The Pierre Auger Observatory

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Latest results and future perspectives

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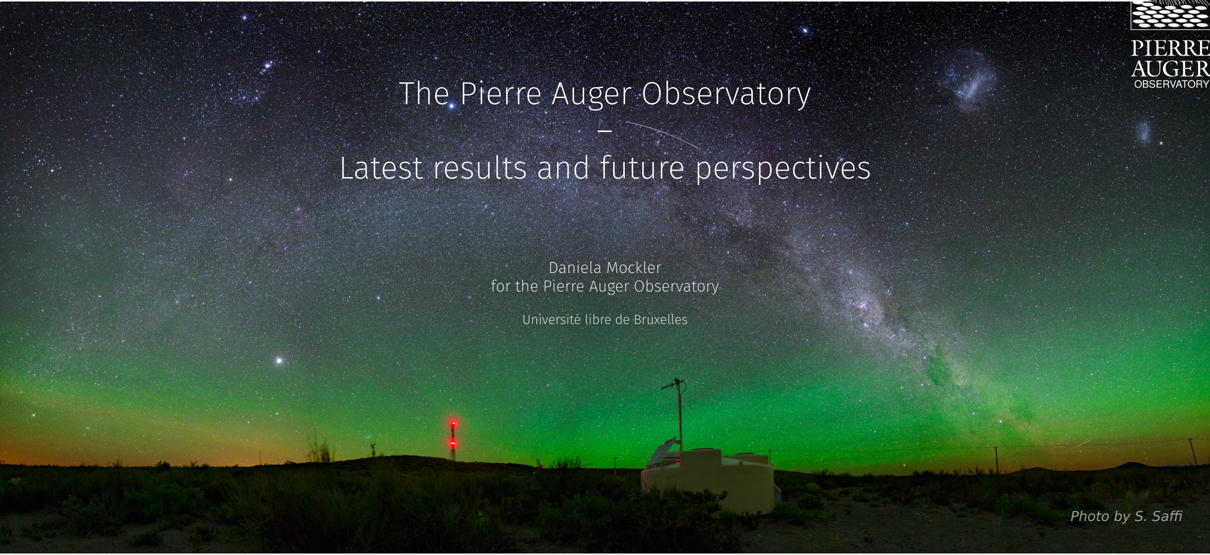
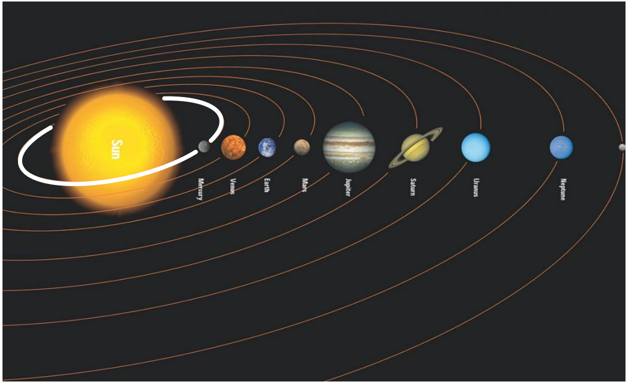


Photo by S. Saffi

Ultra-high energy cosmic rays

10^{18} eV to more than 10^{20} eV



LHC with Mercury orbit @ 10^{20} eV

What are the **sources**?

How are they **accelerated**?

How do they **propagate**?

How do they **interact** in the atmosphere?

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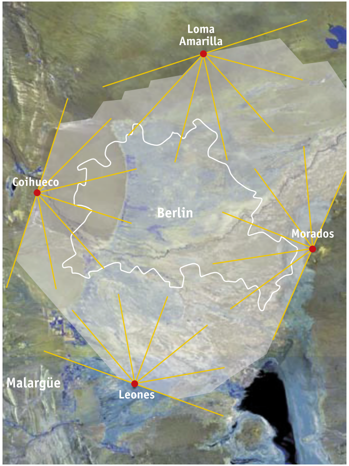

Located in Argentina, Province of Mendoza

Area of 3000 km² (4 x Berlin)

Collaboration includes

- 16 countries
- ∼90 institutions
- ∼450 authors

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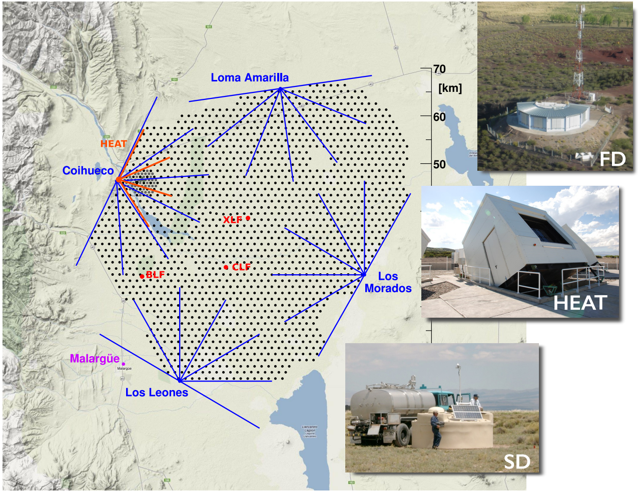


