Current status and future of Ultra High Energy Cosmic Rays experiments

Working groups of Pierre Auger and Telescope Array collaborations

Ioana C. Mariș

Université Libre de Bruxelles

UCL, London
02 November 2018

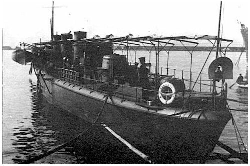
Some history

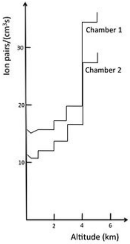
1896-1898 Becquerel, Marie y Pierre Curie

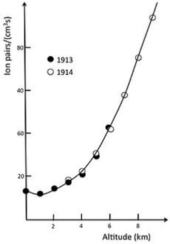
1909-1910 Theodor Wulf measurements on the Eiffel Tower

1907-1911 Domenico Pacini measurements in the sea

1912-1914 Baloon experiments: Gockel (4000 m), Hess (5200 m) y Kolhoester (9200 m) → radiation comes from above







Particles with enourmous energy exist!

1930 Pierre Auger, Bruno Rossi discover air-showers

Pierre Auger

Bruno Rossi

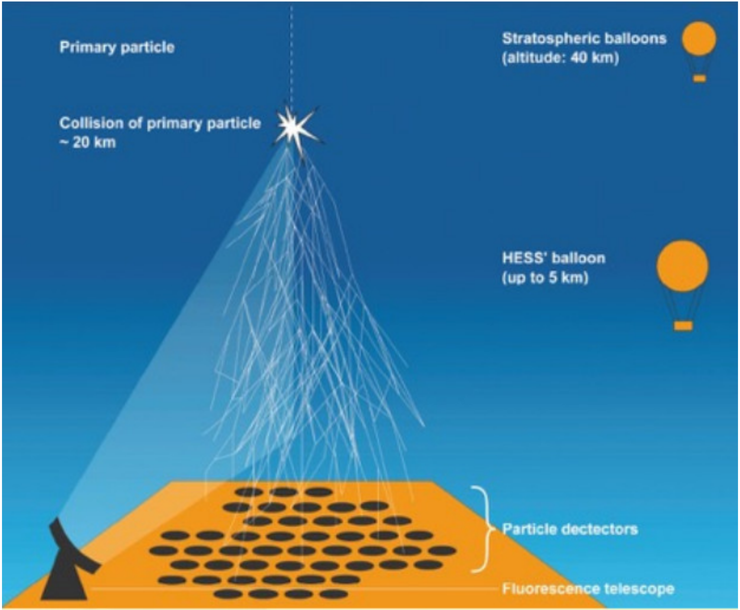
1963 John Linsley at Volcano Ranch: 10^{20} eV

1965 CMB discovered

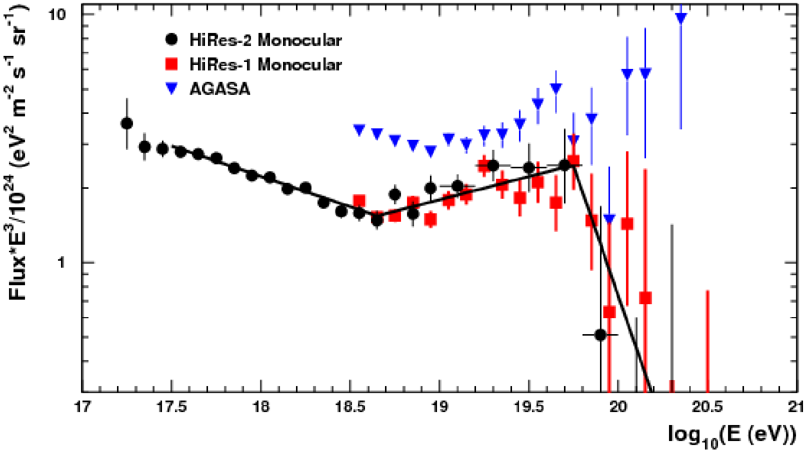
1966 Particles lose energy on the way to Earth

1991 Fly's Eye detector: 3.2×10^{20} eV

How do we measure the air-showers?



15 years ago: Flux suppression or new physics?



1966: Greisen Zatsepin Kuzmin propagation effect

Ultra High Energy Cosmic Rays

Highest energy particles ever measured E $> 10^{20}$ eV

Which are the sources?

How are accelerated?

New fundamental physics?

Build LHC with the Mercury orbit

- Complement multimessenger observations in the nearby Universe
- Charged and deflected in magnetic fields $\Rightarrow$ not trivial to find the sources
- Measurements required: energy, arrival direction and composition

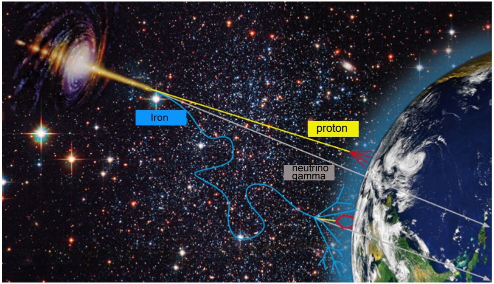
Ultra High Energy Cosmic Rays

Highest energy particles ever measured $E > 10^{20}$ eV

Which are the sources?

How are accelerated?

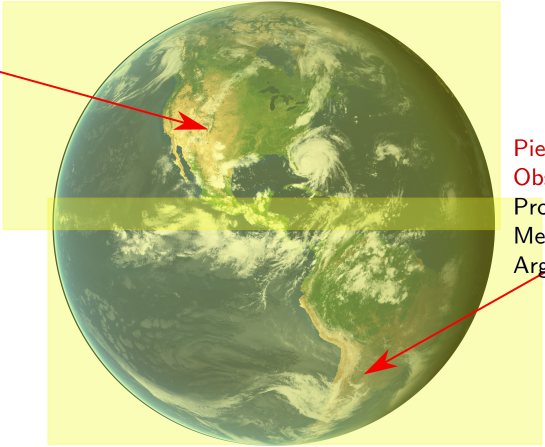
New fundamental physics?



- Complement multimessenger observations in the nearby Universe
- Charged and deflected in magnetic fields $\Rightarrow$ not trivial to find the sources
- Measurements required: energy, arrival direction and composition

World leading experiments

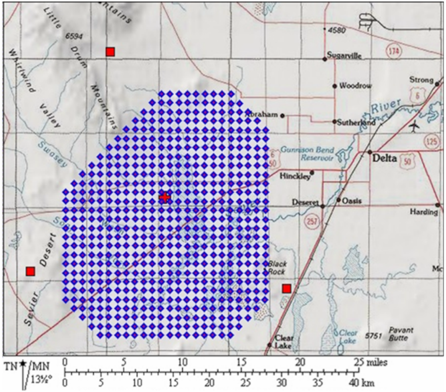
Telescope Array
Delta, Utah,
USA



Pierre Auger Observatory
Province of Mendoza,
Argentina

Comparing and combining the data from the two largest observatories.

Telescope Array



680 km^2(507 scintillators), 36 telescopes

Fluorescence telescopes

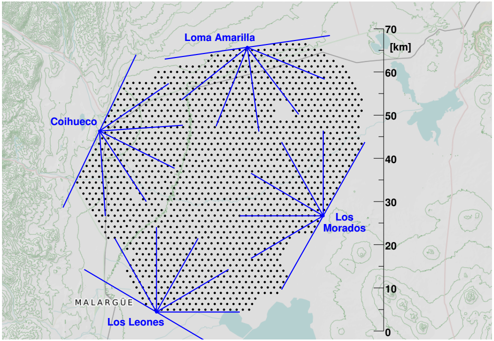
Surface detectors

Pierre Auger collaboration

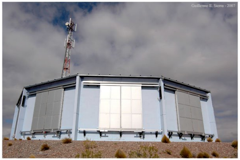
500 scientists from 17 countries and 82 institutions

Argentina, Australia, Belgium, Brazil, Czechia, France, Germany, Italy, Mexico, the Netherlands, Poland, Portugal, Romania, Slovenia, Spain, the United Kingdom and the United States of America

