

First hints of large scale structures in the ultra-high energy sky?

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The result of the recent publication [1] of a broad maximum around 25 degrees in the two-point autocorrelation function of ultra-high energy cosmic ray arrival directions has been intriguingly interpreted as the first imprint of the large scale structures (LSS) of baryonic matter in the near universe. We analyze this suggestion in light of the clustering properties expected from the PSCz astronomical catalogue of LSS. The chance probability of the signal is consistent within 2σ with the predictions based on the catalogue. No evidence for a significant cross-correlation of the observed events with known overdensities in the LSS is found, which may be due to the role of the galactic and extragalactic magnetic fields, and is however consistent with the limited statistics. The larger statistics to be collected by the Pierre Auger Observatory is needed to answer definitely the question.

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I. INTRODUCTION

The origin of ultra-high energy cosmic rays (UHECRs) is still an open problem and, at the present, two different classes of models compete to explain the most energetic events observed. In “bottom-up” mechanisms the acceleration up to extreme energy occurs in suitable astrophysical environments, whereas in “top-down” scenarios UHECRs are produced by the decay or annihilation of super-massive relic particles in the halo of our Galaxy or by cosmological diffuse topological defects. The observation that UHECR arrival directions (in particular at energies $E \gtrsim 8 \times 10^{19}$ eV) may cluster according to the underlying large scale structure (LSS) of the universe would represent a clear evidence in favor of the “bottom-up” mechanisms, and should co-exist with the flux suppression known as the Greisen-Zatsepin-Kuzmin (GZK) effect [2, 3]. The challenging and fascinating problem of determining at which energy (if any) astronomy with charged particles becomes possible is thus strictly related to the identification of the sources of UHECRs, which in turn would constrain the galactic and extragalactic magnetic fields as well as the chemical composition of the primaries. The latter point is an important prerequisite to use UHECR data to study particle interactions at energy scales otherwise inaccessible to laboratory experiments.

It is well known that the chances to perform cosmic rays astronomy increase significantly at extremely high energy, in particular due to the decreasing of deflections in the galactic/extragalactic magnetic fields. Moreover, at $E \gtrsim 4 - 5 \times 10^{19}$ eV the opacity of the interstellar space to protons drastically grows due to the photo-pion production $p + \gamma_{\text{CMB}} \rightarrow \pi^{0(+)} + p(n)$ on cosmic microwave background (CMB) photons (GZK effect). A similar phenomenon at slightly different energies occurs for heavier primaries via photo-disintegration energy losses. Above this range of energy, most of the flux comes from sources within a distance of few hundred Mpc (see e.g. [4]), and this should facilitate the source identification. Thus, the GZK feature in the spectrum and the large-scale

anisotropy should be correlated signatures. The drawback is that in the trans-GZK regime the flux is greatly suppressed, even beyond the expected power-law extrapolation of UHECR spectrum, and instruments with huge collecting areas are required to accumulate sufficient statistics to attack the problem. A final answer is expected when the Pierre Auger Observatory [5, 6] will have detected enough events.

Until now, the experiments of the previous generation have collected $\mathcal{O}(100)$ events above $E \gtrsim 4 - 5 \times 10^{19}$ eV, and one may wonder if any useful hint of the UHECR sources already hides in the available catalogues. In the recent publication [1], the authors found some evidence of a broad maximum of the two-point autocorrelation function of UHECR arrival directions around 25 degrees. The evidence was obtained combining the data with energies above 4×10^{19} eV of several UHECR experiments, after an *a priori* adjustment of their energy scale. This signal becomes significant only when several data-sets are added, but it is not caused solely by an incorrect combination of the exposure of different experiments. Both the signal itself and the exact value of the chance probability have to be interpreted with care, since the authors did not fix a priori the search and cut criteria. Although the nominal value of the chance probability for the signal to arise from random fluctuations is around 0.01%, when taking into account a penalty factor of 30 they estimated the “true chance probability” of the signal to be of the order of $P \sim 0.3\%$. The authors suggest that, given the energy dependence of the signal and its angular scale, it might be interpreted as a first signature of the large-scale structure of UHECR sources and of intervening magnetic fields.

