On the arrival directions of the highest energy cosmic rays detected by the Pierre Auger Observatory

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We report different analyses of the arrival directions of the highest energy cosmic rays detected by the Pierre Auger Observatory between 1 January 2004 and 31 December 2009. We update the measured fraction of arrival directions correlating with the positions of objects in the Véron-Cetty and Véron (VCV) catalog. We examine the arrival directions in relation to other populations of nearby extragalactic objects: galaxies in the 2 Microns All Sky Survey and active galactic nuclei in the Swift-BAT hard X-ray catalog. We also show the 2-point autocorrelation function and analyse the sky region with the largest excess compared to isotropic expectations.

1. Introduction

Using data collected through 31 August 2007, the Pierre Auger Collaboration reported in [1] a correlation between the arrival directions of ultra-high-energy cosmic rays (UHECR) with energies above 56 EeV and the positions of nearby objects from the 12th edition of the catalog of quasars and active galactic nuclei (AGNs) by Véron-Cetty and Véron [2] (VCV catalog). The null hypothesis of isotropy was rejected with 99% c.l. based on a single-trial test that was motivated by early data and confirmed by data collected subsequent to the definition of the test. This correlation with nearby extragalactic objects is consistent with UHECR from more distant sources having lost energy in accordance with the flux suppression seen in the measured energy spectrum [3–5] and the GZK expectation. However, the VCV correlation is not sufficient to identify individual sources or a specific class of astrophysical sites of origin. The VCV catalog is a compilation of known AGNs that is neither homogeneous nor statistically complete. Moreover, active galaxies in this catalog trace the nearby large scale matter distribution, thus including all types of candidate astrophysical sources, not only AGNs and their subclasses.

2. The Observatory and the dataset

The surface array of the Pierre Auger Southern Observatory, located in the Province of Mendoza, Argentina, consists of 1600 water-Cherenkov detectors laid out over 3000 km² on a triangular grid of 1.5 km spacing. It has been in operation since 1 January 2004, increasing its size from 154 detectors up to 1600 by June 2008. In the
present analysis, we consider events recorded between 1 January 2004 and 31 December 2009 with zenith angles $\theta \leq 60^\circ$ and reconstructed energy $E \geq 55$ EeV: 69 events satisfy these requirements. The integrated exposure is $20370 \pm 610$ km$^2$ sr y.

The arrival directions are obtained through the differences in the time of flight of the shower front among the triggered detectors. The angular resolution is better than $0.9^\circ$ for events with $E \geq 10$ EeV [10]. We have tested that the angular resolution has been stable within $0.1^\circ$ during the period of the present analysis.

The estimator for the primary energy is the reconstructed signal at 1000 m from the shower core, $S(1000)$. The conversion from $S(1000)$ to energy is derived experimentally through the use of a subset of showers detected simultaneously by the fluorescence detector and the surface array. The energy resolution is about 15% and the absolute energy scale has a systematic uncertainty of 22% [3,4]. We have checked the time-stability of the energy assignment by studying the fluxes in the energy range from 10 to 55 EeV as a function of time (see [6] for details). We have split the dataset in five different periods with similar exposure. From the obtained fluxes we derive that the energy resolution of the Observatory has been stable to 5% over the six years of data taking. The fluxes derived from the small number of events above 55 EeV are similarly constant.

3. Analysis of the arrival directions

3.1. Update of the correlation study with AGNs in the VCV catalog

The data reported in [1] consist of 27 events with energy larger than $E_{\text{th}} = 55$ EeV (in the present energy calibration). These data provided evidence for anisotropy in the arrival directions of cosmic rays with the highest energies. The confidence level for the rejection of the isotropic hypothesis was established through a specific test using prescribed values of the energy threshold ($E \geq 55$ EeV), maximum angular separation ($\psi \leq 3.1^\circ$), and maximum redshift ($z \leq 0.018$). These were chosen in an exploratory scan as those that minimised the probability that the correlation with AGNs in the VCV catalog could occur by chance if the flux were isotropic. The test was then performed using independent data collected subsequent to the exploratory scan. It measured the fraction of arrival directions that are less than $3.1^\circ$ from the position of an AGN within 75 Mpc in the VCV catalog. The fraction expected under the isotropic hypothesis is 21%. The test passed with 6 out of 8 events correlating under the specified parameters, establishing a 99% confidence level for rejecting the hypothesis that the distribution of arrival directions is isotropic. The fraction of correlating events for the data set reported in [1] (excluding those used in the exploratory scan) was 9 out of 13, i.e., $(69^{+11}_{-13})\%$.

