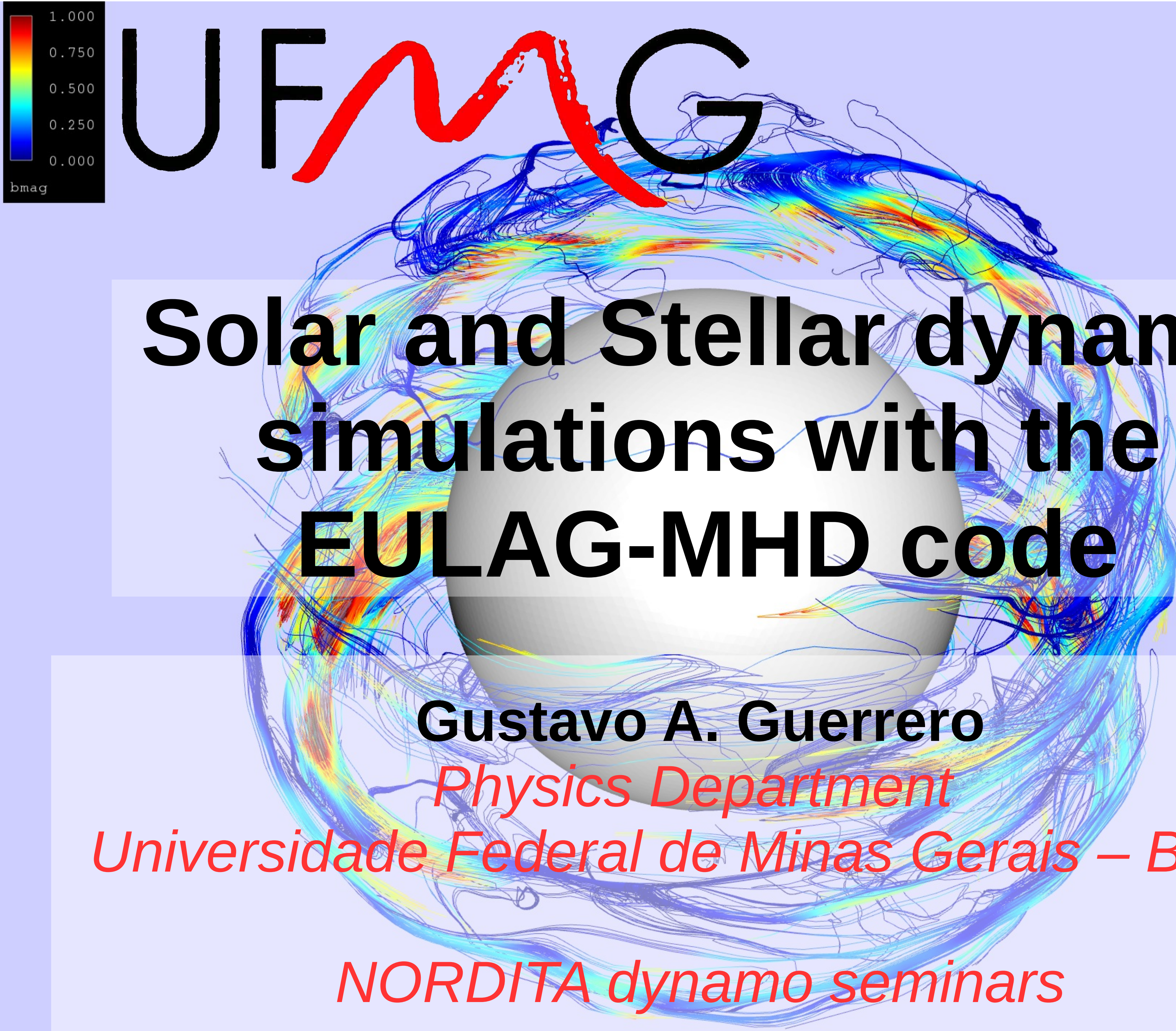

Solar and Stellar dynamo simulations with the EULAG-MHD code

Gustavo A. Guerrero

Physics Department

Universidade Federal de Minas Gerais – Brazil)

NORDITA dynamo seminars

Collaborators:

R. Barbosa (*DF – UFMG*),
G. Monteiro (*DF – UFMG*)
H. de Mattos (*DF – UFMG*)
B. Zaire (*DF – UFMG*)
E. M. de Gouveia dal Pino (*IAG*),
P. Smolarkiewicz (*ECMWF*),
A. Kosovichev (*NJIT*),
N. Mansour (NASA-Ames),
F. del Sordo (INAF)
A. Bonanno (CAO-INAF)

Details can be found in:

- Guerrero et al. (ApJ, 819, 104, 2016)
- Guerrero et al. (ApJL, 828, L3, 2016)
- Guerrero et al. (ApJ, 880, 6, 2019)
- Guerrero et al. (MNRAS, 490, 4281, 2019)
- Stejko et al (ApJ, 888, 16, 2020)
- Guerrero, G. (arXiv:2001.10665, 2020)

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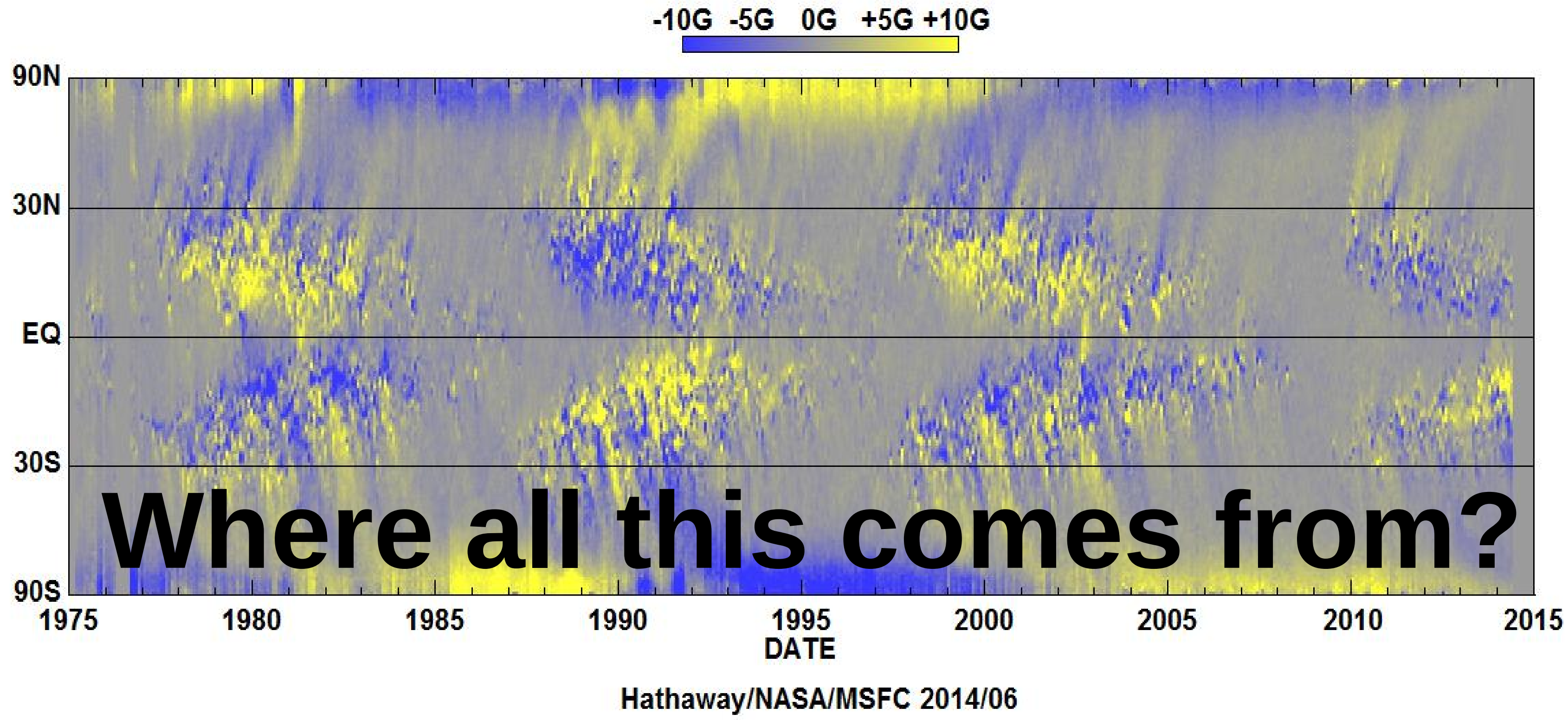
CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

NASA

CINECA

Escola Supercomputador Dumont

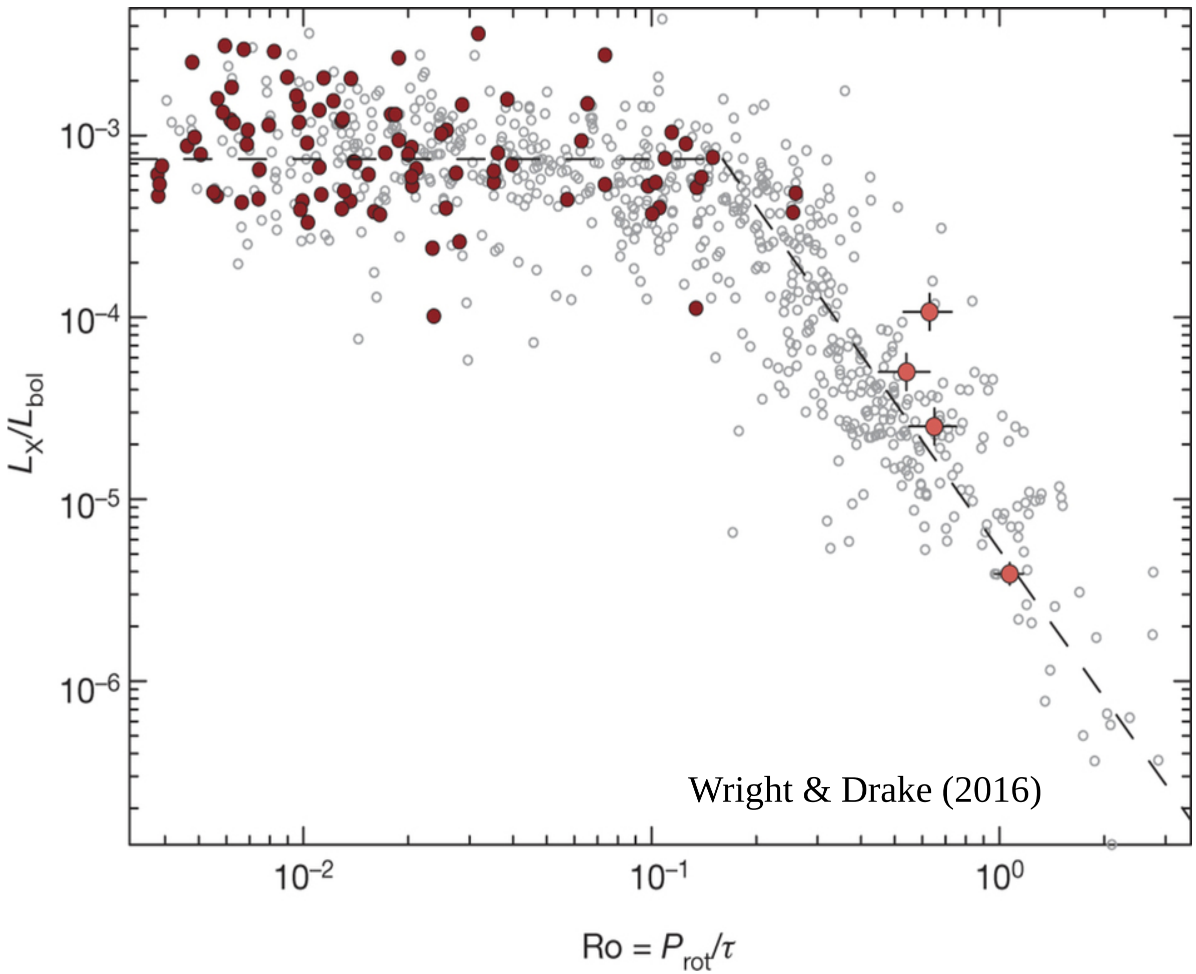
Where all this comes from?



