

Cosmic rays: Highlights from the Pierre Auger Observatory

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for the Pierre Auger collaboration

Université Libre de Bruxelles

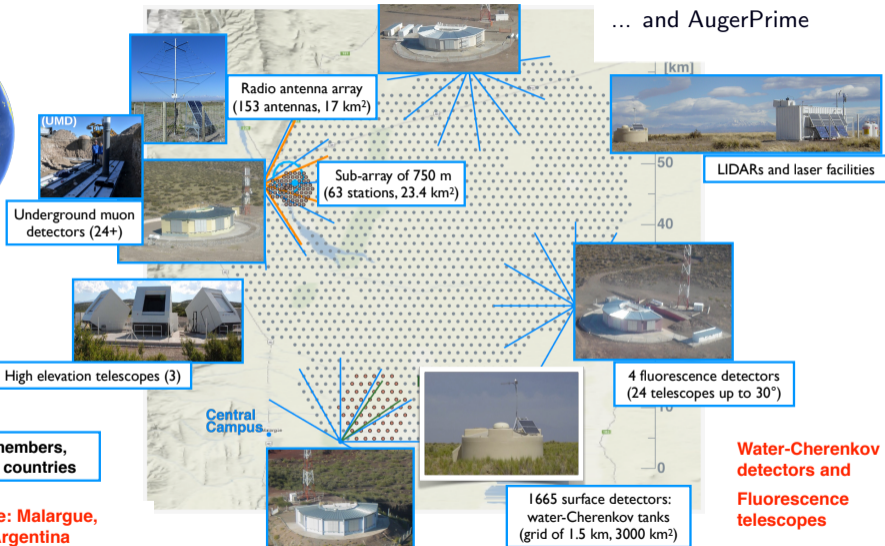


PIC, September 2022

Pierre Auger Observatory



Pierre Auger Observatory
Province Mendoza, Argentina



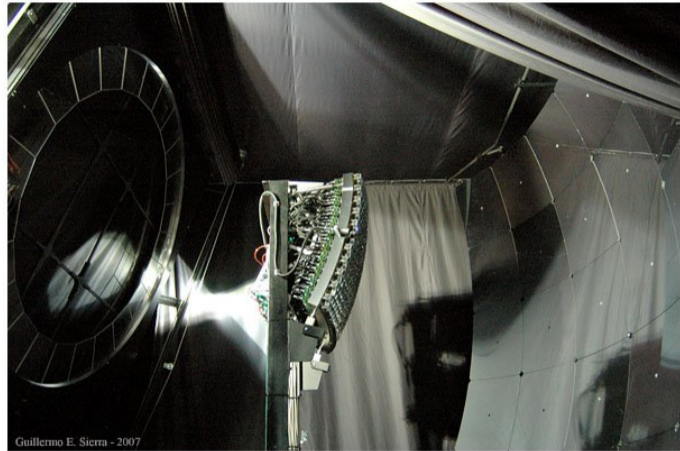
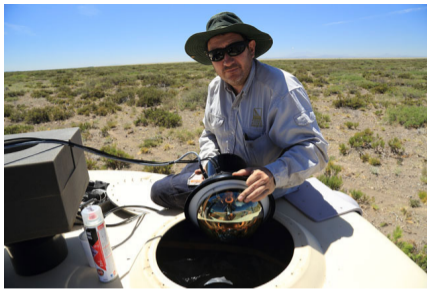
More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue,
Province Mendoza, Argentina

... and AugerPrime

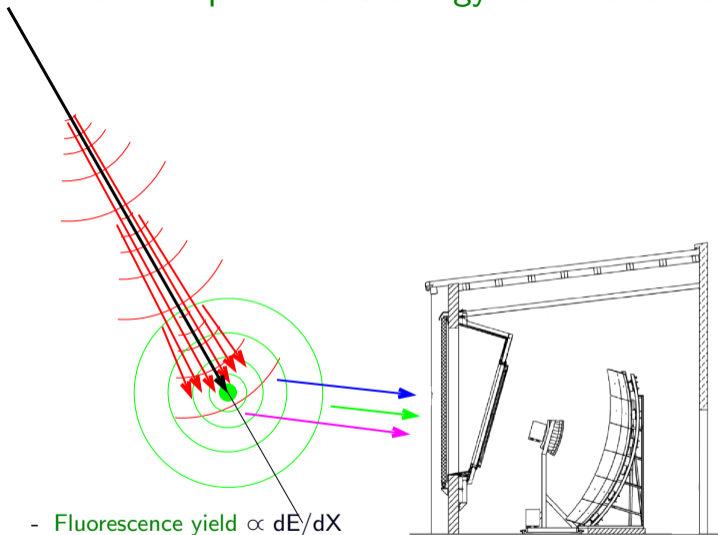
Water-Cherenkov
detectors and
Fluorescence
telescopes