Water-Cherenkov stations

- SD1500: 1600, 1.5 km grid, 3000 km^2
- SD750: 61, 0.75 km grid, 25 km^2
- ∼100% duty cycle

4 Fluorescence Sites

- 24 telescopes, 1-30° field of view
- HEAT: 3 high-elevation FD, 30-60° field of view
- ∼15% duty cycle

+ Atmospheric monitoring devices

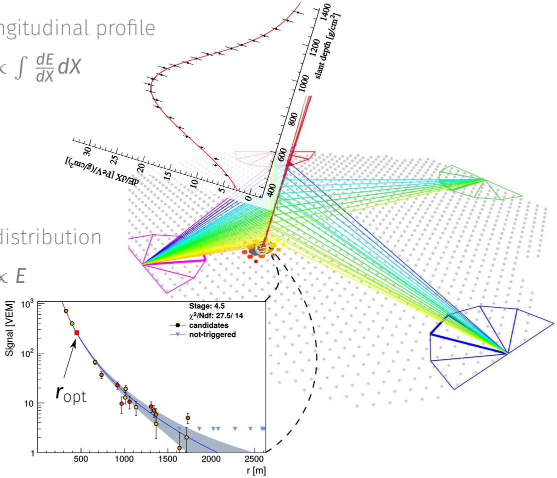
Event reconstruction and energy scale

Longitudinal profile

$E \propto \int \frac{dE}{dX} dX$

Lateral distribution

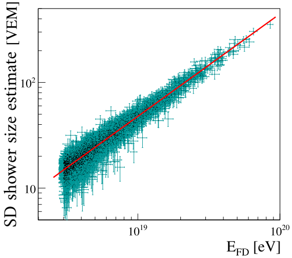
$S(r_{\text{opt}}) \propto E$



Total energy: $E_{\text{FD}} = E_{\text{cal}} + E_{\text{inv}}$

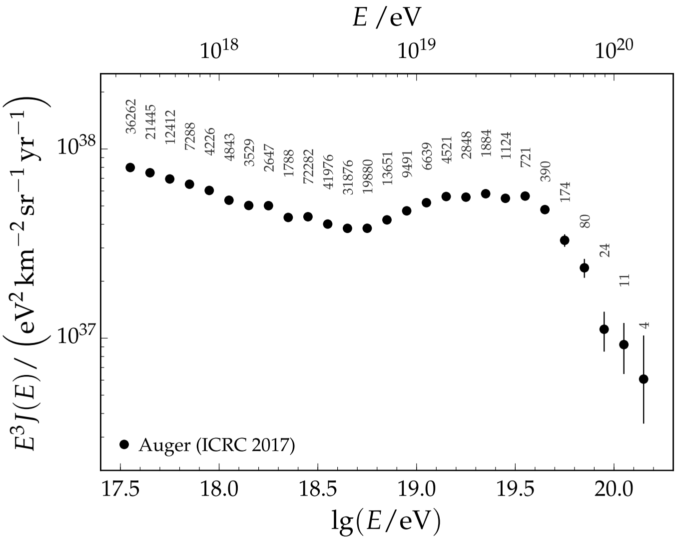
$\sigma(E_{\text{FD}})/E_{\text{FD}} \sim 8\%$

Systematic uncertainty of 14%

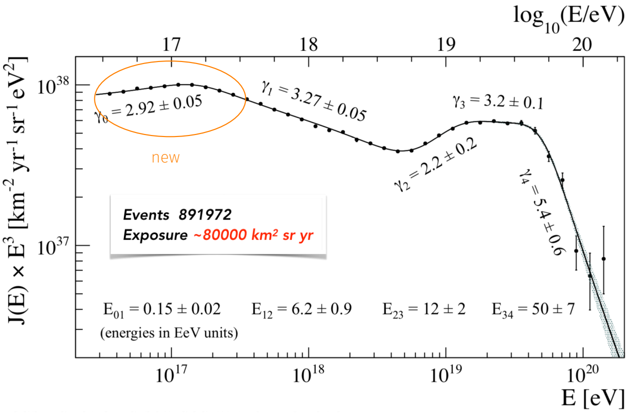


Using events which are well reconstructed by both detectors

Energy spectrum



Energy spectrum



Extension of energy range by

- update to particle triggers in SD stations
- extension of FD reconstruction to low-energetic air showers (showers with high Cherenkov fraction)

