Stellar Dynamos in 90 minutes or less!

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(with contributions and inspiration from Mark Miesch)

Why are we here?

- Stellar dynamos: Outstanding questions
- A closer look at Solar Magnetism
- Dynamo theory in the solar context
- The big question: convective flow speeds
- Today: emphasize induction
- Tomorrow: more on convection

Question

What even is a dynamo?

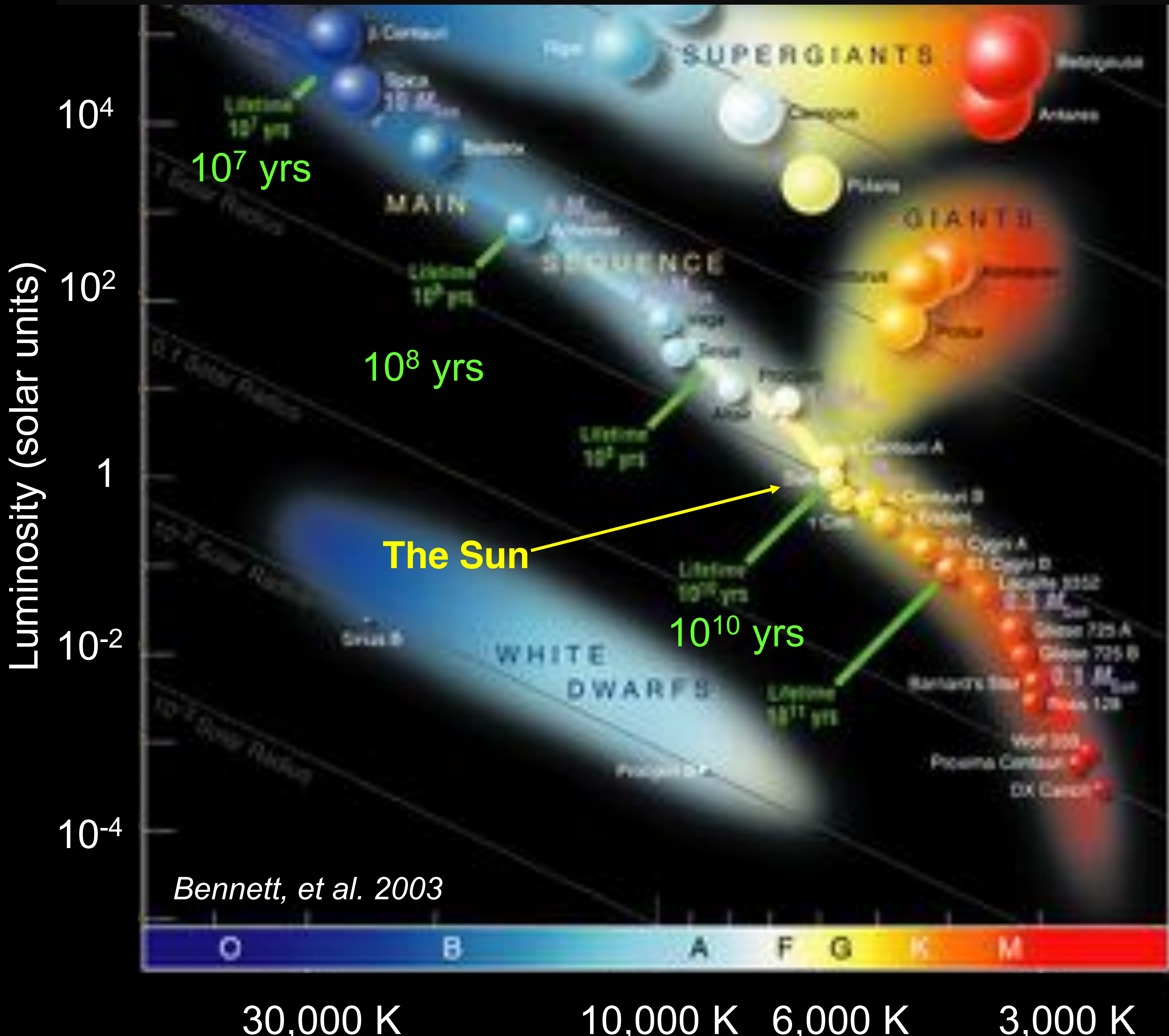
Dynamo

The process by which a magnetic field is sustained against decay through the motion of a conducting fluid.

Stellar Dynamo

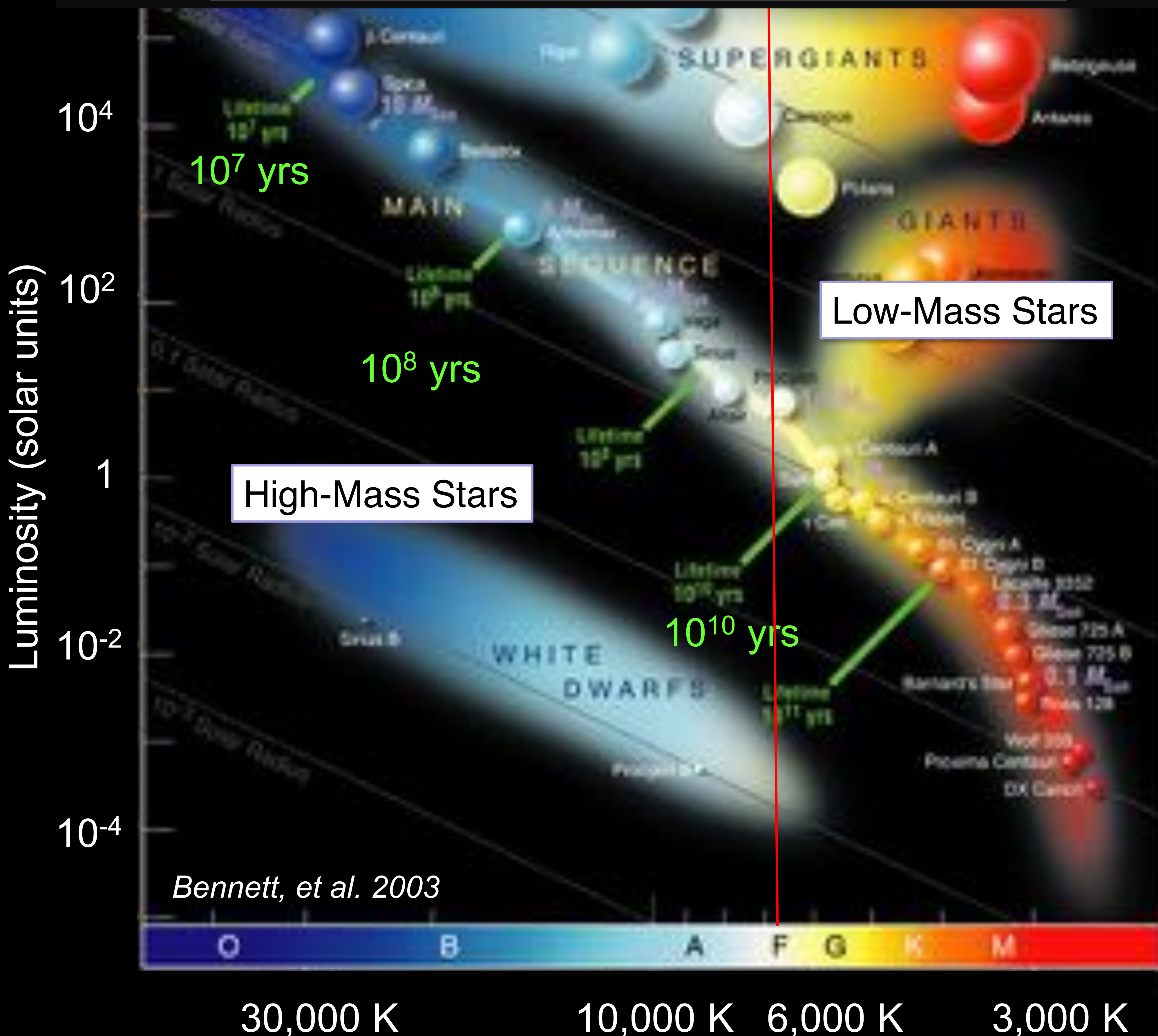
The process by which a star maintains its magnetic field via the convective motion of its interior plasma.

The Stars



SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
10^4
10^2
1
10^-2
10^-4
Luminosity (solar units)
10^7 yrs
10^8 yrs
10^10 yrs
The Sun
Bennett, et al. 2003
O
B
A
F
G
K
M
30,000 K
10,000 K
6,000 K
3,000 K

One Broad Distinction



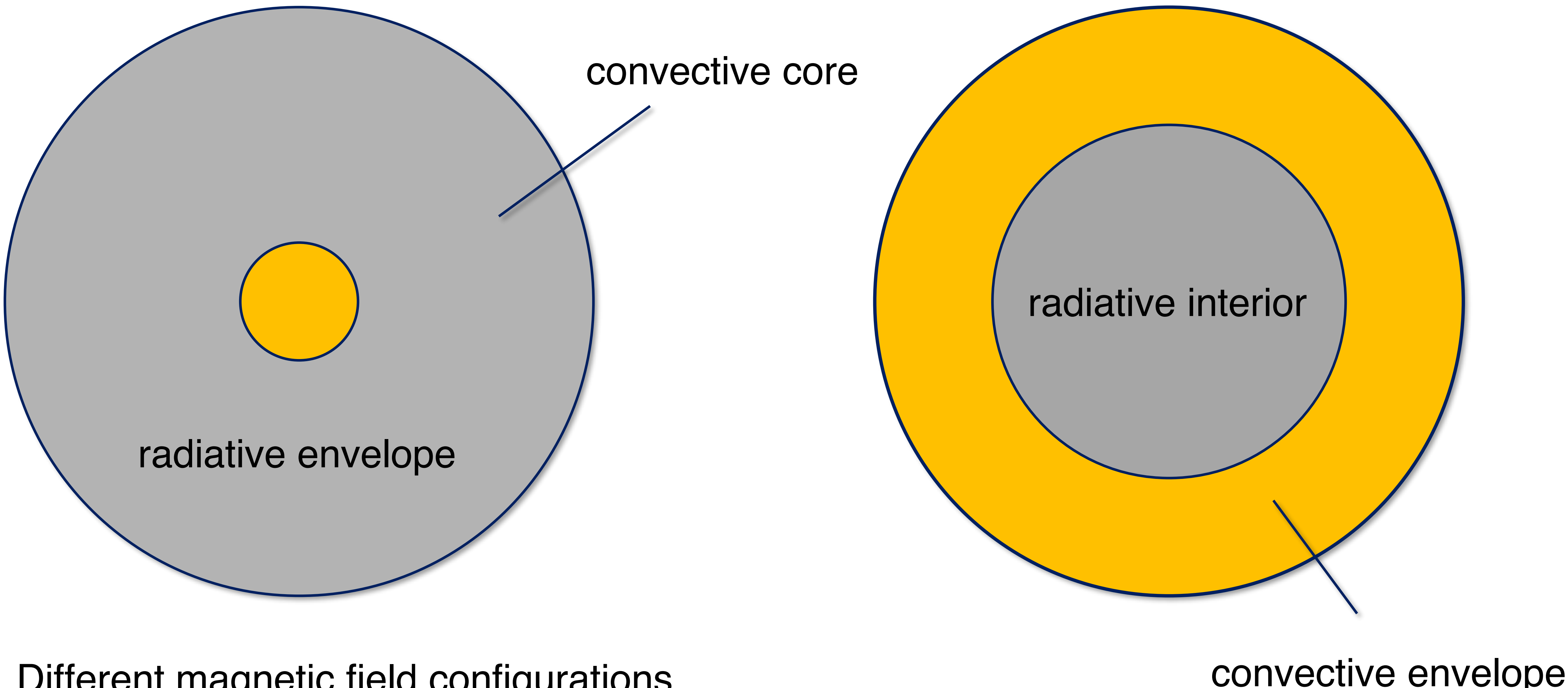
Question

As far as dynamo theory is concerned, what do you think is the main difference between massive and low-mass stars?

Massive vs. Low-Mass Stars

The key difference is…
…~~mass~~, …~~luminosity~~, …~~size~~ … geometry!

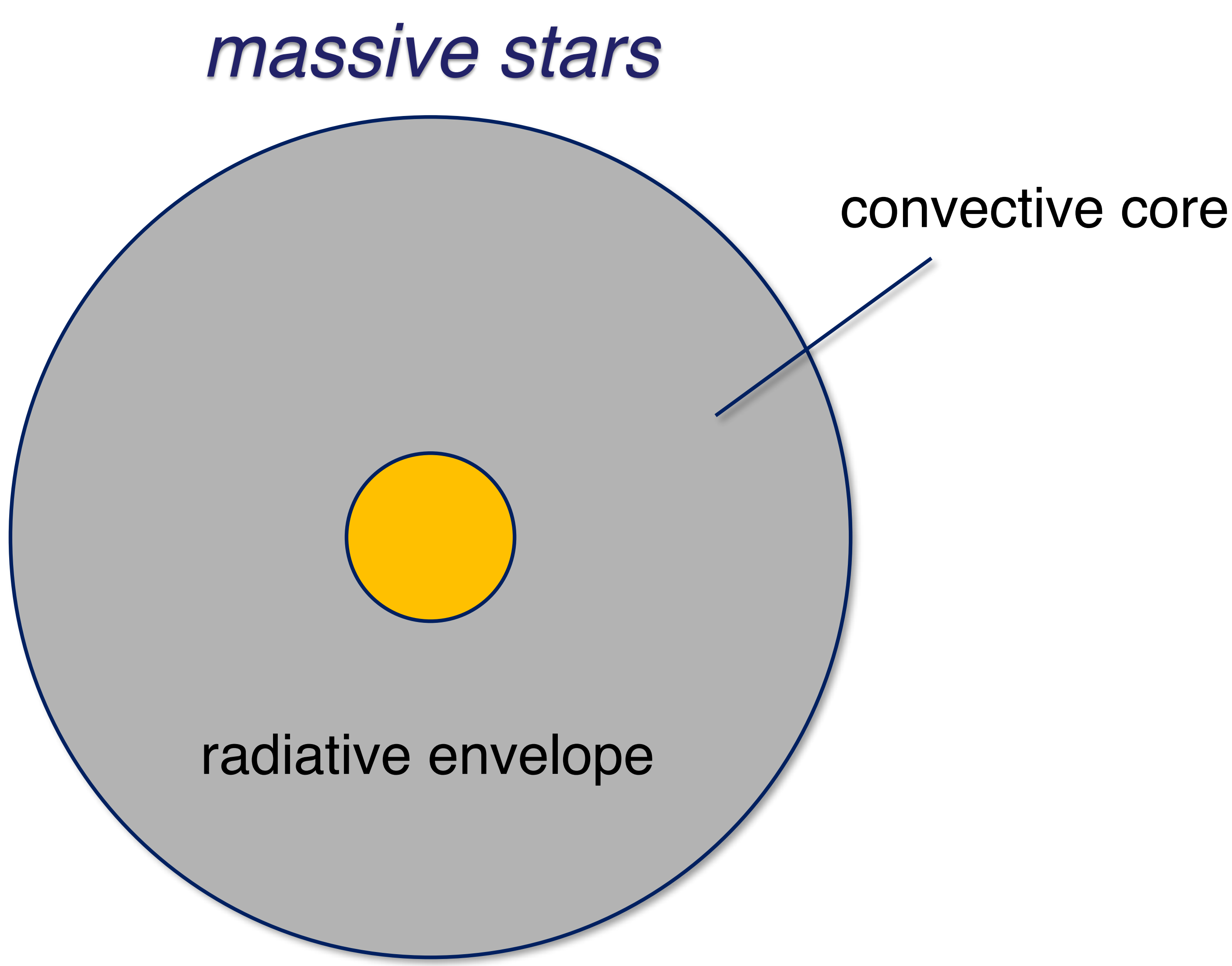
massive stars *low-mass stars*

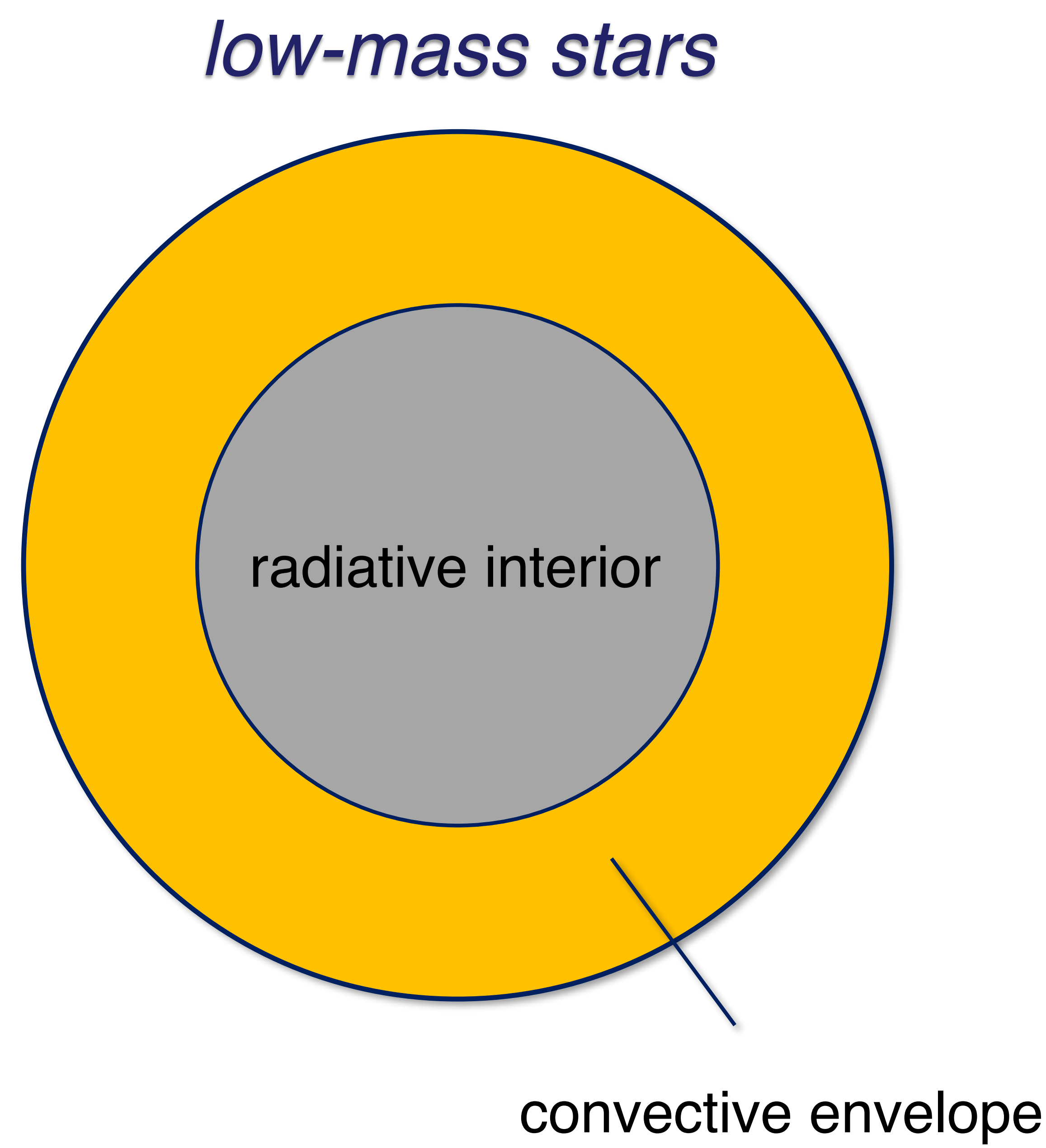


Different magnetic field configurations
arise in different geometries.

Massive vs. Low-Mass Stars

Fundamental questions similar, but some differences.

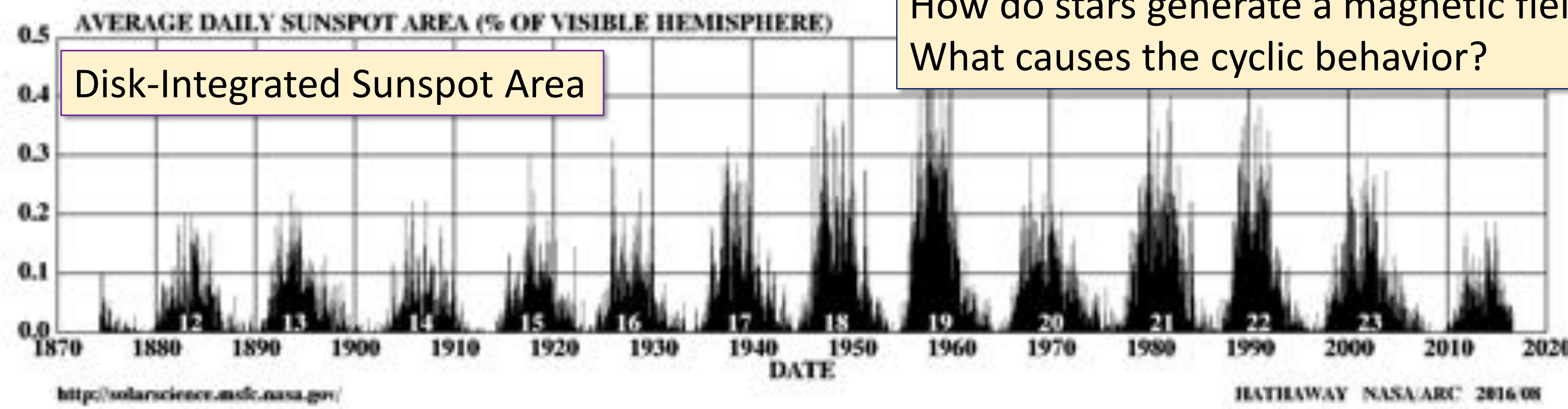


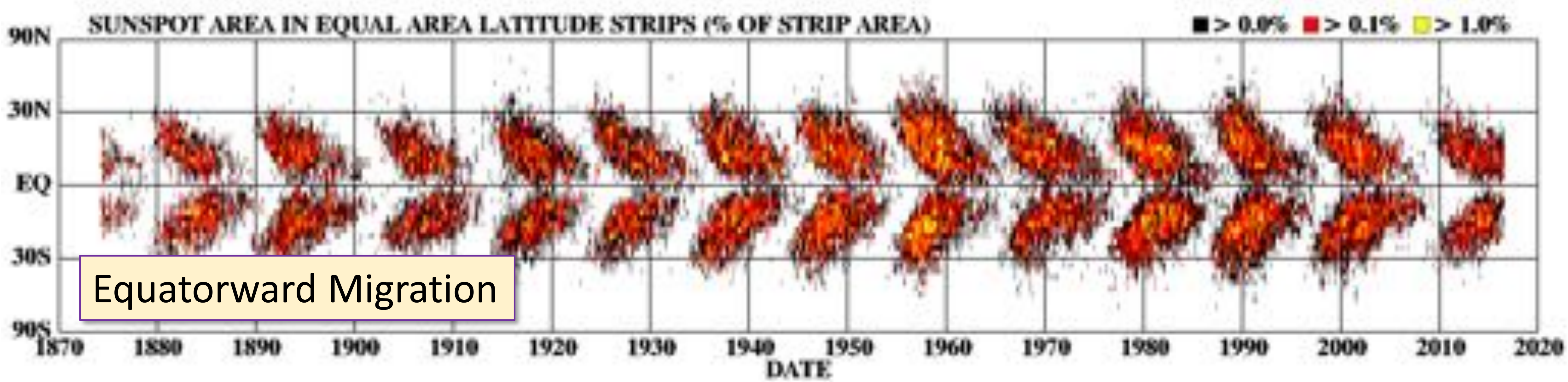


Different magnetic field configurations
arise in different geometries.

Stellar Dynamo Question: The Sun's Magnetic Cycle

How do stars generate a magnetic field?
What causes the cyclic behavior?

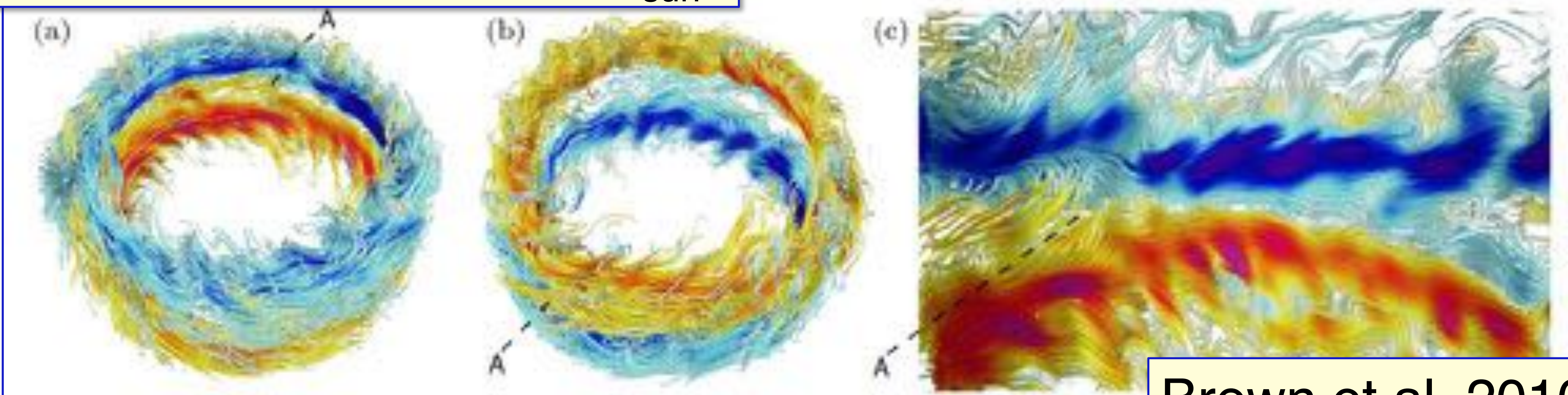




- Magnetic activity increases with integrated sunspot area
- Mean magnetic polarity reverses every 11 years

Big Question:
Magnetism and Stellar Age?

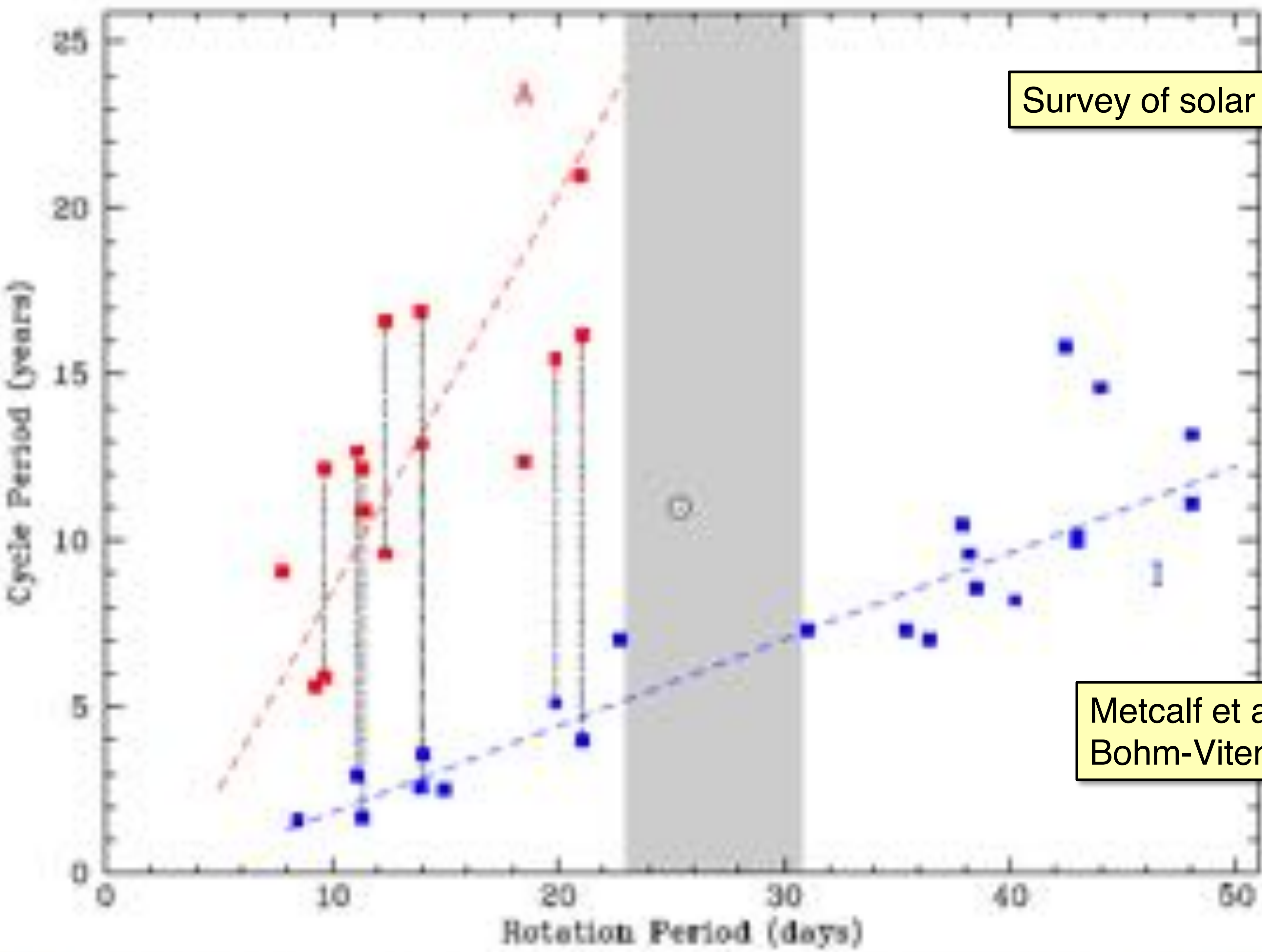
“Young Sun” simulation ($3\Omega_{sun}$)



Brown et al. 2010

- Stars rotate more slowly as they age.
- Rapid rotation favors large-scale magnetic fields.
- Is a tachocline necessary for organized field growth?

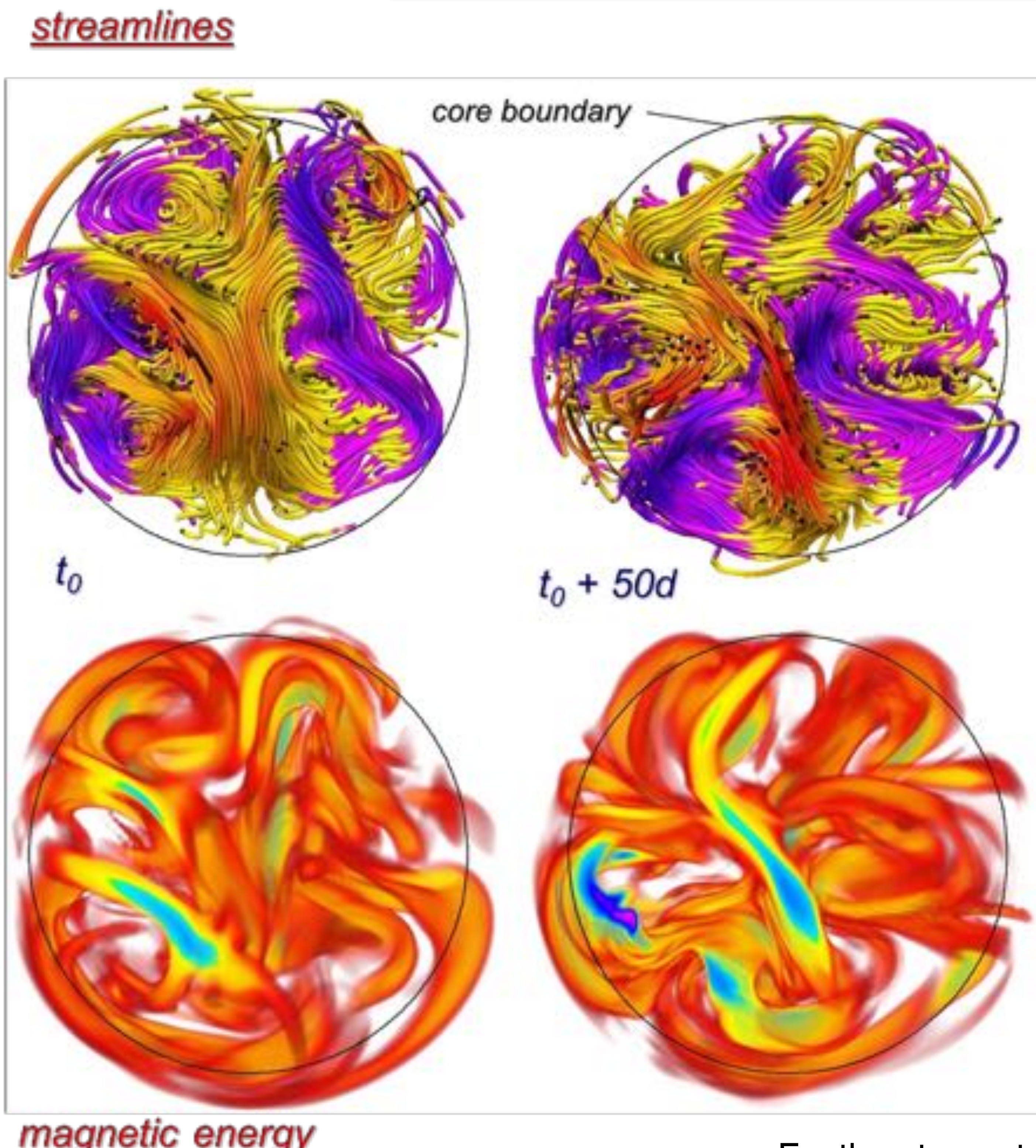
Big Question:
Is the Sun "normal"?