- Many proposals along the years
  - Convection zone, *mean-field αΩ dynamo* (Parker, 1955, Steinbeck, Krause & Radler, 1969, …), *potential problems at high Rm*.
  - Interface dynamo, α (convection zone)+ Ω (tachocline) (Parker 1993, Charbonneau & MacGregor 1996-1997, Tobias 1996-1997)
  - Convection zone + tachocline, *flux-transport αΩ dynamo* (Dikpati & Charbonneau 99, Nandy & Choudhuri 2002, Guerrero & Dal Pino 2008)
  - Near surface layer, distributed *αΩ + negative* $\partial_r\Omega$ (Brandenburg 2005), catastrophic quenching alleviated because magnetic helicity fluxes.

Is the dynamo operating at the tachocline?

- **Arguments against:**
  - Fully convective stars and partially convective stars exhibit the same behavior
  - Global dynamo simulations with only a convective layer reproduce cyclic activity (e.g., Auguston et al. 2015, Strugarek et al., 2017, Warnecke et al. 2017)

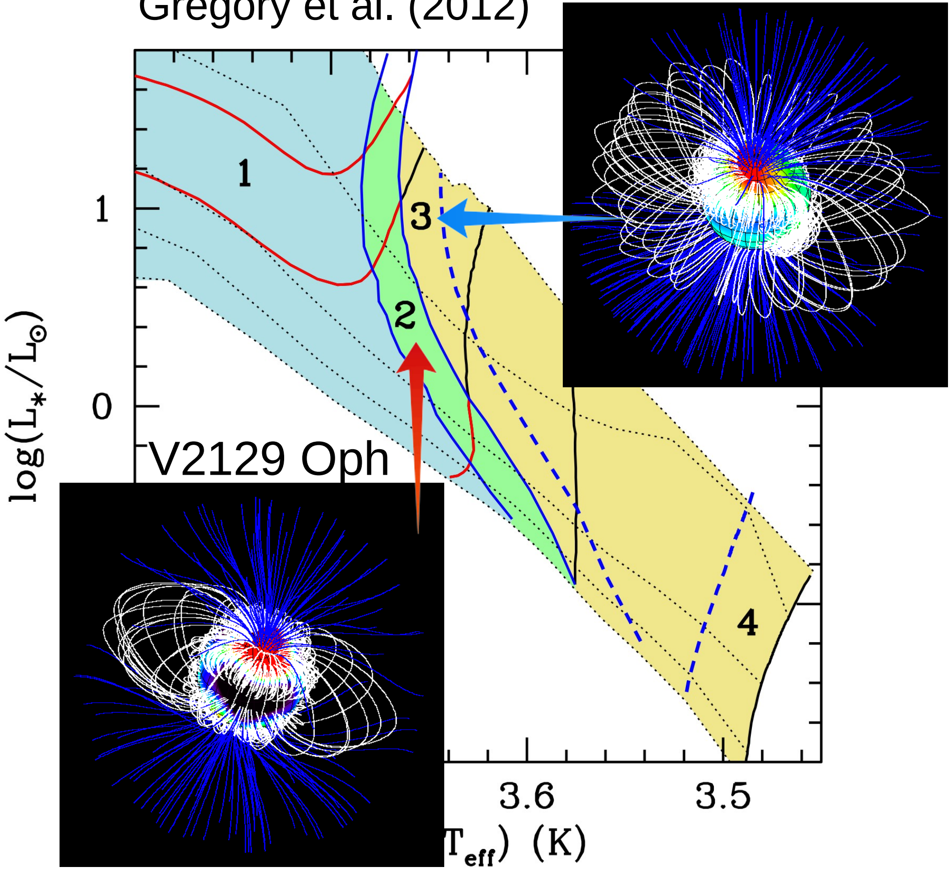


Is the dynamo operating at the tachocline?

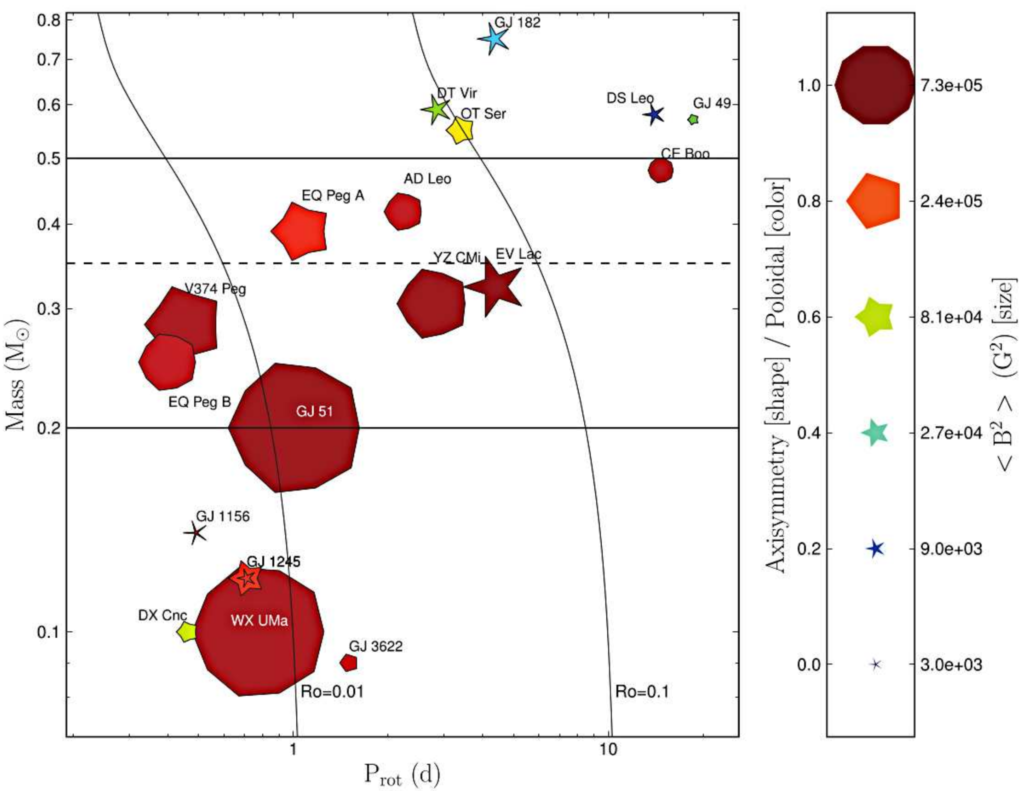
- **Arguments in favor:**
  - Tachocline is there with strong radial shear (helioseismology)
  - ZDI observations of
    - Magnetic topology of young Suns and M-dwarfs (Donati et al. 2007, 2008, Jardine et al. 2008)
    - Magnetic helicity (Lund et al. 2020)

Gregory et al. (2012)

Bp-tau



Confusogram: Morin et al. (2010)



Dynamo simulations with **EULAG-MHD**

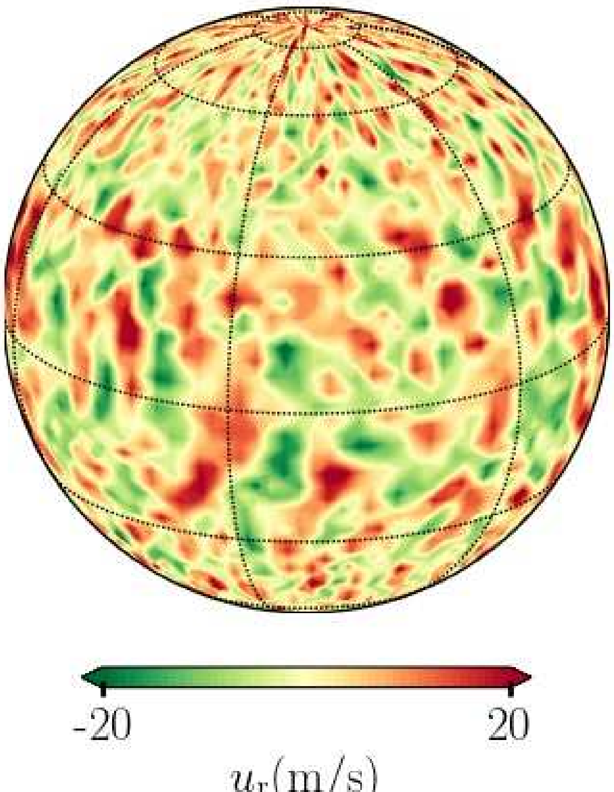
$$\boldsymbol{\nabla} \cdot (\rho_s \boldsymbol{u}) = 0, \quad (2)$$

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

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

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

- ILES: implicit large eddie simulations, maximize *Re* and *Rm* (see Strugarek et al. 2016)
- Energy equation solves for *Θ'* about an ambient state, Θ_e (*forcing and dissipation*)
- Global in *φ* and *θ*, in *r* the simulations span from *0.6R* to *0.96R*
- *128x64x64* grid points resolution
- Impermeable, stress free boundary conditions for the velocity field
- Radial field/Perfect conductor boundary conditions for the magnetic field
- Rotation rates from *7* to *63* days



What Sets the Magnetic Field Strength and Cycle Period in Solar-type Stars?

