Magnetic fields in galaxies:

the small-scale dynamo in a cosmological context

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Ask me your questions!

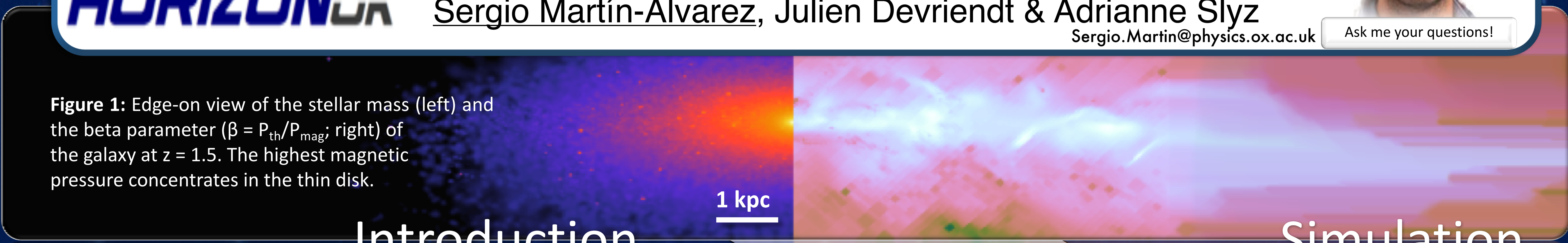


Figure 1: Edge-on view of the stellar mass (left) and the beta parameter ($\beta = P_{th}/P_{mag}$; right) of the galaxy at z = 1.5. The highest magnetic pressure concentrates in the thin disk.

Introduction

Magnetic fields are an important factor in galaxy evolution as they are expected to be in equipartition with other forms of energy in the Interstellar Medium (ISM) and to affect star formation. Observations suggest that magnetic fields reach **μG values in spiral galaxies**, already in place at high redshifts (z≈1.3; Widrow 2002, Bernet et al. 2008, Beck & Wielebinski 2013).

To match these observations, **one of the main problems that simulations have struggled with is the rapid amplification of the field** required to bridge the gap between weak values ($B \in 10^{-20}$–10^{-12}G) predicted in the early matter dominated era and the strong values observed in galaxies (B ~ 10 μG). One of the most promising mechanisms is the **small-scale dynamo**, where the magnetic field is amplified by small-scale turbulence to be later organized by large-scale shear and rotation.

Recently, simulations have tested the small-scale dynamo and found strong amplification in isolated galaxy halos (Rieder & Teyssier, 2016). The crucial question is what happens to this amplification in a **fully cosmological environment**: ***will the inflow of pristine gas and interactions halt this growth or will the turbulent merging and collisions foster a stronger amplification?***

