Auger+TA: full-sky searches

The quest for anisotropies: energy ranges

Two different energy ranges, with possibly different anisotropies

different volume of **observable universe** (anisotropy in the source distribution?),
different **deflections** by magnetic fields – *e.g.* Galactic: $\delta \theta \sim 20\text{-}30^\circ \ Z \ (E / 10 \text{ EeV})^{-1}$

**“Beyond the ankle”**

Large-angular scale patterns

**“Beyond the flux suppression”**

Intermediate-to-small scale patterns
Auger and TA: model-independent anisotropy searches

“Beyond the ankle”

Large-scale anisotropy at $E_{\text{Auger}} > 8$ EeV > 5.2σ post-trial

Flux map - Equatorial coordinates

“Beyond the flux suppression”

Searches for overdensities
- at $E_{\text{TA}} > 57$ EeV: pre-trial 5.1σ
- at $E_{\text{Auger}} > 54$ EeV: pre-trial 4.3σ

→ post-trial σ not (yet) at the discovery level


Significance maps - Equatorial coordinates


Auger Collab., Science 2017
Strength

Full-sky coverage

→ no “windowing” effect, access to anisotropies at all angular scales, without relying on an assumption on the presence / absence of patterns at higher orders
→ unbiased estimation of the angular power spectrum

Weakness

Sensitivity to mismatches in energy

→ for \( \frac{dN}{dE} \propto E^{-\Gamma} \), shift in \( E \)-scale \( E' = r_E E \)
= shift in integral flux \( \Phi' = \Phi / r_E^{\Gamma-1} \)
possibly large effect, particularly with steep indices \( \Gamma \sim 3-4 \)

Method employed

Cross calibration, through flux matching in common declination band, covered by Auger & TA: \( \delta \in [-12^\circ;42^\circ] \)
This full-sky search: datasets

Dataset “above the ankle”

TA data >10 EeV up to **May 2013** – *Auger vertical-only* data >8.5 EeV up to **Dec 2012**

_New_: **TA** data up to **May 2017** (same as ApJL 2018, submitted)
*Auger* vertical and inclined data up to **Aug 2016** (same as Science 2017)

Dataset “above the flux suppression”

TA data >57 EeV up to **May 2013** – *Auger* vert. and inclined data >42 EeV up to **Mar 2014**

_New_: **TA** data up to **May 2017** (cf. supra) – *Auger* data up to **Apr 2017** (same as ApJL 2018)
Flux matching in the common $\delta$ band

**Approach**

Fix one threshold energy, find the other with matching flux

\[ \text{computing the flux in common } \delta \text{ band as } \sum_{\text{events}} 1/\omega(\delta): \text{ unbiased even if anisotropies} \]

energy dispersion near the threshold energy accounted for through unfolding factors

$E$-shifts consistent with the work of the Auger/TA spectrum group in $\delta \in [-15^\circ; 25^\circ]$

**“Beyond the ankle”:**

~ 31,000 events  \quad +200%!

**TA driven:** full efficiency for $E_{\text{TA}} > 10$ EeV $\rightarrow$ corresp. $E_{\text{Auger}} = 8.86$ EeV

**“Beyond the suppression”:**

~ 1,000 events  \quad +60%!

**Auger driven:** indications for $E_{\text{Auger}} > 40$ EeV $\rightarrow$ corresp. $E_{\text{TA}} = 53.2$ EeV
Flux reconstruction

Flux, $\sum_{\text{events}} 1/\omega(\delta)$, in top-hat windows of radius $R$, centered on a $\sim 1^\circ \times 1^\circ$ grid → above $8.86/10$ EeV, top-hat “smoothing” on $R = 45^\circ$ angular scale

Local significance reconstruction

Li & Ma, with ON = top-hat window, OFF = rest of the sky, $\alpha =$ exposure ratio → to first order $\sigma \propto \sqrt{\Phi \omega}$ (larger exposure → easier to detect significant flux excess)

Features “by eye”

Dipolar pattern similar in shape/amplitude to that observed above $E_{\text{Auger}} > 8$ EeV → flux somewhat enhanced in the N–W quadrant, deviation from pure dipole?

