Ultra-High-Energy Cosmic Rays: Highlights from the Pierre Auger Observatory ~~and the Prague Group~~

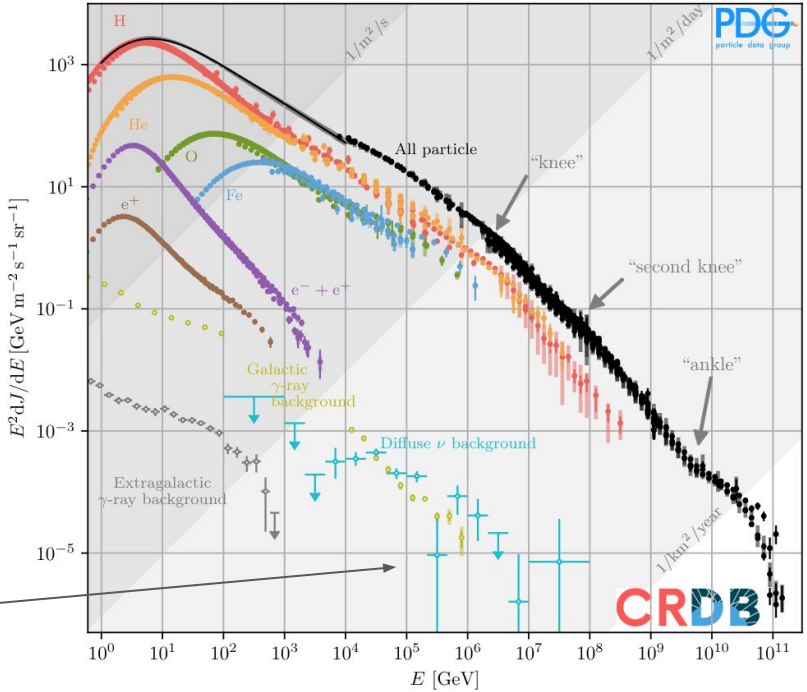


Jiri Blazek
FZU
6.10.2026
Tatra Astro Summit 2026

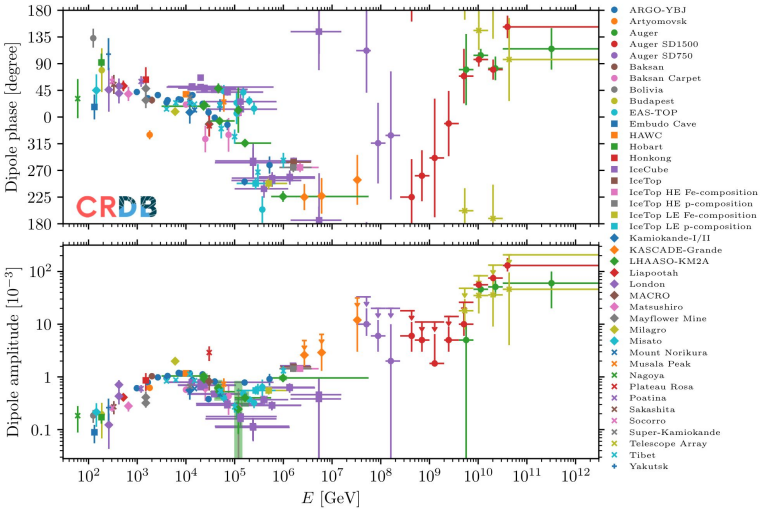
The remarkably universal spectrum of cosmic-rays



Yay!!

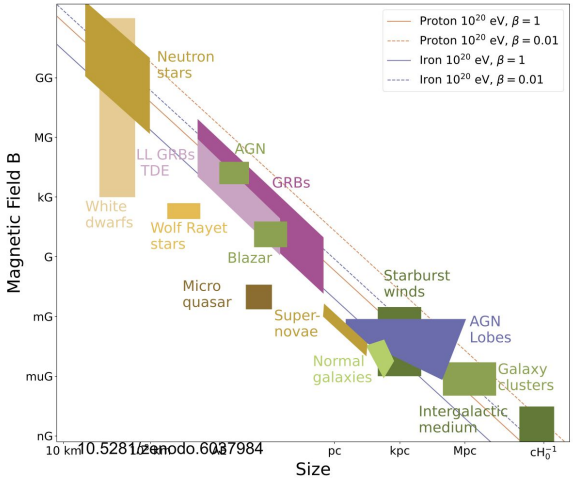


- Small features, but the E^{-3} law appears to hold across 10 decades in energy
- Convincingly isotropic



The open questions

- Nature of the sources, their distribution
- Detailed knowledge of the accelerator process
- Propagation mechanisms
- **Unified coherent picture missing**



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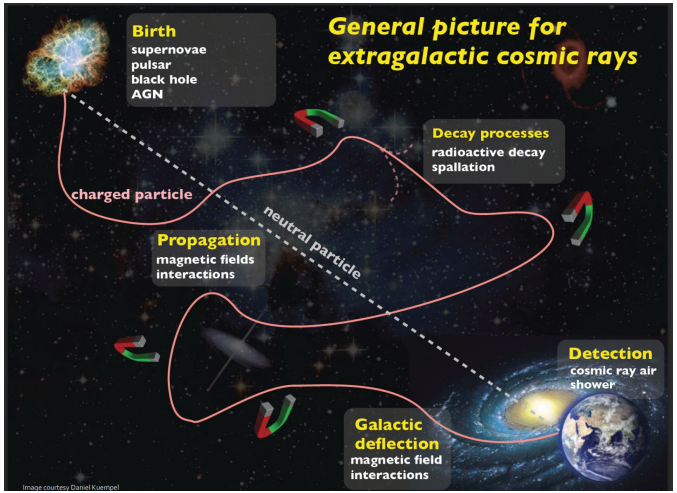
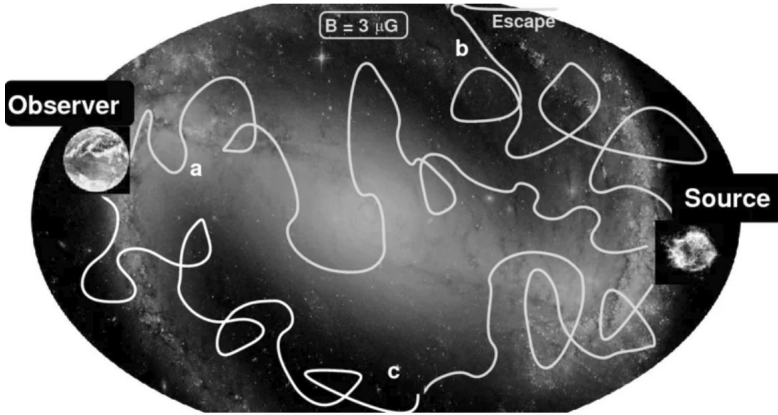




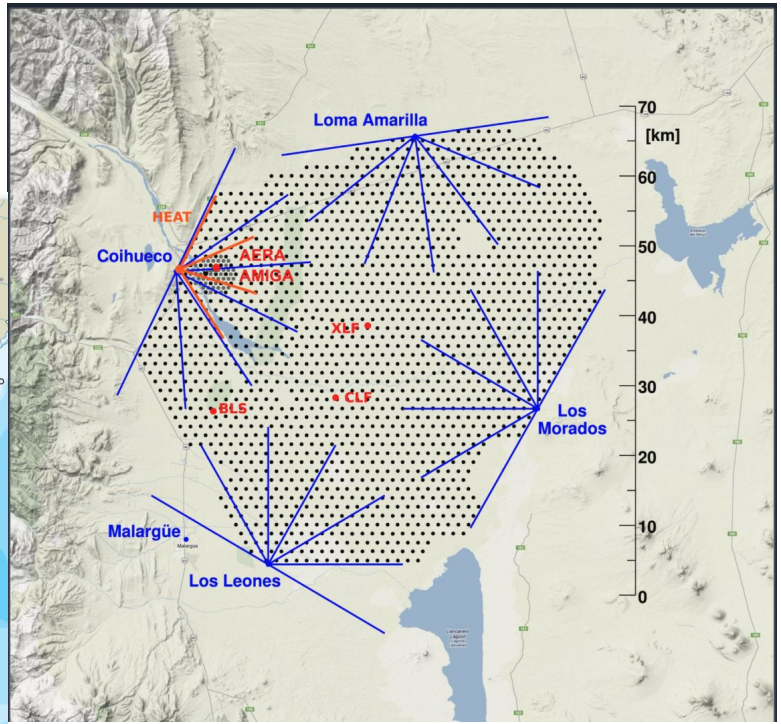
Obermeier, A.. (2011). A Direct Measurement of Cosmic Rays to Very High Energies: Implications for Galactic Propagation and Sources.

