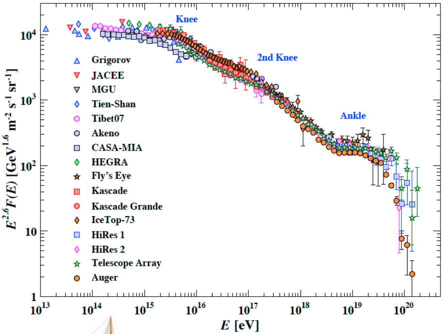
6th International Roma Conference on Astroparticle Physics

The Pierre Auger Observatory status and latest results

Corinne Bérat [1] for the Pierre Auger Collaboration

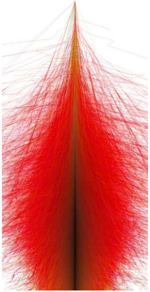
(1) *LPSC, Université Grenoble Alpes, CNRS/IN2P3.*

Science case



Ultra High Energy Cosmic Rays

- nature ?
- origin ?
- sources, acceleration process, propagation ?



⇒ Understanding UHECR nature and origin is the objective of the Pierre Auger Observatory

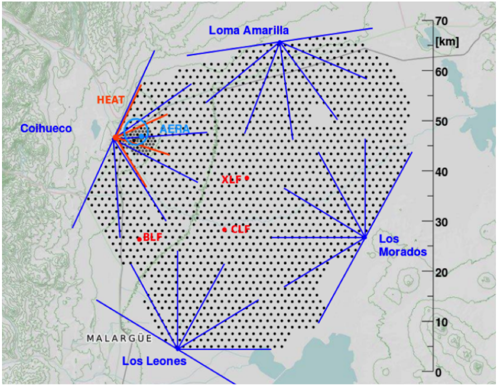
Extensive air shower (EAS)

- produced by UHECR
- used to infer primary cosmic ray characteristics

The Pierre Auger Observatory

The largest cosmic ray detector in operation

3000 km^2 in pampa Argentina



Hybrid detector

- surface detector (SD)
  - 1660 water Cherenkov detectors, triangular grid, 1.5 km spacing
    71 in 0.75 km infill grid ($\sim$ 30 km^2)
  - $\sim$ 100% duty cycle
- Fluorescence detector (FD)
  - 27 optical telescopes
    • 24 in 4 buildings overlooking SD
    • 3 in 1 building overlooking the Infill
  - $\sim$ 15% duty cycle

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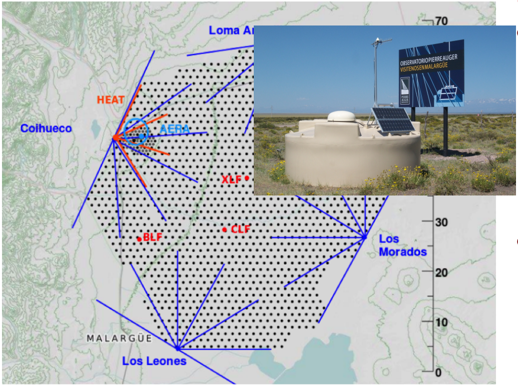

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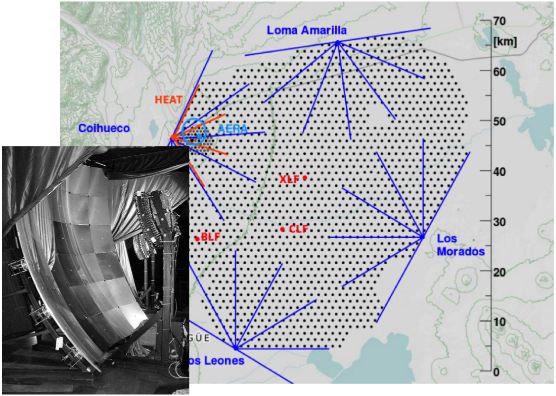

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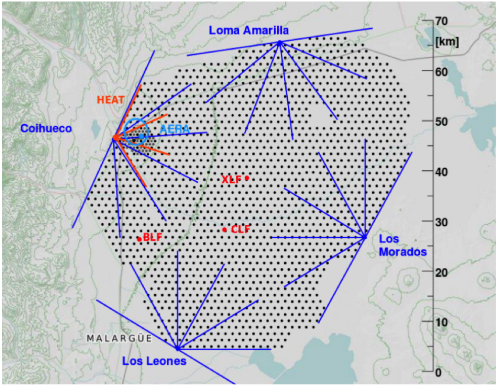

