Recent results in Ultra High Energy Cosmic Rays with the Pierre Auger Observatory

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Université Libre de Bruxelles

PIERRE AUGER OBSERVATORY

BE.HEP
22nd of June 2020

Pierre Auger collaboration

500 scientists from 17 countries and 82 institutions

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

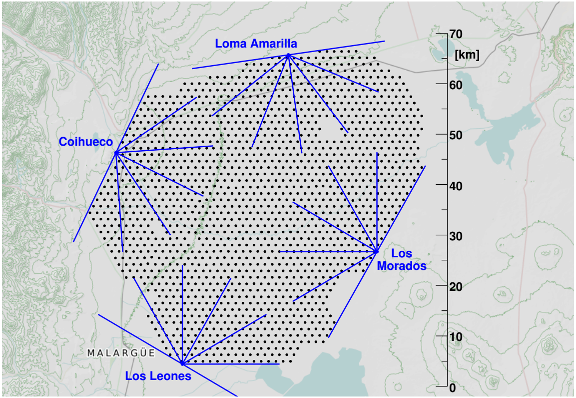
Pierre Auger Observatory

Ultra High Energy Cosmic Rays ($10^{15.5}$ eV to $> 10^{20}$ eV)

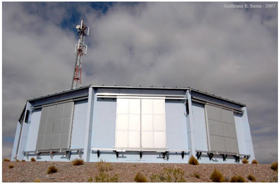
What are their sources? How are accelerated? Physics above LHC energy

Build LHC with the Mercury orbit (@ 10^{20} eV)

