The UHECR dipole and quadrupole in the latest data from the original Auger and TA surface detectors

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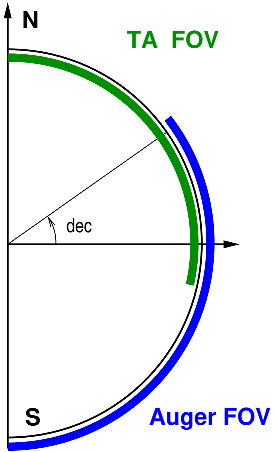
Auger and TA UHECR observatories



cover full sky together!

The data sets

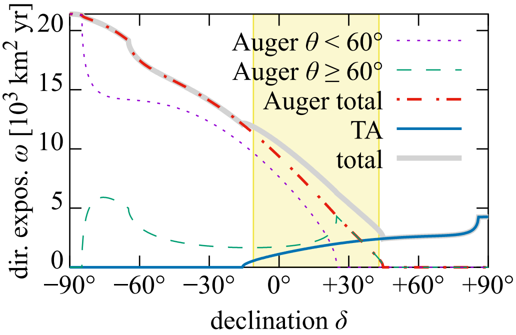
Telescope Array data

- 2008 May 11 – 2019 May 10
- strict cuts, $\theta < 55^\circ$
- $14\,000\ \mathrm{km}^2\ \mathrm{yr\ sr}$ effective exposure

Pierre Auger Observatory data

- 2004 Jan 01 – 2020 Dec 31
- 5T5 events, $\theta < 80^\circ$ (bad periods removed, POS2 condition imposed)
- $112\,000\ \mathrm{km}^2\ \mathrm{yr\ sr}$ effective exposure

Combined Auger + TA exposure



The cross-calibration of energy scales

- For correct determination of flux multipoles one must ensure that the Auger and TA energy scales match as otherwise one gets a spurious N-S anisotropy.
- Key point of the method: the true UHECR flux integrated over the given energy bin and over the common band $\phi_j^{\rm true} = \int_{E_j}^{E_{j+1}} \int_{\delta_{\min}}^{\delta_{\max}} J(E, \mathbf{n})\, \mathrm{d}E\, \mathrm{d}\Omega$ can be independently measured by the two observatories.
  The results must agree in all energy bins when energy scales match.
- Given the directional exposures $\omega_{\rm Auger}(\mathbf{n})$, $\omega_{\rm TA}(\mathbf{n})$ of the two arrays and a declination band $(\delta_{\min}, \delta_{\max})$ where both $\omega_a(\mathbf{n}) \neq 0$,

$$\phi_{aj}^{\rm est.} = \sum_k 1/\omega_a(\mathbf{n}_k)$$

  are unbiased estimators of $\phi_j^{\rm true}$ with the statistical uncertainties $\sigma_{aj} = \sqrt{\sum_k 1/\omega_a^2(\mathbf{n}_k)}$.

Cross-calibration setup:

- The declination band $\delta_{\text{min}} = -11^\circ < \delta < +43^\circ = \delta_{\text{max}}$ (optimized by MC)
- The nominal $\log_{10}(E/\mathrm{eV})$ bins
  - $[19.0, 19.1), [19.1, 19.2), \ldots, [19.9, 20.0), [20.0, +\infty)$ for TA (11 bins)
  - $[18.9, 19.0), [19.0, 19.1), \ldots, [19.8, 19.9), [19.9, +\infty)$ for Auger (11 bins)

  (the last are larger to ensure $\gtrsim 10$ events in the bin)
- Assume a twice-broken power-law model for the energy spectrum in the band (6 params $\boldsymbol{\theta}_J$)
- Assume power-law conversion of TA and Auger nominal energies :

$$E_{\text{Auger}} = E_0 e^{\alpha} \left(E_{\text{TA}}/E_0\right)^{\beta} \qquad E_{\text{TA}} = E_0 e^{-\alpha/\beta} \left(E_{\text{Auger}}/E_0\right)^{1/\beta} \qquad (E_0 = 10\ \mathrm{EeV})$$

