Recent Results from the Pierre Auger Observatory

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for the Pierre Auger collaboration

Université Libre de Bruxelles

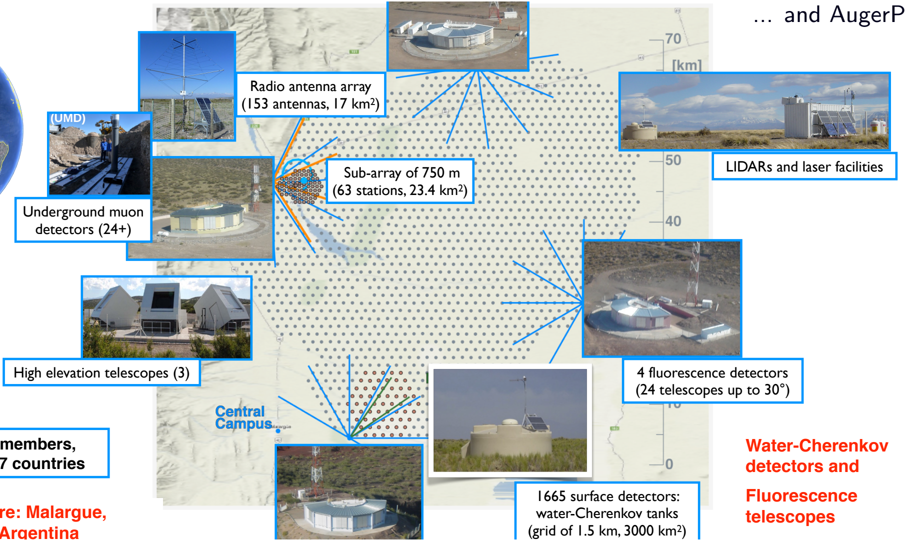
Rencontres de Blois

October 2021

Pierre Auger Observatory

… and AugerPrim

Pierre Auger Observatory
Province Mendoza, Argentina



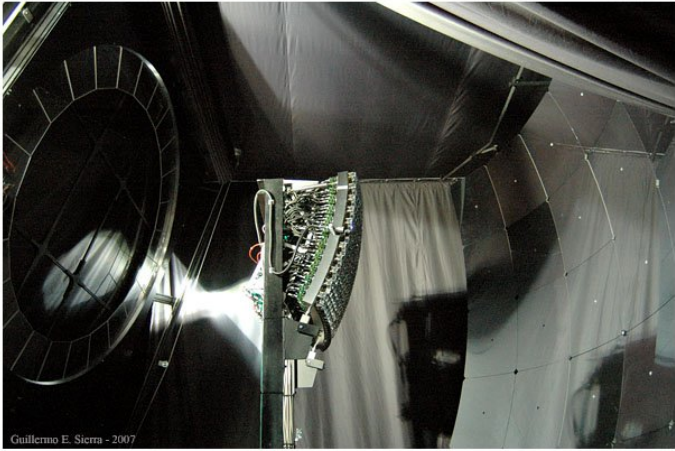
More than 400 members, 98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

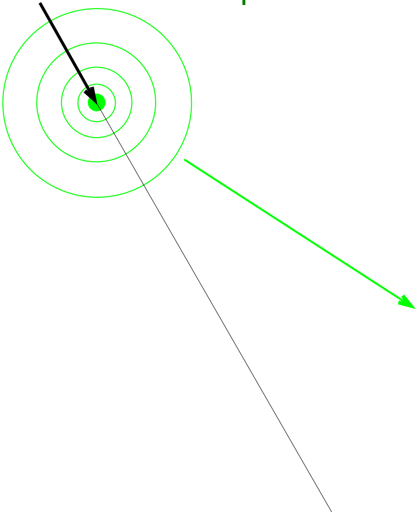
Water-Cherenkov detectors and

Fluorescence telescopes

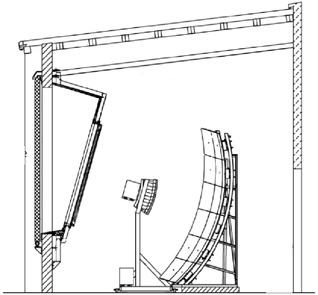
Auger detectors



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 $dE/dX = \alpha_{\rm eff}(s) \cdot N_e$

