Status and perspective for the search for anisotropies in the UHECR sky

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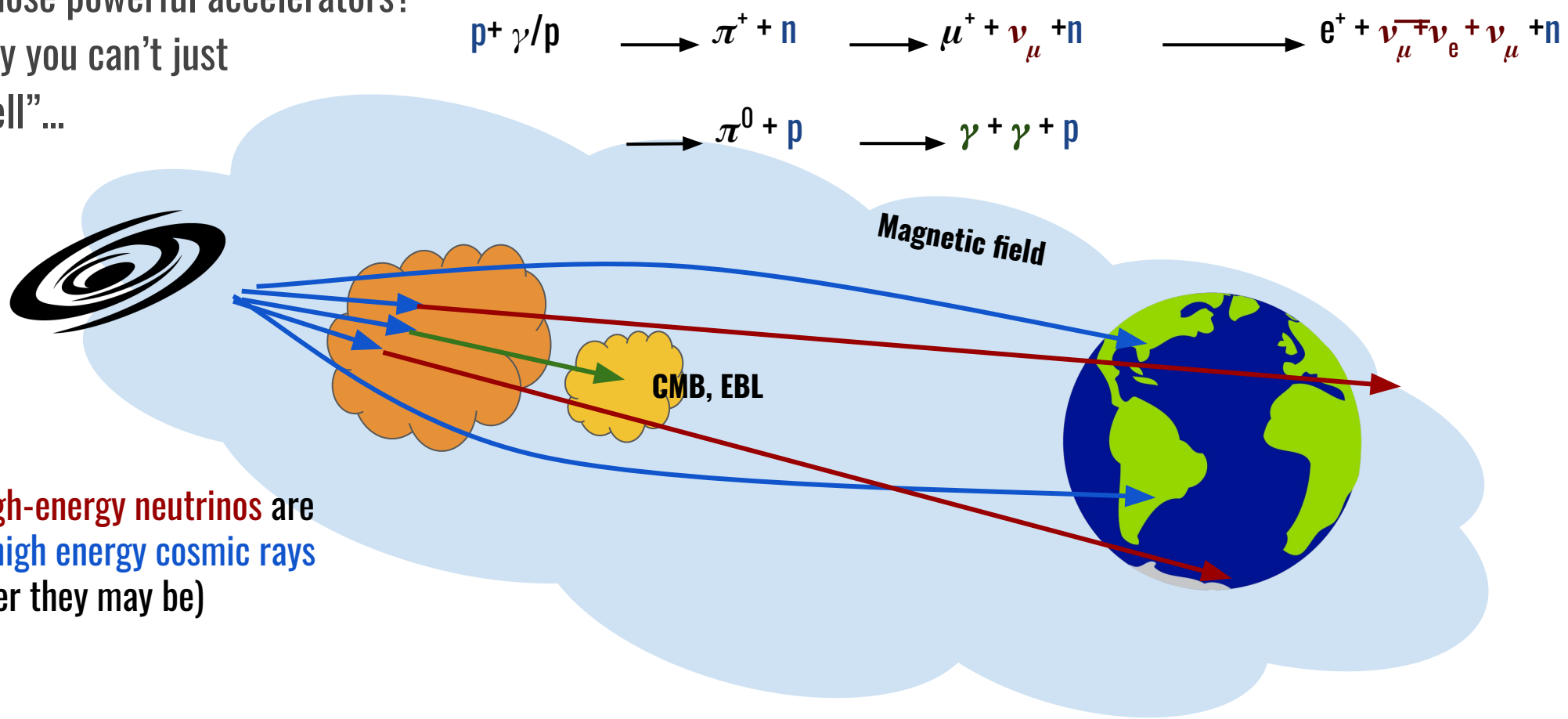
Messengers

UHECRs are the most energetic particle we know of (>100 EeV)

- Understanding where do they come from is of key importance for understanding the astrophysics of these objects
- Where are those powerful accelerators?
- Unfortunately you can't just "point and tell"...

