Confinement of the solar tachocline via a cyclic dynamo magnetic field

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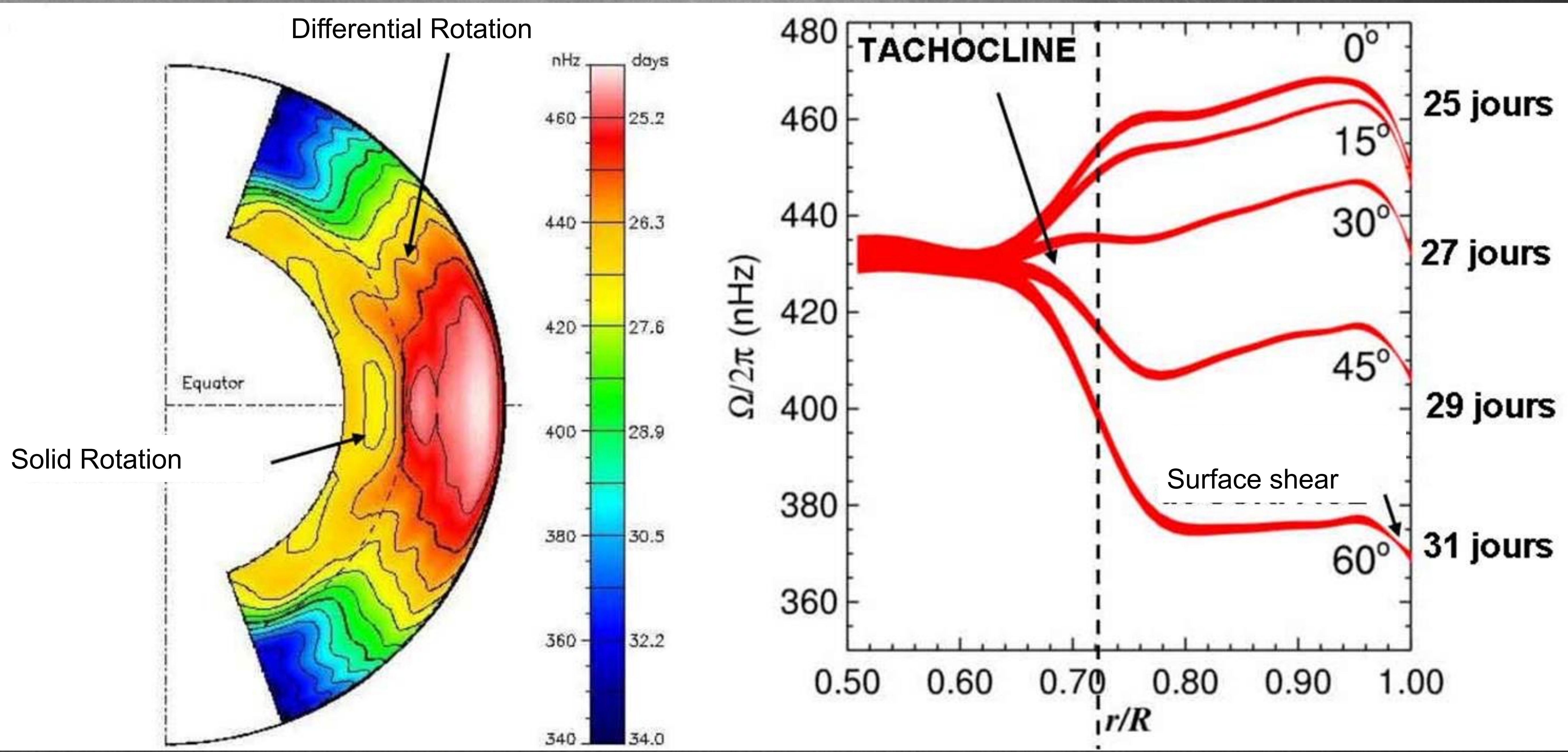
The solar tachocline



Brown *et al.*, 1989
Charbonneau *et al.* 1999
Spiegel & Zahn, 1992
Thompson *et al.*, 2003

