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Anisotropy expectations for UHECRs with future high statistics experiments

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Abstract: We perform extensive simulations of ultra-high-energy cosmic ray (UHECR) propagation for a range of astrophysical source models compatible with the current data, taking into account energy losses and deflections by intervening magnetic fields. We then build simulated sky maps for many realizations of each scenario, as would be obtained by a full sky coverage experiment accumulating an exposure of $300,000\ \mathrm{km}^2\,\mathrm{sr\,yr}$ at the highest energies. Finally, we perform a two-point correlation function analysis on the simulated sky maps to assess their anisotropy level, and find that a significant anisotropy is expected to be detected in essentially all the cases, even if a relatively poor energy resolution of 30% is assumed. This supports the idea that a gain of a factor of ten in exposure around 100 EeV, up to a few $10^5\ \mathrm{km}^2$ sr yr, would allow significant progress in the field of UHECRs and be the first step of a new era in which the study of different regions of the sky becomes meaningful and instructive.

Keywords: cosmic rays, ultra-high-energy, astroparticle physics, source models, sky maps, anisotropy

1 Context and objectives

Discovering the origin of the ultra-high-energy cosmic rays (UHECRs), with energies of the order of 100 eV is widely recognized as an important challenge in the field of astroparticle physics, both from the theoretical and the observational points of view. Among the main scientific goals are a deeper understanding of particle acceleration in the universe and the search for complementary information and constraints on potential sources, in a multi-messenger approach involving photons, energetic nuclei, neutrinos, and, perhaps, gravitational waves.

This quest has been pursued for decades with larger and larger detectors, and is currently led in the Southern hemisphere by the Pierre Auger collaboration, and in the Northern hemisphere by the Telescope Array collaboration. Important milestones have been reached, notably through the confirmation of the so-called GZK-effect [7, 16], which causes a rapid decrease of the UHECR flux around 60 EeV [8, 3, 15] due to the interaction of the UHE protons and/or nuclei with the extragalactic background radiation. Hints of anisotropies in the arrival directions of the UHECRs above ~ 60 EeV have also been reported [2], indicating that the intervening magnetic fields do not completely randomize the distribution of UHECRs on the sky, as it does at lower energies, preventing a direct identification of the sources.

However, the initial hope to reveal the sources by observing an accumulation of UHECR events in well-defined directions has been frustrated up to now. This is either because the number of contributing sources is too large and very few events have been observed from any given source, or because the particles observed from a given source are deflected and spread over too large areas of the sky, or both.

To overcome these difficulties, a natural strategy is to focus on the highest energy cosmic rays, because their magnetic rigidity is expected to be larger (unless they also have a larger charge), and because the number of their visible sources is significantly smaller, due to the GZK-effect. General statistical studies taking into account the relevant propagation effects show that only a handful of sources are responsible for most of the detectable UHECRs around 100 EeV [5, 6]. Depending on the source density and the exact, contingent distribution of the sources around us, the dominant source in the sky typically makes up between 15% and 60% of the total flux at 100 EeV [5, 6]. In such conditions, it seems likely that the very few contributing sources could be distinguished as separate clusters of events on the sky, even if relatively large deflections occur, provided a sufficient number of UHECRs are observed.

This has not yet occurred with the very limited statistics available. No significant anisotropy has been detected at 100 EeV, and even though the Pierre Auger Observatory has reported a departure from isotropy at lower energy, $E \sim 60$ EeV, at the 99% confidence level [2], its interpretation is still unclear and it could not be used to gather information about the sources.

In total, an exposure of the order of $\sim 30,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$ has been accumulated so far, and the most common opinion is that decisive progress will not be possible unless a significant increase in exposure is achieved. In this paper, we investigate a variety of astrophysical models for the origin of UHECRs that are compatible with the current data, and study the corresponding anisotropy expectations for a next-generation detector gathering an exposure of $300,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$ at the highest energy. To be definite, we use the JEM-EUSO mission as a prospective example, i.e. we assume a (nearly) uniform full-sky coverage and the actual detection efficiency of JEM-EUSO as a function of energy [13]. We also assume a conservative energy resolution of 30%, to demonstrate that the resulting spill-over of lower-energy events (whose sources can be more distant and numerous) due to a mis-reconstructed energy does not compromise the main result of this study: significant anisotropy is expected to be detected for essentially all the models studied, even in the extreme case where the UHECRs are dominated by heavy nuclei at the highest energies.

