The Telescope Array experiment

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The Telescope Array collaboration

142 members, 35 institutions, 6 countries

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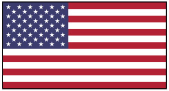
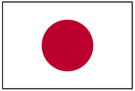
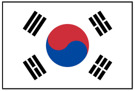
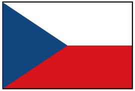





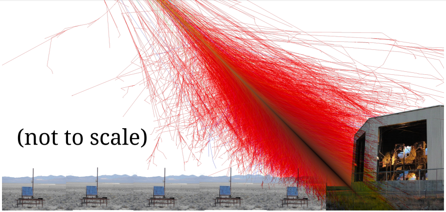


Outline

1. Introduction
   - Ultra-high-energy cosmic rays (UHECRs)
   - The Telescope Array (TA) experiment
2. Main results
   - Energy spectrum
   - Mass composition
   - Arrival directions
3. Future prospects
   - The ongoing Telescope Array extension: TA×4

Outline

Ultra-high-energy cosmic rays (UHECRs)

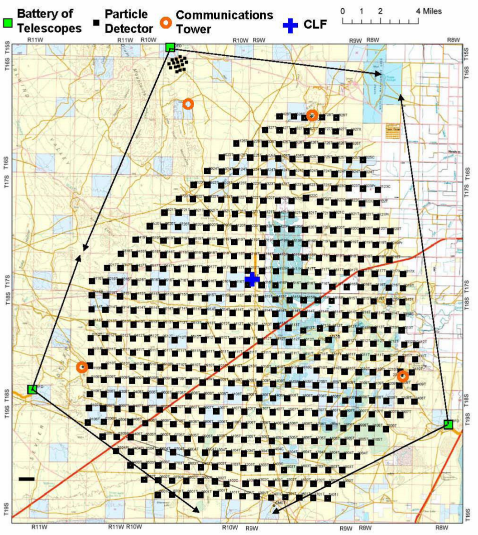


- Atomic nuclei from space with $E > 1\ \text{EeV} = 10^{18}\ \text{eV} \approx 0.16\ \text{J}$
- Deflected by magnetic fields → arrival direction ≠ source position ($\Delta\theta \sim 30Z\left(\frac{E}{10\ \text{EeV}}\right)^{-1}$ degrees)
- In the atmosphere, they initiate extensive air showers (EAS), which can be detected by:
  - Surface detector arrays (duty cycle ∼ 100%, but severely model-dependent)
  - Fluorescence telescopes (more precise reconstruction, but only in clear moonless nights, duty cycle ∼ 15%)
- With hybrid detectors, we can use fluorescence measurements to calibrate the energy scale for surface detectors.

Largest operating UHECR detectors: the Pierre Auger Observatory (Auger; 3 000 km^2, Argentina) and the Telescope Array (TA; 700 km^2, Utah, USA)

The Telescope Array experiment

The largest cosmic-ray detector in the Northern Hemisphere



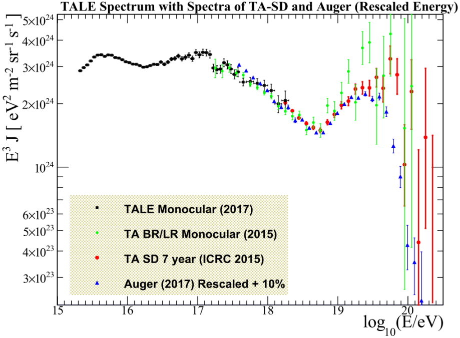
- Location: 39.3° N, 112.9° W, 1400 m a.s.l. (≈ 880 g/cm^2) Millard County, Utah, USA
- Main array for UHE:
  - 507 surface detectors (SD), 1.2 km spacing (700 km^2)
  - 3 fluorescence detector (FD) sites (38 telescopes in total)
- Low-energy extension (TALE):
  - 10 extra FD telescopes at higher elevation
  - 103 extra SDs with 400 m and 600 m spacing
- Main SD array taking data since 11 May 2008