The aim of this work is to test their qualitative interpretation of the result on the light of the signal expected if UHECR data reflect the large scale structure distribution of galaxies in the nearby universe. In Ref. [7], we have performed a forecast analysis for the Pierre Auger Observatory, to derive the minimum statistics needed to test the hypothesis that UHECRs trace the baryonic dis-

tribution in the universe. Assuming proton primaries, we found that a few hundred events at $E \gtrsim 5 \times 10^{19}$ eV are necessary at Auger to have reasonably high chances to identify the signature, independently of the details on the injection spectrum. In this work we calculate the expected signal in terms of the autocorrelation function as in [1] for the presently available statistics, and discuss quantitatively how well predictions based on the LSS distribution can reproduce their findings. The method and the results obtained are presented in Sec. II; in Sec. III we briefly discuss our findings and conclude.

II. UHECR CLUSTERING ON MEDIUM SCALES AND LSS

In our analysis, we closely follow the approach reported in [1], using a similar dataset extracted from available publications or talks of the AGASA [8], Yakutsk [9], SUGAR [10], and HiRes collaborations [11, 12]. In particular, in order to match the flux normalization of HiRes, the energies of the AGASA data must be rescaled downwards by $\sim 30\%$, while the energies of Yakutsk and SUGAR data by $\sim 50\%$. We address the reader to [1] for further details.

We define the (cumulative) autocorrelation function w as a function of the separation angle δ as

$$w(\delta) = \sum_{i=2}^N \sum_{j=1}^{i-1} \Theta(\delta - \delta_{ij}), \quad (1)$$

where Θ is the step function, N the number of CRs considered and $\delta_{ij} = \arccos(\cos \rho_i \cos \rho_j + \sin \rho_i \sin \rho_j \cos(\phi_i - \phi_j))$ is the angular distance between the two cosmic rays i and j with coordinates (ρ, ϕ) on the sphere. We perform a large number $M \simeq 10^5$ of Monte Carlo simulations of N data sampled from an uniform distribution on the sky and for each realization j we calculate the autocorrelation function $w_j^{\text{iso}}(\delta)$. The sets of random data match the number of data for the different experiments passing the cuts after rescaling, and are spatially distributed according to the exposures of the experiments. The formal probability $P(\delta)$ to observe an equal or larger value of the autocorrelation function by chance is

$$P(\delta) = \frac{1}{M} \sum_{j=1}^M \Theta[w_j^{\text{iso}}(\delta) - w_*(\delta)], \quad (2)$$

where $w_*(\delta)$ is the observed value for the cosmic ray dataset and the convention $\Theta(0) = 1$ is being used. Relatively high values of P and $1 - P$ indicate that the data are consistent with the null hypothesis being used to generate the comparison samples, while low values of P or $1 - P$ indicate that the model is inappropriate to explain the data. Note also that by construction the values at different δ of the function $P(\delta)$ are not independent. Nonetheless, studying the cumulative distribution function (as

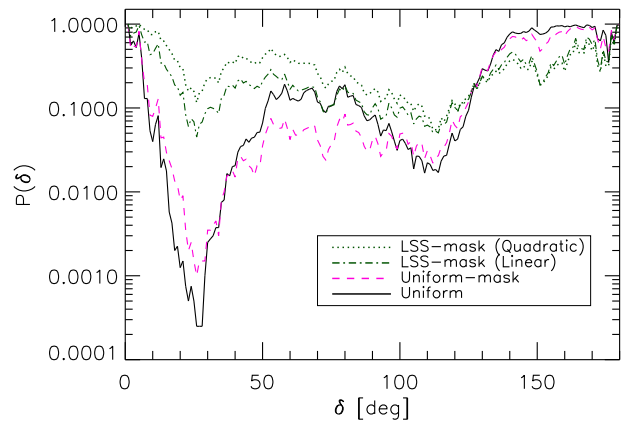


FIG. 1: The solid line shows the chance probability $P(\delta)$ to observe an equal or larger value of the autocorrelation function as function of the angular scale δ for the combination of experimental data of Hires+AGASA+Yakutsk+SUGAR as described in the text. The dashed purple line is the same signal, when cosmic rays falling in the PSCz catalogue mask are disregarded. The dot-dashed green line is the same quantity, if the random events are sampled according to the LSS distribution, instead of an uniform one. The dotted green line is the result for a sample proportional to the square of the LSS distribution.

