UHECR results of combined analyses of TA and Auger experiments

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PIERRE AUGER OBSERVATORY

TELESCOPE ARRAY PROJECT

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Outline

Ultra-high-energy cosmic rays

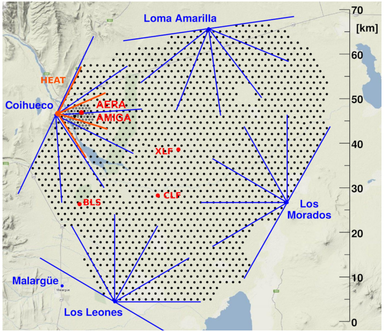
- Particles with energies greater than 1 EeV $= 10^{18}$ eV ≈ 0.16 J are known as ultra-high-energy cosmic rays (UHECRs).
- They can be detected by huge arrays of particle detectors on the ground. The largest ones are the Pierre Auger Observatory and the Telescope Array.
- UHECRs are electrically charged (atomic nuclei, mostly protons); as a result, they are deflected by intergalactic and Galactic magnetic fields by $\mathcal{O}\left(30\left(\frac{10\ \mathrm{EeV}}{E/Z}\right)^{\circ}\right)$ and do not directly point back to their sources.
- Their arrival directions are nearly isotropically distributed over the full sky: the first anisotropy, a 6.5% dipole* at $E \geq 8$ EeV (Aab et al. [Auger collab.] 2017), required 32k events to be detected with $\geq 5\sigma$ significance.
- It is still not known where or how UHECRs achieve such energies.
- At the highest energies, their propagation is limited to distances $\mathcal{O}\left(10^2\ \mathrm{Mpc}\right)$ by interactions with cosmic background photons.

*As of last update (de Almeida [Auger collab.] ICRC2021): 7.3% dipole at 6.6σ using 44k events

The Pierre Auger Observatory (“Auger”)

365 collaborators in 90 institutions in 18 countries

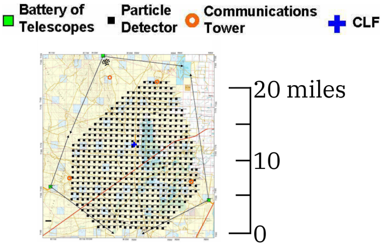
- Located at 35.2° S, 69.2° W, 1 400 m a.s.l. (Mendoza Province, Argentina)
- Main SD array: 1 600 water Cherenkov detectors in a 1.5 km triangular grid (3 000 km^2 total)
- Can detect showers with zenith angles up to 80° (northernmost declination visible: +44.8°)
- Taking data since 01 Jan 2004
- Current dataset: events up to 31 Dec 2020 (17 yr)
  - 123 200 km^2 yr sr effective exposure
  - 39 157 events with $E \geq 8.57$ EeV
  - 2 625 events with $E \geq 32$ EeV

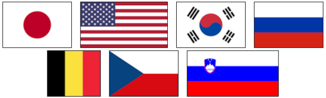


The Telescope Array ("TA")

