Simulations of Solar and Stellar dynamos

Gustavo Guerrero
Physics Department (ICEx-UFMG)

Collaborators:
B. Zaire (*UFMG*), F. Camacho (*UFMG*),
P. Smolarkiewicz (*ECMWF*), A. Kosovichev (*NJIT*),
N. Mansour (NASA-Ames)

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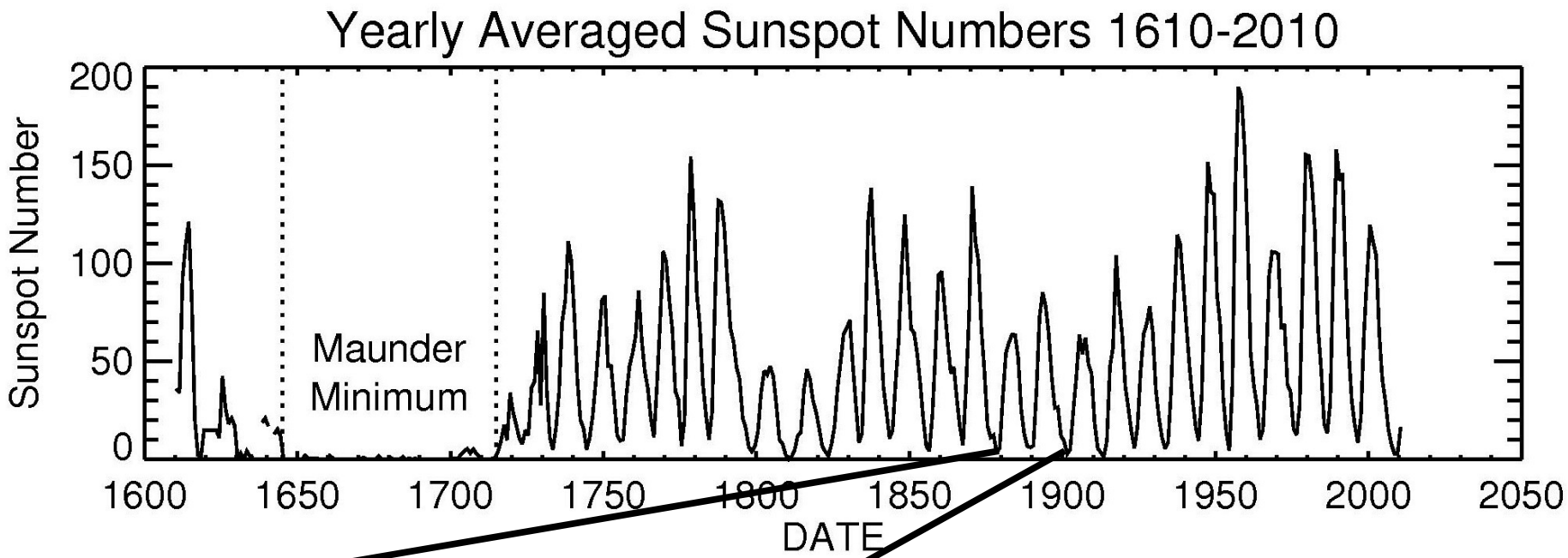
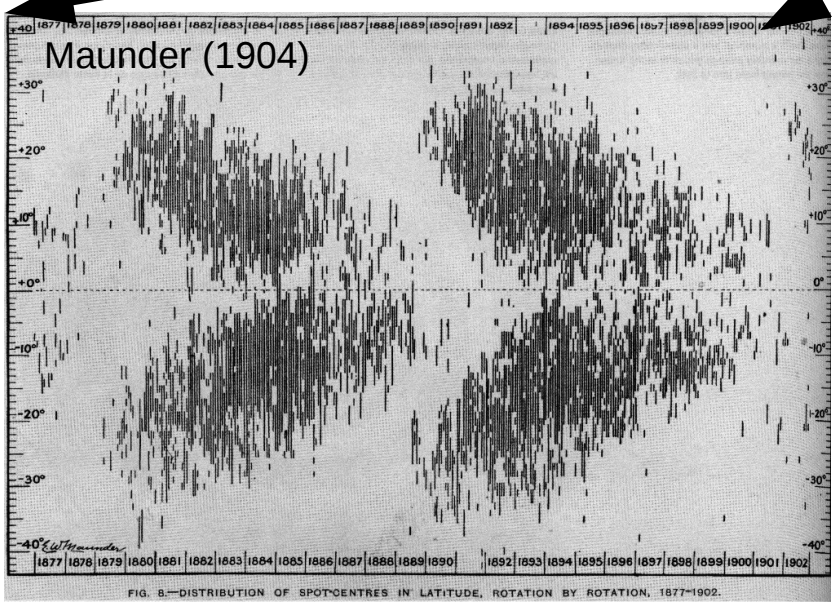
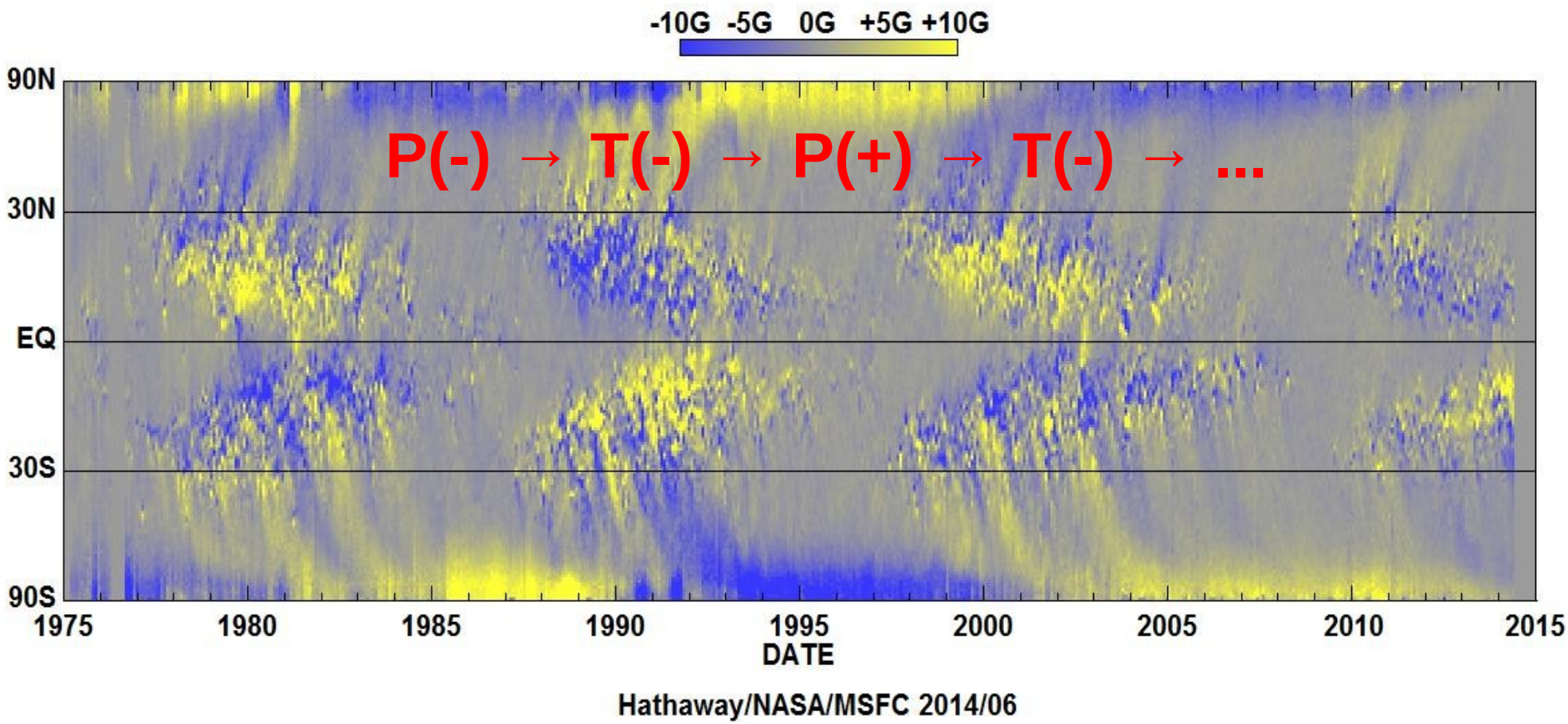
1. Introduction

The solar cycle

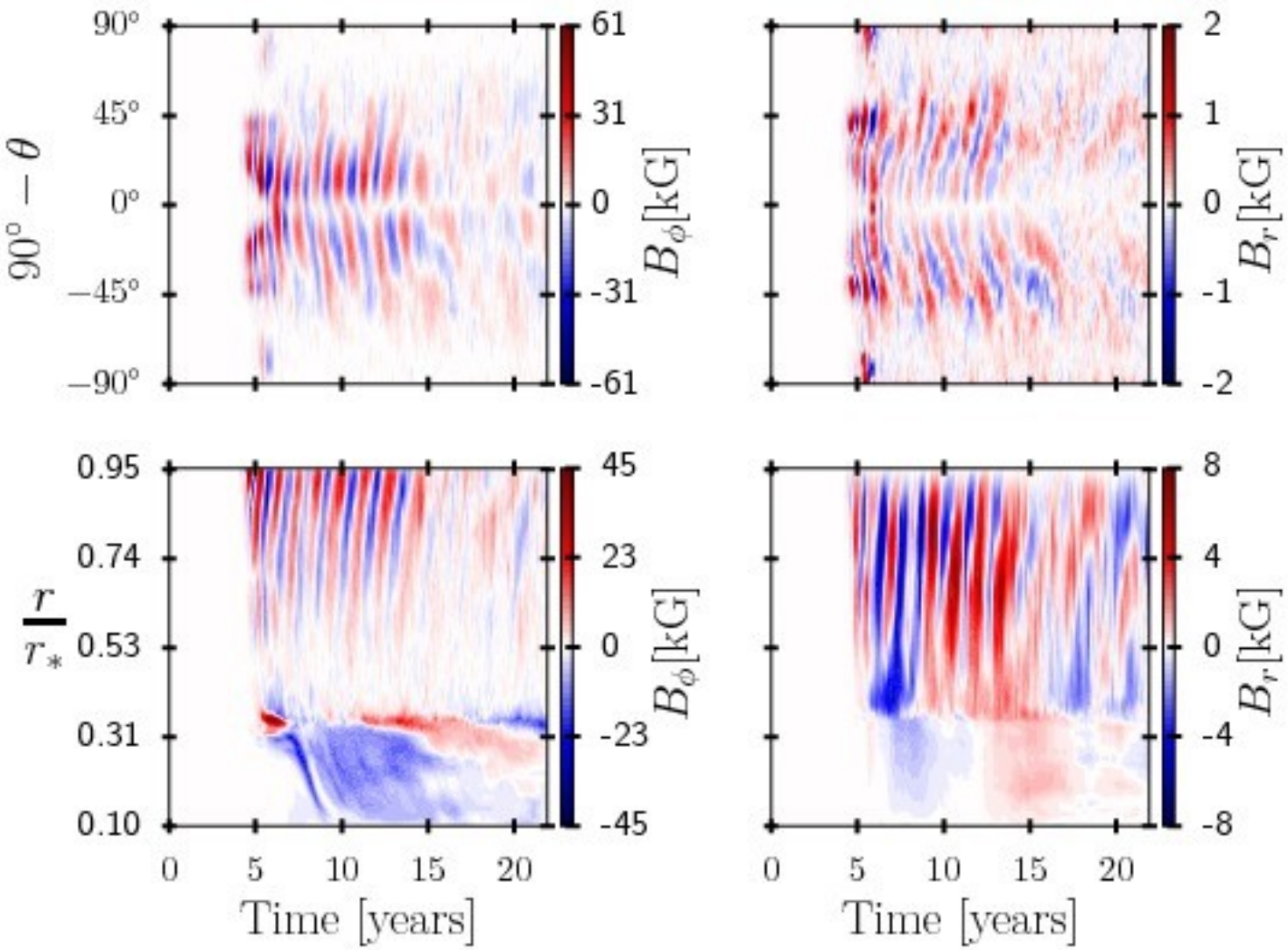




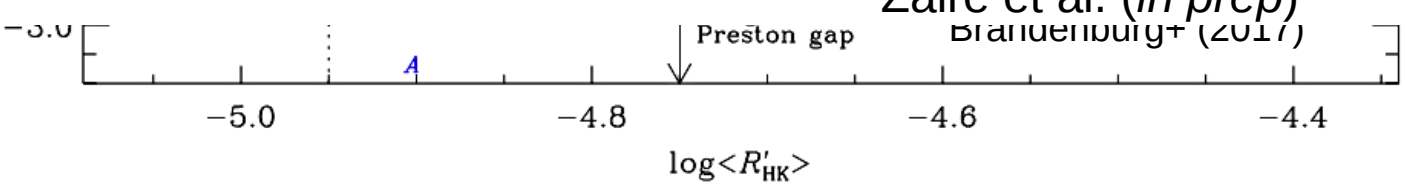
- Besides the 11 yr cycle
- ~80 yr periodicty (Gleissberg, 1973)
- ~2 yr periodicity (Fletcher et al. 2010)
- Mounder-like minimum events



- Where is (are) the solar dynamo (s) located?
- Do sunspots form from magnetic flux tubes or from MHD instabilities near photosphere?