adapted from M.Unger

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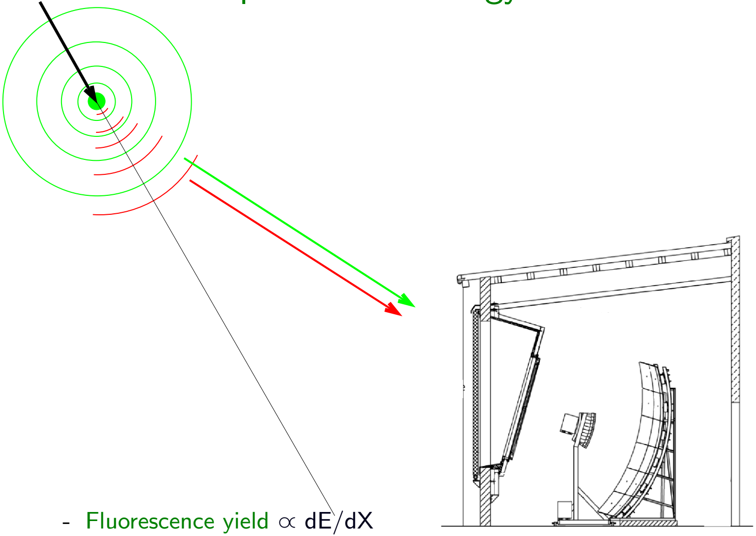

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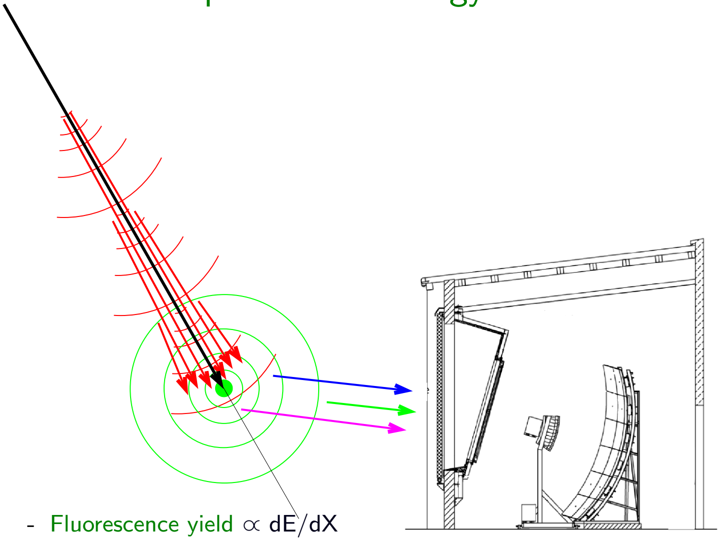

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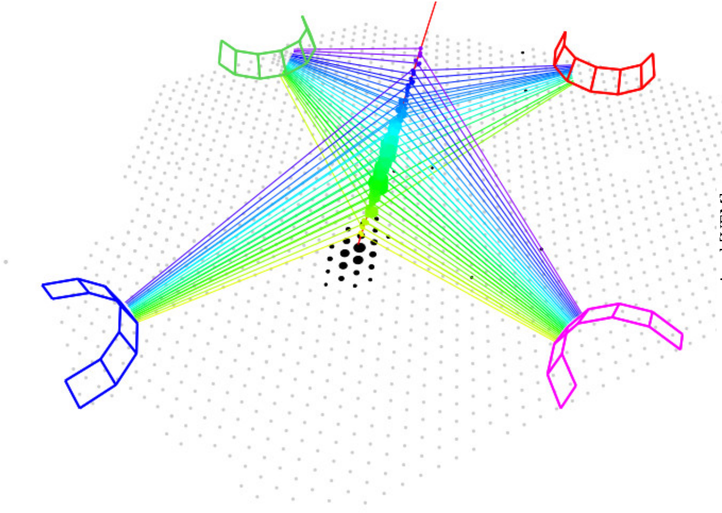
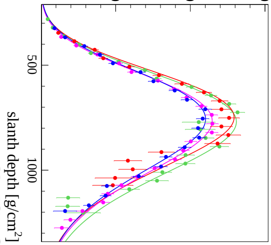
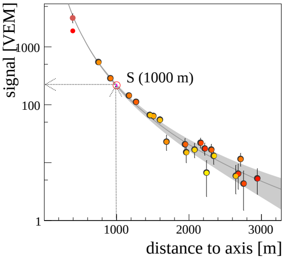
From air-showers to primary particle charateristic







