Studies of a possible large-scale anisotropy of UHECRs with future orbital detectors

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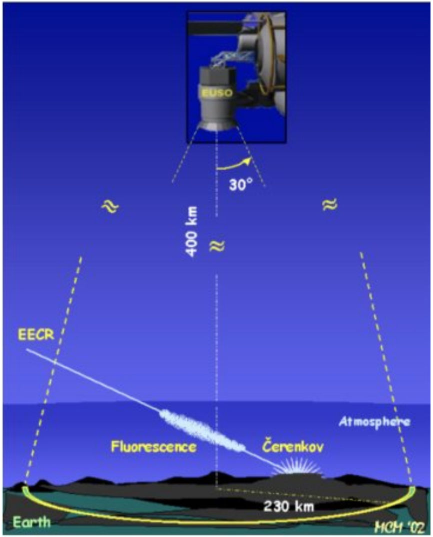
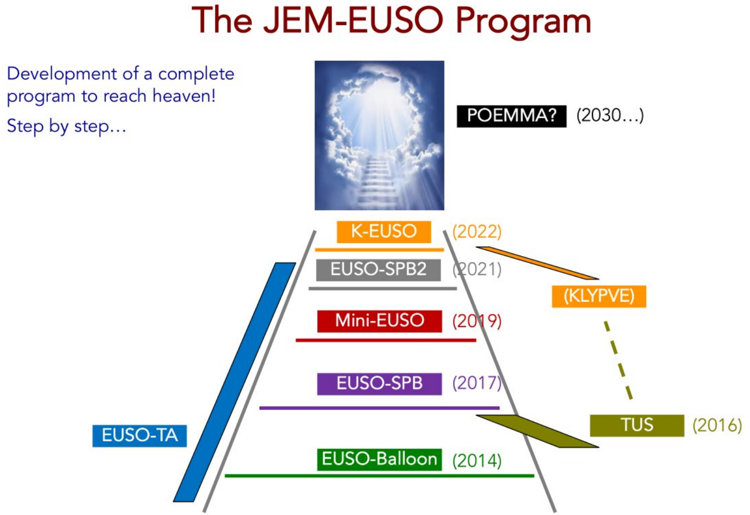
11.07 Satellite Observation of Cosmic-Ray Air Showers*, R.BENSON, TEXAS A & M, and J. LINSLEY, UNIV. OF NEW MEXICO. The arrival trajectories at earth of cosmic rays with energies >10^{18}eV afford the possibility of being traced backwards for distances comparable to the dimensions of the Galaxy. Thus they provide a means of testing models of the Galactic magnetic field as well as models of the origin of extra-galactic cosmic rays. It has been shown that large air showers can be observed electronically by means of the stmospheric scintillation light they produce. A practical ground-based system for carrying out air shower observations by this method has been constructed and put in operation by a group at the University of Utah.[1] It is shown here that a satellite based system consisting of a single very large metallized film mirror with an array of photon sensors at its focal plane would have outstanding advantages for the study of cosmic rays at energies above 10^{18}eV.

[Bull. of the American Astron. Society, 12, 1980, 818]





Slide by E. Parizot (UHECR2018)

Main parameters:

- a Schmidt-type optical system with the main mirror-reflector of a 4 m diameter, an entrance pupil of a 2.5 m diameter and a 1.7 m focal length.
- a round-shaped field of view of **40**° diameter, with an instantaneous geometrical area of nearly 6.7×10^4 km^2 at sea level for the ISS altitude of around 400 km.
- the yearly exposure above ∼40 EeV: $\sim 3 \times 10^4$ km^2 sr yr.

The starting point: the single source class model

M. Kachelrieß, O. Kalashev, S. Ostapchenko, D.V. Semikoz "A minimal model for extragalactic cosmic rays and neutrinos," PRD 96, 083006 (2017); arXiv:1704.06893.