opposed to the differential one) is the only realistic way to extract information in a low statistics “noisy” sample. In addition, an autocorrelation study—differently from the approach of Ref. [7] where a χ^2 -analysis was used—only relies on the clustering probability in the data, while any directionality in the signal is lost. Although providing less compelling evidence, this method has the advantage of being more robust towards large magnetic deflections. As long as the energy and the charge of primaries from the same source are similar, their relative displacement should be small compared with the absolute displacement with respect to their sources. Thus it is natural to expect that the first (although more ambiguous) hints of a signal may come from the study of $w(\delta)$.

Figure 1 summarizes our main results. The solid, black curve shows that under the same assumptions of Ref. [1], we obtain the same behavior for the function $P(\delta)$ (compare with their Fig. 5). To proceed further, we have to compare the previous signature with the one expected from a model of the LSS. As in [7], we use the IRAS PSCz galaxy catalogue [13]. We address to our previous work [7] as well as to the original paper [13] for technical details about the catalogue and about the calculation of the UHECR sky map—which takes into account energy losses as well—that we use in the following. It is important reminding that the catalogue suffers of an incomplete sky coverage. This includes a zone centered on the galactic plane and caused by the galactic extinction and a few, narrow stripes which were not observed with enough sensitivity by the IRAS satellite. These regions are excluded from our analysis with the use of the binary mask

available with the PSCz catalogue itself. This reduces the available sample (by about 10%) to 93 events and the nominal chance probability to 0.1% (Fig. 1, dashed–purple line). Note that this is a quality factor of the catalogue, not an intrinsic problem of the data or theoretical prediction. The green/dot–dashed line in Fig. 1 shows the chance probability of the signature found in [1], if the random events are sampled according to the LSS distribution (obviously convolved with the experimental exposures), rather than from an uniform one. Finally, the dotted line shows the same result if the random events are sampled according to *the square* of the LSS distribution, as one would expect e.g. for a strongly biased population of sources.

The prominent minimum of [1] is greatly reduced when using as null hypothesis the LSS model instead of the uniform one; this effect is even more prominent in the quadratic map. Also, the data are less clustered than expected from an uniform distribution at $\delta \sim 160^\circ$, where $P \sim 1$. This additional puzzling feature disappears when using the LSS null hypothesis, as it appears clearly in Fig. 2, where we plot the function $P(\delta) \times [1 - P(\delta)]$ for the same cases of Fig. 1. This function vanishes if any of P or $1 - P$ vanishes and has the theoretical maximum value of $1/4$. Thus, the higher its value is the more consistent the data are with the underlying hypothesis. Apart from the very small scales, where our results are unrealistic since we did not include magnetic smearing or detector angular resolution, the better concordance of the UHECR distribution with the LSS distribution than with the uniform one is evident at any scale. Taken at face value, our result implies a nominal probability $P \gtrsim 5\%$ that the main signature found in Ref. [1] arises as a chance fluctuation from the LSS distribution. This suggests that the clustering properties of LSS are in much better agreement with the experimental data than a pure isotropic distribution. This is not an unexpected feature given that, as found in [7], the typical size on the sky of the clusters of structures lie in the range 15° – 30° .

The absolute scale of the curves shown in Fig. 1 is affected by an uncertainty due to the true energy scale: we calculated the map assuming that the HiRes energy scale is the correct one, in agreement with Berezhinsky et al.’s fit of the dip due to pair production of protons on CMB [14]. But if the true energy is higher, as a compromise solution with the other experiments may require, the chance probability is slightly higher. In this respect, one may look at our result as a conservative one. Hence, the largest sample of [1] which we chose on the basis of the strongest signal is consistent within “ 2σ ” with the clustering properties expected from LSS distribution¹. Also given the fact that the “true probability” is higher than

the nominal one (due to the penalty factor of the search a posteriori performed in [1]), this may be considered as an argument in favor of their interpretation.

