

# CRPropa high statistics simulations for UHECR anisotropy studies

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**Abstract.** Despite the great progress made by modern cosmic ray observatories, the origin and acceleration mechanism of ultra-high-energy cosmic rays (UHECRs) remains unsolved problems to this day. However, there is experimental evidence for an anisotropic component in the UHECR arrival direction at energies greater than few EeV. The search for UHECR sources is further complicated by two main factors: during extragalactic propagation UHECRs interact with background photon fields (like the CMB and the EBL) and, since they are electrically charged, they are deflected by extragalactic and galactic magnetic fields (EGMF and GMF). Moreover, the strength, structure and origin of the EGMF are still not well known, causing reconstructing the deflection of UHECRs to be a non-trivial task. In this work we consider several EGMF models obtained from constrained MagnetoHydroDynamics (MHD) simulations of our local Universe to study the propagation of UHECRs through such a structured environment. We simulate propagation, interactions and observation of UHECRs by using the Monte Carlo code CRPropa3. We also take into account the effect of the GMF by adopting a lensing procedure of the arrival UHECR sky map. We explore several combination of source distribution, EGMF structure and mass composition. As a reference, we also simulate scenarios without the EGMF and with a statistically homogeneous field. We use our simulation results to compute UHECR observables, such as the energy spectrum, the angular power spectrum and the arrival direction map (before and after the GMF) in order to obtain constraints on possible combinations of source distributions and EGMF models.

## 1 Introduction

The origin of the most energetic particles ever observed in nature still remains an unsolved problem in astrophysics. These particles are called ultra-high-energy cosmic rays (UHECRs) and they consist of ionized nuclei of energy higher than 1 EeV ( $=10^{18}$  eV). The discovery of UHECR sources would offer the possibility of studying environments capable of reaching such high energies, which are not possible even in modern particle accelerators.

In recent years, cosmic ray observatories have reported several observations showing that the UHECR sky does not appear isotropic above the EeV scale. The Pierre Auger Observatory [1] has reported a dipolar anisotropy signal in the arrival directions of UHECRs with energies above 8 EeV which points  $\sim 120^\circ$  away from the galactic center [2]. This observation supports the hypothesis of an extragalactic origin of these incredibly energetic particles.

However, the information we can obtain from the observation of UHECRs must be processed in order to investigate physics at the sources. This is because the propagation in the extragalactic space is perturbed by particle interactions and magnetic deflections. At these high energies, charged nuclei are able to trigger photo-hadronic interactions with the cosmic photon fields, like the CMB and the EBL [3, 4]: these interactions are the electron-positron pair production ( $E_{\text{th}} \simeq 2.5$  EeV for protons with CMB photons), the photo-pion production ( $E_{\text{th}} \simeq 70$  EeV

for protons with CMB photons) and the photodisintegration of heavy nuclei. The presence of magnetic fields in the extragalactic space must also be taken into account. Since UHECRs are electrically charged and they propagate over cosmological distances, a non-negligible deflection can be induced by the Lorentz force (especially in the case of heavy nuclei) hiding the real position of the source in the sky. Since cosmic magnetic fields are poorly known, numerical simulations represent a fundamental tool to study the role that different magnetic field models play on UHECR observables.

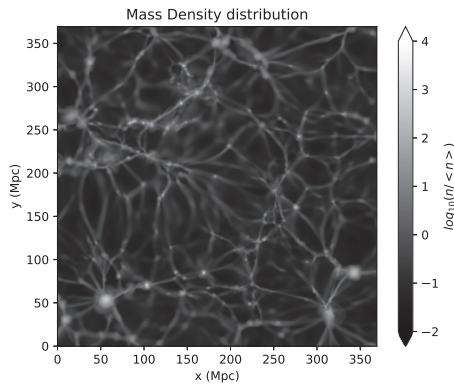
In this work we simulate the propagation of UHECRs in a numerical replica of our local Universe that includes both the structured cosmic magnetic field and the baryon density distribution. We take into account all the relevant interactions and energy loss processes during the extragalactic propagation. Simulation results are then used to compute anisotropy observables to study the resulting UHECR multipole signal when extragalactic and galactic magnetic deflections are considered.