Pierre Auger Observatory



Fluorescence Telescopes

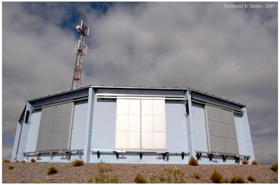


Surface detector array

3000 km^2 (1500 m spacing), 24 telescopes

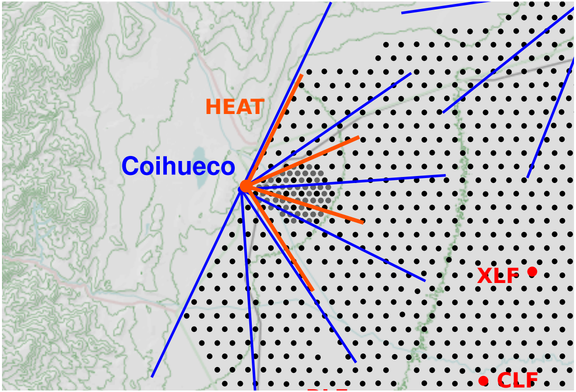
Pierre Auger Observatory

Fluorescence Telescopes



Surface detector array

Pierre Auger Observatory

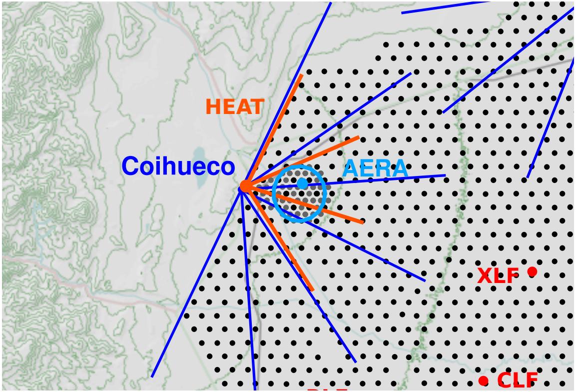


Fluorescence Telescopes

Surface detector array

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

Pierre Auger Observatory

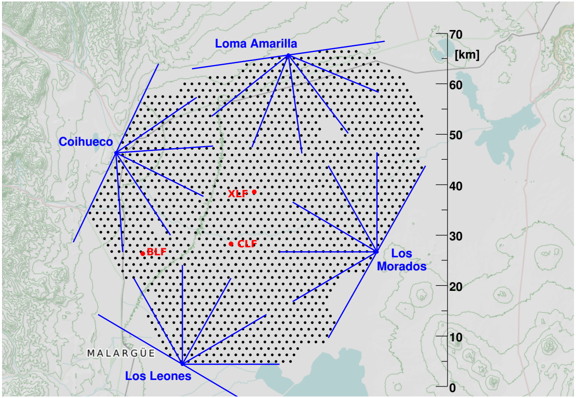


Fluorescence Telescopes

Surface detector array

AERA: radio detectors 17 km^2

Pierre Auger Observatory



Fluorescence Telescopes

Surface detector array

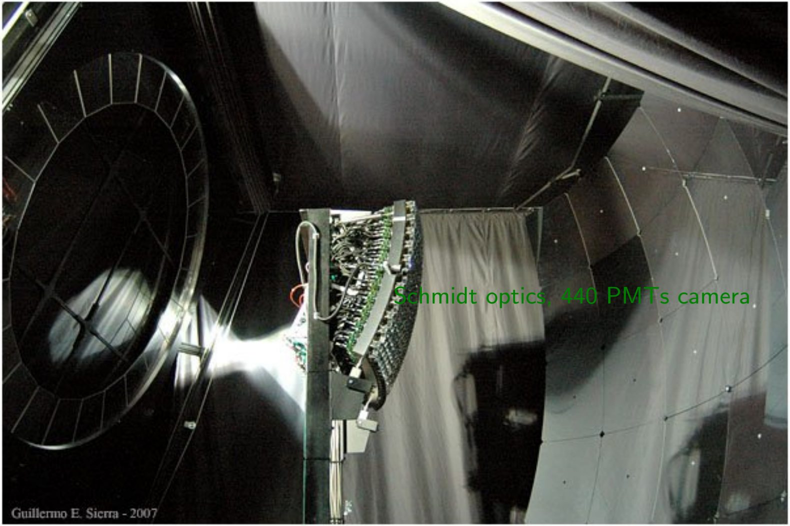
Constant monitoring of the atmosphere

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

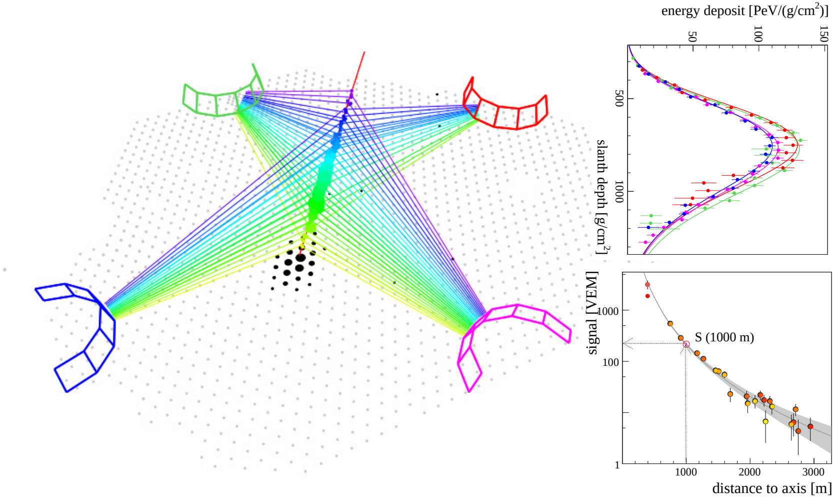
Measurement of the $\mu^{\pm}$, $e^{\pm}$, γ reaching the ground

Fluorescence detectors



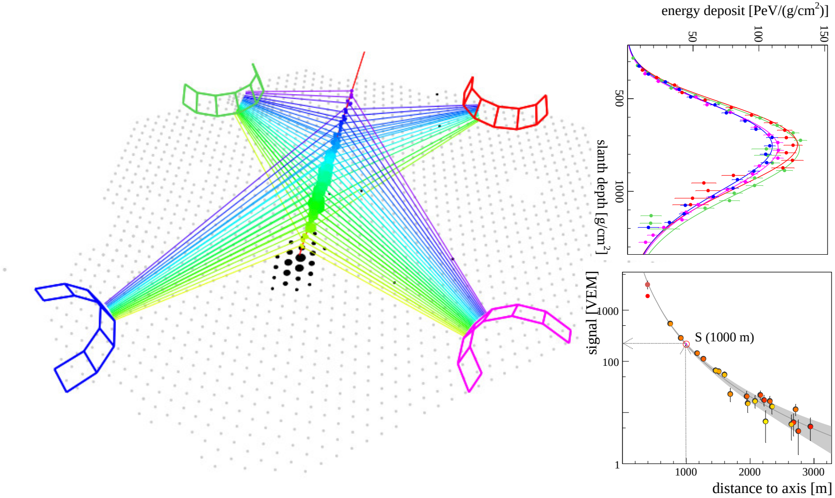
Measurement of the Fluorescence and Cherenkov light

Hybrid detector and energy estimation



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

Hybrid detector and energy estimation



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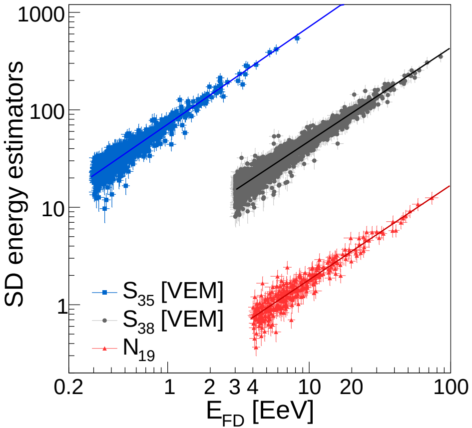
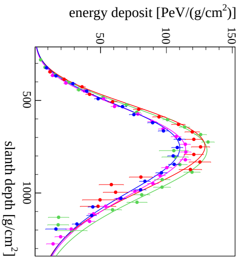
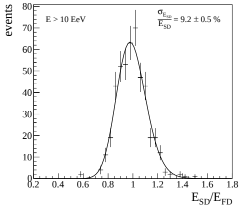
$E_{SD} = f(\theta, S1000)$, $\sigma_E \approx 10\%@10EeV$

