Large-scale anisotropies of ultra-high-energy cosmic rays measured at the Pierre Auger Observatory

Marta Bianciotto for the Pierre Auger Collaboration
Università degli Studi di Torino
RICAP-2024

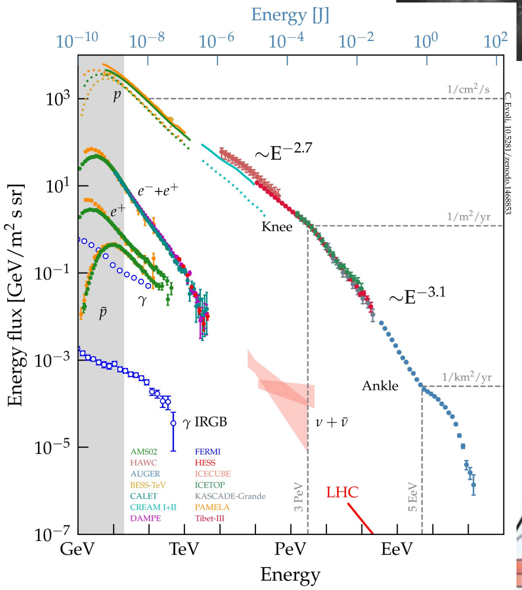
Ultra-high energy cosmic rays

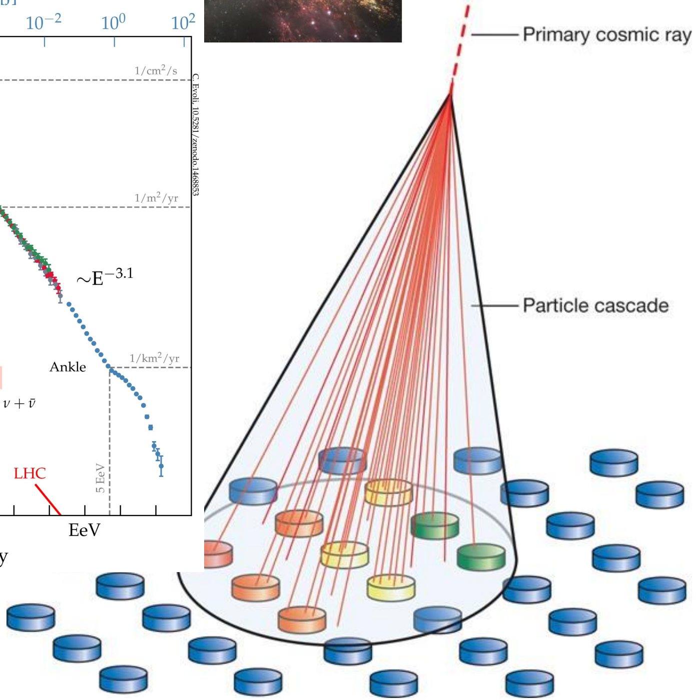
Open questions

- Where do UHECRs come from?
- How are they accelerated?
- What is their mass composition?

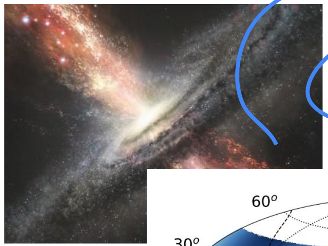
Challenges

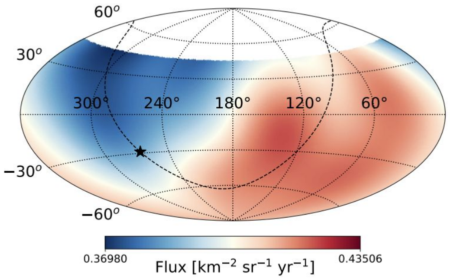
- Very low flux at the highest energies
- Deflections by magnetic fields in propagation





UHECR arrival directions





- UHECR arrival directions are nearly **isotropic** because of **magnetic field deflections $\propto$ R^{-1}**
- **Anisotropies** are very small deviations from isotropic background, usually **a few % of the signal**
- **Long-term observations** are required to distinguish these small deviations from statistical fluctuations

