Solar cycle & Dynamo Modeling

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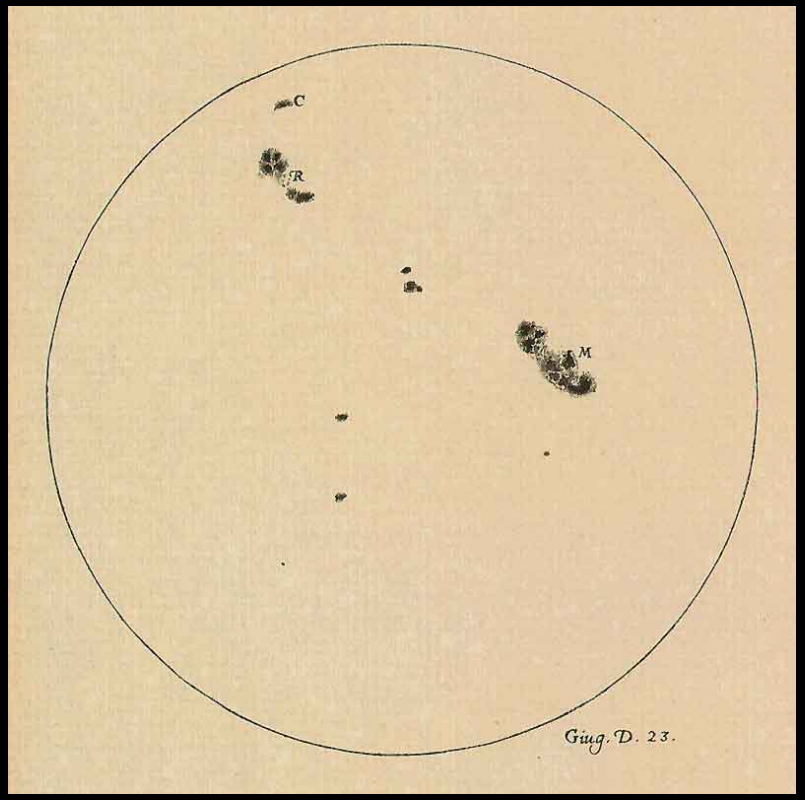
THE SOLAR CYCLE: A MAGNETIC PHENOMENON

Sunspots were first studied with the advent of the telescope (1610)

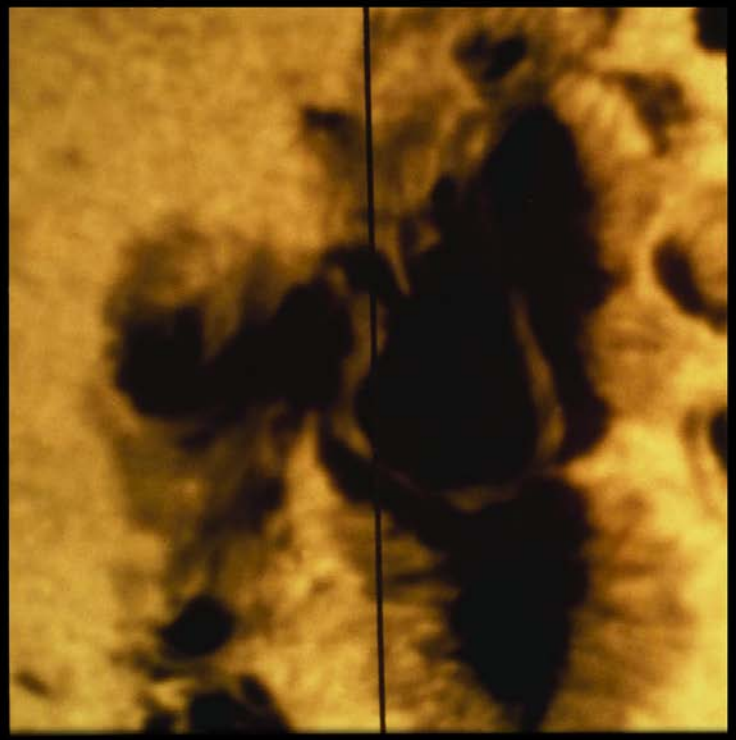


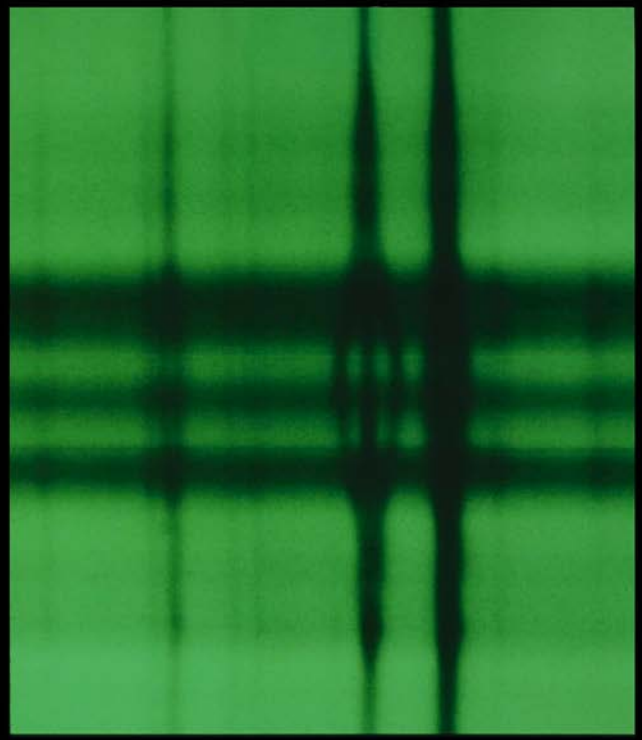
Drawing by Galileo (circa 1610)

SOHO/MDI

Sunspots are associated with regions of very strong magnetic field (Hale 1908)

- Magnetic field is measured using the Zeeman effect.





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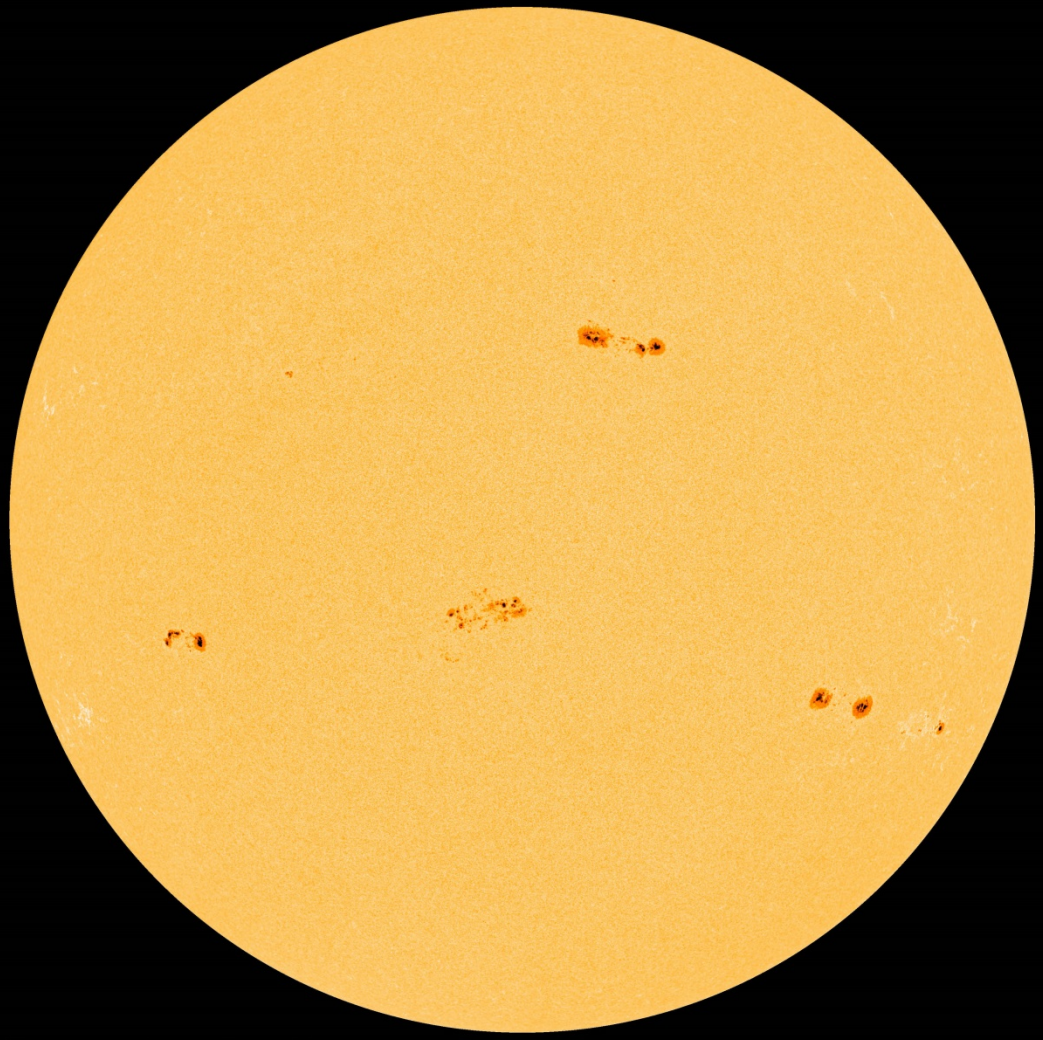

