The flux of UHECRs along the supergalactic plane using Pierre Auger Observatory data

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The distribution of the UHECR flux at intermediate scales

- No intermediate- or small-scale anisotropies in the flux of UHECRs have been conclusively discovered yet.
- A few indications for excesses above a few tens of EeV have been reported:
  - In the region around the position of the Centaurus A radio galaxy (first in Auger *APh* 2010; 4.0σ as of Auger ICRC 2023)
  - Correlating with nearby starburst galaxies (first in Auger *ApJL* 2018; 3.8σ in Auger ICRC 2023; 4.6σ in Auger+TA ICRC 2023)
  - "TA hotspot" in the Ursa Major region (first in TA *ApJL* 2014; 2.8σ as of TA ICRC 2023)
  - In the region around the position of the Perseus–Pisces Supercluster (first in TA arXiv 2021; 3.3σ as of TA ICRC 2023)

The supergalactic plane

- All of these regions are along the supergalactic plane, a great circle in the sky where galaxies within $\mathcal{O}(10^2\ \text{Mpc})$ of us tend to concentrate.
  - The Local Sheet, comprising nearly all bright galaxies within 6 Mpc of us, is also aligned with it to within 8° (McCall *MNRAS* 2014).
- Since at the highest energies UHECR propagation lengths are $\lesssim \mathcal{O}(10^2\ \text{Mpc})$, a correlation with the supergalactic plane wouldn't be surprising — but remember that magnetic deflections can be several tens of degrees.
- In Auger *ApJ* 2022 we found no statistically significant excess of events in bands of 1°–30° around the whole supergalactic plane ($p = 0.13$ post-trial).
- But what about smaller regions along it?

The dataset we use

- Events with $E \geq 20\,\text{EeV}$ detected by the Auger SD array from 2004 to 2022
  - Not using SD stations with upgraded electronics for 2021/2022 events
- Quality cuts optimized for high-energy medium-scale anisotropies (same as in Auger *ApJ* 2022)
- Total exposure: $135,000\,\text{km}^2\,\text{sr}\,\text{yr}$
- Systematic uncertainties: $\pm 14\%$ in energy
- Resolution: $\sim 7\%$ in energy; $< 1^\circ$ in arrival directions
- Field of view: declinations $\delta < +44.8^\circ$
- 6,896 vertical events (zenith angles $\theta < 60^\circ$)
- 1,936 inclined events (zenith angles $60^\circ \leq \theta < 80^\circ$)
  - We rescale vertical and inclined exposures proportionally to numbers of events.
  - As a result, the analysis is pretty robust to possible systematics affecting vertical and inclined events differently (see back-up slides).

The analysis we perform

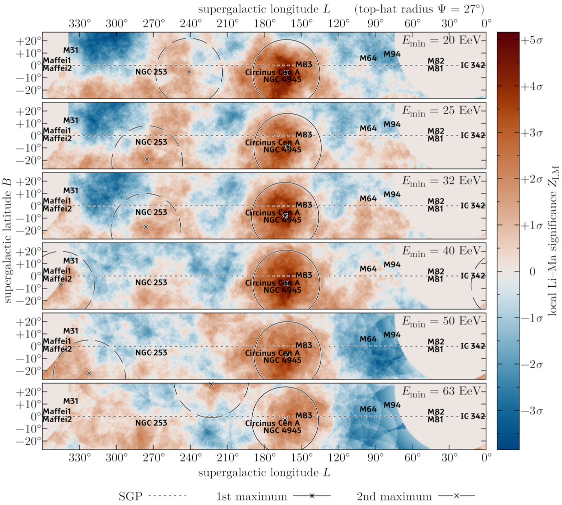
- We use the energy thresholds $E_{\text{min}} \in \{20\,\text{EeV}, 25\,\text{EeV}, 32\,\text{EeV}, 40\,\text{EeV}, 50\,\text{EeV}, 63\,\text{EeV}\}$.*
- For each energy threshold, we consider all possible top-hat windows of radius $\Psi = 27°$† such that:
  1. the window intersects the supergalactic plane, i.e., $|B_{\text{center}}| \leq \Psi$, and
  2. the center of the window is inside our field of view, i.e., $\delta_{\text{center}} < +44.8°$.
- For each threshold and each such window, we compute