The thinness of the tachocline

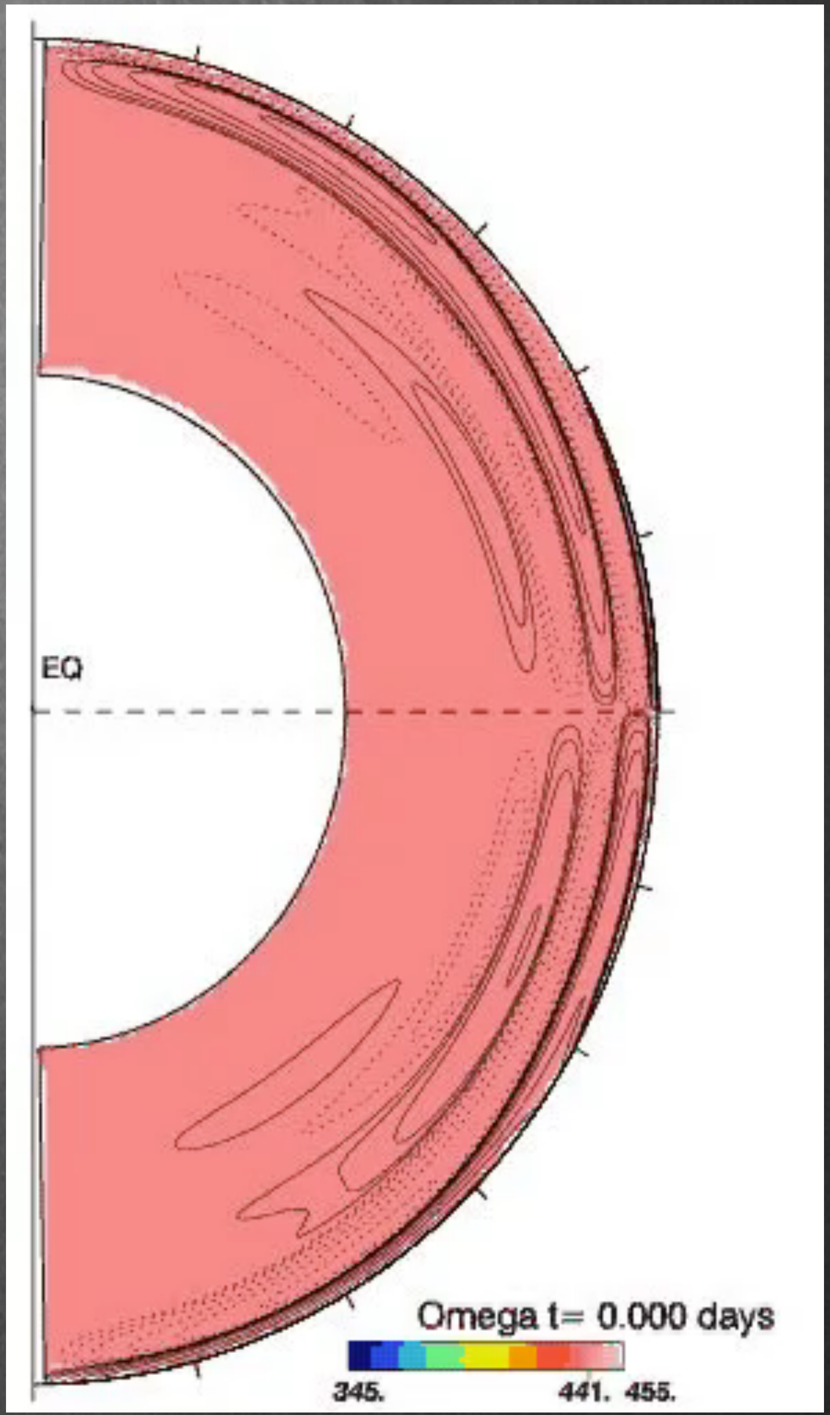
- Spiegel & Zahn (1992) :
  - First HD model of the tachocline
  - Radiative spreading

$$\frac{\partial \widetilde{\Omega}_j}{\partial t} + \kappa \left(\frac{2\Omega_0}{N} \right)^2 \left(\frac{r_{bcz}^2}{\lambda_j} \right)^2 \frac{\partial^4 \widetilde{\Omega}_j}{\partial r^4} - \nu_V \frac{\partial^2 \widetilde{\Omega}_j}{\partial r^2} = 0$$

Spiegel & Zahn, 1992

Should be down to 0.4 $R_\odot$

Contradiction with helioseismology observations



Slow vs fast models

Slow tachocline

- Anisotropic turbulence
  (Spiegel & Zahn, 1992, …)
- Fossil magnetic field
  (Gough & McIntyre, 1998, …)
- Internal waves
  (Kumar *et al.* 1999, …)

