

1. Introduction

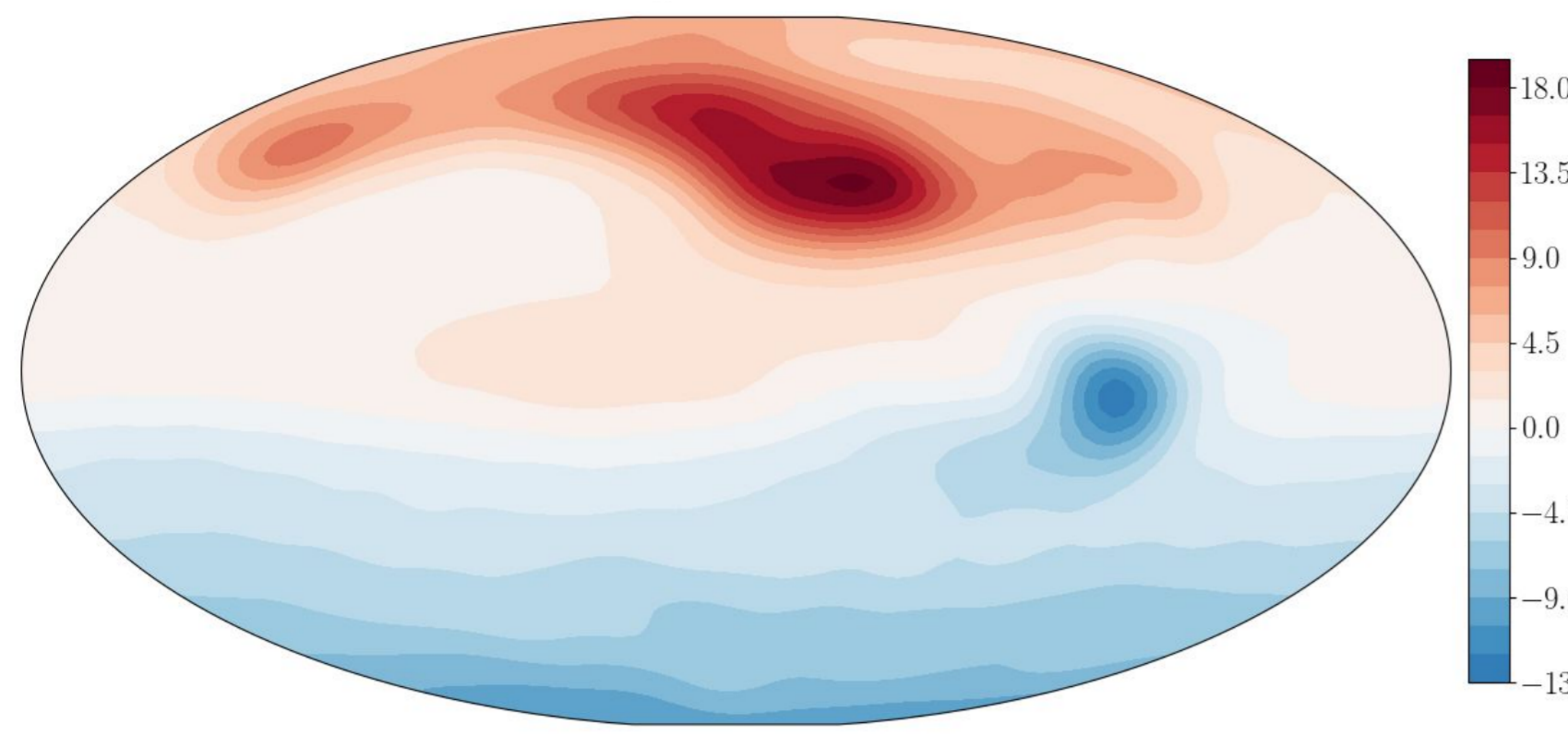
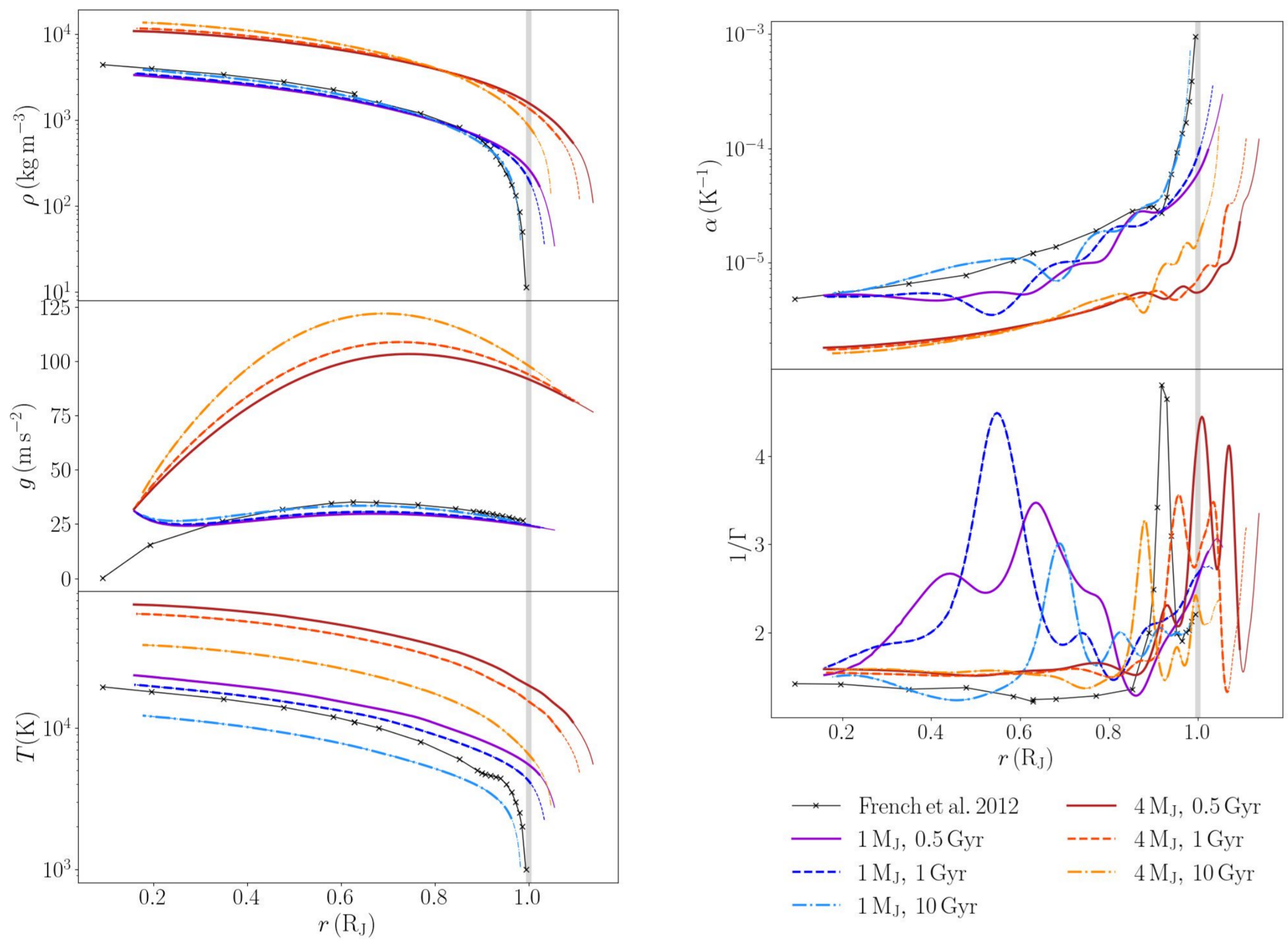