Hybrid detector and energy estimation







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

Energy spectrum

Arrival directions

Mass composition

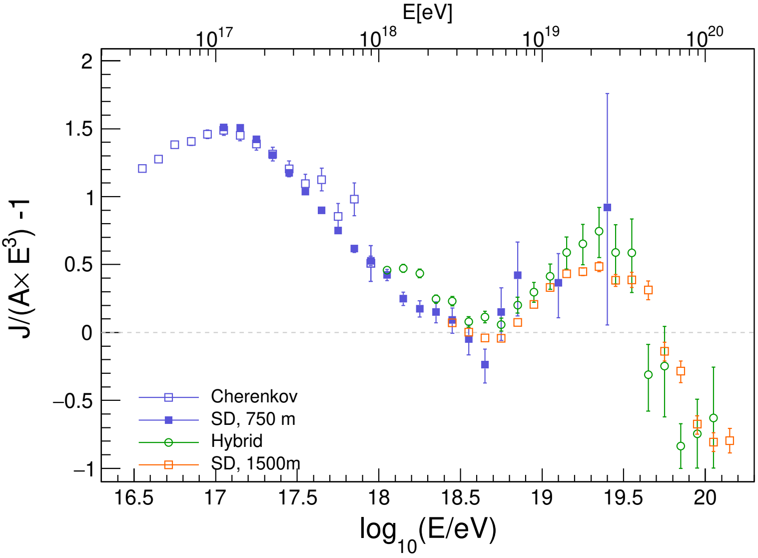
Muon number

Photon/neutrino limits

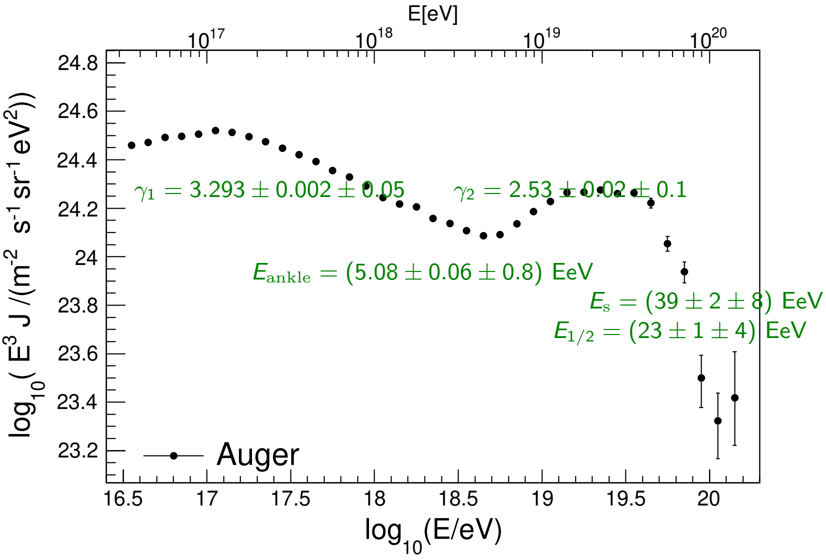
Auger Prime Upgrade

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

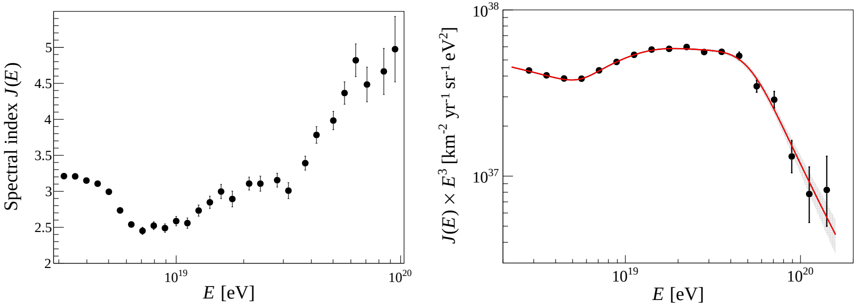
Energy spectrum



Energy spectrum



Energy spectrum at the highest energies



High statistics provides insights to extra structures: things are more complicated than simple power laws

2.51 ± 0.03 (stat) ± 0.05(sys) $\rightarrow$ 3.05 ± 0.05(stat) ± 0.10(sys) $\rightarrow$ 5.1 ± 0.3(stat) ± 0.1(sys)

submitted to PRL

Anisotropy- correlation with catalogues

Active Galactic Nuclei

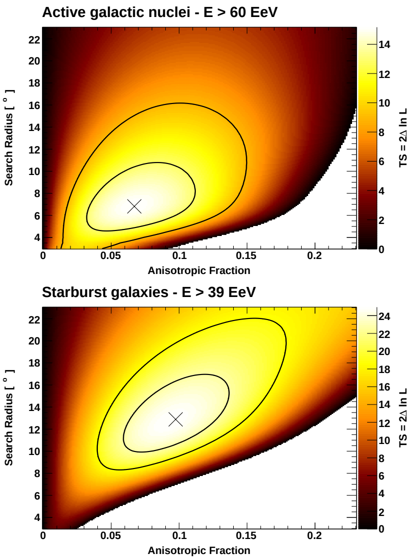
- 2FHL Catalogue (Fermi-LAT, 360 sources): $\Phi(> 50GeV)$
- 17 objects within 250 Mpc
- blazars (BL-Lac) and radio-galaxies (FR-1 type)