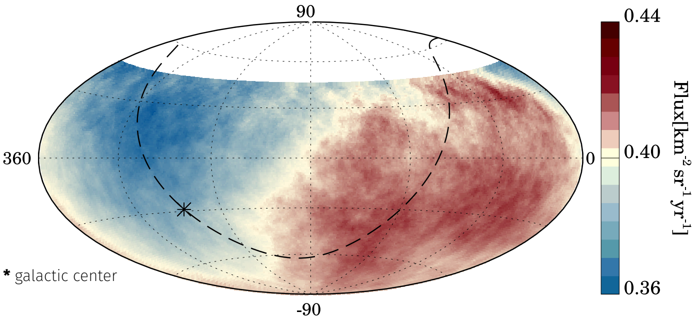
Indication of second knee

Large scale anisotropy

Energies above 8 EeV

Harmonic analysis in right ascension α

Significant dipolar modulation (5.2σ) above 8 EeV: $(6.6^{+1.2}_{-0.8})\%$ at $(\alpha, \delta) = (98^\circ, -25^\circ)$

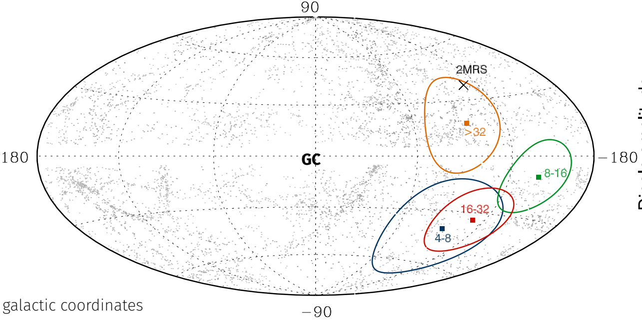


Expected if CRs diffuse to Galaxy from sources distributed similar to nearby galaxies

Dipole points ~125° away from the galactic center→ indication for extragalactic origin

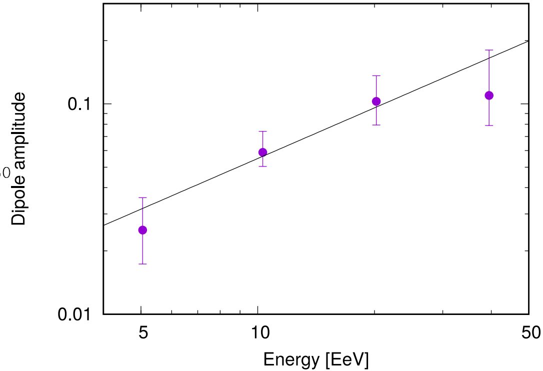
Large scale anisotropy

4 EeV ≤ E



galactic coordinates

Dipole direction for different energy bins

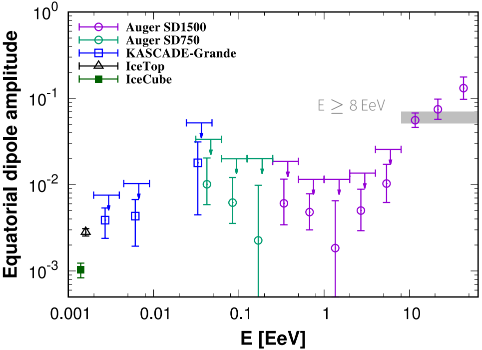


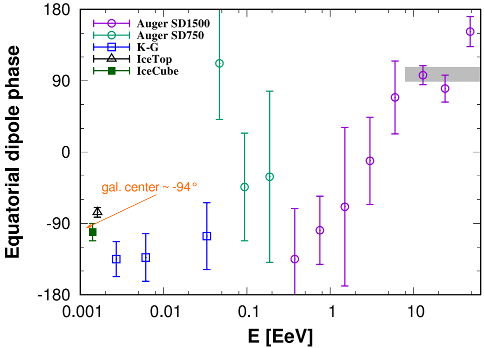
Amplitude increases with energy.

