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The Mysterious Ultrahigh Energy Cosmic Ray Clustering

Luis A. Anchordoqui[a], Haim Goldberg[a], Stephen Reucroft[a], Gustavo E. Romero[b,c], John Swain[a], and Diego F. Torres[b,d]

[a]*Department of Physics, Northeastern University*
Boston, MA 02115, USA

[b]*Instituto Argentino de Radioastronomía*
C.C.5, 1894 Villa Elisa, Buenos Aires, Argentina

[c]*Center for Astrophysics, Guangzhou University*
Guangzhou 510400, China

[d]*Department of Physics, Princeton University,*
NJ 08544, USA

We examine the correlation between compact radio quasars (redshifts in the range $z = 0.3-2.2$) and the arrival direction of ultrahigh energy cosmic rays forming clusters. Our Monte Carlo simulation reveals a statistically significant correlation on the AGASA sample: the chance probability of this effect being less than 1%. The implications of this result on the origin of ultrahigh energy cosmic rays are discussed.

1 Introduction

To date, some 20 giant air showers have been detected confirming the arrival of cosmic rays (CRs) with nominal energies at or above $10^{20} \pm 30\%$ eV, with the record Fly's Eye event having $\sim 3.2 \times 10^{20}$ eV [1]. The mechanism(s) responsible for endowing particles with such enormous energies continues to present a major enigma to high energy physics [2]. As shown in the pioneering works of Greisen-Zatsepin-Kuz'min (GZK) [3], the possible sources are constrained by the observed particle spectra due to the interaction with the universal radiation and magnetic fields on the way to the observer. In particular, any proton energy above 5×10^{19} eV is degraded by resonant scattering via $\gamma + p \to \Delta \to p/n + \pi$, such that less than 20% of protons survive with an energy above 3×10^{20} (1×10^{20}) eV for a distance of 18 (60) Mpc. A typical nucleus of the cosmic radiation is subject to photodisintegration from blue-shifted relic photons, losing about 3-4 nucleons per traveled Mpc. The mean free path of gamma rays on the radio background decreases even more readily. Therefore, if the CR sources are all at cosmological distances, the observed spectrum must virtually end with the GZK cutoff at $E \approx 8 \times 10^{19}$ eV. The spectral cutoff is less sharp for nearby sources (within 50 Mpc or so). The arrival directions of the trans-GZK events are distributed widely over the sky, without apparent counterparts (such as sources in the Galactic Plane or in the Local Supercluster). Moreover, the data are consistent with an isotropic distribution of sources, in sharp constrast to the anisotropic distribution of light within 50 Mpc [4].

There are two extreme explanations for the observed isotropy. On the one hand, it may happen that a bunch of sources that by pure chance are very close to us dominate the spectrum at the highest energies, and the particle orbits are bent [5]. This scenario requires large scale intervening magnetic fields with intensity $\mathcal{O}(\mu\text{G})$, to provide sufficient angular deflection. On the other hand, one can argue that there are many cosmic ray sources, even at the highest energies. The lack of plausible nearby sources in the arrival direction has encouraged the idea of positing undiscovered neutral hadrons, as well as mechanisms which are able to break the GZK barrier. Although sufficiently heavy particles would avoid the GZK cut off (the cut-off energy varies as the square of the mass of the first resonant state) [6], the existence of these particles now appears to be excluded by laboratory experiments [7]. The only standard model (SM) particle that can reach our galaxy from high redshift sources without significance loss of energy is the neutrino. The expected event rate for early development of a neutrino shower, however, is down from that of an electromagnetic or hadronic interaction by six orders of magnitude. This problem can be raised by simply postulating that the total neutrino-proton cross section $\sigma_{\nu p}$ increases at high center of mass energies, $\sqrt{s} >$ TeV. The hypothesis that all particles may have a strong interaction above collider energies is certainly not new [8]. Recently, some scenarii with n large compact dimensions and precocious unification around the TeV-scale have rekindled this idea [9]. Within this framework, SM fields are trapped into a 3+1 dimensional thin shell and only gravity propagates in the higher dimensional space. Therefore, the compactification radius r_c of the extra dimensions can be large, corresponding to a small scale $1/r_c$ of new physics. Here, the weakness of gravitational interactions is a consequence of the large compactification radius, encoded in the relationship between the Newton constant $G = M_{\rm pl}^{-2}$ and the fundamental scale of gravity $M_* \sim$ TeV, $M_{\rm pl}^2 \sim r_c^n M_*^{n+2}$. From the 4-dimensional perspective, the higher dimensional graviton appears as an infinite tower of Kaluza-Klein (KK) excitations [10]. The weakness of the gravitational interaction can be thus compensated by the very large multiplicity of KK states. As a consequence, cross sections mediated by spin 2 particles increase rapidly with energy [11]. The KK model may fail [12] in that the KK modes couple to neutral currents, and the scattered neutrino transfers only about 10% of its energy per interaction, thereby elongating the shower profile. Nevertheless, an s^2 growth of $\sigma_{\nu p}$, supplemented by multiple scatters within the nucleus, yields enough energy transfer to save the model [13].

