Understanding dynamo mechanisms from 3D convection simulations of the Sun

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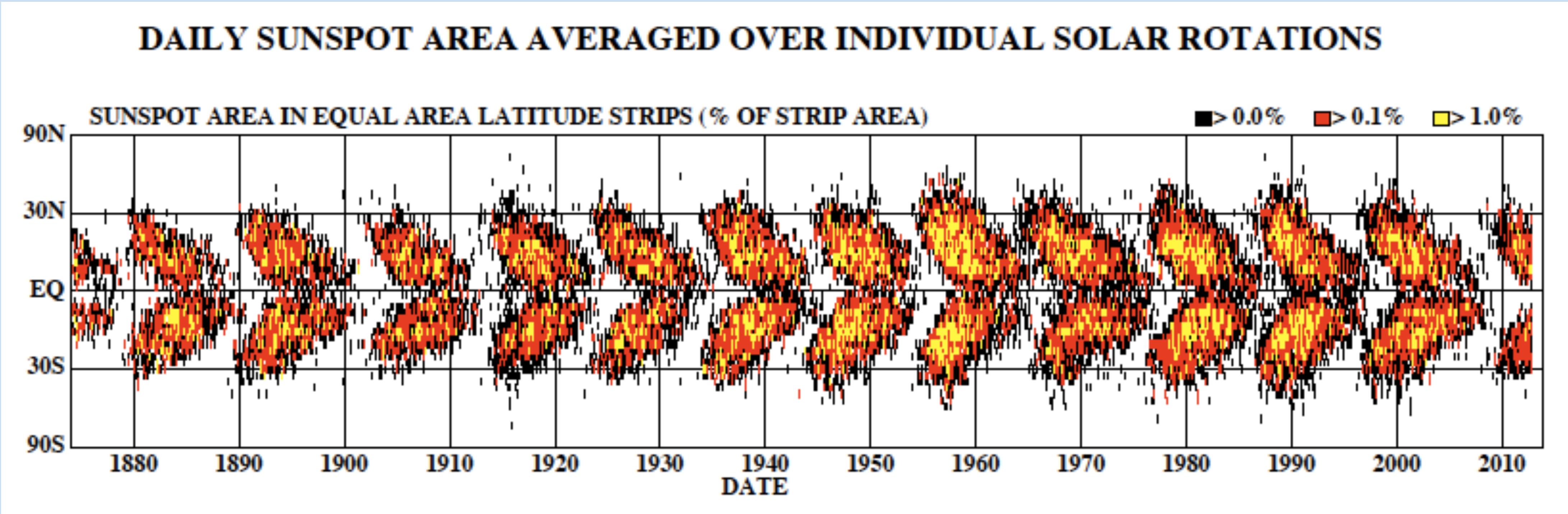
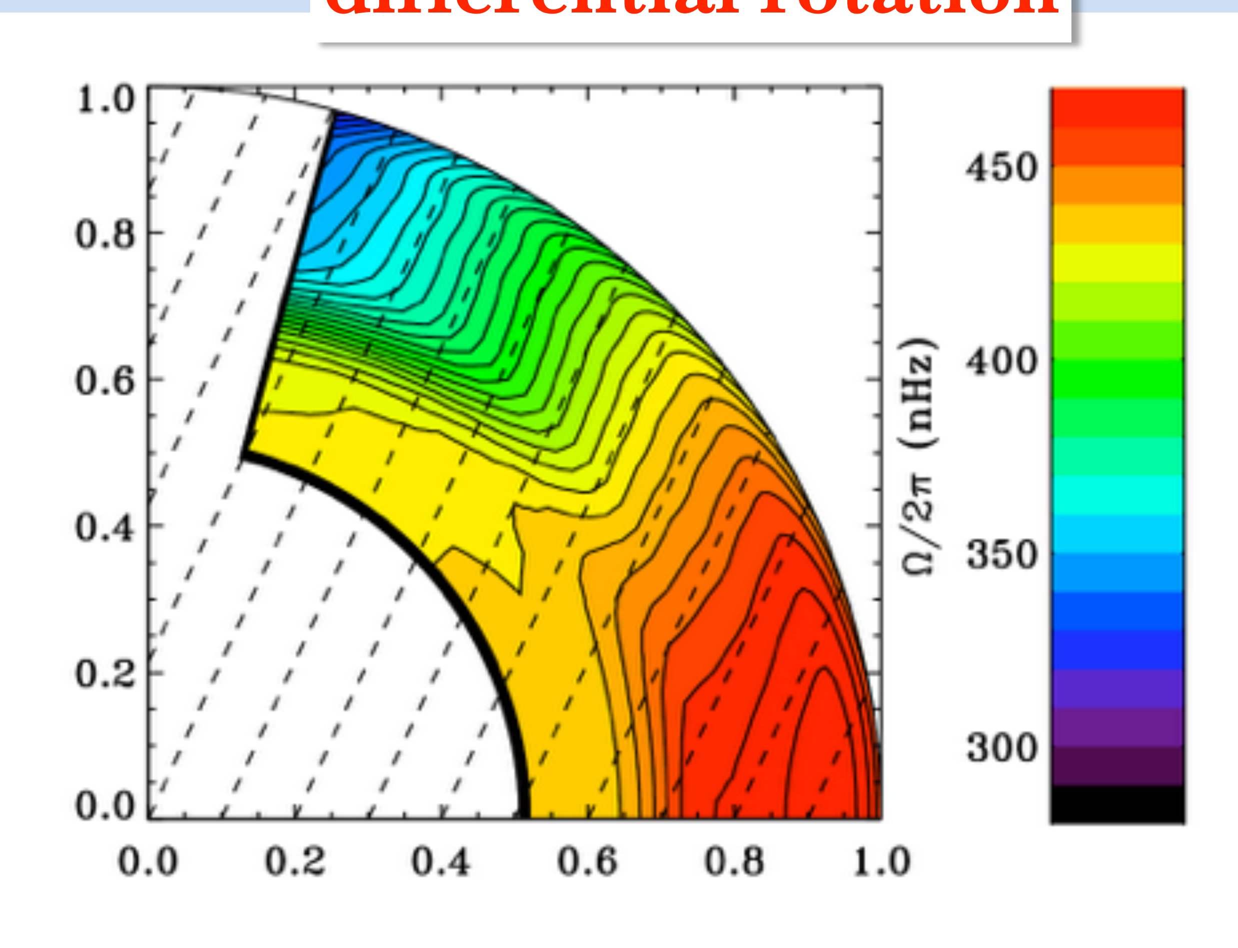
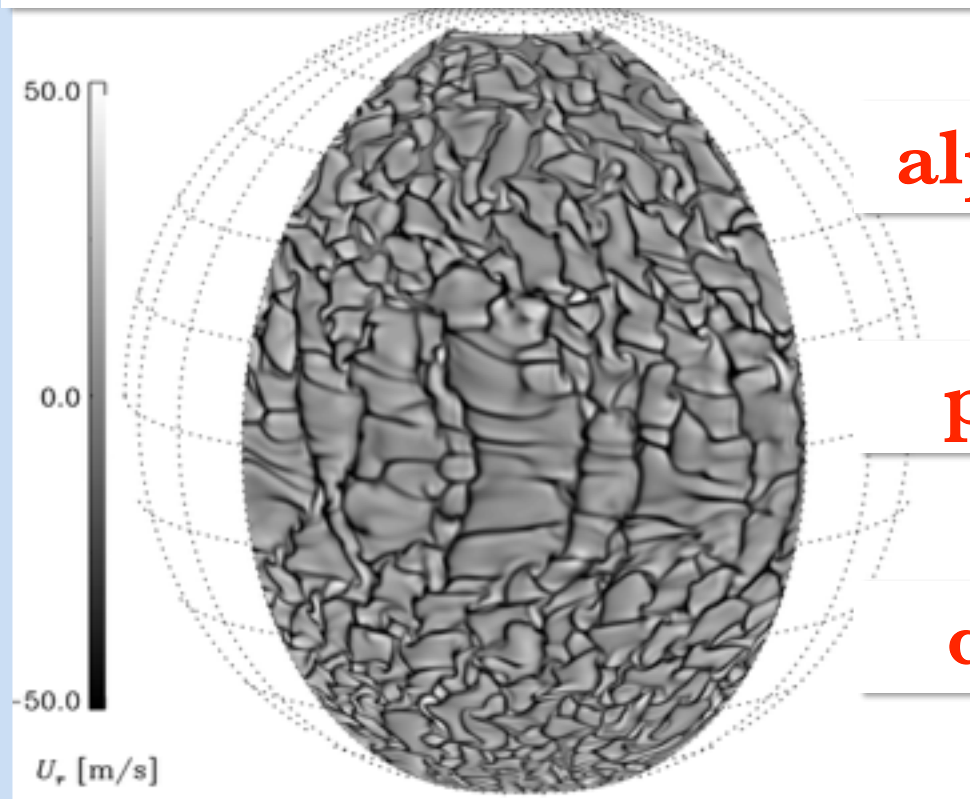
Solar Activity