- Data taking started in 2004, detector completed in 2008
- High quality data in stable and continuous operation

- Atmospheric monitoring
  - Weather Stations, Lidars, IR cameras, lightening detectors...
- In the infill region
  - Muon detectors aside the Infill stations
  - AERA : 153 antennas (MHz) ($\sim$ 17 km^2) radio signal from EAS

  Recent progress:
  Benoit Revenu's talk, this afternoon CR session

- R&D GHz antennas

The Pierre Auger Observatory

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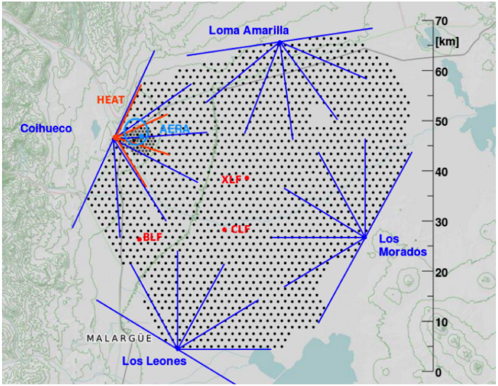

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Many valuable results only a selection shown here !

Shower observables

SD: lateral spread at ground

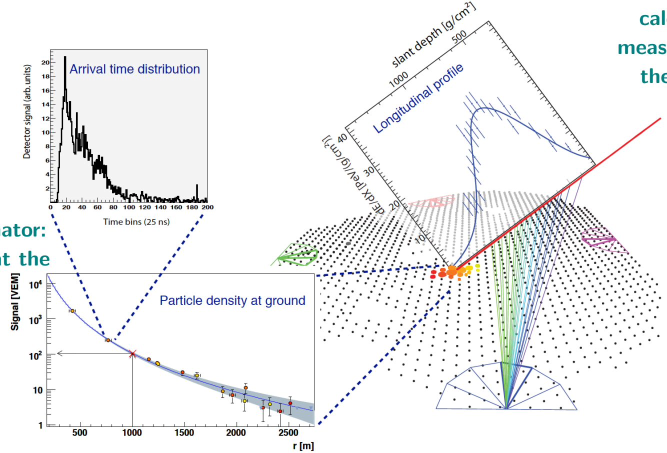
- with ground based particle detectors (WCD)

FD: longitudinal development profile

- with fluorescence light telescopes

calorimetric measurement of the energy

energy estimator: shower size at the ground



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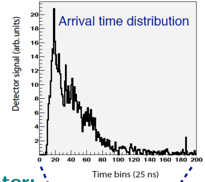

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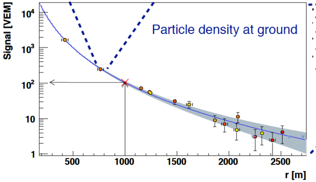
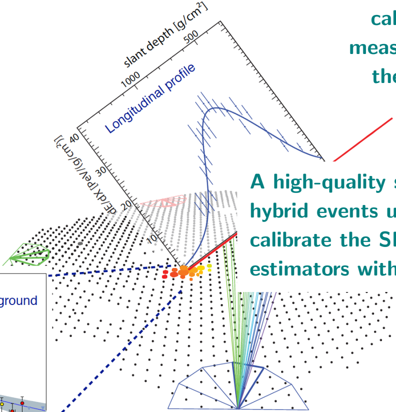




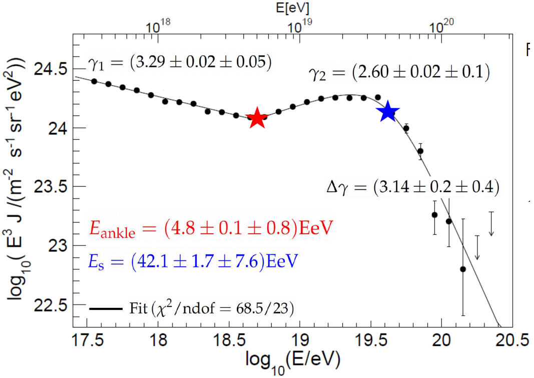
A high-quality subset of hybrid events used to calibrate the SD energy estimators with E_{FD}.

