

Evolution and diversity of solar-type stars dynamo

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AIM/CEA Saclay, France

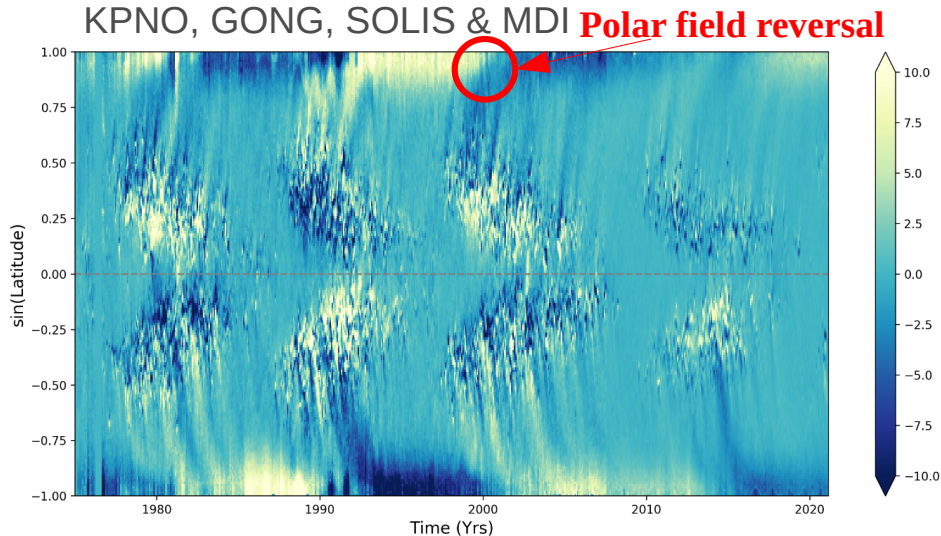
A. S. Brun, A. Strugarek and collaborators

Atelier général du Programme National de
Physique Stellaire - SF2A 2022



Cyclic activity and differential rotation

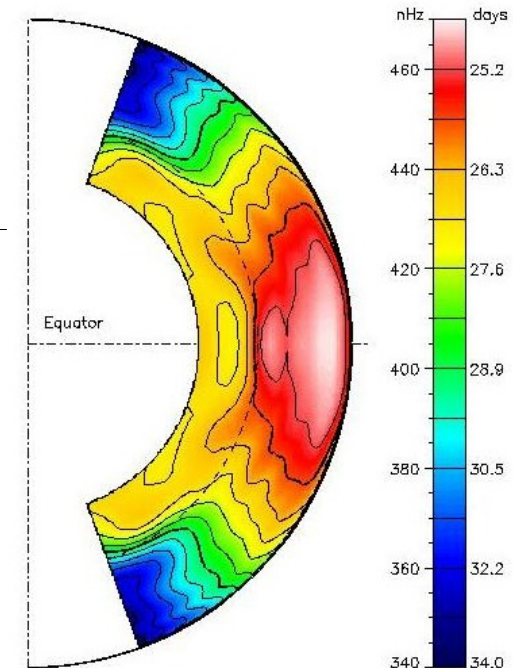
Current Observations :



- 11-years activity cycle
- Migration of structures toward equator
- Opposite hemisphere polarities
- Alternating dipole/quadrupole
- 22-years magnetic cycle

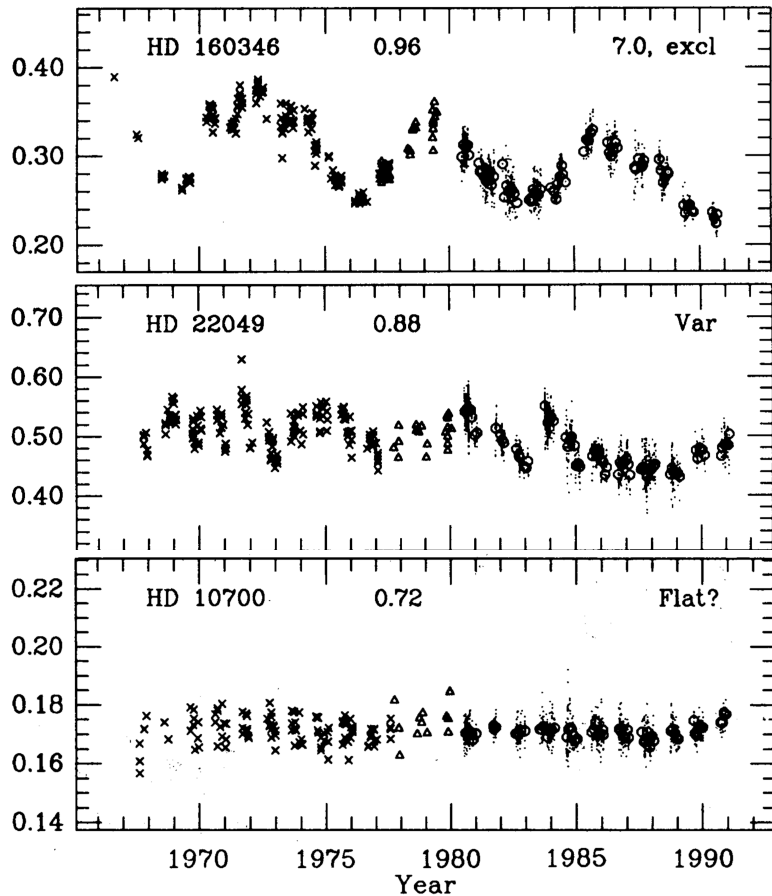
A **solid-body rotation** of the **radiative core**, surrounded by a **differentially rotating convective envelope**

Thompson et al. (2003)
(see also Garcia et al. 2007)

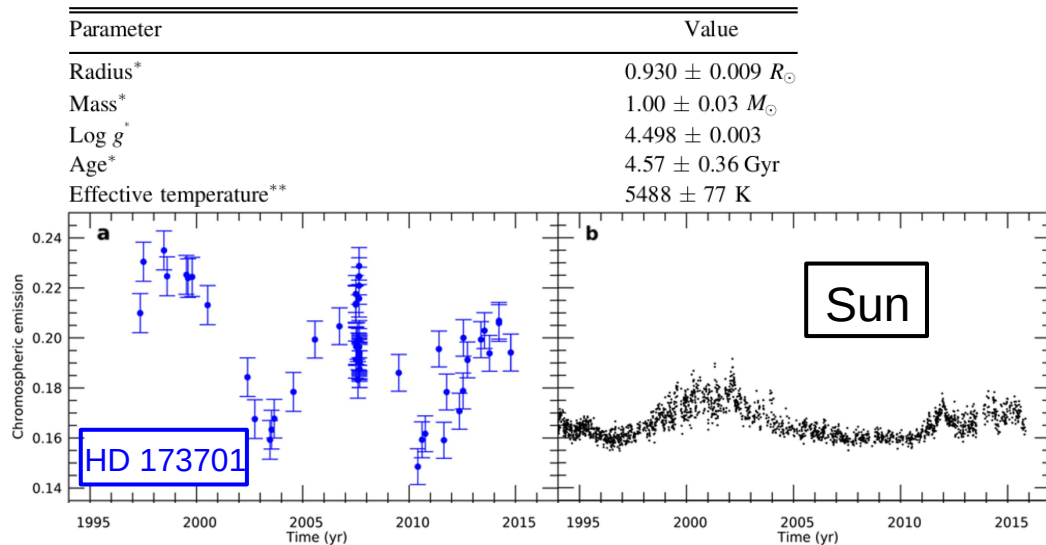


Differential rotation
plays a key role for
dynamo mechanism

Magnetic cycle in other stars

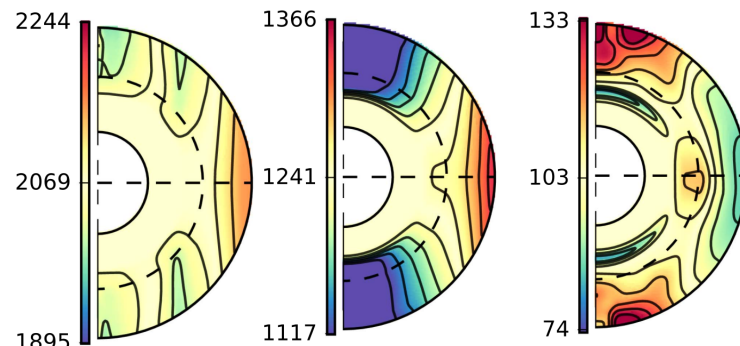
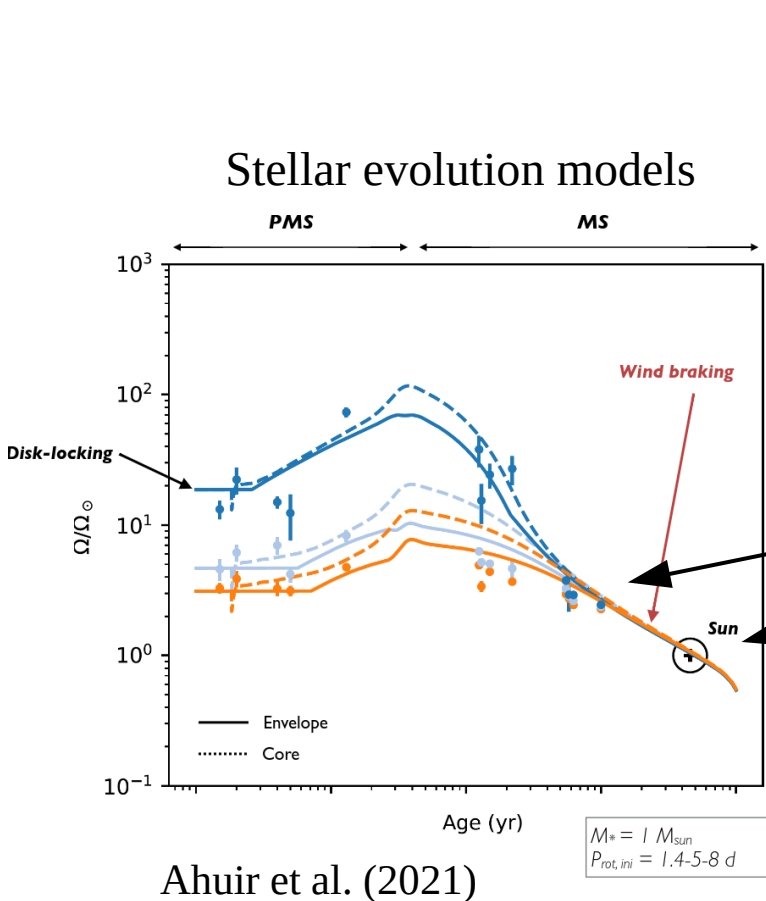


Baliunas et al (1995)



Karoff et al (2017)

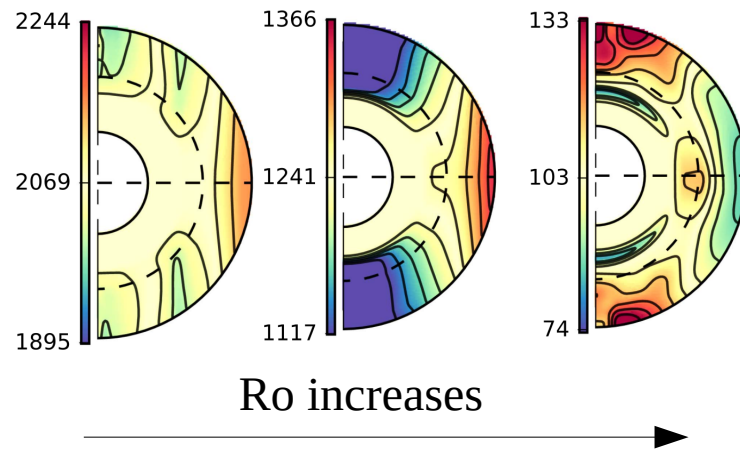
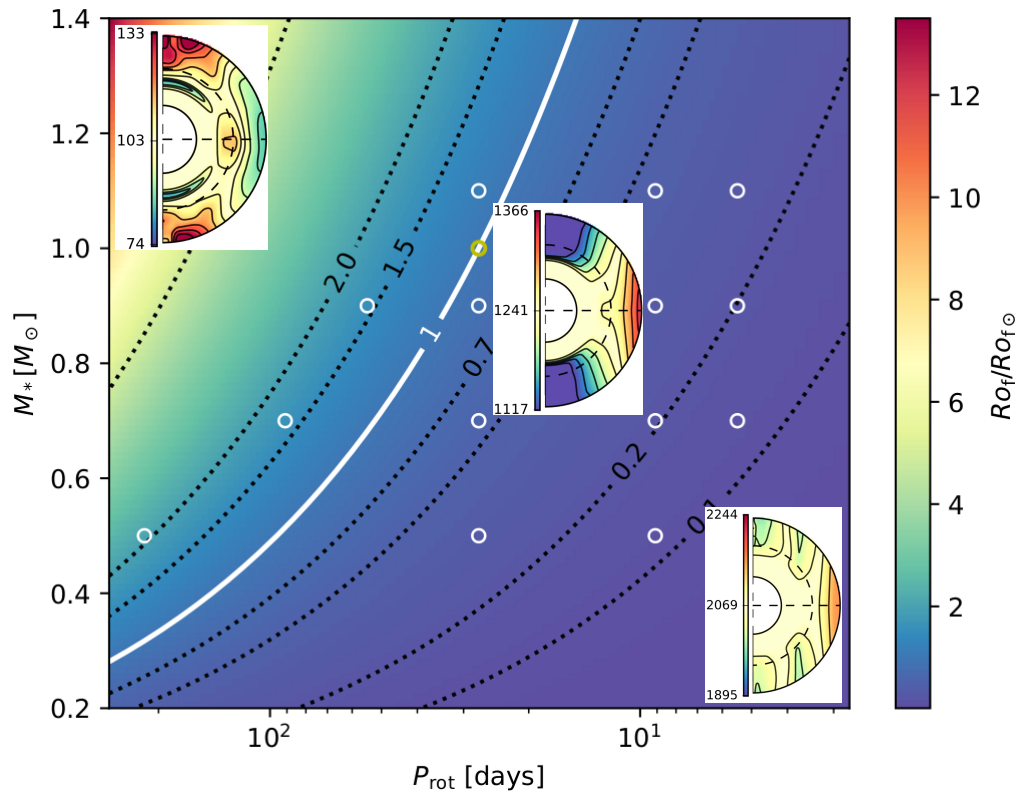
Sun in time: Rotation profile



