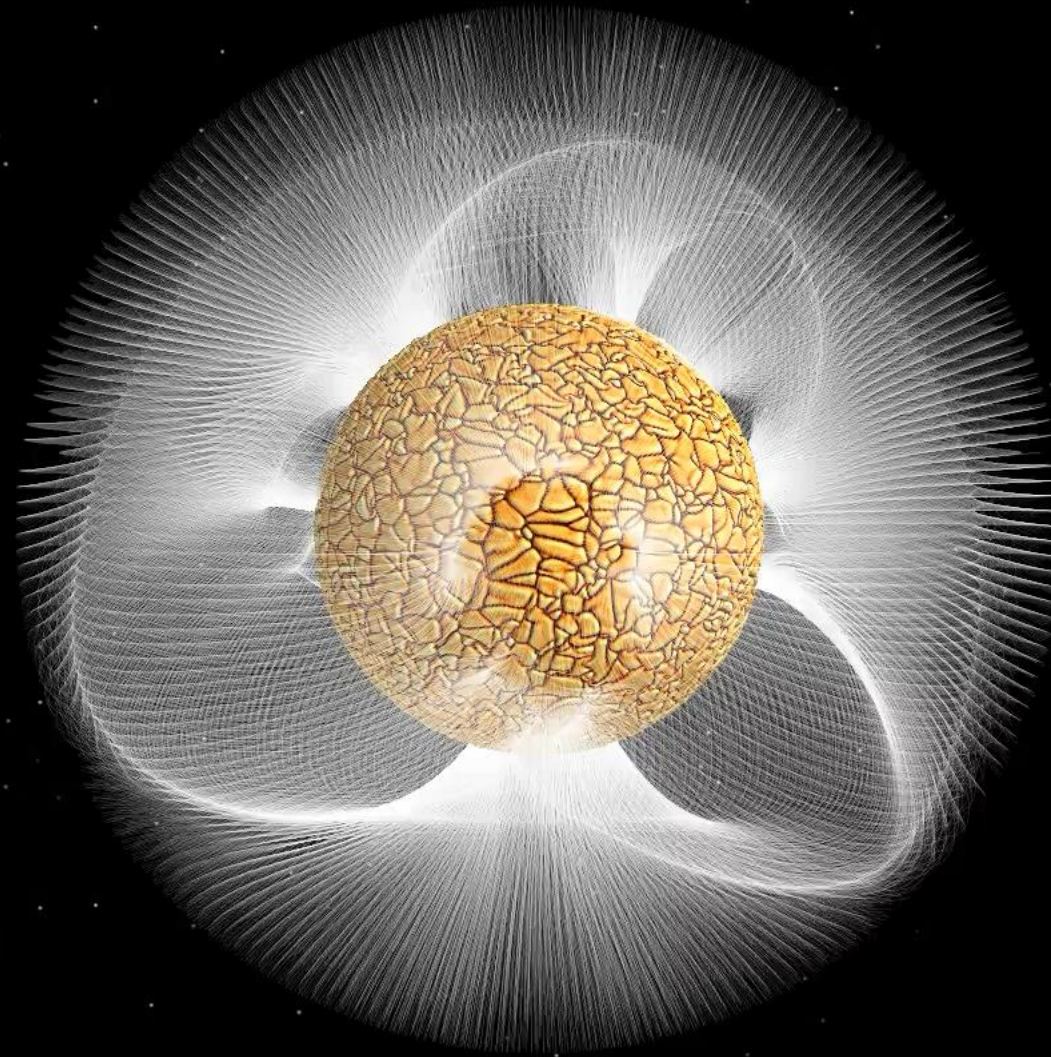


# Dynamo of the solar interior

Powering the decadal cycle and Its comparison to stellar magnetic cycles



simulations observations

**Quentin Noraz**

with A.S.Brun, A. Strugarek  
and collaborators



Roseland  
Centre  
for Solar  
Physics



UNIVERSITY  
OF OSLO



# Solar Activity

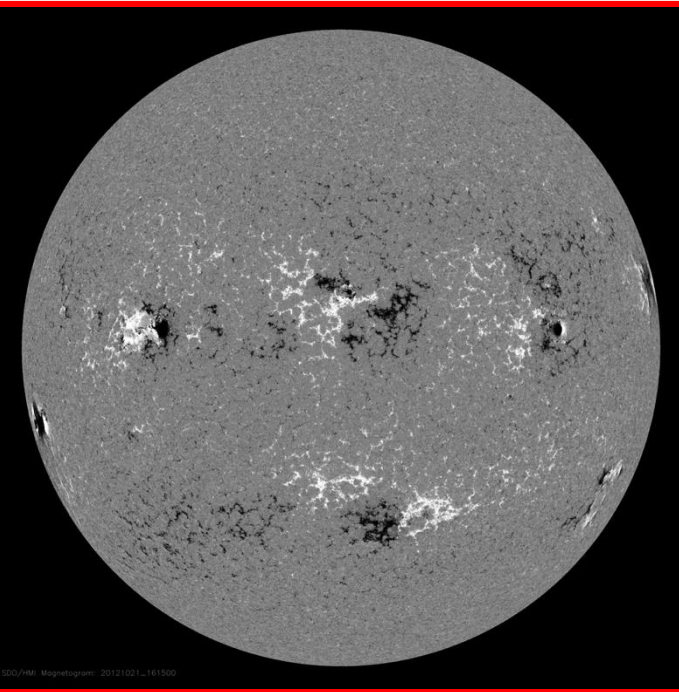
What is the origin of the solar magnetism?

Activity maximum

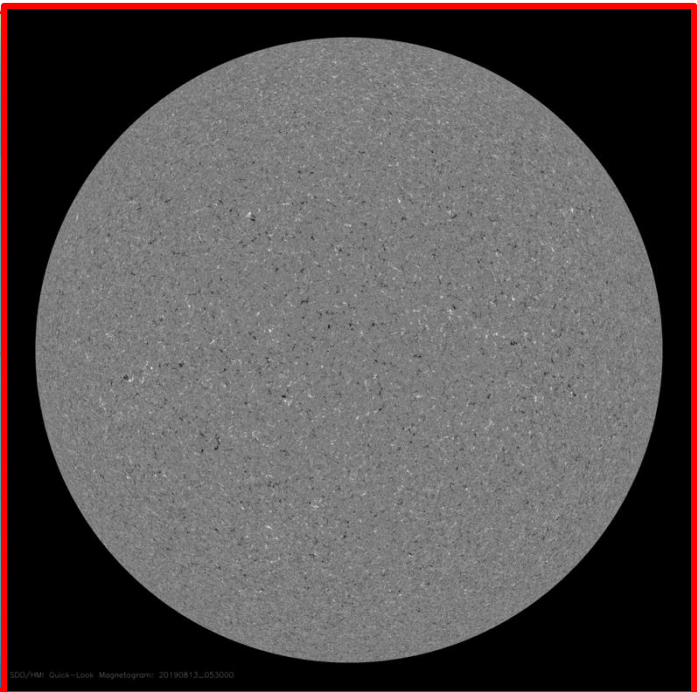
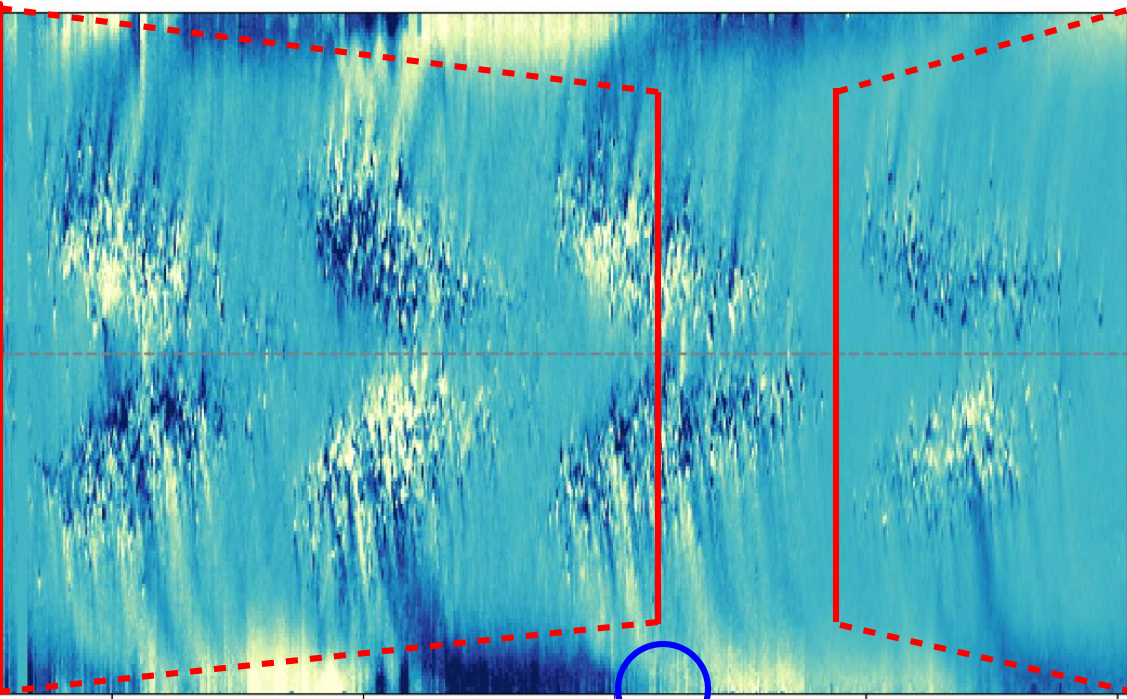
Solar “butterfly diagram”  
[KPNO, GONG, SOLIS & MDI]



Activity minimum

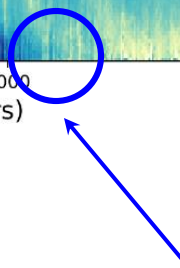


[HMI]

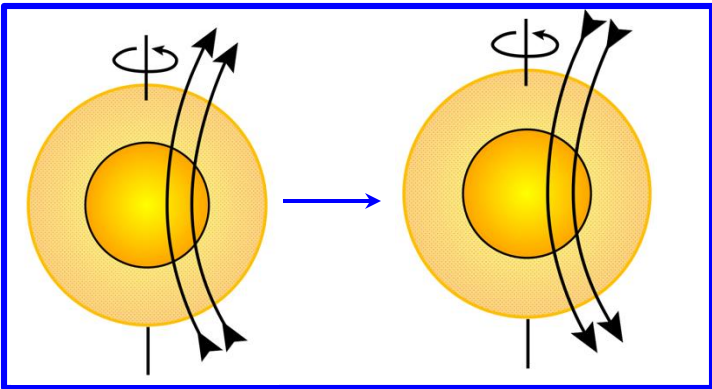


[SDO/HMI, Quick-Look Magnetogram: 20190813\_053000]

- **11-years activity cycle** [Schwabe 1844]
- Equatorward appearance [Carrington 1858]
- Opposite hemisphere polarities [Bumba & Howard 1965]
- **22-years magnetic cycle** [Hale et al. 1919]



