Magnetic cycles of the Sun and solar-type stars

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With P. Beaudoin, P. Charbonneau, A.S. Brun, J.D. do Nascimento Jr.

Outline

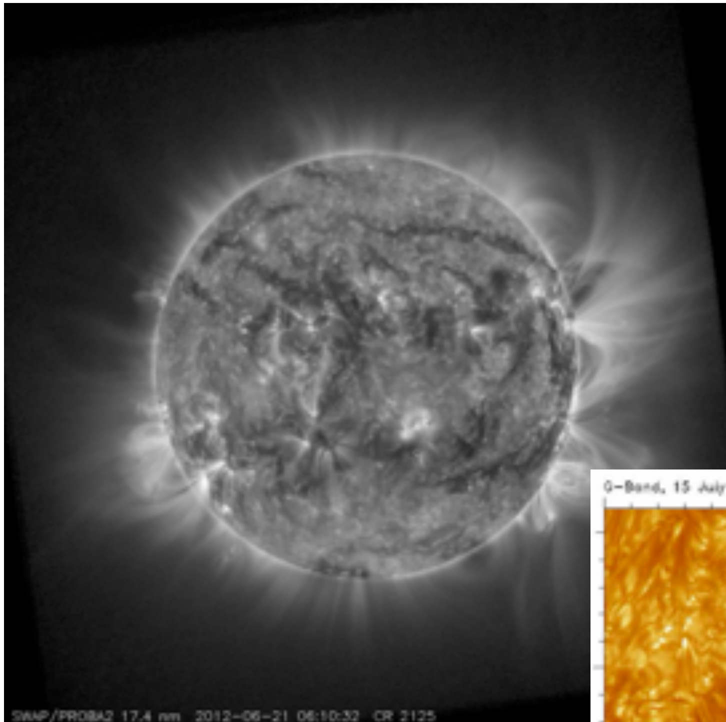
I. Cycles in magnetized stars: observations and theories

- From the solar magnetic cycle to stellar magnetic cycles
- Dynamo theory for stellar magnetic cycles

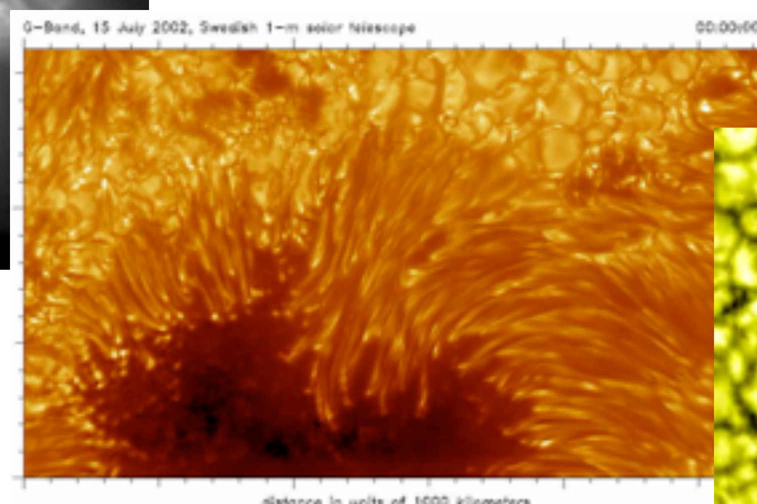
II. Ab-initio modelling of stellar magnetic cycles

- Understanding the basic ingredients of stellar dynamo:
    - Large-scale flows and differential rotation
    - Turbulent electro-motive force
- Cyclic dynamo in 3D models: recent progress

The many scales of solar magnetism

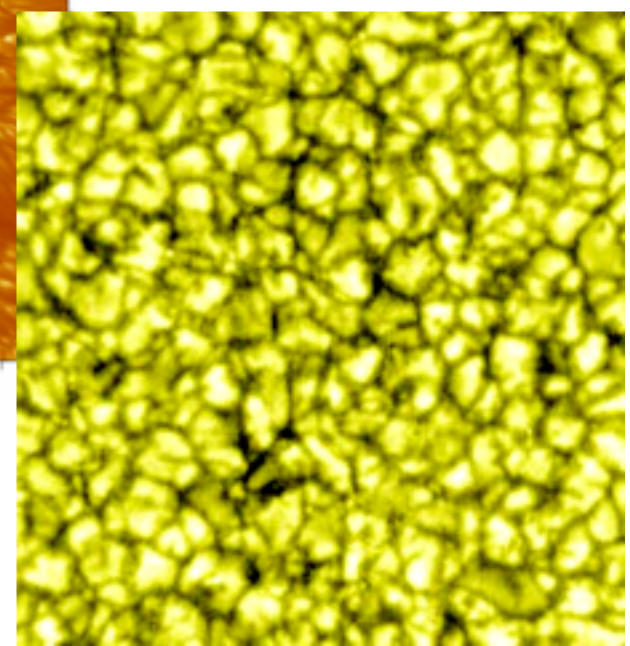


Sun
Size ~ 700 Mm
Rotation ~ month



Spots
Size ~ 10 Mm
Life ~ days

Granules
Size ~ 1 Mm
Life ~ 10 minutes



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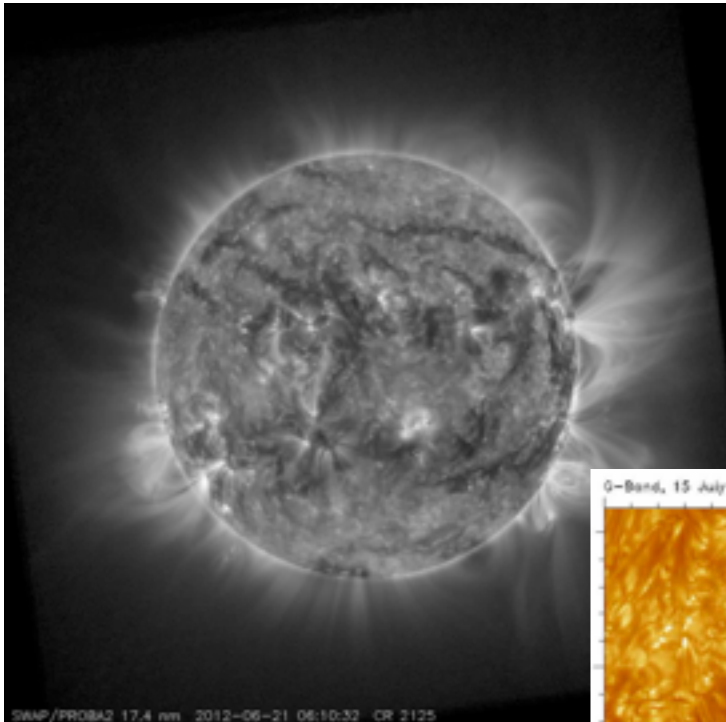

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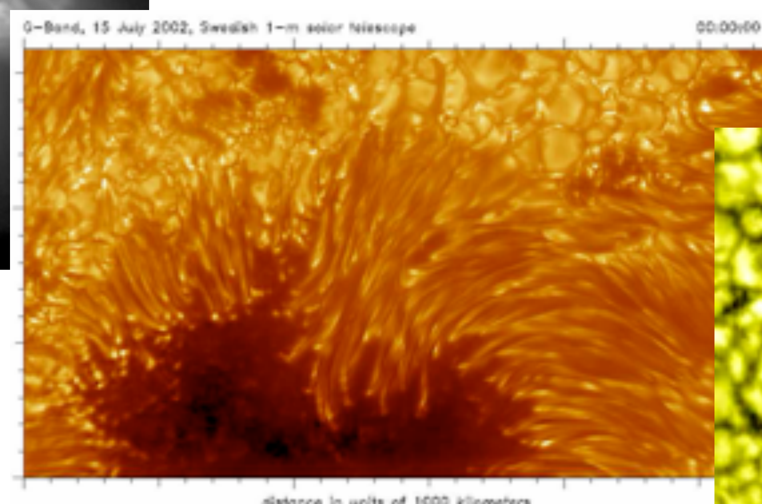
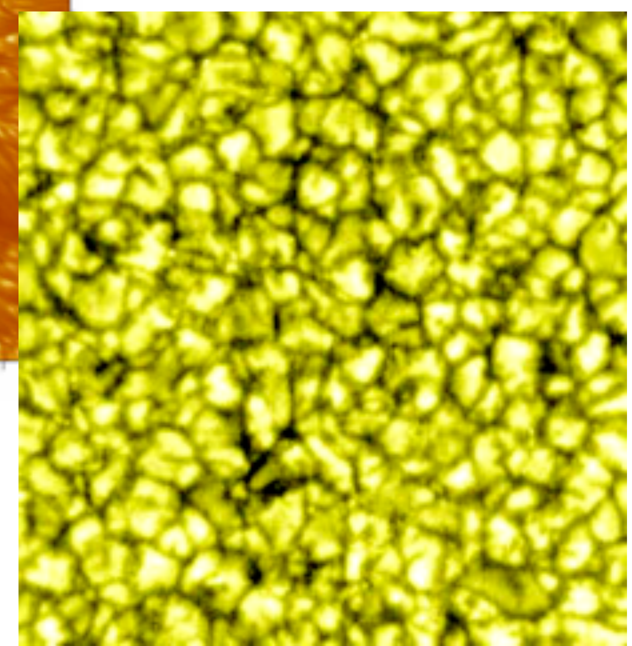
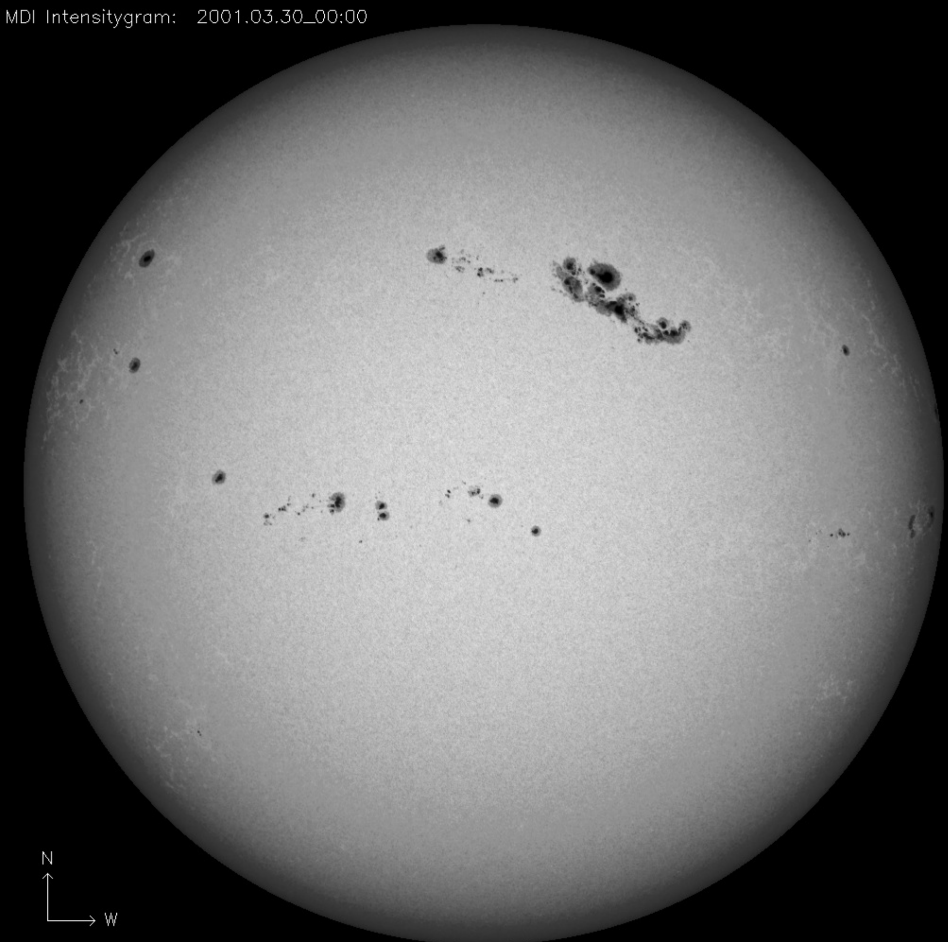


Granules
Size ~ 1 Mm
Life ~ 10 minutes

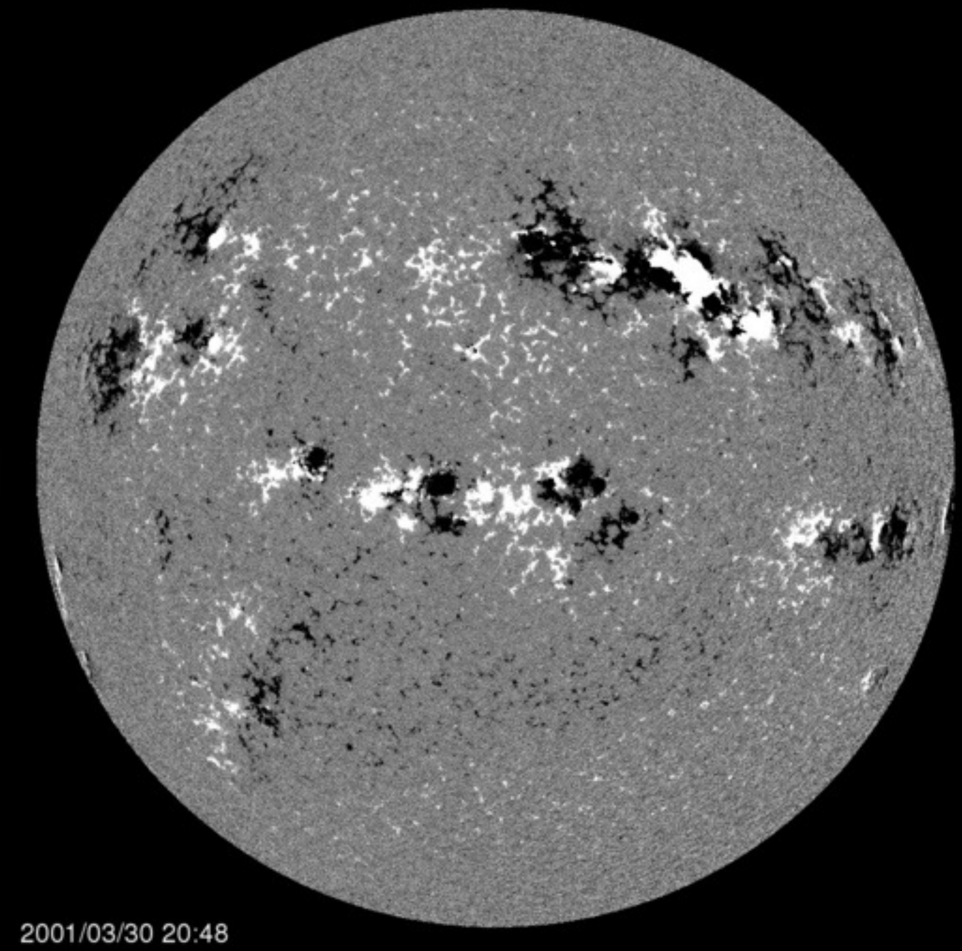


Spots
Size ~ 10 Mm
Life ~ days

Sunspots and their magnetic origin

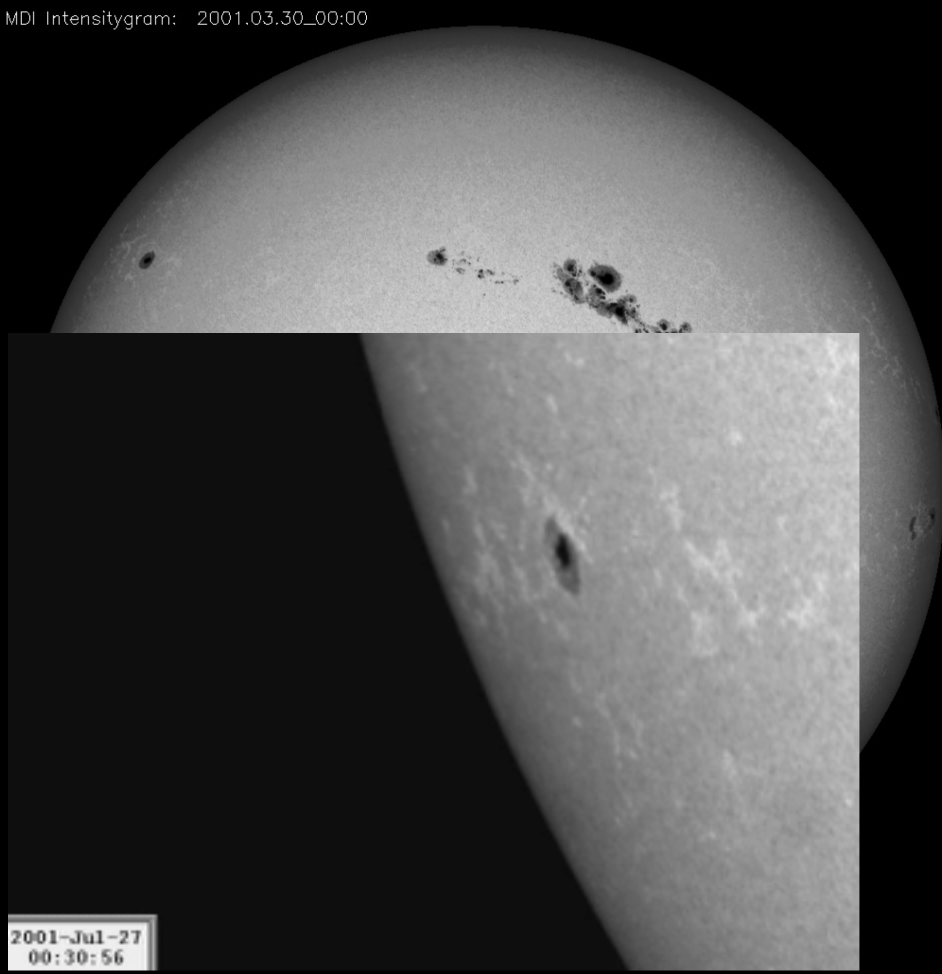


2001, maximum activity



Magnetogram

Sunspots and their magnetic origin



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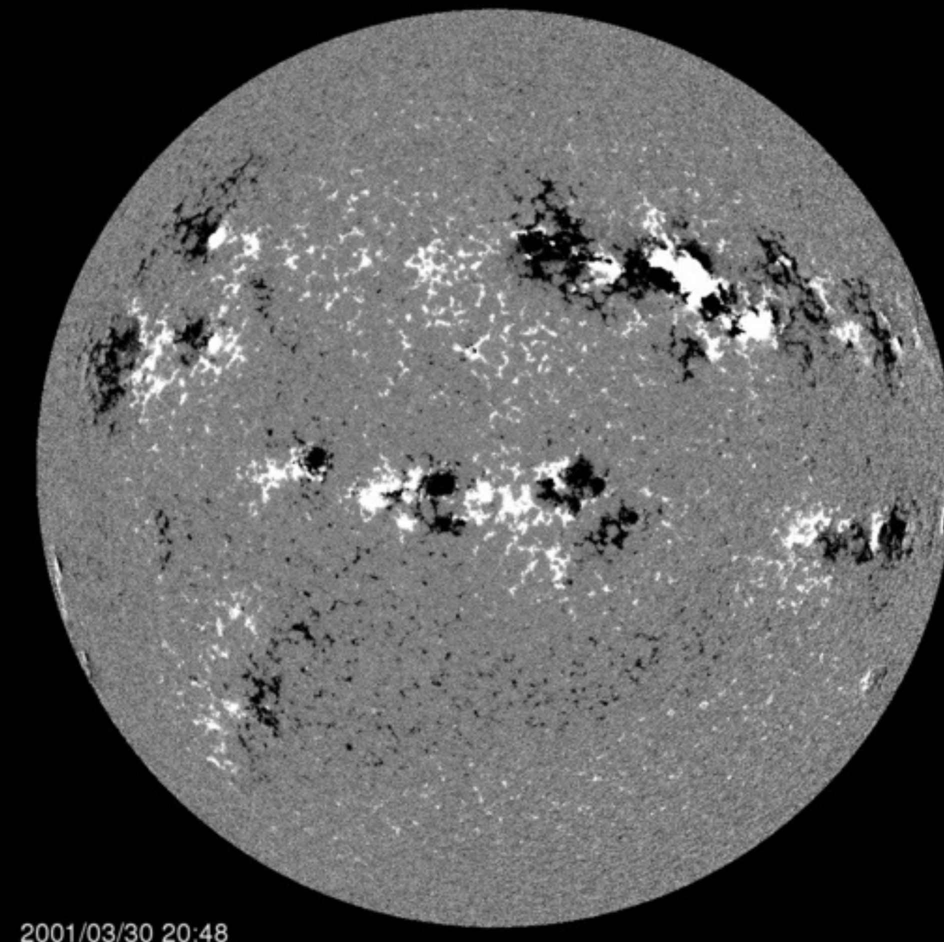
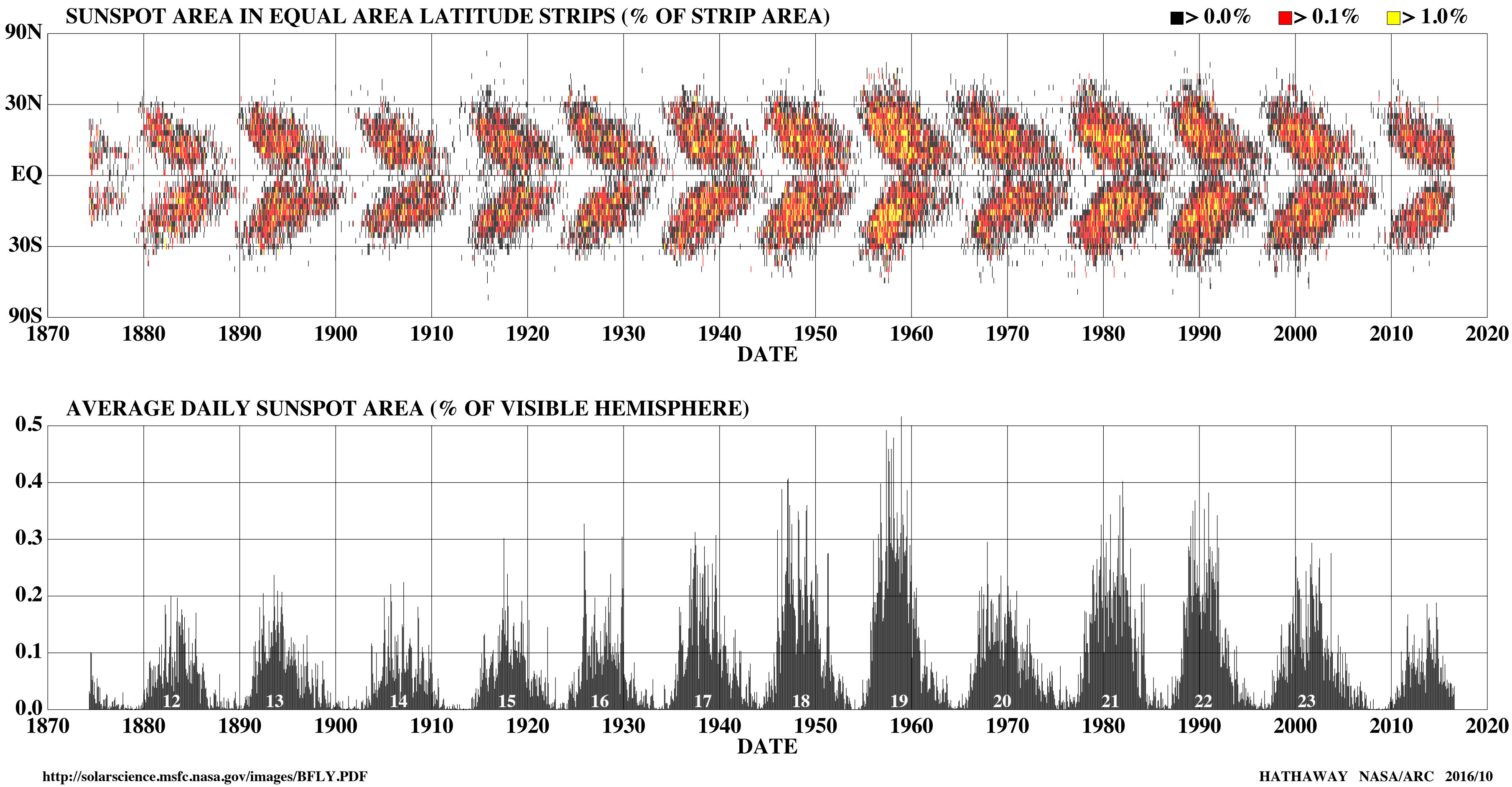
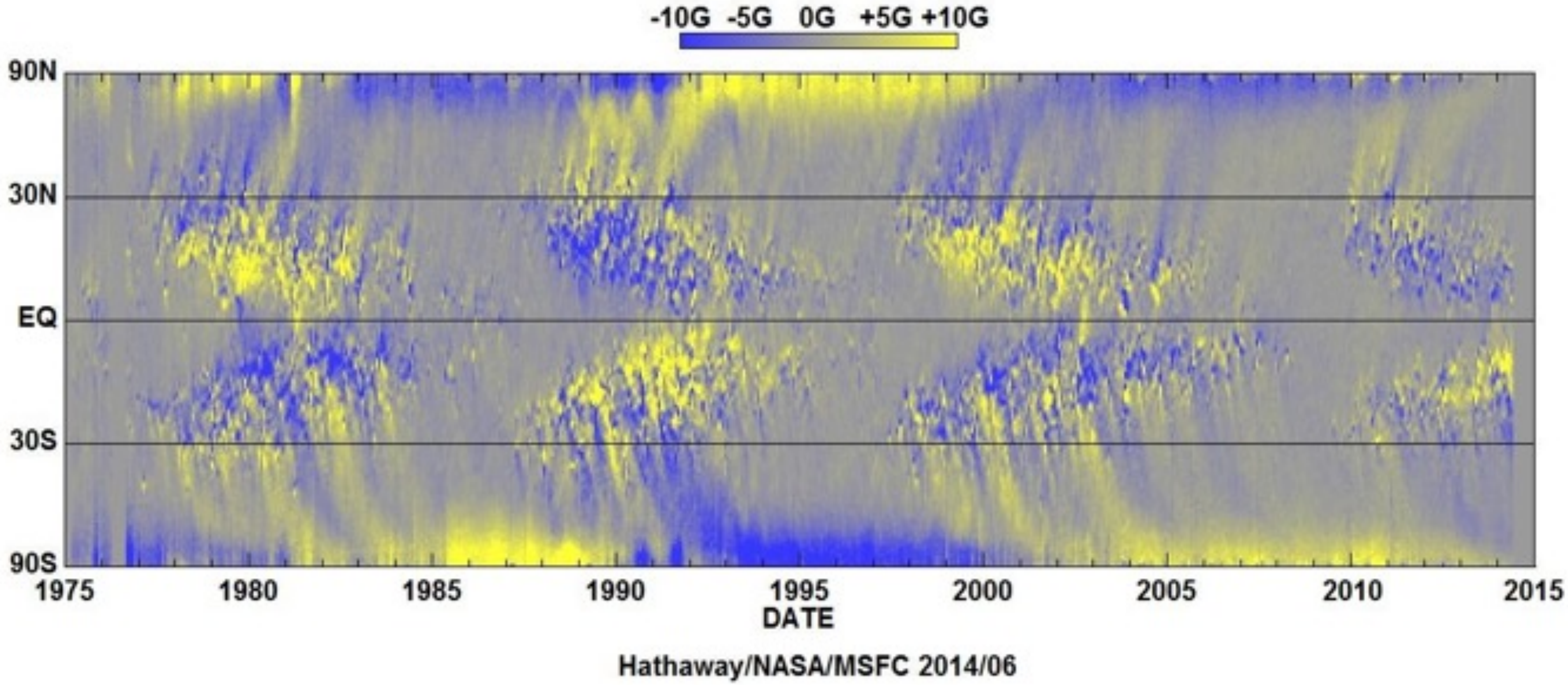


