Auger+TA: full-sky searches

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The quest for anisotropies: energy ranges

Two different energy ranges, with possibly different anisotropies

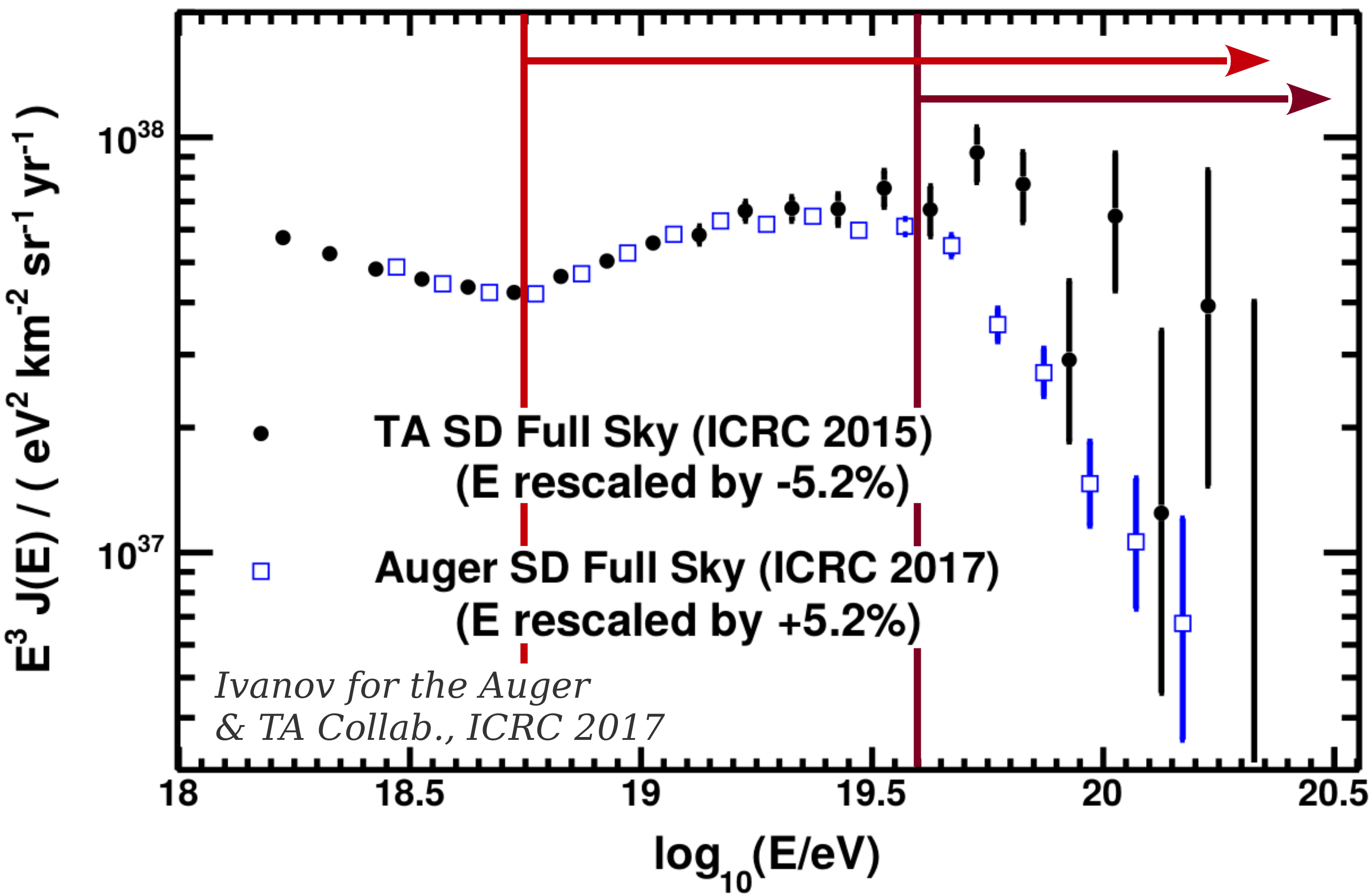
different volume of **observable universe** (anisotropy in the source distribution?),
different **deflections** by magnetic fields – *e.g.* Galactic: $\delta\theta \sim$ 20-30° Z (E / 10 EeV)$^{-1}$

"Beyond the ankle"

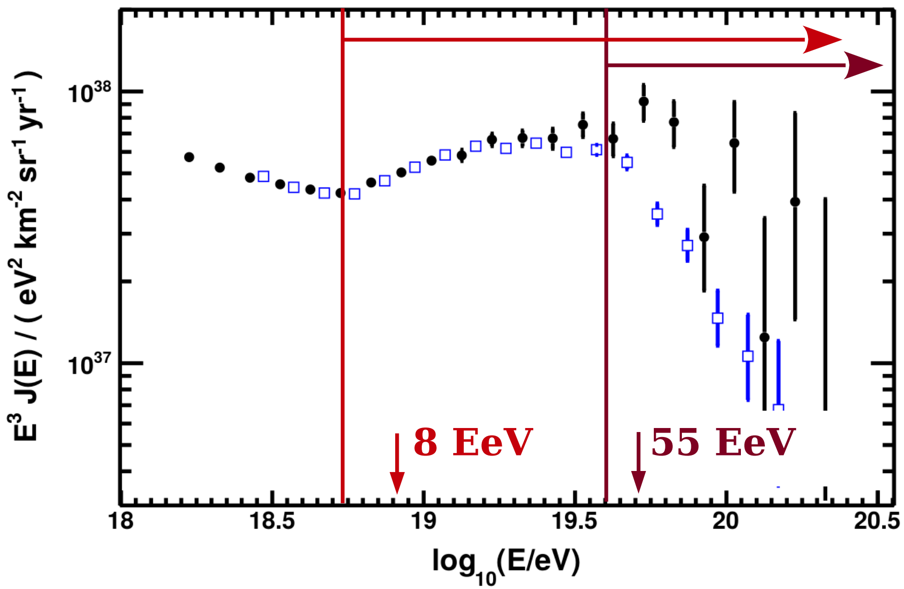
Large-angular scale patterns

"Beyond the flux suppression"

Intermediate-to-small scale patterns



Auger and TA: model-independent anisotropy searches

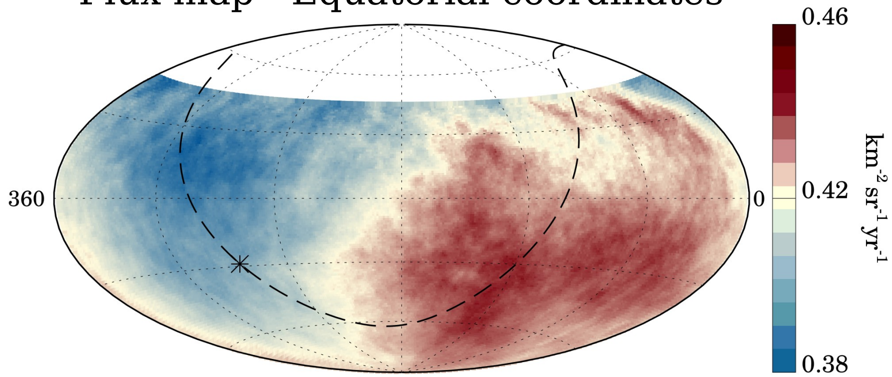


"Beyond the ankle"

Large-scale anisotropy at E_{Auger} > 8 EeV

> 5.2σ *post*-trial

Flux map - Equatorial coordinates



Auger Collab., Science 2017

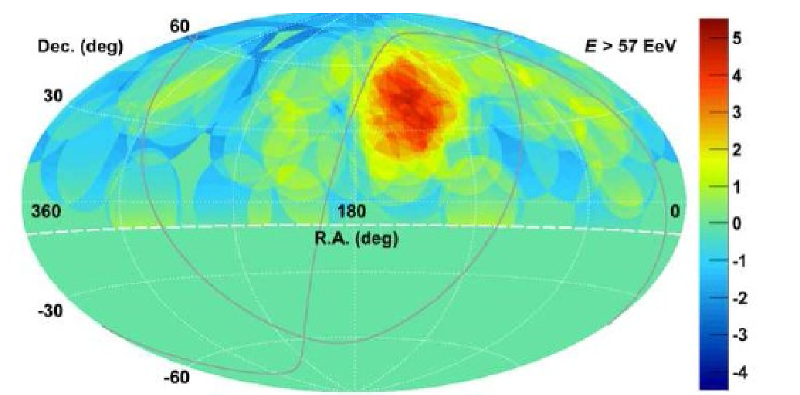
"Beyond the flux suppression"

Searches for overdensities

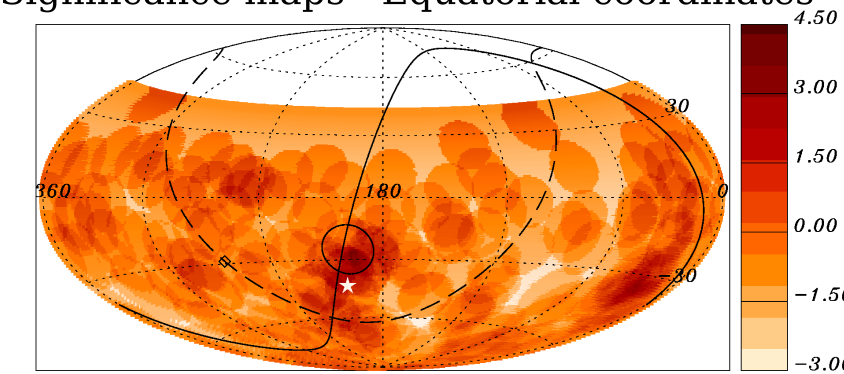
- at E_{TA} > 57 EeV: *pre*-trial 5.1σ
- at E_{Auger} > 54 EeV: *pre*-trial 4.3σ

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

TA Collab., ApJL 2014



Significance maps - Equatorial coordinates



Auger Collab., ApJ 2015

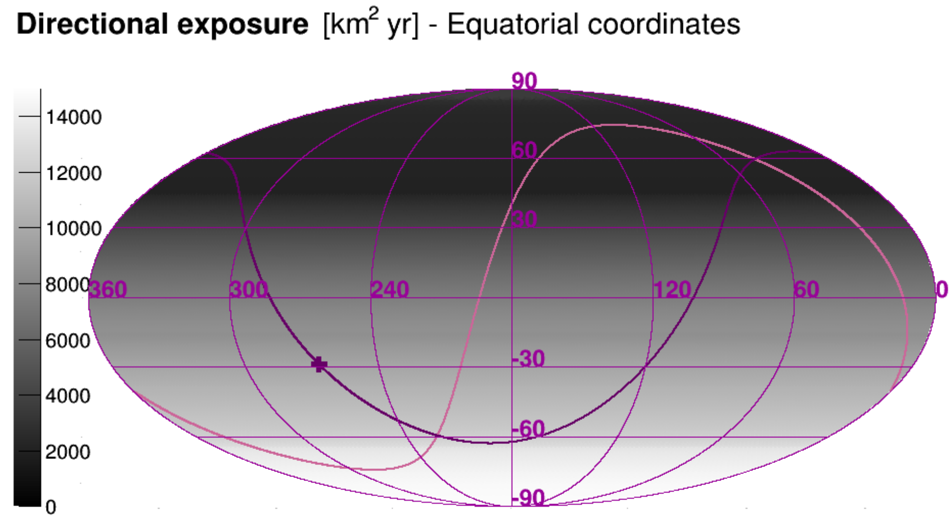
Full-sky searches: strengths and weaknesses

