Discriminating potential astrophysical sources of the highest energy cosmic rays with the Pierre Auger Observatory

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***Abstract*. We compare the distribution of arrival directions of the highest energy cosmic rays detected by the Pierre Auger Observatory from 1 January 2004 to 31 March 2009 with that of populations of potential astrophysical sources. For this purpose, we use several complementary statistical tests allowing one to describe and quantify the degree of compatibility between data and a given catalogue of sources. We applied these tests to active galactic nuclei detected in X-rays by SWIFT-BAT and to galaxies found in the HI Parkes and in the 2 Micron All-Sky Surveys.**

***Keywords*: UHECRs, Anisotropy, Astrophysical catalogues**

I. Introduction

The origin and nature of the ultra high energy cosmic rays (UHECRs) are still unknown after more than half a century since their discovery. The deflections encountered by UHECRs during their propagation through galactic and extra galactic magnetic fields make a direct identification of their sources difficult.

Recently, the Pierre Auger Collaboration reported a correlation between the arrival directions of the highest energy events observed ($E \geq 6 \times 10^{19}$ eV) and the directions of known active galaxies closer than 100 Mpc [1], [2]. An update of this analysis [3] with data collected up to 31 March 2009 shows that the evidence for anisotropy remains at the 99% confidence level, although the correlation has not strenghtened. In any case, this result does not imply that AGN are indeed the actual sources of UHECRs, since many other source scenarios could in principle reproduce the observed data.

In the present study, we compare the arrival directions of data from the Pierre Auger Observatory with the position of potential astrophysical sources. First, we compute the standard cross-correlation function between the observed arrival directions and a volume-selected sample of galaxies from the 2MRS [4] catalogue, under the simple assumption of an equal contribution of each source to the cosmic ray flux. Then we compare our data with three different catalogues (X-ray AGNs detected by SWIFT [5], galaxies in the HI-Parkes [6], [7] and 2MRS surveys) taking into account the intrinsic luminosity and the distance of the sources. For this comparison, we use two complementary methods: a likelihood test and a test based on the scalar product of functions on the sphere.

II. Data set

The data set consists of 58 events recorded by the Pierre Auger Observatory from 1 January 2004 to 31 March 2009, with energies reconstructed above 55 EeV and zenith angles smaller than $60°$. The energy resolution is 17% , with a systematic uncertainty of 22%[8]. The angular resolution, defined as the angular radius that would contain 68% of the reconstructed events is $\leq 0.9°$. We use the energy threshold that maximizes the departure from isotropy through the correlation with AGN [1]. This particular value corresponds to the region where the energy spectrum of UHECRs [8] presents a significant deviation from the power-law extrapolated from lower energy. This supports the idea of a sharp reduction of the cosmic rays horizon due to the GZK effect [9], [10], at energies greater than $\simeq 50 - 60$ EeV, limiting drastically the number of contributing sources.

III. Astrophysical catalogues

Recent analysis comparing Auger data with the SWIFT-BAT and HIPASS catalogues can be found in [11], [12], [13]. The 22 months SWIFT-BAT [5] catalogue provides the most uniform all-sky hard X-ray survey to date, it contains a total of 261 Seyfert galaxies and AGN. The HIPASS [6], [7] galaxy catalogue contains a large number of extragalactic HI sources that could host preferentially GRBs and magnetars producing UHECRs. Here, we adopt the flux limit $S_{int} > 9.4$ Jy km s^{-1} following [13], leading to a total number of 3058 galaxies. As in [12], we also consider a sub-sample of the HIPASS catalogue, that we call HIPASS HL in the following text, that contains the 765 most luminous galaxies. We use the compilation (2MRS) provided by Huchra et al. [4] of the redshifts of the $K_{\rm mag} < 11.25$ brightest galaxies from the 2MASS[14] catalogue. The catalogue, containing $\simeq$ 23000 sources, provides an excellent image of the distribution of local matter. For the cross-correlation analysis, we use a volume-selected sample of galaxies from the 2MRS catalogue (2MRS VS thereafter) to prevent a bias toward the faint galaxies at small distances. We select galaxies with 10 Mpc $<$ $d < 200$ Mpc and absolute magnitudes $M_k < -25.25$, leading to 1940 objects in this sub-sample. For 2MRS, we exclude from the analysis UHECRs events (and sources for 2MRS VS) that have $|b| < 10°$ to avoid a bias due to incompleteness in the galactic plane region.

