Solar-like magnetic cycles in 3D turbulent global models of stars

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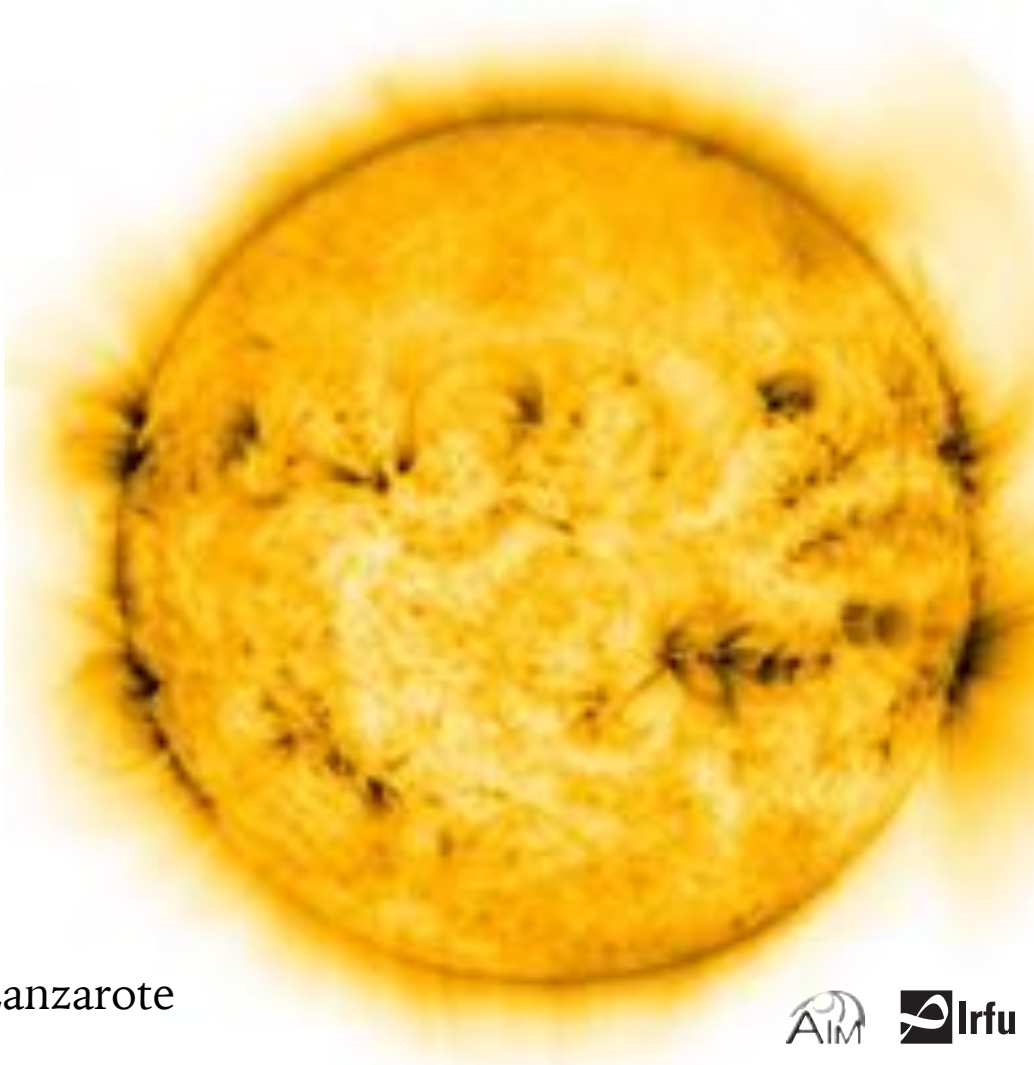
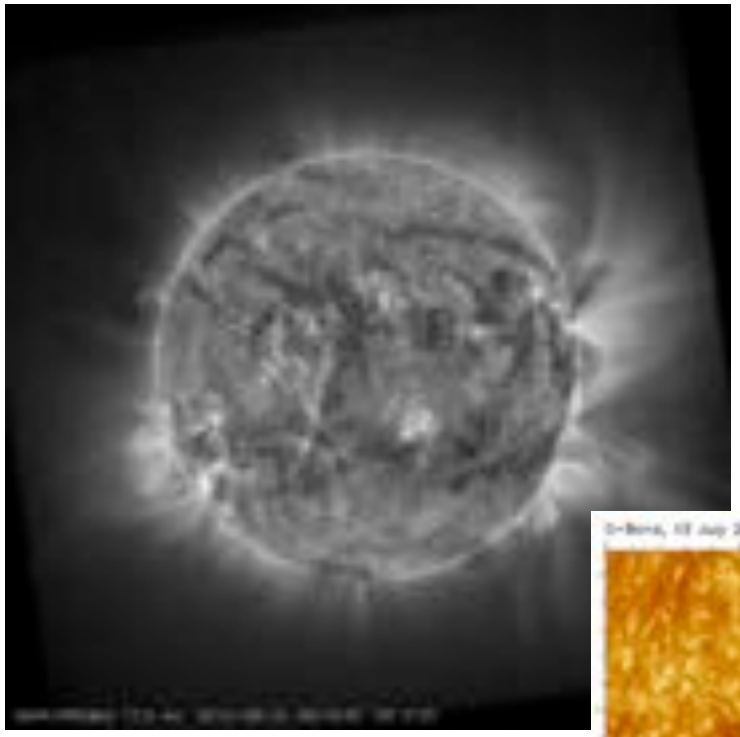
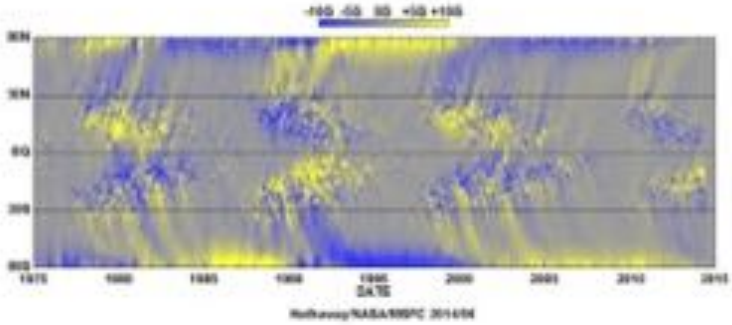