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

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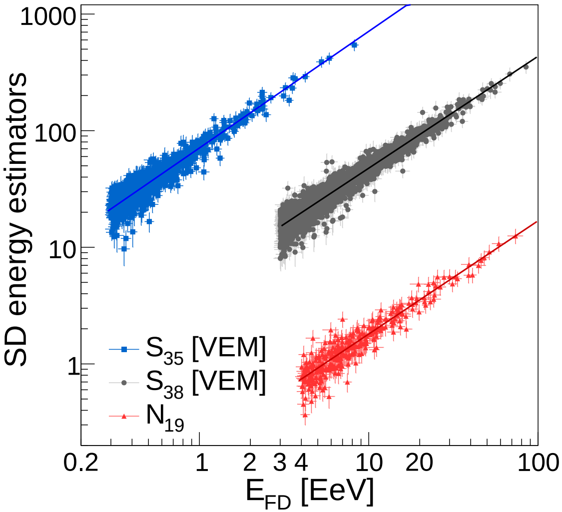
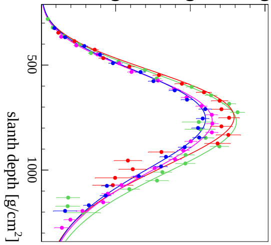
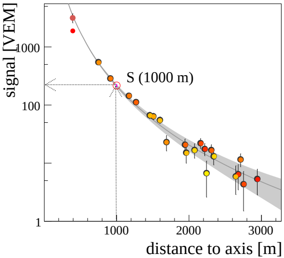
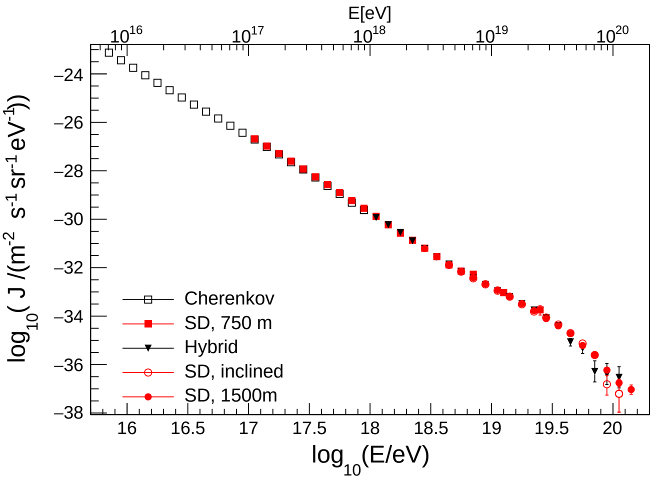


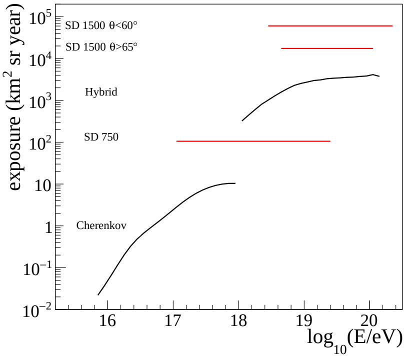




$E_{FD} = \int dE/dX +$ invisible energy correction, $E_{SD} = f(\theta, S1000)$

Five independent measurements of the energy spectrum and the instep





very good agreement between the energy spectra (better than 5%)

common energy scale (14% systematic uncertainty)

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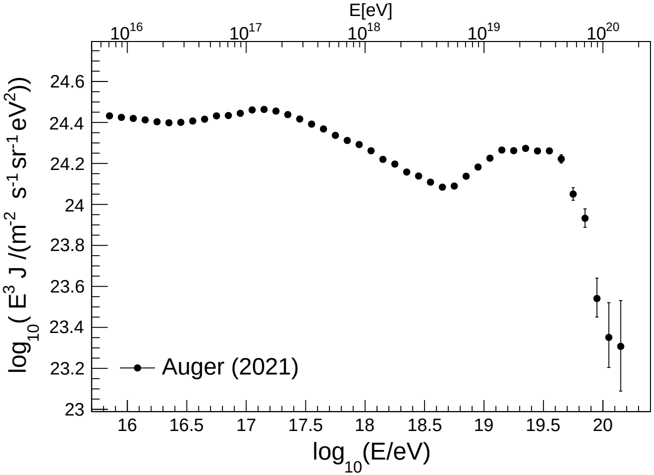
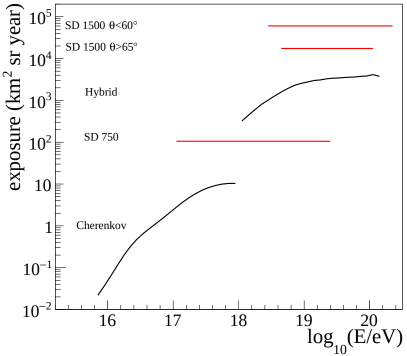


