

## TA anisotropy summary

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**Abstract:** The Telescope Array experiment has collected 5 years of data and accumulated the largest to date UHECR data set in the Northern hemisphere. We make use of this data set to search for large- and small-scale anisotropy of UHECR. We begin by testing the previously existing claims of anisotropy at highest energies, namely, the clustering at small scales and correlations with the nearby AGNs. We then extend the search by including other classes of extragalactic objects – putative sources of UHECR. Finally, we cross-correlate the UHECR events with the large-scale structure of the Universe. We also present the results of the search for point-like sources of neutral particles and for a large-scale anisotropy at energies around 1 EeV. While low-energy sets are compatible with isotropy, the highest-energy set with  $E > 57$  EeV shows deviations from isotropy in most of the tests at  $2 - 3\sigma$  C.L. (pre-trial).

**Keywords:** anisotropy, ultra-high energy cosmic rays, Telescope Array, correlations, autocorrelation function, large-scale structure

## 1 Introduction

The identification of sources of the ultra-high energy cosmic rays (UHECRs) with energies in excess of  $10^{19}$  eV remains one of the most intriguing unsolved problems of particle astrophysics. Small number of events at highest energies and (unknown) deflections of primary particles in the cosmic magnetic fields render this task particularly difficult. There are no obvious bright spots on the UHECR sky. Thus, the search for sources has to rely on statistical methods, of which the most straightforward one is the cross correlation between the UHECR arrival directions and positions of the candidate sources.

A number of attempts have been made in this direction. If the deflections in magnetic fields are not too large, the sources may manifest themselves as close multiplets (pairs, triples etc.) of events, which would result in a non-zero correlation function at small angles. Such a signal was reported in the AGASA data [1]. It was not, however, confirmed in other experiments. Various putative classes of sources have been tested for correlations with UHECR, and several positive signals were reported [2, 3, 4, 5]. These correlations also have not been confirmed with the accumulation of data.

An indirect information about the sources of UHECR and their propagation parameters may be obtained by measuring the large-scale anisotropy of UHECR. Because of limited propagation distance, at highest energies the UHECR flux must have originated in the local ( $< 100$  Mpc) Universe where the distribution of matter is inhomogeneous. If the deflections of UHECR in the magnetic fields do not exceed a 1–2 tens of degrees as set by the typical angular size of the local structures, the observed UHECR flux should peak

in the direction of the latter. Thus, the large-scale anisotropy may be used to directly measure the UHECR deflections, which may shed light on the magnitude of the cosmic magnetic fields and the UHECR charge composition.

In this paper we examine for anisotropy the Telescope Array (TA) surface detector (SD) data collected in the first 5 years of operation. TA is a hybrid UHECR detector located in the Northern hemisphere in Utah, USA ( $39^{\circ}17'48''$  N,  $112^{\circ}54'31''$  W) which has been fully operational since March 2008. It consists of 507 scintillator detectors covering the area of approximately  $700 \text{ km}^2$  (for details see [6]). The atmosphere over the surface array is viewed by 38 fluorescence telescopes arranged in 3 stations [7]. In this analysis we use the SD event set as the one having by far the largest statistics and a simple (geometrical) exposure.

The paper is organized as follows. We begin in Sect. 2 by describing the SD data set. We move then to global distributions of the events in the right ascension and declination. In Sect. 4 we evaluate the autocorrelation function of the UHECR events and consider their clustering. The next Sect. 5 is devoted to correlations of the TA events with AGN and other classes of point sources. In Sect. 6 we study the low-energy set with energies  $E \sim 10^{18}$  EeV. Finally, in Sect. 7 we consider correlations with the large-scale structure (LSS). Sect. 8 contains our conclusions.

## 2 Data

Most part of this analysis makes use of the special data set prepared for anisotropy studies. This set contains SD events until May 2013, that corresponds to first full 5 years of the TA operation. This data set has the zenith angle cut of  $55^{\circ}$

and the relaxed border cut. We have found that relaxing the cuts in this way does not lead to a significant loss of the data quality, while considerably increasing the number of events. This anisotropy set contains 2130 events with energies  $E > 10$  EeV, 132 events with  $E > 40$  EeV, and 52 events with  $E > 57$  EeV.

By comparing the thrown and reconstructed arrival directions of the simulated data sets, the angular resolution of TA events with  $E > 10$  EeV was found to be approximately  $1.5^\circ$ . Events with zenith angles between  $45^\circ$  and  $55^\circ$  have even better angular resolution. The energy resolution of the TA surface detector at  $E > 10$  EeV is close to 20% [8].

In the anisotropy studies the crucial role is played by the exposure function. The exposure of the TA SD detector was calculated by the Monte-Carlo technique with the full simulation of the detector. It follows from these Monte-Carlo simulations that above 10 EeV the efficiency of the TA SD is 100%, while the exposure is indistinguishable from the geometrical one with the current statistics. In order to save computational time, the geometrical exposure is used in this analysis, unless stated otherwise.