On a different track, if some flavor of neutrinos has masses m_{ν_j} $\mathcal{O}(10^{-1})$ eV, the 1.9 K thermal neutrino background is a target for extremely high energy neutrinos to interact forming a Z-boson that subsequently decays producing a "local" flux of nucleons and photons [14]. The energy of the neutrino annihilating at the peak of the Z-pole is well above the GZK limit

$$E_\nu = \frac{M_Z^2}{2 m_{\nu_j}} = 4 \, \left(\frac{\rm eV}{m_{\nu_j}}\right) \times 10^{21}\ {\rm eV}\,. \tag{1}$$

The mean energies of the ~ 2 baryons and ~ 20 γ-rays in each process can be estimated by distributing the resonant energy among the mean multiplicity of 30 secondaries. The proton energy is given by

$$< E_p > \sim \frac{M_Z^2}{60\, m_{\nu_j}} \sim 1.3 \, \left(\frac{\rm eV}{m_{\nu_j}}\right) \times 10^{20}\ {\rm eV}, \tag{2}$$

whereas the γ-ray energy is given by

$$< E_\gamma > \sim \frac{M_Z^2}{120\, m_{\nu_j}} \sim 0.7 \, \left(\frac{\rm eV}{m_{\nu_j}}\right) \times 10^{20}\ {\rm eV}. \tag{3}$$

The latter is a factor of 2 smaller to account for the photon origin in two body π^0 decay. The annihilation/Z-burst rate can be amplified if neutrinos are clustered rather than distributed uniformly throughout the universe [15]. In such a case the probability of neutrinos to annihilate within the GZK zone is on the order of 1%, with the exact value depending on unknown aspects of neutrino mixing and relic neutrino clustering (more on this below).

Adding to the puzzle, the AGASA experiment has already reported data strongly suggesting that the pairing of events on the celestial sky is occurring at higher than chance coincidence [16]. Specifically, four doublets and one triplet of showers with separation angle less than the angular resolution $2.5°$ are observed among the 36 events reported with mean energy above 4×10^{19} eV. The chance probability of observing such a triplet in an isotropic distribution is about 1%. Another doublet is observed if we include events above 3.8×10^{19} eV. The arrival directions in a combined data sample with three other surface experiments further suports non-chance association, especially in the direction of the SuperGalactic plane [17]. If not a statistical fluctuation, the event clustering would have profound implications for models discussing the origin of ultrahigh energy cosmic rays. In this paper we elaborate on this issue.

2 Estimates of cluster probabilities

Let us begin by reviewing the current status of event clustering including the recently enlarged sample reported by the AGASA experiment [16]. To proceed, we adopt the formalism introduced in Ref. [18]. We start considering the solid angle Ω on the celestial sphere covered by an experiment divided into N equal angular bins, each with solid angle $\omega \simeq \pi\theta^2$. Then, by tossing n events randomly into

$$N \simeq \frac{\Omega}{\pi\,\theta^2} = 1045\ \frac{\Omega}{1\ \mathrm{sr}}\ \left(\frac{\theta}{1^\circ}\right)^{-2} \tag{4}$$

bins, one is left with a random distribution. Now, we identify each event distribution by specifying the partition of n total events into a number m_0 of empty bins, a number m_1 of single hits, a number m_2 of double hits, etc., among the N angular bins that constitute the whole exposure. After a bit of algebra, it is easily seen that the probability to obtain a given event topology is [18]

$$P\left(\{m_i\}, n, N\right) = \frac{N!}{N^N}\ \frac{n!}{n^n}\ \prod_{j=0} \frac{(\overline{m_j})^{m_j}}{m_j\,!}\ , \tag{5}$$

where

$$\overline{m_j} \equiv N\ \left(\frac{n}{N}\right)^j\ \frac{1}{j\,!}. \tag{6}$$

Using Stirling's approximation for the factorials with the further assumption $N \gg n \gg 1$, Eq. (5) can be re-written in a quasi-Poisson form

$$P(\{m_i\}, n, N) \approx \mathcal{P}\left[\prod_{j=2} \frac{(\overline{m_j})^{m_j}}{m_j!} e^{-\overline{m_j}\,r^j\,(j-2)!}\right]\ , \tag{7}$$

where $r \equiv (N - m_0)/n \approx 1$, and the prefactor $\mathcal{P}$ is given by

$$\mathcal{P} = e^{-(n-m_1)} \left(\frac{n}{m_1}\right)^{m_1+\frac{1}{2}} . \tag{8}$$

For "sparse events", where $N \gg n$, one expects the number of singlets m_1 to approximate the number of events n. In such a case the prefactor is near unity.

To estimate the celestial sky coverage Ω for ground-based experiments, one rotates the fixed-coordinate solid angle about the earth's axis of rotation. For experiments with vertical acceptance from the zenith to θ_z the relevant formula is [18]

$$\Omega = 2\pi \begin{cases} 2\sin\theta_z \cos\alpha, & \text{for} \quad \alpha + \theta_z < 90^\circ \\ 1 + \sin(\theta_z - \alpha), & \text{for} \quad \alpha + \theta_z > 90^\circ \end{cases}$$

where α is the latitude of the experiment.

The experimental data reported by Volcano Ranch, Haverah Park, Yakutsk and AGASA are used to determine the purely statistical probabilities for various cluster topologies. As recommended in Ref. [17] only extensive air showers with zenith angle $\theta_z < 45^\circ$ (that have good quality in the energy and arrival direction determination) are taken into account. The updated data list of possible cluster members is quoted in Table 1. Using Eqs. (4) and (5) we calculate the inclusive probabilities for various cluster topologies as a function of the angular resolution and the accumulated number of events n. By inclusive probabilities we mean that the specified number of j-plets plus any other cluster, counts as all the j-plets + extra-clusters. The main experimental properties for the four experiments are summarized in Table 2.

