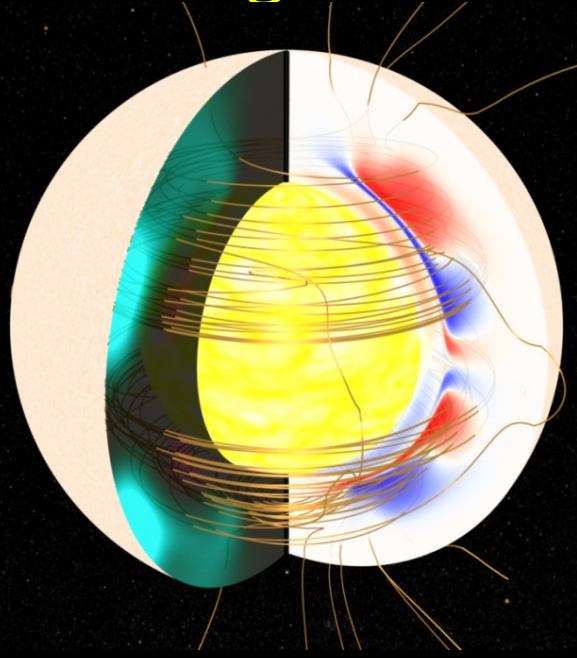


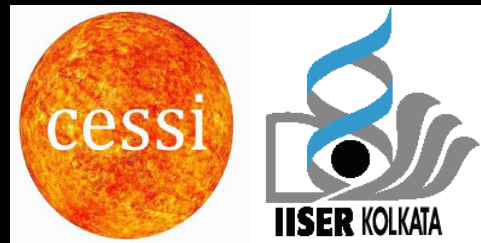
Solar Cycle Forecasting: The Underlying Physics



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Understanding origin of solar magnetism
is a fundamental challenge
and forecasting it is of great practical importance

Magnetic Fields

Solar Storms

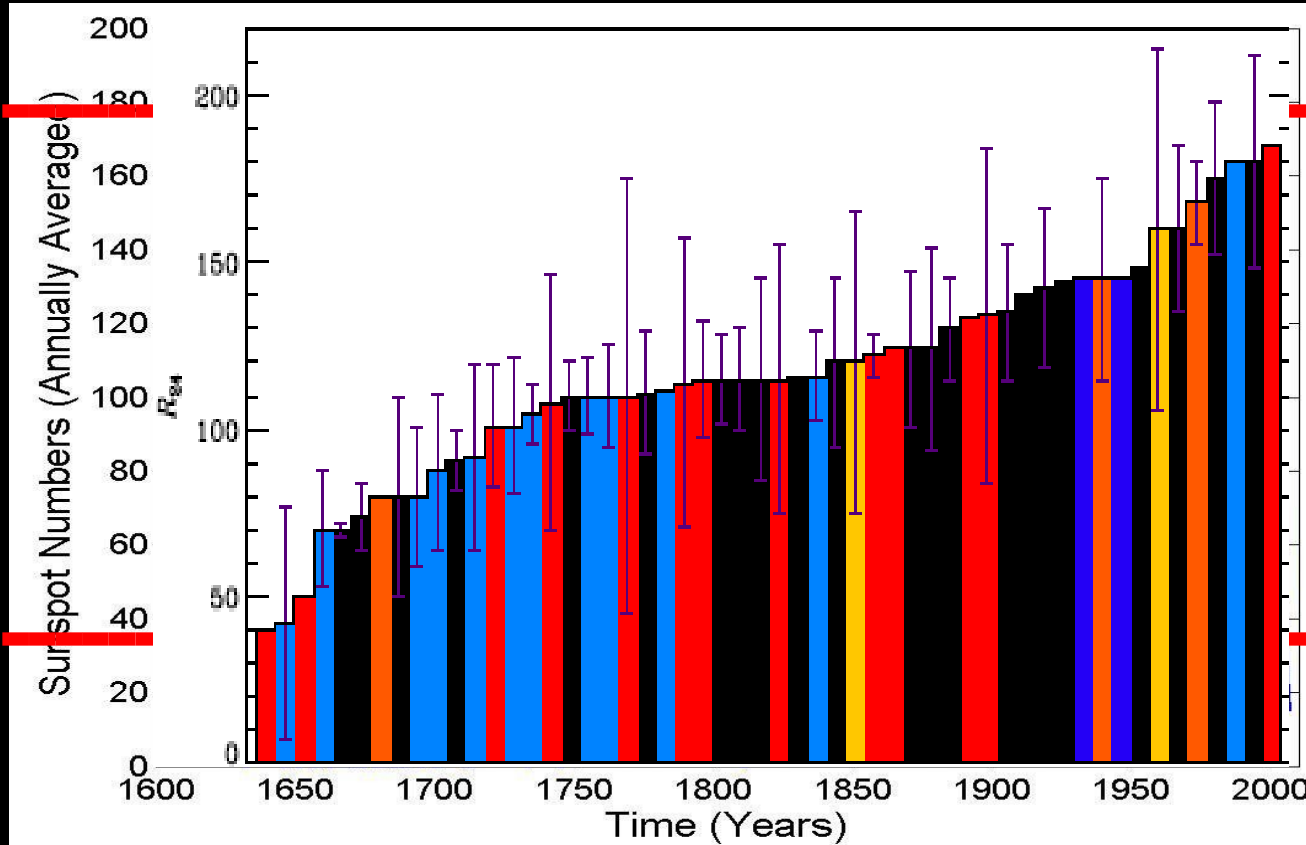
Solar Wind Conditions

Solar Radiation Spectrum

Open Flux

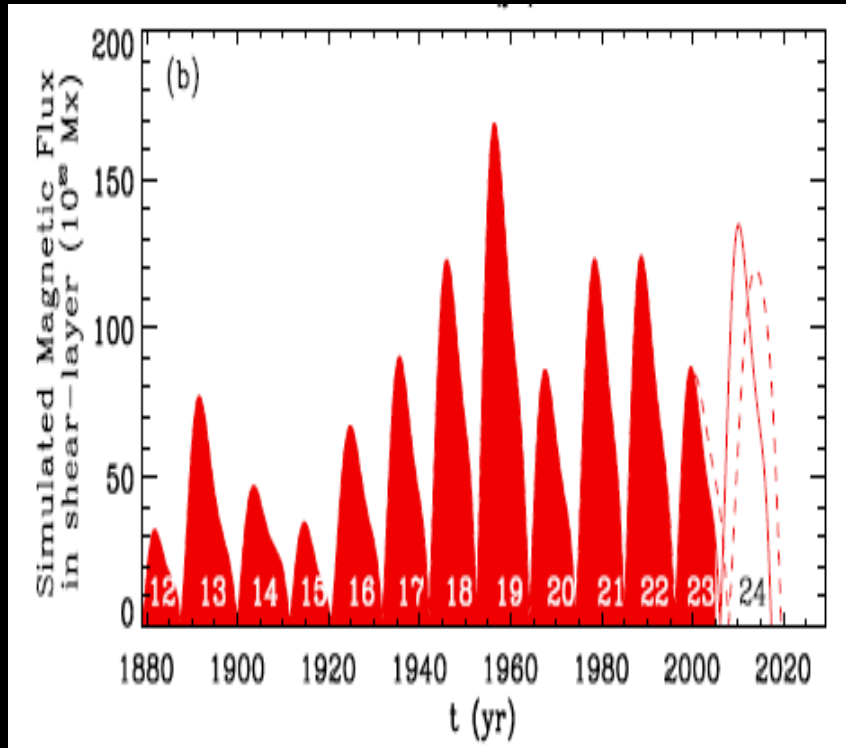
Cosmic Ray Modulation

The bottom-line and how we are doing?