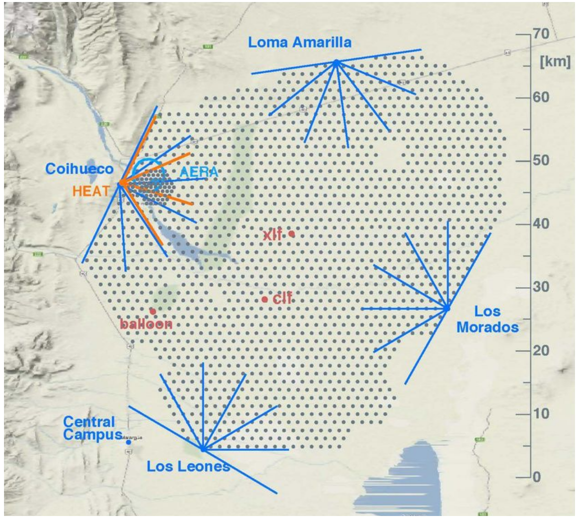
⇩

Large-scale anisotropies expected at all energies, while small and intermediate-scale anisotropies are expected at higher rigidities

Mean deflections at 10 EeV	
➡ protons	$\mathcal{O}(30°)$
➡ nitrogen	$\mathcal{O}(80°)$
➡ iron	$\mathcal{O}(90°)$

Mean deflections at 50 EeV	
➡ protons	$\mathcal{O}(5°)$
➡ nitrogen	$\mathcal{O}(40°)$
➡ iron	$\mathcal{O}(80°)$

The Pierre Auger Observatory



- Largest UHECR detector: its area is 3000 km^2
- It is located in Argentina (province of Mendoza)
- Hybrid detection technique
  - ➡ 1661 Water Cherenkov Detectors, spacing 1500/750 and 433 m
    - Duty cycle 100%
  - ➡ 27 Fluorescence Detectors in 4 sites
    - Duty cycle 15%
- AugerPrime upgrade with a scintillator and a radio antenna on each surface station, underground muon detectors in the infilled area and upgraded electronics

Observables
- Energy spectrum
- Mass composition
- Arrival directions

Large-scale anisotropy analyses and datasets

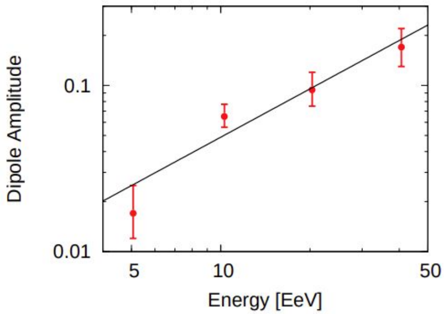
Analyses above 4 EeV

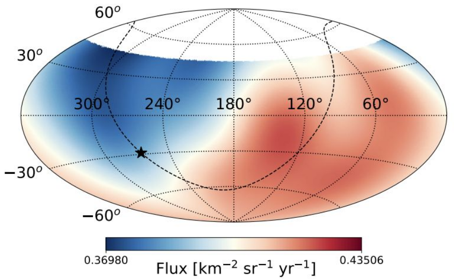
- 3D dipole
- 3D dipole and quadrupole
- Angular power spectrum

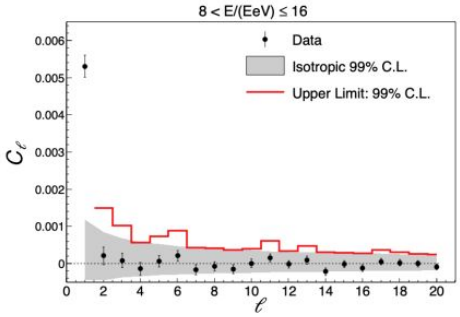
Analysis above 0.03 EeV

- Dipole modulation in right ascension

	E [EeV]	θ_{max} [°]	Exposure [km^2 yr sr]	
SD1500	>32	80	135,000	85% sky coverage
	>4	80	123,000	
	0.25<E<4	60	81,000	71% sky coverage
SD750	>0.03	55	337	67% sky coverage