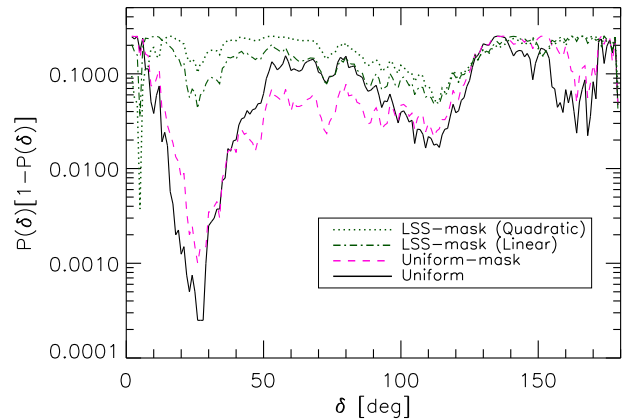


FIG. 2: The function $P(\delta) \times [1 - P(\delta)]$ for the same cases shown in Fig. 1. See text for details.

In order to understand why their result is consistent with our sampled catalogue, it is useful to look at the chance probability of the autocorrelation signal of events sampled from the LSS according to the experimental exposures, assuming linear correlation. We show this function in Fig. 3 for two samples of $N = 93$ and $N = 279$ data, respectively the same statistics of the dashed and dot–dashed curves in Fig. 1, and a factor 3 higher. The curves are obtained as follows: a large number $M (\simeq 10^4)$ Monte Carlo realization of N events is sampled according to the LSS probability distribution, and for each realization i we calculate the function $w_i^{\text{LSS}}(\delta)$. We generate analogously M random datasets from an uniform distribution, and calculate $w_j^{\text{iso}}(\delta)$. We have thus M^2 independent couples of functions (i, j) . The fraction of the M^2 simulations where the condition $w_j^{\text{iso}}(\delta) \geq w_i^{\text{LSS}}(\delta)$ is fulfilled is the probability

$$P_{\text{LSS}}(\delta) = \frac{1}{M^2} \sum_{i=1}^M \sum_{j=1}^M \Theta[w_j^{\text{iso}}(\delta) - w_i^{\text{LSS}}(\delta)], \quad (3)$$

which is the function shown in Fig. 3.

An important qualitative feature is that the shape of the curve presents indeed a broad minimum at scales of $\delta \lesssim 30^\circ$, and a moderate plateau at scales of $70^\circ \lesssim \delta \lesssim 130^\circ$. As shown by the $N = 279$ case, in particular the first feature is intrinsic to the data: the more data are sampled, the more enhanced it appears. This is also the trend shown in [1] when enlarging the experimental statistics considered. Also, the higher the energy cut in the map, the stronger the signature, since the local structures are more and more prominent. Finally, the LSS data samples are typically less clustered than the uniform ones at $\delta \gtrsim 150^\circ$ ($P_{\text{LSS}} > 0.5$).

On the other hand, the minimum found in Fig. 3 for the sample of 93 data is much less prominent than the

¹ Consistent within “ 2σ ” means here at least in 5% of the cases. The distribution is indeed far from gaussian, and the number of σ can be used in its loose sense only.

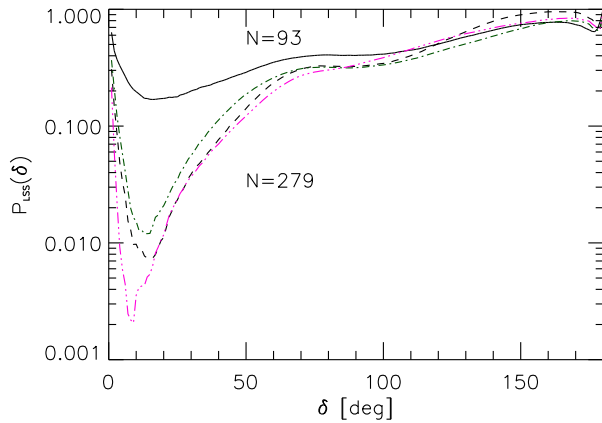


FIG. 3: Chance probability $P_{\text{LSS}}(\delta)$ to observe a larger value of the autocorrelation function as function of the angular scale δ for two samples of 93 and 279 data according to the LSS map cutted at 4×10^{19} eV. The three lower curves for the $N = 279$ case show the signature when the map cutted at $E > 2, 4, 5 \times 10^{19}$ eV—from top to bottom—is used, while the upper solid curve refers to the case $N = 93$, $E > 4 \times 10^{19}$ eV.

