How isotropic can the UHECR sky *really* be?

Based on AdM and P. Tinyakov, *MNRAS* **476** (2018) 715

Armando di Matteo
armando.dimatteo@to.infn.it

Istituto Nazionale di Fisica Nucleare (INFN)
Sezione di Torino
Turin, Italy

GCOS workshop 2022
13–15 July 2022, Wuppertal, Germany

Motivation

- The UHECR propagation length at the highest energies is limited to $\lesssim 100\,\mathrm{Mpc}$.
- The Universe is not homogeneous on such scales
  - Clusters
  - Walls
  - Filaments
  - Voids

  $\rightarrow$ we should be able to see imprints of the source distribution.
- Magnetic fields can rotate and distort the picture, but the dipole and quadrupole amplitude $|\mathbf{d}|, |\mathbf{Q}|$ should mostly survive:
  - Regular deflections can only displace anisotropies, not erase them.
  - Turbulent deflections only attenuate amplitudes by a factor $\mathcal{O}\left(e^{-\ell^2 \Delta\theta^2_{\mathrm{turb}}/2}\right)$
    $\rightarrow$ would have to be $\gtrsim 40^\circ$ ($\gtrsim 20^\circ$) to attenuate a dipole (quadrupole) by $\gtrsim 20\%$.
  - See B. Eichmann & T. Winchen, *JCAP* **04** (2020) 047 for more precise estimates.
- What's the least anisotropy we could expect?

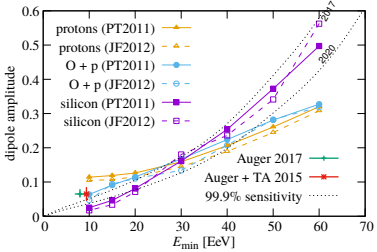
How do we get a lower bound?

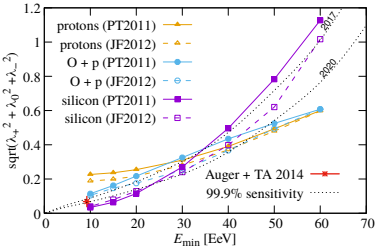
1. Assume that at $D < 5\,\mathrm{Mpc}$ there are no UHECR sources.
2. Assume that at $5\,\mathrm{Mpc} \leq D < 250\,Mpc$ every single galaxy is an UHECR source (XSCz catalog from M.F. Skrutskie et al., *Astron. J.* **131** (2006) 1163).
3. Assume that at $D \geq 250\,Mpc$ the whole sky is a homogeneous isotropic source.

Note: 1 + 2 aren't *mathematically* guaranteed to result in a lower bound: it's possible in principle that in the real world anisotropies from nearby sources cancel out those from faraway sources (but it would have to be an unlikely coincidence).

4. Use several different mass compositions, and see which results in less anisotropies.
5. Use two different regular GMF models, and see which results in less anisotropies.
6. Use an upper bound (M.S. Pshirkov et al., *MNRAS* **436** (2013) 2326) for the turbulent GMF.

The results





Note: Sensitivity predictions marked "2020" were overly optimistic.

- Dipole with $E_{\rm min} = 30\,\text{EeV}$ expected to be $\geq 13\%$.
- At ICRC 2021 we got $(11.6 \pm 3.8_{\rm stat} \pm 1.1_{\rm syst})\%$
  - If we shrink $\sigma_{\rm stat}$ by $\sqrt{10}$ and make $\sigma_{\rm syst}$ negligible, we get $\sim 11\sigma$ significance!
- As for the quadrupole, we expect $10^3 C_2 \geq 19$;
  at ICRC 2021 we got $15.5 \pm 8.9_{\rm stat} \pm 2.4_{\rm syst}$.
  - If we shrink $\sigma_{\rm stat}$ by $\sqrt{10}$ and make $\sigma_{\rm syst}$ negligible, we get $\sim 7\sigma$ significance.

Outlook for the future

- The Auger–TA joint working group on arrival directions is doing similar studies about medium-scale anisotropies (searches for catalog correlations).
- A preview will be shown at the Auger collaboration meeting next week.
- Results will be shown at RICAP-22 and UHECR 2022.