G. Guerrero[1], B. Zaire[2,1], P. K. Smolarkiewicz[3], E. M. de Gouveia Dal Pino[4], A. G. Kosovichev[5], and N. N. Mansour[6]

[1] Physics Department, Universidade Federal de Minas Gerais, Av. Antonio Carlos, 6627, Belo Horizonte, MG 31270-901, Brazil; guerrero@fisica.ufmg.br
[2] IRAP, Université de Toulouse, CNRS/UMR 5277, CNES, UPS, 14 avenue E. Belin, Toulouse, F-31400 France
[3] European Centre for Medium-Range Weather Forecasts, Reading RG2 9AX, UK
[4] Astronomy Department, Universidade de São Paulo, IAG-USP, Rua do Matão, 1226, São Paulo, SP, 05508-090, Brazil
[5] New Jersey Institute of Technology, Newark, NJ 07103, USA
[6] NASA, Ames Research Center, Moffett Field, Mountain View, CA 94040, USA

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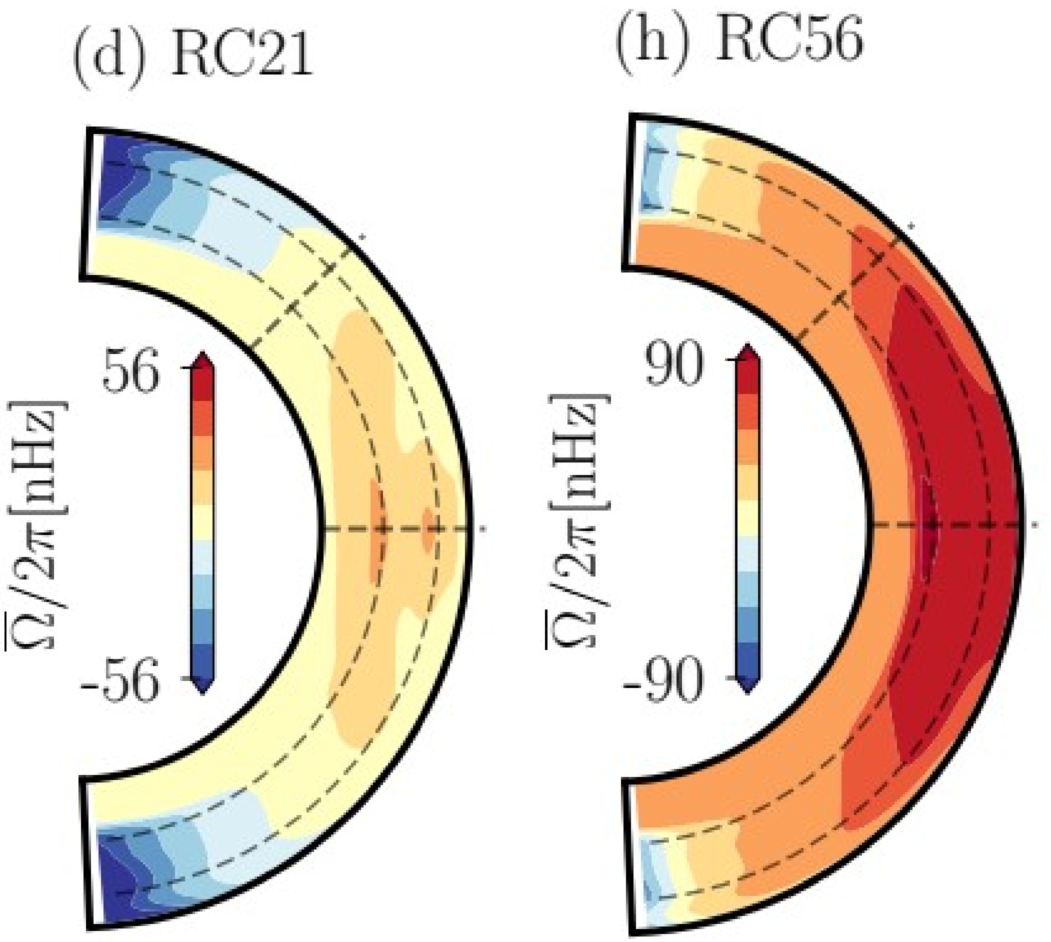
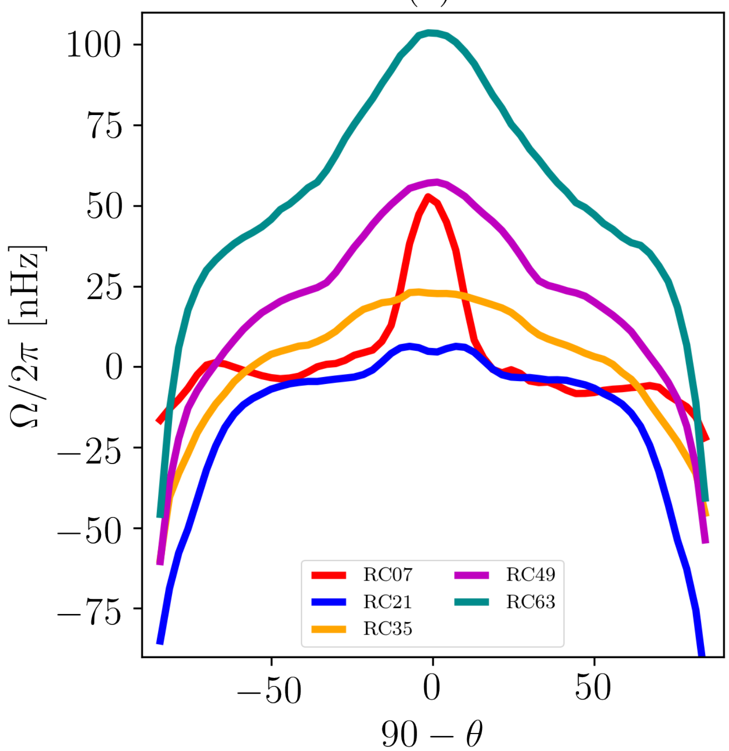


Remarks on differential rotation

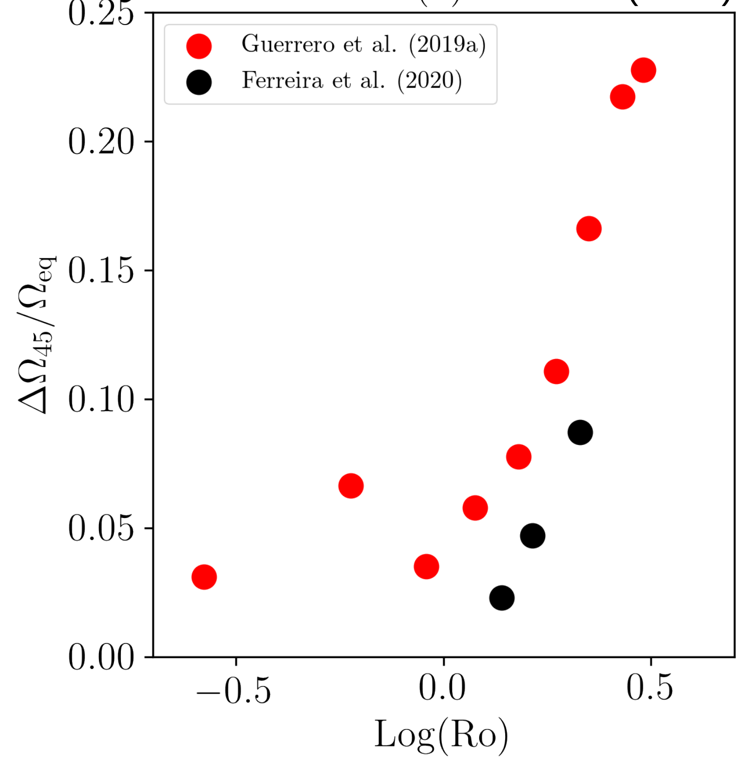
- The simulations develop tachoclines
- develop near-surface shear layers
- in some models the contours of iso-rotation are tilted
- in others they are vertical (Taylor-Proudman balance)
- unlike HD cases (Guerrero et al. 2013), even for the largest *Ro*, the differential rotation in the MHD models is solar-like

Shear profiles

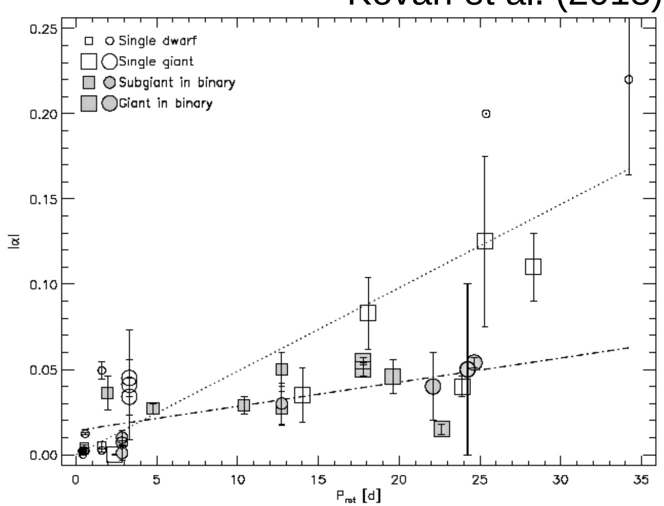
(a)



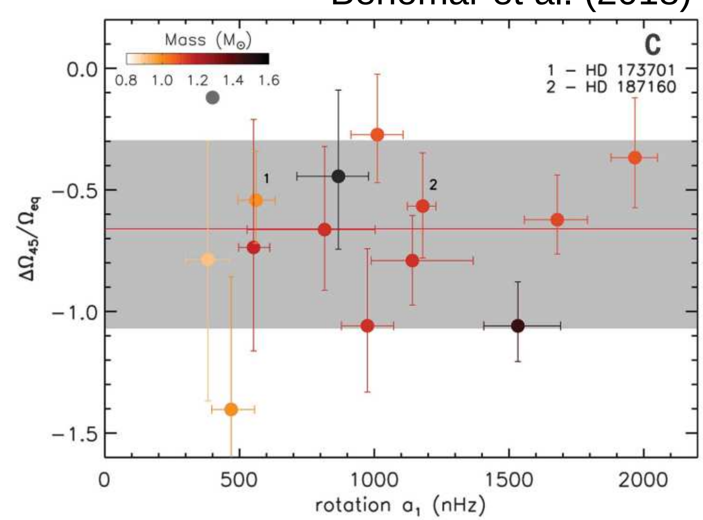
(b) Guerrero (2020)



