On Anisotropy of Ultra-High Energy Cosmic-Rays

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Abstract

We briefly summarize our study on anisotropy of Ultra-High Energy Cosmic-Rays (UHECRs), in which we define a statistics that measures the correlation between UHECRs and Large Scale Structure (LSS). We also comment here on recently published paper by Koers and Tinyakov that compared our statistics to improved KS statistics.

Key words: ultra high energy cosmic rays, cosmic rays, large scale structure

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The origin of cosmic rays of energies $> 10^{19}$ eV is a puzzle [1,2,3]. The arrival direction of UHECRs show no correlation with the galactic disk, which point towards extra-galactic origin. A suppression of the spectrum at $\sim 5 \times 10^{19}$ eV is expected due to the GZK suppression [4,5]. The suppression was observed by HIRES [6] and the new Auger Observatory [7], see fig. 1(a). Thus, cosmic-rays with energies above $\sim 5 \times 10^{19}$ eV can reach us only from sources with distance below $\sim 100$ Mpc. In these distances, the Universe is not isotropic, implying that correlation with LSS can give us information on the origin of UHECRs.

There are few leading candidates as the sources of UHECRs. Assuming that UHECRs are protons, the large magnetic fields needed for acceleration requires source luminosity of $L \gtrsim 10^{12} L_\odot \Gamma^2/\beta$ for protons with $10^{20}$ eV, where $L_\odot$ is the Sun luminosity and $\Gamma$ is Lorentz factor of the magnetized plasma [3]. Therefore, the only known astrophysical sources that reaches these energies are Active Galactic Nuclei (AGNs) and sources of Gamma-ray bursts. The anisotropy of UHECRs from these sources should be correlated with LSS. Another possible source of UHECRs is the decay of new heavy particles coming from top-down models [1], which predict isotropic signal.

In [8], we derive the expected all sky angular distribution of the UHECR intensity, and defined a statistics $X_{C,UB}$ that measures the correlation between the predicted and observed UHECR arrival direction distribution. Following [9], we consider a model where the UHECR flux is produced by cosmological sources of protons tracing the large scale structure.
Fig. 1. (a) The spectrum of HIRES and Auger after a shift of $\Delta E/E = +23\%$ in the calibration of the absolute energy scale of the Auger experiment. The solid line is the spectrum that would be generated by a cosmological distribution of sources of protons, with intrinsic spectrum $d\log n/d\log E = -2$. The positions of the 27 Auger events with energy exceeding $5.7 \times 10^{19}$ eV, overlaid on the intensity map obtained in the biased model, in galactic coordinates.

galaxy distribution. We assume that the sources are intrinsically identical and that the number density of sources is drawn from a Poisson distribution with an average given by $b[\delta]\bar{s}(z)$, where $\bar{s}(z)$ is the average comoving number density of sources at redshift $z$ and $b$ is some bias functional of the local fractional galaxy over density, $\delta \equiv \delta \rho/\bar{\rho}$. The LSS galaxy density field is derived from the PSCz catalogue [10]. For the bias functional we consider three models: an isotropic (I) model, $b[\delta] = 1$; an unbiased (UB) model where the source distribution traces the galaxy distribution with $b[\delta] = 1 + \delta$; and a biased (B) model, $b[\delta] = 1 + \delta$ for $\delta > 0$ and $b[\delta] = 0$ otherwise.

The statistics we defined in [8], which measures the correlation between predicted and observed UHECR arrival direction distributions, is:

$$X_{C,M} = \sum_{\{i\}} \frac{(N_i - N_{i,iso})(N_{i,M} - N_{i,iso})}{N_{i,iso}}.$$  

Here $\{i\}$ is a set of angular bins, $N_i$ is the number of events detected in bin $i$, and $N_{i,M}$ is the average number of events expected to be detected in the $M$ (e.g. isotropic, unbiased, biased) model. In order to avoid sensitivity to the possible distortion of the UHECR intensity map by magnetic fields, we used $6^\circ \times 6^\circ$ angular bins and excluded the Galactic plane region, $|b| < 12^\circ$. The value of $X_{C,UB}$ can be straightforwardly calculated using the numerical representations of the UHECR maps at [http://www.weizmann.ac.il/~waxman/criso](http://www.weizmann.ac.il/~waxman/criso).

The $X_C$ statistics is more sensitive to expected anisotropy signature than the commonly used power spectrum, $C_\ell = \frac{1}{2\pi} \sum_{m=\ell} a_{\ell m}^2$ (e.g. [11]), and the two-point correlation function, $W(D) = \sum_i \sum_{j<i} \Theta(D - D_{ij})$ (e.g. [12]). This can be seen from table II(a). The anisotropy signal is stronger at lower energy: Although the contrast of the fluctuations in the UHECR intensity is higher at high energy, the signal becomes weaker at higher energies since the number of observed UHECR drops rapidly with energy, see table II(b). In [8] we also show that a few fold increase of the Auger exposure is likely to increase the significance to > 99% CL, but not to > 99.9% CL (unless the UHECR source density is comparable or larger than that of galaxies).
Auger reported in [13] a correlation between the arrival direction distribution of 27 UHECRs of $>5.7 \times 10^{19}$ eV and between the angular distribution of low-luminosity AGNs included in the V-C AGN catalog [14]. However, the V-C AGN catalog is merely a compilation of AGN data available in the literature, and is therefore incomplete both in its sky coverage and in its luminosity coverage, hence the results of [13] are unclear. Using the $X_{C,U,B}$ statistics, we analyzed [13] data, see fig. 1(b). According to our analysis, the data is inconsistent with isotropy at $\sim 98\%$ CL, and consistent with a source distribution that traces galaxy density. Note, however, that the optimization of the energy threshold made in [13] raises the concern that the significance with which isotropy is ruled out maybe overestimated.

Recently, [15] compared the $X_{C,U,B}$ statistics to an improved KS statistics. They showed that for most energy thresholds the $X_{C,U,B}$ statistics have higher probability to rule out isotropy (see their table I). However, they get probabilities that are different then ours for $X_{C,U,B}$. This is probably due to the fact that they use a different galaxy redshift catalog, the catalog of Kalashev et al. [16], deduced from 2MASS XSC [17]. We believe that this catalog is not suitable for the analysis of CR anisotropy, since it includes mainly photometric redshifts, which have systematic uncertainty of 30% that depends on the luminosity, thus distorting the density field. Note that the future “2MASS Redshift Survey” [17] will improve PSCz, by measuring redshifts of 100,000 galaxies till 85 Mpc.

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