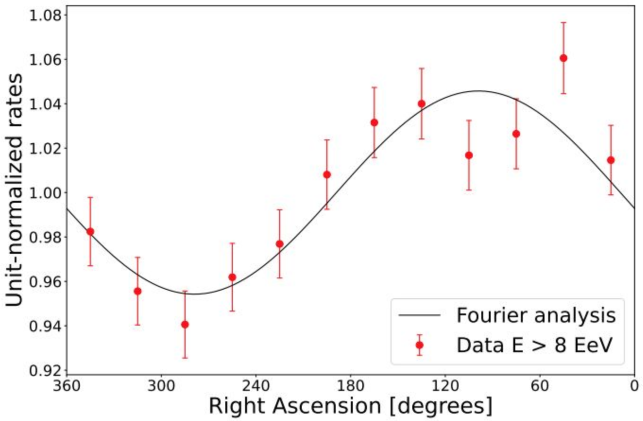


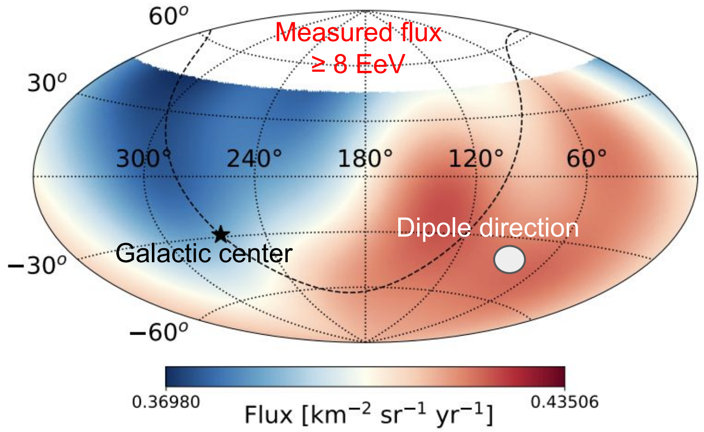
arXiv:2408.05292
[submitted to ApJ]

3D dipole above 4 EeV

Separate harmonic analysis in R.A. (α, sensitive to $d_\perp$) and azimuth (φ, sensitive to d_z)

E [EeV]	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]	$P(\geq d_\perp)$	
4-8	118,835	$0.010^{+0.006}_{-0.004}$	-0.014 ± 0.008	$0.017^{+0.008}_{-0.005}$	91 ± 30	-53^{+21}_{-19}	0.15	
≥8	49,710	$0.058^{+0.009}_{-0.008}$	-0.045 ± 0.012	$0.073^{+0.010}_{-0.008}$	97 ± 8	-37^{+9}_{-9}	7.4×10^{-12}	→ **6.9σ**
8-16	36,683	$0.057^{+0.010}_{-0.009}$	-0.030 ± 0.014	$0.065^{+0.012}_{-0.009}$	92 ± 10	-28^{+11}_{-12}	1.2×10^{-8}	→ **5.7σ**
16-32	10,288	$0.059^{+0.020}_{-0.015}$	-0.07 ± 0.03	$0.094^{+0.026}_{-0.019}$	93 ± 18	-51^{+13}_{-13}	4.5×10^{-3}	
≥32	2,739	$0.11^{+0.04}_{-0.03}$	-0.13 ± 0.05	$0.17^{+0.05}_{-0.04}$	143 ± 19	-51^{+14}_{-13}	8.4×10^{-3}	





Equatorial coords., von-Mises smoothing (top-hat equivalent of 45°)