Section 2 describes the UHECR source models investigated. The method used to build representative sky-maps and study the associated anisotropies are treated in Sect. 3. Some results are presented and discussed in Sect. 4. More details about the simulations and a more thorough analysis of the results can be found in our associated paper [14].

2 The UHECR source models investigated

Standard propagation studies that take into account the energy losses of UHE protons and nuclei allow a reproduction of the whole sky UHECR spectrum with a limited number of parameters. Unfortunately, the current constraints on the UHECR source models are rather weak. This is essentially because the dominant feature in the spectrum is the GZK-cutoff, which is quite generic and can be reproduced by a variety of models. These models range from an extreme (and unrealistic) light composition model, with only protons at the source, to an extreme (and unrealistic) heavy composition model, with only Fe nuclei at the source, to various mixed-composition models, in which the index of the assumed power-law source spectrum can be adjusted to fit the data, with some dependence on the assumed law of evolution of the sources over cosmological times.

Another important parameter is the maximum energy that protons and heavier nuclei can reach in the sources. In order to limit the number of free parameters, we assume that all sources accelerate protons up to the same maximum energy, $E_{\mathrm{p,max}}$, and that heavier nuclei reach the same magnetic rigidity, i.e. the maximum energy of a nucleus of type i, with charge Z_i, is given by $E_{i,\mathrm{max}} = Z_i \times E_{\mathrm{p,max}}$.

We explore three different values for $E_{\mathrm{p,max}}$, which all exhibit different, interesting features. In the so-called MC-high model (where MC stands for mixed-composition), the proton maximum energy is high, at $E_{\mathrm{p,max}} = 300$ EeV, so that protons dominate the UHECR composition at all energies (both at the source and at the Earth, after propagation). This model is found to be compatible with the low level of anisotropy observed only for very large values of the source density (see below). The second type of model, referred to as MC-low, has a low maximum proton energy, $E_{\mathrm{p,max}} = 4$ EeV. It implies that the UHECRs at 50 EeV and above are mostly Fe or sub-Fe nuclei, with charges $Z \gtrsim 20$, and correspondingly much larger deflections than protons. The resulting composition shows a progressive transition from light to heavy across ~ 10 EeV, in conformity with what the Auger data suggest [4]. Finally, an intermediate case is considered with $E_{\mathrm{p,max}} = 15$ EeV, and referred to as MC-mid. In this case, intermediate mass nuclei, notably C, N and O, are still present at 50–60 EeV, resulting in 3–4 times smaller deflections than Fe nuclei at the same energy.

More details on the models and their parameters can be found in [14].

3 Sky maps and anisotropies

To study the anisotropies expected for each model, we simulate realistic UHECR sky-maps by propagating the UHE protons and nuclei from their sources to the Earth, taking into account the various energy loss mechanisms and the deflections by intervening magnetic fields (see [1] and references therein for details). These deflections are found to be dominated by the influence of the Galactic magnetic field, for which we use the modeling of [10, 11] who consider three distinct types of magnetic structures: i) a coherent field with spatial scales of the order of a few kpc, ii) an isotropic turbulent field with spatial scales on the order of tens of pc, and iii) a so-called *striated* field, which refers to an anisotropic turbulent field whose orientation is aligned with the large scale coherent field, but whose strength and sign vary on a small scale. The large scale coherent field is made of three separate components: a disk, a halo and an out-of-plane halo (see [10] and [14] for details).

For the sources, we assume that they are distributed in space in a similar way as the galaxies, and use the 2MASS Redshift Survey catalog (2MRS, [9]) as a reference. A key ingredient of the various astrophysical scenarios is the assumed source density, n_{s}. Obviously, all else equal, low-density models lead to larger anisotropies, because the contributing number of sources is smaller and their angular separation on the sky larger. We explore two different densities, $n_{\mathrm{s}} = 10^{-4}\,\mathrm{Mpc}^{-3}$ and $10^{-5}\,\mathrm{Mpc}^{-3}$, and randomly draw a large number of source realizations by sub-sampling the 2MRS catalog at the intended density (after completion beyond the distance where the catalog ceases to be unbiased, see [14] for details).