The UHECR events additional to those reported in [1] are 42. 12 of them correlate with objects in the VCV catalog under the prescribed parameters. The number of correlations expected by chance if the arrival directions were isotropically distributed is 8.8. To give an updated estimate of the degree of correlation we include all data except those used in the exploratory scan for the optimization of the parameters to maximise the correlation. The usable dataset includes 55 events. The current estimate of the amount of correlation is $(38^{+7}_{-6})\%$, with 21 correlating events out of 55.

The cumulative binomial probability that an isotropic flux would yield 21 or more correlations is $P = 0.003$. This updated measurement with 55 events after the initial scan is a posteriori, with no prescribed rule for rejecting the hypothesis of isotropy as in [1]. No unambiguous confidence level for anisotropy can be derived from the probability $P = 0.003$. $P$ is the probability of finding such a correlation assuming isotropy. It is not the probability of isotropy given such a correlation.

Note that a more recent version of the VCV catalog is available now [11]. Conclusions are similar if the arrival directions are compared to the distribution of objects in this latest version.

3.2. Study of the correlation with other catalogs

We examine here the 69 arrival directions with regard to their correlation with galaxies in the 2MRS catalog and AGNs detected by Swift-BAT. The same minimum energy of UHECR will be
used for these studies as prescribed for the VCV test. It is thus important to note that all of these studies are made *a posteriori*. None of the results can be used to derive unambiguously a confidence level for anisotropy.

The 2MRS catalog, the most densely sampled all-sky redshift survey, is a compilation provided by Huchra et al. [7] of the redshifts of the $K_{\text{mag}} < 11.25$ brightest galaxies from the 2MASS catalog [8]. It contains about 13000 galaxies within 100 Mpc, and 22000 within 200 Mpc. Due to its incompleteness in the galactic plane region, we exclude from all analyses involving this catalog galaxies (as well as UHECR arrival directions) with galactic latitudes $|\theta| < 10^\circ$.

The Swift-BAT hard X-ray catalog is the most sensitive all-sky survey in this band. We use here the 58-month version [9] and we consider all Seyfert galaxies, beamed AGNs, and galaxies likely to be AGN. There are 189 of them within $\approx 100$ Mpc, and 373 within $\approx 200$ Mpc.

### 3.2.1. Cross-correlation of cosmic rays and nearby extragalactic objects

We have performed a cross-correlation analysis between arrival directions of UHECR and positions of the objects in the 2MRS and Swift-BAT catalogs that lie within 200 Mpc. Each arrival direction forms a pair with every object. For the cross-correlation estimator, we use the fractional excess (relative to the isotropic expectation) of pairs having angular separations smaller than any angle $\psi$. We show in Fig. 1 the relative excess of pairs in data (black dots) in the case of Swift-BAT AGNs. The bands in the plot contain the dispersion in 68%, 95%, and 99.7% of simulated sets of the same number of events assuming isotropic cosmic rays. Correlation in excess of the isotropic expectation are observed, this being true also for the case of 2MRS catalogue [6]. Note however that the existence of cross-correlation does not imply that the arrival directions are distributed in the sky in the same manner as the objects under consideration. Note also that in [6] the effect of excluding the events used in the exploratory scan, strongly correlated with VCV objects, has been analysed too. Features in the relative excess of pairs are comparable if these data are excluded.

![Figure 1](image1.png)  
**Figure 1.** Cross-correlation between the arrival directions of UHECR measured by Auger with $E \geq 55$ EeV and Swift-BAT AGN. The bands correspond to the 68%, 95% and 99.7% dispersion expected for an isotropic flux.

### 3.2.2. Statistical tests on smoothed density maps

We have tested some specific models for the origin of the highest energy cosmic rays based on the considered astronomical catalogs. We have built the probability maps of arrival directions of cosmic rays expected from these objects weighted by their flux in the electromagnetic wavelength relevant in the respective survey and by the attenuation factor expected from the GZK effect.

