Tayler instability-driven dynamo in the radiative envelope of a γ Doradus star

P. Barrère[1,⋆], A. Reboul-Salze[2], P. Eggenberger[1]

⋆paul.barrere@unige.ch

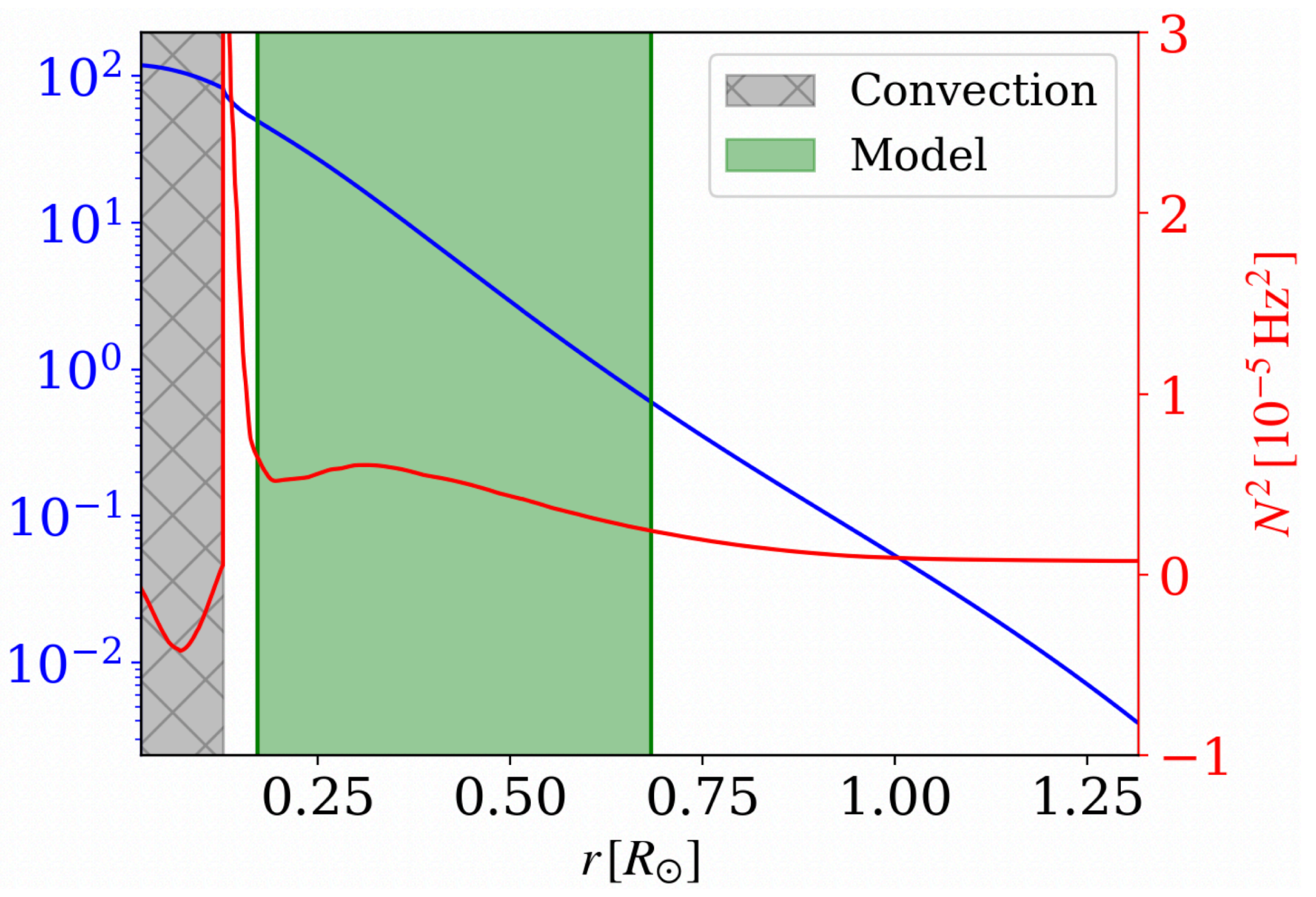
[1]Université de Genève/Département d'astronomie, Switzerland; [2]Max Planck Institute for Gravitational Physics, Germany

ABSTRACT

During the past few years, asteroseismic investigations of γ Doradus stars have revealed the internal rotation rates of hundreds of them, offering insights into the ongoing internal angular momentum (AM) transport mechanisms. Very recently, two other studies also estimated the internal magnetic fields of these stars. While these fields may be produced by a convective core dynamo, the Tayler instability-driven (or Tayler-Spruit) dynamo is a promising candidate to produce the necessary AM transport inside the radiative envelope. Recent numerical studies have demonstrated the existence of this dynamo (Petitdemange *et al.* 2023, Barrère *et al.* 2026), but used very simplistic models of radiative zones by using the Boussinesq approximation (uniform density). Here, we present the first 3D direct numerical simulations of the Tayler-Spruit dynamo in a realistic radiative envelope of $1.5\,\mathrm{M}_\odot$ main-sequence star using the anelastic approximation. The generated magnetic fields are mostly located near the polar axis, making them difficult to detect by asteroseismology. However, their strong strengths ($1-100\,\mathrm{kG}$) produce enough AM transport to explain the observed quasi-solid-body rotation in the radiative zone of γ Doradus stars.

