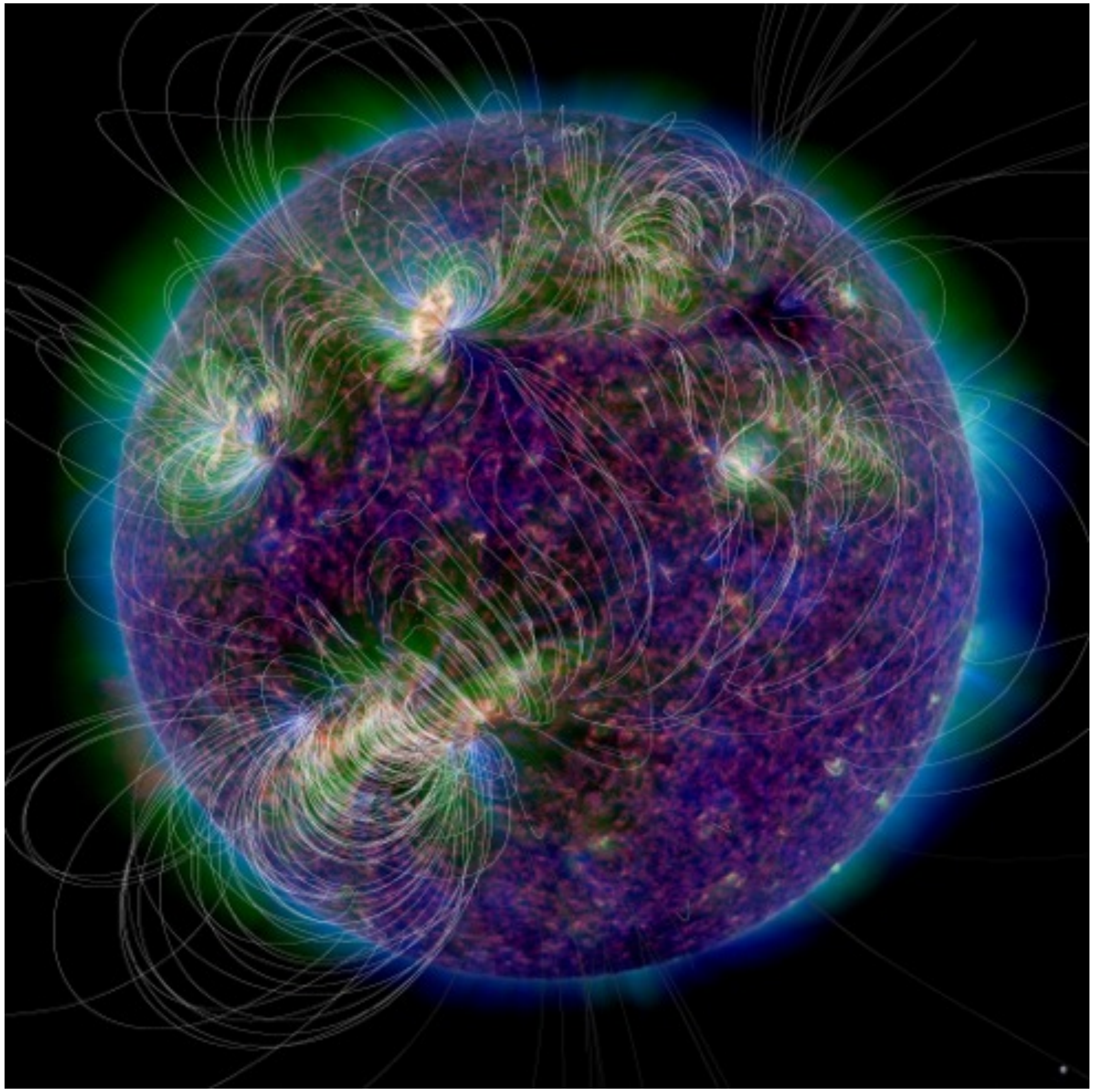
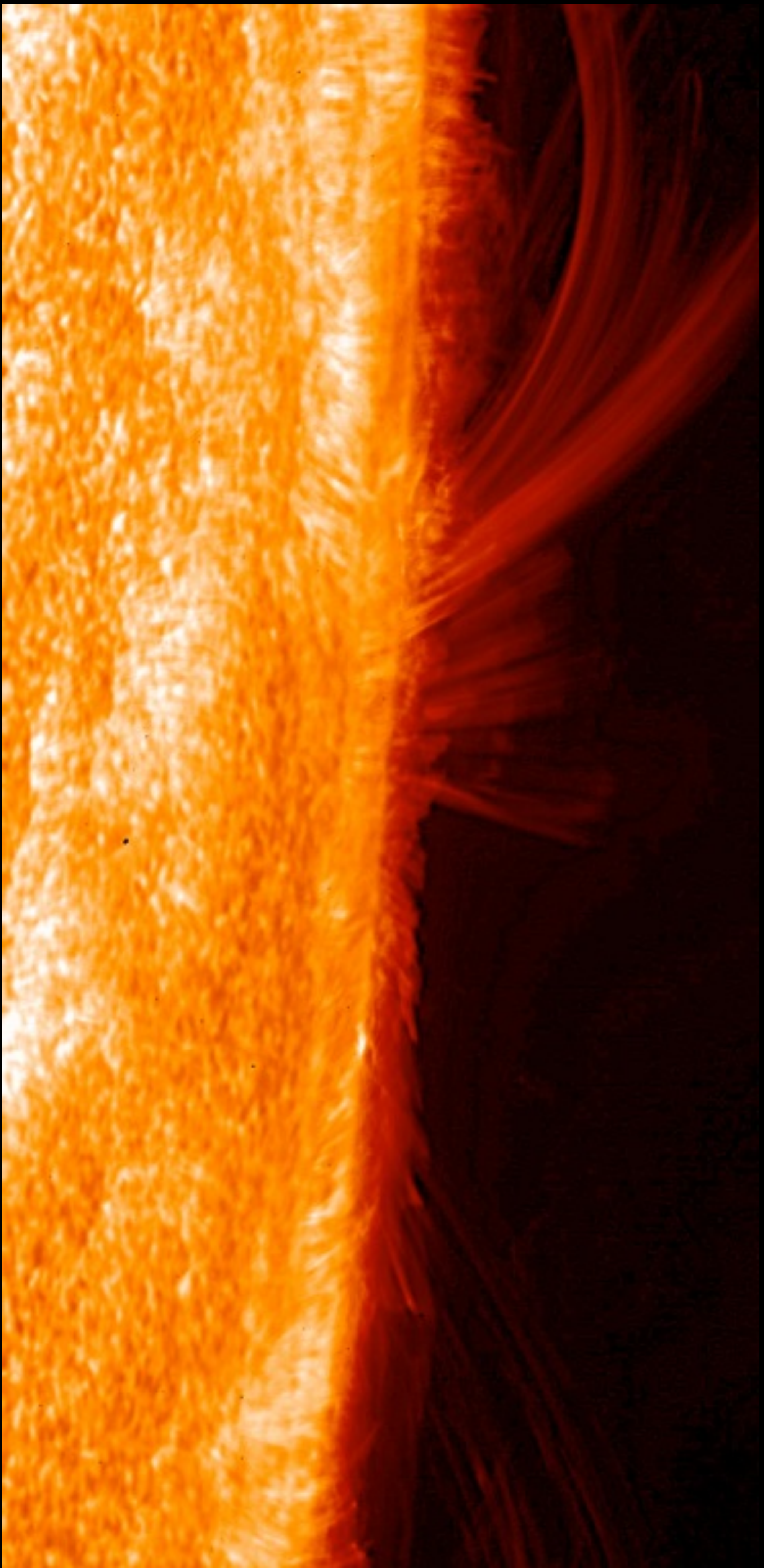
The Solar Dynamo



Mark Miesch
HAO/NCAR

ISWI/SCOSTEP
School on Space Science

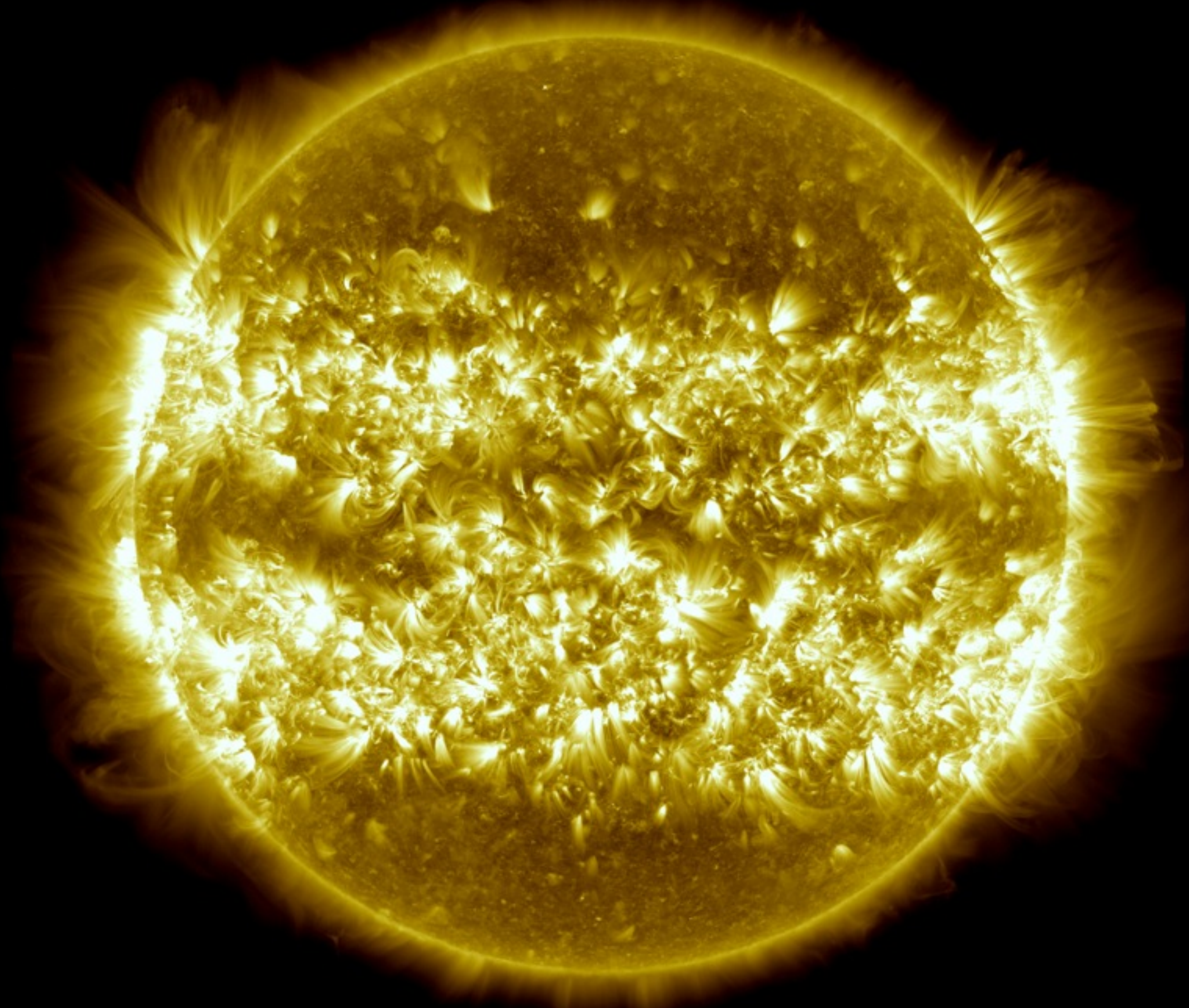
Lima, Peru
September, 2014

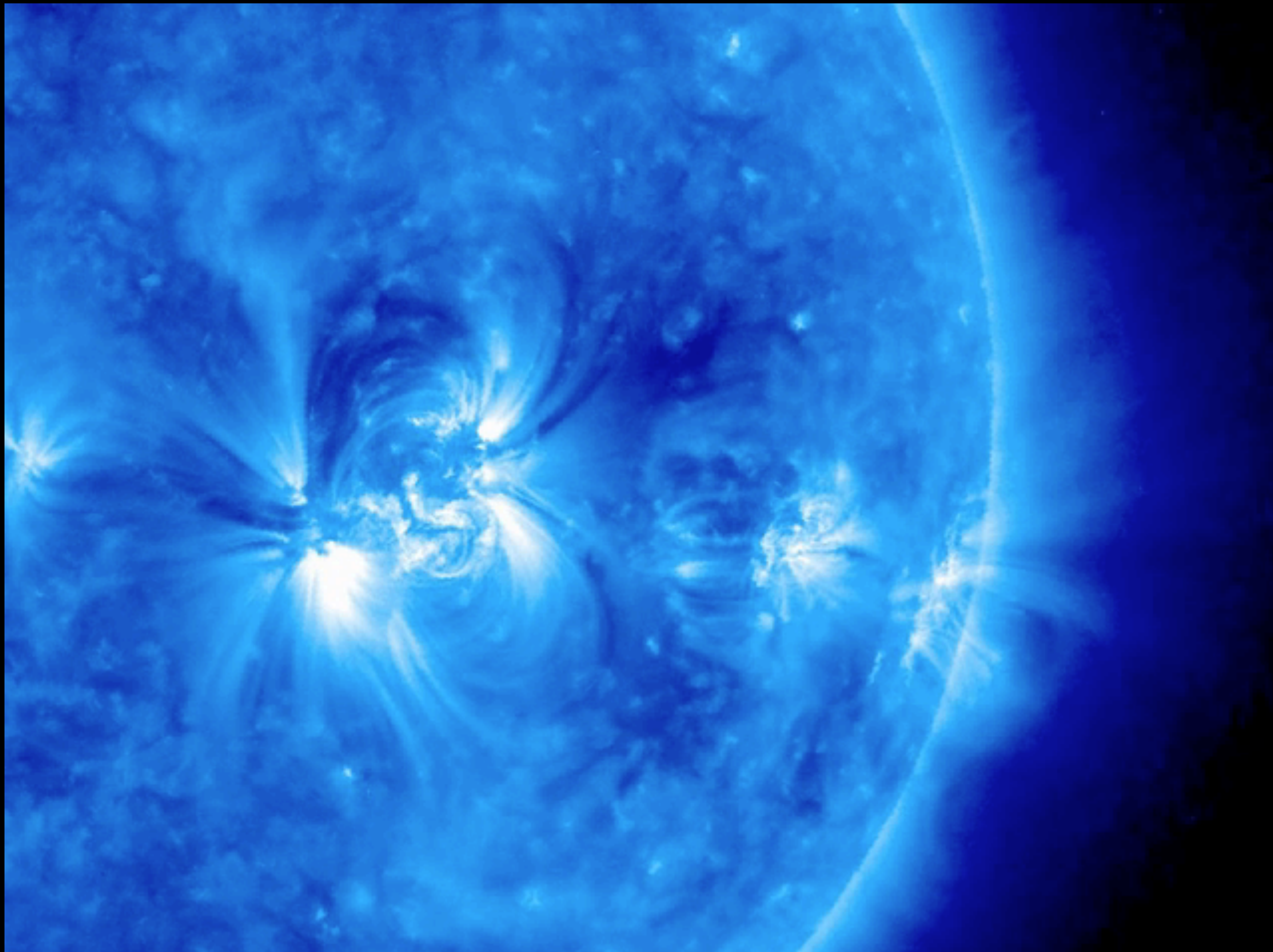
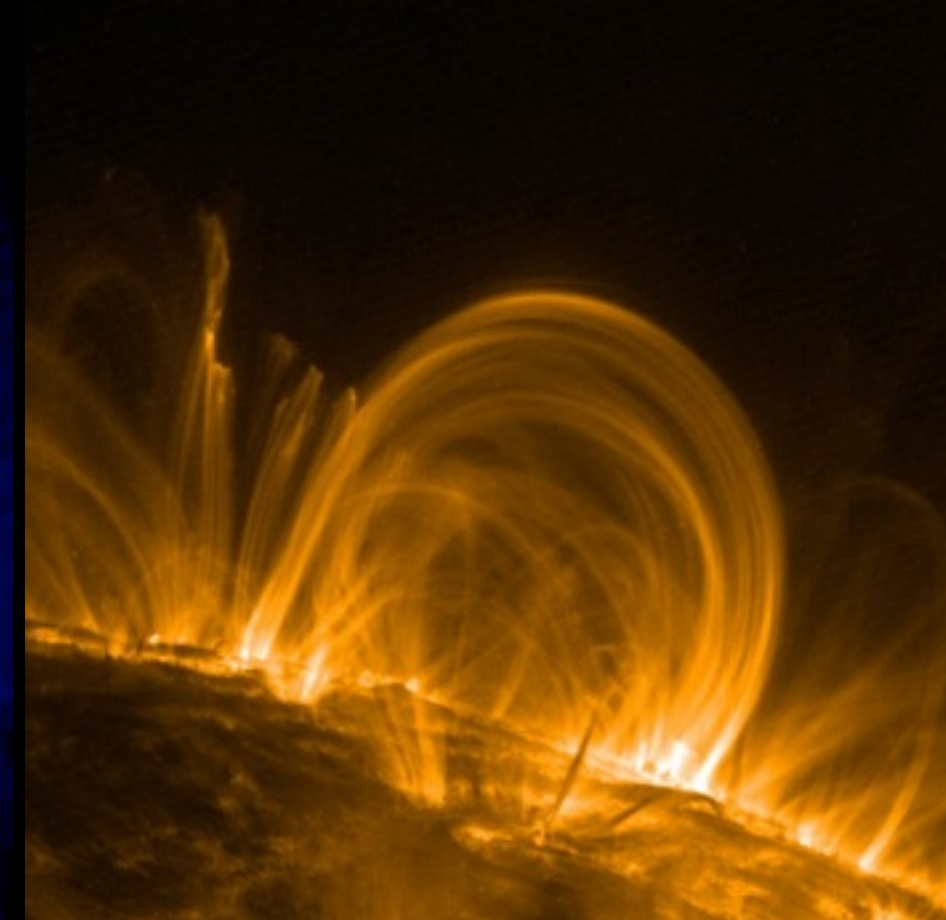
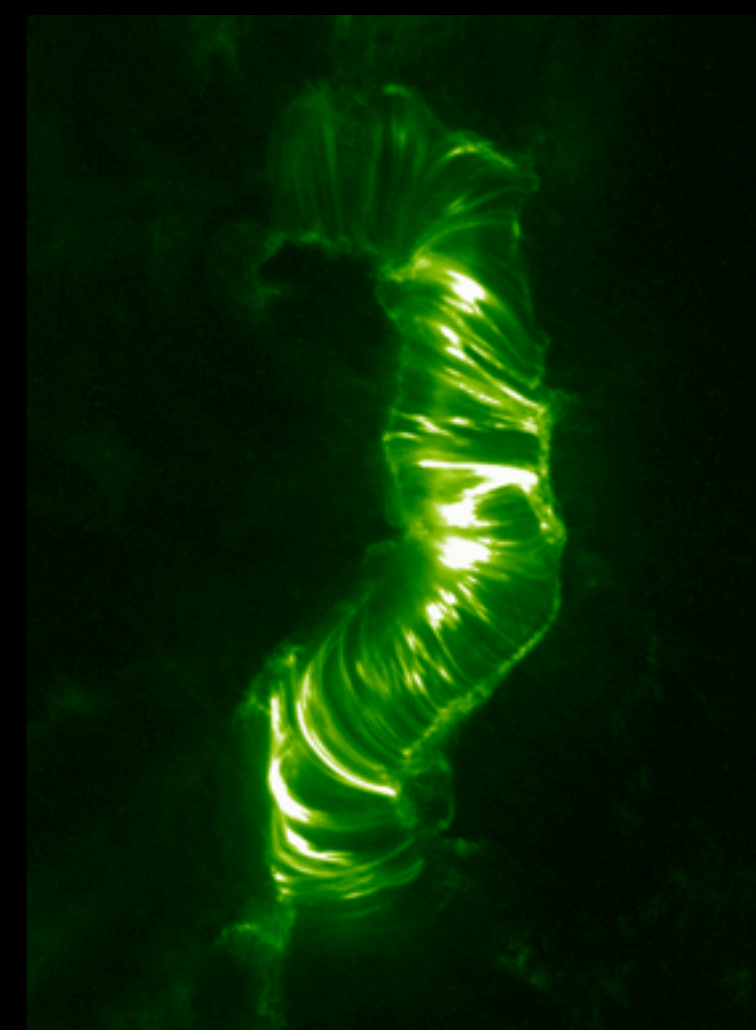
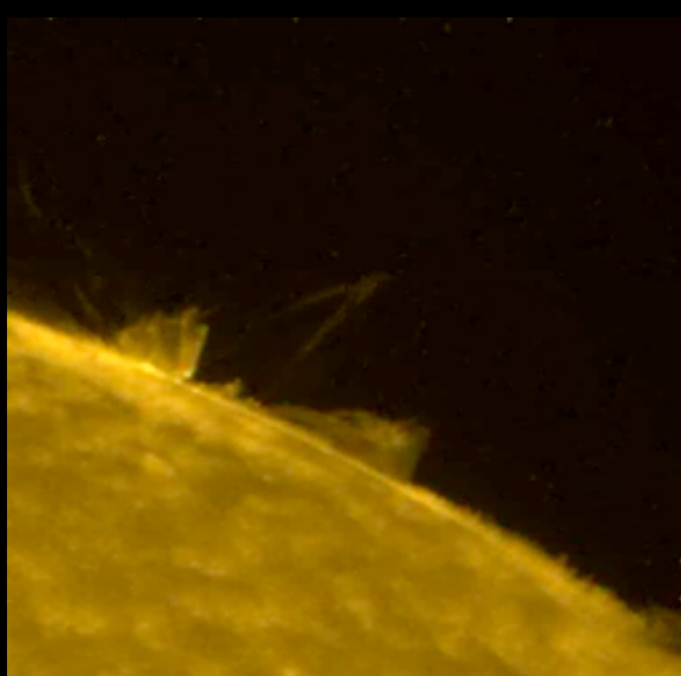
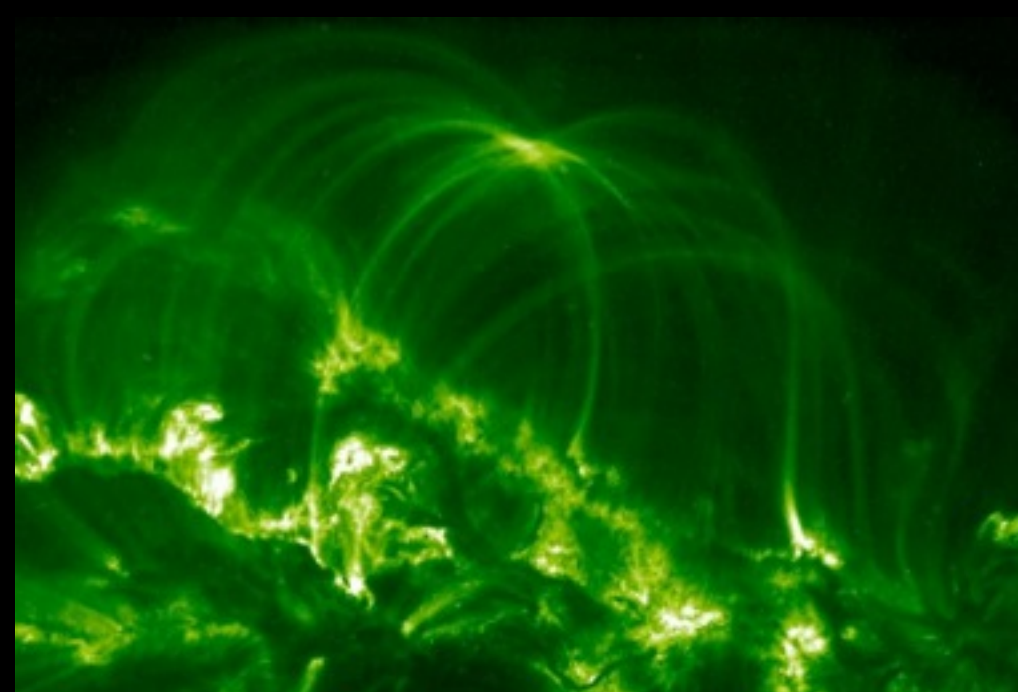


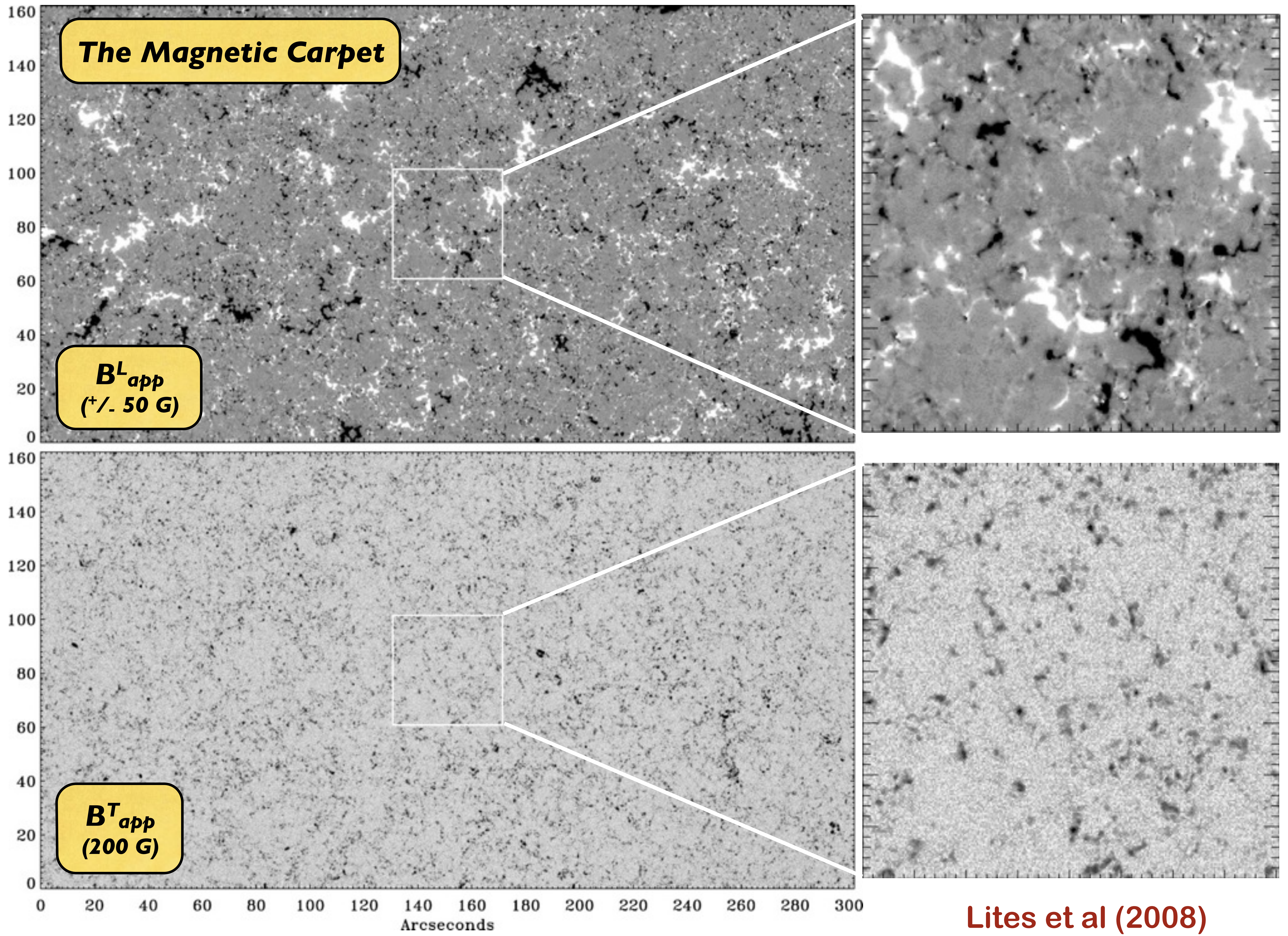
Outline

- ★ ***Solar Magnetism***
  - ***Order amid chaos***
- ★ ***Solar Convection and Mean Flows***
  - ***Heirarchy of convective motions***
  - ***Differential Rotation***
  - ***Meridional Circulation***
- ★ ***Solar Dynamo Models***
  - ***Small-Scale and Large-Scale Dynamos***
  - ***The Solar Cycle***

