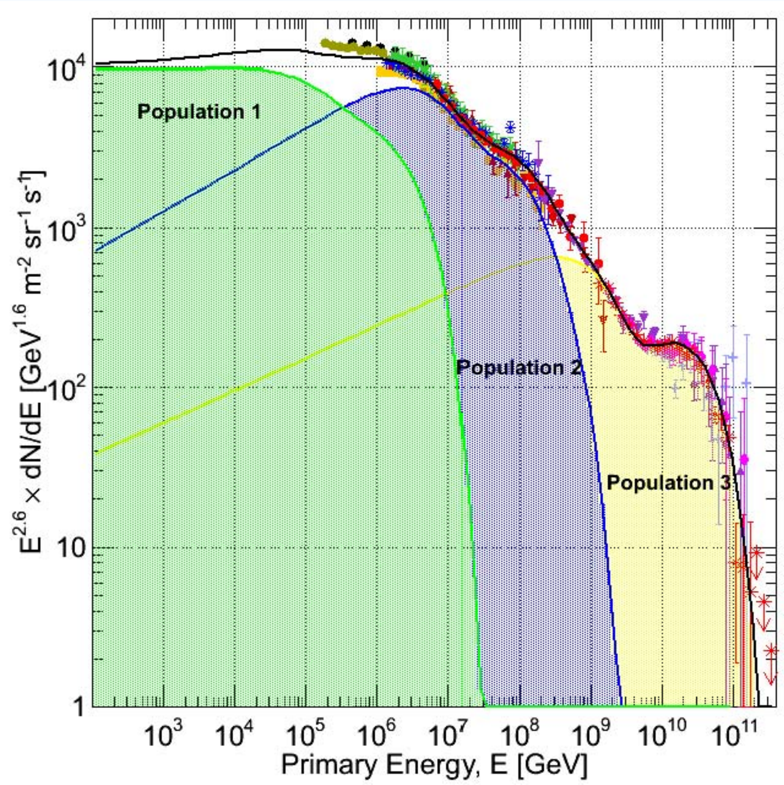
If particles are observed > 5 x 10^{19} eV, then they must be local (GZK cut-off) within ~ 100 Mpc, depending on energy

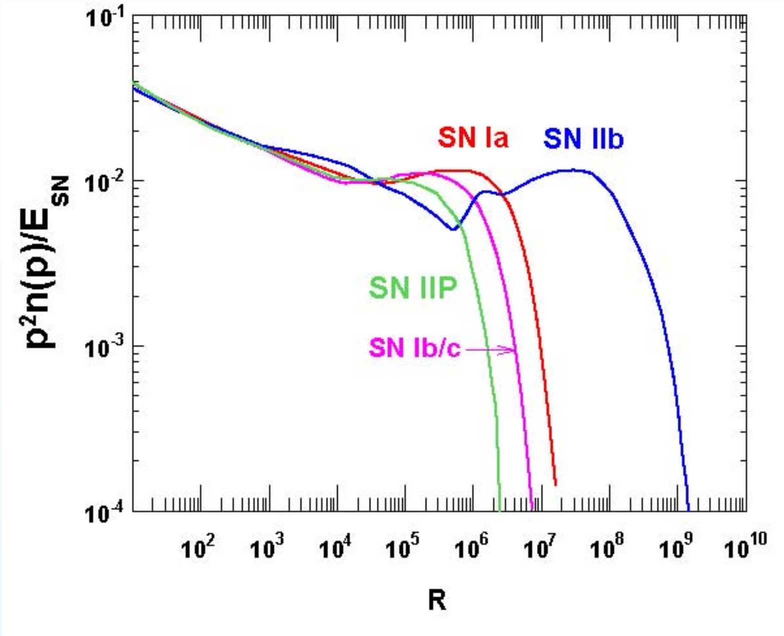
So **ANISOTROPIES** expected from **nearby sources**

Spectrum of high energy cosmic rays (CR)



