UFMG

Global solar dynamo simulations with and without tachocline. The quest for the dynamo location

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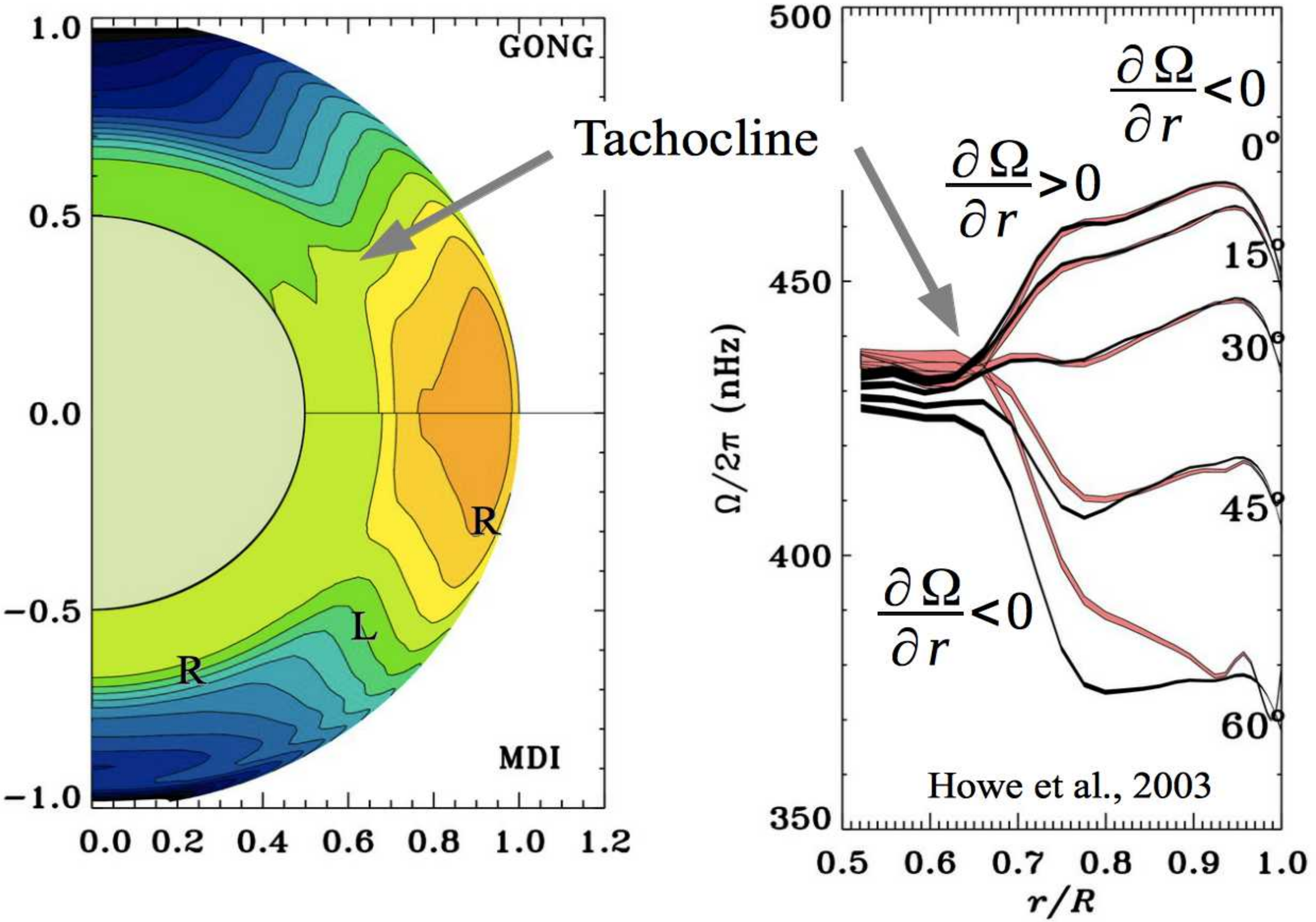
Large-scale motions in the solar interior

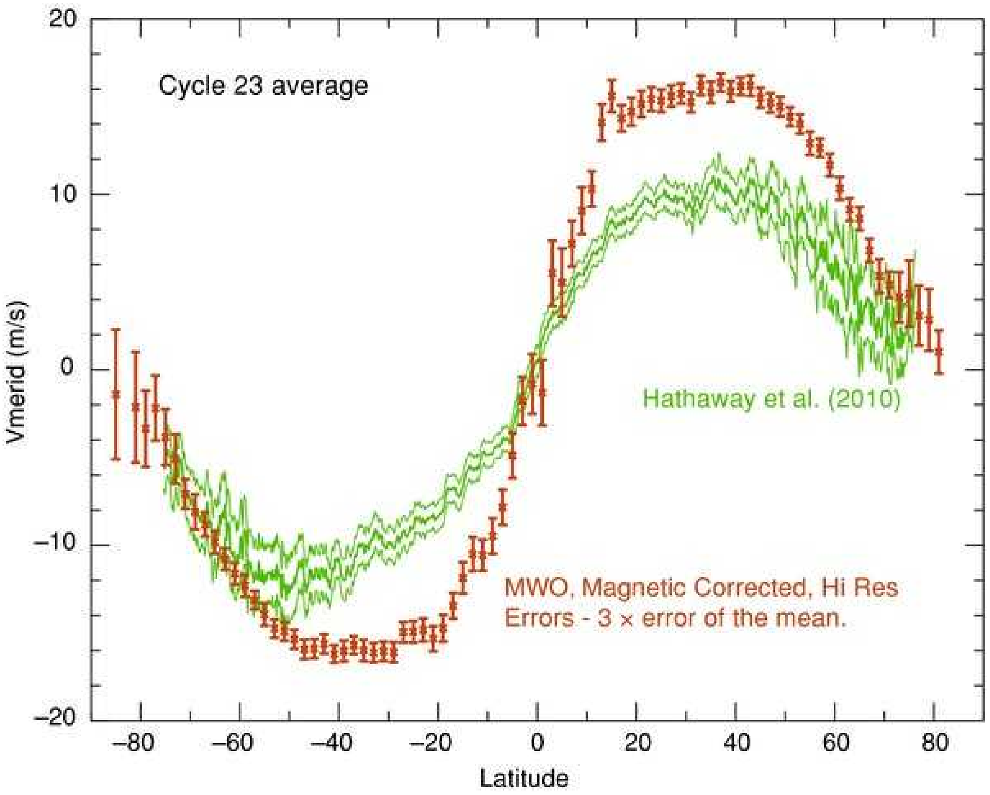
Differential Rotation



Large-scale motions in the solar interior

Meridional Circulation

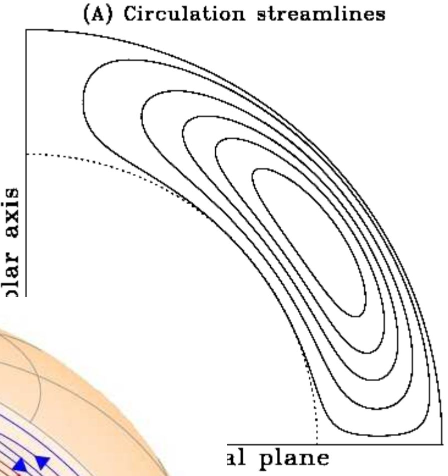
Surface



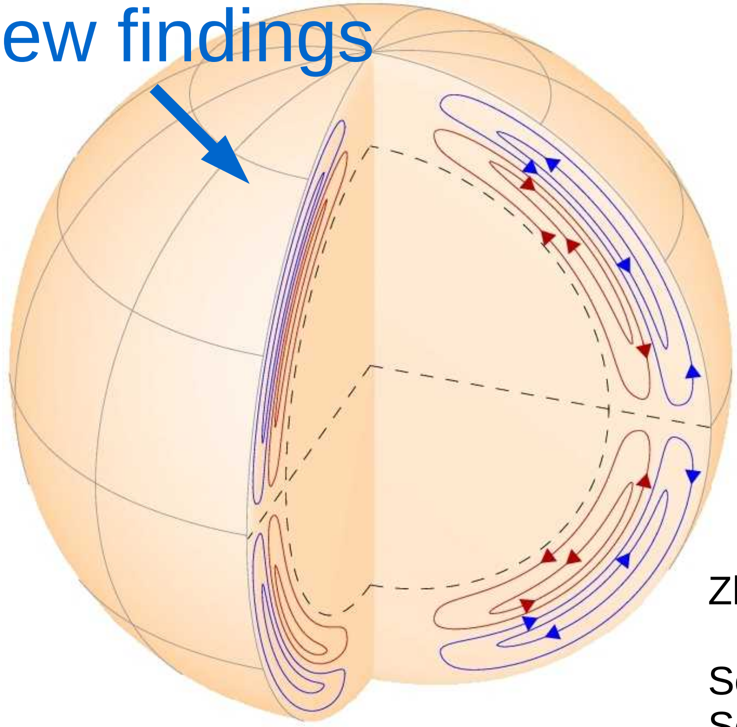
Ulrich (2010)