Auger detectors



Guillermo E. Sierra - 2007

From measured photons to energy: air showers emissions



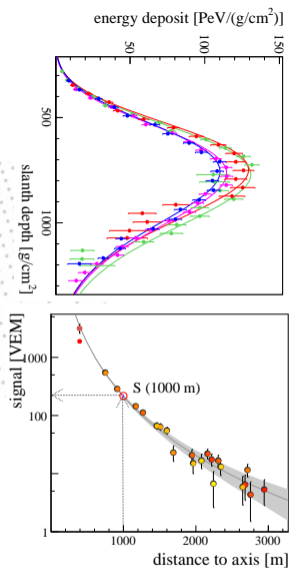
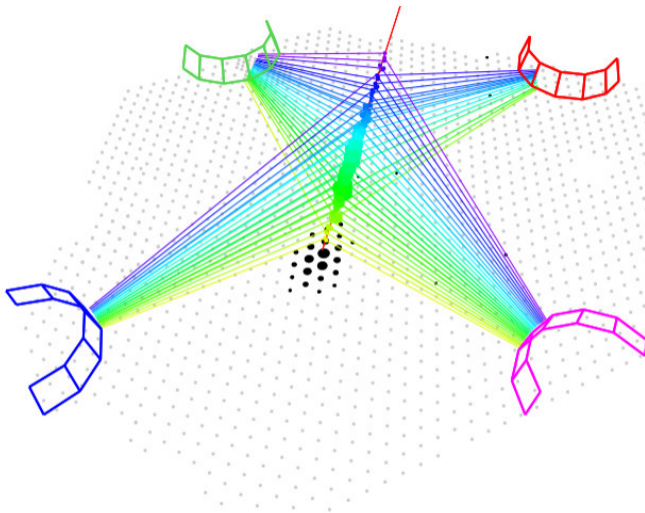
- isotropic **fluorescence** emission
- forward beamed **direct Cherenkov** light
- **Rayleigh**- and **Mie**- scattered light: dependent on the aerosols and atmospheric conditions (VAOD)
- **Invisible energy** correction

- **Fluorescence yield** $\propto dE/dX$

- Cherenkov yield $\propto N_e$, universality of the energy deposit $dE/dX = \alpha_{\text{eff}}(s) \cdot N_e$

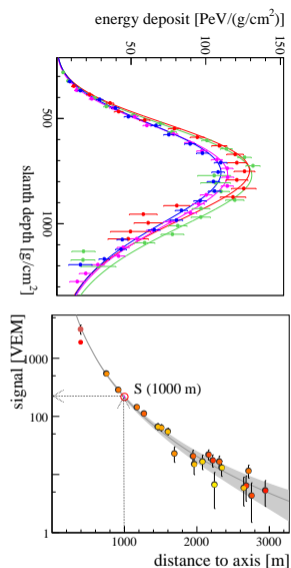
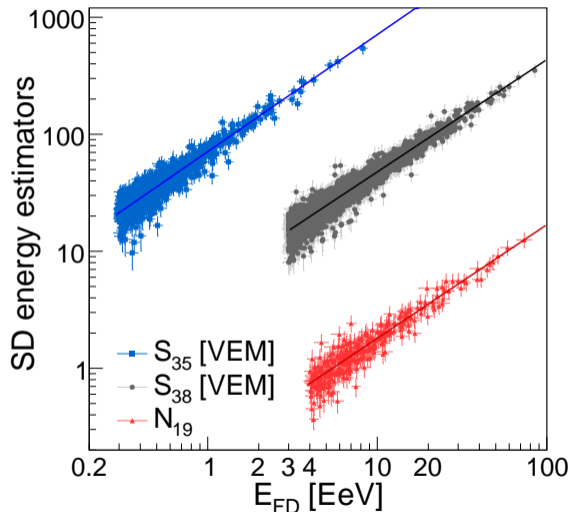
adapted from M.Unger

From air-showers to primary particle



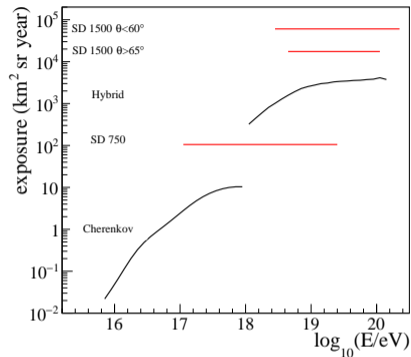
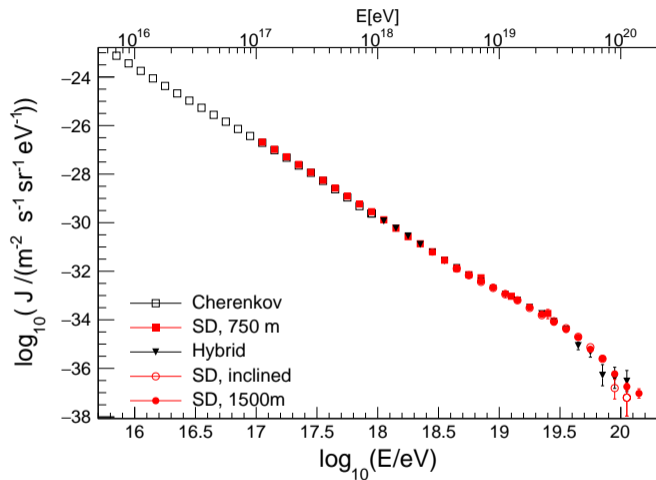
$$E_{FD} = \int dE/dX + \text{invisible energy correction}, \quad E_{SD} = f(\theta, S1000)$$