Dipole direction pointing away from the Galactic center

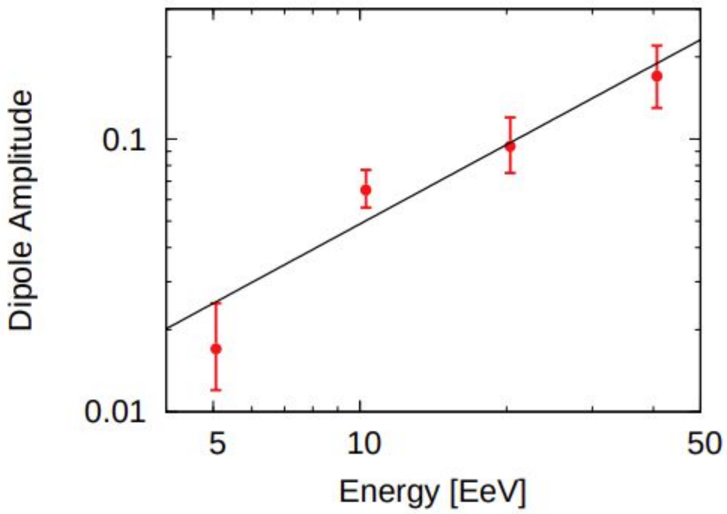
⇩

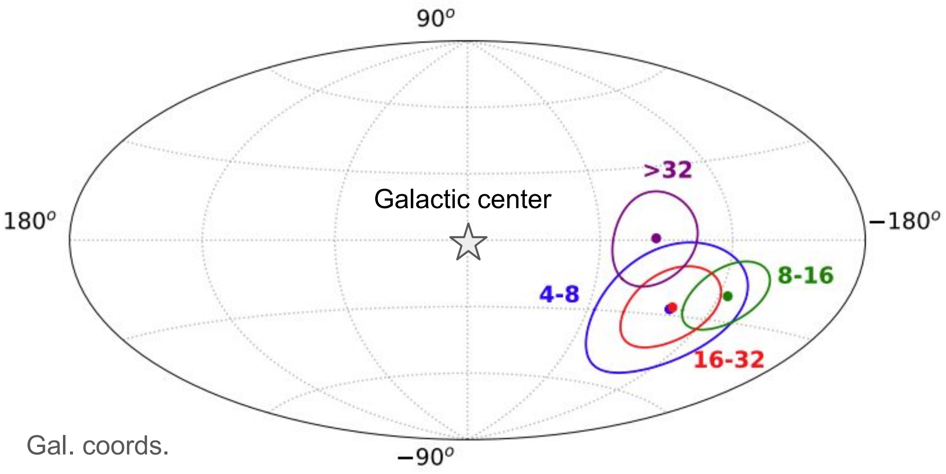
Extragalactic origin of UHECRs above 8 EeV (6.9σ)

3D dipole above 4 EeV: energy evolution

Energy dependence

- Dipole amplitude increases with energy
- Dipole direction does not significantly change





Gal. coords.

Possible explanation: larger relative contribution of nearby sources (more inhomogeneous) and/or growth of mean rigidity (smaller deflections)

C.Ding et al., ApJ 913 (2021) L13

3D dipole and quadrupole above 4 EeV

Separate harmonic analysis in R.A. and azimuth if a quadrupolar component is also included