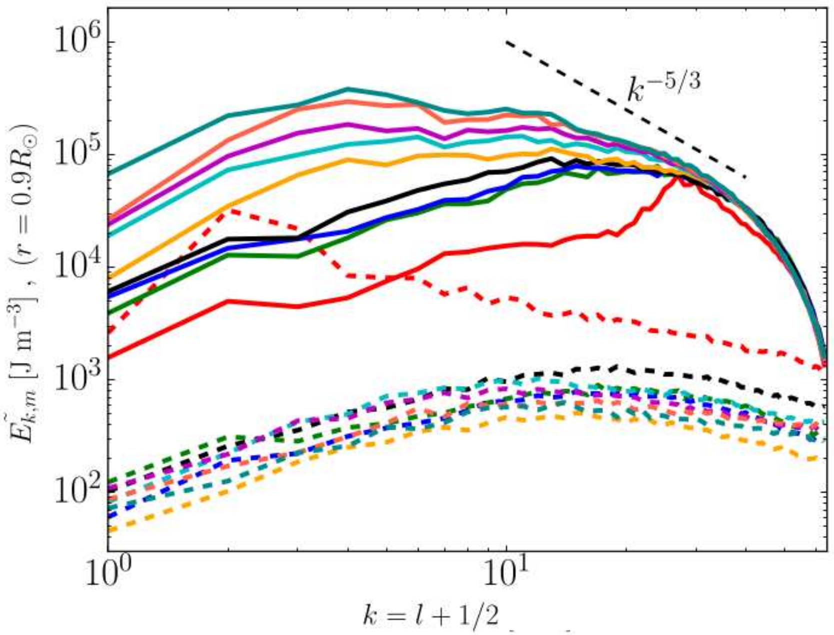
Kovari et al. (2018)

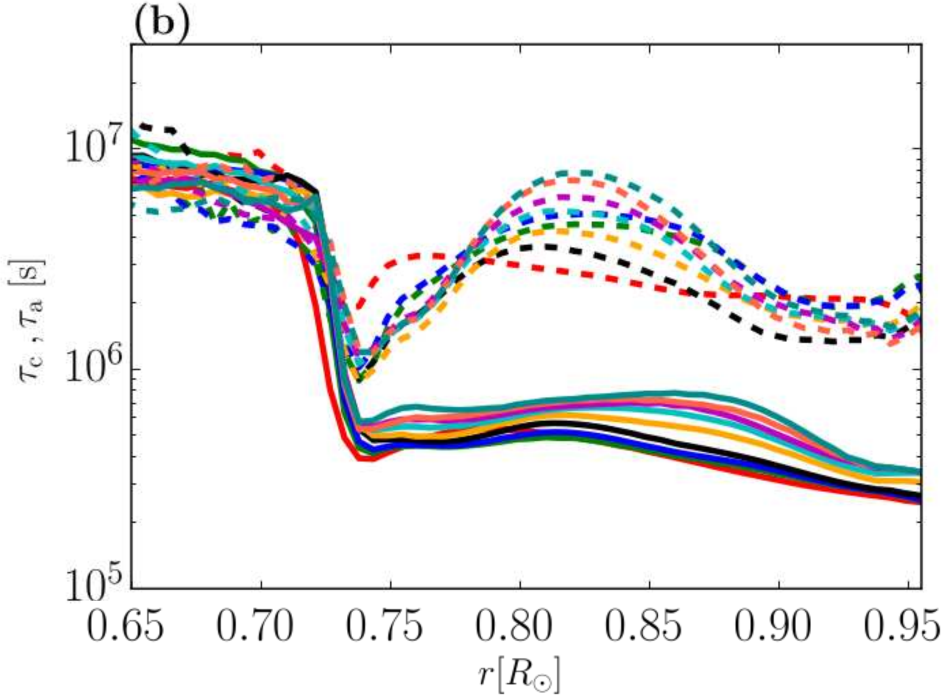


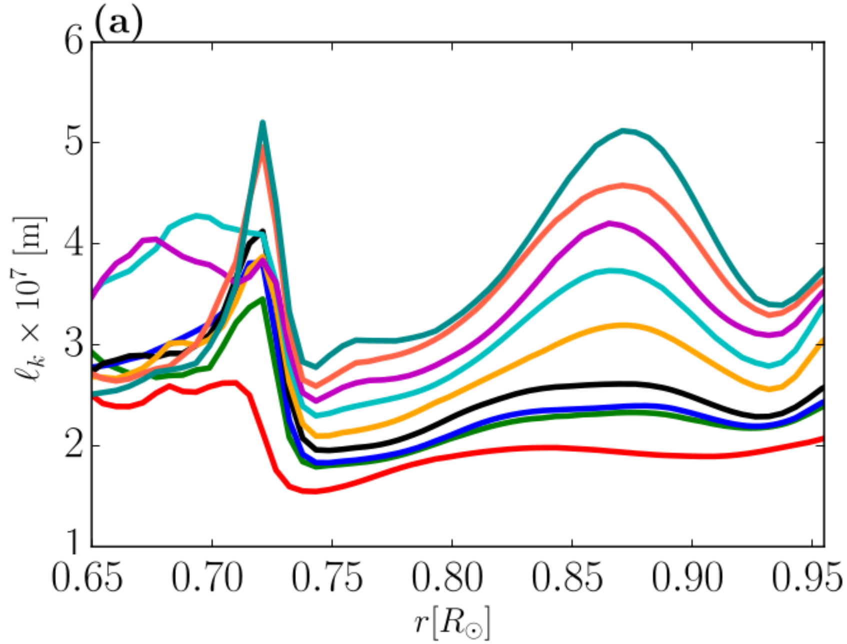
Benomar et al. (2018)

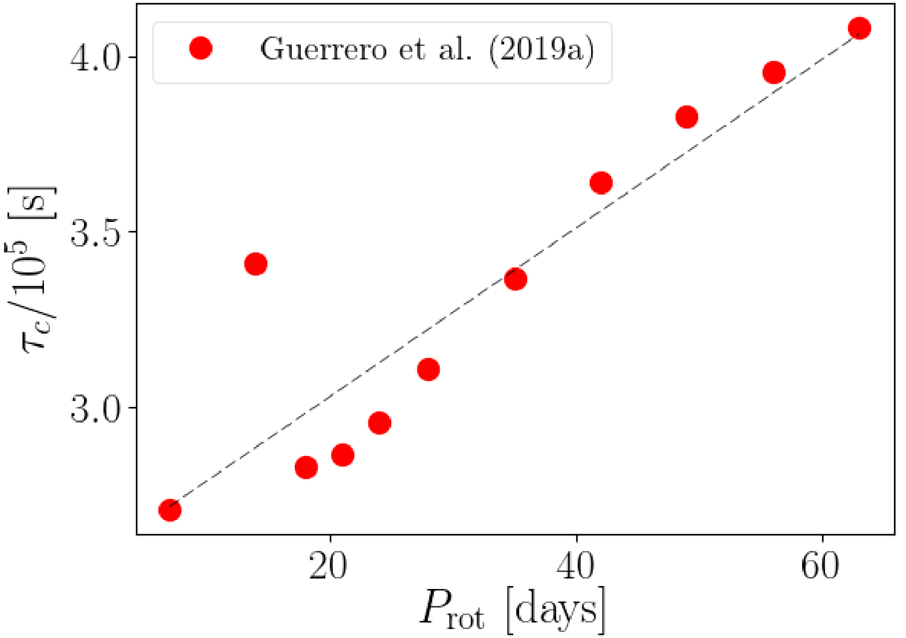


Eddy size and turnover times
(ref: Lehtinen's talk)