1. SIMULATION SETUP

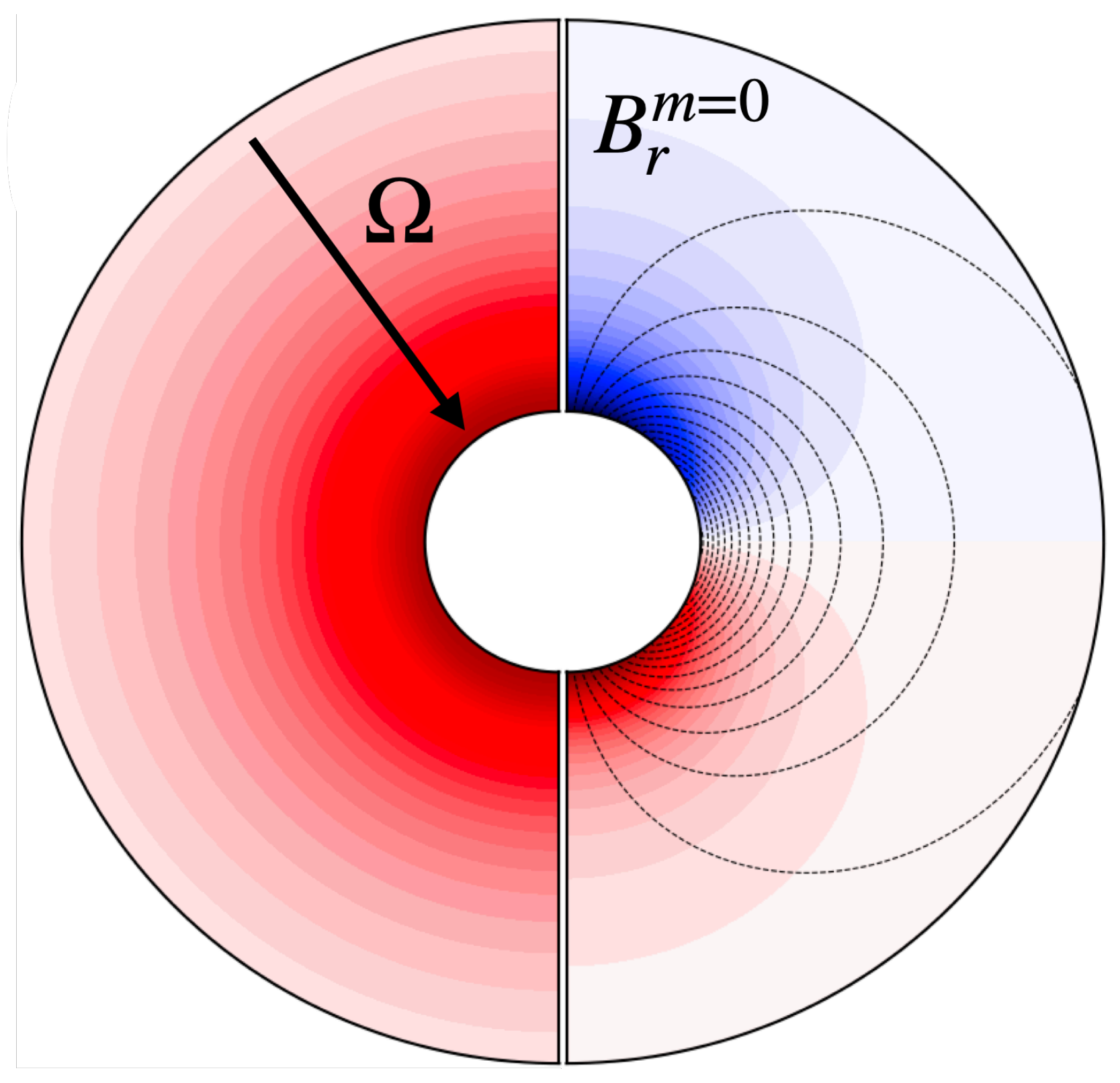
- **MagIC code** (Wicht 2002, Gastine & Wicht 2007)
- **Anelastic model of radiative envelope**
  - **Reference state:** 1D evolution model of a main sequence $1.5\,\mathrm{M}_\odot$-star (core hydrogen fraction of 0.3) calculated with the GENEC code (Eggenberger et al. 2008)
  - **Integration domain:** 0.17 and $0.68\,\mathrm{R}_\odot$ with an **important density contrast** $N_\rho = \ln\left(\rho_o/\rho_i\right) \approx 4.4$



- **Initial fields**
  - **New volumetric forcing of differential rotation**: forced velocity $\mathbf{v} = \mathbf{u} + v_\mathrm{f}\mathbf{e}_\phi$ and dissipation term $\mathbf{f} = -\tau u_\phi^{m=0}\mathbf{e}_\phi$, with a relaxation timescale τ^{-1}
  - Forced rotation profile