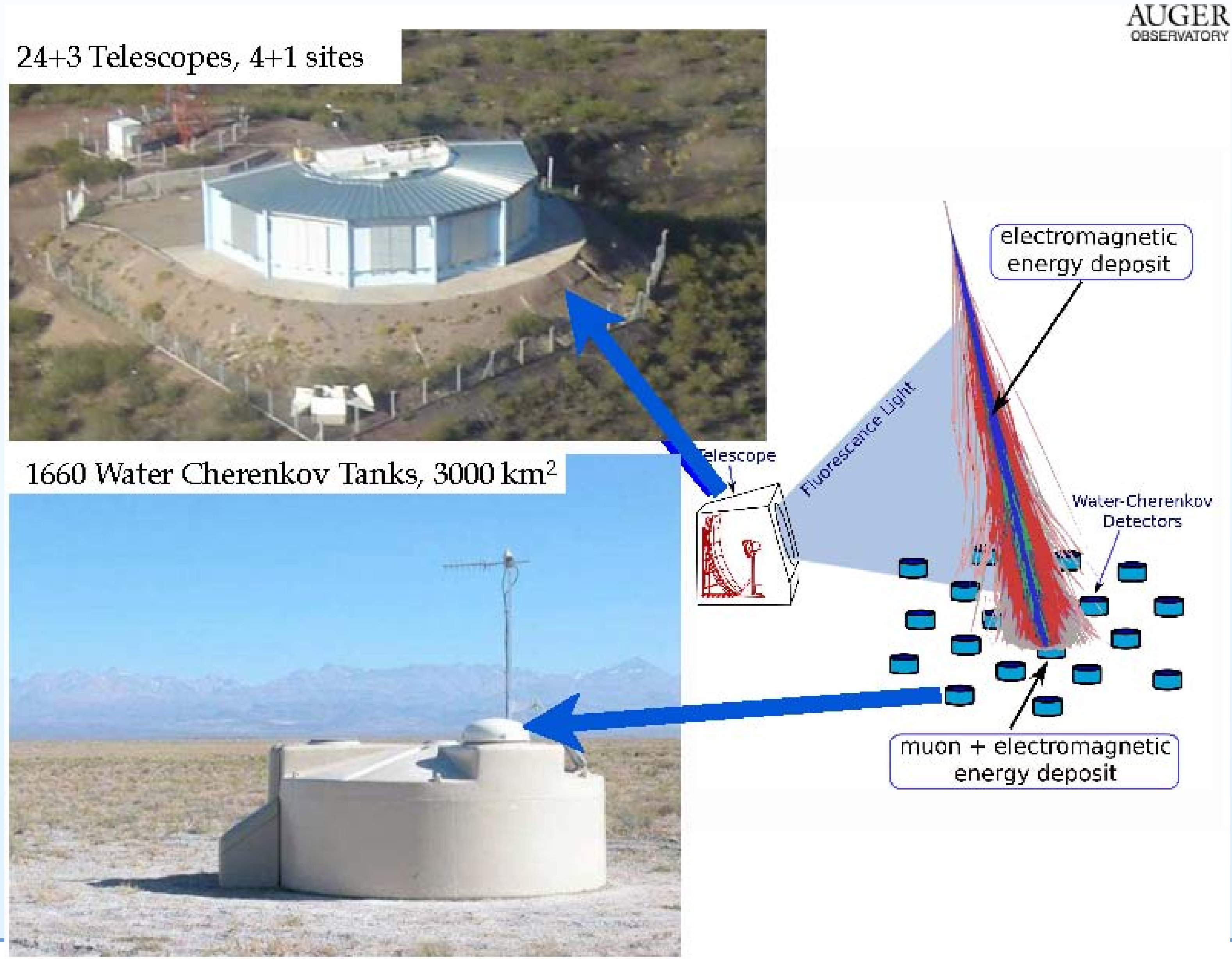
Possible CR *source populations*



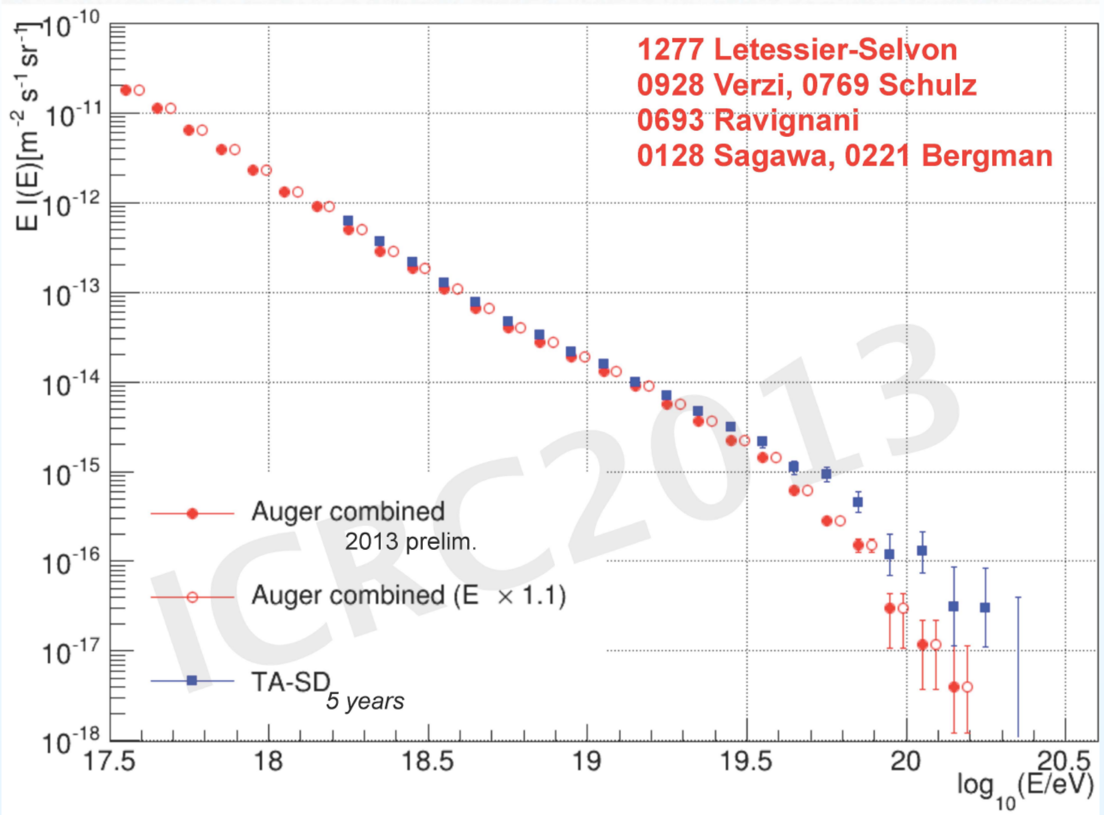


- Left: Gaisser, Stanev and Tilav's 2013 review article suggests several source populations
- Above: Ptuskin, Zirakashvili and Seo (2010) propose a cocktail of supernova types and environments as candidate population 1,2 sources. (R-scale assumes only protons.)
- *rigidity* $R = (pc)/(Zm_N c^2)$ is natural for mixed cosmic ray composition

Hybrid measurement of CR extensive air showers

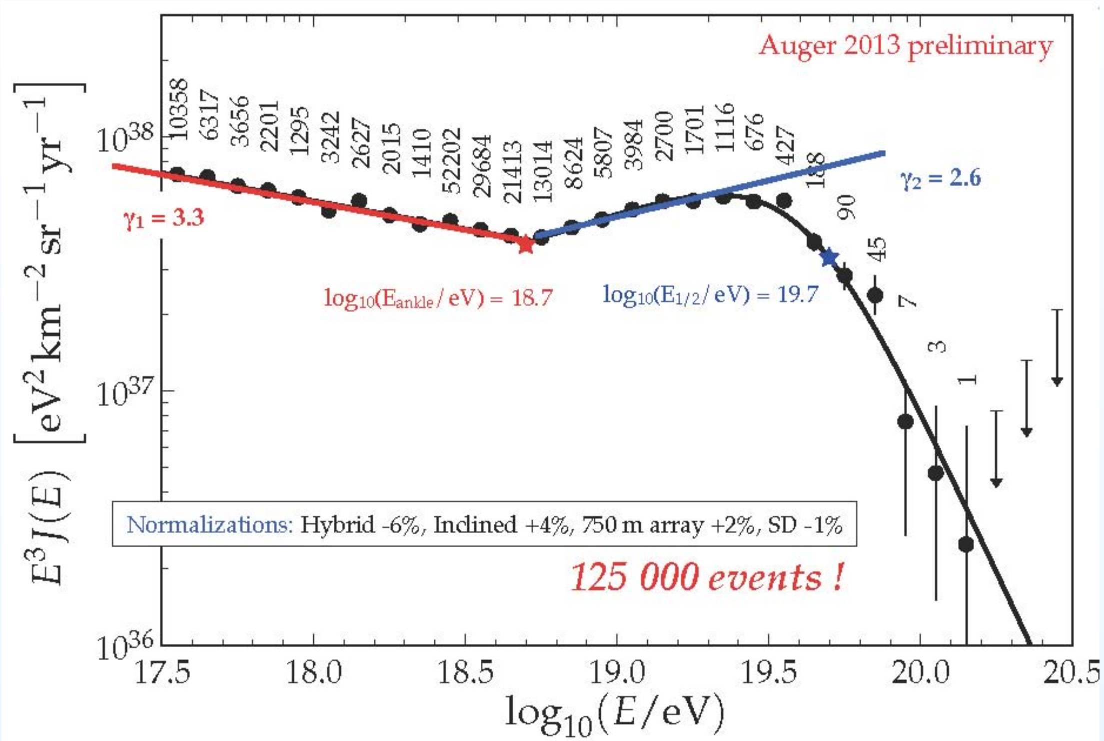


ICRC 2013 comparison of Auger and TA spectra



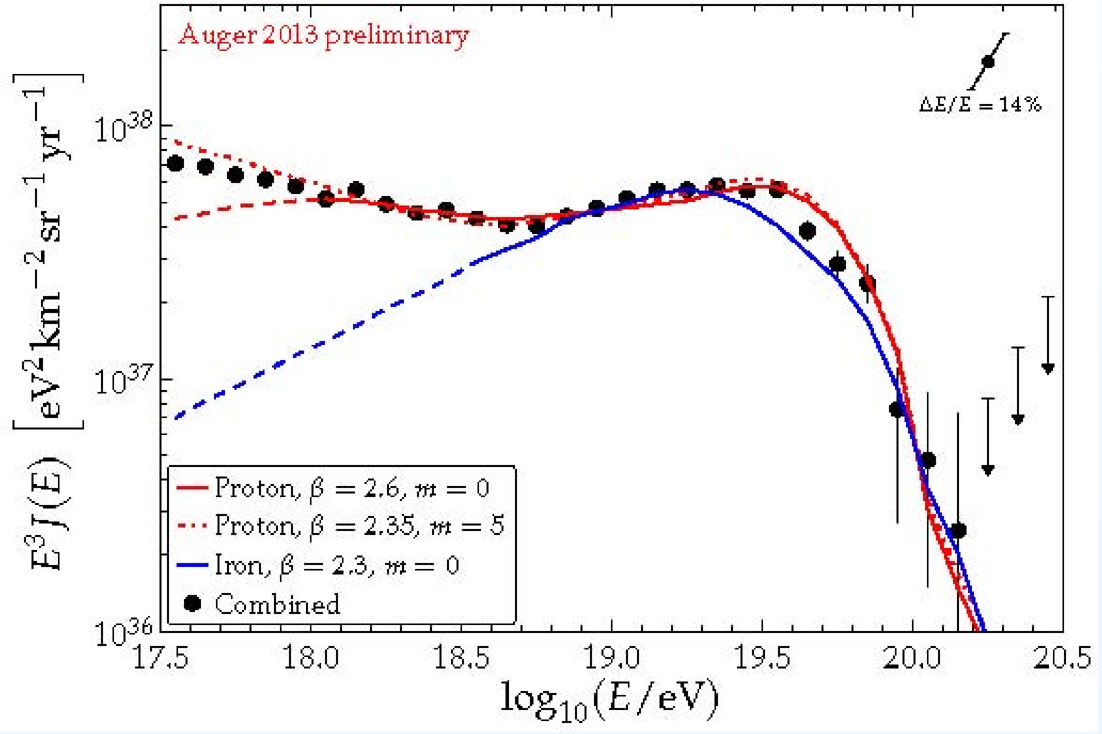
- Auger and TA spectra are presumably Gaisser et al population 3.
- $\sim 10\%$ energy normalization brings spectra into cooincidence
- Curious disagreement at the highest energies! Is this some systematic (energy) error or possibly new physics?

Spectrum analysis for *ankle* and *GZK cutoff*



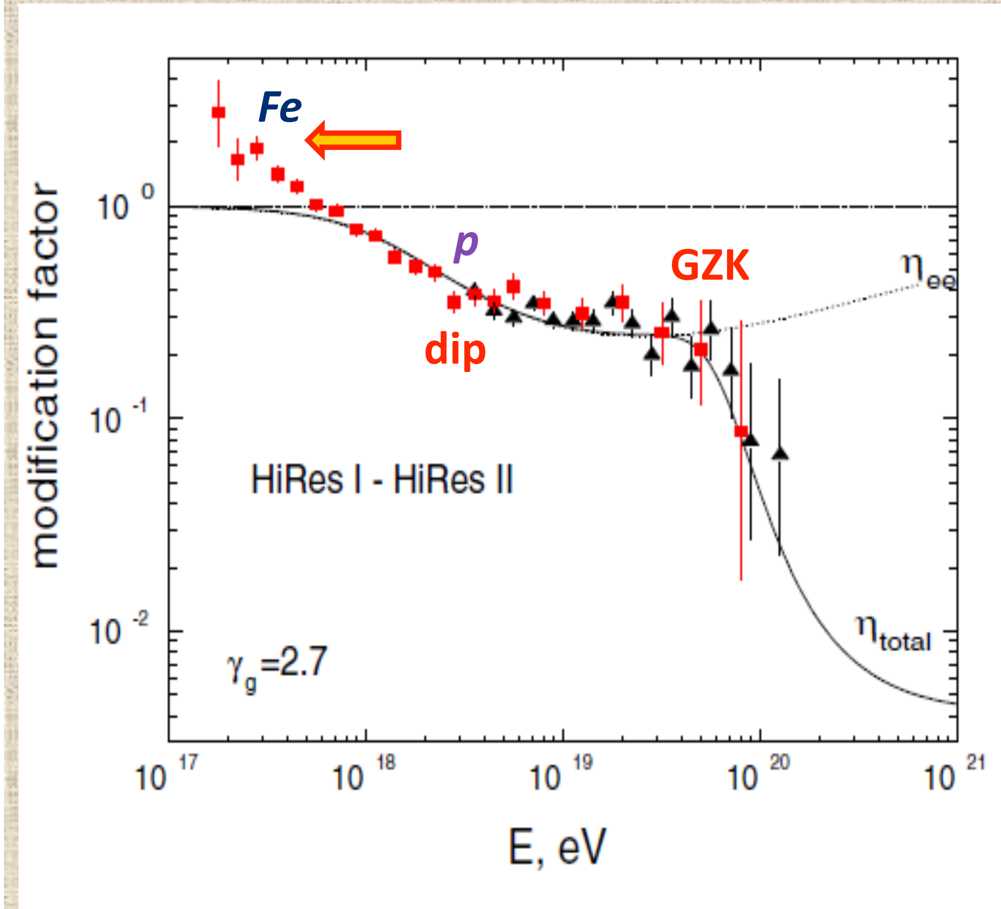
- GZK model predictions typically assume protons with a generation source flux: $\Phi(E_g) \propto E_g^{-\gamma}(1+z)^m$ with γ, m adjustable parameters and z the source redshift.
- The *GZK cutoff*, $E_{1/2}$, is rather insensitive to the source parameters: Aloisio, Berezinsky and Gazizov (2012) predict $\log_{10}(E_{1/2}/eV) = 19.72$
- Auger and TA spectra give: $\log_{10}(E_{1/2}/eV) = 19.63 \pm 0.02$ and 19.74 ± 0.08 respectively. Curiously only TA data favors naive GZK with proton primaries ...