SOLARNET IV Meeting, Lanzarote

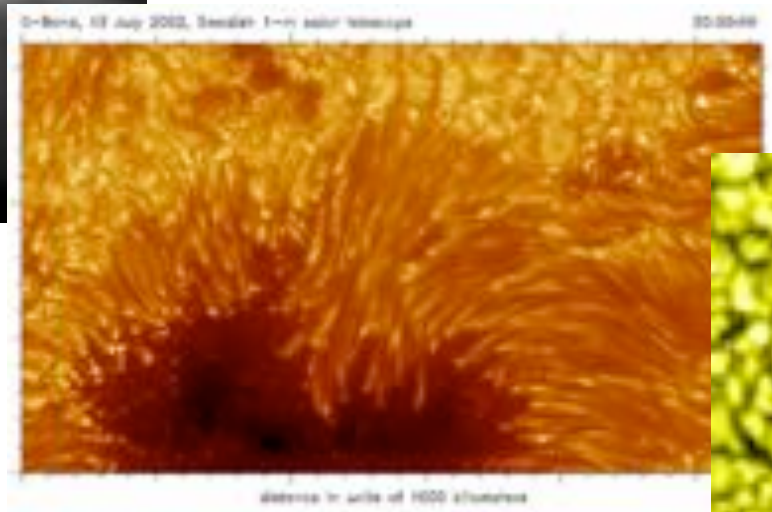
The many scales of solar magnetism

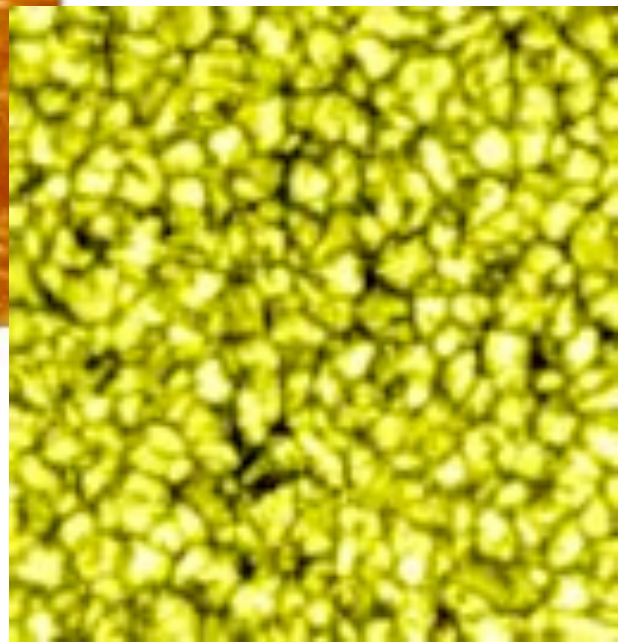


Sun
Size ~ 700 Mm
Rotation ~ month
Cycle ~ 11 years



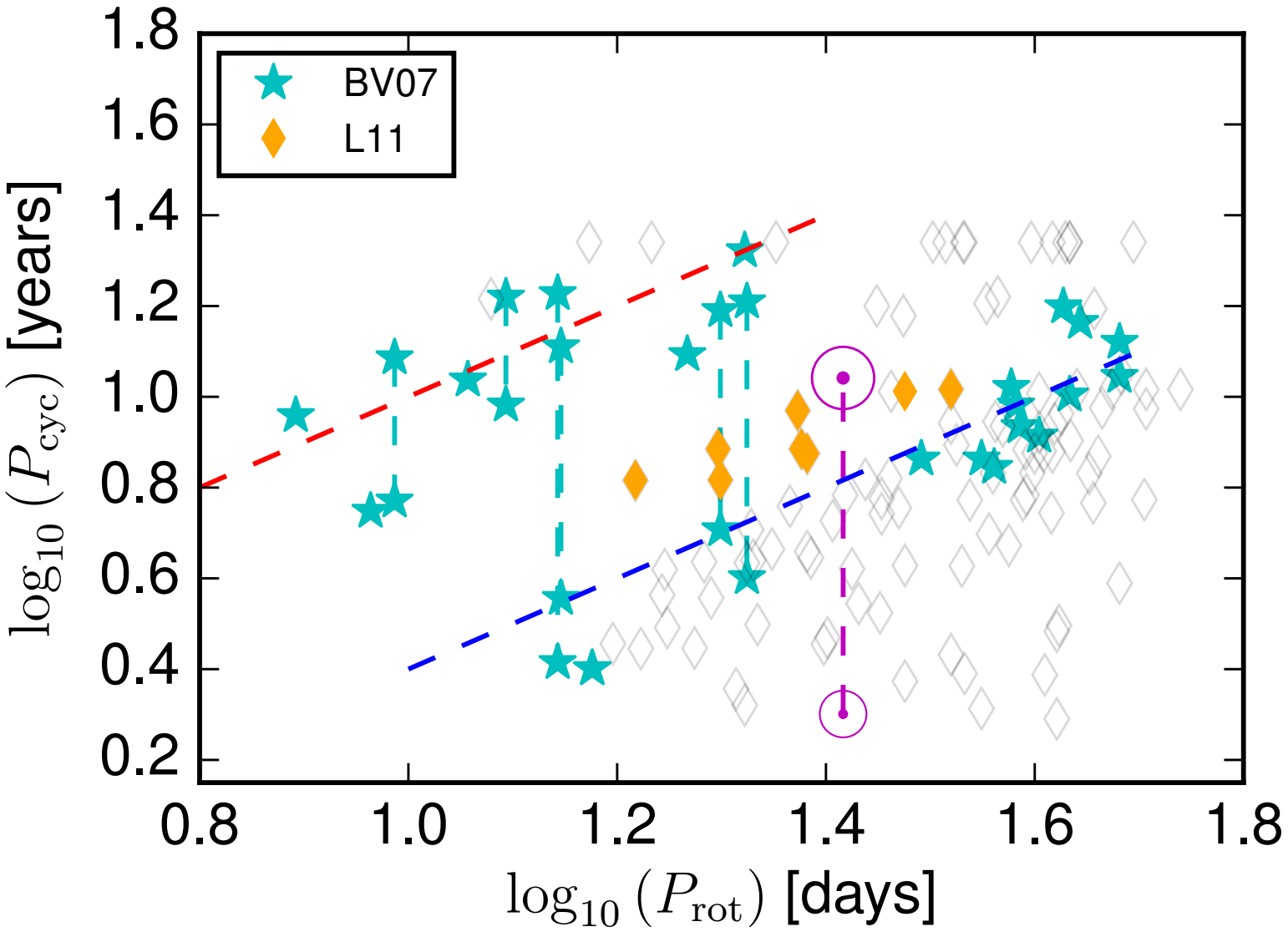
Granules
Size ~ 1 Mm
Life ~ 10 minutes





Spots
Size ~ 10 Mm
Life ~ days

The solar cycle in a stellar context

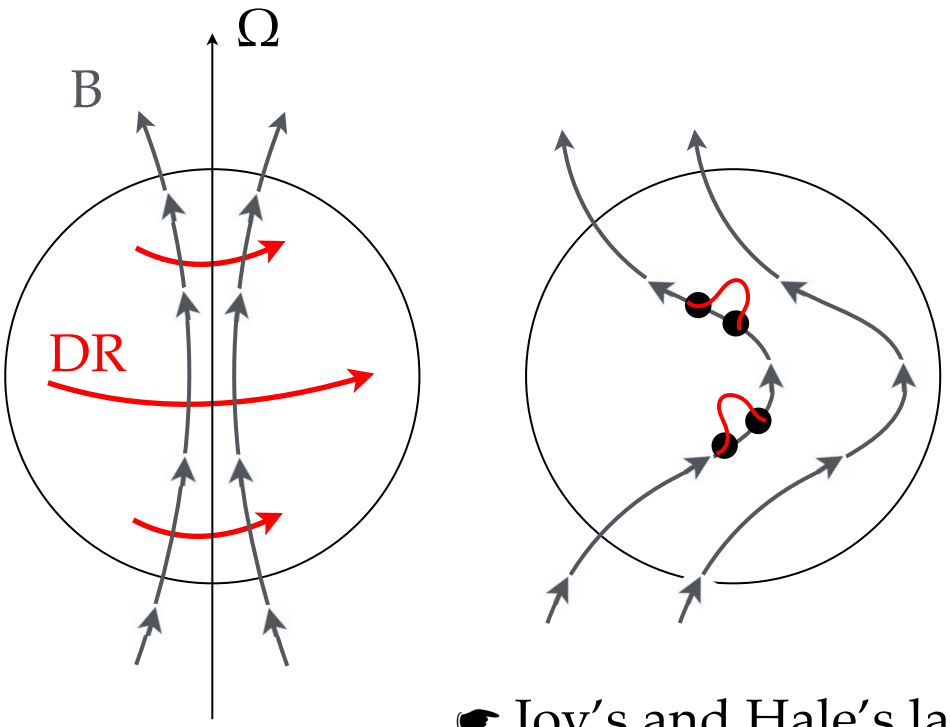


[Noyes et al. 1984; Bohm-Vitense 2007; Saar & Brandenburg 1999; Metcalfe+ 10,13,16; Do Nascimento+ 2015; Egeland+ 15;16]

Classical dynamo picture

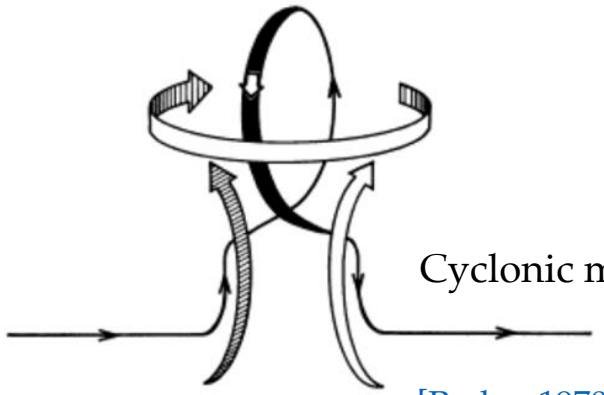
☛ *Cowling's theorem: 3D axisymmetric flows cannot sustain a dynamo action*

« Omega » effet: differential axisymmetric rotation easily convert poloidal field to toroidal field