$$\Omega_\mathrm{f}(r) = \frac{\Omega_i}{\left(1 + (r/r_i)^{20}\right)^{1/20}}$$

  - Initial magnetic field: poloidal scalar potential field $b \propto 1/r$



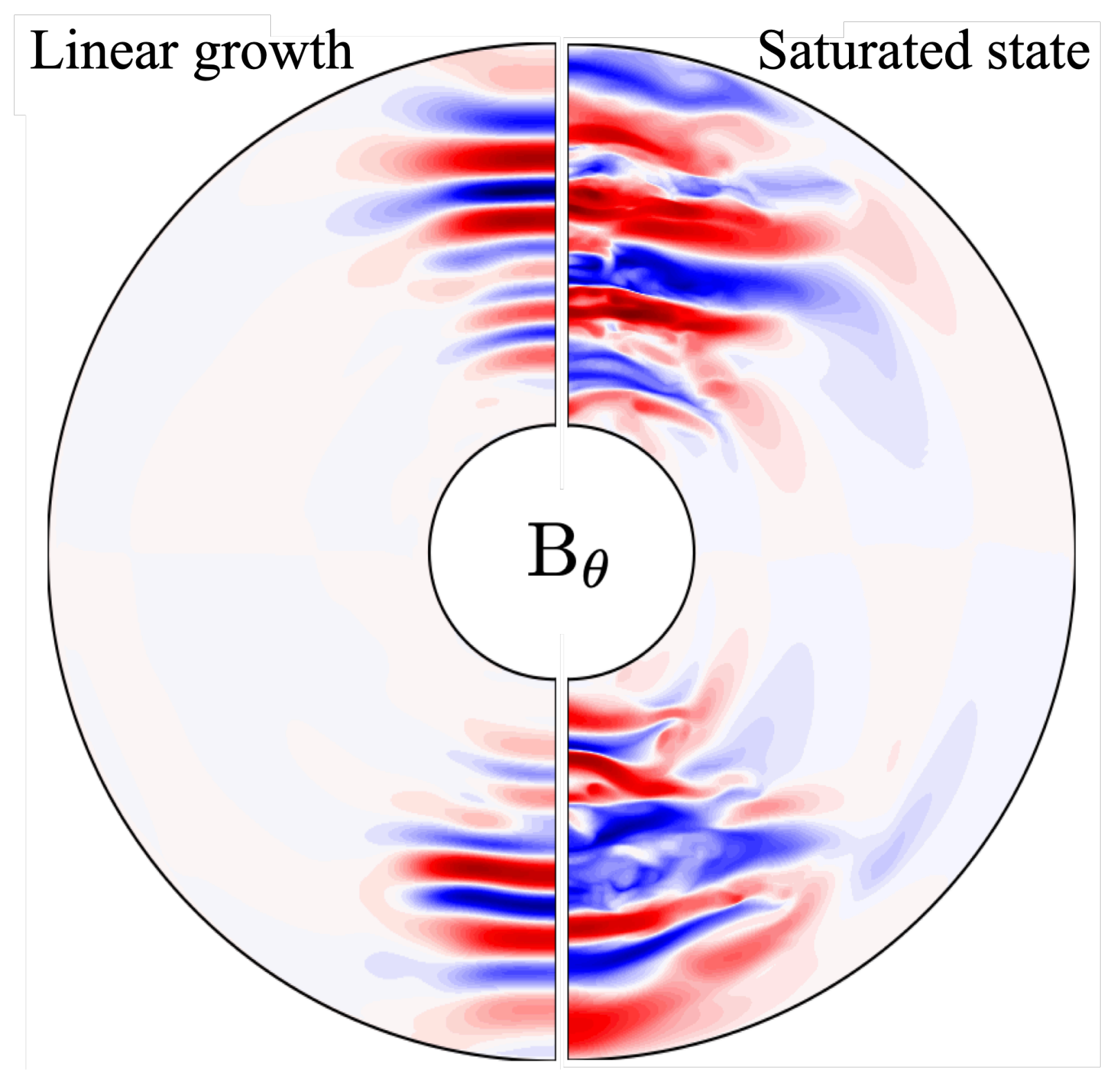
- **Parameters**
  - $(n_r, n_\theta, n_\phi) = (384, 384, 768)$
  - $E = 10^{-5} \gg 10^{-15}$,
  - $Pr = 0.1 \gg 10^{-6} - 10^{-5}$, $\mathbf{Pm} \in [0.4, 4]$
  - $Ra = 4\times10^{11} \ll 10^{23} - 10^{25}$, $N/\Omega_o = 20$

2. TAYLER INSTABILITY

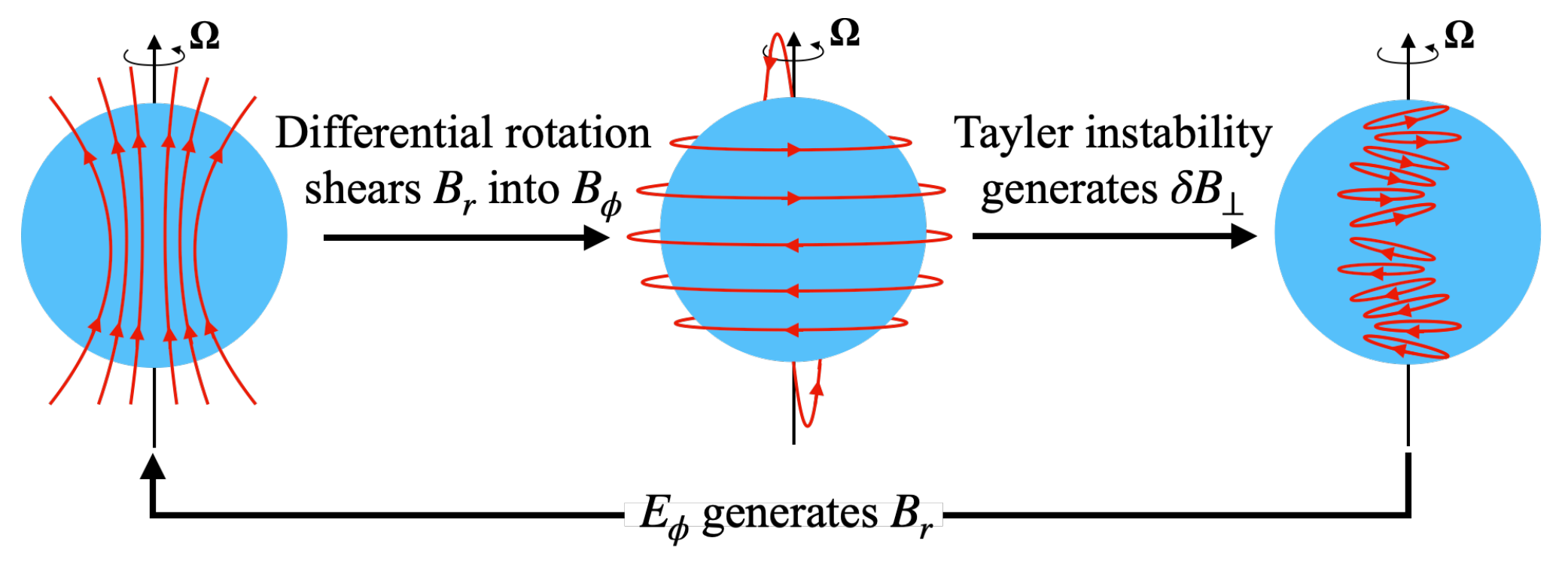
- **Instability criterion (Spruit 2002)**

