Contribution ID: **474** Type: **Contributed e-poster**

Simulating galaxies with cosmic rays - the multi-frequency view

Previously, the non-thermal emission from galaxies has only been modelled with parametrised 1D or 2D models, which is insufficient to explain a multitude of new, spatially resolved multi-messenger data of cosmic ray (CR) spectra, at gamma-rays and in the radio. Instead, we perform high-resolution magneto-hydrodynamic (MHD) simulations of galaxies using the moving mesh code AREPO with self-consistent CR physics. In post-processing, we calculate steady-state spectra of CRs including all relevant cooling and escape losses. Consistent with Voyager-1 and AMS- 02 data, our models show a turn-over of proton spectra below GeV energies due to Coulomb interactions so that electrons start to dominate the total particle spectra and match the shape of the positron fraction up to 10 GeV. Furthermore, from our CR spectra, we calculate multi-frequency spectra, from the radio up to the TeV energy regime, due to all non-thermal emission processes, i.e. synchrotron, bremsstrahlung, inverse Compton (IC) emission and gamma-ray emission from neutral pion decay. This allows us to produce detailed emission maps, luminosities and spectra of our simulated galaxies, that range from dwarfs to Milk-Way analogues to starburst galaxies, at different evolutionary stages. Within our simulations, we can successfully reproduce the observed far infrared (FIR)-gamma-ray and FIR-radio relations. We find that highly star-forming galaxies are close to the calorimetric limit and hence, their gamma-ray emission is dominated by neutral pion decay. However, in low star-forming galaxies, escape losses due to diffusion steepen the spectra and in turn, an increasing contribution from IC emission is needed to reproduce the observed gamma-ray spectra. As a next step, we scrutinise the steady-state modelling in two ways. On the one hand, we evolve CR electron spectra in time which allows us to study highly dynamical regions such as outflows from star-forming galaxies in unprecedented detail, where the steady-state assumption breaks down. Furthermore, we investigate for the first time the influence of spectrally resolved CR protons in MHD simulations on the hadronic gamma-ray emission of star-forming galaxies, revealing new insights into the observational signatures of CR transport both spectrally and spatially.

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Session Classification: Contributed posters