Energy-independent amplitude is disfavored at the level of 5.1σ

Large scale anisotropy

Search at lower energies





Amplitudes grow with energy from sub-% to above 10%

Phases shift from ∼ galactic center direction to ∼ opposite direction

Predominantly galactic origin below ∼1 EeV, extragalactic origin above

Search for Intermediate-scale Anisotropies

Sky models for two distinct populations of extragalactic gamma-ray emmitters

Intermediate: experimental resolution $(\sim 1°)$ < angular scale < $45°$

Active Galactic Nuclei

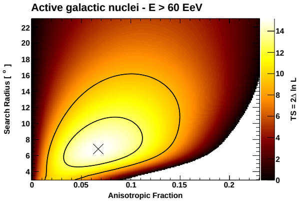
- 2FHL Catalog (*Fermi*-LAT, 360 sources)
- $\phi_\gamma(> 50\,\mathrm{GeV})$ as proxy for UHECR flux
- 17 bright nearby sources ($D < 250\,\mathrm{Mpc}$)

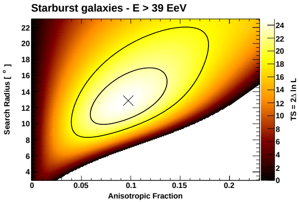
Star-forming or Starburst Galaxies

- *Fermi*-LAT search list
- $\phi_{radio}(> 1.4\,\mathrm{GHz}) > 0.3\,\mathrm{Jy}$ as proxy
- 23 brightest objects ($D < 250\,\mathrm{Mpc}$)

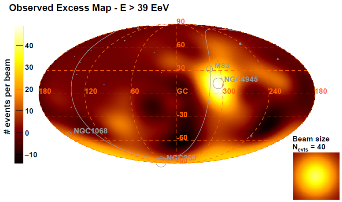
Likelihood ratio analysis

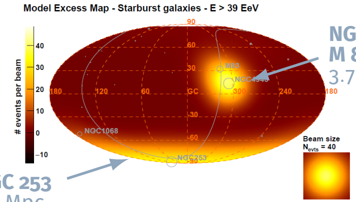
- smearing angle Ψ
- H_0 : isotropy
- H_1 : $(1-f)\times$isotropy + $f\times$fluxMap(Ψ)
- $\mathrm{TS} = 2\log(H_1/H_0)$





Search for Intermediate-scale Anisotropies





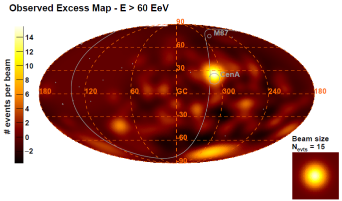
NGC 4945
M 83
3.7 Mpc

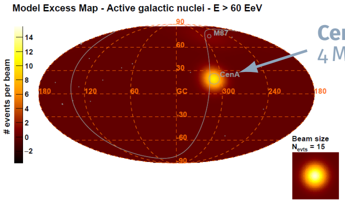
NGC 253
2.5 Mpc

NGC 1068
16.7 Mpc

Starburst

$f = 10\%, \Psi = 13^\circ$
4.0σ





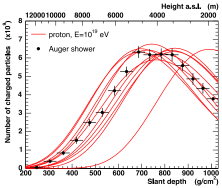
CenA
4 Mpc

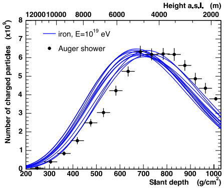
AGN

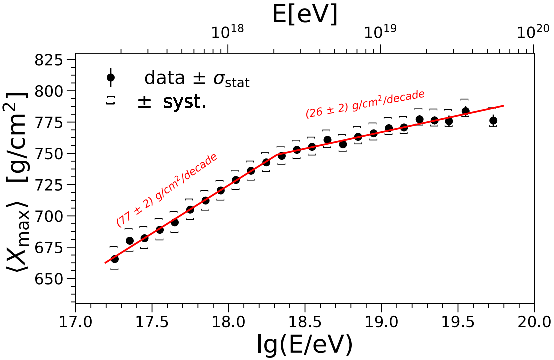
$f = 7\%, \Psi = 7^\circ$
2.7σ

Evolution of $\langle X_{max} \rangle$ with energy

X_{max}: depth of shower maximum, one of the most robust observables for mass composition analysis