The Pierre Auger Observatory

- Located in **Malargue, Argentina**
- 3000 km^2, 1600+ ground stations, 27 fluorescence telescopes
- Phase I: 2004 - 2022
- Phase II: 2023 - 2035







Credit: M. Roth

The Pierre Auger Observatory

Surface Detection (**SD**):

- Water Cherenkov Tanks (WCD)
- Surface Scintillator Detectors (SSD)
- ~100% duty cycle
- Precise geometry reconstruction
- Resolves **em/muonic** part of the shower







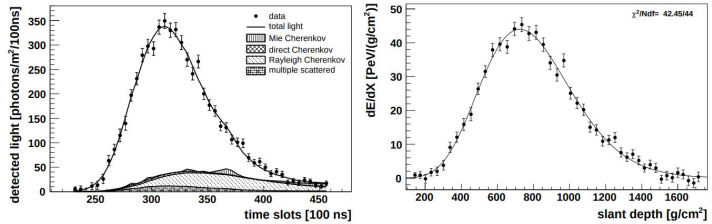
Fluorescence Detection (**FD**):

- ~15% duty cycle
- Resolves X_{max}
- **Calorimetric measurement of energy**

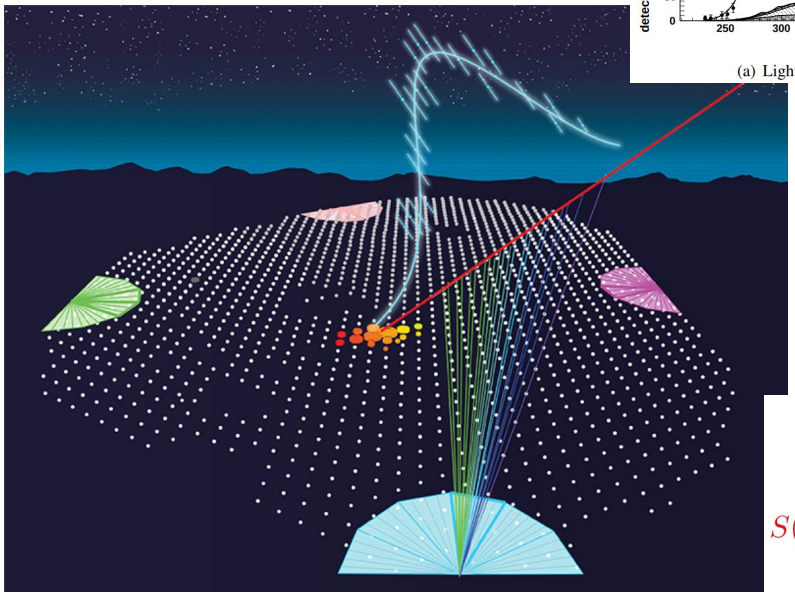
\+ **Radio** (AERA), Underground muon detectors, HEAT, etc.

The Pierre Auger Observatory

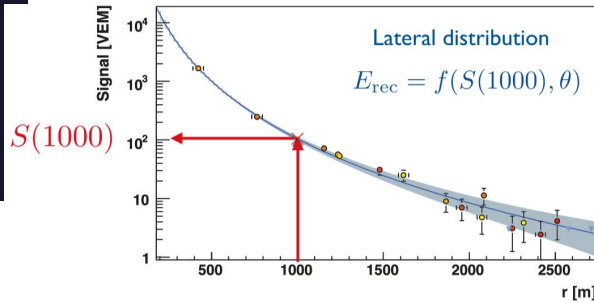
- **Hybrid** detection technique
- Geometry from SD, light profile from FD
- Optimal distance at 1000m
- Precise monitoring of atmospheric conditions needed



(a) Light at aperture. (b) Energy deposit.



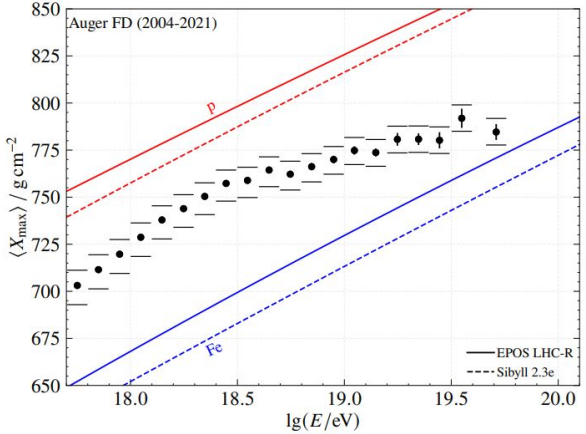
Heros, Carlos & Terzić, Tomislav. (2022)

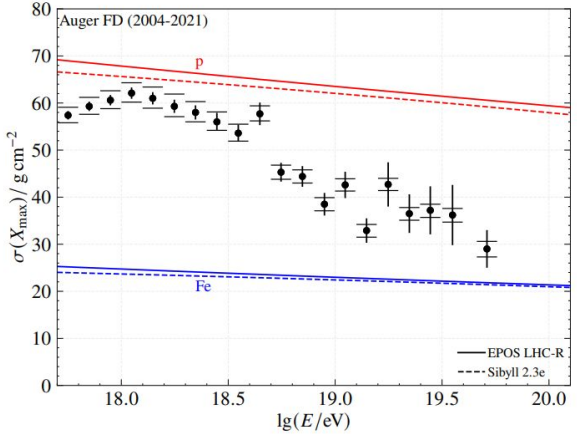


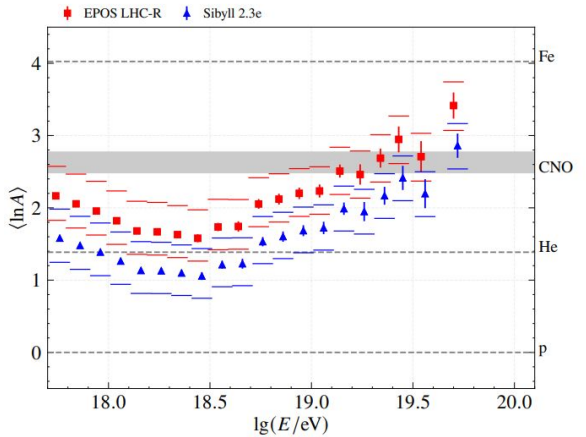
Mass composition

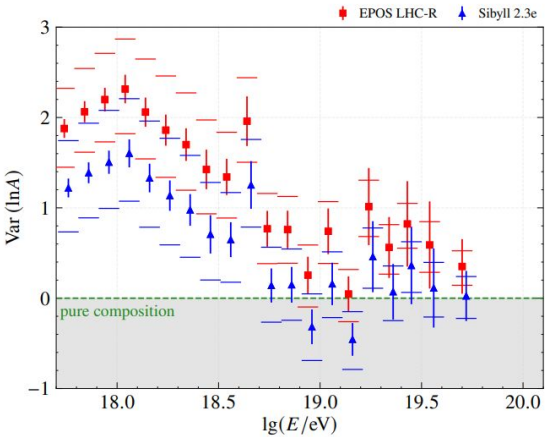
- PRD 114, 043016 (2026)
- **17 years** of data
- Based on the location of X_{max}
- Getting **heavier with energy**

	events	ε / %
air-shower candidates	5 311 333	–
pre-selection:		
hardware status	4 283 450	80.6
aerosols	3 479 008	81.2
hybrid geometry	1 249 849	35.9
profile reconstruction	1 038 782	83.1
clouds	769 699	74.1
$E \geq 10^{17.7}$ eV	281 562	36.6
quality and fiducial selection:		
P(hybrid)	277 378	98.5
X_{max} observed	218 904	78.9
quality	156 015	71.3
fiducial field of view	60 189	38.6
profile	58 887	97.8
unique air-shower events	58 453	