Survey of solar analogues

Metcalf et al. 2016
Bohm-Vitense (2007)

Big Question: Massive Star Dynamos?



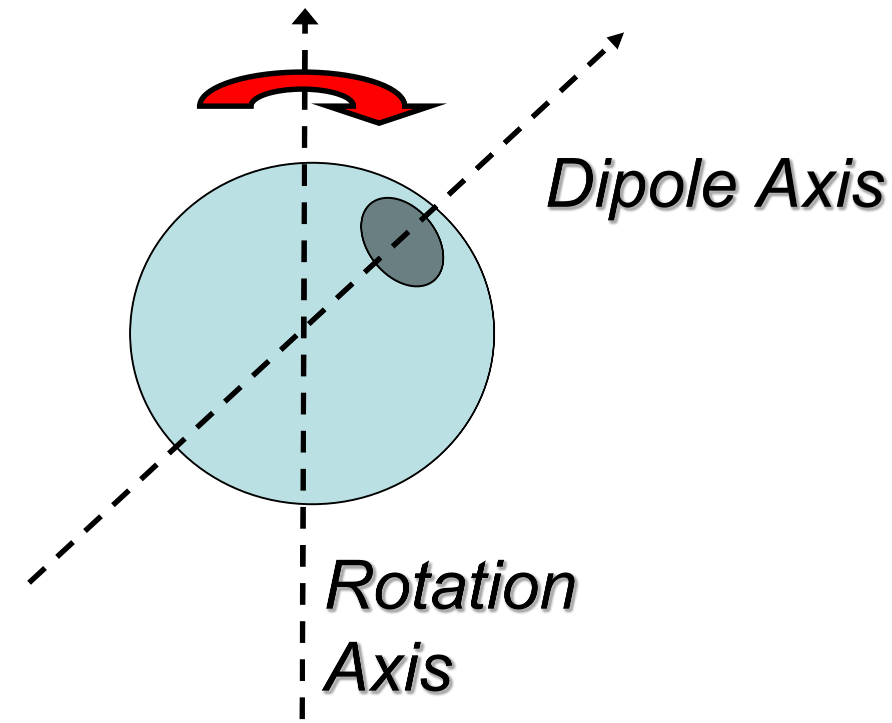
- How is the magnetic field structured?
- Are core-generated fields visible at the surface?
- Can core-generated fields becomes buoyant?

Featherstone et al. 2010 (A stars)
see also Augustson et al. 2016 (B stars)

Peculiar Question: Ap and Bp Stars

- Abnormally strong abundances of Si and various rare earth metals (Hg, etc.)

- Magnetic: typical field strengths of a few hundred Gauss.



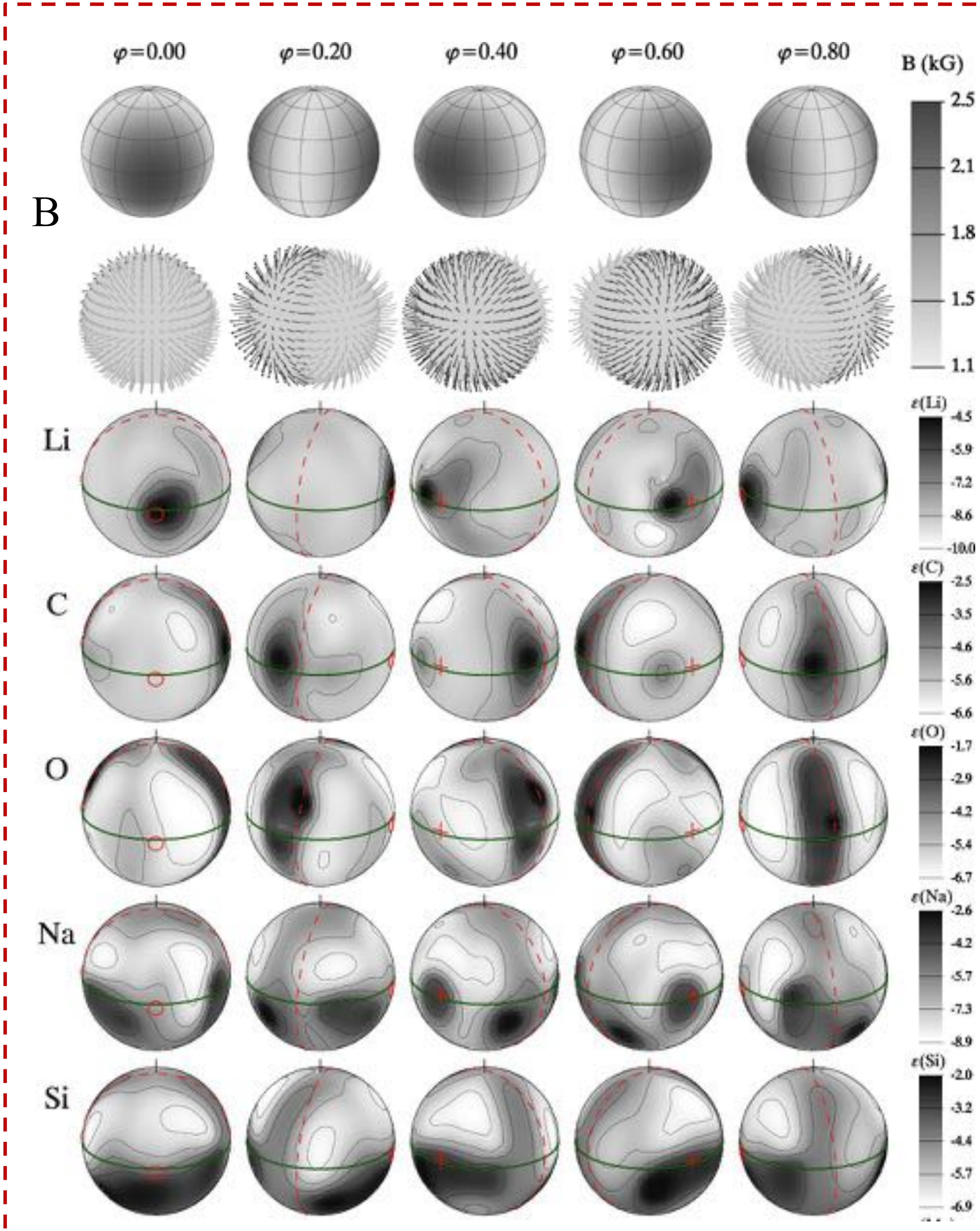
- Field strengths and line widths vary periodically: <u>Oblique Rotator Model</u>

- Rotation periods from days to decades (magnetic braking?)

Source of Magnetic Field?

- Core-dynamo? (but diffusion time through radiative zone very long)

- Primordial magnetic field?



Magnetic Field

Abundance Maps

Magnetic Doppler Imaging

Ap Star HR3831

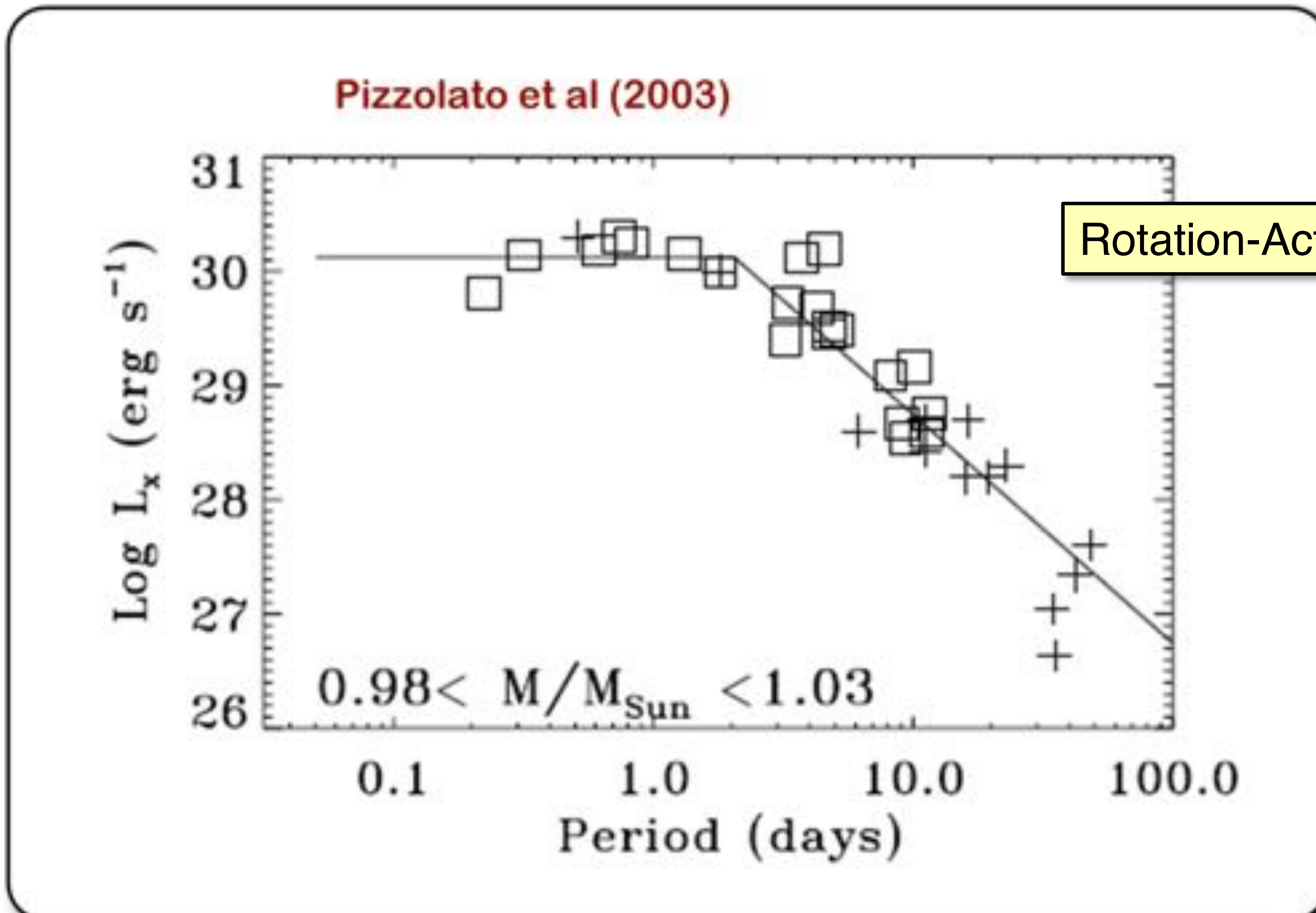
Kochukhov et al. 2004

Big Question: Exoplanets and Host-Star Magnetism

Credit: NASA/JPL-Caltech

- Exoplanets most easily found around low-mass M dwarfs
- Vigorous dynamo action + fierce flaring
- How does magnetism impact habitable zone?

Big Question: Relationship between Magnetism and Stellar Rotation Rate?

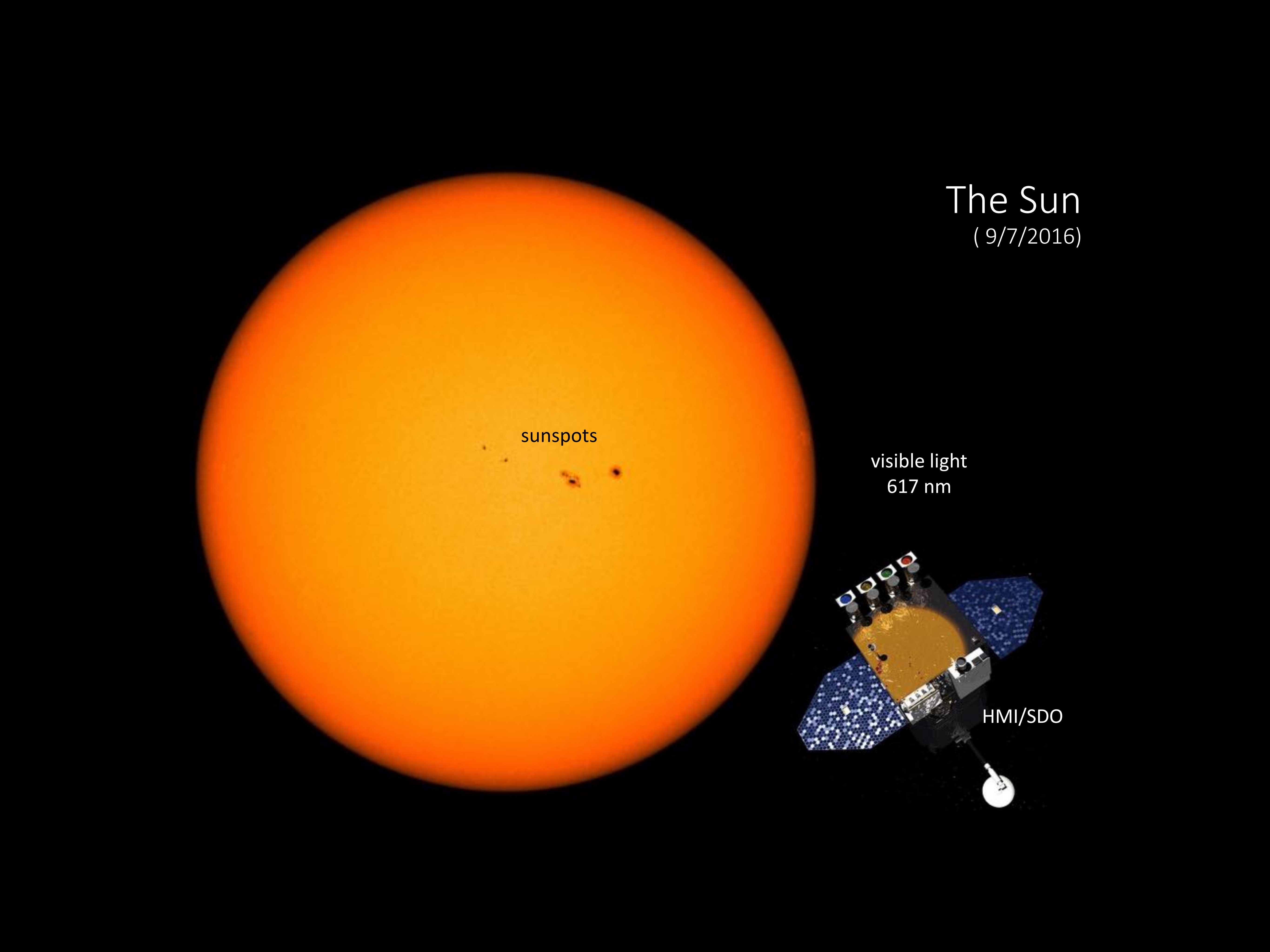


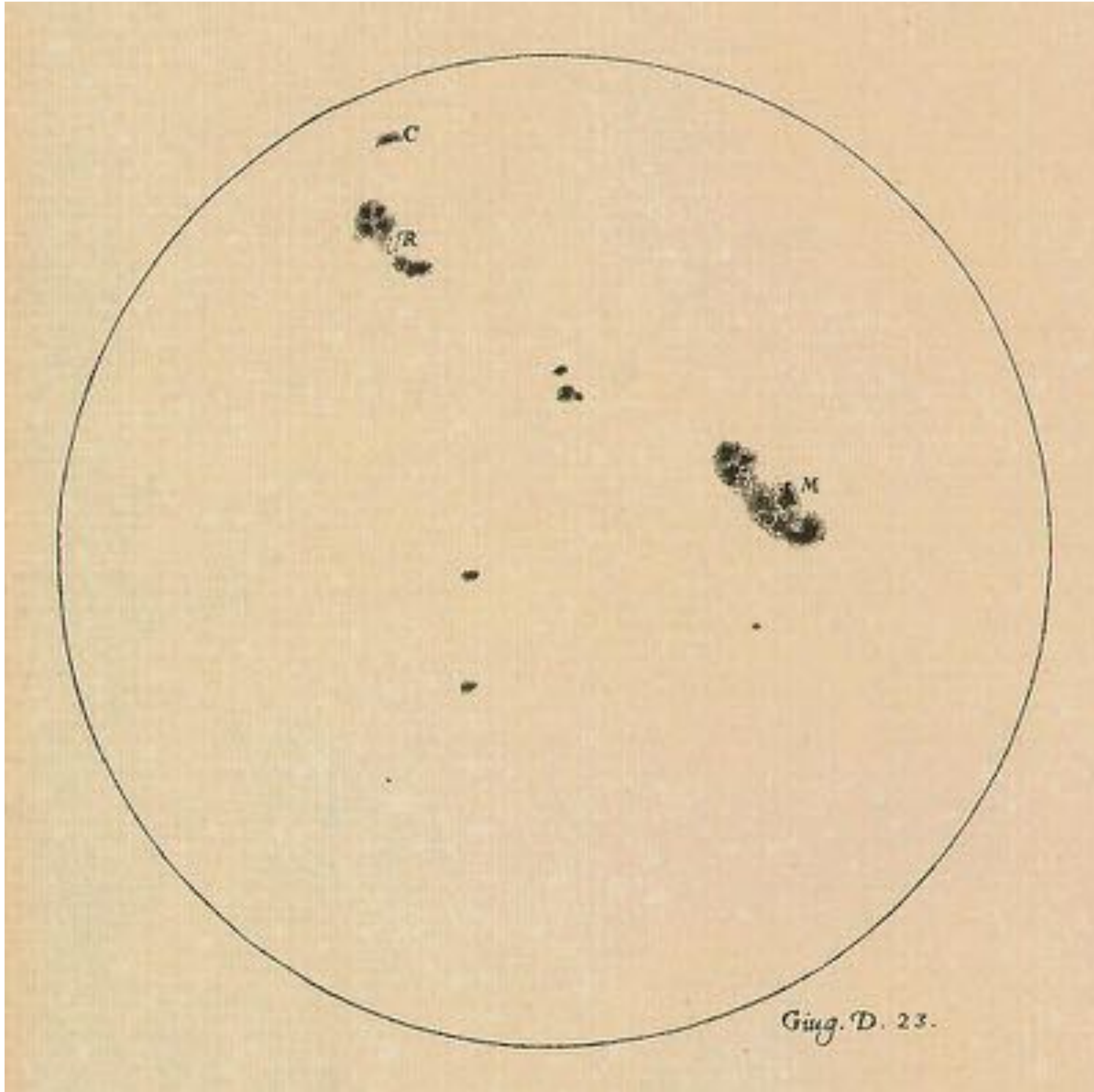
Rotation-Activity Correlation

- Solar-like stars shown
- General trend holds for all low-mass stars
- What causes saturation?

At the end of the day…

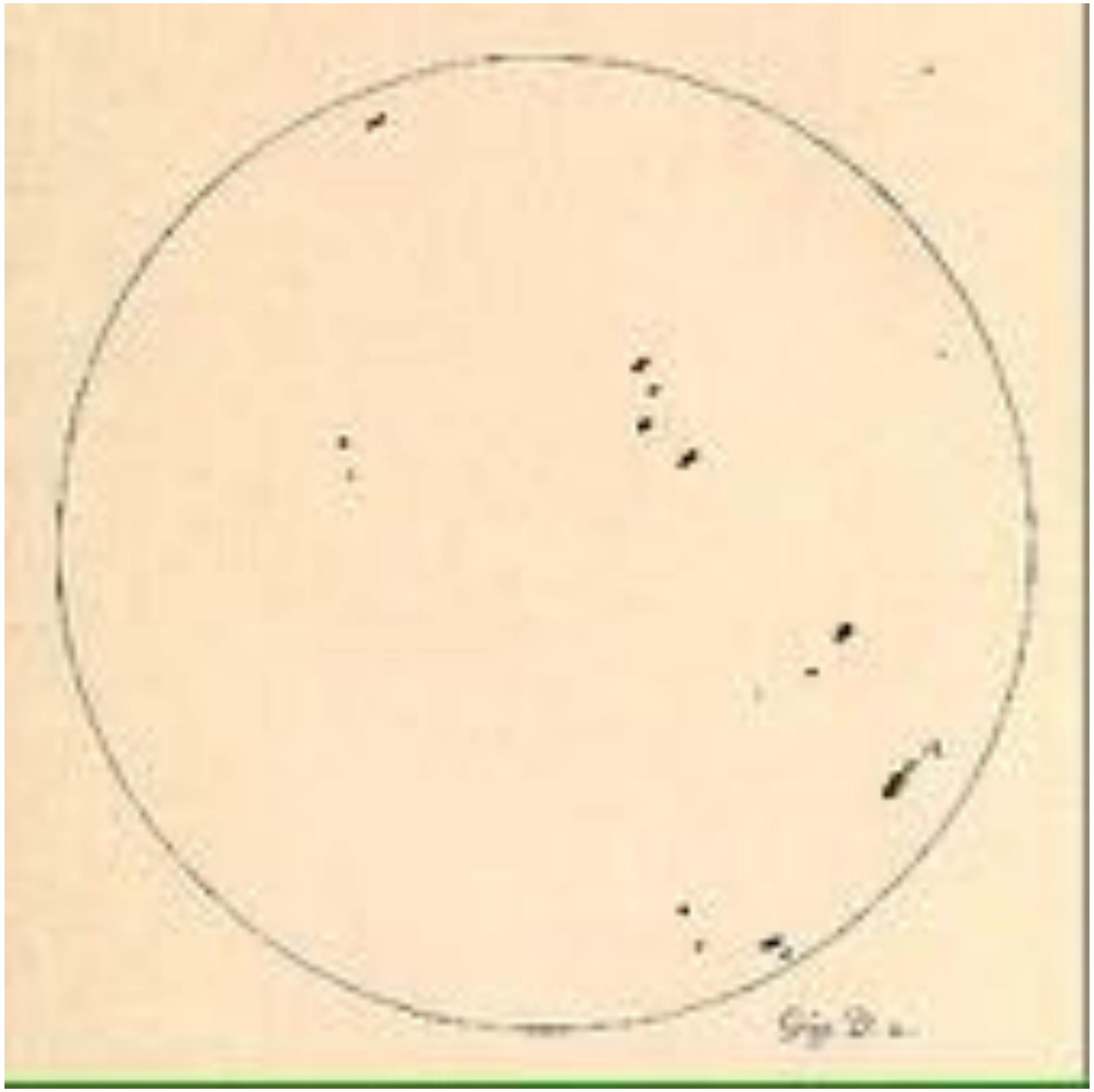
- The Sun is a star
- Stellar magnetism is the superset of solar magnetism
- We study stellar dynamos indirectly via the Sun as much as we do directly via observations
- Let’s turn to the Sun, which we can RESOLVE!


The Sun
(9/7/2016)
sunspots
visible light
617 nm
HMI/SDO



Detailed sunspot records from 1600s onward (Galileo Galilei, 1612)

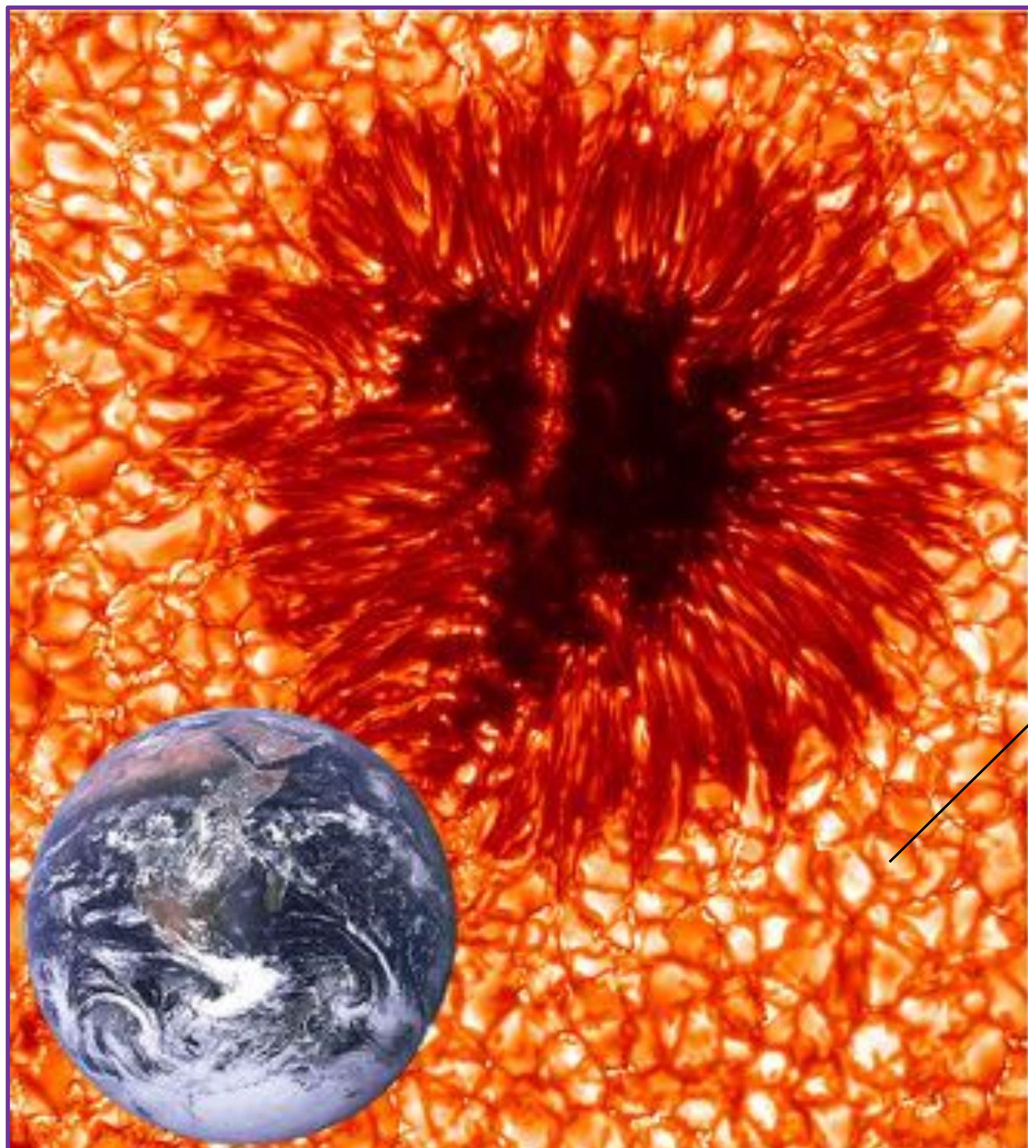
Naked-eye observations from China since 23 BCE



Detailed sunspot records
from 1600s onward
(Galileo Galilei, 1612)

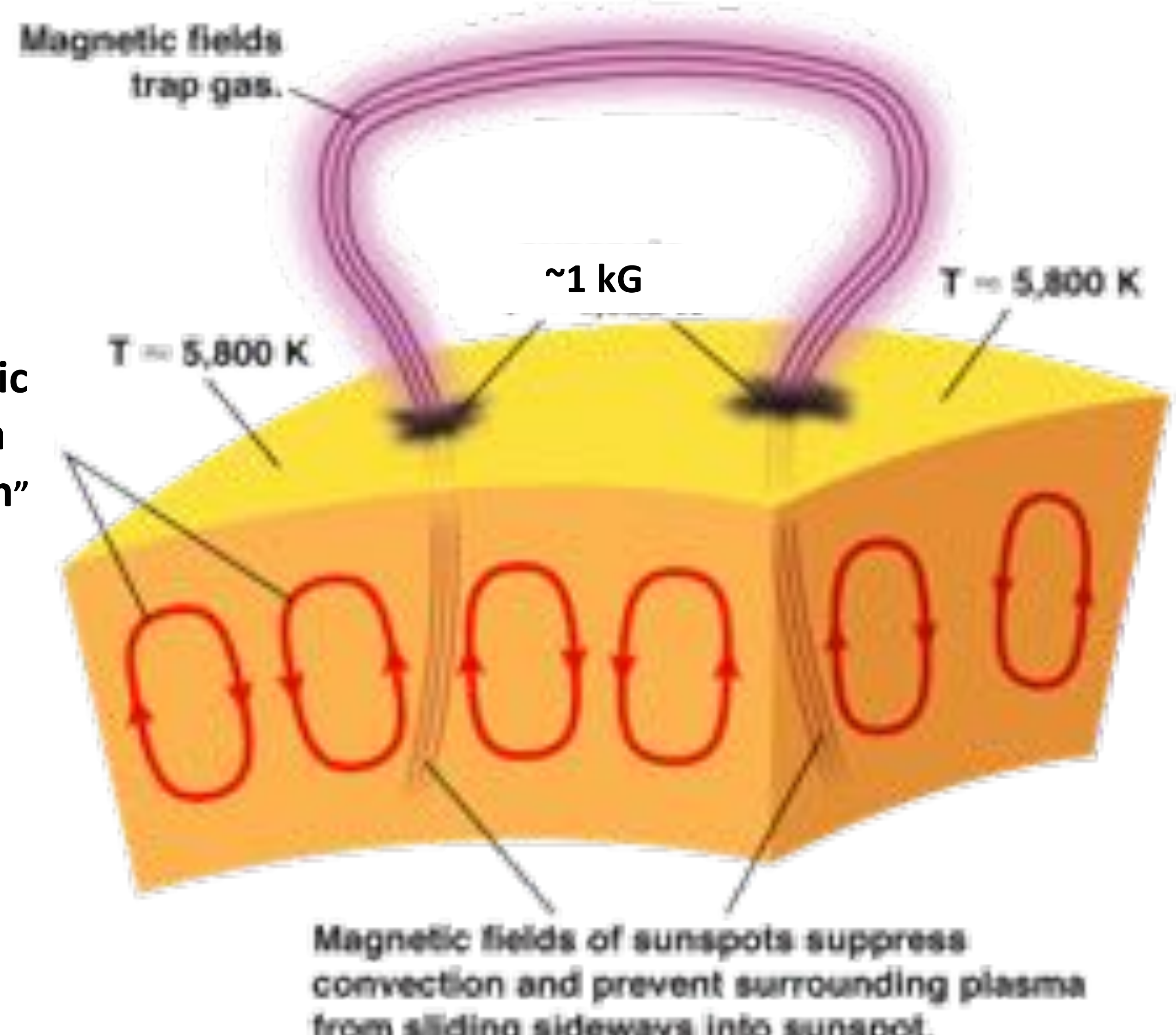
Naked-eye observations
from China since 23 BCE

Sunspots: A Closer Look



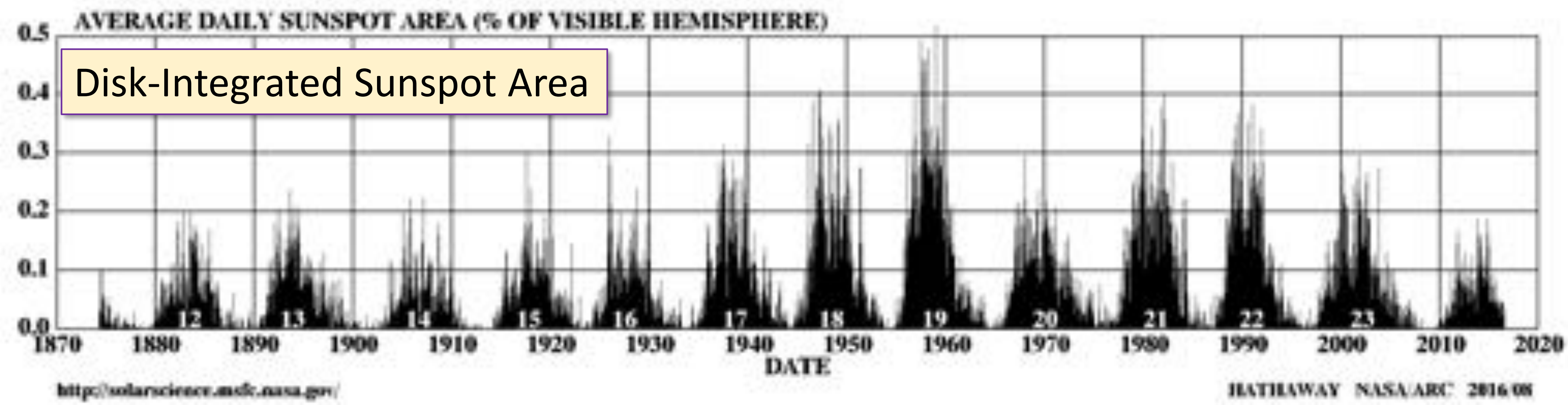
Swedish Solar Telescope (visible; 430 nm)

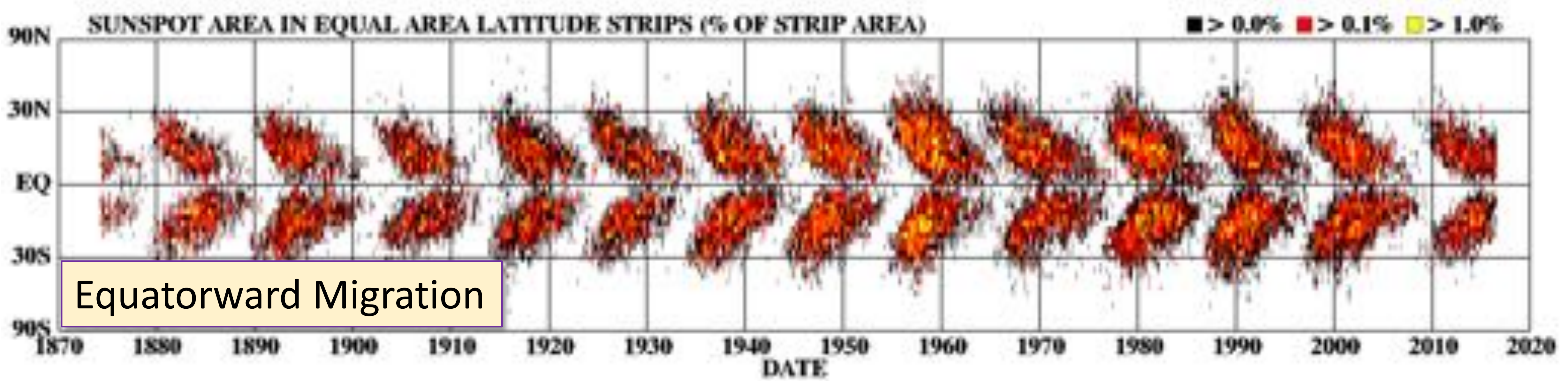
photospheric convection "granulation"



Cosmic Perspective, 3rd Ed.