For each realization of a given astrophysical scenario, we then generate UHECR sky maps by accumulating events up to a fixed statistics above an energy threshold E_{th} that is set either to 50 EeV, 80 EeV or 100 EeV. The statistics are chosen so as to simulate an experiment which would achieve a total exposure of $300,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$ above 100 EeV, and have a detection efficiency similar to that of JEM-EUSO [13]. Two sets of values are obtained depending on what we assume for the actual UHECR flux at Earth. The difference between the fluxes reported by the HiRes and TA collaborations on the one hand, and the Auger collaboration on the other hand, are thought to be essentially due to a systematic uncertainty in the absolute energy scale. Assuming the HiRes-TA (respectively Auger) energy scale, we find that the above-mentioned exposure will allow to collect ~ 2100 (resp. 1100) events above 50 EeV, ~ 580 (resp. 250) events above 80 EeV, and ~ 260 (resp. 100) events above 100 EeV.

For each sky-map generated, we perform a standard 2-point correlation function analysis to determine whether the distribution of UHECRs over the sky is significantly different from what can be expected for sky-maps of the same statistics built from an isotropic flux. The many realizations of a given scenario are used to explore the "cosmic variance", i.e. to determine the probability that, under such an astrophysical scenario, the actual distribution of the sources around the Earth leads to a significantly anisotropic sky (with the chosen statistics).

4 Results and discussion

The basic outcome of our calculations is a large number of sky maps with the above-mentioned statistics at various energy thresholds, corresponding to many realizations of the different astrophysical scenarios under investigation. In Fig. 1, we show one typical example of such sky maps, for an MC-mid model, assuming a source density $n_{\mathrm{s}} = 10^{-5}\,\mathrm{Mpc}^{-3}$ and the Auger energy scale. This sky map shows all the events with an energy reconstructed above 80 EeV (which includes lower-energy events mis-reconstructed with a 30% gaussian energy resolution). UHECR events coming from the same source (represented as a colored star on the map) are shown with symbols of the same color (this applies only to sources contributing 6

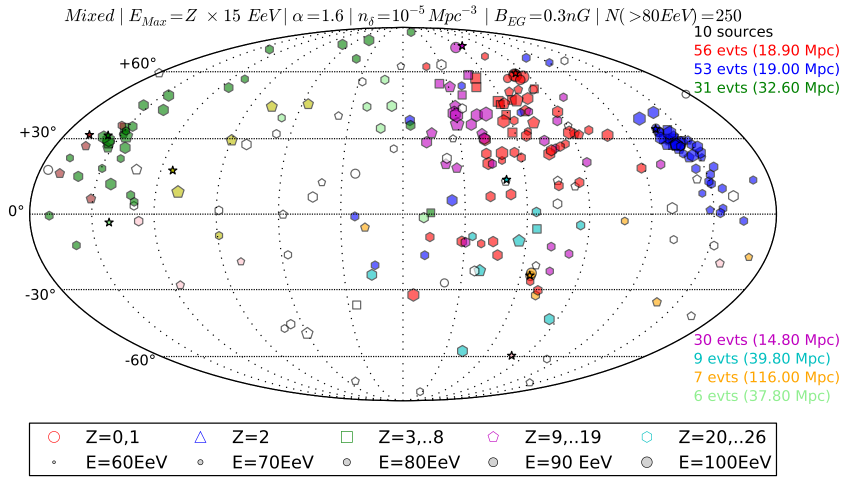

Figure 1: Example of a sky map of UHECR events above 80 EeV obtained with a total exposure of $300,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$ for the MC-mid scenario (see text), assuming a source density of $10^{-5}\,\mathrm{Mpc}^{-3}$ and the Auger energy scale.

events or more in this map). The size of the symbols depends on the energy, and their shape depends on the charge of the received particle: protons are circles and nuclei are polygons with more sides if they are in a higher charge range (see the legend on the figure). In this model, protons are cut exponentially at the sources above 15 EeV, so that heavy nuclei completely dominate above 80 EeV. This does not prevent, however, the presence of some intermediate-charge nuclei in the map, either secondary UHECRs or mis-reconstructed lower-energy particles.