Decreasing Ω

Brun et al. (2017)

Rossby number : Rotation profile



Brun et al.
(2017)

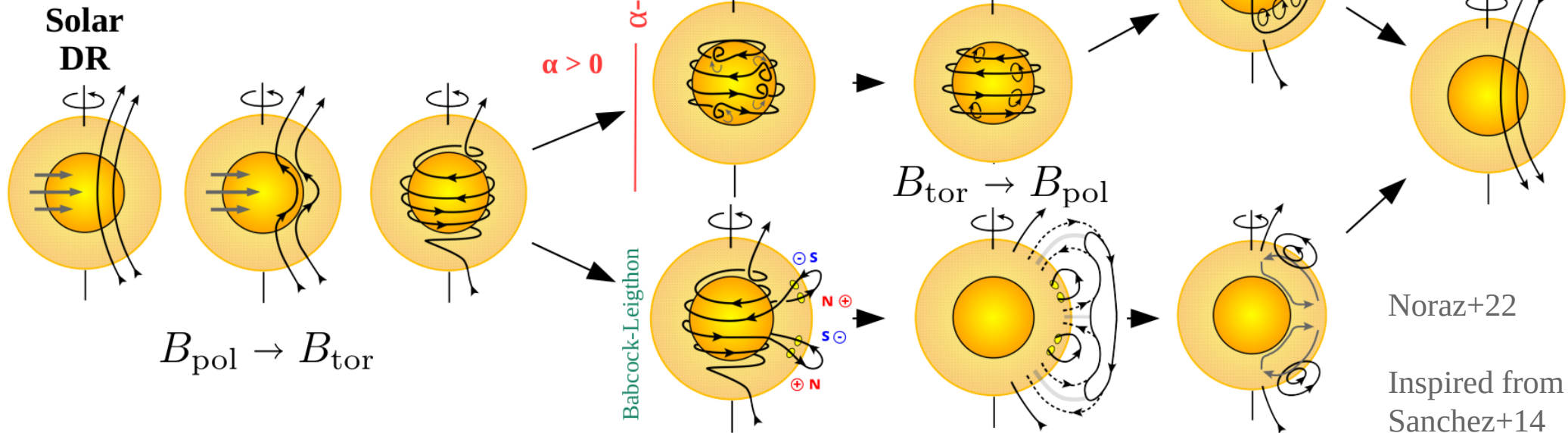
$$Ro = \frac{v}{2\Omega L} \sim \frac{\text{Advection}}{\text{Coriolis}}$$

Dynamo Mechanism

Dynamo effect:

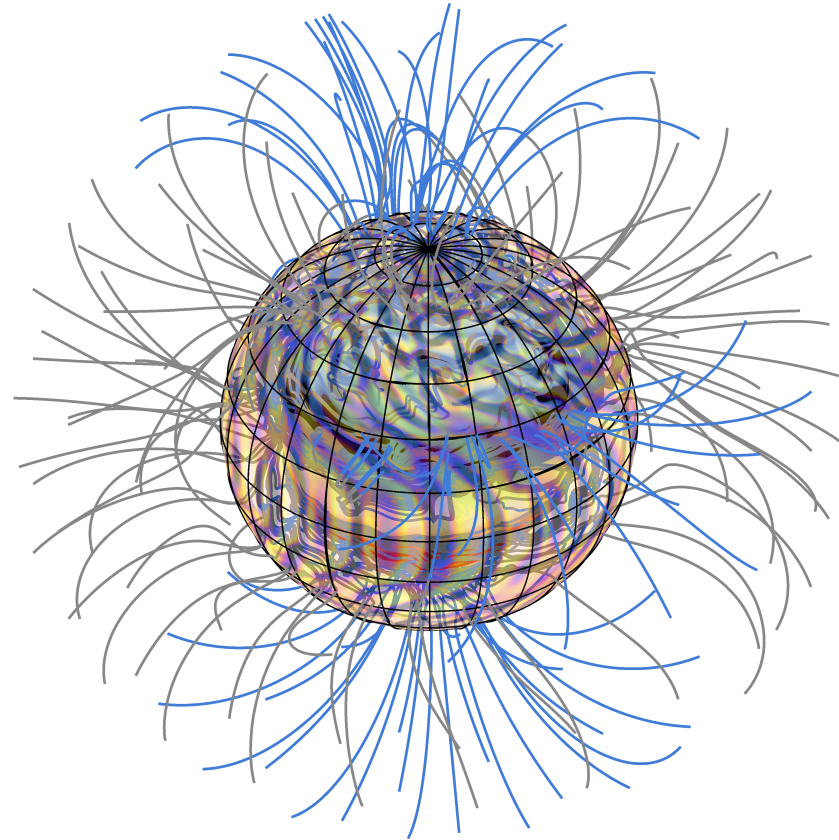
The ability of a conductive fluid (plasma) to **amplify and maintain a magnetic field against its ohmic dissipation.**

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



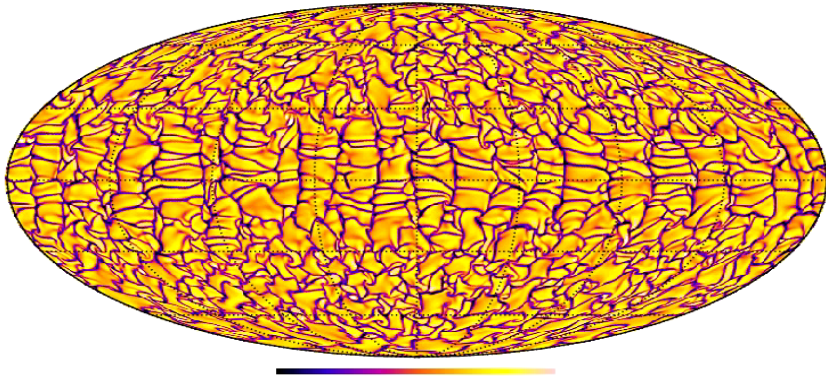
Problematics

- How the rotation regime sets the cyclic magnetic activity ?
- What is sustaining the differential rotation and the magnetic energy?
- Can slowly rotating stars have magnetic cycles?
The case of «anti-solar» dynamo



Global 3D MHD turbulent dynamo

Explicit treatment of the convective motions

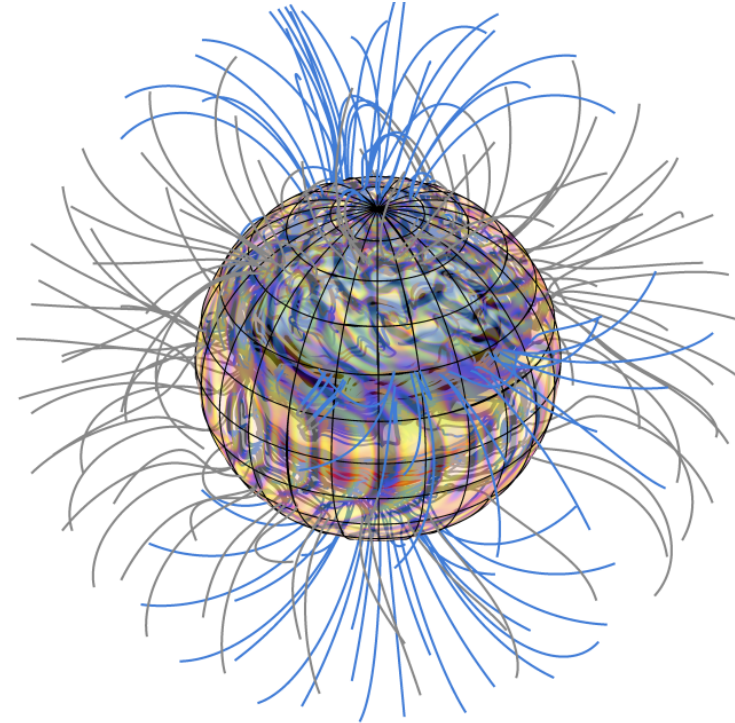


ASH code

Brun et al (2002), Miesch et al (2008)



MHD



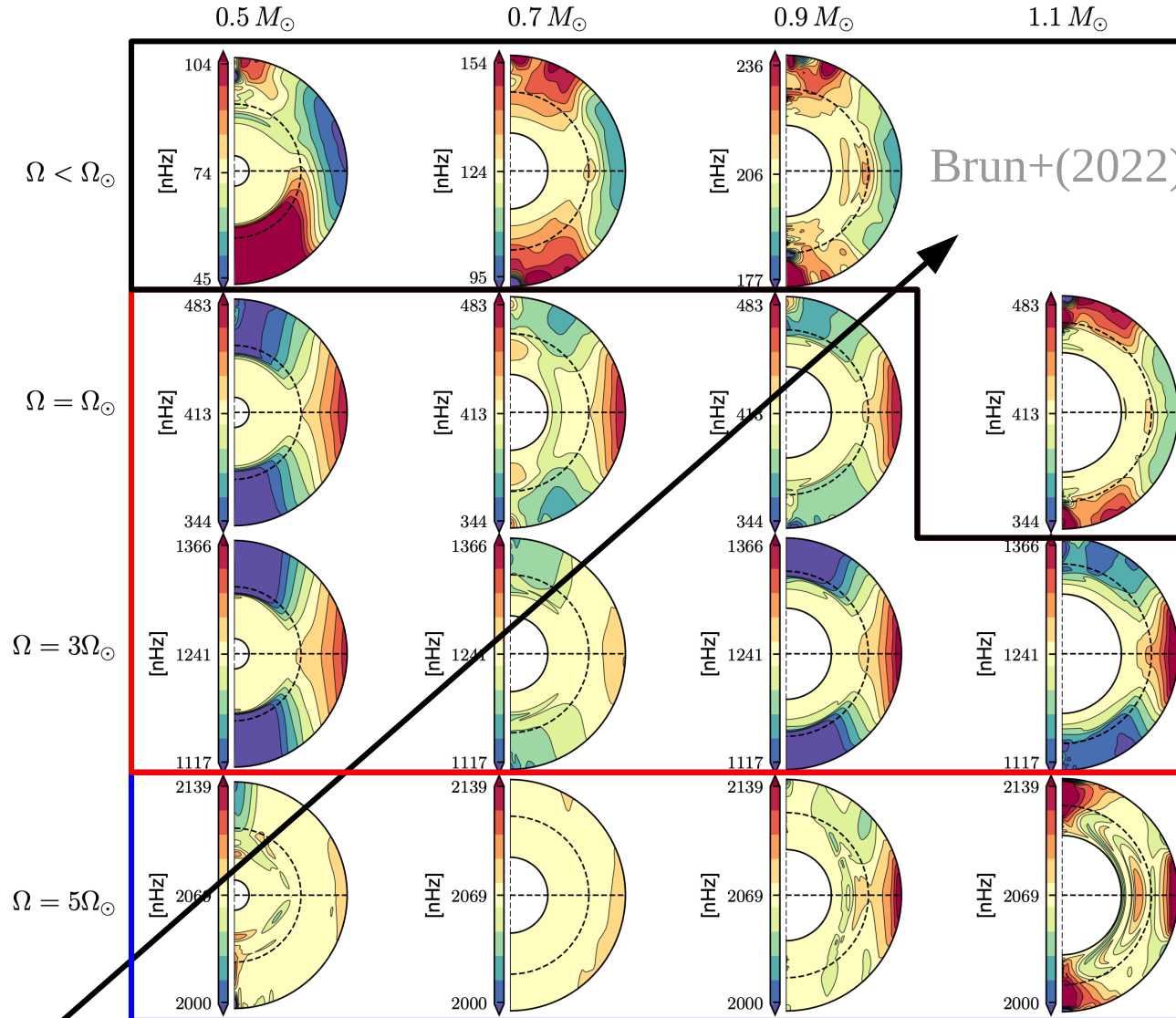
Brun et al (2022)

Parameter space

The Rossby parameter space is spanned with 4 bins in rotation and 4 bins in mass

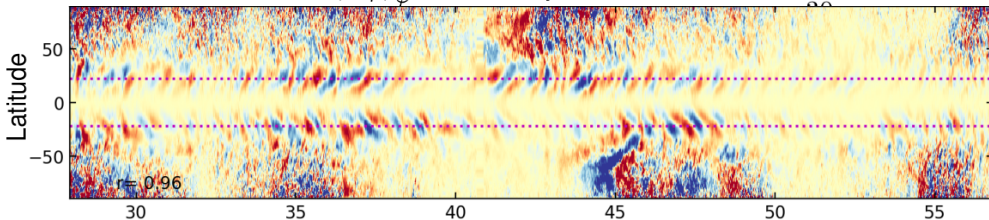
$$Ro_f \propto \frac{M_*^{1.63 \pm 0.24}}{\Omega_*^{0.9 \pm 0.06}}$$