Fast tachocline

- **Dynamo magnetic field**
  (Forgács-Dajka & Petrovay, 2001, Barnabé *et al.*, 2017, …)
- Shear instabilities
  (Gilman, 2000, …)

Magnetic tachocline

Cyclic dynamo-generated magnetic field penetrating below the convective envelope (Forgács-Dajka & Petrovay, 2001)

TACHOCLINE CONFINEMENT BY AN OSCILLATORY MAGNETIC FIELD

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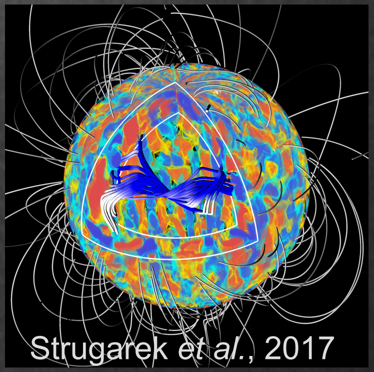
Abstract. Helioseismic measurements indicate that the solar tachocline is very thin, its full thickness not exceeding 4% of the solar radius. The mechanism that inhibits differential rotation to propagate from the convective zone to deeper into the radiative zone is not known, though several propositions have been made. In this paper we demonstrate by numerical models and analytic estimates that the tachocline can be confined to its observed thickness by a poloidal magnetic field B_p of about one kilogauss, penetrating below the convective zone and oscillating with a period of 22 years, if the tachocline region is turbulent with a diffusivity of $\eta \sim 10^{10}$ cm^2 s^{-1} (for a turbulent magnetic Prandtl number of unity). We also show that a similar confinement may be produced for other pairs of the parameter values (B_p, η). The assumption of the dynamo field penetrating into the tachocline is consistent whenever $\eta \gtrsim 10^9$ cm^2 s^{-1}.

$$\frac{\partial a}{\partial \tau} = \frac{\partial^2 a}{\partial \xi^2}$$ poloidal field

$$\frac{\partial b}{\partial \tau} = \frac{\partial^2 b}{\partial \xi^2} - (k\delta)^2 b - C_A a u$$ toroidal field

$$\frac{\partial u}{\partial \tau} = \left(\frac{\nu}{\eta}\right)\left[\frac{\partial^2 u}{\partial \xi^2} - (k\delta)^2 u\right] + C_L a b$$ velocity field


Strugarek *et al.*, 2017

A fast tachocline model

Simplified 1D model

- Poloidal magnetic field *a*
- Toroidal magnetic field *b*
- Latitudinal differential rotation *u*

- New boundary conditions
- Wider parameter exploration
- Viscous vs radiative spreading

$$\frac{\partial a}{\partial \tau} = \frac{\partial^2 a}{\partial \xi^2}$$

Ohmic diffusion

$$\frac{\partial b}{\partial \tau} = \frac{\partial^2 b}{\partial \xi^2} - (k\delta)^2 b - C_A a u$$

Ohmic diffusion — Induction

$$\frac{\partial u}{\partial \tau} = \left(\frac{\nu}{\eta}\right)\left[\frac{\partial^2 u}{\partial \xi^2} - (k\delta)^2 u\right] - \mathrm{Fr}\left(\frac{\kappa}{\eta}\right)\left(\frac{\mathrm{R}}{\delta}\right)^2 \frac{\partial^4 \mathrm{u}}{\partial \xi^4} + C_L a b$$