Zaire et al. (*in prep*)



Two branches: A (active) and I (inactive) stars. Is this trend real?

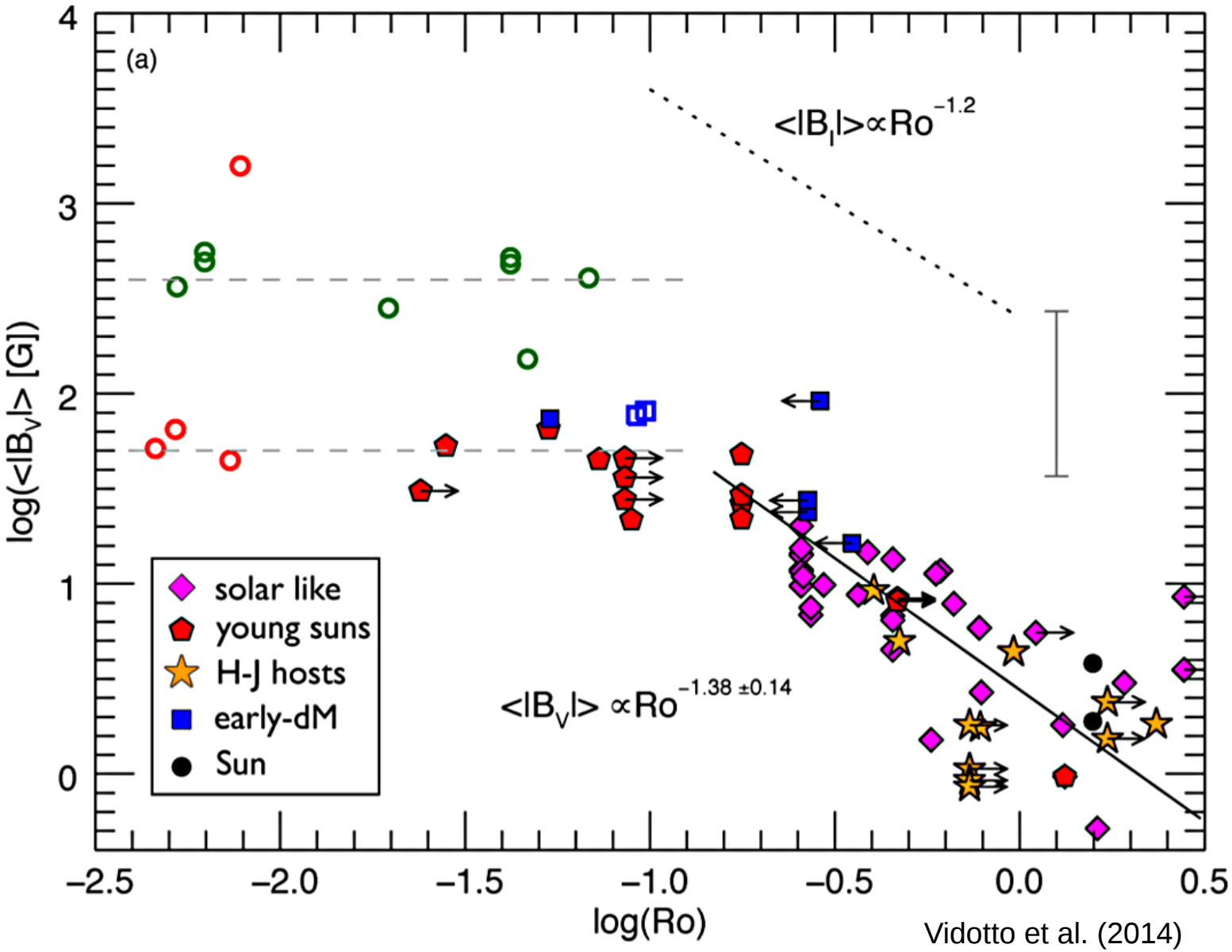
Several stars in the sample exhibit 2 cycle periods: e.g., N/n, E/e, G/g, J/j

Is the Sun a solar-like star?

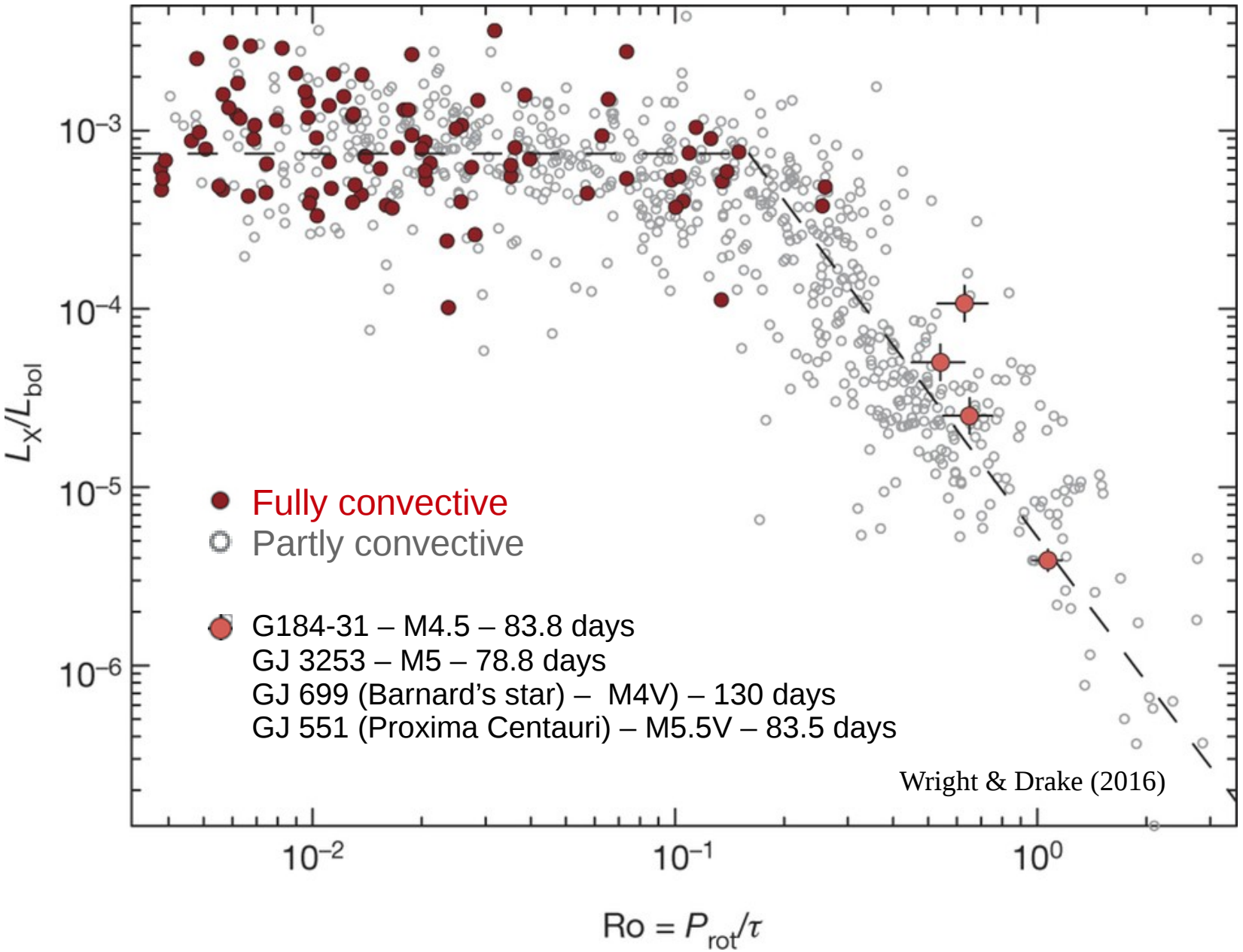
Is this evidence of multiple dynamos operating in the stellar interiors?

See also: Baliunas+ (1995), Metcalfe+ (2010, 2013), Egeland+ (2015) Noyes et al. (1983, 1984), Brandenburg & Saar (1998), Böhm-Vitense (2007), Brandenrburg et al. (2017)

Stars across the HR diagram



Vidotto et al. (2014)



- Is there a fundamental dynamo mechanism able to explain the saturation of magnetic field strength?
- Do stellar tachoclines play a role in this dynamo process?

2. Modeling stellar dynamos

Mean-field dynamo mechanism Parker (1955)

- Induction equation

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

$$\nabla \times (\boldsymbol{U} \times \boldsymbol{B}) = -\underbrace{\boldsymbol{U} \cdot \nabla \boldsymbol{B}}_{\text{advection}} + \underbrace{\boldsymbol{B} \cdot \nabla \boldsymbol{U}}_{\text{stretching}} - \underbrace{\boldsymbol{B} \nabla \cdot \boldsymbol{U}}_{\text{compression}}$$

- Induction/advection vs. diffusion $R_{\mathrm{m}} = u_{\mathrm{rms}}/(\eta k_{\mathrm{f}})$

	T [K]	ρ [g cm^{-3}]	P_{m}	u_{rms} [cm s^{-1}]	L [cm]	R_{m}
Solar CZ (upper part)	10^4	10^{-6}	10^{-7}	10^6	10^8	10^6
Solar CZ (lower part)	10^6	10^{-1}	10^{-4}	10^4	10^{10}	10^9
Protostellar discs	10^3	10^{-10}	10^{-8}	10^5	10^{12}	10
CV discs and similar	10^4	10^{-7}	10^{-6}	10^5	10^7	10^4
AGN discs	10^7	10^{-5}	10^4	10^5	10^9	10^{11}
Galaxy	10^4	10^{-24}	(10^{11})	10^6	10^{20}	(10^{18})
Galaxy clusters	10^8	10^{-26}	(10^{29})	10^8	10^{23}	(10^{29})

$$\frac{\partial \bar{B}}{\partial t}-\frac{1}{r}\left[\frac{\partial}{\partial r}[r(u_r+\gamma_r)\bar{B}]+\frac{\partial}{\partial \theta}[(u_\theta+\gamma_\theta)\bar{B}]\right]=s(\bar{\boldsymbol{B}}_p\cdot\nabla)\Omega$$