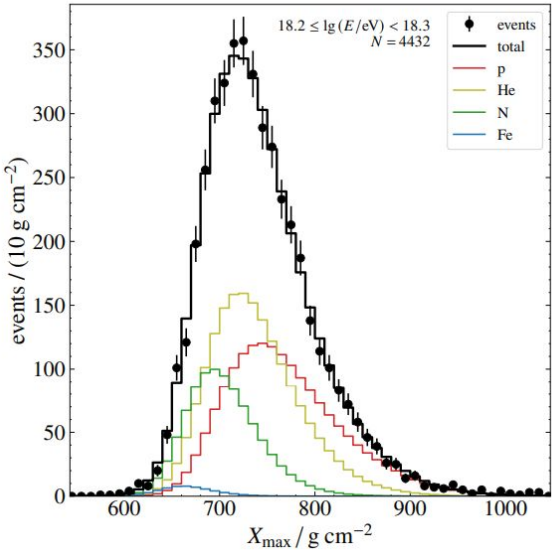


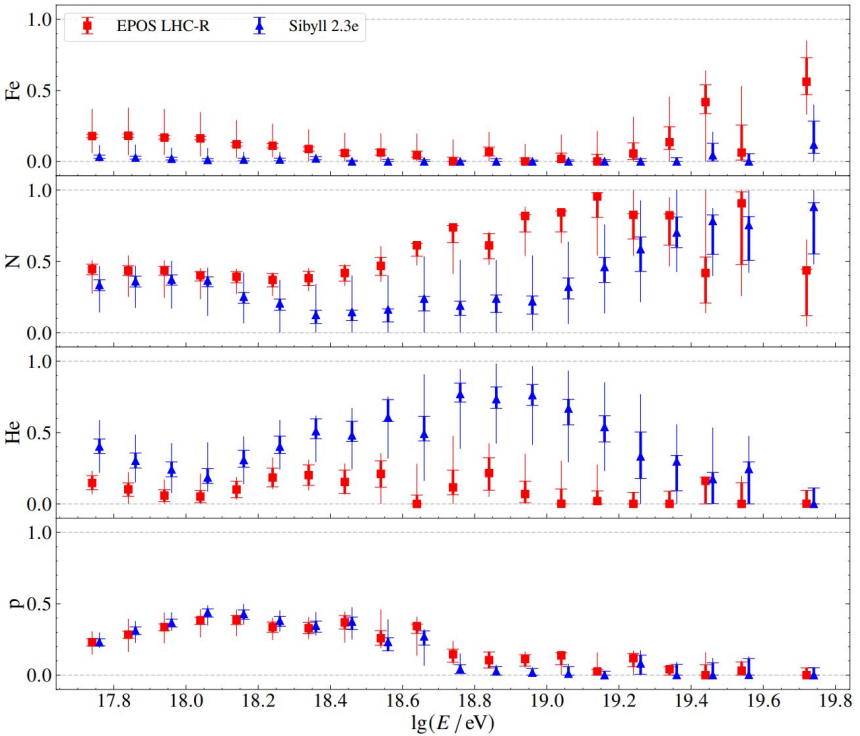


Mass composition

Individual fraction fits from X_{max} distributions

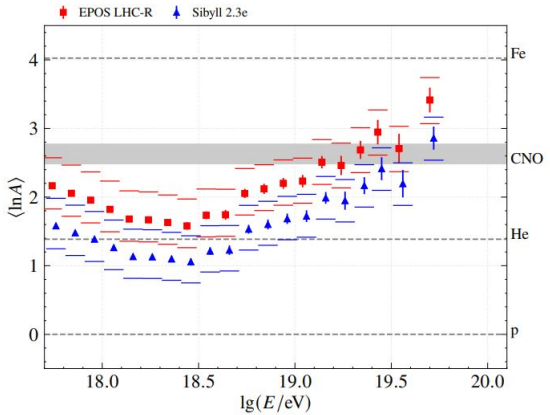
Highly model dependent

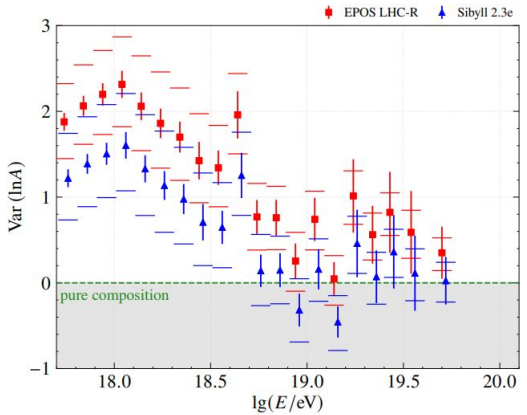


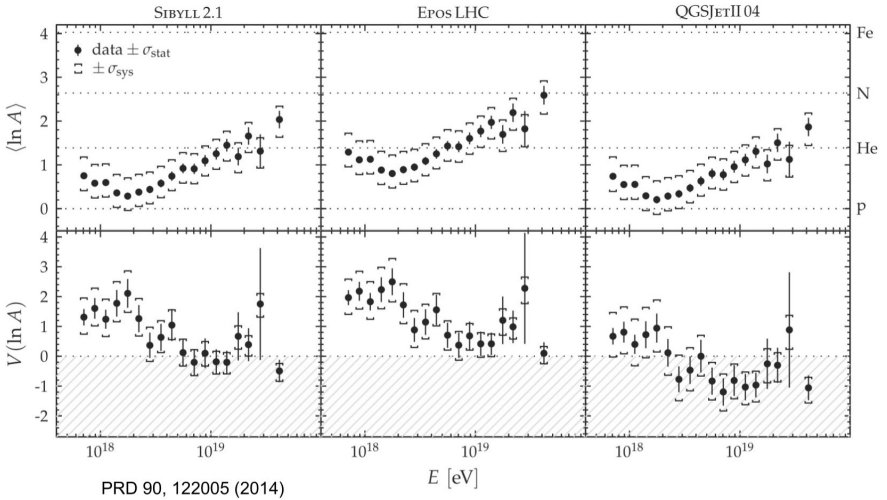


Mass composition

- **New generation** of models much better at describing the data
- Motivated partly by observed **X_{max} shift** of ~20 g/cm^2 (Phys.Rev.D109:102001,2024)
- Area focused by part of the Prague group (Air Shower physics coordinator, etc.)
- **BUT**: issues still remain



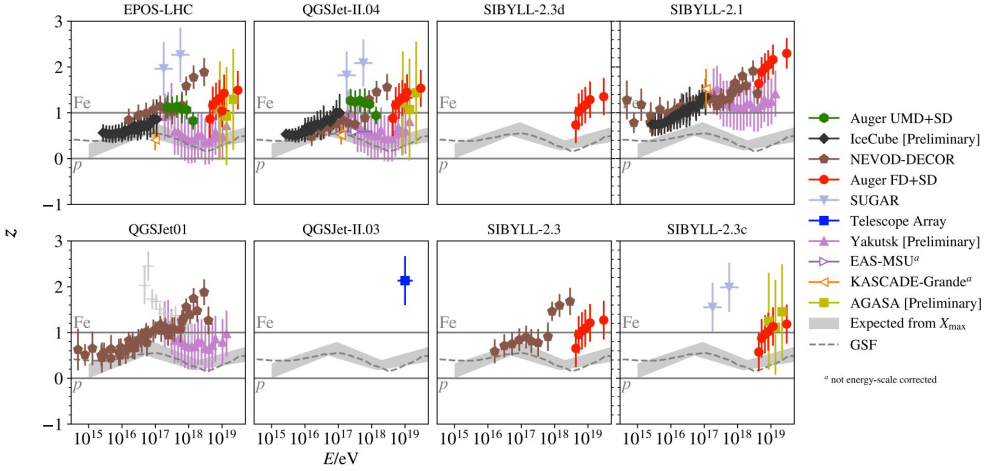


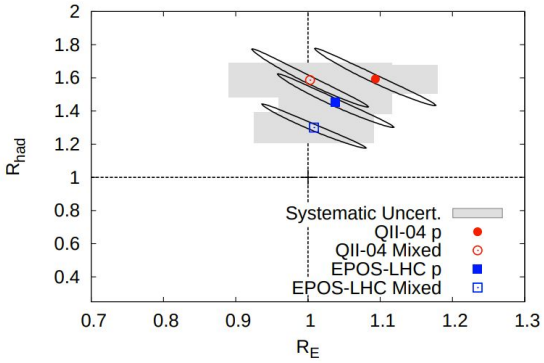


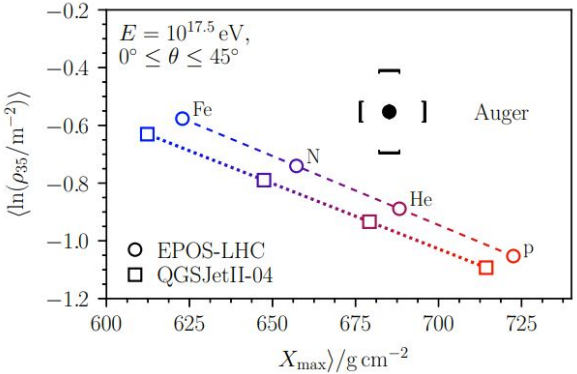
PRD 90, 122005 (2014)

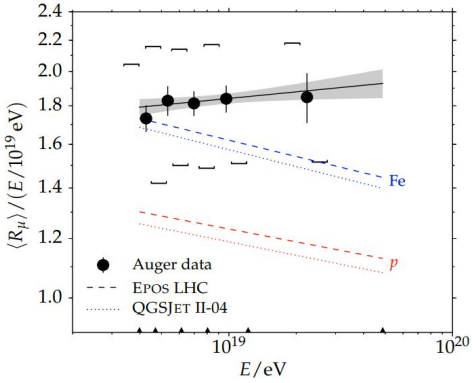
“Muon Puzzle”

- **Excess** of observed **muons** related to the models
- Further systematics on mass composition (shift to heavier)
- Getting better with the latest generation of models
- But: still **discrepancies remain**



