UHECR arrival directions in the latest data from the original Auger and TA surface detectors and nearby galaxies

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Outline

1. Motivation
2. Full-sky search for medium-scale anisotropies
   - The datasets
   - Analysis technique and catalogs of candidate sources
   - Results
3. Future prospects

Motivation

- The origin of ultra-high-energy (≥ 1 EeV) cosmic rays is still unknown, but:
  - Weak anisotropies, large fractions of protons $\longrightarrow$ can't be mostly Galactic
  - Few or no neutrinos or gamma rays among them $\longrightarrow$ can't be mostly "new physics" (except possibly at $E \gtrsim 100$ EeV)
  - Attenuation by the CMB ("GZK limit") $\longrightarrow$ can't be mostly at cosmological distances (except possibly at $E \lesssim 40$ EeV)

  $\longrightarrow$ must be mostly "ordinary" matter in the local extragalactic environment.
- Magnetic deflections prevent us from straightforwardly deducing the positions of sources.
- Two possible ways to minimize their effects:
  1. Studying large-scale anisotropies (dipole and quadrupole), which are the least affected
  2. Studying the highest energies, where deflections are smaller (at the cost of reduced statistics)
- See talk by Peter Tinyakov for the former.
- Here, I'm going to discuss the latter.
- Various hints have already been reported (Auger coll., *ApJL* **853** (2018) L29; TA coll., *ApJ* **899** (2020) 86), but with partial sky coverage.

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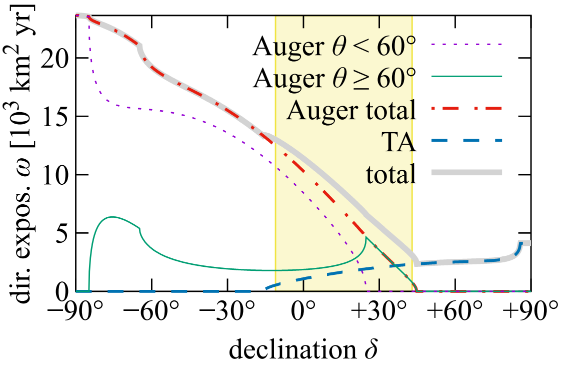
The datasets

Telescope Array (TA) data

- 2008 May 11–2019 May 10 (11 years)
- strict (spectrum) cuts, $\theta < 55^\circ$
- 14 000 km^2 yr sr effective exposure
- 315 events with $E \geq 40.8$ EeV

Pierre Auger Observatory (Auger) data

- 2004 Jan 01–2020 Dec 31 (17 years)
- $\theta < 80^\circ$, with different cuts and reconstructions for $\theta < 60^\circ$ and $\theta \geq 60^\circ$
- 120 000 km^2 yr sr effective exposure
- 2 625 events with $E \geq 32$ EeV



The cross-calibration of energy scales

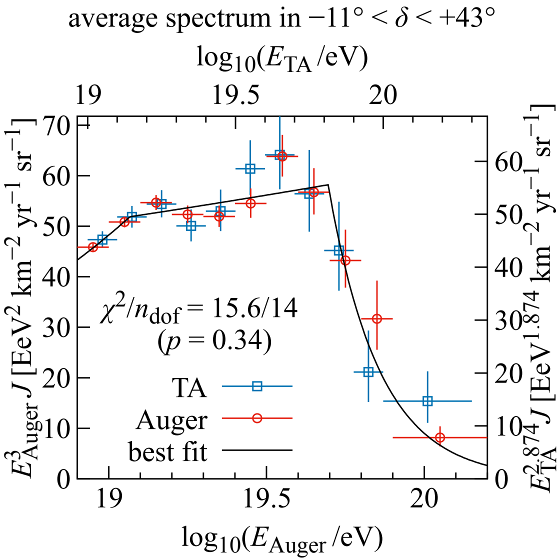
- There is a mismatch between the Auger and TA energy spectrum measurements in the common declination band, which we need to correct for.
- We convert TA energies to the Auger scale according to

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

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

(see talk by Peter Tinyakov for details).

