Pierre Auger Observatory

studying the universe's highest energy particles

Ultrahigh Cosmic Rays: The highest energy frontier

Humberto Salazar (FCFM-BUAP)

for the Pierre Auger Collaboration,

CTEQ- Fermilab School Lima, Peru, August 2012

SCIENTIFIC OBJETIVES:

Spectrum: CR flux for E > 10^{18} eV

Arrival directions: search for anisotropies (identify the sources)

Composition: light or heavy nuclei, photons, neutrinos, others?

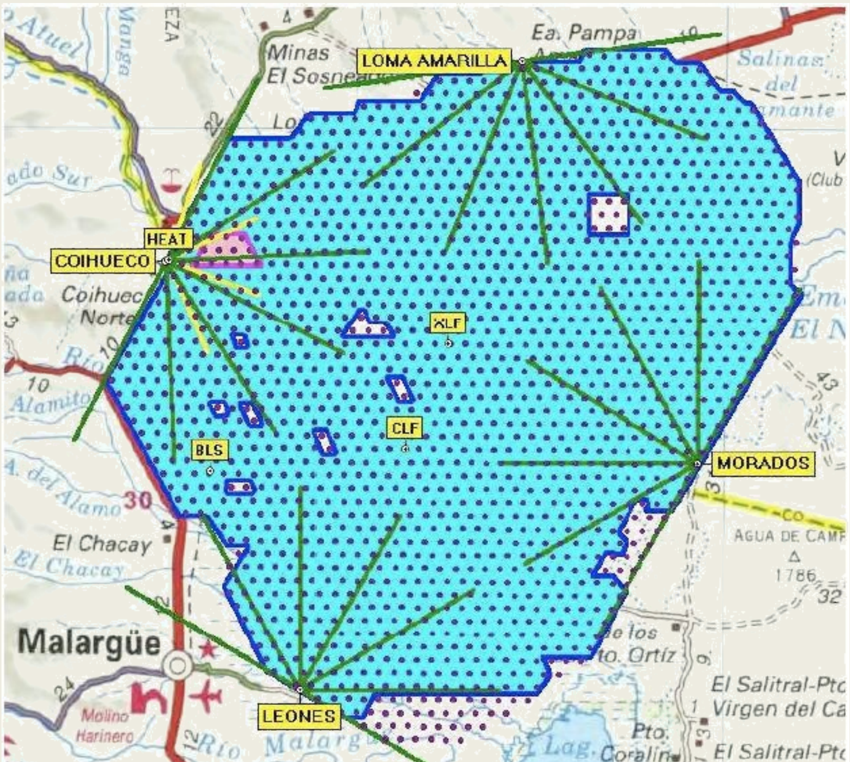
Study of interactions at energies unreachable at accelerators

Auger

The Auger Observatory in the Southern Hemisphere

Hybrid shower measurements

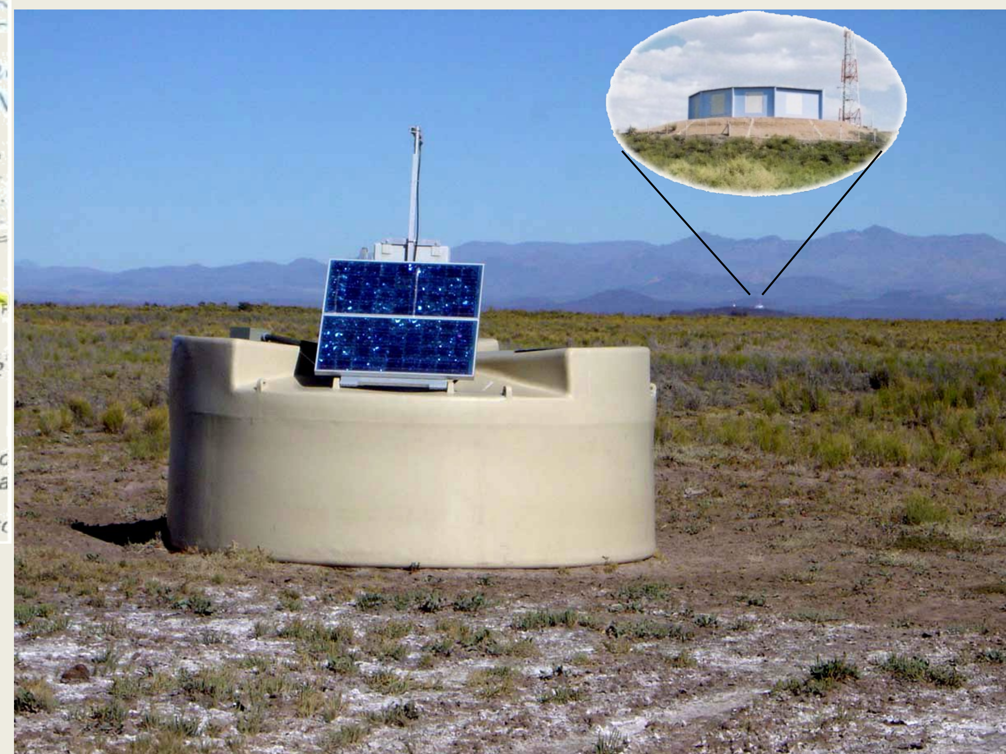
Fully deployed in Argentina since June 2008



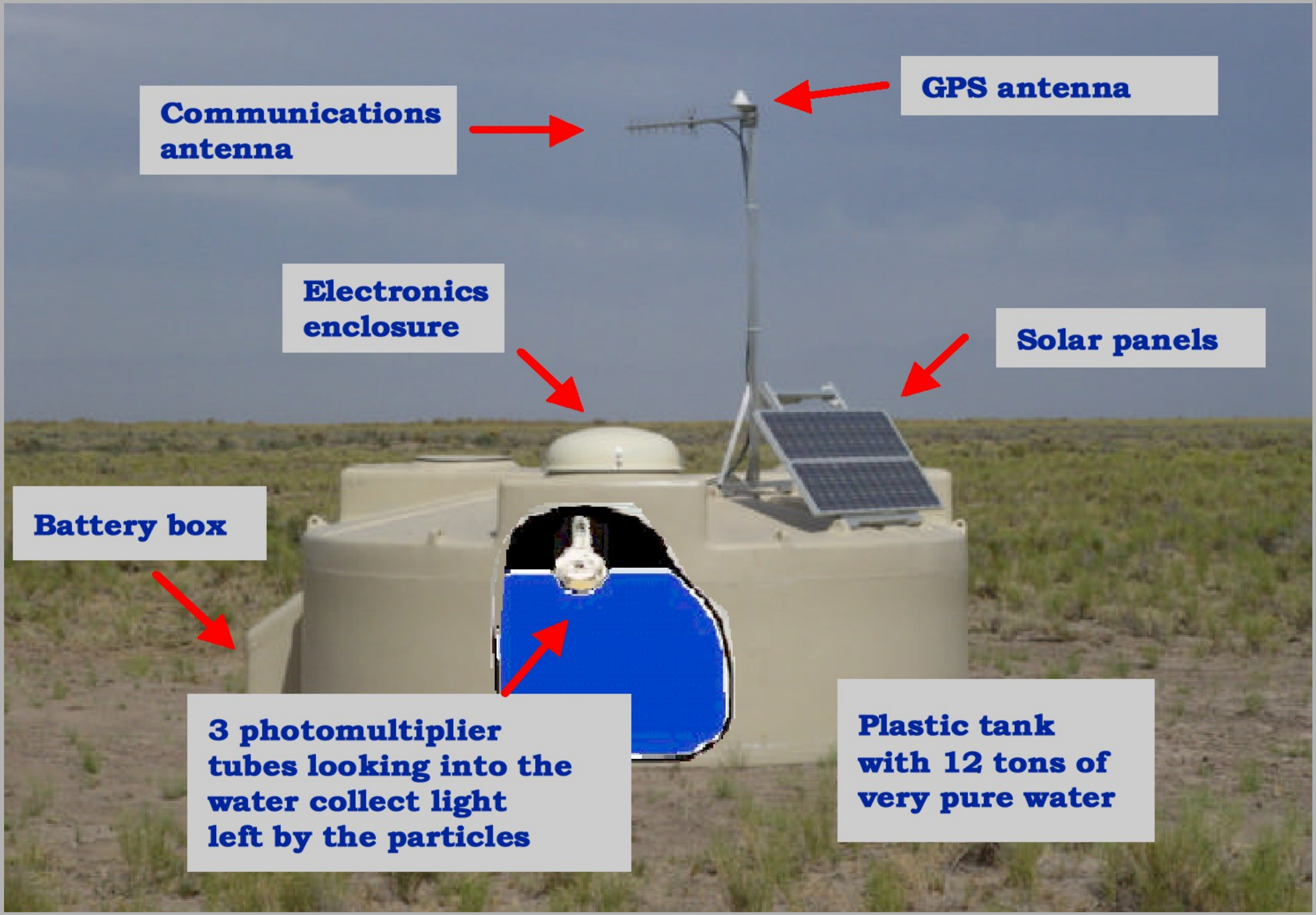
60 km

1600 water Cherenkov stations

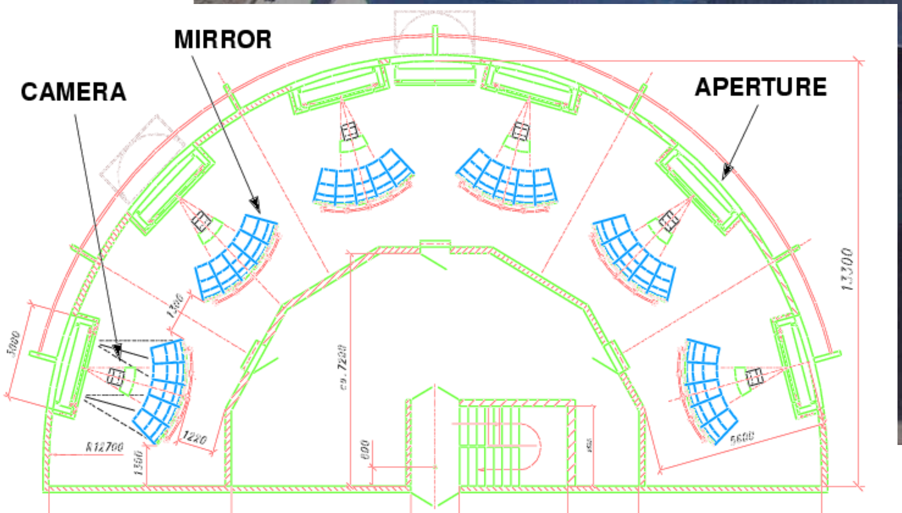
24 fluorescence telescopes (30˚x30˚)



A Water Cherenkov Station



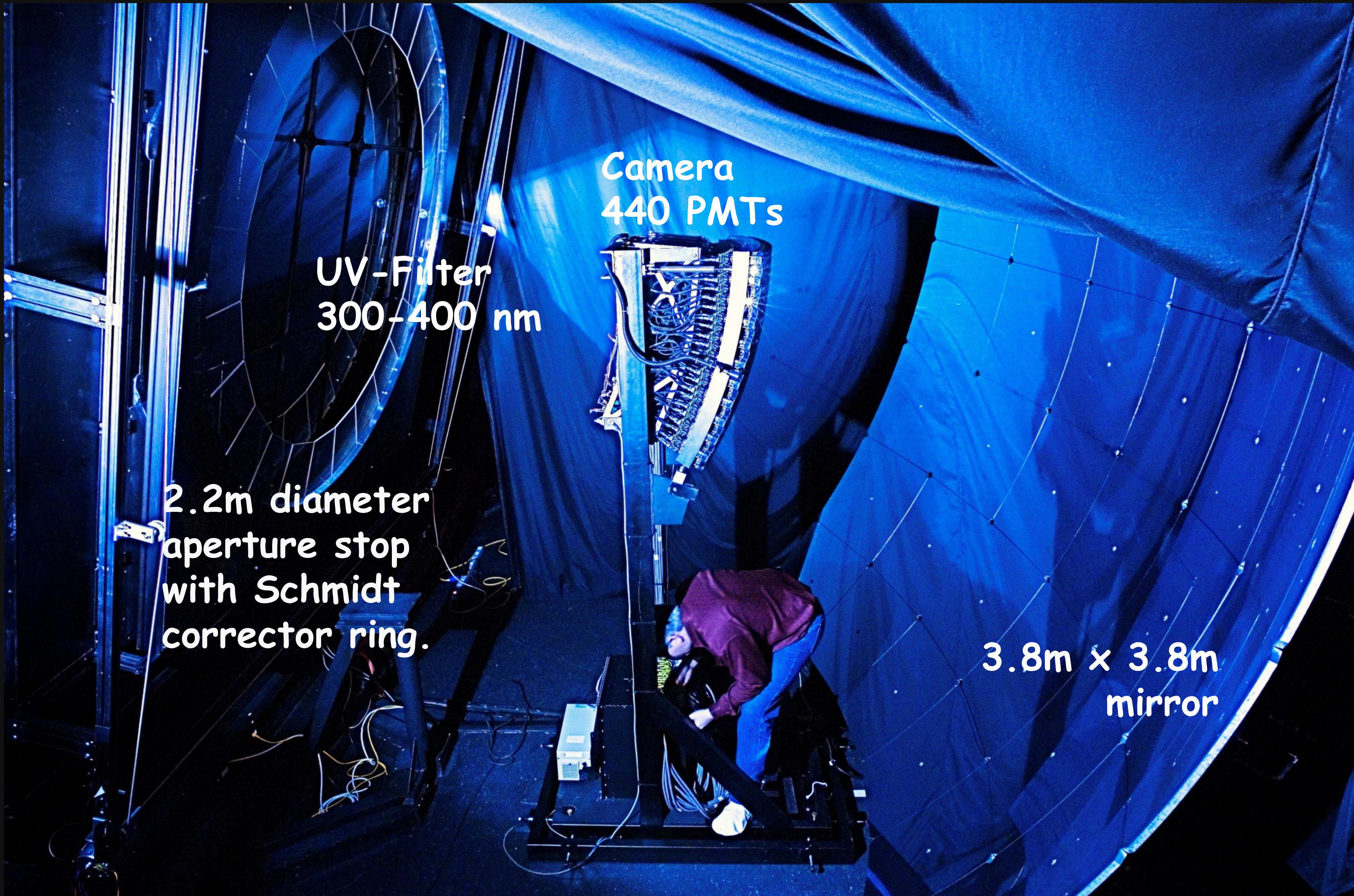
4 Fluorescence Detector Eyes with Six Telescopes (30°x30°) each