Presence of the second knee and a new feature: the instep



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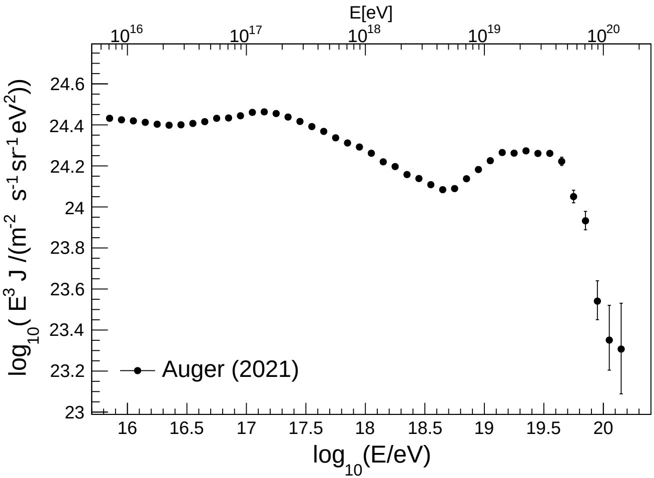
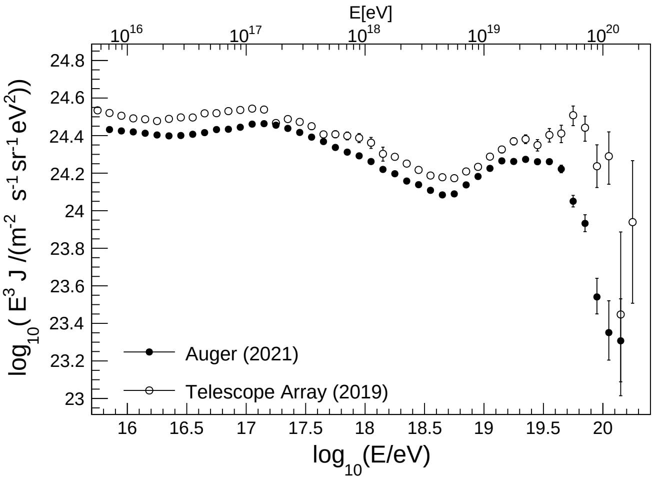
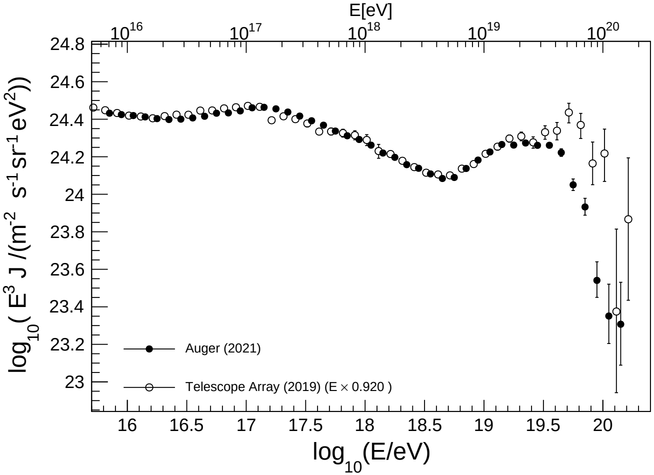


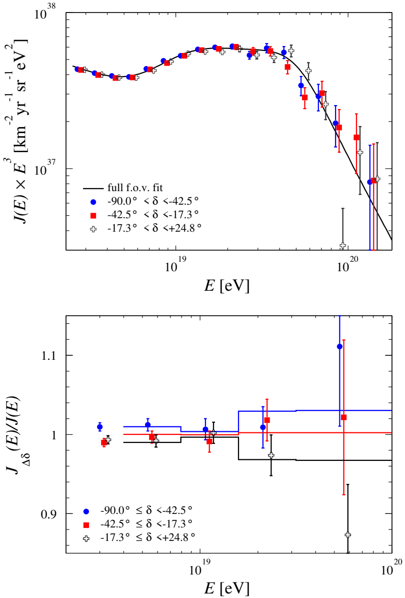
Presence of the second knee and a new feature: the instep