Ro increases

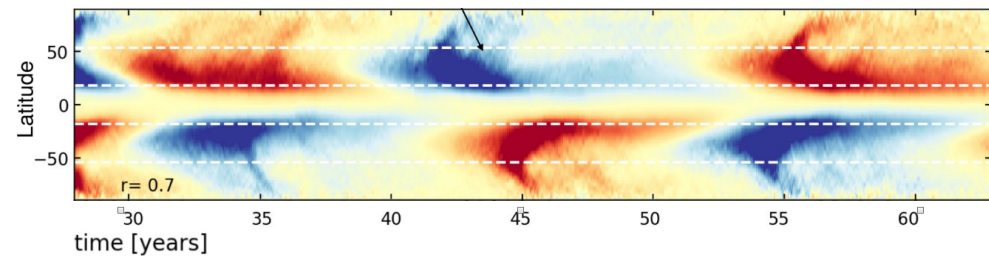


Role of the rotation on dynamos

Detrended $\langle B_\varphi \rangle_\varphi$ at the top of the convection zone

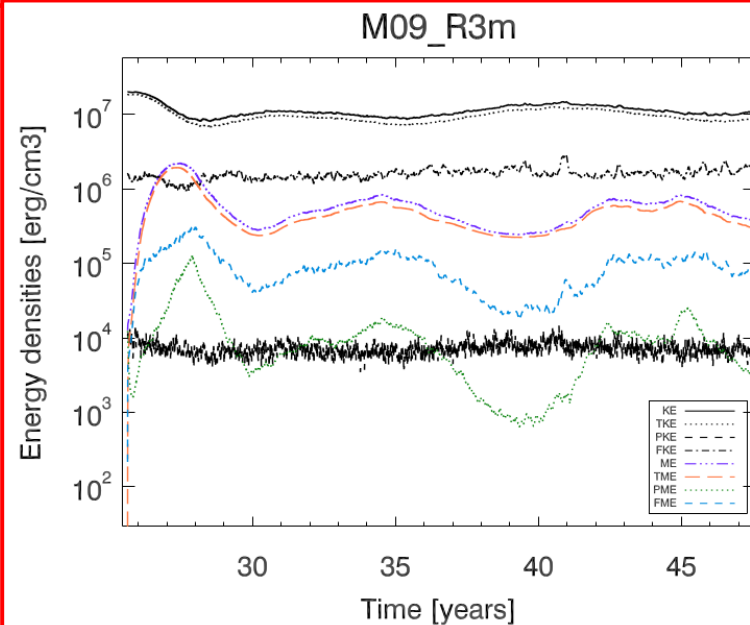
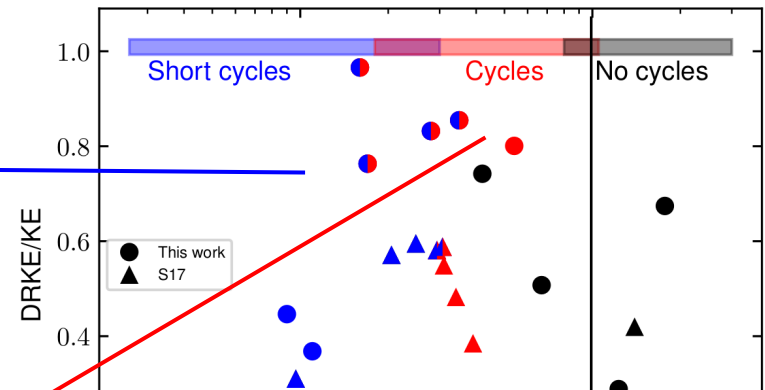
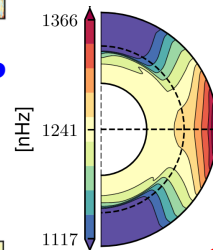


- short cycles (~year) ; quasi-biennial oscillations ?
- surface dynamo
- Parker-Yoshimura type



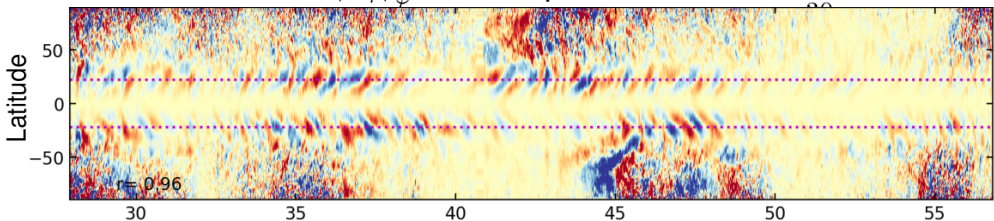
$\langle B_\varphi \rangle_\varphi$ at the base of the convection zone

- long cycles (decadal solar-like)
- deeper dynamo
- non-linear retroaction

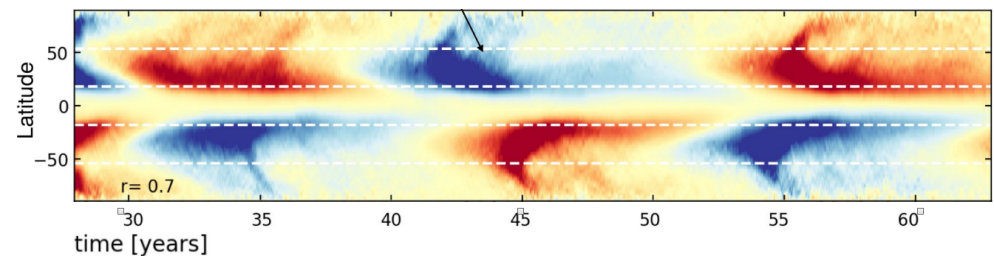


Role of the rotation on dynamos

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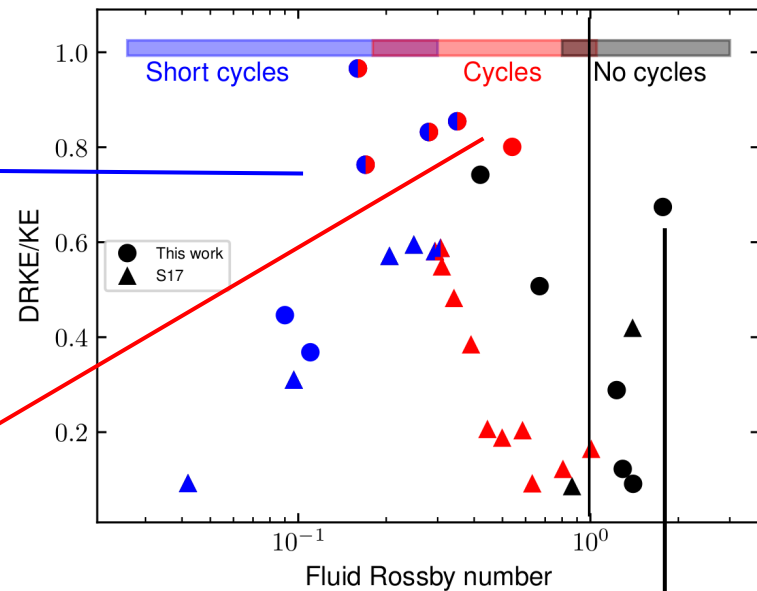
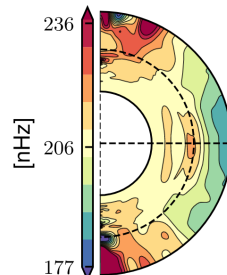
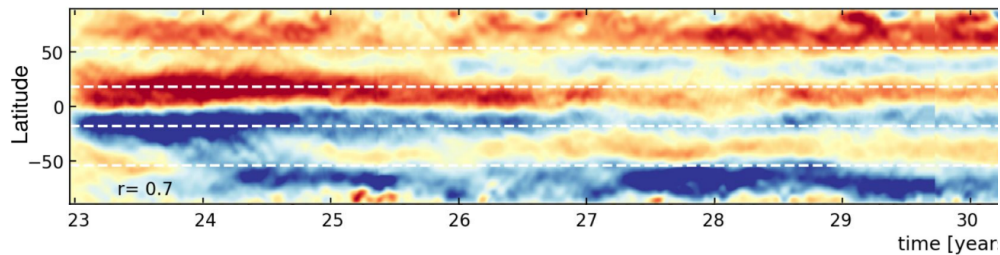
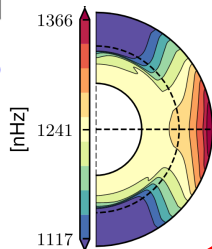


- short cycles (\sim year) ; quasi-biennial oscillations ?
- surface dynamo
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$\langle B_\varphi \rangle_\varphi$ at the base of the convection zone

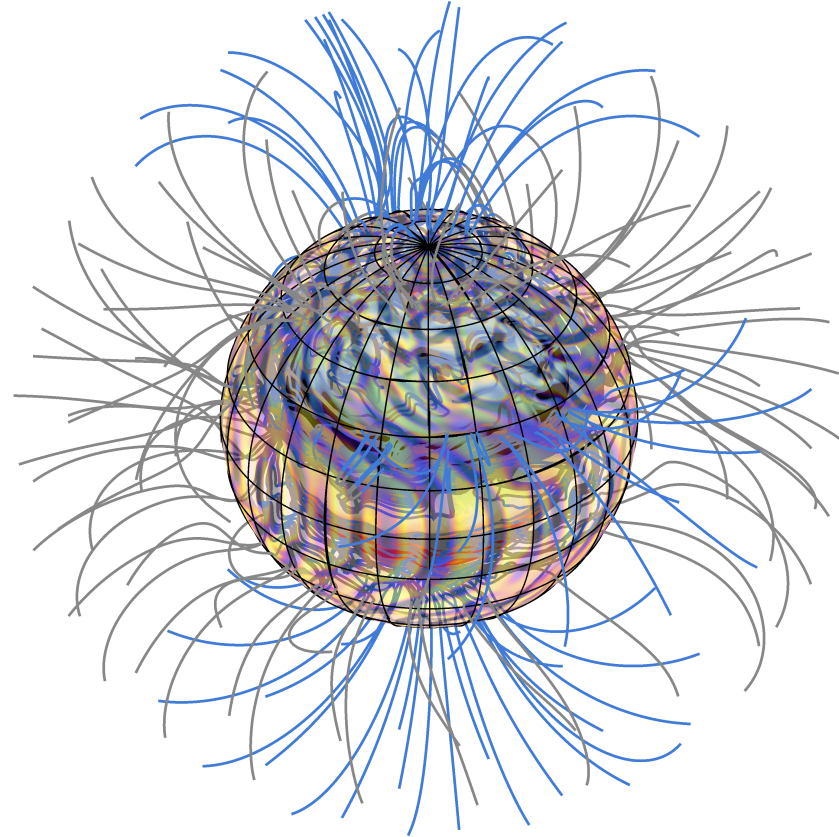
- long cycles (**decadal solar-like**)
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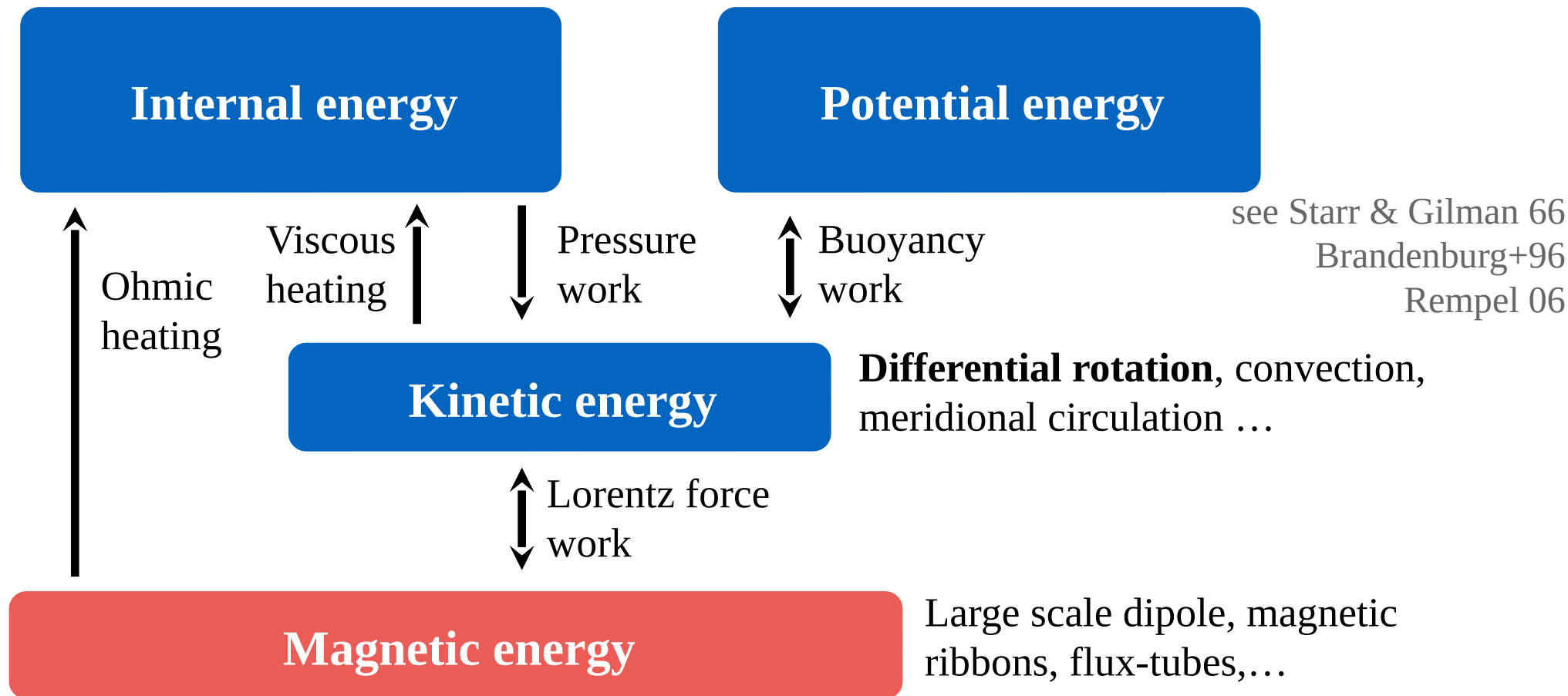
- **Stationary dynamo**
- **Strong deep toroidal field**