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**



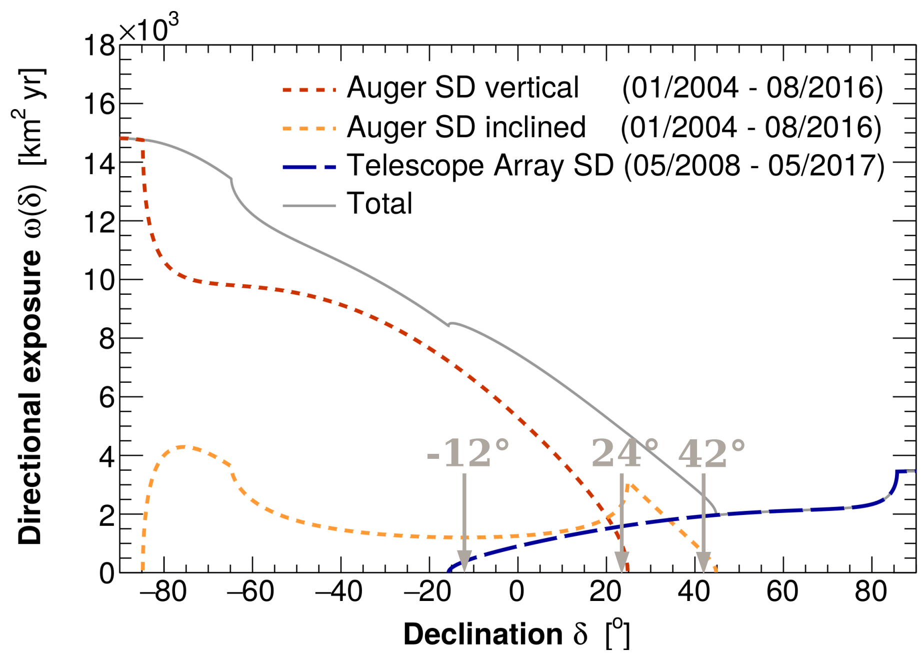
Weakness

Sensitivity to mismatches in energy

→ for $dN/dE \propto E^{-\Gamma}$, shift in E-scale $E' = \boldsymbol{r}_E\, E$

⇒ shift in integral flux $\Phi' = \Phi \,/\, \boldsymbol{r}_E^{\,\Gamma\text{-}1}$!

possibly large effect, particularly with steep indices Γ ~ 3-4



Method employed

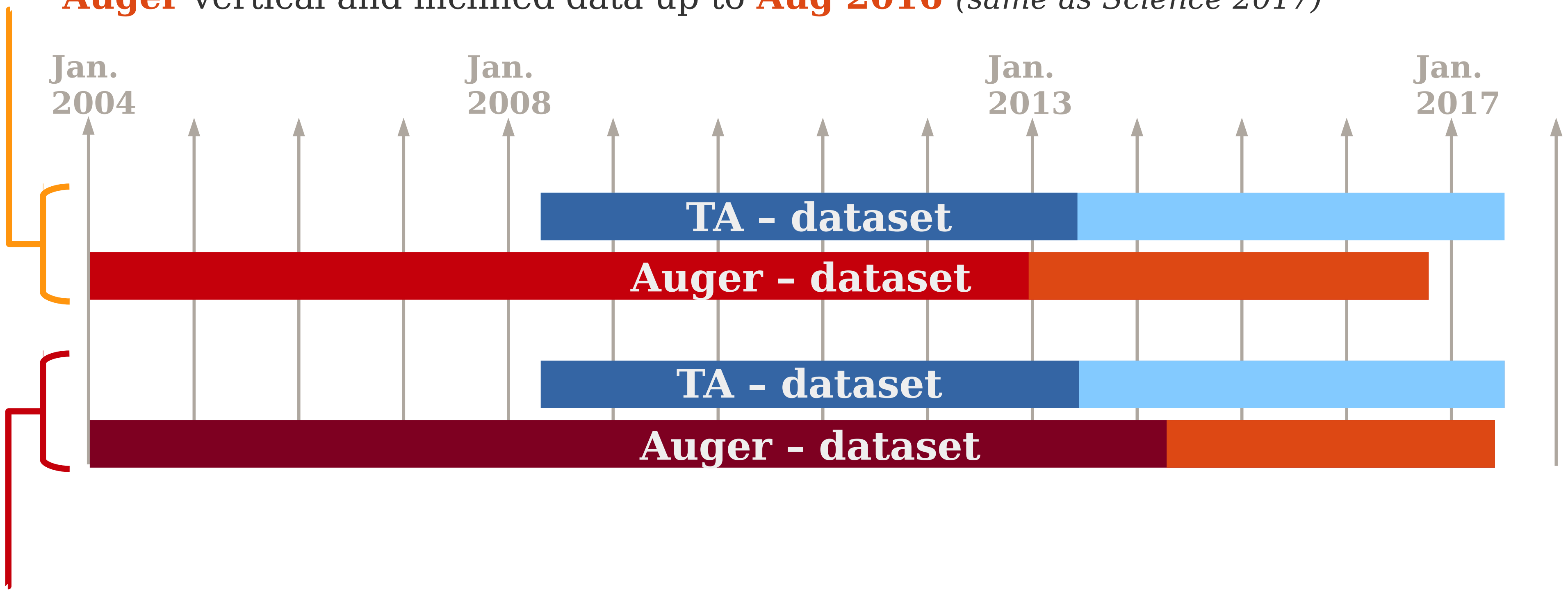
Cross calibration, through **flux matching in common declination band**, covered by Auger & TA: **δ ∈ [-12°;42°]**

This full-sky search: datasets

Dataset "above the ankle"

Previously, joint effort published in *ApJ **794**, 172 (2014)*
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"

Previously, joint effort published in *JPS Conf. Proc. **19**, 011020 (2018)*
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 δ band

Approach

Fix one threshold energy, find the other with matching flux

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

→ energy dispersion near the threshold energy accounted for through unfolding factors

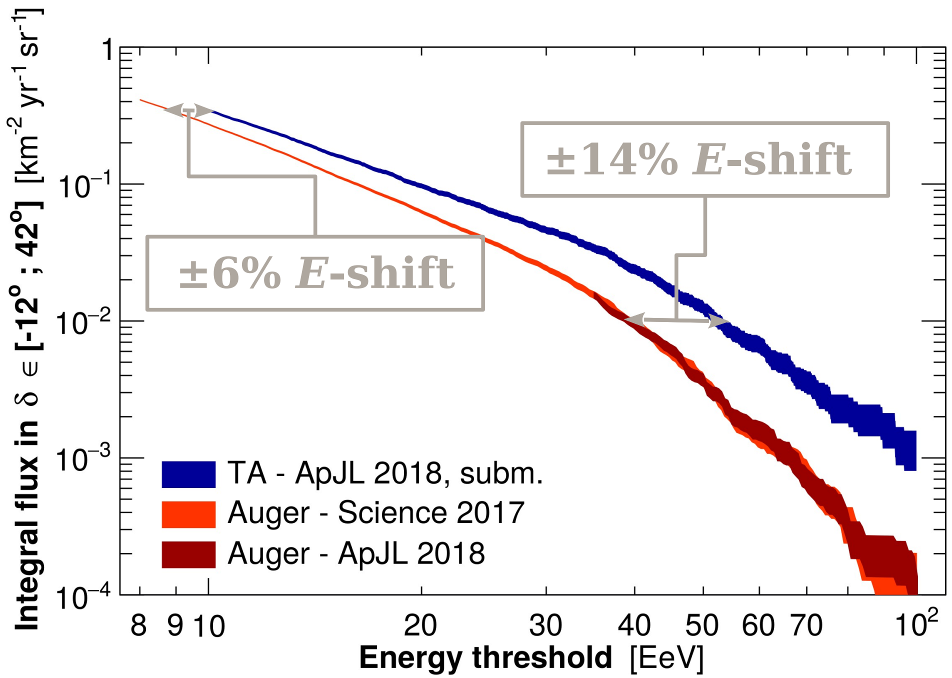
→ *E*-shifts consistent with the work of the Auger/TA spectrum group in δ ∈ [-15°;25°]

"Beyond the ankle":
~ 31,000 events ***+200%!***

TA driven: full efficiency for
E_{TA} **> 10 EeV** → corresp. E_{Auger} **= 8.86 EeV**

"Beyond the suppression":
~ 1,000 events ***+60%!***

Auger driven: indications for
E_{Auger} **> 40 EeV** → corresp. E_{TA} **= 53.2 EeV**



Results > 8.86/10 EeV: flux & significance maps

Flux reconstruction

Flux, $\sum_{\text{events}} 1/\omega(\delta)$, in **top-hat windows of radius *R***, centered on a ~ 1°×1° grid
→ **above 8.86/10 EeV**, top-hat "smoothing" on ***R* = 45°** angular scale

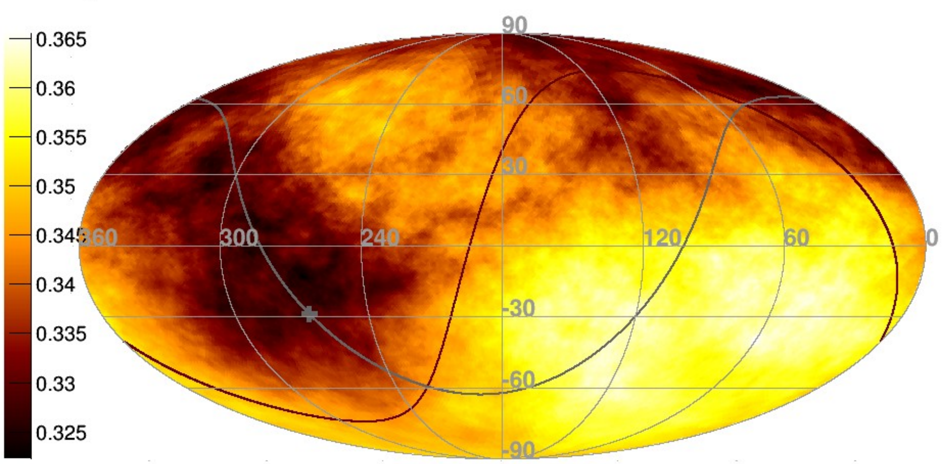
Local significance reconstruction

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

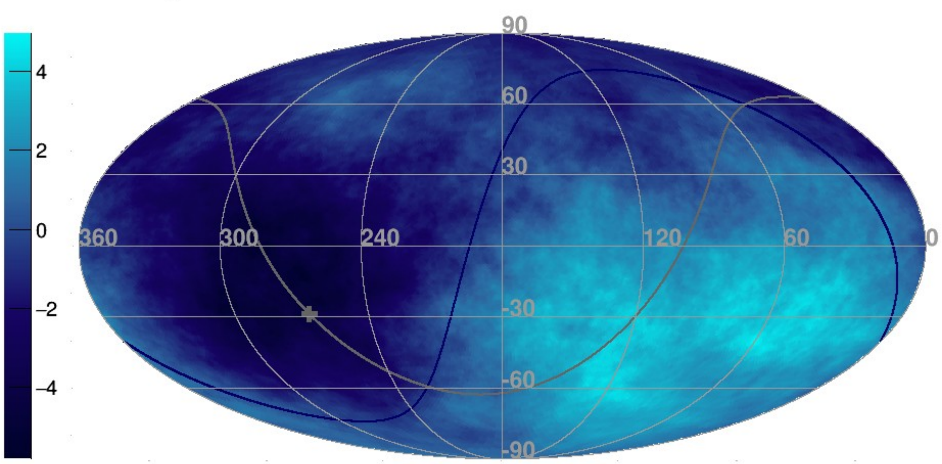
Features "by eye"

Dipolar pattern similar in shape/amplitude to that observed above E_{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°**



Local $\sigma(E_{\text{Auger/TA}}$ **> 8.86/10 EeV)** - Equatorial coordinates - **R = 45°**



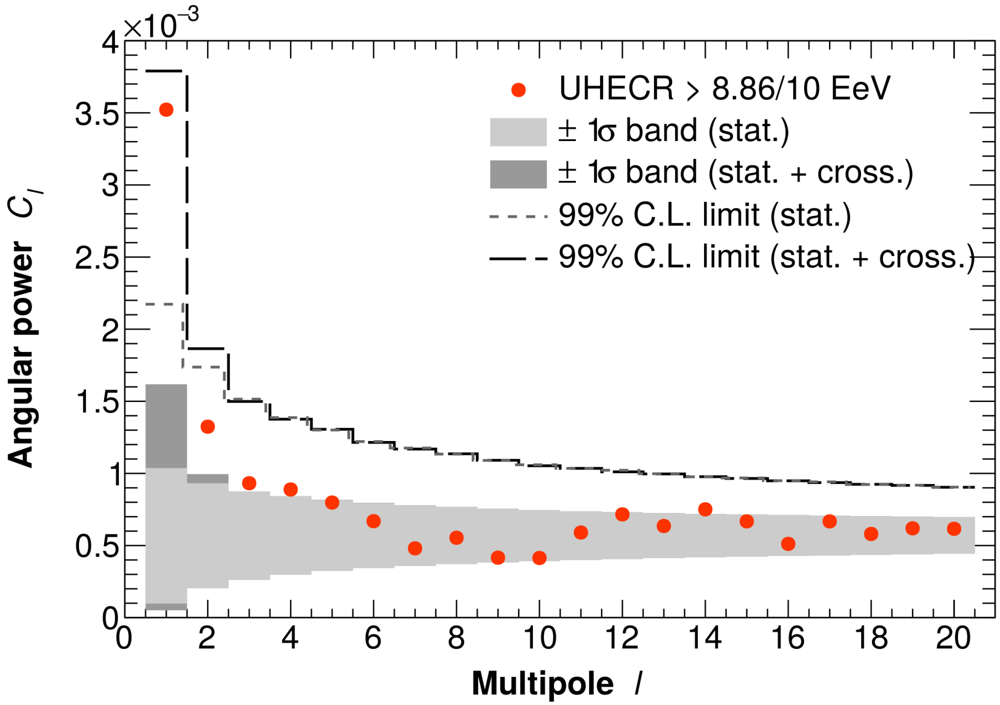
Results above 8.86/10 EeV: power spectrum