Auger spectrum comparison to GZK models



- Comparison of GZK model predictions for proton only or iron only primaries with generation source flux: $\Phi(E_g) \propto E_g^{-\beta}(1+z)^m$, with $E_g < E_{cutoff}$, to the (ICRC 2013 combined) Auger data ($\bullet$).
- The iron model can only reproduce the data above $\log_{10}(E/eV) \approx 18.8$.
- Depending on the redshift evolution enhancement, the proton model can reproduce the data over essentially all the population 3 energy range.

Pair-Production Dip Model



Modification factor

$$\eta(E) = \frac{J_p(E)}{J_p^{unm}(E)}$$

is the ratio of *proton* spectrum $J_p(E)$, calculated with **all** energy losses on ***CMBR***

$$p + \gamma \longrightarrow e^+ + e^- + p$$

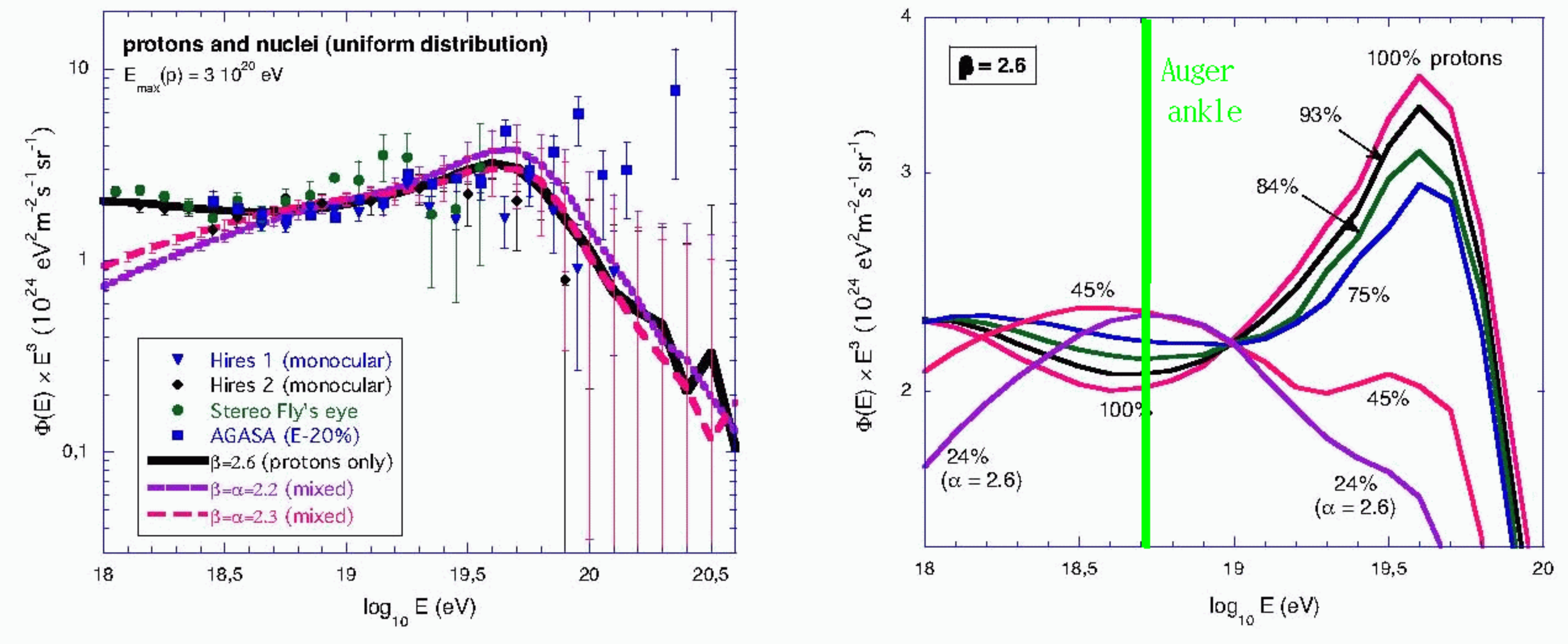
$$p + \gamma \longrightarrow \pi^{\pm,0}(K^{\pm,0}) + X$$

and 'unmodified' spectrum $J_p^{unm}(E)$ with only **adiabatic** energy loss included (due to red-shift).

V. Berezinsky, A.G., S. Grigorieva
Phys. Rev. D74 (2006) 043005

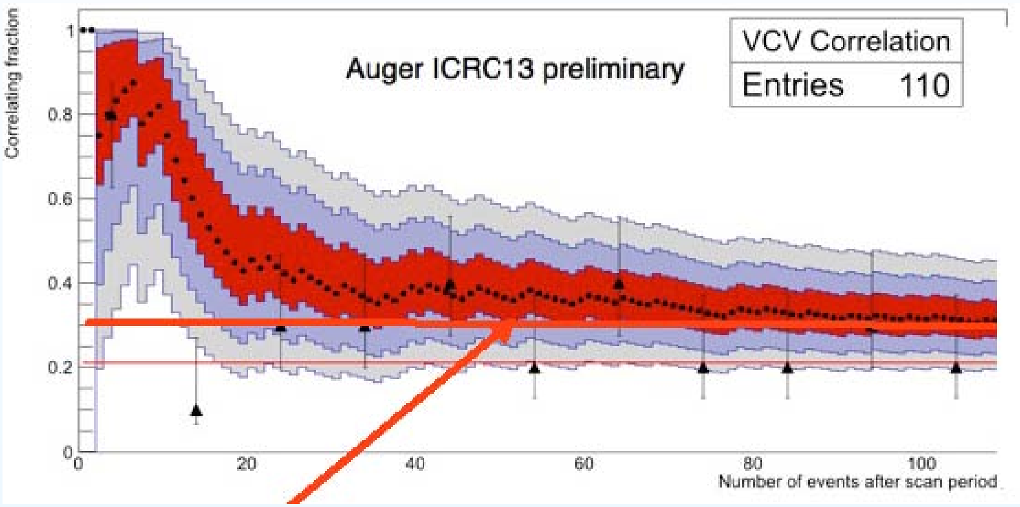
If *UHECRs* are ***protons*** (*HiRes*): all features are well explained.
Transition from galactic ***Iron*** ⟹ to extragalactic ***protons*** occurs at
E ≈ (3÷5)×10^17^ eV.

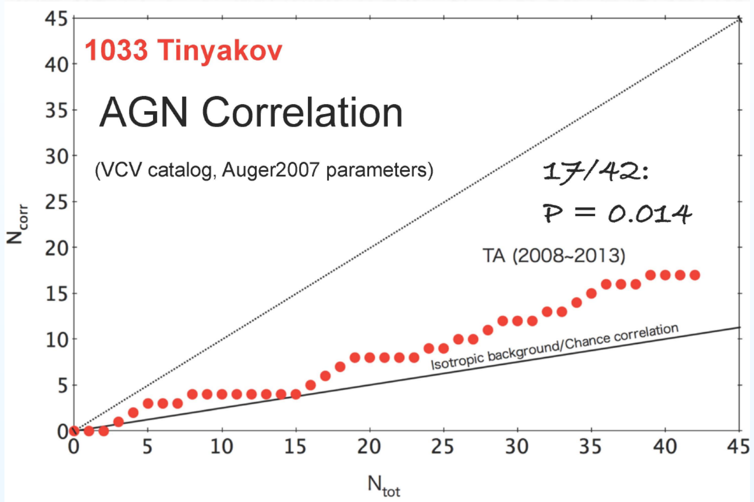
Spectrum analysis for *mixed* composition



- Population 1 and 2 have mixed composition: p, He, ... Fe; why not population 3?
- (Right plot:) Allard, Parizot, Khan, Goriely and Olinto (2008) found that only almost pure protons have a distinct ankle. Left plot confirms that only almost pure protons model the flux over essentially all of the population 3 energy range.
- Does the clear ankle, in Auger/TA data, favor mostly ($> 75\%$) proton composition?