Magnetogram

The solar magnetic cycle: butterfly diagram



The solar magnetic cycle as seen from the surface mag. field



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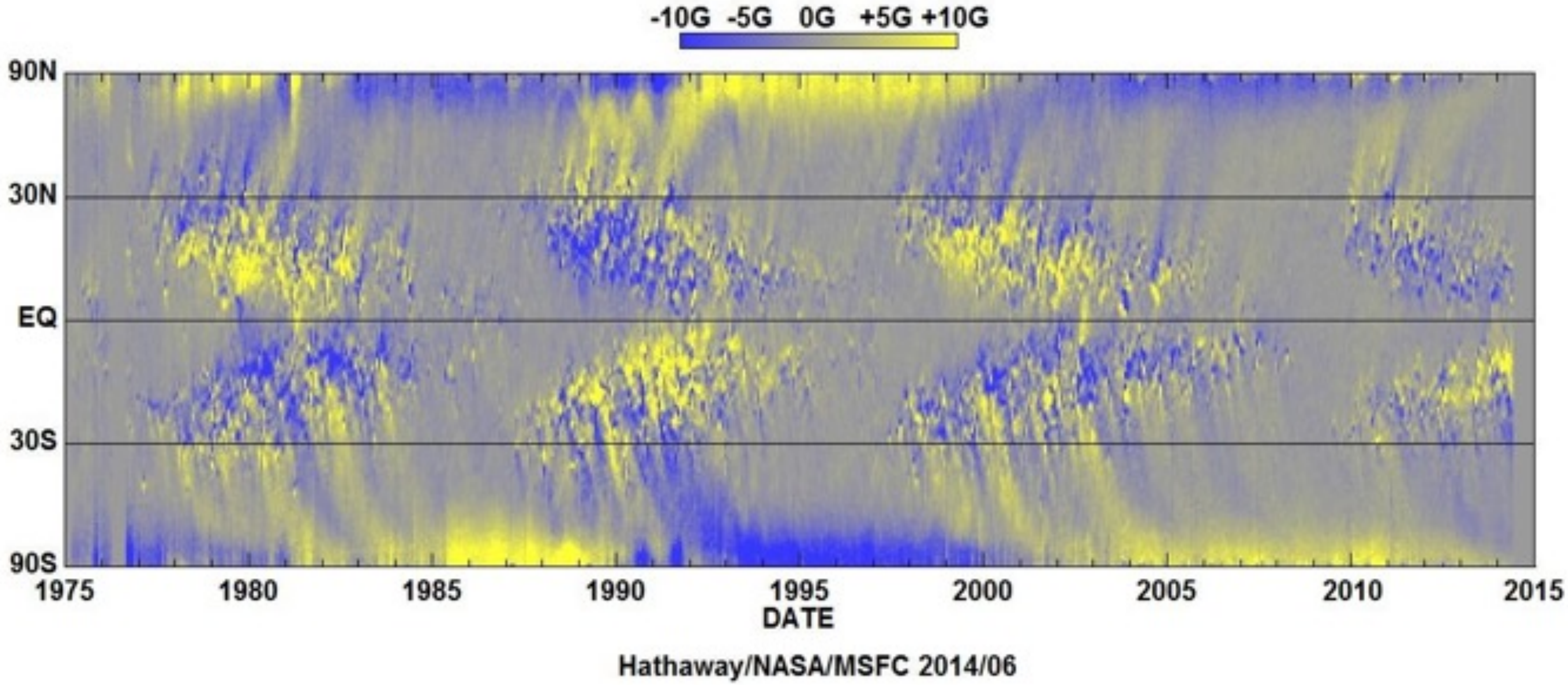
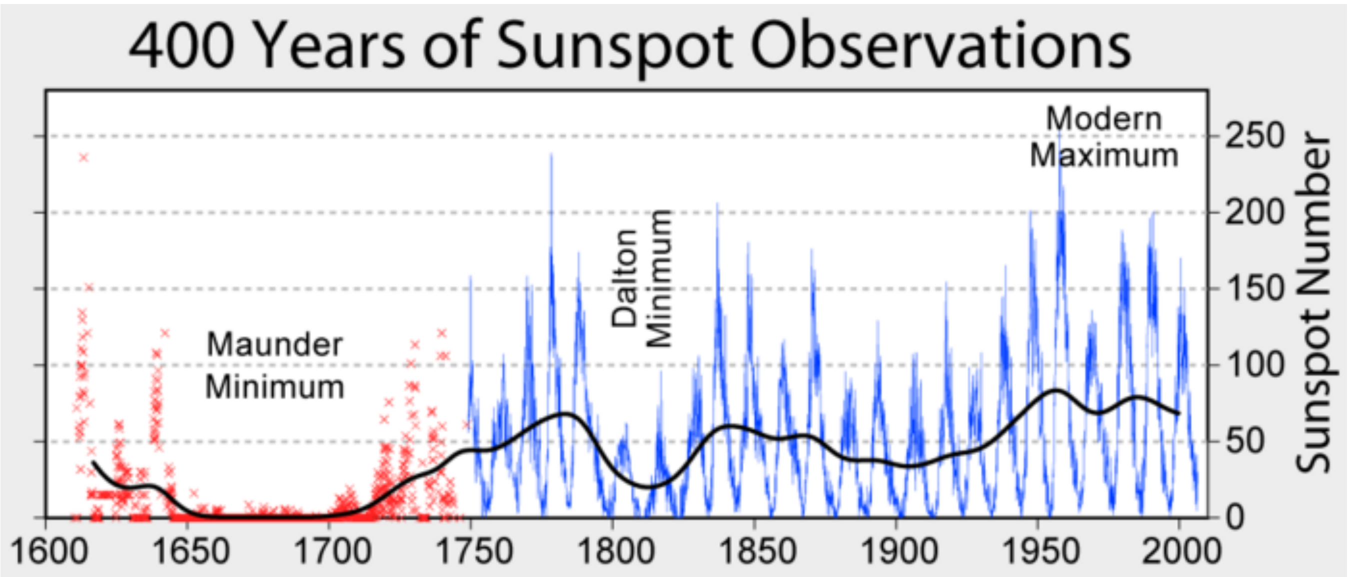


Why 11/22 years?

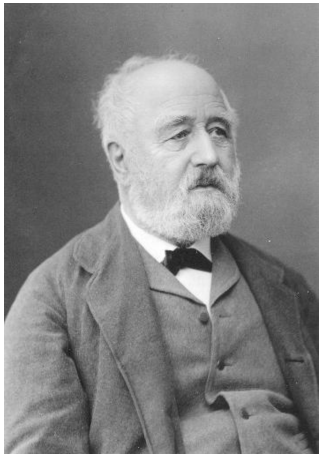
Historical records of the solar cycle

Discovered by H. Schwabe in 1843 after 17 years of observations of the Sun looking for planet Vulcan



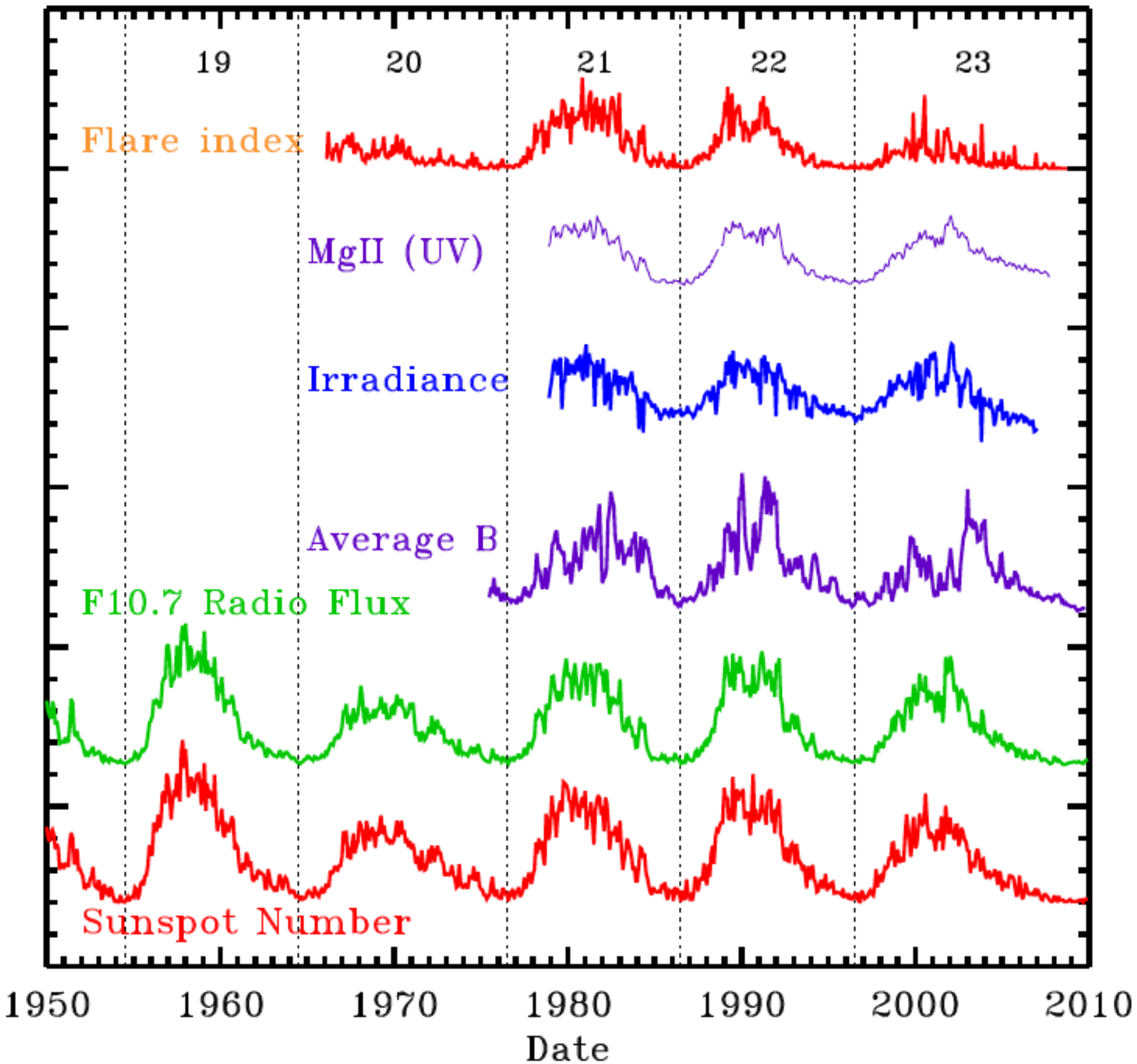
The period of the sunspot cycle is ~ **11 years**, but its amplitude fluctuates significantly from one cycle to the other

Heinrich Schwabe



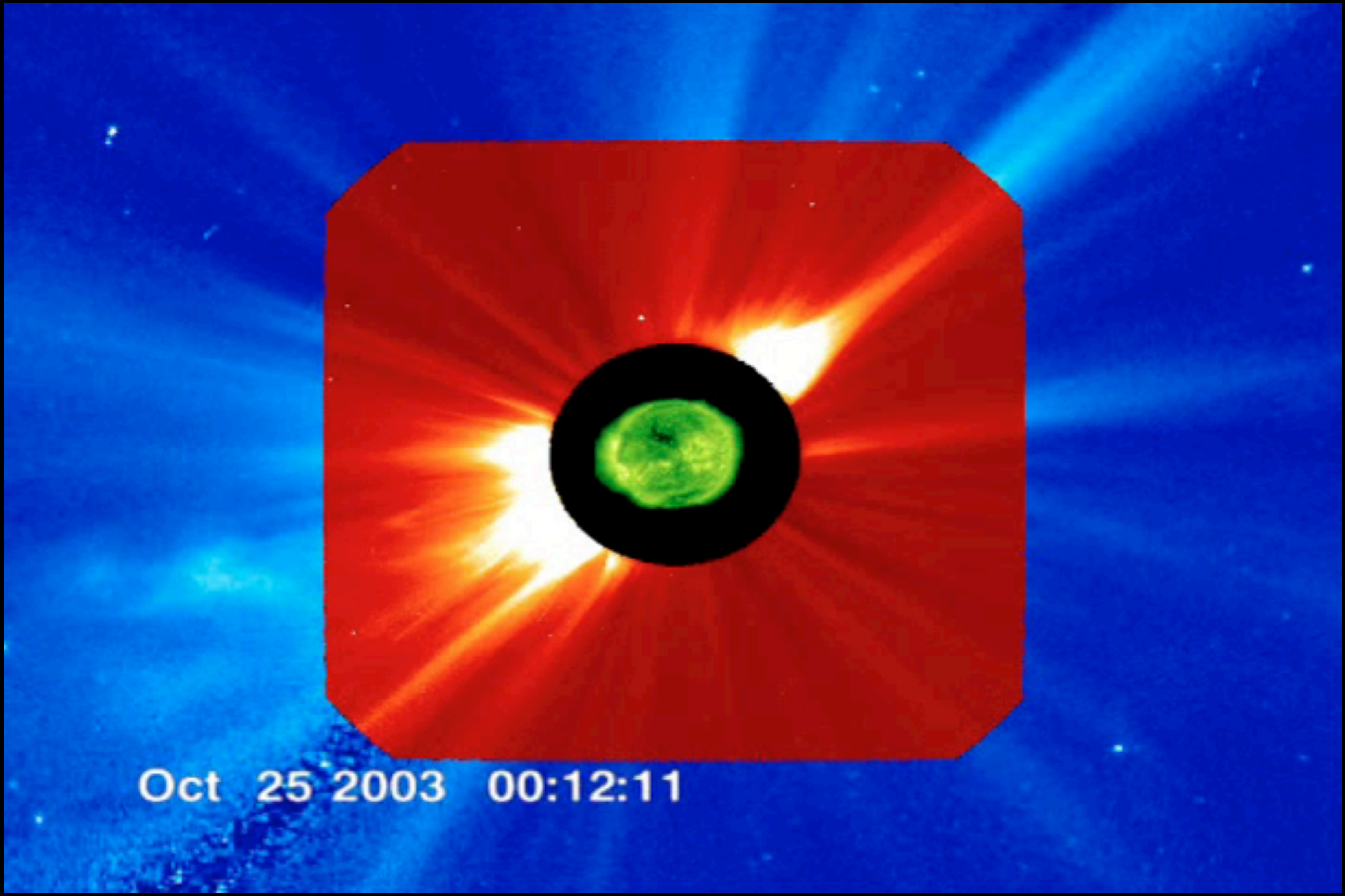
Rudolf Wolf

One cycle to rule them all



Solar cycle and the solar wind

Eruptive events from magnetic active regions



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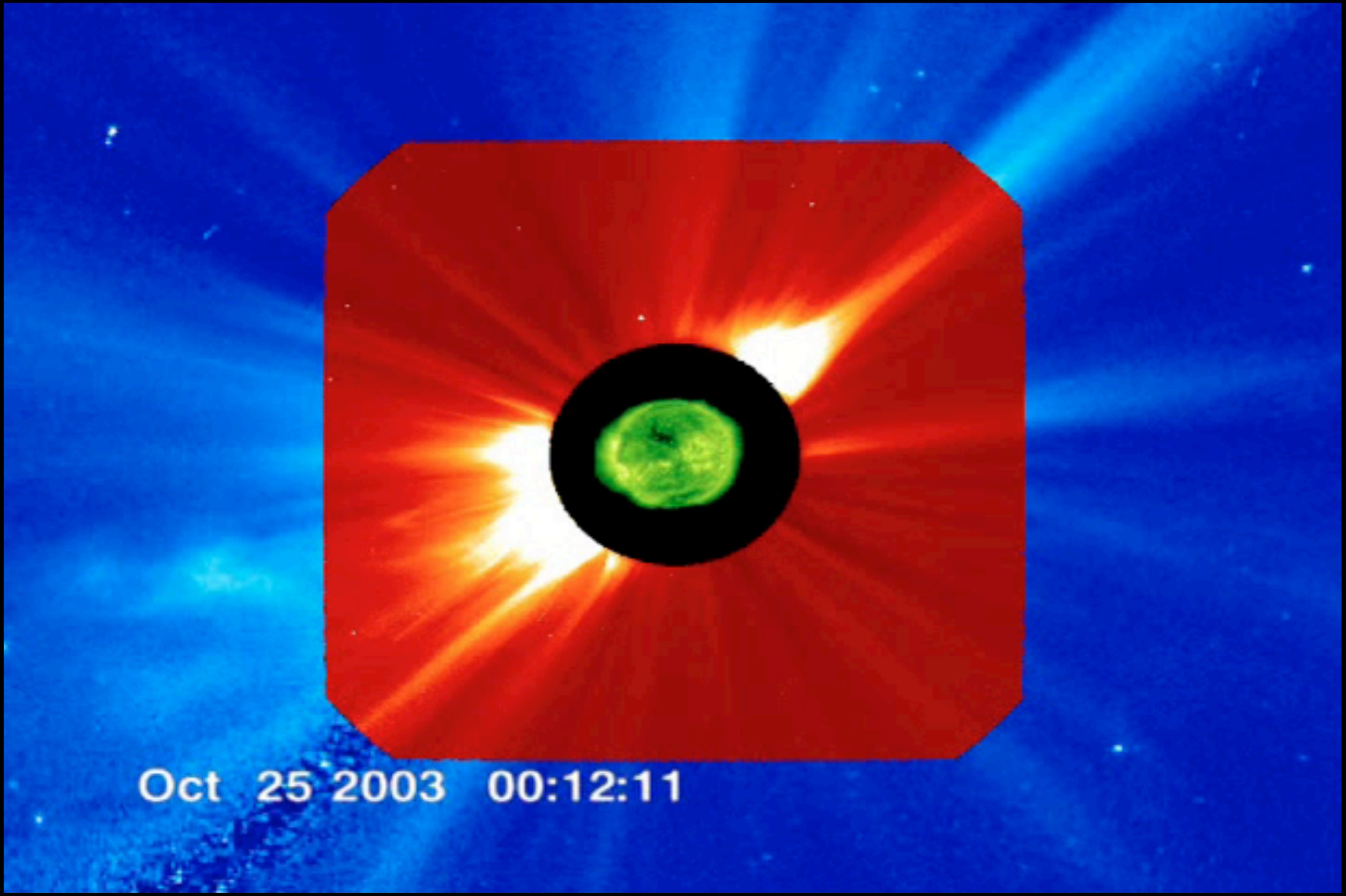
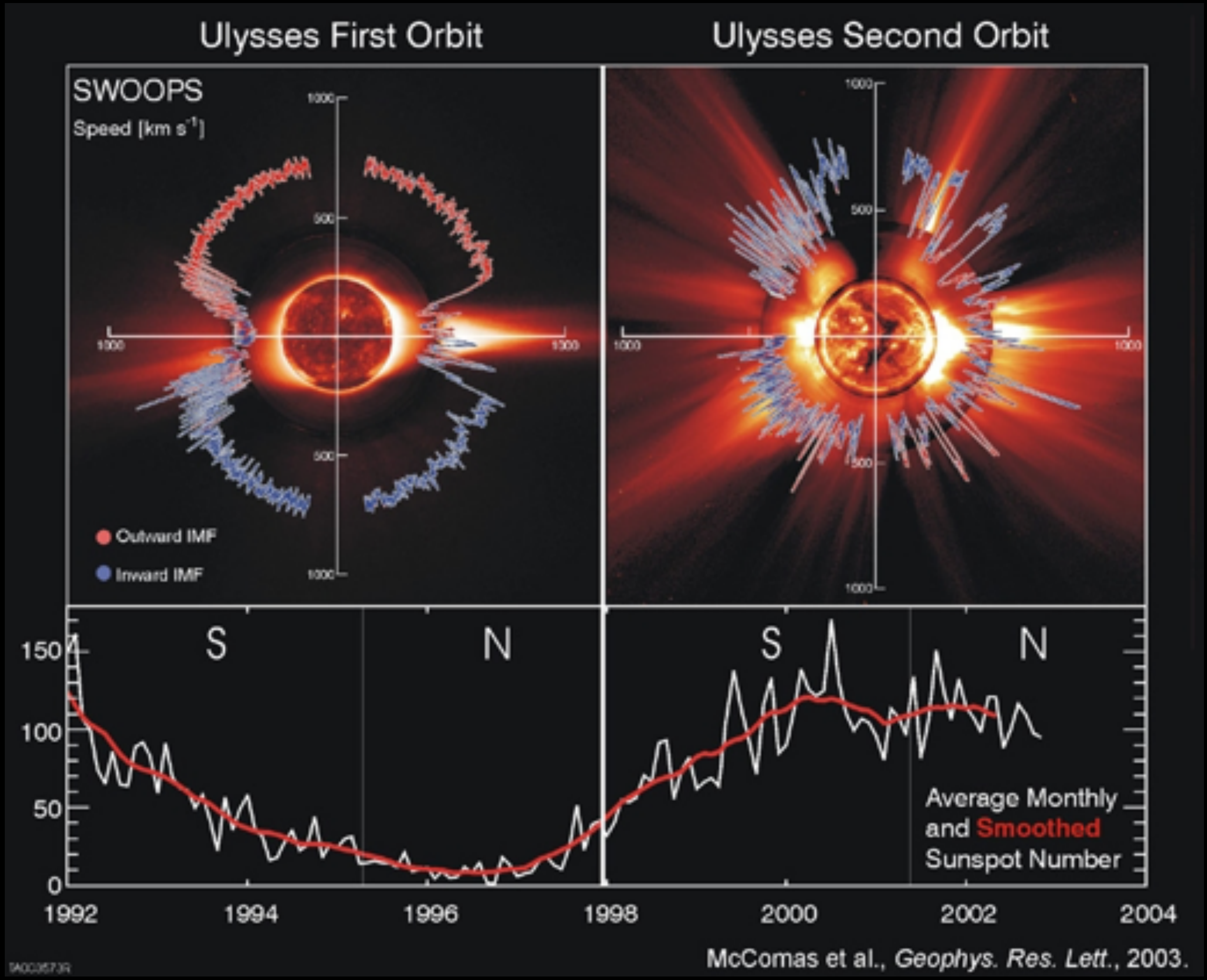
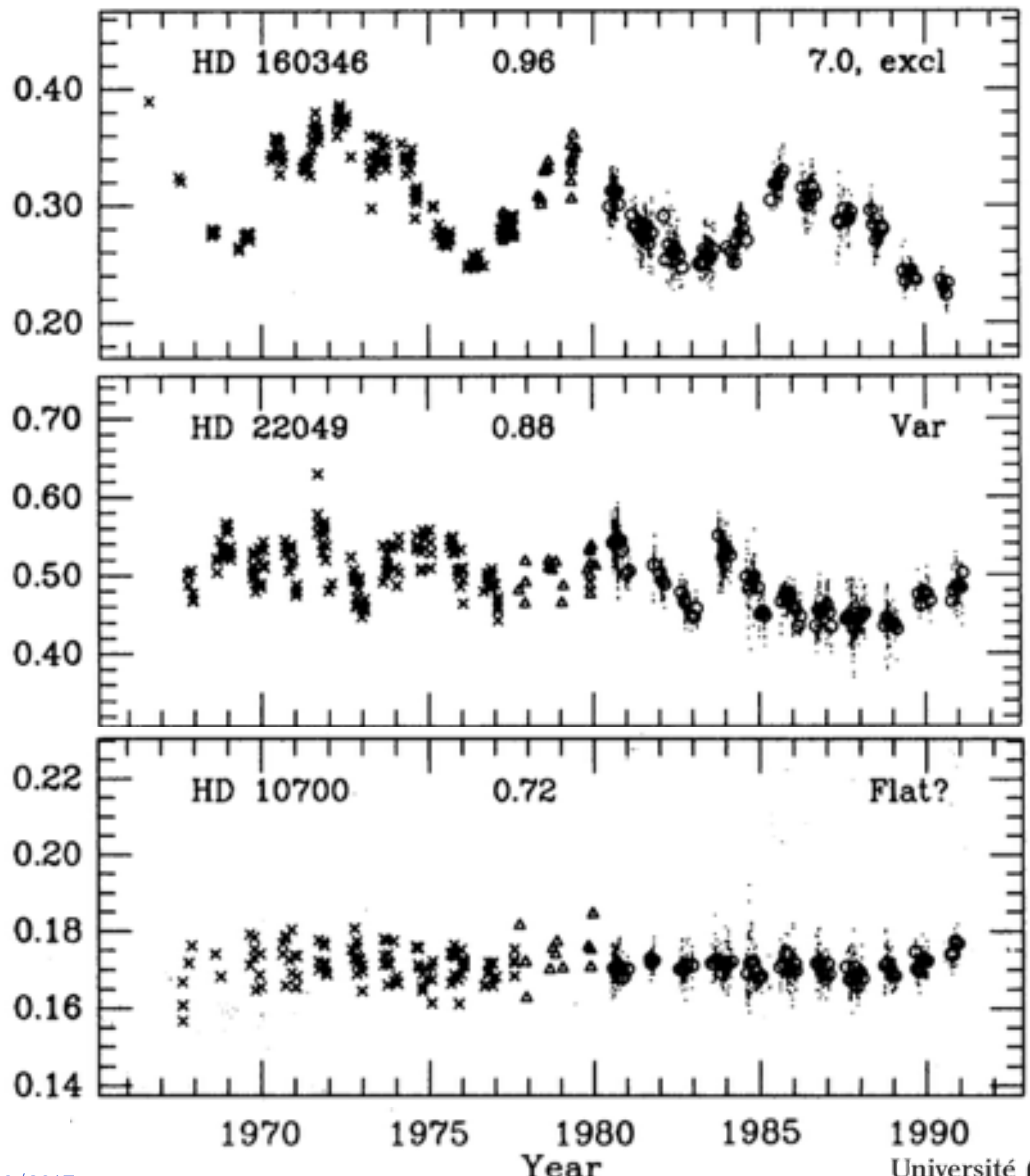


Solar cycle and the solar wind

Long term modulations

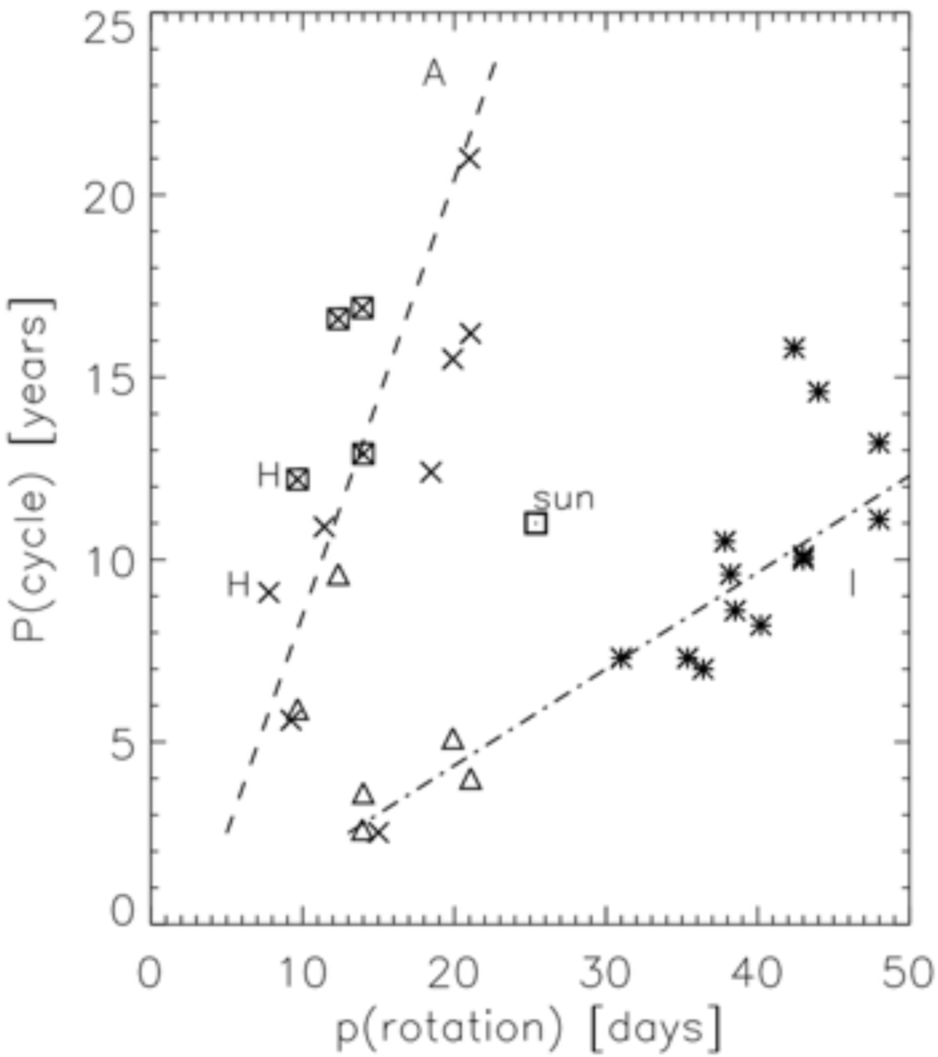


Magnetic activity cycles on other stars from CaII H&K



[Baliunas+, ApJ 1995]

What sets the cycle period of star?