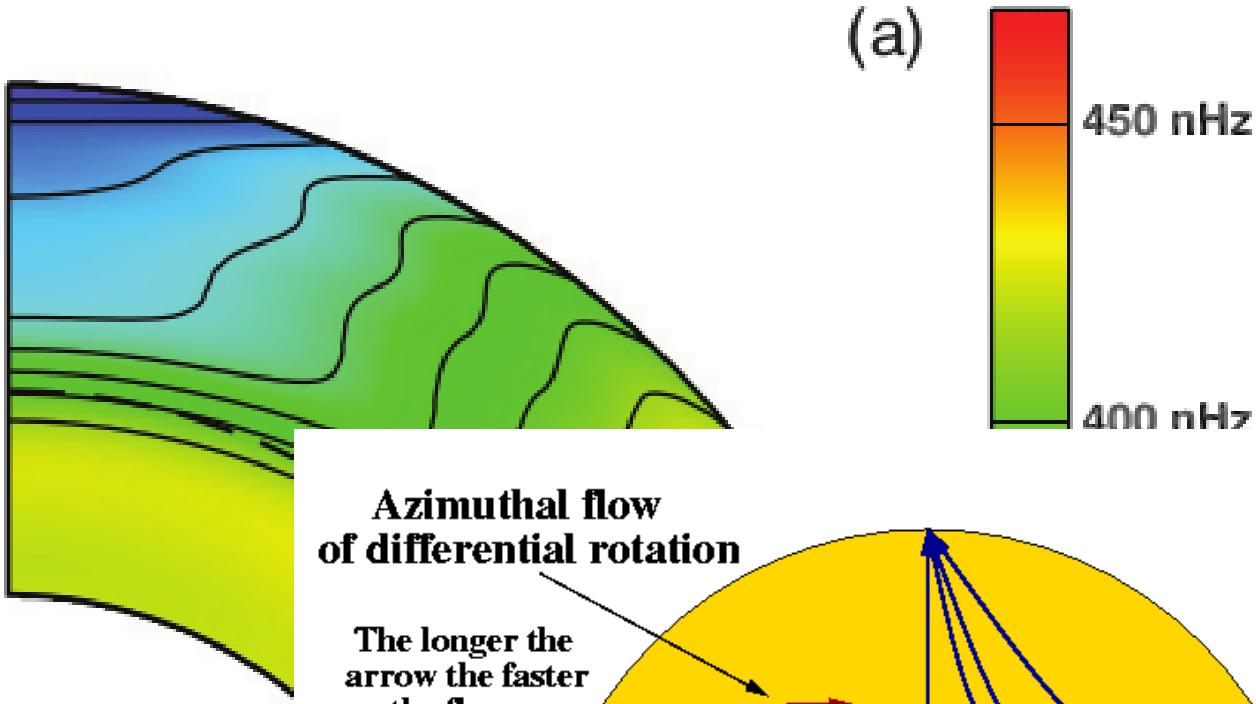
$$-[\nabla \eta_T\times(\nabla\times\bar{B})]_\phi+\eta_T\left(\nabla^2-\frac{1}{r\sin\theta}\right)\bar{B}+[\nabla\times(\alpha^D\bar{B})]_\phi$$

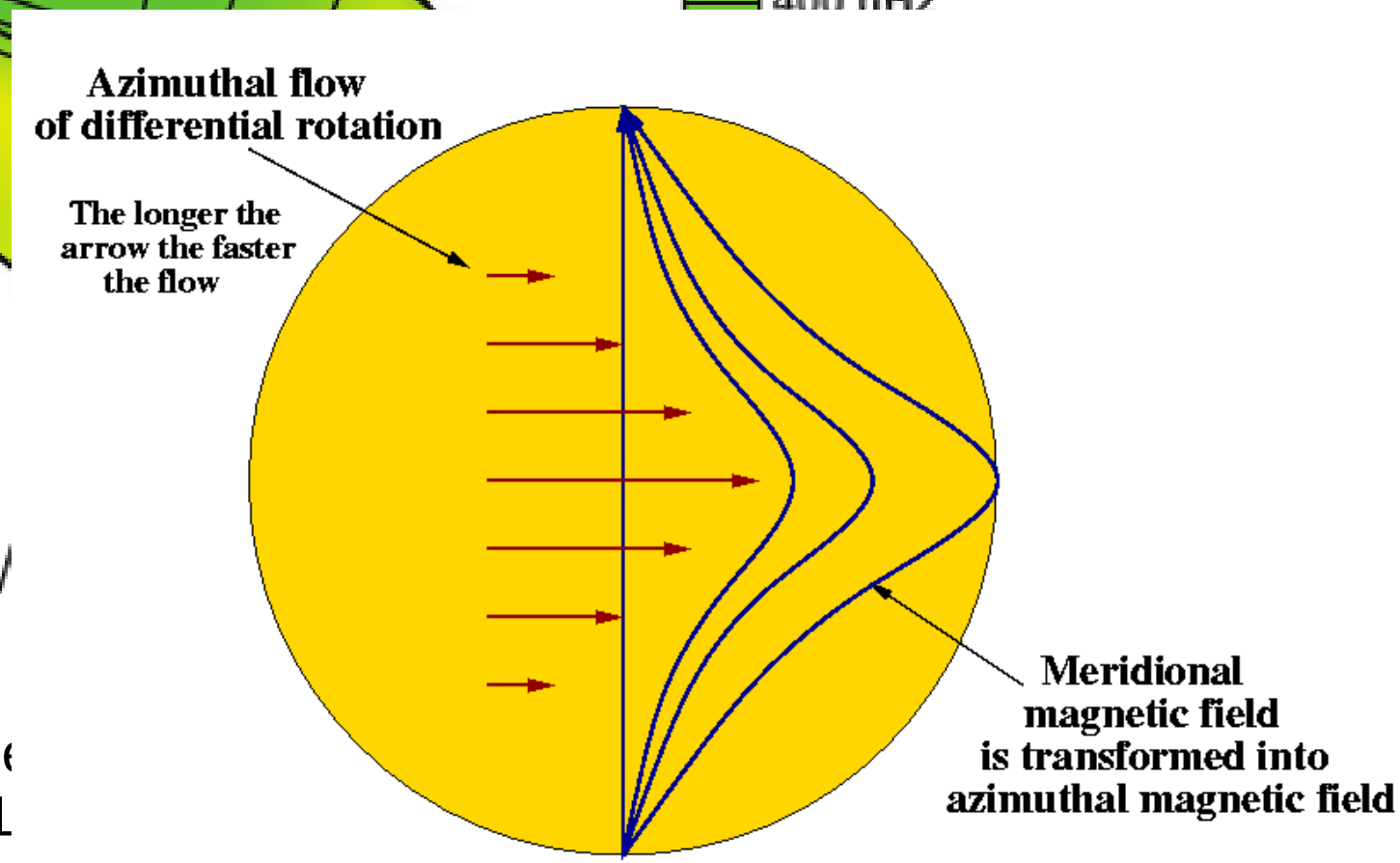
$$\frac{\partial \bar{A}}{\partial t}-\frac{1}{s}[(\bar{u}_p+\gamma_p)\cdot\nabla](s\bar{A})=\eta_T\left(\nabla^2-\frac{1}{r\sin\theta}\right)\bar{A}+(\alpha^D\bar{B})_\phi$$

with $\eta_T=\eta+\beta$ The total magnetic diffusivity

$$C_\alpha=\frac{\alpha_0}{\eta_T k_f},\quad C_\Omega=\frac{\Delta\Omega}{\eta_T k_f^2},\quad C_U=\frac{U_0}{\eta_T k_f}$$

Ω-effect (P → T)





Ω/

Obtained by he
(Schou et al. 1

$$\frac{\partial \bar{B}}{\partial t}-\frac{1}{r}\left[\frac{\partial}{\partial r}[r(u_r+\gamma_r)\bar{B}]+\frac{\partial}{\partial \theta}[(u_\theta+\gamma_\theta)\bar{B}]\right]=s(\bar{\boldsymbol{B}}_p\cdot\nabla)\Omega$$

$$-[\nabla \eta_T\times(\nabla\times\bar{B})]_\phi+\eta_T\left(\nabla^2-\frac{1}{r\sin\theta}\right)\bar{B}+[\nabla\times(\alpha^D\bar{B})]_\phi$$

$$\frac{\partial \bar{A}}{\partial t}-\frac{1}{s}[(\bar{u}_p+\gamma_p)\cdot\nabla](s\bar{A})=\eta_T\left(\nabla^2-\frac{1}{r\sin\theta}\right)\bar{A}+(\alpha^D\bar{B})_\phi$$

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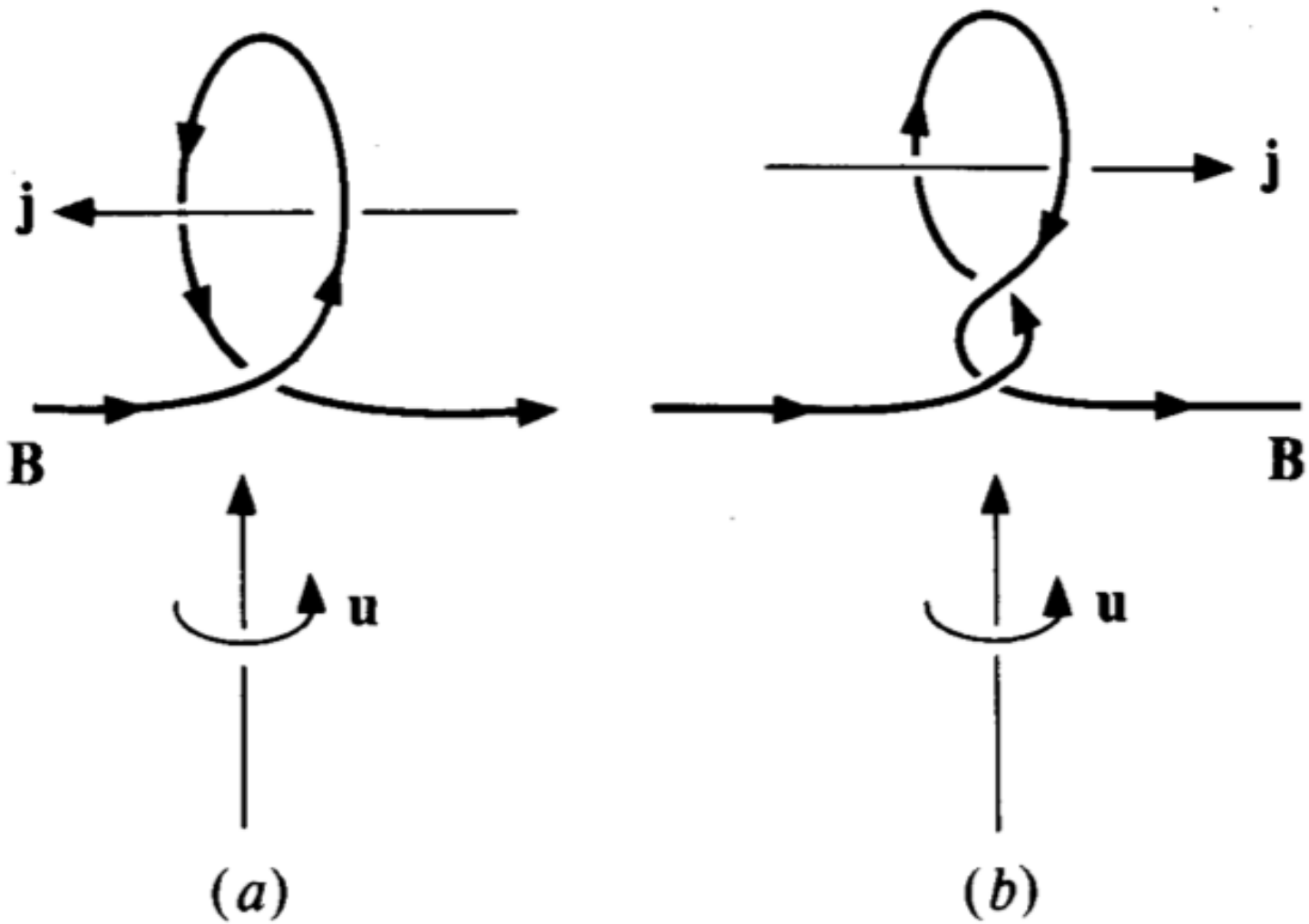
α–effect (P → T): contribution from MHD turbulence

$$\alpha_{ij}\mathbf{B} = \alpha\mathbf{B}$$

and *α* is a pseudo-scalar. It can only exist if the system lacks of reflectional symmetry (e.g., the system is rotating).