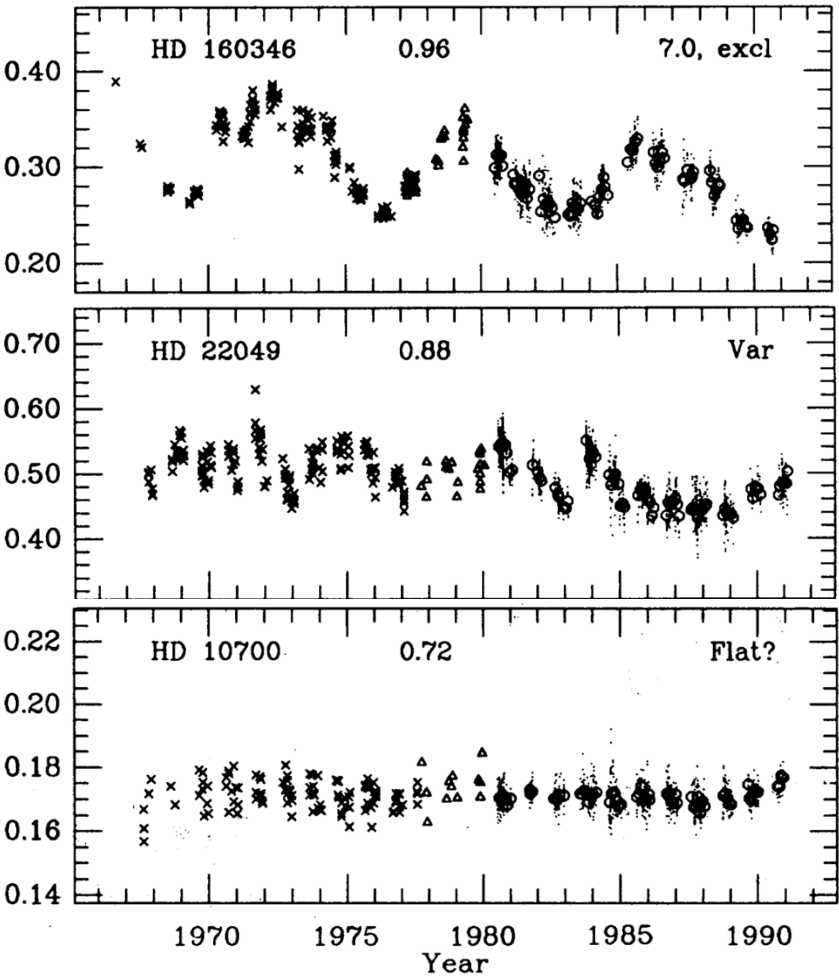
Global polarity reversal



# Solar-type stars Activity

## Stellar cycles

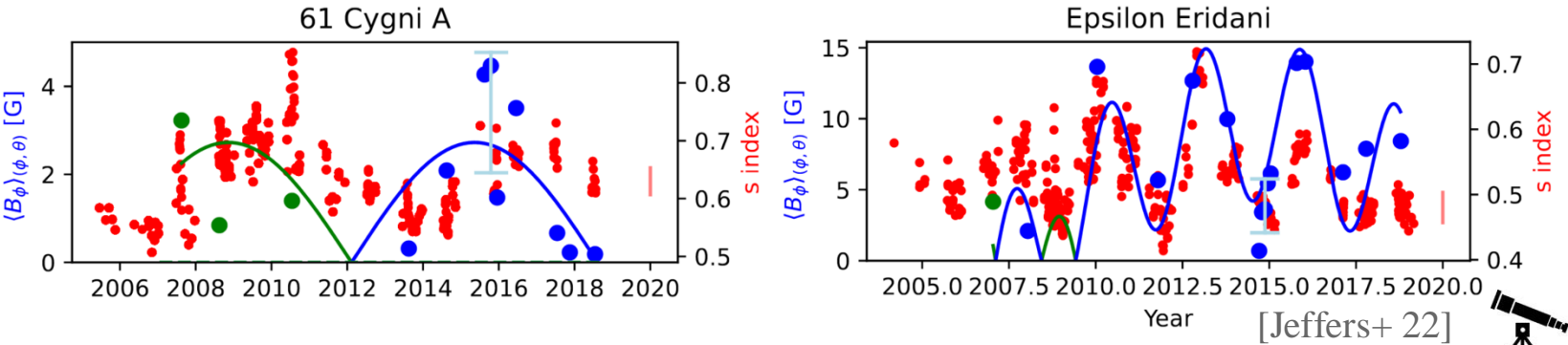
[Wilson 1978; Baliunas+ 95]



- Not all stars show **cyclic** activities  
→ current debate on the dynamo evolution

What controls the cyclic activity and its presence?

- Not all cycles show **polarity reversals**, and several cycles can be found on a star

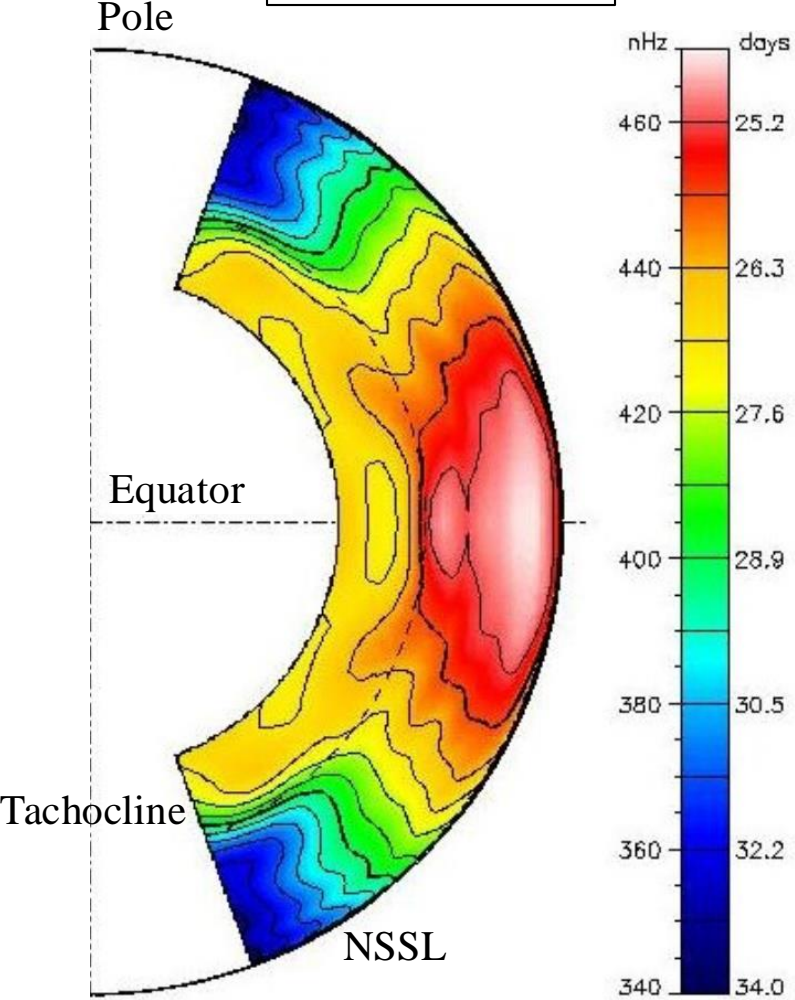


What controls the nature of the activity?



# Differential Rotation

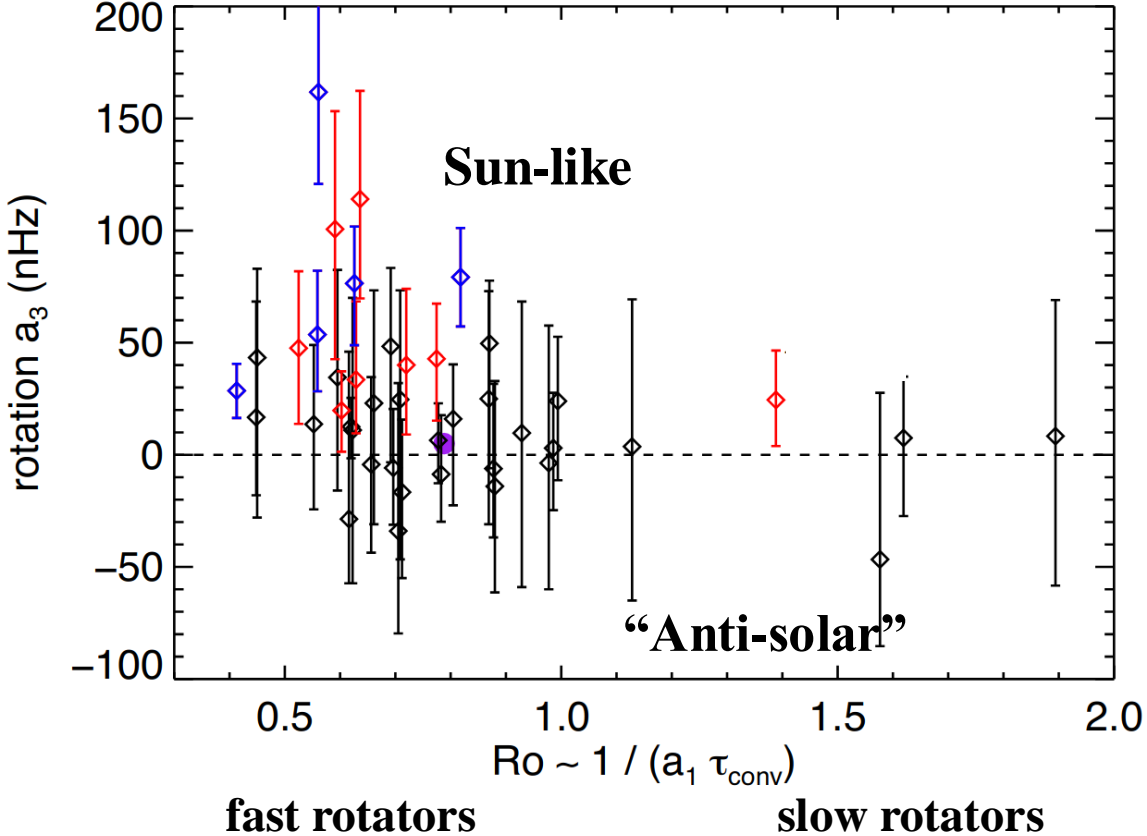
**The Sun**



[see Thompson+ 03]

**Solar-type stars**

[Benomar+ 2017]

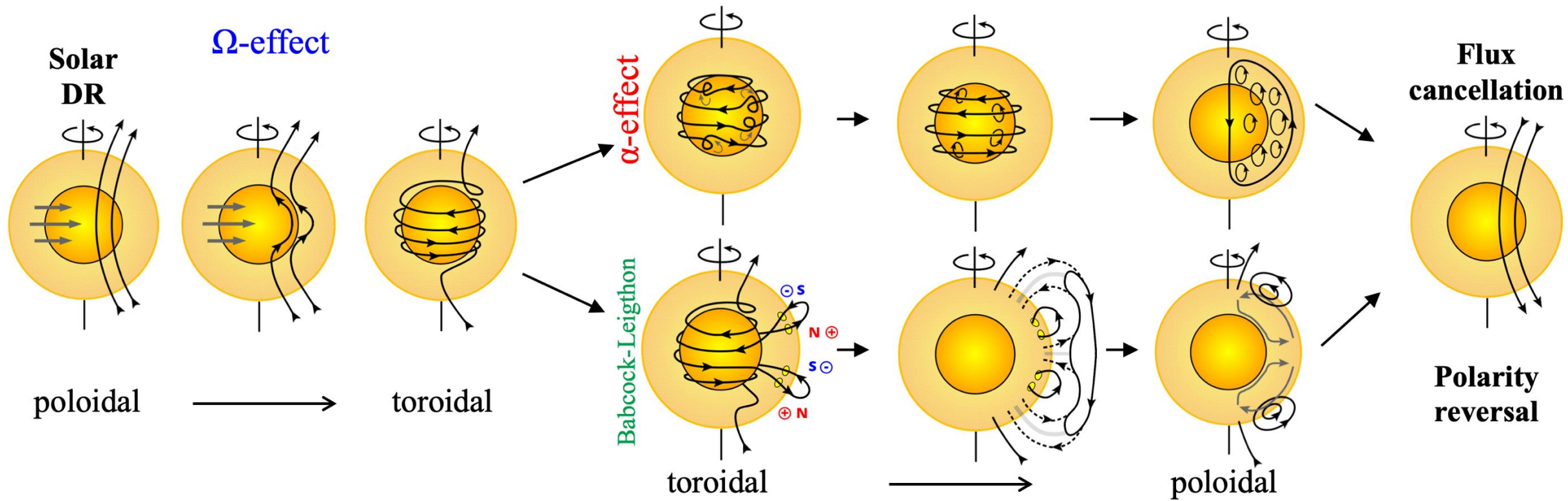


- Not so easy to measure for solar-like stars
- Precision decreases for slow rotators

[Garcia & Ballot 2019 for a review]



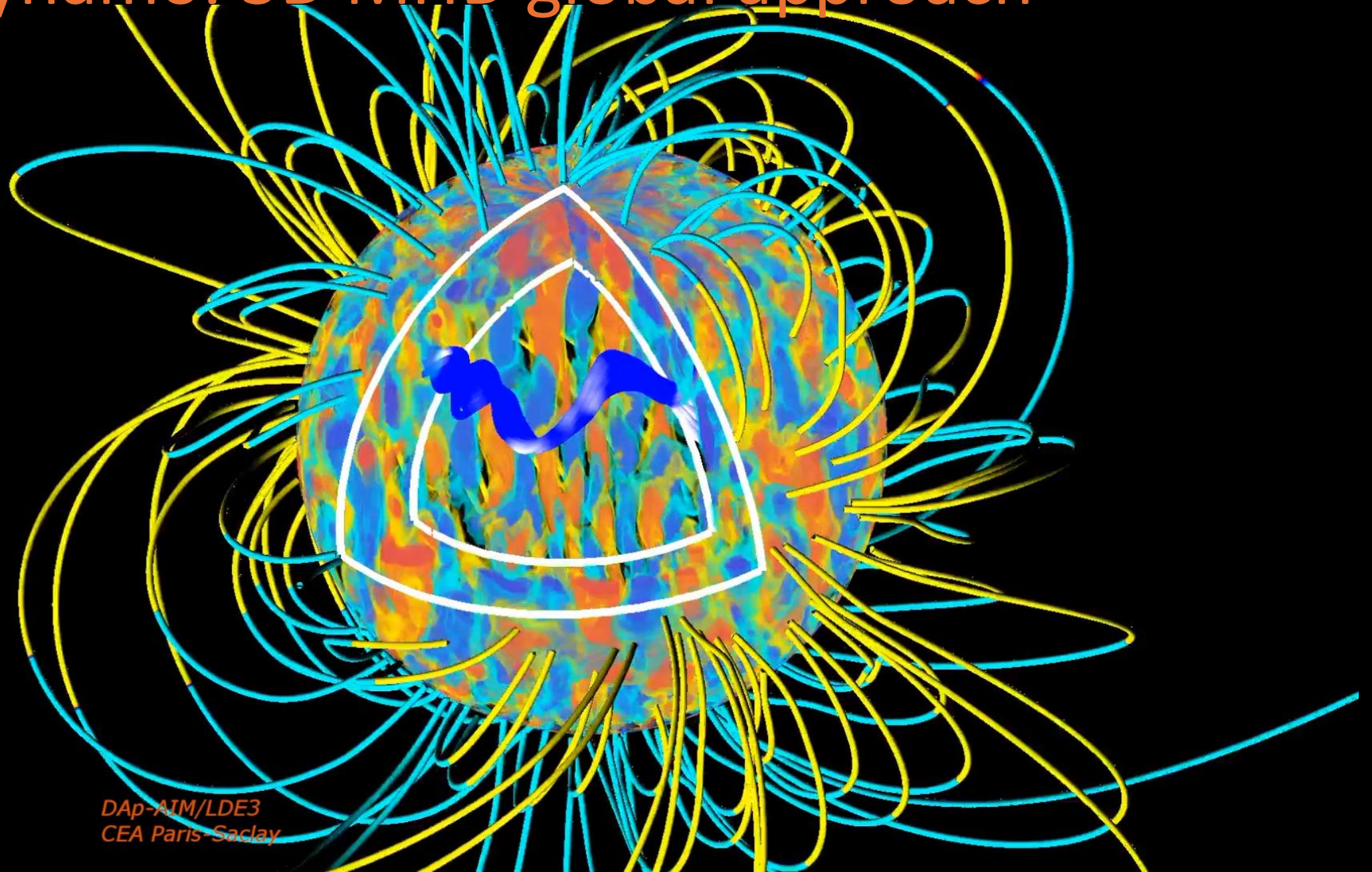
# Solar Dynamo: 2.5D Mean-field view



[Adapted from Noraz et al. 2022a]