140 collaborators in 32 institutions in 7 countries

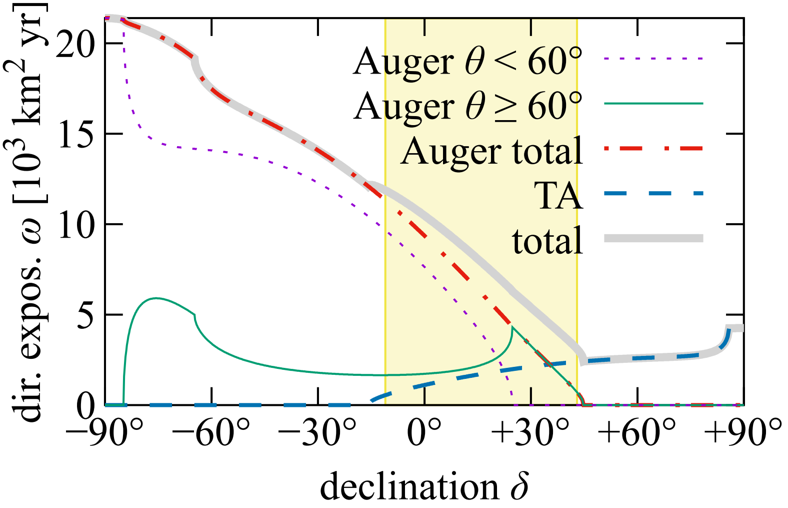
- Located at 39.3° N, 112.9° W, 1 400 m a.s.l. (Millard County, Utah, USA)
- Main SD array: 507 plastic scintillator detectors in a 1.2 km square grid (700 km^2 total)
- Can detect showers with zenith angles up to 55° (southernmost declination visible: −15.7°)
- Taking data since 11 May 2008
- Current dataset: events up to 10 May 2019 (11 yr)
  - 13 700 km^2 yr sr effective exposure
  - 4 801 events with $E \geq 10$ EeV
  - 315 events with $E \geq 40.8$ EeV





Directional exposures of the two detector arrays

- Neither TA alone nor Auger alone covers the full sky.
- Together they do:
  - TA full northern hemisphere plus a part of the southern
  - Auger vice versa
- The two FoVs overlap in a band surrounding the celestial equator.



Auger–TA joint working groups

- Several Auger–TA joint working groups have been established since the early 2010s to perform full-sky UHECR studies:
  - Energy spectrum
  - Mass composition
  - **Arrival directions**
  - Auger@TA
- A few also include other collaborations:
  - Hadronic interactions and shower physics (with EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, SUGAR and Yakutsk)
  - Neutrinos (with ANTARES and IceCube)
- The WGs usually present their results (list at `http://tiny.cc/Auger-TA`) at the International Symposium on Ultra-High-Energy Cosmic Rays (UHECR) and sometimes at the International Cosmic Ray Conference (ICRC).
- This talk is a summary of the contributions on arrival directions at ICRC 2021 plus a "teaser" for the upcoming one at UHECR 2022 (3–7 Oct 2022, GSSI, L'Aquila — registration open until this Friday).

The issue of the energy cross-calibration

- UHECR energy measurements are affected by sizable systematic uncertainties ($\pm 14\%$ for Auger, $\pm 21\%$ for TA).
- If not corrected, a mismatch between energy scales can yield a spurious dipole.
- For example, assume events with $E_{\text{true}} = 10$ EeV are reconstructed as $E_{\text{rec}} = 9$ EeV by Auger and as $E_{\text{rec}} = 11$ EeV by TA:
    - If we analyze all events with $E_{\text{rec}} \geq 10$ EeV, then events with $E_{\text{true}} = 10$ EeV are included if detected by TA but not if detected by Auger.
    - This would look like the UHECR flux from the north was larger than from the south.
- Hence, we should correct for possible mismatches in the energy scales the best we can.
- We can use measurements in the common declination band for this purpose.

Best-fit energy cross-calibration (Tinyakov [Auger and TA collabs.] ICRC2021)

- We can match spectrum measurements in the common declination band via

$$\frac{E_{\text{Auger}}}{10\ \text{EeV}} = 0.857\left(\frac{E_{\text{TA}}}{10\ \text{EeV}}\right)^{0.937}$$

$$\frac{E_{\text{TA}}}{10\ \text{EeV}} = 1.179\left(\frac{E_{\text{Auger}}}{10\ \text{EeV}}\right)^{1.067}$$