From air-showers to primary particle



$$E_{FD} = \int dE/dX + \text{invisible energy correction}, \quad E_{SD} = f(\theta, S1000)$$

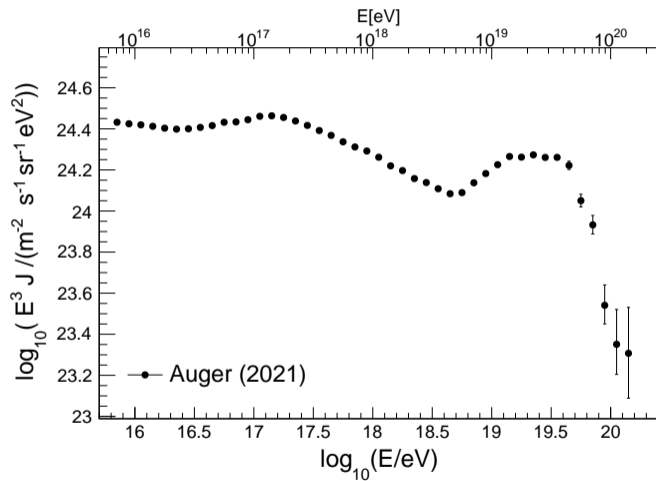
The second knee and the instep



- spectrum obtained from the combination of 5 energy spectra

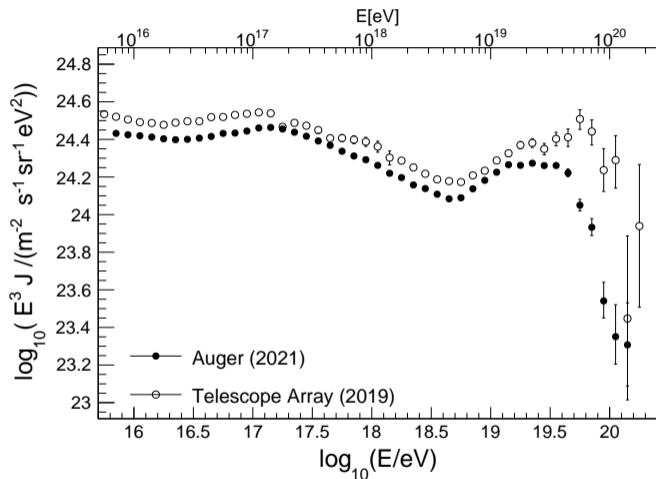
- common energy scale (14% systematic uncertainty)

The second knee and the instep

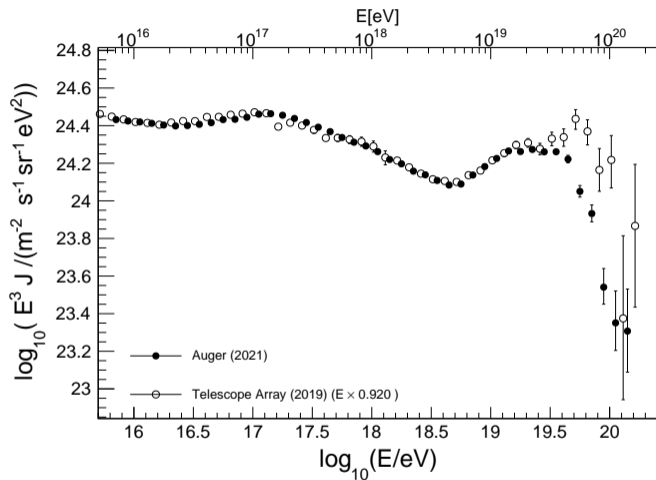


Presence of the second knee and a new feature: the instep

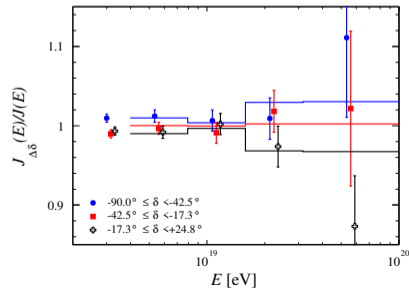
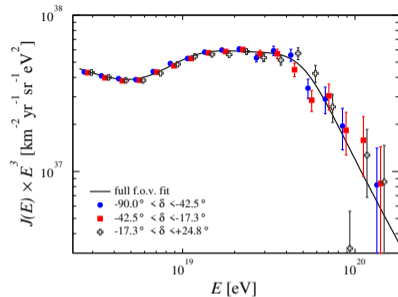
Comparison with Telescope Array measurement



Comparison with Telescope Array measurement: declination dependency?