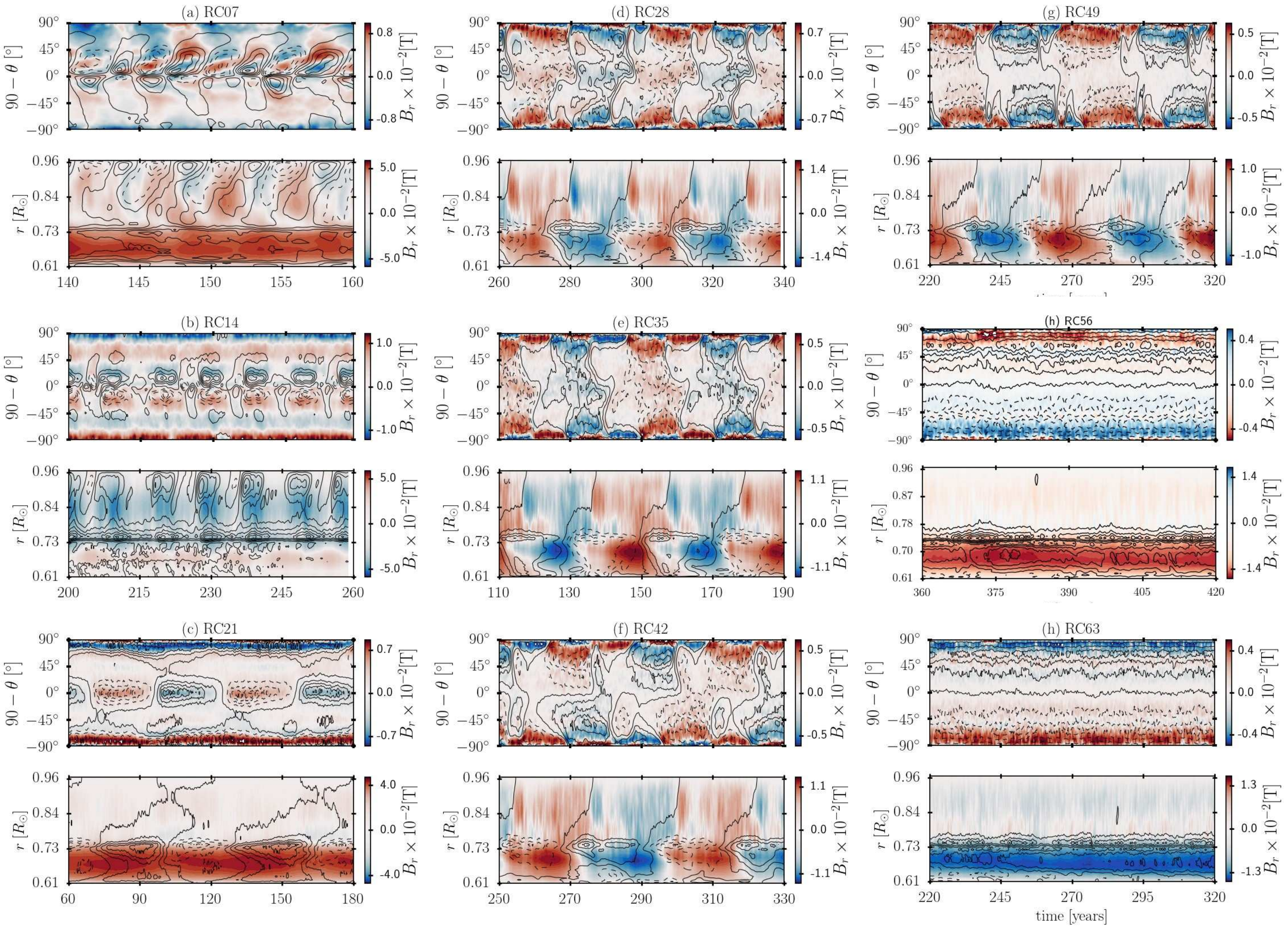




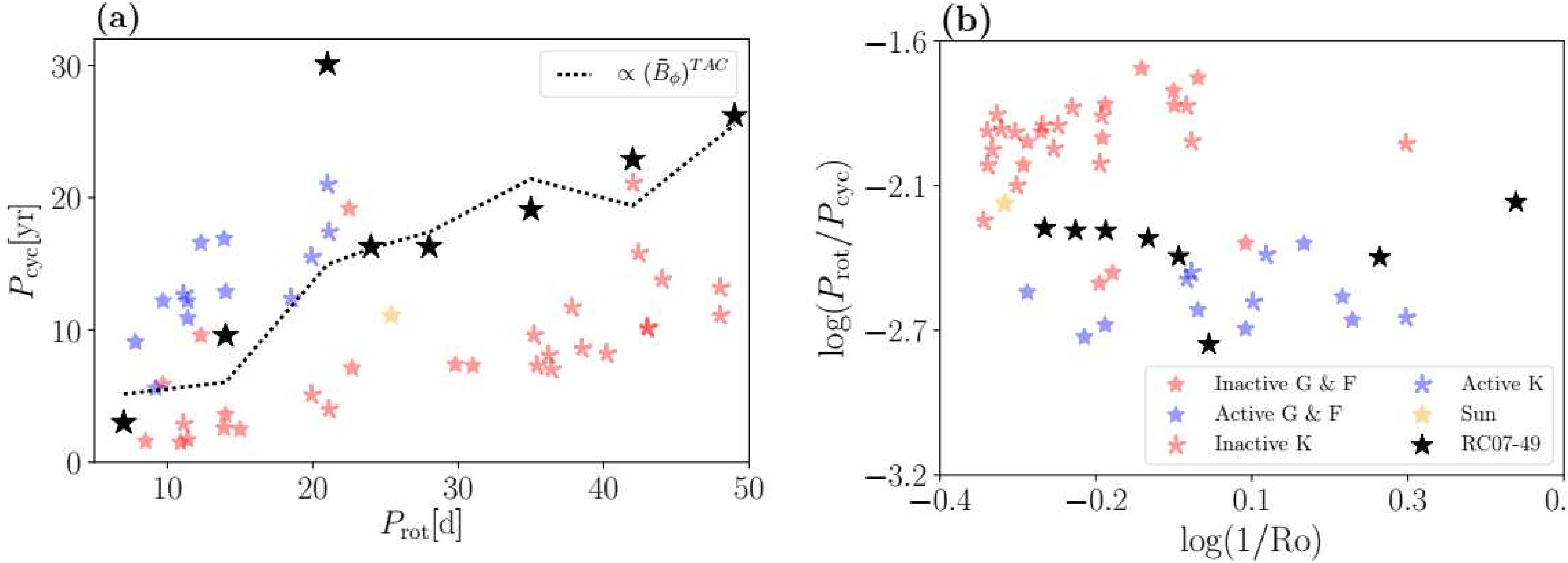


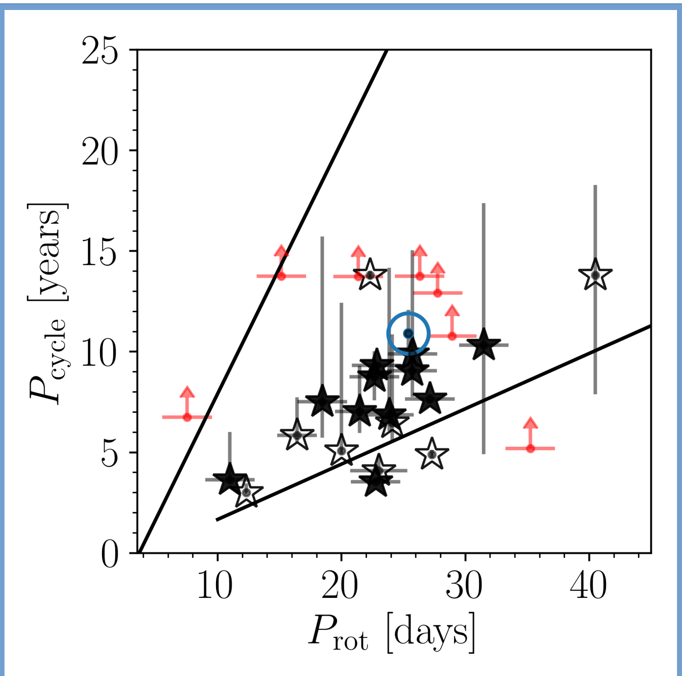


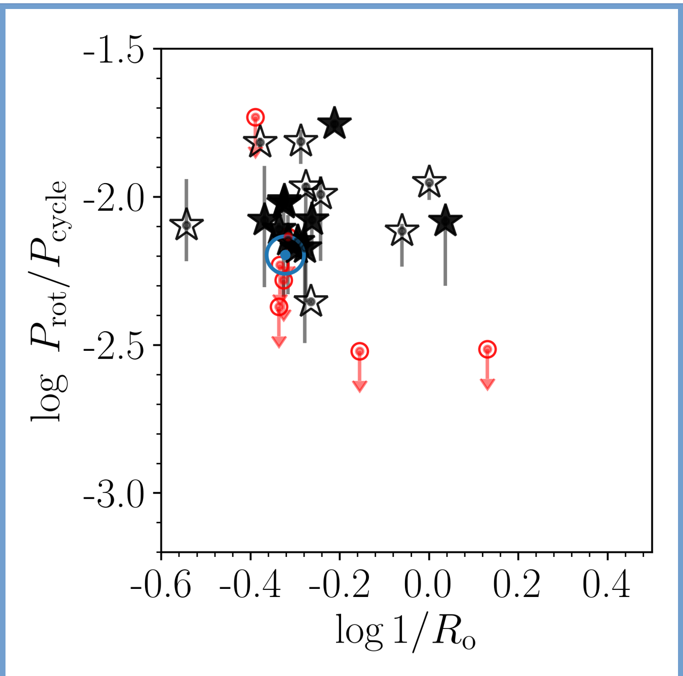
Mean magnetic fields, butterfly diagrams



P_{rot} vs P_{cyc}







Lorenzo Oliveira et al. 2020 (*in preparation*)

Magnetic cycles in solar twins: solar mass, metalicity, surface temperature.

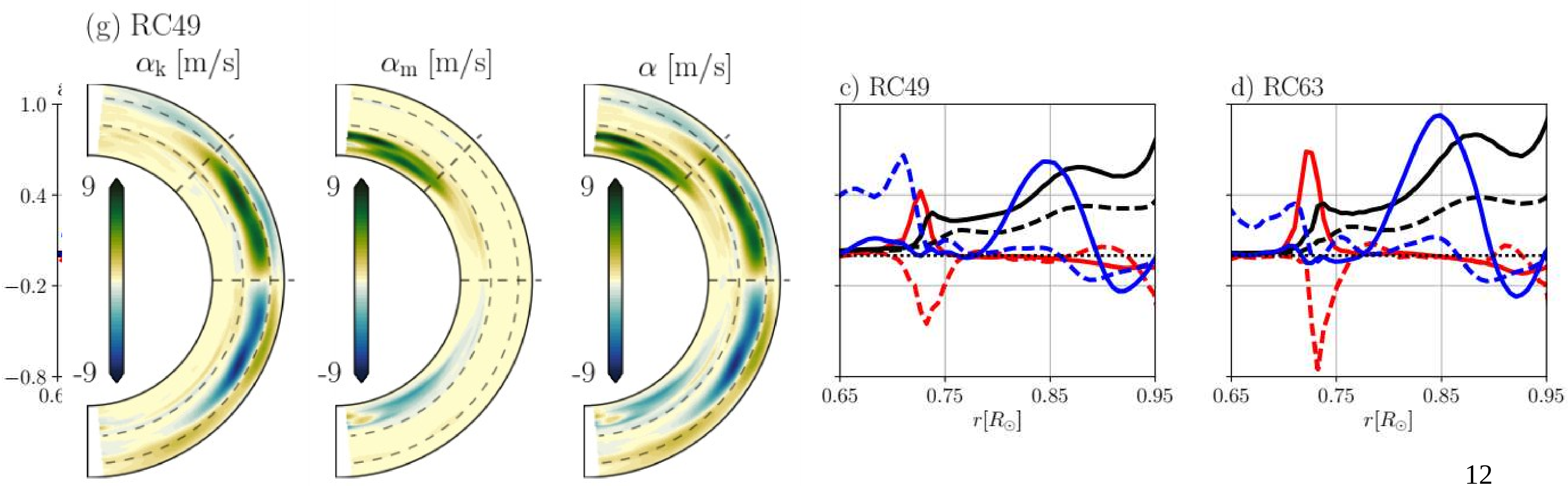
Who sets the cycle period?

A mean-field analysis (with the FOSA approximation) give us some hints

$$\frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \underline{[r \sin\theta \boldsymbol{B}_p \cdot \nabla\Omega]} + \nabla \times (\overline{\boldsymbol{u}_p} \times \overline{\boldsymbol{B}}) + \underline{\nabla \times (\alpha \overline{\boldsymbol{B}})} - \nabla \times (\eta \nabla \times \overline{\boldsymbol{B}})$$

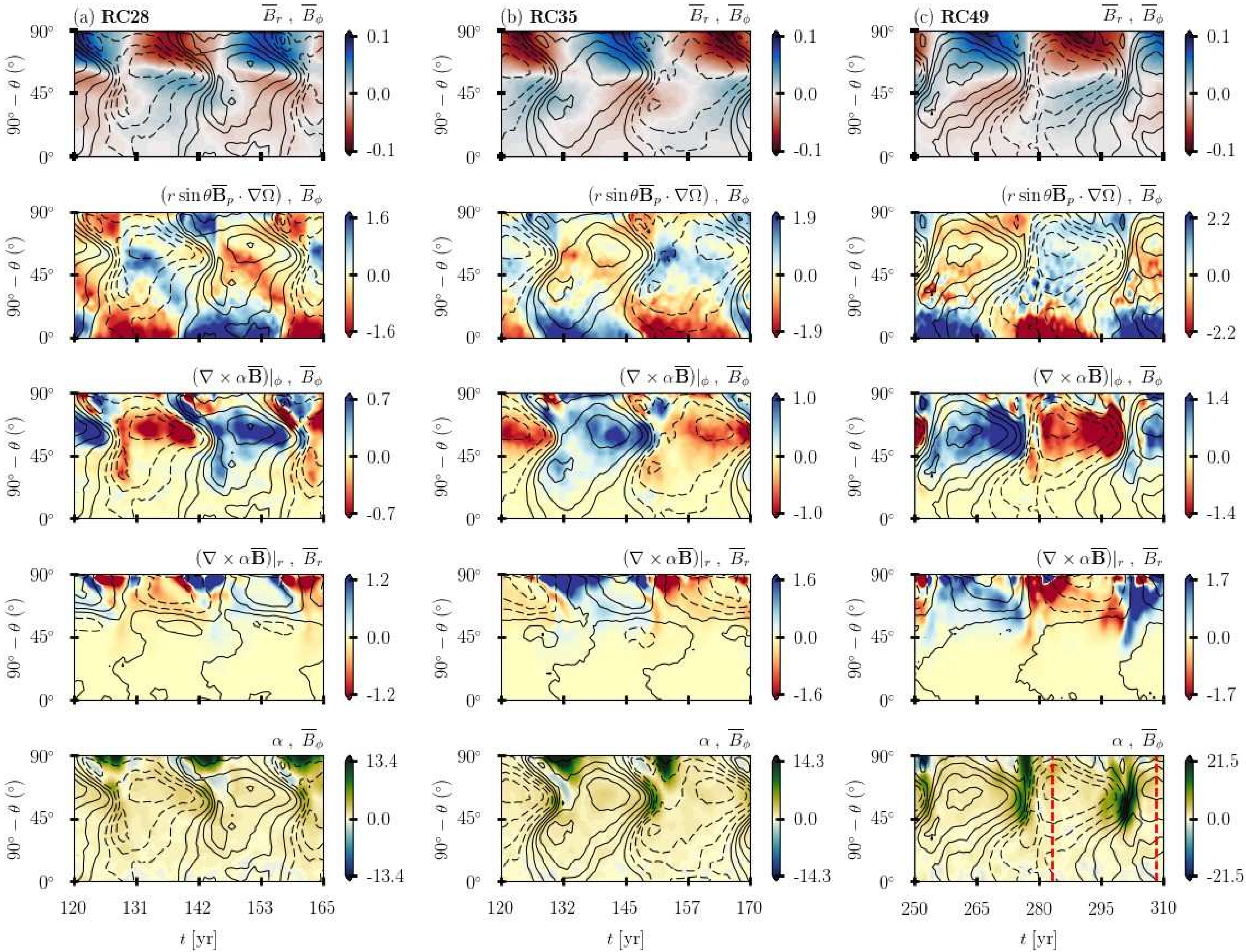
$$\alpha = \alpha_{\rm k} + \alpha_{\rm m} = -\frac{\tau_c}{3}\langle \boldsymbol{\omega}' \cdot \boldsymbol{u}' \rangle + \frac{\tau_c}{3}\langle \boldsymbol{j}' \cdot \boldsymbol{B}' \rangle / \rho_e$$