Sub-surface

old beliefs



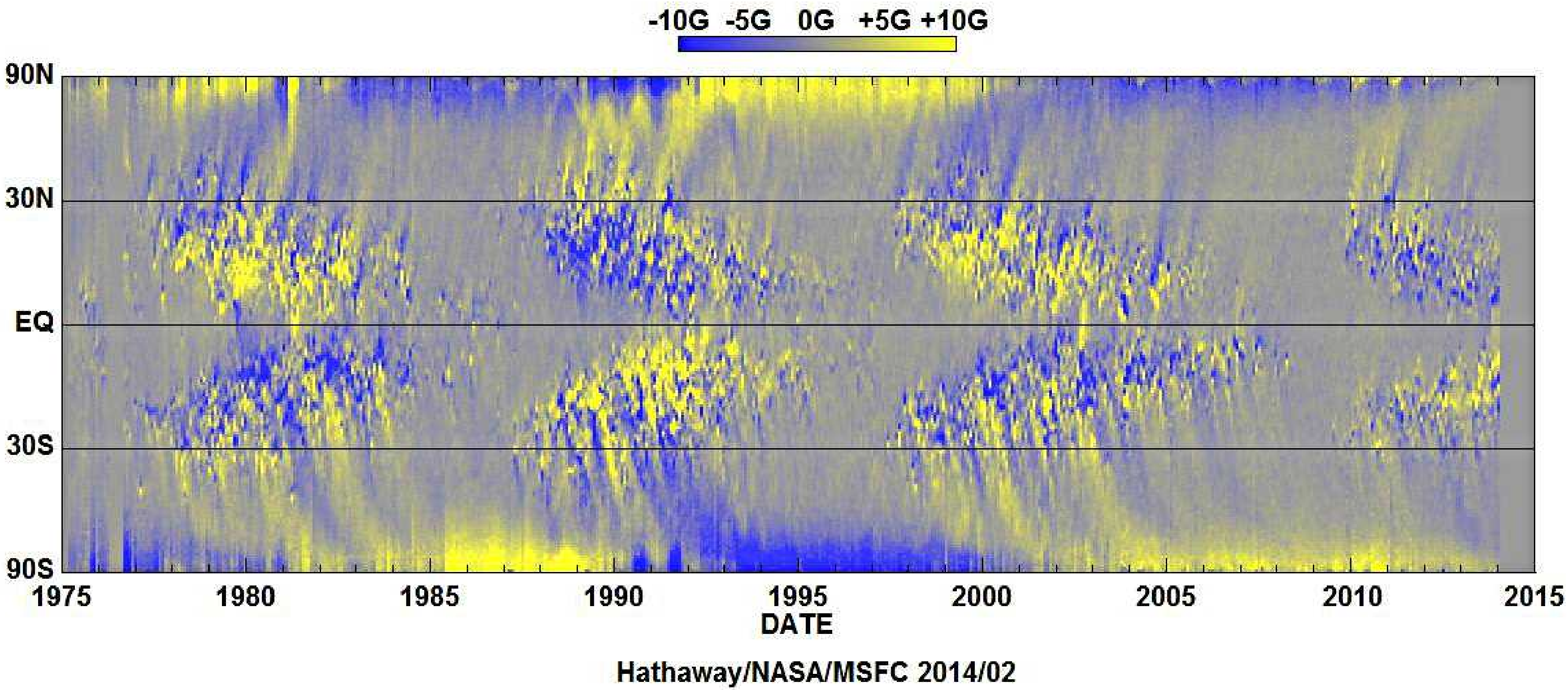
New findings

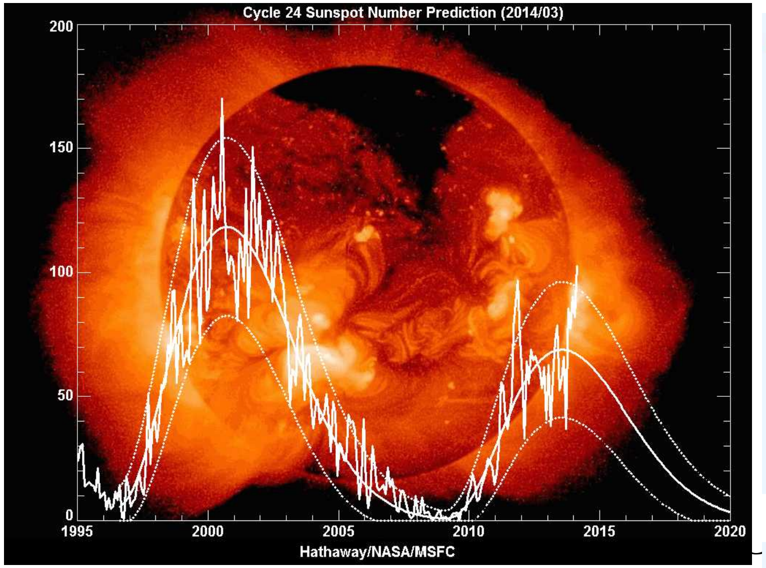


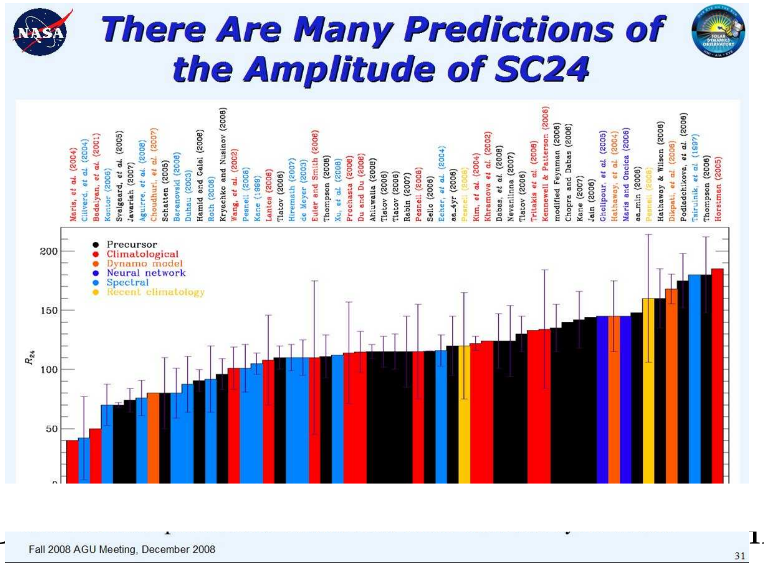
Zhao+ (2103)

See also:
Schad+ (2013)

Large-scale magnetic fields







Solar Cycle 24

Most of the dynamo-based predictions have failed to reproduce the sunspot number and overall solar activity. ***The physics in the models is not complete.***

Anelastic simulations with the **EULAG** code

Anelastic approximation (Lipps & Helmer 1982, Lipps 1990)

(Guizaru+ 2010, Racine+ 2011, Smolarkiewicz & Charbonneau 2013, Cossette+ 2013, Guerrero+ 2013, Guerrero+ 2015)

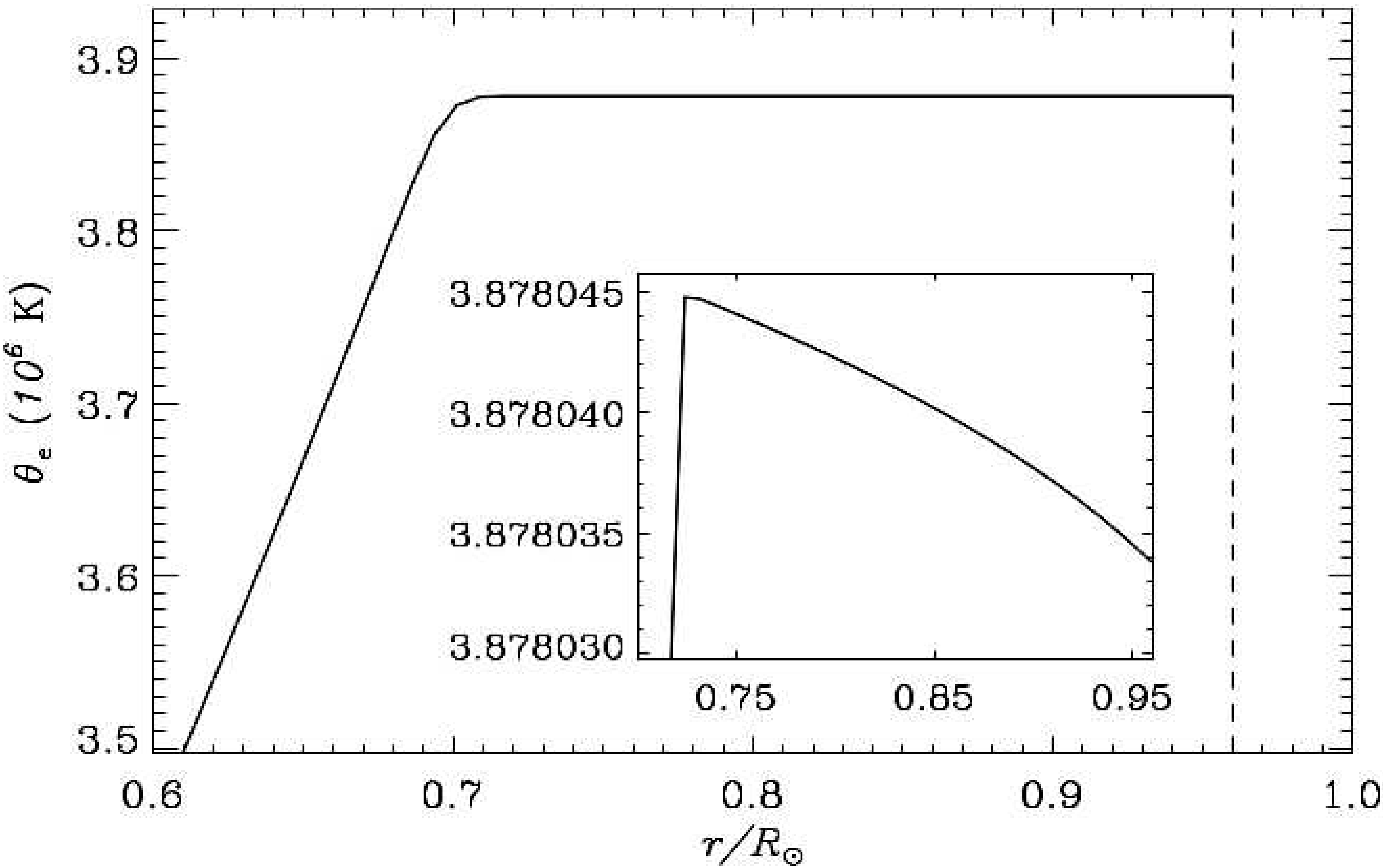
$$\nabla \cdot (\rho_0 \mathbf{u}) = 0, \tag{1}$$

$$\frac{D\mathbf{u}}{Dt} + 2\boldsymbol{\Omega} \times \mathbf{u} = -\nabla\left(\frac{p'}{\rho_0}\right) + \mathbf{g}\frac{\Theta'}{\Theta_0} + \cancel{\frac{\mathbf{F}}{\rho_0}}, \tag{2}$$

$$\frac{D\Theta'}{Dt} = -\mathbf{u} \cdot \nabla\Theta_e + \cancel{\frac{1}{\rho_0}\mathcal{H}(\Theta')} - \alpha\Theta' \tag{3}$$

$$ds = c_p d \ln \Theta \tag{4}$$

$$\frac{D\mathbf{B}}{Dt} = \mathbf{B} \cdot \nabla\mathbf{u} - \mathbf{B}\nabla \cdot \mathbf{u}$$



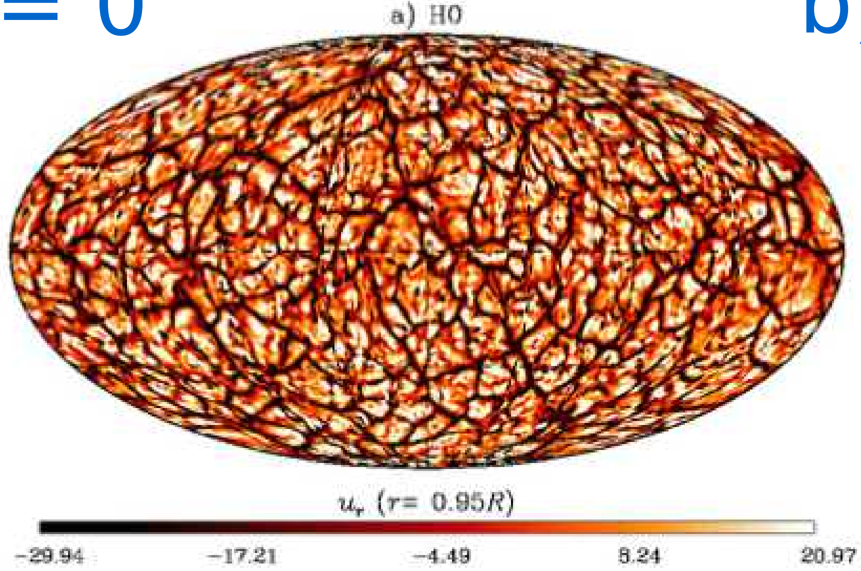
3.9
3.8
3.7
3.6
3.5
θ_e (10^6 K)
3.878045
3.878040
3.878035
3.878030
0.75
0.85
0.95
0.6
0.7
0.8
0.9
1.0
$r/R_\odot$

HD

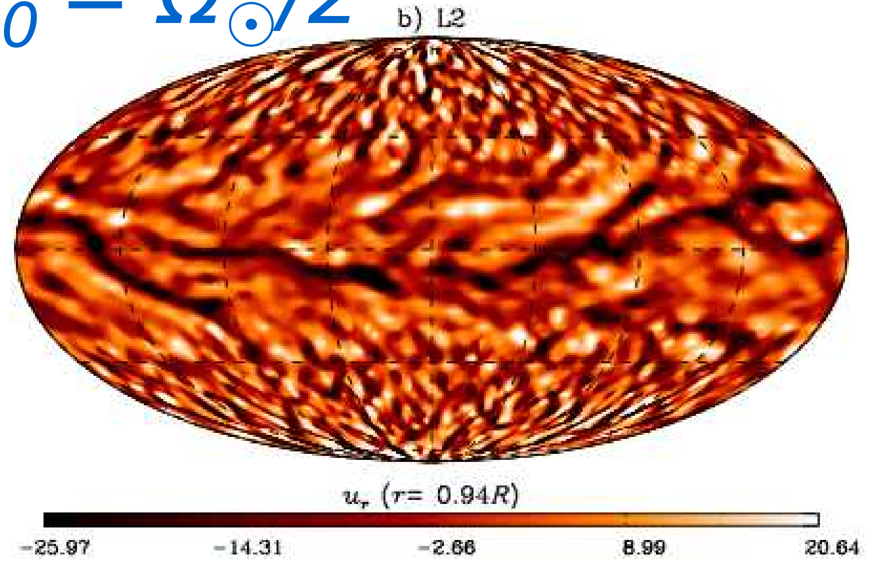
Differential rotation in **solar-like** stars

Guerrero+ (2013)