differential rotation



turbulent convective motions



alpha effect

pumping

diffusion

no direct measurements

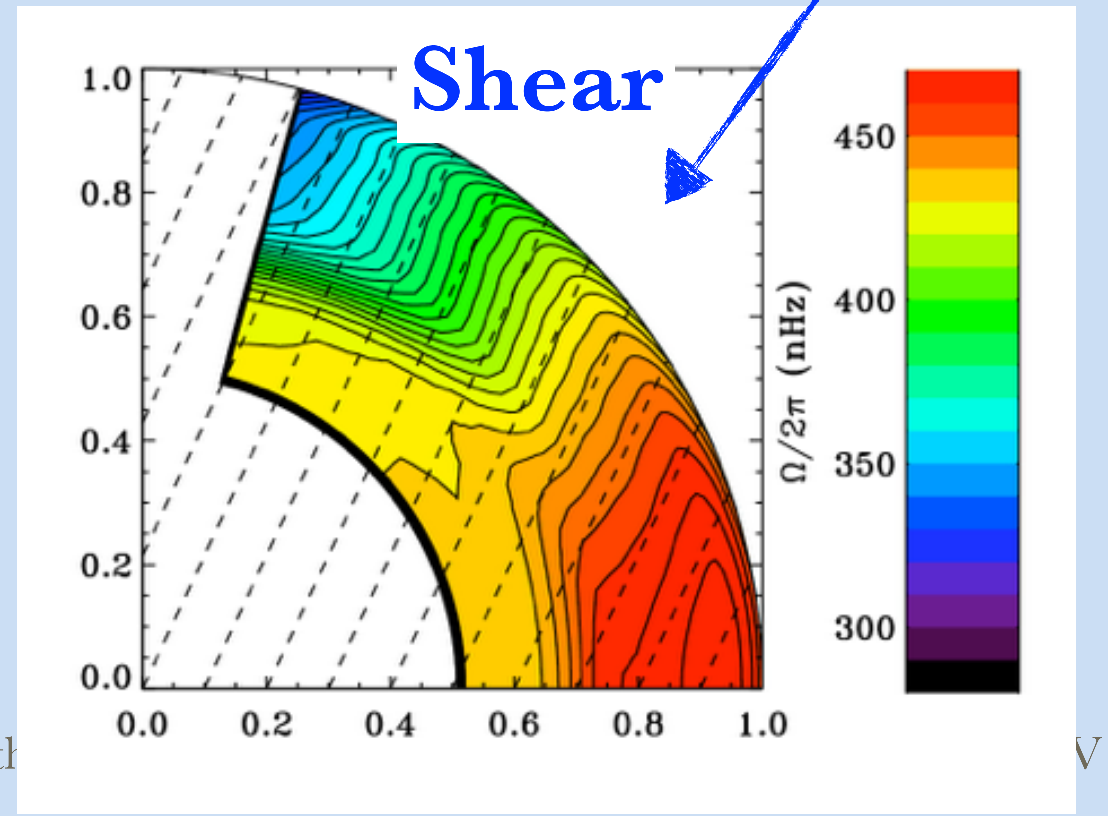
Dynamos

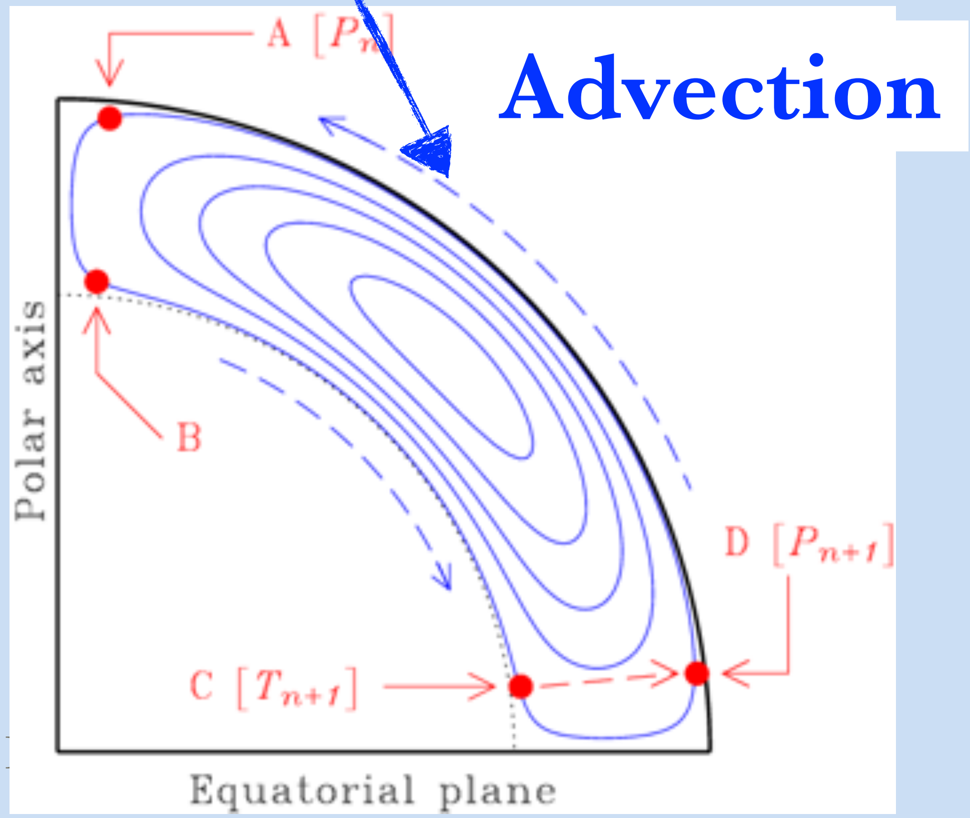
$$\frac{\partial B}{\partial t} = \nabla \times (u \times B) - \nabla \times \eta J$$

$$B = \overline{B} + b' \qquad u = \overline{U} + u'$$

$$\frac{\partial \overline{B}}{\partial t} = \nabla \times (\overline{U} \times \overline{B} + \overline{u' \times b'}) - \nabla \times \eta \overline{J}$$

$$\nabla \times (\overline{U} \times \overline{B}) = (\overline{B} \cdot \nabla)\overline{U} - \overline{B}(\nabla \cdot \overline{U}) - (\overline{U} \cdot \nabla)\overline{B}$$





