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Patterns in ultra-high energy cosmic ray arrival directions: A possible footprint of large scale cosmic structures

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Abstract: The public available data of cosmic ray arrival directions with energies above 4×10^{19} eV present a broad maximum in the cumulative two-point autocorrelation function around 25°. This has been interpreted as the first imprint of the filamentary pattern of large scale structures (LSS) of matter in the near universe. We analyze this suggestion in light of the clustering properties expected from a catalogue of galaxies of the local universe (redshift $z \lesssim 0.06$). The data reproduce particularly well the clustering properties of the nearby universe within $z \lesssim 0.02$. There is no statistically significant cross-correlation between data and structures, although intriguingly the nominal cross-correlation chance probability for displacements within ∼50° drops from $\mathcal{O}$(50%) to $\mathcal{O}$(10%) using the catalogue with a smaller horizon. Our results suggest a relevant role of magnetic fields (possibly extragalactic ones, too) and/or possibly some heavy nuclei fraction in the ultra-high energy cosmic rays.

Introduction

Above $\sim 10^{18}-10^{19}$ eV the rigidity of cosmic rays of galactic origin is high enough that the deflection in the galactic magnetic field (GMF) should not wash out correlations between their arrival directions and the galactic plane. The lack of any correlation down to the percent level and the difficulty to find suitable galactic candidates for acceleration up to $\sim 3 \times 10^{20}$ eV suggest an extragalactic origin for these ultra-high energy cosmic rays (UHECRs). This immediately raises the possibility that UHECRs may be messengers from deep space, and thus potential tracers of cosmic structures. Vice versa, one may exploit the present knowledge of the universe to infer some information on UHECR properties. In the following we summarize the anisotropies expected for extragalactic cosmic rays, while devoting Sec. 2 to treat more extensively the claim [1] of middle-scale clustering in the UHECR arrival directions.

i) Small scale clustering.
At high enough rigidities, point sources may reveal themselves as small-scale clusters in UHECR arrival directions, provided that the probability to observe several events from especially bright sources is large enough. We shall not review here the numerous studies that have been performed on this scenario especially after the AGASA claim of a statistically significant clustering of events [2]; unfortunately, other experiments with comparable or larger statistics have not yet confirmed this claim [3, 4].

ii) Anisotropies at intermediate scales.
At lower energies, the energy-loss horizon of UHECRs and thereby the number of visible sources increases; the number of potential accelerators increases as well. Finally, deflections in magnetic fields become more important. As a result, the identification of single sources is challenging if not impossible. However, the UHECR source distribution may be still reflected in some anisotropy at intermediate scales. In [5] we evaluated the expected anisotropy in the UHECR arrival distribution starting from an astronomical catalogue of nearby galaxies. The conclusion was that about $300-400$ events at $E \gtrsim 4-5\times 10^{19}$ eV are needed to confirm a linear correlation of UHECR sources with baryonic structures, a statistics which should be attained by the Auger Observatory within a few years. Yet, by combining the $\mathcal{O}$(100) events at $E \gtrsim 4 \times 10^{19}$ eV already collected by the pre-

vious generation of instruments, the authors of [1] found some evidence of a broad maximum of the cumulative two-point autocorrelation function of UHECR arrival directions around 25°. The authors suggested 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. We analyzed this claim on the basis of sky maps derived from the PSCz catalogue [6, 7]. The results are summarized in Sec. 2.

iii) Proper motion dipole
At even lower energies, also the LSS structure of sources disappears, both because the inhomogeneities in the source distribution will be averaged out due to the increased energy-loss horizon of UHECRs and because of deflections in the extragalactic magnetic fields. Thus, if the Earth were in the cosmological rest frame the CR sky would appear isotropic. The observation of the cosmic microwave background dipole clearly shows that this is not the case, and a dipole anisotropy of 0.6% in the cosmic ray intensity is expected if the CR flux is dominated by sources at cosmological distance. Although challenging to detect, this is in principle a powerful diagnostic tool for UHECRs. A similar effect also allows one to constrain the fraction of the diffuse gamma-ray background emitted by sources at cosmological distance, with promising detection possibilities for the GLAST satellite [8].

iv) Rigidity effect due to the GMF.
Finally, if the extragalactic flux is still the dominant component at sufficiently low energy, the GMF may introduce blind regions on the external sky, which translate into observable anisotropies for an Earth-based observer, even if the UHECR flux is isotropic at the boundary of the Milky Way [9].

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, Yakutsk, SUGAR, and HiRes collaborations, opportunely rescaled in energy *a priori* to match the ankle-dip (see [1] for details). In Fig. 1 we show the excess map of the observed events in galactic coordinates, properly smoothed with a Gaussian filter of 10° width.