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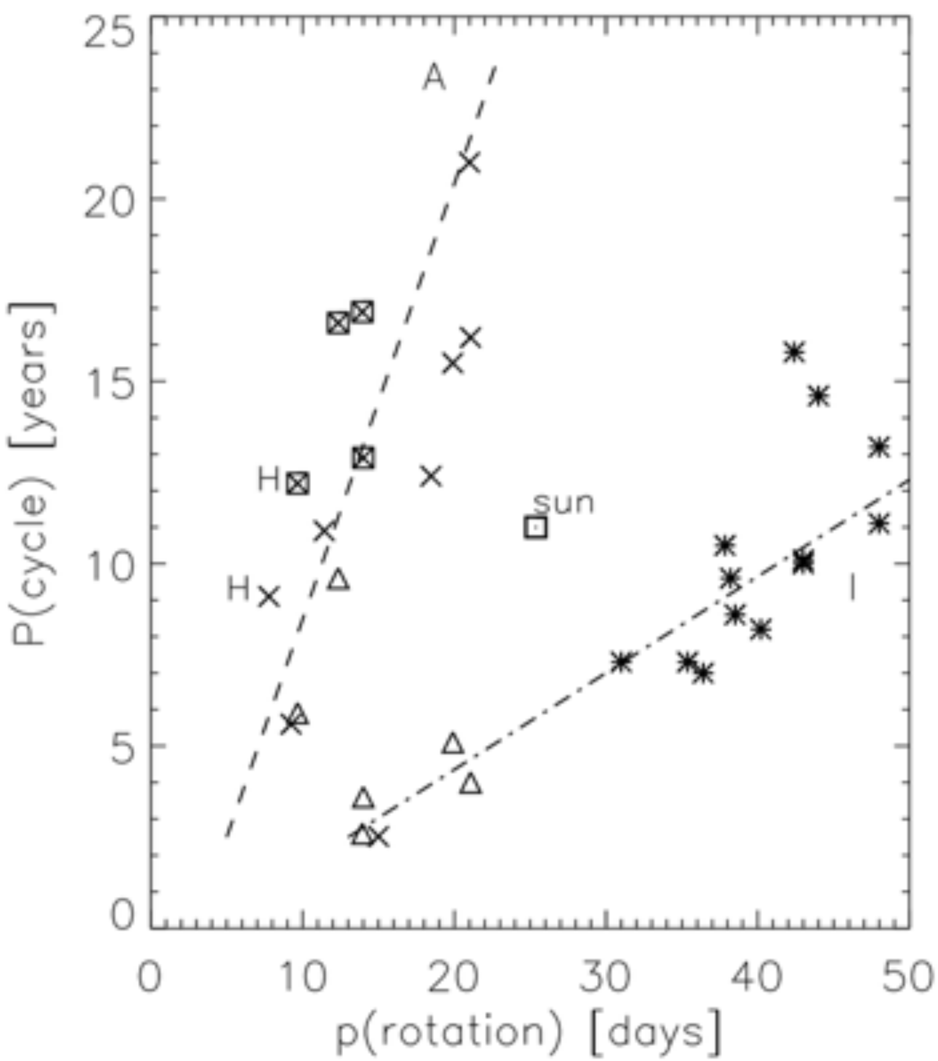

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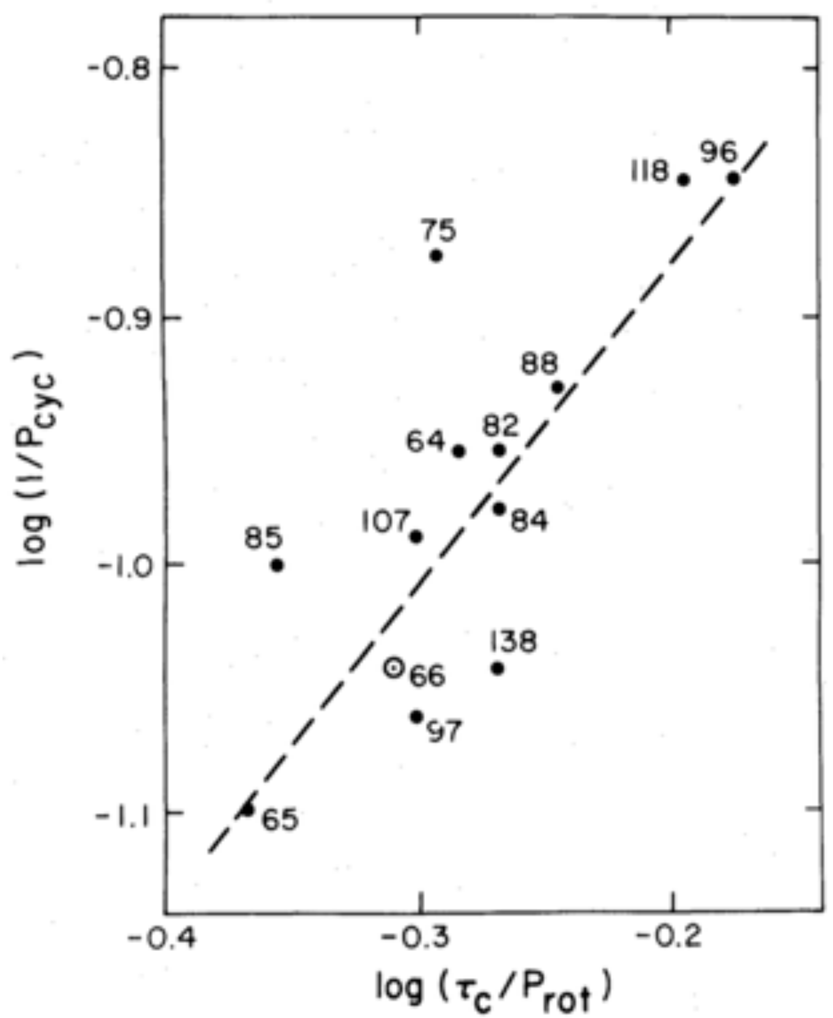
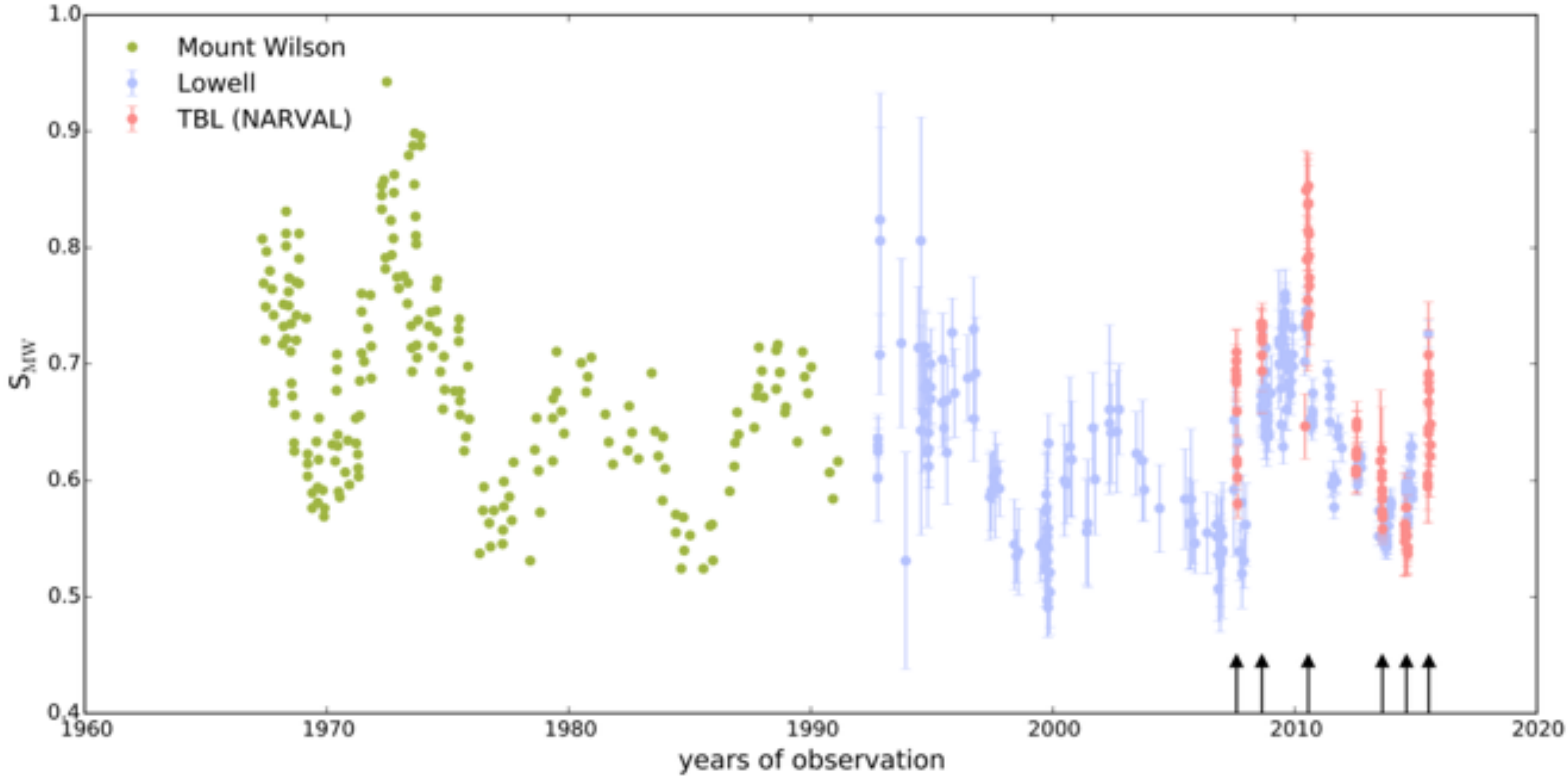


[Noyes+, ApJ 1984]

A true magnetic cycle on 61Cyg A



[Boro-Saikia+, A&A 2016]

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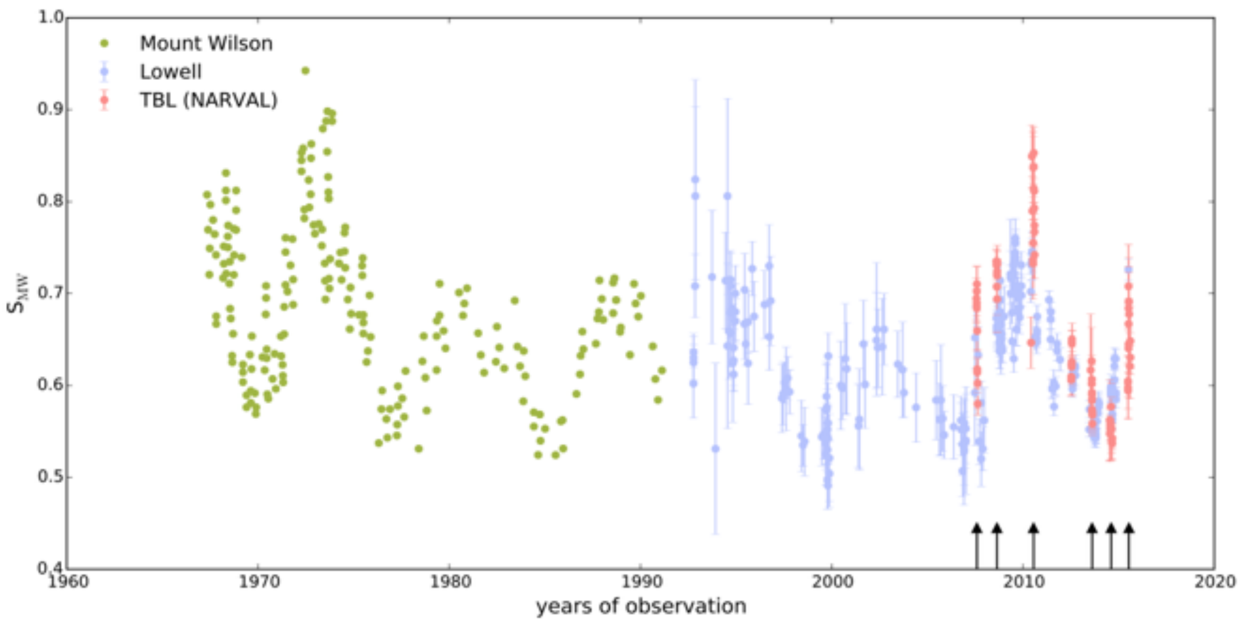
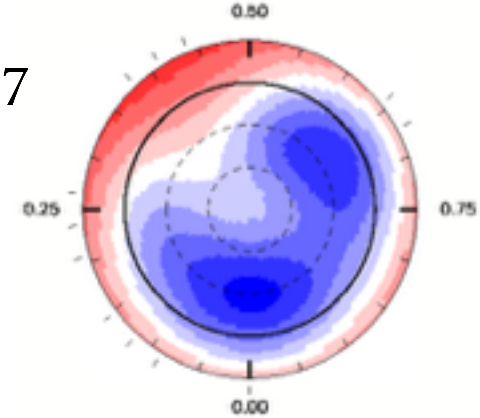
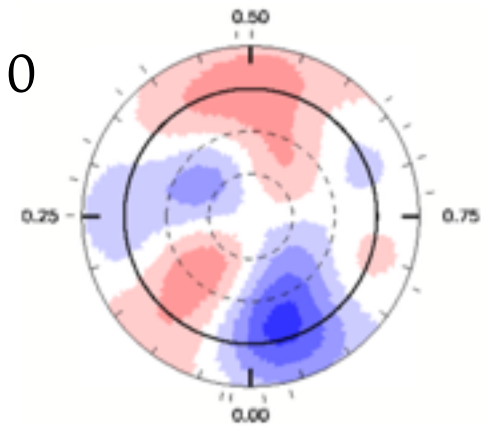


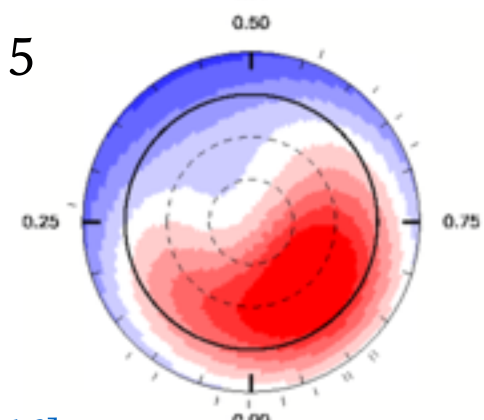
2007



2010



2015



[Boro-Saikia+, A&A 2016]

Elements of dynamo theory for stars: context

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

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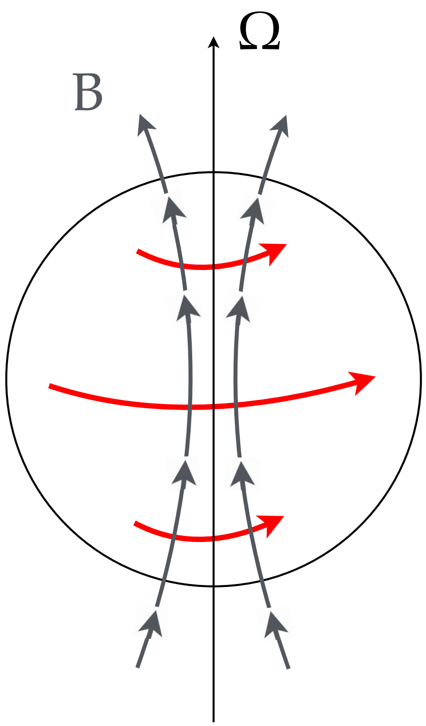
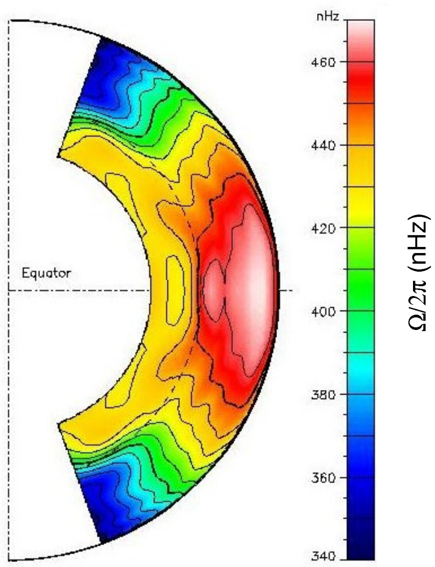
***Cowling's theorem*: 3D axisymmetric flows cannot sustain a dynamo action**

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





Solar Differential Rotation

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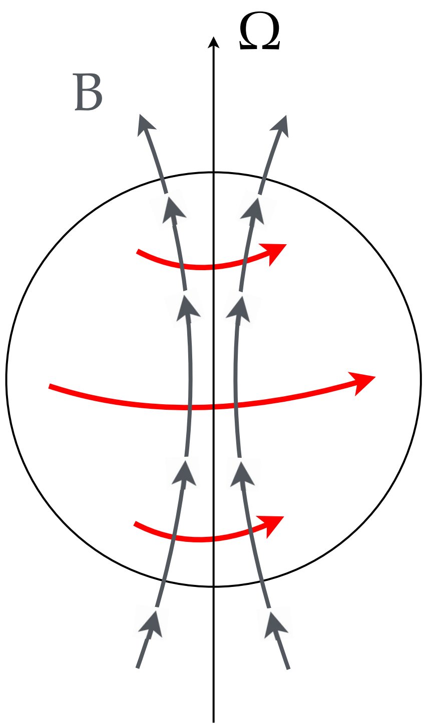

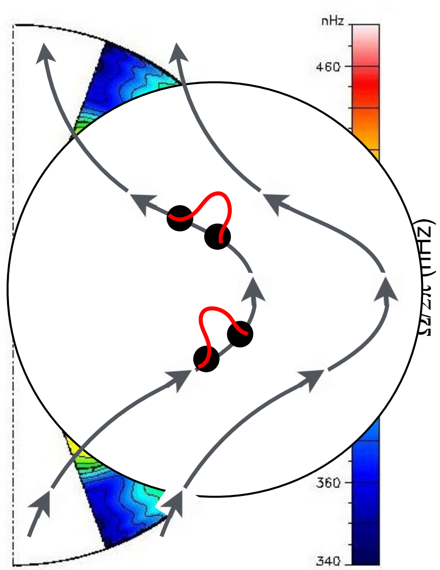

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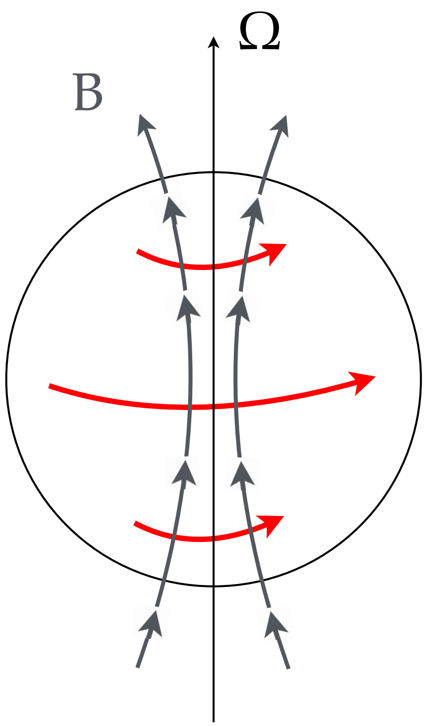
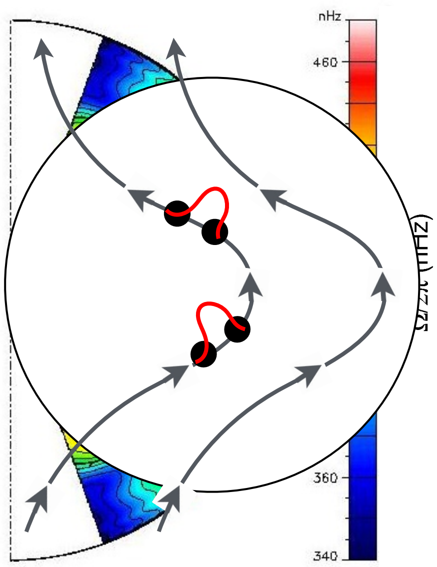
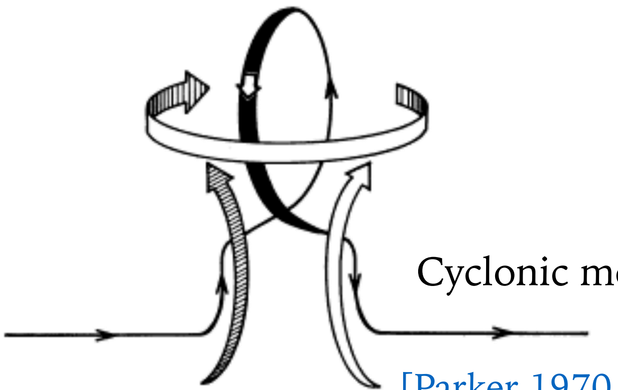


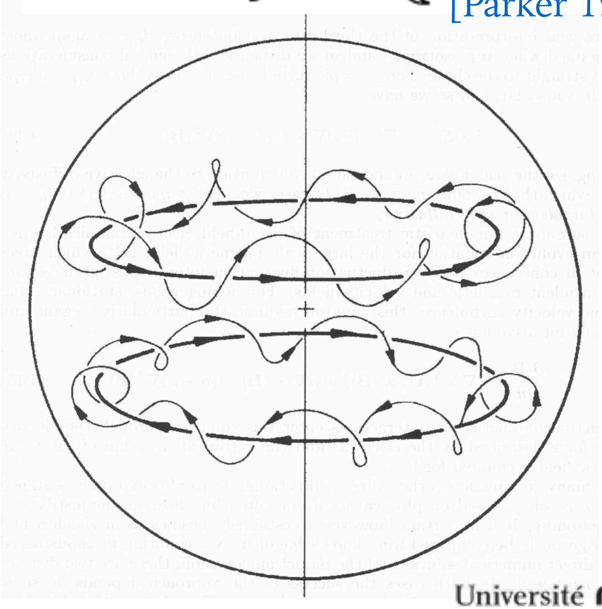


Solar Differential Rotation

Toroidal to poloidal conversion



[Parker 1970, 1979]



Elements of dynamo theory for stars: mean fields models

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{U} \times \boldsymbol{B}) - \nabla \times (\eta_{\mathrm{m}} \nabla \times \boldsymbol{B})$$

Induction equation

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$$\frac{\partial \langle \boldsymbol{B} \rangle}{\partial t} = \nabla \times (\langle \boldsymbol{U} \rangle \times \langle \boldsymbol{B} \rangle) + \nabla \times (\alpha \langle \boldsymbol{B} \rangle) - \nabla \times (\eta \nabla \times \langle \boldsymbol{B} \rangle)$$

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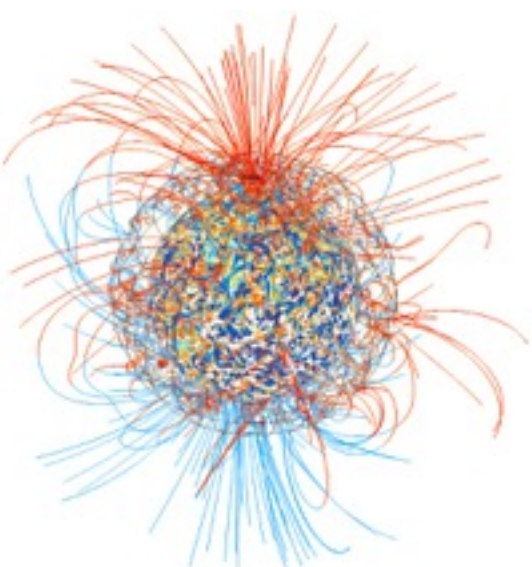

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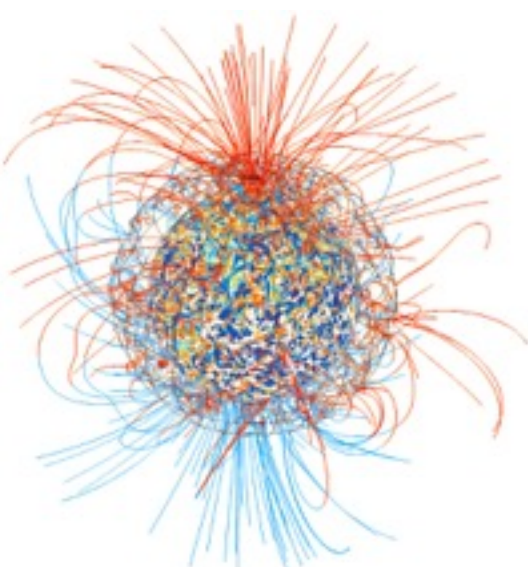

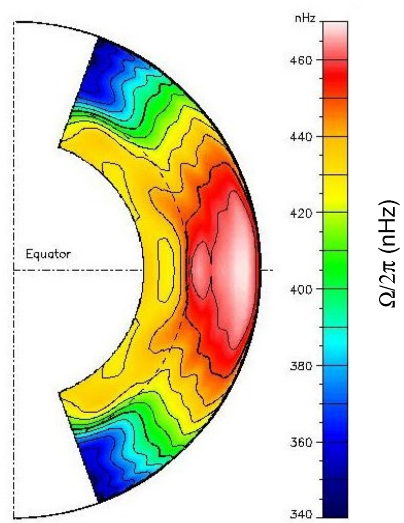

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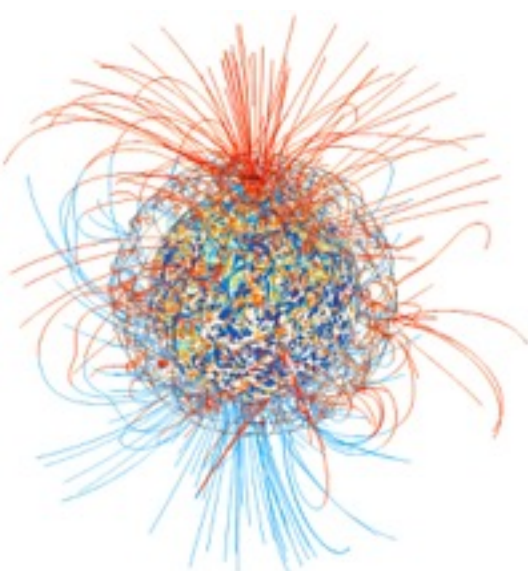

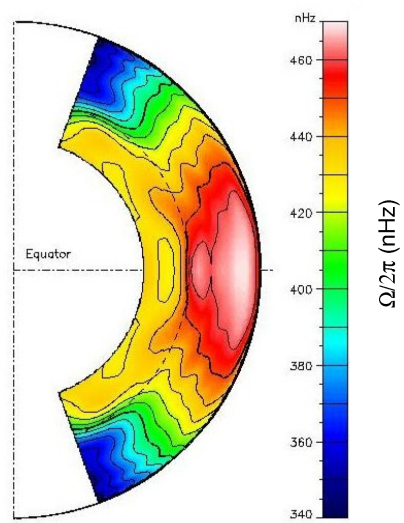

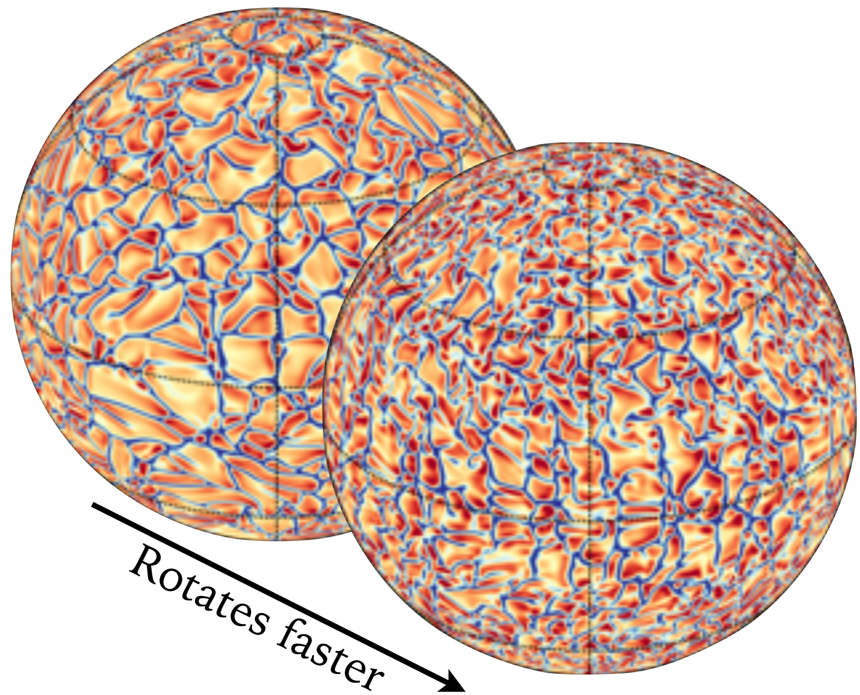

Elements of dynamo theory for stars: mean fields model (II)