The Sun's Magnetic Cycle

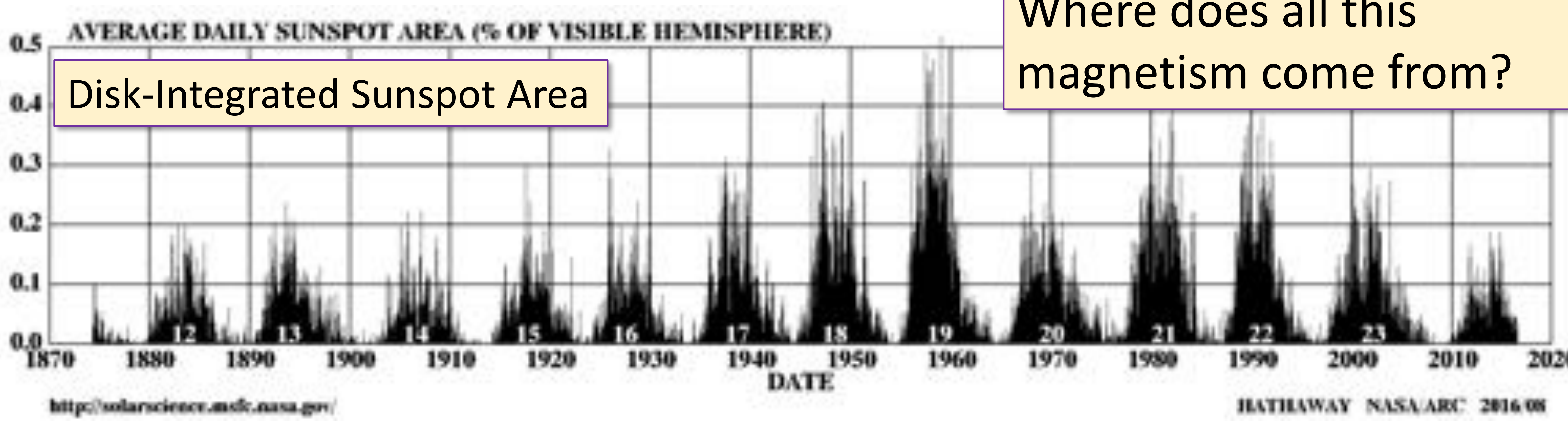




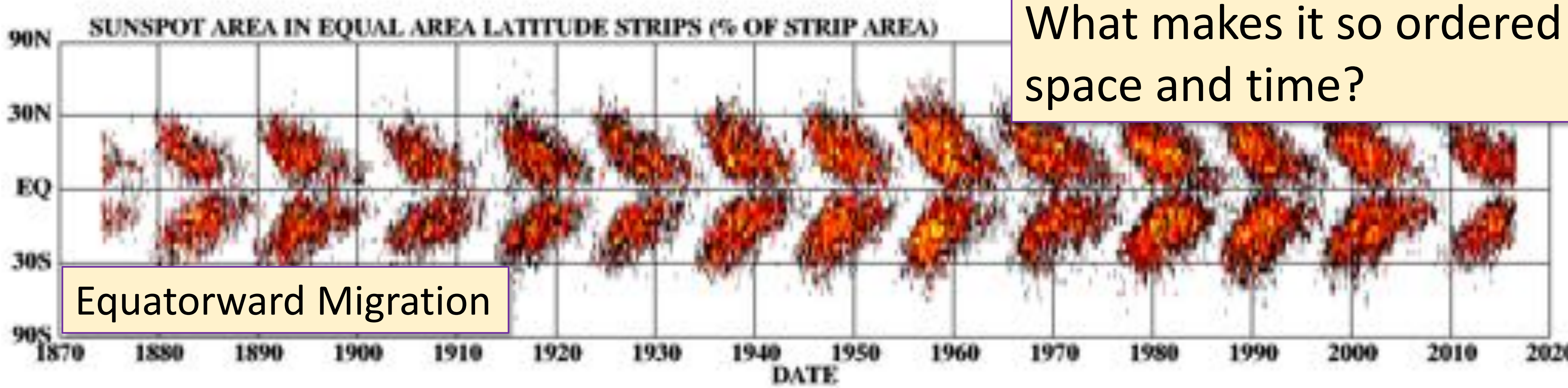
- Magnetic activity increases with integrated sunspot area
- Mean magnetic polarity reverses every 11 years

The Sun's Magnetic Cycle

Where does all this magnetism come from?



What makes it so ordered in space and time?

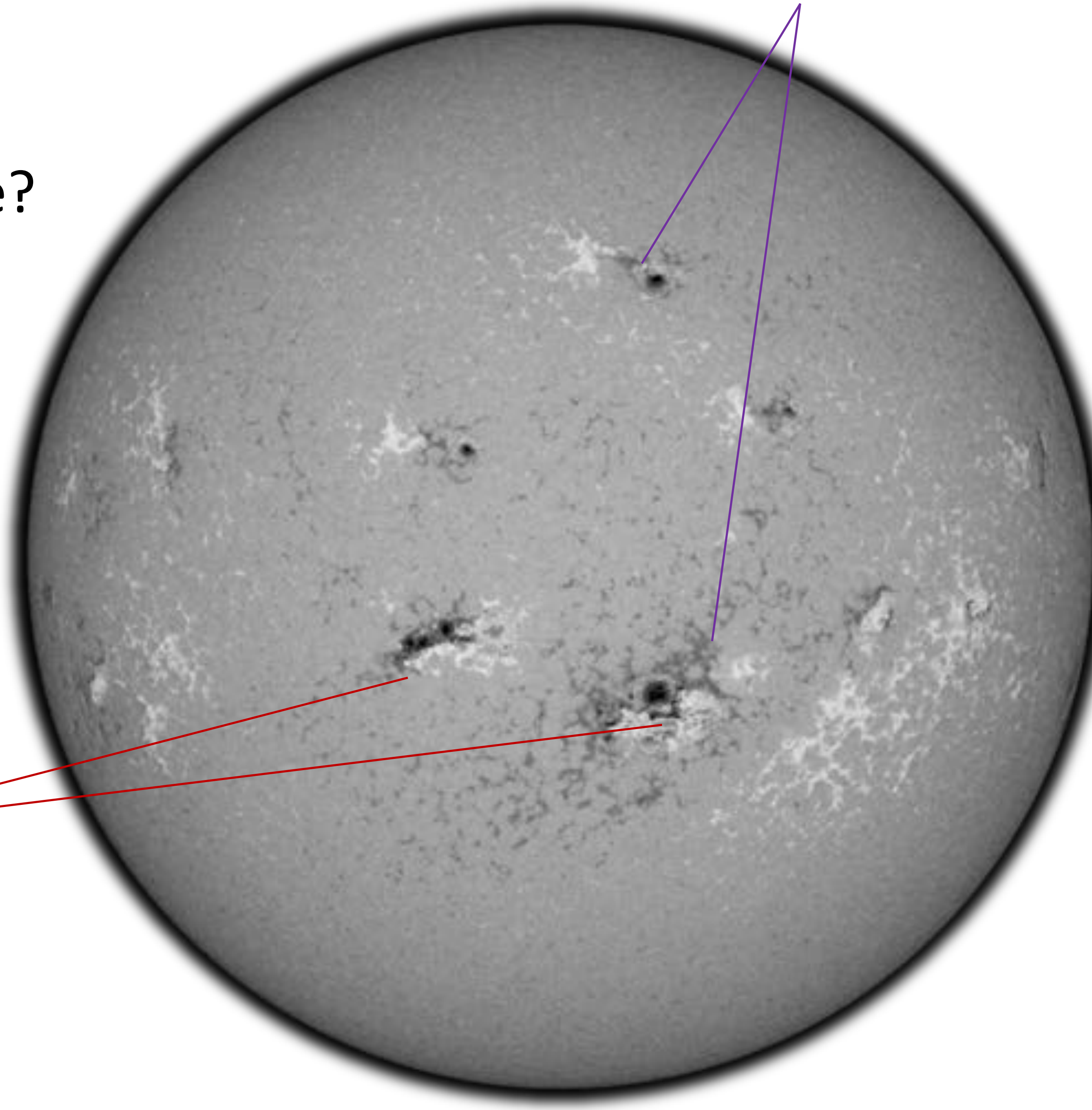


- Magnetic activity increases with integrated sunspot area
- Mean magnetic polarity reverses every 11 years

Solar Dynamo: The Big Questions

Where does solar magnetism originate?

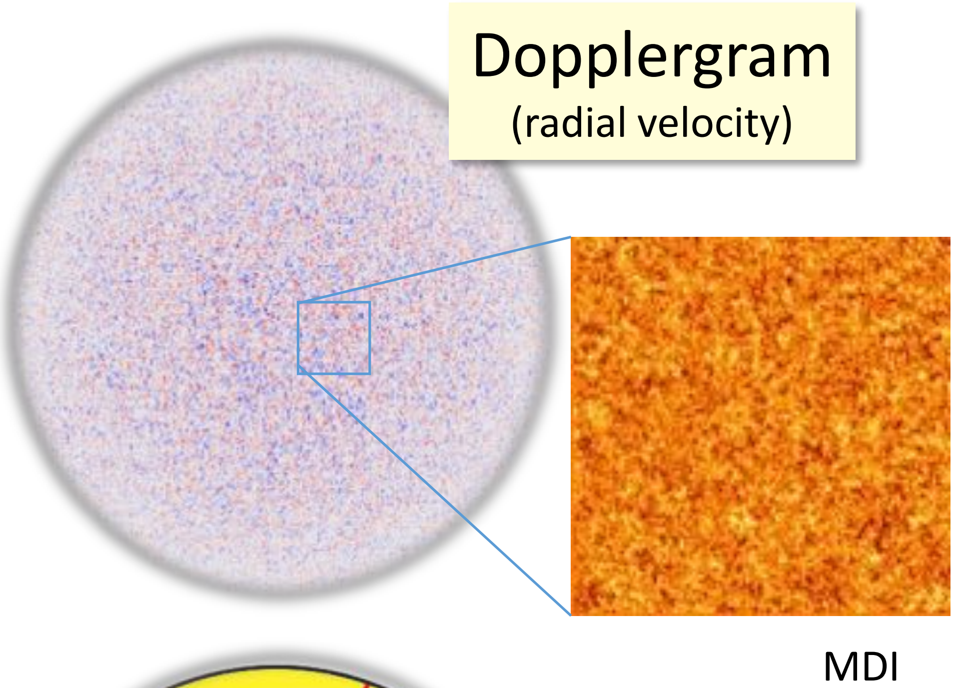
Why is there a solar cycle?

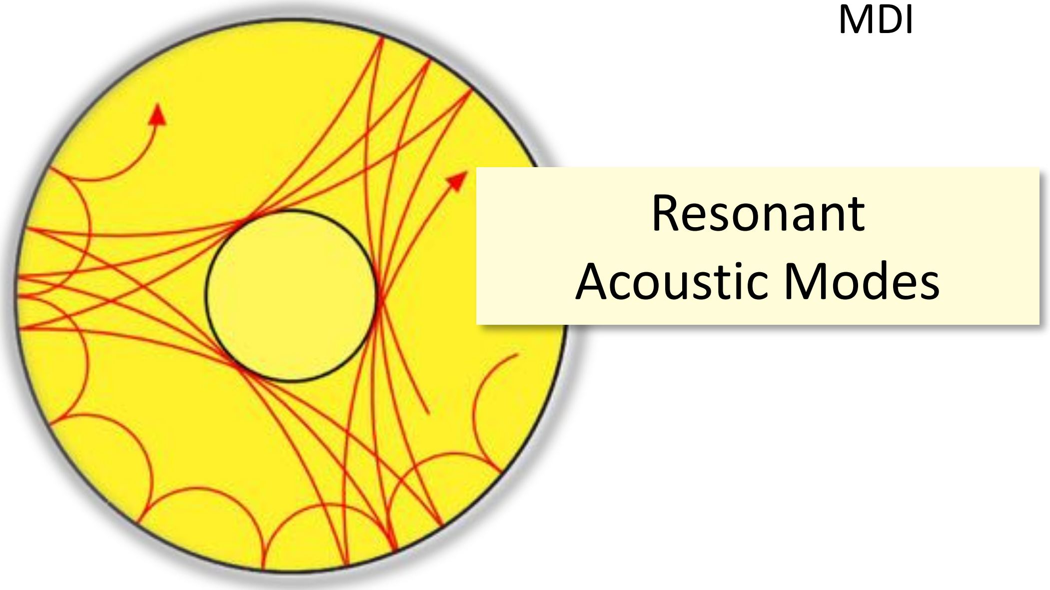


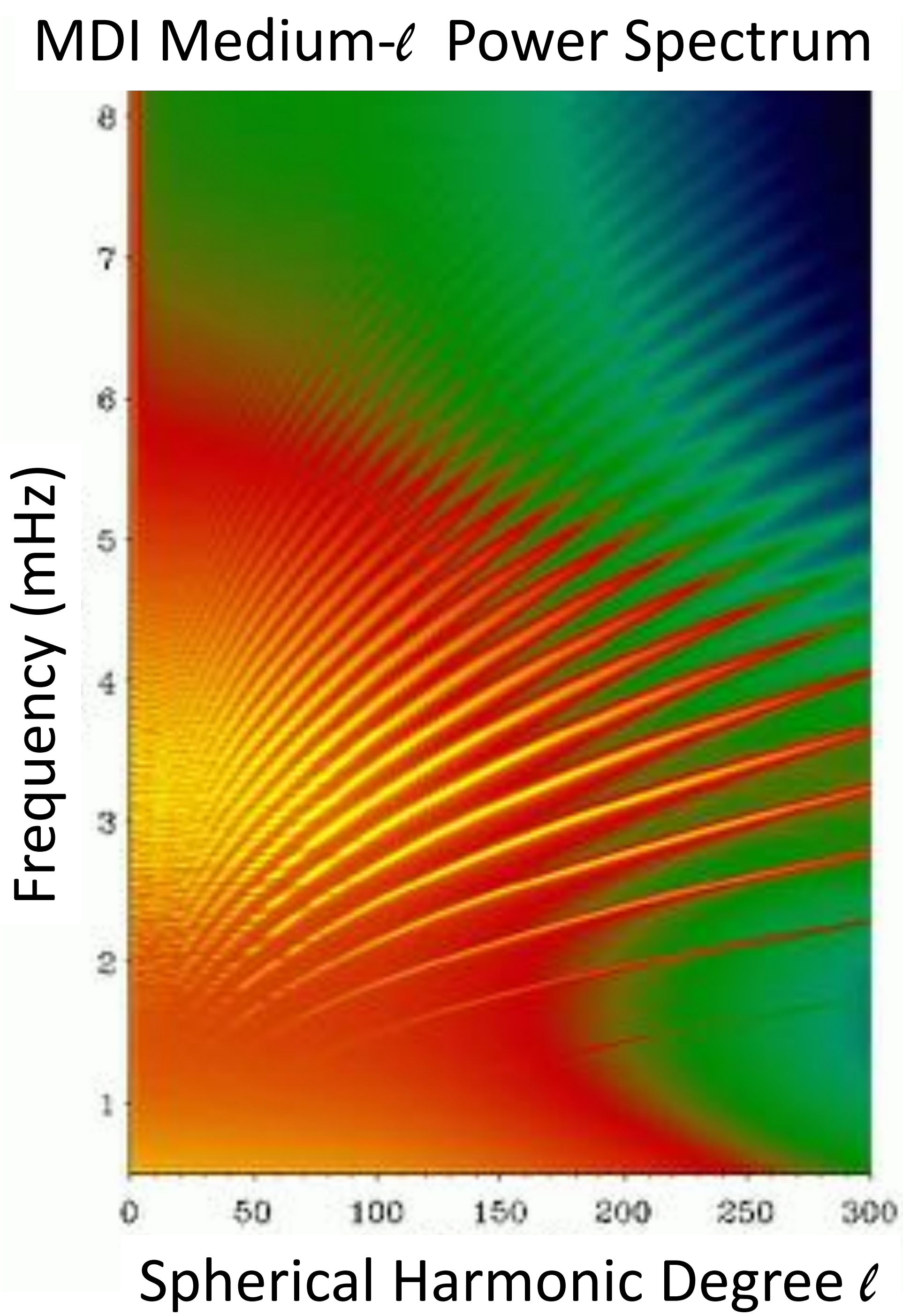
Line-of-sight magnetic Field (HMI)

A deep origin for
solar magnetism?

What Lies Beneath: Solar Helioseismology

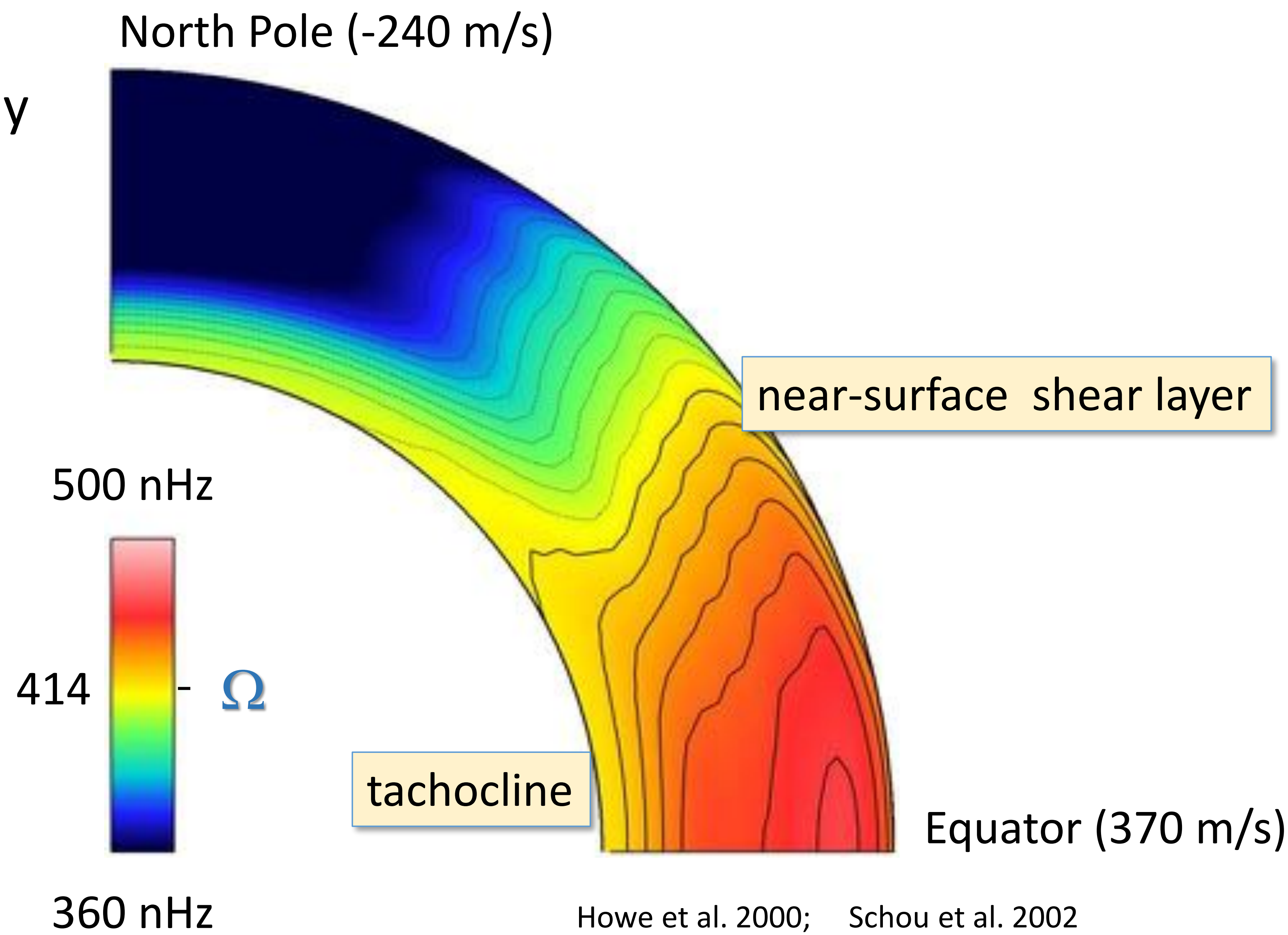






Helioseismology Key Result: Differential Rotation

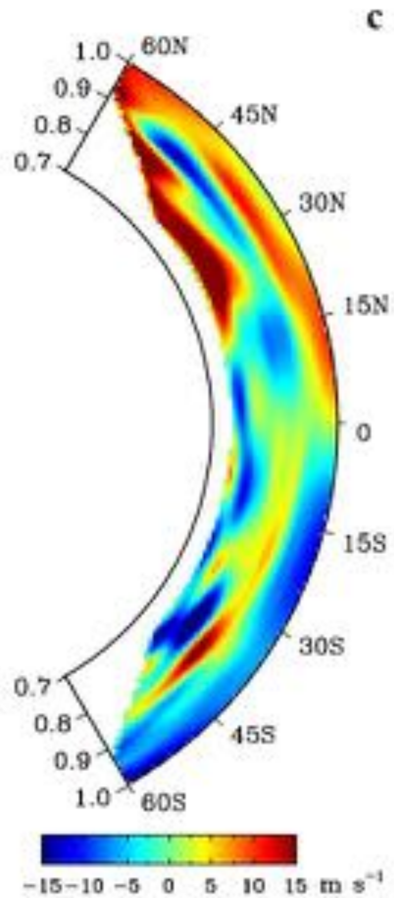
- Sun rotates differentially
- 24-day period equator
- 30-day period poles
- Latitudinal Shear
- Radial Shear



Howe et al. 2000; Schou et al. 2002

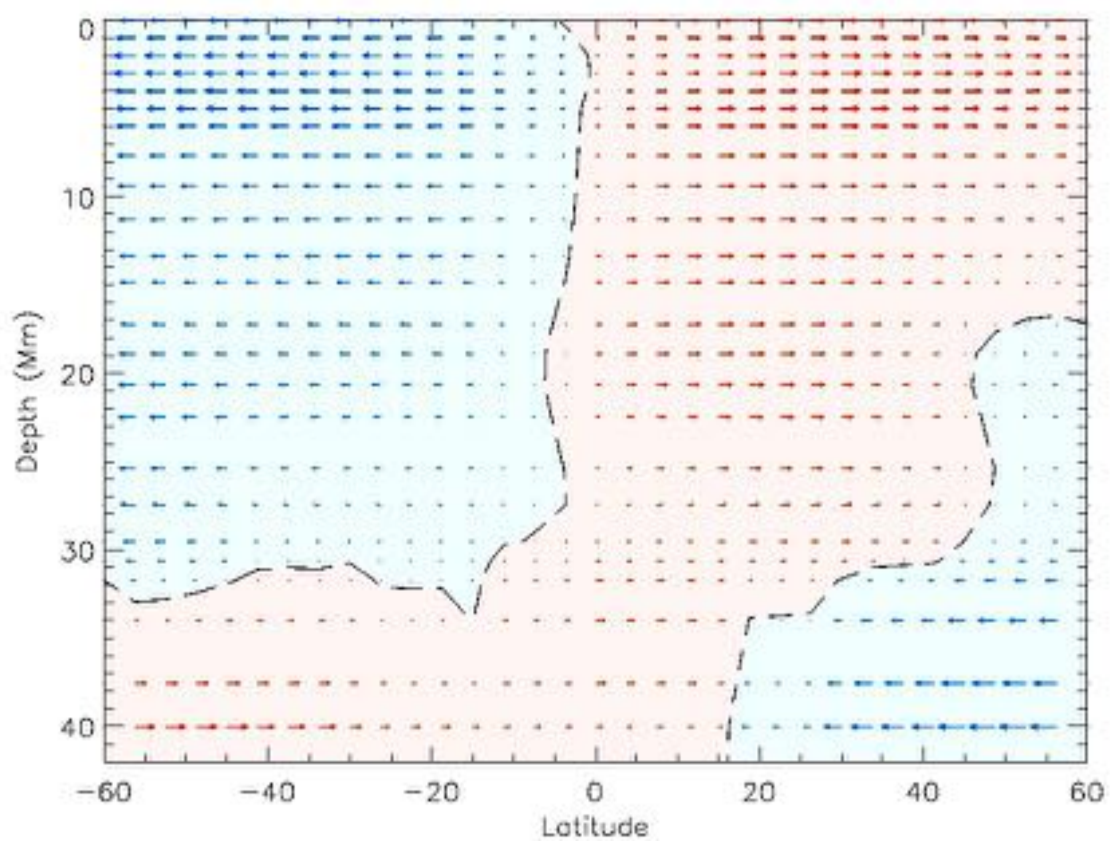
Helioseismology Key Result: Meridional Circulation

Time Distance

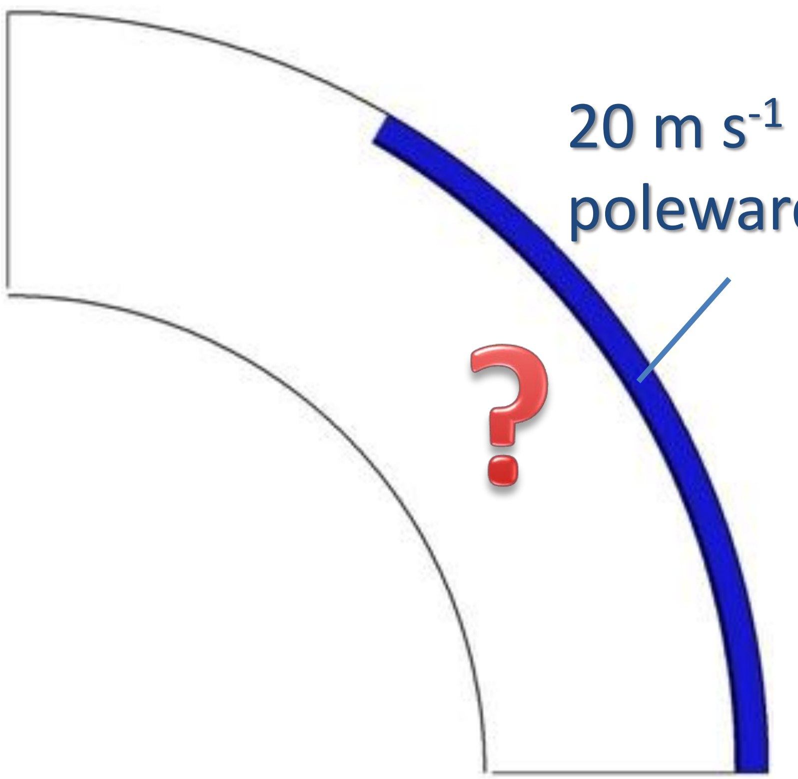


Zhao et al. 2012

Ring Diagrams



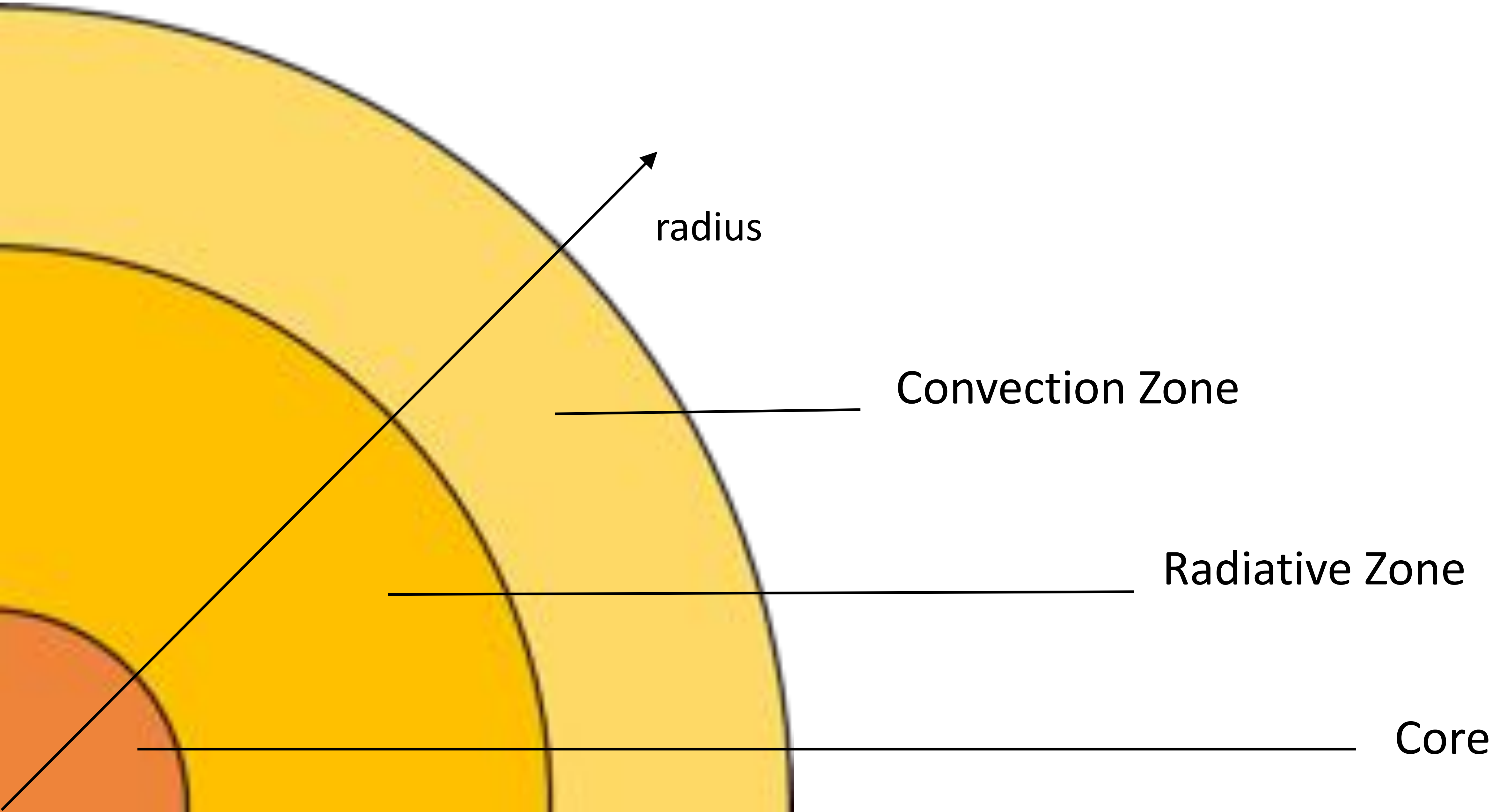
Greer et al. 2013



Shallow or Deep reversal?

