Mechanisms driving solar cycle variability

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1. Dynamos
2. Cycle prediction with dynamo models
3. Stochastic forcing and nonlinearities
4. Modulation on long time scale
5. Where do we go from here ?

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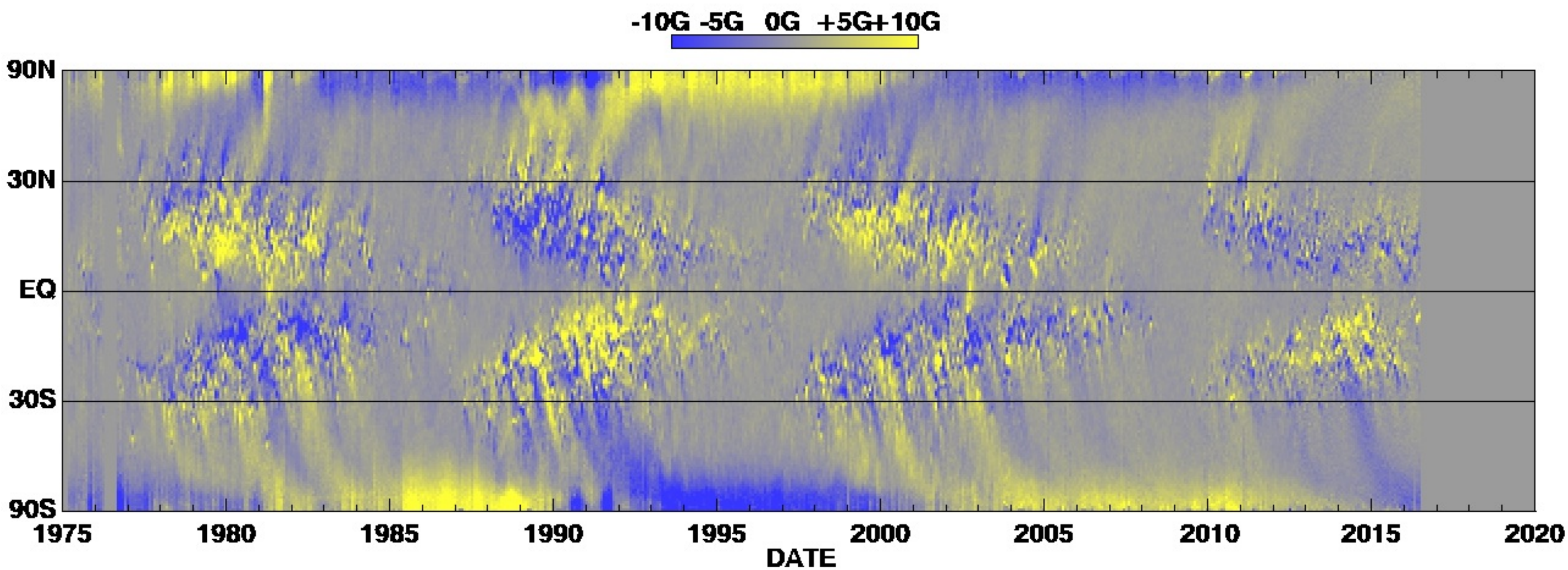
Cycle prediction with dynamos (1)



Hathaway NASA ARC 2016/08

The solar cycle/dynamo as a 2-steps process:

… ⇨ T(+) ⇨ P(+) ⇨ T(-) ⇨ P(-) ⇨ T(+) ⇨ …

Dynamo = kinetic to magnetic energy

Magnetohydrodynamical induction: flow of electrically conducting fluid across magnetic fields, in collisionnally-dominated plasma regime:

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

Form magnetic energy equation by dotting **B** into above, and integrating over volume of the sun/star:

$$\frac{\mathrm{d}E_B}{\mathrm{d}t} \equiv \frac{\mathrm{d}}{\mathrm{d}t} \int_V \frac{\mathrm{B}^2}{2\mu_0} \mathrm{dV} = - \oint_{\partial \mathrm{V}} \mathbf{S} \cdot \hat{\mathbf{n}}\, \mathrm{dA} - \frac{1}{\sigma} \int_{\mathrm{V}} \mathbf{J}^2 \mathrm{dV} - \int_{\mathrm{V}} \mathbf{u} \cdot (\mathbf{J} \times \mathbf{B}) \mathrm{dV}$$

Poynting flux

Current density

Lorentz force

Cycle prediction with dynamos

VOL. 5, NO. 5 GEOPHYSICAL RESEARCH LETTERS MAY 1978

USING DYNAMO THEORY TO PREDICT

THE SUNSPOT NUMBER DURING SOLAR CYCLE 21

Kenneth H. Schatten, Philip H. Scherrer, Leif Svalgaard and John M. Wilcox

Institute for Plasma Research, Stanford University, Stanford, California

Abstract. On physical grounds it is suggested that the sun's polar field strength near a solar minimum is closely related to the following cycle's solar activity. Four methods of estimating the sun's polar magnetic field strength near solar minimum are employed to provide an estimate of cycle 21's yearly mean sunspot number at solar maximum of 140 ± 20. We think of this estimate as a first order attempt to predict the cycle's activity using one parameter of physical importance based upon dynamo theory.

Polar Field Strength

Estimates of the polar magnetic field strength near sunspot minimum may be obtained from the shape of the corona at the time of solar eclipses, or by the amount of flattening of the "warped current sheet" at 1AU as obtained from interplanetary magnetic field measurements analysed in accordance with the methods of Rosenberg and Coleman (1969). A further and more direct estimate of polar field strength is obtained by observing the number of polar faculae

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L05102, doi:10.1029/2005GL025221, 2006

Predicting the strength of solar cycle 24 using a flux-transport dynamo-based tool

Mausumi Dikpati,[1] Giuliana de Toma,[1] and Peter A. Gilman[1]

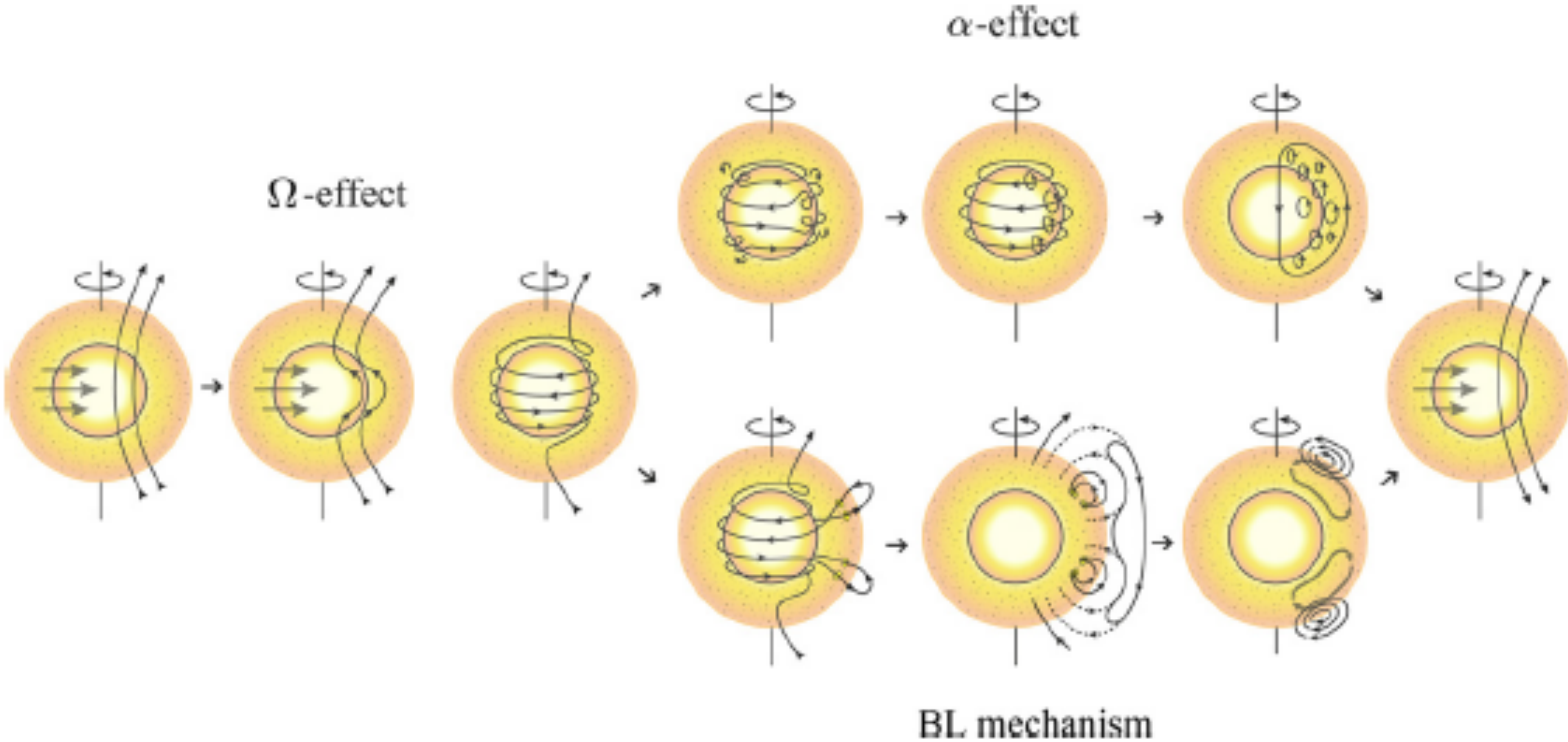
Received 13 November 2005; revised 28 December 2005; accepted 11 January 2006; published 3 March 2006.

[1] We construct a solar cycle strength prediction tool by modifying a calibrated flux-transport dynamo model, and make predictions of the amplitude of upcoming solar cycle 24. We predict that cycle 24 will have a 30–50% higher peak than cycle 23, in contrast to recent predictions by Svalgaard et al. and Schatten, who used a precursor

cause of various features observed in cycle 23. DDGAW also demonstrated (their Figure 1) that the polar fields get advected down to the shear layer at sunspot latitudes after 17–21 years, depending on the assumed meridional flow strength, instead of in just 5.5 years. Therefore the polar fields from the past few cycles (n-1, n-2, n-3) rather than

Dynamo logic: a cartoon

[Schatten et al. 1978, GRL, **5**, 411]



Sanchez et al. 2014, ApJ **781**, 8

The solar cycle/dynamo as a 2-steps process:

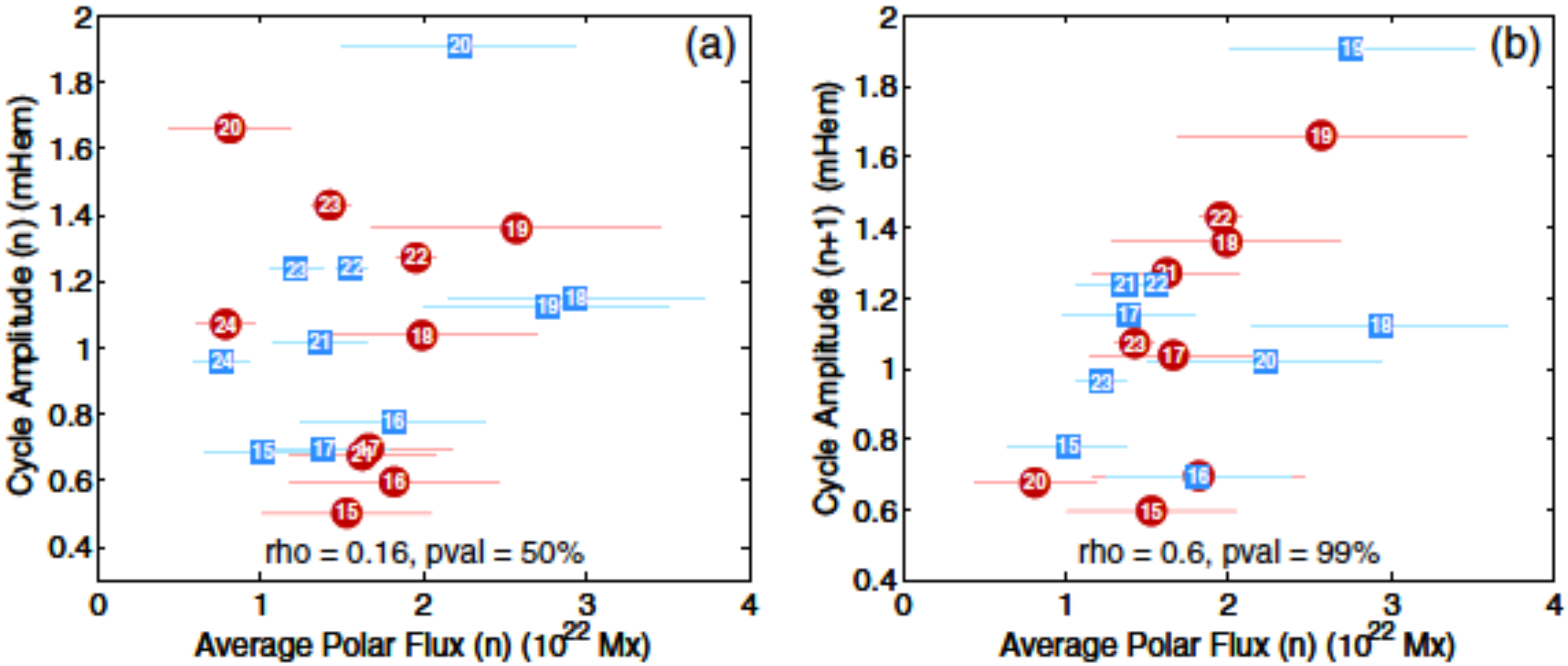
… ⇨ T(+) ⇨ P(+) ⇨ T(-) ⇨ P(-) ⇨ T(+) ⇨ …

Cycle precursors

[Munoz-Jaramillo et al. 2013 ApJ **767**, L25]

SSN **is not** a good precursor of dipole

Dipole **is** a good precursor of SSN



… → T(+) → P(+) → T(-) → P(-) → T(+) → …

→ Fluctuating/Stochastic

→ Deterministic

Choosing a dynamo model (1)

Basic cycle model	Differential rotation Turbulent emf Active region decay Turbulent dissipation Flux Transport mechanisms …
Saturation mechanism(s)	Quenching of turbulent emf Changes in large-scale flows Changes in active region properties MHD Instabilities …
Fluctuation mechanism(s)	Turbulent effects Fluctuations in large-scale flows Stochasticity in active region properties External forcing Deterministic chaos

Choosing a dynamo model (2)

[Lemerle & Charbonneau 2017 ApJ **834**, id133]

Hybrid 2X2D kinematic Babcock-Leighton dynamo model, combining a 2D surface flux transport (SFT) simulation and a 2D mean-field-like flux transport dynamo (FTD) model;

FTD simulation generates active region emergences into SFT model, which in turn provides surface boundary condition for axisymmetric poloidal magnetic field for FTD;