$$\frac{\partial \bar{B}}{\partial t}-\frac{1}{r}\left[\frac{\partial}{\partial r}[r(u_r+\gamma_r)\bar{B}]+\frac{\partial}{\partial \theta}[(u_\theta+\gamma_\theta)\bar{B}]\right]=s(\bar{\boldsymbol{B}}_p\cdot\nabla)\Omega$$

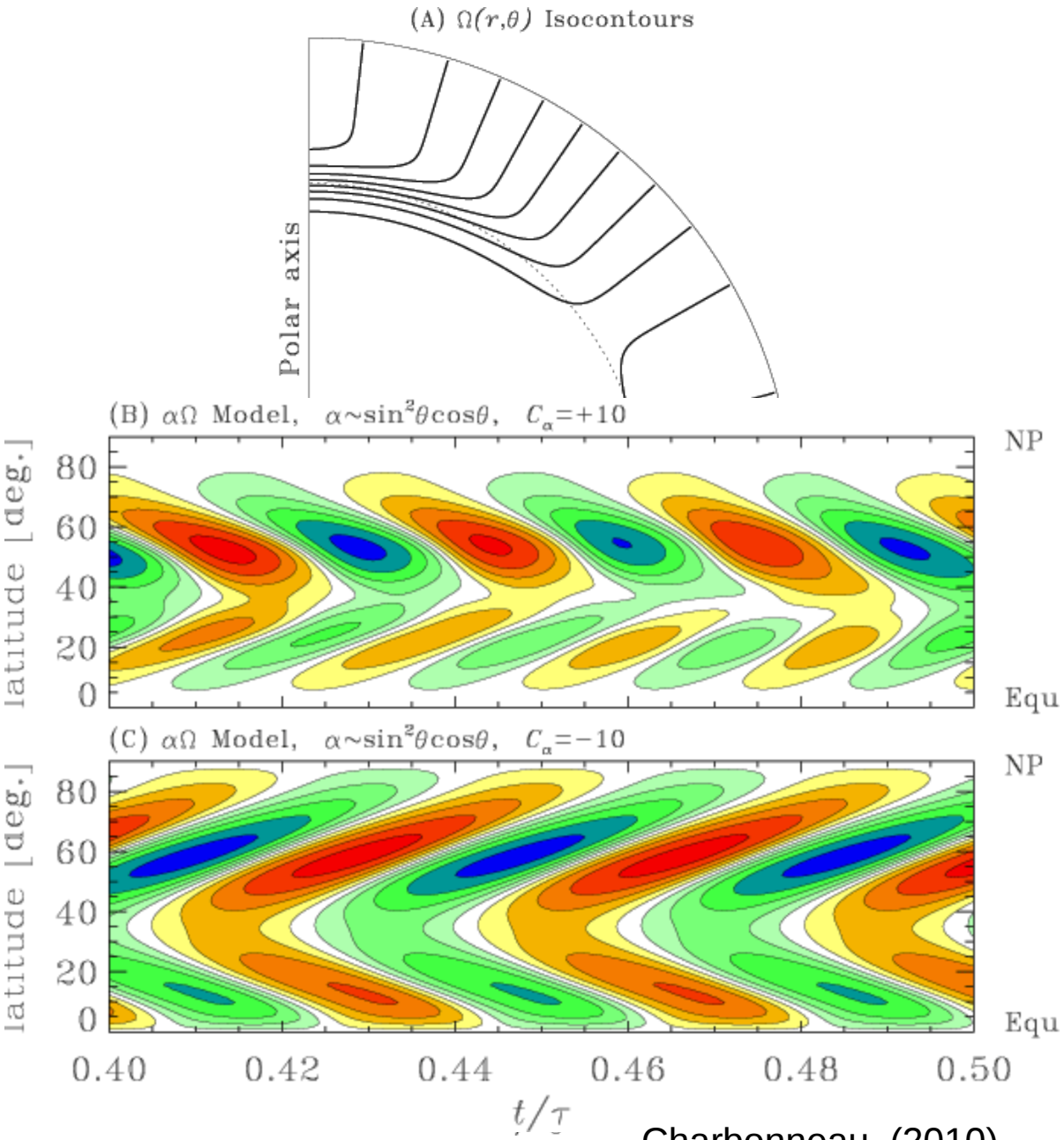
$$-[\nabla \eta_T\times(\nabla\times\bar{B})]_\phi+\eta_T\left(\nabla^2-\frac{1}{r\sin\theta}\right)\bar{B}+[\nabla\times(\alpha^D\bar{B})]_\phi$$

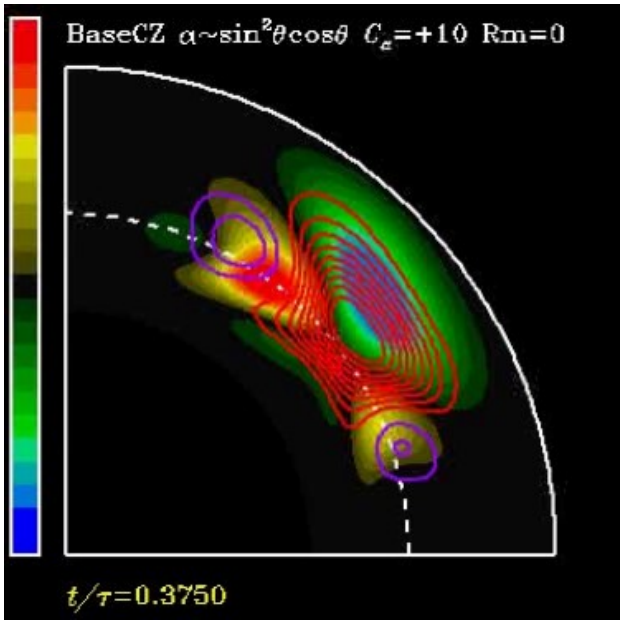
$$\frac{\partial \bar{A}}{\partial t}-\frac{1}{s}[(\bar{u}_p+\gamma_p)\cdot\nabla](s\bar{A})=\eta_T\left(\nabla^2-\frac{1}{r\sin\theta}\right)\bar{A}+(\alpha^D\bar{B})_\phi$$

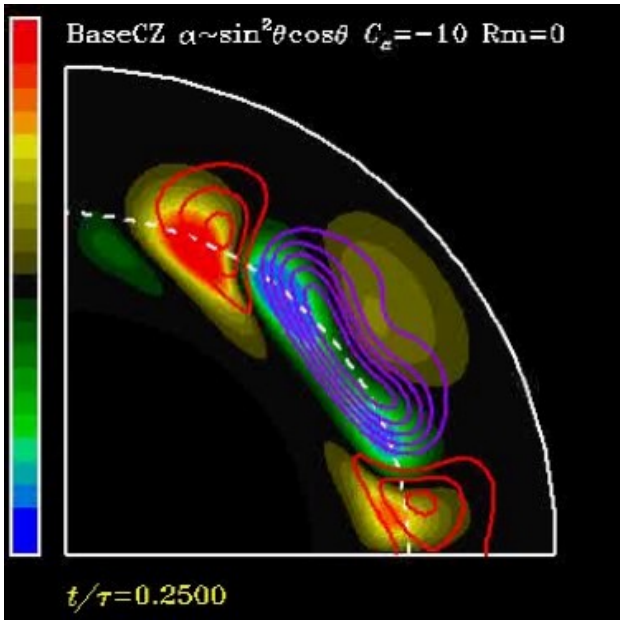
with $\eta_T=\eta+\beta$ The total magnetic diffusivity

$$C_\alpha=\frac{\alpha_0}{\eta_T k_f},\quad C_\Omega=\frac{\Delta\Omega}{\eta_T k_f^2},\quad C_U=\frac{U_0}{\eta_T k_f}$$

α-Ω dynamo with solar differential rotation

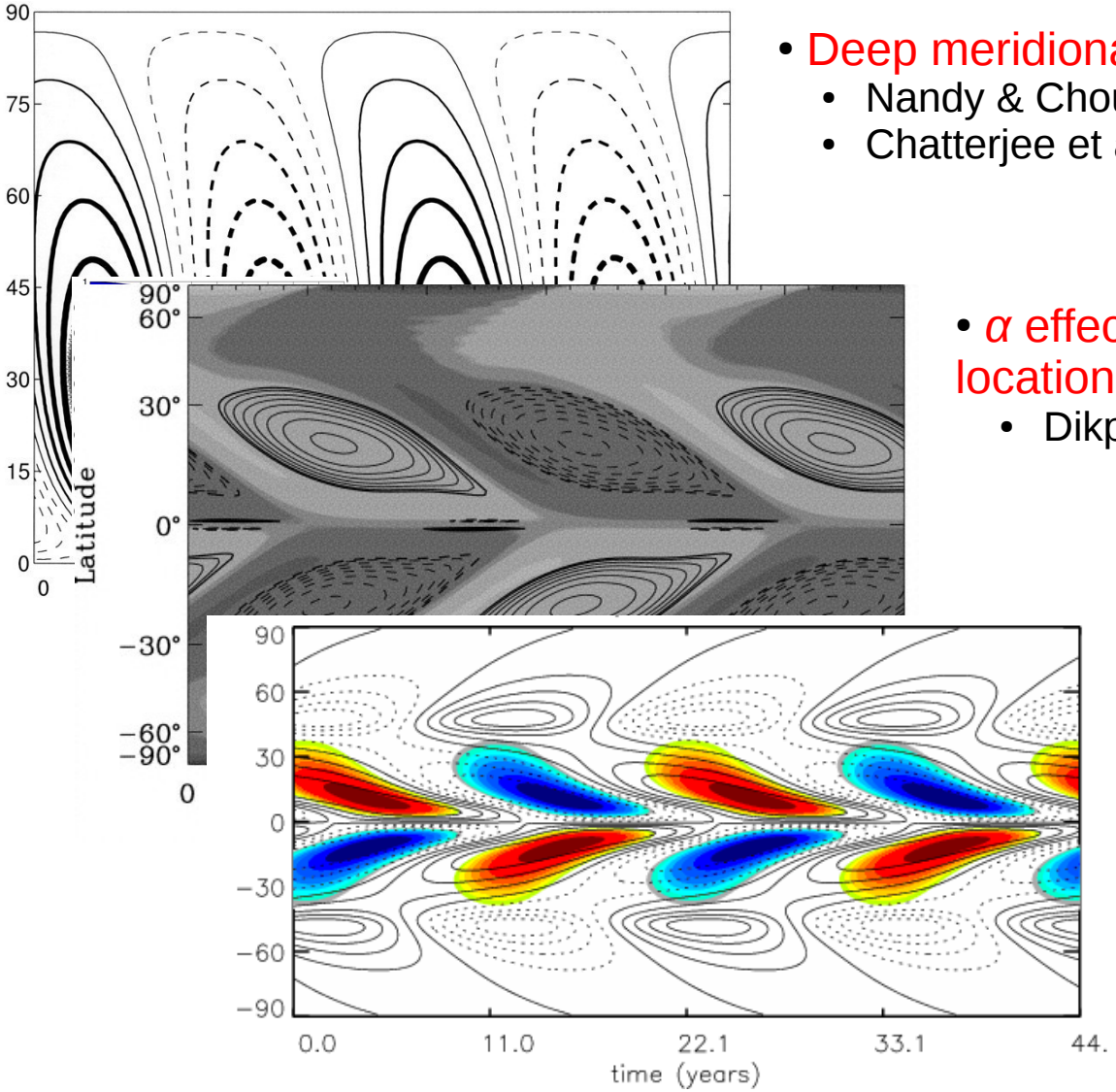






Charbonneau (2010)