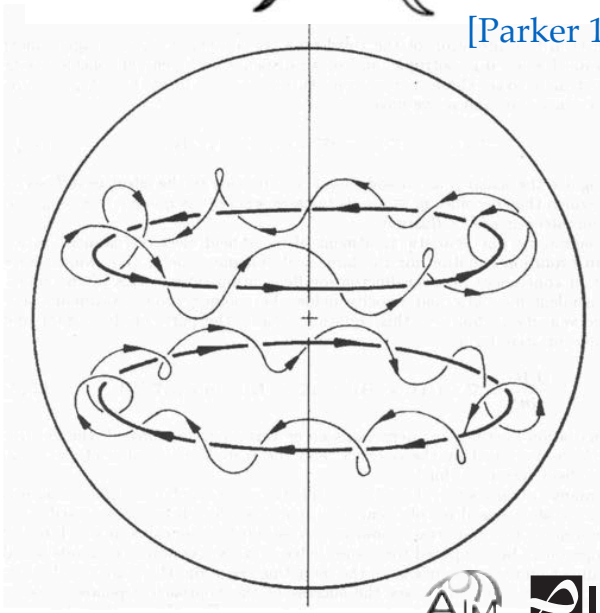


☛ Joy's and Hale's laws

Toroidal to poloidal conversion

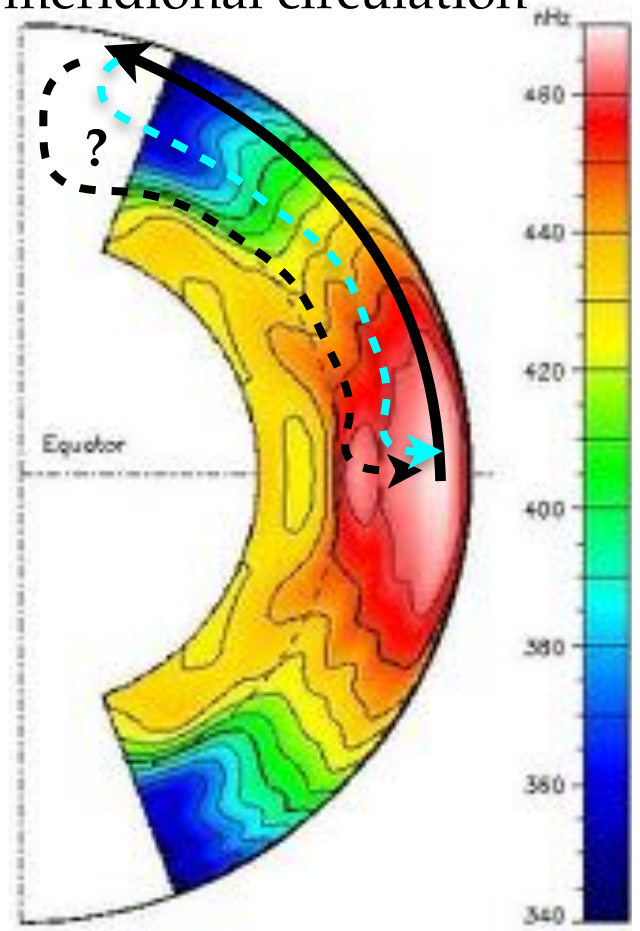


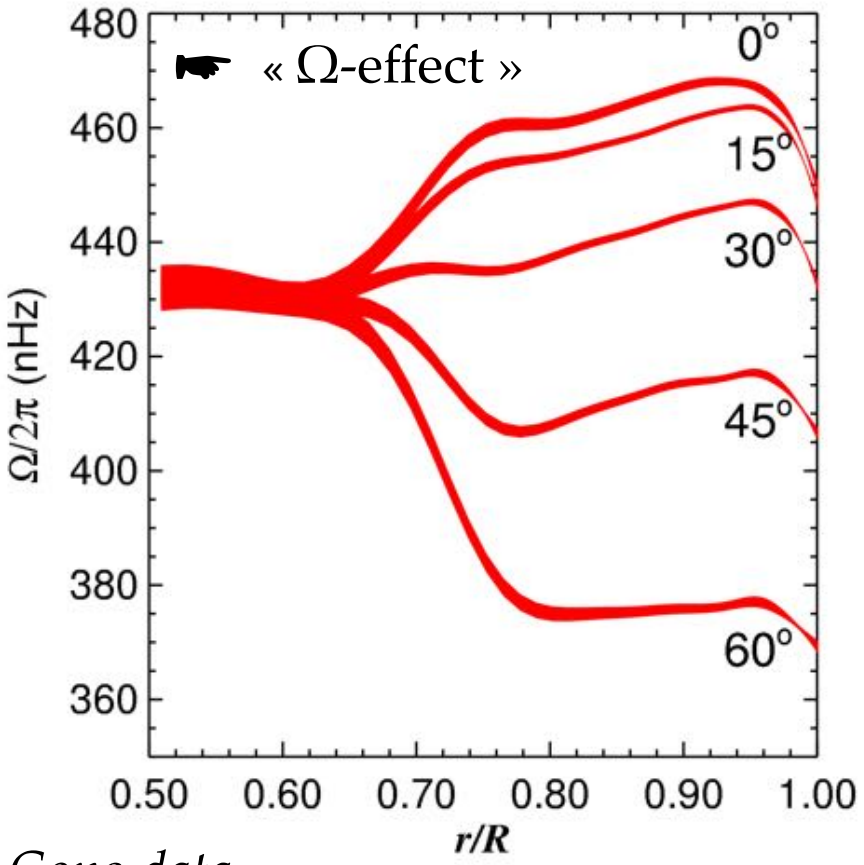
[Parker 1970, 1979]



Known ingredients of the solar dynamo

+ some meridional circulation

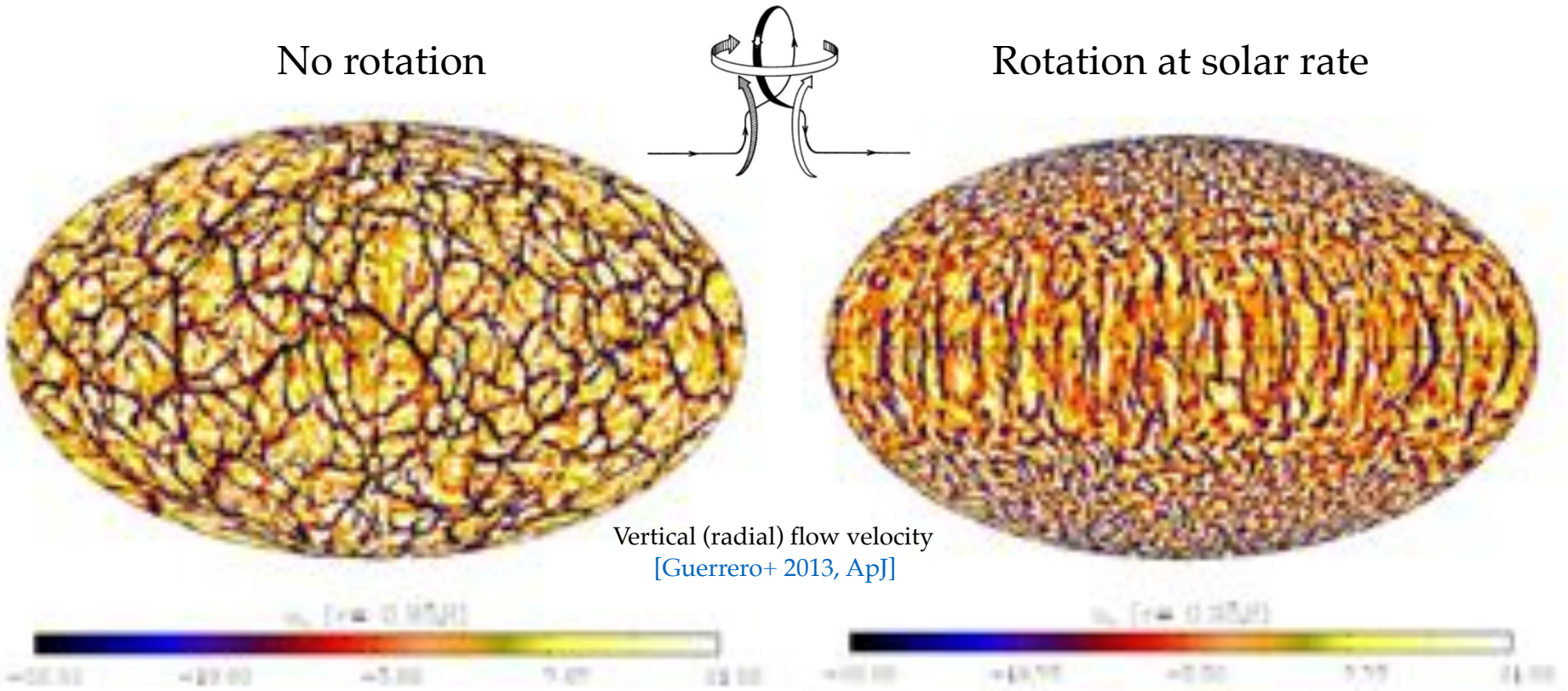




Gong data

The solar differential rotation: we know the large-scale flow structure of the solar dynamo. It is powered by **Reynolds stresses**, arising from rotationally-induced anisotropy in turbulent transport of momentum and heat

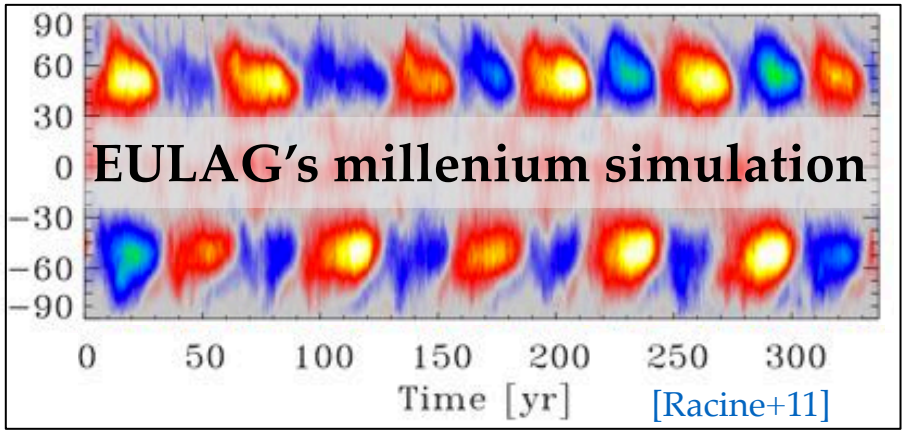
Debated ingredients of the solar dynamo



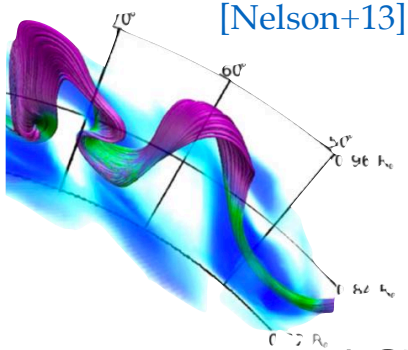
Vertical (radial) flow velocity
[Guerrero+ 2013, ApJ]

