Magnetic fields: Relics from the Early Universe

Primordial Magnetic Fields through Large Scale Structure

P. Domínguez-Fernández, S. Mtchedlidze, F. Vazza, J. Niemeyer, T. Kahniashvili*, Universität Hamburg, Universität Göttingen & Carnegie Mellon University*

In Short

- Large scale magnetic fields are ubiquitous in our Universe. Recent observational evidences strengthen the idea that they should have a primordial origin.
- We study how different primordial magnetogenesis scenarios make an impact during the large-scale formation.
- We use the massively parallel numerical, magneto-hydrodynamical cosmological ENZO code with adaptive mesh refinement in order to study the most massive elements of the cosmic web.

Different astrophysical observations (such as Faraday rotation and synchrotron emission data) performed over the last decades revealed the existence of the large-scale correlated magnetic fields with the strength of order of microGauss on galaxies and galaxy cluster scales. The origin of these extragalactic magnetic fields still remains unknown: it is commonly assumed that these fields are the result of amplification of initial weak seed fields either astrophysical or cosmological origins. The recent observations of blazar spectra suggest the lower bounds order of the femtoGauss for the magnetic fields in cosmic voids (at 1Mpc or higher length scales), and are in favor of the cosmological magnetogenesis possibility. The constraints from big bang nucleosynthesis (BBN) set an upper limit on the strength of these fields of 10^{-6} Gauss by requiring that at the time of Nucleosynthesis average energy density in magnetic fields should be significantly less than the radiation energy density, while this limit is also obtained by the cosmic microwave background anisotropies.

The generation mechanisms of cosmological magnetic fields (or primordial magnetic fields (PMFs)) are divided into two broad classes: (i) inflationary and (ii) phase transition magnetogenesis. Each of these mechanisms lead to different properties, such as strength, spectral signatures, and correlation lengths that can be corroborated with observations. In this project, we study for the first time how magnetic field seeds generated via i) and ii) mechanisms will evolve during large-scale formation (LSS).

Although the PMFs evolve in a distinguishable fashion across the different cosmological epochs, the high conductivity of the plasma ensures the strong coupling between the plasma motions and magnetic fields both - in the early Universe and in the late times of structure formation. This itself leads to the development of magnetohydrodynamic (MHD) turbulent cascades in a magnetized fluid. The role of the MHD turbulence in the evolution of PMFs has widely been studied for the radiation dominated epoch, prior the recombination [1] and in the cosmological context for the post-recombination Universe (see e.g. [2]). In our research project we will extend these previous studies including the effects of different primordial magnetogenesis imprinted in the most massive elements in the cosmic web, namely galaxy clusters.

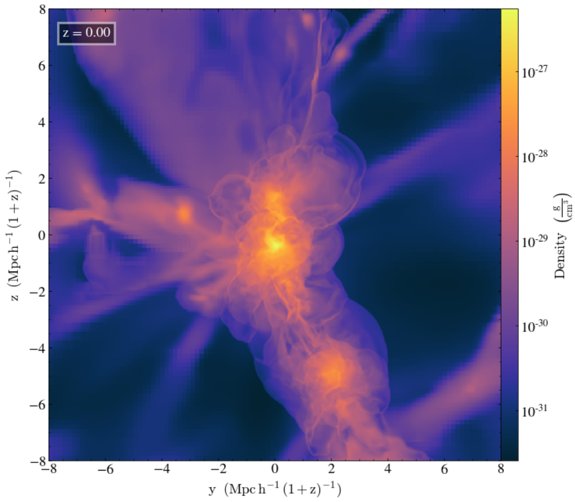

Figure 1: *The projected density of simulated galaxy cluster within 16 (Mpc/h)^3 box.*

During the current stage of our project we could already see the effects of different magnetogenesis scenarios on the magnetized cosmic web using a unigrid set-up of cosmological MHD simulations in ENZO. In Figure 2 we show the two dimensional profiles of the magnetic field versus gas density. As we can see the final distribution of magnetic fields is affected by the different primordial magnetic seeding over a wide range of scales of the cosmic web. We observe that amplification of the magnetic field in the stochastic seeding case (helical and non-helical, phase-transitional scenario) does not follow $\rho^{2/3}$ scaling expected from the adiabatic contraction. This means that stochastic seeding is less affected by the structure formation (i.e. by the spatial perturbations of the density field) than the uniform seed from an inflationary magnetogenesis scenario.

