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

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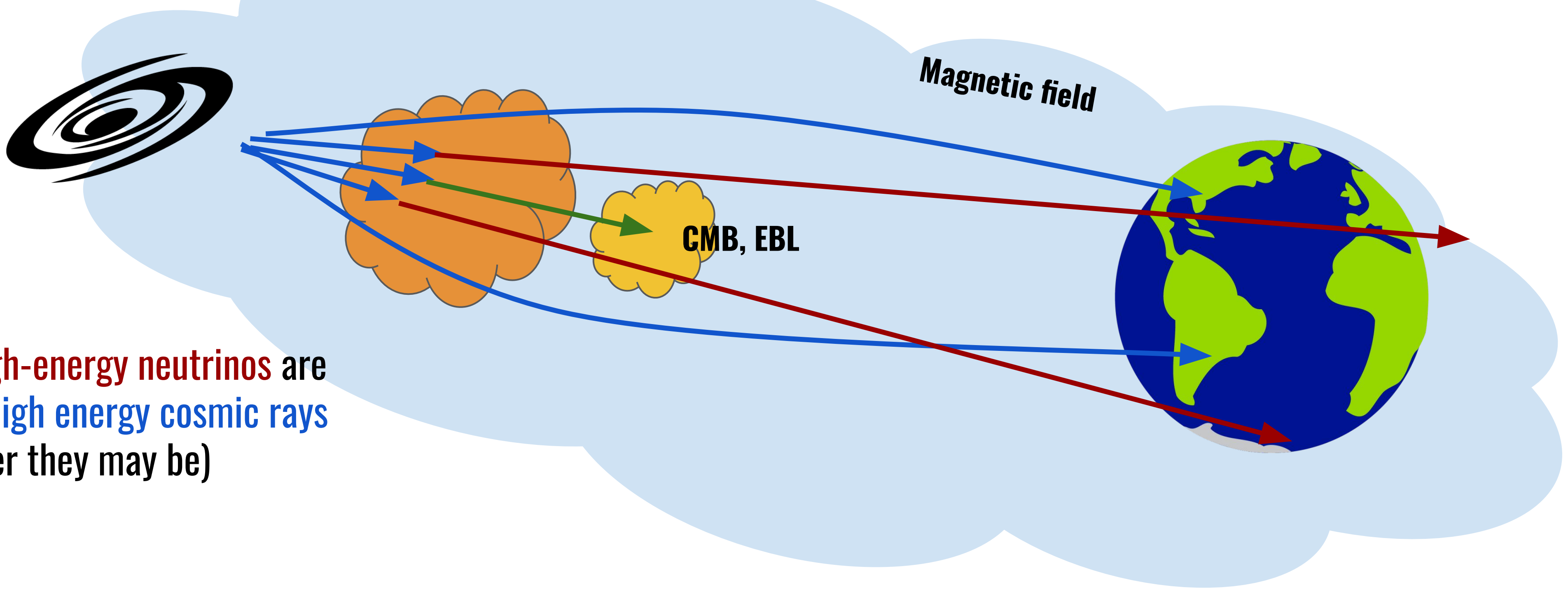
Messengers

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

- Understanding where 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"...

$$p^+ \gamma/p \longrightarrow \pi^+ + n \longrightarrow \mu^+ + \nu_\mu + n \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu + n$$

$$\longrightarrow \pi^0 + p \longrightarrow \gamma + \gamma + p$$

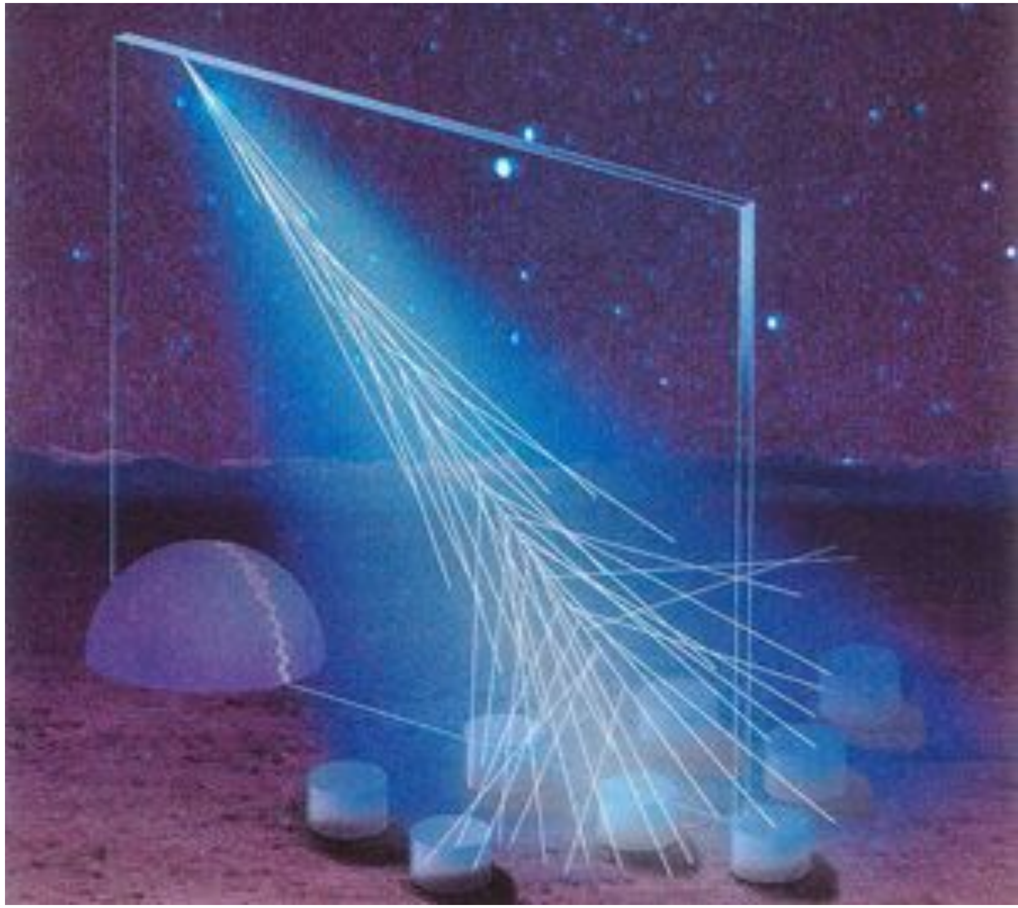


It is expected that high-energy neutrinos are produced near ultra-high energy cosmic rays accelerators (whatever they may be)

Detecting UHECRs

We detect UHECRs by looking at the extensive air showers of particles they produce in the atmosphere.