SDO/HMI

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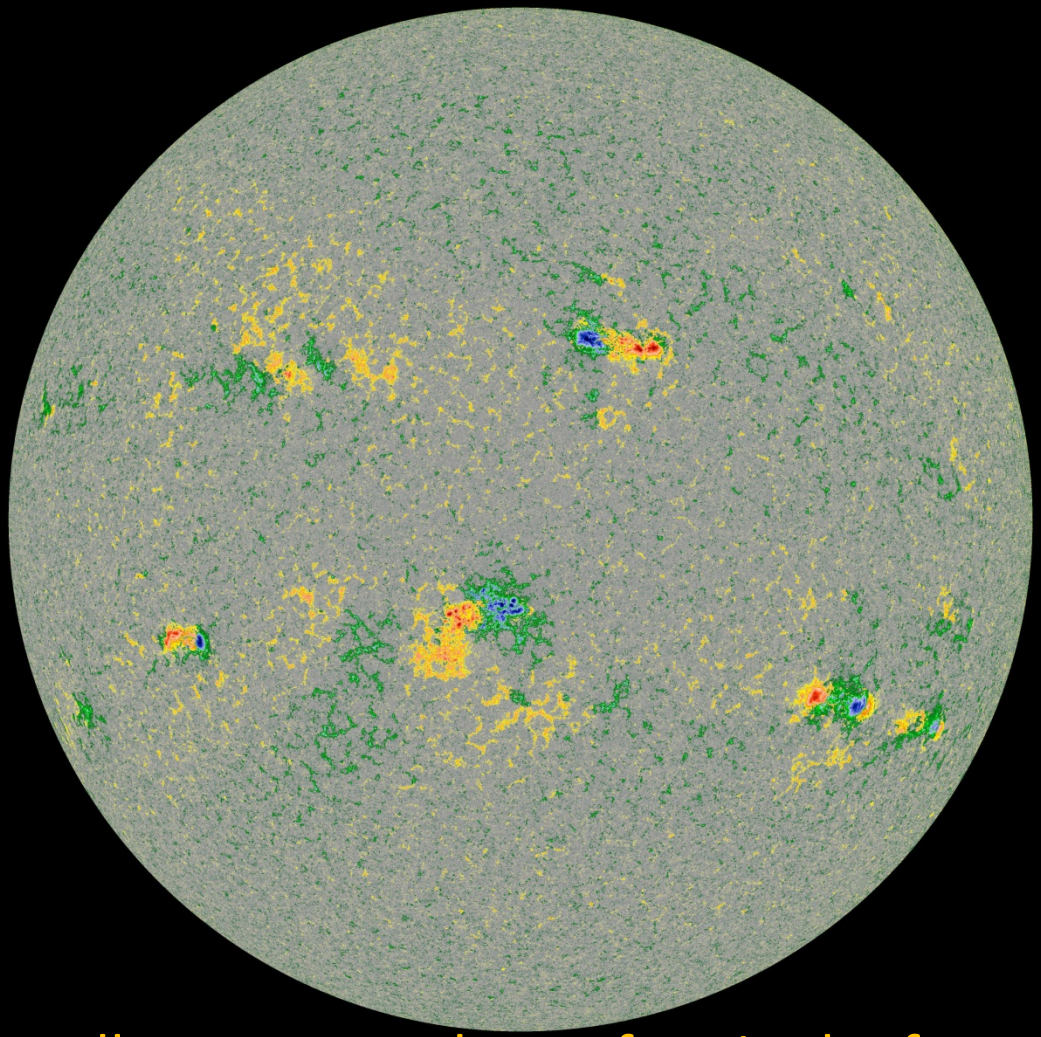
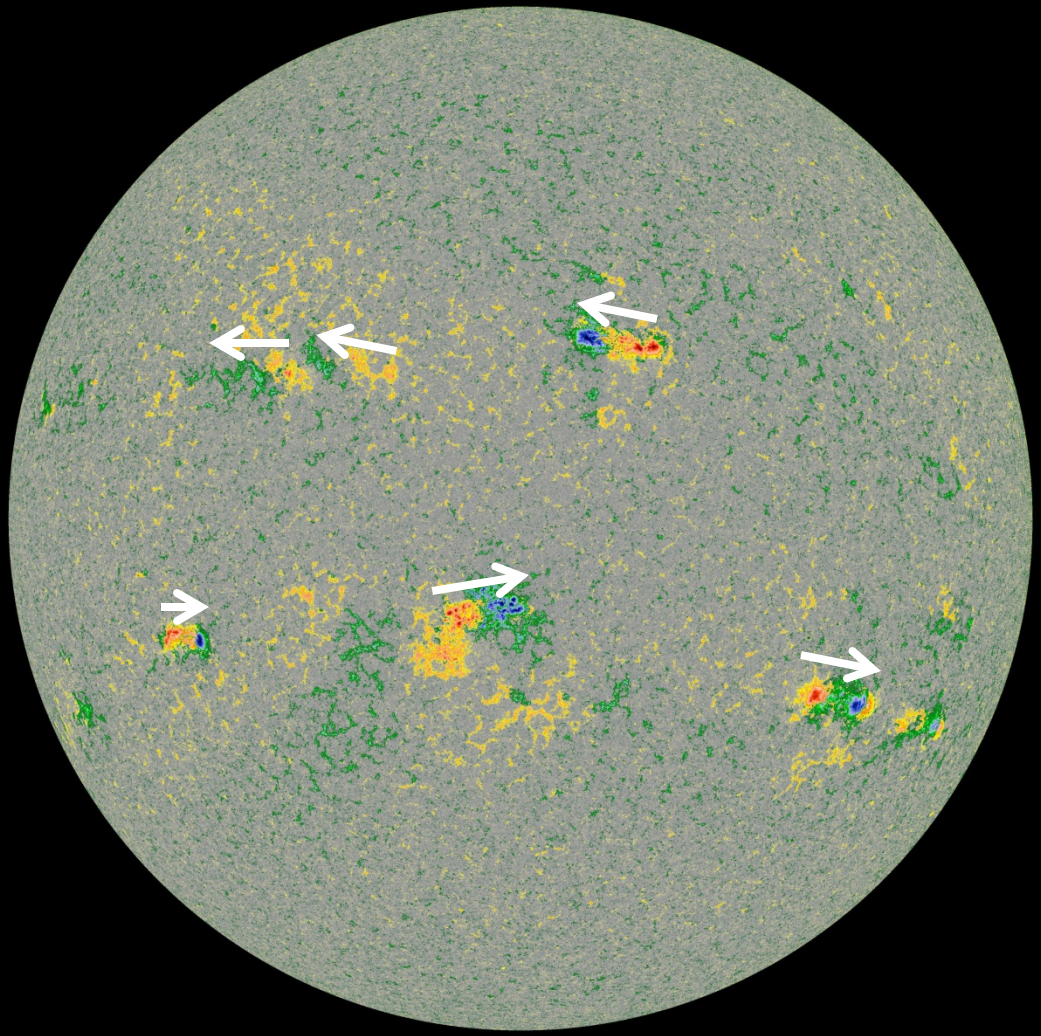


Fields generally appear at the surface in the form of bipolar structures called active regions

SDO/HMI

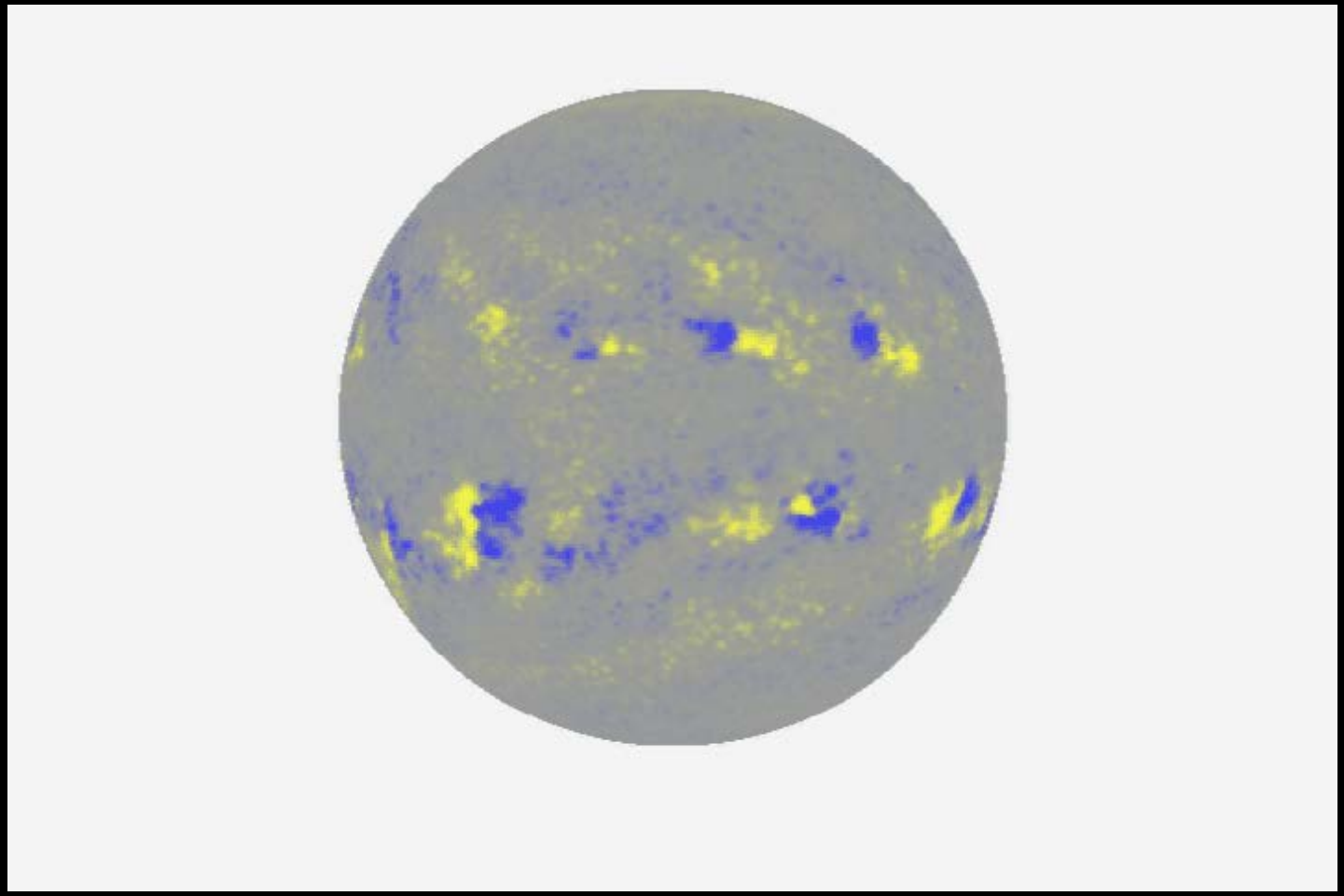
Sunspots are associated with regions of very strong magnetic field (Hale 1908)