Problematics

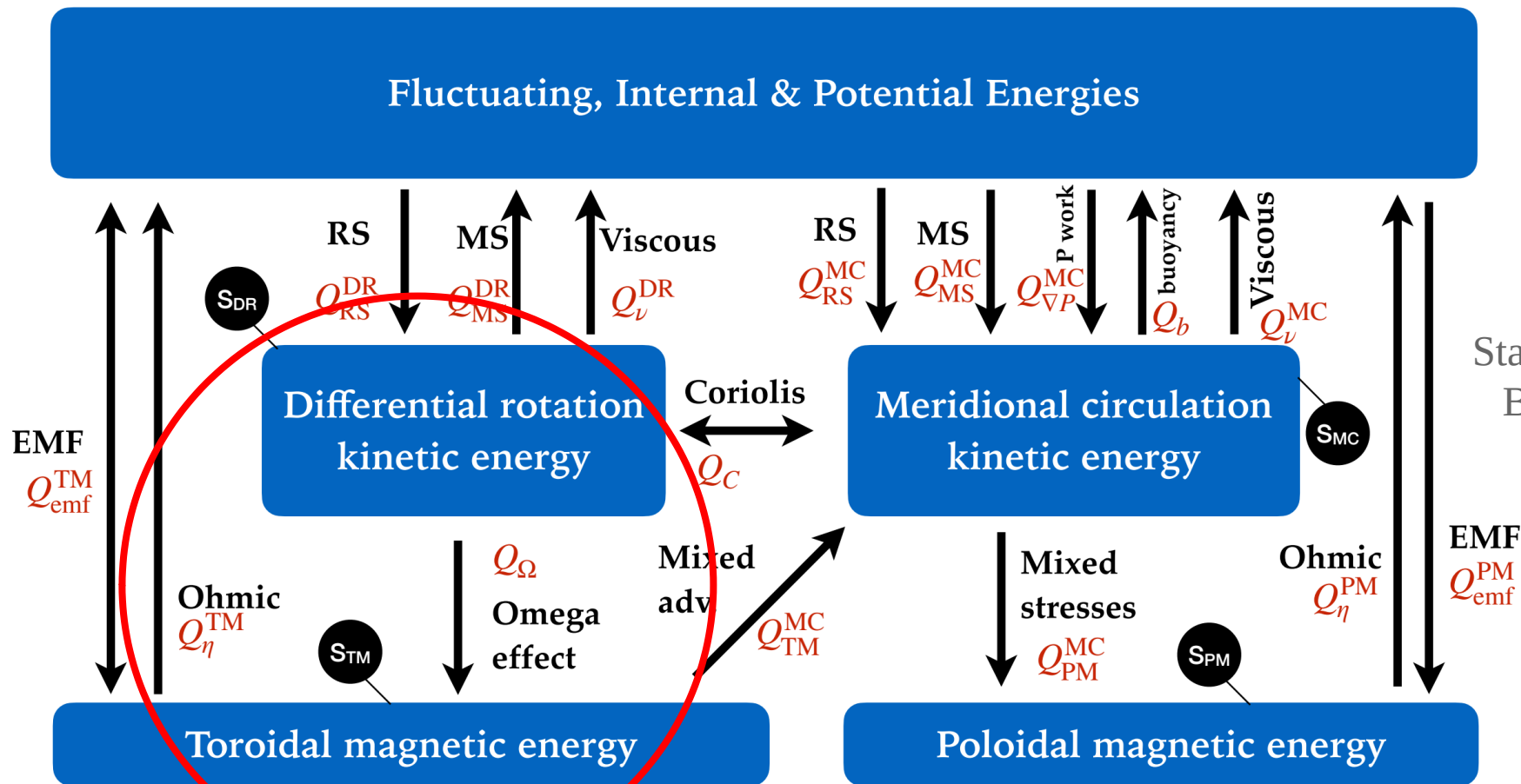
- How the rotation regime sets the cyclic magnetic activity ?
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The case of «anti-solar» dynamo



How energies are exchanged ?



How energies are exchanged ?



Brun+22

see also

Starr & Gilman 66

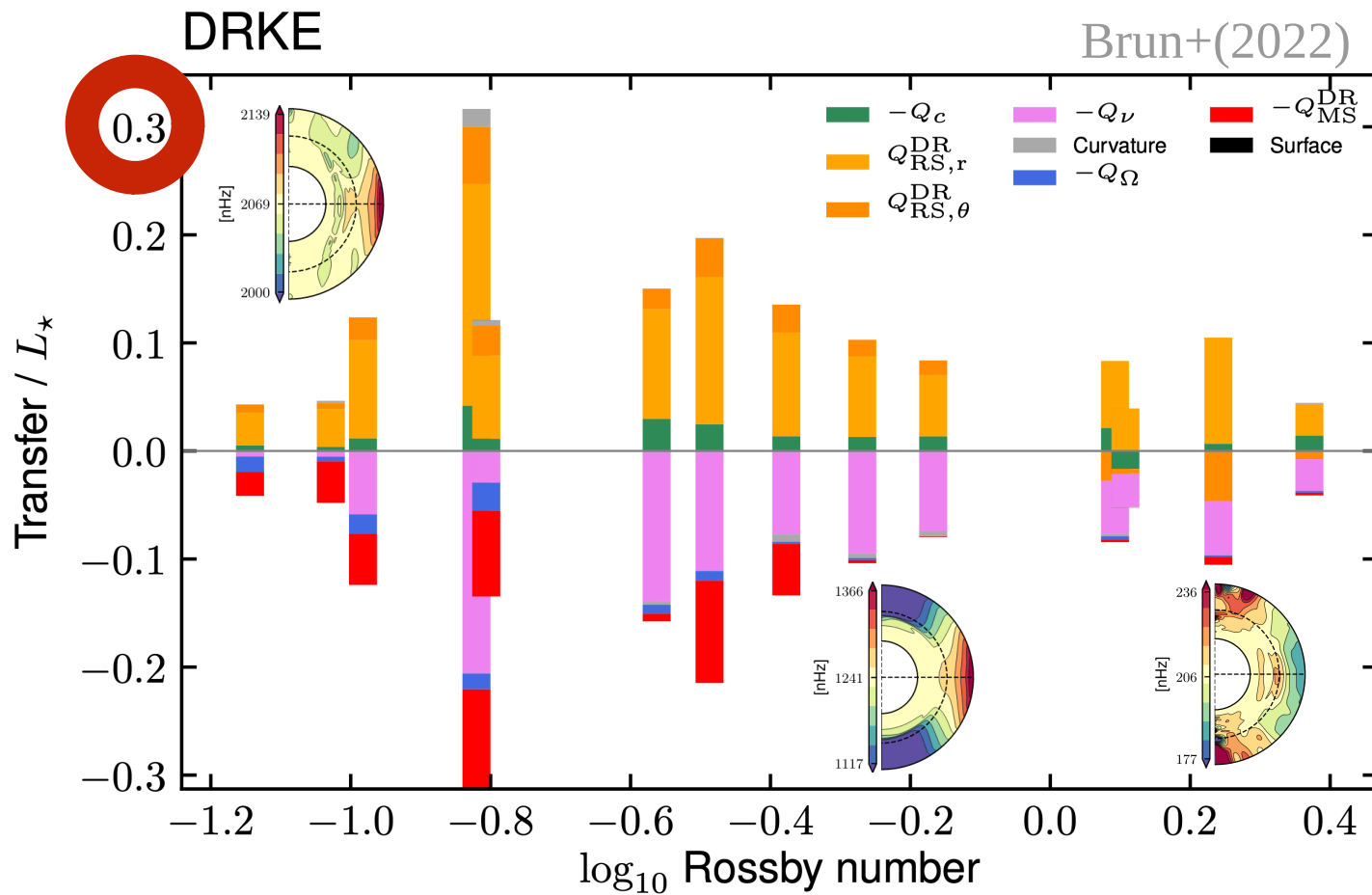
Brandenburg+96

Rempel 06

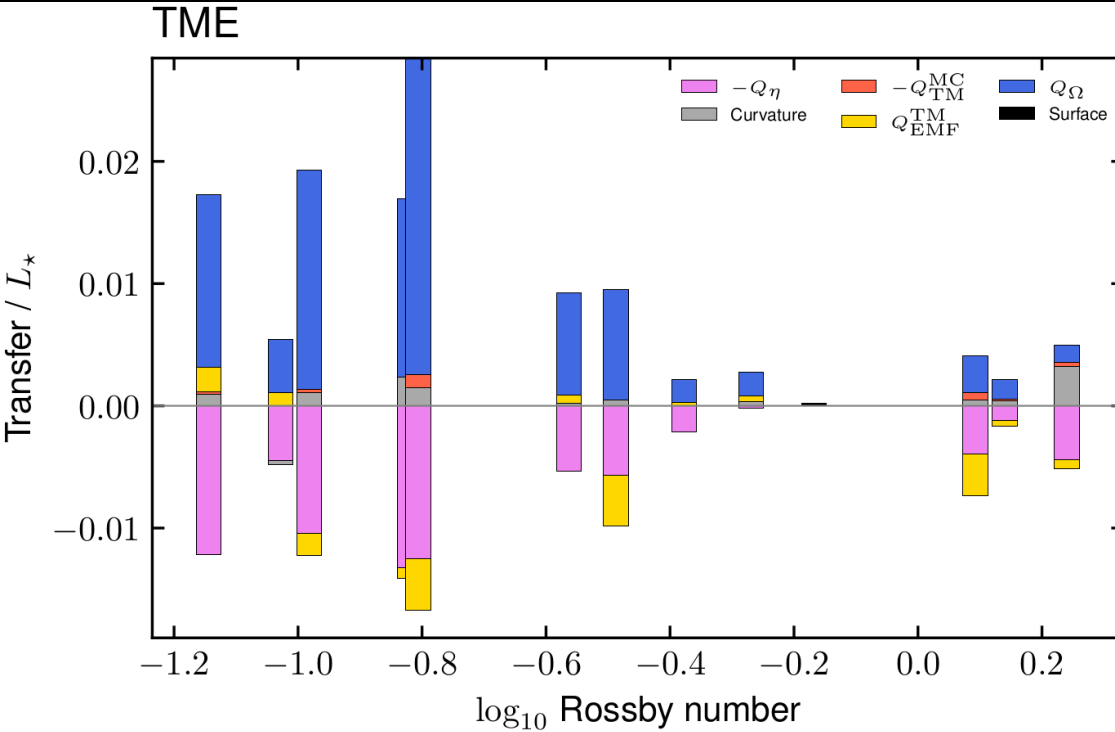
Brun+22;

see also Brandenburg 96, Rempel 06

What powers the differential rotation ?

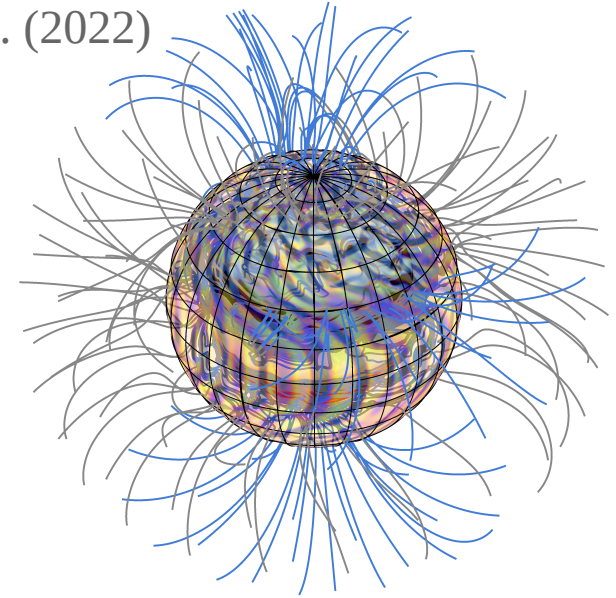


What powers the toroidal magnetic field ?