N_{in}	number of events with $E \geq E_{\text{min}}$ inside the window
N_{out}	number of events with $E \geq E_{\text{min}}$ outside the window
N_{bg}	expected background, $N_{\text{out}}\mathscr{E}_{\text{in}}/\mathscr{E}_{\text{out}}$, where $\mathscr{E}$ = integrated exposure
$\Phi_{\text{in}}/\Phi_{\text{out}}$	flux ratio, estimated as $N_{\text{in}}/N_{\text{bg}}$
Z_{LM}	local Li–Ma significance
99% U.L.	frequentist 99% C.L. upper limit on $\frac{\Phi_{\text{in}}}{\Phi_{\text{out}}}$

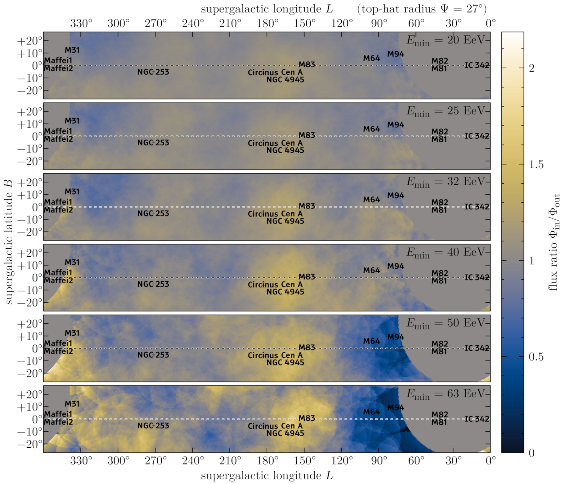
*i.e., $\{10^{19.3}\,\text{eV}, 10^{19.4}\,\text{eV}, \ldots, 10^{19.8}\,\text{eV}\}$ rounded to the nearest EeV

†i.e., the radius maximizing the significance of the excess with $E_{\text{min}} = 38\,\text{EeV}$ in Auger *ApJ* 2022

Our results



supergalactic longitude L (top-hat radius Ψ = 27°)
330° 300° 270° 240° 210° 180° 150° 120° 90° 60° 30° 0°
+20° +10° 0° −10° −20°
E_min = 20 EeV
E_min = 25 EeV
E_min = 32 EeV
E_min = 40 EeV
E_min = 50 EeV
E_min = 63 EeV
M31
Maffei1
Maffei2
NGC 253
Circinus Cen A
NGC 4945
M83
M64
M94
M82
M81
IC 342
supergalactic latitude B
local Li–Ma significance Z_LM
+5σ +4σ +3σ +2σ +1σ 0 −1σ −2σ −3σ
supergalactic longitude L
SGP
1st maximum
2nd maximum



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supergalactic latitude B
flux ratio Φ_in/Φ_out
2 1.5 1 0.5 0
supergalactic longitude L