Active regions present systematic orientation and inclination

SDO/HMI

The most visible features of the cycle are associated with active regions



Movie by David Hathaway

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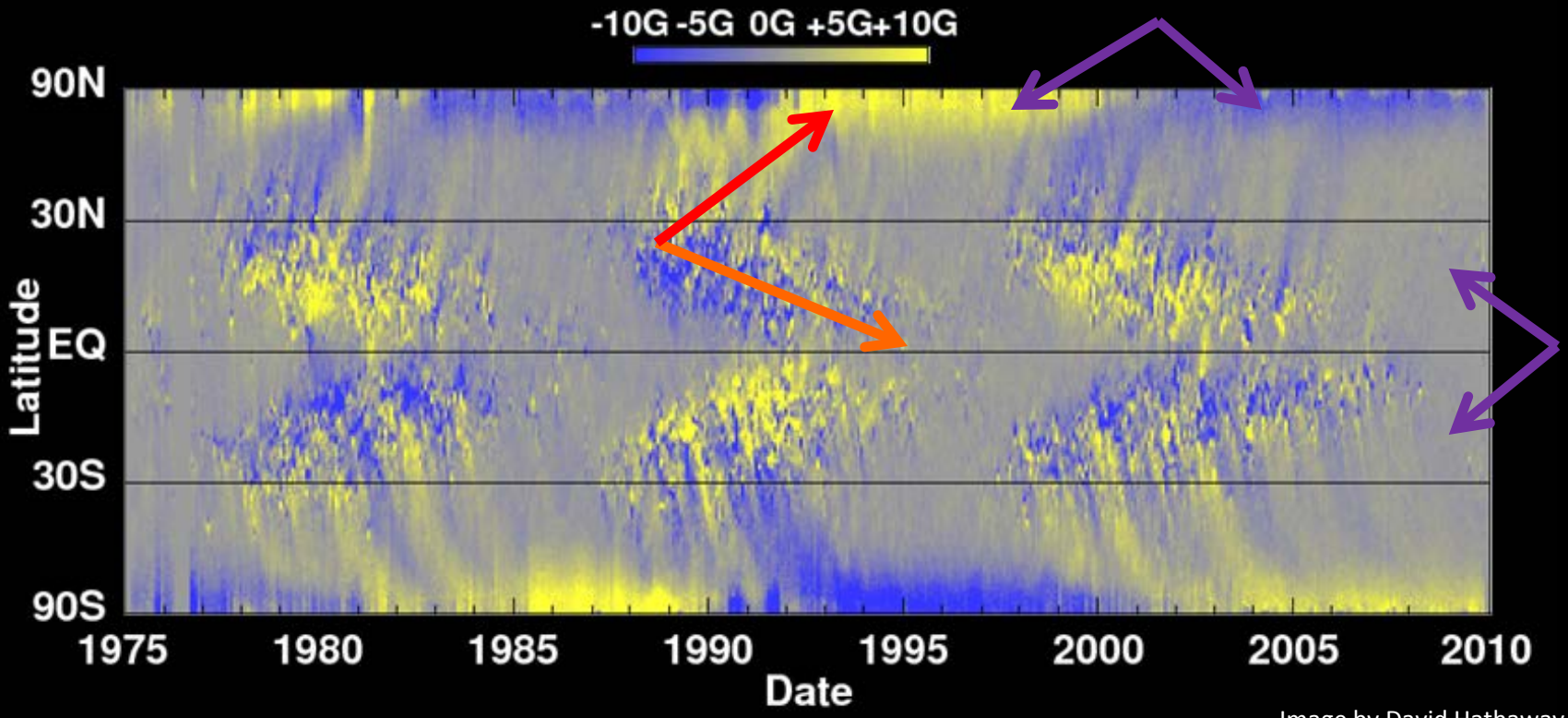
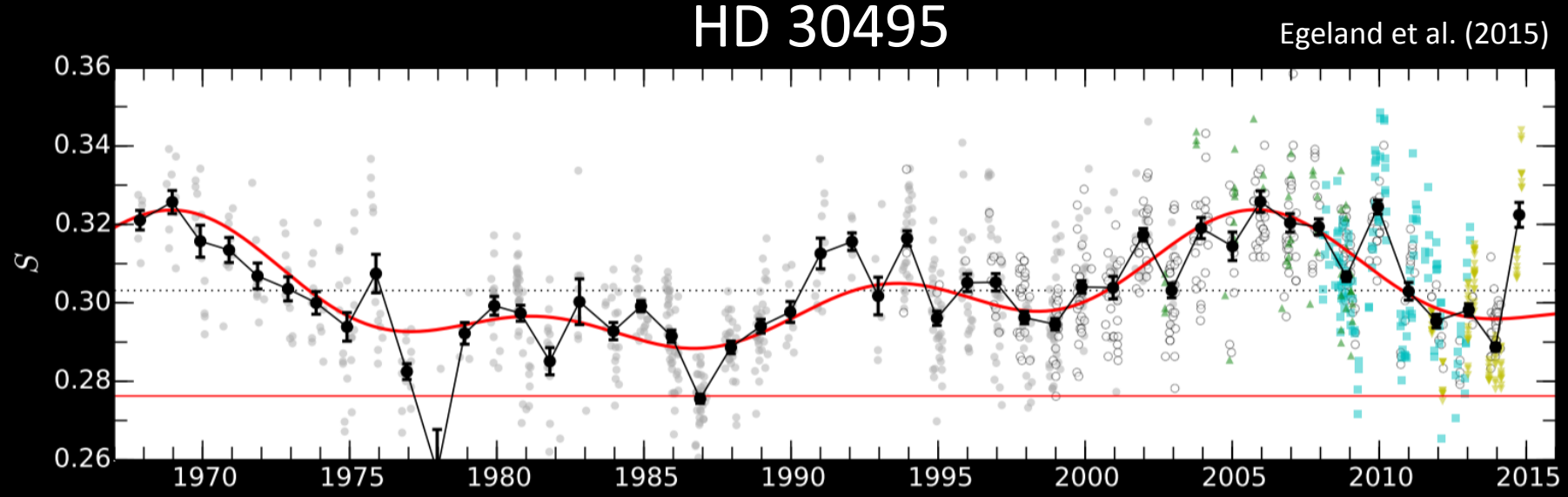
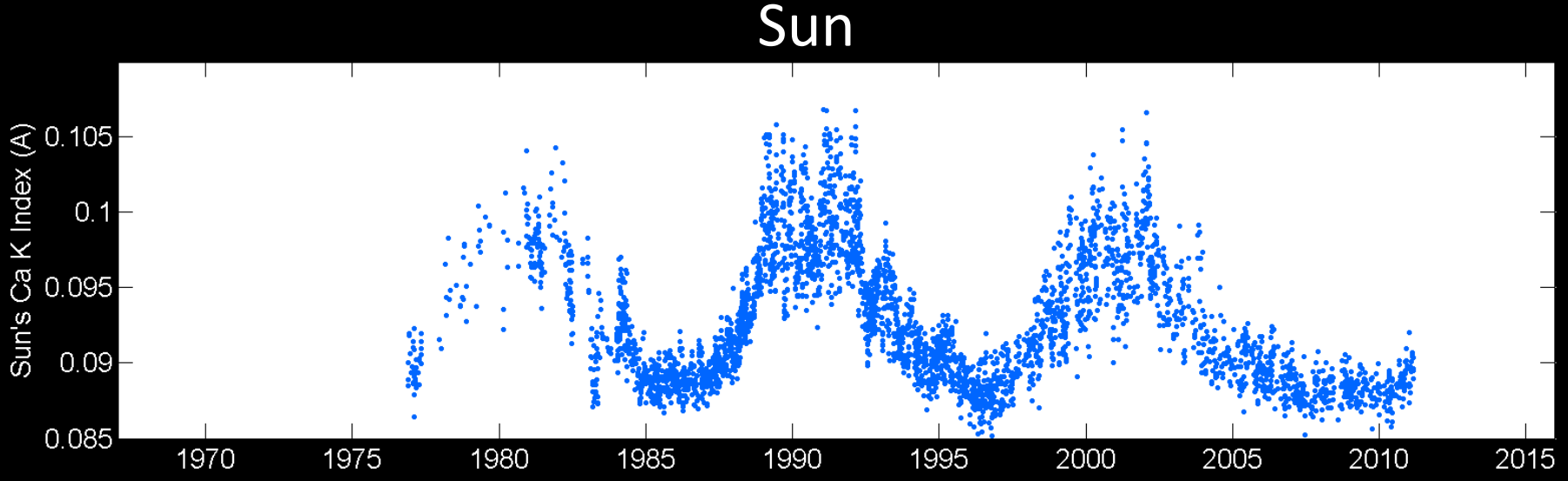


Image by David Hathaway

- Equatorward migration of active latitudes.
- Poleward migration of their decayed diffuse field
- Polar field reversal at the maximum of the cycle and across hemispheres.

