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Ultra-high energy cosmic ray correlations with Active Galactic Nuclei in the world dataset

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Pierre Auger collaboration have recently put forward the hypothesis that the arrival directions of the highest energy cosmic rays correlate with the subset of local active galactic nuclei (AGN). We perform a blind test of AGN hypothesis using publicly available event sets collected by Yakutsk, AGASA, and HiRes experiments. The consistency of the procedure requires the event energies to be normalized towards the common energy scale. The number of correlating events in resulting data-set is 3 of 21 which is consistent with expected random background.

1. Introduction. The question of the origin of ultra-high energy cosmic rays (UHECR) belongs to the list of the most interesting unsolved problems in particle astrophysics. Many very different models were suggested here, including decaying superheavy dark matter, cosmic strings, gamma-ray bursts, AGN, etc. Detection of anisotropy of arrival directions of primaries would be a key to the resolution of this puzzle and identification of the UHECR production mechanism, which is, therefore, of fundamental importance. Establishing the level of anisotropy is also an important step in ironing out the chemical composition of UHECR and measuring parameters of the intergalactic medium such as the strength of magnetic fields and intensity of cosmic background radiation. Search for correlations between cosmic rays (CR) arrival directions and positions on the celestial sphere of prospective astrophysical sources is one of the promising methods to approach these problems, see e.g. [1].

Recently, Pierre Auger Observatory has reported correlation [2] between the highest energy cosmic rays and population of all known nearby (closer than 75 Mpc) AGNs. The correlation was observed at an angle of 3.1°. In the control data set, the number of correlating events was 9 out of 13, which corresponds to about 69% of events. This analysis has been later updated by the Auger collaboration using larger dataset of latest events [3]. In the latter, the smaller fraction of UHECR correlates with the same set of AGNs. Namely, arrival directions of 28 events were found to correlate with AGNs positions, out of 84 events with $E > 55\,\mathrm{EeV}$. This corresponds to the fraction of correlating events equal to 33%.

This important claim has been put to the test by other CR collaborations using their own data, namely, by the HiRes [4], Yakutsk [5], and the Telescope Array [6]. The results obtained range from support of correlation claim [5] to complete absence of correlations [4].

It should be stressed, however, that a verification of such delicate hypotheses as a claim of correlations should be done on the basis of so-called "blind test". Namely, all cuts on energy, source catalog, angular scale of correlations, etc., should be kept strictly at the same values as in original hypotheses. Requirements of keeping the original source catalog and unchanged angular scale are easy to fulfill. On the contrary, the issue with CR catalogs is more complicated, especially regarding the cut on the energy. The complication stems from the fact that different experiments have different energy scales. This is apparent since cosmic ray fluxes measured by different experiments differ at the same values of nominal energy, even in the energy regions where statistics is abundant and there is no doubt that the physical sky is close to isotropic.

Requirement of choosing the same energy cut for all experiments is extremely important. We are searching for correlation signal with the sources in the region of Greisen–Zatsepin–Kuzmin [7] suppression. Here the horizon (i.e. the distance to sources from which CR can reach us) changes exponentially with energy. Small change in energy leads to dramatic change in horizon and, respectively, in the subset of sources being probed. The cross-calibration of different experiments is therefore pressing issue.

Despite of importance, tests of AGN correlation hypothesis using common energy scale for different experiments has not been done in the past. We do it in this paper.

2. Energy scales estimate. As it was first shown by V. Berezinsky [8] the cosmic ray spectra measured by different giant air-shower observatories become identical at lower energies after simple overall rescaling of energy

$$E \to EC, \tag{1}$$

with the constant factor C, which is different for individual experiments. This opens the way for cross-calibration of energy scales, c.f. [9]. To handle this issue the Spectrum Working Group (WG) has been recently formed consisting of members of Auger, Telescope Array, HiRes and Yakutsk collaborations. Results were reported at International Symposium on Future Directions in UHECR Physics, UHECR2012 [10]. Note, that true, physical, energy scale cannot be determined in this approach. One may only make sure that quoted values of energy for different experiments are based on the same energy scale. However, this is sufficient for our purpose of blind testing the correlation hypothesis. For definiteness and in order to avoid biases towards one or the other modern experiments, it was decided to choose common energy scale as a mean between Auger and Telescope Array energy scales.

$$E_{\text{com}} = \frac{1}{2}(E_{\text{Auger}} + E_{\text{TA}}). \tag{2}$$

Resulting values of the scaling constant C, reported by the WG [11], are reproduced in Table.[1)]

Values of the energy scaling constant, C, for listed experiments

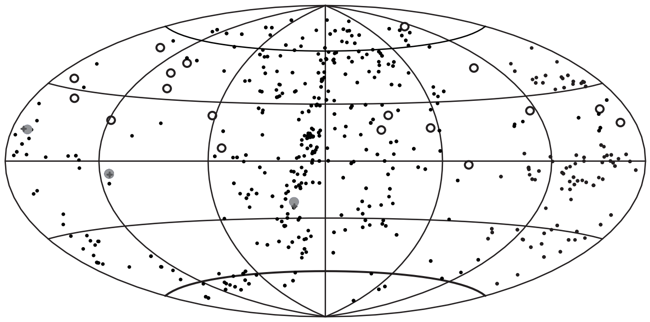
Experiment	C
Auger	1.102
Telescope Array	0.906
HiRes	0.911
AGASA	0.652
Yakutsk	0.561

3. Correlation study with AGNs. For this study we used publicly available catalogs of cosmic ray events of AGASA [12], Yakutsk [13], and HiRes-stereo [14]. Telescope Array data are not publicly available yet.

[1)] http://indico.cern.ch/contributionDisplay.py?contribId=6&confId=152124

Auger energy cut of 55 EeV [3] corresponds to the cut $E_{\text{com}} > 60.61$ EeV in terms of the common energy scale adopted. With this energy cut we have 21 events in combined world catalog. This makes largest to date public event list in the Northern Hemisphere for testing AGN hypothesis. Out of these 21 events 9 are from HiRes, 3 from Yakutsk and 9 contributed by AGASA.

Only 3 out of 21 events correlate with AGNs within 3.1 degrees, while the expected background of random coincidences for the isotropic distribution of arrival directions equals to 5. Map of arrival directions in equatorial coordinate system is shown in Figure. We see that



Hammer projection of CR arrival directions of Yakutsk, AGASA and HiRes-stereo in equatorial coordinate system with $E_{\text{com}} > 60.61$ EeV. Correlating and non-correlating events are represented by filled and empty circles, respectively. AGNs are shown by dots

correlations are absent not only with AGNs as point sources, but, remarkably, CR events are avoiding the Large Scale Structure. In particular, there are no events from the Virgo region (represented by the dense concentration of dots near the center of Figure), while there is one event in reasonable vicinity (22 degrees) from Cen A despite exposure is low here (cf. Ref. [15]).

4. Conclusions. Common energy scale established by the WG opened up the possibility to search for correlations using the combined dataset. Based on the common energy scale we performed a blind test of Pierre Auger AGN hypothesis using the data of Yakutsk, AGASA, and HiRes experiments. The analysis shown 3 correlating events out of 21, which is compatible with the expected random background of 5 events. Difference in the fraction of correlating events in South and North may be attributed to the existence of peculiar sources in South (e.g. Cen A [15]) or to statistical fluctuations.

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