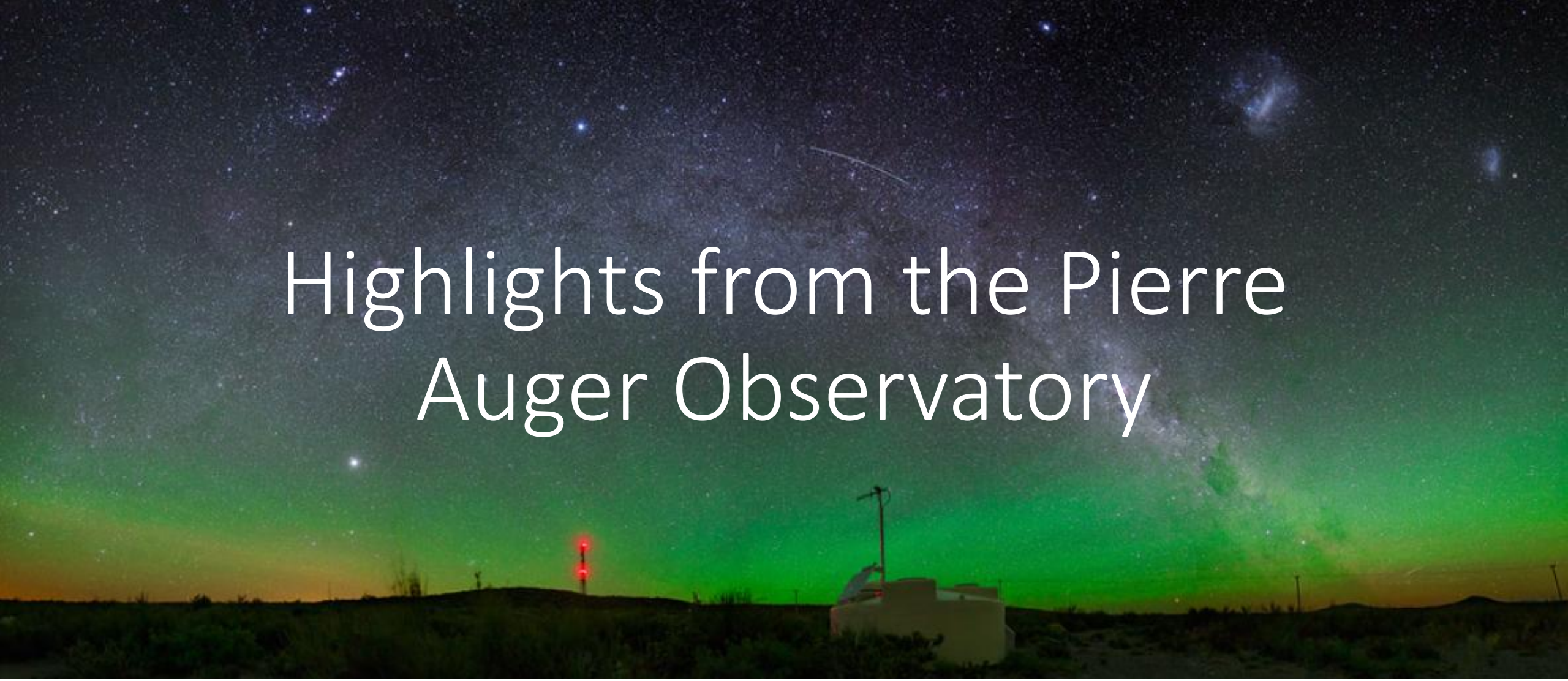


Highlights from the Pierre Auger Observatory

Petr Travnicek for the **Pierre Auger Collaboration**

FZU - Institute of Physics Czech Academy of Sciences

Tatra Astro Summit 2025, 22 – 26 September, 2025 / Stara Lesna, Slovakia

Outline

- Pierre Auger Observatory (+ CZ activities)
- Energy spectrum measurement
- Depth of shower maximum, Composition related studies
- Large and medium size anisotropies
- Neutral particles
- Muon puzzle

- Phase II data - AugerPrime and its scientific potential

UHECR observatory – connecting Particle physics and Astrophysics

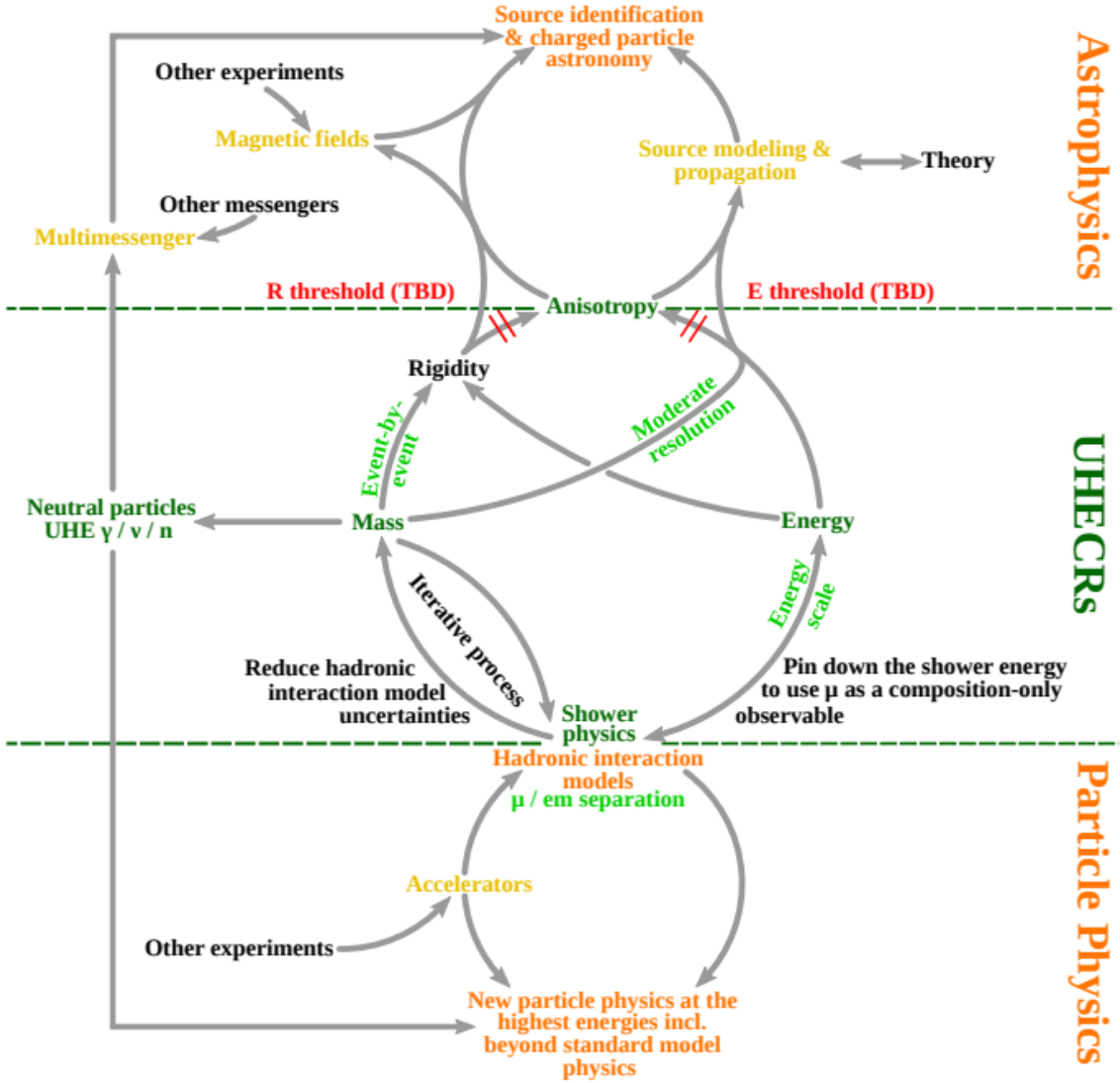
50 years of searching for ultra-high energy (>10 EeV) sources – energy far beyond man made accelerators

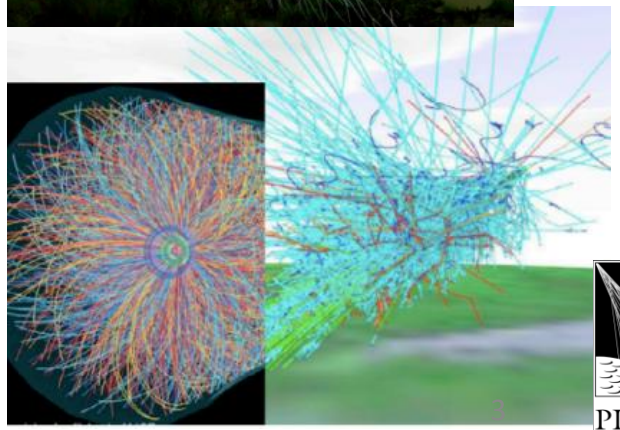
New opportunities in multi-messenger observations