- EAS can be measured by sampling the particles that arrive at ground with an array of particle detectors, so-called "**surface detector**" -> **Study the lateral profile**
- Alternatively, one can look at the fluorescence light induced in the atmosphere via dedicated telescope (**Fluorescence Detector**) -> **Study the longitudinal profile**
- Additional methods in testing phase, e.g. study **radio emission**
- By studying the characteristics of the shower we can reconstruct the key informations about the primary:
  - **Arrival direction**
    (from timing, better with SD and best with Hybrid detection)
  - **Energy**
    (best with FD which can measure the whole energy deposit in the atmosphere)
  - **Mass**
    (the tougher one, which is done best with FD looking at the depth of the maximum of the shower, or with SD by looking at the muon content)



Detecting UHECRs

There are two main UHECR observatories currently in operation:

The Pierre Auger Observatory

- Operating since 2004
- 3000 km^2 area
- 27 FD telescopes in 4 sites
- 1660 water cherenkov surface detector stations

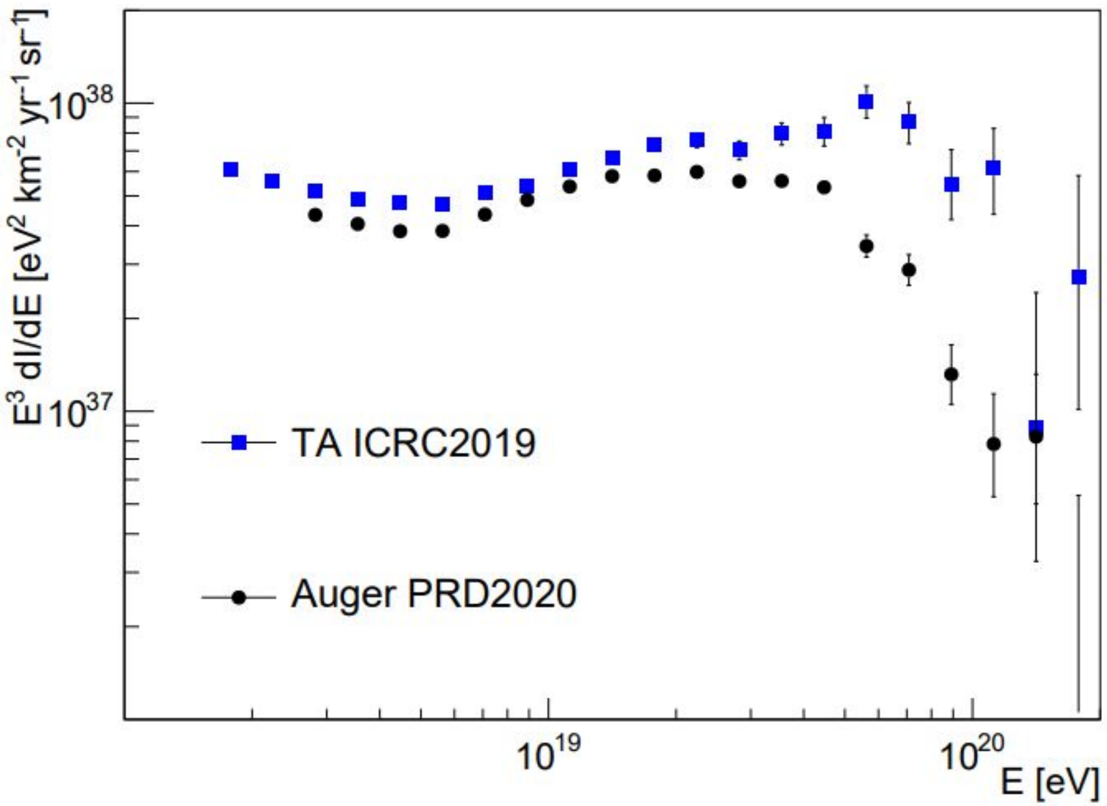
The Telescope Array

- Operating since 2008
- 700 km^2 area
- Three FD sites
- 507 scintillators as surface detector stations

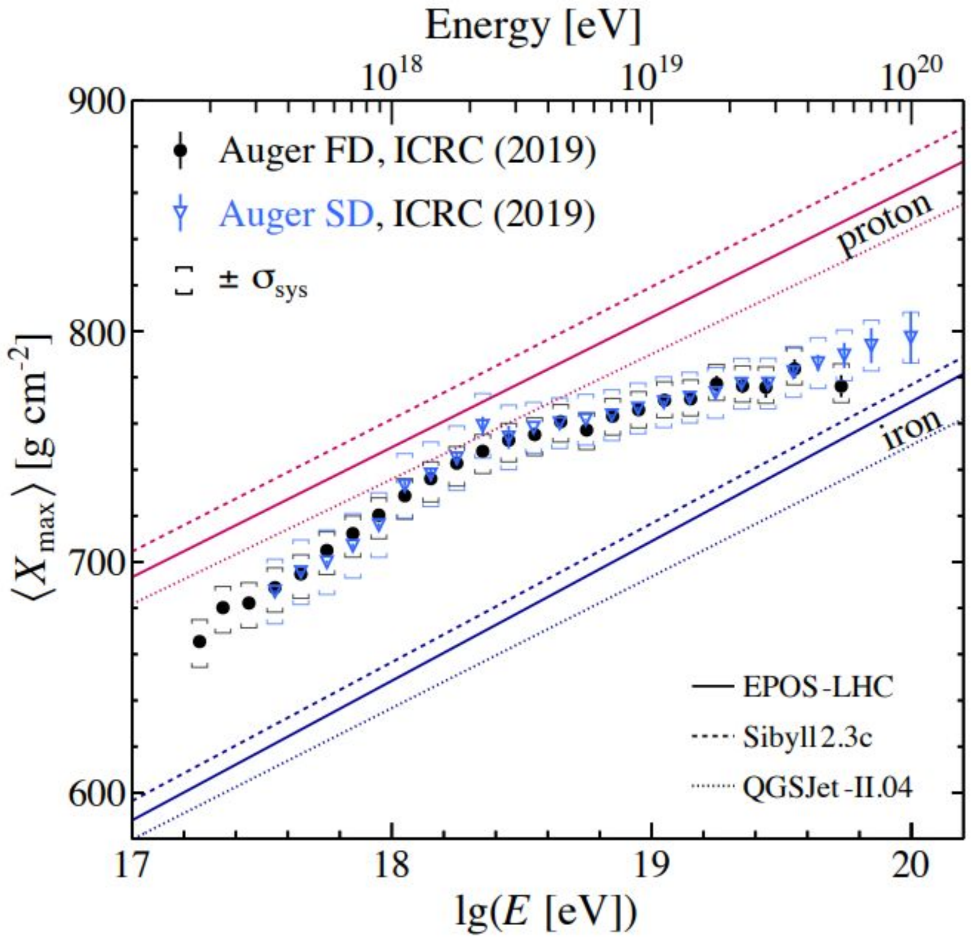
Both are Hybrid detectors, using Fluorescence Detectors, which operate only ~10% of the time to calibrate Surface Detectors, which have ~100% duty cycle

UHECR spectrum and composition

Newly observed “instep” feature at 20-40 EeV. Disagreement with TA at the highest energies
Obtaining reliable absolute mass estimates is difficult



Y. Tsunesada for the TA and Auger Collaborations PoS(ICRC2021)337



(Phys. Rev. D90 (2014), 122005 & 122005, updated ICRC 2019)
(Phys. Rev. D96 (2017), 122003)

UHECR Anisotropy

Angular Resolution

180° 120° 60° 1°

Large scale **Intermediate scale** **Small scale**

Identify the distribution of the main sources, put lower limit to their anisotropy
(An isotropic flux of cosmic rays remains isotropic after propagating through a magnetic field)