- Use χ^2 based on a log-normal likelihood (found accurate in simulations provided $\gtrsim 10$ events):

$$\chi^2(\boldsymbol{\theta}_J, \alpha, \beta) = \sum_{aj} \frac{\left(\ln \phi_{aj}^{\text{est.}} - \ln \phi_{aj}^{\text{pred.}}(\boldsymbol{\theta}_J, \alpha, \beta)\right)^2}{\left(\sigma_{aj}/\phi_{aj}^{\text{est.}}\right)^2}.$$

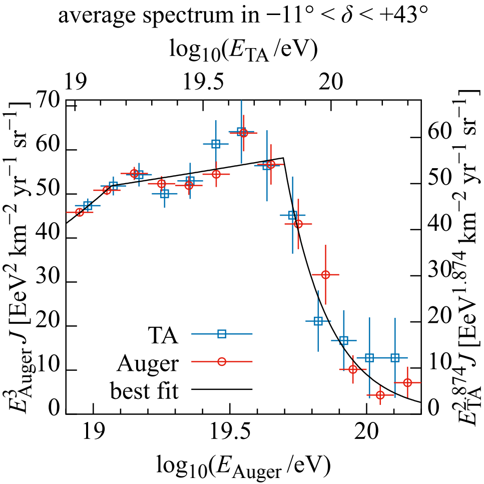
Cross-calibration result

- $\alpha = -0.154 \pm 0.013$
- $\beta = 0.937 \pm 0.017$

  $\rho_{\alpha\beta} = -0.177 \quad \chi^2/n = 15.6/14$
  $(p = 0.34)$

Last three bins are shown separately in the plot but combined into one for the fit.

NOTE: event selection is not optimized for energy spectrum measurements.
$\Longrightarrow$ Results are NOT to be used as Auger $\leftrightarrow$ TA energy conversion rule outside of this study.



The energy bins for large-scale anisotropy searches

- We choose three energy bins for dipole and quadrupole searches. The first bin boundary is fixed by the availability of TA data, 10 EeV (TA) $= (8.57 \pm 0.11)$ EeV (Auger)
- For the second and third bin we use the same boundaries as in Auger-only studies: 16 EeV (Auger) $= (19.47 \pm 0.32)$ EeV (TA), 32 EeV (Auger) $= (40.8 \pm 1.1)$ EeV (TA)
- In summary, the following 3 energy bins were used:
  - TA energy (EeV): $[10 - 19.47]$, $[19.47 - 40.8]$, $[40.8 - \infty]$
  - Auger energy (EeV): $[8.57 - 16]$, $[16 - 32]$, $[32 - \infty]$
- Uncertainties on the conversion treated as "effective" exposure corrections, e.g.

$$\omega_{\mathrm{TA}} + \sigma_{\mathrm{TA}}^{\mathrm{eff.}} = \omega_{\mathrm{TA}} \frac{\int_{40.8\ \mathrm{EeV}}^{+\infty} J(E)\,\mathrm{d}E}{\int_{41.9\ \mathrm{EeV}}^{+\infty} J(E)\,\mathrm{d}E}$$

Dipole and quadrupole measurement

- UHECR flux is decomposed in the sum of spherical harmonics

$$\Phi(\mathbf{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\mathbf{n}) = \Phi_0 \left(1 + \mathbf{d} \cdot \mathbf{n} + \frac{1}{2}\mathbf{n} \cdot \mathbf{Q}\mathbf{n} + \ldots\right)$$

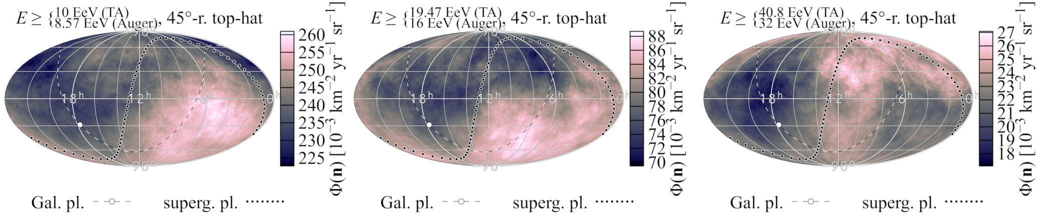
  where dipole vector $\mathbf{d}$ and quadrupole tensor $\mathbf{Q}$ are combinations of a_{1m} and a_{2m}, respectively.

