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Large-Angular-Scale Clustering as a Clue to the Source of UHECRs

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Abstract: We show that future Ultra-High Energy Cosmic Ray samples should be able to distinguish whether the sources of UHECRs are hosted by galaxy clusters or ordinary galaxies, or whether the sources are uncorrelated with the large-scale structure of the universe. Moreover, this is true independently of arrival direction uncertainty due to magnetic deflection or measurement error. The reason for this is the simple property that the strength of large-scale clustering for extragalactic sources depends on their mass, with more massive objects, such as galaxy clusters, clustering more strongly than lower mass objects, such as ordinary galaxies.

Introduction

Identifying the sources of ultrahigh energy cosmic rays (UHECRs, here $E > 10^{19}$eV $\equiv$ 10 EeV) is complicated by the deflection they presumably experience in Galactic and extragalactic magnetic fields, as well as their relatively poor arrival direction determinations, typically $\sim 1^\circ$. Arrival directions of most UHECRs are thus not known well enough to match their positions with specific astrophysical objects. However, there is also useful information in the clustering of UHECRs on large scales, where $\sim$ few degree uncertainties in position become unimportant. The clustering of galaxies in the universe is typically quantified by the two-point correlation function or its analog in Fourier space, the power spectrum. The two-point correlation function $\xi(r)$ of any class of objects (e.g., galaxies of a certain luminosity or color) is defined as the excess number of pairs of such objects at physical separation r over that expected for a random (Poisson) distribution. In Cold Dark Matter models, the large-scale amplitude of $\xi(r)$ (usually referred to as the bias) of a population of objects depends only on their mass, with more massive objects, such as clusters of galaxies, clustering more strongly than less massive objects, such as ordinary galaxies [1, 2, 3]. The large-scale bias of a UHECR sample is therefore a robust and informative measure of the clustering properties of the source. We cannot measure physical separations for pairs involving UHECRs because they do not have measured redshifts. However, we can measure the angular correlation function $\omega(\theta)$. As is the case for $\xi(r)$, the large-scale amplitude of $\omega(\theta)$ for a UHECR sample depends on the nature of the astrophysical source. However, it also depends on the depth of the sample because deeper samples mix more physically uncorrelated pairs and thus show weaker angular clustering. In order to access the information in the large-scale angular clustering of UHECRs, we must therefore know the depth of our UHECR sample. In this paper, we demonstrate what can be learned from the large-scale angular clustering of UHECRs, we estimate what kind of sample is needed to do this analysis, and we show how to deal with the unknown depth of a UHECR sample, using the GZK effect.

Large-Angle Clustering of UHECRs

We demonstrate what can be learned from the large-angle clustering of UHECRs by creating mock samples of UHECRs assuming different astrophysical sources and examining their resulting clustering. We use the Sloan Digital Sky Survey (SDSS) [4] to create a volume-limited sample of galaxies that is complete out to a distance of 286Mpc. We select a sample of massive galaxy clusters in the same volume taken from a SDSS group and cluster catalog [5]. Based on their luminosities, we estimate these clusters to have masses greater than $10^{14}h^{-1}M_{\odot}$. We then measure angular cross-correlation functions of each of these samples with the galaxy sample (so, for the galaxy case, we are measuring the autocorrelation) using the Landy-Szalay [6] estimator:

$$\omega_{12}(\theta) = \frac{N_{D_1D_2} - N_{D_1R} - N_{D_2R} + N_{RR}}{N_{RR}},$$

where $N_{D_1D_2}$ is the number of pairs as a function of θ between the two data samples (in this case, galaxies and something else), N_{D_1R} and N_{D_2R} are the number of pairs as a function of θ between each data sample and a random sample, and N_{RR} is the number of random-random pairs. Figure 1 shows the resulting angular correlation functions: cluster-galaxy, galaxy-galaxy, as well as the random-galaxy case. As expected, the cluster-galaxy correlation function has a higher amplitude than the galaxy-galaxy correlation function on all angular scales, and the random-galaxy correlation function is equal to zero by construction.

These three curves represent predictions for the UHECR-galaxy cross-correlation function in the three distinct cases that UHECRs originate from astrophysical sources that: (1) live in massive clusters, (2) live in ordinary galaxies, and (3) are uncorrelated with the large-scale structure of the universe, such as sources within the Milky Way galaxy. The three cases predict different measured UHECR-galaxy correlation functions even at large angles, where UHECR direction uncertainties due to measurement error and magnetic deflections are unimportant.