Combined spectrum

Four different data sets → Total exposure exceeding 50 000 km^2 sr yr

Four measurements of the CR flux are combined

I. Valiño for the Pierre Auger Coll., ICRC 2015; The Pierre Auger Coll, JCAP08(2015)049



$\sim$ 190000 CR

Fit of the differential flux

$E < E_{ankle}$: $J(E) \propto E^{-\gamma_1}$

$E > E_{ankle}$: $J(E) \propto$

$E^{-\gamma_2}\left[1 + (\frac{E}{E_s})^{\Delta\gamma}\right]^{-1}$

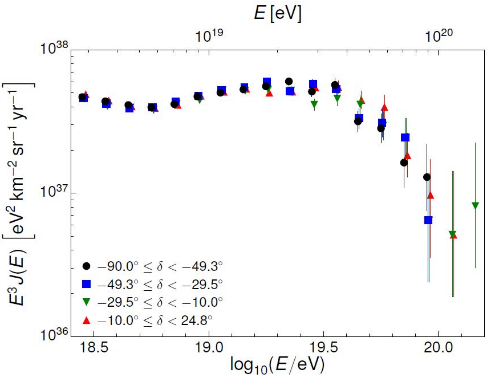
- GZK-like suppression definitely confirmed ($> 20\sigma$)
- E_s: energy at which the differential flux falls to 1/2 of the value of the power-law extrapolation from the intermediate region

Declination dependence of the flux ?

Search for declination dependence

- The large number of events and wide FOV allow for the study of the flux vs declination
- Four declination bands of equal exposure

I. Valiño for the Pierre Auger Coll., ICRC 2015



- Differences between sub-spectra and all-sky flux:
  $< 5\%$ below E_s
  $< 13\%$ above E_s
  $\Rightarrow$ No indication of a δ-dependent flux

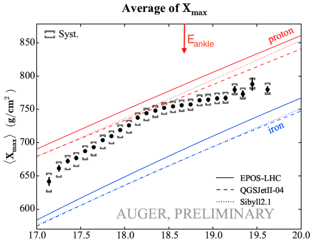
Average composition from $\langle X_{max} \rangle$ and $\sigma(X_{max})$

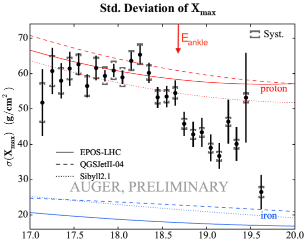
X_{max}: maximum of the shower development

Sensitive to the mass of primary particle, measured directly with the FD

- FD standard analysis ($E > 10^{17.8}$ eV)
- Extension to low energies ($E > 10^{17} eV$) : HEAT + 1 FD (Coihueco site)
- Selection of high quality hybrid events

A. Porcelli for the Pierre Auger Coll., ICRC 2015





Non constant average composition

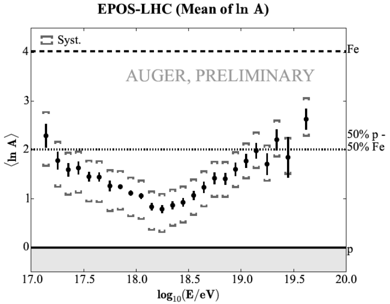
- Increase of the elongation rate up to $\sim$ 2 EeV: mean primary mass getting lighter
- decrease of the elongation rate above $\sim$ 2 EeV: composition becoming heavier

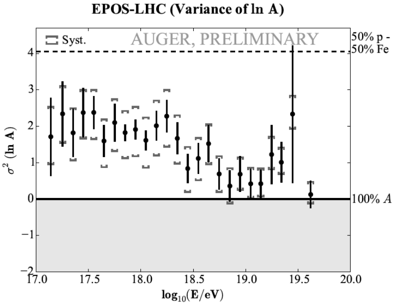
Interpretation of results: conversion to $\langle lnA \rangle$

From $\langle X_{max} \rangle$ to $< lnA >$

Conversion based on simulations using current hadronic interaction models (EPOS-LHC, QGSJetII-04)

The Pierre Auger Collaboration, Phys.Rev. D90 12 (2014) 122005





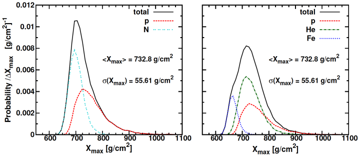
For both models: similar trends with E for mean & variance of *lnA*