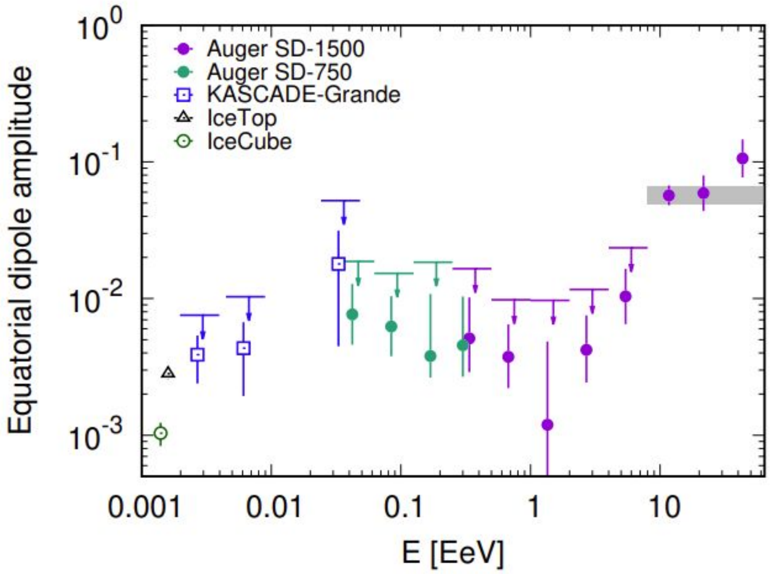
	4–8 EeV	$\geq$ 8 EeV	8–16 EeV	16–32 EeV	$\geq$ 32 EeV
d_x	0.003 ± 0.007	-0.002 ± 0.011	-0.002 ± 0.012	0.029 ± 0.024	-0.1 ± 0.5
d_y	0.005 ± 0.007	0.059 ± 0.011	0.048 ± 0.012	0.088 ± 0.024	0.1 ± 0.5
d_z	0.002 ± 0.019	-0.02 ± 0.03	0.02 ± 0.04	-0.15 ± 0.07	-0.23 ± 0.13
Q_{zz}	0.03 ± 0.03	0.04 ± 0.05	0.10 ± 0.06	-0.13 ± 0.13	-0.16 ± 0.25
$Q_{xx} - Q_{yy}$	0.018 ± 0.025	0.07 ± 0.04	0.03 ± 0.04	0.18 ± 0.08	0.30 ± 0.17
Q_{xy}	-0.016 ± 0.012	0.026 ± 0.019	0.041 ± 0.022	-0.05 ± 0.04	0.11 ± 0.08
Q_{xz}	-0.010 ± 0.016	0.017 ± 0.025	0.003 ± 0.029	0.10 ± 0.06	-0.10 ± 0.10
Q_{yz}	-0.019 ± 0.016	0.005 ± 0.025	-0.029 ± 0.029	0.09 ± 0.06	0.13 ± 0.10

$< 2\sigma$

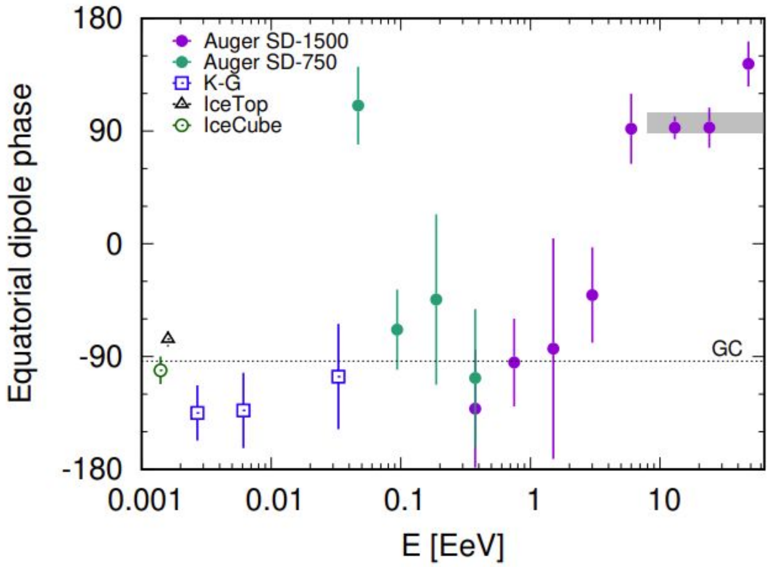
⇒ Quadrupolar components are not significant and dipole amplitudes are consistent with results assuming only dipole