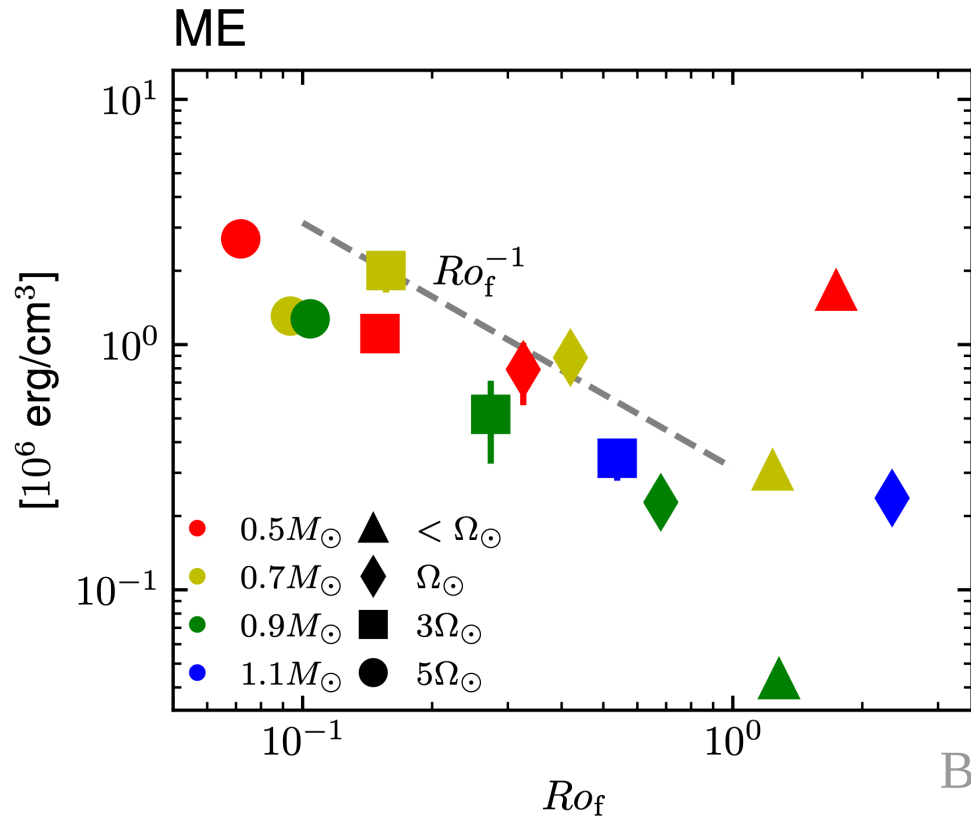
1 % of the solar luminosity : $3,828 \times 10^{31}$ erg/s !

Brun et al. (2022)

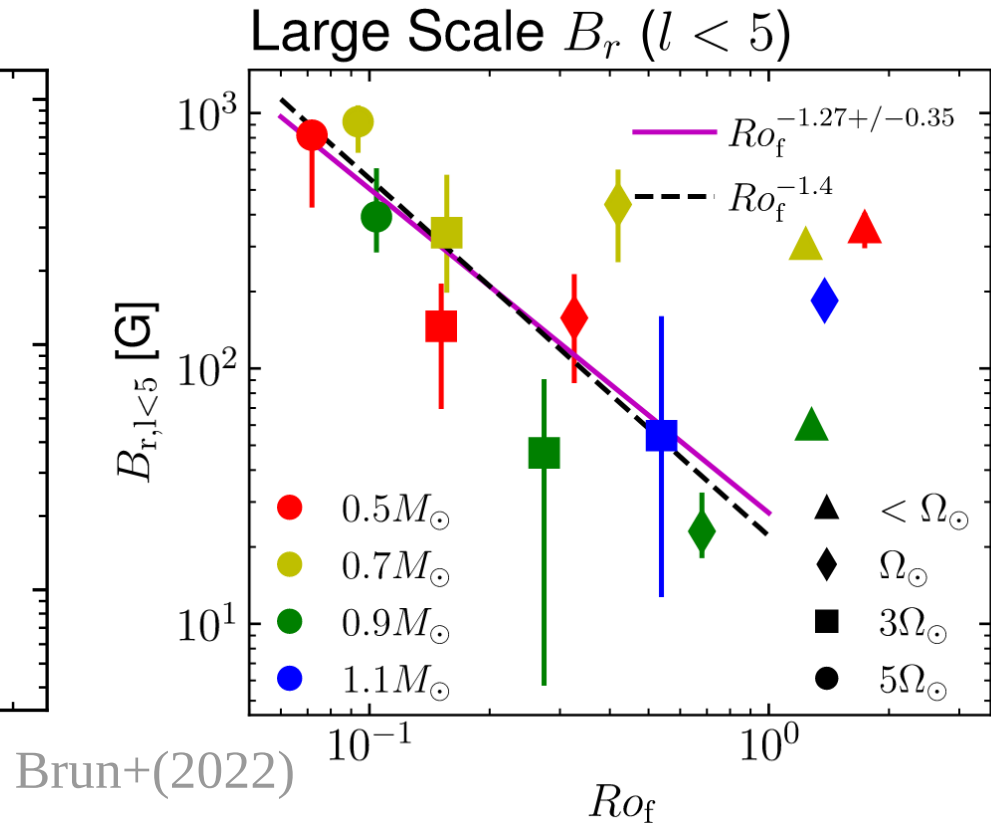


	Powering magnetism
Slow rotator	$\sim 0.01\% L_{\star}$
Solar-like rotator	$\sim 0.1-3\% L_{\star}$
Fast rotator	$\sim 1\% L_{\star}$

Magnetic field scalings : Bulk field vs. Surface field



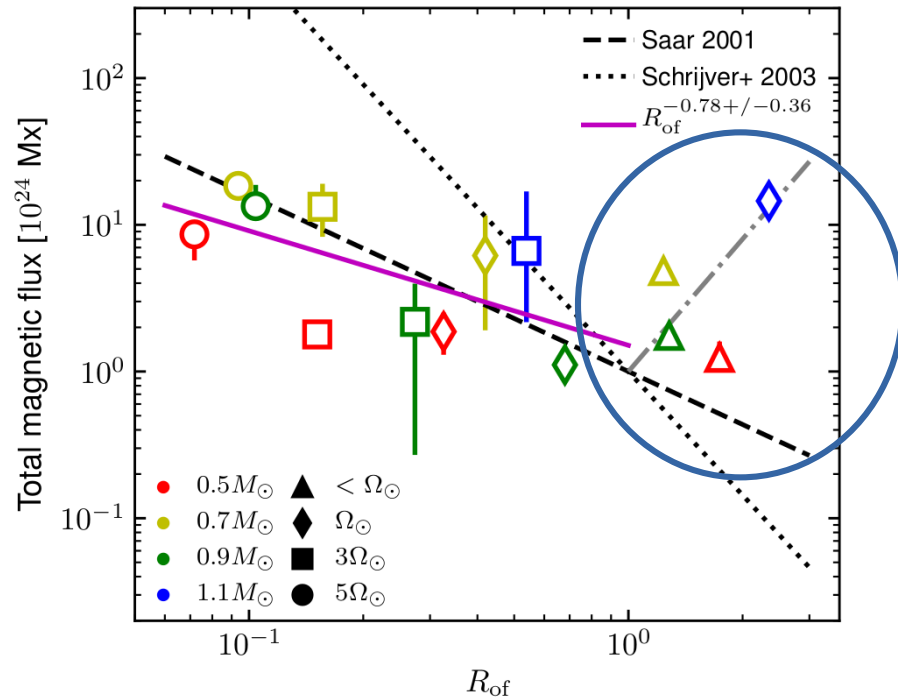
-> Compatible with magnetostrophic-type scaling laws, with $B_{\text{bulk}} \propto Ro_f^{-0.5}$



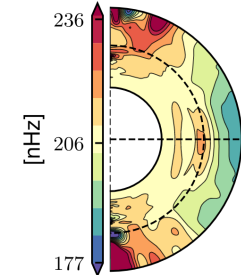
-> Compatible with ZDI observation with $B_{\text{dip}} \propto Ro_f^{-1.3}$

Magnetic field scalings : Change of regime?

Brun et al. (2022)

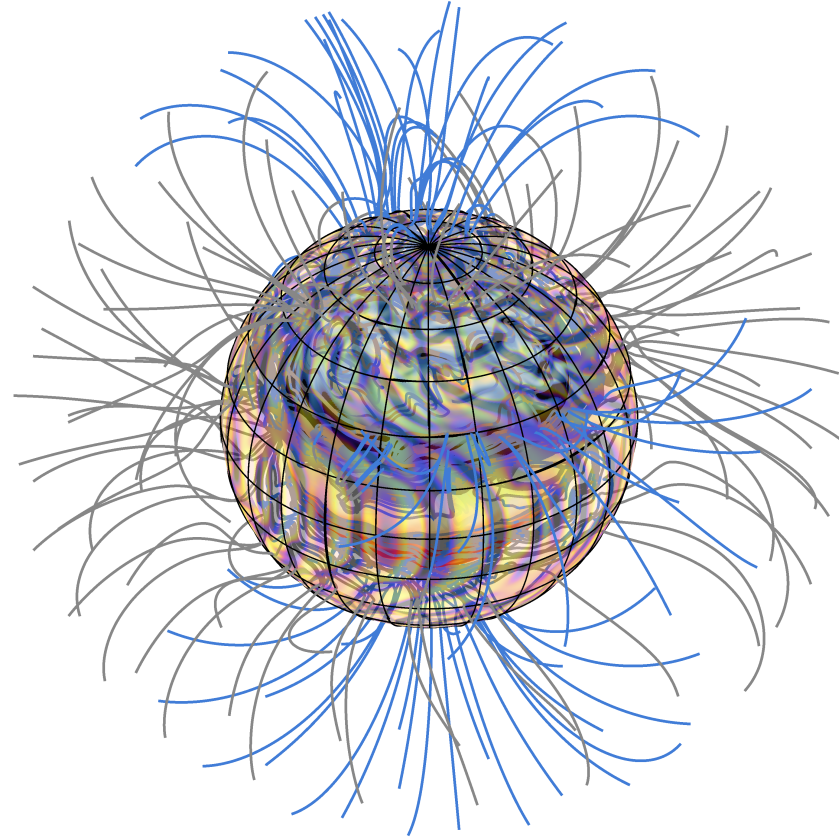


- Solar magnetic flux $\sim 10^{24}$ Mx
Schrijver & Harvey (1994)
- Possible change of behavior for anti-solar models at high Rossby ?



Problematics

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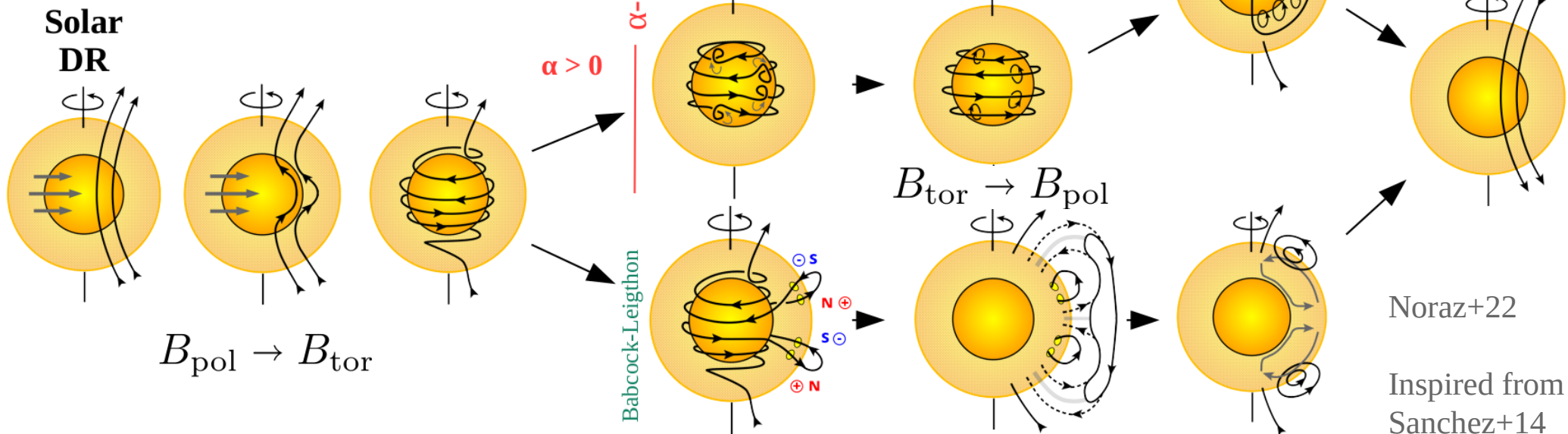


Dynamo Mechanism

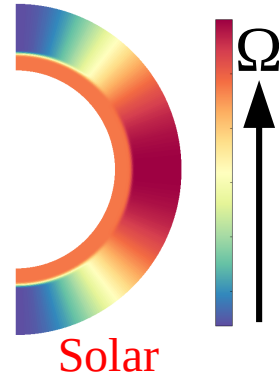
Dynamo effect:

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



2D Kinematic Approach: Solar reference cases

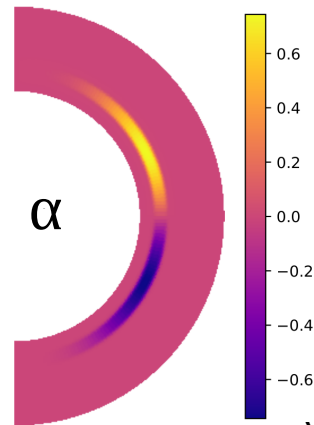


Solar

Rotation profile

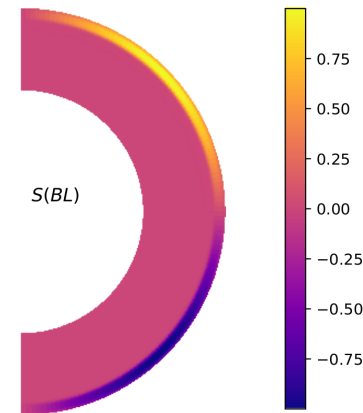
Dynamo $\alpha\Omega$

Dynamo Babcock-Leighton + MC



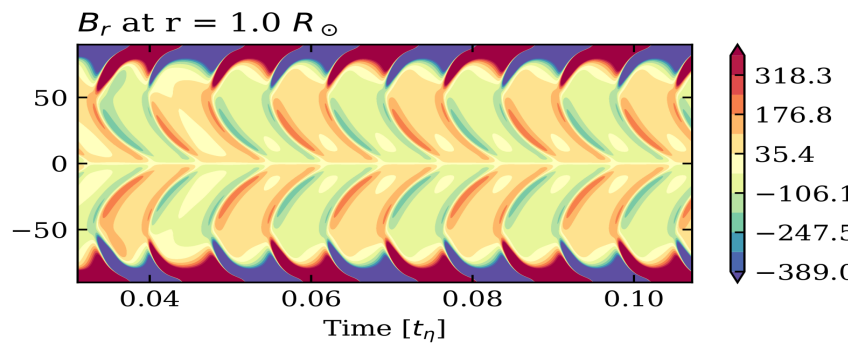
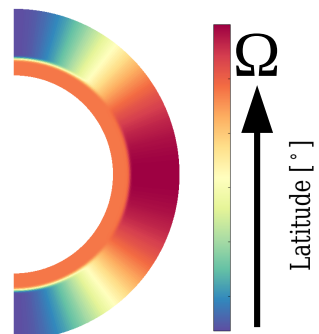
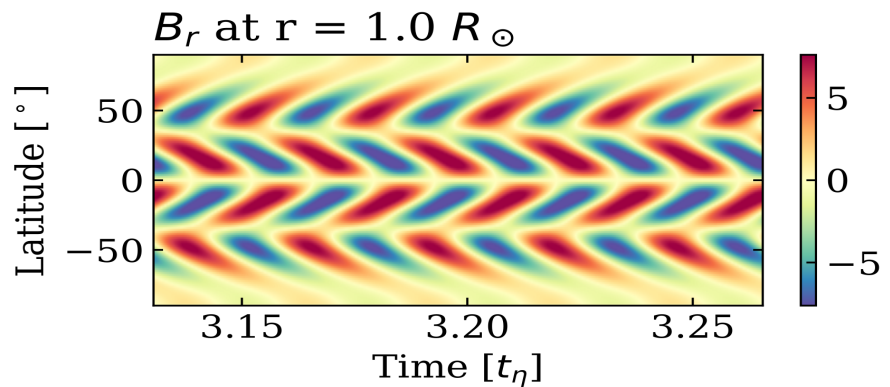
α