Outline

The energy spectrum

ApJ **865** (2018) 74 (TALE), APh **80** (2016) 131 (TA FD), PoS **ICRC2015** (2016) 035 (TA SD)

- Self-consistent measurements of spectrum over 5 decades



- (TALE, TA FD and TA SD data not artificially shifted in energy or normalization)

- Features:

	$\gamma \approx 2.7$
knee*, $10^{15.6}$ eV	
	$\gamma = 3.1$
low-E ankle, $10^{16.2}$ eV	
	$\gamma = 2.9$
2nd knee, $10^{17.0}$ eV	
	$\gamma = 3.2$
ankle, $10^{18.7}$ eV	
	$\gamma = 2.7$
cutoff, $10^{19.8}$ eV	
	$\gamma = 4.6$

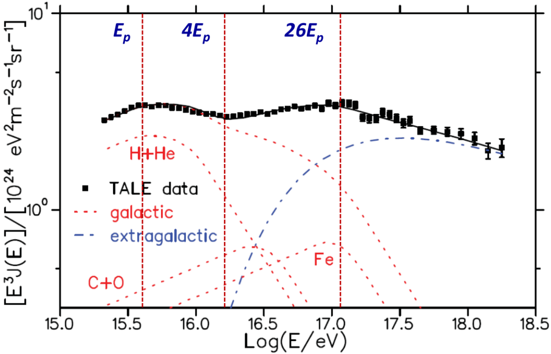
*We haven't tried to fit it with TALE data (reduced efficiency, large systematics), but low-energy experiments see it there, too.

- Compatible with Auger, except for $\approx 10\%$ E shift (well within systematics, $\pm14\%_{\text{Auger}} \pm 21\%_{\text{TA}}$), except at the highest energies

Possible interpretation of the spectrum

T. Abu-Zayyad et al., `arXiv:1803.07052` **(not a full TA collaboration paper!)**

(Galactic composition extrapolated from satellite measurements at lower E; cutoff assumed rigidity-dependent, i.e. proportional to Z)

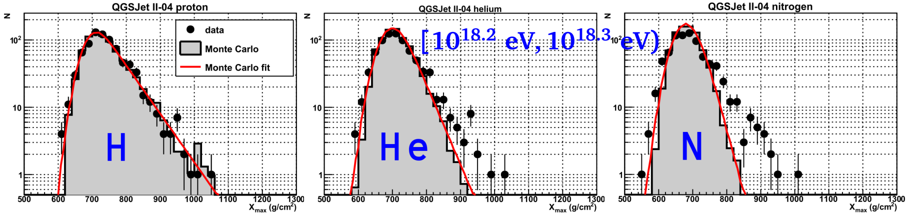


Knee due to Galactic H/He cutoff, low-energy ankle due to Li/Be/B scarcity, second knee due to Galactic Fe cutoff?

Mass composition from FD measurements (X_{max})

Astrophys. J. **858** (2018) 76, arXiv:1801.09784

- X_{max} distribution predicted by QGSJet II-04, but allowed to be shifted to take into account model uncertainty (and measurement systematics)



$E \lesssim 10^{18.8}$ eV Any pure element other than H excluded at $p < 10^{-3}$

- Auger-like H+He+N mix not excluded (PoS **ICRC2017** (2018) 522), but mixed compositions outside the scope of the work

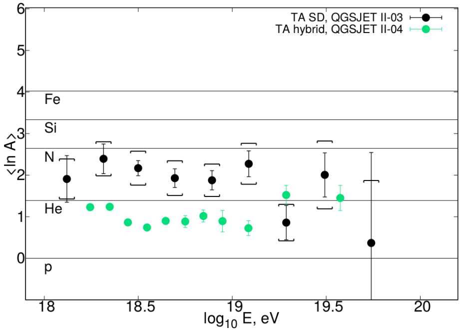
$E \lesssim 10^{19.2}$ eV Pure elements other than H or He excluded at $p < 10^{-3}$