- From the data, harmonic amplitudes $a_{\ell m}$ and their uncertainties are calculated as follows:

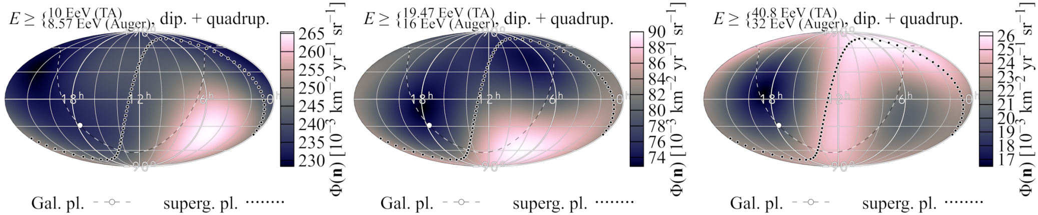
$$a_{\ell m} = \sum_k \frac{Y_{\ell m}(\mathbf{n}_k)}{\omega(\mathbf{n}_k)}, \qquad \sigma_{\ell m}\sigma_{\ell' m'}\rho_{\ell m,\ell' m'} = \sum_k \frac{Y_{\ell m}(\mathbf{n}_k)Y_{\ell' m'}(\mathbf{n}_k)}{\omega^2(\mathbf{n}_k)}$$

Full sky flux maps in 3 energy bins

Flux averaged over 45° top-hat window



Reconstructed dipole + quadrupole



Full-sky dipole and quadrupole components

energies (Auger) energies (TA)	$[8.57\ \mathrm{EeV}, 16\ \mathrm{EeV})$ $[10\ \mathrm{EeV}, 19.47\ \mathrm{EeV})$	$[16\ \mathrm{EeV}, 32\ \mathrm{EeV})$ $[19.47\ \mathrm{EeV}, 40.8\ \mathrm{EeV})$	$[32\ \mathrm{EeV}, +\infty)$ $[40.8\ \mathrm{EeV}, +\infty)$
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 [%]	$+4.8 \pm 1.1 \pm 0.0$	$+3.9 \pm 1.9 \pm 0.1$	$+9.7 \pm 3.7 \pm 0.0$
d_z [%]	$-3.3 \pm 1.4 \pm 1.3$	$-6.0 \pm 2.4 \pm 1.3$	$+3.4 \pm 4.7 \pm 3.6$
$Q_{xx} - Q_{yy}$ [%]	$-5.1 \pm 4.8 \pm 0.0$	$+13.6 \pm 8.3 \pm 0.0$	$+43 \pm 16 \pm 0$
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} [%]	$+2.2 \pm 2.4 \pm 0.0$	$+0.2 \pm 4.2 \pm 0.1$	$+4.5 \pm 8.1 \pm 0.1$
C_1 $[10^{-3}]$	$4.8 \pm 2.0 \pm 1.2$	$7.6 \pm 4.6 \pm 2.2$	$19 \pm 12 \pm 4$
C_2 $[10^{-3}]$	$0.85 \pm 0.66 \pm 0.02$	$3.1 \pm 2.2 \pm 0.2$	$15.5 \pm 8.9 \pm 2.4$

Table: Uncertainties: $\pm$ statistical $\pm$ cross-calibration. Statistical uncertainties are uncorrelated except $\rho(d_x, Q_{xz}) = \rho(d_y, Q_{yz}) = 0.45$ and $\rho(d_z, Q_{zz}) = 0.53$

Comparison to Auger-only result

Auger-only (see talk by Rogério de Almeida)