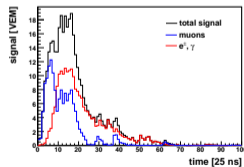
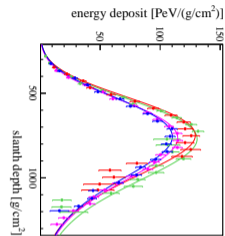
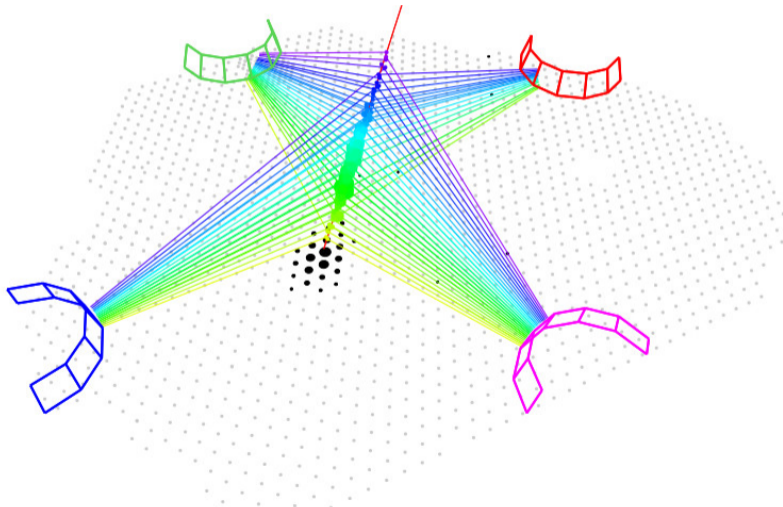
Auger data: the expected flux difference from the dipole
Difference at the highest energies not fully understood



Sensitivity to mass composition with FD and SD

FD: heavier particles develop **higher** in the atmosphere, with **less fluctuations**

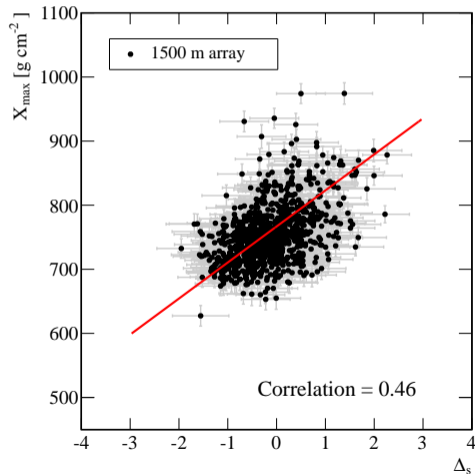
SD: heavier particles produce **more muons** on the ground, thus **smaller risetime**



Sensitivity to mass composition with FD and SD

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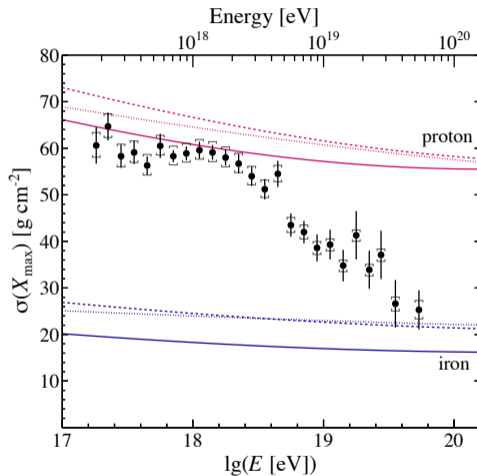
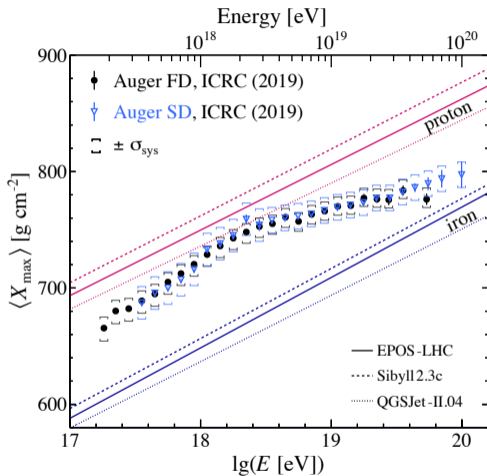
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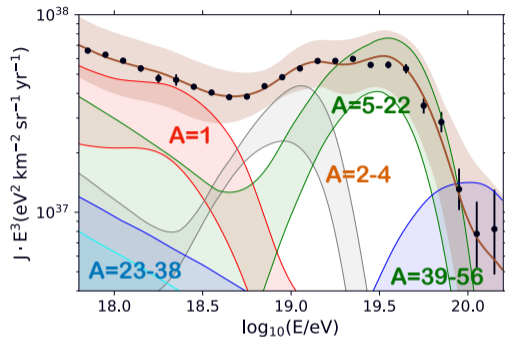
X_{\max} : depth of the maximum of the air-shower development

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

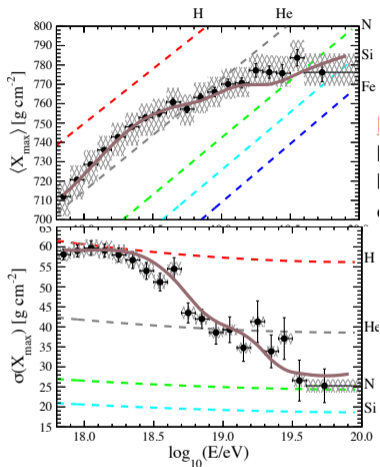
Using the surface and fluorescence detectors for mass composition