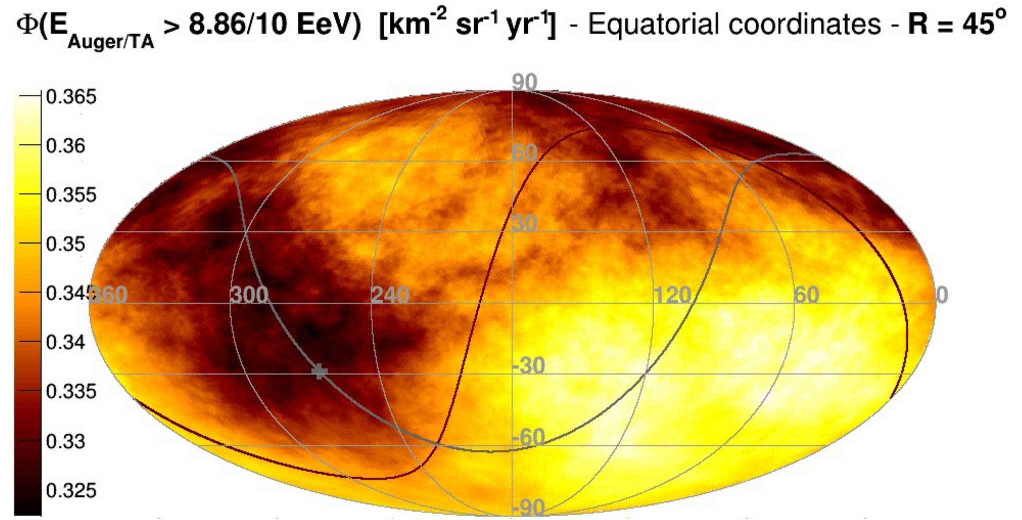
Approach

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 2.5σ)
$d_\perp = 4.3 \pm 1.1_{\text{stat}} \pm \mathbf{0.04}_{\mathbf{cross}}$ % (local 3.5σ)

→ vs Rayleigh analysis E_{Auger} > 8 EeV:
l=1: $d_\perp = 6.0 \pm 1.0$ % *Science 2017*
$l \leq 2$: $d_\perp = 5.0 \pm 1.3$ % *ApJ 2018, in press*

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

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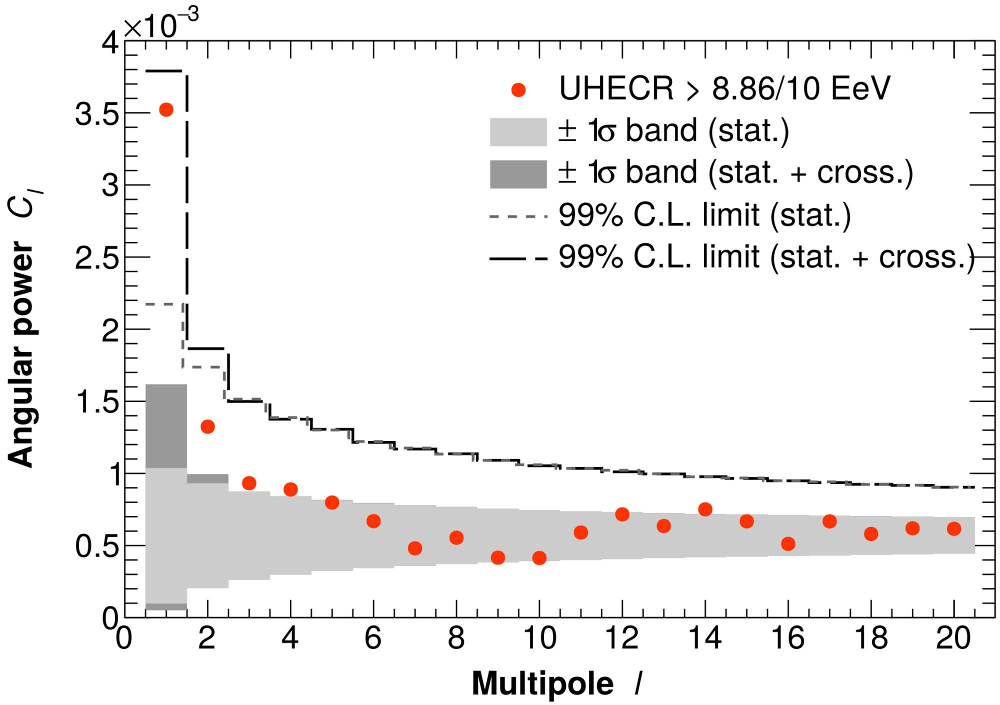
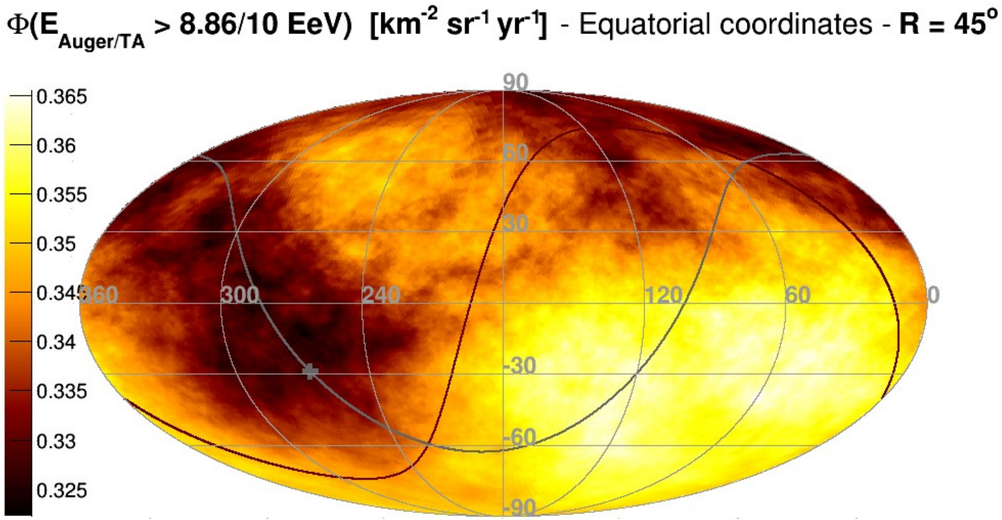




Results

Largest deviation for C_1 (local 2.5σ)

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

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

$l=1$: $d_z = -2.6 \pm 1.5$ % *Science 2017*

$l\leq2$: $d_z = -2 \pm 4$ % *ApJ 2018, in press*

Results above 40/53.2 EeV: flux & significance maps

Flux reconstruction

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

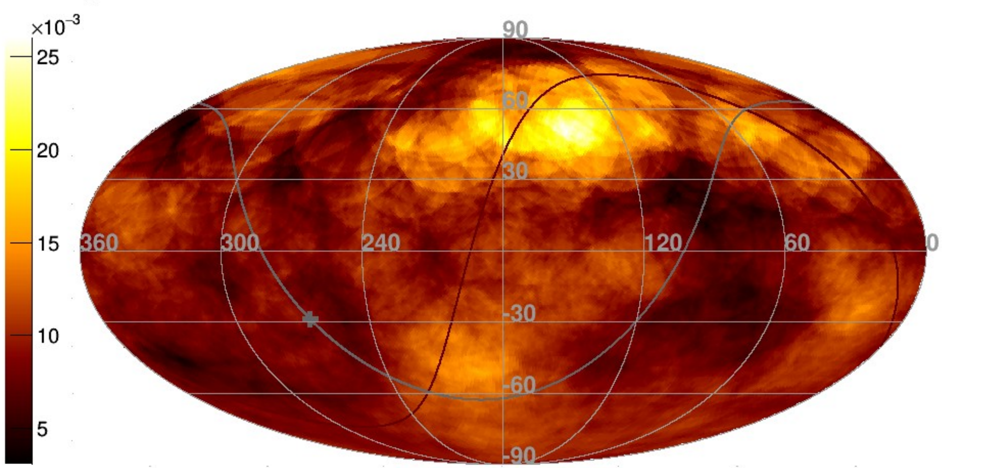
Local significance reconstruction

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

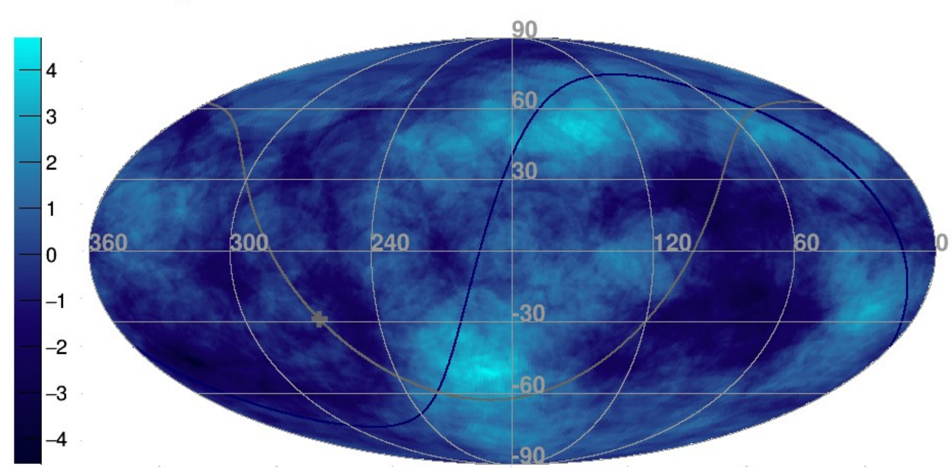
Features “by eye”

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

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



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



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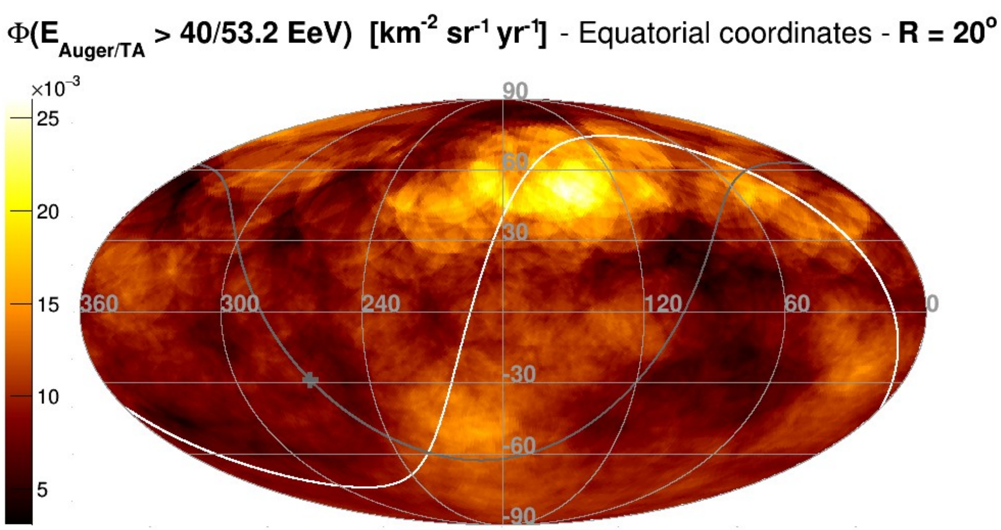