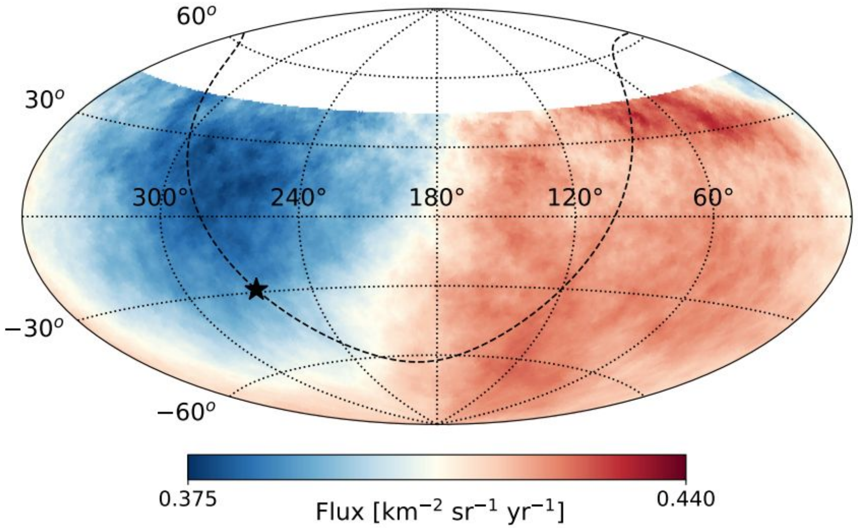
Pinpoint different classes of sources, single dominant emitters with the most energetic charged particles

Neutral particles creating excesses of the size of the angular resolution

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)



R. Menez for the Auger Coll.
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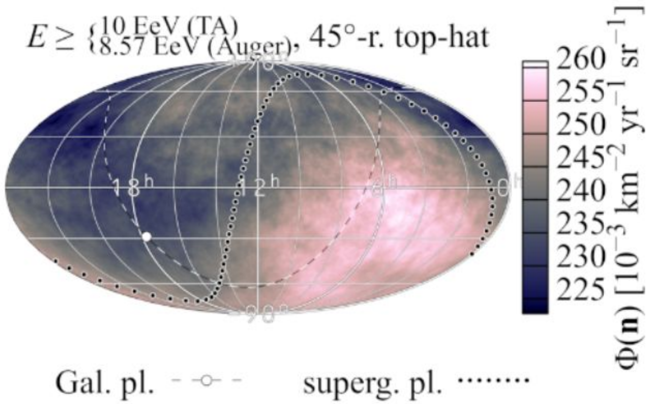
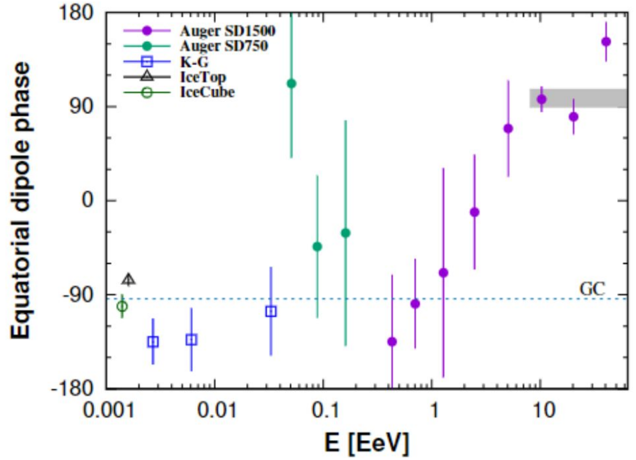
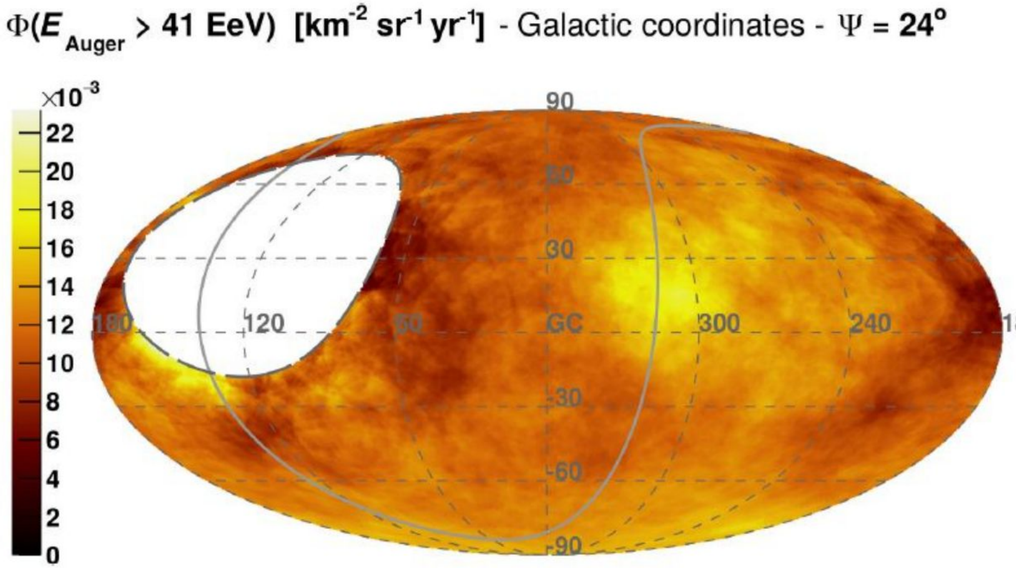


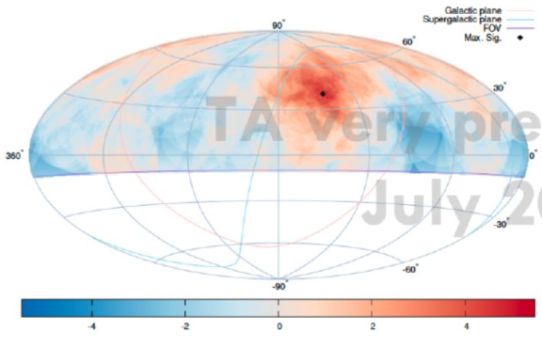


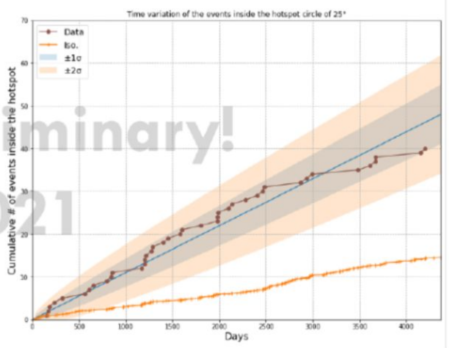
intermediate-scale anisotropy

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)
- Interesting possible connection with the Perseus-Pisces supercluster reported recently by TA
- Multiplets searched but never found so far