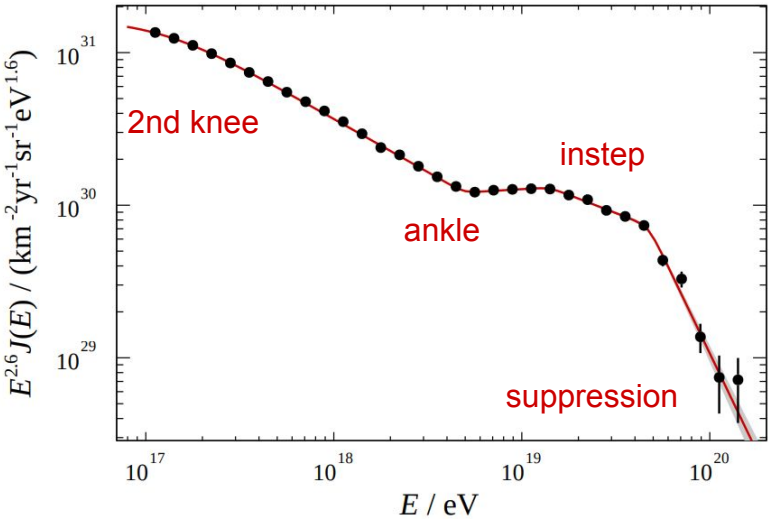






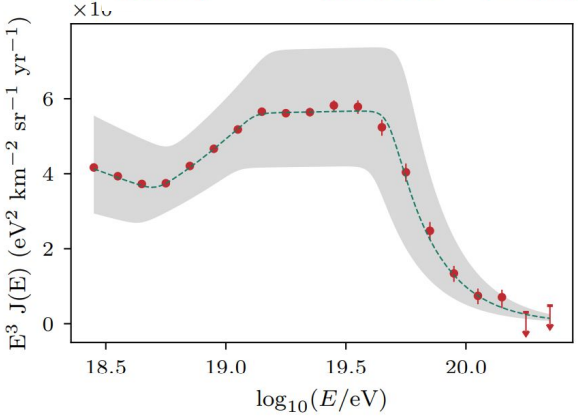
Cosmic-ray spectrum

- Systematic **uncertainty** on the energy scale **~14%**
- Auger spectrum a combination of **5 different techniques**
- Exposure 104 900 ± 3000 km sr yr
- **Instep** feature significance above **5 σ**



Eur. Phys. J. C (2021) 81:966

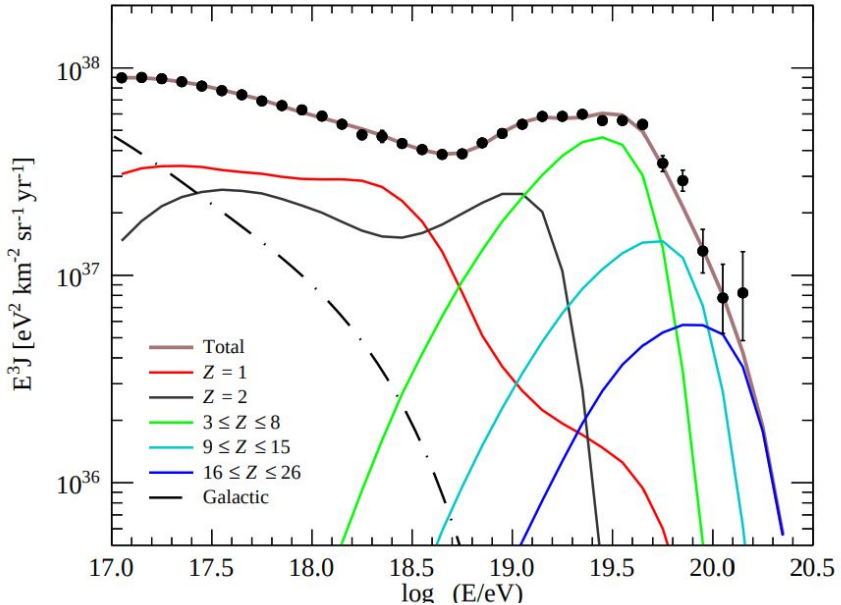
Cherenkov:	0°<θ<60°	E> 6x10^{15} eV
750m:	0°<θ<55°	E> 3x10^{17} eV
Hybrid:	0°<θ<60°	E> 3x10^{18} eV
1500m:	0°<θ<60°	E> 3x10^{18} eV
1500m:	60°<θ<80°	E> 4x10^{18} eV

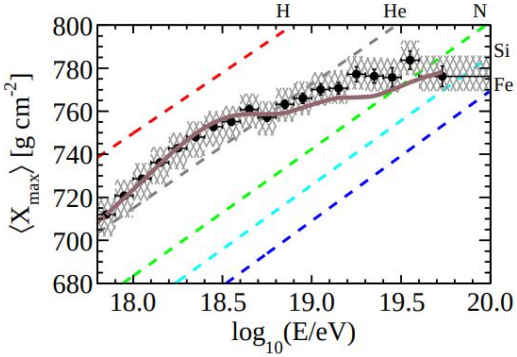


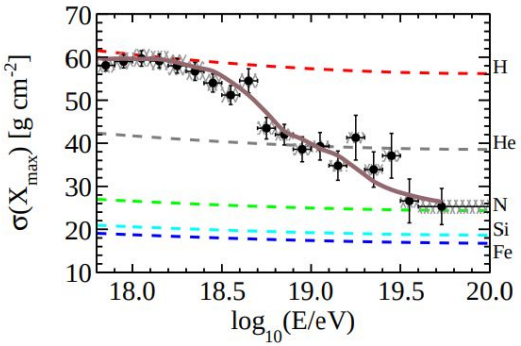
PoS(ICRC2025)370 D. Ravignani

Combined fit

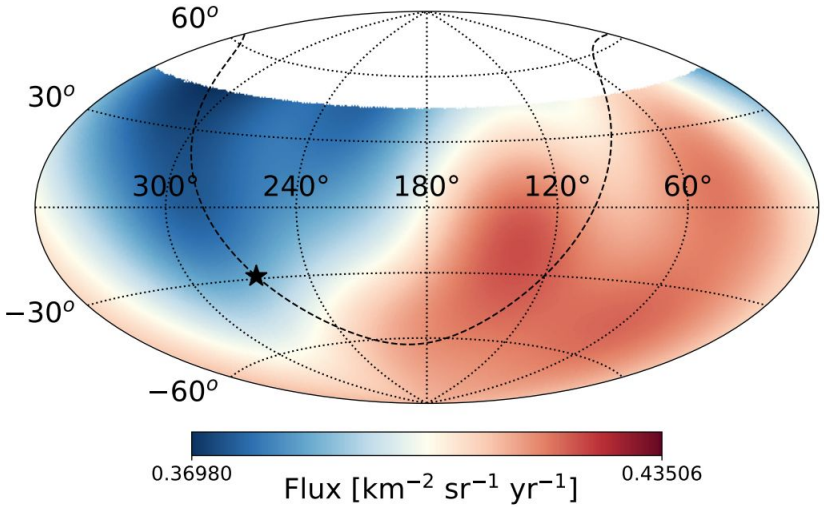
- Spectrum + composition fitted at the same time
- **New: extended down to 0.1 EeV**
- Galactic -> Extra-galactic **transition at ~ 0.1 EeV**
- **Galactic tail** in general helps to reproduce observations
- **New extra-galactic component at lower energy** with steep injection and cut-off spectra
- The extra-galactic population needs to be suppressed at ~ 100 PeV -> **magnetic horizon effect**