Electromotive force

$$\boldsymbol{\mathcal{E}} = \boldsymbol{a} \cdot \overline{\boldsymbol{B}} + \boldsymbol{b} \cdot \nabla \overline{\boldsymbol{B}} + \ldots$$

$$\mathcal{E}_i = a_{ij} \overline{B}_j + b_{ijk} \partial_j \overline{B}_k + \ldots$$

$$\boldsymbol{\mathcal{E}} = \boldsymbol{\alpha} \cdot \overline{\boldsymbol{B}} + \boldsymbol{\gamma} \times \overline{\boldsymbol{B}} - \boldsymbol{\beta} \cdot (\nabla \times \overline{\boldsymbol{B}}) - \boldsymbol{\delta} \times (\nabla \times \overline{\boldsymbol{B}}) - \boldsymbol{\kappa} \cdot (\nabla \overline{\boldsymbol{B}})^{(S)}$$

Test-field method

Schrinner et al. 2005, 2007, 2012

$$\frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \boldsymbol{\nabla} \times (\overline{\boldsymbol{u}} \times \overline{\boldsymbol{B}} + \overline{\boldsymbol{u}' \times \boldsymbol{B}'}) - \boldsymbol{\nabla} \times \eta \boldsymbol{\nabla} \times \overline{\boldsymbol{B}},$$

$$\boldsymbol{\mathcal{E}} = \boldsymbol{\alpha} \cdot \overline{\boldsymbol{B}} + \boldsymbol{\gamma} \times \overline{\boldsymbol{B}} - \boldsymbol{\beta} \cdot (\boldsymbol{\nabla} \times \overline{\boldsymbol{B}}) - \boldsymbol{\delta} \times (\boldsymbol{\nabla} \times \overline{\boldsymbol{B}}) - \boldsymbol{\kappa} \cdot (\boldsymbol{\nabla} \overline{\boldsymbol{B}})^{(S)}$$

$$\frac{\partial \boldsymbol{B}'}{\partial t} = \boldsymbol{\nabla} \times \left(\boldsymbol{u}' \times \overline{\boldsymbol{B}}^{\mathrm{T}} + \overline{\boldsymbol{u}} \times \boldsymbol{B}' + \boldsymbol{u}' \times \boldsymbol{B}' - \overline{\boldsymbol{u}' \times \boldsymbol{B}'} \right) - \boldsymbol{\nabla} \times \eta \boldsymbol{\nabla} \times \boldsymbol{B}'$$

i	1	2	3	4	5	6	7	8	9
$\overline{B}^{(i)}_{\mathrm{T}r}$						0	ϑ	0	0
$\overline{B}^{(i)}_{\mathrm{T}\vartheta}$	0	1	0	0	r	0	0	ϑ	0
$\overline{B}^{(i)}_{\mathrm{T}\varphi}$	0	0	1	0	0	r	0	0	ϑ

see talk by Fred Gent

The Simulation

Global convective dynamo simulations

$$\frac{\partial A}{\partial t} = u \times B + \eta \nabla^2 A$$

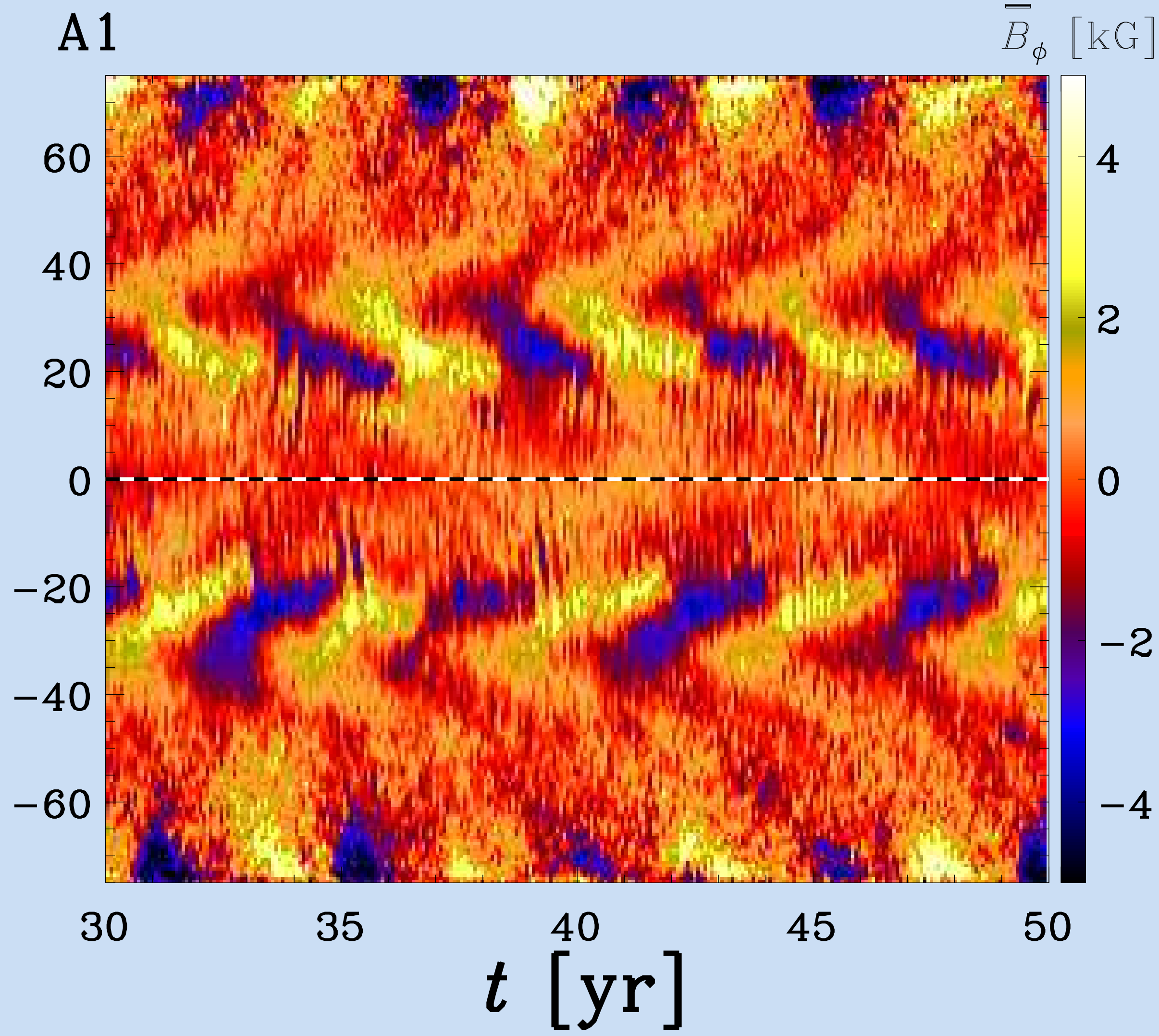
$$\frac{D \ln \rho}{Dt} = -\nabla \cdot u$$