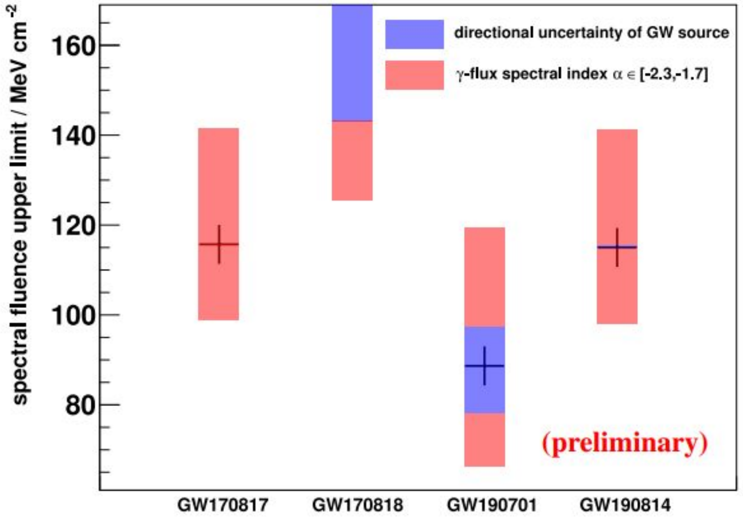


J. Biteau for the Auger Collaboration PoS(ICRC2021)307

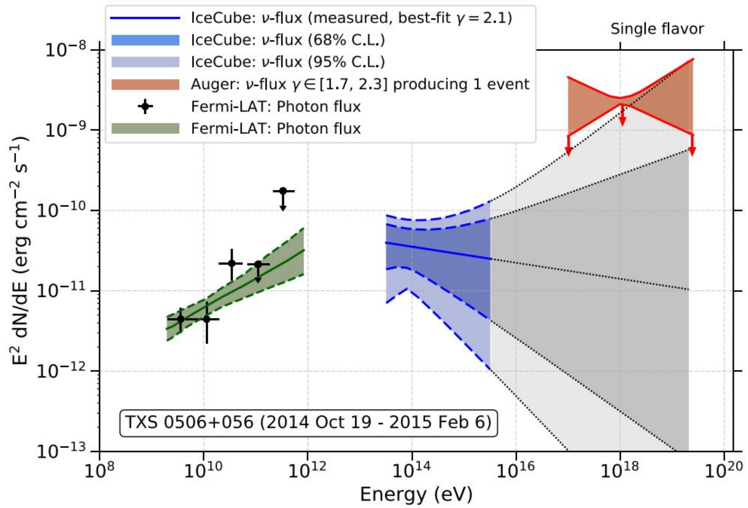
Small-scale anisotropy

Neutral particles are not deflected by magnetic fields and thus should give rise to excesses of the order of the angular resolution. Also, no time delay!

- Neutrons are indistinguishable from protons. They can travel up to a distance of 9.2 kpc x E(EeV) i.e. only from Galactic sources. No neutron-like excesses in the sky have been found neither by looking at candidate sources (e.g. galactic center, compact objects) nor with a blind search. Latest results published with Auger data up to 2012-2013, updates are going to be released soon.
- Photons and neutrinos have been searched based on the different characteristics of the EAS they produce. No UHE photon or ν have been observed so far. Targeted searches (including with GW events) have been attempted but no excess was found.



P. Ruhel for the Auger Coll. PoS(ICRC2021)973



The Astrophysical Journal, 902:105 (8pp), 2020 October 20

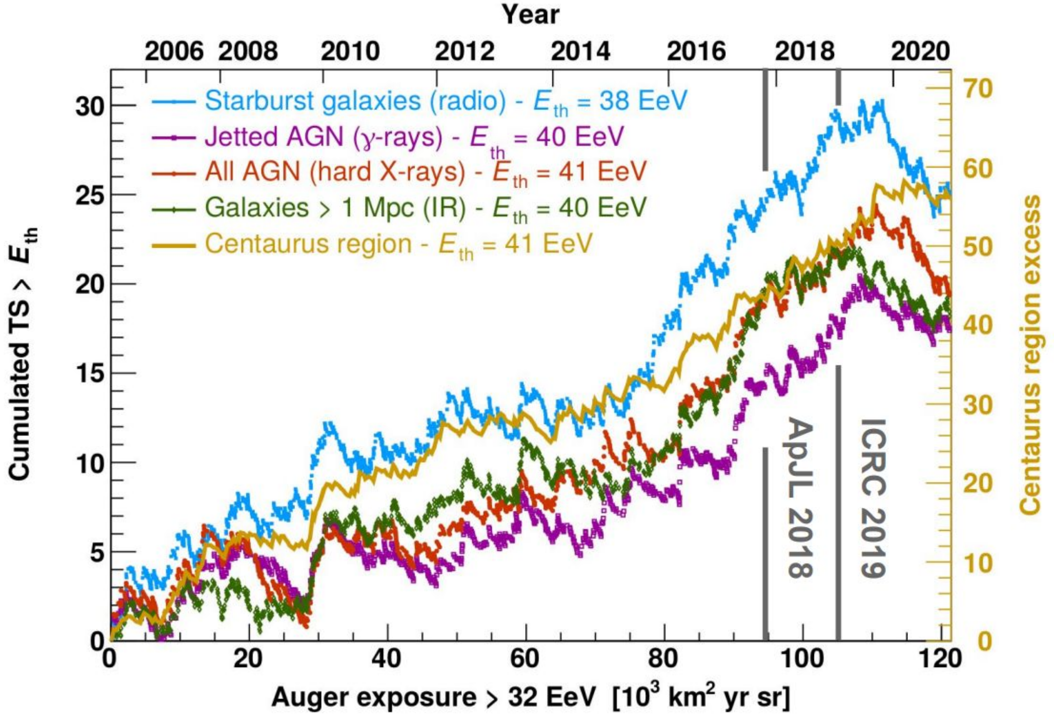
Towards the future: the next decade

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.

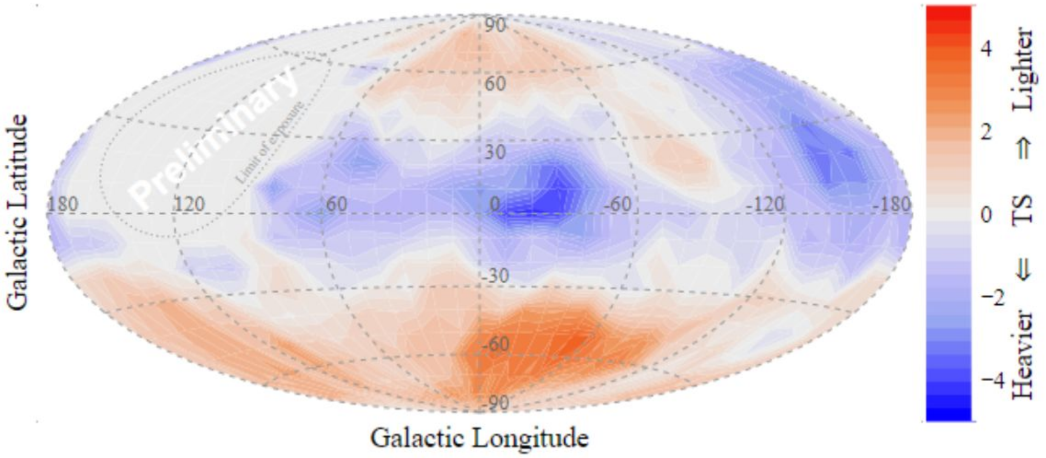
- Auger is developing techniques (e.g DNN, Universality…) to extract mass information from SD events
- The Auger Prime upgrade will increase this capability, potentially being able to calibrate techniques to be applied to the previous 18-years dataset