one shown by the dashed curve in Fig. 1. This explains why the consistency is “only” at the level of $\sim 5\%$. This fact is not unexpected, given the predictions of Ref. [7]: ~ 100 events are too few to *guarantee* a detection of the imprint of the LSS with a high significance. Consistently with the results of Fig. 1, we checked that the dip in Fig. 3 becomes more pronounced if we use a quadratic bias with LSS. Although not statistically significant at the moment, a confirmation of a highly clustered signal at intermediate scales may suggest thus a more than linear correlation of UHECR sources with the galaxy density field. Alternatively, the signal may be due to the magnetic smearing of a few relatively strong point-sources.

Clearly, a smoking gun in favor of the LSS-distribution would be a correlation between the data and the expected excess in the LSS map. By performing an analysis similar to the previous one, but in terms of the cross-correlation function between simulated data and sampled ones, we did not find any evidence favoring a LSS origin with respect to the uniform case. Actually this is not unexpected within the model considered in [7], since ~ 100 data at energy $\gtrsim 4 \times 10^{19}$ eV is still a too low statistics to draw a firm conclusion in this sense. However, the lack of this signature may also be related to the role of intervening magnetic fields. Acting on an energetically (and possibly chemically) inhomogeneous sample, magnetic fields may displace the observed positions with respect to the original ones in a non trivial way, without evidence for a characteristic scale, at least in a poor statistics regime. A possible hint towards a non-negligible role of magnetic fields is given also by the fact that the dip in the LSS signal is already present at relatively small angles. This feature may have disappeared in the UHECR sample due to a smearing effect of the magnetic fields.

III. DISCUSSION AND CONCLUSIONS

We have analyzed the hypothesis that the broad maximum of the two-point autocorrelation function of the UHECRs arrival directions around 25° found in Ref. [1] may be due to the imprint of the LSS. We have concluded that this suggestion is at least partially supported by the UHECR sky map constructed starting from a LSS catalogue. Even their nominal (non penalty factor-corrected) result for the autocorrelation function is consistent within 2σ with our expectations. A stronger correlation with source luminosity or a more-than-linear bias with overdensity may improve the agreement. Also, the correlation may not be directly with the LSS themselves: any class of sources which is numerous enough is expected to show some indication in favor of this correlation. The low statistics and the role of the magnetic field deflections may explain why no significant *cross-correlation* between data and LSS overdensities is found.

The authors of Ref. [1] also claim that the if the signal found is real, a heavy composition of the UHECRs is disfavored. However, we note that a heavy or mixed composition of the UHECRs may well be consistent with the signature. If we limit to the role of the (relatively well known) galactic magnetic field, a naive extrapolation of the simulations performed in [15] would indicate in the linear regime deflections for iron nuclei of about 130° with respect to the incoming direction. UHE iron nuclei would then be in a transition from diffusive to ballistic regime. Nonetheless, the signal is sensitive to the *relative* deflections of “bunches” of cosmic rays originating from a similar region of the extragalactic sky, for which typical models of the regular galactic magnetic field predict a smearing $\lesssim 40^\circ$ even for iron nuclei, as long as their energies do not differ by more than about 30%. One may even speculate that the second dip at large angles (arising from cross-correlation of different groups of overdensities) might originate from primaries of different rigidity coming from the same few sources, splitted apart by intervening fields. Also, the consideration in [1] that accounting for the medium scale structure in UHECRs may change the significance of claims of small-scale clustering should be carefully examined. If the picture emerging from Ref. [1] and this paper is consistent, *both* LSS and magnetic fields play a role in shaping the signal, otherwise it is hard to explain the lack of cross-correlation with known overdensities of LSS. “Filaments and voids” in the observed data do not match the position of filaments and voids in the LSS. But if they are nonetheless connected, this difference must be rigidity-dependent. Thus, a cluster of events with high rigidity may well arise in a void of the presently known UHECR filamentary structure, which may sit closer to an overdensity of the LSS. Indeed, the clustered component of the AGASA data favoring small-scale clustering does show a different energy spectrum than the non-clustered component. This discussion emphasizes that, unfortunately, it is virtually impossible to draw strong conclusions at present, even assuming that

the clustering at intermediate scales is physical.

