CRPropa high statistic simulations for Ultra-High-Energy Cosmic Ray anisotropy studies

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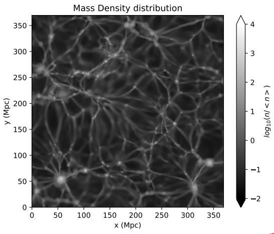
Abstract

Despite the great progress made by modern cosmic ray observatories, the origin and acceleration mechanism of Ultra-High-Energy Cosmic Rays (UHECRs) remains an unsolved problem to this day. However, there is experimental evidence for an anisotropic component in the UHECR arrival direction greater then 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 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.

Constrained MHD simulations – Baryon density

Numerical replica of our local Universe from cosmological simulation (ENZO) with constrained initial condition back to z=60 in a comoving volume of 500 Mpc each side [1][2].

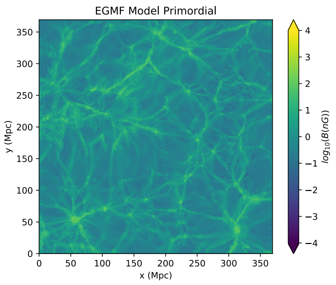


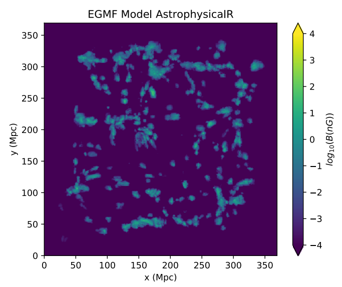
Constrained MHD simulations – EGMF

The EGMF is simulated together with the baryonic density [3].

Primordial: the EGMF is generated by drawing from power law distributions at z=60.

Astrophysical: the EGMF is produced by the magnetic feedback within high number density halos.

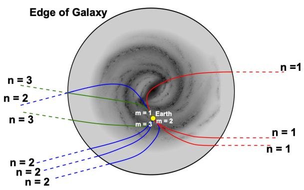




3D CRPropa simulations

3D propagation of UHECRs through the EGMF with the Monte Carlo code CRPropa [4] in a comoving volume of 250 Mpc each side.

Source models: homogeneous, mass density (baryonic density distribution), mass halos (point-like sources from the baryonic density) with Periodic Boundary Condition (PBC).



Picture from [5].

EGMF models: no EGMF, statistically uniform, primordial and astrophysical models.

GMF models: Jansson and Farrar 2012 (lensing).

Observer: spherical observer at the center with radius 1 Mpc.

Interactions: photohadronic interactions with CMB and EBL, nuclear decay and energy redshift.

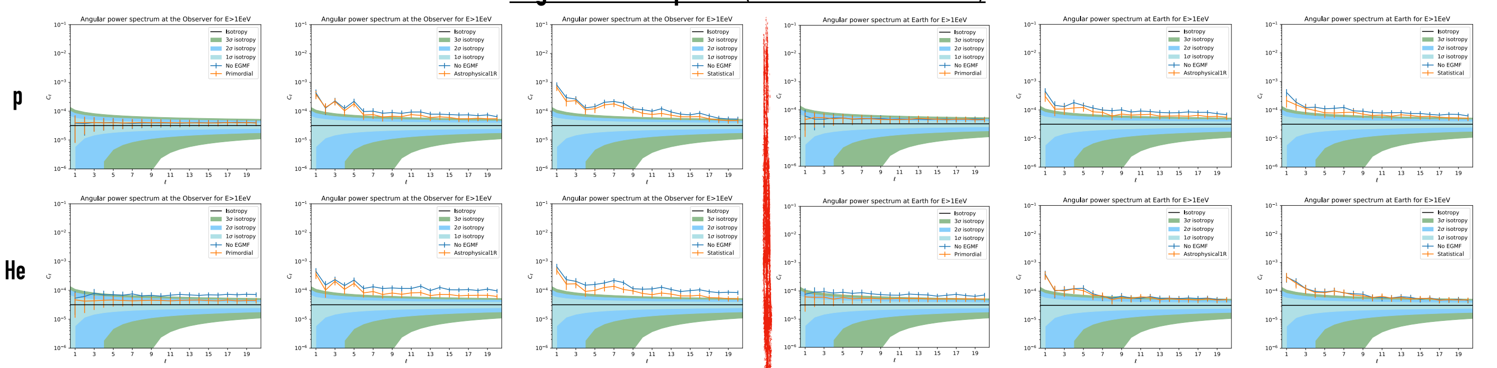
Injection: isotropically from equal luminosity sources. Pure composition of protons or helium nuclei with energy spectrum

$$\frac{dN}{dE} \propto E^{-1} \qquad 1\,\text{EeV} \le E \le 1000\,\text{EeV}$$

Realizations: 10 simulations of each combination of injection, source and EGMF model.

Analysis: angular power spectrum before and after the lensing with theoretical isotropic prediction. Study of residual effects of the source/EGMF model in the arrival directions.

Angular Power Spectra (2500 observed UHECRs)



Homogeneous | Mass Halos | Mass Density | Homogeneous | Mass Halos | Mass Density

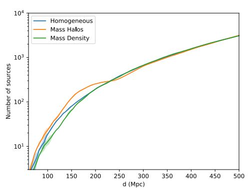
Before lensing: the main effect is given by the structure of the source distribution. If the source distribution is structured, the low-multipoles disagree with the isotropic prediction. As the injected charge increases, a deviation from the case without EGMF appears.

After lensing: the value of the high-multipole components is reduced and the difference to the scenario without EGMF induced by the electric charge disappears.

Next steps

Sources: 10 different samples of point-like sources from the 3 distributions used before.

$n \sim 10^{-4}\,\text{Mpc}^{-3}$



No PBC: several replicas of the fundamental volume given by a minimum observed energy of 8 EeV and a maximum injection of 1000 EeV.

$$z_{max} \simeq 0.33 \Rightarrow d_{max} \simeq 2.0\,\text{Gpc}$$

Injection: heavier nuclei (N, Si and Fe) emitted with a von Mises-Fischer distribution and reweighing of observed events [6].

$$\Pi(\hat{x};\hat{\mu},\kappa) = \frac{\kappa}{2\pi(1-e^{-2\kappa})} e^{\kappa(\hat{\mu}\cdot\hat{x}-1)}$$

Analysis: simulations with 25000 observed UHECRs and study of the dipole, quadrupole, mass composition and average deflection angle. Computation of the statistical and cosmological variance.

[1] The ENZO Collaboration: G.L.Bryan et al, ApJS (2013)
[2] J.G.Source et al, Mon. Not. R. Astron. Soc. (2015)
[3] S.Hackstein et al, Mon. Not. R. Astron. Soc. (2017)
[4] R.A.Batista et al, JCAP (2016)
[5] H.Bretz et al, Astropatricle Physics (2014)
[6] J.Jasche et al, ICRC2021 proceeding (2021)