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Propagation of cosmic rays and their secondaries in the intracluster medium

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Abstract. We present results of the propagation of high-energy cosmic rays (CRs) and their secondaries in the intracluster medium (ICM). To this end, we employ three-dimensional cosmological magnetohydrodynamical simulations of the turbulent intergalactic medium to explore the propagation of CRs with energies between 10^{14} and 10^{19} eV. We study the interaction of test particles with this environment considering all relevant electromagnetic, photohadronic, photonuclear, and hadronuclear processes. Finally, we discuss the consequences of the confinement of high-energy CRs in clusters for the production of gamma rays and neutrinos.

Keywords. cosmic rays, gamma rays, neutrinos, cluster of galaxies

1. Simulation of CRs propagation

In this work we study the propagation of CRs in the turbulent environments built out of three-dimensional magnetohydrodynamical (MHD) cosmological simulations of the distribution of filaments and clusters of galaxies in the local universe within a 260 Mpc scale, performed with the GADGET code (see Dolag *et al.* 2005). Then, we employ the code CRPropa 3 (Alves Batista *et al.* 2016) to study the particles propagation in this environment. We consider all relevant CR interactions, namely, photopion production, photodisintegration, and Bethe-Heitler pair production with the background photon fields that include the cosmic microwave background (CMB), the extragalactic background light (EBL), and the thermal Bremsstrahlung field at X-rays from clusters of galaxies primarily due to the emission of hot plasma with temperatures 10^6-10^8 K. We also consider CR proton interactions with the background gas of the ICM.

2. Results and Discussion

The spectra of CRs and neutrinos are given in Fig. 1. We considered different clusters of distinct masses and magnetic field distributions in the local universe ($z < 0.1$). We find a significant suppression in the flux of CRs (Fig. 1) at an energy around 10^{17} eV, which indicates a trapping of CRs within the clusters at energies of this order and below. This upper limit is more constraining than the one we obtained previously when neglecting the CR interactions with the background protons and thermal photon field (Alves Batista *et al.* 2019). It is found that the CR interactions with thermal Bremsstrahlung radiation are

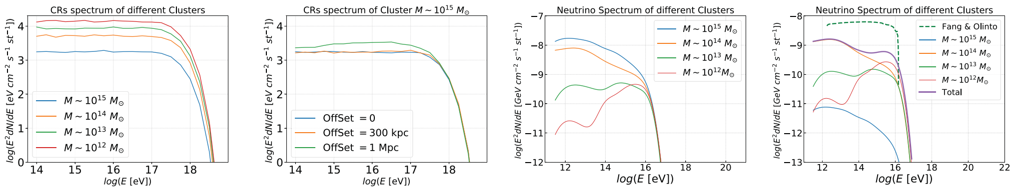

Figure 1. The first panelv(from left) shows the CR spectrum for clusters of different masses. The second shows the spectrum of CRs for one cluster of mass $M = 2 \times 10^{15}$, computed at its edge, assuming sources at: the centre of the cluster, and at 300 kpc and 1 Mpc away from the centre. The third and fourth panels show, respectively, the neutrino spectra for individual clusters, and the total spectrum. The label 'Total' in the last panel corresponds to the sum of the fluxes of neutrinos from all clusters of the background simulation. Our results are compared to Fang & Olinto (2016).

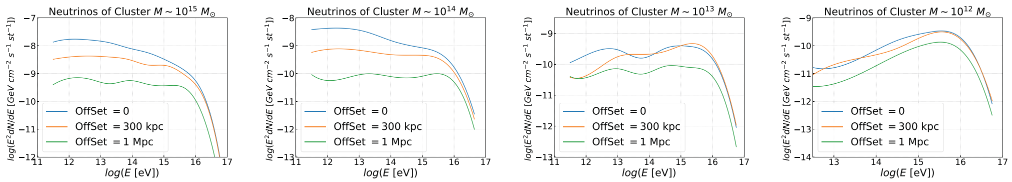

Figure 2. Spectrum of neutrinos for individual clusters of distinct masses, computed at their edge, assuming sources: in the centre of the cluster, at 300 kpc and 1 Mpc away from the centre.

negligible compared to the proton-proton interactions. Clusters are unique environments. Due to their magnetic field, the confinement of CRs for long periods of time enhances the interaction rates, increasing the production of secondary particles including neutrinos and gamma rays (e. g., Brunetti & Jones 2014, Blasi 2013 and Amato & Blasi 2018). These high-energy gamma rays and neutrino fluxes can be measured with the Cherenkov Telescope Array (CTA), the IceCube Neutrino Observatory, and the Giant Radio Array for Neutrino Detection (GRAND). We also present the flux of neutrinos generated by the interactions of CR protons with the background protons of the ICM (Figs. 2 & 1). We plotted both, the flux of neutrinos for individual clusters in Fig. 2 and the total flux from all clusters in Fig. 1, and compared with Fang & Olinto 2016 (therein see Fig. 3, $0.01 < z < 0.3$). In the latter, the authors employed a simplified model of the baryon distribution and the turbulent magnetic field, and then extrapolated their results for the entire distribution of galaxy clusters. Besides, our total flux has been integrated up to $z < 0.1$, while in their work, this integration stops at $z = 0.3$. This may explain the minor discrepancy between their and our results. Finally, we note that these results are still preliminary and we are still limited by our poor statistics, which is a consequence of the high computational load required by the particle-by-particle approach employed. Any potential statistical fluctuations will be mitigated in our future works.

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