$E \gtrsim 10^{19.4}$ eV Not enough data to exclude anything from H to Fe at $p < 5\%$

Mass composition from SD measurements

Phys. Rev. **D** (in press), `arXiv:1808.03680`

- Boosted decision tree using 14 observables, trained on QGSJet II-03 proton and iron simulations



- Medium-light composition, $\langle \ln A \rangle = 2.0 \pm 0.1_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}}$
- No evidence for energy dependence

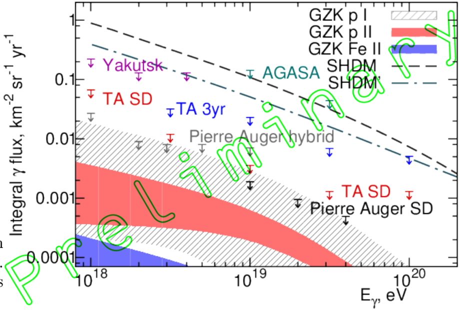
Limits on diffuse UHE photon fluxes

arXiv:1811.03920

- Boosted decision tree using 16 observables,
  trained on QGSJet II-03 proton and EGS4 photon simulations

	E_0, eV				
	$10^{18.0}$	$10^{18.5}$	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	1	0	0	0	1
b	0.55	1.01	0.97	0.80	0.49
$\bar{n}$ <	5.14	3.09	3.09	3.09	5.14
A_{eff}	77	255	852	2351	4055
F_γ <	0.067	0.012	0.0036	0.0013	0.0013

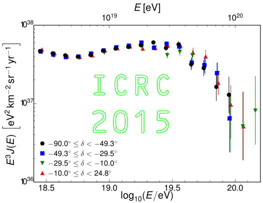
TABLE II. 95% CL upper limits on the number of photons in the data set $\bar{n}_\gamma$ and on the photon flux F_γ ($\mathrm{km}^{-2}\mathrm{yr}^{-1}\mathrm{sr}^{-1}$). b is an expected number of background photon candidates obtained with proton MC.

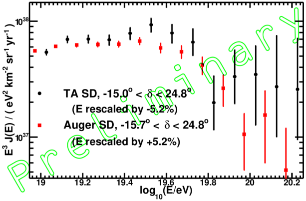


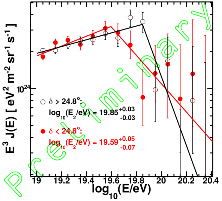
preliminary

Declination dependence of spectrum

Preliminary!





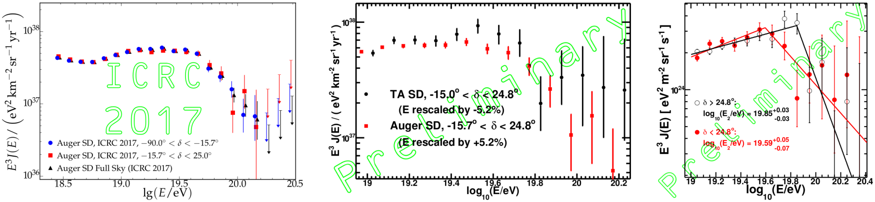


Comparison	Result	Reference
TA, north vs. TA, equator	large difference ($3.5\sigma_{post}$)	arXiv:1801.07820
TA, equator vs. Auger + 11%, equator	small difference?	PoS (ICRC 2017) 498
Auger + 11%, equator vs. Auger + 11%, south	no difference	PoS (ICRC 2015) 271

- Remaining difference in common declination band being investigated by joint Auger–TA spectrum working group (see UHECR18 report)

Declination dependence of spectrum

Preliminary!