Everything I say also applies in some form to other stars

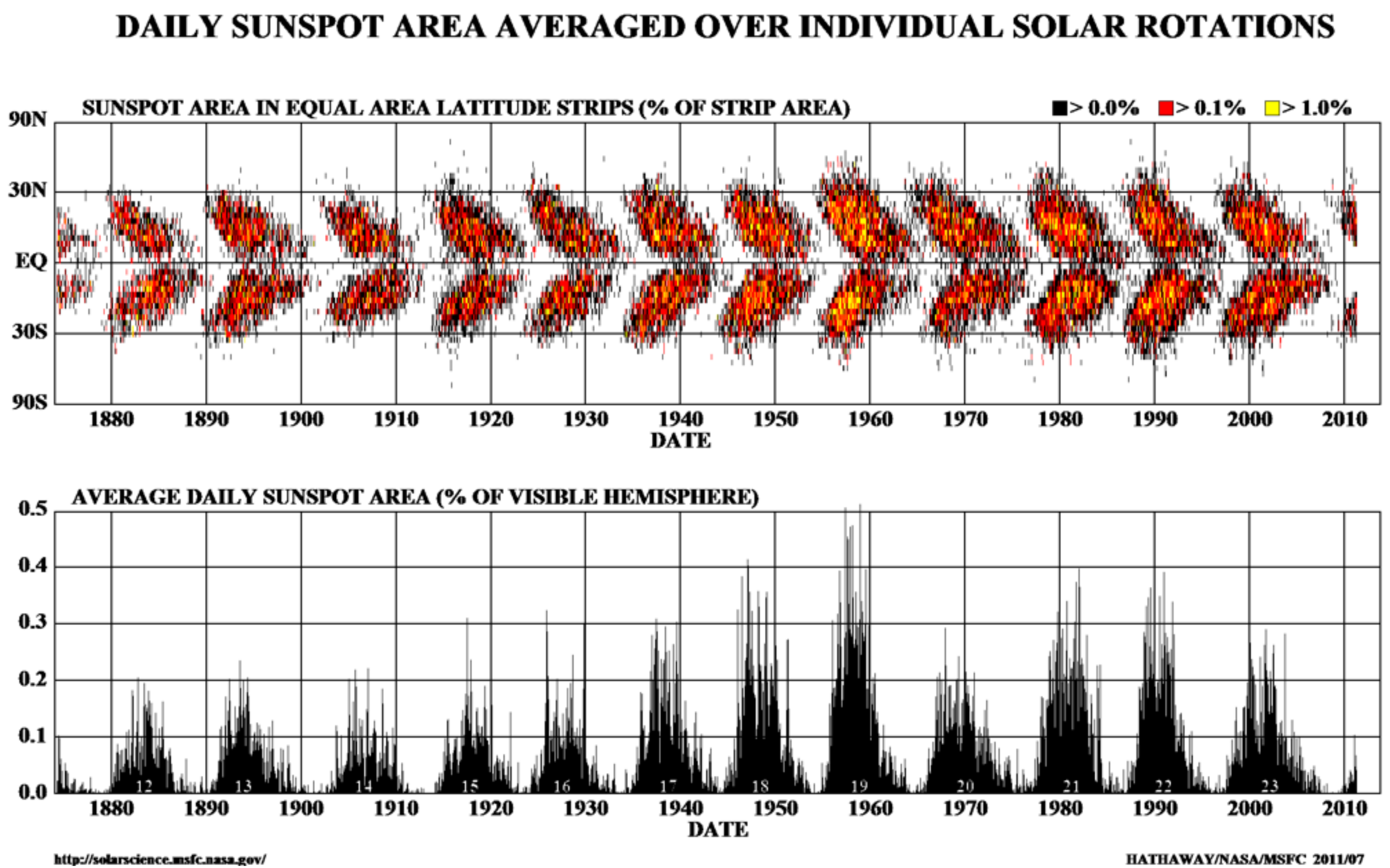


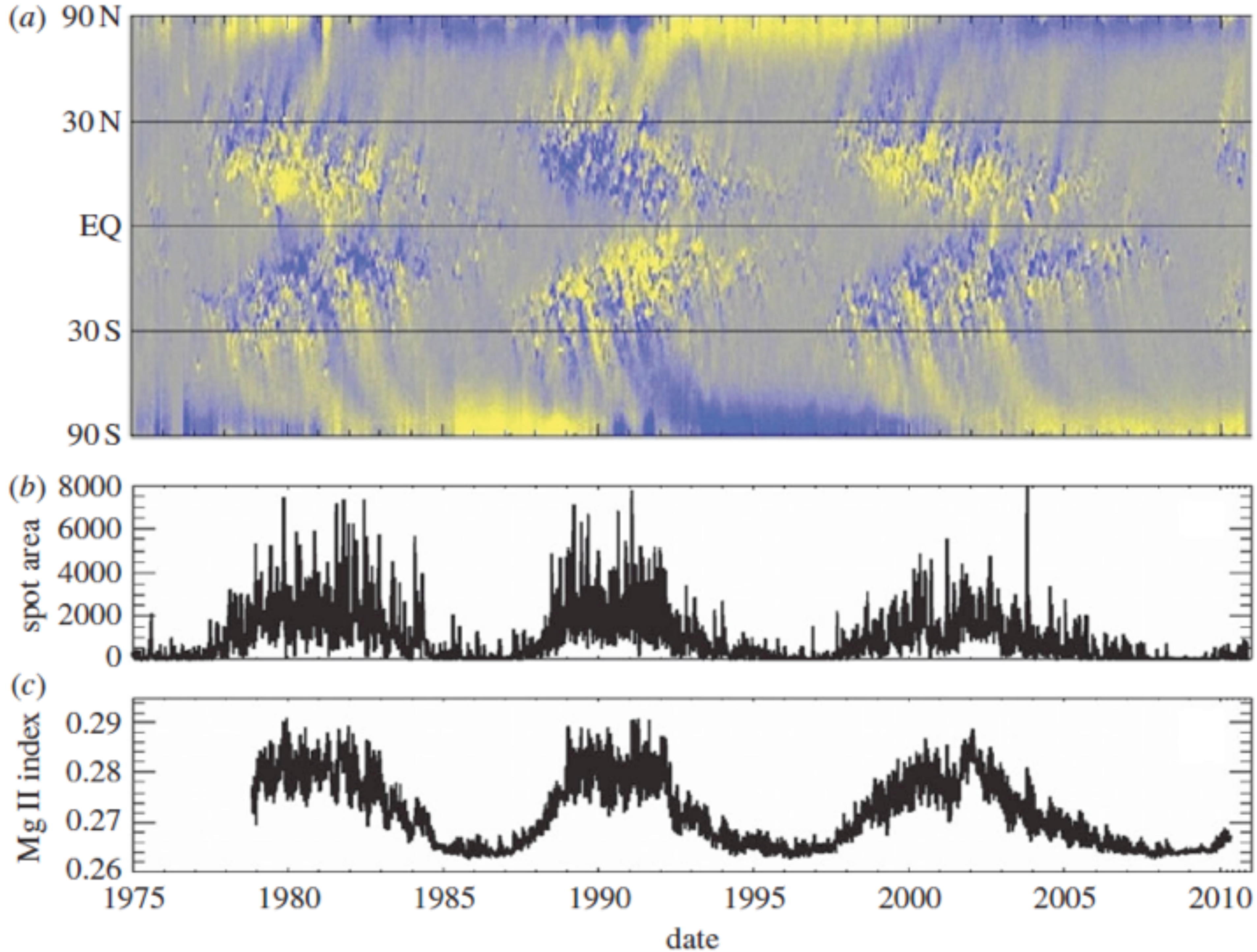


The Magnetic Carpet
B^L_{app}
($^+$/. 50 G)
B^T_{app}
(200 G)
Arcseconds
Lites et al (2008)

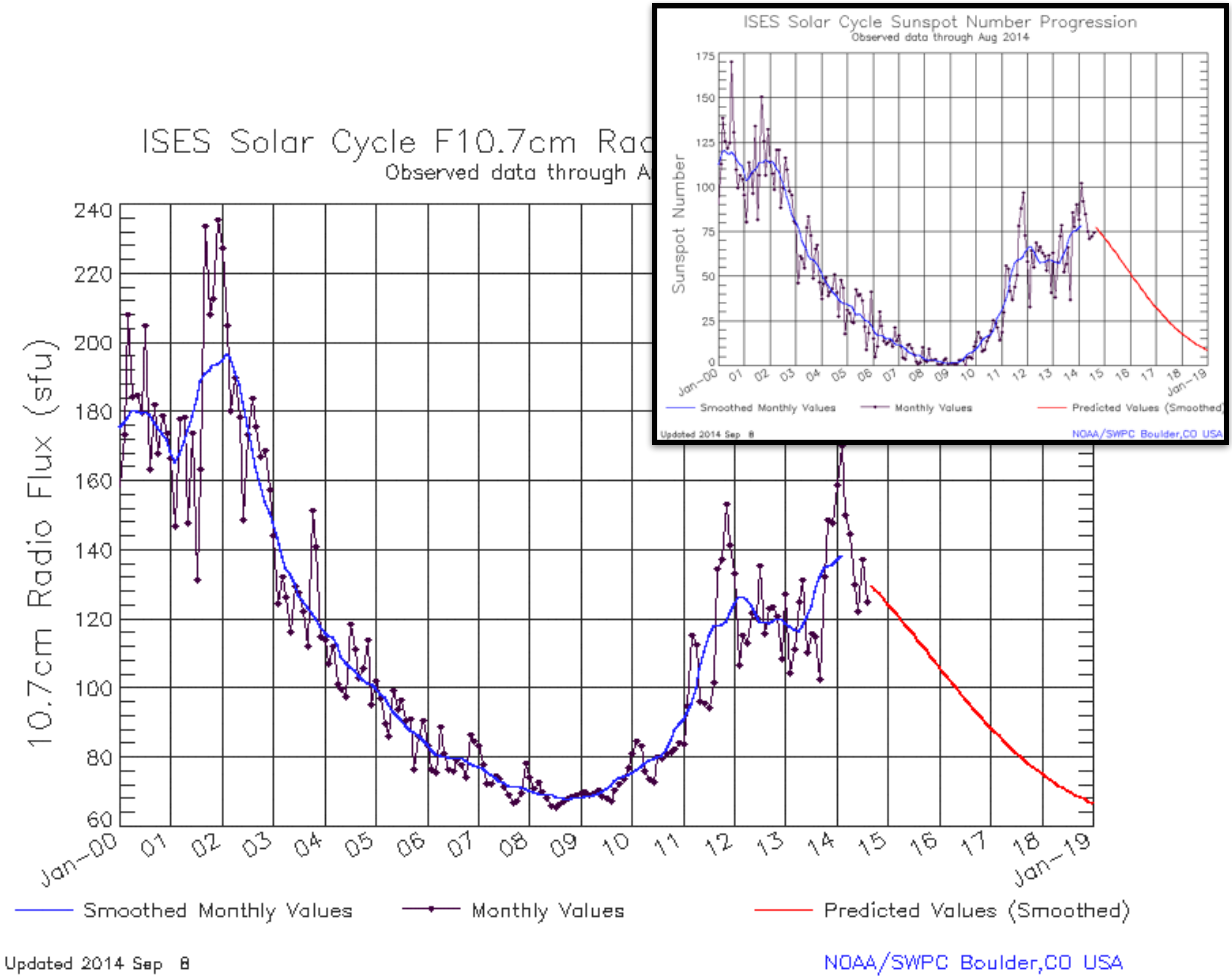
The Solar Cycle: Order Amid chaos



Cycles are numbered with respect to the 11-year sunspot cycle (we're now in cycle 24) but the true magnetic cycle length is 22 years (on average)



...and it's not just spots!
The solar cycle regulates nearly all solar variability: irradiance, solar wind, flares, CMEs, etc.

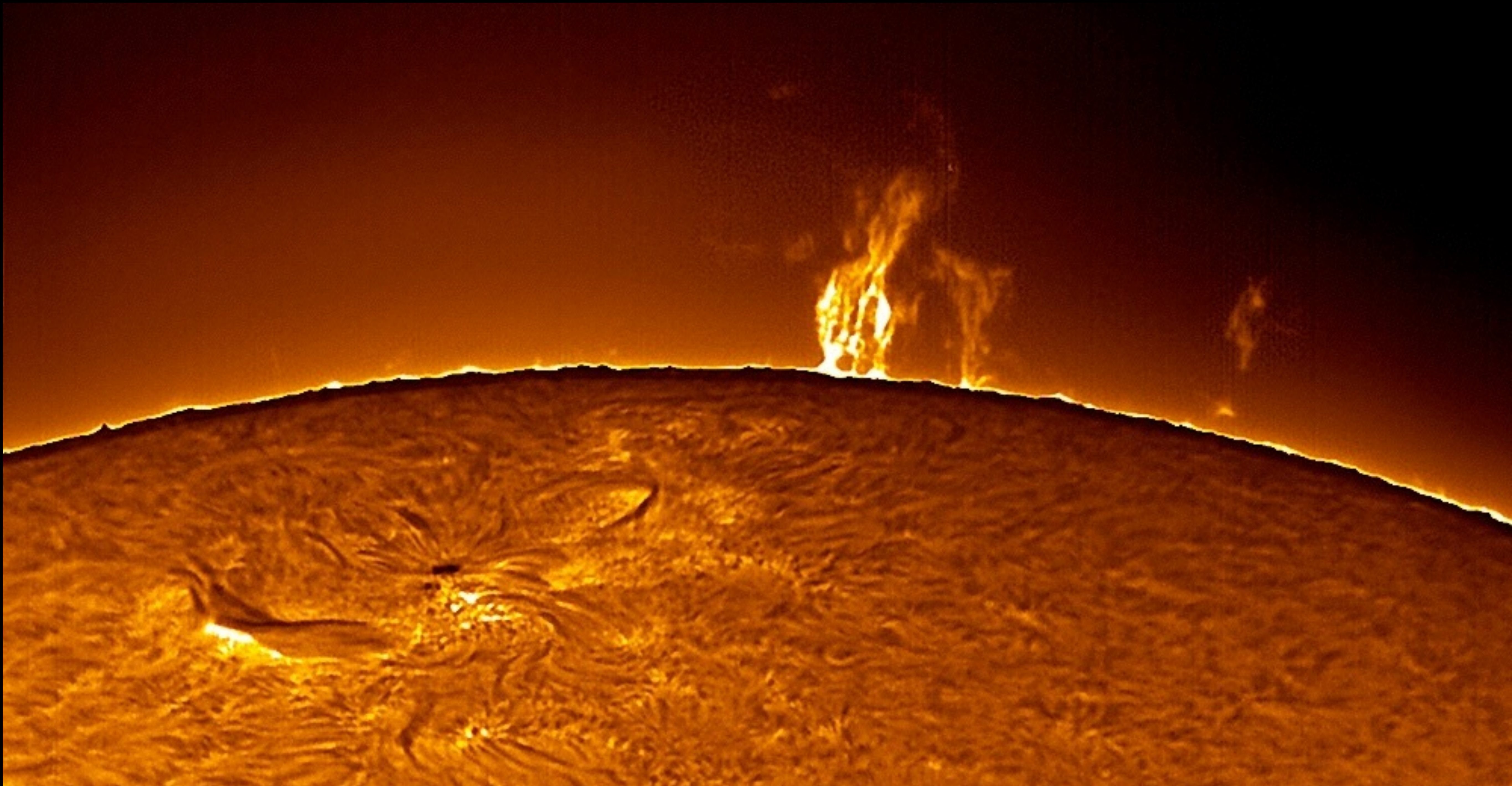


ISES Solar Cycle F10.7cm Rad
Observed data through A
10.7cm Radio Flux (sfu)
240
220
200
180
160
140
120
100
80
60
Jan-00
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
Jan-19
Smoothed Monthly Values
Monthly Values
Predicted Values (Smoothed)
Updated 2014 Sep 8
NOAA/SWPC Boulder,CO USA
ISES Solar Cycle Sunspot Number Progression
Observed data through Aug 2014
Sunspot Number
175
150
125
100
75
50
25
0
Jan-00
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
Jan-19
Smoothed Monthly Values
Monthly Values
Predicted Values (Smoothed)
Updated 2014 Sep 8
NOAA/SWPC Boulder,CO USA


COSMOLOGY MARCHES ON
Where the hell did it all come from?
Where the hell did it all come from?
s. harris

Where does this magnetism come from?

The Solar Dynamo



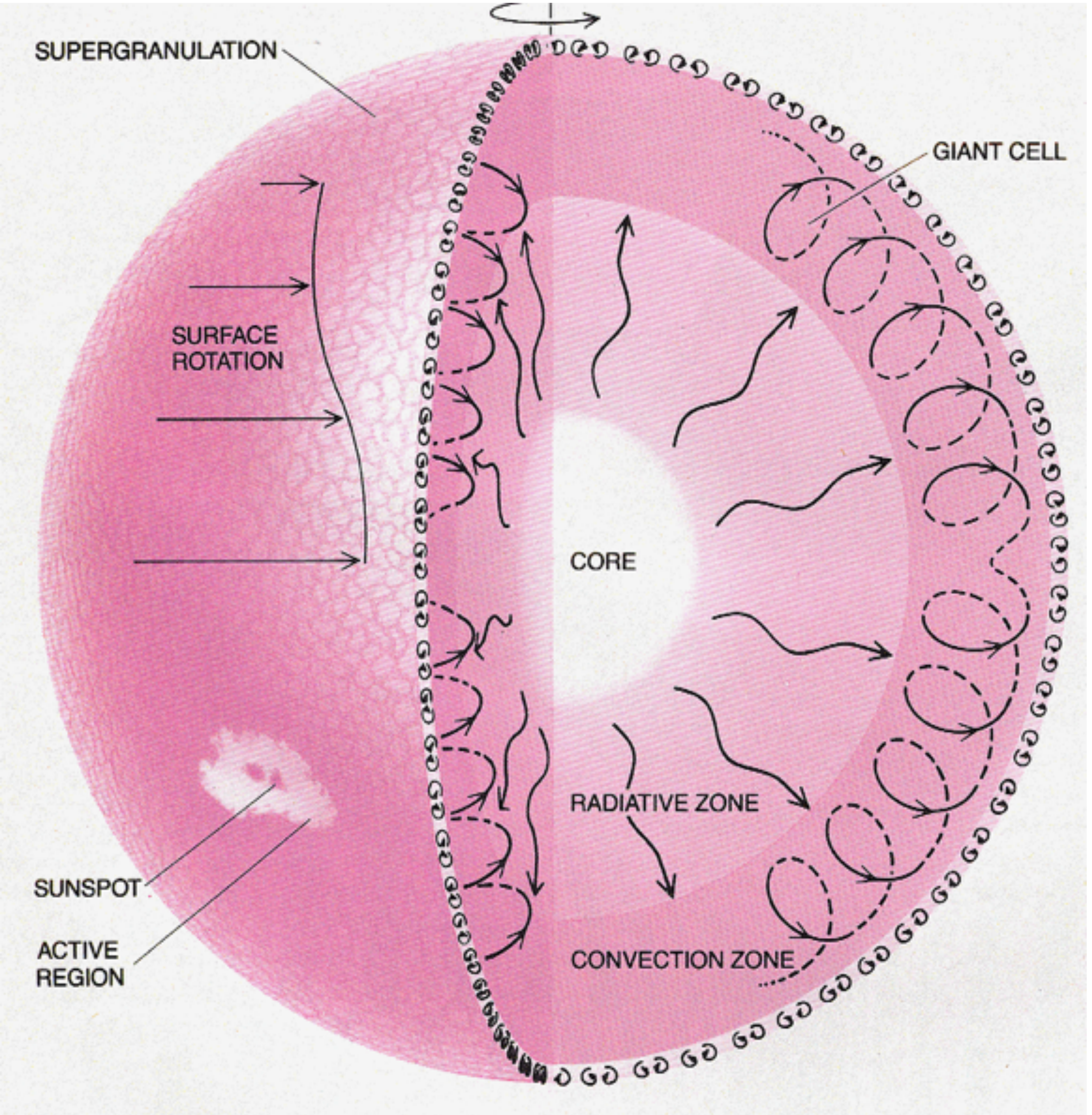
The *Solar Dynamo* generates magnetic fields from flows

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

convection

differential rotation

meridional circulation



magnetic energy ultimately comes from the Sun's own mass

Fusion

mass ⇒ radiation & thermal energy

Convection

thermal energy ⇒ kinetic energy

Dynamo

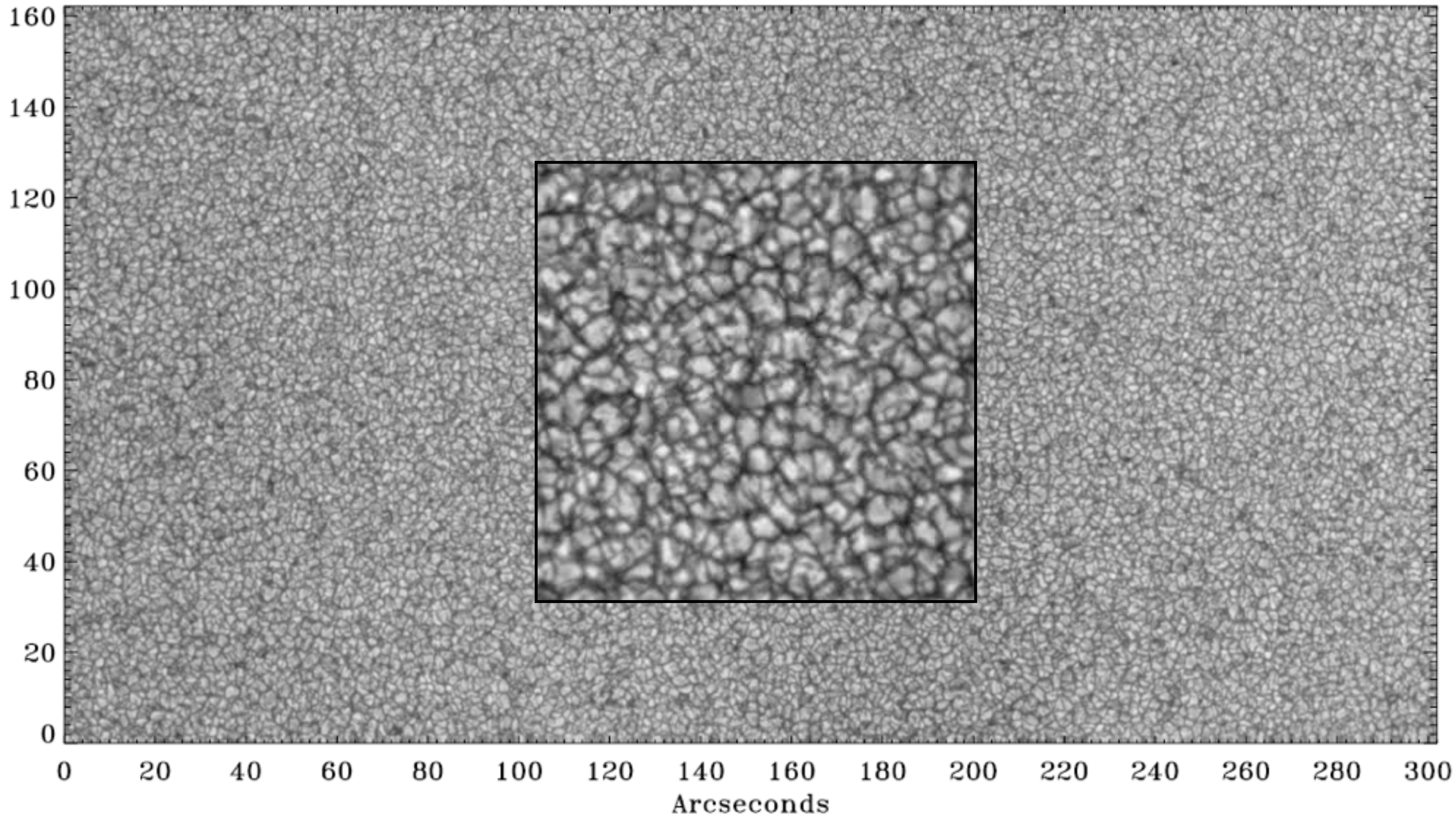
kinetic energy ⇒ magnetic energy

Part 2 (of 3)

- ★ Solar and Stellar Magnetism
- ★ Solar Convection and Mean Flows
- ★ Solar Dynamo Models

Granulation in the Quiet Sun

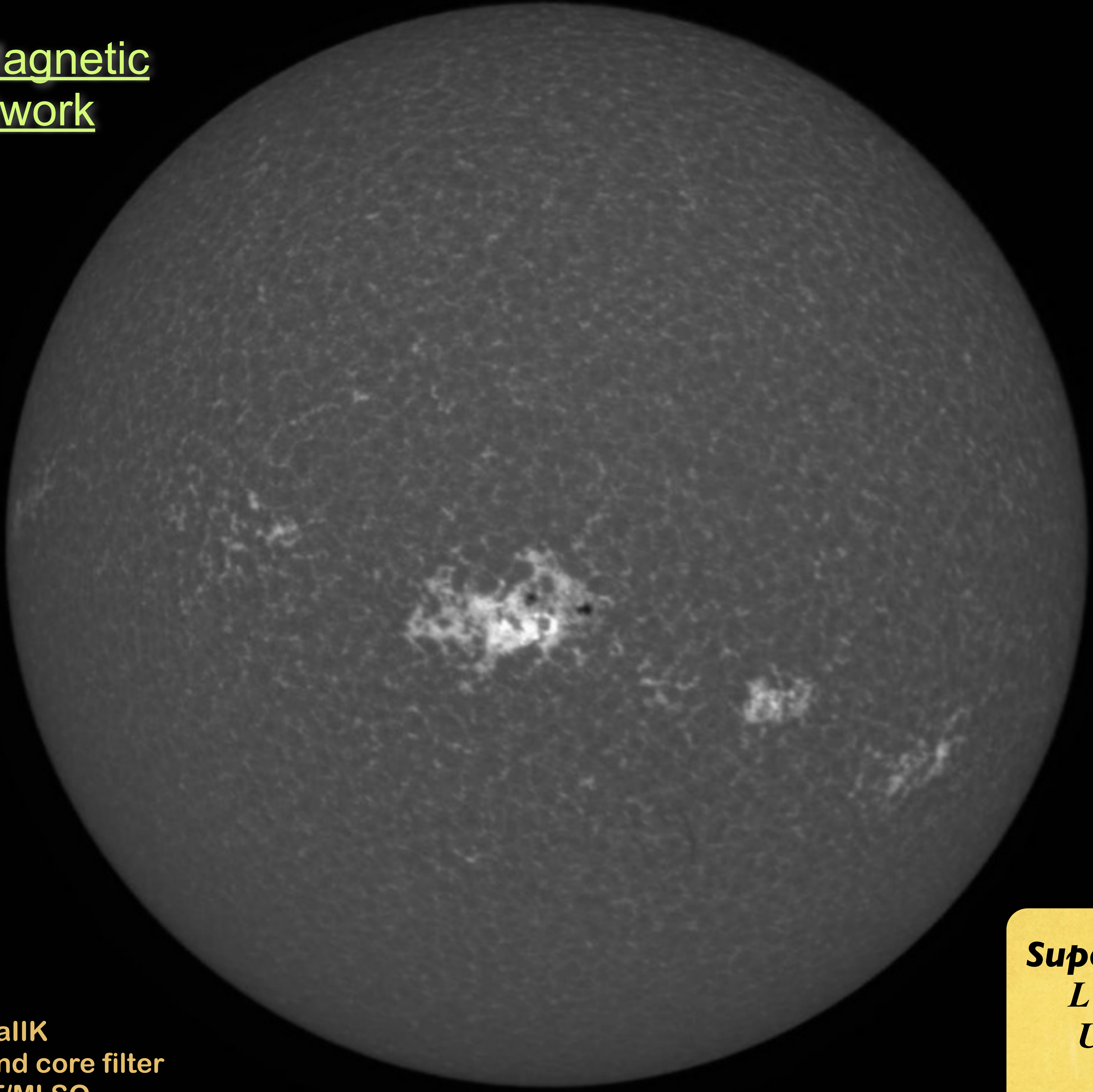
Lites et al (2008)