Pierre Auger Observatory



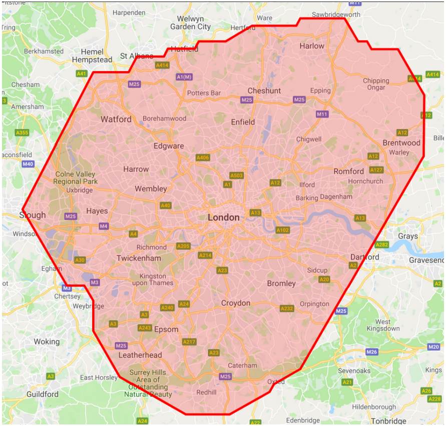
Fluorescence Telescopes



Surface detectors

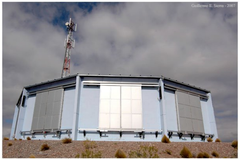
3000 km^2 (1660 water Cherenkov detectors), 27 telescopes

Pierre Auger Observatory



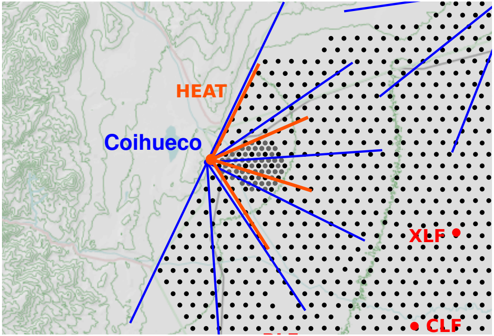
3000 km^2 (1660 water Cherenkov detectors), 27 telescopes

Fluorescence Telescopes



Surface detectors

Pierre Auger Observatory

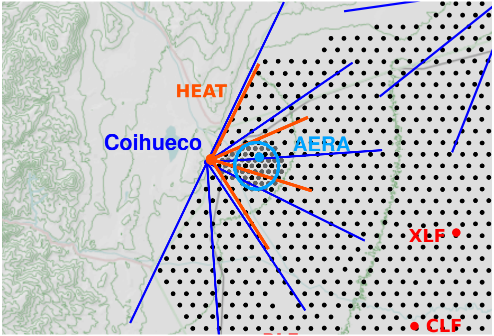


Fluorescence Telescopes

Surface detectors

27 km^2 (750 m spacing), 3 HEAT telescopes

Pierre Auger Observatory



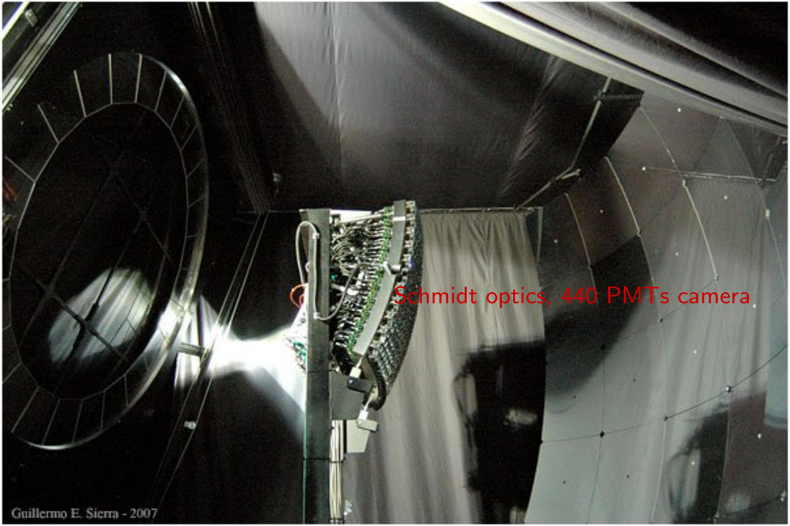
Fluorescence Telescopes

Surface detectors

Water Cherenkov detectors

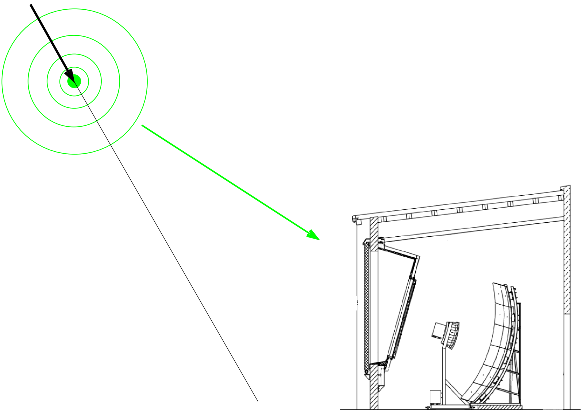
- 1660 independent units
- 3 m diameter, 1.2 m height, 12T
- equipped with solar panels, GPS and radio antennas
- 3 PMTs (8 inch)
- 10 bits FADCs, 40MHz
- calibrated each minute with muons

Measurement of the $\mu^{\pm}$, $e^{\pm}$, γ reaching the ground



Measurement of the Fluorescence and Cherenkov light

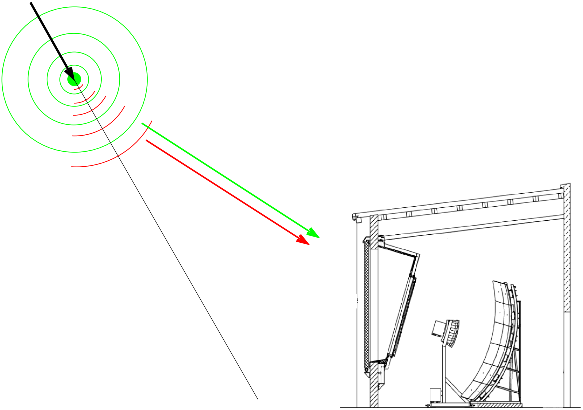
Light Production in UHECR air showers



- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light

- Fluorescence yield $\propto$ dE/dX
- Cherenkov yield $\propto$ $\mathrm{N_e}$, but energy deposit universal: $\mathrm{dE/dX} = \alpha_{\mathrm{eff}}(s) \cdot \mathrm{N_e}$

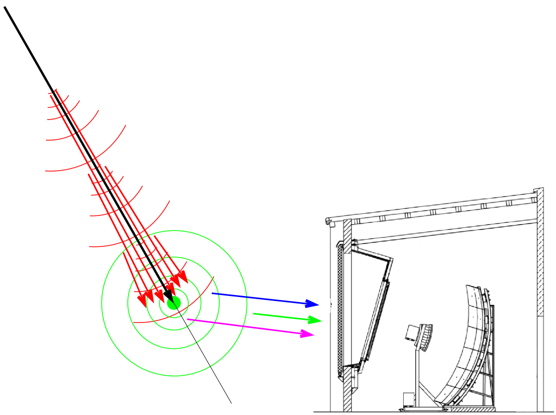
Light Production in UHECR air showers



- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light

- Fluorescence yield $\propto$ dE/dX
- Cherenkov yield $\propto N_e$, but energy deposit universal: $dE/dX = \alpha_{\mathrm{eff}}(s) \cdot N_e$

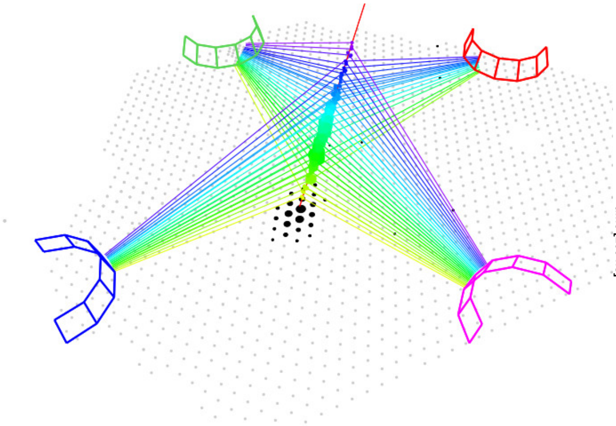
Light Production in UHECR air showers

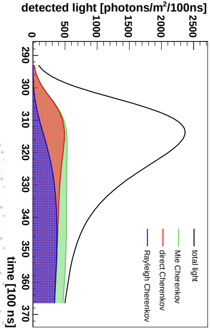


- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light

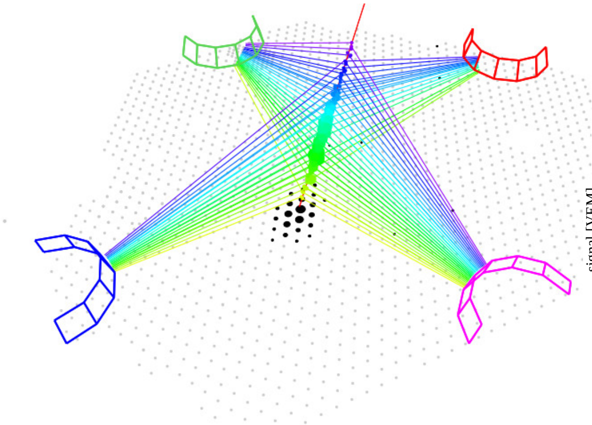
- Fluorescence yield $\propto$ dE/dX
- Cherenkov yield $\propto N_e$, but energy deposit universal: $dE/dX = \alpha_{\mathrm{eff}}(s) \cdot N_e$