IV. Data analysis

A. Cross-correlation

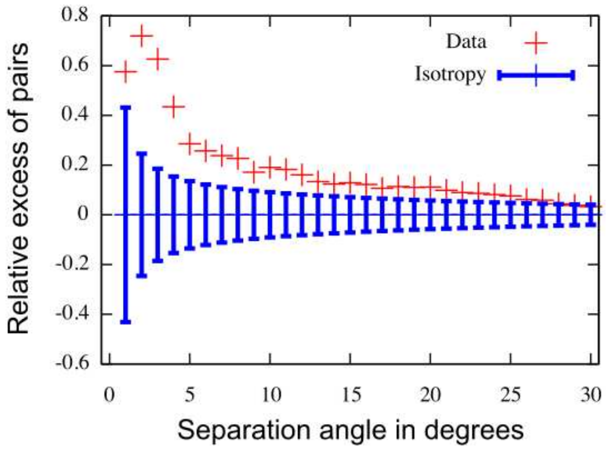


Fig. 1. Cross-correlation between Auger data and 2MRS VS galaxies: cumulative relative excess of pairs as a function of the separation angle. Error bars represent the dispersion in 68% of isotropic realizations.

The cross-correlation function with 2MRS VS is shown in figure 1. There is a clear excess of pairs for separation angles smaller than 30°. The most significant departure from isotropy is observed at 3°: the fraction of simulated samples that give a higher number of pairs than in the data is $f \simeq 1.5 \times 10^{-3}$. Under the basic assumption of an equal contribution of each source to the cosmic ray flux, this simple result is an indication that the arrival directions of the UHECRs are partially correlated to the local distribution of matter.

B. Smoothed density maps

For each catalogue, we can build a density map with two free parameters: the smoothing angle and the fraction of isotropic background. Because of the lack of strong physical input for these parameters, we use the data to determine their best fit values for each catalogue. The smoothed maps are described by a function $F_c(\mathbf{n})$, which is normalized such that its value in a given direction $\mathbf{n}$ corresponds to the predicted probability of detecting a cosmic ray in that direction, according to the model.

We add an isotropic background in the density map as a free parameter to account for the missing flux, for it is very likely that the catalogue does not contain all the cosmic rays sources.

We write the function $F_c(\mathbf{n})$ as :

$$F_c(\mathbf{n}) = I^{-1}\,\varepsilon(\mathbf{n})\mu(\mathbf{n})\left[\frac{f_{\rm iso}}{\Omega} + (1-f_{\rm iso})\frac{\phi_c(\mathbf{n})}{\langle\phi\rangle}\right]$$

where $\phi_c(\mathbf{n})$ is the flux coming from the catalogue objects and $f_{\rm iso}$ the fraction of isotropic background, the quantities $\Omega = \int \mathrm{d}\Omega' \mu(\mathbf{n})$ and $\langle\phi\rangle = \int \mathrm{d}\Omega \mu(\mathbf{n})\phi_c(\mathbf{n})$ accounting for the normalization. The relative exposure of the Pierre Auger Observatory is taken into account by a purely geometrical function $\varepsilon(\mathbf{n})$ computed analytically. The catalogue mask function $\mu(\mathbf{n})$ is equal to 0 in the regions of the sky that must be removed, and 1 elsewhere. Finally, the global normalization constant I ensures that the integral of $F_c(\mathbf{n})$ is equal to unity.

The flux coming from the $N_{\rm cat}$ sources is given by:

$$\phi_c(\mathbf{n}) = \sum_{i=1}^{N_{\rm cat}} w(z_i)\, e^{-\frac{d(\mathbf{n_i},\mathbf{n})^2}{2\sigma^2}}$$

where $d(\mathbf{n_i},\mathbf{n})$ is the angle between the direction of the source $\mathbf{n_i}$ and the direction of interest $\mathbf{n}$. The free parameter σ (smoothing angle) enables us to take into account the angular resolution of the Pierre Auger Observatory and the deflections experienced by cosmic rays, under the simplifying assumption that these deflections are purely random and gaussian. A weight $w(z_i)$ is attributed to the ith source located at redshift z_i. In this study, we assume a weight proportional to the flux ϕ_i of the source, measured in a given range of wavelengths (X-rays for SWIFT-BAT, radio for HIPASS and near IR for 2MRS), multiplied by an attenuation factor due to the GZK suppression, that is implemented following [13].