Not unique to the Sun

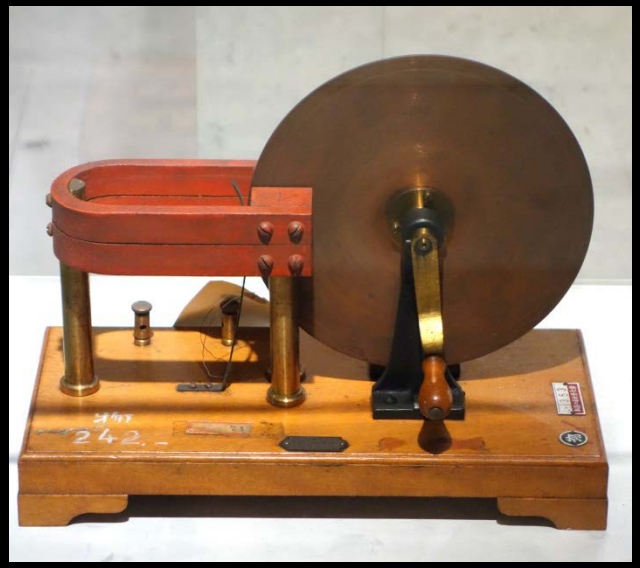


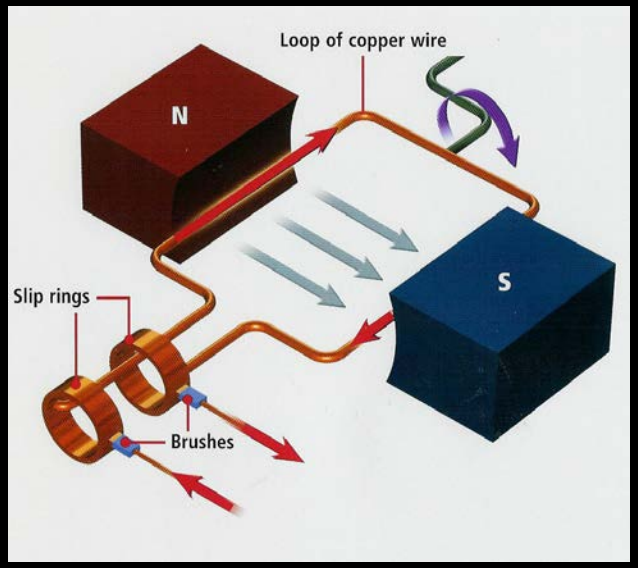


THE STELLAR DYNAMO

What is a Dynamo?

A machine that converts kinetic energy into electric energy by moving a conductor inside a magnetic field.



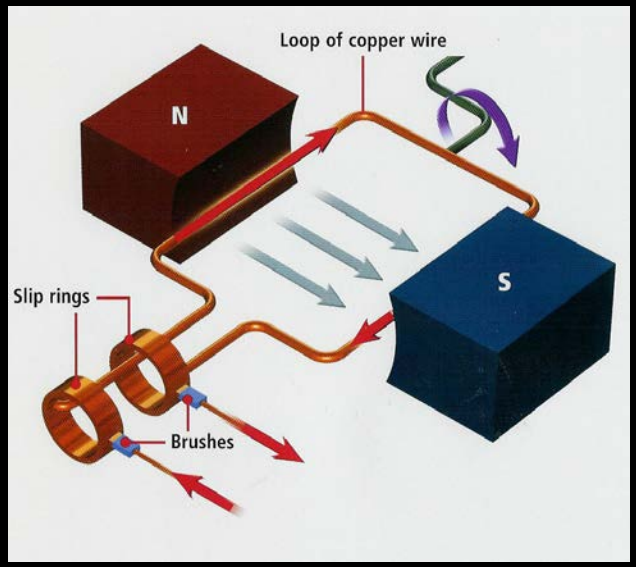


In stellar dynamos things are much more complicated

- The shape of the current loop can change freely to create very stable magnetic structures.

- The magnetic field restricts the movement of particles resulting in elastic behavior.

- The magnetic field used to induce the current is sustained by the induced current.



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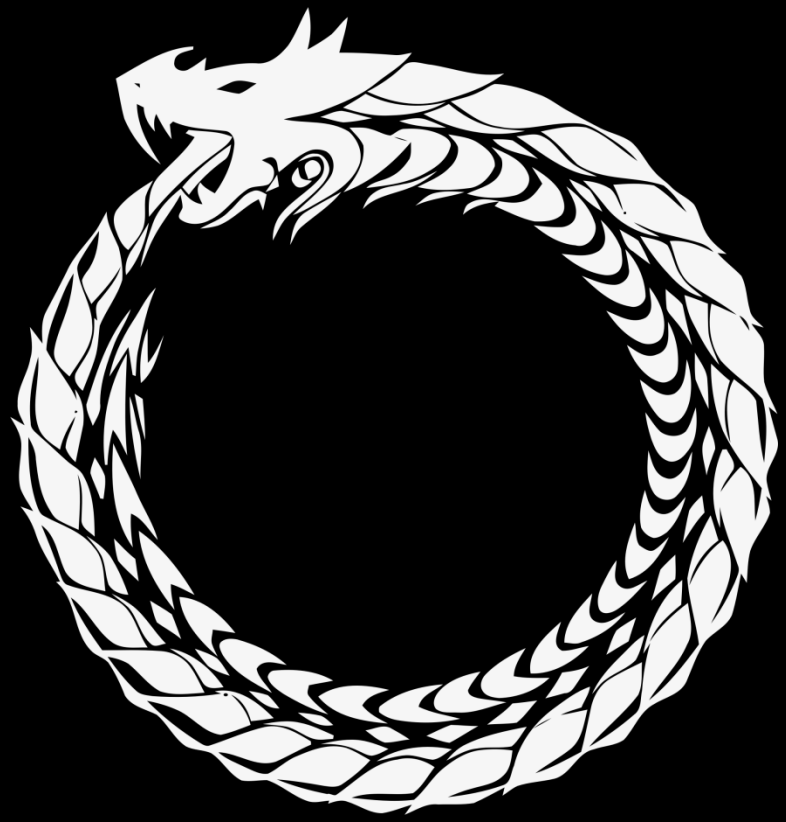
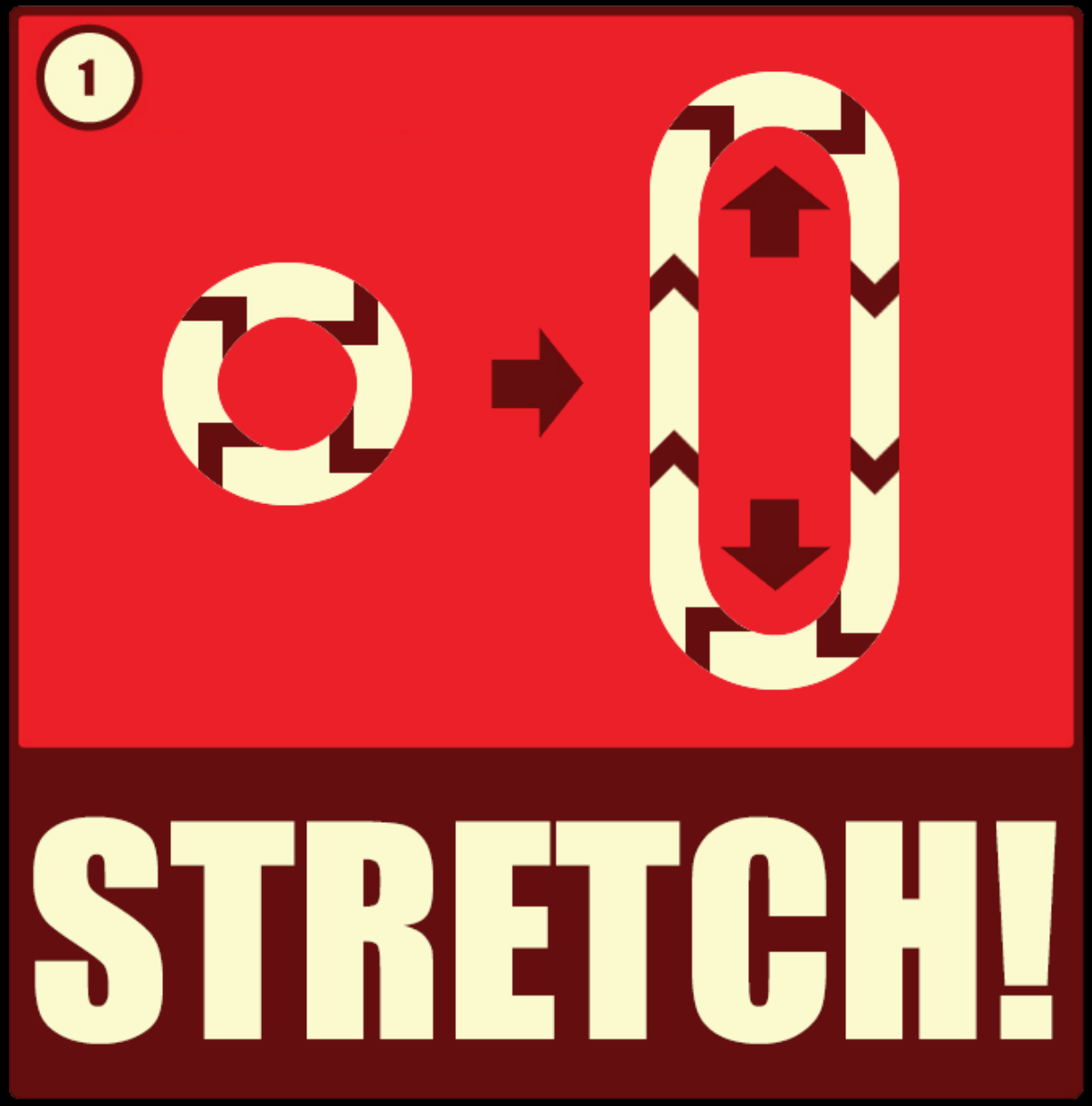