$$\omega_\mathrm{A}^\mathrm{c} \equiv \frac{B_\phi^\mathrm{c}}{\sqrt{\mu_o\rho r^2}} \gtrsim \Omega\left(\frac{N}{\Omega}\right)^{1/2}\left(\frac{\eta}{r^2\Omega}\right)^{1/4}$$

- **Tayler instability structure**



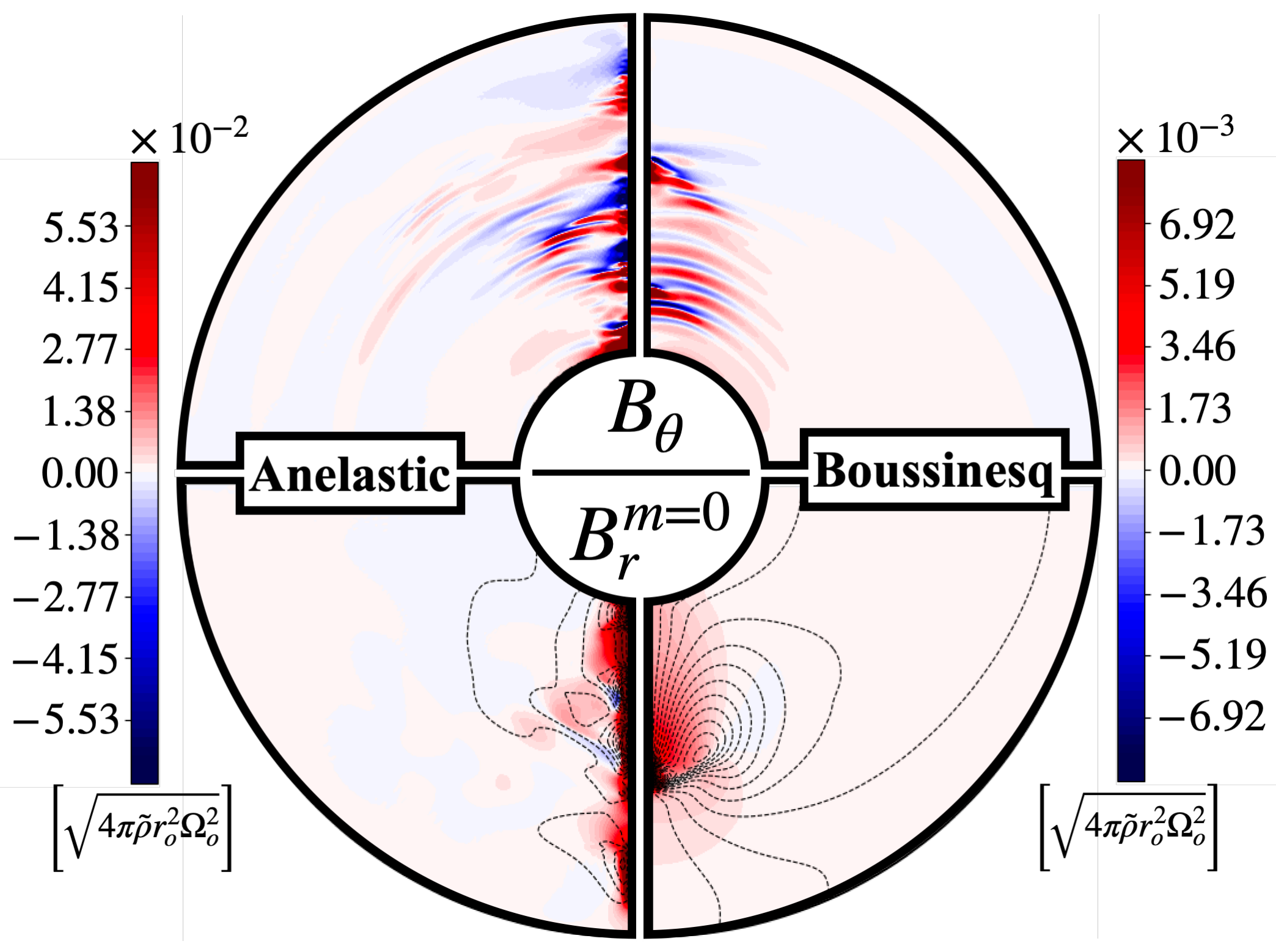
- **Tayler-Spruit dynamo loop**



3. MAGNETIC FIELDS

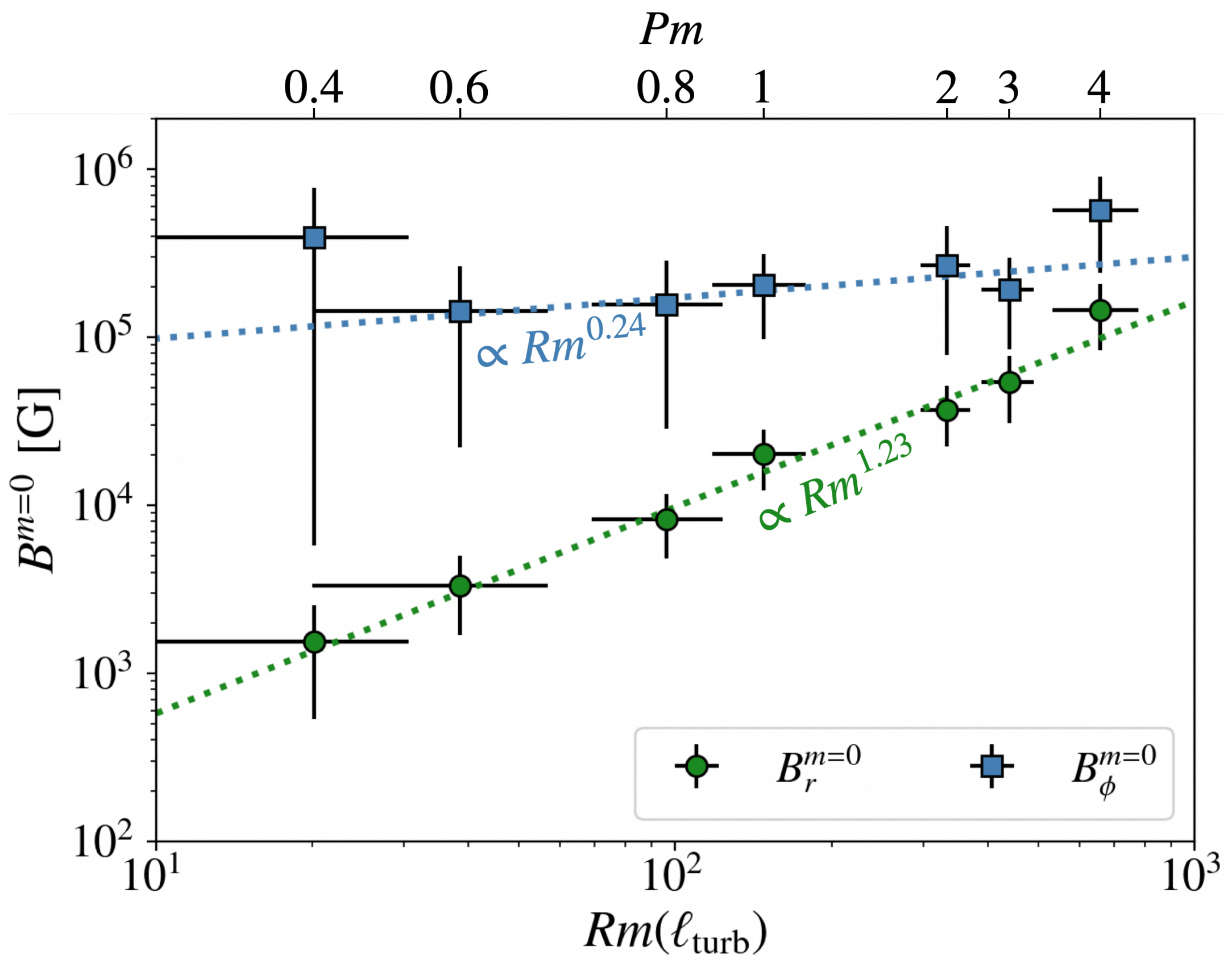
- **Comparison with a Boussinesq simulation**

$$Ra = 4\times10^{11},\ E = 10^{-5},\ Pr = 0.1,\ Pm = 4$$



$\Longrightarrow$ Similar magnetic field large- and small-scale structure but **stronger fields in the anelastic model**.

- **Scaling laws**



$\Longrightarrow$ **Strong (horizontally-averaged) magnetic fields** between 1 and $100\,\mathrm{kG}$

$\Longrightarrow$ Mostly located **near the polar axis** (more difficult to detect by asteroseismology)

$\Longrightarrow$ $B_\phi^{m=0} \propto Pm^{0.76}$ and $B_r^{m=0} \propto Pm^{2.17}$

$\Longrightarrow$ Turbulent magnetic Reynolds number:

