

Analysis of large-scale anisotropy of ultra-high energy cosmic rays in HiRes data

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ABSTRACT

Stereo data collected by the HiRes experiment over a six year period are examined for large-scale anisotropy related to the inhomogeneous distribution of matter in the nearby Universe. We consider the generic case of small cosmic-ray deflections and a large number of sources tracing the matter distribution. In this matter tracer model the expected cosmic ray flux depends essentially on a single free parameter, the typical deflection angle θ_s . We find that the HiRes data with threshold energies of 40 EeV and 57 EeV are incompatible with the matter tracer model at a 95% confidence level unless $\theta_s > 10^\circ$ and are compatible with an isotropic flux. The data set above 10 EeV is compatible with both the matter tracer model and an isotropic flux.

1. Introduction

The observation of the cutoff in the spectrum of Ultra-High Energy Cosmic Rays (UHECRs) (Abbasi et al. 2008a; Abraham et al. 2008a) as predicted by Greisen (1966); Zatsepin and Kuzmin (1966) provides compelling evidence for the shortening of the UHECR propagation length at high energies. The highest energy events then must have come from relatively close sources (within 250 Mpc). At these length scales the matter in the Universe is distributed inhomogeneously, being organized into clusters and superclusters. One should, therefore, expect the flux of highest-energy cosmic rays to be anisotropic.

In astrophysical scenarios, it is natural to assume that the number of sources within 250 Mpc is large, and that these sources trace the distri-

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bution of matter. Under these assumptions, the anisotropy at Earth depends only on the nature and size of UHECR deflections. Measurement of the anisotropy, therefore, gives direct experimental access to parameters that determine the deflections, notably to the UHECR charge composition and cosmic magnetic fields.

Several investigations of anisotropy in arrival directions of UHECRs have been previously undertaken. At small angular scales, correlations with different classes of putative sources were claimed (e.g. Gorbunov et al. 2004; Abbasi et al. 2006; Abraham et al. 2007, 2008b). At larger angular scales and energies below 10 EeV possible anisotropy towards the Galactic center was reported in Hayashida et al. (1999a,b); Bellido et al. (2001), but not supported by more recent studies (Santos 2007). At higher energies, Stanev et al. (1995) found evidence against an isotropic flux above 40 EeV through correlations with the supergalactic plane, but this was not confirmed by other authors (Hayashida et al. 1996; Kewley et al. 1996; Bird et al. 1998). Finally, using the Pierre Auger Observatory (PAO) data, Kashti and Waxman (2008) have found correlations between UHECR arrival directions and the large-scale structure of the Universe which are incompatible with an isotropic flux (see, however, Koers and Tinyakov 2009a).

In this paper, we analyze the data accumulated by the HiRes experiment for anisotropy associated with the large-scale structure of the Universe. The HiRes experiment has been described previously (Abu-Zayyad et al. 1999; Boyer et al. 2002; Hanlon 2008). It studied ultrahigh energy cosmic rays from $10^{17.2}$ eV to $10^{20.2}$ eV using the fluorescence technique. HiRes operated two fluorescence detectors located atop desert mountains in west-central Utah. The data set used in this study consists of events observed by both detectors, analyzed jointly in what is commonly called “stereo mode”. In this mode the angular resolution in cosmic rays’ pointing directions is about 0.8 degrees, and the energy resolution is about 10%. The HiRes experiment operated in stereo mode between December, 1999, and April, 2006. At the highest energies HiRes has the largest data set in the Northern hemisphere. Large number of events, good angular resolution (better than the bending angles expected from Galactic and ex-

tragalactic magnetic fields) and the wide energy range covered make the HiRes data particularly suitable for anisotropy studies. The exact data set used in this study was described previously in Abbasi et al. (2008b).

We consider here a generic model that assumes many sources within 250 Mpc tracing the distribution of matter, which we refer to as the “matter tracer” model. We also assume that deflections of UHECR do not exceed the angular size of the nearby structures, that is $10\text{-}20^\circ$. In this regime, both regular and random deflections in magnetic fields can be modeled with a one-parameter distribution, for which we take a Gaussian distribution centered at zero with width θ_s . This width is treated as a free parameter, whose value we aim to constrain from the data. Constraints on θ_s may then be used to obtain information on the strength of Galactic and extragalactic magnetic fields. In keeping with our assumption of small deflections, we assume a proton composition in this study, which is consistent with the X_{max} analysis based on the same dataset (for confirmation see Abbasi et al. 2009).