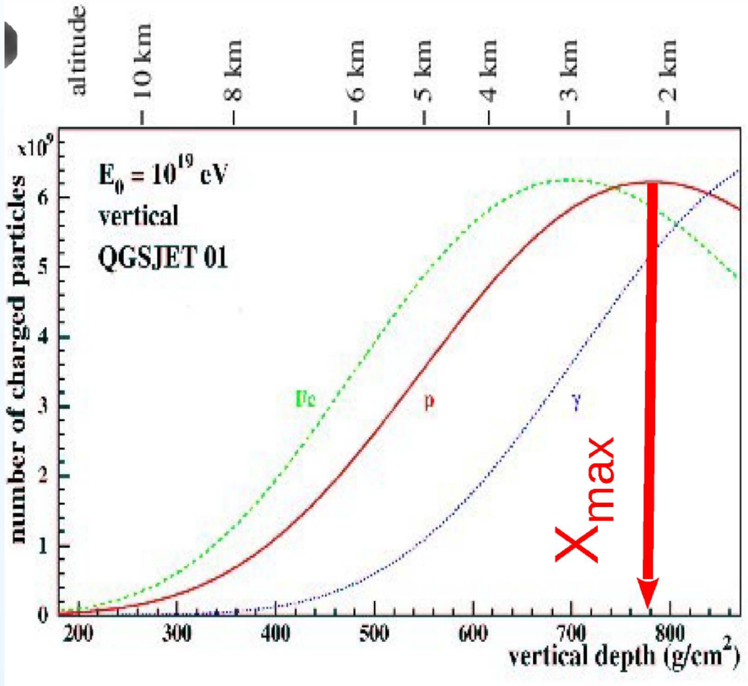
Proton composition favors CR:source correlations

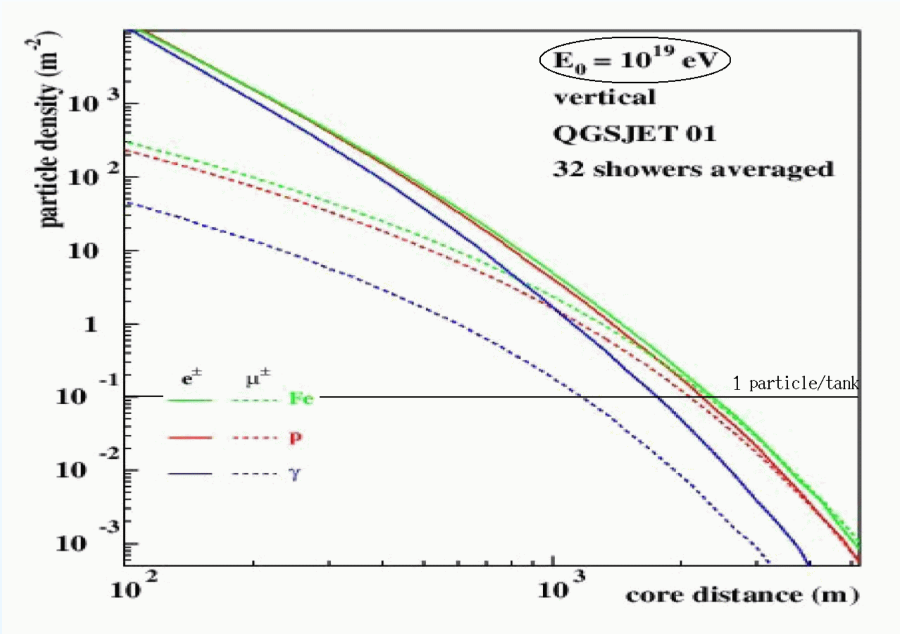




- (Left:) Fraction of Auger CRs correlated with VCV catalog AGNs. While the initial magnitude of the CR:AGN correlation was probably over-estimated, 5 years later is Auger observing a weak but stable signal?
- (Right:) Is the TA experiment also observing a weak but non-zero correlation?
- Is this too uncertain to tell us about AGNs as the sources and the possible proton composition of the highest energy CRs?

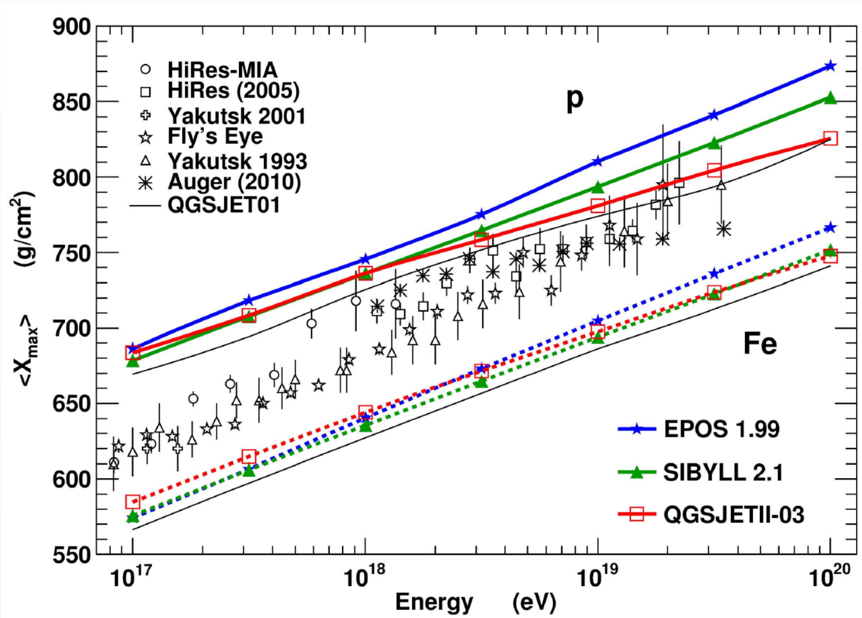
Experimental sensitivity to CR composition

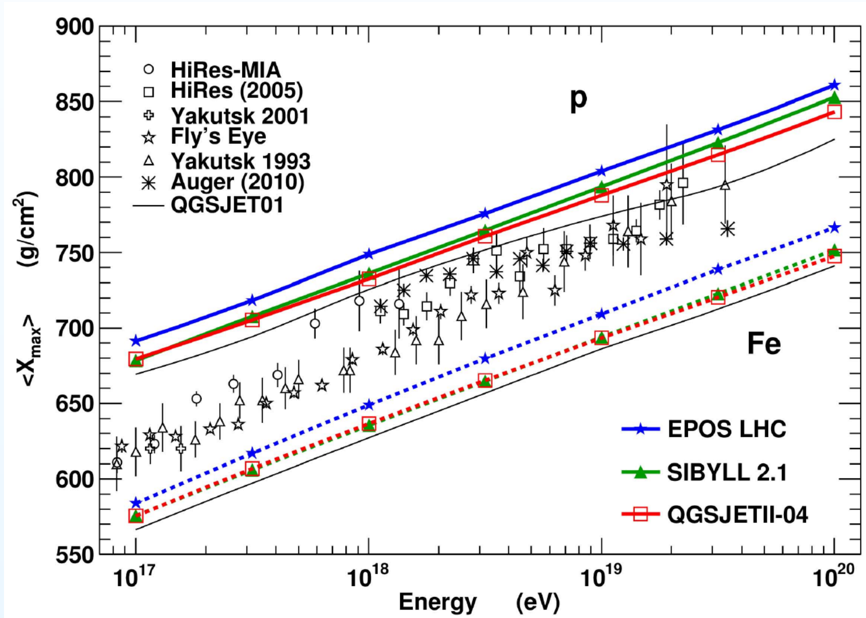




- Extensive air showers differ for iron(Fe), proton(p) and photon(γ) primaries.
- (Left:) The position of shower maximum, X_{max}, is measured by fluorescence telescopes.
- (Right:) The radial densities of muons(μ) and electro-magnetic($e^\pm$) particles from the shower core are measured by the Auger surface detectors.

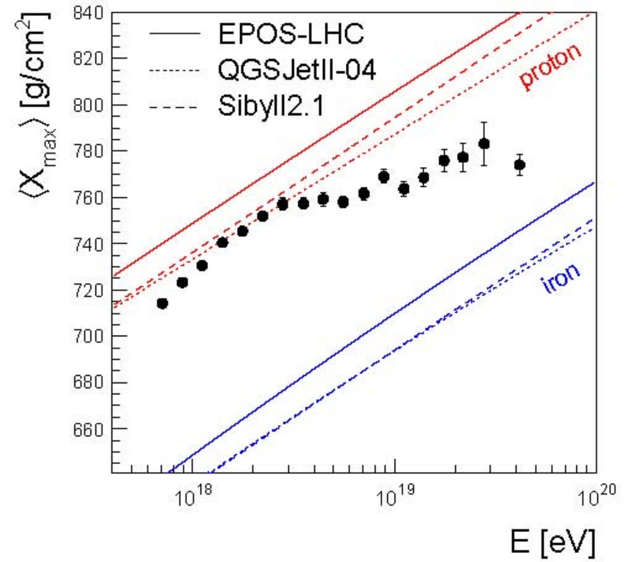
Shower Monte Carlo (MC) predictions

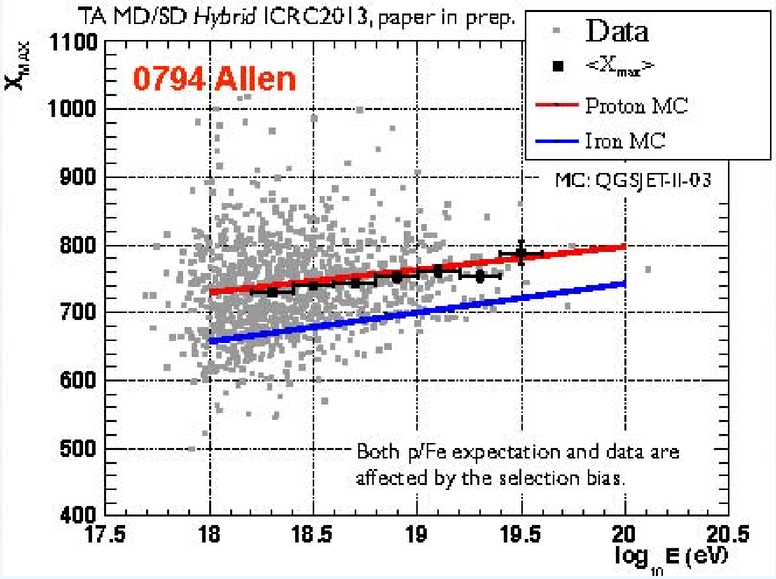




- Shower MCs include known particle physics plus phenomenological models to extend to Auger/TA CR energies but not "1σ" possibilities ...
- (Left:) Predictions for X_{max} for p and Fe primaries from MC version "n".
- (Right:) Predictions from MC version "n+1" tuned to the latest collider data.
- MC differences may under (or over) estimate systematic uncertainties.
- Experimental data are "noisy" but MC predictions disfavor pure proton composition!