NOTE: This conversion only fitted to $E_{\mathrm{TA}} \geq 10$ EeV – **do not extrapolate to lower energies!**



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The log-likelihood-ratio analysis

Based on A. Aab et al. [Pierre Auger collab.], *Astrophys. J. Lett.* **853** (2018) L29 [1801.06160]

The flux model

Weighted sum of von Mises–Fisher distributions centered around source candidates, with ψ = r.m.s. deflection per transverse dimension (total r.m.s. = $\sqrt{2} \times \psi$, equiv. top-hat $\approx 1.59\psi$):

$$\Phi(\hat{\mathbf{n}}; \psi, f) = f\Phi_{\text{signal}}(\hat{\mathbf{n}}; \psi) + (1-f)\Phi_{\text{background}},$$

where:

$$\Phi_{\text{signal}}(\hat{\mathbf{n}}; \psi) = \frac{1}{\sum_j w_s} \sum_j w_s \frac{\psi^{-2}}{4\pi \sinh \psi^{-2}} \exp\left(\psi^{-2}\hat{\mathbf{n}}_s \cdot \hat{\mathbf{n}}\right) \qquad \Phi_{\text{background}} = \frac{1}{4\pi}$$

The test statistic (max$_{f,\psi}$ TS is χ^2_2-distributed)

$$\text{TS}(\psi, f, E_{\min}) = 2 \ln \frac{L(\psi, f, E_{\min})}{L(\psi, 0, E_{\min})}, \qquad L(\psi, f, E_{\min}) = \prod_{E_i \geq E_{\min}} \frac{\Phi(\hat{\mathbf{n}}_i; \psi, f)\omega(\hat{\mathbf{n}}_i)}{\int_{4\pi} \Phi(\hat{\mathbf{n}}; \psi, f)\omega(\hat{\mathbf{n}})\, d\Omega},$$

where $\omega(\hat{\mathbf{n}})$ = combined directional exposure

THRESHOLDS: $\{32\text{ EeV}, 33\text{ EeV}, \ldots, 80\text{ EeV}\}$ on the Auger scale ($\{40.8\text{ EeV}, \ldots, 108.4\text{ EeV}\}$ on the TA scale)

The catalogs of candidate sources

All types of galaxies, 1 Mpc $\leq D <$ 250 Mpc (44 113 items)

- Angular positions and K-band magnitudes from 2MASS catalog
- Distances from HyperLEDA when avaliable, estimated from redshifts otherwise
- UHECR flux assumed proportional to the near-IR flux in the K-band (2.2 μm)

Starburst galaxies, 1 Mpc $\leq D <$ 130 Mpc (44 items)

- Based on C. Lunardini et al., *J. Cosmol. Astropart. Phys.* **10** (2019) 073 [1902.09663], but:
  - SMC and LMC removed (dwarf irregular, not starburst — very low IR-to-radio ratio)
  - Circinus added ($\alpha = 213.29°$, $\delta = -65.34°$, $D = 4.21$ Mpc, $S = 1.50$ Jy from the Parkes telescope)
- UHECR flux assumed proportional to the radio flux at 1.4 GHz