$\Phi(E_{\text{Auger/TA}} > 8.86/10$ EeV) [km$^{-2}$ sr$^{-1}$ yr$^{-1}$] - Equatorial coordinates - $R = 45^\circ$

Local $\sigma(E_{\text{Auger/TA}} > 8.86/10$ EeV) - Equatorial coordinates - $R = 45^\circ$
Results above 8.86/10 EeV: power spectrum

**Approach**

Spherical harmonic transform of the unsmoothed flux map, $N(\alpha, \delta)/\omega(\delta)$

→ with full-sky coverage, unbiased estimator:

$$a_{lm} = \sum_{\text{events}} Y_{lm}(\alpha, \delta)/\omega(\delta)$$

→ Power spectrum retrieved as

$$C_l = \frac{4\pi}{(2l+1)} \times \sum_m (a_{lm}/a_{00})^2$$

so that $C_0 = 4\pi$

**Results**

Largest deviation for $C_1$ (local 2.5σ)

$$d_\perp = 4.3 \pm 1.1 \text{ stat} \pm 0.04 \text{ cross} \% \text{ (local 3.5σ)}$$

→ vs Rayleigh analysis $E_{\text{Auger}} > 8$ EeV:

$l=1$: $d_\perp = 6.0 \pm 1.0 \%$

$l \leq 2$: $d_\perp = 5.0 \pm 1.3 \%$

Science 2017


Small difference in $d_\perp$ & small deviation for $C_2$ (loc. 1.9σ) → quadrupole to be further studied
Results above 8.86/10 EeV: power spectrum

**Approach**

Spherical harmonic transform of the unsmoothed flux map, $N(\alpha, \delta)/\omega(\delta)$

→ with full-sky coverage, unbiased estimator:

$$a_{lm} = \sum_{\text{events}} Y_{lm}(\alpha, \delta)/\omega(\delta)$$

→ Power spectrum retrieved as

$$C_l = 4\pi/(2l+1) \times \sum_m (a_{lm}/a_{00})^2$$

so that $C_0 = 4\pi$

**Results**

Largest deviation for $C_1$ (local 2.5$\sigma$)

$$d_z = -2.6 \pm 1.3_{\text{stat}} \pm 1.4_{\text{cross}} \% \text{ (local 1.4$\sigma$)}$$

→ vs Rayleigh analysis $E_{\text{Auger}} > 8$ EeV:

$l=1$: $d_z = -2.6 \pm 1.5 \%$  

$l\leq2$: $d_z = -2 \pm 4 \%$  

*Science 2017* 

*ApJ 2018, in press*
Flux reconstruction

Flux, $\sum_{\text{events}} 1/\omega(\delta)$, in top-hat windows of radius $R$, centered on a $\sim 1^\circ \times 1^\circ$ grid → above 40/53.2 EeV, top-hat “smoothing” on $R = 20^\circ$ angular scale

Local significance reconstruction

Li & Ma, with ON = top-hat window, OFF = rest of the sky, $\alpha$ = exposure ratio → to first order $\sigma \propto \sqrt{\Phi \omega}$ (larger exposure → easier to detect significant flux excess)

Features “by eye”

Most noticeably, flux enhancements around (RA, Dec) ≈ (180°, ±50°) → appears brighter in the North, smaller exposure ⇒ comparable significance in the South
Flux reconstruction

Flux, $\Sigma_{\text{events}} 1/\omega(\delta)$, in top-hat windows of radius $R$, centered on a $\sim 1^\circ \times 1^\circ$ grid
→ above 40/53.2 EeV, top-hat “smoothing” on $R = 20^\circ$ angular scale

Local significance reconstruction

Li & Ma, with ON = top-hat window, OFF = rest of the sky, $\alpha = $ exposure ratio
→ to first order $\sigma \propto \sqrt{\Phi \omega}$ (larger exposure → easier to detect significant flux excess)

Features “by eye”

Most noticeably, flux enhancements around (RA, Dec) $\approx (180^\circ, \pm 50^\circ)$
→ appears brighter in the North, smaller exposure = comparable significance in the South