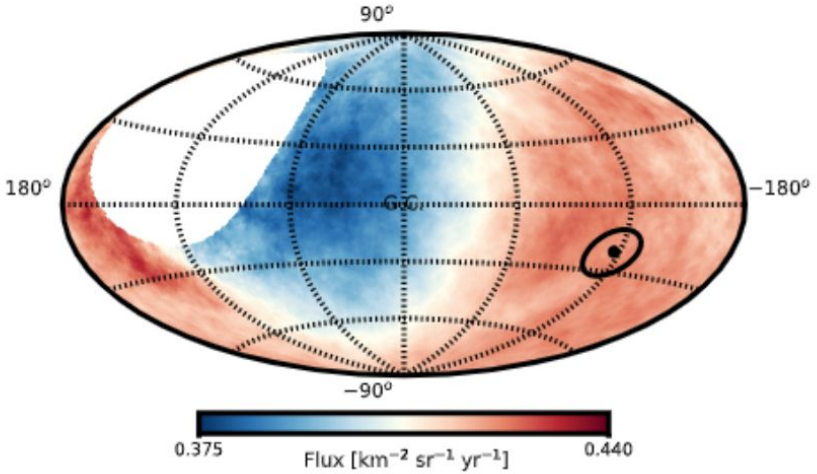


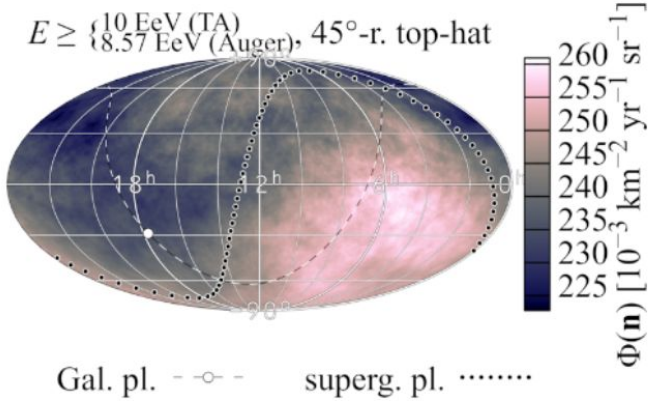
It is expected that high-energy neutrinos are produced near ultra-high energy cosmic rays accelerators (whatever they may be)

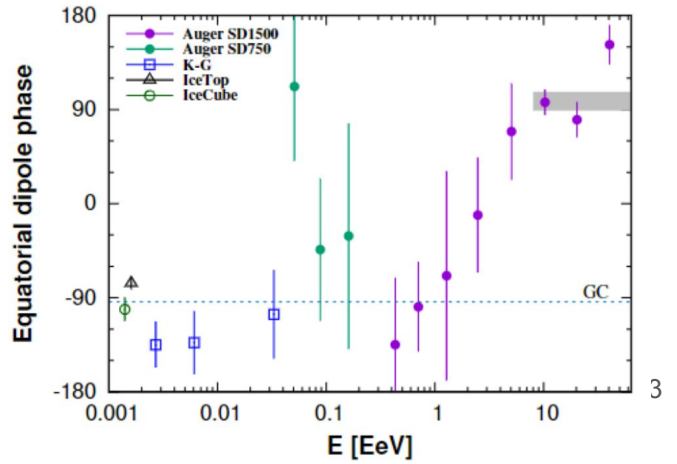
What we know: large scale anisotropy

Anisotropies are the key to getting directional information on where the sources are

- So far, only large-scale anisotropies (a dipole) have been observed with a level of confidence higher than 5σ for the events with energy larger than 8 EeV.
- The dipole points away from the Galactic Center -> evidence of extragalactic origin
- This result by Auger was confirmed with an all-sky study joint with TA -> All-sky coverage allows us to derive dipole amplitude without assumptions on the higher multipoles
- Phase shift in the observed dipole at lower energy suggests transition between Galactic and extra-galactic sources happens between ~1 and ~8 EeV (though these bins don't reach statistical significance of 5σ)