The HiRes data is compared to model predictions using the “flux sampling” test put forward by Koers and Tinyakov (2009a). This test has good discrimination power at small statistics and is insensitive to the details of deflections. The comparison is performed at three different threshold energies that have been used in previous studies: 10 EeV, 40 EeV, and 57 EeV (Hayashida et al. 1996; Abbasi et al. 2006; Abraham et al. 2007). An *a priori* significance of 5%, corresponding to a confidence level (CL) of 95%, is chosen for this work.

The paper is organized as follows. In section 2 we discuss the modeling of UHECR arrival directions. Section 3 concerns the HiRes data used in the analysis, while section 4 describes the flux sampling method. We present our results in section 5 and conclude in section 6.

2. Modeling of UHECR arrival directions

Galaxy catalog — The distribution of matter in the local Universe is modeled with the 2 Micron All-Sky Redshift Survey (2MRS; Huchra et al. 2009) galaxy catalog, using galaxies as samplers of

the underlying matter density field.¹ The 2MRS is a flux-limited sample of galaxies, that is, the sample containing all galaxies with observed magnitude in the K_s band $m \leq 11.25$. It contains spectroscopically measured redshifts for all but a few galaxies. A number of cuts have been applied to the galaxy sample. First, the Galactic plane, where the sample is incomplete, has been excluded from the sample by removing all galaxies with $|b| < 10^\circ$. Second, objects with $D < 5$ Mpc are removed because such objects should be treated on an individual basis.² Finally, the catalog is cut at 250 Mpc because the sample becomes too sparse. The resulting sample provides an accurate statistical description at smearing angles $\theta_s > 2^\circ$. The flux from sources beyond 250 Mpc is taken to be isotropic. A total of 15508 galaxies remain in the HiRes field of view after the cuts. To compensate for observational selection effects in the (flux-limited) 2MRS catalog, weights w_i^{cat} are assigned to the galaxies with the sliding-box method as described in Koers and Tinyakov (2009b).

Energy loss — UHECR fluxes are affected by energy loss due to redshift and interactions with the Cosmic Microwave Background (CMB). To account for the resulting flux suppression, the integral flux, φ_i , from a single source is expressed as follows:

$$\varphi_i(E, D_i) = \frac{J(E)f(E, D_i)}{4\pi D_i^2}, \quad (1)$$

where E is the threshold energy, D_i is the source distance, J stands for the integral injection spectrum at the source, and f represents the flux fraction that remains after interactions and redshift. We take an injection spectrum $J(E) \propto E^{-1.2}$ extending to very high energies. The function f is determined using a numerical propagation code based on the continuous loss approximation that is described in Koers and Tinyakov (2008, 2009a). Energy loss due to interactions with the extragalactic background light is neglected. In Figure 1, top panel, the fraction f is shown as a function of distance for the different energies considered in this work.

¹This sample was kindly provided by John Huchra.

²This corresponds to the *ad hoc* assumption that there are no UHECR sources within 5 Mpc. Different analyses are more appropriate to test this possibility.

The strength of the isotropic flux component that is added to account for sources beyond 250 Mpc also depends on UHECR energy loss. Using the computer code described in the previous paragraph, we estimate the fraction g of total flux contributed by sources within 250 Mpc to be 0.4, 0.7, and 1.0 for threshold energies $E = 10$ EeV, 40 EeV, and 57 EeV, respectively (see Figure 1, bottom panel).

Deflections — UHECR protons (as well as nuclei) are deflected by Galactic and intergalactic magnetic fields. These deflections are taken into account by an angular smearing procedure, which replaces the point-source flux, φ , by a flux density distribution:

$$\varphi_i \rightarrow \varphi_i w^s(\theta_i), \quad (2)$$

where $w^s(\theta_i)$ represents the probability density that an UHECR is deflected by θ_i , the angle between galaxy i and the line of sight. This procedure also accounts for the detector's angular resolution and prevents unphysical fluctuations due to the use of a catalog of point sources. In the absence of detailed knowledge on the structure of Galactic and extragalactic magnetic fields, we adopt a simple Gaussian probability density distribution with characteristic angle, θ_s . This angle is treated as a free model parameter. The Gaussian distribution is a fair approximation when the deflections are small. For large deflections, details on the structure of the Galactic and extragalactic magnetic fields become important. Accounting for these details goes beyond the scope of the present study.