After an educated (not always possible) fine tuning of parameters



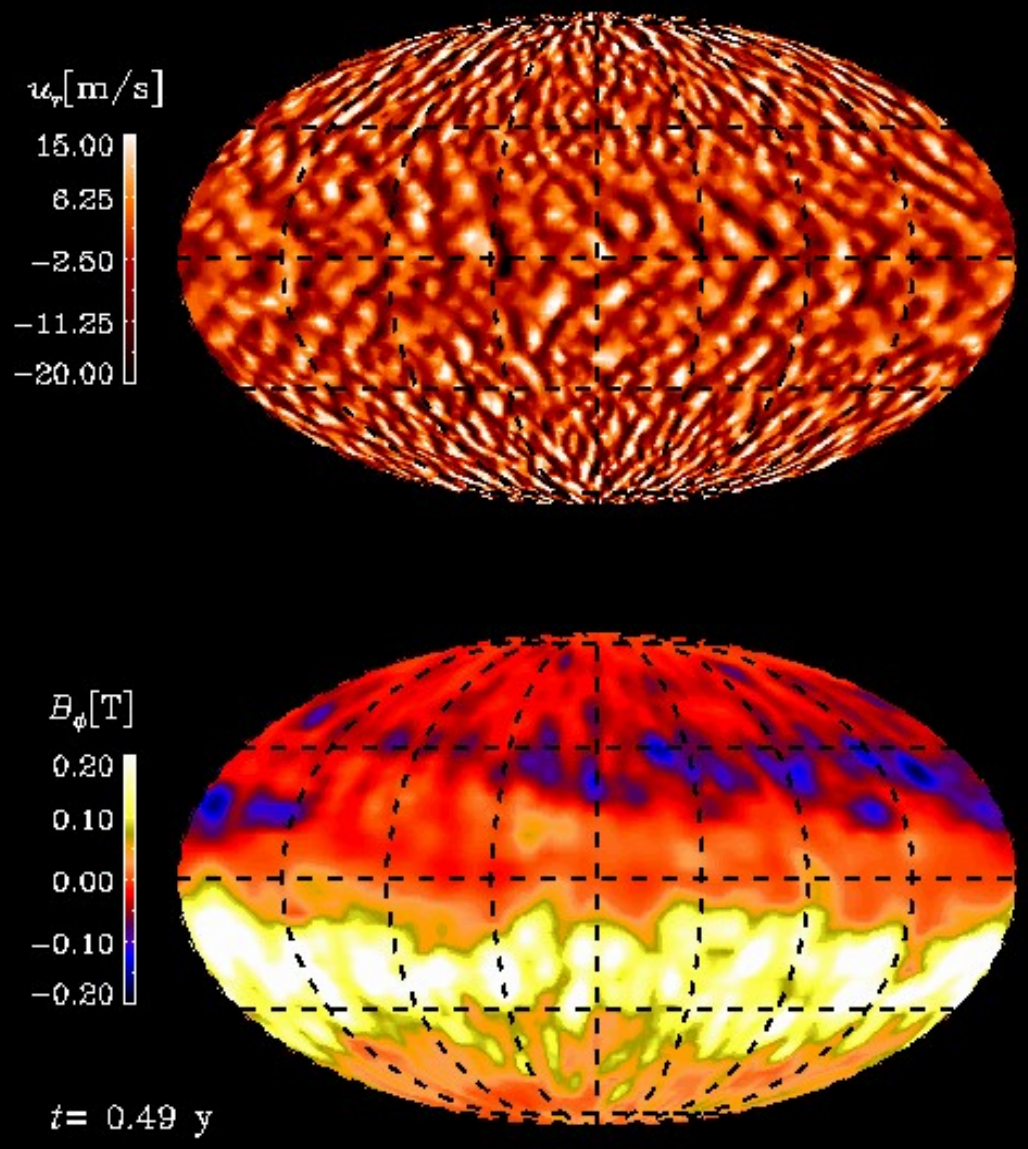
- Deep meridional flow
  - Nandy & Choudhuri (2002)
  - Chatterjee et al. (2004)

- *α* effect in two different locations
  - Dikpati et al. (2004)

- Turbulent pumping
  - Guerrero & de Gouveia Dal Pino (2008)
  - Kitchatinov & Olenskoi (2011)

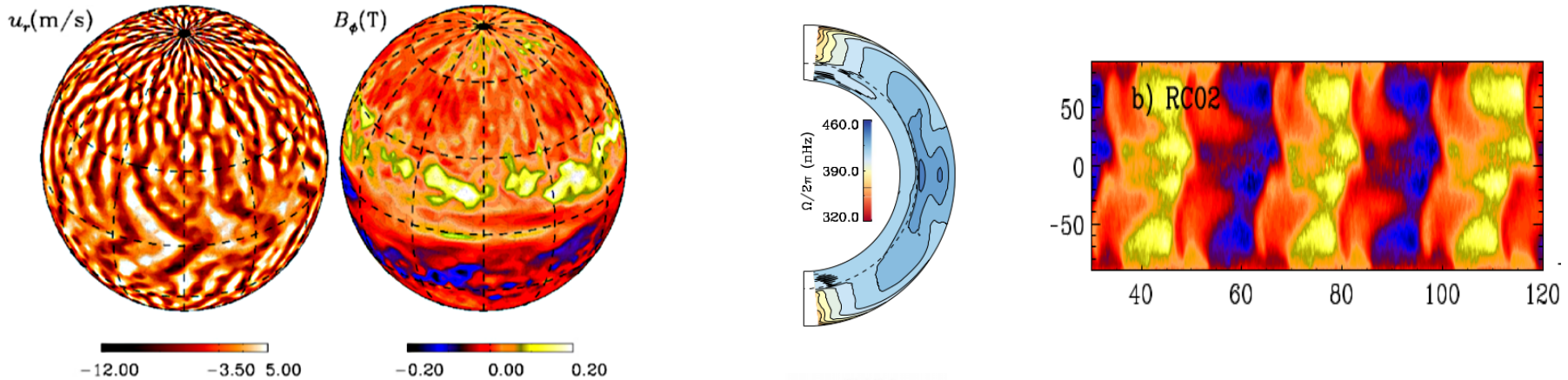
See also: Bonanno et al. (2002), Jouve et al. (2008), Käpylä et al. (2006)

Global simulations, solve the full set of MHD equations in 3D and spherical geometry

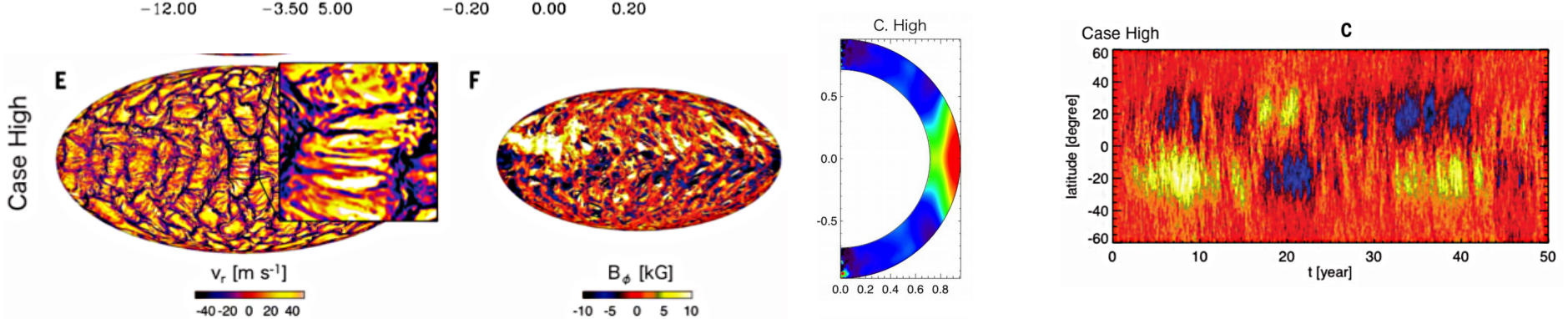


Guerrero et al. (2016)

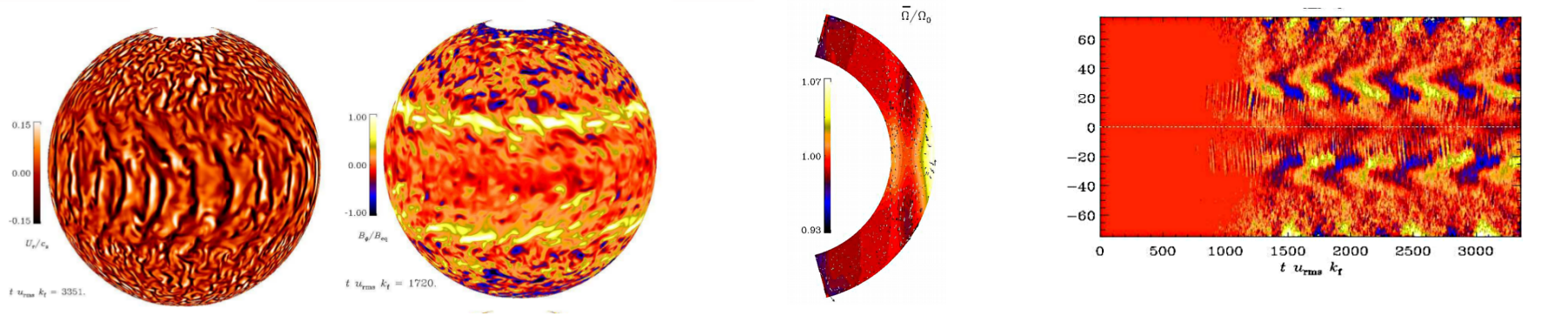
EULAG-MHD
Guerrero+2016 a,b



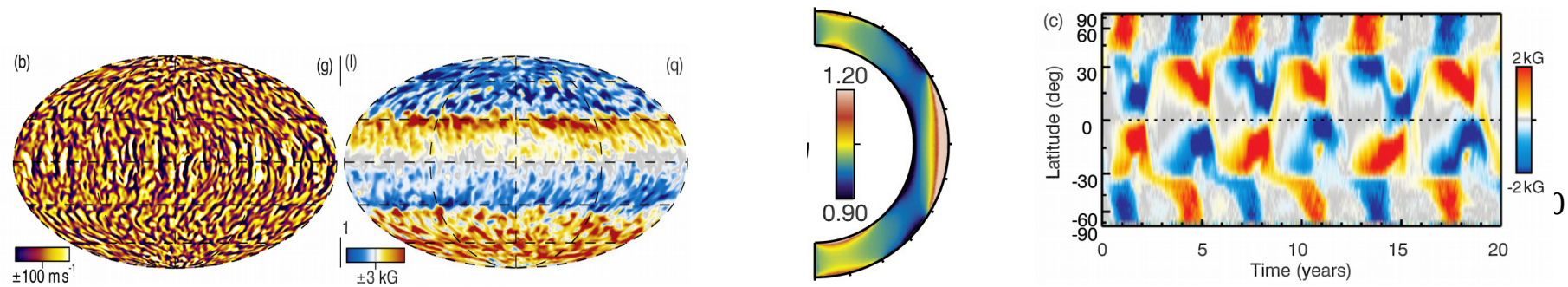
Hotta's code
Hotta+ 2016



Pencil-code
Kapyla+ 2012



ASH-code
Auguston+ 2015



Difficulties

$$\mathrm{Re} = \frac{u_{\mathrm{rms}} L}{\nu} \sim 10^{12} \qquad \left(10^{2}\right)$$

$$\mathrm{Rm} = \frac{u_{\mathrm{rms}} L}{\eta} \sim 10^{9} \qquad \left(10^{2}\right)$$

$$\mathrm{Ra} = \frac{G M \left(\Delta r\right)^{4}}{\nu \kappa R^{2}} \frac{-1}{c_p} \frac{ds}{dr} \geq 10^{15} \qquad \left(10^{6}\right)$$

- Important dynamical scales go from *km*'s to hundreds of *Mm*.
- Energy transfer from bottom to top
- Simulations use large values for dissipative terms to keep stable
- Large-scale fields evolve in time scales going from years to decades
- Simulations take long time to achieve HD and MHD steady states