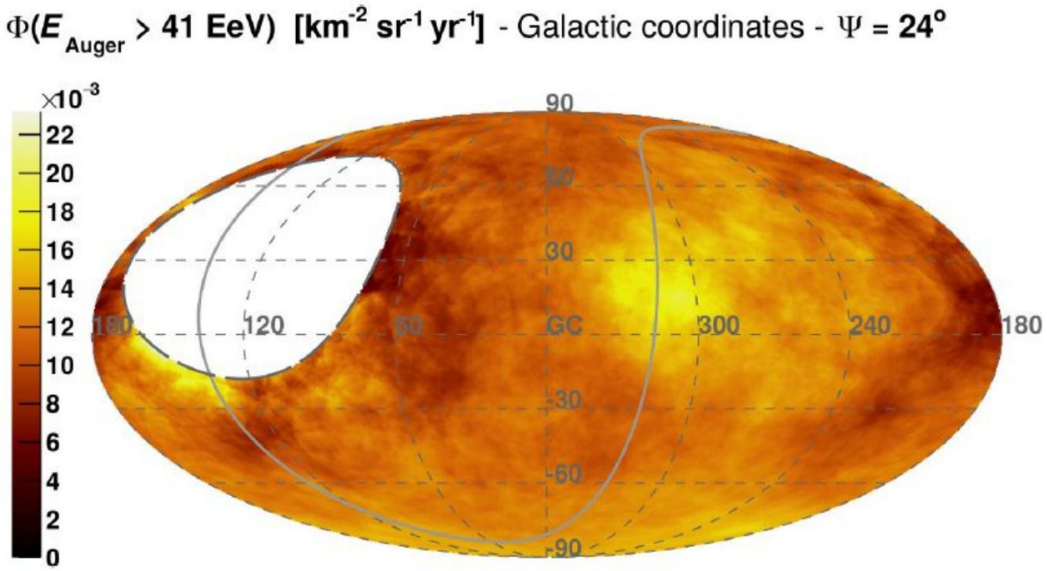


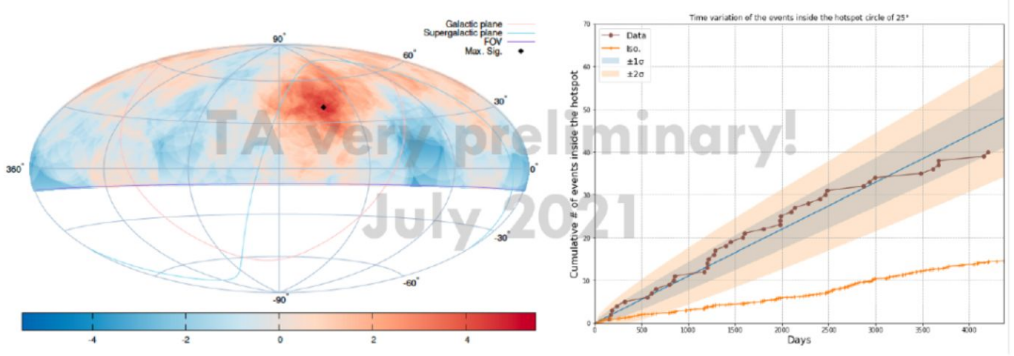


Small/intermediate-scale anisotropy

At high energies, deflections from magnetic fields may be low enough to observe small/intermediate scale anisotropy

- No excess at 5σ observed, but two "hot spots" are found, one in the northern and one in the southern hemisphere
- The southern excess points in the direction of Centaurus, where the closest AGN, Centaurus A, is but also two of the most prominent starburst galaxies.
- Search for correlation with catalogs of specific source candidates gives mildly higher significance when using starburst galaxies (thanks to an object close to the Galactic south pole)
- No multiplets or very small-scale excesses (that could arise in case of Galactic neutron sources) found