Combining the energy spectrum and the mass composition measurements



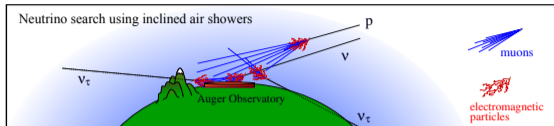
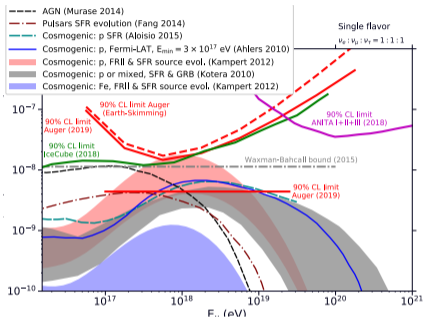
- uniformly distributed identical sources
- rigidity dependent cut-off at sources
- accounting for the energy losses in the propagation



Error bands
correspond to the
systematic
uncertainties
(14% E, 6-9 g/cm²
 X_{\max})

The flux suppression seems to be dominated by an acceleration cut-off at the sources

Ultra high energy neutrinos: cosmogenic fluxes

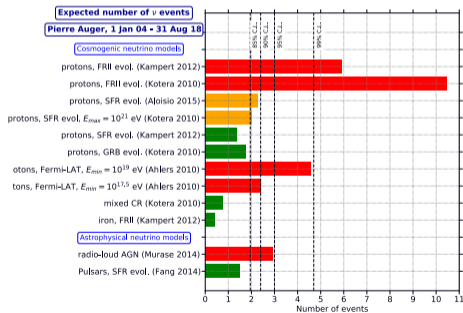


(JCAP 10 (2019) 022,
JCAP 11 (2019) 004)

Expectations in case of maximum energy acceleration scenario ≈ 0.001 neutrinos

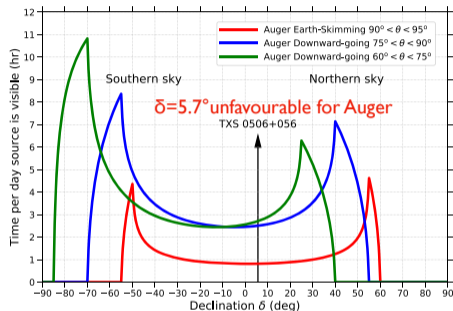
Sources searches: aperture compatible to IceCube for preferential directions

Future: lower the detection threshold with AugerPrime

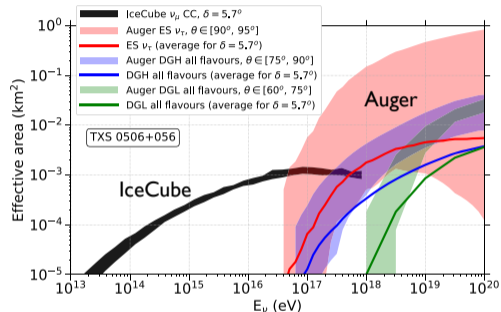


Search for neutrinos from TXS 0506+56

daily visibility in ES channel of Auger: < 1 hrs



effective area in comparison to IceCube

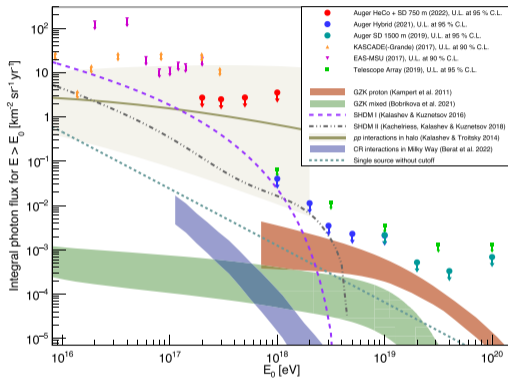
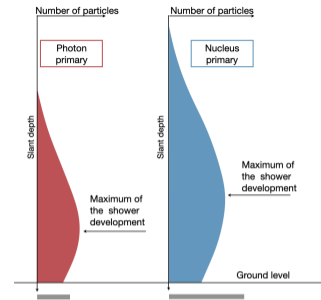


IceCube observed a 290 TeV ν from the direction of TXS 0506+59 during a flaring state

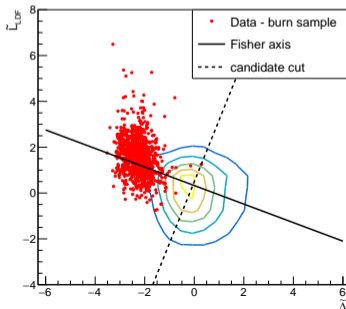
talk by Julia Tjus, Science 361, 146 (2018)