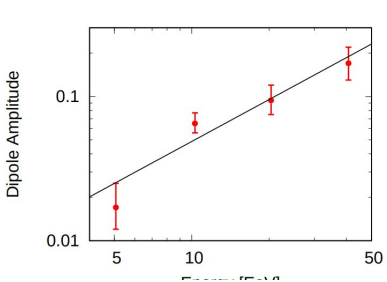


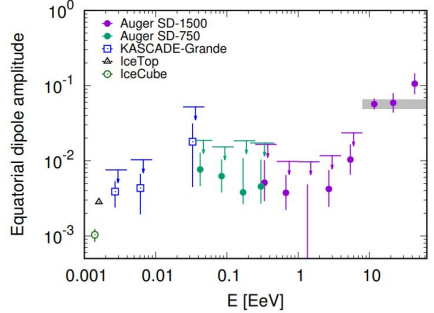


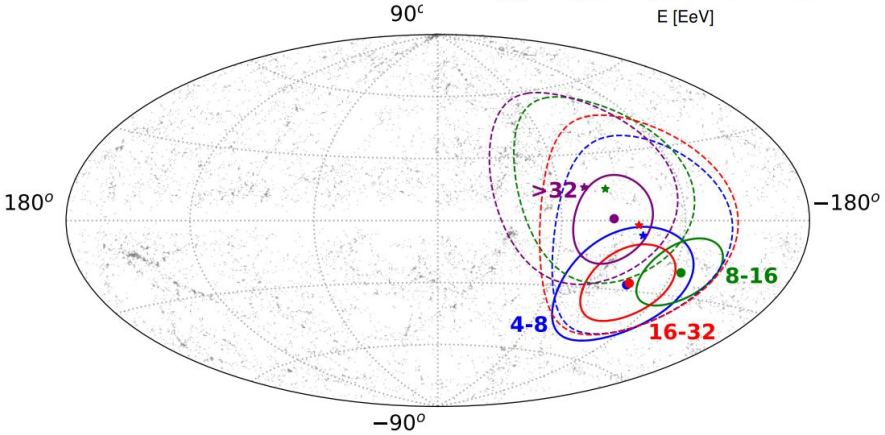


Large-scale Anisotropy







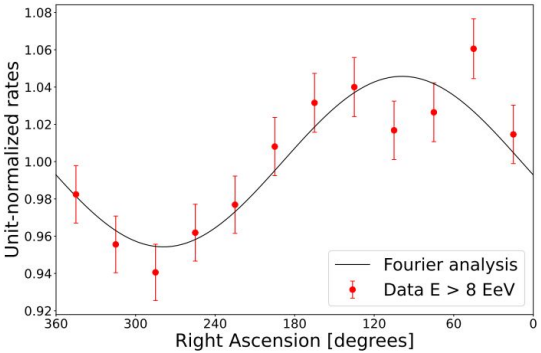


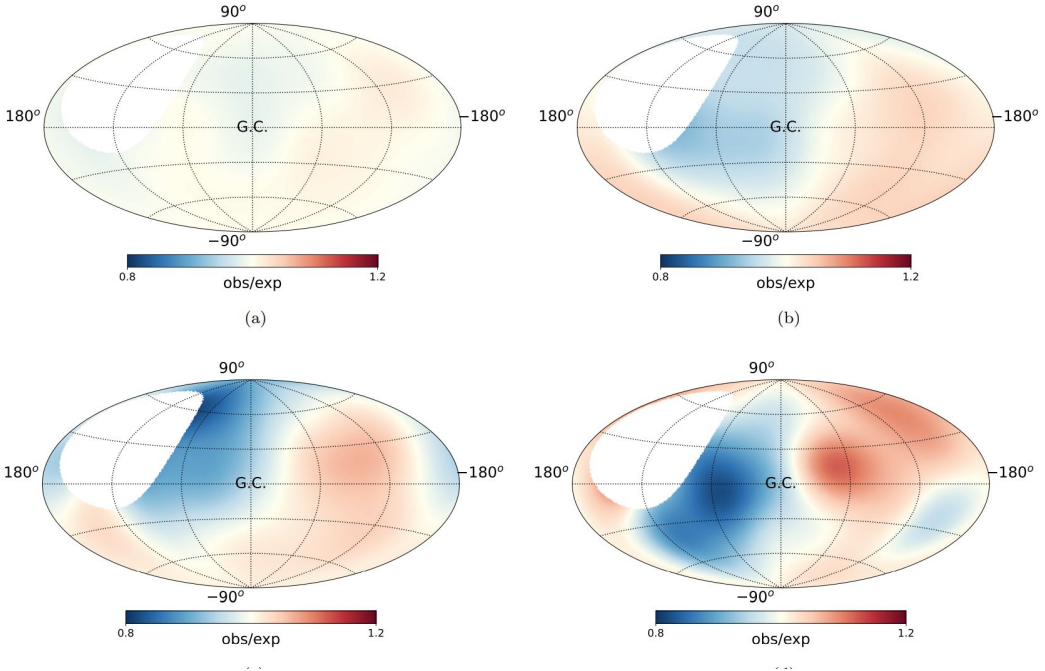
Science 357 (2017)
ApJ 976 (2024)

- Dipole amplitude ~ **6.5%** (E>8 EeV) at **6.8σ** level
- Away from the galactic centre -> A very strong hint of **extragalactic origin** of UHECR

- Location of the **dipole shifts** with energy (solid lines)
- Dashed lines: predictions from sampled source realisations

Large-scale Anisotropy





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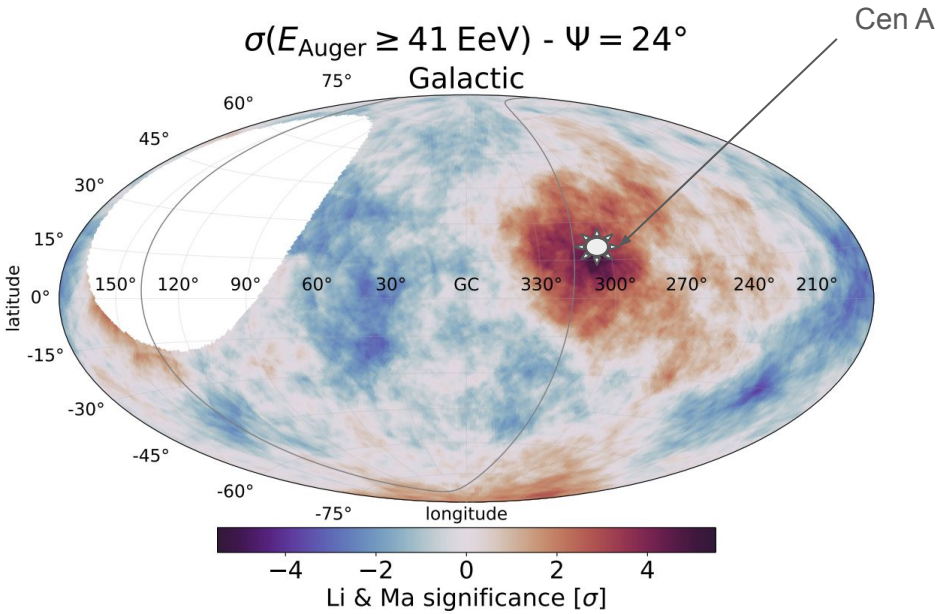
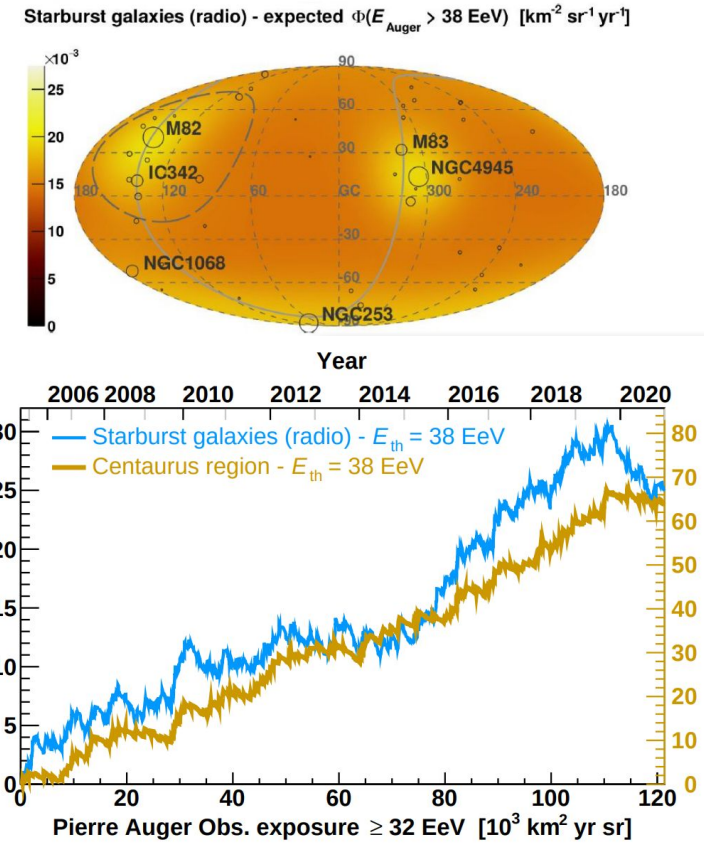
Arrival Directions



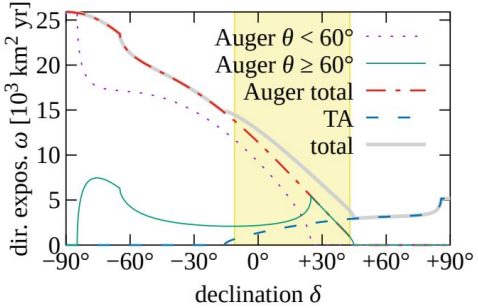
ApJ 935 170 (2022)