This particular map has been selected as a typical sky map among 500 realizations of the same astrophysical scenario, being located at the median of the distribution of sky maps ordered by the significance level of their associated anisotropy signal (using the 2-point correlation function test). It illustrates a number of features common to most models and realizations. First, as expected, a handful of sources are found to contribute most of the observed flux. Second, it appears that, despite large deflections on average, distinct sources appear to be separated in the sky. Third, in some regions of the sky, source confusion occurs (of course, the UHE events will not be labeled with a color code in the actual experiments!). Fourth, the UHECR deflections depend on the location of their source in the sky: most dark blue events are found near their actual source on the right of the figure, while the rose events are observed far away from theirs, in the lower right. This is due to non uniform structure of the Galactic magnetic field. Even though the particular deflections patterns in our simulations depend on the actual choice of this magnetic field (see [14] for details), similar features are expected for other possible choices.

It is important to note that, although the sky map of Fig. 1 is clearly anisotropic with the simulated statistics at 80 EeV, this astrophysical scenario is fully compatible with the current UHECR data, both concerning the composition trends reported by Auger and the absence of significant anisotropy at ~ 60 EeV, beyond the 99% confidence level. This is a generic result of our simulations: for essentially all the scenarios investigated (pure p, pure Fe, MC-low/mid/high at all source densities), a significant anisotropy is found at the highest energies with a $300,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$ exposure, even

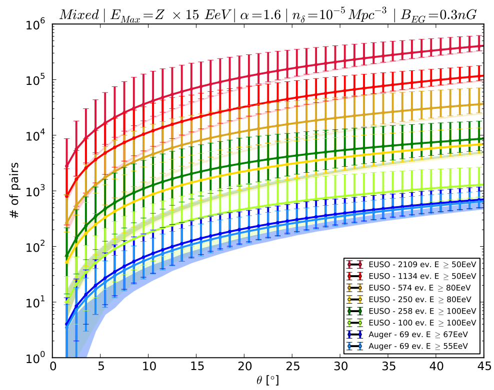

Figure 2: Number of pairs of UHECR events as a function of their maximum separation angle for many realizations of the same source scenario as in Fig. 1. Different colors correspond to different UHECR statistics and energy thresholds, as indicated. The isotropic expectations for the same statistics are shown by shaded areas of the same color. The cosmic variance in the simulated models is shown through the error bars which contain 90% of the realizations.

though only marginal anisotropy can be detected with the currently available statistics.

To assess this point quantitatively, we perform a 2-point correlation function analysis on each realization of each UHECR source scenario, i.e. we count the number of pairs of UHECRs at a given angular scale in the simulated sky maps and compare it with the number of pairs obtained in similar realizations of an isotropic sky. We repeat the procedure at angular scales ranging from 2° to 45° for all the models and quantify the corresponding anisotropies in terms of a confidence level in a standard way.

An example of such results is shown in Fig. 2 for many realizations of the same UHECR source scenario as in Fig. 1. The different curves correspond to different energy thresholds and statistics (assuming either the Auger or the HiRes-TA energy scales), for a total exposure of $300,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$.

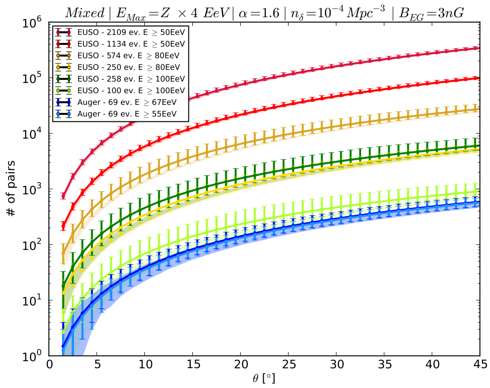

Figure 3: Same as Fig. 2, for the MC-low scenario with a source density of 10^{-4} Mpc^{-3}.