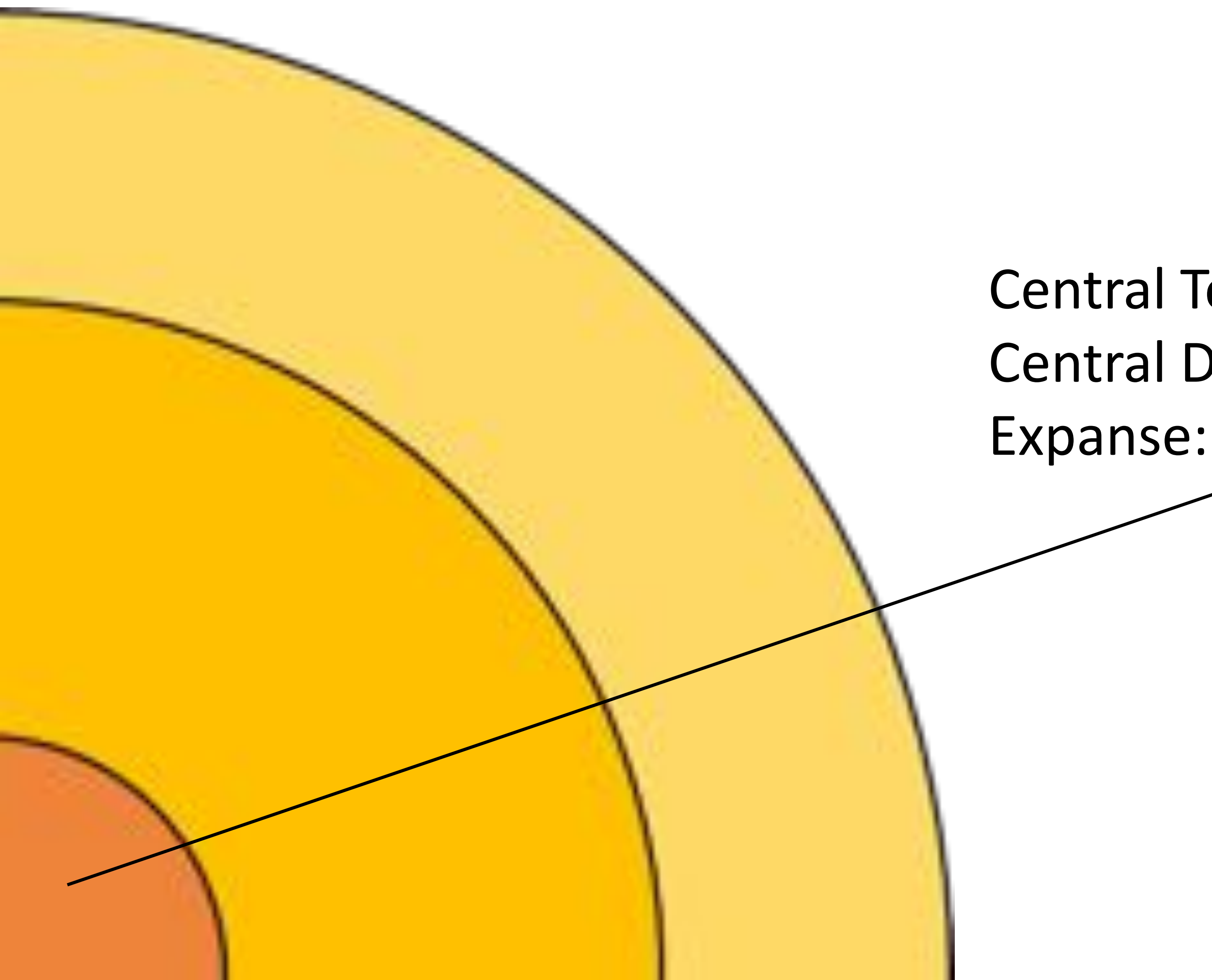
Latitudinal variation?

Helioseismology Key Result: Solar Structure



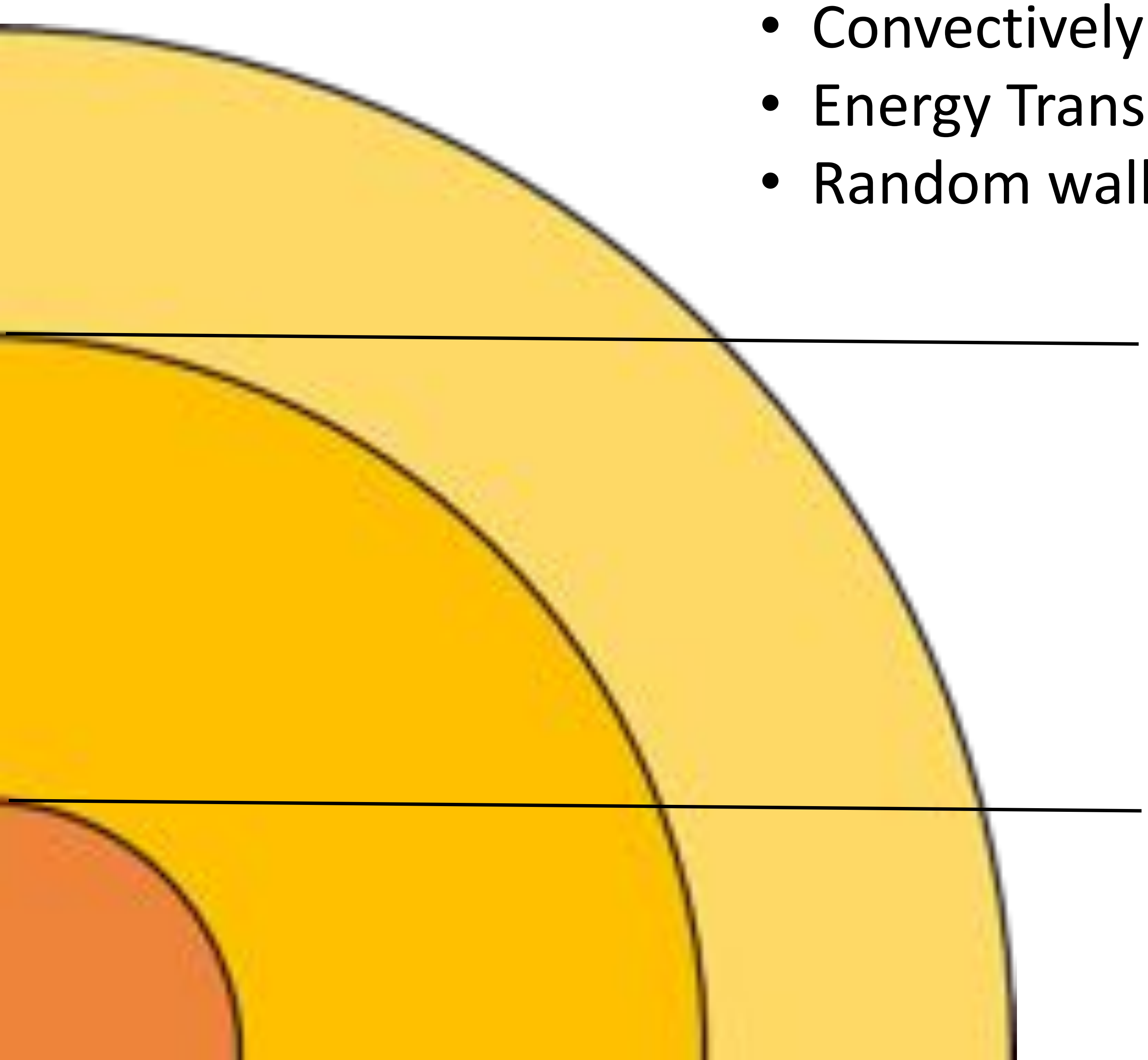
Fusion Core

Central Temperature: 15.7 million K
Central Density: 154 g cm^{-3}
Expanse: 0 – 0.25 R_{sun}



Radiative Zone

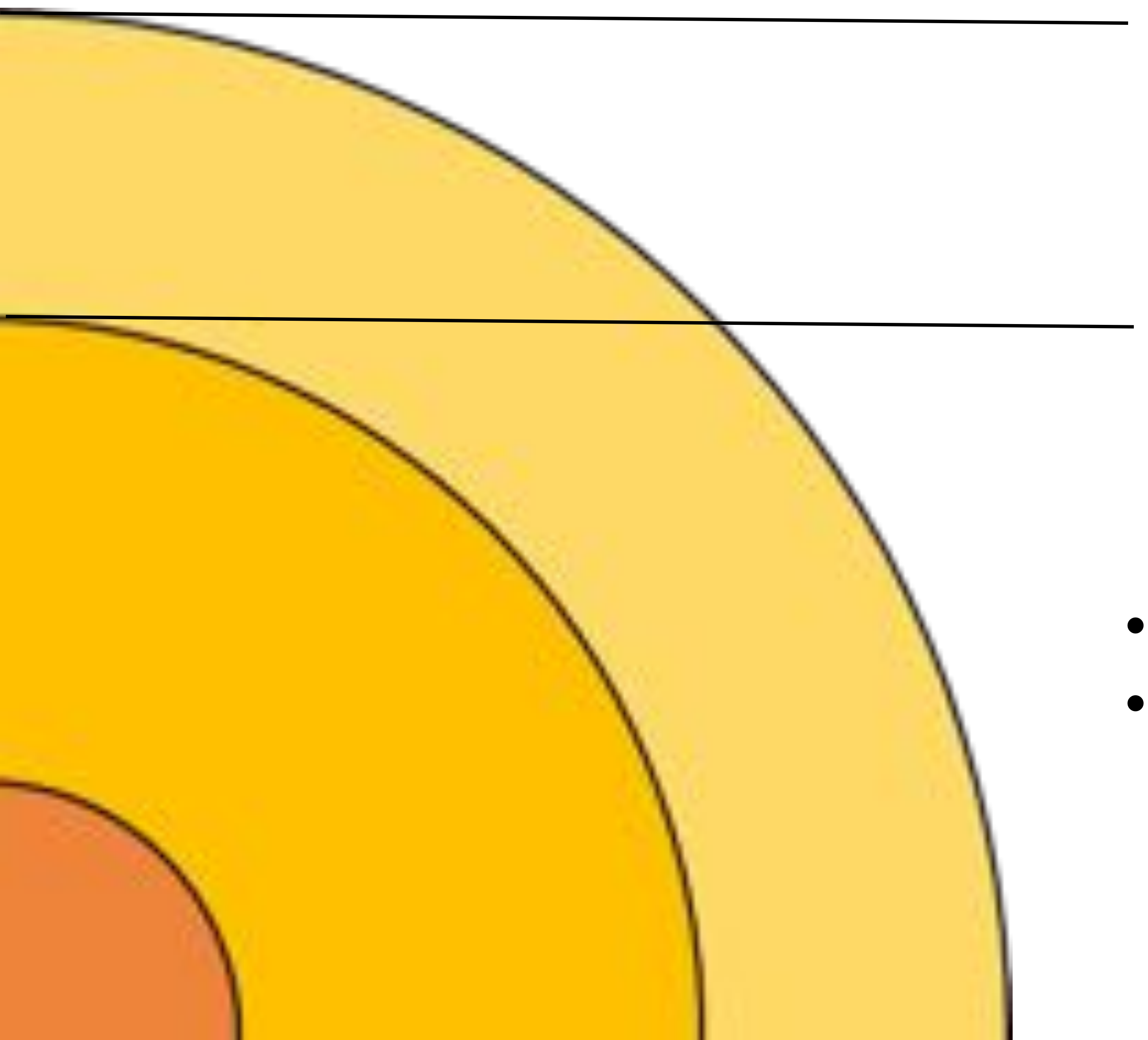
- Convectively Stable
- Energy Transport: photon scattering
- Random walk time: 100,000 years



Temperature: 2.3 million K
Density: 0.2 g cm^{-3}
Radius: 0.7 R_{sun}

Temperature: 8 million K
Density: 20 g cm^{-3}
Radius: 0.25 R_{sun}

Convection Zone

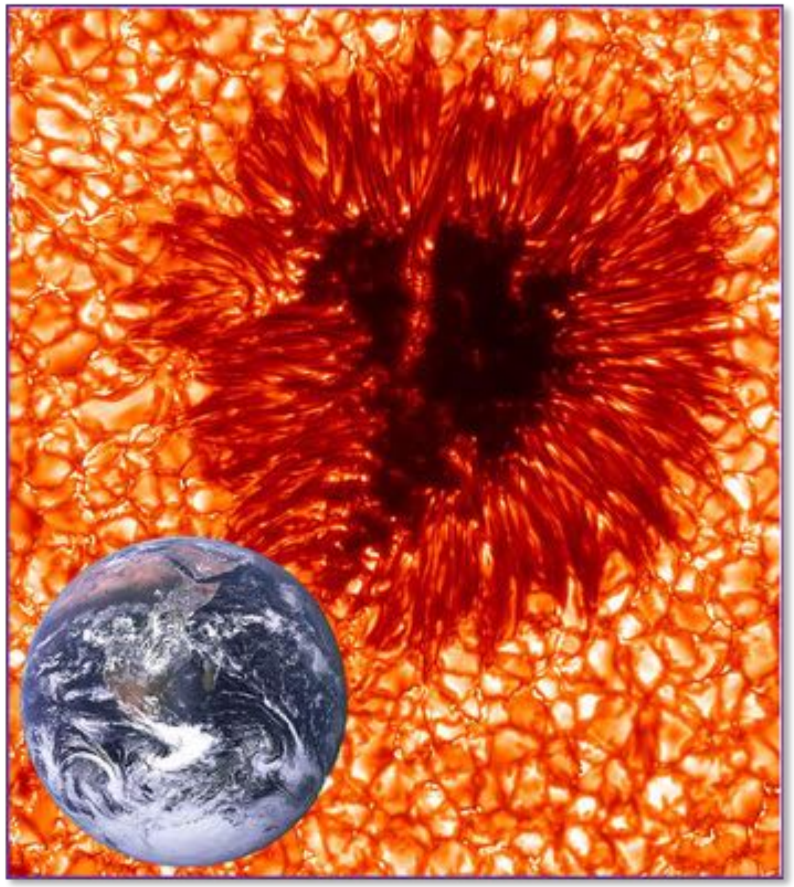


Temperature: 5800K
Density: 2×10^{-7} g cm^{-3}
Radius: 1 R_{sun}

Temperature: 2.3 million K
Density: 0.2 g cm^{-3}
Radius: 0.7 R_{sun}

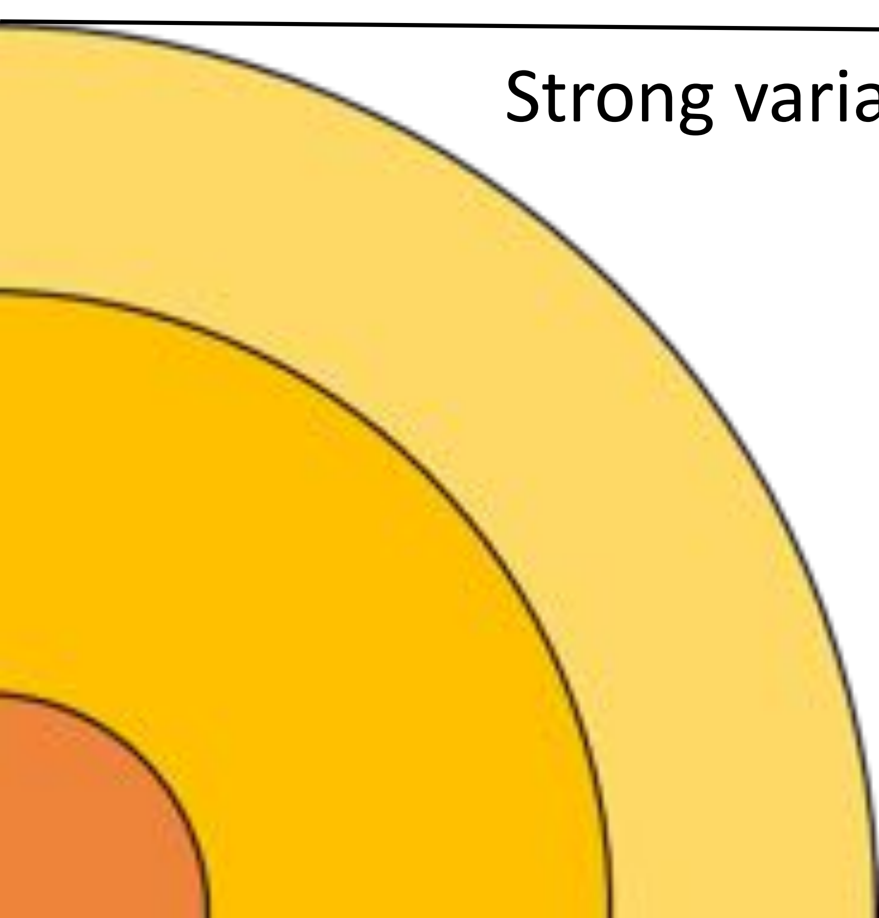
- Convectively unstable
- Convective timescale: months, years?

region of extreme contrasts…
… *ionized plasma!*



Note:

The convection that we can see occurs in a region thinner than the width of this line (about 1,000 km in depth)

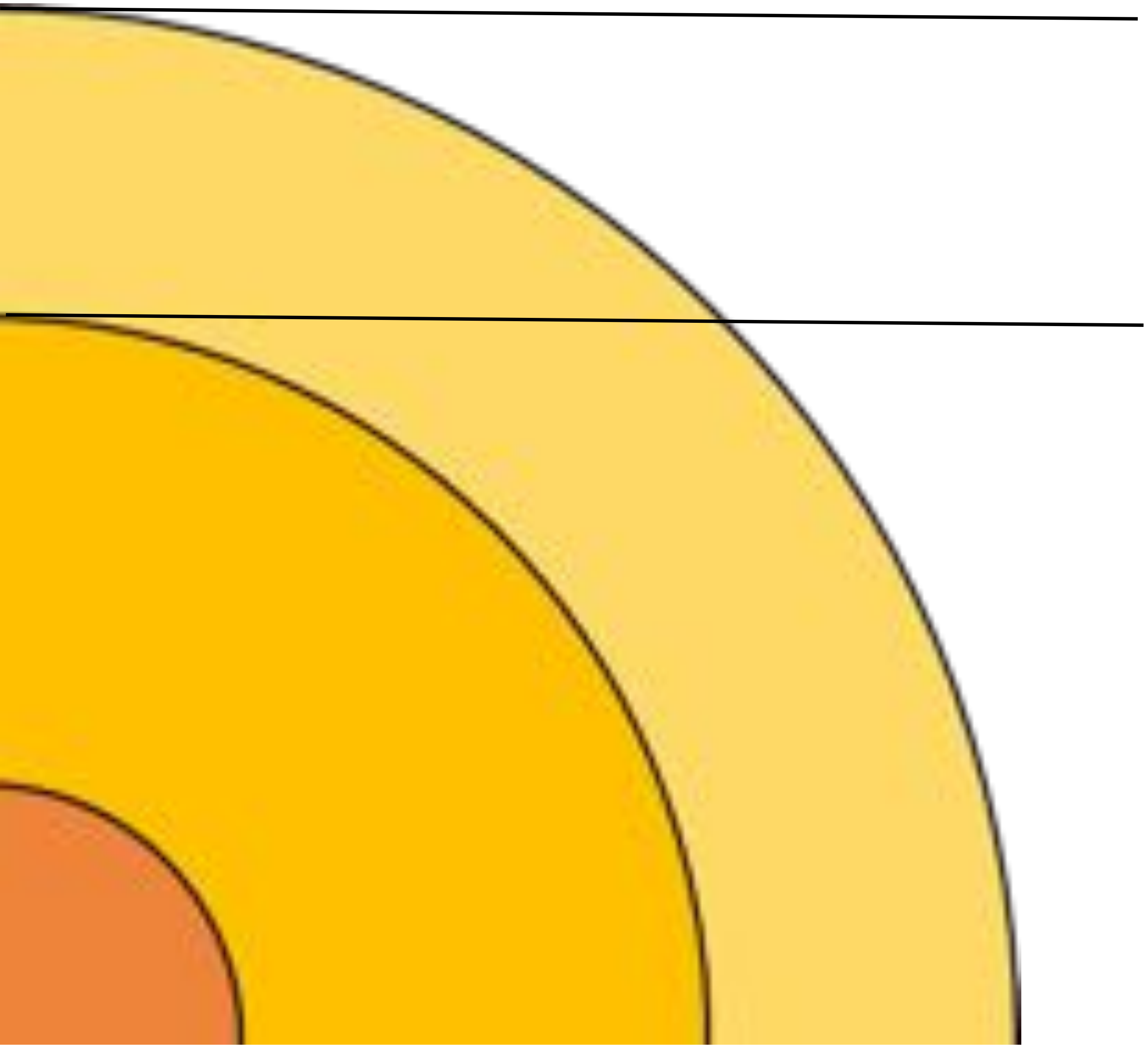


Strong variation with depth

Temperature:	5,800K
Density:	2×10^{-7} g cm^{-3}
Radius:	1 R_{sun}

Temperature:	14,400K
Density:	2×10^{-6} g cm^{-3}
Radius:	0.9985 R_{sun}

Convection Zone Bulk



Temperature: 14,400K
Density: 2×10^{-6} g cm^{-3}

Temperature: 2.3 million K
Density: 0.2 g cm^{-3}

- 11 density scaleheights
- 17 pressure scaleheights
- Reynolds Number $\approx 10^{12} – 10^{14}$
- Rayleigh Number $\approx 10^{22} – 10^{24}$
- Magnetic Prandtl Number ≈ 0.01
- Prandtl Number $\approx 10^{-7}$
- Ekman Number $\approx 10^{-15}$

Question

Where does the energy in the solar magnetic field come from?

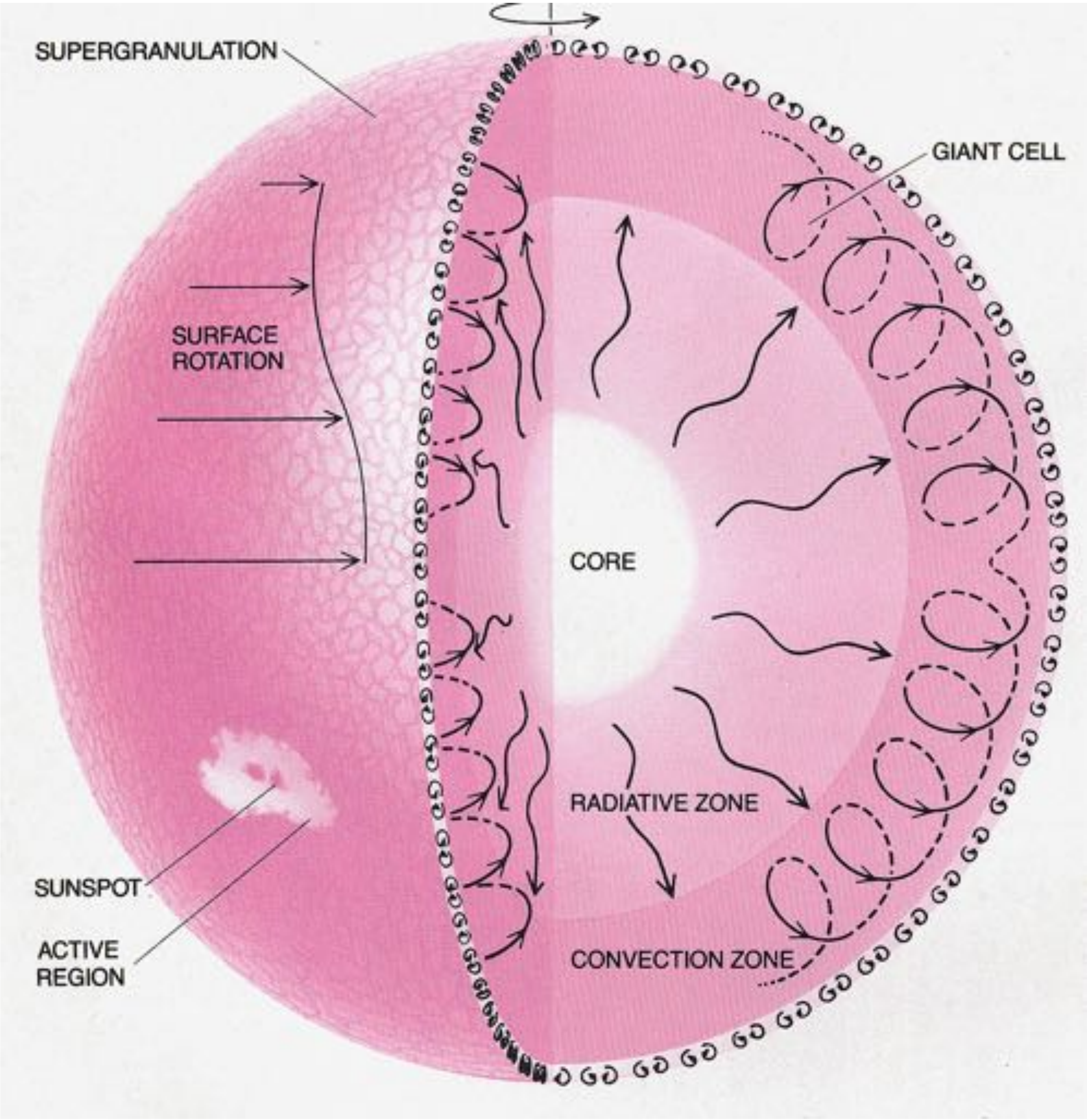
The Solar Dynamo generates magnetic fields from flows

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

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

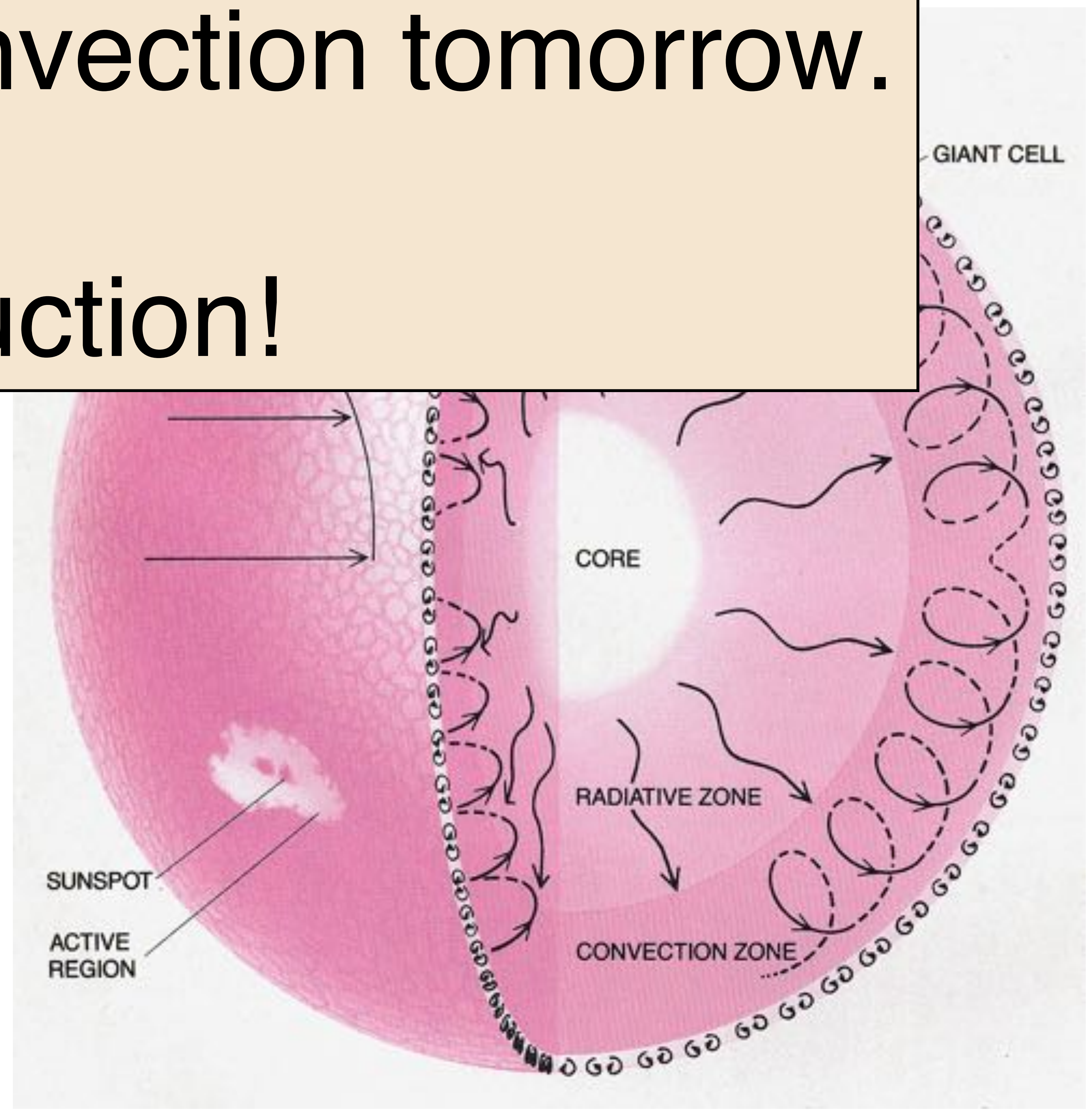
Dynamo

kinetic energy ⇒ magnetic energy

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

More on convection tomorrow.

Today: Induction!



MHD Magnetic Induction equation

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

Comes from Maxwell's equations (Faraday's Law and Ampere's Law)

$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = -\boldsymbol{\nabla} \times \mathbf{E}$$

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

And Ohm's Law

$$\tilde{\mathbf{J}} = \sigma \tilde{\mathbf{E}}$$

electrical conductivity

Magnetic diffusivity

$$\eta = \frac{c^2}{4\pi\sigma}$$

Creation and destruction of magnetic fields

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

Source of Magnetic Energy

Sink of Magnetic Energy

How would you demonstrate this?

(Hint: have a sheet handy with lots of vector identities!)

$$E_m = \frac{B^2}{8\pi}$$

Creation and destruction of magnetic fields

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

Source of Magnetic Energy

Sink of Magnetic Energy

Dot with B…

$$E_m = \frac{B^2}{8\pi}$$

$$\frac{\partial E_m}{\partial t} = -\nabla \cdot \mathbf{F}_P - \frac{\mathbf{v}}{c} \cdot (\mathbf{J} \times \mathbf{B}) - \Phi_o$$

Poynting Flux

$$\mathbf{F}_P = \mathbf{E} \times \mathbf{B} = \left[\frac{\eta}{c} \mathbf{J} - \frac{1}{4\pi} (\mathbf{v} \times \mathbf{B}) \right] \times \mathbf{B}$$

Ohmic Heating

$$\Phi_o = \frac{4\pi\eta}{c^2} J^2$$

Creation and destruction of magnetic fields

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

Source of Magnetic Energy
~ U B / D

Sink of Magnetic Energy
~ η B / D^2

$$\mathrm{Rm} = \frac{UD}{\eta}$$

ratio of source and sink terms

If Rm >> 1 the source term is much bigger than the sink term

....Or is it???