Amplification

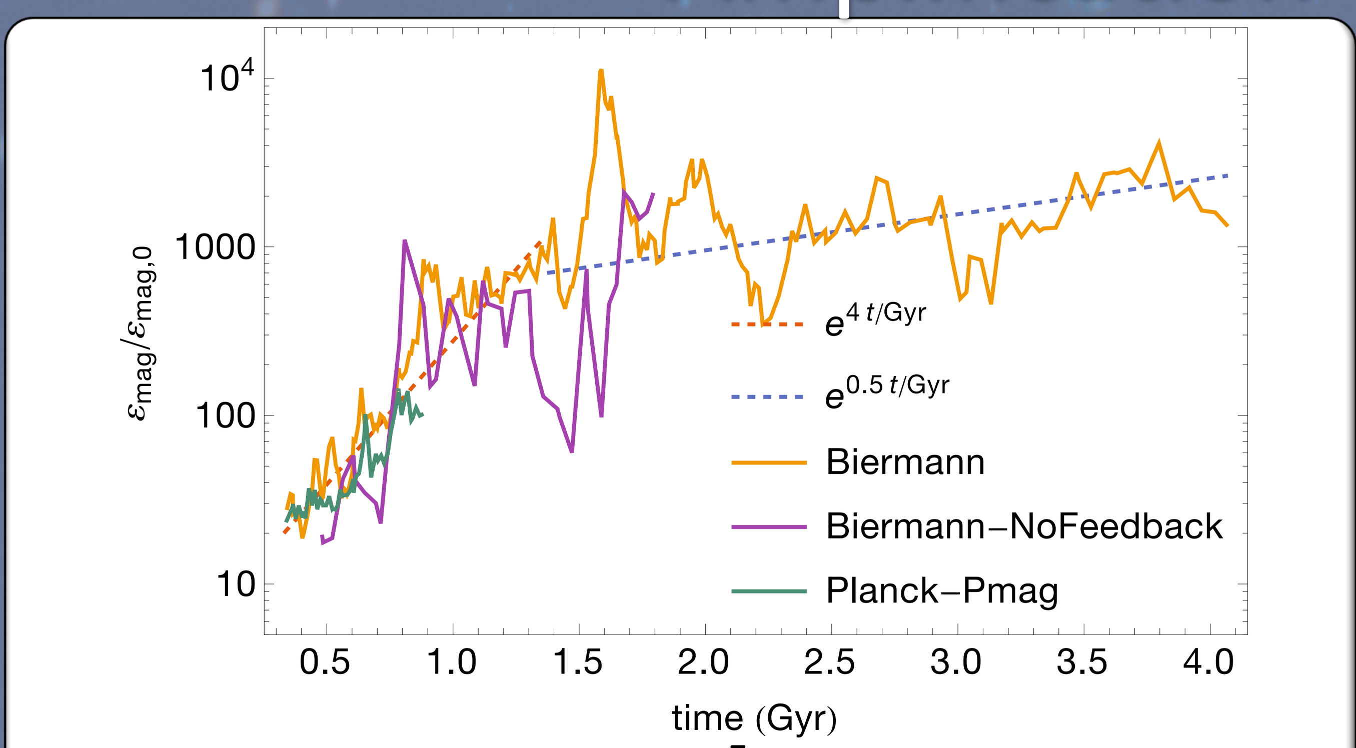


Figure 3: Exponential amplification $e^{\Gamma t}$ (with Γ_{in}=4 Gyr^{-1}and Γ_{late}= 0.5 Gyr^{-1}) is found for the magnetic energy per unit mass in the galaxy. This is consistent with the presence of **Kazantsev's dynamo** (Schekochihin et al. 2004). The inflow of unprocessed gas is not enough to stop the growth of the magnetic energy. A complex epoch of merging fosters a large increase around t = 1.5 Gyrs.

Simulation

Table 1: Ongoing simulations in the study. Different initial magnetic field values, presence of SNe feedback and inclusion of magnetic pressure in the turbulent star formation are shown.

Simulation	B_0	Feedback	SF-P_{mag}
Biermann	10^{-20} G	✓	—
Biermann-NoFB	10^{-20} G	✗	—
Planck-Pmag	10^{-12} G	✓	✓
Planck	10^{-12} G	✓	✗

The suite of ongoing simulations (called NUT, Table 1) has a concordant WMAP5 cosmology (Komatsu et al. 2009), and includes **turbulent star formation** (Federrath & Klessen, 2012), **dynamical supernovae (SNe) feedback** (Kimm et al. 2015), a UV background model for reionization (Haardt & Madau, 1996), metals and metal cooling for the gas. The magnetic field is seeded as an **initial homogeneous field.**

We use a modified MHD version of the AMR code **RAMSES** (Teyssier 2002; Teyssier et al. 2006). Initial conditions consist of a 9 h^{-1} Mpc on a side comoving **cosmological box** containing a high-res ($M_{DM} = 5{\cdot}10^4\,M_\odot$ and $M_* = 5{\cdot}10^3 M_\odot$ and up to **10 pc spatial resolution**) spherical region with diameter 3h^{-1} Mpc within which a **Milky-Way like** halo forms.