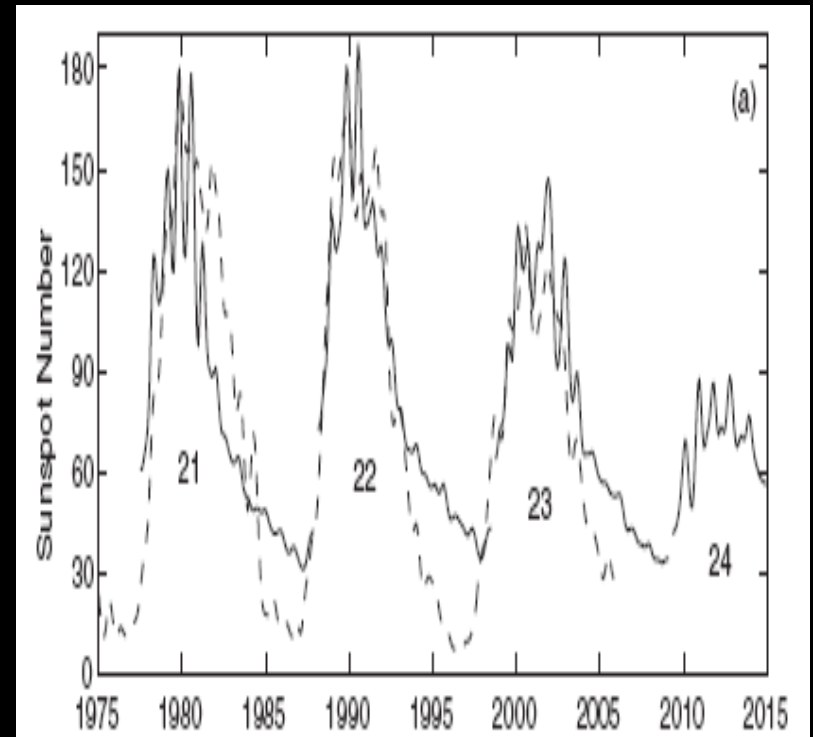


Range of predictions for one cycle (24) spans the entire amplitude range of all sunspot cycles ever directly observed!
(Pesnell 2008, Sol. Phys.)

How about dynamo-based predictions?

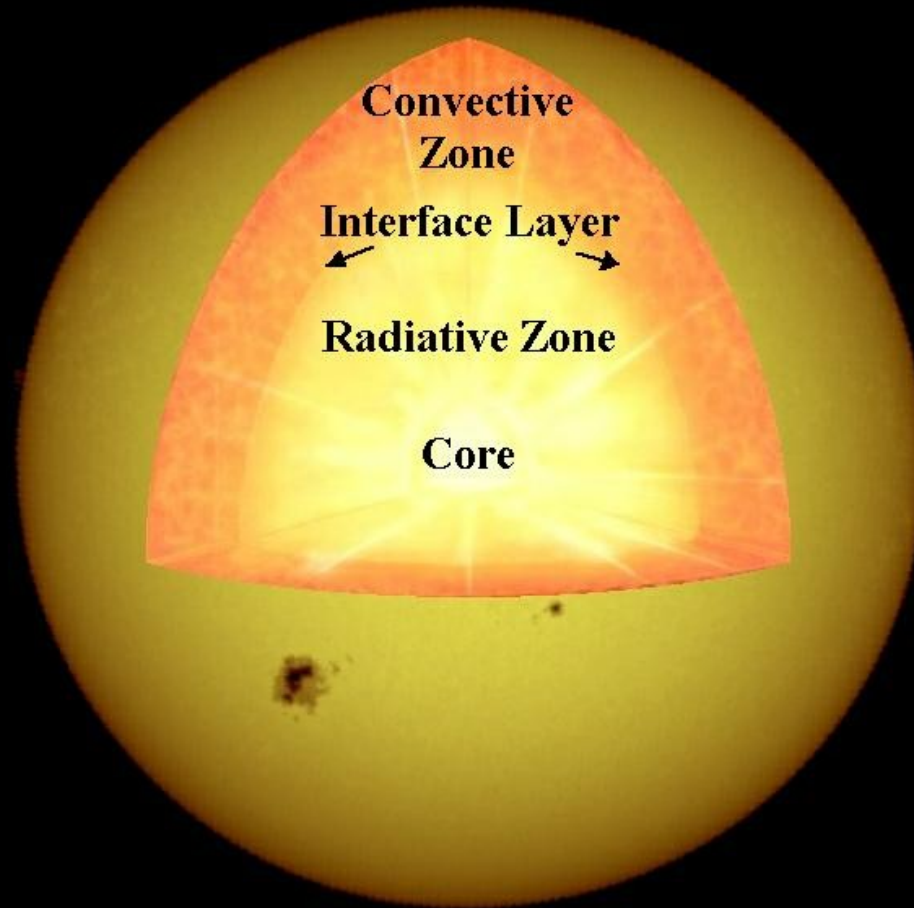


Dikpati et al. (2006, GRL)
Very Strong Cycle



Choudhuri et al. (2007, PRL)
Very Weak Cycle

Window to the Solar Interior



- Matter exists in the ionized state in the solar interior
- Convection zone sustains plasma motion and magnetic fields
- Enter magnetohydrodynamics

Basic Physics: Plasma Flows Govern Magnetic Field Generation

- Governing equation:

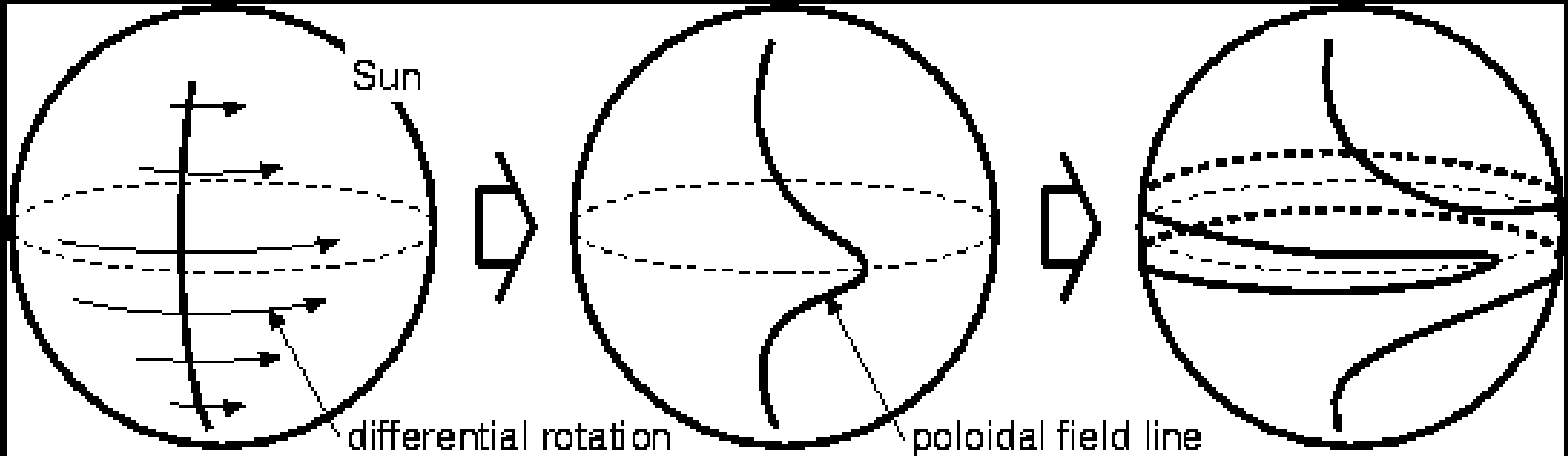
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