We next examine how well we can distinguish between these different predictions assuming a sample of 1000 UHECRs. For the purpose of this test, we assume that the sources of UHECRs are, in fact, ordinary galaxies. We create a mock UHECR sample by randomly selecting 1000 galaxies from our SDSS galaxy sample. We create 200 independent mock samples in this way and measure their cross correlation with all galaxies. The shaded blue region in Figure 1 contains 95% (2σ) of the mock realizations. We then simulate arrival direction

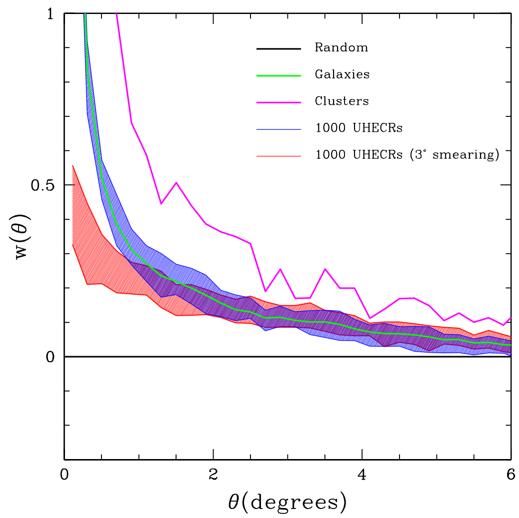

Figure 1: Predicted UHECR-galaxy angular cross-correlation functions for the cases that the astrophysical sources of UHECRs are (1) uncorrelated with the large-scale structure in the universe (*black line*), (2) ordinary galaxies (*green curve*), and (3) clusters of galaxies (*magenta curve*). The blue shaded region shows the 95% (2σ) measurements using 200 mock samples of 1000 UHECRs each, where the UHECRs are assumed to originate in galaxies. The red shaded region shows the same, but for mock UHECR arrival directions containing 3° random Gaussian errors. For this calculation, a SDSS galaxy sample of median depth 230Mpc was used.

uncertainties by applying a random 3° Gaussian smearing to all our mock UHECRs and repeating the correlation function measurements. The red shaded region in Figure 1 shows the 95% dispersion for these new measurements. As expected, the 3° smearing drastically reduces the correlation function at small angular scales, but has a negligible effect on scales larger than $\sim 2°$. Figure 1 shows that with a sample of 1000 UHECRs, the measured clustering at large angles ($\geq 4°$) alone can easily distinguish between the "cluster", "galaxy", and "random" hypotheses.

In this exercise, our mock UHECR samples were created in the same volume as the potential astrophysical sources we considered (galaxies and clusters). In reality, however, we do not know the distance of a given UHECR source, so comparing the clustering of UHECRs and a given candidate population of sources is not straightforward. The angular correlation function on a given angular scale includes a mixture of pairs at different physical scales. The deeper a given sample of objects is, the lower its measured angular correlation function because each angular bin includes more physically uncorrelated pairs that dilute the signal. We therefore must know the depth of our UHECR sample in order to interpret the measured angular correlations. For example, if we cross-correlate a sample of UHECRs of unknown depth with a sample of galaxies of depth 100Mpc and measure a low amplitude of $\omega(\theta)$, that could mean either that the sources of the UHECRs are low mass objects in the galaxy sample volume, or are high mass objects in a deeper volume. In the next section we show how to deal with the unknown depth of UHECR samples.

What Kind of UHECR Sample Do We Need?

Although the sample of 1000 UHECRs used in Figure 1 is large compared to current available samples, the sample depth in the above illustration is also large (median depth=230Mpc). The angular clustering will have a higher signal in shallower samples because each angular bin will mix in fewer uncorrelated pairs, so we can get away with smaller UHECR samples in shallower volumes in spite of the reduced number of galaxies in the sample. We explore this in Figure 2, where we show the signal-to-noise (S/N) of a measured UHECR-galaxy cross-correlation on large angular scales ($6-8°$), as a function of sample size $N_{\rm CR}$ and depth. In order to calculate this, we do the same sort of mock UHECR analysis as in Figure 1, but using galaxies from the 2MASS survey [7].