Modulation in R.A. above 0.03 EeV

Harmonic analysis in R.A. down to 0.03 EeV



Dipole amplitude increases with energy



Dipole phase shifts from the GC to the opposite direction

⇨ Suggests transition from Galactic to Extragalactic origin

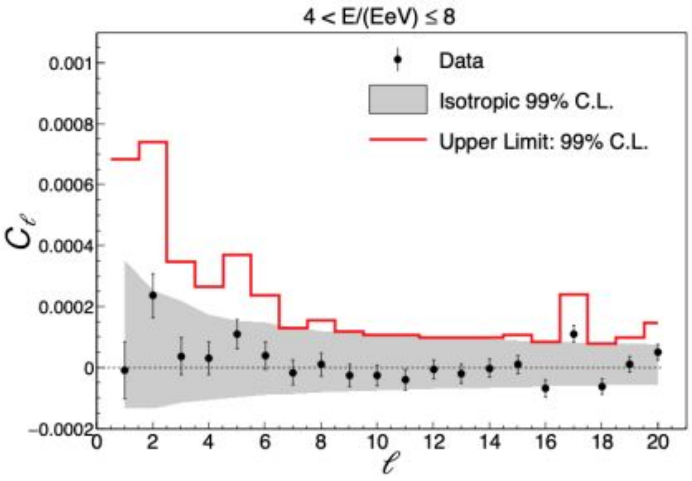
Angular power spectrum above 4 EeV

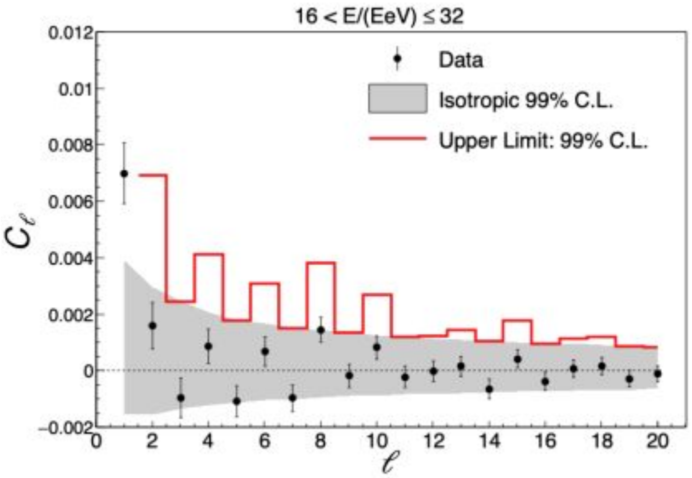
To search for anisotropies at various angular scales it can be useful to study the angular power spectrum:

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}|a_{\ell m}|^2$$

Sensitive to angular scales of ~180°/ℓ

Besides the dipole, the only orders above the 99% CL are ℓ=17 and ℓ=8 for the energy bins of (4,8) EeV and (16,32) EeV respectively





Conclusions and outlook

3D dipole analysis above 4 EeV

- 6.9σ at E > 8 EeV and 5.7σ at 8-16 EeV
- Direction pointing away from the GC indicating extragalactic origin of UHECRs
- Amplitude rising with the energy due to larger relative contribution of nearby sources and growth in mean rigidity

3D dipole and quadrupole analysis above 4 EeV

- Dipole amplitudes are compatible with dipole only analysis
- Quadrupolar components are not significant

Dipole analysis above 0.03 EeV

- Amplitude and phase evolution of the dipole suggesting a transition from Galactic to Extragalactic origin of UHECRs

Angular power spectrum analysis above 4 EeV

- No significant components besides the dipole except ℓ=17 and ℓ=8 for the energy bins of (4,8) EeV and (16,32) EeV respectively

Future perspectives: promising event-by-event mass estimates using the *AugerPrime* upgrade

Thank you
for your attention!