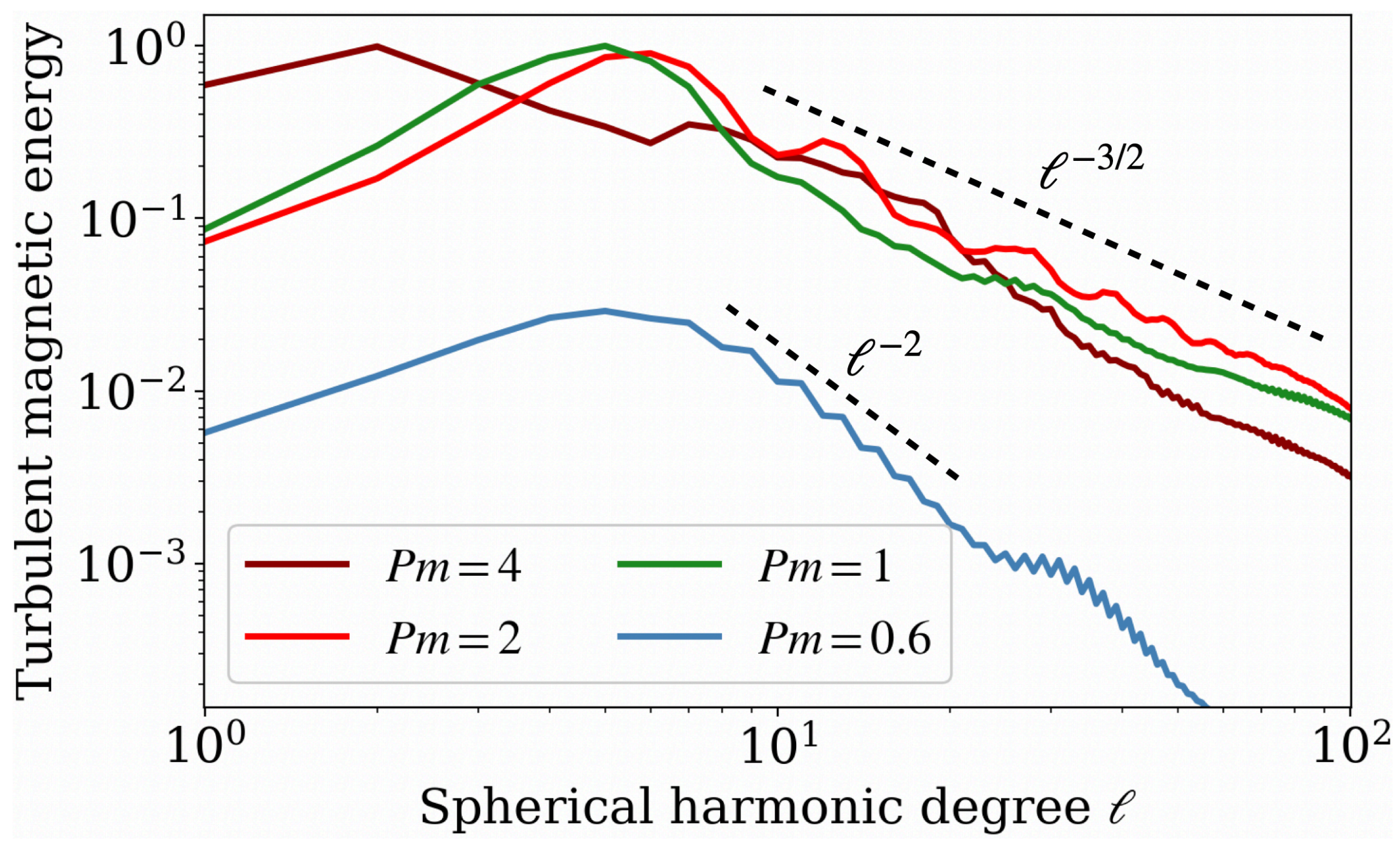
$$Rm(\ell_\mathrm{turb}) = v_\mathrm{RMS}^{m\neq0}\ell_\mathrm{turb}/\eta$$

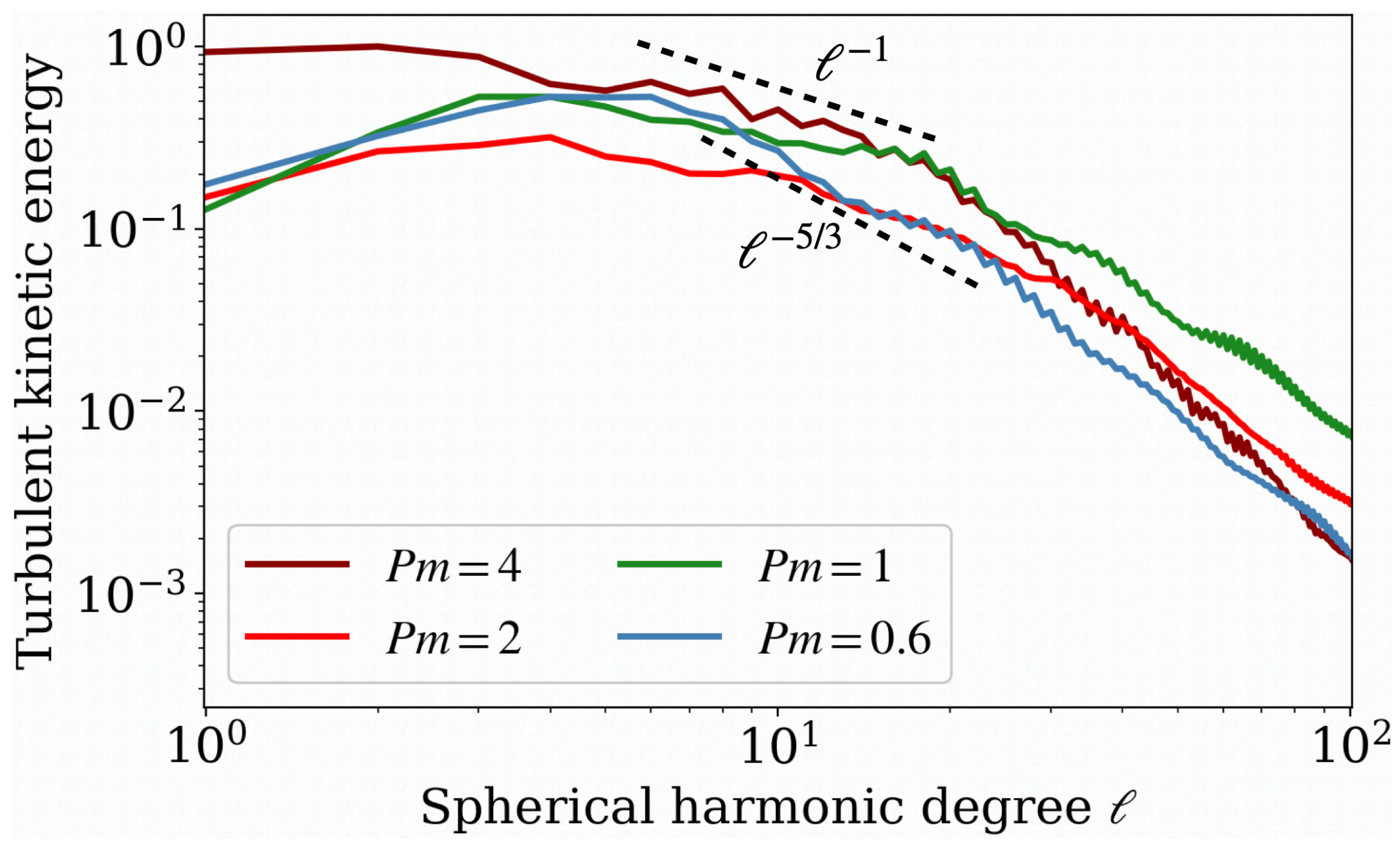
Similar scaling laws as in our Boussinesq study:

$$B_\phi^{m=0} \propto Rm^{0.24}\ \text{and}\ B_r^{m=0} \propto Rm^{1.23}$$

5. SPECTRA

- **Turbulent cascade**

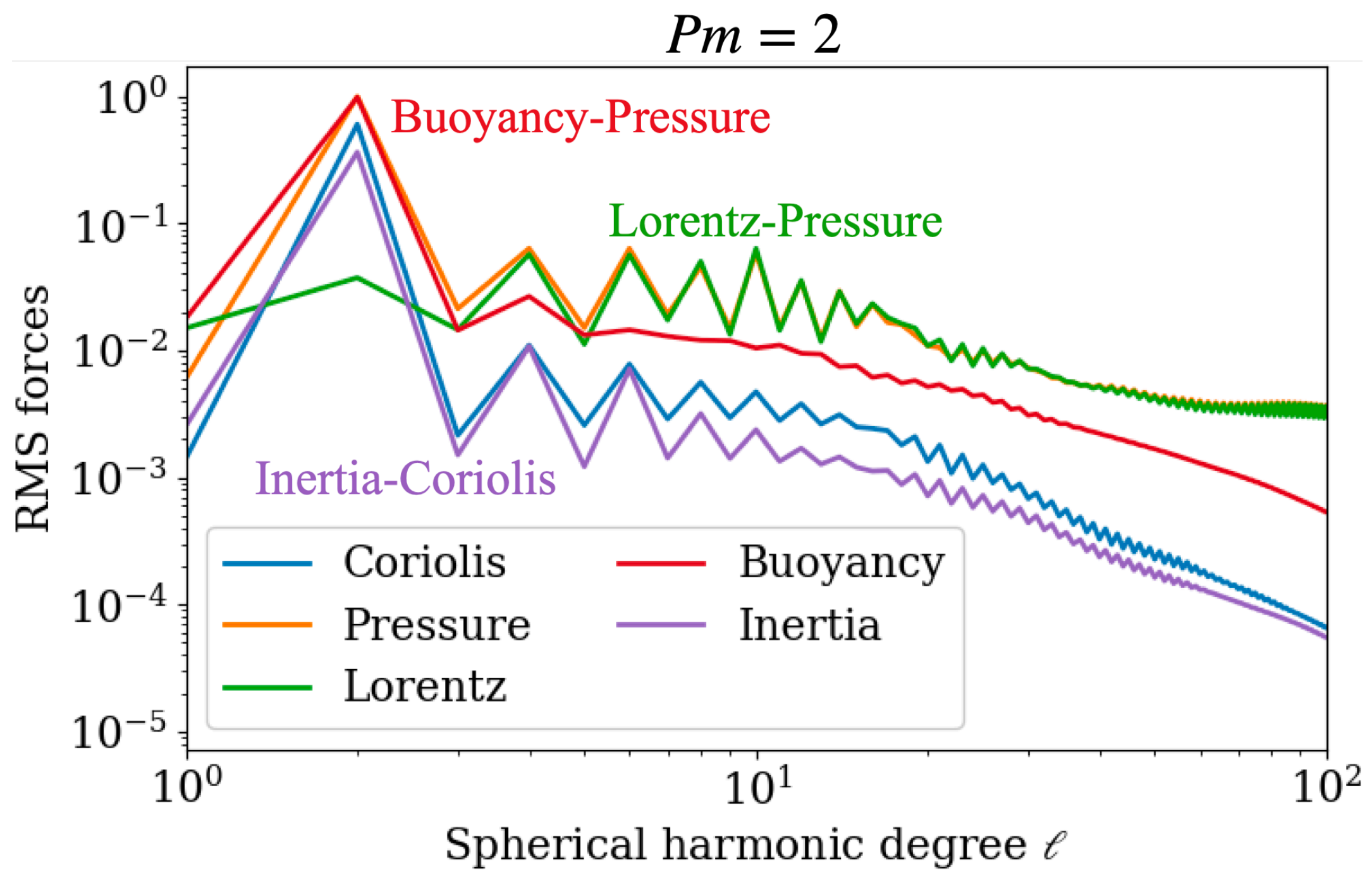




$\Longrightarrow$ **Magnetic: Weak turbulence** regime ℓ^{-2} near dynamo threshold ($Pm \in [0.4, 0.8]$), and **classical IK or aligned MHD turbulence** scaling $\ell^{-3/2}$ for $Pm \gtrsim 0.8$.

