ULTRA HIGH ENERGY COSMIC RAYS

Diego Harari

Centro Atómico Bariloche & Instituto Balseiro
Argentina

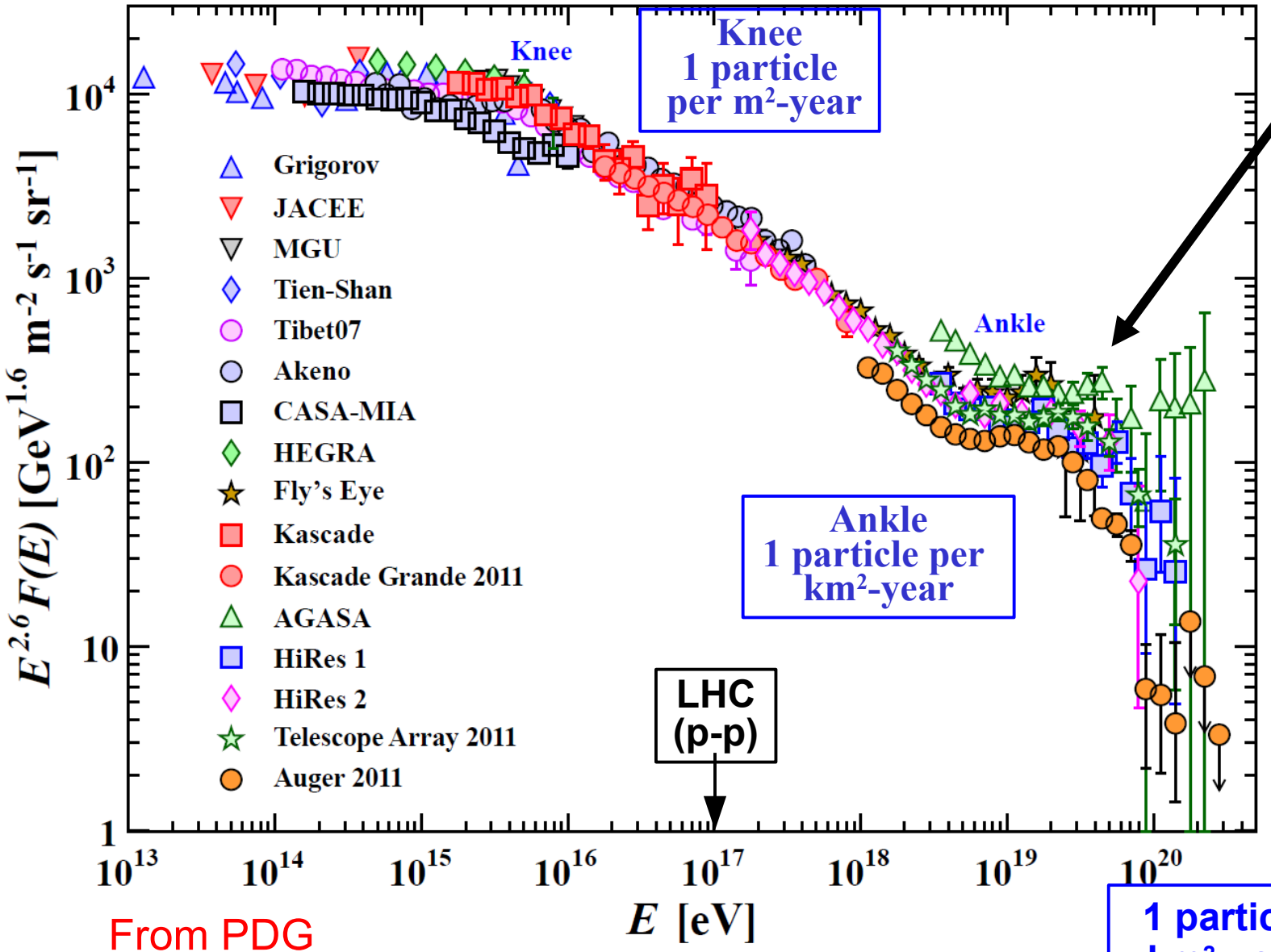
TAUP – 13 September 2013

Summary of recent measurements of

ENERGY SPECTRUM
COMPOSITION
ANISOTROPIES

FLUX OF COSMIC RAYS

from air-shower experiments



UHECRS

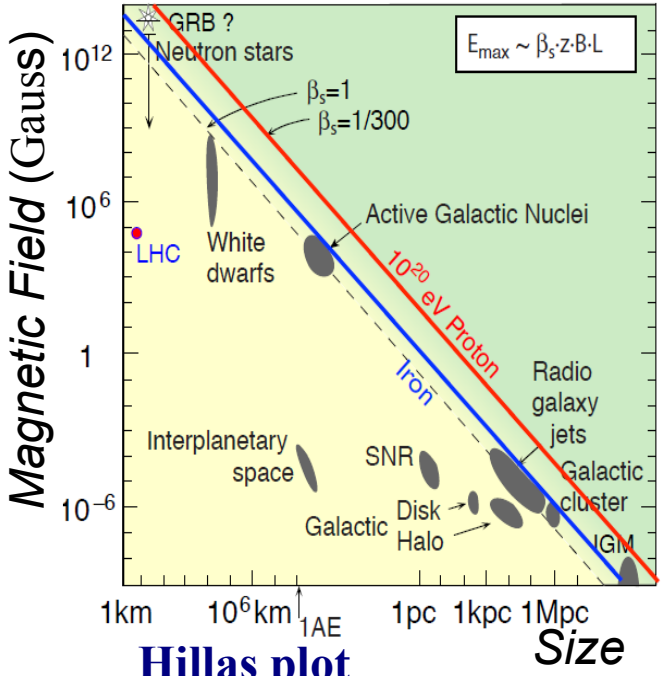
- Volcano Ranch
- Haverah Park
- Sugar
- Yakutsk
- Agasa
- Fly's Eye
- HiRes
- Auger
- Telescope Array

1 particle per km² - century

From PDG
(Stanev,Gaisser-Matthews,Beatty)

3 PIECES OF A PUZZLE

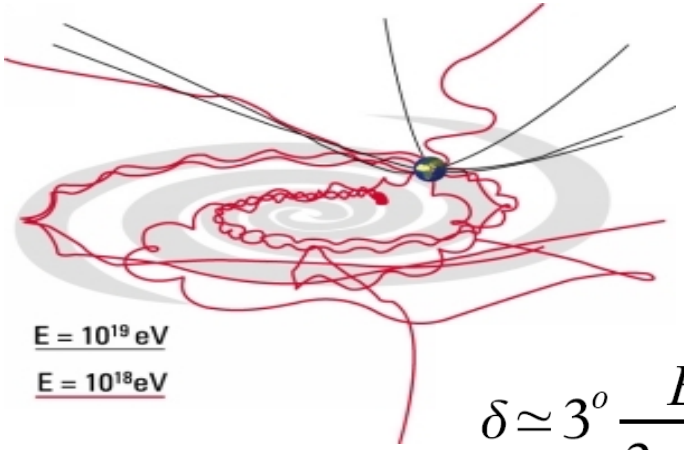
SOURCES



Hillas plot

Extra-galactic?
AGNs? GRBs?
… ?

COMPOSITION / MAGNETIC FIELDS

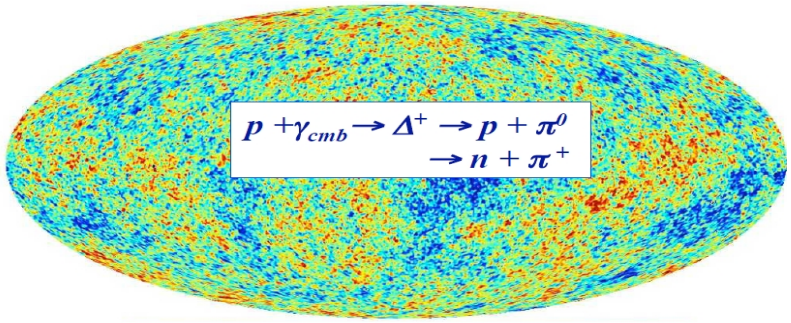


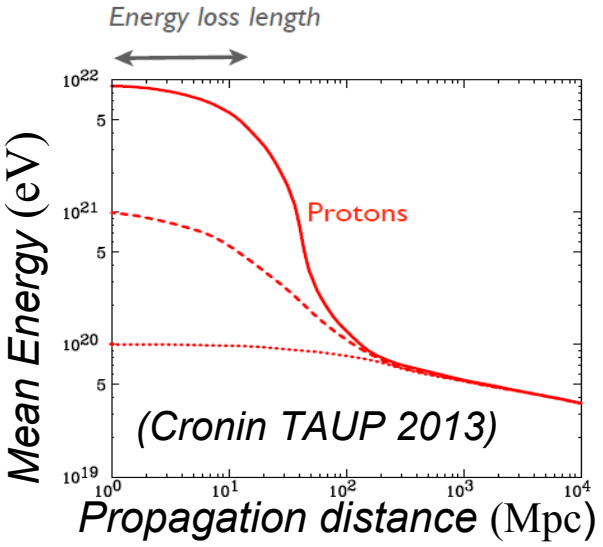
Deflections

~ Z/E

$$\delta \simeq 3^{o} \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E/Z}$$

GZK HORIZON





Interaction with CMB → Sources within ~ 100 Mpc
Expect flux suppression and anisotropy of light component

GZK EFFECT

(Greisen-Zatsepin-Kuzmin 1966)

PHYSICAL REVIEW LETTERS

VOLUME 16, NUMBER 17 25 APRIL 1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

Flux suppression confirmed

PRL 100, 101101 (2008)

First Observation of the Greisen-Zatsepin-Kuzmin Suppression

(High Resolution Fly's Eye Collaboration)

PRL 101, 061101 (2008)

Observation of the Suppression of the Flux of Cosmic Rays above 4×10^{19} eV

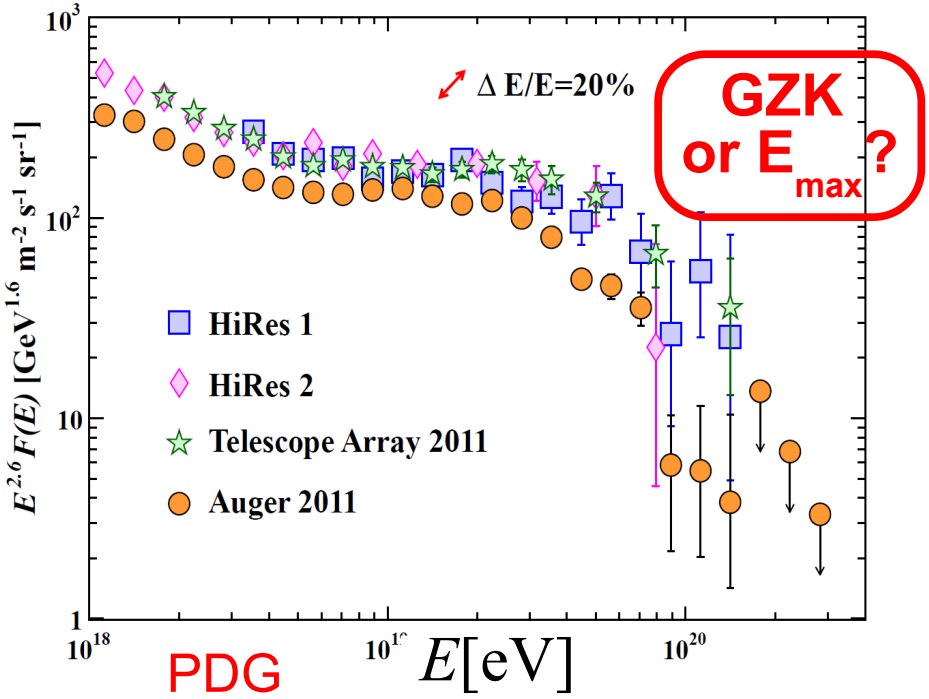
(The Pierre Auger Collaboration)

BUT: is it due to a "cosmologically meaningful termination"?

or something else?

(such as maximum acceleration)

We need more pieces to solve the puzzle …

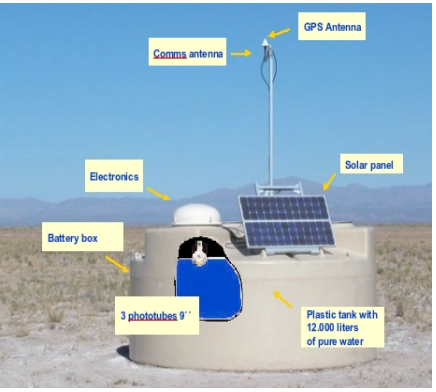


Pierre Auger Observatory

Malargüe, Argentina

Surface Detector

1660 water-Cherenkov stations



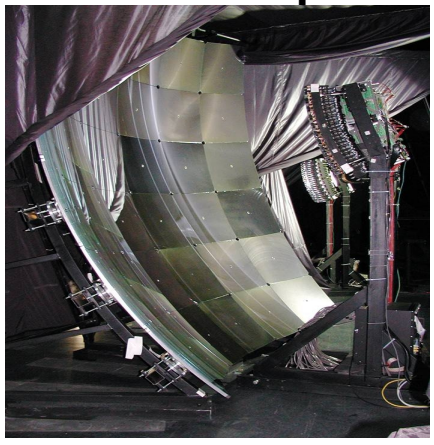
3,000 km²
1,5 km grid

25 km²
750 m grid

AMIGA: muon detectors

Fluorescence Detector

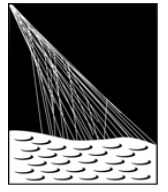
27 telescopes in 4 locations



HEAT: 3 higher elevation telescopes

AERA: radio detection
AMBER, EASIER, MIDAS: GHz

Argentina Australia Brazil Croatia Czech Republic France Germany Italy Mexico Netherlands Poland Portugal Slovenia Spain United Kingdom USA
Bolivia* Romania* Vietnam* (*Associated)



PIERRE AUGER OBSERVATORY

TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.

3 com. towers

Middle Drum (MD)

~30 km

Long Ridge (LR)

Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

700 km²

Fluorescence Detector(FD)

3 stations

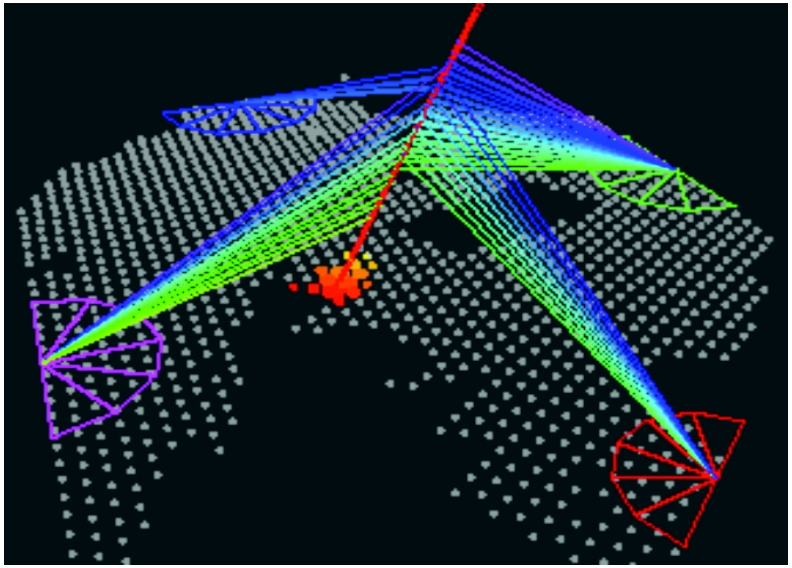
38 telescopes

TELESCOPE ARRAY PROJECT

(P. Sokolsky @TAUP2013)

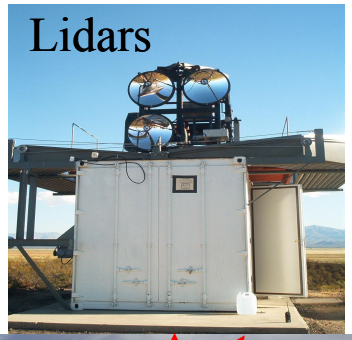
Belgium, Korea, Japan, Russia, USA

HYBRID OBSERVATORIES



Surface detectors
"statistical power"
~ 100% duty cycle
Fluorescence detectors
Complementary view
(~13% duty cycle)
Hybrid operation:
improves precision of energy/angular calibration, consistency tests, etc.