For each catalogue, we find the values of σ and $f_{\rm iso}$ that maximize the log-likelihood of the data sample:

$$\mathcal{LL} = \sum_{k=1}^{N_{\rm data}} \ln F_c(\mathbf{n_k})$$

where $\mathbf{n_k}$ is the direction of the kth event. The results are shown in fig. 2 (a). We find $(\sigma, f_{\rm iso}) = (7.1°, 0.65)$ for SWIFT-BAT, $(1.4°, 0.7)$ for 2MRS, $(6°, 0.64)$ for HIPASS and $(5.3°, 0.67)$ for HIPASS HL. For the following analyses, we use these parameters, though they are not strongly constrained with the present statistics.

C. Results of the likelihood test

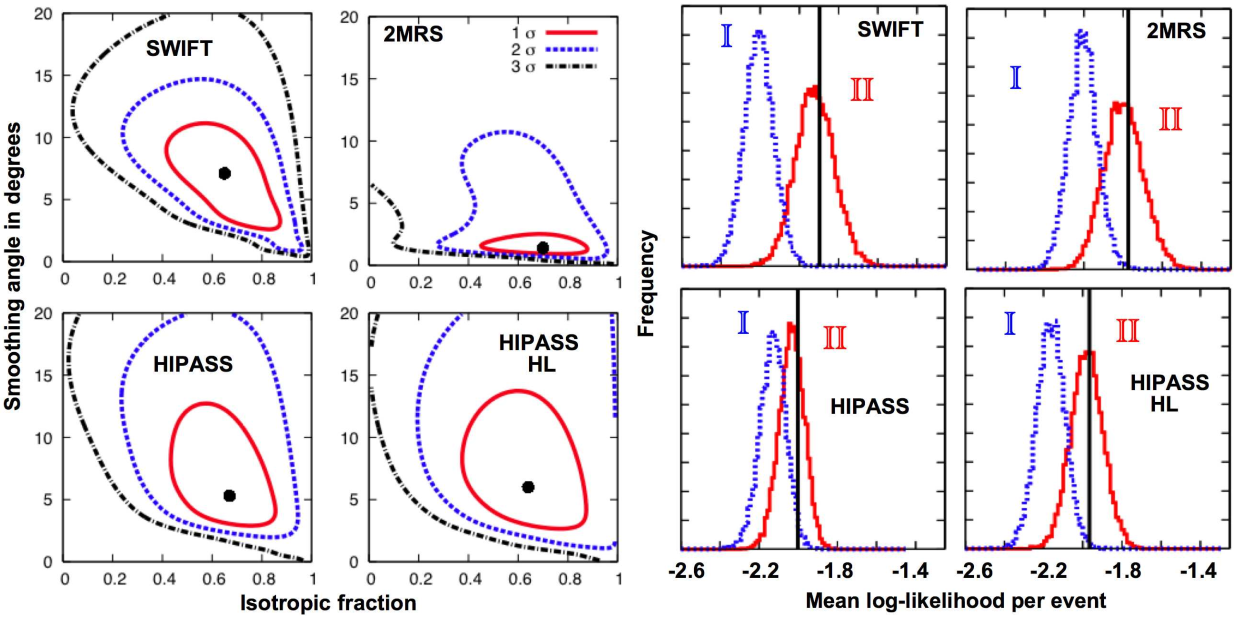
Finding the values of σ and $f_{\rm iso}$ that maximize the log-likelihood does not ensure that the model fits well the data. To test the compatibility between data and model, we generate 10^4 simulated data samples, containing the same number of events as in the data. The points are either drawn from the model density map or isotropically, and we compare the distributions of the mean log-likelihood ($\mathcal{LL}/N_{\rm data}$) with the value obtained for the data. The results are illustrated in fig. 2 (b).