Unfortunate none seen by Auger during the flare

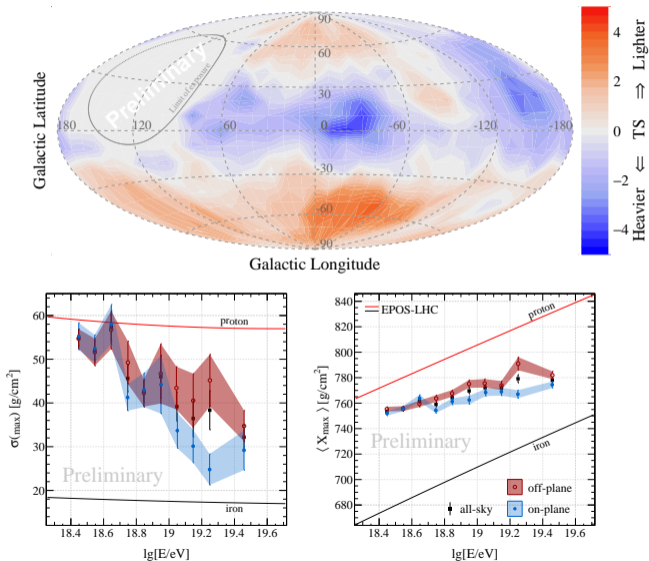
Limits on ultra high energy photons



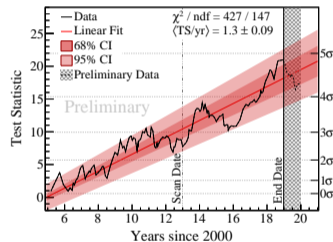
Limits start to probe proton-dominated scenarios
 Increase in the photon/hadron separation needed
 Exploit lower energies with the underground muon detectors



Mass composition distribution over the sky



- Scan over data recorder before 2013
- 5° steps in latitude and 0.1 in $\lg(E/\text{eV})$
- Highest test statistics for $(\lg(E_{\min}/\text{eV}), b) = (18.7, 30^\circ)$

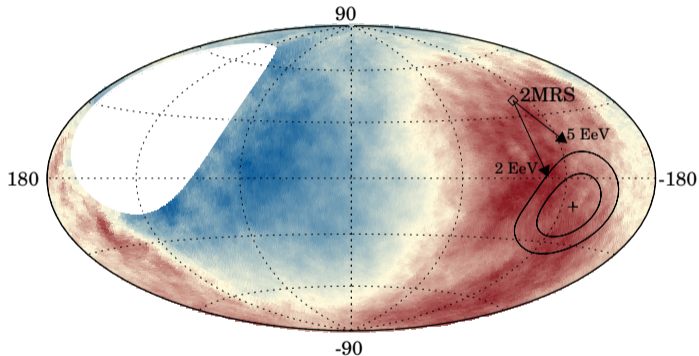


Confirmation from other variables pending:
more data and better sensitivity needed

Large scale anisotropy

Harmonic analysis in right ascension α

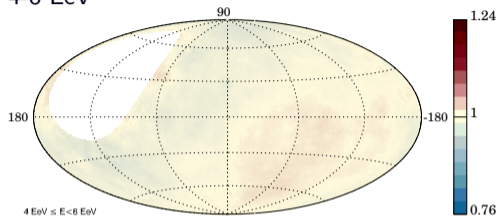
Significant dipolar modulation (6.6σ) above 8×10^{18} eV: $(7.3^{+1.1}_{-0.9})\%$ at $(\alpha, \delta) = (95^\circ, -36^\circ)$



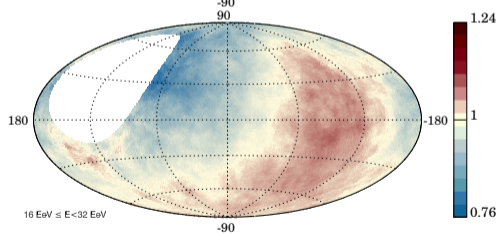
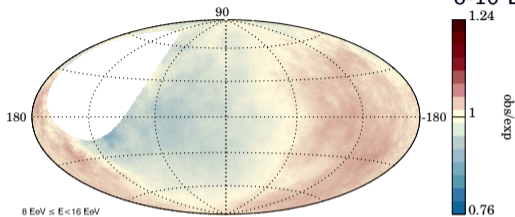
- Expected if cosmic rays diffuse in Galaxy from sources distributed similar to near-by galaxies (dipole structure in near-IR)
- Anti-dipole in the direction of the local void

Large scale anisotropy

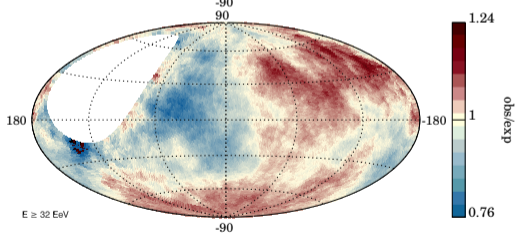
4-8 EeV



8-16 EeV

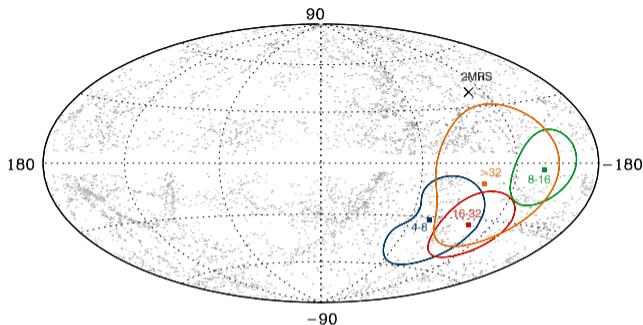
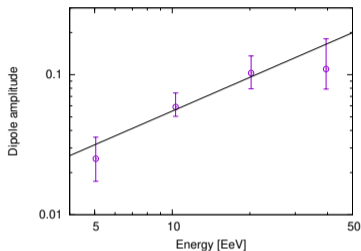