Comparison with Telescope Array measurement



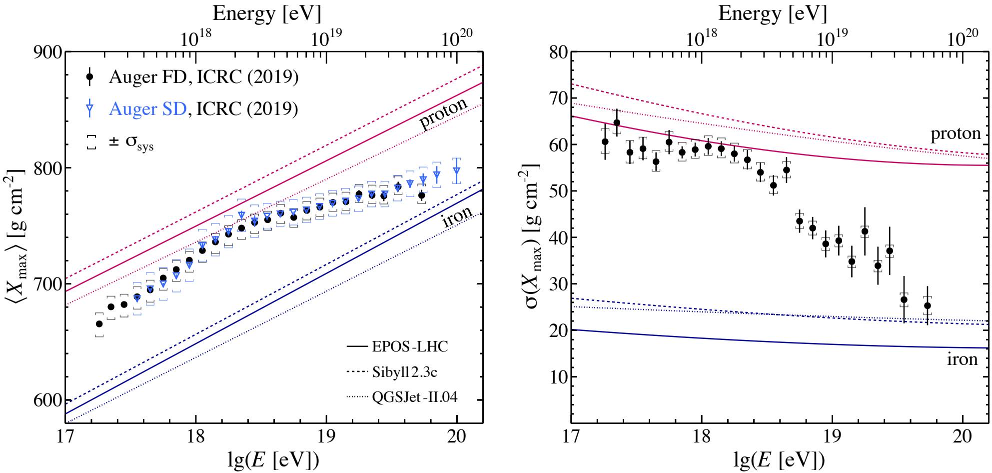
Comparison with Telescope Array measurement: declination dependency?





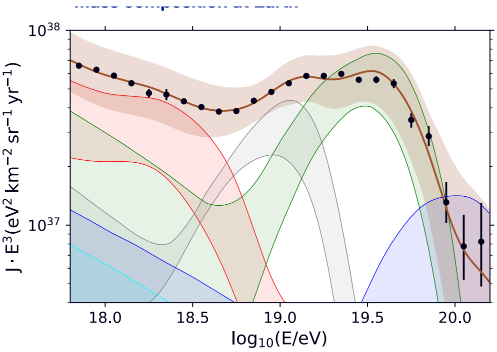
Auger data: the expected flux difference from the dipole
Difference at the highest energies not fully understood

Using the surface and fluorescence detectors for mass composition



Position of the maximum of the air-shower development and its fluctuations retalted to the first interaction: deeper showers more fluctuating showers correspond to lighter composition

What can we say about the UHECRs sources from energy spectrum and mass composition measurements?

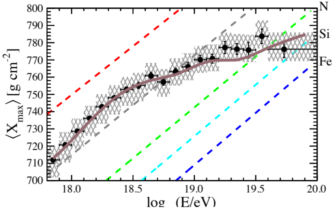


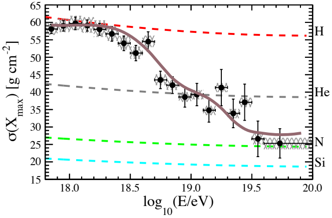
$A = 1$
$1 < A < 5$
$4 < A < 23$
$22 < A < 39$
$38 < A < 57$

Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{sys}(E)/E = 14\,\%$

X_{max} scale: $\sigma_{sys}(X_{max}) = 6 \div 9$ g cm^{-2}

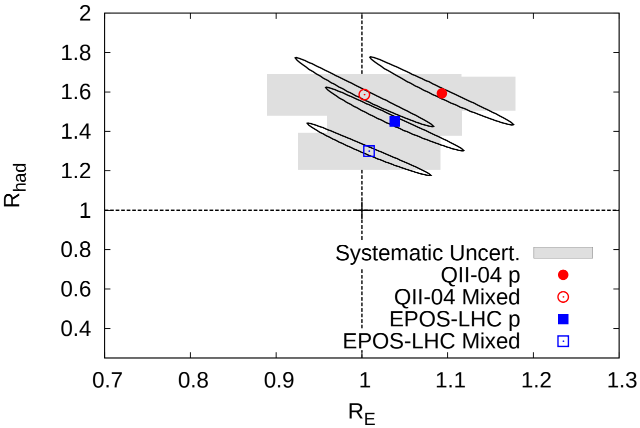


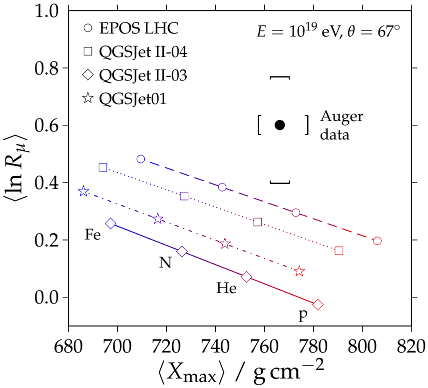


Different model scenarios considered for low-energy part
(transition to galactic component), similar results for total composition obtained