![Figure 2](image2.png)  
**Figure 2.** Sky map in galactic coordinates including Auger UHECR (black dots) and the AGNs of the 58-month Swift-BAT catalog (red stars with area proportional to the assigned weight). The solid line indicates the Auger field of view. Coloured bands have equal integrated exposure, the darker the color the larger the exposure.

In Fig. 2 we illustrate the construction of the map with the Swift-BAT catalog of AGNs. The red stars are centred at the positions of the AGNs, and the area of each star is proportional to the
weight of its AGN, determined by the X-ray flux, the relative Auger exposure and the GZK effect. The black dots indicate the arrival directions of the 69 events. Smoothed maps are then constructed by the weighted superposition of Gaussian distributions centred at each object position with a certain angular width $\sigma$. For each model, the density map has two free parameters: the smoothing angle $\sigma$ and an isotropic fraction $f_{\text{iso}}$. The smoothing angle serves to account for typical (but unknown) magnetic deflections in the UHECR trajectories. The addition of an isotropic fraction is a way to account for UHECR trajectories that have been bent by wide angles due to large charges and/or encounters with strong fields. A large isotropic fraction could also indicate that the model is not using a set of objects that includes all of the contributing UHECR sources.

Figure 3. Confidence intervals for the parameters $(\sigma, f_{\text{iso}})$ (best fit indicated by a black dot) derived from the likelihood function for the Swift-BAT model.

We use the data to determine the best fit values of these parameters, as those that maximise the likelihood of the data sample. The result obtained for the model relative to Swift-BAT is shown in Fig. 3 as a black dot. Contours of 68%, 95%, and 99.7% confidence intervals are shown. The best-fit values of $(\sigma, f_{\text{iso}})$ are in this case $(7.8^\circ, 0.56)$ while for 2MRS they are $(1.5^\circ, 0.64)$ [6]. Note that these values are not strongly constrained with the present statistics for both models.

Finding the values of $\sigma$ and $f_{\text{iso}}$ 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 simulated sets with the same number of arrival directions as in the data, drawn either from the density map of the models or isotropically. We compare the distributions of the mean log-likelihood ($LL/N_{\text{data}}$) with the value obtained for the data. The result for the Swift-BAT model is shown in Fig. 4.

![Figure 4. Distributions of mean log-likelihood per event for isotropic arrival directions (blue, dashed line histograms) and for the Swift-BAT model predictions (red, solid line histograms). The value of the log-likelihood for the data is indicated by a black vertical line. Data are compatible with the models and differ from the average isotropic expectation (see [6] for the 2MRS model). The fraction $f$ of isotropic realizations that have a higher likelihood than the data is $2 \times 10^{-4}$ for the Swift-BAT model ($4 \times 10^{-3}$ for the 2MRS model). As explained above, these figures are a posteriori, and do not represent a confidence level on anisotropy. Note that in [6] the effect of excluding the events used in the exploratory scan has been analysed too. With the same values of $\sigma$ and $f_{\text{iso}}$ as above, $f \approx 0.02$ in both models.

3.2.3. Autocorrelation and the largest excess

The autocorrelation of the arrival directions can provide information about clustering without reference to any catalog. We show in Fig. 5 the autocorrelation function for the set of the 69 events. The number of pairs of events with an angular separation smaller than a given value are plotted as black dots. The 68%, 95%, and 99.7% dispersion expected in the case of an isotropic
flux is represented by coloured bands. For angles greater than 45° (not shown) the black dots lie within the 68% band. The largest deviation from the isotropic expectation occurs for an angular scale of 11°, where 51 pairs have a smaller separation compared with 34.8 pairs expected. In isotropic realizations of 69 events, a fraction \( f(11°) = 0.013 \) have 51 or more pairs within 11°. The fraction of isotropic realizations that achieve \( f(\psi) \leq 0.013 \) for any angle \( \psi \) is \( P = 0.10 \).