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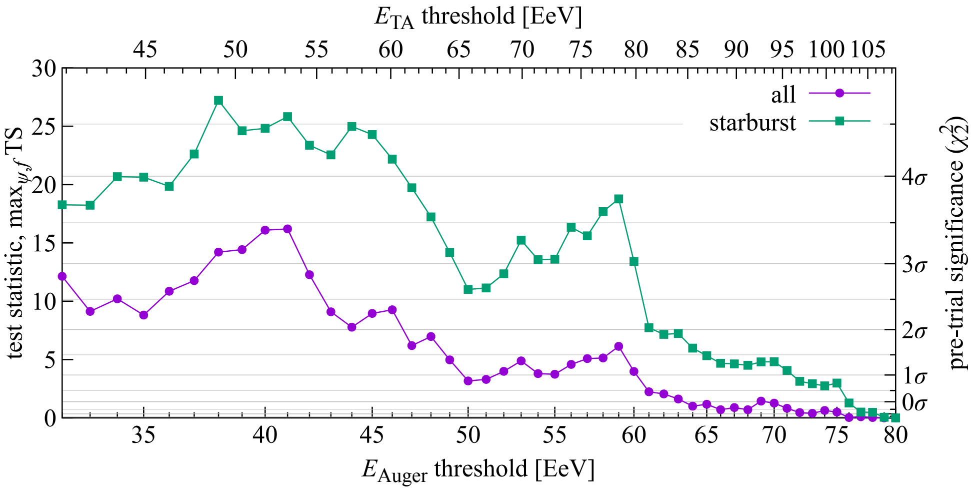
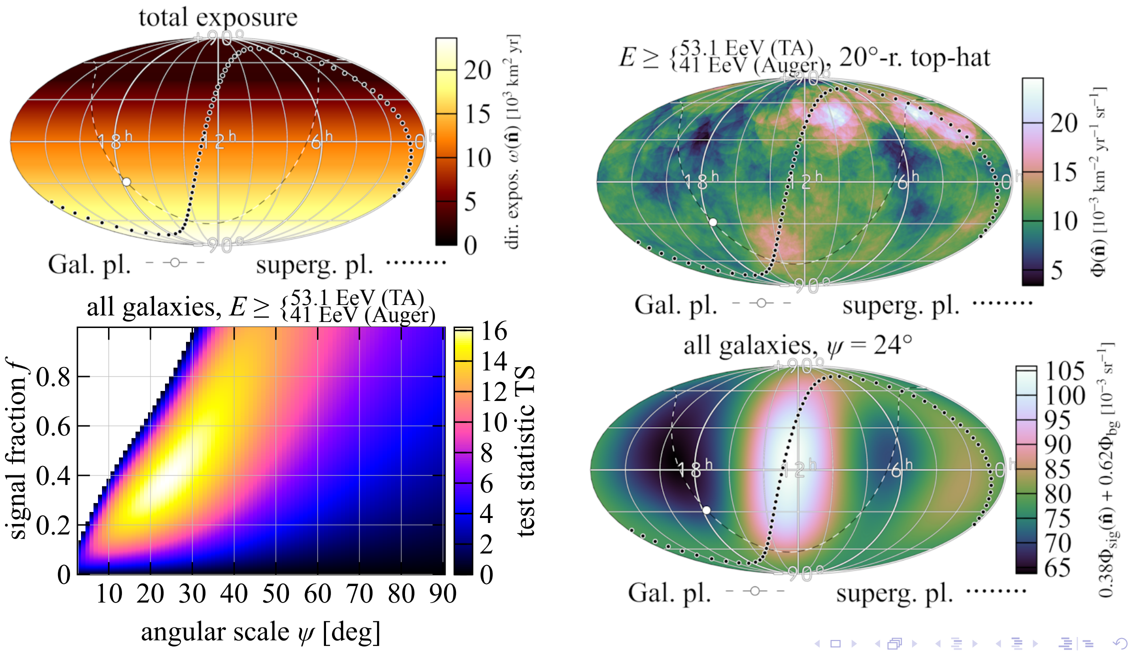
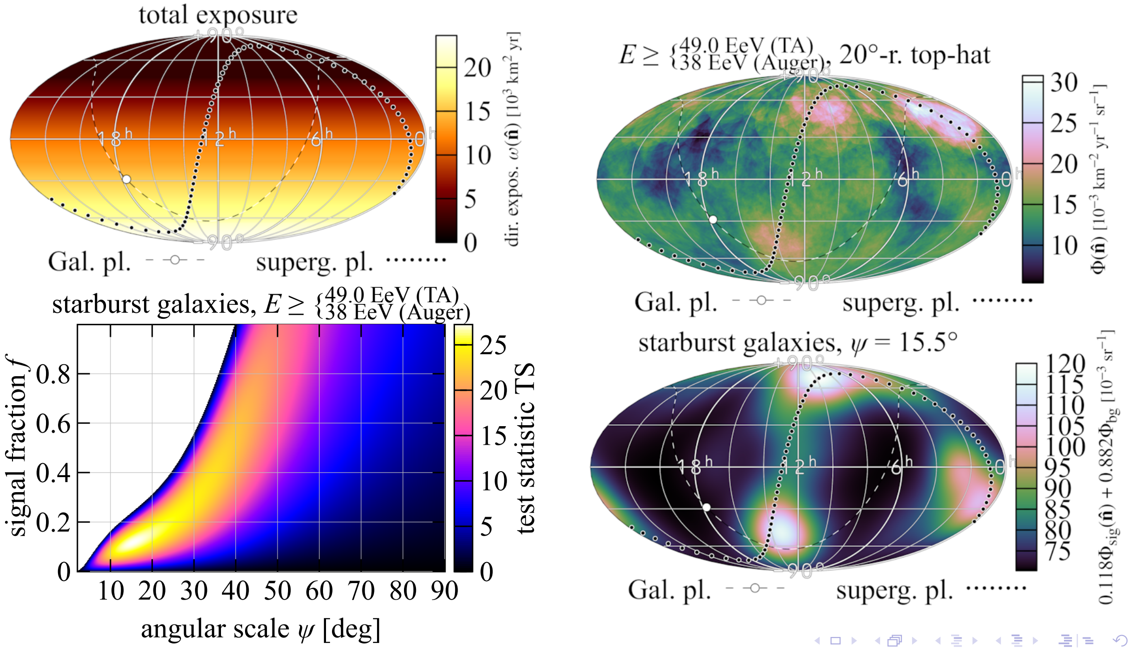
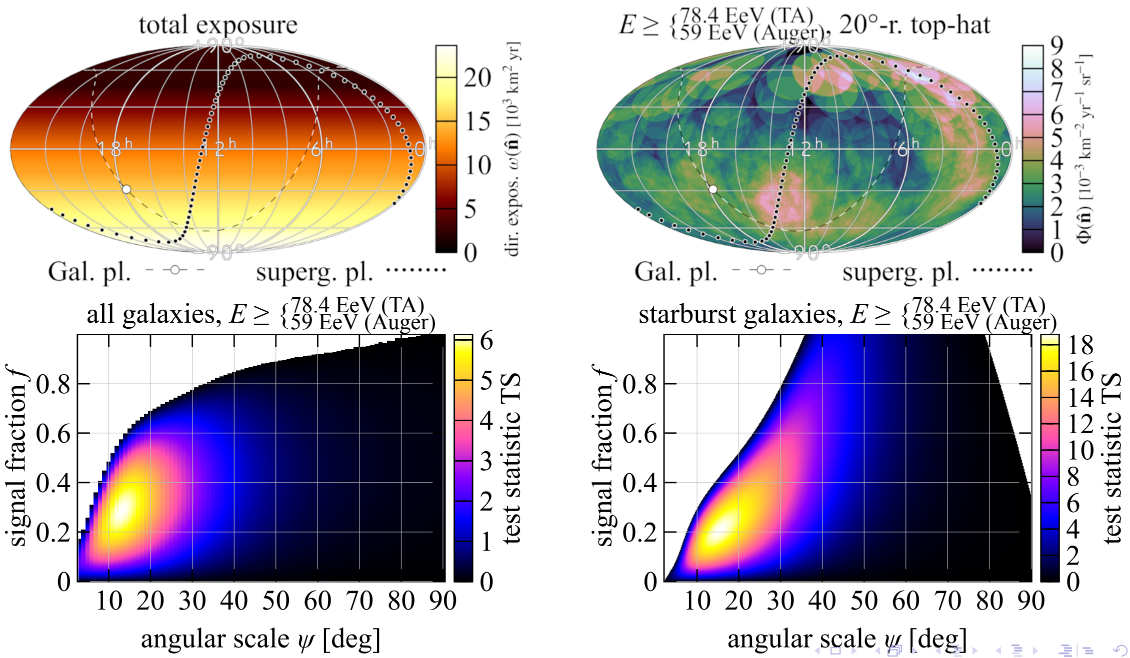