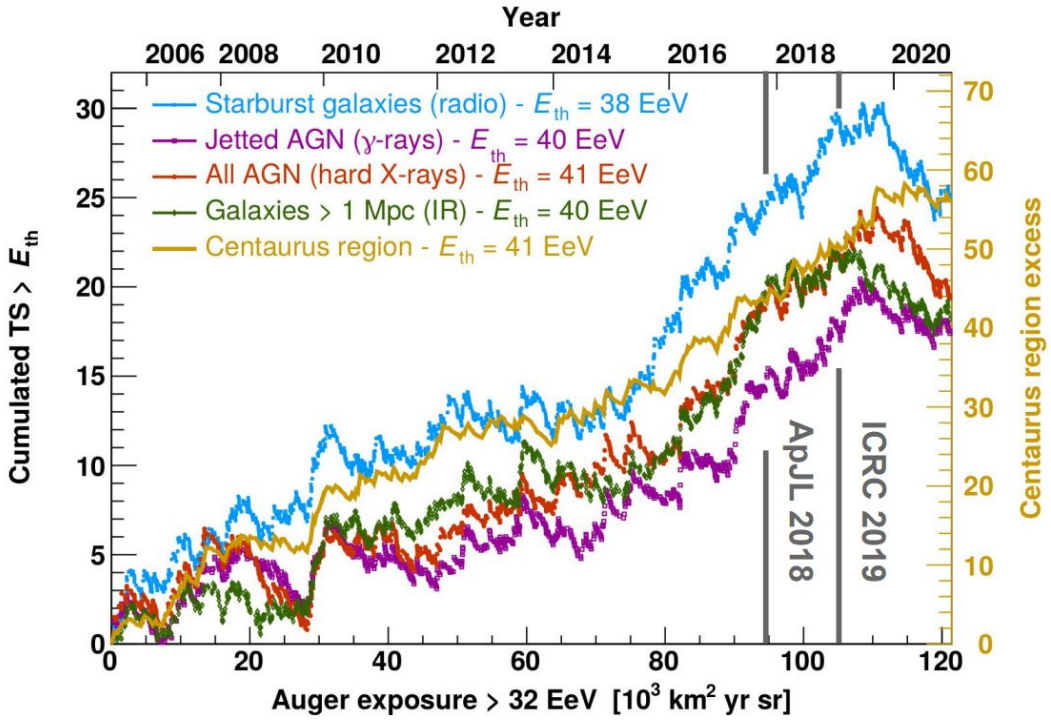
Towards the future: the next decade

Increasing statistics will tell us if the indication of small scale anisotropy is real or a statistical fluctuation

- 5σ might be reached by Auger for the centaurus region by the end of 2026
- TAx4 will greatly increase exposure in the northern hemisphere

Information on the mass of each cosmic ray event will make it possible to select only "light" events.

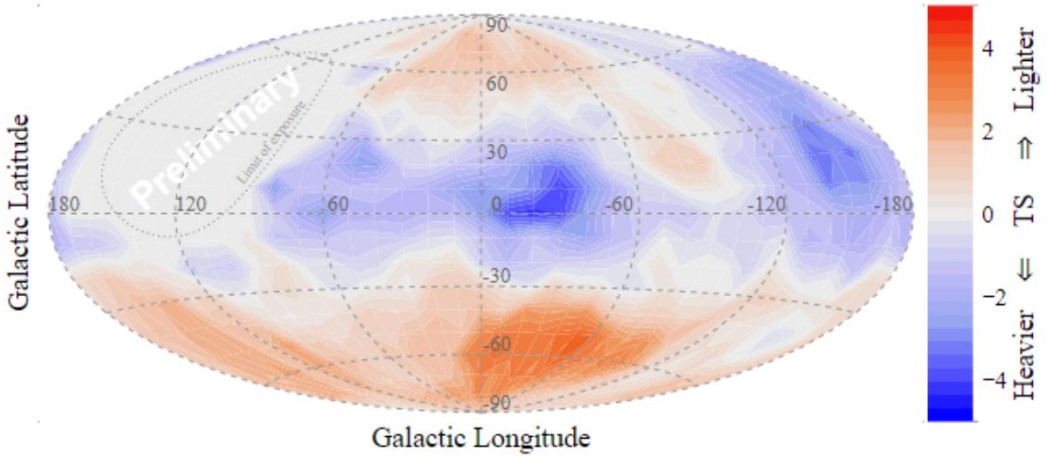
- Auger is developing techniques (e.g DNN, Universality...) to extract mass information from SD events
- The Auger Prime upgrade will increase this capability, potentially being able to calibrate techniques to be applied to the previous 18-years dataset



