Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

# Solar Internal Flows and Dynamo Action


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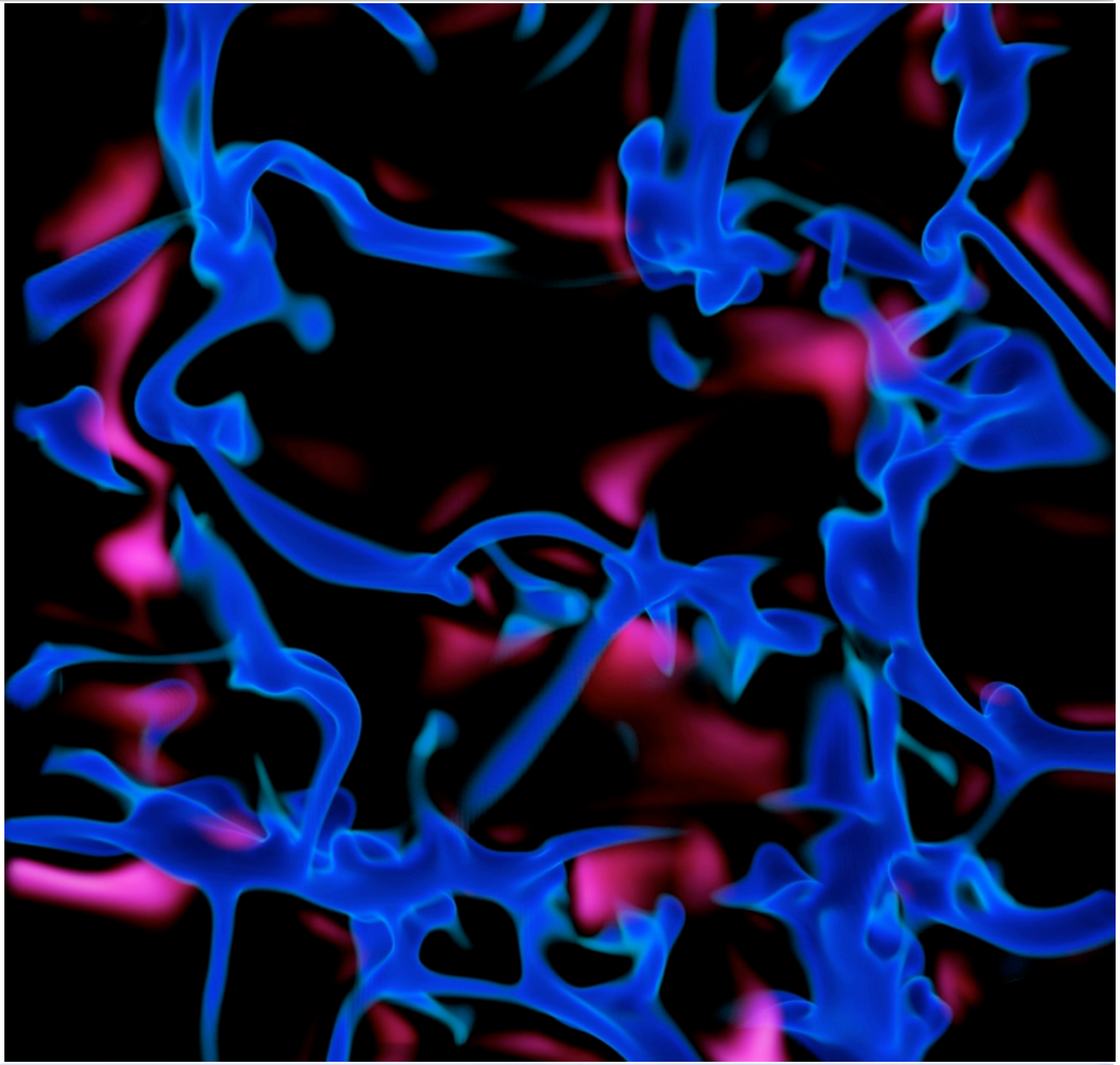
HAO/NCAR

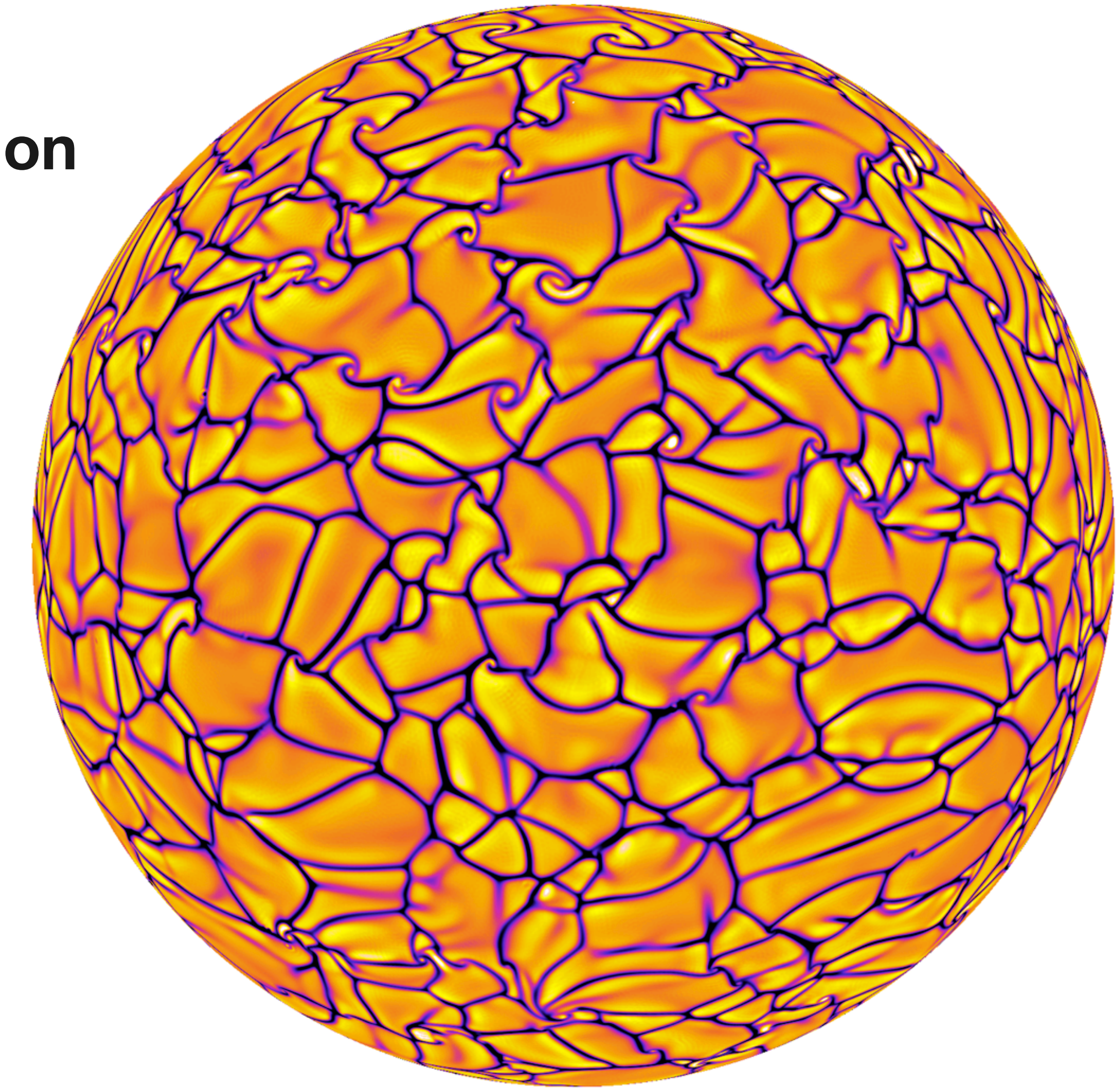

NASA Heliophysics Summer School
Year 3
The Earth's Climate System and Long-Term Solar Activity

22-29 July, 2009
Boulder, CO



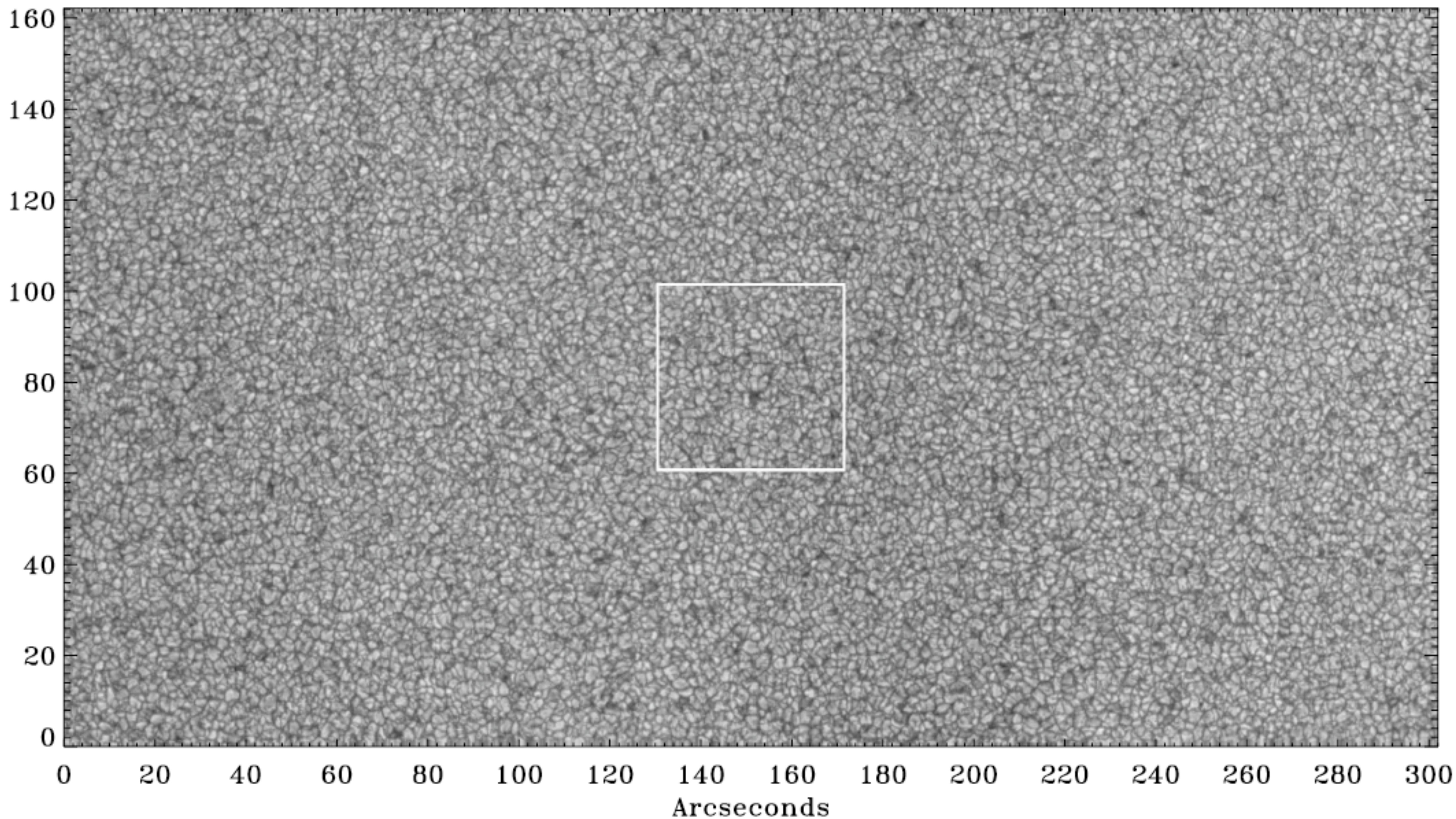
# Outline

- **Solar Convection**
  - Granulation
  - Supergranulation, Mesogranulation
  - Giant Cells
- **Rotational Shear and Meridional Flow**
  - Helioseismology
  - The Solar Internal Rotation
  - Maintenance of mean flows
- **Convection, Shear and Magnetism**
  - Local Dynamos
  - Global Dynamos



# Granulation in the Quiet Sun

**Lites et al (2008)**




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

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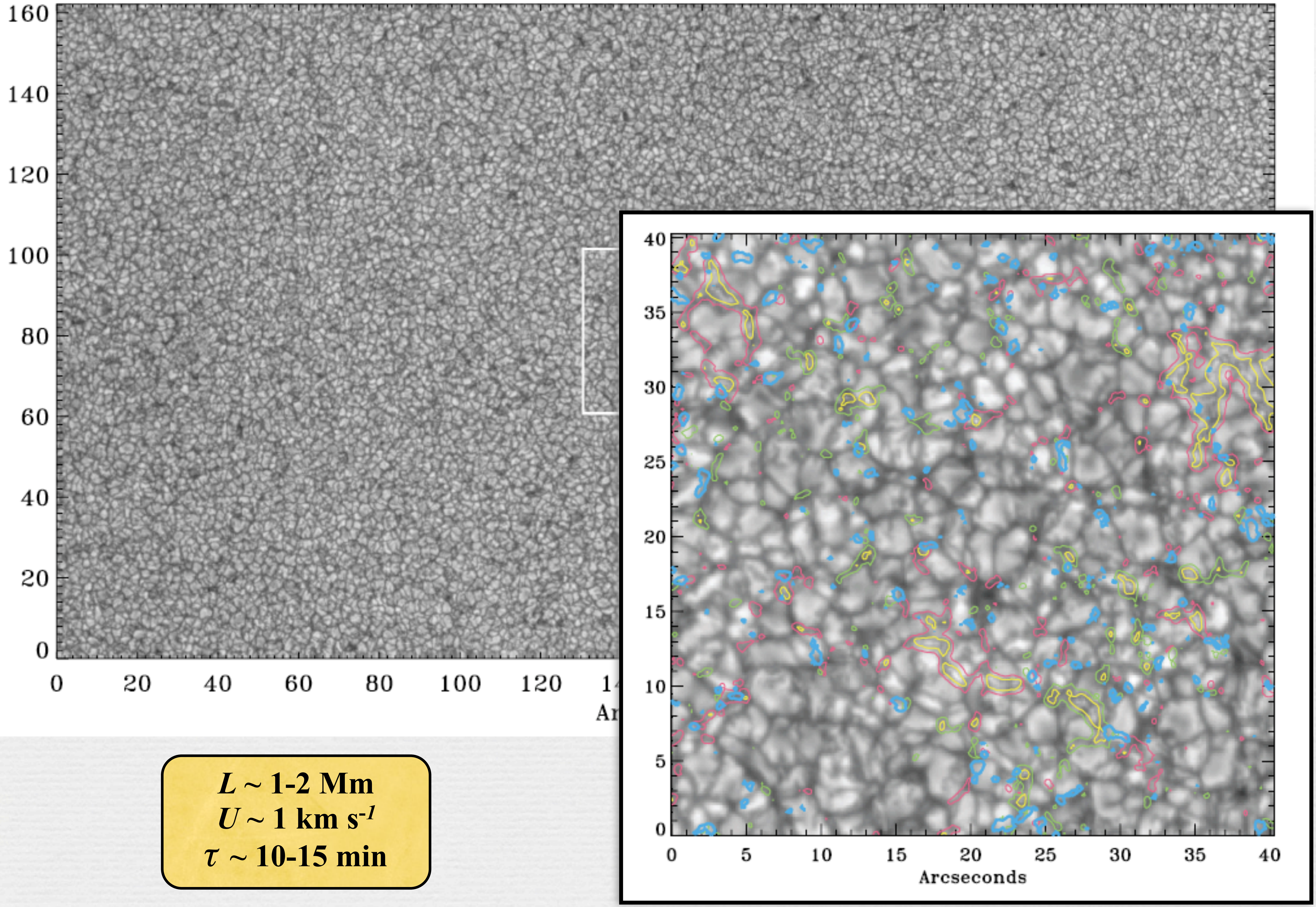


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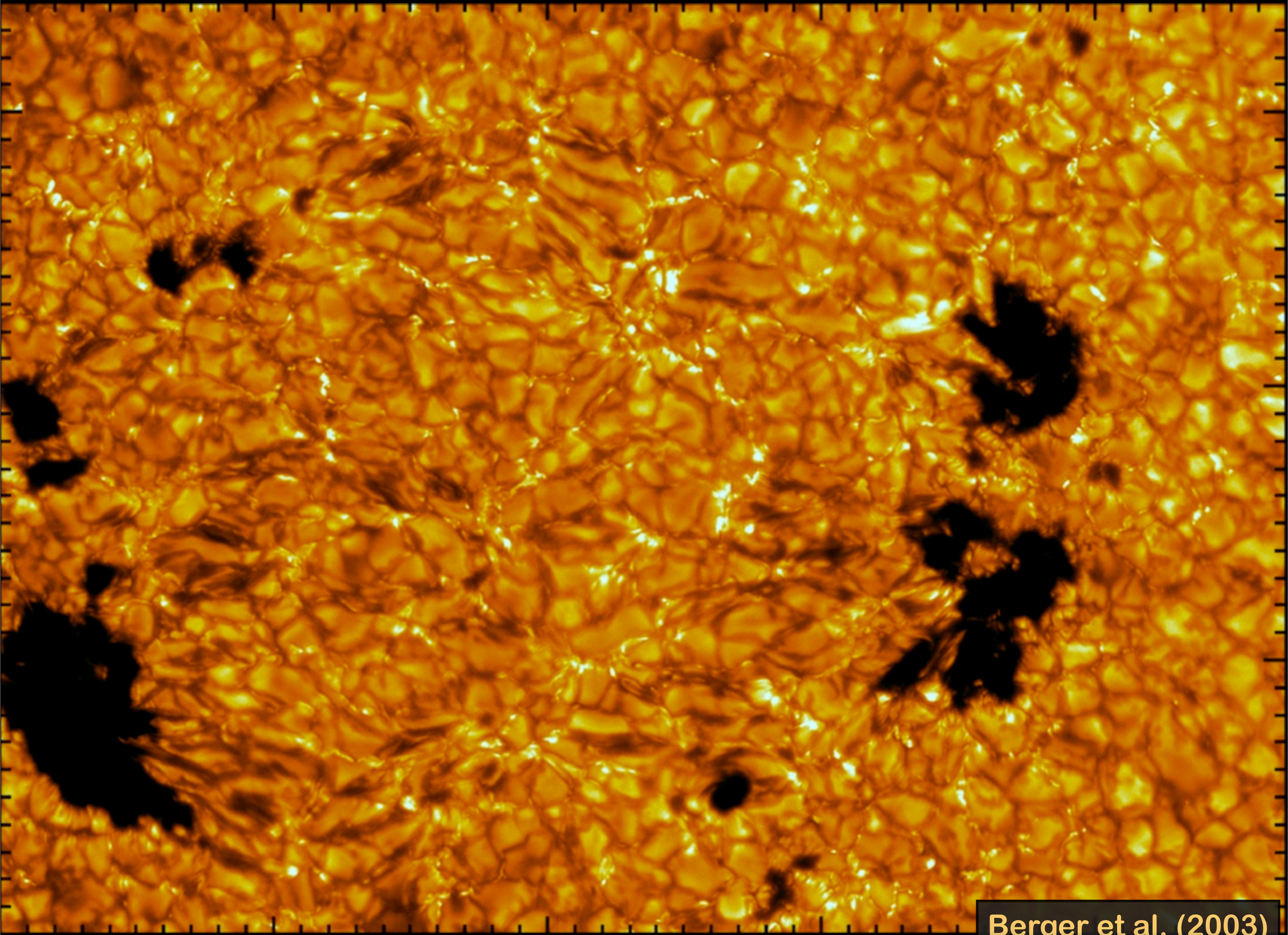

Berger et al. (2003)

# Radiative MHD Simulations of Solar Granulation

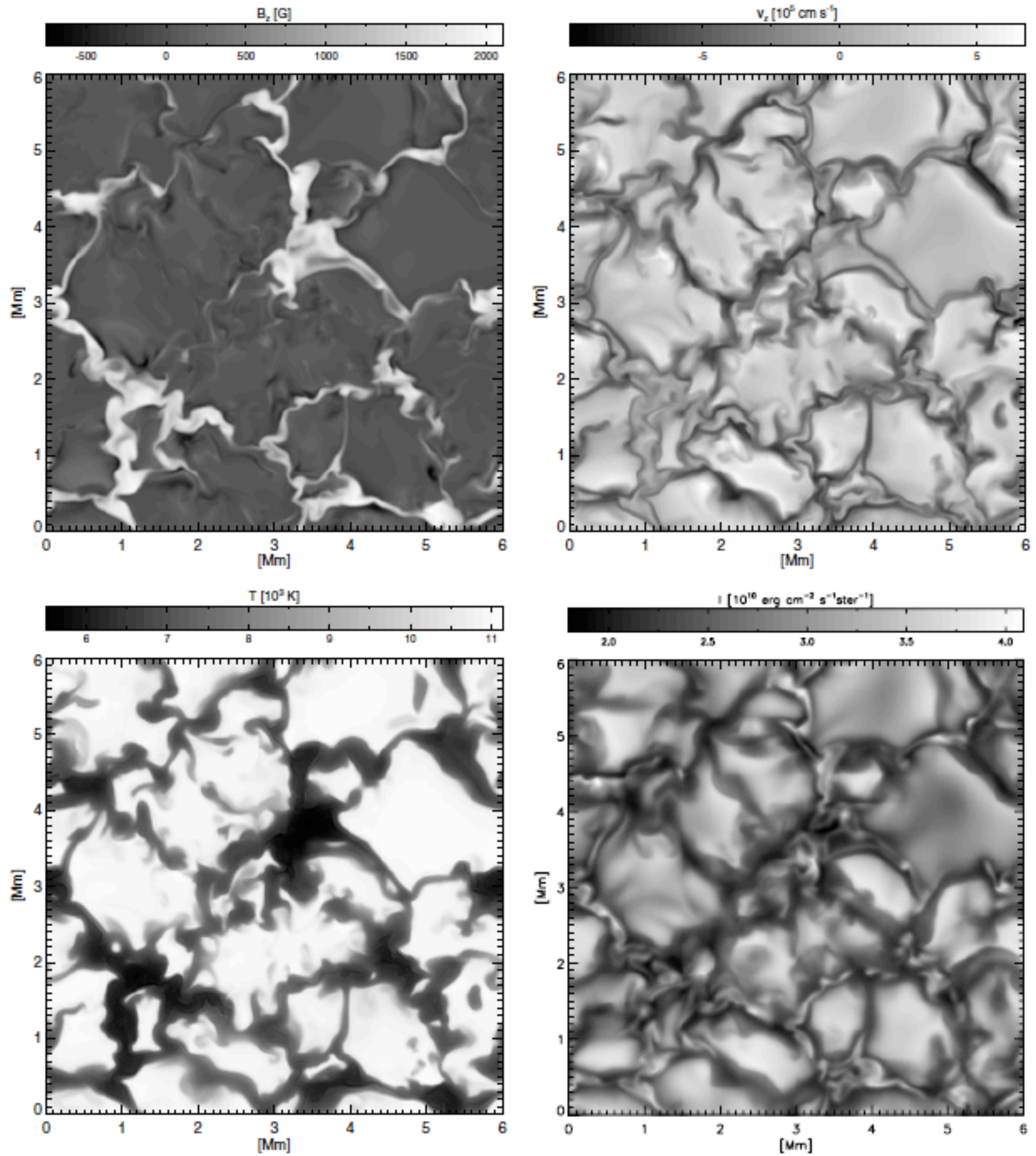
***Upflows***
***warm, bright***

***Downflows***
***cool, dark***

***Vertical magnetic fields swept to downflow lanes by converging horizontal flows***

***Bright spots in downflow lanes attributed to magnetism***

Vogler et al. (2005)



# Cool doesn't necessarily mean dark

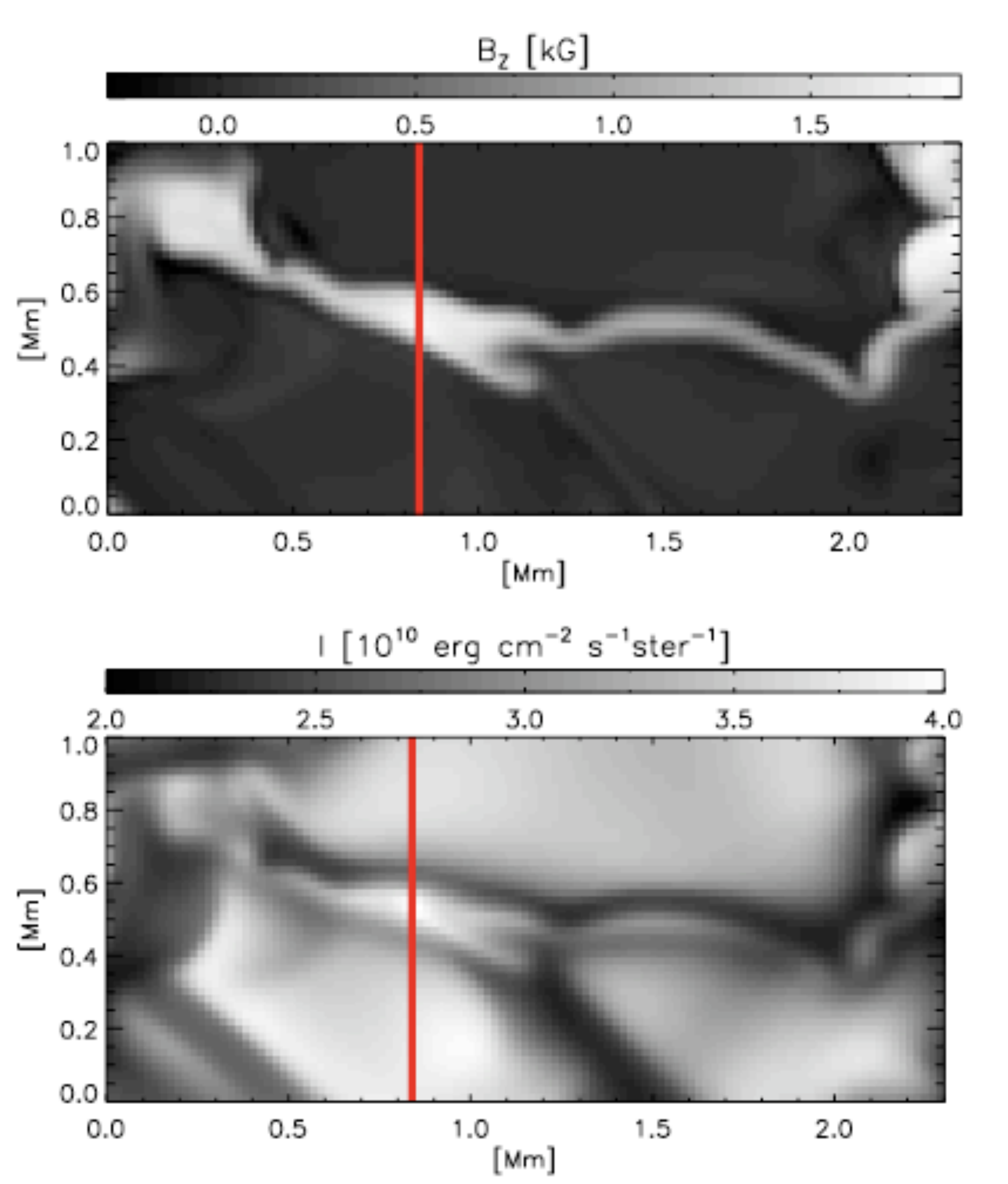
***Channelling of radiation in magnetic flux concentrations*** **($B_z > 1$ kG)**

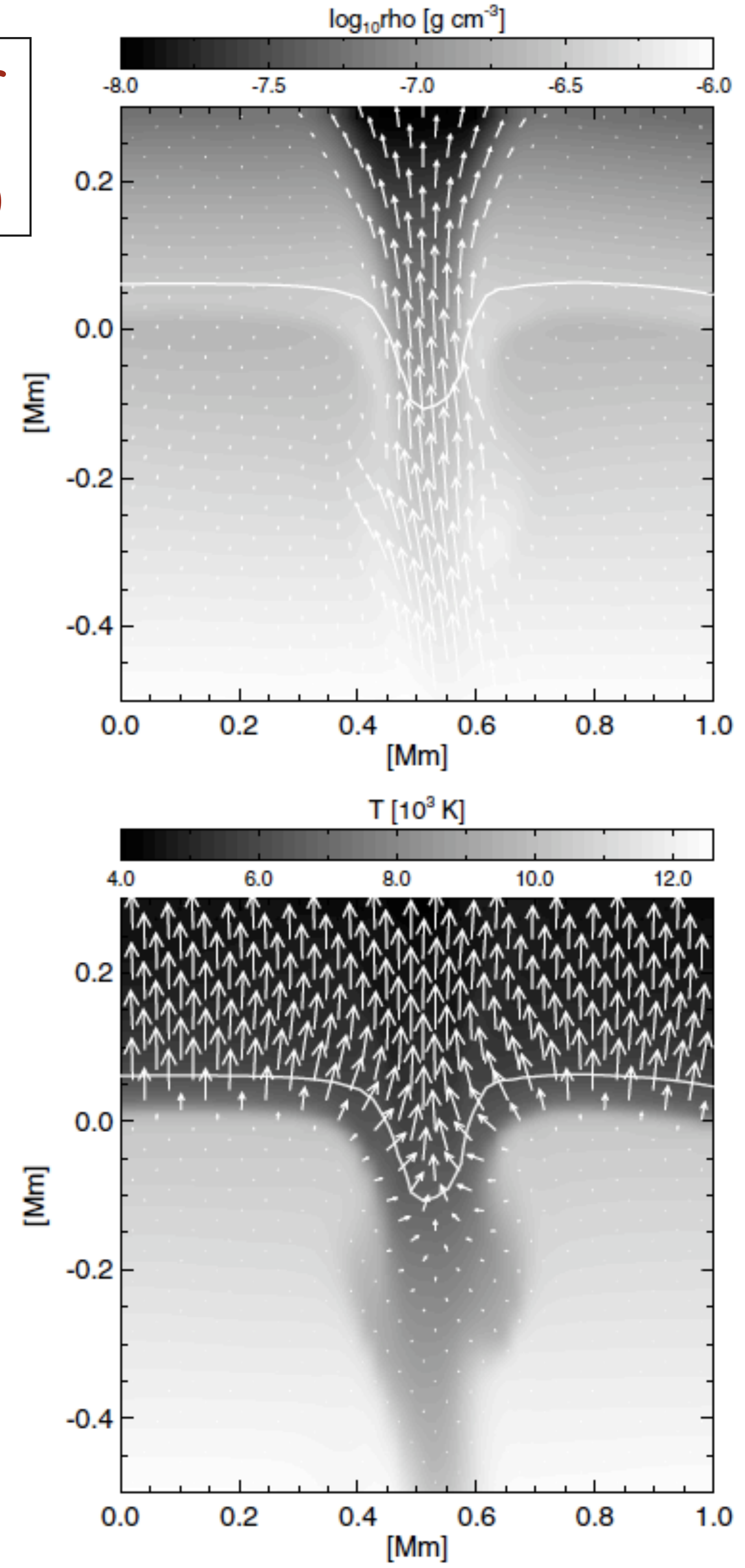
**Vogler et al. (2005)**

***Viewed at an angle they look brighter still***

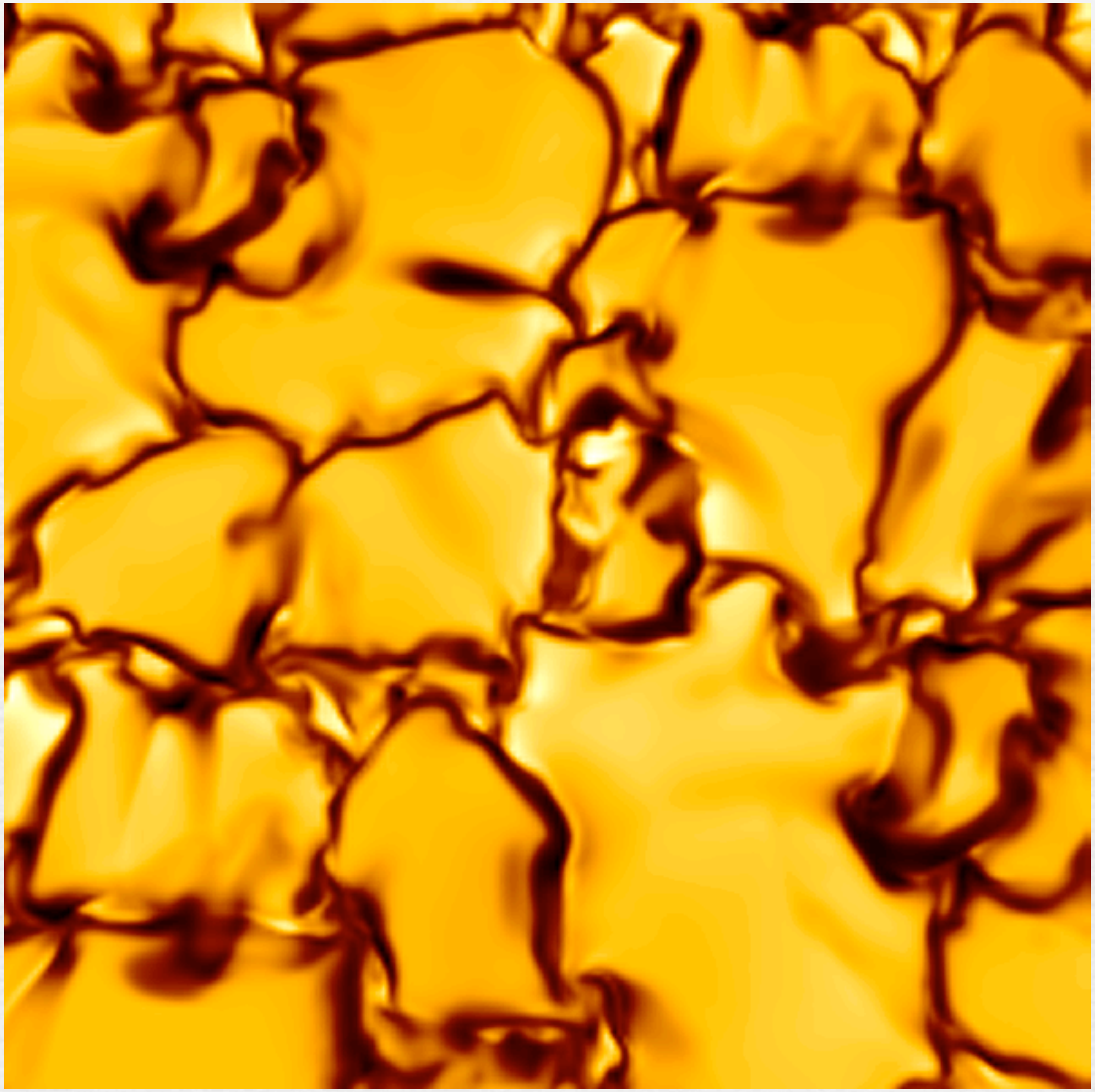
***Faculae***

**Keller et al (2004)**

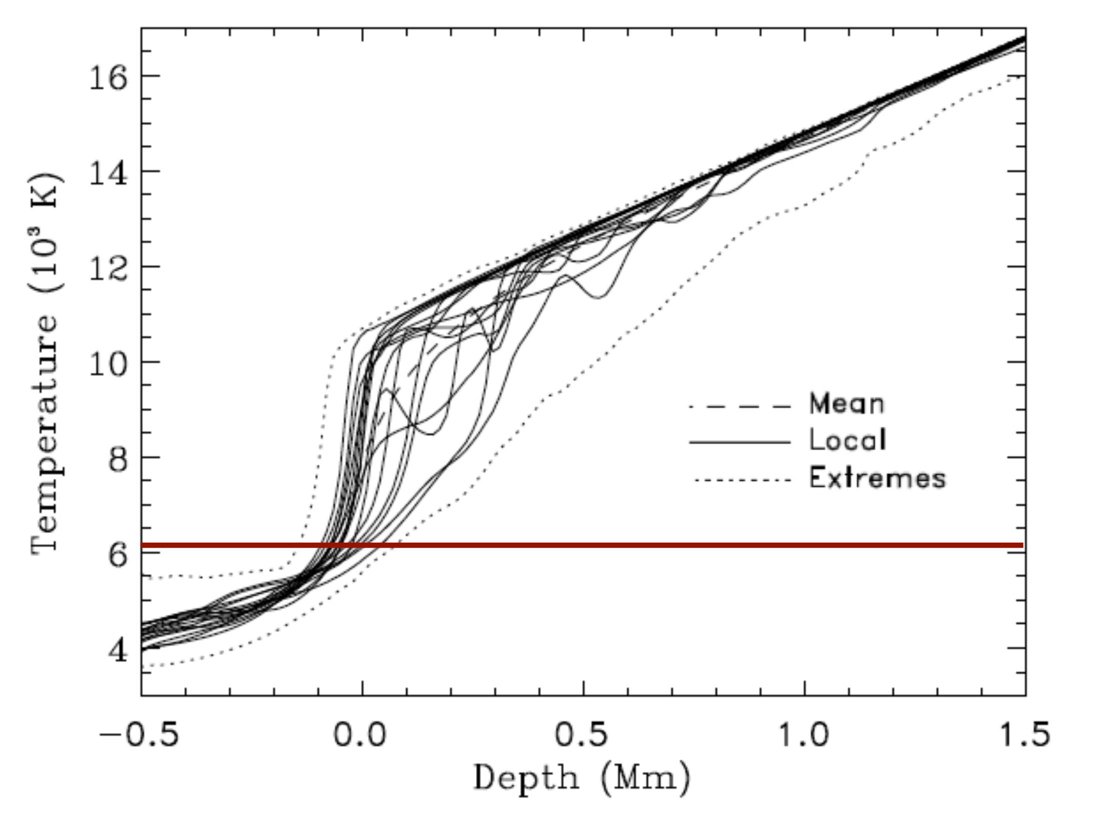


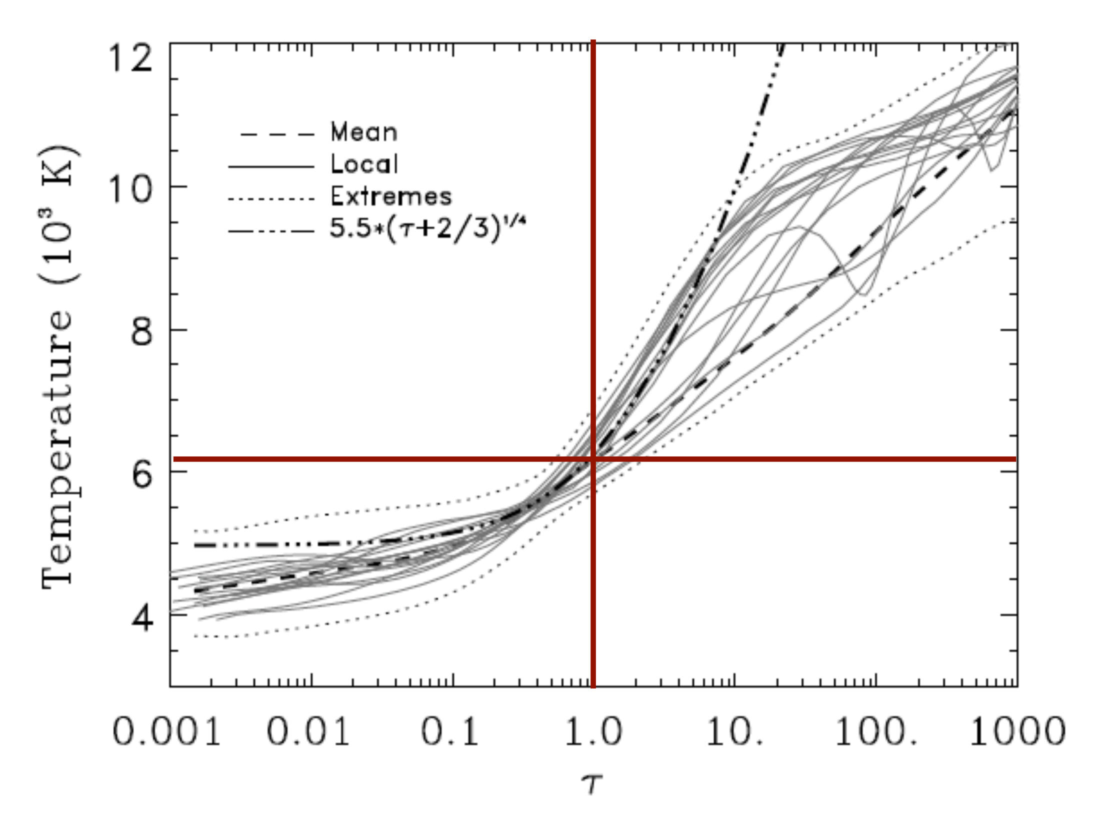
# The Surface of the Sun is Corregated!