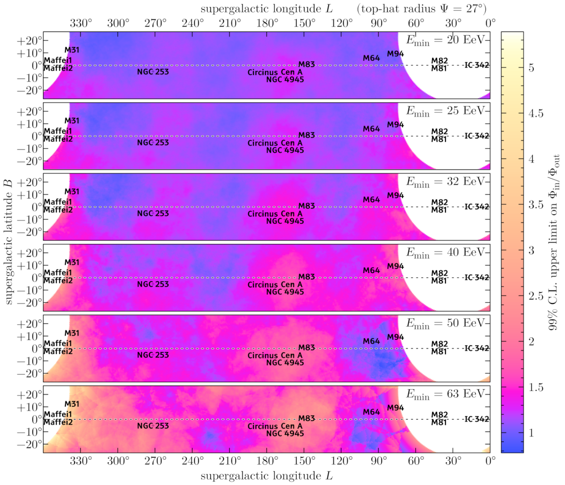
Our results

		1st maximum								2nd maximum							
E_{min}	N_{tot}	L	B	$\frac{\mathcal{E}_{\text{in}}}{\mathcal{E}_{\text{tot}}}$	N_{bg}	N_{in}	$\frac{\Phi_{\text{in}}}{\Phi_{\text{out}}}$	Z_{LM}	99% U.L.	L	B	$\frac{\mathcal{E}_{\text{in}}}{\mathcal{E}_{\text{tot}}}$	N_{bg}	N_{in}	$\frac{\Phi_{\text{in}}}{\Phi_{\text{out}}}$	Z_{LM}	99% U.L.
20 EeV	8832	162°	−6°	9.56%	829.	990	$1.19^{+0.04}_{-0.04}$	$+5.2\sigma$	1.29	241°	−5°	10.27%	900.	971	$1.08^{+0.04}_{-0.04}$	$+2.2\sigma$	1.17
25 EeV	5380	161°	−9°	9.56%	504.	608	$1.21^{+0.05}_{-0.05}$	$+4.2\sigma$	1.33	275°	−19°	8.00%	426.	482	$1.13^{+0.05}_{-0.05}$	$+2.6\sigma$	1.26
32 EeV	2936	163°	−8°	9.68%	276.	363	$1.32^{+0.08}_{-0.07}$	$+4.7\sigma$	1.50	276°	−17°	7.89%	229.	264	$1.15^{+0.08}_{-0.07}$	$+2.2\sigma$	1.34
40 EeV	1533	162°	−6°	9.56%	140.	208	$1.49^{+0.11}_{-0.11}$	$+5.1\sigma$	1.77	345°	−7°	1.00%	15.2	26	$1.71^{+0.36}_{-0.32}$	$+2.5\sigma$	2.68
50 EeV	713	161°	−7°	9.56%	64.4	103	$1.60^{+0.18}_{-0.16}$	$+4.2\sigma$	2.05	322°	−22°	3.69%	25.9	39	$1.51^{+0.26}_{-0.23}$	$+2.4\sigma$	2.20
63 EeV	295	163°	−3°	9.56%	26.3	46	$1.75^{+0.30}_{-0.26}$	$+3.3\sigma$	2.54	223°	+26°	9.56%	26.7	42	$1.57^{+0.28}_{-0.25}$	$+2.6\sigma$	2.31

("2nd maximum" among windows not overlapping with the 1st maximum one, i.e., distance between centers $> 2\Psi$)

- Most significant excess consistently very close to Centaurus A for all E_{min}
- Excess growing with E_{min}, but not its significance due to decreasing statistics
  - 5.2σ pre-trial $\mapsto$ 3.1σ post-trial
- Nothing anywhere else significant at $> 2.7\sigma$ pre-trial, regardless of E_{min}

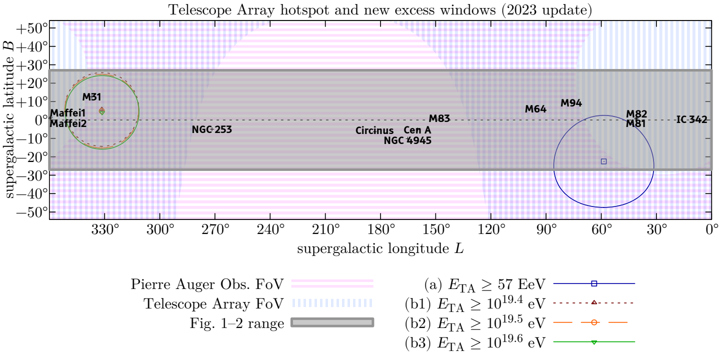
Upper limits

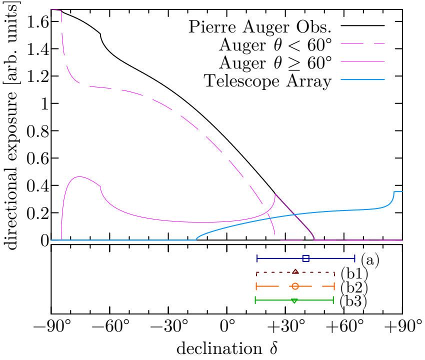


- Stringent upper limits to flux excesses, except with highest energy thresholds and near the edge of our field of view

Comparison with Telescope Array results

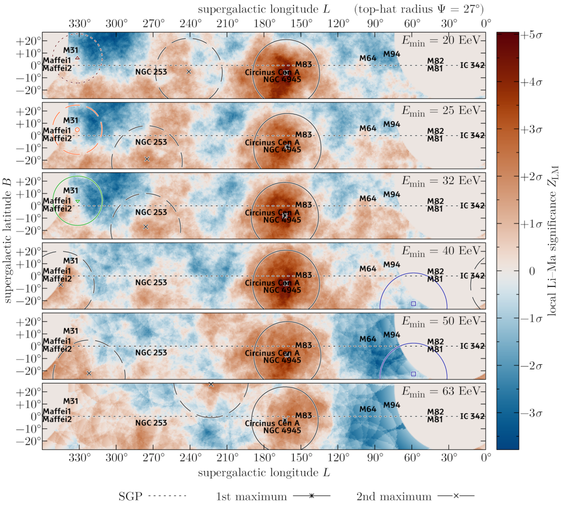
- The centers (though not all) of the regions from which TA reported excesses in TA ICRC 2023 are inside the part of the sky we studied.