Towards the future: the next decade

Accessing mass information could show different anisotropies in different regions of the sky.

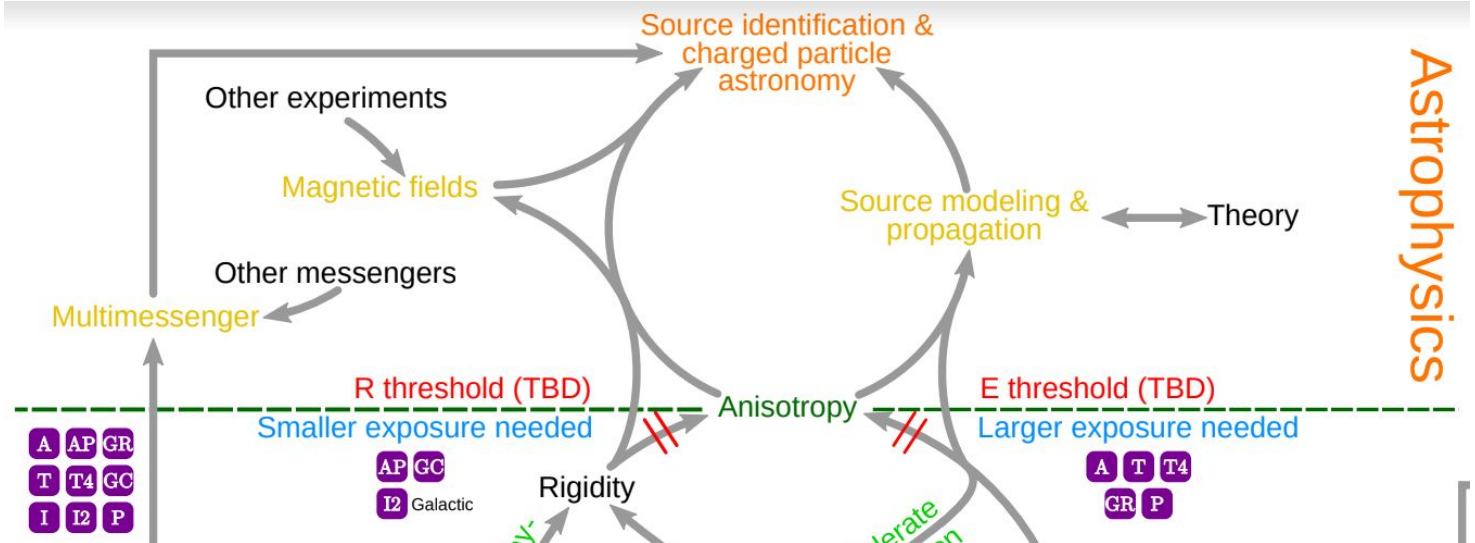
- Auger sees a hint of a difference between the composition along the galactic plane and outside (with FD data, above 5 EeV)
- Multiplets tracing magnetic deflections for light nuclei might be found
- Evidence of Peters' cycle structure (maximum energy achievable at the accelerator depending on the rigidity) might be found
- Combined fit bringing together mass information, arrival direction and spectrum could be even more refined and give insight on the sources' properties