Basic assumptions:

- UHECRs are accelerated by (a subclass of) AGN
- the energy spectra of nuclei after the acceleration phase follow a power-law with a rigidity-dependent cutoff: $j_{\rm inj}(E) \propto E^{-\alpha} \exp[-E/(ZE_{\rm max})]$
- the CR nuclei diffuse first through a zone dominated by photo-hadronic interactions, and then they escape into a second zone dominated by hadronic interactions with gas.

The model matches:

- experimental data on the total CR flux, the mean EAS maximum depth $X_{\rm max}$ and its width RMS($X_{\rm max}$) above $\sim 10^{17}$ eV
- HE neutrino flux measured by IceCube

One of the consequences: there should be a source of UHECRs within $\sim$ 20 Mpc

The main idea of the study

0. K-EUSO is expected to register from 120 to 500 CRs at $E \gtrsim 57$ EeV in 2 years
   [M. Casolino *et al.* PoS (ICRC2017) 368]
1. Assume EECRs propagate from a source to the Galaxy in the ballistic regime, so that deflections from the direction to the source are $\leq 1^\circ$.
2. Take a spectrum at the source and obtain a spectrum after propagating to the Galaxy: `TransportCR` code
   [O. Kalashev, E. Kido, J. Exp. Theor. Phys. 120 (2015) 790; arXiv:1406.0735]
3. Propagate CRs from the boundary of the Galaxy to Earth with `CRPropa3`
   [R. Alves Batista *et al.* JCAP 05 (2016) 038; arXiv:1603.07142]
   assuming the Jansson–Farrar (2012) GMF model (actually backtrack)
4. Study large-scale anisotropy of CRs with the angular power spectrum.

Five AGN were chosen for the analysis: Cen A, NGC253, M82, M87, Fornax A.

Search for large-scale anisotropy

1. Build maps of the relative intensity of the CR flux

$$\delta I_i = \frac{N_i - \langle N \rangle_i}{\langle N \rangle_i},$$

   where N_i and $\langle N \rangle_i$ are the number of “observed” events and the number of “reference” events assuming the isotropic flux in the ith pixel of the HEALPix map (CRPropa)

2. Calculate coefficients of the angular power spectrum

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{+\ell} |a_{\ell m}|^2$$

   (`anafast` of HEALPix)

3. Estimate a deviation of the flux from isotropic expectations, if any

Estimator

IceCube, Auger [Hülss, Wiebusch, ICRC2007; Aab *et al.* JCAP 06 (2017) 026]:

$$D^2(\text{sample}) = \frac{1}{\ell_{\max}} \sum_{\ell=1}^{\ell_{\max}} \left(\frac{C_{\ell,\text{sample}} - \langle C_{\ell,\text{iso}} \rangle}{\sigma_{\ell,\text{iso}}} \right)^2,$$

where "sample" is either "data" when applied to experimental data or "iso" when applied to estimate the deviation of one isotropic sample from an averaged isotropic flux. Variables $C_{\ell,\text{sample}}$, $\langle C_{\ell,\text{iso}} \rangle$ and $\sigma_{\ell,\text{iso}}$ are, respectively, the C_ℓ observed in the sample (either "data" or "iso"), and the average and the standard deviation of C_ℓ for isotropic expectations, all of them calculated at a given scale ℓ.

One can choose a certain confidence level for defining a threshold to accept or reject the isotropy hypothesis and then compare a value of $D^2(\text{data})$ calculated for the data to the distribution of $D^2(\text{iso})$ obtained for the isotropic flux.