[see also Parker 1955b, Babcock 1961, Steenbeck et al. 1966, Leighton 1969, Sanchez et al. 2014, review Charbonneau 2020]

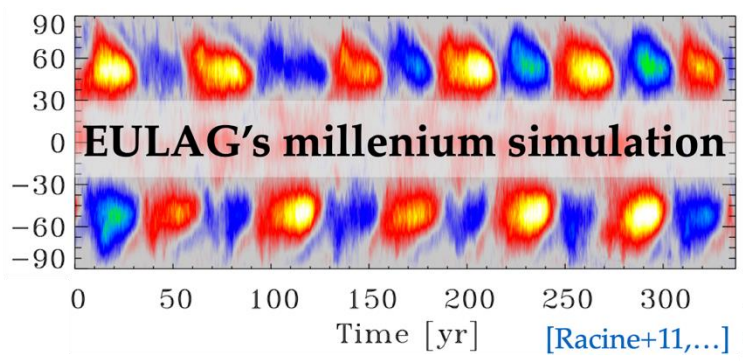
# Solar Dynamo: 3D MHD global approach



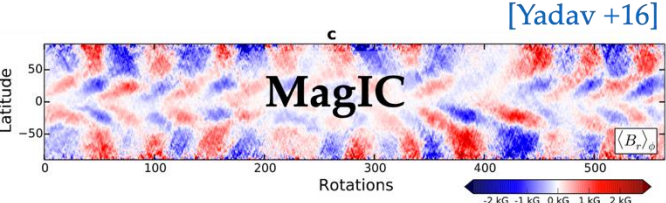
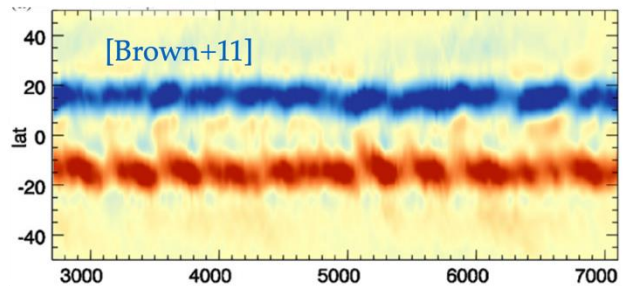
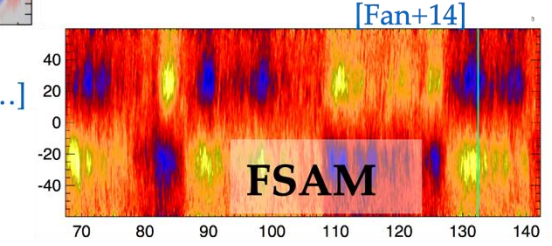
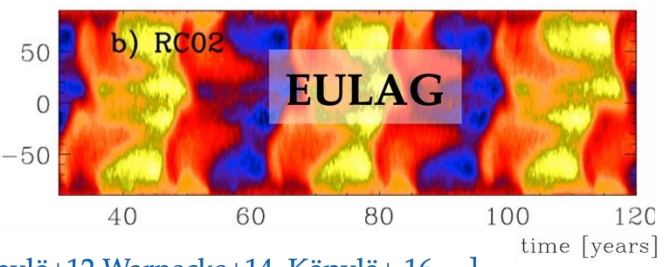
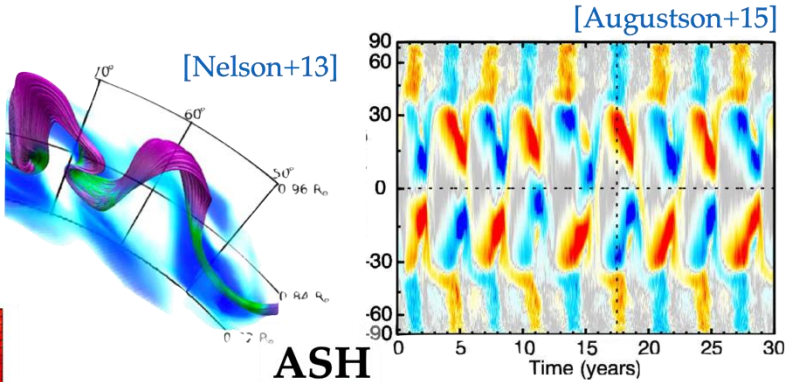
DAp-AIM/LDE3  
CEA Paris-Saclay



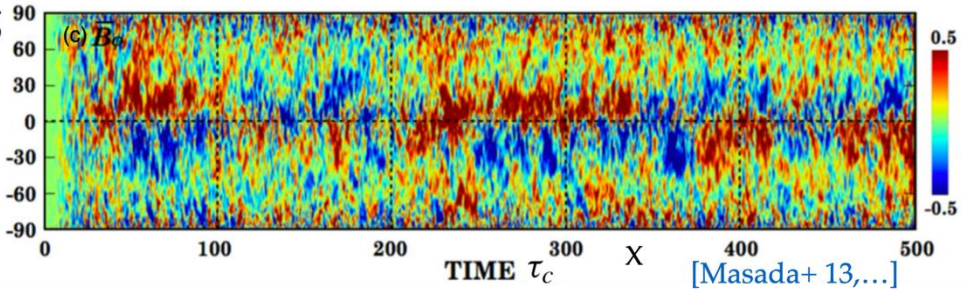
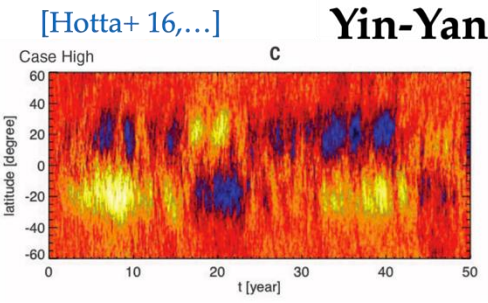
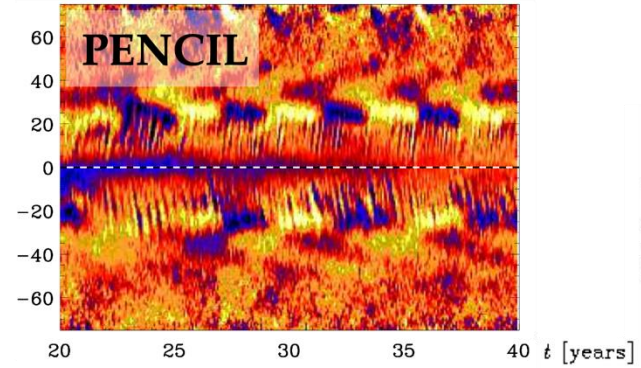
# Global turbulent models of Solar-like dynamo



and more...



[Käpylä+12,Warnecke+14, Käpylä+ 16,...]



Many different results...

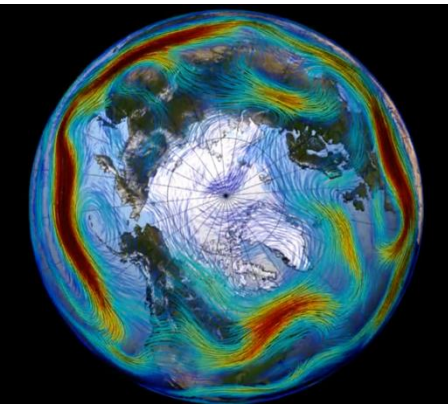
Can we reach a consensus on solar-type dynamo modeling?

# Normalizing Prot by $\tau_{conv}$

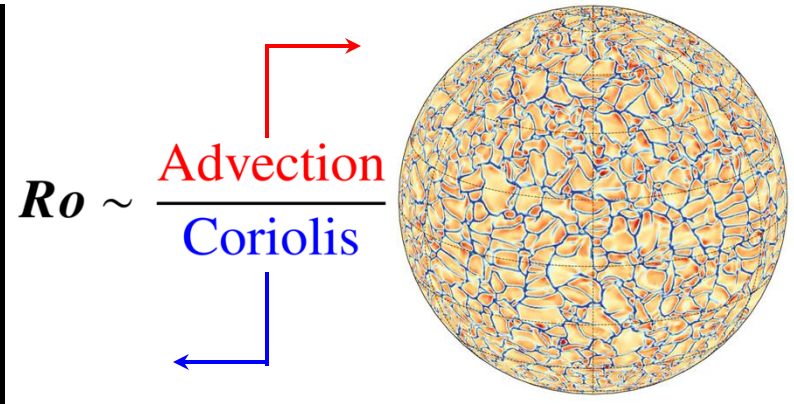
[See+ 2019  
see also Wright+ 2011, Reiners+ 2014, 2022]



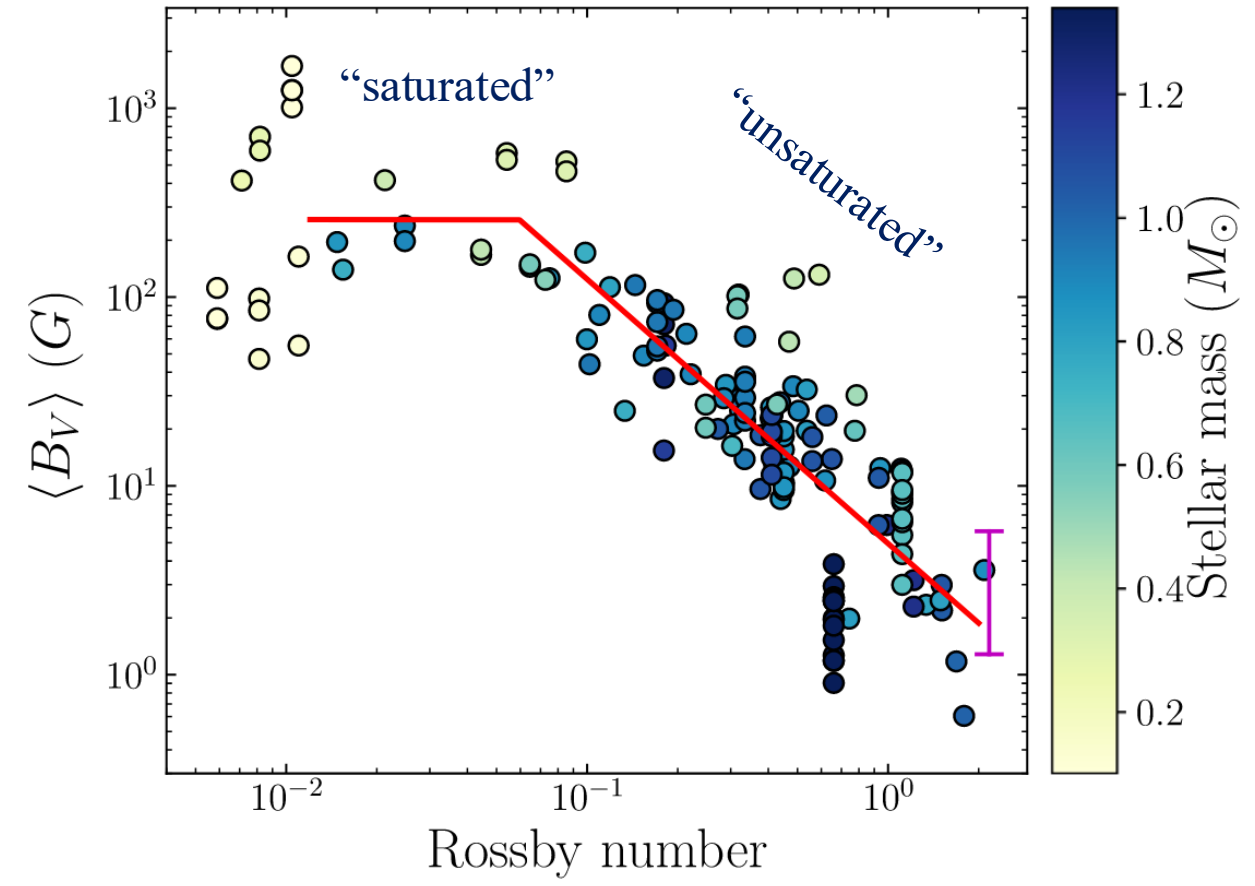
Rossby number



[NASA]



[ASH code]