Figure: Radial component the magnetic field (in Gauss) of Jupiter from Connery et al. (2021).

Exoplanetary magnetism is still largely unknown despite having more than 5700 confirmed candidates. Based on Solar System planets, giants planets are expected to host the strongest magnetic fields and thus be the easiest to detect. We aim to address the **long-term (Gyr) evolutionary changes of the convection driven interior dynamos** (in terms of **magnetic field intensity and morphology**) of Jupiter-like planets by using MHD simulations. The results shown here are a summary of Elias-López et al., 2025.

2. 1D hydrostatic profiles for gas giants

We use MESA [a] to model the change of radially dependent thermodynamic quantities by solving the stellar structure equations: the **mass and energy conservation, hydrostatic equilibrium, energy transport, and EoS of H-He mixtures** in the gas-giant regime (Paxton et al., 2019, Saumon et al., 1995).



$$\frac{dm}{dr} = 4\pi r^2 \rho,$$

$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4},$$

$$\frac{dL}{dm} = \epsilon_{\text{grav}} + \epsilon_{\text{irr}} + \epsilon_{\text{dep}},$$

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4} \nabla$$

Figure: Normalized MESA hydrostatic quantities at three different evolutionary times for a $1M_J$ planet. They are implemented in MagIC as **high degree polynomial fits**. The real physical units are used for the dimensionless parameters.