In the proposed project we will use the same setup for the MHD cosmological code ENZO as is used in [4], which will evolve primordial magnetic field seeds resulted from plausible magnetogenesis scenarios. We will run our simulations in a comoving volume of 80 Mpc^3 and 256^3 root grid making use of the adaptive mesh refinement (AMR) feature of ENZO. Regions of interest, such as galaxy clusters will be re-simulated with higher resolution using an AMR inside the selected regions. This will allow us to follow the evolution of the magnetic fields from the early universe till late times of the large scale structure (LSS) formation and to produce a statistically significant sample of cosmic objects that can be used for comparison with current observations. In Figure 1 we show the density projection of one of the highly refined galaxy cluster which was simulated with the optimized refinement criteria (using the baryon and particle overdensity, and shock detection).

Our previous and present studies have shown that ENZO is a robust code for the studying the effects of magnetic fields on large-scale formation. The combination of our two recent studies (i.e [3,4]) gives us the unique opportunity to link this new project with a clear observational signature of extragalactic magnetic fields. The outcome of the desired cosmological simulations with different realistic magnetic field initial conditions will allow us to give a step further in the quest of understanding the origin of magnetic fields in our Universe.

More Information

[1] T. Kahniashvili, A. Brandenburg, A. Kosowsky, S. Mandal, A. Roper Pol *arXiv e-prints* (2020) doi:10.1017/S1743921319004447

[2] A. Beresnyak, F. Miniati, *Astrophys. CO* **817** 127 (2016) doi:10.3847/0004-637X/817/2/127

[3] A. Brandenburg, T. Kahniashvili, S. Mandal, A. R. Pol, A. G. Tevzadze, T. Vachaspati *Phys. Rev.* **D96** 123528 (2017) doi:10.1103/PhysRevD.96.123528

[4] P. D. Fernández, F. Vazza, M. Brüggen, G. Brunetti *Mon. Not. Roy. Astron. Soc.* **486** 623–638 (2019) *arXiv e-prints* (2018) doi: arXiv:1810.08009

Funding

- European Union's Horizon 2020 program under the ERC Starting Grant "MAGCOW", no. 714196
- Shota Rustaveli National Science Foundation, no. 04/46-3., PHDF-19-4101.

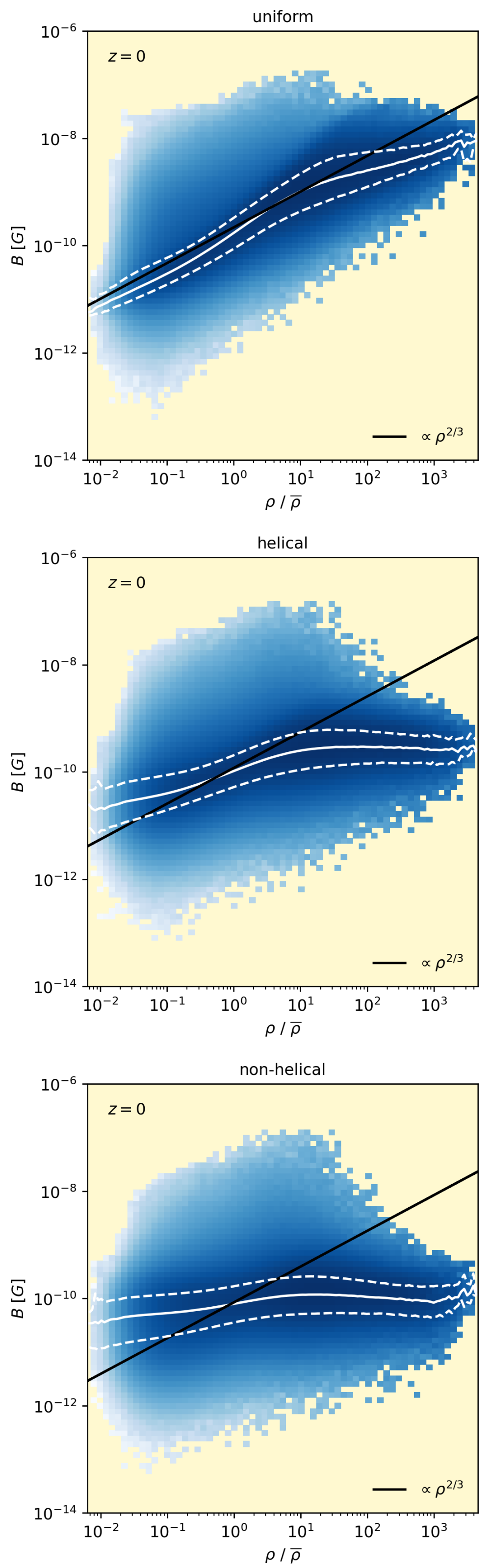

Figure 2: *B-ρ profile at redshift $z = 0$ for the uniform (upper panel, helical (middle panel), and non-helical (bottom panel) seeding. The panels show two-dimensional histograms color coded according to the cell mass. White lines represent median (solid) and 16th and 84th percentiles (dashed) accordingly. The black solid line is the expected $\rho^{2/3}$ relation between the magnetic field strength and density in the case of adiabatic contraction.*