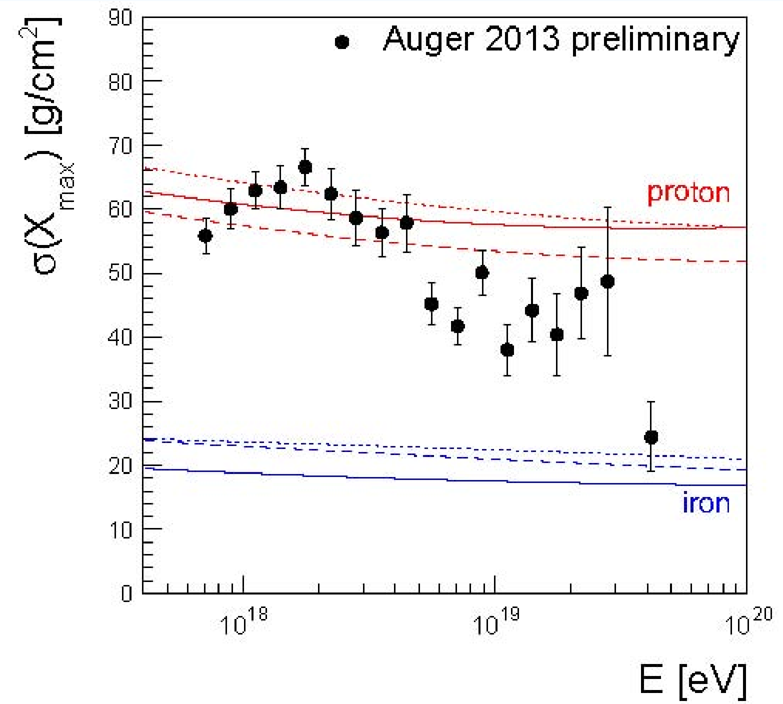
ICRC2013 Auger and TA $< X_{max} >$ data





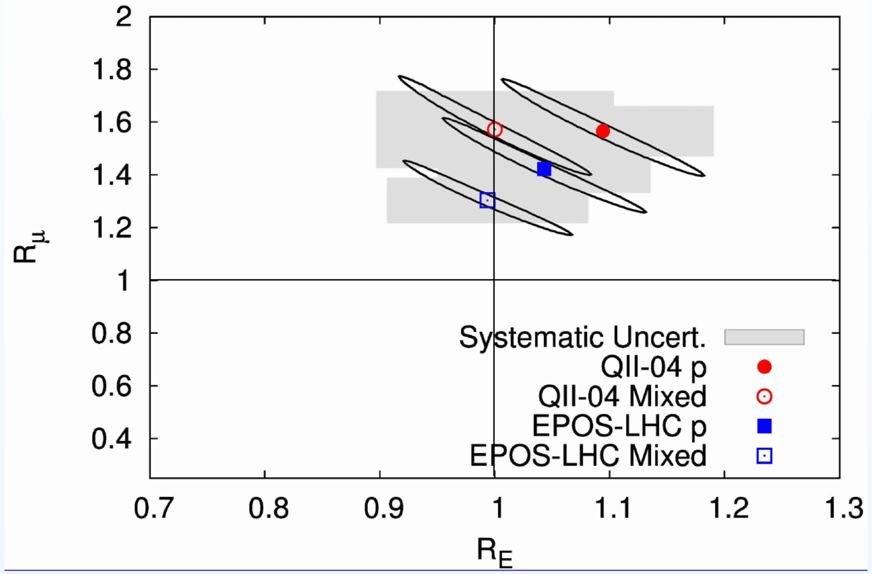
- (Left:) Comparison of MC predictions to Auger data suggest a mostly proton composition at 2×10^{18}eV transition to mixed composition by 4×10^{19}eV.
- (Right:) A similar study by TA (when compared to version "n" MC predictions) is more compatible with a mostly proton composition ...
- Do these results rule out, or confirm, $>$75% proton composition?
- If the primaries are $>$75% proton composition, what are the data telling us about MC extrapolations of LHC physics to Auger/TA energies?

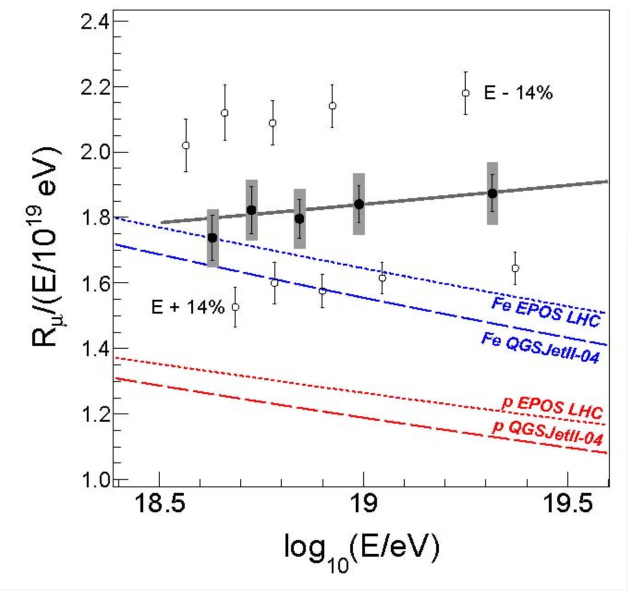
ICRC2013 Auger X_{max} RMS data



- Auger also measures the width of the X_{max} distribution, X_{max} RMS, which provides independent information on CR composition ...
- (Left:) Data to MC comparisons (also) suggest a mostly light (proton) composition at 2×10^{18}eV transition to mixed or heavy (iron) composition by 4×10^{19}eV.
- What are shown are statistical uncertainties ...
- While these measurements are straightforward in principle, in practice they are challenging without incurring significant systematic errors.

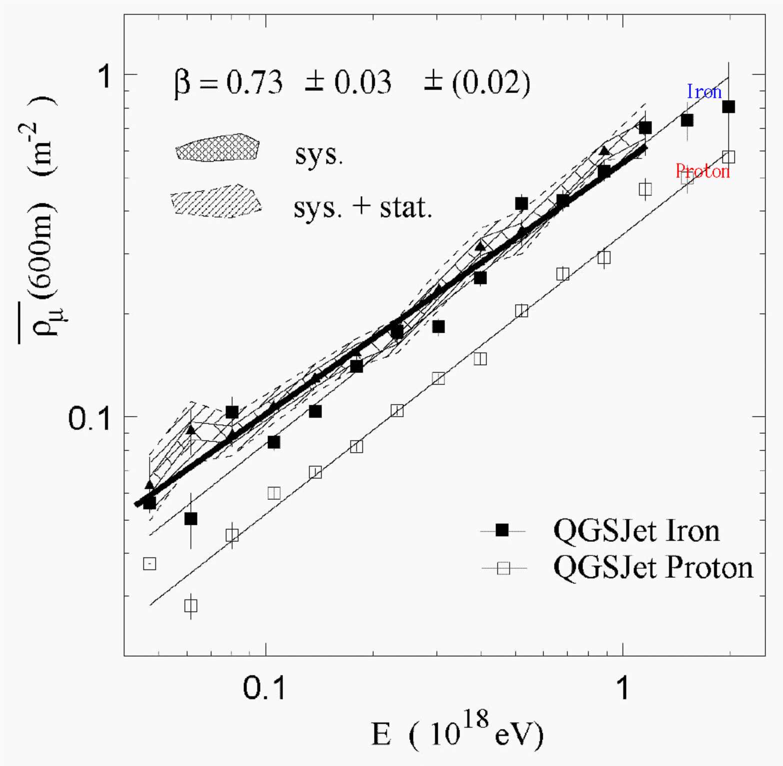
Auger breaks the silence on muon data





- (Left:) Ratio of Auger surface detector (SD) muon signal to MC predictions, R_μ, VS ratio of SD EM signal to MC predictions, R_E, in Auger hybrid events.
- (Right:) Auger SD muon signal VS CR energy in large zenith angle SD events
- Unlike X_{max} data, the muon data are INconsistent with all MC predictions ...
- And the muon signal INcreases with energy contrary to all MC predictions ...
- A $> 75\%$ proton composition would only INcrease the DISagreement!

Does the muon excess require new physics?