An Air Fluorescence Telescope

$30^{o} \times 30^{o}$

Field of View

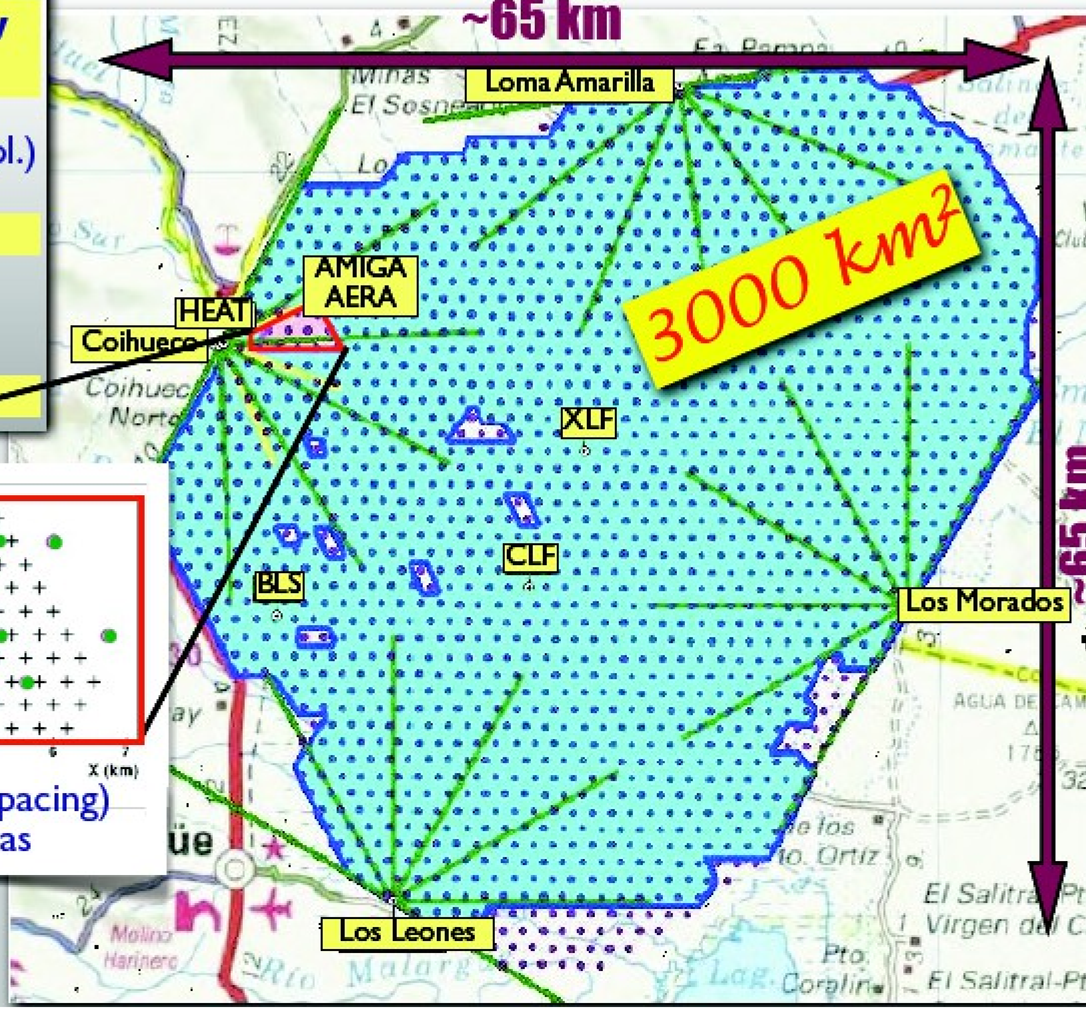


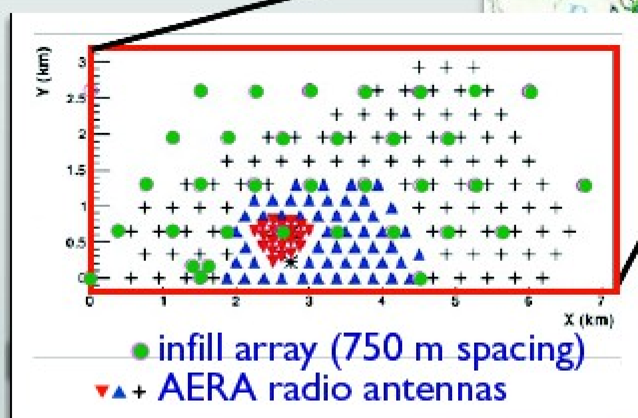
Pierre Auger Observatory in Argentina

1660 Water-Cherenkov tanks
1.5 km standard grid
0.75 km infill-grid (53/61 depl.)

27 telescopes
in 4+1 buildings at the periphery

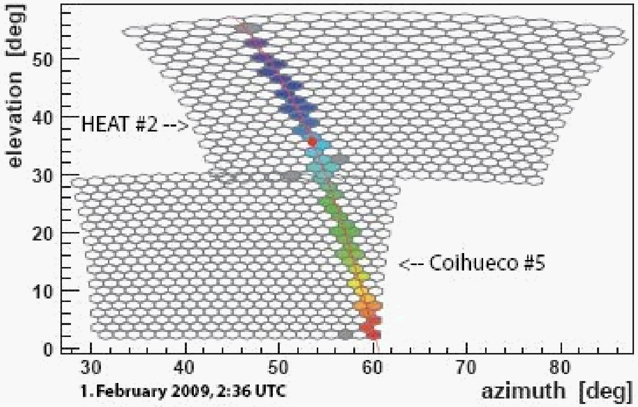
3000 km² area

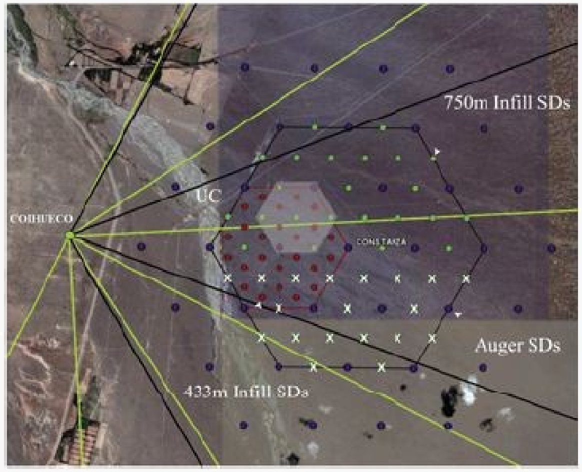




Enhancements at Auger South

HEAT: High Elevation Auger Telescopes

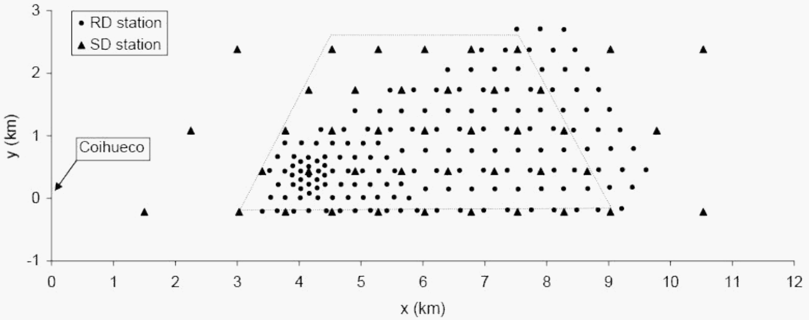




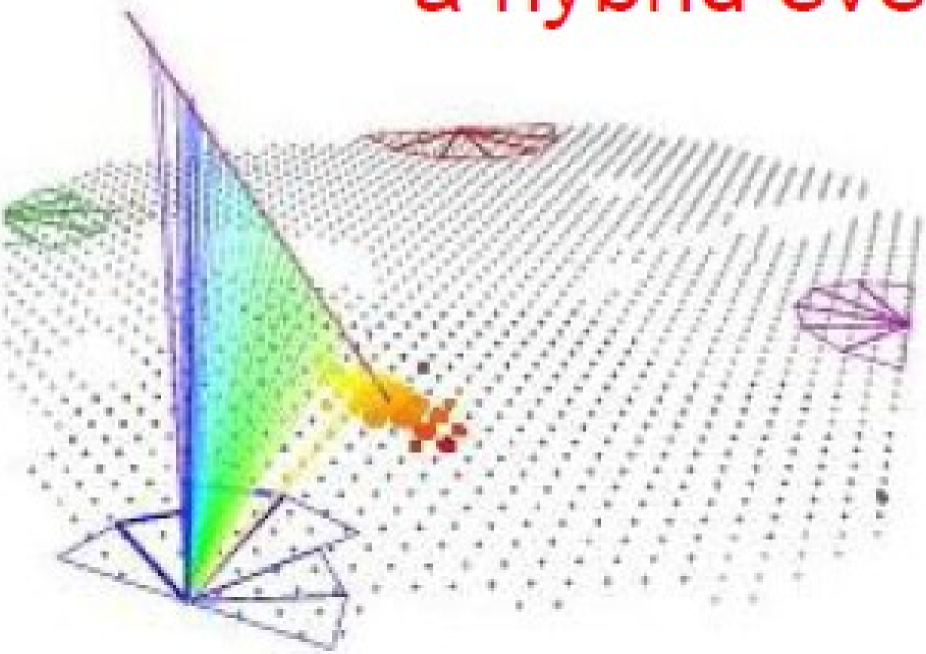
AMIGA: Auger Muon and Infill Ground Array

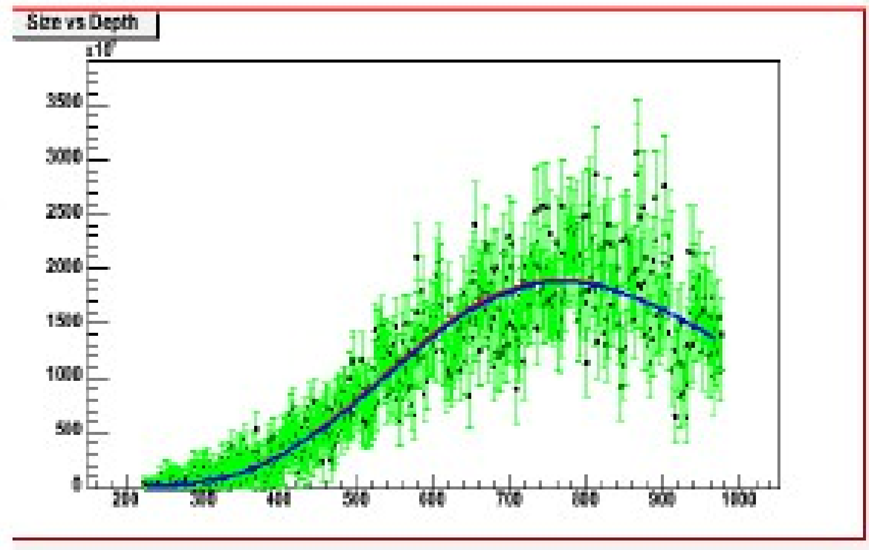
,

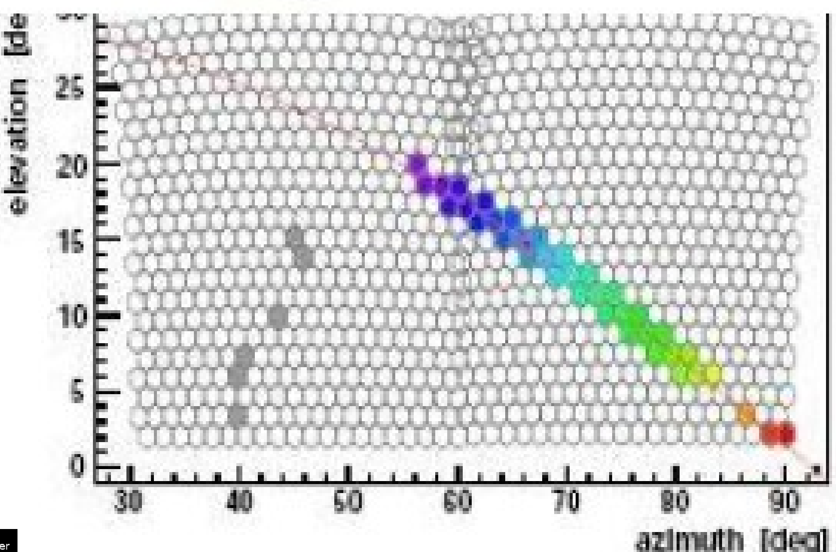
AERA: Auger Engineering Radio Array



a hybrid event





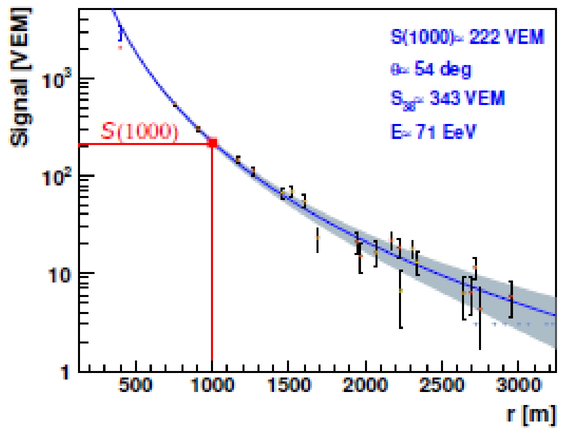


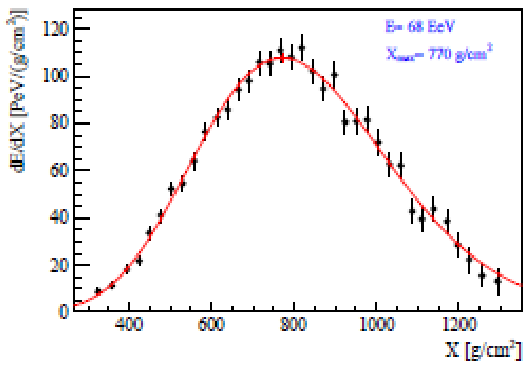
Measure Xmax
Energy calibration
angular resolution studies ...

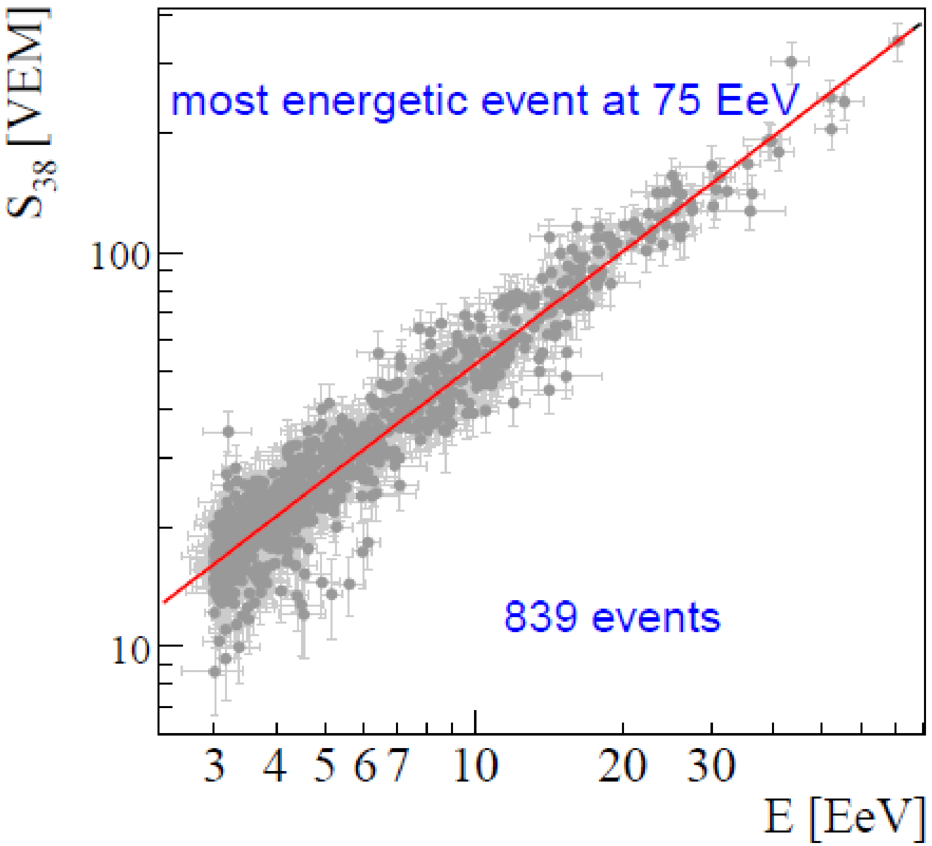
(but duty cycle ~15%)

SD energy calibration with FD

Calibration made using events with independent SD and Hybrid trigger and reconstruction