### 3 Global distribution of the TA events

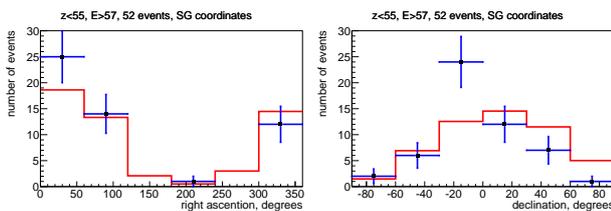
First, we examine the distributions of the TA events in the right ascension and declination in two coordinate systems: equatorial and supergalactic (SG), and three energy thresholds of 10 EeV, 40 EeV and 57 EeV. To this end we generate a large ( $10^5$ ) Monte-Carlo event set corresponding to the uniform UHECR flux modulated with the TA exposure. We then compare the distribution of the right ascensions and declinations of the events in the data and in the MC set by the Kolmogorov-Smirnov (KS) test.

No significant deviations are found in the sets with the energy thresholds of 10 EeV and 40 EeV. The smallest  $p$ -value found in these sets is 0.19. The highest-energy set with  $E > 57$  EeV shows a deviation from isotropy. The results of the KS test for this case are summarized in Table 3. The strongest deviation occurs in the supergalactic decli-

$E > 57$ EeV		
frame	right ascension	declination
equatorial	<b>0.015</b>	0.15
SG	0.06	<b>0.003</b>

**Table 1:** Results of the comparison of the data set with  $E > 57$  EeV with the uniform distribution by the KS test.

nation where the KS  $p$ -value is 0.003. The corresponding histograms are shown in Fig. 1. As is seen from from Fig. 1,



**Figure 1:** Distributions of events with  $E > 57$  EeV in right ascension (upper panel) and declination (lower panel) in supergalactic coordinates.

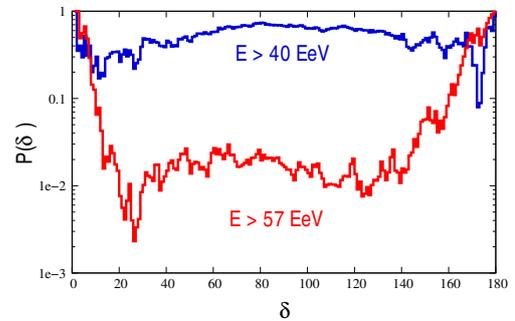
the deviation is due to an excess of events close to the supergalactic plane, as would be expected if the UHECRs were produced in the sources following the matter distribution. However, given the number of performed trials, the  $p$ -value is not sufficiently low to exclude a statistical fluctuation.

### 4 Clustering and autocorrelation function

The AGASA experiment reported clustering of UHECR events with  $E > 40$  EeV at the angular scale of  $2.5^\circ$  [1]. We repeat this analysis using the TA data set. The procedure is as follows: for a given angular separation  $\delta$  we count the number of pairs of the observed events that are separated by an angular distance less than  $\delta$ . We then generate a large number of random UHECR event sets, each having the same number of events as the data, and repeat pair counting in each of these sets. For each value of  $\delta$  we determine the fraction of simulated sets in which the number of pairs is larger than, or equal to, the number of pairs in the data. This gives the  $p$ -value,  $P(\delta)$ , which describes how likely the excess of pairs, if found in the data, is to occur as a result of a fluctuation in a random set.

First, we perform a blind test of the AGASA result. We fix the energy threshold to 40 EeV and the separation angle to  $\delta = 2.5^\circ$  and find 0 pairs while 1.5 pairs are expected in the case of a uniform distribution. Therefore, there is no excess of small-scale clusters in the TA data.

Next, we treat the separation angle  $\delta$  as a free parameter and determine the dependence  $P(\delta)$ . This test has been performed at two energy thresholds, 40 EeV and 57 EeV. The result is presented in Fig. 2 where the upper blue and



**Figure 2:** The dependence of the  $p$ -value  $P(\delta)$  on the pair separation angle  $\delta$  for two energy thresholds: 40 EeV and 57 EeV (upper blue and lower red lines, respectively).

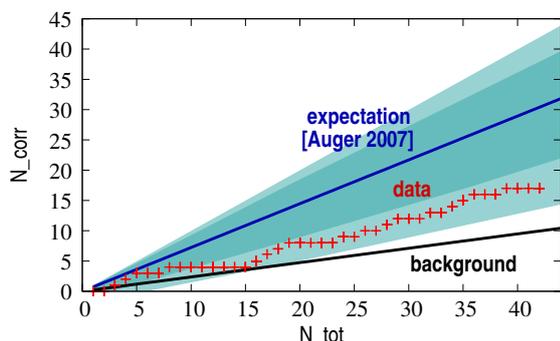
the lower red lines correspond to the thresholds 40 EeV and 57 EeV, respectively. As one can see, there is a deviation from the isotropy at angular scales  $\sim 20^\circ$  in the highest-energy data set. This deviation is consistent in angular scale with the one discussed in Sect. 3.