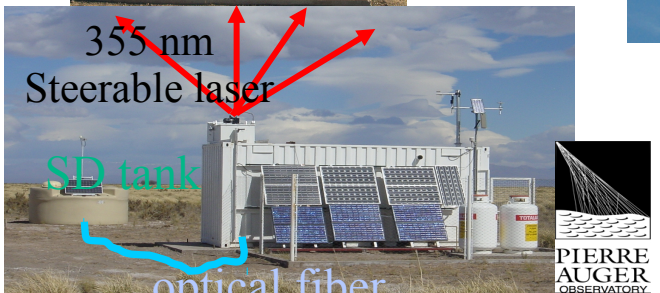
Extensive atmospheric monitoring and calibration



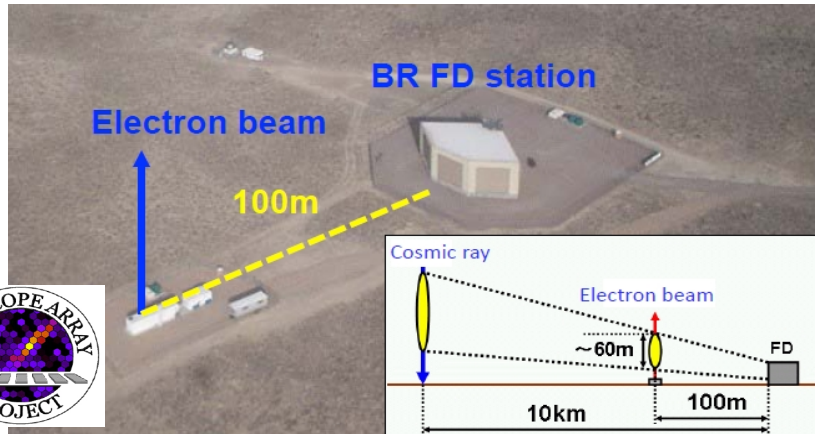

Ballons

"Octocopter"


(used in recent joint calibration campaign)



PIERRE AUGER OBSERVATORY



TELESCOPE ARRAY PROJECT

SD DETECTORS

Telescope Array

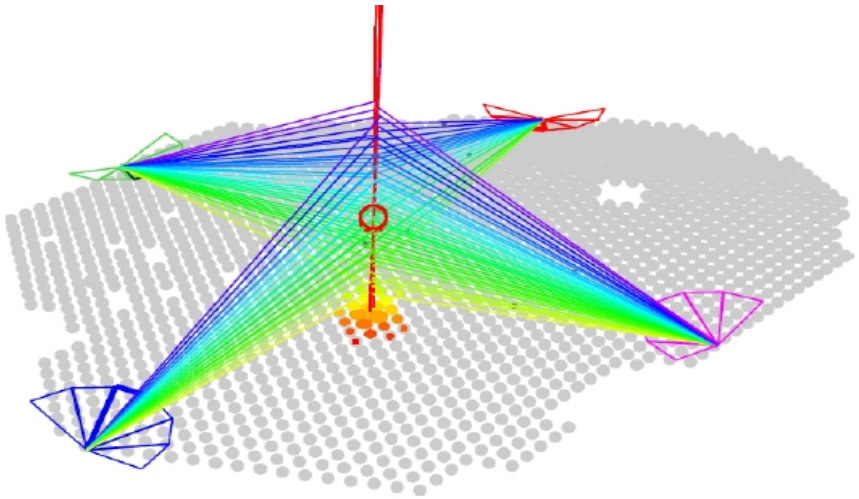
Thin scintillators.
Main part of signal due to e.m. particles
Low sensitivity to muons.

Auger

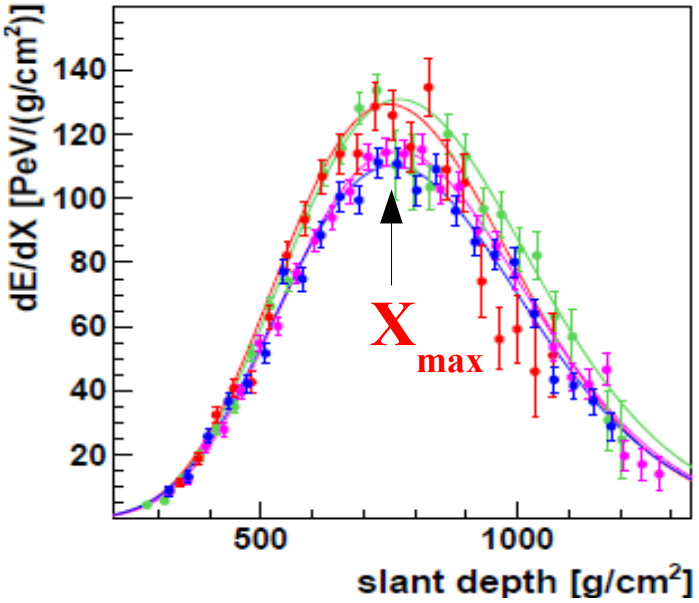
Water-Cherenkov detectors.
Main part of signal due to muons.
Good acceptance to inclined showers.

Complementary measurements

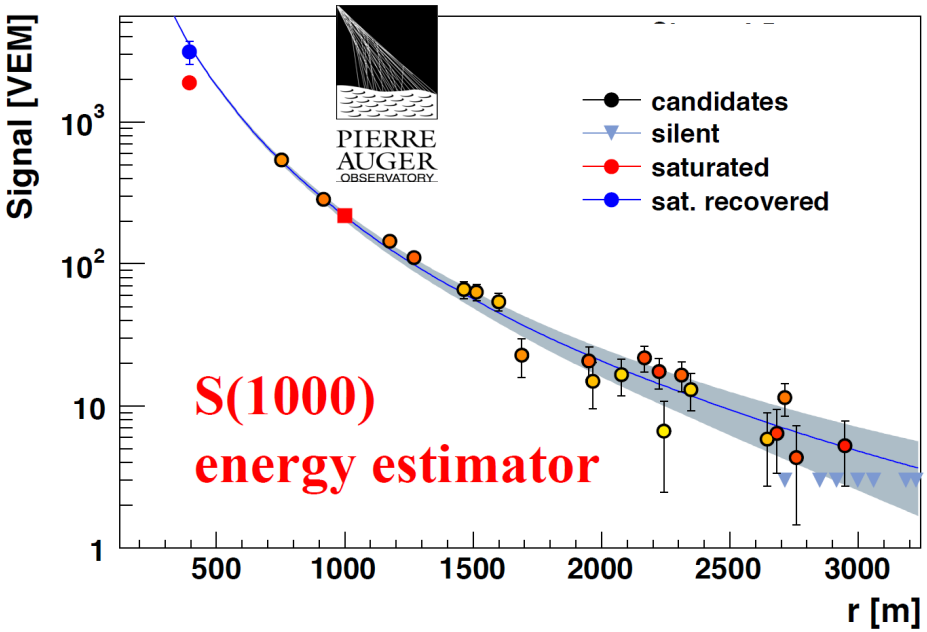
Air Shower Reconstruction

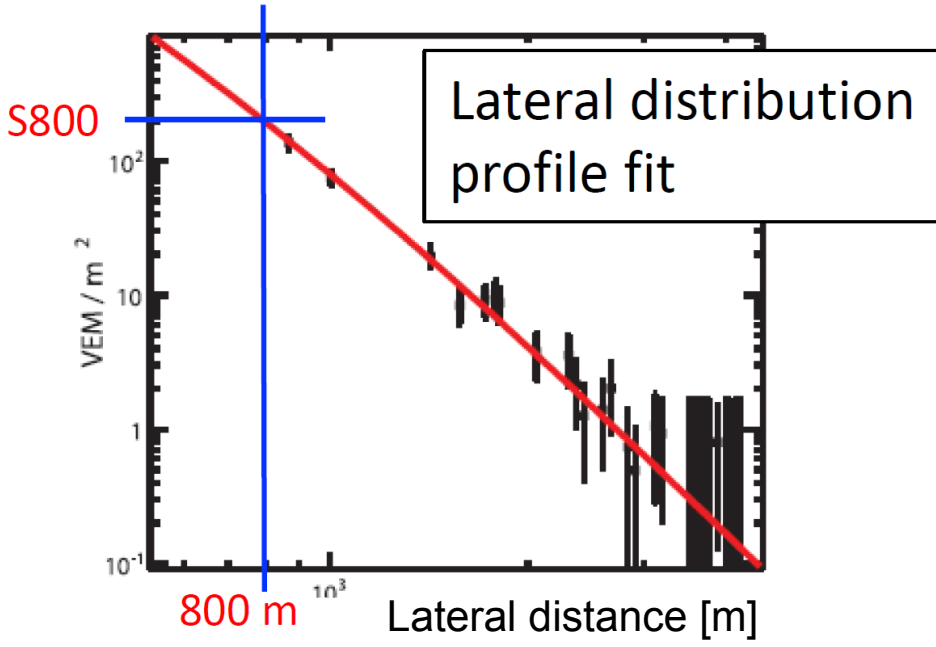


FD: fit toGaisser-Hillas profile



SD: Lateral density distribution at optimal distance

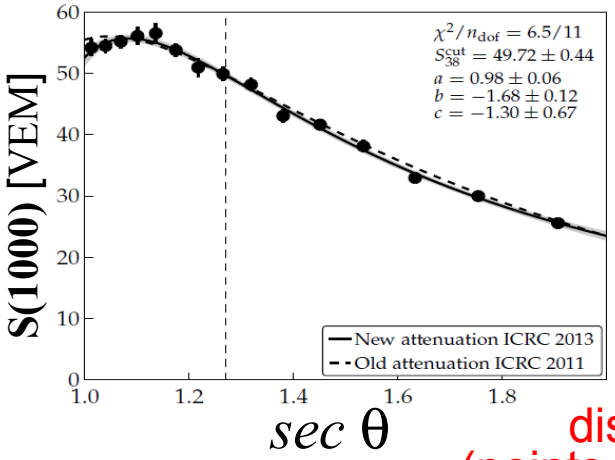




Energy Calibration

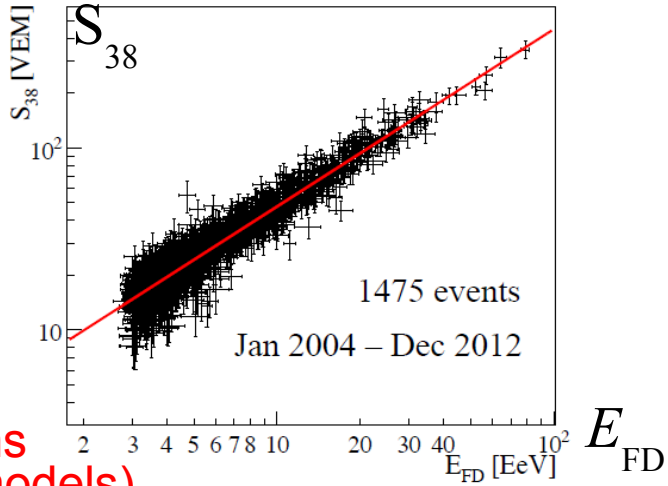
Surface detectors calibrated with Fluorescence detector

FD (calorimetric) energy largely independent on composition and hadronic models

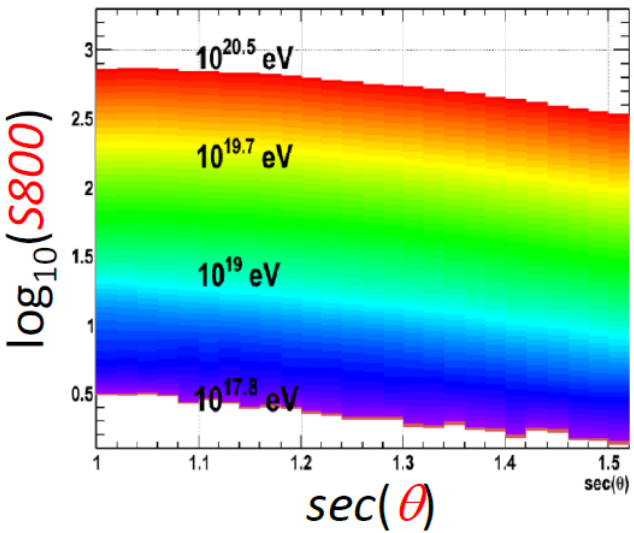


Atmospheric attenuation derived from data (constant intensity)

S_{38}=S(1000)/CIC(θ)



Zenith angle-dependent discrepancy with MC-simulations (points to muon deficit in hadronic models)



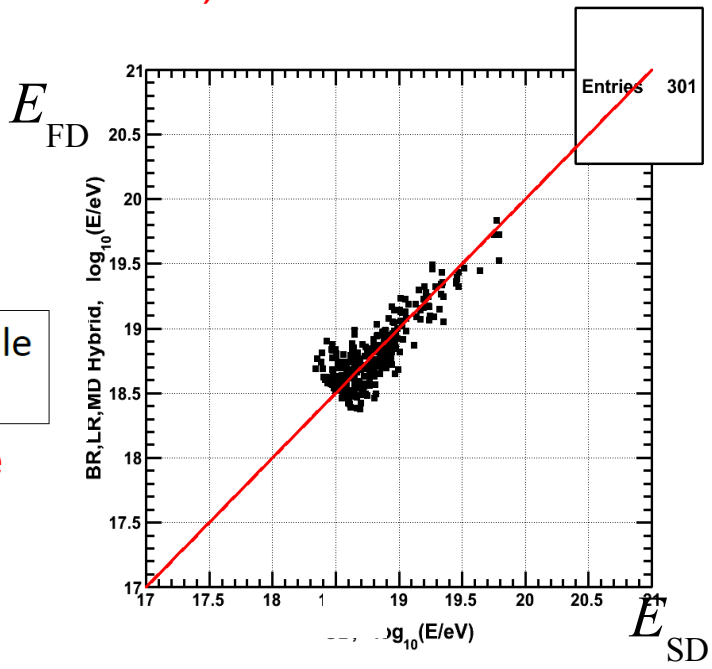
Monte Carlo → Energy table

$E'_{SD} = E'_{SD}(S800, \theta)$

MC energy too large

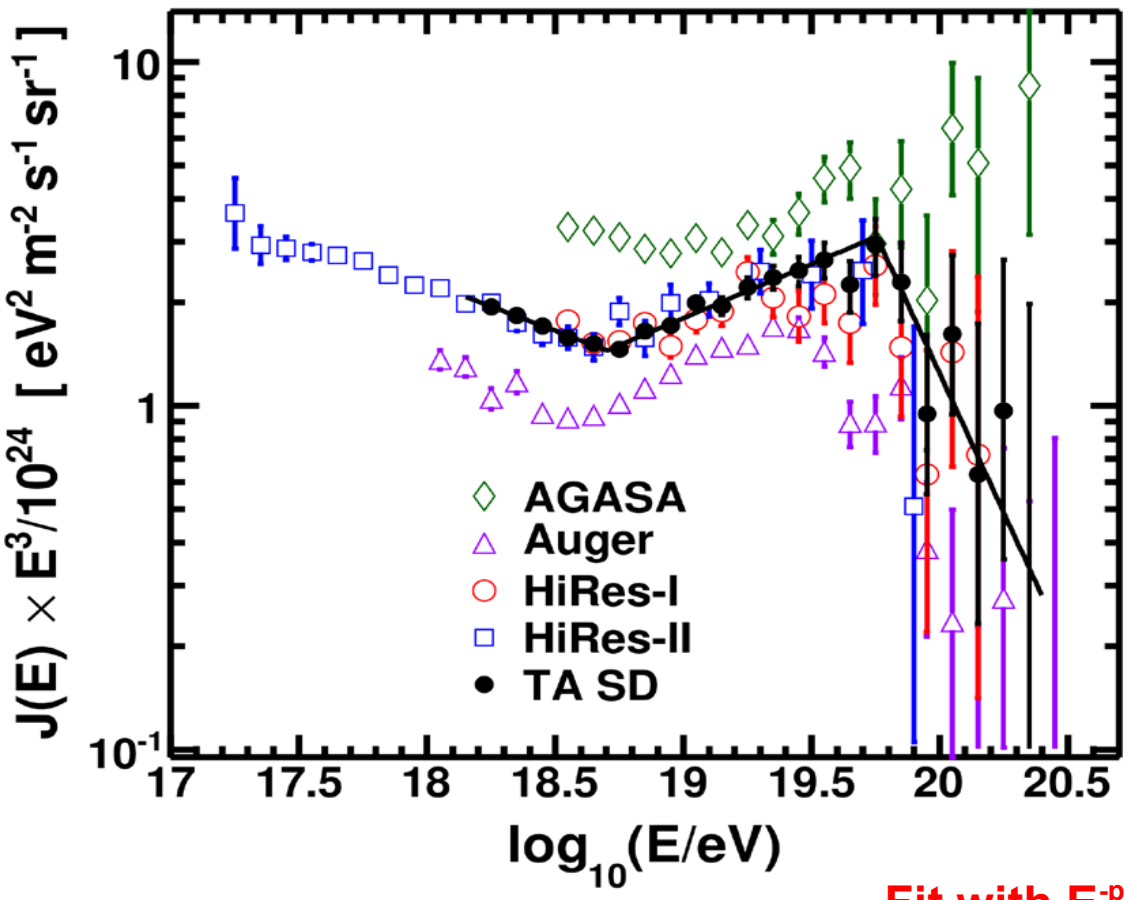
Rescaled with FD

$E_{SD} = E'_{SD}/1.27$



TA Spectrum by SD (2008-2013)