4. General behaviour and energy spectra

We use trends in dimensionless numbers that reflect the evolutionary changes dictated by MESA (despite usual caveat of being orders of magnitude away from the physical values). We choose appropriate values that, for all evolutionary 1D structures, have high enough Ra to develop convection all over the volume which leads to **saturated dynamo solutions with similar topology but different saturation levels**.

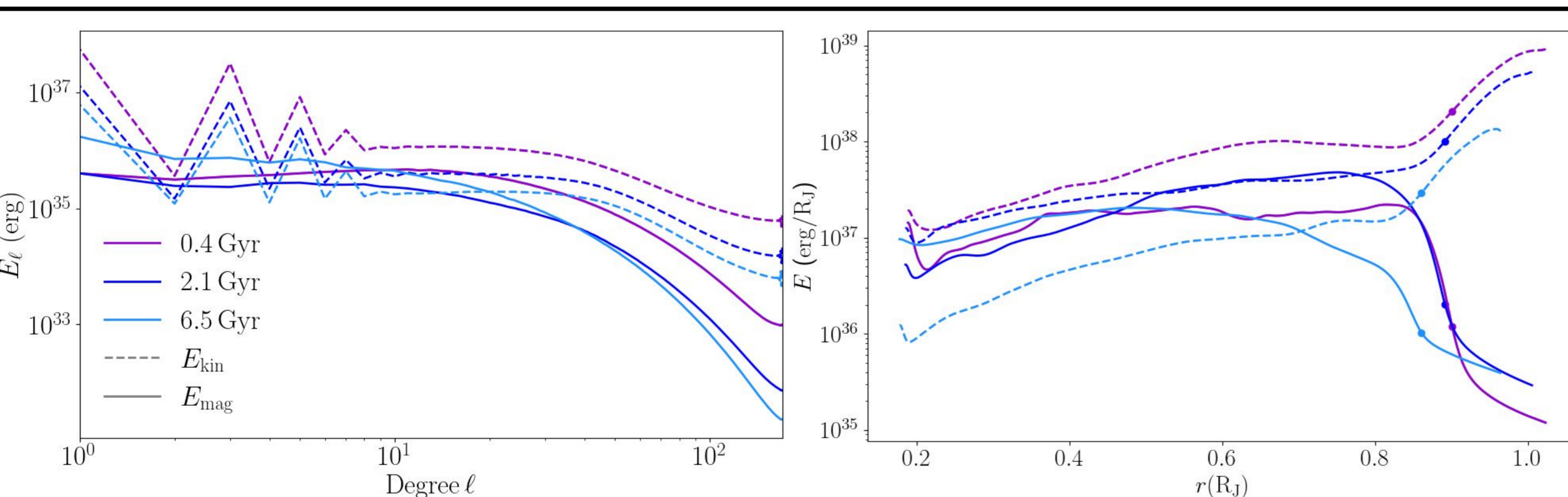
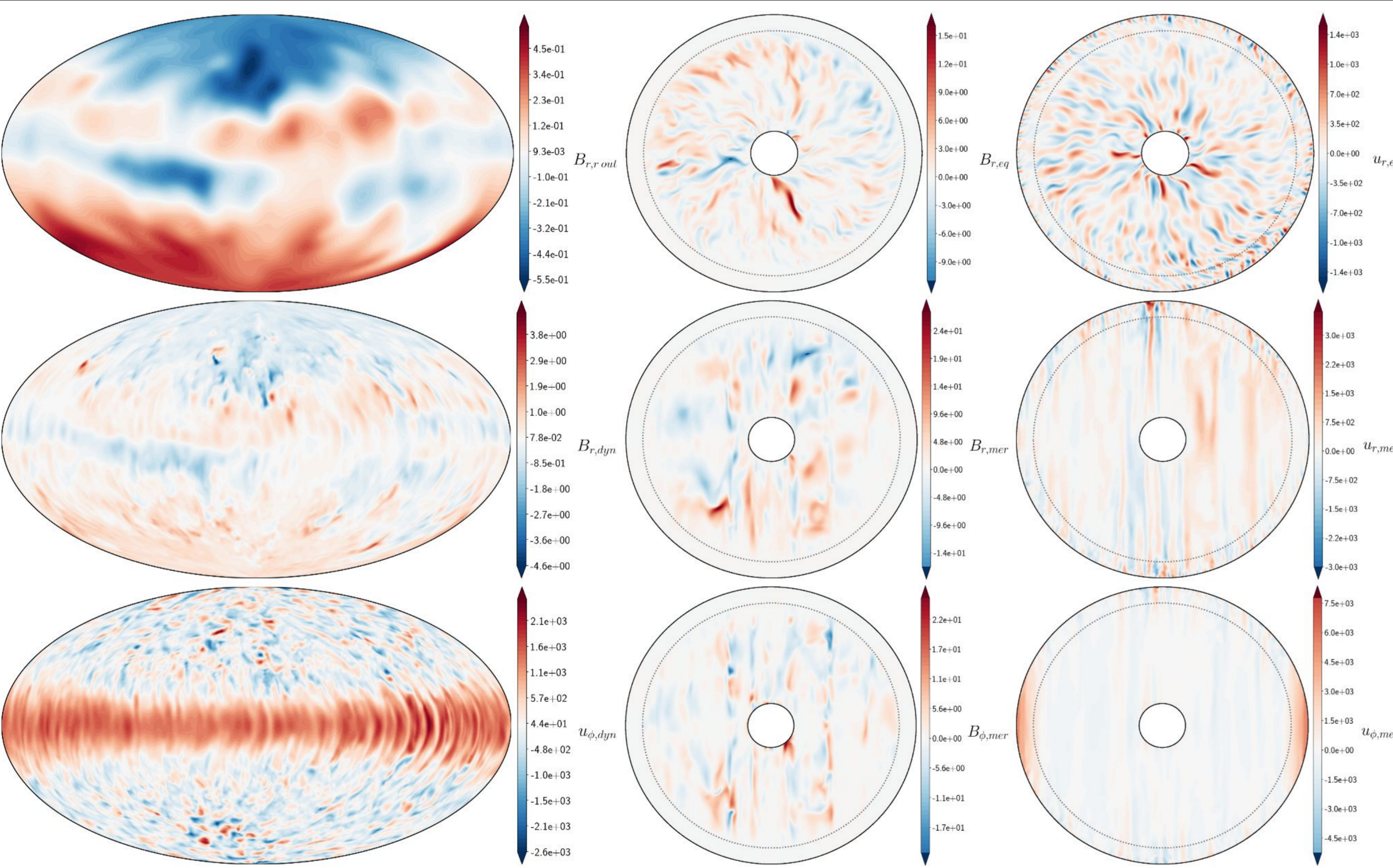