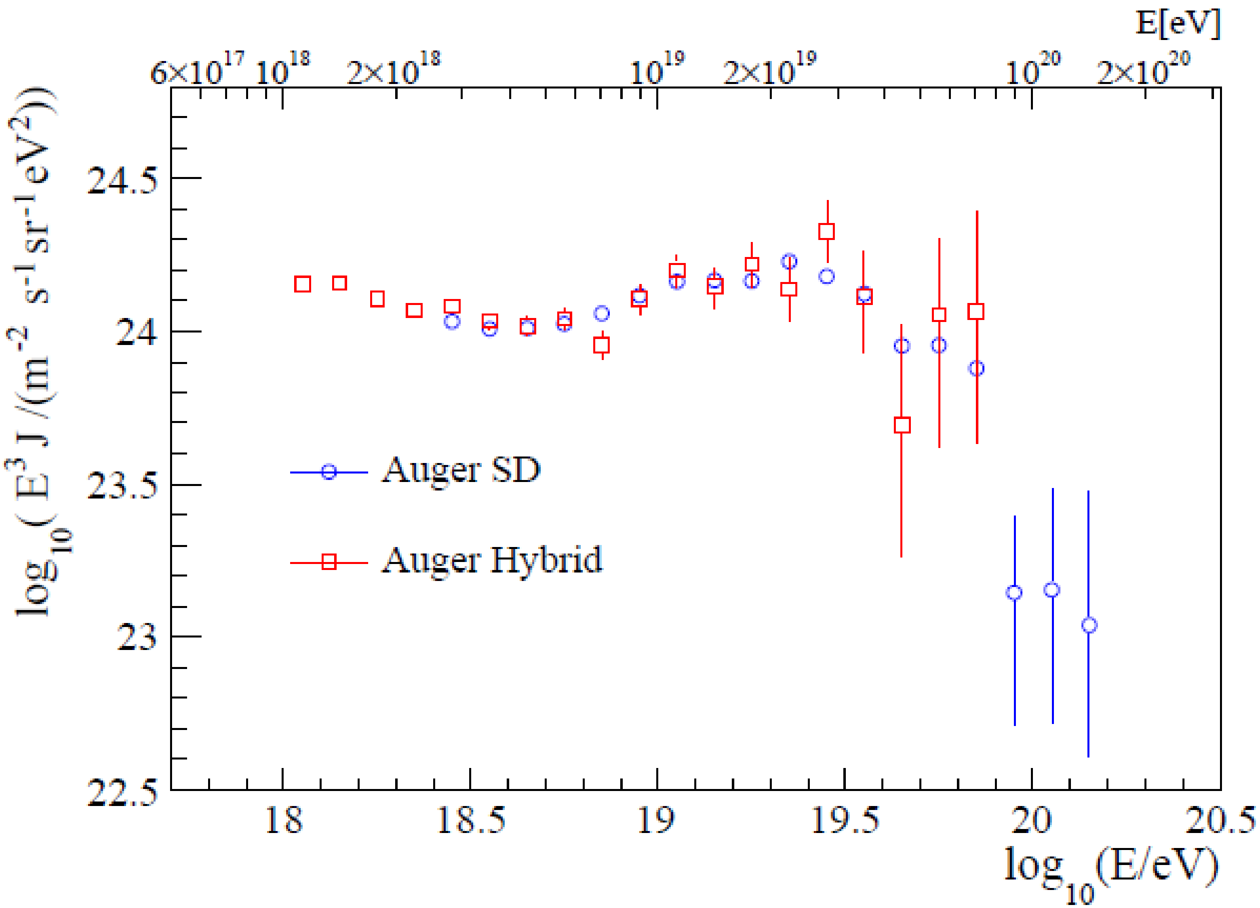




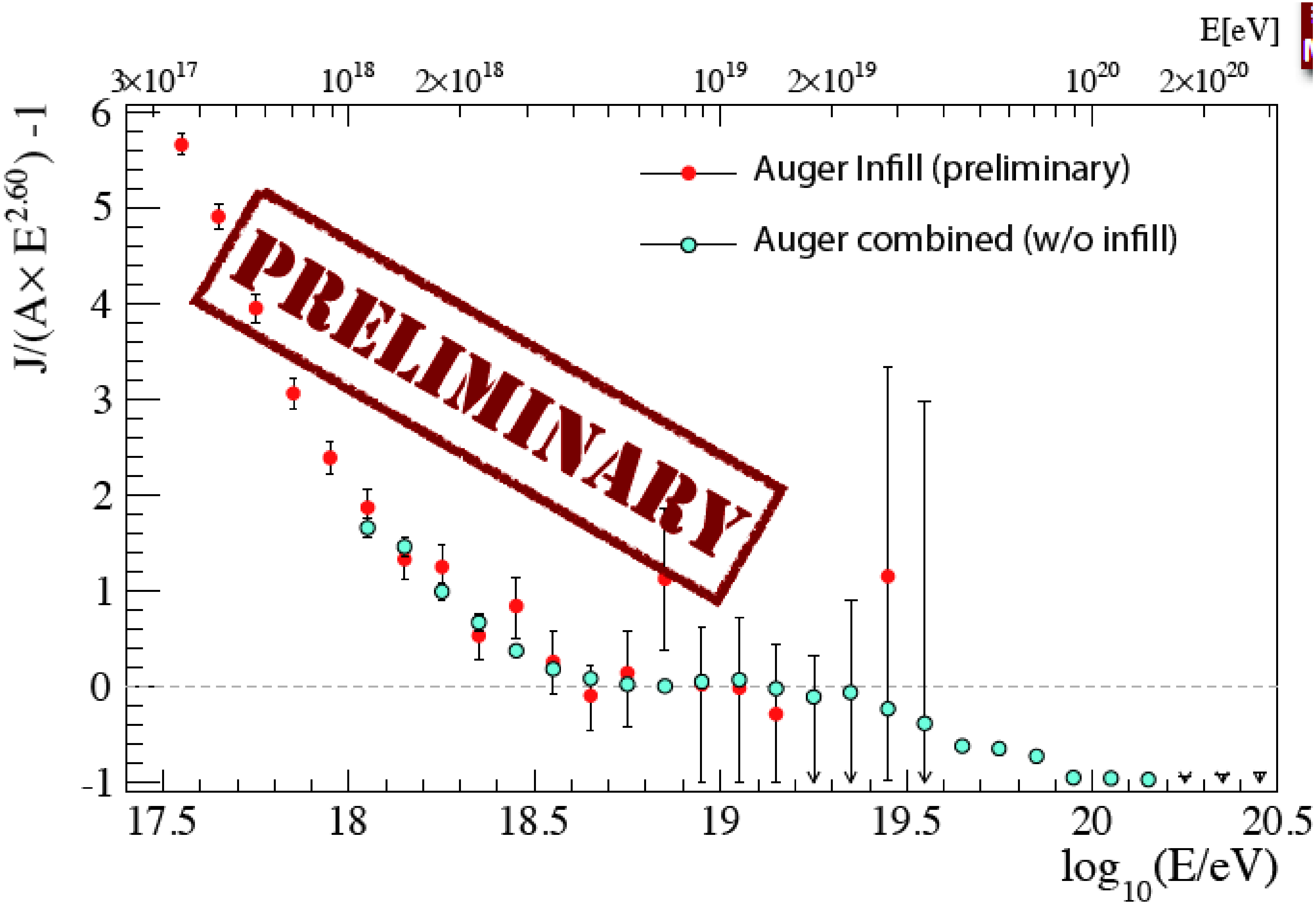


Systematic uncertainty 7% (15%) at 10 EeV (100 EeV)

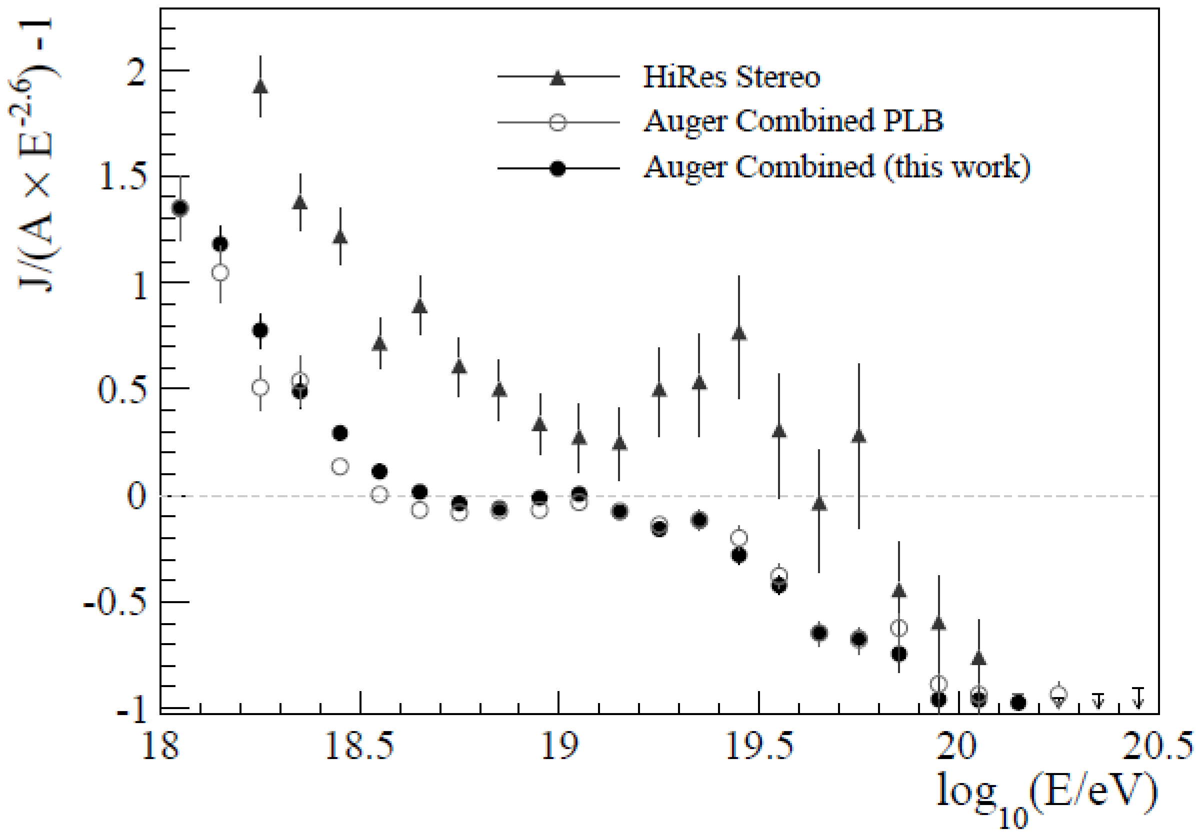
Hybrid energy spectrum



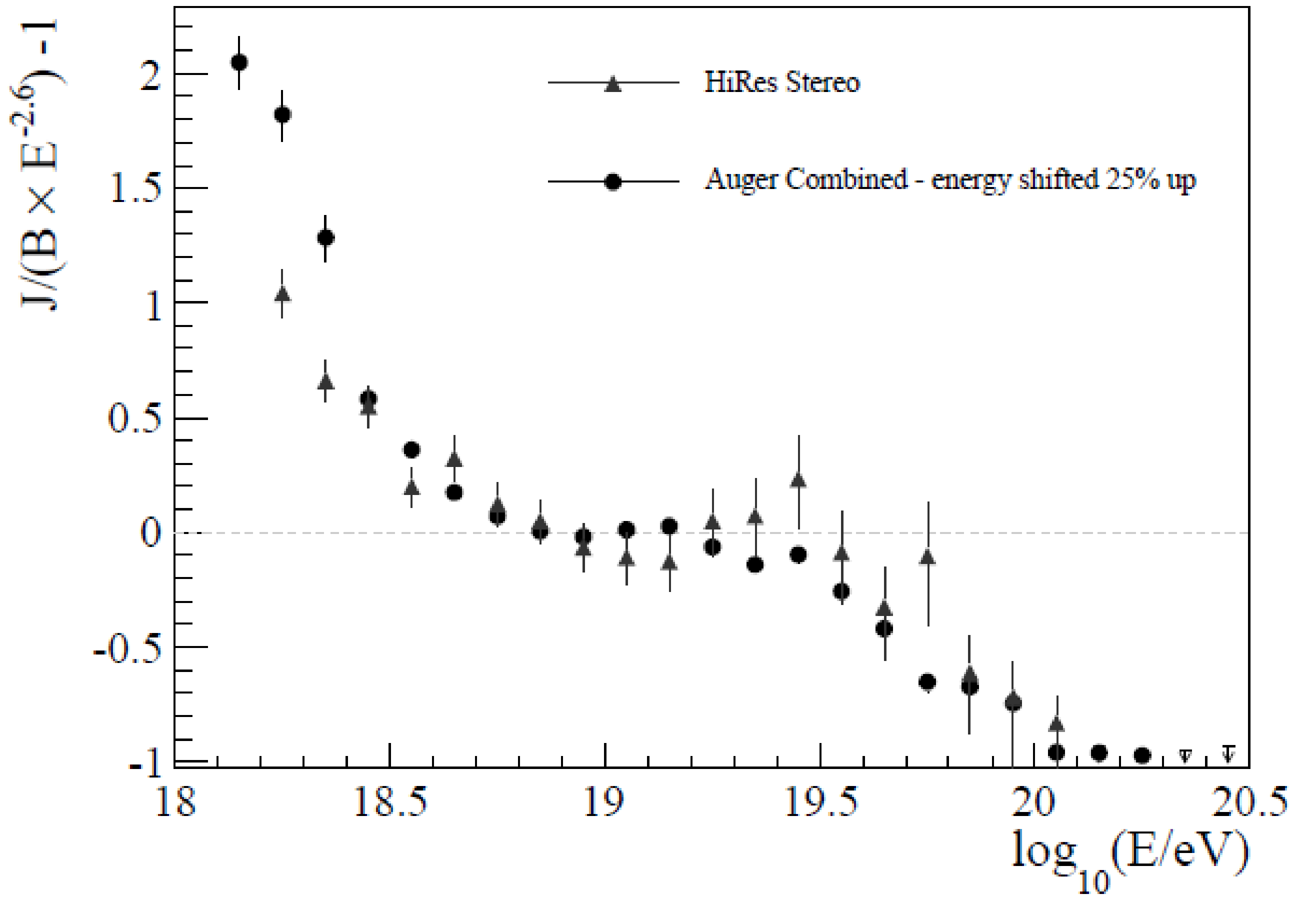
- very good agreement with SD
- difference in flux with old publication less than 2%



Exposure of infill array: (26.4±1.3) km² sr yr

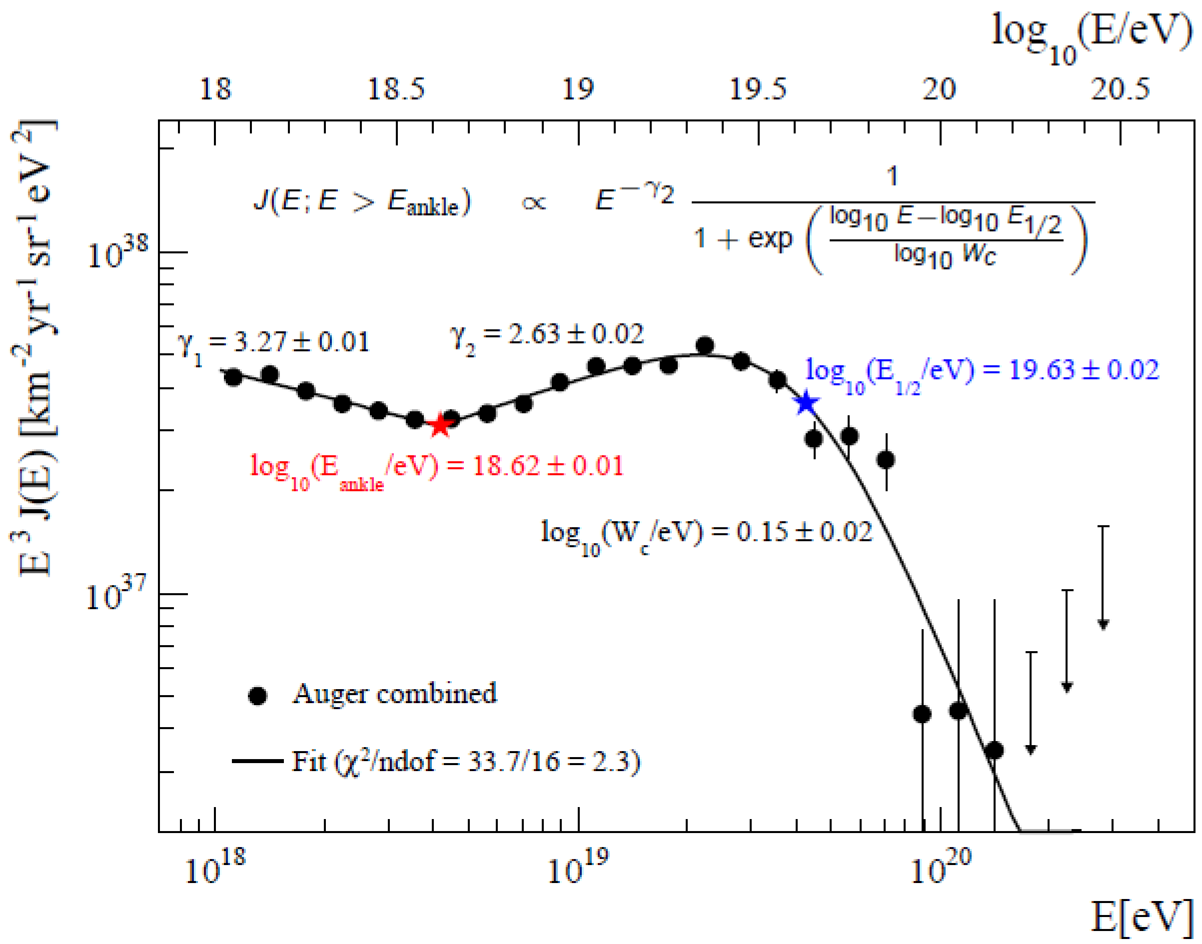


- difference w.r.t PLB due to changes in calibration curve
- very high statistics, spectral features very well defined



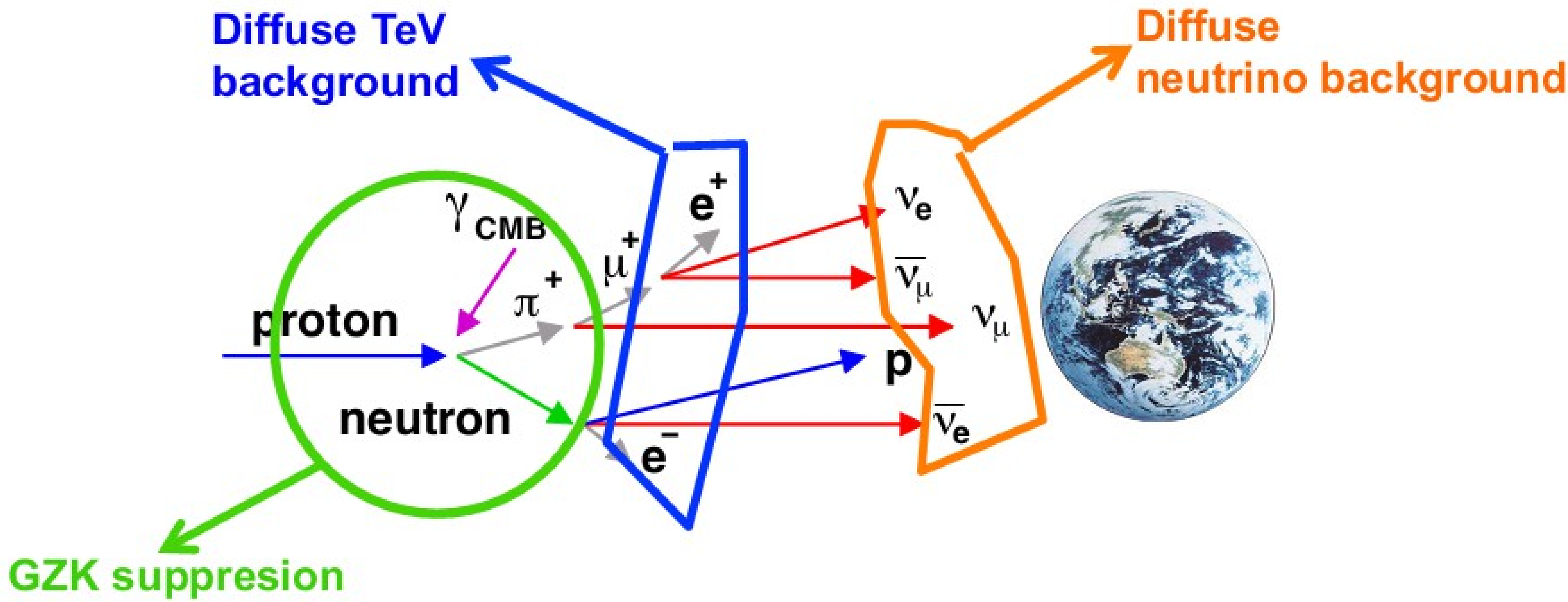
- Energy shift of 25% applied to Auger combined spectrum