- Magnetic Reynolds Number:

$$R_m = \frac{VB/L}{\eta B/L^2} = \frac{VL}{\eta}$$

- In Astrophysical systems, R_M usually high, magnetic field creation possible and fields frozen-in with plasma
 - Diffusion timescale $\tau_\eta >$ Flow timescale τ_v
- In solar interior, plasma $\beta \gg 1$ (gas pressure higher than magnetic pressure and therefore, plasma flows govern field dynamics
 - **Solar Dynamo Models**

Elements of the Dynamo: Toroidal Field Generation (Omega Effect)

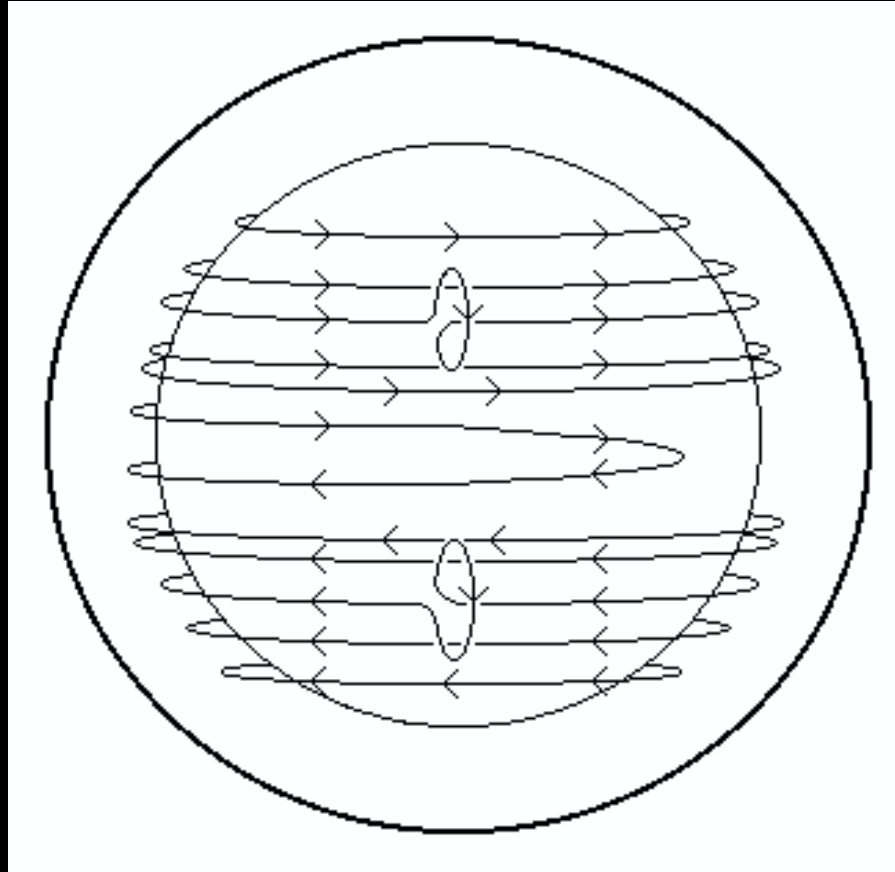


Poloidal field

Toroidal Field

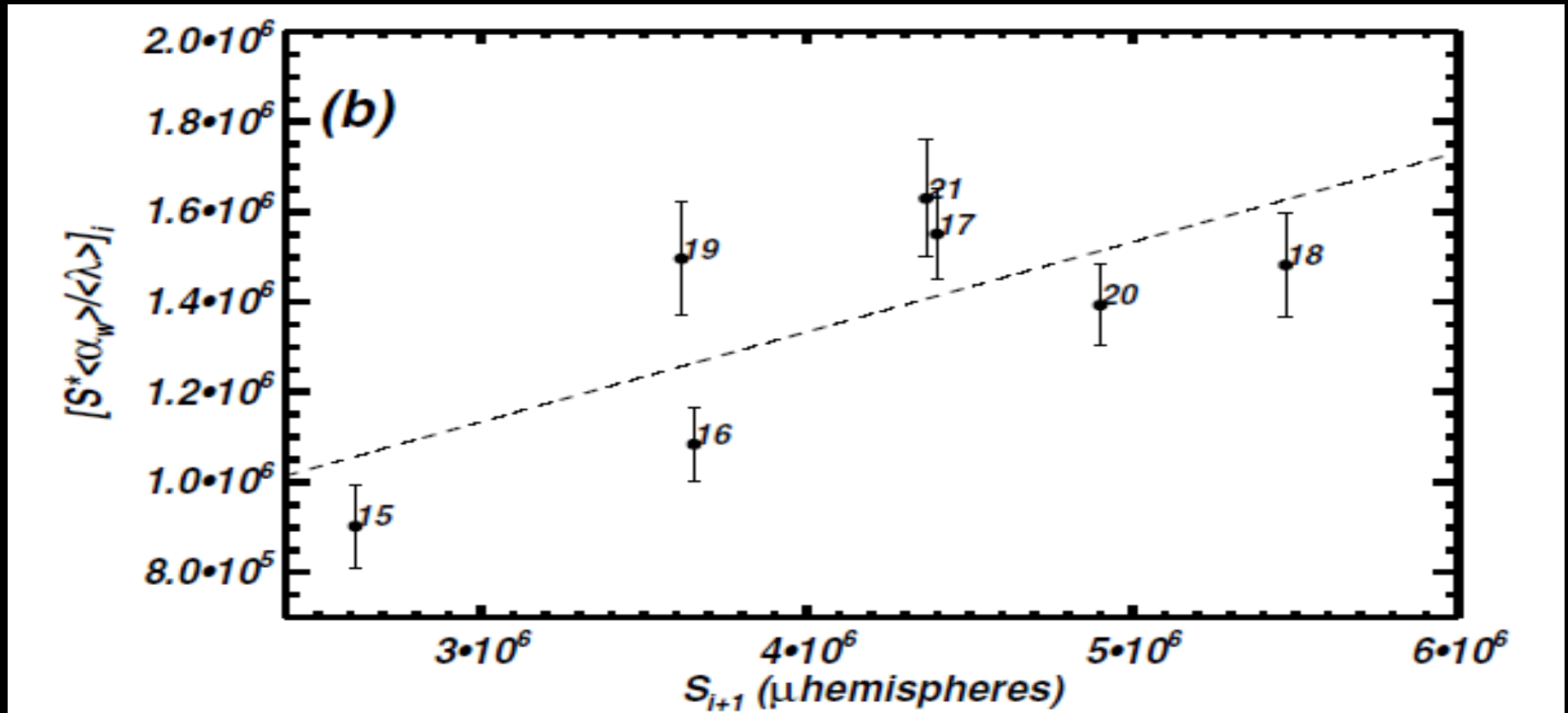
- Differential rotation will stretch a pre-existing poloidal field in the direction of rotation – creating a toroidal component (Parker 1955, ApJ)
- Occurs within the solar interior
- Toroidal flux tubes stored at the base of the convection zone

