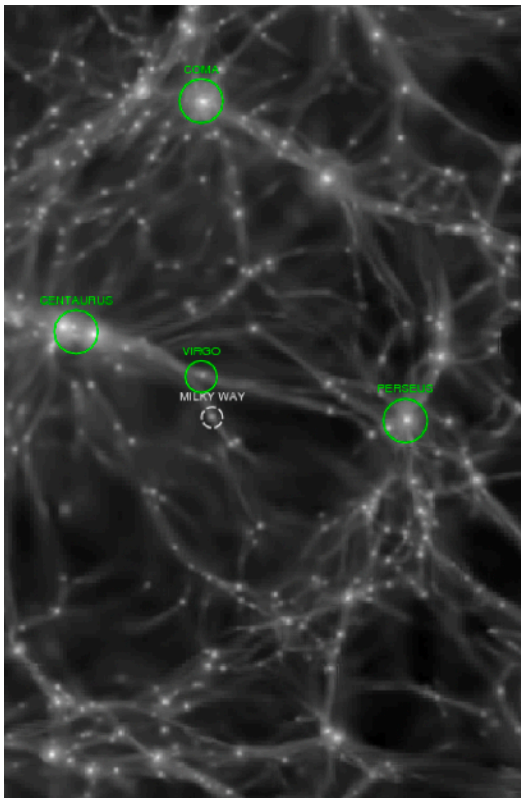
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Studying cosmic magnetism with constrained simulations of the local Universe
Simulazioni vincolate all'Universo Locale per studiare il magnetismo cosmico

Supervisor : *Prof. F. Vazza (Università di Bologna)*
Co-supervisor*: Prof. A. Neronov (APC-Paris)*
Collaborators: *A. Andrews (OAS/INAF), D. Paoletti (OAS/INAF)*



Distribution of baryons in an early constrained simulation of the local Universe

Scientific Case: observations in the radio and in the gamma ray domain have since recently provided tantalising indications for the existence of volume filling magnetic fields in filaments of the cosmic web (e.g. Carretti et al. 2025) and in cosmic voids (e.g. Blunier et al. 2025, Neronov et al. 2024).
The robust detection of such volume-filling magnetic fields in the local Universe is of pivotal importance, because magnetic fields on this large scales could only be produced in the very early Universe, plausibly during inflation, or in out-of-equilibrium transitions in the very early Universe, like the Electro-Weak phase transition or before the confinement of Quarks, in the Quark-Gluon plasma stage of the Universe (less than a *micro-second* after the big bang). Primordial magnetic fields have also been proposed as a plausible explanation for the already detected background of stochastic gravitational waves (in addition to the possible contribution by supermassive black holes) and hence they represent a potentially unique probe of extremely early high-energy cosmological processes, extending our observational capabilities much beyond the epoch of the formation of the cosmic microwave background, which cannot be crossed by photons.

Several of the key observations of magnetism (especially in the gamma-ray window, or from the study of ultra high energy cosmic rays) are particularly sensitive to probe the "local" Universe, i.e. a sphere with approximate radius 300-400 Megaparsec from Earth (corresponding to a redshift $z<0.1$). This is volume is "small" in comparison to the scales at which the distribution of matter can be considered homogenous and isotropic, and this calls for a more accurate mapping of the real 3-D distribution of matter around the observer and towards the direction of specific sources. Advanced statistical techniques are already available to take the matter distribution measured from several galaxy survey data, map it backward in time, and use this matter distribution as initial conditions for realistic "constrained" cosmological simulations of the Local Universe.

Outline of the Project: The PhD candidate will generate new constrained simulations of the local Universe and predict signatures of cosmic magnetic fields, and their influence on γ-ray, radio and Ultra High Energy Cosmic ray observables, starting from constrained initial conditions fro the Local Universe. In the first stage of the PhD, the candidate will produce and test new simulations with the ENZO code of initial conditions produced by the Bayesian reconstruction algorithm BORG and based on the mass distribution measured in the 2M++ galaxy survey. The properties of cosmological simulations evolved until the present day will be compared to available constrains for the Local Universe, in order to select the best possible compromise of resolution and volume. In a second stage, the candidate will produce ideal magneto-hydrodynamical resimulations of the Local Universe to test several realistic models of primordial magnetic fields (i.e. inflationary-like or causal-like), and assess which observations can better test them in reality.

By robustly constraining the amplitude and spectral shape of allowed primordial magnetic fields, **the candidate will be able to produce key scientific results to connect cosmology of the primordial Universe to observable properties of local large-scale structures**. This project calls for candidates with experience (or curiosity) in numerics, magnetic field theory and the physics of cosmic structures.

The PhD candidate will be part of the COSMOMAG group, a collaborative project funded for six years by a Synergy Grant from the European Research Council, based in four different institutions (University of Paris in France, CERN in Switzerland, Nordita in Sweden and University of Bologna in Italy) and with the ambitious goal of investigating the connection between primordial magnetism and the generation of the stochastic gravitational waves background as powerful probes of the very early Universe.

Contacts: franco.vazza2@unibo.it