catalog	E_{min} (Auger)	E_{min} (TA)	ψ	equiv. top-hat radius	f	TS
all galaxies	41 EeV	53 EeV	$24^{\circ}{}^{+13^{\circ}}_{-8^{\circ}}$	$38^{\circ}{}^{+21^{\circ}}_{-13^{\circ}}$	$38\%^{+28\%}_{-14\%}$	16.2
starburst galaxies	38 EeV	49 EeV	$15.5^{\circ}{}^{+5.3^{\circ}}_{-3.2^{\circ}}$	$24.6^{\circ}{}^{+8.4^{\circ}}_{-5.1^{\circ}}$	$11.8\%^{+5.0\%}_{-3.1\%}$	27.2


total exposure
dir. expos. $\omega(\hat{\mathbf{n}})$ [10^3 km^2 yr]
Gal. pl.
superg. pl.
$E \geq \{^{53.1\text{ EeV (TA)}}_{41\text{ EeV (Auger)}}$, 20°-r. top-hat
$\Phi(\hat{\mathbf{n}})$ [10^{-3} km^{-2} yr^{-1} sr^{-1}]
Gal. pl.
superg. pl.
all galaxies, $E \geq \{^{53.1\text{ EeV (TA)}}_{41\text{ EeV (Auger)}}$
signal fraction f
angular scale ψ [deg]
test statistic TS
all galaxies, $\psi = 24°$
$0.38\Phi_{\text{sig}}(\hat{\mathbf{n}}) + 0.62\Phi_{\text{bg}}$ [10^{-3} sr^{-1}]
Gal. pl.
superg. pl.