$L \sim$ 1-2 Mm
$U \sim 1$ km s^{-1}
$t \sim$ 10-15 min

Dominant size scale of solar convection

The Magnetic Network

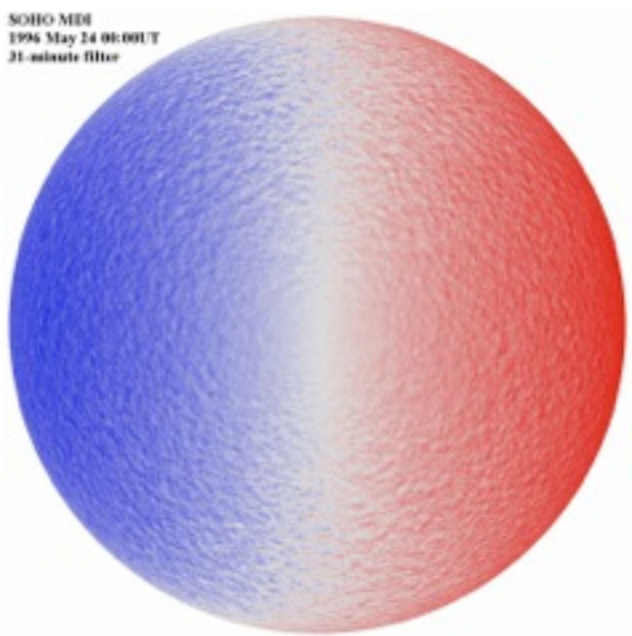


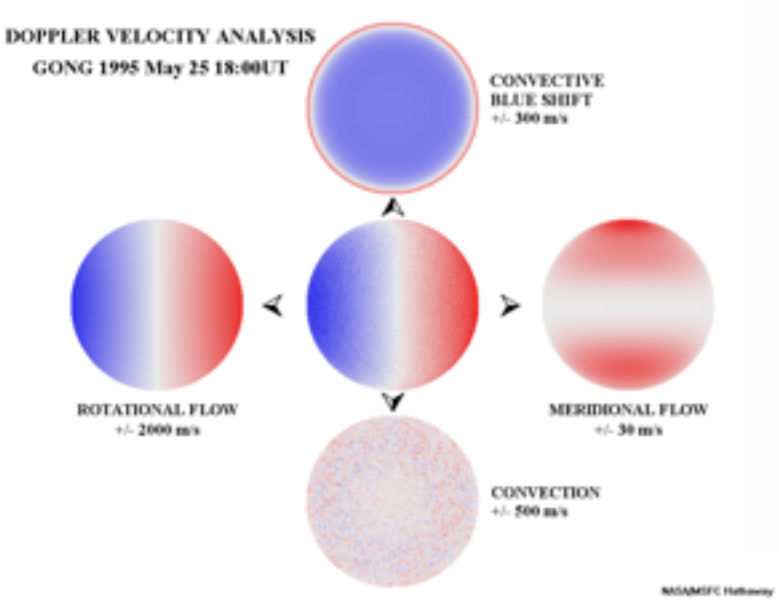
CaIIK
narrow-band core filter
PSPT/MLSO

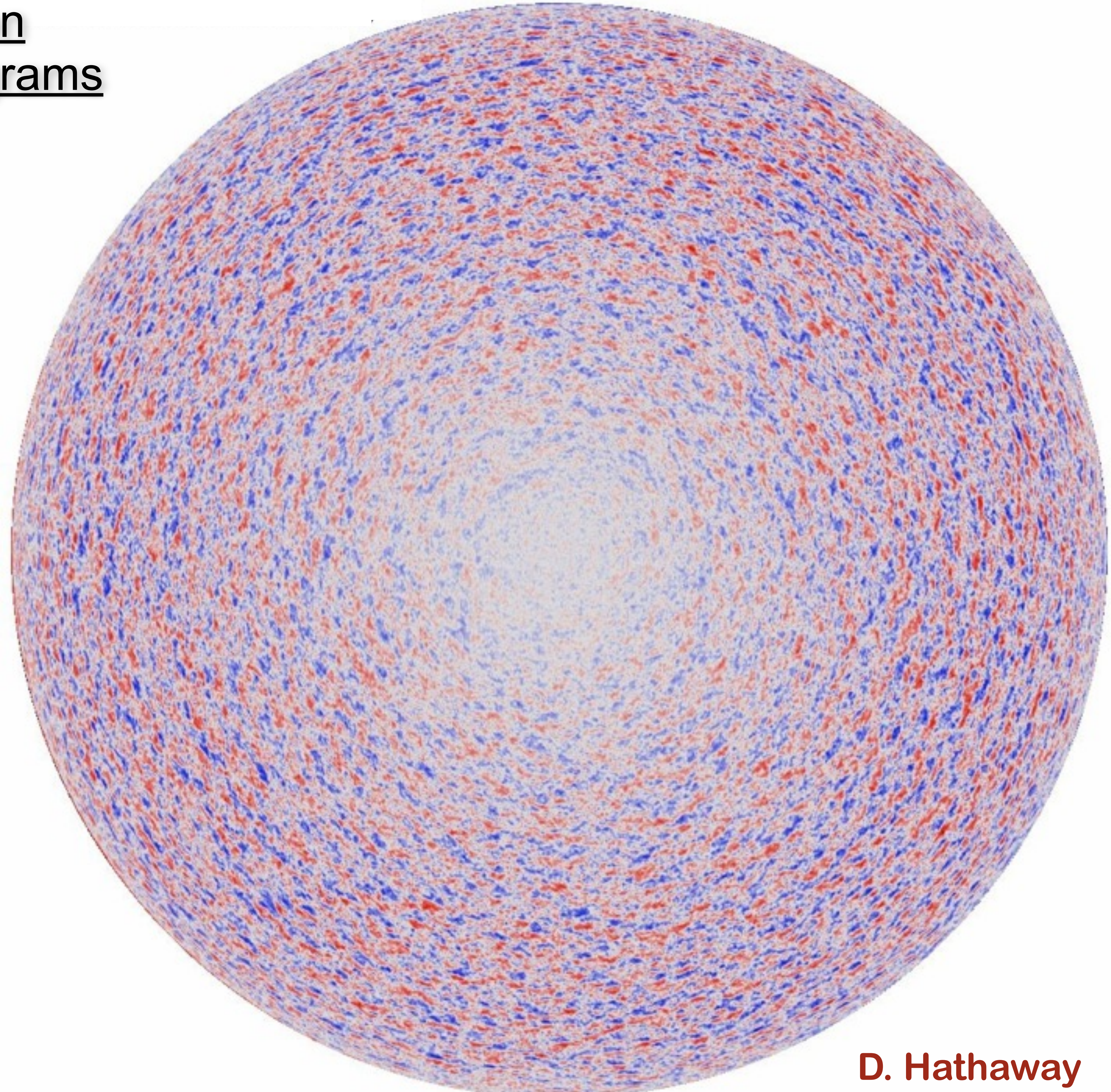
Supergranulation
$L \sim 30\text{-}35$ Mm
$U \sim 500$ m s^{-1}
$t \sim 20$ hr

Supergranulation in Filtered Dopplergrams

Most prominent in horizontal velocities near the limb







D. Hathaway
(NASA MSFC)

A hierarchy of convective scales

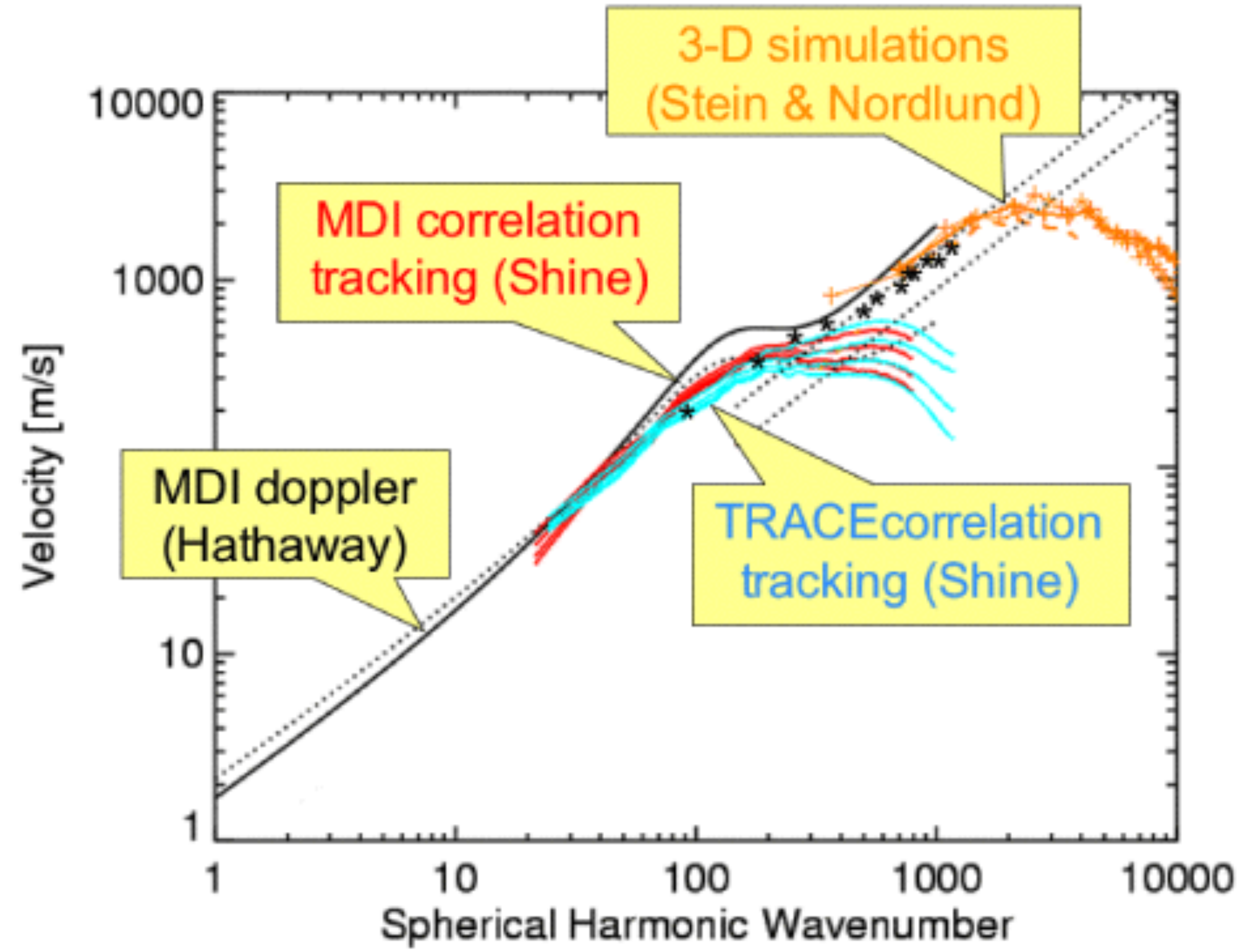
In the Sun, density and dynamical time scales increase with depth

Most of the mass flowing upward does not make it to the photosphere

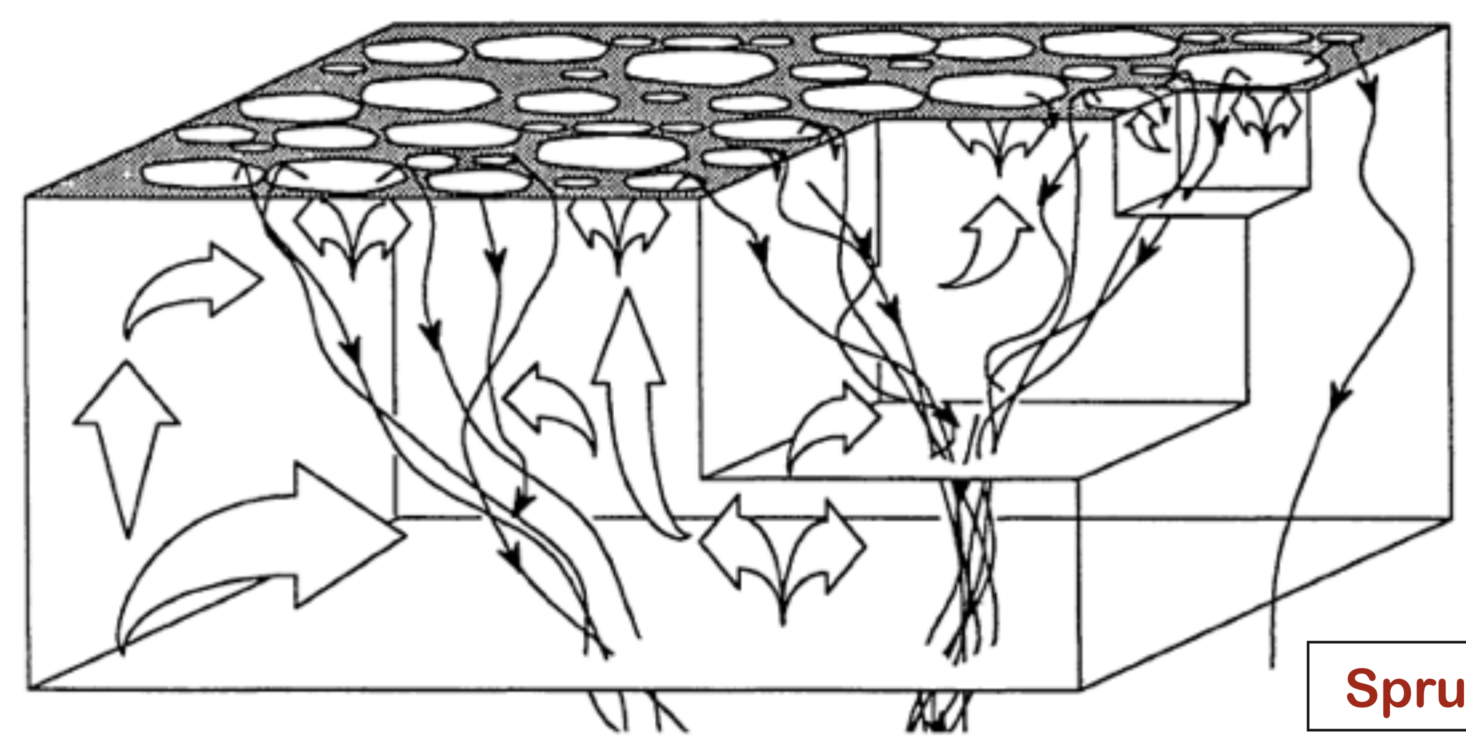
Downward plumes merge into superplumes that penetrate deeper

Deep-seated pressure variations drive surface flows

Velocity spectrum $[kP(k)]^{1/2}$



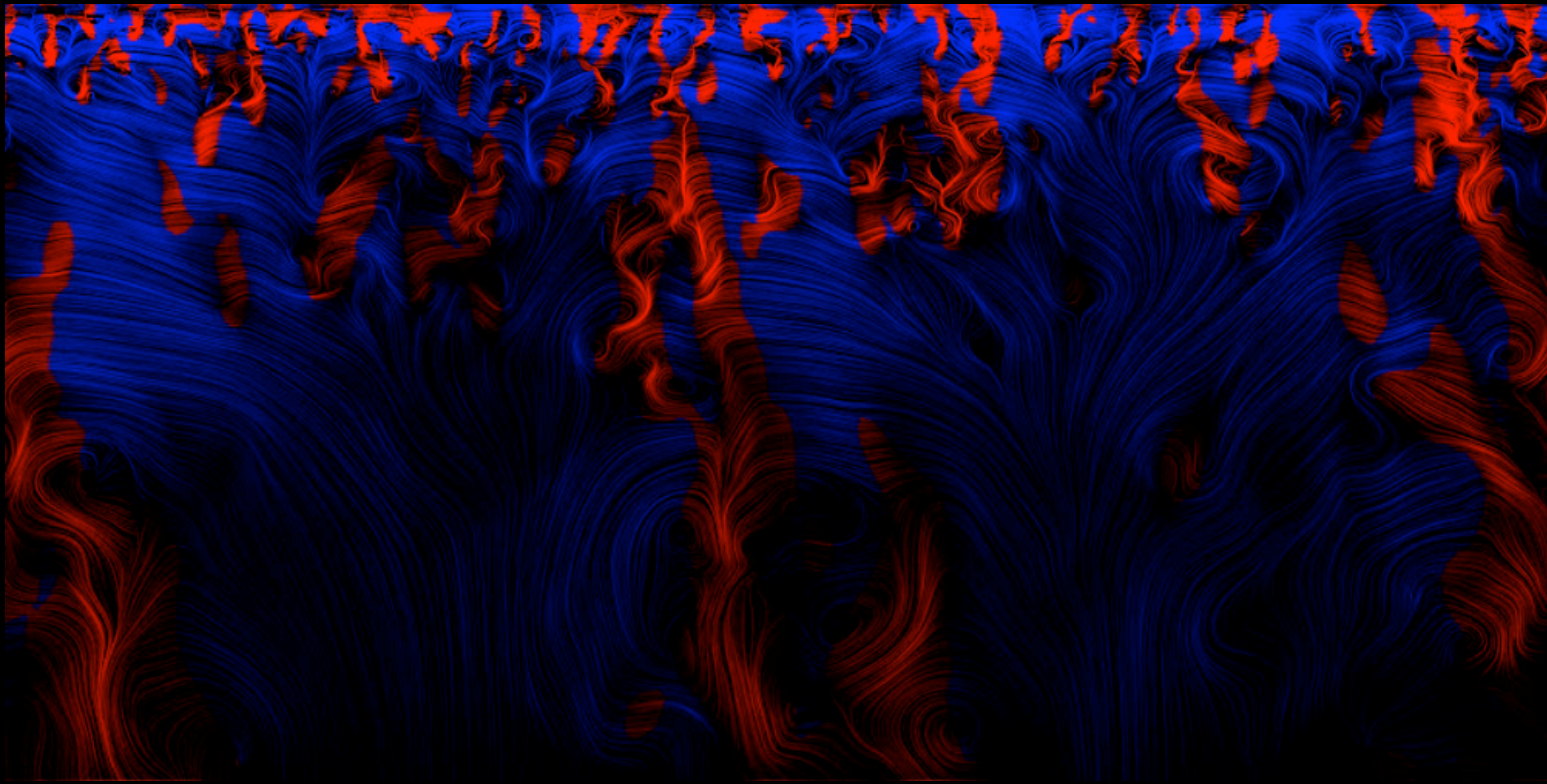
Nordlund, Stein & Asplund (2009)



Spruit, Nordlund & Title (1990)

Supergranulation and mesogranulation are part of a continuous (self-similar?) spectrum of convective motions

simulation by Stein et al (2006), visualization by Henze (2008)



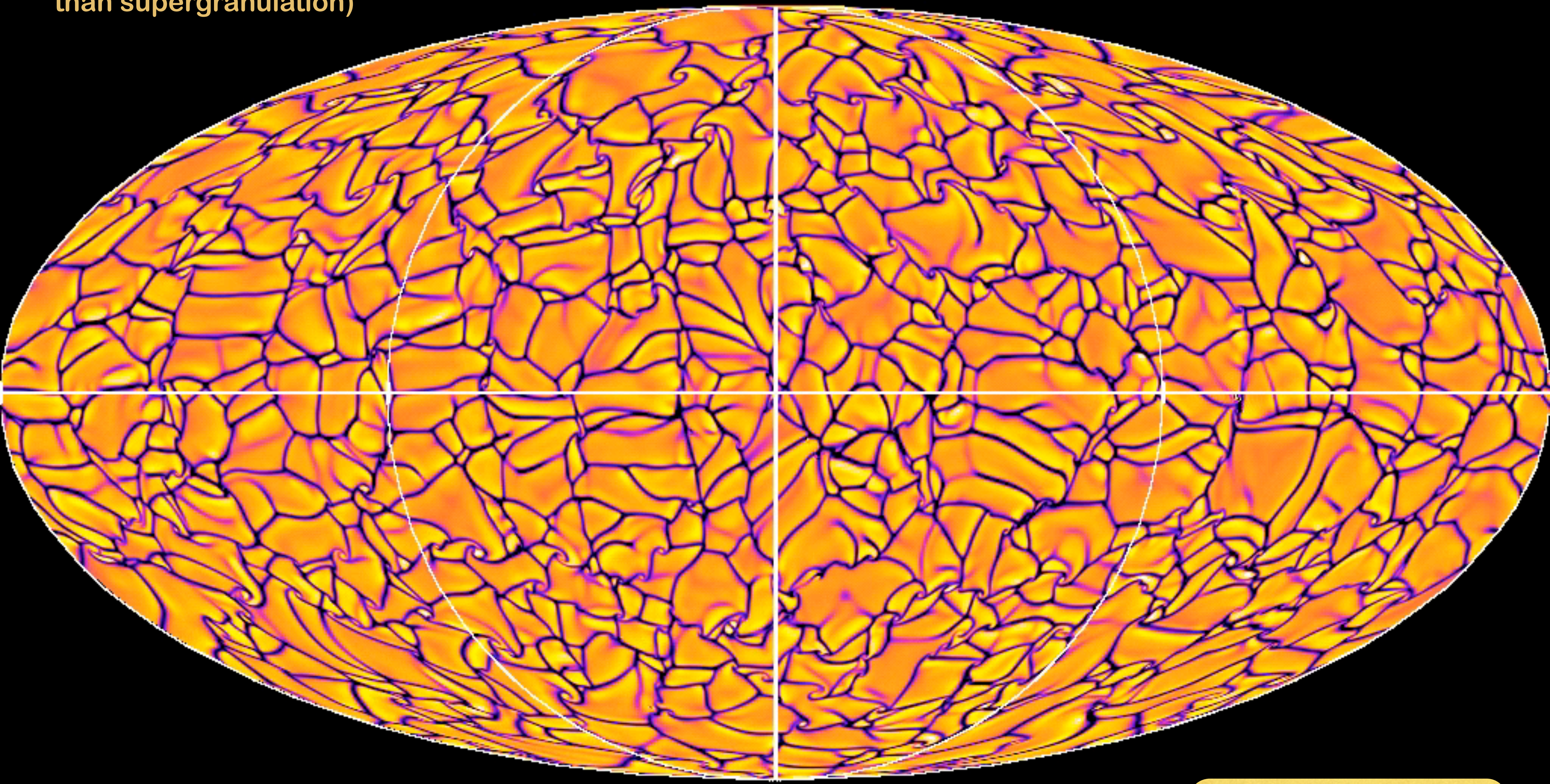
Size, time scales of convection cells increases with depth

Beyond Solar Dermatology
But still stops at 0.97R!
what lies deeper still?

Giant Cells

(Loosely, anything bigger than supergranulation)

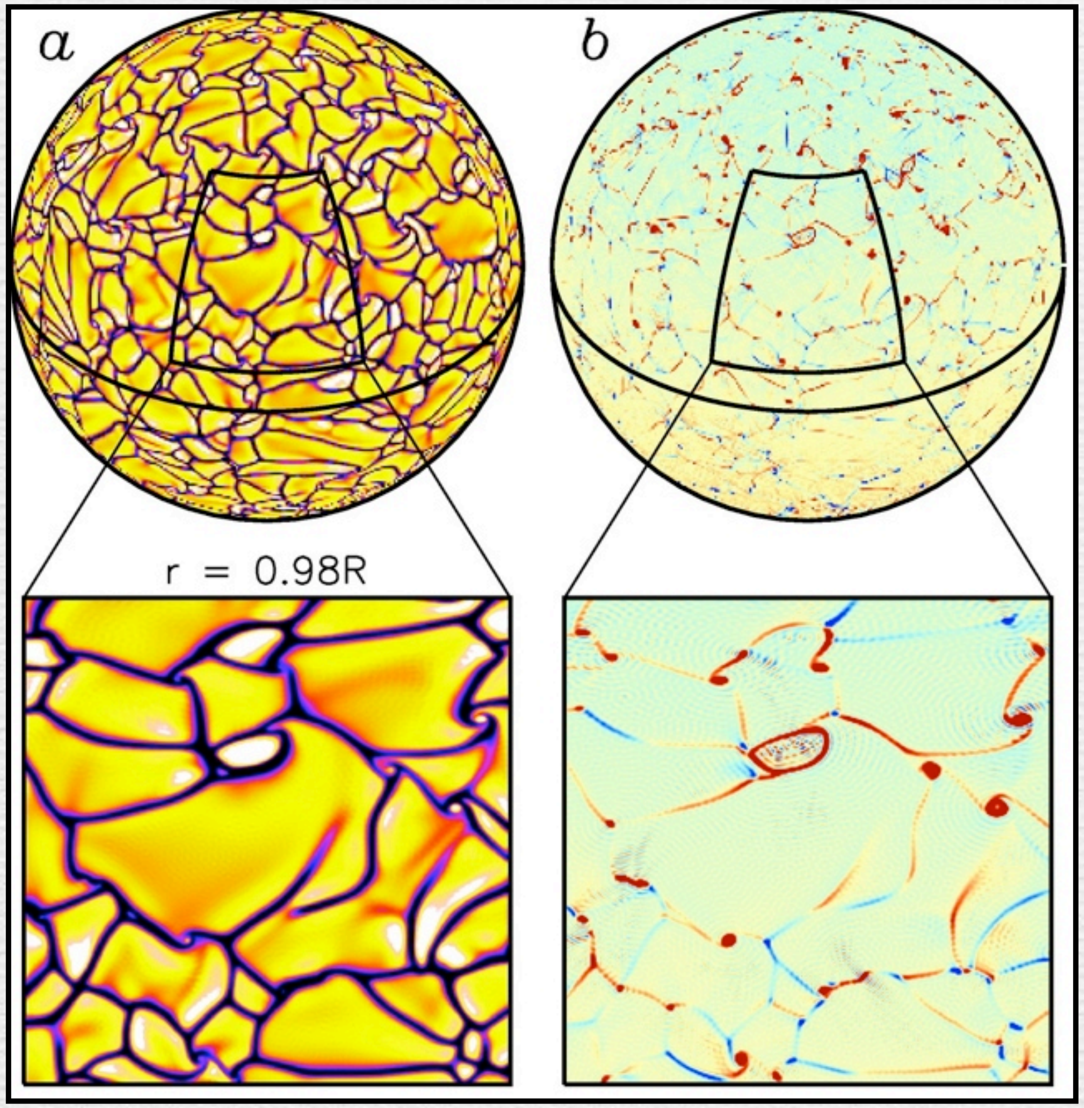
Eventually the heirarchy must culminate in motions large enough to sense the spherical geometry and rotation