BASIC NECESSARY STEPS FOR A SAFE AND FULFILLING DYNAMO EXPERIENCE

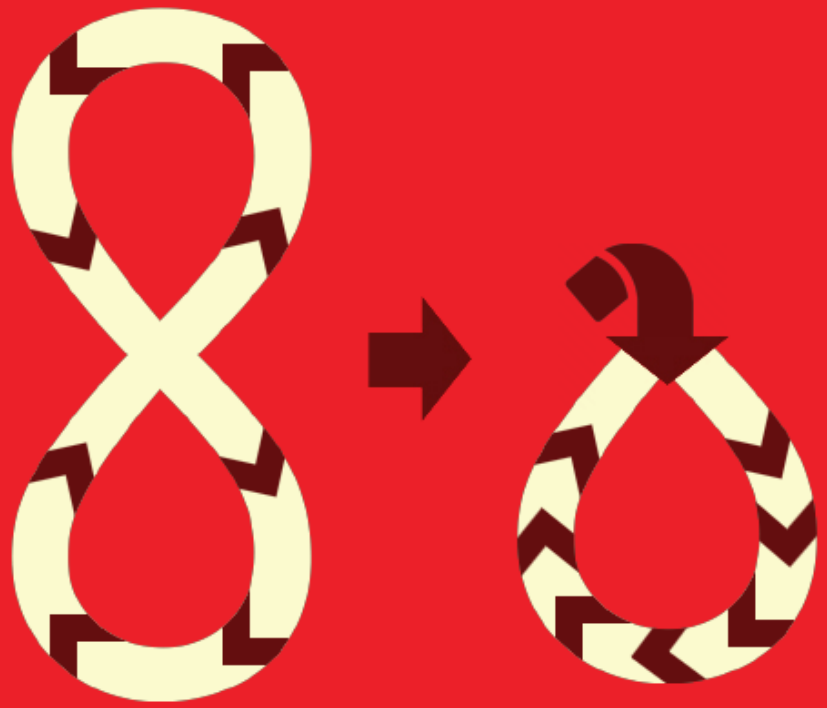
*NOT RECOMMENDED IN AN ACTUAL EMERGENCY


1
STRETCH!

2

TWIST!

3

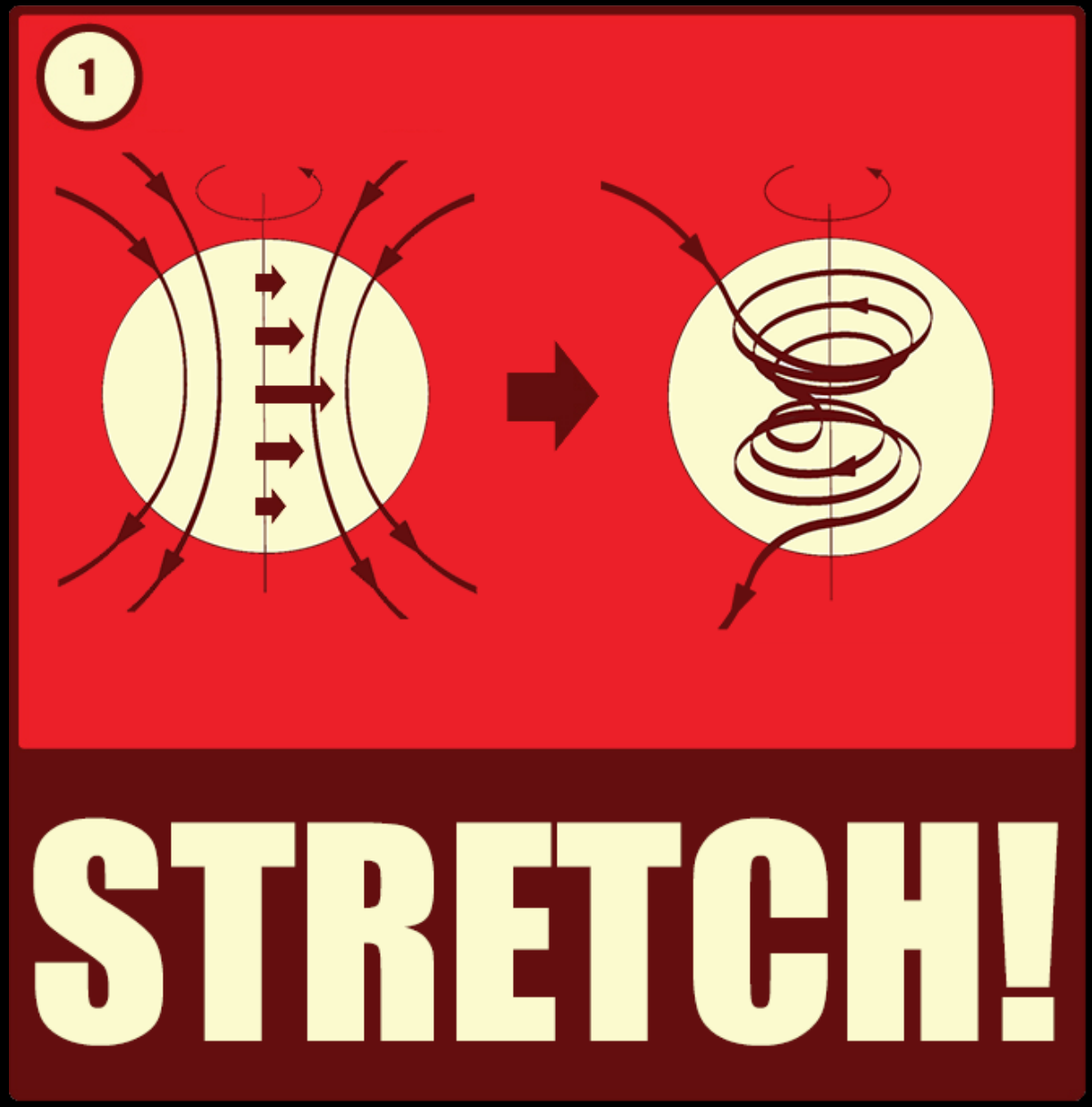


FOLD!

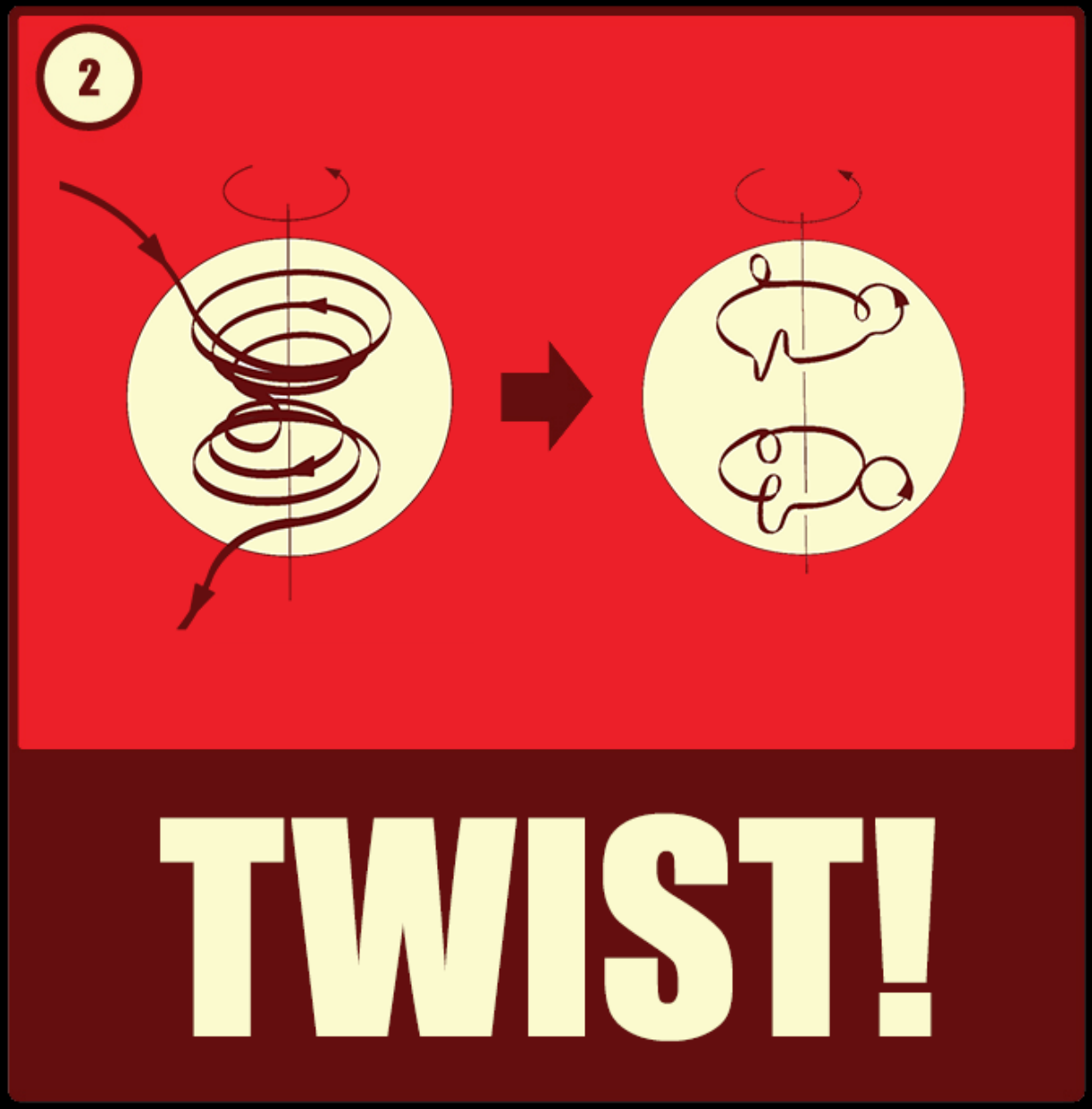
4

SELFIE!