Poloidal Field Generation – The MF α -effect



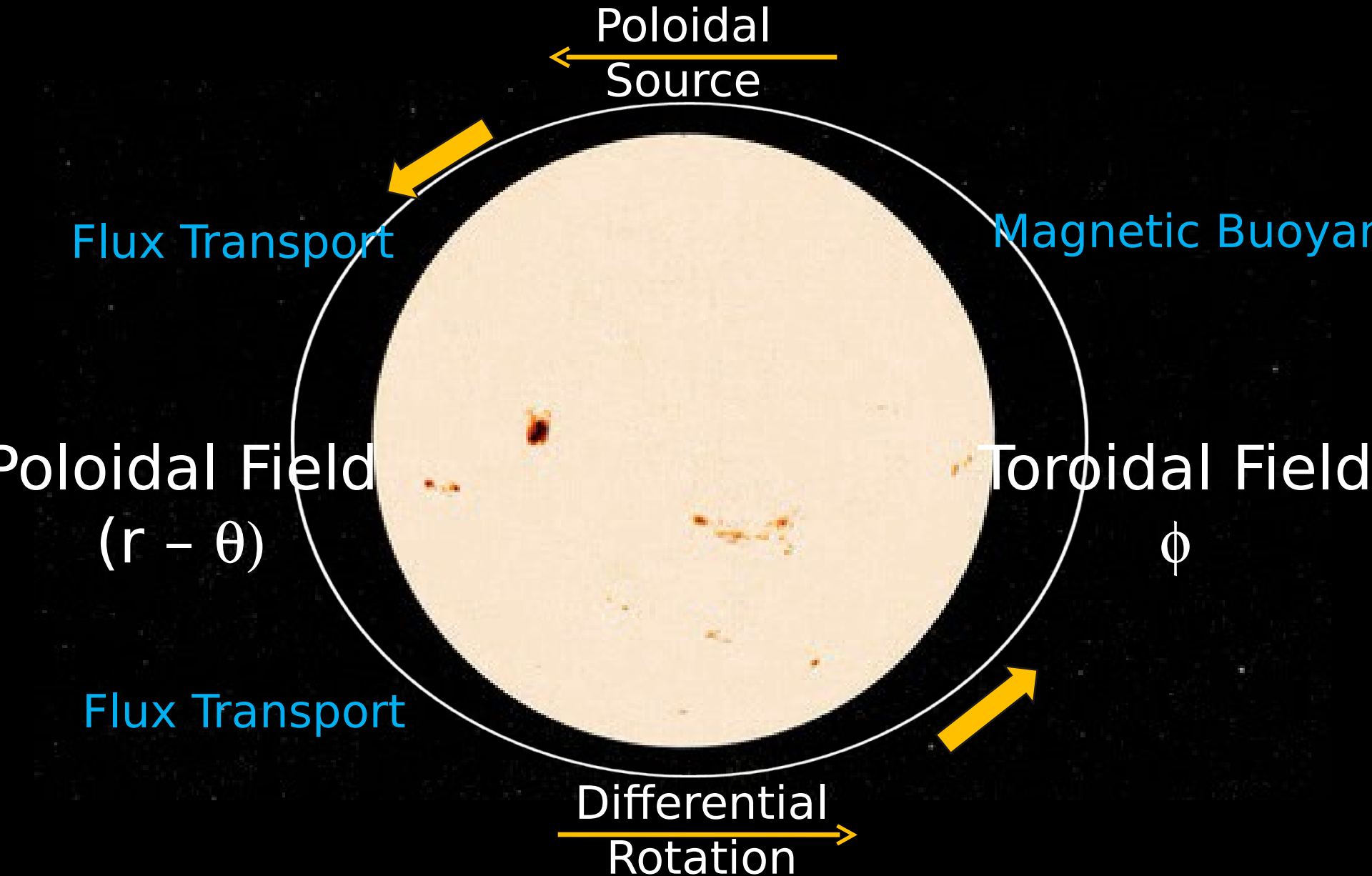
- Helical convection – Mean-Field α -effect (Parker 1955, ApJ)
- Buoyantly rising toroidal field is twisted by helical turbulent convection, creating loops in the poloidal plane
- Strong flux tubes will quench this mechanism, alternatives required...

Poloidal Field Generation: Dispersal of Tilted Bipolar Sunspot Flux



- Babcock (1961, ApJ) & Leighton (1969, ApJ) idea: tilted bipolar sunspots pairs decay and disperse near surface – is observed
- Numerous models have been constructed based on the BL idea — Strong observational support (Dasi-Espuig et al. 2010, A&A)

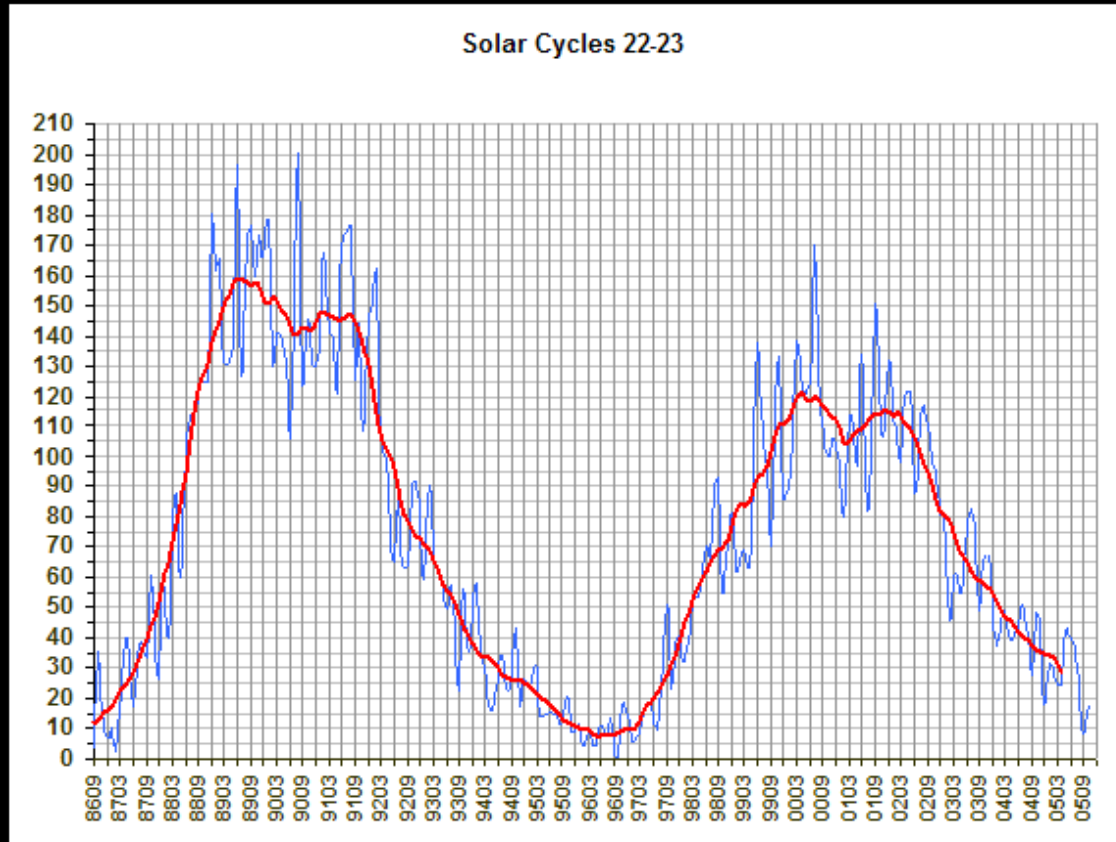
Solar Cycle Dynamics in a Kinematic Dynamo Simulation