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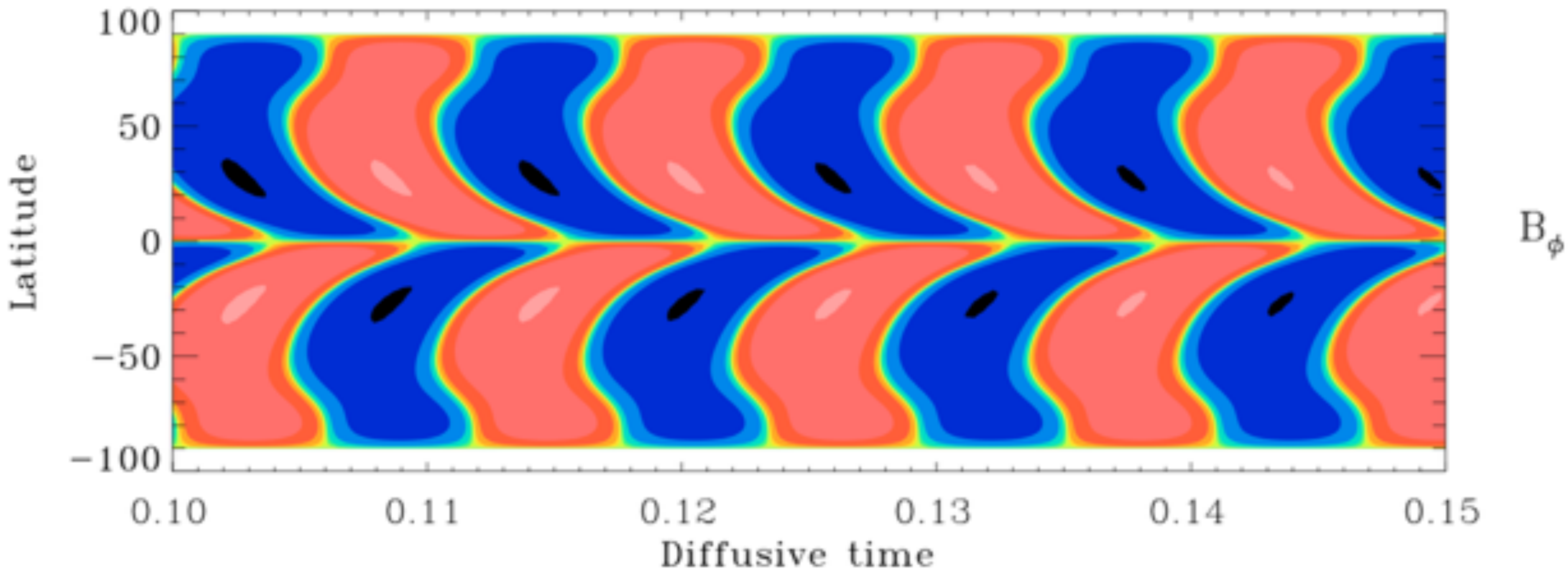
Butterfly diagram resembling the Sun's



[Jouve+, A&A 2008]

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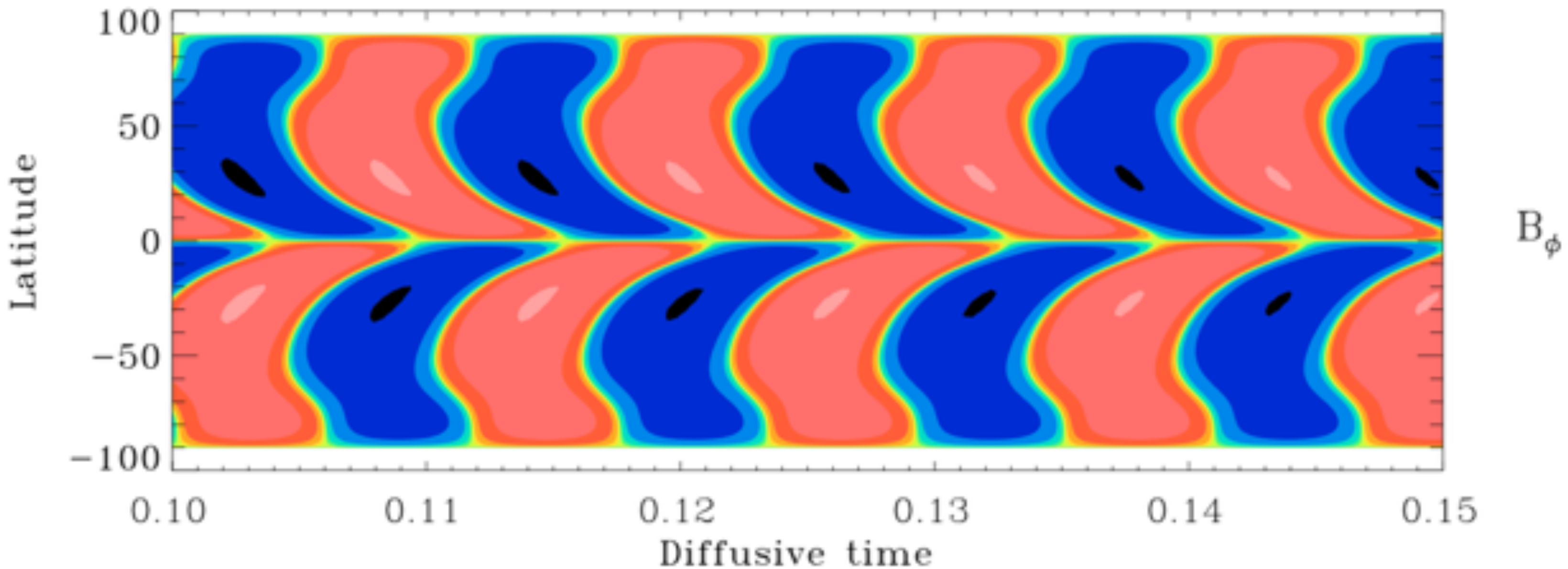
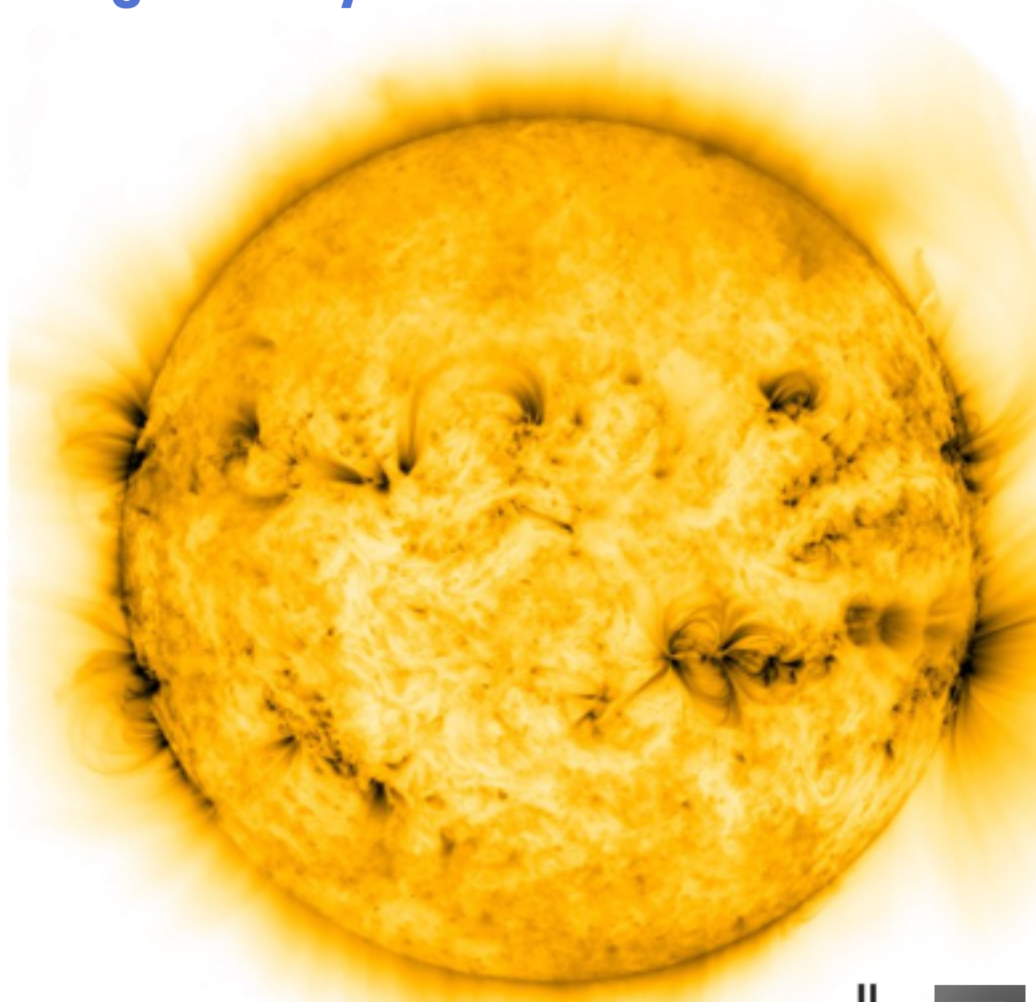


BUT still several ad-hoc parameters tweaked to reproduce the Sun

[Jouve+, A&A 2008]

Ab-initio modelling of stellar magnetic cycles



A. Strugarek, Seminar at Laboratoire Leprince-Ringuet, 25/09/2017

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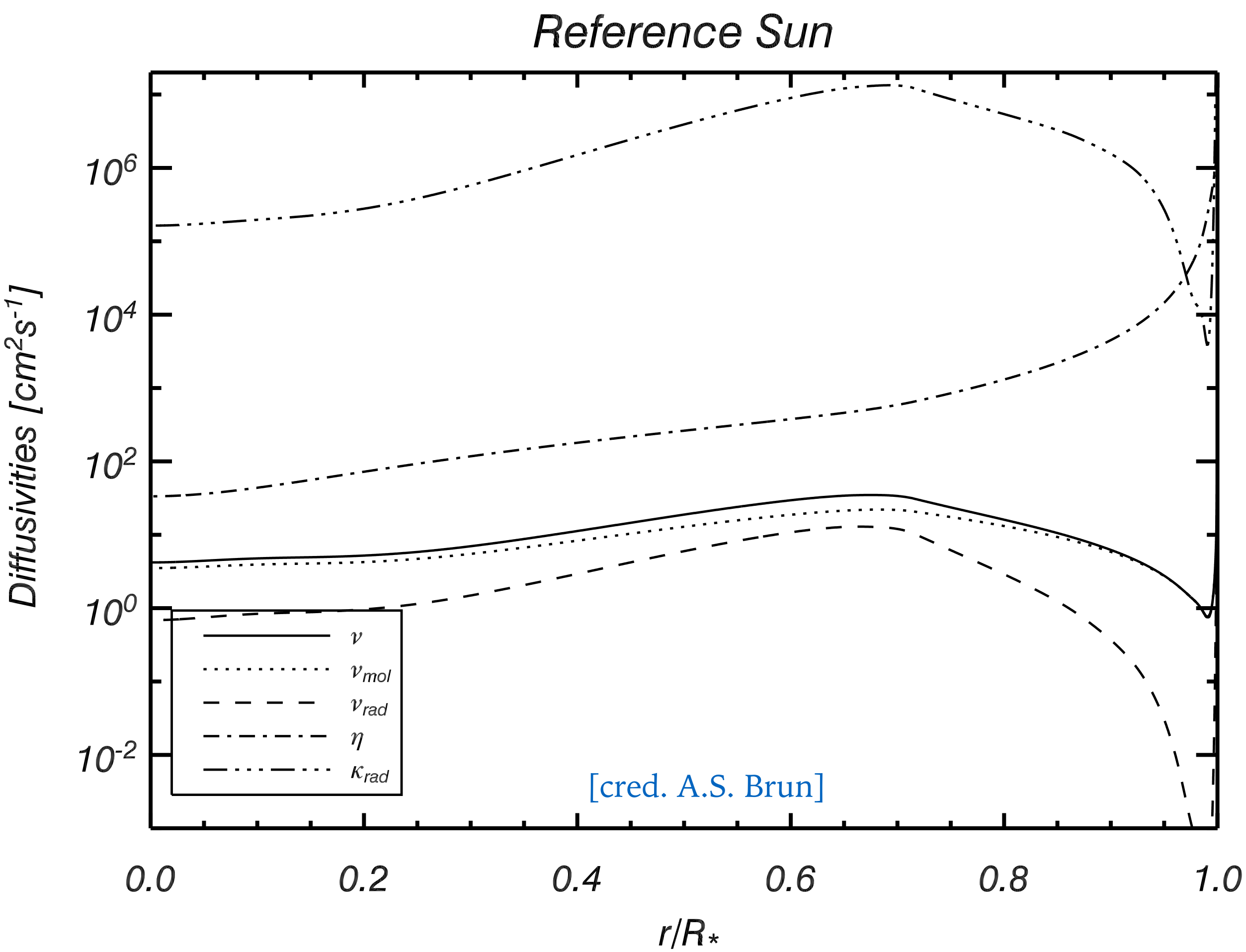
Challenge: ab-initio models of stellar convective dynamos



Extremely high (>10^{10}) Reynolds (flow), Taylor (rotation), and Rayleigh (buoyancy,heat) numbers

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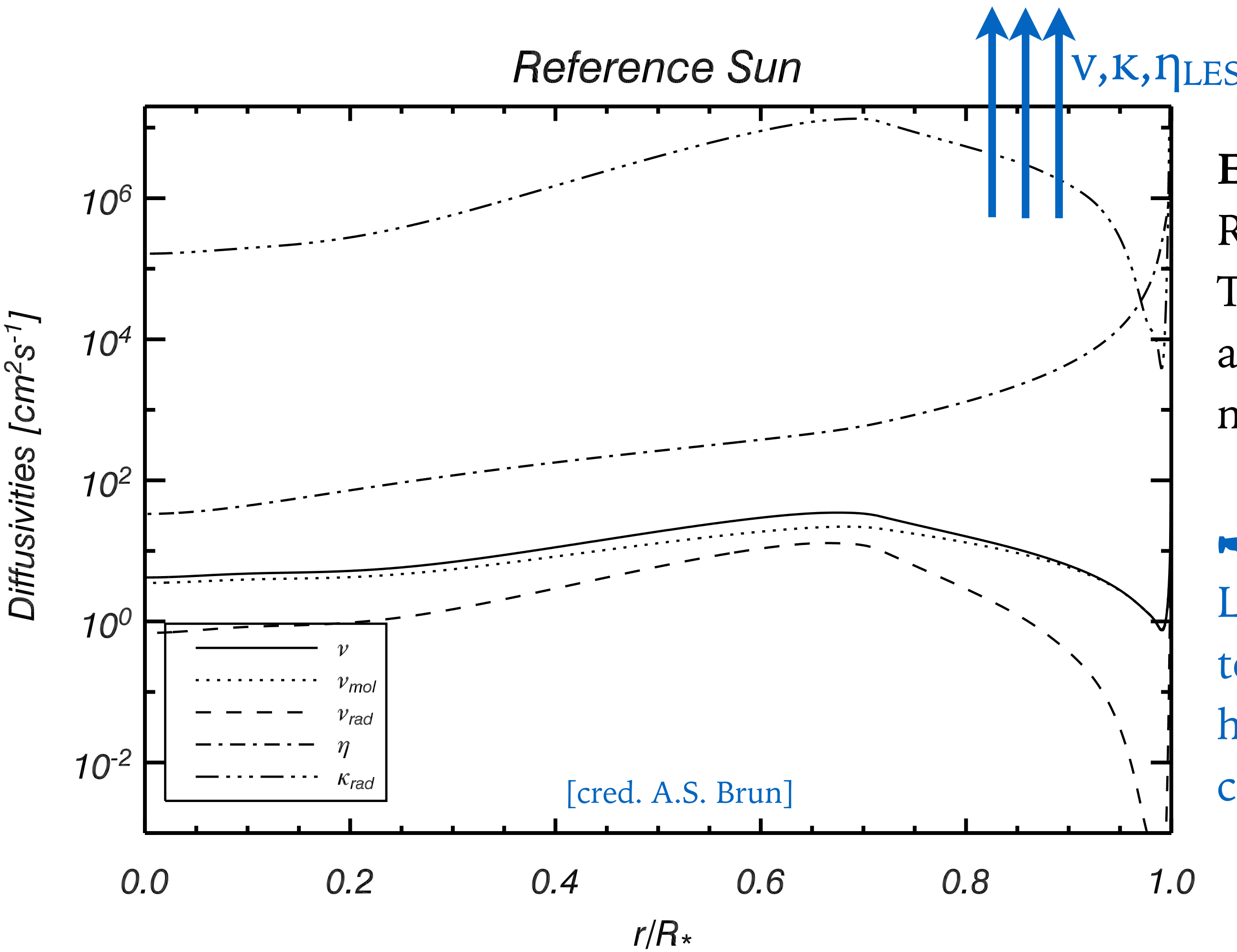

Extremely high (>10^{10}) Reynolds (flow), Taylor (rotation), and Rayleigh (buoyancy,heat) numbers

☛ Help of the so-called Large-Eddy Simulation (LES) techniques to consider much higher dissipation coefficients

Modelling the effect of unresolved scales

Modelling the effect of unresolved scales

Resolve it with a separate adequate set of equations

Hardest, yet to be done for convective dynamos

Modelling the effect of unresolved scales

'Dissipative', model it as effective dissipation coefficients

Eddy viscosity
(dynamic) Smagorinsky

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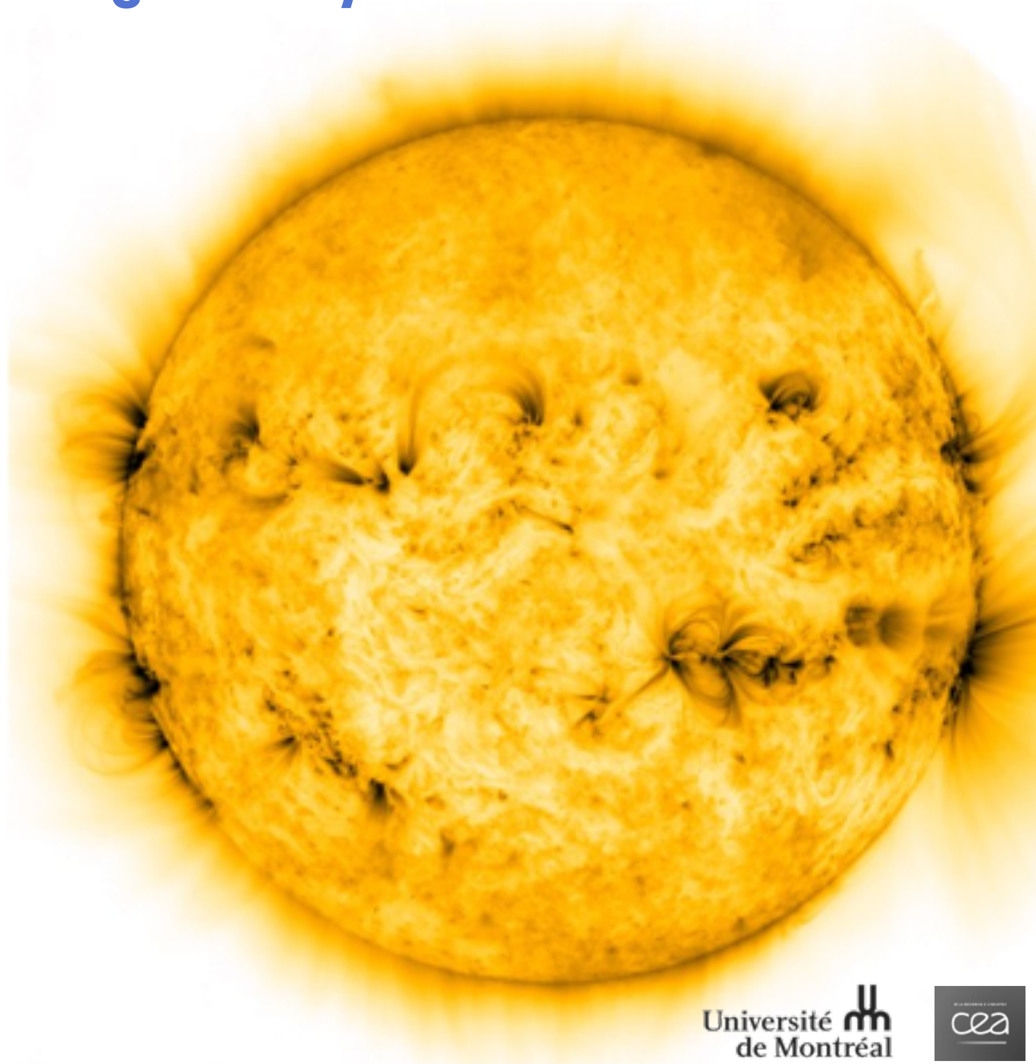
Hardest, yet to be done for convective dynamos

Minimize it as much as possible through ad-hoc numerical methods

Implicit-LES

Ab-initio modelling of stellar magnetic cycles

Basic ingredients of stellar dynamos



A. Strugarek, Seminar at Laboratoire Leprince-Ringuet, 25/09/2017

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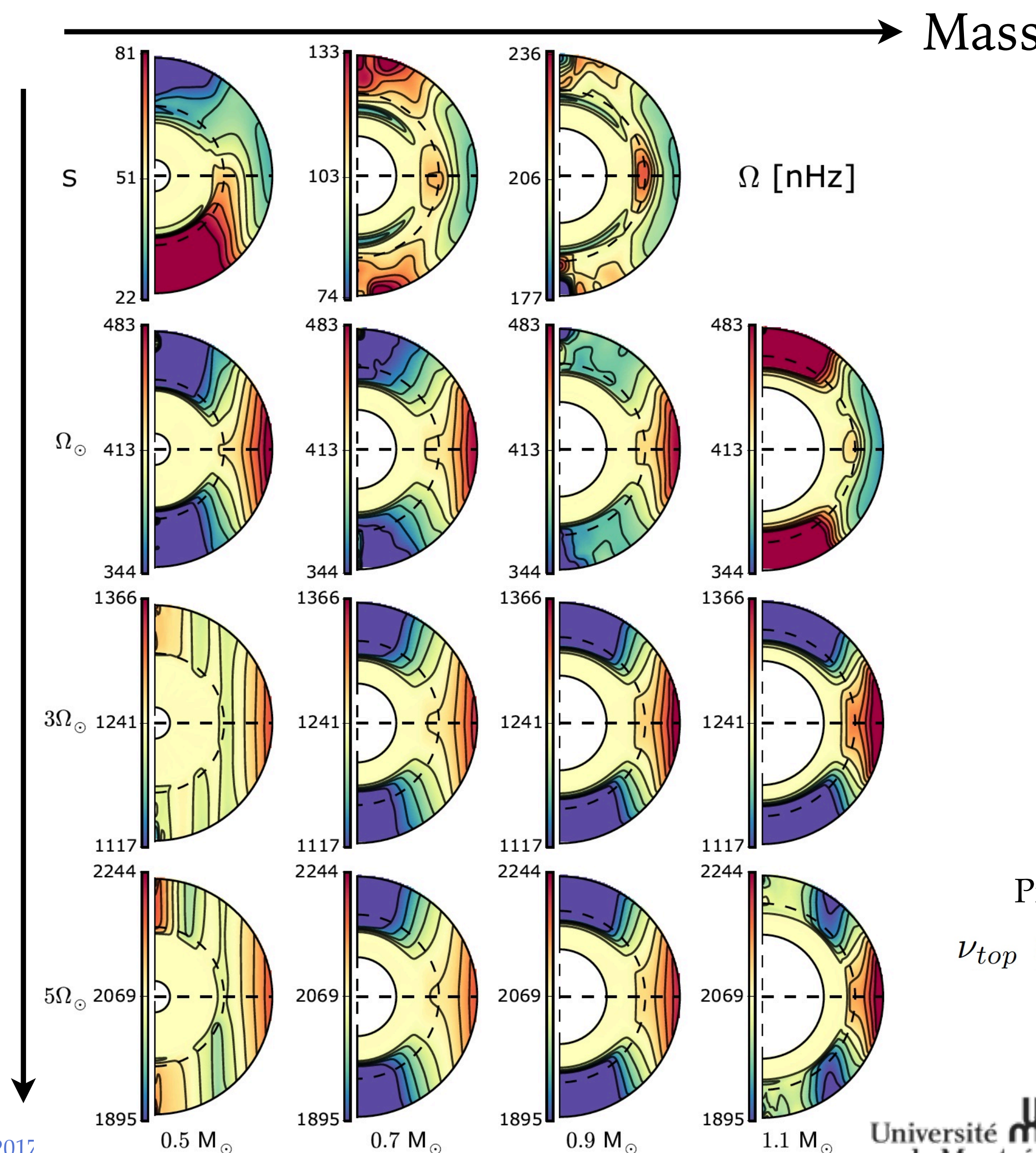
Understanding the basic ingredients of stellar dynamos

What determines the shape and amplitude of the differential rotation?