	E (Auger)	$8 - 16$ EeV	$16 - 32$ EeV	$32 - \infty$ EeV
$\ell_{max} = 1$	d_z [%]	-3 ± 1	-7 ± 3	-12 ± 5
$\ell_{max} = 2$	d_z [%]	$+1 \pm 4$	-15 ± 7	-22 ± 13
	Q_{zz} [%]	$+7.4 \pm 6.4$	-14 ± 14	-17 ± 26

Auger + TA, this work

	E (Auger)	$8.57 - 16$ EeV	$16 - 32$ EeV	$32 - \infty$ EeV
	E (TA)	$10 - 19.47$ EeV	$19.47 - 40.8$ EeV	$40.8 - \infty$ EeV
$\ell_{max} = \infty$	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_{zz} [%]	$+0.5 \pm 3.3 \pm 1.7$	$+5.2 \pm 5.8 \pm 1.7$	$+20 \pm 11 \pm 5$

- Uncertainties on d_z, Q_{zz} halved compared to Auger-only with $\ell_{max}=2$
- Other uncertainties only slightly smaller

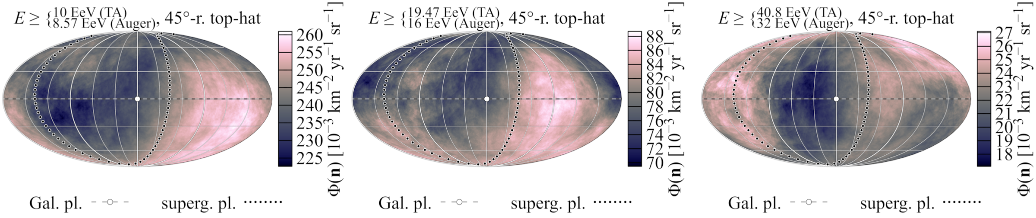
Discussion & conclusions

- Results are compatible with Auger-only ones obtained under assumption $\ell \leq 2$, but d_z and Q_{zz} have smaller uncertainly
- None of the moments are significant with $> 3\sigma$ except d_y in the lowest energy bin (already reported by Auger)
- Uncertainties can be further reduced by having more exposure in the Northern hemisphere; TA$\times$4 will be crucial for this purpose.

BACKUP SLIDES

Full sky flux maps in Galactic coordinates

Flux averaged over 45° top-hat window



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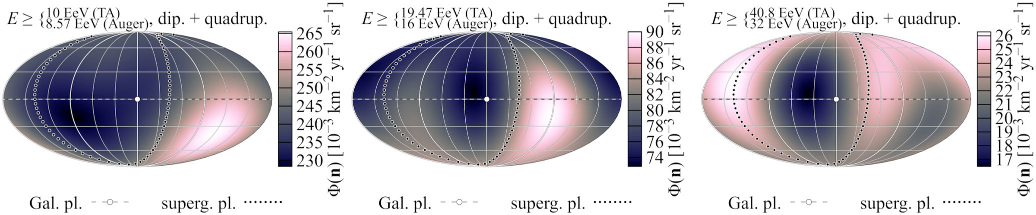

Comparison to Auger-only result: all dipole components

Energy bin, EeV			
this work	8.57 – 16	16 – 32	32 – ∞
Auger-only	8 – 16	16 – 32	32 – ∞
d_x, %	$-0.7 \pm 1.1 \pm 0.0$	$+1.6 \pm 2.0 \pm 0.0$	$-5.3 \pm 3.9 \pm 0.1$
	-0.5 ± 1.3	$+5 \pm 2$	-12 ± 5
d_y, %	$+4.8 \pm 1.1 \pm 0.0$	$+3.9 \pm 1.9 \pm 0.1$	$+9.7 \pm 3.7 \pm 0.0$
	$+4.5 \pm 1.3$	$+9 \pm 2$	$+11 \pm 5$
d_z, %	$-3.3 \pm 1.4 \pm 1.3$	$-6.0 \pm 2.4 \pm 1.3$	$+3.4 \pm 4.7 \pm 3.6$
	$+1 \pm 4$	-15 ± 7	-22 ± 13

- Energies are in Auger energy scale
- Auger-only results are from the talk by Rogério de Almeida

The energy conversion: comparison to spectrum WG results