Probing hadronic interactions at UHE

R_{had} and R_{μ} related to the muonic component
R_{E} and X_{max} related to the electromagnetic component

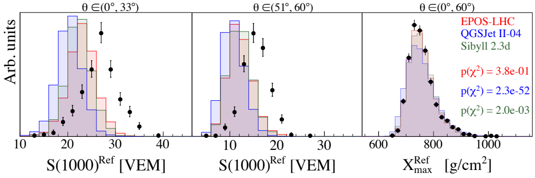




→ the number of produced muons is underestimated in simulations (see also contribution by Hans Dembinski)

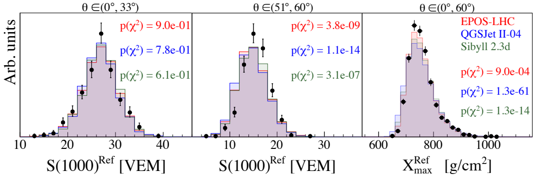
Modification of hadronic models

Combined fit of correlated Xmax distribution and S(1000) signal at ground



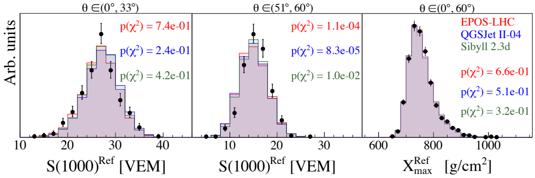
(a) No MC corrections

Combined fit of correlated Xmax distribution and S(1000) signal at ground allowing for an **angular-dependent muon re-scaling** (only mean muon number changed)



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

Combined fit of correlated Xmax distribution and S(1000) signal at ground allowing for an **angular-dependent muon re-scaling** (only mean muon number changed) and **shifting Xmax** of all primaries by fixed value

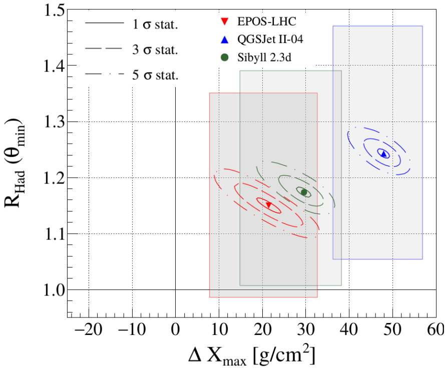


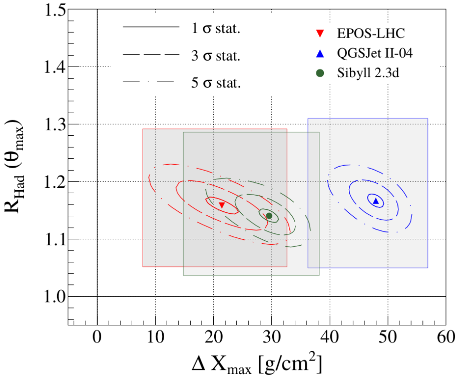
(c) MC corrections: ΔX_{max} and $R_{\mathrm{Had}}(\theta)$

(Jakub Vícha)

A shift in X_{max} and muon number required

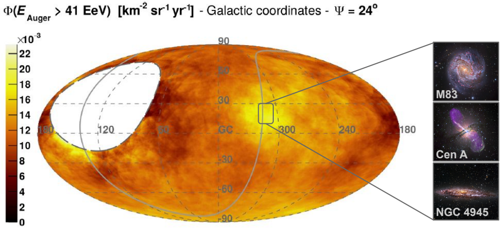
Assumptions: relative fluctuations no changed





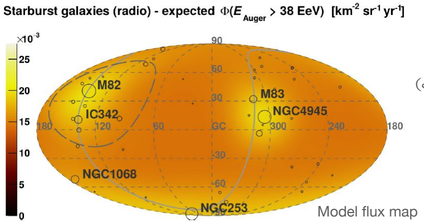
Main effect from re-scalling muon component in a zenih angle dependent way
Scalling X_{max} leads to further improvements