Three regimes:

- Anti-Solar like
- Solar-like
- Jupiter-like

[Brun, Strugarek et al. 2017]



Pr=0.25

$\nu_{top} \propto 1/\Omega_*^{0.5}$

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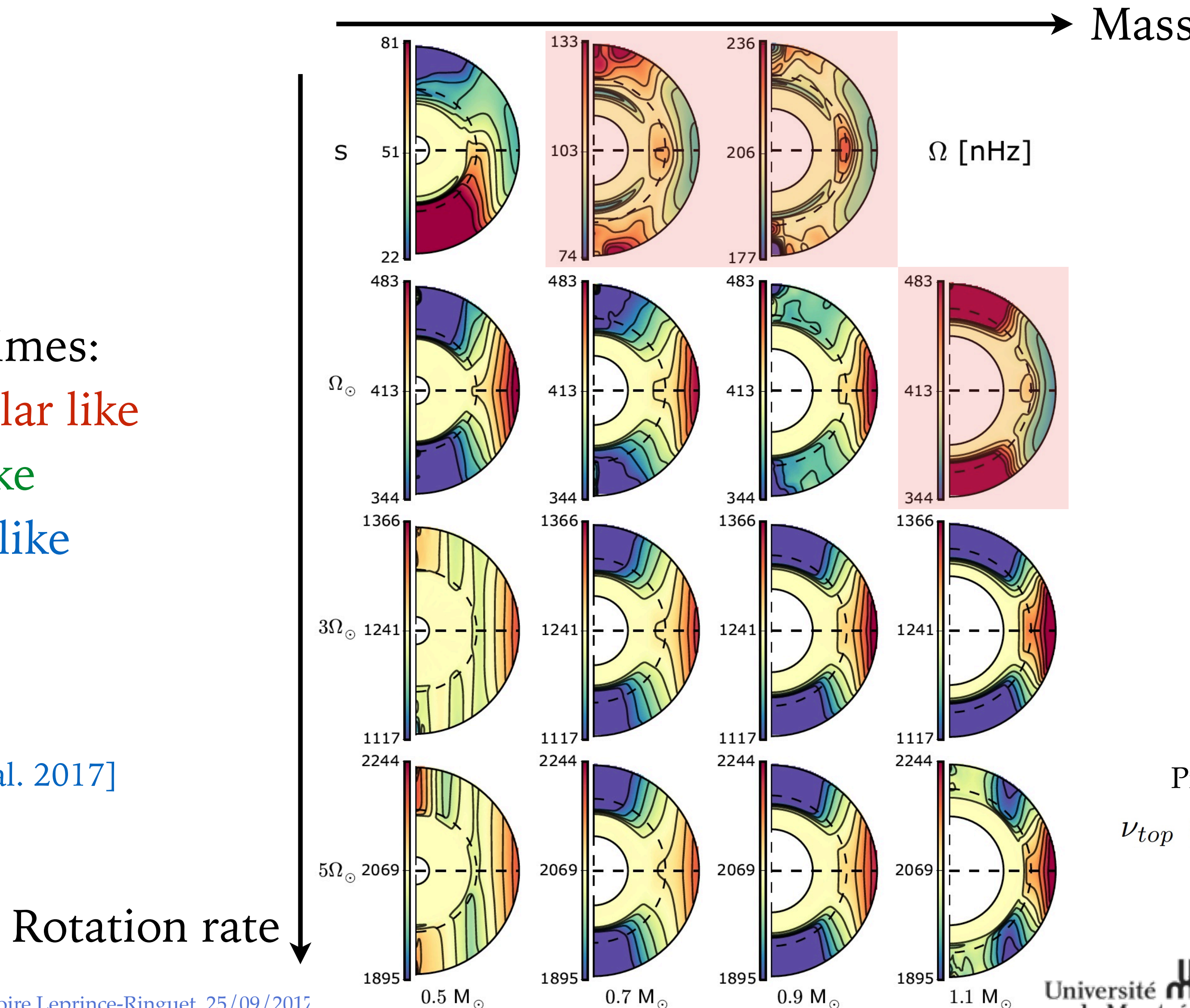

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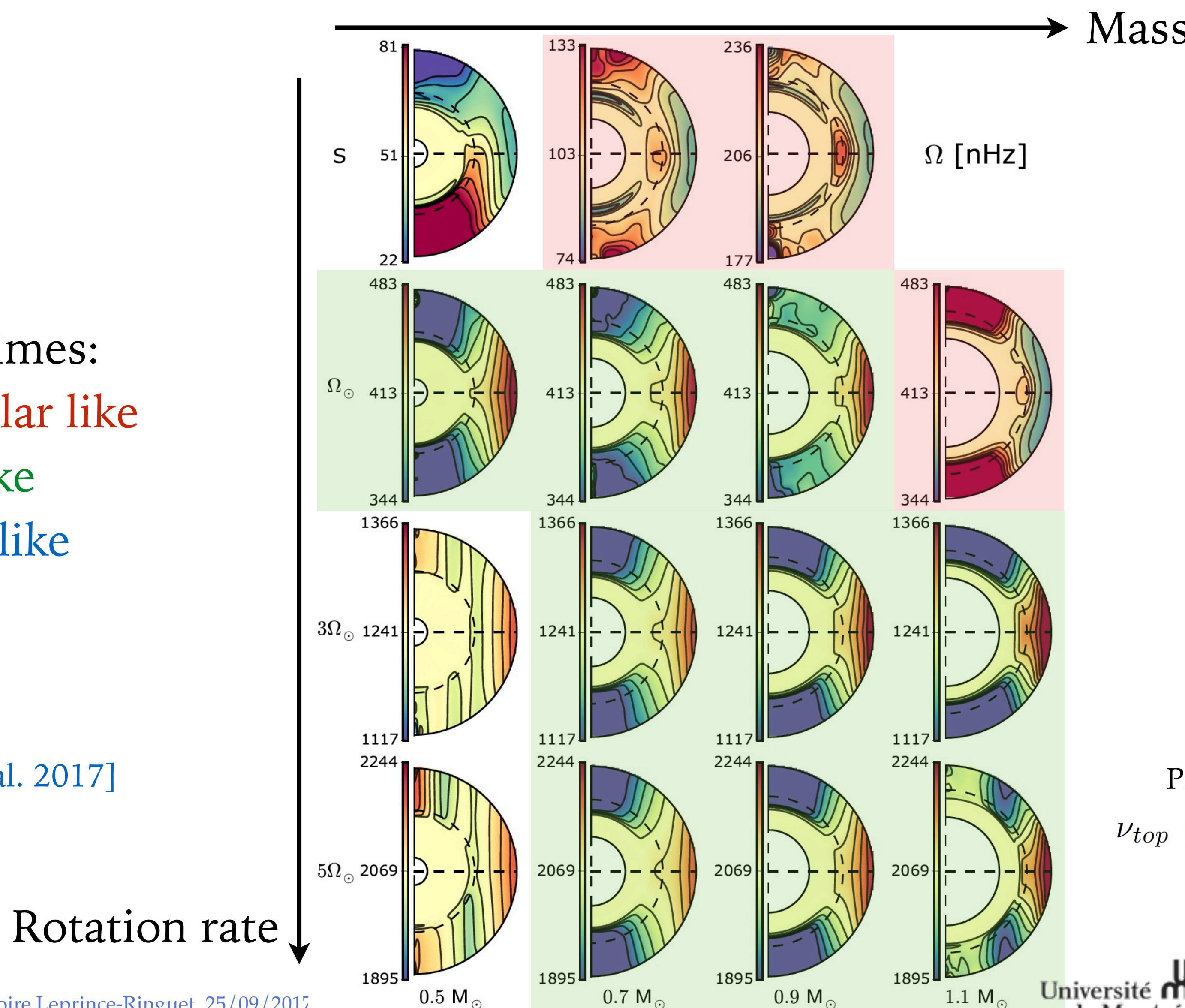

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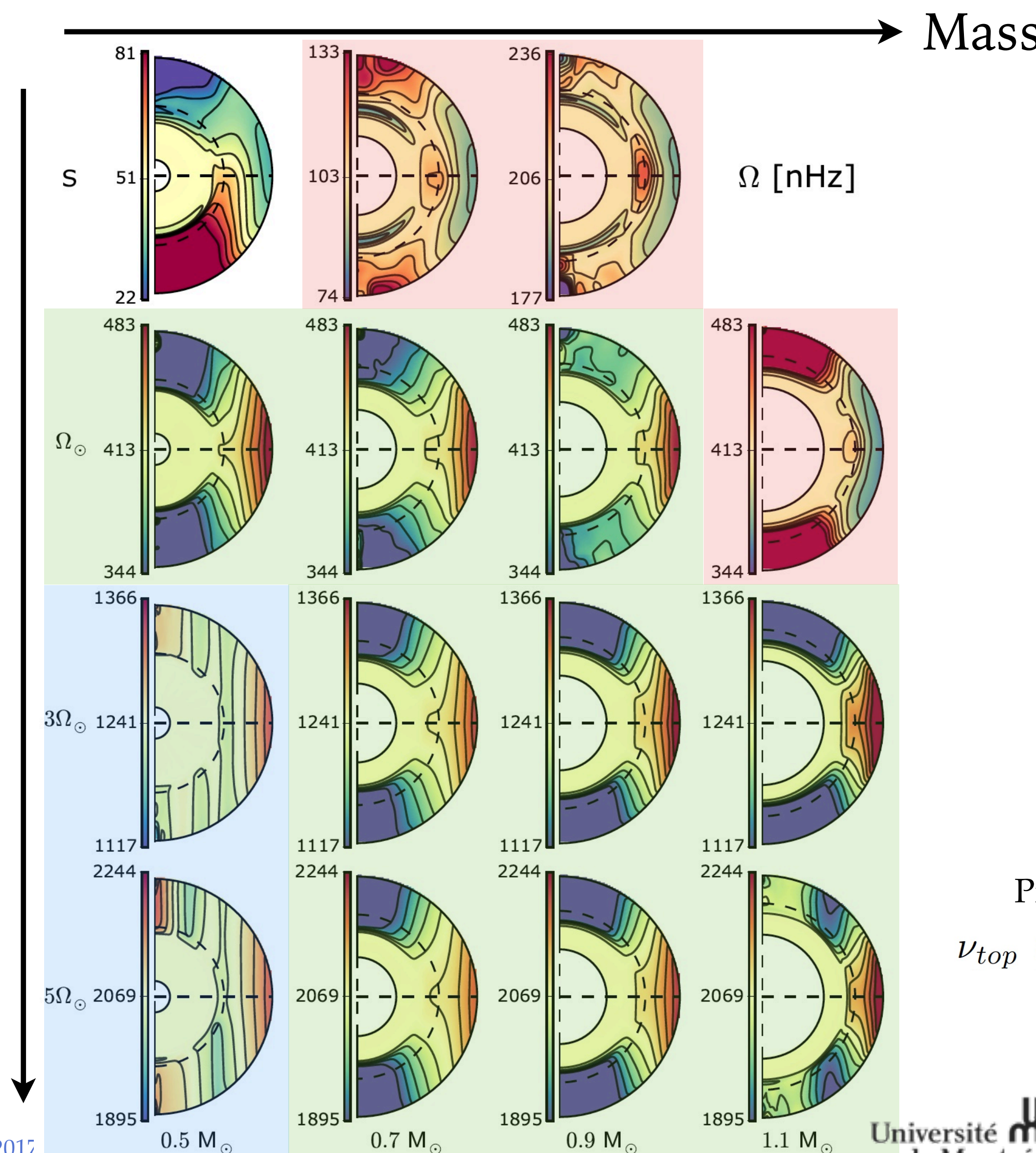

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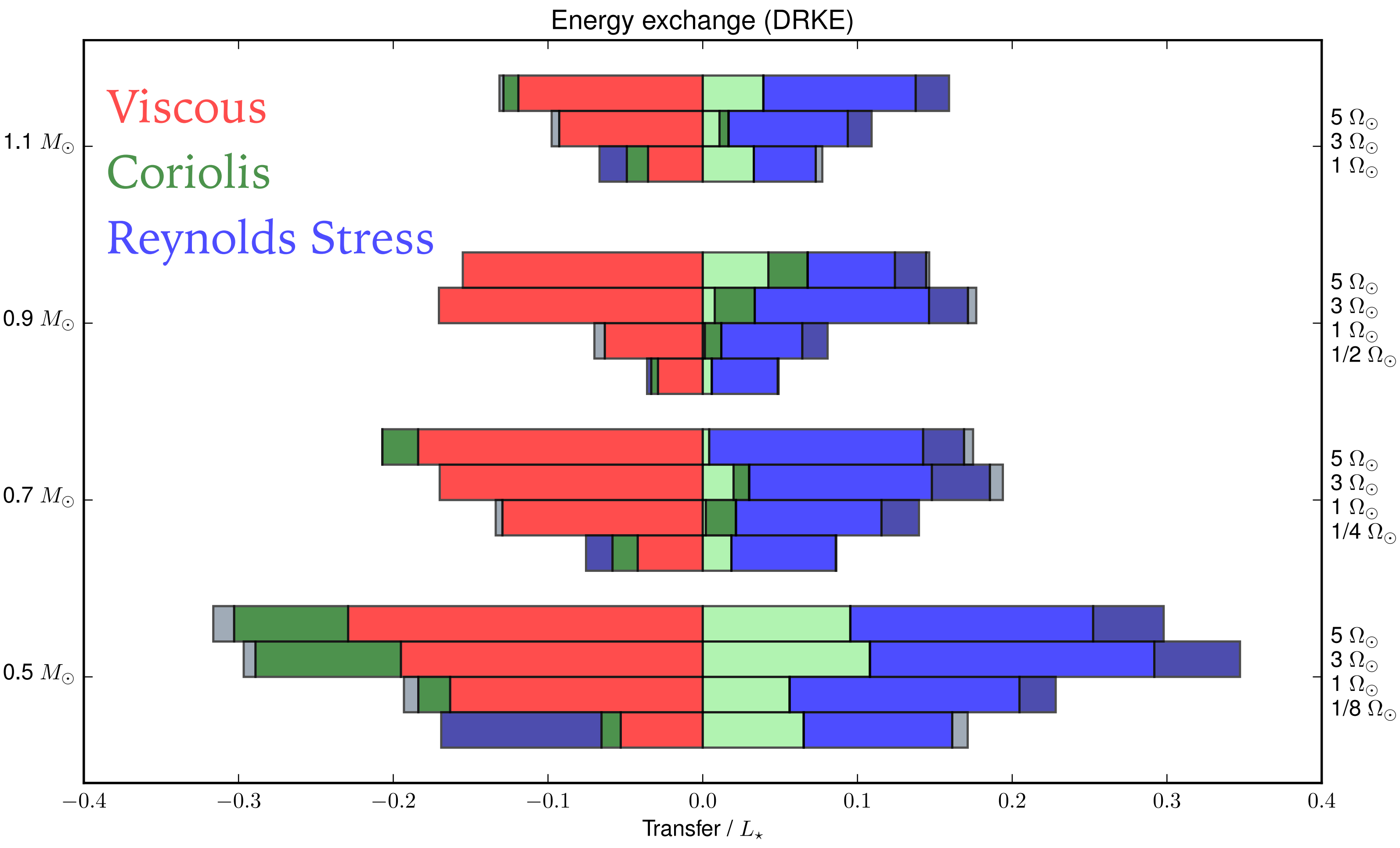

[Brun, Strugarek+ 2016]

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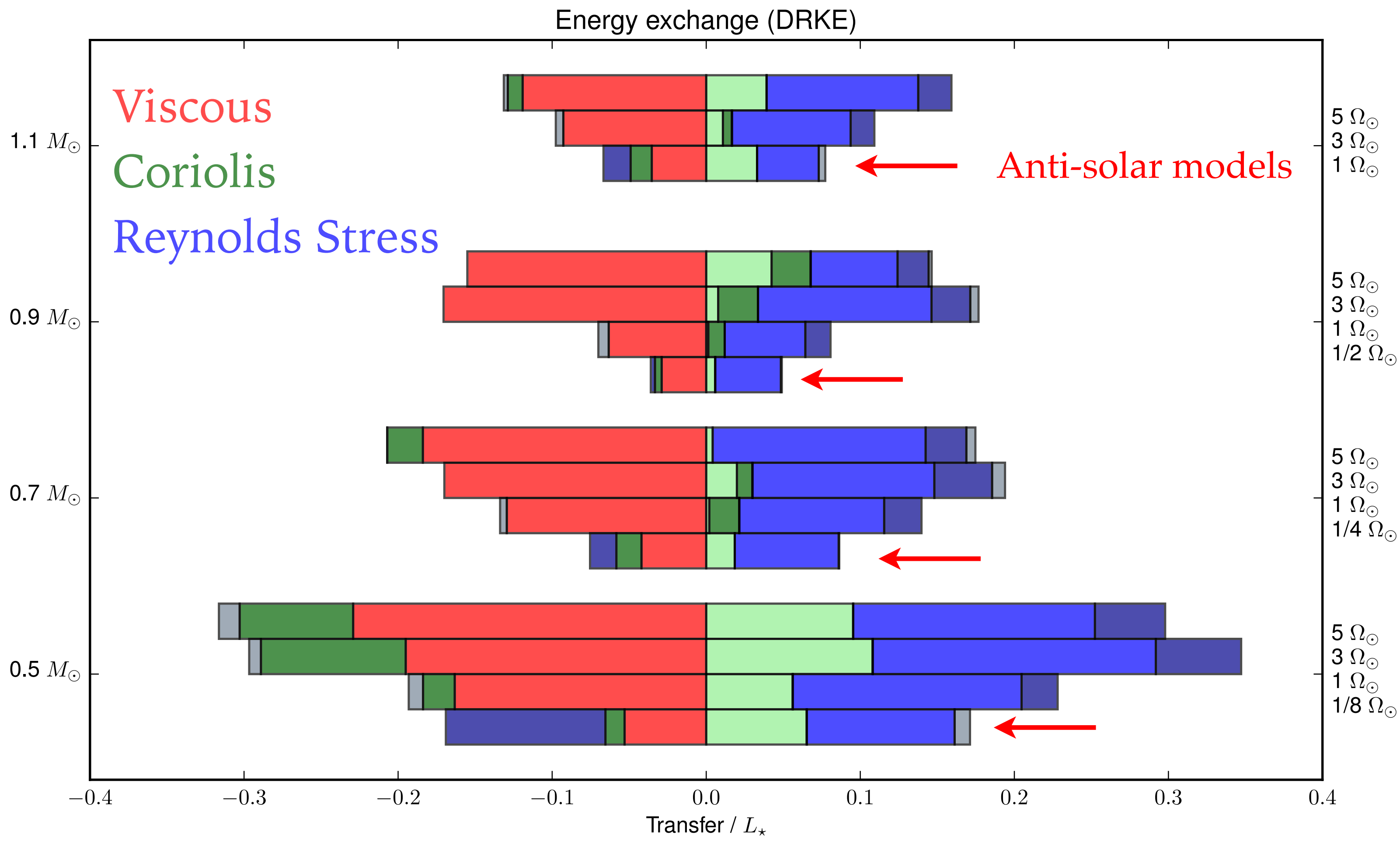

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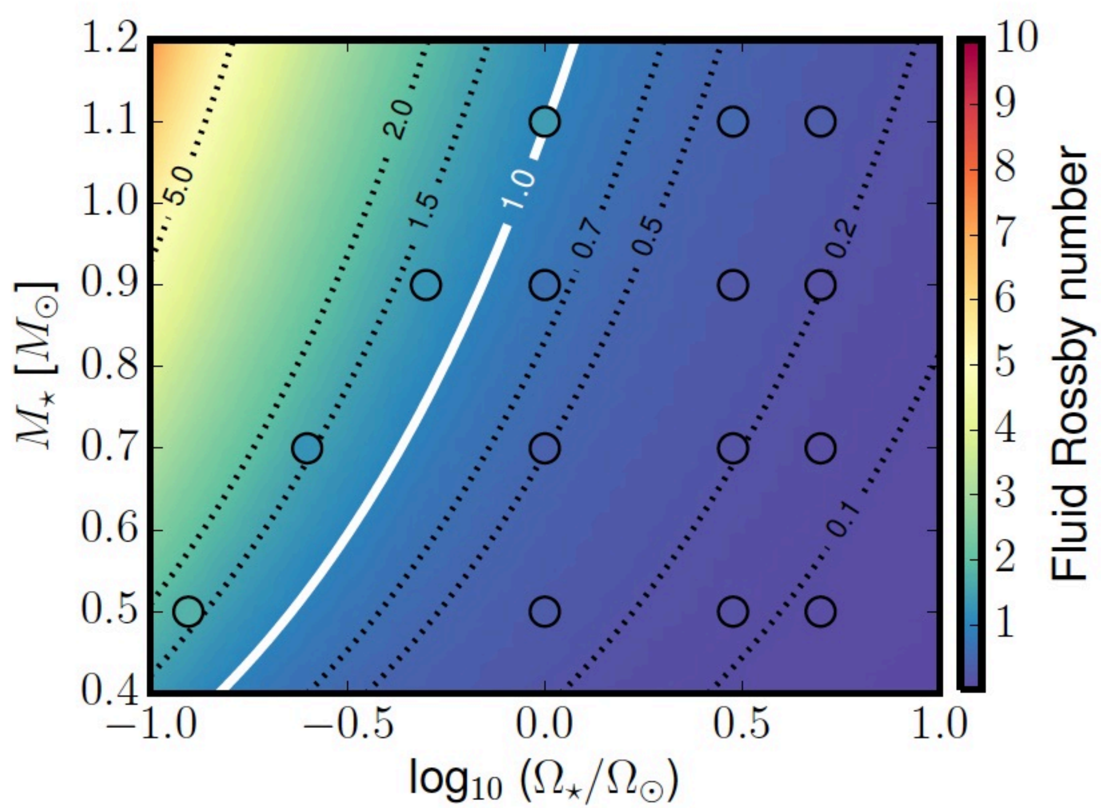

Trend from numerical simulations:

$$R_{of} = 0.87 \times \Omega_*^{-0.81 \pm 0.06} M_*^{1.53 \pm 0.22}$$

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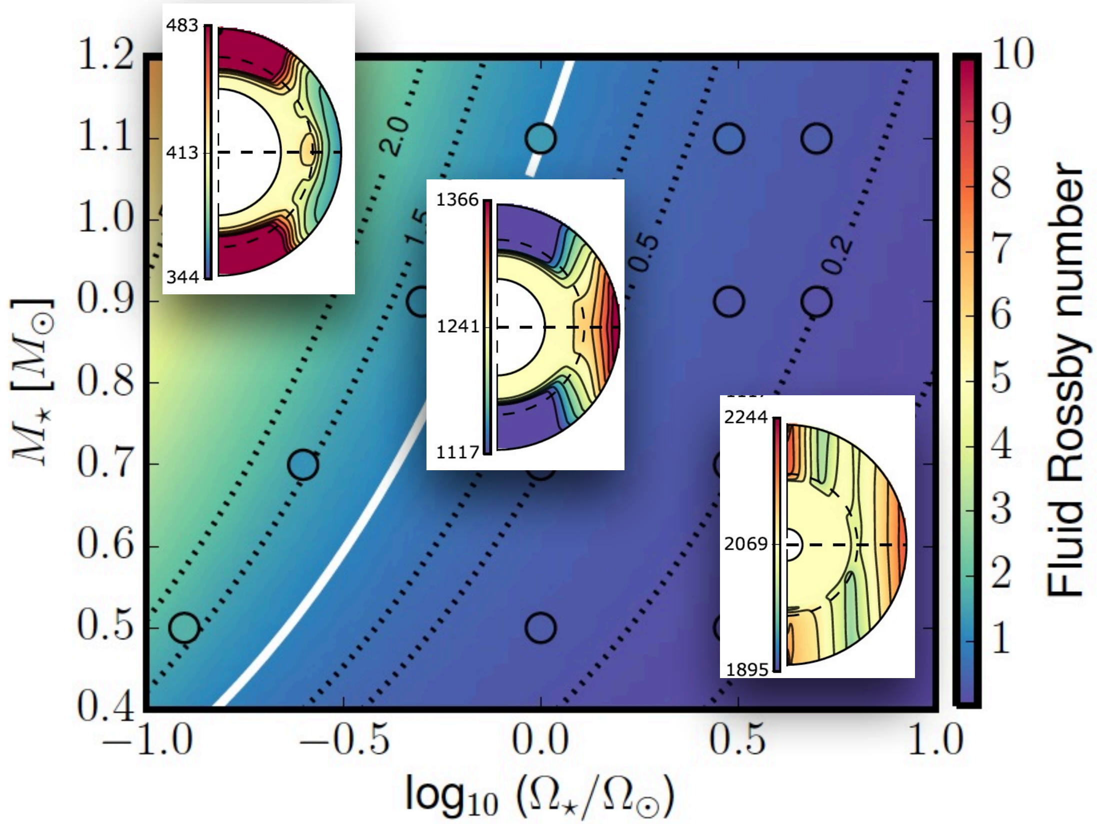

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Understanding the basic ingredients of stellar dynamos

Can the turbulent electromotive force be modelled as an 'alpha' effect?

$$\frac{\partial \langle \boldsymbol{B} \rangle}{\partial t} = \nabla \times (\langle \boldsymbol{U} \rangle \times \langle \boldsymbol{B} \rangle) + \nabla \times (\alpha \langle \boldsymbol{B} \rangle) - \nabla \times (\eta \nabla \times \langle \boldsymbol{B} \rangle).$$

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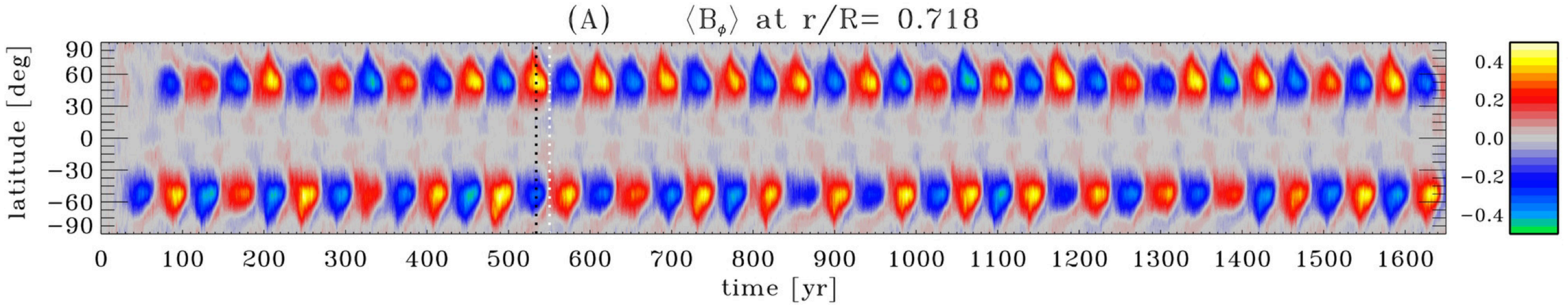

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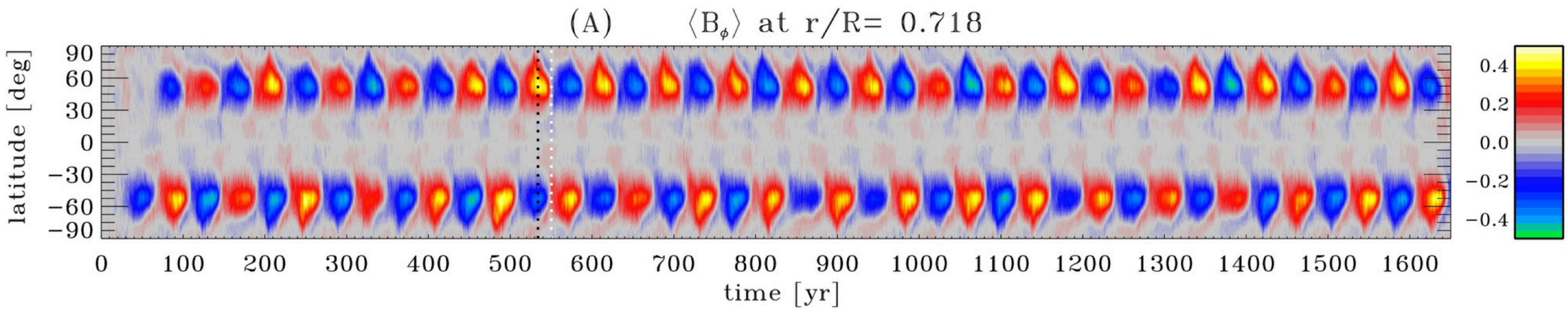

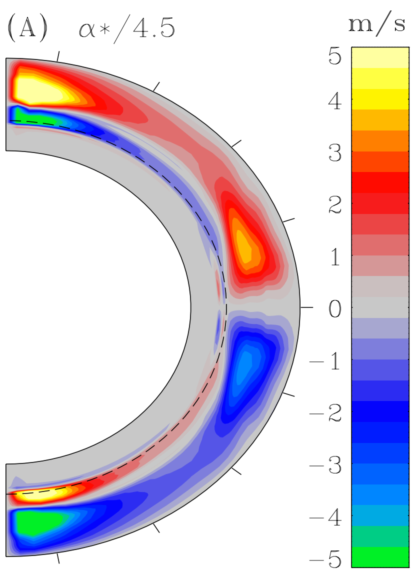

α

Singular Value Decomposition

[Schrinner+ 2007; Simard+ 2016]

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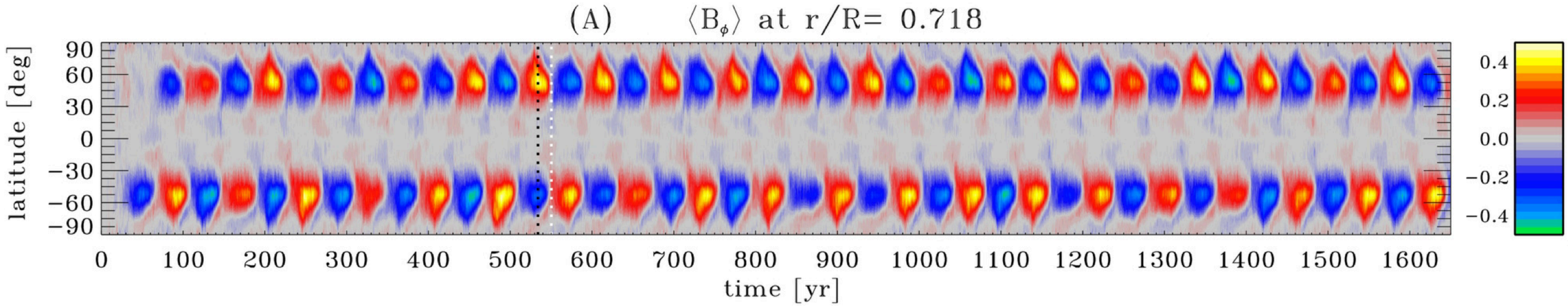