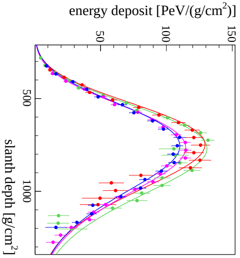
Hybrid detector and energy estimation

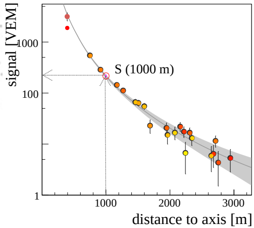




Hybrid detector and energy estimation



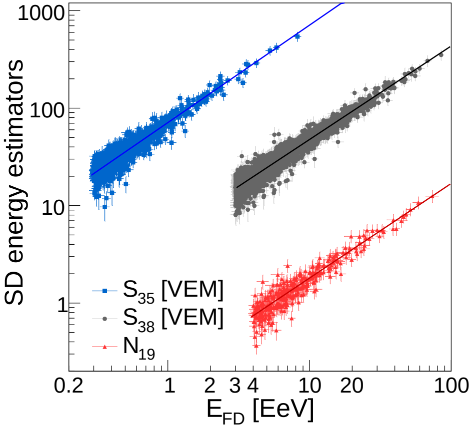


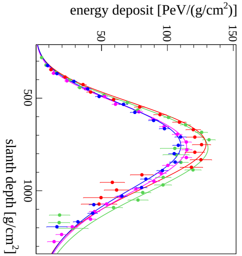


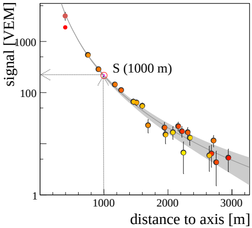
$E_{FD} = \int dE/dX +$ invisible energy correction, $\sigma_E \approx 8\%$, $\sigma_{sys} \approx 15\%$

$E_{SD} = f(\theta, S1000)$, $\sigma_E \approx 10\%@10EeV$

Hybrid detector and energy estimation







$E_{FD} = \int dE/dX +$ invisible energy correction, $\sigma_E \approx 8\%$, $\sigma_{sys} \approx 15\%$

$E_{SD} = f(\theta, S1000)$, $\sigma_E \approx 10\%@10EeV$

Energy spectrum

Arrival directions

Mass composition

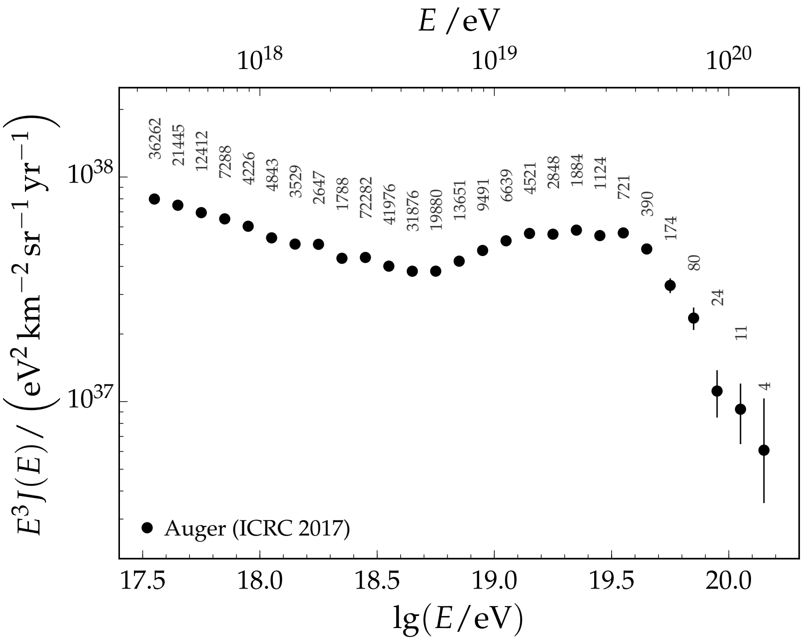
Photon/neutrino limits

Muon number

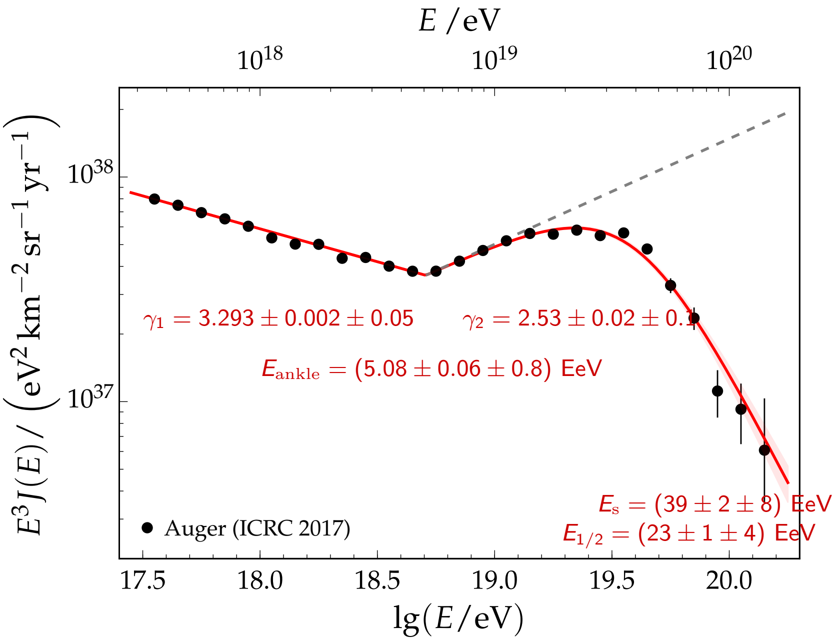
Upgrades and future

Not included: p-p cross-section, monopoles limits, radio, elves, ...

Combined energy spectrum

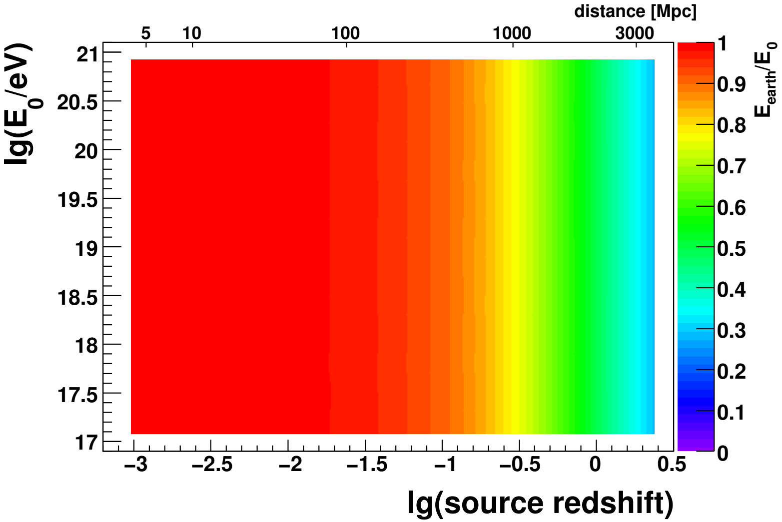


Combined energy spectrum



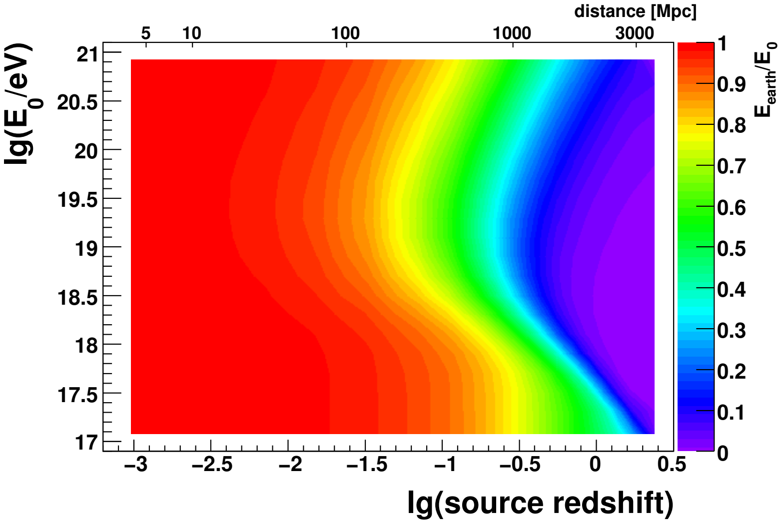
Simple propagation effect?