- SGS parametrization is needed
  Guizaru et al. (2010), Guerrero et al. (2016), Auguston et al. (2015)

Dynamo simulations with **EULAG-MHD**

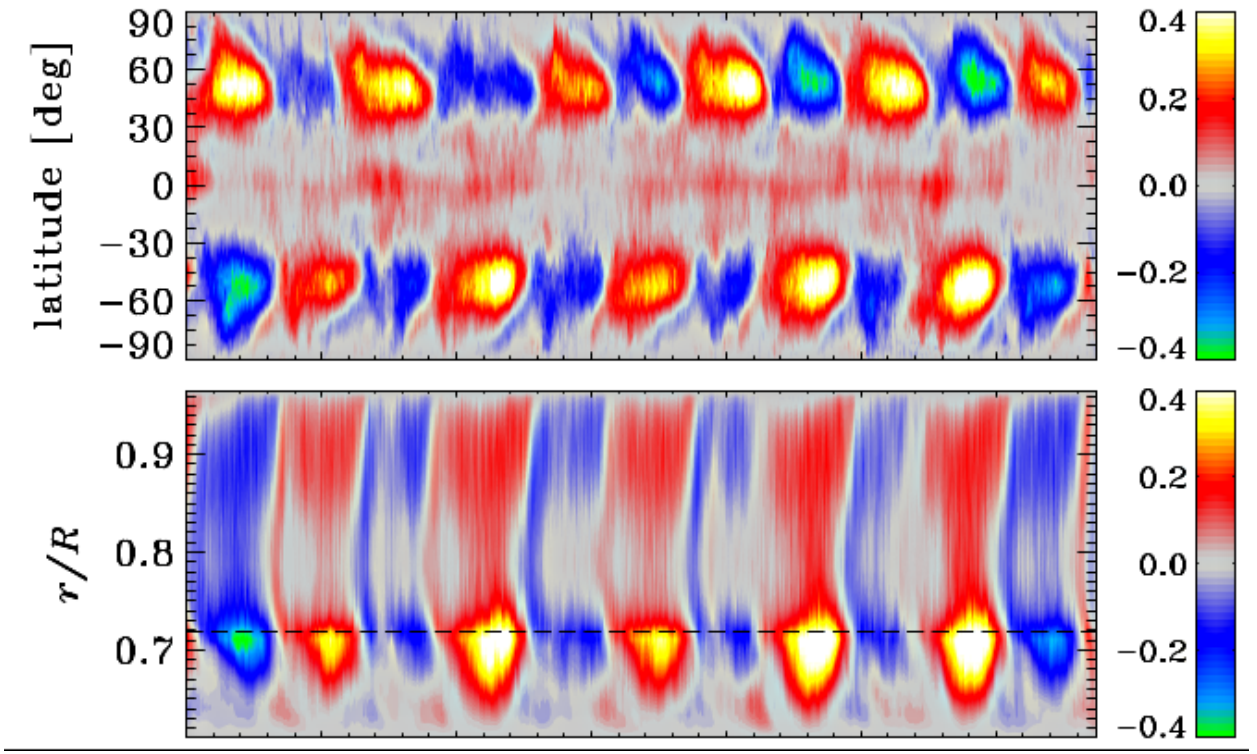
$$\boldsymbol{\nabla} \cdot (\rho_s \boldsymbol{u}) = 0, \tag{2}$$

$$\frac{D\boldsymbol{u}}{Dt} + 2\boldsymbol{\Omega} \times \boldsymbol{u} = -\boldsymbol{\nabla}\left(\frac{p'}{\rho_s}\right) + \boldsymbol{g}\frac{\Theta'}{\Theta_s} + \frac{1}{\mu_0 \rho_s}(\boldsymbol{B} \cdot \nabla)\boldsymbol{B}, \tag{3}$$

$$\frac{D\Theta'}{Dt} = -\boldsymbol{u} \cdot \boldsymbol{\nabla}\Theta_e - \frac{\Theta'}{\tau}, \tag{4}$$

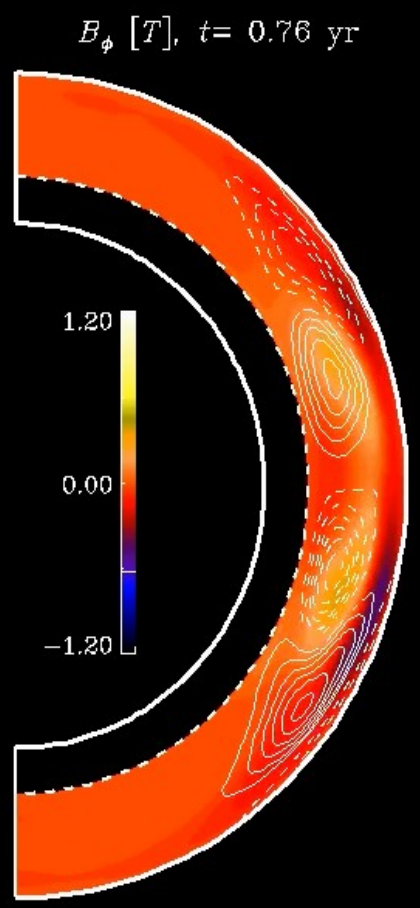
$$\frac{D\boldsymbol{B}}{Dt} = (\boldsymbol{B} \cdot \nabla)\boldsymbol{u} - \boldsymbol{B}(\nabla \cdot \boldsymbol{u}), \tag{5}$$

- ILES: implicit large eddie simulations, maximizes Re and Rm (see Strugarek et al. 2015)
- Energy equation solves for *Θ'* (stolen from meteorology)
- Able to resolve a tachocline
- *Ghizaru et al (2010)* was the first global MHD simulation able to produce magnetic cycles

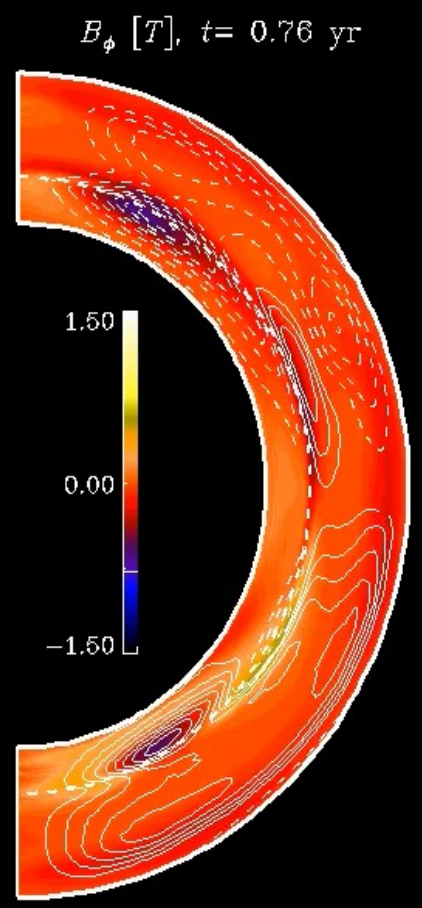


Are tachoclines relevant?

Models **CZ** (convection zone only)



Models **RC** (radiative/convective zones)

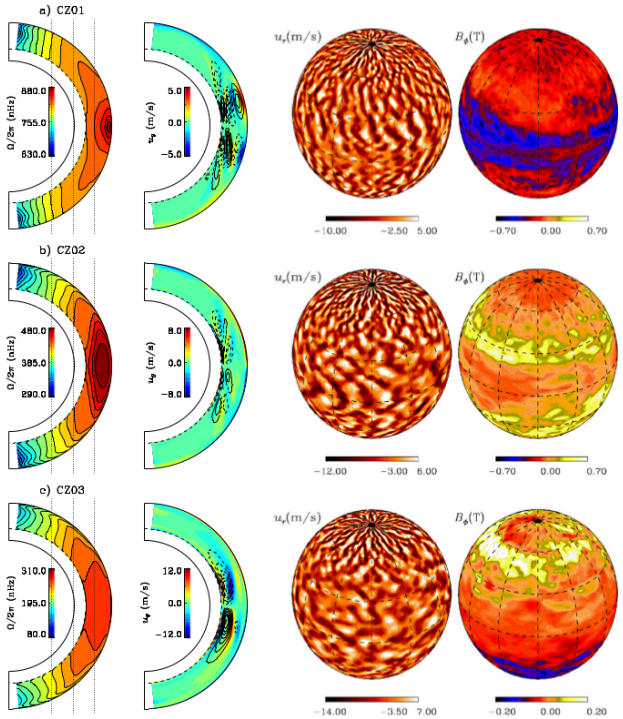


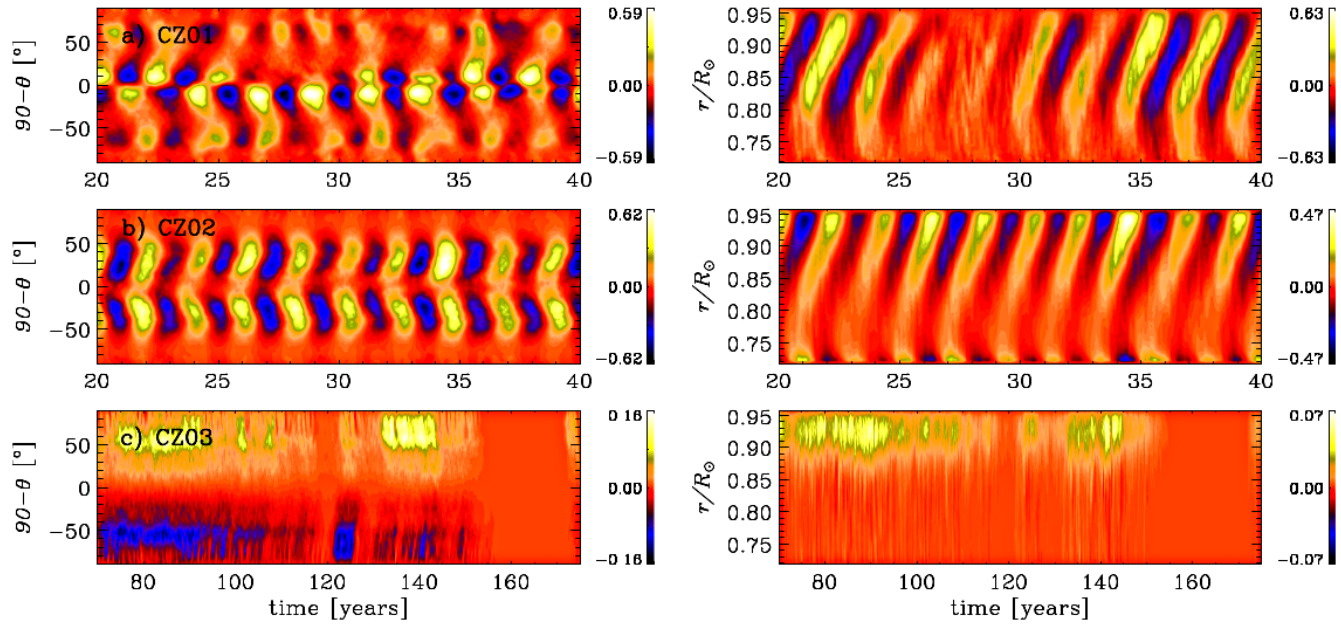
MODELS CZ (without tachocline)