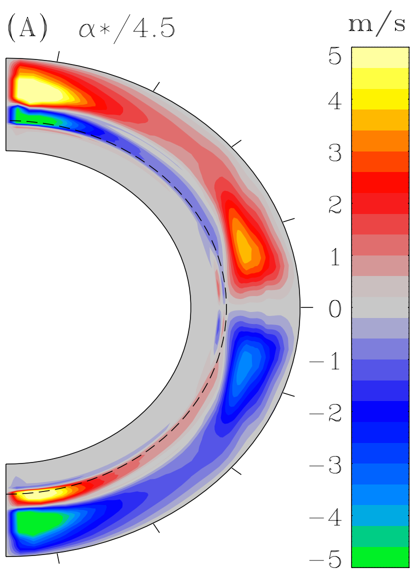

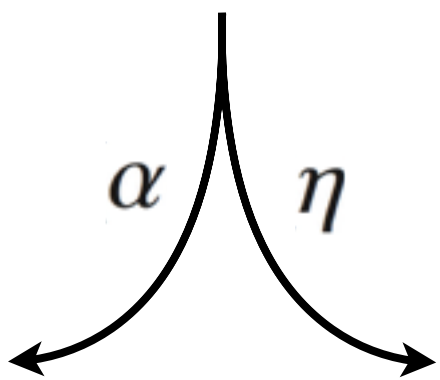

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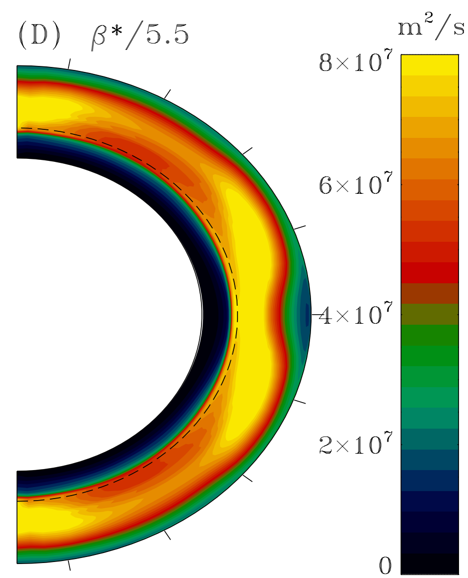

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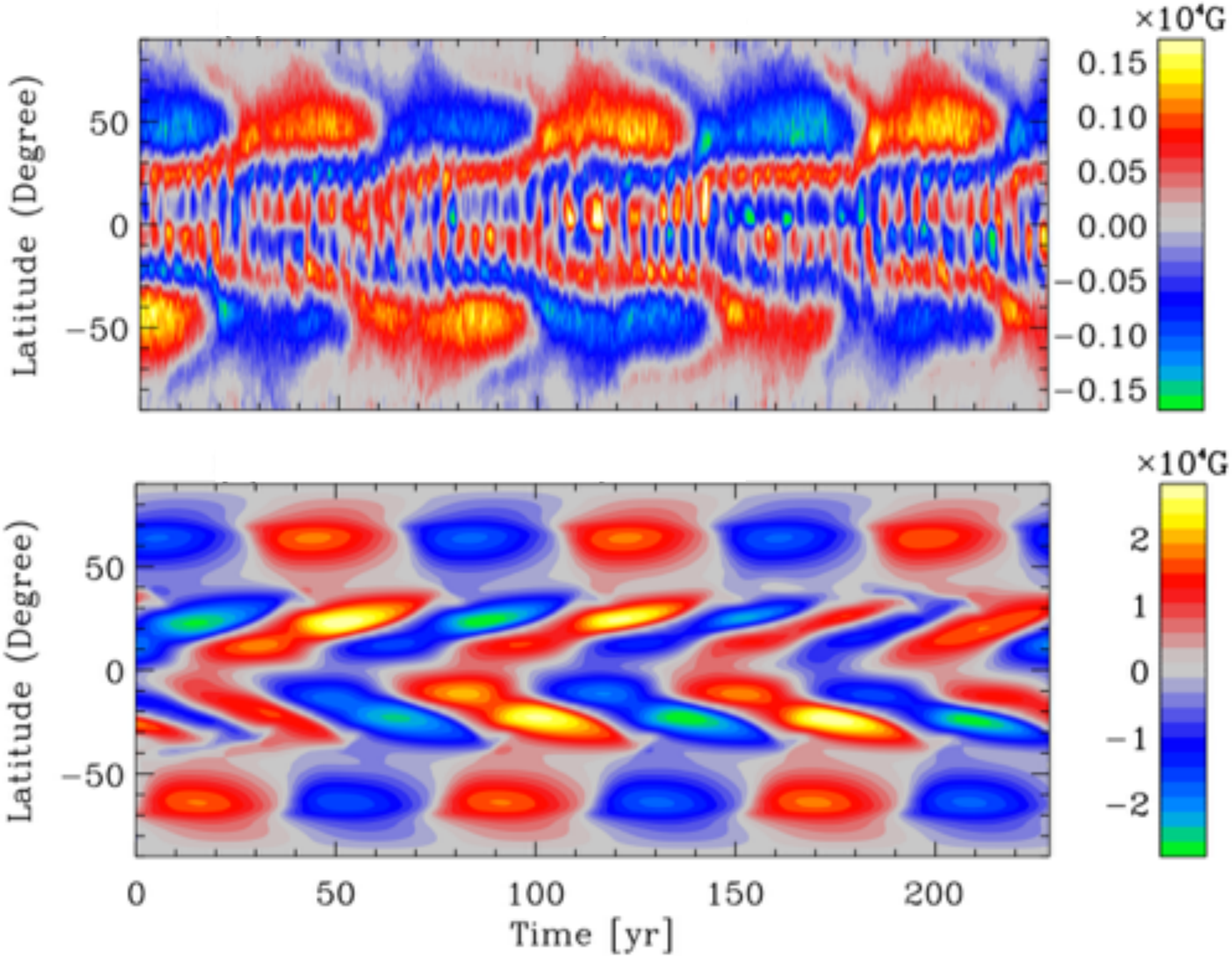


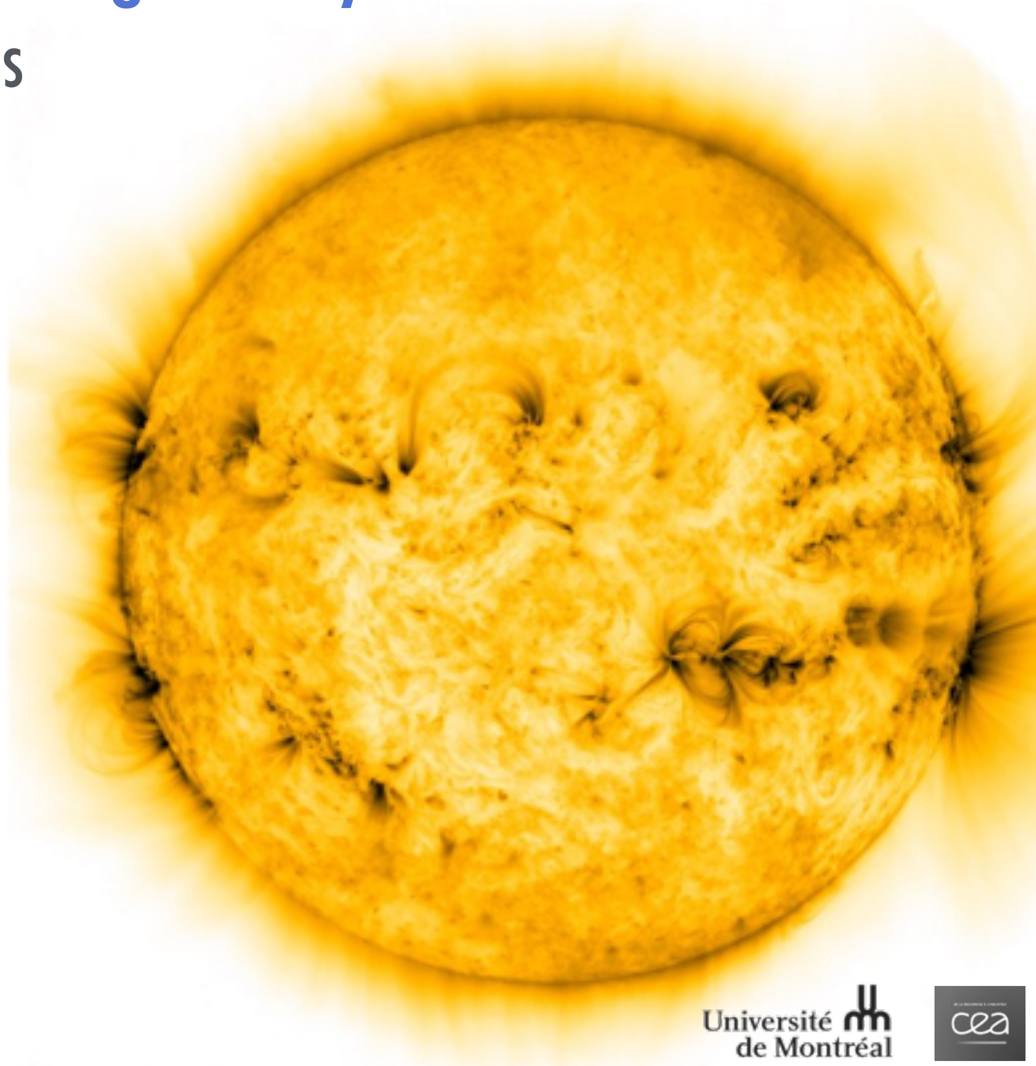
3D Model

Mean field model using extracted α, η

[Simard+, ApJ 2013, Augustson+ ApJ 2016]

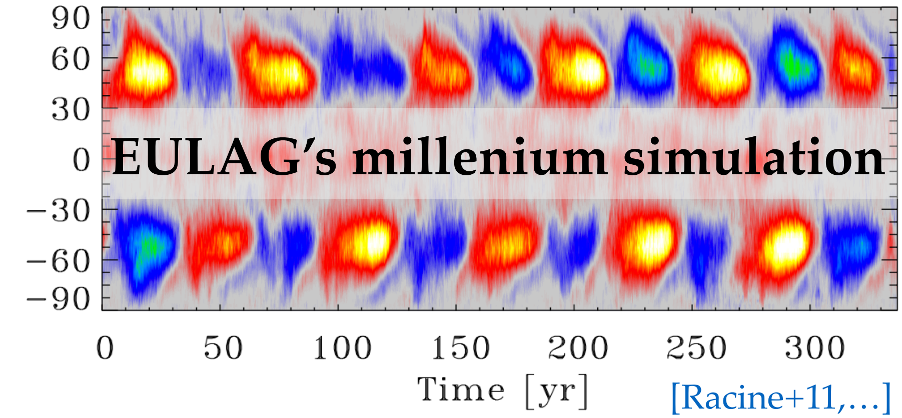
Ab-initio modelling of stellar magnetic cycles

Non-linear, 3D stellar dynamo models



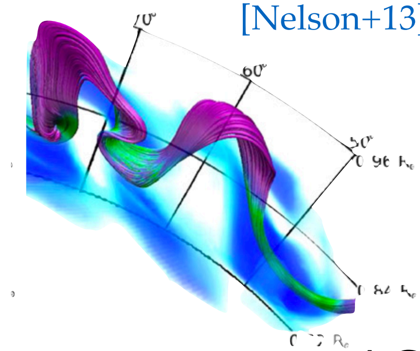
A. Strugarek, Seminar at Laboratoire Leprince-Ringuet, 25/09/2017

The zoo of 3D models

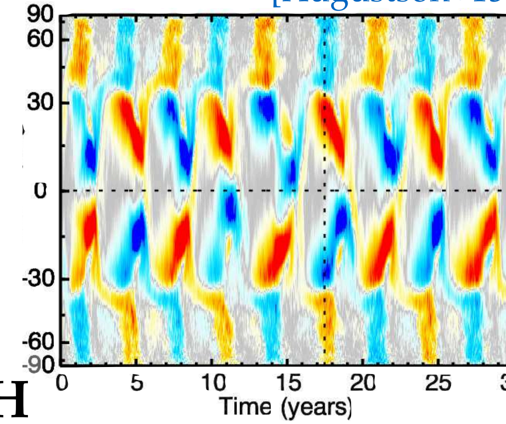


[Racine+11,…]

[Nelson+13]

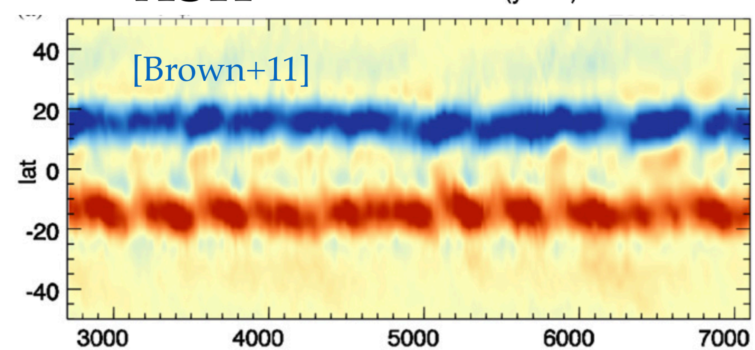


[Augustson+15]

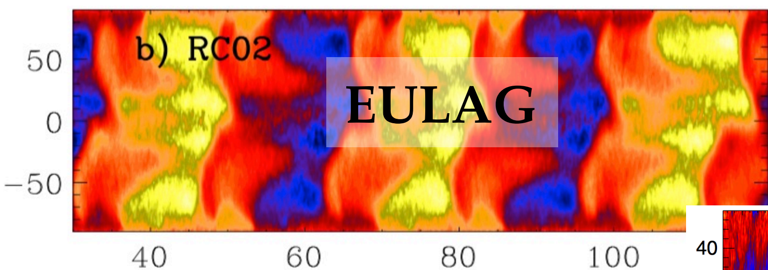


ASH

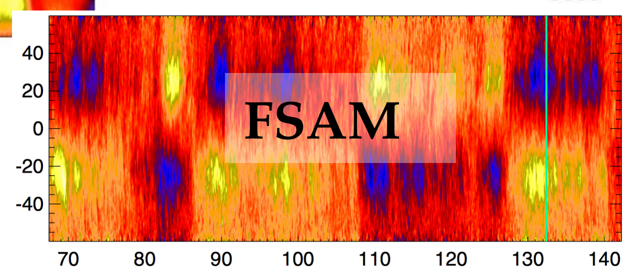
[Brown+11]



[Guerrero+16]

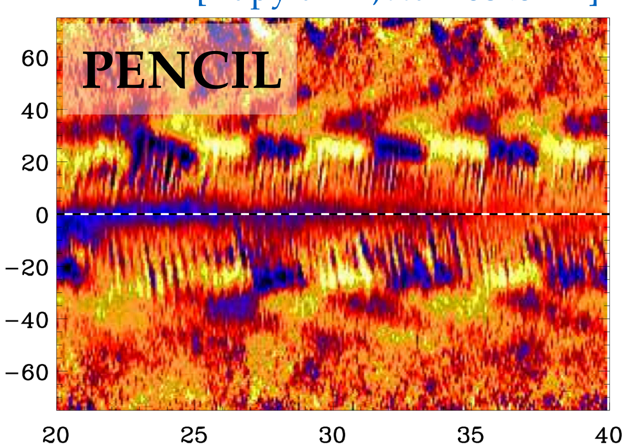


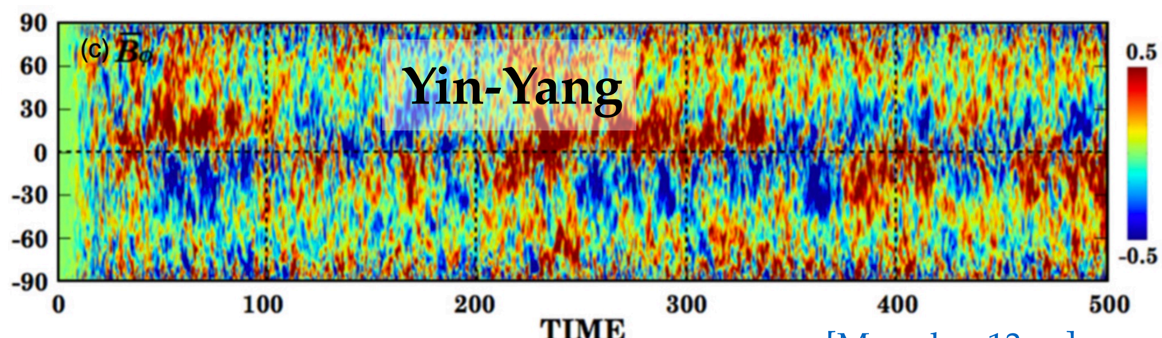
and much more…



[Fan+14]

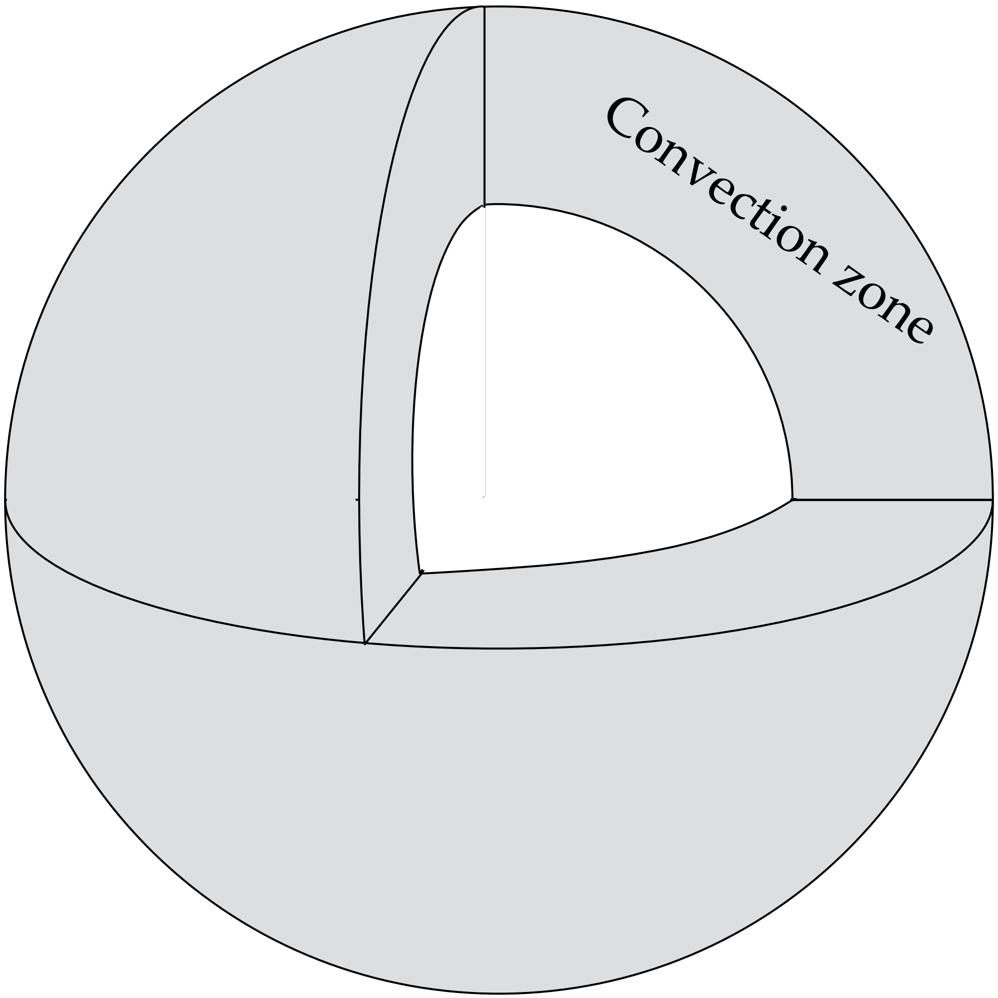
[Kapyla+12,Warnecke+14]





[Masada+ 13,…]

Tool: the EULAG-MHD CODE



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

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

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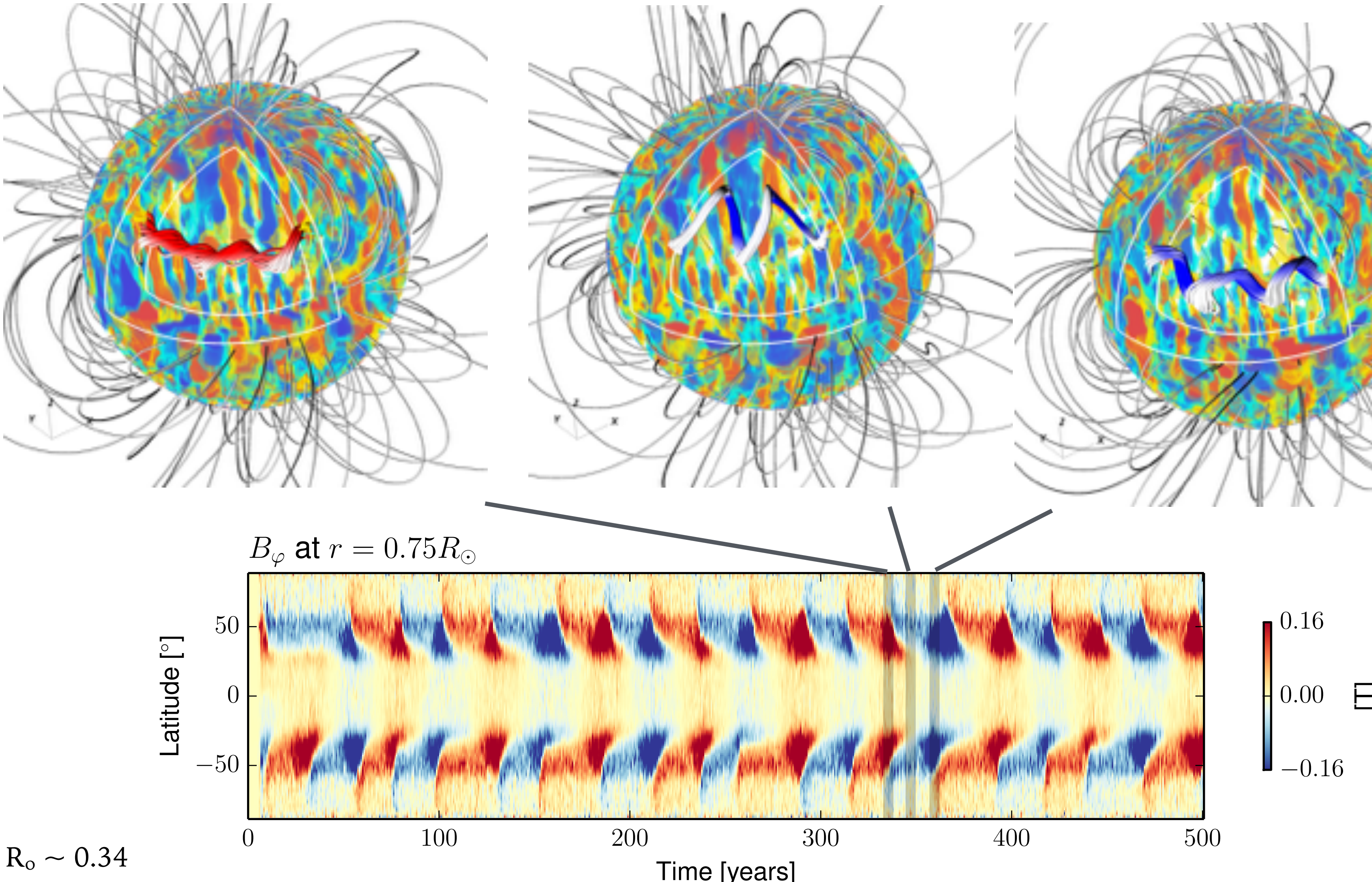
Prototype cyclic dynamo in a convective enveloppe



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

<u>No stable radiative zone</u>

[Strugarek+, Science 2017]

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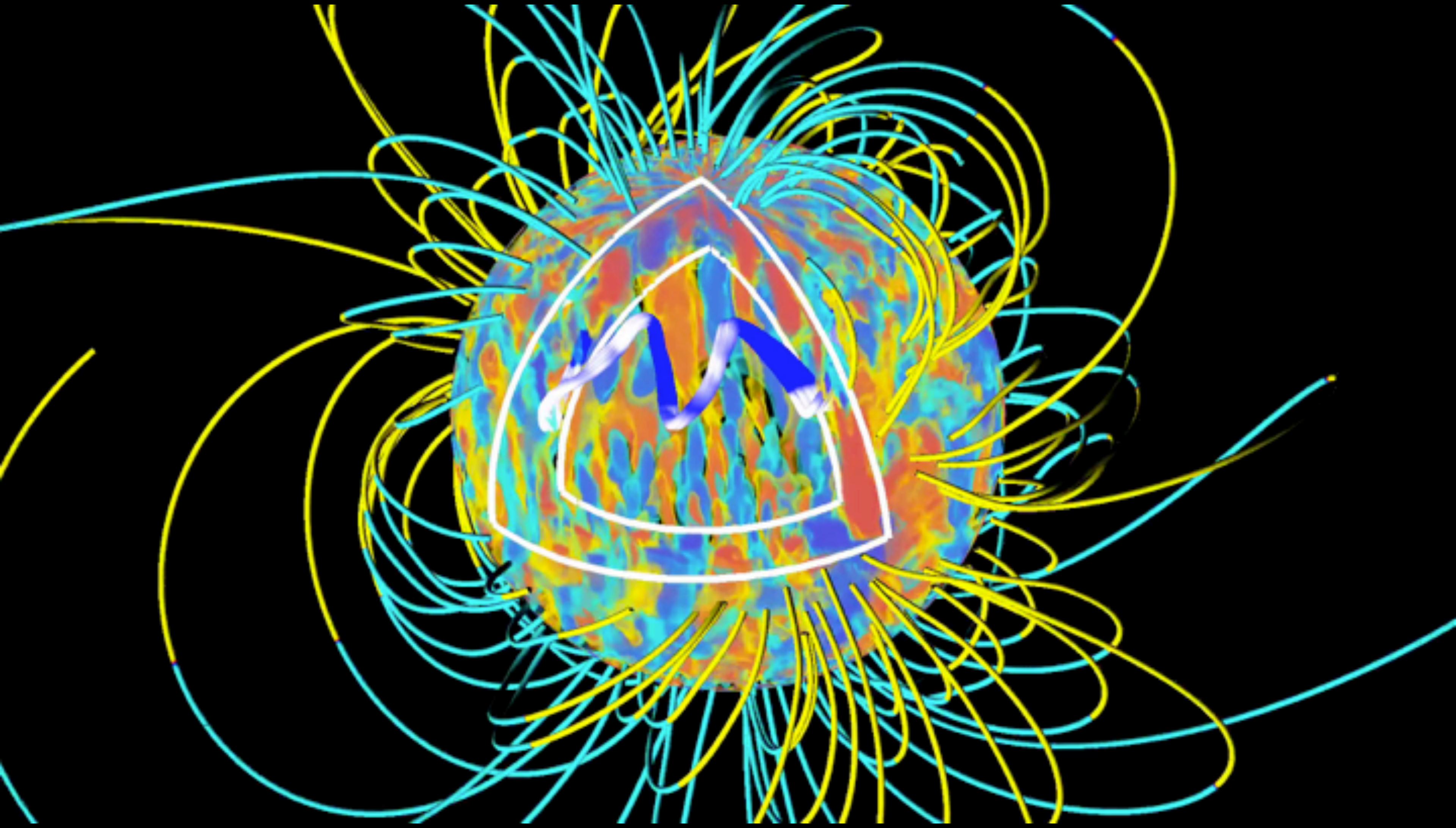