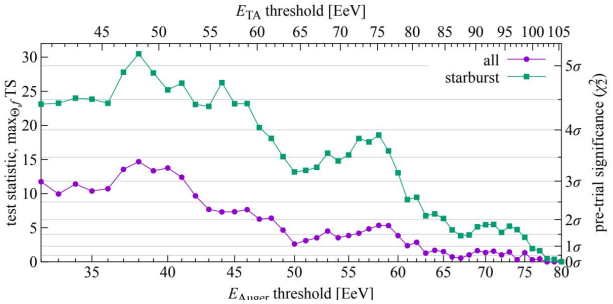
Centaurus A region: E > 38 EeV, ~27° radius 4.0 σ (post trial)
Starburst galaxies: E > 38 EeV, ~25° radius 3.8 σ (post trial)

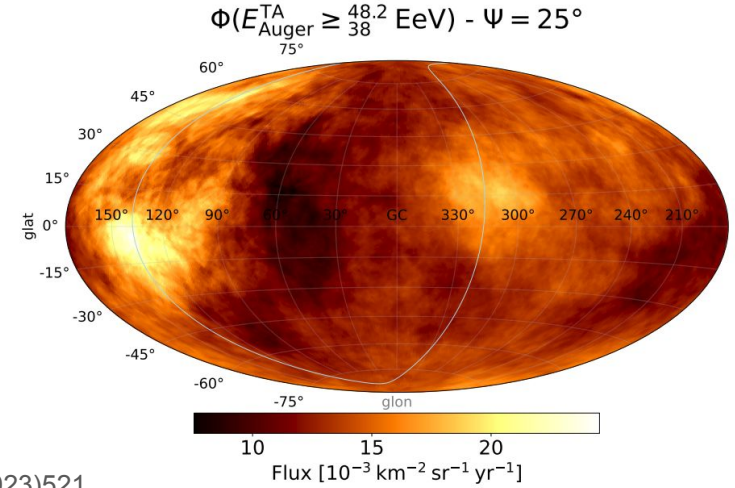
- Uncertain magnetic deflections
- **Correlations with matter**

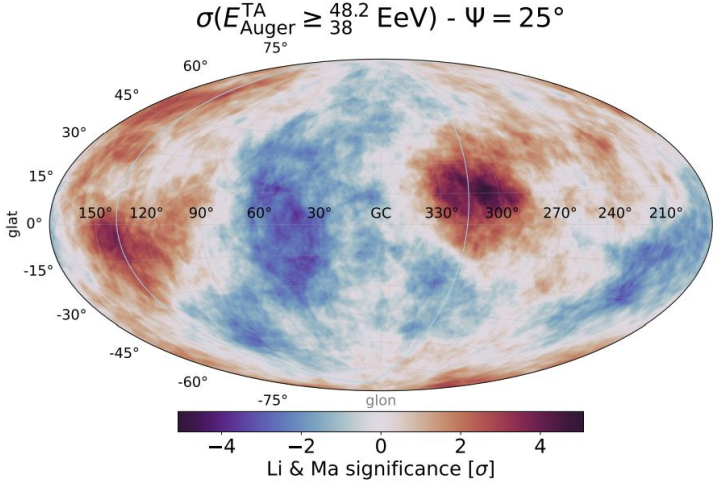
Arrival Directions (Auger + TA)



PoS (ICRC2023)521



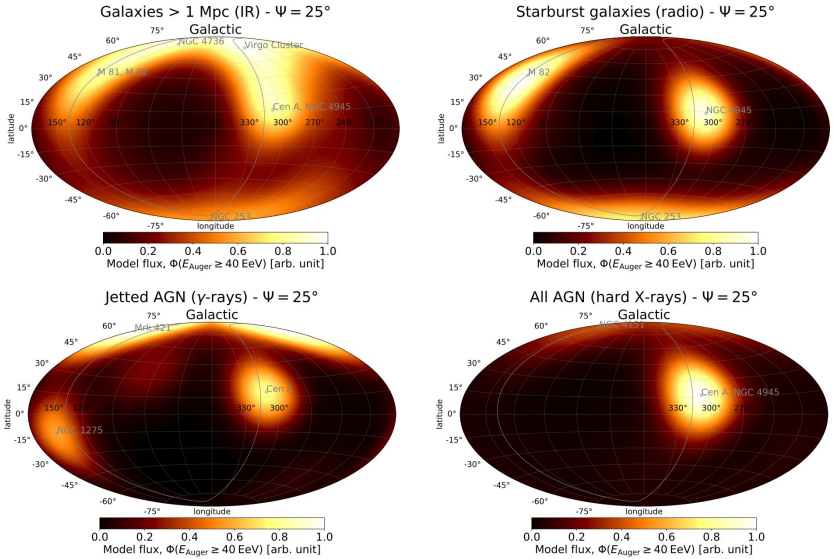


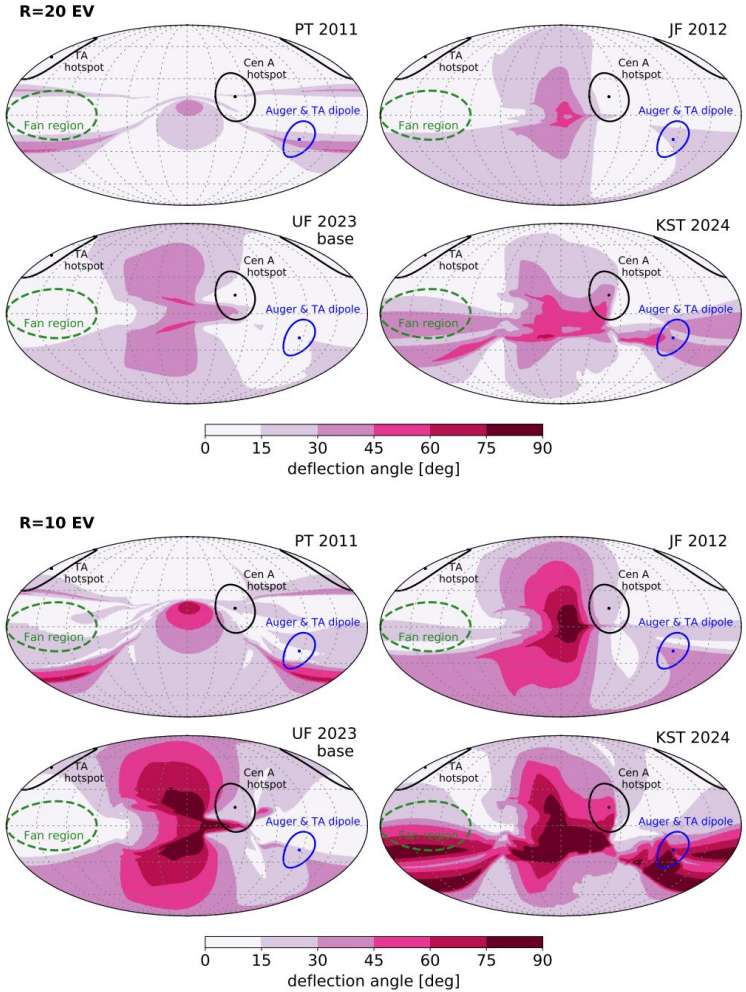


- **Allsky** coverage
- Auger + TA compatible within common declination
- **SBGs** the most significant candidates

Galactic MF

Large effect on source modelling

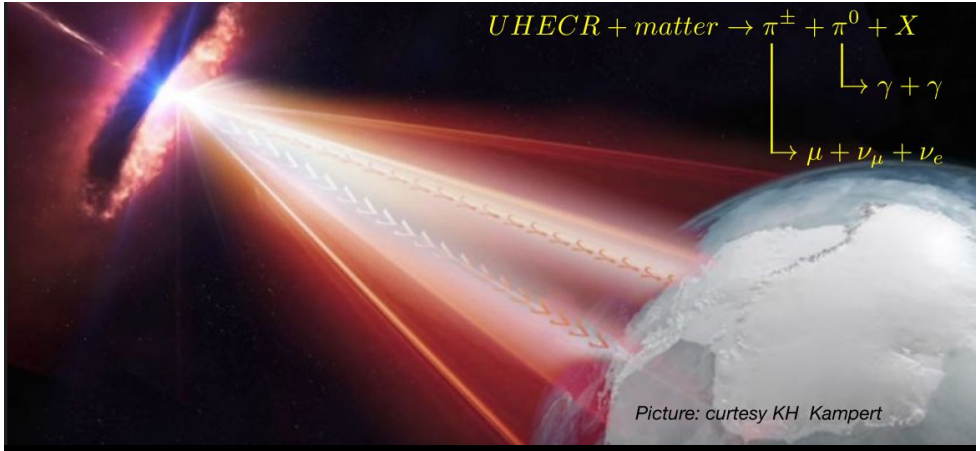


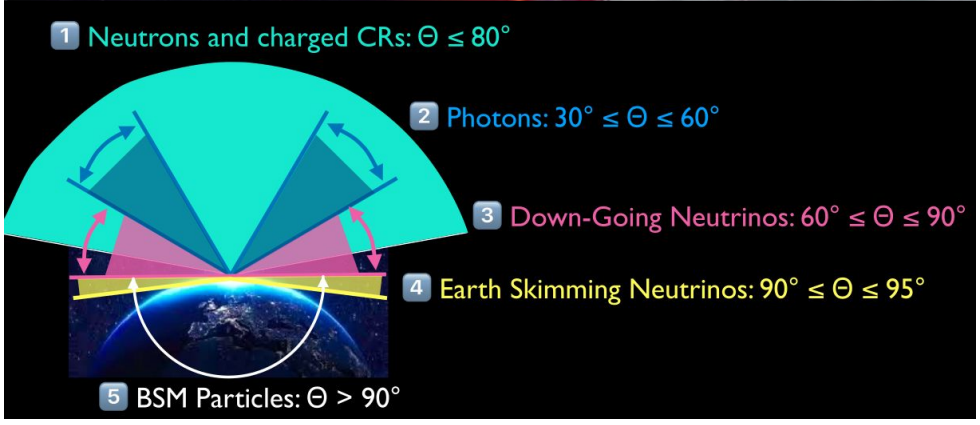


4 scenarios considered (ApJ 935 170 (2022))