## 2 Simulations and results

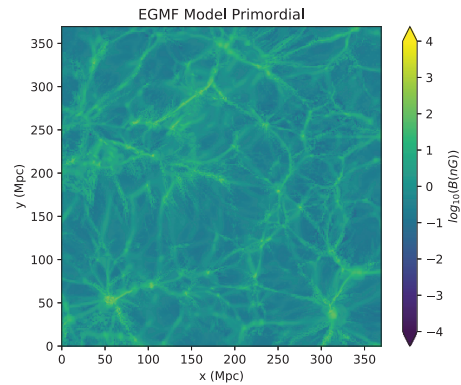
In order to reproduce all the relevant physical processes for the extragalactic propagation of UHECRs a numerical framework is necessary. In this work we consider the Monte Carlo code CRPropa 3 [5], a publicly available simulation code for UHECR propagation and interac-

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**Figure 1.** Mass density distribution in super-galactic coordinates at  $z = 0$ . The mass density  $n$  is normalized to the average density in the simulation volume  $\langle n \rangle$ . The plot shows the super-galactic plane orthogonal to the  $Z$ -axis including the Milky Way at the centre.



**Figure 2.** EGMF strength in nG for the *primordial* configuration in super-galactic coordinates at  $z = 0$ . Same coordinate system as Figure 1.

tions<sup>1</sup>. With CRPropa 3 the Lorentz equation is numerically integrated taking into account all energy loss mechanisms, photodisintegration and nuclear decay of heavy nuclei in a 3D volume. In this work we simulate the propagation of UHECRs within a cubic volume of 250 Mpc/h each side. We define a periodic boundary condition: if a particle leaves the volume, its trajectory is continued on the opposite side. An event is observed when it intersects the observer, represented by sphere of radius 1 Mpc located in the centre of the simulation volume.

To study the effect induced by the distribution of cosmic structures in the local Universe, we consider constrained MagnetoHydroDynamics (MHD) cosmological simulations to account the evolution of both the matter distribution and the cosmic magnetic field. The MHD simulations used in this work were obtained with the cosmological grid code ENZO [6]. The numerical replica of our local Universe at redshift  $z = 0$  is obtained from MHD simulations started at  $z = 60$  within a volume of  $(500 \text{ Mpc}/h)^3$  with the Milky Way at the centre, as extensively described in [7]. In Figure 1 the normalized mass density distribution at  $z = 0$  in the super-galactic plane is shown. Figure 1 shows how the matter distribution of the local Universe is complex and characterized by various types of structures (e.g. clusters, filaments and voids).

The evolution of the extragalactic magnetic field (EGMF) is simulated together with the matter evolution for different assumptions on the origin of the field. Three primordial models for the EGMF origin were considered. In the *primordial* model a uniform magnetic field of strength 0.1 nG along each axis at  $z = 60$  is assumed. In both the *primordial2R* and *primordial3R* models the magnetic field is obtained from a power-law distribution with two different slopes for the power spectrum,  $n_B = -3$  and  $n_B = -4$ , respectively. The normalisation of the spectra was chosen such that the root-mean-square field is the same of the *primordial* scenario. The EGMF strength for

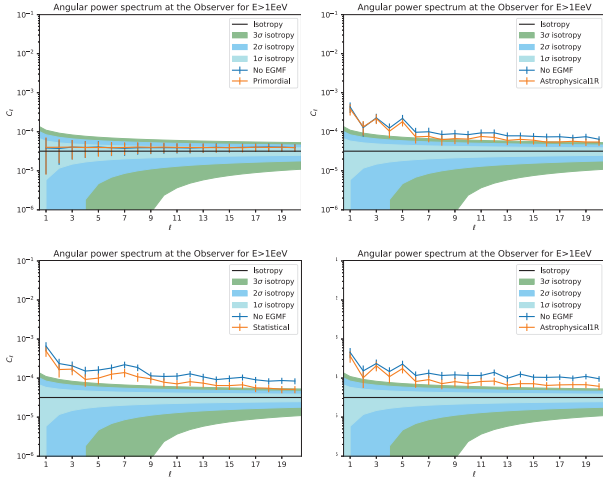
the *primordial* scenario at  $z = 0$  in the super-galactic plane is shown in Figure 2, where the strong correlation between the mass distribution and the EGMF structure is visible. Three cases of astrophysical origin of the magnetic field were also considered. These configurations are called *astrophysical*, *astrophysicalR* and *astrophysicalIR* and in each of them the magnetic energy is assumed to be the 50% of the injected thermal energy and it is released as dipoles around the injection region. Further details on the EGMF seeds and the corresponding volume filling factors can be found in [7]. All of these EGMF configurations are considered in our UHECR simulations.