In Fig. 1 we show the inclusive probabilities for one and more doublets and two and more doublets for the sample of Haverah Park. The chance probability for clustering within 3° is larger than 50% and hence not statistically significant. In Fig. 2 we show the inclusive probabilities for 8 doublets and 2 triplets at different CR-sky coverages. The probability of chance association is only "small" for angular binning tighter than 3°, and $\Omega > 4$. The chance probability for clustering within 4° and 5° remains always larger than 10%. Therefore, the observation of this topology within the approximate angular resolution of the combined data set, is not statistically significant. This result agrees with previous numerical simulations [17].

We now examine whether there is any evidence for clustering above the statistical expectation when considering the AGASA subsample. The latter has much better angular resolution. In Fig. 3 we show the chance probabilities of observing 5 doublets and one triplet given 58 events at AGASA. The probability is extremely sensitive to the angular binning. In this case, the chance probability within the experimental angular resolution is less than 10^{-3}. This result is in very good agreement with the one recently obtained using numerical simulations of the angular two point correlation function of ultrahigh energy CRs: A 3×10^{-4} probability of chance clustering with a bin size of $2.5°$ and an energy cut-off at 4.8×10^{19} eV [19]. Furthermore, when including data from Yakutsk's experiment above 2.4×10^{19} eV, the combined probability of chance clustering is reported to be as small as 4×10^{-6}, strongly suggesting that CR sources are point-like on cosmological scales [19].

3 Correlation with high redshift objects

Compact radio quasars (CRQSOs) are strong radio emitters, a fact that along with their variability, is indicative of strong beaming. The bulk of the observed non-thermal emission of these objects is thought to be produced in strong, relativistic jets of charged particles emitted by the active nucleus, which is likely formed by an accreting supermassive black hole. These powerful objects have been under suspicion as the primary source of ultrahigh energy CRs for some time now [20, 21, 22]. Therefore, we find it particularly attractive to examine whether there exists a correlation between CR-clusters and CRQSOs. We shall use the 451 CRQSOs with flat spectrum and declination above $-10°$ degrees taken from the surveys of Ref. [23]. With the aim of finding the positional coincidences and evaluating their significance, we adopt the procedure of Ref. [21]. First, we look for real correlations between the two sets. In order to do so, we consider a circle around the centroid of each CR event, this circle has a radius equal to the reported 1 sigma positional error (see Table 2). If a CRQSO is within the circle of all members of the cluster, we say that there is a positional coincidence. We are not giving a higher significance to directional coincidences with small offsets than to coincidences that are not so close, just because the original errors of the CRs are of the order of degrees. As a first trial, we look for positional coincidences between the CRQSO sample and all the events listed in Table 1. We have found that there are no objects which correlate with the direction of triplets, so in the following a cluster denotes a pair of events. Just 4 clusters (out of 10) of the sample are positionally coincident with CRQSOs. Numerical simulations using large numbers of synthetic populations (thousands of them were made for each correlation study) sampled randomly and uniformly in right ascension and declination, are then performed in order to determine the probability of pure chance spatial association. Strictly speaking, we generate synthetic populations of 451 CRQSOs and compare them with the actual positions of the CRs. We have taken into account that the artificial sets of CRQSOs are constrained (as are the actual ones) to the declination range $\delta > -10°$. In Fig. 4 we show the sky distribution of 451 CRQSOs in equatorial coordinates. The apparent anisotropy is due to obscuration from the galactic plane of our galaxy. Since only one ultrahigh energy CR cluster lies in this region, the real level of positional coincidences (even considering that an uniform distribution of CRQSOs is there) cannot significantly differ from what is observed. The present Monte Carlo simulations preserve an isotropic distribution for background sources. The level of random positional coincidence after 5000 simulations (a larger number of simulations does not significantly modify the result) is shown in Fig. 5. Notice that the actual coincidences are less than 1 standard deviation away from the simulated mean value 3.5 ± 1.8. As a second trial, we repeat the whole analysis but considering only CRs in the AGASA sample above 4×10^{19} eV. In this case we found that the number of real matches is 3, whereas the expected number from pure chance estimated from the simulations is 0.45 ± 0.66, i.e., 3.8 standard deviations below (see Fig. 6). The Poisson probability of a random occurrence of any number of coincidences greater than or equal to the real positional coincidence is $P = 9.7 \times 10^{-3}$.

4 Outlook

Let us end with a discussion (and some speculations) on the implications of our result. The clustering beyond statistics by itself imposes certain constraints on possible CR-sources. As can be read in Table 1, the event-pairing has members with rather different energies. The energy spread would have profound consequences for the propagation of charged ultrahigh energy CRs, even in the regular magnetic field of $\mathcal{O}$(nG). Strictly speaking, if the Larmor radius of a particle ($r_{\rm L} \simeq 10^2$ Mpc E_{20}/B_{-9}) is much larger than the coherence length of the magnetic field $\ell_{\rm coh}$, the typical deflection angle from the direction of the source, located at a distance d, can be estimated assuming that the particle makes a random walk in the magnetic field [24]

$$\theta(E) \simeq 3.8^\circ \left(\frac{d}{50 \text{ Mpc}}\right)^{1/2} \left(\frac{\ell_{\rm coh}}{1 \text{ Mpc}}\right)^{1/2} \left(\frac{B_{-9}}{E_{20}}\right) , \tag{9}$$