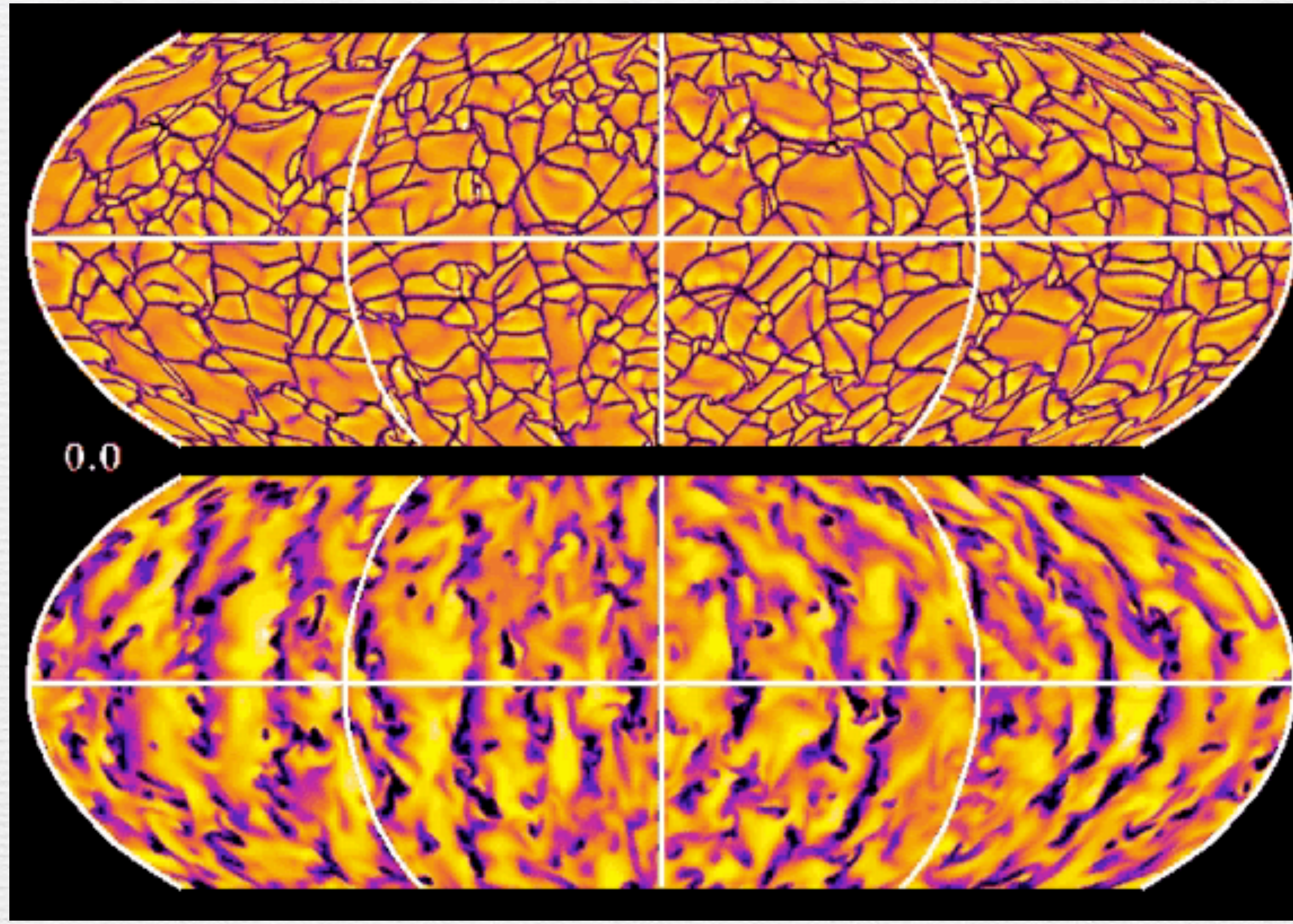


radial velocity, r = 0.98R

L ~ 100 Mm
U ~ 100 m s^{-1}
t ~ days - months

Structure of Giant Cells





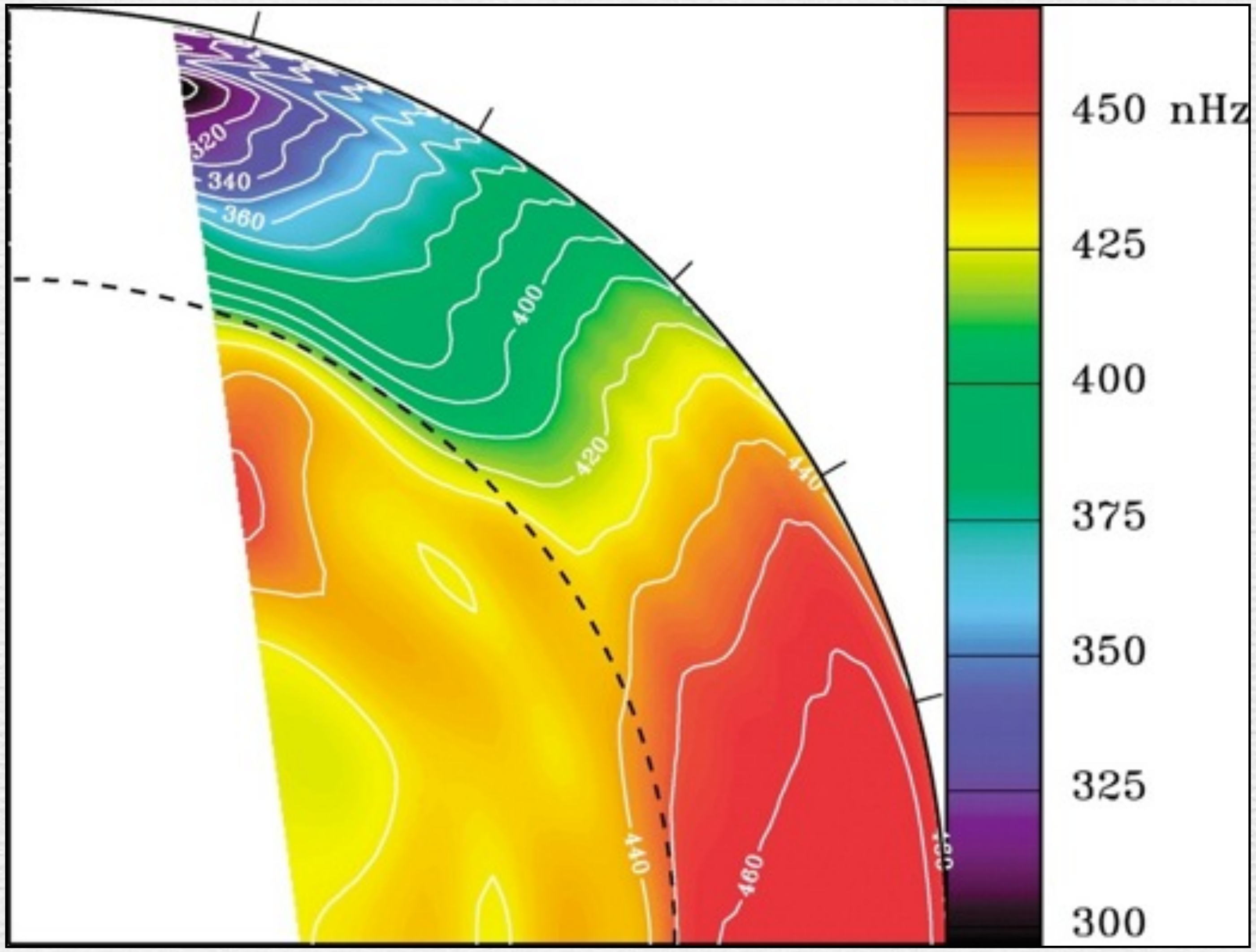
Solar Cyclones at high latitudes (cool, helical downflows)

Convective columns at low latitudes (thermal Rossby waves: prograde propagation)

Giant cells are notoriously difficult to detect (masked by more vigorous surface convection)

However, we're pretty sure they are there Because…

Giant Cells carry energy and redistribute angular momentum



That's how the Sun shines
(Carrying energy from 0.7R to surface)

That's why
the equator spins faster than the poles
(Only giant cells are big and slow enough to sense the rotation and spherical geometry)

Differential Rotation

Monotonic decrease in Ω of ~30% from equator to high latitudes in CZ

Nearly uniform rotation in radiative zone

Convection Implicated as source of DR

Nearly radial contours at mid-latitudes in CZ

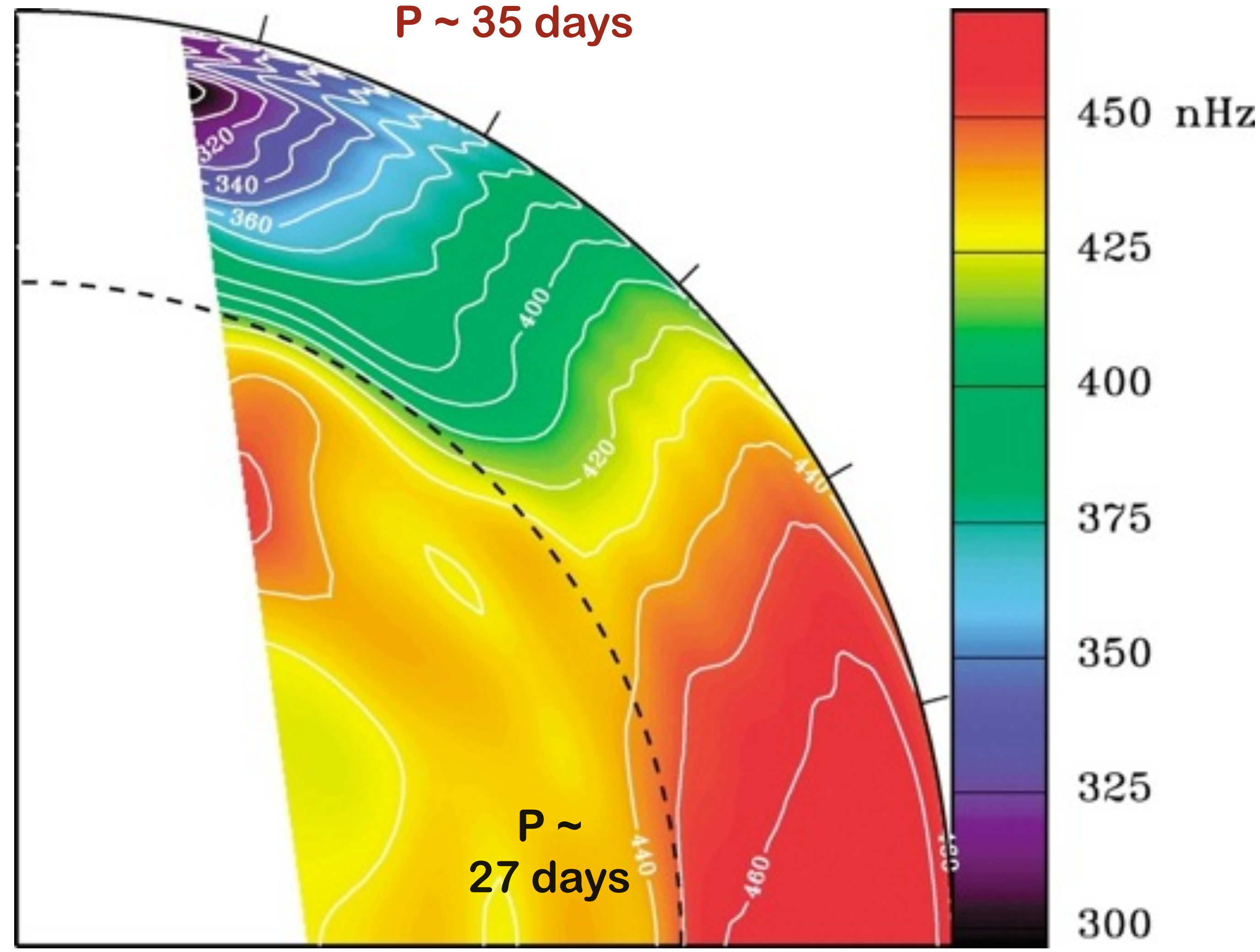
Radial Ω gradients near top & bottom:

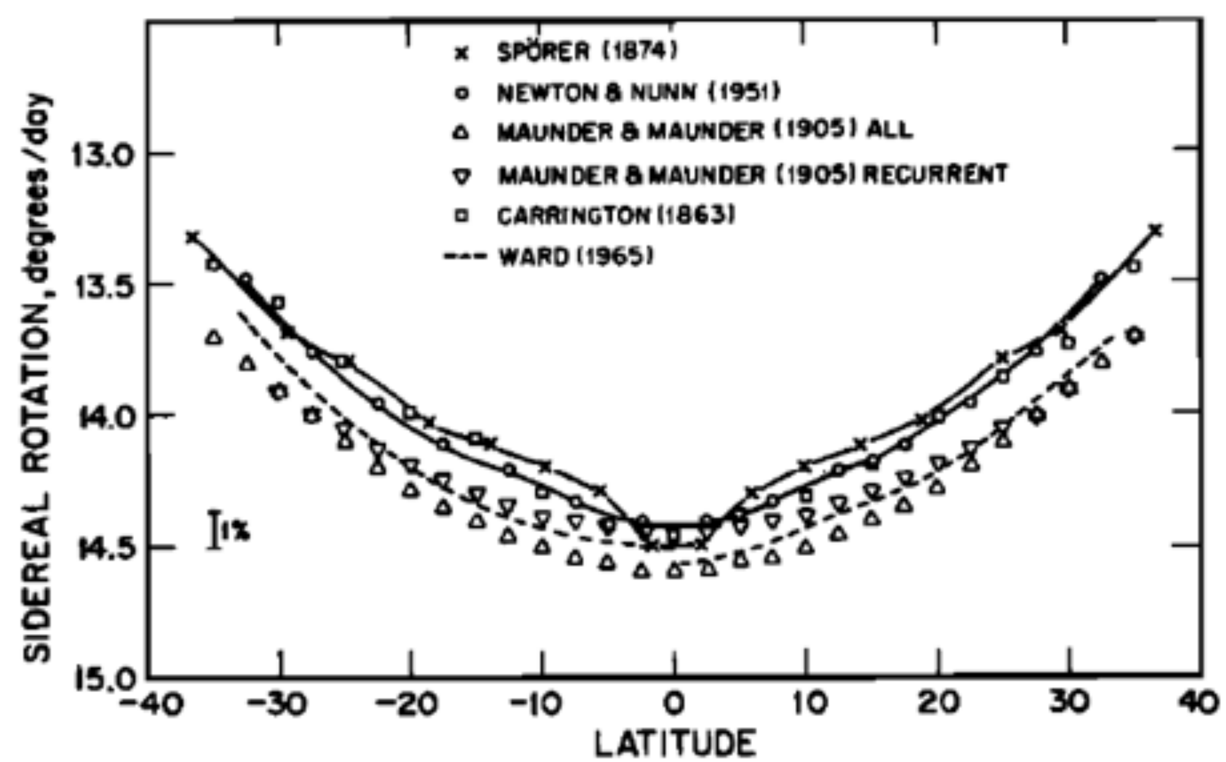
Tachocline

Near-surface shear layer

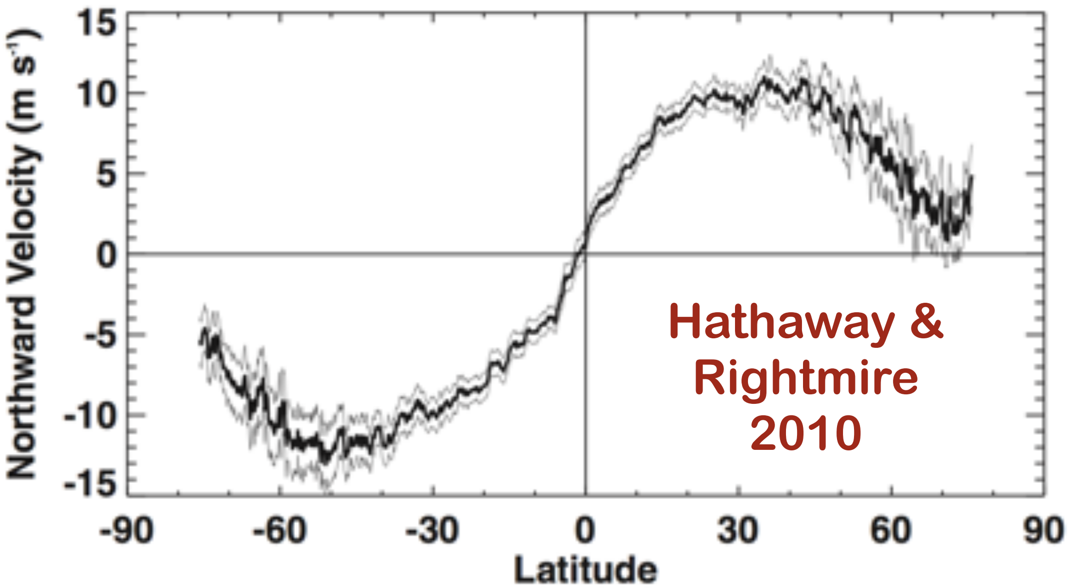
Interior rate intermediate between equator & poles in CZ

Persistent in time





Meridional Circulation



Systematically poleward at mid latitudes near surface (r > 0.95R)

Much weaker that differential rotation (~ 20 m/s)

Variable in time

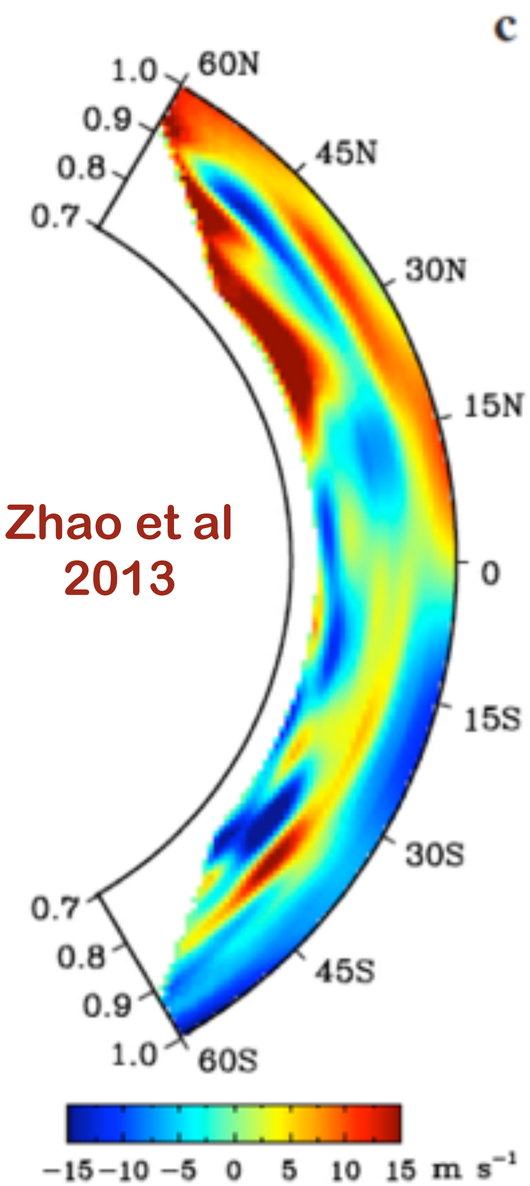
...and that's about all we know!

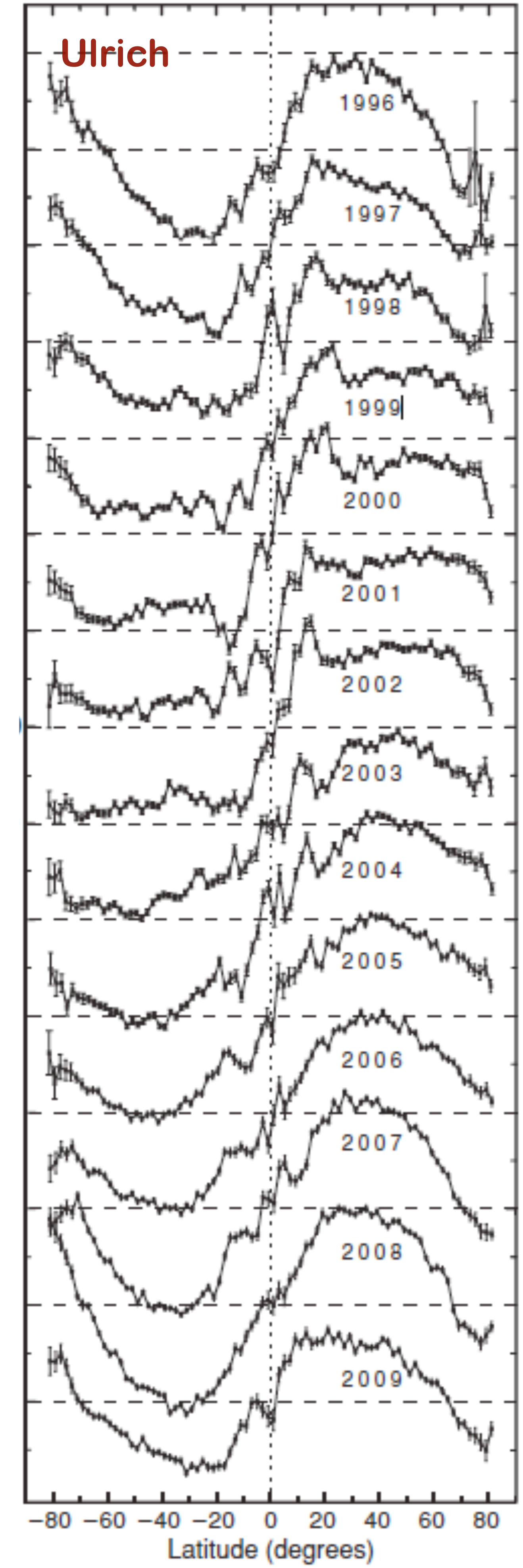
Observational techniques

Local helioseismology ***(left and below)***

Surface Doppler measurements ***(right)***

Feature Tracking





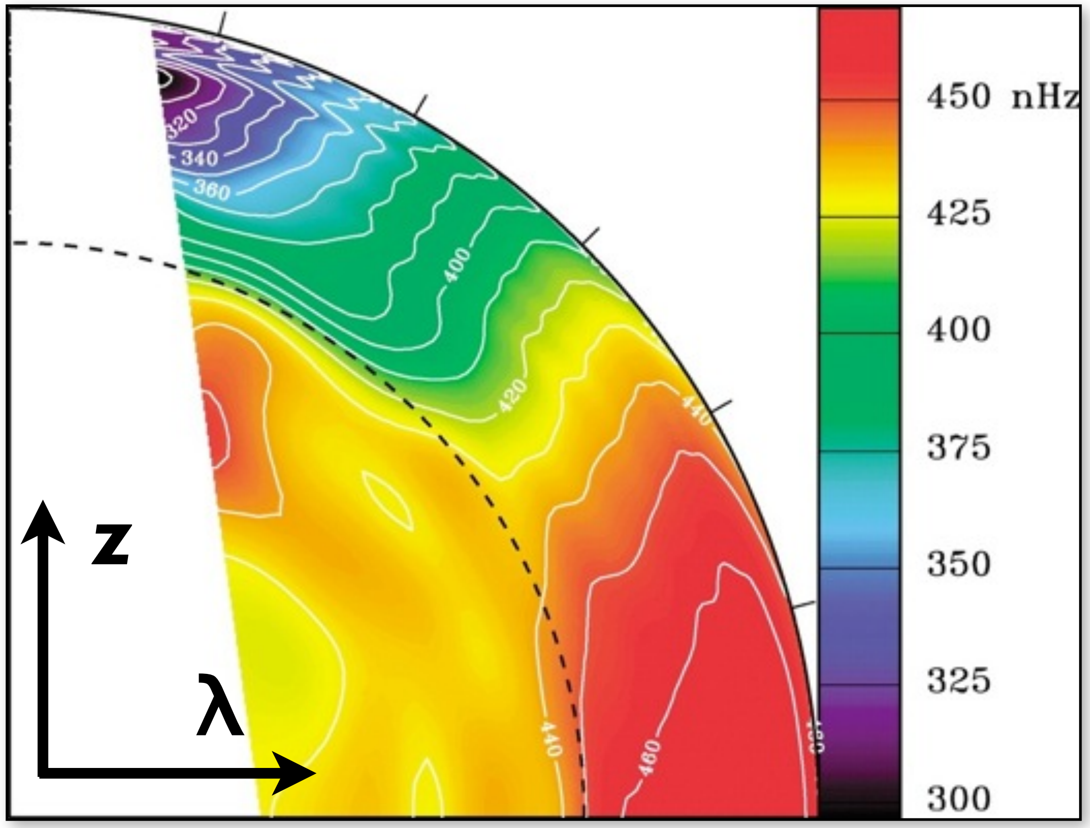
Reynolds Stress

Angular momentum per unit mass

$$\mathcal{L}^* = \lambda v_\phi$$

Average over longitude

$$\mathcal{L} = \langle \lambda v_\phi \rangle$$



Conservation of ϕ momentum

$$\frac{\partial}{\partial t}(\rho\mathcal{L}^*) = -\boldsymbol{\nabla}\cdot(\rho\mathbf{v}\mathcal{L}^*) - \frac{1}{r\sin\theta}\frac{\partial P}{\partial \phi}$$

Now average over longitude and write it as follows

$$\boldsymbol{\mathcal{F}}_{mc} = \langle \rho \mathbf{v}_m \rangle \mathcal{L}$$

$$\frac{\partial}{\partial t}(\rho\mathcal{L}) = -\boldsymbol{\nabla}\cdot(\boldsymbol{\mathcal{F}}_{mc} + \boldsymbol{\mathcal{F}}_{rs})$$

Reynolds stress

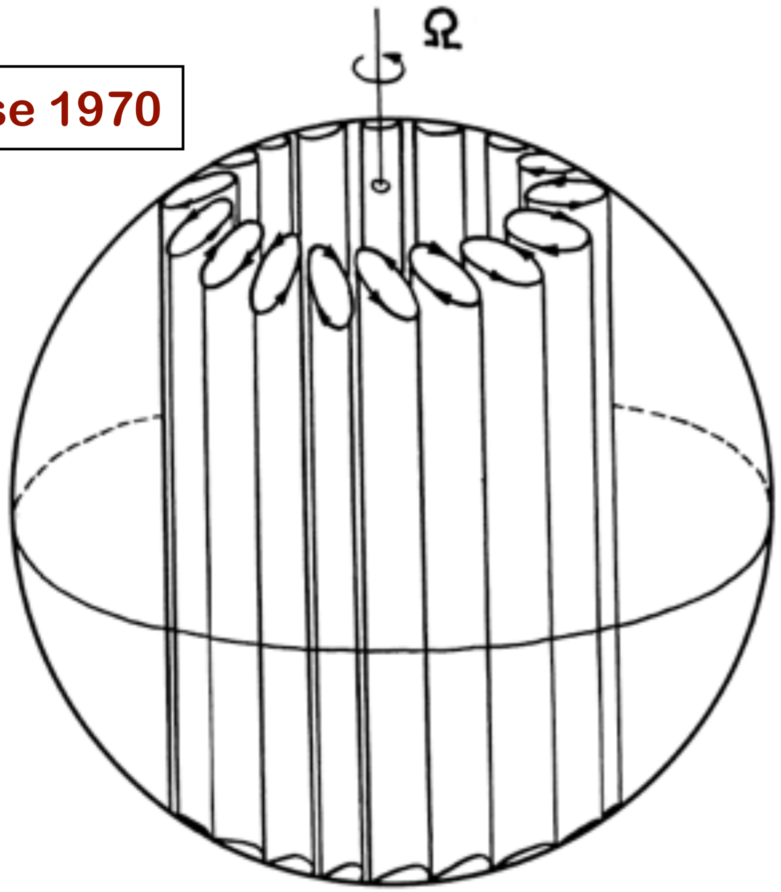
$$\boldsymbol{\mathcal{F}}_{rs} = \left\langle \rho \lambda \mathbf{v}_m' v_\phi' \right\rangle$$