- Left: HiRes-MIA, T.Abu-Zayyad et al (1999), measurement of muon density compared to (old) shower MC models
- The CR energy range of 0.1 EeV to 1 EeV is believed to be a transition region from heavy (significant iron) to light (significant proton) composition ...
- Newer shower MCs predict $\sim 15\%$ increased muon flux; nevertheless HiRes-MIA data show marginal agreement with MC predictions.
- HiRes-MIA + Auger muon data are consistent with an increase in the "observed to predicted" muon signal with increasing energy.
- Is there flexibility in the MCs to accommodate the Hires-Mia/Auger muon results?
- Arguably both X_{max} and muon data show energy dependent "observed to predicted" differences. Is this a clue or a red herring?

Why are we still studying Cosmic Rays?

The University of New Mexico

- Modern CR experiments have progressed a long way from the (Left photos) pioneering experiments ...
- Do we now know the source of the highest energy CRs? No ... but the CR:AGN correlations continue to be suggestive or maybe just seductive!
- Do we now know the composition of the highest energy CRs? No ... but (arguably) GZK predictions for the CR spectrum favor a high percentage ($> 75\%$) protons.
- Are CR showers in the atmosphere consistent with MC expectations? No ... perhaps it is time (cautiously) to consider new physics!
- So why are we still studying cosmic rays? Maybe even refined tuning of shower MCs is insufficient, maybe most of the flux is not protons and maybe the AGNs are not the sources ...

Additional/backup slides

Additional slides

THE WORLD'S LARGEST COSMIC RAY OBSERVATORY

PIERRE AUGER OBSERVATORY

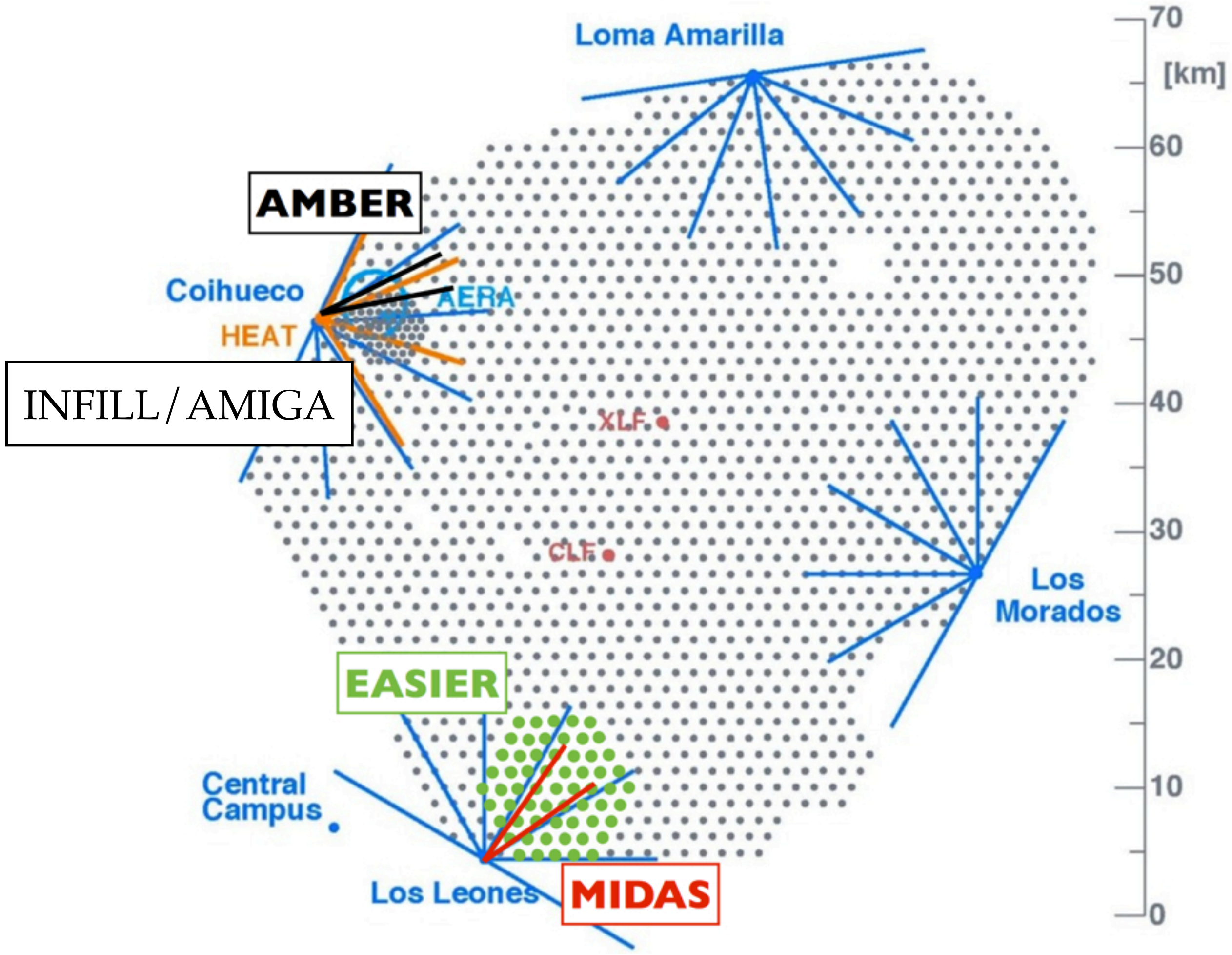
Collaboration : ~ 500 members & 19 countries

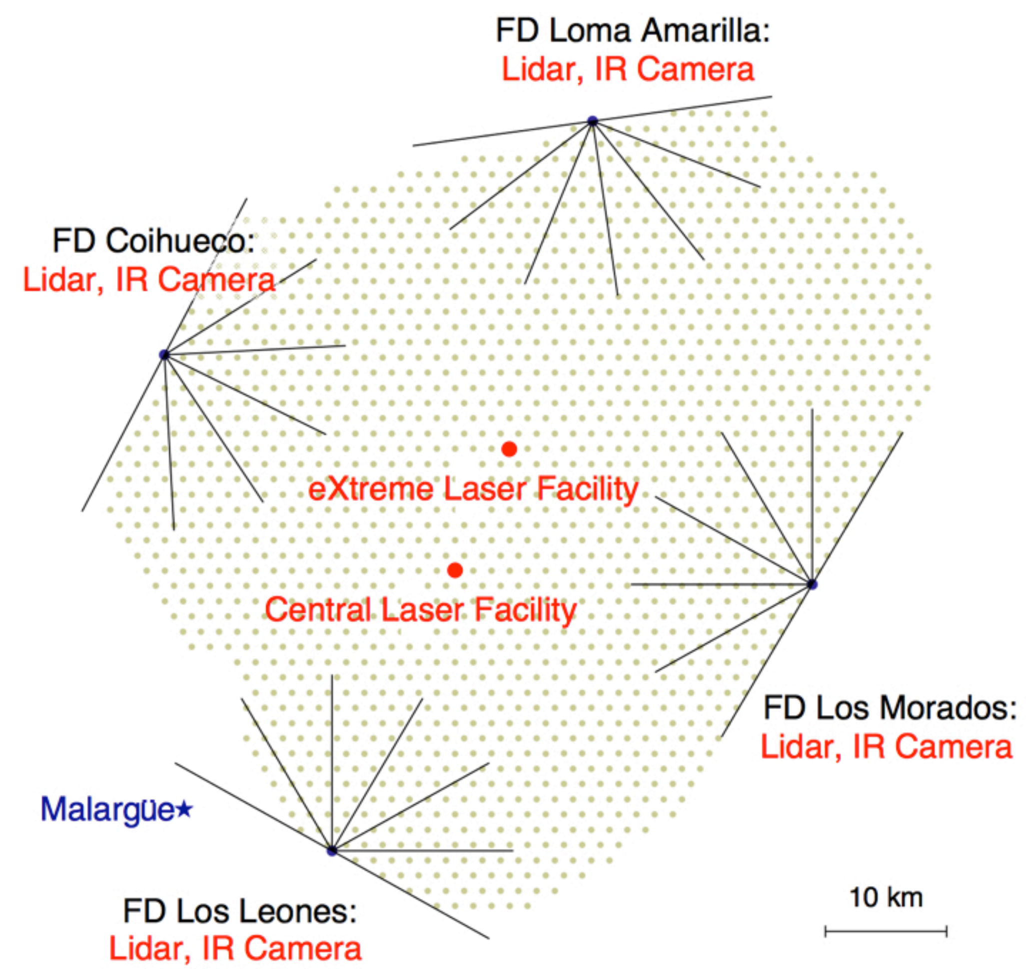
Argentina
Australia
Brazil
Croatia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
United Kingdom
USA