TA data
May 2008 – May 2013
Zenith angle < 45°
14787 events ($E > 10^{18.2}$ eV)
Exposure 4500 km^2 sr yr



Broken power law fit

$\gamma_1 = -3.283 \pm 0.032$

$E_{ankle} = (5.04 \pm 0.27) \times 10^{18}$ eV

$\gamma_2 = -2.685 \pm 0.030$

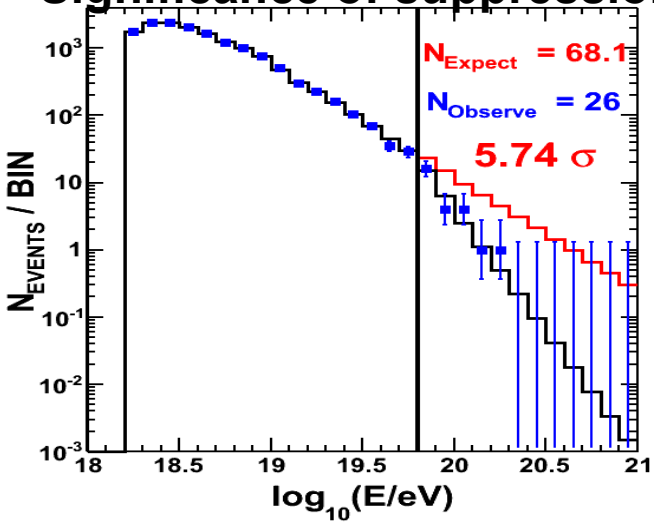
$E_{GZK} = (5.68 \pm 1.05) \times 10^{19}$ eV

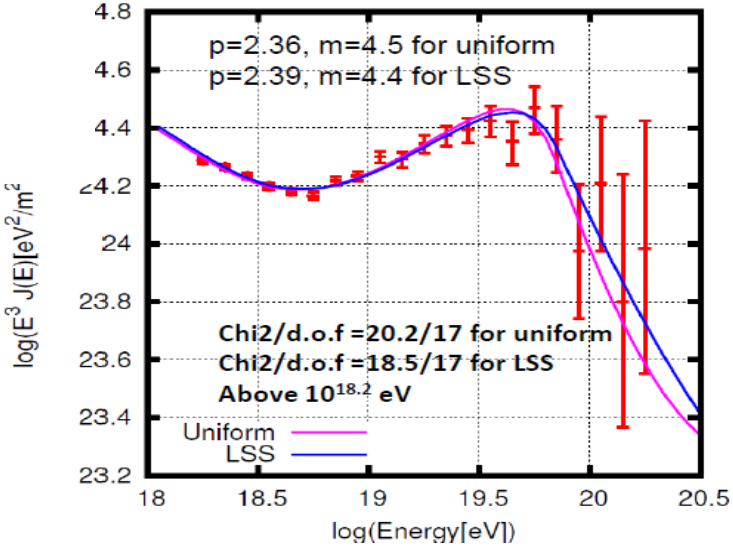
$\gamma_3 = -4.62 \pm 0.74$

H. Sagawa ICRC 2013

Fit with E^{-p} source spectrum (protons) and $(1+z)^m$ evolution

Significance of suppression

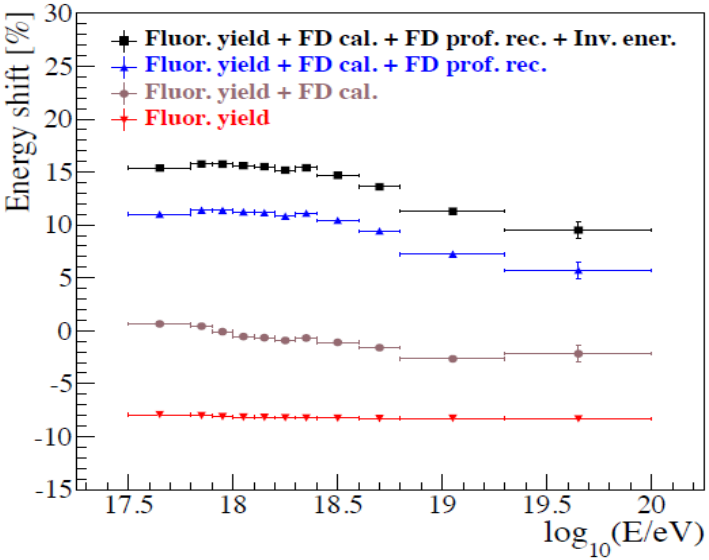




Auger energy scale

Impact of recent improvements

Absolute fluorescence yield	**-8.2%**
New opt. eff.	4.3%
Calibr. database update	3.5%
Sub total (FD cal.)	**7.8%**
Likelihood fit of dE/dX	2.2%
Folding with point. spr. func.	9.4%
Sub total (FD prof. rec.)	**11.6%**
Invisible energy	**4.4%**
Total	**15.6%**



Systematics uncertainties

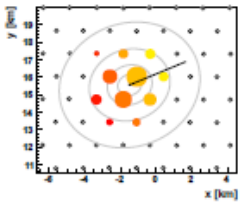
Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	3.6%
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	3.4% ÷ 6.2%
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	9.9%
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile reconstruction)	6.5% ÷ 5.6%
Invisible energy	3% ÷ 1.5%
Statistical error of the SD calib. fit	0.7% ÷ 1.8%
Stability of the energy scale	5%
TOTAL	14%

(Down from 22%)

Auger energy spectrum

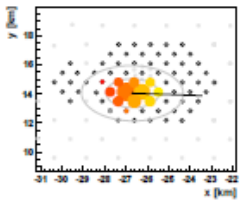
Schulz ICRC 2013

SD 1500 m, $\theta < 60°$



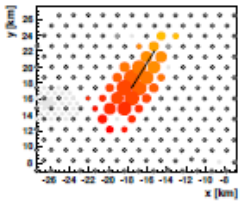
Vertical events
fully efficient:
$E \geq 3$ EeV
energy estimator:
S_{38}

SD 750 m, $\theta < 55°$



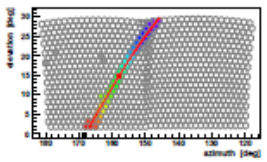
750 m events
fully efficient:
$E \geq 0.3$ EeV
energy estimator:
S_{35}

SD 1500 m, $62° < \theta < 80°$



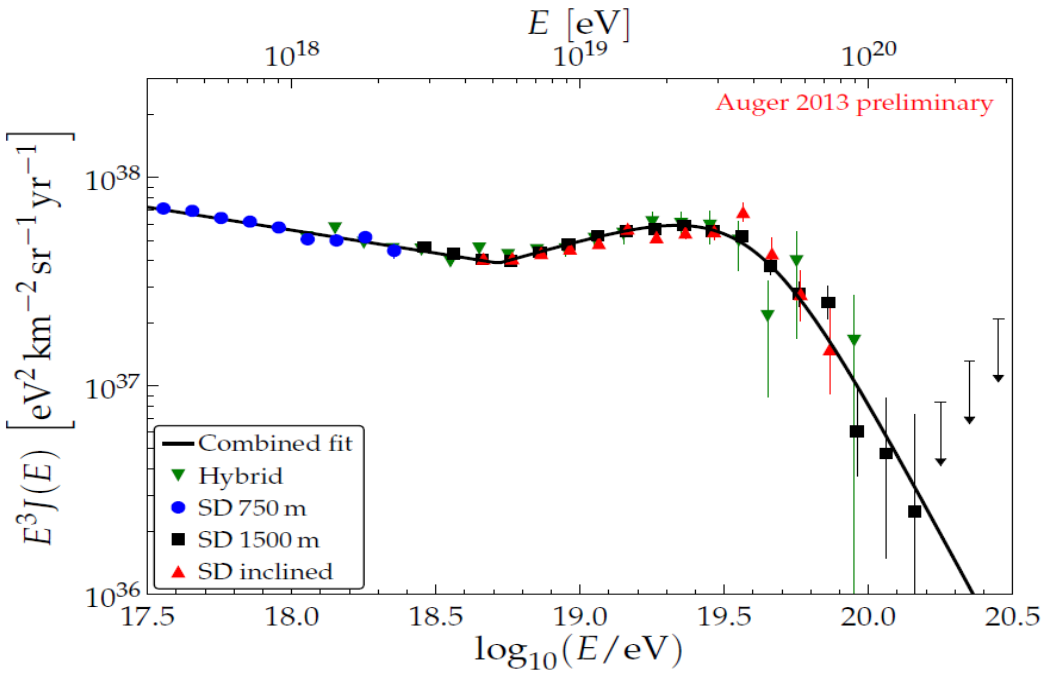
Inclined events
fully efficient:
$E \geq 4$ EeV
energy estimator:
N_{19}

Hybrid (FD + 1 SD), $\theta < 60°$

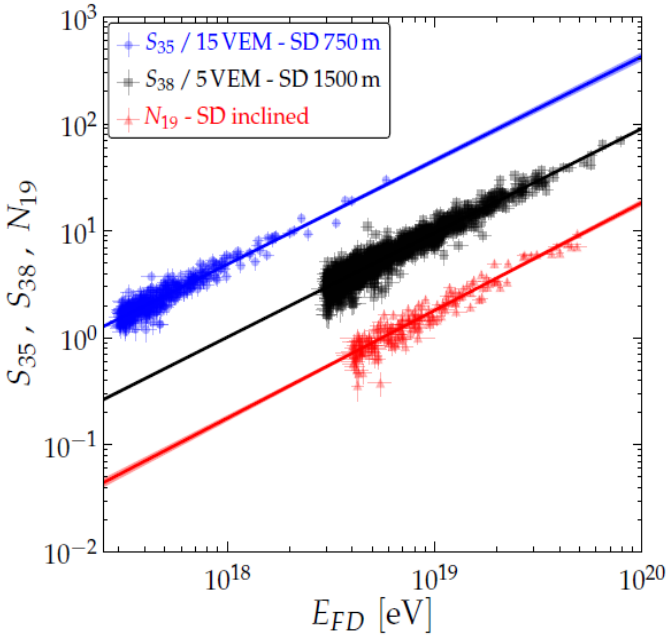


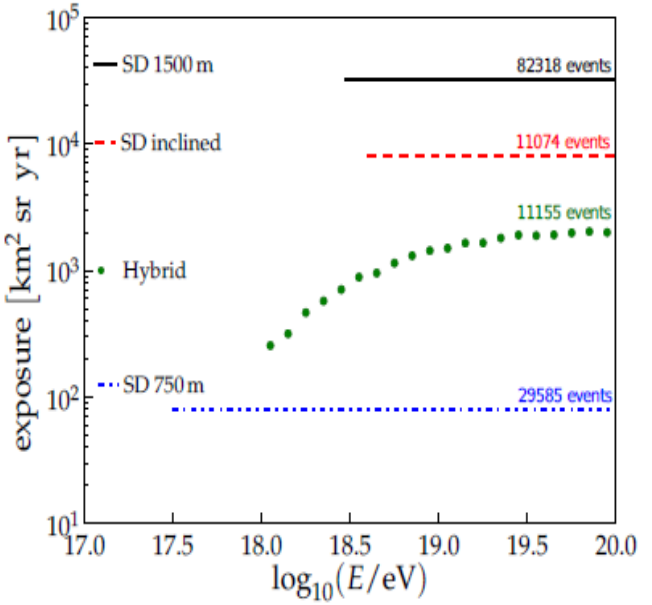
Hybrid events
fully efficient:
$E \geq 1$ EeV
energy meas.:
E_{FD}

⇒ Combined measurement of UHECRs over almost 3 decades in energy!