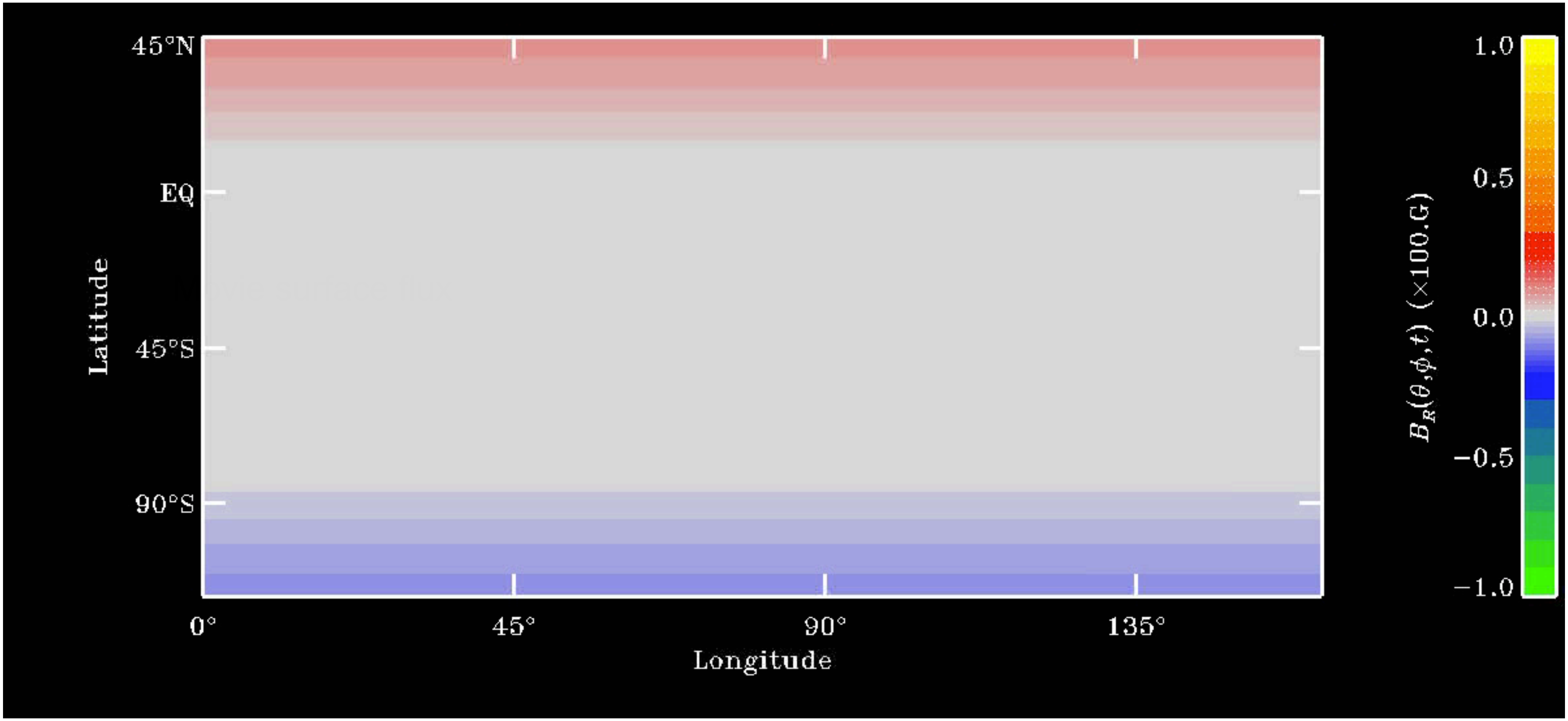
Use genetic algorithm to fit model parameter to cycle 21 magnetogram and active region emergence data (courtesy Wang & Sheeley);

Average cycle period set by (steady) meridional flow speed.

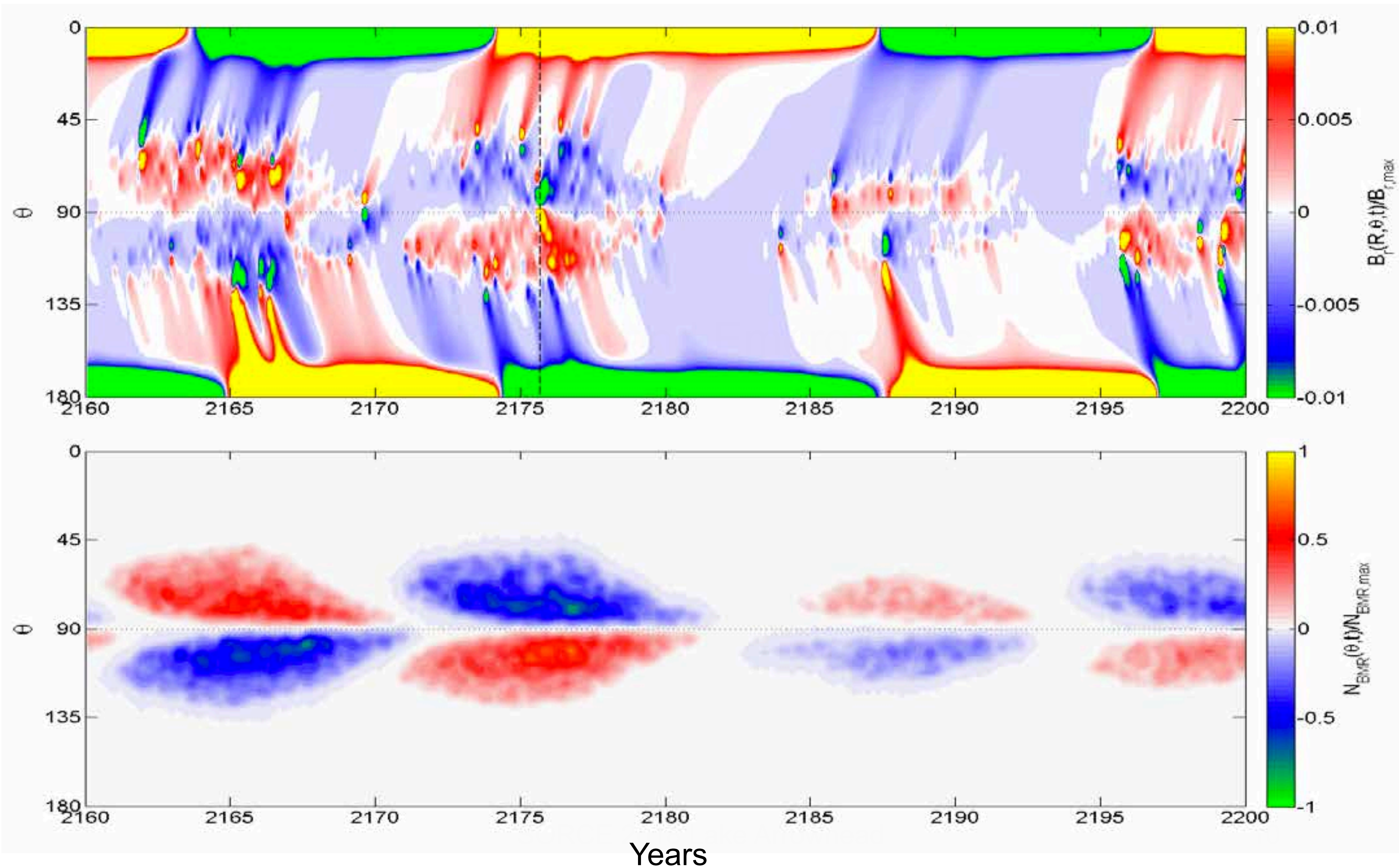
In similar vein see also: Yeates & Munoz-Jaramillo et al. 2013, MNRAS **436**, 3366; Miesch & Dikpati 2014, ApJ, **785**, L8; Miesch & Teweldebirhan 2016, *Adv. Sp. Res*. **58**, 1571.

Choosing a dynamo model (3)

[Lemerle & Charbonneau 2017 ApJ **834**, id133]

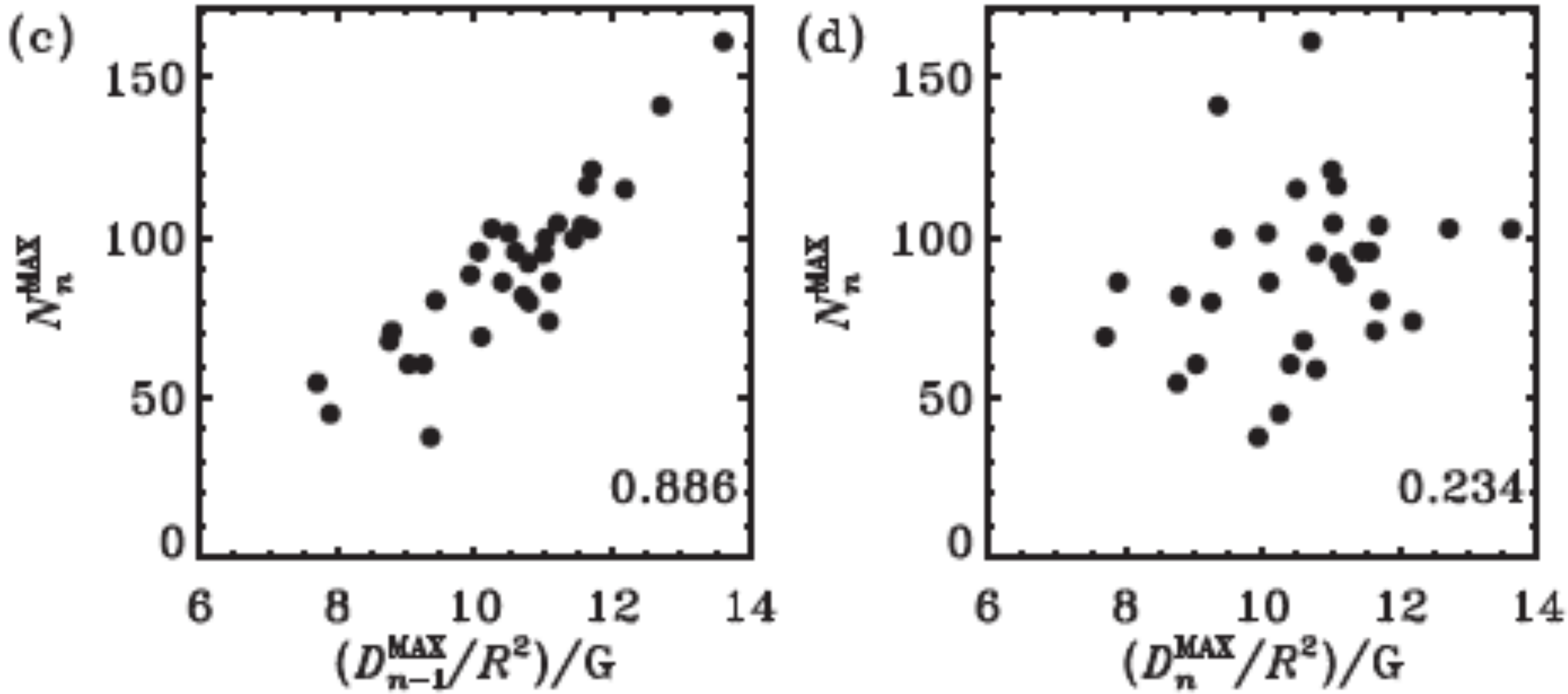


Choosing a dynamo model (4)



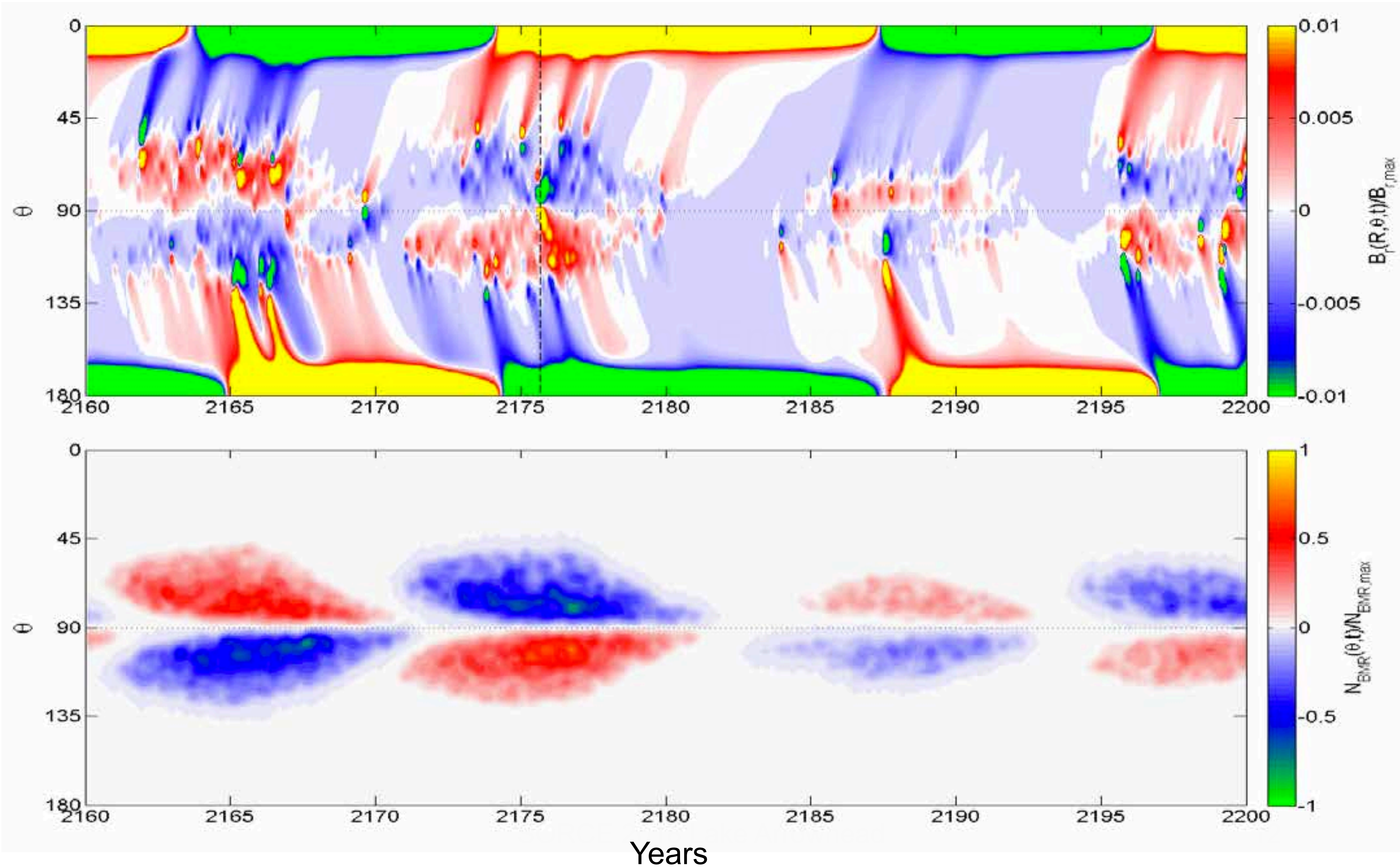
Surface dipole as precursor (1)

Dipole **is** a good precursor of SSN   SSN **is not** a good precursor of dipole