In conclusion, the analysis performed in this paper does not exclude that the signal found in [1] may be due to the imprint of the LSS, an indeed gives some support in this sense. Definitely, the larger statistics that the Auger Observatory is going to collect in the next years is needed to tell us finally if astronomy is possible with UHECRs or, equivalently, if we will be ever able to look

at the sky with new and “ultra-energetic” eyes.

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- [1] M. Kachelrieß and D. V. Semikoz, “Clustering of ultra-high energy cosmic ray arrival directions on medium scales,” *Astrop. Phys.* **26**, 10-15 [astro-ph/0512498].
 - [2] K. Greisen, “End To The Cosmic Ray Spectrum?,” *Phys. Rev. Lett.* **16**, 748 (1966).
 - [3] G. T. Zatsepin and V. A. Kuzmin, “Upper Limit Of The Spectrum Of Cosmic Rays,” *JETP Lett.* **4**, 78 (1966) [*Pisma Zh. Eksp. Teor. Fiz.* **4**, 114 (1966)].
 - [4] D. Harari, S. Mollerach and E. Roulet, “On the ultra-high energy cosmic ray horizon,” *J. Cosmol. Astropart. Phys.* **11** (2006) 012 [astro-ph/0609294].
 - [5] Pierre Auger Collaboration, 1996 *The Pierre Auger Project Design Report*, FERMILAB-PUB-96-024.
 - [6] Abraham J *et al.* (Pierre Auger Collaboration), “Properties and performance of the prototype instrument for the Pierre Auger Observatory,” 2004 *Nucl. Instrum. Meth. A* **523** 50.
 - [7] A. Cuoco *et al.*, “The footprint of large scale cosmic structure on the ultra-high energy cosmic ray distribution,” *JCAP* **0601**, 009 (2006) [astro-ph/0510765].
 - [8] N. Hayashida *et al.*, “Updated AGASA event list above 4×10^{19} eV,” astro-ph/0008102.
 - [9] Talk of M. Pravdin at the 29th ICRC Pune 2005, <http://icrc2005.tifr.res.in/htm/PAPERS/HE14/rus-pravdin-MI-abs1-he14-poster.pdf>
 - [10] M. M. Winn *et al.*, “The cosmic ray energy spectrum above 10^{17} eV,” *J. Phys. G* **12** (1986) 653.
 - [11] R. U. Abbasi *et al.* [The High Resolution Fly’s Eye Collaboration (HIRES)], “Study of small-scale anisotropy of ultrahigh energy cosmic rays observed in stereo by HiRes,” *Astrophys. J.* **610**, L73 (2004). [astro-ph/0404137].
 - [12] Talk of S. Westerhoff at the CRIS-2004 workshop “GZK and Surrounding”, Catania, Italy, <http://www.ct.infn.it/cris2004/talk/westerhoff.pdf>
 - [13] W. Saunders *et al.*, “The PSCz Catalogue,” *Mon. Not. Roy. Astron. Soc.* **317**, 55 (2000). [astro-ph/0001117].
 - [14] V. Berezhinsky, A. Z. Gazizov and S. I. Grigorieva, “Dip in UHECR spectrum as signature of proton interaction with CMB,” *Phys. Lett. B* **612**, 147 (2005). [astro-ph/0502550].
 - [15] M. Kachelrieß, P. D. Serpico and M. Teshima, “The Galactic magnetic field as spectrograph for ultra-high energy cosmic rays,” *Astropart. Phys.* **26**, 378-386 [astro-ph/0510444].