Phys. Rev. D 112, 103046

Multi-messenger Studies



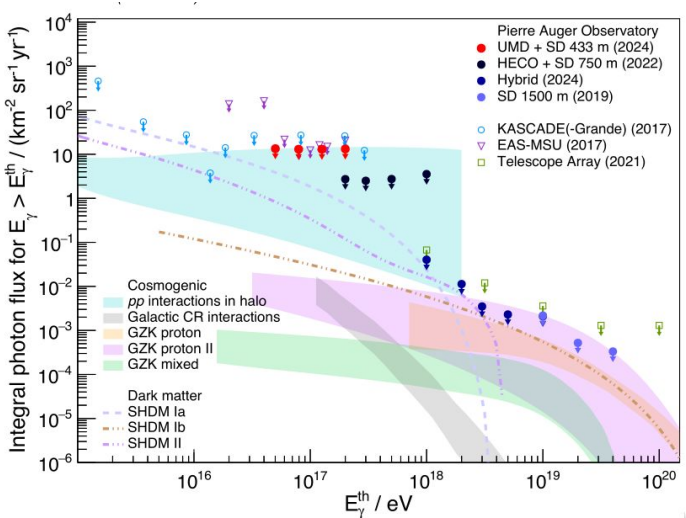


- Several independent observation windows
- Coincident searches with LIGO&VIRGO

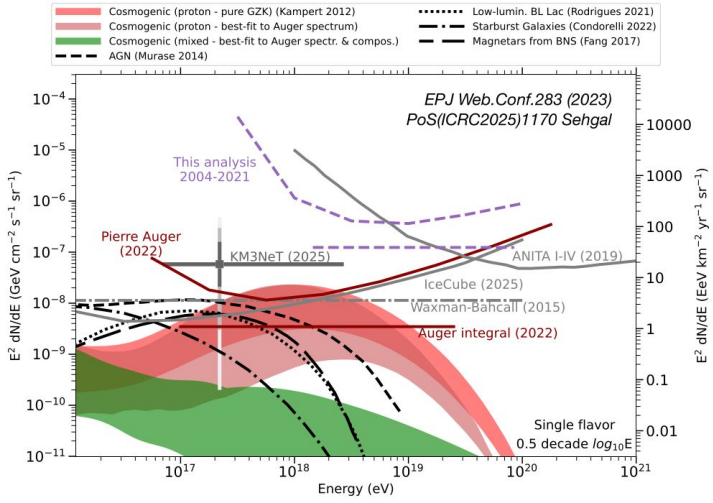
Graphics courtesy of M. Roth

Multi-messenger Studies

- **Gamma** search used to explore **GZK** predictions and constrain **DM** models
- **No candidates** found yet
- Leading limits across 4 decades of energy

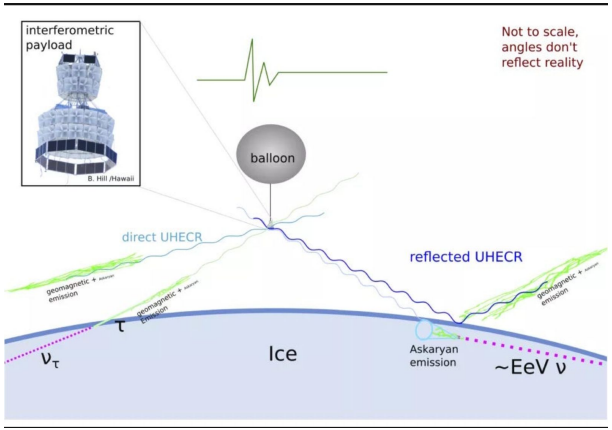


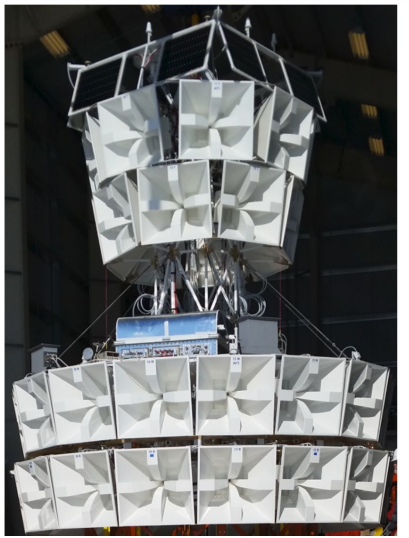
- **Neutrino** search constraints **GZK** and astrophysical neutrino sources
- **No candidates** found
- Aperture comparable to IceCube for certain source topologies

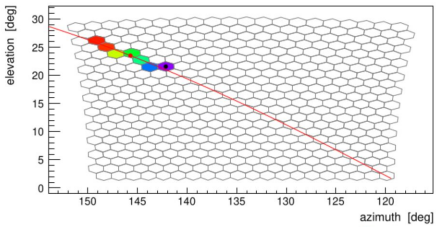


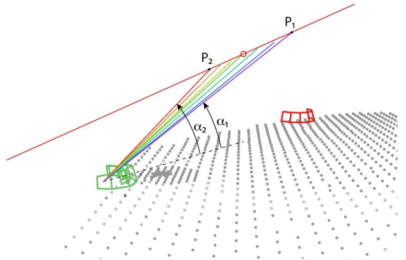
Upward-going Showers

- **ANITA** (ANtarctic Impulsive Transient Antenna) found several events with direction coming from deep below the Earth (θ = 116.7◦ and θ = 124.5◦)
- Energies ≈ 0.2 EeV
- 8 - 10 interaction lengths needed for ν_τ , in tension with current limits (~ **8σ**)
- Lots of proposed explanations, from standard physics to BSM
- The standard neutrino searches at PAO not sensitive
- But might be visible in **FD**!



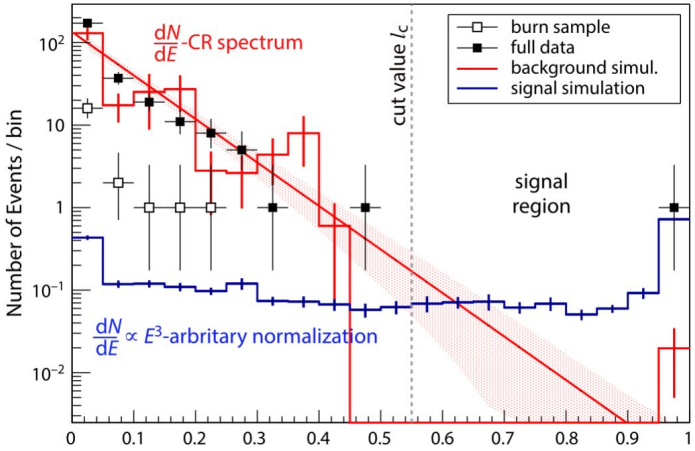




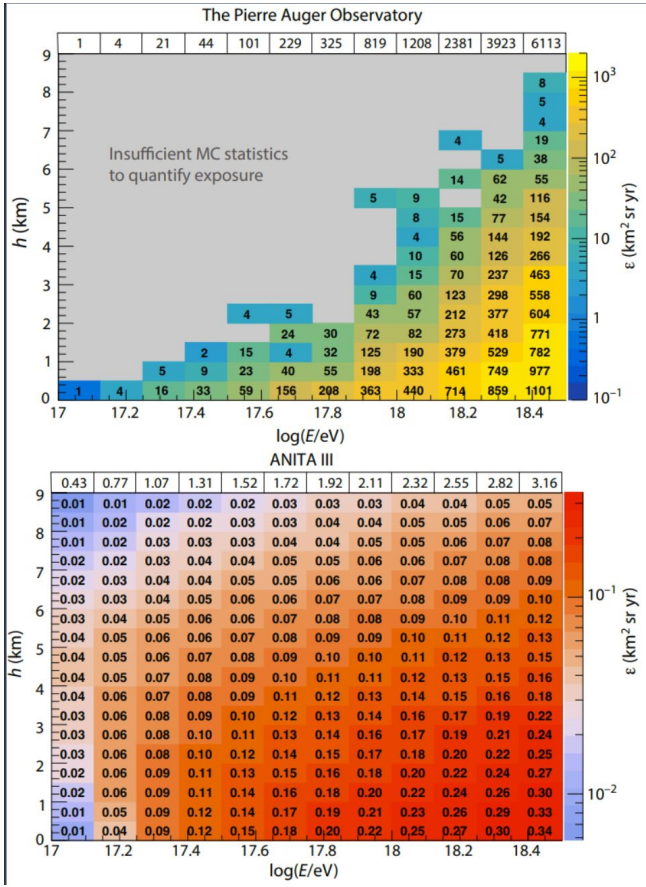


Upward-going Showers

- Challenge: extensive background from mis-reconstructed showers
- New MC-generation method devised
- **1 event** found (0.3 expected)
- **Strong tension**



$$I = \frac{\arctan\left(\ln\left[\frac{\max(L_{up}, L_{down})}{L_{down}}\right] \cdot \zeta\right)}{\frac{\pi}{2}}$$