Fitting the combined spectrum II - smooth cut-off



- precise measurement of spectral features
- results compatible with PLB publication

p + CMBR: Photo-pion production & GZK feature



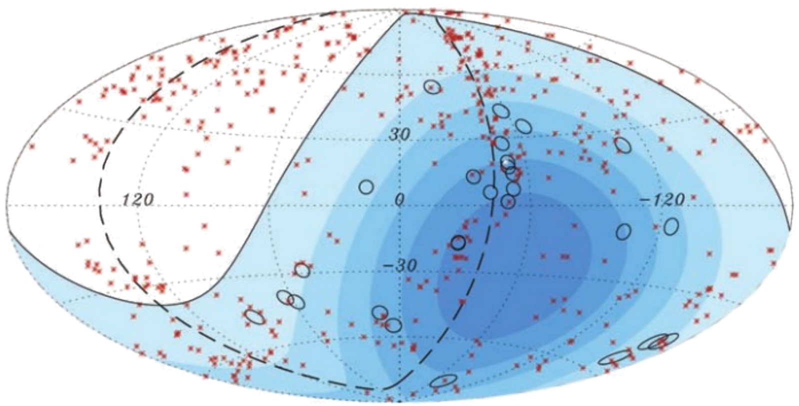
$$p+\gamma_{CMB} = \begin{cases} \to n+\pi^+ \\ \to p+\pi^0 \\ \to p+e^+ + e^- \end{cases}$$

$\lambda \approx 6$ Mpc / E_{th} ~$10^{19.6}$ eV
ΔE~20% per interaction

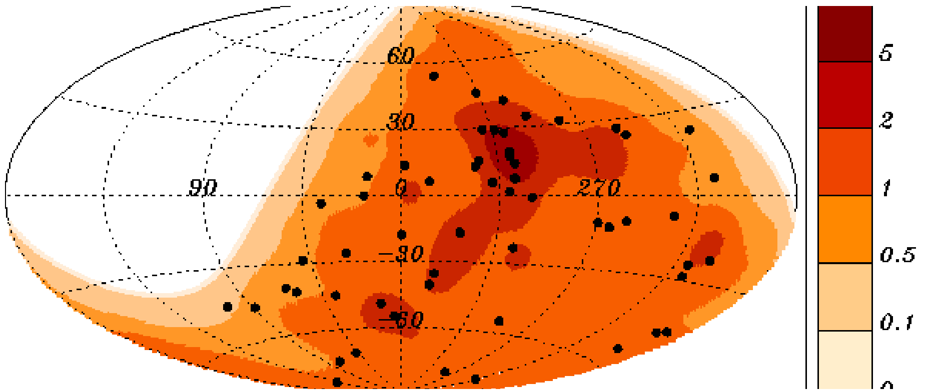
$\lambda \approx 1$ Mpc / E_{th} ~10^{18} eV
ΔE~0.1% per interaction

ankle

The Auger Sky above 60 EeV

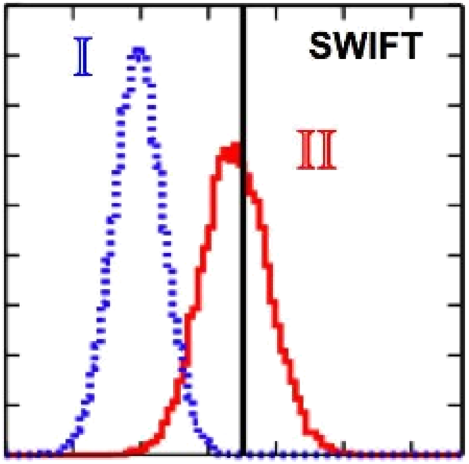


27 events as of November 2007



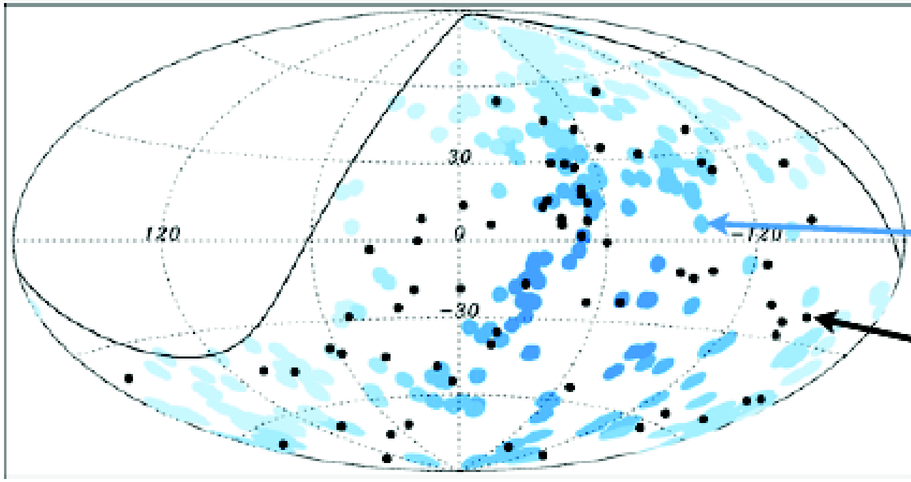
58 events now (with Swift-BAT AGN density map)

Simulated data sets based on isotropy (I) and Swift-BAT model (II) compared to data (black line/point).



Log(Likelihood)

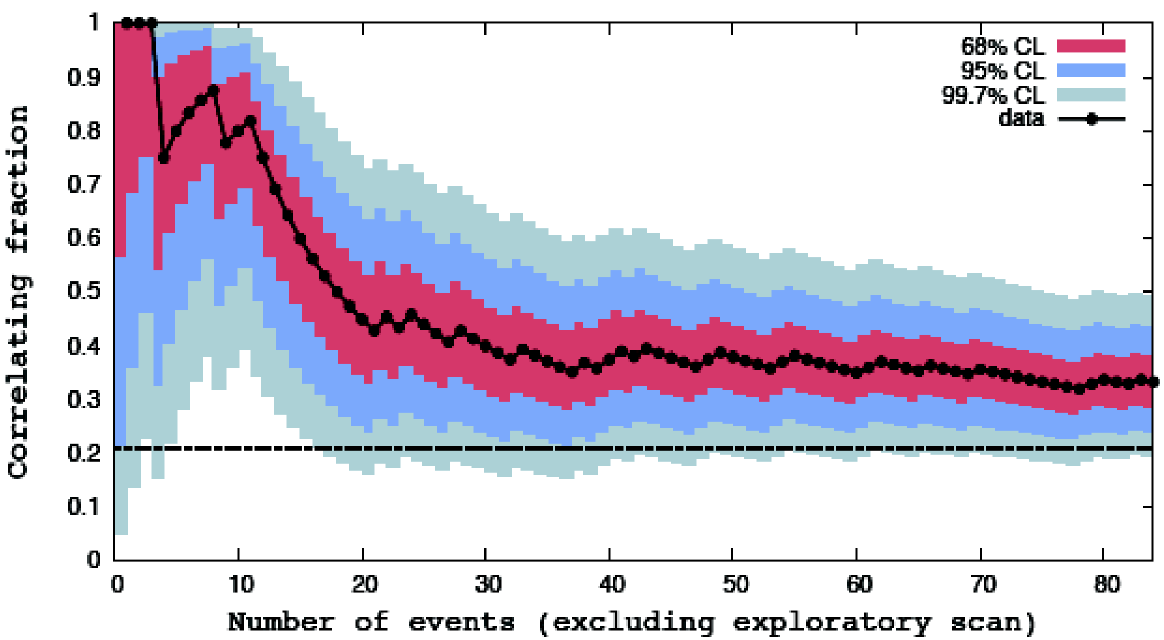
Update of Correlation with VCV-AGN



Astropart. Phys. 34 (2010) 314

AGN position (3.1° circle)

event position



Update including June 2011

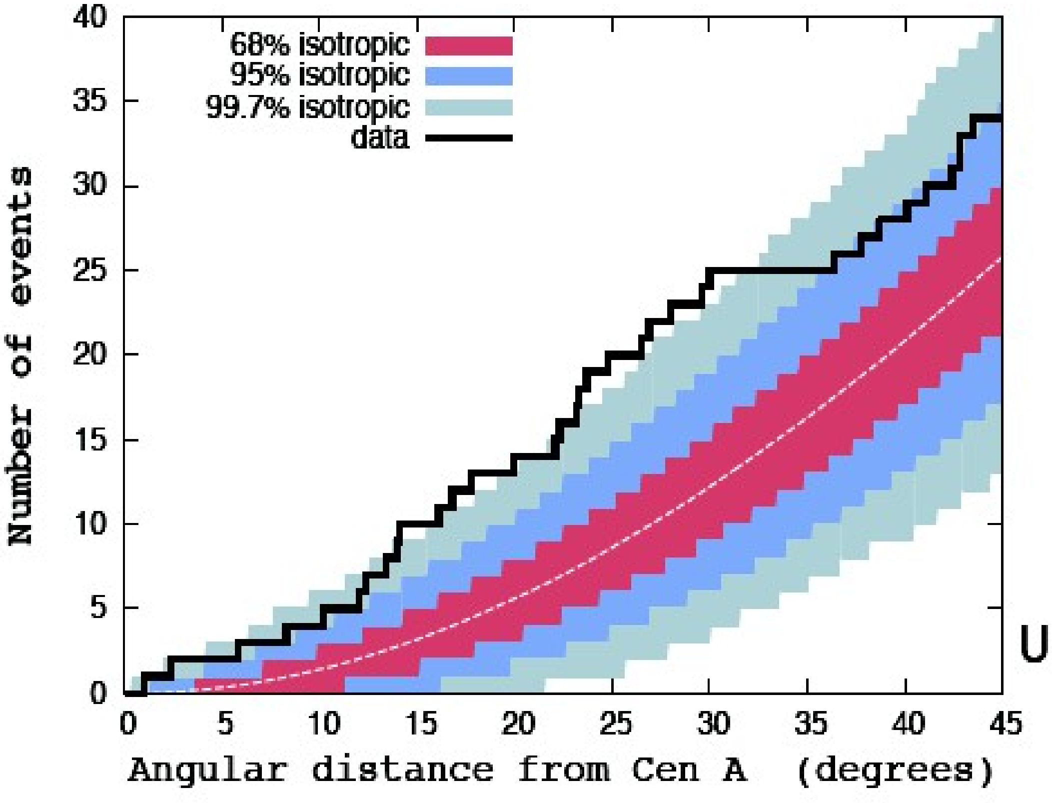
33±5%

Total: 28/84

P=0.006

Telescope Array:
8/20 = 40%
with iso-bkg = 24%

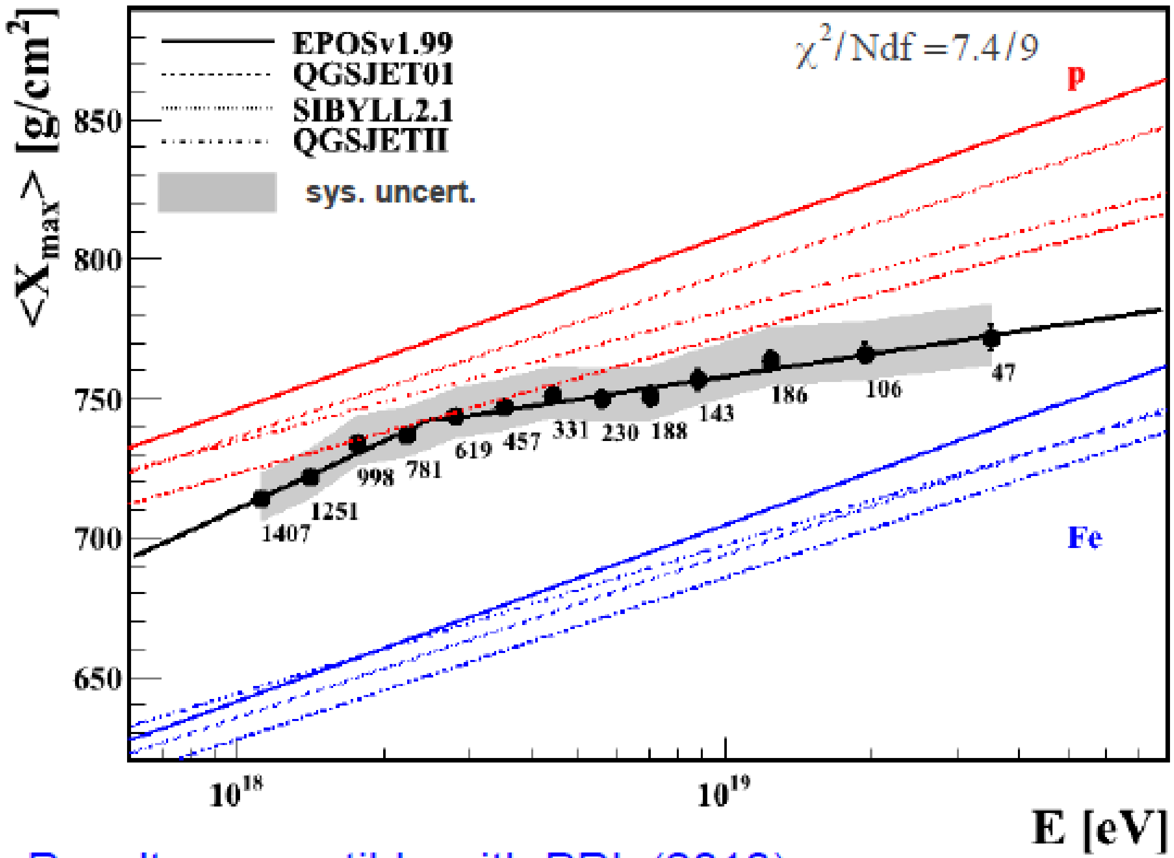
Update on Cen A



Update including June 2011

KS test yields 4% isotropic probability
Largest departure now at 24°: 19 observed / 7.6 expected

$<X_{max}>$ vs. Energy



Low Energy

$D_{10} = 82^{+48}_{-8}\ \mathrm{g/cm^2/decade}$

High Energy

$D_{10} = 27^{+3}_{-8}\ \mathrm{g/cm^2/decade}$

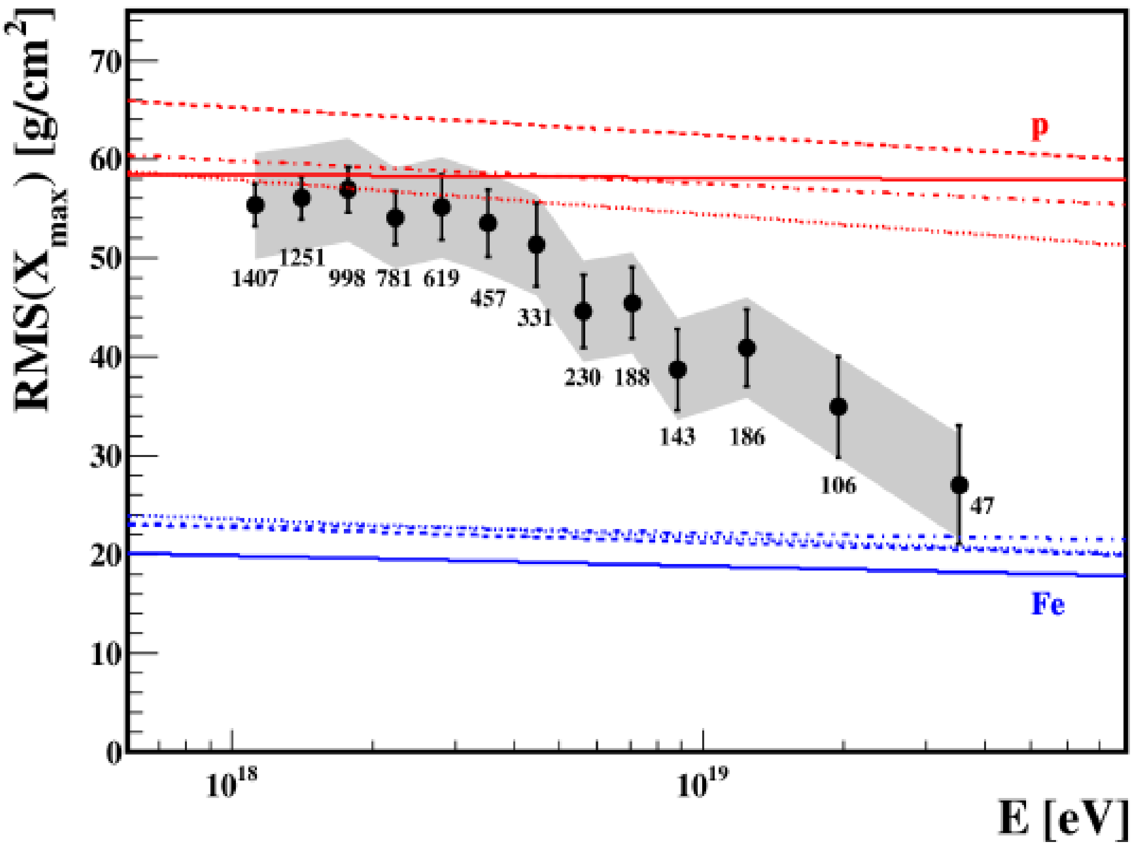
Energy break

$\log(E_{break}/\mathrm{eV}) = 18.38^{+0.07}_{-0.17}$

Below E_{break} the small lever arm of the fit results in higher statical uncertainties in D_{10}

- Results compatible with PRL (2010)
- Data are best described with two slopes; break is near the same energy as the ankle feature of the spectrum
- At high energy $<X_{max}>$ increases *slowly* with energy.