Recent Insights

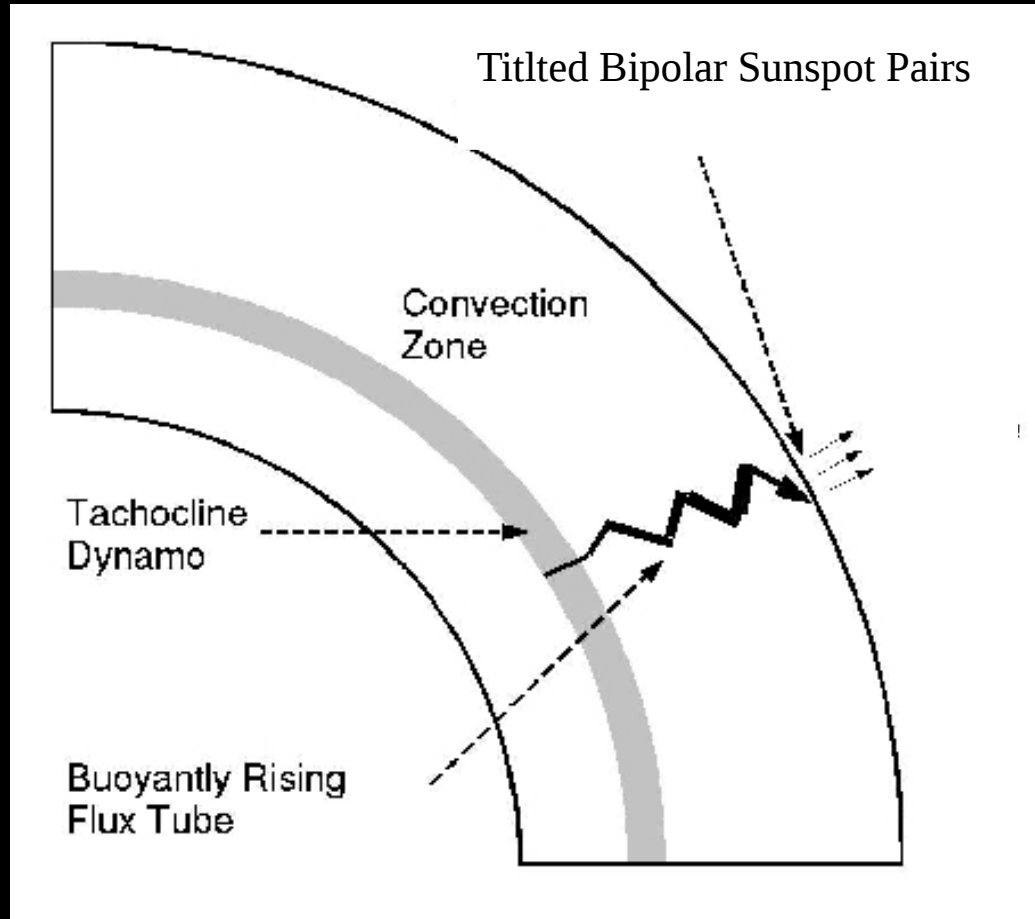
*Less than a decade of efforts spent to develop models
for solar cycle predictions;
in contrast, organized efforts for predicting
weather on Earth have evolved for many decades!*

Fluctuations and Predictability of the Solar Cycle



The first step towards predictions is to understand the origin of solar cycle fluctuations

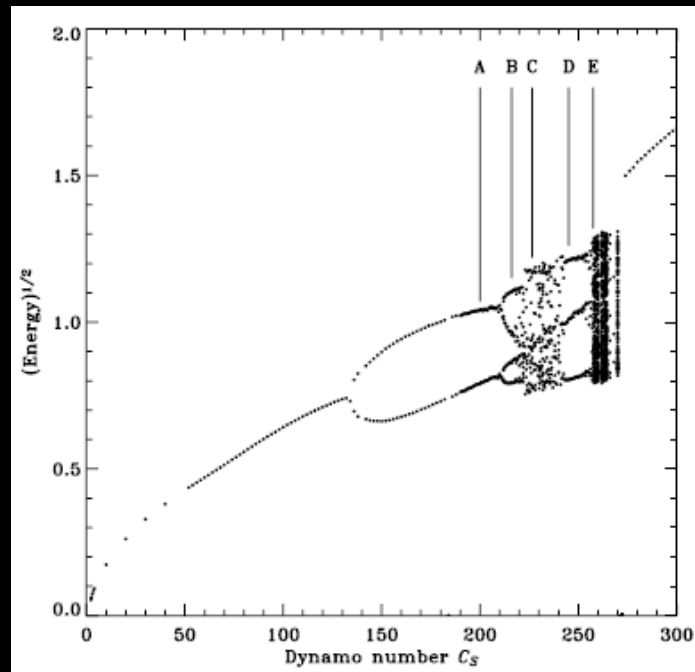
Origin of Solar Cycle Irregularities?



- Poloidal field source (eruption of tilted bipolar sunspots) is stochastic
- Feedback of field on flows introduces non-linearity
- But in weakly non-linear, near-critical dynamo number regime, stochastic fluctuations primary source of short-term modulation

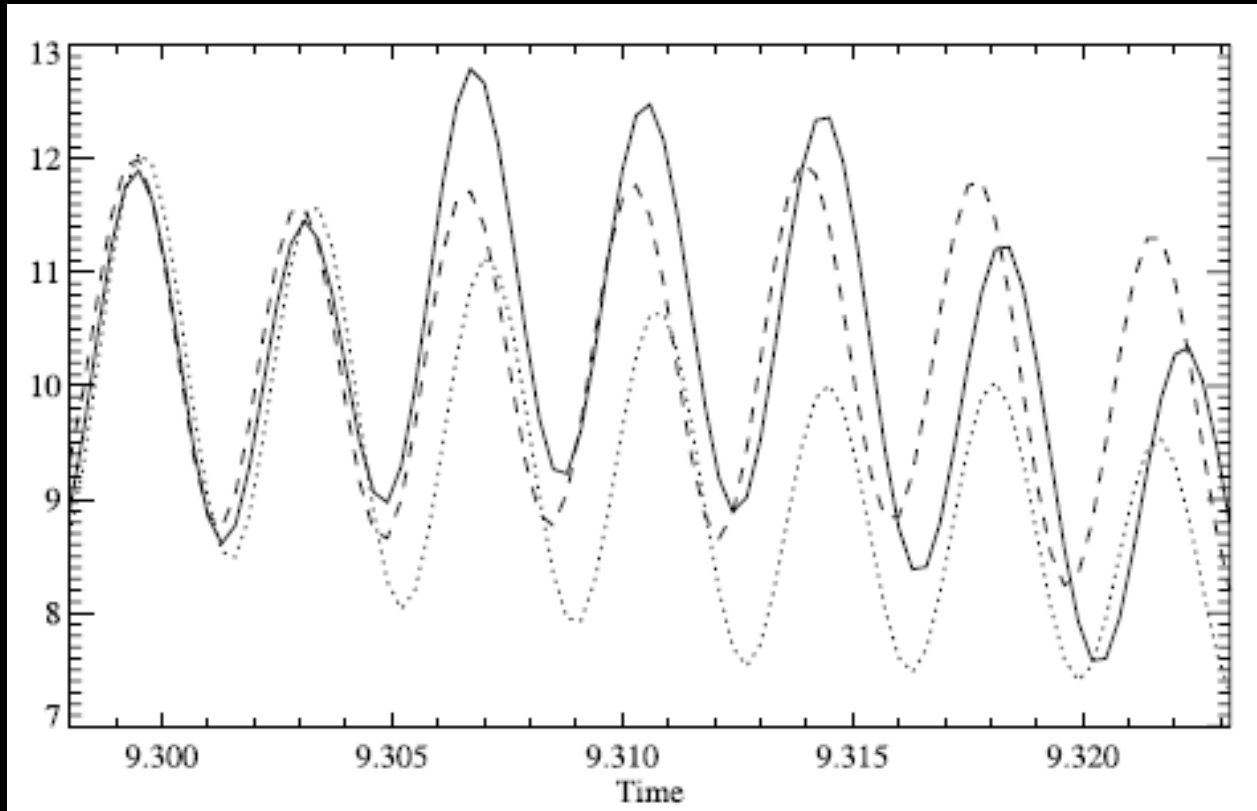
Origin of Fluctuations in the Solar Cycle: Path to Chaos

- Dynamical nonlinearities especially important in super-critical regimes
—Tobias (1997, A&A)
—Wilmot-Smith et al. (2005-MNRAS, 2006-ApJ)
- When source terms dominate over sink terms, random “kicks” in the forcing of the system become very important
- Can lead to chaotic behavior...