Auger dipole anisotropy

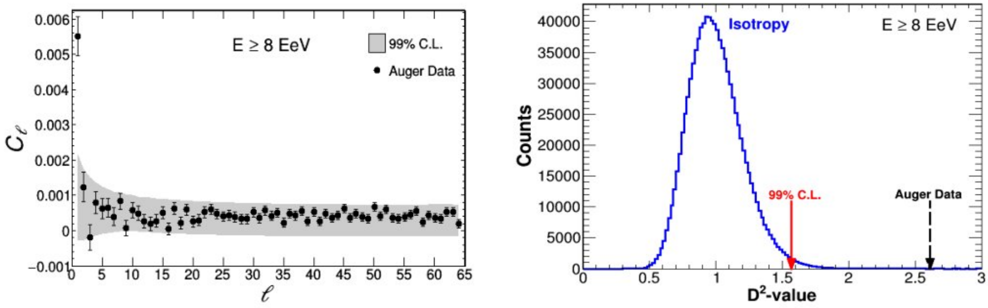


Figure 3: Angular power spectrum for $E \geq 8$ EeV. On the left a clear indication for a departure from isotropy is captured in the dipole scale. On the right the D^2-value distribution from 1,000,000 isotropic sky maps is shown. The D^2-value from data, represented by the black (dashed) arrow, is larger than the threshold of isotropy presenting an indication of anisotropy with $> 99\%$ C.L..

[Pierre Auger Collaboration, JCAP 06 (2017) 026]

Our estimator:

$$D(\text{sample}) = \frac{1}{\ell_{\max}} \sum_{\ell=1}^{\ell_{\max}} \frac{C_{\ell,\text{sample}} - \langle C_{\ell,\text{iso}} \rangle}{\sigma_{\ell,\text{iso}}},$$

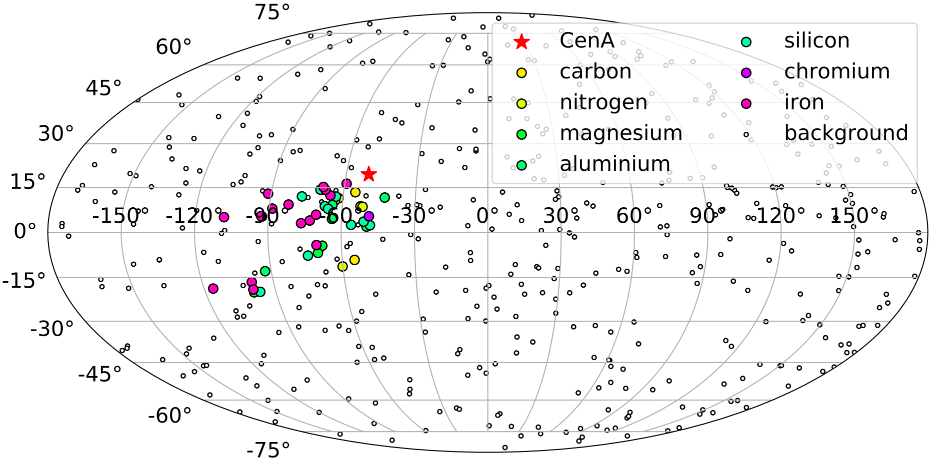
- The $C_{\ell,\text{data}}$ coefficients are to be replaced with $C_{\ell,\text{mix}}$, which denote C_ℓ obtained for a simulated mixture of an isotropic flux and cosmic rays arriving from a particular source.
- One needs to simulate many mixed samples to obtain the distribution of $D(\text{mix})$ for each source: 500,000 isotropic samples and at least 10,000 mixed samples for each N_{UHECR}.

The null hypothesis: an isotropic distribution of arrival directions of a mixed sample of UHECRs.

We adopted the value of the error of the second kind $\beta = 0.05$ and searched for a fraction F_1/F_{tot} of from-source events in the total flux such that the error of the first kind $\alpha \lesssim 0.01$.

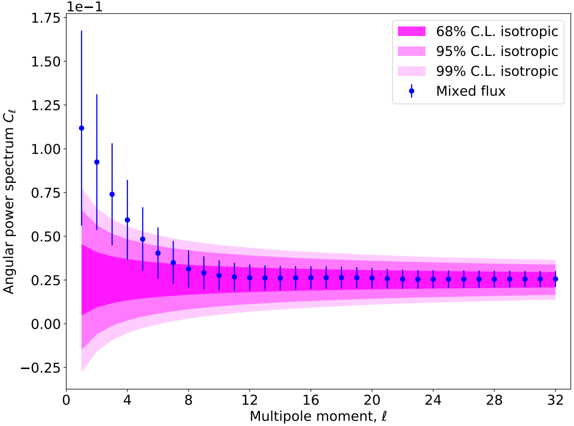
Reminder: a type I error stands for false positive errors, i.e., the rejection of a true null hypothesis; a type II error is committed when a false null hypothesis is not rejected.