Figure: (Top) 3D slices of the $1M_J$ 0.5 Gy model, similar to all other saturated dynamos. (Bottom) **Radial and spectral energy distributions** for three models. The outer equatorial jet makes external spikes (i.e. high E_{kin} with reduced E_{mag}) in the radial distribution as well as the kinetic zig-zag at the lowest multipoles in the spectra. The jet starts to become dominant at radii above r_m , i.e. when the conductivity drops, magnetic diffusion is stronger and the Lorentz force does not act on the fluid. They are a common trait with models having both stress free boundary conditions and a decaying outer σ . Both energies decrease over time, but the kinetic energy diminishes faster (see the evolution of energy equipartition). By analyzing the surface at the outer spectra we can assess if the models are resolved.

Method

(i) Time evolve (in a Gyr timescale) a **1D hydrostatic model** of a gas giant with MESA

(ii) Implement the radial profiles as the **background state** of an anelastic 3D model

(iii) Time evolve (in a Ky timescale) the **3D MHD equations** with MagIC in spherical shell to obtain self sustained dynamo solution

(iv) Repeat the process for **multiple stages** of the life of a gas giant

3. 3D Magnetohydrodynamic (MHD) model

We run **3D MHD numerical simulations** using MagIC [b] (spherical harmonics in θ, φ and Chebyshev polynomials in r) under the **anelastic approximation**, typically used for modeling convection in gas giants and stars. We time-evolve the **mass continuity, momentum, the induction and entropy** equations.

$$\nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{E} \nabla \left(\frac{P'}{\rho} \right) - \frac{2}{E} \mathbf{e}_z \times \mathbf{u} + \frac{Ra}{Pr} \mathbf{g} s \mathbf{e}_r + \frac{1}{Pm_i E \rho} (\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{1}{\rho} \nabla \cdot \mathbf{S},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \frac{1}{Pm} \nabla \times (\lambda_{\text{norm}}(r) \nabla \times \mathbf{B}), \quad \nabla \cdot \mathbf{B} = 0,$$

$$\rho \bar{T} \left(\frac{\partial s}{\partial t} + \mathbf{u} \cdot \nabla s \right) = \frac{1}{Pr} \nabla \cdot (\rho \bar{T} \nabla s) + \frac{Pr Di}{Ra} Q_v + \frac{Pr Di}{Pm_i^2 E Ra} \lambda_{\text{norm}} (\nabla \times \mathbf{B})^2,$$

