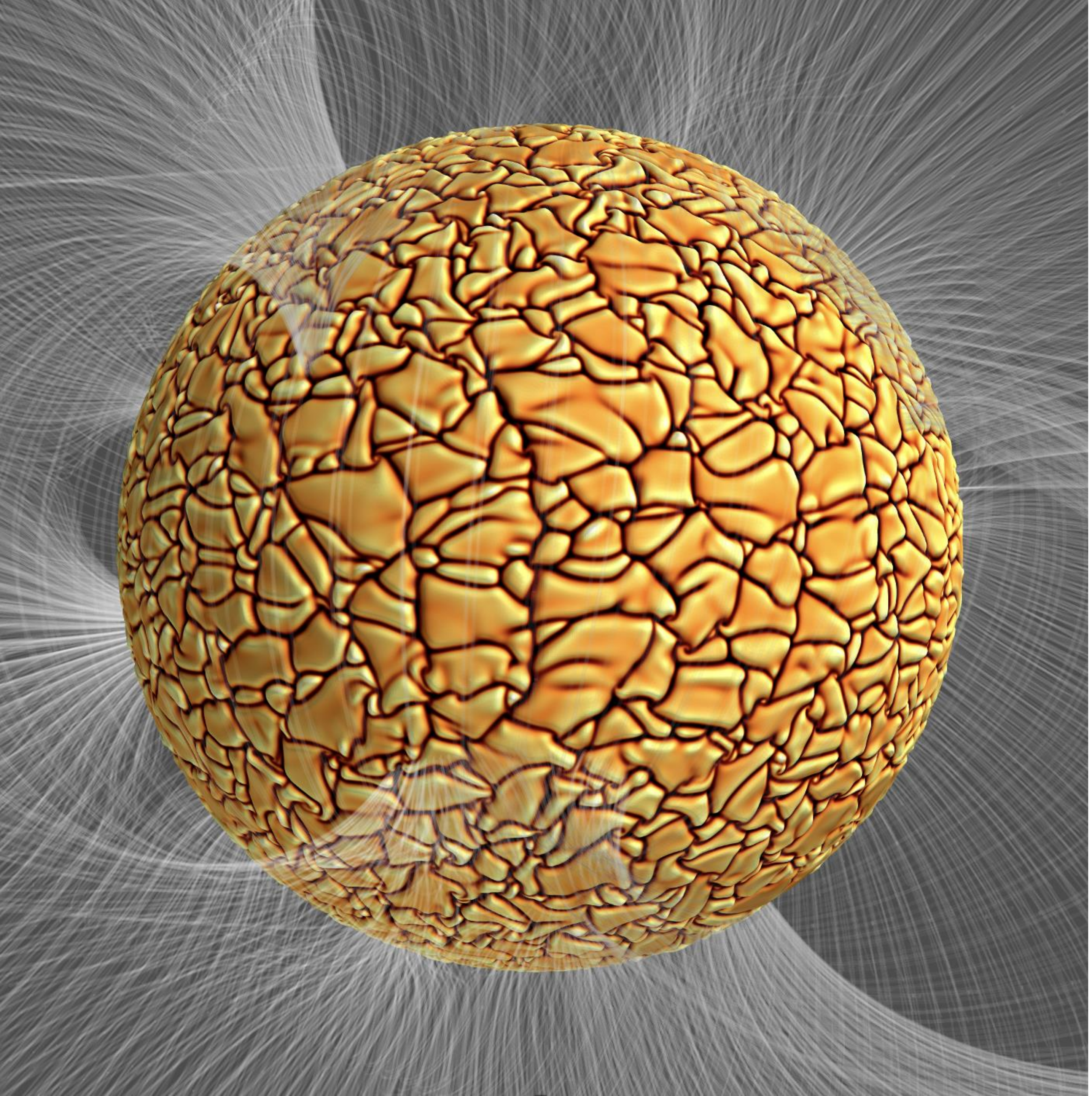

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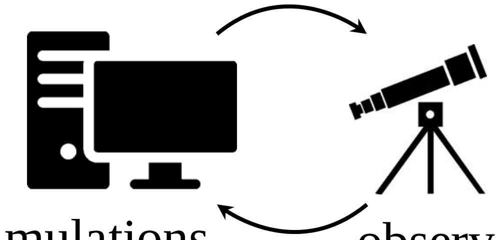
for Solar
Physics

Magnetochronology of solar-type stars dynamos

Quentin NORAZ
Nordita 2024



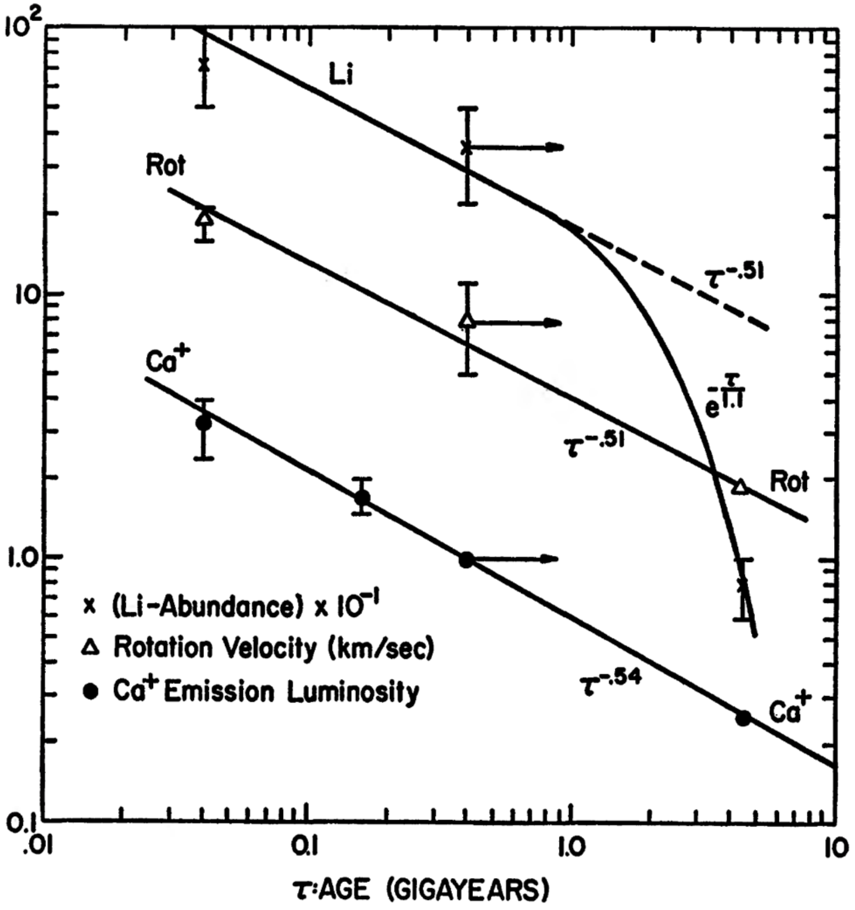
simulations observations

with A.S. Brun, A. Strugarek, B. Perri,
L. Amard & collaborators

Stellar Rotation

”Gyro-chronology” (Barnes+ 2003)

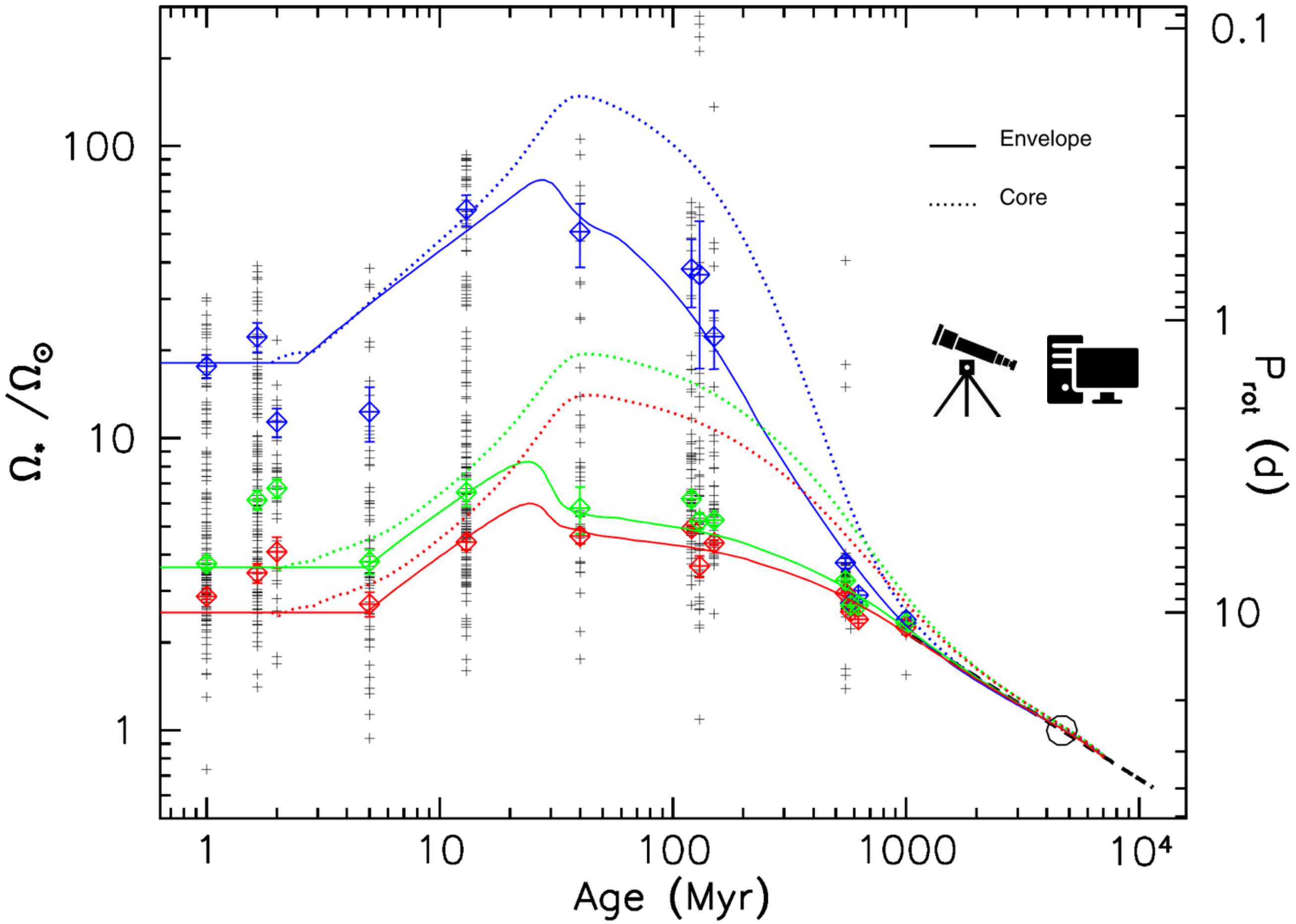
[Skumanich 1972]



Skumanich law

$$\boxed{\Omega(t) \propto t^{-1/2}}$$

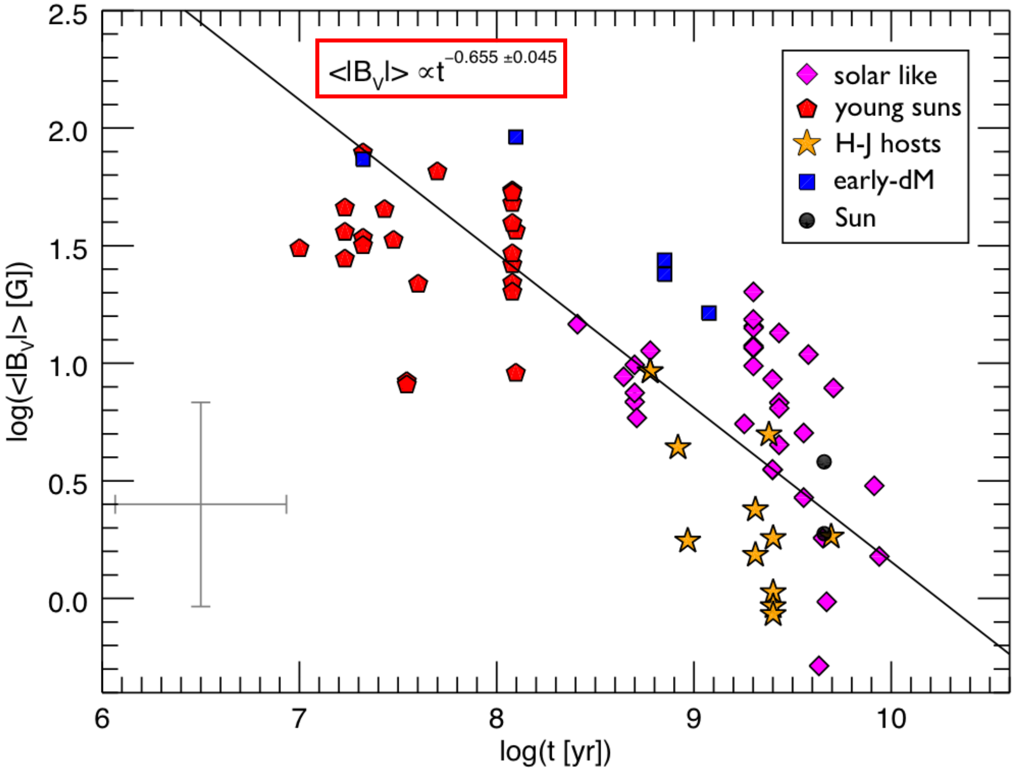
[Gallet & Bouvier2013]