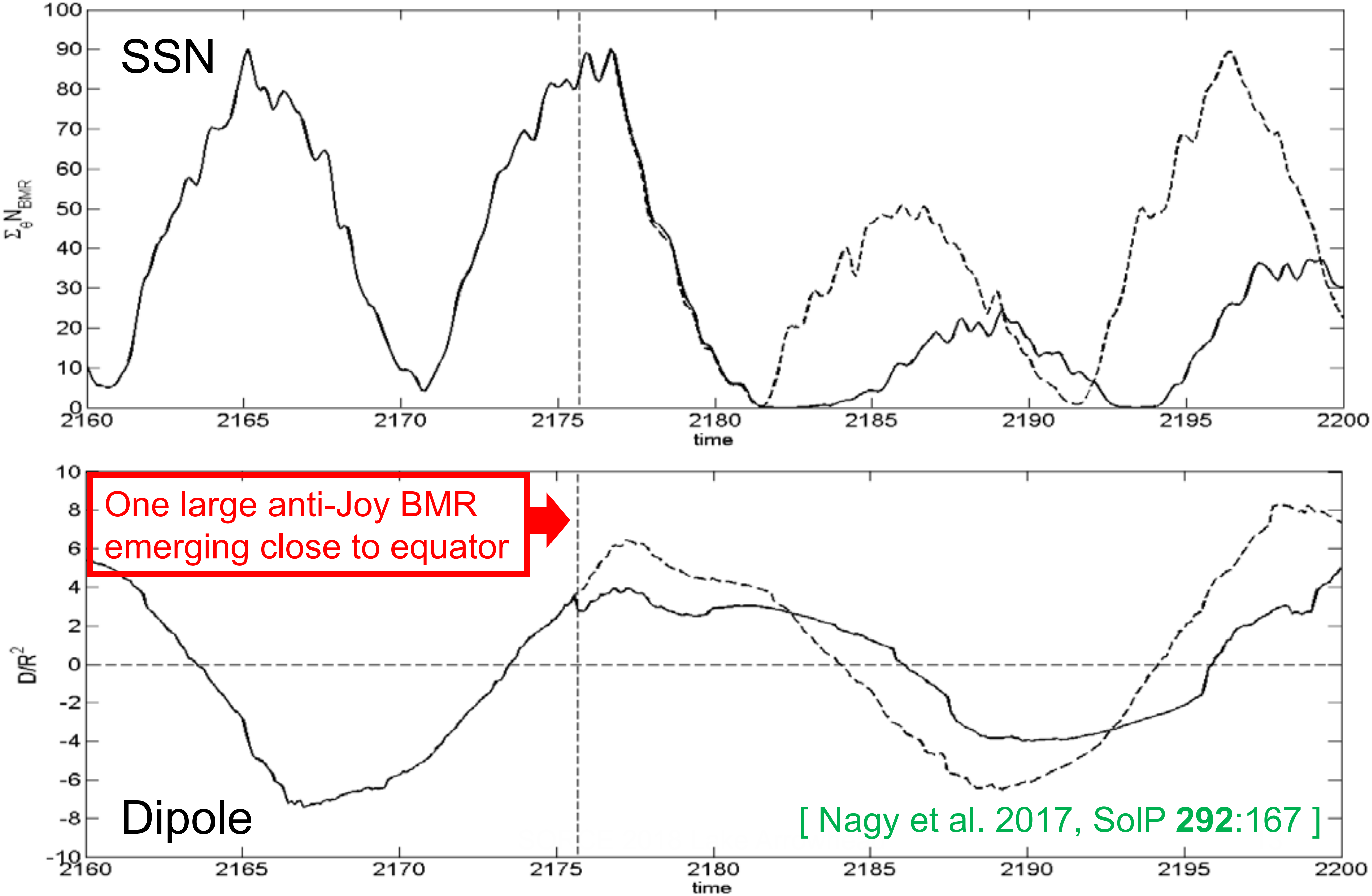


Polar cap flux = unsigned flux of one large BMR; dipole buildup sensitive to specifics of active region emergences [See Cameron & Schüssler 2015, JGR **119**, 680]

Choosing a dynamo model (4)



« Rogue » active regions (1)



« Rogue » active regions (2)

THE ASTROPHYSICAL JOURNAL LETTERS, 808:L28 (6pp), 2015 July 20 JIANG, CAMERON, & SCHÜSSLER

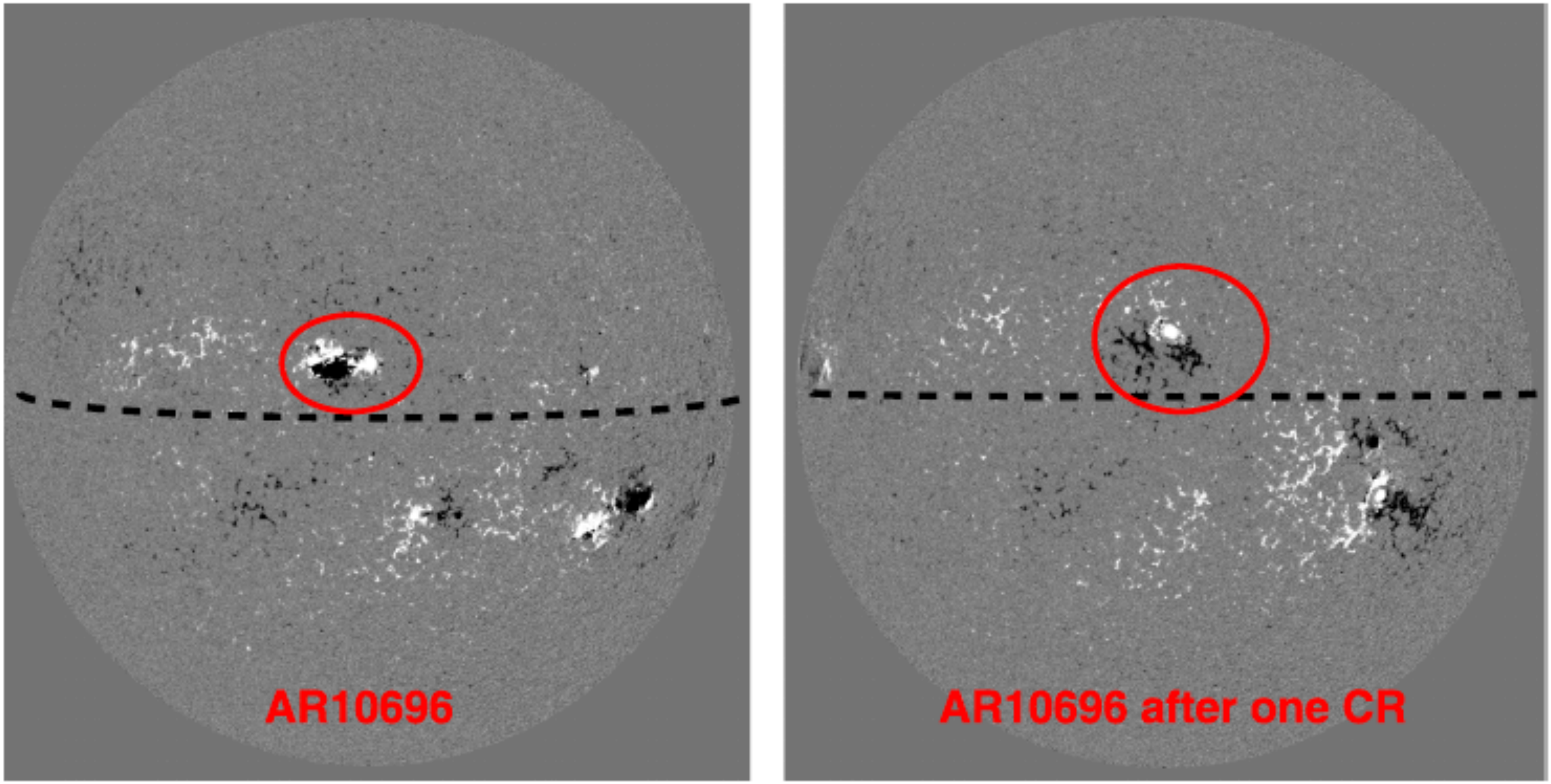
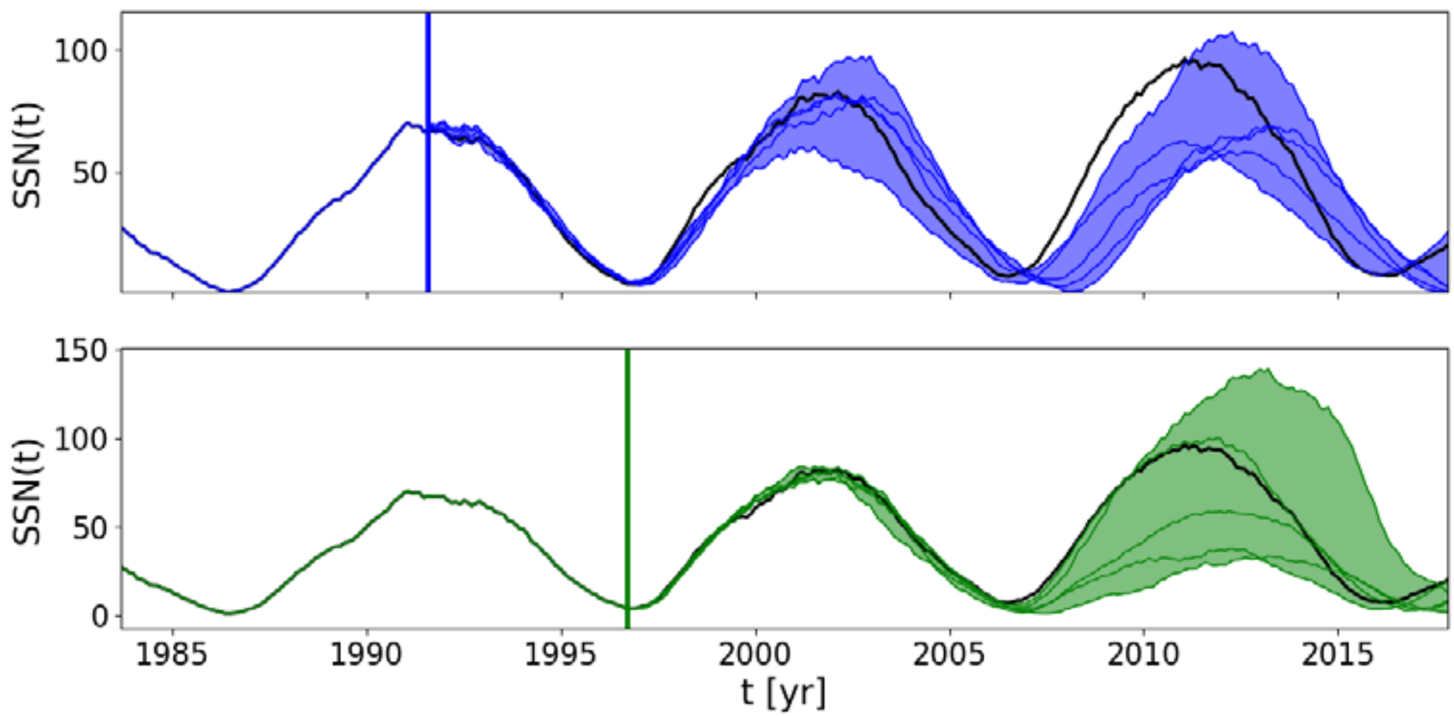


Figure 4. Example of a bipolar magnetic region that significantly weakened the axial dipole moment in the declining phase of cycle 23. Shown are *SOHO*/MDI magnetic maps of the active region AR10696 taken 2004 November 5 (left panel) and 2004 December 2 (right panel, after one solar rotation, then denominated AR10708), respectively. Positive magnetic flux is indicated in white, negative flux in black. Owing to its near-equator emergence, high tilt, and abnormal polarity orientation in the north/south direction, the region provides a significant amount of negative flux that is transported over the equator (by supergranular random walk) to the southern hemisphere. Through poleward advection (mainly by meridional flow) this flux eventually weakened the buildup of positive flux around the south pole of the Sun, thus lowering the axial dipole moment.

[Jiang et al. 2015, ApJL **808**:L28]

Surface dipole as precursor (3)

Experiment: reset random number generator setting properties of emerging bipolar active regions.

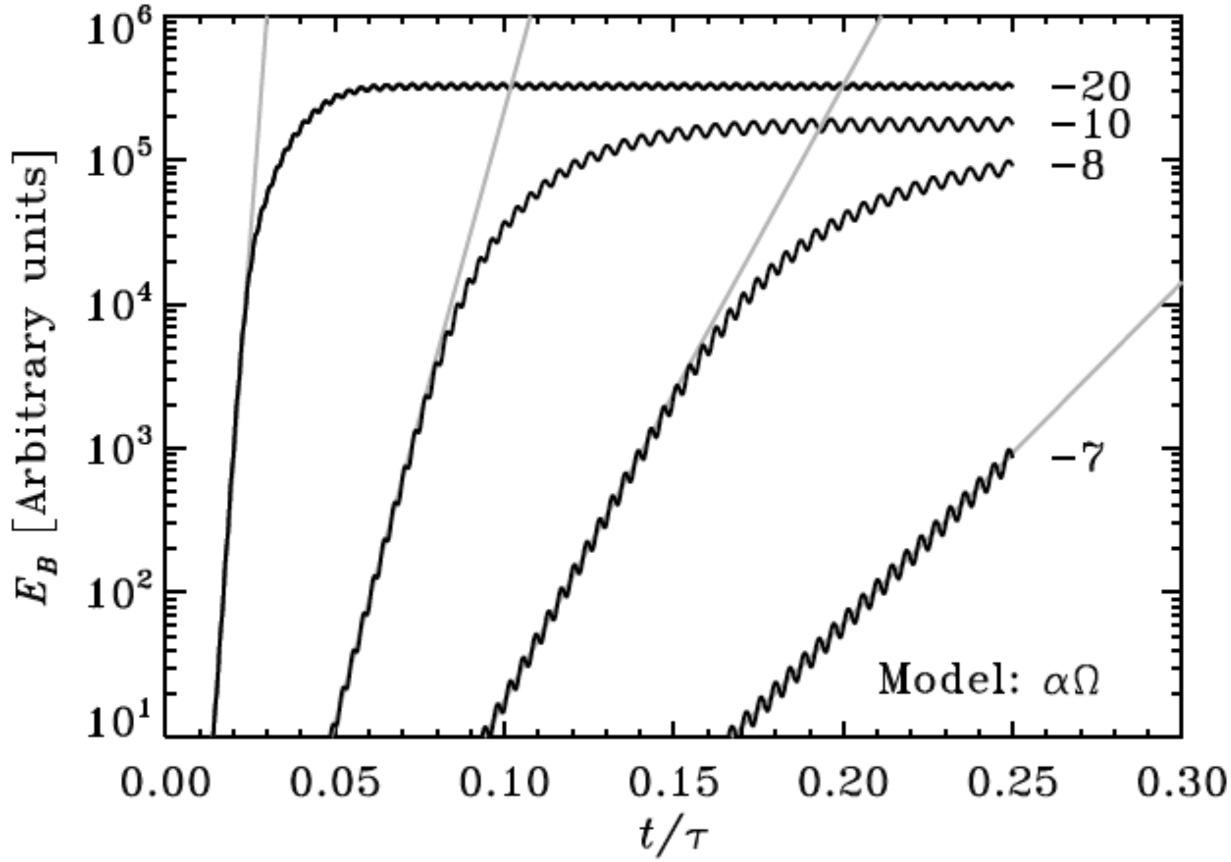


At activity **maximum**, fate of subsequent SSN cycle **is not** set;
At activity **minimum**, fate of subsequent SSN cycle **is** set .