where

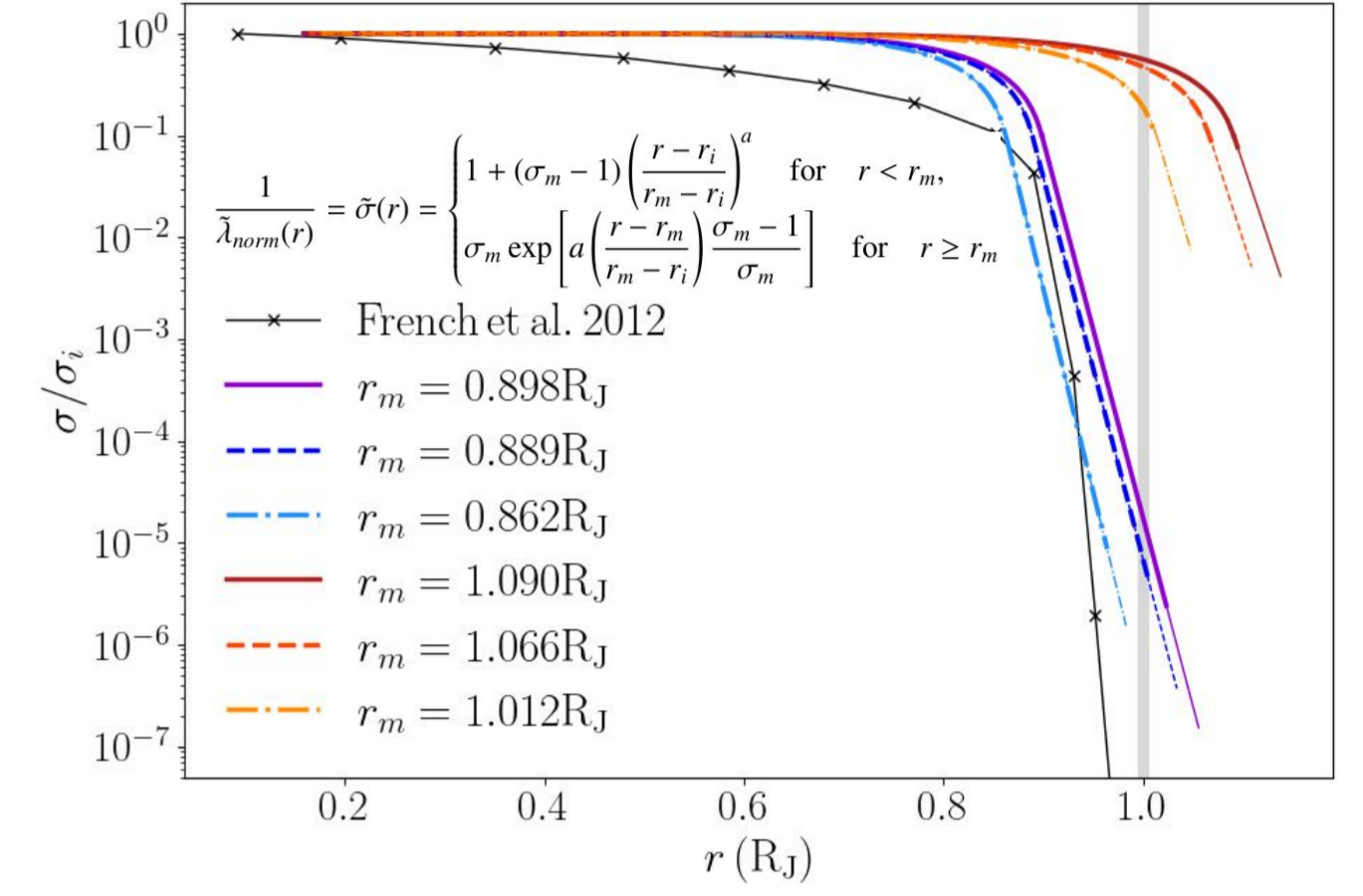
$$E = \frac{v}{\Omega d^2} \quad Pr = \frac{\nu}{\kappa}$$

$$Ra = \frac{g_0 d^3 \Delta s}{c_p \nu \kappa} \quad Pm_i = \frac{\nu}{\lambda_i}$$

Parameter evolution

$$E' = E_0 \frac{d_0^2}{d^2}, \quad Ra' = Ra_0 \frac{d'^3 \Delta T'}{d_0^3 \Delta T_0}$$

The dimensionless input parameters are Ekman, the Rayleigh, the Prandtl and magnetic Prandtl numbers. **Figure:** Normalized the magnetic conductivity $\sigma(r)$, i.e. inverse of $\lambda_{\text{norm}}(r)$, taken from Gómez-Pérez et al. (2010) which is similar to jovian interior structure models (French et al., 2012). For the models shown here we use $\sigma_m = 0.1$, $a = 7$ and r_m the radius where MESA pressure reaches just above 100 GPa (metallic hydrogen transition). For every 1D model r_m changes, but usually falls between 0.85 and 0.90 r/R_p .