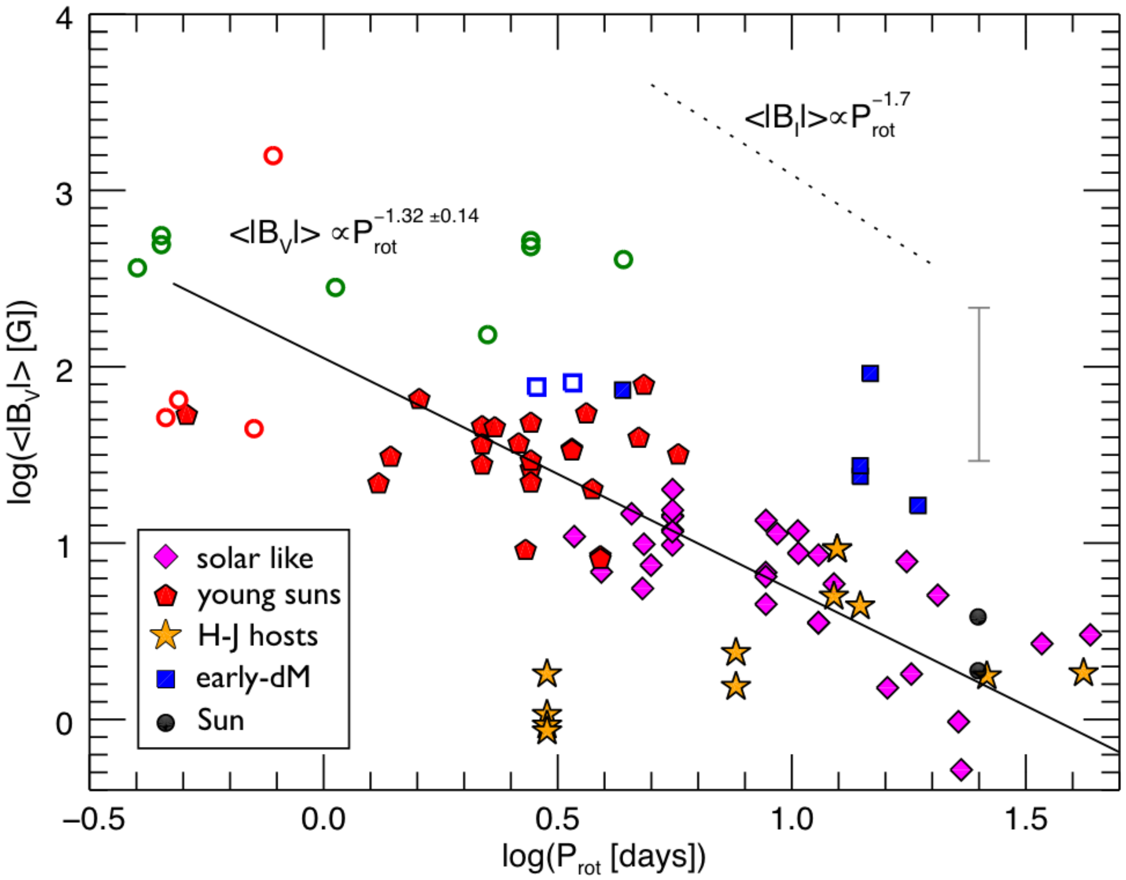


[see also Barnes 2007, Gallet & Bouvier 2015, Benbakoura+19, Mathur+ 23]

Stellar Magnetism

”Magneto-chronology” [Vidotto+ 2014]





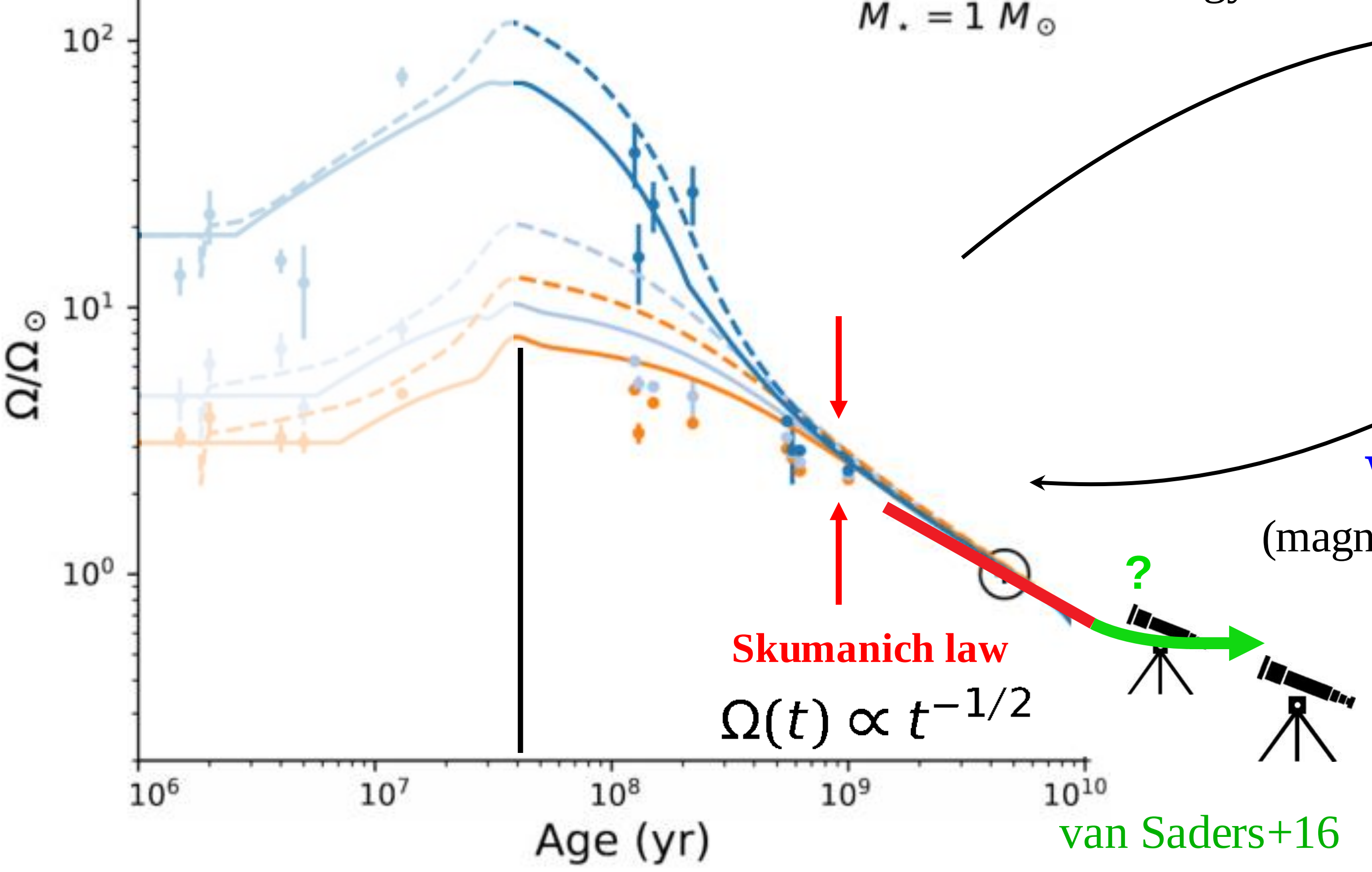
- |Bv| obtain with ZDI

- Both **B** and **Prot** relate with age, can be linked! but data **spread** stays important…

Magneto-rotational evolution

Rotation

[e.g. Gallet & Bouvier 15; Ahuir+ 21]



Skumanich law

$\Omega(t) \propto t^{-1/2}$

van Saders+16
Curtis+20, Metcalfe+ 22

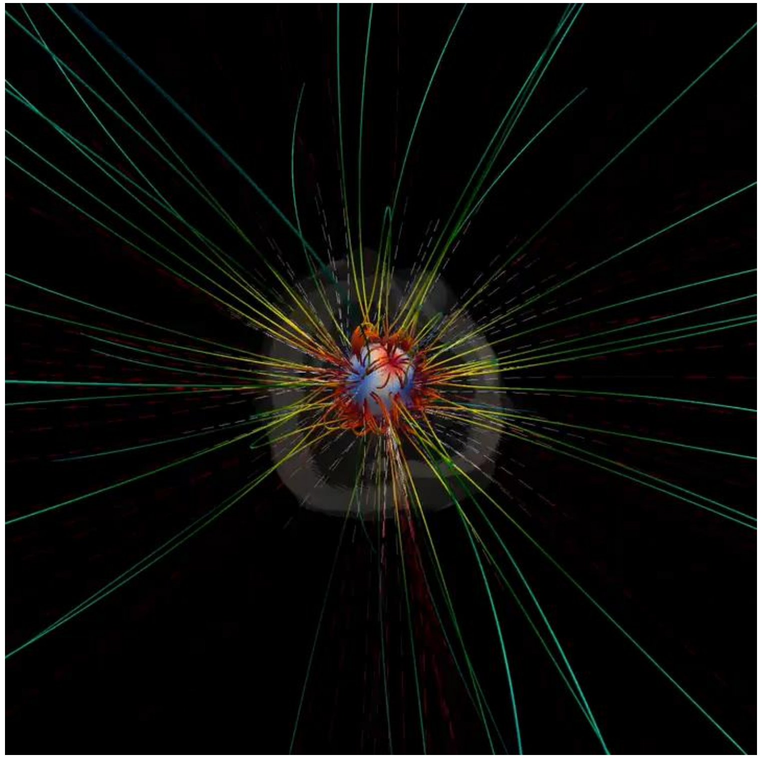
Dynamo

(from kinetic to magnetic energy transformation)

Wind

(magnetic braking)

Magnetism



© A. Strugarek

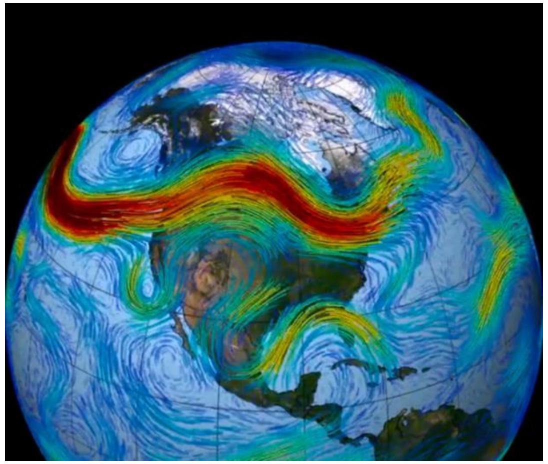
What controls the spin-down?

$\langle r_A \rangle \propto B$; **But…** $\Omega_* \leftrightarrow B$?

Rossby number : Normalizing Prot by τ_{conv}

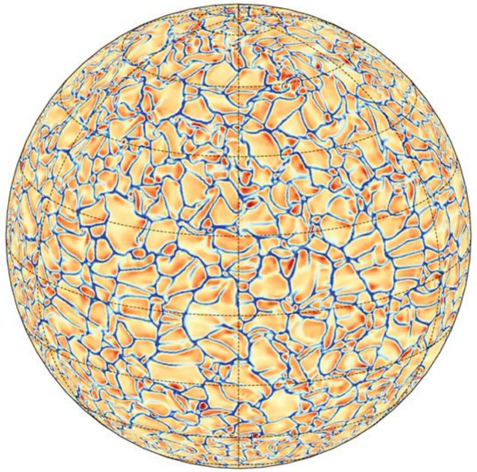
Fluid Rossby number

Stellar Rossby number



[NASA]

$$\boldsymbol{Ro} \sim \frac{\text{Advection}}{\text{Coriolis}}$$



[ASH code]

$$Ro_s = \frac{P_{\mathrm{rot}}}{\tau_c}$$

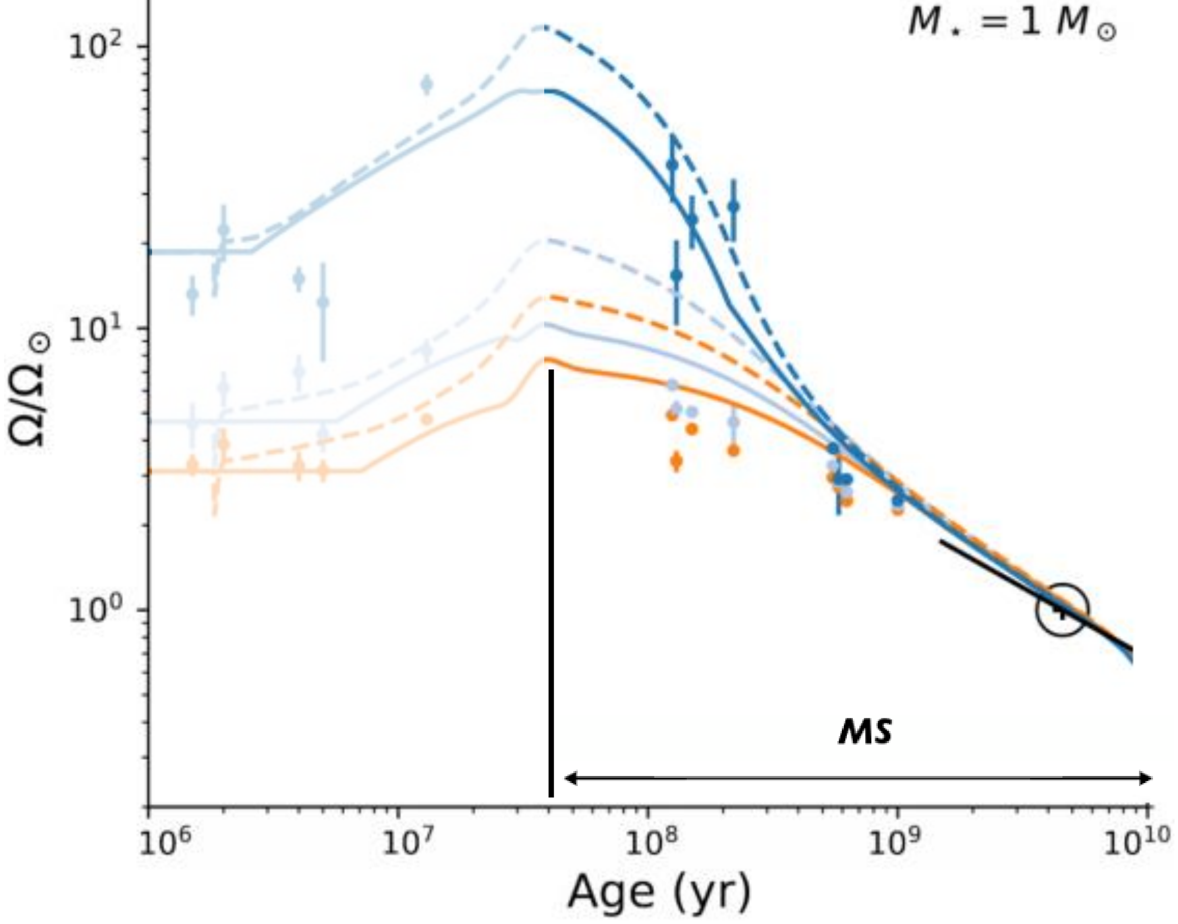
With $\boldsymbol{\tau_c}$
the convective turnover time