Carlsson et al. (2004)




Stein & Nordlund (1998)




***Photosphere depressed in downflow lanes even without magnetism***
***Photospheric temperature variations relatively small***

***$H^-$ opacity***
***$\sim T^{10}$***

# Scale Selection

***Granulation is driven by strong radiative cooling in the photosphere***

***Downflows dominate buoyancy work***

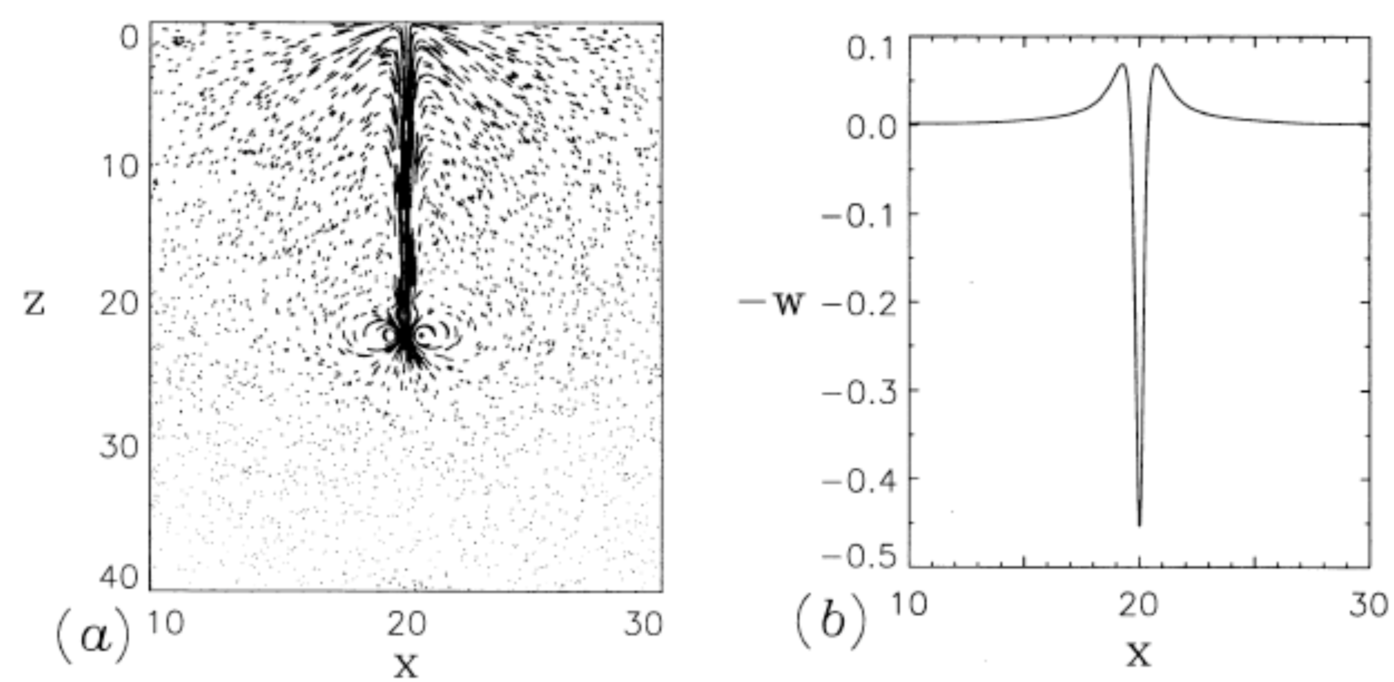
***Upflows are largely a passive response induced by horizontal pressure gradients; peak velocities occur adjacent to downflows***

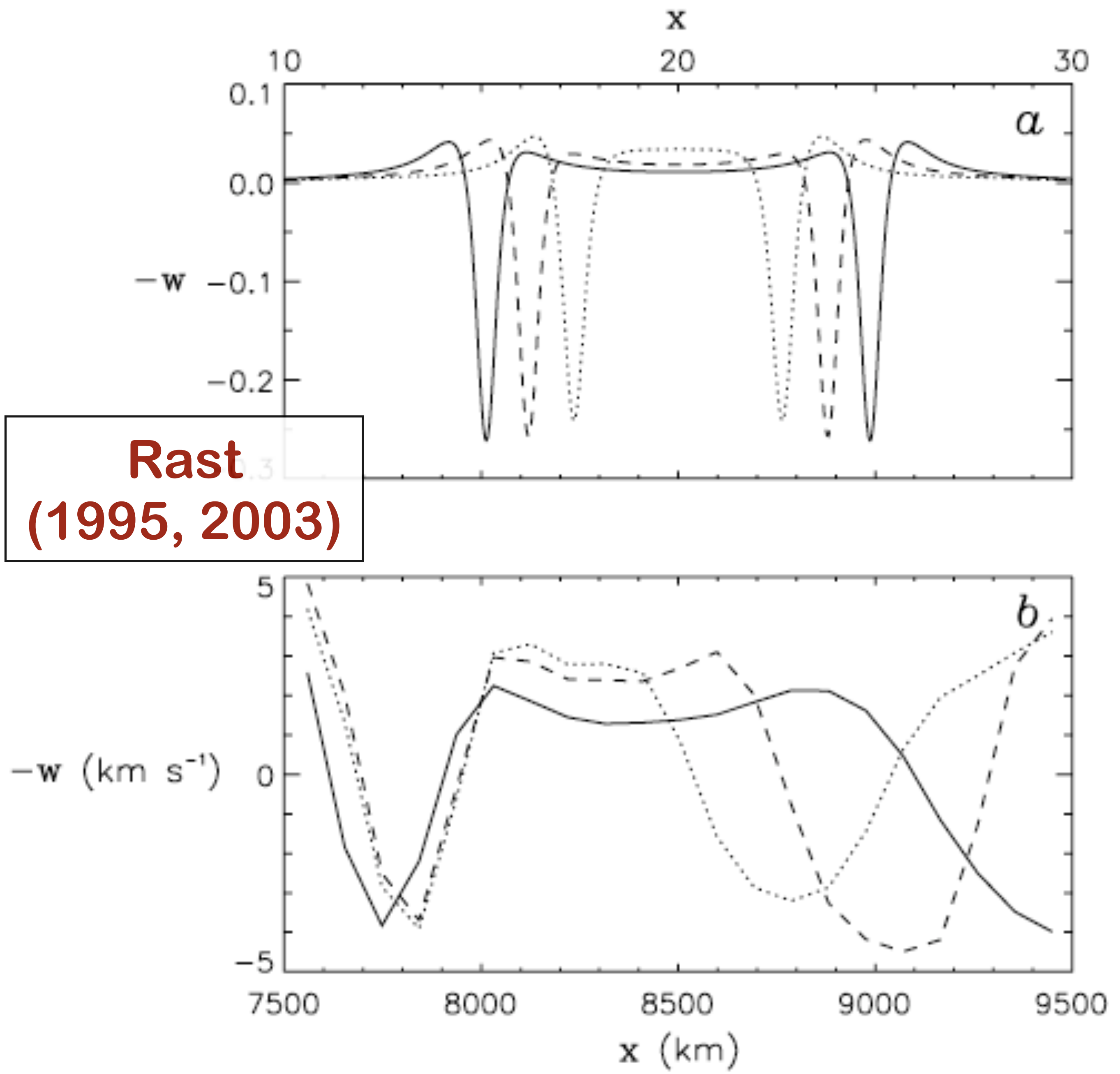
***When granules get too wide, radiative cooling overcomes the convective flux coming up from below, reversing the buoyancy driving in the center of the granule***

***Upflow becomes downflow and the granule bisects (exploding granules)***

$$\rho v_z y N_A \chi_H \gtrsim \sigma T^4$$

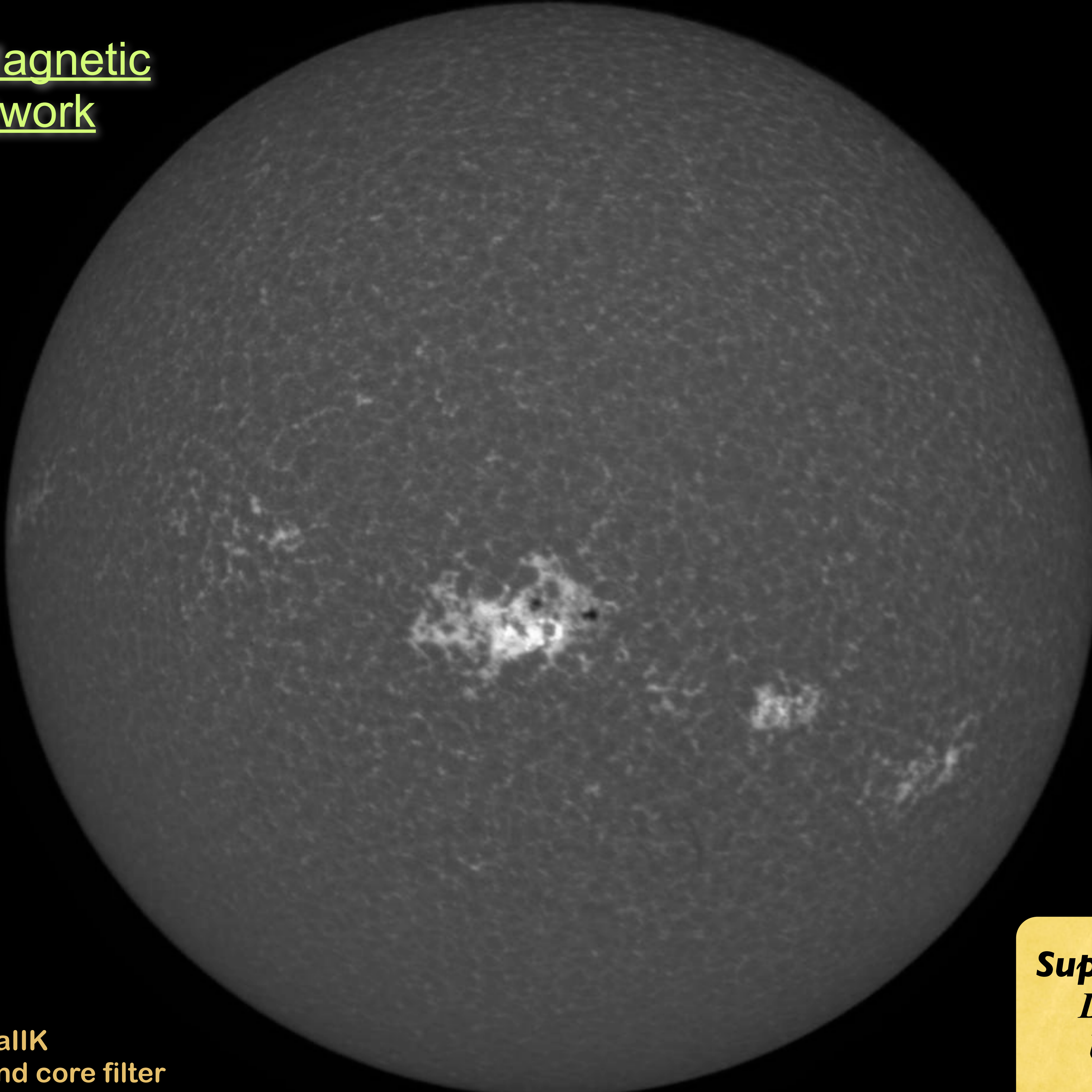
$$L \sim D \frac{v_h}{v_z} \qquad v_h \lesssim c_s \qquad D \sim H_\rho$$




**Rast (1995, 2003)**

# The Magnetic Network

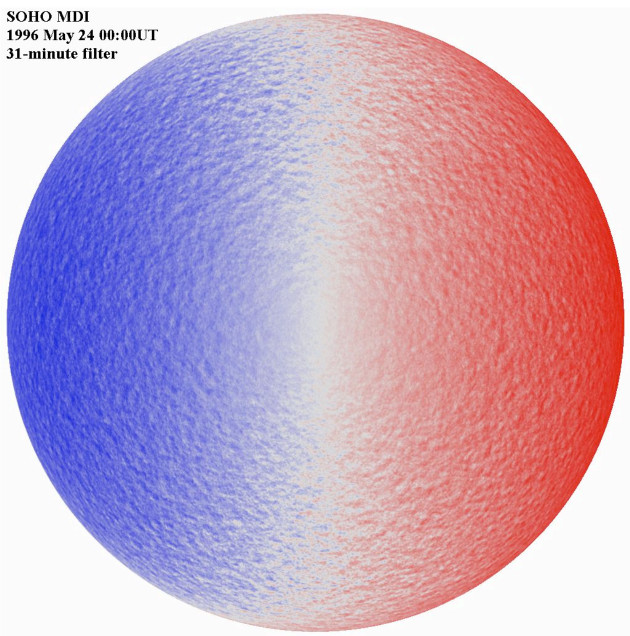


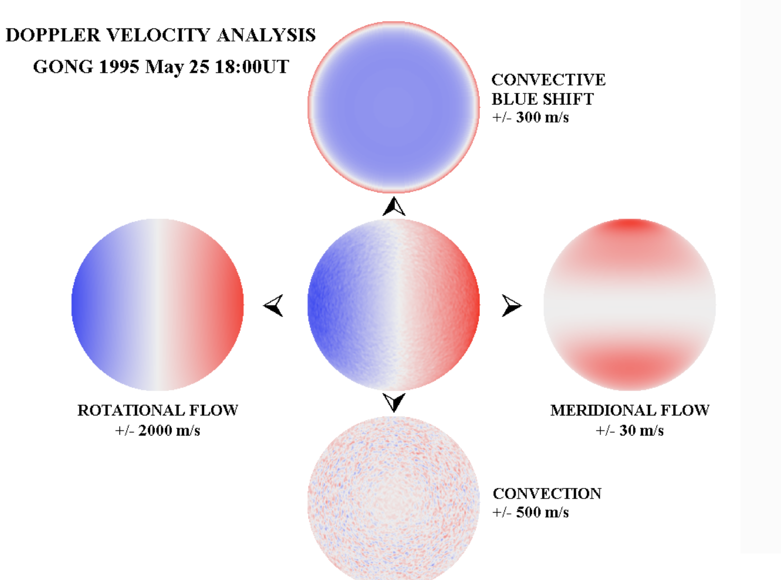
CaIIK
narrow-band core filter
PSPT/MLSO

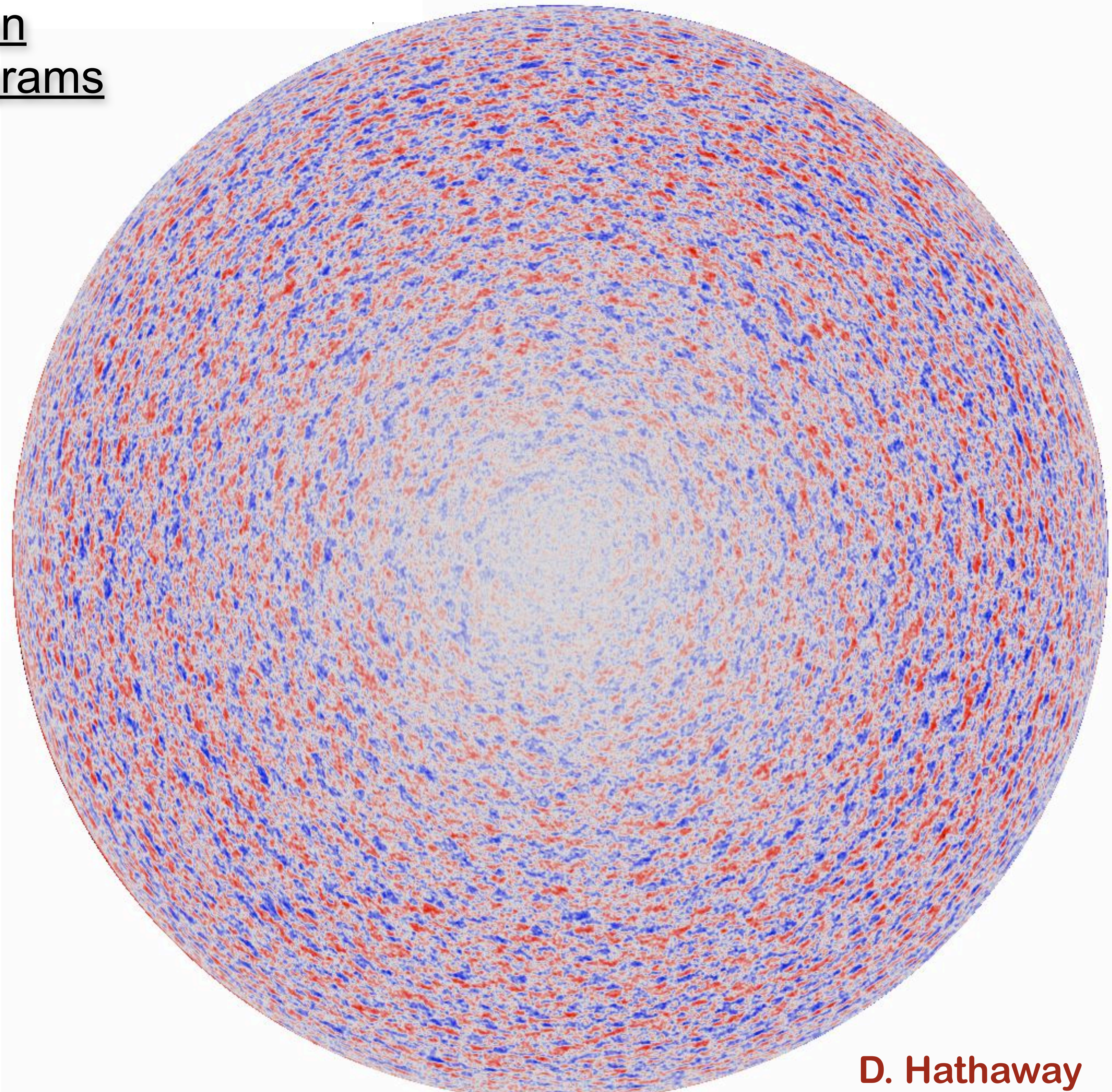
***Supergranulation***
$L \sim$ 30-35 Mm
$U \sim$ 500 m $s^{-1}$
$\tau \sim$ 20 hr

# Supergranulation in Filtered Dopplergrams

***Most prominent in horizontal velocities near the limb***

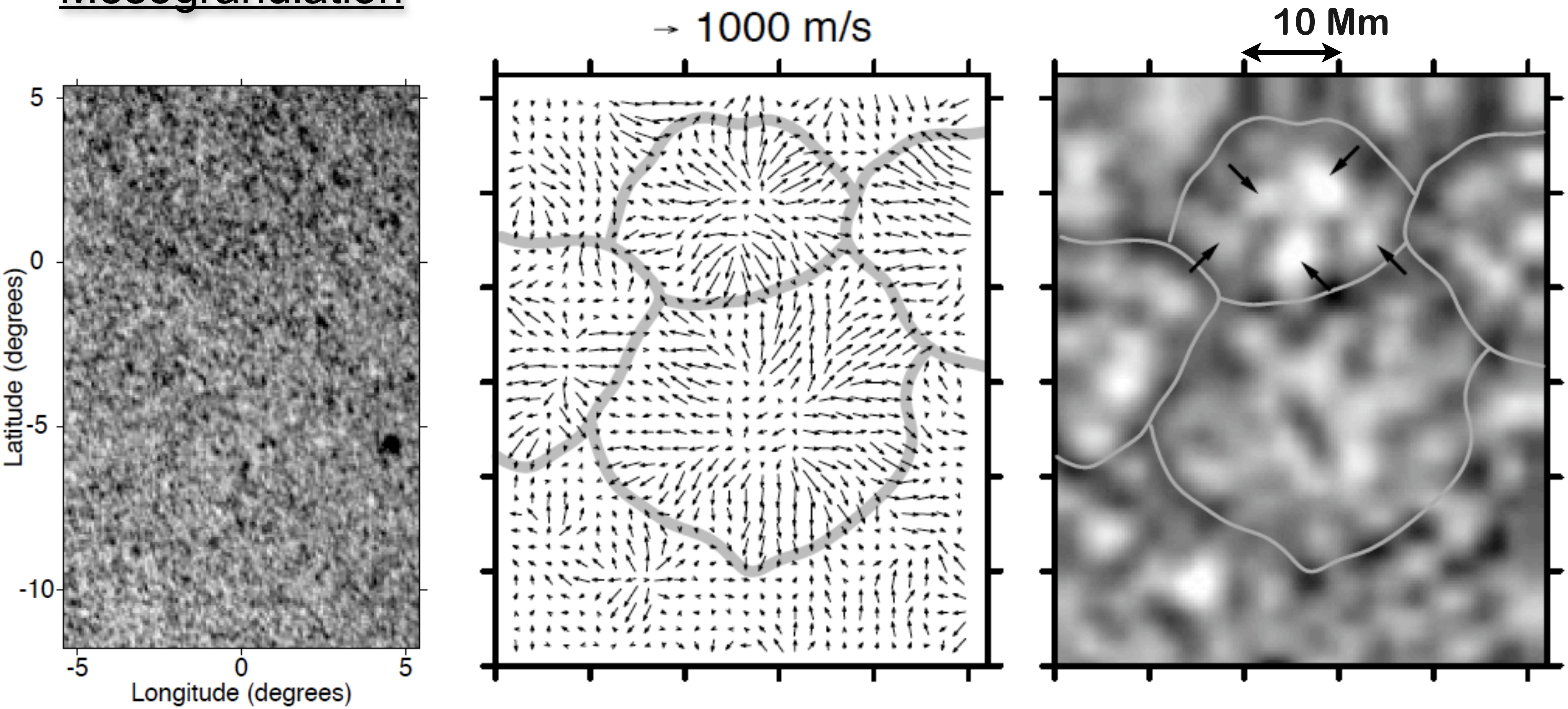


D. Hathaway
(NASA MSFC)

# Mesogranulation



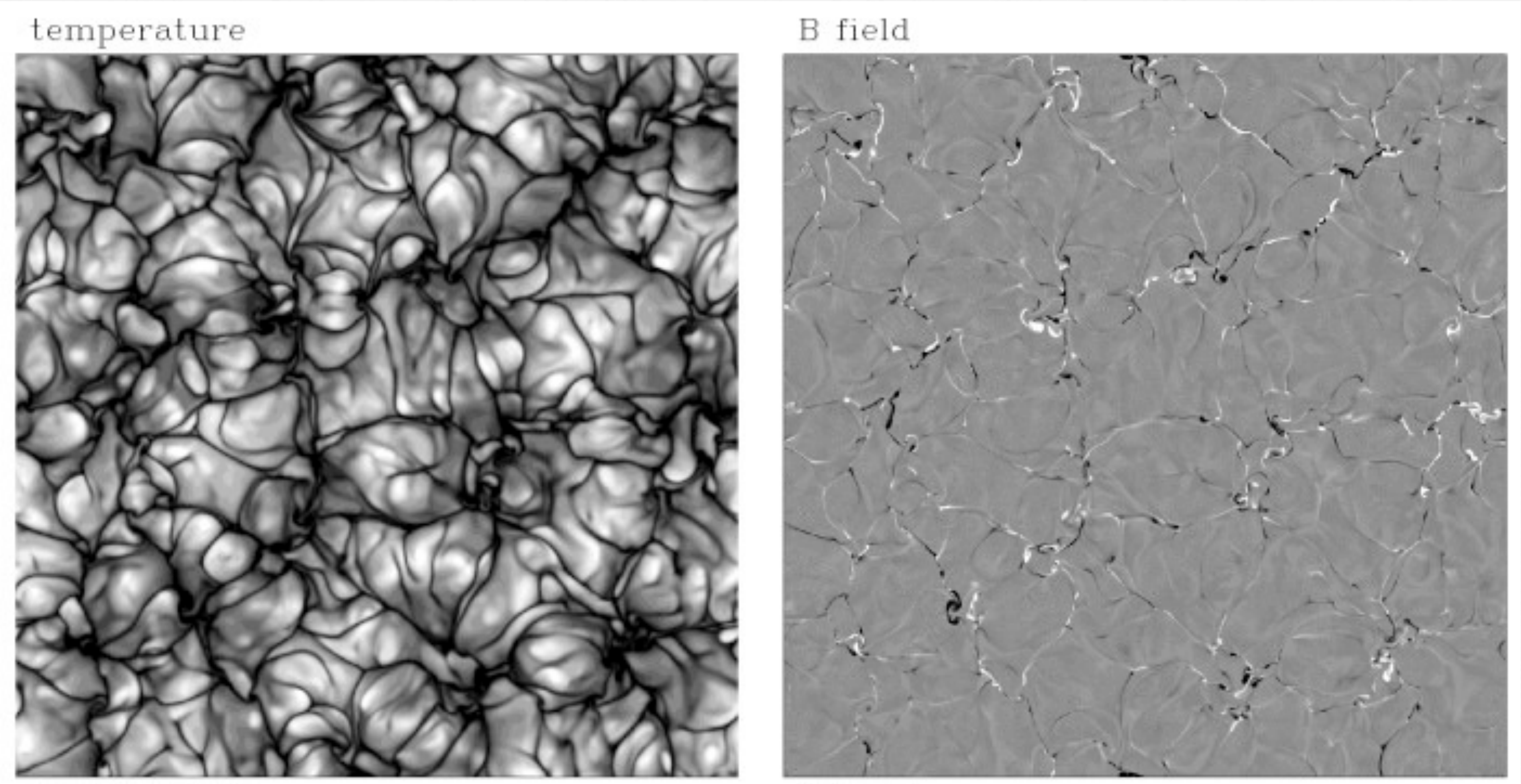

Shine, Simon & Hurlburt (2000)

***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
$\tau \sim 3\text{-}4$ hr

# Self-Organization of convective plumes




Cattaneo, Lenz & Weiss (2001)

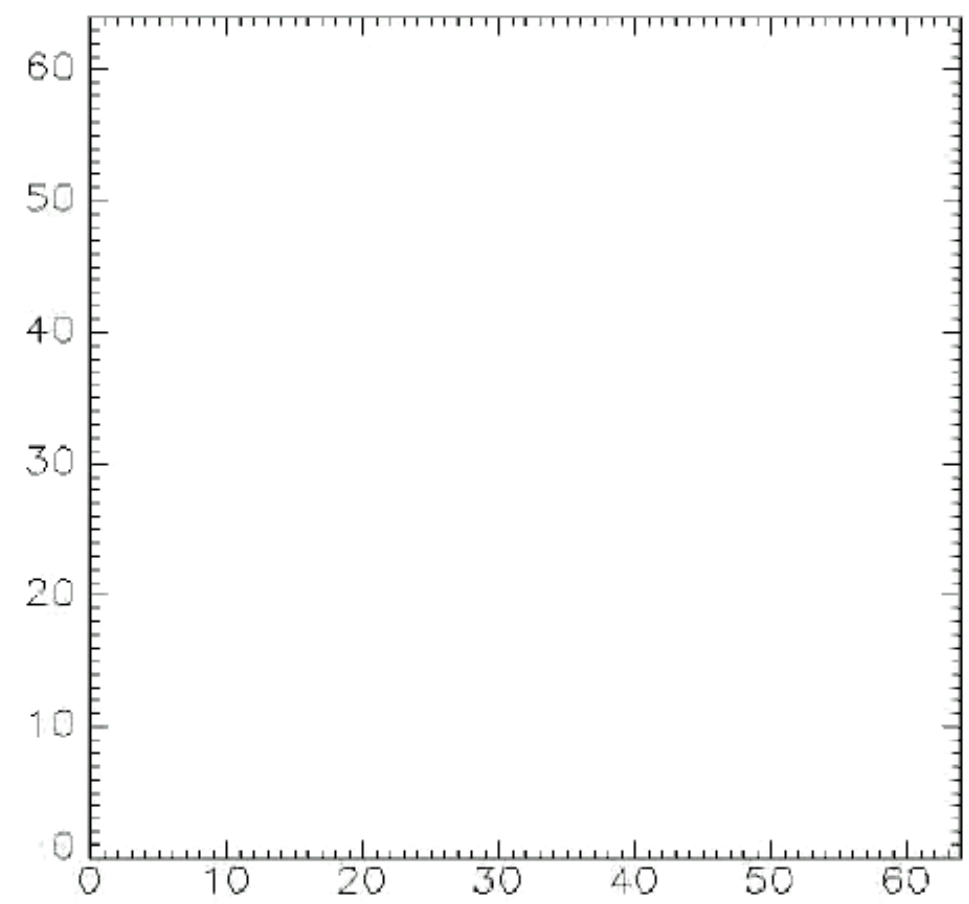
***Convective plumes cluster on larger scales due to kinematic advection from the converging horizonal flows that feed them***

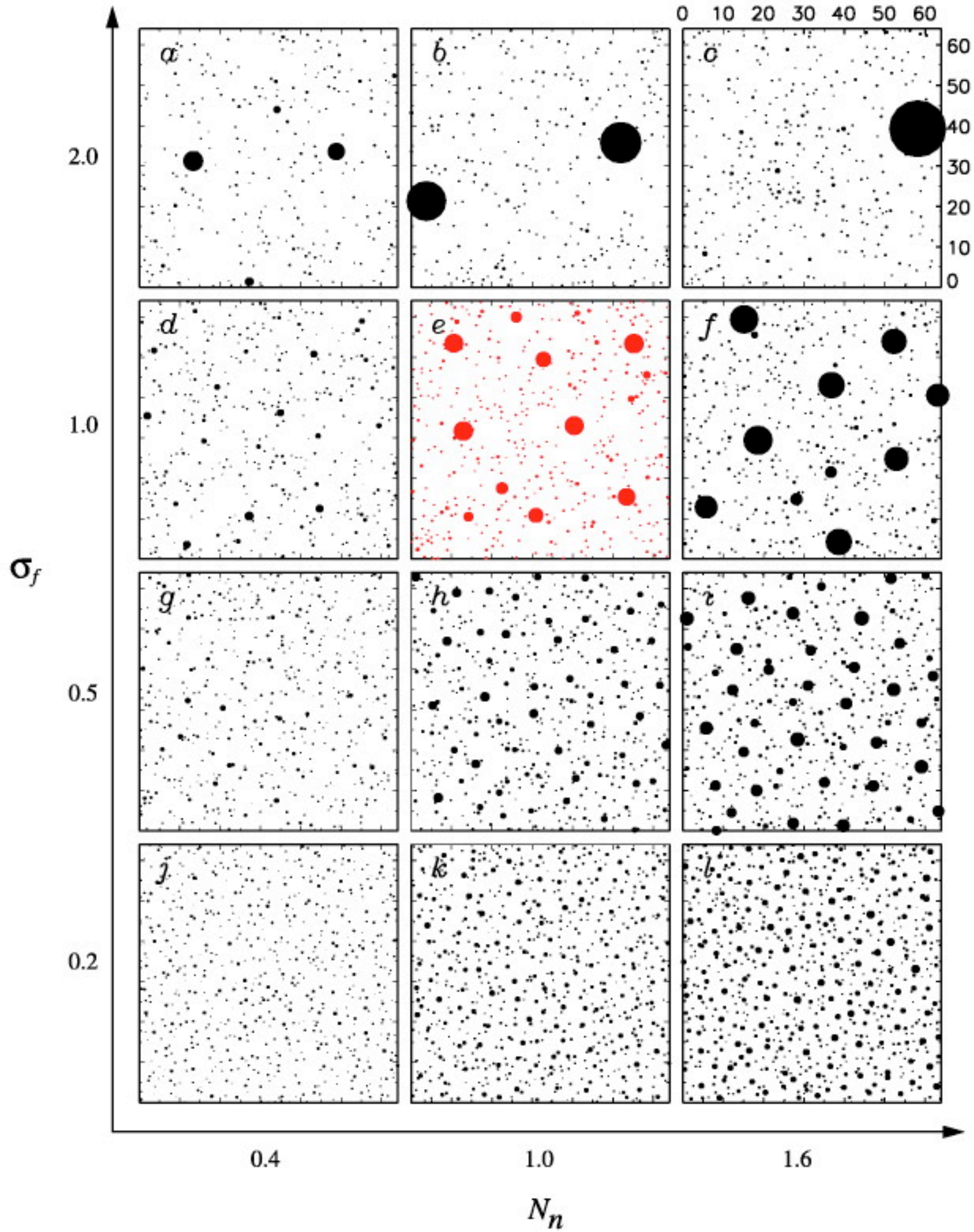
# A toy model of interacting plumes

Rast (2003)