Towards the future: what after?

Based mostly on what the "light" fraction of events at the highest energy is, we can draw a couple of scenarios:

- If a sensible light fraction is found, we can foresee beginning the "charged particle astronomy era"
- If not, crucial information on the sources can still be obtained by a thorough analysis of all the pieces of the puzzle, in particular as our knowledge of magnetic fields improves (possibly with the help of feedbacks from anisotropy studies)
- In any case, if future observatories can grant whole-sky coverage, this will greatly improve our ability of measuring large scale anisotropies



Thanks for the attention!

Plots from the current draft

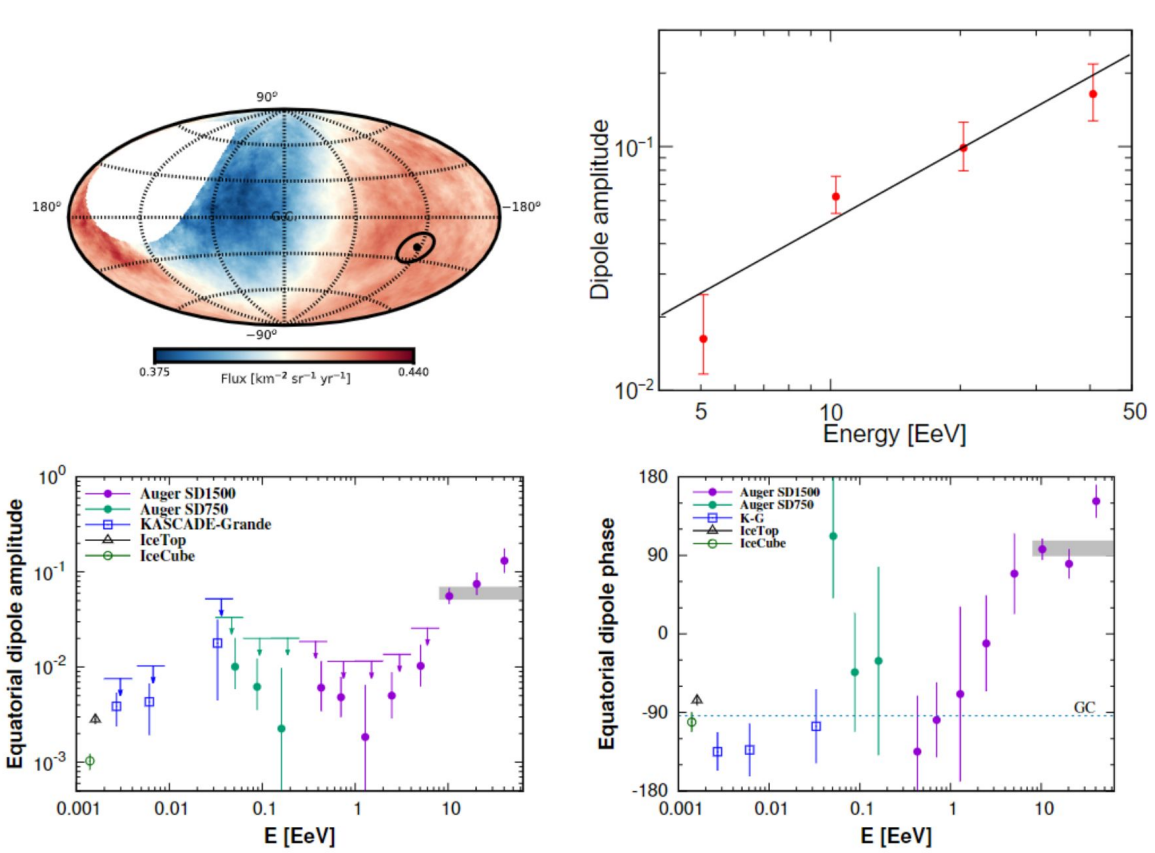


Figure 1: Upper left panel: map showing the cosmic-ray flux detected by the Pierre Auger Observatory above 8 EeV, in Galactic coordinates, smoothed with a 45° top-hat function (the Galactic Center, GC, is at the origin). The dot indicates the measured dipole direction and the contour denotes the 68% confidence level region, from [3]. Upper right panel: amplitude of the 3D dipole determined in four energy bins above 4 EeV with the Auger data set, from [3]. Lower panels: reconstructed equatorial dipole amplitude (left) and phase (right), published in [5] by the Pierre Auger Collaboration. Results from other experiments are shown for comparison.

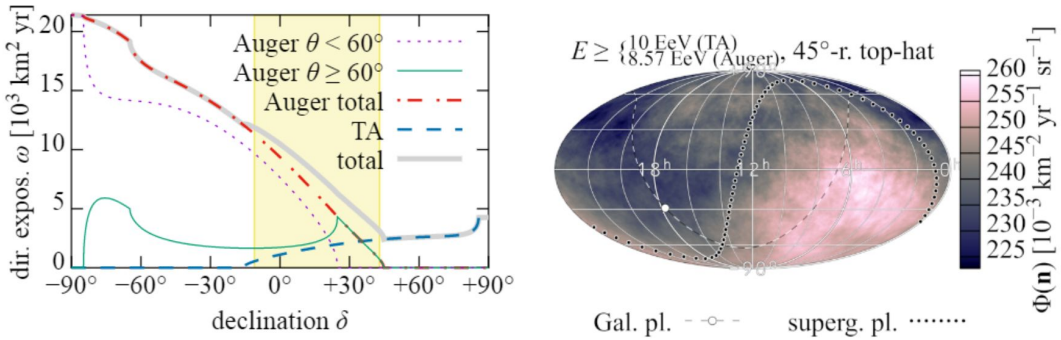


Figure 2: Left panel: Auger and TA effective exposure, the yellow band shows the common declination band used for the cross-calibration of energy scales. Right panel: map showing the cosmic-ray flux detected by the Pierre Auger Observatory and Telescope Array above 8.57 EeV and 10 EeV, respectively, in equatorial coordinates, smoothed with a 45° top-hat function. From [7].