Starburst or star-forming galaxies

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

Statistical test

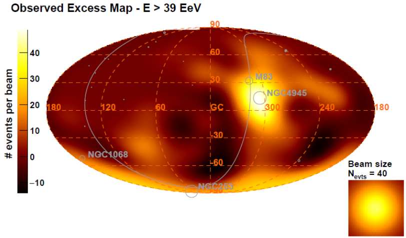
- smearing angle ψ
- H_0: isotropy
- H_1: $(1 - f)\times$ isotropy $+f\times$ fluxMap(ψ)

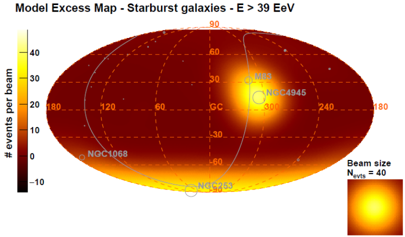


$$\mathrm{TS} = 2\log(H_1/H_0)$$

Anisotropy- correlation with catalogues

Starburst



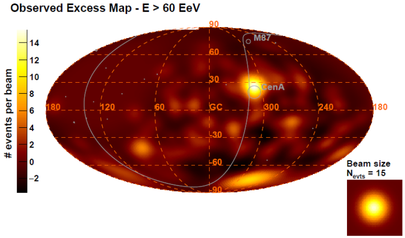


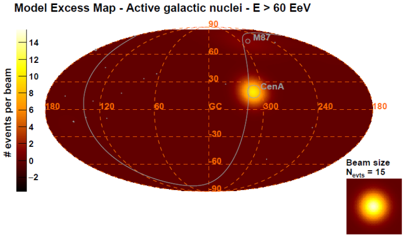
$f = 10\%,\ \psi = 13^\circ$

post-trial** p-value: 4×10^{-5}

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

AGN





$f = 7\%,\ \psi = 7^\circ$

post-trial** p-value: 3×10^{-3}

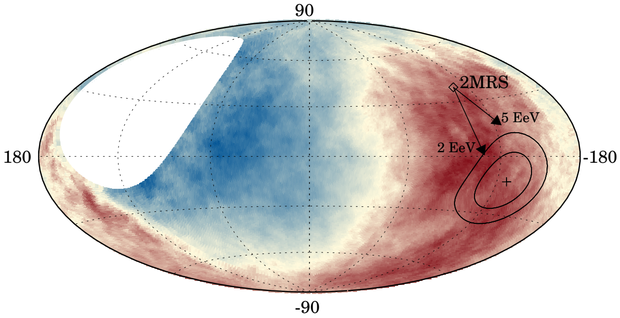
post-trial** significance: $2.7\,\sigma$

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

Large scale anisotropy

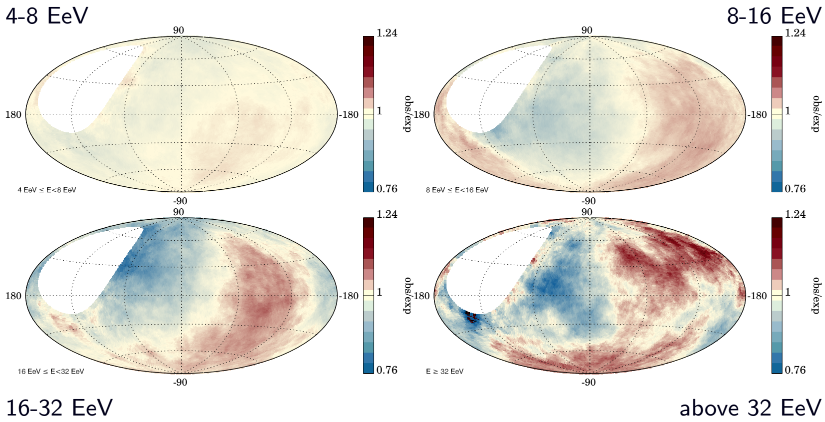
Harmonic analysis in right ascension α

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

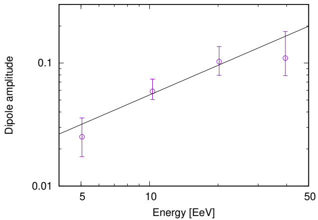


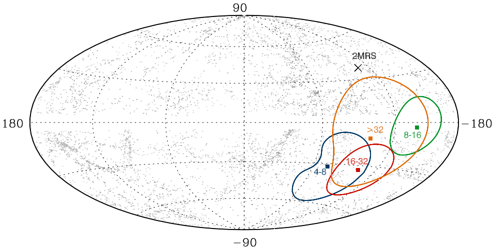
- Expected if cosmic rays diffuse in Galaxy from sources distributed similar to near-by galaxies
- Strong indication for extragalactic origin