(Charbonneau, St-Jean & Zacharias 2005, ApJ)

Chaotic Systems and Predictability



(Bushby & Tobias 2007, ApJ)

- Chaotic regime: small differences in initial conditions diverge
- Is short-term prediction possible?
- Yes; based on the flux-transport mediated memory of the system

Towards Prediction: The Underlying Physics

Flux Transport Terms Deterministic
 Introduces time delay = memory

- Toroidal field evolution:

$$\frac{\partial B_\phi}{\partial t} + \frac{1}{r} \left[\frac{\partial}{\partial r} (r v_r B_\phi) + \frac{\partial}{\partial \theta} (v_\theta B_\phi) \right]$$

$$= \eta \left(\nabla^2 - \frac{1}{r^2 \sin^2 \theta} \right) B_\phi + r \sin \theta (B_P \cdot \nabla) \Omega - \nabla \eta \times (\nabla \times B_\phi)$$

- Poloidal field

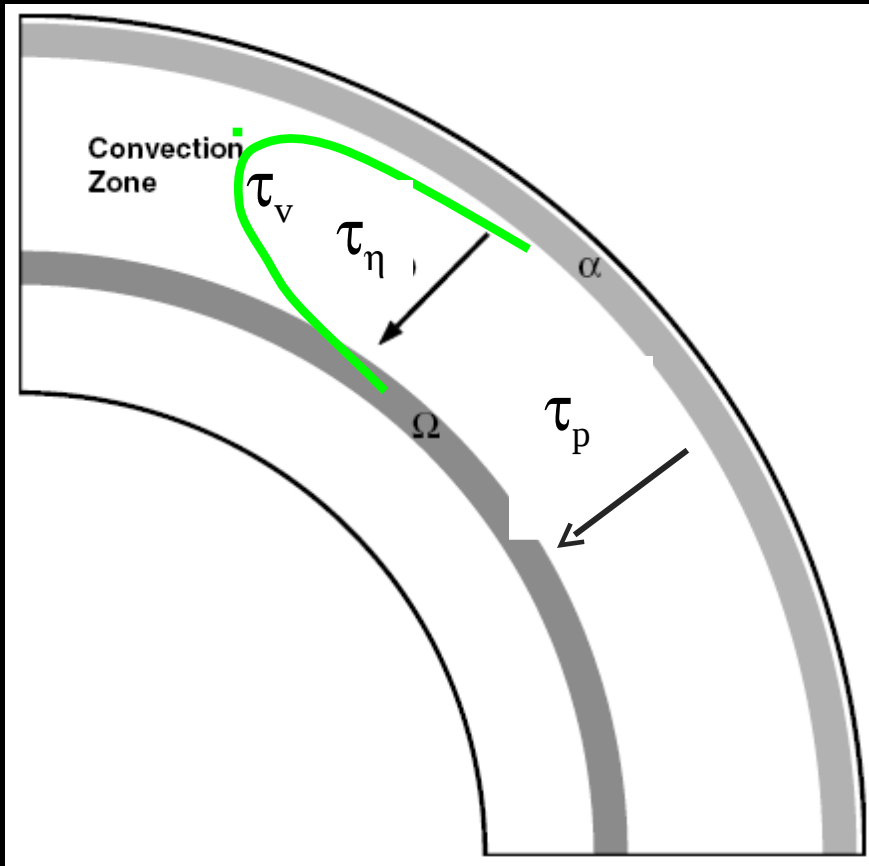
$$\frac{dB_\phi(t)}{dt} = \frac{\omega}{L} A(t - T_0)$$

$$\frac{\partial A}{\partial t} + \frac{1}{r \sin \theta} (v_P \cdot \nabla) A$$

Poloidal Source Stochastic
 Random buffeting of
 Rising flux tubes –
 Tilt angle distribution

But Poloidal Source Observed!

Competing Flux Transport Mechanisms in the Solar Interior



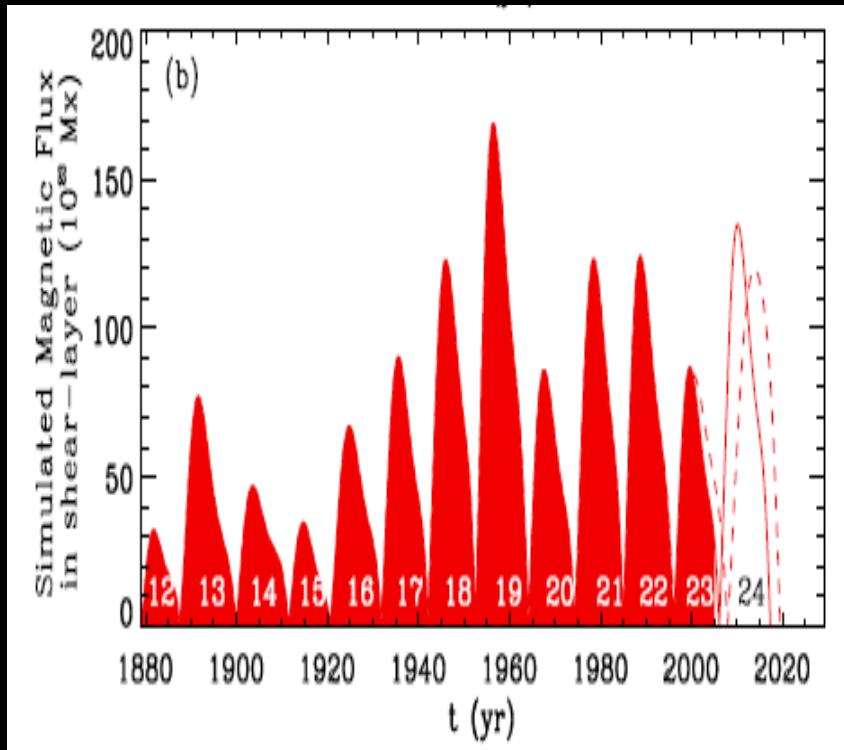
Dijpati & Charbonneau 1999, ApJ
Nandy & Choudhuri, 2002, Science
Chatterjee et al. 2004, A&A
Yeates, Nandy & Mackay 2008, ApJ
Hotta & Yokoyama 2010, ApJ
Karak & Nandy 2012, ApJL

- Meridional Flow (15—20 m/s)
 $\tau_v = 20$ yrs (slow process)
- Turbulent Diffusion (1×10^{12} cm²/s)
 $\tau_\eta = 14$ yrs (moderate)
- Turbulent Pumping ($v = 2$ m/s)
 $\tau_{\text{pumping}} = 3.4$ yrs (fast process)

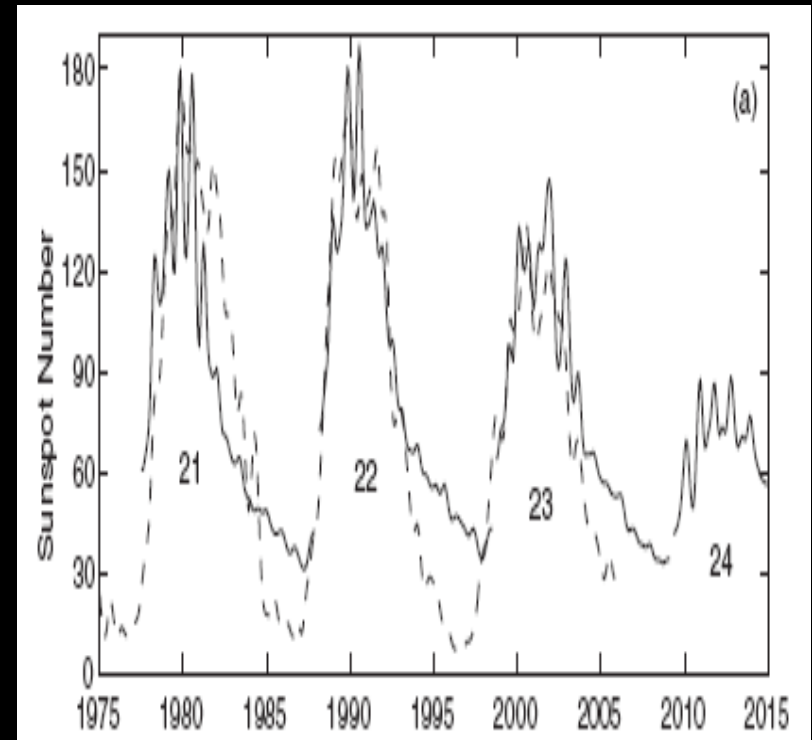
Dynamo models used for prediction
ignored turbulent pumping

Explored in other contexts recently
Guerrero & Dal Pino 2008, A&A
Do Cao & Brun, 2011, AN

Can we explain the cause of diverging dynamo-based forecasts?