where E_{20} is the energy of the particle in units of 10^{20} eV, and B_{-9} is the magnetic field in units of 10^{-9} G. Now, it is straightforward to check that scatterings in large scale magnetic irregularities $\mathcal{O}$ (nG) [25] are enough to bend the orbits of trans-GZK protons more than 5° in a 50 Mpc trip. The time delay in the arrival of cosmic ray pairs can be used to impose additional constraints on the nature of the sources. In particular, the time lags shown in Table 1 are long enough to rule out an origin based on bursting sources. The average time delay in the pairs of the sample (with real positional coincidences) is 3 yr ± 7 months, favoring a compact (but not transient) source. Typical source sizes for the production of high energy particles in AGNs are smaller that the radius of the outer gamma-spheres, i.e. $< 10^{15}$ cm [26]. All in all, if forthcoming data confirm that the clustering is not a statistical artifact, we are left with two main possibilities: (i) the particles are charged but then the sources should be very nearby (which is hard to accept already), or (ii) the CR constituents of the clusters are neutral particles! The first option is very problematic because if the sources are nearby (say located within our own Galaxy) global isotropy should not be observed, contrary to the evidence, unless strong magentic fields could produce the required isotropization, in which case the clustering effect is broken.

In order to explain the event-pairs (pointing towards distant sources) by neutrino showers with TeV-scale quantum gravity, neutrinos must be capable of generating vertical atmospheric cascade developments both at the lower and higher energy pair. The rapid energy behaviour of cross section in KK models makes this requirement rather difficult [27]. The Z-burst, however, still appears as a viable model. As stated above the secondaries produced by Z decay are mainly photons. Because cascading by e^+e^- pairs (produced by double pair production on the microwave background, or pair production on the radio background) is rapid, the photon energy is quickly reduced below the GZK-limit. Just to get an estimate, the mean interaction length at 3×10^{20} eV is a few Mpc, and the energy attenuation length (which is very sensitive to the magnetic field because of synchrotron losses) assuming extragalactic magnetic fields $\mathcal{O}$ (nG) is ~ 20 Mpc. Both increase with decreasing energy. As mentioned above, some protons are able to survive a 60 Mpc trip with energies above 10^{20} eV. Besides, the nucleon-channel would suffer magnetic field deflections reducing the correlation with the neutrino-emitting-source. For instance, $B_{-9} \sim 2$ would defocus a proton $E_p \sim 1.5 \times 10^{20}$ eV (as the one detected by AGASA on 97/03/30) more than $5°$ [21]. Therefore, since the photon flux is depleted through interactions with the radiation backgrounds, the relation 10:1 of photon/nucleon in the Z decay is significantly reduced, reducing also the correlation with CRQSOs (because the protons are bent in the magnetic field). In other words, the Z-burst model predicts a correlation between ultrahigh energy CRs and highly redshifted background sources [22], which diminishes with increasing energy (say $E > 8 \times 10^{19}$ at 1 σ level) [21]. We note that none of the members of clusters with real matches in our analysis satisfy the above energy cut-off. We do not attempt to make yet another estimate here and only note that on average, proton deflections of $\simeq 10°$ [28] are consistent with existing bounds on neutrino masses, relic neutrino density and magnetic field strengths.

In closing we would like to note that the Z-burst model is not free of problems: Firstly, it is desirable to understand more completely the depletion of high energy photon flux, since the characteristcs of the air showers detected so far do not seem to resemble an electromagnetic γ-ray shower [29]. Secondly, there is the additional difficulty of getting neutrinos with energies $\sim 10^{22}$ eV. If these are secondaries from pion production, this implies that the primary protons which produce them must have energies of $\sim 10^{23}$ eV. While standard acceleration mechanisms require quite extreme parameters to achieve such extraordinary energy, we note that only a few dozen of such sources in the whole visible Universe would suffice.

Mysterious: adj. Having an import not apparent to the senses nor obvious to the *intelligence; beyond ordinary understanding* [30]. This appears to be the situation concerning the seeming ultrahigh energy cosmic ray clustering discussed in this paper.