redshift



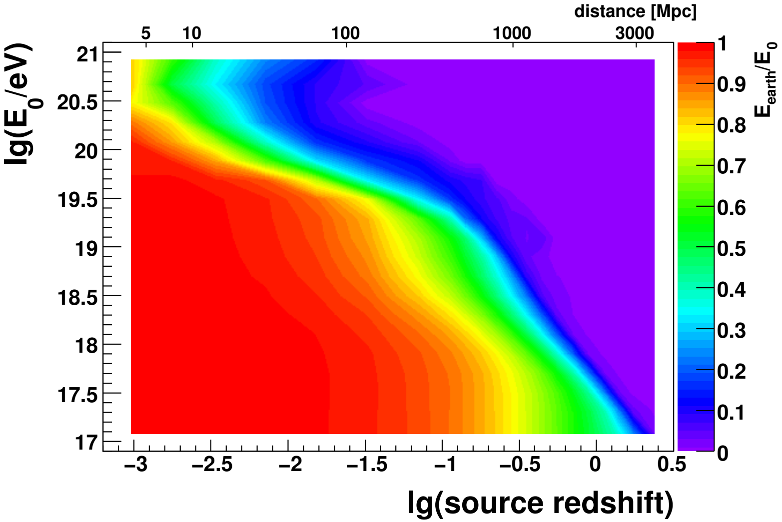
Simple propagation effect?

redshift $+ (p + \gamma_{\mathrm{CMB}} \rightarrow p + e^{+} + e^{-})$

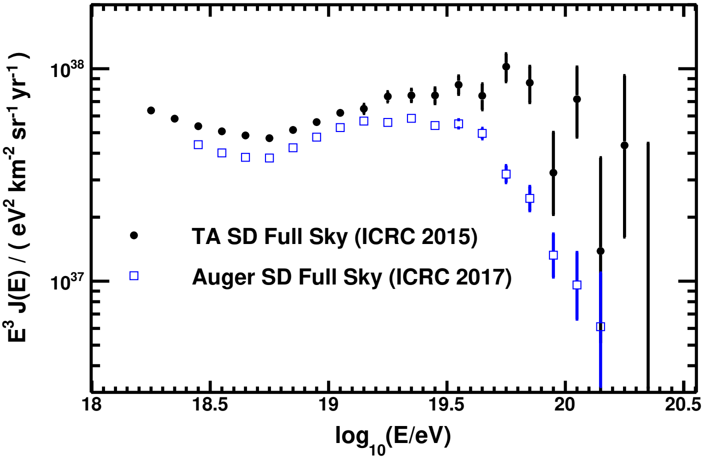


Simple propagation effect?

redshift $+ (p + \gamma_{\mathrm{CMB}} \to p + e^{+} + e^{-}) + (p + \gamma_{\mathrm{CMB}} \to p + \pi^{0})$

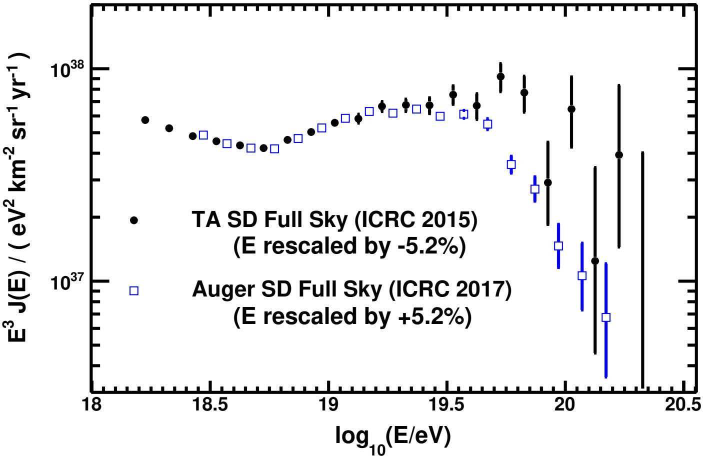


Comparison with Telescope Array



TA-Auger energy spectrum working group

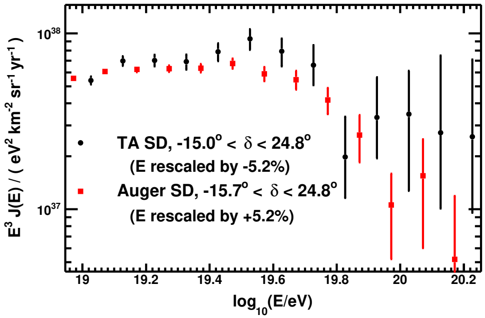
Comparison with Telescope Array

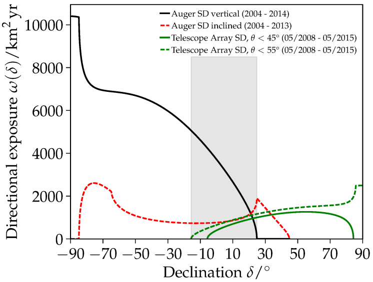


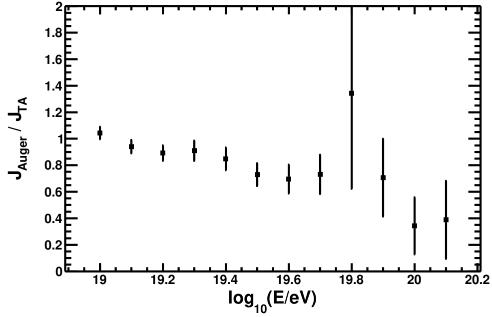
TA-Auger energy spectrum working group

⇒ difference above 40 EeV (caused by different sky coverages?)

Looking at the same part of the sky

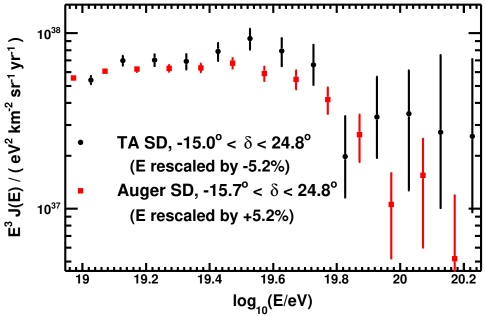


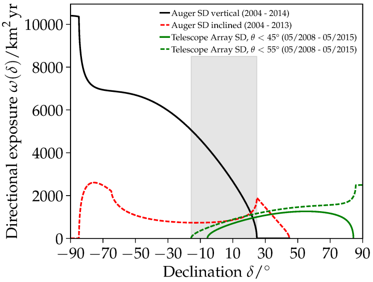


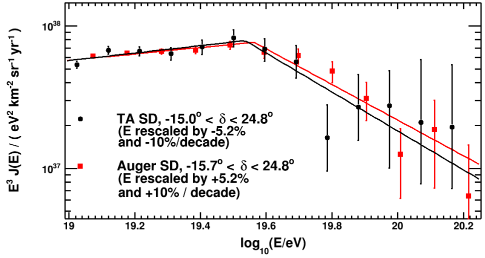


- slightly better agreement, but an energy dependent difference still present
- 10% per decade energy systematic uncertainty still not understood

Looking at the same part of the sky







- slightly better agreement, but an energy dependent difference still present
- 10% per decade energy systematic uncertainty still not understood