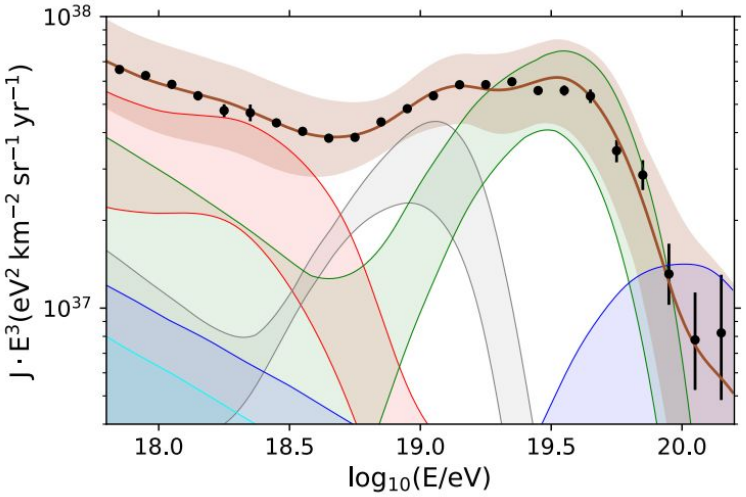
Towards the future: the next decade

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



E. Mayotte for the Auger Coll. PoS(ICRC2021)321



E. Guido and T. Bister for the Auger Coll. PoS(ICRC2021)311 PoS(ICRC2021)368

Towards the future: what after?

Based mostly on what the “light” fraction of events at the highest energy is, we can draw few scenarios:

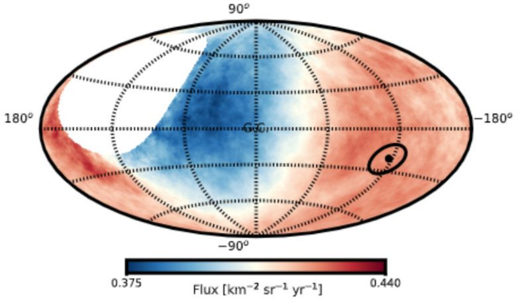
- If a sensible light fraction is found, we can foresee beginning the “**charged particle astronomy era**”
- If not, crucial **information on the sources can still be obtained** by a thorough analysis of all the pieces of the puzzle, in particular as our knowledge of magnetic fields improves (possibly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

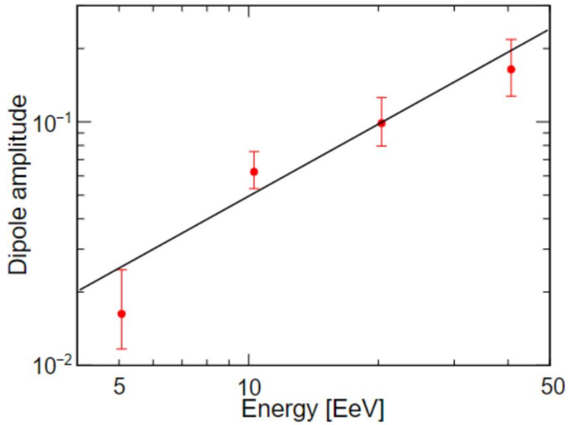
In conclusion:

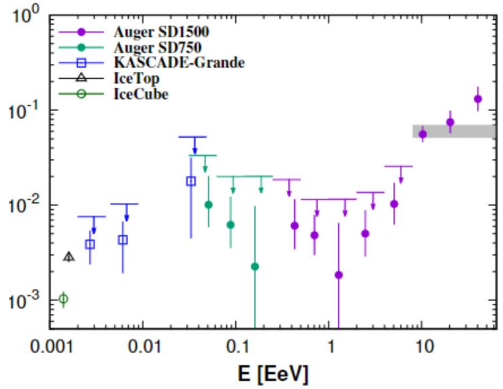
- We have now **observed** for the first time an **anisotropy** in the arrival direction of the **most energetic particle known.**
- **Indications** of other anisotropies at different energy scales have been spotted and the next years of data taking will tell us if they’re indeed true.
- Studying the **connection between these anisotropies**, ameliorating our **knowledge on the magnetic fields** and getting **composition measurements event-by-event** will boost these efforts and make possible to identify the sources of ultra-high energy cosmic rays.

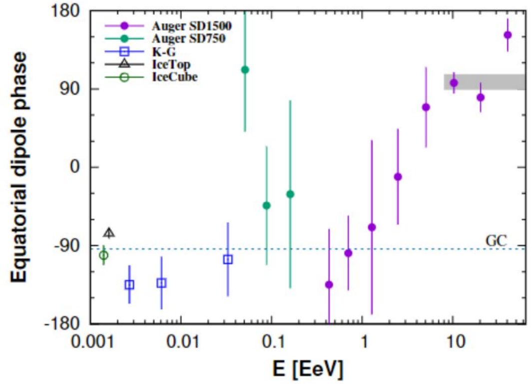
Thanks for the attention!