Revealing unknown UHECR composition

Particle physics beyond LHC capabilities

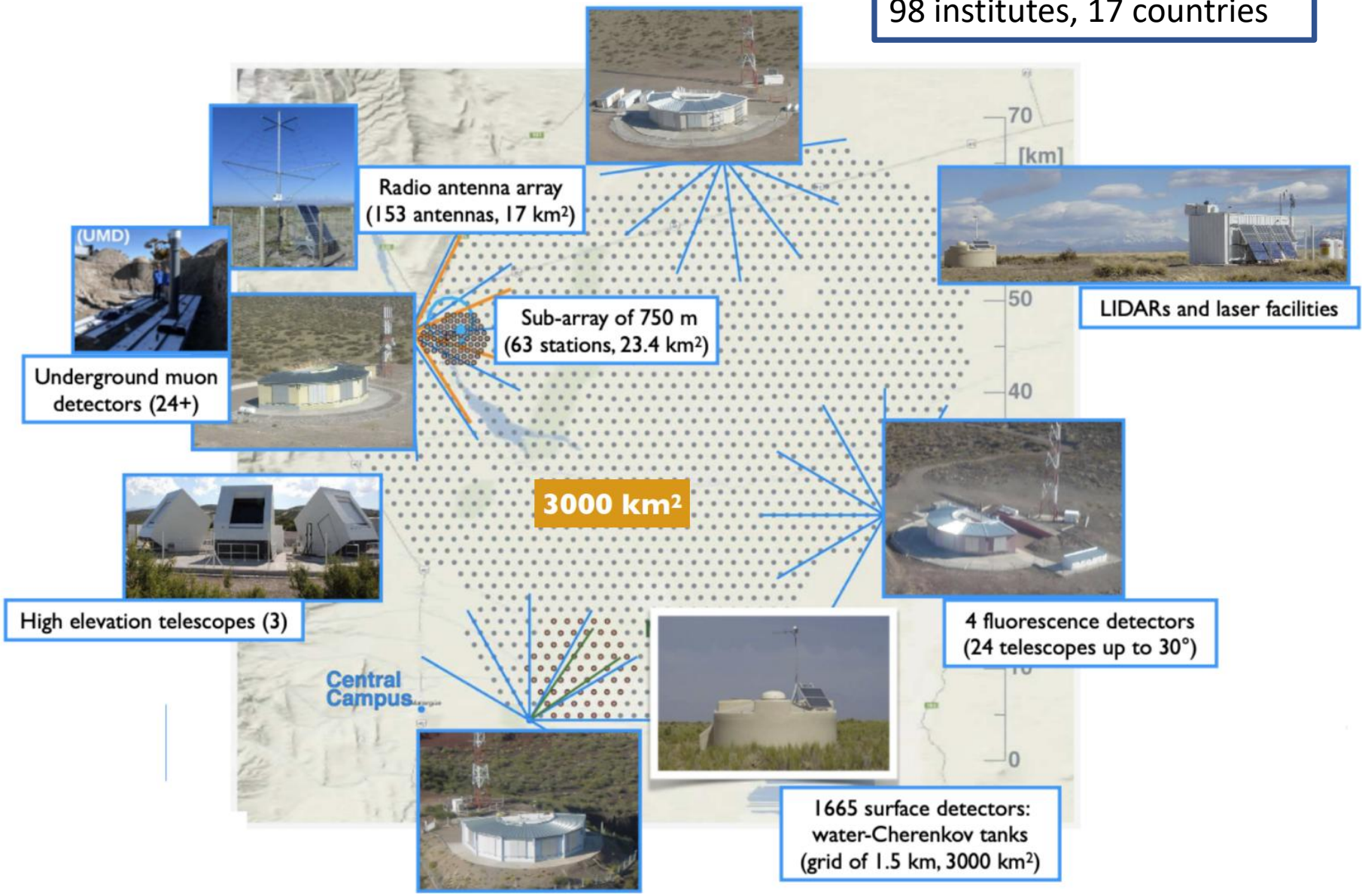
Picture from
https://arxiv.org/pdf/2205.05845.pdf





Pierre Auger Observatory

More than 400 members,
98 institutes, 17 countries



Phase 1 : data taking from 2004 on (from 2008 with the full array in operation):
✓ Over 120, 000 km^2 sr yr for anisotropy studies
✓ Over 90, 000 km^2 sr yr for spectrum studies

Phase 2 : the AugerPrime upgrade Data taking from 2025 to 2030…
✓ + 40, 000 km^2 sr yr
✓ Multi-hybrid events : FD, SD, SSD, RD, UMD

Pierre Auger Observatory – CZ activities - aim to be a valuable partner in the international team

HW:

- Optical lab in Olomouc – see Petr Hamal talk
- AUGERPrime – new electronics
- Atmospheric monitoring – FRAM + related astronomical research
- MC@GRID computing leadership
- Fluorescence detector leadership

Data analysis:

- Hadronic interactions
- CR phenomenology and theory (new) – V. Karas impact A. Araudo forming a new team now within FZU
- Cosmic ray composition
- Energy spectrum – low energy extension

First CZ “astroparticle” project and mother of our other activities:

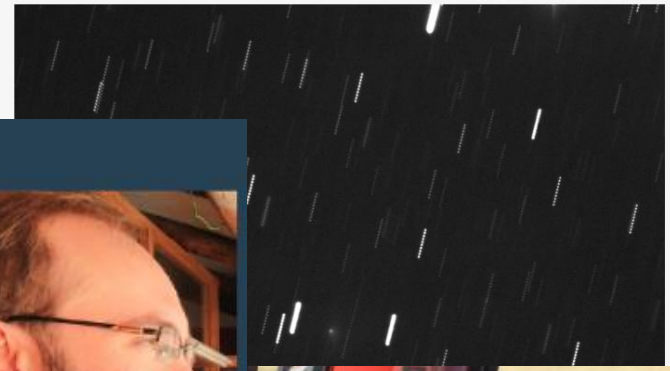
- Cherenkov Telescope Array + SST-1M (see Patrik Čechvala talk)
- SWGO, …

Eva Maria Martins dos Santos of the FZU received the Auger Impact Award 2023

New "Christmas" comet discovered by Czech, named C/2024 Y1 (Mašek).

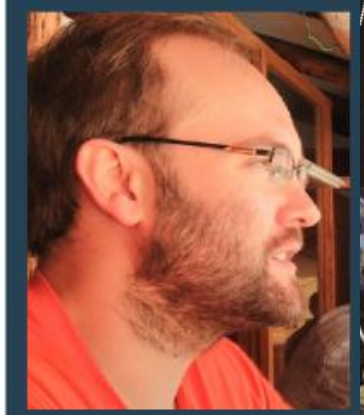
12/31/2024 Mgr. Petra Köppl Research

Update 1. 1. 2025 A new comet was spotted on the night of 24–25 December 2024 by scientist Martin Mašek from the Institute of Physics over the western horizon in Argentina. He operated the telescope onli from Liberec (city in the Czech Republic). This is the first Czech discove a comet where the observer was not physically present in the observatory, and the first Czech discovery from the southern hemisphere. The comet will not appear above our horizon until late February or early March.



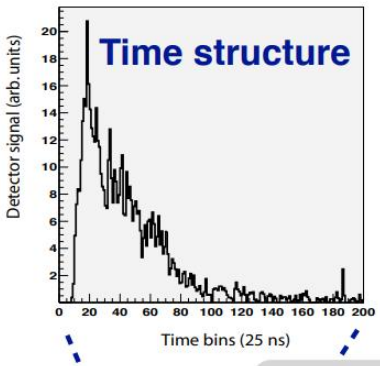
PIERRE AUGER OBSERVATORY

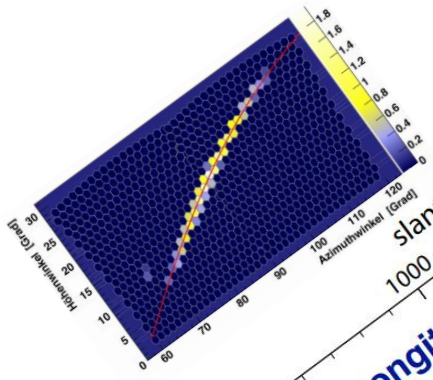
Impact Award 2021

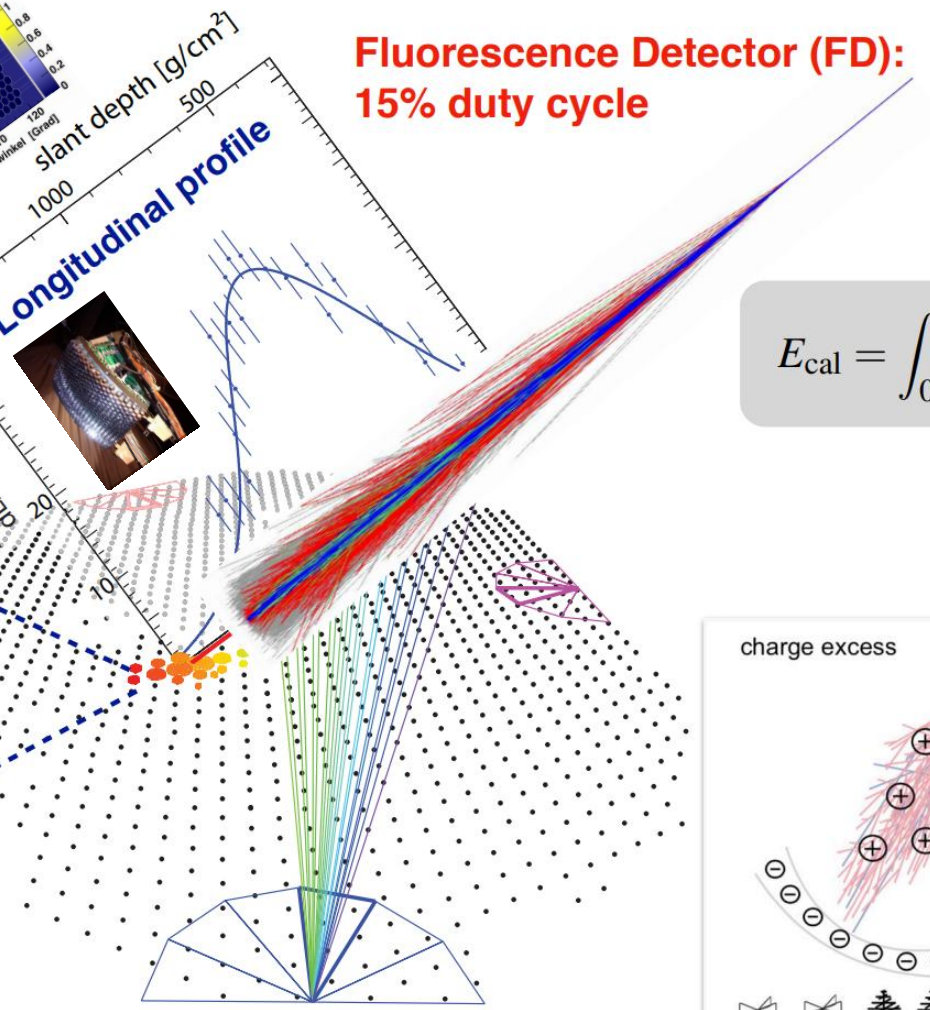


Vladimir Novotny

How Pierre Auger Observatory measures UHECR ?