Viscosity — Radiative spreading — Lorentz force

$$C_A = \frac{R_m}{\beta} \qquad C_L = R_m \beta \Lambda$$

$$\Lambda = \frac{B_0^2}{\rho U_0^2} \qquad R_m = \frac{k\delta^2 U_0}{\eta}$$

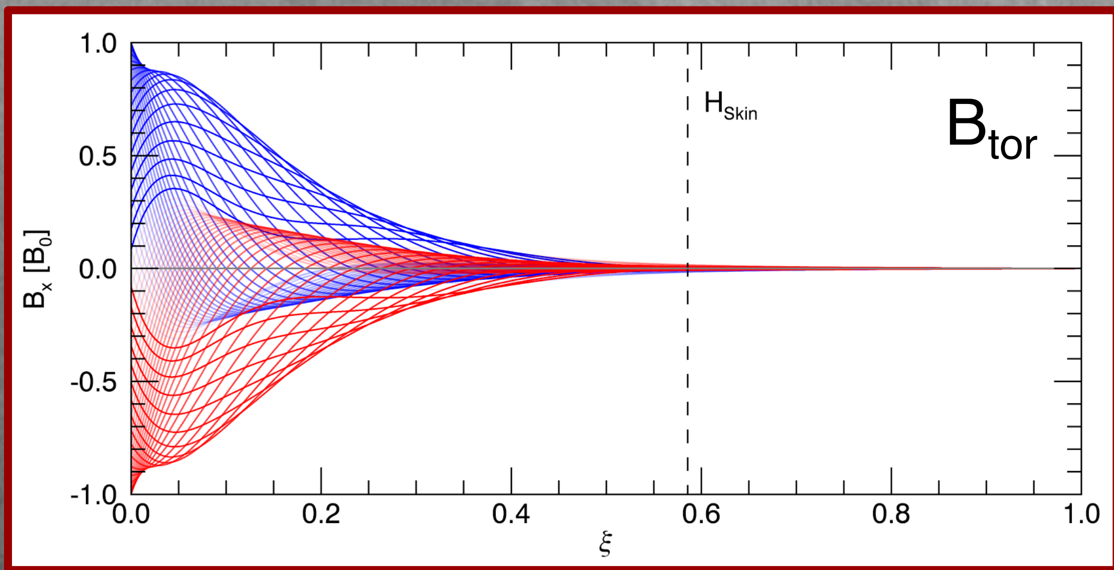
$$F = \left(\frac{\Omega}{N}\right)^2$$

Magnetic tachocline

- **Viscous spreading**
- Radiative spreading

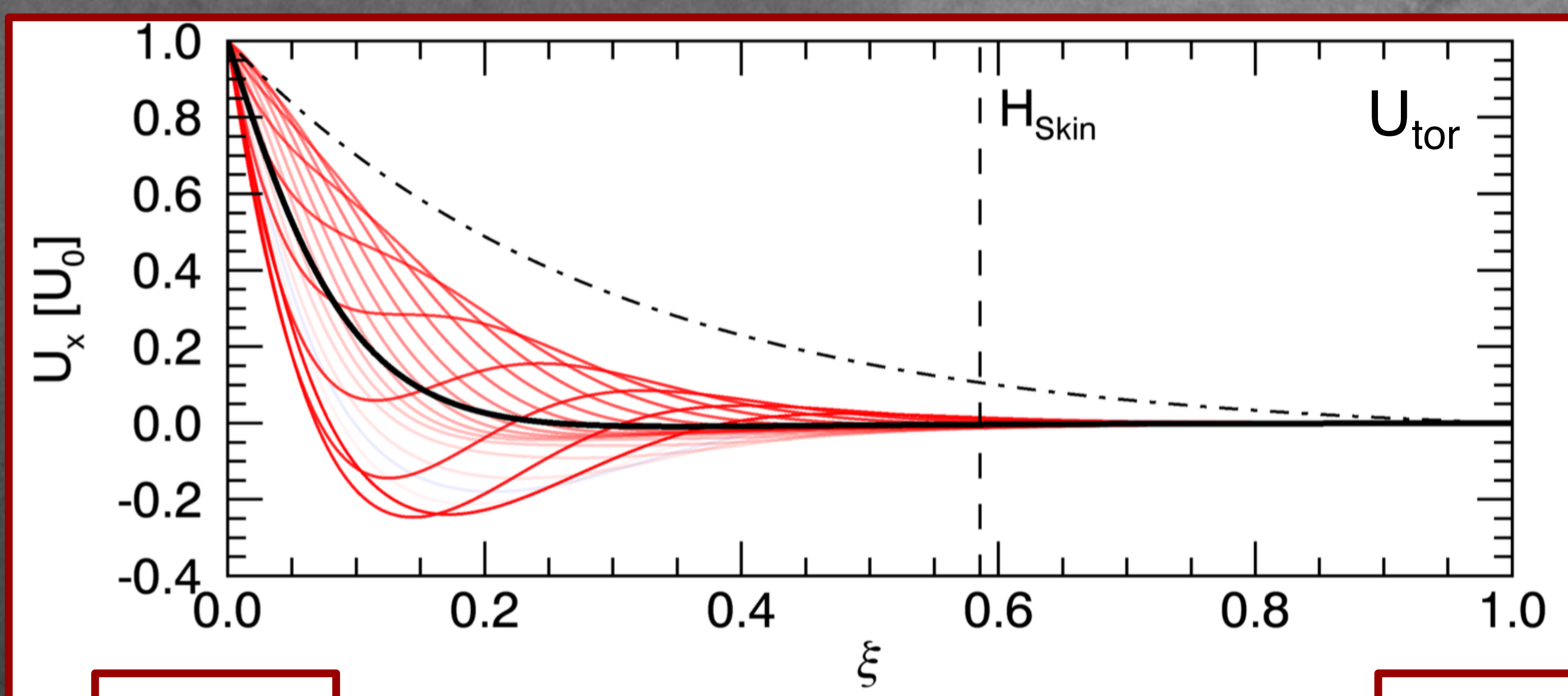
$$\frac{\partial u}{\partial \tau} = \left(\frac{\nu}{\eta}\right)\left[\frac{\partial^2 u}{\partial \xi^2} - (k\delta)^2 u\right] - \frac{\kappa}{\eta} Fr R^2 \frac{\partial^4 u}{\partial \xi^4} + C_L ab$$