Anisotropy- correlation with catalogues

Active Galactic Nuclei

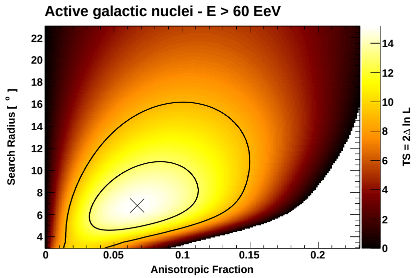
- 2FHL Catalogue (Fermi-LAT, 360 sources): $\Phi(> 50 GeV)$
- 17 objects within 250 Mpc
- blazars (BL-Lac) and radio-galaxies (FR-1 type)

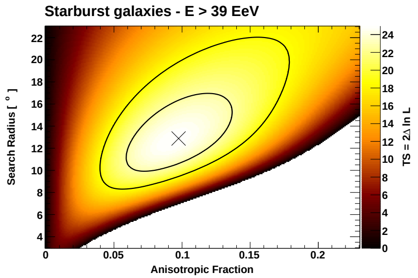
Starburst or star-forming galaxies

- Fermi-LAT search list (Ackerman+ 2012)
- 63 objects within 250 Mpc (4 detected in gamma rays)
- $\Phi(> 1.4 GHz) > 0.3 Jy$
- 23 objects

Statistical test

- smearing angle ψ
- H_0: isotropy
- H_1: $(1 - f)\times$ isotropy $+f\times$ fluxMap(ψ)

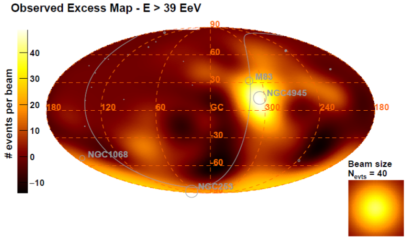


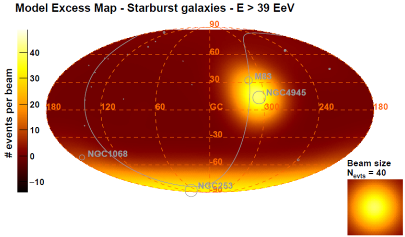


$$\mathrm{TS} = 2\log(H_1/H_0)$$

Anisotropy- correlation with catalogues

Starburst



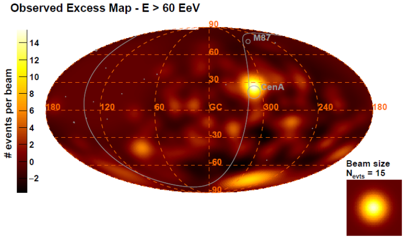


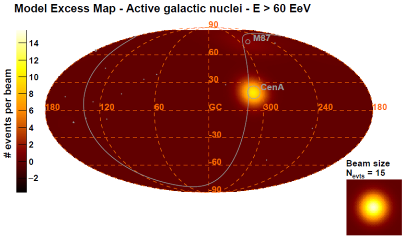
$f = 10\%$, $\psi = 13°$

post-trial** p-value: 4×10^{-5}

post-trial** significance: $3.9\,\sigma$

AGN





$f = 7\%$, $\psi = 7°$

post-trial** p-value: 3×10^{-3}

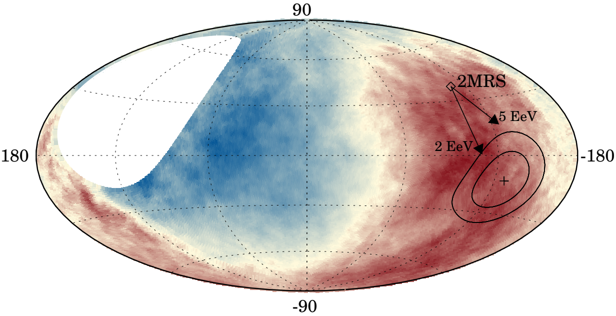
post-trial** significance: $2.7\,\sigma$

** penalization for energy scan only. $N_{\rm cat} = 3$, previous searches and hidden trials not accounted for.

Large-scale anisotropy

Harmonic analysis in right ascension α

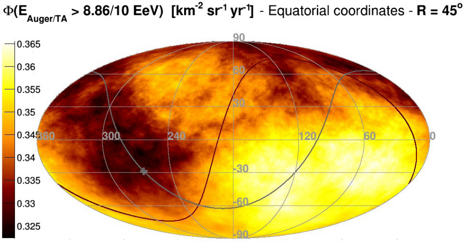
Significant dipolar modulation (5.2σ) above 8×10^{18} eV:
$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100^\circ, -24^\circ)$



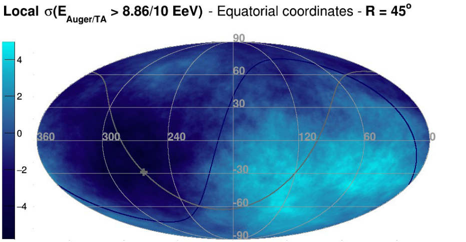
physicsworld TOP 10 BREAKTHROUGH 2017

- Expected if cosmic rays diffuse in Galaxy from sources distributed similar to near-by galaxies
- Strong indication for extragalactic origin

Full sky coverage with Auger and TA above 10 EeV

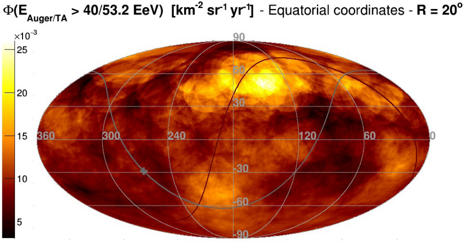


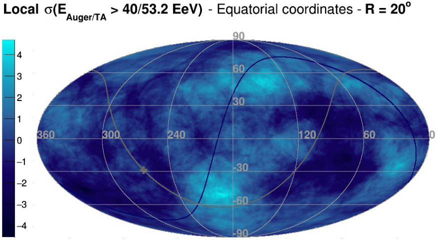
No "windowing" effect, access to anisotropies at all angular scales, without relying on an assumption on the presence / absence of patterns at higher orders



Dipolar pattern similar in shape/amplitude to that observed above $E_{Auger} > 8$ EeV

Full sky coverage with Auger and TA above 40 EeV



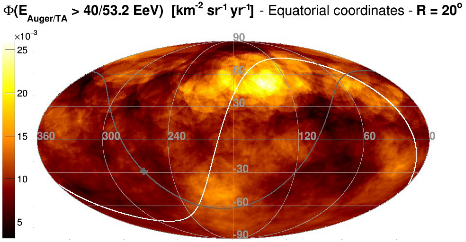


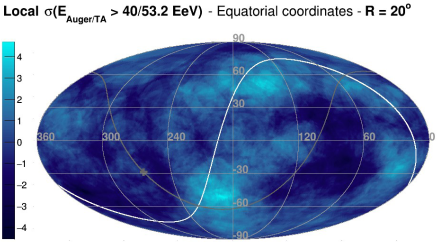
Two warm spots along super-Galactic plane

Largest σ spot: 4.7σ (20°)
2nd largest spot: 4.2σ (15°)

1st / 2nd spots: post-trial 2.2/1.3σ
Flux 1st / 2nd spots $\approx$ 1.5-2

Full sky coverage with Auger and TA above 40 EeV





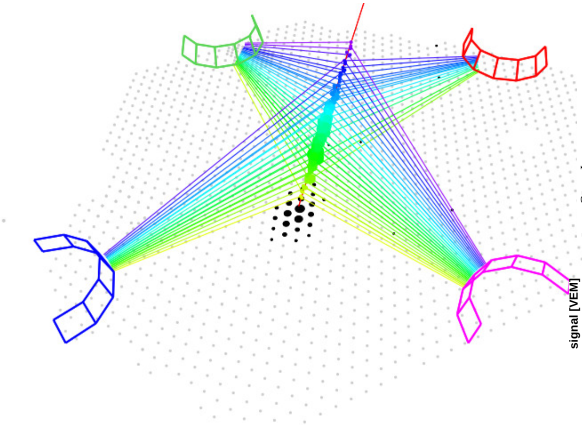
Two warm spots along super-Galactic plane

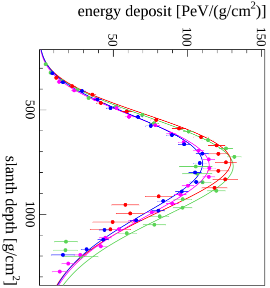
Largest σ spot: 4.7σ (20°)
2nd largest spot: 4.2σ (15°)

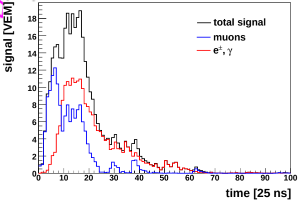
1st / 2nd spots: post-trial $2.2/1.3\sigma$
Flux 1st / 2nd spots $\approx$ 1.5-2

Supergalactic ring of fire?