Plots from the current draft

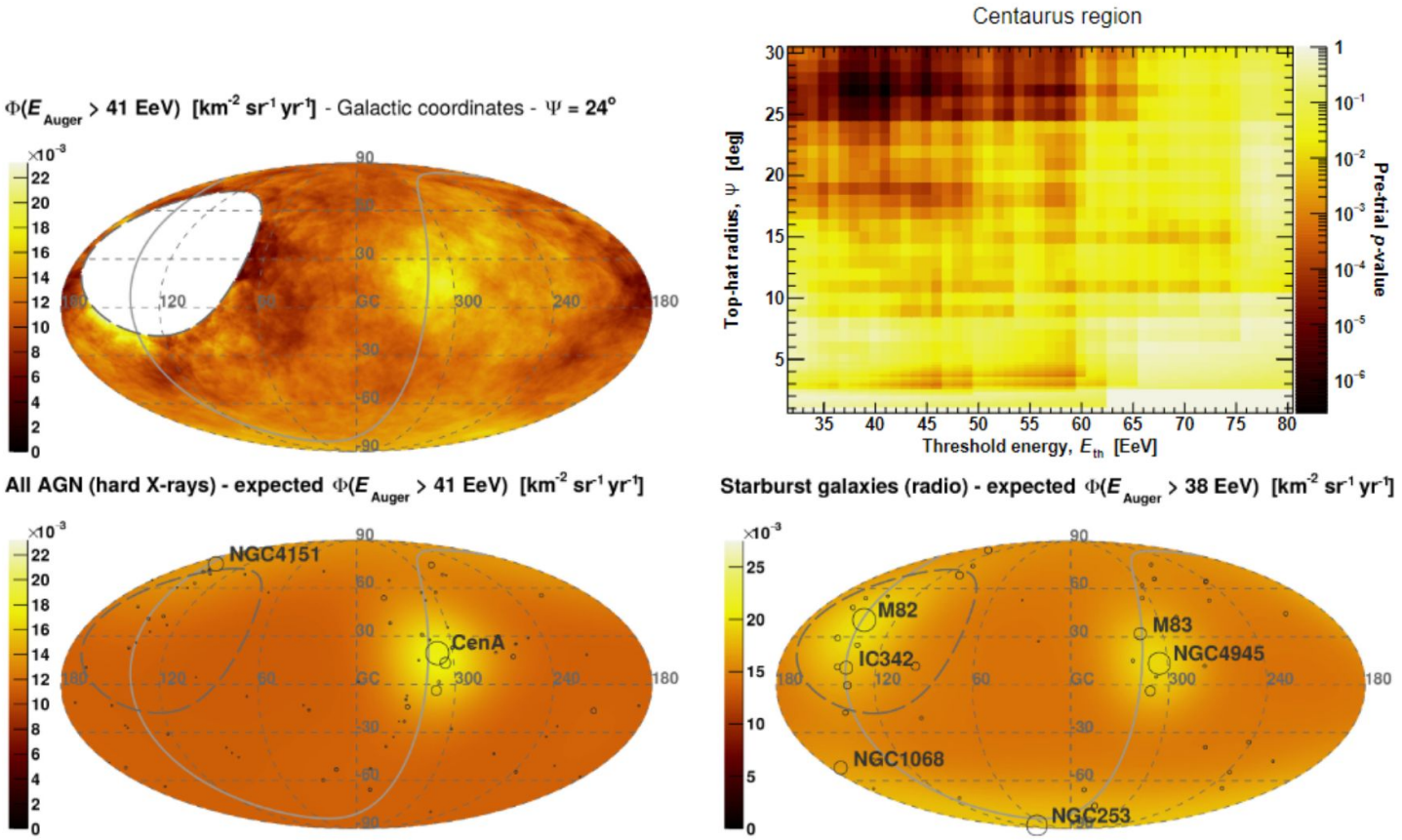


Figure 3: Upper left panel: map showing the CR flux detected by the Pierre Auger Observatory above 41 EeV, in Galactic coordinates, smoothed with a 24° top-hat function. Upper right panel: Pre-trial p-value as a function of the energy threshold and top-hat radius for an overdensity search centered in the Centaurus region. Lower panels: best-fit models of the All AGNs (left) and starburst galaxies (right) catalogs used in Galactic coordinates. From [11].