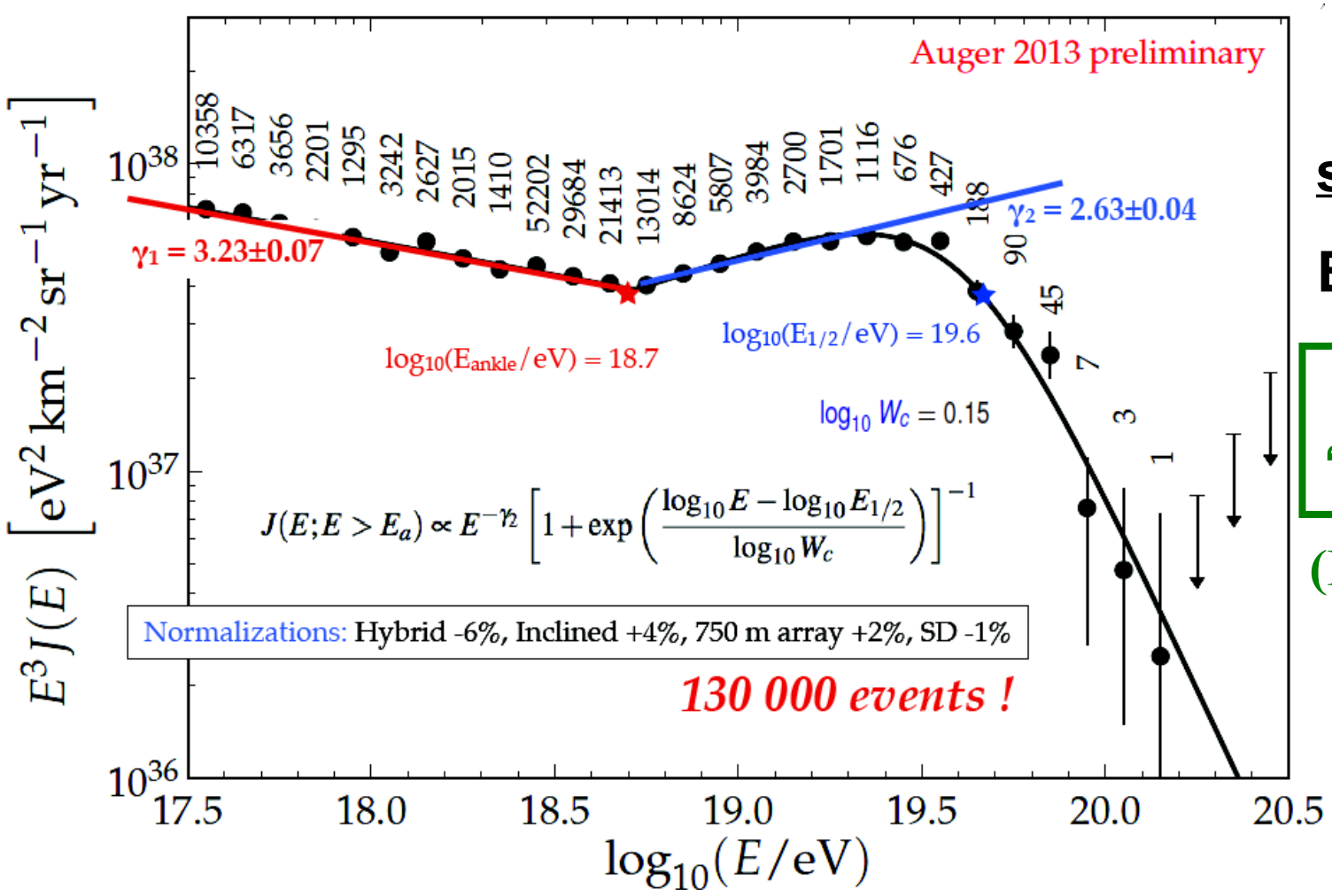


Normalizations: Hybrid: 0.94, 750 m array: 1.02, Inclined: 1.05





Auger energy spectrum



Flux suppression

E> 4x10^{19} eV

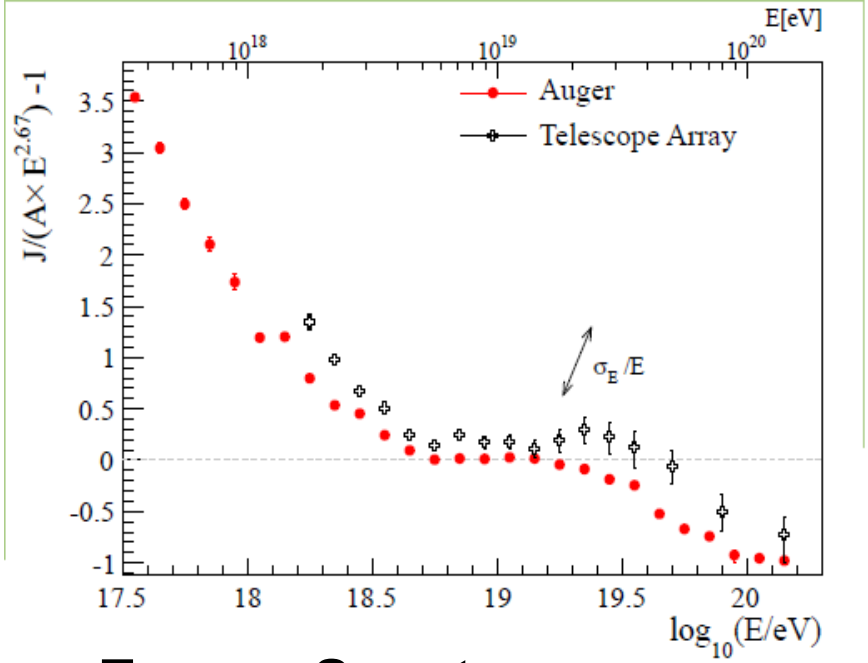
Compatible with "GZK" effect

(Fe, p or mixed)

Or source acceleration limit?

Spectrum alone is not enough to discriminate alternative scenarios

AUGER – TA - HiRes spectra
agree within systematic uncertainties

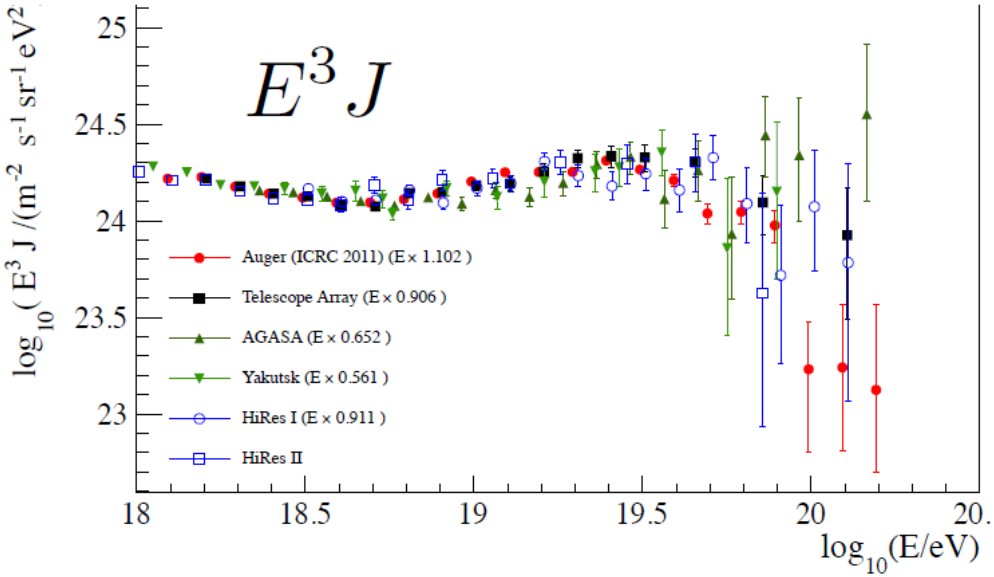


UHECR 2012: working group on Energy Spectrum

HiRes/TA: T. AbuZayyad, D. Ikeda, D. Ivanov, Y. Tsunesada

Yakutsk: M. Oravdin, A. Sabourov

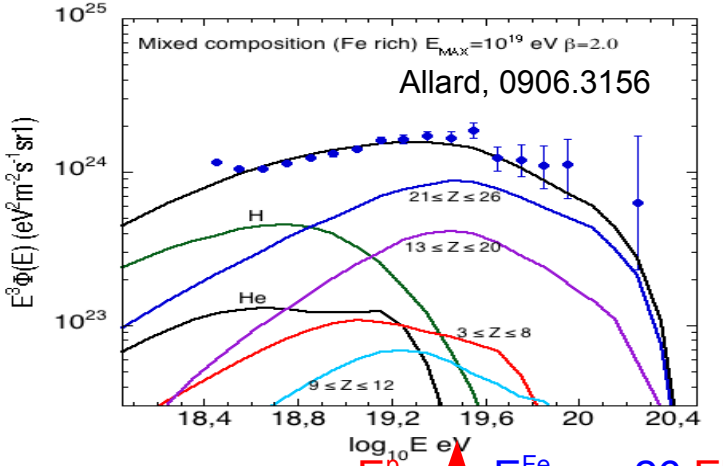
Auger: B. Dawson, I. Maris, M. Roth, F. Salamida



Similar shape:
the ankle/steepening energies are consistent after energy-independent scaling

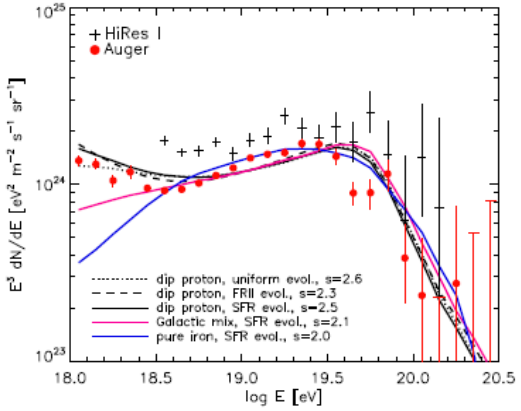
Astrophysical scenarios

MANY FREE PARAMETERS
fits to models sensitive to composition,
nearby source distribution,
maximum acceleration,
source spectral index and evolution,
diffusion in magnetic fields, …

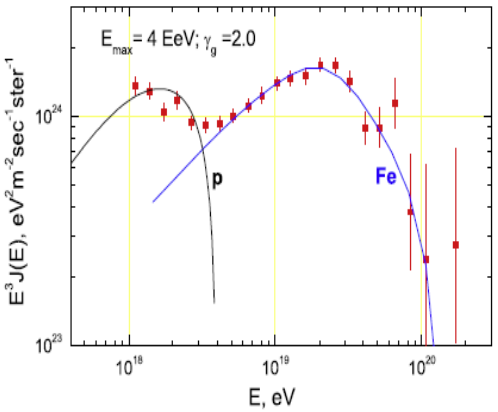


E^p_{max} E^{Fe}_{max} = 26 E^p_{max}

Suppression due to interaction with CMB
or to maximum injection energy?



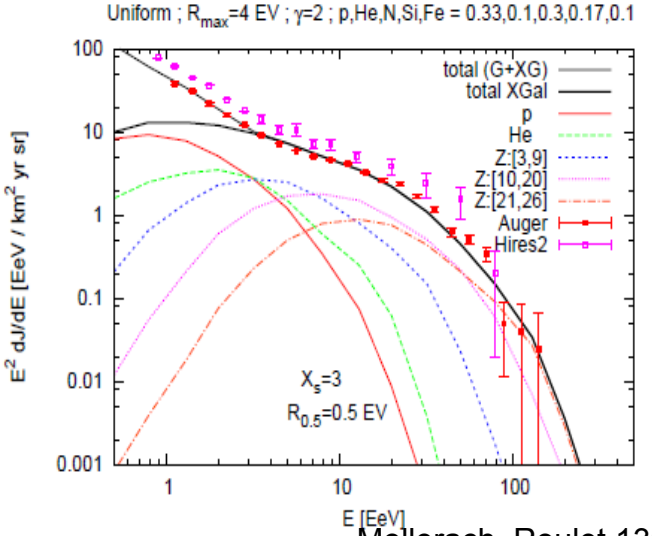
Kotera, Olinto 1101.4256



Aloisio, Berezinskii, Gazizov 1211.0494

Scenarios with mixed composition and rigidity-dependent maximum acceleration.

Magnetic diffusion may suppress XG-nuclei at low energies

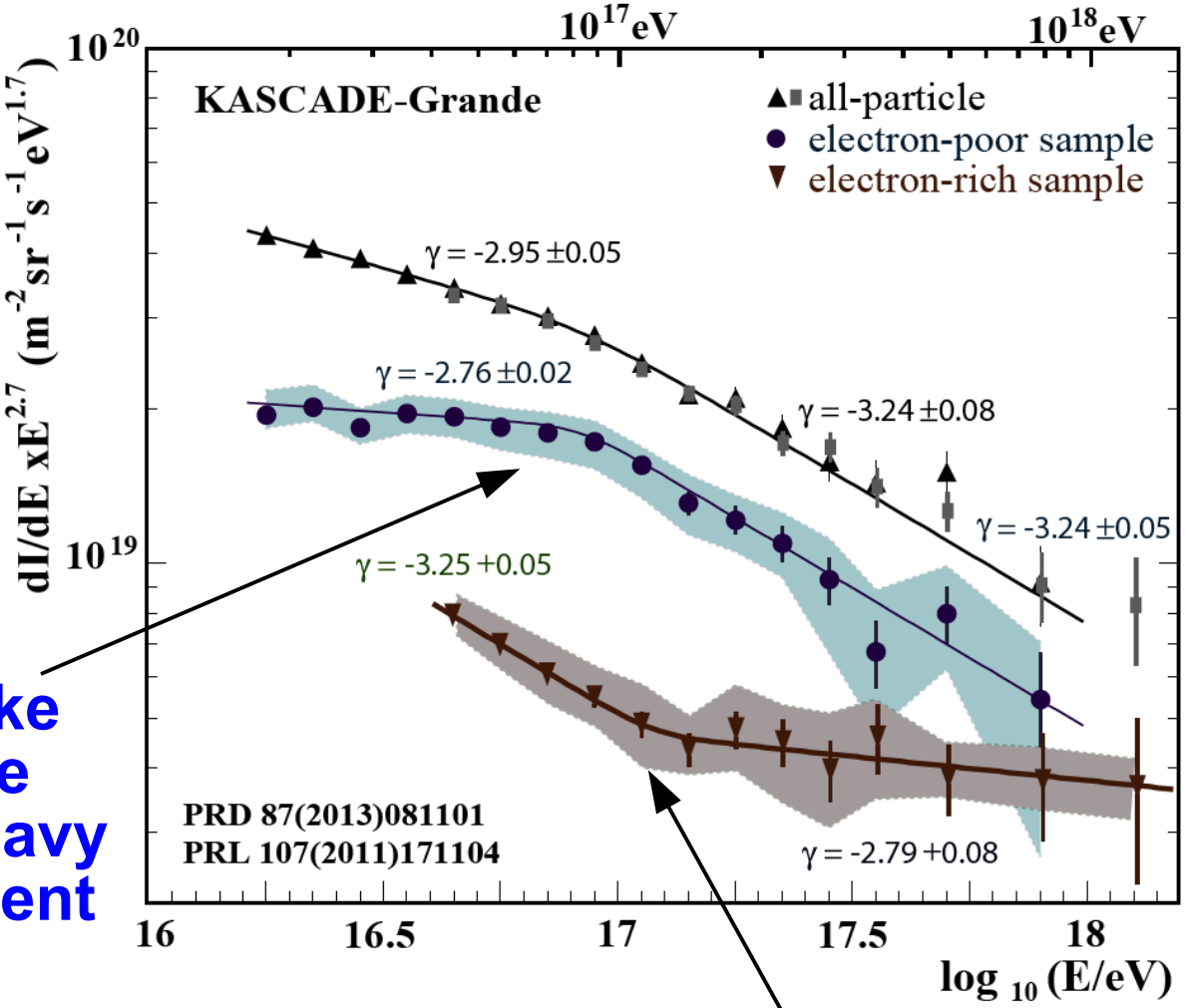


Mollerach, Roulet 1305.6519

Ankle: transition galactic-extragalactic
or e+e- dip from extragalactic protons?

Between the Knee and the Ankle

(A. Haungs @TAUP2013)

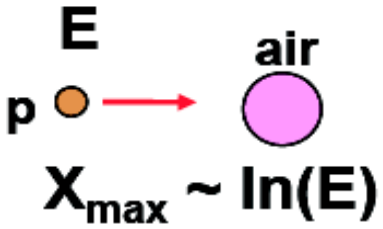


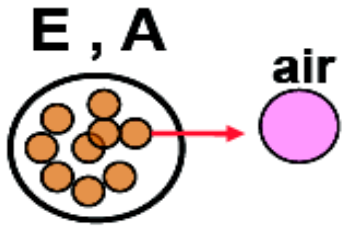
knee-like feature in the heavy component

ankle-like feature in the light component

$10^{17.08\pm0.08}$ eV

COMPOSITION: LIGHT OR HEAVY?