Creation and destruction of magnetic fields

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

Source of Magnetic Energy
~ U B / D

Sink of Magnetic Energy
~ η B / δ^2

δ can get so small that the two terms are comparable

It's not obvious which term will "win" - it depends on the subtleties of the flow, including geometry & boundary conditions

Creation and destruction of magnetic fields

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

Source of Magnetic Energy
$\sim U\,B\,/\,D$

Sink of Magnetic Energy
$\sim \eta\,B\,/\,\delta^2$

What is a Dynamo? (A corollary)

A dynamo must sustain the magnetic energy (through the conversion of kinetic energy) against Ohmic dissipation

How exactly does this work? It depends on the nature of the flow…

Large Scale Dynamos: The Mean Induction Equation

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

Go back to our basic induction equation

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

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

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

Ω-effect (large-scale shear)

Meridional circulation (transport)

Diffusion (molecular)

Fluctuating emf (small-scale shear)

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

Straightforward to show that if E=0, the dynamo dies (Cowling's theorem)

The MHD Induction Equation: Alternate View

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

compression

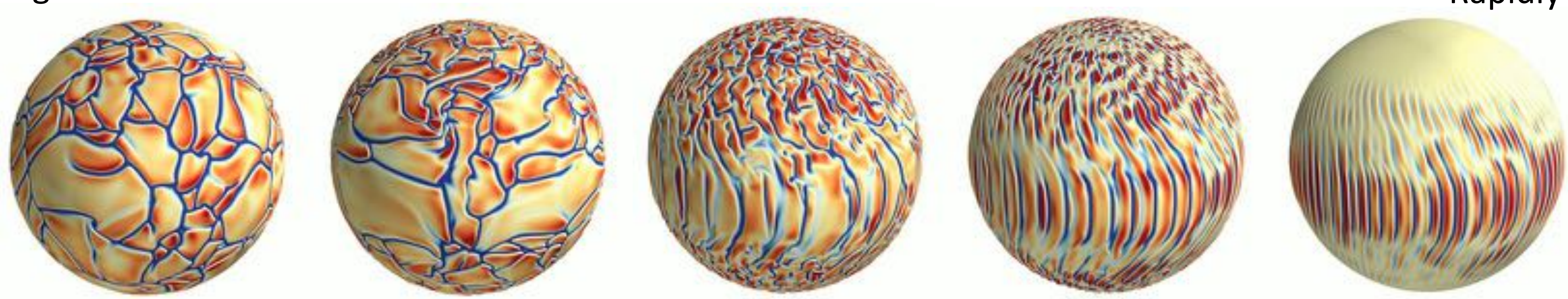
advection

diffusion

shear production ← Rotation → Large-Scale Shear (differential rotation); Small-Scale Shear (helical rolls)

Convection Simulations

Non-rotating → Rapidly-rotating



red upflow

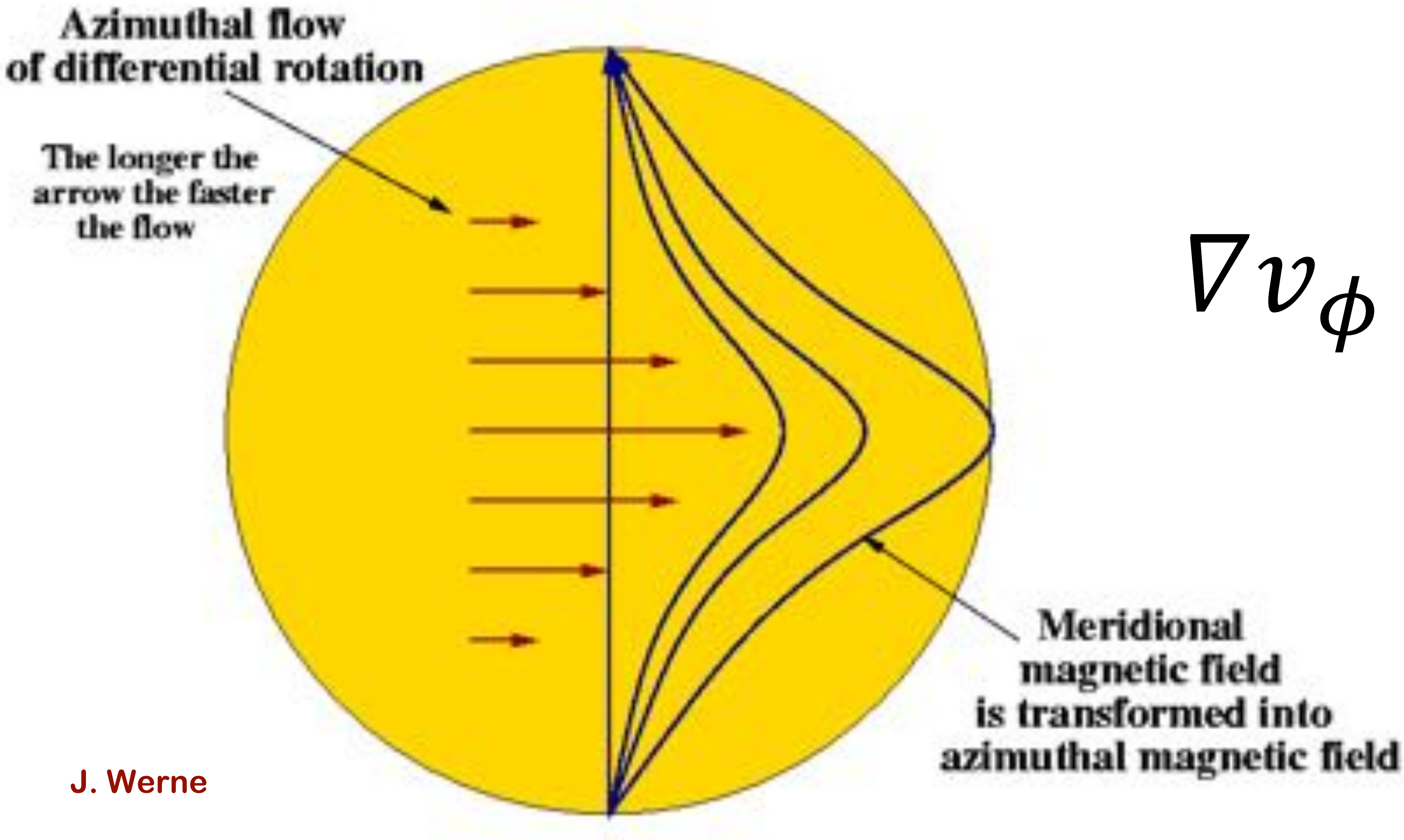
blue downflow

Rotating convection naturally generates both small-scale and large-scale shear!

The **Ω**-effect (large-scale shear)

Converts poloidal to toroidal field and amplifies it

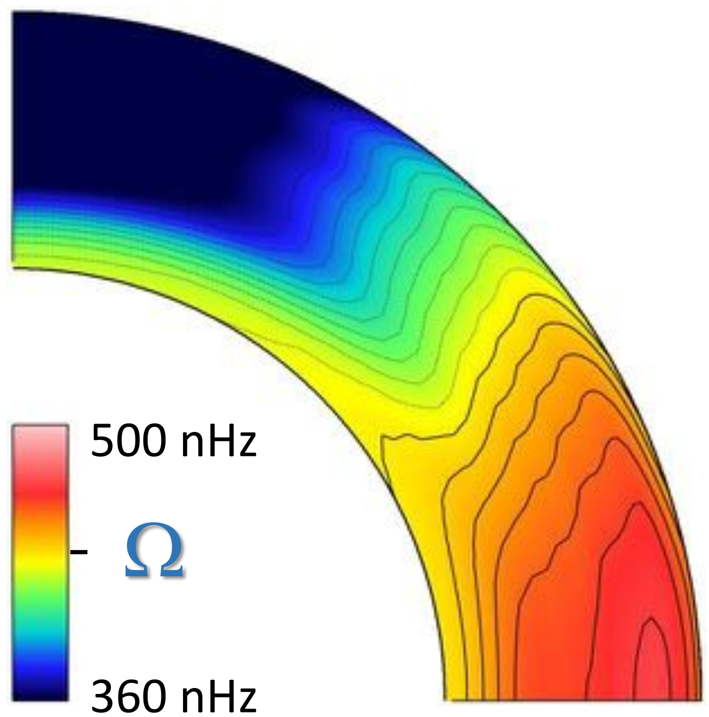
...by tapping the kinetic energy of the differential rotation



$$\nabla v_{\phi}$$

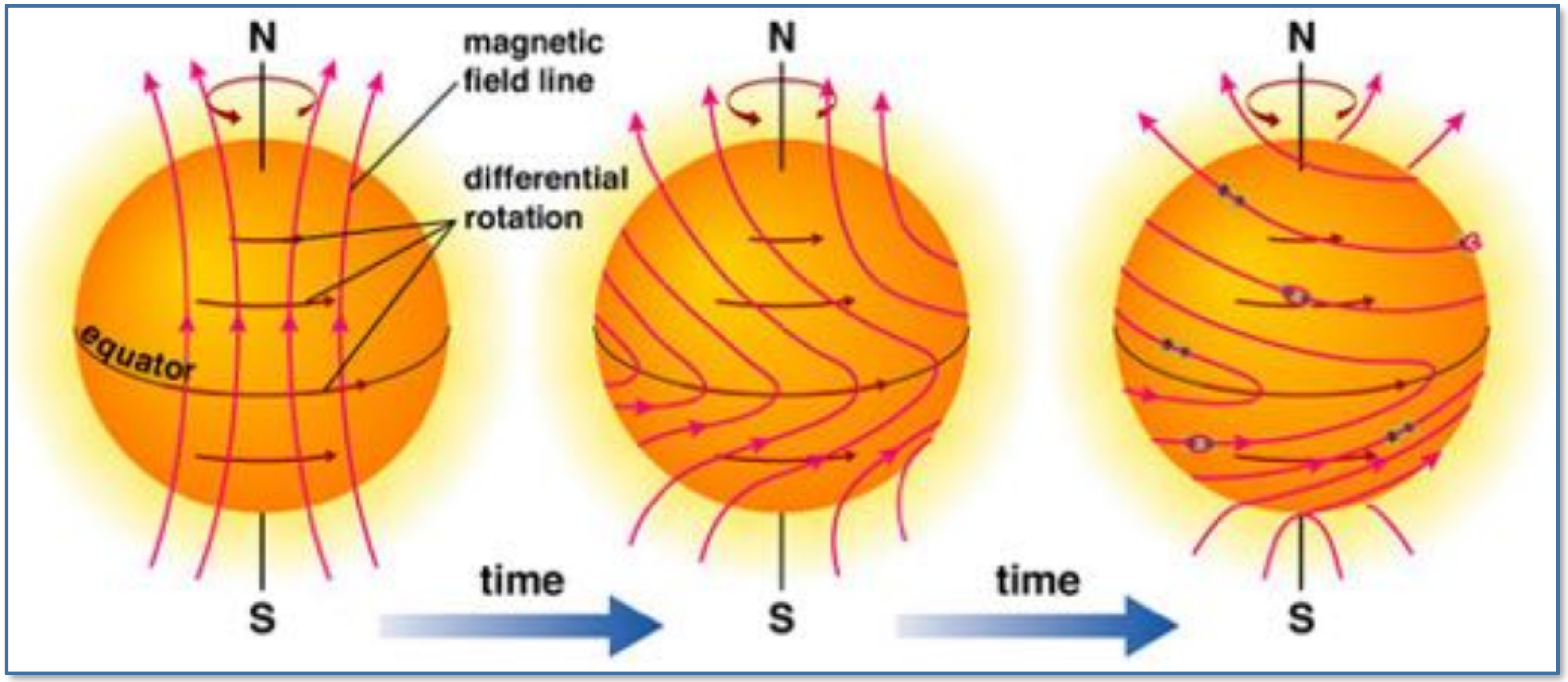
J. Werne

The **Ω**-effect (large-scale shear via helical convection)



Howe et al. 2000; Schou et al. 2002

"Omega-effect"



Bennett, et al. 2003

- 24-day period equator
- 30-day period poles

Mean shear:

- Latitudinal (Omega effect)
- Radial (Tachocline; Interface Dynamo)

Converts poloidal to toroidal field and amplifies it

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

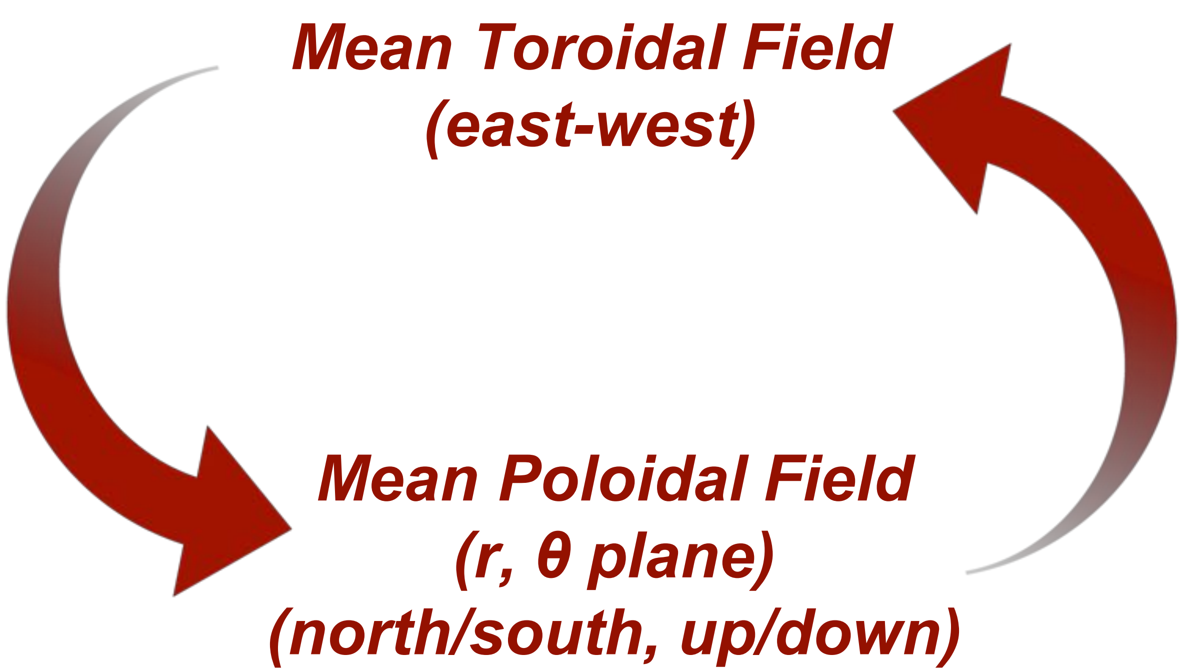
The turbulent α-effect (small-scale shear via helical convection)

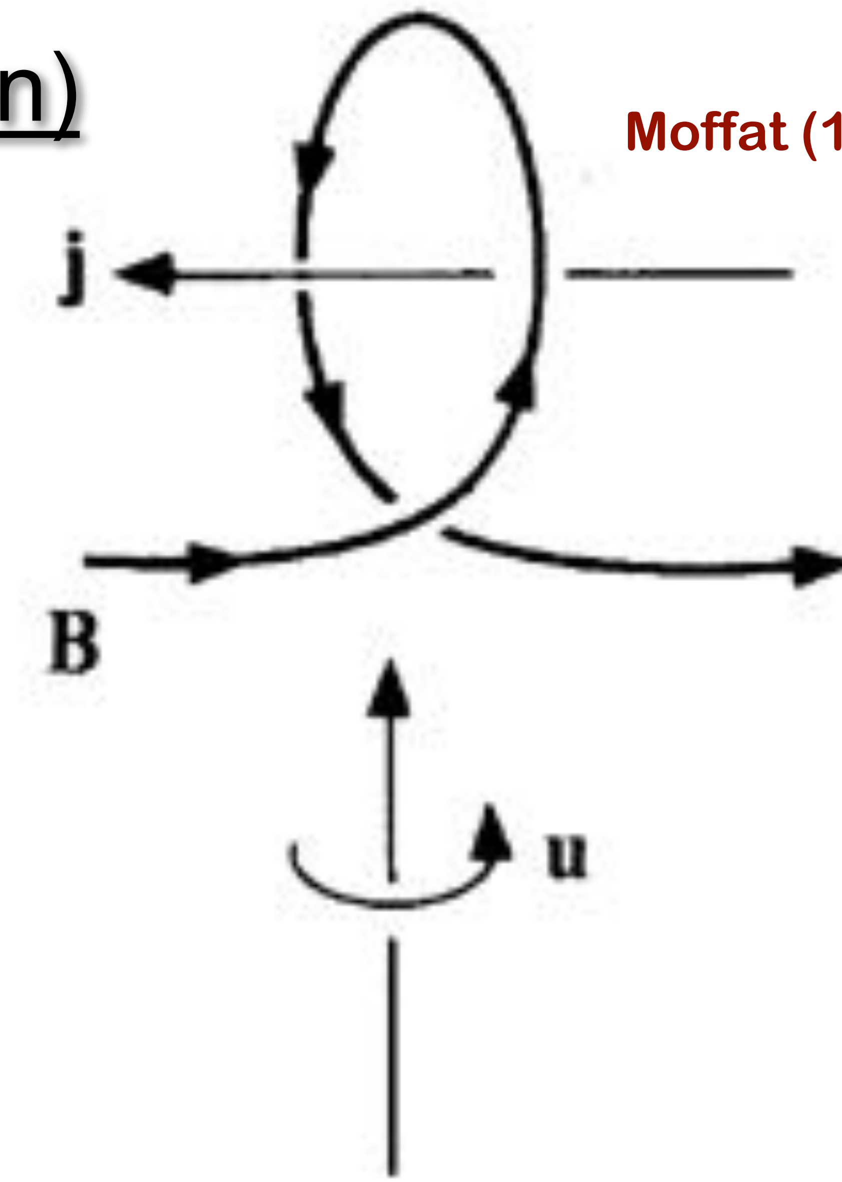
Helical motions (lift, twist) can induce an emf that is parallel to the mean field

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

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

which closes the Dynamo Loop





Moffat (1978)

Linked to kinetic, magnetic helicity

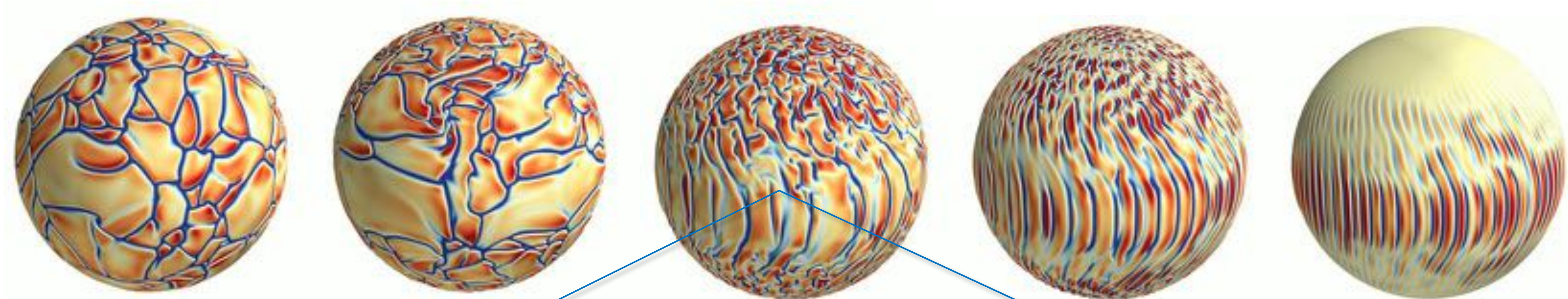
Linked to large-scale dynamo action

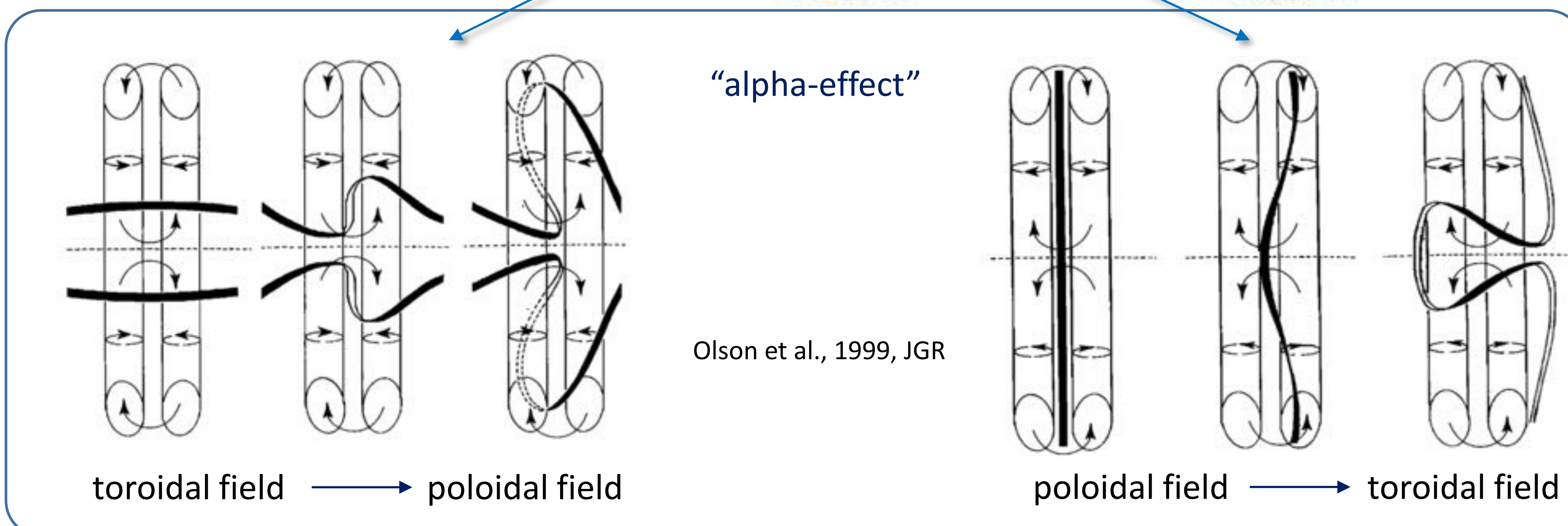
Illustrates the 3D nature of dynamos

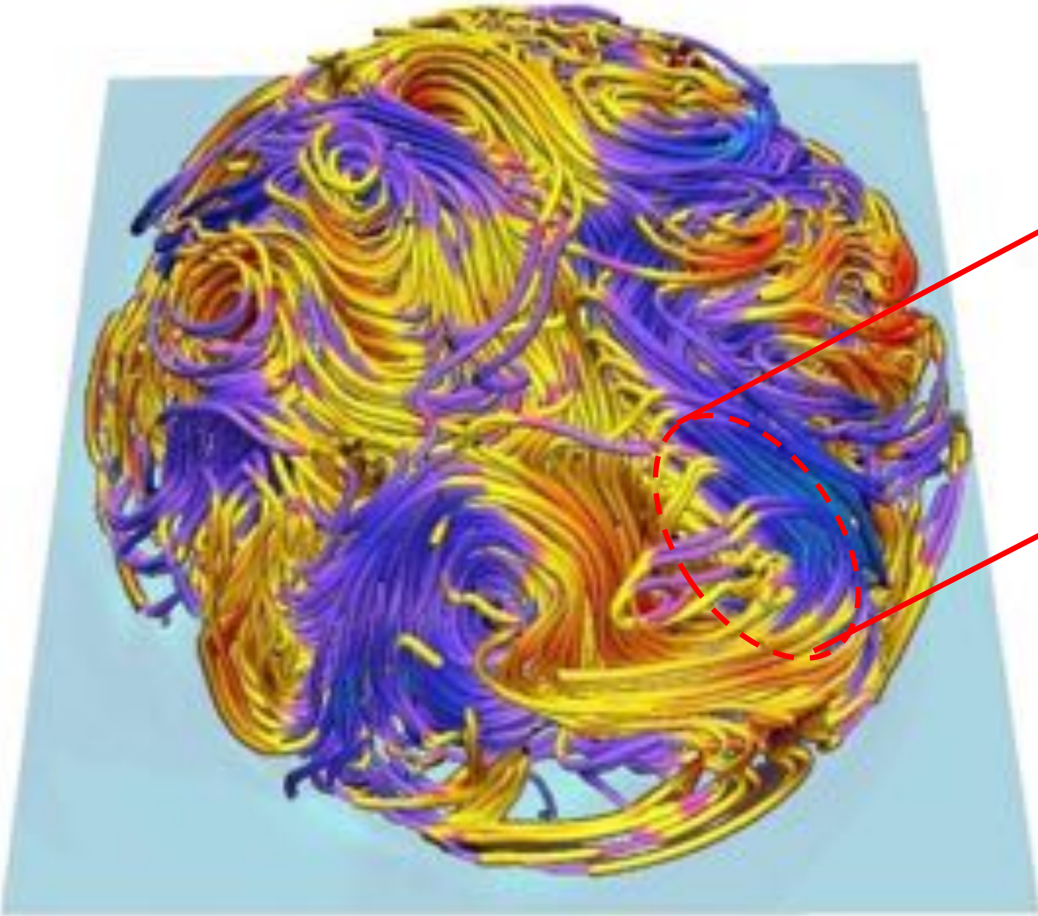
Rotation Yields Helical Convection

Non-rotating
or
Fast Convection

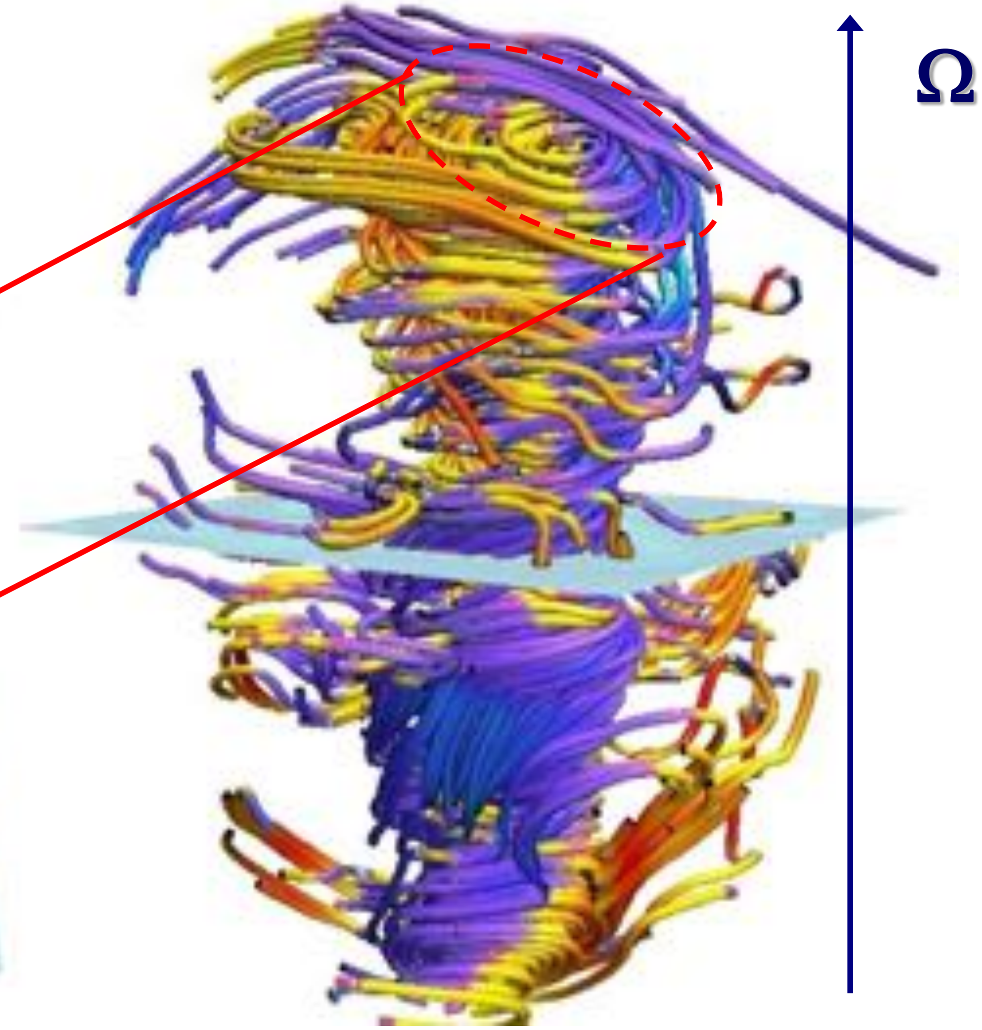
Rapidly-rotating
or
Slow Convection







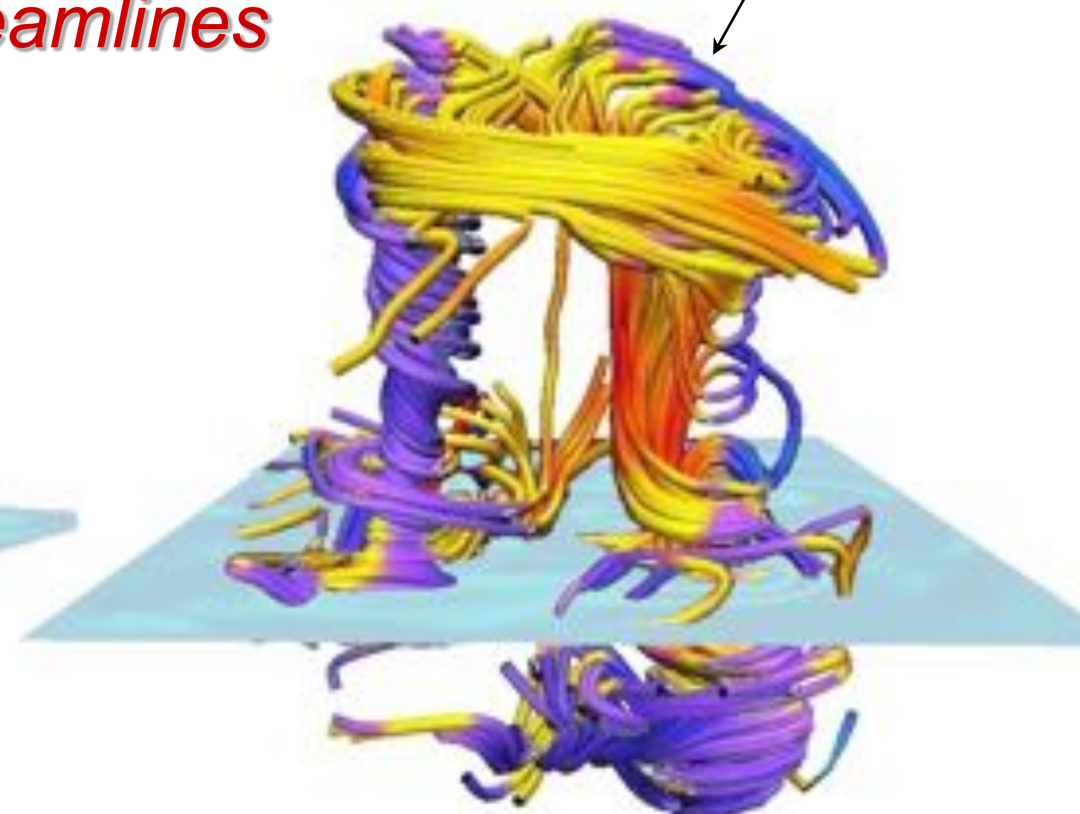
Northern Hemisphere



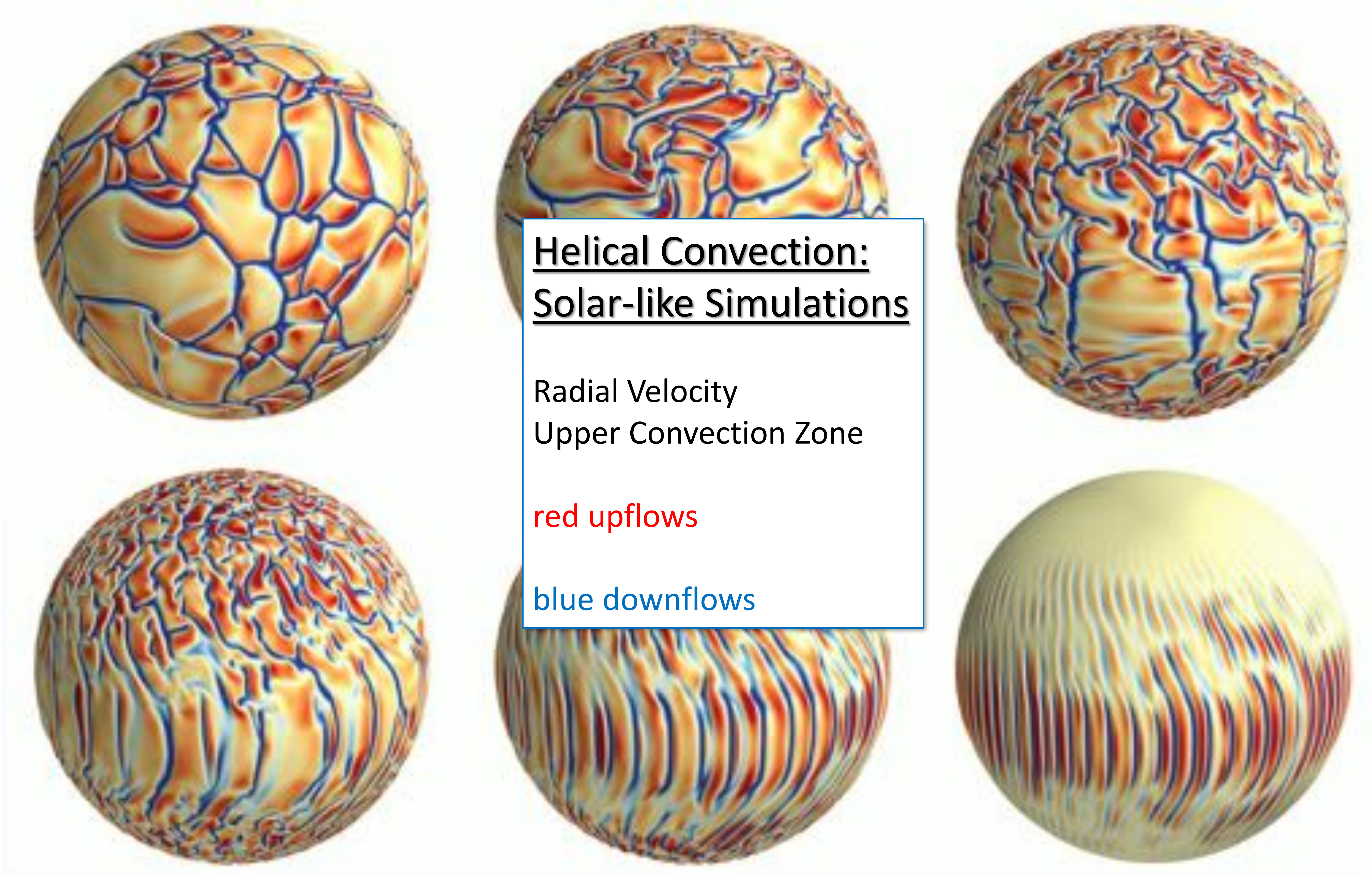
Tilted orbits

Helical Convection (Deep Shells)