Q. Noraz - SF2A 2022 - PNST



$S(BL)$

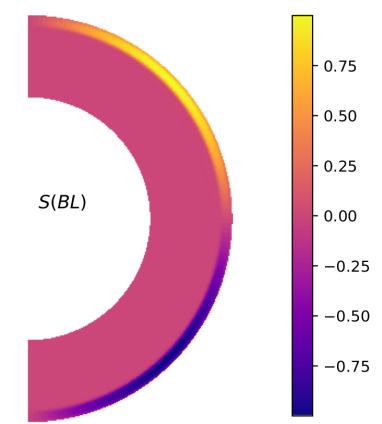
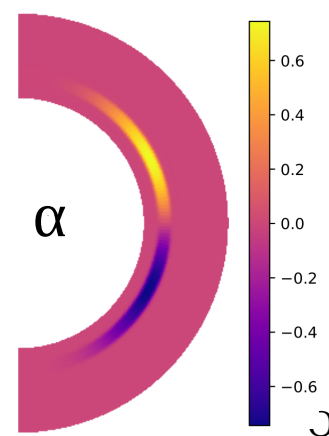
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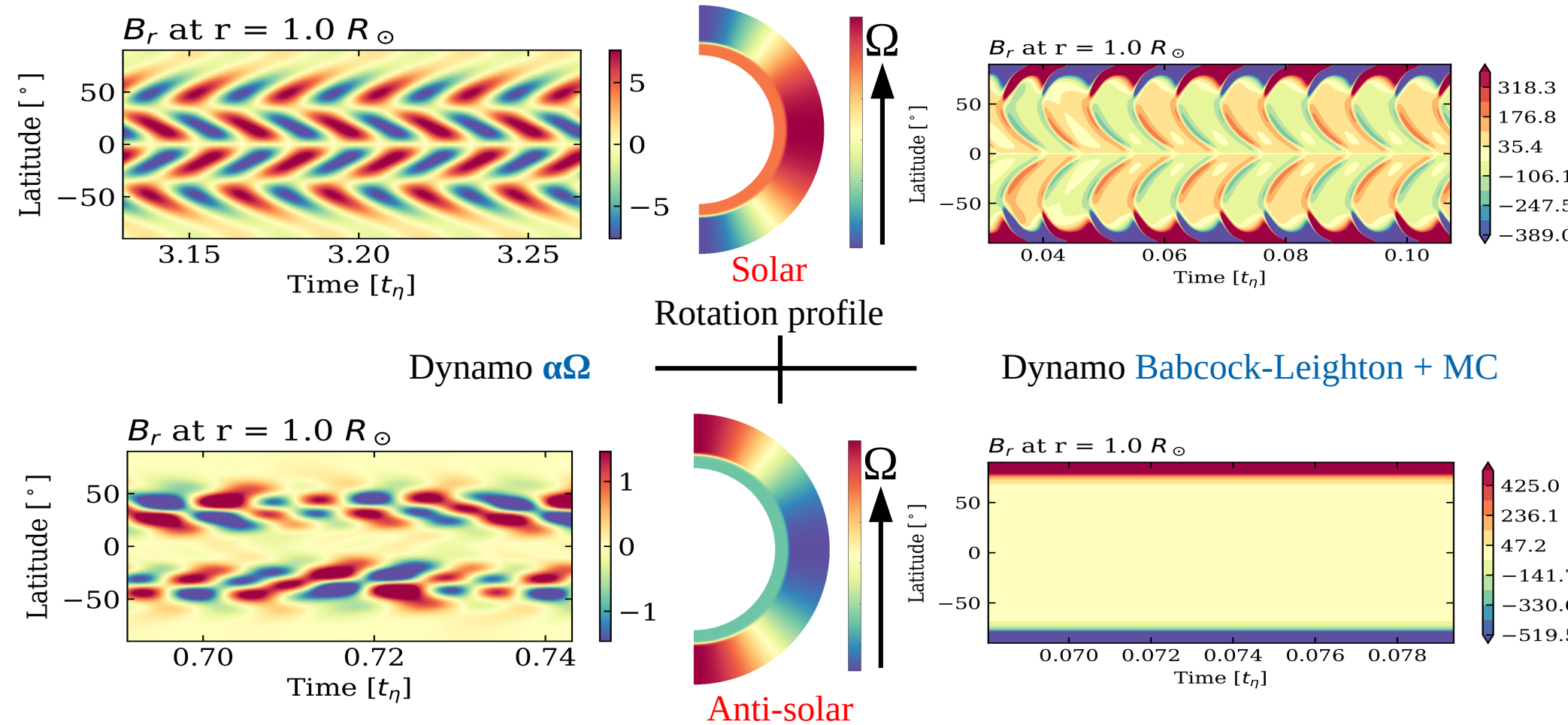
Dynamo $\alpha\Omega$

Rotation profile

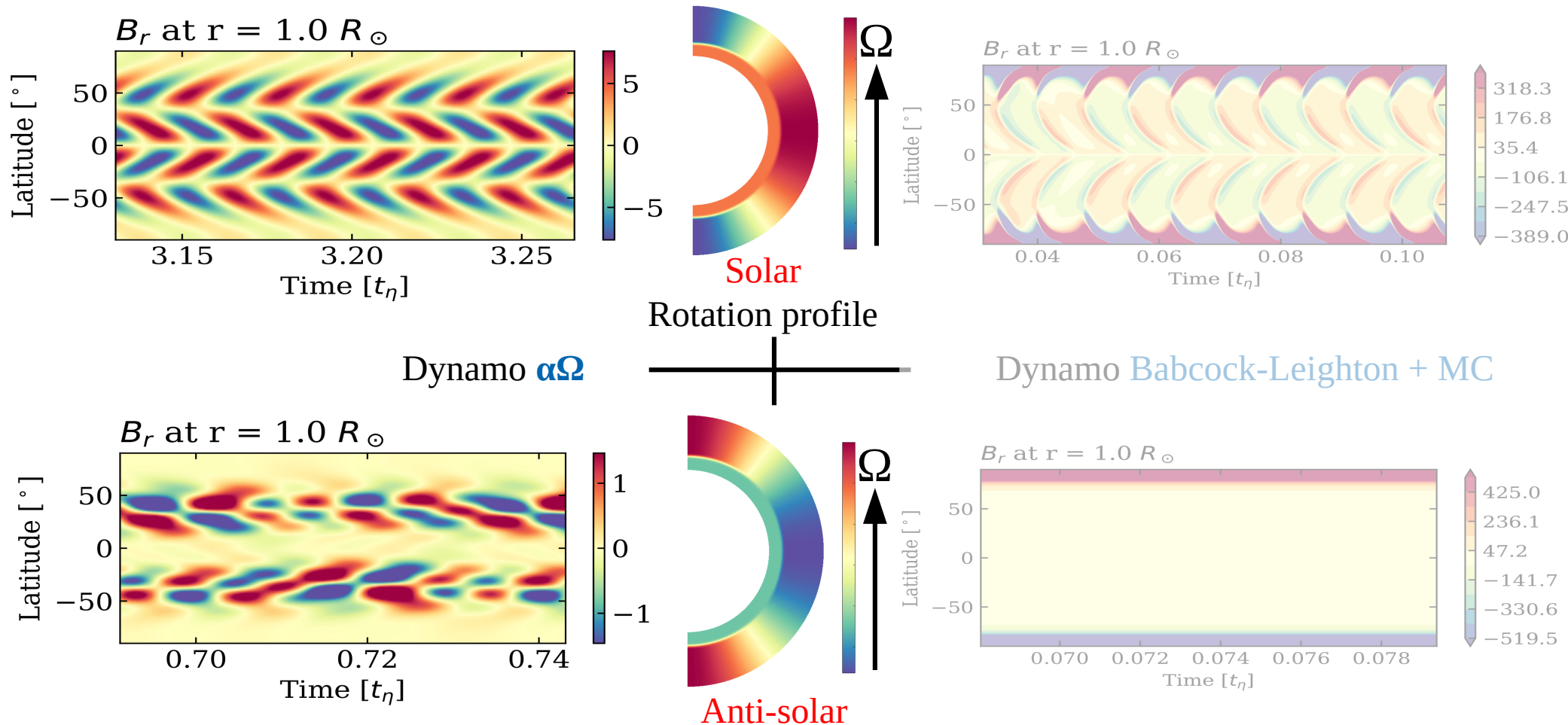
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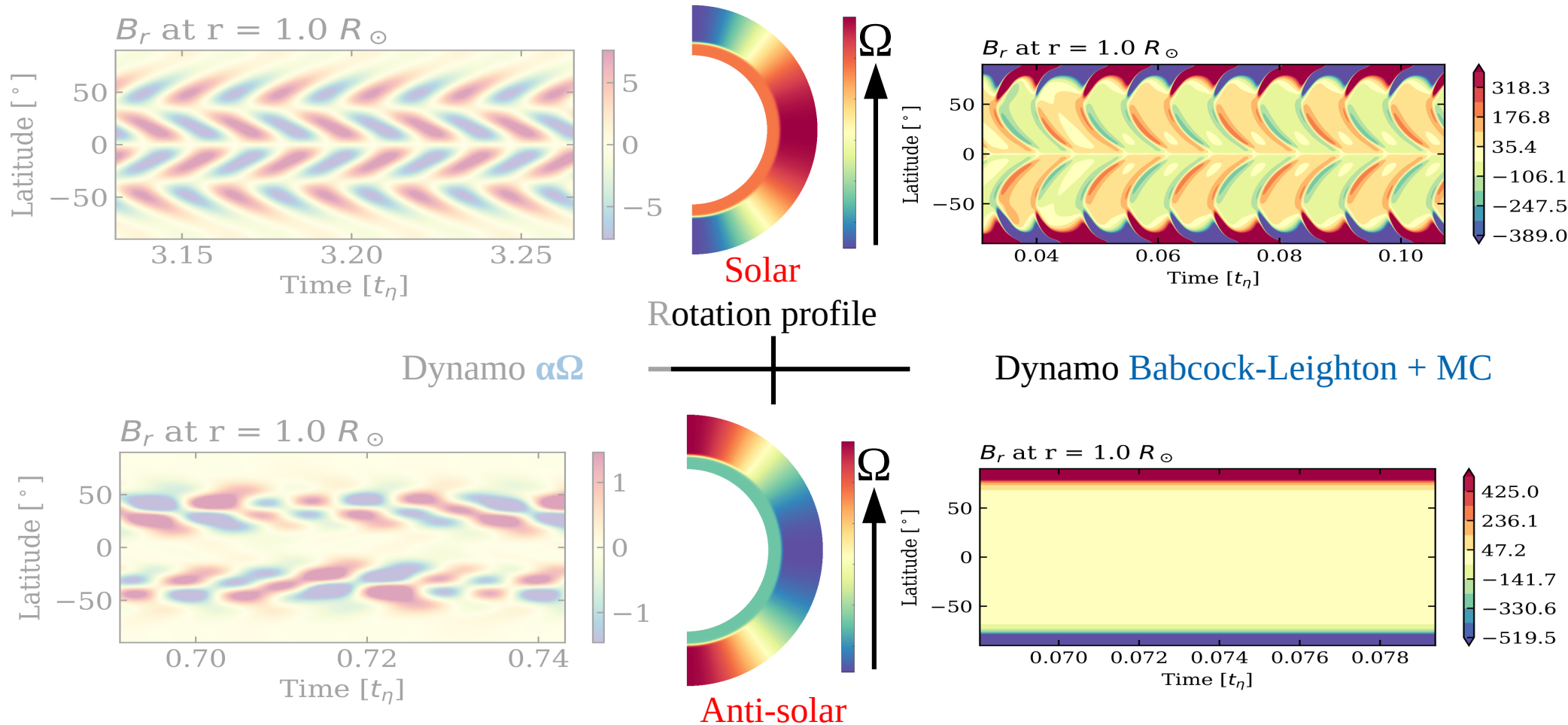
2D Kinematic Approach: Application to the anti-solar DR