[Ongoing M.Sc. by F. Labonville, UdeM]

Nonlinear cycle amplitude saturation

Magnetic energy vs time
starting from weak seed field

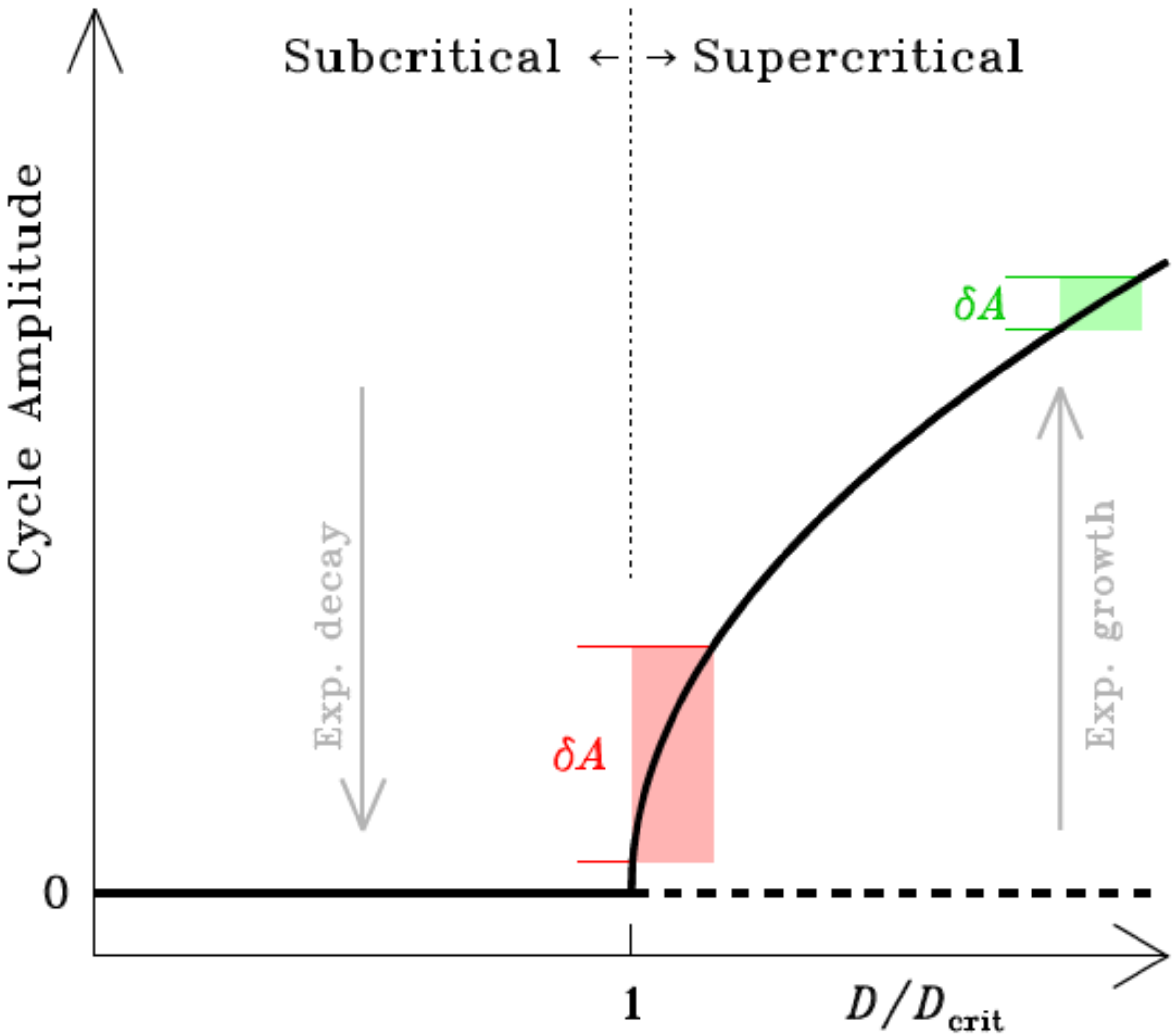


A « textbook » model: kinematic mean-field dynamo with simple « quenching » of the turbulent EMF:

Both the **linear growth rate** and **saturated amplitude** increase with the dynamo number.

Typical of many classes of dynamos

Stochasticity + Nonlinearities (1)

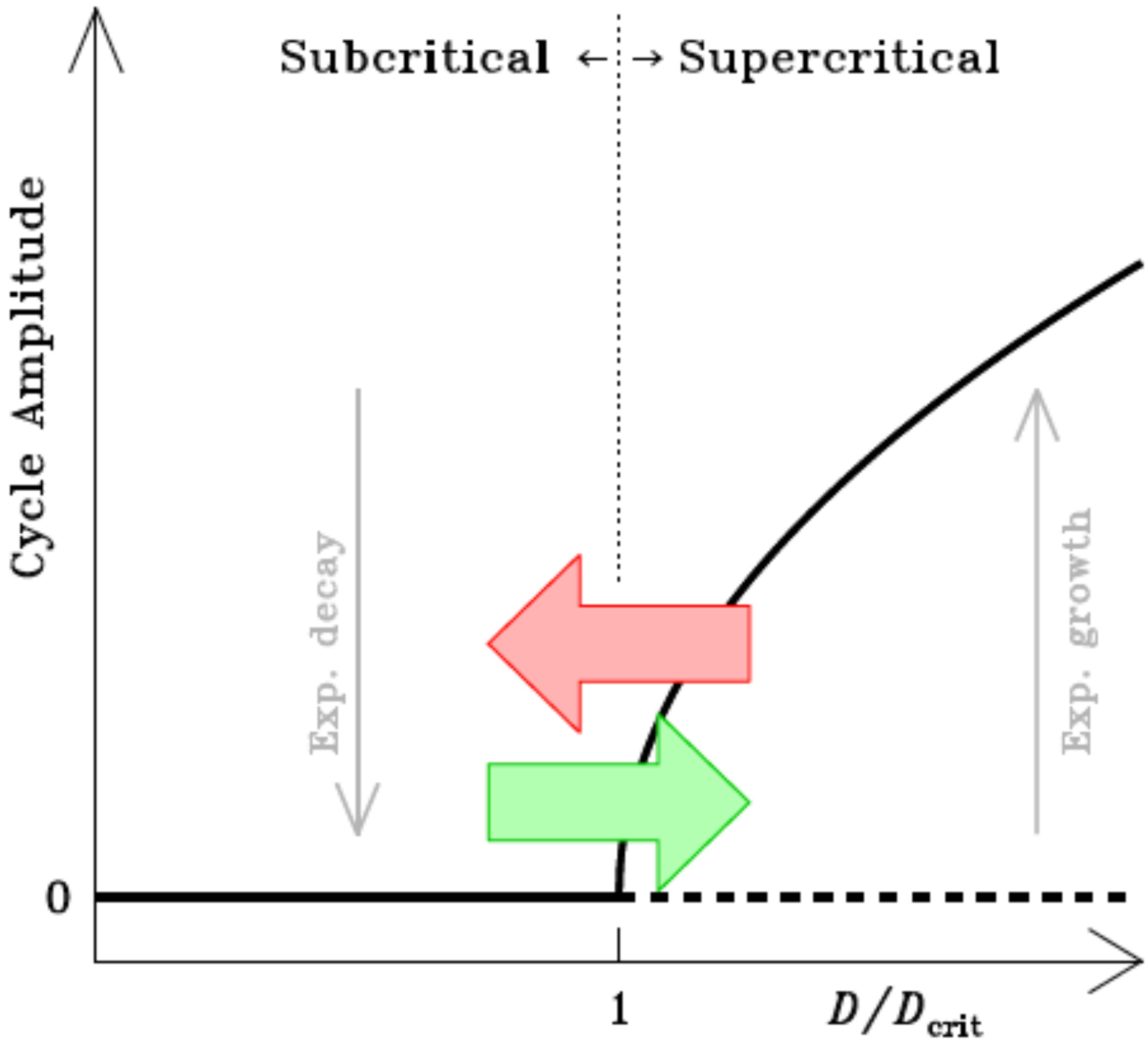


If dynamo is operating **close to criticality**, small fluctuation in dynamo number can drive:

Large cycle amplitude fluctuations,

and even intermittency (Grand Minima)

Stochasticity + Nonlinearities (2)



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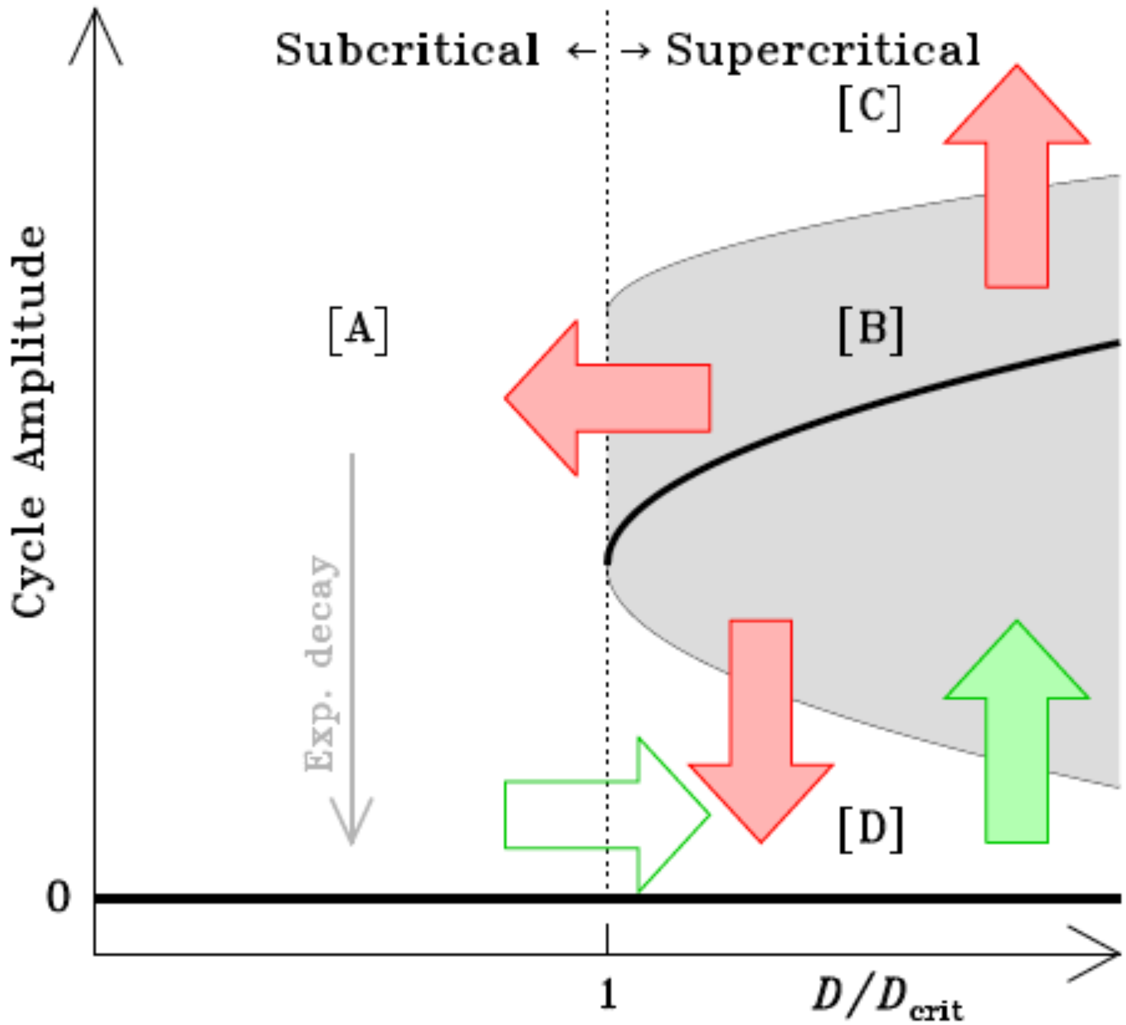
Stochasticity + Nonlinearities (3)



Threshold on magnetic field strength + stochasticity + nonlinear modulation = **intermittency**

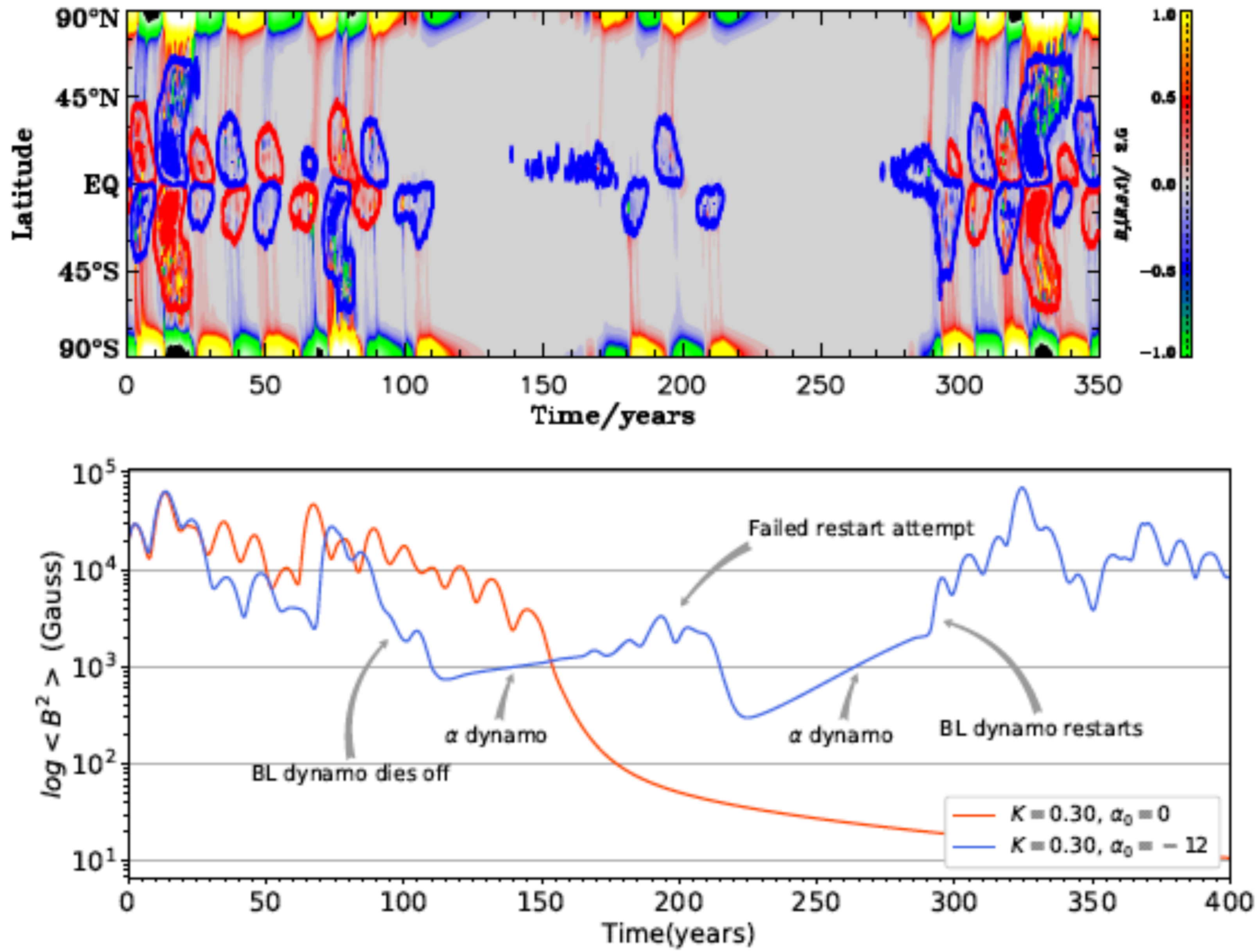
An additional inductive mechanism needed to push dynamo back onto the attractor characterizing « normal » cyclic behavior.

Dual-dynamo systems !