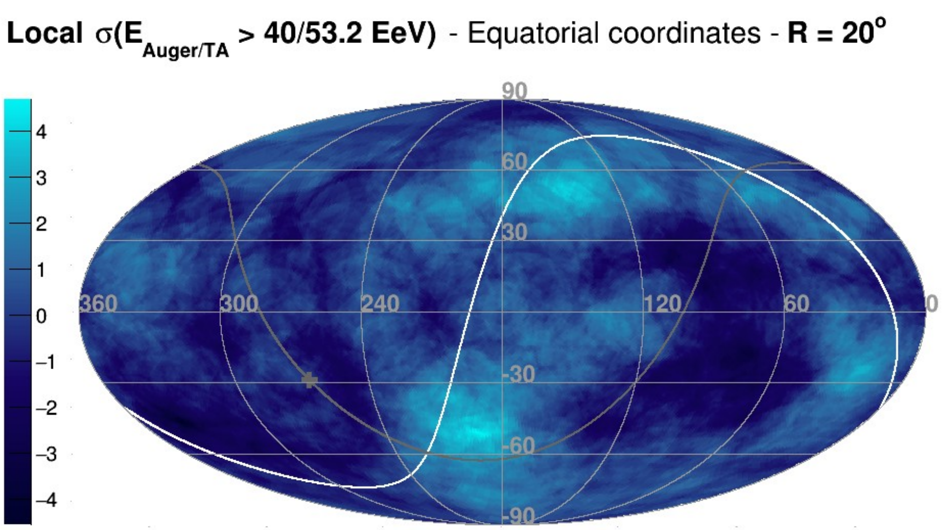

Results above 40/53.2 EeV: power spectrum

Approach

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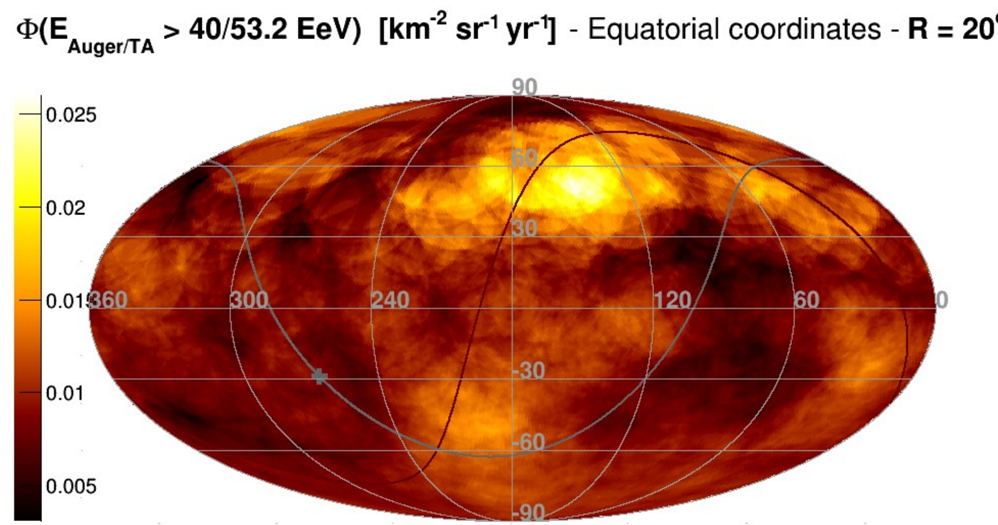
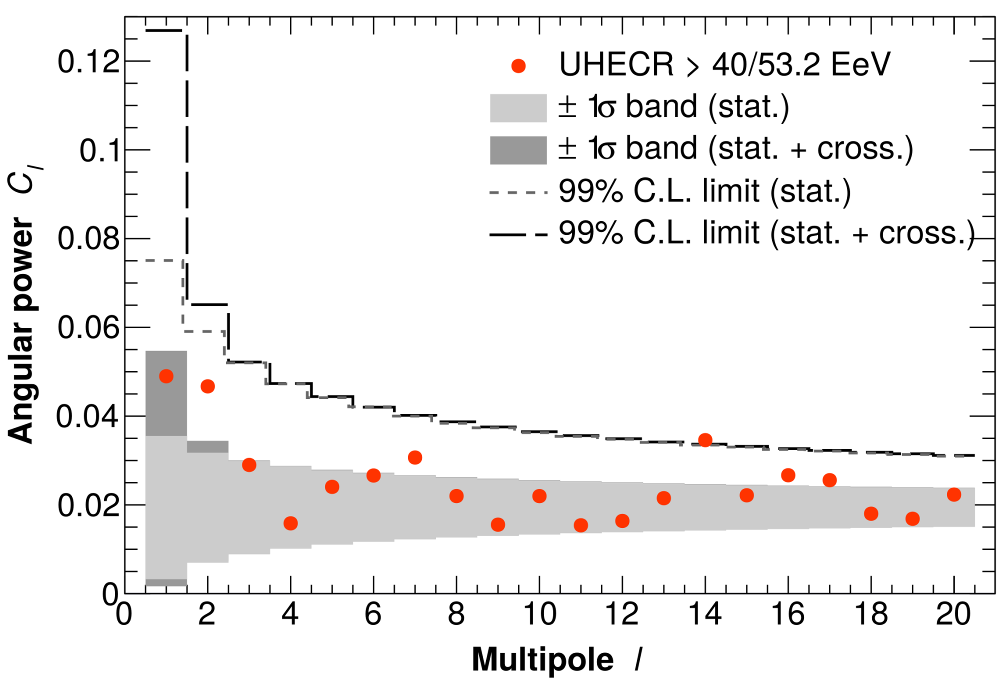
→ with full-sky coverage, unbiased estimator: $a_{lm} = \sum_{\text{events}} Y_{lm}(\alpha,\delta)/\omega(\delta)$

→ 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 deviations found for C_{14} (loc. 2.8σ) → angular scale of 180°/14 ~ 13°

Noting that given 20 trials (l's tested), assumed independent → **post-trial 1.6σ**

No indication of deviation from isotropy based on full-sky power spectrum

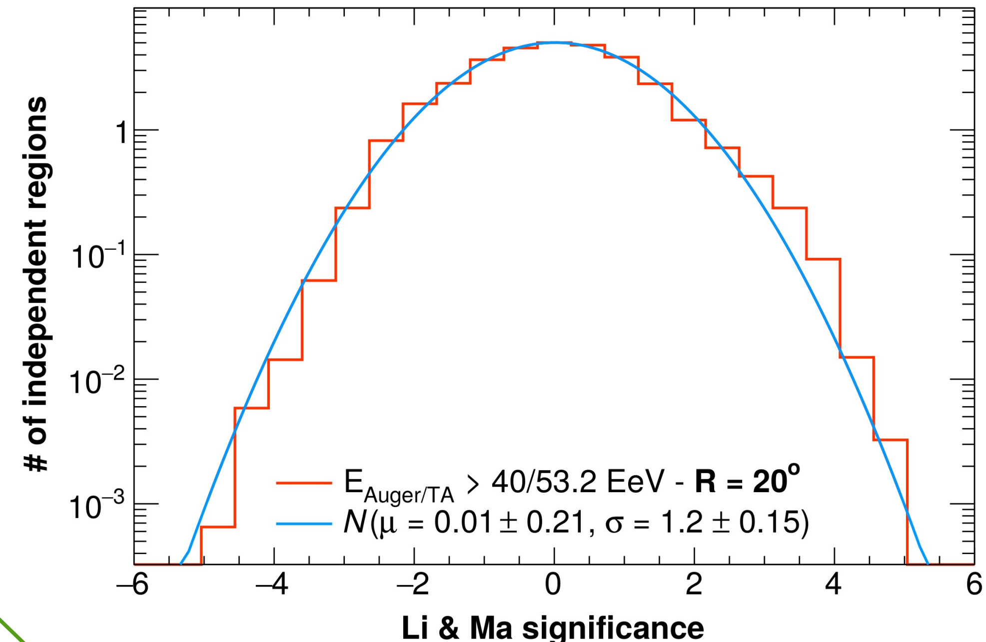
Results above 40/53.2 EeV: overdensity search

Approach

Reconstruction of Li & Ma significance in circular ON regions of radius θ, centered on a ~ 1°×1° grid

→ scan over **θ ∈ [5°;35°]**, with **δθ = 5°**

→ study performed above single *E*-threshold

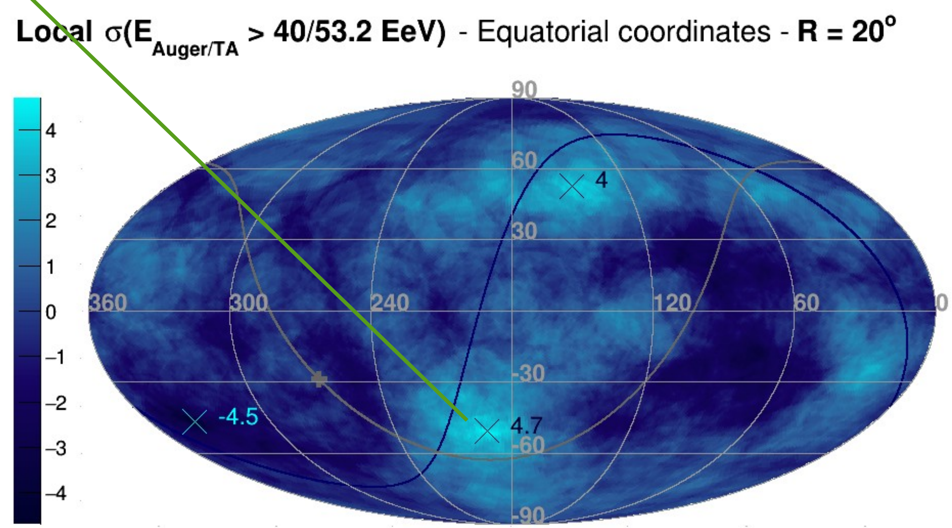


Most significant excesses

Largest σ spot: local 4.7σ obtained for 20°

2nd largest spot: local 4.2σ obtained for 15°

Note 20° / 15° radius – Gaussian σ_θ~ 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(10⁴)

Note: penalty factors based on previous searches by
Auger: 1-30°, δθ = 1°+ E-scan ≈ O(10⁵)
TA: 15-35°, δθ = 5° + fixed E ≈ O(10³)

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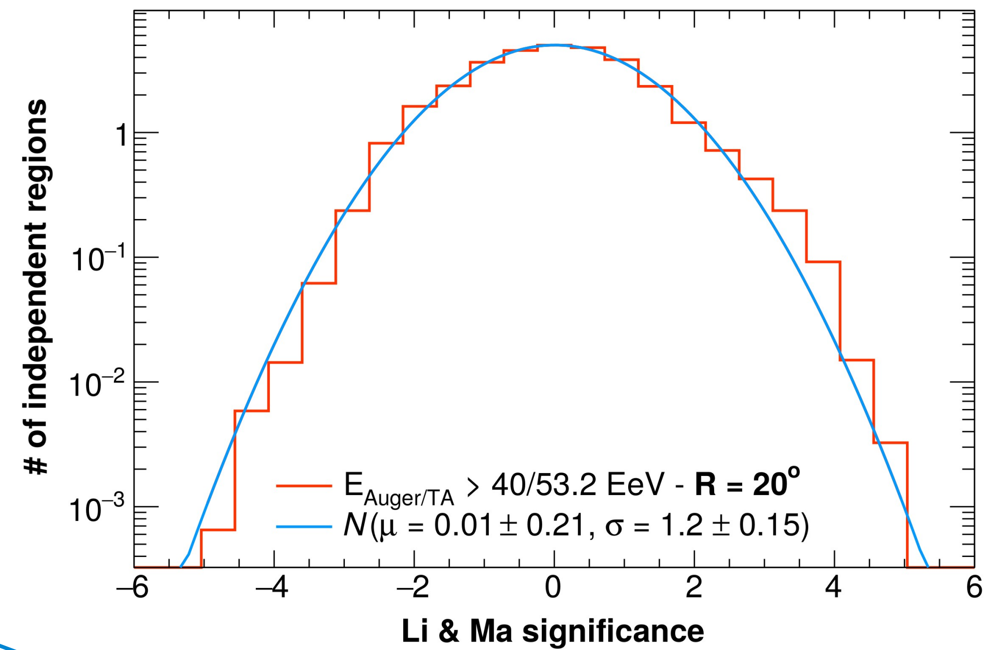
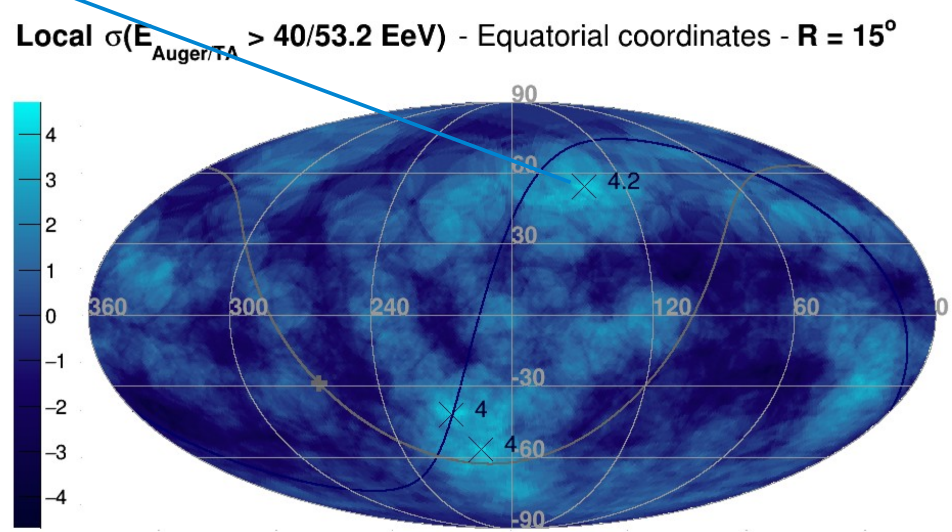