- Do we see anything in particular there?

Our results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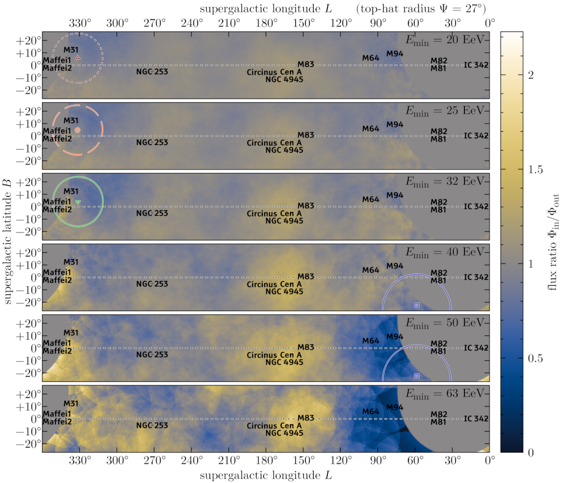
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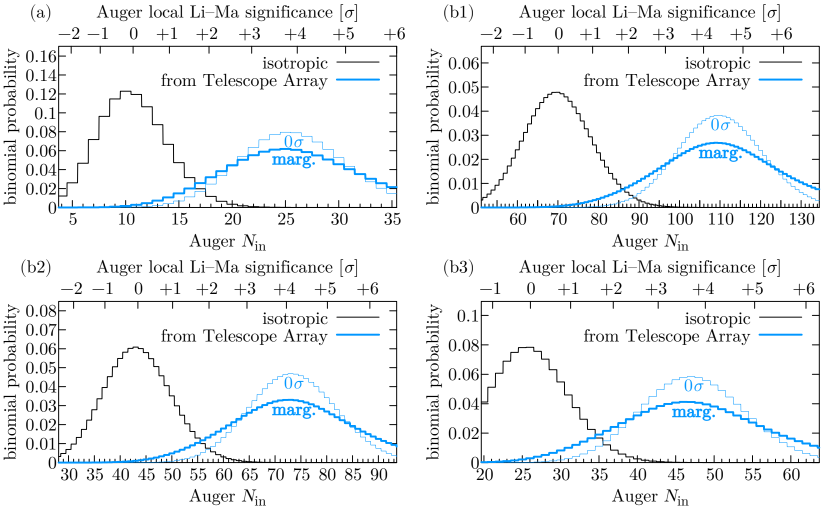
What if we used the same E_{min} and Ψ as TA?

$E_{\mathrm{TA}} \mapsto E_{\mathrm{Auger}}$ based on the Auger+TA ICRC 2023 energy scale conversion



What if we used the same $E_{\min}$ and Ψ as TA?