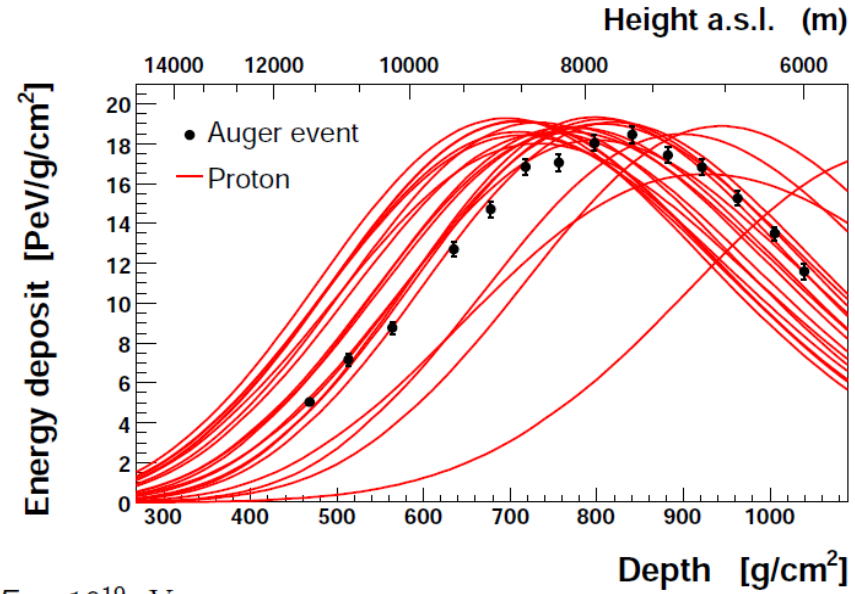




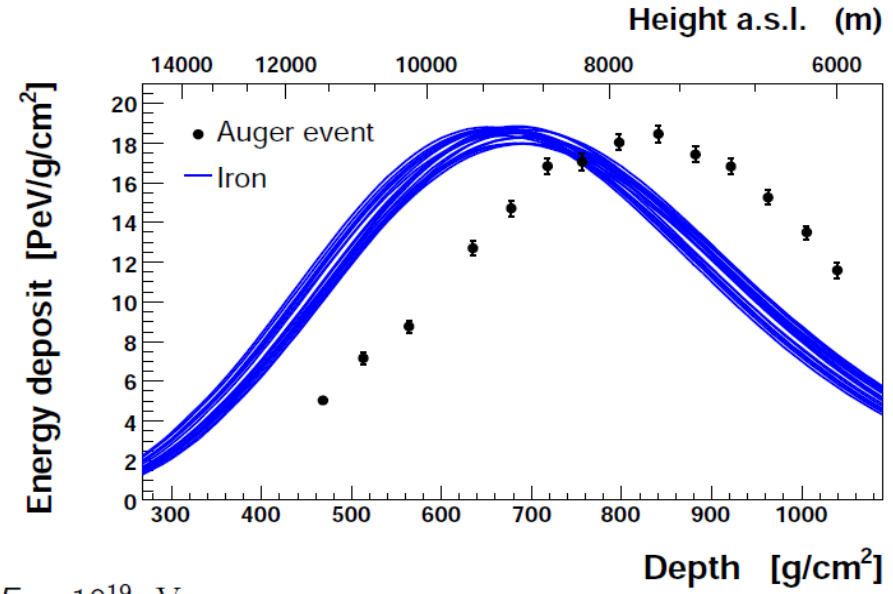
X_{max} ~ ln(E/A)

Large fluctuations of X_{max} from shower to shower

Smaller fluctuations



$E \sim 10^{19}$ eV



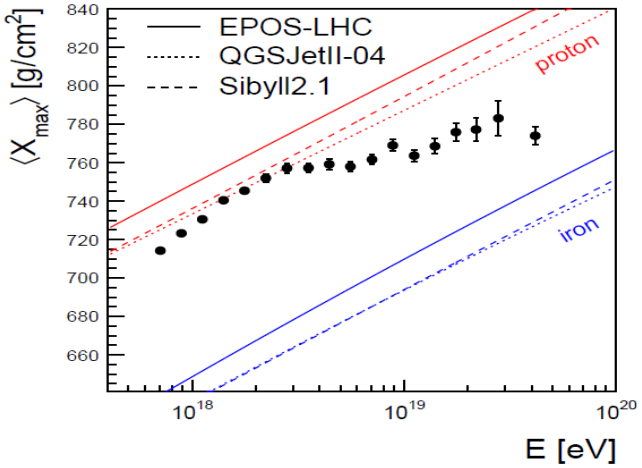
$E \sim 10^{19}$ eV

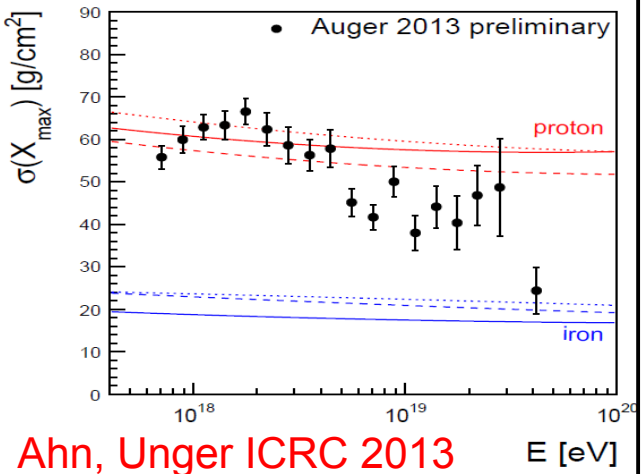
$<X_{max}>$ and $\sigma(X_{max})$

ARE SENSITIVE TO COMPOSITION

UPDATED MEASUREMENTS OF X_{max}

(J. Bellido @TAUP2013)



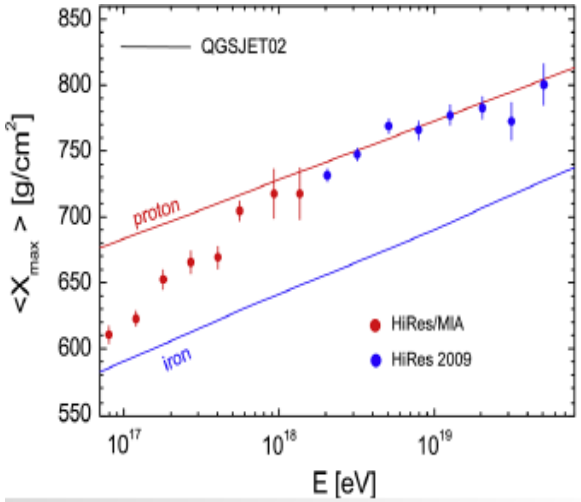


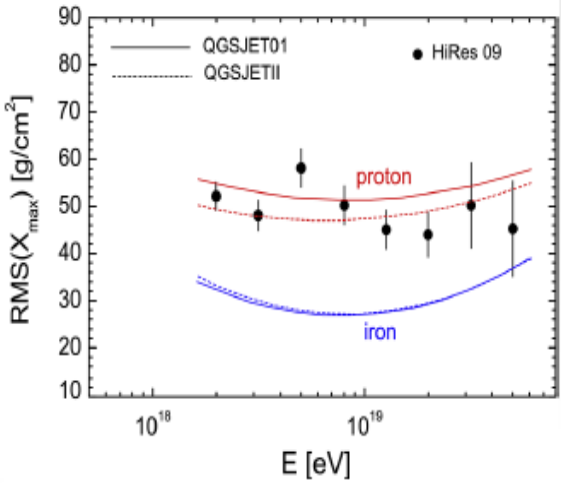
Ahn, Unger ICRC 2013

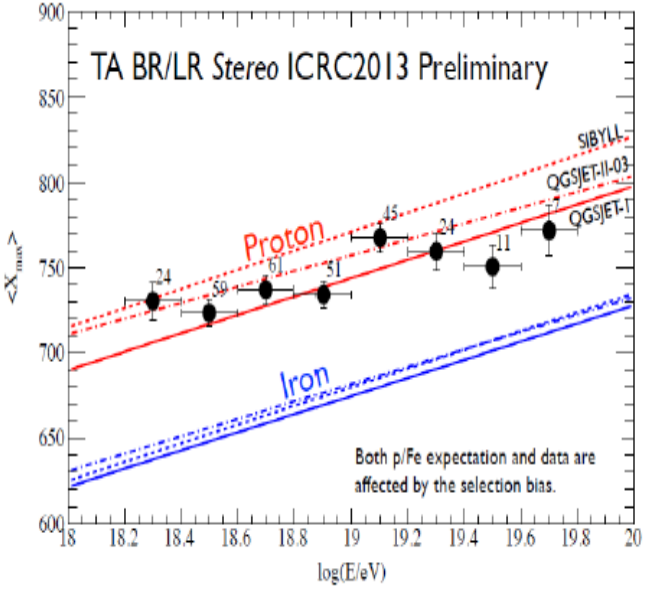
AUGER

Showers at ultrahigh energies are shallower and fluctuate less than predicted by proton simulations

Suggests a change in composition above 2-3 EeV with increasing average mass and small mixing







TA and HiRes

Measurements are compatible with expectations for proton simulations

Y. Tsunesada ICRC 2013

CAVEAT #1

AUGER and TA-HiRes make different analyses

X_{max} acceptance bias in data and model MC for HiRes and TA

Fiducial volume cuts: no bias for Auger

Joint work has begun to understand differences

UHECR 2012: working group Auger-TA on composition analysis

HiRes/TA: E. Barcikowski, J. Belz, Y. Tameda, Y. Tsunesada

Yakutsk: S. Knurenko, Y. Egorov Auger: J. Bellido, V. de Souza, M. Unger

Current data in the Northern Hemisphere consistent with a constant light composition cannot definitively exclude a changing composition as suggested by Auger measurements.

ICRC 2013: joint Auger-TA presentation

Simulations indicate TA could distinguish (with more statistics) a pure proton composition from a mixture that fits Auger measurements

NO STRONG INCOMPATIBILITY WITHIN STATISTICS

CAVEAT #2

SENSITIVITY TO EXTRAPOLATION OF HADRONIC INTERACTIONS

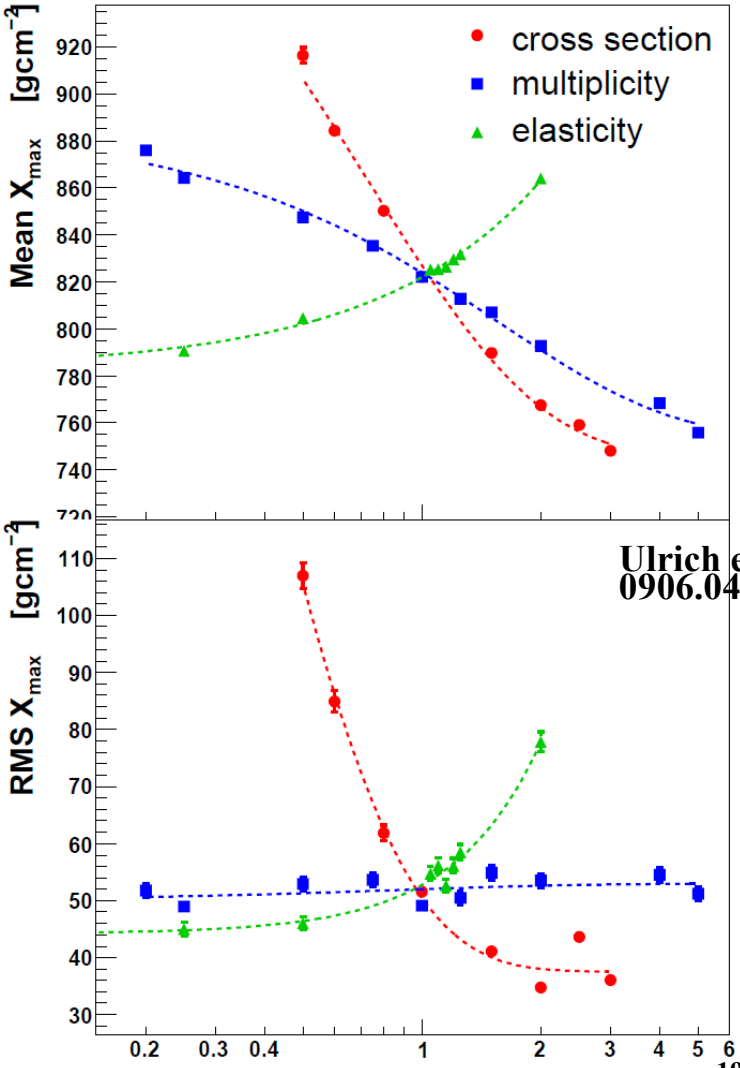
Composition estimates depend on simulations

Uncertainties due to extrapolation of hadronic interactions

(muon deficit compared to model predictions)

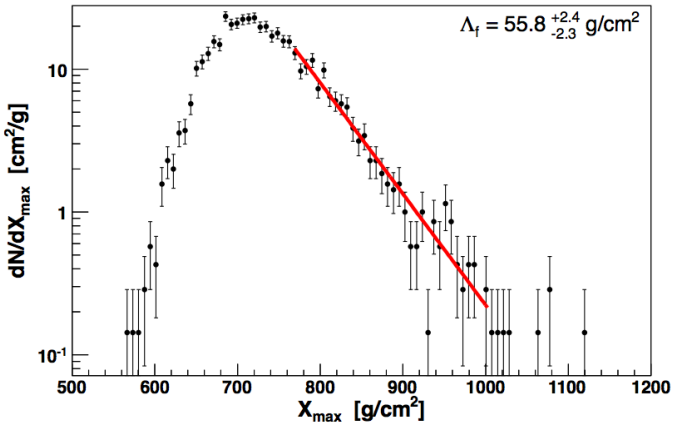
Dependence on cross sections multiplicity, elasticity

If composition were known → hadronic interactions at ~ 300 TeV

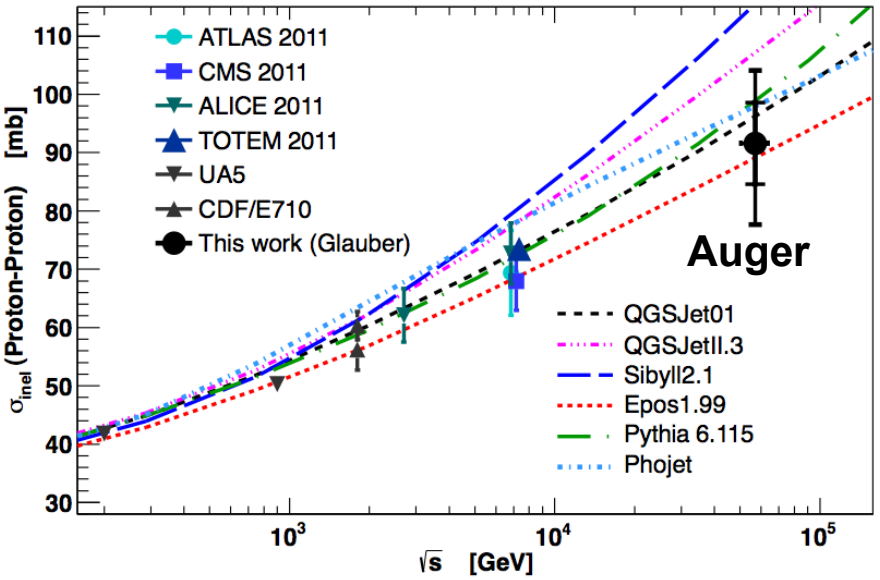


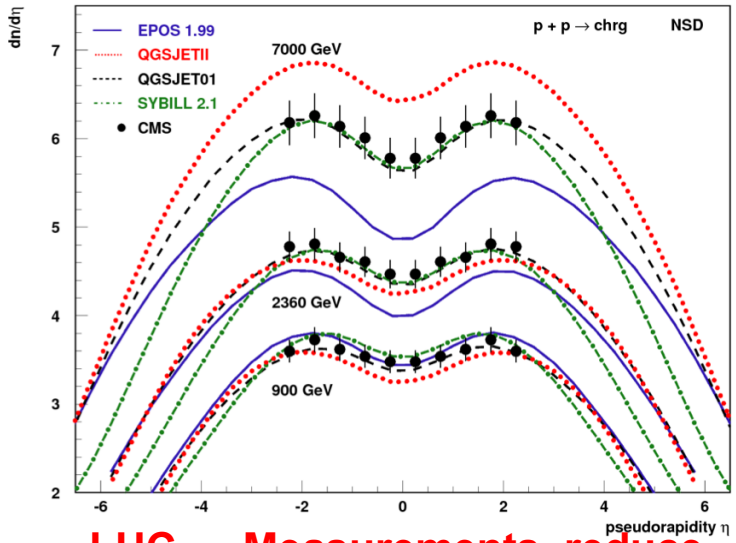
UHECRs ↔ Hadronic Interactions

(L. Cazón@TAUP2013)