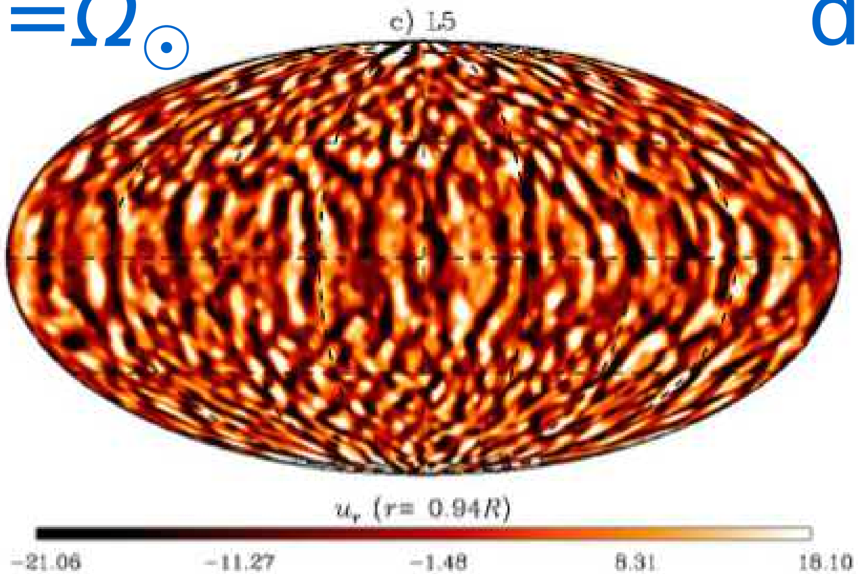
a) $\Omega_0 = 0$



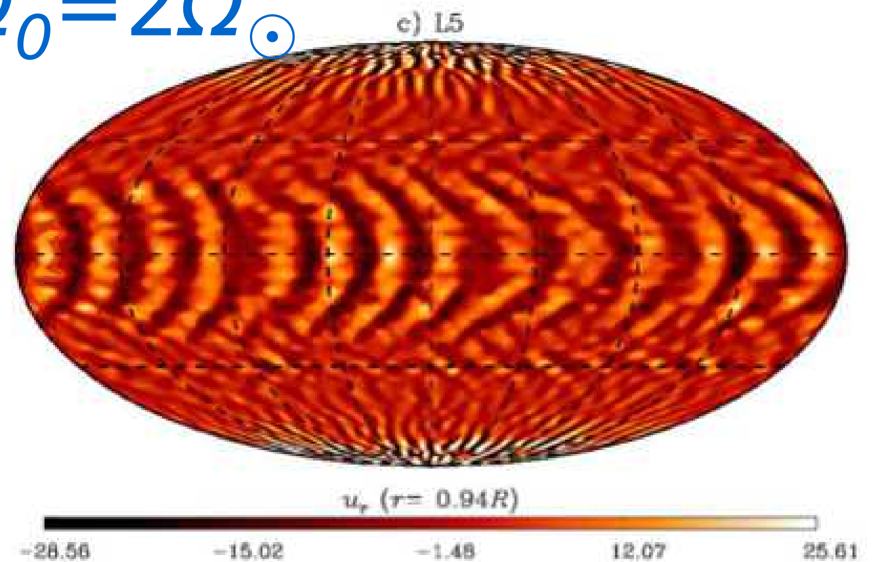
b) $\Omega_0 = \Omega_\odot/2$



c) $\Omega_0 = \Omega_\odot$

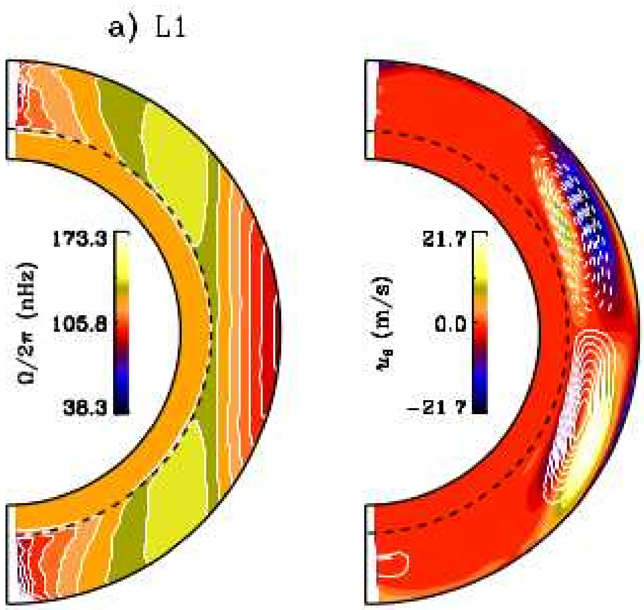


d) $\Omega_0 = 2\Omega_\odot$

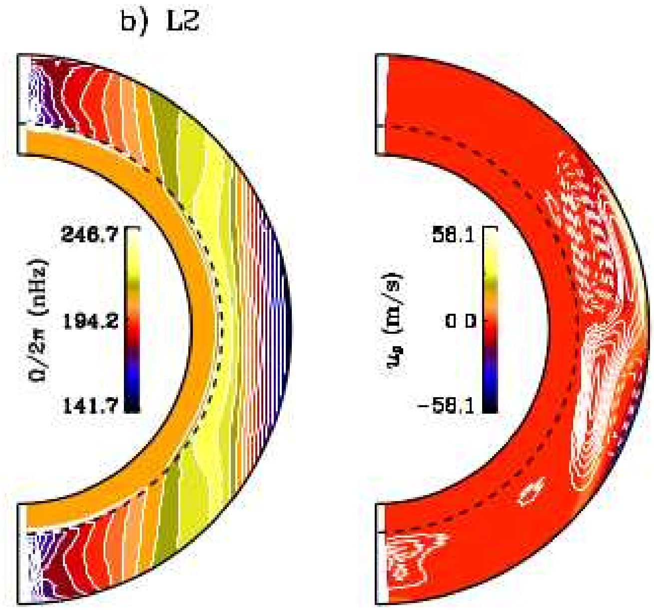


G.

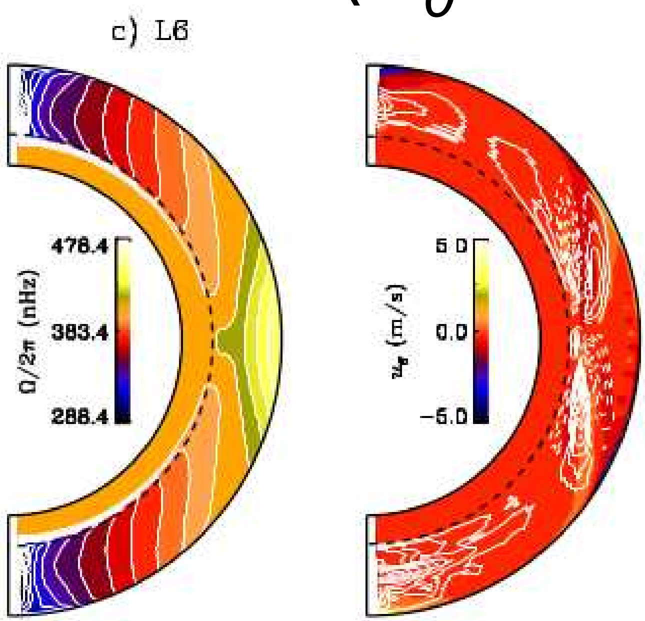
a) $T = 112$d ($\Omega_0 = \Omega_\odot/4$)



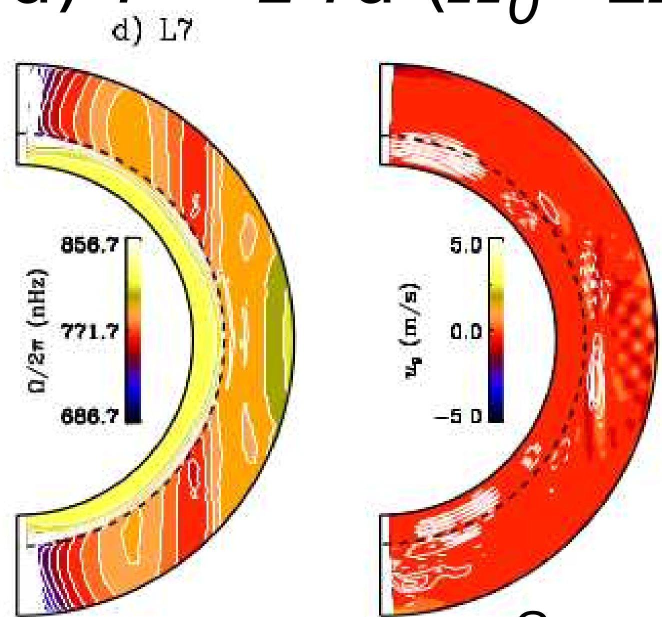
b) $T = 56$d ($\Omega_0 = \Omega_\odot/2$)



c) $T = 28$d ($\Omega_0 = \Omega_\odot$)



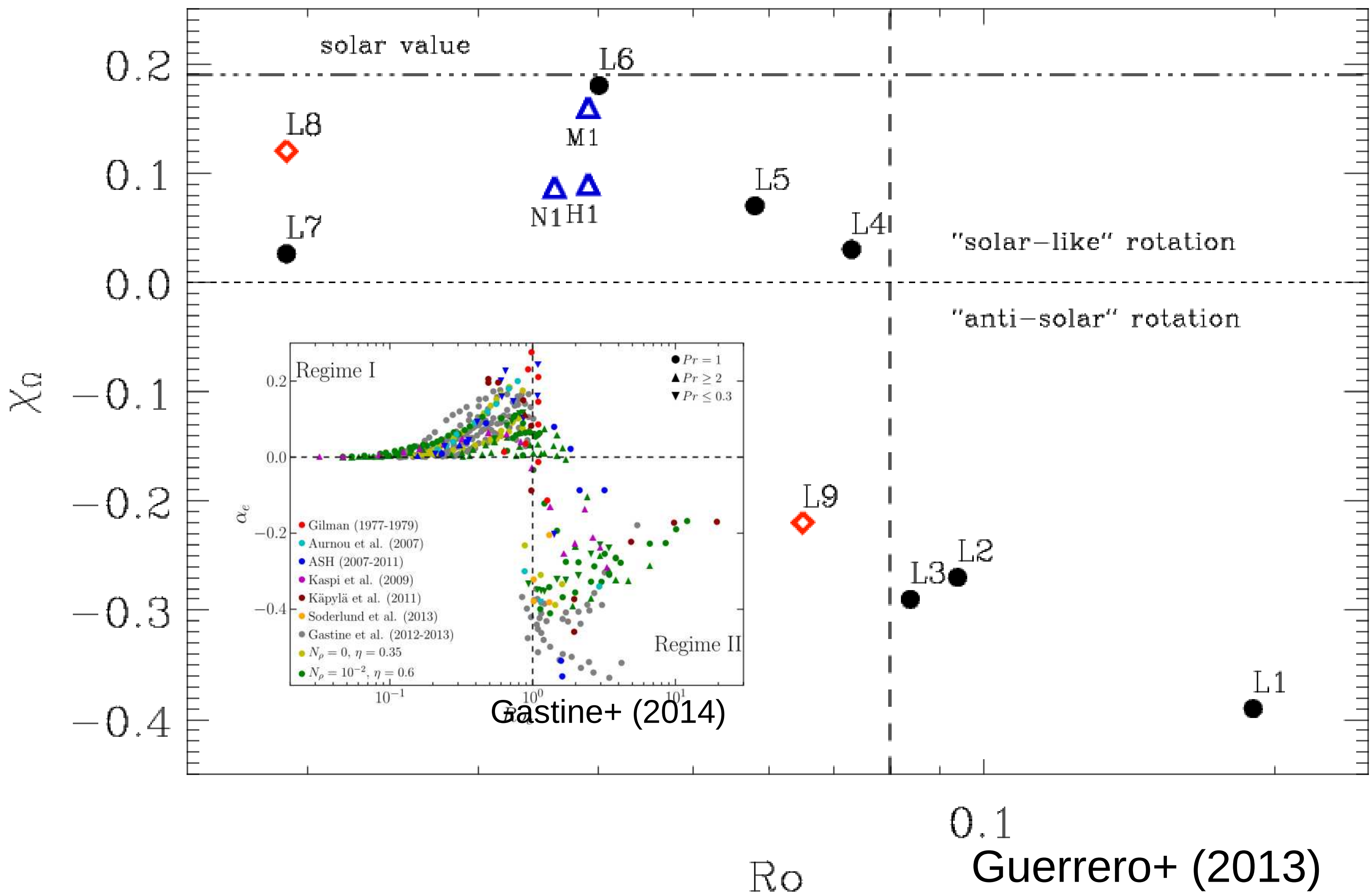
d) $T = 14$d ($\Omega_0 = 2\Omega_\odot$)