16-32 EeV



above 32 EeV

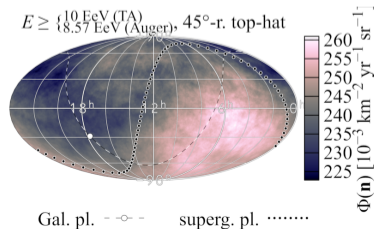
Large scale anisotropy



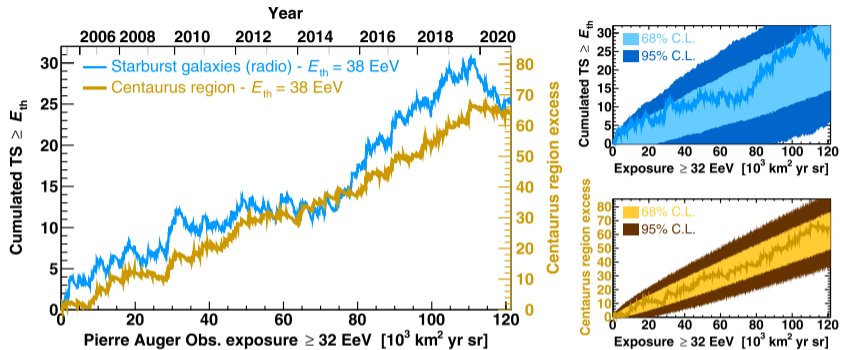
Energy-independent amplitude disfavored at the level of 3.7σ

Emergence of a new classes of sources?

Combined analysis with Telescope Array coll.:
better constrain on the dipole reconstruction (due
to full sky coverage)



Anisotropies at smaller scales: angular correlations with sources



Catalog	E_{th} [EeV]	Fisher Search Radius, Θ [deg]	Signal Fraction, α [%]	TS_{max}	Post-trial p -value
All galaxies (IR)	40	16^{+11}_{-6}	16^{+10}_{-7}	18.0	7.9×10^{-4}
Starbursts (radio)	38	15^{+8}_{-4}	9^{+6}_{-4}	25.0	3.2×10^{-5}
All AGNs (X-rays)	39	16^{+8}_{-5}	7^{+5}_{-3}	19.4	4.2×10^{-4}
Jetted AGNs (γ -rays)	39	14^{+6}_{-4}	6^{+4}_{-3}	17.9	8.3×10^{-4}

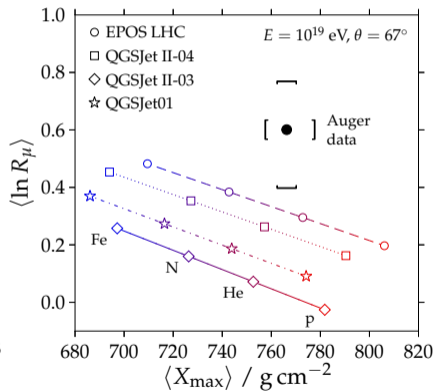
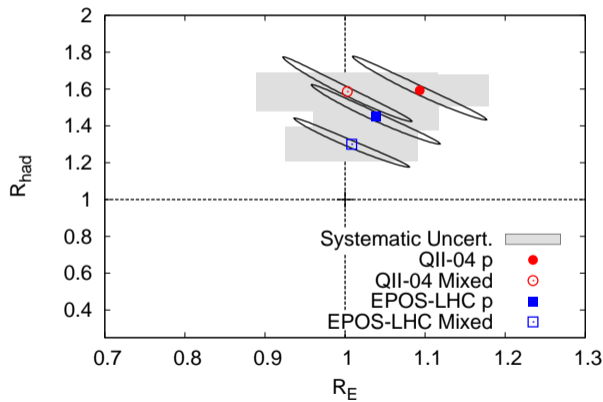
Model: signal fraction (α) above an isotropic background within an angular range (Φ) about a certain energy (E_{thr})

Expected 5σ reach in 2025-2030

Probing hadronic interactions at ultra high energies

By matching the longitudinal profiles and/or footprints on the ground

R_{had} and R_{μ} related to the muonic component on the ground
 R_E and X_{max} related to the electromagnetic component



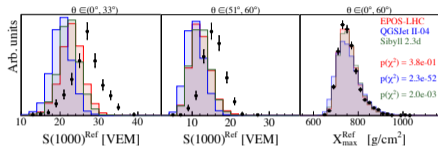
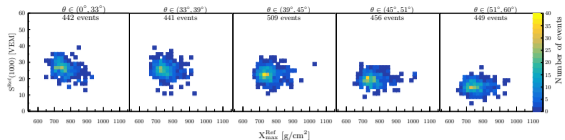
The number of muons is underestimated in simulations: at 10^{19} eV 30% to $80^{+17}_{-20}\%$ more needed