→ In the following, we used the thresholds

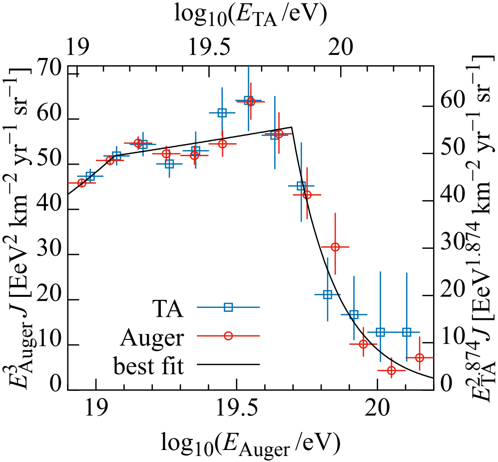
$$E_{\text{Auger}} \geq 8.57\ \text{EeV} \longleftrightarrow E_{\text{TA}} \geq 10\ \text{EeV}$$

$$E_{\text{Auger}} \geq 16\ \text{EeV} \longleftrightarrow E_{\text{TA}} \geq 19.47\ \text{EeV}$$

$$E_{\text{Auger}} \geq 32\ \text{EeV} \longleftrightarrow E_{\text{TA}} \geq 40.8\ \text{EeV}$$

Note: Only $E_{\text{TA}} \geq 10$ EeV used in this fit — **do not extrapolate to lower energies!**

average spectrum in $-11° < \delta < +43°$



$\chi^2/n_{\text{dof}} = 15.6/14\ (p = 0.34)$

The dipole and quadrupole moment

- We can expand the flux Φ of UHECRs coming from the sky direction $\hat{\mathbf{n}}$ into spherical harmonics:
  $\Phi(\hat{\mathbf{n}}) = \sum_{\ell=0}^{+\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}}) = \Phi_{\text{avg}} \left(1 + \mathbf{d} \cdot \hat{\mathbf{n}} + \frac{1}{2} \hat{\mathbf{n}} \cdot \mathbf{Q} \hat{\mathbf{n}} + \cdots \right)$
  - Small $\ell \longleftrightarrow$ large-scale anisotropies ($\sim 180°/\ell$) and vice versa
  - $\mathbf{d} = \frac{\sqrt{3}}{a_{00}} (a_{11} \hat{\mathbf{x}} + a_{1-1} \hat{\mathbf{y}} + a_{10} \hat{\mathbf{z}})$
  - Likewise, Q_{ij} = combinations of $\frac{a_{2m}}{a_{00}}$ $\binom{i,j=x,y,z,}{m=-2,-1,0,1,2}$
- The dipole amplitude $|\mathbf{d}|$ and the quadrupole amplitude $|\mathbf{Q}|$ are relatively insensitive to magnetic fields, providing some information about sources:
  - Coherent deflections mostly only affect the directions of $\mathbf{d}, \mathbf{Q}$, not their amplitudes.
  - Turbulent deflections attenuate a 2^ℓ-upole by a factor $\mathcal{O}\left(e^{-\ell^2 \Delta\theta^2_{\text{turb}}/2}\right)$
    $\rightarrow$ most of the $|\mathbf{d}|$ and a sizable fraction of the $|\mathbf{Q}|$ should survive
    (see also Eichmann & Winchen 2020).
- Only with full-sky coverage can we measure a_{1m}, a_{2m} with no assumptions about $a_{3m}, a_{4m}, \ldots$.

Results from Auger and TA data (Tinyakov [Auger and TA collabs.] ICRC2021)