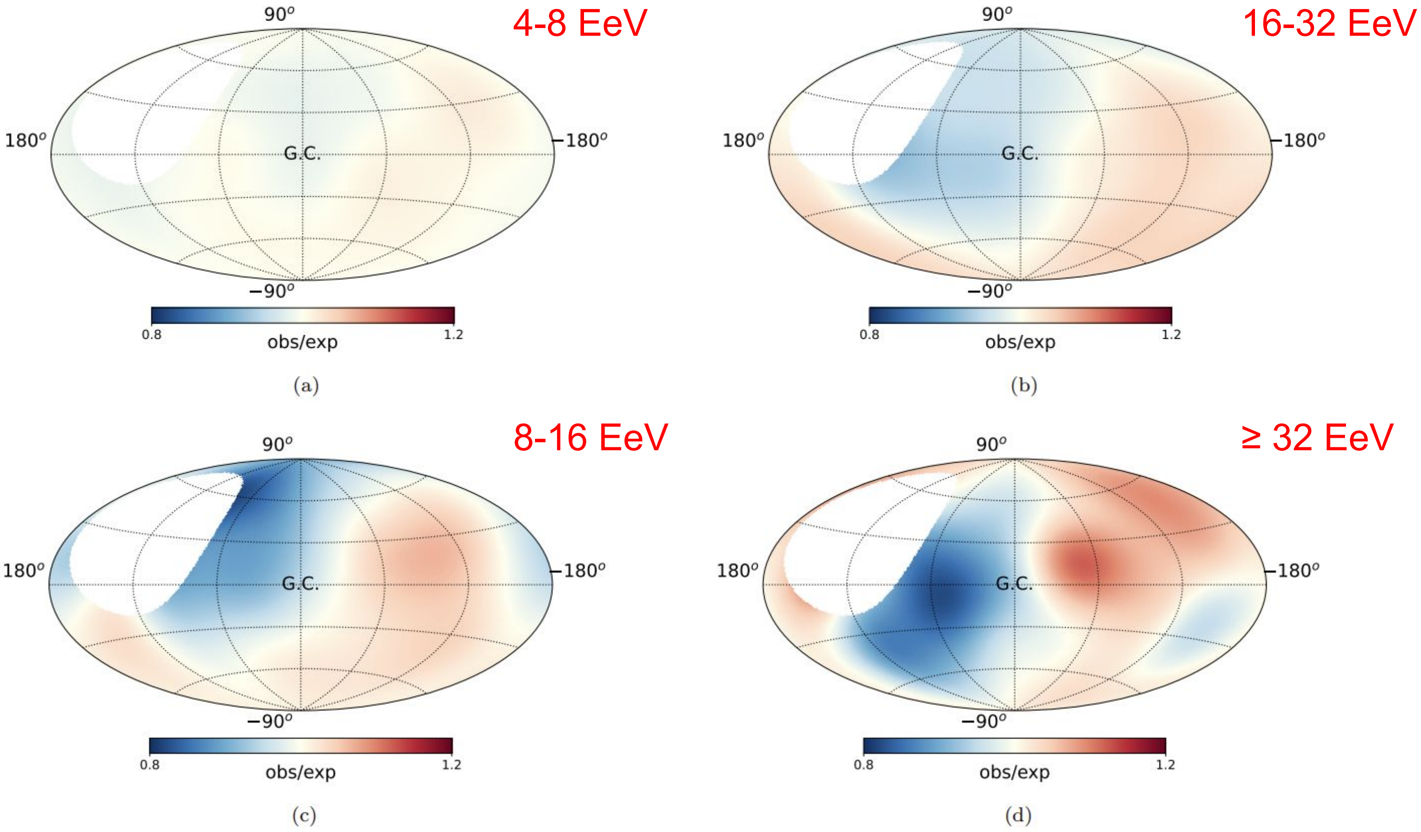
RICAP 24

UNIVERSITÀ DI TORINO

PIERRE AUGER OBSERVATORY

Backup slides

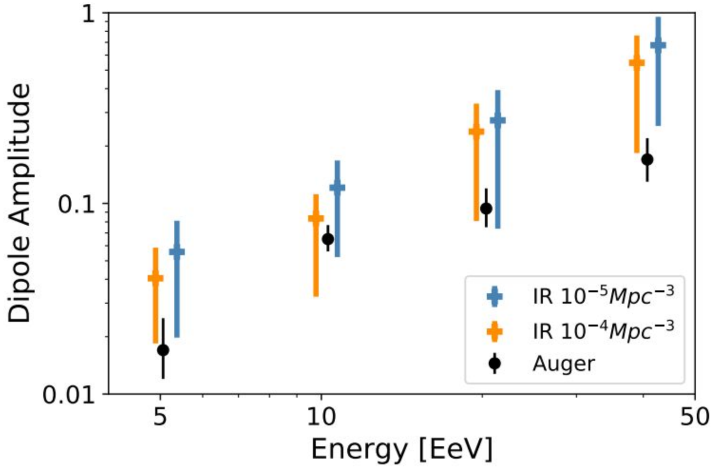
3D dipole above 4 EeV: energy evolution

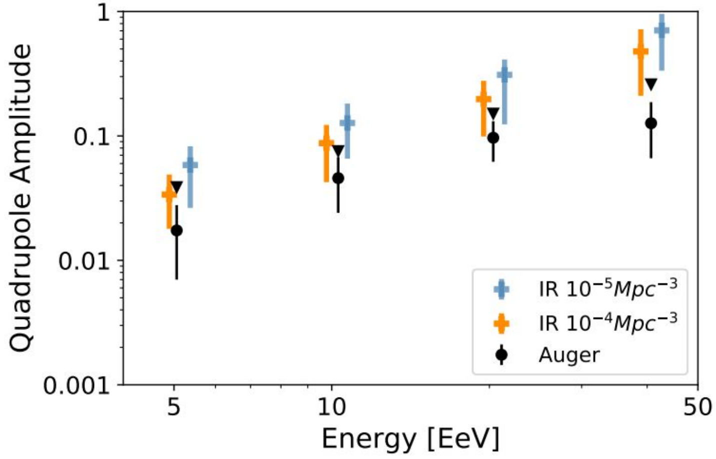


Model predictions

Simulations

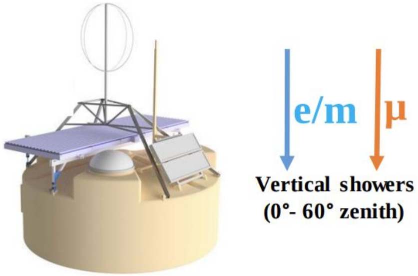
- Four energy bins at E ≥ 4 EeV
- Population of equal-luminosity sources with number density 10^{-5} Mpc^{-3} and 10^{-4} Mpc^{-3} selected randomly from a volume limited sample of the IR catalog up to 120 Mpc



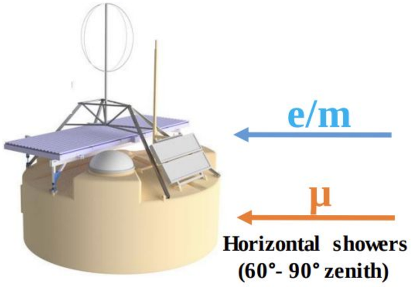


Dipolar and quadrupolar amplitudes are compatible with experimental results within uncertainties, although for the smallest source density the quadrupole prediction is in slight tension, especially in the highest energy bin.