The data are in agreement with all models and significantly different from isotropic expectations. The fraction of simulated isotropic realizations that give a higher value than the data is around 10^{-5} for SWIFT, 10^{-3} for 2MRS and HIPASS HL and 10^{-2} for HIPASS.

The likelihood test is, by its intrinsic nature, only sensitive to the fact that data points lie or not in high density regions of the catalogue. We thus use a complementary method to test if all regions of the catalogue are fairly represented in the data set.

D. The 2-fold correlation coefficients method

This test is based on the computation of two coefficients characterizing the compatibility between the smoothed density map of the model and a similar density



(a) (b)

Fig. 2. (a) Probability contours for the log-likelihood maximisation. The maximum is indicated by a black point. (b) Distributions of mean log-likelihood per event for the isotropy (labelled as I) and for the model (II). Data is indicated by a black vertical line.

map computed for the data. We apply a gaussian filtering to the $N_{\rm data}$ data points to obtain the following density map:

$$F_d(\mathbf{n}) = \frac{\mu(\mathbf{n})}{2\pi\sigma^2\, N_{\rm data}} \sum_{j=1}^{N_{\rm data}} \exp\left(-\frac{d(\mathbf{n_j},\mathbf{n})^2}{2\sigma^2}\right)$$

The first coefficient, called ”correlation coefficient” is given by:

$$C(F_d, F_c) = \frac{\int F_c(\mathbf{n})F_d(\mathbf{n})\,{\rm d}\Omega}{\sqrt{\int \left(F_c(\mathbf{n})\right)^2 {\rm d}\Omega \;\int \left(F_d(\mathbf{n})\right)^2 {\rm d}\Omega}}$$

This coefficient ranges from 0 (F_c and F_d are anticorrelated) to 1 (F_c and F_d are identical). A high value of $C(F_d, F_c)$ indicates a good match between data and model distributions. The second coefficient, called ”concentration coefficient” is defined by:

$$I_{dd} = \int F_d^2(\mathbf{n})\,{\rm d}\Omega.$$

This second observable carries the information about the intrinsic clustering properties of the angular distribution of the data. The magnitude of I_{dd} depends on the density map contrast: it is maximum if all the data points have the same position on the sky, and minimum if the points are uniformly distributed on the sphere. These coefficients are related to the standard two point cross and auto-correlation functions.

For each model, we generate 10^4 simulated samples containing the same number of events as in the data. The points are either drawn from the model density map or isotropically. Fulfilling the test requires that both C and $I_{\rm dd}$ distributions obtained with simulated sample are compatible with the values computed with the data.