Bolivia*
Romania*
Vietnam*
*Associated

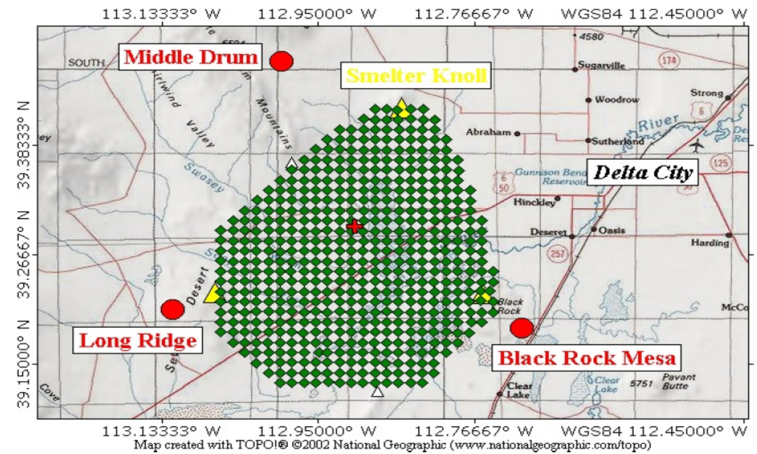
STATUS & PERFORMANCE

The world's largest cosmic ray observatory
In operation since 2004





TA HYBRID DETECTOR



- 507 scintillator detectors covering 680 km^2
- 3 fluorescence sites, 38 telescopes
- SD fully operational from March 2008
- SD relative size: TA $\sim 9 \times$ AGASA $\sim$ PAO/4

SD

Surface
Detector

S=10m^2, h=1.2m
Water Tank

S=3m^2, t=1.2cm
Plastic Scint.
2-layer

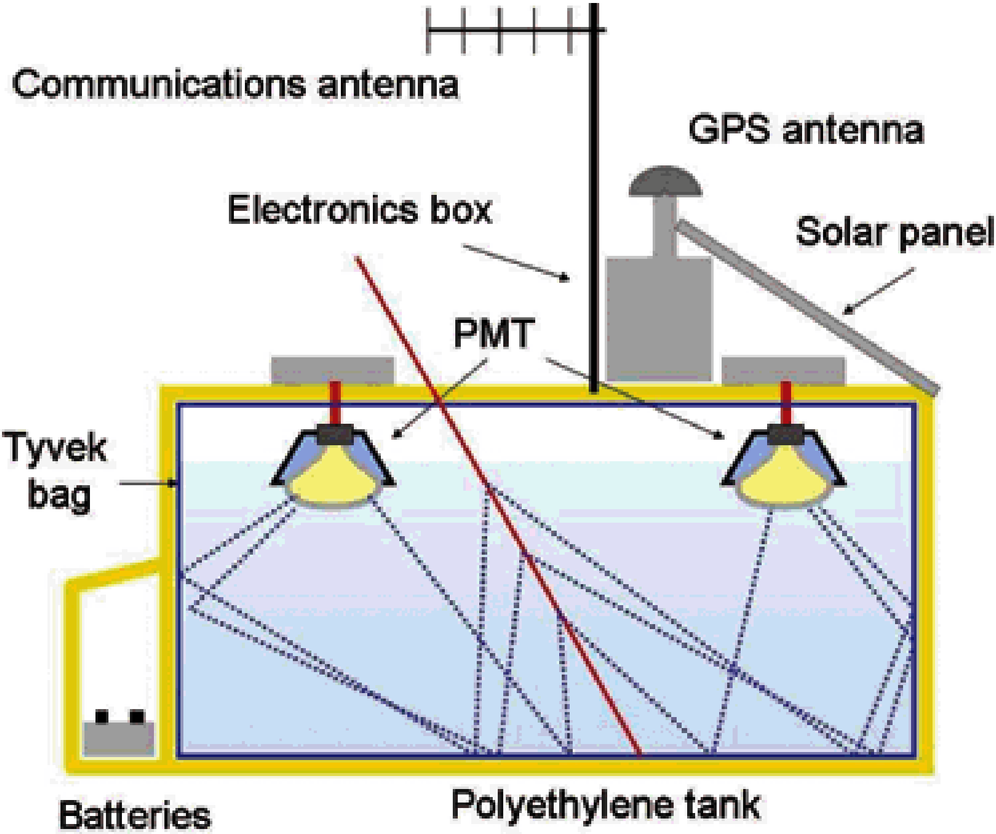
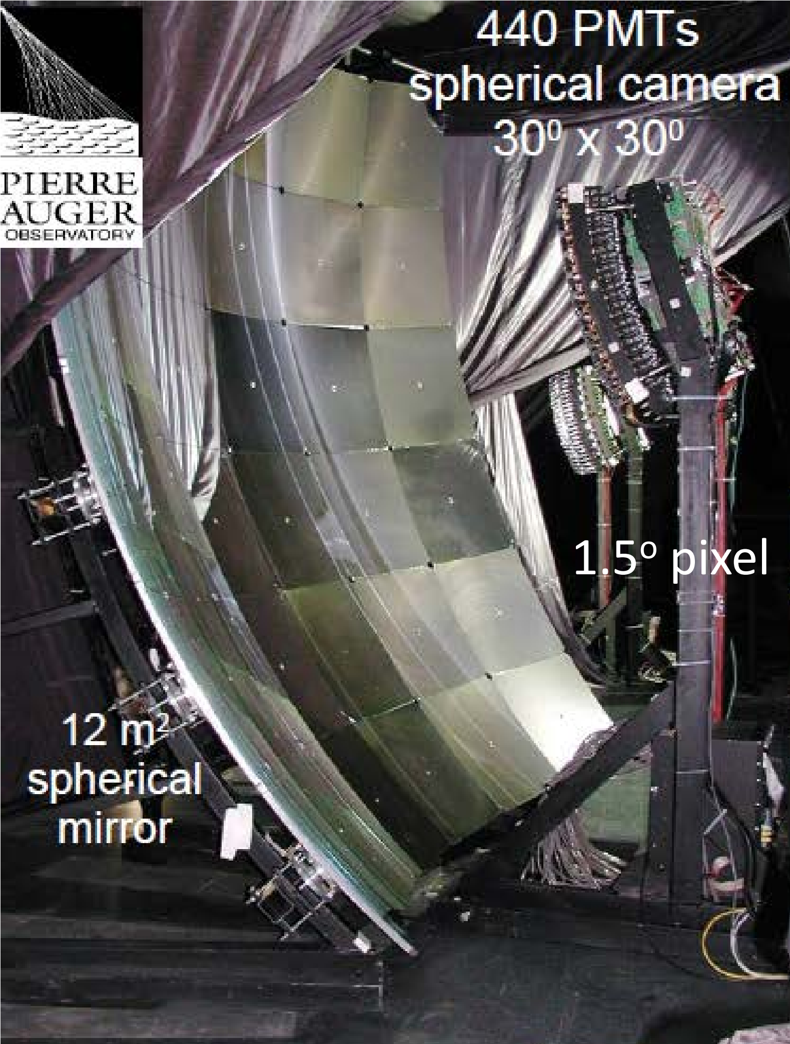


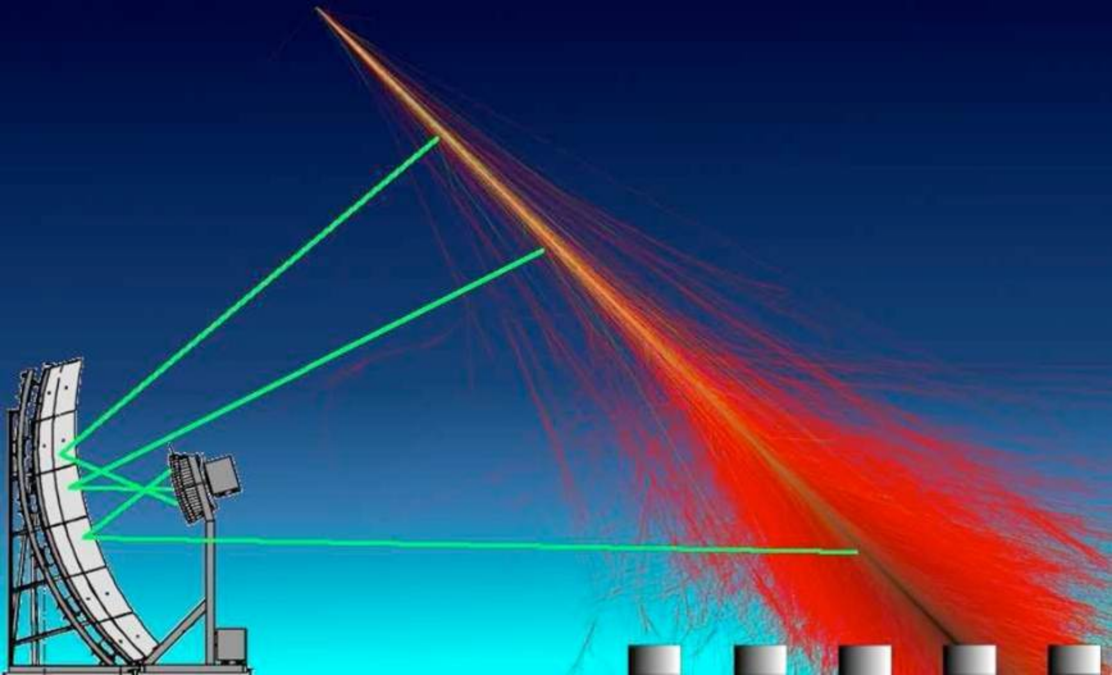
FIG. 2: A schematic view of the Cherenkov water tanks, with the components indicated in the figure.