5. Evolutionary trends

We assess the evolutionary changes with the different saturated numerical dynamos. Generally, planetary parameters do not vary more than one order of magnitude. The decay in magnetic field makes agrees with **dimensional scaling law for fast rotators**. (Figure: Comparison between the magnetic field decay and the scaling law of Christensen et al 2009, Reiners & Christensen 2010) But additionally we have many other 3D global information which can be used to derive other trends.

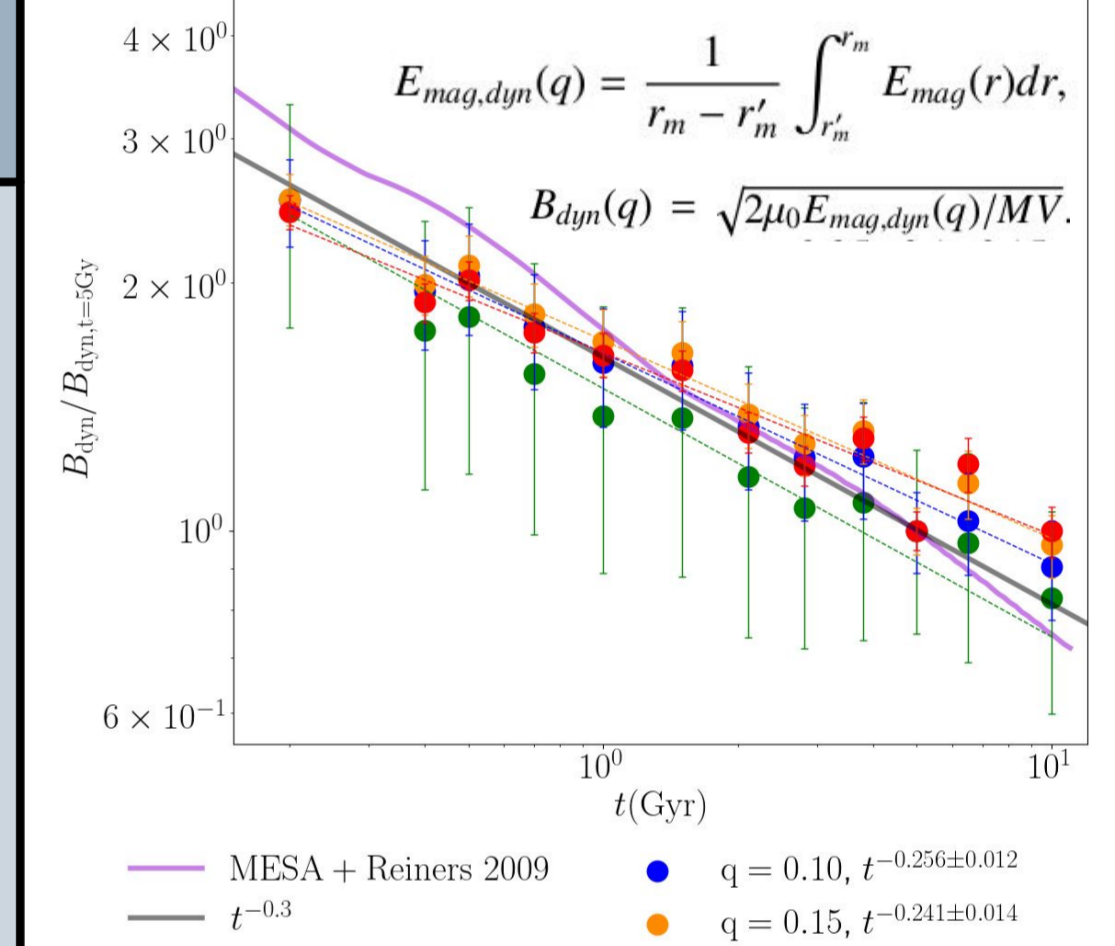


Figure: Evolutionary trends for output diagnostics: magnetic Reynolds number, Lorentz number, energy equipartition, ohmic dissipation factor, total dipolarity and dipolarity at the dynamo surface. Notice **multipolar to dipolar dominated transition**.