Streamlines



Fast Convection / slow rotation



Helical Convection: Solar-like Simulations

Radial Velocity
Upper Convection Zone

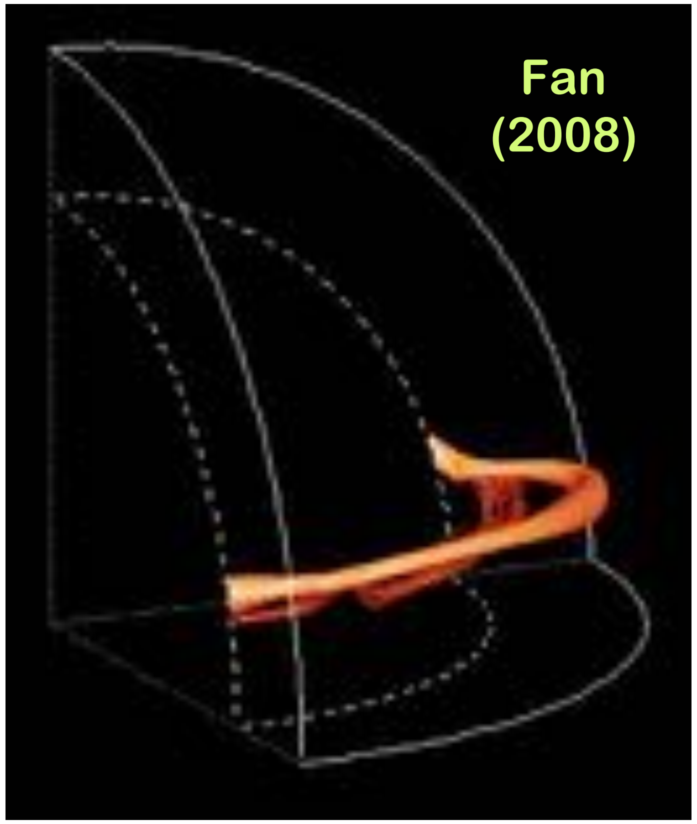
red upflows

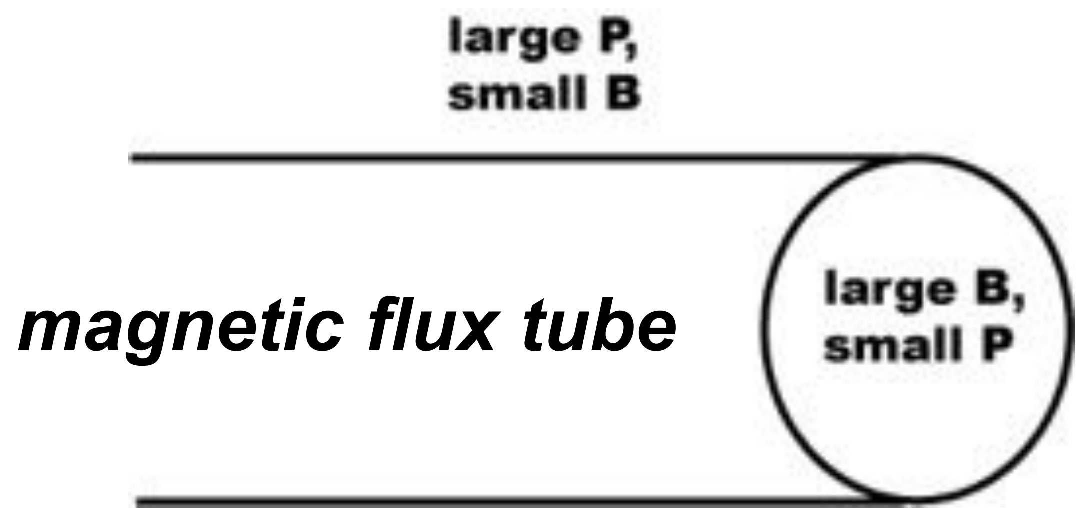
blue downflows

Featherstone & Hindman 2016

Slow convection / rapid rotation

Another Way: Starts with Magnetic Buoyancy





$$P = \mathcal{R}\rho T$$

$$P^{(tube)} + P_m^{(tube)} \approx P^{(ext)}$$

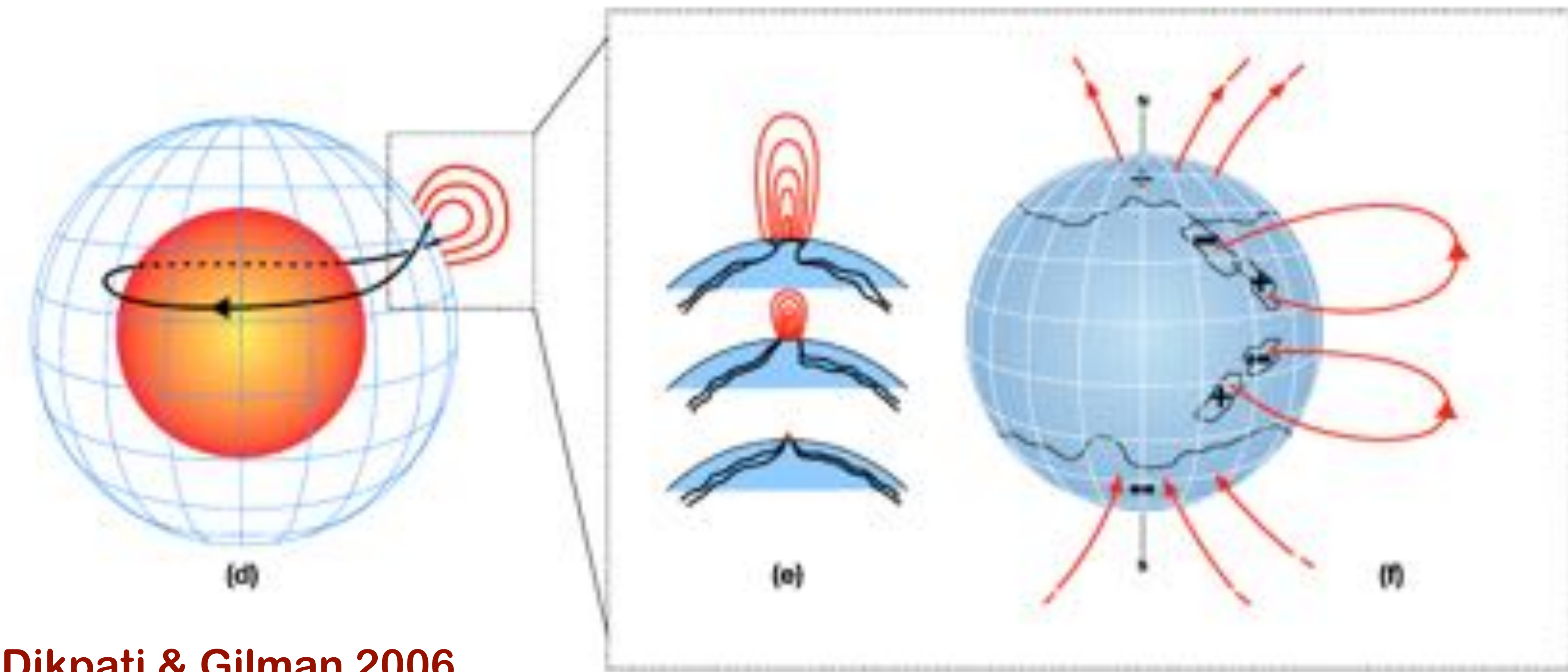
$$P_m = \frac{B^2}{8\pi}$$

$$P^{(tube)} \approx P^{(ext)} - P_m^{(tube)} < P^{(ext)}$$

If $T^{(tube)} \approx T^{(ext)}$

$$\rho^{(tube)} < \rho^{(ext)}$$

The Babcock-Leighton Mechanism



Dikpati & Gilman 2006

Trailing member of the spot pair is displaced poleward relative to leading edge by the Coriolis force (Joy's law: the higher the latitude, the more the tilt)

Polarity of trailing spot is opposite to pre-existing polar field

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

Babcock-Leighton Dynamo Models

Dikpati & Gilman 2006

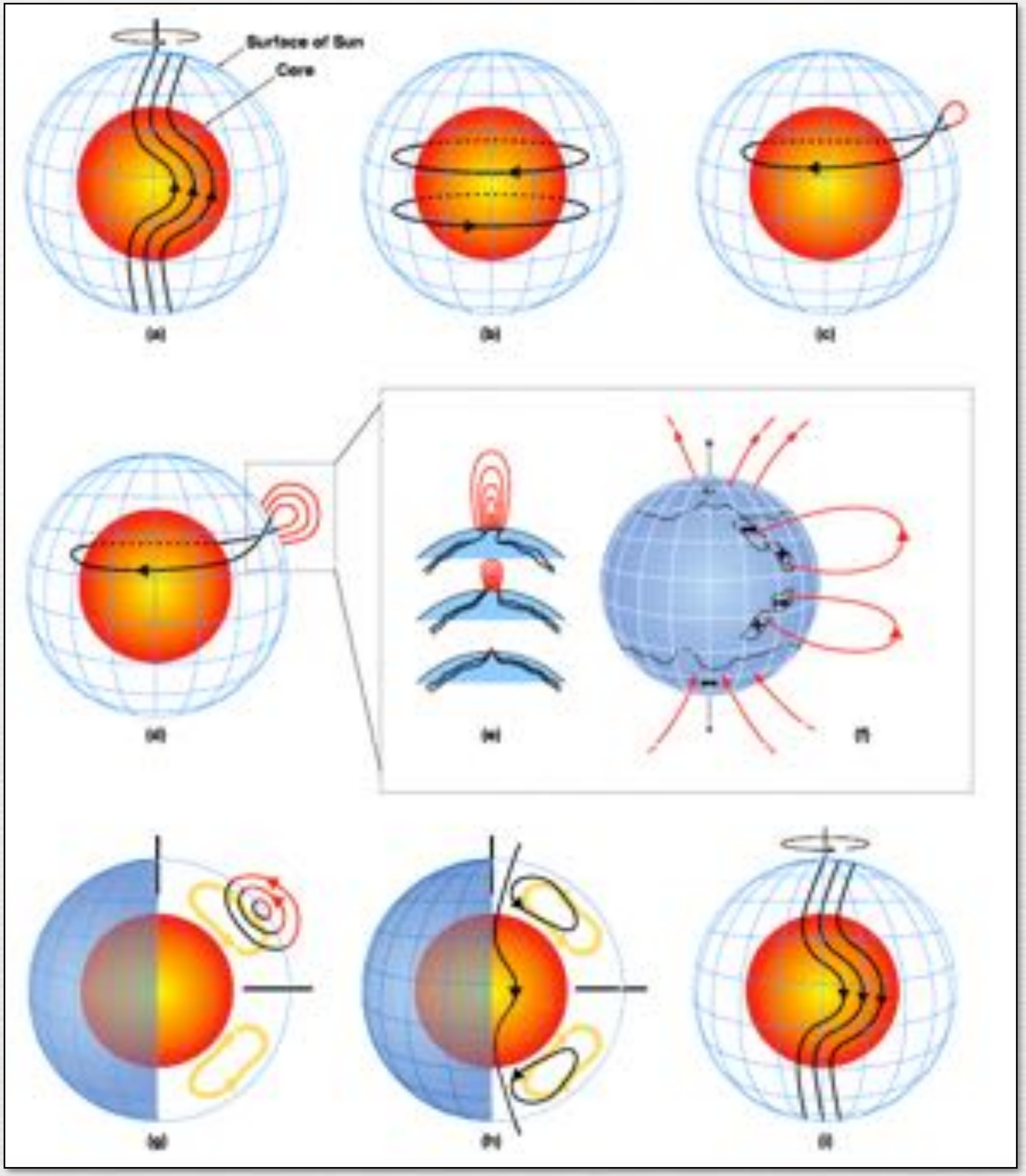
Poloidal field is generated by the Babcock-Leighton Mechanism

Cycle period is regulated by the equatorward advection of toroidal field by the meridional circulation at the base of the CZ

2-3 m/s gives you about 11 years

For this reason, they are also called

Flux-Transport Dynamo Models



Final Thoughts on the Dynamo Process

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

- v influences B …
- … AND vice versa

$$\rho \frac{\partial \mathbf{v}}{\partial t} = -(\rho \mathbf{v} \cdot \boldsymbol{\nabla})\, \mathbf{v} - 2\rho\, (\boldsymbol{\Omega} \times \mathbf{v}) - \boldsymbol{\nabla} P + \rho \mathbf{g} + c^{-1} \mathbf{J} \times \mathbf{B} - \boldsymbol{\nabla} \cdot \boldsymbol{\mathcal{D}}$$

Final Thoughts on the Dynamo Process

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

- v influences B …
- … AND vice versa

$$\rho \frac{\partial \mathbf{v}}{\partial t} = -(\rho \mathbf{v} \cdot \nabla)\mathbf{v} - 2\rho(\mathbf{\Omega} \times \mathbf{v}) - \nabla P + \rho \mathbf{g} + c^{-1} \mathbf{J} \times \mathbf{B} - \nabla \cdot \mathcal{D}$$

This suggests two classes of dynamos:

Essentially Kinematic:

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:

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

The focus then shifts toward: Dynamo Excitation + Dynamics

Ultimately, convective flows drive a stellar dynamo.

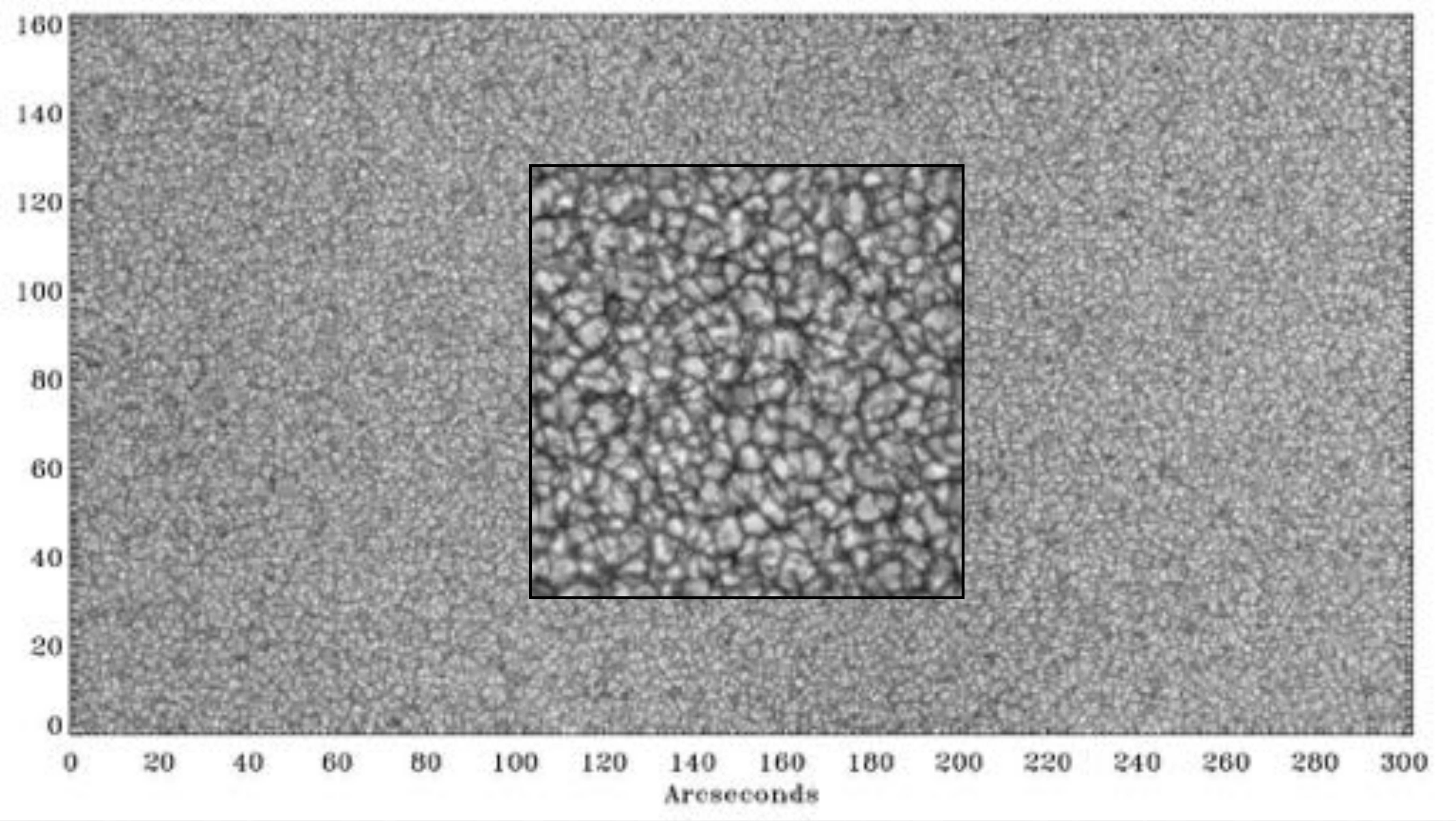
How fast are those flows?

What is their structure?

These are NOT easy questions to answer

Granulation in the Quiet Sun

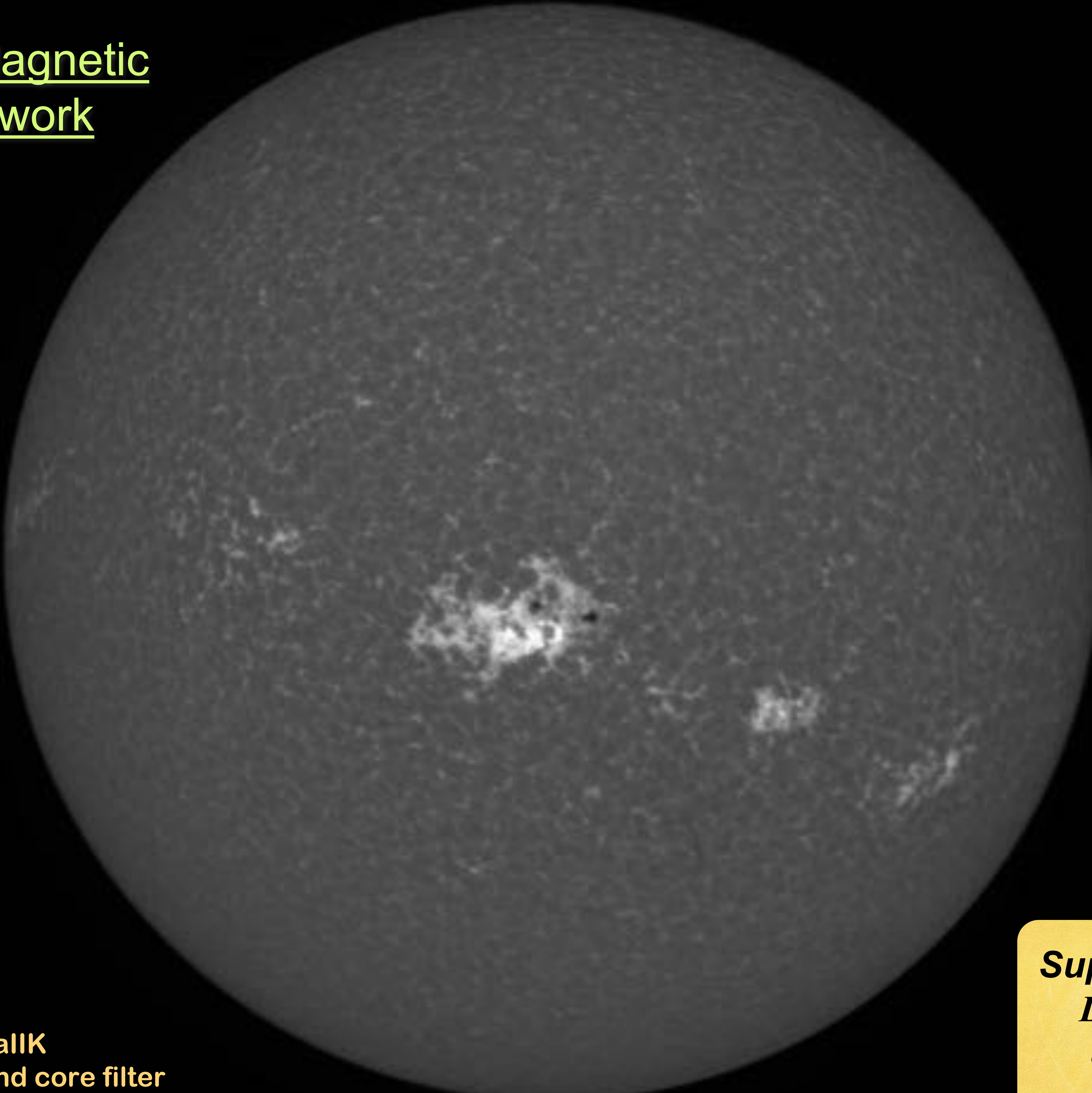
Lites et al (2008)



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

Dominant size scale of solar convection

The Magnetic Network

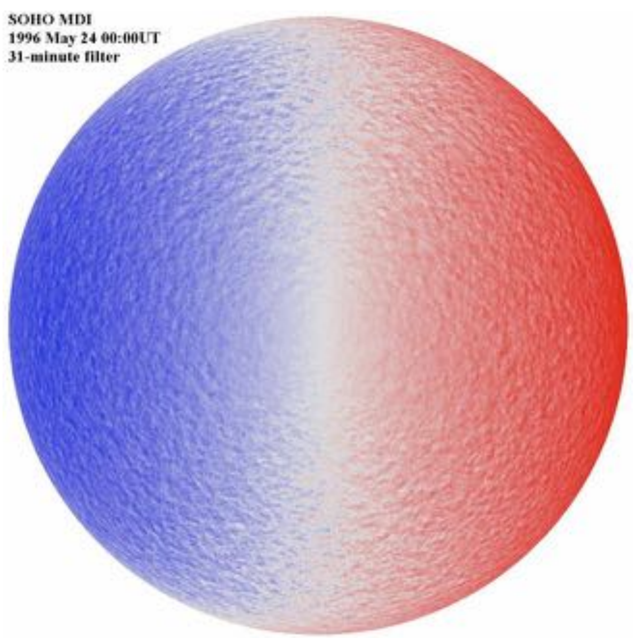


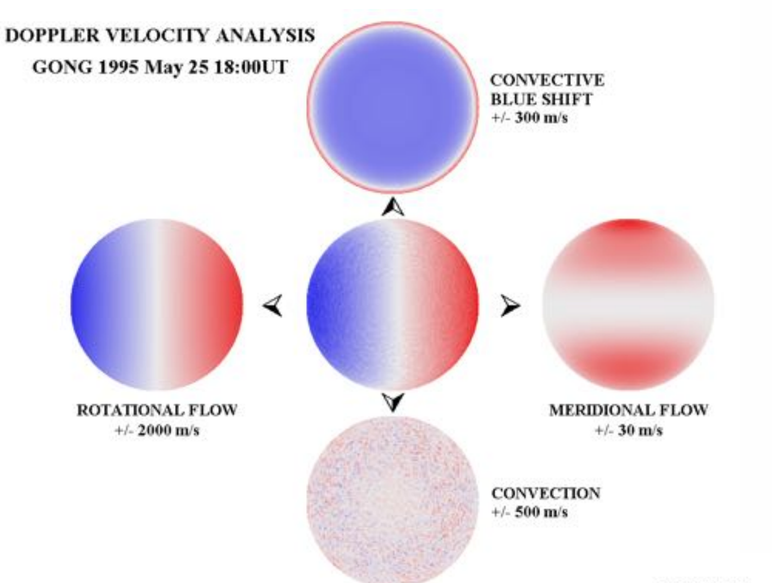
CaIIK
narrow-band core filter
PSPT/MLSO

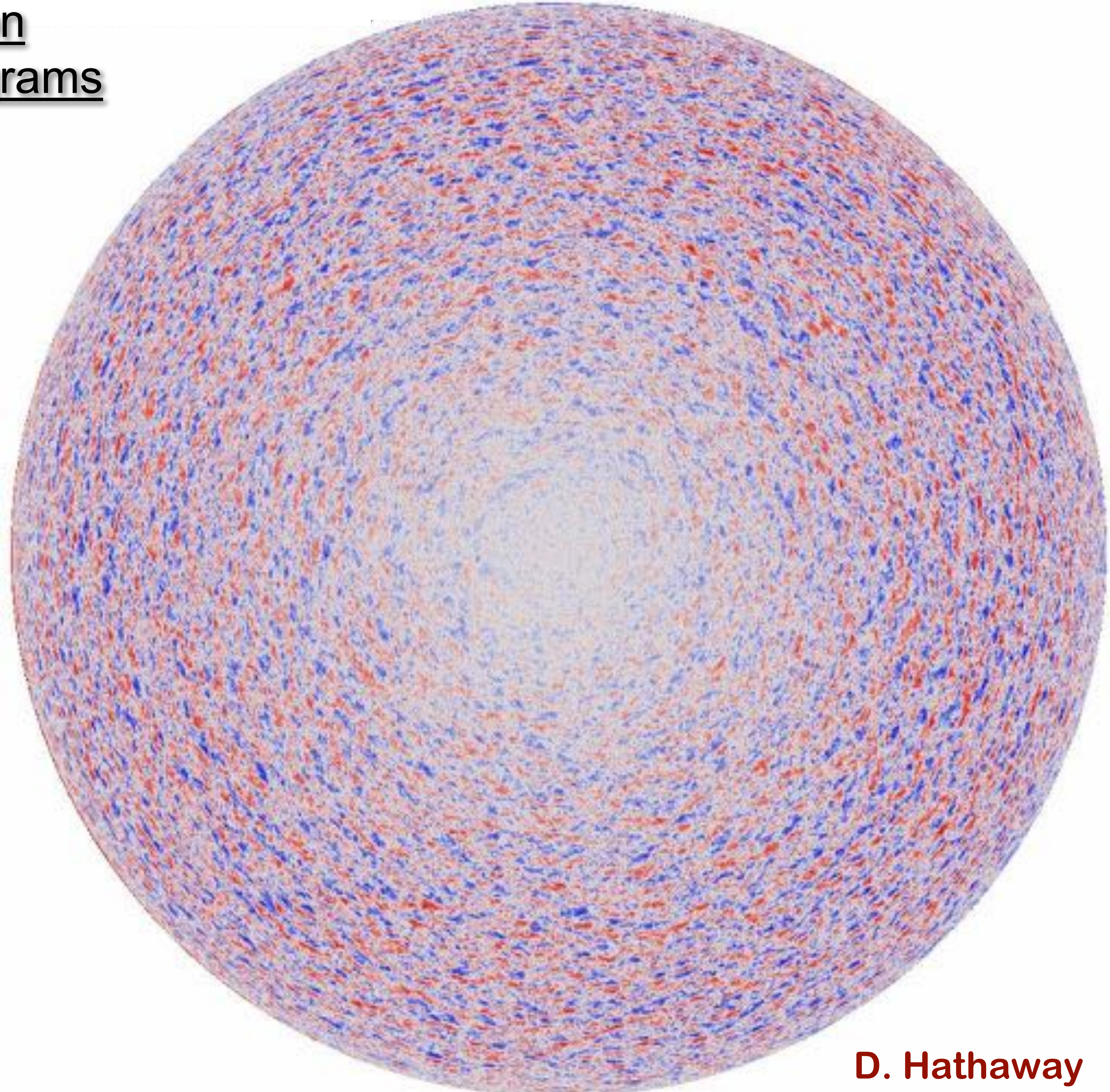
Supergranulation
$L \sim$ 30-35 Mm
$U \sim$ 500 m s^{-1}
$\tau_c \sim$ 20 hr