Wrap-up and future: full-sky anisotropy searches

Full-sky searches

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

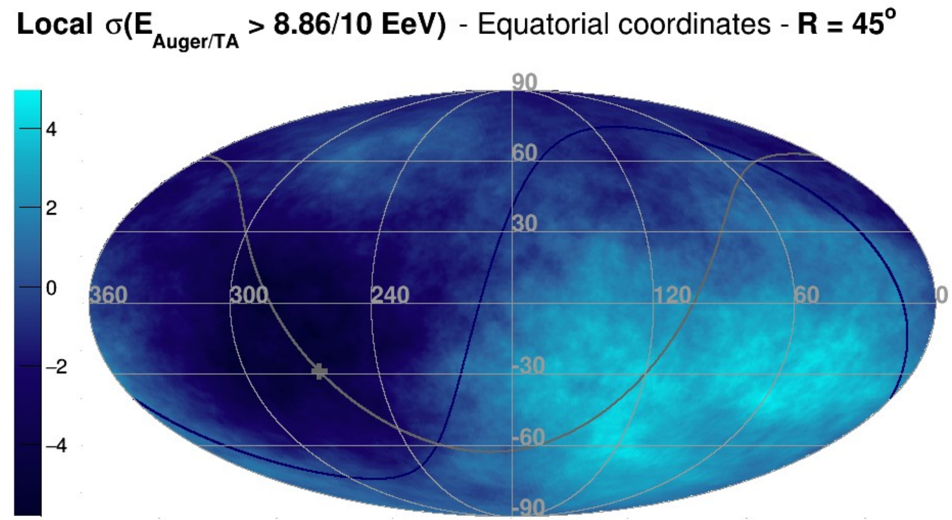
→ energy-scale mismatch (6% / 14%)
⇒ relative flux: non-negligible source of uncertainty, possibly alleviated with further spectral studies

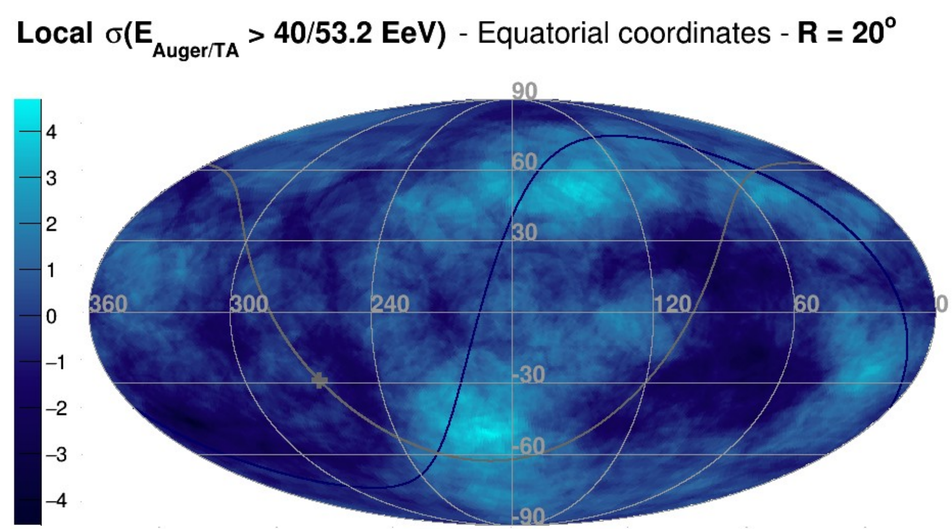
Beyond 8.86/10 EeV – main result

- 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
- $\Phi_{spot}(N) \sim 1.5\text{-}2 \times \Phi_{spot}(S)$, $\sigma_{local}(N) \sim \sigma_{local}(S)$





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 δ ∈ [-12°;24°]

Φ_{TA}(>10 EeV) = 0.345±0.008 km⁻² yr⁻¹ sr⁻¹

~3,900 evts

Φ_{Auger}(>8.86 EeV) = 0.345±0.004 km⁻² yr⁻¹ sr⁻¹

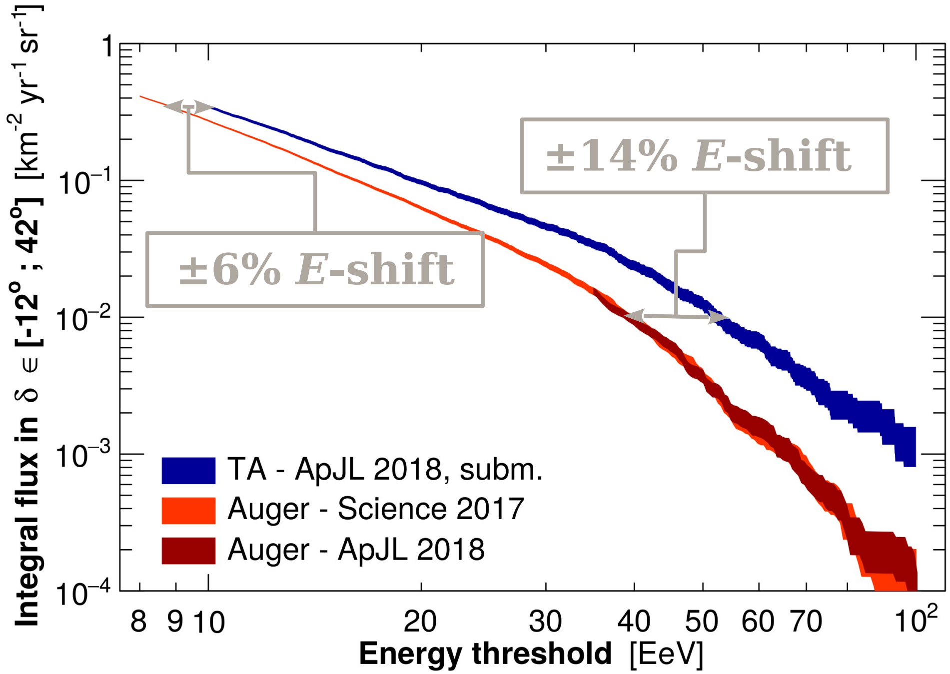
~27,300 evts

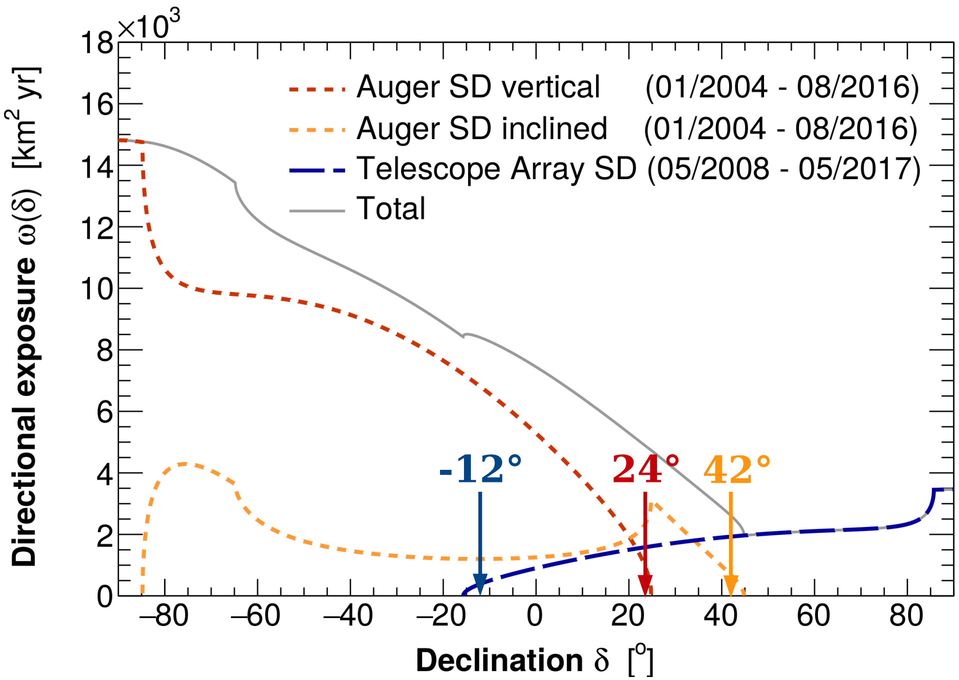
Φ_{Auger}(> 40 EeV) = (9.3±0.7)×10⁻³ km⁻² yr⁻¹ sr⁻¹