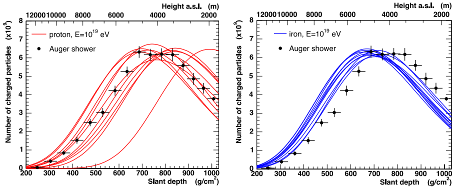


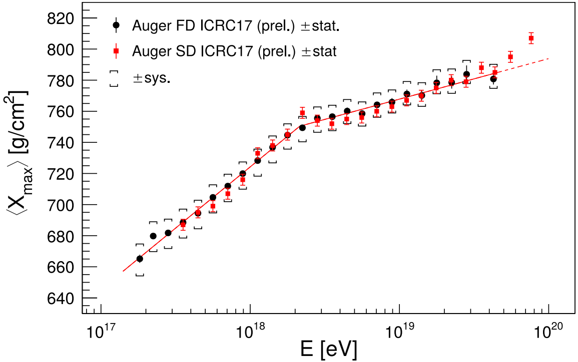


Change of composition @ $E \sim 2$ EeV

Evolution of $\langle X_{max} \rangle$ with energy

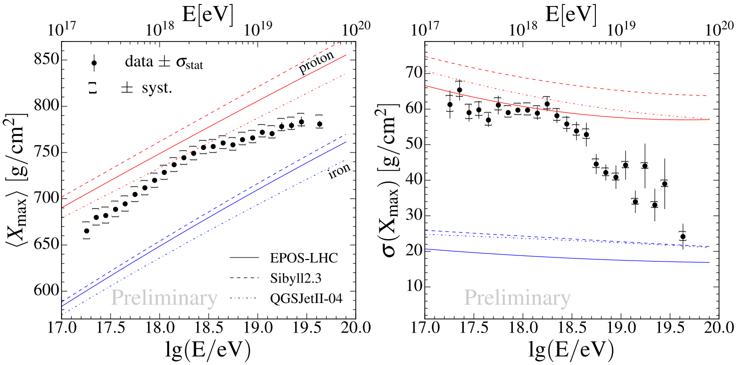
X_{max}: depth of shower maximum, one of the most robust observables for mass composition analysis





Change of composition @ $E \sim 2$ EeV

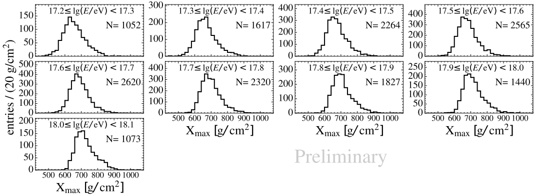
$\langle X_{\max} \rangle$ and its fluctuations

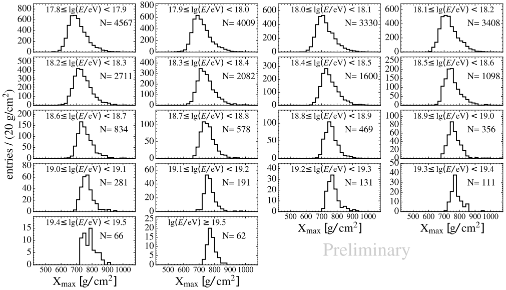


Composition is getting lighter below $E \sim 2$ EeV and heavier above

Decrease of fluctuations above $10^{18.3}$ eV indicates trend towards heavier composition

X_{max} distributions - shape sensitivity

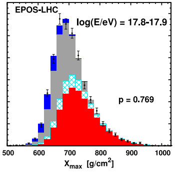


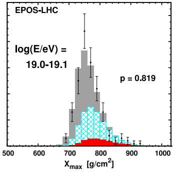


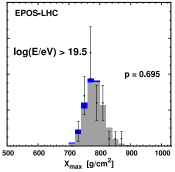
Composition fractions from description of full X_{max} distribution

Example of 4-component fit:

proton
helium
nitrogen
iron

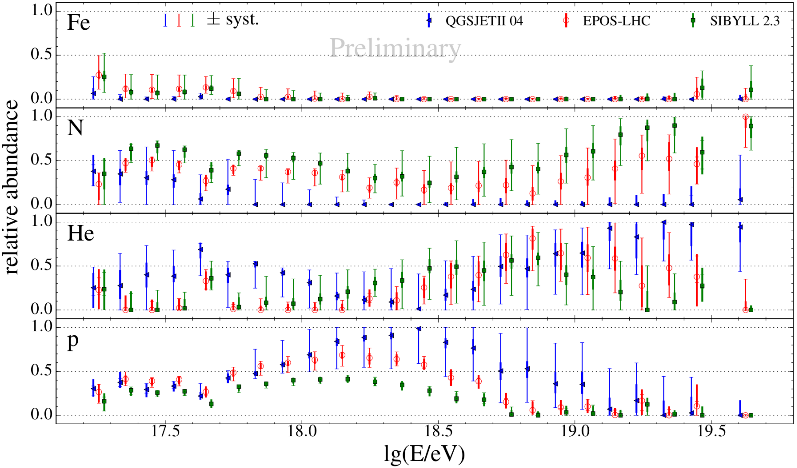






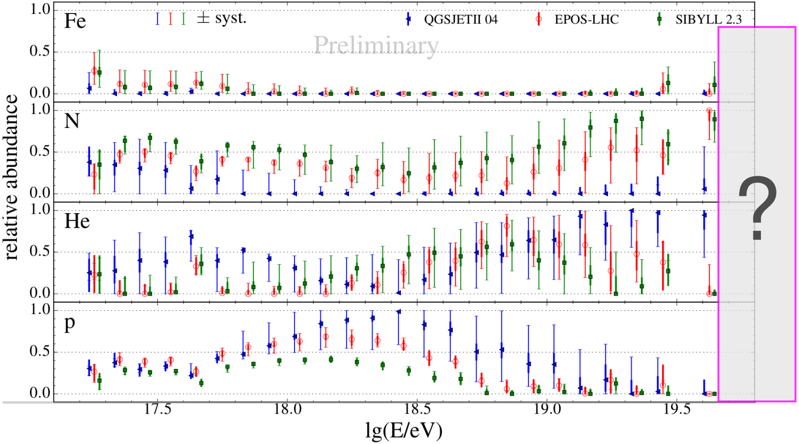
increasing energy →

Composition fractions



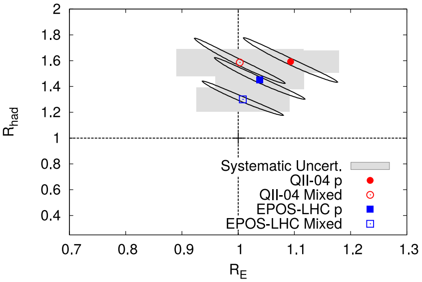
No composition data @ and above onset of suppression

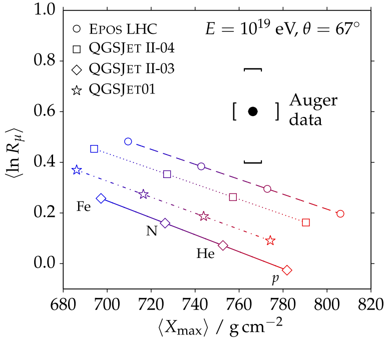
Composition fractions



No composition data @ and above onset of suppression

Probing hadronic interactions at ultra-high energies





R_{had}: rescaling factor for hadronic component (muons)

R_E: rescaling factor for electromagnetic component

R_μ: muon content

X_{max}: related to electromagnetic component

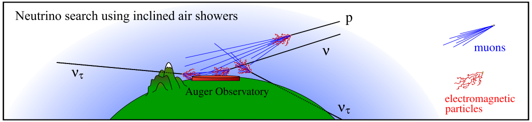
Number of produced muons is underestimated in simulations

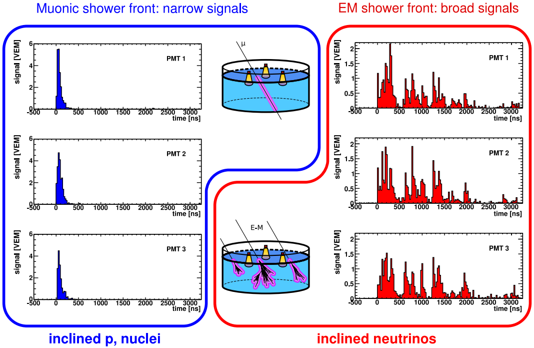
Searches for cosmogenic neutrinos

Production: $N + \gamma_{\mathrm{CMB}} \rightarrow N + \pi^{\pm}$ and $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$ and $\mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e})$

Identification: Highly inclined showers.

Nuclei: no electromagnetic. component. **Neutrinos**: deep showers, large electromagnetic. component

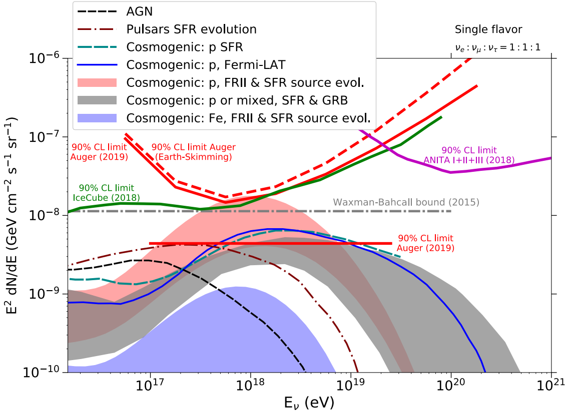




Searches for cosmogenic neutrinos

Assumption of differential neutrino flux: $dN(E_\nu)/dE_\nu = k \cdot E_\nu^{-2}$

$k \sim 4.4 \times 10^{-9}\ GeV\,cm^{-2}\,s^{-1}\,sr^{-1}$



Upgrade - Motivations

Study the origin of suppression at the highest energies

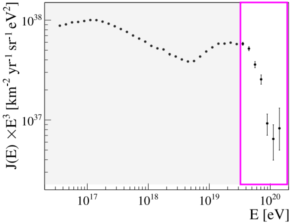
Mass composition at the highest energies