Large scale anisotropy



Large scale anisotropy





Energy [EeV] interval	$d_\perp$	d_z	d	α_d [°]	δ_d [°]
4 - 8	$0.006^{+0.007}_{-0.003}$	-0.024 ± 0.009	$0.025^{+0.010}_{-0.007}$	80 ± 60	-75^{+17}_{-8}
≥ 8	$0.060^{+0.011}_{-0.010}$	-0.026 ± 0.015	$0.065^{+0.013}_{-0.009}$	100 ± 10	-24^{+12}_{-13}
8 - 16	$0.058^{+0.013}_{-0.011}$	-0.008 ± 0.017	$0.059^{+0.015}_{-0.008}$	104 ± 11	-8^{+16}_{-16}
16 - 32	$0.065^{+0.025}_{-0.018}$	-0.08 ± 0.03	$0.10^{+0.03}_{-0.02}$	82 ± 20	-50^{+15}_{-14}
≥ 32	$0.08^{+0.05}_{-0.03}$	-0.08 ± 0.07	$0.11^{+0.07}_{-0.03}$	115 ± 35	-46^{+28}_{-26}

Energy-independent dipole amplitude disfavored at the level of 3.7σ

$$d(E) = (0.055 \pm 0.008) \times (E/10\ \mathrm{EeV})^{0.79 \pm 0.19}$$

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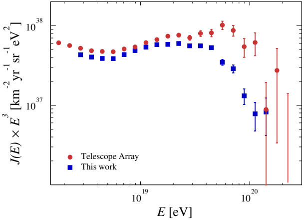
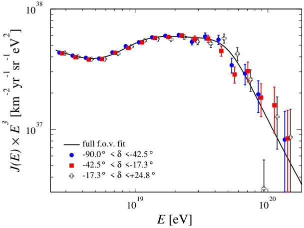
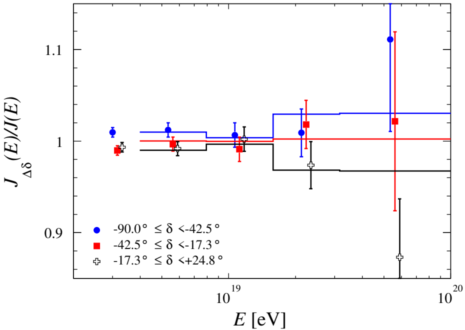
Energy spectrum and large scale anisotropy



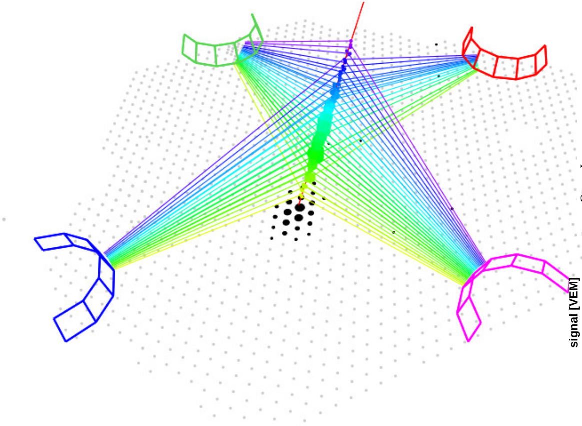


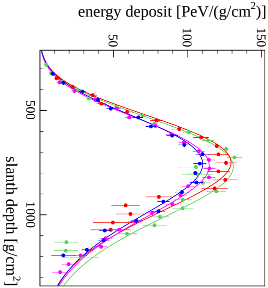


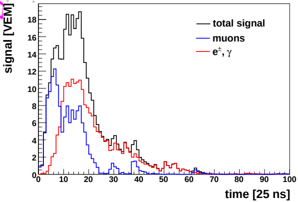
Besides the expected small dipole induced differences (lines), no declination dependence observed

Sensitivity to mass composition with FD and SD

FD: heavier particles develop higher in the atmosphere, with less fluctuations
SD: heavier particles produce more muons on the ground, thus smaller risetime







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

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

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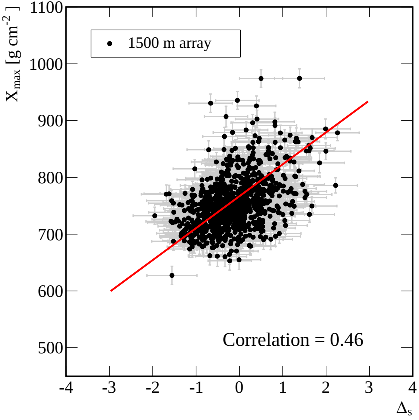