Anisotropies at small scales: correlations with catalogues



Direction fixed to that of Cen A, free E_{th} and Ψ

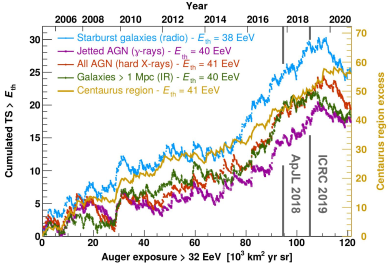
E_{th} > 41 EeV, Ψ = 27°: **3.9σ post-trial** deviation from isotropy (5% excess)



(Jonathan Biteau)

All data until end of 2020, optimized quality cuts: 120,000 km² s

Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}



4.(

3.1

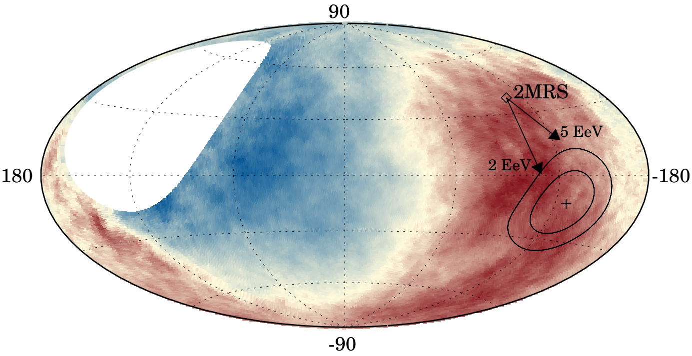
Linear growth of the TS

Expected 5σ reach in 2025-2030

Large scale anisotropy

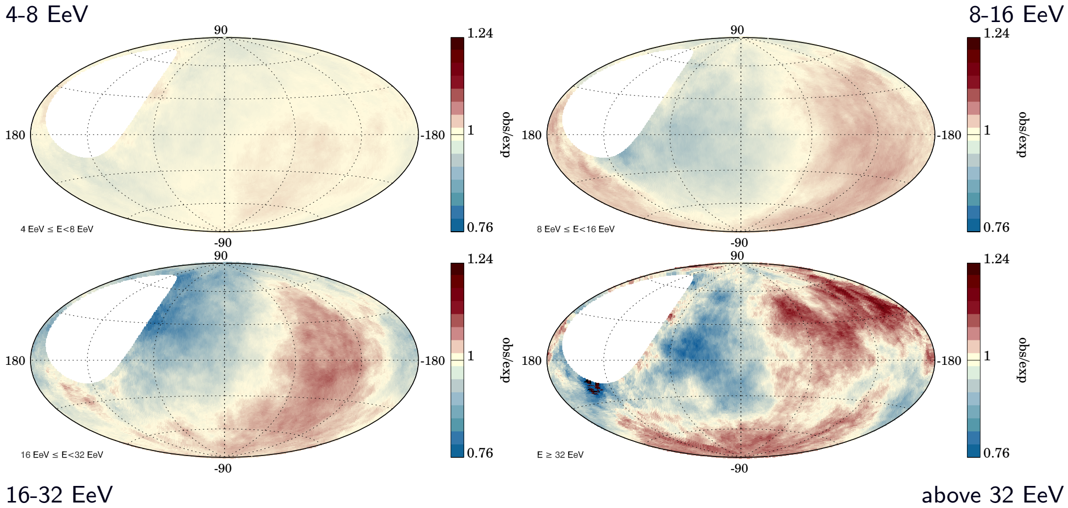
Harmonic analysis in right ascension α

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



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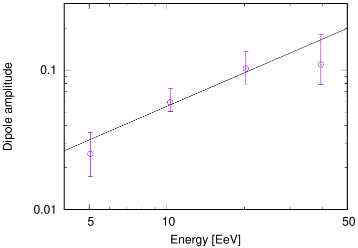
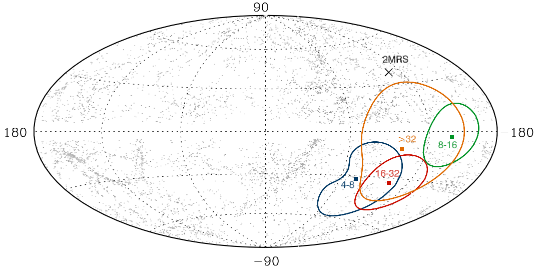
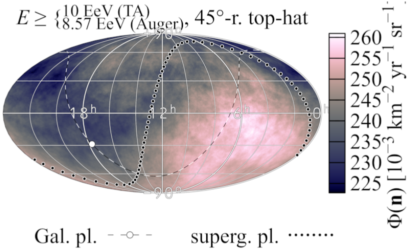