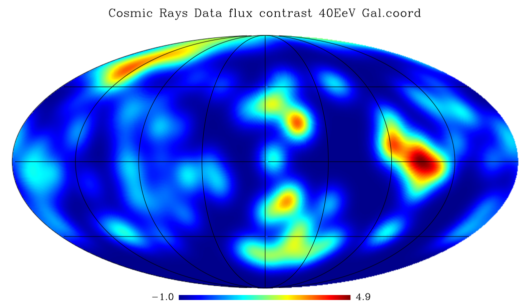

Figure 1: The UHECR flux contrast map (or excess map) properly smoothed with a Gaussian filter of 10° width in galactic coordinates.

In order to interpret the apparent pattern, we shall consider three hypotheses H: an isotropic sky; the linear correlation model for proton primaries already introduced in [6] ($z \lesssim$0.06, LSS-PH model); a toy model characterized by a horizon smaller than in the PH case roughly by a factor 3 ($z \lesssim$0.02, LSS-SH model). The latter model is practically implemented assuming the mean free-path of protons with $E = 8 \times 10^{19}$ eV [7]; although the details of this model are surely unrealistic, it may be indicative of a plausible situation where at least for anisotropy searches the useful UHECR horizon is relatively short. For example, because of a mixed chemical composition, of the effects of a magnetic horizon, or both. The sky-maps corresponding to the latter two hypotheses are shown in Fig. 2. As in [5], we use the IRAS PSCz galaxy catalogue [10] to produce these maps. We address to our previous work [5] as well as to the original paper [10] for technical details about the catalogue and about the calculation of the UHECR sky map—which takes into account energy losses as well. It is important to remind that the catalogue suffers of an incomplete sky coverage. For consistency, in all the models the unmapped regions are excluded from our analysis with the use of the binary mask available with the PSCz catalogue itself (enclosed by the grey band in Fig. 2).

For a quantitative statistical analysis, we introduce $w(\delta)$, the (cumulative) two-point autocorrelation function as a function of the separation angle δ. We

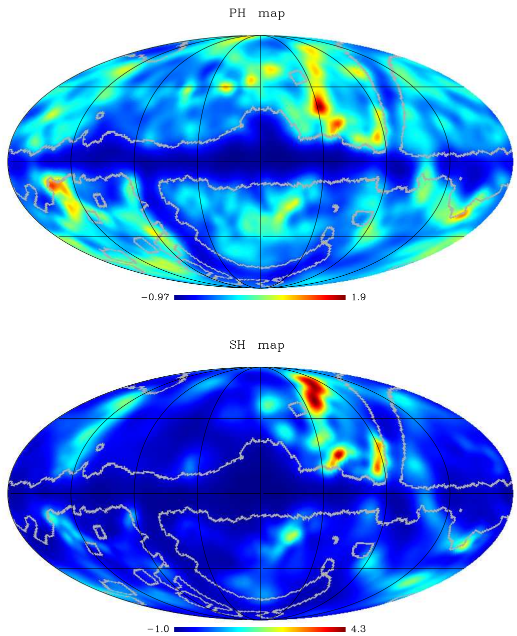

Figure 2: Excess maps of the LSS-PH (top panel) and LSS-SH models (bottom panel). The grey contour bounds the blind region of PSCz catalogue.

perform a large number M of Monte Carlo simulations of N data sampled from a distribution on the sky corresponding to the hypothesis H and for each realization j we calculate the autocorrelation function $w_j^H(\delta)$. 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 $P^H(\delta)$ to observe an equal or larger value of the autocorrelation function by chance is

$$P^H(\delta) = \frac{1}{M}\sum_{j=1}^{M}\Theta[w_j^H(\delta) - w_\star(\delta)], \quad (1)$$

where $w_\star(\delta)$ is the observed value for the cosmic ray dataset and the convention $\Theta(0) = 1$ is being used. Relatively high (low) values of P *and (or)* $1 - P$ indicate that the model is appropriate (inappropriate) to explain the data. For this reason in the following we shall plot the function $P(\delta) \times [1 - P(\delta)]$, which vanishes if any of P or $1 - P$ vanishes and has the theoretical maximum value of $1/4$.

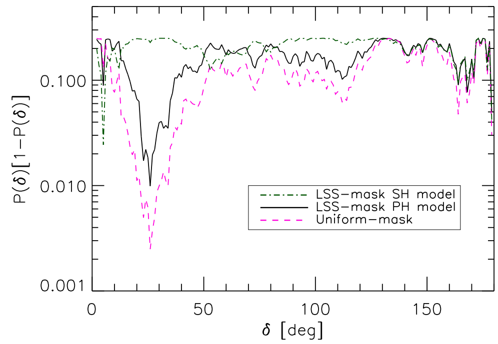

Figure 3: Chance probability of auto correlation taking as reference model an uniform distribution, the linear correlation model of [6] (LSS-PH model) and the presently considered model with a smaller horizon (LSS-SH model). See text for details.