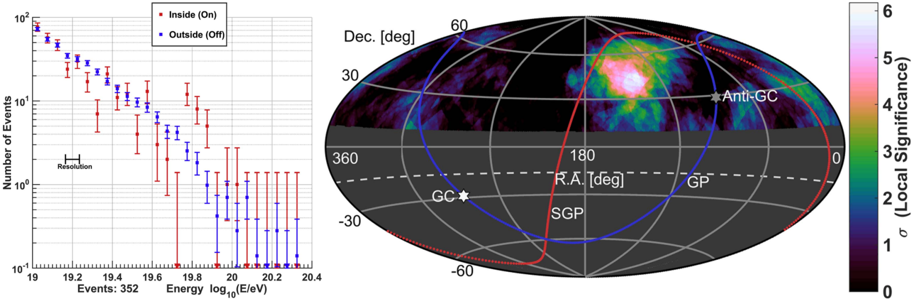
TA, north / TA, equator	large difference ($3.5\sigma_{\text{post}}$)	arXiv:1801.07820
TA, equator / Auger + 11%, equator	small difference?	PoS (ICRC 2017) 498
Auger + 11%, equator / Auger + 11%, south	no difference	PoS (ICRC 2017) 486

- Remaining difference in common declination band being investigated by joint Auger–TA spectrum working group (see UHECR18 report)

Hotspot and coldspot

Astrophys. J. **862** (2018) 91, arXiv:1802.05003

- Excess of events $> 10^{19.75}$ eV within $\approx 30°$ of $(\alpha = 9^{\mathrm{h}}16^{\mathrm{m}}, \delta = +45°)$
- Deficit of lower-energy events in the same region

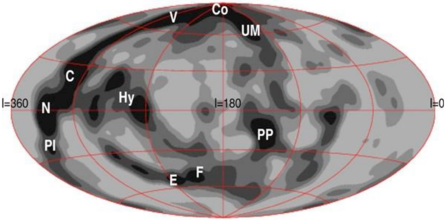


- 6.17σ pre-trial significance (3.74σ post-trial)

Correlation with large-scale structures

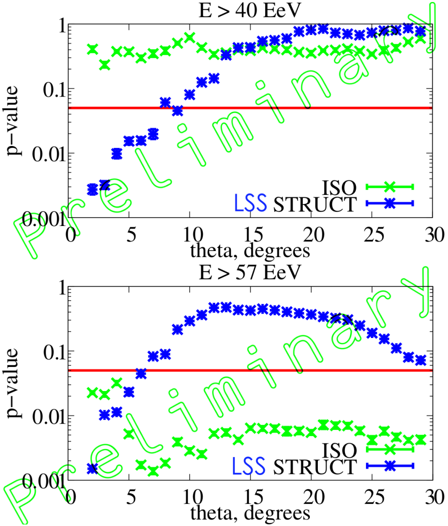
Preliminary update of Astrophys. J. **757** (2012) 26, `arXiv:1205.5984`

- LSS from the 2MASS galaxy catalog (XSCz), assuming CR lumin. $\propto$ matter density



(6° smearing; rotated Galactic coordinates)

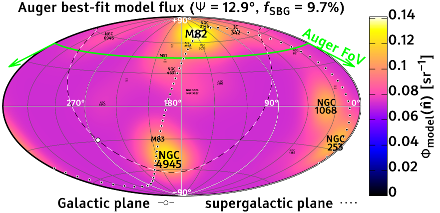
- Data above 57 EeV in tension with isotropic expectations

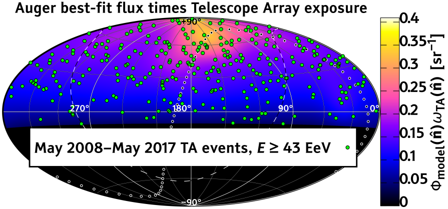


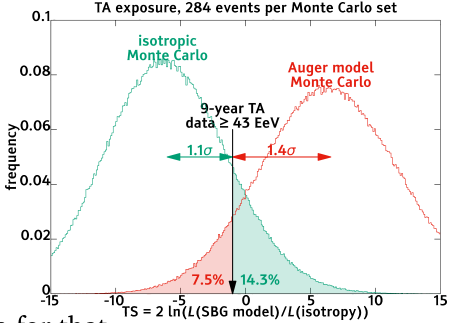
Correlation with starburst galaxies (or lack thereof)