Turbulent anelastic convection under the **influence of rotation** is cyclonic and can *a priori* close the dynamo loop

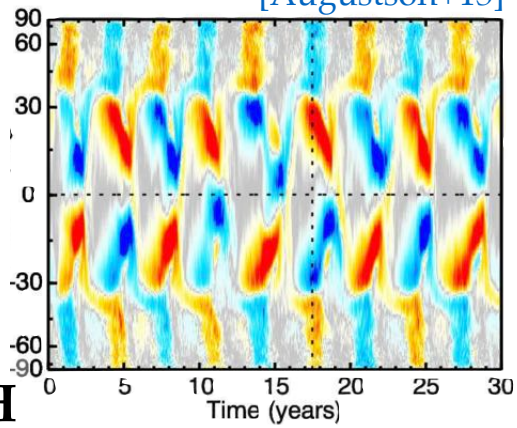
The zoo of 3D models…



[Racine+11]

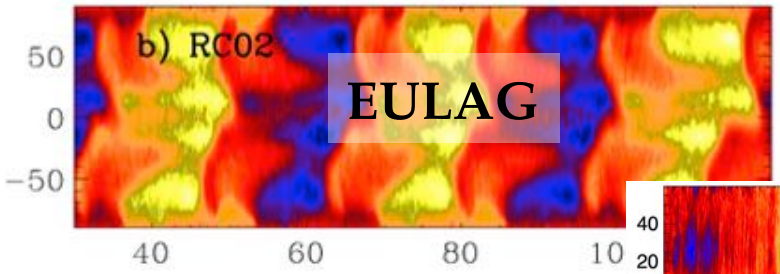

[Nelson+13]

[Augustson+15]

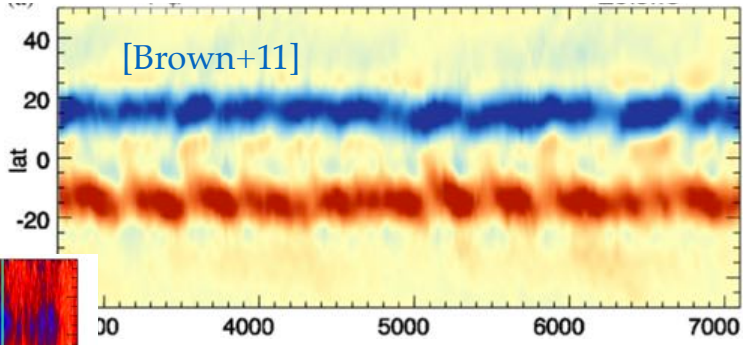


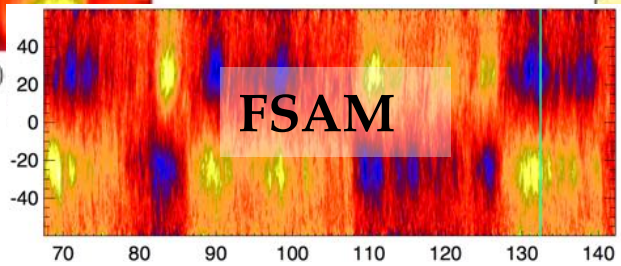
ASH

[Guerrero+16]



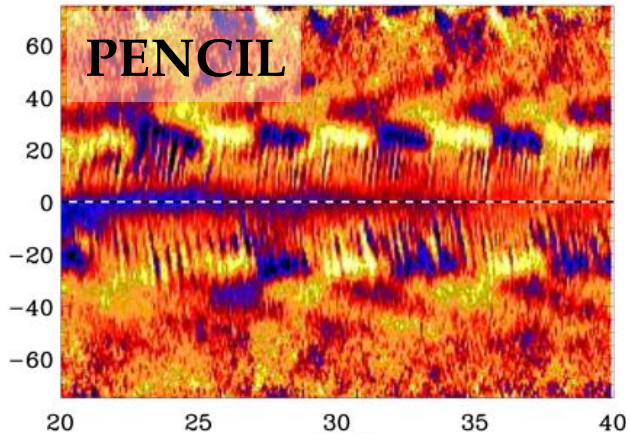
and much more…

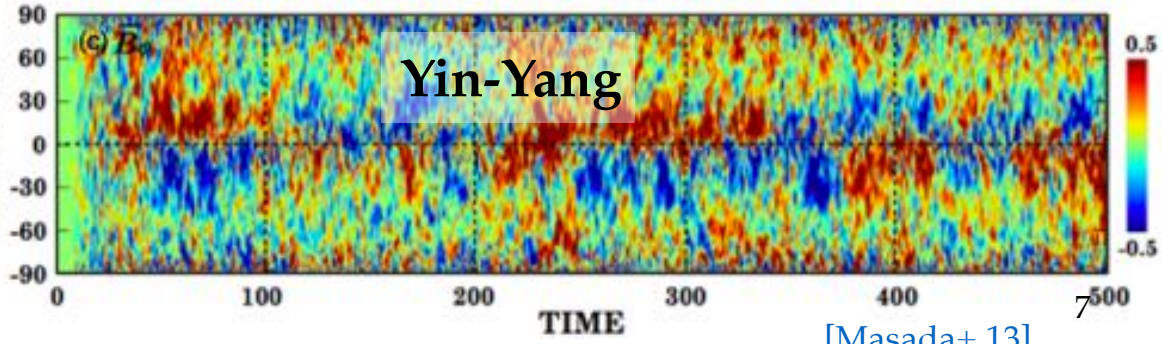




[Fan+14]

[Kapyla+12,Warnecke+14]

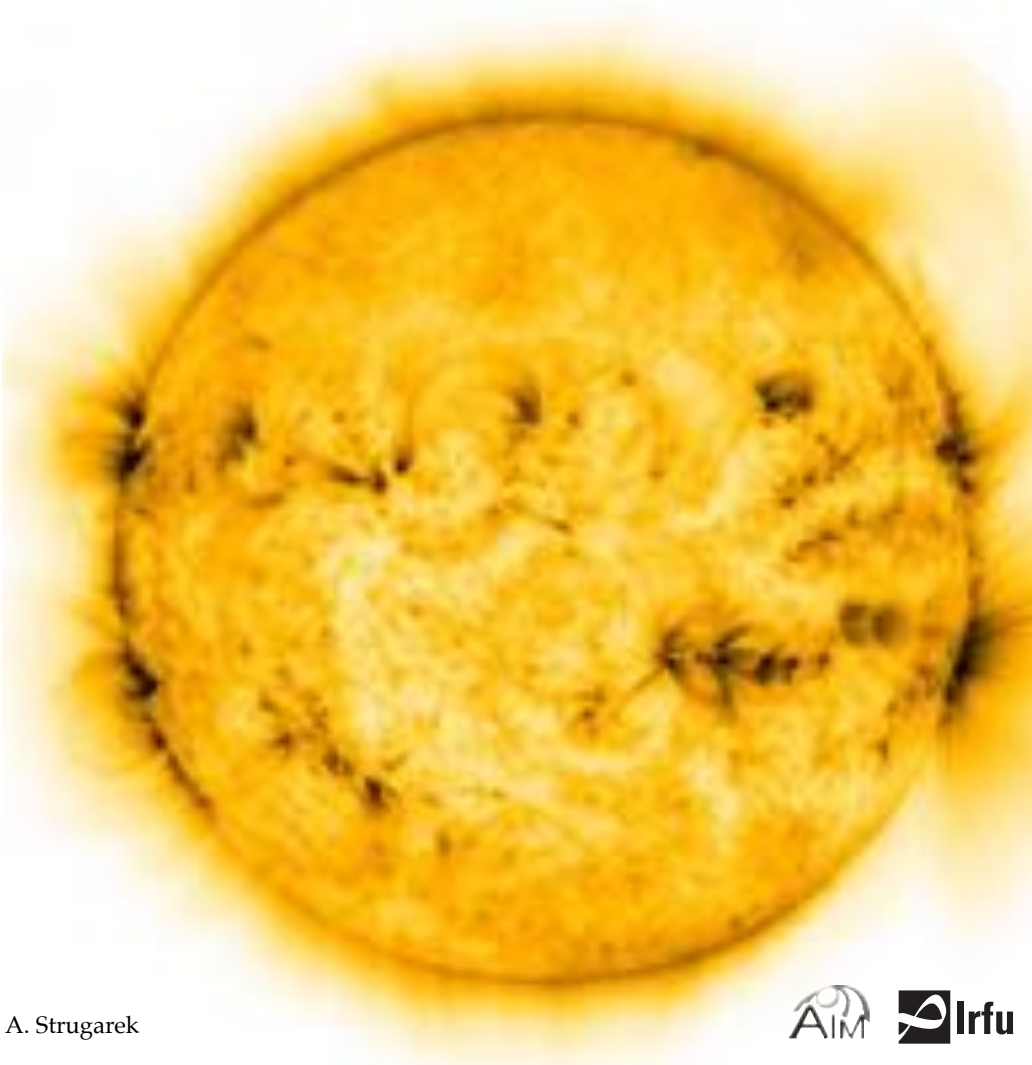




[Masada+ 13]

What sets the magnetic cycle periods in (solar-like) stars?