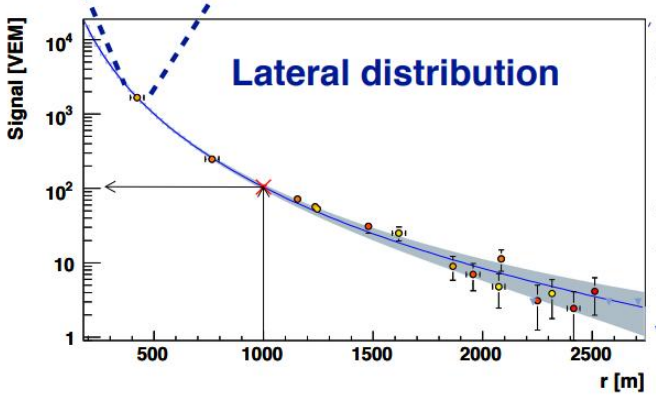




Fluorescence Detector (FD):
15% duty cycle

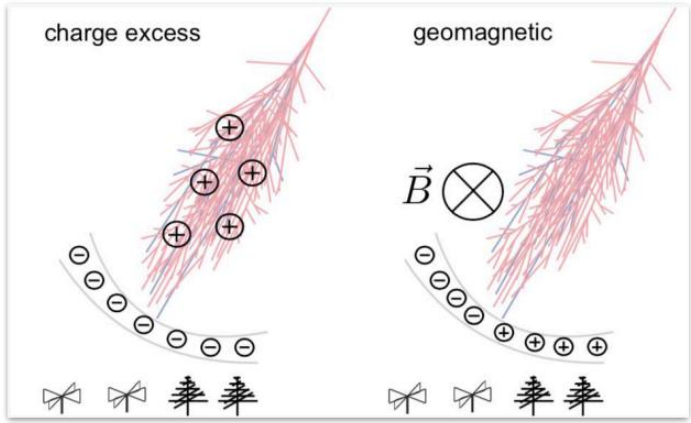
$$E_{\mathrm{cal}} = \int_0^{\infty} \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$



Surface Detector (SD)
100% duty cycle

Radio Detector (RD):
100% duty cycle



Picture from Ralph Engel, ICRC2021

How precise is the reconstructed energy?

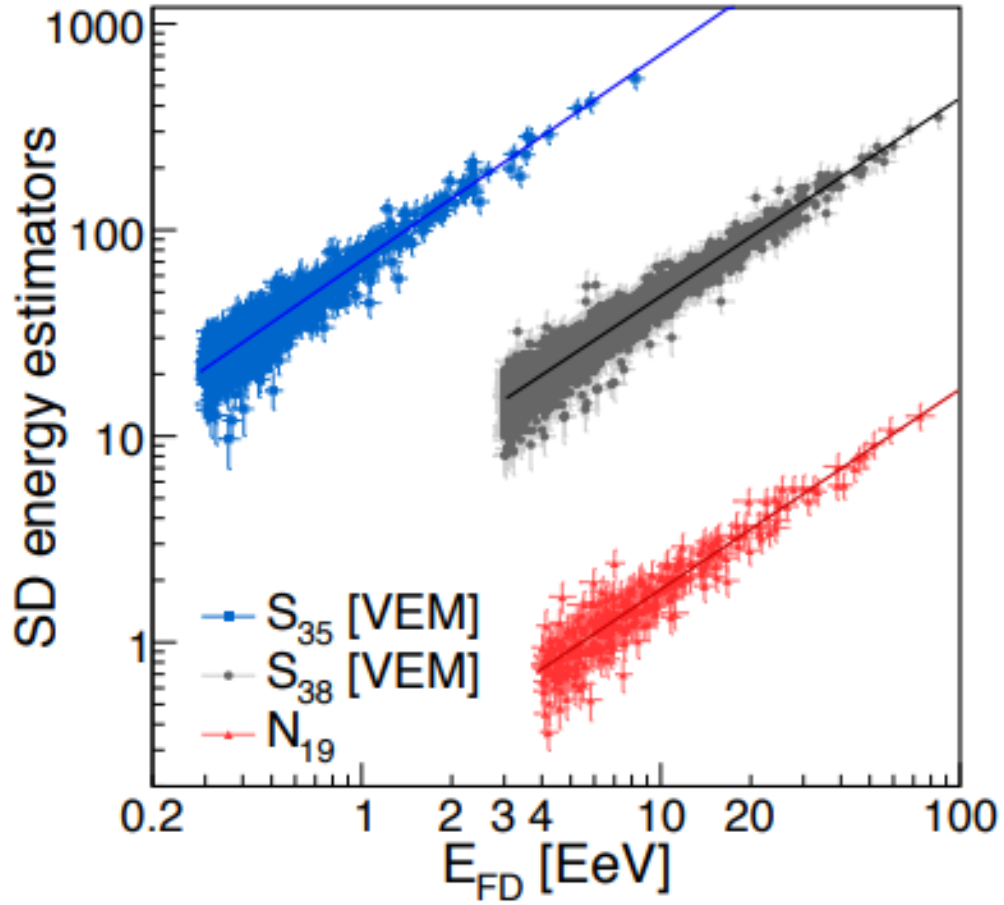
Energy systematic uncertainties:

FD profile reconstruction, Atmospheric conditions, Stability of the energy scale, Fluorescence yield, Invisible energy, Statistical error of SD calibration fit

FD energy scale: ~ 14%

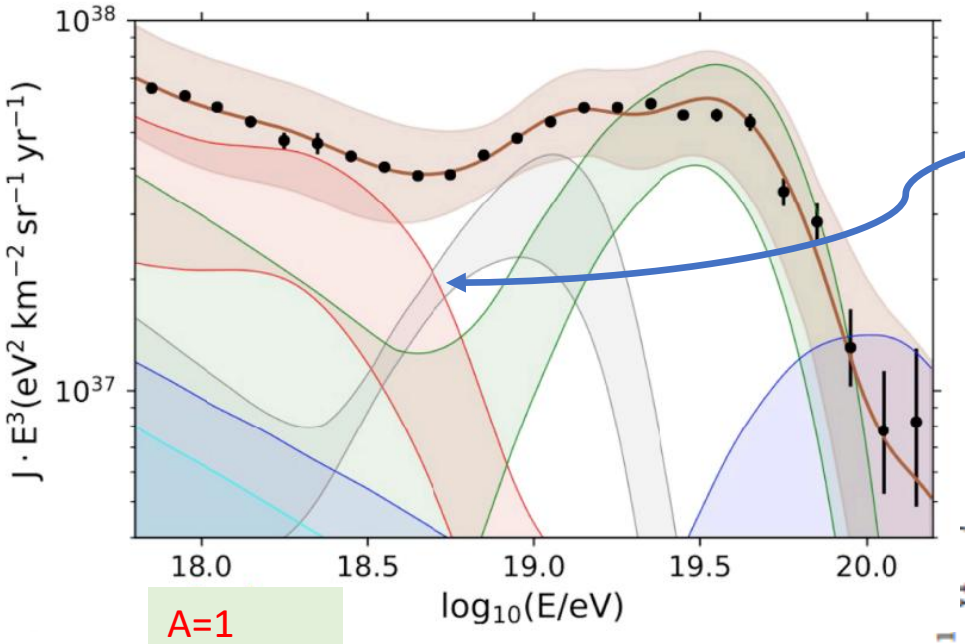
SD resolution for energy reconstruction: **Energy: ~ 20% (@2 EeV) to ~ 7% (@ >20 EeV)**