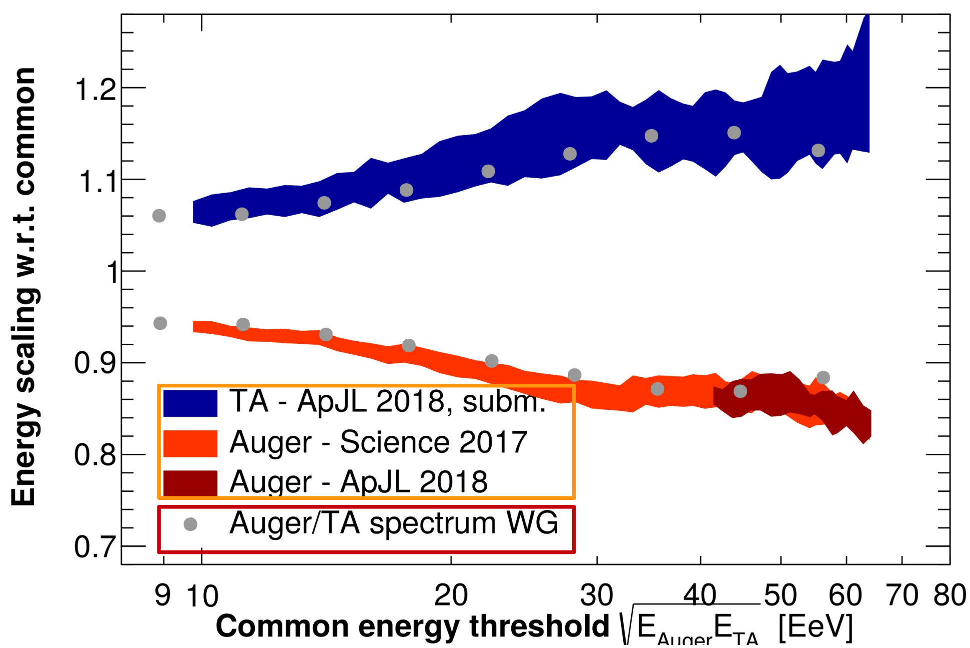
~840 evts

Φ_{TA}(> 53.2 EeV) = (9.6±1.2)×10⁻³ km⁻² yr⁻¹ sr⁻¹

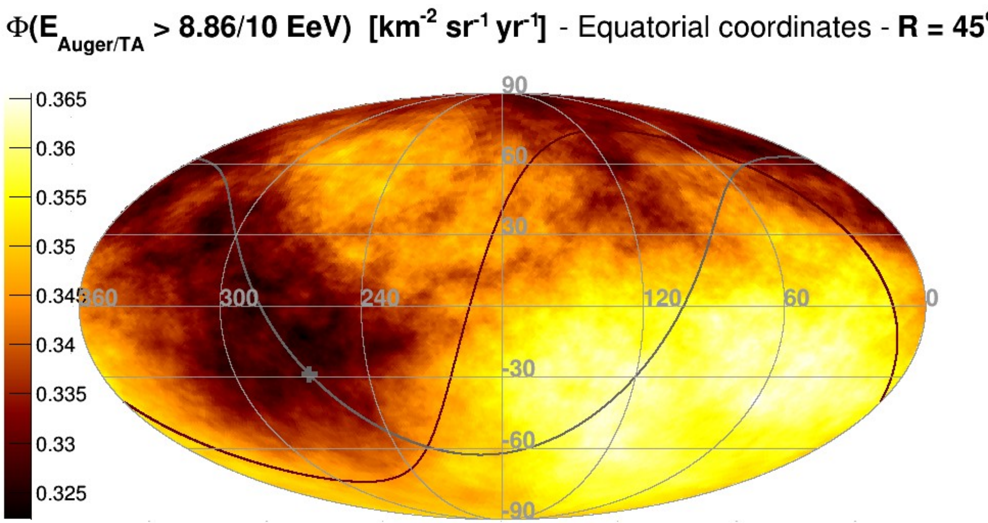
~130 evts

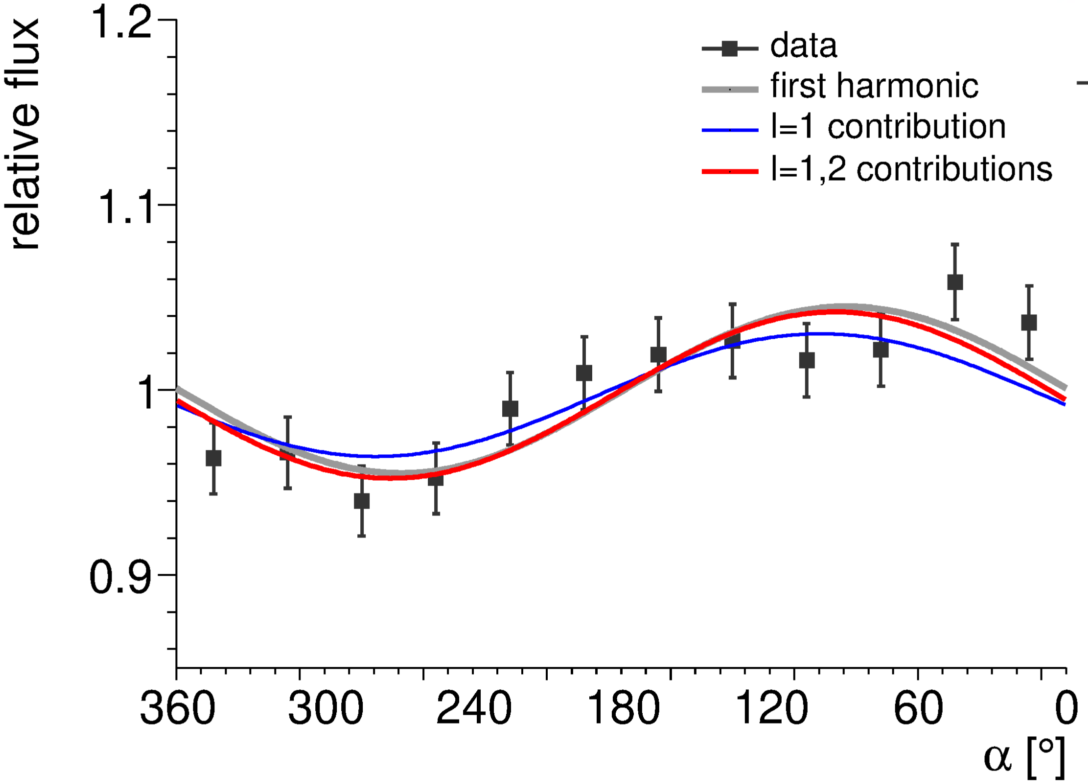






Dipole (and quadrupole?) - R.A. distribution

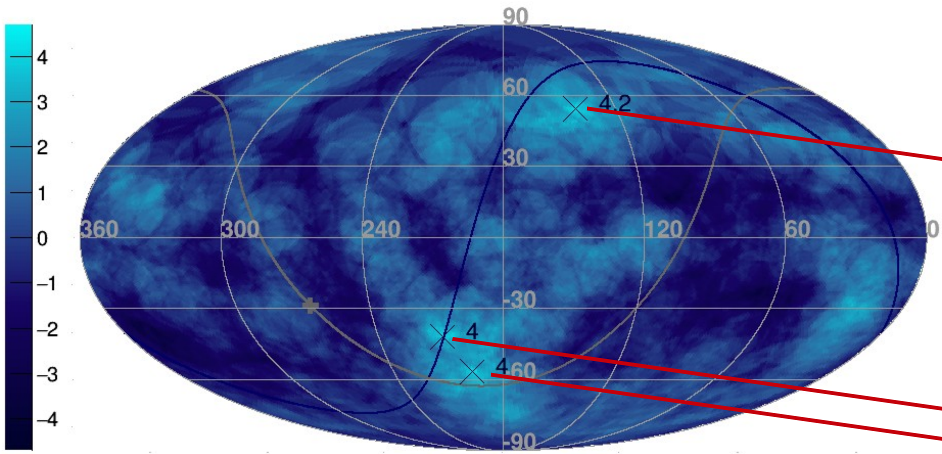




→ here display only of contributions to 1st harmonics: $e^{\pm i\varphi}$ terms i.e. Y_{lm}, $m=\pm 1$

Most significant excesses

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

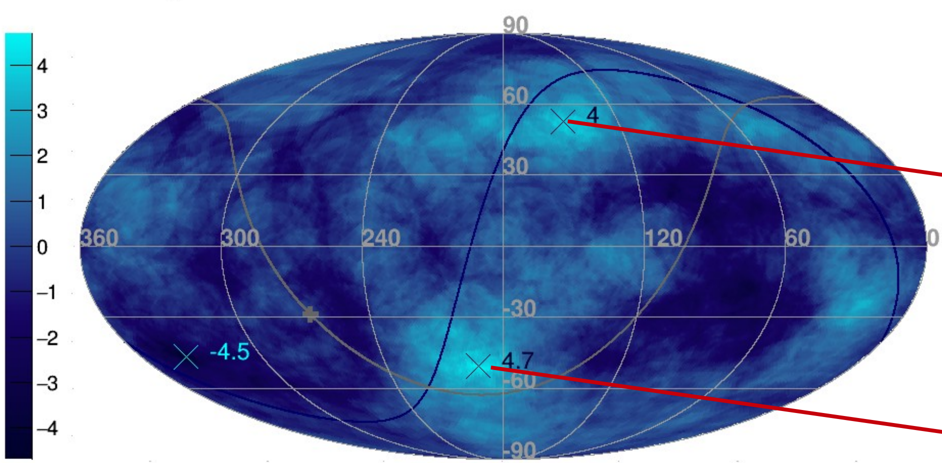


$N_{ON} = 16$ $\alpha N_{OFF} = 4.3$

$N_{ON} = 48$ $\alpha N_{OFF} = 24.6$

$N_{ON} = 52$ $\alpha N_{OFF} = 27.6$

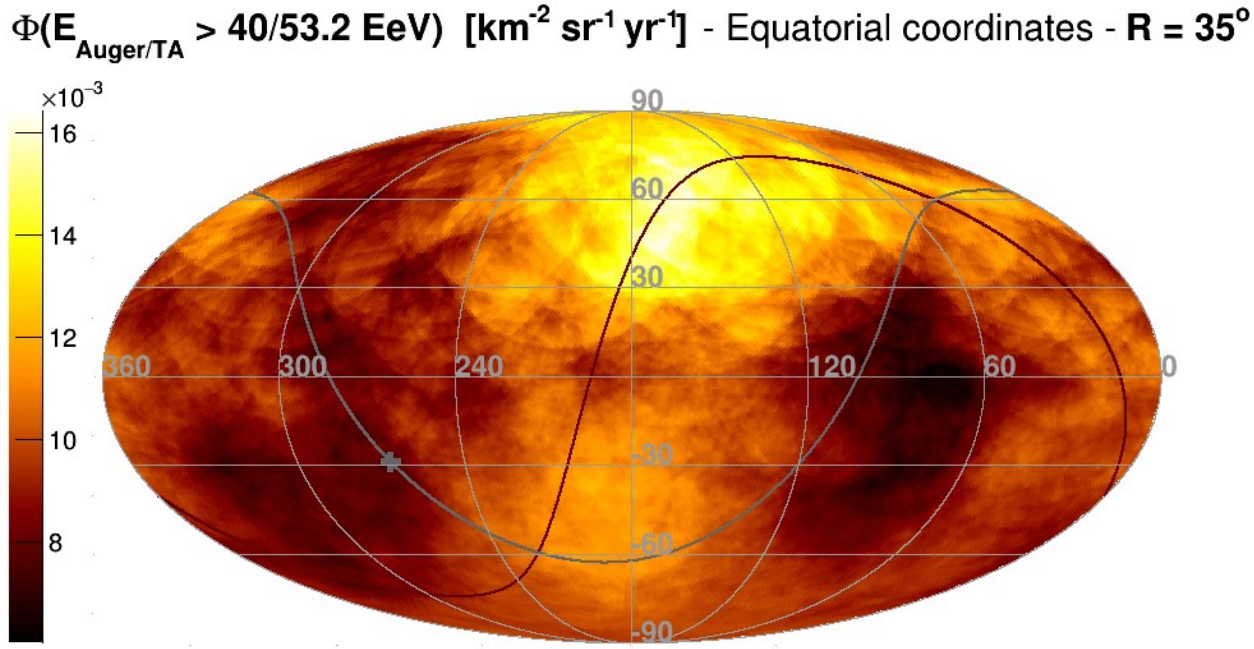
Local $\sigma(E_{Auger/TA} > 40/53.2$ EeV) - Equatorial coordinates - **R = 20°**