3D STELLAR DYNAMO SIMULATION

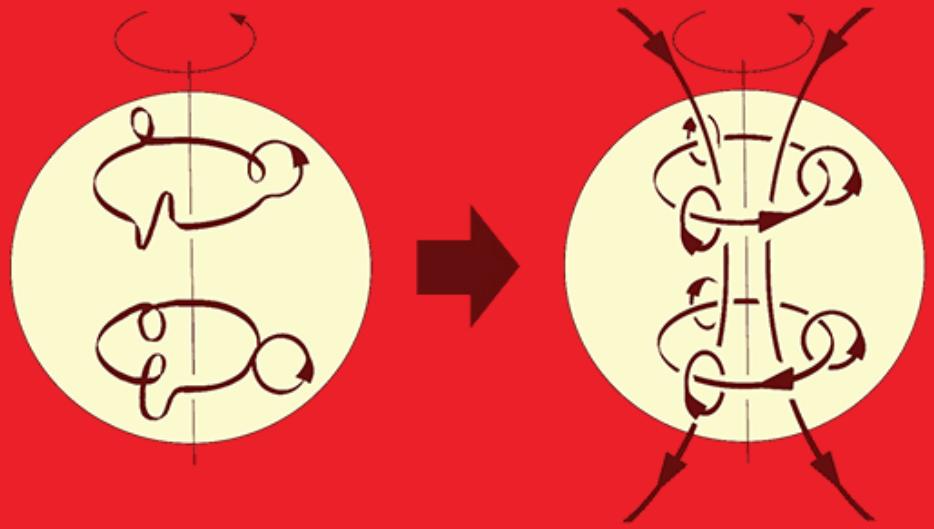


Schematic by J. J. Love



Schematic by J. J. Love

3



FOLD!

Schematic by J. J. Love

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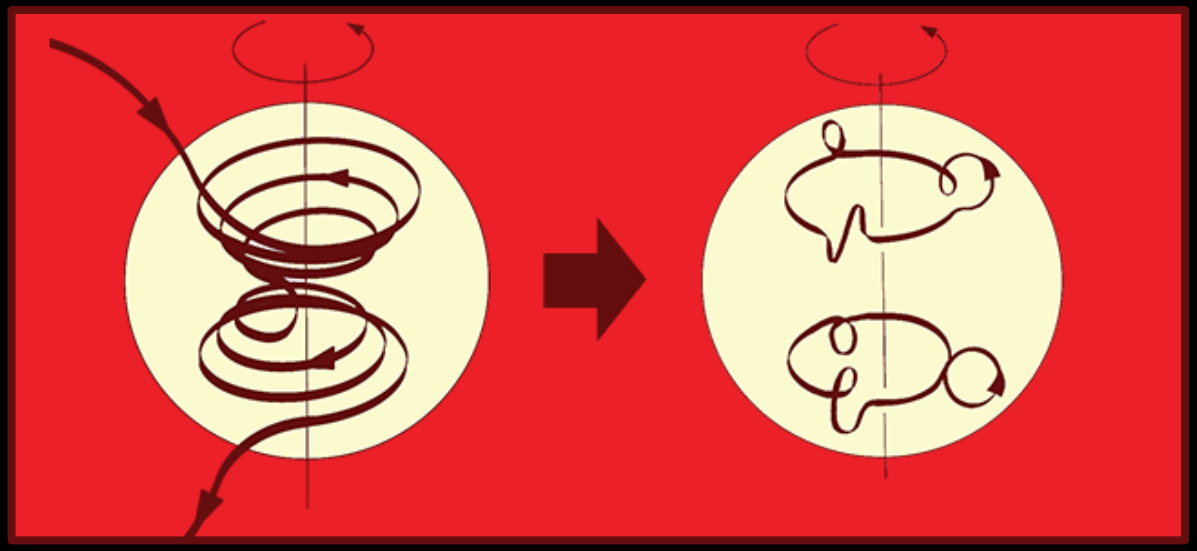
Small-scale vs. Large-scale "Twist"



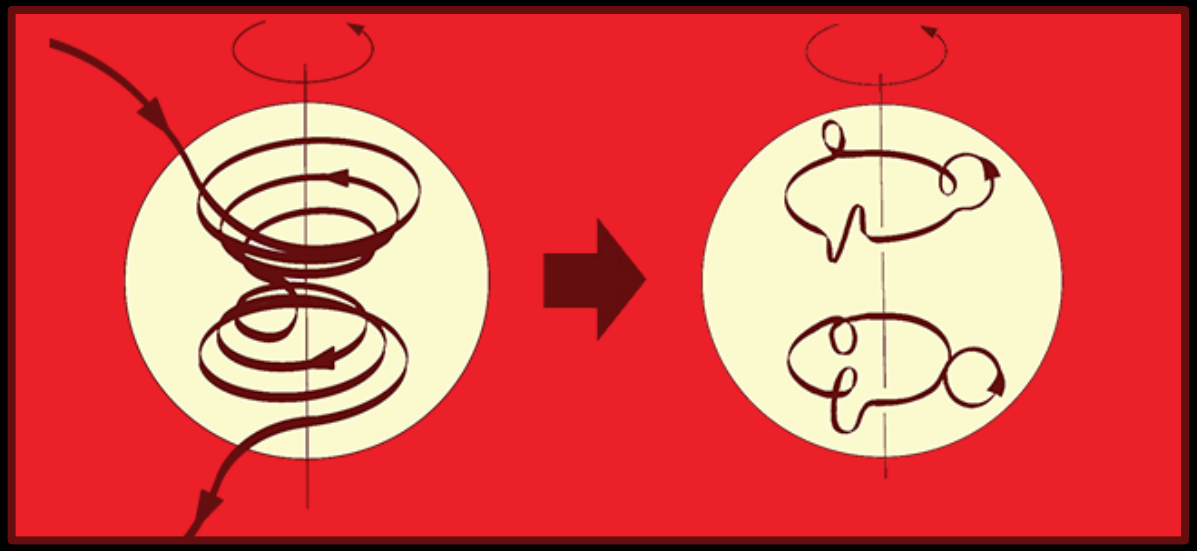
Small-Scale and Local

- Helical convection acting on the magnetic field.
- Also known as α-effect.
- Limited by the relative amount energy available in convection.

Large-Scale and Global

- Coriolis force acting on rising flux-tubes.
- Also known as Babcock-Leighton effect.
- Limited to strong flux-tubes.

Small-scale vs. Large-scale "Twist"



Small-Scale and Local

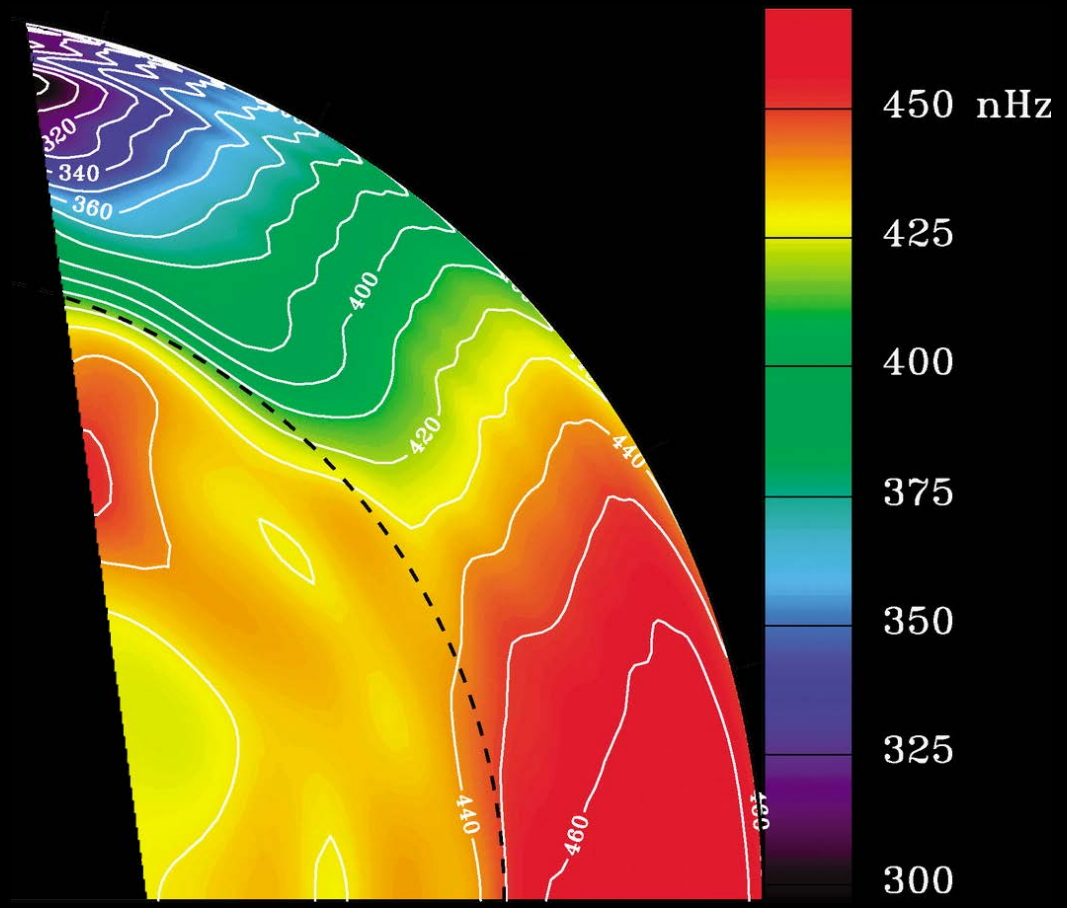
Large-Scale and Global

$\alpha\Omega$ Dynamo

Babcock-Leighton Dynamo

MAGNETIC FLUX TRANSPORT

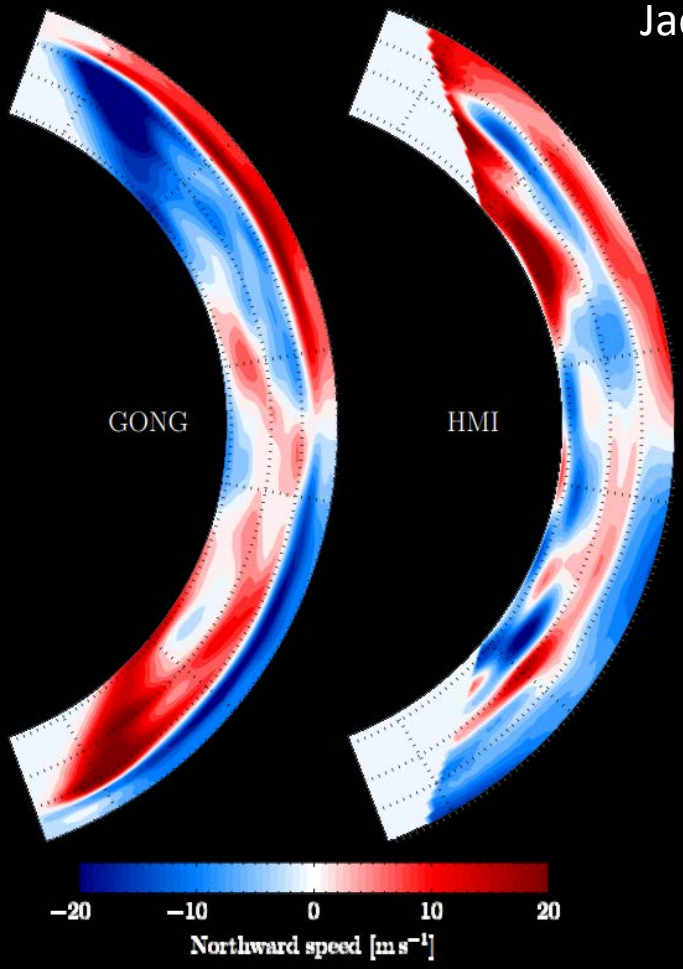
Differential Rotation



Stretches poloidal fields. Main source of energy for the dynamo.