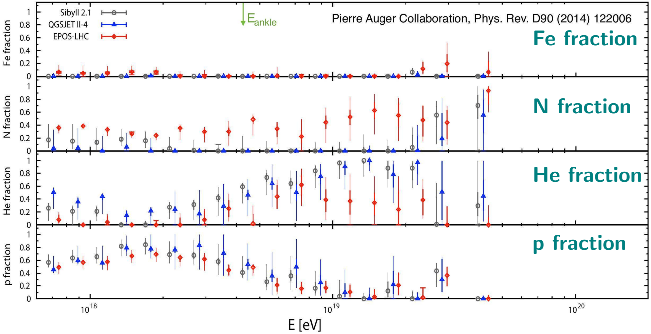
- Low energy: from intermediate to light, several components
- High energy: from light to heavy, (one or) few components

QGSJet-II.04 disfavored (unphysical results at high energy)

Study of X_{max} distributions

- Different primary mixtures can lead to same $\langle X_{max} \rangle$ and $\sigma(X_{max})$
- Study of the X_{max} distributions: fit them assuming different numbers of species (and mixing), using several interaction models





The results suggest a mixed composition.

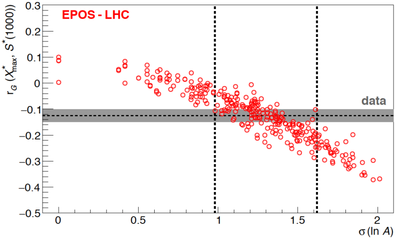
Alternative mass composition study : FD vs SD

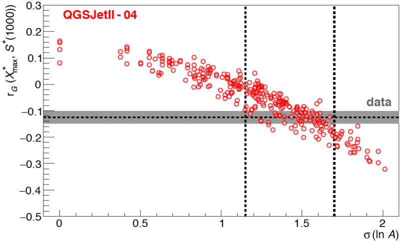
Correlation of shower observables from FD (X_{max}) and SD ($S(1000)$)

A. Yushkov for the Pierre Auger Coll., ICRC 2015

- direct and robust estimation of the spread of masses in the primary beam
  - For single nuclear components: correlation $\gtrsim 0$
  - For mixed compositions: correlation < 0

Hybrid data: $\log_{10}(E/eV) = 18.5 - 19.0$





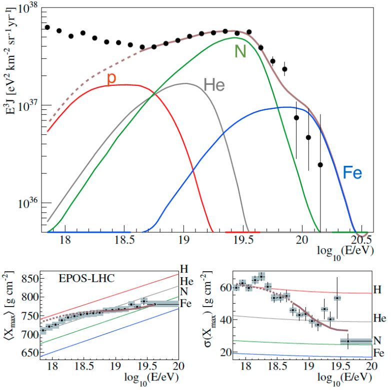
- significant negative correlation
- consistent with a spread of masses $\sigma(lnA) \gtrsim 1$
  $\rightarrow$ mixed mass composition in the ankle region

Astrophysical Interpretation: combining X_{max} and spectrum

Simple astrophysical scenario

- homogeneous distribution of identical sources of p, He, N and Fe nuclei
- Power-law spectrum with rigidity-dependent broken exponential cutoff

A. di Matteo for the Pierre Auger Coll., ICRC 2015



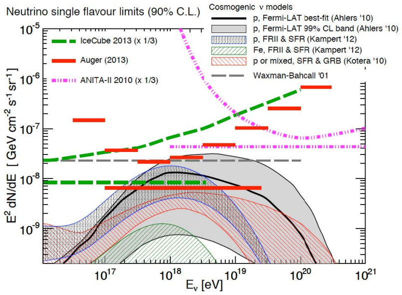
More info: Armando di Matteo's talk, this afternoon @ CR session

- best fit favouring
  - Hard injection ($\gamma \lesssim 1$).
  - Low cutoff ($R_{cut} \lesssim 10^{18.7}$ V)
  - suppression : maximum source energy
- 2nd local minimum
  - $\gamma \simeq 2$ injection much less sensitive on propagation details
  - suppression : GZK
  - disfavoured by $\sigma(X_{max})$ distribution

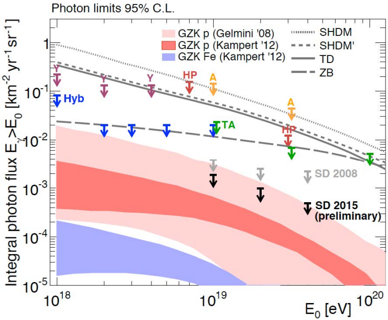
Needs enhanced composition sensitivity !