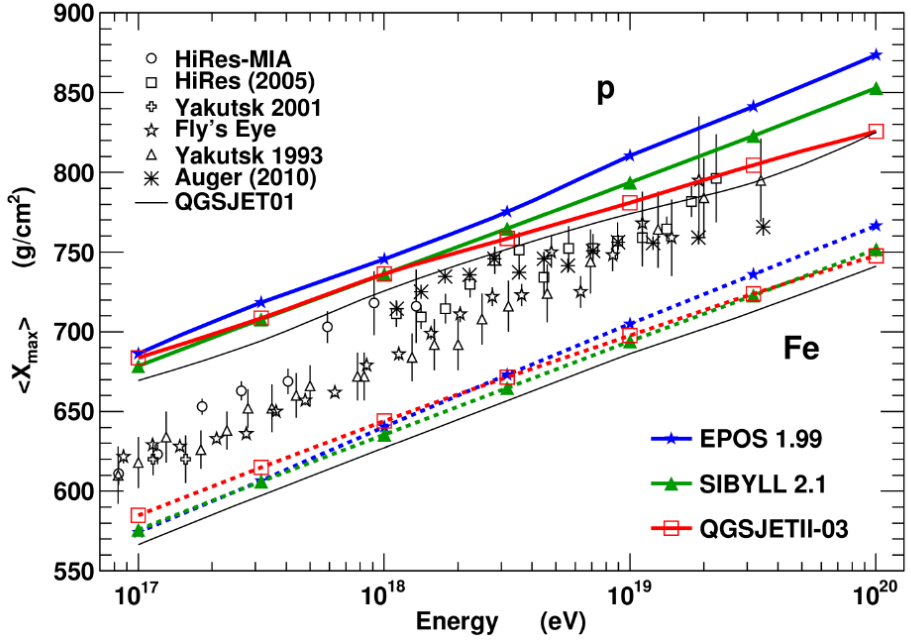


UHECRS → Measurement of proton-air cross section at energies beyond LHC

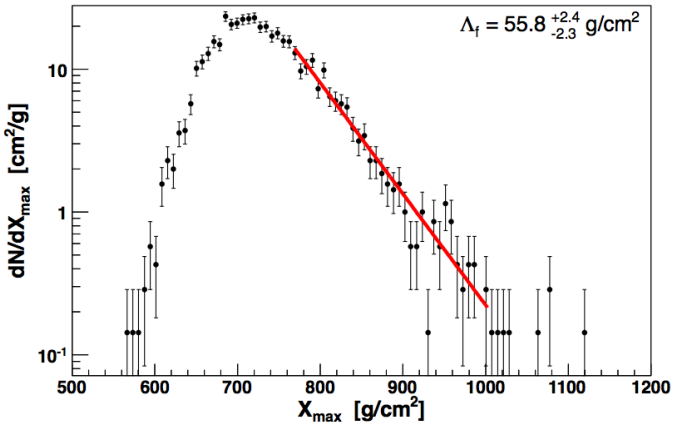




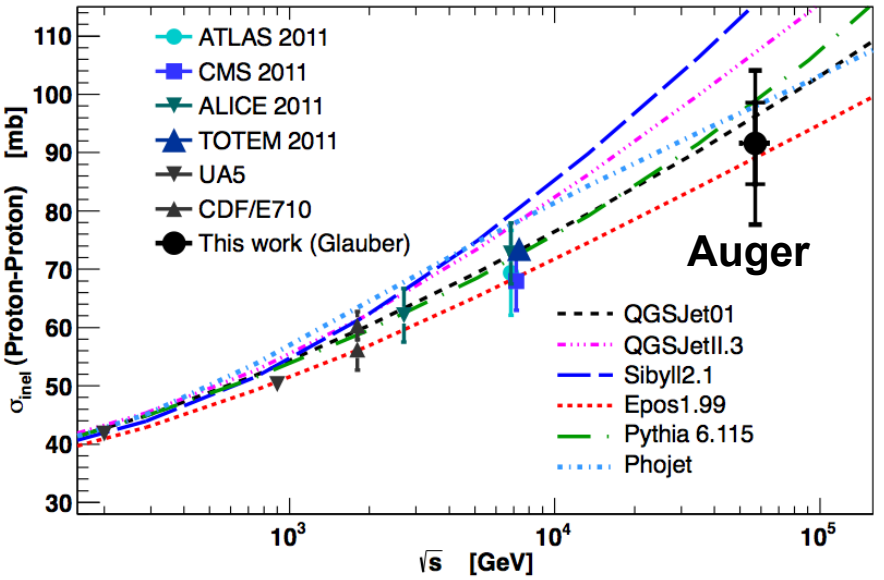
LHC → Measurements reduce extrapolation uncertainties

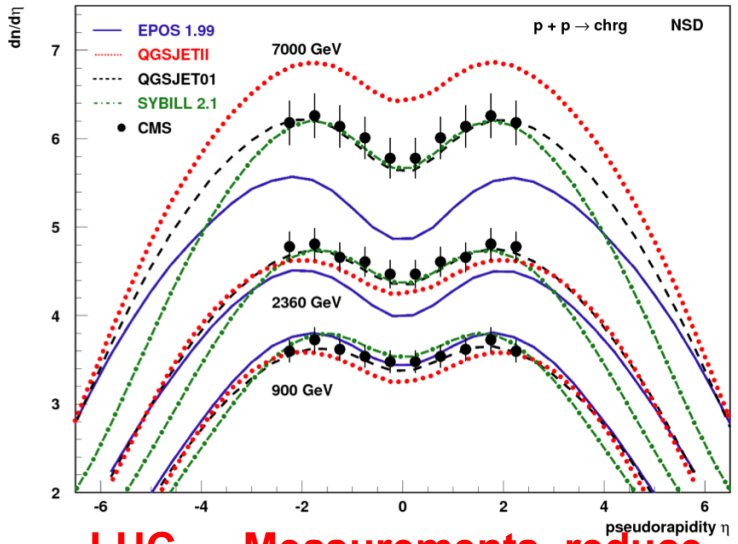


UHECRs ↔ Hadronic Interactions

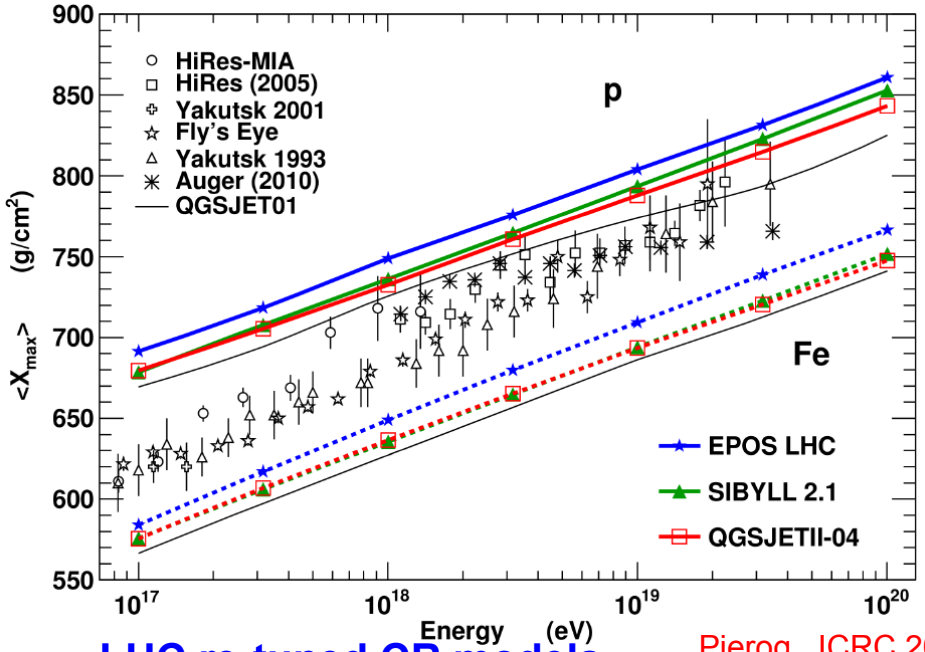


UHECRS → Measurement of proton-air cross section at energies beyond LHC





LHC → Measurements reduce extrapolation uncertainties



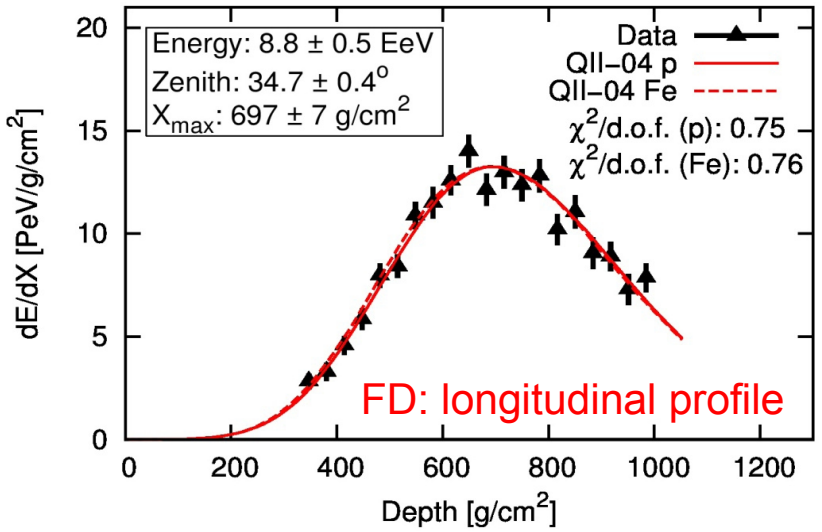
LHC re-tuned CR models

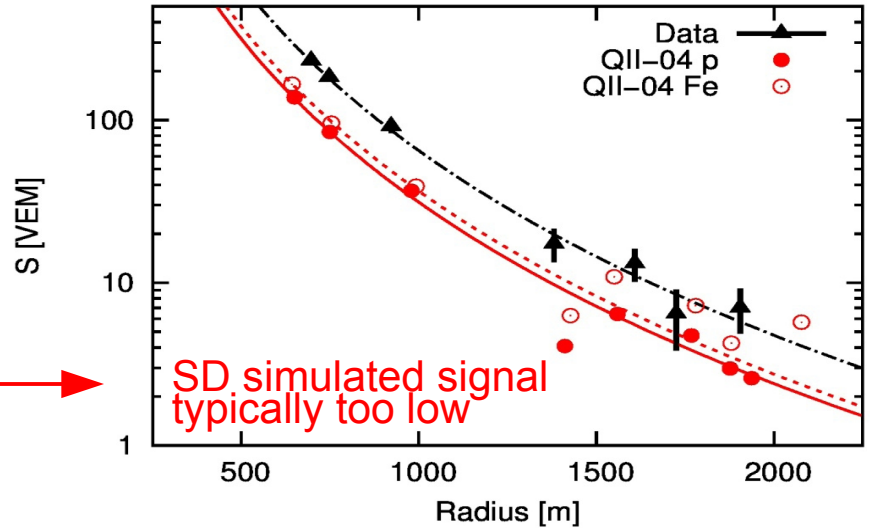
Pierog ICRC 2013

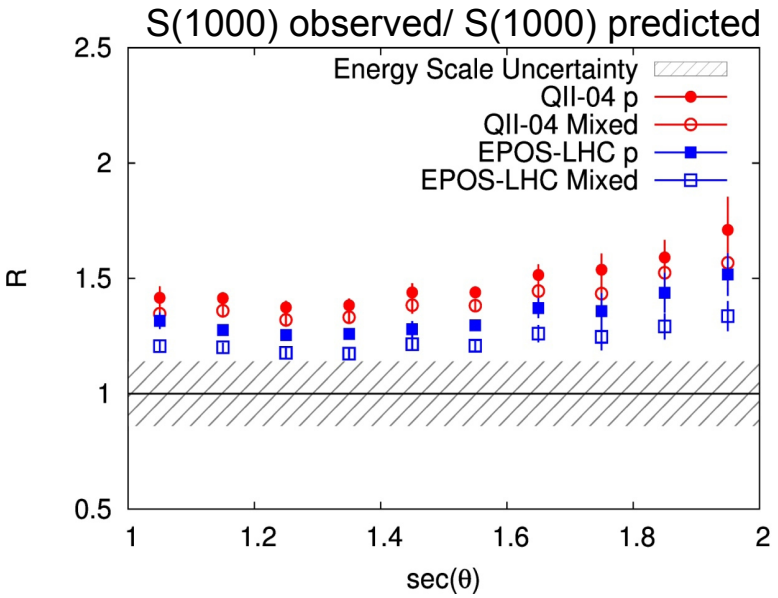
UHECRs ↔ Hadronic Interactions: MUON DEFICIT

Simulations that match FD profile have too low SD signal compared to data

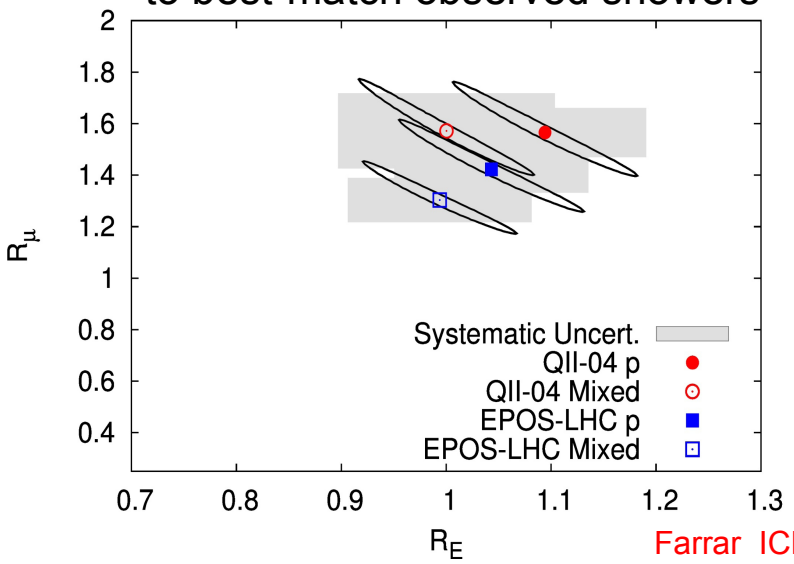
Discrepancy grows with zenith angle (so does muon component)