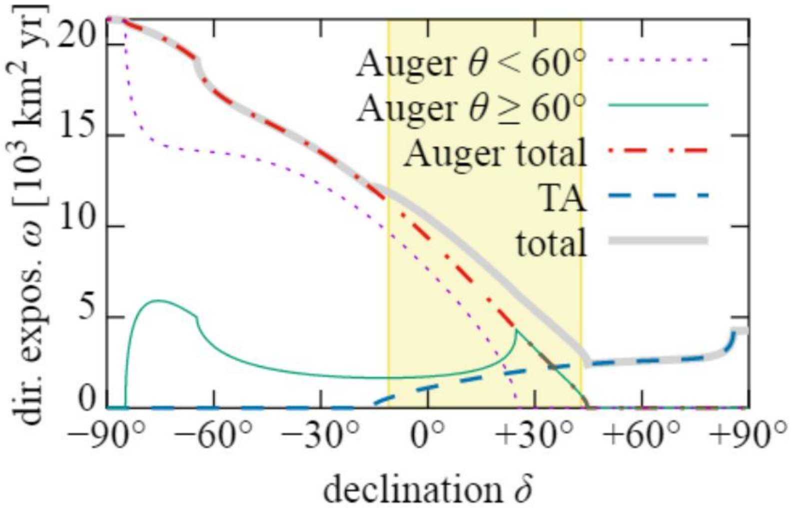
Large scale anisotropy

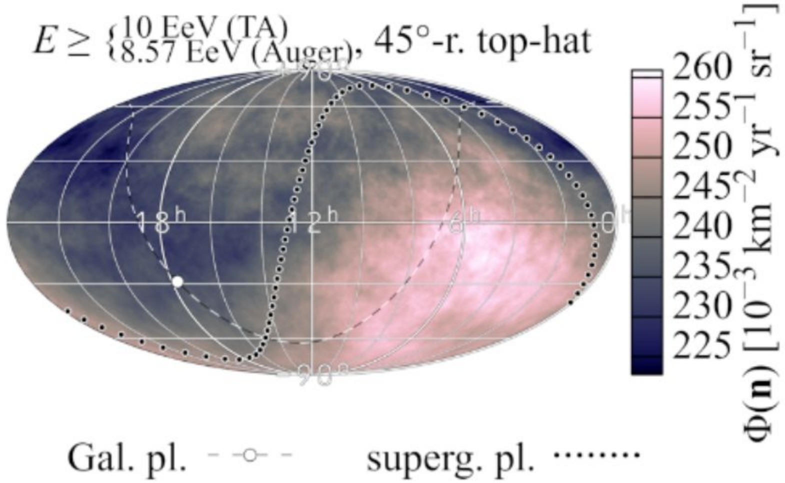












Intermediate scale anisotropy

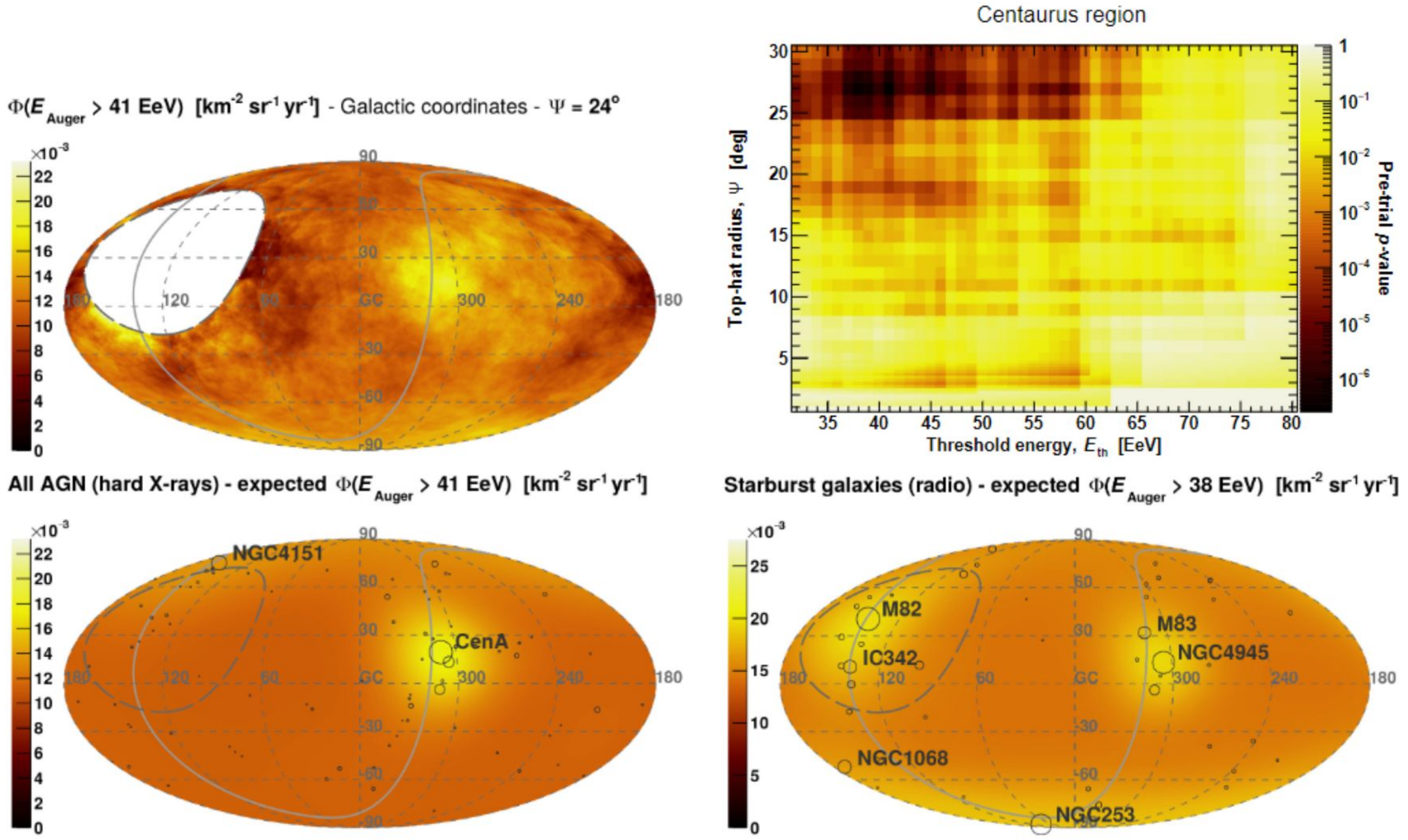


Figure 3: Upper left panel: map showing the CR flux detected by the Pierre Auger Observatory above 41 EeV, in Galactic coordinates, smoothed with a 24° top-hat function. Upper right panel: Pre-trial p-value as a function of the energy threshold and top-hat radius for an overdensity search centered in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