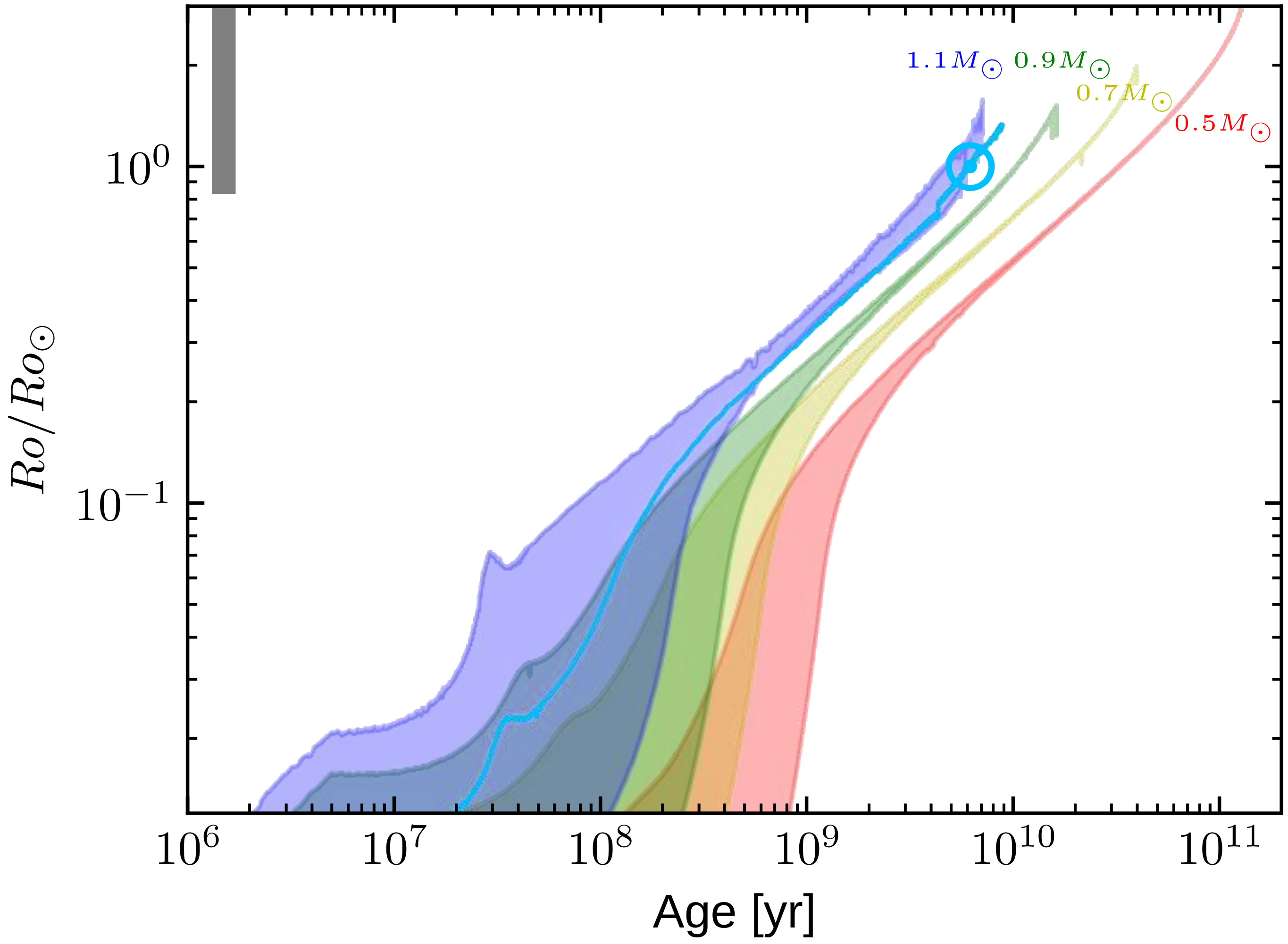
Evolution of the Rossby number

Rotation

Rossby $\propto \Omega^{-1}$

[e.g. Gallet & Bouvier 15; Ahuir+ 21]



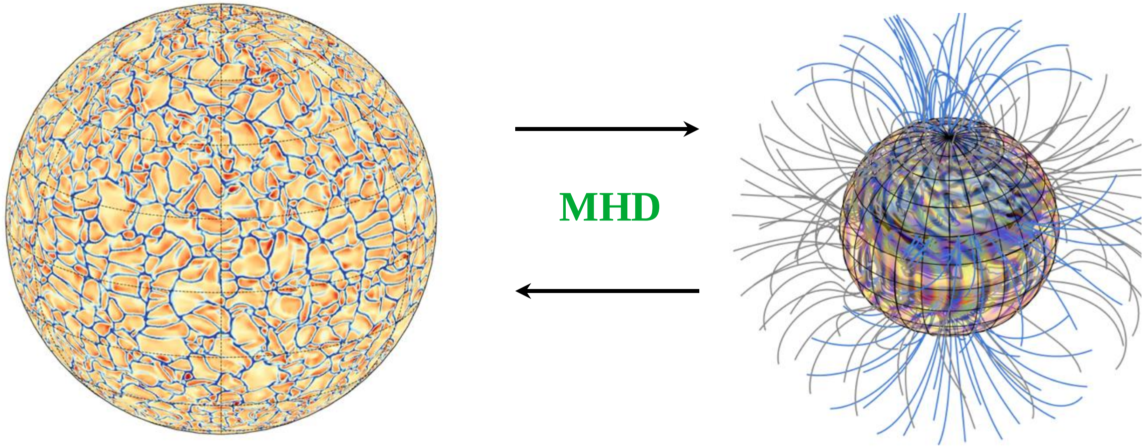


New insights from simulations

Numerical setup:

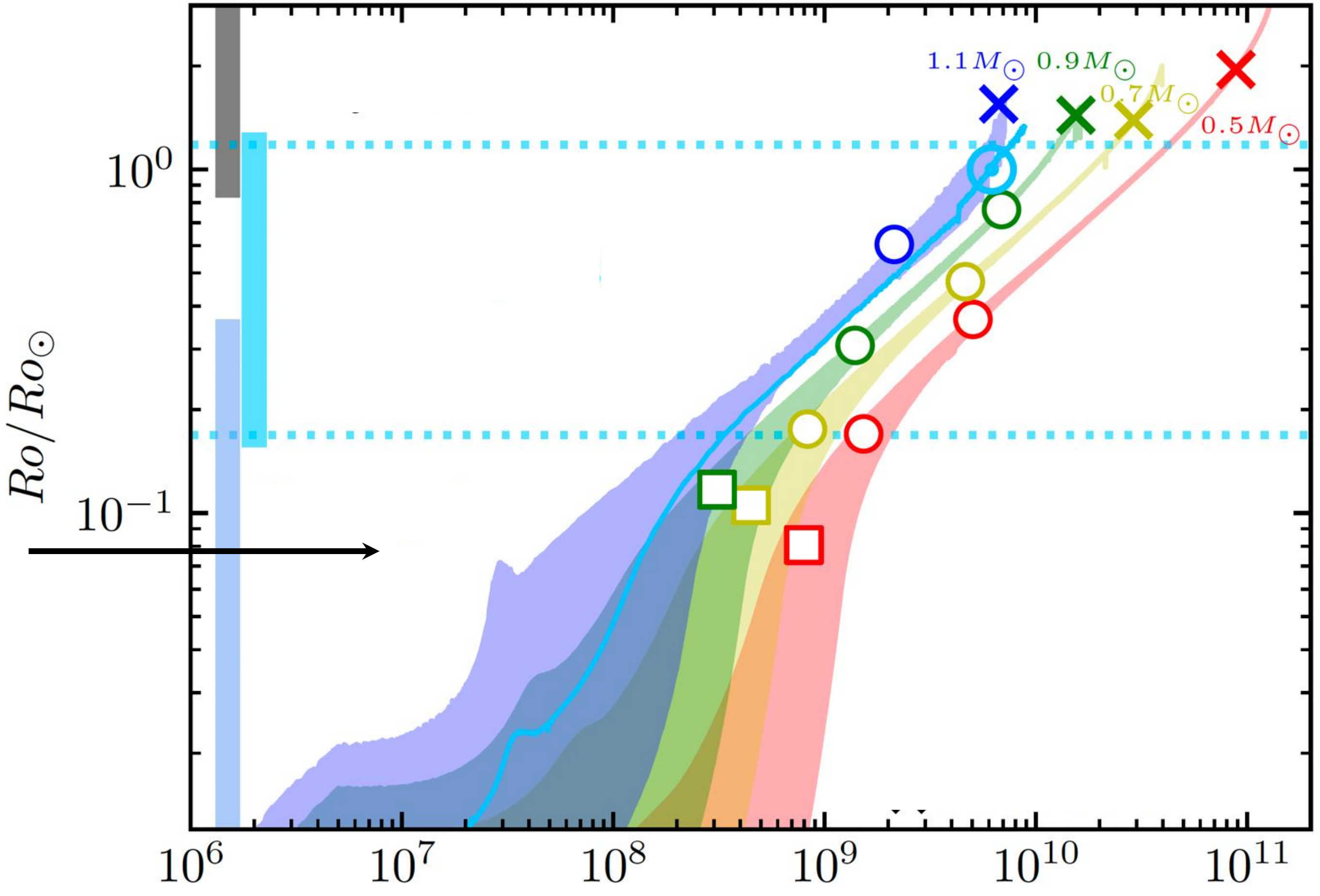
- Code : ASH (global)
  3D MHD spherical (r,θ,φ)

→ **convection** is explicitly resolved,
magnetic retroaction on the flow ←



15 models of solar-type [Brun et al. 2022]

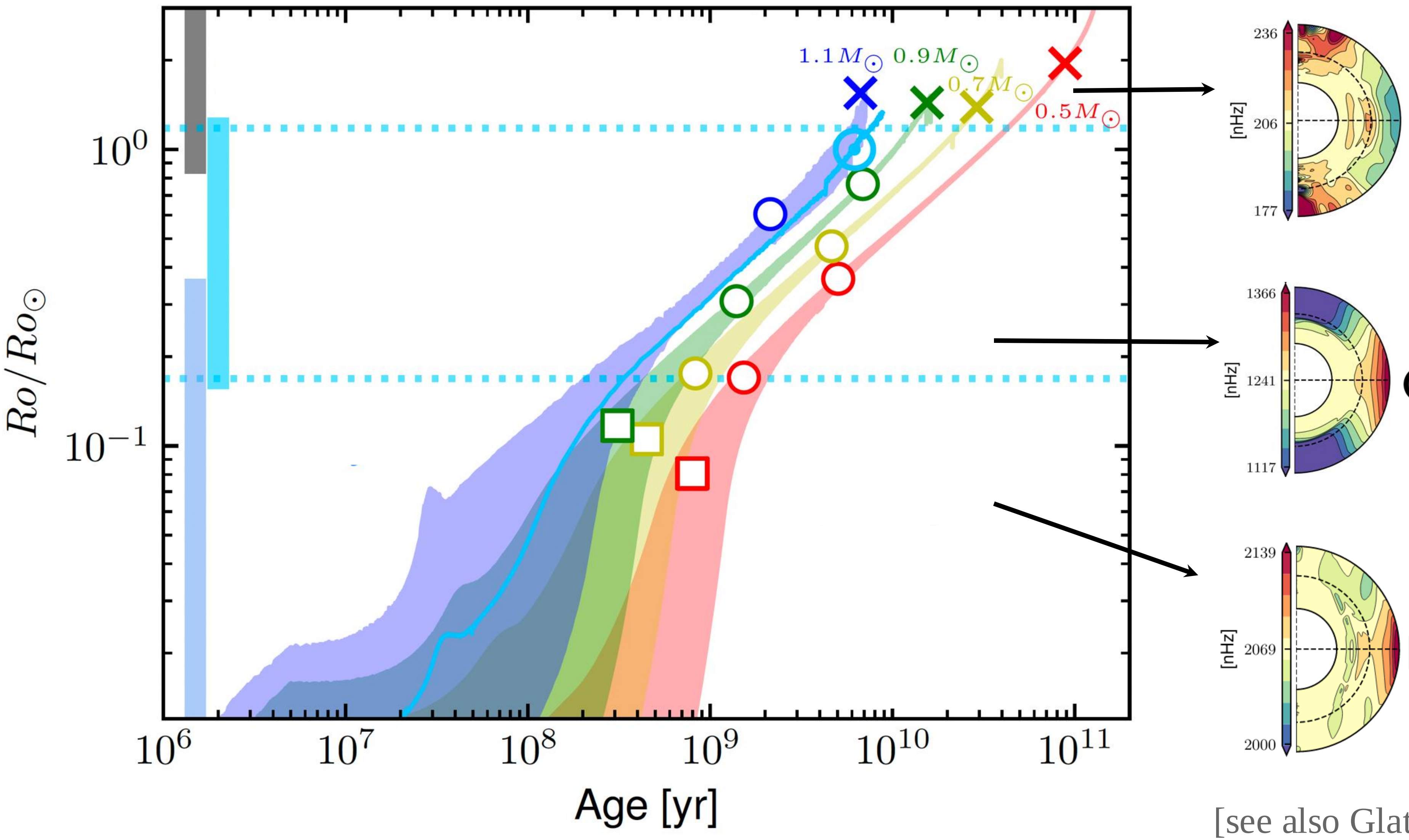
- from 0.25 $\Omega_\odot$ to 5 $\Omega_\odot$
- from 0.5 $M_\odot$ to 1.1 $M_\odot$
- Resolution 769 x 256 x 512