Exposure — The HiRes exposure is modeled using our Monte Carlo simulation of the experiment (Abbasi et al. 2007; Bergman 2007). The aim of this simulation was to create a set of Monte Carlo events that would be in all essences identical to the actual data. In making the simulation we put in the properties of cosmic ray air showers as measured by previous experiments (Bird et al. 1993; Abu-Zayyad et al. 2000, 2001; Abbasi et al. 2005). We used cosmic ray showers generated by the Corsika and QGSJet programs (Heck et al. 1998; Kalmykov et al. 1997) and simulated the generation of fluorescence light (see references in Abbasi et al. 2008a) and its propagation through the atmosphere (see references in Abbasi et al. 2008a). A complete simulation of the

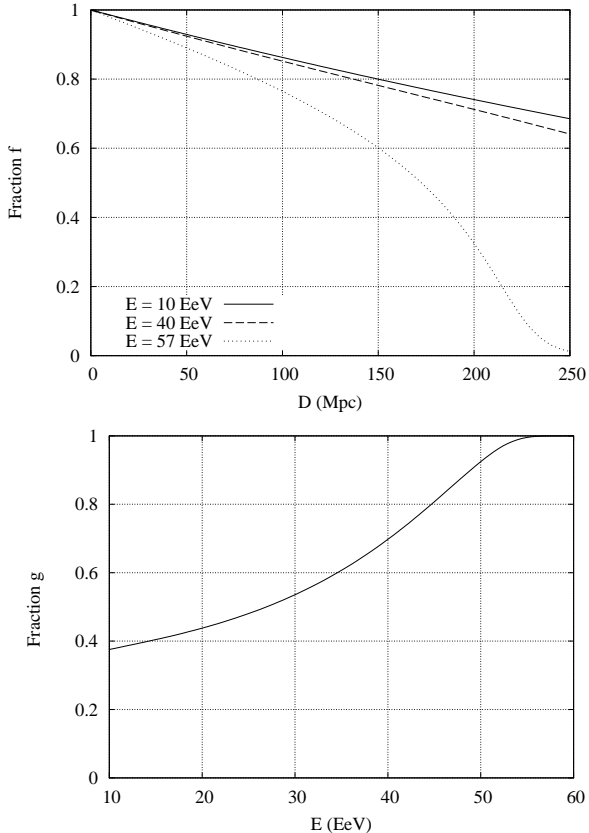


Fig. 1.— *Top panel:* Fraction f of integral CR flux that survives after interactions with the CMB and cosmological redshift as a function of distance D for threshold energies 10 EeV (solid line), 40 EeV (dashed), and 57 EeV (dotted). *Bottom panel:* Fraction g of total flux that is produced by sources within 250 Mpc, as a function of energy E .

optics and electronics (trigger and front-end electronics) of our detectors was performed. The result was an excellent simulation of our experiment as evidenced by the very good agreement between data and simulated events in the distribution of all kinematic variables, e.g. zenith angle, impact parameter to detector, etc. By assigning Monte Carlo events times of occurrence taken from the actual on-time of the experiment we are able to calculate the exposure on the sky very accurately.

Model flux maps — The integral UHECR flux from a given direction is expressed as follows:

$$\tilde{\Phi} = \sum_i \varphi_i w_i^{\text{cat}} w^s(\theta_i) + \Phi_{\text{iso}}, \quad (3)$$

where i enumerates galaxies in the 2MRS sample, w_i^{cat} denotes the weight assigned to galaxy i in the catalog, $w^s(\theta_i)$ is the deflection probability distribution, and Φ_{iso} is the UHECR flux arising from sources beyond 250 Mpc.

The probability to observe a CR from a given direction is proportional to the product of flux and exposure. We denote this probability as

$$\tilde{\Phi} = \Phi \Xi, \quad (4)$$

where Ξ stands for exposure. In Figure 2, the distribution of $\tilde{\Phi}$ over the sky is shown for three different threshold energies. The contrast in the flux distributions becomes more pronounced with increasing energy. Also shown are the arrival directions of UHECRs in the HiRes data to which the model flux has to be compared.