Moffatt (1968)
Pouquet et al. (1976)



Dynamo sources **below** the convection zone

$\alpha^2\Omega$-dynamo driven by magnetic *α*-effect

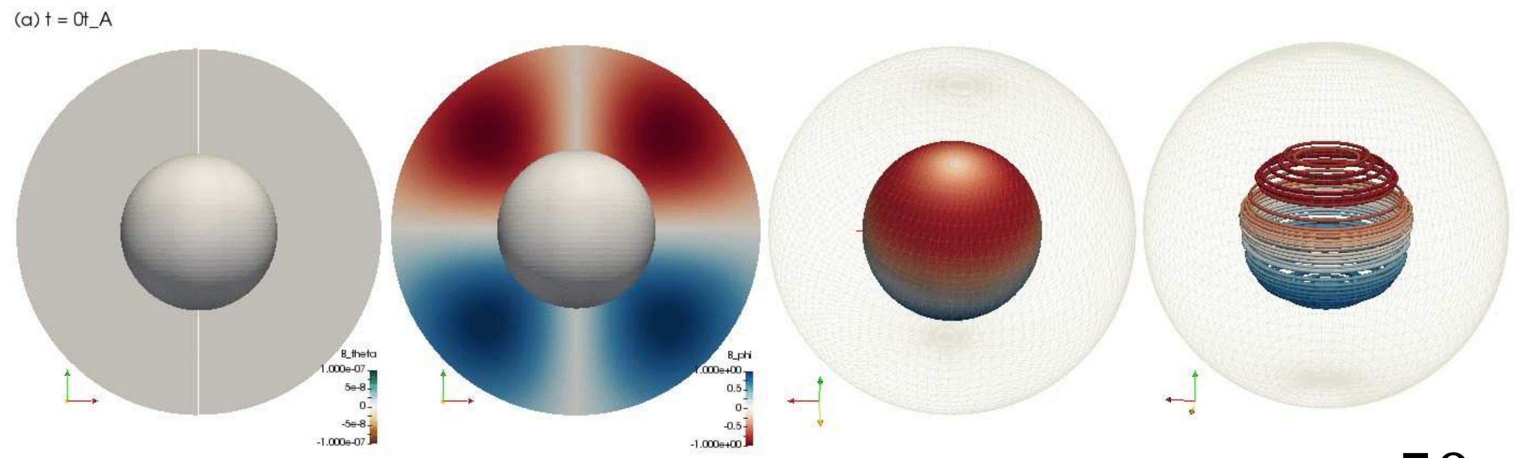


Global simulations of Tayler instability in stellar interiors: the stabilizing effect of gravity

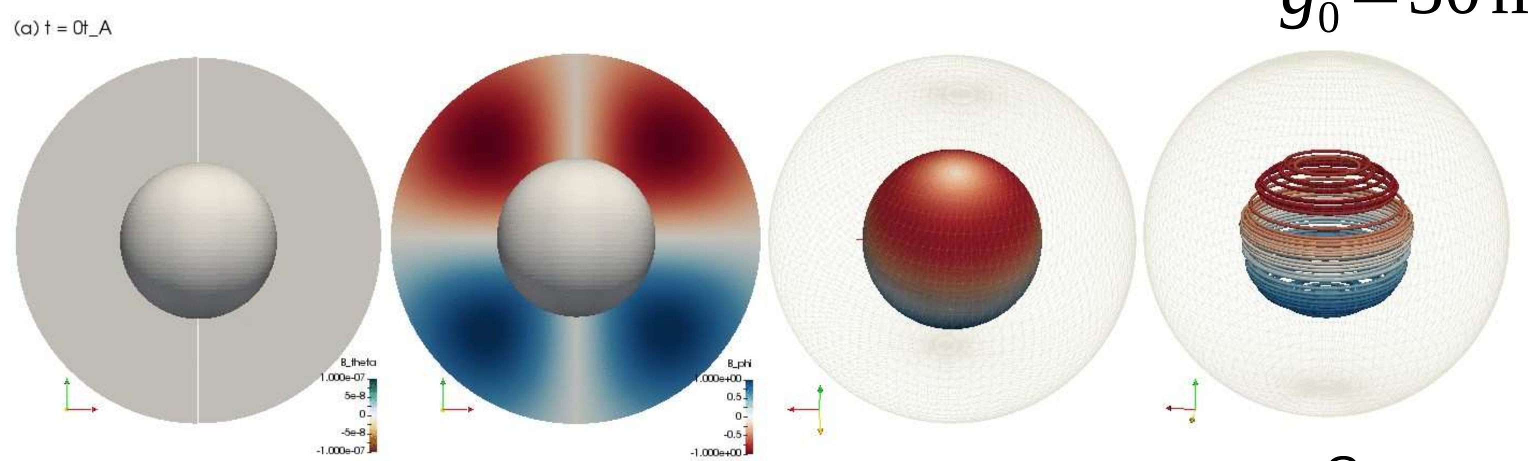
G. Guerrero,[1★] F. Del Sordo ,[2,3★] A. Bonanno[4] and P. K. Smolarkiewicz[5]

[1] Physics Department, Universidade Federal de Minas Gerais, Av. Antonio Carlos, 6627, Belo Horizonte, MG 31270-901, Brazil
[2] Institute of Astrophysics, FORTH, GR-71110 Heraklion, Greece
[3] Department of Physics, University of Crete, GR-70013 Heraklion, Greece
[4] INAF, Osservatorio Astrofisico di Catania, via S. Sofia, 78, I-95123 Catania, Italy
[5] European Centre for Medium-Range Weather Forecasts, Reading RG2 9AX, UK

$$g_0 = 1\,\mathrm{m} / \mathrm{s}^2$$



$$g_0 = 50\,\mathrm{m} / \mathrm{s}^2$$



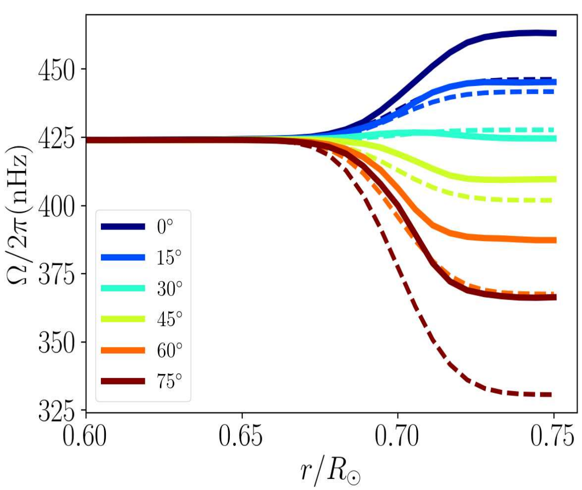
Guerrero et al. 2019b

Dynamo driven by shear and tachocline instabilities (G. Monteiro, preliminary results)

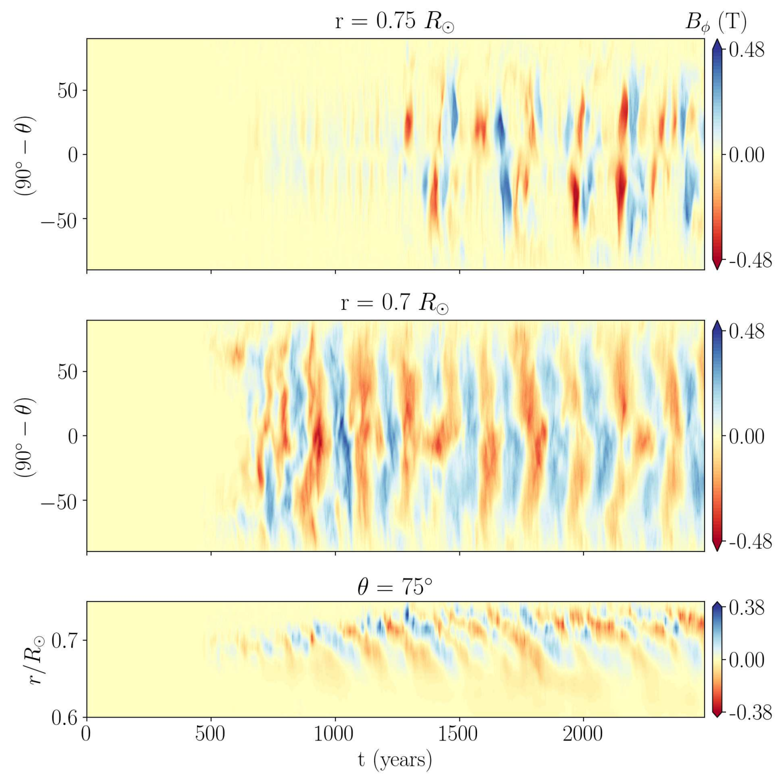
- Inspired by Miesch et al. (ApJS, 2007), Miesch (ApJL, 2007)
- In collaboration with F. del Sordo, A. Bonanno and P. Smolarkiewicz