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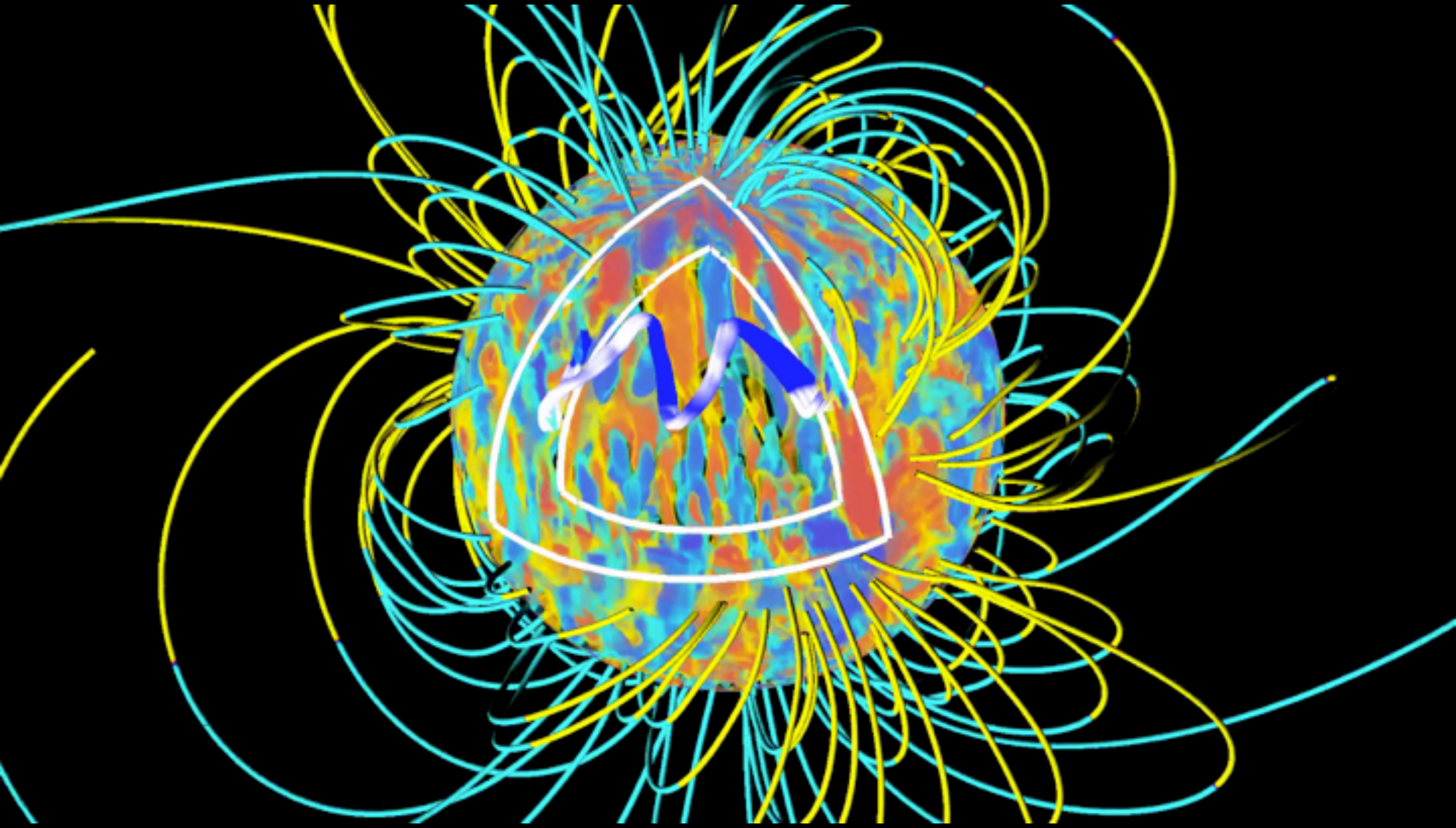
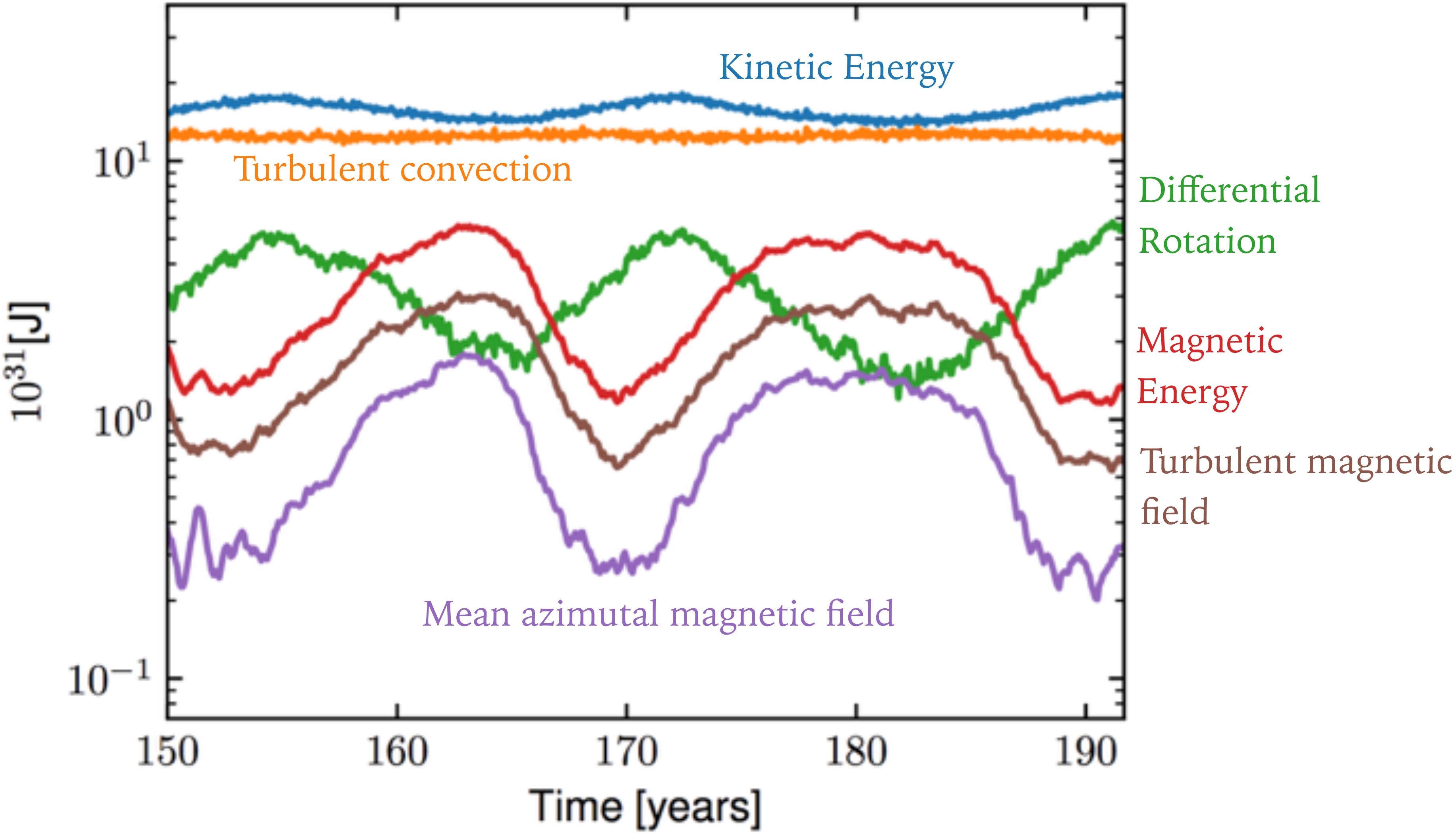
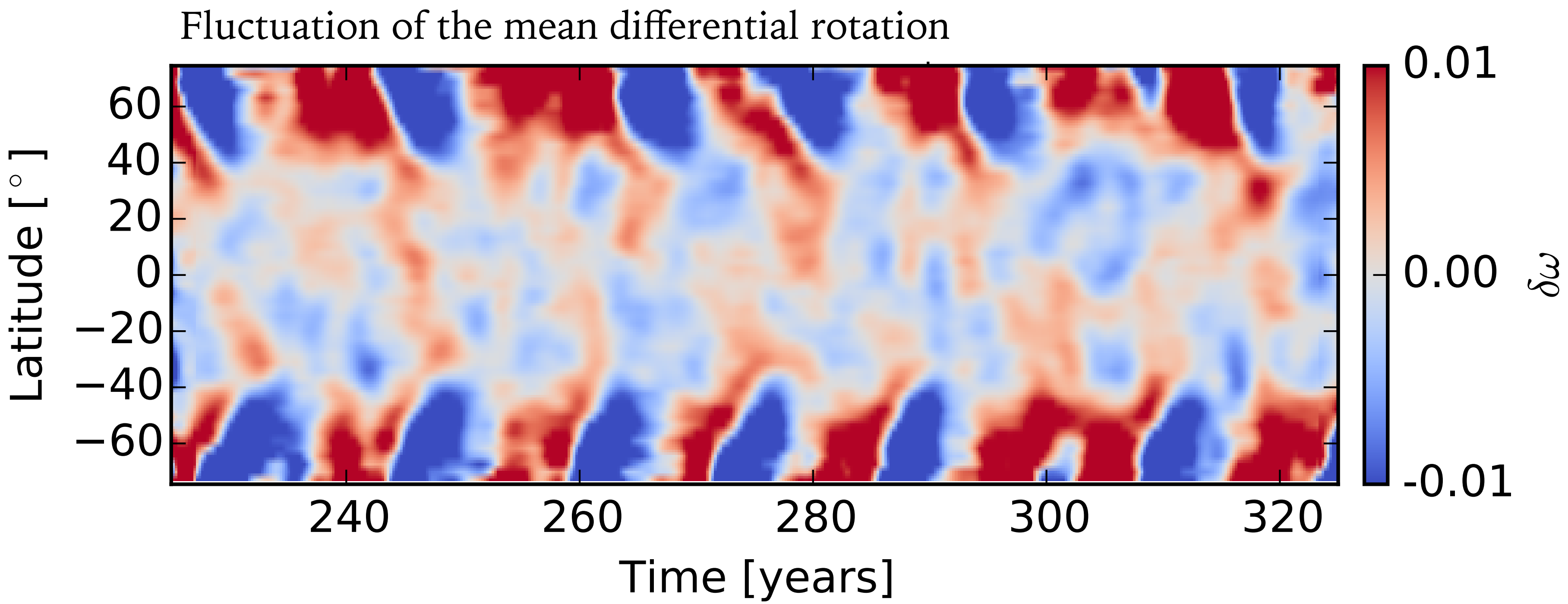


Energetics of the prototype cyclic dynamo



Fluctuations of the differential rotation drive the reversals



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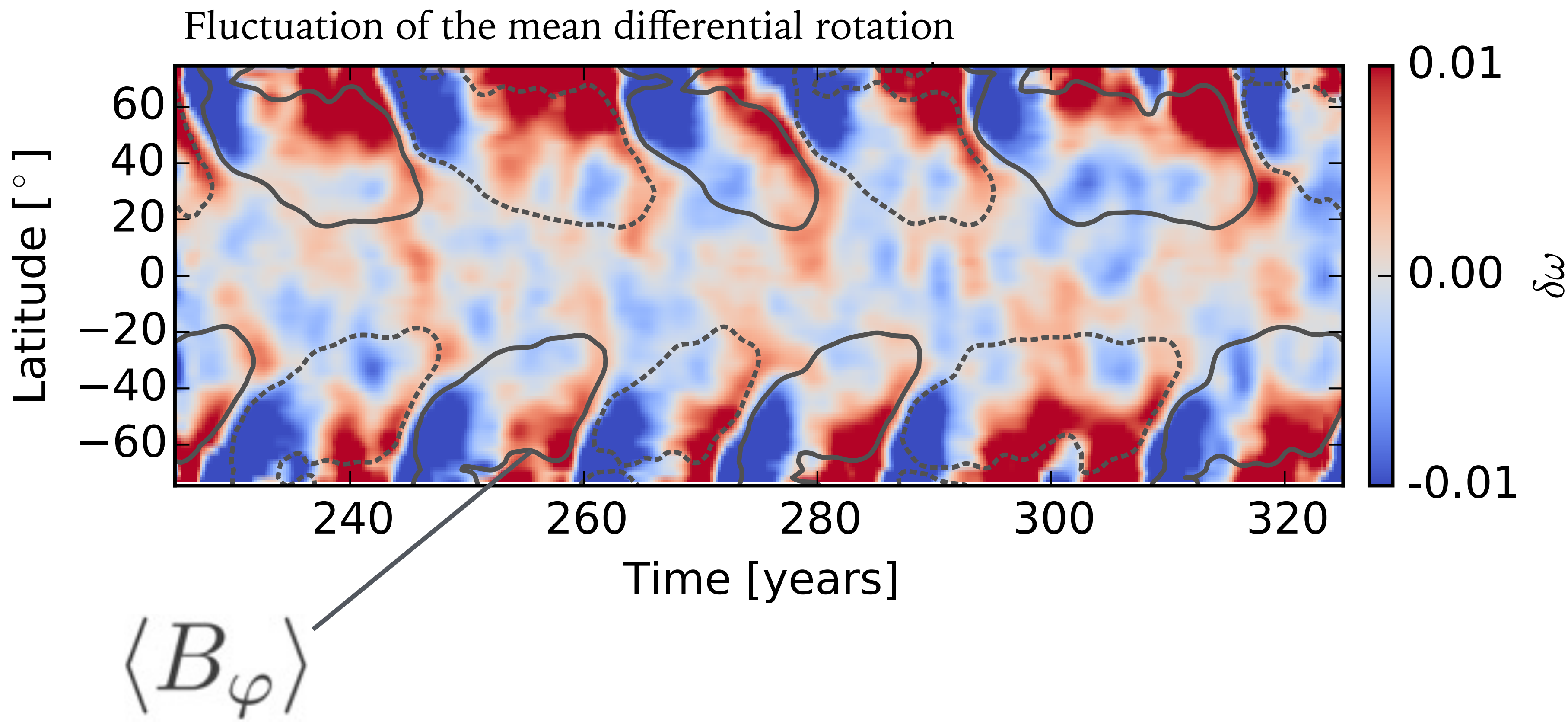

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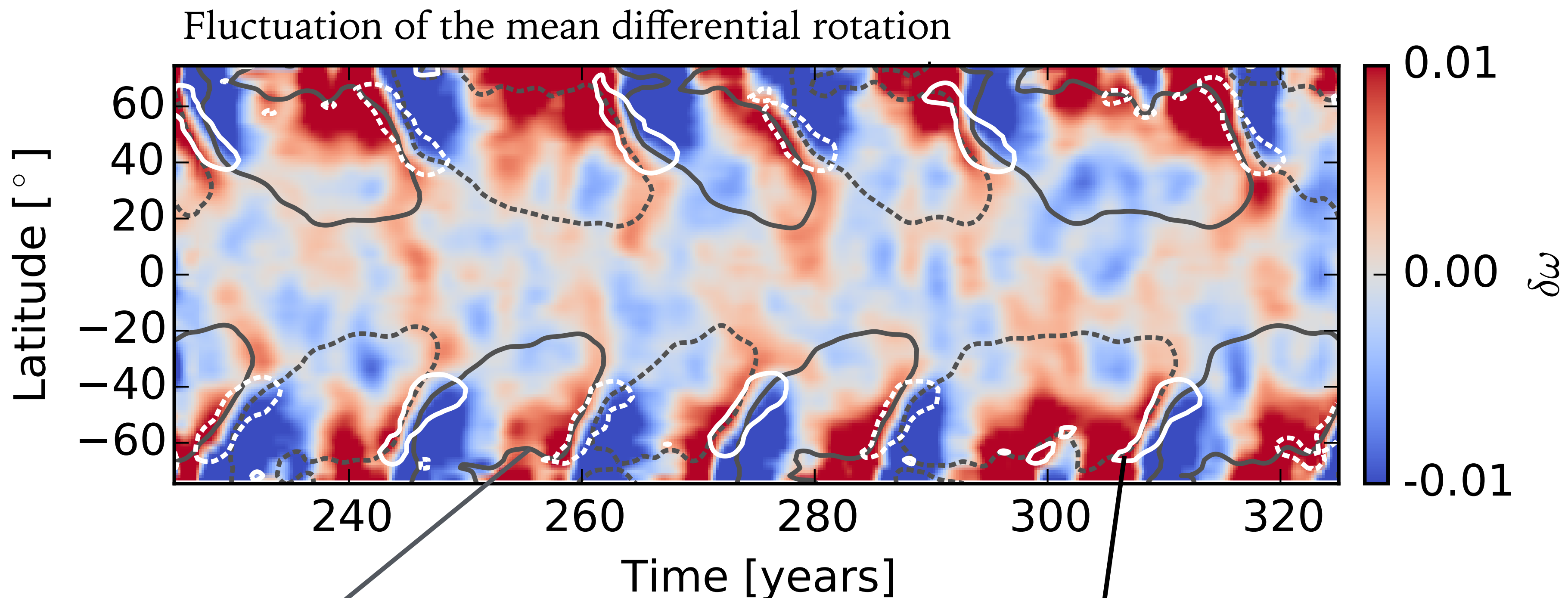
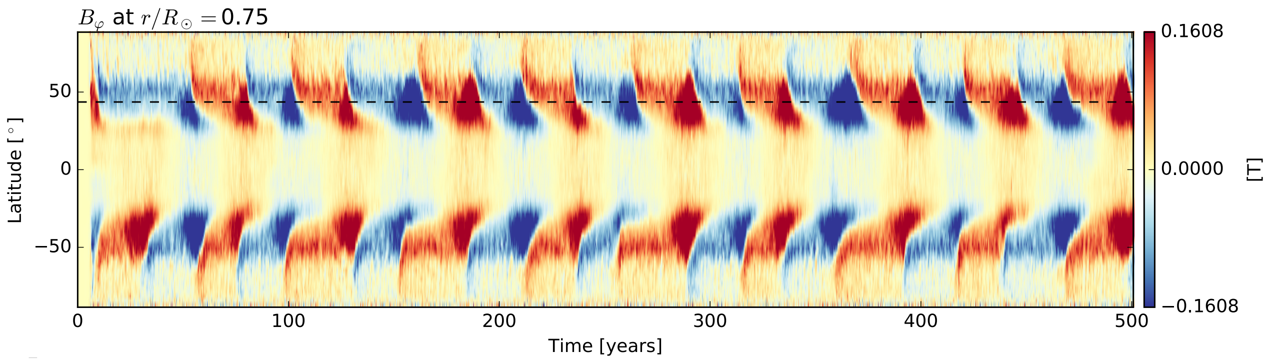


$$\langle B_\varphi \rangle$$

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

Systematic modulation of the cycle period

Ref.



$$P_{\rm cyc} = 28 \text{ yrs}$$

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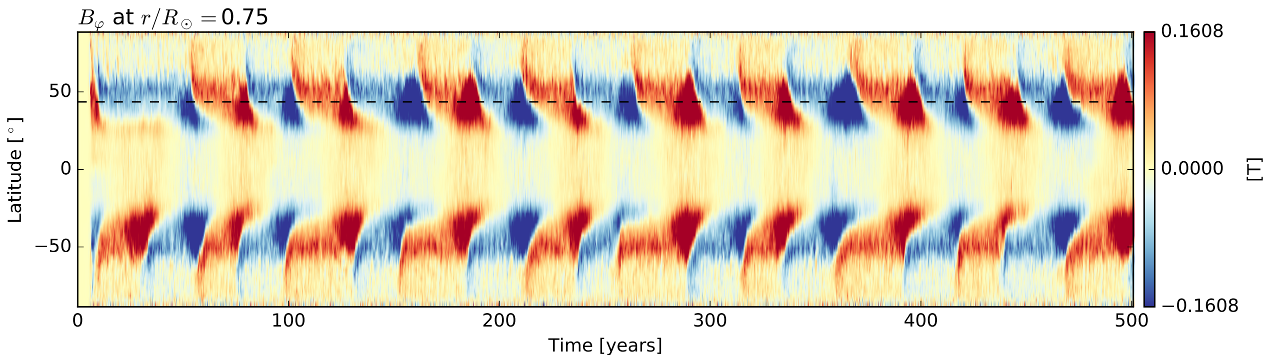

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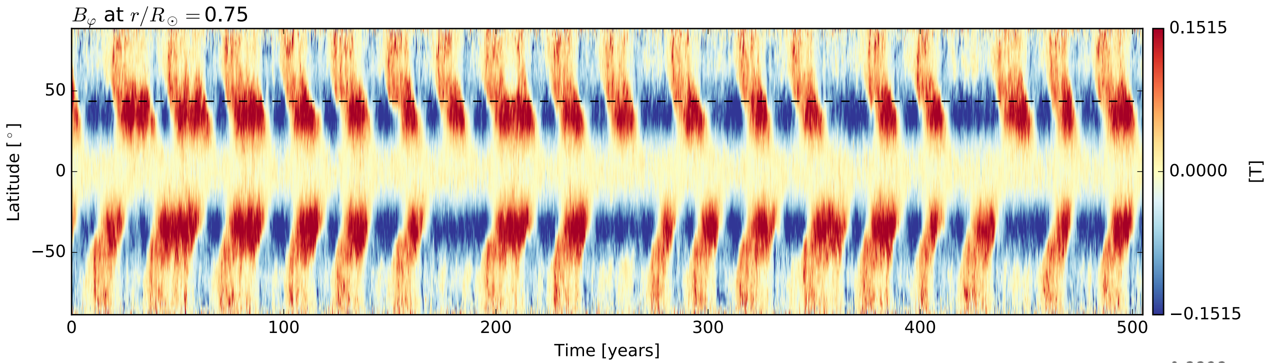
$\Omega/2$



$$P_{\rm cyc} = 13 \text{ yrs}$$

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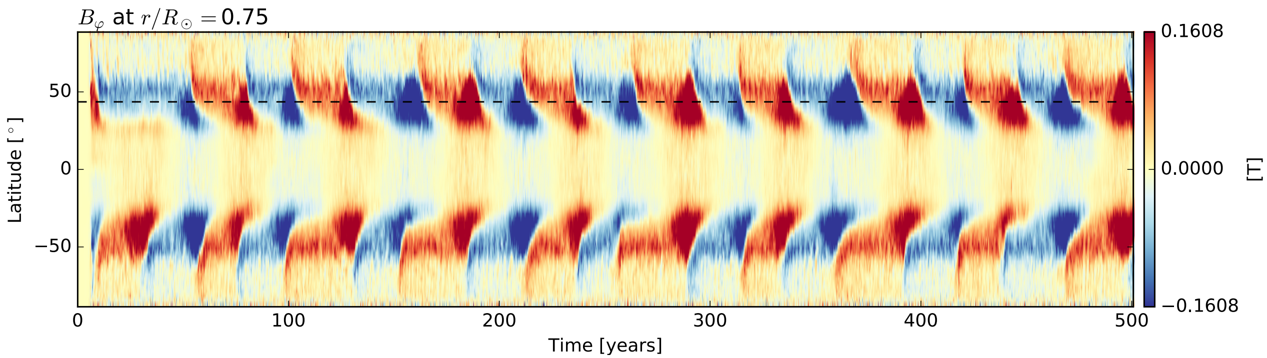

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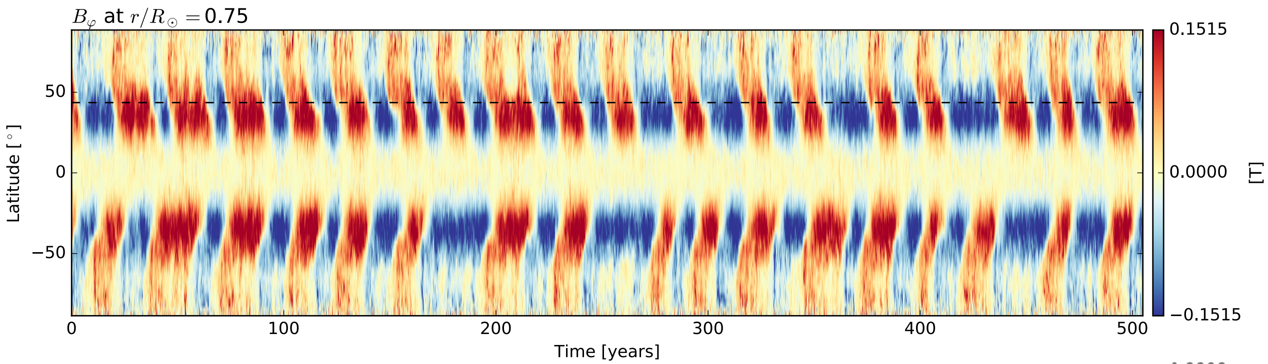

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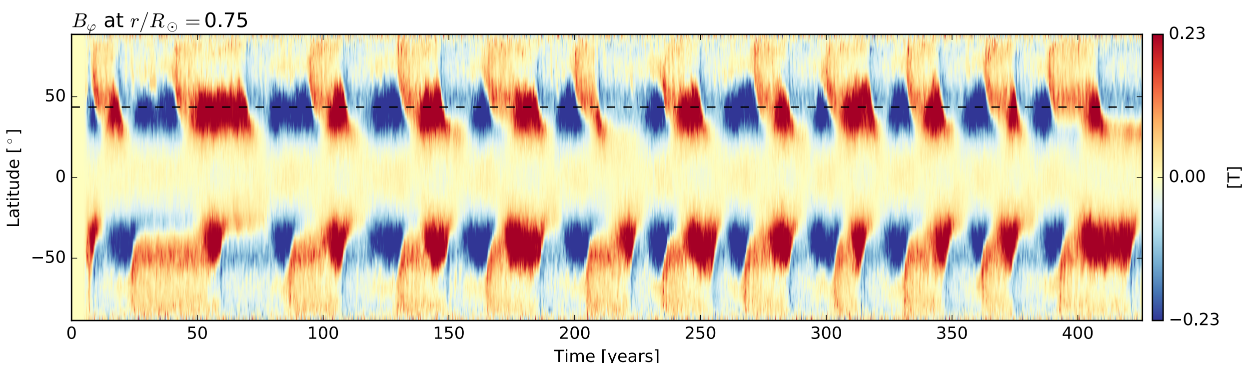
Lum. x 2



$P_{\mathrm{cyc}} = 17$ yrs

Cycle period is inversely prop. to the Rossby number

Basic ingredients of stellar dynamos

- Differential rotation
- Cyclonic turbulence

'Go to' parameter is the
Rossby number

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

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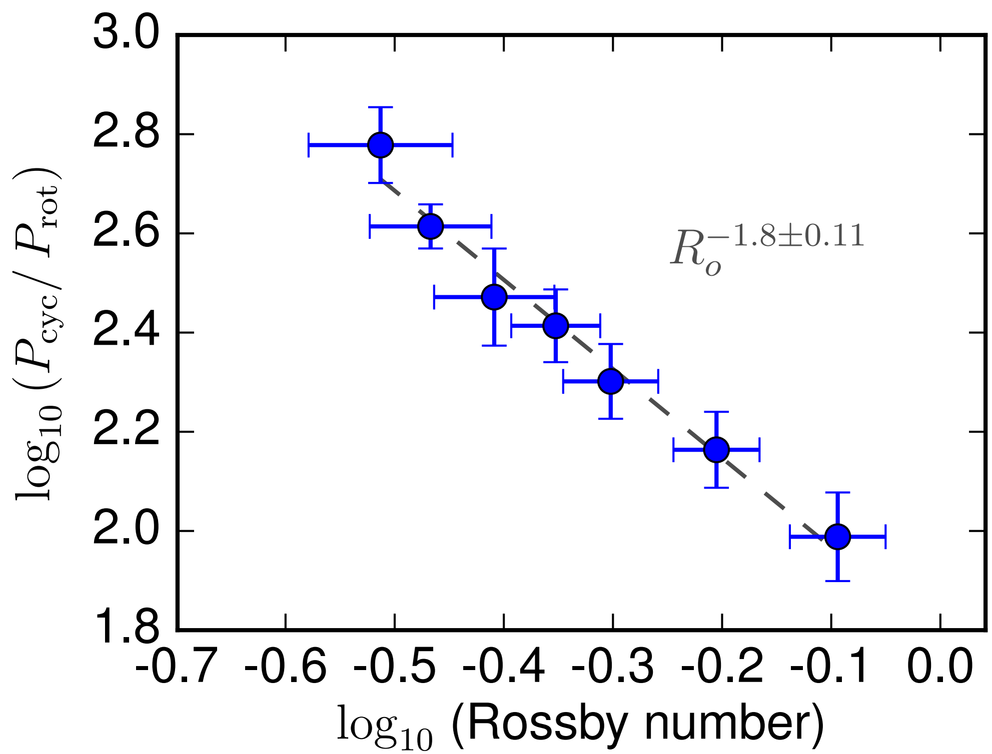