Conservation of angular momentum

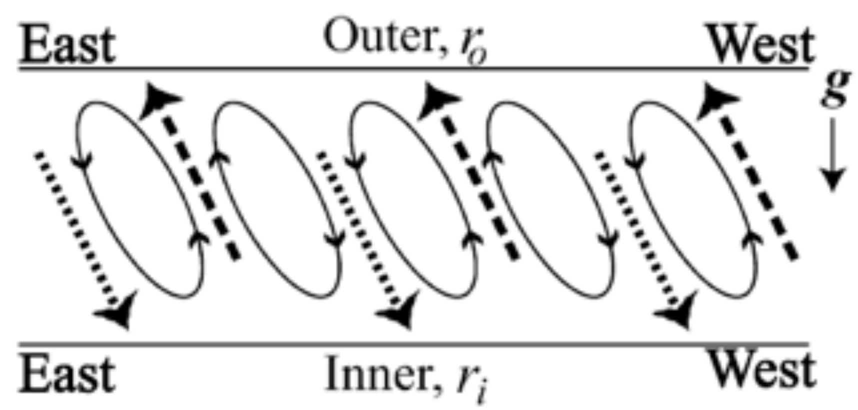
Angular Momentum Transport

Coriolis-induced tilting of convective structures

Busse 1970



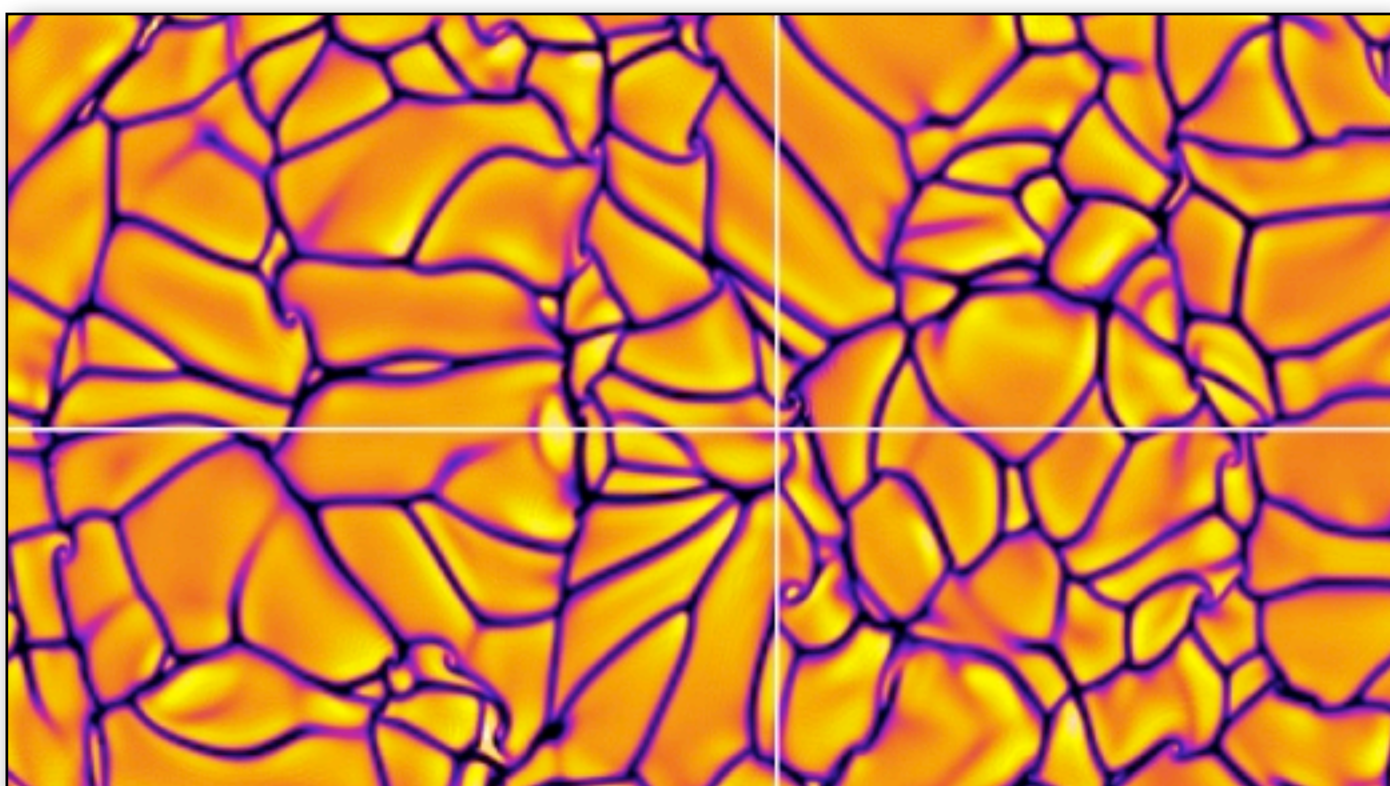
Ro << 1



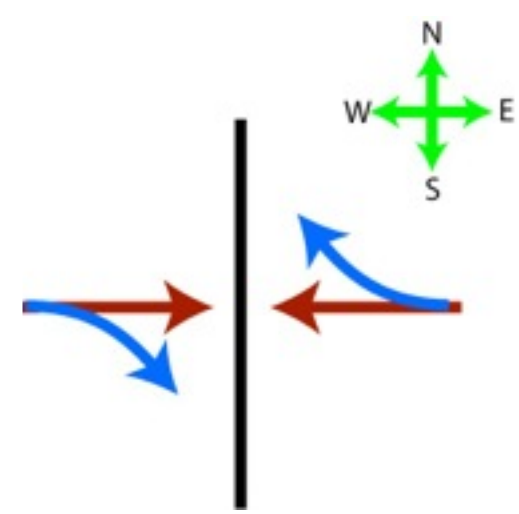
Aurnou et al 2007

$$\langle v'_\lambda v'_\phi \rangle > 0$$

angular momentum transport away from the rotation axis



Ro ~ 1

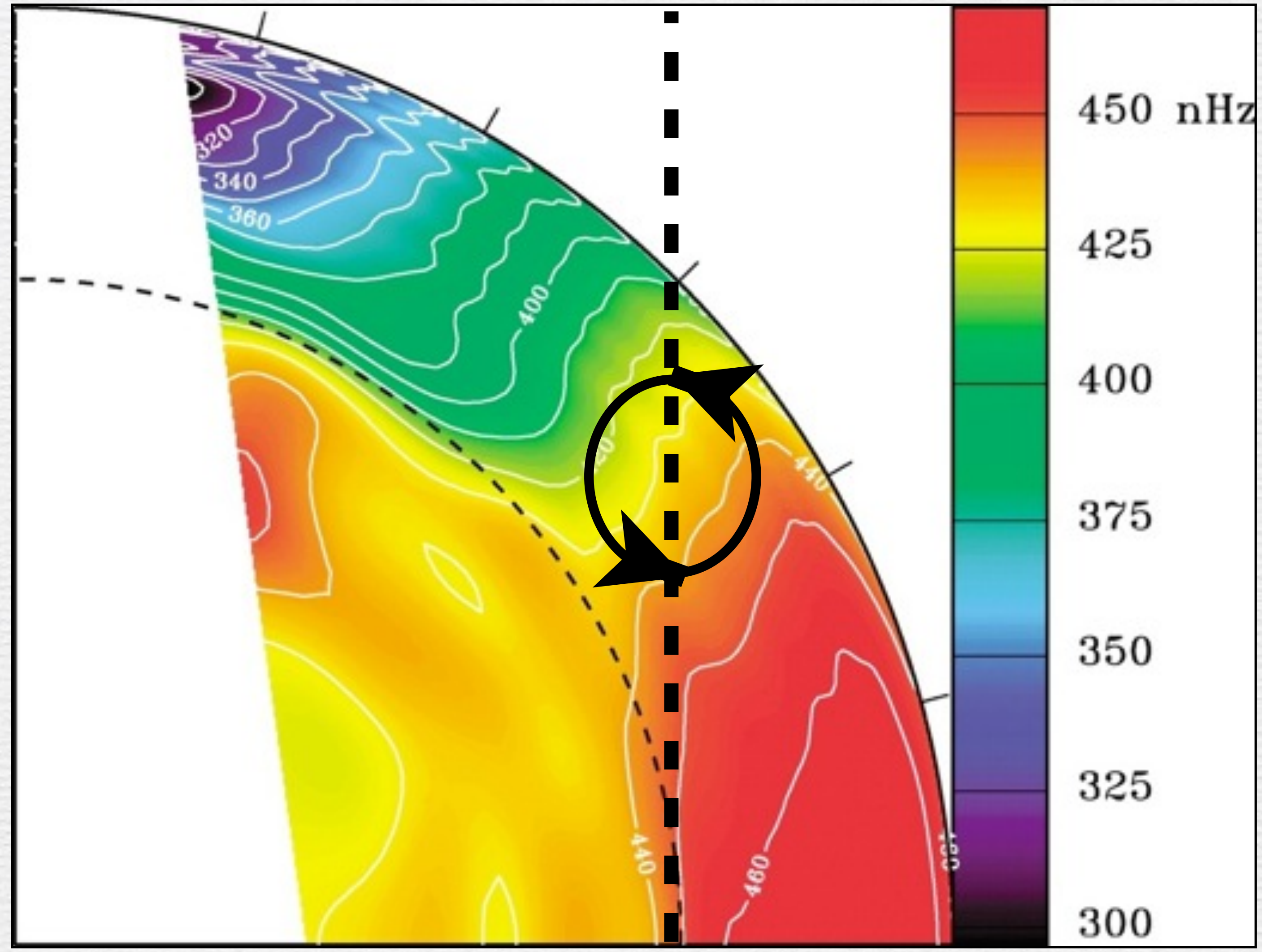


$$\langle v'_\theta v'_\phi \rangle > 0$$

(NH)

angular momentum transport toward the equator

Differential Rotation



ΔΩ Established by convective angular momentum transport (Reynolds Stress)

Conical orientation of Ω surfaces attributed to thermal gradients

$$\frac{\partial \Omega^2}{\partial z} = \frac{g}{r \lambda C_P} \frac{\partial \langle S \rangle}{\partial \theta}$$

Thermal Wind Balance

Warm poles

offset inertia of differential rotation

Required amplitudes of thermal variations tiny: one part in 10
(δ
2.2million K background)

What about the Meridional Circulation?

How is it maintained?

Answer: it feeds off the differential rotation

Maintenance of MC: Gyroscopic Pumping

Miesch & Hindman (2011)

$$\langle \rho \mathbf{v}_m \rangle \cdot \nabla \mathcal{L} = \mathcal{F}$$

$$\frac{\partial}{\partial t}(\rho \mathcal{L}) + \langle \rho \mathbf{v}_m \rangle \cdot \nabla \mathcal{L} = \mathcal{F}$$

No assumptions beyond basic MHD!

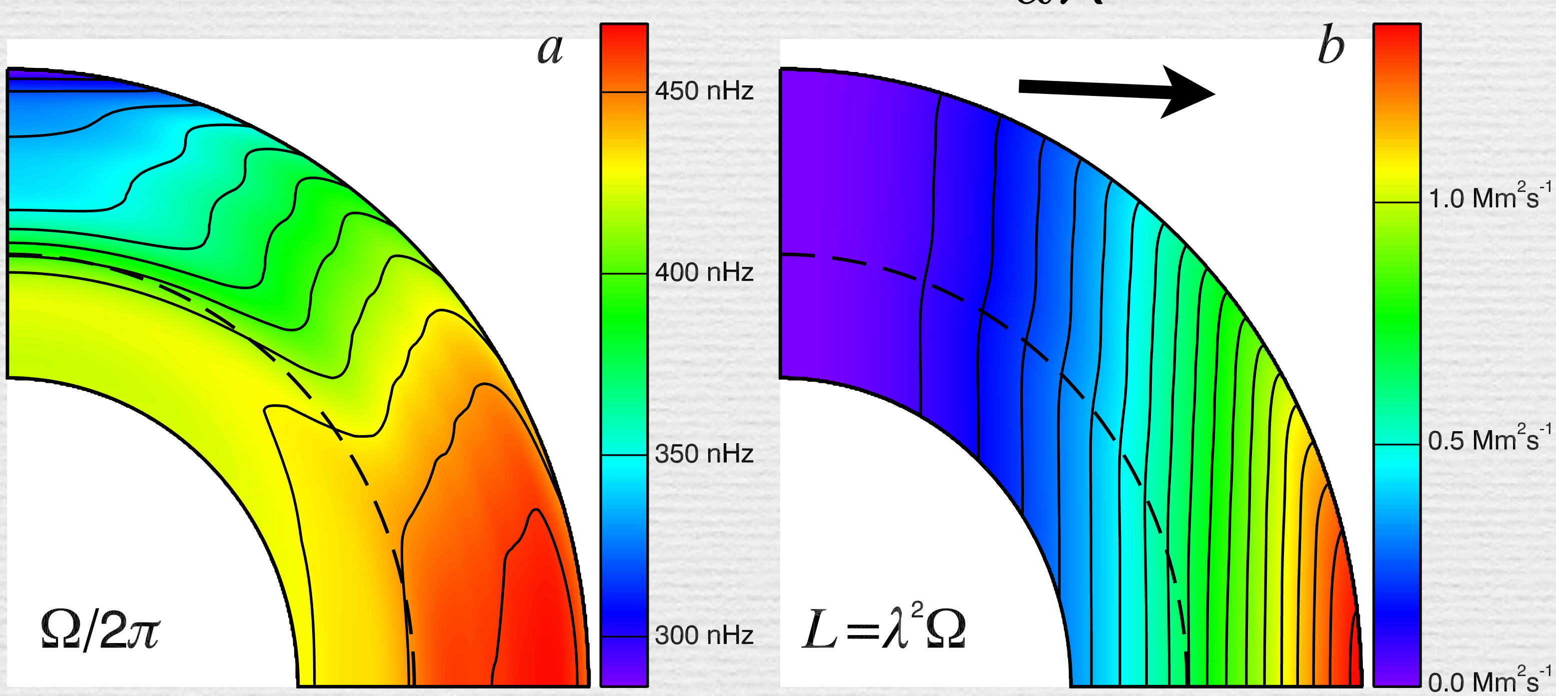
$$\mathcal{F} = -\nabla \cdot \left[\lambda \langle \rho \mathbf{v}' v'_\phi \rangle - \lambda \langle \mathbf{B} B_\phi \rangle - \rho \nu \lambda^2 \nabla \Omega\right]$$

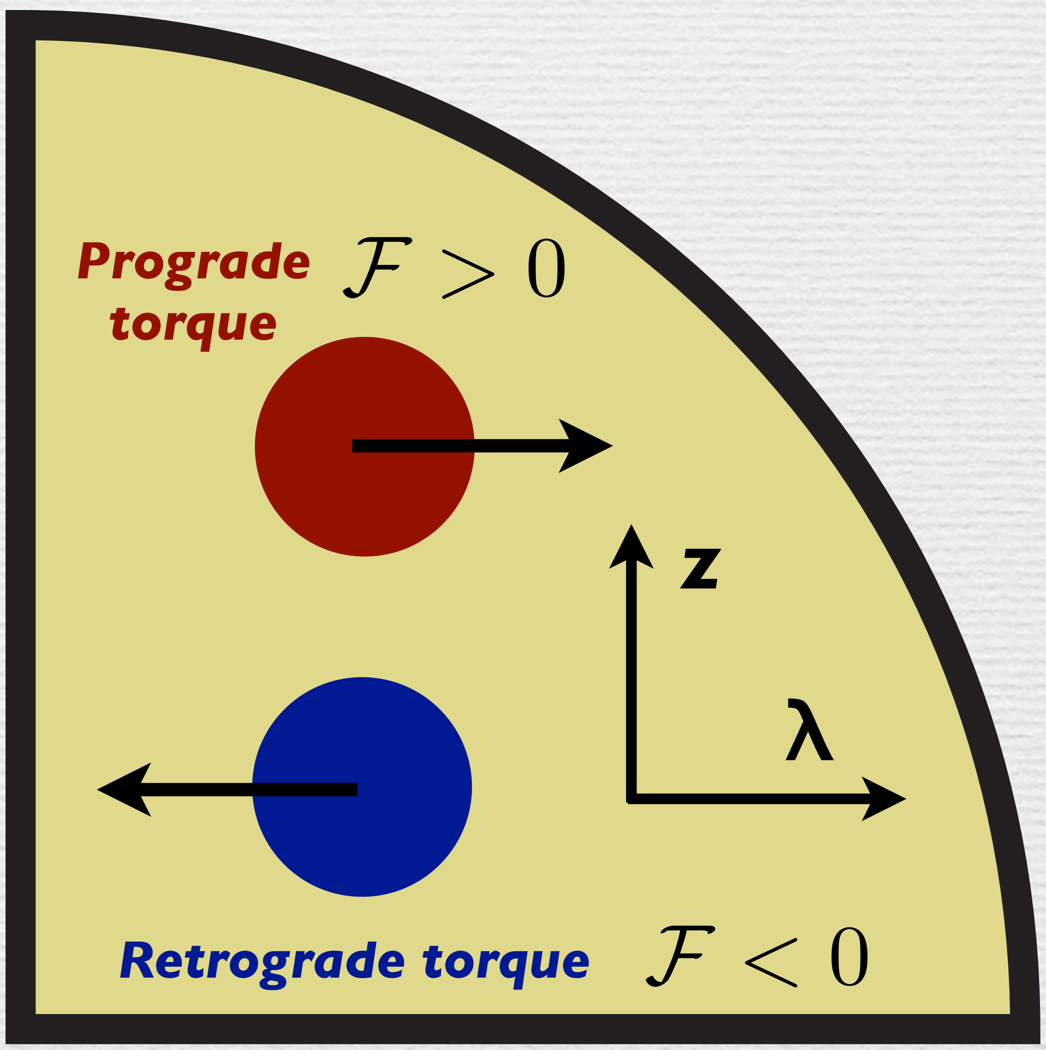
Reynolds stress | **Lorentz force** | **Viscous diffusion**

$$\mathcal{L} = \lambda^2 \Omega = \lambda \langle v_\phi \rangle$$

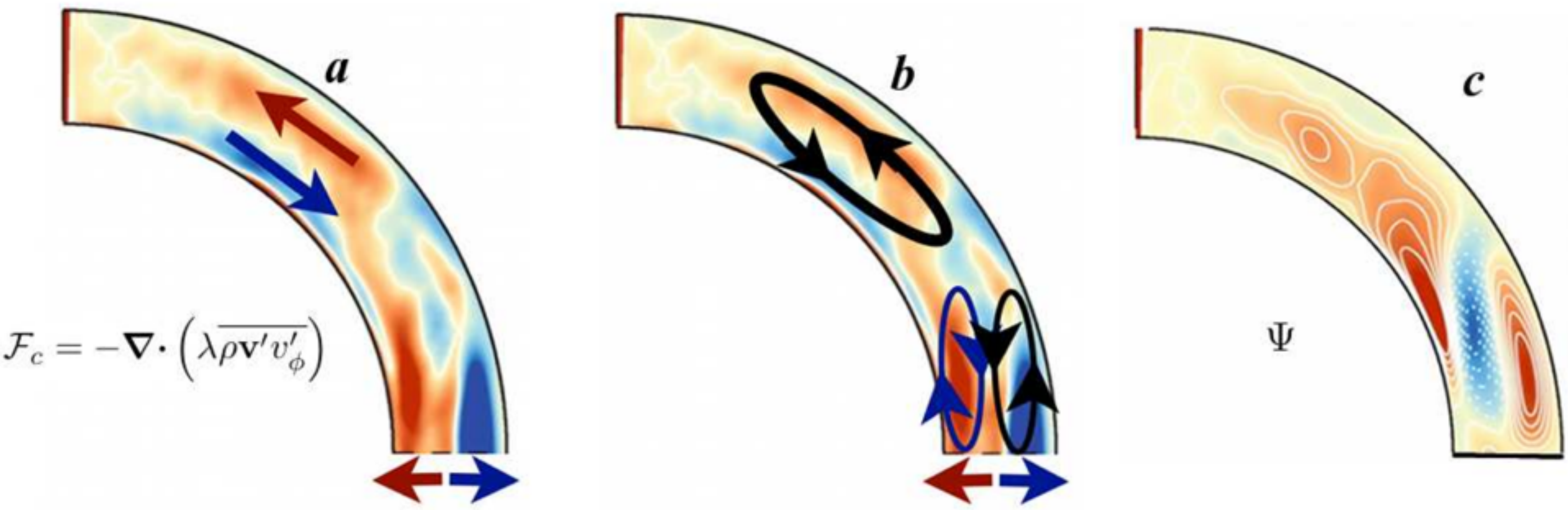
$$\nabla \mathcal{L} \approx \frac{d\mathcal{L}}{d\lambda}\,\hat{\boldsymbol{\lambda}}$$

(GONG inversions, courtesy Rachel Howe)





Gyroscopic Pumping in Convection Simulations



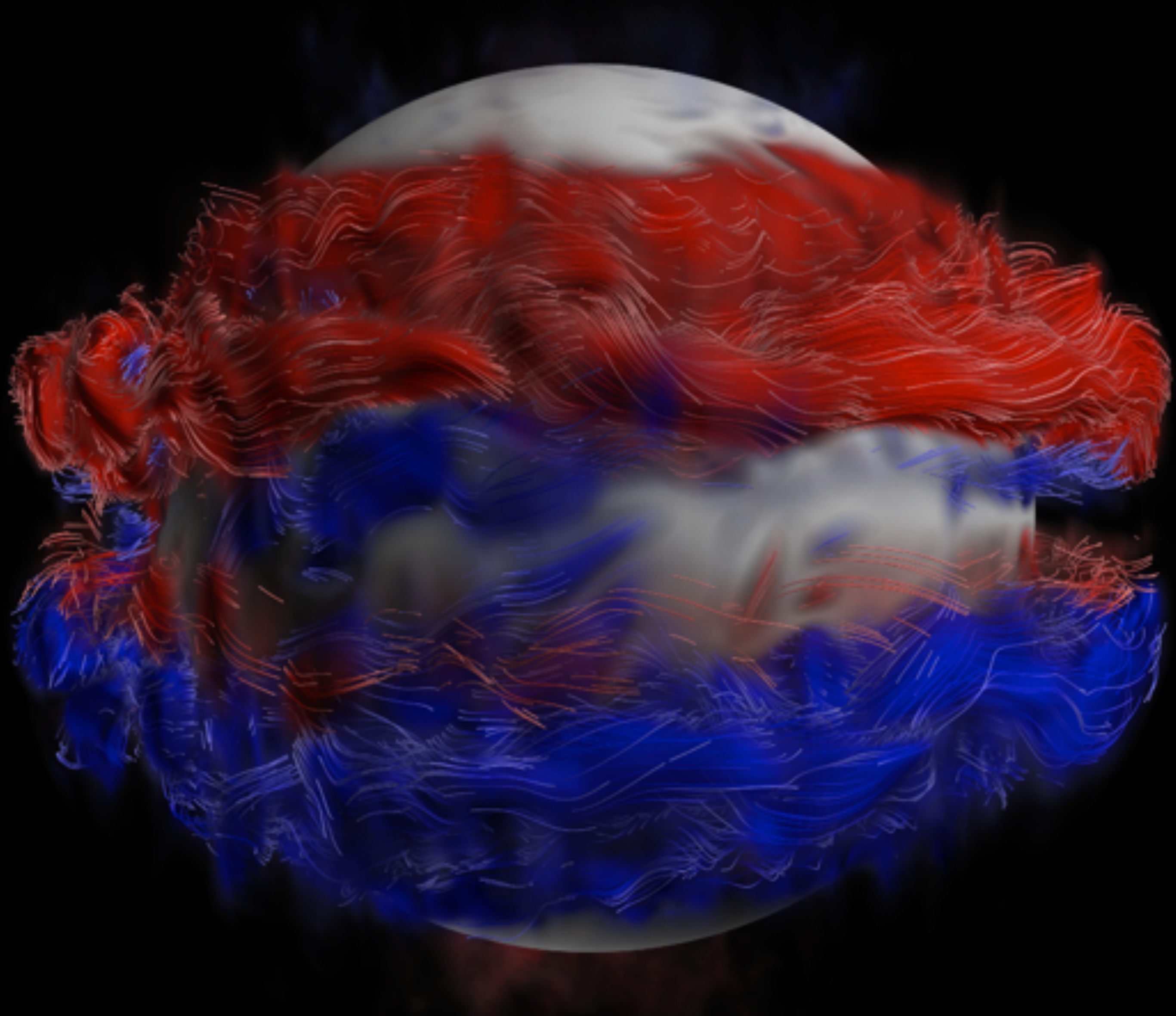
Meridional Circulation mainly depends on the convective angular momentum transport too

$$\langle\rho\mathbf{v}_m\rangle\cdot\nabla\mathcal{L} = \mathcal{F}$$

...Though magnetic fields and thermal variations (baroclinicity) can also contribute

Part 3 (of 3)

- ★ Solar and Stellar Magnetism
- ★ Solar Convection and Mean Flows
- ★ Solar Dynamo Models



Definition

<u>Hydromagnetic Dynamo</u>

A physical object or system that converts the kinetic energy of fluid motions into magnetic energy and sustains that magnetic energy indefinitely against ohmic decay (magnetic diffusion)

Generation of Magnetic Fields: The MHD Magnetic Induction Equation

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

$$R_m = \frac{UL}{\eta}$$

Follows from Faraday's Law of Induction

$$\boldsymbol{\nabla} \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

And Ohm's Law (with a Galilean transformation)

$$\mathbf{J} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

MHD assumptions

Highly ionized, Quasi-neutral

High collision frequency/short mean-free paths (high density, temperature)

sub-relativistic bulk velocity

Lesson #1 in Solar Dynamo Theory: If the velocity is specified (kinematic), the induction equation is Linear

Note: this is the definition of "kinematic"

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

Profound implications (immensely useful for theory):

Asking whether or not a given (steady) velocity field will or will not be a dynamo then reduces to a linear instability problem

Solutions are a linear superposition of different modes, each with its own (complex) eigenvalue and eigenfunction

Real part of eigenvalue indicates whether the solution exponentially grows or exponentially decays

Imaginary part determines whether or not the solution is oscillatory (cyclic)

Lesson #2 in Solar Dynamo Theory:
No real dynamo in nature is kinematic

Profound pain in the neck (..or opportunity, depending on your perspective)

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

This suggests two classes of dynamos:

Essentially kinematic:

Make it stop!

Small seed field that is initially kinematic (too weak to induce a significant Lorentz force) grows exponentially until it becomes big enough to modify the velocity field

This brings up the crucial issue of: Dynamo Saturation

Essentially Nonlinear:

Make it go!