Astrophys. J. Lett. **867** (2018) L27, arXiv:1809.01573

- Auger arr. directions > 39 EeV been reported to correlate with a catalog of nearby SBGs ($4\sigma_{\text{post}}$ over isotropy, $3\sigma_{\text{post}}$ over LSS)





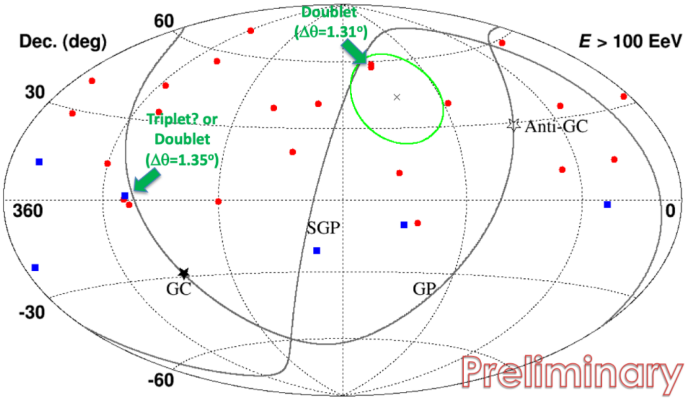


- North polar cap (incl. e.g. M82) outside the Auger field of view → TA replication interesting

  … but not (yet) enough data for that.

Small-scale anisotropy search above 100 EeV

Very preliminary!



• TA 9 years (23 events) ■ Auger 10 years (6 events) (nominal energies)

$$p(\geq 2 \text{ doublets within } \sqrt{2}^\circ) = 0.3\% \; (2.8\sigma)$$

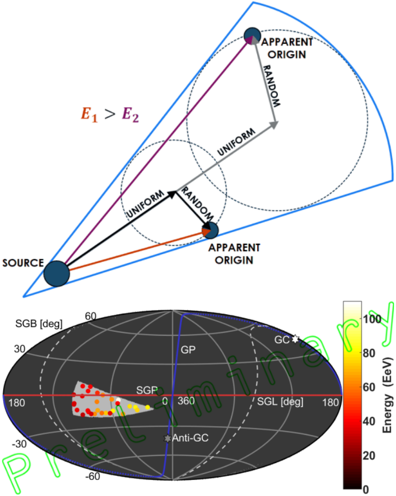
Supergalactic structure of multiplets 1/2

Presented at the UHECR2018 conference (Paris, October 2018), proceedings in preparation

- UHECRs from a point source deflected by coherent and turbulent magnetic fields should form “wedges” in which the distance from the vertex anticorrelates with the energy.
- We can estimate the density of sources at a given point from the strength of the most significant anticorrelation among all possible energy thresholds and wedge widths, lengths and orientations.

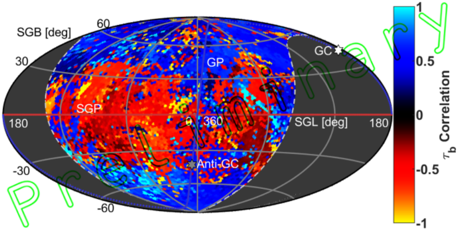
  $E \geq 30$ EeV, wedge width $= 30^\circ$, length $= 80^\circ$, orientation $= 270^\circ$ (supergal. coordinates) →

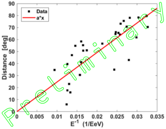
- We did this everywhere in our FoV . . .



