A COMMENT ON CATALOG SEARCHES

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We illustrate in a concrete example that a mere positional correlation of highest-energy cosmic rays with active galactic nuclei (AGN), although suggests, does not necessarily imply that the latter are sources of the cosmic rays. Different interpretations of this correlation are possible, and signatures other than positional correlations are needed to discriminate between them. We point out that some of these signatures seem to disfavor the AGN interpretation with already existing data.

In this talk I would like to clarify two points related to the correlations between the ultra-high energy comic rays (UHECR) and nearby active galactic nuclei (AGN) from the catalog [1], which were recently found by the Pierre Auger Observatory (PAO) [2,3].

1 Contrary to naive expectation, a correlation of cosmic rays with AGN (or any other objects) *does not* automatically imply that the latter are cosmic ray sources. This is not related to the significance of the correlation, but follows from the very nature of the statistical test performed to establish the correlation. In positional correlation analysis one compares the distribution of the data events over the sky with the *isotropic* distribution. If the two distributions are found to be incompatible, this means simply that the data are *not isotropic*. The actual sources should be identified by different methods.

To illustrate the relevance of this point consider a concrete example. The same set of cosmic ray events which correlate with AGN in the PAO analysis may be cross-correlated, by the same method, with just one object for which we take Cen A, an active galaxy in the direction of the Centaurus supercluster. Cen A is a radio-galaxy which is exceptionally close to us: the distance to Cen A is about 3.5 Mpc. It possesses jets and radio lobes, the usual attributes of a potential acceleration site.

There is an excess of events in the data in the direction of Cen A. The significance of the excess at a given angular scale δ can be characterized by the probability $P(\delta)$ that equal or larger excess occurs by chance as a result of a fluctuation in the uniform distribution. The smaller is the probability to obtain a given excess by chance, the more significant it is. This probability may be determined by

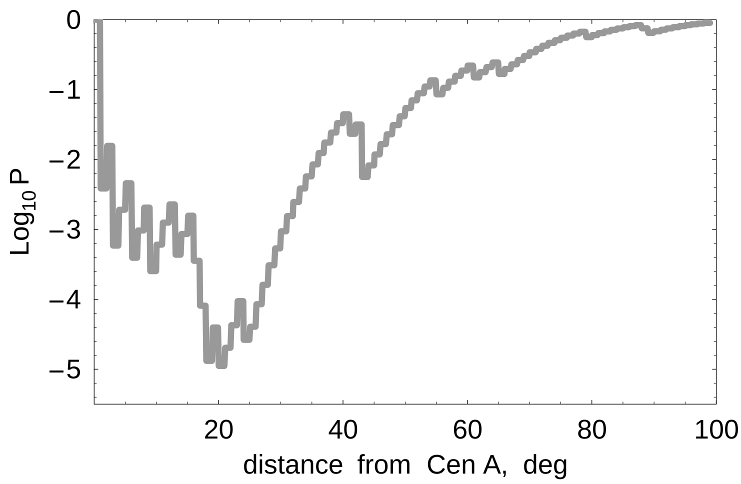

Figure 1: The probability P that the observed excess of events within angular distance δ around Cen A has occured by chance. The values of P are indicative only since their calculation accounts neither for the statistical penalty associated with the choice of angular scale nor for the bias in the sample.

the Monte-Carlo simulation. The result of the simulation is shown in Fig. 1. One can see that the excess is most significant at about 20°. Out of 27 events in total, 9 events fall within 20° from Cen A while only 1.5 are expected for the uniform distribution. Note that the events contributing to this correlation with Cen A are the same events that contribute to the correlation with AGN if the latter are assumed to be sources.

Such a situation is explained in the following way. The distribution of the nearby AGN is rather inhomogeneous. Moreover, Cen A is projected onto one of the largest nearby structures, the Centaurus supercluster, as can be seen on Fig.2. For this reason, the same data show correlations with both Cen A and AGN. Importantly, if either AGN or Cen A are indeed sources of highest-energy cosmic rays, *both* correlation signals will *increase* with the accumulation of statistics. So, a mere increase of significance will not allow to discriminate between the two possibilities.

2 It follows from the above that alternative signatures are needed to distinguish between the two cases. We present here one of such signatures.

The idea is that the cosmic ray flux predicted by the AGN hypothesis can be computed and compared to the observed one. In this way the AGN hypothesis itself will be subject to a test, not the hypothesis of the isotropic distribution.