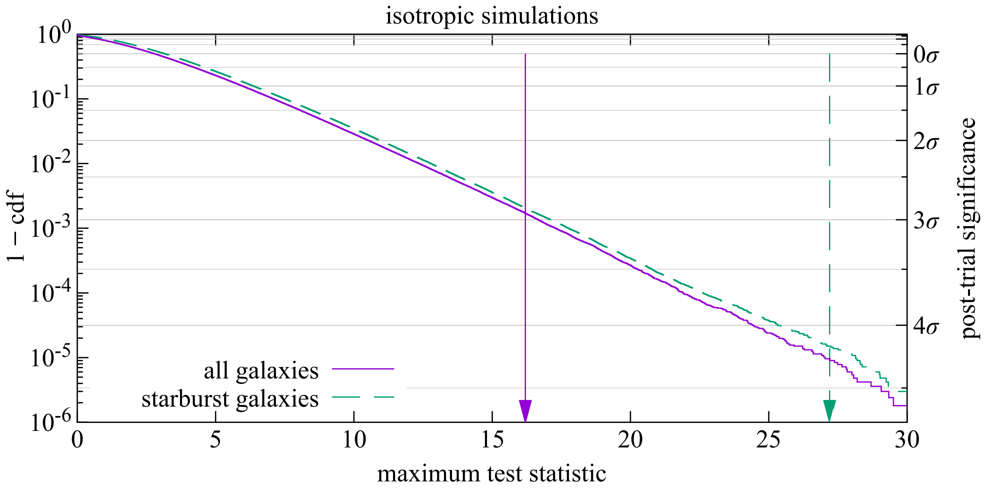


total exposure
+90°
18h
12h
6h
0h
-90°
dir. expos. ω(n̂) [10³ km² yr]
0
5
10
15
20
Gal. pl.
superg. pl.
E ≥ {49.0 EeV (TA), 38 EeV (Auger)}, 20°-r. top-hat
Φ(n̂) [10⁻³ km⁻² yr⁻¹ sr⁻¹]
10
15
20
25
30
starburst galaxies, E ≥ {49.0 EeV (TA), 38 EeV (Auger)}
signal fraction f
angular scale ψ [deg]
test statistic TS
starburst galaxies, ψ = 15.5°
0.118Φsig(n̂) + 0.882Φbg [10⁻³ sr⁻¹]
75
80
85
90
95
100
105
110
115
120



total exposure
dir. expos. ω(n̂) [10³ km² yr]
Gal. pl.
superg. pl.
E ≥ {78.4 EeV (TA), 59 EeV (Auger)}, 20°-r. top-hat
Φ(n̂) [10⁻³ km⁻² yr⁻¹ sr⁻¹]
Gal. pl.
superg. pl.
all galaxies, E ≥ {78.4 EeV (TA), 59 EeV (Auger)}
signal fraction f
test statistic TS
angular scale ψ [deg]
starburst galaxies, E ≥ {78.4 EeV (TA), 59 EeV (Auger)}
signal fraction f
test statistic TS
angular scale ψ [deg]

Post-trial significance



- 2.9σ for the all-galaxy catalog
- 4.2σ for the starburst galaxy catalog

Future prospects

- Simulation-based estimation of the effects of UHECR energy losses and magnetic deflections on such analyses
- AugerPrime and TA×4 → more statistics
- Machine learning, new AugerPrime detectors, … → event-by-event estimates of mass → high-rigidity event samples (less deflected by magnetic fields)

STAY TUNED!