**Low Rossby  
Fast / Young  
rotators**

**High Rossby  
slow / old  
rotators**



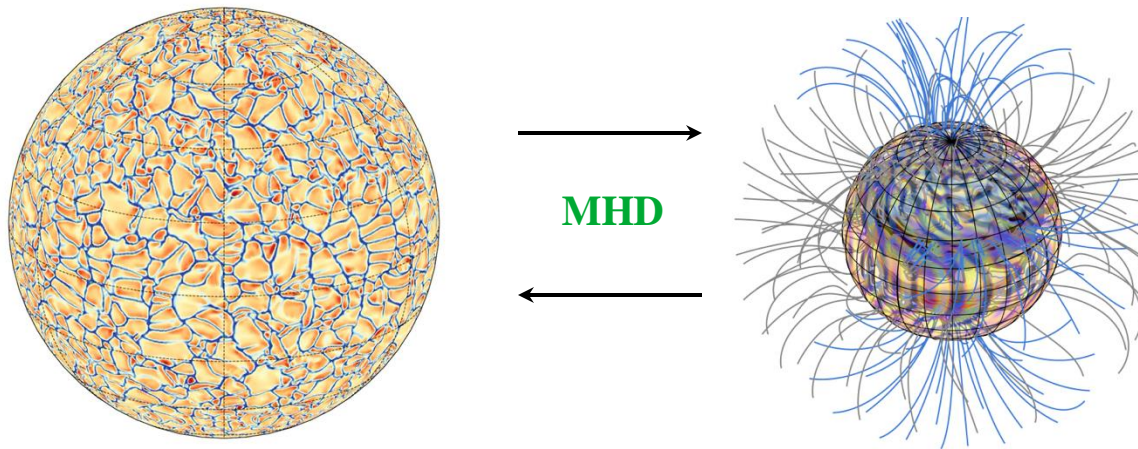
# New insights from simulations



## Numerical setup:

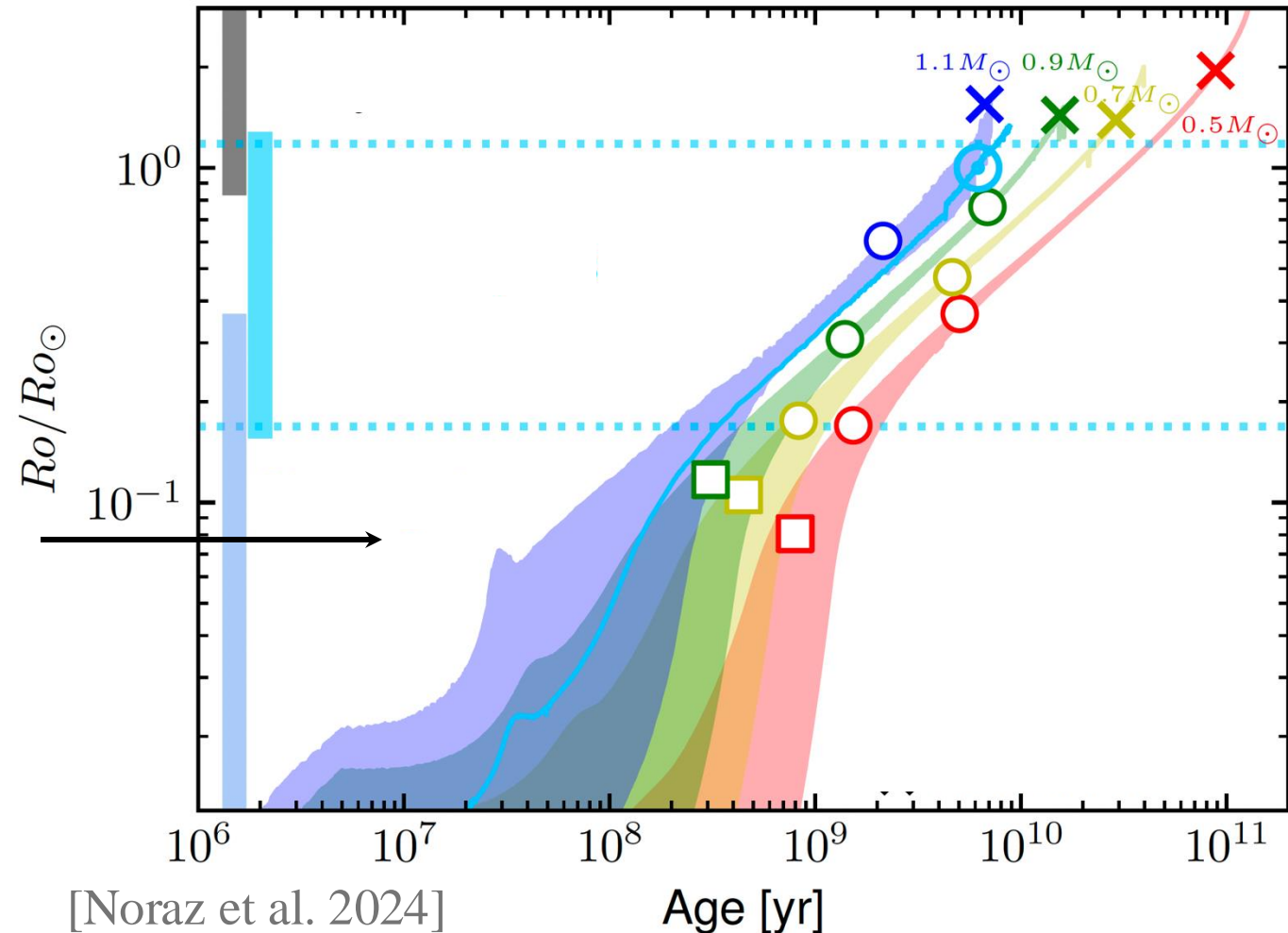
- Code : ASH (global)  
3D MHD spherical ( $r, \theta, \phi$ )

→ **convection** is explicitly resolved,  
**magnetic retro-action** on the flow ←



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

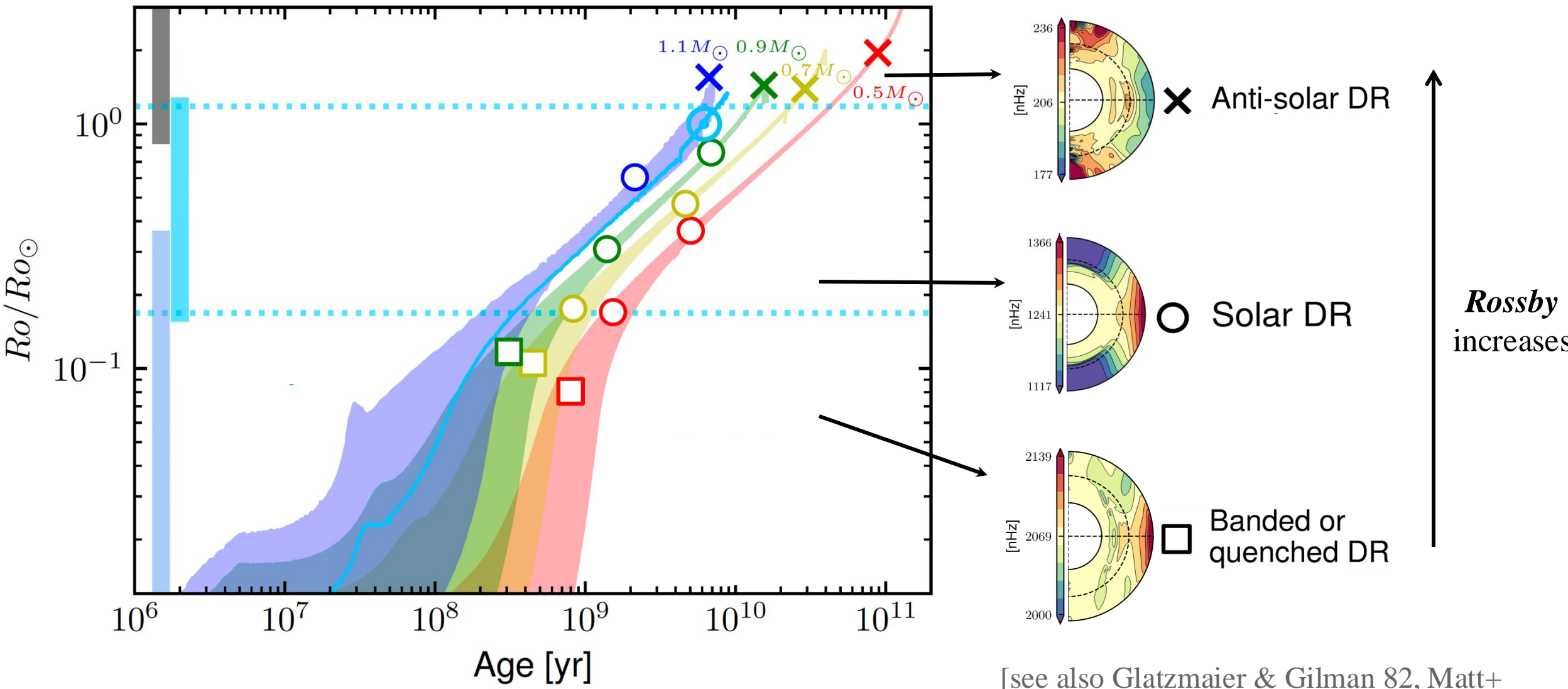
- from  $0.25 \Omega_{\odot}$  to  $5 \Omega_{\odot}$
- from  $0.5 M_{\odot}$  to  $1.1 M_{\odot}$
- Resolution  $769 \times 256 \times 512$



# Rotational transitions



[Brun+ 22, Noraz+ 24]



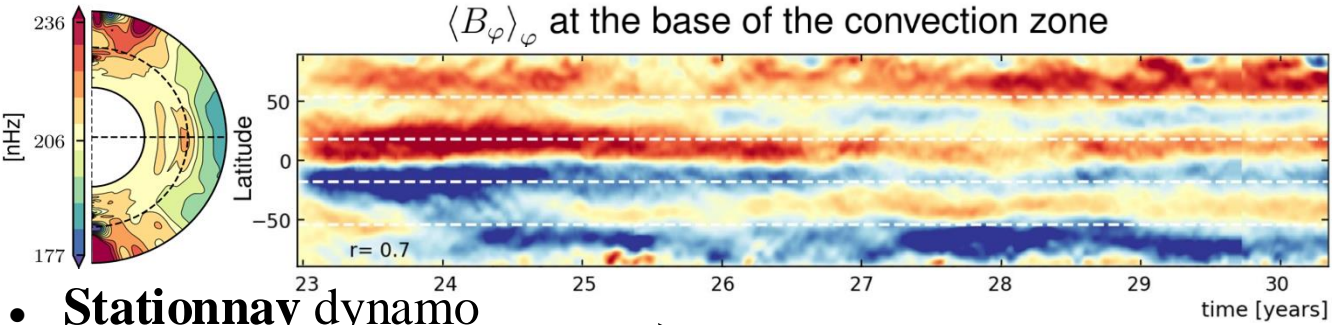
[see also Glatzmaier & Gilman 82, Matt+ 11, Käpylä+ 14; Gastine+ 14, Simitev+15, Karak+ 18, Hindman+ 20...]