***Granulation modeled as distributed points of horizontal convergence (representing downflow plumes) on a 2D surface***

***Kinematic advection and merging produces a larger-scale lattice of stronger convergence points***



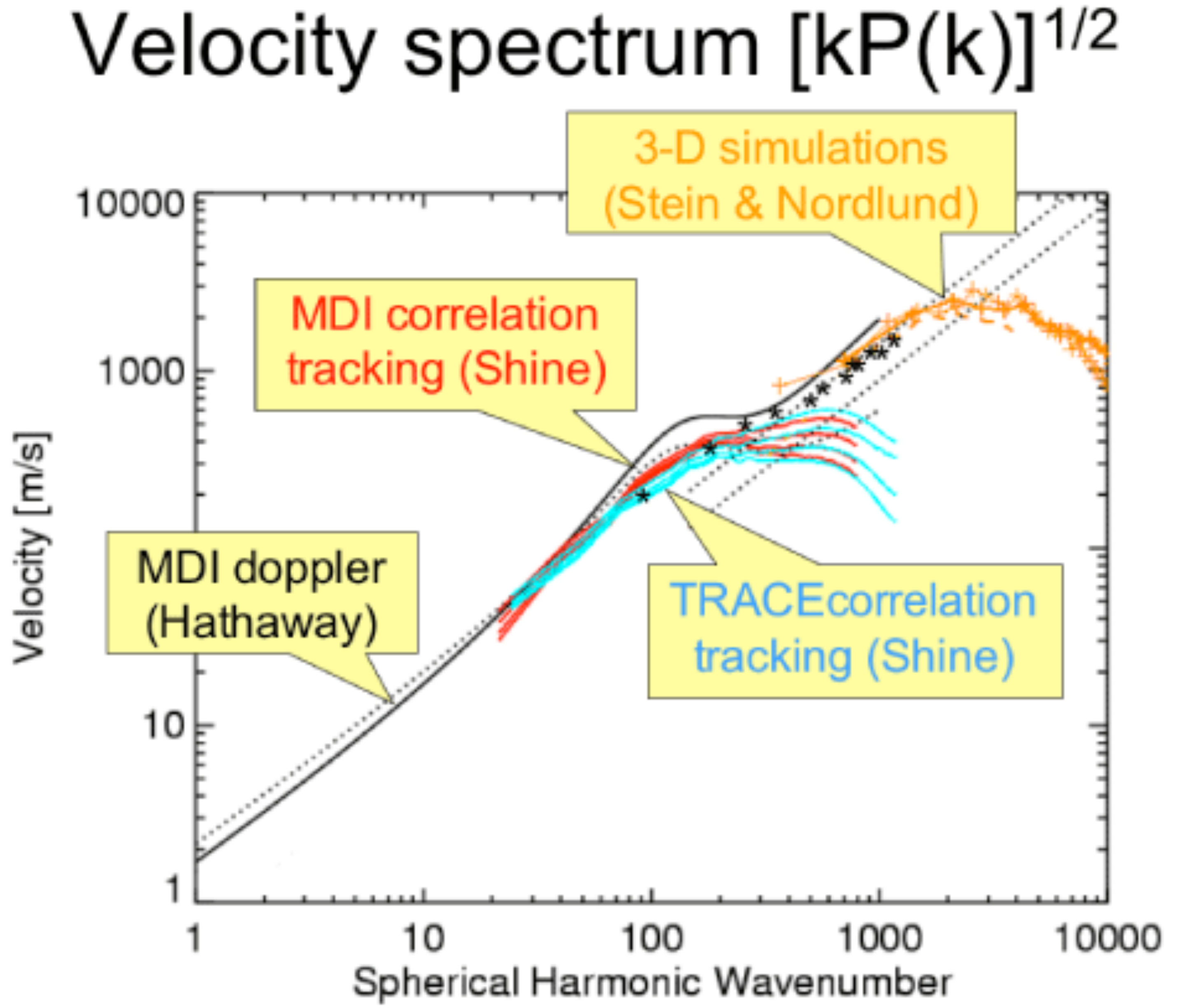
# A hierarchy of convective scales

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

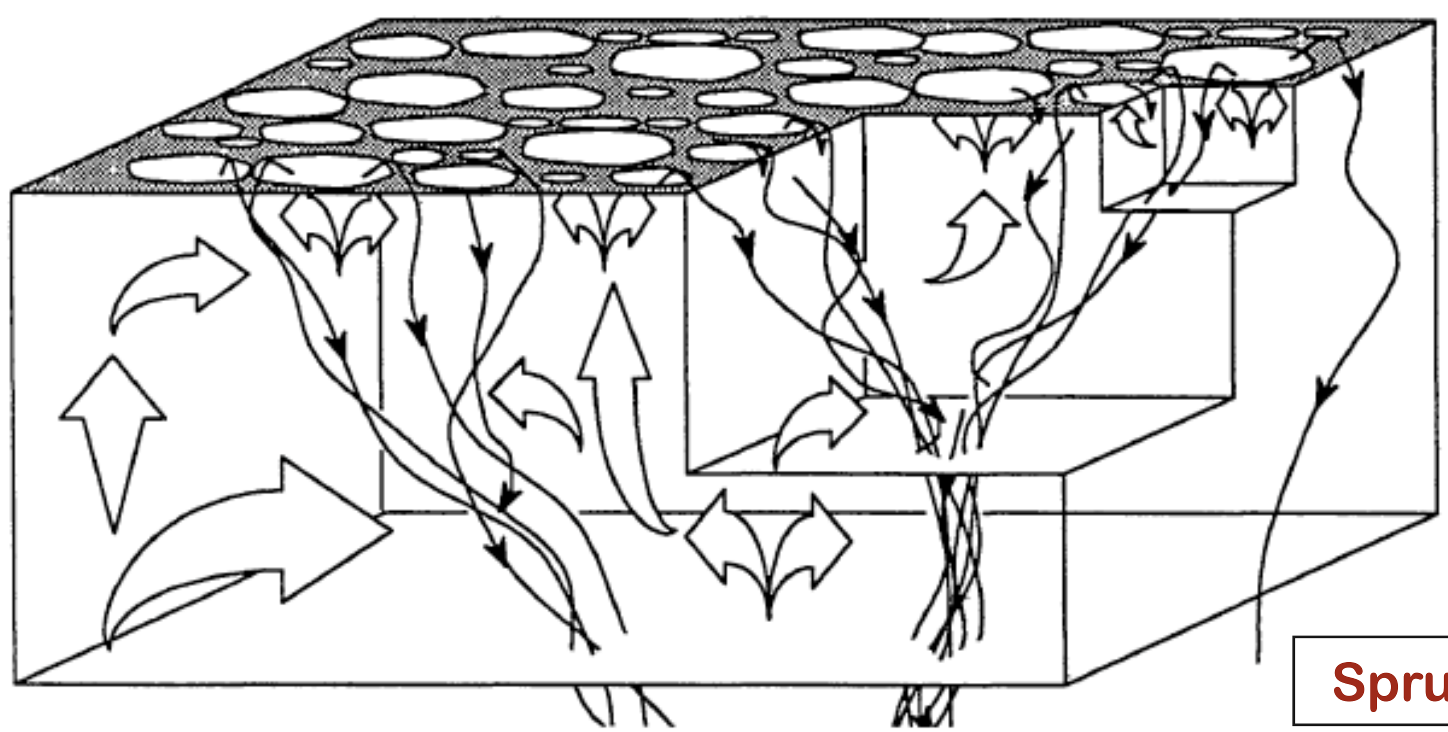
***Most of the mass flowing upward does not make it to the photosphere***

***Downward plumes merge into superplumes that penetrate deeper***

***Deep-seated pressure variations drive surface flows***




Nordlund, Stein & Asplund (2009)



Spruit, Nordlund & Title (1990)

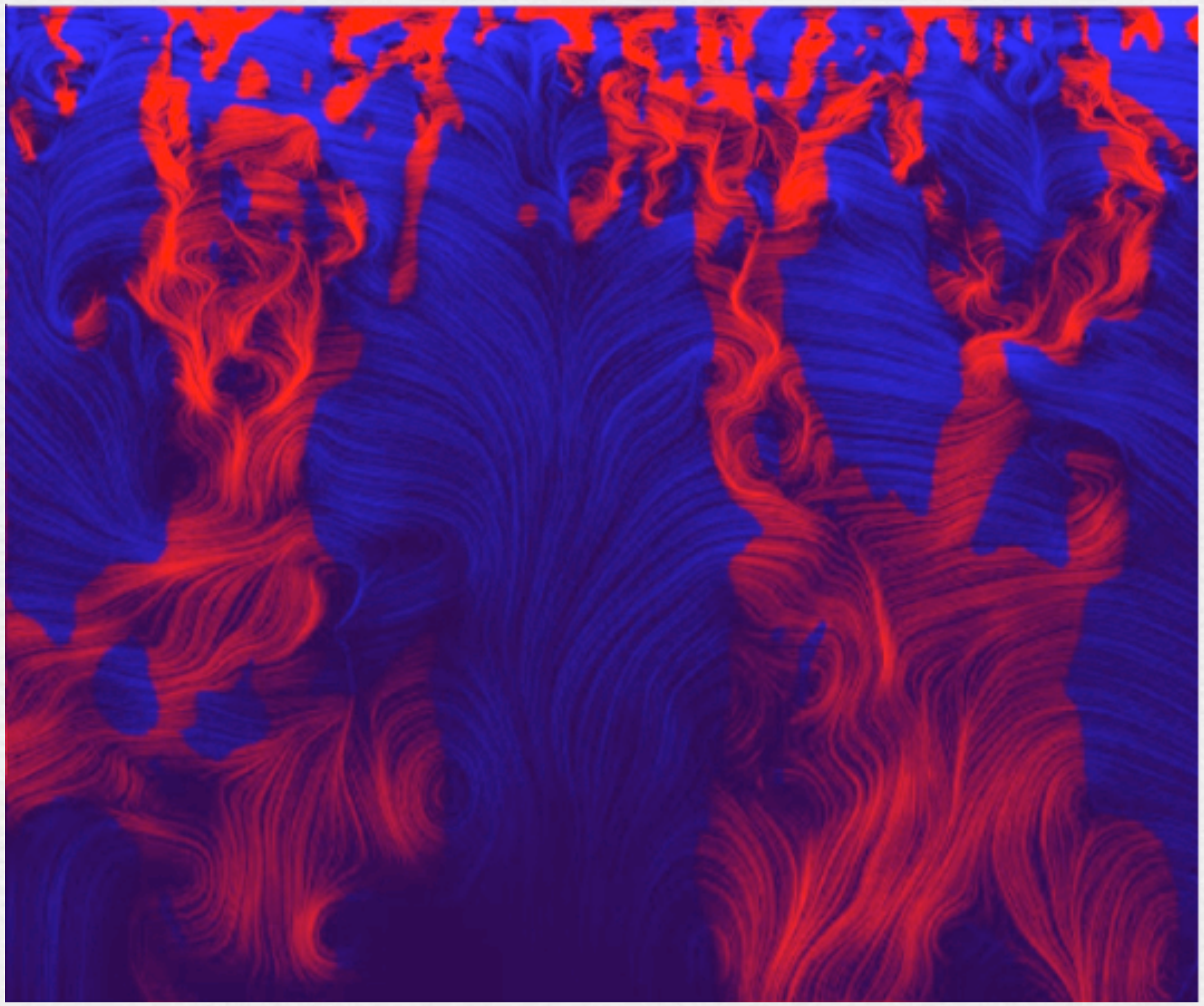
***Supergranulation and mesogranulation are part of a continuous (self-similar?) spectrum of convective motions***

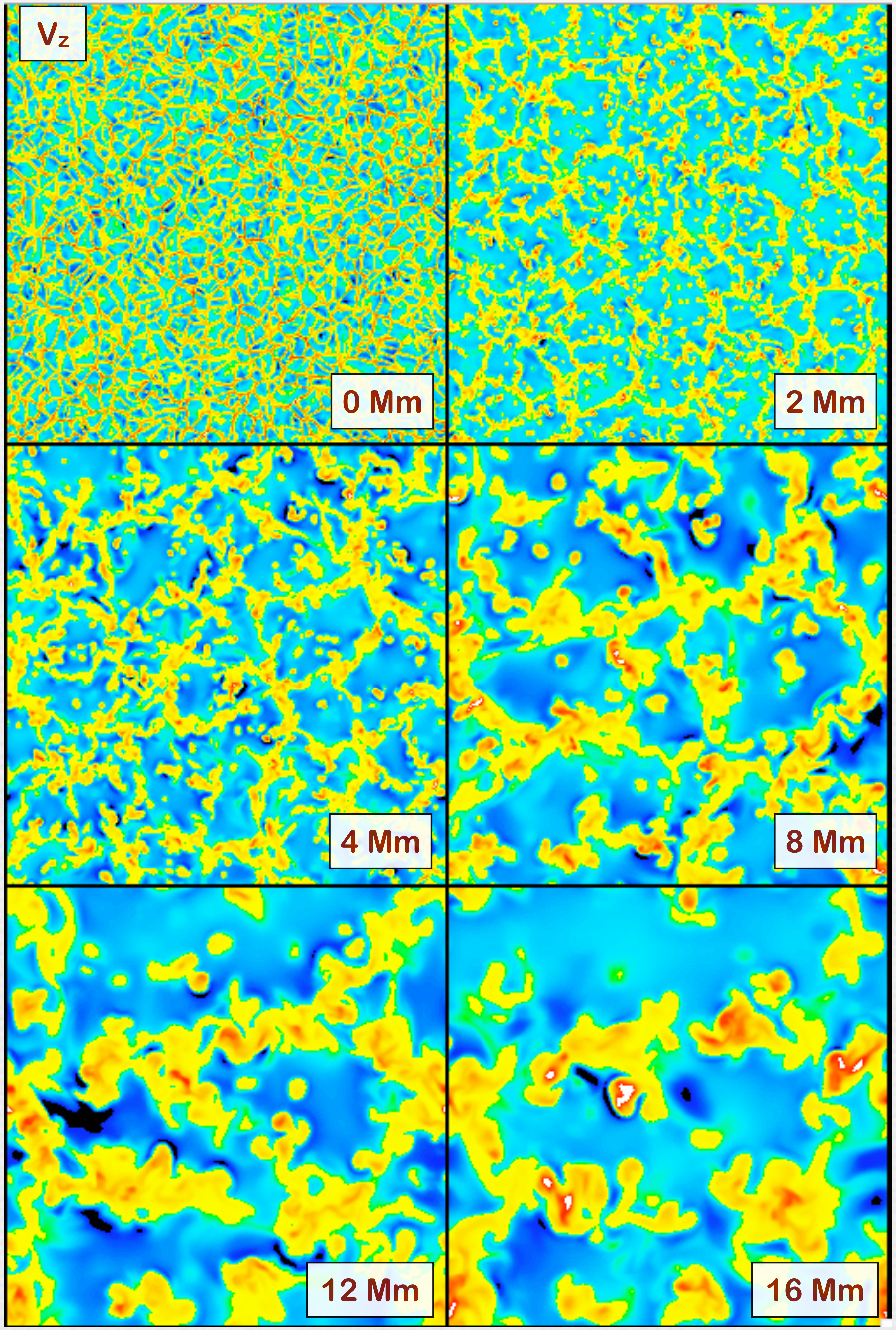
# Bigger Boxes

***Latest local simulations are now achieving supergranular scales***

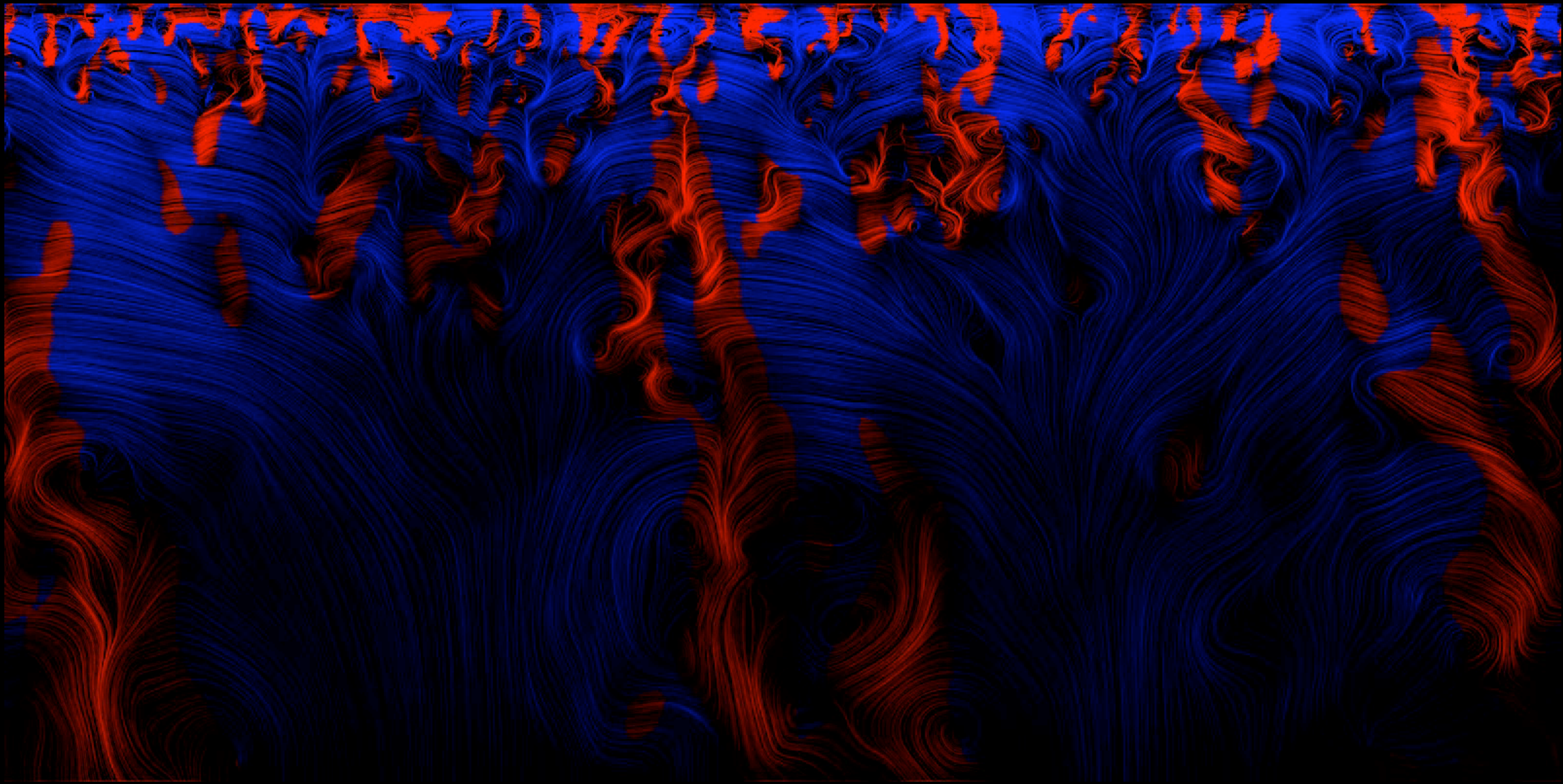
***Size, time scales of convection cells increases with depth***

Stein et al (2006)





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

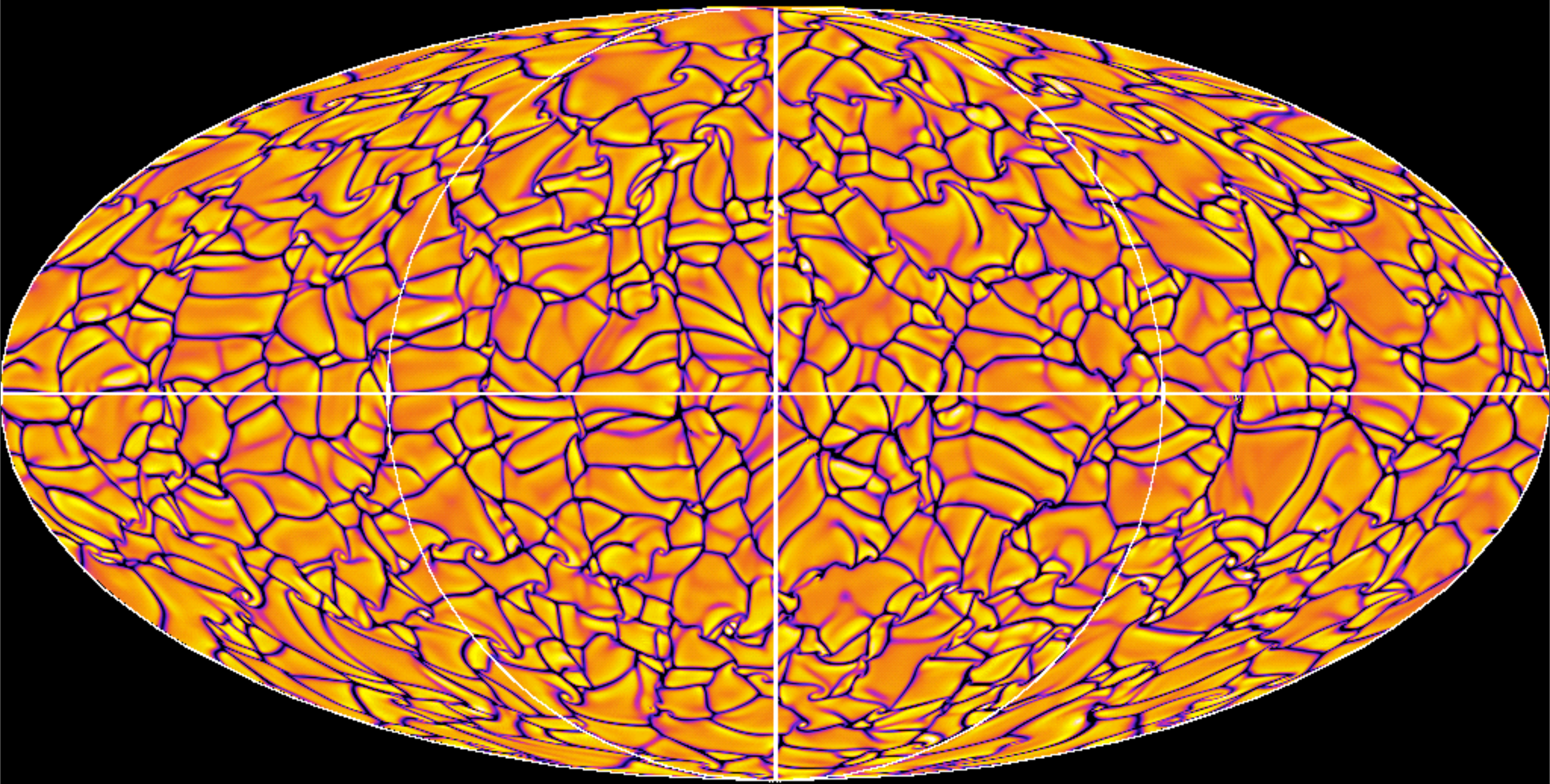


**Beyond Solar Dermitology**

**But what lies deeper still?**

# Giant Cells

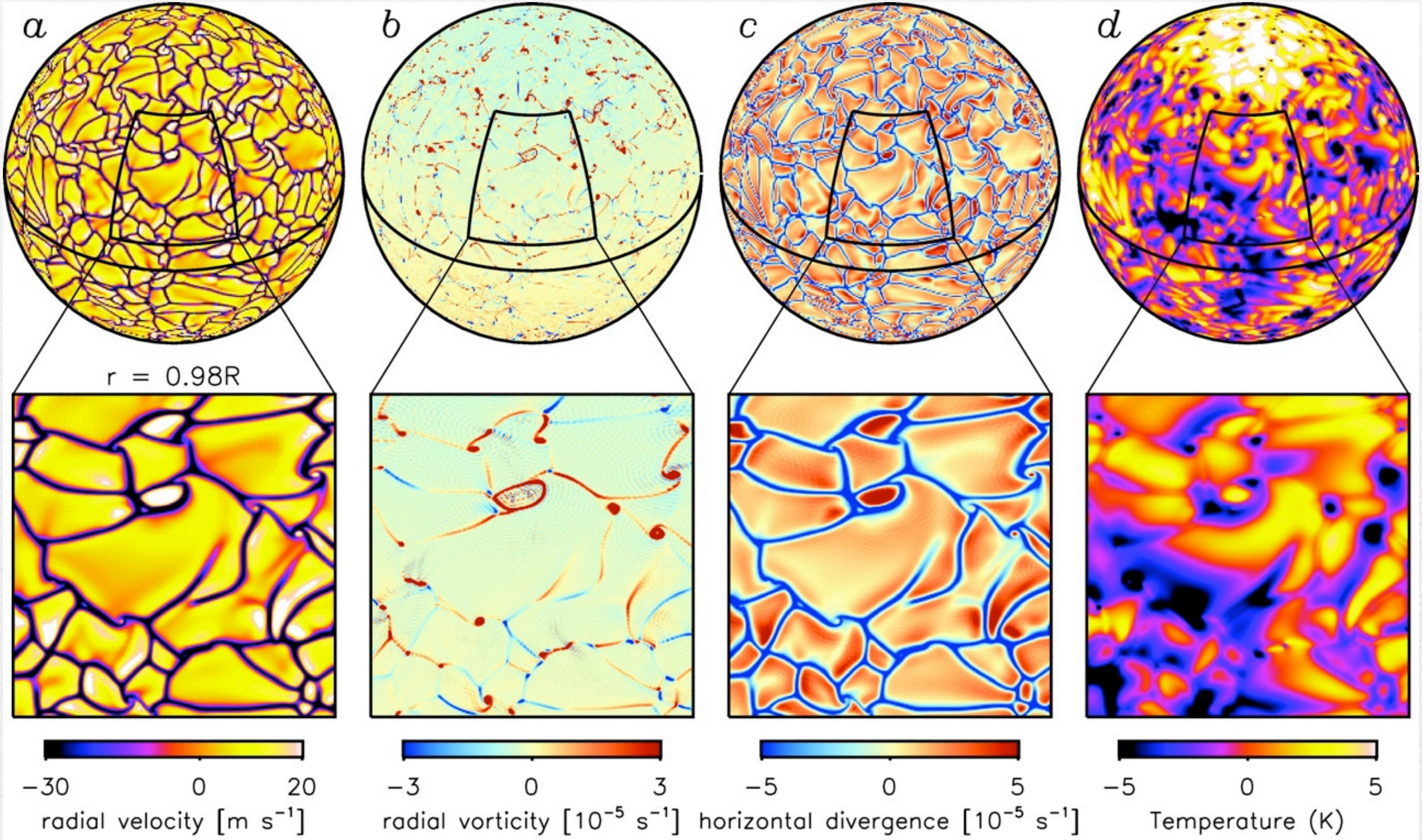
radial velocity, r = 0.98R




Miesch, Brun, DeRosa & Toomre (2008)

ASH

# Granulation-like network of downflow lanes and plumes

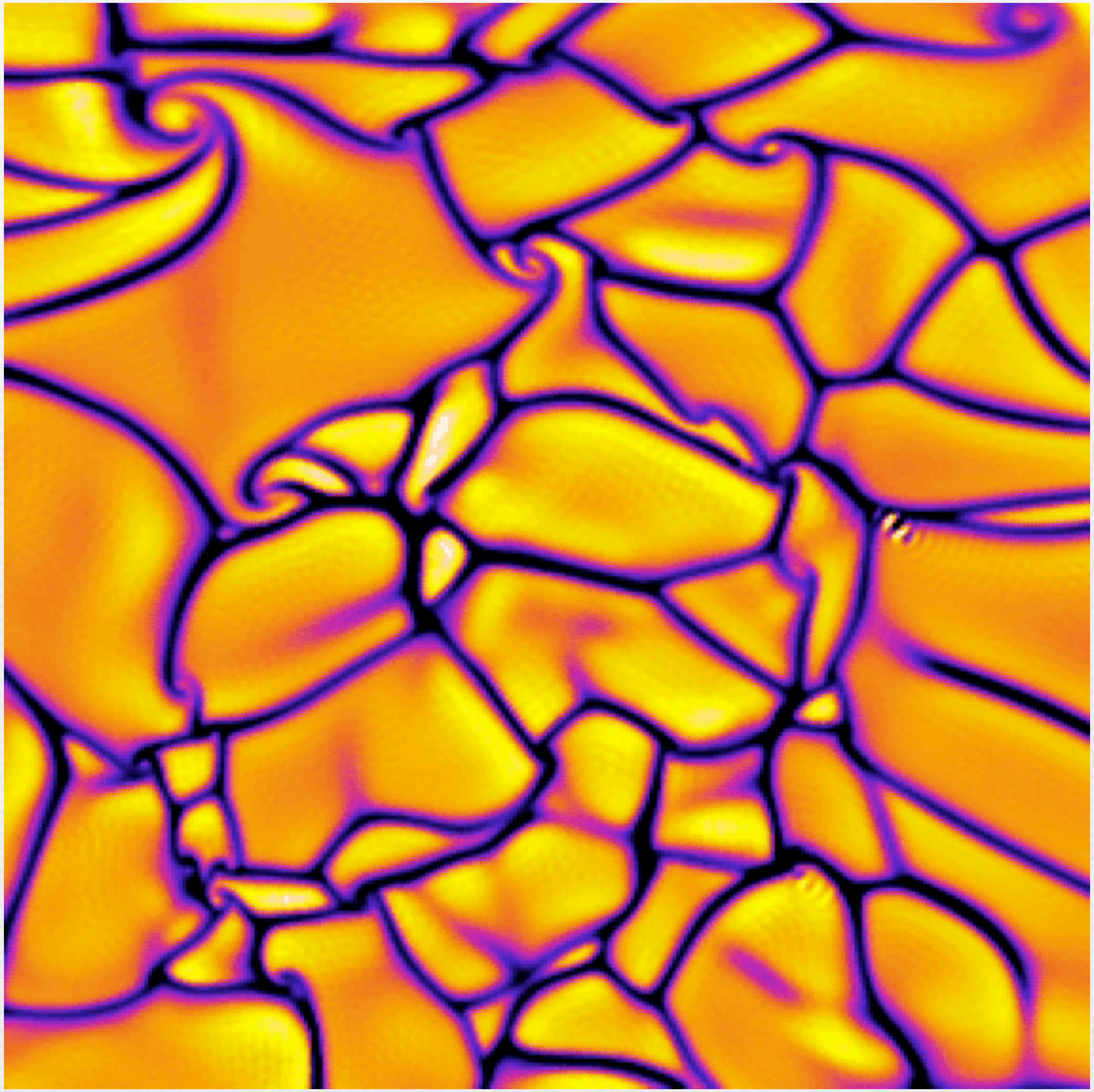


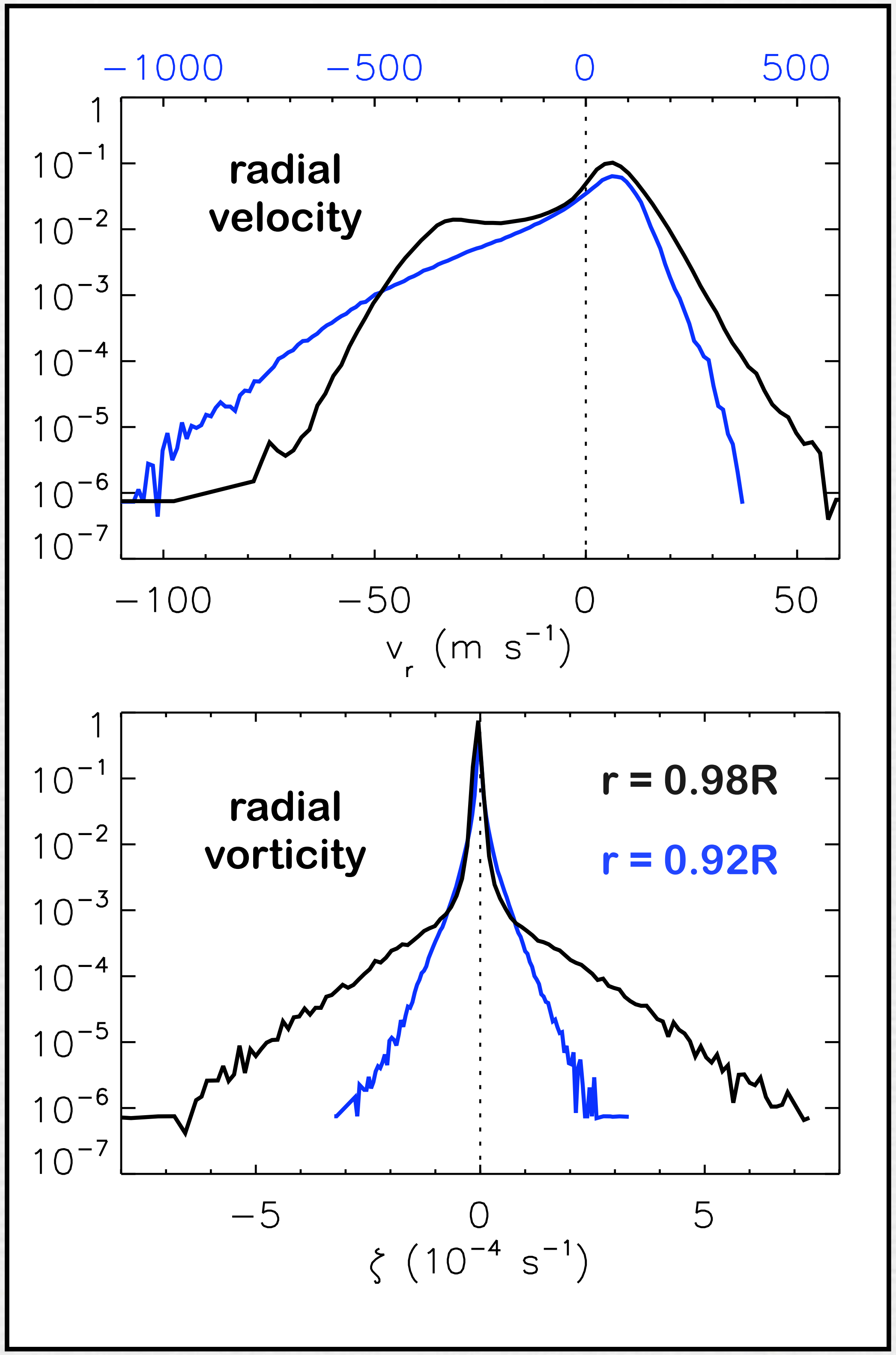

**Cool, Helical Downflows**

**Solar Cyclones**

$\omega_r$ **- $\Delta$ anticorrelation**

# Solar Cyclones are strong, helical, rapidly evolving and highly intermittent

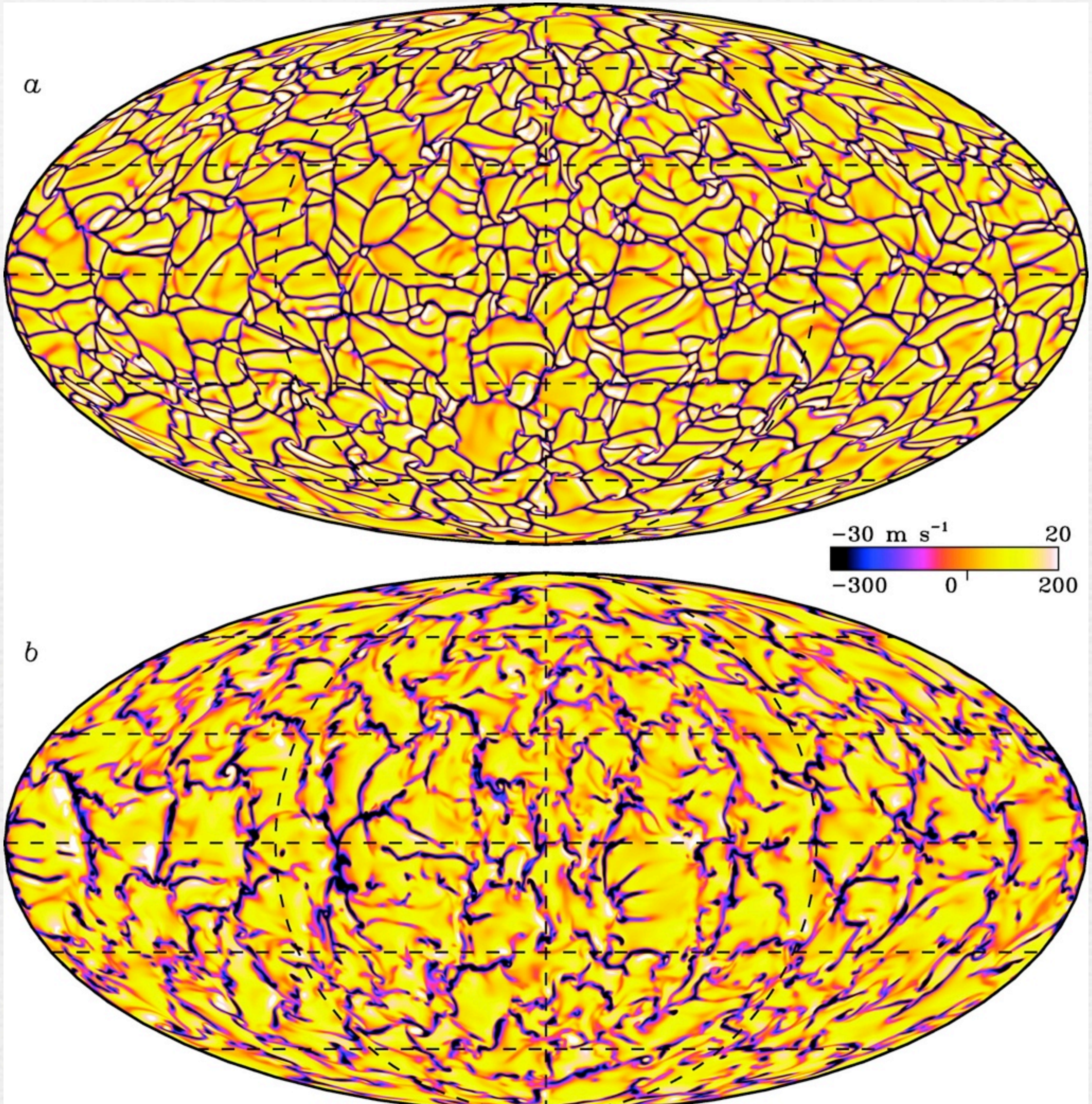


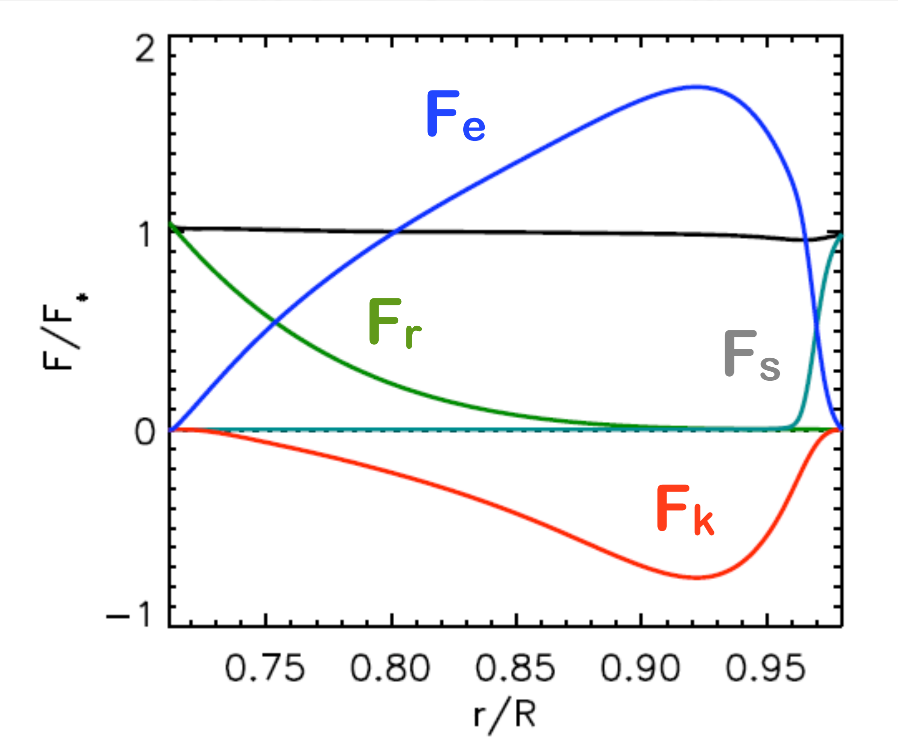



***Cells bisect and fragment due to efficient cooling in the thermal boundary layer***

***Cyclones localized near the surface***

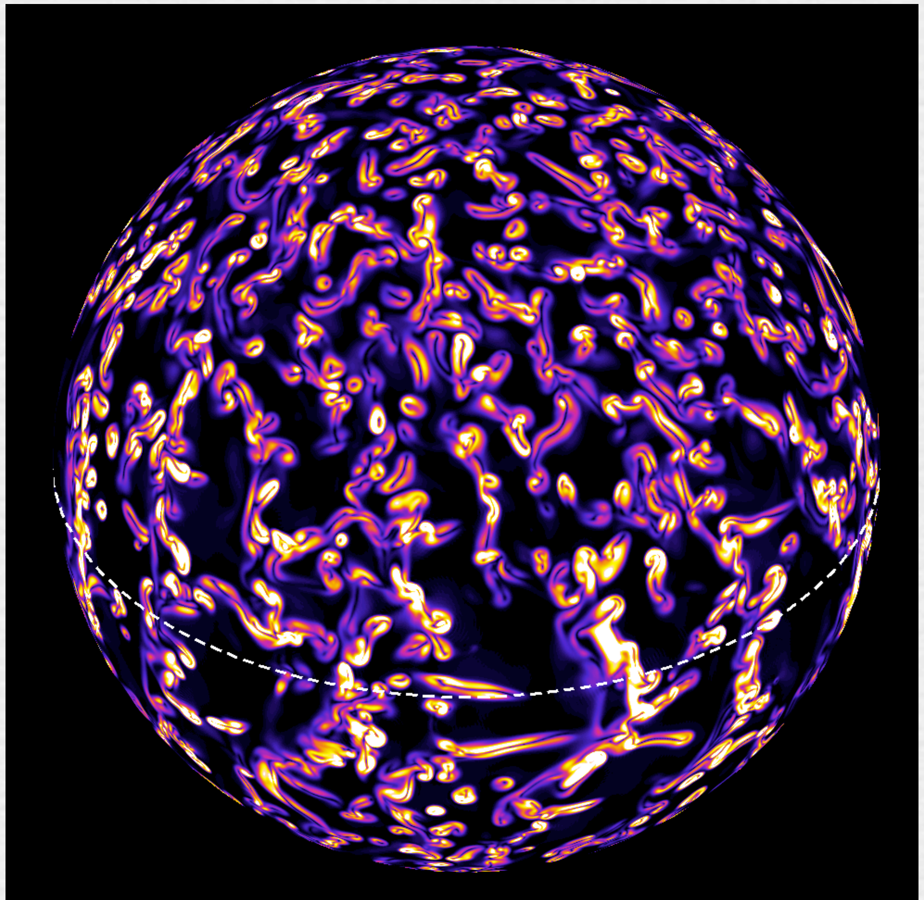
# Disconnected lanes and plumes deeper down