Dikpati et al. (2006, GRL)
Very Strong Cycle
Advection Dominated

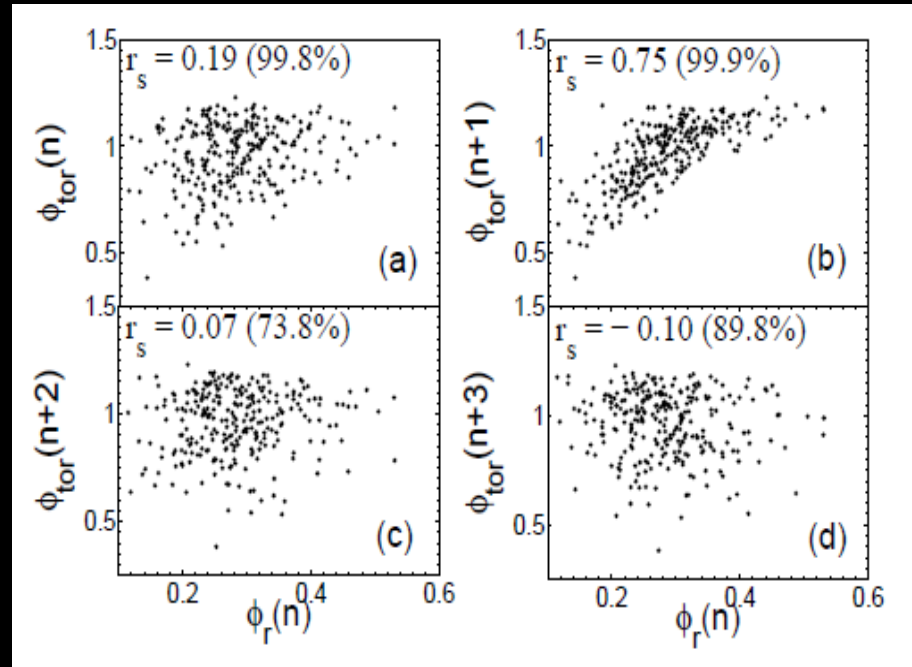


Choudhuri et al. (2007, PRL)
Very Weak Cycle
Diffusion Dominated

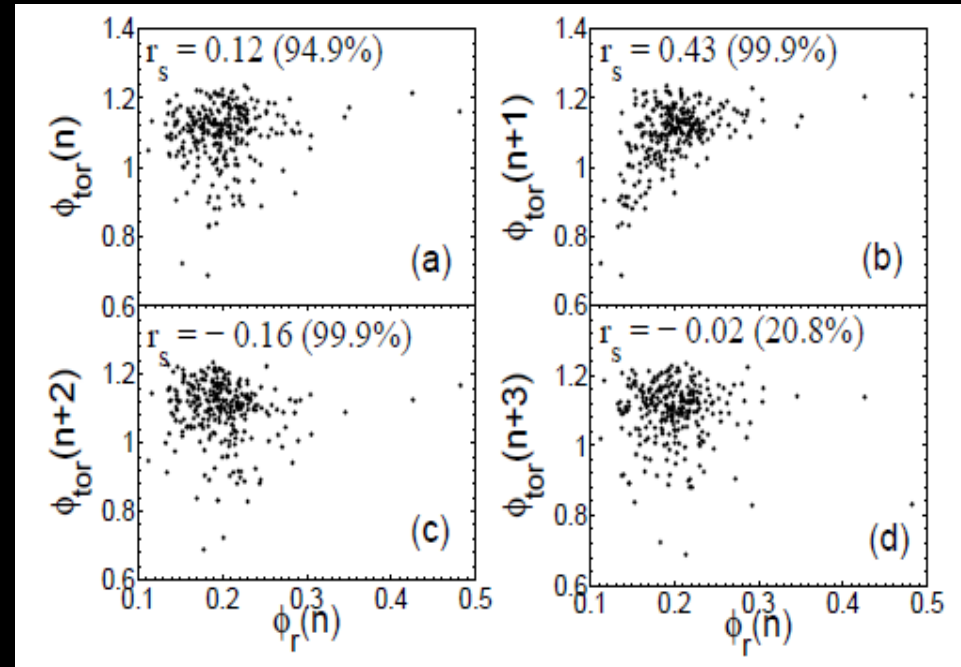
- Yeates, Nandy & Mackay (2008, ApJ): Diverging predictions due to the persistence of long-term memory in advection dominated models, as opposed to a one cycle memory in diffusion dominated models

Theoretical Modeling with Turbulent Pumping Indicates Short Memory

(Karak & Nandy 2012, ApJL; based on stochastically forced dynamo)



(Advection dominated – low η)

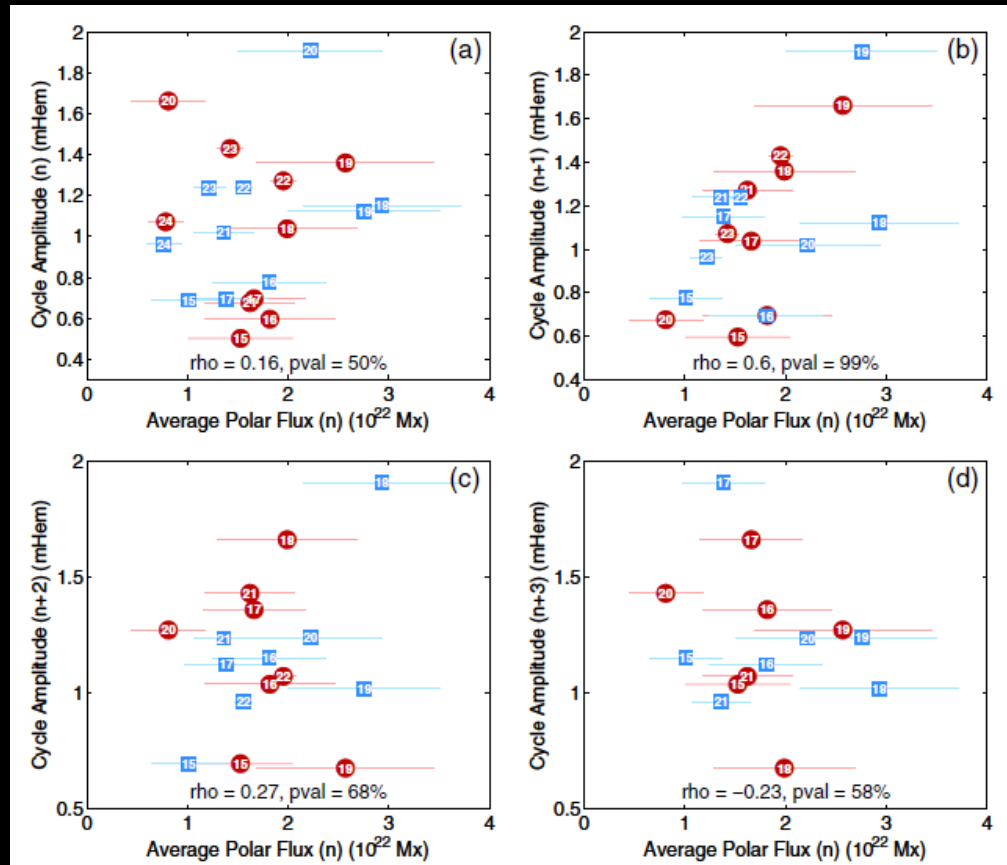
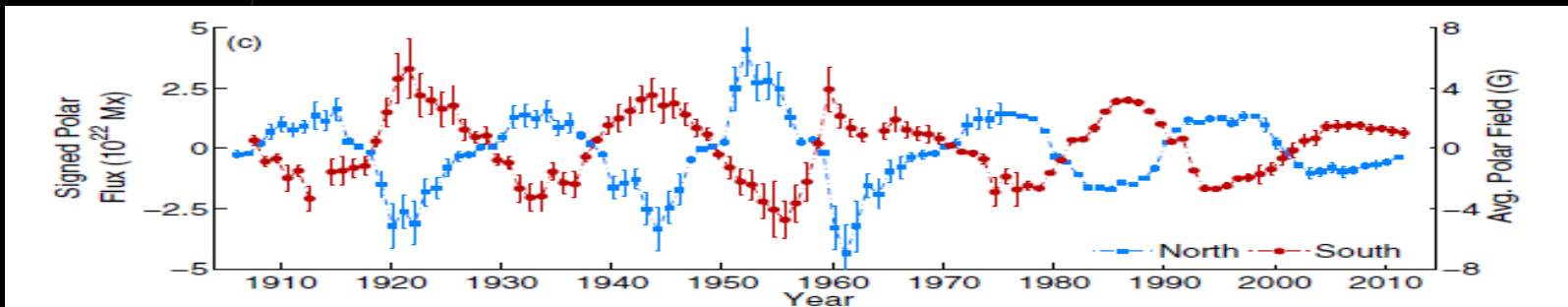