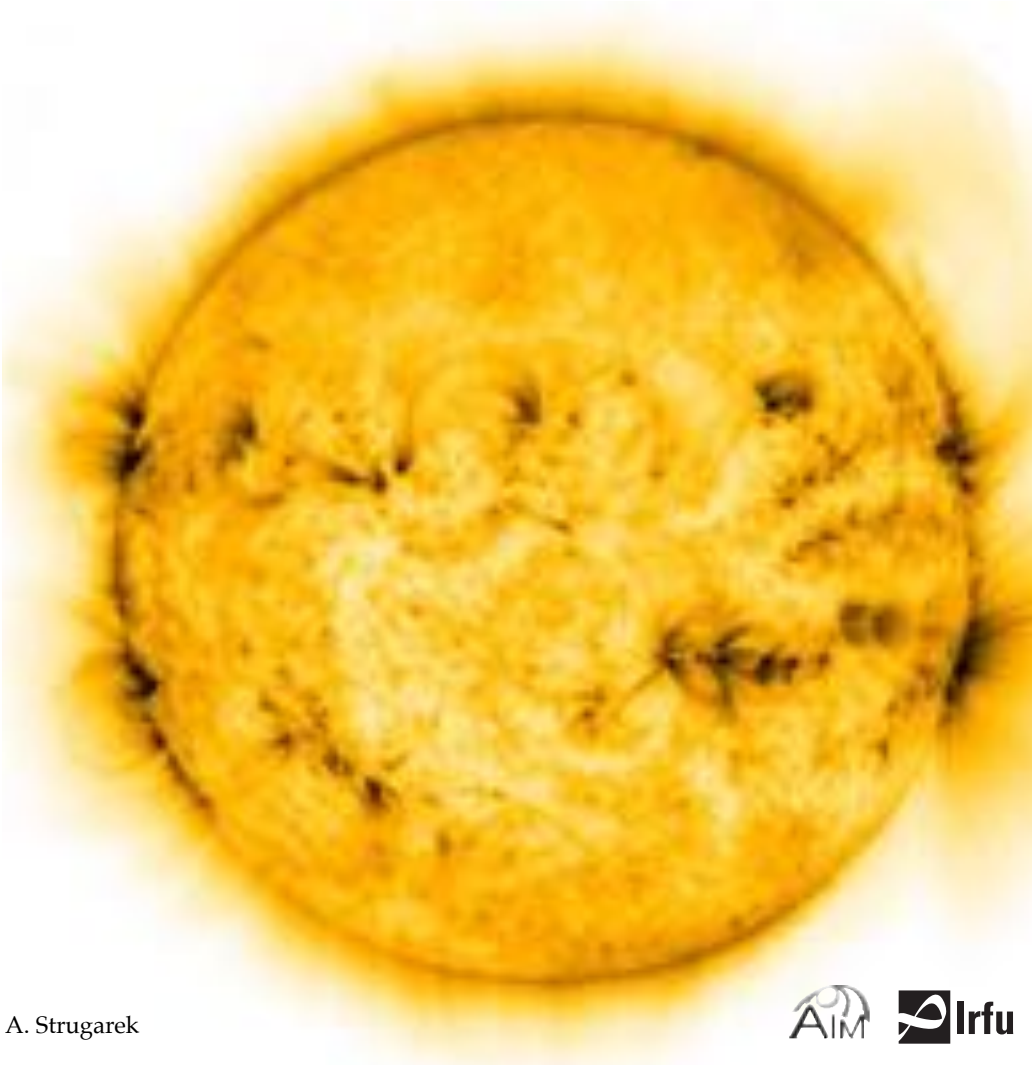
Strugarek+ 2017, submitted



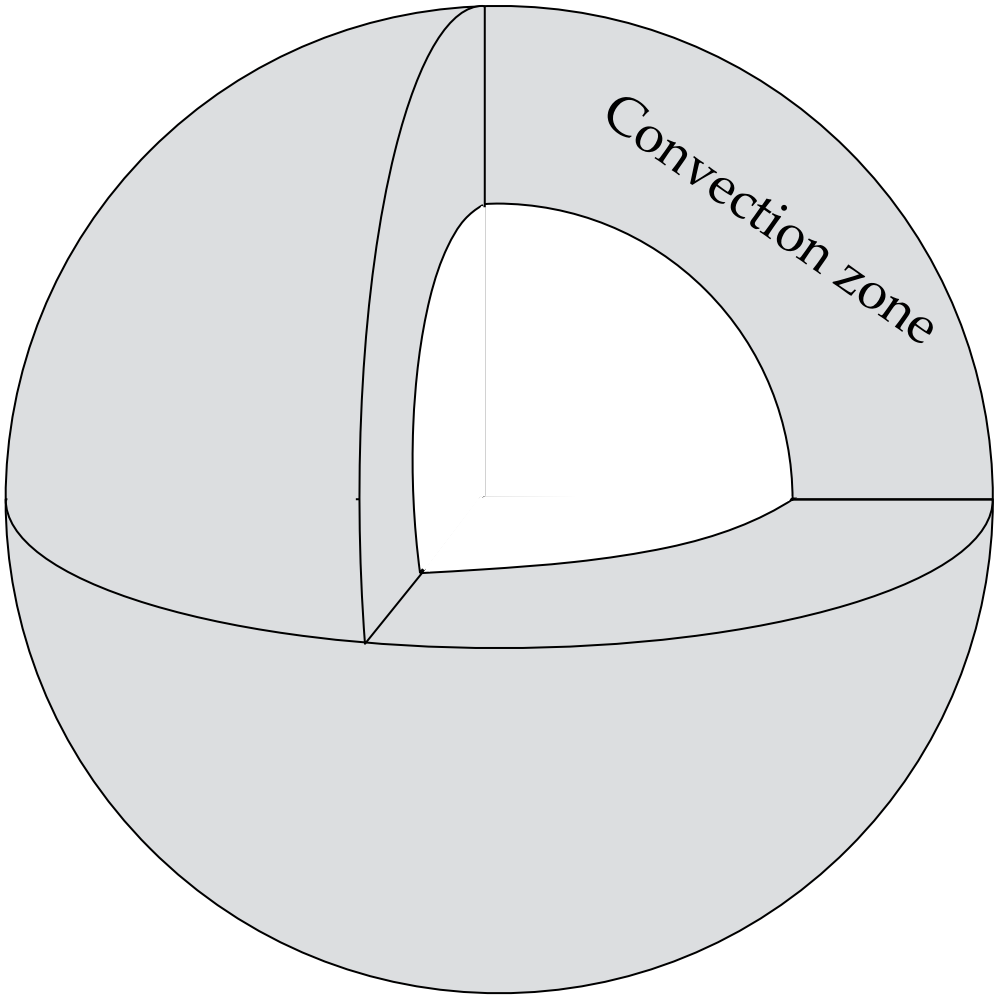
some global 3D models

What sets the magnetic cycle periods in ~~(solar-like) stars~~?