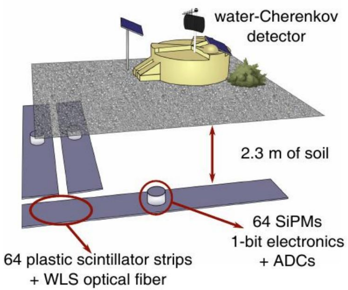
The *AugerPrime* Upgrade



Scintillator-based surface detector (SSD) to sample the shower along with the WCD having different responses

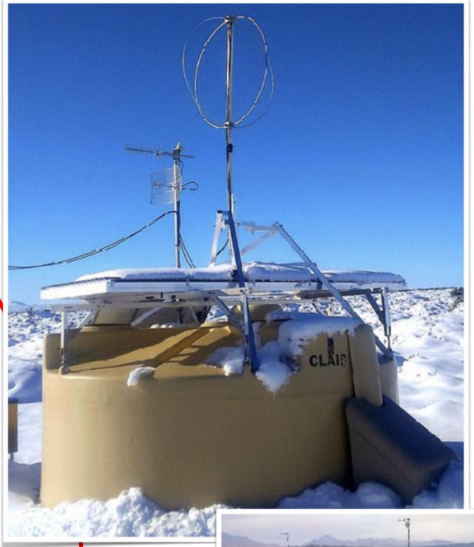


Radio antenna to exploit the correlation of the electromagnetic energy and the number of muons for horizontal air showers



Underground muon detectors (UMD) to measure the muon component directly

+ faster electronics (UUB)



Disentangling the muonic and electromagnetic components of the EAS at ground allows mass composition estimation on a event-by-event basis