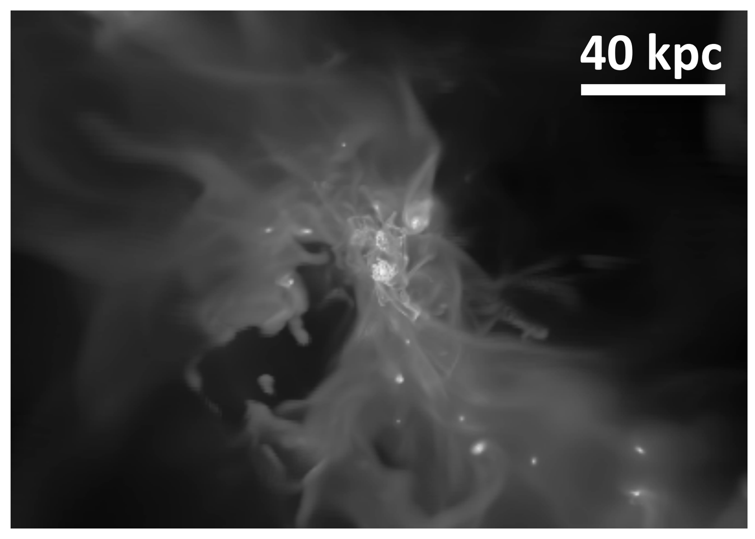
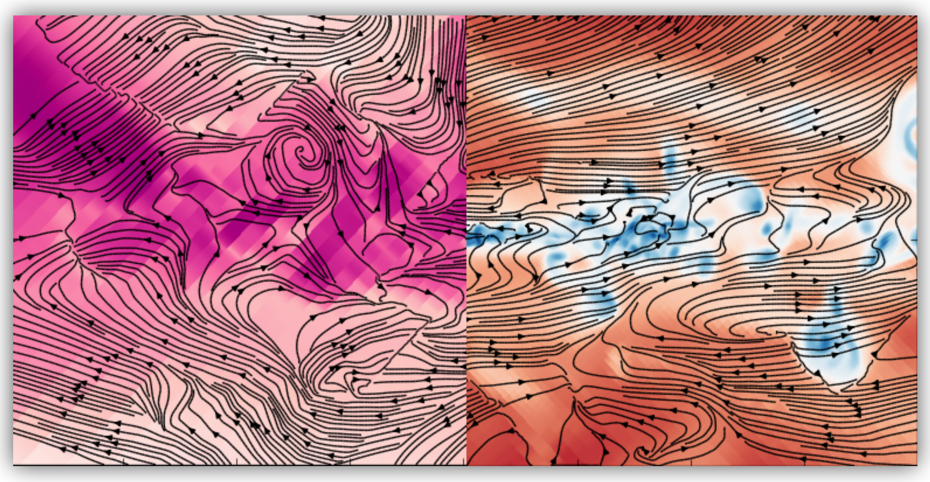


Figure 2: The NUT galaxy (gas density) forms in a cosmological simulation

Small-Scale Dynamo

Figure 4: Magnetic field and magnetic lines (left) and gas density and flow (right) in an edge-on section of the galaxy at z=1.5. The **highly entangled structure of the magnetic field** is the result of Kolmogorov turbulence, which activates the small-scale dynamo. The bulk flow streamlines are more homogeneous, as turbulence occurs on small scales.