Viscous magnetic tachocline



$$\frac{\partial b}{\partial \tau} = \frac{\partial^2 b}{\partial \xi^2} - (k\delta)^2 b - C_A a u$$

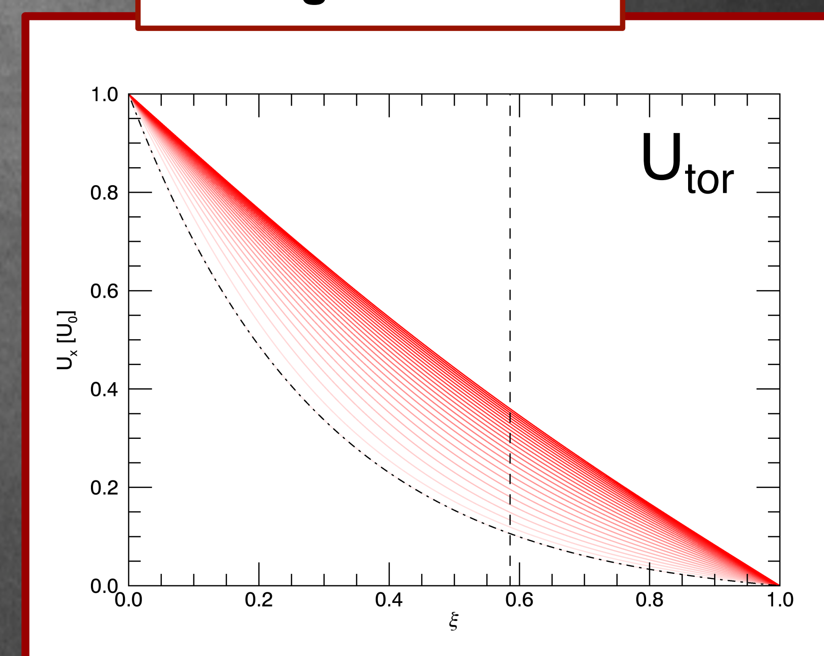
$$\frac{\partial u}{\partial \tau} = \left(\frac{\nu}{\eta}\right)\left[\frac{\partial^2 u}{\partial \xi^2} - (k\delta)^2 u\right] + C_L a b$$