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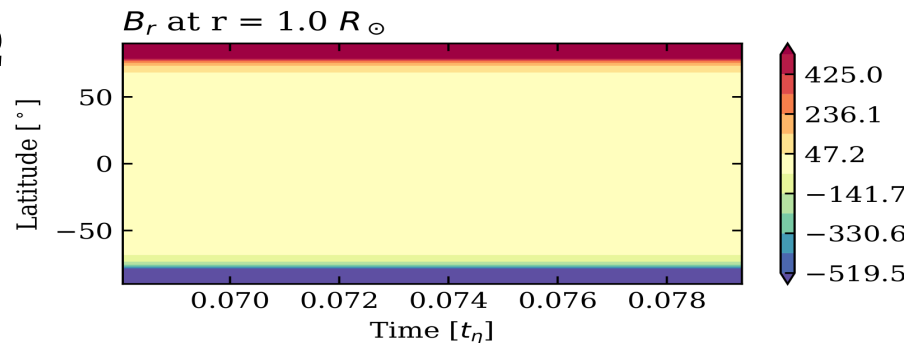
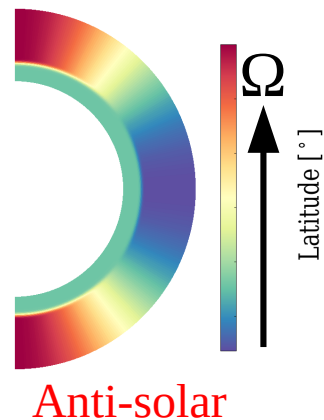
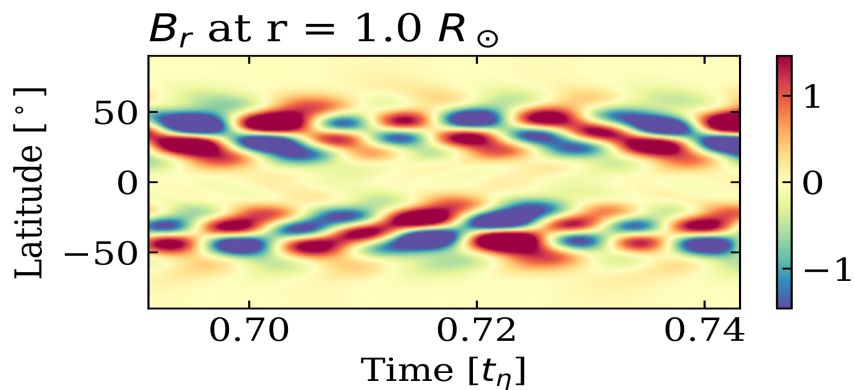
2D Kinematic Approach: Application to the anti-solar DR

The dynamo still occurs,
but how is the magnetic cycle lost?

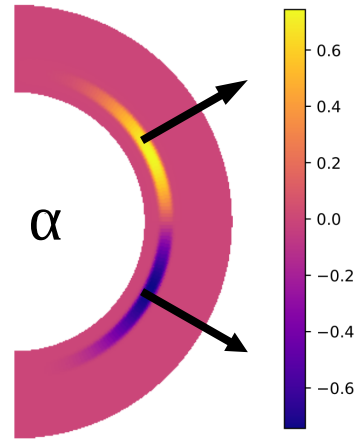


Dynamo $\alpha\Omega$

Dynamo Babcock-Leighton + MC

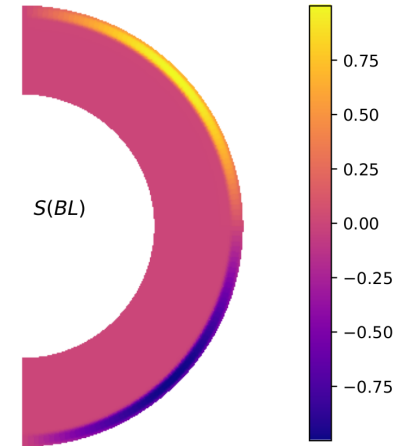


2D Kinematic Approach: Localisation of the Dynamo



α -source

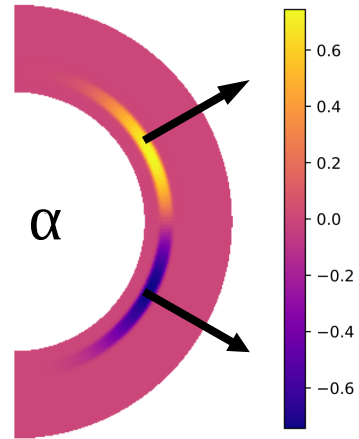
α -effect location:
From the tachocline to the surface



Babcock-Leighton
source

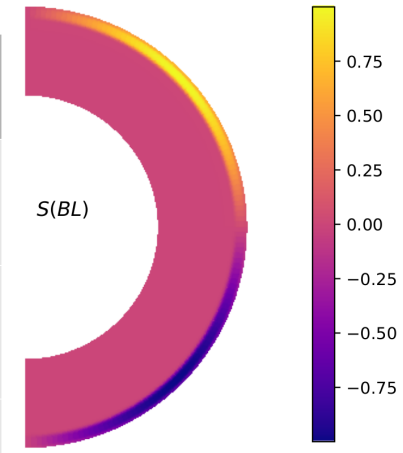
2D Kinematic Approach: Localisation of the Dynamo

For **anti-solar DR** the dynamo becomes **stationnary** once α is leaving the tachocline (*ie. the radial shear*)



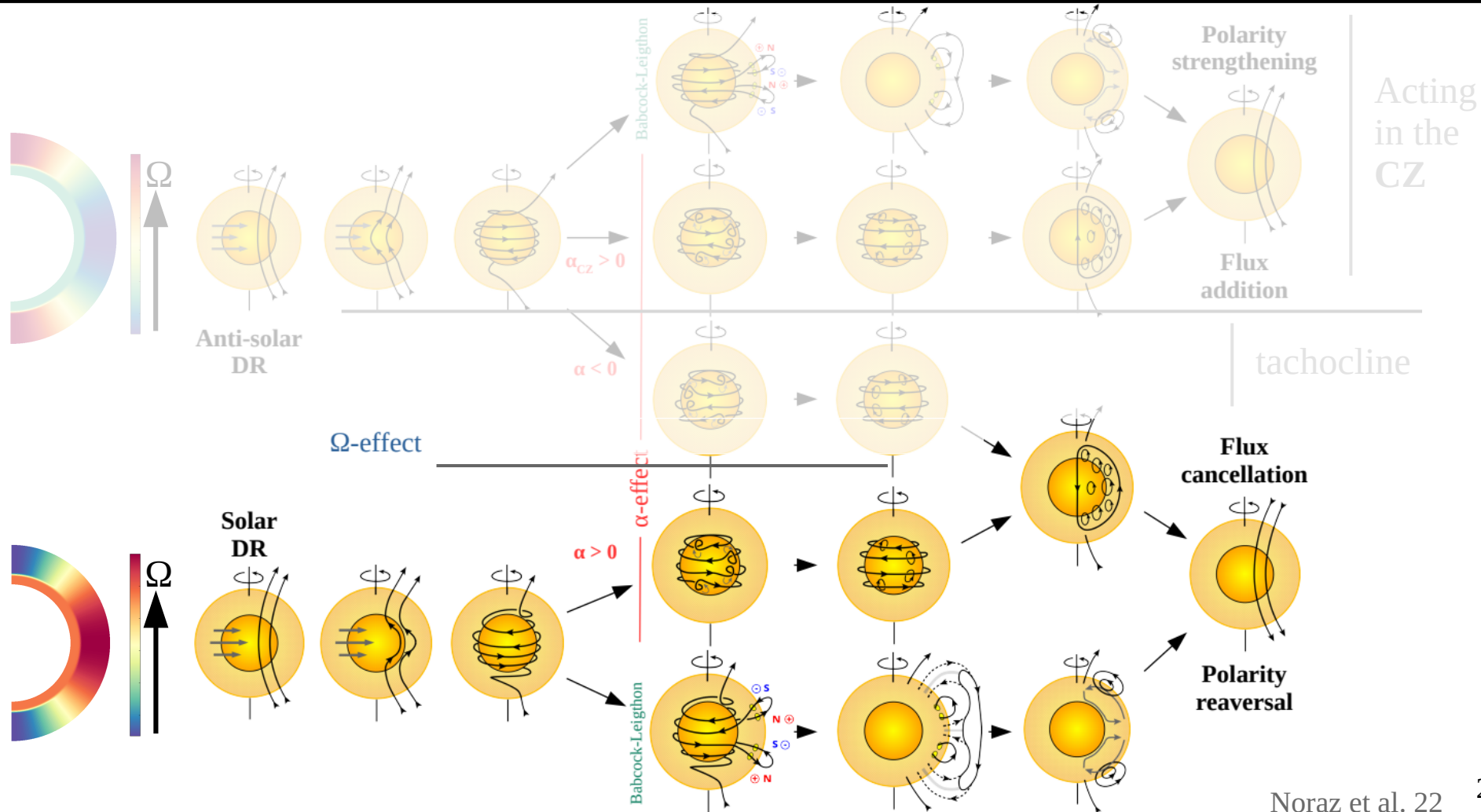
α -source

	Solar-like DR	Anti-solar DR
Surface of CZ	cycle	No cycle
Convection zone (CZ)	cycle	No cycle
Tachocline (RZ/CZ)	cycle	cycle