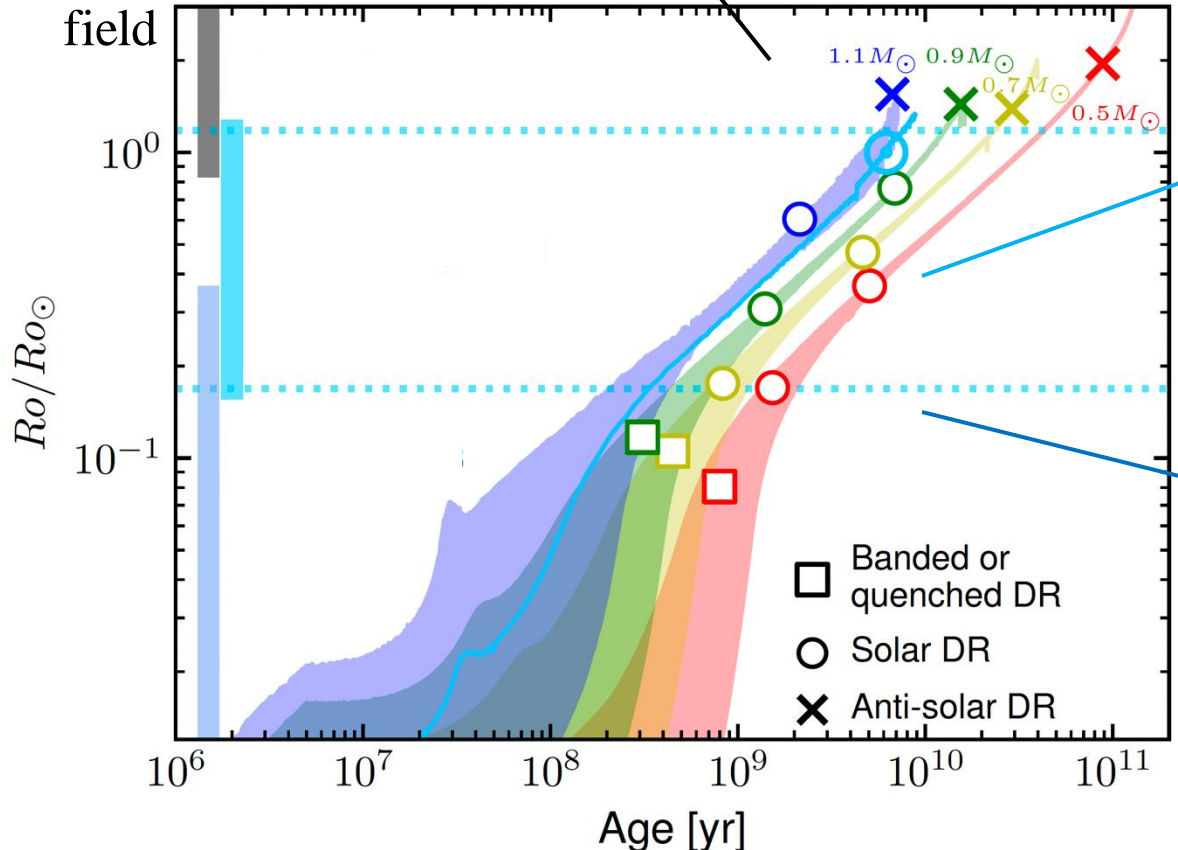
# Magnetic transitions



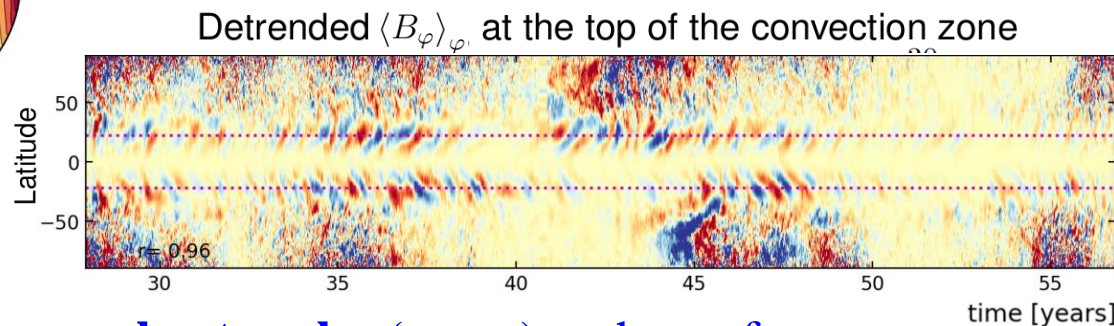
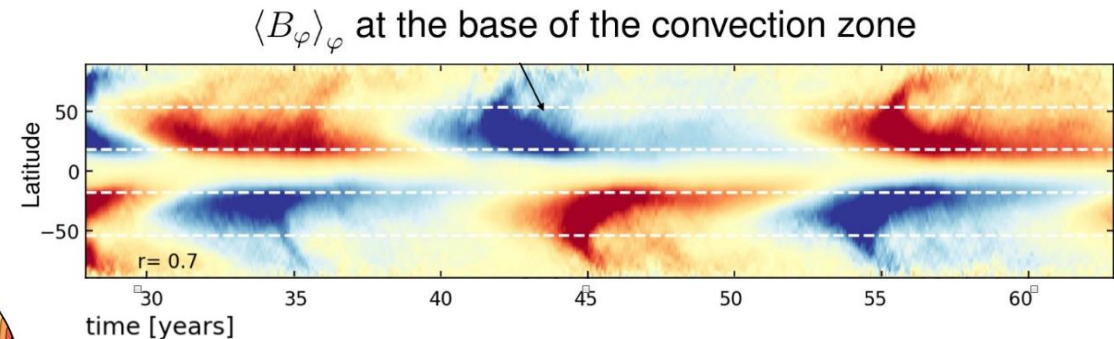
[Brun+ 22, Noraz+ 24]



- **Stagnant dynamo**
- hemispherical toroidal field



- **long cycles (decadal solar-like)**
- **Global polarity reversals**
- **Torsional oscillations (prey-predator)**



- **short cycles (~year) at the surface**
- **Local equatorial polarity reversals (P-Y)**
- **quasi-biennial oscillations ?**

# Energy transfers in dynamo solutions

see Starr & Gilman 66  
Brandenburg+96  
Rempel 06  
Brun+ 22

Nuclear  
generation



**Internal energy**

**Potential energy**

Viscous  
heating



Pressure work  
(compression & expansion)



Buoyancy  
work

Ohmic  
heating



**Kinetic energy**

**Differential rotation**, convection,  
meridional circulation ...



Lorentz force work  
(dynamo + mag. retro-action)

**Magnetic energy**

Large scale dipole, magnetic  
ribbons, flux-tubes,...

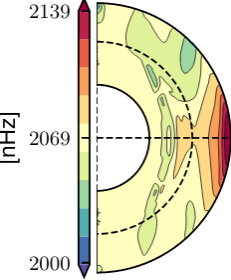
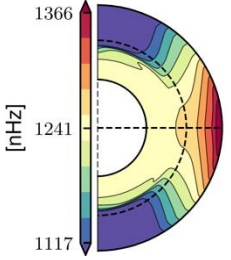
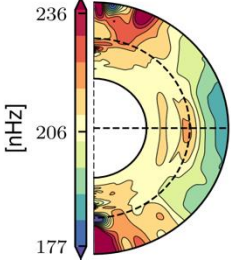


# Powering the Differential Rotation



[Brun+ 22]

|                           | Powering Differential rotation |
|---------------------------|--------------------------------|
| Slow rotator              | $\sim 10\% L_{\star}$          |
| <b>Solar-like rotator</b> | $\sim 10-30\% L_{\star}$       |
| Fast rotator              | $\sim 5\% L_{\star}$           |



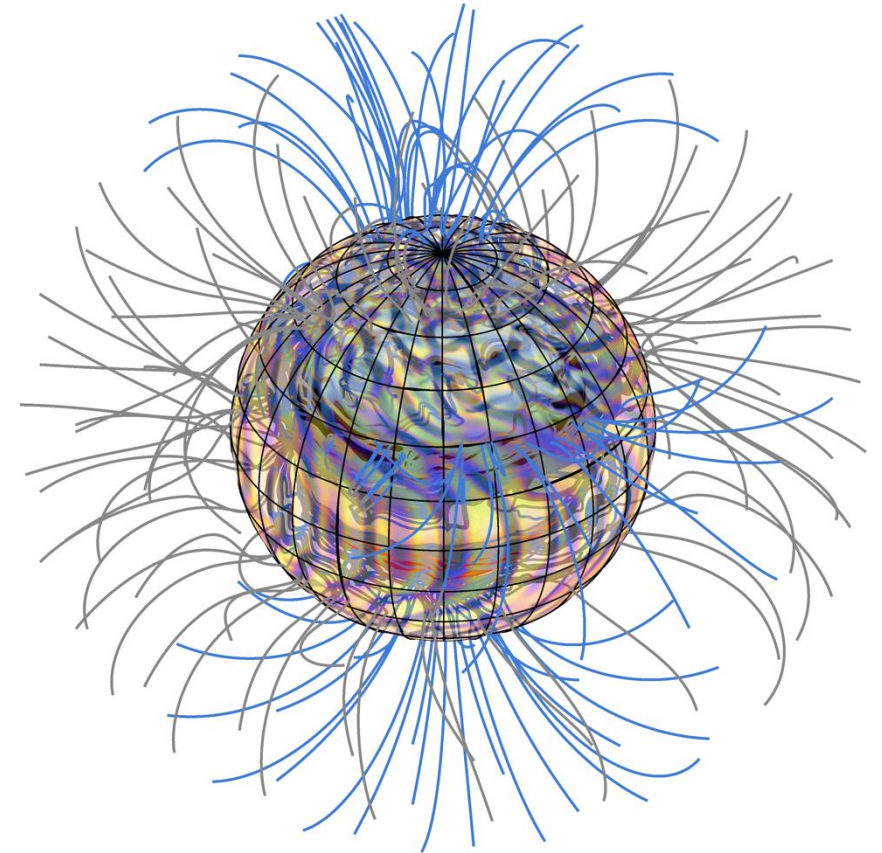
**10 % of the solar luminosity :  $\sim 4 \times 10^{32}$  erg/s !**

# Powering the Dynamo



[Brun+ 22]

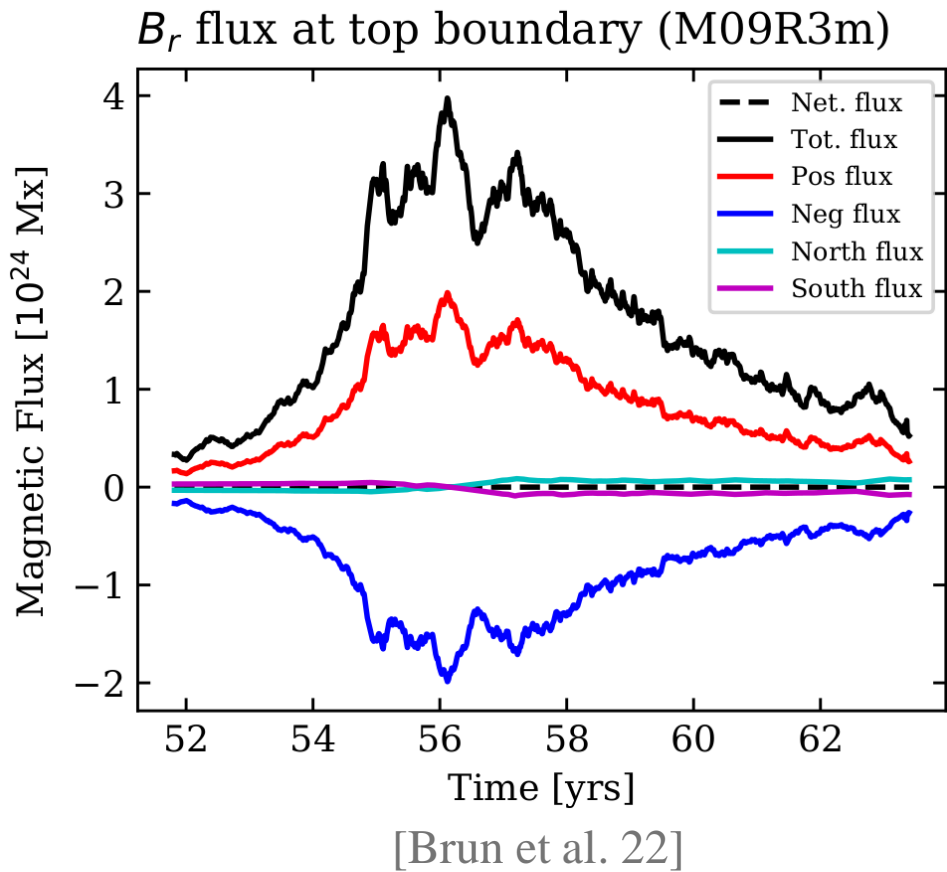
|                           | Powering magnetism       |
|---------------------------|--------------------------|
| Slow rotator              | $\sim 0.1\% L_{\star}$   |
| <b>Solar-like rotator</b> | $\sim 0.1-3\% L_{\star}$ |
| Fast rotator              | $\sim 1\% L_{\star}$     |



**1 %** of the solar luminosity :  $\sim 4 \times 10^{31}$  erg/s !



# Comparison to solar observations

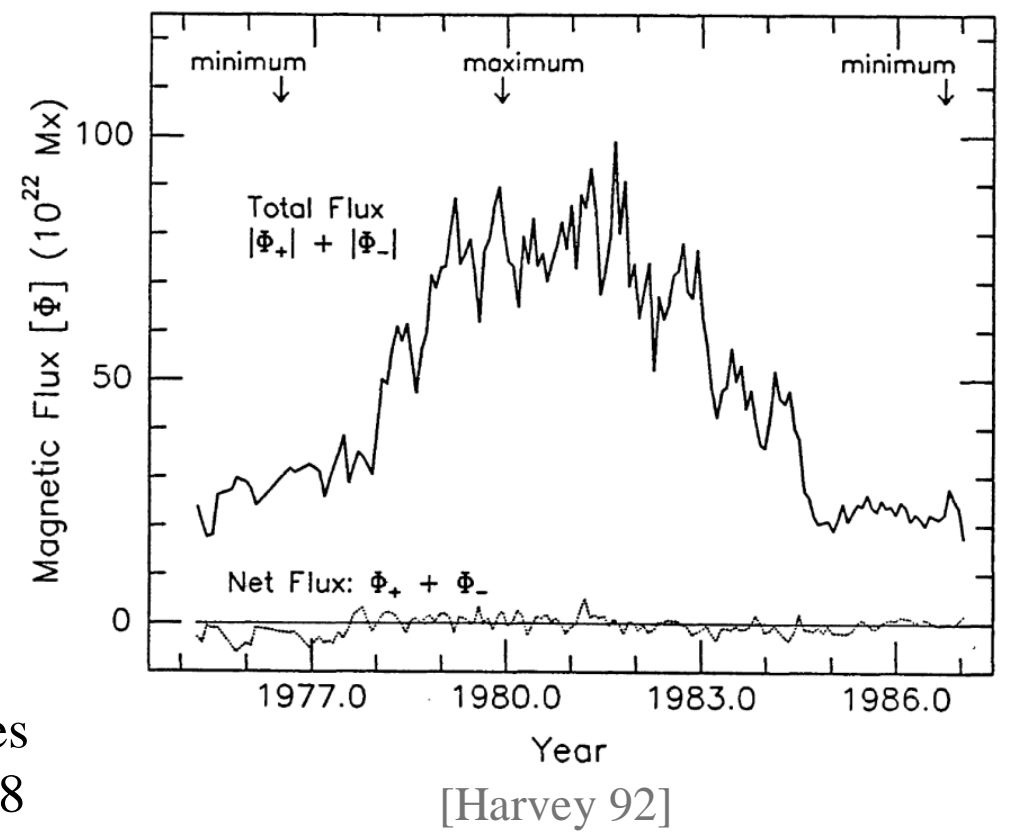


Magnetic fluxes from  $10^{24}$  to  $10^{25}$  Mx, in good agreement with values observed on the Sun.