0.72 R⊙

0.65 R⊙

No magnetic field



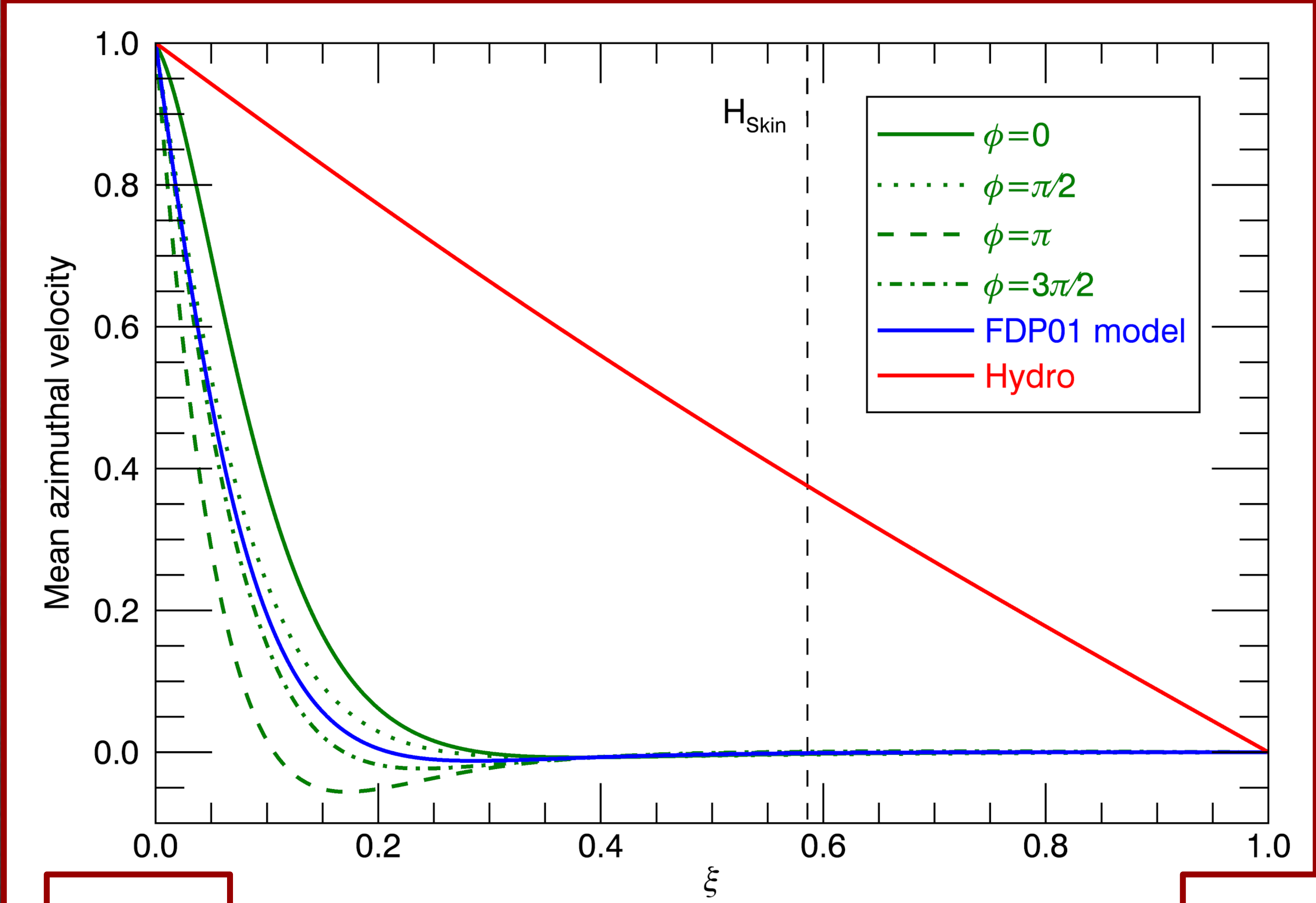
η = 7 x 10^9 cm^2/s B_{pol}= 1375 G

ν = 7 x 10^9 cm^2/s B_{tor}= 13750 G

Viscous magnetic tachocline

Mean azimuthal velocity

$$\frac{\partial u}{\partial \tau} = \left(\frac{\nu}{\eta}\right)\left[\frac{\partial^2 u}{\partial \xi^2} - (k\delta)^2 u\right] + C_L ab$$