Plots from the current draft

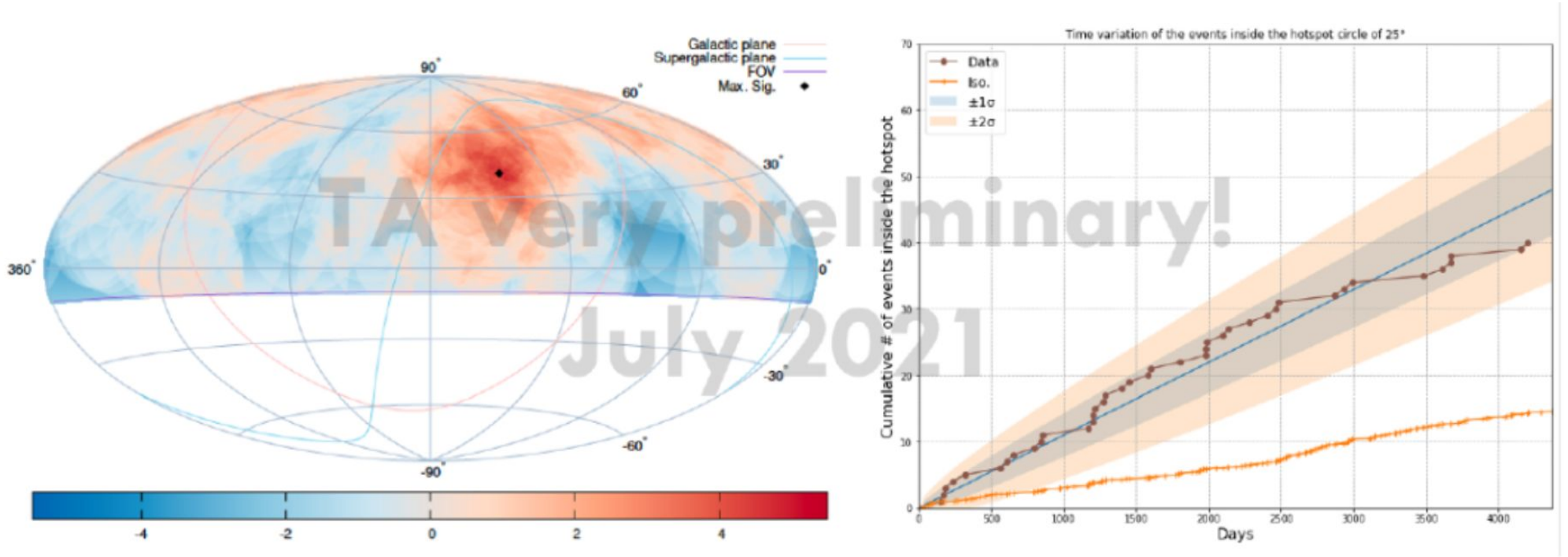


Figure 4: Left panel: The sky map of the Li-Ma significance of the cosmic ray excess in the circle of 25° radius. Black dot shows the position of the most significant excess (Hammer projection, Equatorial coordinates). Right panel: brown dots show evolution of the cumulative number of observed events inside the hot spot region with time. Orange crosses indicate that of isotropic background events. The bands show $\pm 1\sigma$ and $\pm 2\sigma$ deviations from a linear increase rate. From [43]. WE WERE ASKED TO REMOVE "VERY PRELIMINARY!"

Plots from the current draft

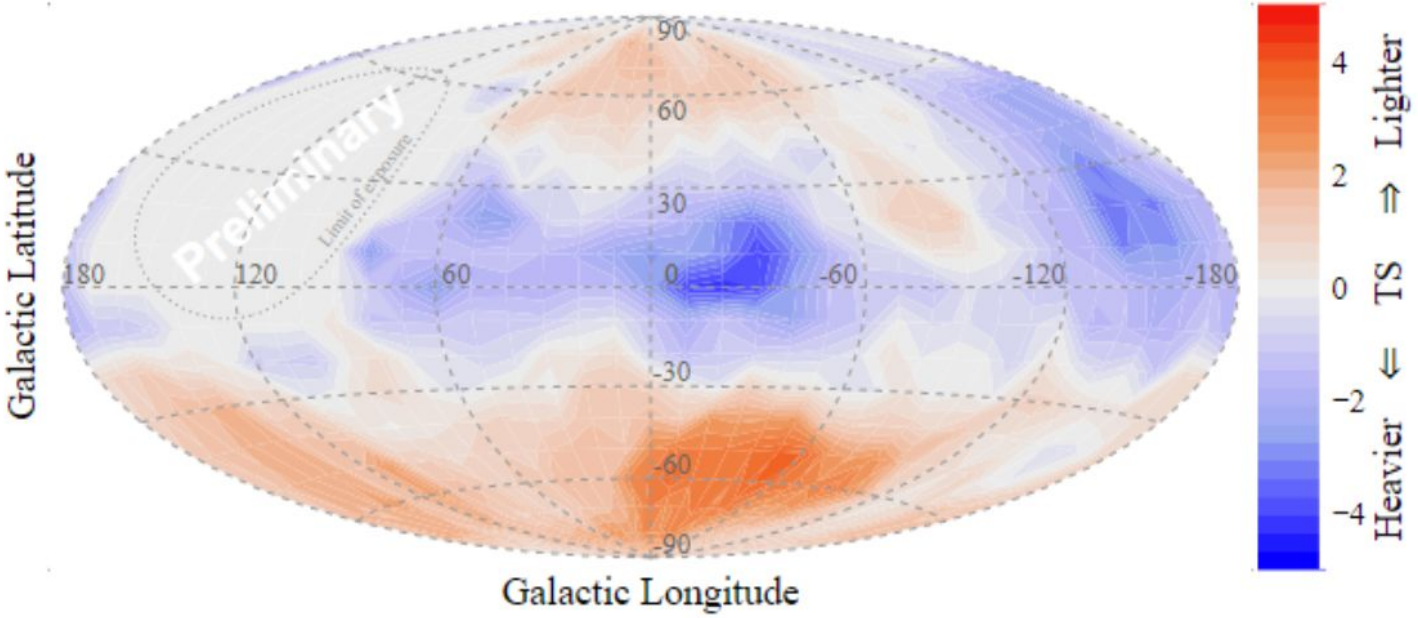


Figure 5: Map showing the cosmic-ray composition detected by the Pierre Auger Observatory above $10^{18.7}$ eV with the fluorescence detector, in Galactic coordinates. From [31].