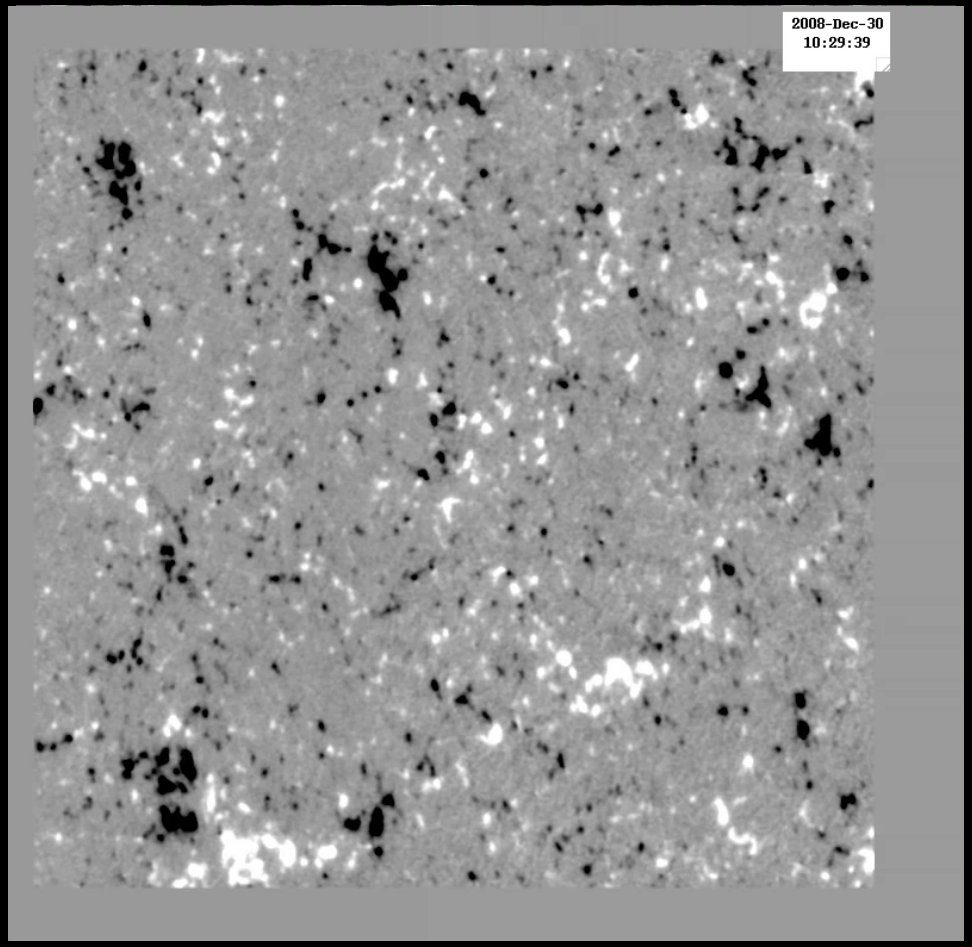
Meridional flow

Jackiewicz et al. (2015)



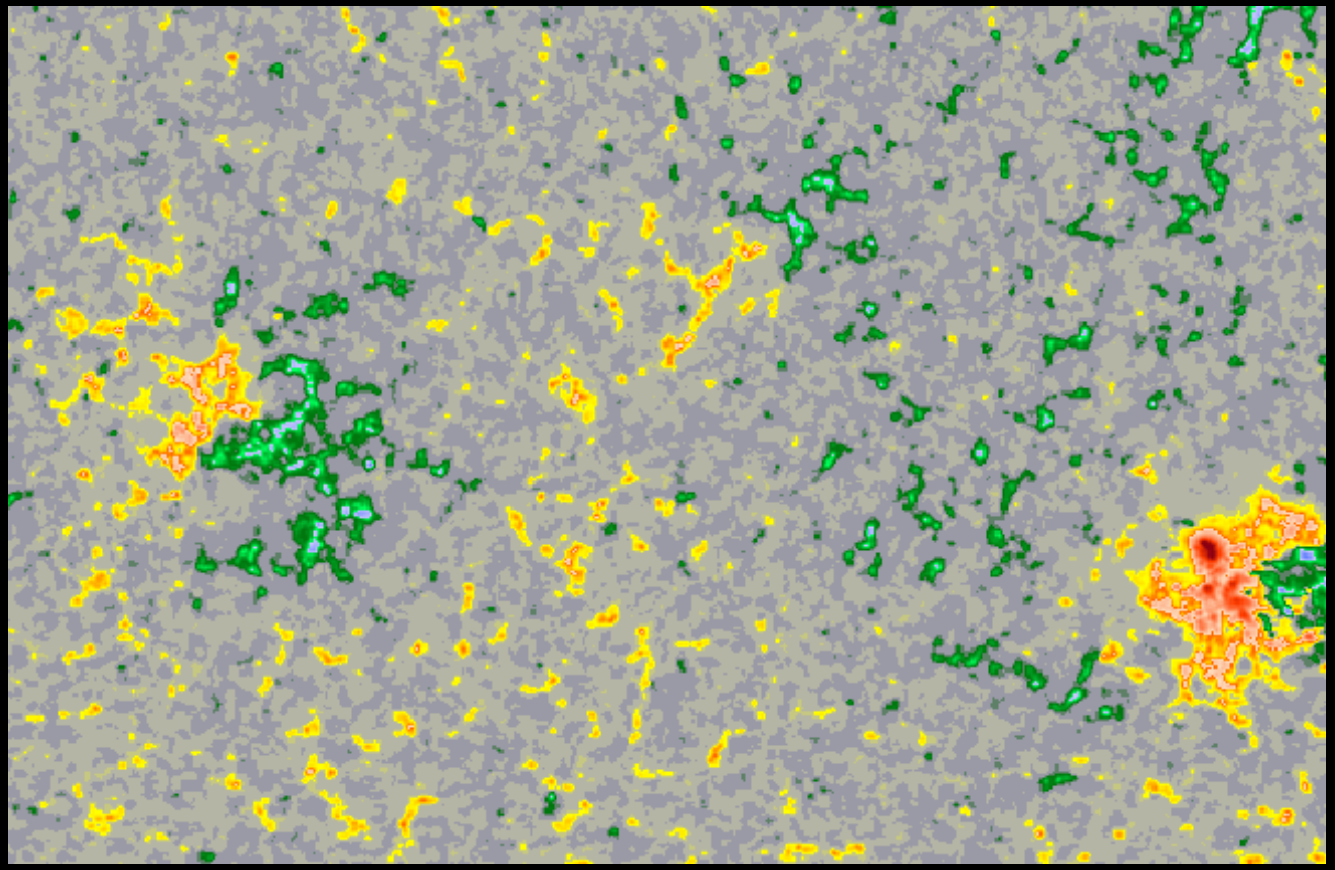
Connects different layers in the convection zone and drives the toroidal field towards the equator. Strong impact on cycle period.

Turbulent diffusion



Spreads magnetic flux around contributing to flux transport, but also leads to cancellation of opposite polarities.

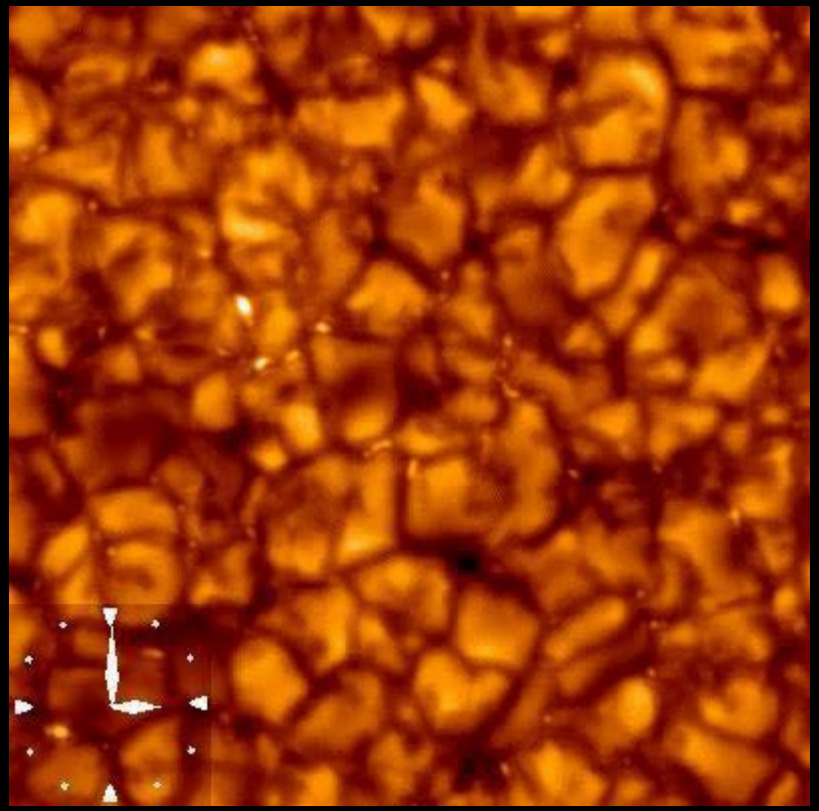
Turbulent diffusion



SDO/HMI

Spreads magnetic flux around contributing to flux transport, but also leads to cancellation of opposite polarities.