RMS(X_{max}) vs. Energy



Resolution is subtracted from data:
27 g/cm^2 → low energy
18 g/cm^2 → high energy

- Compatible with published results PRL(2010)
- There is a change in behavior around the same energy as <X_{max}>: above 2.5 10^{18} eV there is a fast decrease of RMS(X_{max}) towards the values expected for heavy primaries.

Shower Depths of Maximum X_{max}

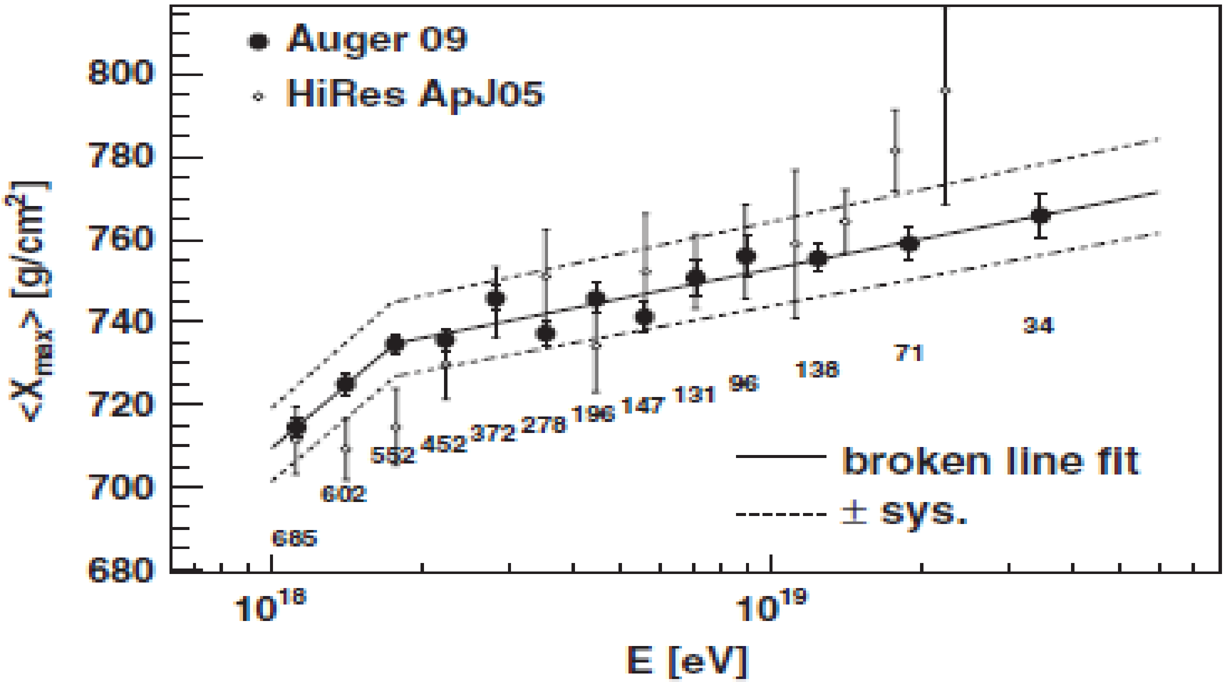
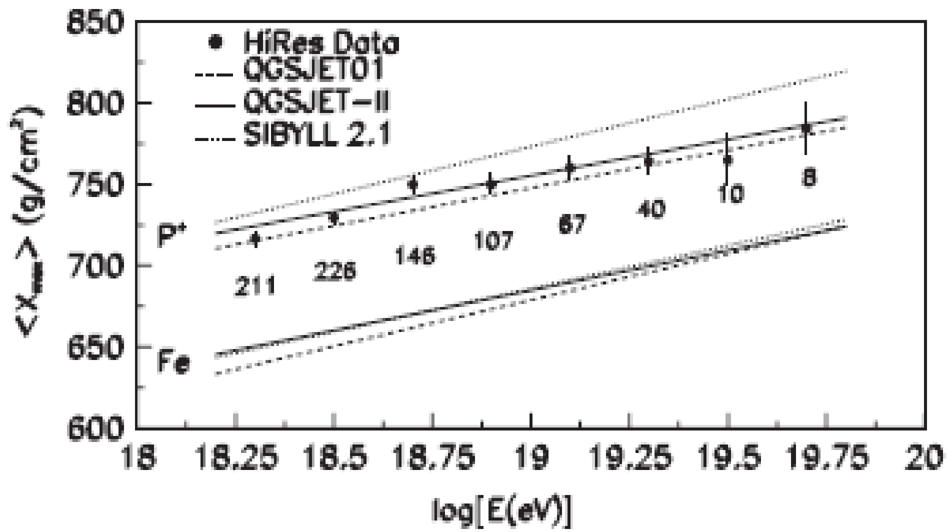


FIG. 2. $\langle X_{\max} \rangle$ as a function of energy. Lines denote a fit with a broken line in $\lg E$. The systematic uncertainties of $\langle X_{\max} \rangle$ are indicated by a dashed line. The number of events in each energy bin is displayed below the data points. HiRes data [10] are shown for comparison.

PRL **104,** 091101 (2010) PHYSICAL REVIEW LETTERS week ending 5 MARCH 2010

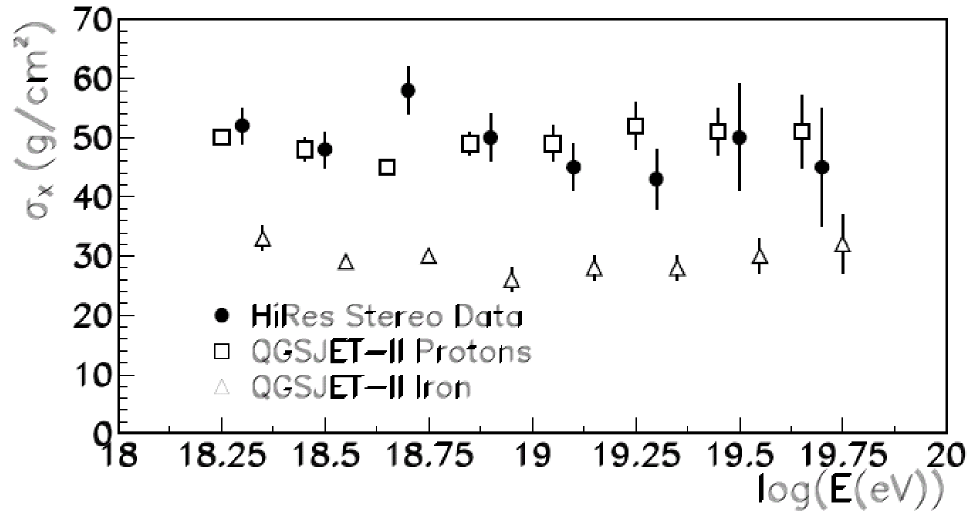
Measurement of the Depth of Maximum of Extensive Air Showers above 10^{18} eV

Hi-Res X_m - results favor protons



Evidence for proton dominated composition above 1.6 EeV

Mean depth of maximum vs energy



PRL 104 161101 (2010)

HiRes Collaboration arXiv:0910.4184

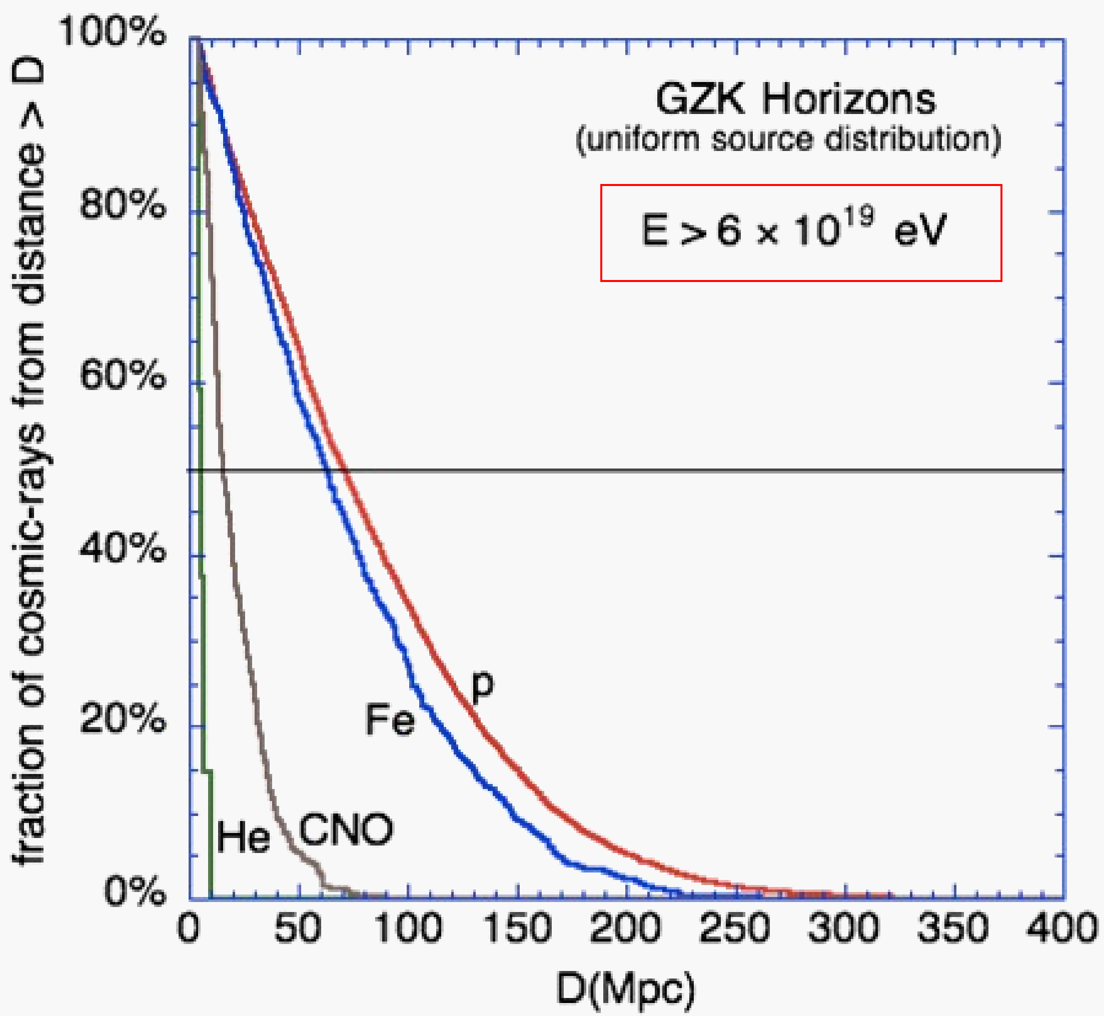
Width of distribution vs energy

Trans-GZK composition is simpler

Light and intermediate nuclei photodisintegrate rapidly.

Only protons and/or heavy nuclei survive more than 20 Mpc distances.

Cosmic magnetic fields should make highly charged nuclei almost isotropic.

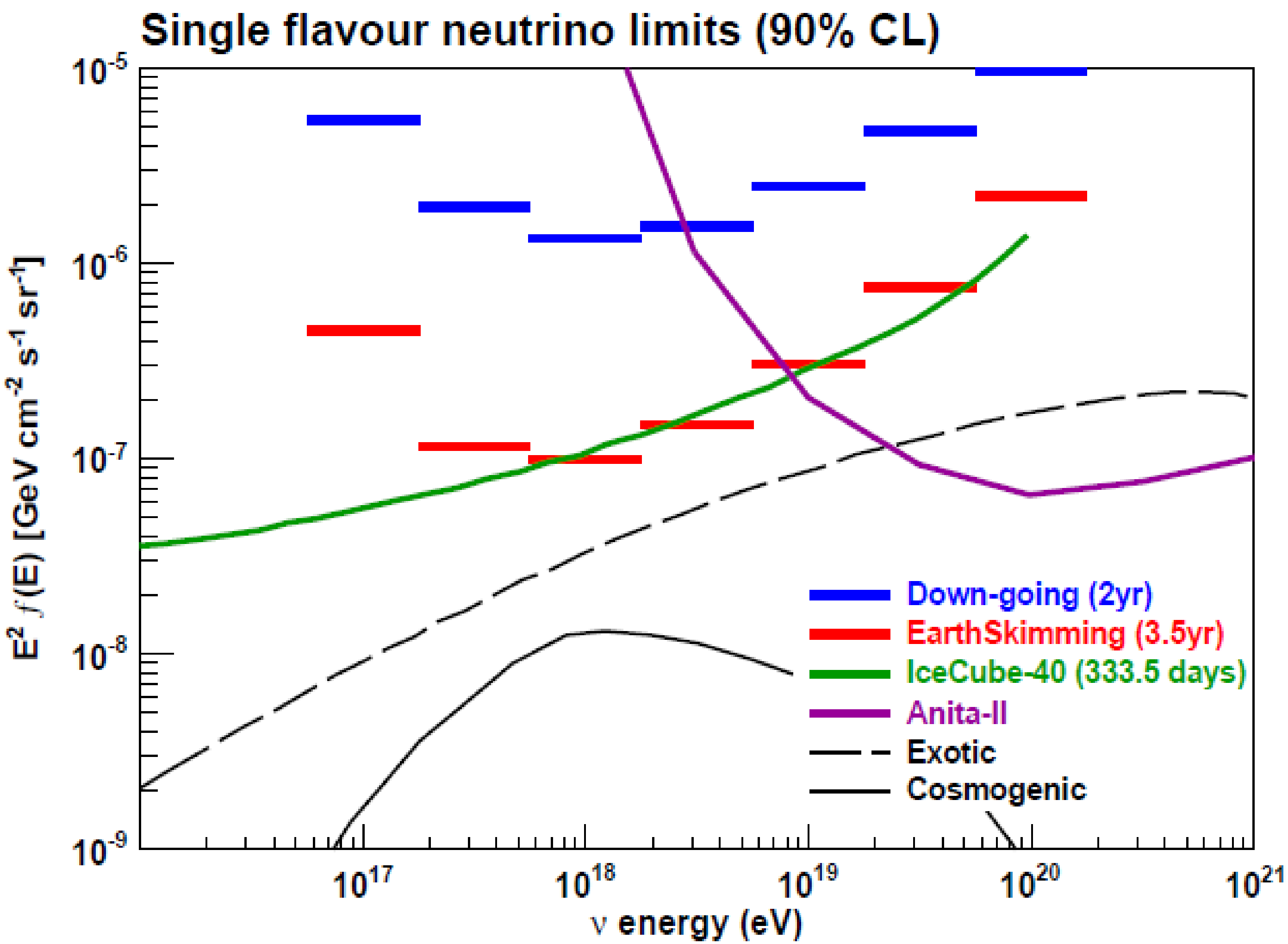


The Auger UHE Neutrino Observatory

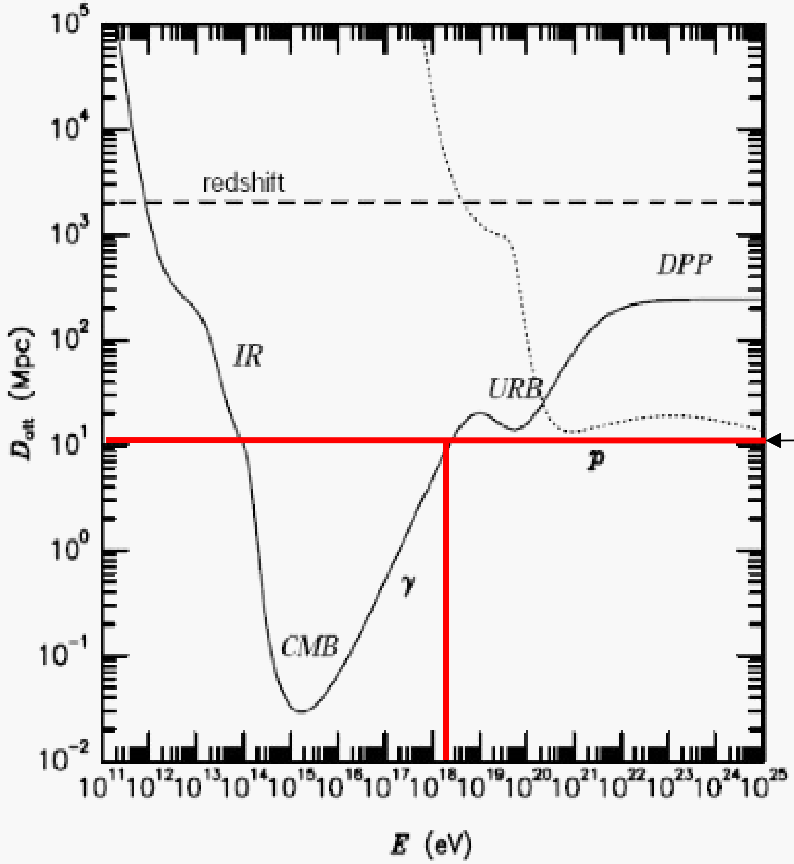
Neutrinos can be identified as "young" showers at very great atmospheric slant depth (either upward or downward).