Stringent limits on neutrinos and photon flux

The Pierre Auger Coll., Phys. Rev. D 91, 092008 (2015)



C. Bleve for the Pierre Auger Coll. ICRC2015



- $dN/dE = kE^{-2} \rightarrow$
  $k = 6.4x10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}
  [0.1 – 25] EeV

- 4 photon candidates above 10 EeV
- Strictest limits for $E > 1$EeV

- Top-down model strongly disfavored
- Auger limits constrain models with pure proton primaries

Anisotropies at small/intermediate scale

Structure in the distribution of arrival directions → help to understand UHECRs nature and origin

The Pierre Auger Coll., ApJ 804, 15 (2015);

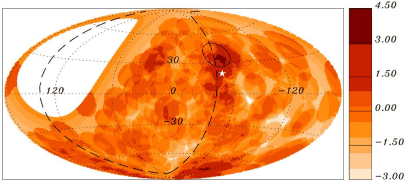
J. Aublin for the Pierre Auger Coll., ICRC 2015

Arrival direction of most energetic CRs

602 events with $E > 40\text{EeV}$ and $\theta < 80^\circ$

"Intrinsic" anisotropy tests

- autocorrelation (looking for pairs of events)
- blind search for localized excesses of events



Most significant excess 4.3 σ for $E_{th} = 54$ EeV and angular radius $\Psi = 12^\circ$

Search for correlations with sources from several catalogs

- Galactic Center, CenA region, Galactic and Super-Galactic planes, 2MRS galaxies, Swift-BAT AGNs, radio galaxies with jets

Data compatible with isotropic expectations

Large Scale Anisotropies

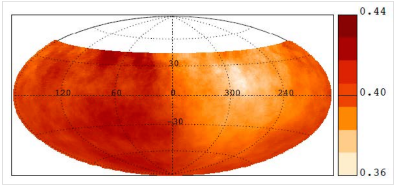
Could sign galactic - extragalactic transition

- Search for dipolar and quadrupolar patterns
- Analyses rely on a harmonic expansion of the cosmic rays flux distribution

Auger

$\sim$ 70k events with $E > 4$ EeV and $\theta < 80°$.
2 energy bins: $4 - 8$ EeV , > 8 EeV.

Largest departure from isotropy $E > 8$ EeV



sky map of the CR flux

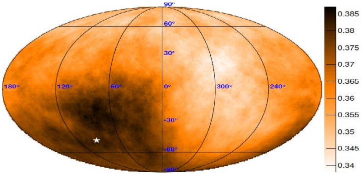
I. Al Samarai for the Pierre Auger Coll., ICRC 2015

Dipole of amplitude $7.3 \pm 1.5\% (p = 6.4 \times 10^{-5})$, pointing to $(\alpha, \delta) = (95° \pm 13°\ , -39° \pm 13°)$.

Auger + TA

Measurements of spherical harmonic coefficients $E > 10^{19}$ eV with full-sky coverage

Interesting hint for a dipole



Dipole of amplitude $6.5 \pm 1.9\% (p = 5 \times 10^{-3})$, pointing to $(\alpha, \delta) = (93° \pm 24°\ , -46° \pm 18°)$.

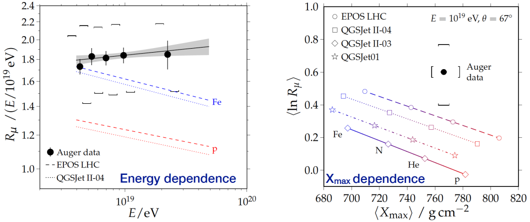
O. Deligny for Pierre Auger Observatory and Telescope Array: Joint Contributions, ICRC 2015

Muons to test hadronic interaction models

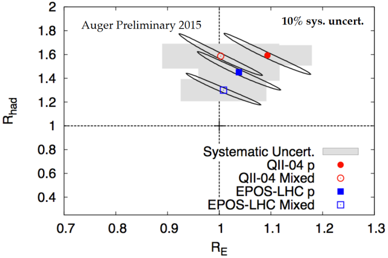
Muon content of the showers

- Observable very sensitive to hadronic interaction models.

The Pierre Auger Coll., Phys. Rev. D 91, 032003 (2015)



L.Collica for the Pierre Auger Coll., ICRC 2015



Measurement of the muon shower size

- in inclined events (EM component is largely absorbed before ground)
- in hybrid events (comparison ground signal to longitudinal profile)

$\Rightarrow$ Muon deficit in simulations

(from 30% to 80% at 10^{19} eV depending on models)

More on hadronic interactions & CR physics: Ralph Engel's talk on Friday morning

Summary and perspectives

Spectrum All-particle spectrum: unquestionable existence of a flux suppression above 40 EeV; its nature still not fully understood.