Strugarek+ 2017, submitted



Tool: the EULAG-MHD code

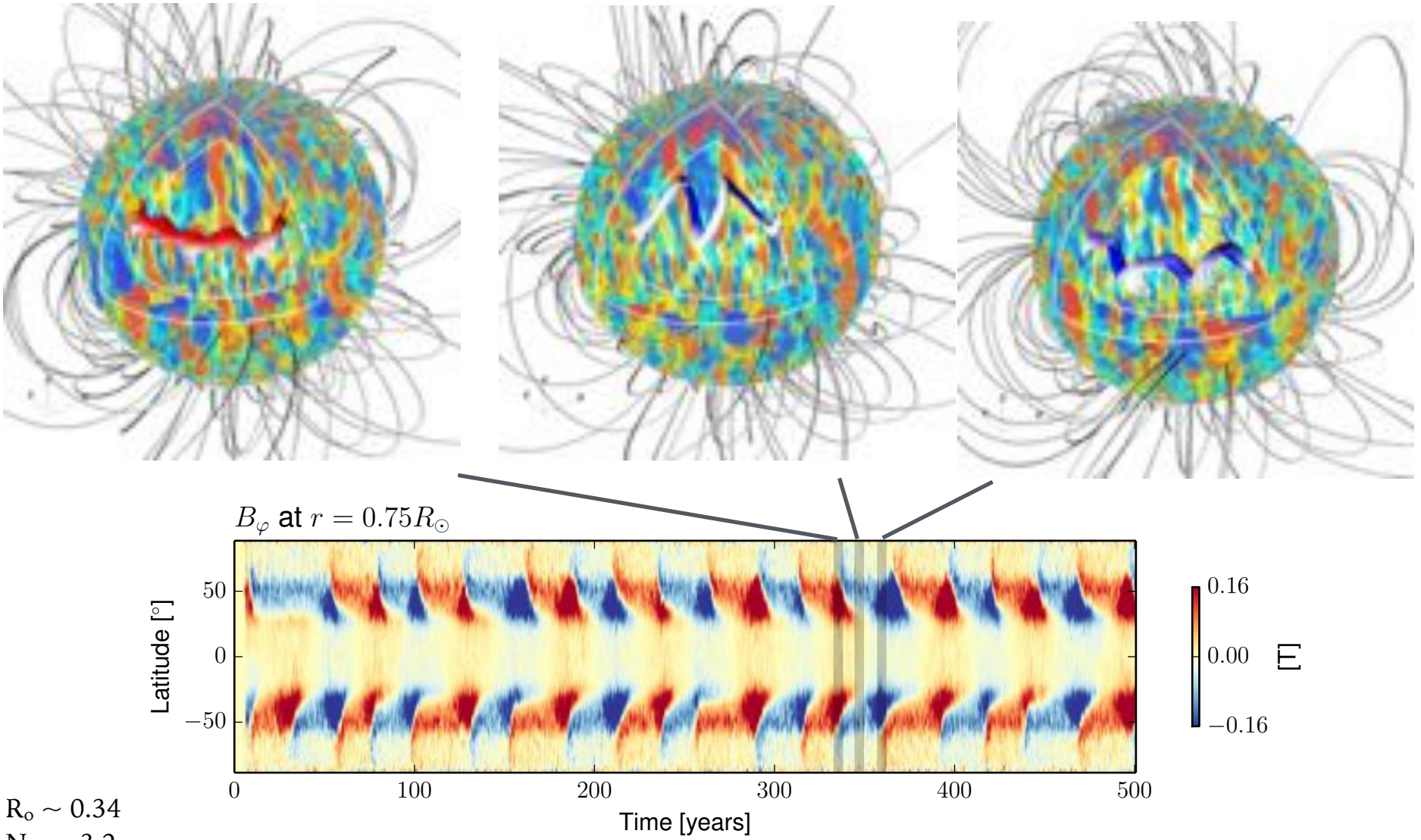


[Smolarkiewicz & Charbonneau 2013, JCP]

Core advection scheme:
MPDATA, a minimally dissipative iterative upwind NFT scheme; equivalent to a dynamical, adaptive subgrid model

Convective instability,
superadiabatic ambiant profile combined with Newtonian cooling in energy equation

Prototype cyclic dynamo in a convective enveloppe

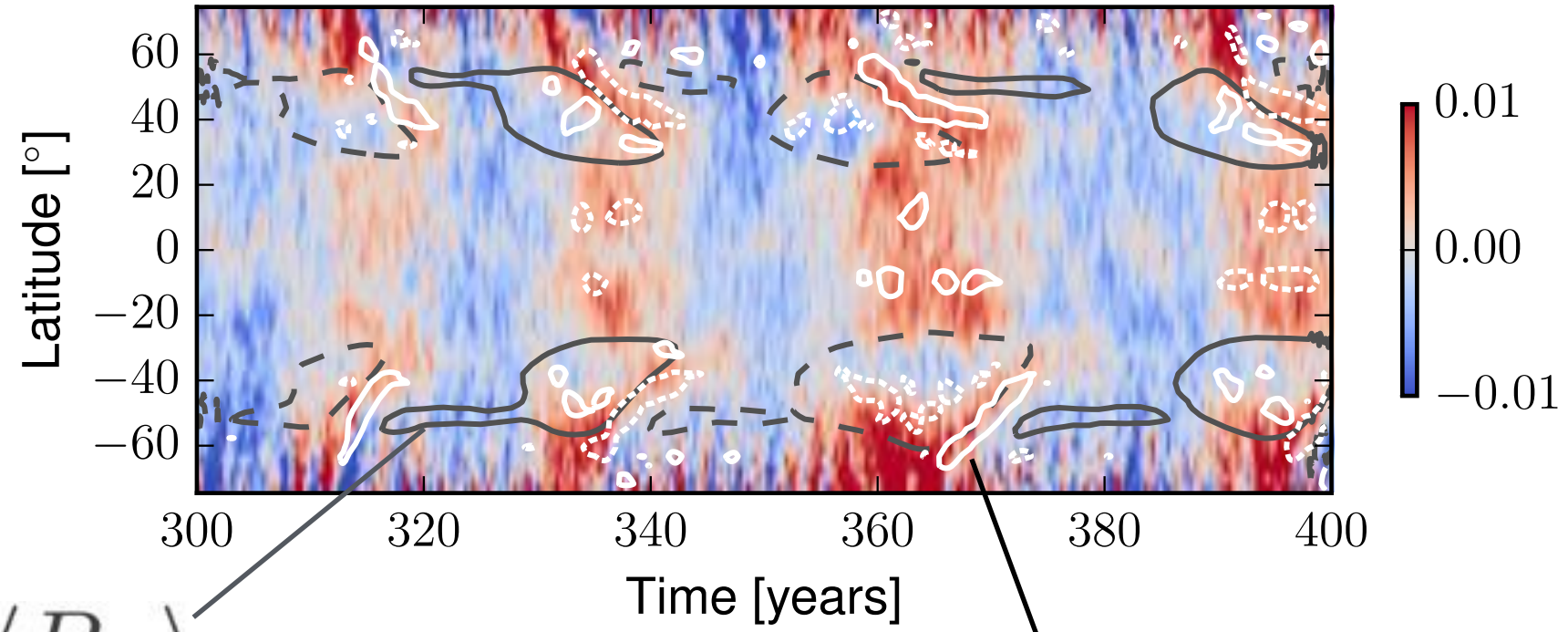


$R_o \sim 0.34$
$N_\rho = 3.2$
$\Delta S = 10^4$ erg/K/g

No stable radiative zone

Perturbations of the differential rotation drive the dynamo

$\delta\Omega = (\Omega - \langle\Omega\rangle_t) / \langle\Omega\rangle_t$ at $r = 0.75 R_\odot$

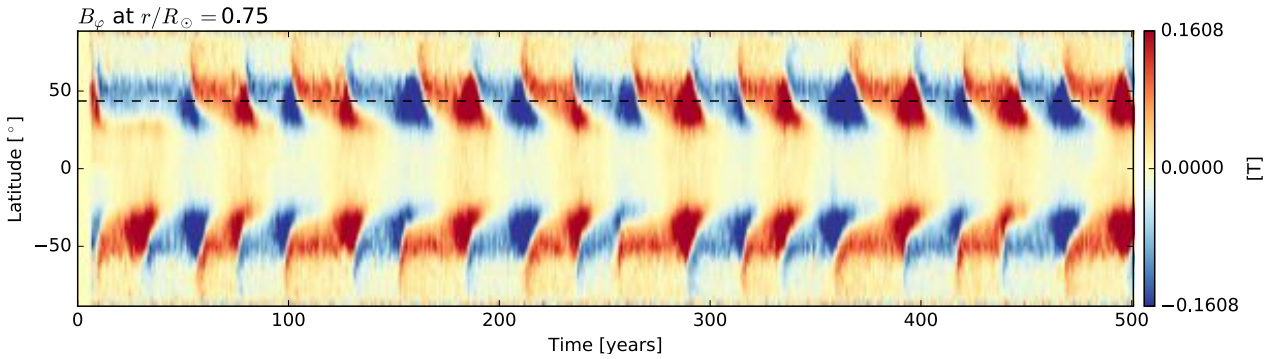


$\langle B_\varphi \rangle$

$$\partial_t \langle B_\varphi \rangle = \boldsymbol{\nabla} \times (\langle \mathbf{U}_\varphi \rangle \times \langle \mathbf{B}_{\mathrm{pol}} \rangle)|_\varphi$$

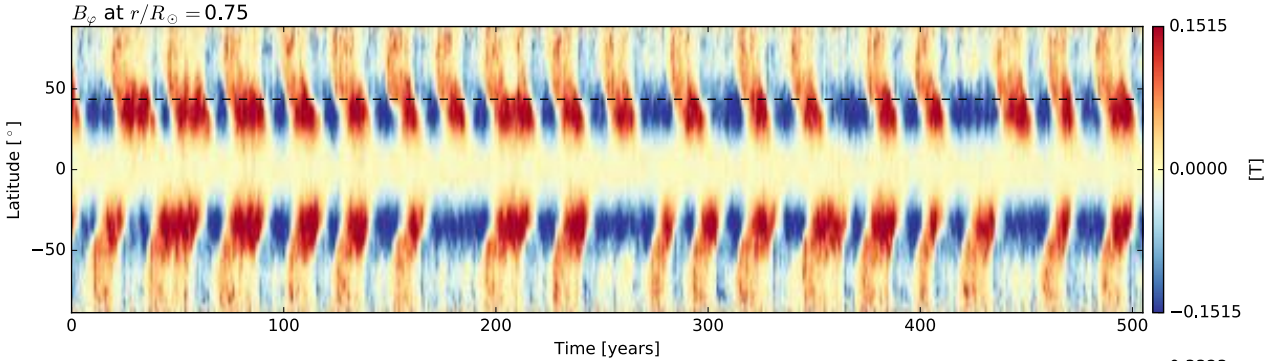
Systematic modulation of the cycle period

Ref.