Auger exposure to tau Neutrinos

Differential limits to diffuse fluxes



The UHE Gamma Ray Astronomical Window



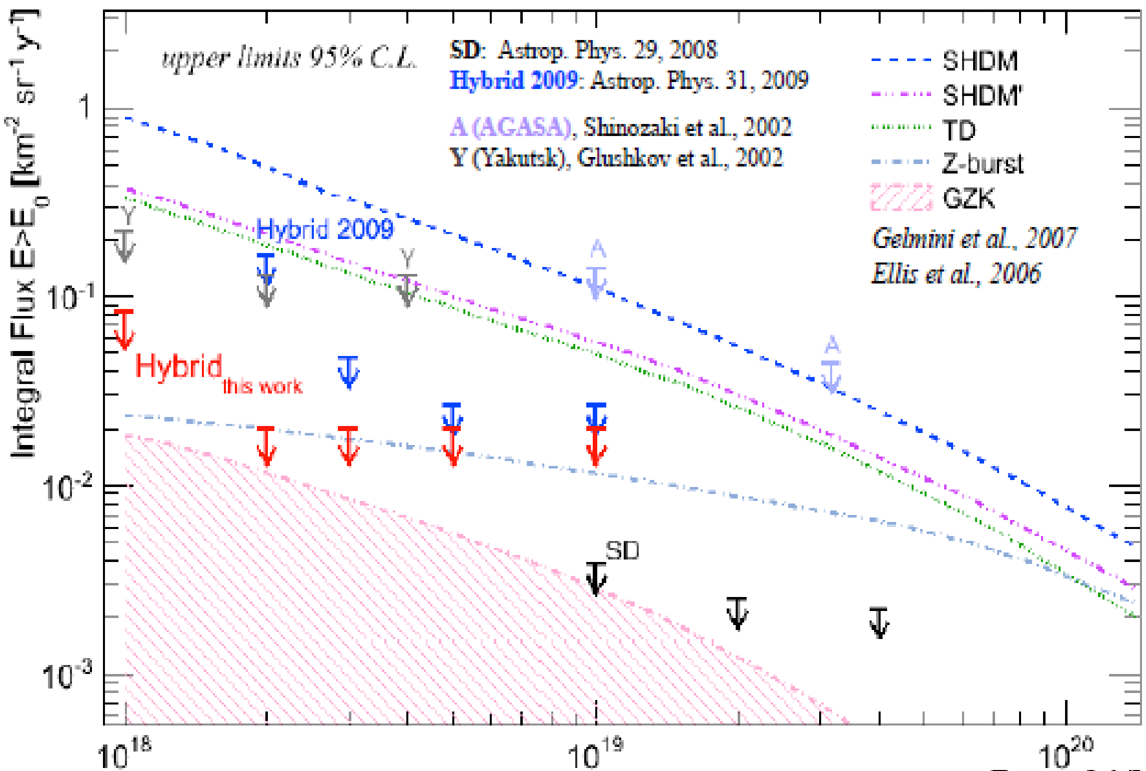
Photon attenuation length exceeds 10 Mpc for E > 2 EeV

Photon showers penetrate deeper than hadronic showers.

They can be recognized individually with hybrid measurements.

A photon component can be measured statistically by the surface array.

Upper Limits to the Integral Photon Flux



* Fraction limits **Hybrid 2009** converted to flux scaling for the Auger spectrum

E_0 [EeV]	N_γ	$\phi_\gamma^{95CL}(E_\gamma > E_0)$ [km^{-2} sr^{-1} y^{-1}]
1	6	8.2×10^{-2}
2	0	2.0×10^{-2}
3	0	2.0×10^{-2}
5	0	2.0×10^{-2}
10	0	2.0×10^{-2}

Impact of systematic uncertainties

(Exposure, ΔX_{max}, ΔS_b, Energy scale, hadronic interaction model and mass composition assumptions)

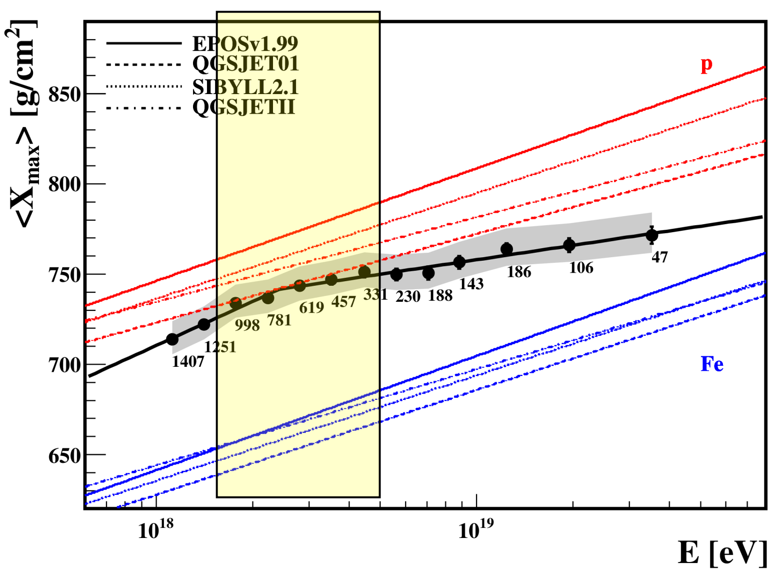
$$^{+20\%}_{-64\%} \; (E_0 = 1 \text{ EeV})$$

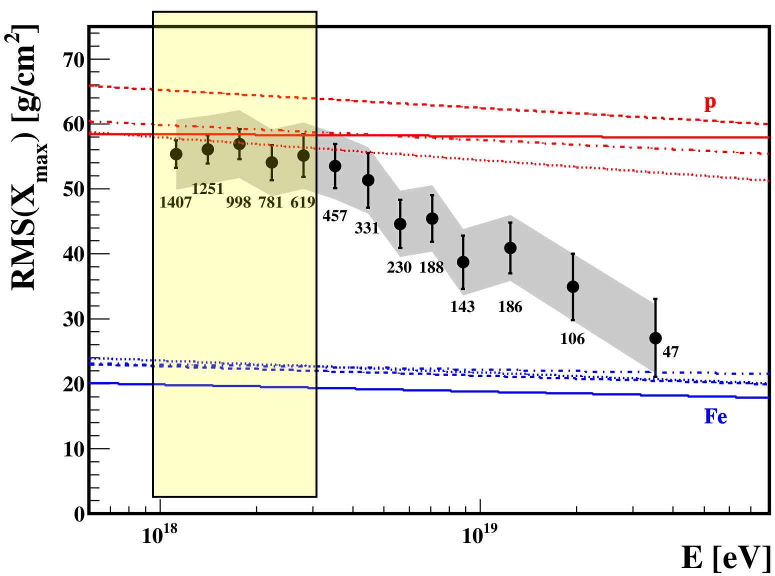
$$^{+15\%}_{-36\%} \; (E_0 > 1 \text{ EeV})$$

Measurement of the proton-air cross-section at $\sqrt{s} = 57$ TeV with the Pierre Auger Observatory

Accepted for publication in PRL July, 2012

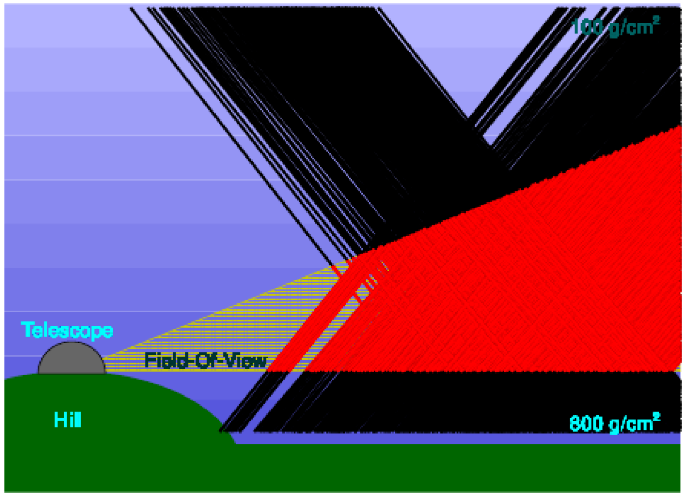
We report a measurement of the proton-air cross-section for particle production at the center-of-mass energy per nucleon of 57 TeV. This is derived from the distribution of the depths of shower maxima observed with the Pierre Auger Observatory: systematic uncertainties are studied in detail. Analysing the tail of the distribution of the shower maxima, a proton-air cross-section of $[505 \pm 22(\mathrm{stat})\ ^{+28}_{-36}(\mathrm{sys})]$ mb is found.

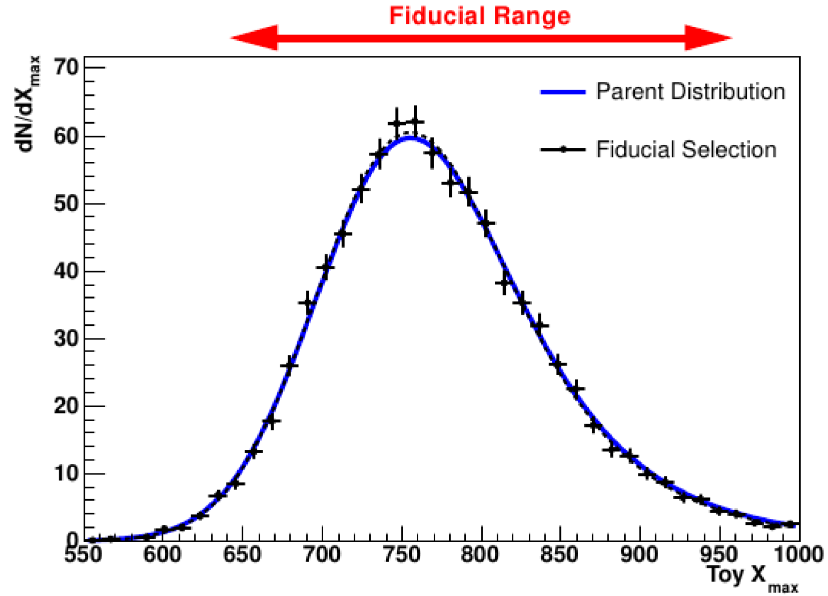


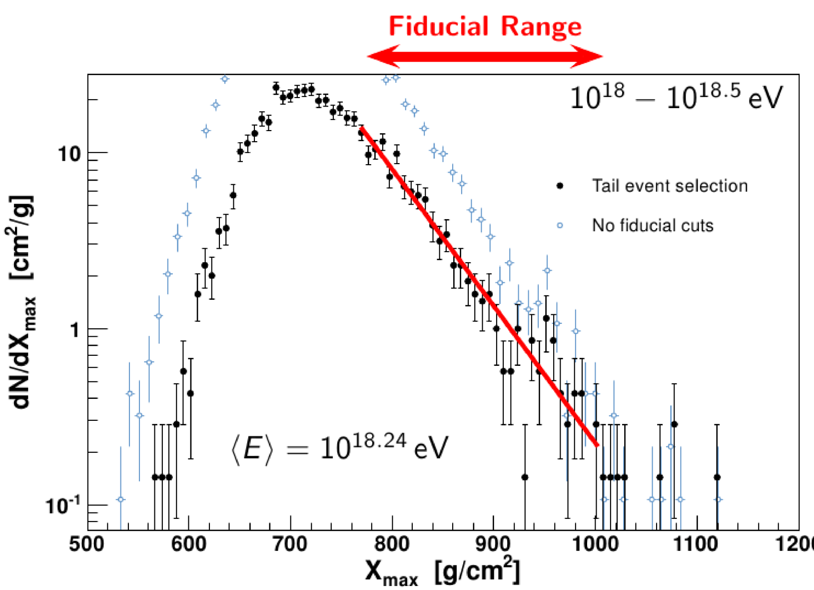


According to composition studies, primaries are mainly protons at energies 10^{18} - $10^{18.5}$ eV.

proton-air production cross section





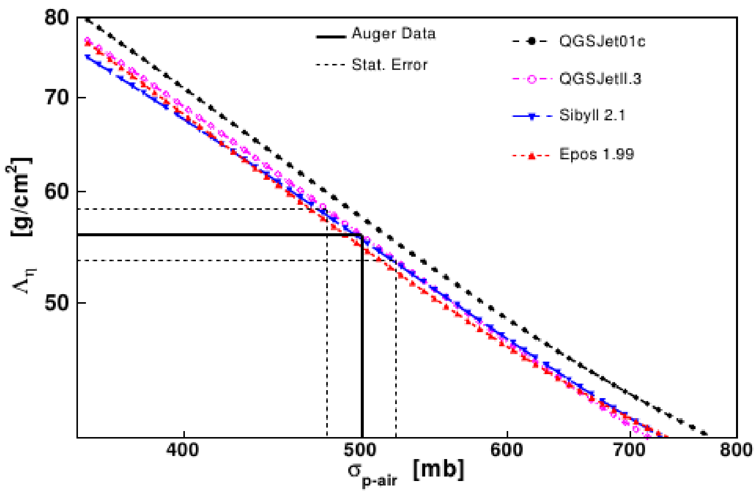


The p-air cross section can be deduced from the average penetration length that is related to the tail of *X*max distribution.

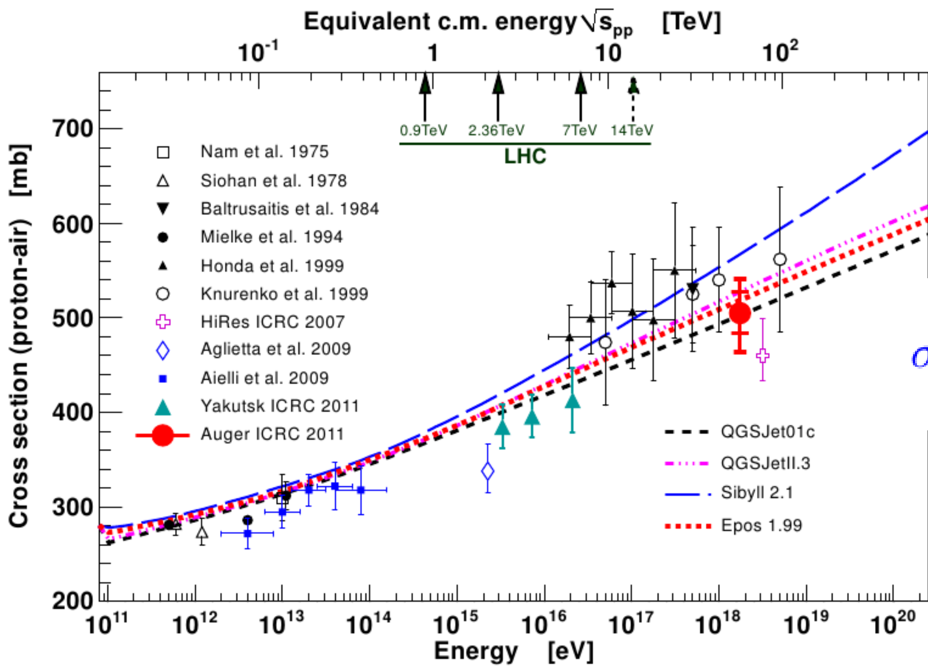
$$dN/dX_{\rm max} \sim \exp\left(-X_{\rm max}/\Lambda_\eta\right)$$

$$\Lambda_\eta = [55.8 \pm 2.3_{\rm stat} \pm 1.6_{\rm sys}]\ {\rm g/cm^2}$$

The relation between penetration length and p-air cross section can be found from simulations after correcting the low energy values using Tevatron measurements, and Glauber theory.