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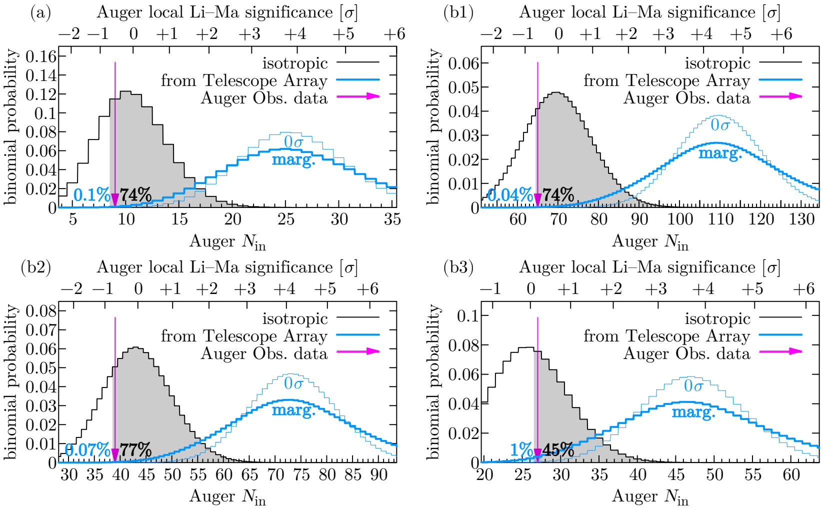
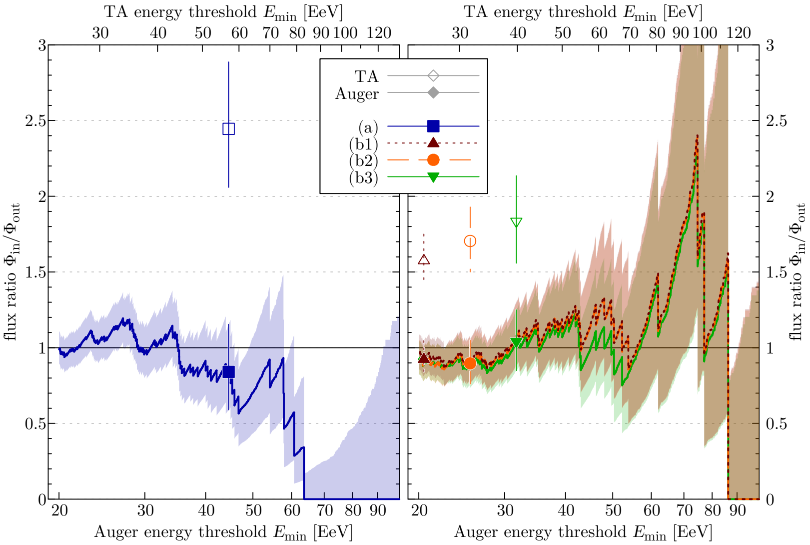


	Telescope Array									Pierre Auger Observatory							
	$E_{\rm min}$	$N_{\rm tot}$	$\frac{\mathcal{E}_{\rm in}}{\mathcal{E}_{\rm tot}}$	$N_{\rm bg}$	$N_{\rm in}$	$\frac{\Phi_{\rm in}}{\Phi_{\rm out}}$	$Z_{\rm LM}$	99% L.L.	post-trial	$E_{\rm min}$	$N_{\rm tot}$	$\frac{\mathcal{E}_{\rm in}}{\mathcal{E}_{\rm tot}}$	$N_{\rm bg}$	$N_{\rm in}$	$\frac{\Phi_{\rm in}}{\Phi_{\rm out}}$	$Z_{\rm LM}$	99% U.L.
(a)	57 EeV	216	9.47%	18.0	44	$2.44^{+0.44}_{-0.39}$	$+4.8\sigma$	1.60	2.8σ	44.6 EeV	1074	1.00%	10.7	9	$0.84^{+0.31}_{-0.25}$	-0.5σ	1.76
(b1)	$10^{19.4}$ eV	1125	5.88%	64.0	101	$1.58^{+0.17}_{-0.16}$	$+4.1\sigma$	1.22	3.3σ	20.5 EeV	8374	0.84%	70.1	65	$0.93^{+0.12}_{-0.11}$	-0.6σ	1.23
(b2)	$10^{19.5}$ eV	728	5.87%	41.1	70	$1.70^{+0.22}_{-0.20}$	$+4.0\sigma$	1.25	3.2σ	25.5 EeV	5156	0.84%	43.5	39	$0.90^{+0.15}_{-0.14}$	-0.7σ	1.29
(b3)	$10^{19.6}$ eV	441	5.84%	24.6	45	$1.83^{+0.31}_{-0.27}$	$+3.6\sigma$	1.23	3.0σ	31.7 EeV	2990	0.87%	26.0	27	$1.04^{+0.21}_{-0.19}$	$+0.2\sigma$	1.61

- In spite of comparable integrated exposures (similar $N_{\rm bg}$) within those windows, our data **do not confirm the Telescope Array reported excesses** and are in **good agreement with isotropic expectations**.
  - On the other hand, in each window there are possible values of $\Phi_{\rm in}/\Phi_{\rm out}$ that neither dataset can exclude at the 99% C.L. (e.g., 1.68 in (a), 1.225 in (b1), ...).

- **Caveat:** This implicitly assume a flux excess uniform within the window. An excess more concentrated in the north than in the south of the window would be underestimated using Auger data.
  - But the TA reported window position was the result of a scan – wouldn't that have resulted in a more northern maximum-significance window position?