A **zoo** of possible fluctuation patterns on long timescales

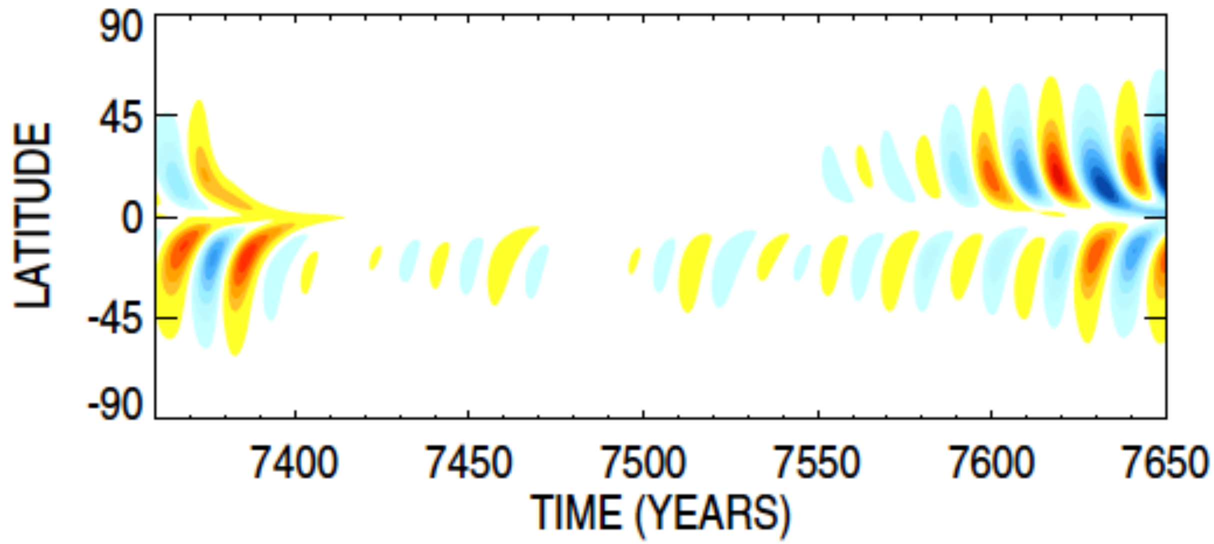
Grand Minima (1)

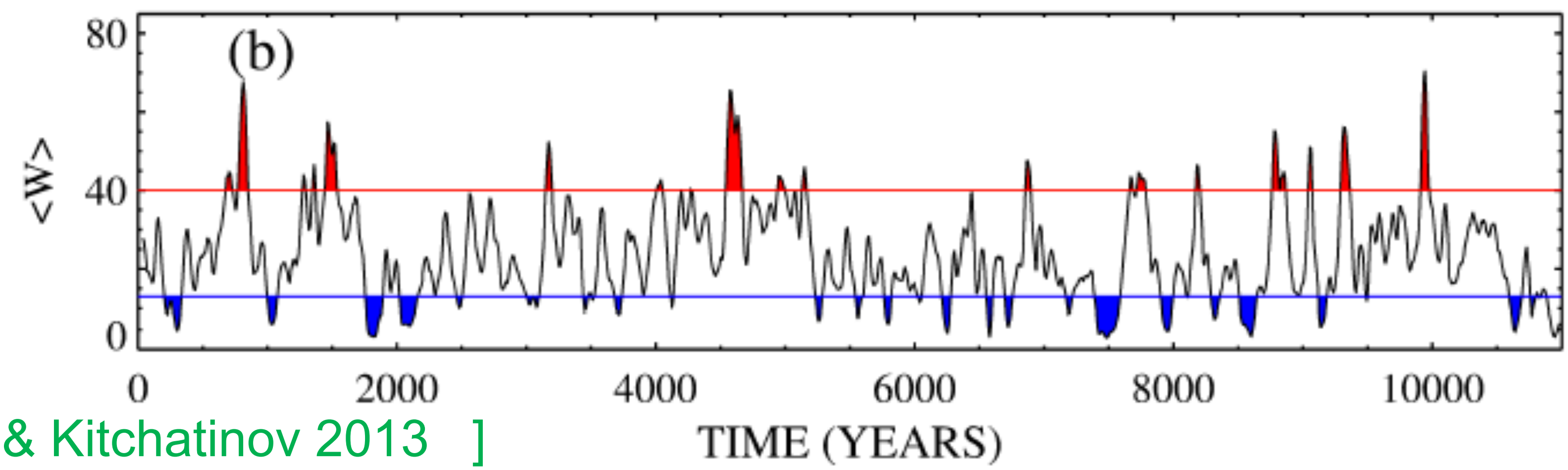
[Ölçek et al. SolP, in prep.]



Grand Minima (2)

A mean-field dynamo model with a stochastic noise model for the turbulent alpha-effect: strong hemispheric asymetries going in and out of Grand Minima

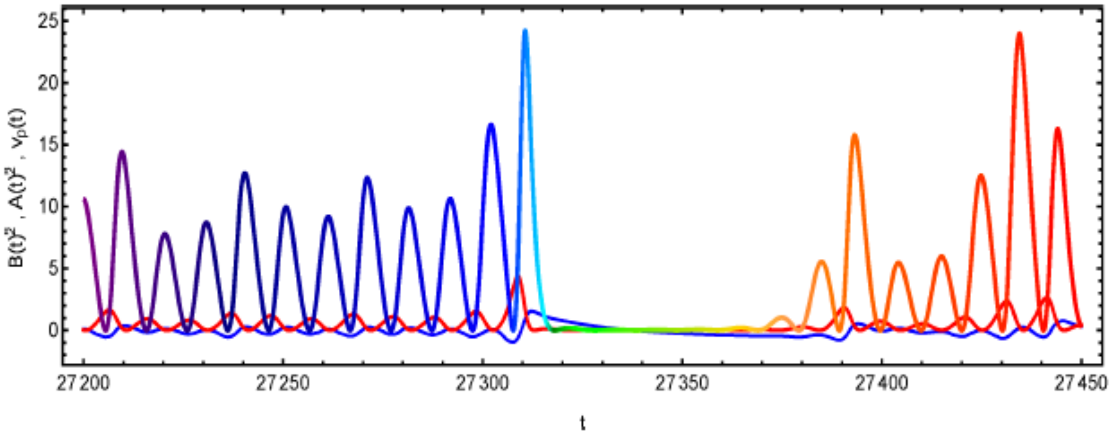


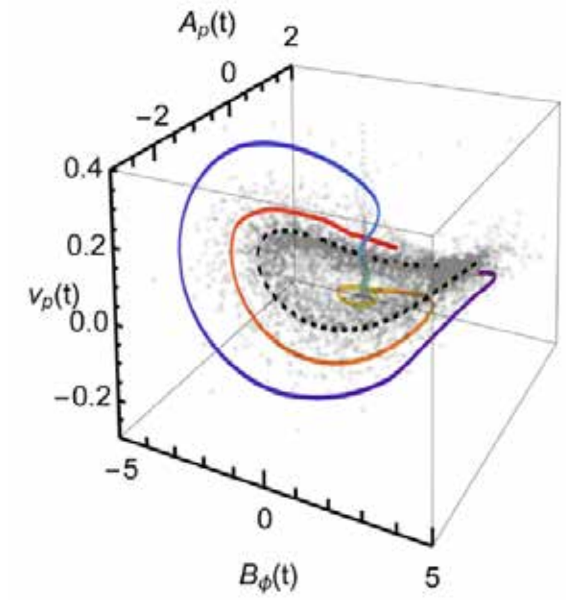


[Olemskoy & Kitchatinov 2013]

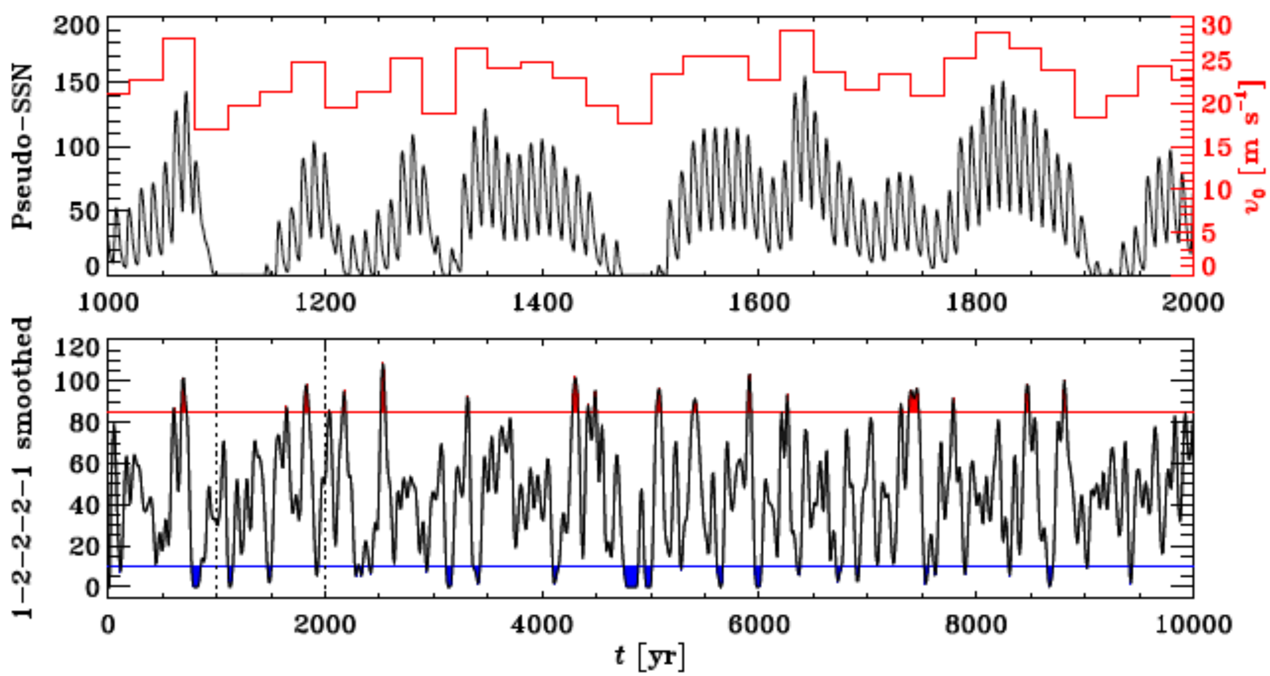
Grand Minima (3)

[Passos et al. 2012, SolP **279**:1-22]



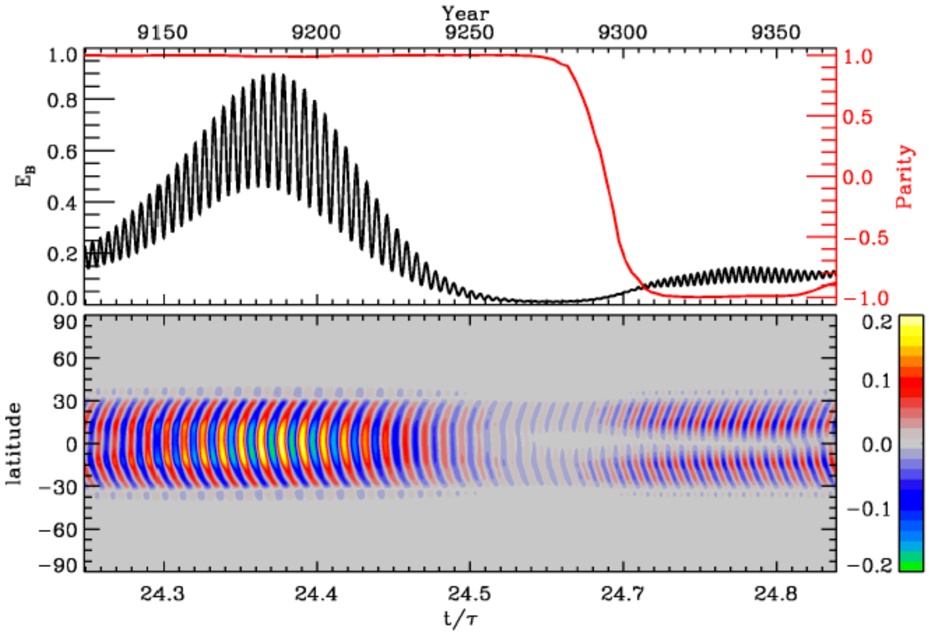


[Karak & Choudhuri 2013, RAA **13**, **1339**]

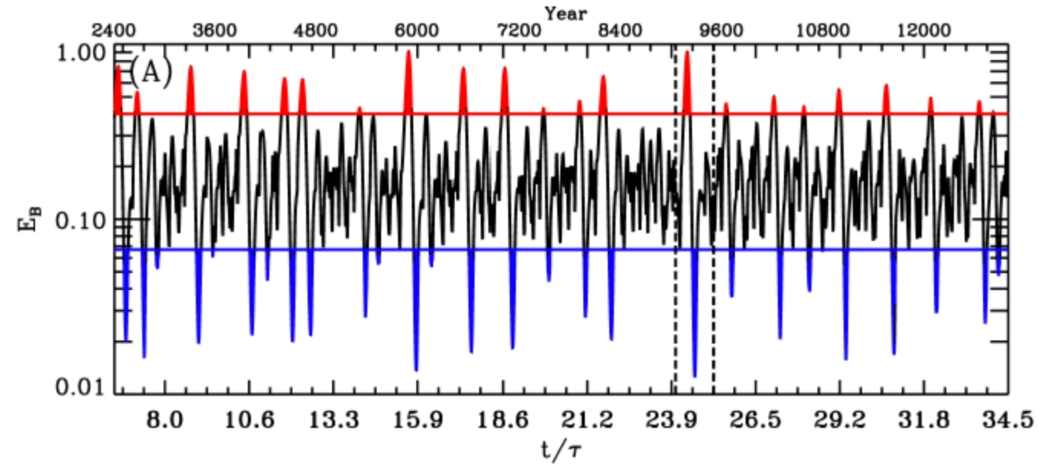


Two flux transport dynamo models with variations in the meridional flow (forced vs dynamical)

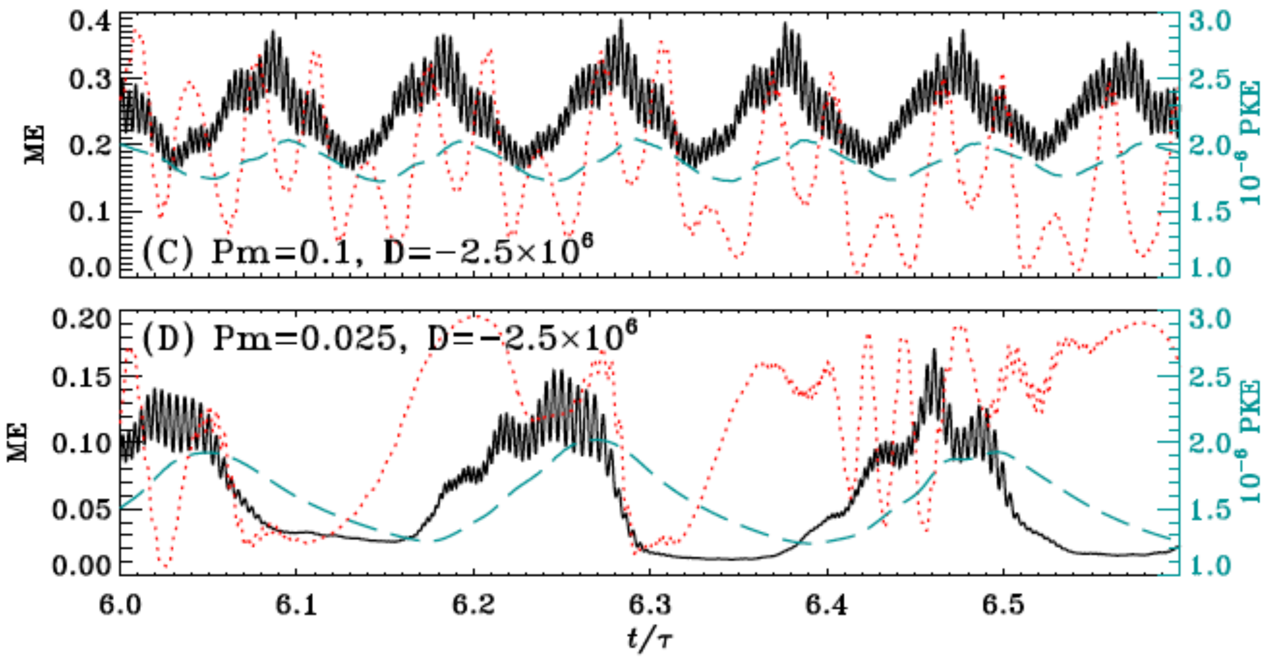
Grand Minima (4)



[Simard et al. 2018, SolP, in prep.]