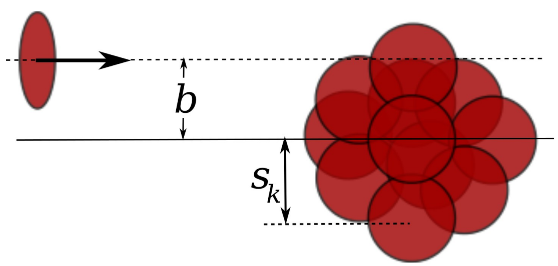
Description	Impact on $\sigma_{\text{p-air}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma^{\text{prod}}_{p\text{-air}}$	± 7 mb
Photons, $<0.5\,\%$	$< +10$ mb
Helium, 10 %	-12 mb
Helium, 25 %	-30 mb
Helium, 50 %	-80 mb
Total (25 % helium)	-36 mb, $+28$ mb



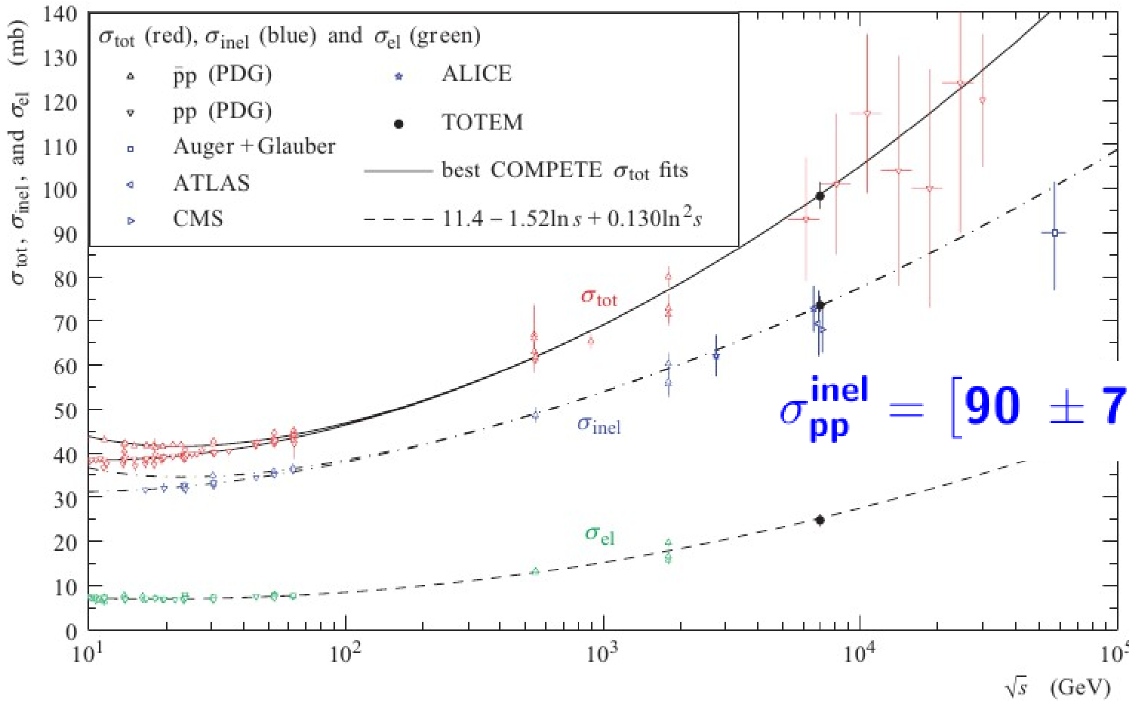
$$\sigma_{\mathrm{p-air}} = \left[505 \pm 22_{\mathrm{stat}} \pm \left(\begin{array}{c} +28 \\ -34 \end{array} \right)_{\mathrm{sys}} \right] \mathrm{mb}$$

Proton-proton cross section

Using Glauber theory is possible to estimate the proton-proton inelastic cross section.



$$\sigma_{pA}^{\mathrm{prod}} \approx \int d^2\vec{b}\left\{1-\left[1-\sigma_{pp}^{\mathrm{inel}}\frac{\rho_A(\vec{b})}{A}\right]^A\right\}$$



$$\sigma_{pp}^{\mathrm{inel}} = \left[90 \pm 7_{\mathrm{stat}} \ \left(^{+9}_{-11}\right)_{\mathrm{sys}} \pm 1.5_{\mathrm{Glauber}}\right] \ \mathrm{mb}$$

$$\sqrt{s_{pp}} = [57 \pm 6] \ \mathrm{TeV}$$

$$(73.5 \pm 0.6^{\mathrm{stat}} \ {}^{+1.8}_{-1.3} \ {}^{\mathrm{syst}}) \ \mathrm{mb}$$

- Far greater exposure is needed to
  - Identify the class of sources via anisotropy
  - Measure the spectra of bright sources or source regions
  - Determine the particle type(s) above 55 EeV
  - If protons, measure interaction properties above 250 TeV (CM)
  - Determine the diffuse cosmogenic intensity of neutrinos and photons
  - Detect cosmogenic neutrinos and photons

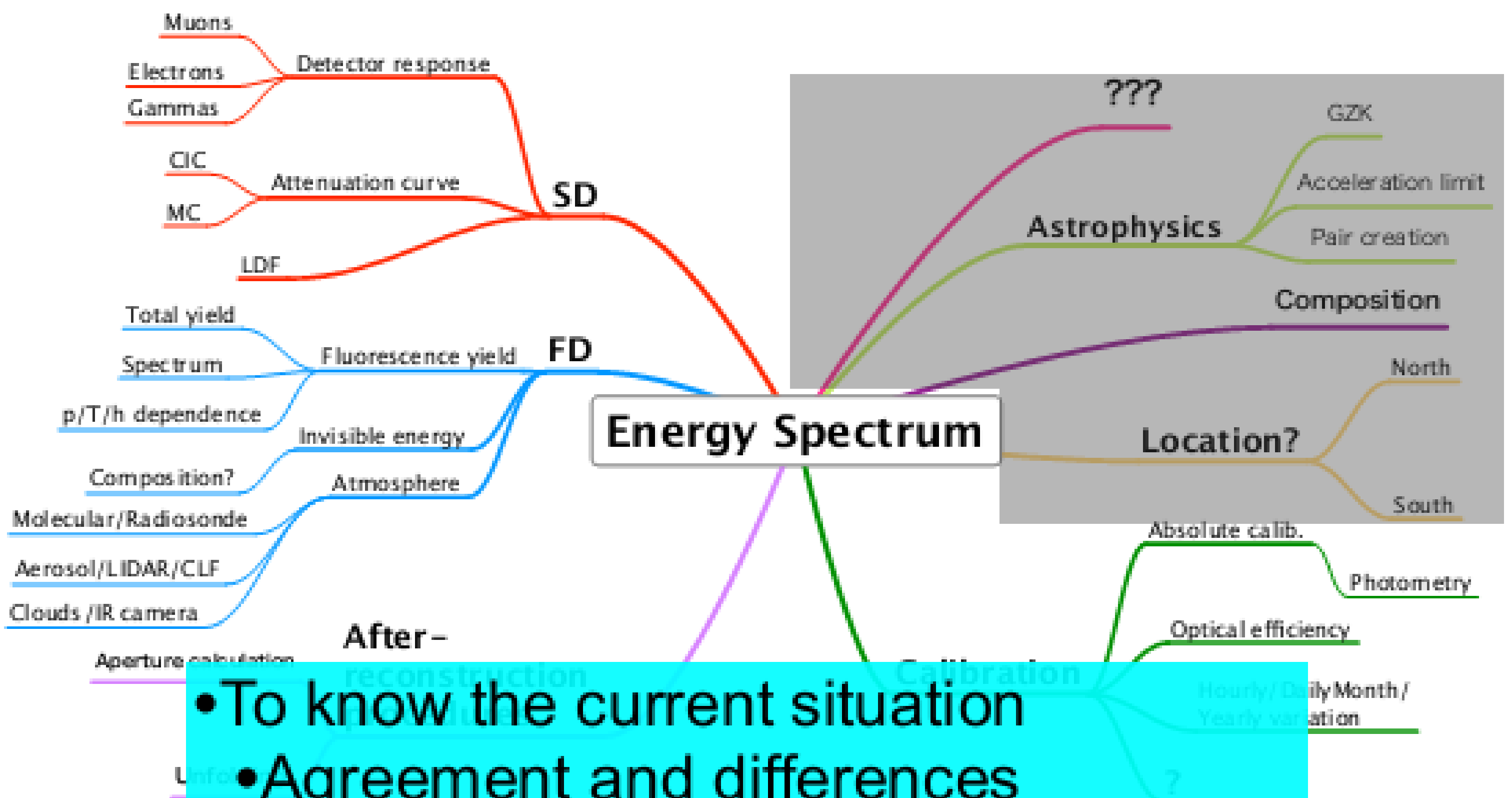
Science Latest Results

- Spectrum with clear ankle and “GZK” suppression
- Anisotropy of arrival directions above 55 EeV
- Limit on photon flux at 10 EeV using surface detector
- Limit on photon flux at 3 EeV using fluorescence detector
- Limit on Earth-skimming tau neutrinos
- New limit on all flavors of neutrinos using near-horizontal showers
- Statistical analysis of X_{max} values for energies up to 30 EeV

UHECR 2012: CERN Meeting, Future directions

- **Five Working Groups**
  - Energy spectrum
  - Composition
  - Anisotropy
  - Modeling and description or air showers
  - Multi-messenger data
- 1~4 people from each group (HiRes/Yakutsk/Auger/TA)
- Discussion in advance
- Give a joint talk at UHECR2012

Scope of the WG



- To know the current situation
  - Agreement and differences
- Technical details in the analyses
- Future directions

Energy Uncertainty Budget

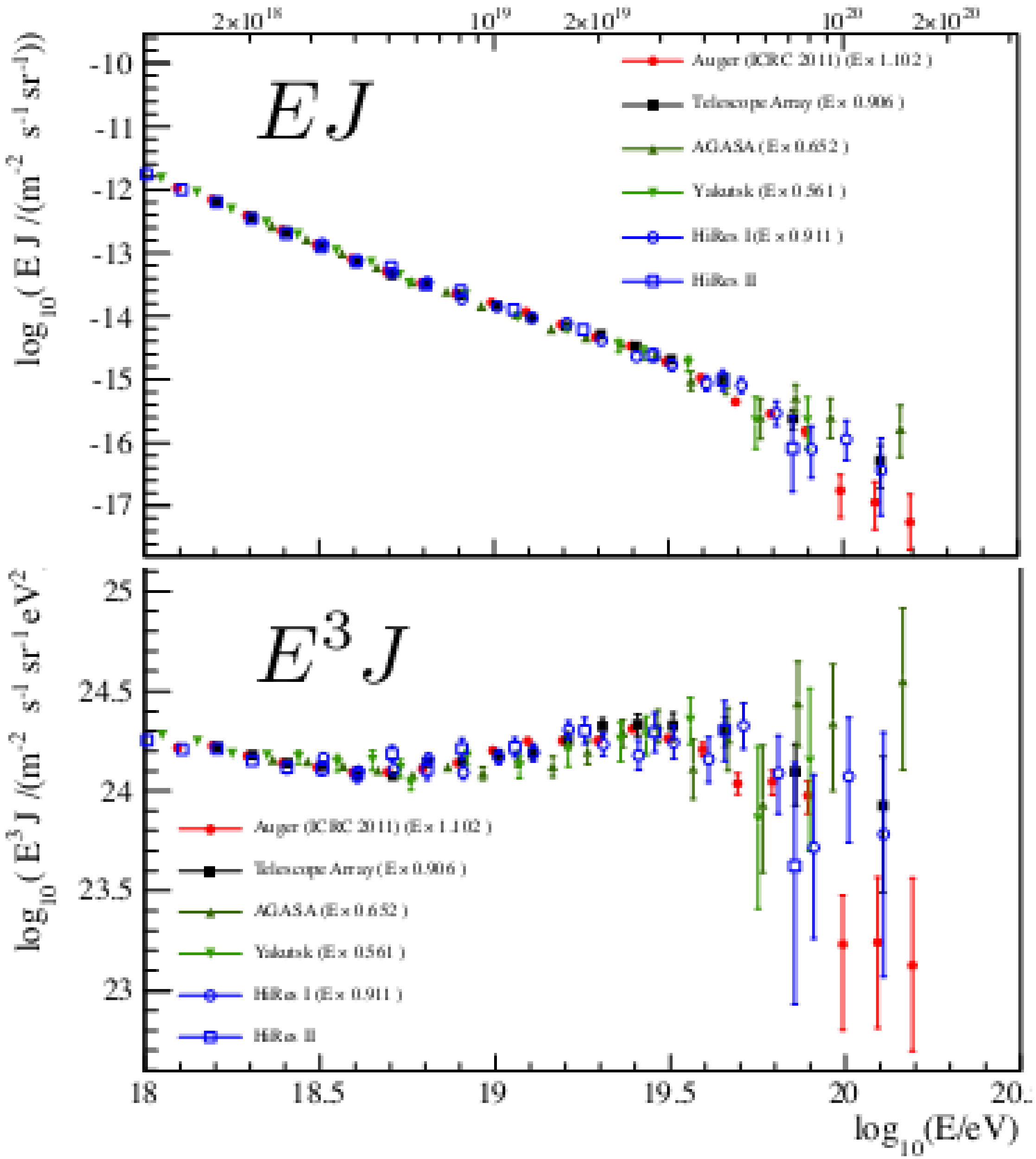
	HiRes	Auger	TA
Calibration	10%	9.5%	10%
Fluorescence yield	6%	14%	11%
Atmosphere	5%	8%	11%
Reconstruction	15%	10%	10%
Invisible energy	5%	4%	(included above)
Total	**17%**	**22%**	**21%**

- HiRes: Abbasi et al., PRL 100 101101 (2008)
- Auger: ICRC2011
- TA: ICRC2011

Energy Spectra
(after the scaling)

- We can find scaling factors to match the spectra: shape are similar (below log*E*=19.5)

- Auger/HiRes/TA are in agreement well within the systematic uncertainties



Conclusions (1)

- All of the spectra are in agreement within the systematic energy uncertainties.
  - Spectral shapes are very similar: positions of the first bend is in agreement, and marginally consistent for the second bend after the energy scaling.
- Status of the spectral structures
  - Ankle: CONFIRMED
  - *Suppression*
    - AGASA: not compatible
    - Yakutsk: “Deficit”, no sign of an extended spectrum
    - HiRes/Auger/TA: Confirmed with good statistical significance
    - HiRes claimed the GZK cutoff
      - Protonic composition
      - Position of the steepening is consistent with theoretical expectation
    - Composition and anisotropy (UHECR horizon?)

Conclusions (2)

- There are many differences in methods, but these are equivalent in principle.
- The 20% difference has not been fully explained.
- Need comparison in more low level.
- Need high level contact.
- Now we have a channel.
  - TA: AGASA + HiRes
    - Reported by Japanese press as “呉越同舟”
    - Successful collaboration
  - Yakutsk, Auger and TA!

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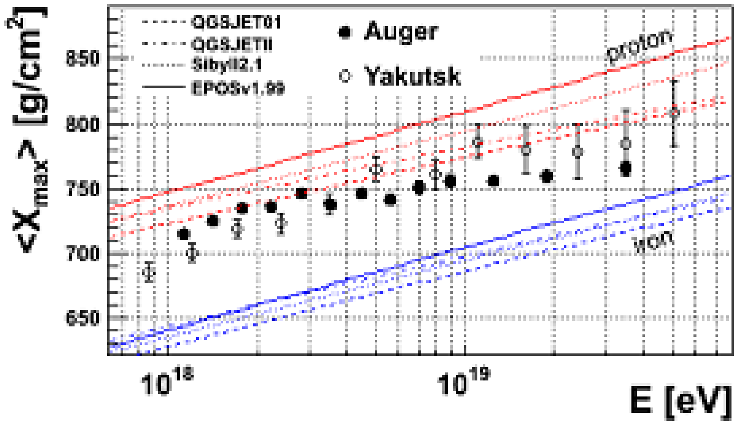
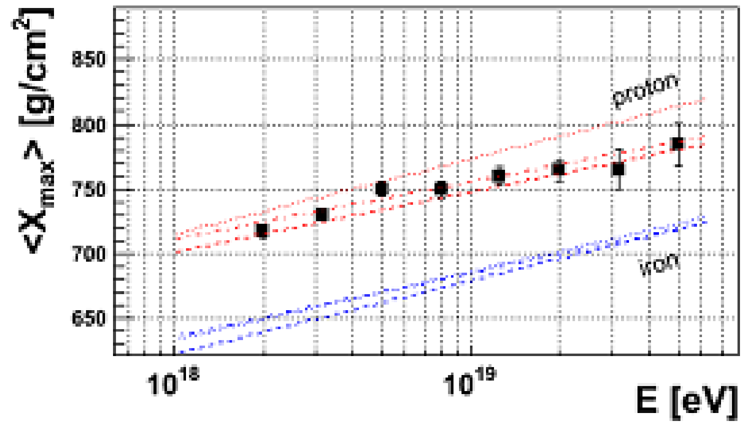
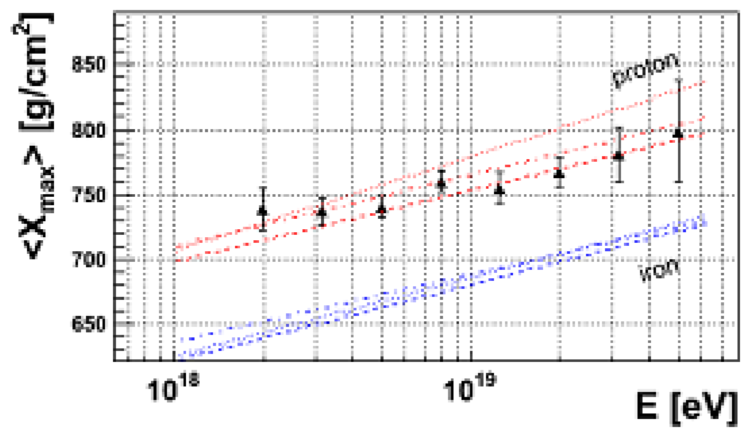
Comparing the observed <Xmax> values with the expectations for proton and iron