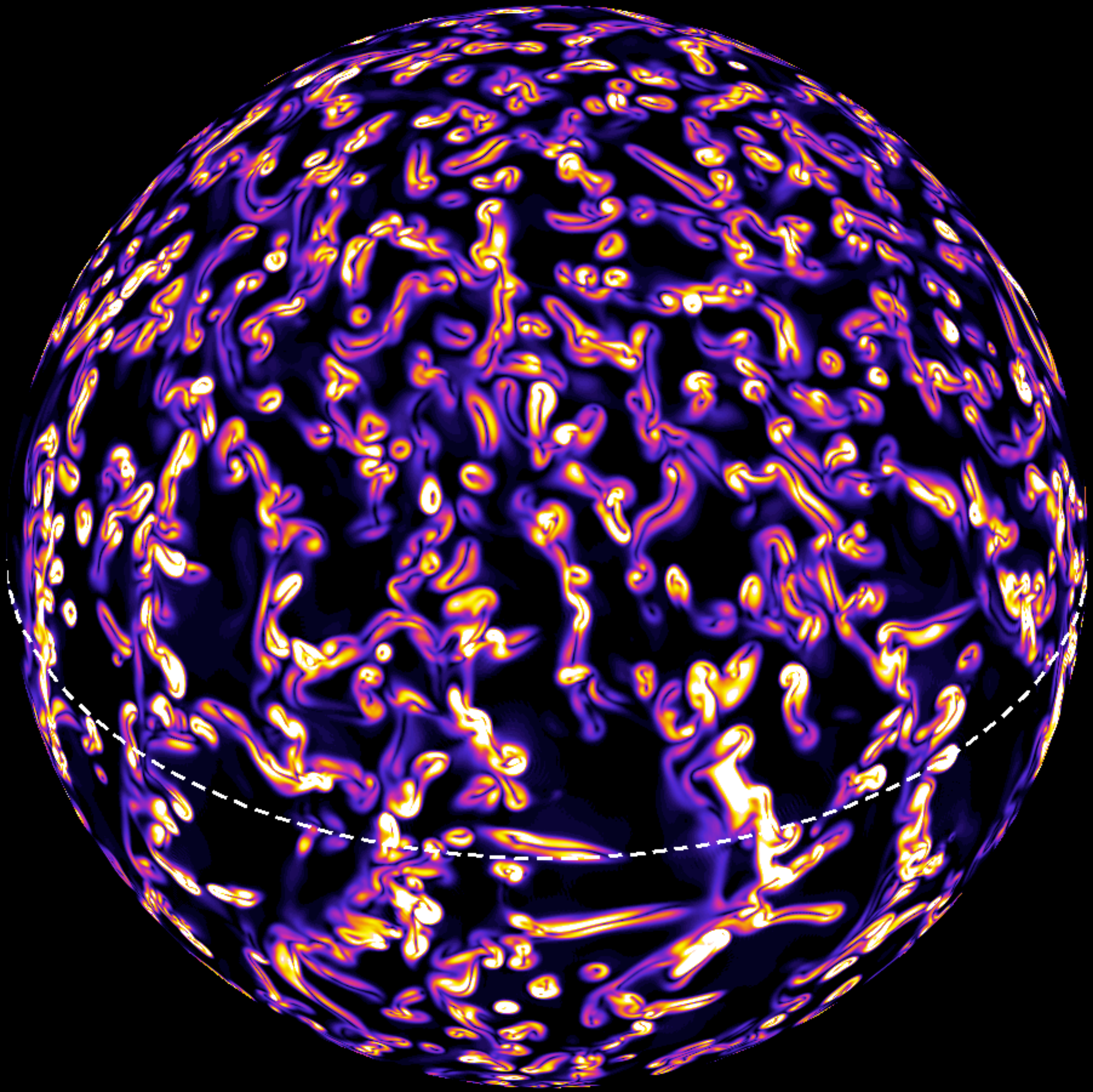




**Inward KE flux**

**Turbulent entrainment**



## Vorticity in Downflows!

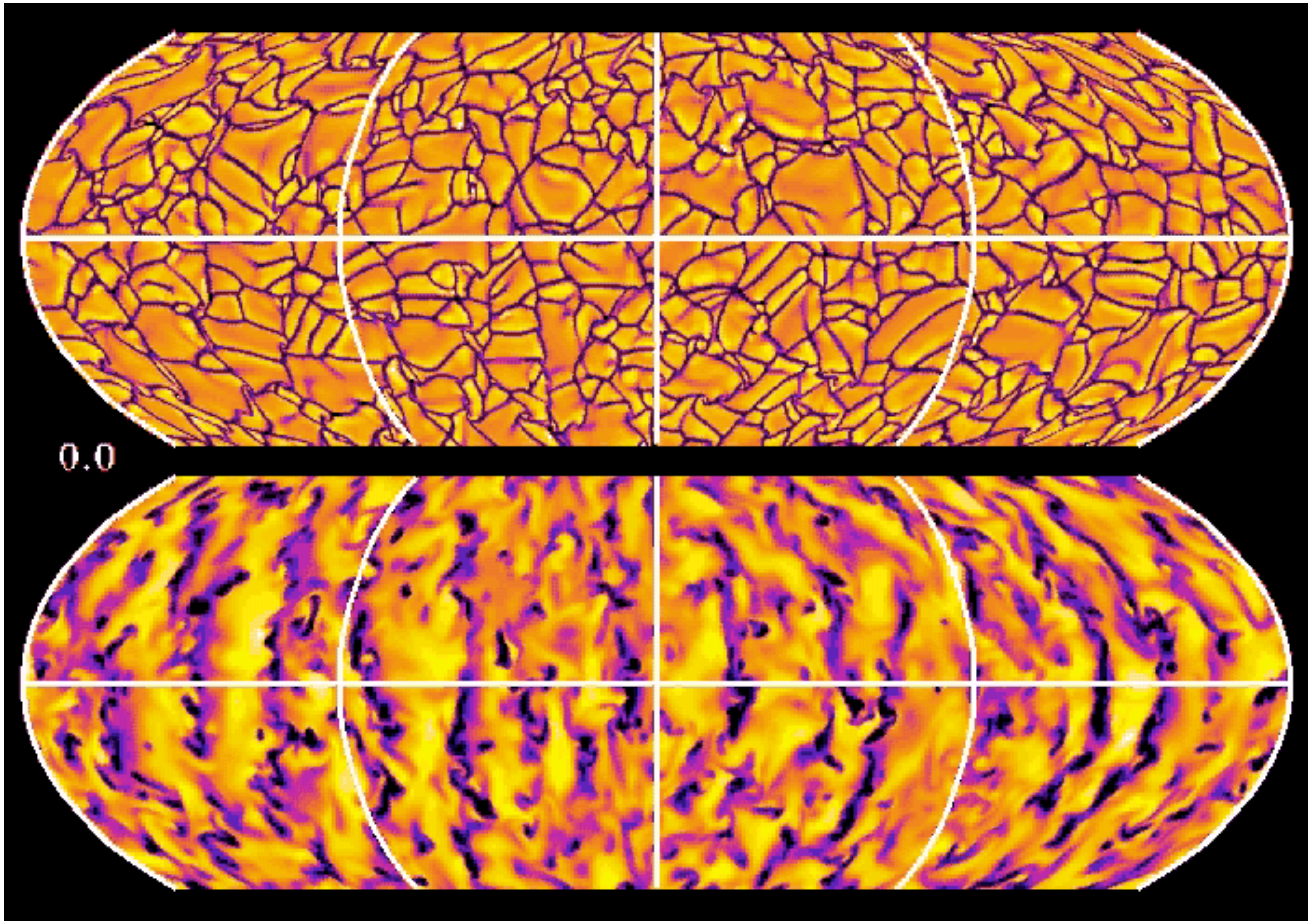


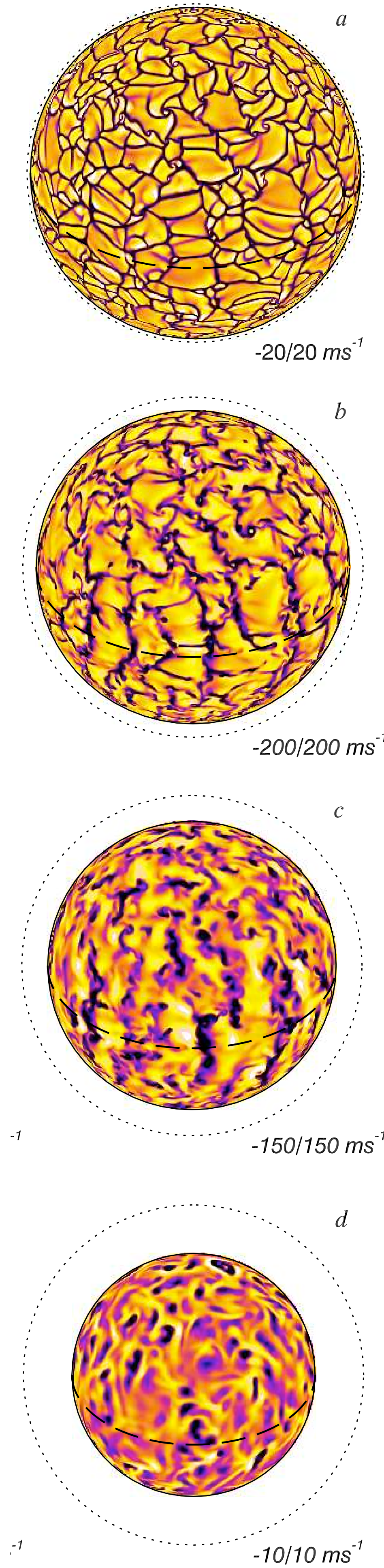
***Turbulent entrainment***

***Compression***

***Vortex stretching***

# North-South (NS) Downflow Lanes



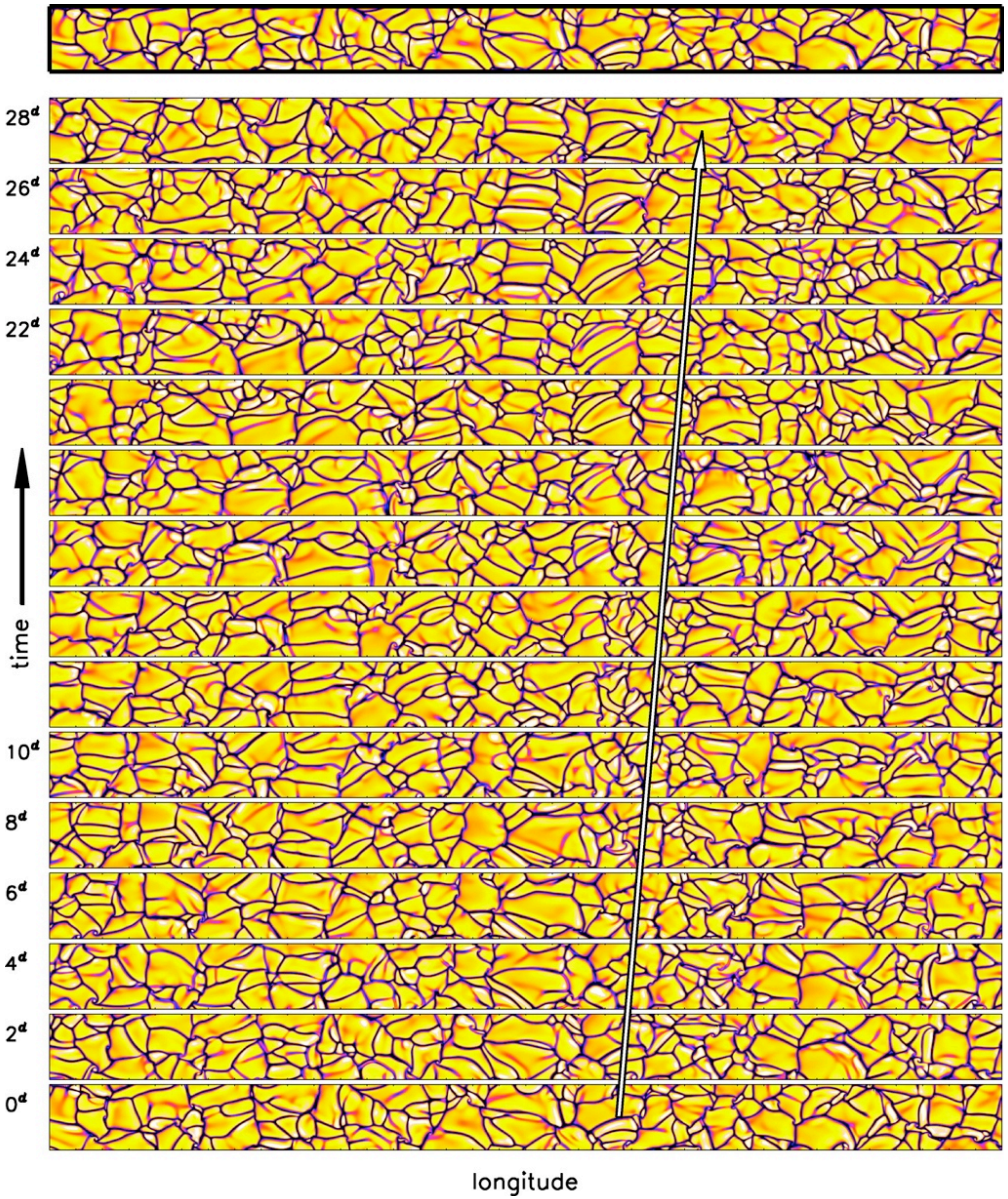



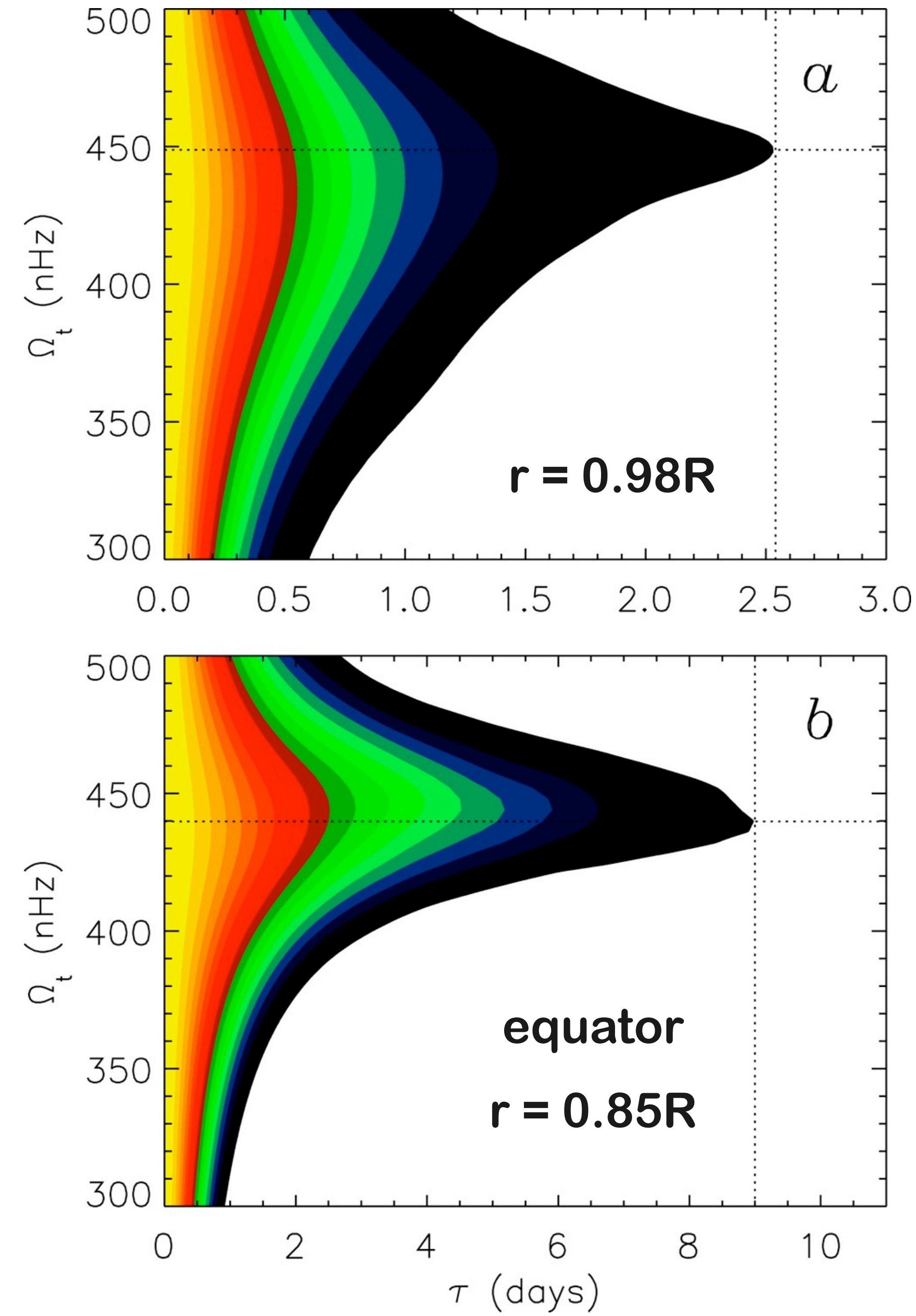

**Prograde propagation: Traveling convection modes!**

**Coherence through most of the convection zone**

**Turbulent Transport: especially angular momentum!**

# Propagation and Lifetime




***Correlation time ~ 2.5 - 9 days but NS lanes can live for months***

***Optimal tracking rate faster than local rotation rate***

# Summary: Solar Convection

- **Granulation**
  - Driven by radiative cooling in the photospheric boundary layer
  - Strong downflow plumes, lanes
  - Weaker upflows are a passive reponse

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

- **Supergranulation and Mesogranulation**
  - Self-organization of granular plumes
  - Density stratification, plume interactions
  - Part of a continuous hierarchy

$L \sim$ 5 Mm
$U \sim$ 300 m $s^{-1}$
$\tau \sim$ 3-4 hrs

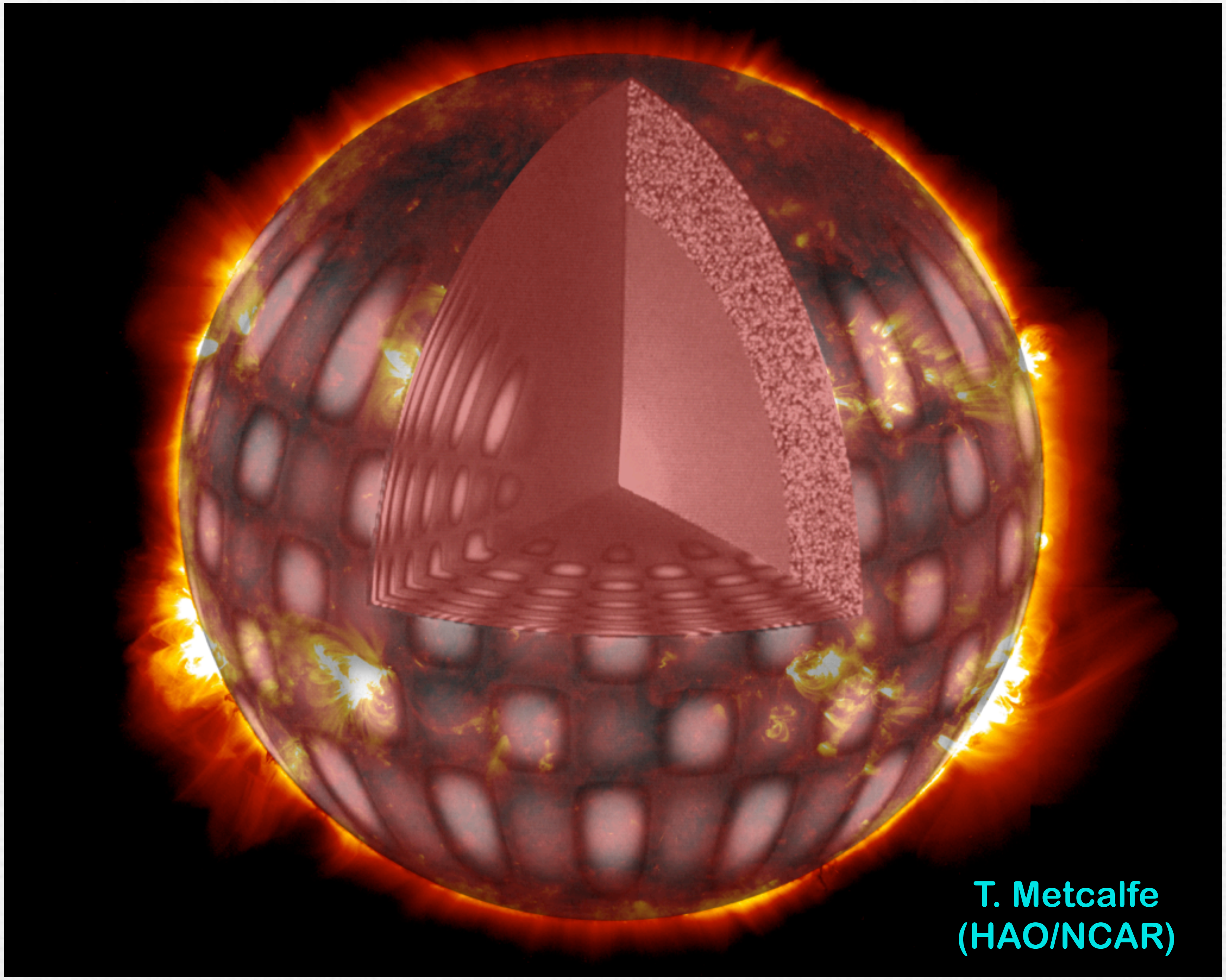
$L \sim$ 30-35 Mm
$U \sim$ 400 m $s^{-1}$
$\tau \sim$ 20 hours

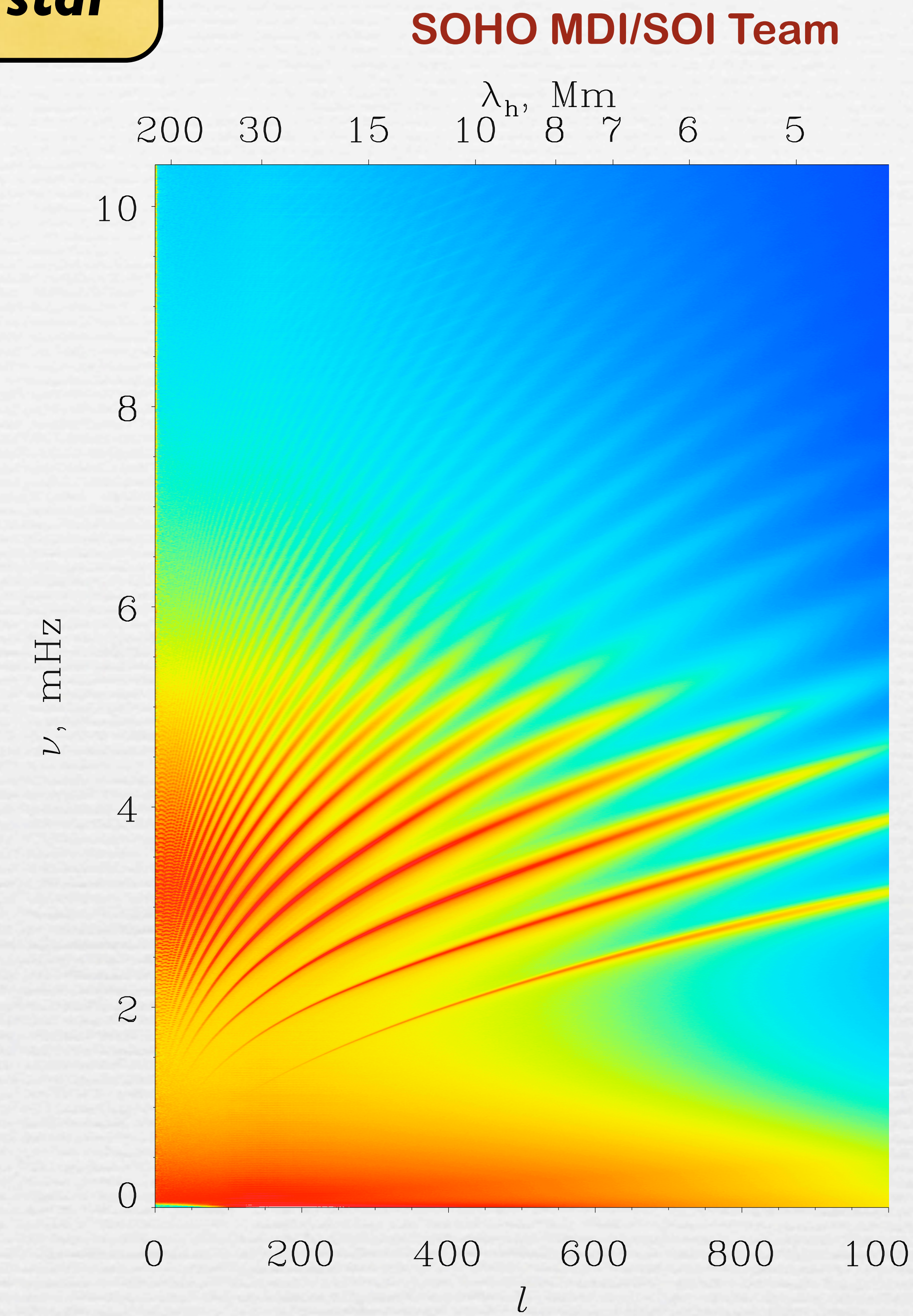
- **Giant Cells**
  - Strong downflow lanes & plumes, weaker upflows
  - Propagating NS downflow lanes at low latitudes
  - Solar cyclones at high latitudes
  - Kinetic helicity

$L \sim$ 100 Mm
$U \sim$ 100 m $s^{-1}$
$\tau \sim$ days - months

# Helioseismology

**Peering inside a star**



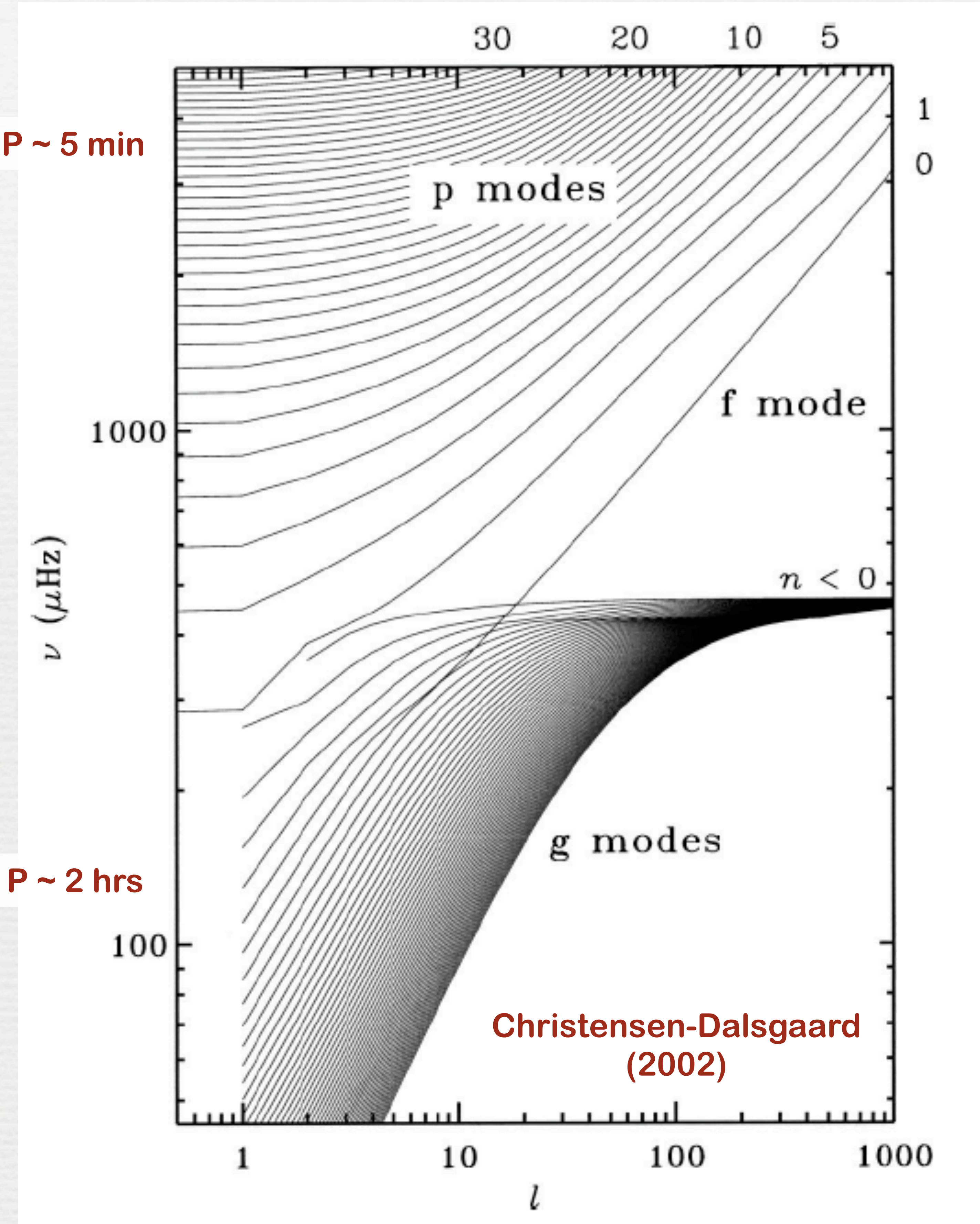

***Most reliable observable is doppler velocity of the photosphere, although intensity may also be used***

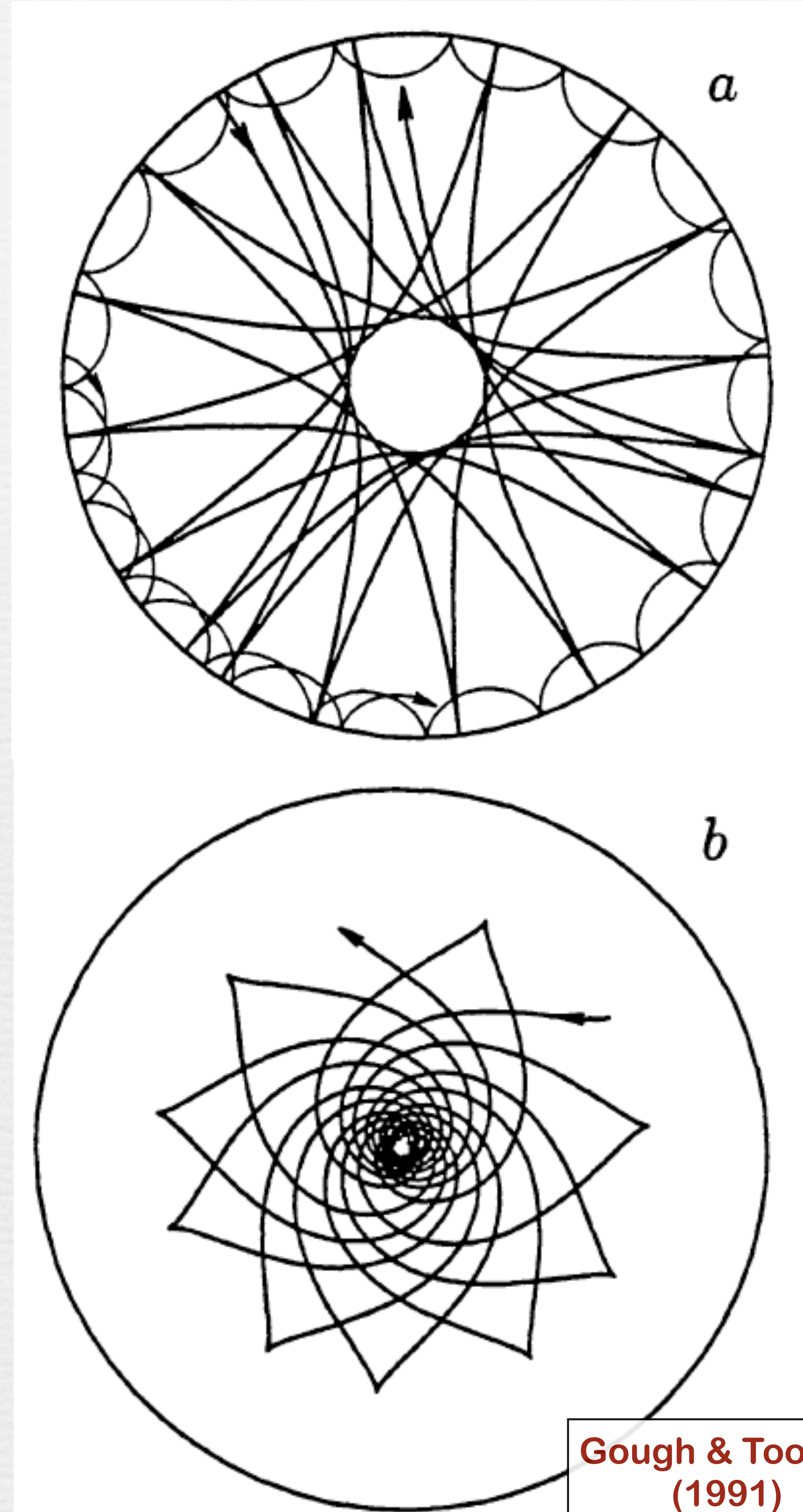
***p-modes excited by granulation, g-modes (theoretically) excited by giant cells***