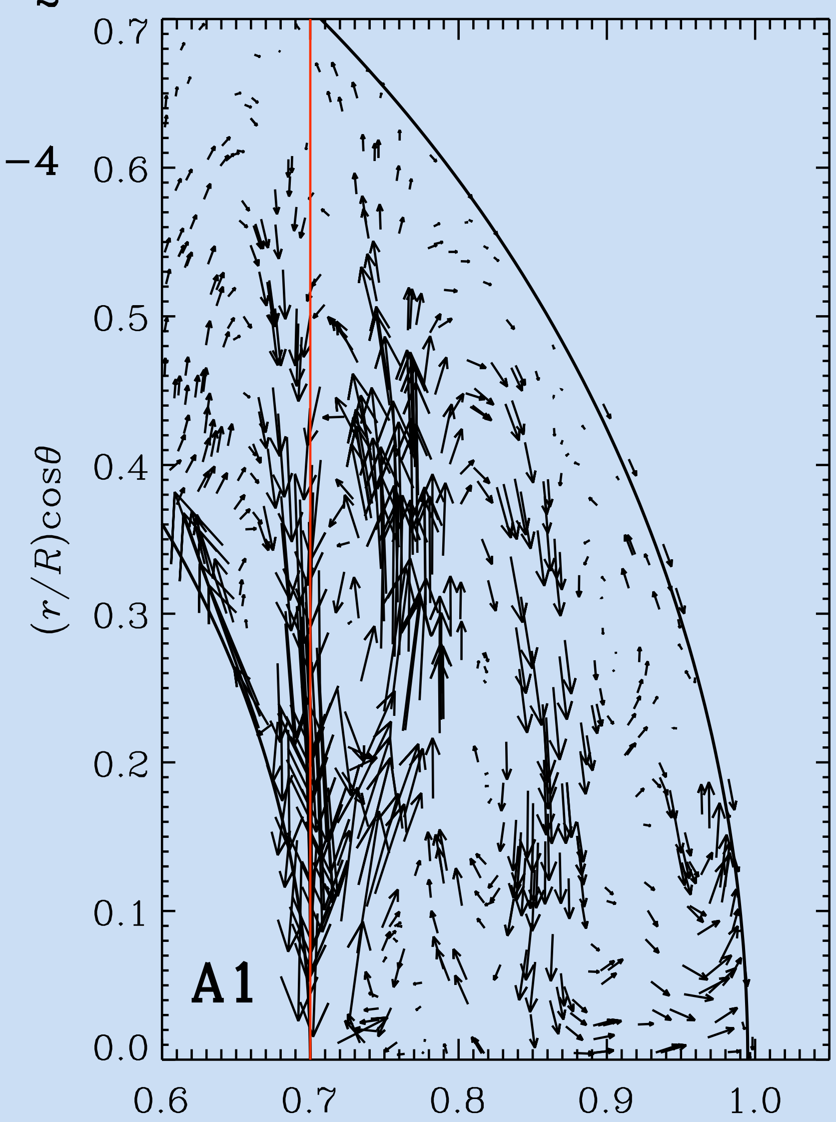
$$\frac{Du}{Dt} = g - 2\Omega_0 \times u + \frac{1}{\rho}\left(J \times B - \nabla p + \nabla \cdot 2\nu\rho S\right)$$

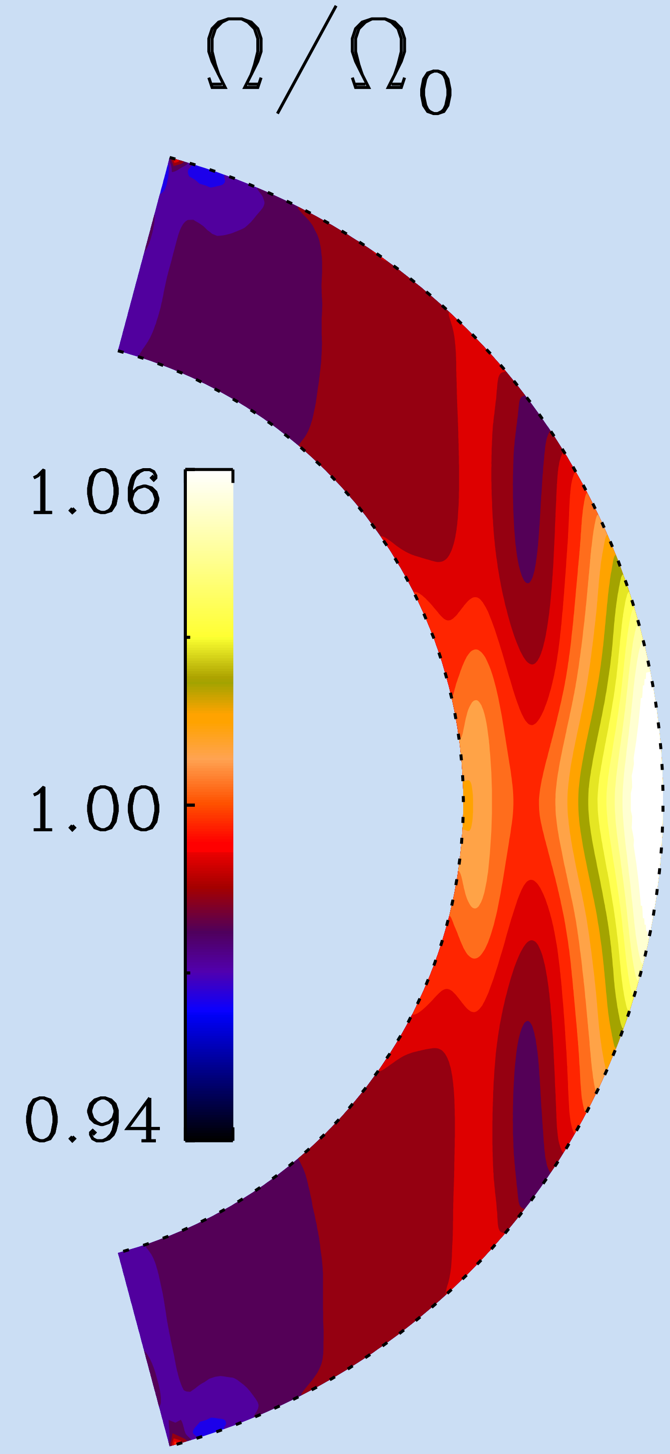
$$T\frac{Ds}{Dt} = \frac{1}{\rho}\nabla \cdot (K\nabla T + \chi_t \rho T \nabla s) + 2\nu S^2 + \frac{\mu_0 \eta}{\rho} J^2 - \Gamma_{\mathrm{cool}}(r),$$