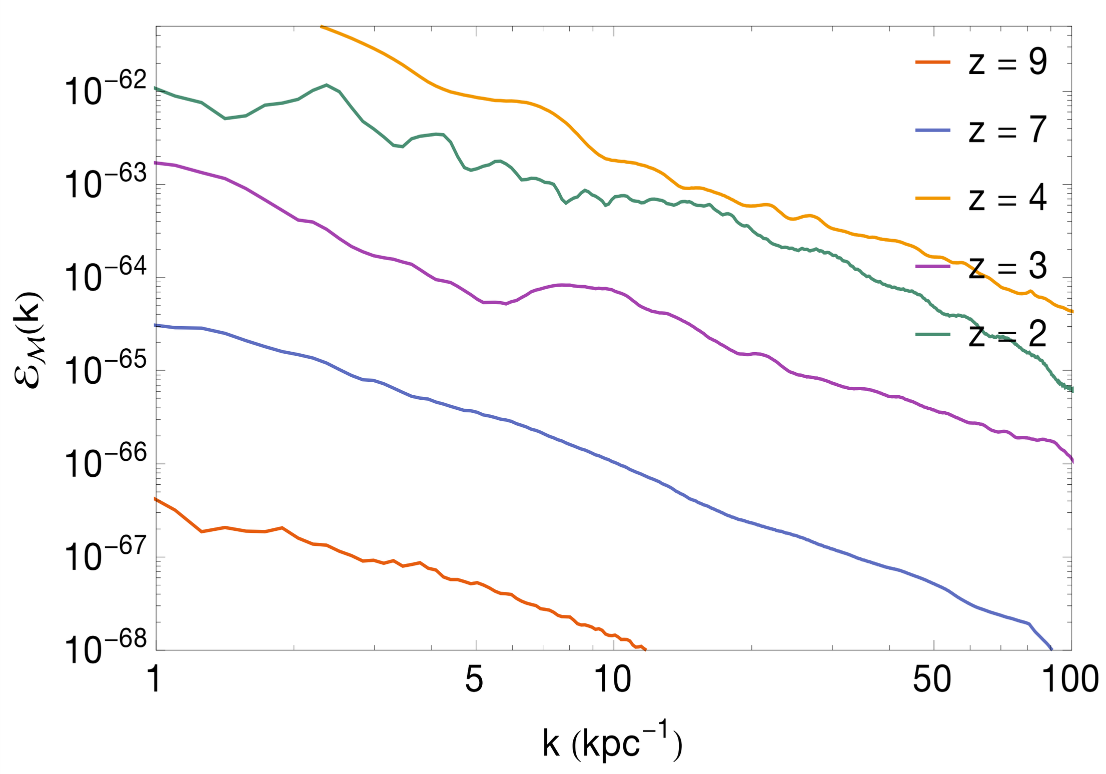


Figure 5: The **Kolmogorov turbulence** spectrum found for the kinetic energy, which indicates that a small-scale dynamo is acting in our galaxy. The plot contains the spectra for the magnetic energy density in a 30kpc box around the galaxy. **This dynamo is responsible for the shallower magnetic energy power-law** compared with the expectation from a purely hydrodynamical cascade. Once the dissipation wavenumber is reached, we find a bottleneck profile that falls as $k^{3/2}$ (Dobler et al. 2003).

Conclusions And Future Work

So far:

- <u>**Magnetic energy amplification occurs**</u> in our cosmological simulations of Milky-Way like galaxies.
- The turbulence spectra found are in agreement with <u>**Kolmogorov turbulence**</u>.
- The magnetic energy spectrum shows evidence of the presence of <u>**small-scale dynamo amplification**</u>.

Ongoing work:

- Magnetic field removal during star formation and injection by SNe.
- Simulations still running!

References: Beck, R. & Wielebinski, R. 2013, Magnetic Fields in Galaxies, ed. T. D. Oswalt & G. Gilmore, 641; Dobler, W., Haugen, N. E., Yousef, T. A., & Brandenburg, A. 2003, Phys. Rev. E, 68, 026304; Haardt, F. & Madau, P. 1996, ApJ, 461, 20; Kimm, T., Cen, R., Devriendt, J., Dubois, Y., & Slyz, A. 2015, MNRAS, 451, 2900; Komatsu, E., Dunkley, J., Nolta, M. R., et al. 2009, ApJS, 180, 330; Federrath, C. & Klessen, R. S. 2012, ApJ, 761, 156; Rieder, M. & Teyssier, R. 2016, MNRAS, 457, 1722; Schekochihin, A. A., Cowley, S. C., Taylor, S. F., Maron, J. L., & McWilliams, J. C. 2004, ApJ, 612, 276; Teyssier, R. 2002, A&A, 385, 337; Teyssier, R., Fromang, S., & Dormy, E. 2006, Journal of Computational Physics, 218, 44; Widrow, L. M. 2002, Reviews of Modern Physics, 74, 775.

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