[Noraz et al. (2024)]

Rotational transitions

[Brun+ 22, Noraz+ 24]



✕ Anti-solar DR

○ Solar DR

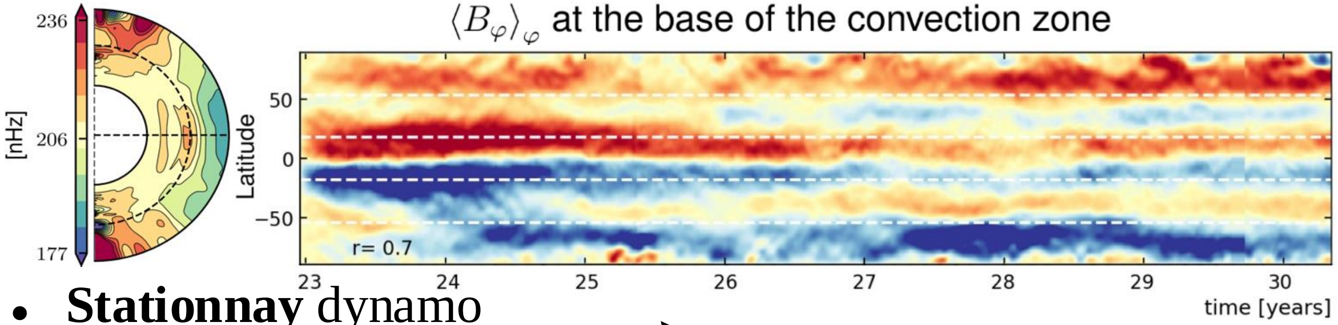
□ Banded or quenched DR

Rossby increases

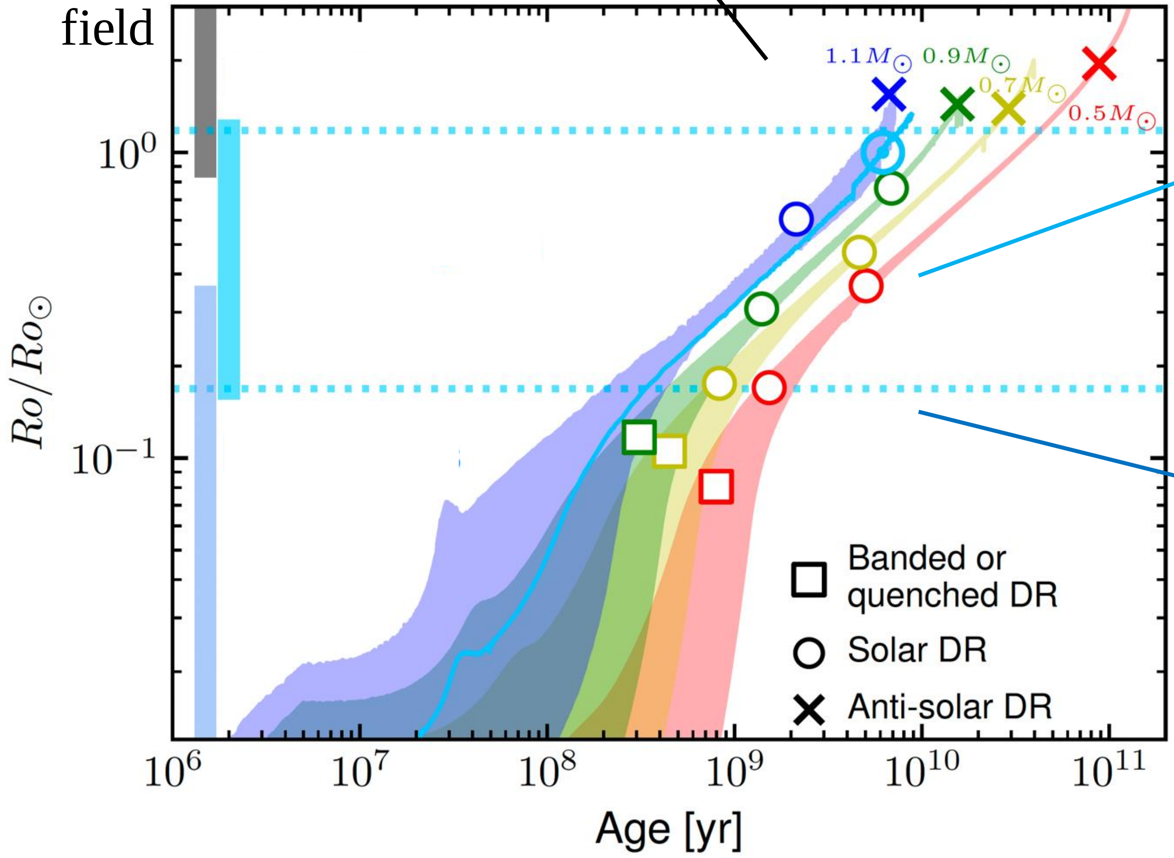
[see also Glatzmaier & Gilman 82, Matt+ 11, Käpylä+ 14; Gastine+ 14, Simitev+15, Karak+ 18, Hindman+ 20…]

Magnetic transitions

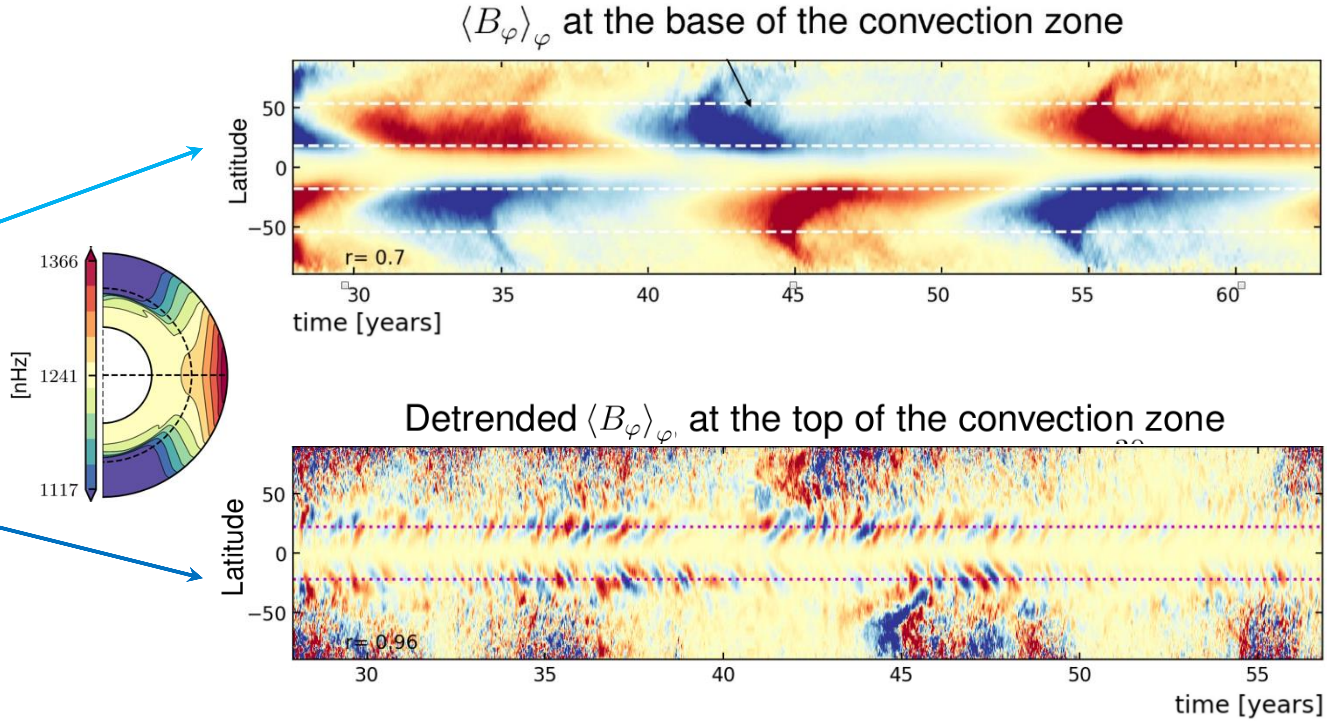
[Brun+ 22, Noraz+ 24]



- **Stationnay** dynamo
- hemispherical toroidal field



- long cycles (**decadal solar-like**)
- **Global** polarity reversals



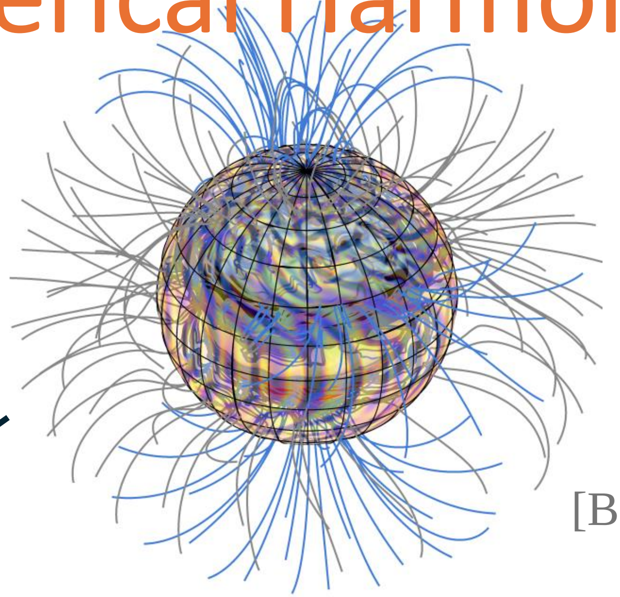
- **short cycles** (~year) at the surface
- **Local** equatorial polarity reversals

ZDI observations & Vectorial Spherical Harmonics

$$\begin{cases} \mathbf{R}_l^m & = & Y_l^m \mathbf{e}_r \\ \mathbf{S}_l^m & = & \boldsymbol{\nabla}_\perp Y_l^m = \partial_\theta Y_l^m \mathbf{e}_\theta + \frac{1}{\sin\theta}\partial_\varphi Y_l^m \mathbf{e}_\varphi \\ \mathbf{T}_l^m & = & \boldsymbol{\nabla}_\perp \times \mathbf{R}_l^m = \frac{1}{\sin\theta}\partial_\varphi Y_l^m \mathbf{e}_\theta - \partial_\theta Y_l^m \mathbf{e}_\varphi \end{cases}$$

$$\mathbf{B} = \sum_{\substack{\ell,m \\ \ell\leq\ell_{\mathrm{cut}} \\ -\ell\leq m\leq\ell}} \mathcal{A}_{l,m}\mathbf{R}_l^m + \mathcal{B}_{l,m}\mathbf{S}_l^m + \mathcal{C}_{l,m}\mathbf{T}_l^m$$

[Rieutord 1987]



?

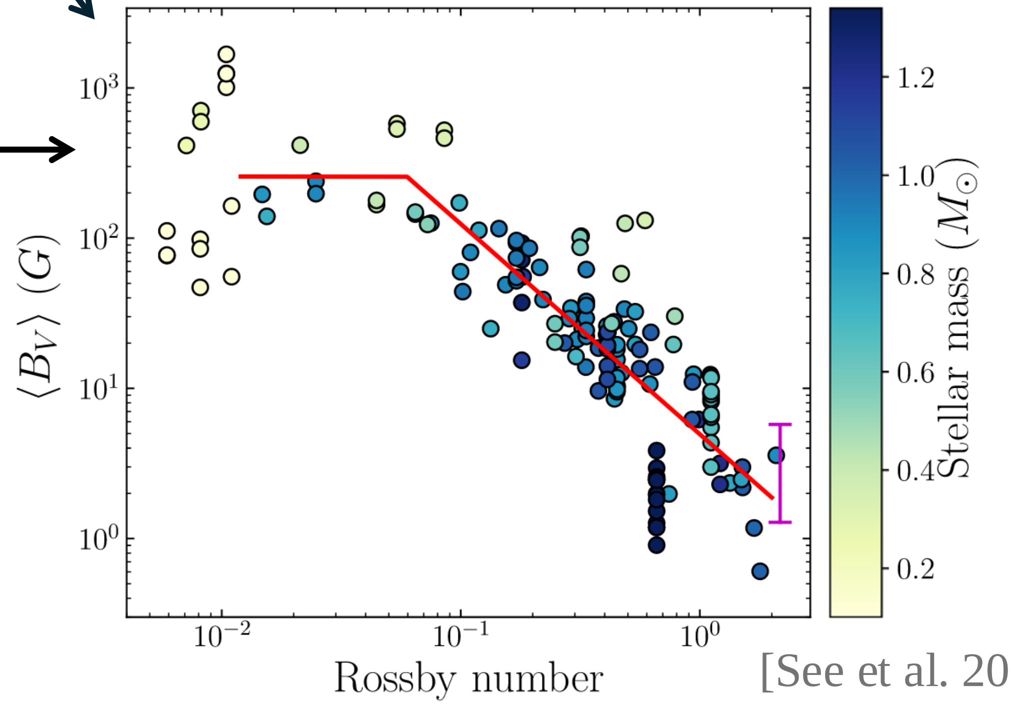
[Brun et al. 2022]

$$B_V^2 = \frac{1}{4\pi} \sum_{\substack{\ell,m \\ \ell\leq\ell_{\mathrm{cut}} \\ -\ell\leq m\leq\ell}} |\mathcal{A}_{\ell,m}|^2 + \ell(\ell+1)(|\mathcal{B}_{\ell,m}|^2 + |\mathcal{C}_{\ell,m}|^2)$$

$$B_{\mathrm{pol}}^2 = \frac{1}{4\pi} \sum_{\substack{\ell,m \\ \ell\leq\ell_{\mathrm{cut}} \\ -\ell\leq m\leq\ell}} |\mathcal{A}_{\ell,m}|^2 + \ell(\ell+1)|\mathcal{B}_{\ell,m}|^2$$

$$B_{\mathrm{tor}}^2 = \frac{1}{4\pi} \sum_{\substack{\ell,m \\ \ell\leq\ell_{\mathrm{cut}} \\ -\ell\leq m\leq\ell}} \ell(\ell+1)|\mathcal{C}_{\ell,m}|^2$$

