

## The quest for extragalactic magnetic fields

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I review the observational and theoretical constraints on extragalactic magnetic fields across cosmic environment. In the next decade, the combined use of sophisticated theoretical models and of complementary observation techniques might be able to constrain the still elusive origin of magnetic fields on the largest scales in the Universe.

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## 1. Introduction - The mystery of magnetogenesis

Understanding the origin of observed magnetic fields on  $\gg$  Mpc scales is still a challenge. While we roughly understand how primordial energy fluctuations of the cosmic microwave background (CMB) originated cosmic structures, we have yet no clear view of the origin of extragalactic magnetic fields [1]. Were weak (and yet undetected) seed magnetic fields already present at the CMB, or were they only later released by forming galaxies? The observed properties of magnetic fields in galaxy clusters can roughly be reproduced by simulations, starting either from primordial fields or through the magnetisation from galactic winds and jets (e.g. [2] and references therein). On the other hand, the distribution of magnetic fields in cluster outskirts and in filaments is yet poorly constrained from observations and simulations, and there we expect the different scenarios of magnetogenesis to diverge, owing to the weaker (or absent) level of dynamo amplification [3]. Future observations should be able to kill alternative scenarios, by constraining the real distribution of magnetic fields across scales. In this work we present an overview of possible future ways to do so, based on our ongoing campaign of large magneto-hydrodynamical (MHD) simulation with *ENZO* [4].