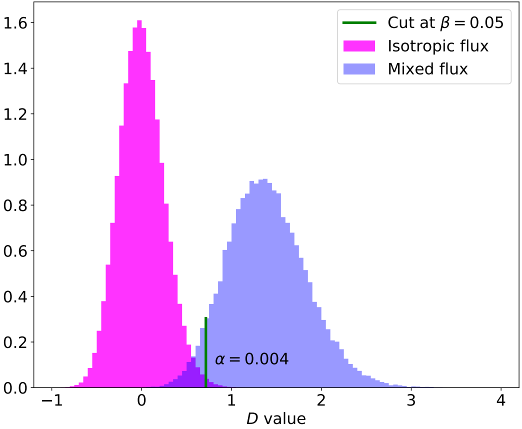
Centaurus A



The case of $N_{\mathrm{UHECR}} = 500$ and 9% events coming from Cen A.

Centaurus A

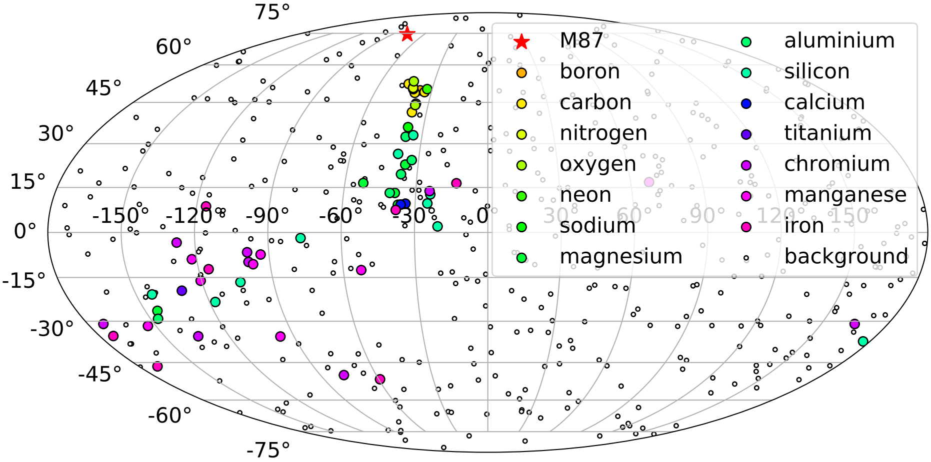




Cen A, $N_{\mathrm{UHECR}} = 500$ and $F_1/F_{\mathrm{tot}} = 9\%$

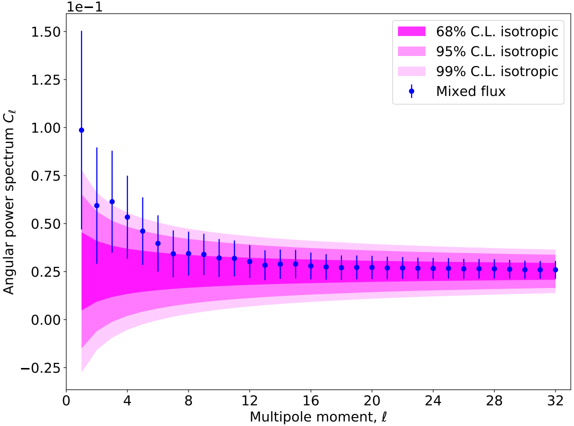
Left: angular power spectrum C_ℓ for isotropic and mixed samples.
Right: empirical probability distribution functions of $D(\mathrm{iso})$ and $D(\mathrm{mix})$.