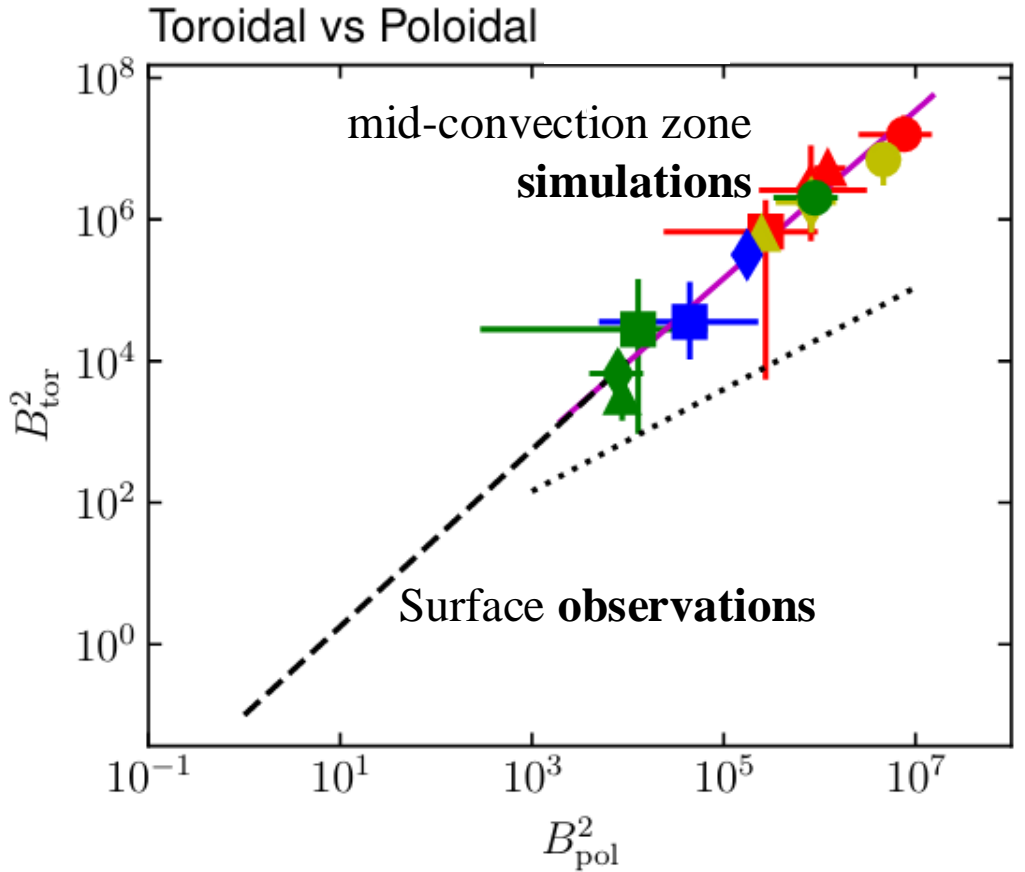
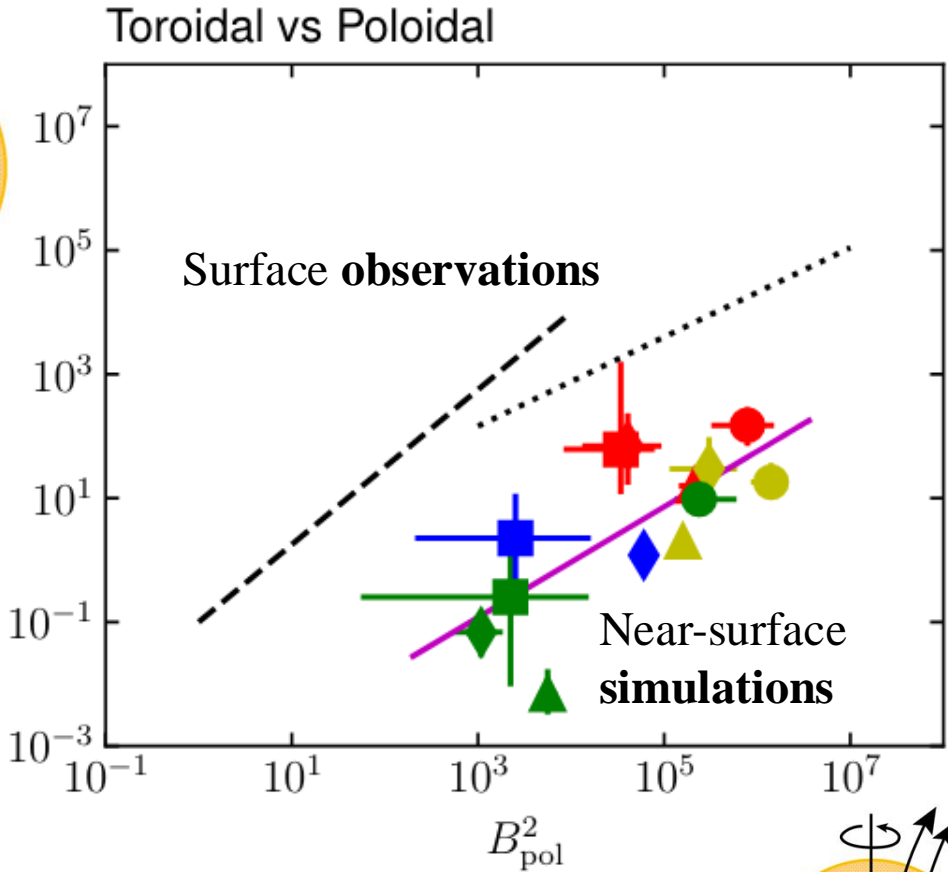
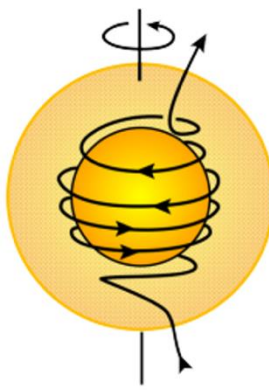
$$\Phi = \int_S \mathbf{B} d\mathbf{S}$$

Modulation reaches almost a factor of 8 (compared to 5 for the Sun).

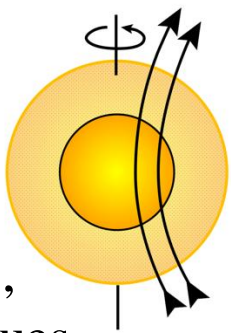


# Observational constraints: Topology

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

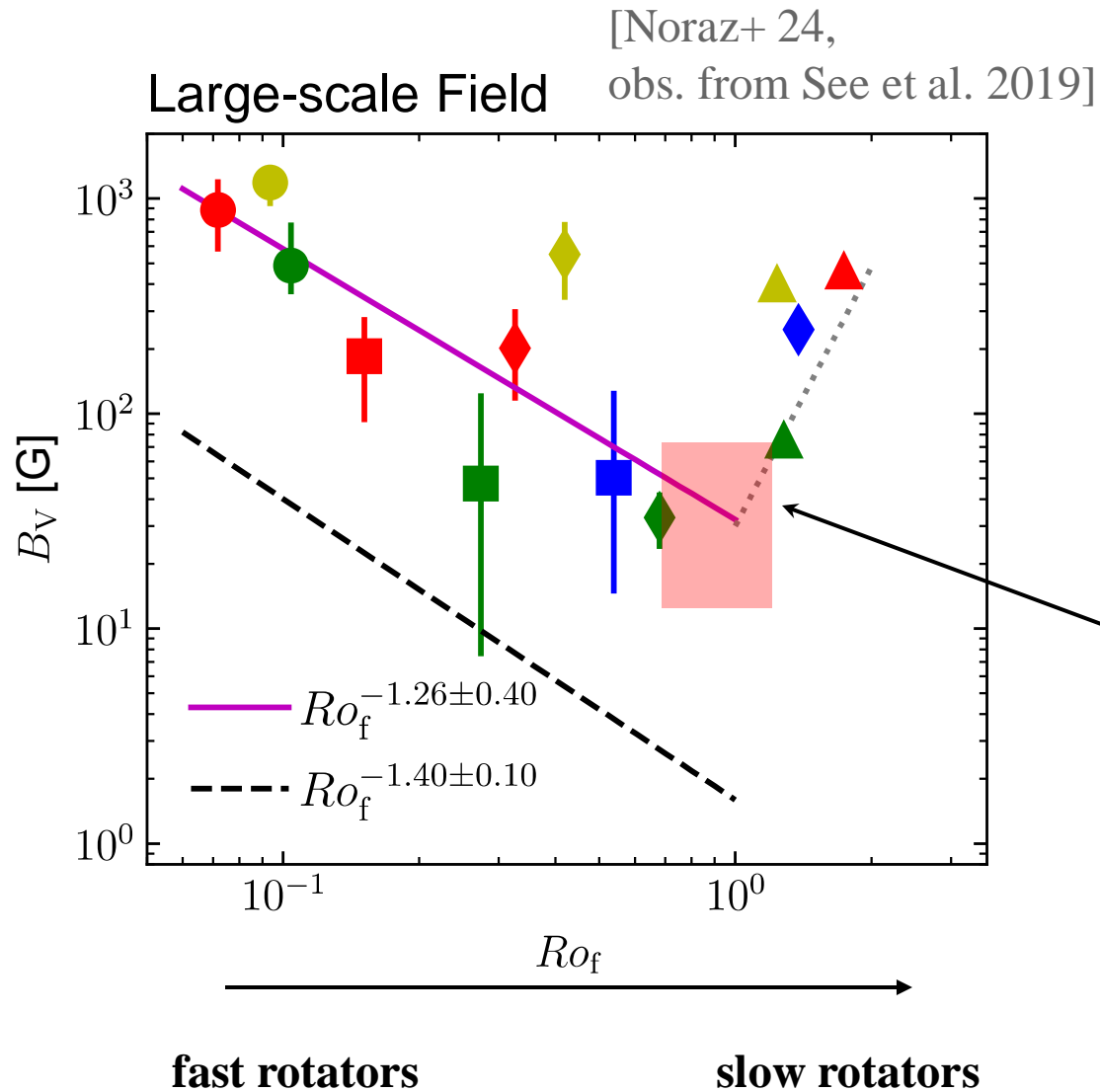


- **Trends consistent** with observations (See+ 2015), surface BCs offset toroidal values



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

# Magnetochronology of old solar-type stars



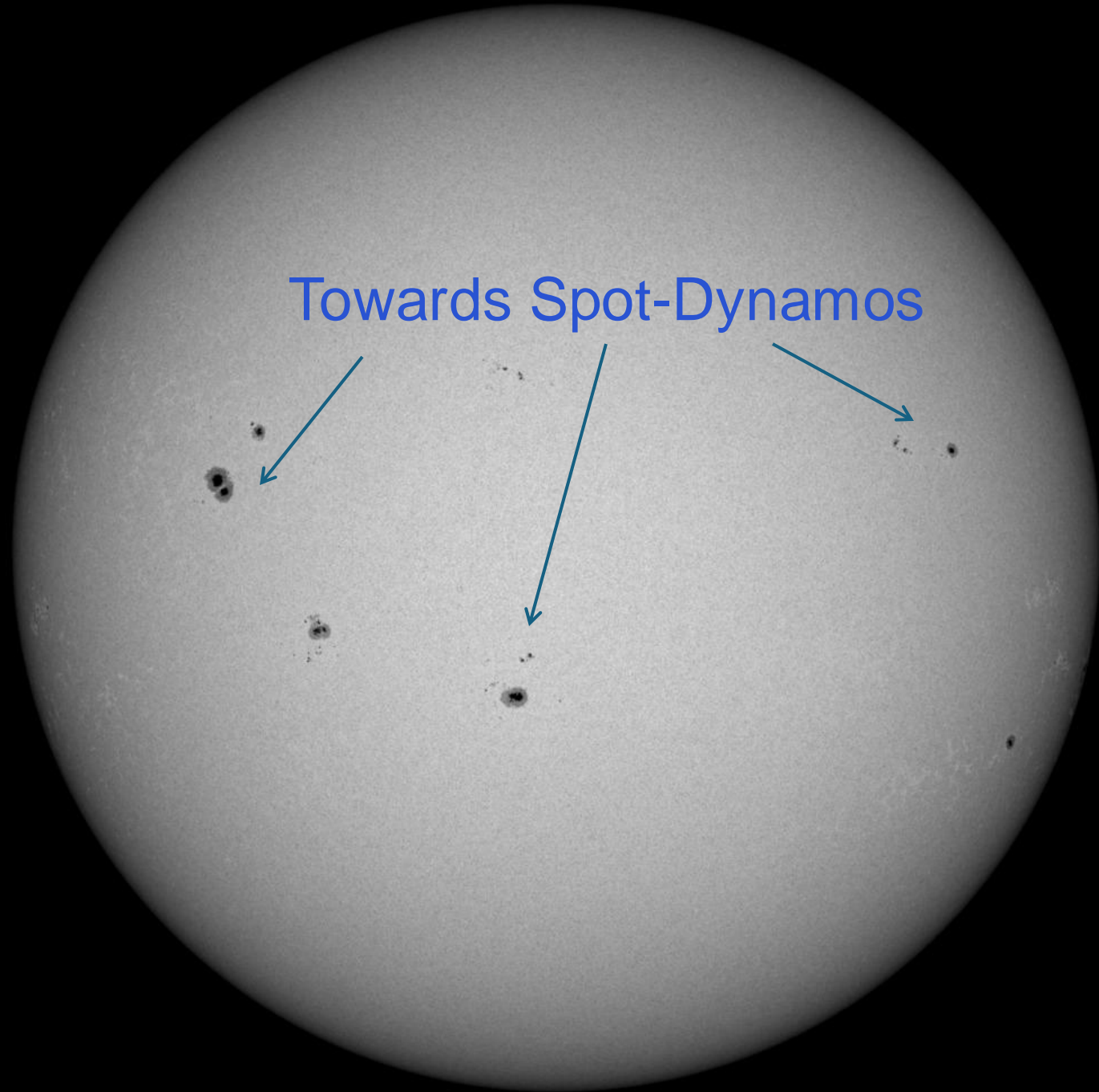
- Offset of the simulations, likely because we probe deeper, and ZDI partially miss flux
- The large-scale **decreases**, **agrees** with observational trends,