Composition Trend towards a heavier composition at the highest energies, and a mixed composition around the ankle

Spectrum and X_{max} data together seem to favor the scenario where the suppression is a source effect.

neutrinos, photons top-down models disfavored, limits disfavor pure proton composition models

Anisotropy At small scale, high degree of isotropy, challenging the original expectation of few sources and light primaries

Hadronic Serious hints for deficiencies in UHE interaction models (muon number).

Open science case at the highest energy

- need composition data in suppression region
- selecting light primaries pointing back to astrophysical sources
- better understanding of hadronic interaction models

Auger upgrade program: Auger Prime

Aim :Improve the knowledge on mass composition

the key: discriminating electromagnetic and muonic components from SD based observables, on an event by event basis.

How: having a further and independent measurement

New detectors

- Equip each SD tank with a 4 m^2 (1 cm thick) scintillator layer on top
- Scintillators sensitive to the electromagnetic content of the shower

Moreover

- Upgraded and faster electronics
- Extension of the dynamic range
- Cross check with AMIGA detectors
- Extension of the FD duty cycle

Timeline and exposure

- Fall 2016: engineering array
- End 2017-2018: deployment
- 2018-2024: data taking

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Don't miss Giovanni Marsella's talk this afternoon !

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THANK YOU FOR YOUR ATTENTION
Photographed by Radomir Smida

Backup slides

The Pierre Auger collaboration

16 countries, $\sim$ 90 institutions, $\sim$ 500 authors

The SD and FD detectors

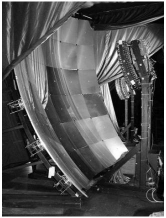
Water Cherenkov detector

Detection of charged particles and γ

- 1 tank: 12 tonnes of pure water
- 3PMTs, signals digitized in 25 ns bin
- time stamp: GPS receiver
- trigger and signal sent to the CDAS (communication antenna)
- autonomous power supply (solar panels and batteries)

Telescope

Detection of fluorescence light from excited N_2



- field of view : 30° in azimuth, 1.5 to 30° in elevation
- spherical mirror of 11 m^2
- corrector rings (lenses)
- camera with 440 hexagonals PMTs
- signal sampled at 100 MHz

Key performance parameters for the Auger Observatory

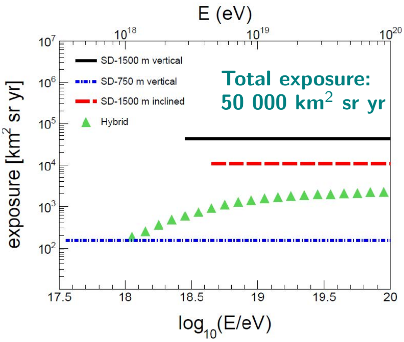
Pierre Auger Collaboration, NIM A 798 (2015) 172-213

SD	
SD Annual Exposure	$\sim$5500 km^2 sr yr
T3 rate	0.1 Hz
T5 events/yr, $E > 3$ EeV	$\sim$14, 500
T5 events/yr, $E > 10$ EeV	$\sim$1500
Reconstruction accuracy (S_{1000})	22 % (low E) to 12 % (high E)
Angular resolution	1.6° (3 stations)
	0.9° (>5 stations)
Energy resolution	16 % (low E) to 12 % (high E)
FD	
On-time	$\sim$15 %
Rate per building	0.012 Hz
Rate per HEAT	0.026 Hz
Hybrid	
Core resolution	50 m
Angular resolution	0.6°
Energy resolution (FD)	8 %
X_{max} resolution	$<$20 g/cm^2

Energy calibration - Exposure

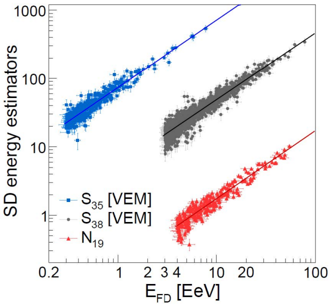
Four data sets

- SD−1500 m $\theta < 60°$: 102901 events
- SD−1500 m $\theta > 60°$: 15614 events
- SD−750 m: 61130 events
- Hybrid: 9346 events



Calibration

- SD absolute calibration using a subset of hybrid events → SD-energy estimation weakly reliant upon shower simulations.
- Calibration function $E_{FD} = A(\hat{S})^B$