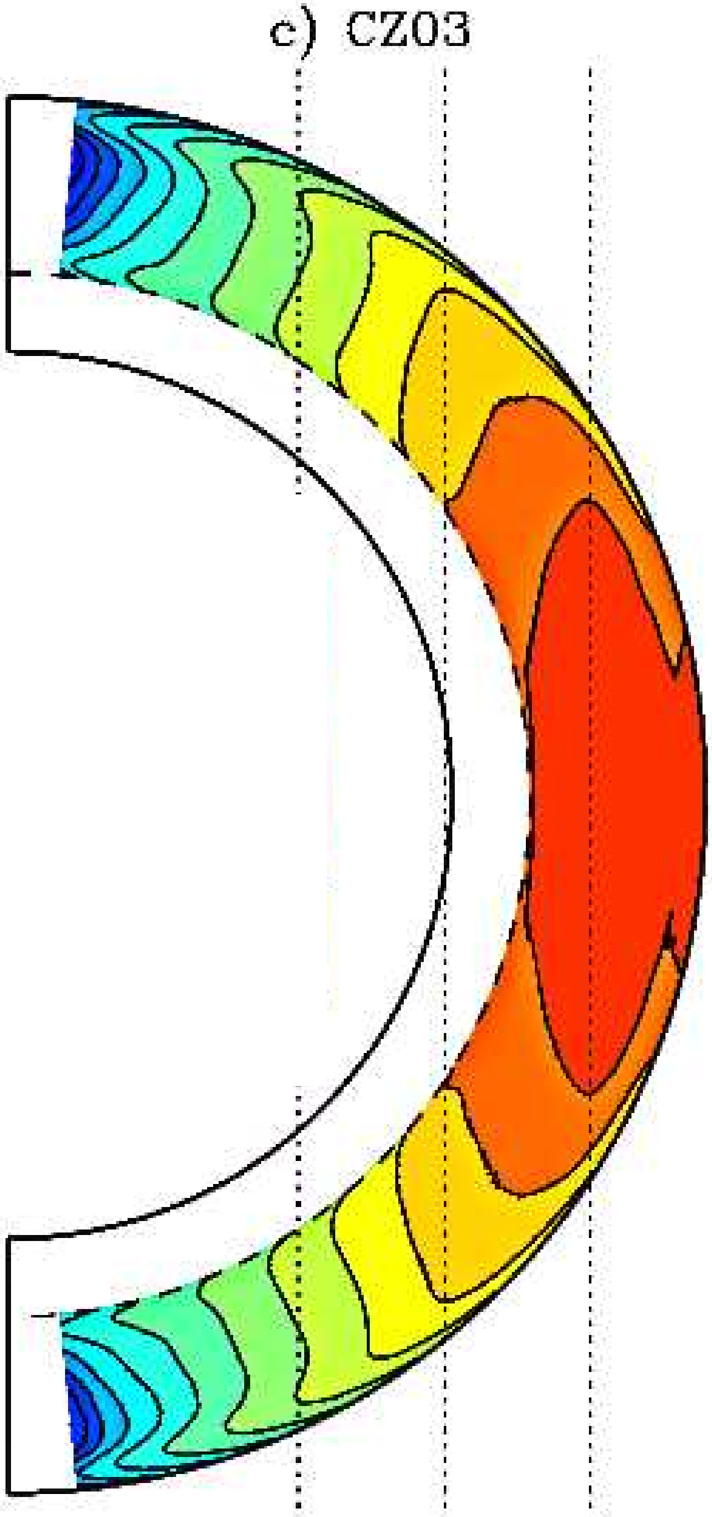
SUNSPOTS, (

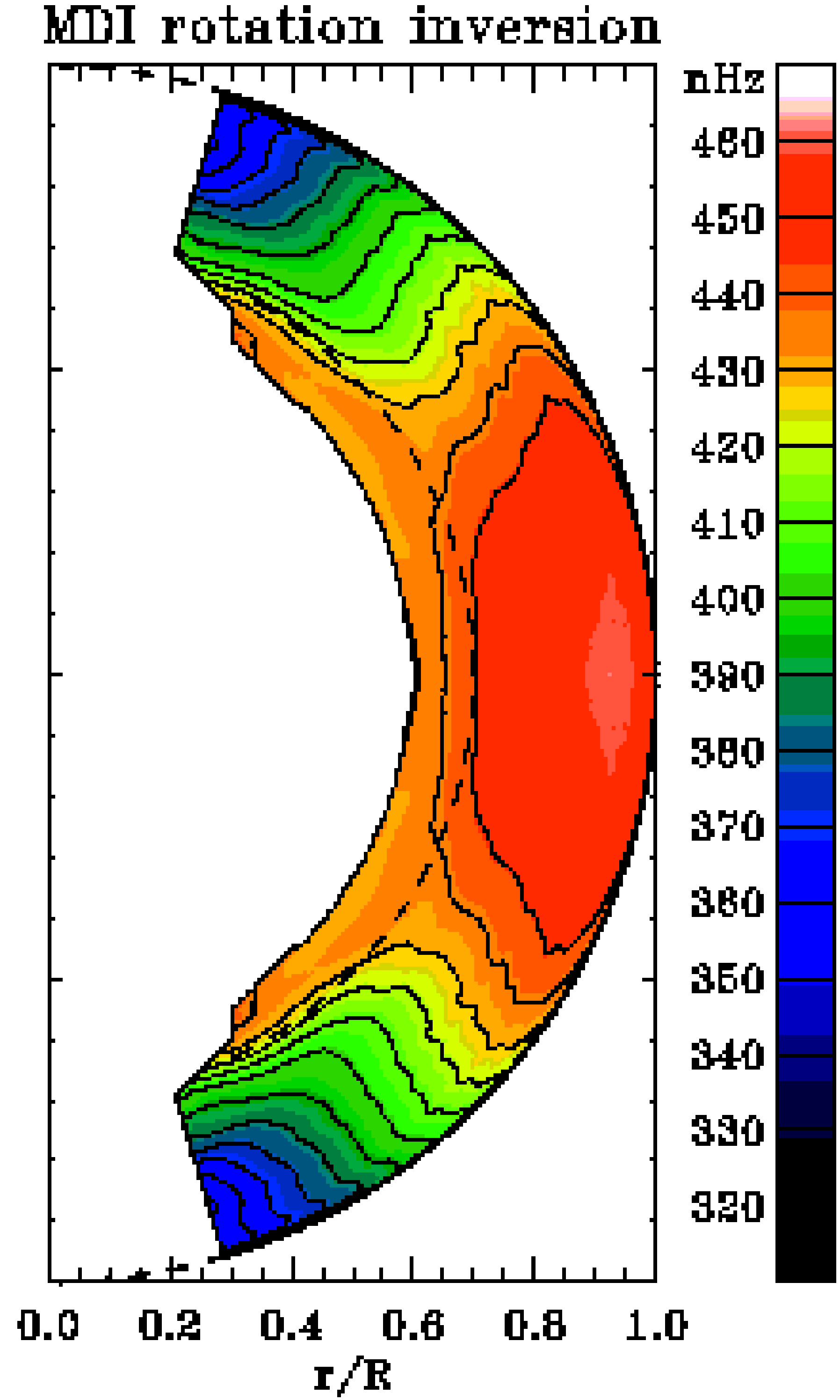
Guerrero+ (2013)

The differential rotation profile is defined by the delicate balance between **buoyancy** and **Coriolis** forces defined by the **Rossby** number (Ro). **Solar-like** (fast equator) and **anti-solar** modes (faster poles) are obtained. The transition between the two regimes is sharp.



MHD


c) CZ03


MDI rotation inversion
nHz
460
450
440
430
420
410
400
390
380
370
360
350
340
330
320
0.0
0.2
0.4
0.6
0.8
1.0
r/R

SUNS

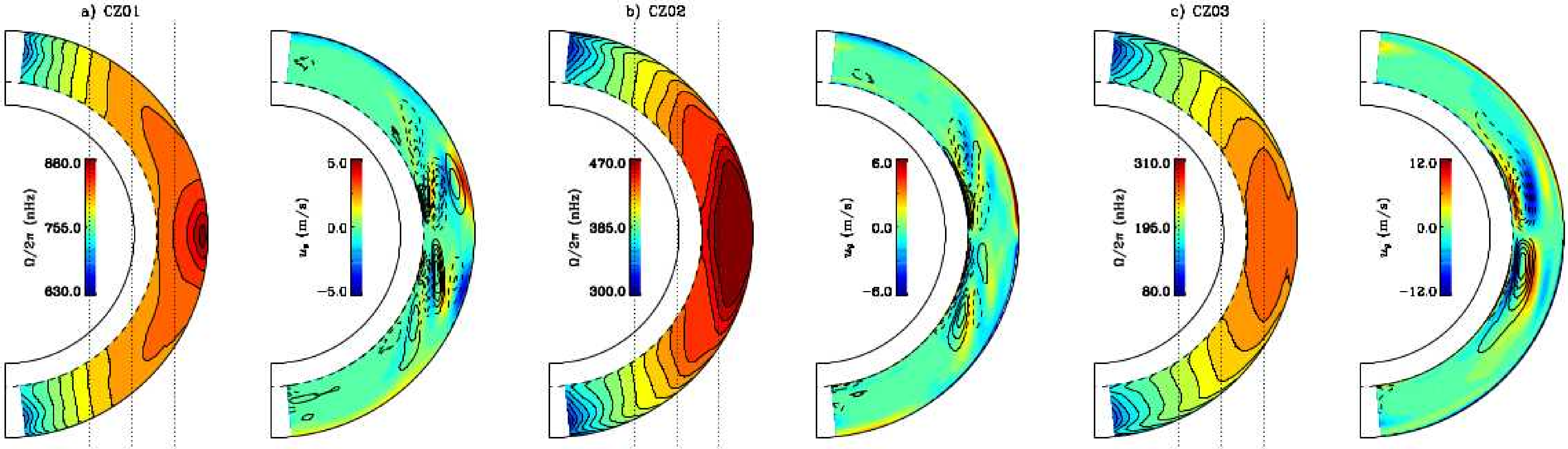
Dynamo

(Guerrero+ 2015, *in preparation*)

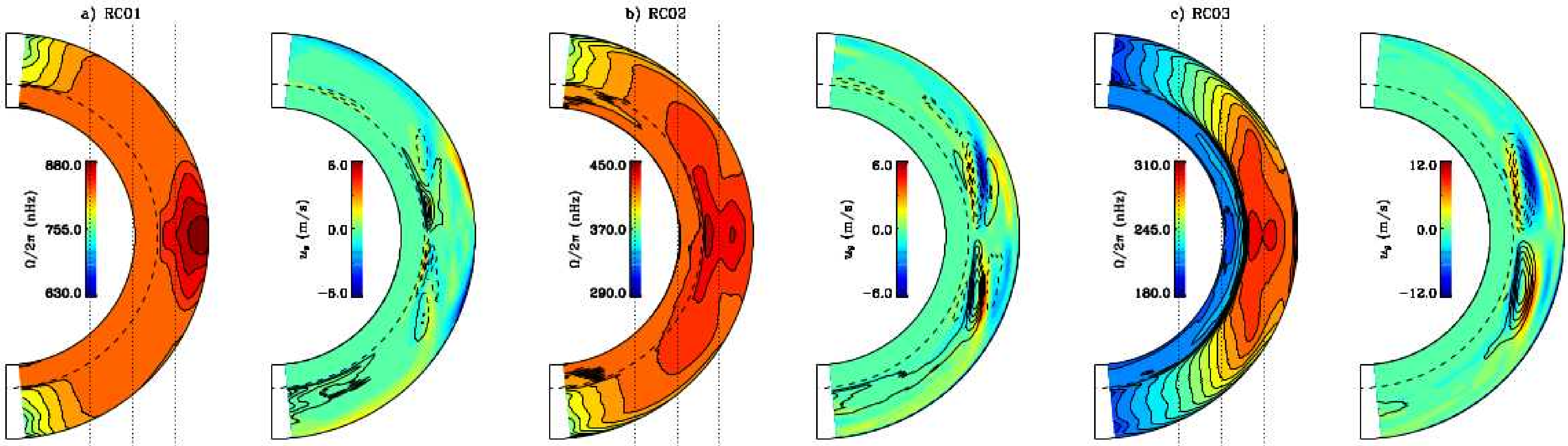
Table 1: Simulation parameters and outputs. The quantities in the table are defined as follows: $\mathrm{Ra}^* = \frac{1}{c_\mathrm{p}\Omega_0^2} g \frac{\partial s_e}{\partial r}$, u_rms is the volume average rms velocity (in m/s) in the unstable layer, $\mathrm{Ma} = u_\mathrm{rms}/c_\mathrm{s}^*$ is the Mach number, with $c_\mathrm{s}^* = \sqrt{\gamma R T_s^*}\,|_{r=0.85R_\odot}$ being the sound speed at the middle of the unstable layer, $\mathrm{Ro} = \frac{u_\mathrm{rms}}{2\Omega_0 L}$ and $\chi_\Omega = (\Omega_\mathrm{eq} - \Omega_\mathrm{p})/\Omega_0$, where $\Omega_\mathrm{eq} = \overline{\Omega}(R_\odot, 90°)$, $\Omega_\mathrm{p} = \overline{\Omega}(R_\odot, 30°)$ and Ω_0 is the frame rotation rate. The growth rate of the magnetic field, λ, is given in yr^{-1}. The kinetic and magnetic energy densities, in Jm^{-3} are: $e_\mathrm{K} = \overline{\rho}_s \overline{\boldsymbol{u}}^2/2$, $e_\mathrm{M} = \overline{\boldsymbol{B}}^2/2\mu_0$, $e_\phi = \overline{B}_\phi^2/2\mu_0$ and $e_{\boldsymbol{p}} = (\overline{B}_r^2 + \overline{B}_\theta^2)/2\mu_0$. Finally, the full cycle period, T_M, is expressed in years. Models starting with the letter CZ consider the convection zone only, models starting with RC include both, radiative and convective zones. The resolution considered is $N_\phi = 128$, $N_\theta = 64$ and $N_r = 47$ for CZ models, and $N_r = 64$ for RC models.