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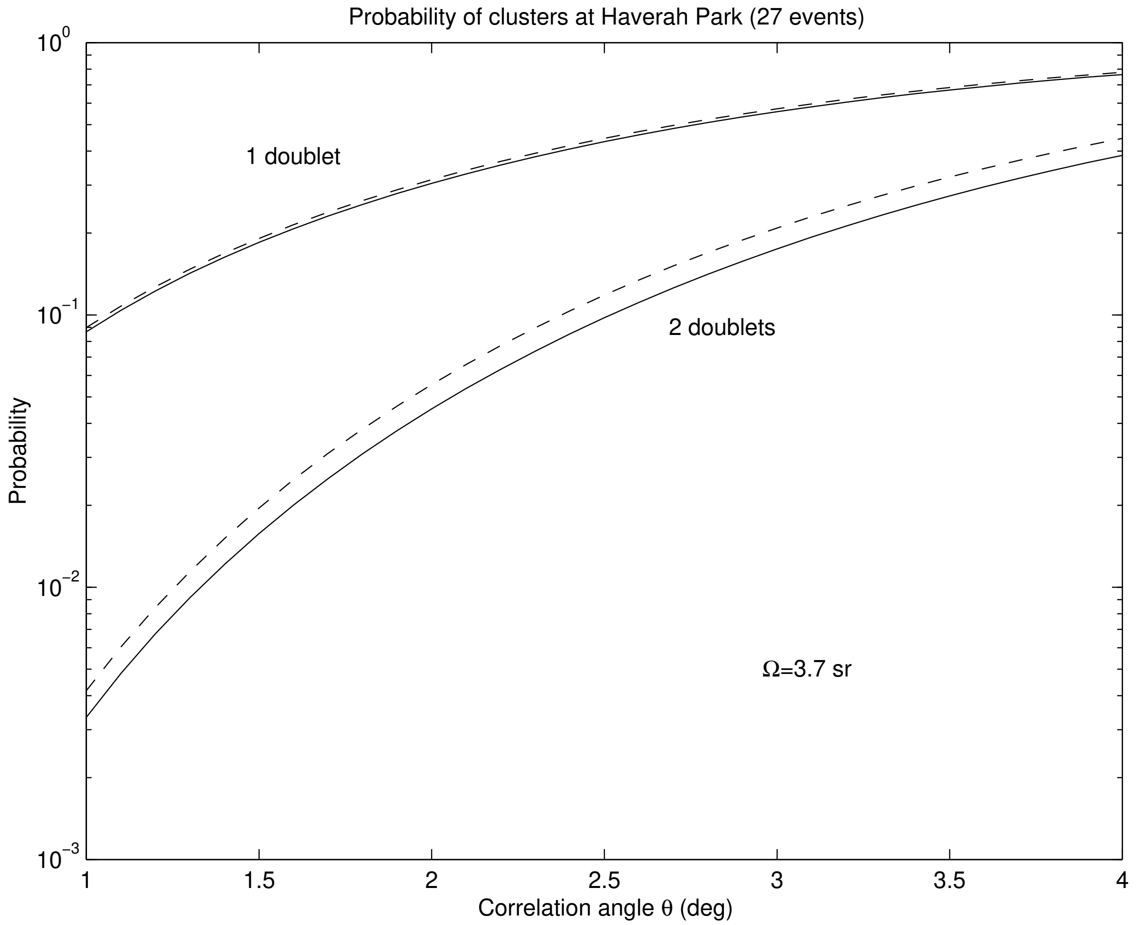

Figure 1: Inclusive probabilities for various clusters in a 27 event sample as seen by the Haverah Park experiment. The solid line is the exact result, whereas the dashed line is the Poisson approximation.

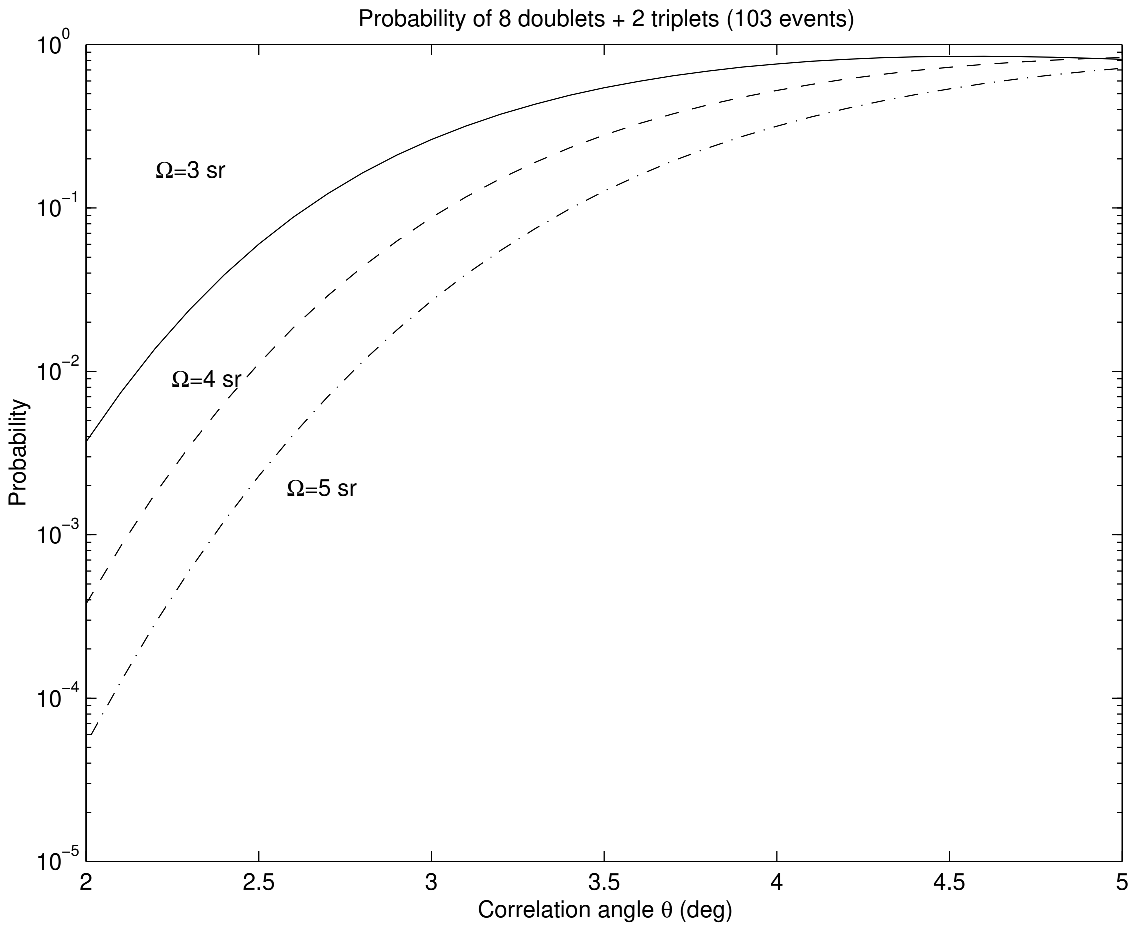

Figure 2: Inclusive probabilities for 8 doublets and 2 triplets in a 103 event sample for various celestial solid angles.