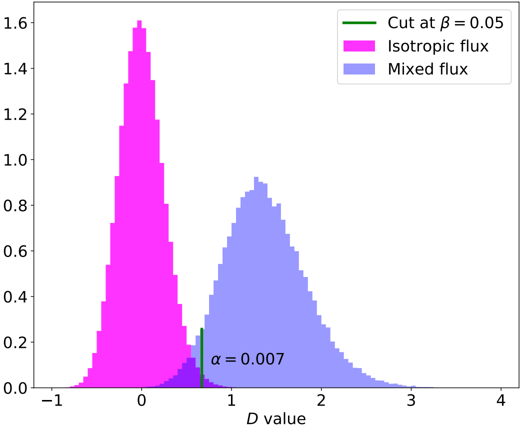
M87



The case of $N_{\mathrm{UHECR}} = 500$ and 12% events coming from M87.

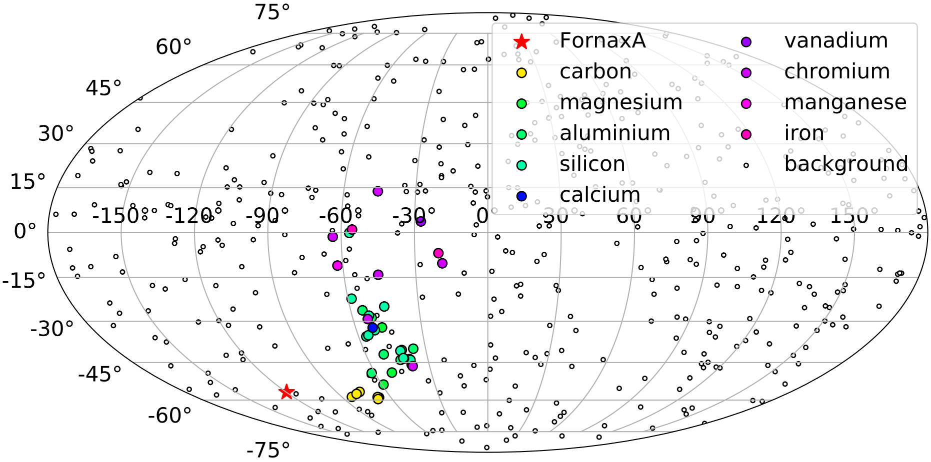
M87





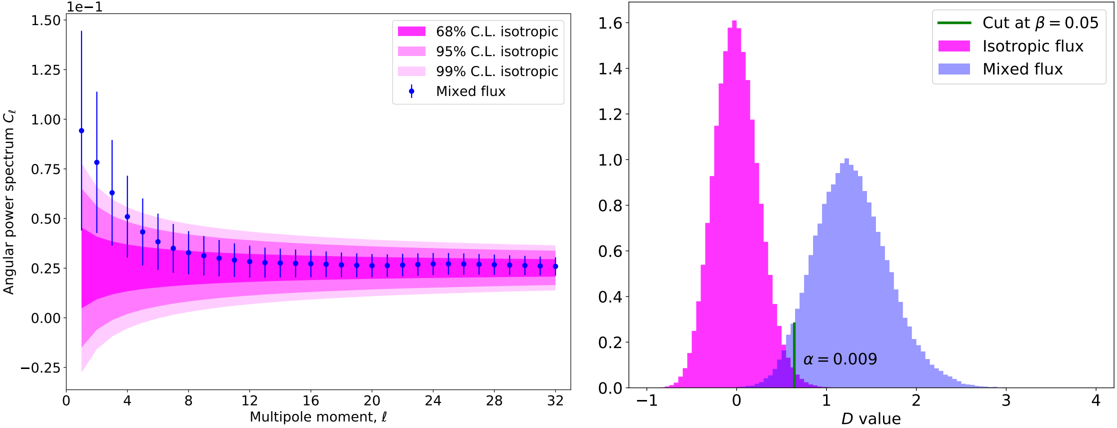
M87: $N_{\mathrm{UHECR}} = 500$ and $F_1/F_{\mathrm{tot}} = 12\%$

Fornax A



The case of $N_{\mathrm{UHECR}} = 500$ and 8% events coming from Fornax A.

Fornax A



Fornax A: $N_{\mathrm{UHECR}} = 500$ and $F_1/F_{\mathrm{tot}} = 8\%$

The main results for $E \geq 57$ EeV

Percentage of UHECRs arriving from five candidate sources in samples of sizes $N_{\mathrm{UHECR}} = 100, \ldots, 500$ such that $\alpha \lesssim 0.01$ providing $\beta = 0.05$.