Might this be due to a wrong energy threshold conversion?



No.

Conclusions

- Previously reported indication for an excess near Cen A tentatively confirmed (3.1σ post-trial), extending down to at least 20 EeV in the same position
  - Approximately constant rigidity (i.e., $Z \propto E$) of excess particles?
- No strong indication for excesses anywhere else along the supergalactic plane
- In particular, no confirmation of the indications reported by TA
- More statistics needed to be sure what's going on

  → Stay tuned for data from AugerPrime and TA×4 (and GRAND, POEMMA, ..., GCOS)!
- If any excesses are confirmed, does their mass composition differ from the background?

  → Stay tuned for event-by-event mass information!

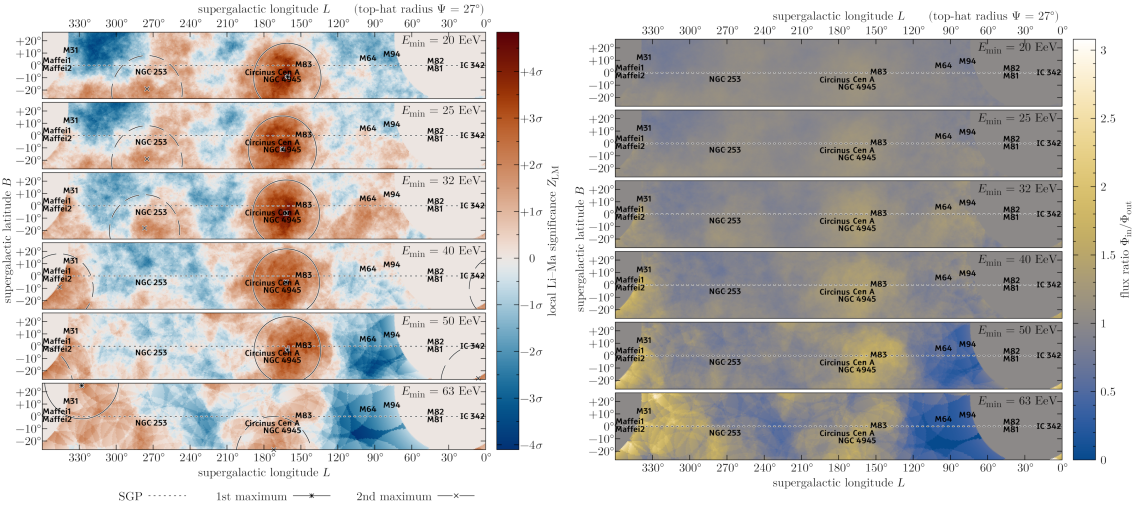

That's all Folks!