3. Data

The data set used in this study was described previously in Abbasi et al. (2008b), including selection criteria and a correction to the energy scale. Our sample of the 2MRS catalog does not cover the region near the Galactic plane with $|b| < 10^\circ$. We therefore removed cosmic ray events with $|b| < 10^\circ$ from the analysis. The resulting sample contains:

- 309 events with $E > 10$ EeV;
- 27 events with $E > 40$ EeV;
- 10 events with $E > 57$ EeV.

The arrival directions of these events are shown as white dots in Fig. 2.

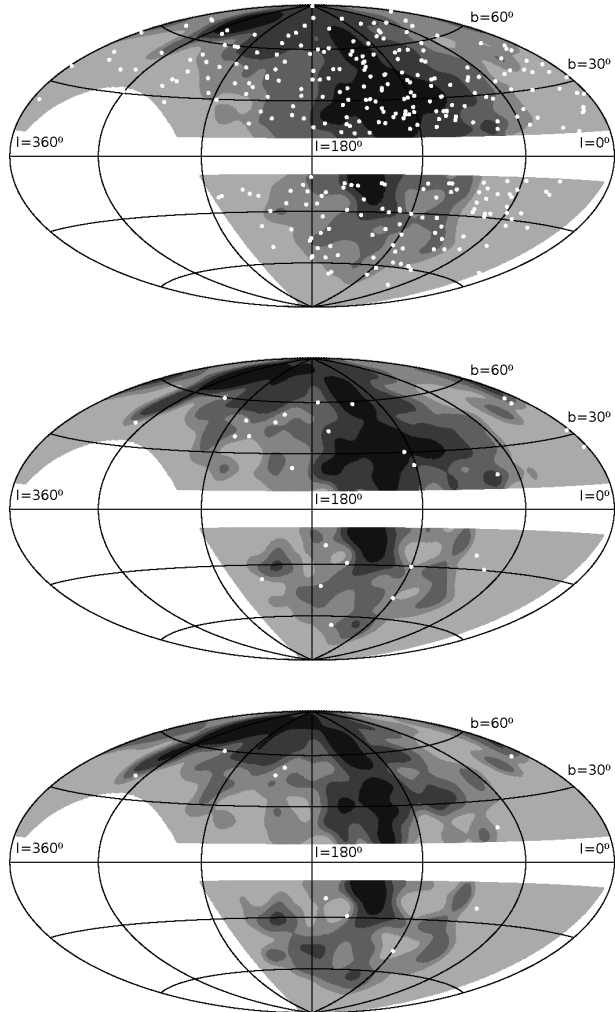


Fig. 2.— Hammer projection (galactic coordinates) of $\tilde{\Phi}$ (flux times exposure) with threshold energies 10 EeV (top panel), 40 EeV (middle), and 57 EeV (bottom). Darker gray indicates a higher value; the bands are chosen such that each band contains 1/5 of the total flux (weighted with exposure). Excluded regions, viz. the galactic plane ($|b| < 10^\circ$) and the region outside the HiRes field of view, are shown in white. White dots indicate HiRes events. All maps are produced with $\theta_s = 6^\circ$.

4. Statistical test

The compatibility of a model flux map with the set of UHECR arrival directions is quantified by the flux sampling method introduced by Koers and Tinyakov (2009a). The idea of the method is as follows. To any set of arrival directions one associates the set of flux values that are obtained by sampling a given flux map (such as the map shown in fig. 2), i.e. by extracting the flux values at corresponding points on the sphere. The two-dimensional distribution of arrival directions thus translates into a one-dimensional distribution of flux values. If the reference model is true, this flux distribution will tend to high values since events fall preferentially into regions where the model flux (times exposure) is high. If, on the other hand, the reference model is not true, the flux distribution is more uniform because the correlation between arrival directions and regions of high model flux is (partly) destroyed. By comparing the flux distribution to a model flux distribution, the compatibility between a set of arrival directions and model predictions can be quantified. This comparison is performed by the Kolmogorov-Smirnov (KS) test, which yields a test statistic D . The relevant statistical quantities, in particular powers and p -values, are computed from the distribution of this test statistic. Note that this test does not involve any additional parameters like bin size.