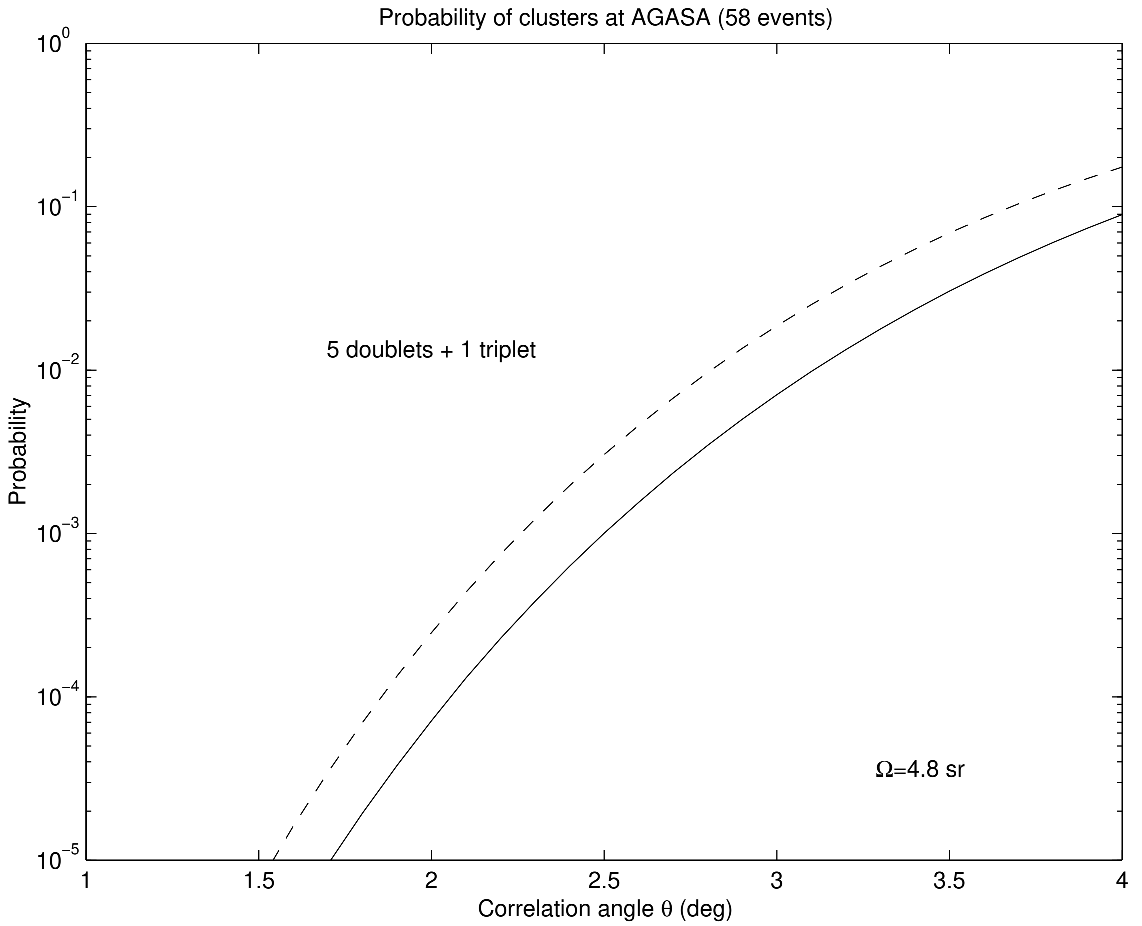

Figure 3: Inclusive probabilities for 5 doublets and 1 triplet in a 58 event sample at AGASA. Solid (exact), dashed (Poisson).

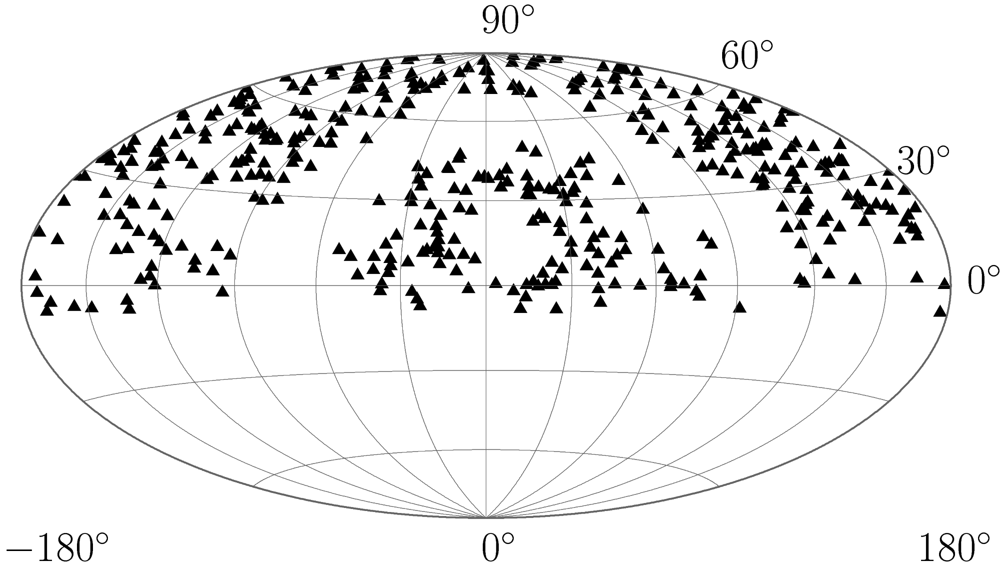

Figure 4: Sky distribution of 451 CRQSOs in equatorial coordinates. The sample is complete within the sensitivity of the radio surveys (see Ref. [23]). The apparent anisotropy is due to obscuration from the galactic plane of our galaxy.