# Global Oscillation Modes

P ~ 5 min

P ~ 2 hrs




Gough & Toomre
(1991)

# Global Rotational Inversions

$$\omega_{nlm} = \omega_{nl0} + m \int_0^R \int_0^\pi K_{nlm}(r,\theta)\Omega(r,\theta) r dr d\theta$$

$\omega_{nlm}$ **Observed**

$$\Delta_{nlm} \equiv \frac{\omega_{nlm} - \omega_{nl0}}{m}$$

**Rotational Splitting**

$\omega_{nl0}$ , $K_{nlm}(r,\theta)$

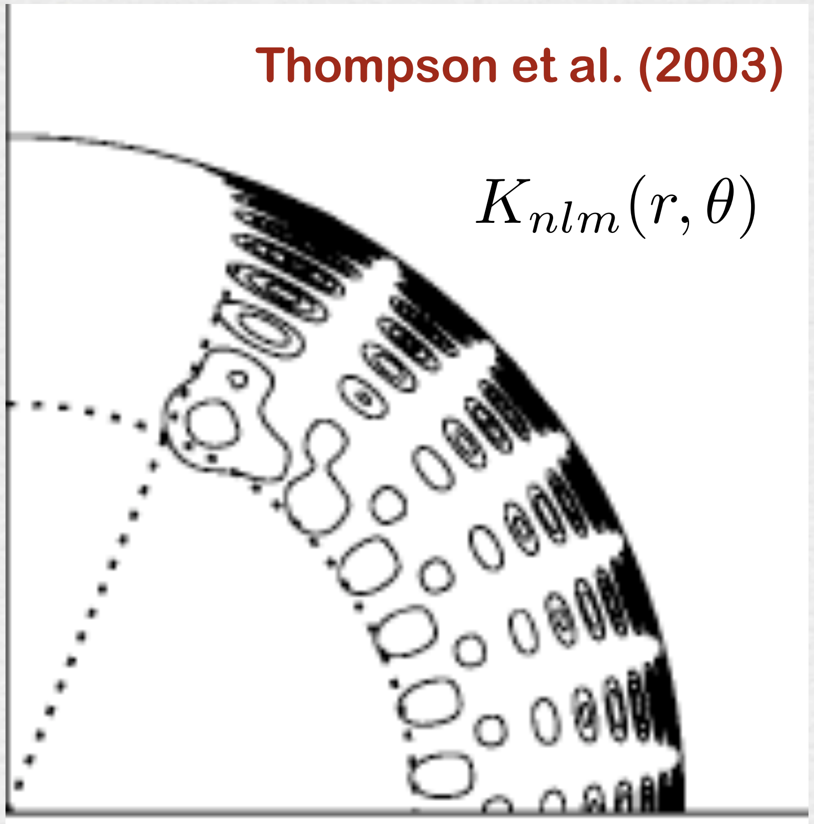
**Solar Structure Model**

$$\sum_{nlm} c_{nlm}(r_0,\theta_0)\Delta_{nlm} = \int_0^R \int_0^\pi \mathcal{K}(r_0,\theta_0;r,\theta)\Omega(r,\theta) r dr d\theta$$

$$= \overline{\Omega}(r_0,\theta_0)$$

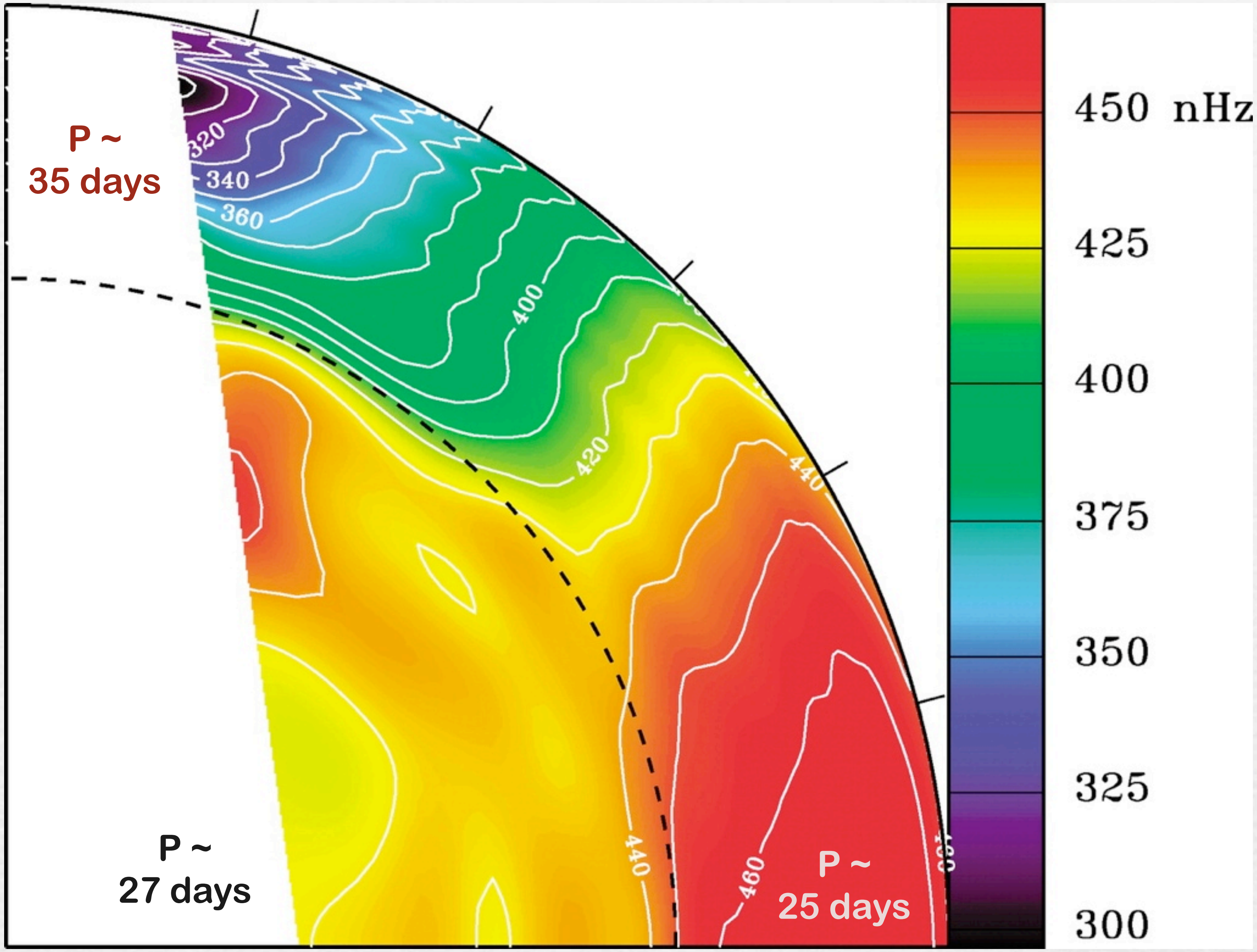
$$\mathcal{K}(r_0,\theta_0;r,\theta) = \sum_{nlm} c_{nlm}(r_0,\theta_0) K_{nlm}(r,\theta)$$

$c_{nlm}(r_0,\theta_0)$ **You pick!**



# The Internal Rotation of the Sun

Thompson et al. (2003)




***Differential Rotation (DR)***
***Monotonic decrease in Ω of ~ 30% from equator to high latitudes in CZ***

***Nearly uniform rotation in radiative interior***

***Convection implicated as source of DR***

***Interior rate intermediate relative to CZ***

***Conical isosurfaces at mid-latitudes***

***Near-surface shear layer*** ($0.95R < r < R$)

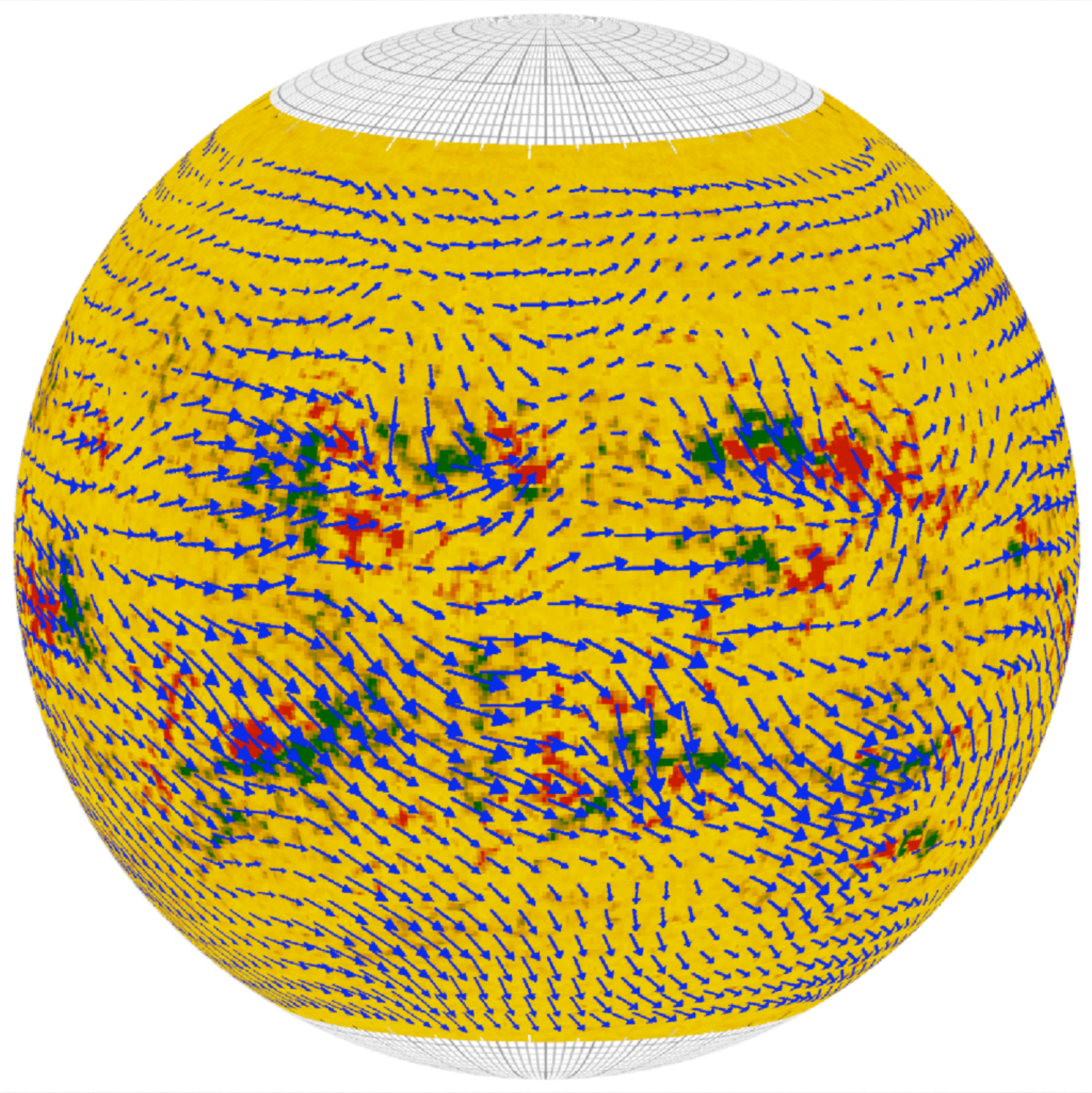
***Tachocline*** ($0.69R < r < 0.72R$; CZ base = $0.713R$ +/- 0.003)

- ***Toroidal field generation by rotational shear (critical for global dynamo)***
- ***Penetrative convection, internal gravity waves***
- ***Instabilities (magnetic buoyancy, magneto-shear)***
- ***Confinement***

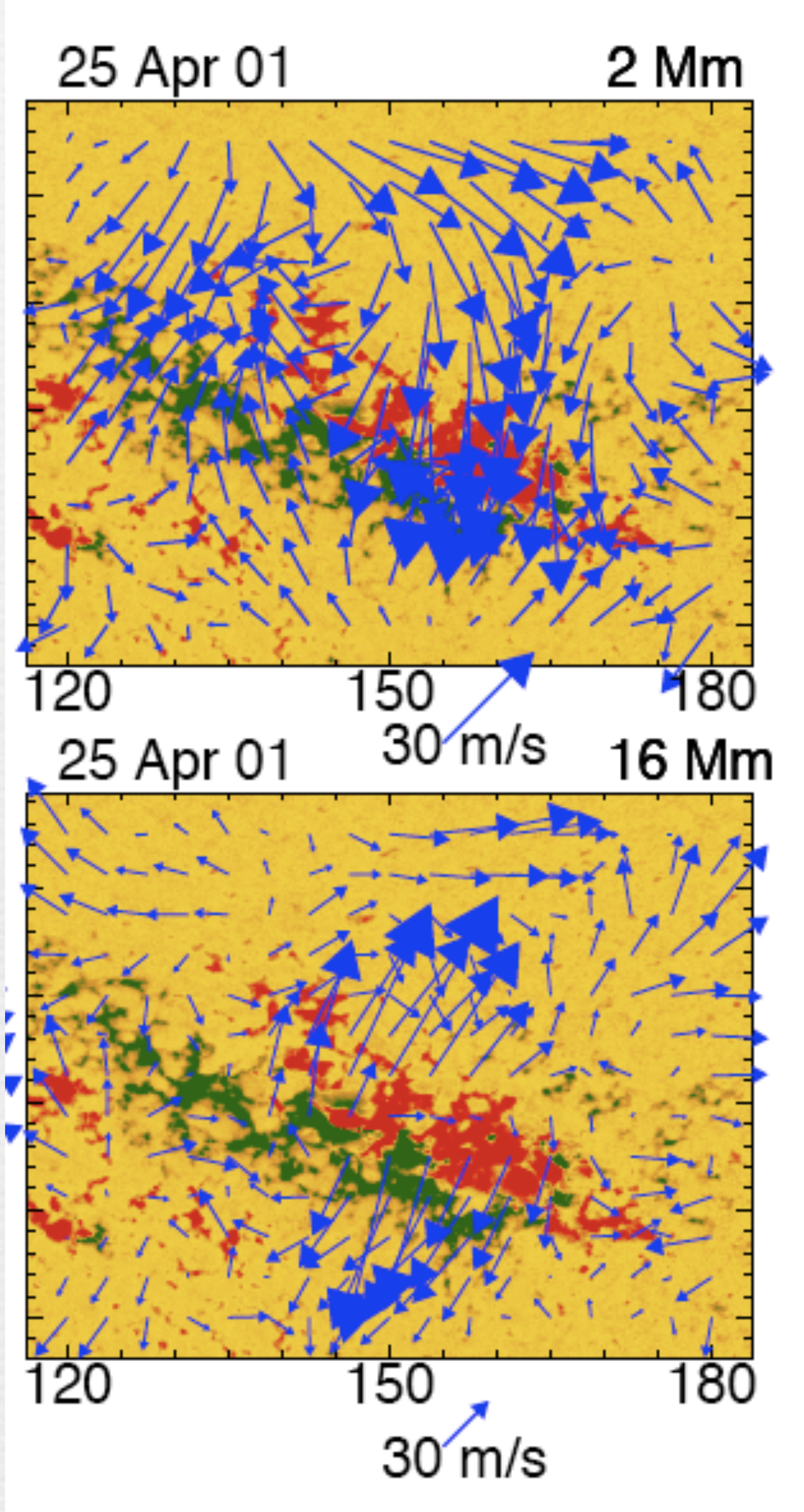
See "The Solar Tachocline", ed. D.W. Hughes, R. Rosner, N.O. Weiss, Cambridge Univ. Press (2007)

# Local Helioseismology

**Solar Subsurface Weather (SSW)**



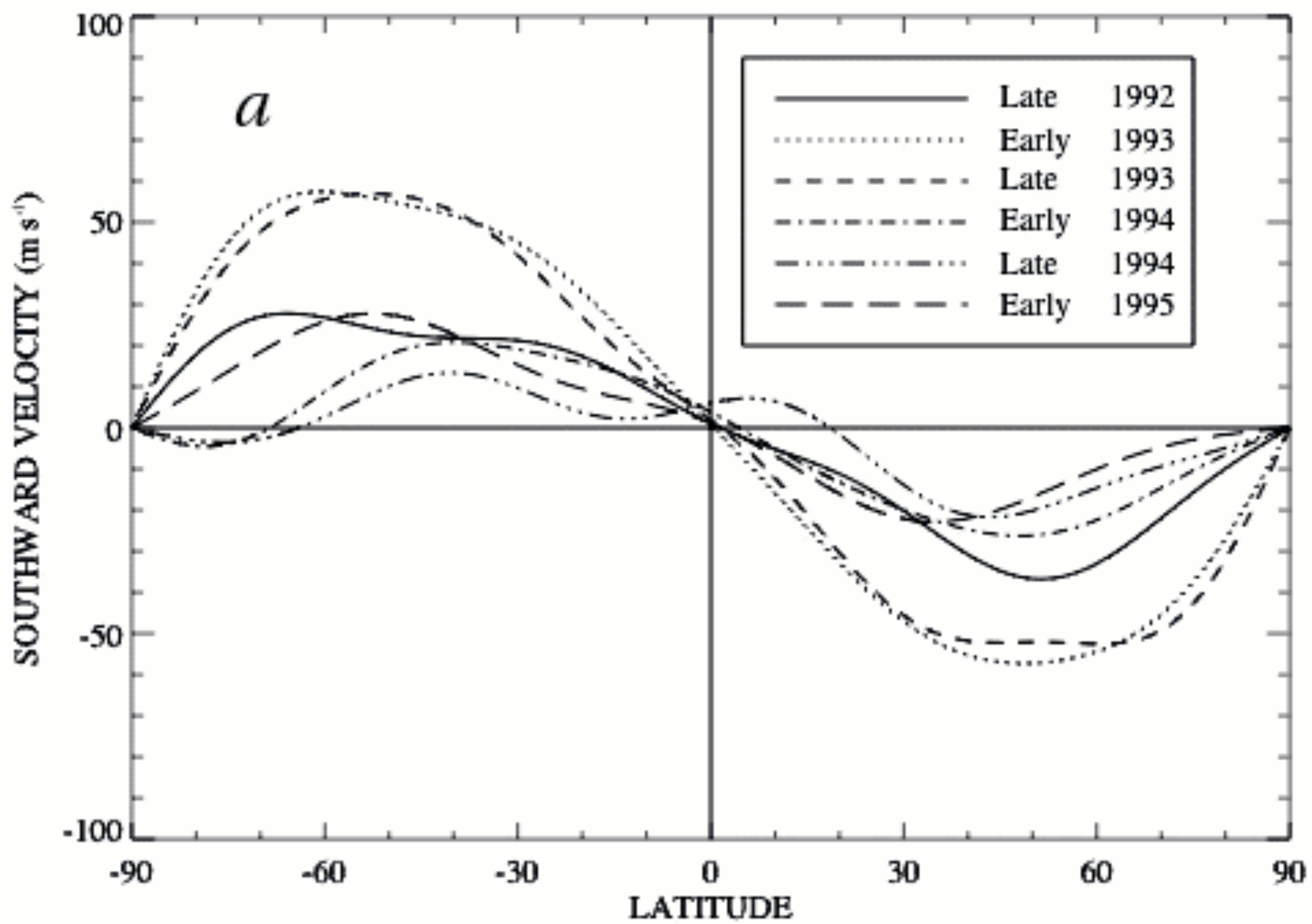
B. Hindman, D. Haber, J. Toomre (JILA/Univ. of Colorado)



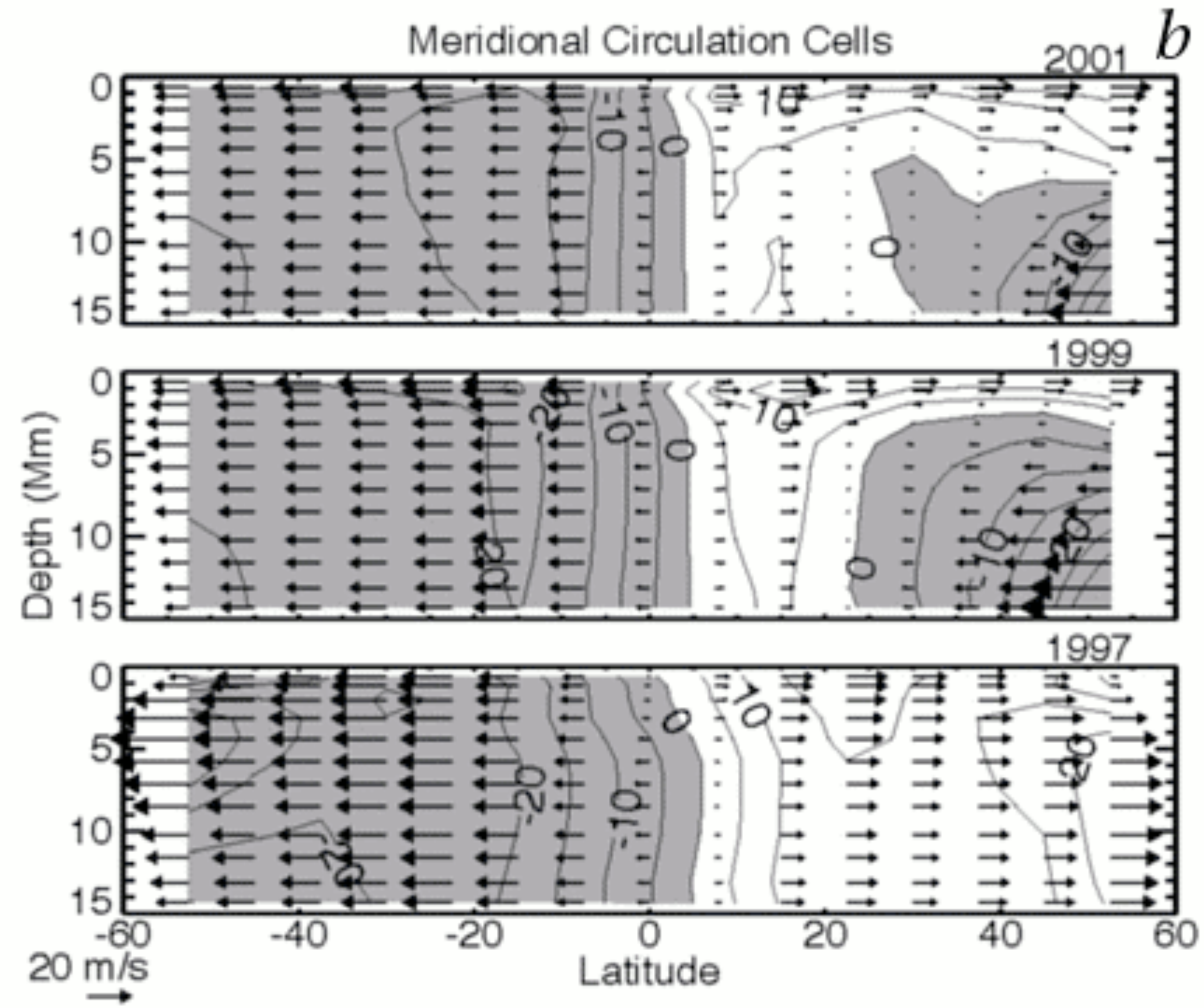

***Inferring subsurface flows from local high-wavenumber, non-resonant acoustic wave fields (see Gizon & Birch http://solarphysics.livingreviews.org)***

# Meridional Flow

**Photospheric Doppler measurements**




**Local Helioseismology**




**Poleward near surface at latitudes < 60° (unknown elsewhere)**

**Amplitude ~ 10-20 m $s^{-1}$ but highly variable**

**Possible evidence for multiple cells at high latitudes, deeper levels**

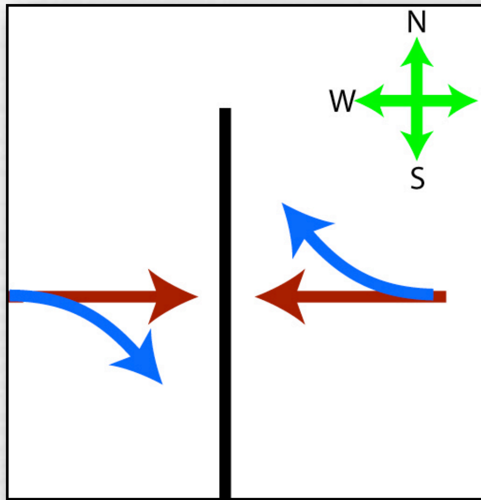
**Solar cycle variations; convergence into activity bands (near surface)**

# Maintenance of Mean Flows: Dynamical balances!

## (1) Meridional Circulation = Reynolds stress

$$\nabla\cdot\left(\bar{\rho}\left\langle \mathbf{v}_m\right\rangle \mathcal{L}\right) = -\nabla\cdot\left(\bar{\rho} r \sin\theta \left\langle v'_\phi \mathbf{v}'_m \right\rangle\right)$$

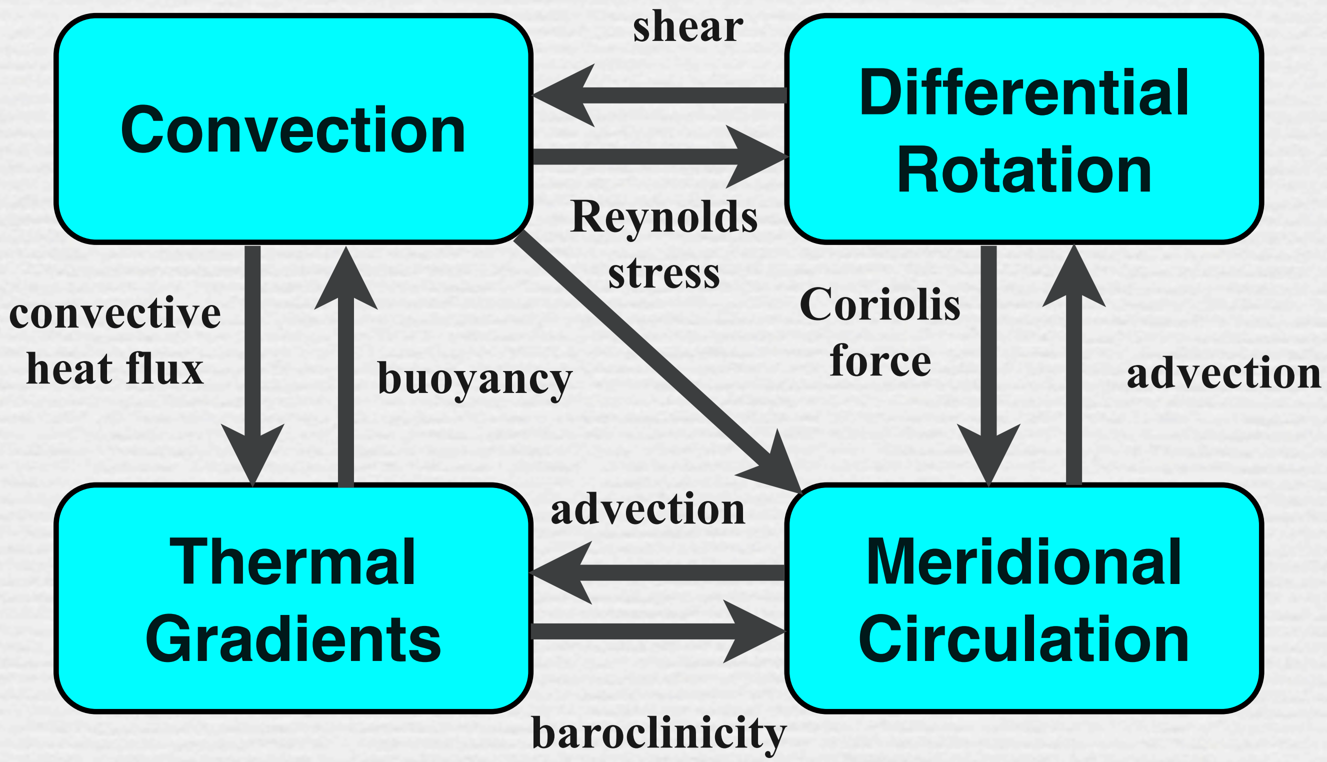
***Coriolis-induced tilting of convective structures***




## (2) Thermal Wind Balance *(Taylor-Proudman theorem)*

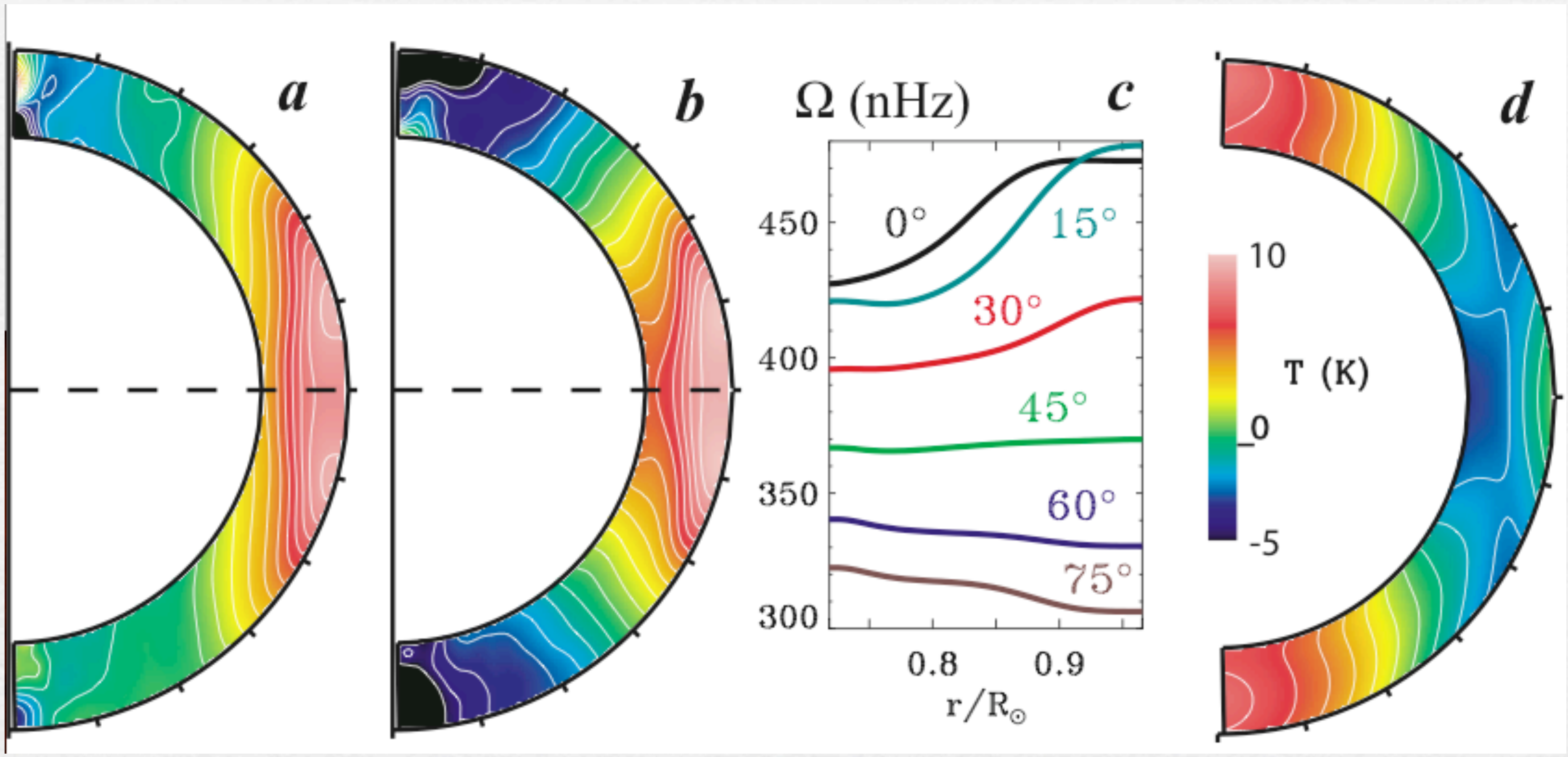
$$\Omega\cdot\nabla\left\langle v_\phi\right\rangle = \frac{g}{2rC_P}\frac{\partial\left\langle S\right\rangle}{\partial\theta}$$

- Steady State
- Neglect LF, VD
- Rapid Rotation RS << CF
- ideal gas
- hydrostatic, adiabatic background

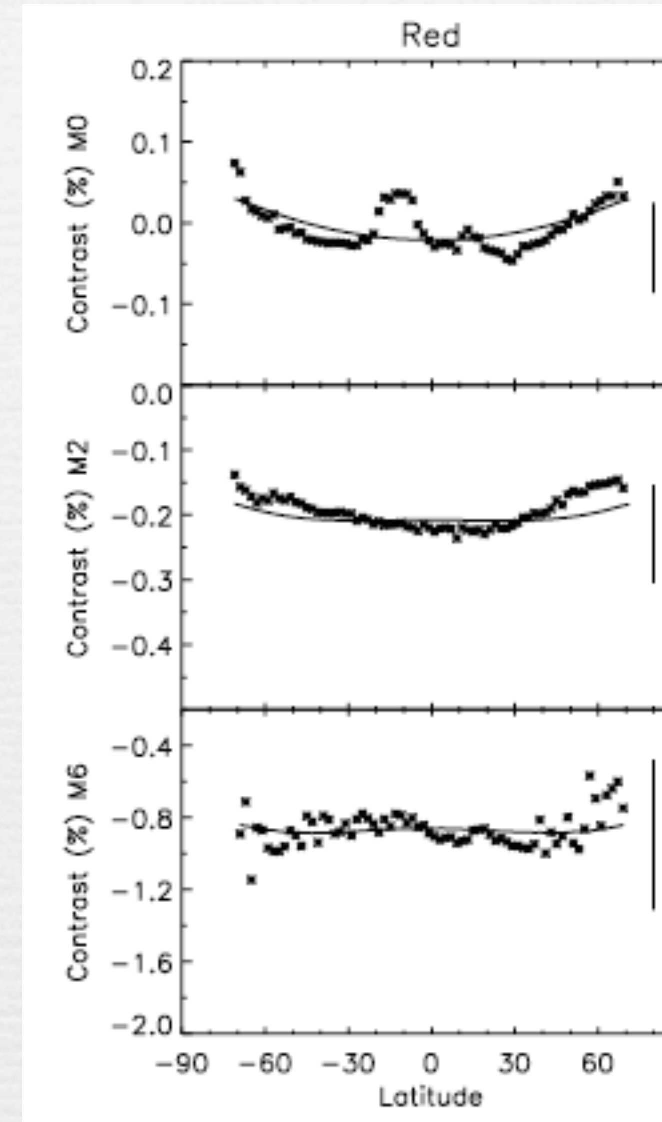



$$\mathcal{L} = r\sin\theta\left(\Omega r\sin\theta + \left\langle v_\phi\right\rangle\right)$$

# Example 1: Thermal coupling to the tachocline




Miesch, Brun & Toomre (2006)



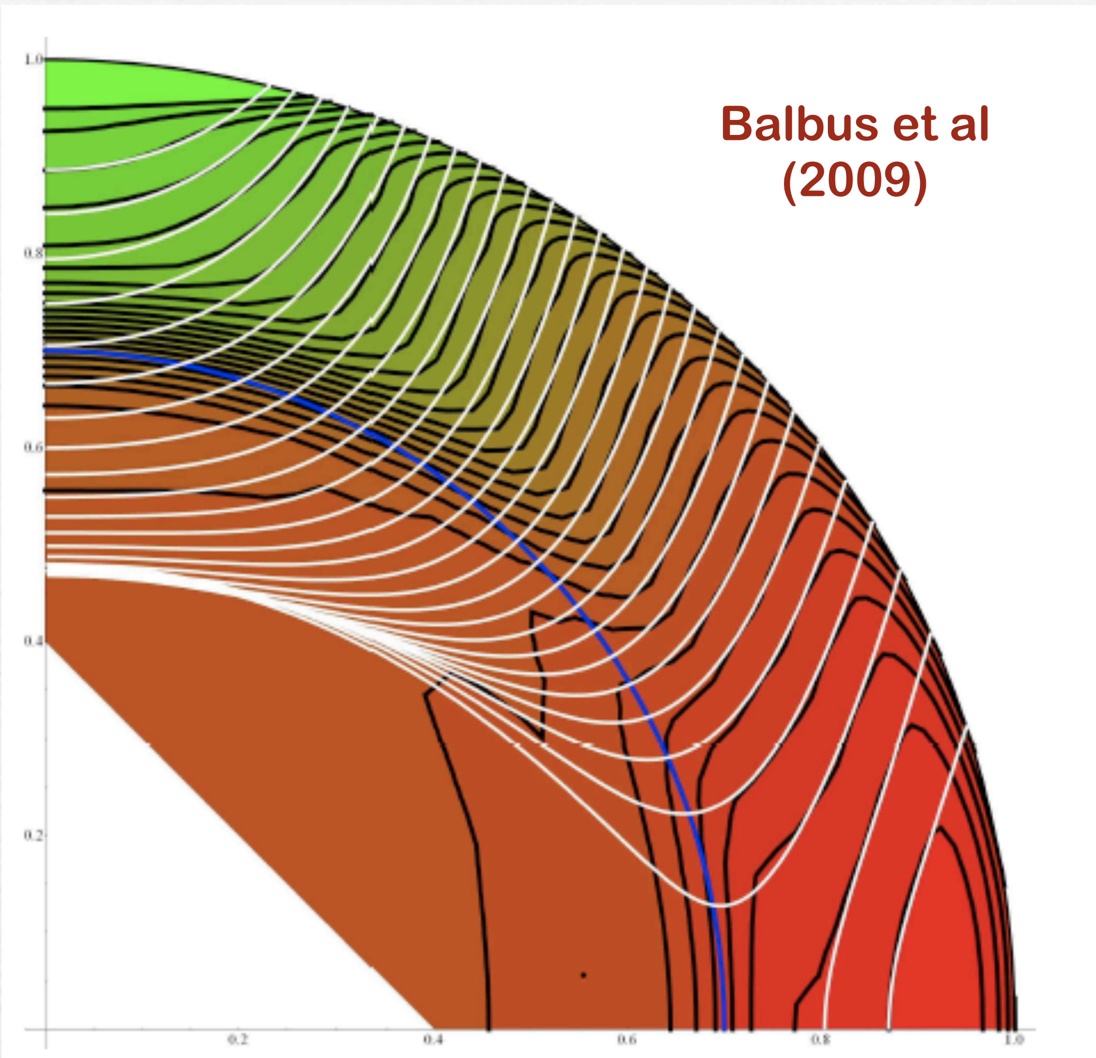

Rast et al. (2007)