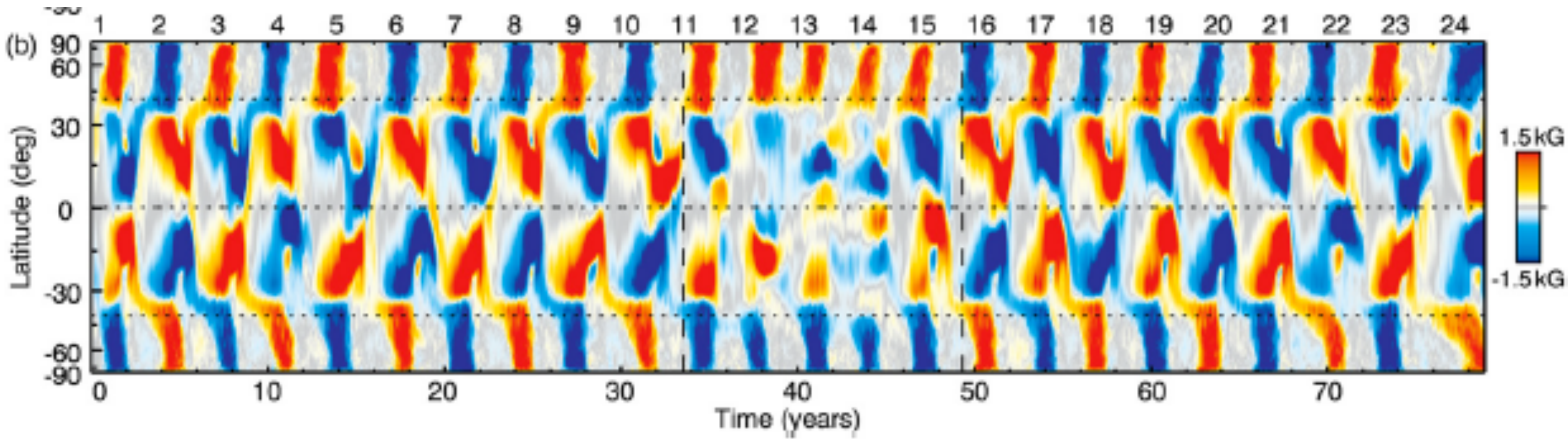
[Bushby 2006, MNRAS **371**:772]



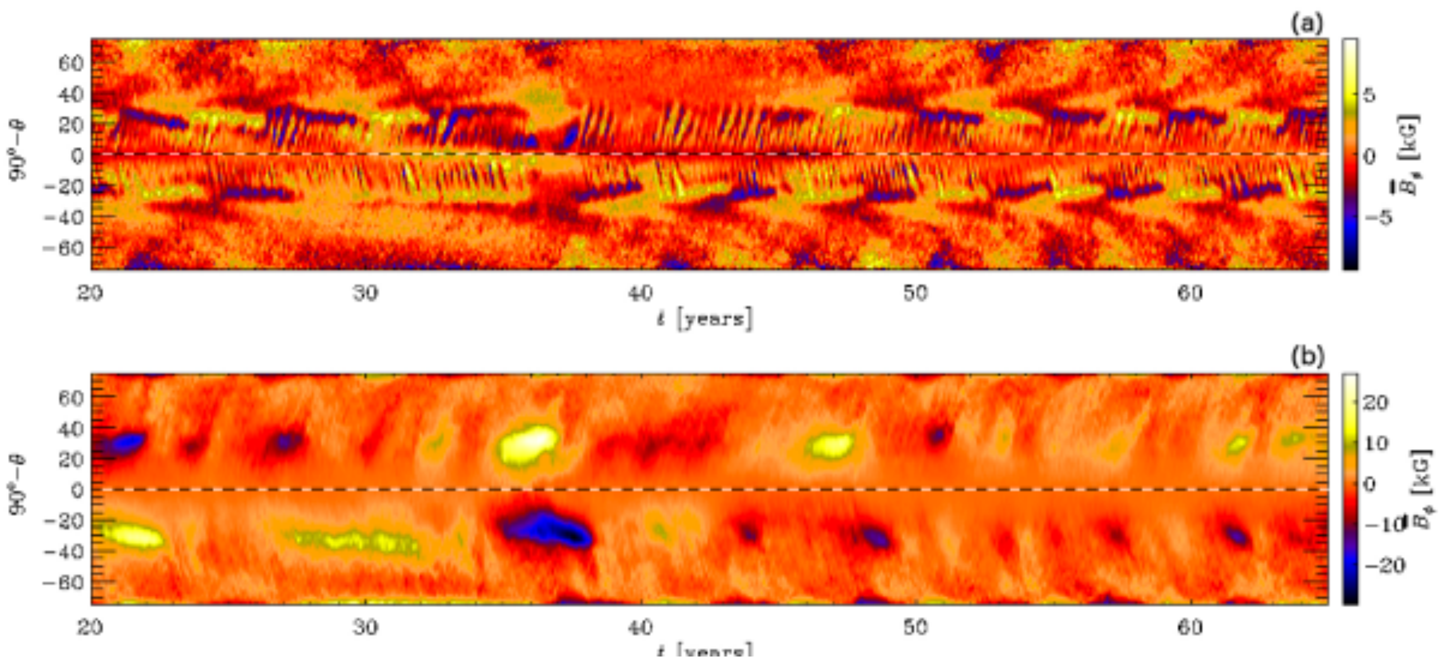
Two mean-field dynamo models with nonlinear backreaction of the large-scale magnetic field on differential rotation [A. Ruzmaikin's talk]

Grand Minima (5)

[Augustson et al. 2015, ApJ **809**, id149]



[Käpylä et al. 2016, A&A **589**, A56]



Global MHD simulations : parity modulation and/or mode interactions

A few take-home items

Next-cycle prediction going beyond « dipole-as-precursor » must account for stochasticity of active region emergence (dynamo models + data assimilation)

Finding precursor patterns for Grand Minima may be possible if nature of dynamo saturation mechanism(s) is understood

In some classes of dynamo models, useful predictions on timescales centennial or even longer may be possible; interesting for climate !

We currently do not have a « concensus » basic dynamo model for the sun, not for the physical mechanism(s) regulating cycle amplitude and driving cycle variability.

CRSNG
NSERC

FIN

CSA ASC

Fondation canadienne
pour l'innovation
Canada Foundation
for Innovation

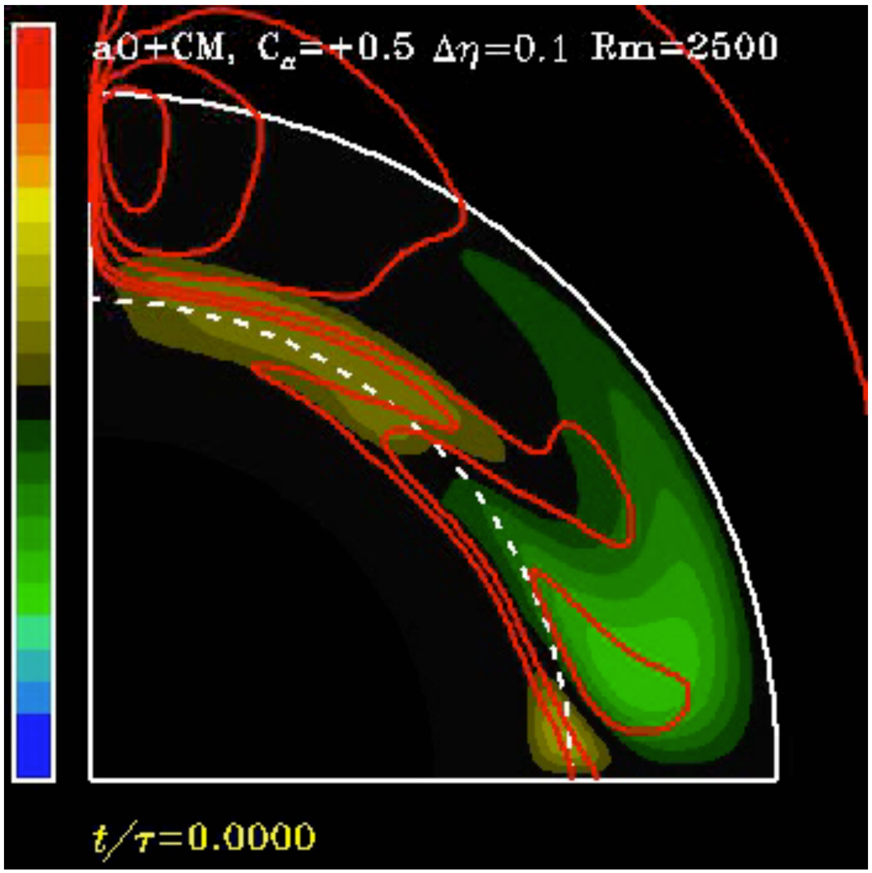
Calcul Québec

Fonds de recherche
sur la nature
et les technologies
Québec

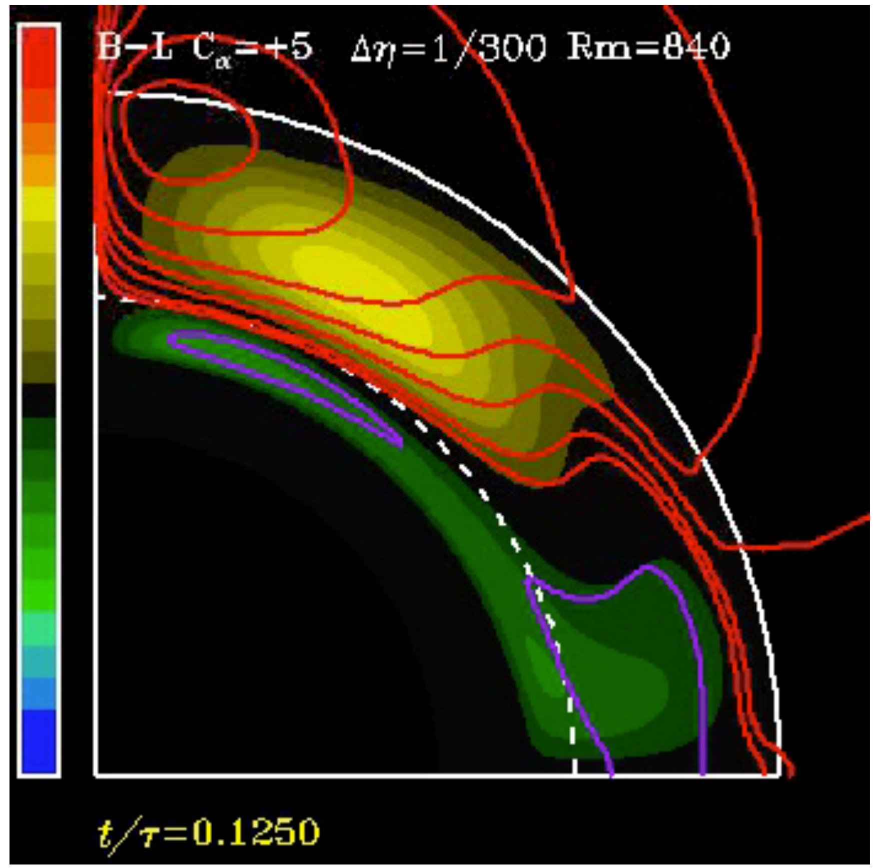
Collaborators: Piotr Smolarkiewicz, Dario Passos, Antoine Strugarek, Alexandre Lemerle, Patrice Beaudoin, Corinne Simard, Deniz Ölçek, François Labonville, Melinda Nagy

Surface dipole as precursor (4)

Consider the following two kinematic axisymmetric mean-field like dynamo models, using a solar-like differential rotation and quadrupolar meridional flow, and a simple algebraic quenching nonlinearity.



T > P : alpha-effect

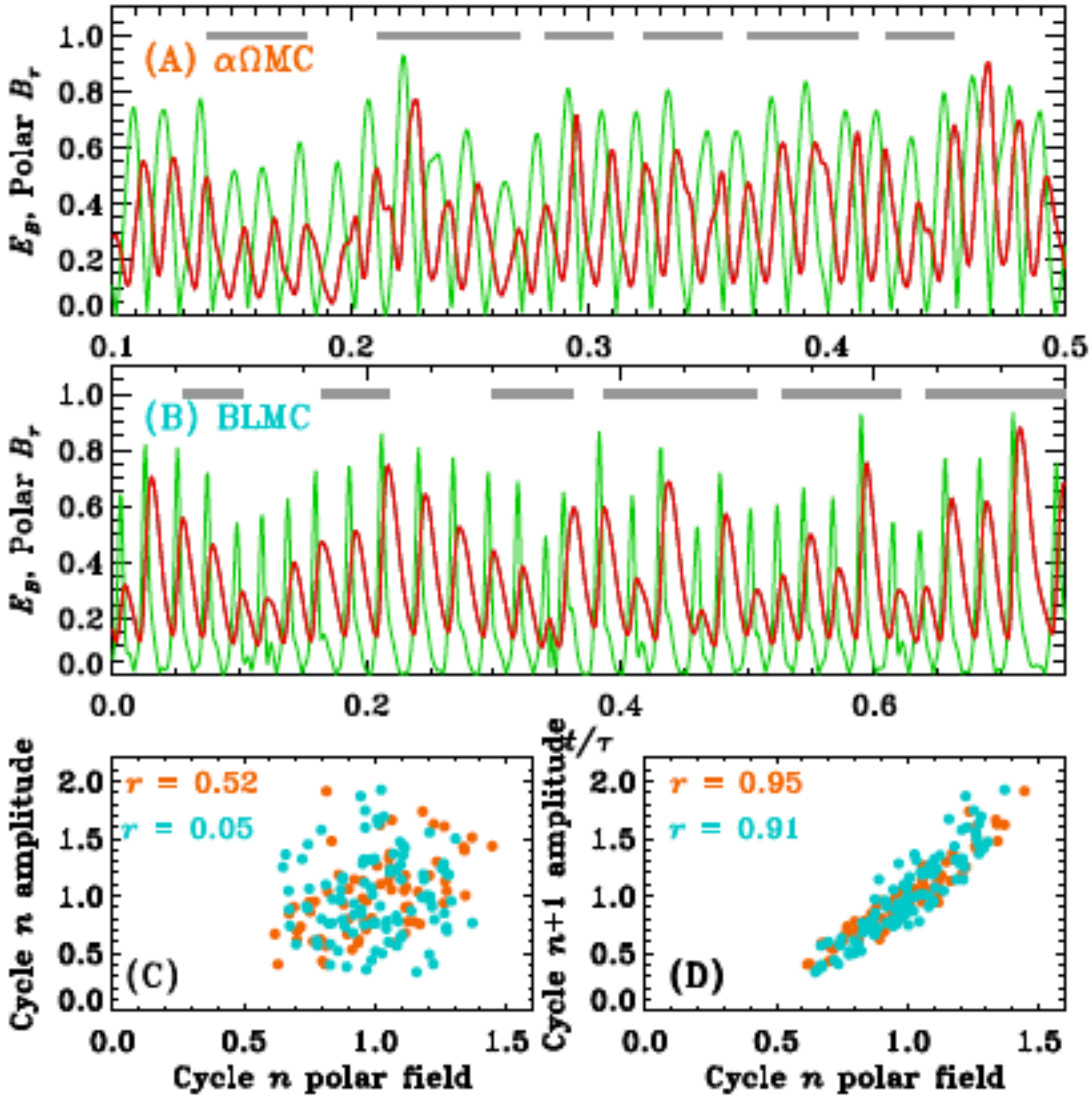


T > P : Babcock-Leighton

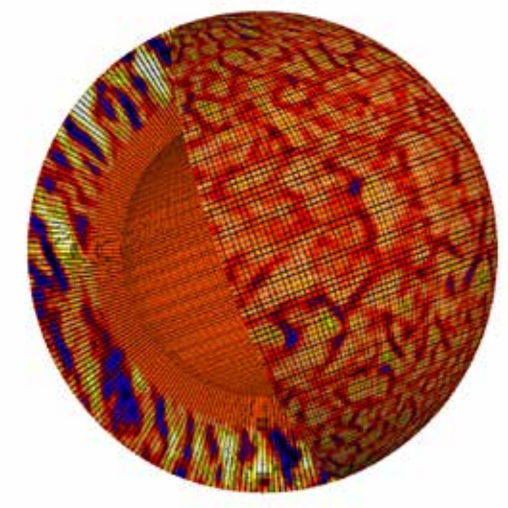
Surface dipole as precursor (5)

In itself, **does not** imply that the sun is **necessarily** a Babcock-Leighton dynamo !