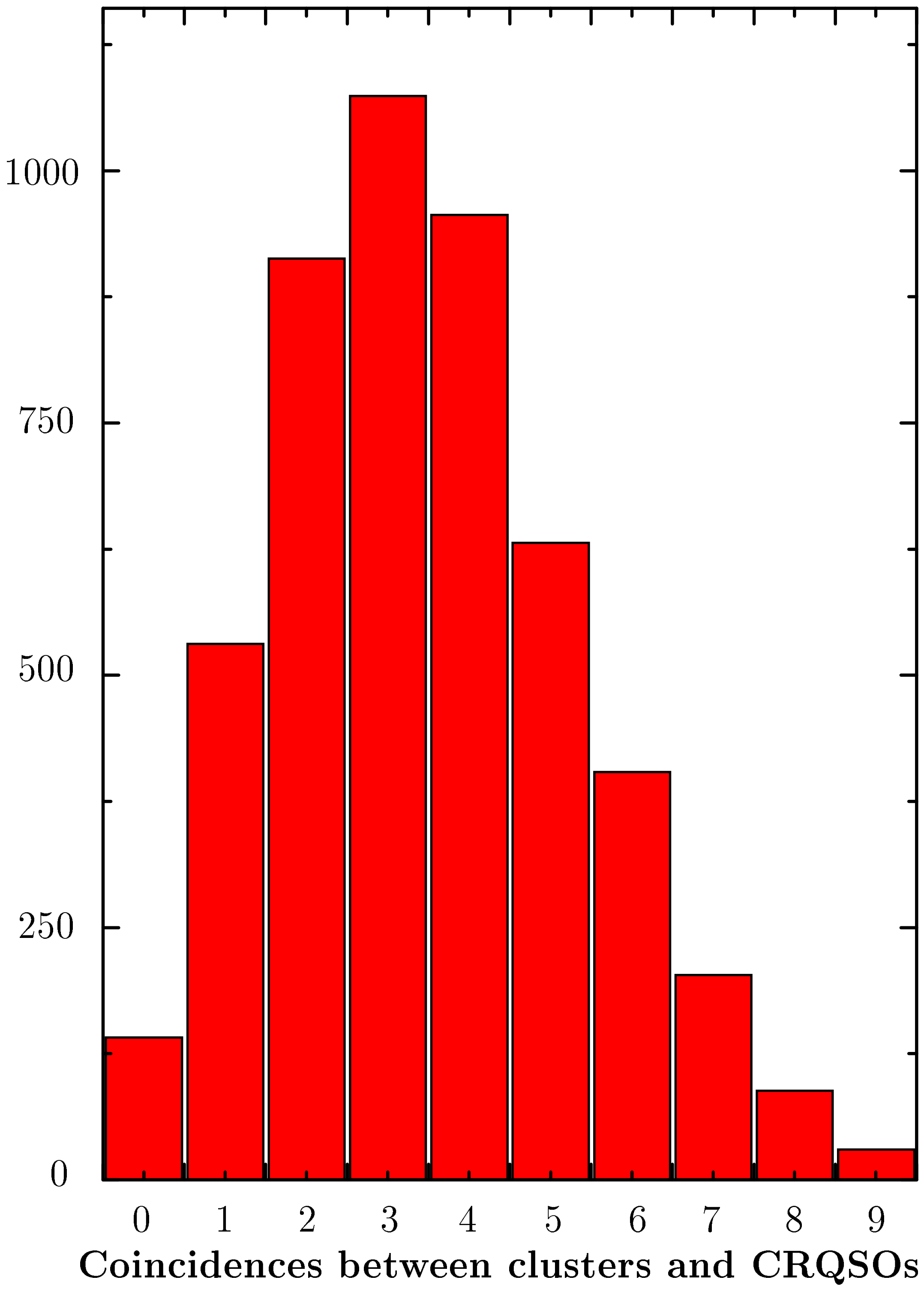

Figure 5: Simulated positional coincidence between all CR-clusters taken from Table 1 and CRQSOs for 5000 runs.