energies (Auger) energies (TA)	$[8.57\ \text{EeV}, 16\ \text{EeV})$ $[10\ \text{EeV}, 19.47\ \text{EeV})$	$[16\ \text{EeV}, 32\ \text{EeV})$ $[19.47\ \text{EeV}, 40.8\ \text{EeV})$	$[32\ \text{EeV}, +\infty)$ $[40.8\ \text{EeV}, +\infty)$
d_x [%]	$-0.7 \pm 1.1 \pm 0.0$	$+1.6 \pm 2.0 \pm 0.0$	$-5.3 \pm 3.9 \pm 0.1$
d_y [%]	$\mathbf{+4.8 \pm 1.1 \pm 0.0}$	$\mathbf{+3.9 \pm 1.9 \pm 0.1}$	$\mathbf{+9.7 \pm 3.7 \pm 0.0}$
d_z [%]	$-3.3 \pm 1.4 \pm 1.3$	$-6.0 \pm 2.4 \pm 1.3$	$+3.4 \pm 4.7 \pm 3.6$
$Q_{xx} - Q_{yy}$ [%]	$-5.1 \pm 4.8 \pm 0.0$	$+13.6 \pm 8.3 \pm 0.0$	$\mathbf{+43 \pm 16 \pm 0}$
Q_{xz} [%]	$-3.9 \pm 2.9 \pm 0.1$	$+5.4 \pm 5.1 \pm 0.0$	$+5 \pm 11 \pm 0$
Q_{yz} [%]	$-4.9 \pm 2.9 \pm 0.0$	$-9.6 \pm 5.0 \pm 0.1$	$+11.9 \pm 9.8 \pm 0.2$
Q_{zz} [%]	$+0.5 \pm 3.3 \pm 1.7$	$+5.2 \pm 5.8 \pm 1.7$	$+20 \pm 11 \pm 5$
Q_{xy} [%]	$+2.2 \pm 2.4 \pm 0.0$	$+0.2 \pm 4.2 \pm 0.1$	$+4.5 \pm 8.1 \pm 0.1$

($> 4\sigma$ $> 2\sigma$)

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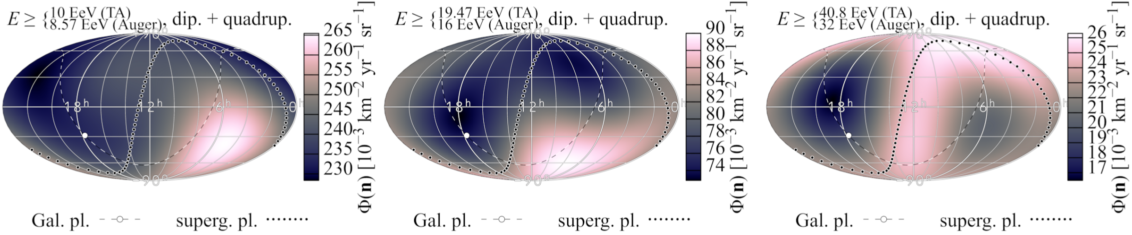
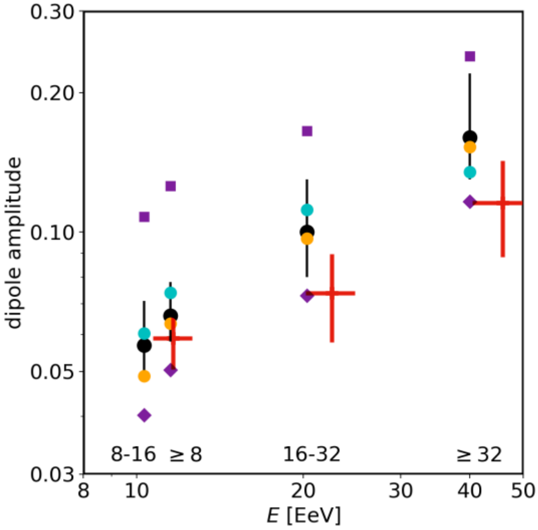


- A weakly energy-dependent dipole towards a direction far away from the GC
- A hint of a quadrupole roughly along the SGP at the highest energies