Hybrids (FD + at least 1 SD station): **Energy resolution ~ 7%**

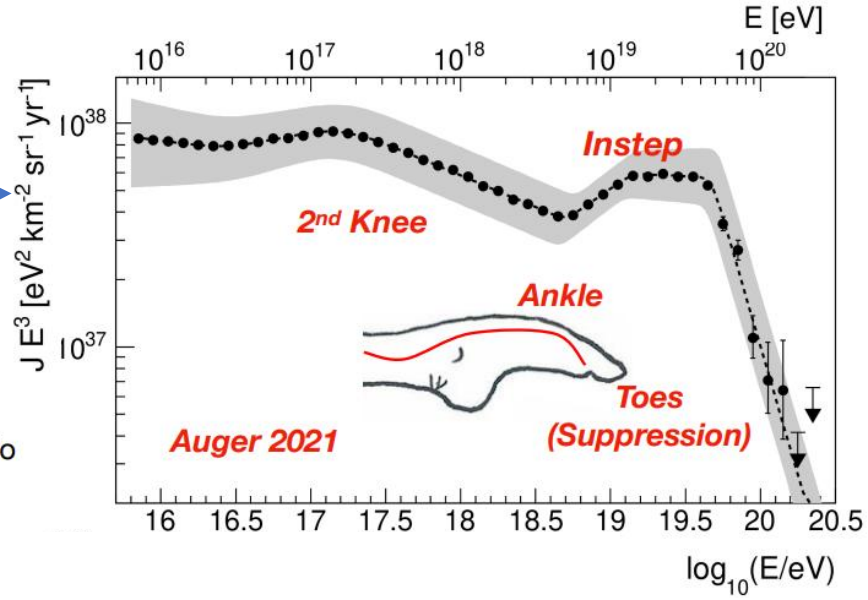


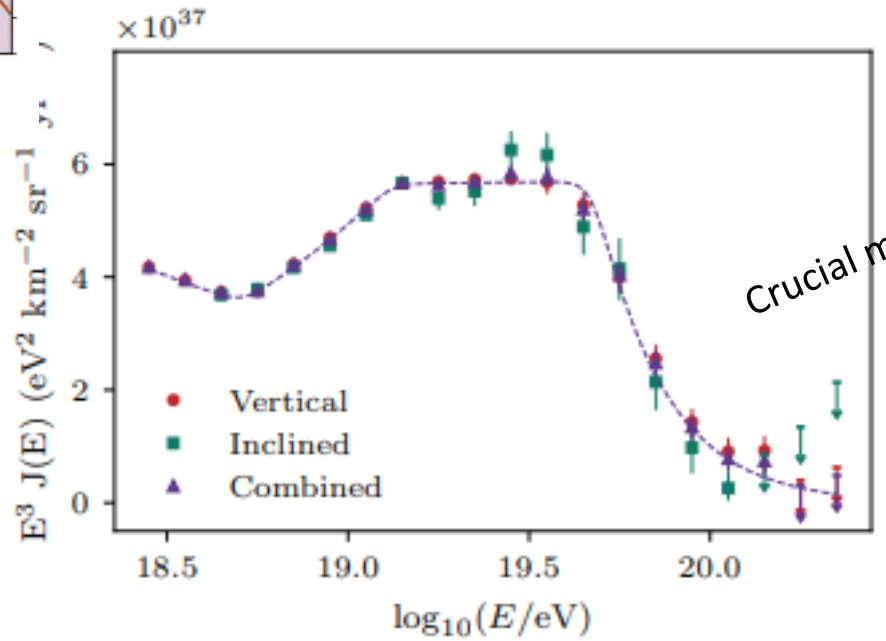
Features of the energy spectrum of cosmic rays above 2.5 x 10^{18} eV using the Pierre Auger Observatory, Phys. Rev. Lett. 125, 121106 (2020)
Measurement of the cosmic ray energy spectrum above 2.5 x 10^{18} eV using the Pierre Auger Observatory, Phys. Rev. D 102, 062005 (2020)

Energy spectrum of UHECR



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



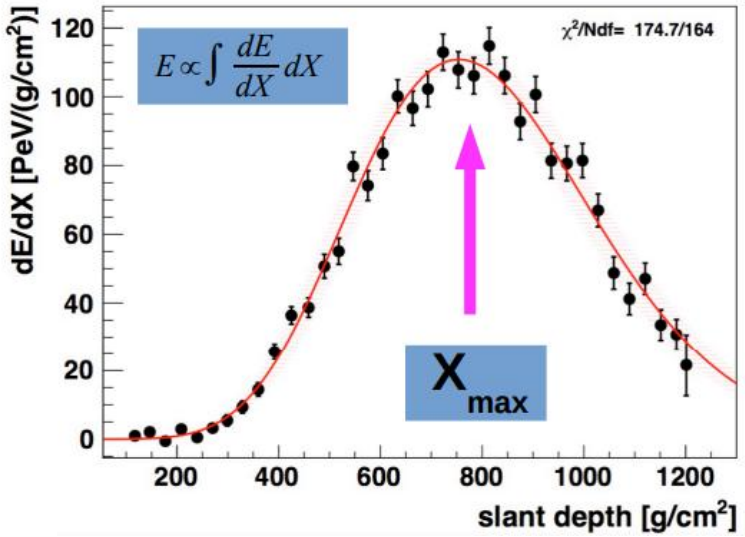


Crucial measurement with astroph. implications

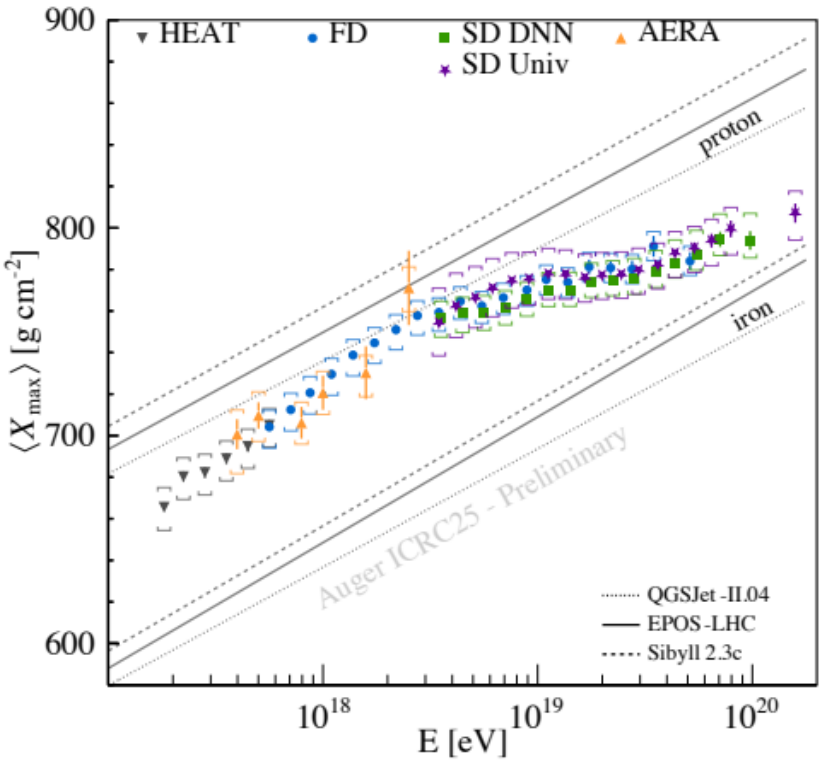
A.Aab et al., PRL 125, 121106 (2020)
A.Aab et al., PRD 102, 062005 (2020)
A.Aab et al., Eur. Phys. J. C81 (2021)
V.Novotny for the Pierre Auger Coll., ICRC 2021, #324
Diego Ravignani ICRC 2025

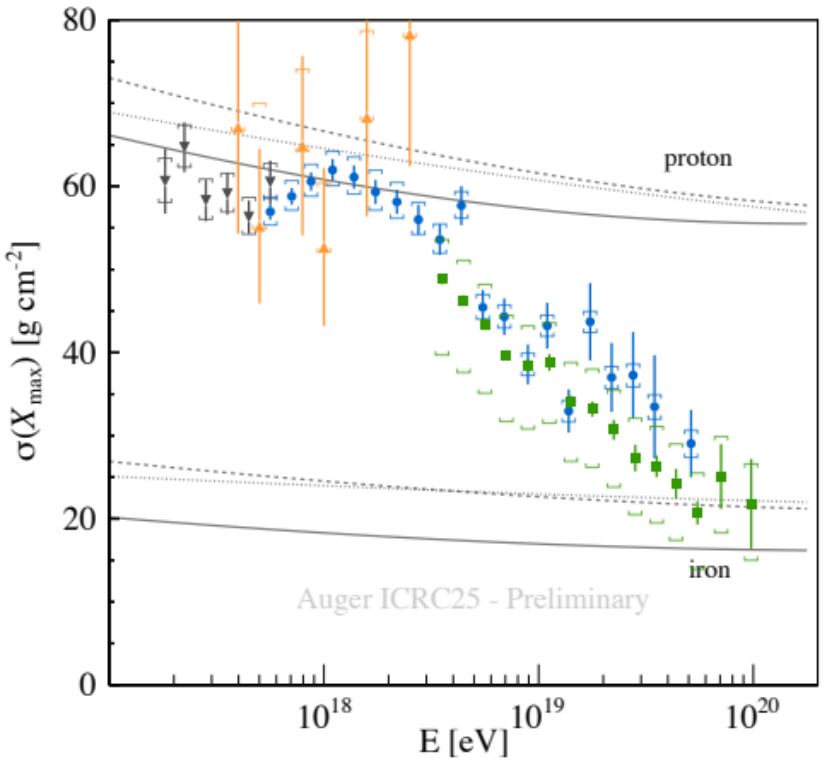
Position of shower maximum

- Transition towards heavier composition around 2 EeV
- Break in $\langle X_{max} \rangle$ vs E below the Ankle energy (break in RMS(X_{max}) at roughly the same energy)



E. Mayotte at ICRC 2025





Elongation rates
(~80) g/cm^2/decade below and
(~26) g/cm^2/decade above ~ 2 EeV

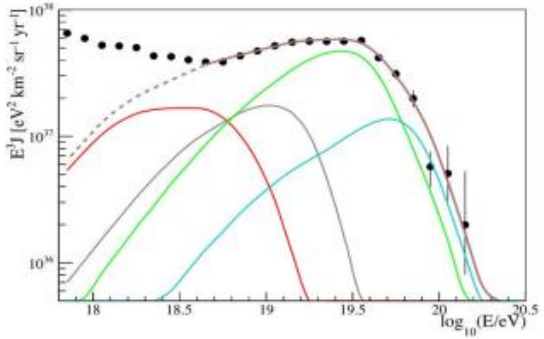
X_max from SD
NEW methods from SD data (see baskup slides Phys. Rev. Lett. 134 (2025) 021001)