- high-order finite-difference code
- scales up efficiently to over 60.000 cores
- compressible MHD

https://github.com/pencil-code/pencil-code/



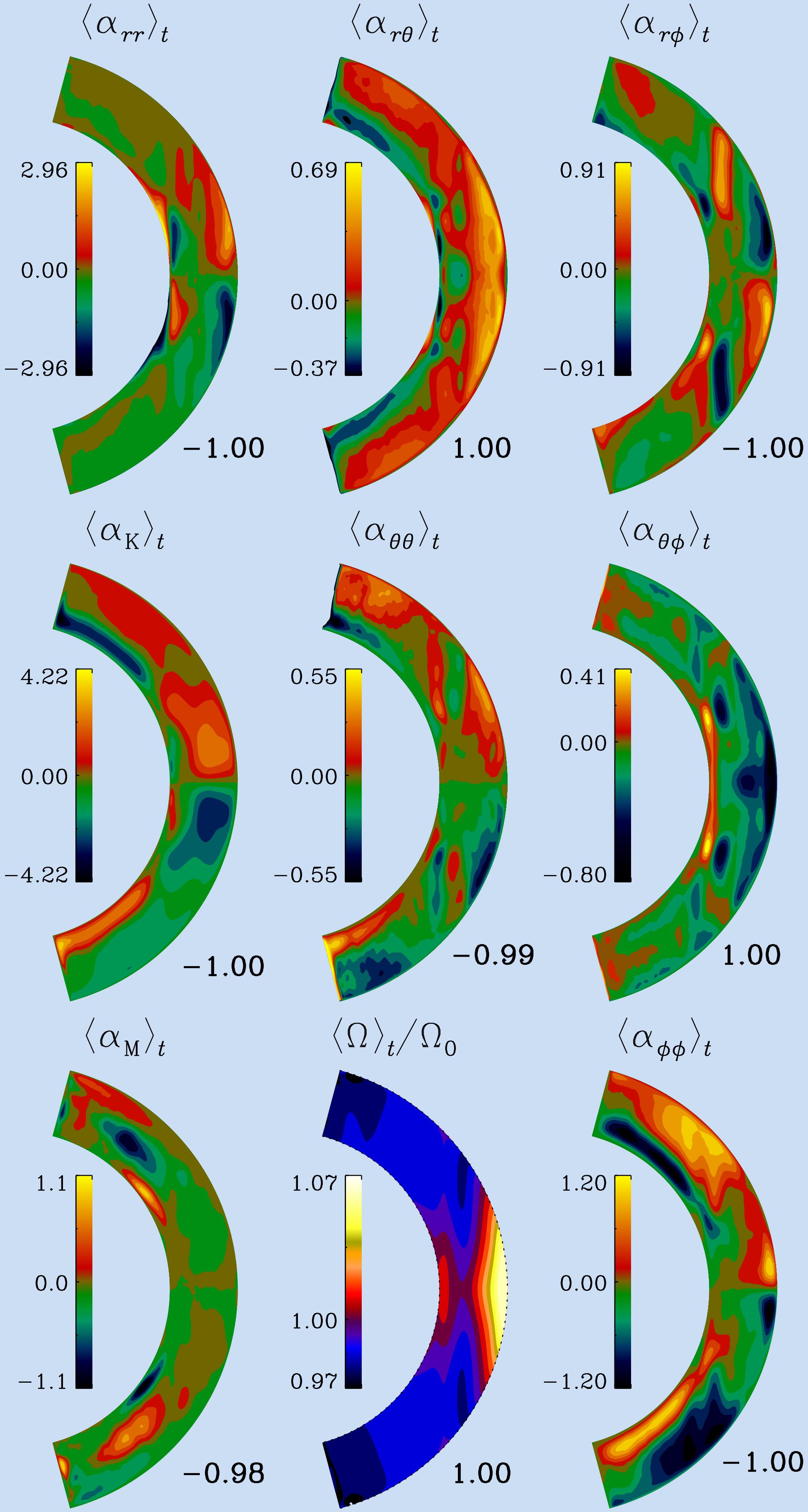


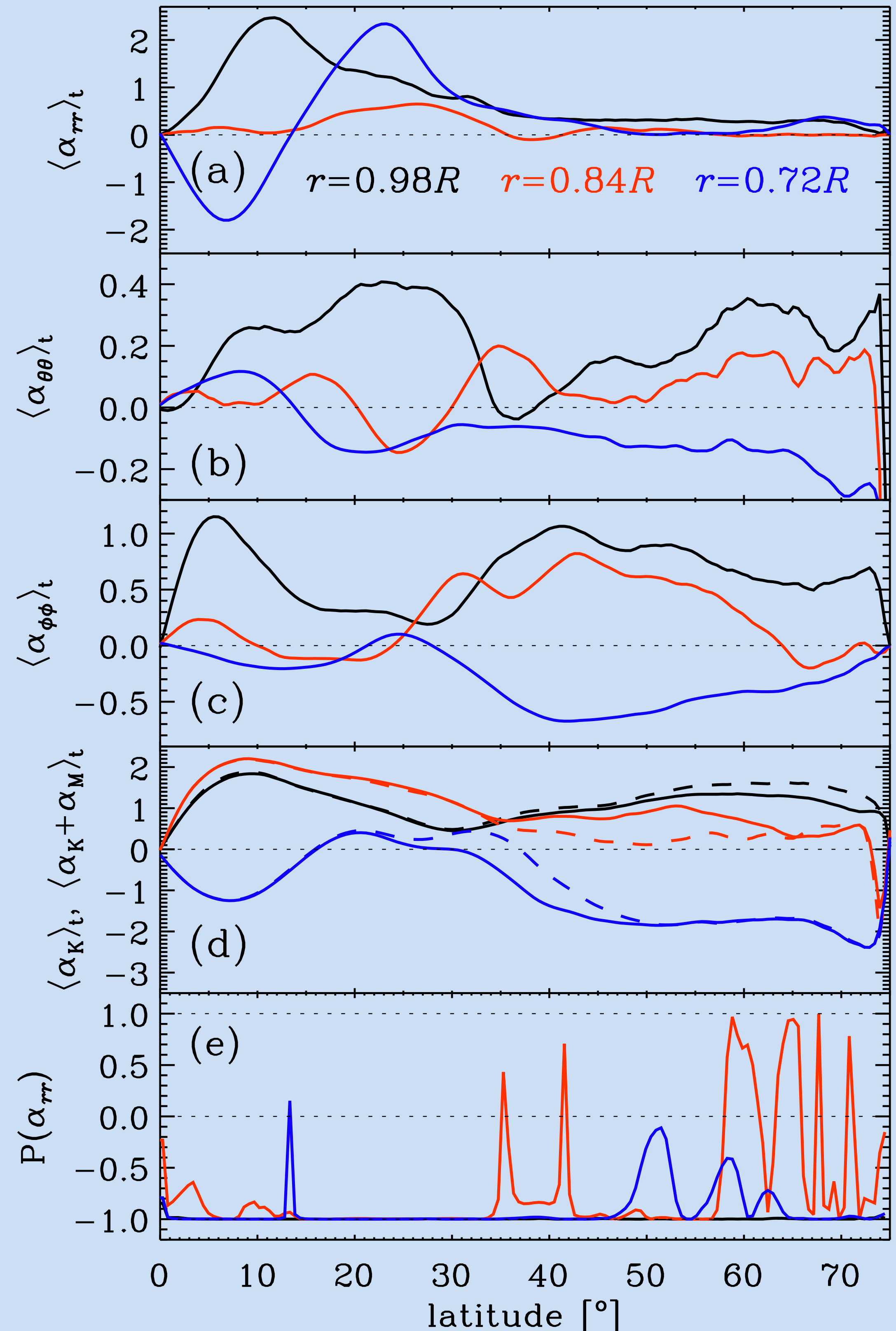


Käpylä et al.
2012, 2013, 2016, 2017

Warnecke et al.
2014, 2016

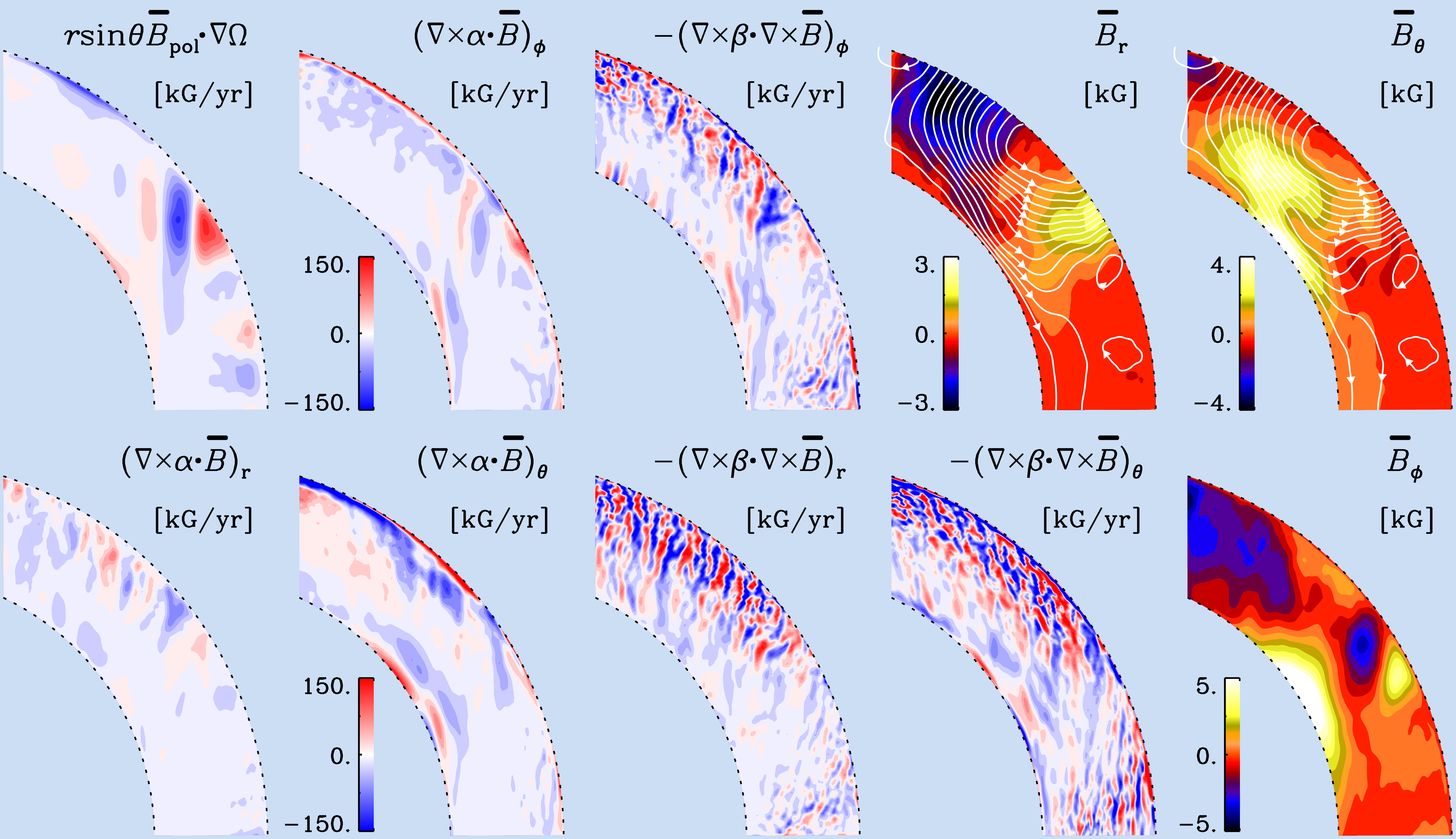
Results





$$P(\alpha_{ij}) = \frac{\left(\alpha_{ij}^{\rm es}\right)^2 - \left(\alpha_{ij}^{\rm ea}\right)^2}{\left(\alpha_{ij}^{\rm es}\right)^2 + \left(\alpha_{ij}^{\rm ea}\right)^2},$$