### 5 Correlations with AGN and other classes of point sources

Given the catalog of putative sources, one may check whether the objects in the catalog correlate with the arrival directions of UHECRs. This can be done as follows. First, the probability  $p_0$  is determined by the Monte-Carlo simulation that, for a given set of sources and a fixed angular separation  $\delta$ , a single UHECR event falls within the angle  $\delta$  from any of the sources, assuming the events are dis-

tributed uniformly. Then one counts the number  $n$  of pairs source – observed UHECR event that are separated by an angular distance less than  $\delta$ . The  $p$ -value that characterizes the correlation at the angular scale  $\delta$  is then obtained from the cumulative binomial distribution. The angular scale  $\delta$  can either be fixed *a priori*, or scanned over, in which case the penalty should be applied.

We first apply this formalism to the nearby AGNs from the Veron-Cetty & Veron 2006 catalog [9]. We fix the parameters following Ref.[4] as follows:  $\delta = 3.1^\circ$ ,  $E > 57$  EeV, the maximum redshift is 0.018 (472 AGNs in total). Following the previous analysis [10], we apply the zenith angle cut of  $45^\circ$  and tight border cuts. The evolution of the number of correlating events with the total number of events is shown in Fig. 3. With these parameters one



**Figure 3:** The number of TA events correlating with nearby AGN vs. total number of events.

finds  $p_0 = 0.24$ , while the number of correlating events corresponding to the total of  $N = 42$  events is  $n = 17$ . This gives the  $p$ -value  $p = 0.013$ .

Similar to the AGN, other classes of putative sources may be tested for correlations with UHECR. The difference, however, is that in the case of other sources the parameters of the correlations (such as, e.g., the separation angle and the maximum redshift of the sources) are not set in advance and should be scanned over. When assessing the statistical significance, the scanning over parameters should be compensated by a penalty factor, which is calculated by the simulation of the entire search procedure.

As candidate sources of UHECR we have examined the objects in the 13th edition of the Veron-Cetty & Veron catalog [11], and in several compilations based on measurements at different wavelength, namely (1) radio: the third Cambridge catalog of radio sources catalog (3CRR) [12] (2) infrared: the 2MASS (the Two Micron All-Sky Survey) redshift survey catalog (2MRS) [13] (3) X-Ray: Swift BAT (Burst Alert Telescope) 58-Month hard X-ray survey catalog (SB-58M) [14] and 60-Month AGN survey catalog (SB-AGN) [15] (4) and Gamma-ray: 2nd Fermi large area telescope AGN catalog (2LAC) [16]. In each catalog, only those objects that have redshift information were selected. The following parameters were adjusted during the scan: the separation angle from  $0$  to  $15^\circ$ , the maximum redshift from  $0$  to  $0.03$  and the UHECR subset threshold energy from  $40$  EeV to infinity. We found that the best correlation occurs with the Swift BAT (60-month) AGN catalog, with the pre-trial  $p$ -value  $p = 1.3 \times 10^{-5}$  and the post-trial  $p$ -value with all penalties included  $p = 0.09$ . Thus, no significant correlation is found with any of the considered catalogs.

## 6 Point sources and large-scale anisotropy at low energies

The AGASA experiment has reported an excess of UHECR in the direction of the Galactic center at energies around  $10^{18}$  EeV [17]. To check this claim, we have prepared a special low-energy set of events observed by the TA SD where the tight cuts optimized to improve the energy resolution were relaxed and the number of events has significantly increased. In the energy region  $10^{18} - 10^{18.4}$  EeV relevant for the AGASA excess this set contains  $\sim 1.6$  times more events than were used in the AGASA analysis.

To check for large-scale excesses/deficits of the UHECR events we constructed the event density map averaged over the circles of  $20^\circ$  centered on the  $1^\circ \times 1^\circ$  grid. The background was estimated by the time-swapping method. No significant excesses or deficits were found, while the estimates making use of the AGASA results show that  $\sim 5 - 6\sigma$  deviations are expected.