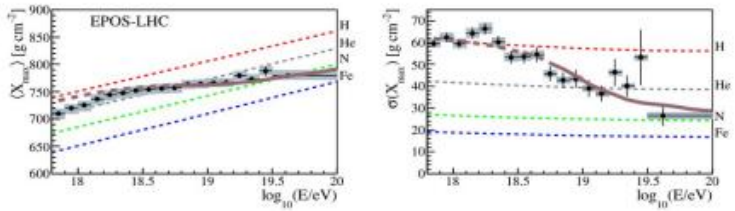
Combined fit: spectrum + composition

E. Roulet at ICRC 2025

$E > 10^{18.7}$ eV JCAP 04 (2017) 038

fit with one population above ankle



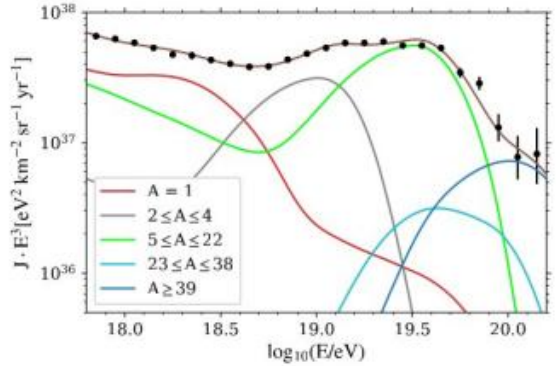


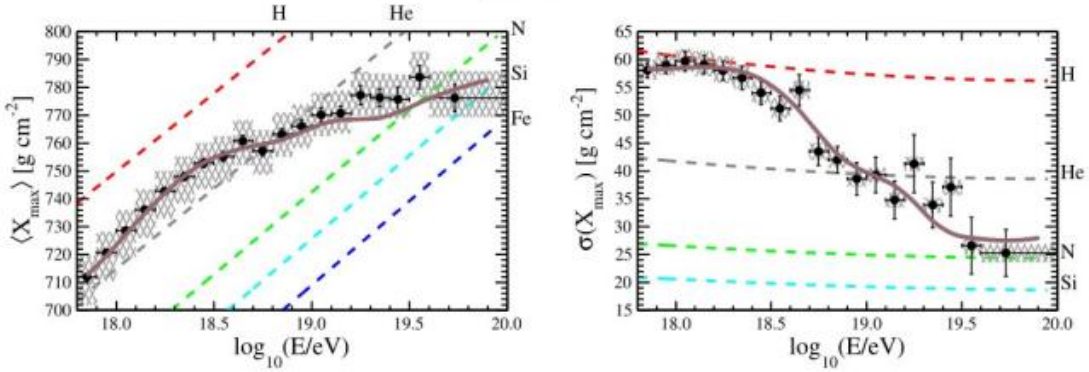
model	γ	$\log_{10}(R_{cut}/V)$
EPOS-LHC	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$
Sibyll 2.1	$-1.50^{+0.05}$	$18.28^{+0.00}_{-0.01}$

hard spectrum, low cutoff, increasingly heavy

$E > 10^{17.8}$ eV JCAP 05 (2023) 024

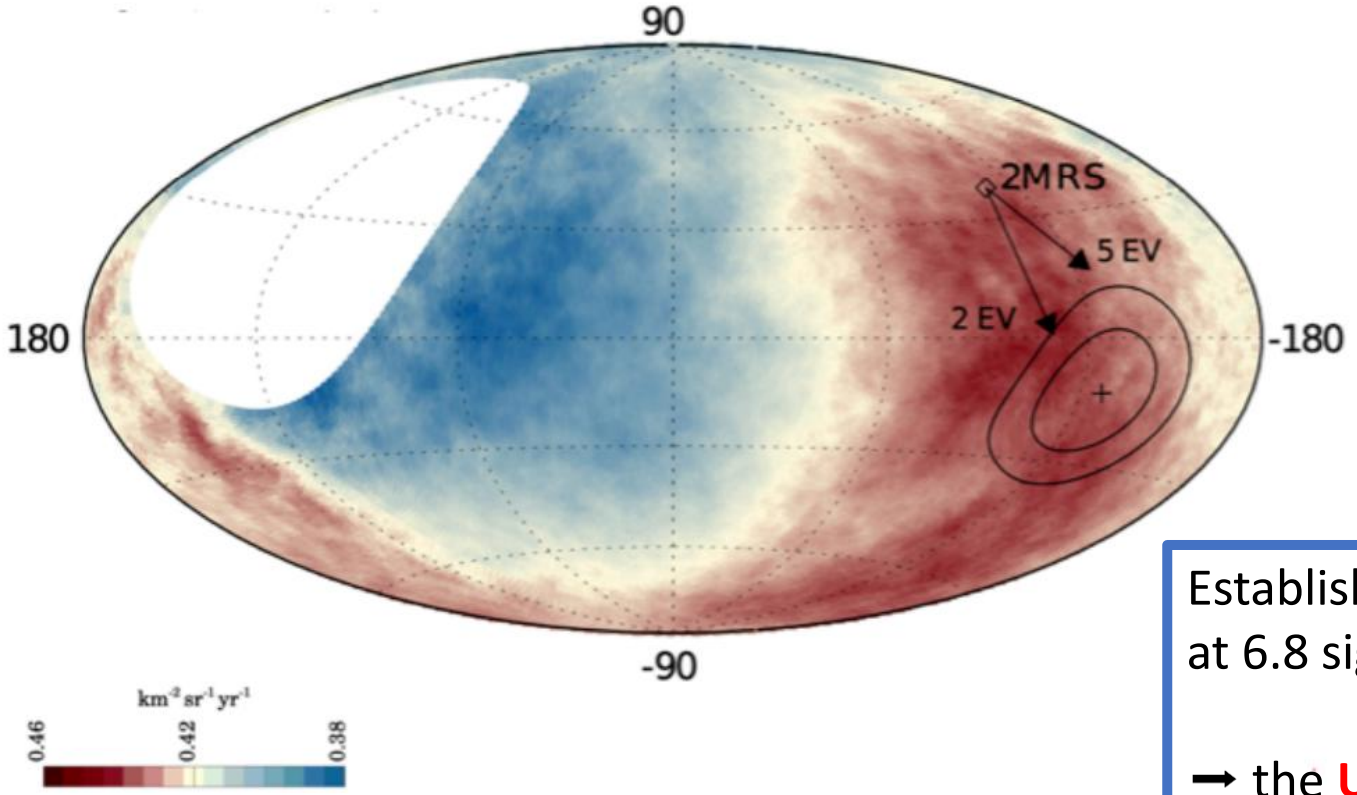
fit with two populations across ankle





low energy population lighter and steeper

Large scale anisotropy



Auger Coll., Science 357 (2017) 1266;
ApJ. 891 (2020) 142;
Auger Coll., ApJ 976(2024)48

Established dipolar modulation in RA: E >8 EeV at 6.8 sigma and 8 EeV<E<16EeV at 5,7 sigma

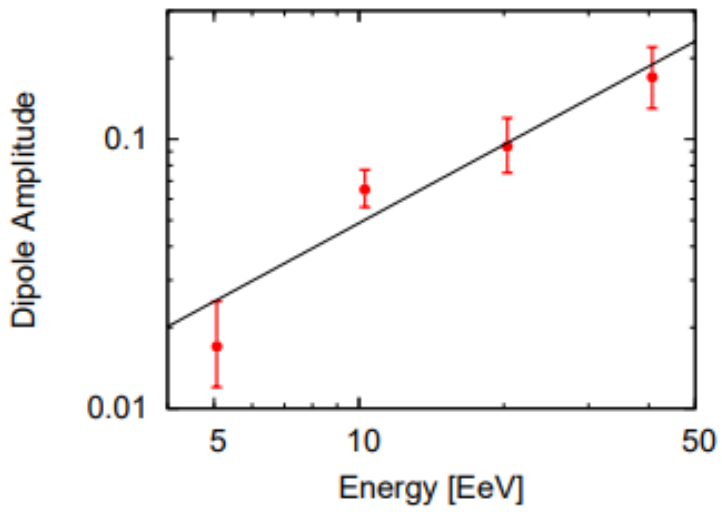
➞ the **UHECRs are extra-galactic** above 8 EeV, while predominantly Galactic below few EeV

Important factors

- Mass composition
- Source distributions
- Magnetic fields deflections
- Quadrupole components not significant

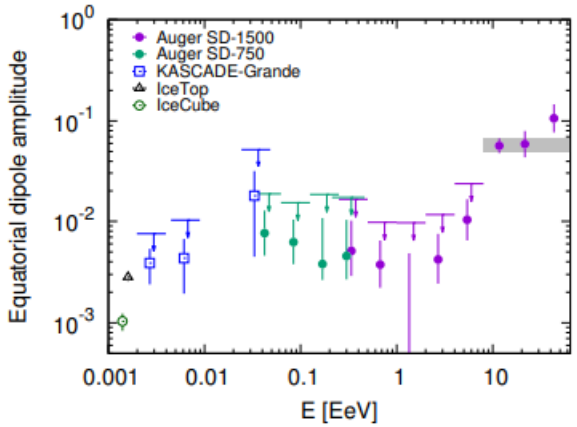
Large scale anisotropy

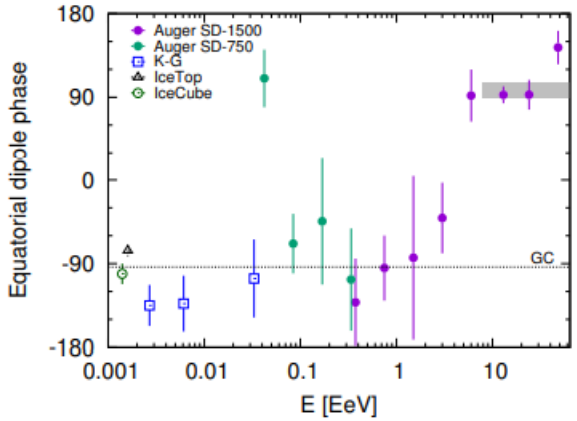
Auger Coll., Science 357 (2017) 1266;
ApJ. 891 (2020) 142;
R. De Almeida, PoS(ICRC2021) 335
Auger Coll., ApJ 976(2024)48