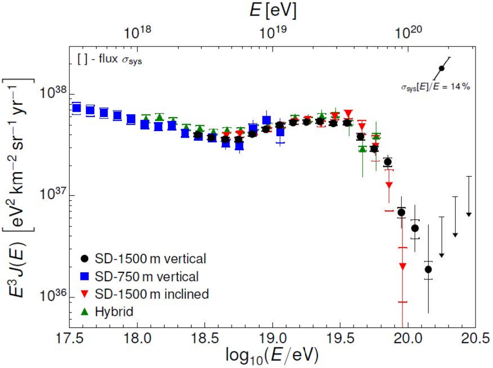


Four measurements of the CR flux

Flux systematic uncertainties

- SD$-$1500 m $\theta < 60^\circ$: 5.8%
- SD$-$1500 m $\theta > 60^\circ$: 5%
- SD$-$750 m: 14%($<$ 7%) at 0.3(3) EeV
- Hybrid: 10%(6%) at 1(10) EeV

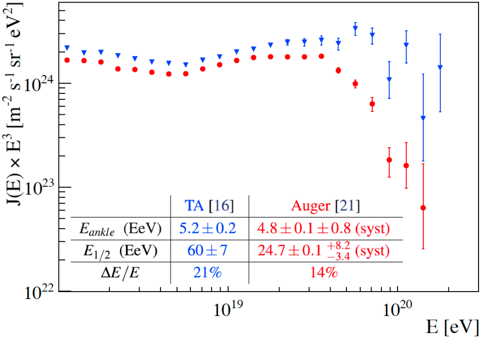
I. Valiño for the Pierre Auger Coll., ICRC 2015



- Energy systematic uncertainties
  FD energy scale: 14%
- Spectra corrected for finite energy resolution, responsible for event-to-event bin migration ($<$ 15% SD, $<$ 3% Hybrid)

Auger / TA spectra

Auger-TA spectra

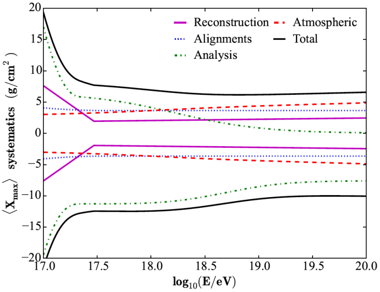


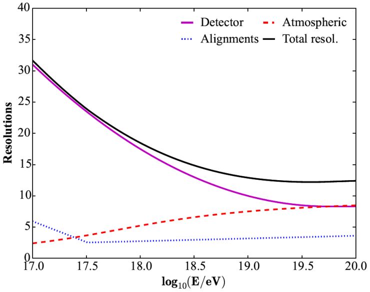
V. Verzi, Rapporteur Talk, ICRC2015

- 2 measurements in good agreement at energies below 210^{19}eV with a difference in the flux of $\sim$ 20%
- Significant discrepancy in the suppression region: position and steepness

Auger/TA are observing the sky from different hemispheres: does this matter?

Measurement of X_{max}: systematics and resolution





Reconstruction and residual acceptance biases estimated through simulations and corrected for.
The observed width of the distribution is corrected by subtracting the detector resolution in quadrature to obtain $\sigma(X_{max})$.

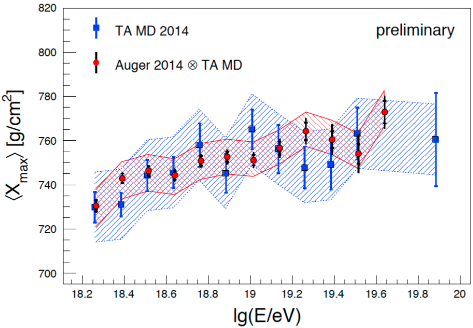
The systematic uncertainty in the X_{max} scale
at low energies : dominated by uncertainties of the analysis procedure
at high energies: atmospheric uncertainties give a significant contribution.

Comparison of $\langle X_{max} \rangle$ by Auger & TA

Common effort of the Auger and TA collaborations: compare X_{max} results

- Simulation and reconstruction in TA of events with a mass composition compatible with the Auger X_{max} distributions
- Reconstructed $\langle X_{max} \rangle$ compared to the measured ones.

M. Unger for Pierre Auger Observatory and Telescope Array: Joint Contributions, ICRC 2015

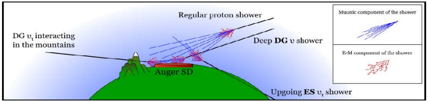


⇒ good agreement within the systematic uncertainties.