The error bars illustrate the cosmic variance associated with the different realizations of the same astrophysical scenario. The isotropic expectations are shown by the shaded areas. As can be seen, sky maps with (reconstructed) energy thresholds at either 50, 80 or 100 EeV are expected to exhibit significant anisotropies for essentially 100% of the realizations of this scenario. For comparison, the current status with the Auger statistics (i.e. 69 events above 55 EeV or 67 EeV depending on the assumed energy scale) is shown in blue. With this statistics, the 2-point correlation function analysis is found to detect only marginal anisotropy signals in most realizations, or even no signal at all.

Similar results are found in the other astrophysical scenarios. In Fig. 3, we show the rather extreme, unfavorable case of a MC-low scenario, with a maximum proton energy of 4 EeV (thus completely dominated by Fe nuclei at high energy) and a high source density of 10^{-4} Mpc^{-3}. This model is found to be indistinguishable from an isotropic model for most of the realizations with the Auger statistics, while the sky maps above 80 EeV or above 100 EeV exhibit significant anisotropies in the vast majority of the realizations with the statistics of a 300,000 km^2 sr yr exposure.

In conclusion, our simulations show that a future experiment with full-sky coverage achieving an exposure ten times larger than the current Auger exposure would be able to detect significant anisotropies at the highest energies in essentially all the scenarios investigated here, including the most pessimistic ones where the UHECRs are dominated by heavy nuclei, with a high source density. We note, in addition, that more optimistic scenarios should not be discarded at this stage. While the composition trend reported by Auger suggests a transition towards heavy nuclei above 10 EeV, a sub-dominant component of protons remains compatible with the data, and would manifest itself as tight multiplets in the sky maps with larger statistics, reviving the quest of a direct, astronomical identification of a UHECR source. Furthermore, as the hadronic models are not yet fully reliable in the relevant energy range, the composition trend still remains to be confirmed. Leaving aside composition, we found that proton-dominated scenarios can be reconciled with the lack of significant anisotropies above 60 EeV if the source density is particularly high, $n_s \gtrsim 10^{-3}$ Mpc^{-3}. In this case, the above-mentioned statistics would easily reveal the most nearby UHECR sources at the highest energies, as in the beautiful example shown in Fig. 4, where the top panel shows the low level of anisotropy obtained with the Auger statistics at 55 EeV, and the bottom panel shows a typical sky map expected above 100 EeV for the same model with ten times the current Auger exposure.

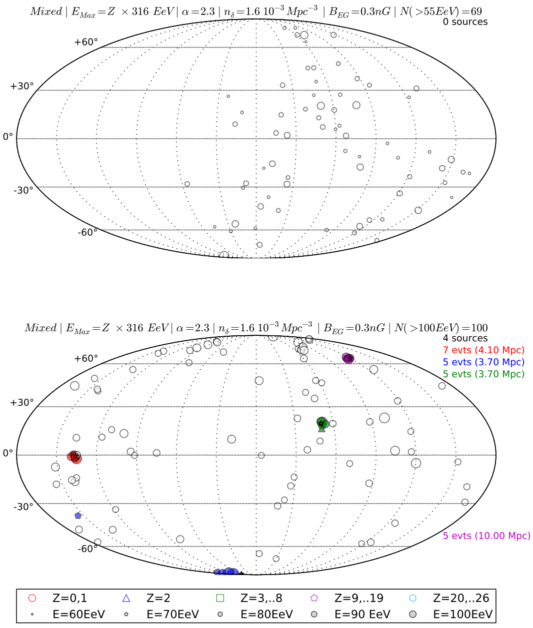

Figure 4: Simulated sky maps for a proton-dominated scenario with a source density of 10^{-3} Mpc^{-3}, with the Auger statistics above 55 EeV (top), and with a 300,000 km^2 sr yr exposure above 100 EeV (bottom).

Many features of our results relevant to the current stage of development of the field of UHECR physics could not be discussed in this paper, due to lack of space. We refer the reader to our associated works for a more detailed discussion of the simulations and their implications [14].

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