Back-up slides

5 Effects of possible systematics affecting inclined and vertical events differently

- On the TA comparison

After reducing energies of vertical events by 20%



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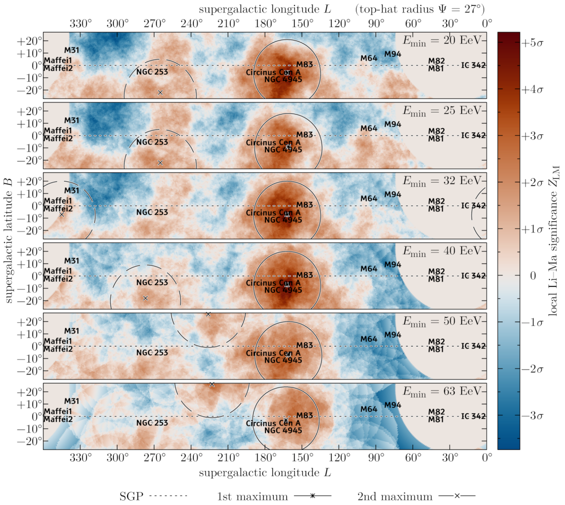
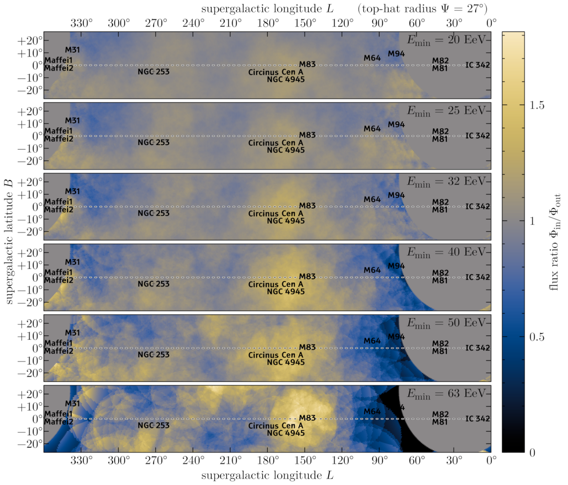
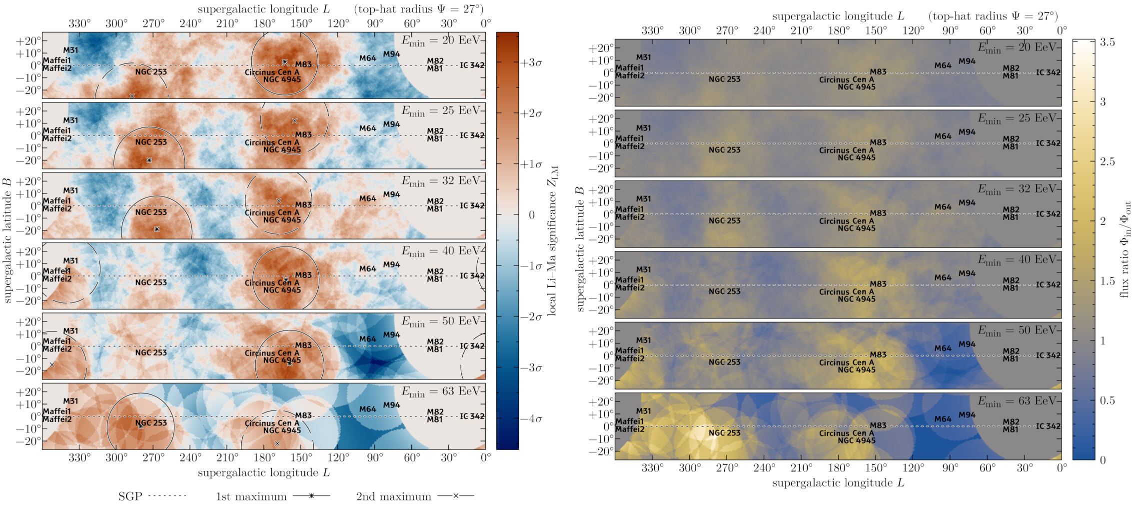




Using inclined events only



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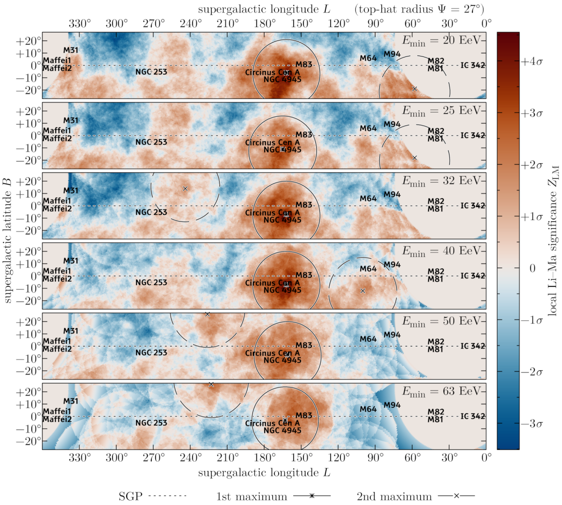

