PhD project in ASTROPHYSICS

Title: Efficient Diffuse Radio Emission in the Cosmic Web: Modelling Particle Acceleration in Cosmological Simulations

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Scientific case and objectives

Diffuse radio emission in galaxy clusters and in the surrounding cosmic web provides one of the most direct probes of non-thermal processes in large-scale structure formation. Over the last decade, radio observations have revealed an increasingly diverse population of extended, low-surface-brightness sources, including radio halos, relics, inter-cluster bridges, and megahalos. These sources trace cosmic-ray electrons and magnetic fields over megaparsec scales, from cluster cores to outskirts and filamentary environments.

Despite these observational advances, the origin of diffuse radio sources remains only partially understood. A central open problem is to determine how relativistic particles are accelerated and reaccelerated in different environments, and whether apparently distinct classes of emission can be interpreted within a common physical framework. In particular, turbulence and shocks associated with mergers and accretion are expected to play a key role, but their relative importance and efficiency remain poorly constrained.

The goal of this PhD project is therefore to investigate the formation of diffuse radio sources in cosmological environments through advanced numerical modelling, with particular emphasis on the link between particle transport, turbulent reacceleration, and observable synchrotron emission. Accurately modelling these processes in realistic cosmological volumes requires the development of new computational frameworks optimized for high-performance computing architectures, including GPU-enabled implementations. The project will aim to:

- model the evolution of cosmic-ray electron populations in cosmological simulations of galaxy clusters and filaments,
- test the viability of turbulent reacceleration in generating diffuse radio emission across different source classes,
- and develop computational strategies that make such calculations feasible at larger scale and higher fidelity.

Outline of the project

The project will focus primarily on cosmological MHD simulations with Enzo, extending the tracer-based framework introduced by Nishiwaki et al. to follow the evolution of relativistic electrons along Lagrangian trajectories and to compute their spectra through the numerical solution of the Fokker–Planck equation. In this framework, tracer particles sample the baryonic flow and record local thermodynamical and magnetic properties, allowing the non-thermal particle distribution and the associated synchrotron emission to be reconstructed consistently in post-processing.

A major component of the work will be the integration and optimization of this tracer-based methodology within the Enzo ecosystem, with the goal of making it computationally sustainable for large cosmological datasets. Since solving the Fokker–Planck equation for millions of tracers is extremely expensive, a key objective will be to accelerate the workflow on multiple GPUs, enabling massively parallel computation of particle spectra and synchrotron emissivities. This will allow the exploration of larger simulation volumes, higher tracer counts, and broader parameter spaces than currently practical. In parallel, the project will investigate the feasibility of machine-learning surrogate models to approximate the spectral evolution and synchrotron emission from tracer histories.

The simulated observables will then be compared with radio properties of diffuse sources such as halos, bridges, and megahalos, to test whether a common physical scenario can explain their morphology, extent, spectra, and correlation with the thermal intra-cluster medium.

This project will deliver both physical and computational advances. On the physical side, it will improve our understanding of particle reacceleration and diffuse synchrotron emission in galaxy clusters and filaments, helping to clarify the origin of multiple classes of extended radio sources. On the computational side, it will provide an optimized framework for tracer-based cosmic-ray modelling in cosmological simulations, potentially combining multi-GPU acceleration with surrogate models for further speed-up.