0.72 $R_\odot$

0.65 $R_\odot$

Different phase lags between B_{pol} and B_{tor}

η = 7 x 10^9 cm^2/s

ν = 7 x 10^9 cm^2/s

B_{pol}= 1375 G

B_{tor}= 13750 G

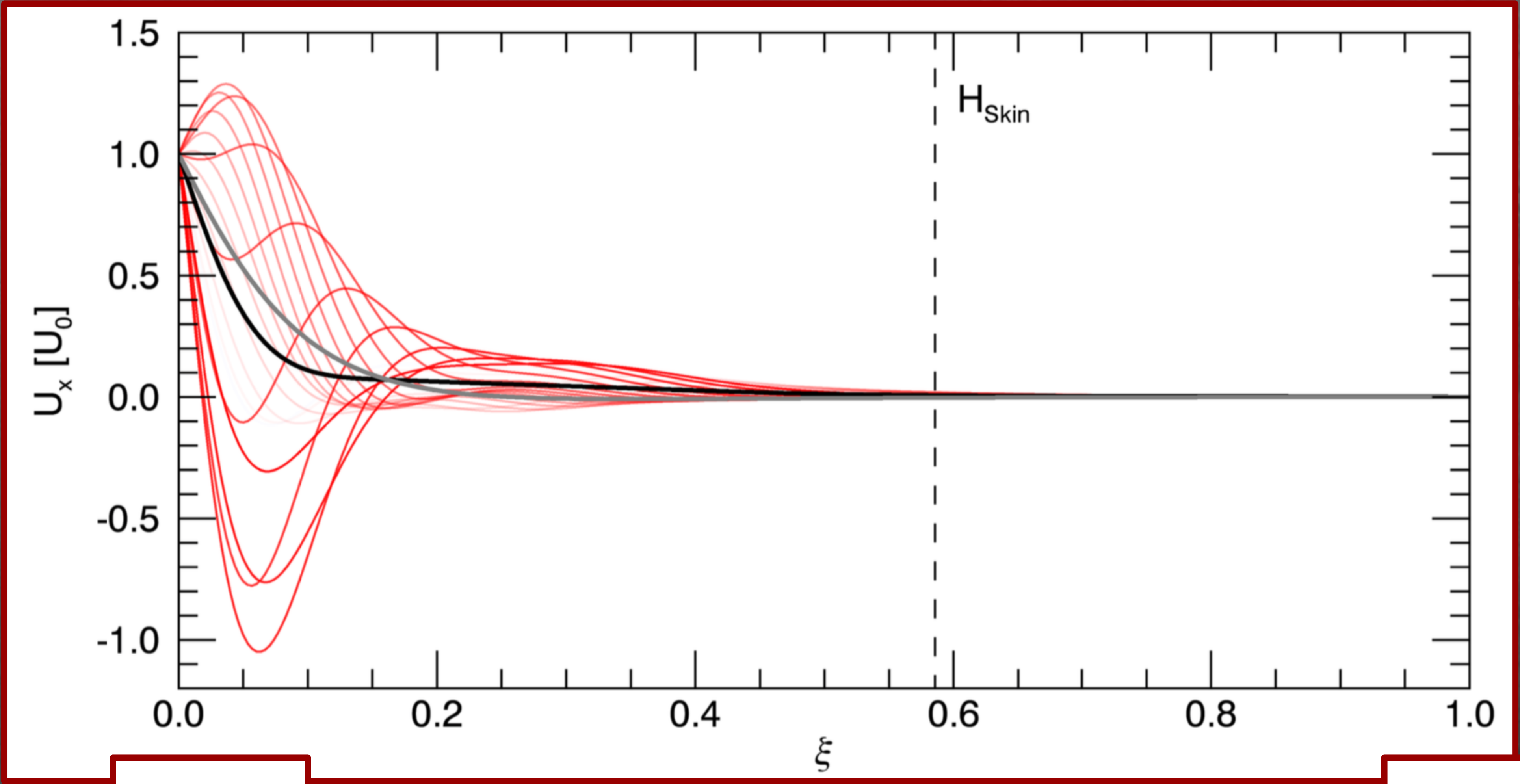
Magnetic tachocline

- Viscous spreading
- **<u>Radiative spreading</u>**

$$\frac{\partial u}{\partial \tau} = \left(\frac{\nu}{\eta}\right)\left[\frac{\partial^2 u}{\partial \xi^2} - (k\delta)^2 u\right] - \frac{\kappa}{\eta} Fr R^2 \frac{\partial^4 u}{\partial \xi^4} + C_L ab$$

Magnetic tachocline subject to radiative spreading

$$\frac{\partial u}{\partial \tau} = C_L ab - \mathrm{Fr}\left(\frac{\kappa}{\eta}\right)\left(\frac{\mathrm{R}}{\delta}\right)^2 \frac{\partial^4 \mathrm{u}}{\partial \xi^4}$$