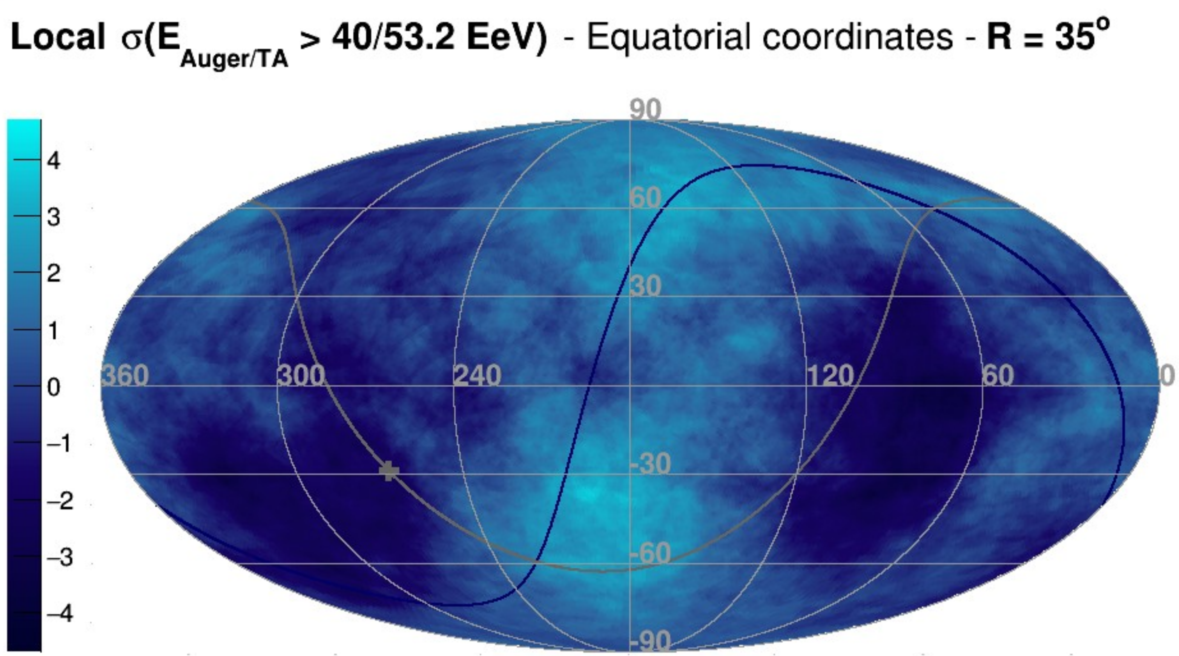


$N_{ON} = 23$ $\alpha N_{OFF} = 8.4$

$N_{ON} = 83$ $\alpha N_{OFF} = 46.1$

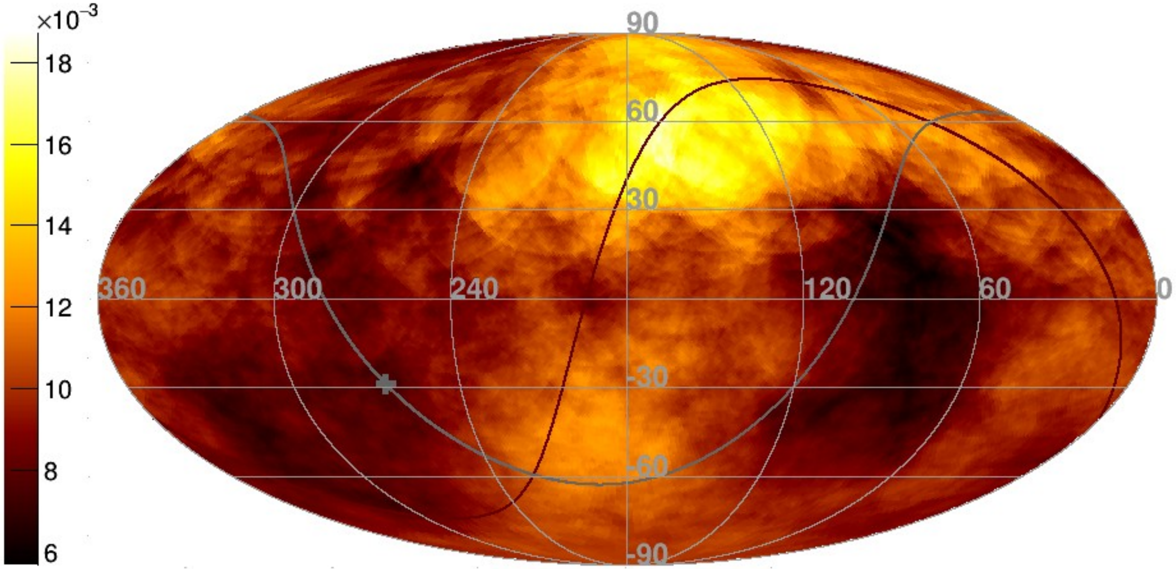
Overdensity searches - R = 35°



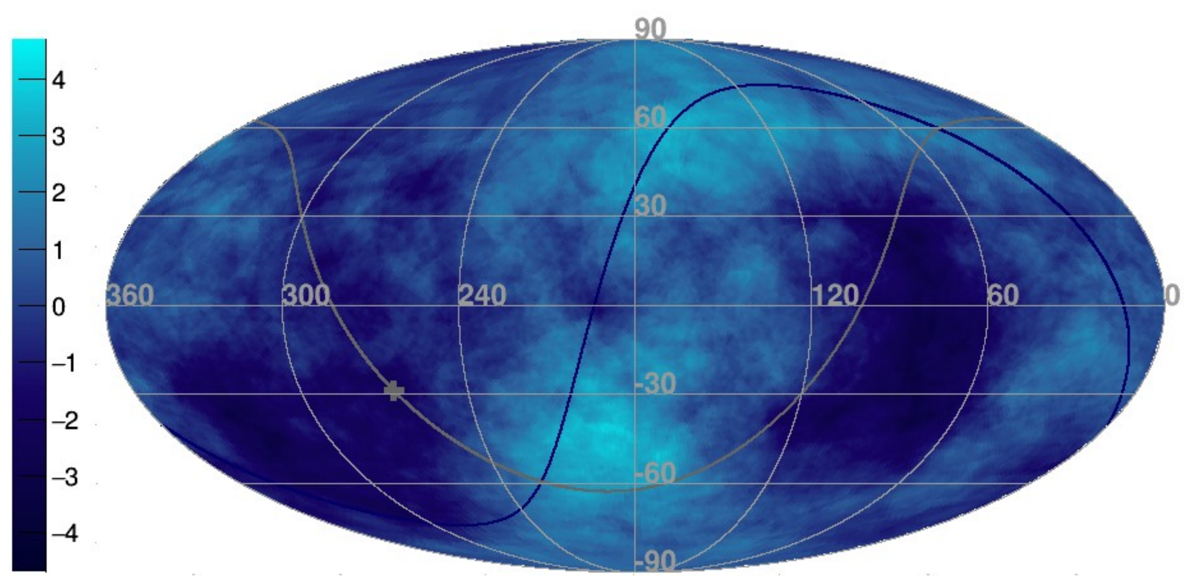


Overdensity searches - *R* = 30°

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

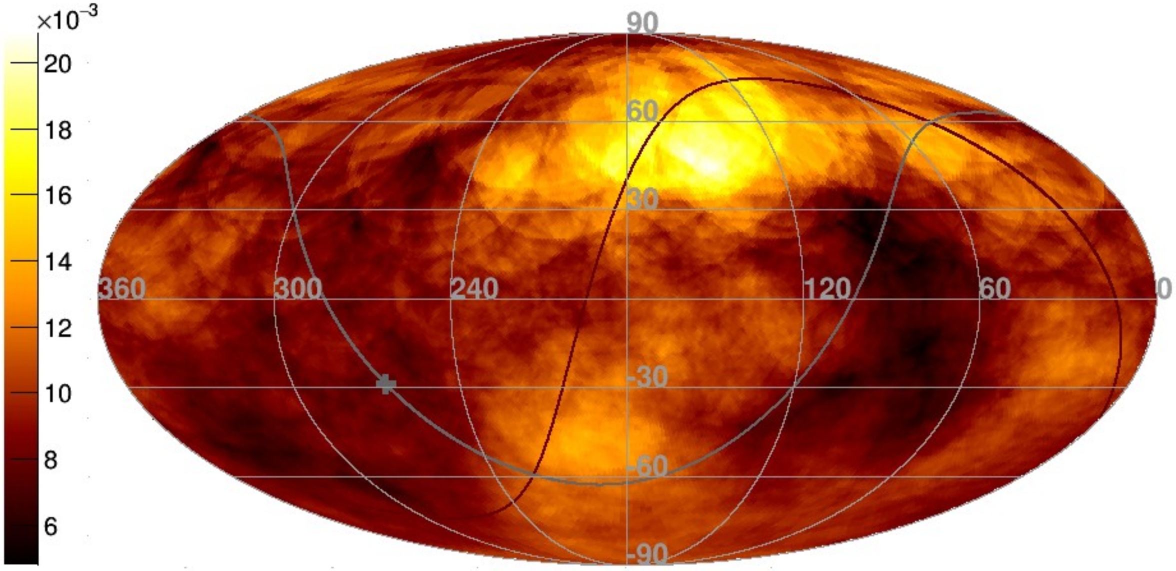


Local $\sigma(E_{Auger/TA} > 40/53.2$ EeV) - Equatorial coordinates - **R = 30°**