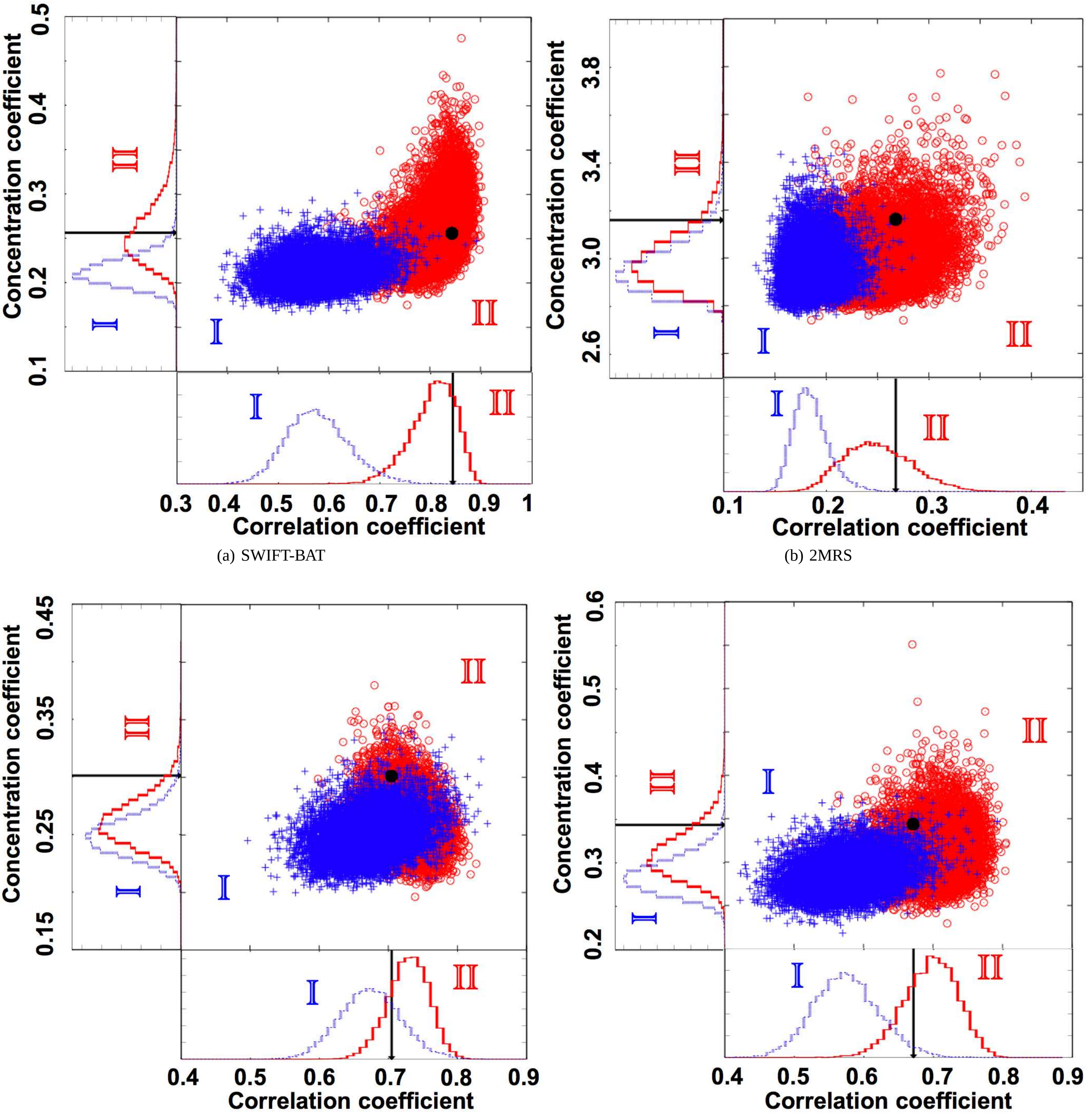
The results of the test are shown in fig. 3. The data are compatible with all models, the map based on SWIFT-BAT gives, as in the likelihood test, the most discriminant test against isotropy. The fraction of isotropic simulations that have both a higher correlation and concentration coefficients than the data is $\sim 4{\times}10^{-3}$ for HIPASS and lower than 10^{-4} for SWIFT-BAT.

V. Conclusion

The Pierre Auger Observatory has recorded 58 cosmic rays with energies $E > 55$ EeV between 1 January 2004 and 31 March 2009. Different complementary tests are applied to extract information about the compatibility between the arrival directions of Auger events and models based on catalogues of potential astrophysical sources or isotropic distributions.

When performing a cross-correlation analysis with the 2MRS VS catalogue, we find an excess of pairs over a range of angular scales, indicating that the UHECRs may be partially correlated to the distribution of local matter (under a basic ”equal flux” assumption). We then apply two other tests that require the computation of smoothed maps of expected cosmic ray flux. The maps have two free parameters, that are determined through the maximization of the likelihood of the data.

The log-likelihood and the 2-fold correlation coefficients tests show that our data are different from isotropic expectations and compatible with the models based on SWIFT-BAT, 2MRS and HIPASS catalogues with the parameters maximizing the likelihood. Within one standard deviation, these parameters are $\sigma \leq 10°$ and $f_{\rm iso} \in [0.4; 0.8]$. The map based on SWIFT-BAT gives the most discriminant test against isotropy.



(a) SWIFT-BAT

(b) 2MRS

(c) HIPASS

(d) HIPASS High Luminosity

Fig. 3. Two dimensional distributions of the correlation and concentration coefficient for isotropic simulations (labelled as I) and for the model (labelled as II). The value obtained with data is indicated by a black point. The individual distributions of the correlation and concentration coefficients are shown, the data being indicated by a vertical line.

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