Modification of hadronic interaction models

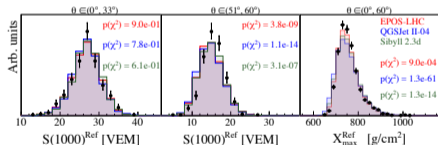
Combined fit of (S_{1000} , X_{\max})
(hybrid events, 3 EeV - 10 EeV)

Combined fit of (S_{1000} , X_{\max}) allowing
for an angular dependent rescaling of N_{μ}

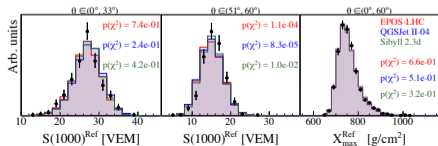
Combined fit of (S_{1000} , X_{\max}) allowing
for an angular dependent rescaling of N_{μ}
and shifting X_{\max} of all primaries



(a) No MC corrections



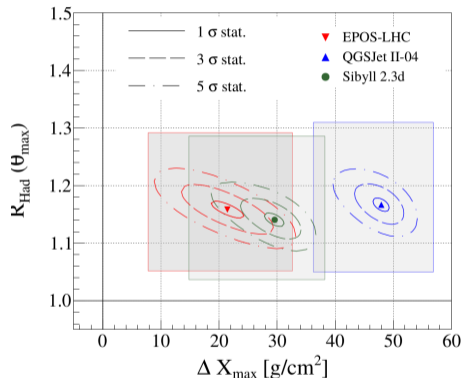
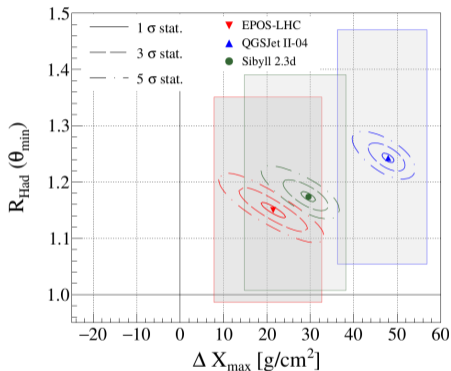
(b) MC corrections: $R_{\text{Had}}(\theta)$



(c) MC corrections: ΔX_{\max} and $R_{\text{Had}}(\theta)$

A shift in X_{\max} and muon number required

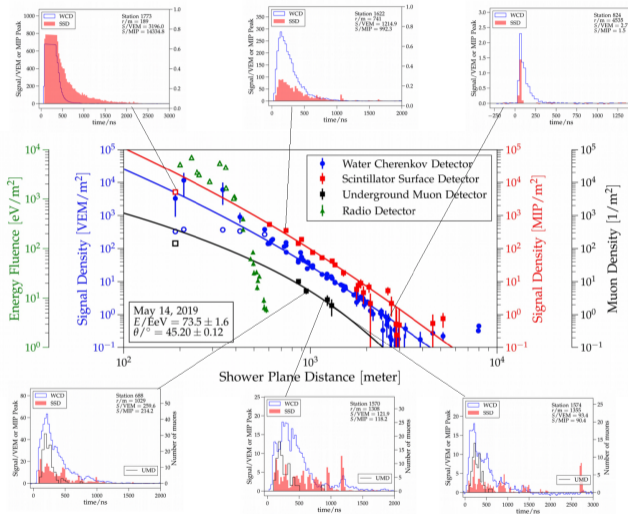
Assumptions: relative fluctuations no changed



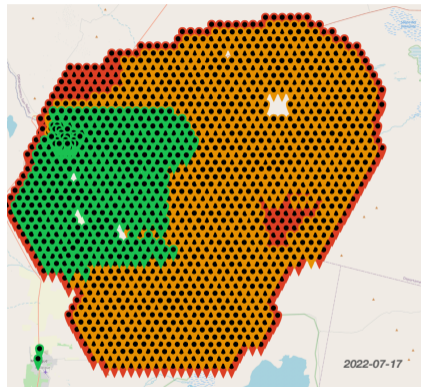
Main effect from re-scaling muon component in a zenith angle dependent way
Scaling X_{\max} leads to further improvements



Auger Prime upgrade



deployment status



SSD modules 1518 (without the borders)
 1473 SSD installed in the field
 405 electronics and small PMT installed

Summary

Pierre Auger Observatory: Phase I

- Large accumulated exposure of $120\,000\text{ km}^2\text{ sr year}$
- The instep, a new unexpected spetral feature that could naturally be explained by the change in mass composition
- UHECR composition and energy spectrum decisive for next generation EeV neutrino observatories
- Clear mismatch between the hadronic interaction models and data regarding the number of muons (and probably X_{max})
- Large scale anisotropies have been measured in the form of a dipole, indications for small scale anisotropies are present

Phase II

- At least $40\,000\text{ km}^2\text{ sr year}$ additional exposure expected
- Increased sensitivity towards mass composition
- Usage of modern techniques (deep learning) to data analysis

10% of Auger data are public: opendata.auger.org