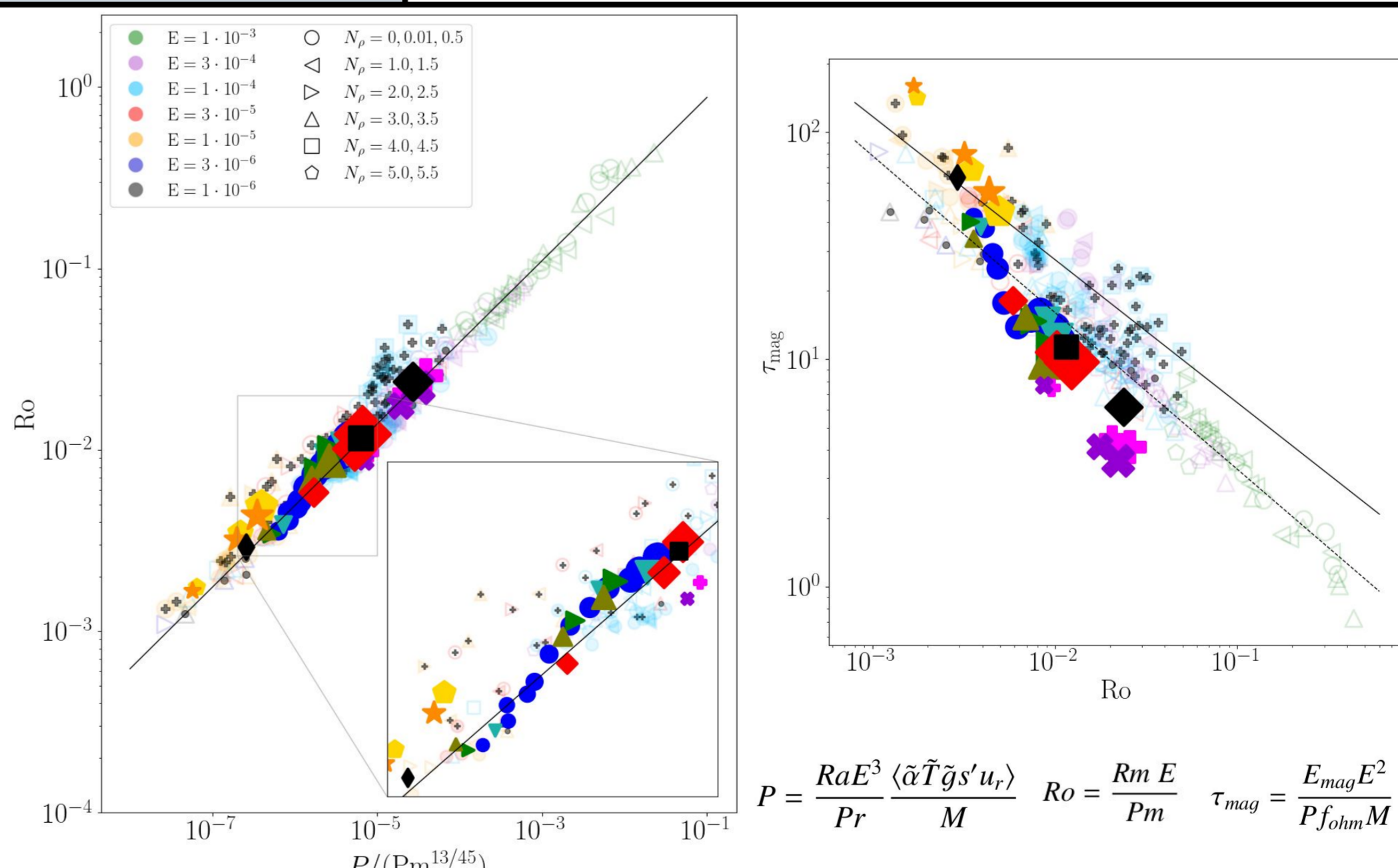
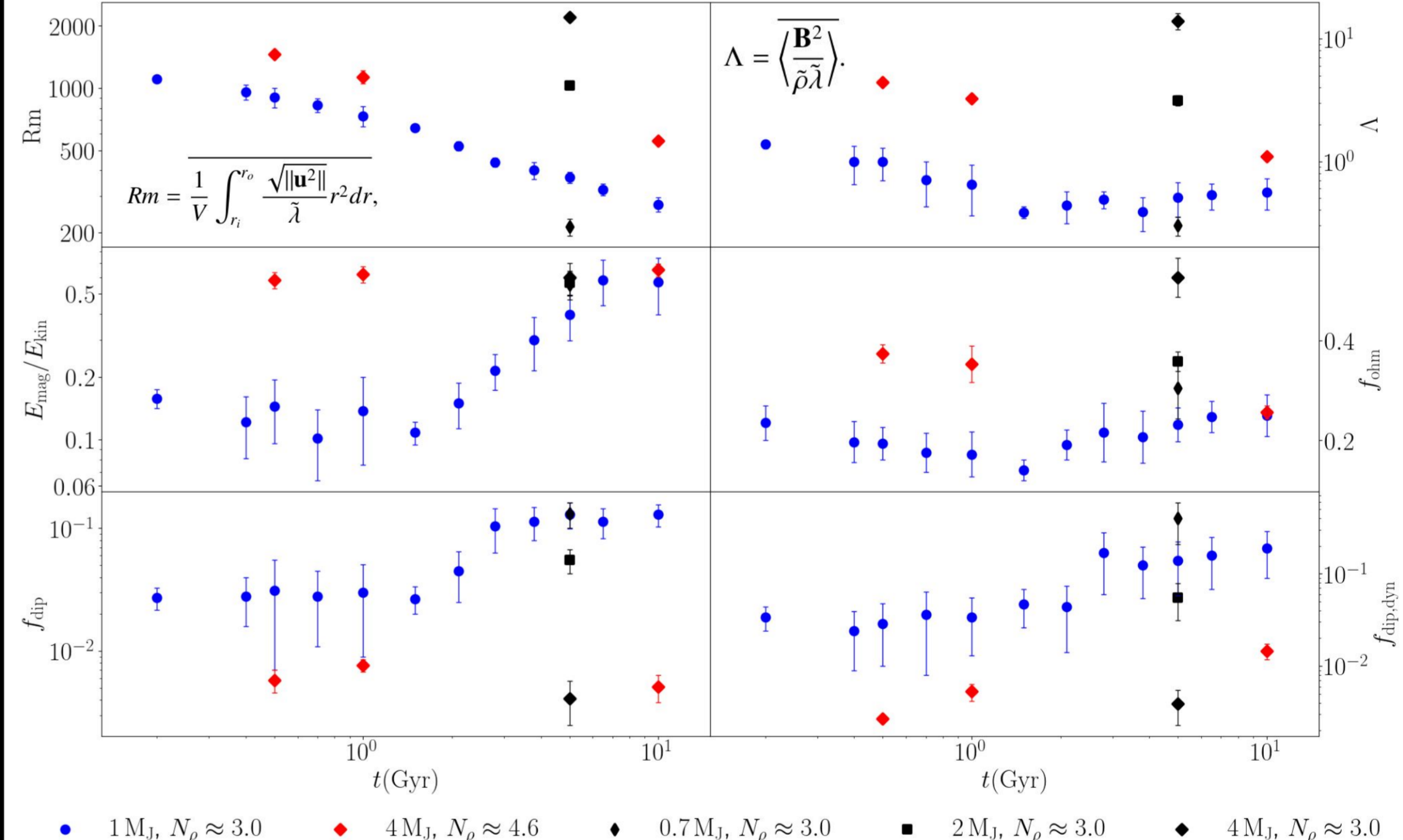