Figure 2 shows that if we want a S/N=3 (99.7% significance) detection of UHECRs clustering like ordinary 2MASS galaxies, we need 40 UHECRs of median source-distance $d_{\rm med}$ = 50Mpc, or $N_{\rm CR} = 80$ with $d_{\rm med} = 80$Mpc, or $N_{\rm CR} = 160$ with $d_{\rm med} = 110$Mpc, or $N_{\rm CR} = 320$ with $d_{\rm med} = 150$Mpc.

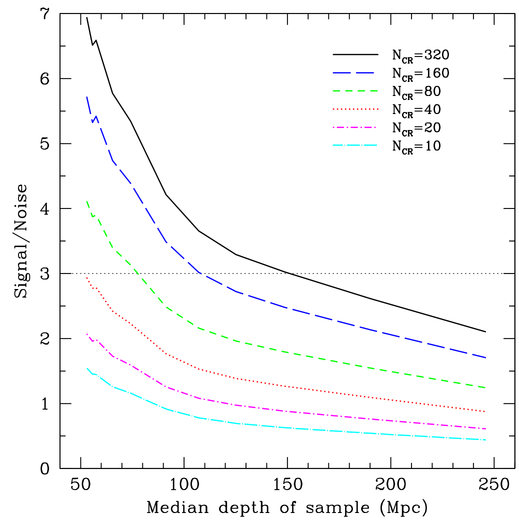

Figure 2: Estimated signal-to-noise (S/N) for measurements of the UHECR-galaxy cross-correlation function on large angular scales ($6-8°$) as a function of median sample depth and size of UHECR sample. This calculation was done using 2MASS galaxy samples of various sample depths, and assuming that UHECRs originate from these same galaxies. Different colored curves represent different size UHECR samples, as listed in the panel. This plot answers the question: At what significance can we detect the cross-correlation between UHECRs and 2MASS galaxies at large angular scales, if we have a UHECR sample of size $N_{\rm CR}$ and a given galaxy and UHECR sample depth?

We now return to the issue of the unknown depth of a given UHECR sample. Fortunately, the GZK energy loss phenomenon provides a way to put a limit on the depth of a UHECR sample. The rapid variation with energy of the energy loss means that an ensemble of UHECRs of a given energy has a rather well-defined horizon within which they are produced. If we assume that the energies of UHECRs are well determined, we can use the GZK effect to solve for the distance distribution of a UHECR sample, given an initial energy spectrum of cosmic rays. Assuming an $E^{-2.7}$ energy spectrum, we compute the median depth of an UHECR sample as a function of its lower energy cutoff, and show the result in Figure 3. We can now use Fig-

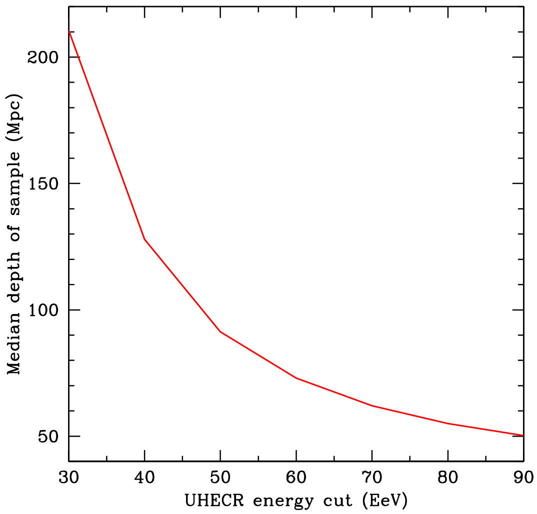

Figure 3: Median depth of a UHECR sample as a function of its lower energy cutoff, assuming that the probability distribution of distances for a single UHECR is given by that from the GZK effect weighted with the volume element. This calculation was done assuming a UHECR energy spectrum of $E^{-2.7}$. For each energy threshold, a total distance distribution was computed by weighting the probability distributions of individual energies by the overall energy spectrum. The sample depth decreases with energy because of the GZK effect.

ure 3 to connect the sample depths shown in Figure 2 with energy cutoffs for UHECR samples. In our S/N=3 example, the required samples would have 40, 80, 160, and 320 UHECRs with energies above 90EeV, 56EeV, 45EeV, and 37EeV, respectively. These samples are larger than currently available samples from AGASA+HiRes [8, 9], but should be available in the near future by the Pierre Auger experiment [10].

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