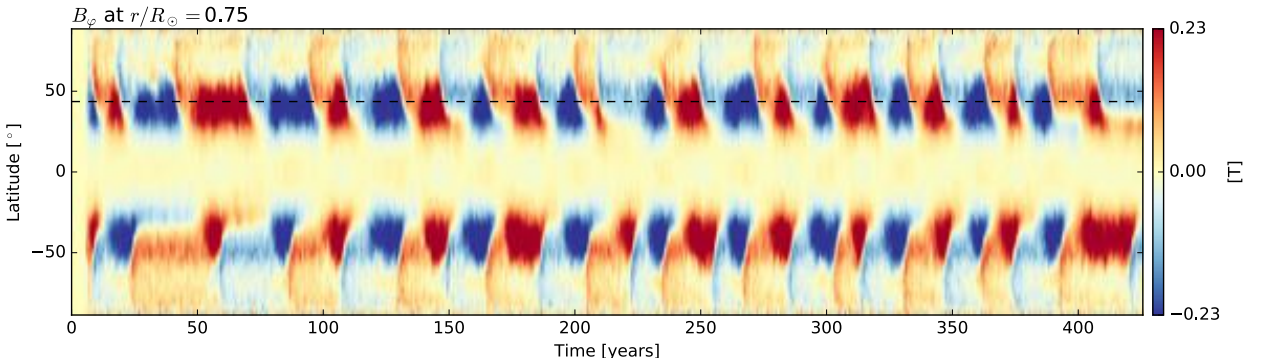
$P_{\rm cyc} = 28$ yrs

$\Omega/2$



$P_{\rm cyc} = 13$ yrs

Lum. x 2



$P_{\rm cyc} = 17$ yrs

Cycle period is inversely proportional to the Rossby number

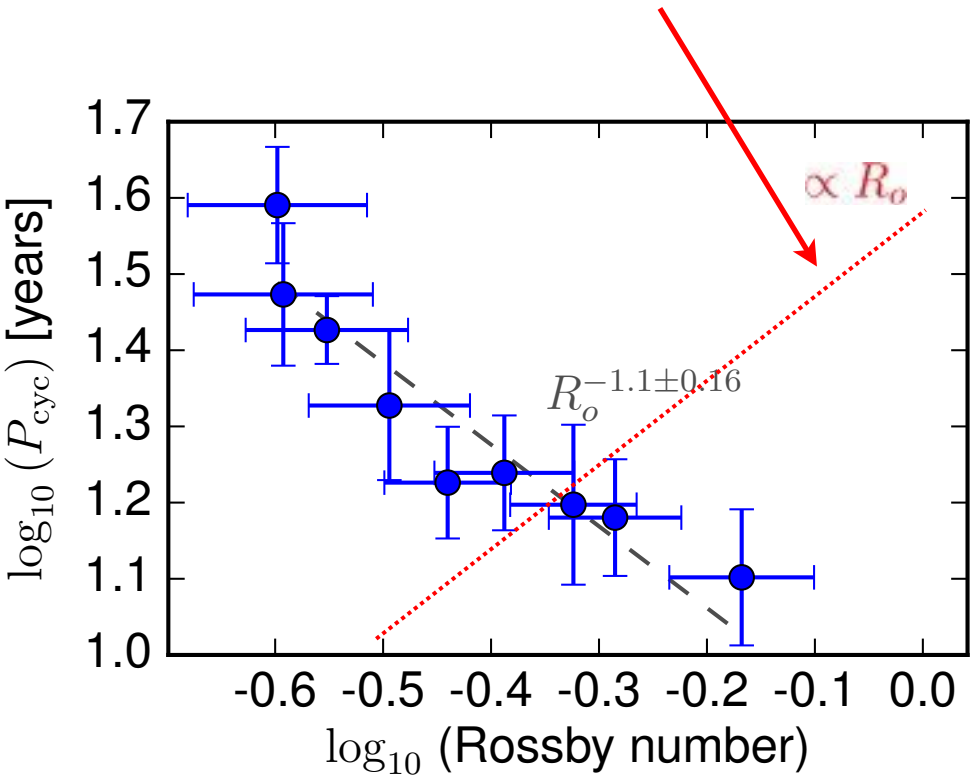
Basic linear $\alpha\Omega$ kinematic dynamo theory

Basic ingredients of stellar dynamos

- Differential rotation
- Cyclonic turbulence

'Go to' parameter is the **Rossby number**

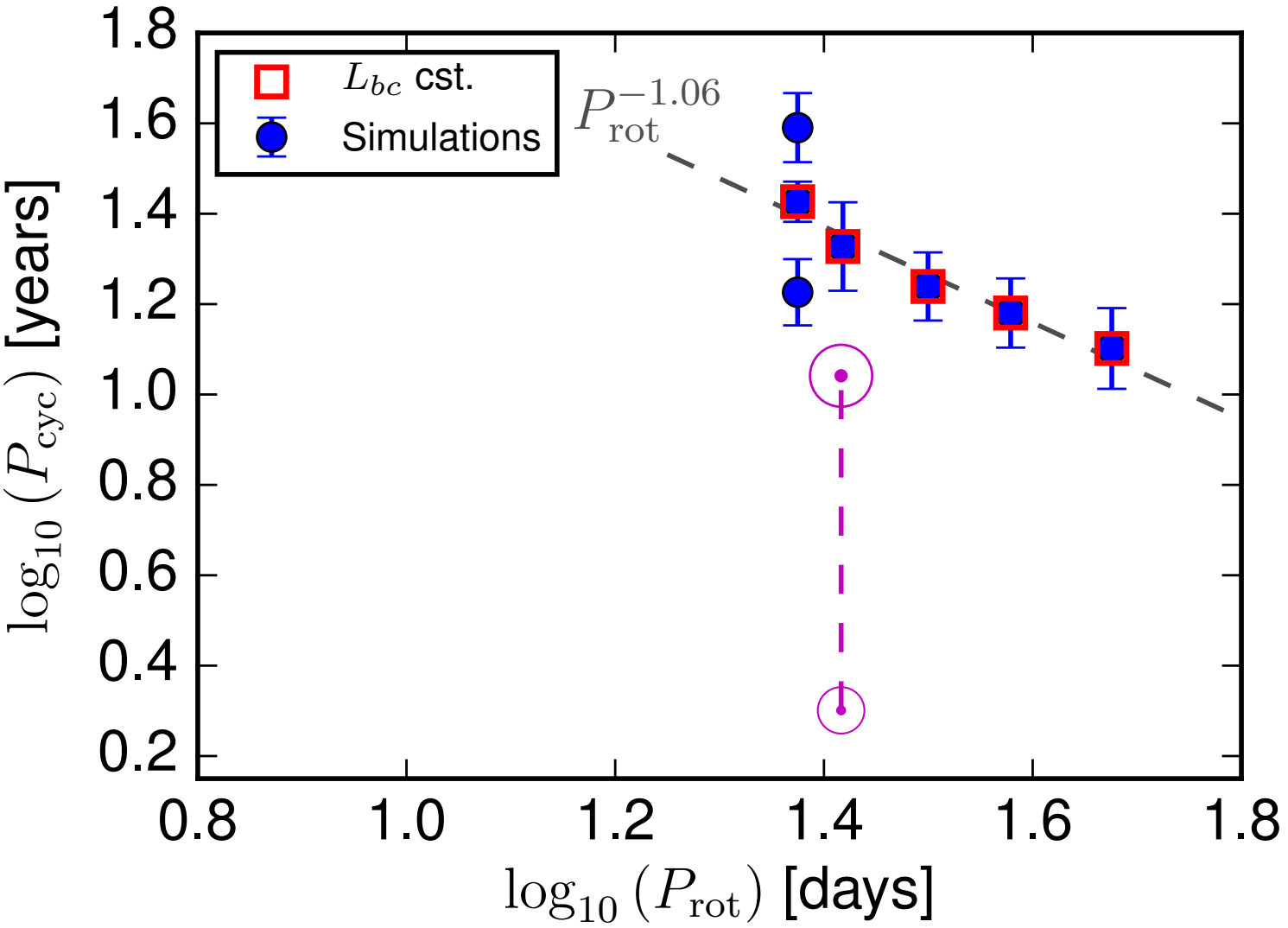
$$R_o = \frac{\text{NL Advection}}{\text{Coriolis}} \sim \frac{|\nabla \times \mathbf{U}|}{2\Omega_\star}$$