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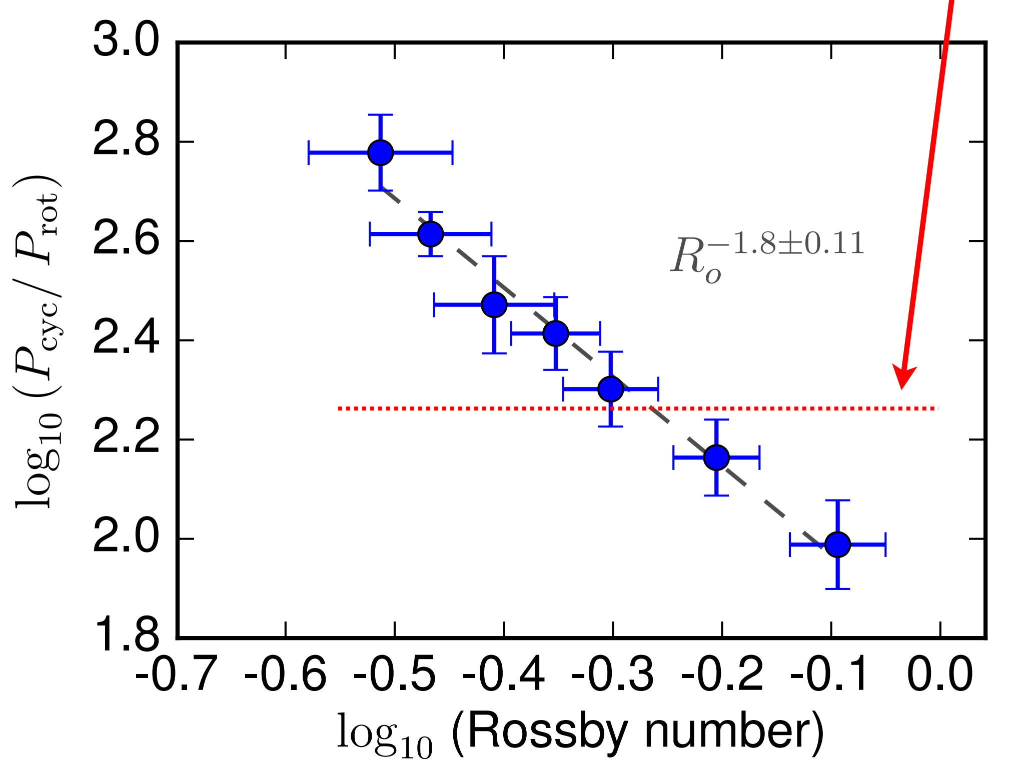
Basic linear αΩ kinematic dynamo theory



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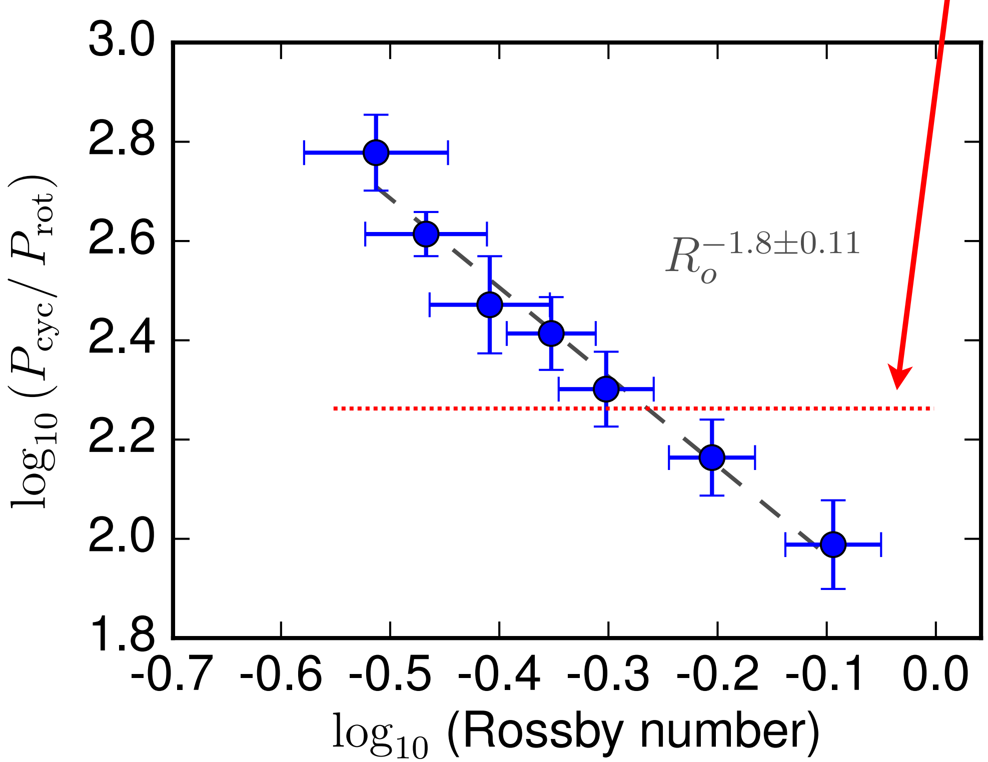
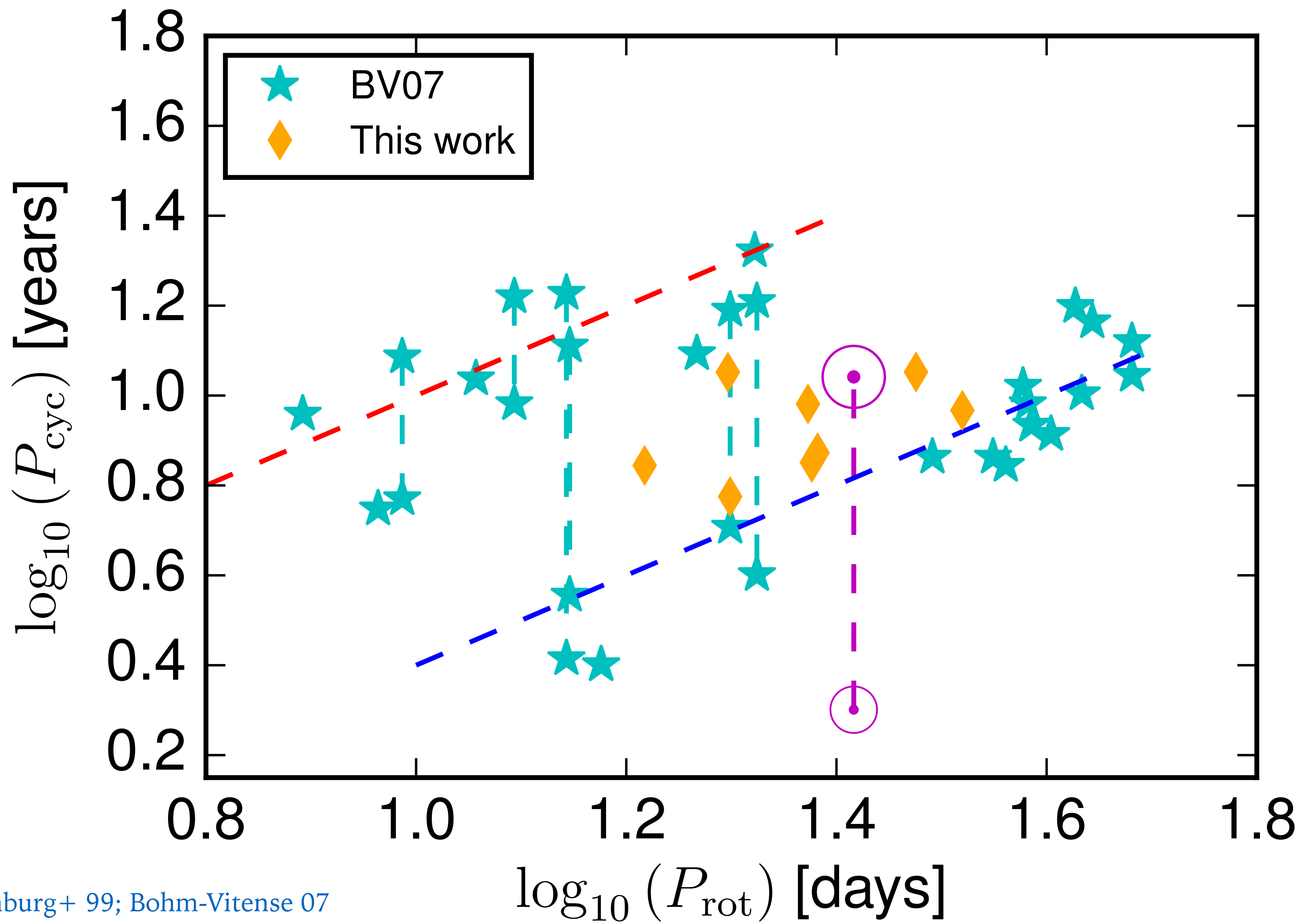


Fundamentally non-linear convective dynamo: not a classical dynamo wave

Could this be realistic?

Cycle period – Rotation period diagram



Brandenburg+ 99; Bohm-Vitense 07
Metcalfe+ 16; Strugarek+ 17

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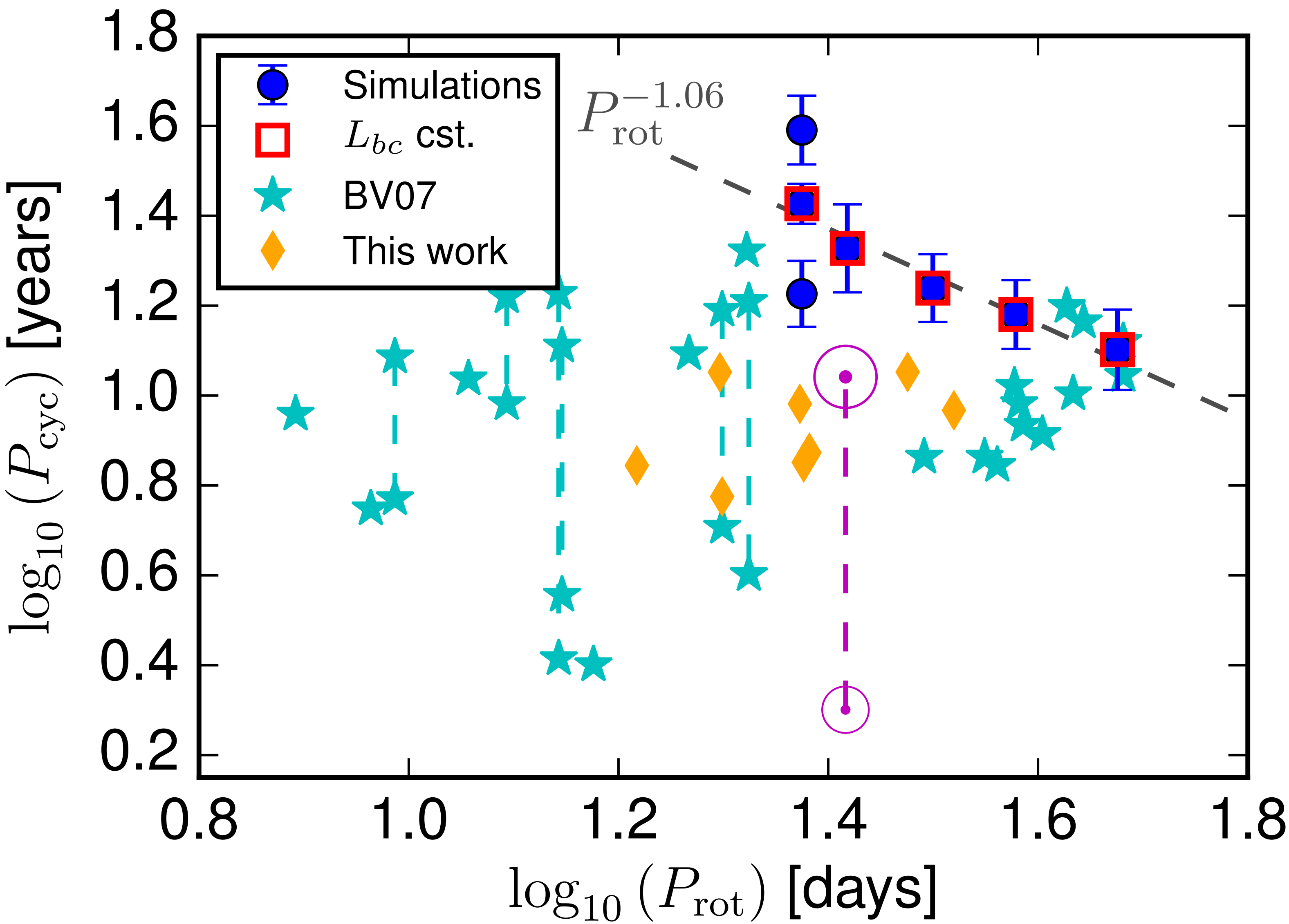
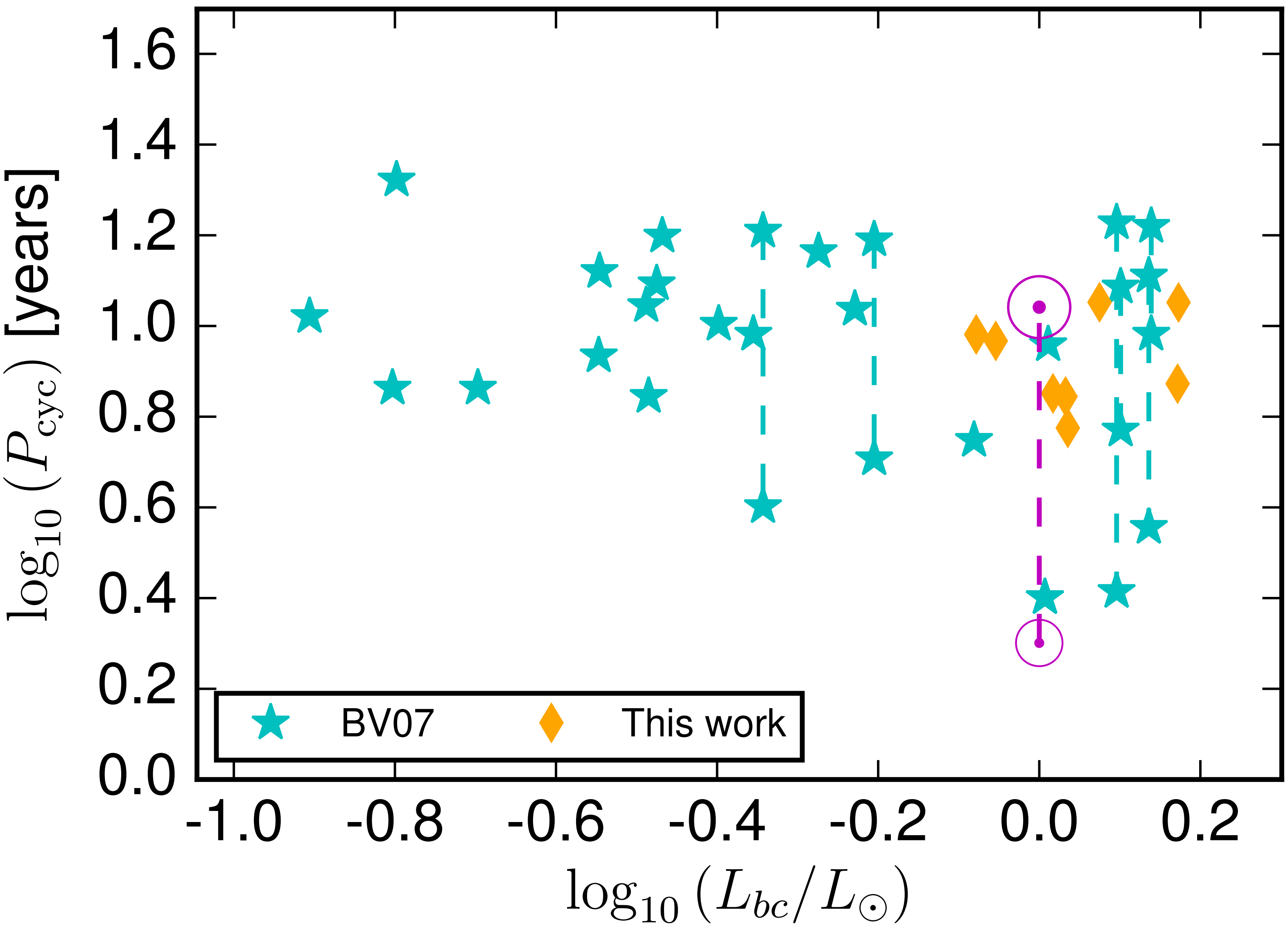


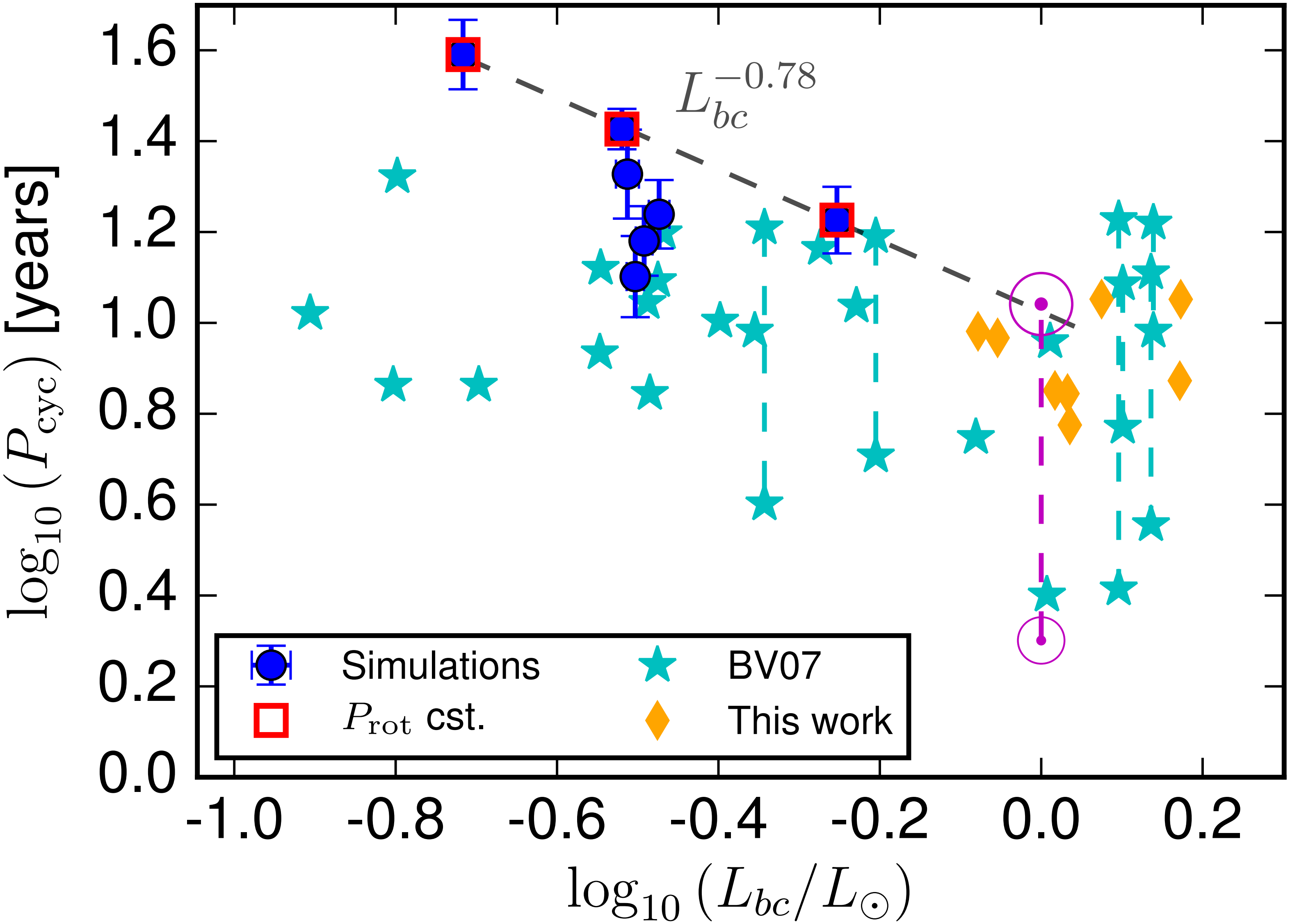
[Strugarek+ 17]

Cycle period – Luminosity diagram



[Strugarek+ 17]

Cycle period parametrization in the stellar context



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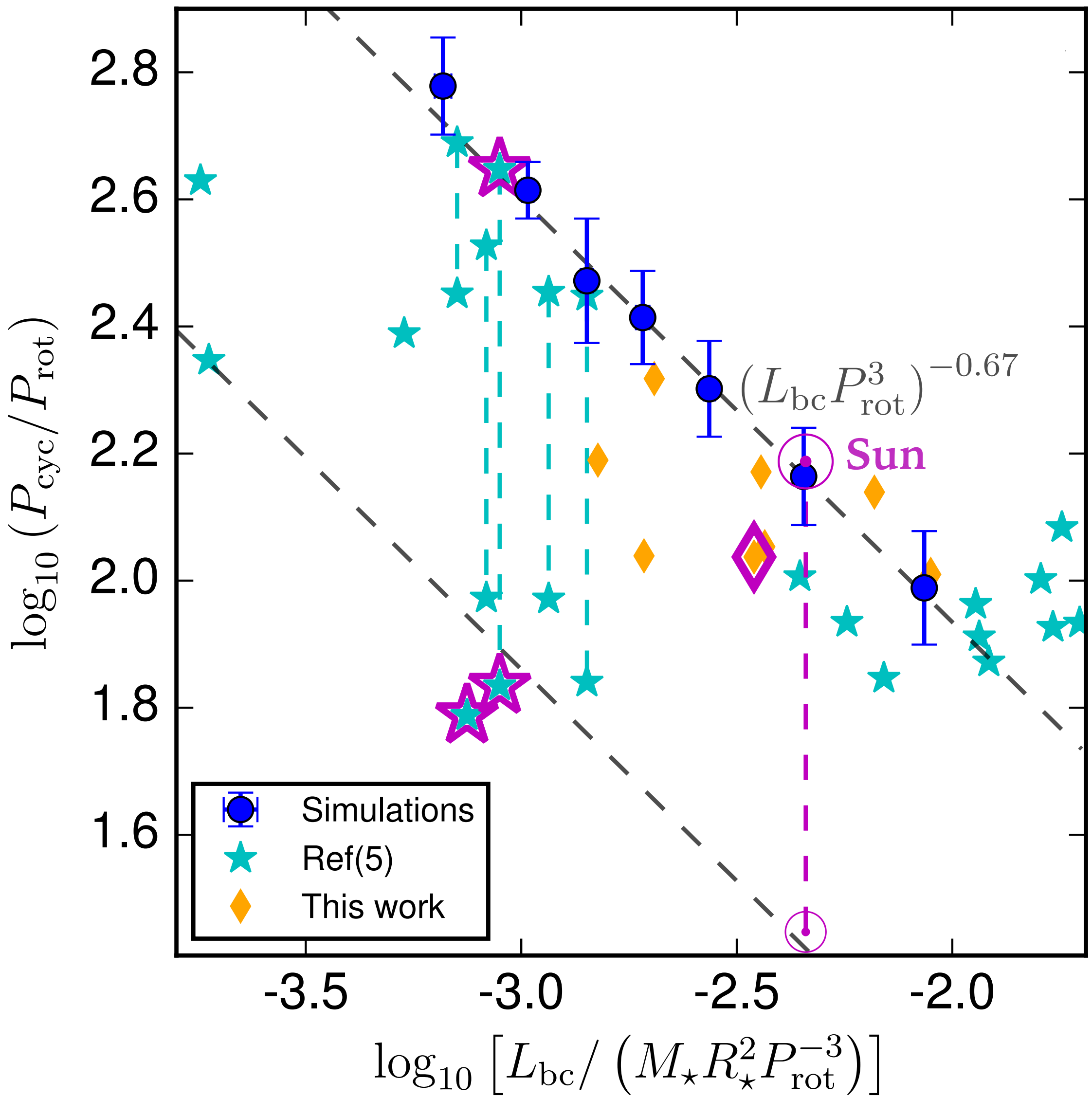

A **non-linear dynamo mechanism** relying on the temporal **fluctuation** of the **large-scale differential rotation, reconciling solar and stellar magnetic cycle periods**

[Strugarek+ 17]

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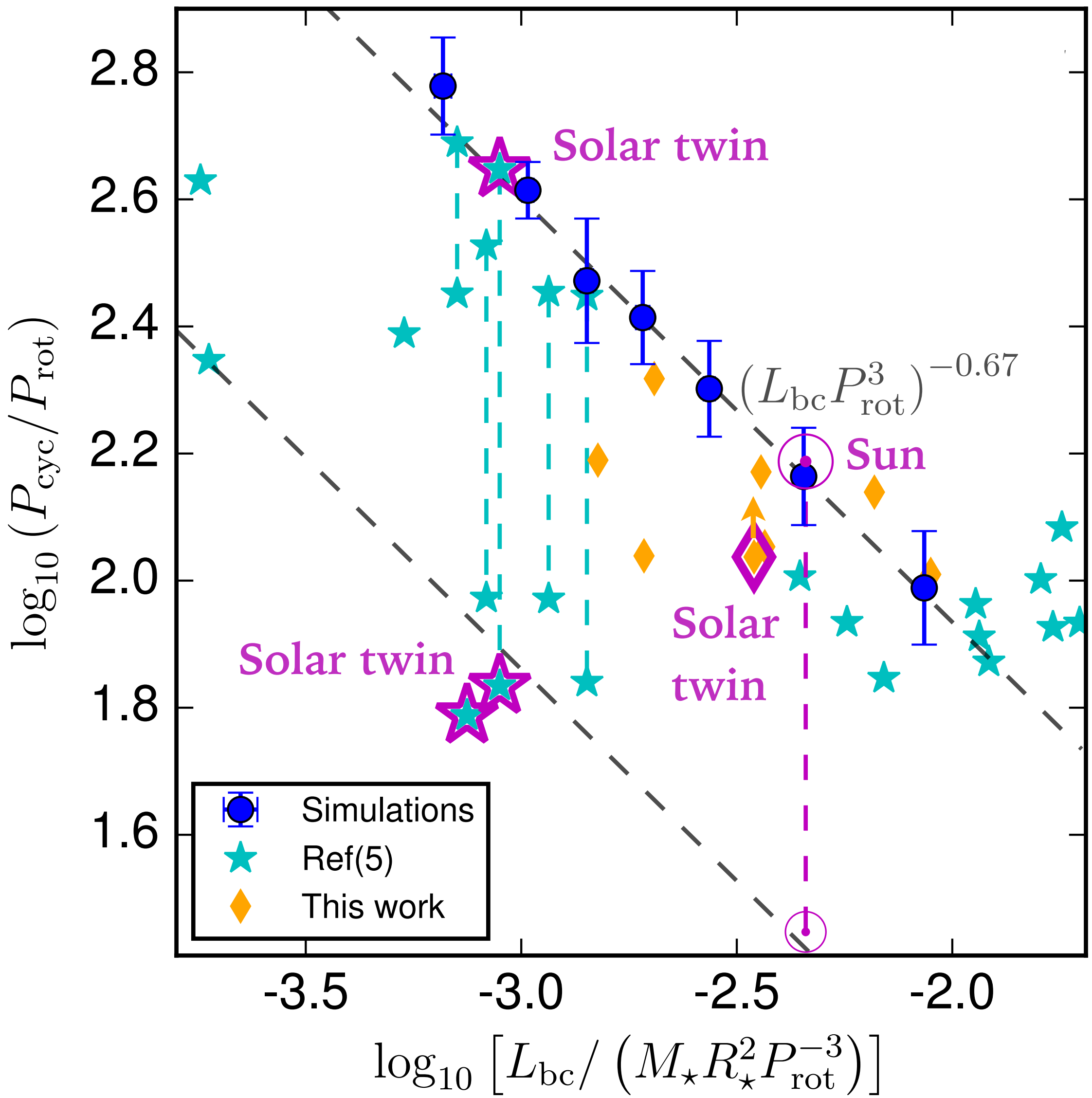

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[Strugarek+ 17]

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Conclusions

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

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Exciting times as fundamental aspects of stellar dynamos are being revised from both observations and theories

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