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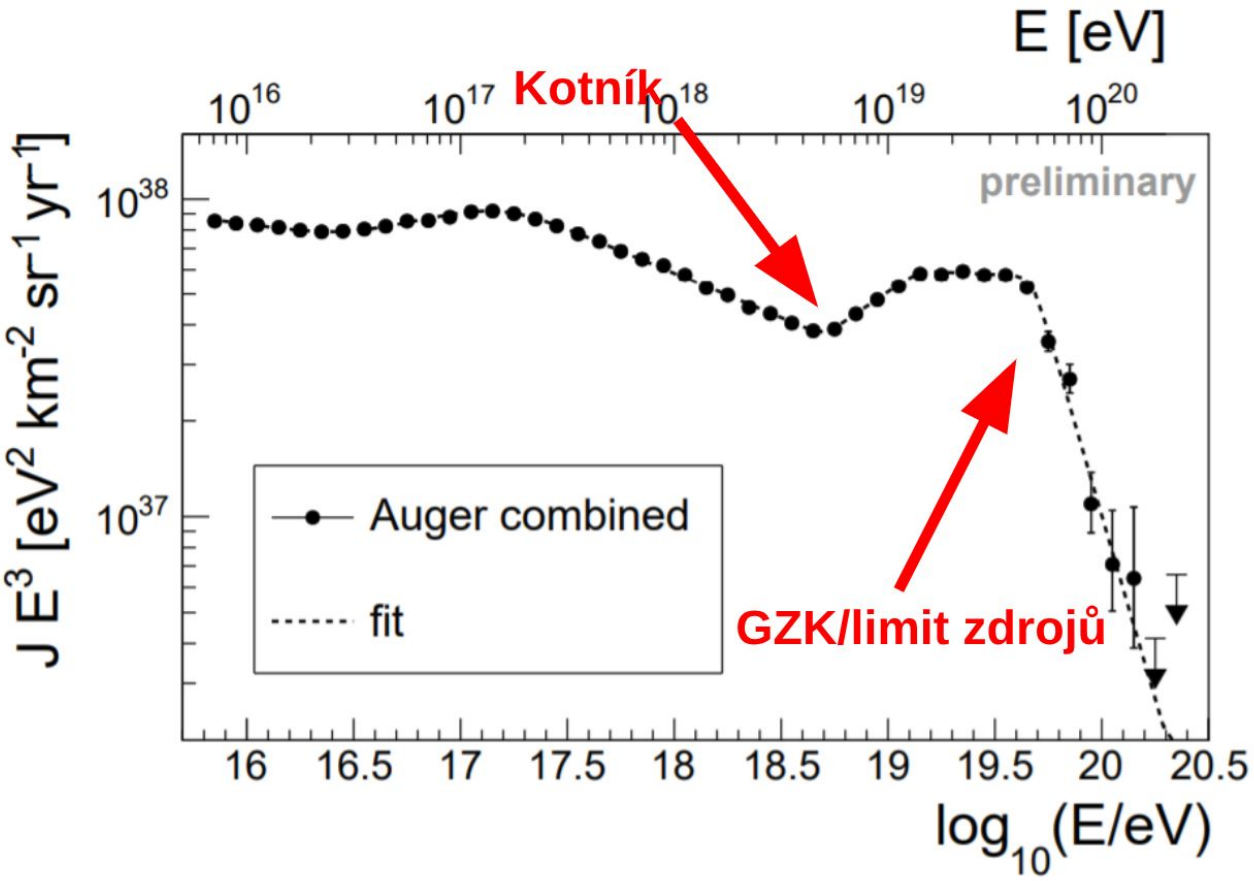
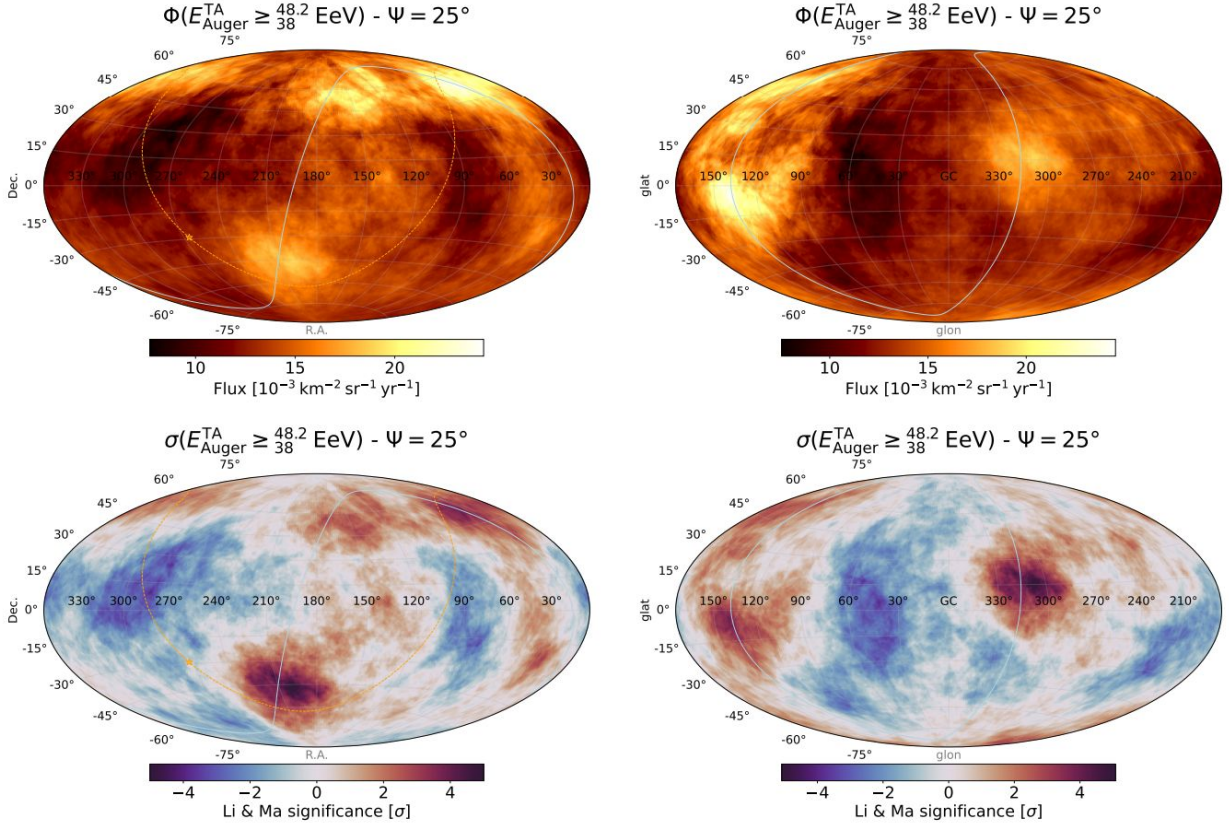
Conclusions

- The Pierre Auger Observatory is successfully taking data for **20+ years**
- Scheduled for **10+ years more**
- Recent upgrade to **AugerPrime** (+ underground muon detectors) delivers new capabilities in shower component discrimination and for detailed studies of particle spectra
- **Radio**! (AERA)
- Ancillary prototype experiments co-existing at the Auger site:
  - FAST
  - GRAND antenna
  - IceCube scintillator prototypes
  - PEPS & GCOS prototypes
  - **SST-1M?**

Thank you!


E [eV]
Kotník
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
preliminary
10^{38}
10^{37}
J E^3 [eV^2 km^{-2} sr^{-1} yr^{-1}]
Auger combined
fit
GZK/limit zdrojů
16
16.5
17
17.5
18
18.5
19
19.5
20
20.5
log$_{10}$(E/eV)



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