Back-up slides

4 The energy conversion and its uncertainties

5 Sky maps with more energy thresholds

6 Sky maps in Galactic coordinates

7 Statistical penalty for the use of two catalogs

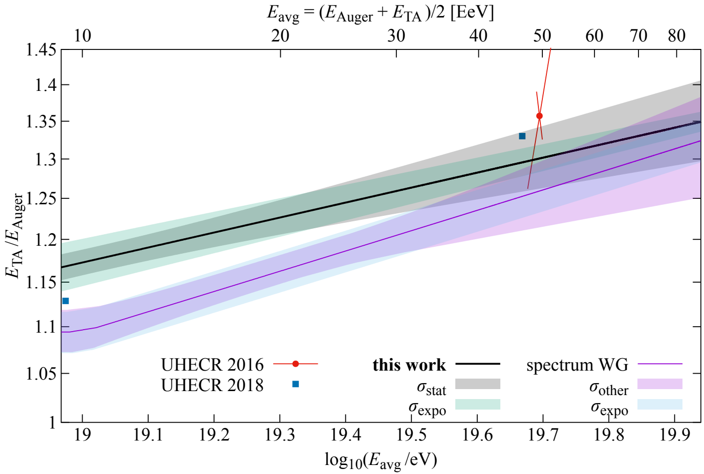
The energy conversion and its uncertainties