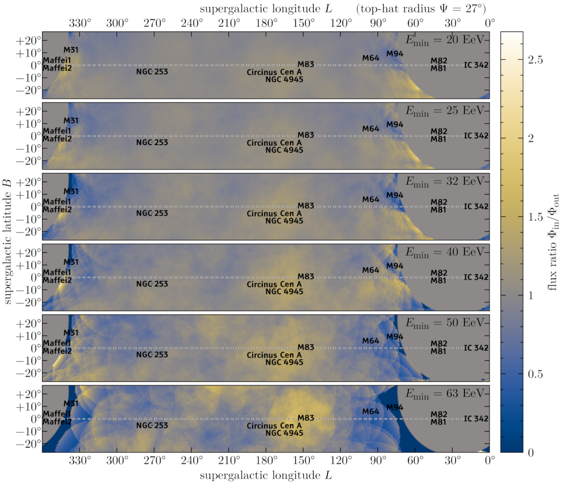

Back-up slides

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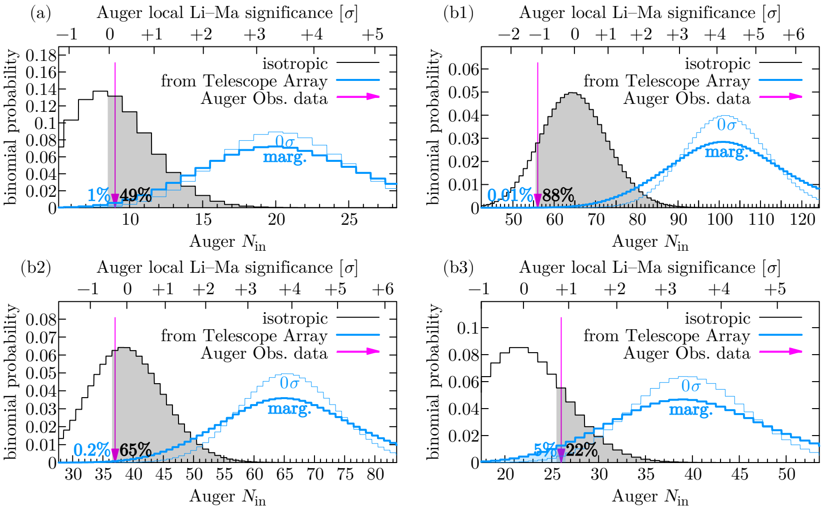
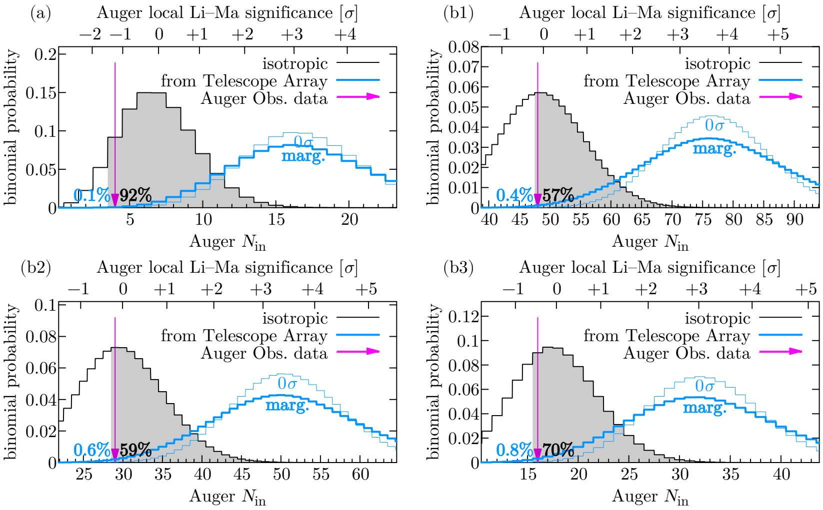


After reducing energies of inclined events by 20%



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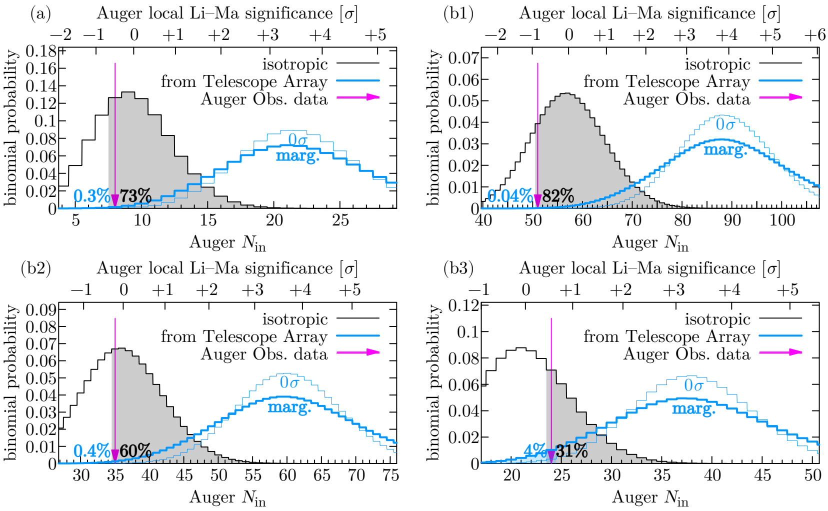

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