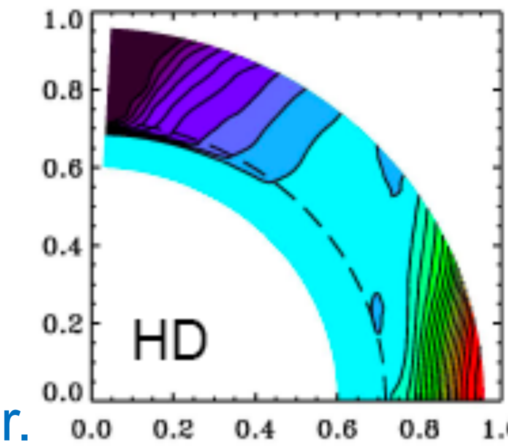
What it **does** imply is that the surface magnetic field feeds back into the dynamo loop



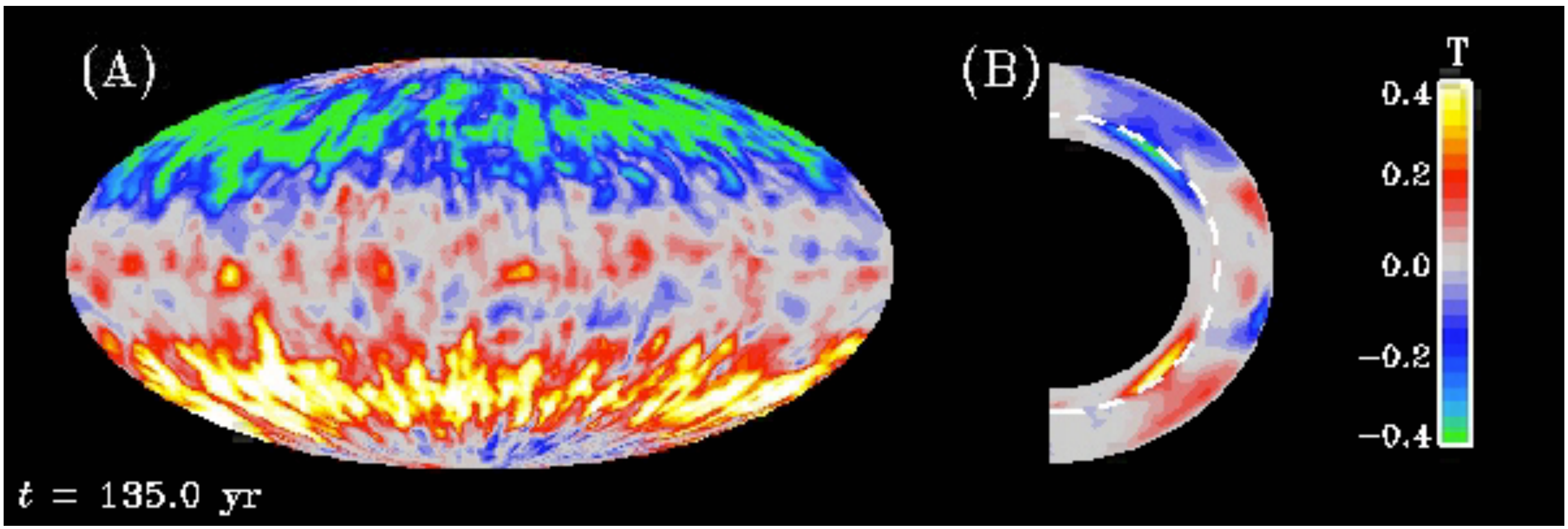
Charbonneau & Barlet 2011, JASTP **73**,206Z



Magnetic cycles (1)

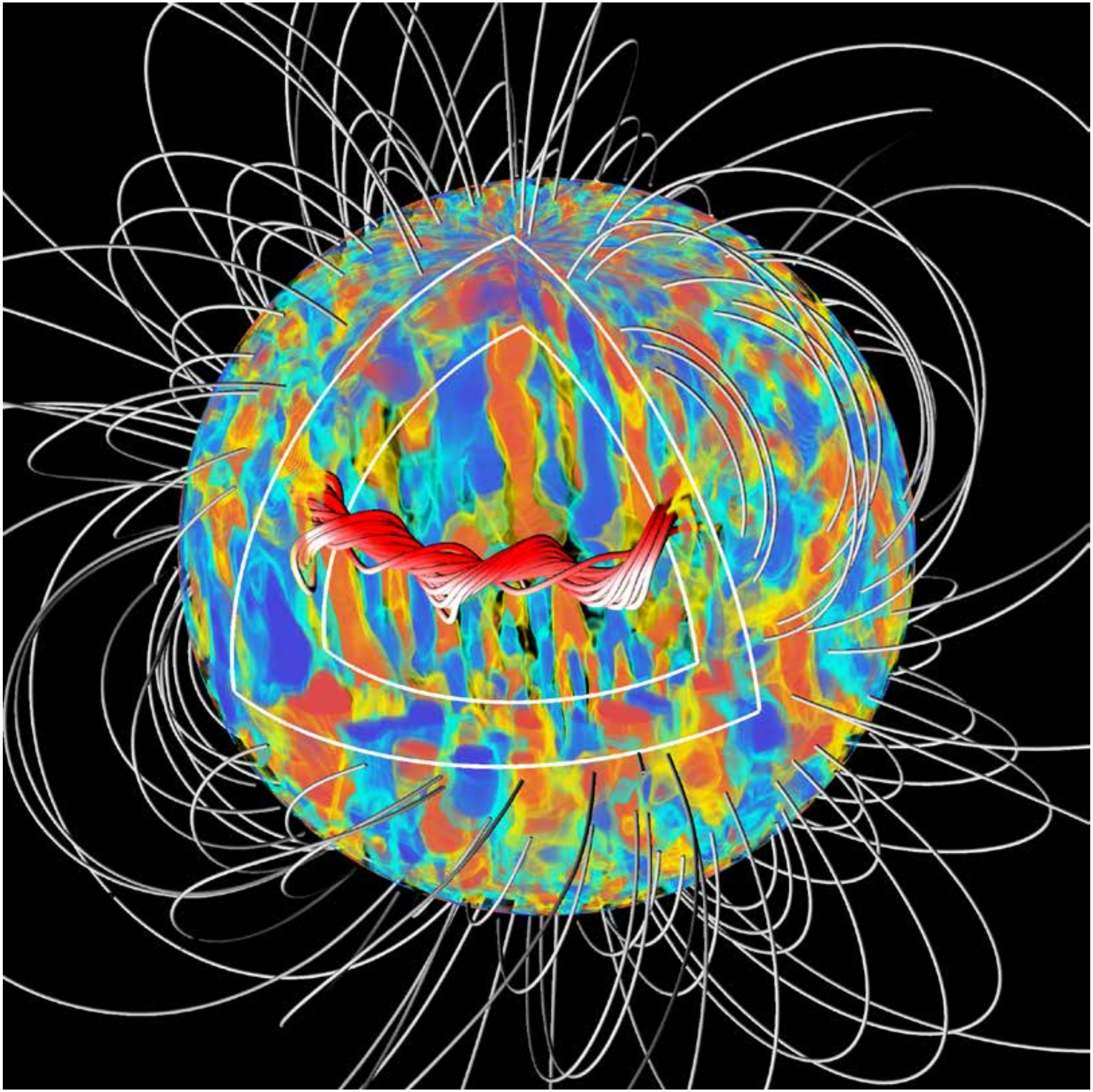


EULAG-MHD solves anelastic MHD equations in a thick, rotating stratified fluid shell; includes stable fluid layer underneath convectively unstable layer.

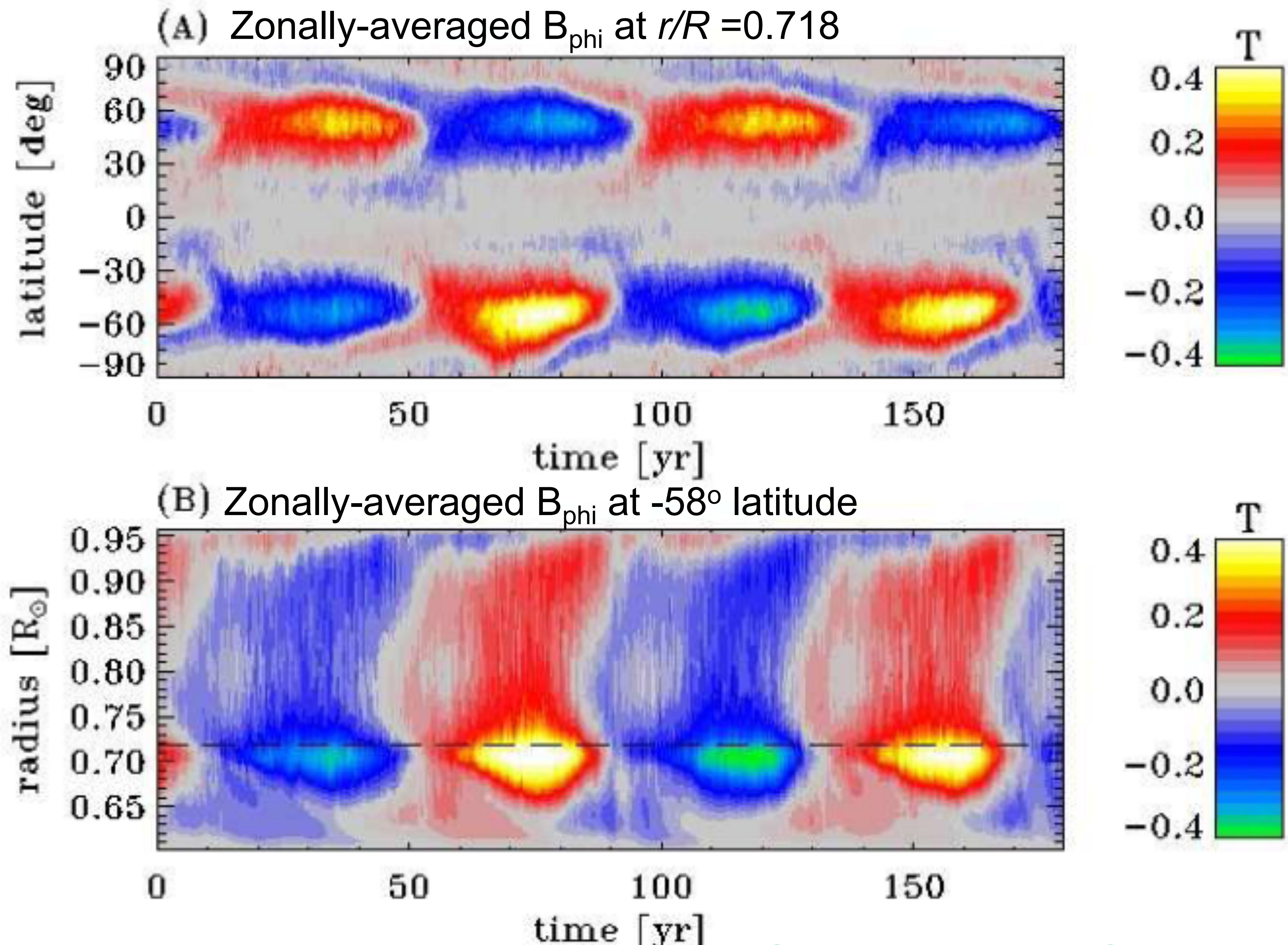


Despite strongly turbulent nature of induction, simulation develops a strong and spatially well-organized axisymmetric magnetic field, antisymmetric about equatorial plane and undergoing regular and hemispherically synchronized polarity reversals.

EULAG-MHD simulation of solar convection



Strugarek et al. 2017, *Science*, July 14 issue



[See also poster by Stejko et al.]

MHD: extracting the turbulent EMF

[Simard et al., Adv. Sp. Res. **58**, 1522 (2016)]

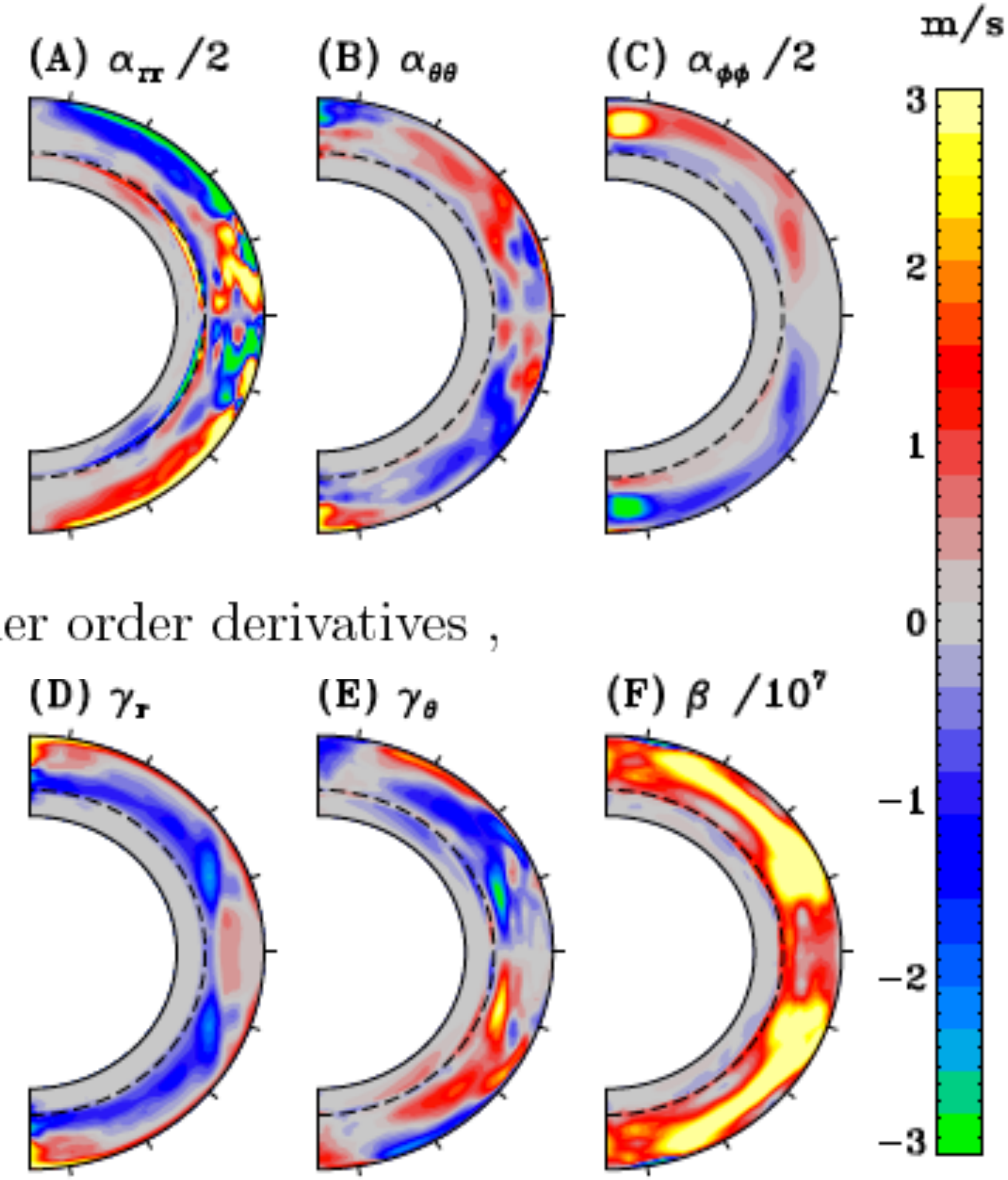
Get these from simulation

$$\boldsymbol{\mathcal{E}} = \langle \boldsymbol{u}' \times \boldsymbol{B}' \rangle$$

Compute this

$$\mathcal{E}_i = \alpha_{ij}\langle B_j\rangle + \beta_{ijk}\partial_j\langle B_k\rangle + \text{ higher order derivatives ,}$$