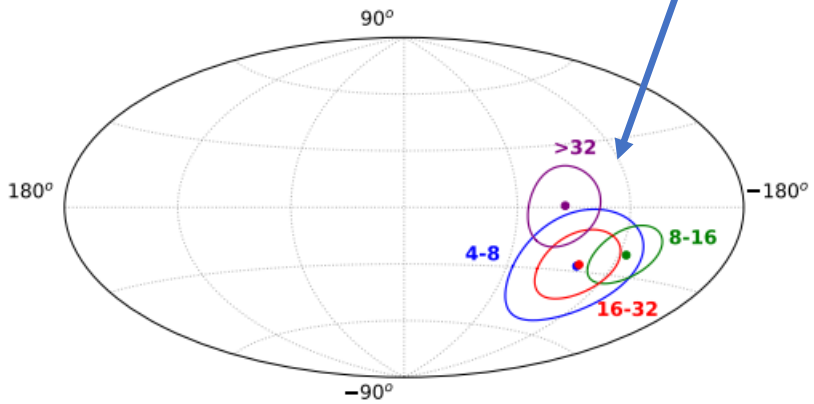


- Increase of amplitude with energy
- Dipole direction stays in the same region
- Location consistent with mixed composition deflected by galactic magnetic fields

> 100 deg from Galactic center !!! – extragalactic origin!

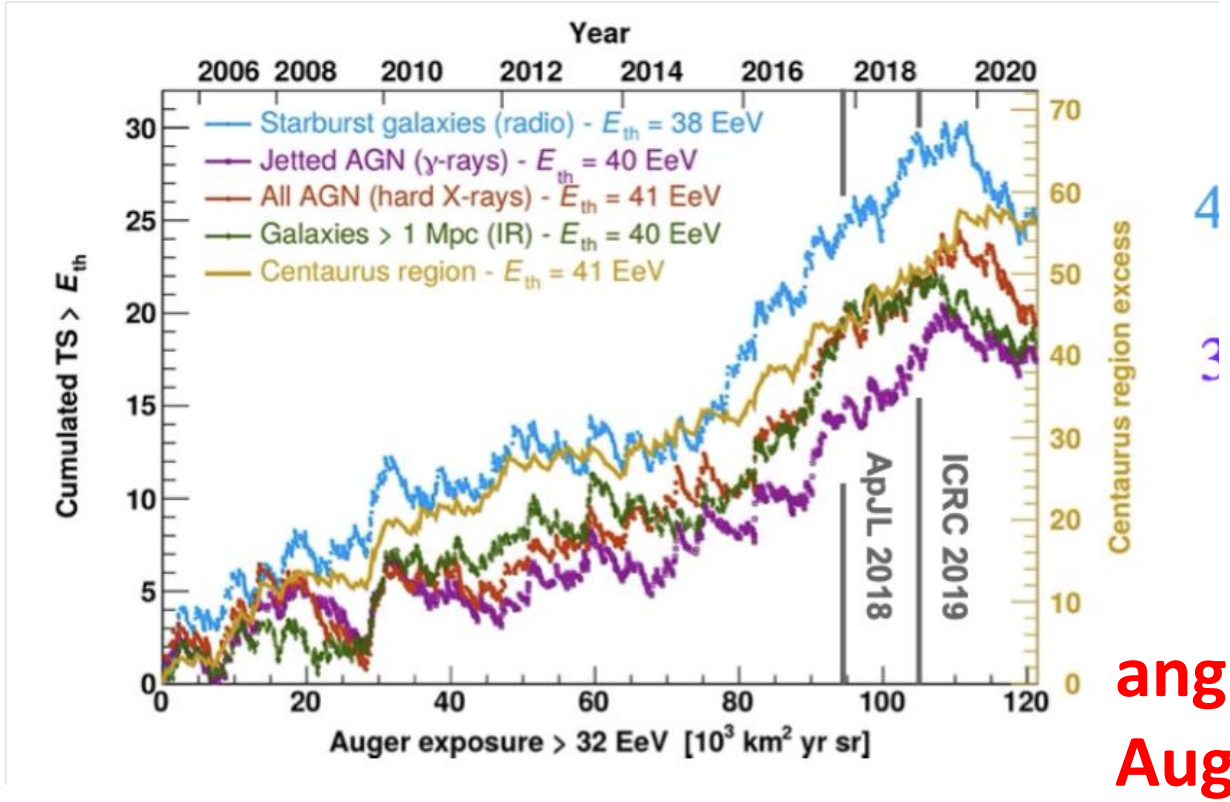


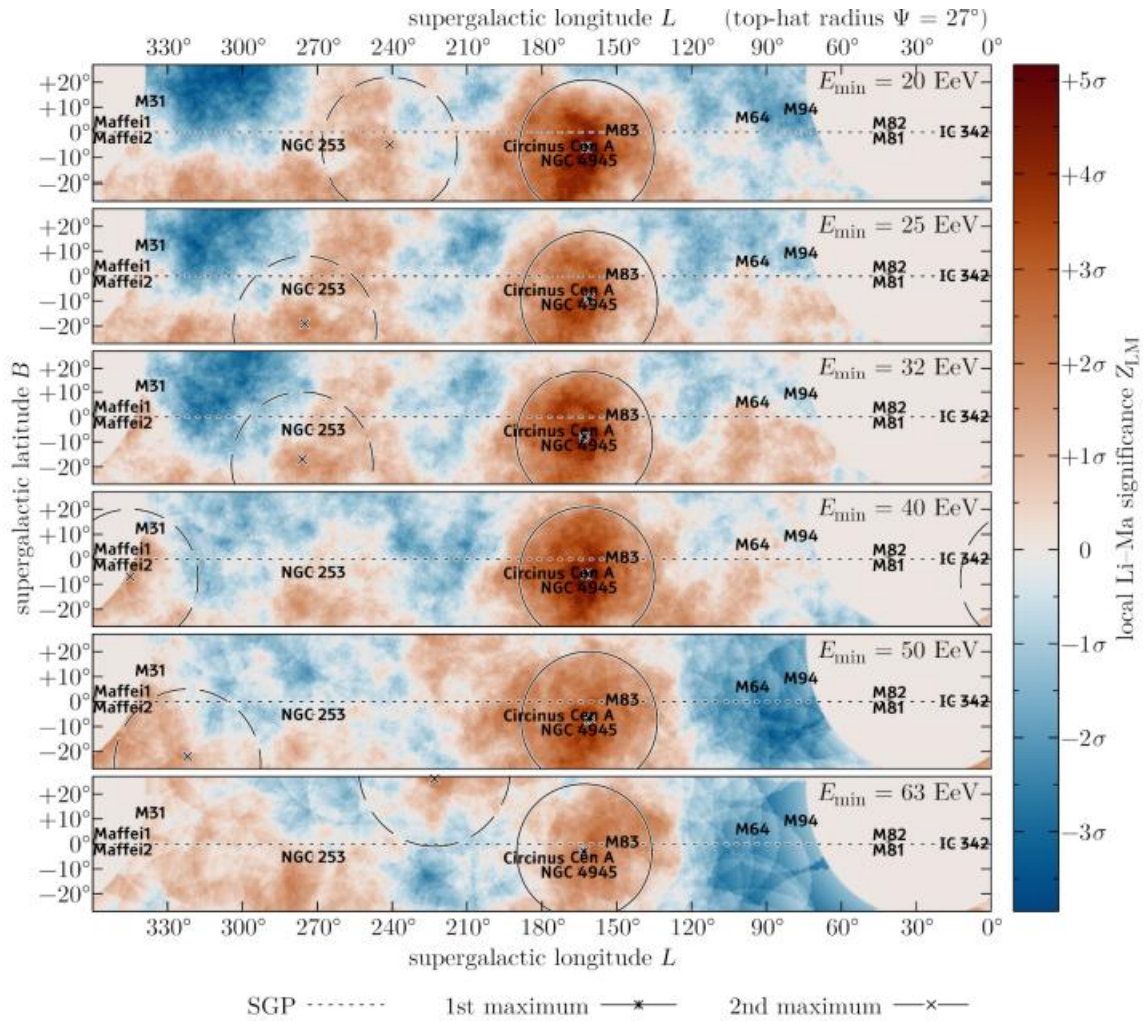




Intermediate scale anisotropy

J.Biteau for the Pierre Auger Collaboration, ICRC2021 #307
A.Aab et al., Ap. J. Lett 853 L29 (2018)
The Astrophysical Journal 935 (2022)170 – Startburts, jetted, Centaurus
ApJ 984 (2025) 123 – *Galactic plane*