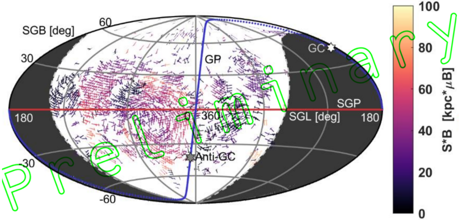
Supergalactic structure of multiplets 2/2

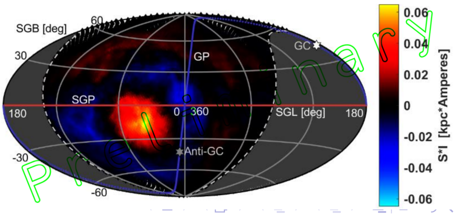
- Anticorrelations stronger near supergalactic plane (significant at $\gtrsim 4\sigma_{\text{post}}$)
- Coh. field strength at each point estimated by fitting $\Delta\theta \propto 1/E$ in 'best' wedge; field direction: wedge orientation rotated by 90°
- Current flowing towards us estimated as $\propto \nabla \times \mathbf{B}$





$B = 13$ nG
if $Z = 1$, $D = 3.7$ Mpc
(e.g. M82)



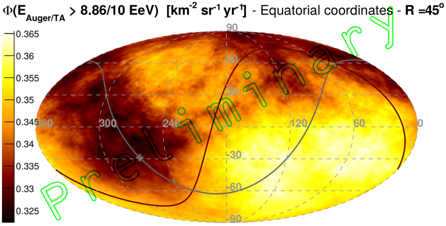


Full-sky anisotropy searches with Auger + TA

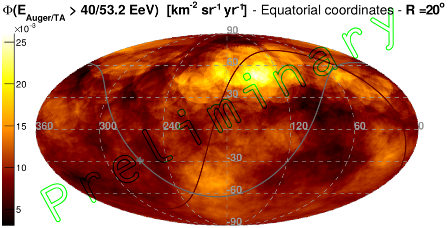
Presented at the UHECR2018 conference (Paris, October 2018), proceedings in preparation

Energy thresholds cross-calibrated via events in the intersection of FoVs

$E_{\mathrm{Auger}} > 8.86\ \mathrm{EeV}, E_{\mathrm{TA}} > 10\ \mathrm{EeV}$:



$E_{\mathrm{Auger}} > 40\ \mathrm{EeV}, E_{\mathrm{TA}} > 53.2\ \mathrm{EeV}$:

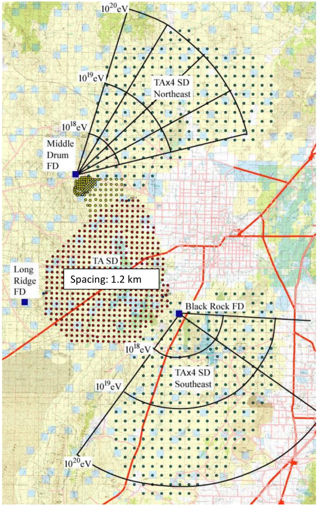


- Indications for a dipole moment (possibly also a quadrupole)
- Indications for warmspots along the supergalactic plane

Further analyses in preparation — stay tuned!

Outline

The ongoing Telescope Array extension: TA×4



- 500 new SDs with 2.08 km spacing (construction ongoing)
- 4 + 8 new FD telescopes (northern site already taking data; southern site under construction)
- 4 times the TA aperture at highest energies
  - → Anisotropy studies with 4× more statistics

Stay tuned!

Back-up slides

4. SD observables used by boosted decision trees
   - For the composition study
   - For the search for photons
5. More about Auger–TA working group reports
   - Spectrum
   - Composition
   - Anisotropy
6. Details about the supergalactic multiplet study