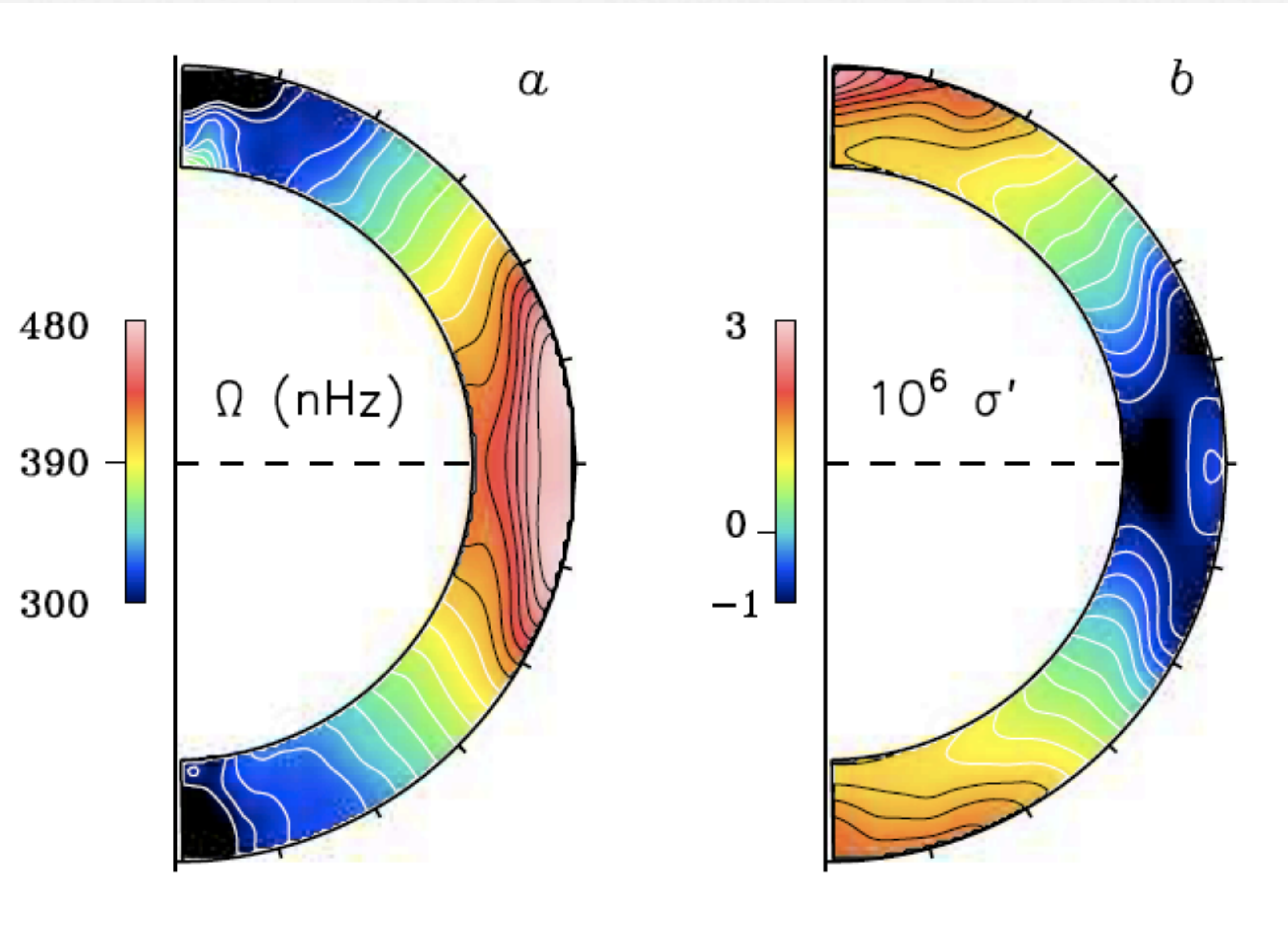
- Prograde equator maintained by Reynolds stresses
- Conical profile maintained by baroclinicity
  - thermal wind balance in lower CZ
  - latitude-dependent convective heat flux
  - enhanced by thermal gradients in the tachocline
  - mediated by induced circulations

**Warm Poles!**

$$\Omega \cdot \nabla \langle v_\phi \rangle = \frac{g}{2rC_P}\frac{\partial \langle S \rangle}{\partial \theta}$$

# Example 2: Isorotation contours as characteristics of the Thermal Wind equation

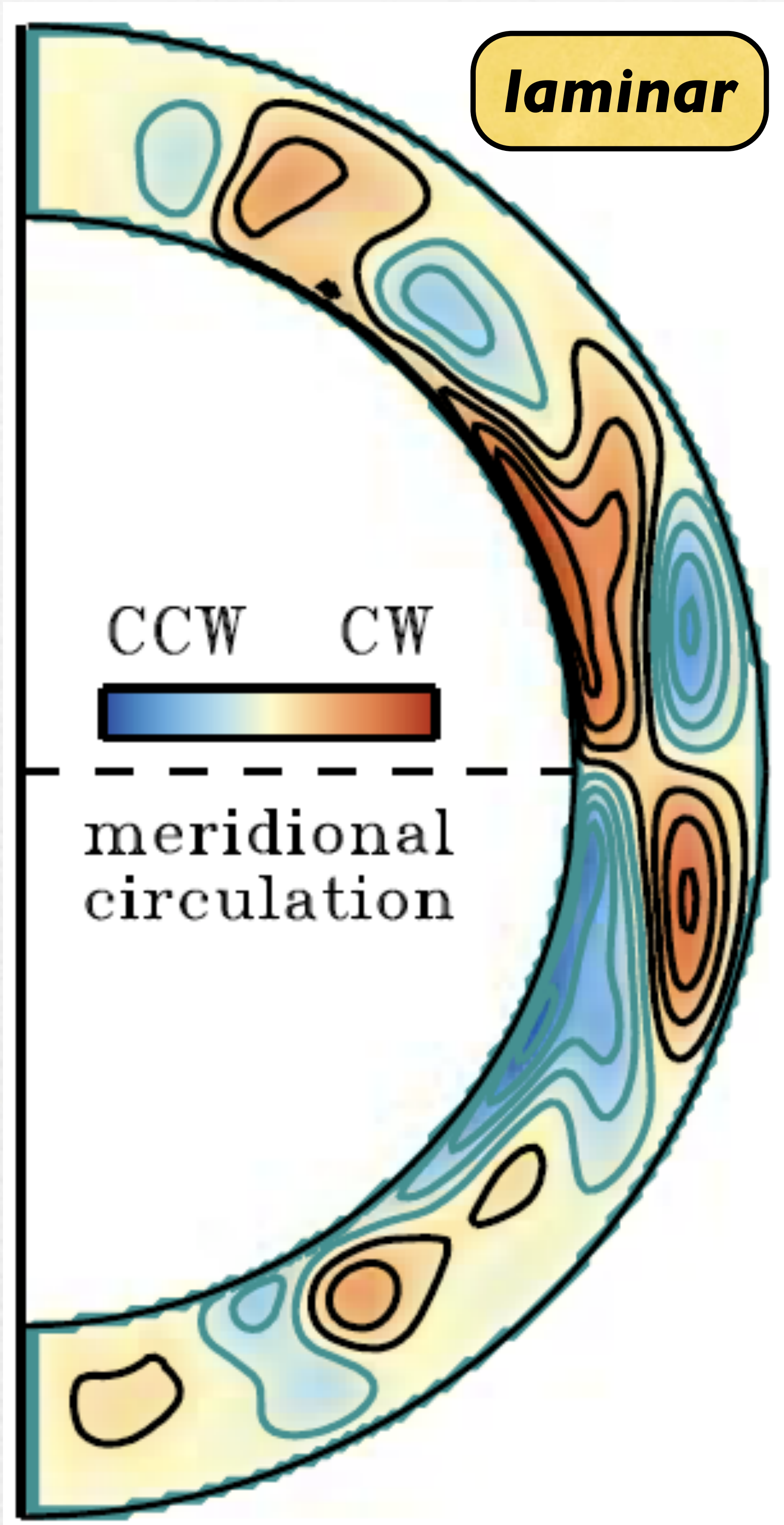


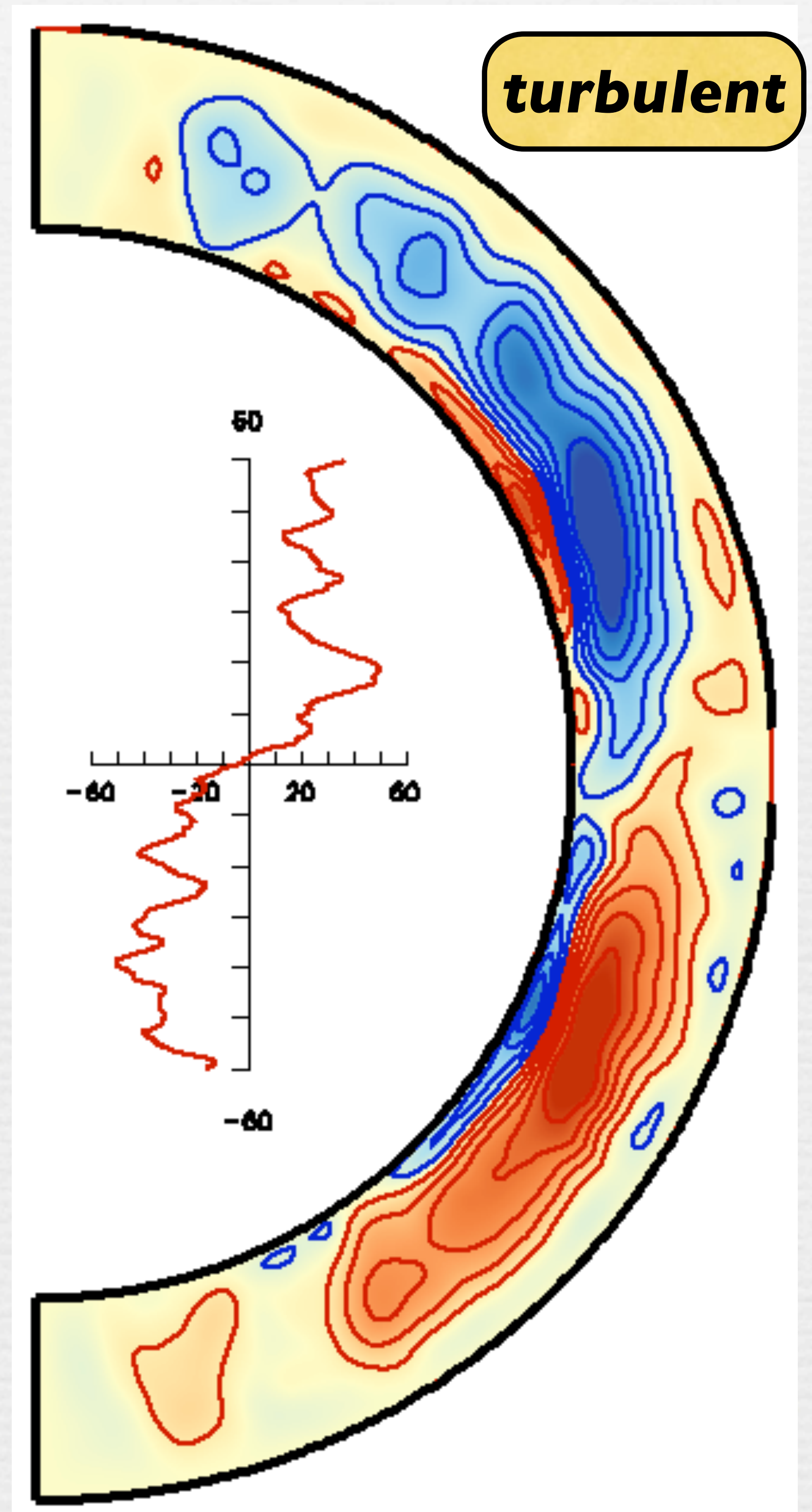



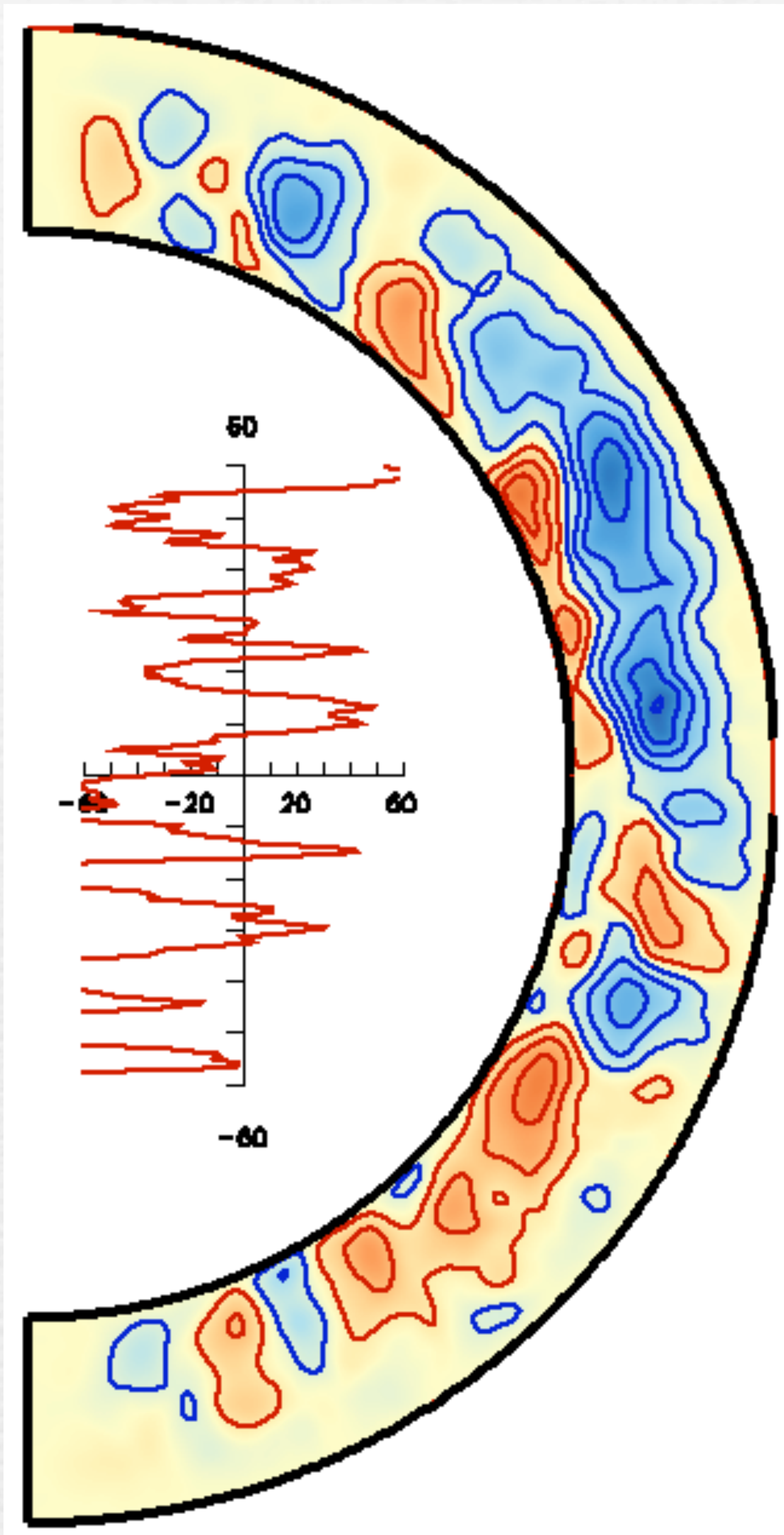

- Assume, for the sake of argument that $S' = S - \langle S \rangle_{\theta\phi} = S'(\Omega^2)$
- Then TW eqn is hyperbolic and may be solved by means of characteristics
- Characteristics trace out $\Omega$, $S'$ isosurfaces
- Possible mechanism: coherent structures *(downflow plumes)*
  - Those that cross $\Omega$ contours are sheared out
  - Conduits for heat transport (mixing S)

$$\Omega \cdot \nabla \langle v_\phi \rangle = \frac{g}{2rC_P} \frac{\partial \langle S \rangle}{\partial \theta}$$

# Example 3: Delicate Maintenance of Meridional Circulation



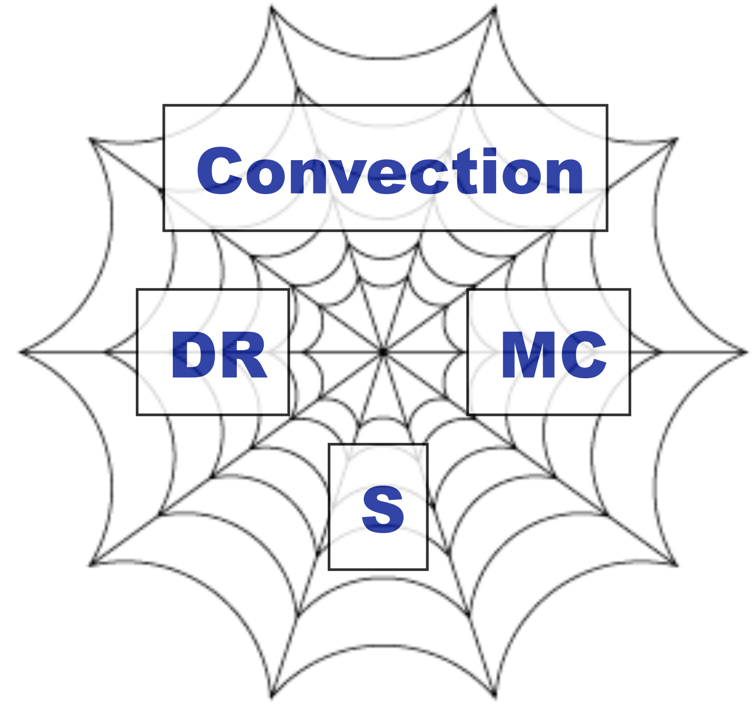




$$\nabla\cdot\left(\overline{\rho}\left\langle \mathbf{v}_m\right\rangle \mathcal{L}\right) = -\nabla\cdot\left(\overline{\rho} r\sin\theta\left\langle v'_\phi \mathbf{v}'_m\right\rangle\right)$$

$$\overline{\rho}\left\langle \mathbf{v}_m\right\rangle\cdot\nabla\mathcal{L} = F_\phi$$

***gyroscopic pumping***

# Summary: Rotational Shear and Meridional Flow



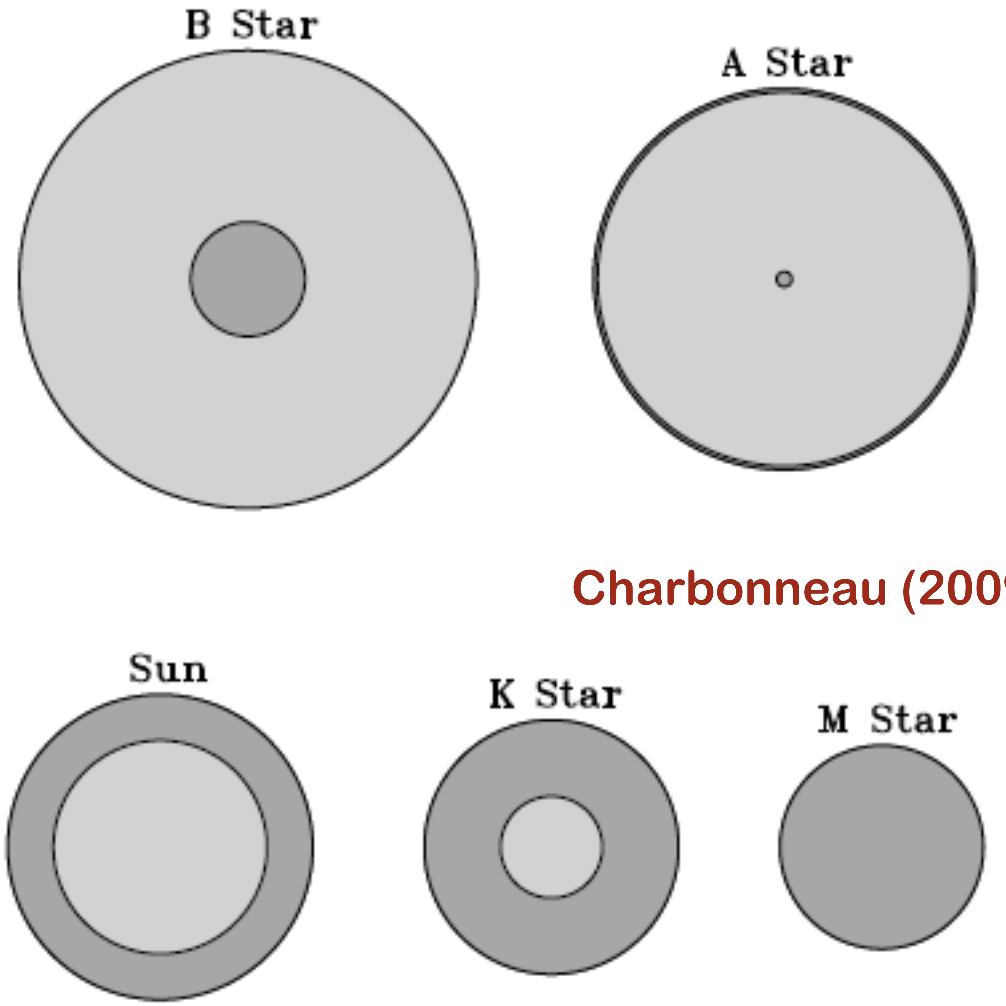

- **Helioseismology**
  - p-modes, f-modes, g-modes
  - Global oscillations: $\Omega$, $c_s$, $\rho$, $\Gamma$
  - Local patches: horizontal flow fields (SSW)

    $(r > 0.97R)$

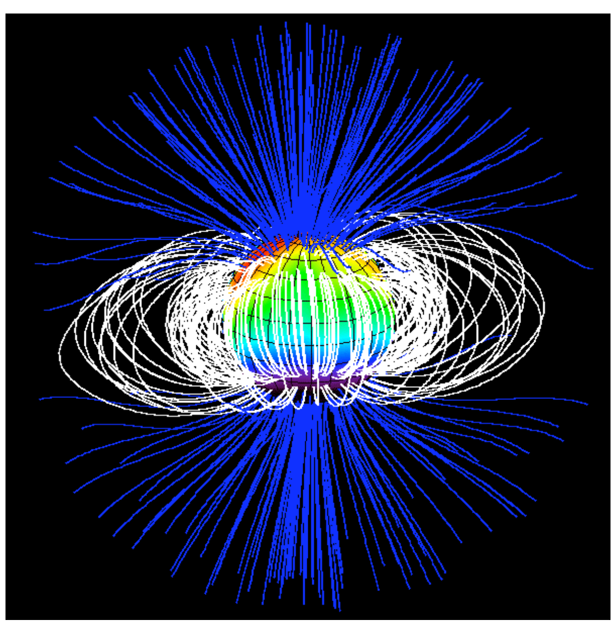
- **Differential Rotation**
  - Monotonic decrease from equator to pole
  - Conical mid-latitude contours
  - Tachocline, near-surface shear layer
  - Maintained by convective Reynolds stress, baroclinicity

- **Meridional Circulation**
  - Poleward near the surface $(r > 0.97R$, latitude $< 60^\circ)$
  - Relatively weak and highly variable
  - Maintained by gyroscopic pumping and baroclinicity

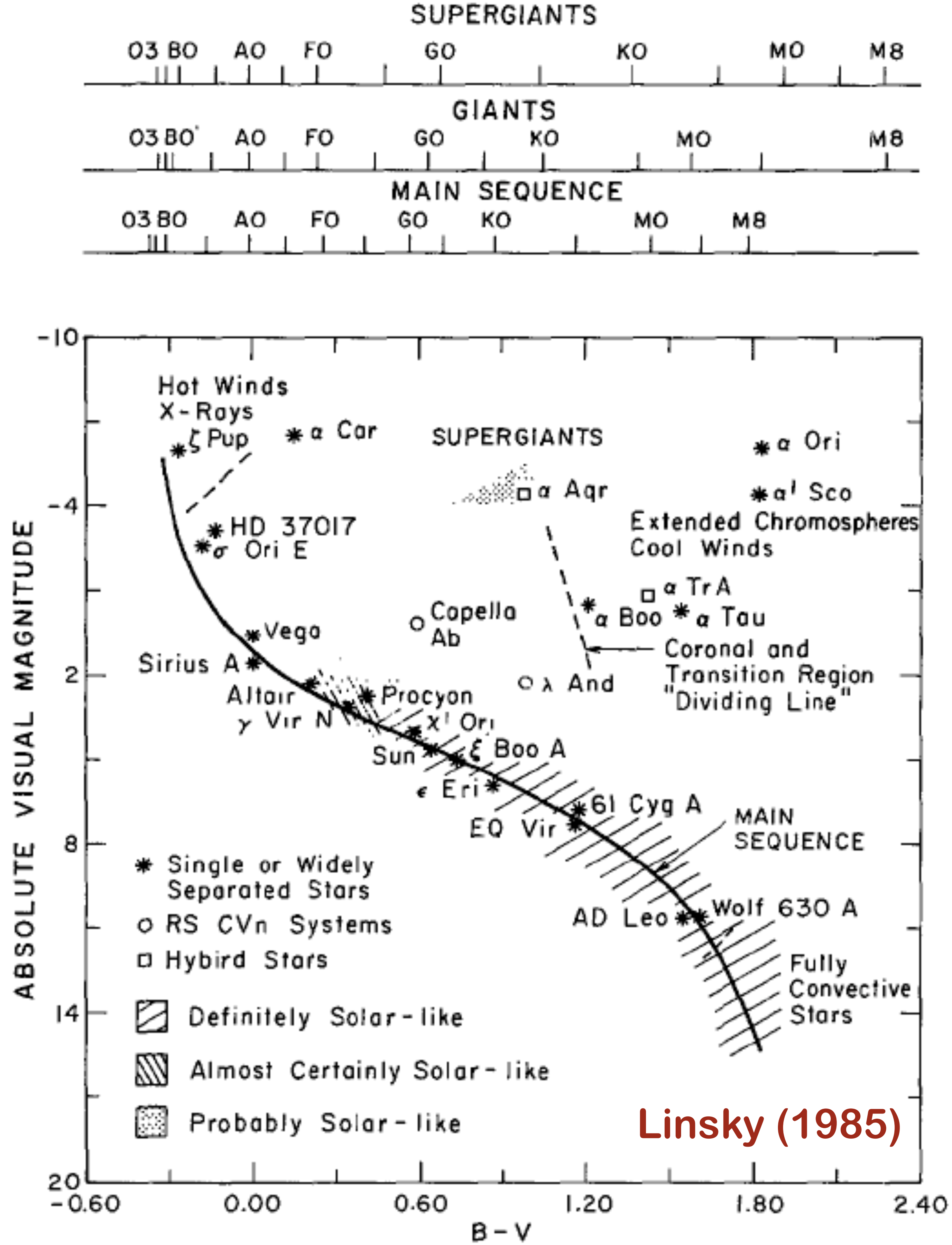
# Convection Breeds Magnetism



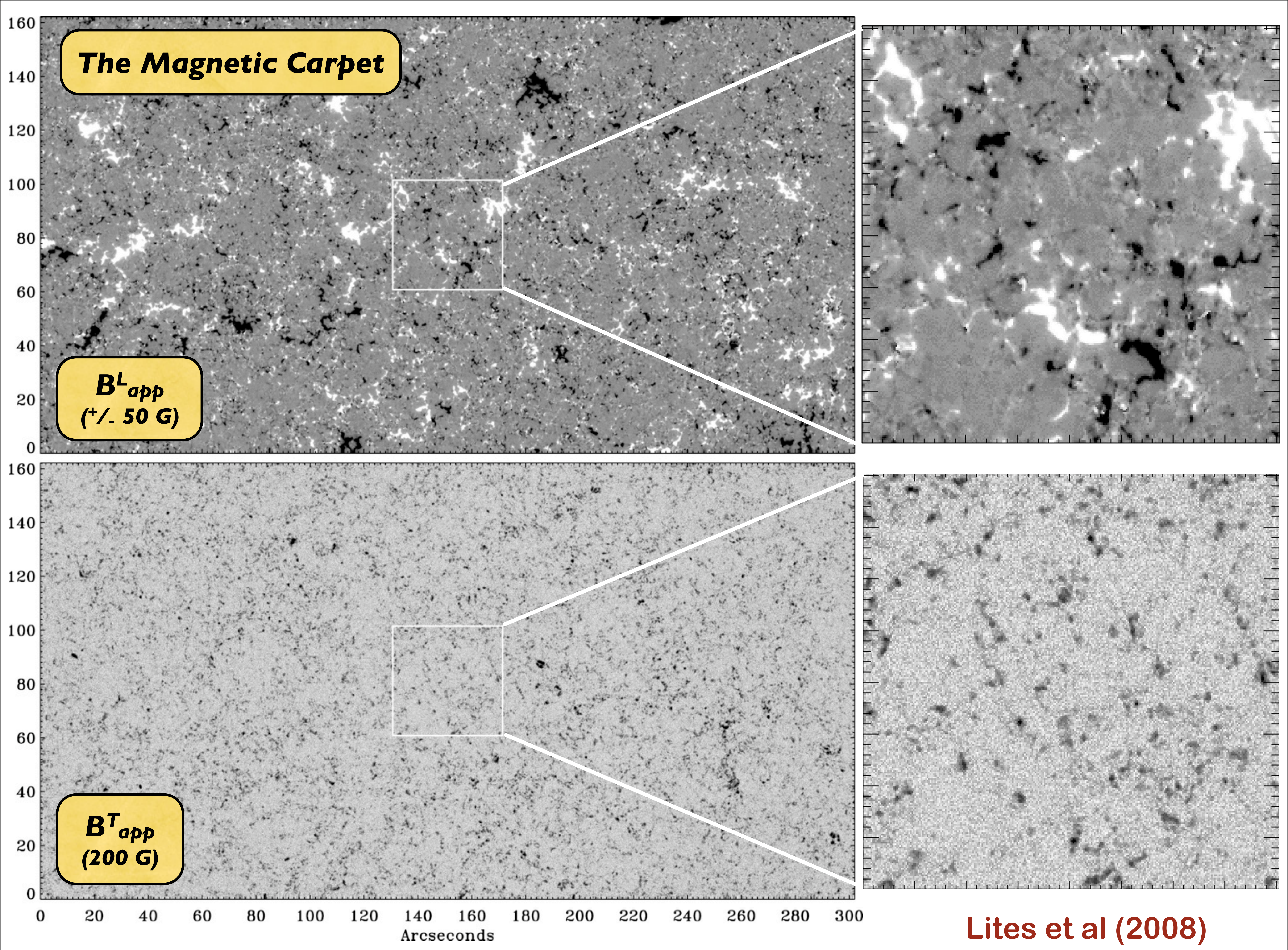

Charbonneau (2009)



Donati et al (2006)




Linsky (1985)


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

# Lagrangian Chaos

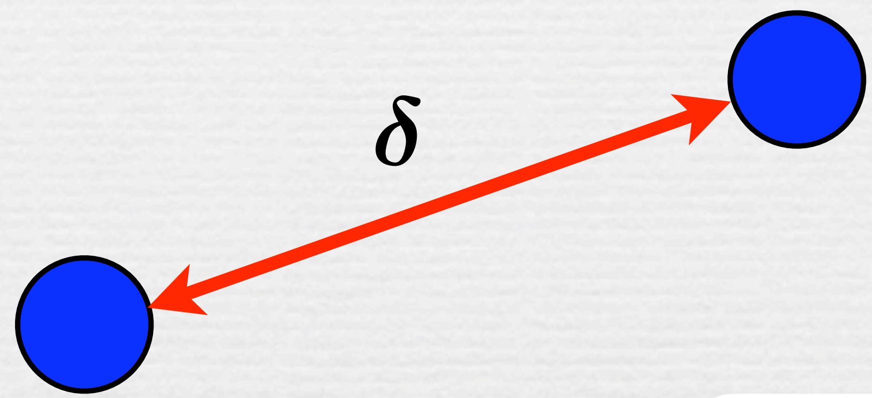
**Chaotic fluid trajectories amplify magnetic fields**

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

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

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

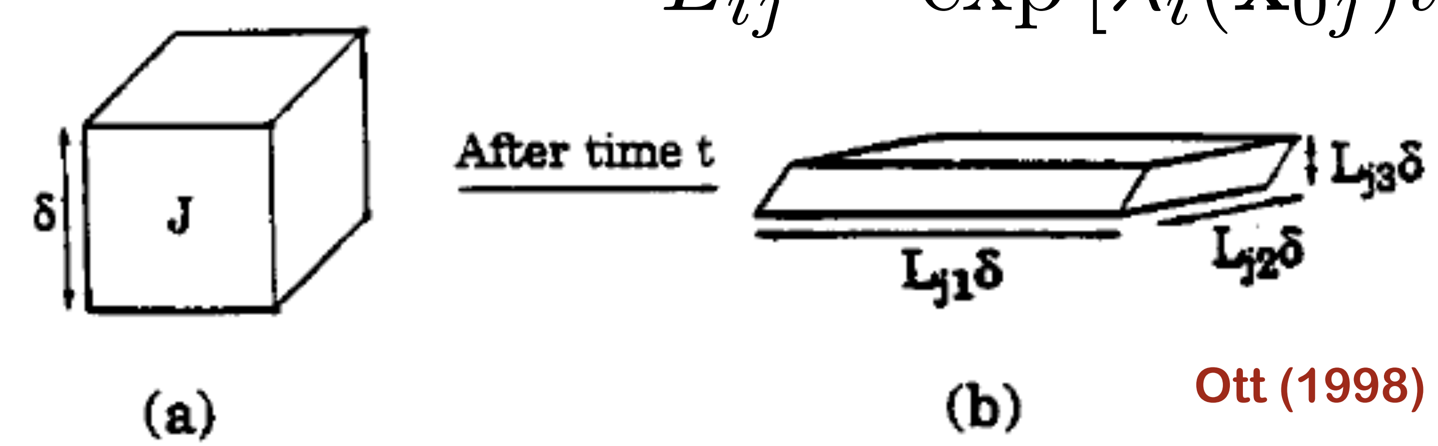
**If** $\boldsymbol{\nabla}\cdot\mathbf{v} = \eta = 0$ **then**




**λ = Local Lyapunov exponents**

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

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




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

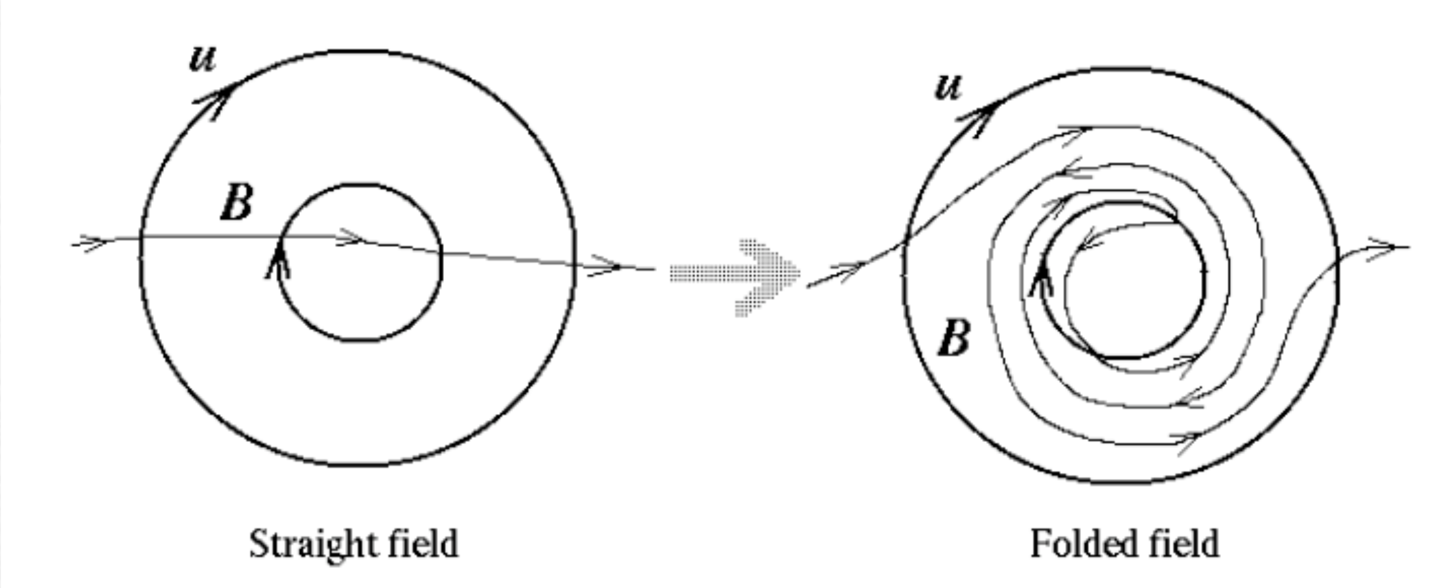
$$\frac{d\delta_i(\mathbf{x}_0,t)}{dt} = \mathcal{J}_{ij}(\mathbf{x}_0,t)\;\delta_j\,(\mathbf{x}_0,t)$$