- The EULAG-MHD simulations consider of a **stable** layer with forced shear

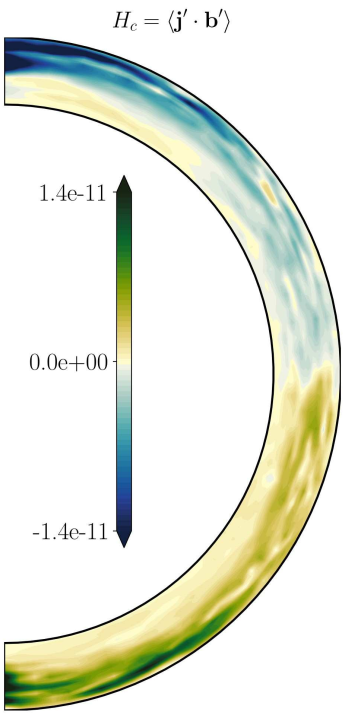
Shear profile forced on a time-scale, τ_s



Resulting $\langle B_\varphi \rangle$, P_{cyc} = *190* yr



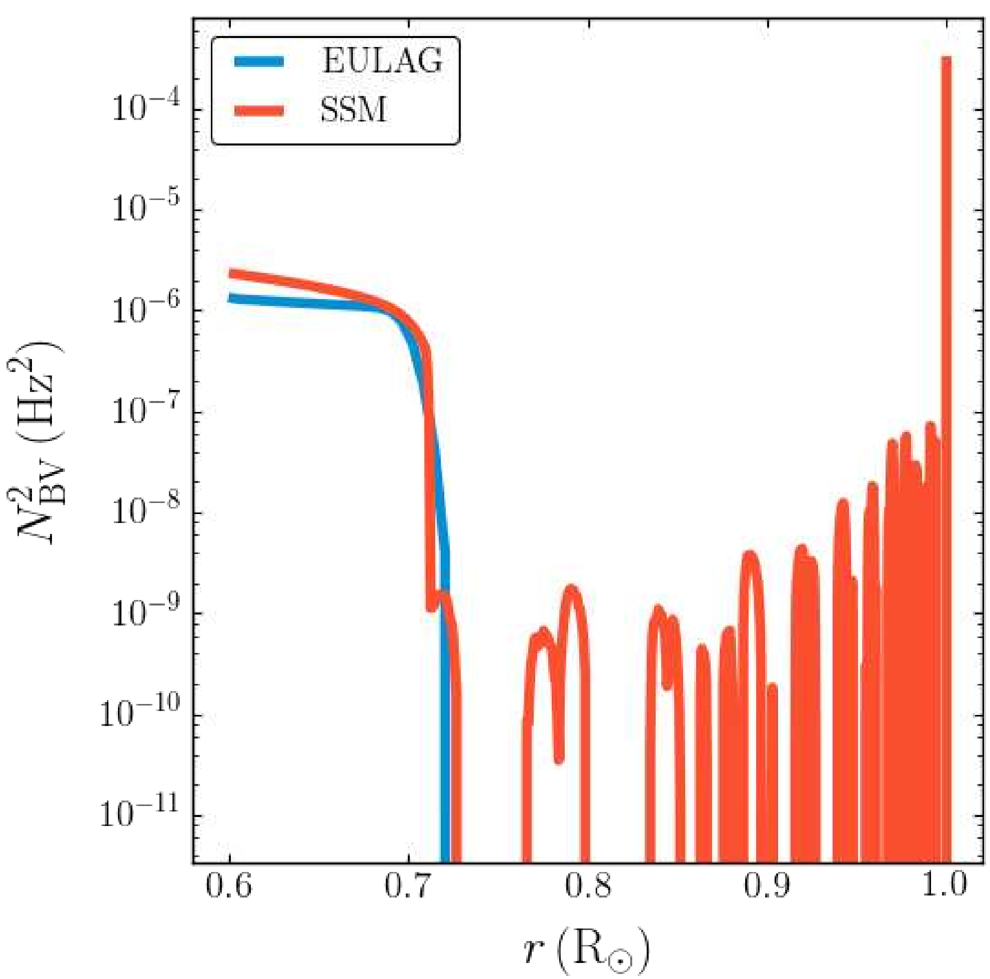
Resulting $\langle H_c \rangle$

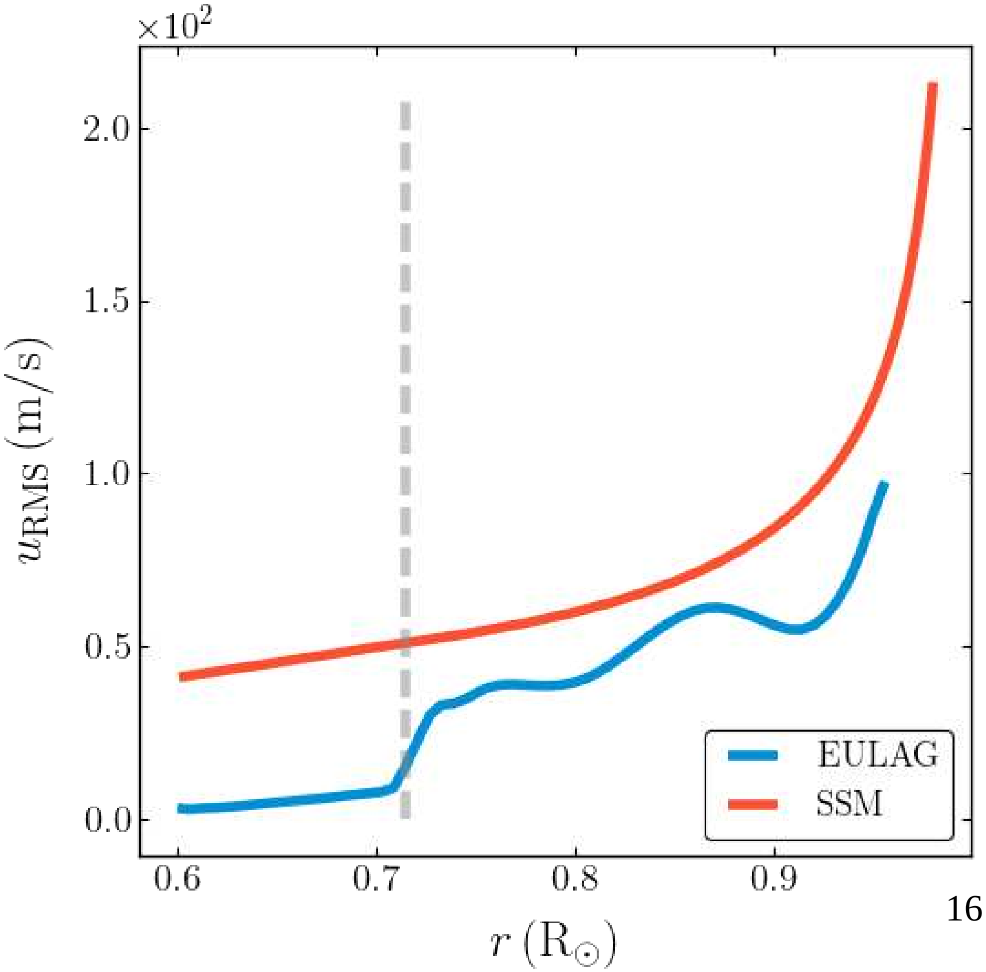


New solar dynamo model (R. Barbosa, preliminary results)

- Brunt-Väisäla frequency fundamental defining the growth rate of the instabilities

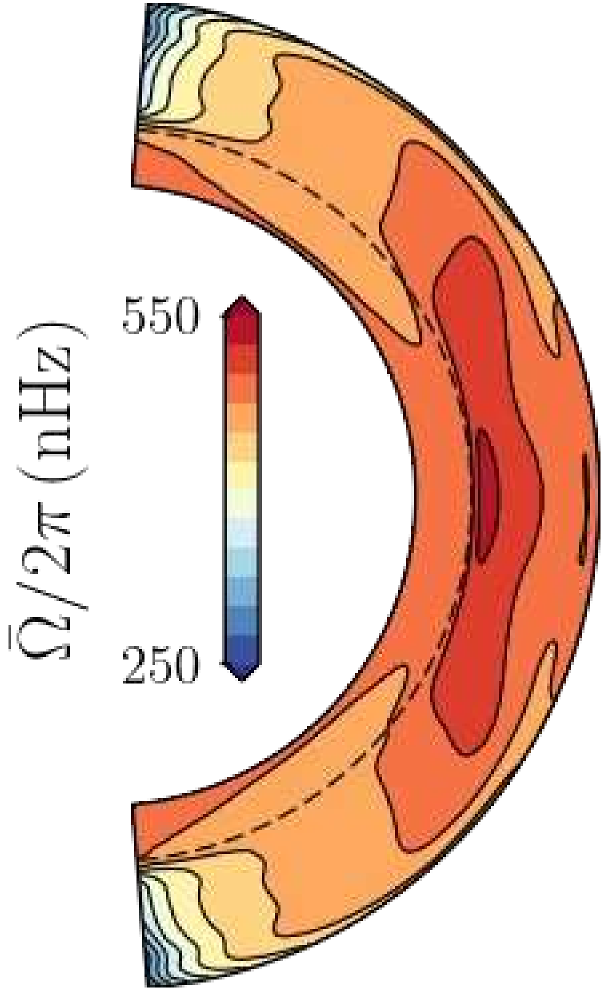
- In the convection zone the amplitude of the convective motions define the differential rotation



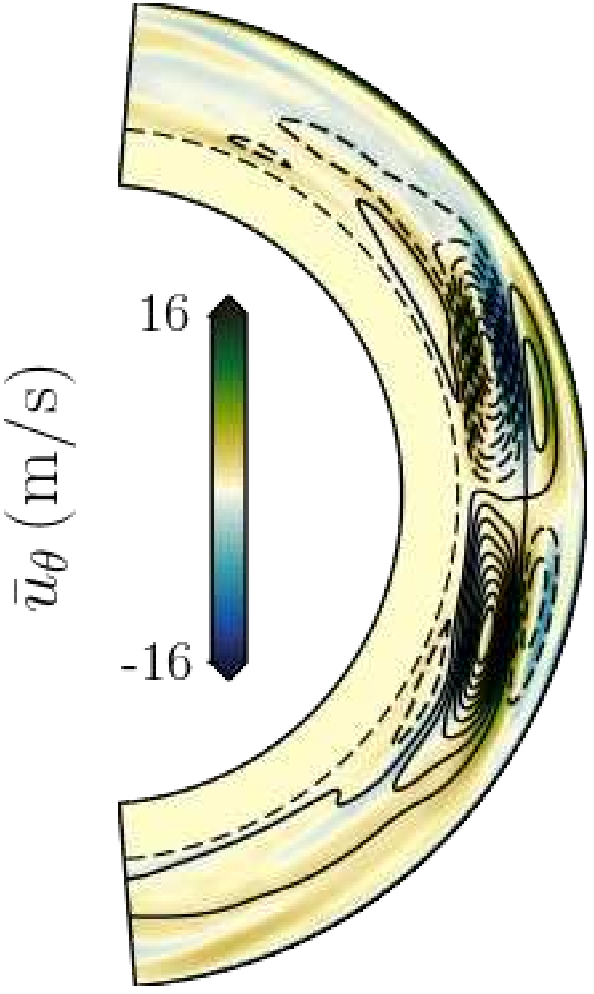


New solar dynamo model (preliminary results)