Model	Ro	Ra^*	u_rms	$\mathrm{Ma}(10^{-4})$	χ_Ω	λ	$e_\mathrm{M}/e_\mathrm{K}$	e_ϕ/e_K	$e_{\boldsymbol{p}}/e_\mathrm{K}$	T_M
CZ01	0.030	1.29	55.12	3.85	0.09	2.26	0.098	0.080	0.018	2.26
CZ02	0.067	5.16	60.91	4.25	0.17	0.65	0.010	0.009	0.001	2.21
CZ03	0.150	20.65	67.18	4.69	0.18	0.56	2e-4	2e-4	1e-5	-
RC01	0.033	1.36	60.80	4.10	0.07	0.84	0.249	0.042	0.206	-
RC02	0.069	5.45	62.27	4.30	0.05	0.85	0.247	0.218	0.028	30.90
RC03	0.161	21.80	72.88	5.04	0.28	0.06	0.001	0.001	4e-6	68.38

Models without tachocline

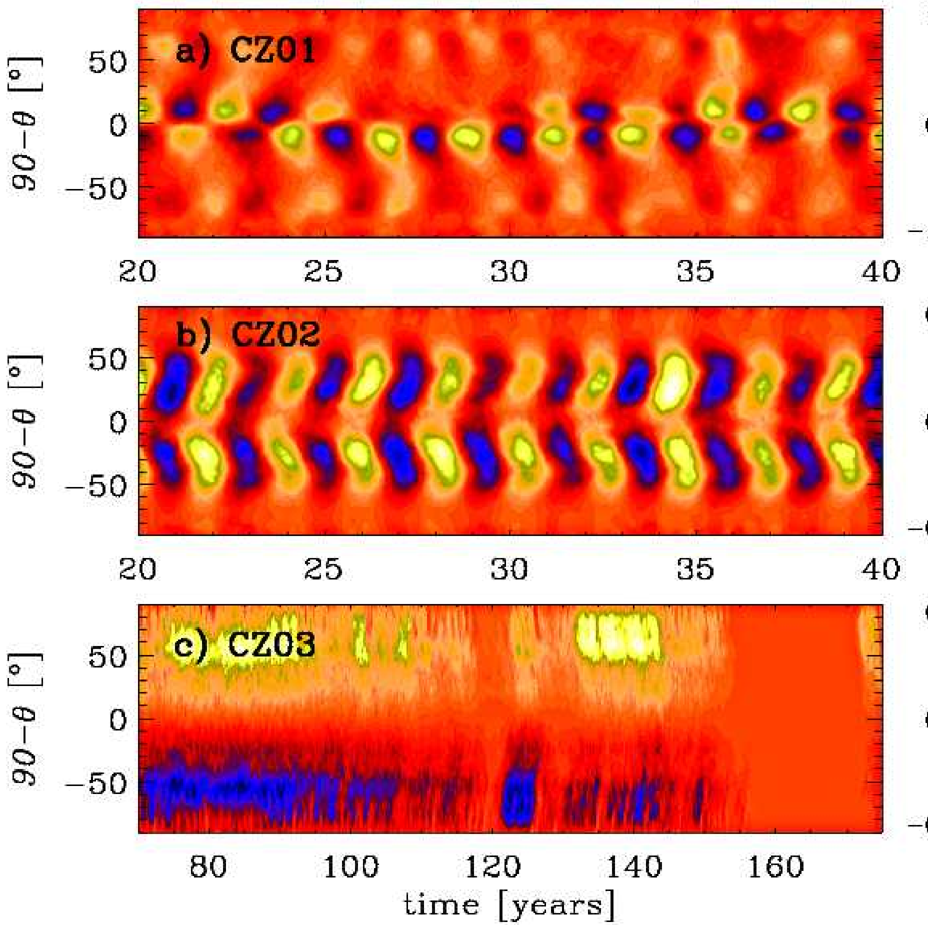


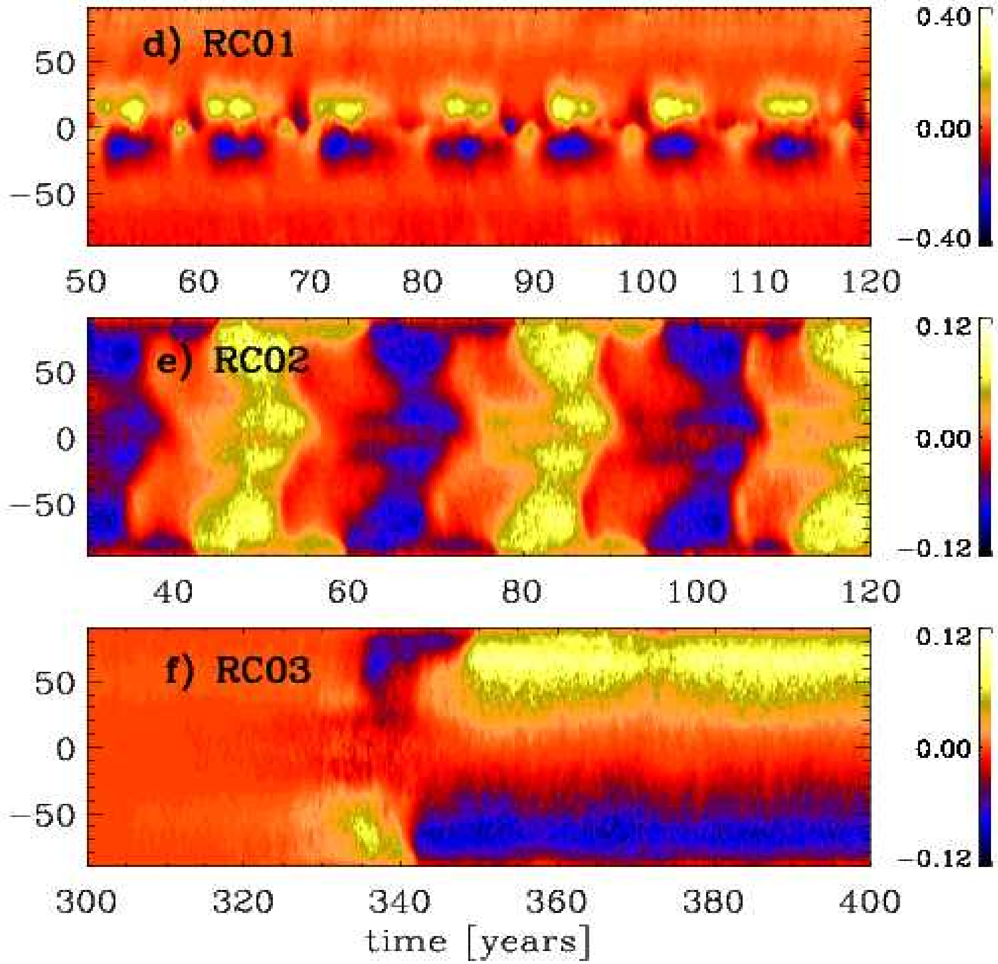
Models with tachocline