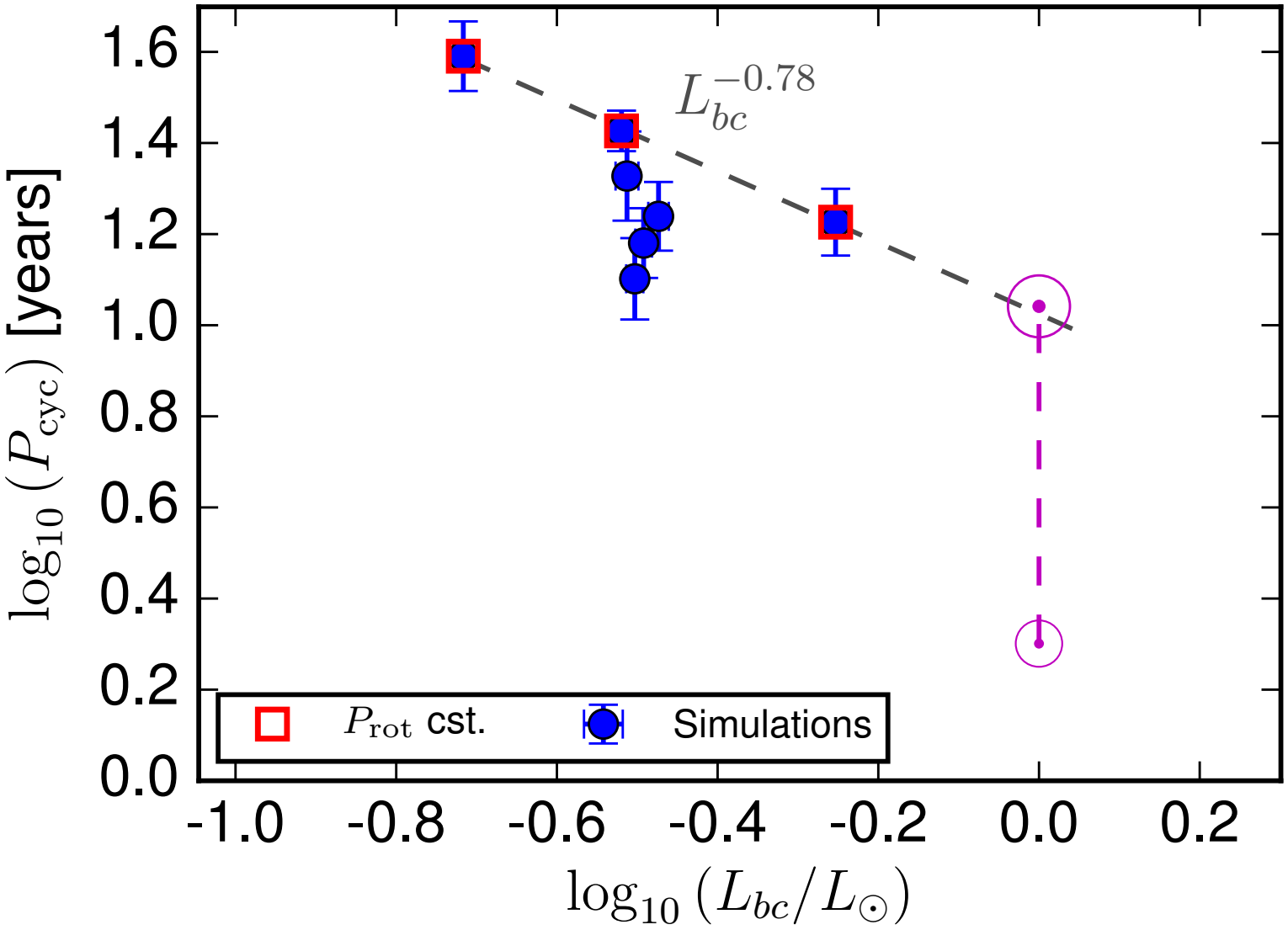
Fundamentally non-linear convective dynamo: not a classical dynamo wave

How does this relate to the Sun?

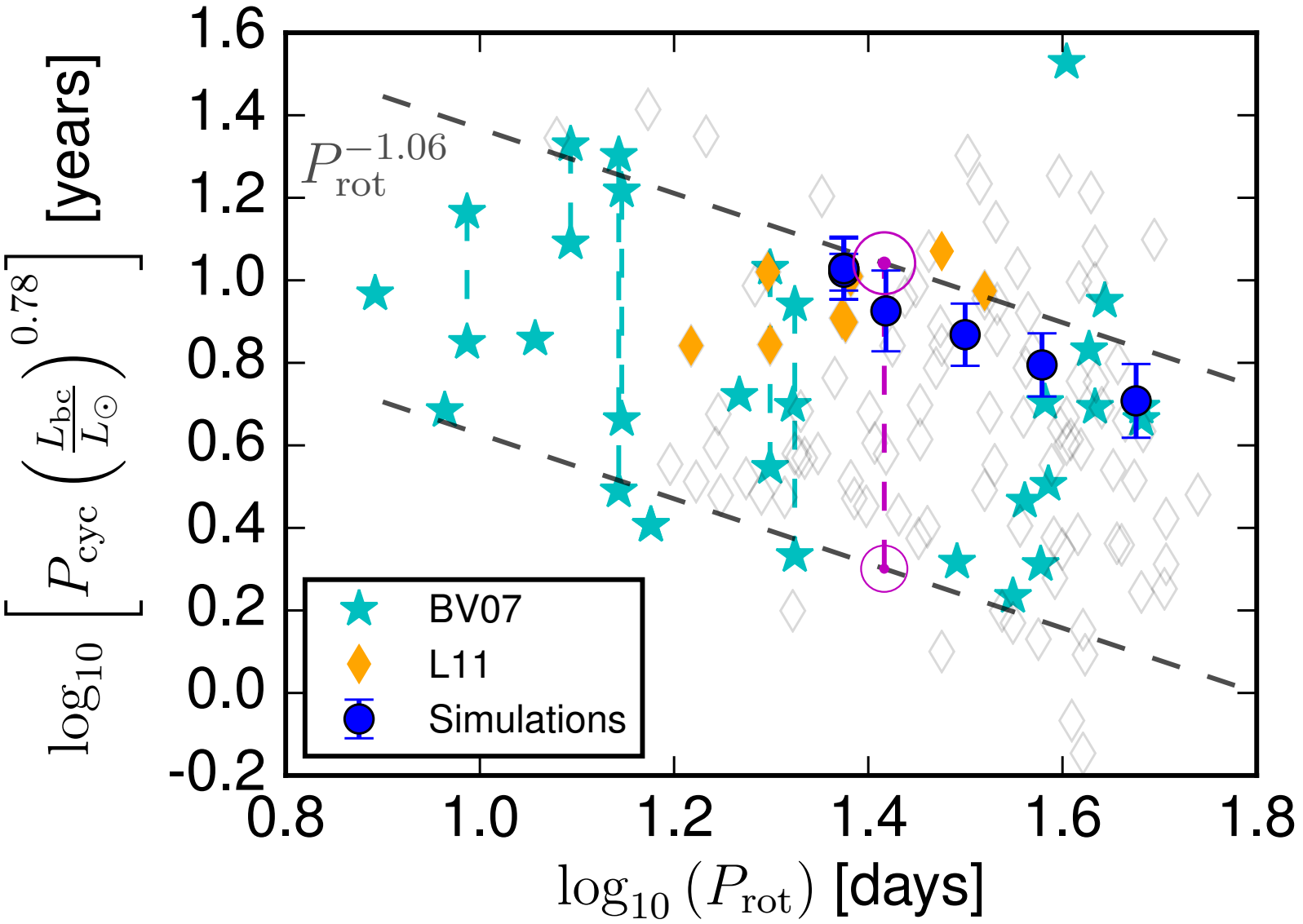
Cycle period — Rotation period diagram



Cycle period — Luminosity diagram



Cycle period parametrization in the stellar context



Conclusions

Global, non-linear 3D turbulent simulations have been very useful in the past decade to refine our understanding of the dynamics of magnetized stellar convection zones

Such simulations produced a **large variety of solutions** over the past decade: l**arge-scale field self-organization**, **reversals**, and **magnetic cycles.**

New result: a non-linear dynamo producing a **stable cycles**, with **a period varying systematically with luminosity and rotation period**, **agreeing with the solar cycle period**. It suggests a new paradigm with the **cycle period proportional to the inverse of the Rossby number.**

All the simulations worldwide are today still very far from ***stellar turbulent regime…***

Thank you for your attention