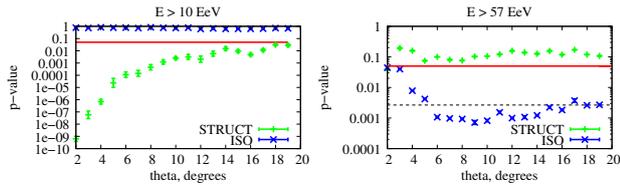
With the same data set we have searched for point sources. At energies  $\sim 10^{18}$  EeV the deflections in the magnetic fields are large and completely destroy source images unless the primary particles are neutral, an example being neutrons from the Galactic sources. The background was estimated by the on source – off source method developed by the Tibet AS $\gamma$  experiment [18]. No significant point-like excess has been found. Hence, the upper limit on the neutron flux corresponding to an averaged flux  $0.067 \text{ km}^{-2} \text{ yr}^{-1}$  above  $1$  EeV in the Northern sky has been set at the 95% confidence level.

## 7 Correlation with the LSS

The UHECR sources, regardless of their nature, are expected to trace the matter distribution. In the limit when the density of sources is sufficiently high so that they can be treated statistically, the UHECR flux can be calculated, as a function of energy, with essentially one free parameter, the typical deflection angle  $\theta$ . The predicted flux may be compared to observations and thus give constraints on the possible values of  $\theta$ . The analysis of this type has been previously performed using the HiRes [19], the PAO [20, 21] and the TA [10] data.

We have examined the most recent TA data set for correlations with the LSS. The mass distribution in the Universe was inferred from the 2MASS Galaxy Redshift Catalog (XSCz) that is derived from the 2MASS Extended Source Catalog (XSC). We have assumed that sources follow the matter distribution, and propagated UHECRs from sources to the Earth taking full account of the energy attenuation processes under the assumption that the primary particles are protons. The arrival directions were smeared with the 2d Gaussian function of the angular width  $\theta$ .

The map of the predicted flux was compared to the sky distribution of the observed UHECR events by the parameter-free flux-sampling test (see Refs. [22, 10] for details). At a given value of  $\theta$ , the result of the test is the  $p$ -value that shows how likely it is that the UHECR distribution follows the one expected in a given model (LSS or isotropy). The results of the test, as a function of  $\theta$ , are shown in Fig. 4 for two energy thresholds of  $10$  EeV and  $57$  EeV as indicated on the plots. The blue crosses and green pluses show the  $p$ -values obtained by testing the isotropy and the LSS model, respectively. The red horizontal line shows the confidence level of 95%.



**Figure 4:** P-values obtained by the flux-sampling test. The blue crosses and green pluses correspond to testing the isotropy and the LSS model, respectively. The red horizontal line shows the *a priori* chosen confidence level of 95%.

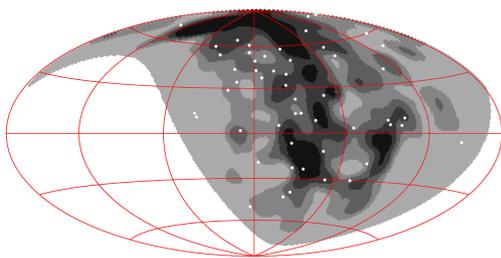
At low energies  $E > 10$  EeV, the data are compatible with isotropy and not compatible with the structure model unless the smearing angle is larger than  $\sim 20^\circ$ . This is expected, since even in the case of protons, and taking into account the regular component of the Galactic magnetic field only, the deflections of the UHECR at  $E \sim 10$  EeV are expected to be of the order of  $20 - 40^\circ$ , depending on the direction.

At intermediate energies  $E > 40$  EeV (not shown on Fig. 4), the situation is similar. The TA data are compatible with the isotropic distribution and not compatible with the LSS model unless the deflections exceed  $\sim 10^\circ$ .

Finally, at the highest energies  $E > 57$  EeV, the behavior is different. The data are compatible with the structure model but incompatible with the isotropic distribution at the  $\sim 3\sigma$  C.L. (pre-trial), for most values of the smearing angle.

## 8 Summary and conclusions

In summary, we have examined the 5-year TA SD data set for various possible deviations from isotropy: distributions in the right ascension and declination in equatorial and supergalactic coordinates, clustering, correlations with AGNs and other putative sources, correlation with the LSS of the Universe.



**Figure 5:** Sky map of the TA events with  $E > 57$  EeV in the Galactic coordinates. Bands of gray show the flux distribution expected in the LSS model of sources with the smearing angle of  $6^\circ$ .

The low-energy set  $E \sim 10^{18}$  EeV and the two sets with  $E > 10$  EeV and  $E > 40$  EeV show no deviation from isotropy in any of the performed tests. At the same time, the highest-energy set with  $E > 57$  EeV behaves differently and deviates from isotropy in a number of tests, including global distribution of events, autocorrelation function, correlation with AGNs and with the LSS. Inspection of the event distribution in Fig. 5 suggest that all these deviations may result from a concentration of the events in a region around ( $l \sim 180^\circ$ ,  $b \sim 45^\circ$ ), which is not far from the supergalactic

plane. However, the statistical significance of this “hot spot” is not yet sufficient to exclude a fluctuation.

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