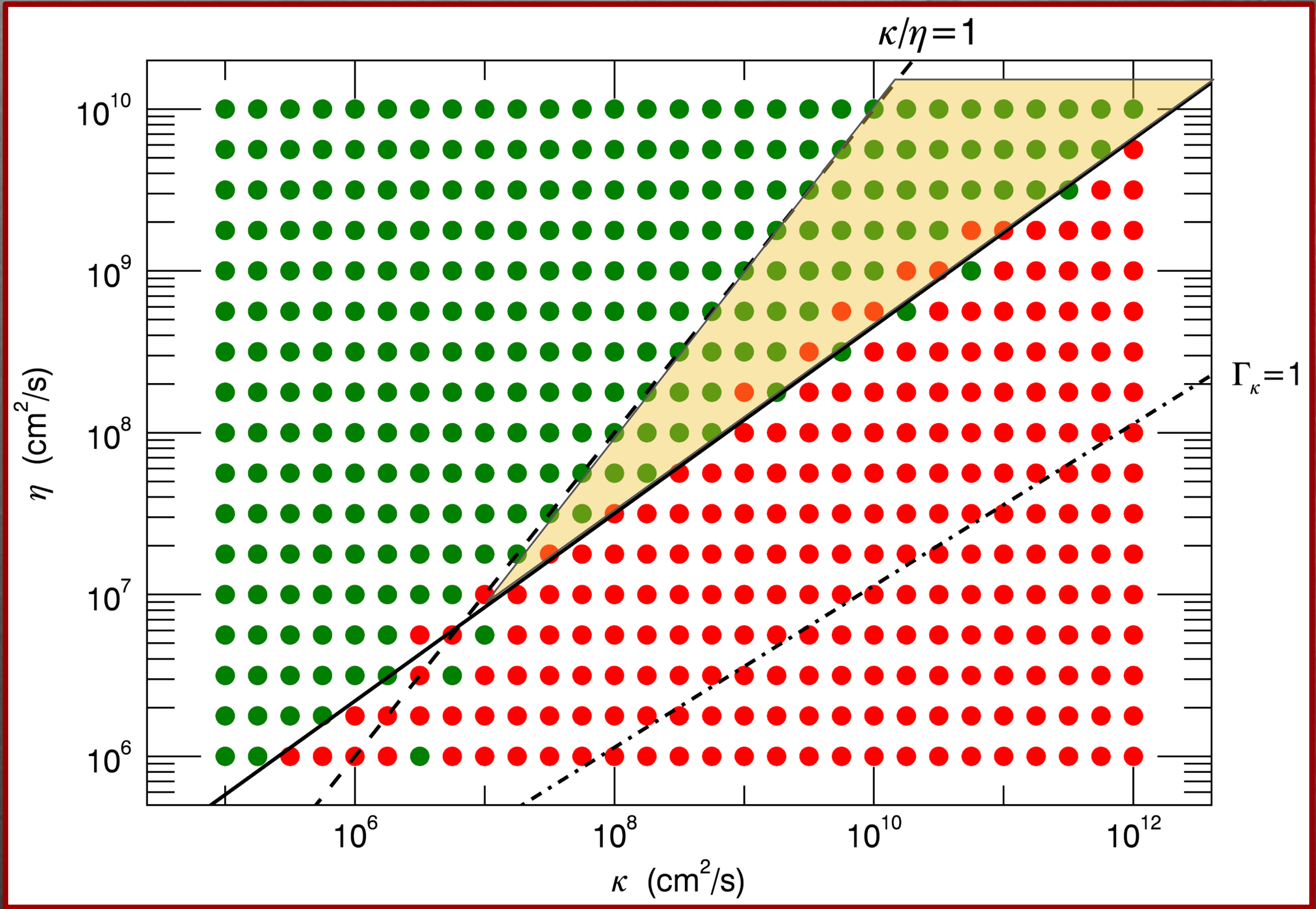
0.72 $R_\odot$

0.65 $R_\odot$

η = 7 x 10^9 cm^2/s
κ = 7 x 10^9 cm^2/s

B_{pol}= 1375 G
B_{tor}= 13750 G

Magnetic tachocline subject to radiative spreading



Ohmic diffusivity η

Thermal diffusivity **κ**

Parameter exploration

κ > η

B_{pol}= 5000 G
B_{tor}= 50000 G

Conclusions

- A **dynamo** magnetic field penetrating below the convective envelope can prevent the inward burrowing of a tachocline
- We tested our model with a tachocline subject to **viscous** diffusion or to **radiative spreading**
- Results show that this would require a weakly **turbulent** tachocline (κ~1o^{9} cm^{2}/s, η~10^{8} cm^{2}/s)
- Barnabé *et al.* 2017, submitted to A&A

Thank you!