(Diffusion dominated – high η)

- Advection and diffusion dominated regimes behave similarly!
- Memory reduces to one cycle for a pumping speed of 2 m/s
- Our results indicate that the solar cycle has a short memory
- We argue that long-term accurate predictions not possible

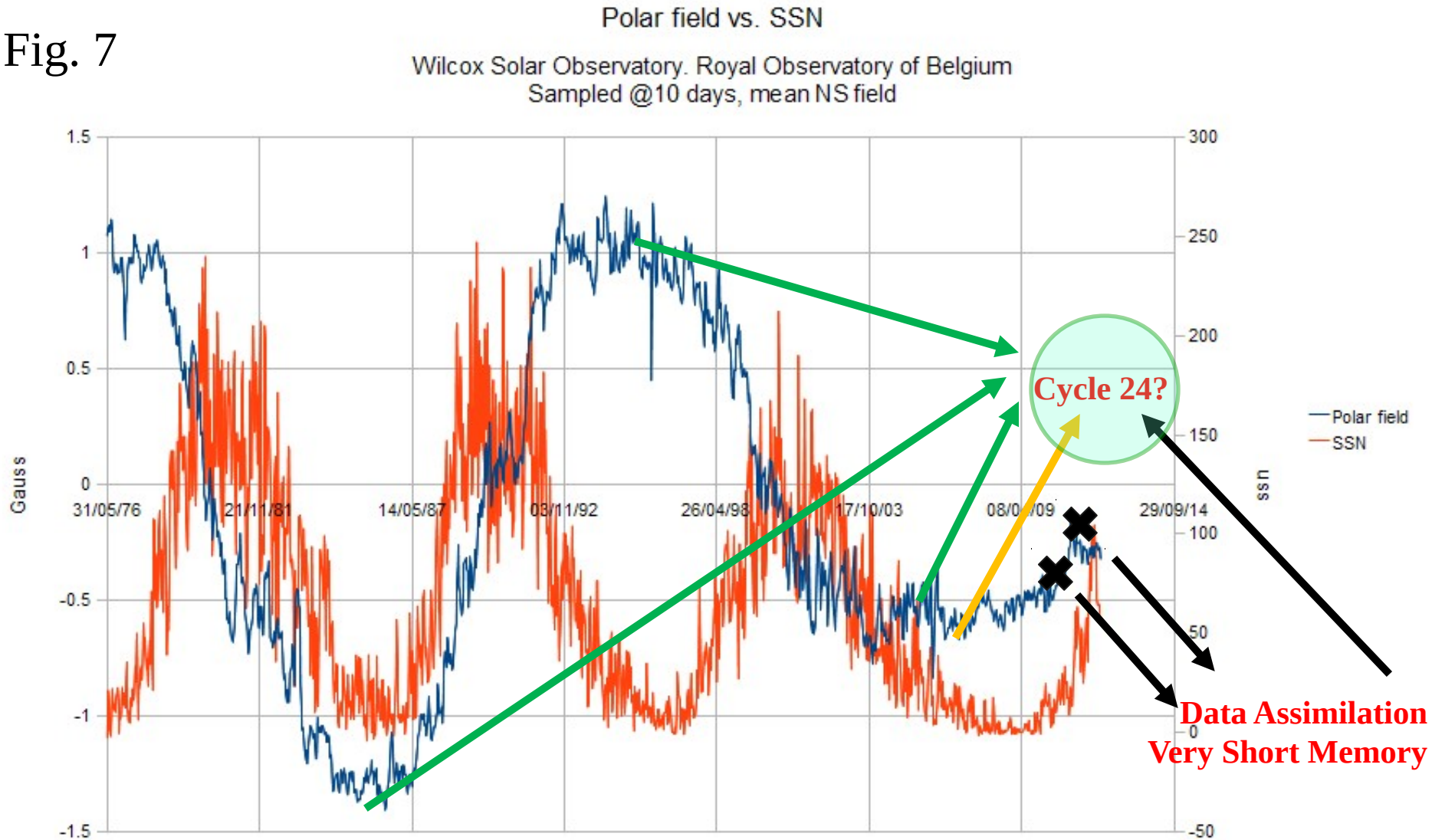
Observational Verification of Short Solar Cycle Memory

(Munoz et al. 2013, ApJL; based on polar faculae data)



Long Memory: Polar field of multiple cycles seeds next sunspot cycle

Fig. 7



Short Memory: Polar field of previous cycle seeds next cycle

Concluding Summary

- We are beginning to understand the physical processes that govern solar cycle predictability
- We are now confident that the Sun's dynamical memory is short
- This implies that accurate, long-term predictions beyond one cycle are not possible (sorry to disappoint!)
- Operational forecasting necessitates data assimilation at intervals shorter than shortest flux transport timescale
- First attempts on data assimilated dynamo models encouraging (Kitiashvili & Kosovichev 2008, ApJ; Jouve, Brun & Talagrand, 2011, ApJ; Yeates & Munoz-Jaramillo 2013, MNRAS)

Outstanding Issues

- Can non-linear feedback mechanisms impact predictions?
 - Strong-cycle predictions may be compromised...
- Does fluctuations in mean-field poloidal source matter?
 - Certainly in other aspects, e.g., cycle recovery post grand minima
Passos, Nandy, Hazra & Lopes, 2014, A&A
Hazra, Passos & Nandy, 2014, ApJ
- Exact nature of meridional circulation: Does internal structure (one cell, two cells, multiple cells) or shallow flow make a difference?
 - Turbulent pumping reduces role of circulation
(Karak & Nandy 2012, ApJ)
 - Recent simulations with turbulent pumping indicates dynamo can function even with a shallow flow
(Hazra & Nandy 2014, in preparation)