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

# Spatially smooth, temporally chaotic flows work best

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

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

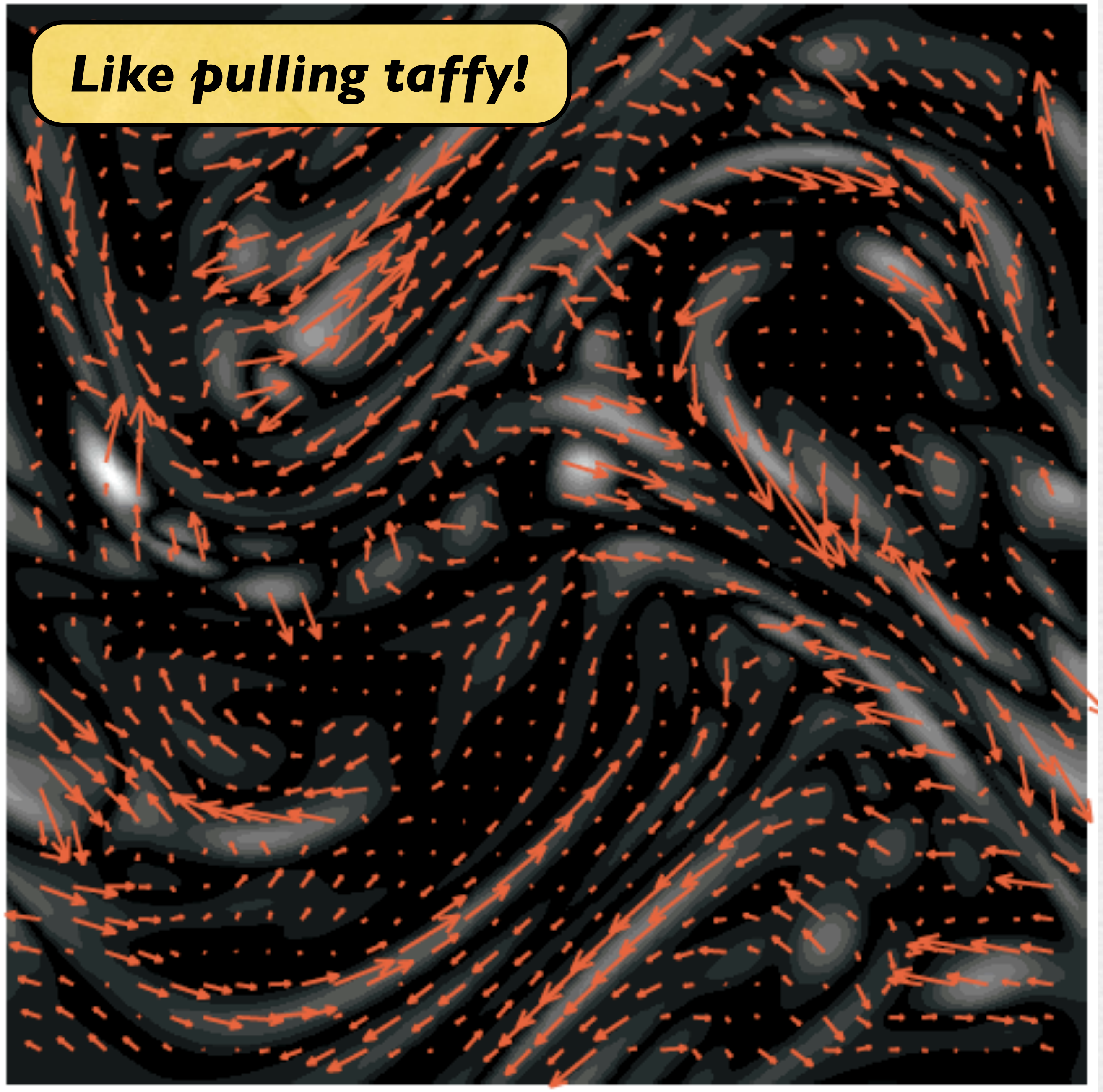


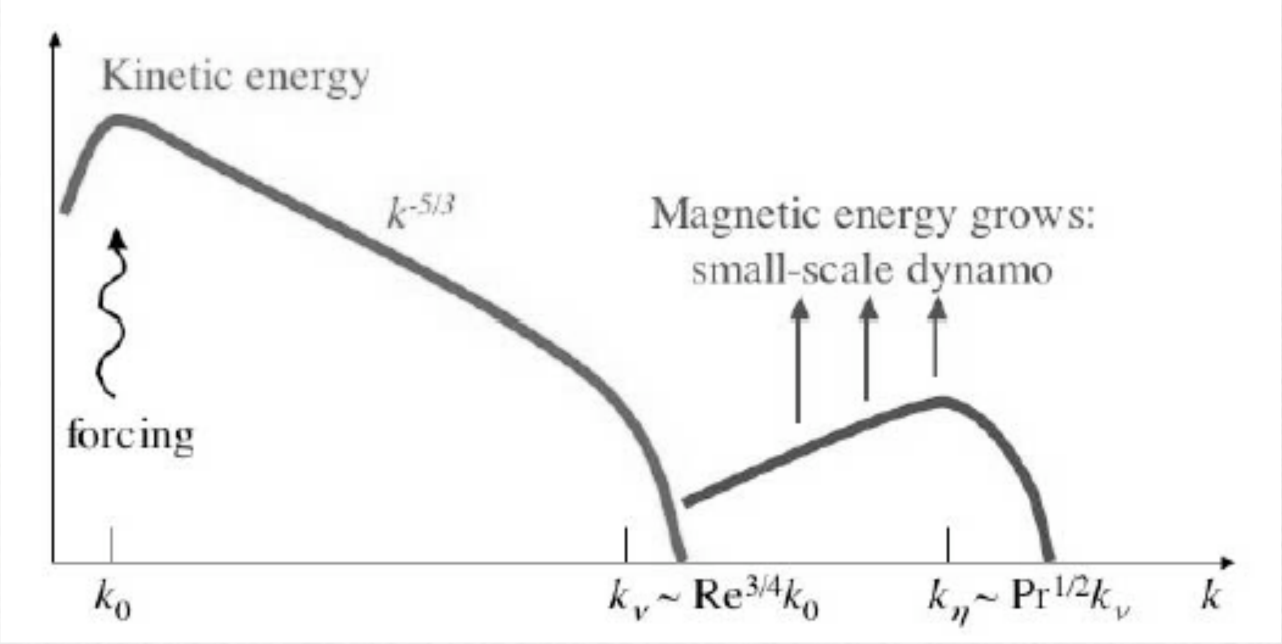

Schekochihin et al (2004)

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

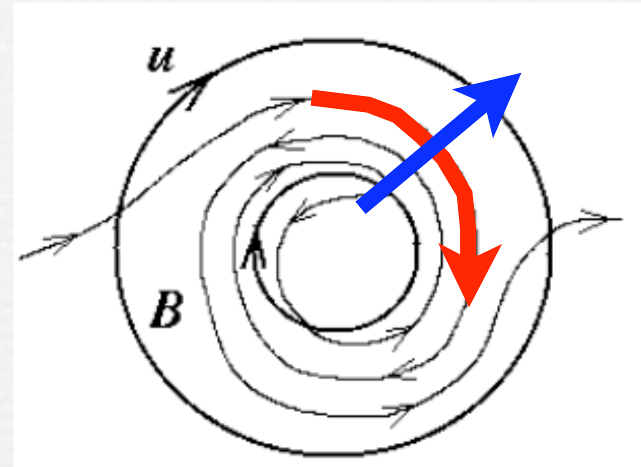
***Magnetic energy peaks near resistive scale***

***Turbulent flows beget turbulent fields!***



# Folded Field Structure




$$k_\parallel \sim k_\lambda$$

$$k_{B\times J} \sim R_m^{1/2}$$

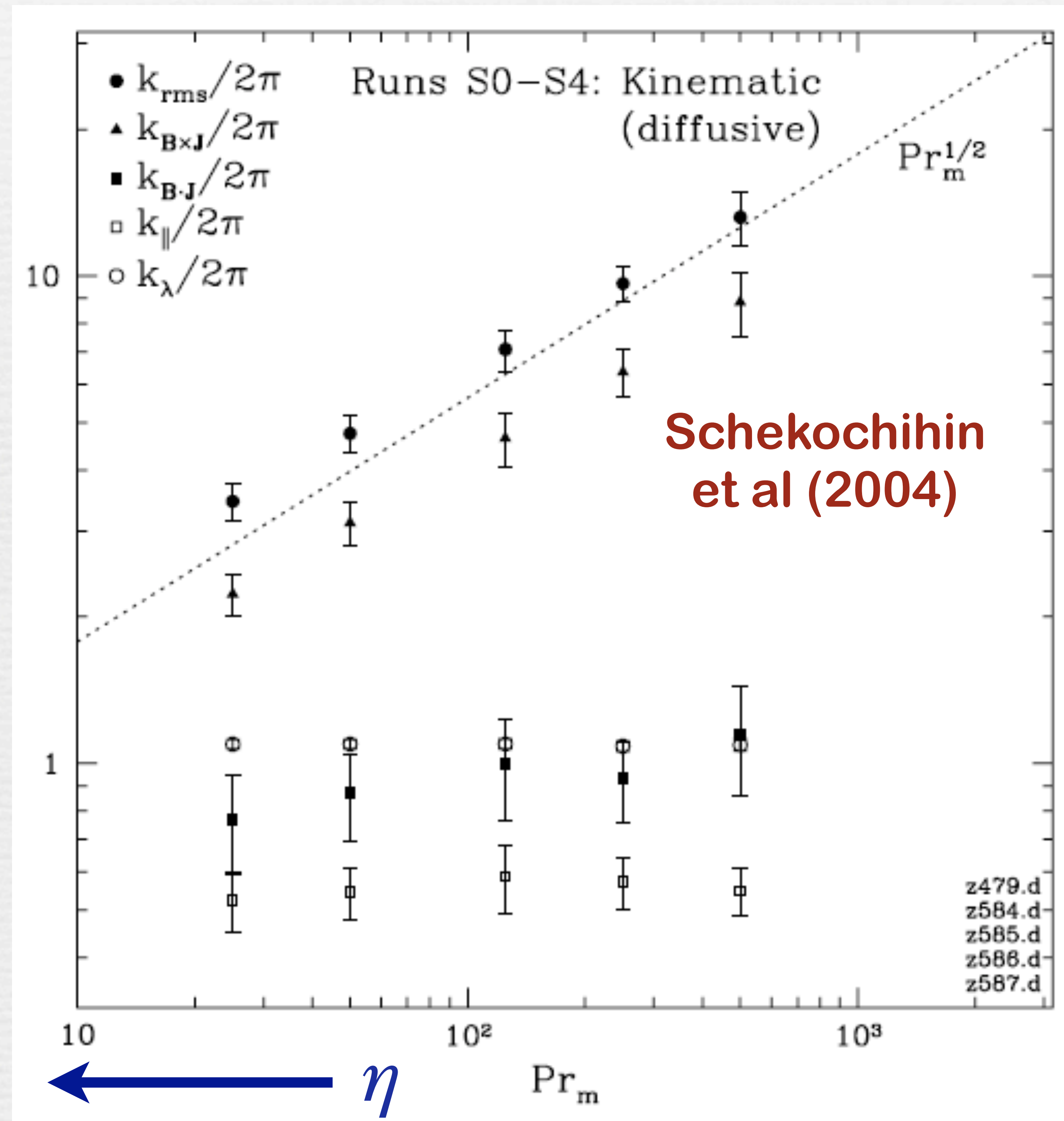
$$k_\parallel = \left( \frac{\left\langle |(\boldsymbol{B}\cdot\boldsymbol{\nabla})\boldsymbol{B}|^2 \right\rangle}{\langle B^4 \rangle} \right)^{1/2}$$

$$k_{\boldsymbol{B}\times\boldsymbol{J}} = \left( \frac{\left\langle |\boldsymbol{B}\times\boldsymbol{J}|^2 \right\rangle}{\langle B^4 \rangle} \right)^{1/2}$$

$$k_{\boldsymbol{B}\cdot\boldsymbol{J}} = \left( \frac{\left\langle |\boldsymbol{B}\cdot\boldsymbol{J}|^2 \right\rangle}{\langle B^4 \rangle} \right)^{1/2}$$

$$k_{\rm rms} = \left( \frac{\left\langle |(\boldsymbol{\nabla}\boldsymbol{B})|^2 \right\rangle}{\langle B^2 \rangle} \right)^{1/2}$$

$$k_\lambda = \left( \frac{\left\langle |(\boldsymbol{\nabla}\boldsymbol{v})|^2 \right\rangle}{\langle v^2 \rangle} \right)^{1/2}$$



# But Stars have $P_m$ < 1!

***Now chaotic streching must overcome ohmic diffusion <u>and</u> turbulent diffusion***

***Still, the dynamo prevails if $R_m$ is large enough***

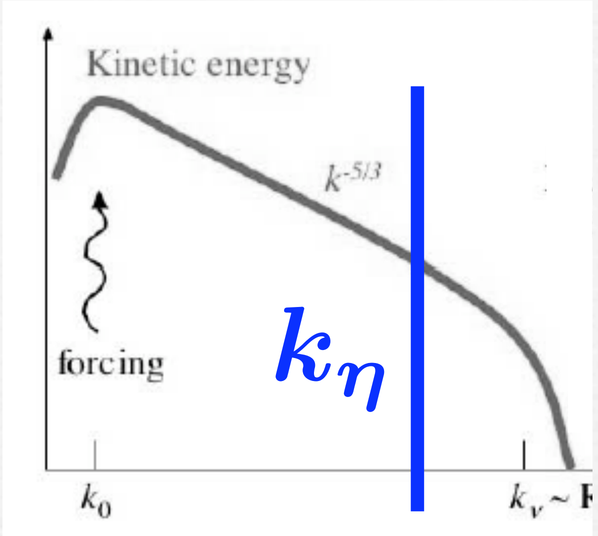
$$E_k \sim k^{-p}$$

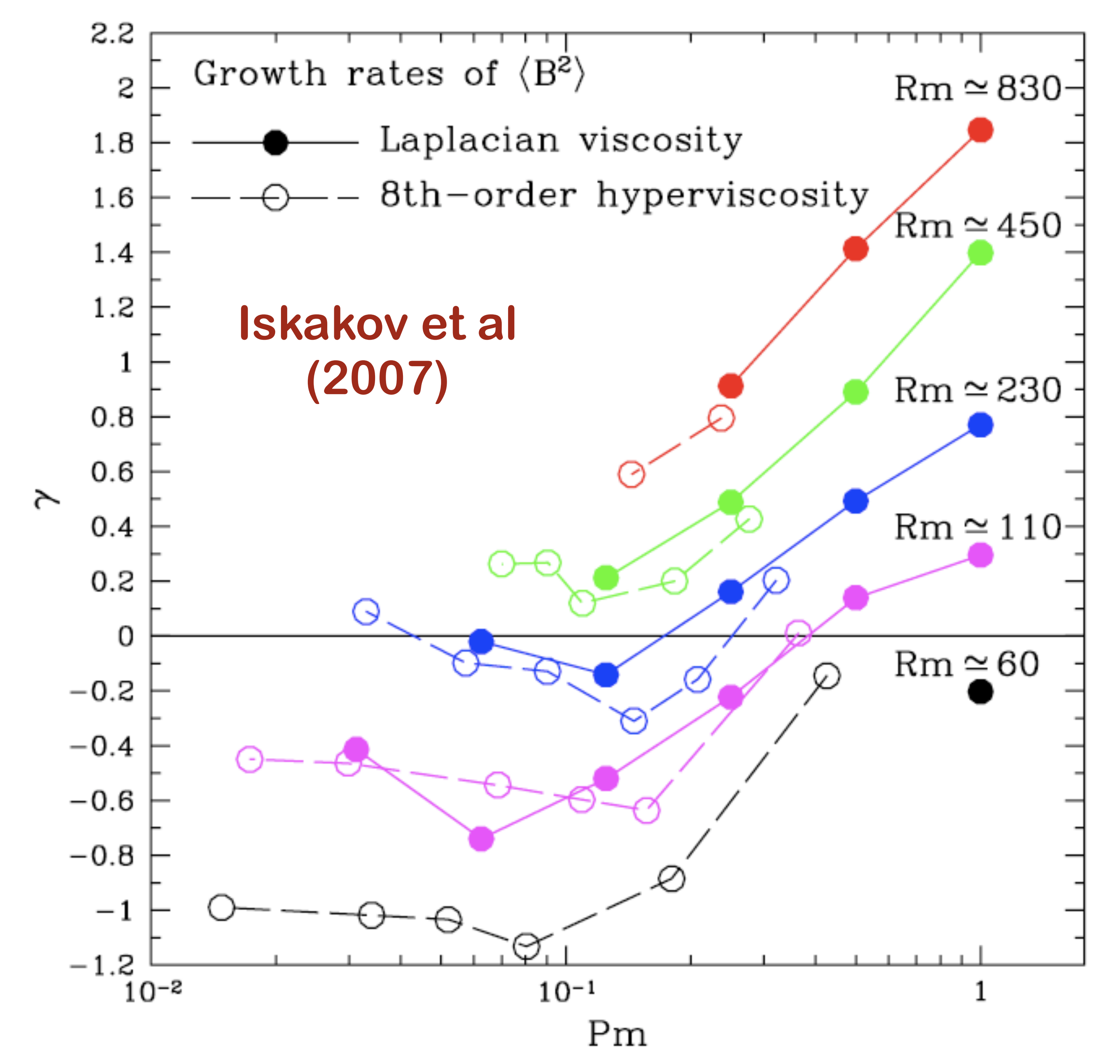
$$\gamma \sim k v_k \sim k^{(3-p)/2}$$

***Rough velocity fields ($p < 3$)***
***Smallest eddies are best at amplifying field because they have the fastest turnover time***

***Magnetic energy still peaks near the resistive scale, at least in the kinematic regime***

***Small-scale Fields!***



# Local Dynamo Action in the Sun and Stars

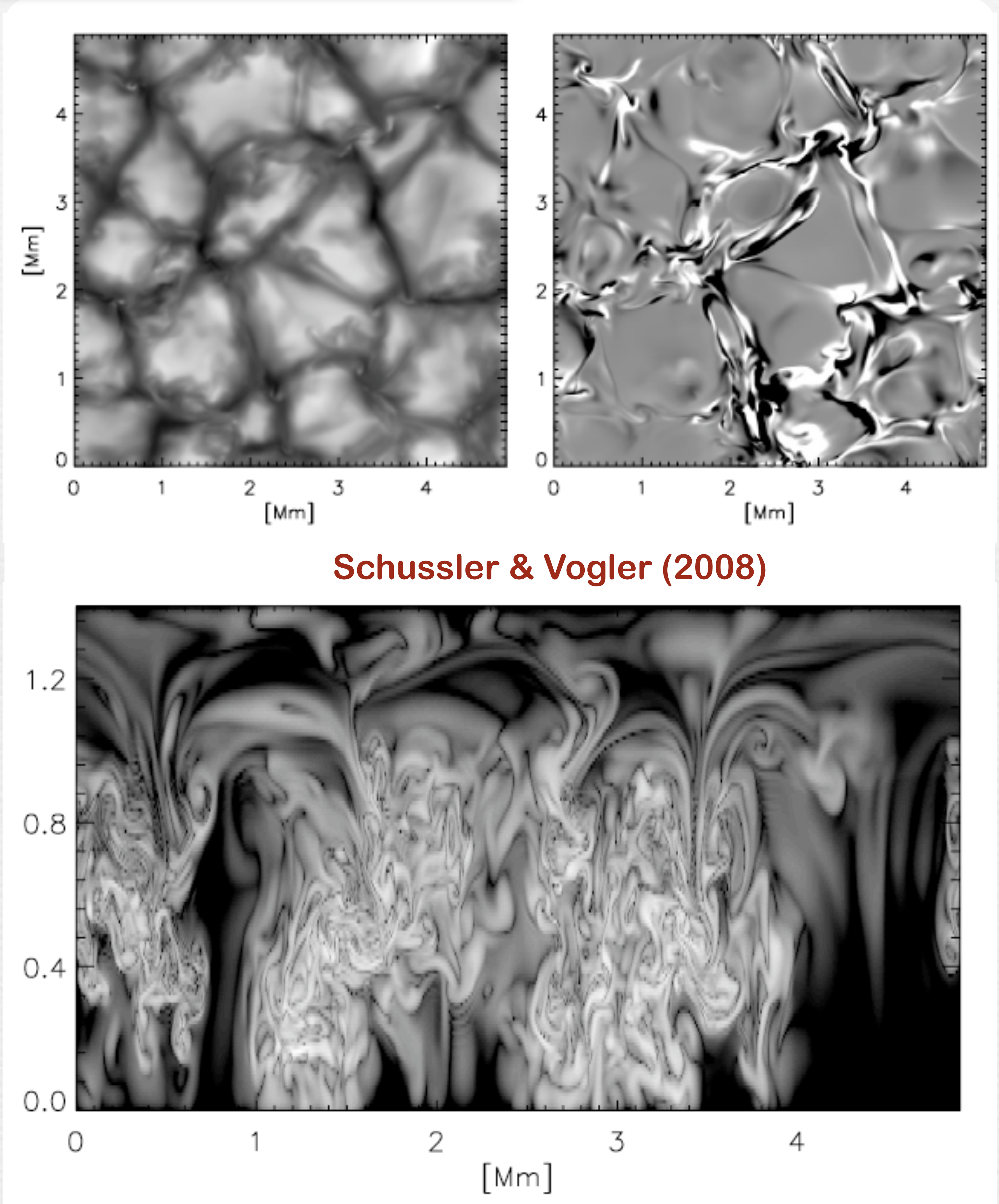
**Granulation:** $\tau \sim$ 10-15 min
**Giant Cells:** $\tau \sim$ days - months

***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***

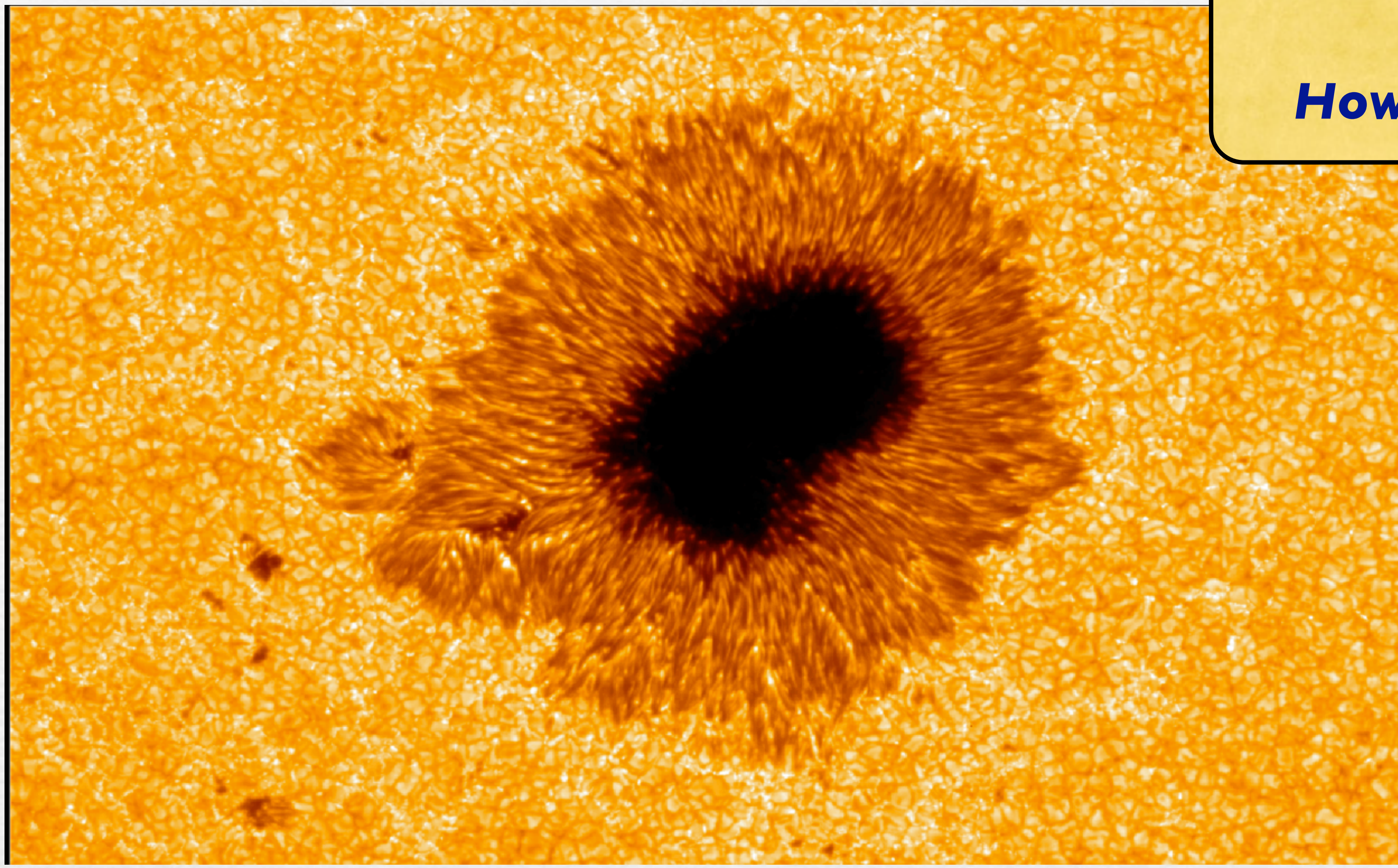
***Magnetic pumping of flux through lower boundary can inhibit the surface dynamo in simulations***

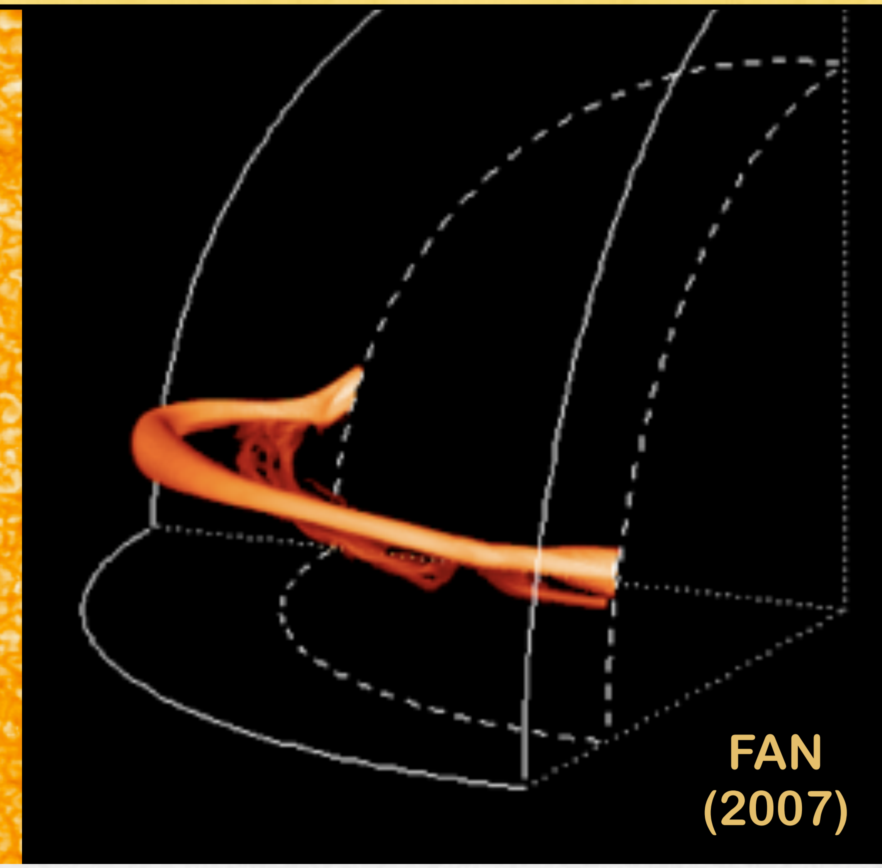
***In the Sun the local dynamo is likely intimately coupled to the global dynamo***

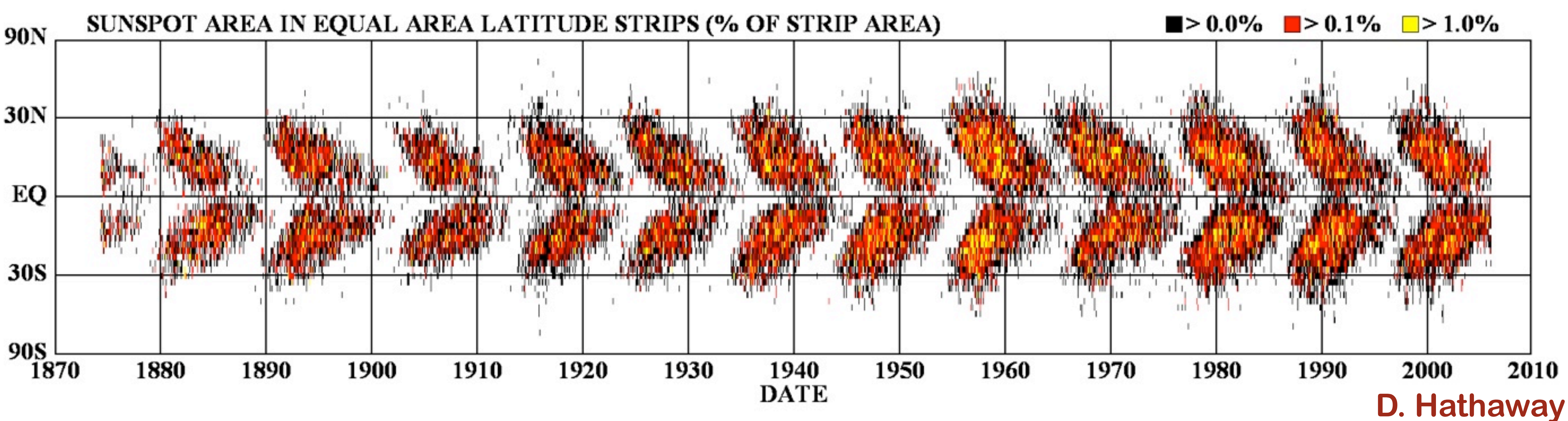


# The Global Solar Dynamo

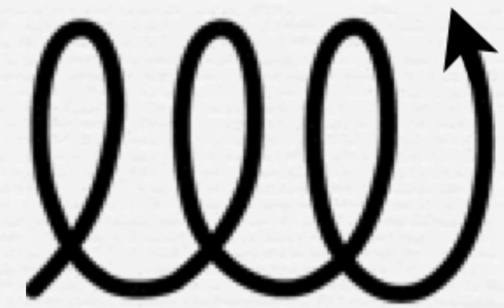
***Ask not:***
***How to generate Magnetic Energy?***
***but rather:***
***How to generate Magnetic Flux?***





# Recipe for a Global Dynamo



## Lagrangian Chaos
- Builds magnetic energy

## Rotational Shear
- Builds non-helical large-scale toroidal flux ($\Omega$-effect)
- 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: inverse cascade of magnetic helicity
  - Nonlocal transfer: $\alpha$-effect

***Small-Scale Dynamo:*** $L_B < L_v$
***Large-Scale Dynamo:*** $L_B >> L_v$

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

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

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

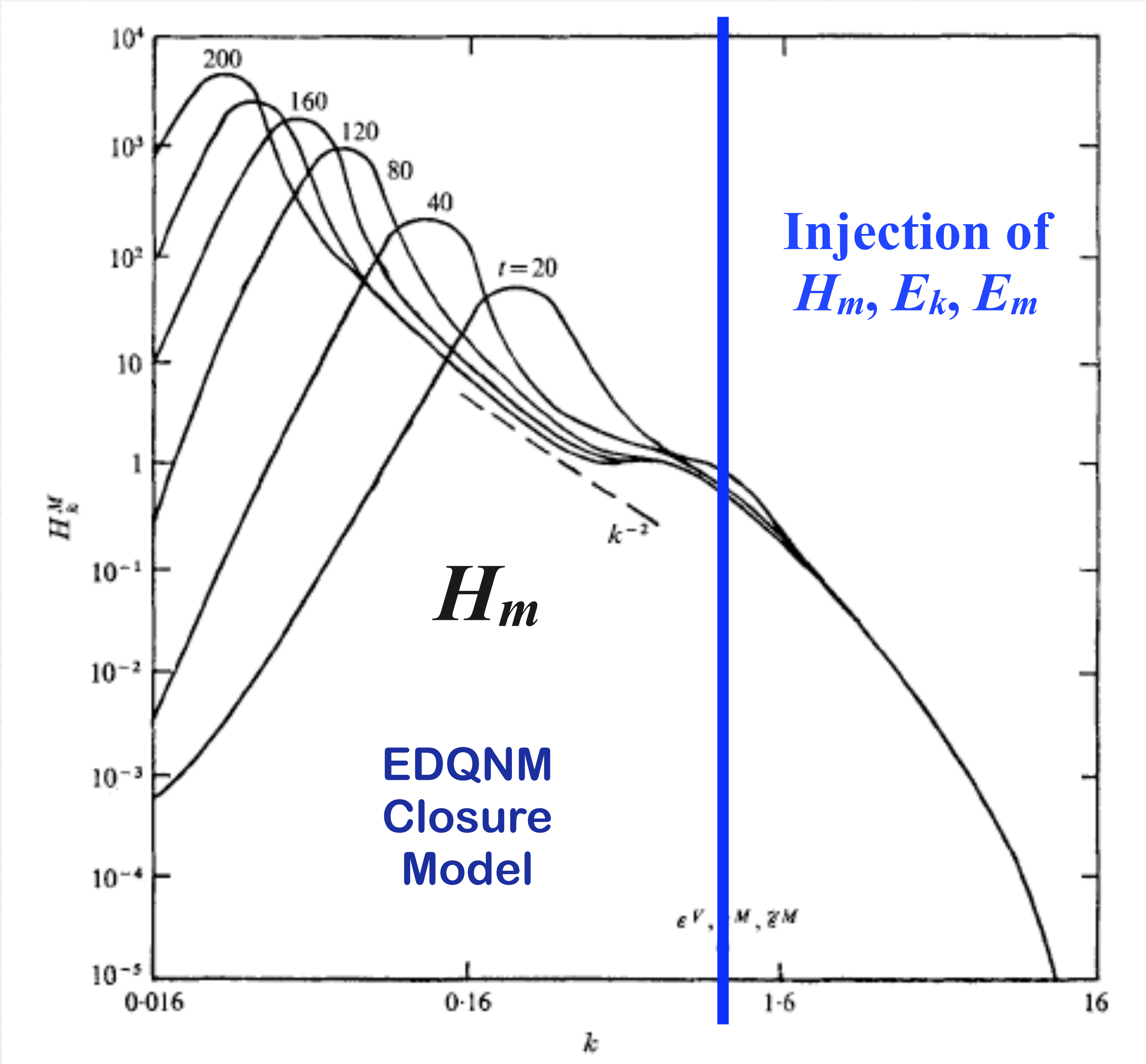
$$\boldsymbol{\omega} = \boldsymbol{\nabla} \times \boldsymbol{v}$$