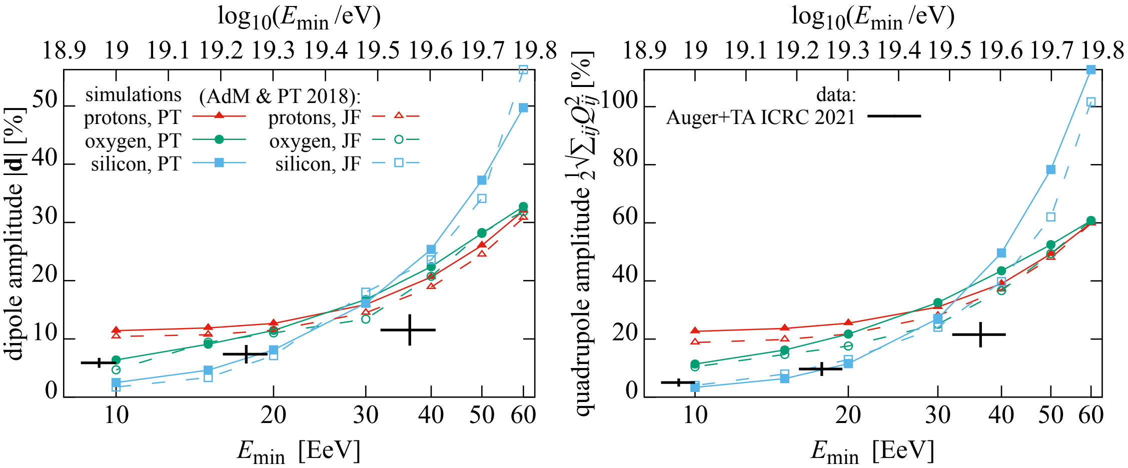
Comparison with theoretical expectations (Ding, Globus & Farrar 2021)

- observation, Auger exposure $l_{max} = 1$
- Case d90, Auger exposure $l_{max} = 1$
- Case d90, full sky $l_{max} \gg 1$
- Case d90, full sky, illumination
- Case SH*, Auger exposure $l_{max} = 1$

+ Auger+TA ICRC 2021



Comparison with theoretical expectations (di Matteo & Tinyakov 2018)



- Large-scale anisotropies at the low edge of the range of model expectations, suggesting a medium to heavy mass composition

Correlations with nearby galaxies

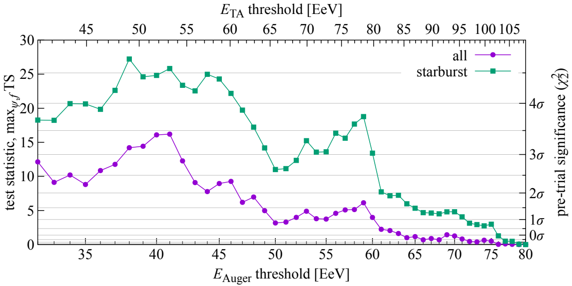
- We can search for smaller-scale anisotropies as well, but we need to focus on the highest energies, where magnetic deflections are expected to be smaller.
- But this way the amount of statistics available is severely reduced, making "blind" searches hopeless.

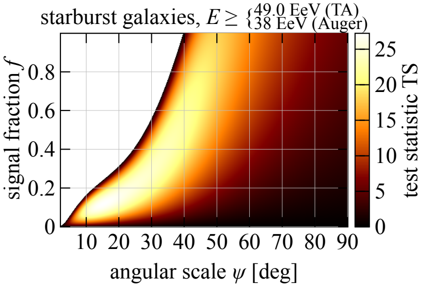
- Hence, we performed targeted searches based on two different catalogs:
  - all types of galaxies at $1\ \mathrm{Mpc} \leq D < 250\ \mathrm{Mpc}$, based on 2MASS
  - starburst galaxies at $1\ \mathrm{Mpc} \leq D < 130\ \mathrm{Mpc}$ (based on Lunardini et al. 2019)

- Test statistics: 2×log-likelihood ratio between a model (an isotropic background plus a weighted sum of Fisher distributions) and the null hypothesis (isotropy), scanned over the energy threshold E_{min}, angular scale ψ and signal fraction f