We define three source distribution models: in the *homogeneous* model the injection positions is chosen within the simulated volume with the same injection rate everywhere, in the *mass density* model the injection position is chosen with a probability density function proportional to the mass density distribution shown in Figure 1 and, lastly, in the *mass halos* model the injection is chosen with the same probability from several point-like sources located at the center of halos identified by the gas number density. In the latter case, the number of halos is such that the average number density is  $\sim 2 \cdot 10^{-4} \text{ Mpc}^{-3}$ .

Together with the EGMF models described above, we also consider the case without any magnetic field (*NoEGMF*) and with a statistically uniform EGMF with a Kolmogorov-like power law spectrum and  $B_{\text{rms}} = 1 \text{ nG}$  (*statistical*). The combination of the various models for the source distribution and the EGMF gives us the opportunity to explore the effects induced on the arrival directions of UHECRs by the presence of structures in both the matter and the magnetic content of the local Universe.

We simulate the propagation of two pure compositions at the injection, one of protons and one of helium nuclei. The initial energy is extracted between 1 EeV and 1000 EeV following a power law spectrum of  $E^{-1}$  and the initial momentum is chosen isotropically. We run 10 different simulations for each configuration described above, requesting the observation of 2500 UHECRs with  $E \geq 1 \text{ EeV}$ .

<sup>1</sup>Version 3.1.7 of CRPropa 3 is used in this work.



**Figure 3.** APSs at the observer for 2500 UHECRs with  $E \geq 1$  EeV. Top left: proton injection and *homogeneous* source distribution. Top right: proton injection and *mass density* source distribution. Bottom left: helium injection and *mass halos* source distribution. Bottom right: helium injection and *mass halos* source distribution. In each panel the isotropic prediction given by (2) (black line and coloured areas), the APS without EGMF (blue line) and the APS with one EGMF model (orange line) are shown.

The detected events are used to construct the sky map distribution of the UHECR arrival directions. We use the python package HEALPY, based on the Hierarchical Equal Area isoLatitude Pixelization (HEALPix) scheme [8]<sup>2</sup>, to handle pixelated data on a sphere. Starting from the sky maps, the Angular Power Spectrum (APS)  $C_l$  is defined as

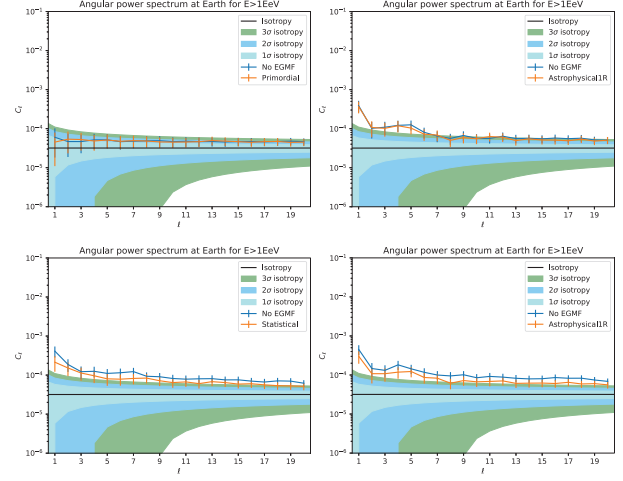
$$C_l = \frac{1}{2l+1} \sum_{m=-l}^l |a_{lm}|^2, \quad (1)$$

where  $a_{lm}$  are the spherical coefficients of the sky map spherical decomposition. We compute (1) by using the developed tools in HEALPY for the multipoles  $l \leq 20$ . We compare these APSs with the expected isotropic prediction given by the same number of observed particles

$$C_l^{\text{iso}} = \frac{1}{4\pi N}, \quad \sigma_l^{\text{iso}} = \sqrt{\frac{2}{2l+1}} C_l^{\text{iso}}. \quad (2)$$

The APSs for several configurations are shown in Figure 3. The blue and orange lines represent the mean value of  $C_l$  obtained from the average of the 10 simulations and the error bars represent the corresponding standard deviations. We also show the prediction (2) with the  $1\sigma_l^{\text{iso}}$ ,  $2\sigma_l^{\text{iso}}$  and  $3\sigma_l^{\text{iso}}$  areas (cyan, blue and green respectively).