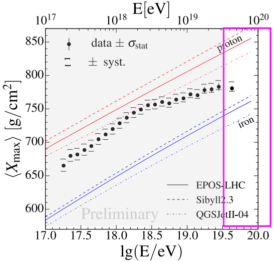
Select light primaries for charged particle astronomy

Improve estimates of neutrino and gamma flux

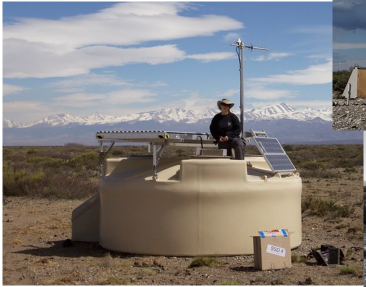
Improve measurement of shower components to deepen the study of hadronic interactions at ultra-high energies

Improve sensitivity to composition by disentangling the electromagnetic and muonic components



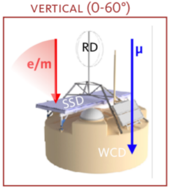


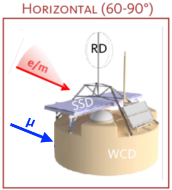
Upgrade to AugerPrime



+ extended dynamic range and
new electronics of the SD,
extended duty cycle of the FD

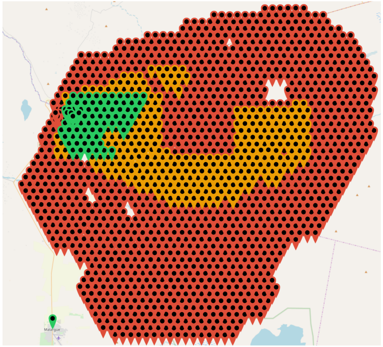
Complementarity of particle response used to discriminate electromagnetic and muonic components

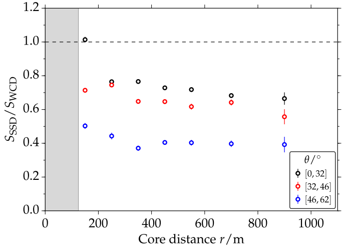


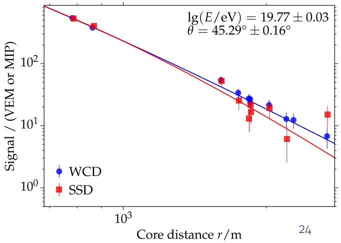


hybrid: E_{rad} from radio,
muons from water-Cherenkov stations

Upgrade to AugerPrime







→ 12 upgraded stations (Engineering Array) since 2016 with new electronics, higher sampling, large dynamic range

→ SSD preproduction array: 80 stations (since 03/2019)

→ 356 SSD stations already deployed

+ Underground Muon detector, + largest radio detector

Summary

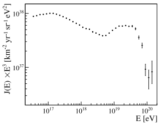
Spectrum $\to$ high statistics measurement from $10^{17.5}$ eV to $\sim 10^{19.5}$ eV, 15 events above 10^{20} eV

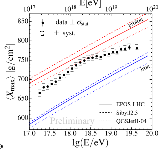
Mass composition $\to$ light @ ankle, mixed @ higher energies

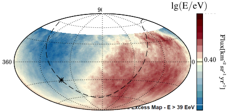
Arrival direction $\to$ dipolar modulation @ large scales
$\to$ amplitude increasing with energy

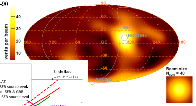
$\to$ @ intermediate scales, most significant excess found for densely-populated region, significance of starburst model increased with more data

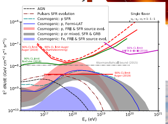
Neutrino search $\to$ constraints on p-dominated sources

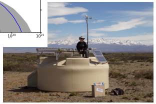












Thanks for your attention!

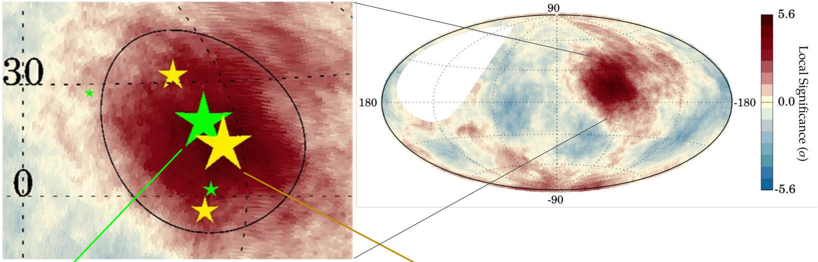
Backup slides

Intermediate scale anisotropy

Search for event excess using a blind search

Events with E>32 EeV: 2157

Total exposure: 101,400 km² sr yr



Cen A (active galactic nucleus)