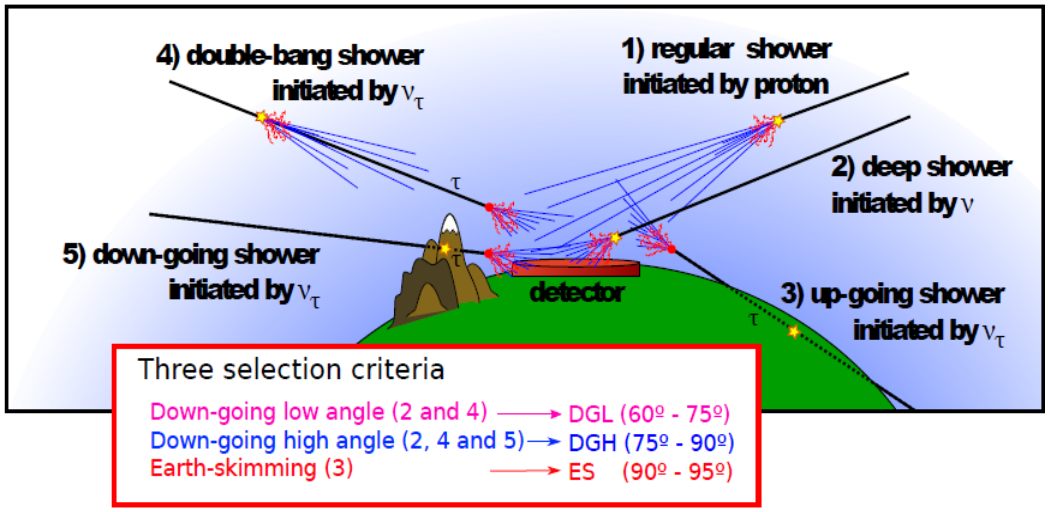


Rescale muon content in simulations to best-match observed showers

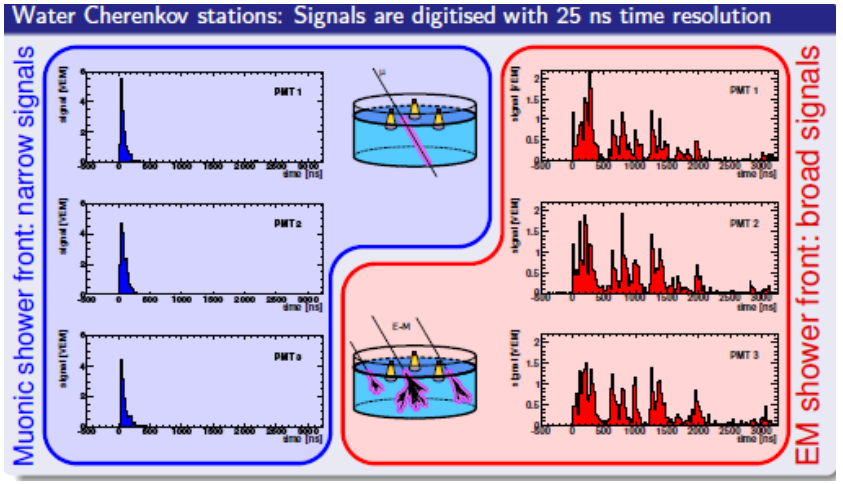


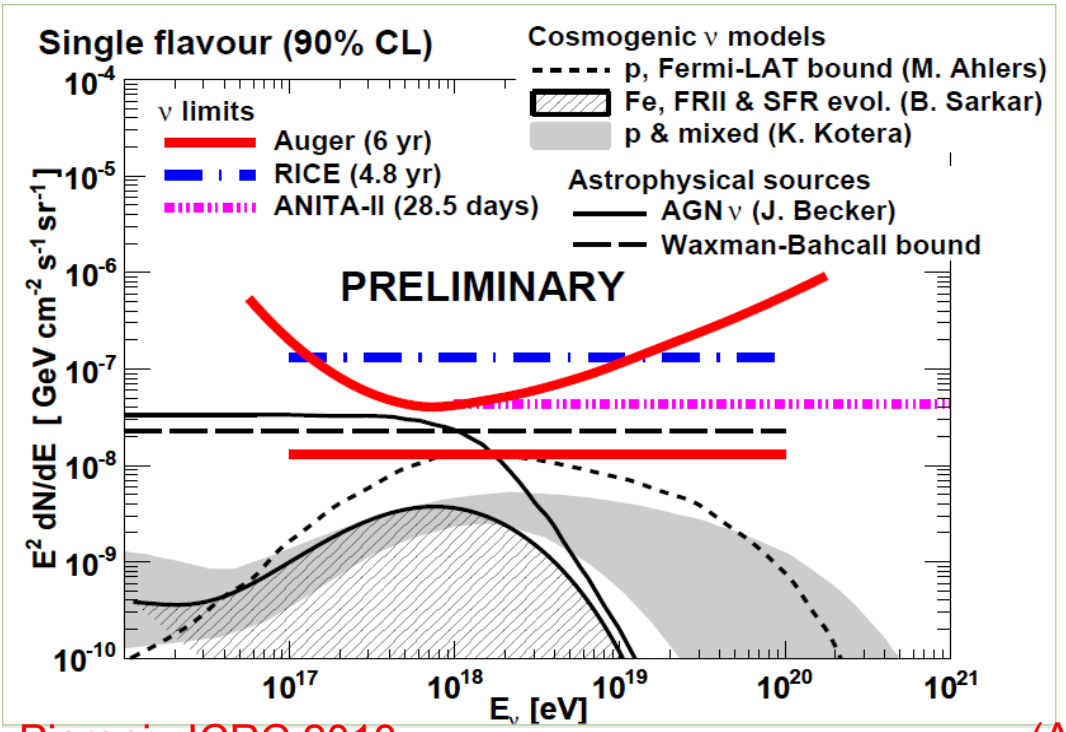
Farrar ICRC 2013

COMPOSITION: BOUNDS ON NEUTRINOS



Neutrinos, unlike hadrons, can induce "young" showers close to the ground





CANDIDATES: 0 → Bounds

Predictions for cosmogenic neutrinos are sensitive to composition (more for lighter nuclei)

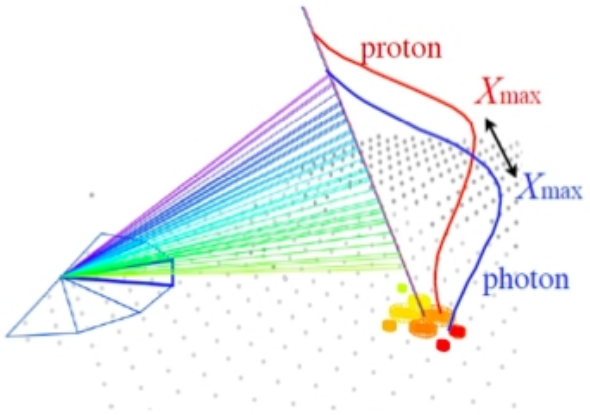
Model	Expected number of events
AGN (Becker)	~ 3.1
Cosmogenic (Ahlers) proton (Fermi-LAT bound)	~ 1.4
Cosmogenic (Kotera) proton & mixed compos.	~ 0.2 - 0.6
IceCube PeV flux, E^{-2} extrapolation	~ 2.2

Pieroni ICRC 2013

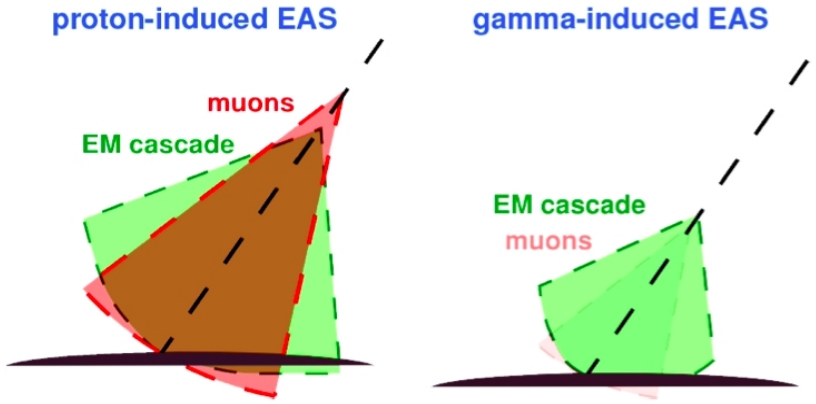
(Also Kopper, Mohrmann, Ahlers@TAUP2013)

COMPOSITION: BOUNDS ON PHOTONS

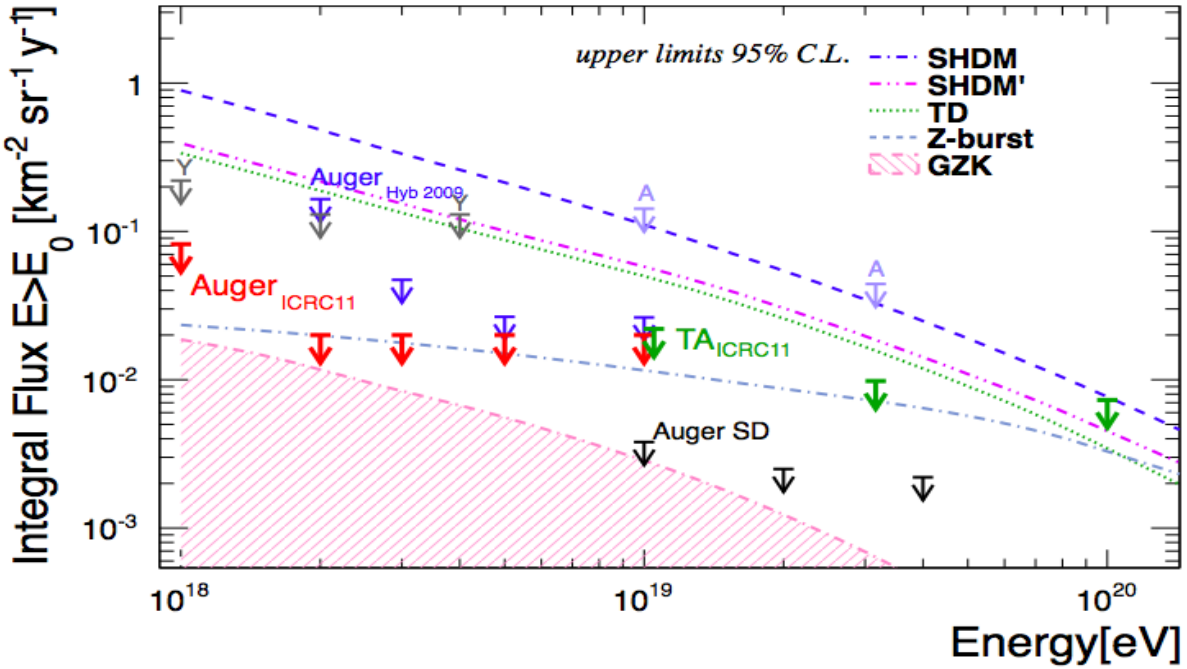
Good photon-hadron discrimination



Slower shower development: larger X_{max}



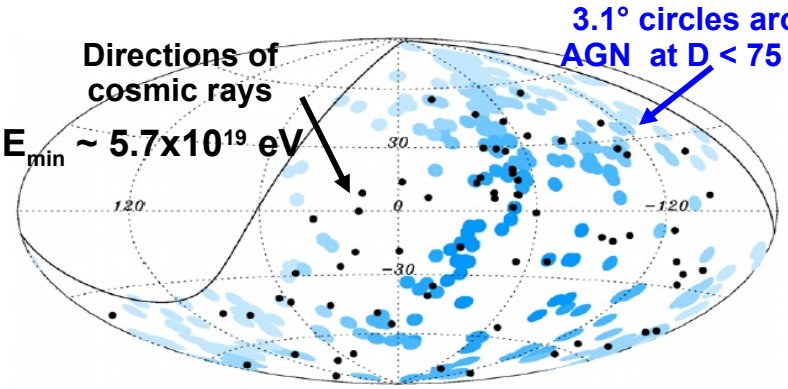
Predominantly electromagnetic.
Smaller curvature radius and longer "risetimes" and steeper lateral distribution



Strong constraints on:
Super-Heavy DM & Topological Defect models

GZK photons may be in reach

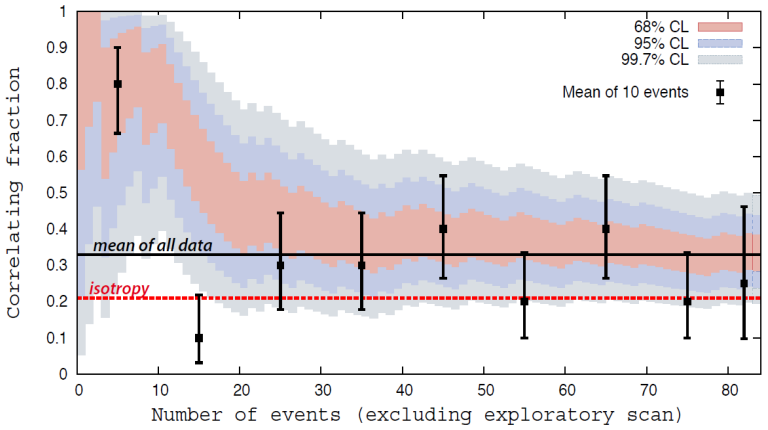
SEARCH FOR ANISOTROPIES



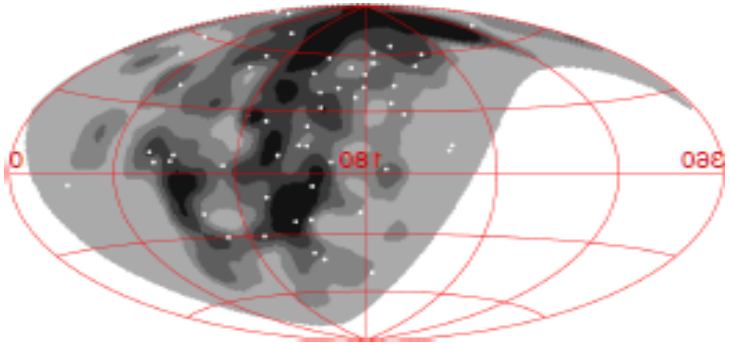
TA: 17/42 correlations p=0.014
Compatible with level of correlation measured by Auger

GZK HORIZON → Nearby (inhomogeneous) sources
Expect flux suppression + correlation with LSS
if deflections are small (light component)

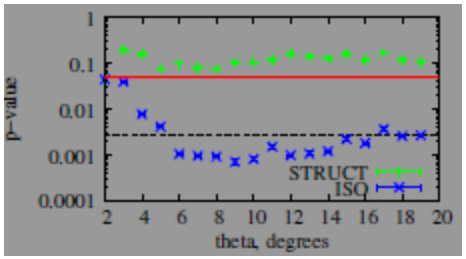
AUGER: 9/13 correlations in early independent data → 99%CL anisotropy



Larger dataset: 28/84 correlations (33% vs. 21% isotropic expectation)



TA: correlation with LSS better fit than isotropy. Some excess near SG plane on 20° scale

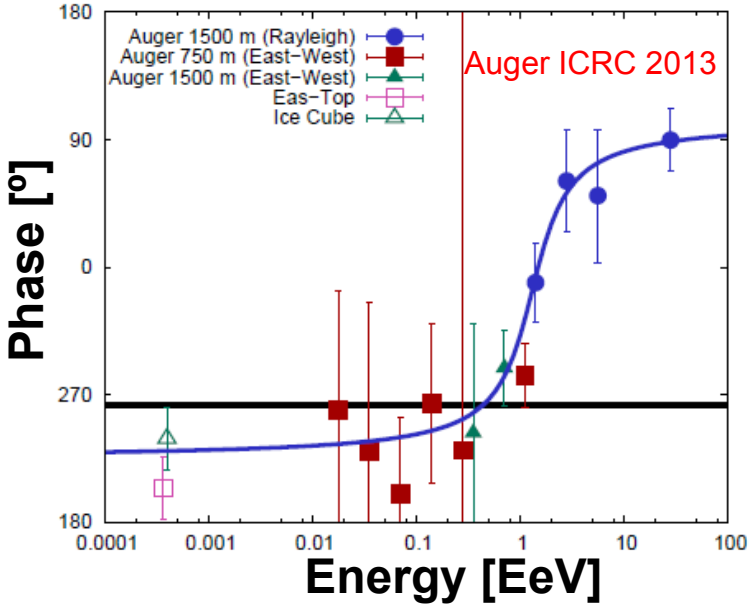


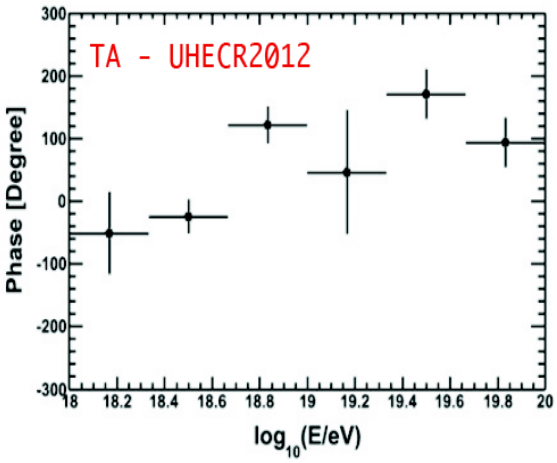
I. Tinyakov ICRC 2013

Inconclusive evidence with current statistics

SEARCH FOR LARGE-SCALE ANISOTROPIES

First-Harmonic analysis in Right Ascension





DIPOLE PHASE

hints to a constant value consistent with RA ~ 270º below 1 EeV

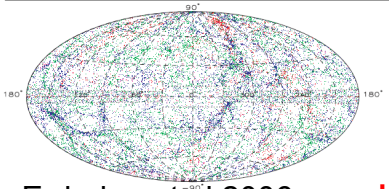
and a constant value (RA ~ 90º) above 4 EeV