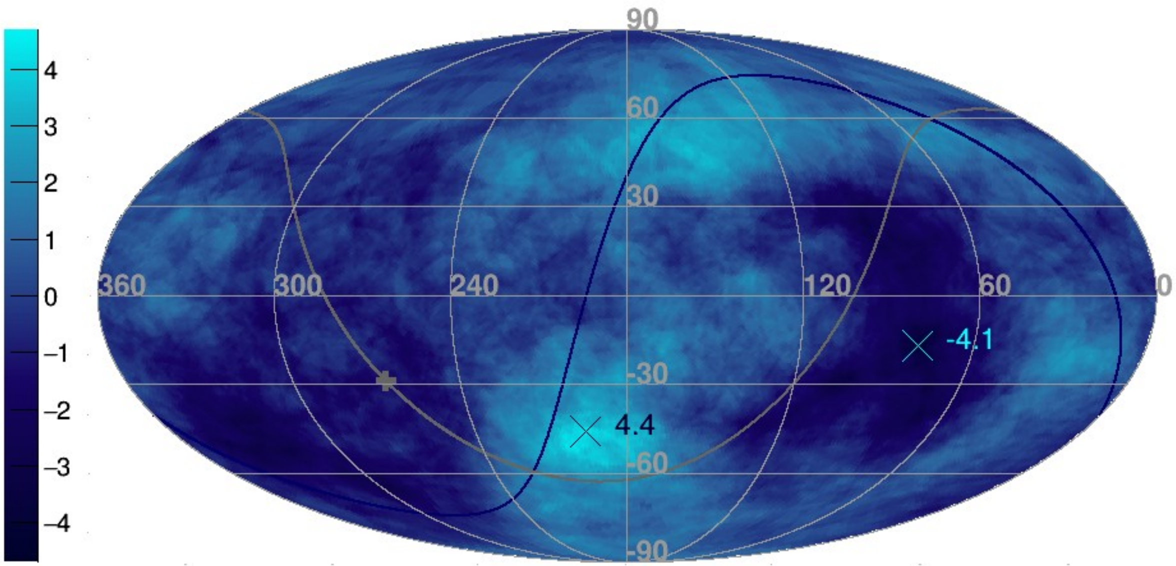


Overdensity searches - *R* = 25°

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

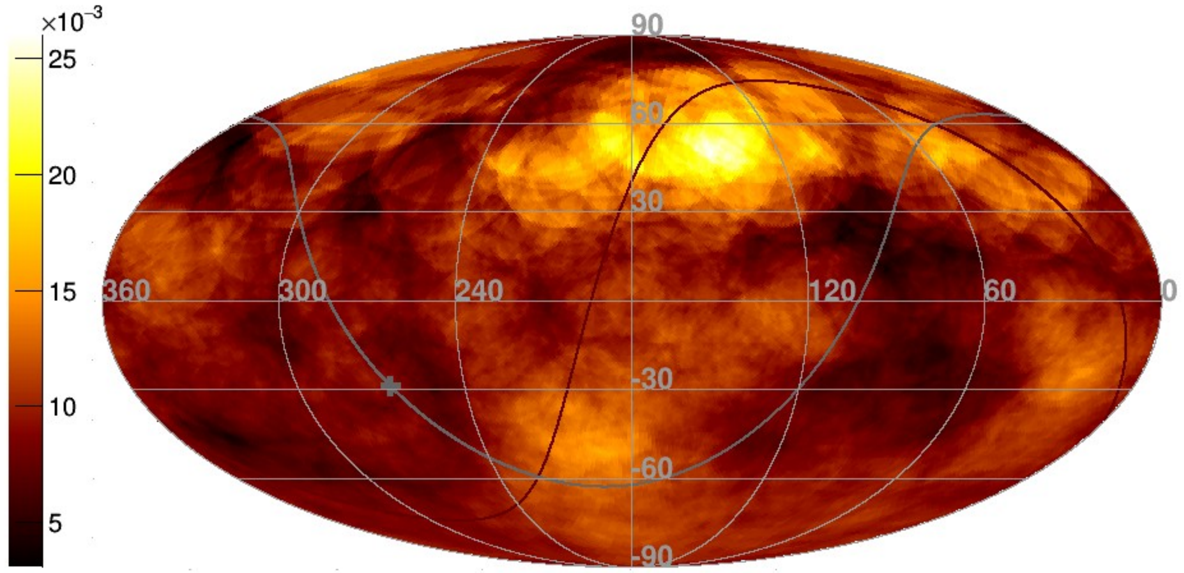


Local $\sigma(E_{Auger/TA} > 40/53.2$ EeV) - Equatorial coordinates - R = 25°

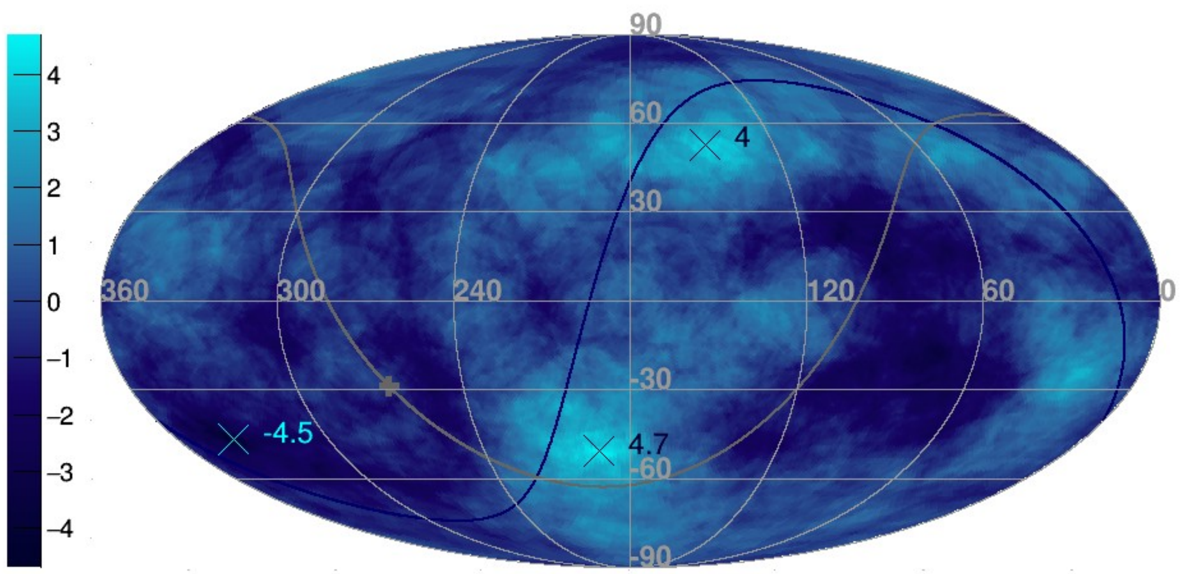


Overdensity searches - R = 20°

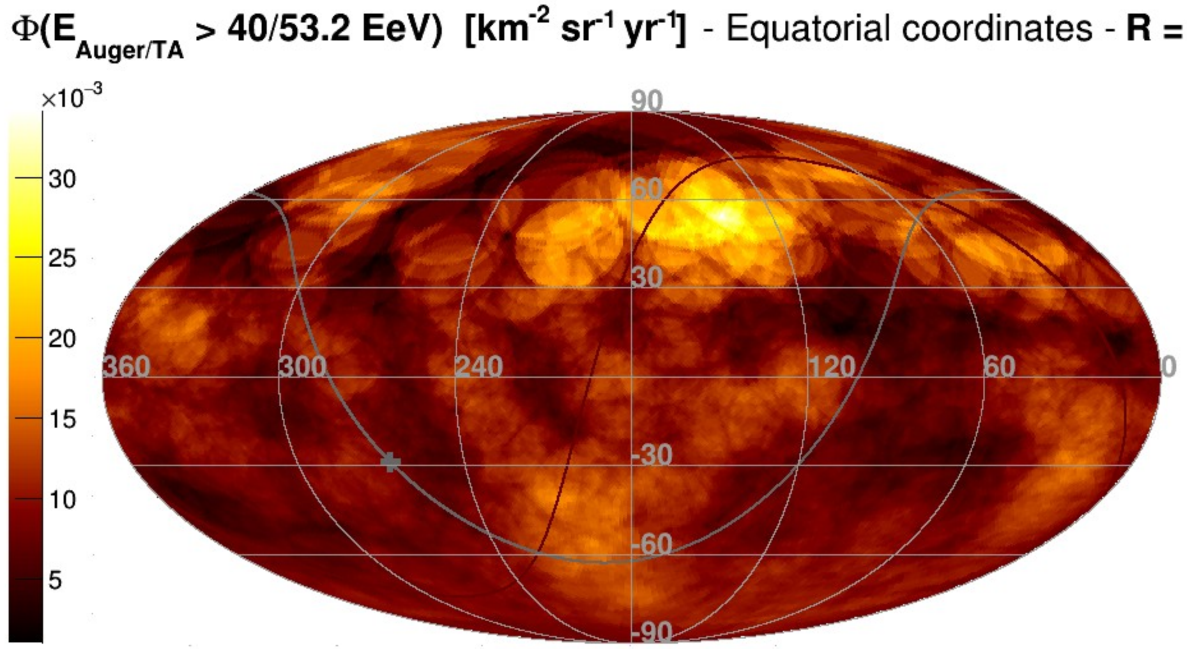
$\Phi(E_{Auger/TA} > 40/53.2\ \mathrm{EeV})$ [km^{-2} sr^{-1} yr^{-1}] - Equatorial coordinates - **R = 20°**

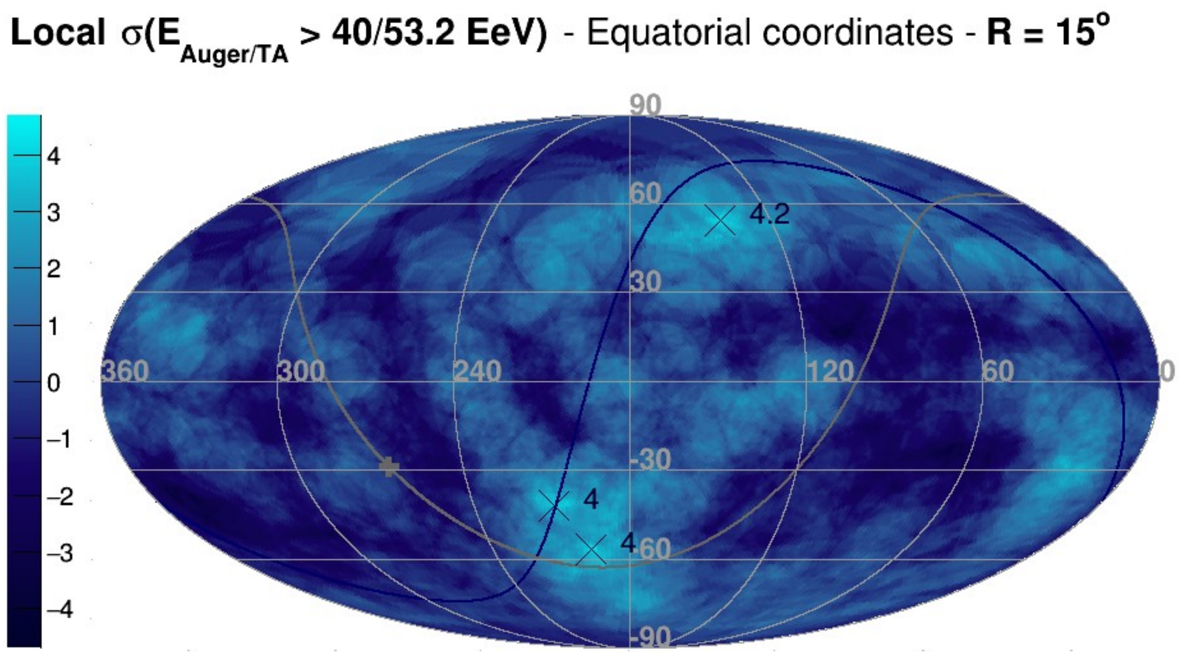


Local $\sigma(E_{Auger/TA} > 40/53.2\ \mathrm{EeV})$ - Equatorial coordinates - **R = 20°**



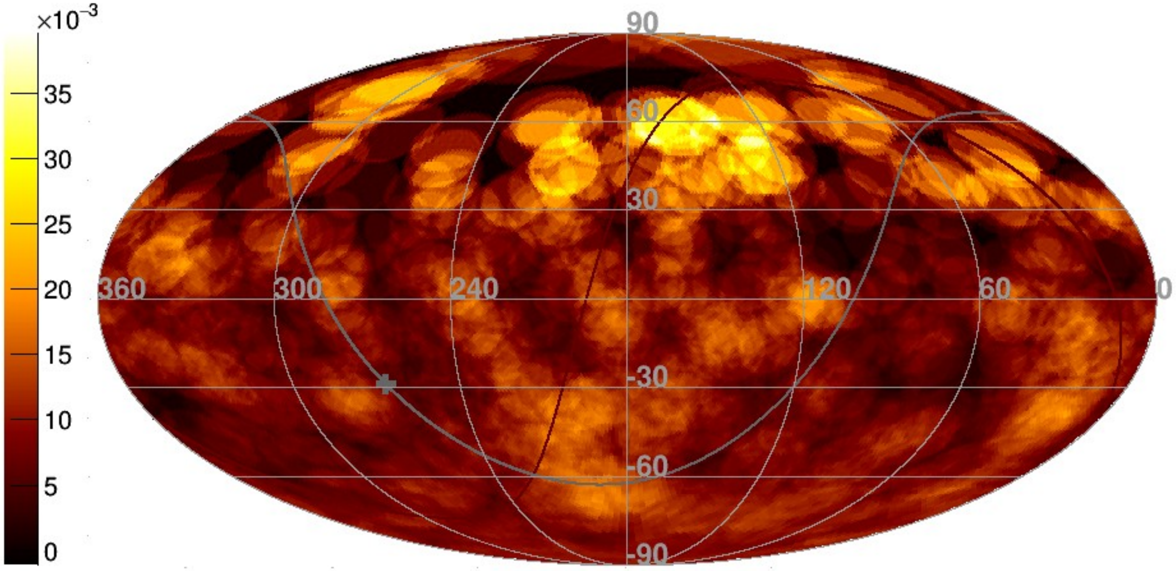
Overdensity searches - R = 15°



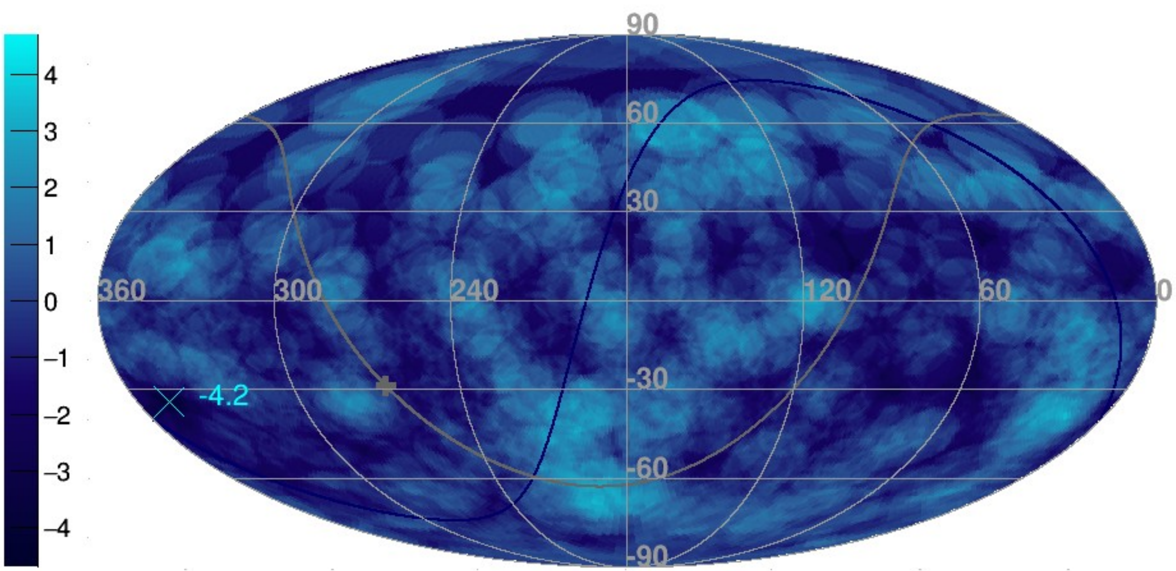


Overdensity searches - R = 10°

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

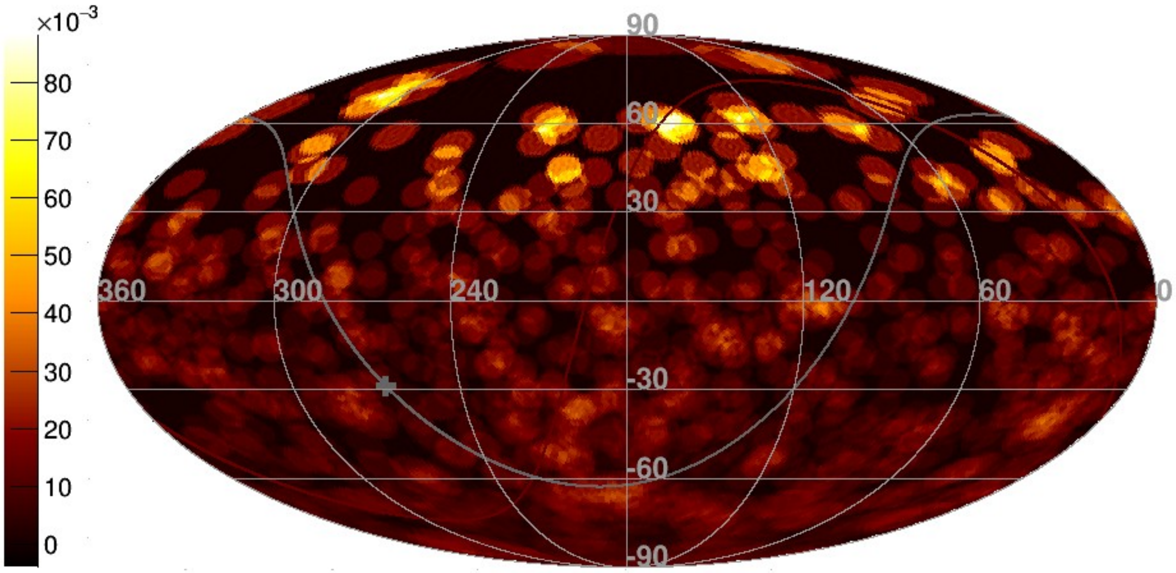


Local $\sigma(E_{Auger/TA} > 40/53.2$ EeV) - Equatorial coordinates - **R = 10°**



Overdensity searches - R = 5°

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



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