Sensitivity to mass composition with FD and SD



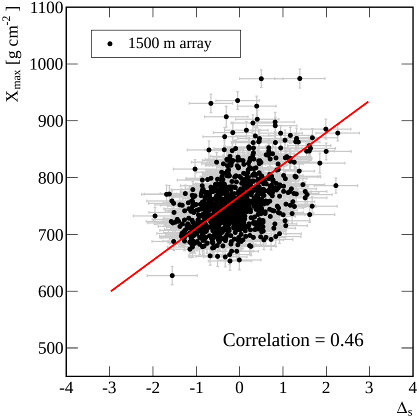


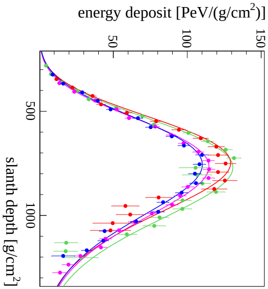


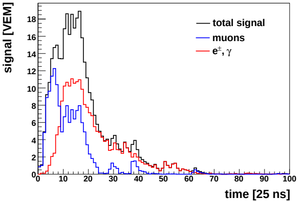
X_{max}: depth of the maximum of the air-shower development

Δ_S: evolution of the signal with time, related to the risetime

Sensitivity to mass composition with FD and SD



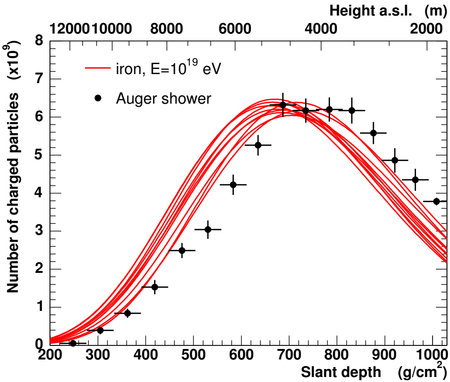




X_{max}: depth of the maximum of the air-shower development

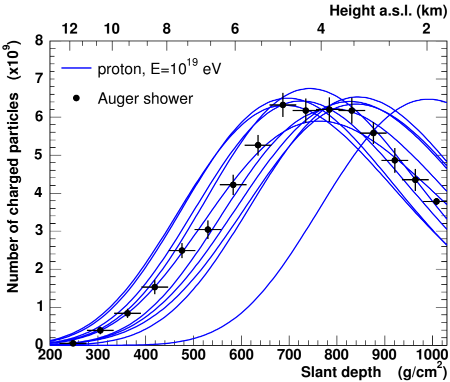
Δ_S: evolution of the signal with time, related to the risetime

Mass composition with FD



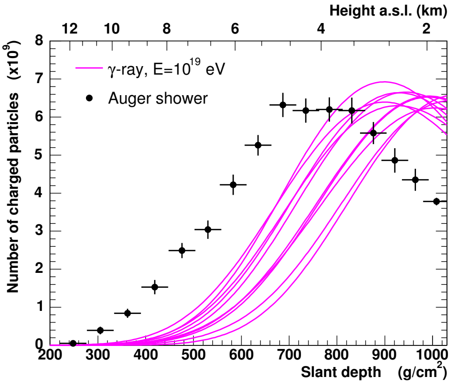
- heavier particles develop higher in the atmosphere, with less fluctuations
- $X_{\max}$ and $\sigma(X_{\max})$ the most sensitive parameters to chemical composition

Mass composition with FD



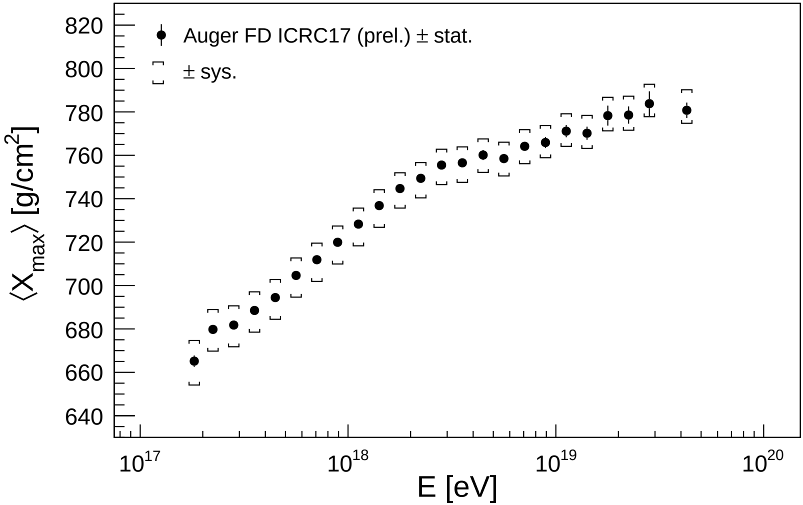
- heavier particles develop higher in the atmosphere, with less fluctuations
- $X_{\max}$ and $\sigma(X_{\max})$ the most sensitive parameters to chemical composition

Mass composition with FD

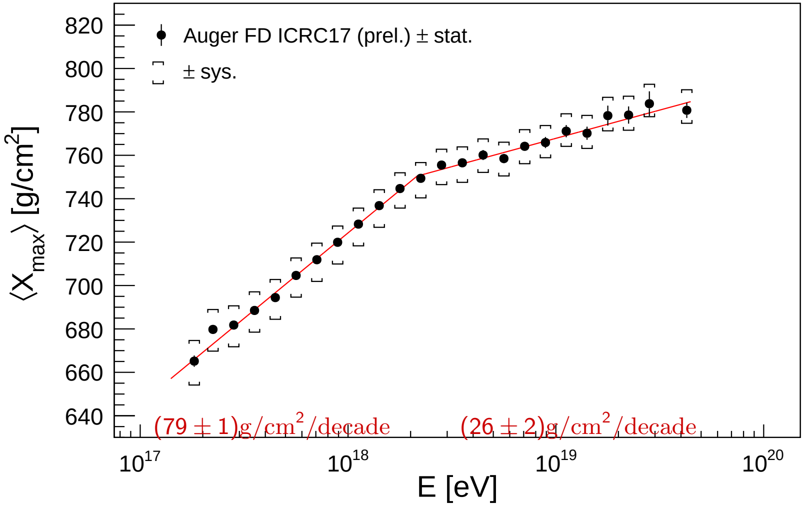


- heavier particles develop higher in the atmosphere, with less fluctuations
- $X_{\max}$ and $\sigma(X_{\max})$ the most sensitive parameters to chemical composition

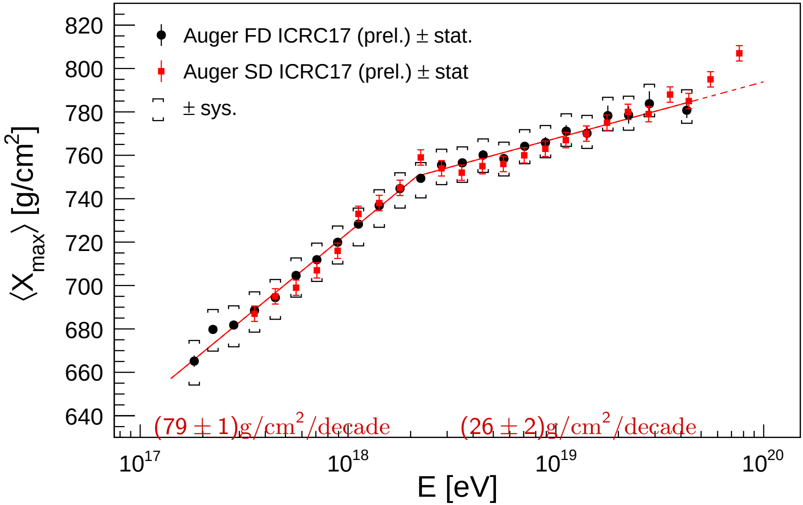
Average $X_{\max}$ with Fluorescence Detector