Magnetic field generation



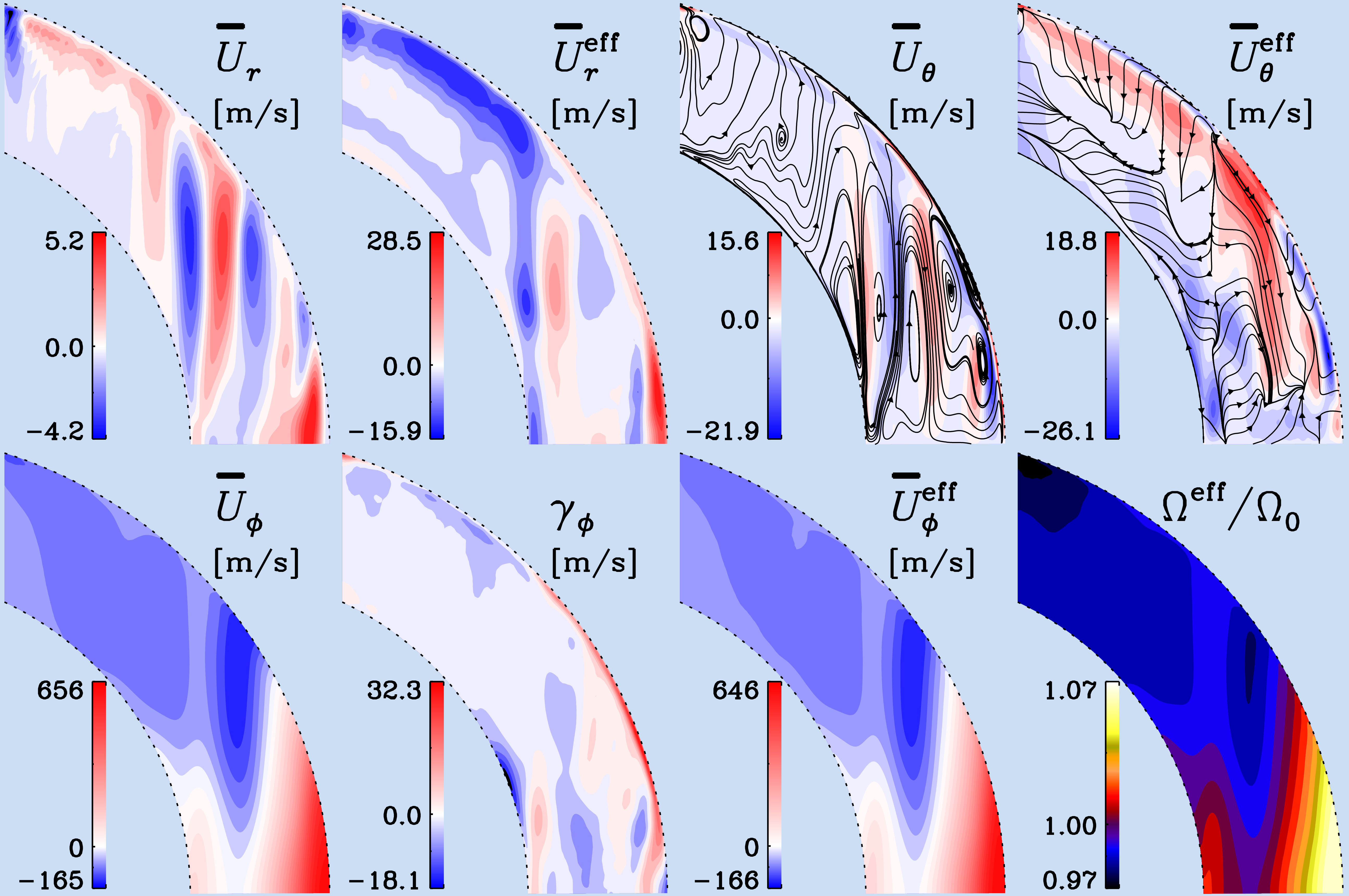
Turbulent pumping

$$\mathcal{E} = \boldsymbol{\alpha} \cdot \overline{\boldsymbol{B}} + \boldsymbol{\gamma} \times \overline{\boldsymbol{B}} - \boldsymbol{\beta} \cdot (\nabla \times \overline{\boldsymbol{B}}) - \boldsymbol{\delta} \times (\nabla \times \overline{\boldsymbol{B}}) - \boldsymbol{\kappa} \cdot (\nabla \overline{\boldsymbol{B}})^{(S)}$$

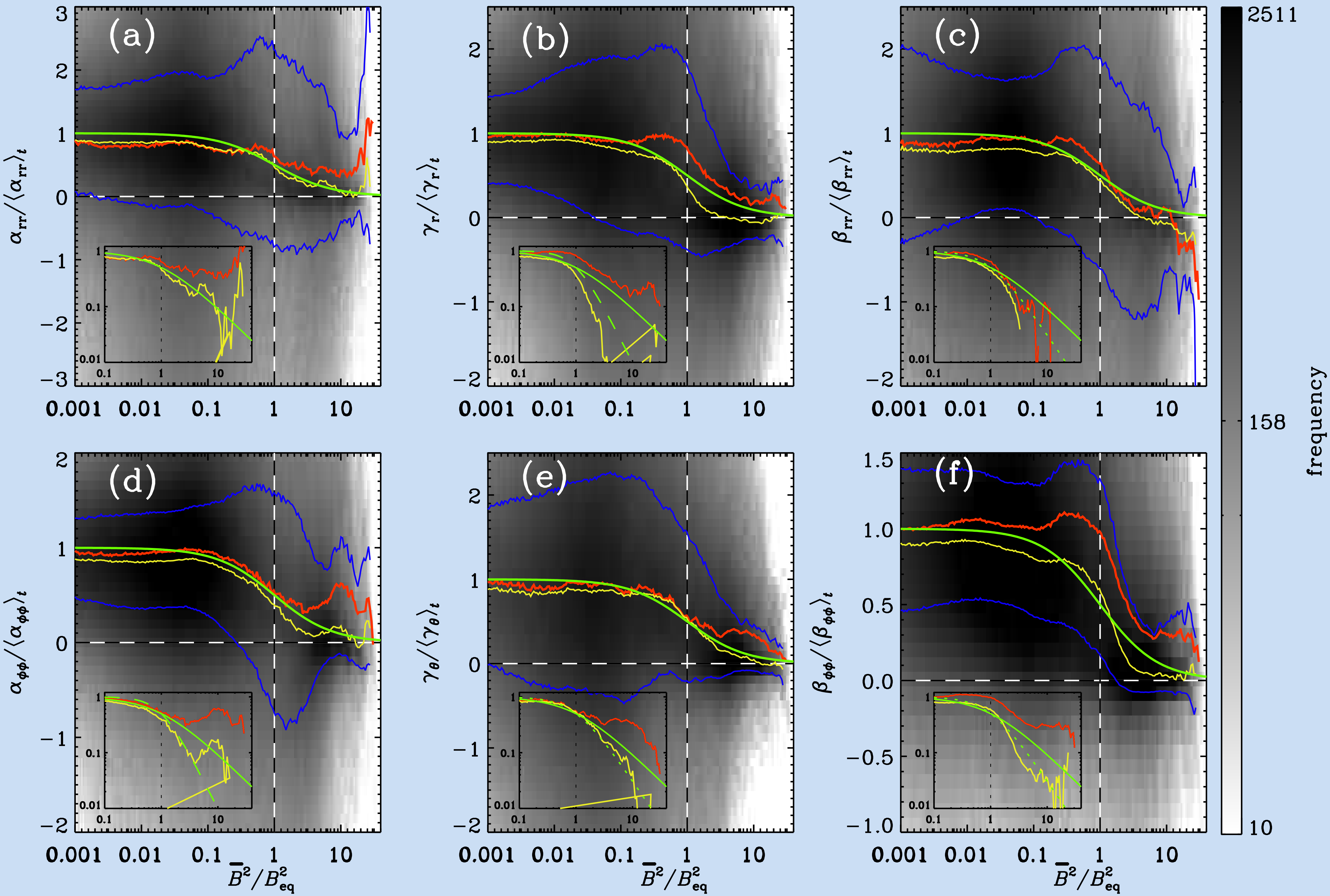