From Figure 3 we can see that the combination of *homogeneous* source distribution and *NoEGMF* reproduces the isotropic prediction. The main deviation from the isotropic prediction is introduced by the presence of a structured source distribution regardless of the presence or the model for the EGMF. The low-multipole components decrease towards the isotropic prediction, however



**Figure 4.** Same as Figure 3 after the galactic lensing.

the high-multipole components ( $l \lesssim 5$ ) strongly deviate from the isotropy, in particular the dipole component ( $l = 1$ ). The presence of a generic EGMF model, when the source distribution is structured, introduces an additional, but minor, deviation between the corresponding configuration without any magnetic field. This result tells us that the effect of the magnetic deflection is to reduce the anisotropies purely induced by the morphology of the source distribution. This latter effect increases with the increasing of the electric charge at the injection (as expected from the fact that the magnetic deflection depends linearly on the atomic number  $Z$ ). However, this suppression is not strong enough to make the APS compatible with the isotropic prediction.

The results described in the previous paragraphs were obtained by assuming the observation of UHECRs on the observer's surface (a sphere of radius 1 Mpc located in the centre of the simulation volume). If we assume that this surface represents the edge of the Milky Way, then we must take into account the propagation through the galactic environment to compare the angular spectra with experimental data. The galactic propagation can induce further effects on the distribution of the arrival directions because, even if photo-hadronic interactions are negligible on galactic scales, the galactic magnetic field (GMF) strength is  $\sim 1 - 10 \mu\text{G}$ , and thus the magnetic deflection can be of several degrees. The effect of the galactic propagation on the arrival directions can be reproduced by applying a specific magnetic lens to the sky map obtained at the edge of the Galaxy. Thus, the lensing technique maps a given bin on the surface at the edge of the Galaxy into several bins in the sky (further details on the magnetic lensing technique can be found in [9]). Several magnetic lenses are implemented in CRPropa 3; in this work we use the implementation of the JF12 GMF model [10].

In Figure 4 we report the APSs after the galactic lensing for the same configurations of Figure 3. The effect of the GMF is to suppress the deviation for the isotropy for the high-multipole components ( $l \gtrsim 5$ ). However, the deviations of the low-multipole components are still observ-

<sup>2</sup><http://healpix.sourceforge.net>

able. As before the galactic lensing, the main source of anisotropies still remains the structured distribution of the sources. The presence of an EGMF model induces only a weak separation with the ballistic propagation cases. Moreover, this separation is slightly reduced by the galactic deflection.

### 3 Conclusions

In this work we studied the propagation of ultra-high-energy protons and helium nuclei with the Monte Carlo code CRPropa 3. We considered all the relevant interaction processes with the background photo fields and the adiabatic energy loss due to the expansion of the Universe. We reproduced the matter and magnetic field distributions of the local Universe by using MHD simulation results. The evolution of the EGMF has been simulated under several assumptions on the origin of the field. We considered six EGMF models, one statistically homogeneous field and the case without magnetic field together with structured and homogeneous source distributions. We also introduced the impact of the GMF using the magnetic lensing technique.

In Figure 3 we can see that deviations from isotropy are mainly due to the structure of the source distribution, which has a greater effect on the low-multipole components. The effect of the EGMF is the introduction of a small deviation from the same configuration obtained without any magnetic field. This effect is more evident in case of heavier nuclei at the injection. After the galactic propagation (Figure 4) the previously mentioned results are still valid. However, the separation between the APSs obtained with and without the EGMF is slightly suppressed.

In the next developments of this work we will be focused on the anisotropic signal due to observed UHECRs with energy above 8 EeV. The propagation of nuclei heavier than helium nuclei (e.g. N, Si and Fe) will be included in order to be able to compare simulated spectra with real anisotropy data. To improve the efficiency of our CRPropa 3 simulations the recently developed targeted injection technique will be used [11, 12]. This will also give us the possibility to simulate propagation in a larger simulation volume without having to use periodic boundary conditions. The study of the energy spectrum, the mass composition and the dipole direction will allow us to further investigate the impact of different assumptions of the EGMF origin on the UHECR observables.

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