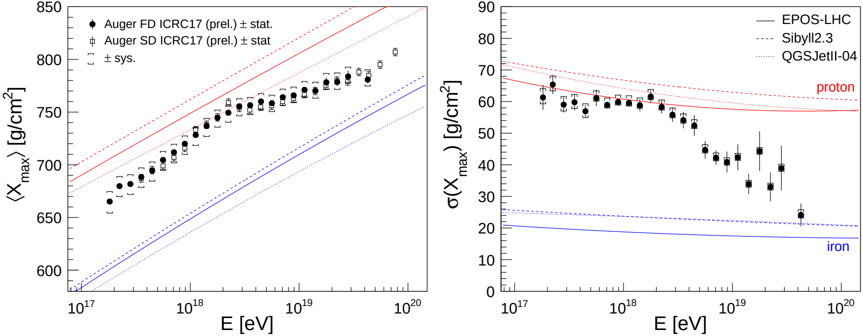
Average $X_{\max}$ with Fluorescence Detector



Average $X_{\max}$ with Fluorescence and Surface Detector



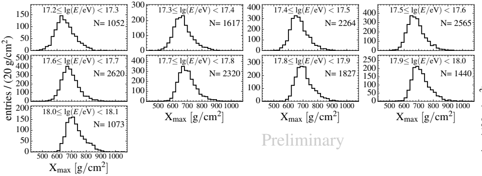
Average $X_{\max}$ and $X_{\max}$-fluctuations



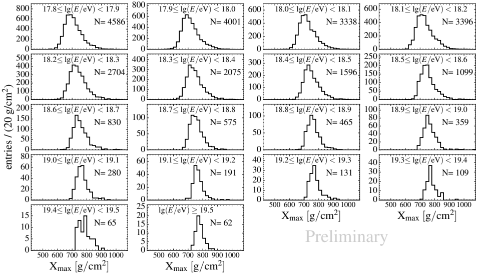
lines: simulations using post-LHC hadronic interaction models

Fits of the full distributions: p He N Fe

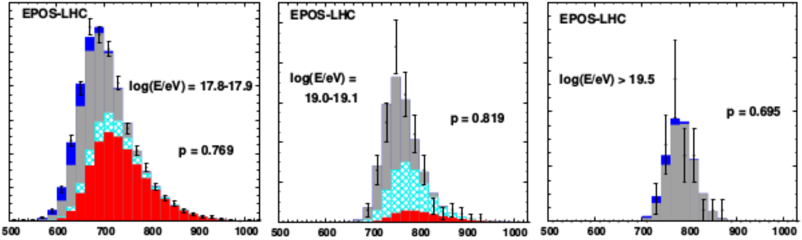
$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$



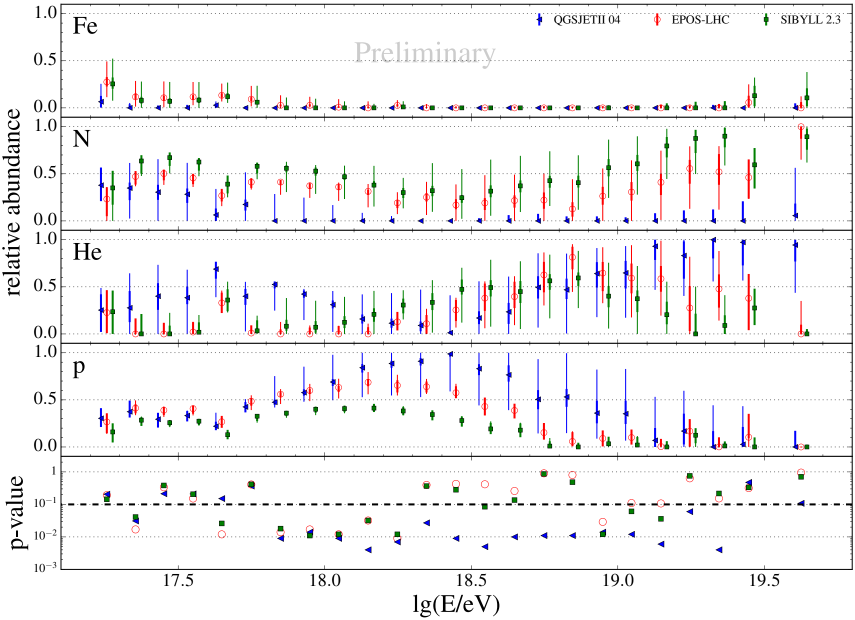
$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$



Examples of 4-component fit:

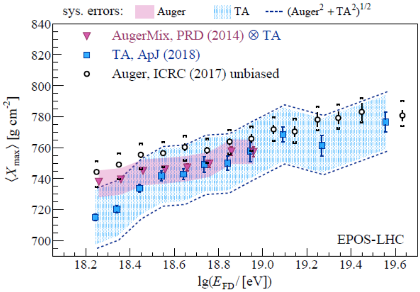


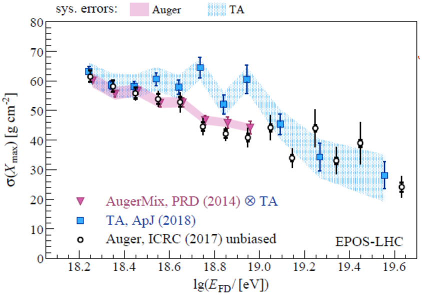
Composition fractions



Telescope Array- Auger comparison

Difference in reconstruction/selection of events





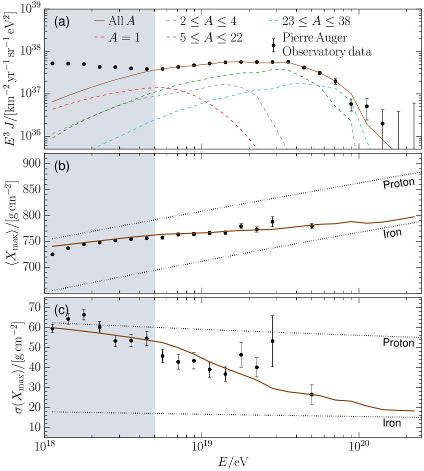
Pass Auger composition through TA detector simulations, reconstruction and analysis (Auger at TA): bias on $X_{\max}$ of -5 g cm^2, bias on σ of few g cm^2

Agreement within (stat+sys) uncertainties

Mass composition at sources

rigidity-dependent cutoff at source: $E_{\mathrm{max}} = R_{\mathrm{cut}}\, Z$, power law injection $E^{-\gamma}$

no EGMF



Source properties	4D with EGMF	4D no EGMF	1D no EGMF
γ	1.61	0.61	0.87
$\log_{10}(R_{\mathrm{cut}}/\mathrm{eV})$	18.88	18.48	18.62
f_{H}	3 %	11 %	0 %
f_{He}	2 %	14 %	0 %
f_{N}	74 %	68 %	88 %
f_{Si}	21 %	7 %	12 %
f_{Fe}	0 %	0 %	0 %

Suppression of the flux dominated by maximum injection energy

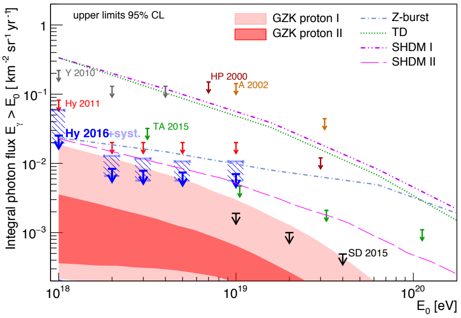
Very hard index of power law at injection

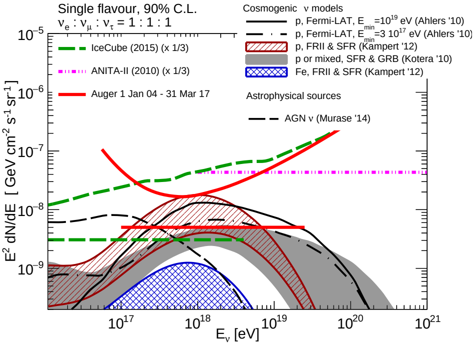
Mainly primaries of the CNO and Si group injected, no Fe, very little p (spallation)