Outline

4. SD observables used by boosted decision trees
   - For the composition study
   - For the search for photons

5. More about Auger–TA working group reports
   - Spectrum
   - Composition
   - Anisotropy

6. Details about the supergalactic multiplet study

SD observables used by BDTs for the composition study

1. Linsley front curv. param., a
2. Area-over-peak (AoP) of signal at $r_0 = 1\,200$ m, α
3. AoP slope parameter, β $(\mathrm{AoP}(r) = \alpha - \beta(r/r_0 - 1))$
4. Number of detectors hit
5. Number of detectors excluded from shower front fit
6. χ^2/n of joint geometry–LDF fit
7. S_b parameter for $b = 3$ $(S_b = \sum_{i=1}^{N} S_i (r_i/r_0)^b$, $S_i =$ signal in i-th detector)
8. S_b parameter for $b = 4.5$
9. Sum of all signals $(S_{b=0})$
10. Asymm. of signal at upper and lower layers of detectors
11. Total number of peaks within all FADC traces
12. Number of peaks in detector with largest signal
13. No. of peaks only in upp. layer
14. No. of peaks only in lower layer

SD observables used by BDTs for the photon search

1. Zenith angle, θ
2. Signal at 800 m from core
3. Linsley front curv. param., a
4. Area-over-peak (AoP) of signal at $r_0 = 1\,200$ m, α
5. AoP slope parameter, β $(\mathrm{AoP}(r) = \alpha - \beta(r/r_0 - 1))$
6. Number of detectors hit
7. Number of detectors excluded from shower front fit
8. χ^2/n of joint geometry–LDF fit
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Outline

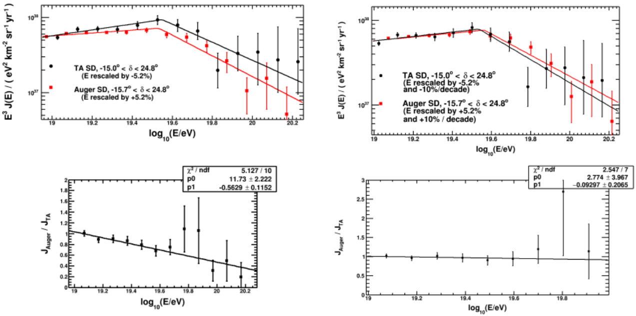
4 SD observables used by boosted decision trees
- For the composition study
- For the search for photons

5 More about Auger–TA working group reports
- Spectrum
- Composition
- Anisotropy

6 Details about the supergalactic multiplet study

From the last Auger–TA spectrum WG report

TA-Auger Difference



- Agreement in the common declination band after a correction of Auger energies by +10% per decade, and TA by -10% per decade, starting at 10^{19} eV
- TA energy-dependent bias: -0.3 +/- 9% per decade of energy, and SD reconstruction checked using Monte Carlo and constant intensity cut reconstruction methods.
- Auger energy-dependent bias: within 3% per decade of energy and SD reconstruction checked using two different constant intensity cut methods.

From the last Auger–TA composition WG report

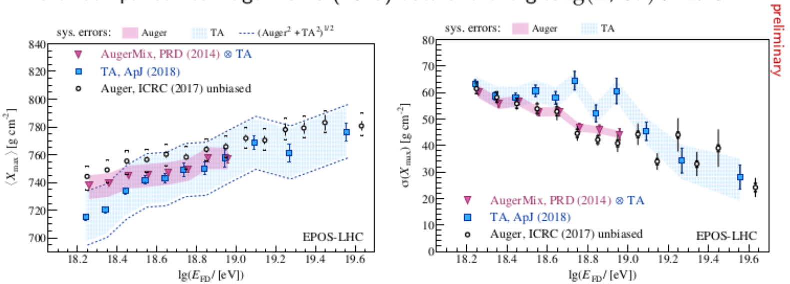
Summary

$\langle X_{\max}^{\mathrm{TA}} \rangle < \langle X_{\max}^{\mathrm{Auger}} \rangle$ for almost all energies

agreement within $(\mathrm{stat} + \mathrm{sys})$ errors

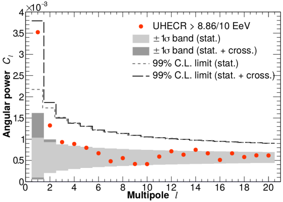
$\sigma(X_{\max}^{\mathrm{TA}}) > \sigma(X_{\max}^{\mathrm{Auger}})$ for $\lg(E/\mathrm{eV}) = 18.6 - 19.0$