Models without tachocline
Butterfly diagram at $r=0.95R_\odot$

Models with tachocline
Butterfly diagram at $r=0.95R_\odot$





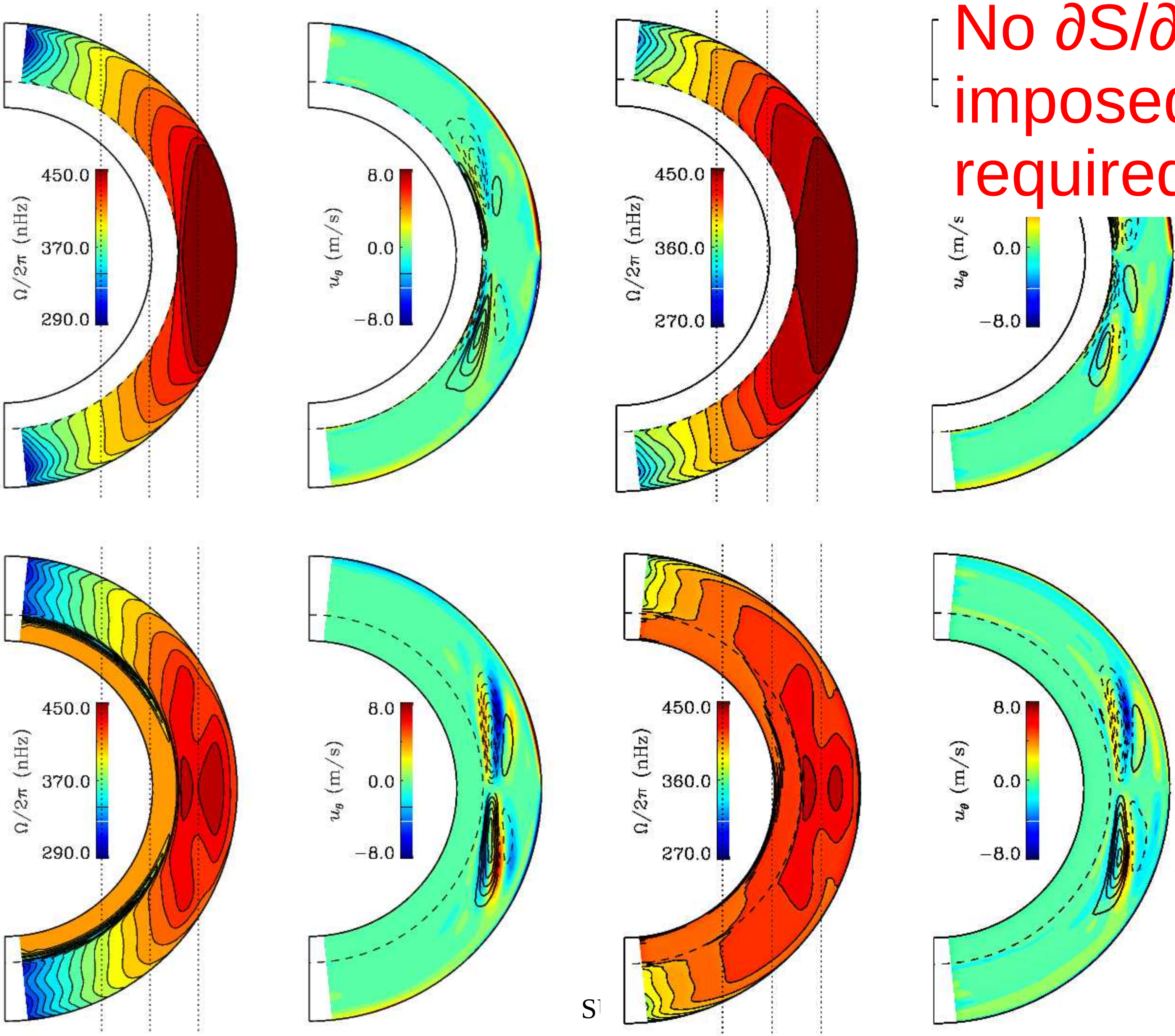
HD progenitors

MHD result

No ∂S/∂θ imposed nor required

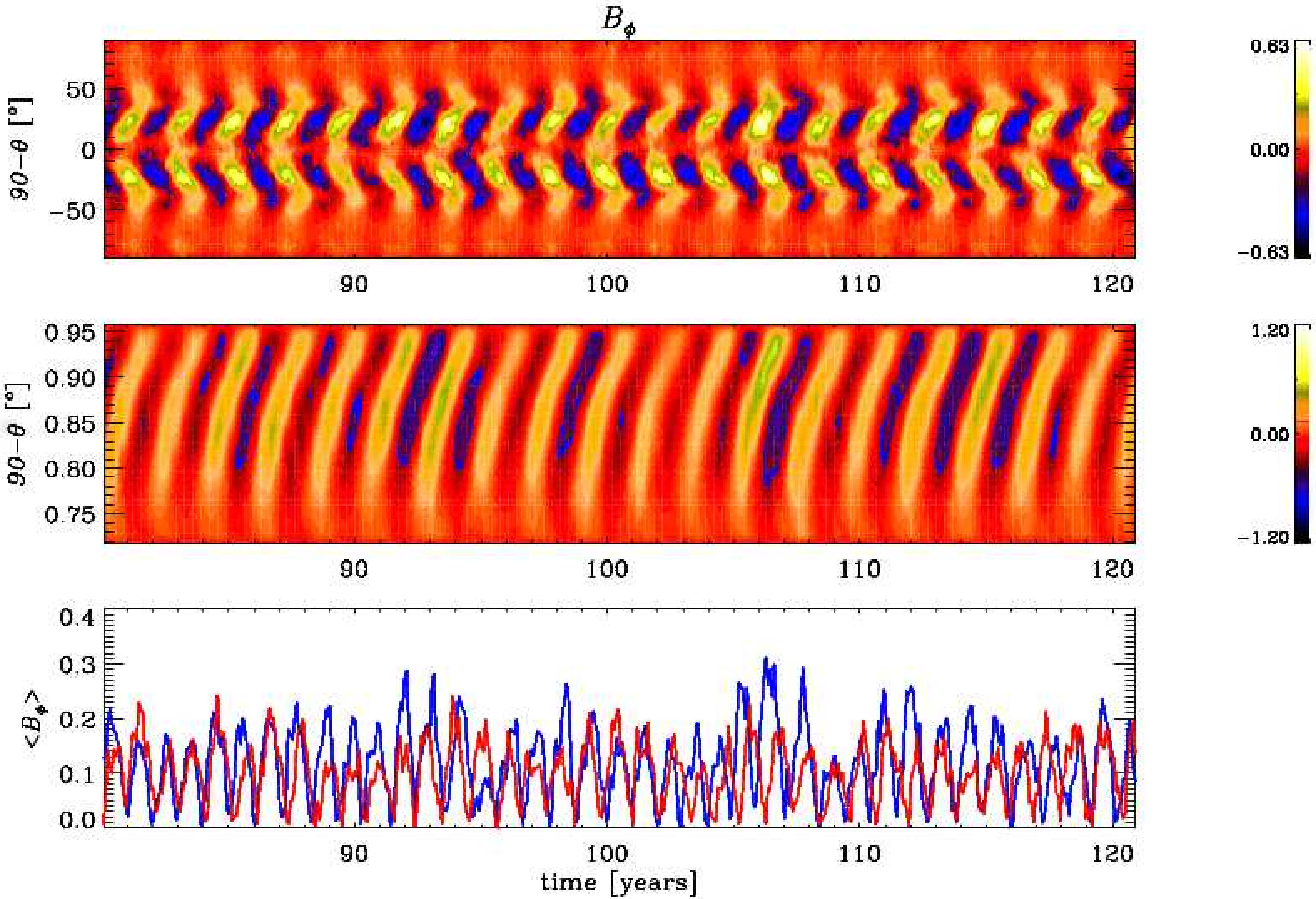
CZ02

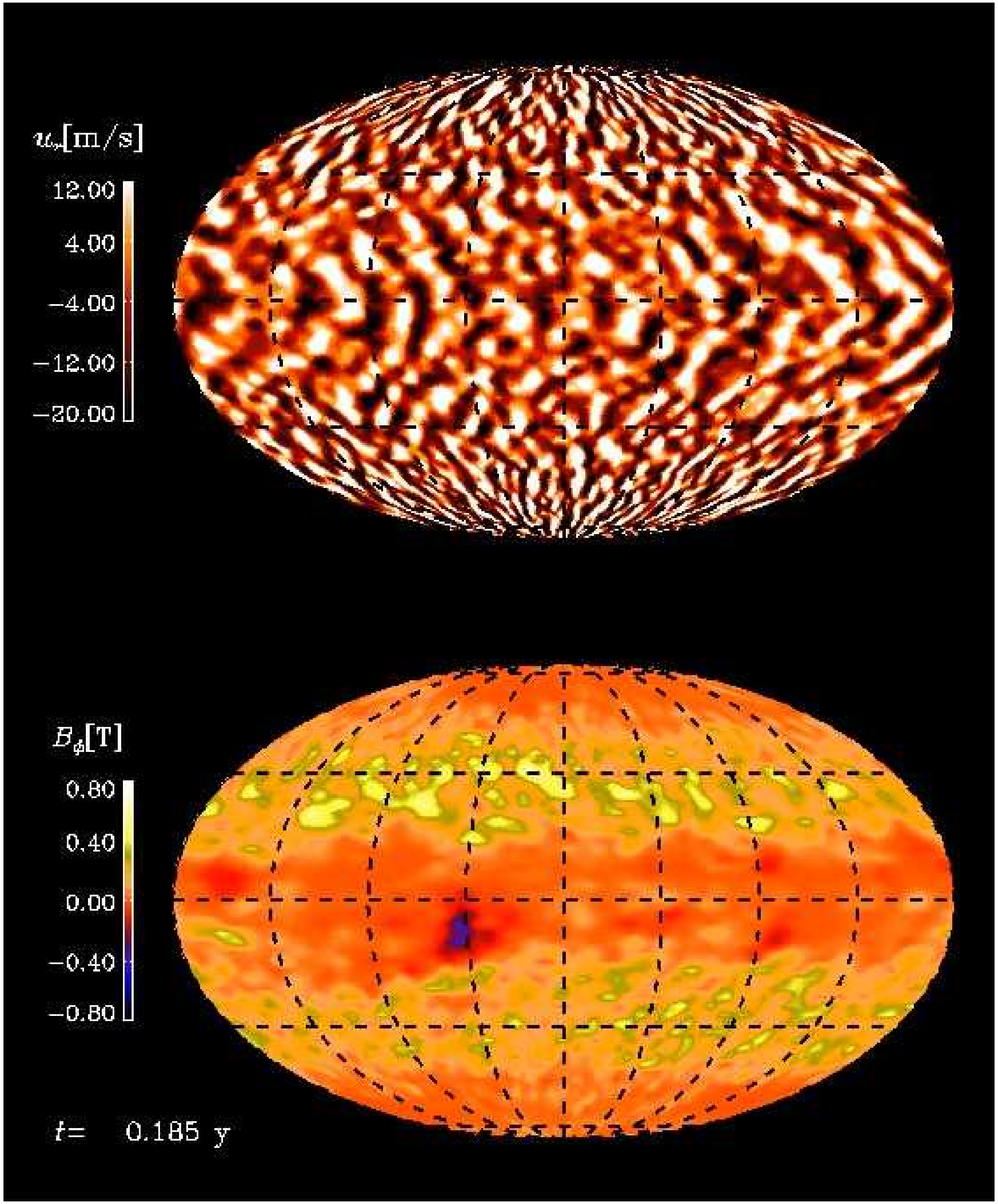
RC02

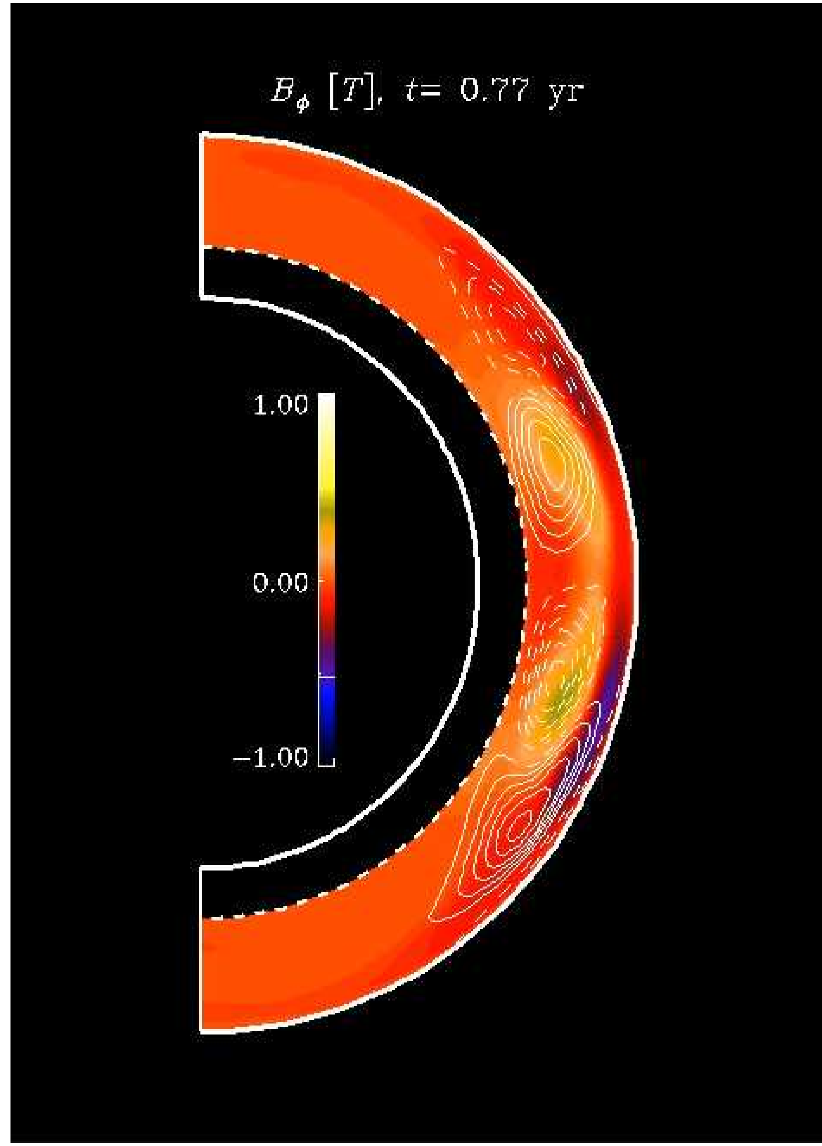


Model without tachocline

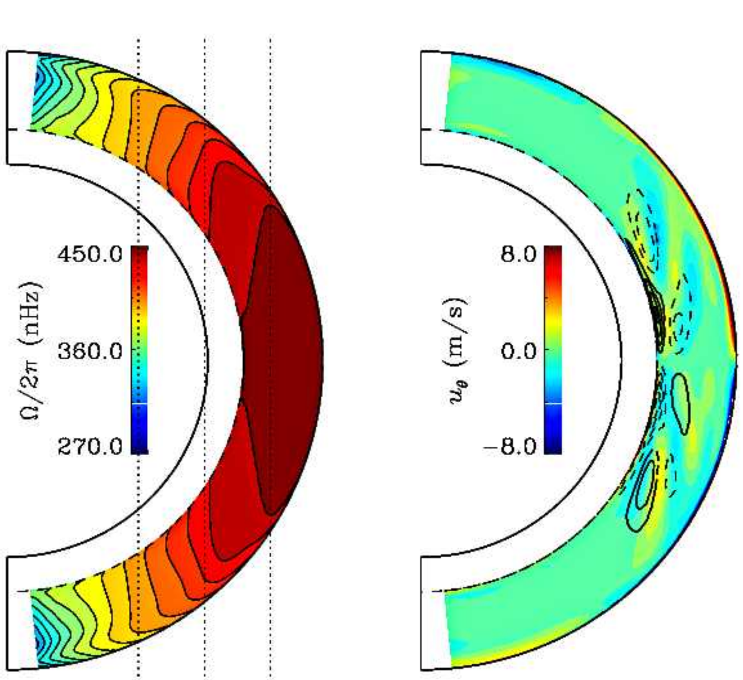
Model CZ02
T=2.1 yr

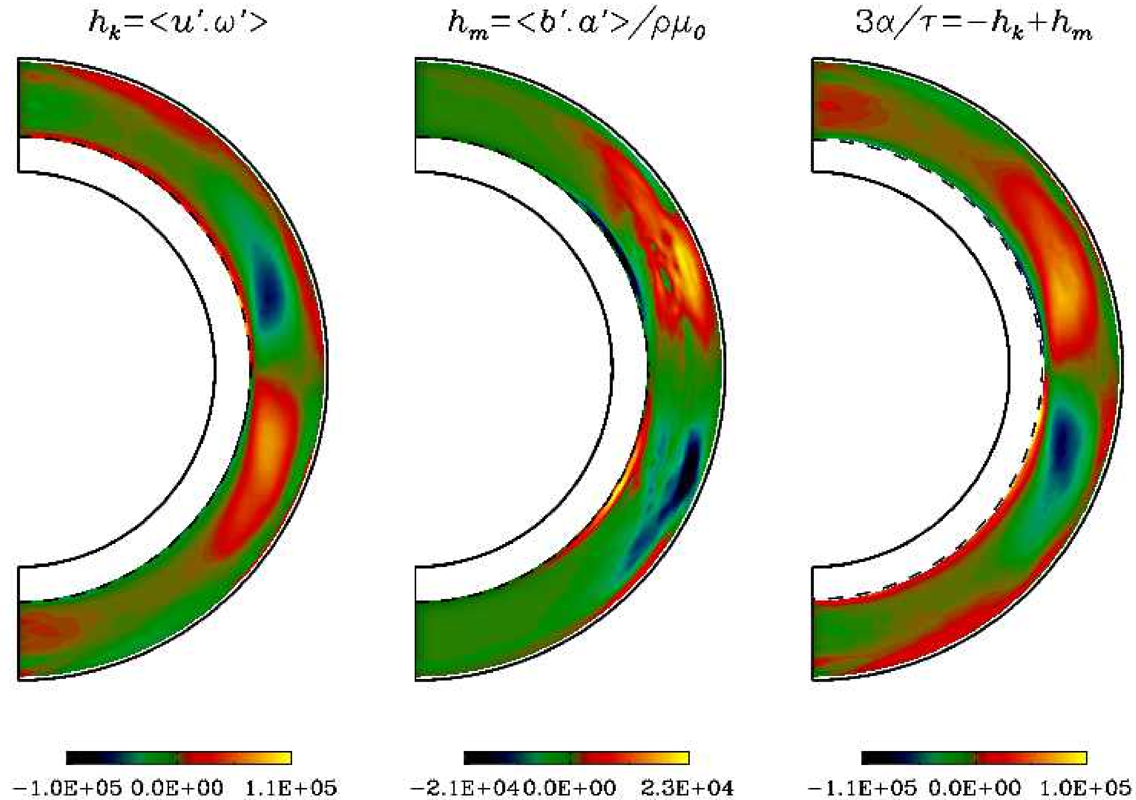


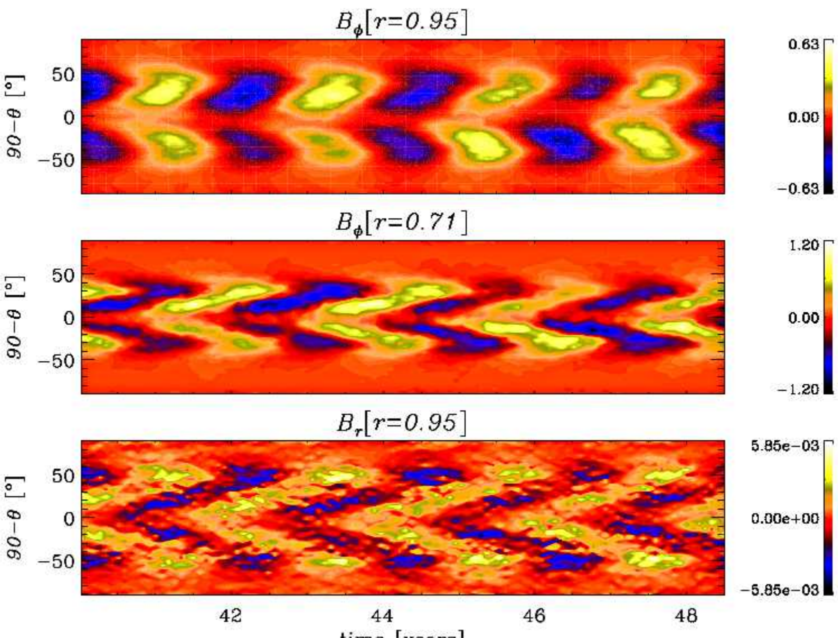

u_r[m/s]
12.00
4.00
−4.00
−12.00
−20.00
B_ϕ[T]
0.80
0.40
0.00
−0.40
−0.80
$t=$ 0.185 y