HiRes



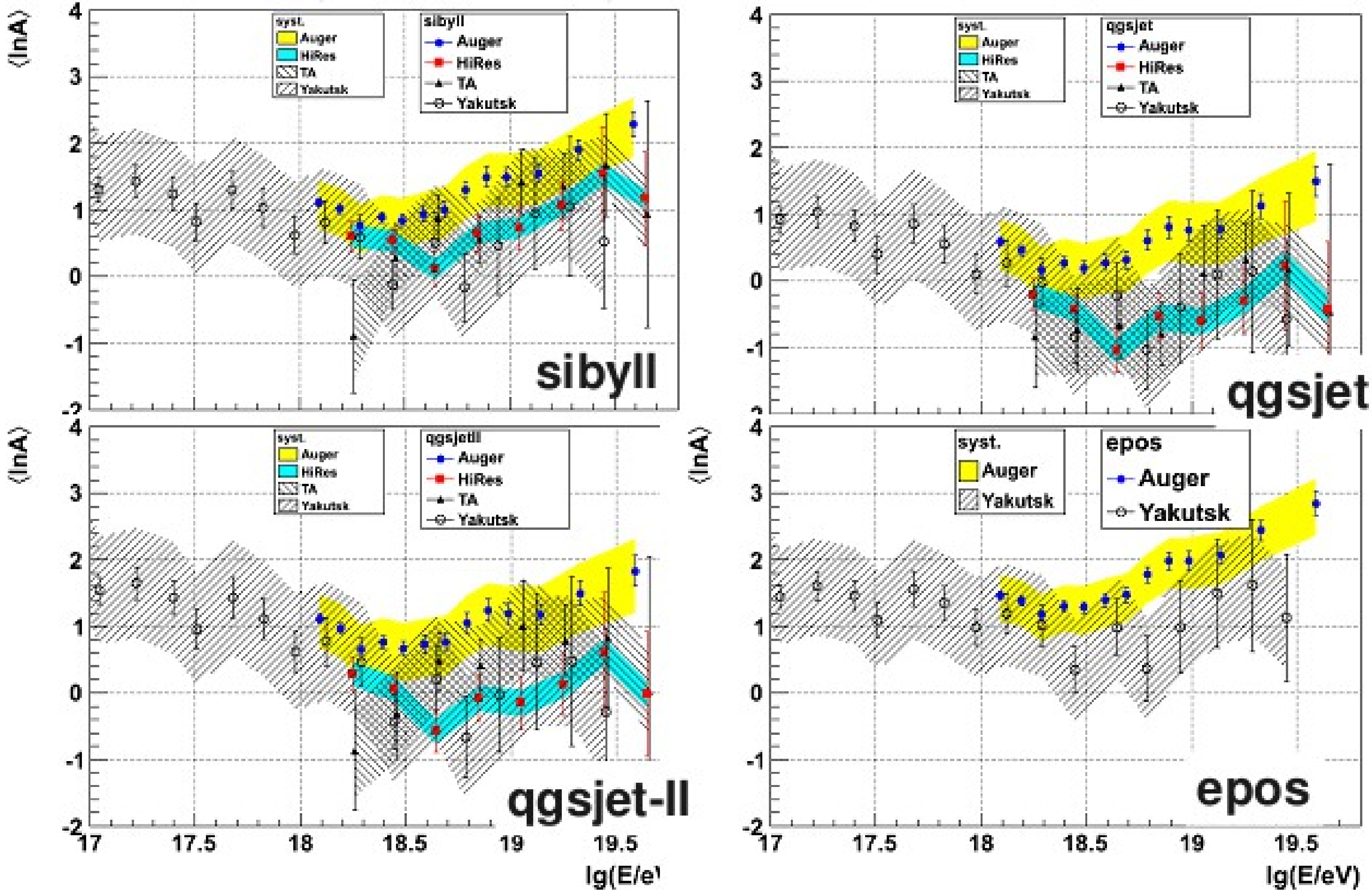
TA



- Are the differences due to issues in any of the analysis?
- Are the differences within systematic uncertainties?
- Are the Southern and Northern sky different in terms of composition?

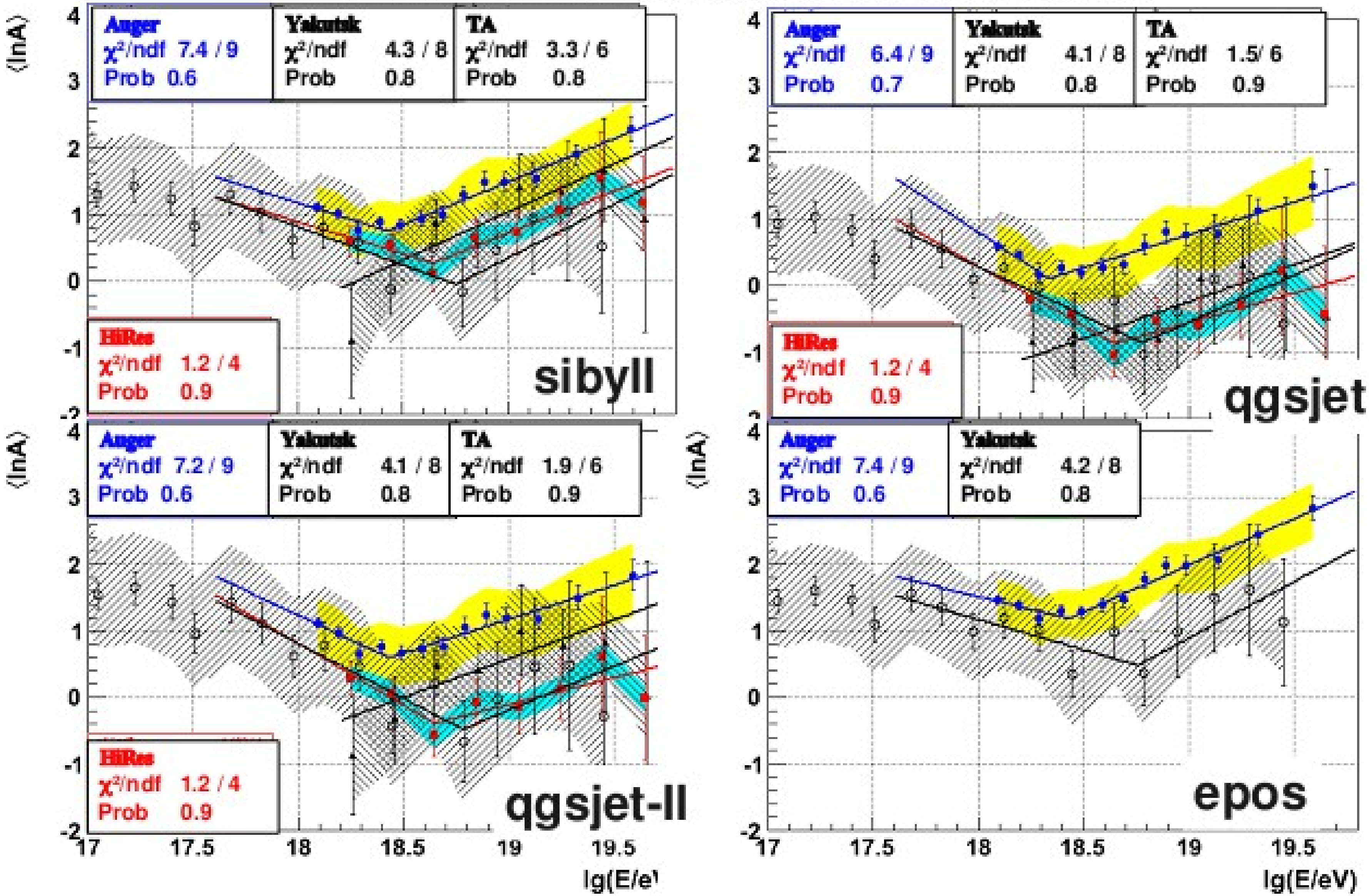
After normalizing the energy scales to half way between TA and Auger spectrums

corrections in lgE: TA =-0.042, Auger=0.042, HiRes=-0.054, Yakutsk=-0.256



After normalizing the energy scales to half way between TA and Auger spectrums

Are the results consistent with a changing composition?

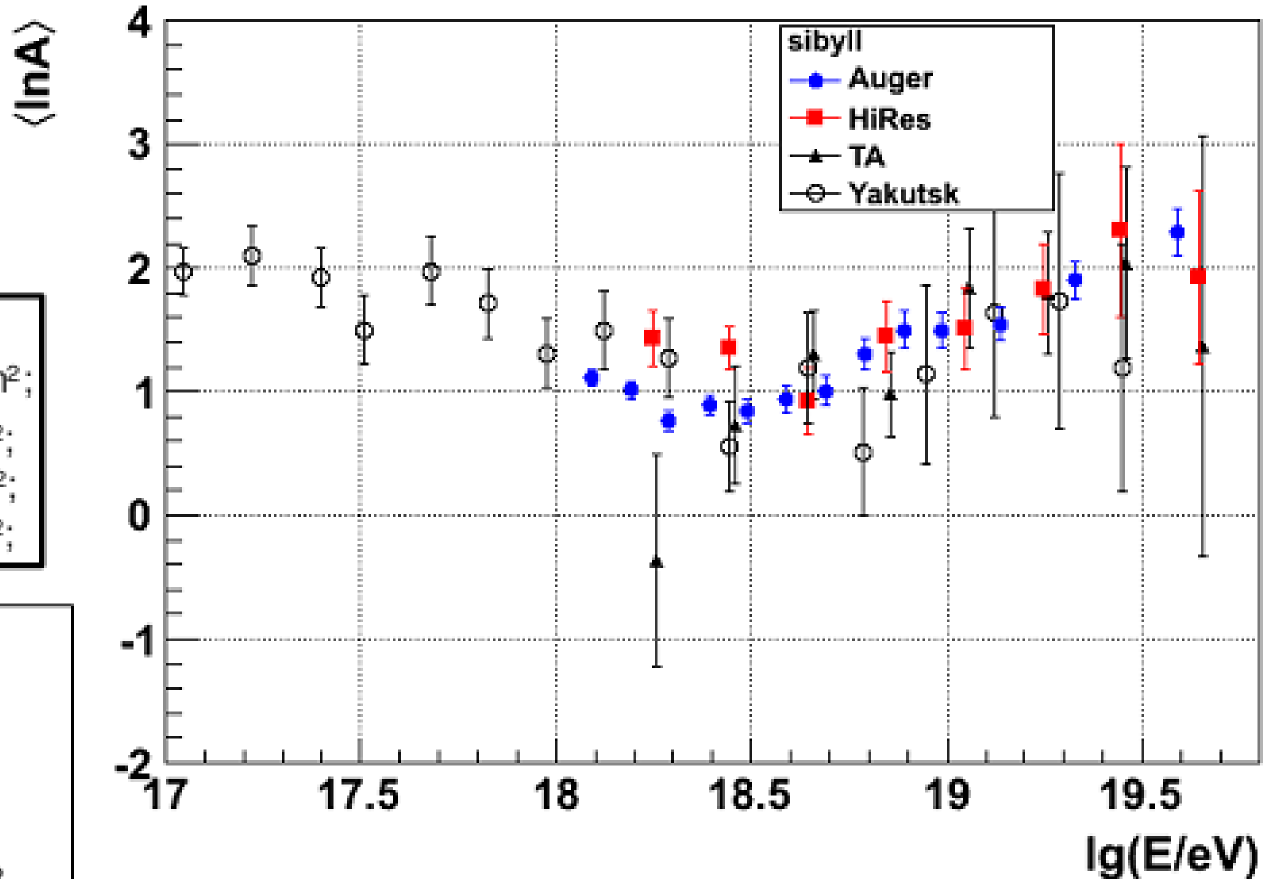


Does a shift in <Xmax> bring the results to agreement?

(After normalizing the energy scales to half way between TA and Auger spectrums)

Xmax shifts:

Auger = +16 g/cm²;
TA = -10 g/cm²;
HiRes = -17 g/cm²;
Yakutsk = -17 g/cm²;

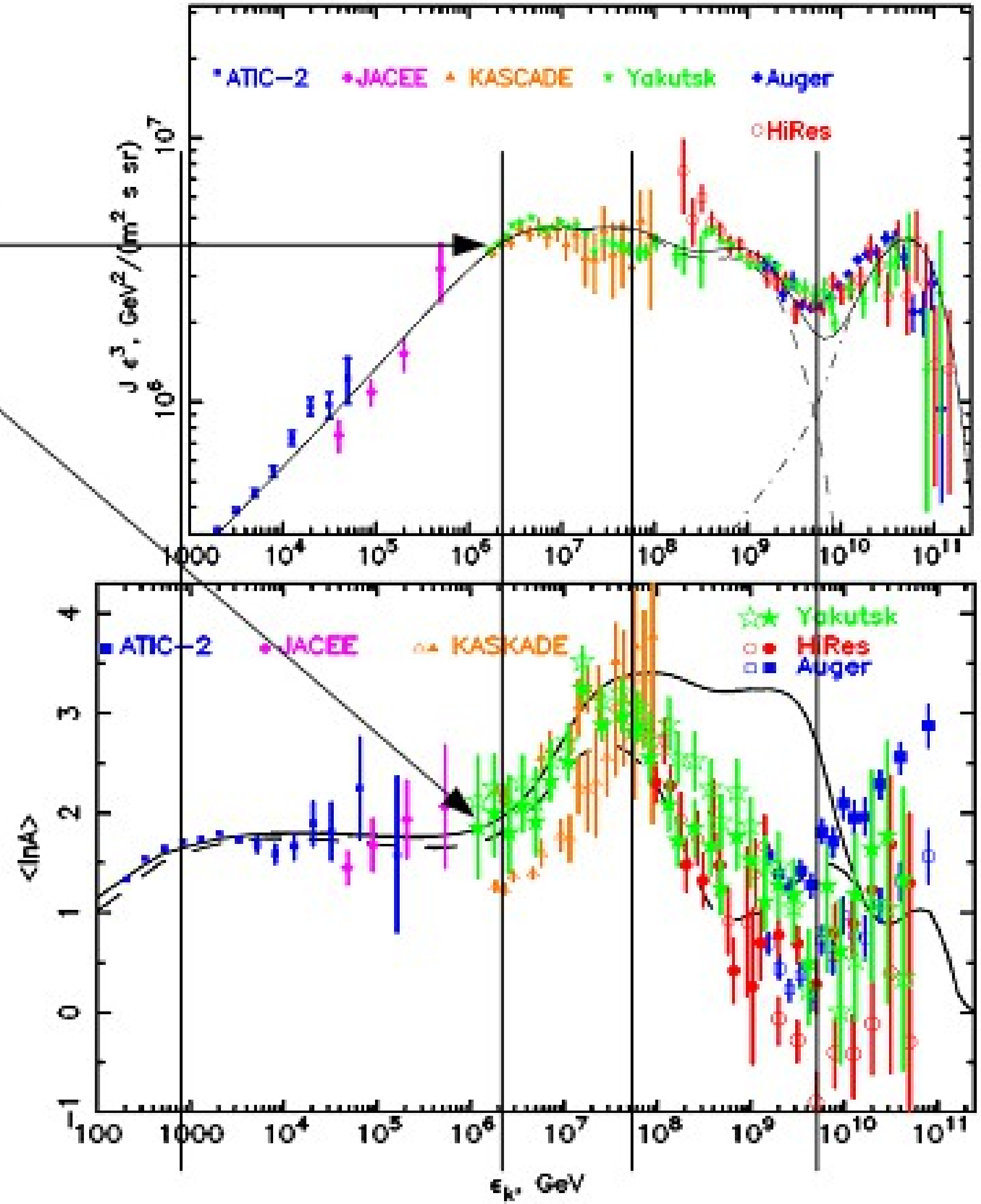


Quoted syst. uncertainties

Auger	12 g/cm²
HiRes	3.3 g/cm²
TA	12.4 g/cm²
Yakustk	20 g/cm²

The Big Picture

Features in the evolution of <lnA> with energy seem to correlate with features in the energy spectrum.



Plots provided by our Yakutsk colleagues (to be published this year).

Conclusions

•Are the differences due to issues in any of the analysis?

Apparently no.

• Are the differences within systematic uncertainties?

Auger and HiRes are not consistent within the **quoted** systematic uncertainties.

• Are the Southern and Northern sky different in terms of composition?

We need more statistics in the Northern hemisphere (about 4 times the current statistics) to give a conclusive answer. The current statistics in the northern hemisphere do not allow to discriminate between a constant composition or a changing composition as suggested by Auger. More statistics is also necessary to establish whether there is a systematic difference in the RMS(Xmax) at higher energies.

• It is interesting to point out that all three experiments (Yakutsk, HiRes and TA) are consistent (within ~5g/cm^2). But, there is a large systematic difference in <lnA> equivalent to about 30 g/cm^2 between Auger and the other experiments.

INTRODUCTION

- Modern detectors use both fluorescence telescopes and ground arrays
- In this talk – surface detector data mostly

	exposure (km^2 yr sr)	angular resolution	energy resolution	# of events at $E > 10$ EeV
Auger	$\sim 21\,000$	$0.9°$	$\sim 17\%$	4727
HiRes	$\sim 2\,500$*	$0.6°$	$\sim 14\%$	378
TA	$\sim 2\,900$	$1.5°$	$\sim 20\%$	854
Yakutsk	824	$2.5°$	$\sim 30\%$	364

* at $E = 10^{20}$ eV

Note: absolute energy calibration affects the number of events with $E > 10$ EeV

Summary I: isotropy/anisotropy of data

- No major departure from isotropy
- No evidence for small-scale clustering similar to the one observed in AGASA
- Some hints at anisotropy at highest energies at scales $10-20^\circ$ (Auger, TA); not conclusive
- Intriguing regularity in phase of the dipole in Auger; possible signal in TA?
- Larger statistics is needed to investigate these hints
- Parameters for the future blind tests should be set up

Summary II: search for point sources

- Correlations with nearby AGN indicate possible anisotropy at highest energies (Southern hemisphere)
- No such indications in the North [note: smaller statistics]
- Whether AGNs themselves are sources of UHECR is unclear
- Excess in the Cen A region (a real source of AGN anisotropy?)
- Blind test of Cen A excess is needed with larger statistics
- Correlations with BLL not confirmed by Auger
- No significant clustering at $E \sim 1$ EeV (limits on neutron flux from GC and other sources)

Summary III: correlations with matter distribution

- Hints on correlation with the LSS in the Auger data, no indications in TA and HiRes. Possible reason:
  - Auger statistics is higher
  - Southern sky is different from the Northern one (different structures in the field of view). No Cen A in the North.
- More statistics ($O(500)$ events at $E > 57$ EeV) is needed to perform a definitive test of the LSS model
- Absolute energy scale matters for this test because of the strong dependence of the GZK horizon on energy