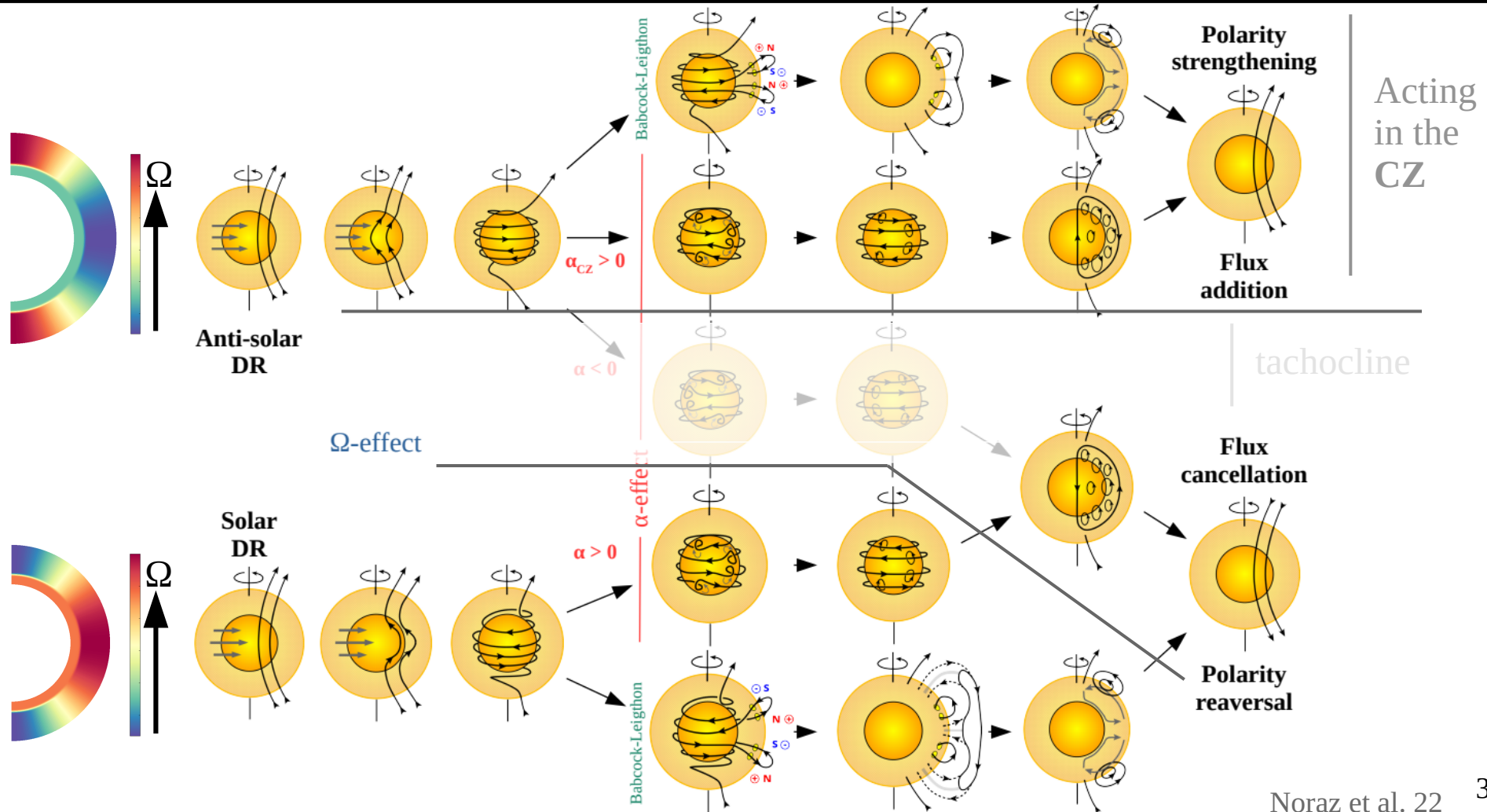


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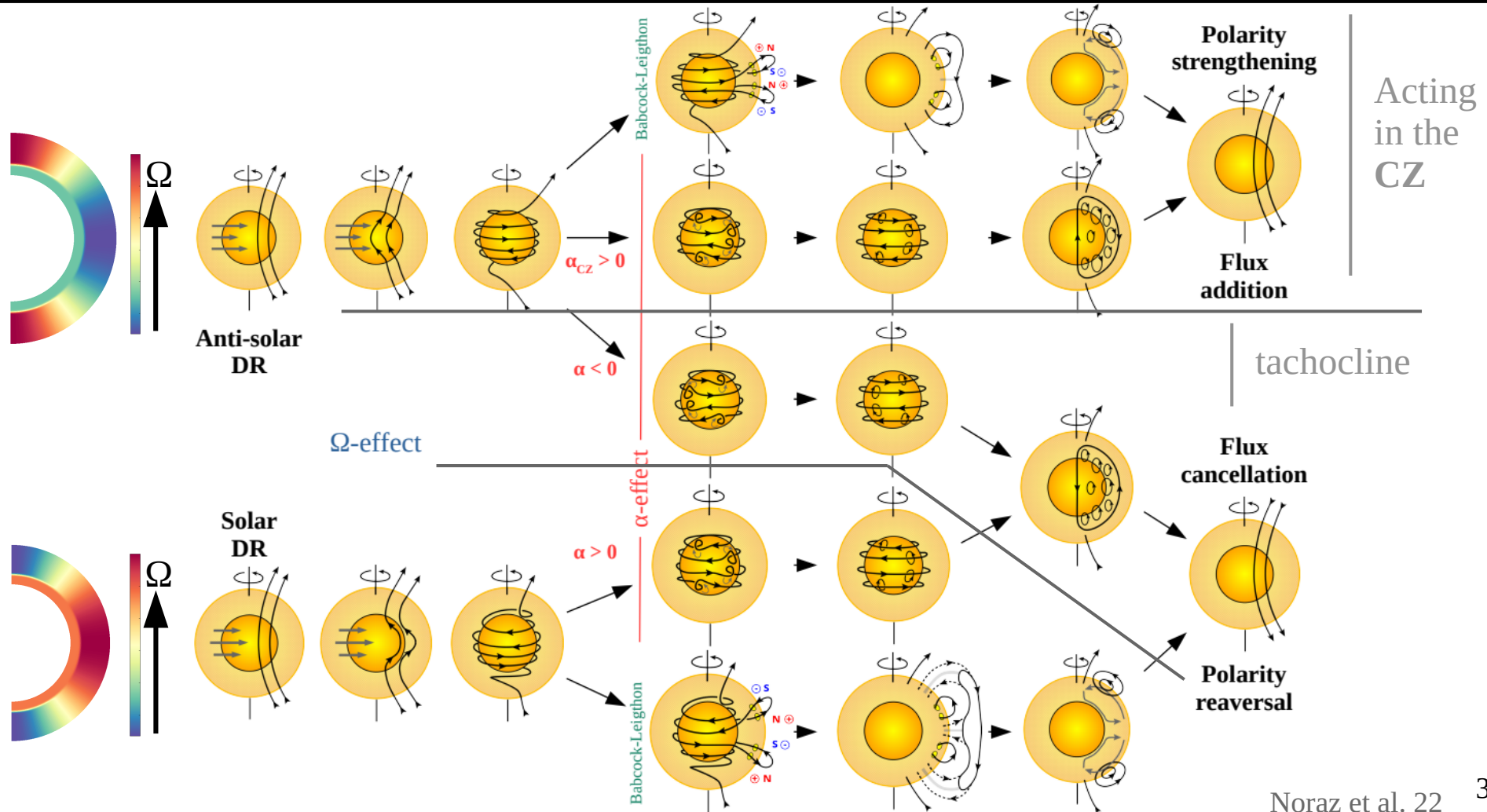
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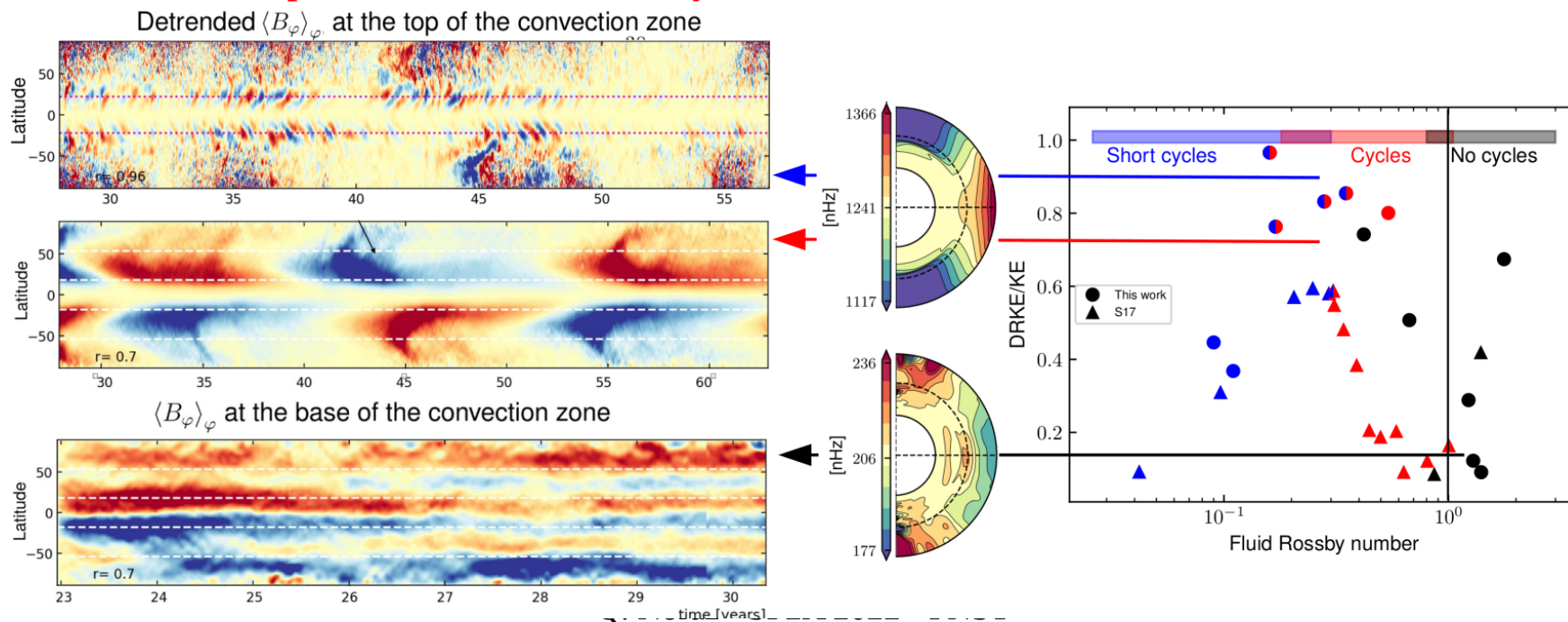


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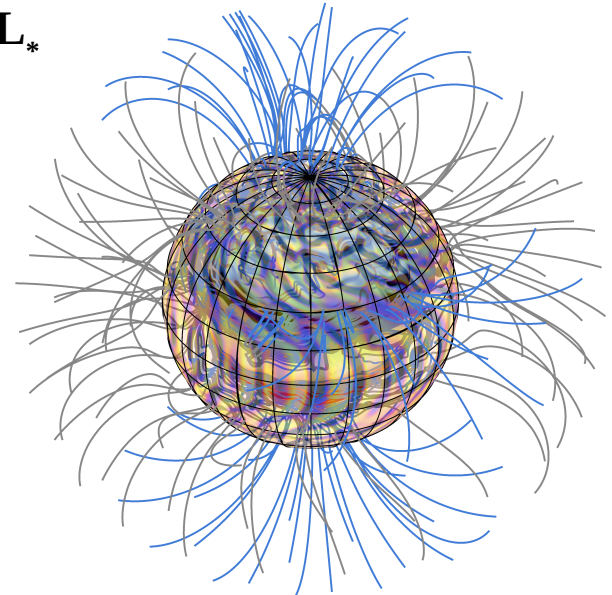
Conclusions

- **Rotational and magnetic transitions** are likely to appear during stellar evolution. For our Sun we propose (Brun+22):
 - **Short cycle** for **young fast rotating** Sun, with constrained DR,
 - **Longer cycle** appearing at intermediate Rossby, with prograde equator,
 - **Stationary dynamo** for **old slow rotating Sun** with retrograde equator.
- Which impact from the metallicity ?



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 - Which impact from the metallicity?
- The large scale **magnetism** is sustained by means of $\sim 0.01-1\% L_*$ available for surface magnetic activity.
 - **More models are needed for high rossby!**

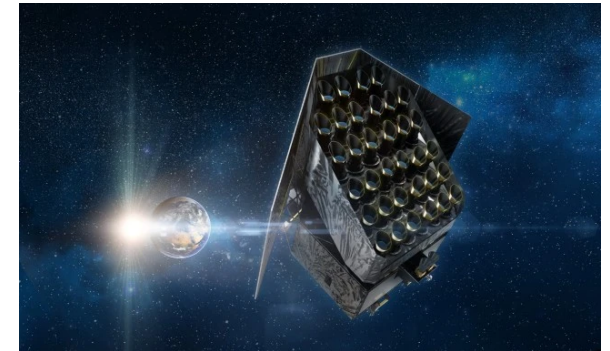
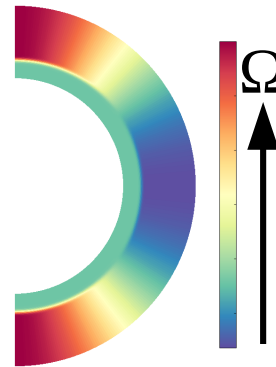


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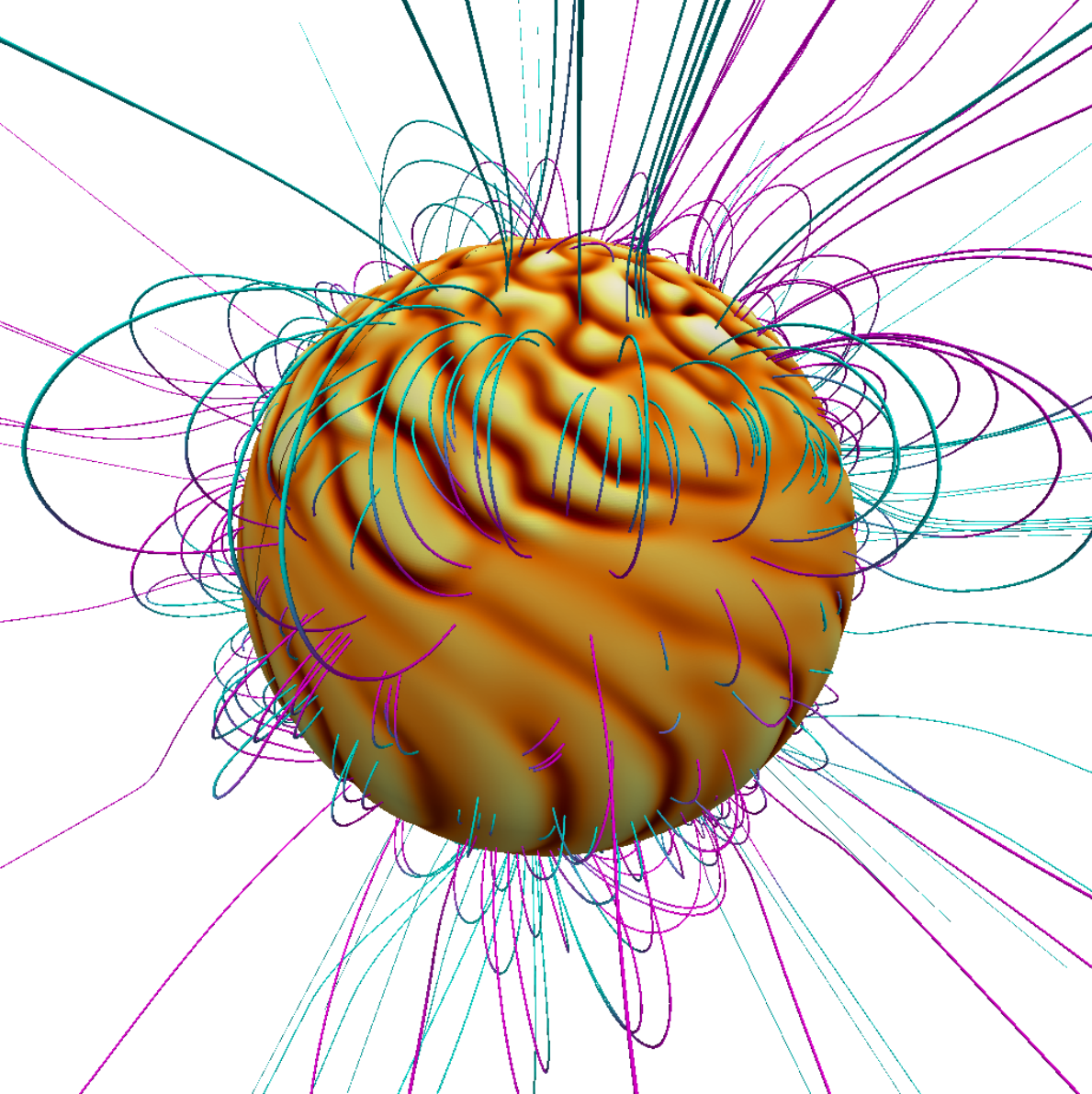
- The large scale **magnetism** is sustained by means of $\sim 0.01-1\% L_*$ available for surface magnetic activity.
→ **More models are needed for high rossby!**

- The **anti-solar regime** is mainly **unknown**:
 - majoritary **of stationary dynamos**, however **magnetic cycles** can be produced in specific models (Noraz+22)



PLATO WP-123400
differential rotation and dynamo

→ **Need observational constraints, we are looking for them, stay tuned! Noraz et al (submitted)**



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Contact: quentin.noraz@cea.fr

Thank you for your attention!