In Fig. 3 we present our main results. The dashed–purple line represents the nominal chance probability of clustering found in [1] assuming an uniform sky (obviously convolved with the experimental exposures) and excluding events falling in the mask. The solid line in Fig. 2 shows the chance probability of the clustering signature if the random events are sampled according to the LSS-PH distribution. Finally, the green-dotted line shows the same result if the random events are sampled according to the LSS-SH distribution. The prominent minimum of [1] is reduced when using as null hypothesis the LSS-PH model; this effect is even more pronounced in the LSS-SH map. The better concordance of the UHECR distribution with the LSS hypothesis than with the uniform one is evident. This is not unexpected given that the typical size on the sky of the clusters of structures lies in the range 15°-30° [5]. The prominence of the features already visible with $\mathcal{O}(100)$ events actually suggests that UHECR sources may trace in a biased way the LSS.

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 a cross-correlation analysis we did not find any evidence favoring a LSS origin with respect to the uniform case. Although the present statistics is still too low to draw a firm conclusion, the lack of this signature is likely related to the role of intervening magnetic fields. Acting on an energetically (and possibly chemically) diverse 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.

Conclusions

Anisotropies are an important tool to distinguish between different origin and primary models for the UHECRs, nicely complementing the information on the energy spectrum and chemical composition. We have briefly summarized several signatures which one expects to show up in the pattern of UHECR arrival directions at different energies. In particular, we have commented upon the broad maximum of the two-point autocorrelation function within a scale of $20°$-$30°$ found in Ref. [1] in the combined UHECR data arrival directions, and recently confirmed by Auger [4]. At the moment, the most likely explanation seems to be that the signature reflects the LSS distribution of UHECR sources, probably of nearby ones. The autocorrelation analyses reported in this paper show that this interpretation is indeed favored in particular if the effective horizon is smaller than the GZK one for protons of the assumed energy. Both a significant fraction of heavier nuclei and a significant role of extragalatic magnetic fields may cause this effect. A significant displacement from the LSS overdensities is indeed necessary to destroy the expected cross-correlation signal, while preserving the autocorrelation pattern (relative displacements among UHECRs from the same region are much smaller than their overall deflection). This interpretation may be supported by a weak (unfortunately not statistically significant) hint of a broad minimum in the chance probability of cross correlation around 50° if a small horizon ($z \lesssim 0.02$) is assumed. Both signatures are relatively robust with respect to deflections in typical GMF models, although some marginal improvement or worsening may arise for some choices of the GMF model and effective rigidities (for a throughout discussion of this point, we address to [7]). However, the hints for some structures in the data are very exciting, and future studies of the larger dataset being collected by Auger should clarify several points. Together with the indication for the presence of a GZK-like feature in the energy spectrum of HiRes [11] and Auger [12] and the stringent limits on the fraction of photon events, this probably implies that UHECRs are dominated by astrophysical sources (as opposed to exotic scenarios). However, far from being the end of the UHECR saga, the combined use of spectral information, chemical composition constraints, and anisotropy maps at different energies would offer the tools for the long-awaited hunt for the UHECR accelerators, finally opening the era of UHECR astronomy.

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References

[1] M. Kachelrieß and D. V. Semikoz, Astropart. Phys. **26**, 10 (2006).
[2] M. Takeda *et al.* [AGASA collaboration], Astrophys. J. **522** 225 (1999); See also M. Takeda *et al.*, Proc. 27$^{\rm th}$ ICRC, Hamburg 2001.
[3] R. U. Abbasi *et al.* [The HiRes Collaboration], Astrophys. J. **623**, 164 (2005).
[4] S. Mollerach [Pierre Auger Collaboration], arXiv:0706.1749 [astro-ph].
[5] A. Cuoco *et al.*, JCAP **0601**, 009 (2006).
[6] A. Cuoco, G. Miele and P. D. Serpico, Phys. Rev. D **74**, 123008 (2006).
[7] A. Cuoco, G. Miele and P. D. Serpico, arXiv:0706.2864 [astro-ph].
[8] M. Kachelrieß and P. D. Serpico, Phys. Lett. B **640**, 225-229 (2006). See also D. Hooper and P. D. Serpico, JCAP **0706**, 013 (2007).
[9] M. Kachelrieß, P. D. Serpico and M. Teshima, Astropart. Phys. **26/6**, 378 (2007).
[10] W. Saunders *et al.*, Mon. Not. Roy. Astron. Soc. **317**, 55 (2000). [astro-ph/0001117].
[11] R. Abbasi *et al.* [HiRes Collaboration], arXiv:astro-ph/0703099.
[12] T. Yamamoto [Pierre Auger Collaboration] these proceedings, (2007) #0318.