Figure: Comparison between the scaling laws of Yadav et al., 2013 with the evolutionary series of this work. The additional data points correspond to simulations with Pm or Pr different from 1 (see Elias-López et al., 2025). Through its evolution from 0.2 to 10 Gyr, a planet travels to lower Ra and buoyancy power for about an order of magnitude. The multipolar to dipolar transition can also be seen in the magnetic diffusion timescale.

Conclusions and references

1. **Saturated dynamo solutions** are obtained throughout a planets life time.
 2. We obtain the evolutionary changes of dimensionless dynamo parameters ($Rm, Ro, \Lambda, f_{\text{dip}}, f_{\text{ohm}}$), which are **different for dipolar and multipolar dynamo branches**. Few stages (3 or 4) are enough to assess the general behaviour, within a branch.
 3. Results are **compatible with scaling laws** (Christensen et al 2009, Yadav et al., 2013).
- Future work: apply the same method for the Hot Jupiter dynamos, add a T dependency to Pm, Pr.

[1] Christensen et al., Nature 457, 7226, 167-169, 2009
 [2] Connery et al. JGR Planets 127, 2, 2021
 [3] French et al., ApJS 202, 5, 2012
 [4] Gómez-Pérez et al., PEPI 181, 1, 42-53, 2010
 [5] Paxton et al., ApJS 243, 10, 2019
 [6] Reiners & Christensen, A&A 522, A13, 2010
 [7] Saumon et al., ApJS 99, 713-741, 1995
 [8] Yadav et al., ApJS 774, 6, 2013