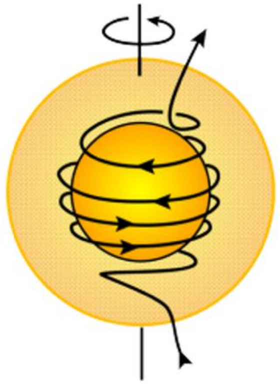
[Donati et al. 2006;
Vidotto et al. 2016;
Folsom et al. 2018]

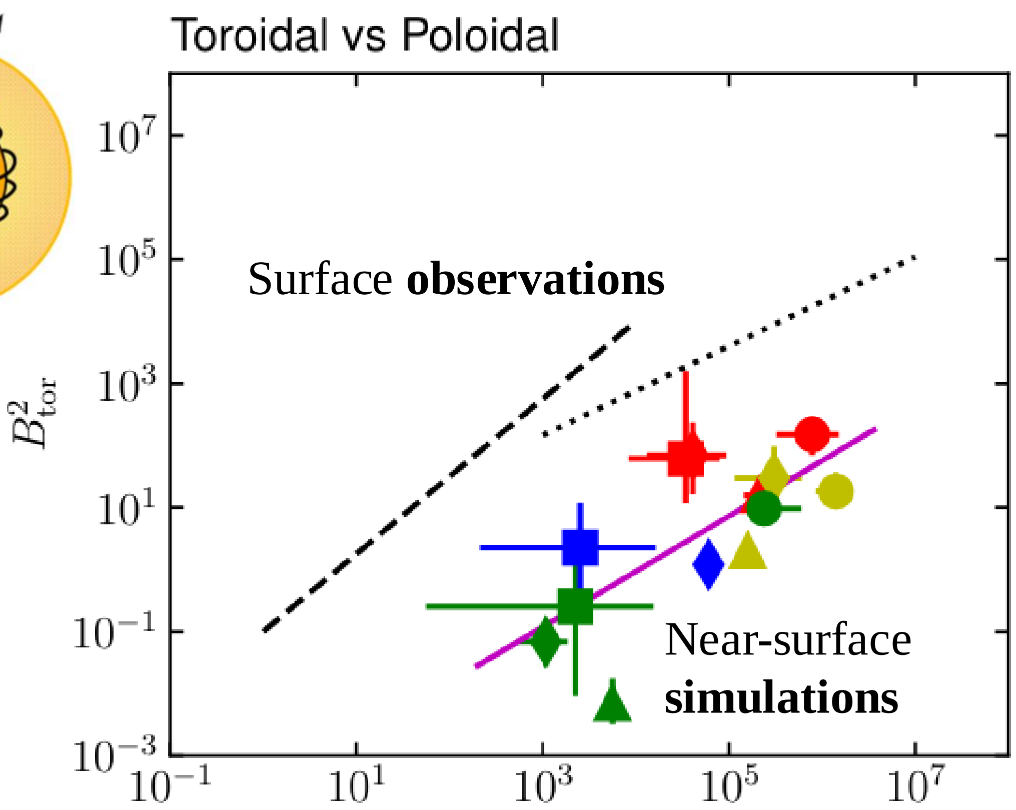


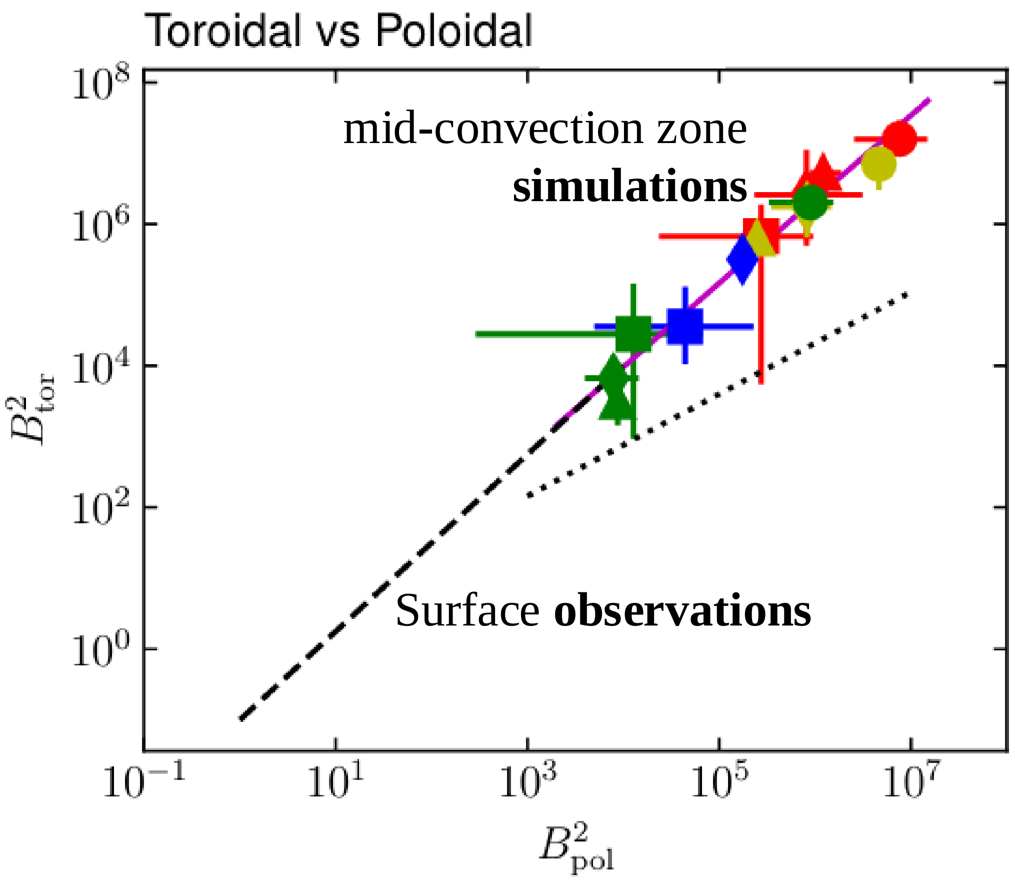
[See et al. 2019]

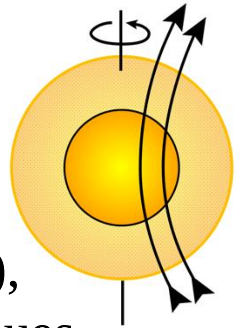
Observational constraints: Topology

[Noraz+ 24,
obs. from See et al. 2015, 19]









- **Trends consistent** with observations (See+ 2015), surface BCs offset toroidal values

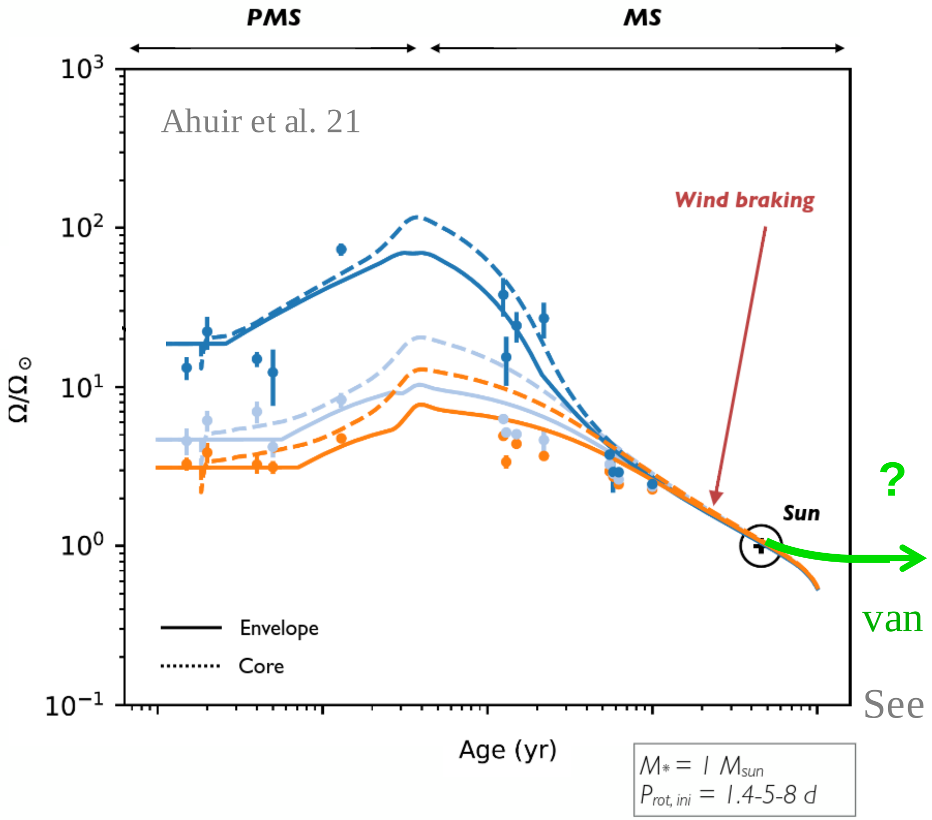
- Mid-CZ **simulated dynamo geometry** may be **linked to the one observed** on stellar surfaces

Impact on the magnetic braking

Angular momentum loss

$$\boxed{\dot{J} \propto \dot{M} \Omega_* \langle r_A \rangle^2}$$

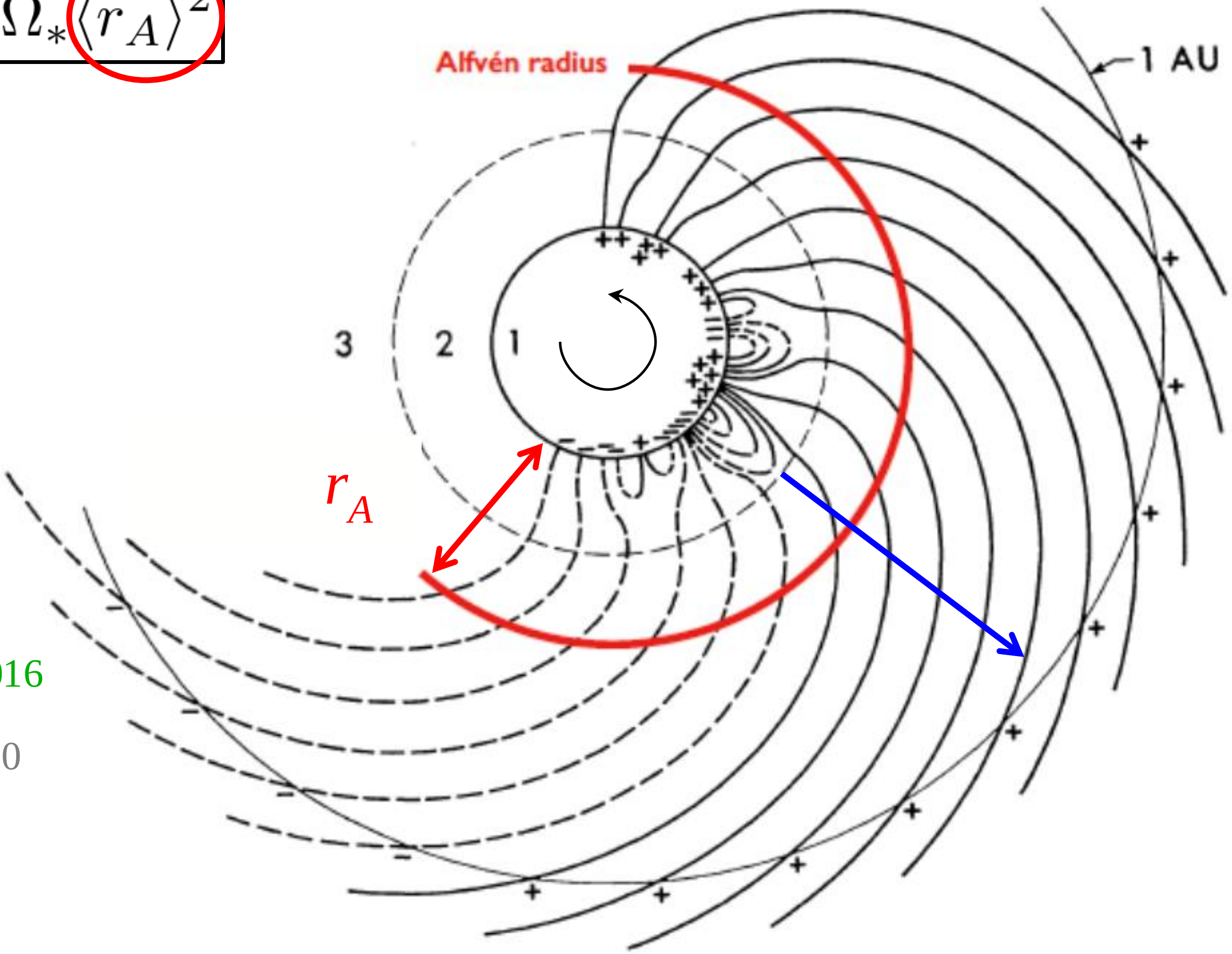
[Schatzman 62; Weber & Davis 67
Schatten et al. 69; Ahuir PhD]