Searches for cosmogenic photons and neutrinos

$$\mathrm{p} + \gamma_{\mathrm{CMB}} \rightarrow \mathrm{p} + \pi^0 \searrow \gamma\gamma$$

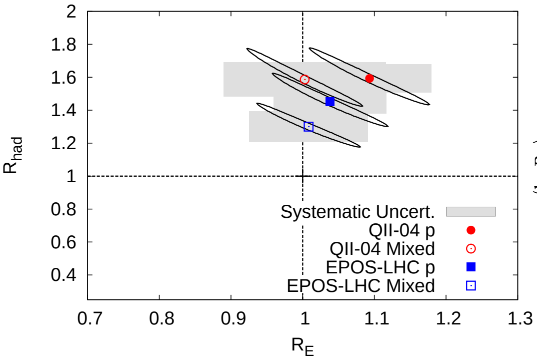
$$\mathrm{p} + \gamma_{\mathrm{CMB}} \rightarrow \mathrm{n} + \pi^+ \searrow \mathrm{e}^+ + 3\nu$$

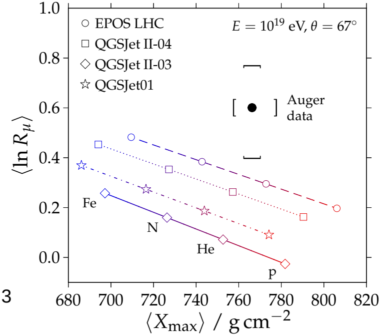




Difficulties to obtain the mass composition with SD only

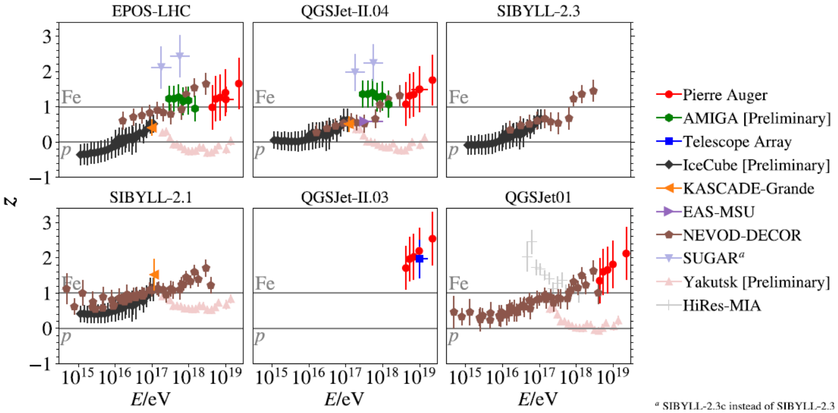
$R_{\rm had}$ and R_μ related to the muonic component
$R_{\rm E}$ and $X_{\rm max}$ related to the electromagnetic component





→ the number of produced muons is underestimated in simulations

Probing hadronic interactions with multiple experiments



$$z = \frac{\ln N_{\mu} - \ln N_{\mu,p}}{\ln N_{\mu,Fe} - \ln N_{\mu,p}}$$

Reasonable agreement in very diverse experiments

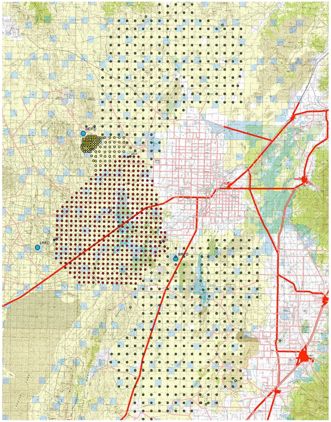
AugerPrime

Telescope Array x 4

Water Cherenkov detectors with $4m^2$ scintillators

Enhance the sensitivity of the surface detectors

Increase the surface detector by a factor 4!



Upgrade of the Surface Detector (AugerPrime)

Which is the origin of the flux suppression?

Which is the fraction of protons at the highest energies?

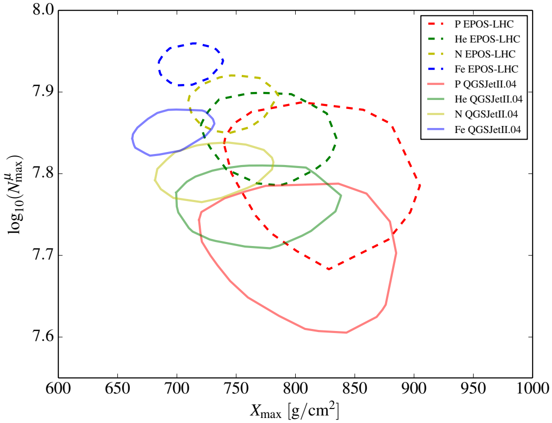
Can we do particle astronomy?

Hadronic interactions above 10^{19} eV?

$\rightarrow$ Enhance the capabilities of SD to mass composition

Universality of air-shower development

10 EeV, 38 degrees

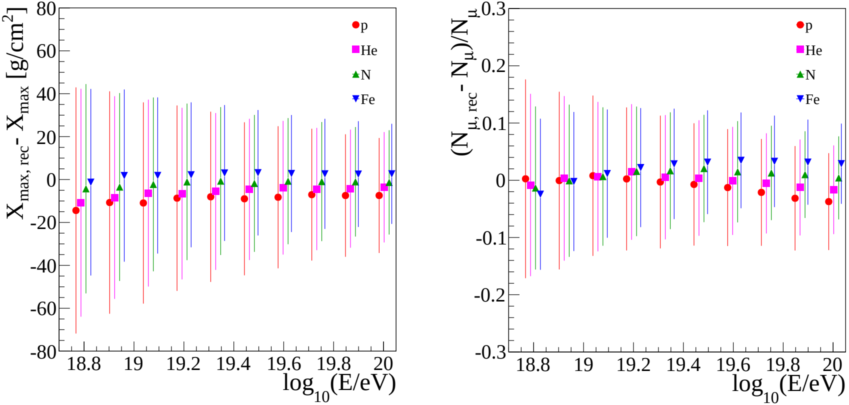


Obtain N_μ and $X_{\max}$

(i.e. separate the electromagnetic and the muonic components on the ground)

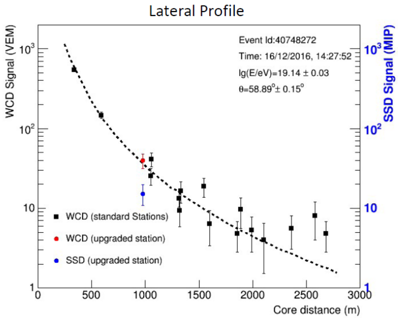
AugerPrime Engineering Array

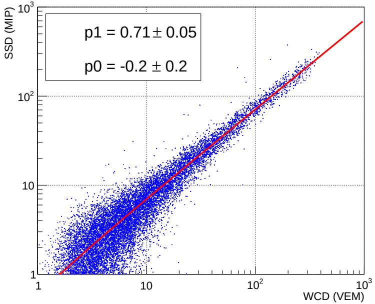
Expected performances

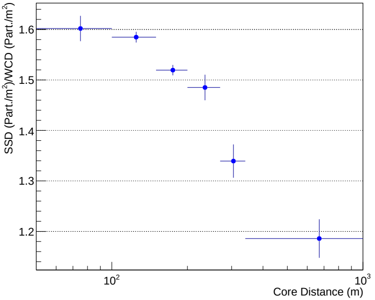


- Resolution obtained by using the Universality reconstruction: On ground, for a fixed energy, age, and geometry the lateral distribution functions (LDF) are universal

AugerPrime Engineering Array: First data







- design finalized and tested
- SSDs are currently installed
- deployment in the next 2 years
- data taking until 2025

Summary

High exposure study of the UHE flux: strong flux suppression

FD/SD composition: light composition at the ankle, mixed at UHE

Combined fit: flux compatible with rigidity dependent E_{max}

Hadronic interactions: UHE cross-section, muon deficit in models

Arrival directions: indication for intermediate scale anisotropy, observation of dipolar anisotropy, super-Galactic ring of fire?

Telescope Array- Auger working groups: collaboration between the two experiments brings new understandings of the UHECRs physics

Future of current experiments: upgrade of the Pierre Auger Observatory (AugerPrime), extension of Telescope Array

New ideas: JEM-EUSO, POEMA, GRAND, FAST,....