Supergranulation in Filtered Dopplergrams

Most prominent in horizontal velocities near the limb







D. Hathaway (NASA MSFC)

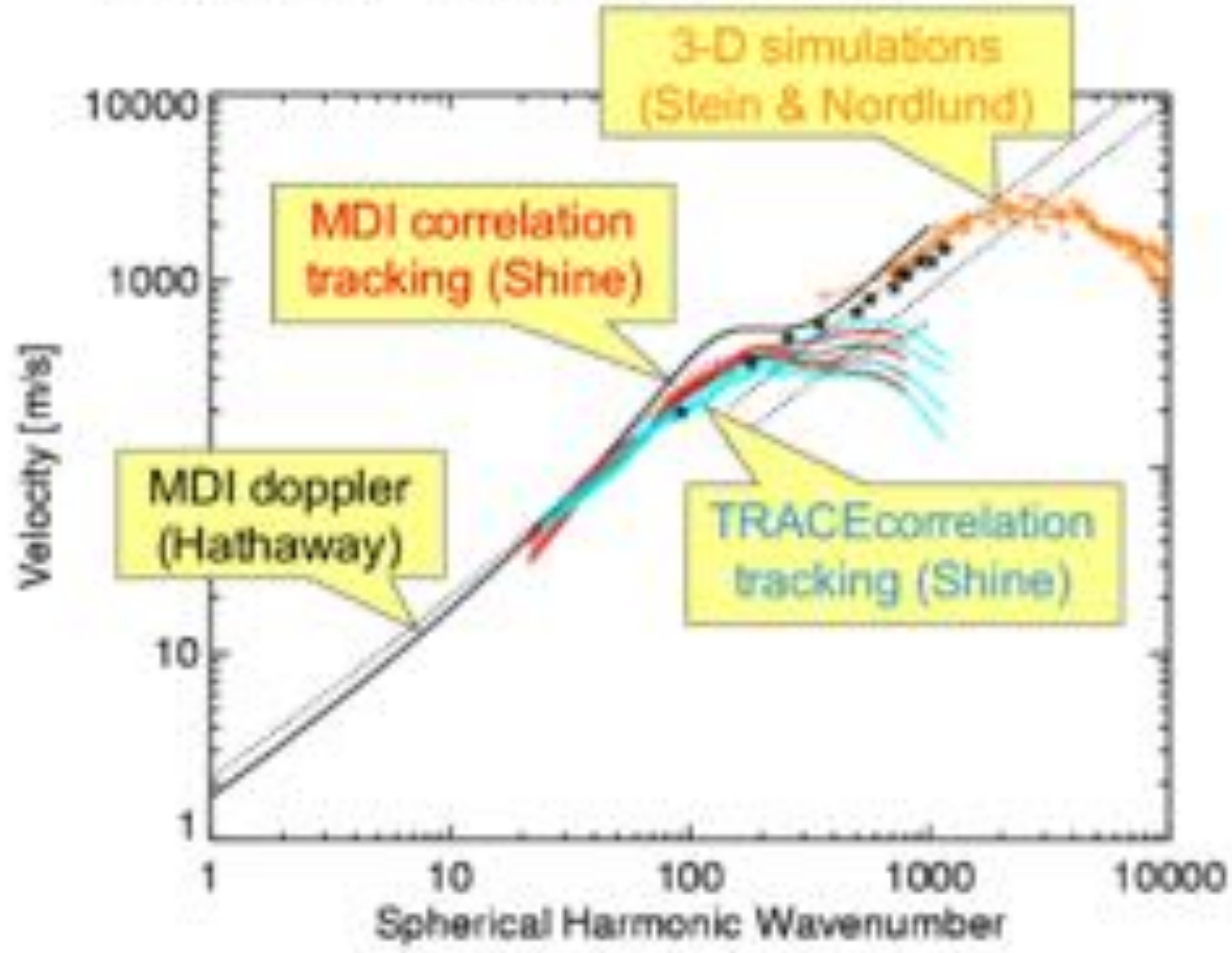
A hierarchy of convective scales

Density increases dramatically with depth below the solar surface

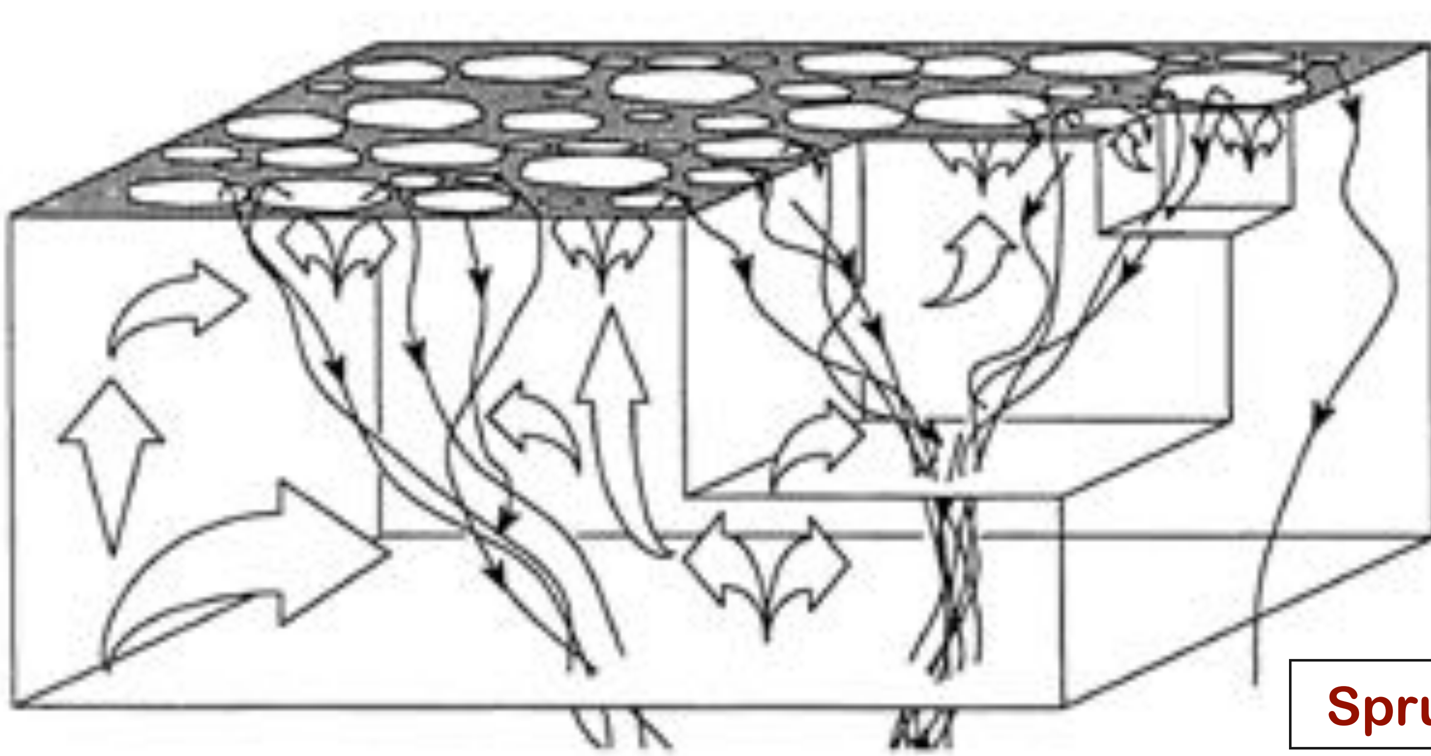
Fast, narrow down flows (plumes) Slow, broad upflows

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

Downward plumes merge into superplumes that penetrate deeper



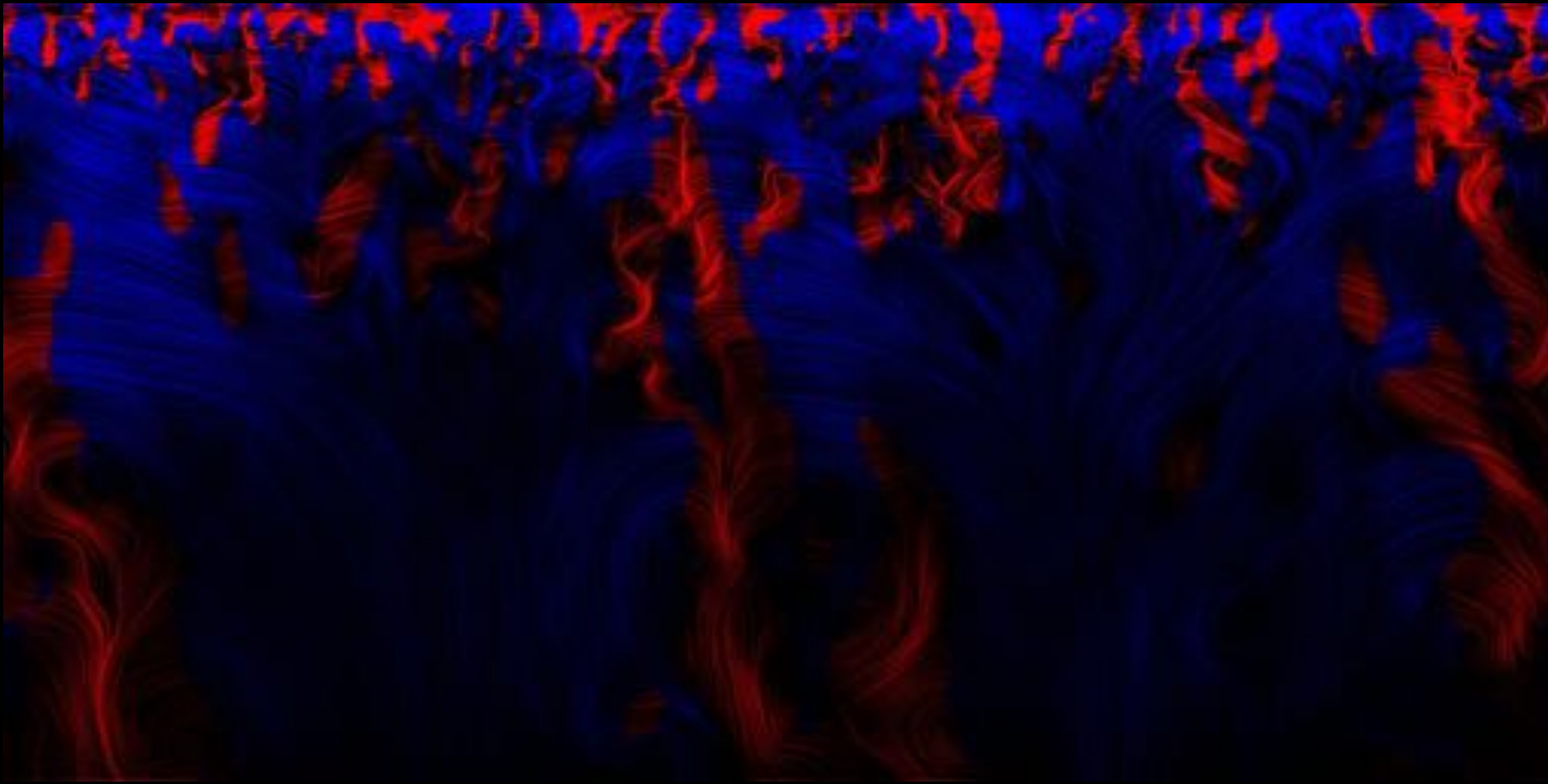
Nordlund, Stein & Asplund (2009)



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

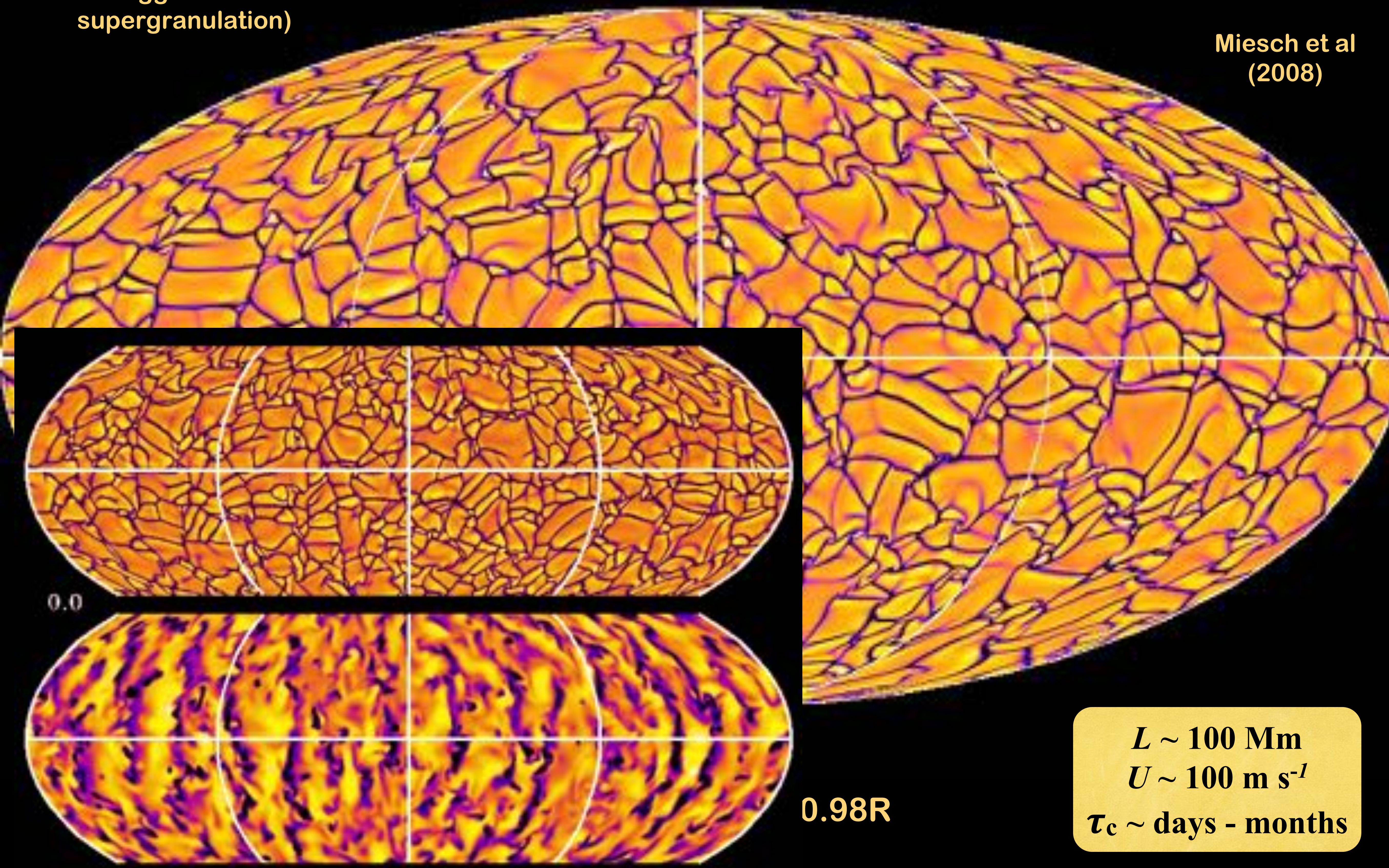
But still stops at 0.97R!
what lies deeper still?

Giant Cells

(Loosely, anything bigger than supergranulation)

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

Miesch et al (2008)



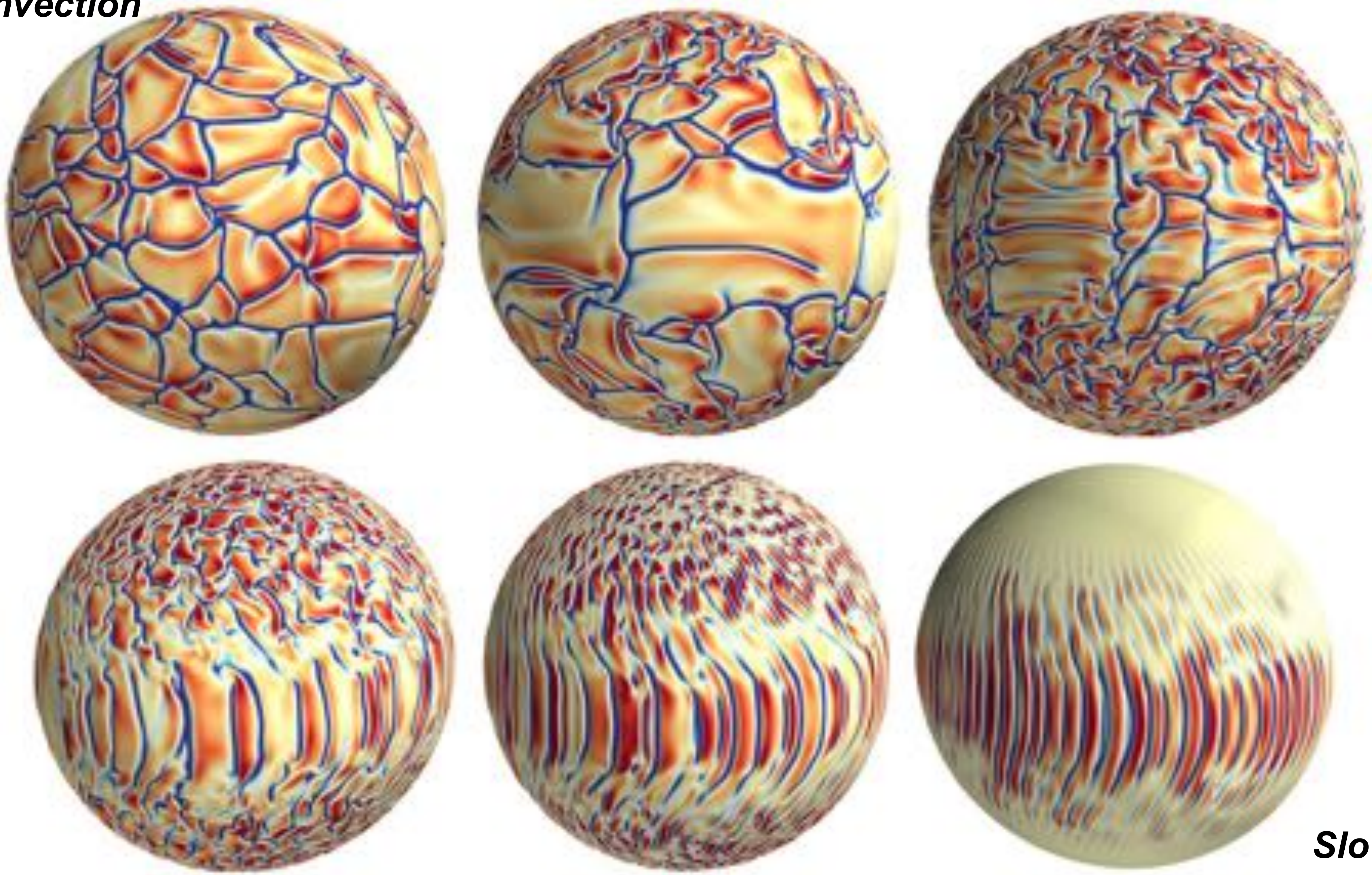
$L \sim 100$ Mm

$U \sim 100$ m s^{-1}

$\tau_c \sim$ days - months

Rapid Convection

N. Featherstone



Slow Convection

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

How do we know they are there?

We don’t.

This is a major puzzle for solar (and also stellar) dynamo theory and brings us to one of the major outstanding questions.

What is the solar Rossby Number?

typical velocity

$$Ro = \frac{v}{2\Omega L} = \frac{\text{Rotational Timescale}}{\text{Convective Timescale}}$$

rotation rate

typical length scale

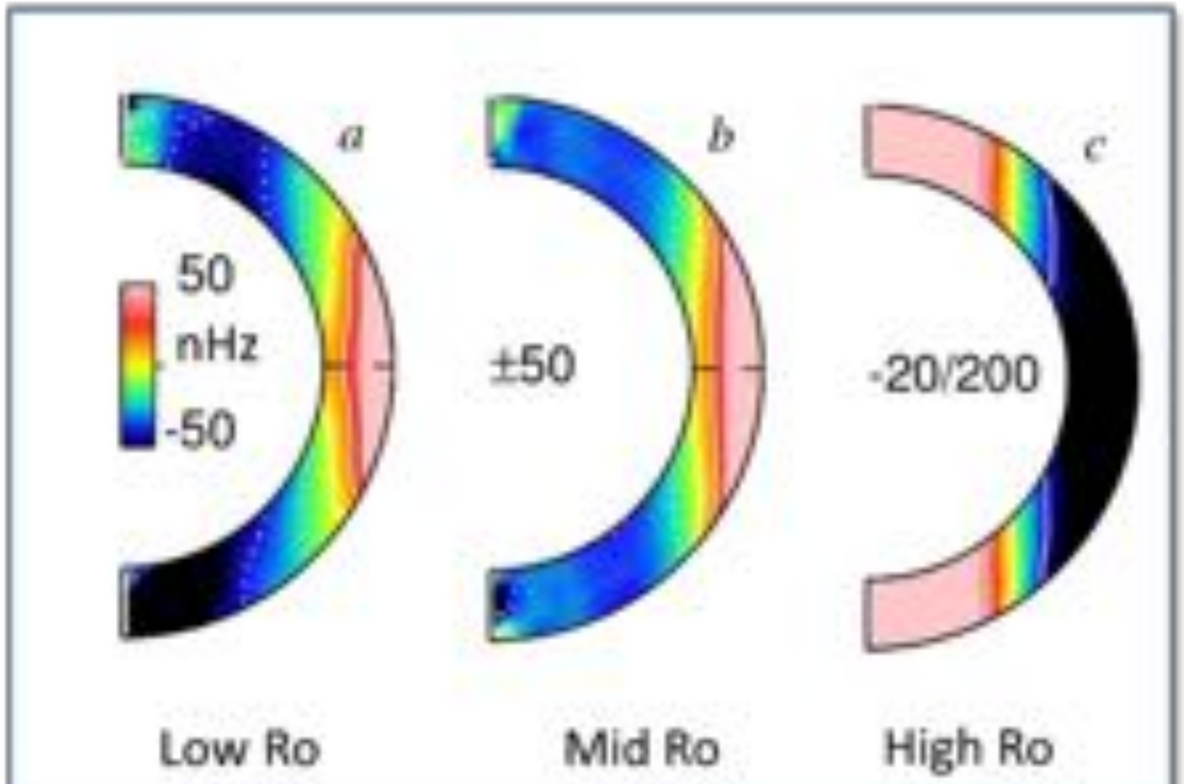
What is Ro in the Sun?

What is v?

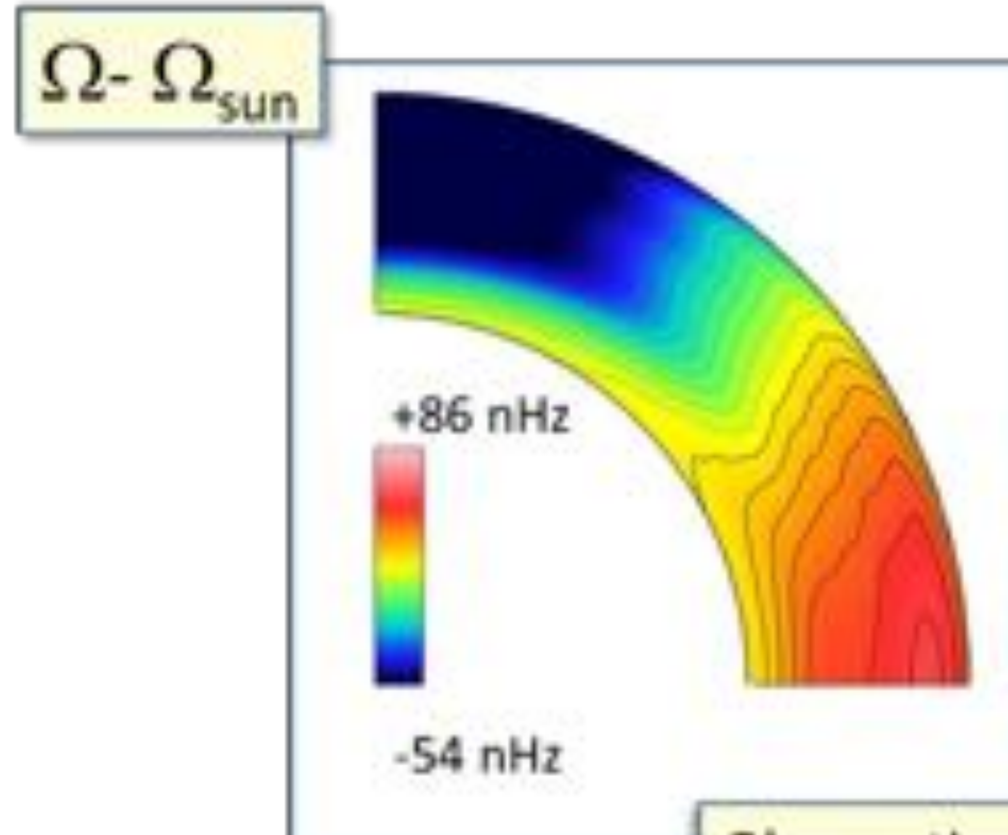
Aside
1. Consider system-scale Ro
2. v = rms convective flow speed
3. L = shell depth

Ro influences the structure of the convection and so too MANY aspects of the dynamo!

Ro determines differential rotation



Models
Featherstone & Miesch 2015

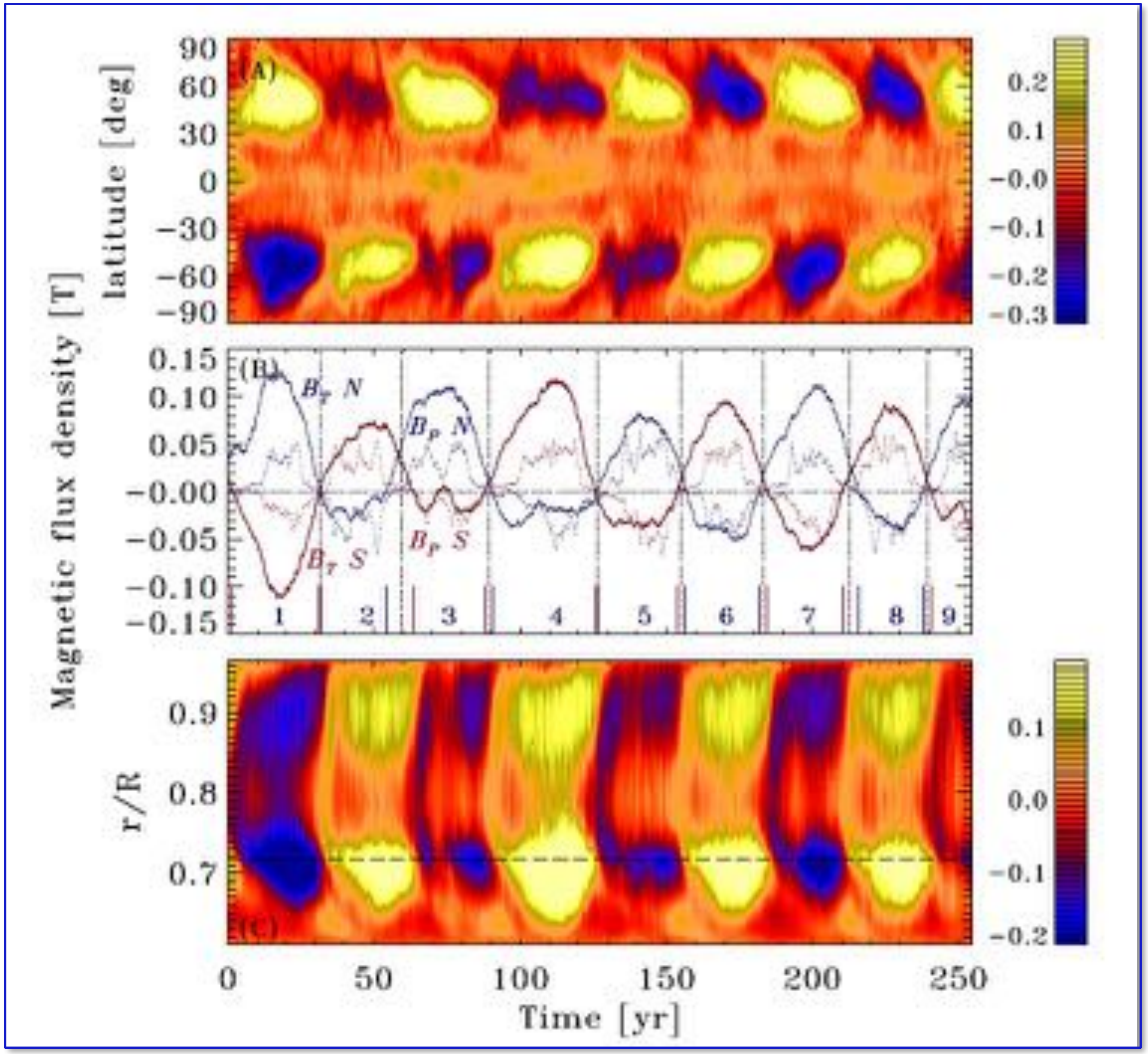


Observations
Howe et al. 2000;
Schou et al. 2002

AND: Glatzmaier & Gilman 1982; Brun & Toomre 2002; Gastine et al. 2014; Guerrero et al 2013; Kapyla et al. 2014 ...

Aside: differential rotation may be indirect evidence of giant cells, but see tomorrow's discussion!