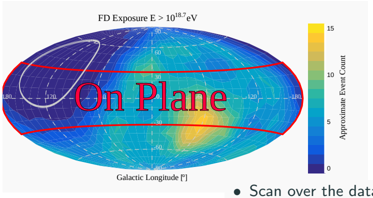


Energy-independent dipole amplitude disfavored at the level of 3.7σ

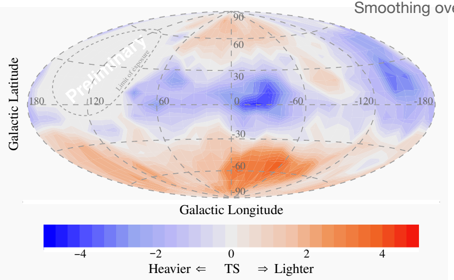
Combined analysis with Telescope Array coll.:
better constrain on the dipole direction



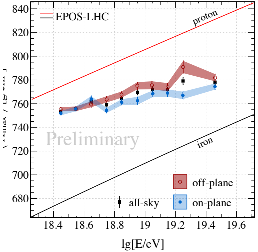
Mass composition ditribution over the sky

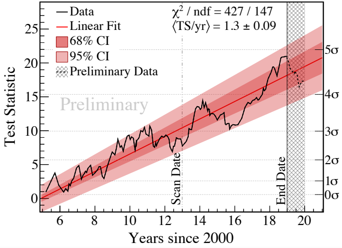


Smoothing over 30° b



- Scan over the data recorded before 01.01.2013 (54 %)
- 5° steps in b and 0.1 $\lg(E/\mathrm{eV})$ steps in energy
- Highest TS of 8.35 for: $\rightarrow E_{\mathrm{min}} = 10^{18.7}$ eV
  $\rightarrow b_{\mathrm{split}} = 30°$



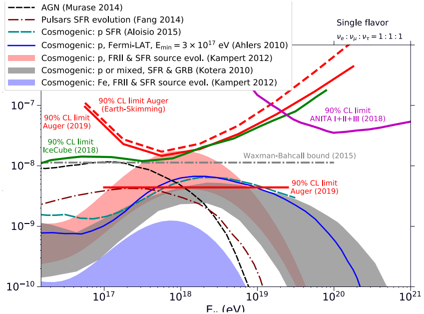


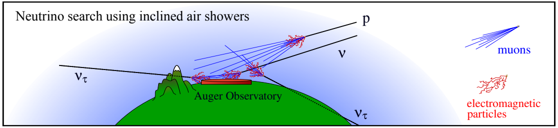
Mass dependent horizon effect?

No confrmation from other variables yet

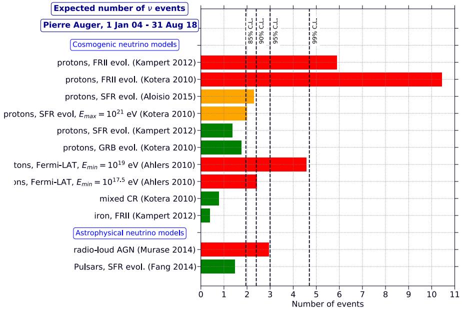
More data are needed (and more sensitivity)

Ultra high energy neutrinos





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



Multimessenger: searches of neutrinos in coincidence with GW

Sources searches: aperture compatible to IceCube for preferential directions

Future: we will lower the detection threshold with new electronics

Auger Prime upgrade

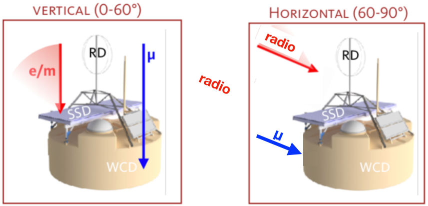
Physics motivation

- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers
- Much better understanding of **new and old** data

Components of AugerPrime

- 3.8 m^2 scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

Composition sensitivity with 100% duty cycle



(AugerPrime design report 1604.03637,

Construction of the SSDs complete

Summary

Pierre Auger Observatory: Phase I

- Very large exposure: 80000 up to 120000 km^2 sr year depending on the analysis
- The instep: a new unexpected spetral feature that could naturally be explained by the change in mass composition
- A change in the mass composition is established (light at 1 EeV getting heavier with energy)
- Composition highly linked to hadronic interactions and air-shower simulations
- Large scale anysotropies have been measured, small scale anisotropies hard to assess. The dipole and its energy dependency needs a complex interpretation involving the mass composition, the particle horizon, magnetic fields, local source distribution

Phase II

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

Auger data are now public (10%): opendata.auger.org