$$\frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \nabla \times (\overline{\boldsymbol{u}} \times \overline{\boldsymbol{B}} + \overline{\boldsymbol{u}' \times \boldsymbol{B}'}) - \nabla \times \eta \nabla \times \overline{\boldsymbol{B}},$$

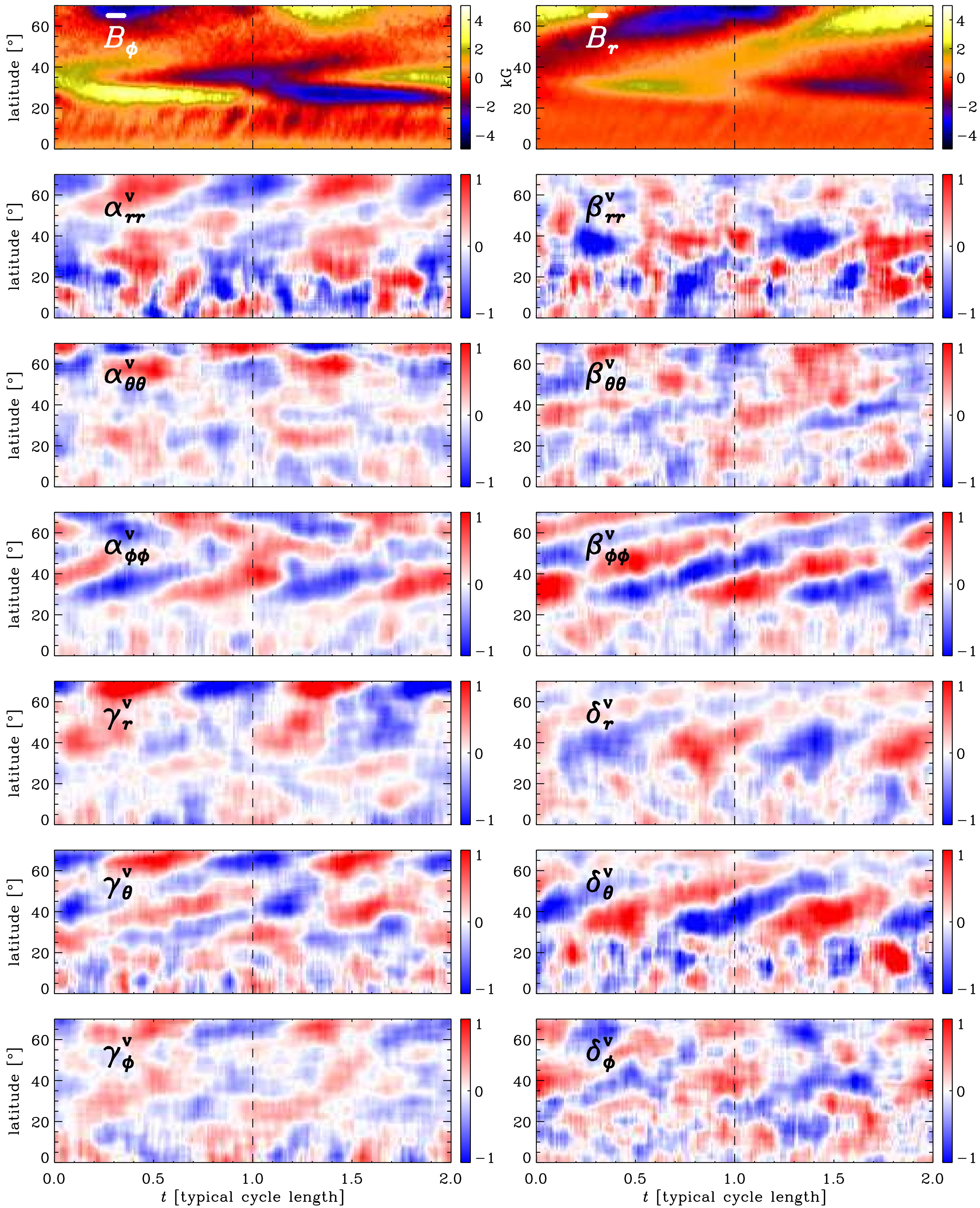
$$\partial_t \overline{\boldsymbol{B}}^{\text{pol}} = \nabla \times \left[\ldots + \left(\boldsymbol{\gamma}^{\text{pol}} + \overline{\boldsymbol{U}}^{\text{pol}} \right) \times \overline{\boldsymbol{B}}^{\text{pol}} \right] \tag{16}$$