Ahuir et al. 21

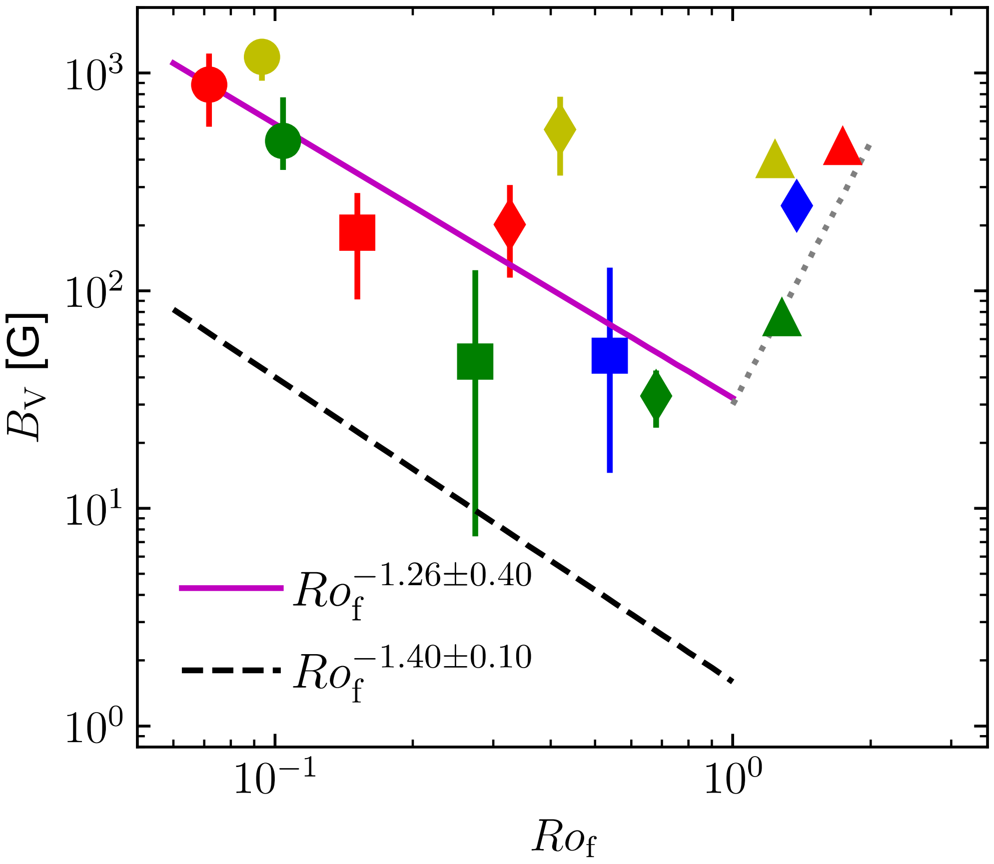
van Saders et al. 2016

See also Curtis 2020



Trend as a function of the Rossby number

Near-surface

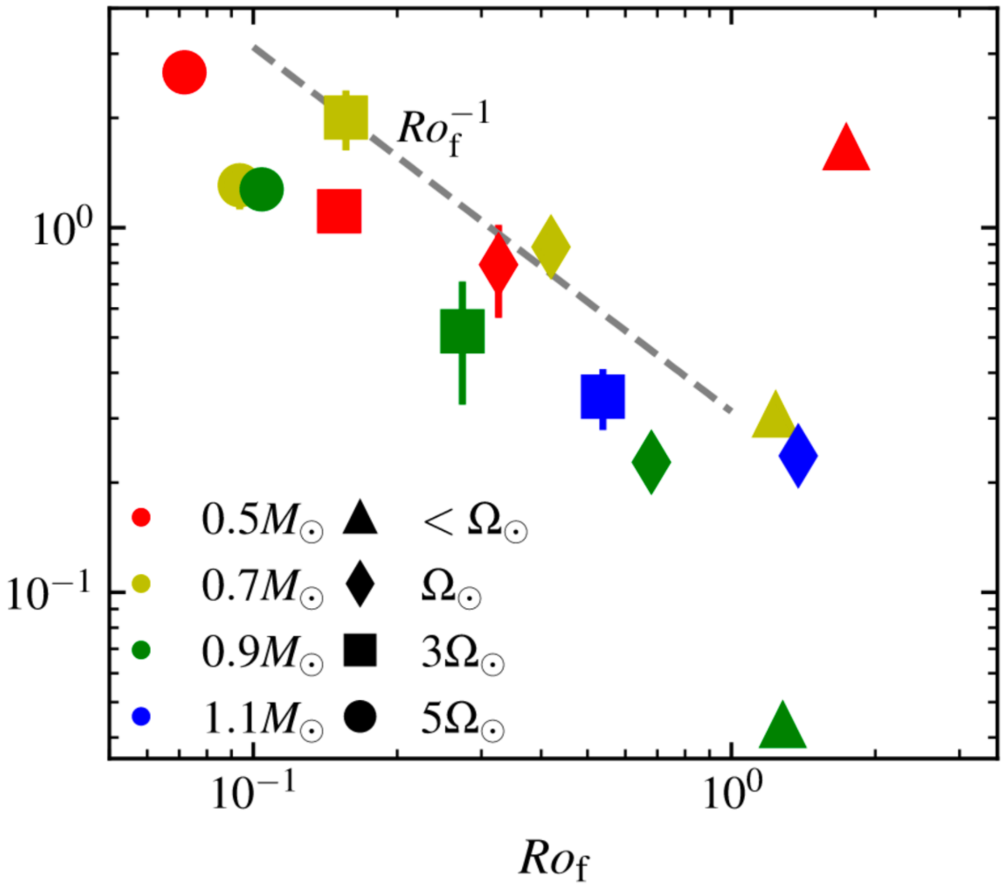


Large-scale field

[Noraz+ 24]

Surface large-scale magnetic-field is consistent with **ZDI** observations

CZ bulk

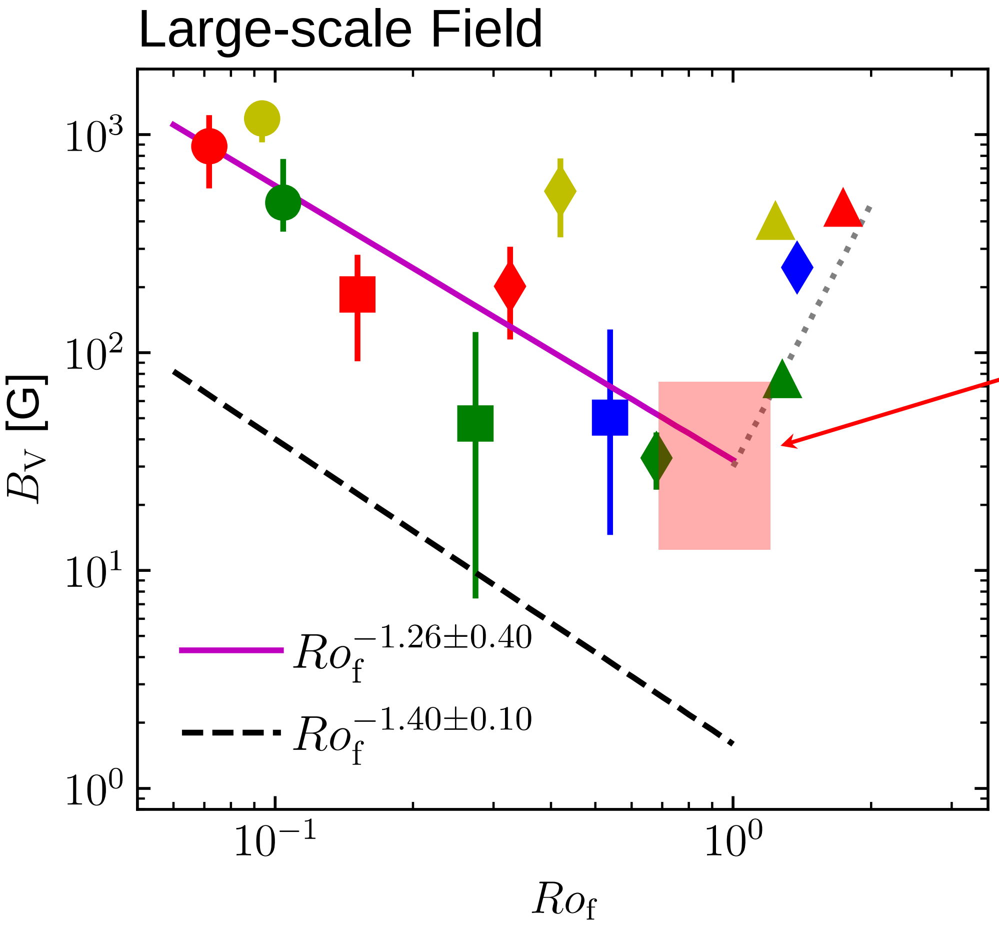


Magnetic energy

[Brun+ 22]

Magnetism in the **bulk of the CZ** is consistent with a **magnetostrophic balance** $B^2 \propto \Omega$

Magnetochronology of old solar-type stars



fast rotators **slow rotators**

- The large-scale decreases, agrees with observational trends, but does not disappear,

There may be a minimum around the solar Rossby value.

- Can a star be trapped in this regime with **weakened magnetism** and **mass loss rate?** [see also Metcalfe et al. 2022]

$$\boxed{\dot{J} \propto \dot{M}\Omega_* \langle r_A \rangle^2}$$

- We need further constraints for the **high-Rossby regime** [see also Brandenburg & Giampapa 2018]

Parametric study: Mean-field dynamo

Numerical setup:

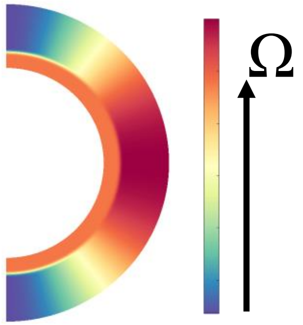
- Code : STELEM
- Dimensions : 2D5
- Regime : Kinematic

  → DR is imposed

  → convection parameterized

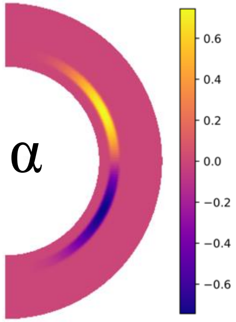
[Noraz et al. 22a]

$$\frac{\partial \mathbf{B}}{\partial t} = \overset{\textbf{generation}}{\boxed{\nabla \times (\mathbf{v} \times \mathbf{B})}} - \overset{\textbf{dissipation}}{\boxed{\nabla \times (\eta \nabla \times \mathbf{B})}}$$