The velocity field that gives rise to the dynamo mechanism depends on the existence of the field

The focus then shifts toward: Dynamo Excitation

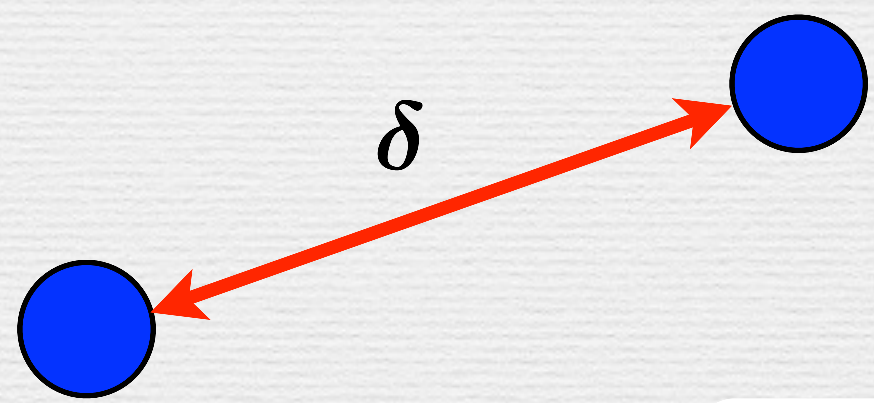
Lagrangian Chaos

Chaotic fluid trajectories amplify magnetic fields

(provided that chaotic stretching wins the battle against ohmic diffusion)

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

$$\frac{D\mathbf{B}}{Dt} = \frac{\partial \mathbf{B}}{\partial t} + (\mathbf{v}\cdot\boldsymbol{\nabla})\,\mathbf{B} = (\mathbf{B}\cdot\boldsymbol{\nabla})\,\mathbf{v} - \mathbf{B}\,(\boldsymbol{\nabla}\cdot\mathbf{v}) - \boldsymbol{\nabla}\times(\eta\boldsymbol{\nabla}\times\mathbf{B})$$



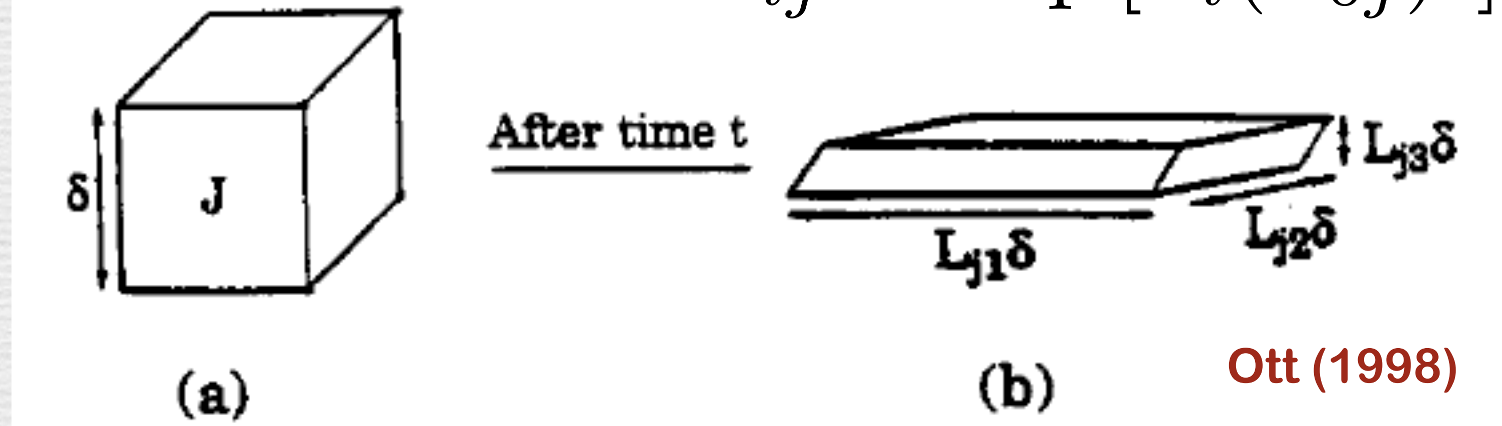
l = Local Lyapunov exponents

If $\boldsymbol{\nabla}\cdot\mathbf{v} = \eta = 0$ **then**

$$\frac{D\mathbf{B}}{Dt} = (\mathbf{B}\cdot\boldsymbol{\nabla})\,\mathbf{v}$$

$$\frac{d\boldsymbol{\delta}}{dt} = (\boldsymbol{\delta}\cdot\boldsymbol{\nabla})\,\mathbf{v}$$

$$L_{ij} = \exp\left[\lambda_i(\mathbf{x}_{0j})t\right]$$



Ott (1998)

$$\frac{d\delta_i(\mathbf{x}_0,t)}{dt} = \mathcal{J}_{ij}(\mathbf{x}_0,t)\;\delta_j\,(\mathbf{x}_0,t)$$

$$\lambda_1 + \lambda_2 + \lambda_3 = 0$$

Spatially smooth, temporally chaotic flows work best

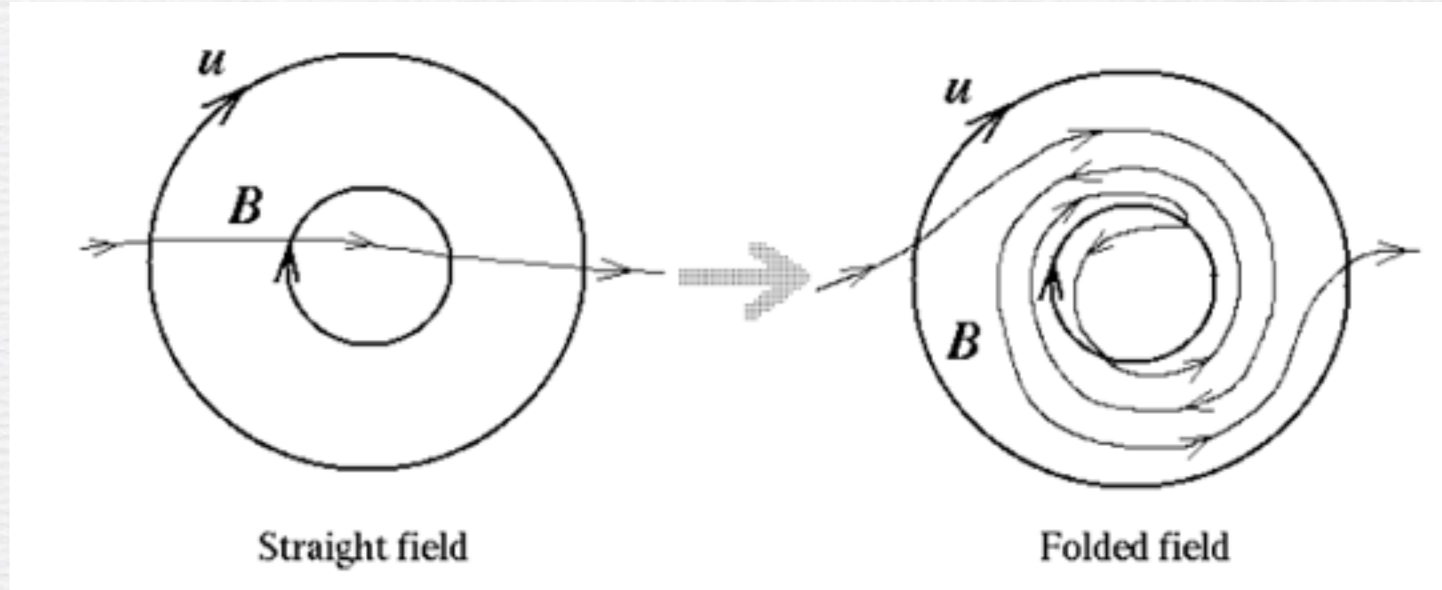
$$R_m = \frac{UL}{\eta}$$

$$P_m = \frac{\nu}{\eta}$$

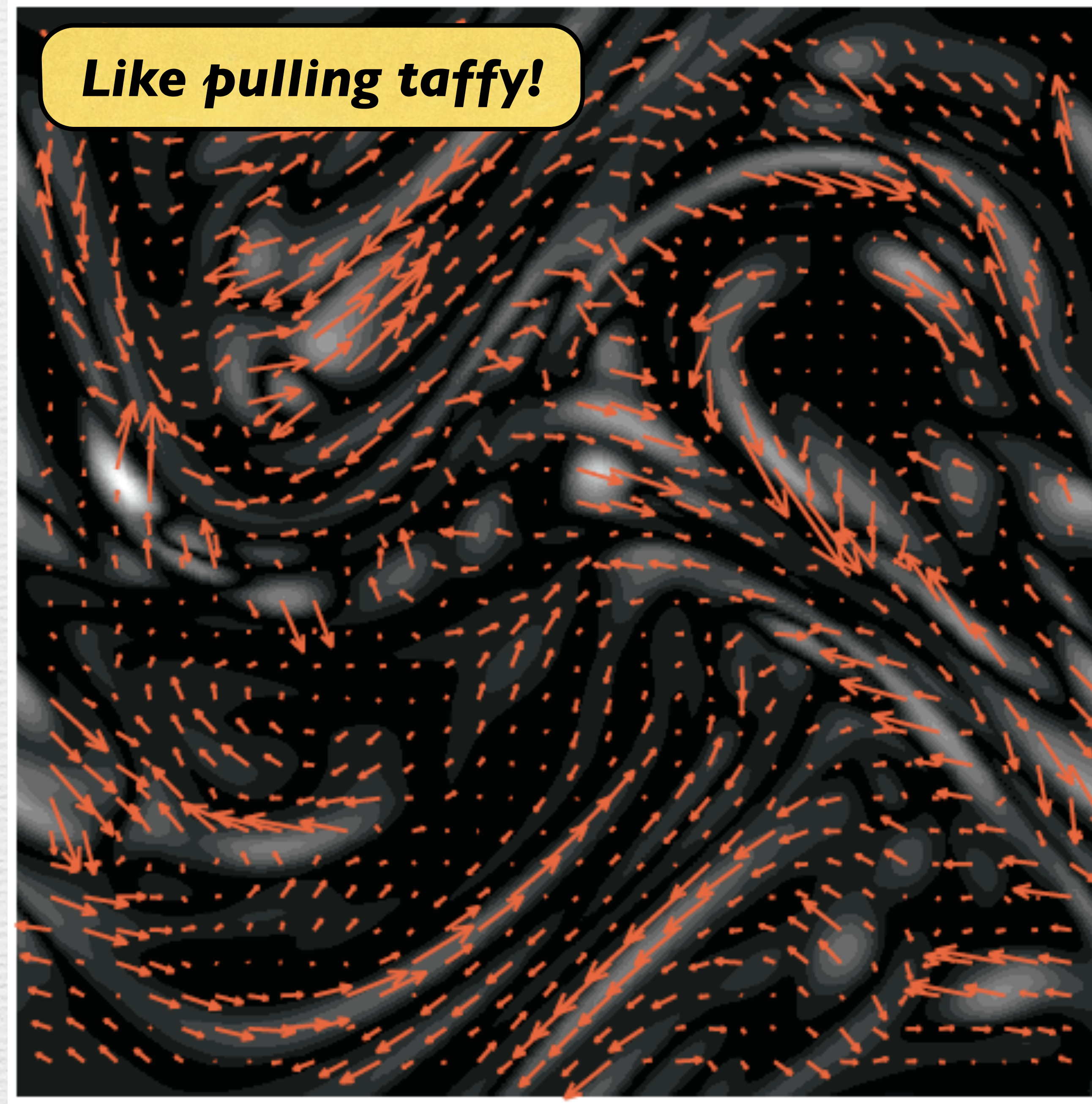
If $P_m > 1$ then turbulent dynamos build fields on sub-viscous scales

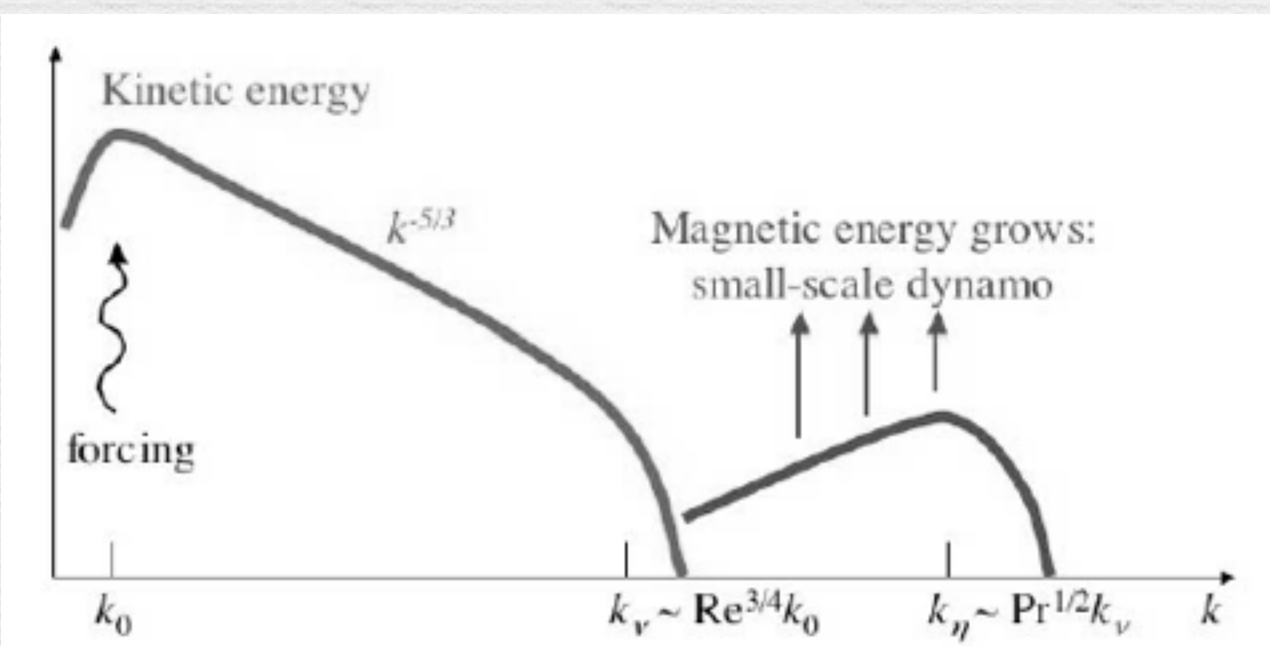
Magnetic energy peaks near resistive scale

Turbulent flows beget turbulent fields!



Schekochihin et al (2004)





Local Dynamo Action in the Sun and Stars

Granulation: t ~ 10-15 min

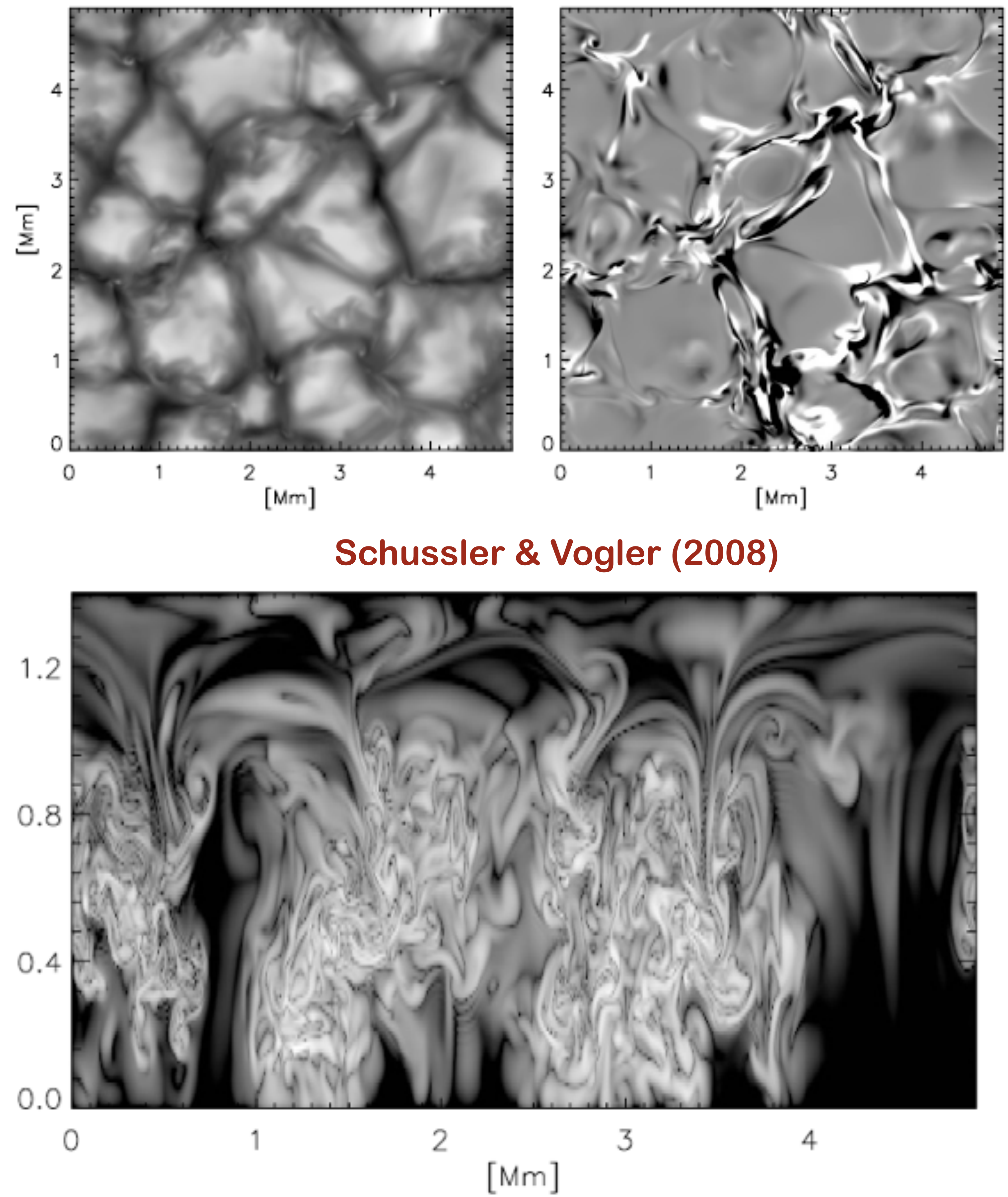
Giant Cells: t ~ days - months

Granulation may generate field locally by chaotic stretching with little regard for the deeper convection zone

Flux expulsion and reconnection produce strong horizontal fields near photosphere

Magnetic pumping of flux through lower boundary can inhibit the surface dynamo in simulations

In the Sun the local dynamo is likely intimately coupled to the global dynamo



Schussler & Vogler (2008)

Types of Dynamos

define
Small-scale dynamo

Generates magnetic fields on scales smaller than the velocity field

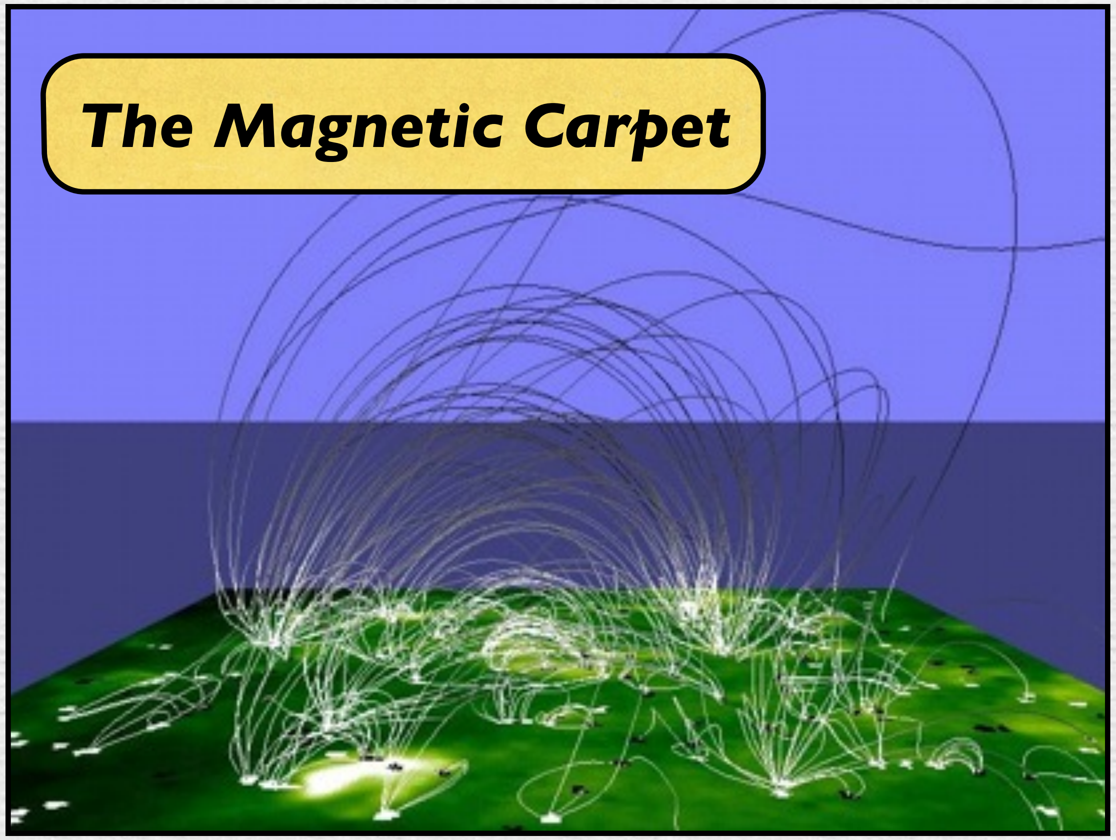
$$\ell_B \leq \ell_v$$

define
Large-scale dynamo

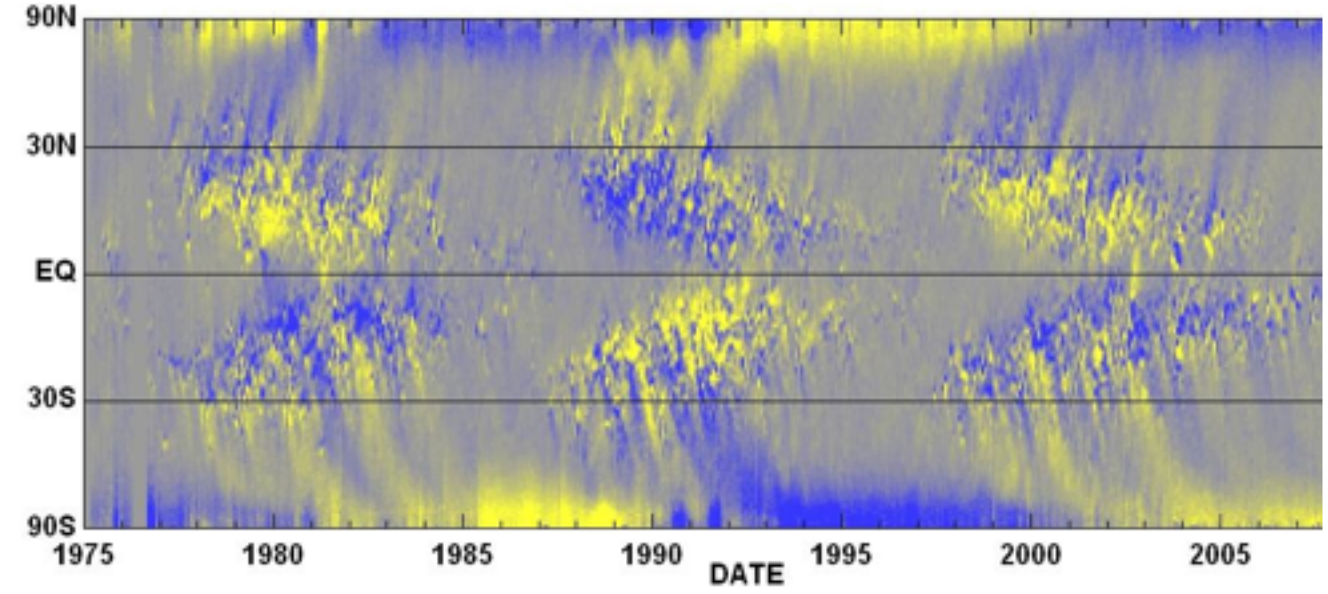
Generates magnetic fields on scales larger than the velocity field

$$\ell_B >> \ell_v$$

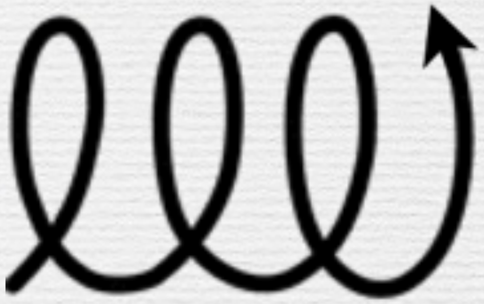
The Magnetic Carpet



The Solar Cycle



Recipe for Building Large-Scale Fields



Lagrangian Chaos

- Builds magnetic energy

Rotational Shear

- Builds large-scale toroidal flux (
- Enhances dissipation of small-scale fields
- Promotes magnetic helicity flux

Helicity

- Rotation and stratification generate kinetic helicity
- Kinetic helicity generates magnetic helicity
- Upscale spectral transfer of magnetic helicity generates large-scale fields
  - Local transfer: helicity
  - Nonlocal transfer:

$$H_k = \langle \boldsymbol{\omega} \cdot \boldsymbol{v} \rangle$$

$$H_m = \langle \boldsymbol{A} \cdot \boldsymbol{B} \rangle$$

$$H_c = \langle \boldsymbol{J} \cdot \boldsymbol{B} \rangle$$

$$\boldsymbol{\omega} = \boldsymbol{\nabla} \times \boldsymbol{v}$$

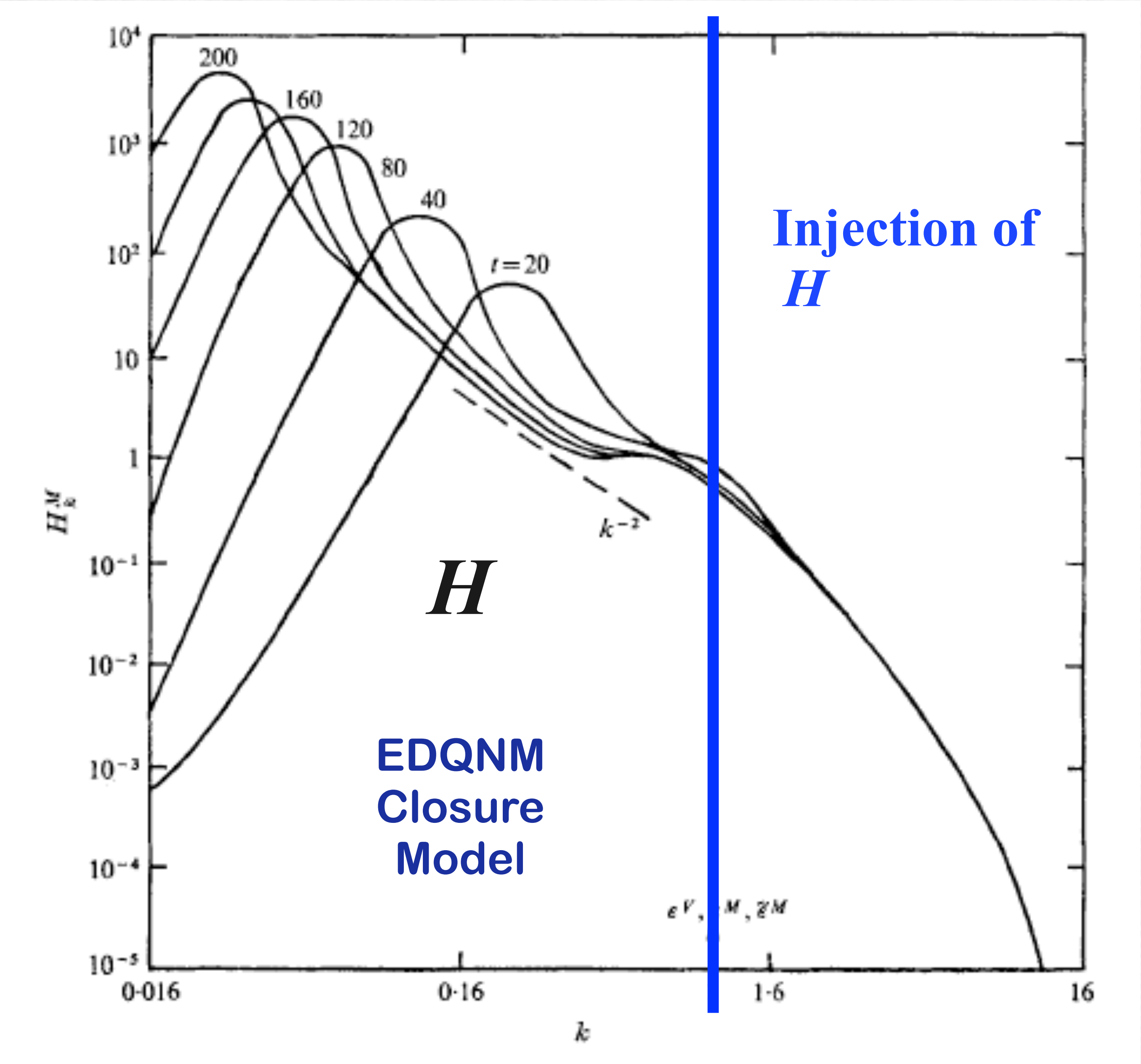
$$\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A}$$

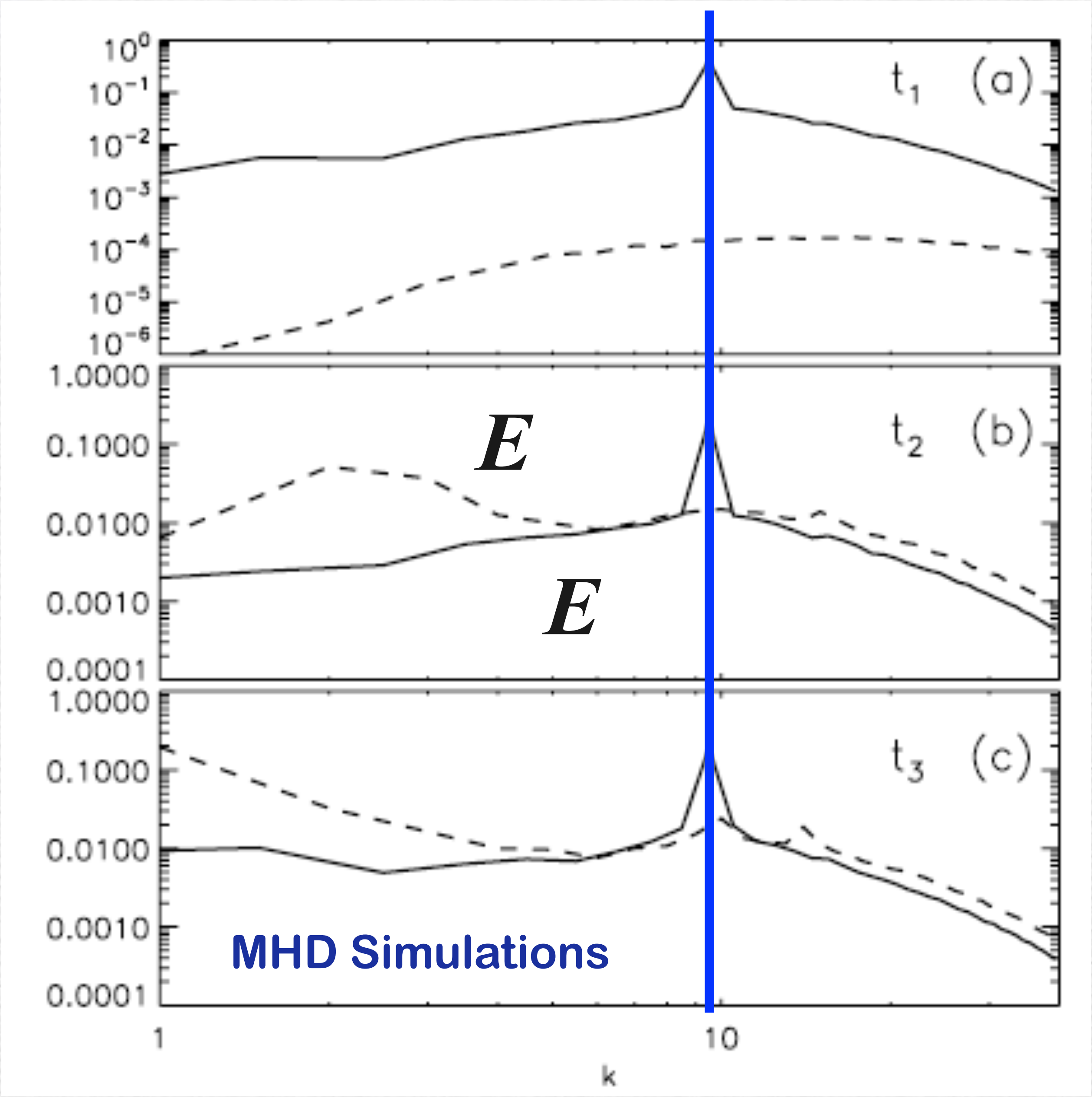
$$\boldsymbol{J} = \frac{c}{4\pi} \boldsymbol{\nabla} \times \boldsymbol{B}$$