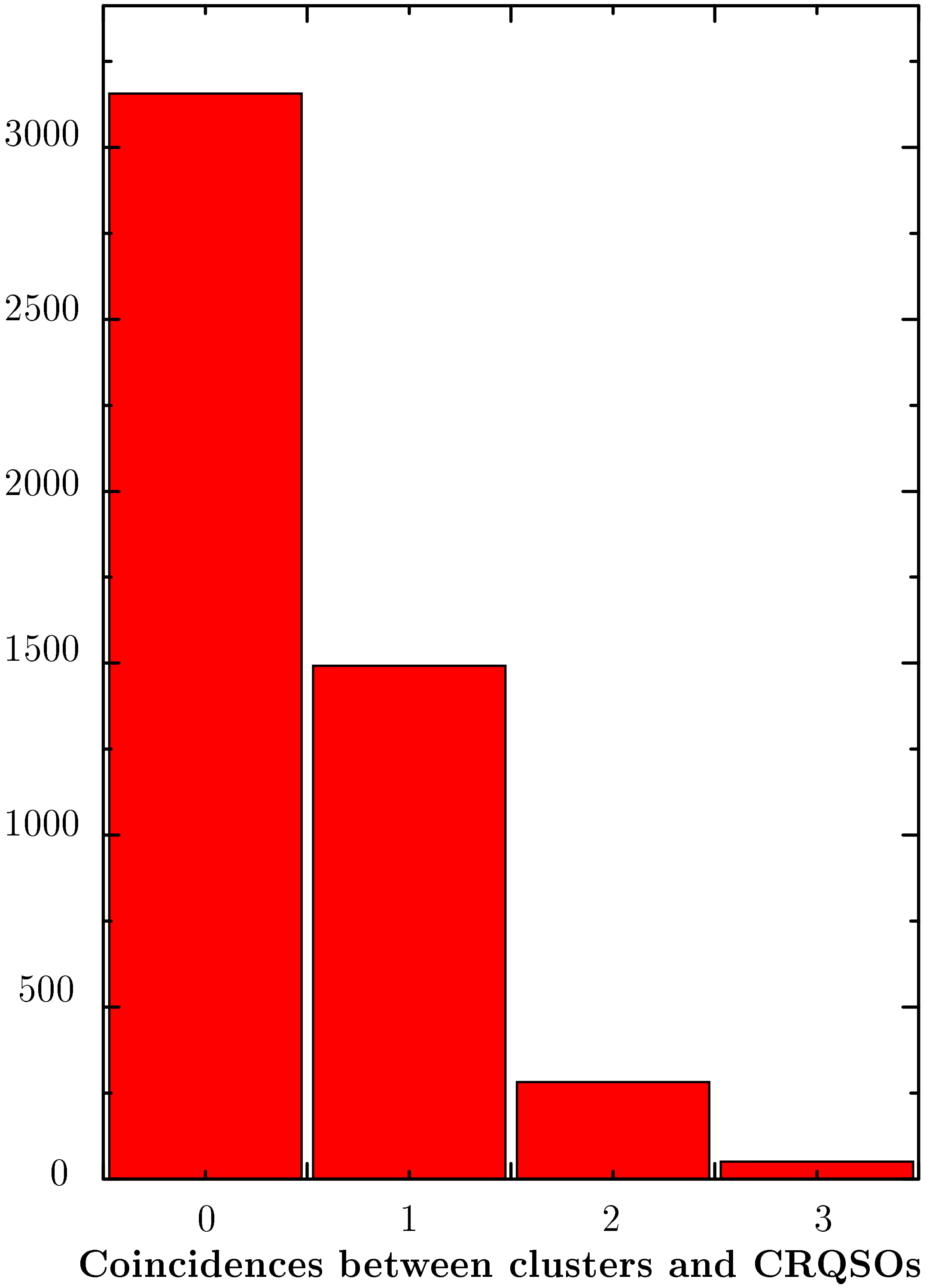

Figure 6: Simulated positional coincidence between AGASA-clusters with energies above 4×10^{19} eV and CRQSOs for 5000 runs.

Cluster	Experiment	Date	Log E	R.A.	Dec.
Triplet #1	Haverah Park	810105	19.99	20.00	20.00
	AGASA	931203	20.33	18.91	21.07
	AGASA	951029	19.71	18.53	20.03
Triplet #2	AGASA	920801	19.74	172.30	57.14
	AGASA	950126	19.89	168.65	57.58
	AGASA	980404	19.73	168.44	55.99
Doublet #1	AGASA	910420	19.64	284.90	47.79
	AGASA	940706	20.03	281.36	48.32
Doublet #2	AGASA	860105	19.74	69.03	30.15
	AGASA	951115	19.69	70.39	29.85
Doublet #3	Haverah Park	860315	19.71	267.00	77.00
	AGASA	960513	19.68	269.05	74.12
Doublet #4	Haverah Park	720525	19.65	239.00	79.00
	Yakutsk	911201	19.62	235.40	79.80
Doublet #5	Volcano Ranch	610319	19.73	154.10	66.70
	Haverah Park	850313	19.62	157.00	65.00
Doublet #6	Haverah Park	661008	19.67	164.00	50.00
	Yakutsk	750317	19.67	163.70	52.90
Doublet #7	Haverah Park	740228	19.86	264.00	58.00
	AGASA	980330	19.84	259.16	56.32
Doublet #8	Haverah Park	760206	19.62	165.00	64.00
	Haverah Park	850313	19.62	157.00	65.00
Doublet #9	AGASA	960111	20.16	241.5	23.00
	AGASA	970410	19.58	239.50	23.70
Doublet #10	AGASA	961224	19.70	213.75	37.7
	AGASA	000526	19.70	212.00	37.1

Table 1: *Updated list of triplets and doublets within space angles of* 3°, 4° *and* 5°.

Experiment	Begin	End/status	Latitude	Longitude	Ω (sr)	$\theta_{\min}$	n
AGASA	1990	in operation	35° 47′ N	138° 30′ E	4.8	1.8°	58
Haverah Park	1968	1987	53° 58′ N	1° 38′ W	3.7	3.0°	27
Yakutsk	1972	in operation	61° 42′ N	129° 24′ E	3.1	3.0°	12
Volcano Ranch	1959 1972	1963 1974	35° 09′ N	106° 47′ W	5.0	3.0°	6

Table 2: *Event rates, celestial solid angles* Ω *(sr), and angular resolutions* $\theta_{\min}$. *We remark that the celestial solid angles have been reduced by a factor of 0.7 (see [18] for details).*