$\Phi(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ [km$^{-2}$ sr$^{-1}$ yr$^{-1}$] - Equatorial coordinates - $R = 20^\circ$

$\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 20^\circ$
Results above 40/53.2 EeV: power spectrum

Approach

. Spherical harmonic transform of the unsmoothed flux map, \( N(\alpha, \delta)/\omega(\delta) \)

→ with full-sky coverage, unbiased estimator:

\[
a_{lm} = \sum_{\text{events}} Y_{lm}(\alpha, \delta)/\omega(\delta)
\]

→ Power spectrum retrieved as

\[
C_l = \frac{4\pi}{(2l+1)} \times \sum_m (a_{lm}/a_{00})^2
\]

so that \( C_0 = 4\pi \)

Results

Largest deviations found for \( C_{14} \) (loc. 2.8\( \sigma \))

→ angular scale of 180°/14 ~ 13°

Noting that given 20 trials (l’s tested), assumed independent → **post-trial 1.6\( \sigma \)**

No indication of deviation from isotropy based on full-sky power spectrum
Results above 40/53.2 EeV: overdensity search

Approach
Reconstruction of Li & Ma significance in circular ON regions of radius $\theta$, centered on a $\sim 1^\circ \times 1^\circ$ grid
→ scan over $\theta \in [5^\circ; 35^\circ]$, with $\delta \theta = 5^\circ$
→ study performed above single $E$-threshold

Most significant excesses
Largest $\sigma$ spot: local $4.7\sigma$ obtained for $20^\circ$
2$^{nd}$ largest spot: local $4.2\sigma$ obtained for $15^\circ$

Note $20^\circ / 15^\circ$ radius - Gaussian $\sigma_{\theta} \sim 9-12^\circ$

Penalty factors
Evaluated through MC, accounting for $\theta$-scan & uncertainty on relative exposure:
→ 1$^{st}$/ 2$^{nd}$ spots: post-trial 2.2/1.3$\sigma$

Post trial: $p$-value $\times O(10^4)$

Note: penalty factors based on previous searches by
Auger: 1-30$^\circ$, $\delta \theta = 1^\circ + E$-scan $\approx O(10^5)$
TA: 15-35$^\circ$, $\delta \theta = 5^\circ +$ fixed $E \approx O(10^3)$
Results above 40/53.2 EeV: overdensity search

Approach
Reconstruction of Li & Ma significance in circular ON regions of radius θ, centered on a ~ 1°×1° grid
→ scan over θ ∈ [5°;35°], with δθ = 5°
→ study performed above single E-threshold

Most significant excesses
Largest σ spot: local 4.7σ obtained for 20°
2nd largest spot: local 4.2σ obtained for 15°

Note 20° / 15° radius - Gaussian σθ ~ 9-12°

Penalty factors
Evaluated through MC, accounting for θ-scan & uncertainty on relative exposure:
→ 1st / 2nd spots: post-trial 2.2/1.3σ
Post trial: p-value × O(10^4)

Note: penalty factors based on previous searches by
Auger: 1-30°, δθ = 1°+ E-scan ≈ O(10^5)
TA: 15-35°, δθ = 5° + fixed E ≈ O(10^3)
Full-sky searches

Based on flux cross-calibration in the common declination band, $\delta \in [-12^\circ; 42^\circ]$

→ energy-scale mismatch (6% / 14%)

⇒ relative flux: non-negligible source of uncertainty, possibly alleviated with further spectral studies

Beyond 8.86/10 EeV - main result

- $l=1$ mainly in line with Auger dipole
- interest in further studies of the quadrupole

Beyond 40/53.2 EeV - main result

- Two warm spots along super-Galactic plane
  - $\Phi_{\text{spot}}(N) \sim 1.5-2 \times \Phi_{\text{spot}}(S)$, $\sigma_{\text{local}}(N) \sim \sigma_{\text{local}}(S)$

Possible future studies

- Studies on quadrupole. Rayleigh analysis.
- Super-Galactic plane?
- Model-dependent study against catalogs?
→ To be discussed, stay tuned!
Backup
Energy mismatch