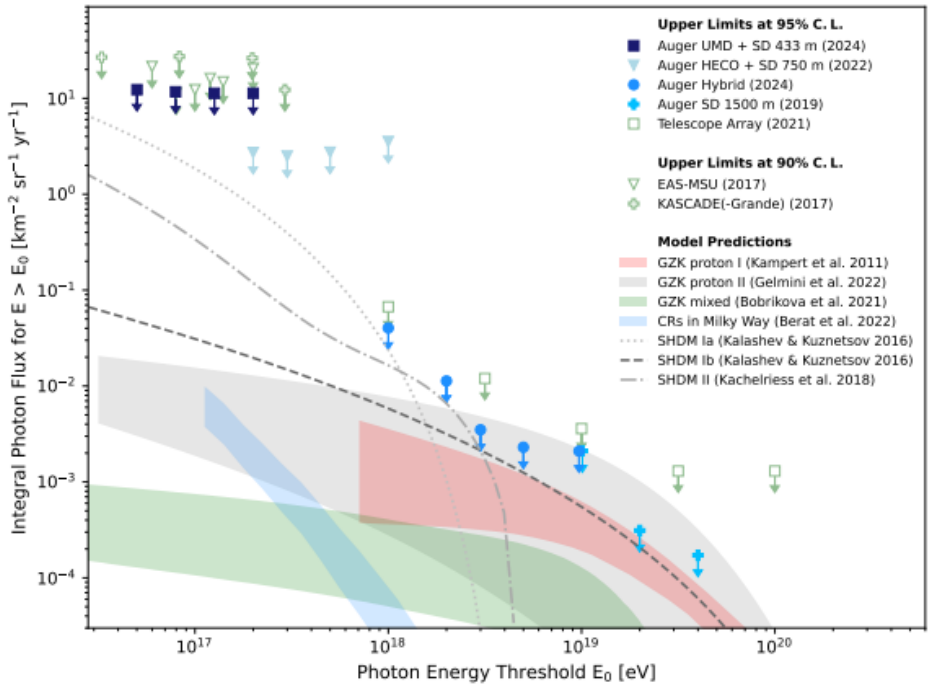


angular scale of ~ 25 deg and E ~ 40 EeV
AugerPrime – discoveries reachable

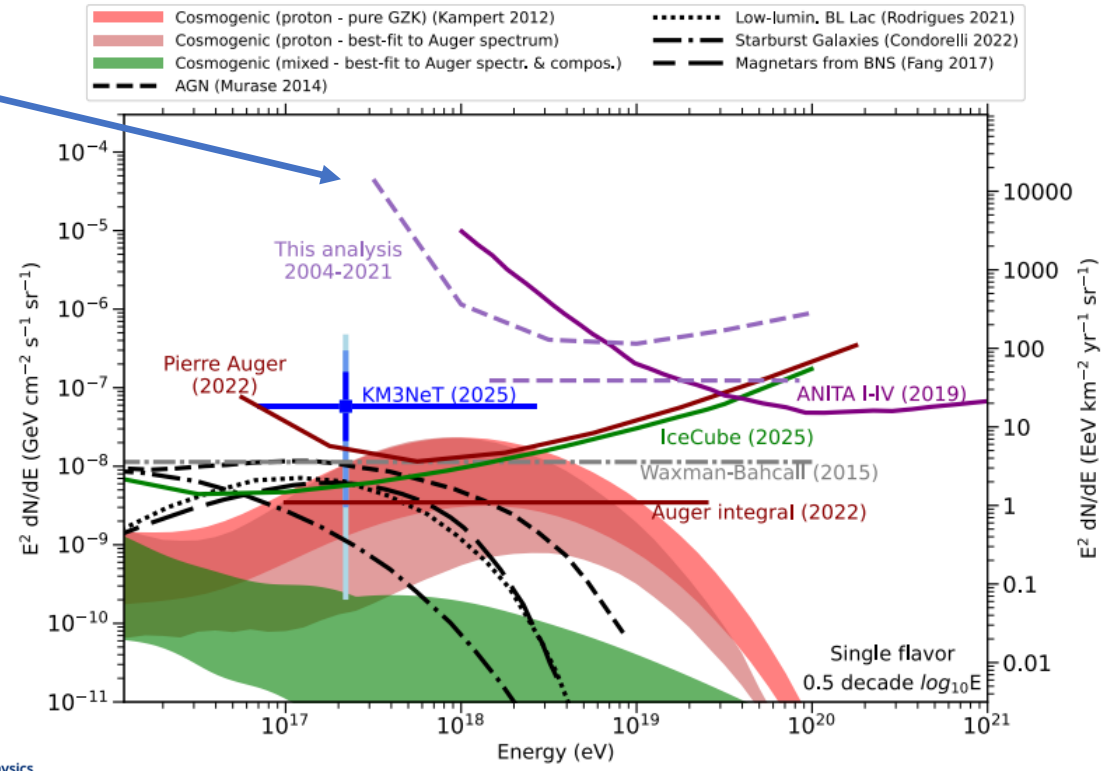
Neutral particles

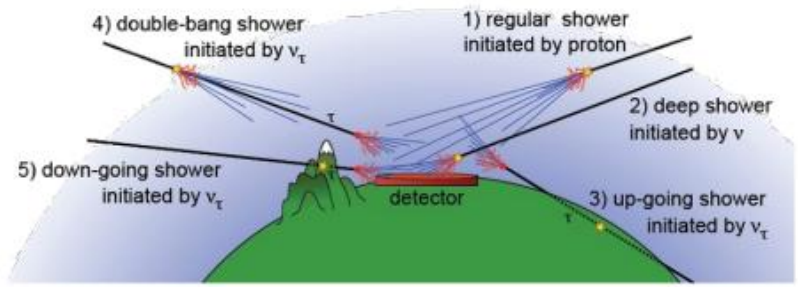
Photons: Pierre Auger Collaboration, Astrophys. J. 933 (2022) P. Savina at ICRC 2025
Neutrinos: Aab et al., JCAP 10 (2019), JCAP 11 (2019)
A.Sehgal at ICRC 2025

Photons



Neutrinos



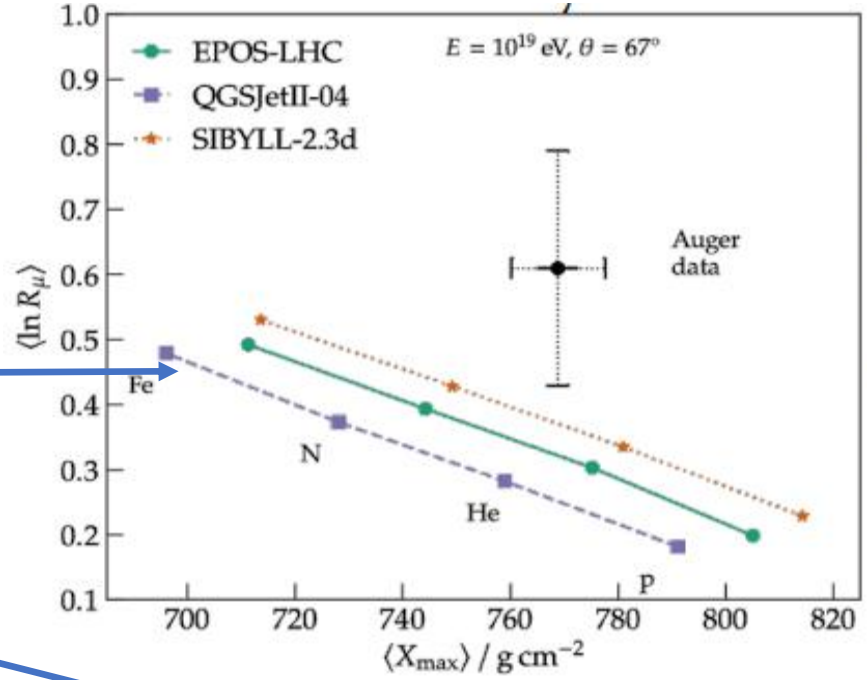


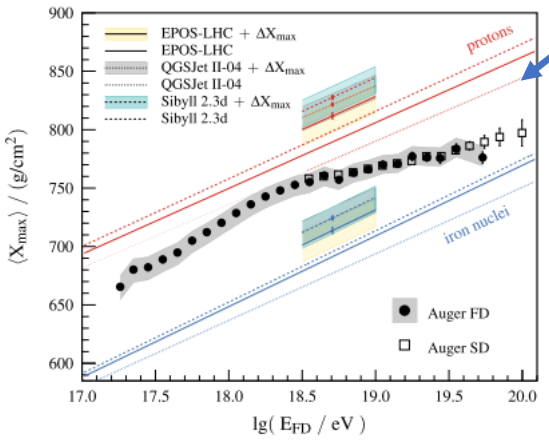
Muon puzzle

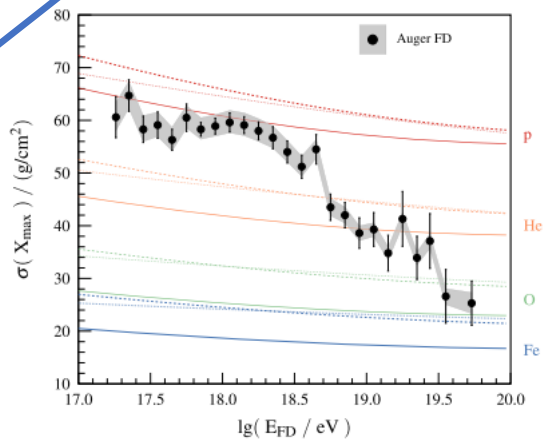
A.Aab et al., PRL 126 (2021) 152002
Pierre Auger Collaboration, Eur. Phys. J. C80 (2020)
J. Vicha, et al, PoS(ICRC2021)310
Pierre Auger Collaboration, Phys. Rev. D 109 (2024) 102001.