The ability of the test to discriminate between models may be quantified in terms of the statistical power, P , i.e. the probability to rule out, at a given confidence level, the reference model when an alternative model is true. Within numerical uncertainties, the statistical power is equal to the fraction of event sets generated under the alternative model that leads to rejecting the reference model. Figure 3 shows the number of events required for a power $P = 0.5$ (i.e., a 50% probability) to rule out (at 95% CL) the matter tracer model when the true flux is isotropic. The number of events increases with increasing smearing angle and decreasing energy: the decreasing flux contrasts in the matter tracer model call for an increase in statistics to achieve the same discriminatory power. Observe that the event numbers indicated in Figure 3 are of the same order as the data analyzed in this work. We thus expect that

there is sufficient data to obtain meaningful constraints at 95% CL.

5. Results

5.1. Scan over smearing angles

The level of compatibility between data and model predictions is quantified by a p -value, which represents the model probability of obtaining a measurement that is at least as extreme as the actual measurement. With our *a priori* choice of significance, a p -value smaller than 0.05 rules out the model. The probability of falsely excluding the model is then 5%, translating to a CL of 95%.

Figure 4 shows the p -values obtained by the flux sampling method for the HiRes data and predictions of the matter tracer model. The smearing angle, θ_s , is treated as a free parameter. That is, at each value of θ_s and each threshold energy a flux map is generated and compared to the HiRes data as described above. The results can be summarized as follows:

- (a) For the threshold energies of 40 EeV and 57 EeV, the tests show disagreement between data and the matter tracer model for $\theta_s \leq 10^\circ$. Within this parameter range, a source distribution tracing the distribution of matter is excluded at a 95% confidence level.
- (b) For the threshold energy of 10 EeV, the test shows agreement between data and the matter tracer model.

The incompatibility between data and matter tracer model is illustrated by the non-correlation between the observed arrival directions and regions of high model flux shown in the two lower panels of Figure 2.

We have also tested the data for compatibility with an isotropic model flux and found no disagreement, at 95% CL, for any of the three tested threshold energies (the data with threshold energy 57 EeV are marginally consistent with an isotropic flux).

5.2. Case study: $E = 57$ EeV, $\theta_s = 3.2^\circ$

At energy threshold $E > 57$ EeV a correlation between the arrival directions of UHECRs and the location of AGNs contained in the

12th edition of the Véron-Cetty & Véron catalog (Véron-Cetty and Véron 2006) was reported by the PAO (Abraham et al. 2007, 2008b). This correlation was found to be maximal for $\psi = 3.2^\circ$, where ψ denotes the maximum angular distance between UHECRs and AGNs. In the Northern hemisphere, correlation with AGN was not confirmed by the HiRes experiment (Abbasi et al. 2008b).

Since AGNs are tracers of the distribution of matter in the Universe, the PAO result is suggestive of a more general correlation between UHECRs and the local structure of the Universe on an angular scale of a few degrees. The methods presented in this paper allow a check on the existence of such correlations in the HiRes data.

The results presented in the previous section disfavor a correlation between UHECRs and the local structure of the Universe. In fact, the flux sampling test yields p -values smaller than 10^{-2} for the matter tracer model with $\theta_s \lesssim 6^\circ$, with a p -value of 7×10^{-4} for $\theta_s = 3.2^\circ$. (Note that θ_s is not in 1 : 1 correspondence with ψ ; both quantities are however representative of the angular scale of the problem). Focusing on the case of $\theta_s = 3.2^\circ$ in more detail, Figure 5 shows the distribution of the test statistic D for the matter tracer model and for an isotropic flux for this smearing angle. The vertical line shows the value $D_{\text{obs}} = 0.59$ obtained for the HiRes data. This demonstrates the strong incompatibility between HiRes data and the matter tracer model for smearing angle $\theta_s = 3.2^\circ$ and threshold energy $E = 57$ EeV.

6. Conclusions

To summarize, we have confronted the stereo data collected by the HiRes experiment with predictions of the matter tracer model, a generic model of cosmic ray origin and propagation. The model assumes a large number of cosmic ray sources within 250 Mpc whose distribution traces that of matter, and relatively small deflections characterized by a single parameter, the typical deflection angle θ_s . We have found that the HiRes data with energy thresholds $E = 40$ EeV and $E = 57$ EeV are incompatible with the matter tracer model for $\theta_s < 10^\circ$ at 95% CL. With an energy threshold $E = 10$ EeV the HiRes data are compatible with the matter tracer model. At all

three energy thresholds, the data are compatible with an isotropic flux at 95% CL.