B_ϕ $[T]$, $t=$ 0.77 yr
1.00
0.00
−1.00

Source terms





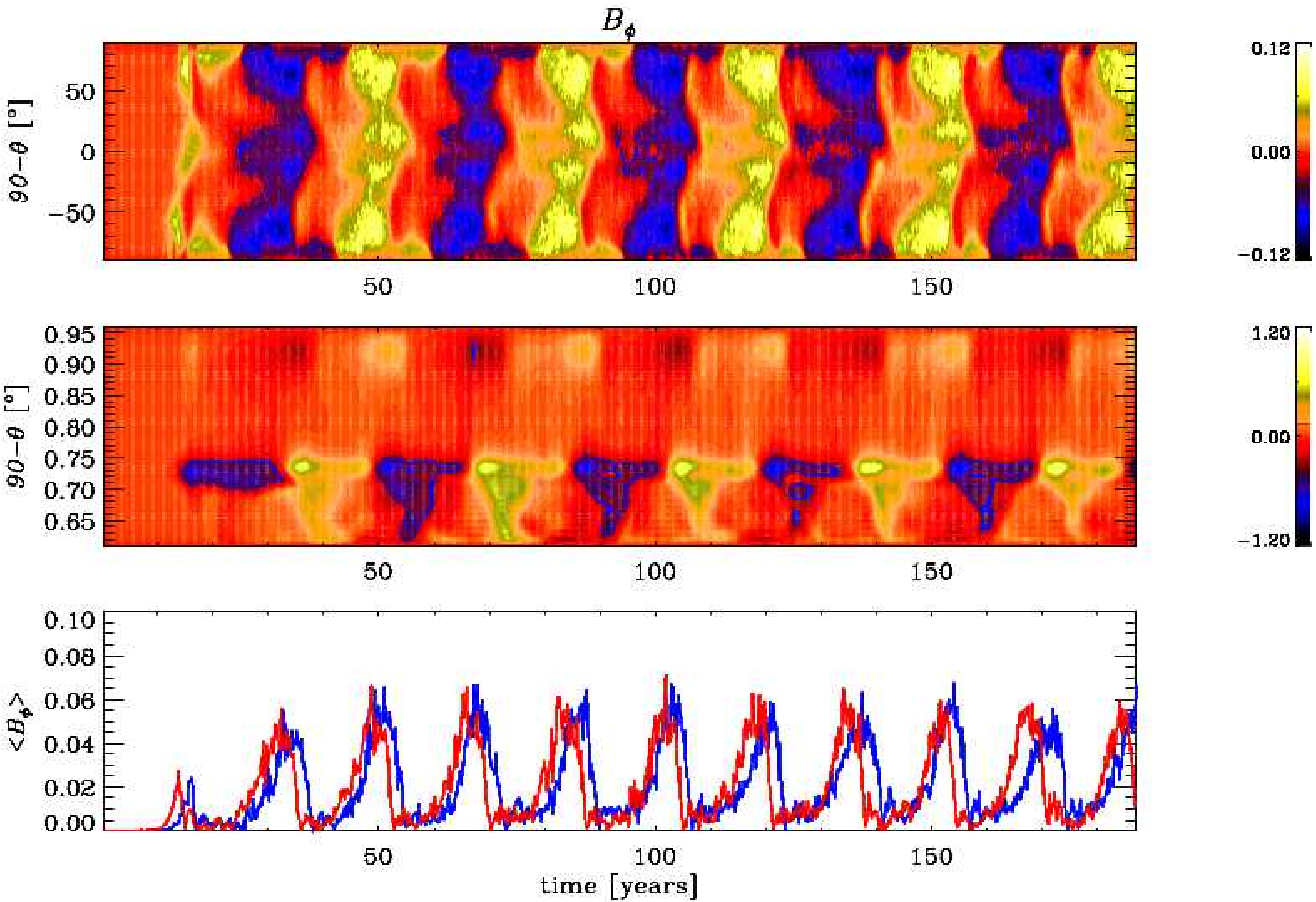


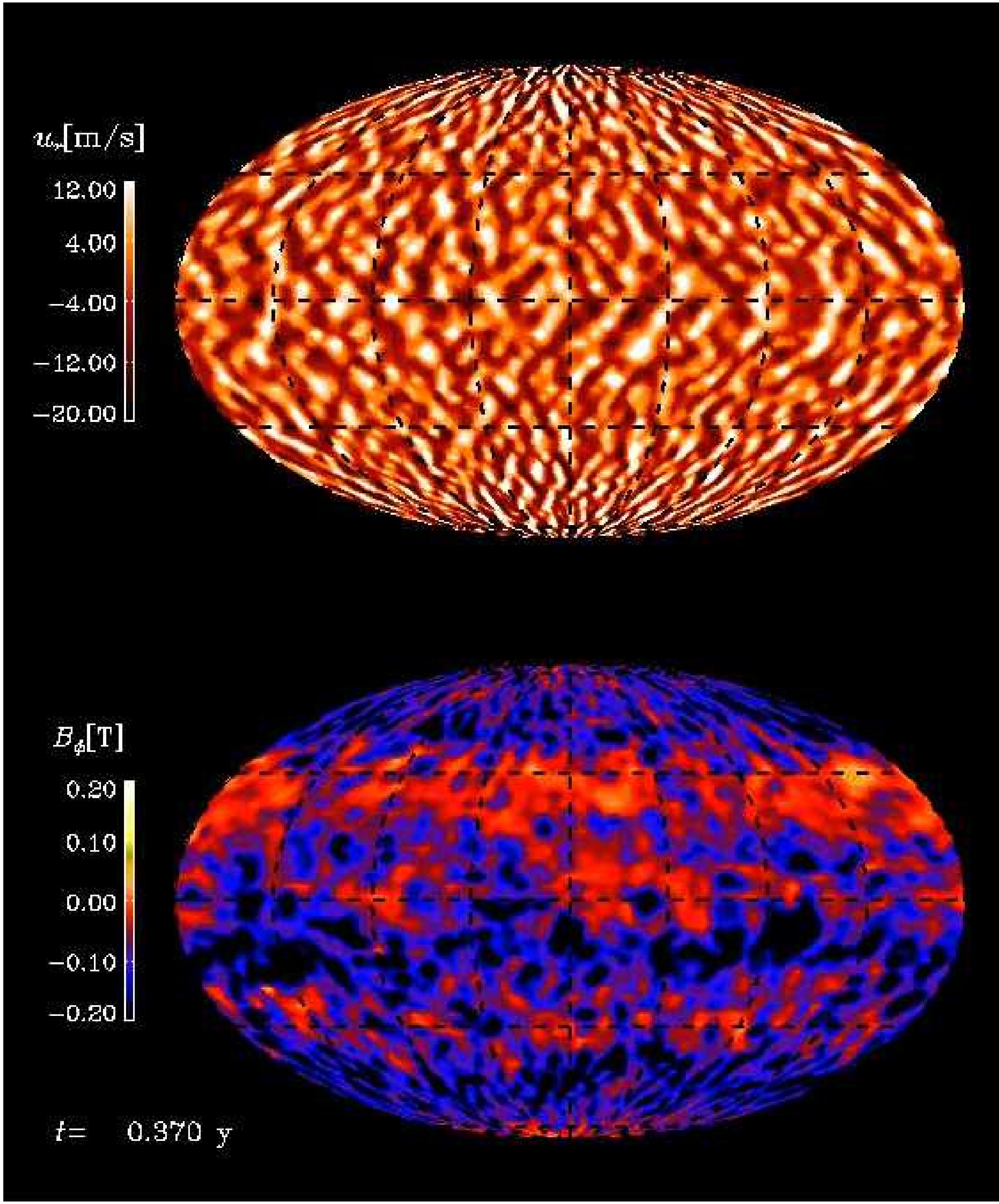
$$\partial_\theta \Omega > 0, \quad \alpha > 0$$