- Differential Rotation

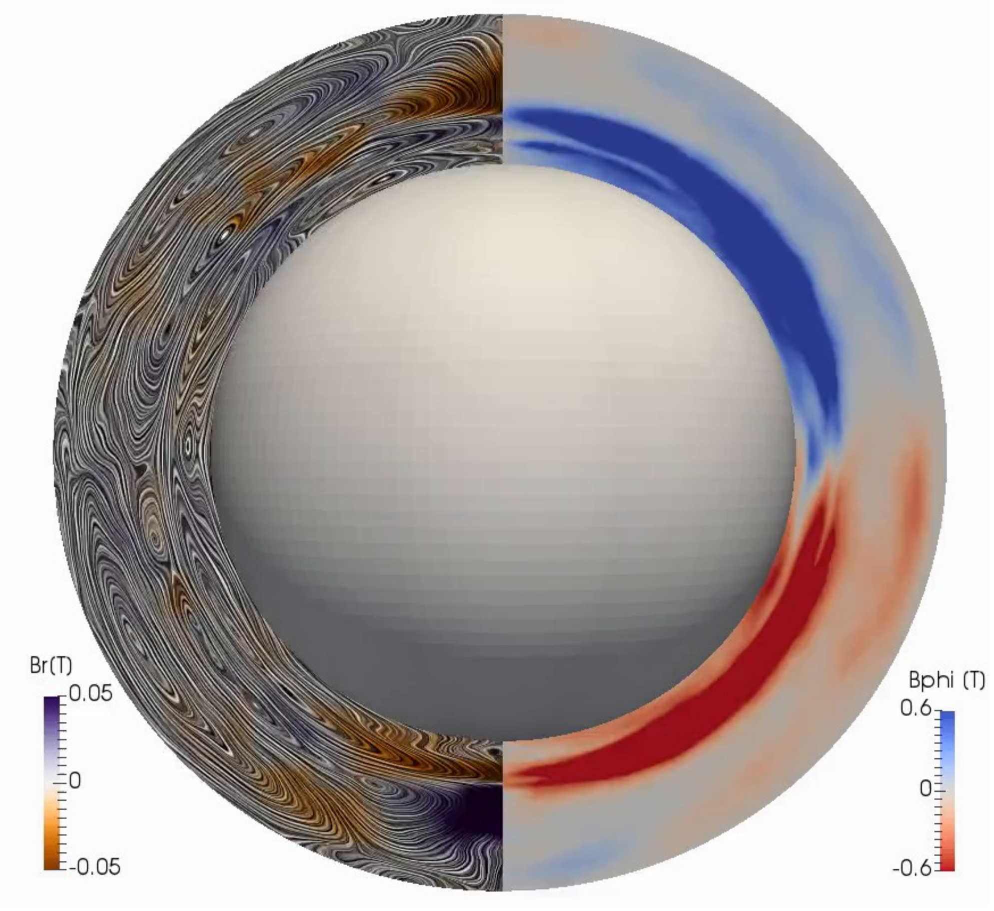


- Meridional Circulation



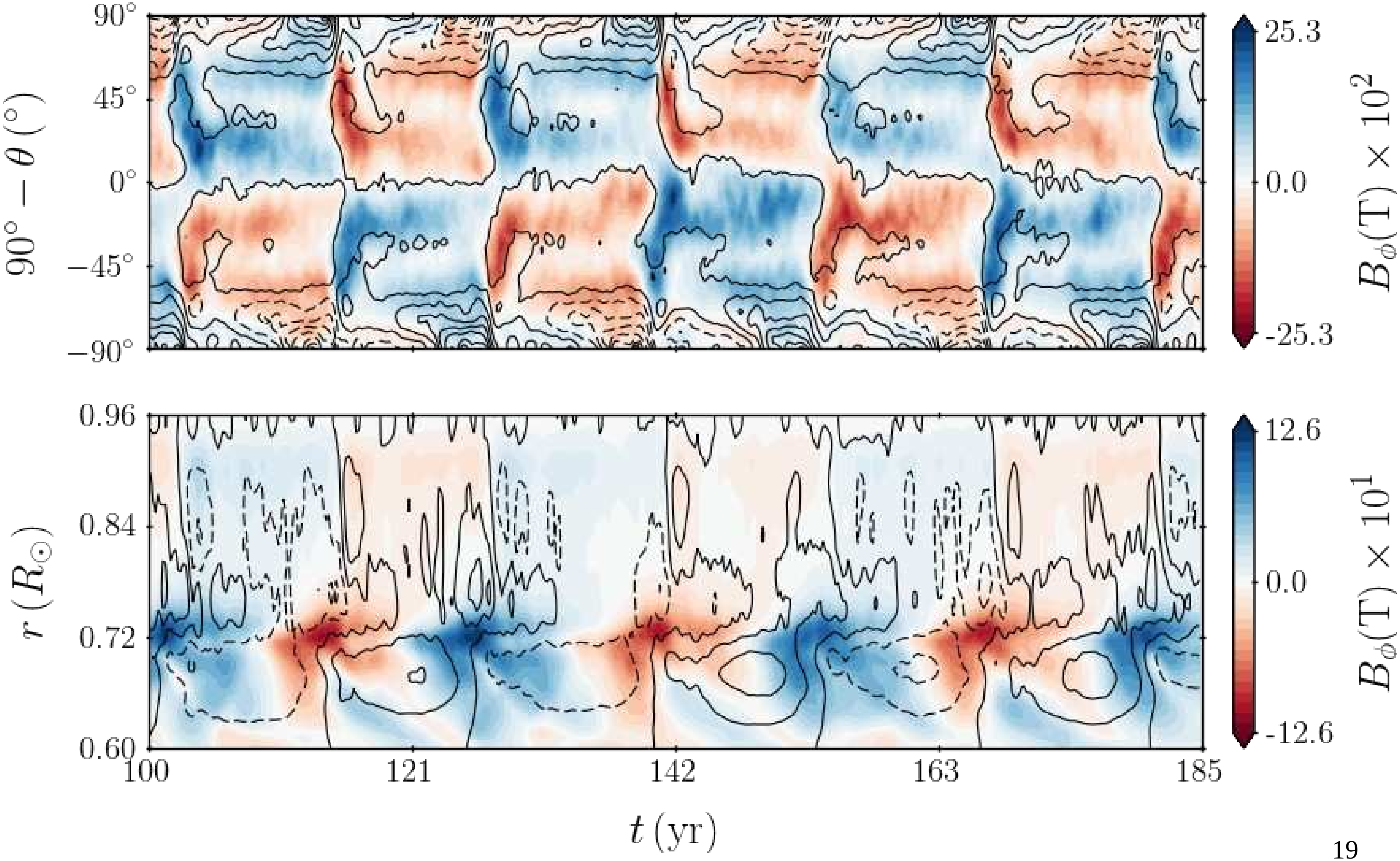
New solar dynamo model (preliminary results)

- Mean magnetic field (averaged in φ)



- Antisymmetric fields
- P_{cyc} = *12* yr
- **Magnetic buoyancy** at middle to lower latitudes, stops before reaching the surface
- Field transported at $r=0.85$ R_0 towards equator and poles
- $\langle B_r \rangle \sim 0.004$ T mostly dipolar configuration

- $\langle B_\varphi \rangle$ ($r=0.85R_0$)

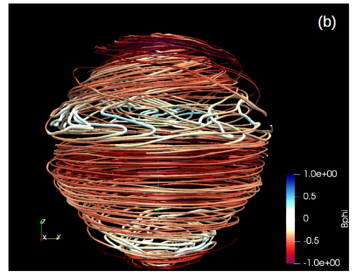


New solar dynamo model (preliminary results)

- Magnetic field lines

Dynamo loop

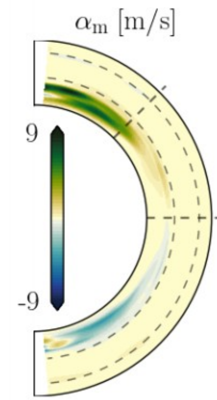
$\Omega-\text{effect}$



$B_\phi(m=0)$

Shear-current instability

$\boldsymbol{b}'(m\neq0)$

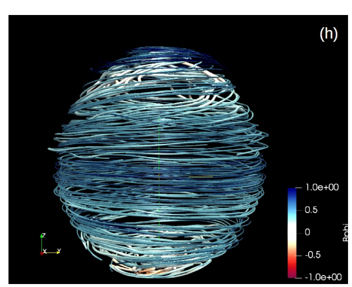


$$\alpha_m=\frac{\tau_c}{3\rho}\langle \boldsymbol{j}'\cdot\boldsymbol{b}'\rangle$$

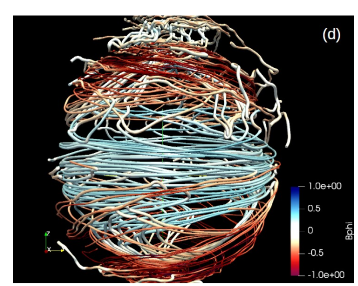
$(m=0)$

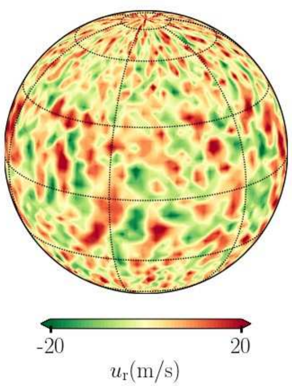
$\alpha^2-\text{effect}$

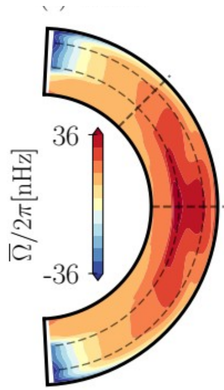
$B_\phi(m=0)$



$B_p(m=0)$







Rotating turbulent convection

$\nabla\Omega(m=0)$

Torsional oscillations
(Guerrero et al., 2016
Kosovichev & Pipin, 2019)

Conclusions

- We present global simulations where the dynamo operates in the radiative zone due to magneto-shear instabilities which result in non-zero magnetic and kinetic helicities
- The dynamos are of $\alpha^2\Omega$ type
- The toroidal field at the bottom gets unstable and buoyantly rises to the top
- New models are closer to the observations

Things to be done

- Upper 0.05% of the solar radius is missing. A compressible solver is needed to resolve this region.
- Convergence of the results with numerical resolution. This requires improving parallelism and lots of computing time.
- Fiduciary determination of the dynamo coefficients (test-field method)