Beautiful Eyes

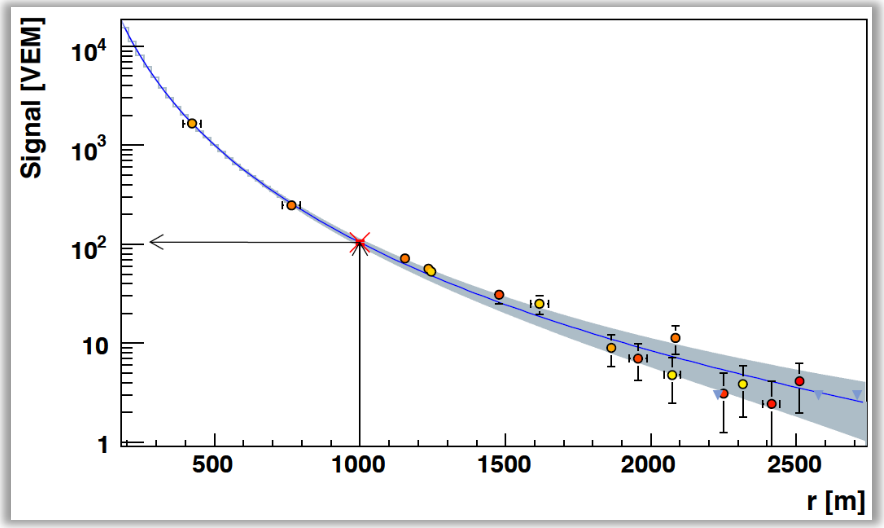
FD

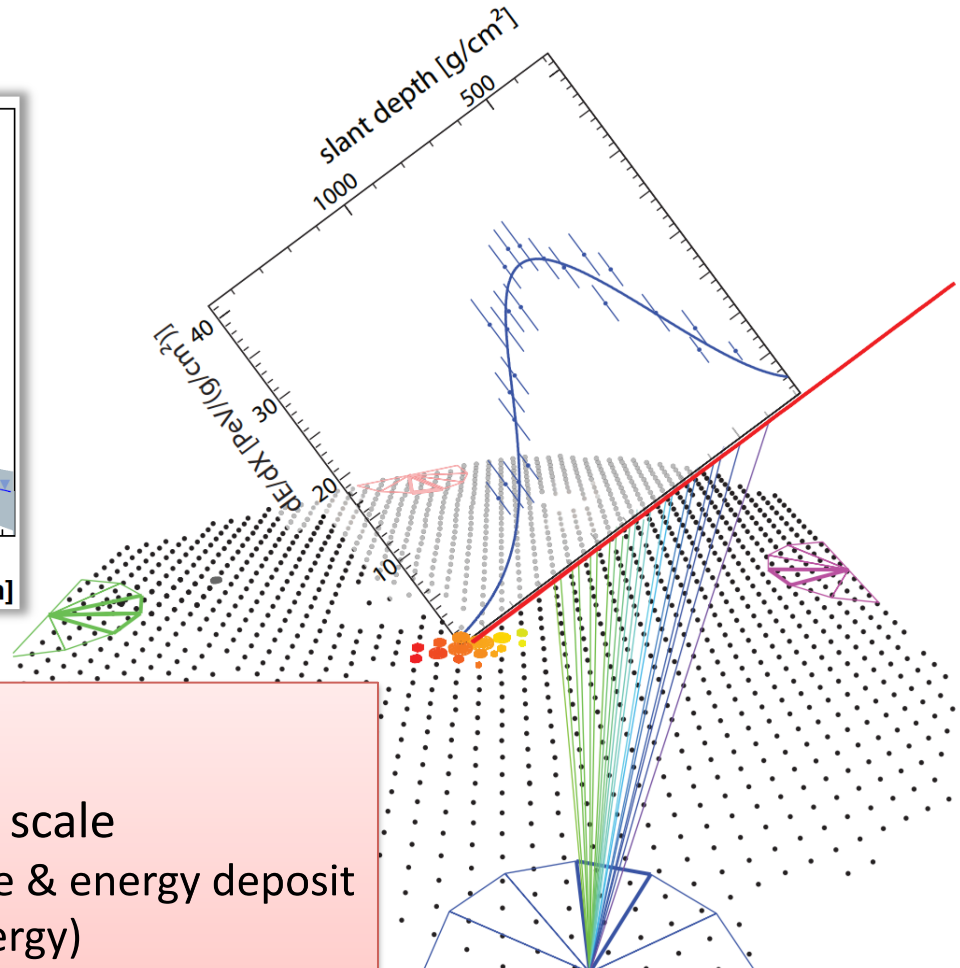
Fluorescence
Detector





Hybrid Events at the Auger Observatory





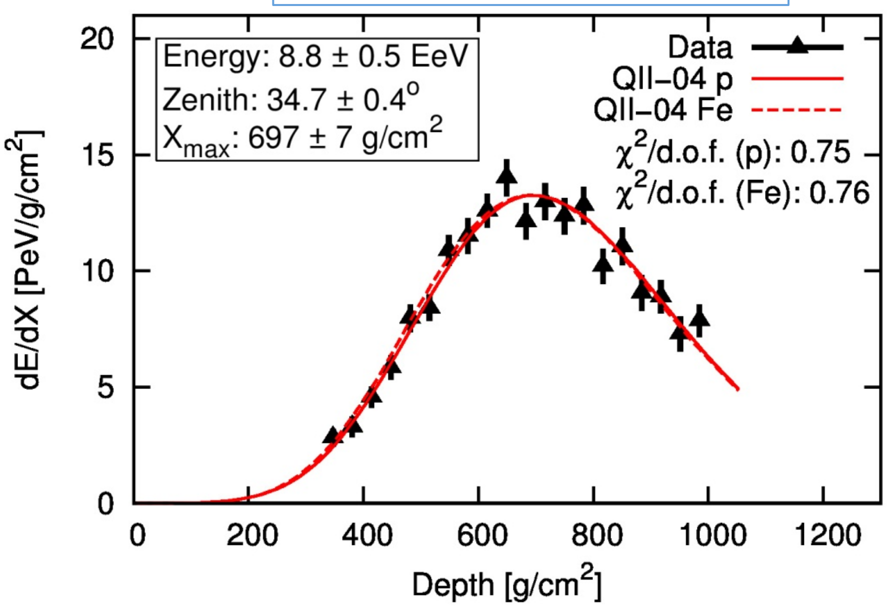
Key Facts

- Fluorescence Detector (FD) sets energy scale
  - Telescopes measure longitudinal profile & energy deposit
  - Sensitive primarily to EM (≈ 90% of energy)
- Surface Detector Array (SD) measures ground particles
  - Water-Cherenkov detectors
  - Sensitive to both EM and muons

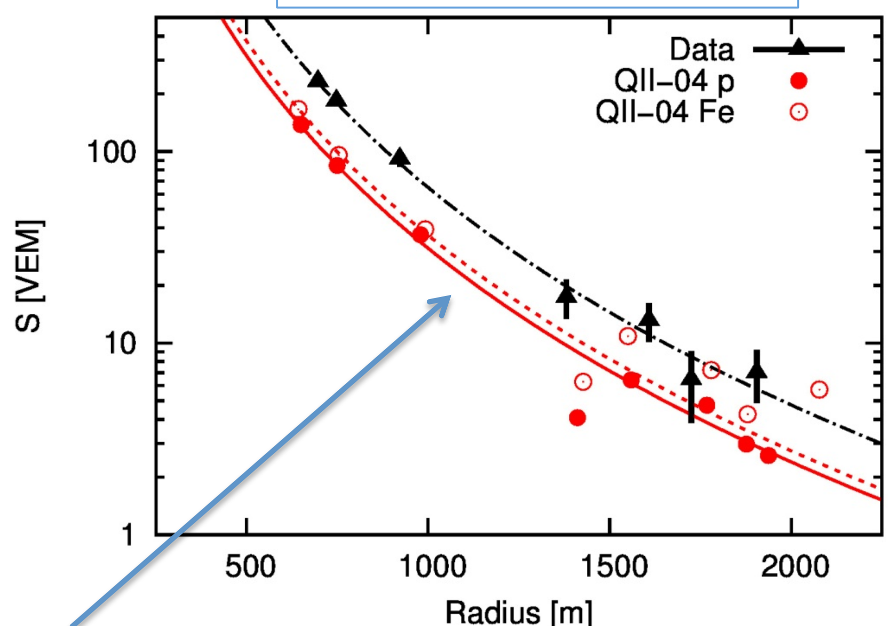
Can models match both FD and SD?

- Find simulations which match measured FD profile, ***for each event***
- Compare the ground signals between the simulations and data
- Rescale muon content so that simulated ground showers best-match observed ones.

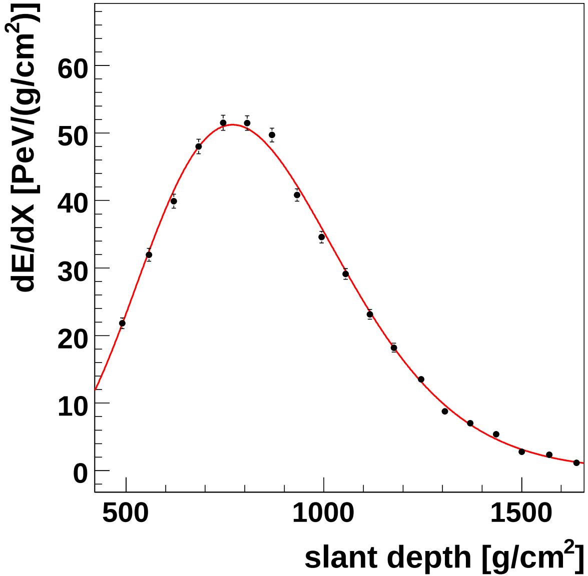
FD: longitudinal profile



SD: lateral distribution



Typical example: model ground signal is too low



(b) event 4742735, LM, $E = (3.5 \pm 0.2) \times 10^{19}$ eV