Ongoing AUGER test with independent data

Note:

Galactic center is at RA=268.4º

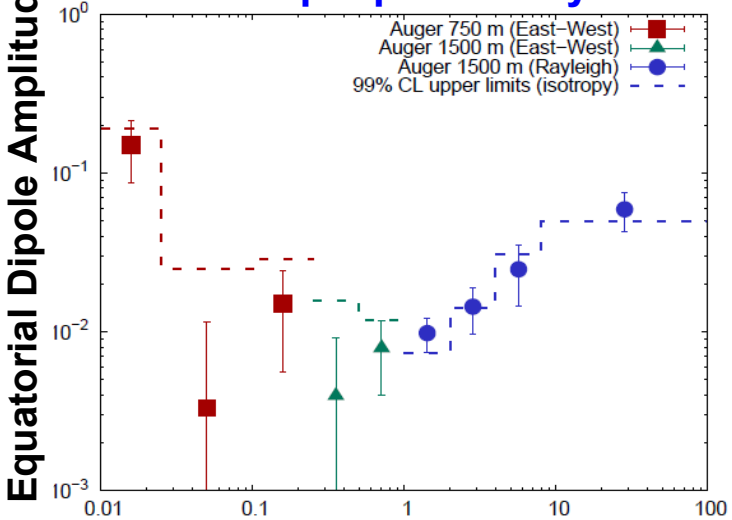
2MRS galaxies: dipole points to RA=153º+-10º



Erdodgu et al 2006

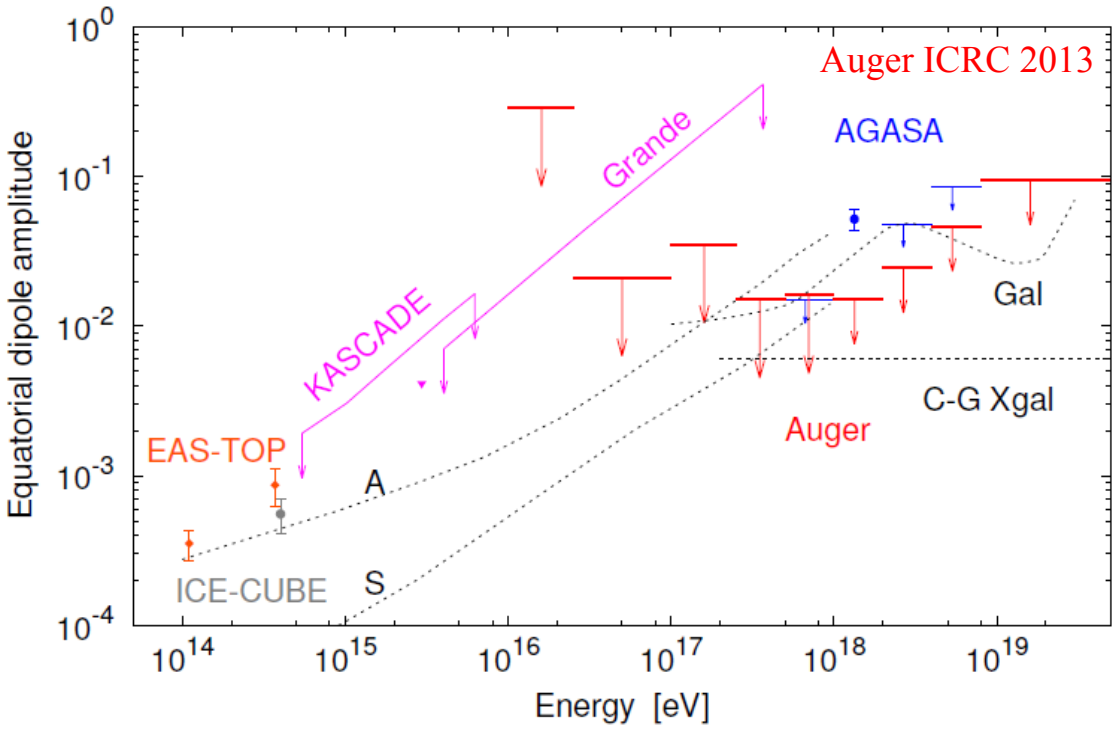
DIPOLE AMPLITUDE

3 bins above 1 EeV (out of 4) have isotropic probability < 1%

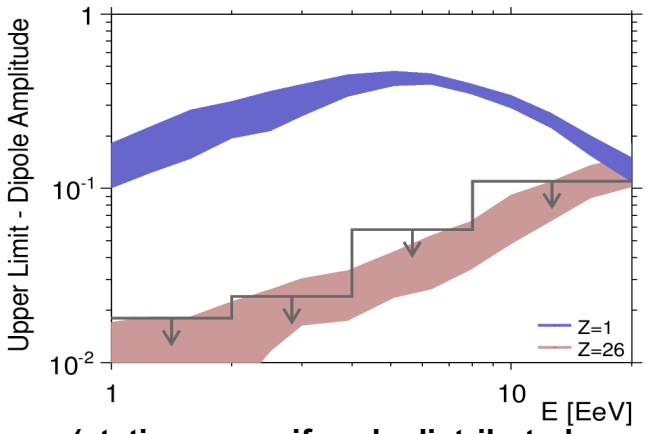


I. Sidelnik ICRC 2013

DIPOLE UPPER LIMITS (99%CL)

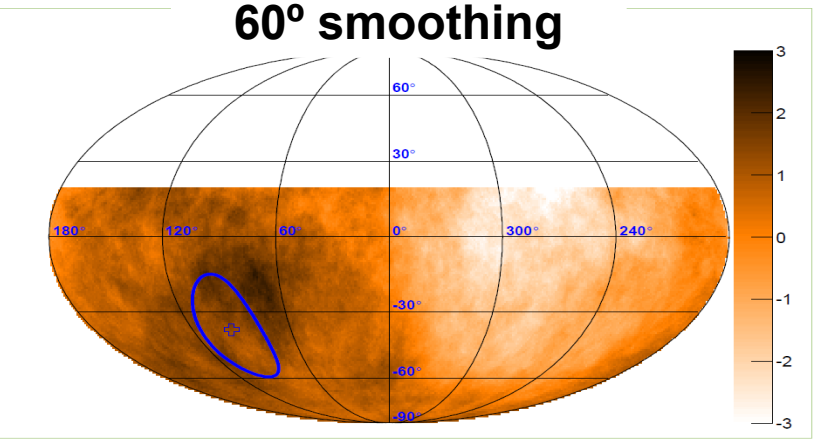


Constrains galactic origin of light component

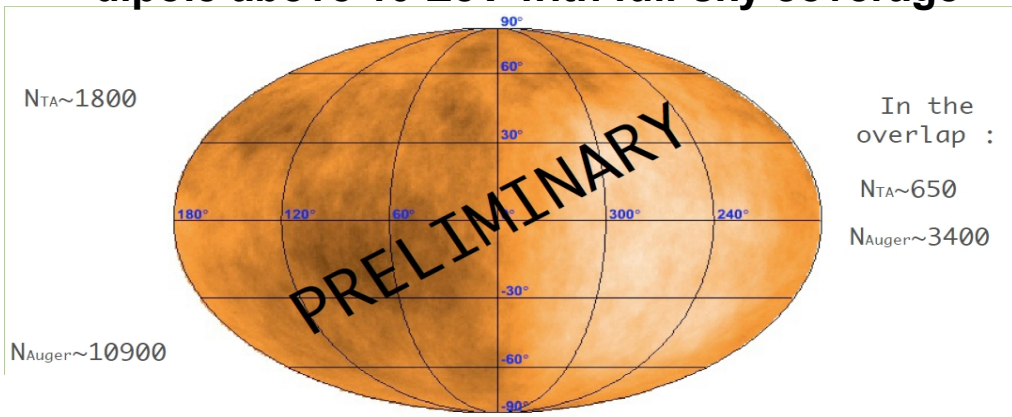


(stationary, uniformly distributed Isotropic sources in the galactic disk)

AUGER E > 8 EeV 60º smoothing



Ongoing joint Auger-TA project to combine data from two hemispheres and measure dipole above 10 EeV with full-sky coverage



O. Deligny ICRC 2013

SUMMARY/OUTLOOK

NOTORIUS FLUX SUPPRESSION E > 4x10^{19} eV ESTABLISHED

Compatible with GZK attenuation

but "source exhaustion" is also a possible cause

COMPATIBLE DATA FROM DIFFERENT EXPERIMENTS

Within systematic uncertainties and statistical limitations

Ongoing effort to compare and combine results

(Energy calibration, composition analyses, anisotropy studies ...)

INTRIGUING COMPOSITION RESULTS ABOVE 10^{19}eV

Or hint to changes in hadronic interactions?

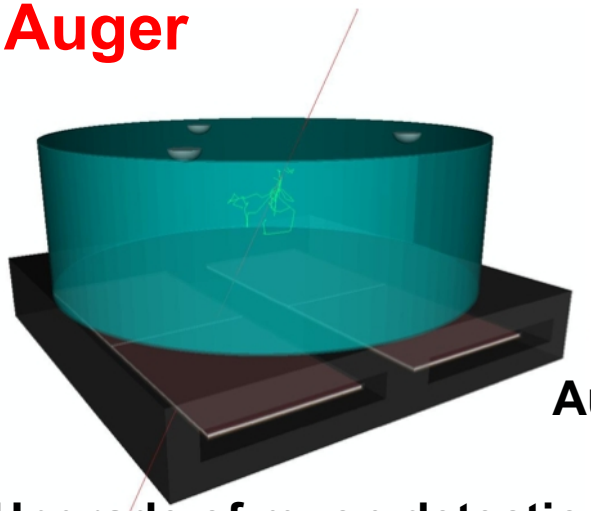
Correlation at small angles unexpected if Z is large

What is the fraction of light elements at the highest energies?

THE UHECR PUZLE IS NOT SOLVED

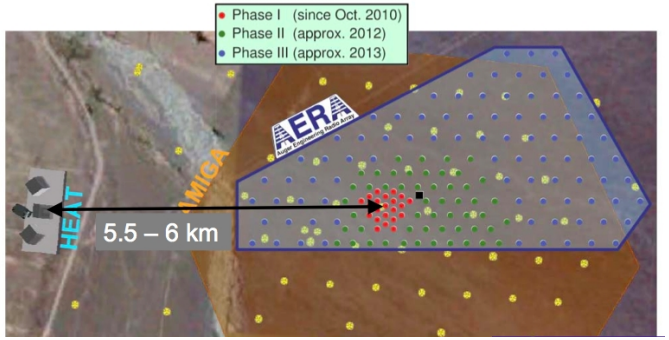
Expect more pieces to be added ...

Auger

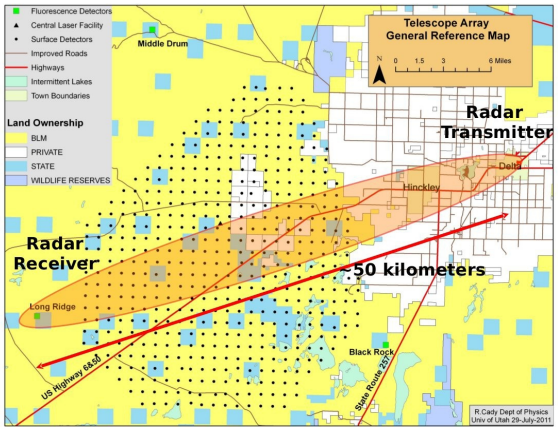


Upgrade of muon detection capabilities

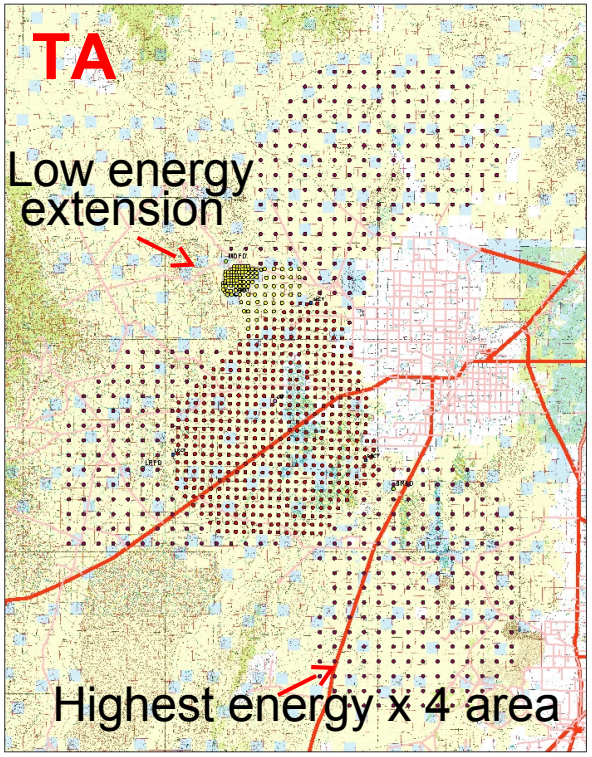
R&D on radio detection

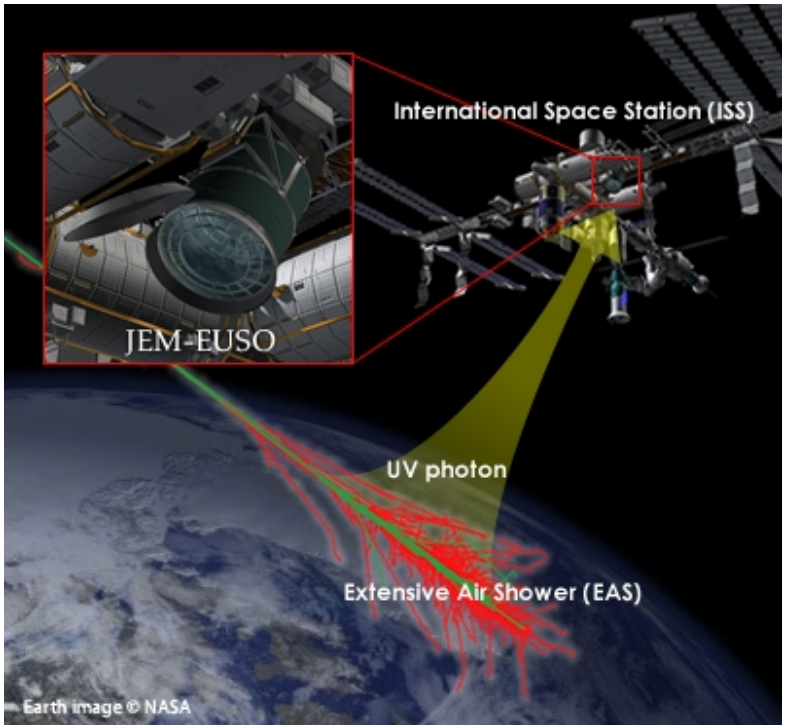


Auger Engineering Radio Array and other MHz and GHz detectors



Radar detection at TA





Extreme Universe Space Observatory at the Japanese Experiment Module