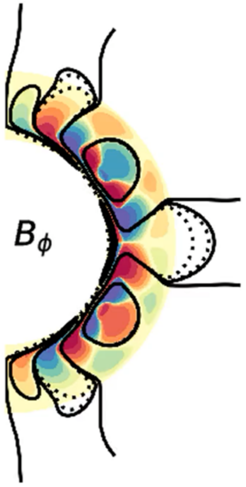


Solar
Rotation profile

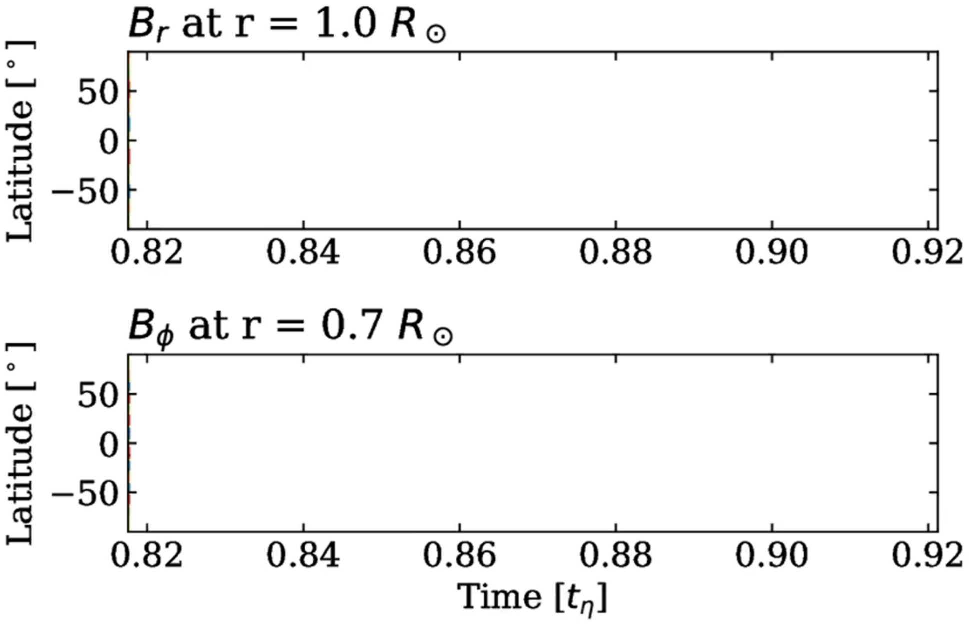
+



αΩ
Dynamo

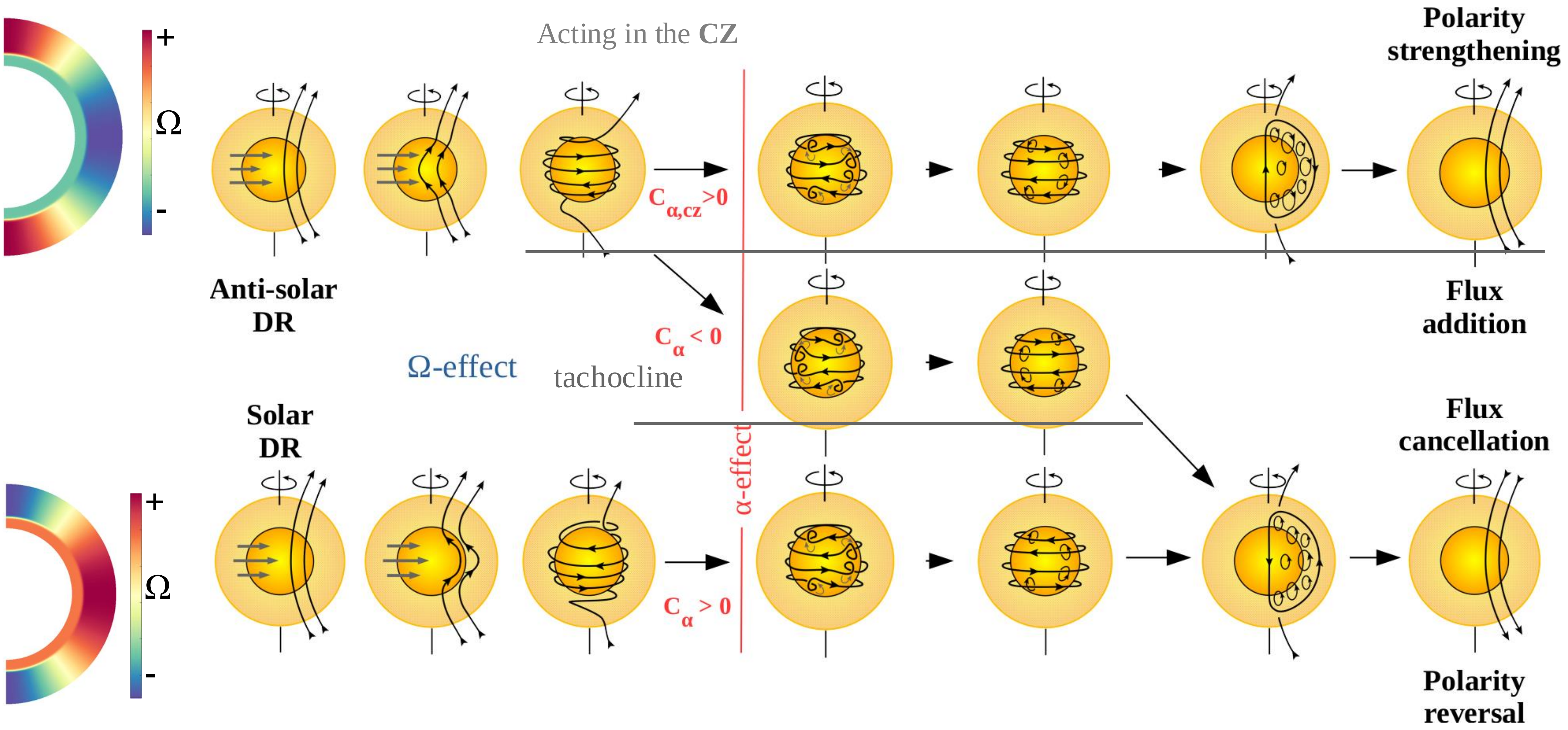


Solar reference case



What is the impact of an antisolar profile?

Anti-solar DR: Geometrical Interpretation



Acting in the **CZ**

Polarity strengthening

No cycle

$C_{\alpha,cz}>0$

Anti-solar DR

Flux addition

Cycle

$C_\alpha < 0$

Ω-effect

tachocline

Solar DR

Flux cancellation

α-effect

$C_\alpha > 0$

Cycle

Polarity reversal

[Noraz+ 22a, inspired from Sanchez+ 14]

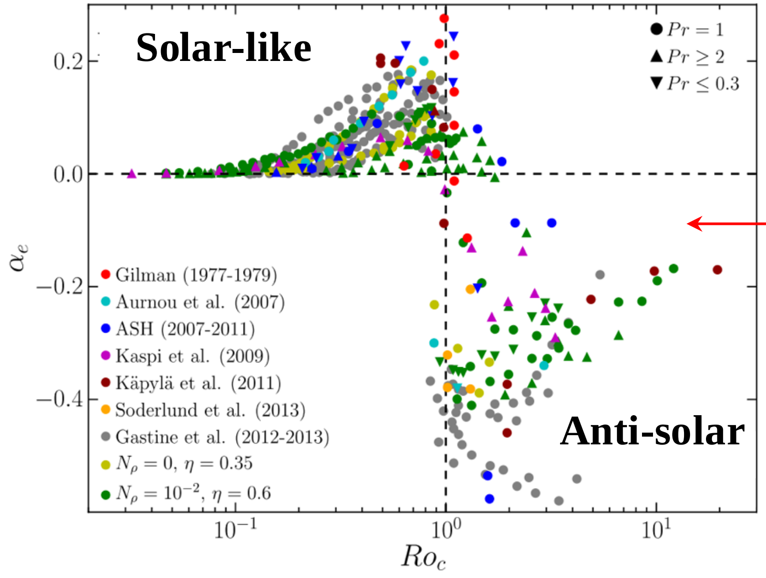
Where are Antisolar rotators?

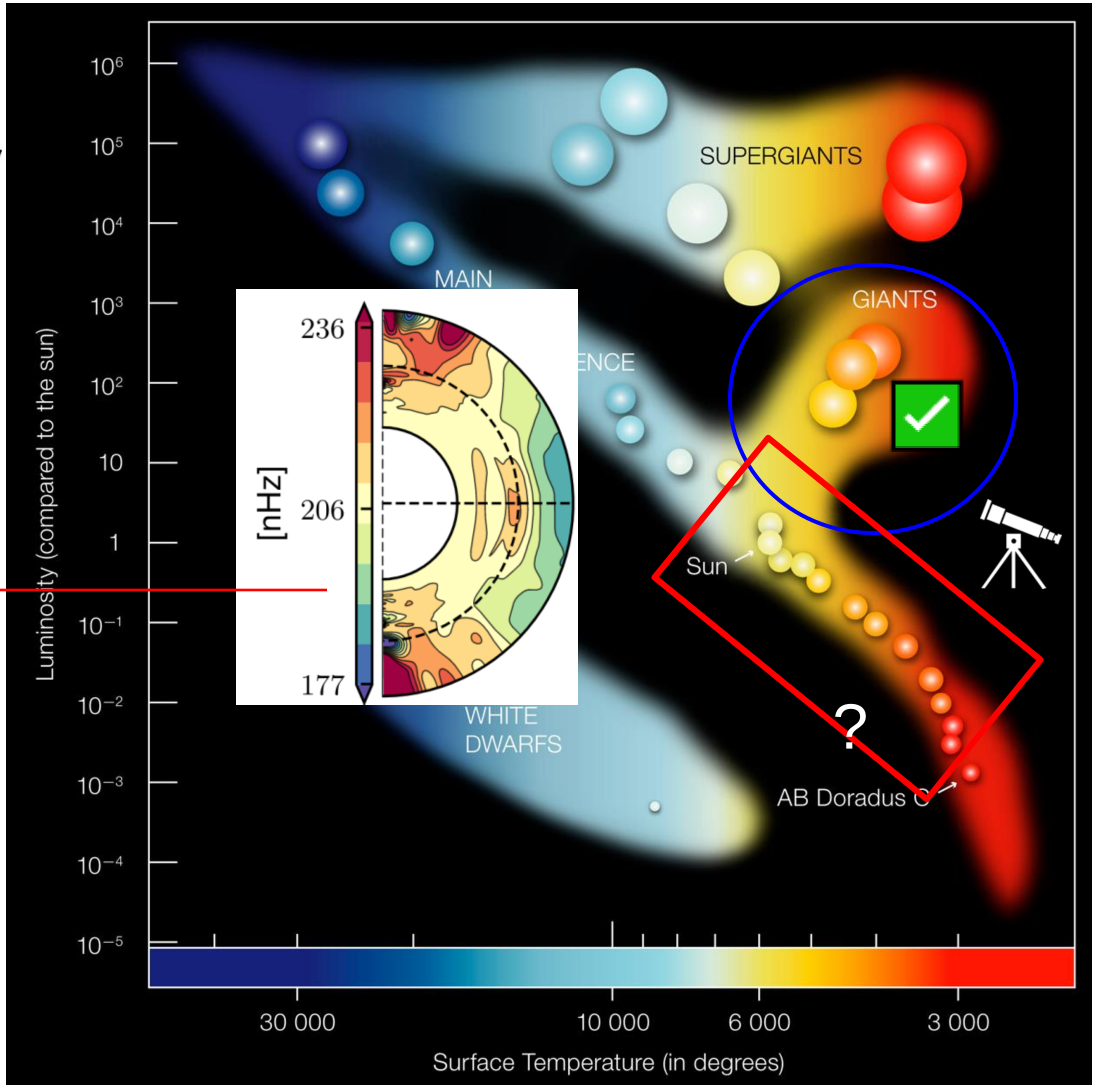
- Observational evidences reported during **evolved phases** [e.g. Harutyunyan+ 16; Kővári+ 17]

→ **But no robust detections for MS solar-like stars**.

- Strong result from global models

Gastine+14 ; see also
Warnecke+19
Brun+ 22
Kapyla+ 22





Adapted from ESO

- Let's look for candidates with the fluid Rossby number

$$R_{of} = \frac{v_{conv}}{2\Omega_* R_*}$$

Compute fluid Rossby from observables

$$v_{\mathrm{conv}} \propto f_S(M_*)\left(\frac{L_* R_*}{M_*}\right)^{1/3}$$

Convection transports L_*
+ structural effects

$$f_S(M_*) \propto M_*^q \; ; \; L_* \sim M_*^m \quad \text{and} \quad R_* \sim M_*^n \longrightarrow \boxed{v_{\mathrm{conv}} \propto M_*^{q+(m+n-1)/3}}$$

$$L_* = 4\pi R_*^2 \sigma T_{eff}^4 \longrightarrow T_{eff} \propto M_*^{\frac{m-2n}{4}}$$

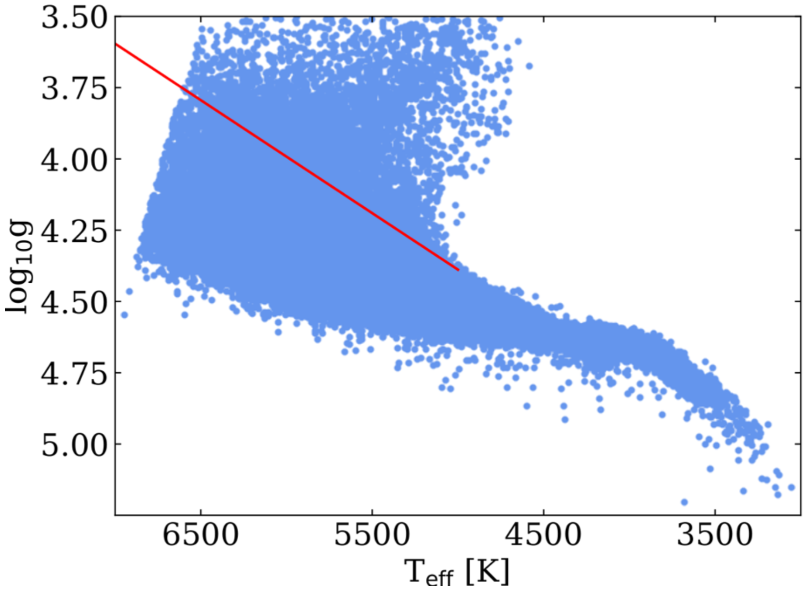
Calibration with Amard+ 19 evolution models

$$\boxed{\frac{Ro_{\mathrm{f}}}{\mathrm{Ro}_{\mathrm{f},\odot}} = \left(\frac{P_{\mathrm{rot},*}}{\mathrm{P}_{\mathrm{rot},\odot}}\right) \times \left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^{3.29}}$$