The computation can be performed in a straightforward way taking into account the distance to AGN and the attenuation of protons of different energies (see Refs.[7,8] for details). The results are presented in Fig. 2 in the form of red crosses which show the positions of the nearby AGN. The intensity of a cross represents its expected contribution to the flux. This figure should be understood in a statistical sense: the fluxes of individual sources cannot, of course, be predicted without the detailed modeling of corresponding AGN (for which modeling there is probably not enough information anyway). However, in large groups of galaxies like galaxy clusters individual differences in luminosity will average away and only the common factors determined by the distance will remain. The relative contributions to the total flux from such groups can thus be reliably predicted.

One can observe the overdensity of the events in the direction of the Centaurus supercluster. The second region where a high flux is expected, the Virgo cluster, is completely devoid of events. This is a strange feature that does not look compatible with the AGN hypothesis.

The latter statement can be quantified by comparing the expected and observed distributions of events in the angular distance from the center of the Virgo cluster, as well as their distributions in Galactic and supergalactic longitudes and latitudes. The comparison may be performed by the Kolmogorov-Smirnov test. The results of different tests show different degree of incompatibility between the predicted and observed distributions with the probability that it has occured as a result of a

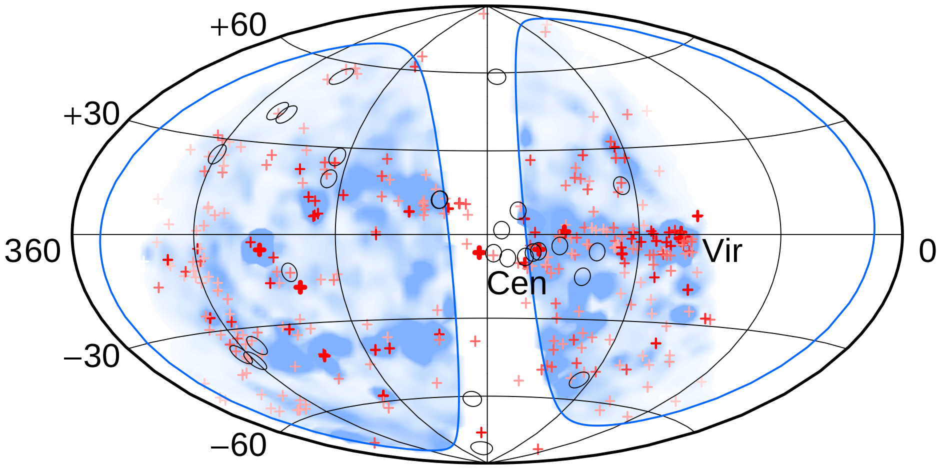

Figure 2: Hammer projection of the celestial sphere in supergalactic coordinates. Crosses show positions of nearby AGN. The color saturation of a given cross indicates the expected cosmic-ray flux with the account of the PAO exposure and the $1/r^2$ suppression, r being the distance to the source. Open circles represent 27 highest-energy cosmic rays detected by PAO. Shading shows the expected cosmic-ray flux from sources that follow the local matter distribution smoothed at the angular scale of 3.1° and convoluted with the PAO exposure (darker regions correspond to higher cosmic-ray flux). Blue lines cut out the region with Galactic latitude $|b| < 15^\circ$ where the latter flux cannot be determined because of incompleteness of the source catalog. The positions of the Centaurus (Cen) and Virgo (Vir) superclusters are indicated.

fluctuation varying from 10% to 10^{-4}. Taking into account the strongest discrepancy and the number of tests performed, we estimate the significance of the tension between the AGN hypothesis and the data to be of order 99%.

One of the drawbacks of the analysis just described is the incompleteness of the AGN catalog. To check how much our results depend on this incompleteness we have replaced the catalog of AGN by a complete catalog of galaxies containing objects up to 270 Mpc [9]. The above tests performed with the AGN catalog replaced by the complete galaxy catalog show similar results. We think therefore that incompleteness of the catalog is not an issue.

Another drawback, which unfortunately cannot be avoided at present, is the *a posteriori* nature of the tests performed. To avoid this problem, the tests which we have described will have to be repeated with the new independent data. This is why now, before the new data arrive, it is particularly important to formulate other hypotheses and procedures to test them which may then be performed in a more reliable *a priori* way with independent data sets.

Acknowledgments

This work is supported in part by Belgian Science Policy under IUAP VI/11, by IISN and by the FNRS contract 1.5.335.08.

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