14d

28d

56d



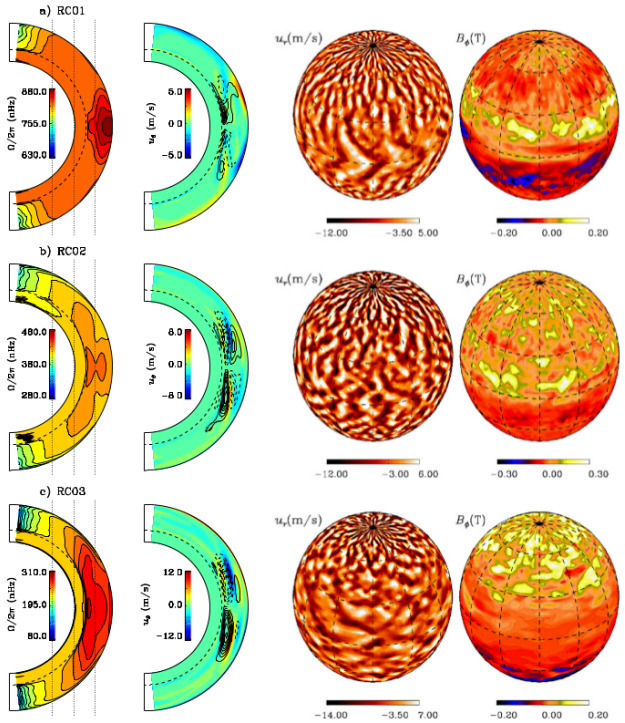


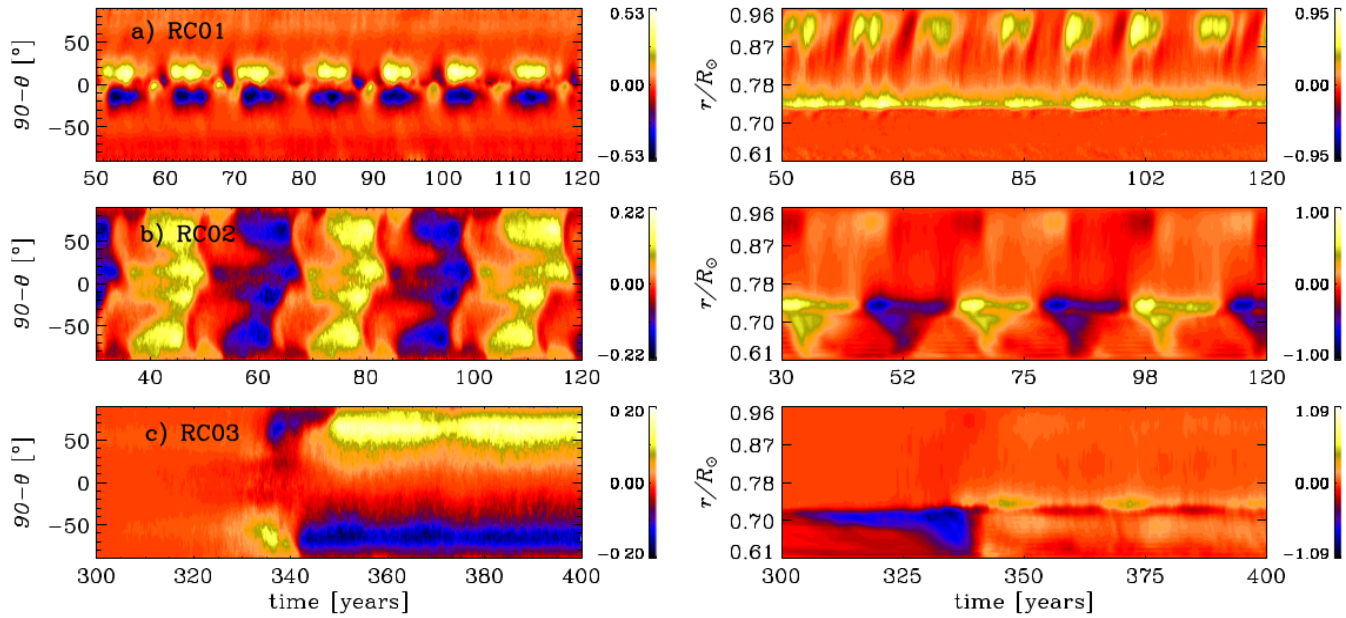
MODELS RC (include rad. and conv. zones)

14d

28d

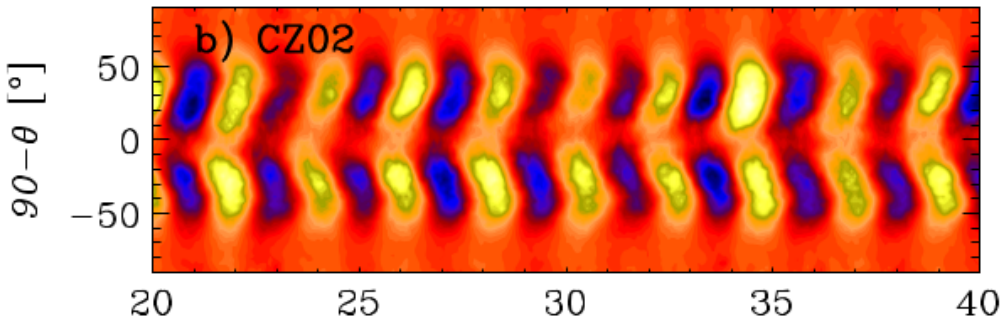
56d



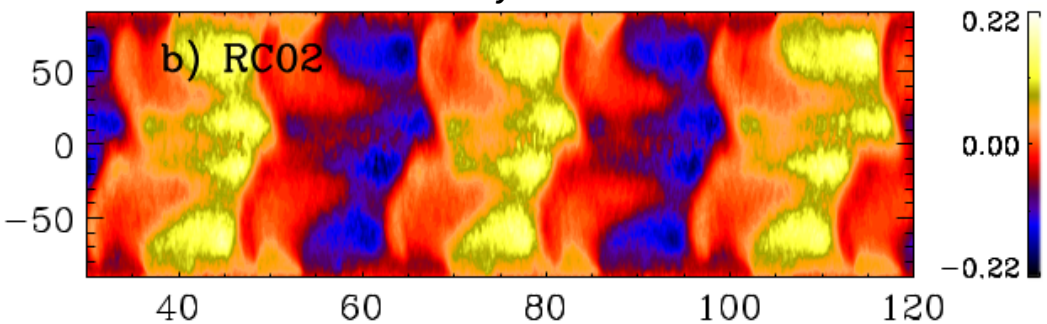


The dynamo period

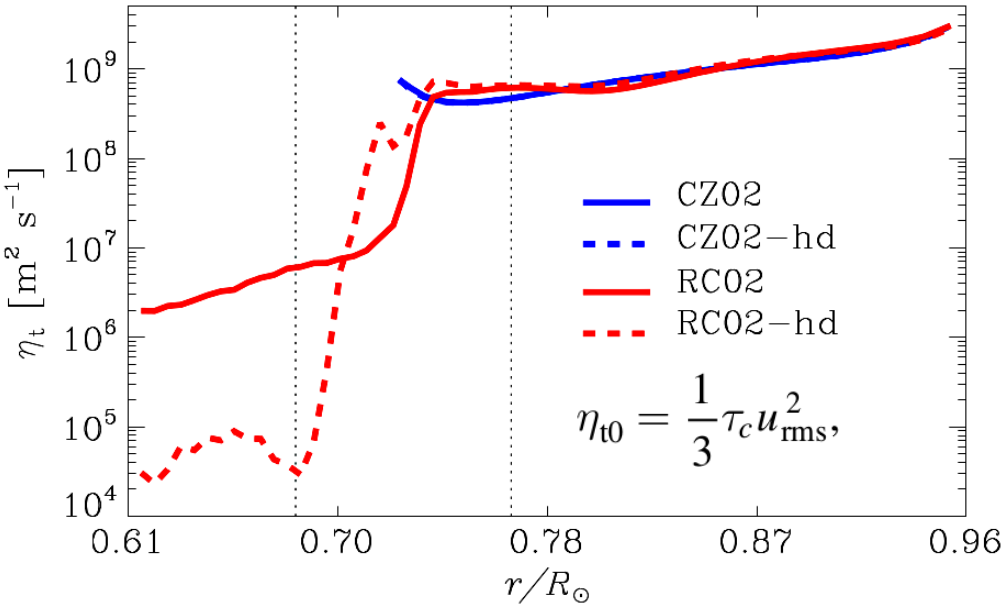
***T_{rot} = 28* days, *T_{cyc} = 1* yr**



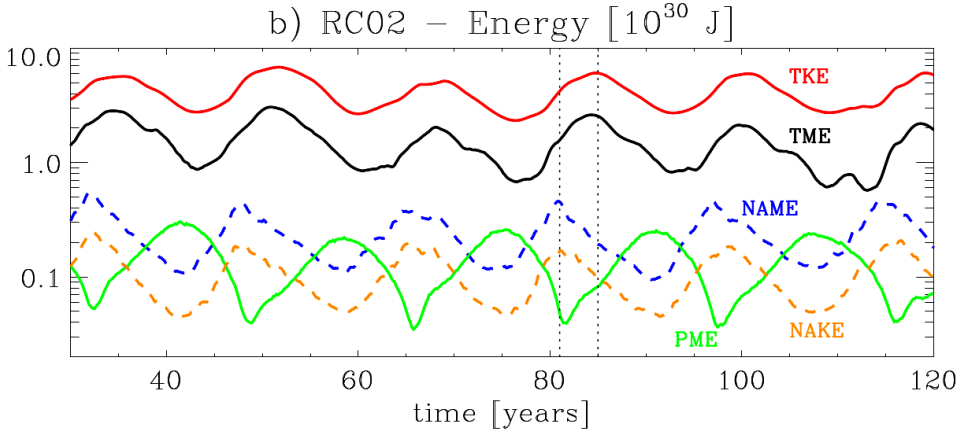
***T_{rot} = 28* days, *T_{cyc} = 15.6* yr**



Turbulent magnetic diffusivity

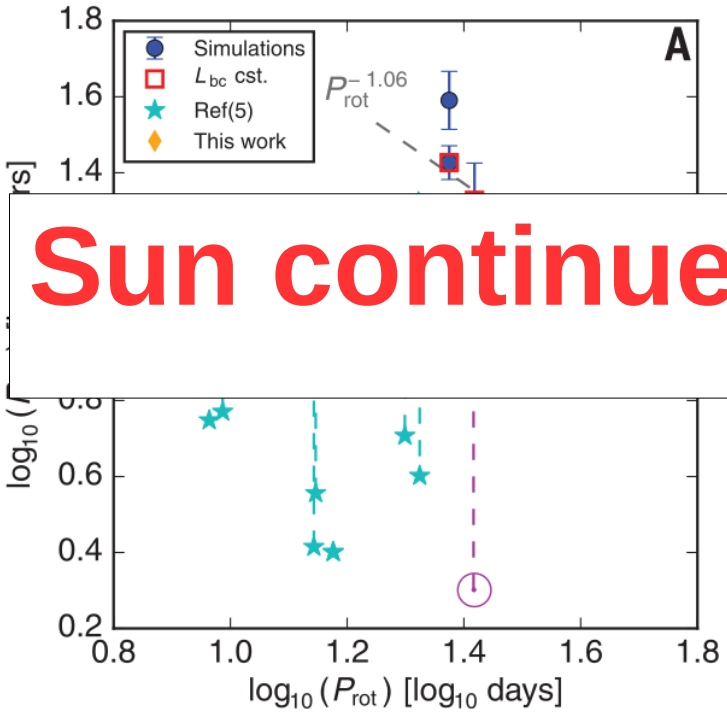


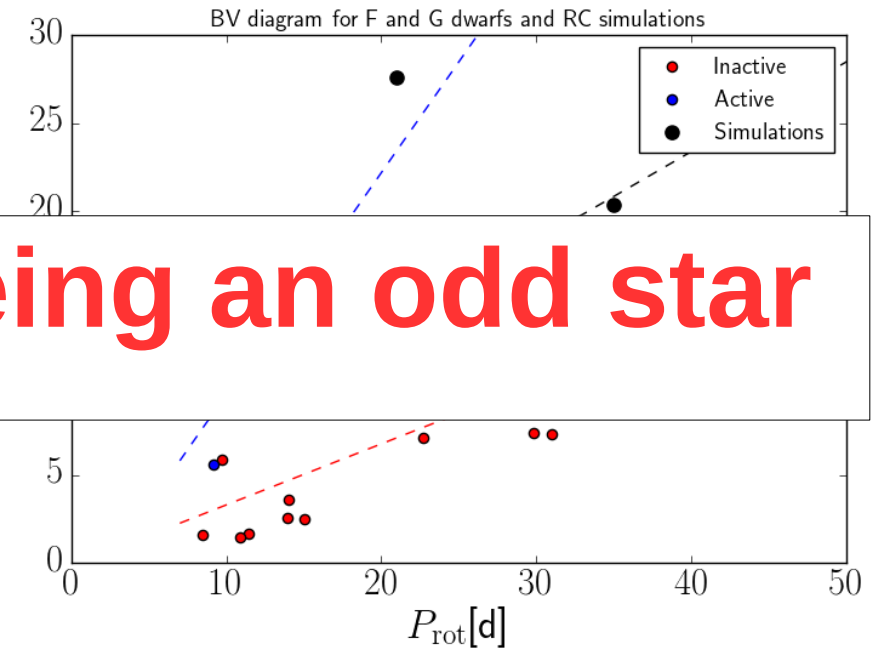
- *Tachocline Instabilities:* develop turbulence in the stable layer
- (To be confirmed by other codes)