- The fluid Rossby number can now be computed with **observables quantities**

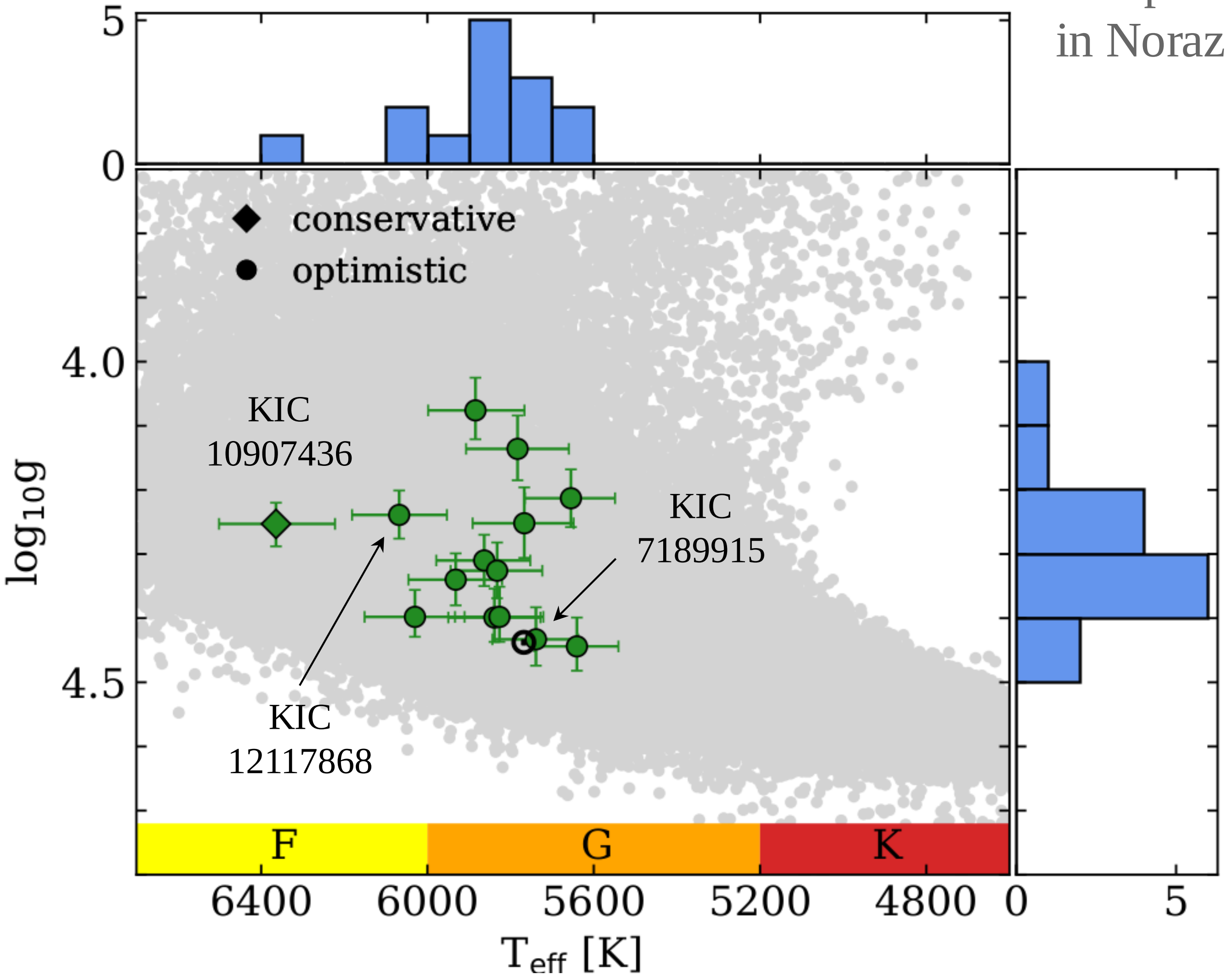
Promising solar analogs

- Periods are taken from the recent **Santos+ 21 catalog** of *Kepler* rotations



- Main-sequence stars
- $Ro_{f,*}/Ro_{f,\odot} > 1.4$
- Individual checks

14 candidates for solar metallicity



List published in Noraz+ 22b

Looking at other metallicities

- Same selection
- Analytical development with metallic dependance

$$L_* \propto M_*^{m_1}([Fe/H]+2)^{m_2}$$

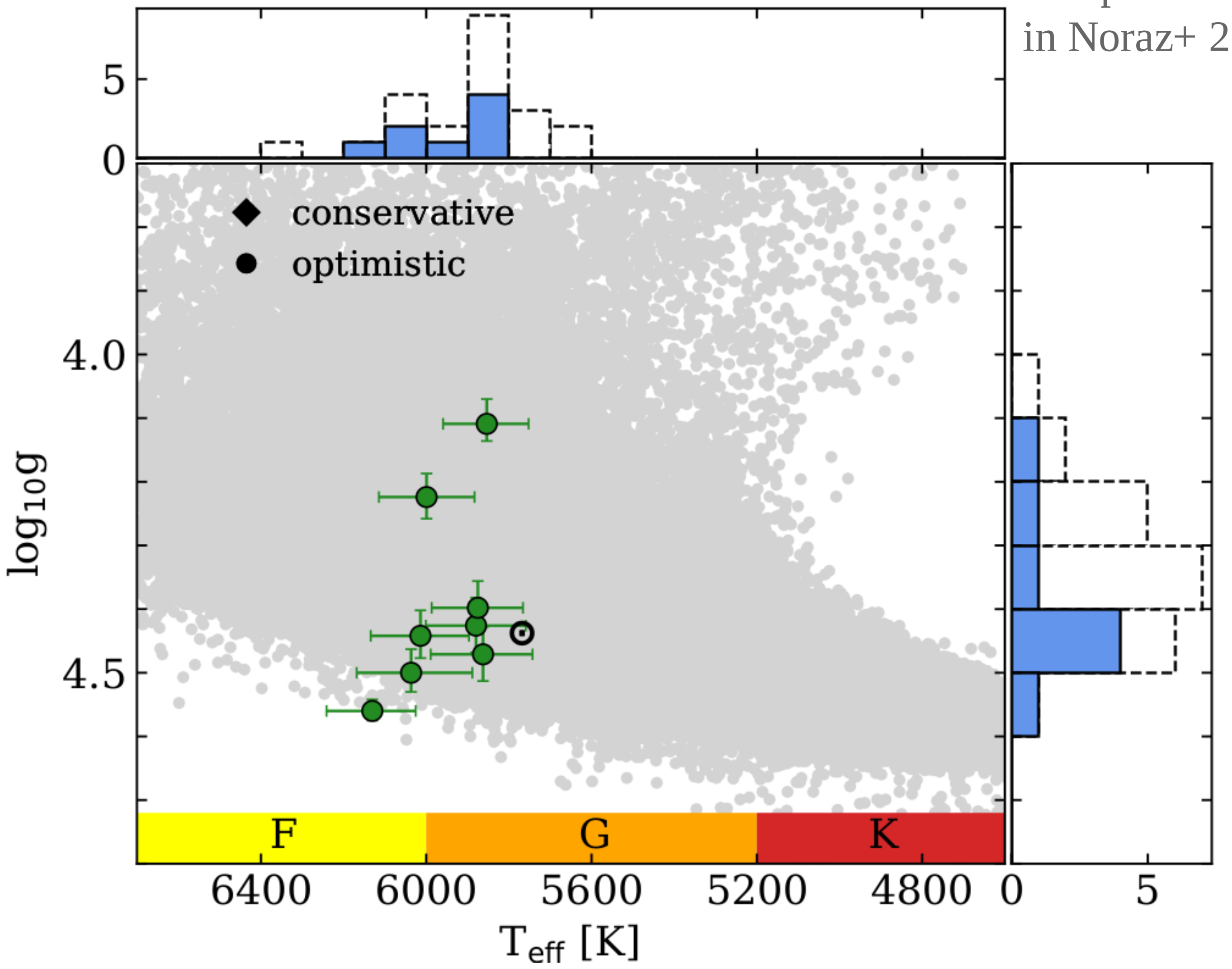
$$R_* \propto M_*^{n_1}([Fe/H]+2)^{n_2}$$

$$f_S(M_*) \propto M_*^{q_1}([Fe/H]+2)^{q_2}$$

$$\downarrow$$

$$\boxed{\frac{Ro_{\mathrm{f}}}{\mathrm{Ro}_{\mathrm{f},\odot}} = \left(\frac{\mathrm{P}_{\mathrm{rot},*}}{\mathrm{P}_{\mathrm{rot},\odot}}\right) \times \left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^{3.29} \times \left(\frac{[Fe/H]+2}{2}\right)^{-0.31}}$$

8 candidates at other metallicities



List published in Noraz+ 22b

Conclusion: Take-home messages

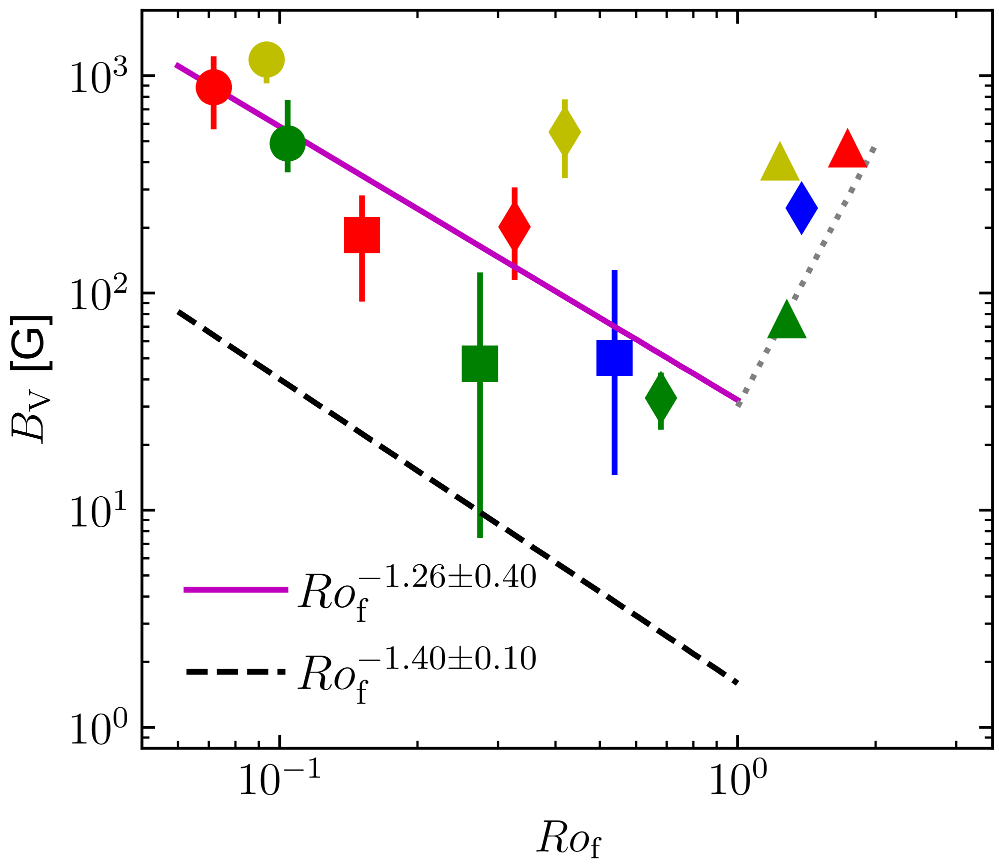
quentin.noraz@astro.uio.no
@Norastraz

- **Scenario for the Sun's life** [Strugarek+ 17, Brun +22, Noraz +24]
  young (fast-rotating) - **short cycle** - constrained DR
  solar age - **decadal cycle** - prograde equator,
  older - **stationnary dynamo** - retrograde equator?

- Such results are **reproduced** with other numerical methods,
  [Strugarek+ 17,18, EULAG code, see Manfred Küker's work]
  Good qualitative **agreement with observations**,

- **These are only simulations**:
  Still far from stellar turbulence regime,
  Rossby trends are robust,
  but the exact solar value is still uncertain:
  see *Convective conundrum*,
  [see Hanasoge+12,16, Hotta+ 23, Warnecke+ 24]

Large-scale Field



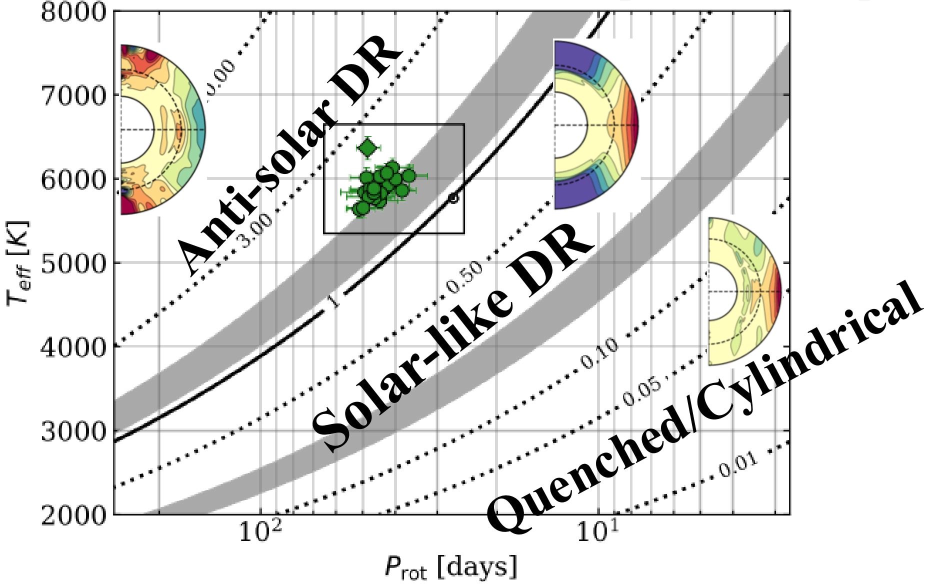
Perspectives

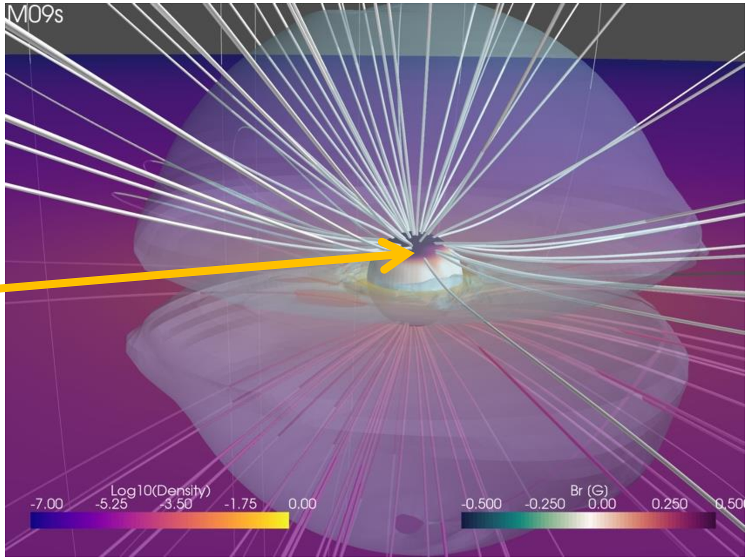
- **Expand the Rossby range of investigation**:
  - low-Rossby/*saturated* regime
    [see e.g. Reiners+ 2022, Shimada et al. in prep.]
  - high-Rossby regime
    [see e.g. Brandenburg & Giampapa 2018, Donati et al. 2023, Cristofari et al. 2023; Lehmann et al. 2023]

- **Mass loss rate evolution**:
  How do low-atmospheric quantities vary as a function of stellar parameters.

$$\boxed{\dot{J} \propto \dot{M}\Omega_*\langle r_A\rangle^2}$$

[Noraz+ 22a]





[Noraz Q. PhD]