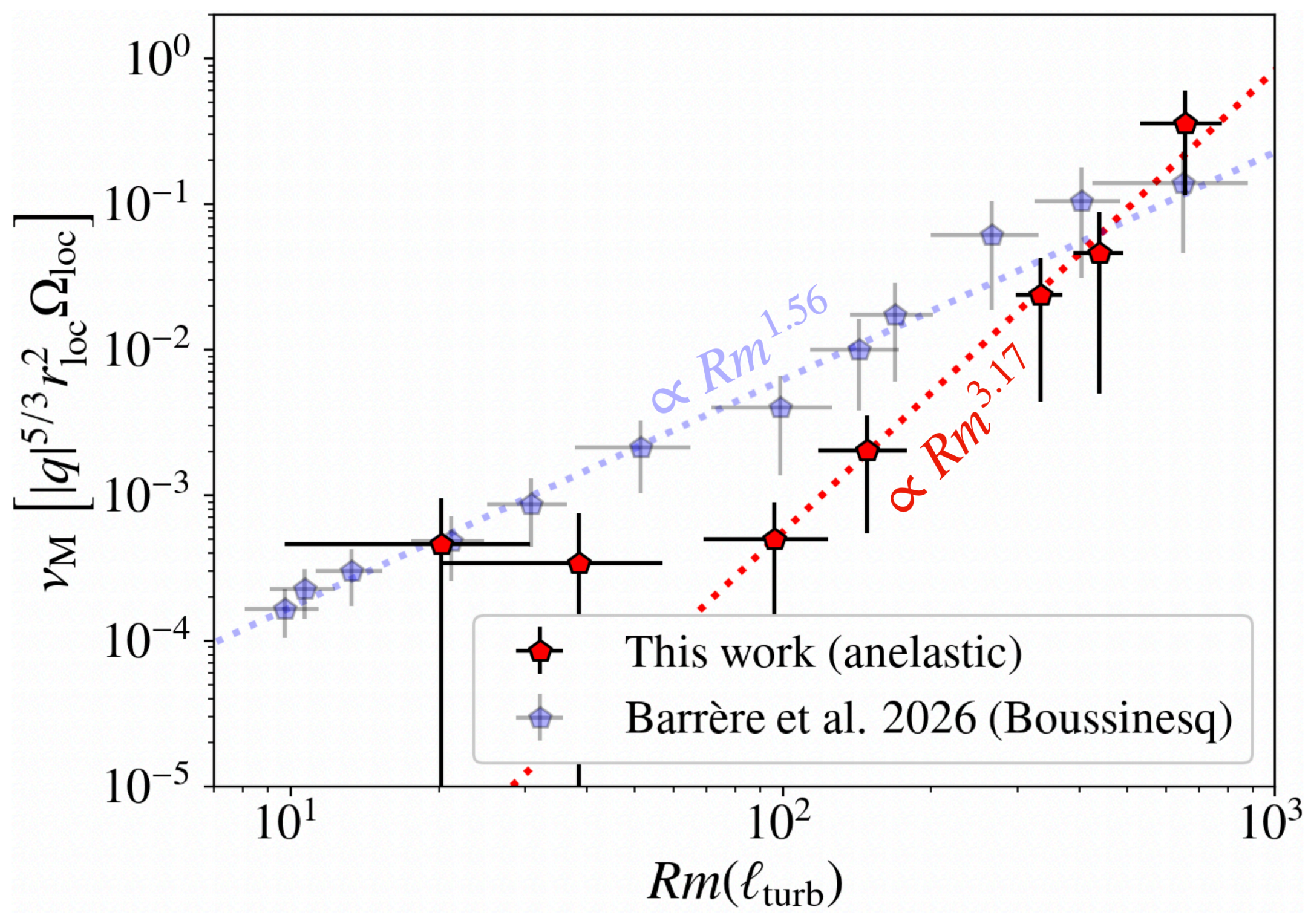
$\Longrightarrow$ **Kinetic:** While the cascade tends towards the **classical K41** regime $\ell^{-5/3}$ near the dynamo threshold, the scaling is **shallower** (nearly ℓ^{-1}) for $Pm \gtrsim 0.8$.

- **Force balances**



6. AM TRANSPORT

- **Maxwell torques**



$\Longrightarrow$ The magnetic torques are similar in the anelastic and Boussinesq models when $Rm(\ell_\mathrm{turb}) \gtrsim 300$ (i.e. $Pm \in [2, 4]$).

$\Longrightarrow$ However, the anelastic models follow a steeper scaling law ($Rm^{3.17}$) than Boussinesq models ($Rm^{1.56}$)

$\Longrightarrow$ The dynamo thresholds are similar for Boussinesq and anelastic models: $\mathbf{Rm(\ell_\mathrm{turb}) \approx 10-20}$

$\Longrightarrow$ The behaviour at $Rm(\ell_\mathrm{turb}) \gtrsim 10^3$, and so the astrophysical regime ($Rm(\ell_\mathrm{turb}) \approx 10^{10}$), remains unknown since no simulations of this dynamo reached these values (see e.g. Guilet *et al.* 2022, Rincon *et al.* 2026).

REFERENCES

- Barrère, P., Reboul-Salze, A., Eggenberger, P., *et al.* 2026, A&A
- Gastine, T., & Wicht, J., 2012, Icarus, 219, 428
- Petitdemange, L., Marcotte, F., Gissinger, C., 2022, Science