Low Ro Promotes Magnetic Cycles (models)

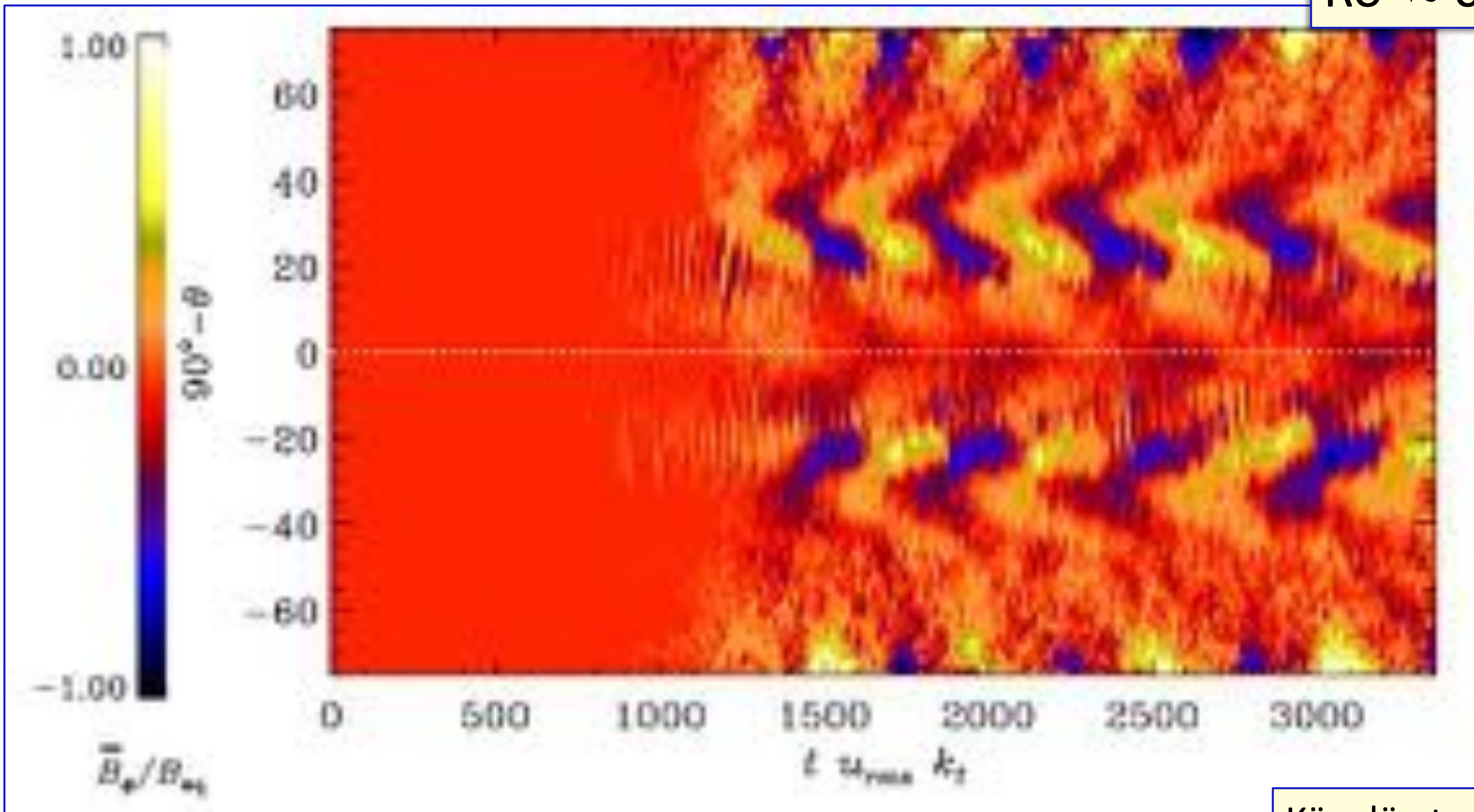


Ro ≈ 0.01

Ghizaru,
Charbonneau
& Schmolarkiewicz
2010

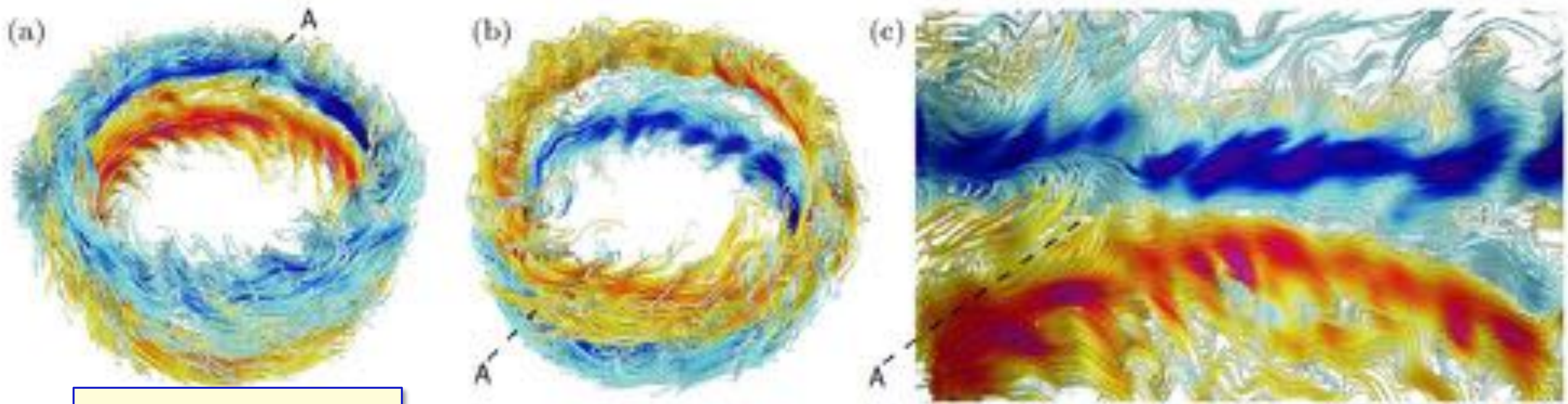
... and Equatorward Propagation of Magnetic Features (models)

Ro ≈ 0.02



Käpylä et al. 2013

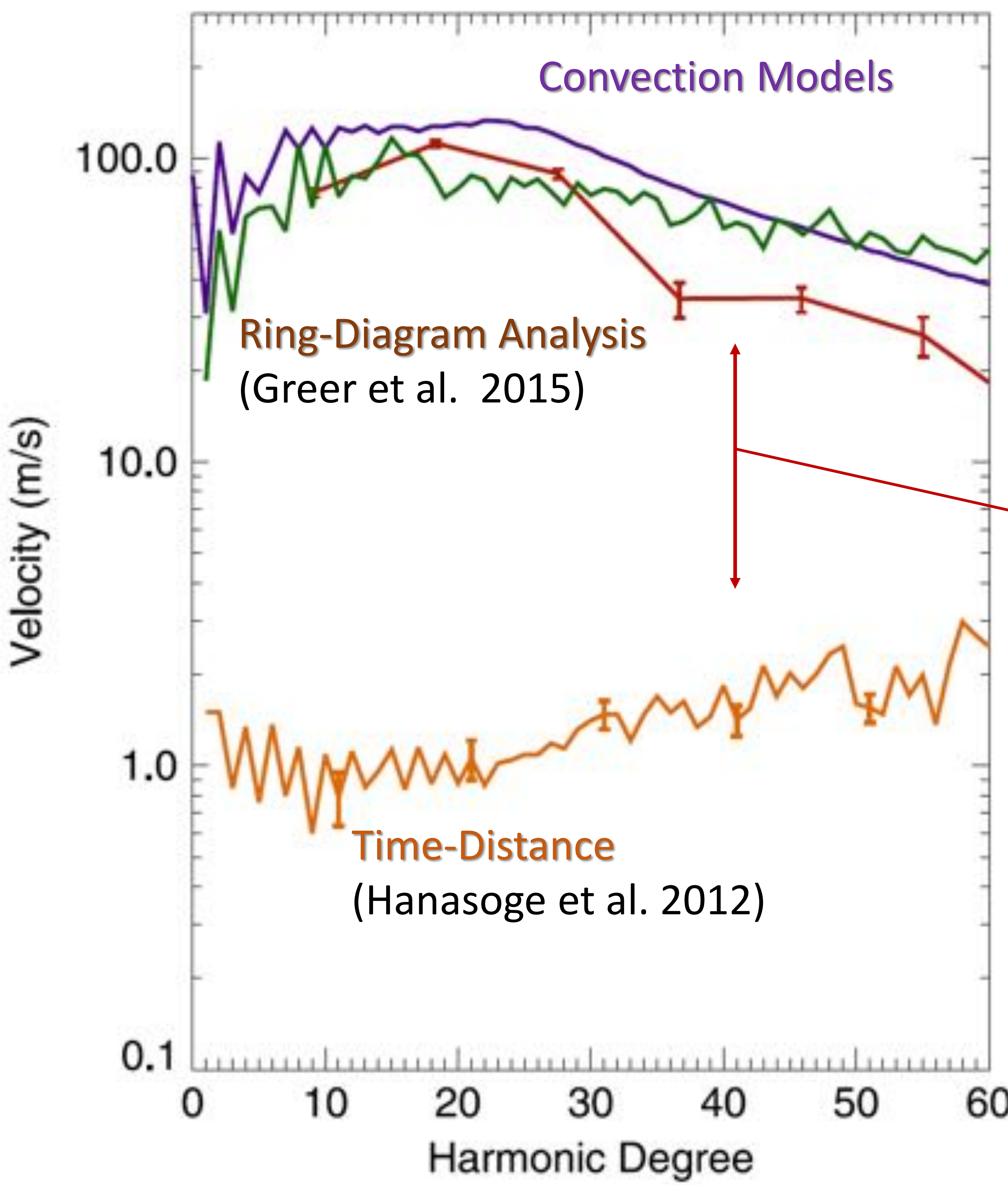
… and Large-Scale Magnetic Structure (models)



Brown et al. 2010

"wreathy" dynamos

Ro ≈ 0.03



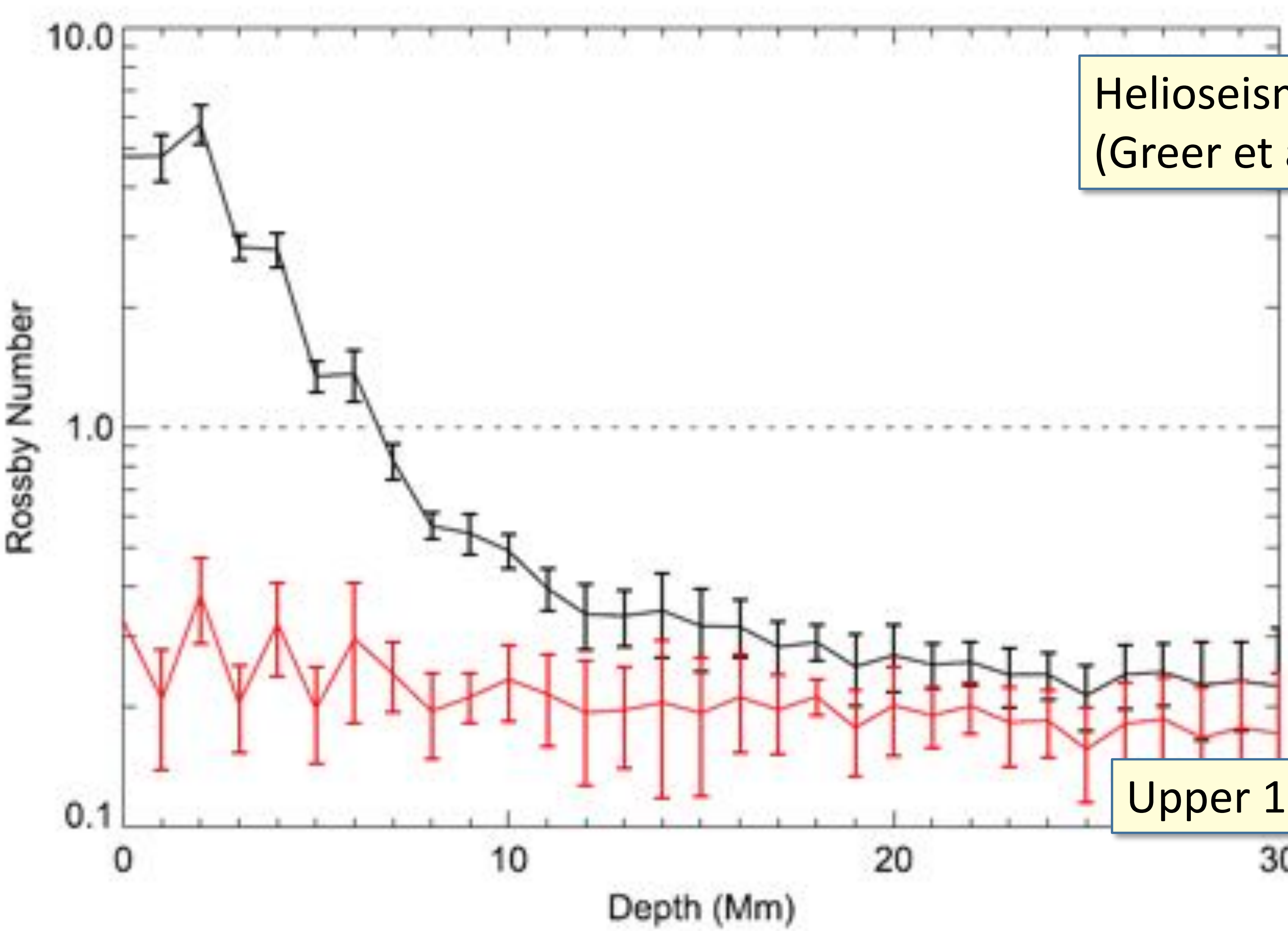
What do measurements tell us?

Disagreeing Observations (0.96 R_{sun})

Open Question:

How fast is deep solar convection?

What we know: at Depth ... Ro is LOW



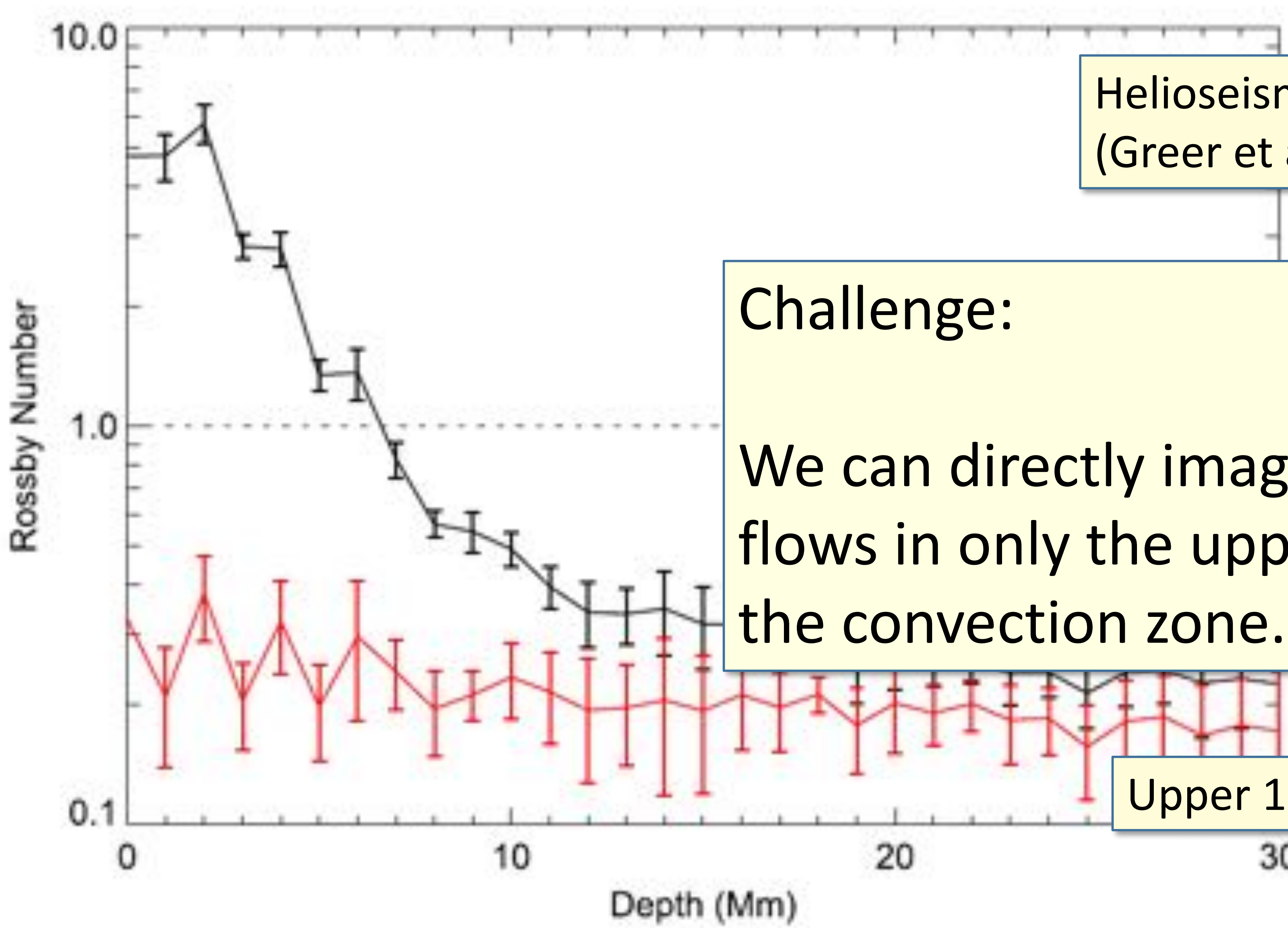
Helioseismology
(Greer et al. 2016)

Upper 15% of solar CZ

But how low?
Open Question!

Possibly even lower:
See non-detection of Hanasoge et al. 2012, PNAS, 109, 11928

What we know: at Depth …   Ro is LOW



Helioseismology
(Greer et al. 2016)

Challenge:

We can directly image convective flows in only the upper 15% of the convection zone.

Upper 15% of solar CZ

But how low?
Open Question!

Possibly even lower:
See non-detection of Hanasoge et al. 2012, PNAS, 109, 11928

What do we expect at the solar surface?

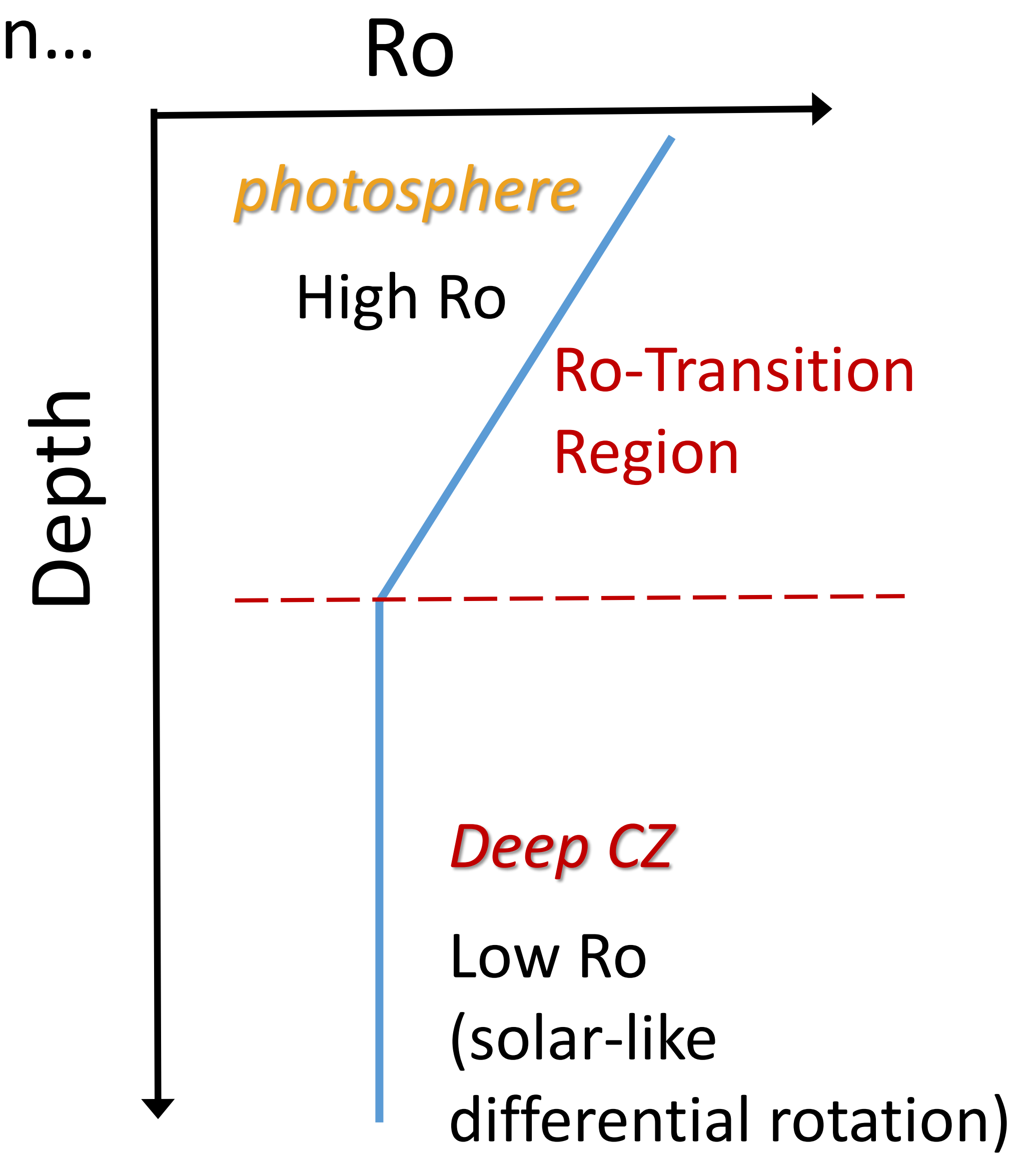
We might expect to see two types of convection…

1. Small-scale motions:
   - Near-surface features
   - high-Ro
   - Spatial-scale depends on Ro-transition depth

Observed:
30 Mm size
Ro = 3

2. Large-scale motions:
   - deep-seated, global
   - low-Ro

Unobserved…



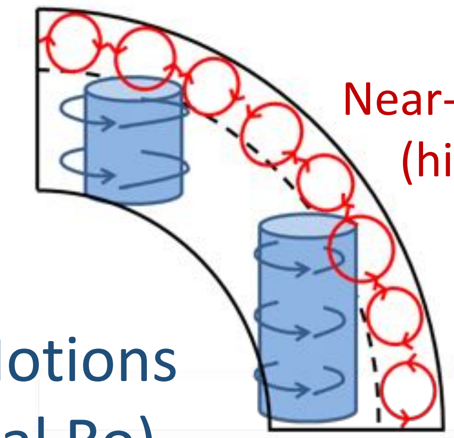
Lack of #2 may be telling us something…

Deep Motions & Their Spectra

Cellular Structure

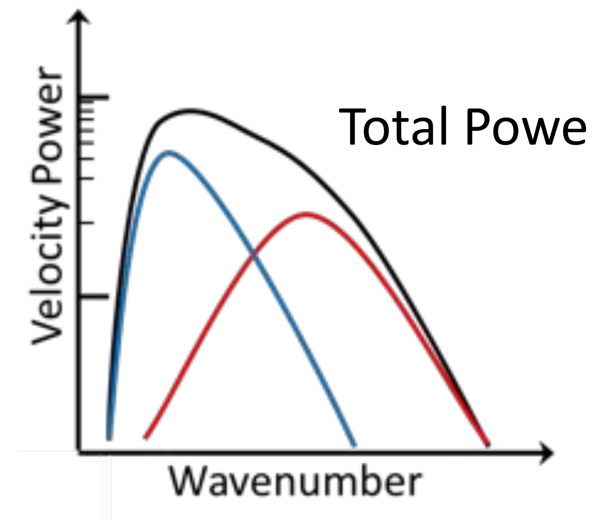
Photospheric Power

Classic Cartoon
(not observed)

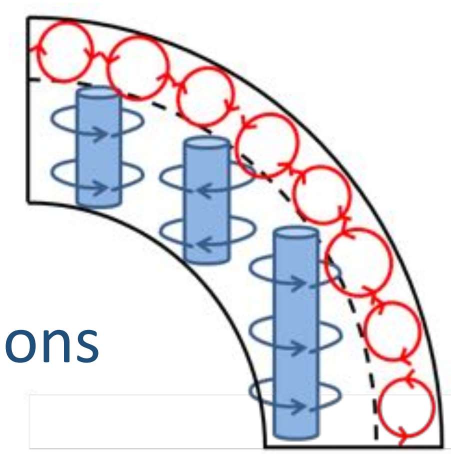


Near-Surface Motions
(high-Ro)

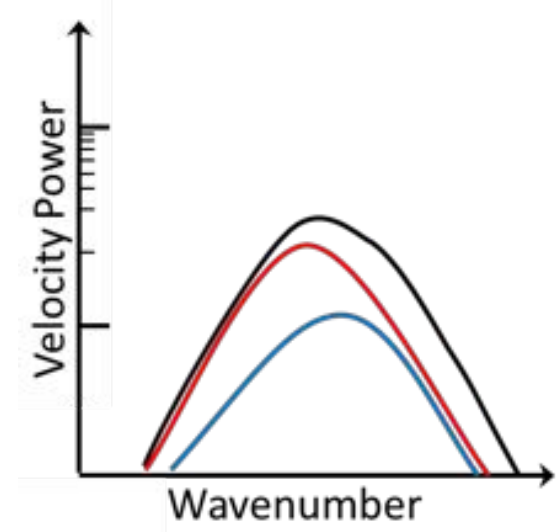
Deep Motions
(marginal Ro)



Alternative
Possibility



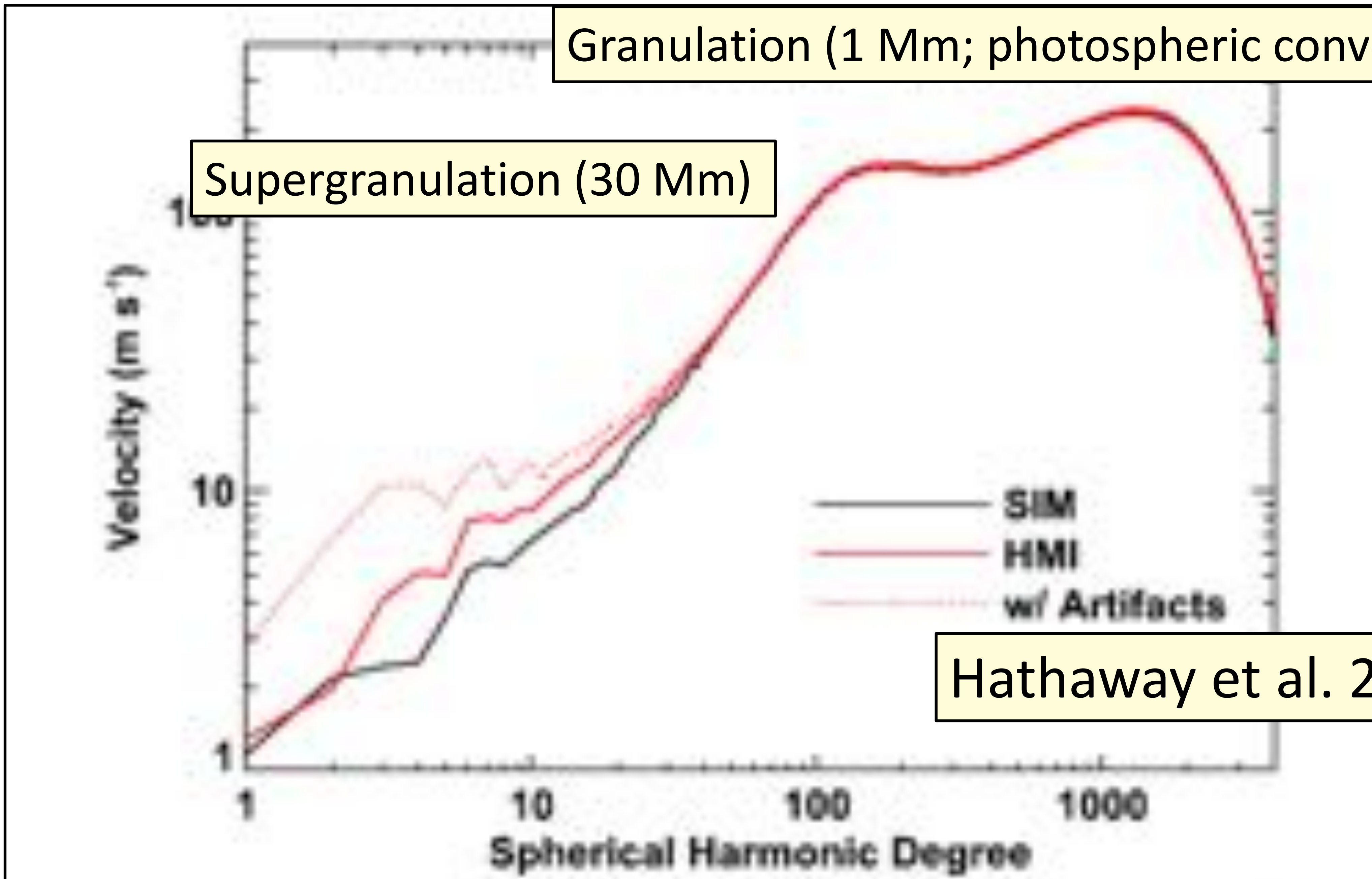
Deep Motions
(Low- Ro)



Featherstone & Hindman 2016

Photospheric Doppler Velocity Spectra

Giant Cells (200 Mm, Not here)



Granulation (1 Mm; photospheric convection)

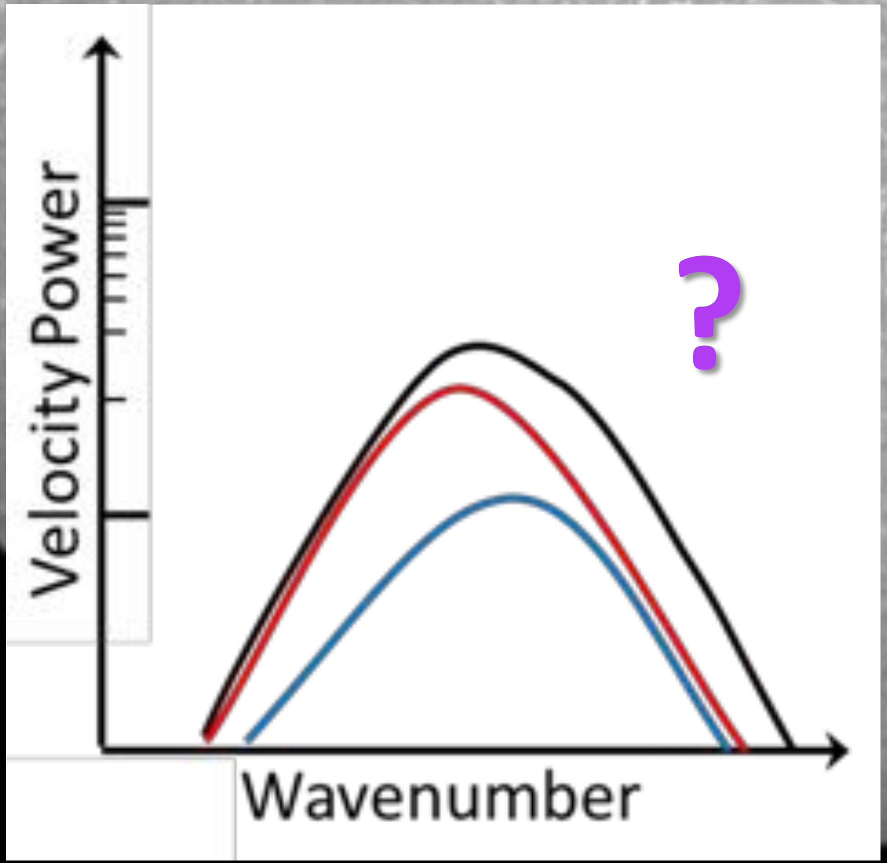
Supergranulation (30 Mm)

Hathaway et al. 2015

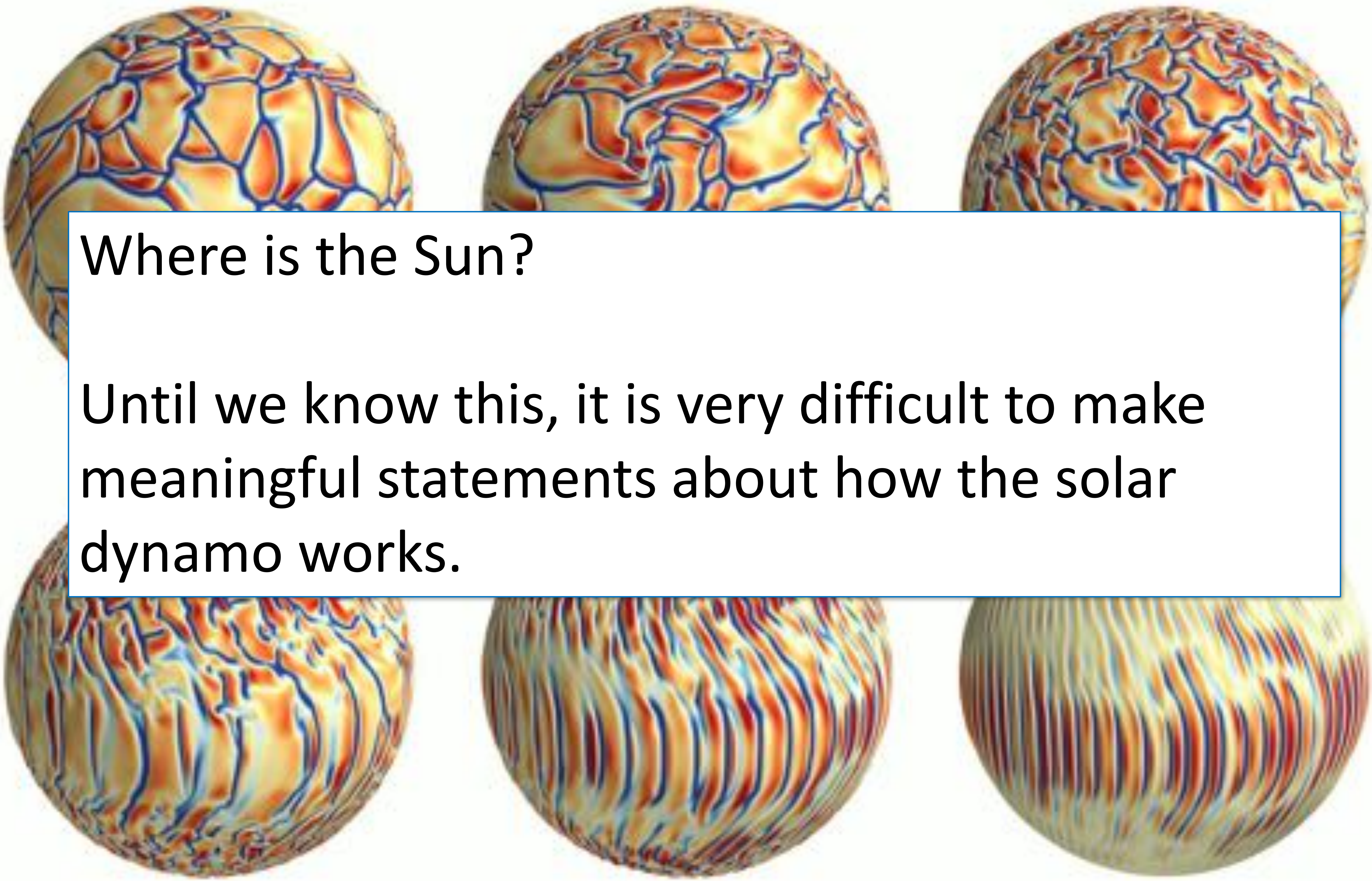
Supergranulation

The largest, distinctly visible mode of solar convection is not rotationally constrained at the surface.

$L \approx 30$ Mm
$U \approx 400$ m s^{-1}
$Ro \approx 2.7$



AIA 1700



Where is the Sun?

Until we know this, it is very difficult to make meaningful statements about how the solar dynamo works.