Turbulent pumping



Turbulent pumping

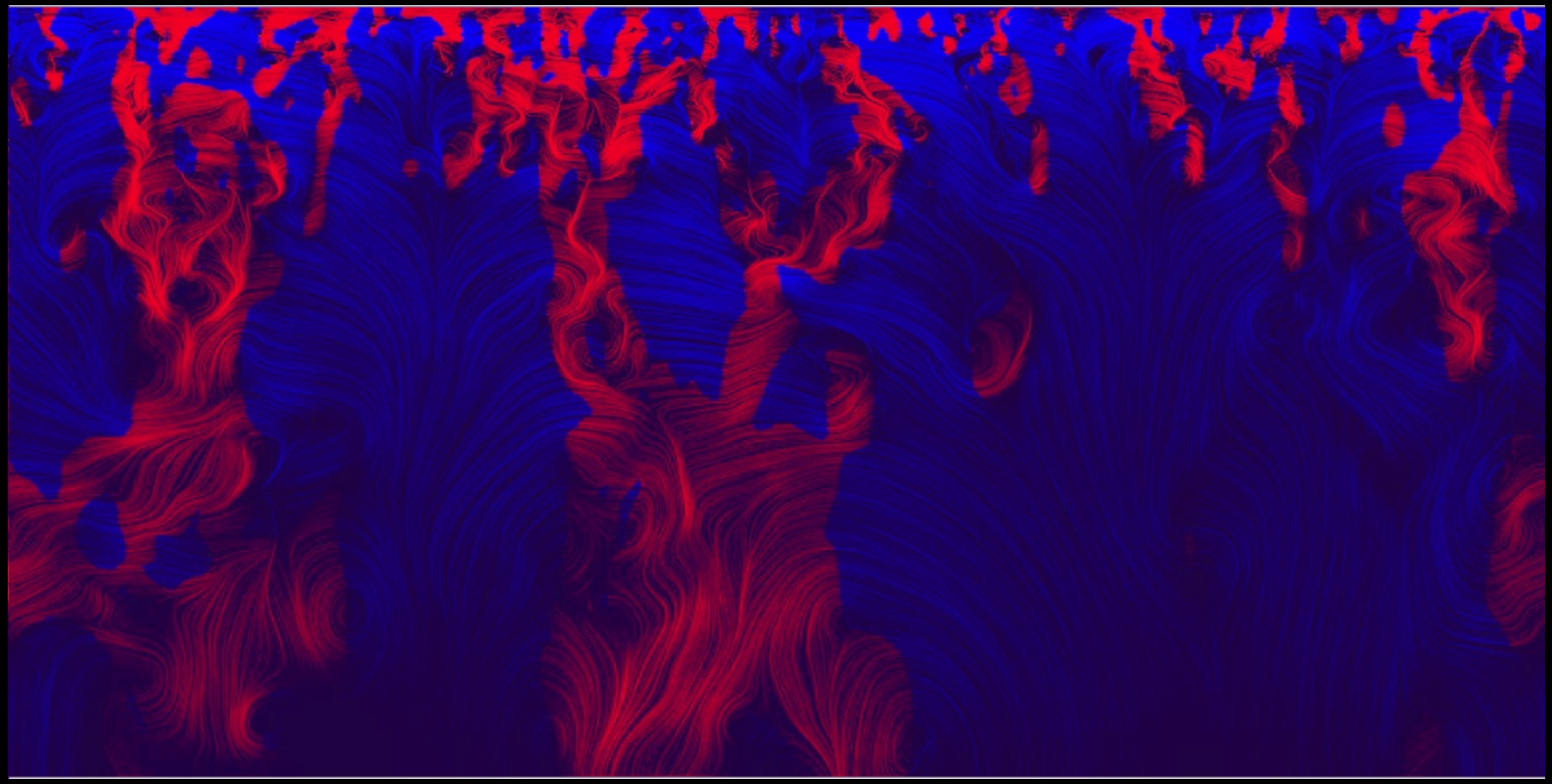


Image by Bob Stein

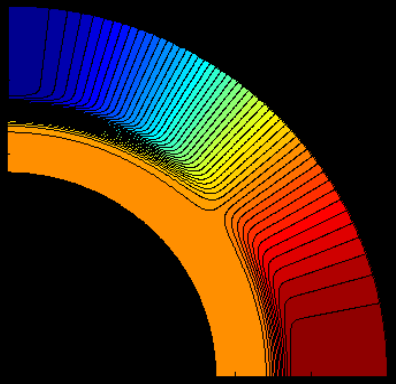
Fast downflows and slow upflows result in net downward magnetic transport.

BALANCE AND COUNTERBALANCE OF COMPETING EFFECTS

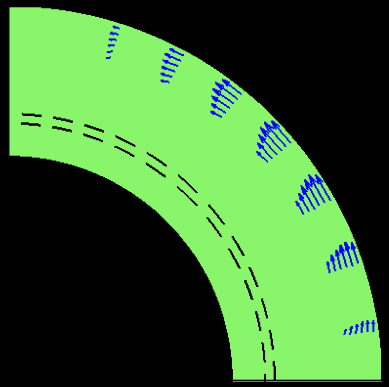
MHD Induction equation and the Flux-Transport Dynamo Model

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v} \times \mathbf{B} + \eta \nabla \times \mathbf{B} + \alpha \mathbf{B} \right)$$

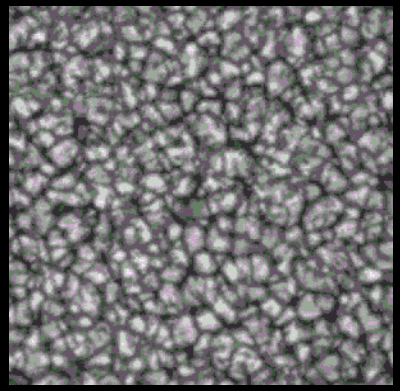
$$\mathbf{v} = r \sin(\theta) \Omega \hat{e}_{\phi} + \mathbf{v}_{\mathbf{p}}$$



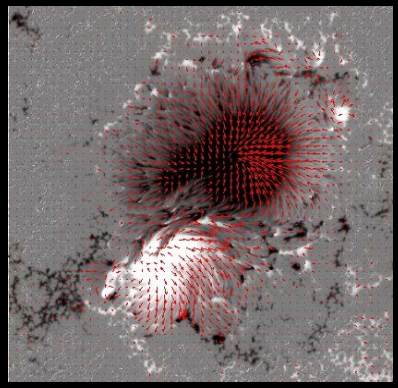
Differential Rotation



Meridional Flow



Turbulent transport



Poloidal magnetic Sources

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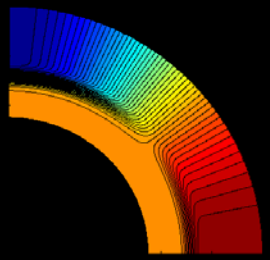
1 PLAYER OR 2 PLAYERS ?

Magnetic Sources vs. Decay

Advective vs. Diffuse Transport

Getting to know your dynamo: The Dynamo Numbers

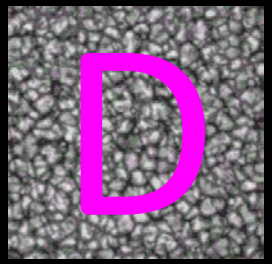
Magnetic Sources vs. Decay:



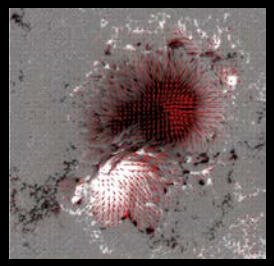
Differential Rotation

$$C_\Omega \propto \frac{\Omega_0}{\eta_0}$$

VS.



Turbulent Diffusion

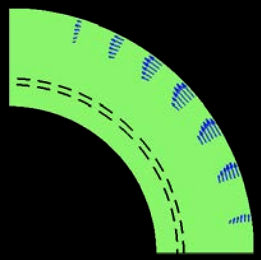


Poloidal magnetic Sources

$$C_\alpha \propto \frac{\alpha_0}{\eta_0}$$

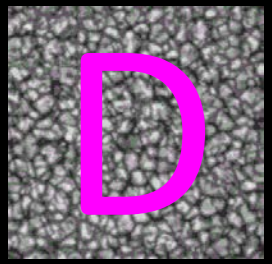
Getting to know your dynamo: The Reynolds Numbers

Advective vs. Diffuse Transport

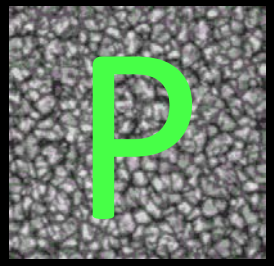


Meridional Flow

VS.



Turbulent Diffusion



Turbulent Pumping

$$R_M \propto \frac{u_0}{\eta_0}$$

$$R_T \propto \frac{\gamma_0}{\eta_0}$$

Dynamo Model Exploration

- Solar and Stellar cycles are magnetic in nature and are powered by a dynamo mechanism.

- Differential rotation, helical turbulence, and the twist of emergent flux-tubes by Coriolis are main mechanisms that keep stellar cycles going.

- The relative importance of the different mechanisms involved in magnetic field generation and transport determine the properties of each dynamo.