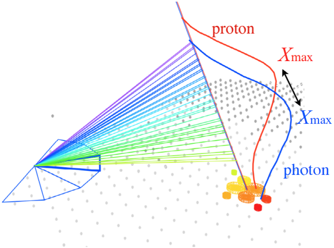
Search for UHE photons and neutrinos

- evidence of their existence → new window on the most extreme Universe
- produced by the decay of charged and neutral pions respectively, → independent proof of the GZK-effect
- result of their search constraining astrophysical scenarios for the origin and the propagation of UHECR and exotic models

Searches based on particular shower developments



- ν shower observable only if almost horizontal
- Signature: an inclined shower with large electromagnetic component



- Photon showers develop deeper in the atmosphere→ FD: deeper X_{max}
- Mostly EM showers (less muons) → SD: steeper LDF and longer

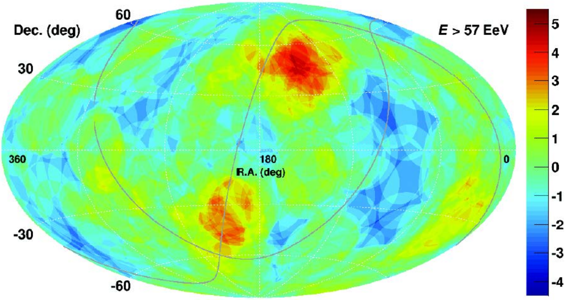
Sky survey with Auger and TA

Auger

- 10 years, 157 events (> 57 EeV)
- Southern Hemisphere: hot spot seen by Auger (post-trial prob 1.4%) near to Cen A

TA

- 7 years, 109 Events (> 57 EeV)
- Northern Hemisphere: hot spot seen by TA (3.4σ) near the Ursa Major cluster

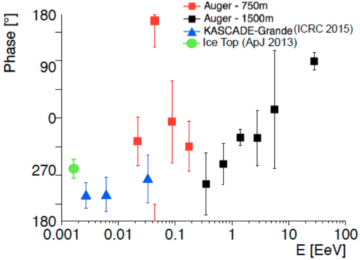


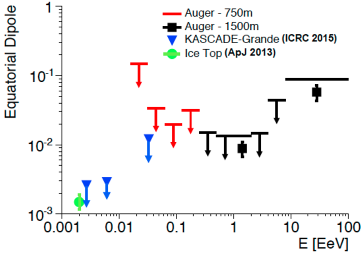
Auger and TA @ ICRC 2015

Large Scale Anisotropies

- Could sign galactic - extragalactic transition
- search for dipolar and quadrupolar
- Analyses rely on a harmonic expansion of the cosmic rays flux distribution, different analyses (Rayleigh analysis, East-West method)

Results on the phase measurements and upper limits on equatorial amplitudes from 10 PeV to the highest energies

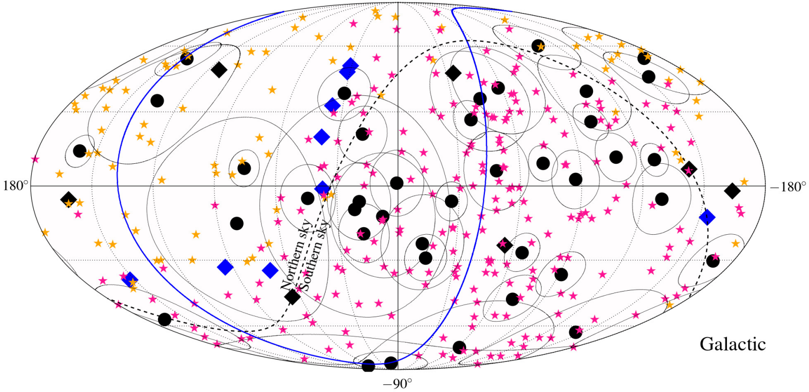




Amplitudes reported in the two energy bins where the corresponding p-value expected from isotropy is below 10^{-3}

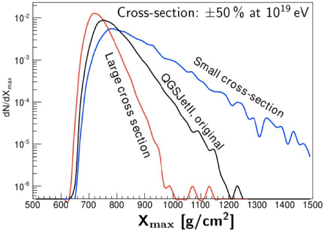
Correlation with UHE neutrinos

Joint analysis of 3 Collaborations!



- All correlations less than 3.3 sigma significance
- To be monitored with larger data set (in particular the analysis with cascades)

p-air cross sections



Tail of X_{max} distribution sensitive to p-air cross section

Energy range

$10^{17.8} - 10^{18.0} - 10^{18.5}$ eV

- Most compatible with high proton fraction
- Helium fraction smallest