$E$-shifts consistent with the work of the Auger/TA spectrum group in $\delta \in [-12^\circ;24^\circ]$

$\Phi_{TA}(> 10 \text{ EeV}) = 0.345 \pm 0.008 \text{ km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1}$

$\Phi_{Auger}(> 8.86 \text{ EeV}) = 0.345 \pm 0.004 \text{ km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1}$

$\Phi_{Auger}(> 40 \text{ EeV}) = (9.3 \pm 0.7) \times 10^{-3} \text{ km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1}$

$\Phi_{TA}(> 53.2 \text{ EeV}) = (9.6 \pm 1.2) \times 10^{-3} \text{ km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1}$

$\sim 3,900 \text{ evts}$

$\sim 27,300 \text{ evts}$

$\sim 840 \text{ evts}$

$\sim 130 \text{ evts}$
Dipole (and quadrupole?) - R.A. distribution

\[ \Phi(E_{\text{Auger/TA}} > 8.86/10 \text{ EeV}) \text{ [km}^2 \text{ sr}^{-1} \text{ yr}^{-1}] - \text{Equatorial coordinates - R} = 45^\circ \]

\[ \rightarrow \text{here display only of contributions to } 1^{\text{st}} \text{ harmonics: } e^{\pm i \phi} \text{ terms i.e. } Y_{lm}, m = \pm 1 \]
Most significant excesses

Local $\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 15^\circ$

$N_{\text{ON}} = 16$ \hspace{1cm} $\alpha N_{\text{OFF}} = 4.3$

$N_{\text{ON}} = 48$ \hspace{1cm} $\alpha N_{\text{OFF}} = 24.6$

$N_{\text{ON}} = 52$ \hspace{1cm} $\alpha N_{\text{OFF}} = 27.6$

Local $\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 20^\circ$

$N_{\text{ON}} = 23$ \hspace{1cm} $\alpha N_{\text{OFF}} = 8.4$

$N_{\text{ON}} = 83$ \hspace{1cm} $\alpha N_{\text{OFF}} = 46.1$
Overdensity searches - $R = 35^\circ$

$\Phi(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ [km$^2$ sr$^{-1}$ yr$^{-1}$] - Equatorial coordinates - $R = 35^\circ$

Local $\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 35^\circ$
Overdensity searches - $R = 30^\circ$

\[ \Phi(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV}) \ [\text{km}^2 \text{ sr}^{-1} \text{ yr}^{-1}] \ - \text{Equatorial coordinates - } R = 30^\circ \]

Local $\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV}) \ - \text{Equatorial coordinates - } R = 30^\circ $
Overdensity searches - $R = 25^\circ$

$\Phi(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV}) \ [\text{km}^2 \text{ sr}^{-1} \text{ yr}^{-1}]$ - Equatorial coordinates - $R = 25^\circ$

Local $\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 25^\circ$
Overdensity searches - $R = 20^\circ$

$\Phi(E_{\text{Auger}/TA} > 40/53.2 \text{ EeV}) \ [\text{km}^2 \text{ sr}^{-1} \text{ yr}^{-1}]$ - Equatorial coordinates - $R = 20^\circ$

Local $\sigma(E_{\text{Auger}/TA} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 20^\circ$
Overdensity searches - $R = 15^\circ$

$\Phi(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ [km$^2$ sr$^{-1}$ yr$^{-1}$] - Equatorial coordinates - $R = 15^\circ$

Local $\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 15^\circ$
Overdensity searches - $R = 10^\circ$

$\Phi(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV}) \text{ [km}^2 \text{ sr}^{-1} \text{ yr}^{-1}]$ - Equatorial coordinates - $R = 10^\circ$

Local $\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 10^\circ$
Overdensity searches - $R = 5^\circ$

$\Phi(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV}) \ [\text{km}^2 \text{ sr}^{-1} \text{ yr}^{-1}]$ - Equatorial coordinates - $R = 5^\circ$

Local $\sigma(E_{\text{Auger/TA}} > 40/53.2 \text{ EeV})$ - Equatorial coordinates - $R = 5^\circ$