The best fit (di Matteo [Auger and TA collabs.] ICRC2021)

catalog	$E_{\text{min}}^{(\text{Auger})}$	$E_{\text{min}}^{(\text{TA})}$	ψ	f	TS	significance
all galaxies	41 EeV	53 EeV	$24°^{+13°}_{-8°}$	$38\%^{+28\%}_{-14\%}$	16.2	$2.9\sigma_{\text{global}}$
starburst galaxies	38 EeV	49 EeV	$15.5°^{+5.3°}_{-3.2°}$	$11.8\%^{+5.0\%}_{-3.1\%}$	27.2	$4.2\sigma_{\text{global}}$





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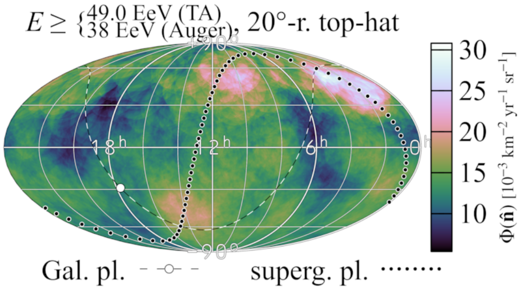

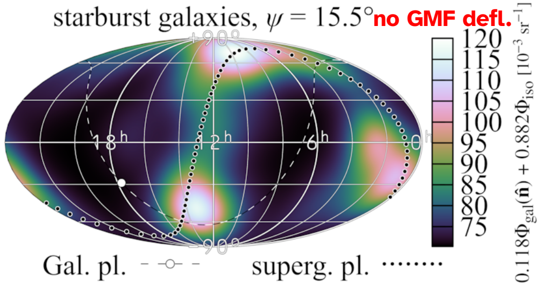

Estimates of the impact of propagation effects

- In order to reduce statistical penalties, the TS was based on a simple model, not taking into account:
  - The energy losses of UHECRs (which depend on their mass composition)
  - Coherent magnetic deflections
  - The rigidity dependence of magnetic deflections
  - The possibility of several anisotropic classes of sources at once
- We can try to estimate their effects by:
  1. Generating lots of simulated datasets based on a variety of realistic scenarios
  2. Analyzing each simulation the same way as the real data at ICRC 2021
  3. Looking at which simulations result in similar ψ, f, TS as the real data
- We find that to reproduce the observed results:
  - The background must be from near-isotropic sources or very heavy ($\gtrsim$ Si).
  - The foreground must be medium-heavy (N $\lesssim$ foreground $\lesssim$ Si).
  - The injected foreground fraction must be a few times larger than reconstructed.
- More details to be presented at UHECR 2022 (3–7 Oct 2022, GSSI, L'Aquila)

Upcoming extensions of the datasets

- Starting from UHECR 2022, TA events detected until 10 May 2022 will be available (14 years, i.e. 3 more years than at ICRC 2021).
- Starting from ICRC 2023, more recently detected Auger events will be available (we had 17 years of data at ICRC 2021).

- We can expect this to reduce uncertainties by around 10% (e.g. the local significance of d_y in the low-energy bin to go from 4.3σ to 4.7σ).
- Continued work by the spectrum working group might reduce uncertainties in the energy cross-calibration even more than this.

- Possible joint journal papers in the next years

Outlook for the further future

- TA is undergoing an upgrade (TA×4) which will increase its area by a factor of 4, helping reduce statistical uncertainties in the northern hemisphere.
- Auger is undergoing an upgrade (AugerPrime) which will add new scintillation and radio detectors to the existing water-Cherenkov and fluorescence detectors, reducing statistical and systematic uncertainties on UHECR masses.
- Better UHECR mass estimates will help us study mass-dependent anisotropies, potentially allowing us to disentangle the effects of magnetic deflections from the distribution of UHECR sources.
- In the further future, new experiments such as GRAND, POEMMA and GCOS are hopefully going to gather even more data.

Stay tuned!