Specific manifestations of a more general (and more profound) phenomenon

Inverse Cascade of Magnetic Helicity

Injection of





Pouquet, Frisch & Leorat (1976)

Alexakis, Mininni & Pouquet (2006)

Magnetic Helicity is conserved in the limit $\eta \longrightarrow 0$

Provides an essential link between large and small scales

If you twist the field on small scales, large scales will respond

Large Scale Dynamos: The Mean Induction Equation

Ω-effect — Meridional circulation — Diffusion (plasma)

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \lambda \overline{\mathbf{B}}_p \cdot \nabla \Omega \ \hat{\phi} + \nabla \times \left(\overline{\mathbf{v}}_m \times \overline{\mathbf{B}} \right) + \eta \nabla^2 \overline{\mathbf{B}} + \nabla \times \mathcal{E}$$

Kinematic, mean-field models

- **Specify Ω, V_m, $\mathcal{E}$ as a function of r, θ, t, $\langle B \rangle$**

Non-kinematic mean-field models:

- **Solve mean momentum, continuity, and energy equations to obtain Ω, V_m, as a function of r, θ, t, $\langle B \rangle$**
- **Still have to specify $\mathcal{E}$ as a function of r, θ, t, $\langle B \rangle$**
- **Also have to specify convective momentum, heat transport as a function of mean fields (hydro analogues of $\mathcal{E}$)**

3D MHD simulations:

- **Solve 3D momentum, continuity, energy, and induction equations to obtain Ω, V_m, $\mathcal{E}$ as a function of r, θ, t, $\langle B \rangle$**

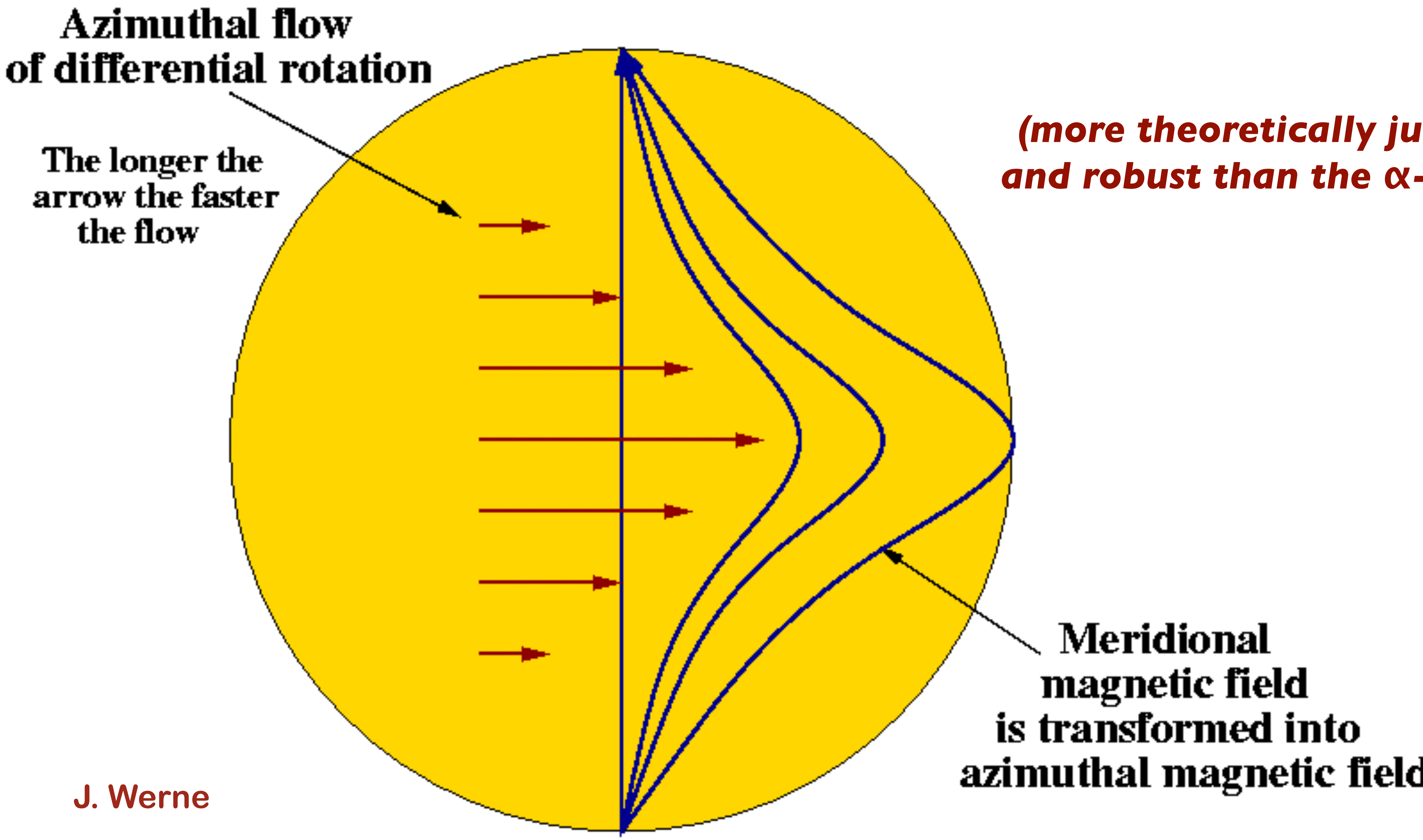
Plasma diffusion is typically neglected ($\eta = 0$)

The Ω-effect

Converts poloidal to toroidal field and amplifies it

...by tapping the kinetic energy of the differential rotation

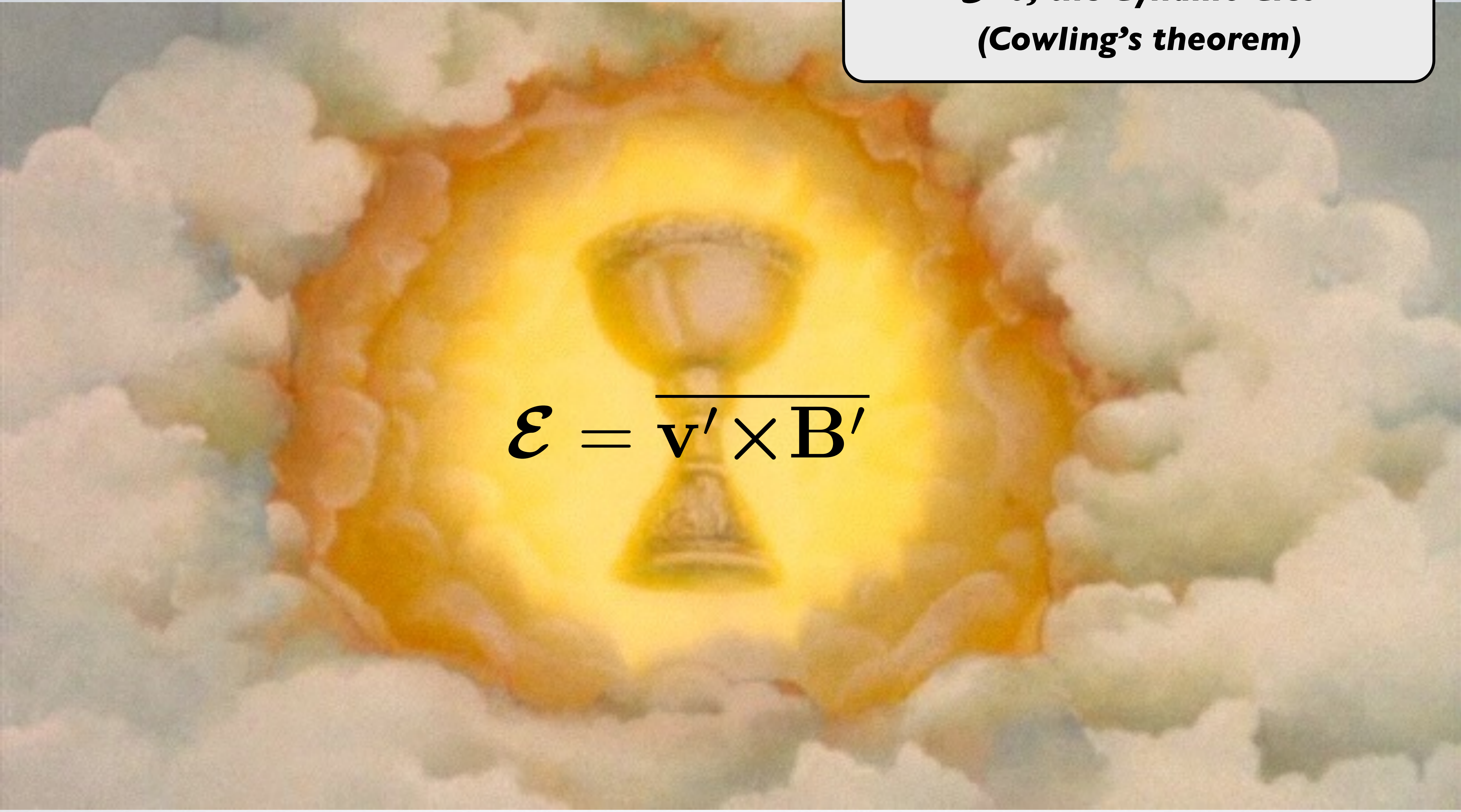
(more theoretically justified and robust than the α-effect)



J. Werne

The Fluctuating emf

Straightforward to show that if $\mathcal{E}$=0, the dynamo dies (Cowling's theorem)



$$\mathcal{E} = \overline{\mathbf{v}' \times \mathbf{B}'}$$

How can a non-axisymmetric flow across magnetic field lines produce an axisymmetric field?

$$\mathbf{v}' = \mathbf{v} - \overline{\mathbf{v}}$$

$$\mathbf{B}' = \mathbf{B} - \overline{\mathbf{B}}$$

Commonly used components of $\mathcal{E}$

(in Mean-Field Dynamo Models)

$$\mathcal{E} = \overline{\mathbf{v}' \times \mathbf{B}'}$$

Turbulent α-effect $\mathcal{E} = \alpha \overline{\mathbf{B}} + \ldots$

Amplificaton

Babcock-Leighton α-effect $\mathcal{E} = \alpha \widetilde{\mathbf{B}} + \ldots$ ***(non-local)***

where $\widetilde{\mathrm{B}} = \int_{r_1}^{r_2} \int_{\theta_1}^{\theta_2} \overline{\mathrm{B}} \, \sin\theta \; r dr d\theta$ ***is the mean toroidal flux near the bottom of the CZ***

and $\alpha(r, \theta)$ ***is confined to the top of the CZ***

mathematically very similar to turbulent α-effect but physical justification is very different: see next slide

Turbulent Diffusion $\mathcal{E} = \eta_t \nabla \times \overline{\mathbf{B}} + \ldots$

Magnetic Pumping $\mathcal{E} = \gamma \times \overline{\mathbf{B}} + \ldots$

Transport

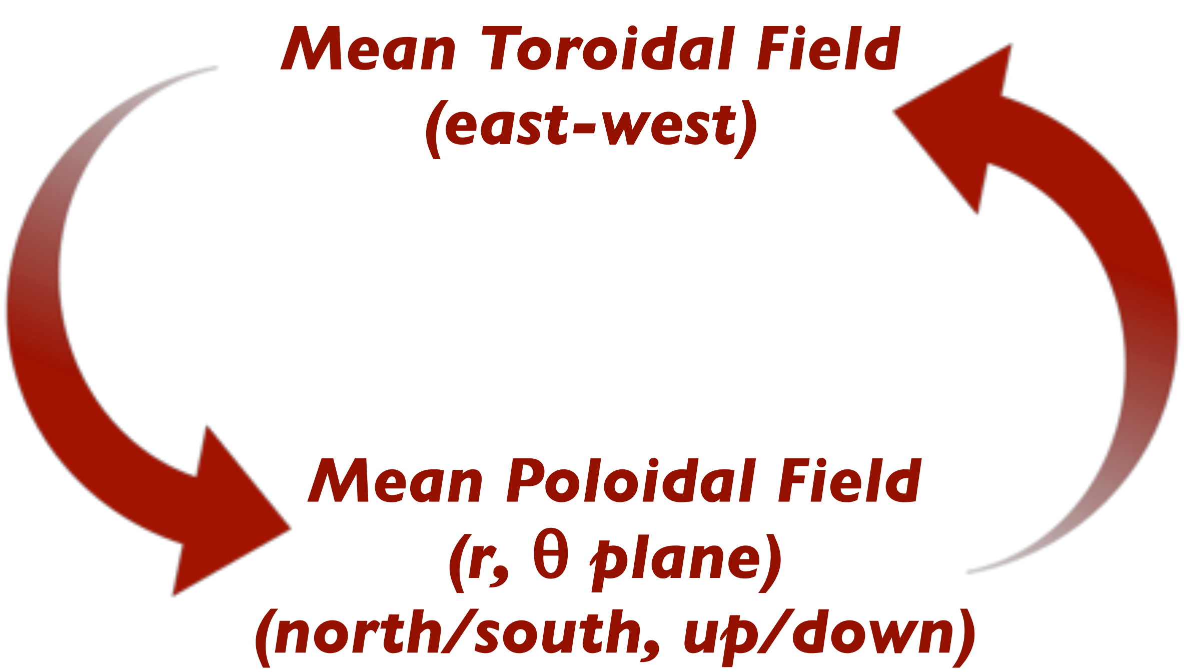
The turbulent α-effect

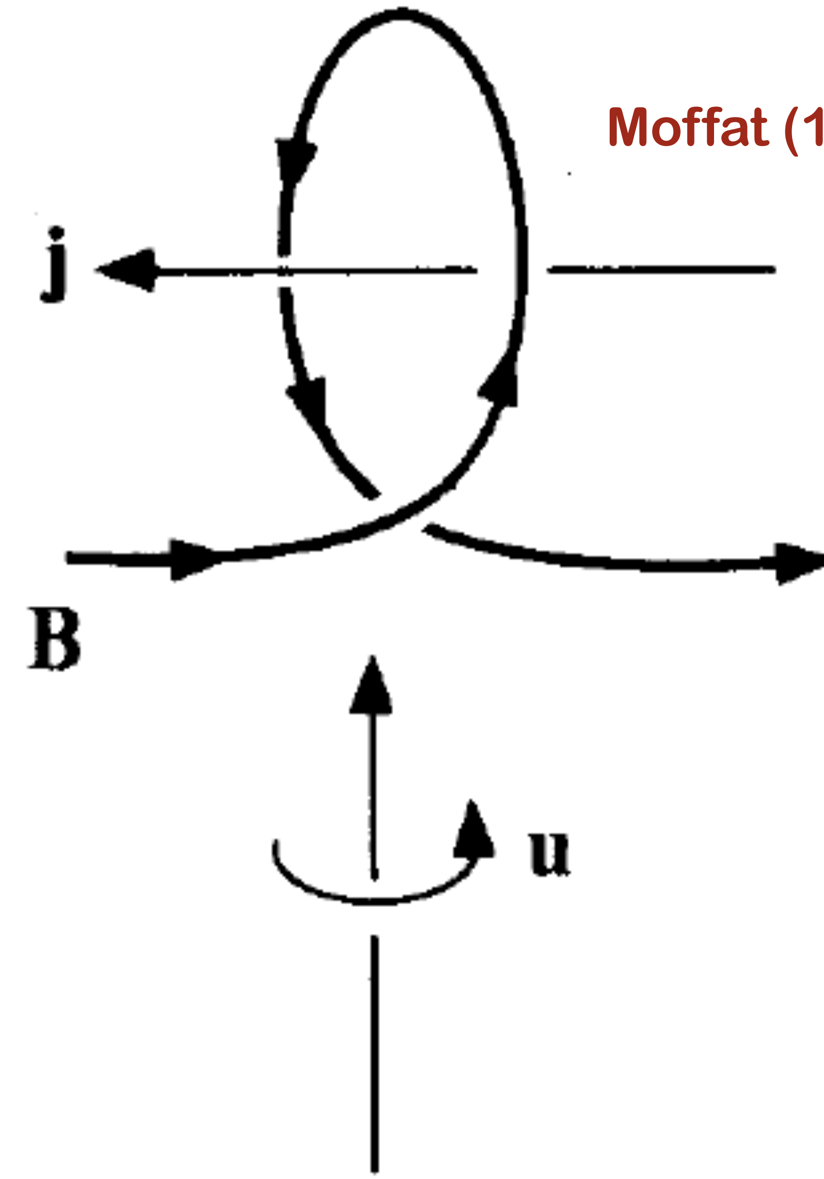
Helical motions (lift, twist) can induce an emf that is parallel to the mean field

$$\mathcal{E} = \overline{\mathbf{v}' \times \mathbf{B}'} = \alpha \overline{\mathbf{B}}$$

This creates mean [poloidal](#) (r, θ) field from [toroidal](#) (ϕ) field

which closes the [Dynamo Loop](#)





Moffat (1978)

Linked to kinetic, magnetic helicity

Linked to large-scale dynamo action

Illustrates the 3D nature of dynamos

Flux Emergence and the Babcock-Leighton Mechanism

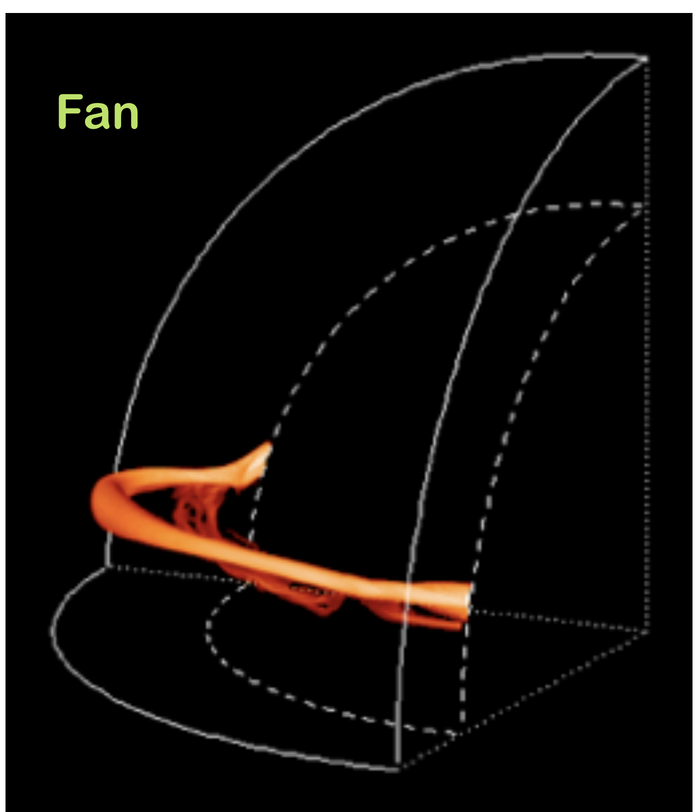
Toroidal flux tubes form in the lower CZ through differential rotation (Ω-effect)

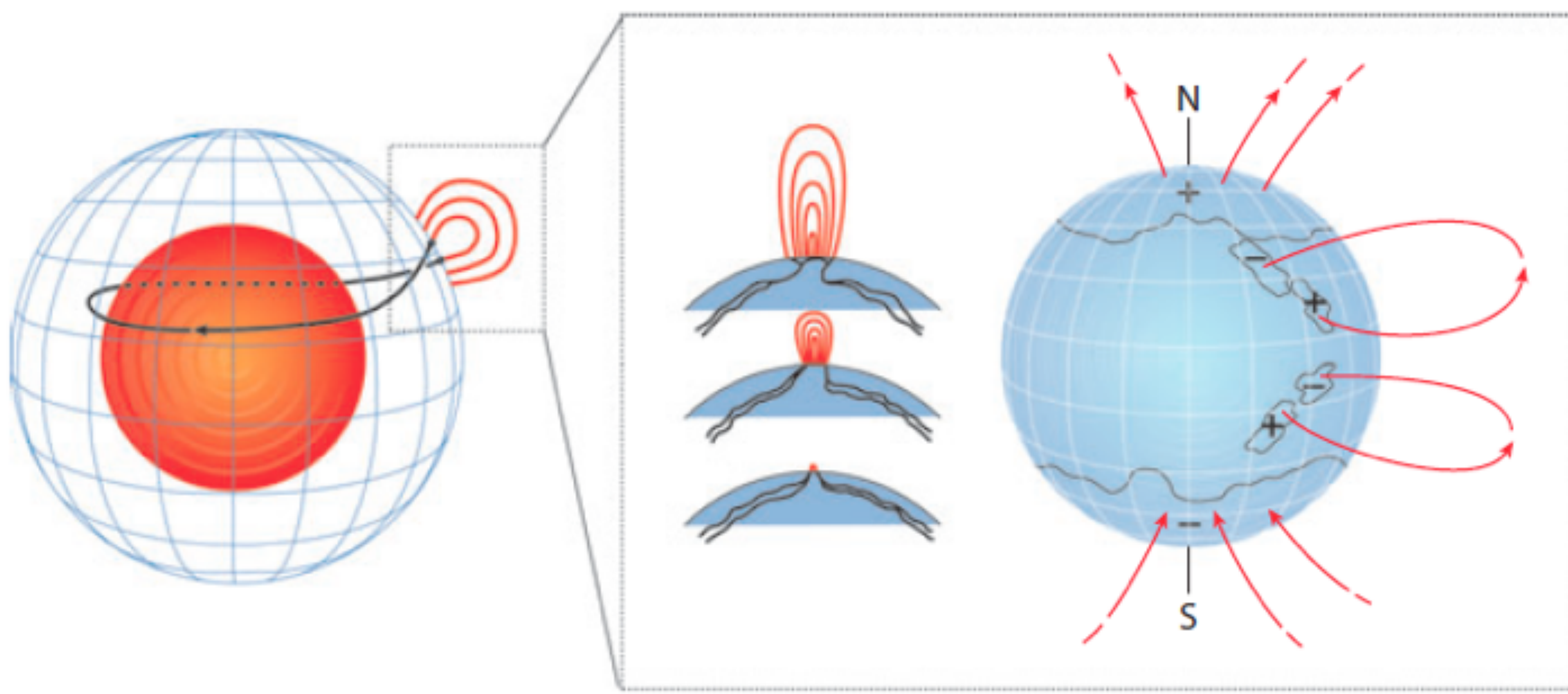
They destabilize and rise through the CZ by means of magnetic buoyancy

Trailing member of the spot pair is displaced poleward relative to leading edge (Joy's law: thought to be a consequence of the Coriolis force)

Polarity of leading and trailing spots is opposite in each hemisphere and reverses each sunspot cycle (Hale's law)

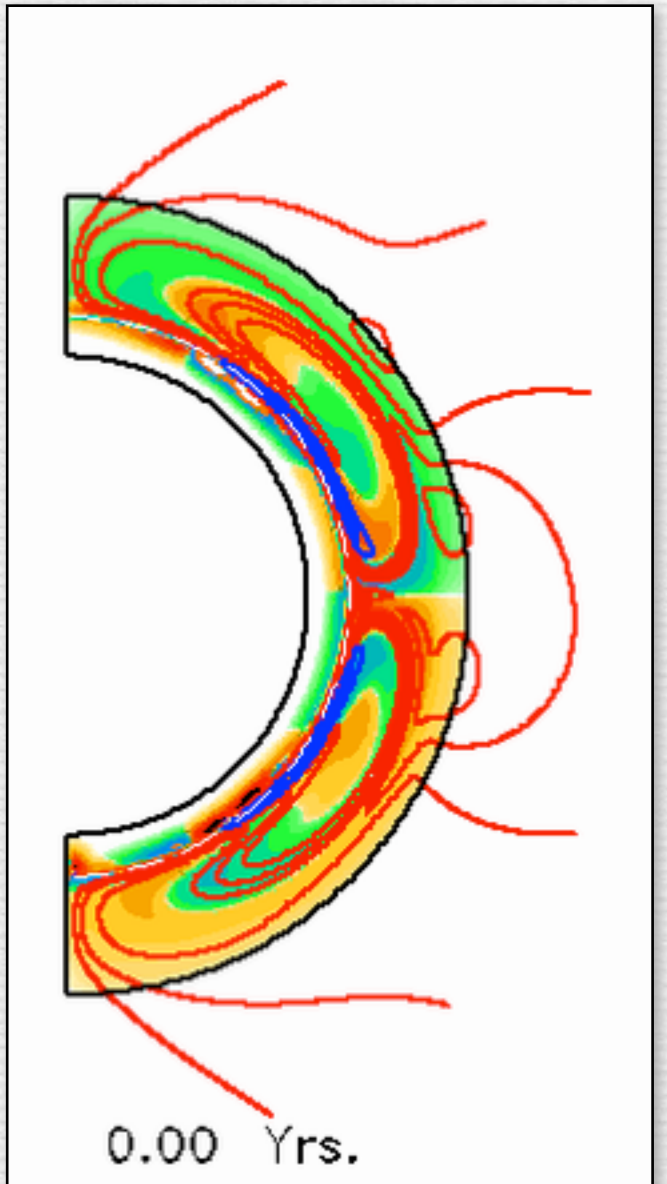
Dispersal by convection and meridional flow acts to reverse the pre-existing poloidal field