FD composition anisotropy

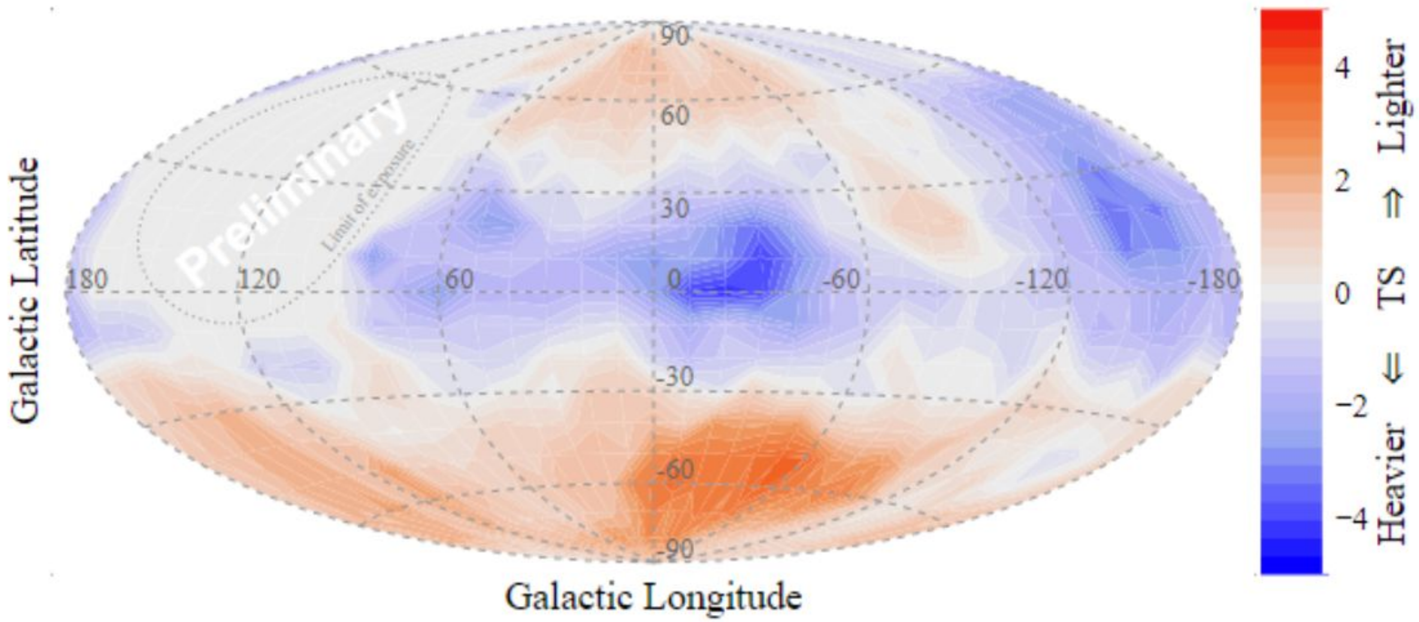
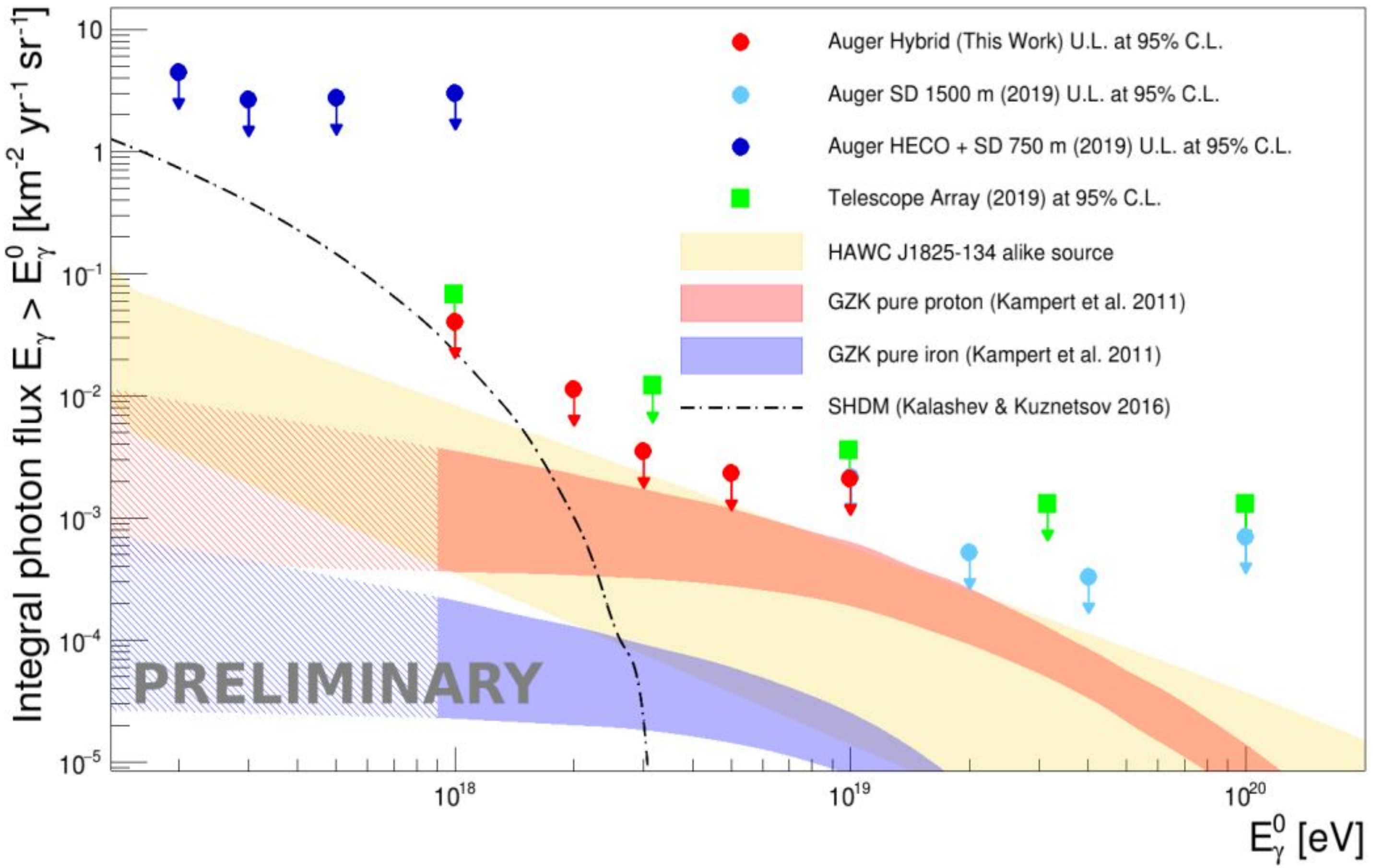


Figure 5: Map showing the cosmic-ray composition detected by the Pierre Auger Observatory above $10^{18.7}$ eV with the fluorescence detector, in Galactic coordinates. From [31].