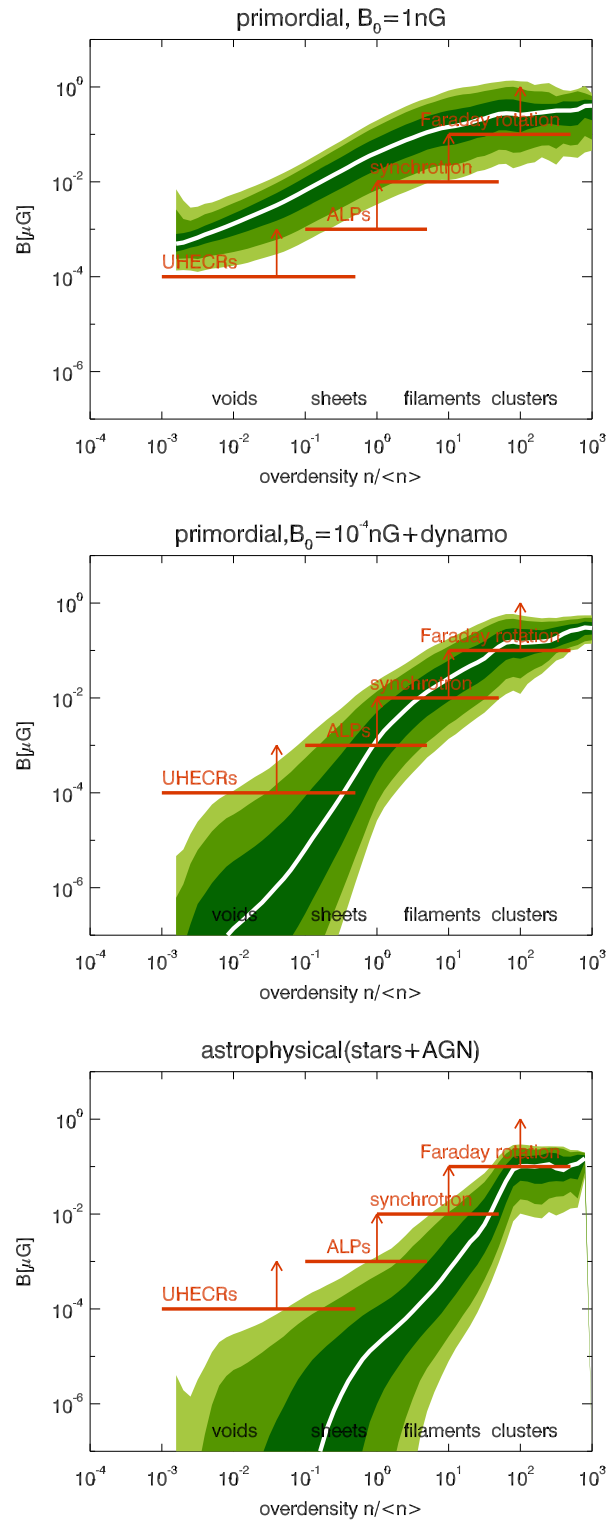
## 2. Cosmological MHD simulations

Figure 2 shows the predicted distribution of magnetic field strength across different bins in gas overdensity, for 3 of our *ENZO* resimulations of a  $85^3 \text{Mpc}^3$  volume using  $1024^3$  cells/dark matter particles, metal-dependent gas cooling, feedback from star formation and active galactic nuclei (simulated using black-hole sink particles) and alternative including: a) a primordial uniform field of  $B_0 = 1 \text{ nG}$  (comoving); b) a primordial uniform field of  $B_0 = 10^{-4} \text{ nG}$  (comoving) with a run-time sub-grid modelling of dynamo amplification from solenoidal motions; c) only seeding from star and AGN feedback, assuming a  $\sim 10\%$  release of feedback energy into magnetic energy. Magnetic fields in high density regions are very similar in the different models, yet the trends diverge moving towards low density regions. The same figure also show different observational probes should be sensitive to extragalactic magnetic fields, based on our latest works (see below).

## 3. Observational techniques and constraints

Relativistic electrons accelerated by strong shocks in the cosmic web should emit continuum and polarised radio emission (e.g. [5]). SKA-LOW and its pathfinders and precursors may detect the tip of the iceberg of such emission, provided that the magnetic fields are  $\geq 10 \text{ nG}$  [6, 7]. Detections (or even robust upper limits) will constrain: a) the combination of magnetic fields and electron acceleration efficiency at shocks,  $\propto B^2 \times \xi_e$ ; b) the distribution of magnetic fields on  $\geq 10 \text{ Mpc}$ , yielding fundamental clues on their origin [7]; c) the magnetic field obliquity at shocks accelerating radio emitting electrons [8].

Additionally, future large surveys in polarisation (e.g. with ASKAP, MEERKAT and SKA-MID) will probe the topology of extragalactic fields through Faraday Rotation ( $\propto B_{\text{par}} n_e$ , where  $B_{\text{par}}$  is the magnetic field along the line of sight and  $n_e$  is the electron density), either with long exposures [9], or statistical techniques [10]. Our simulations suggest that detections should be feasible for  $\geq 0.1 \mu\text{G}$  fields in cluster outskirts.



**Figure 1:** Magnetic field strength as a function of gas overdensity in different seeding models. The colors mark the 5th,10th,25th, 50th, 75th, 90th and 95th percentile of the distributions. The additional red arrows mark the observational constraints discussed in the main text.

The arrival direction at Earth of ultra-high energy cosmic rays (UHECRs) carries information in the large-scale distribution of magnetic fields (e.g. [11]). With recent simulations, we showed that the distribution of UHECRs is sensitive to the magnetisation of voids, because the angular distribution of UHECRs gets too anisotropic compared to present observational constraints, if voids are magnetised  $\geq 0.1$  nG [12].

Finally, extragalactic magnetic fields may also cause the oscillation of high-energy photons into axion-like particles (ALPs), a possibility has been suggested to explain the lack of absorption in the spectra of distant blazars [13]. In recent work [14] we simulated the propagation of ALPs in our MHD runs, finding that significant photon-ALPs conversions are produced in lines of sight crossing structures with  $\sim 1 - 10$  nG on scales of a few  $\sim$  Mpc, i.e. in filaments and cosmic sheets along the line of sight of high- $z$  sources.

#### 4. Conclusion

In the near future we may solve the puzzle of magnetogenesis, by combining complex simulations and observational of cosmic magnetism fields on different scales.

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