We show in Fig. 6 the number of UHECR arrival directions within a variable angular radius from Cen A. In a Kolmogorov-Smirnov test, 4% of the realizations of 69 arrival directions isotropically drawn have a maximum departure from the isotropic expectation greater than or equal to the maximum departure observed in data. The excess with largest significance is given by 13 arrival directions within 18°, where 3.2 are expected from an isotropic flux. The UHECR in this region of the sky make a dominant contribution to the autocorrelation signal. For instance, the 13 arrival directions that are within 18° from Cen A form 6 pairs separated by less than 4°, and 28 pairs by less than 11°. These events also make a large contribution to the correlation with different populations of nearby extragalactic objects, both because they are in excess above isotropic expectations and because this region is densely populated with galaxies (see e.g. Fig. 2). In contrast to the region around Cen A and the Centaurus cluster, there is a paucity of events from the region around the radiogalaxy M87 and the Virgo cluster. None of the 69 events with \( E \geq 55 \) EeV is within 18° of M87. Due to its northern declination, however, M87 gets only one-third the exposure that Cen A gets at Auger. Only 1.1 events are expected within that 18° circle for an isotropic flux.

4. Conclusions

Between January 2004 and December 2009 the Pierre Auger Observatory has detected 69 cosmic rays with energy above 55 EeV. This data set is more than twice as large as the one analysed in [1], which provided evidence of anisotropy in UHECR arrival directions at the 99% c.l. The anisotropy was tested with a priori parameters through the correlation between the arrival directions of UHECR and the positions of nearby active galaxies from the VCV catalog. The currently measured degree of that correlation is \((38_{-6}^{+7})\%\), to be compared with the 21% expected to occur by chance if the flux were isotropic. Given the current correlation fraction, a 5σ significance \((P < 6 \times 10^{-7})\) will require 165 events subsequent to the exploratory scan. That larger data set will not be available for at least another
four years.

In the meantime, we have examined the present data set with a posteriori explorations to see if scenarios other than the simple VCV correlation are supported. We have compared the distribution of arrival directions with the positions of galaxies in the 2MRS survey and AGNs detected by Swift-BAT. We have considered models in which the cosmic ray luminosity is proportional to the flux in the respective wavelength for the objects in these catalogs. Data are readily compatible with the models for suitable parameters (smoothing angle $\sigma$ and isotropic fraction $f_{\text{iso}}$). The values of these parameters have been obtained for each model as best fits to the data. Not strongly constrained with the present statistics, they are around a few degrees for $\sigma$ and between 0.56 and 0.88 for $f_{\text{iso}}$. Large values of $f_{\text{iso}}$ may be an indication of catalog incompleteness, or that proportionality between cosmic ray luminosity and electromagnetic flux is unrealistic, or that a fraction of the arrival directions are isotropized by large magnetic deflections due to large charges and/or encounters with strong field regions.

The autocorrelation analysis shows a modest excess of pairs over a broad range of small angles. This absence of strong clustering may be interpreted as evidence of many contributing sources and/or large angular separations between arrival directions from the same source.

Finally, we have analyzed the region of the sky close to the location of the radiogalaxy Cen A, since this corresponds to the largest observed excess with respect to isotropic expectations. The UHECR in this region strongly contribute to the autocorrelation and to the correlation with different populations of nearby extragalactic objects. From the 69 UHECR arrival directions, 18.8% lie within 18° of Cen A, while 4.7% is the isotropic expectation. This region is densely populated with different types of nearby extragalactic objects. Flux-weighted models based on 2MRS galaxies and on Swift-BAT AGNs predict a fraction of UHECR from this region of 13% and 29% respectively [6].

Definitive conclusions must await additional data and measurements. If the evidence for anisotropy is substantiated by future data, then it should also become possible to discriminate between different astrophysical scenarios using techniques of the type that have been presented here. In particular, more data is needed to discern if it is the correlation on small angles of a few events with the very high-density regions of the considered models (such as the region in the direction to the radiogalaxy Centaurus A) that masks a potentially larger correlating fraction (hence a smaller $f_{\text{iso}}$) over larger angular scales. Note that larger deflections of the UHECR trajectories would be expected in the case of presence of highly charged nuclei among the primaries, as suggested by measurements by the Pierre Auger Observatory [12], although currently limited up to about 55 EeV. Larger statistics measurements of arrival directions and composition of ultra-high-energy cosmic rays are thus demanded for a thorough investigation of their origin.

REFERENCES