In the present analysis we have treated the deflections as random and Gaussian, which is only appropriate for small deflection angles and limited number of events. The actual deflections are expected to contain a coherent component due to the Galactic magnetic field. With the accumulation of UHECR events by PAO in the Southern hemisphere and by Telescope Array in the Northern hemisphere, our analysis will become sensitive to the nature of deflections and thus, with proper modifications of the statistical procedure, may give direct access to the parameters of cosmic magnetic fields.

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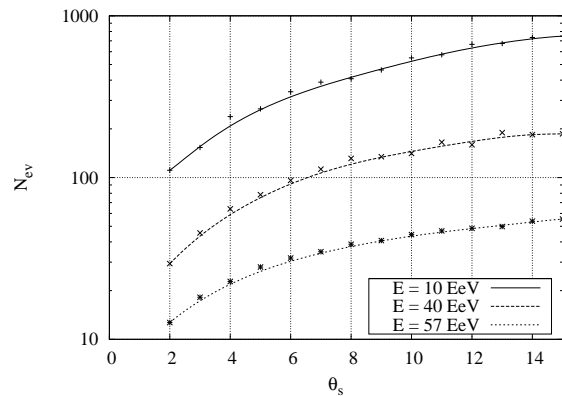


Fig. 3.— Number of events required for a 50% probability to rule out, at 95% CL, the matter tracer model if the true flux is isotropic.

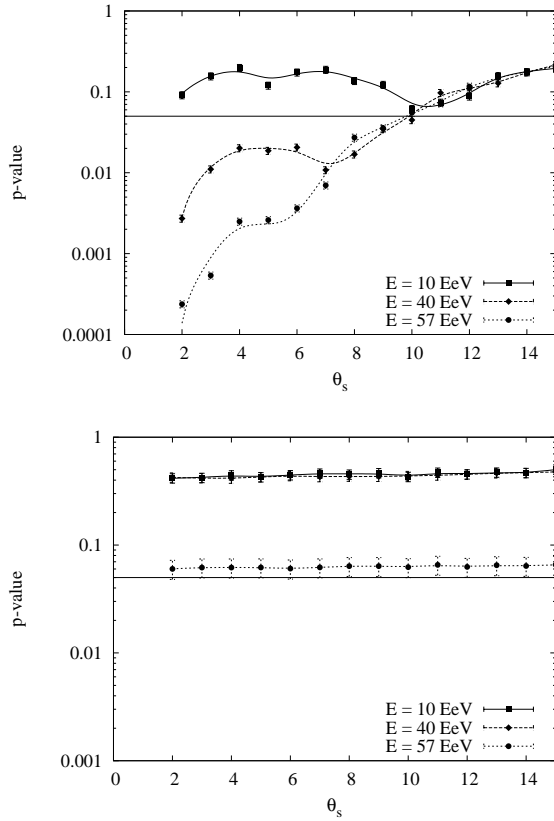


Fig. 4.— The dependence of p -value indicating the level of (in)compatibility between HiRes data and model predictions on the smearing angle θ_s . Solid lines indicate a p -value equal to 0.05, below which the model is ruled out at 95% CL. The points represent numerical results (with estimated uncertainties of 20%); the lines are smooth interpolations between these points. Top panel: data vs. matter-tracer model; bottom panel: data vs. isotropic distribution.

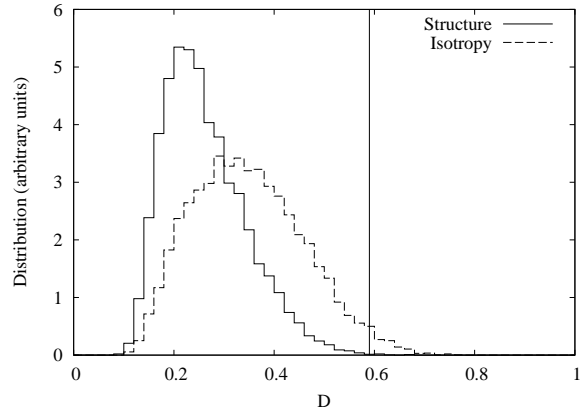


Fig. 5.— Model distribution of test statistic D when testing the matter tracer model, for both the matter tracer model (“Structure”) and an isotropic flux distribution (“Isotropy”). Here $E = 57$ EeV and $\theta_s = 3.2^\circ$. The vertical line indicates the observed value $D_{\text{obs}} = 0.59$.