Next: comparison to Auger ICRC (2017) data and energies $\lg(E/\mathrm{eV}) > 19.0$



From the last Auger–TA anisotropy WG report

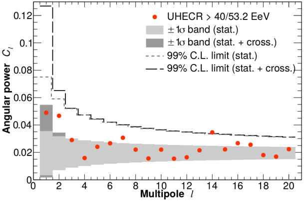
Low-energy angular power spectrum and dipole components

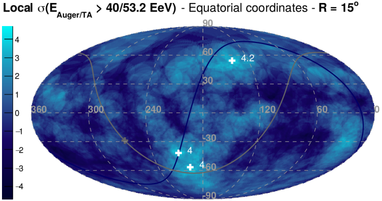


Dipole along (d_z) and perpendicular to ($d_\perp$) Earth's axis:

	d_z [%]	$d_\perp$ [%]
Auger only, $\ell \leq 1$ [1]	-2.6 ± 1.5	6.0 ± 1.0
Auger only, $\ell \leq 2$ [2]	-2 ± 4	5.0 ± 1.3
Auger + TA (this work)	$-2.6 \pm 1.3_{\text{stat}} \pm 1.4_{\text{cross}}$	$4.3 \pm 1.1_{\text{stat}} \pm 0.04_{\text{cross}}$

High-energy angular power spectrum and blind search for excesses





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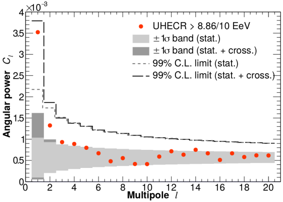

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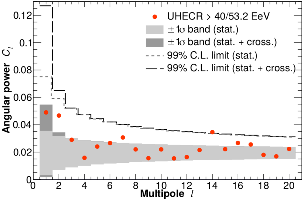
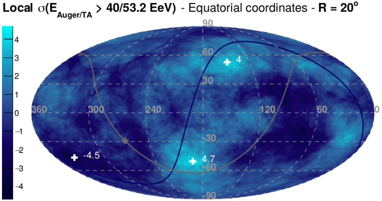




Outline

4 SD observables used by boosted decision trees
- For the composition study
- For the search for photons

5 More about Auger–TA working group reports
- Spectrum
- Composition
- Anisotropy

6 Details about the supergalactic multiplet study

Details about the supergalactic multiplet study

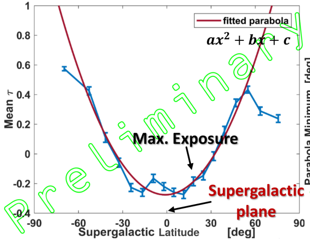
p-values computed by permutation

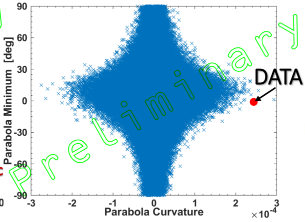
Parameter scan ranges:

- thresh. E/EeV: 10, 15, . . . , 100
- wedge vertex: on a $2° \times 2°$ grid
- " width: 10°, 20°, . . . , 90°
- " length: 15°, 20°, . . . , 90°
- " pointing: 0°, 5°, . . . , 355°

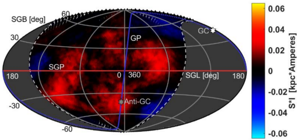
Kendall's correlation coefficient:
$\tau = \mathrm{avg}_{i<j}\,\mathrm{sign}((E_i - E_j)(\theta_i - \theta_j))$,
only depends on rankings
($\tau = 1$ for any monotonic function)

Most signif. τ value for each vertex binned in supergalactic latitude and fitted to $ax^2 + bx + c$;
a value compared to MC distribution





estim. current



MC Example