N_{UHECR}	100	200	300	400	500
NGC 253	17	12	10	8	7
Cen A	21	14	12	10	9
M82	26	18	14	12	11
M87	29	20	16	14	12
Fornax A	19	13	11	9	8

Conclusion: an observation of $\gtrsim 300$ events will allow detecting a large-scale anisotropy with a high confidence level providing the fraction of from-source events is $\simeq$10–15%, depending on a particular source.

The threshold fraction decreases with an increasing sample size.

Does the 10–15% fraction of from-source events make sense?

Simulations: identical sources uniformly distributed with a number density $n = 10^{-4} \ldots 10^{-6}$ Mpc^{-3}.

Box $V_{\rm box} = (600\ {\rm Mpc})^3$ box centered at the observer. Less than 5% of the total flux comes from outside this box, ignored. The total number of simulated sources: $N_{\rm src} = nV_{\rm box}$.

The contribution from an individual source located at a distance d:

$$\Phi = \exp(-d/L_c)/d^2.$$

Finally, all contributions were summed up, and fractions of CRs from the brightest (the closest in this set up) and the second-brightest sources were calculated. This procedure was repeated 100,000 times. $L_c \sim 100$ Mpc is a characteristic path length.

Result: an impact of the nearest source $> 10\%$ if $n < (1-2) \times 10^{-5}$ Mpc^{-3}.

Auger: $n > 6 \times 10^{-6}$ Mpc^{-3} (from the non-observation of significant clustering at intermediate angular scales [JCAP 5 (2013) 009])

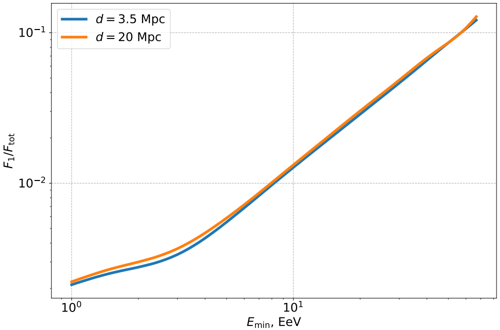
Any signatures of LSA at lower energies?

Lemoine and Waxman suggested that if anisotropy is found above some energy E and the composition is assumed to be heavy at that energy (with nuclei of charge Z), one should also observe an even stronger anisotropy at energies above rigidity E/Z due to the proton component of the flux emitted by the source that is responsible for the observed anisotropy. The statement was based on an assumption that the cosmic ray injection spectrum at the source depends on rigidity only [JCAP, 2009].

Liu et al. argued that if anisotropy is detected at energies above ~ 60 EeV and is caused by heavy nuclei, then an even more significant anisotropy signal should be present at energies close to the ankle due to the proton component [ApJ, 2013].

However, the significance of an anisotropy predicted in this case at lower energies is weaker than at higher ones unless the nearest source is distant enough (typically beyond 30 Mpc) and the maximal cosmic ray injection energy $E_{\max} \gtrsim Z/26 \times 10^3$ EeV.

From-source CR flux at lower energies



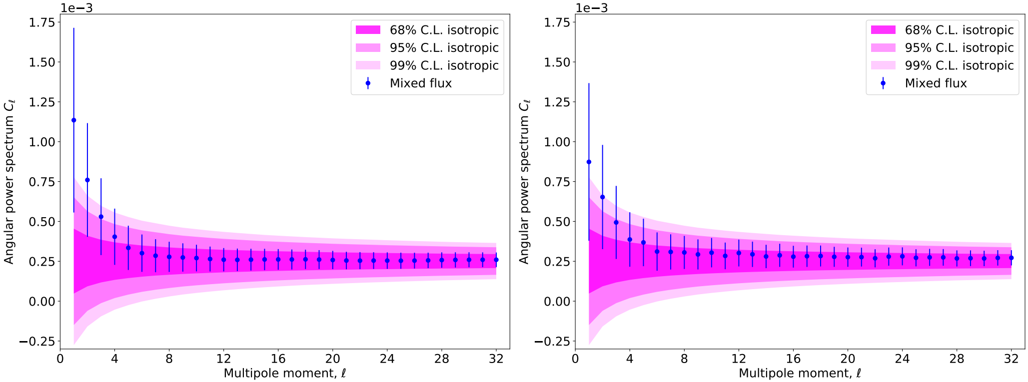
Dependence of the fraction of the flux F_1 coming from a single source located at the given distance from the observer (3.5 Mpc and 20 Mpc) in the total incoming flux F_{tot} above some energy threshold E_{min}.