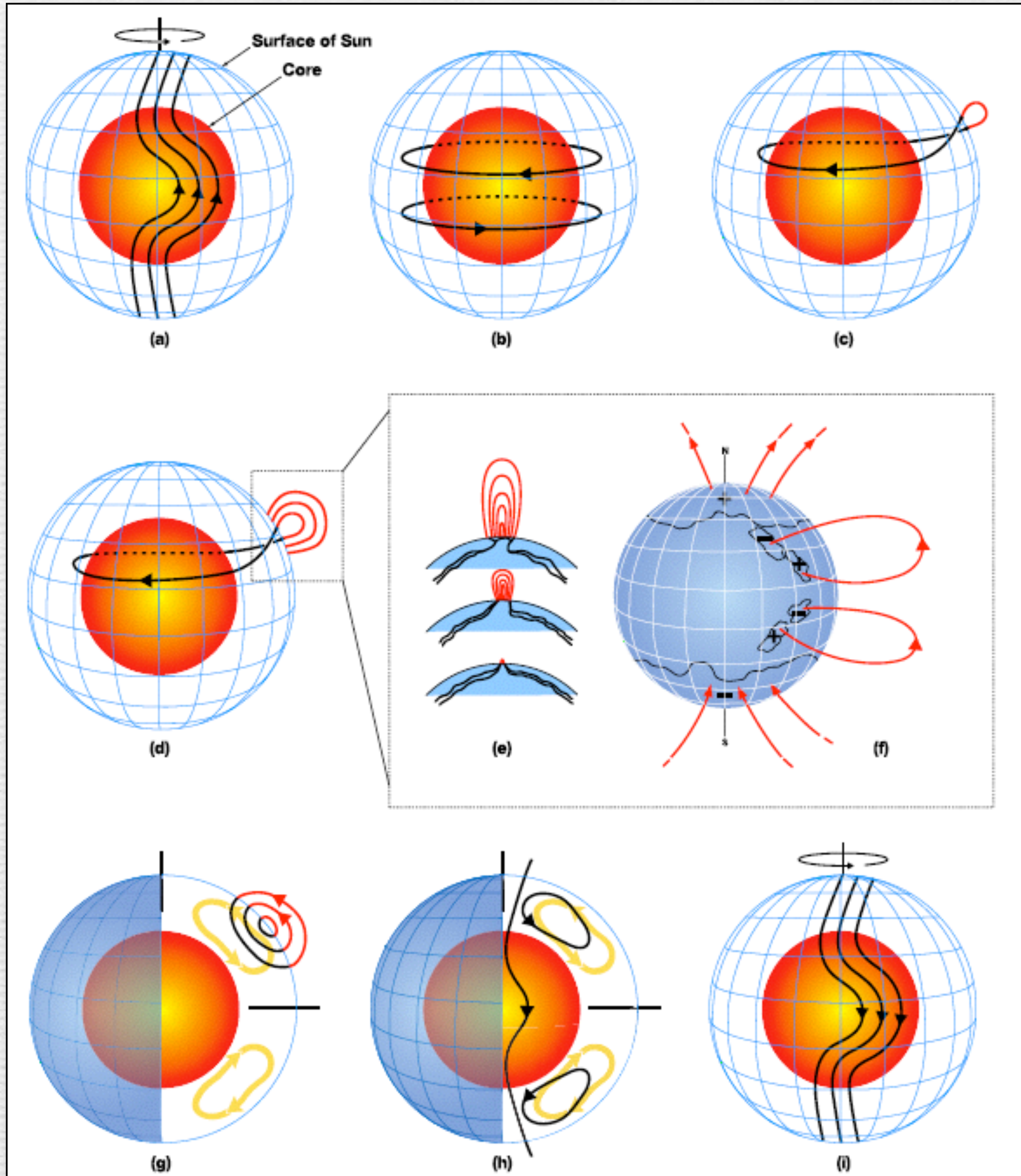
Dikpati & Gilman

Babcock-Leighton Dynamo Models

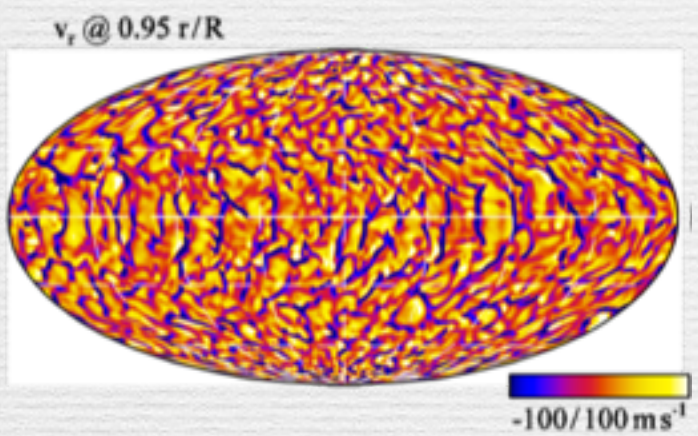


Dikpati & Gilman 2006

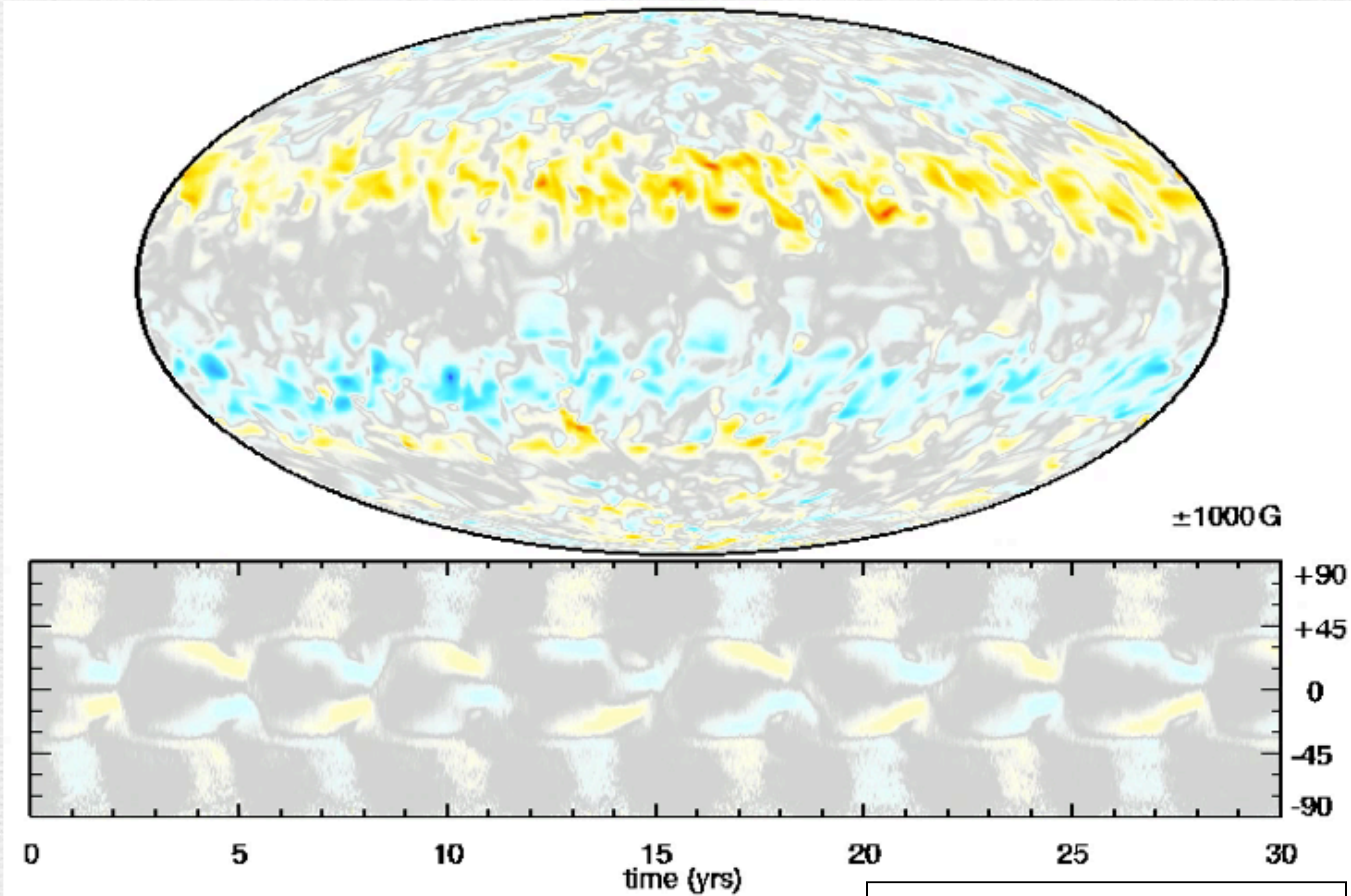
a.k.a. Flux-Transport Dynamo Models



Magnetic Cycles in Convective Dynamos

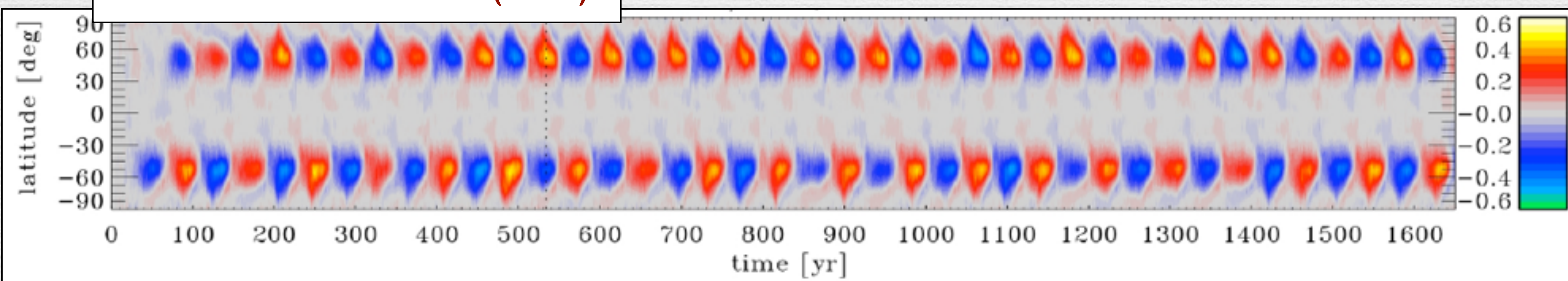


Dramatic progress in the last 5 years



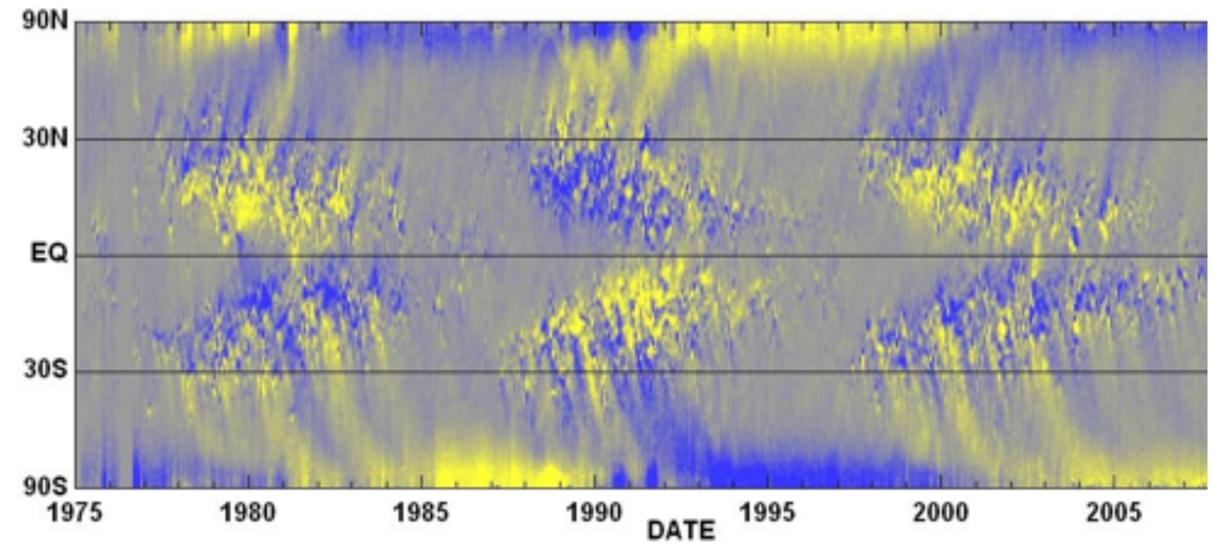
Augustson et al. (2014)

Passos & Charbonneau (2014)



Why 11 years?

Cycle linked to propagation of toroidal flux (Butterfly diagram)



Three ways to get propagation

❧ Meridional circulation

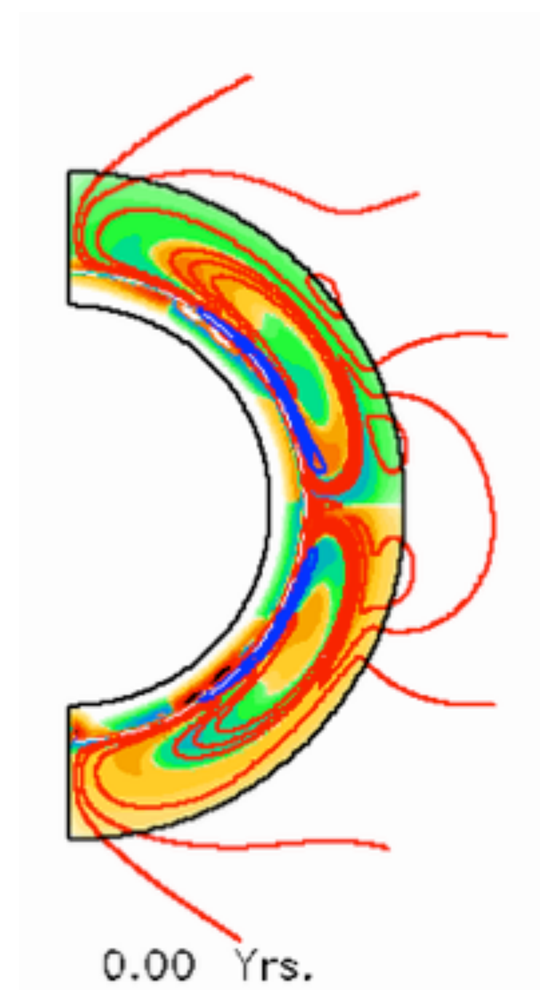
- Flux-Transport Dynamo models
- 2-3 m/s at CZ base

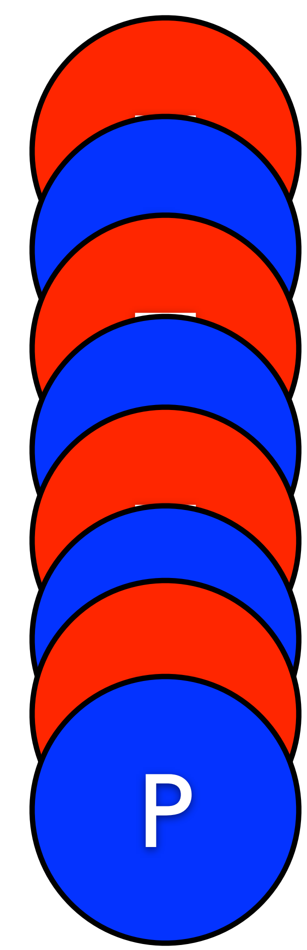
❧ Turbulent transport

- magnetic pumping
- Mean-Field and convective dynamos

❧ Dynamo wave

- Early α-
- some modern convective dynamos

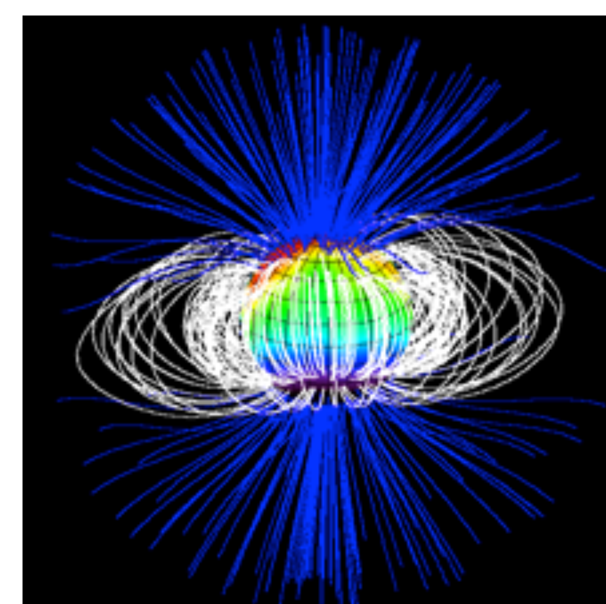




Puzzles

- **Amplitude and Structure of Deep Solar Convection**
  - Models appear to be over-estimating amplitude
  - small-scale magnetism may explain why
- **Mean Flows**
  - How are the thermal gradients needed for conical Ω surfaces established?
  - What is the subsurface structure of the MC?
- **The Solar Dynamo**
  - How and where is mean poloidal field being generated?
  - How do convective dynamos produce sunspots/active regions and what role do they play in the dynamo?
  - How do small-scale and large-scale dynamo action couple?
  - What sets the 11-year period?

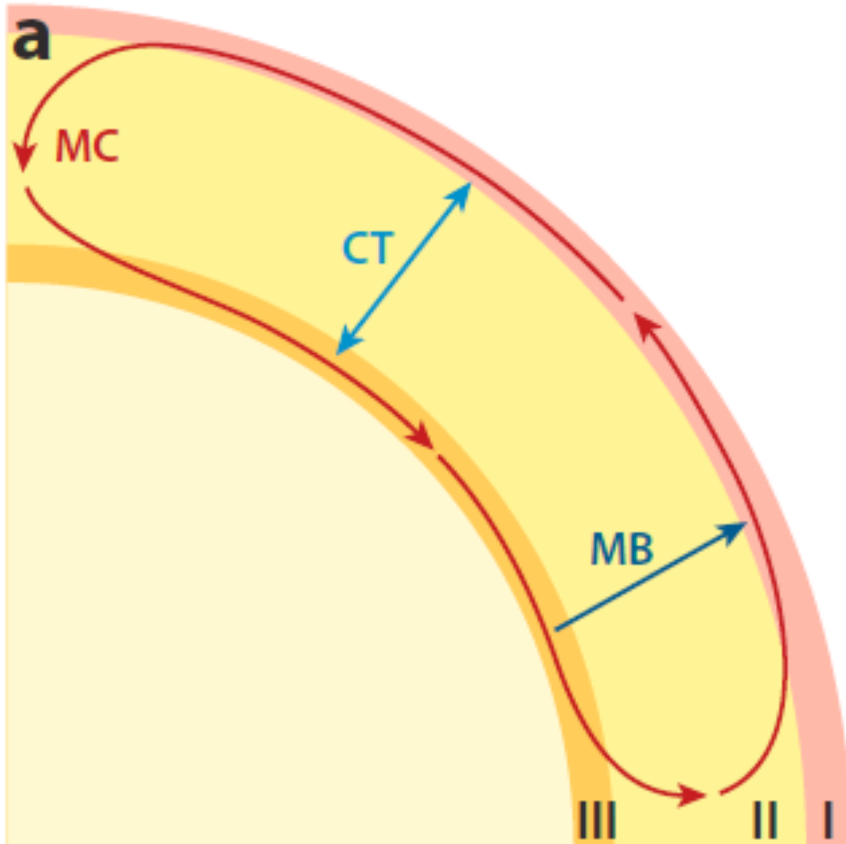
Answers may be found by looking to the stars!

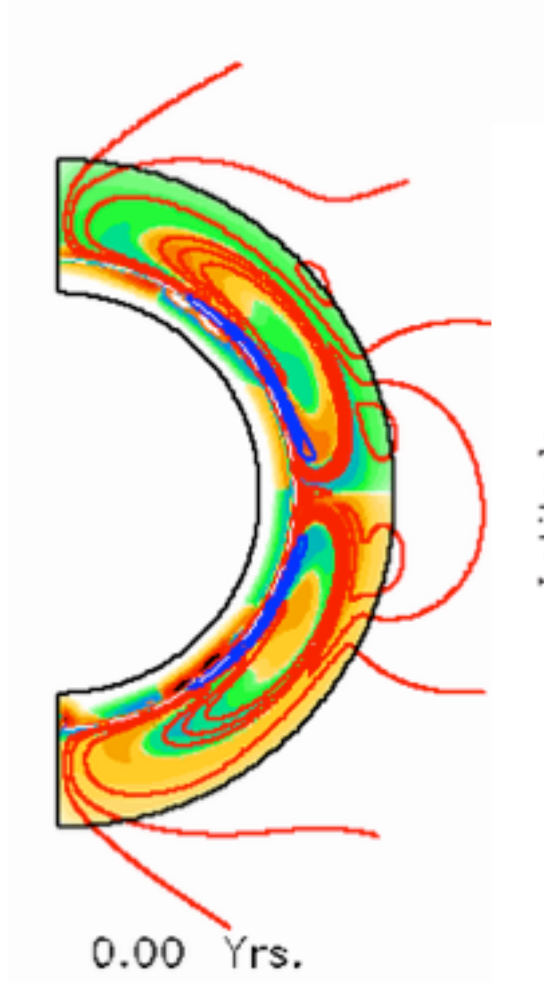


Donati et al (2006)

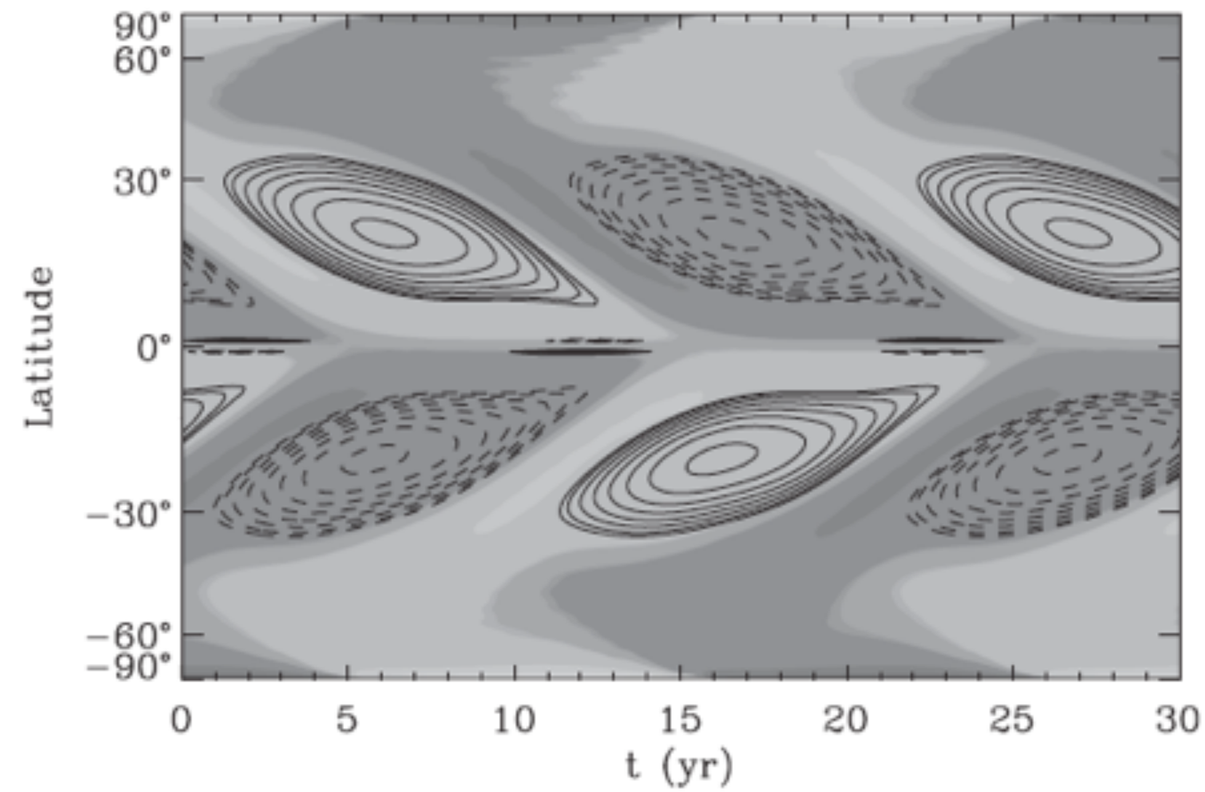
Supplemental Slides

Solar Dynamo Models





Dikpati & Gilman



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	Toroidal field generation	Poloidal field generation	Principal coupling mechanisms	Cycle period determined by
BLFT models	Region III	Region I	MC, MB	Meridional flow
Interface models	Region III	Region II	CT	Dynamo waves[a]

a. Dispersion relation involving α, $\Delta\,\Omega$, and η_t.

Large Scale Dynamos: The Mean Induction Equation

Go back to our basic induction equation

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

Note:
The B field in the Sun is clearly not axisymmetric. Still, the solar cycle does have an axisymmetric component so that's a good place to start

Now just average over longitude and rearrange a bit
(other averages are possible but we'll stick to this for simplicity)

$$\lambda = r \sin\theta$$

The equation for the mean field comes out to be

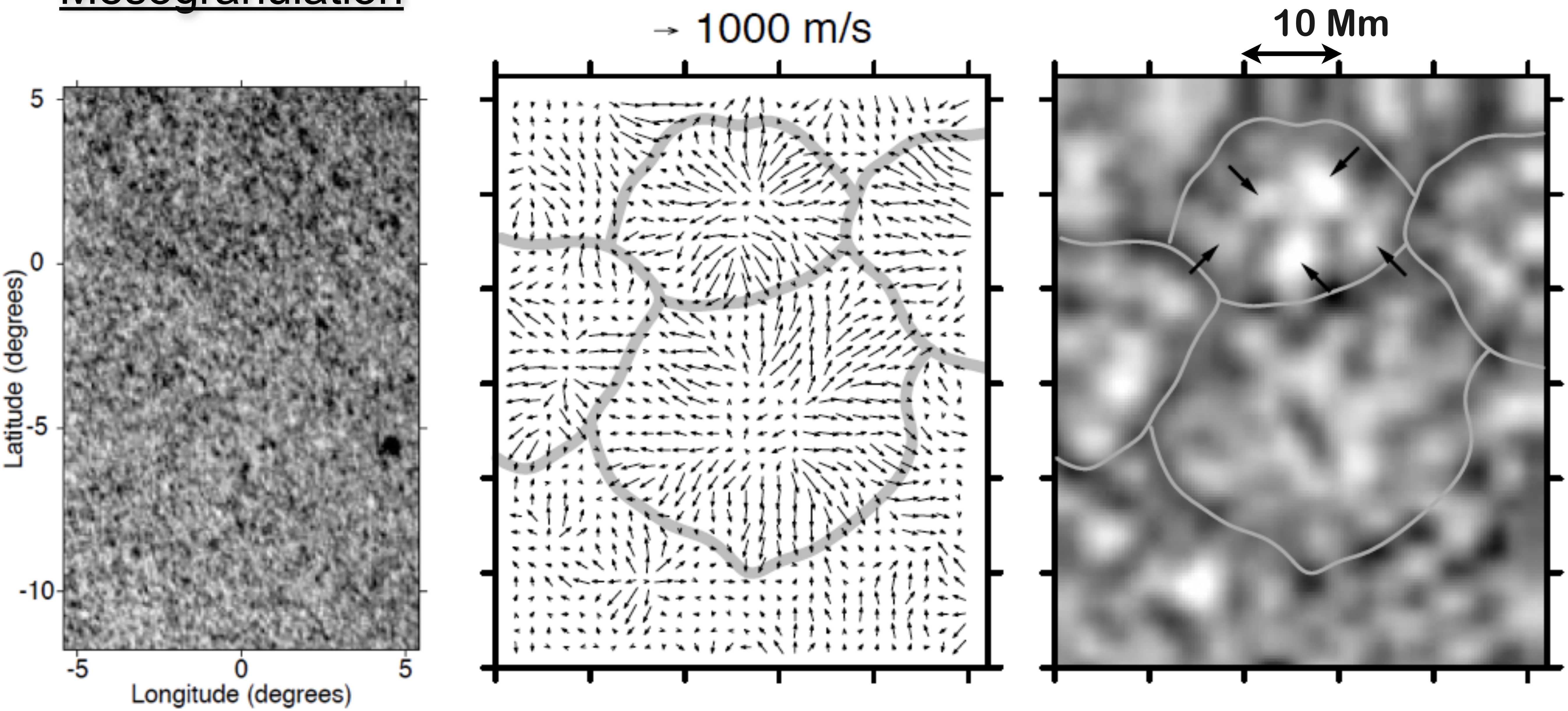
$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \lambda \overline{\mathbf{B}}_p \cdot \boldsymbol{\nabla} \Omega \ \hat{\phi} + \boldsymbol{\nabla} \times \left(\overline{\mathbf{v}}_m \times \overline{\mathbf{B}} \right) + \eta \nabla^2 \overline{\mathbf{B}} + \boldsymbol{\nabla} \times \boldsymbol{\mathcal{E}}$$

Ω-effect | **Meridional circulation** | **Diffusion (molecular)** | **Fluctuating emf**

No assumptions made up to this point beyond the basic MHD induction equation

Straightforward to show that if $\mathcal{E}$=0, the dynamo dies (Cowling's theorem)

Mesogranulation



Shine, Simon & Hurlburt (2000)

Most readily seen in horizontal velocity divergence maps obtained from local correlation tracking (LCT)

Vertical velocity and temperature signatures of mesogranulation and supergranulation are still elusive
hard to verify that they are convection per se

$L \sim 5$ Mm
$t \sim 3\text{-}4$ hr