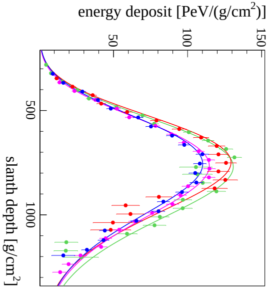

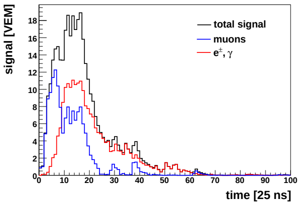

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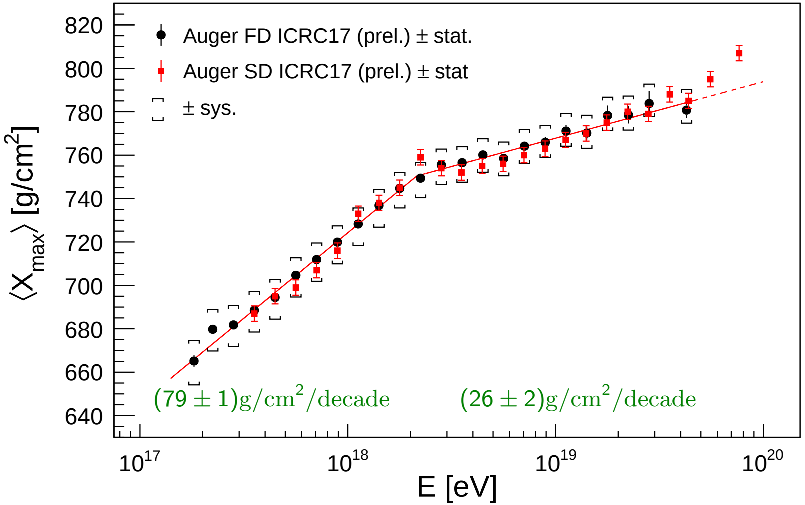
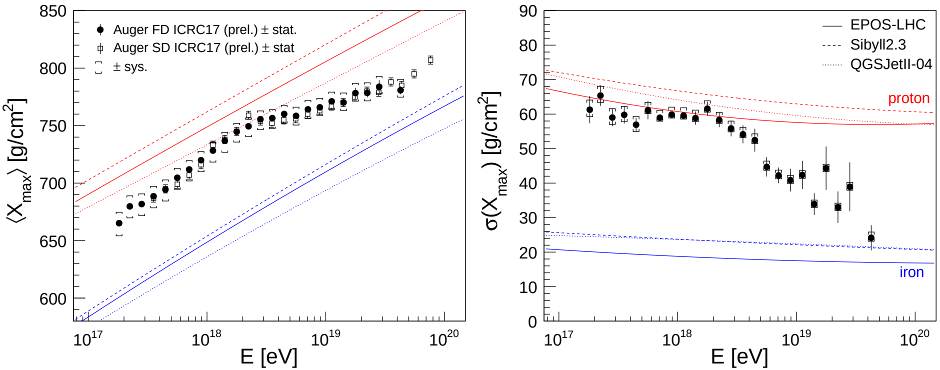
Average $X_{\max}$ with Fluorescence and Surface Detector



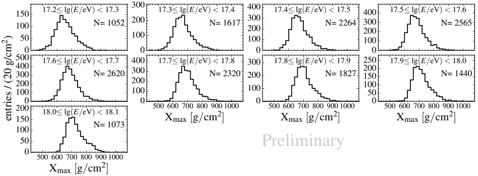
Average $X_{\max}$ and $X_{\max}$-fluctuations



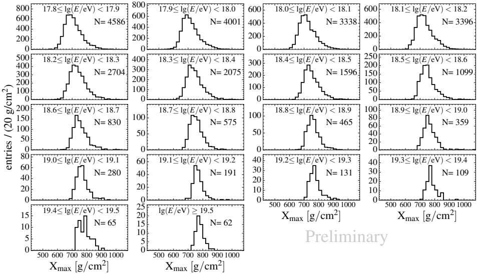
lines: simulations using post-LHC hadronic interaction models

Fits of the full distributions: p He N Fe

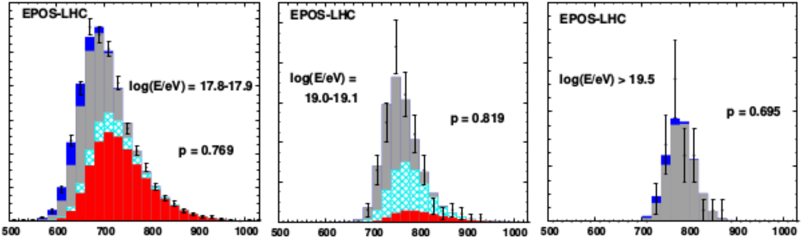
$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$



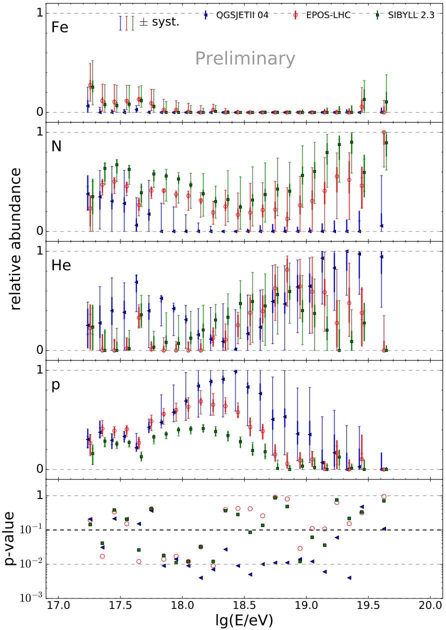
$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$

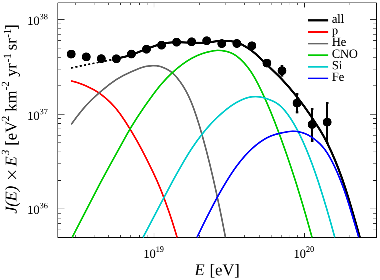


Examples of 4-component fit:



Mass composition and energy spectrum





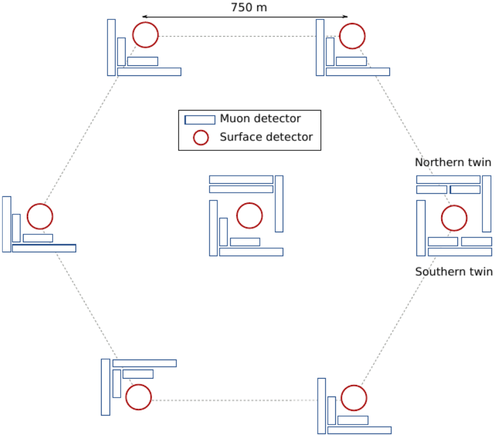
Transition from proton dominated composition towards heavier elements

A He component could explain the new spectral feature

submitted to PRL

Probing hadronic interactions at UHE

→ measuring directly the muons
with underground scintillators
(buried 2.3 m deep)



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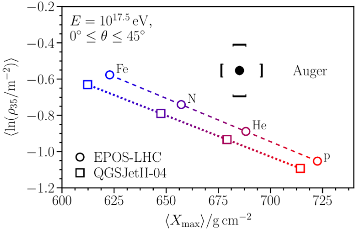
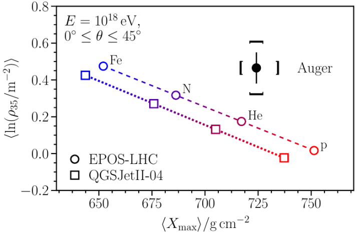
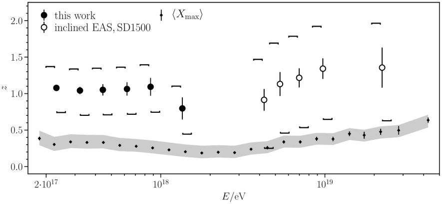


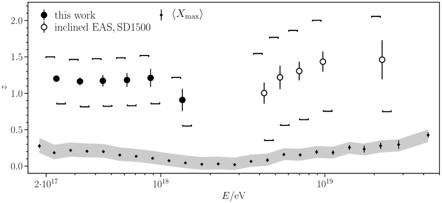
(a) $E = 10^{17.5}$ eV



(b) $E = 10^{18}$ eV



(a) EPOS-LHC



(b) QGSJetII-04

ρ_{35} related to the muonic component

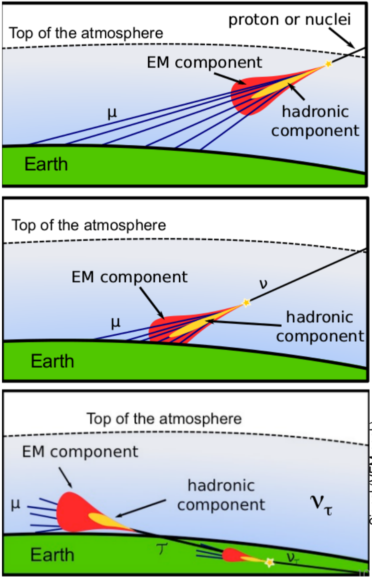
X_{max} to the electromagnetic component

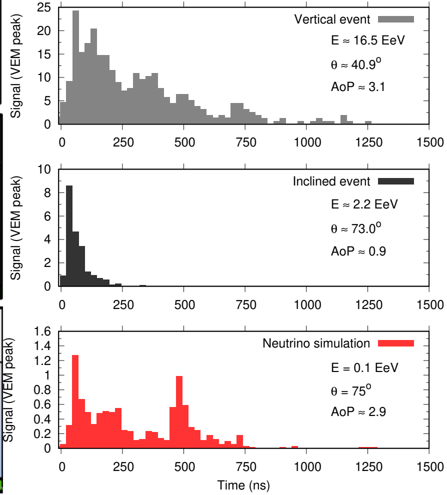
$z = (\ln x - \ln x_{\mathrm{p}})/(\ln x_{\mathrm{Fe}} - \ln x_{\mathrm{p}})$

less muons in simulations compared to data

accepted to EPJ

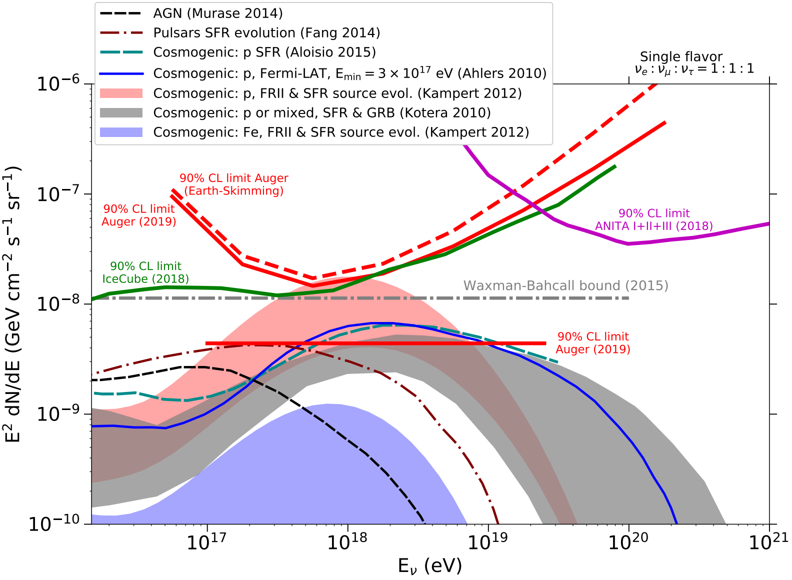
How to detect neutrinos?