Get these by least-squares fit

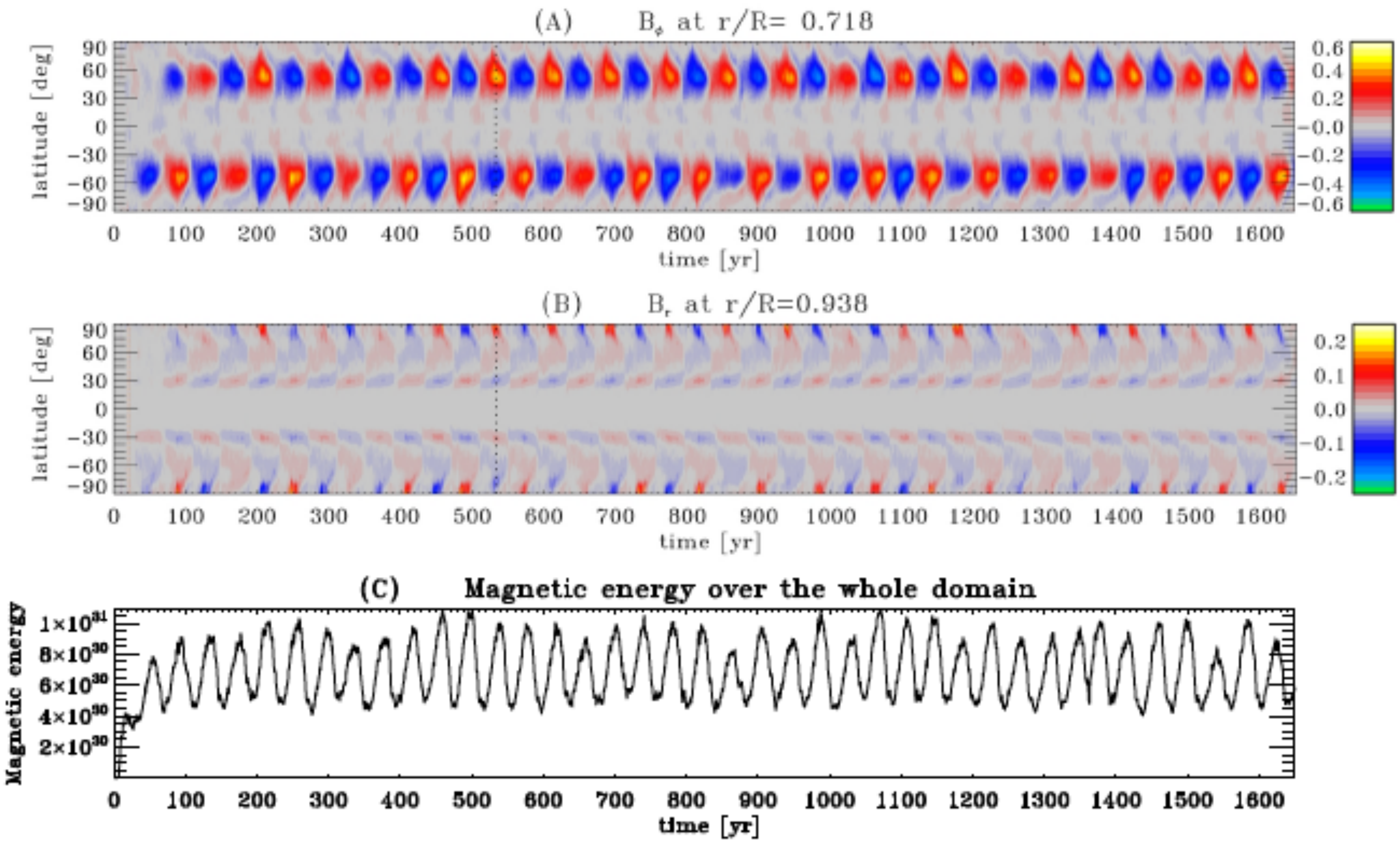


See also Augustson et al. 2015, ApJ **809**, id149; Warnecke et al. 2016, on ArXiv

SORCE

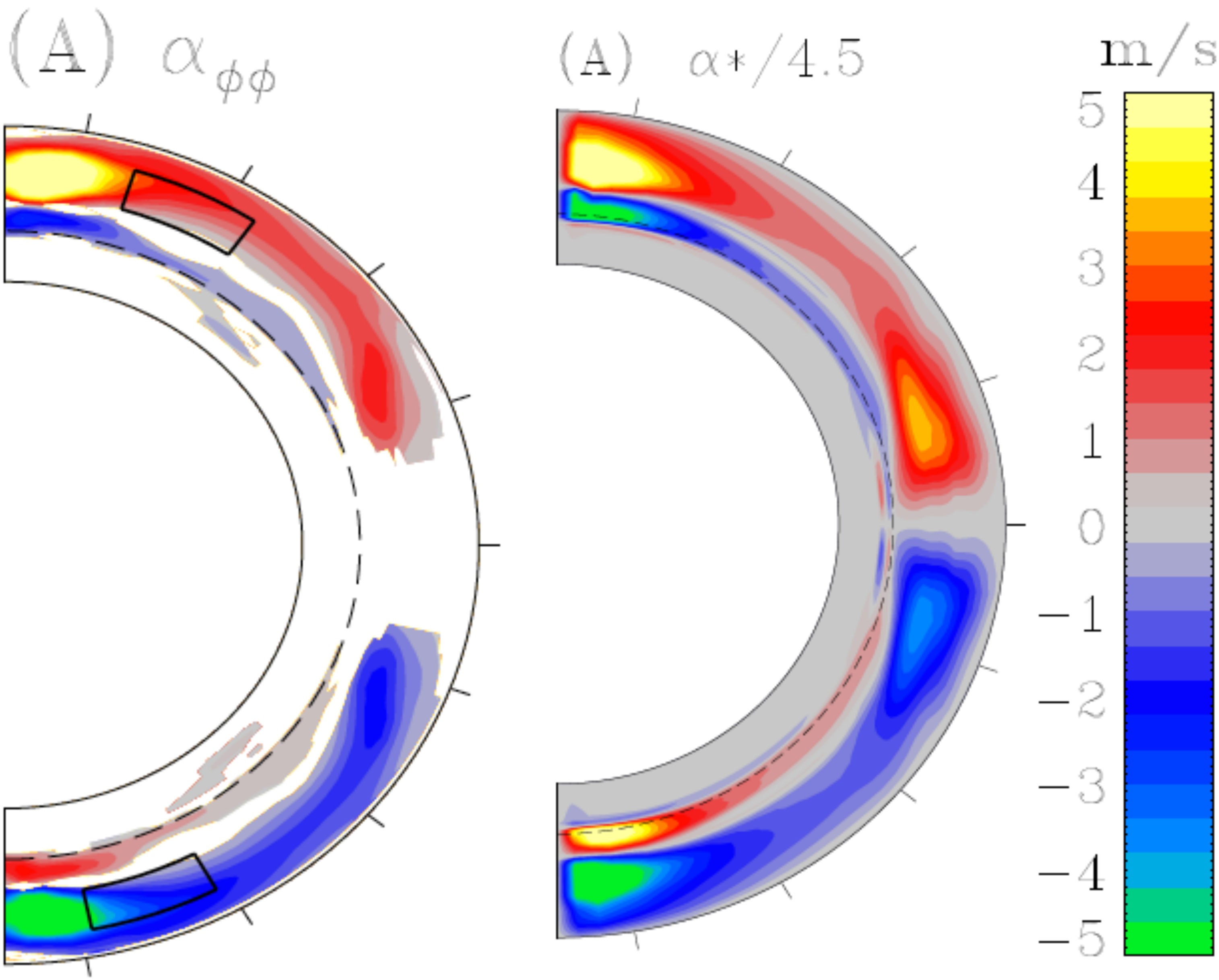
The « millenium simulation »

[Passos & Charbonneau 2014, *Astron. & Ap.*, **568**, 113]



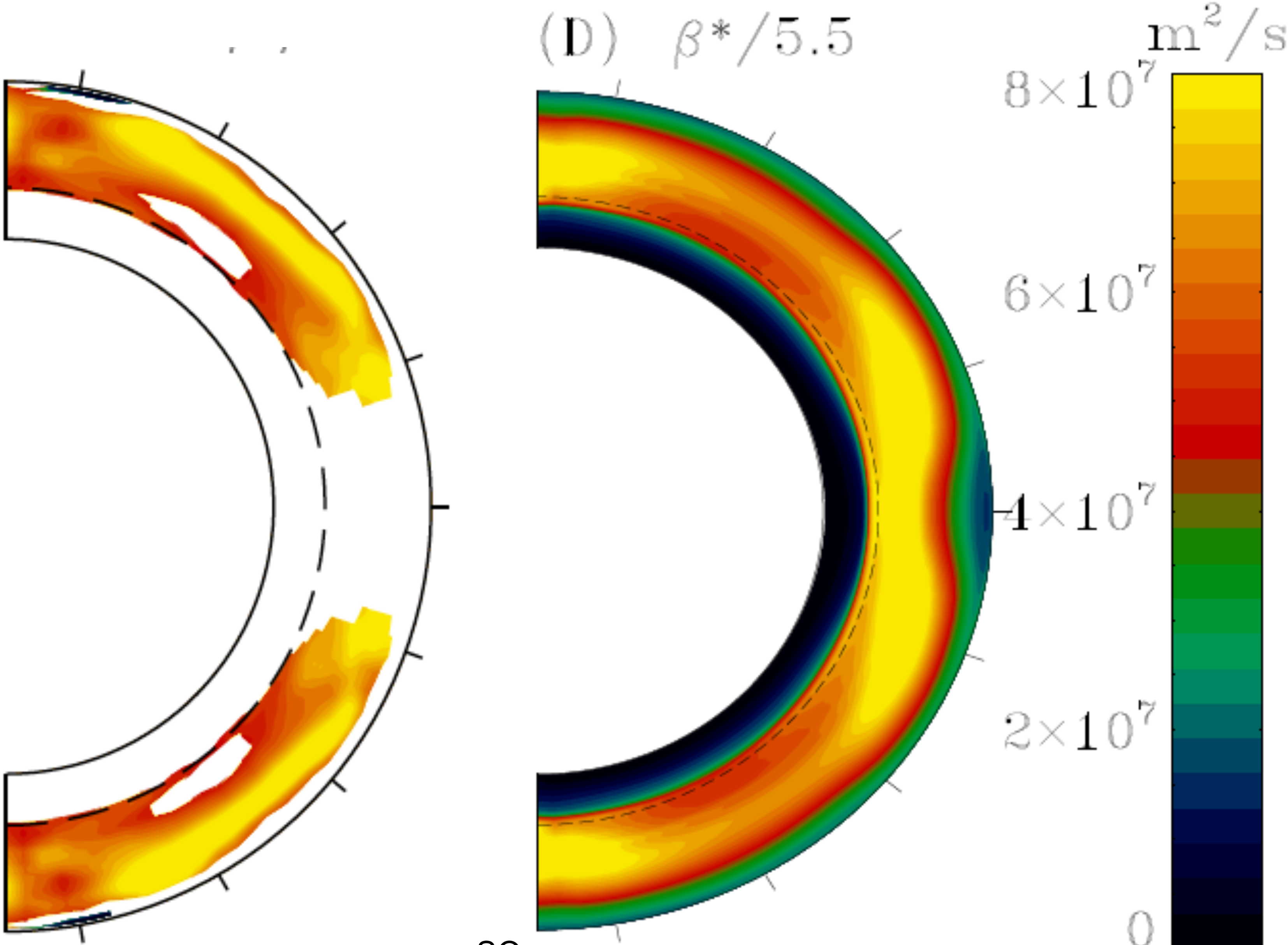
MHD: alpha vs kinetic helicity

[Simard et al., Adv. Sp. Res. **58**, 1522 (2016)]



MHD: beta vs turbulent intensity

[Simard et al., Adv. Sp. Res. **58**, 1522 (2016)]

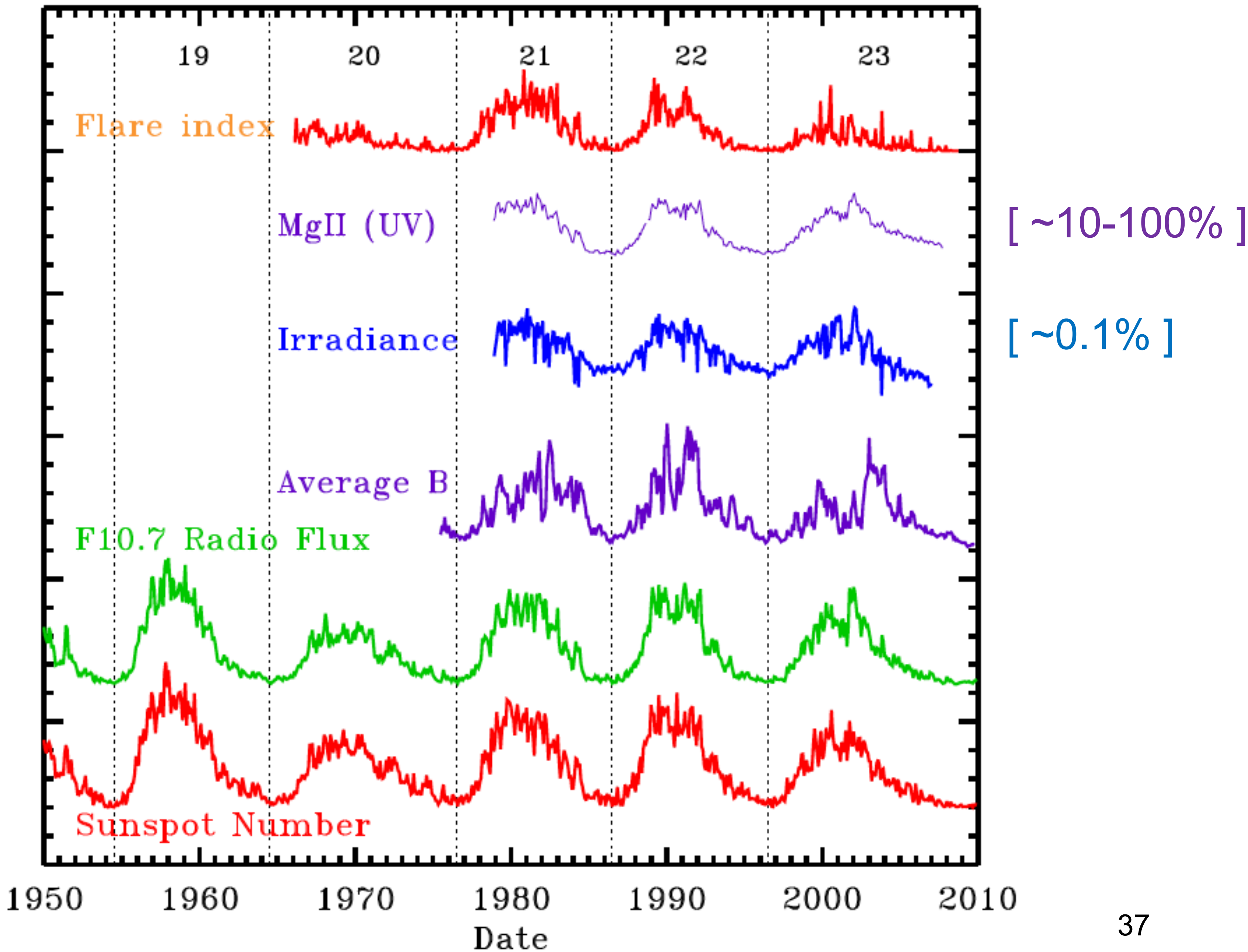


SO

Solar cycle prediction

Predicting what ?	Sunspot number Interplanetary magnetic field Radiative variability, SEP events Flare/CME frequency/characteristics …
Over what time frame ?	Individual geoeffective events Characteristics of next cycle Supra-cycle timescales Grand Minima/Maxima
With what accuracy ?	The proverbial factor of 2 1 % … 10 % … False Alarms vs Misses

Magnetic cycle = pulse of solar activity



Can the solar cycle be predicted ?

$\boxed{\text{Yes !!}}$

(… but your should not be too greedy …)