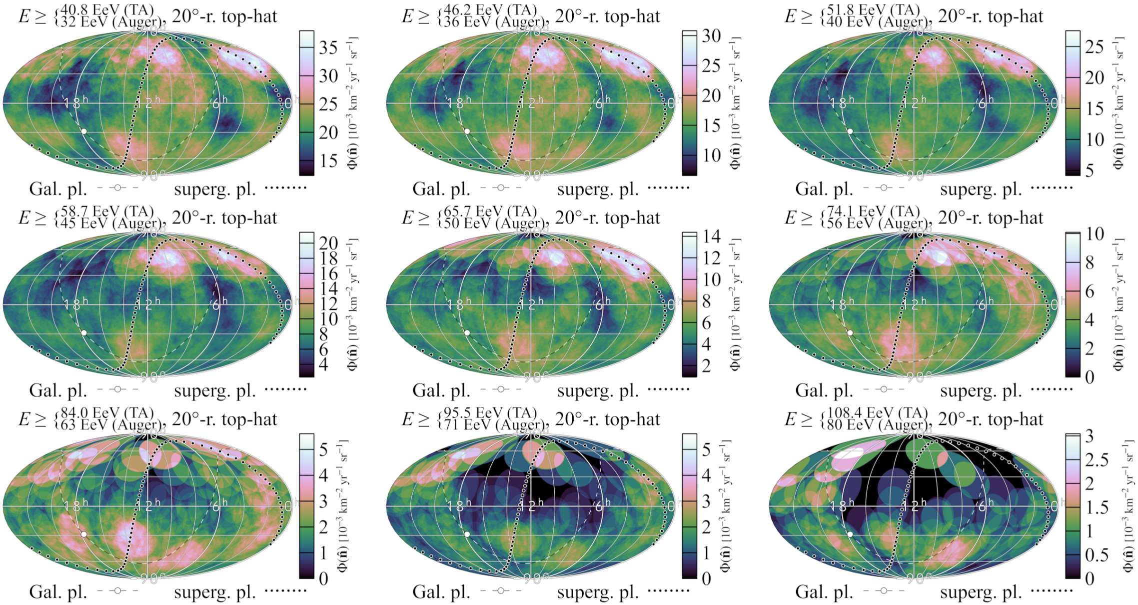
See talk by Peter Tinyakov for details

- ±2.7% statistical uncertainty on energy matching at 32 EeV

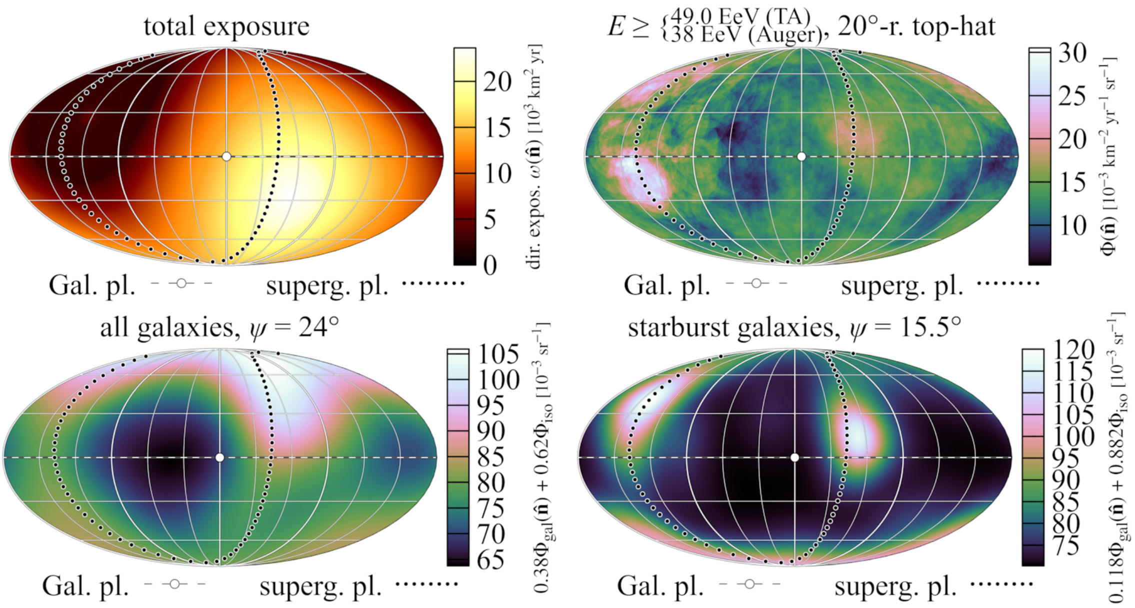
→ 6.5% flux ratio uncertainty

- Unlike on the large-scale anisotropy searches, changing the exposure ratio by ±6.5% would have negligible effects on the searches shown here (a few units in the last place for both TS and f, ψ).





E ≥ {40.8 EeV (TA), 32 EeV (Auger)}, 20°-r. top-hat
E ≥ {46.2 EeV (TA), 36 EeV (Auger)}, 20°-r. top-hat
E ≥ {51.8 EeV (TA), 40 EeV (Auger)}, 20°-r. top-hat
E ≥ {58.7 EeV (TA), 45 EeV (Auger)}, 20°-r. top-hat
E ≥ {65.7 EeV (TA), 50 EeV (Auger)}, 20°-r. top-hat
E ≥ {74.1 EeV (TA), 56 EeV (Auger)}, 20°-r. top-hat
E ≥ {84.0 EeV (TA), 63 EeV (Auger)}, 20°-r. top-hat
E ≥ {95.5 EeV (TA), 71 EeV (Auger)}, 20°-r. top-hat
E ≥ {108.4 EeV (TA), 80 EeV (Auger)}, 20°-r. top-hat
18h
12h
6h
Φ(n̂) [10⁻³ km⁻² yr⁻¹ sr⁻¹]
Gal. pl.
superg. pl.



total exposure
dir. expos. $\omega(\hat{\mathbf{n}})$ [10^3 km^2 yr]
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Gal. pl.
superg. pl.
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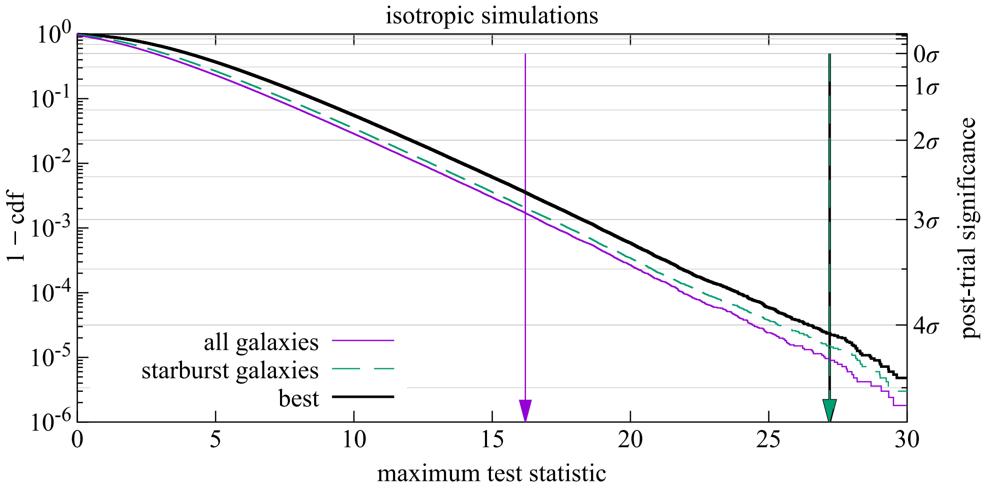

- 4.1σ