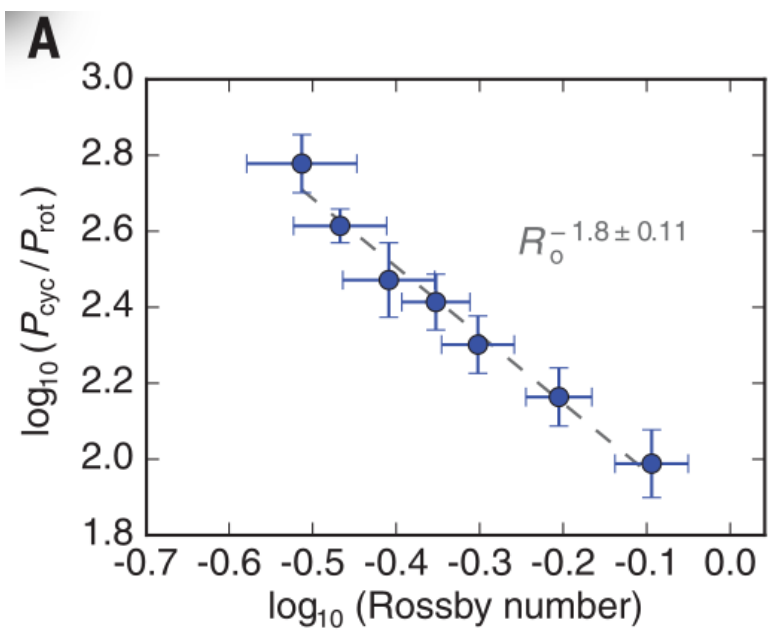


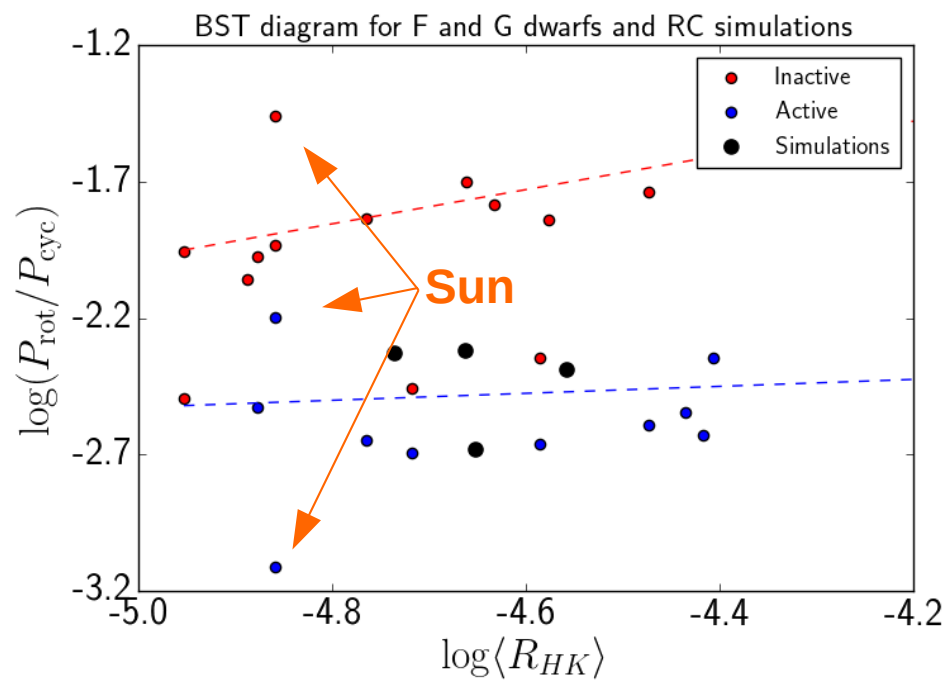
Guerrero+ (2016a)

Sun continues being an odd star







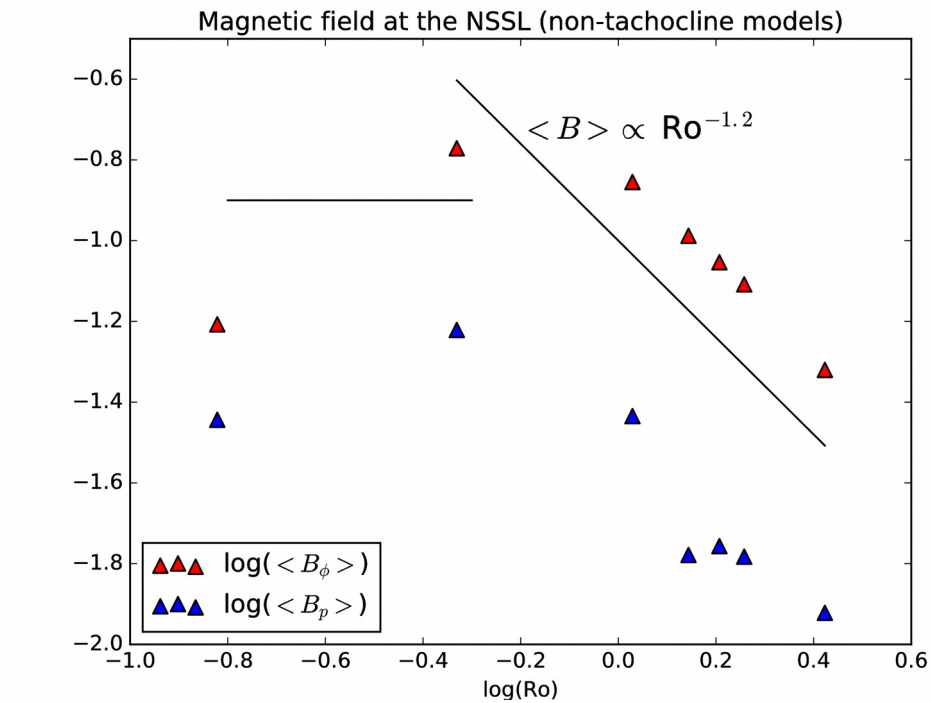


Strugarek et al (2017)
Models with convective zone only

Guerrero et al (2017, *in prep*)
Models with tachocline

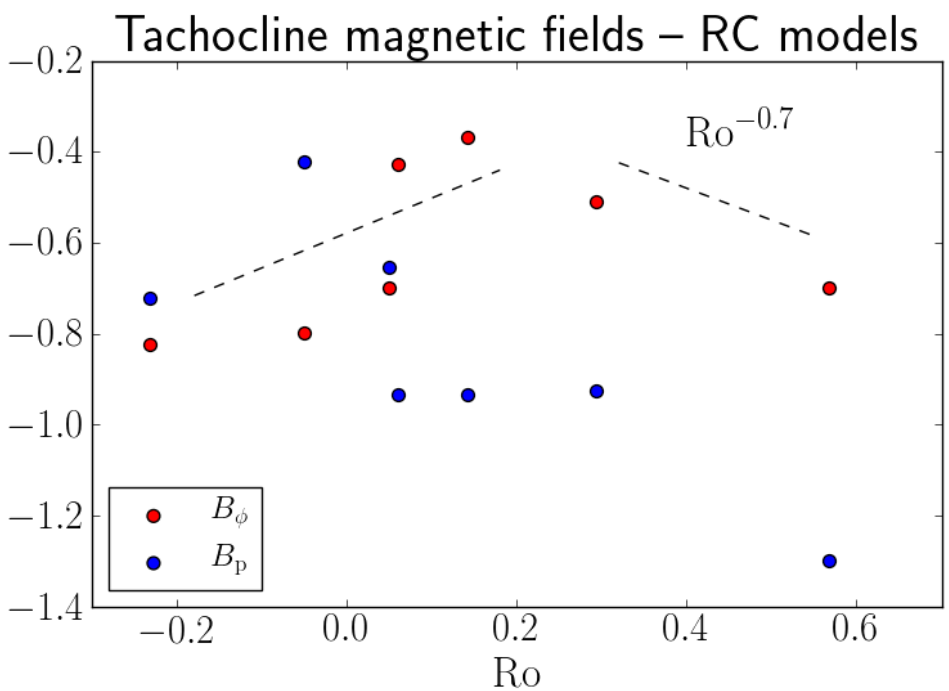
Dynamo saturation

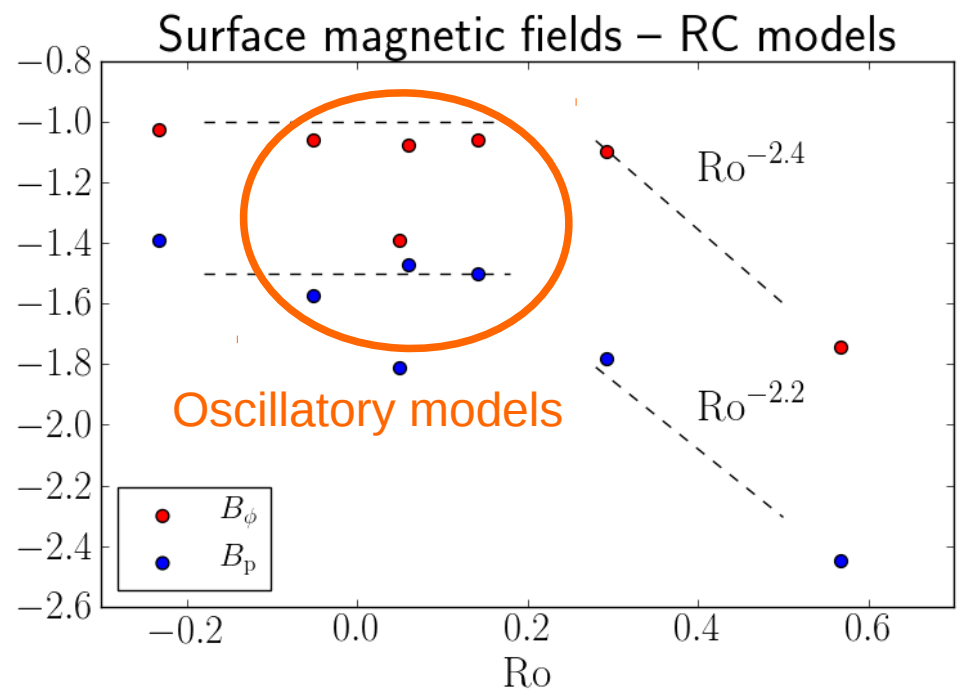
MODELS WITHOUT *TACHOCLINE*



- The results of global simulations resemble the regimes observed
- Local dynamo sources *vs* deep seated dissipation rate
- Meridional circulation and magnetic buoyancy **do not** contribute to the dynamo process

MODELS WITH *TACHOCLINE*





Guerrero et al. 2017, *in prep.*

Conclusions

- Tachoclines play a relevant role in turbulent global dynamos
- Dynamo periods in RC models increase with the rotation period (the Sun is still a weird star)
- The dynamo saturation relation, *B* vs *Ro* is reproduced in RC models
- Shear-current instabilities at the tachocline might determine the dynamo cycle.

Thanks!