Photon limits



P. Savina for the Auger Collaboration
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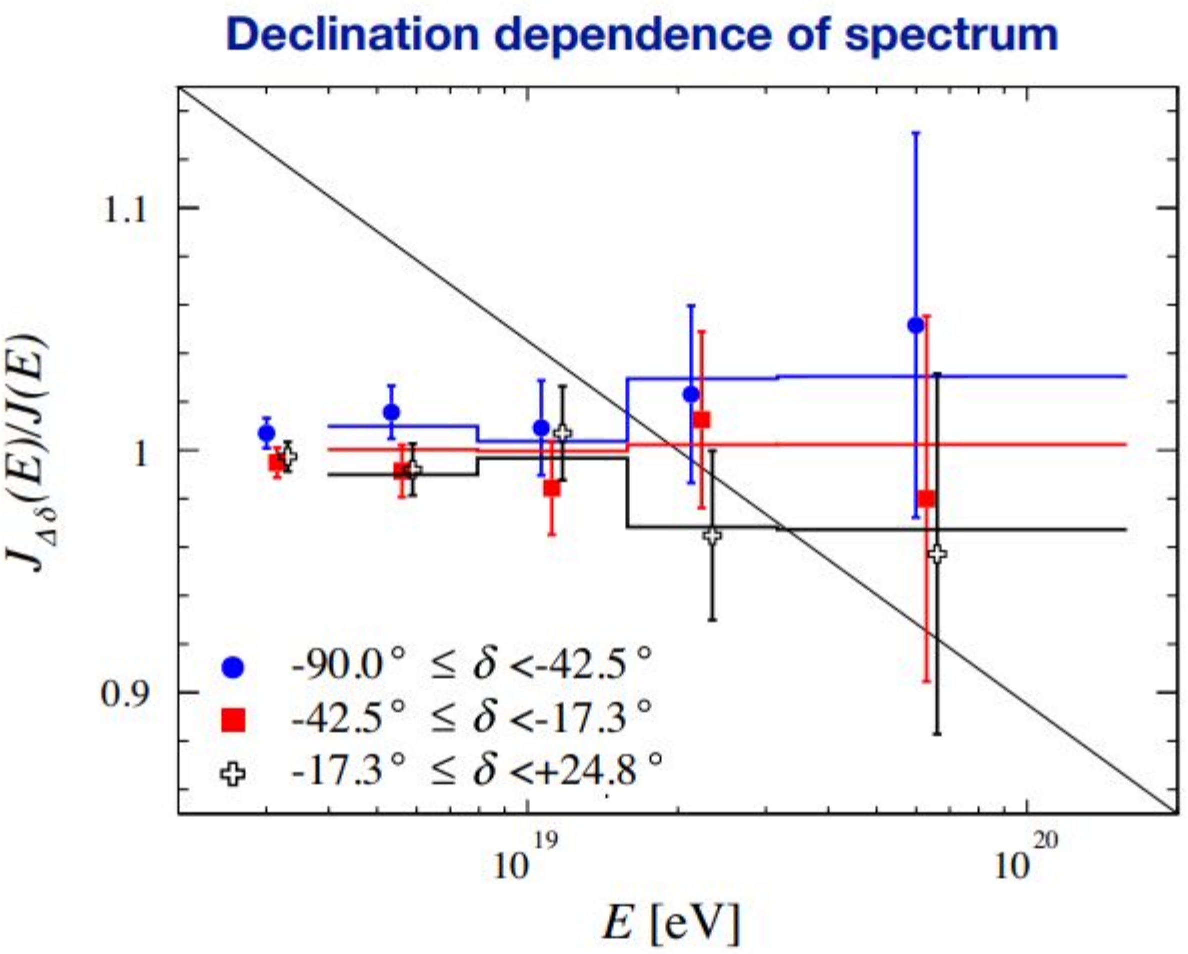
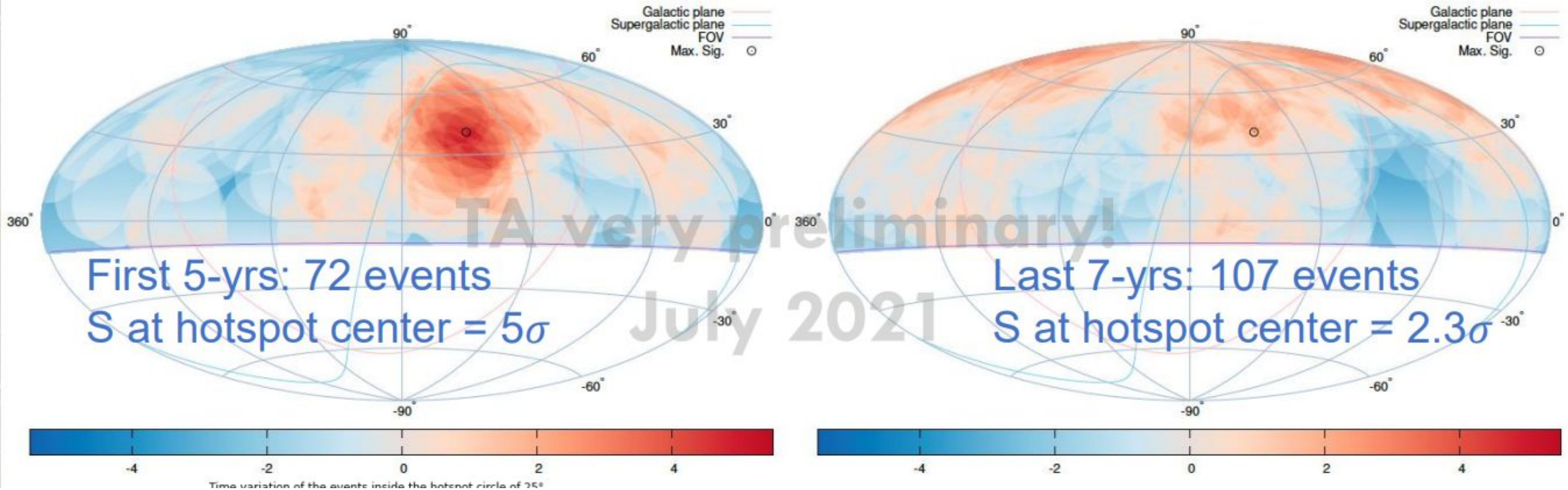
Declination dependence of the spectrum



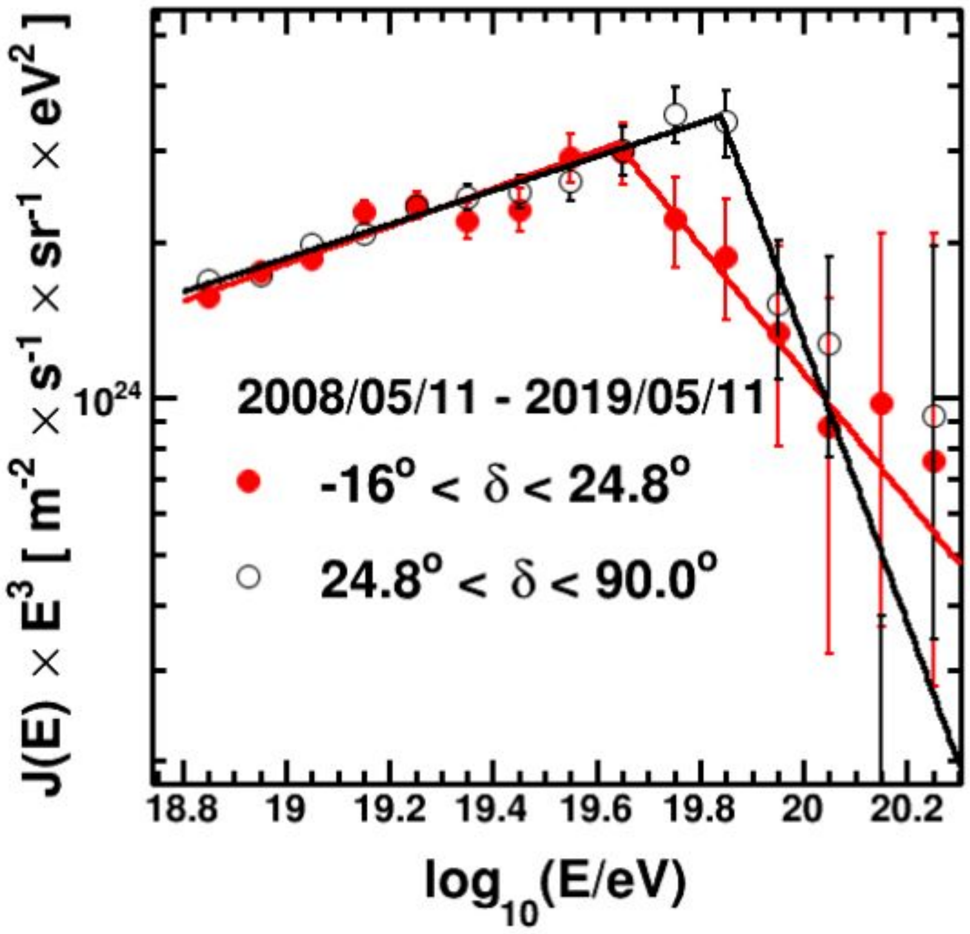
Lines: Expectation from observed dipole

TA Hotspot



Jihyun Kim ICRC 2021

TA Spectrum



- Cutoff energies in lower and higher declination bands now 4.7 σ different.
  - **4.3 σ global chance probability of the effect**
- **Strong evidence of cosmic ray spectrum declination dependence in the Northern Hemisphere**

D. Ivanov ICRC 2021