**minimum around the solar?**  
→ stalling of the spin-down?

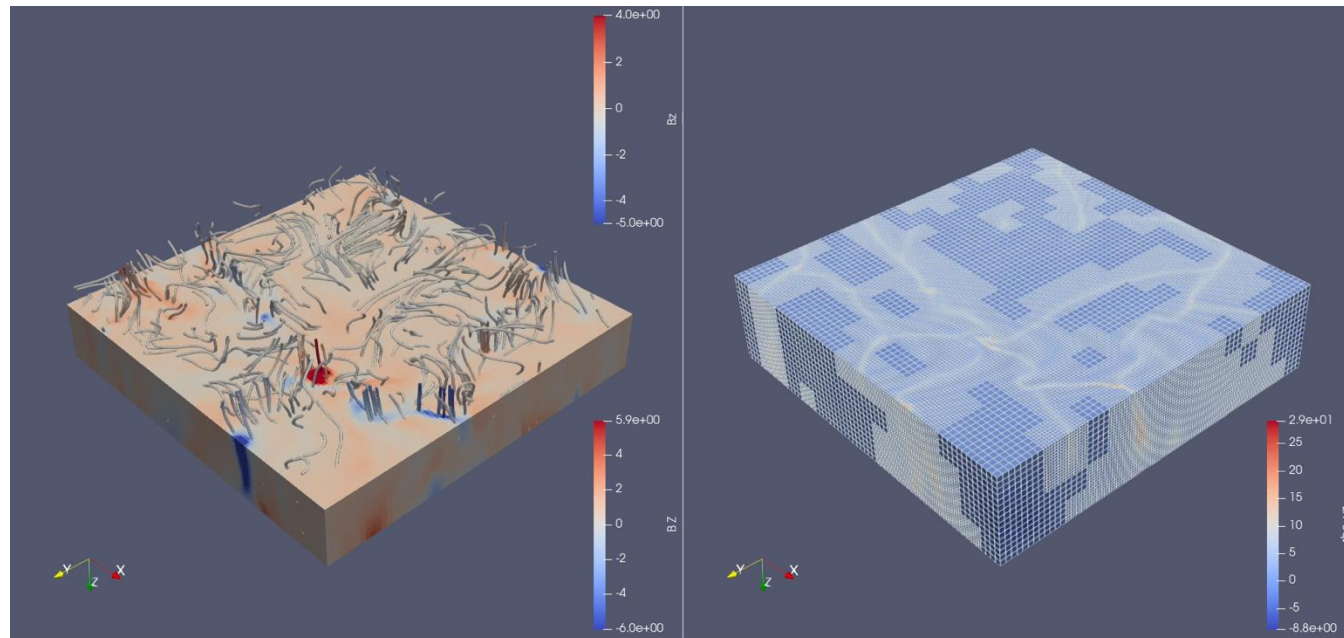
- We need further constraints for the **high-Rossby regime**  
[see also Brandenburg & Giampapa 2018, Noraz+22b]



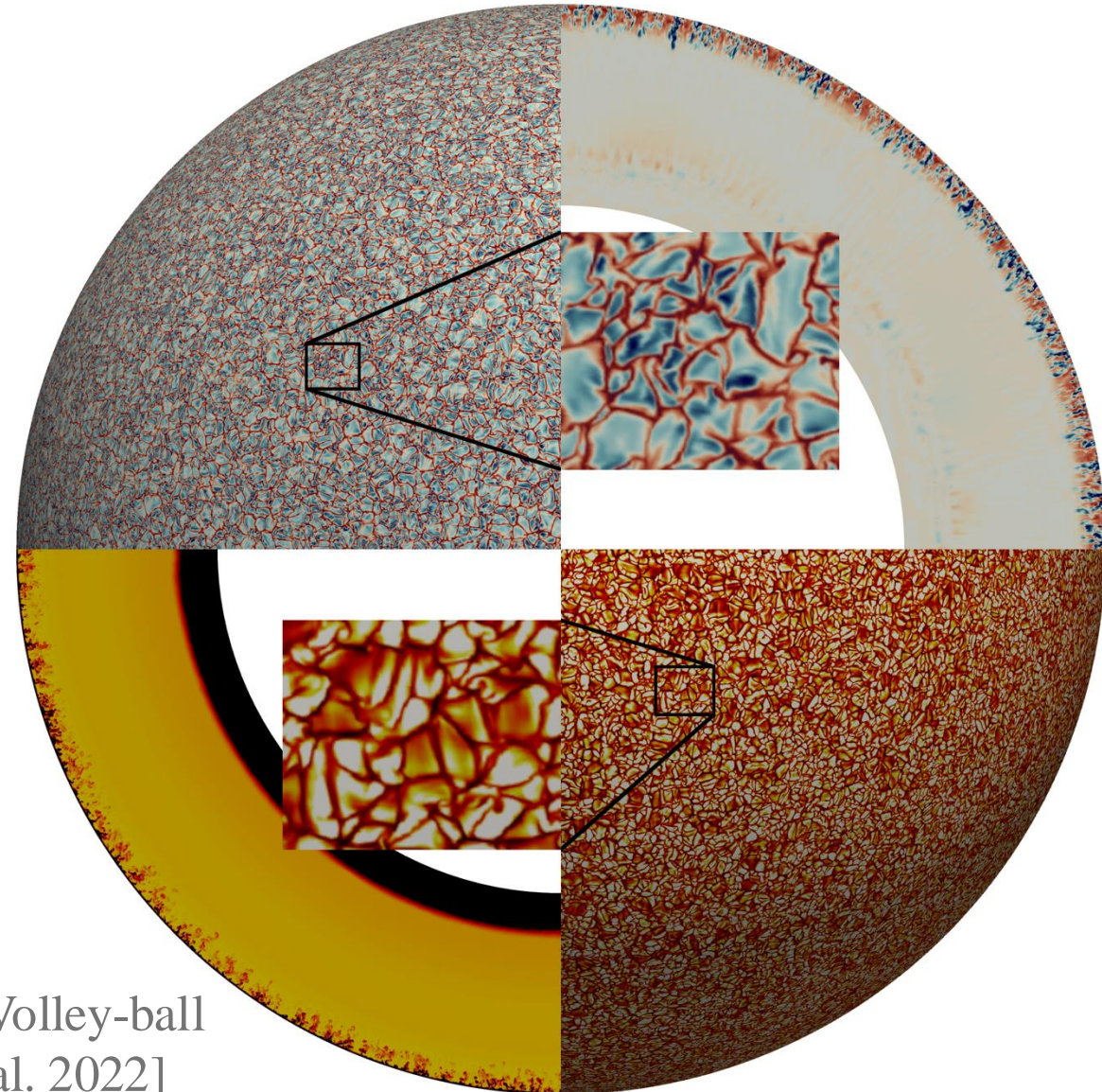
# Towards Spot-Dynamos



# Coupling global codes with the Surface



[MHD Dyablo code  
Delorme et al. 2023]



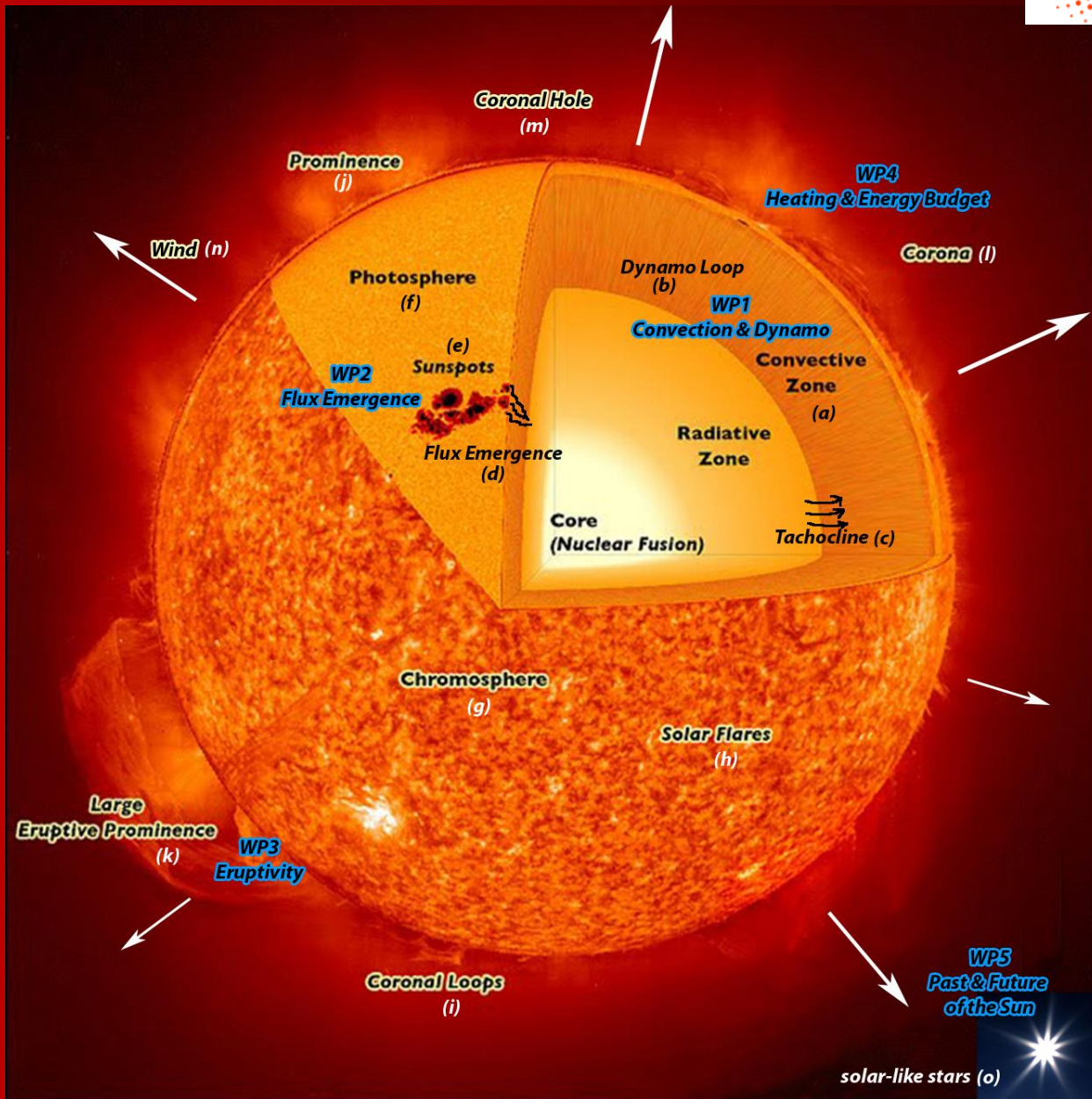
[DISPATCH Volley-ball  
Popovas et al. 2022]