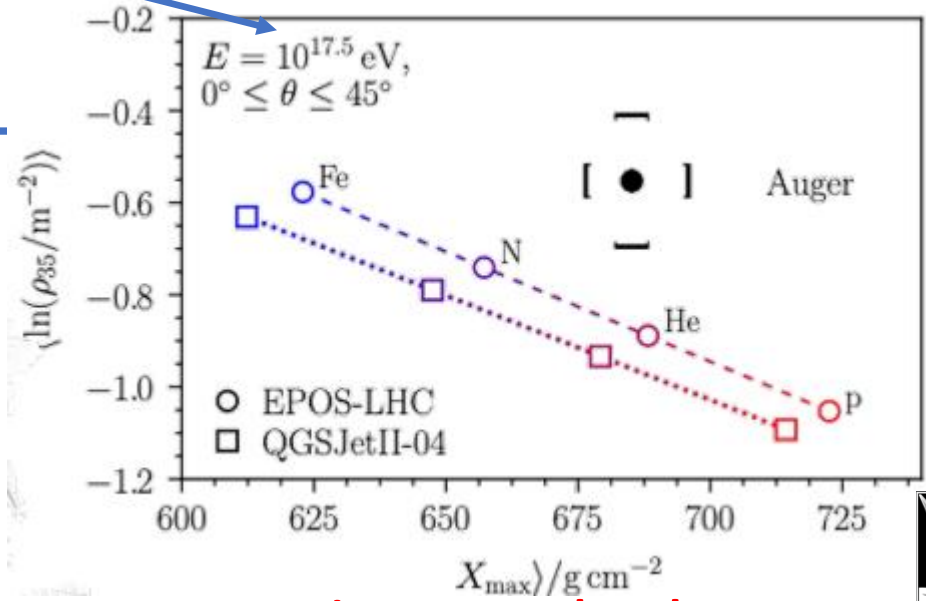
- Muon excess (30 - 80 %) in data wrt simulations seen in all analyses
- Inclined hybrid events
- Muon detectors (AMIGA)
- SD only – universality
- Muon number fluctuations OK (cumulation effect in many interactions)

- Many attempts to explain muon puzzle – modification of interaction models, phenomenology, data driven (muon and X_{max} shifts) …









AugerPrime – to solve the muon puzzle !

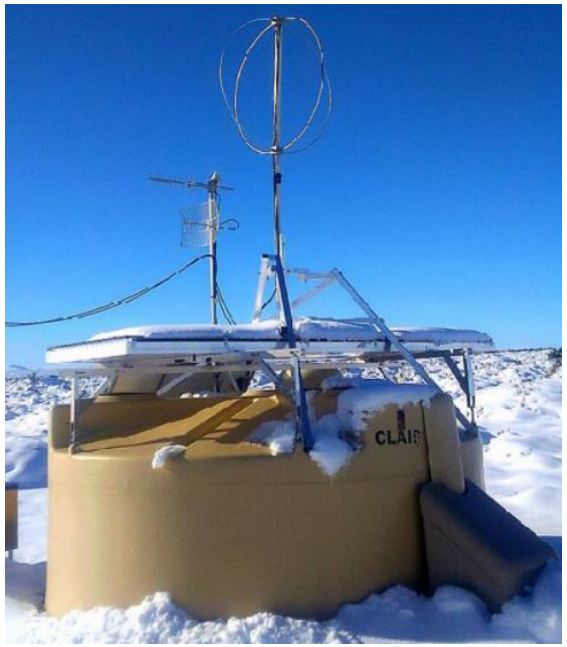
Results of Phase I (before AugerPrime)

- **Flux suppression well established** : the UHECR sources must be nearby (< 200 Mpc)
- **Composition mixed and heavier above ~ 2×10^{18} eV** from Xmax measurements … but statistics too low above ~$10^{19.5}$ eV due to FD duty cycle ~15%
- **Large scale dipolar anisotropy (6.8 σ) : extragalactic origin for UHECR > 8 EeV** + Hints of correlation with at intermediate angular scale
- **Muon puzzle**: muon content in simulations lower than in data ⇝ Tension with all hadronic models
- **Strong limits on the flux of neutrinos and gammas**: "standard" astrophysical scenarios of UHECR production
- … and many more

Future of the Observatory - AugerPrime – Phase 2

Water-Cherenkov station (WCD):

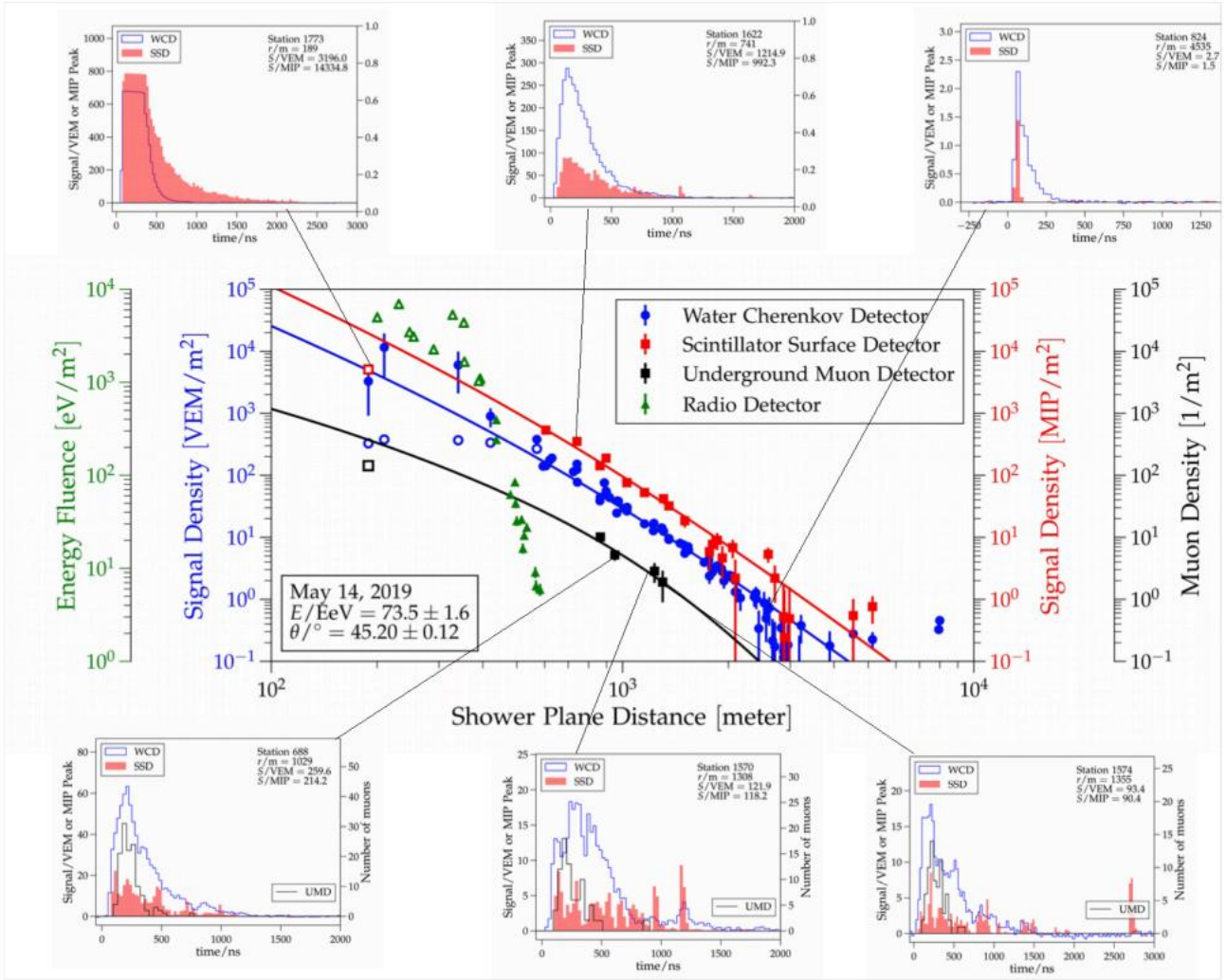
- addition of the the SSD (Surface Scintillator Detector) - to measure the mass composition in combination with the WCD
- addition of the RD (Radio Detector) - to measure the radio emission of showers in atmosphere (30-80 MHz)
- New electronics, wider dynamic range - to process the signals of all detectors (40 MHz -> 120 MHz, better GPS timing), small PMT (sPMT) to increase the dynamic range of the WCD ($\gtrsim$ 20,000 VEM)



Infill region (61 WCD):

- the UMD (Underground Muon Detector) - to have a direct muon measurement (infill area, 30 m^2, 2.3 m underground)

Future of the Observatory –AugerPrime - Phase 2



SCIENCE CASE

1. **Elucidate the origin of the flux suppression, i.e. GZK vs. maximum energy scenario** - fundamental constraints on UHECR sources - galactic vs extragalactic origin - reliable prediction of GZK ν- and -γ fluxes
2. **Search for a flux contribution of protons up to the highest energies at a level of ~ 10%** - proton astronomy up to highest energies - prospects of future UHECR experiments
3. **Study of extensive air showers and hadronic multiparticle production above √s=70 TeV** - particle physics beyond man-made accelerators - derivation of constraints on new physics phenomena

Where is the piano now?

Exkluzivní reportáž z hvězdárny Antonína Bečváře. Nahlédněte pod kopuli brandýského pokladu 20 května, 2025

Jak si na Antonína Bečváře pamatujete, ptám se. „Posledních 14 let jsme zde žili spolu, ale i když byl na Slovensku, tak jsem ho tam každé prázdniny navštěvoval. Samozřejmě jsme spolu koukali do dalekohledu a pozorovali měsíc i komety. Byl to pozoruhodný člověk a vlastně takový můj třetí rodič. Hrávali jsme spolu čtyřručně na klavír," zavzpomínal Bečvářův synovec. …Antonín Bečvář byl nejen světově uznávaný astronom, ale doma hrál také velmi rád na klavír. **Jeho původní nástroj lze stále slyšet v brandýské synagoze.** Výbornou klavíristkou byla jeho manželka, kterou potkal ve Vysokých Tatrách.


Transport of the piano to Skalnate Pleso


Vojtech Vancura, musician from Brandys nad Labem and nephew of Antonin Becvar


Synagog in Brandys nad Labem


Antonin Becvar

and THANK YOU Michal, Natalia and Patrik for organizing this meeting… !