$F_1/F_{tot} = 0.1$ for CRs above $E_{\mathrm{min}} = 57$ EeV.

The fraction of from-source events scales nearly linearly for $E_{\mathrm{min}} \gtrsim 3$ EeV, and there is very little difference between sources located at distances 3.5 Mpc and 20 Mpc.

The fraction equals approximately 1% for $E \geq 8$ EeV (the threshold value beyond which a dipole anisotropy was detected by the Pierre Auger Collaboration at more than a 5.2σ level of significance [PAO, Science 357 (2017) 1266]).

Cen A, Fornax A: angular power spectrum for $E \geq 8$ EeV



Angular power spectrum C_ℓ for isotropic and mixed samples arriving from Cen A (left) and Fornax A (right) for cosmic rays above 8 EeV and $F_1/F_{\text{tot}} = 0.01$. $N_{\text{UHECR}} = 50,000$.

The dipole amplitude $\sqrt{9C_1/4\pi}$: 2.9% and 2.5% respectively.

Auger: $(6.0 \pm 1.5)\%$ with 20,000 events [JCAP, 2017]

The main conclusion

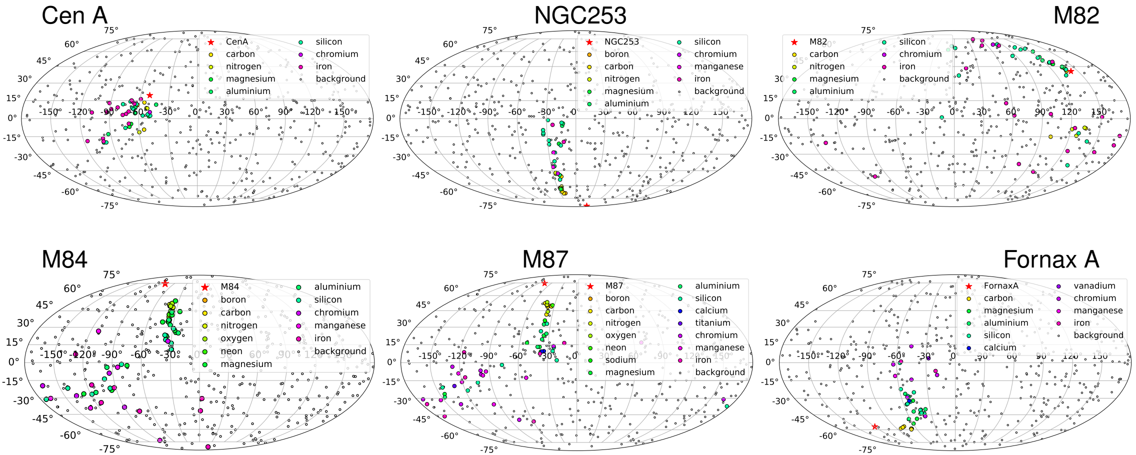
An orbital detector with a uniform exposure will allow detecting a large-scale anisotropy arising from a nearby AGN after observing $\gtrsim 300$ events providing the fraction of from-source events is $\simeq$10–15%.

This kind of LSA might exist even though it is not (has not been) observed by the current ground-based experiments.

NB: the GMF model and the other assumptions.

Still promising!

What's next? Pattern recognition



See: Oleg Kalashev, Using Machine Learning to Interpret Arrival Directions of Ultra-high-energy Cosmic Rays. **Tuesday, 16:00**