NGC 4945 (starburst galaxy)

Scan ranges:

32 EeV $\leq$ E $\leq$ 80 EeV in 1 EeV steps

$1^\circ \leq \Psi \leq 30^\circ$ in 1° steps

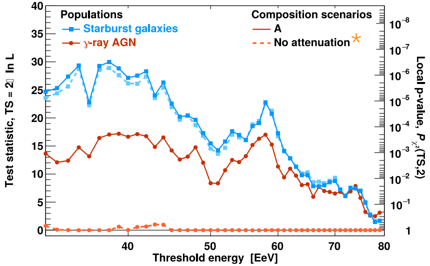
Most significant excess found for E>38 EeV with a local significance of 5.6σ (2.5σ post-trial)

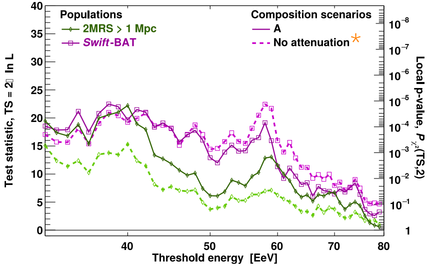
Intermediate scale anisotropy

Matching with candidate sources

Assumption: bright objects have a higher contribution to the CR flux

Likelihood analysis *TS = 2 Log[L(Ψ, f)/L(f=0)]*. Ψ = search radius, f = anisotropy fraction



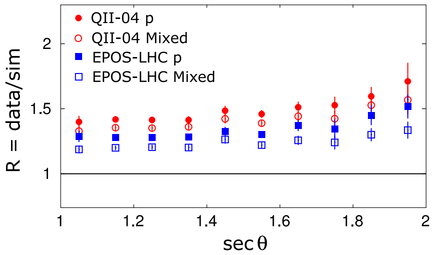


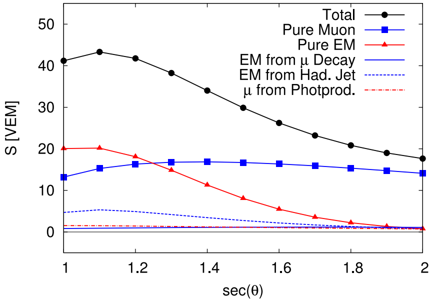
*flux attenuation due to propagation

Catalog	E / EeV	Ψ / °	f / %	TS	Post-trial
Starburst	38	15^{+5}_{-4}	11^{+5}_{-4}	29.5	4.5σ
γ-AGNs	39	14^{+6}_{-4}	6^{+4}_{-3}	17.8	3.1σ
Swift-Bat	38	15^{+6}_{-4}	8^{+4}_{-3}	22.2	3.7σ
2MRS	40	15^{+7}_{-4}	19^{+10}_{-7}	22.0	3.7σ

Arrival direction of CRs above 38 EeV best matched by model with ∼11% clustered around nearby & bright starburst galaxies

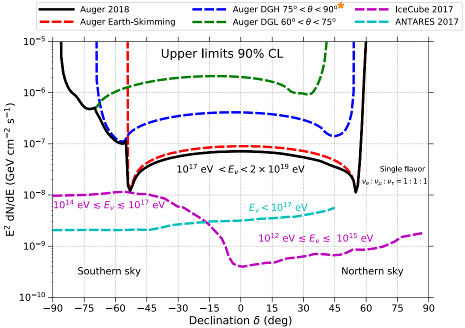
Probing hadronic interactions at ultra-high energies





Point-like sources of UHE ν

Steady sources



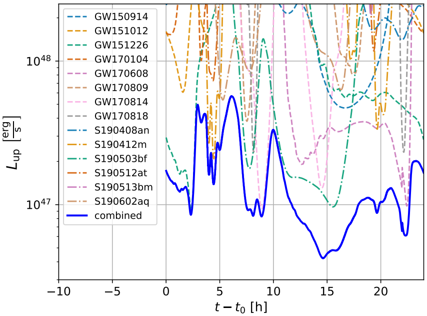
* DG = downward-going high/low

Complementary energy range to IceCube and ANTARES

Good sensitivity at EeV energies in a broad declination range

Best sensitivity where sources spend more time in Earth-skimming field of view

Transient sources



Example of transient sources: 21 binary black hole mergers detected by Ligo-Virgo

24h follow-up search after BBH merger

No neutrinos found

Sensitivity improved by combining the sources