# WholeSun



# Synergy



WP1: *Dynamo, Convection*

WP2: *Flux Emergence*

WP3: *Eruptions, Flares & Jets*

WP4: *Heating & Coupling of Atmosphere*

WP5: *Solar-Stellar Connection*

WPX: *Generation of Next-Gen Codes*

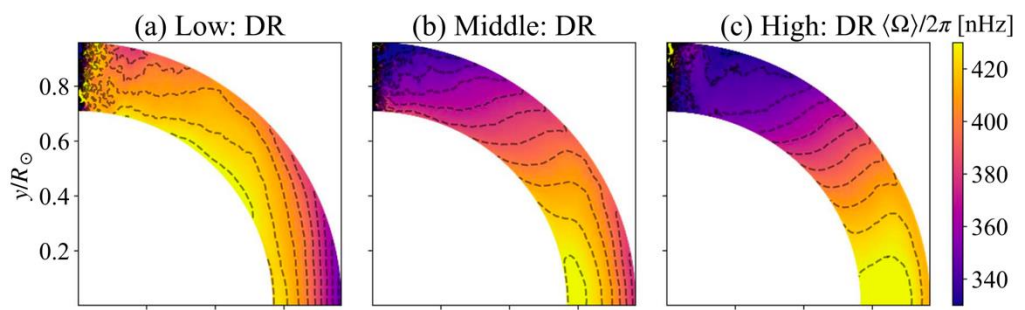


# Convective conundrum : Towards more turbulent regimes

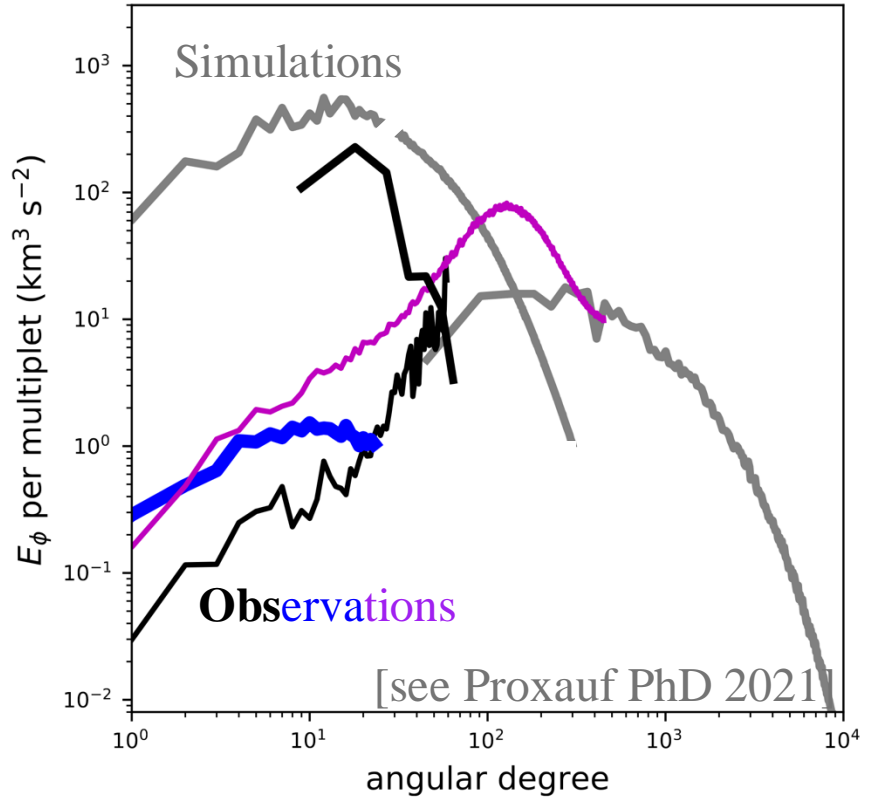
The amplitude of giant **convection** cells in global convection **simulations** is **stronger than the one observed**. [Hanasoge+ 2012,16]

=> **Rossby** number achieved is **too large** → transitions to “anti-solar”

**Possibility 1 : Limiting convection** amplitudes?  $R_o \sim \frac{\text{Convection}}{\text{Rotation}}$



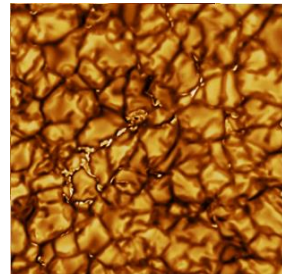
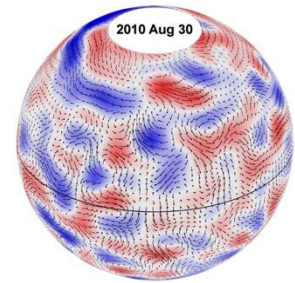
- **Hotta et al. 2022** report a strong **impact of the small-scales magnetism, on the large-scale convection**, with R2D2 code
- **But No Cycle...**



[see Proxauf PhD 2021]

**Large scales**

**small scales**



# Non-local convective transport

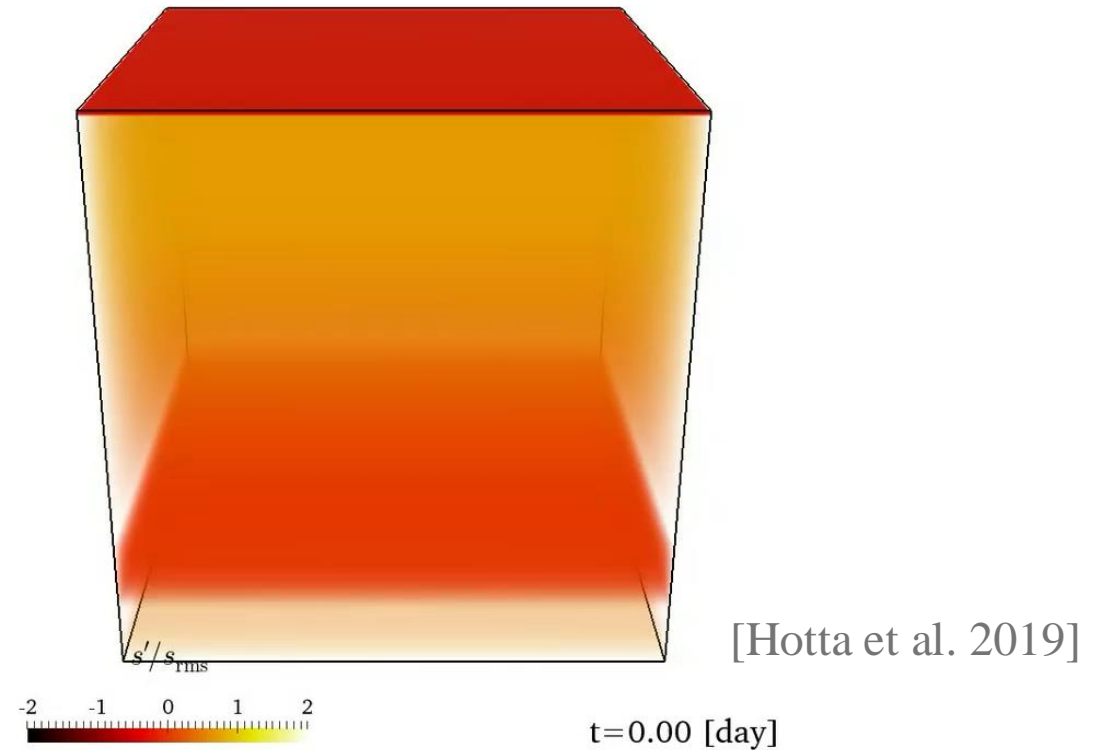
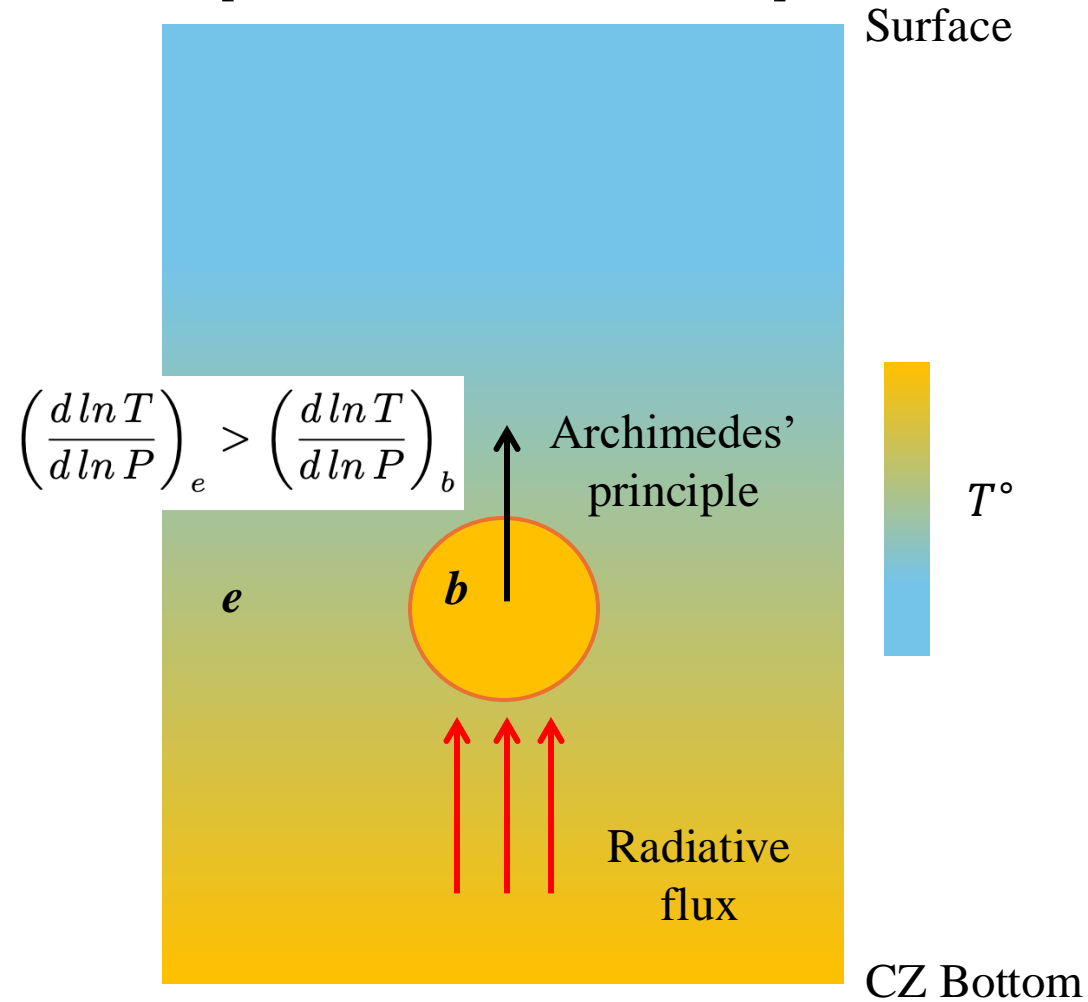
Thermal instability

Vs.

Mechanical perturbation

*Schwarzschild criterion*  
[see also *Ledoux criterion*]

*“Entropy rain”*  
[see Stein & Nordlund (1989, 1998),  
Spruit (1997), Brandenburg 2017]



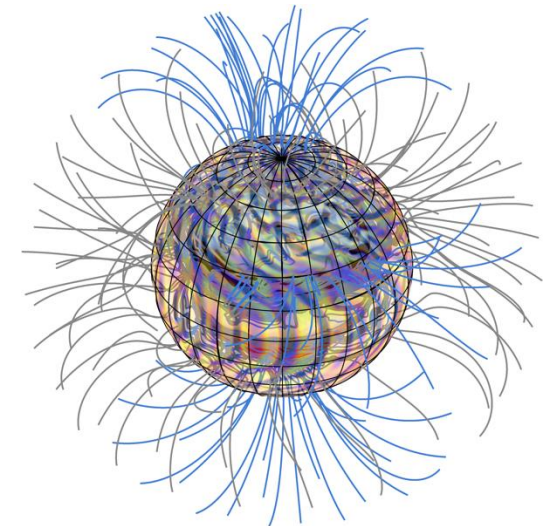
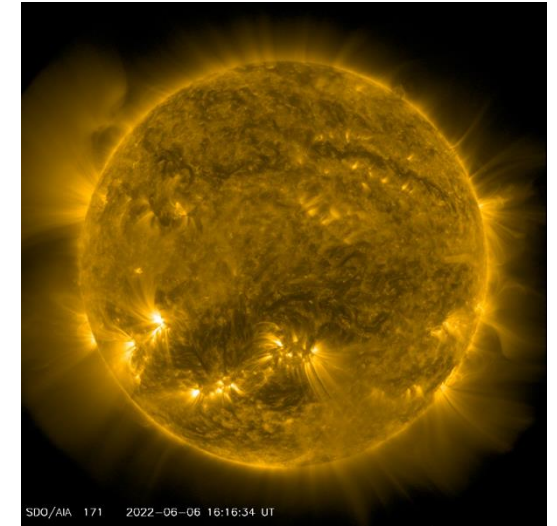
- Helioseismology can give us constraint on superadiabaticity  
-> recent work with Rossby modes  
[Gizon et al. 2021, Bekki et al. 2022]

# Conclusion: Take-home messages

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@Norastraz

- **Scenario for the Sun's life** [Strugarek+ 17, Brun +22, Noraz +24]  
young (fast-rotating) - **short cycle** – no global polarity reversal  
solar age - prograde equator - **decadal cycle**,  
older - **stationary dynamo** - anti-solar profile?
- **Possible mechanism** of the solar cycle:  
**Prey-predator** mechanism deep-within the convection zone,
- **Differential rotation** can be sustained by means of **10%** of the stellar luminosity  
**Magnetism** by means of **1%** : cyclic reversals + surface eruptive events,
- Such results are **reproduced** with other numerical methods,  
[Strugarek+ 17,18, EULAG code,  
Küker 2023, Rayleigh code]





# Perspectives

- **These are only simulations:**

Not yet at the solar turbulence regime, but good qualitative **agreement with observations**,  
Rossby trends are robust, but the exact solar one is questioned: see *Convective conundrum*,  
[see Hanasoge+12,16, Hotta+ 23, Warnecke+ 24]

- Need for new constraints for the interior dynamics

-> Helioseismology with Rossby modes

[see Gizon+21, Bekki+22]

see *Yuto Bekki's talk this morning*

- Need to further understand the link with surface activity  
(Active Regions)

see *Hannah Schunker's talk this morning*

(Atmospheric response)

see *Evangelia Deliporanidou's talk this morning*