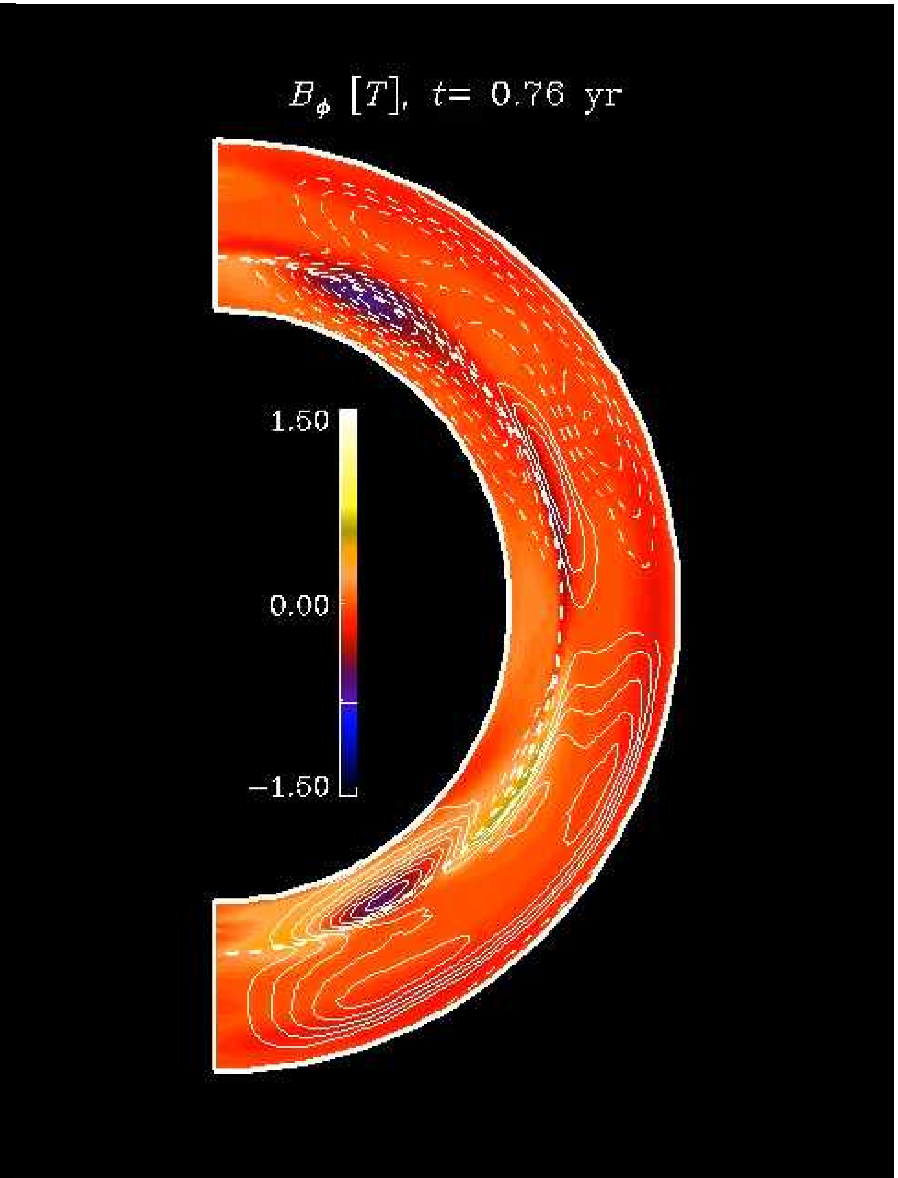
Radial dynamo wave upwards

Model with tachocline

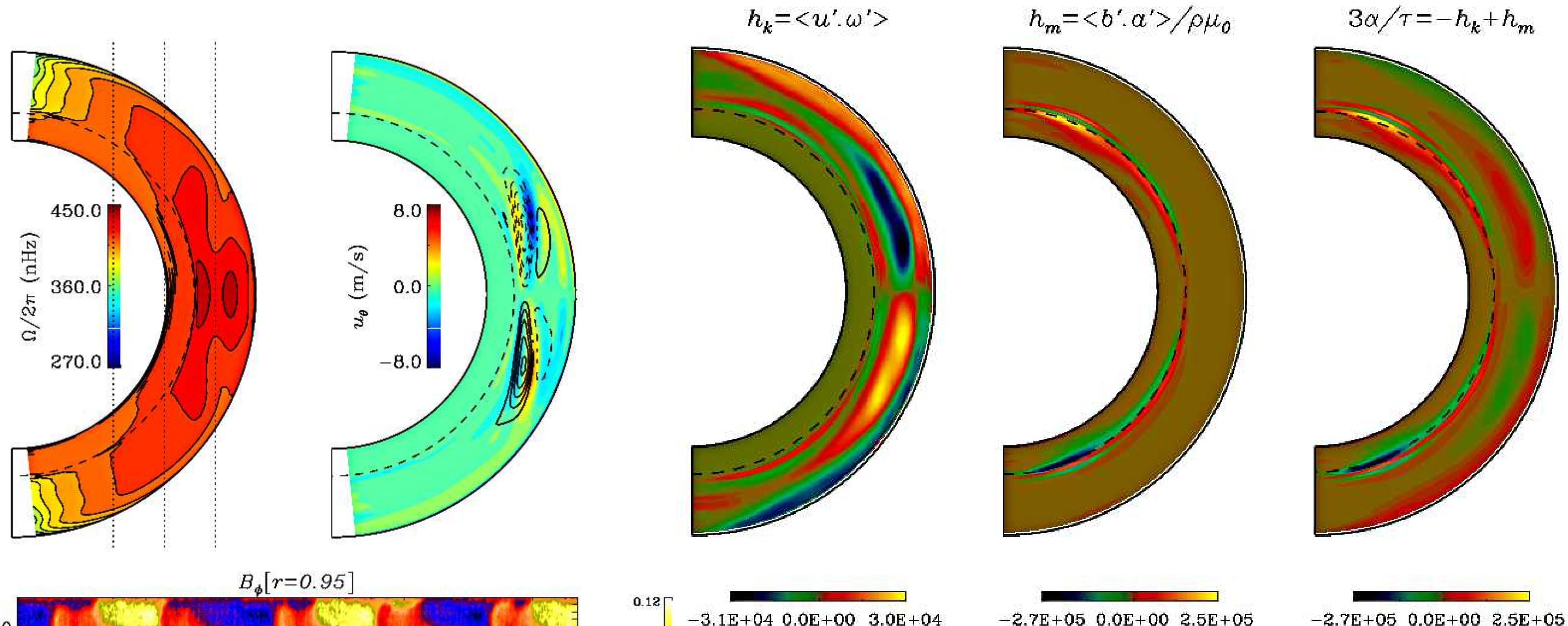
Model RC02
T=30.9 yr

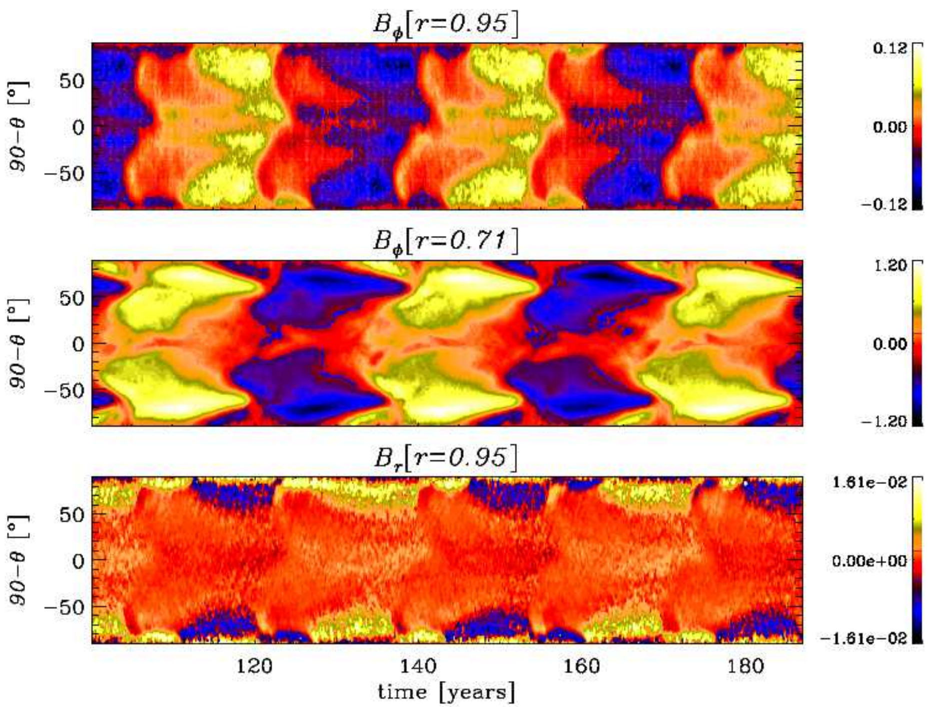



u_r[m/s]
12.00
4.00
−4.00
−12.00
−20.00
B_ϕ[T]
0.20
0.10
0.00
−0.10
−0.20
t= 0.370 y


B_ϕ [T], t= 0.76 yr
1.50
0.00
−1.50

Source terms



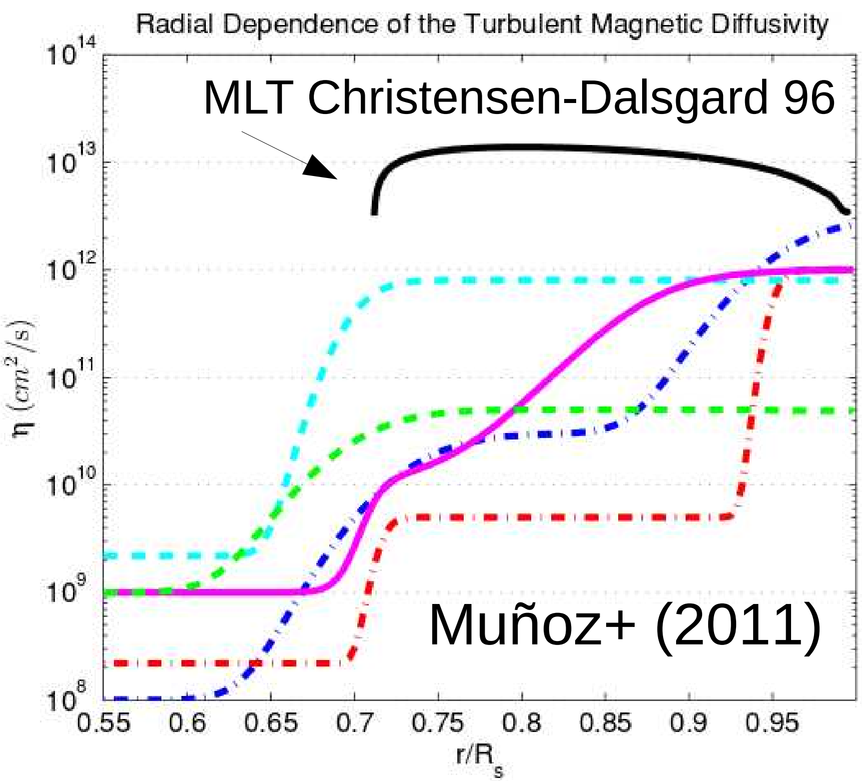


- Convection zone $\partial_\theta \Omega > 0, \quad \alpha > 0$ Upwards
- Bottom (equator) $\partial_r \Omega > 0, \quad \alpha < 0$ poleward
- Bottom (poles) $\partial_r \Omega < 0, \quad \alpha > 0$ equatorward
- Top (poles) $\partial_r \Omega < 0, \quad \alpha < 0$ poleward

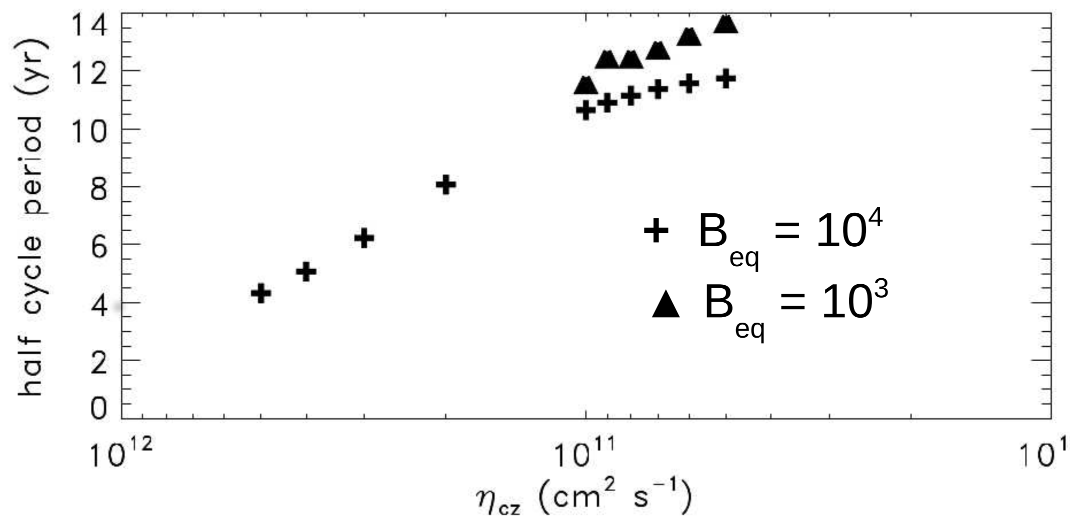
SUNSPOTS, OBSERVATIONS, THEORY AND SIMULATIONS

Cycle period

According with MLT estimations, a dynamo in the CZ should be in the diffusion dominated regime (half-cycle period *2-8* yr) , ***η*-quenching** does not help much with the cycle period (Rudiger+ 94, Tobias 96, Gilman & Rempel 05, Guerrero+ 09, Muñoz+11).



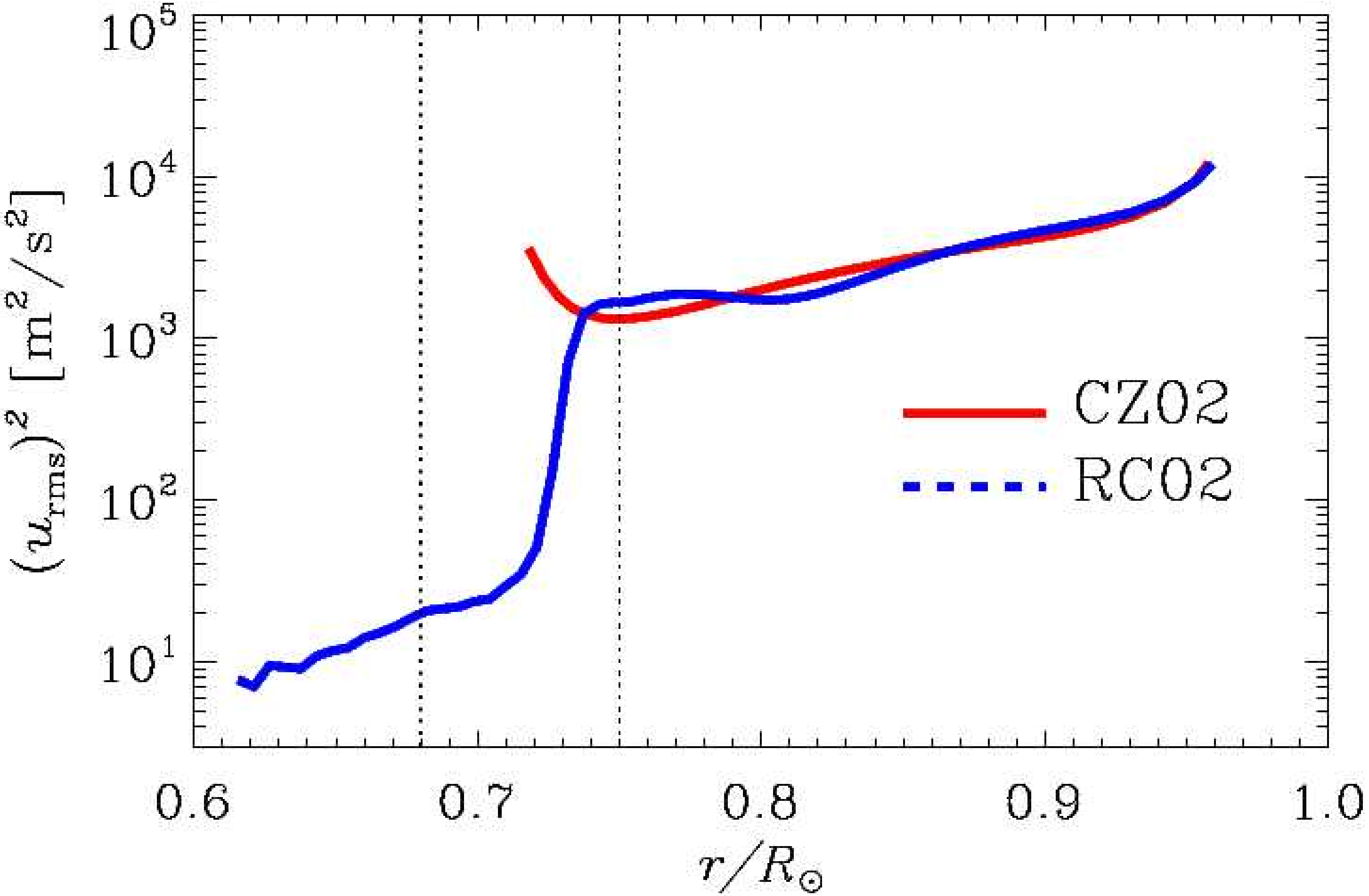
η-quenching effect on mean-field dynamo models



Guerrero+ (2009)

$$\eta_t = \frac{\tau}{3} u_{rms}^2 \quad (FOSA)$$

$$\frac{t_d^{RC}}{t_d^{CZ}} = \frac{L_{RC}^2/\eta_t^{RC}}{L_{CZ}^2/\eta_t^{CZ}} \approx 19$$



CONCLUSIONS

•**LES** & **ILES** are promising tools to explore turbulent problems. **EULAG** code is a powerful code to study solar/stellar rotation and dynamo

- Due to the highly sub-adiabatic stable region, all the simulations exhibit the formation of a *tachocline.* Besides, by choosing the appropriate stratification, a *near-surface shear layer* is obtained.
- For all the simulations at the solar rotation rate the meridional flow is multicellular. The simulations that reproduce the NSSL develop a poleward meridional flow at the surface and higher latitudes.
- Dynamo models ***without tachocline*** result in oscillatory solutions with short cycle period (~2yr). Dynamo models ***including a tachocline*** result in oscillatory solutions with long cycle period (>30yr). The strongest field developed in this radial shear layers dominates the evolution of the global field.

Thanks