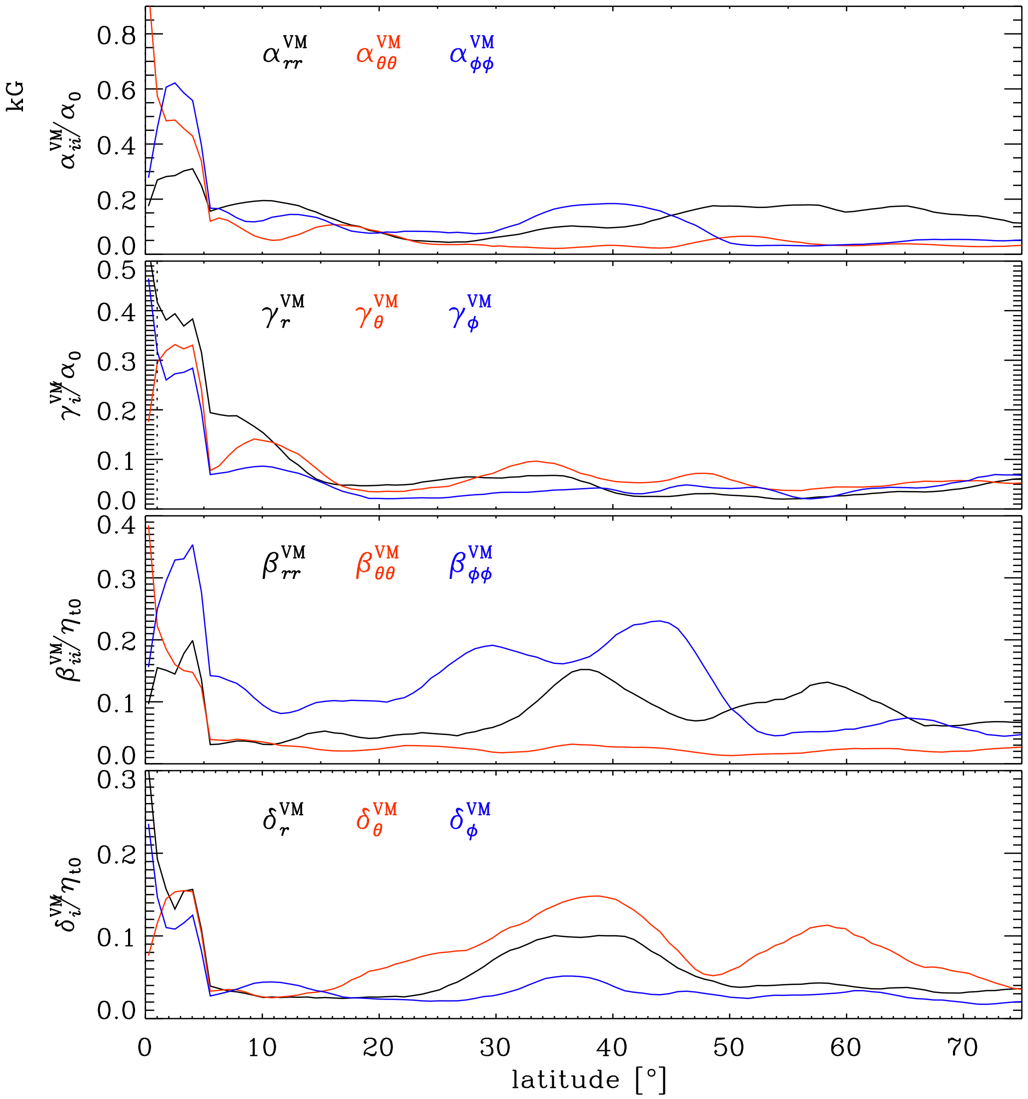
$$\partial_t \overline{\boldsymbol{B}}^{\text{tor}} = \nabla \times \left[\ldots + \left(\boldsymbol{\gamma}^{\text{pol}} + \overline{\boldsymbol{U}}^{\text{pol}} \right) \times \overline{\boldsymbol{B}}^{\text{tor}} + \left(\boldsymbol{\gamma}^{\text{tor}} + \overline{\boldsymbol{U}}^{\text{tor}} \right) \times \overline{\boldsymbol{B}}^{\text{pol}} \right] \tag{17}$$


$\overline{U}_r$ [m/s]
5.2
0.0
−4.2
$\overline{U}_r^{\text{eff}}$ [m/s]
28.5
0.0
−15.9
$\overline{U}_\theta$ [m/s]
15.6
0.0
−21.9
$\overline{U}_\theta^{\text{eff}}$ [m/s]
18.8
0.0
−26.1
$\overline{U}_\phi$ [m/s]
656
0
−165
γ_ϕ [m/s]
32.3
0.0
−18.1
$\overline{U}_\phi^{\text{eff}}$ [m/s]
646
0
−166
$\Omega^{\text{eff}}/\Omega_0$
1.07
1.00
0.97

Magnetic quenching







$$\alpha = \langle \alpha \rangle_t + \alpha^{\mathrm{v}}.$$

$$\alpha_{ij}^{\mathrm{V}} = \sqrt{\langle \alpha_{ij}^{\mathrm{v}\,2} \rangle_t}\,,$$

Conclusions

- Test-field method is one way to understand dynamo simulations.
- Alpha deviates from helicity expression.
- Complicated mixture of dynamo effects.
- Turbulent pumping changes significantly the eff. flow.
- Quenching does not depends analytical on B
- Strong cyclic variations of coefficients