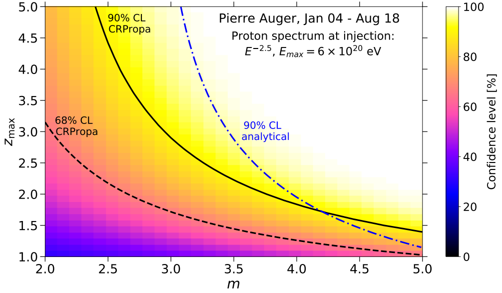


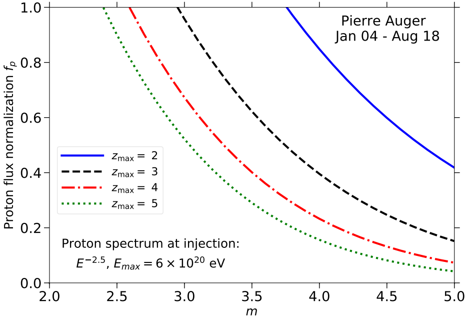
⇒ Inclined air-showers with large e.m. component (young)

Neutrino limits and UHECR origin



Neutrino limits and UHECR origin





UHECR source evolution: $\psi(z) \propto (1+z)^m$

Homogenuous distributed

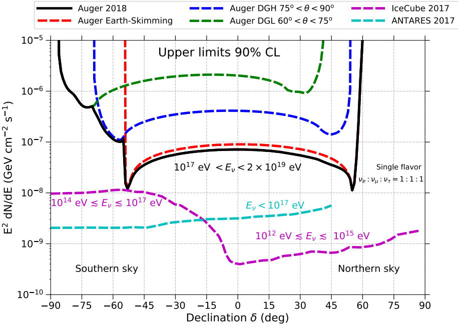
$\mathrm{d}N/\mathrm{d}E \propto E^{-2.5}$

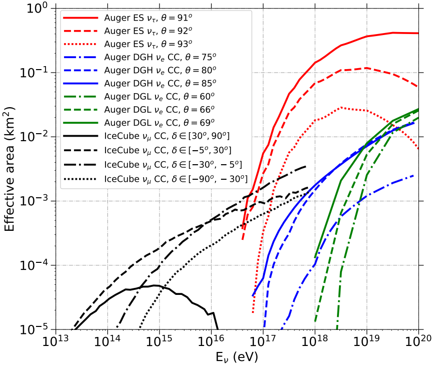
Proton flux: matched to the Auger spectrum at 7×10^{18} eV

Regions above the lines excluded

JCAP10(2019)022

Limits on point-like neutrino sources



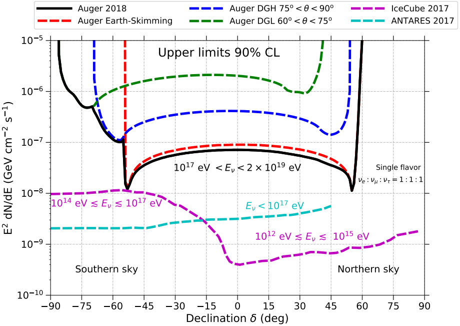


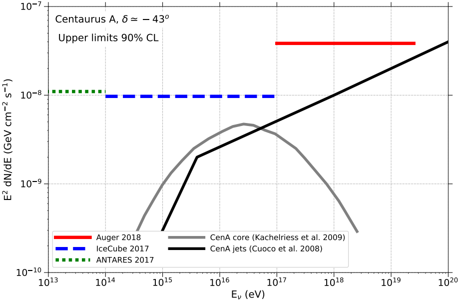
No neutrinos identified (data period January 2004 to 31 August 2018)

Unmatched sensitivity to potential sources of EeV neutrinos in the Northern terrestrial hemisphere

JCAP11(2019)004

Limits on point-like neutrino sources





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JCAP11(2019)004

AugerPrime

AugerPrime deployment

98% of the detectors built
deployment running smoothly
(724 already deployed)

test

Summary

High exposure study of the UHE flux: strong flux suppression and new features observed

FD/SD composition: light composition at the ankle, mixed at UHE
Hadronic interactions: UHE cross-section, muon deficit in models

Arrival directions: indication for intermediate scale anisotropy, observation of dipolar anisotropy (rigidity dependent anisotropies?)

Neutrinos: multimessengers at EeV energies

Future: upgrade of the Observatory, AugerPrime results soon