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

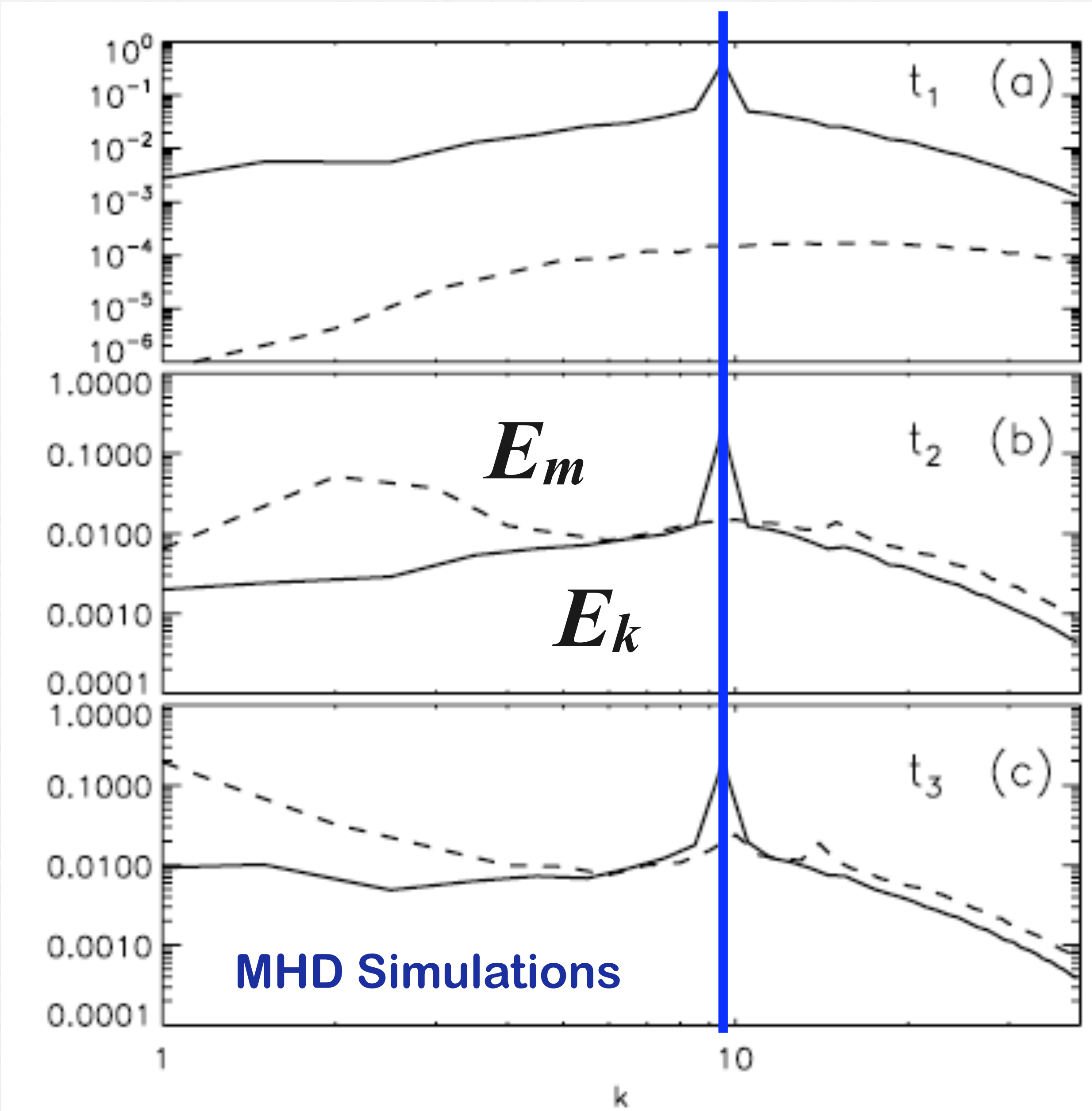
$$\boldsymbol{J} = \frac{c}{4\pi} \boldsymbol{\nabla} \times \boldsymbol{B}$$

# Inverse Cascade of Magnetic Helicity

Injection of $E_k$, $H_k$




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***

# Dynamical (*aka Catastrophic*) $\alpha$ Quenching

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

(kinematic mean-field dynamo theory, EDQNM, or ansatz)

Pouquet, Frisch & Leorat (1976), Gruzinov & Diamond (1994)

$$\alpha = \alpha_k + \alpha_m = -\frac{\tau}{3} \langle \boldsymbol{v}' \cdot (\boldsymbol{\nabla} \times \boldsymbol{v}') \rangle + \frac{\tau}{12\pi\rho} \langle \boldsymbol{B}' \cdot (\boldsymbol{\nabla} \times \boldsymbol{B}') \rangle$$

$$\frac{d}{dt} \langle \boldsymbol{A}' \cdot \boldsymbol{B}' \rangle = -2 \, \langle \boldsymbol{\mathcal{E}} \cdot \overline{\boldsymbol{B}} \rangle - 2\eta \langle \boldsymbol{B}' \cdot (\boldsymbol{\nabla} \times \boldsymbol{B}') \rangle$$

$$\alpha = \frac{\alpha_k}{1 + R_m \frac{\langle \overline{B}^2 \rangle}{B_{eq}^2}}$$

***In stars $R_m \sim 10^5$ - $10^9$ !!***
***Turbulent $\alpha$-effect may be extremely inefficient!***

$$\frac{B_{eq}^2}{8\pi} = \frac{1}{2} \rho U^2$$

***In order to sustain the inverse cascade of $H_m$ toward large scales, helicity of the opposite sign is necessarily generated on small scales***

***If small-scale magnetic helicity is not dissipated or otherwise removed from the system, the resulting Lorentz force will inhibit chaotic stretching and kill the large-scale dynamo***

# Avoiding Catastrophe

## ❧ Dissipating small-scale helicity

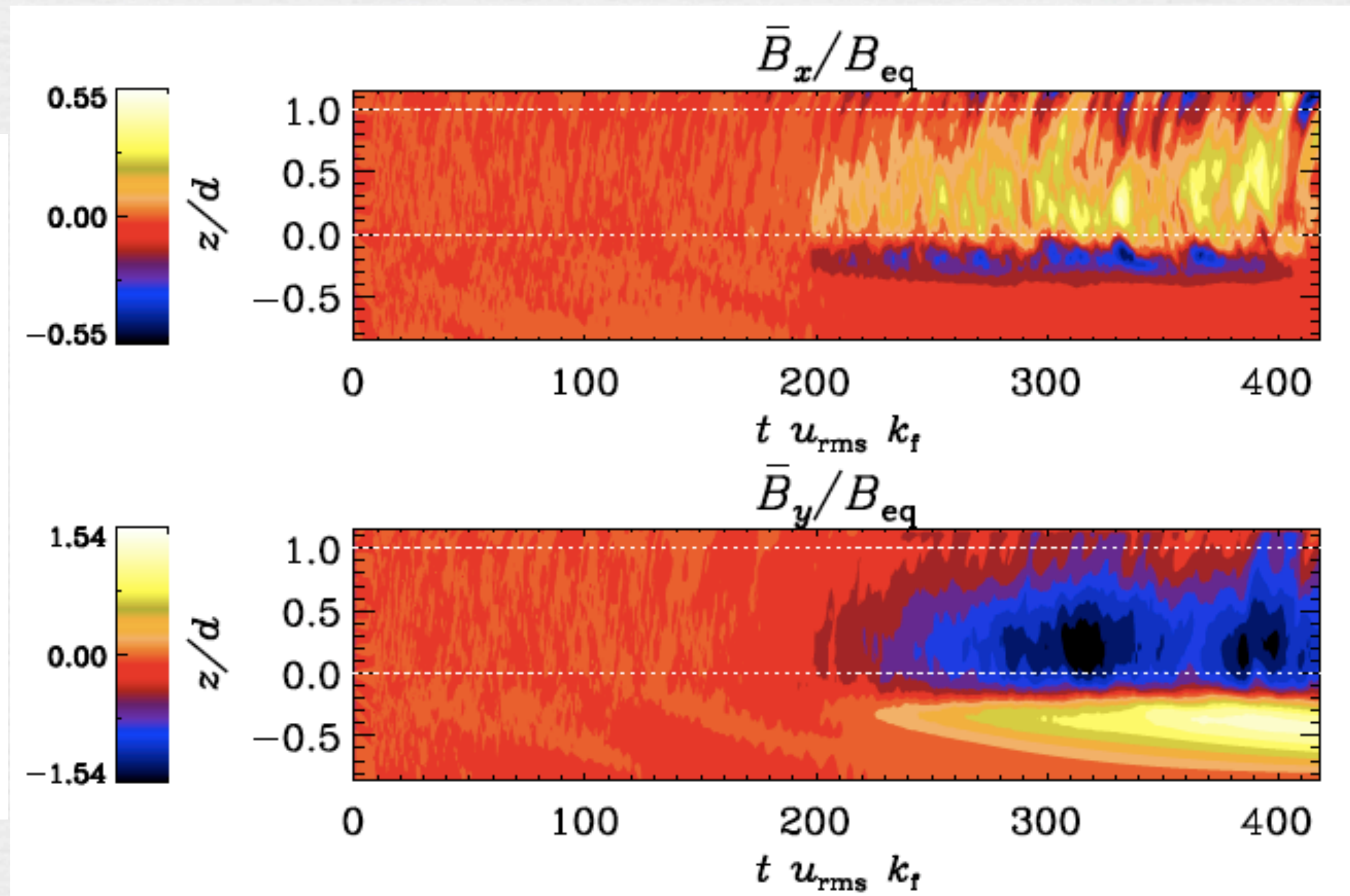
- Forward cascade on sub-forcing scales may help
- Turbulent diffusion (but this may be quenched as well)

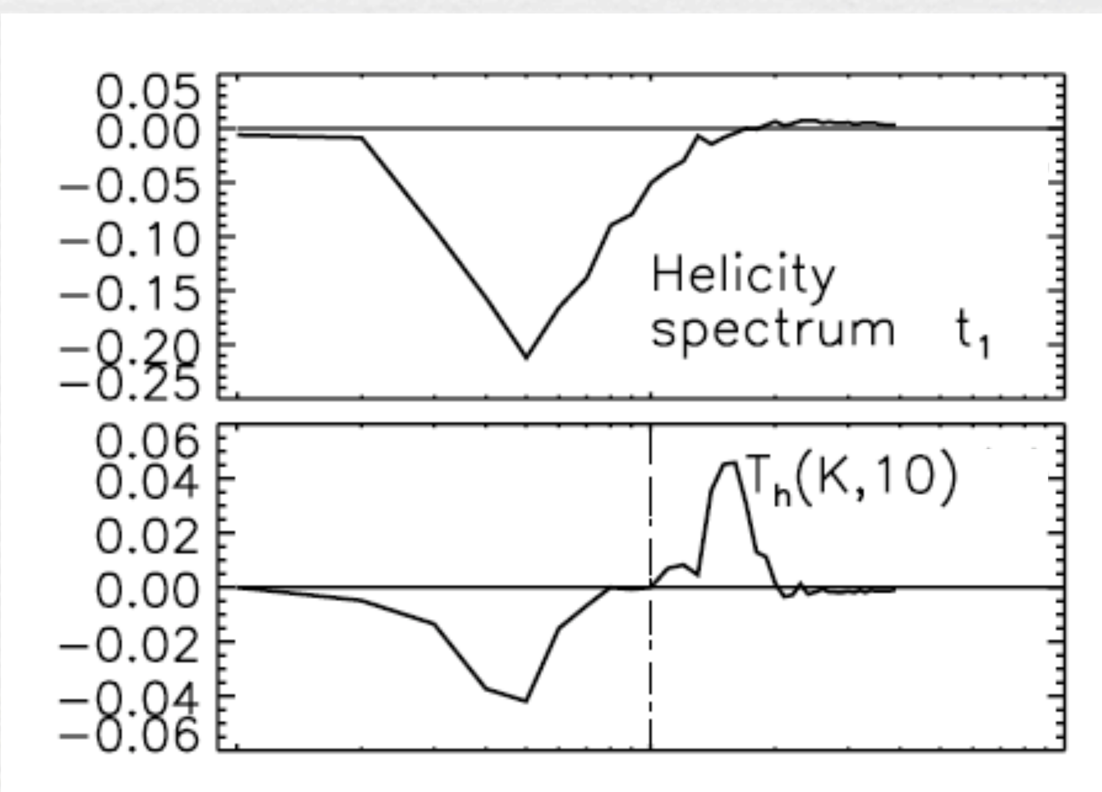
***Magnetic helicity flux through the photosphere may play a crucial role in the operation of the global solar dynamo***

## ❧ Open Boundaries

- Helicity loss must occur preferentially on small scales
- Anisotropy needed to promote helicity flux
    - ✦ Rotational shear
- Coronal Mass Ejections

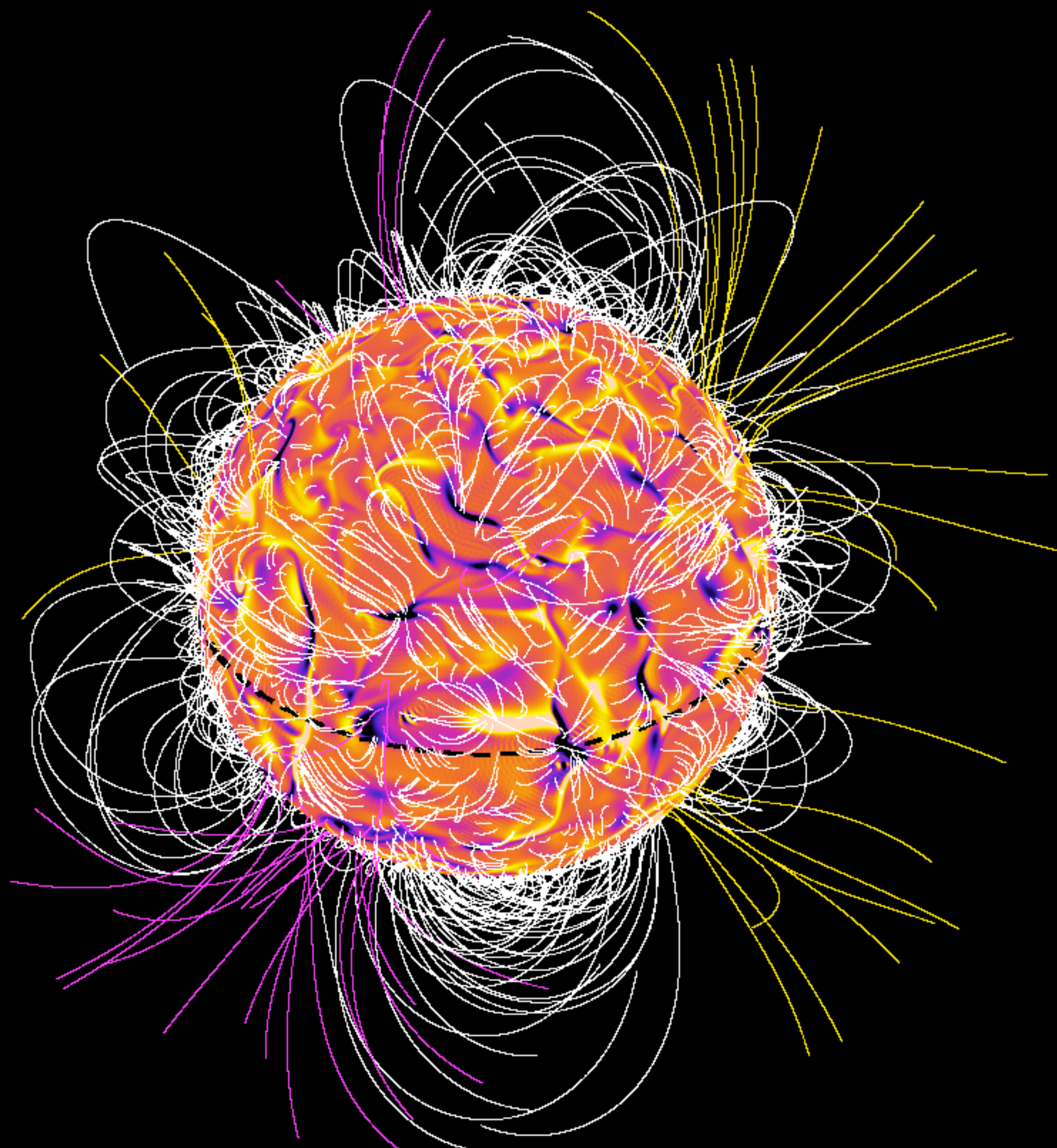
Kapyla, Korpi & Brandenburg (2008)

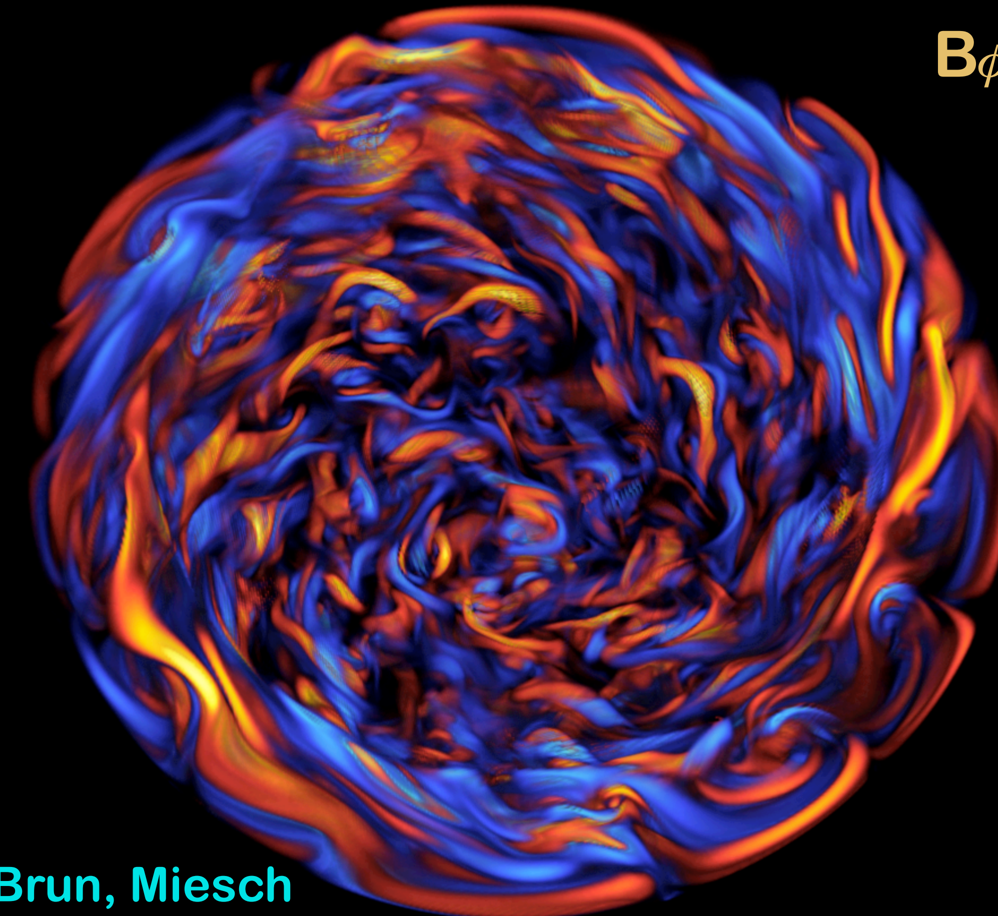


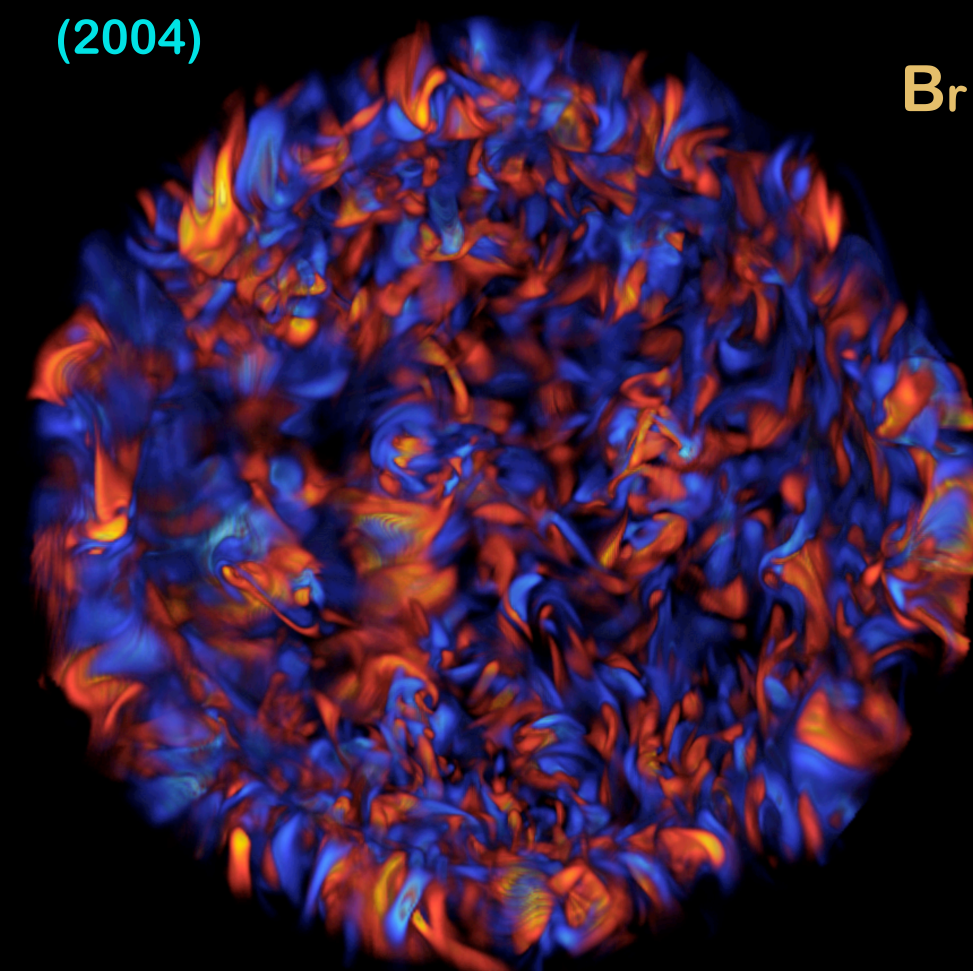

Alexakis, Mininni & Pouquet (2006)

# A Global Small-Scale Dynamo





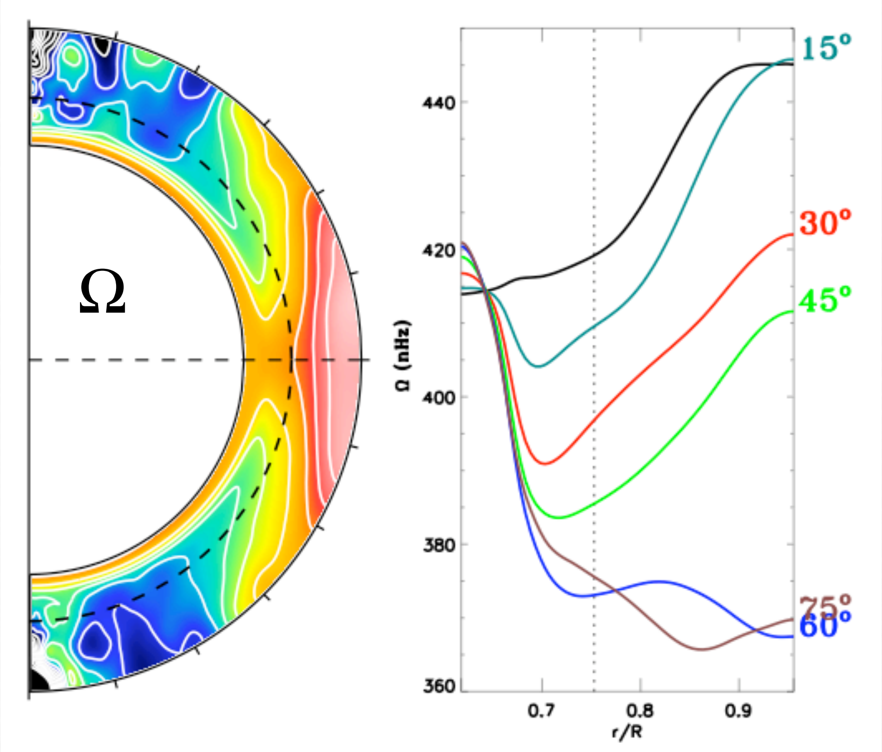

Brun, Miesch & Toomre (2004)



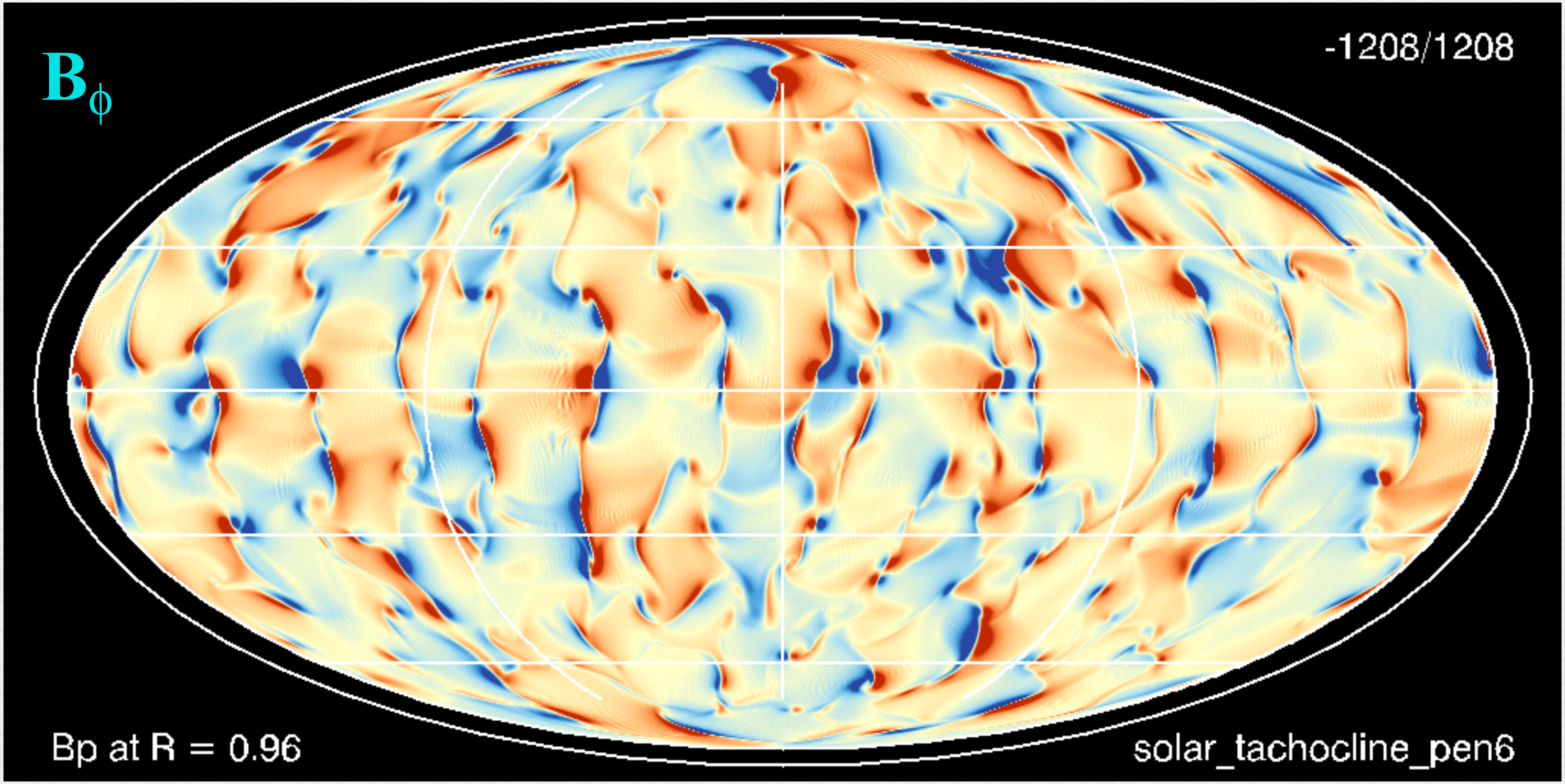

***Spherical geometry is essential to understand global dynamos but not all global dynamos build strong mean fields***

# A Turbulent, Convective Dynamo with a Tachocline

***Pumping, amplification, organization of toroidal flux***



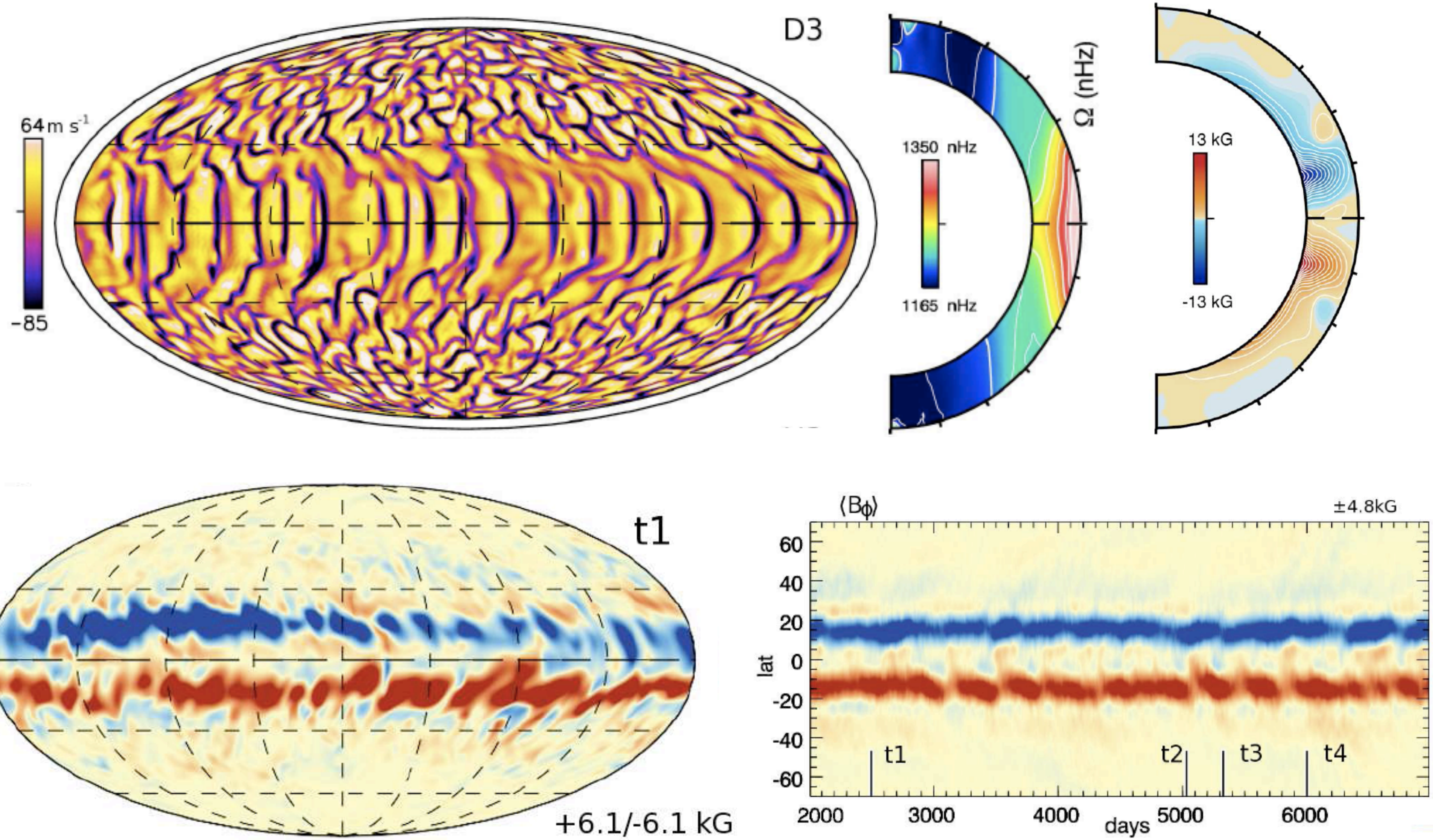

Browning et al (2006)



# A Dynamo with a Different Spin

$\Omega = 3\Omega_{\odot} \quad P = 9.3$ days

Brown et al (2009)

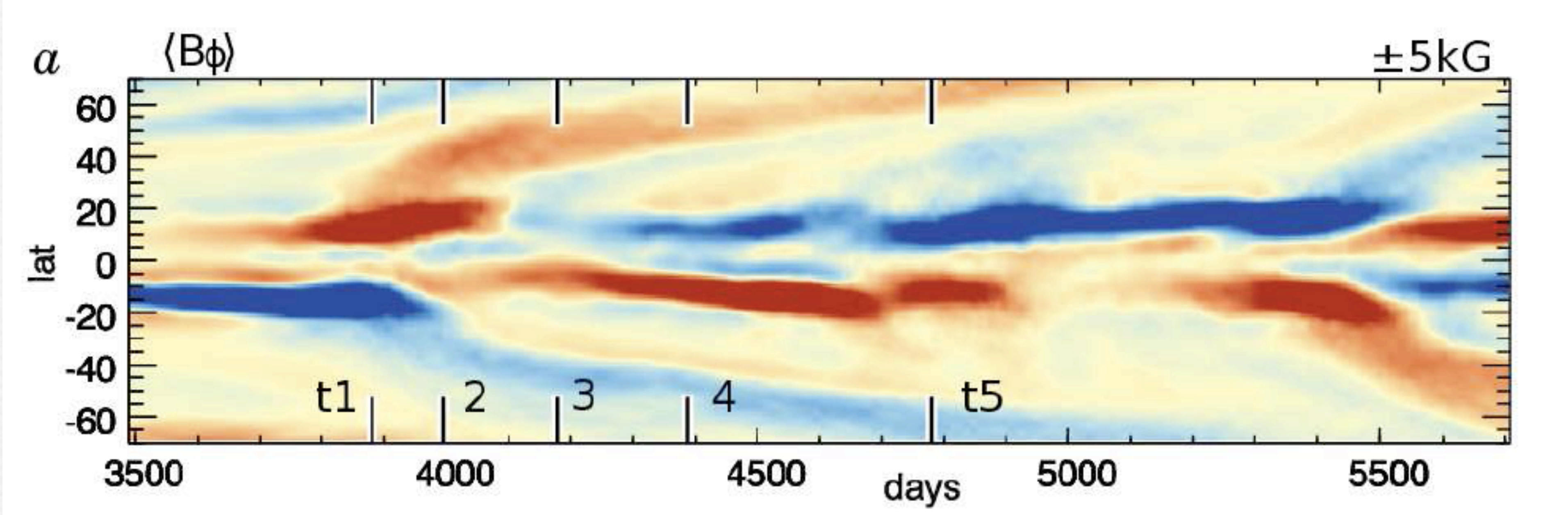


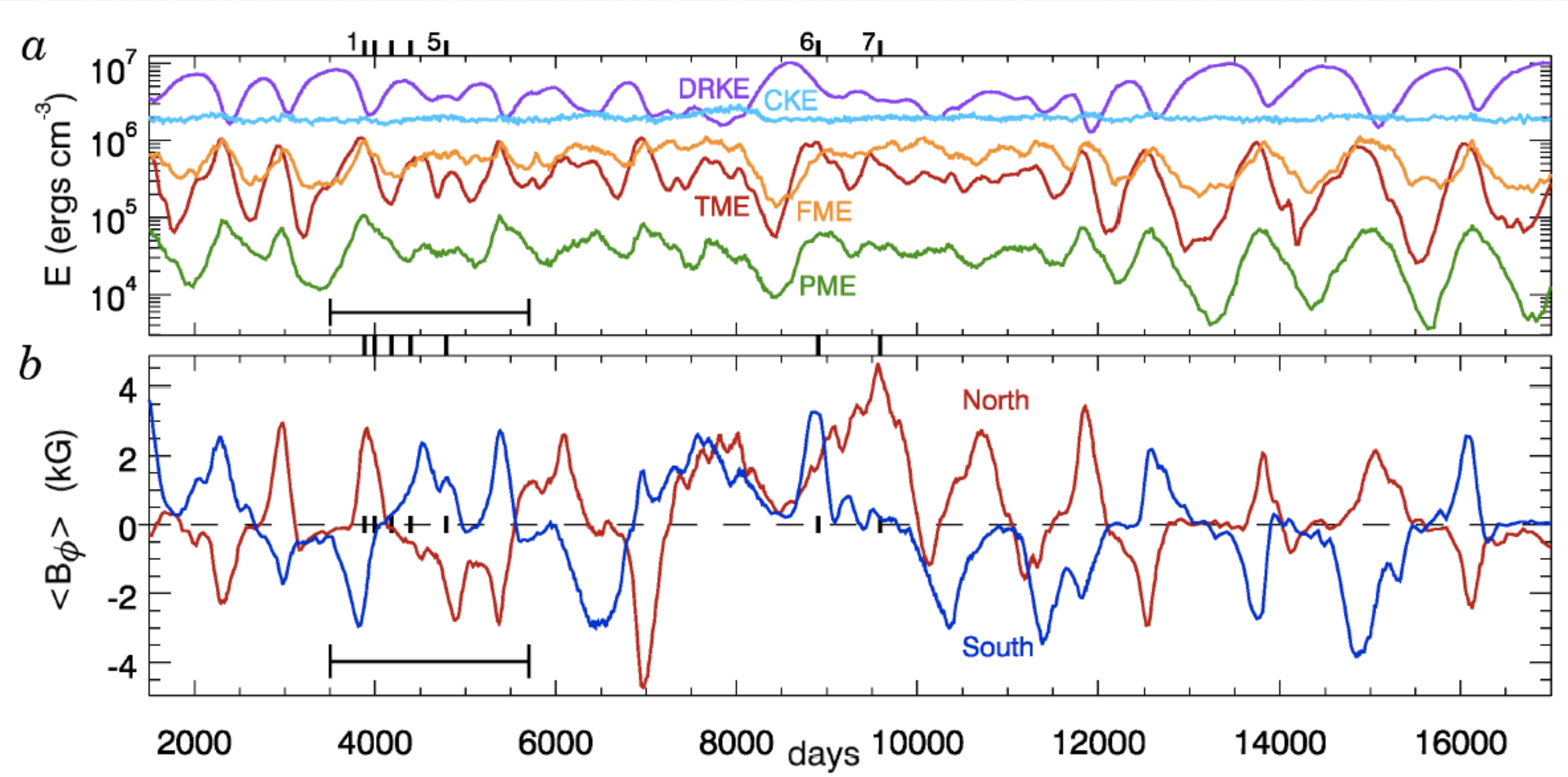

***Persistent toroidal wreathes of magnetism in midst of the convection zone***

# Faster still - Cycles!

$$\Omega = 5\Omega_\odot$$
$$P = 5.6 \text{ days}$$

Brown et al (2009)



# Faster still - Cycles!

$$\Omega = 5\Omega_{\odot}$$

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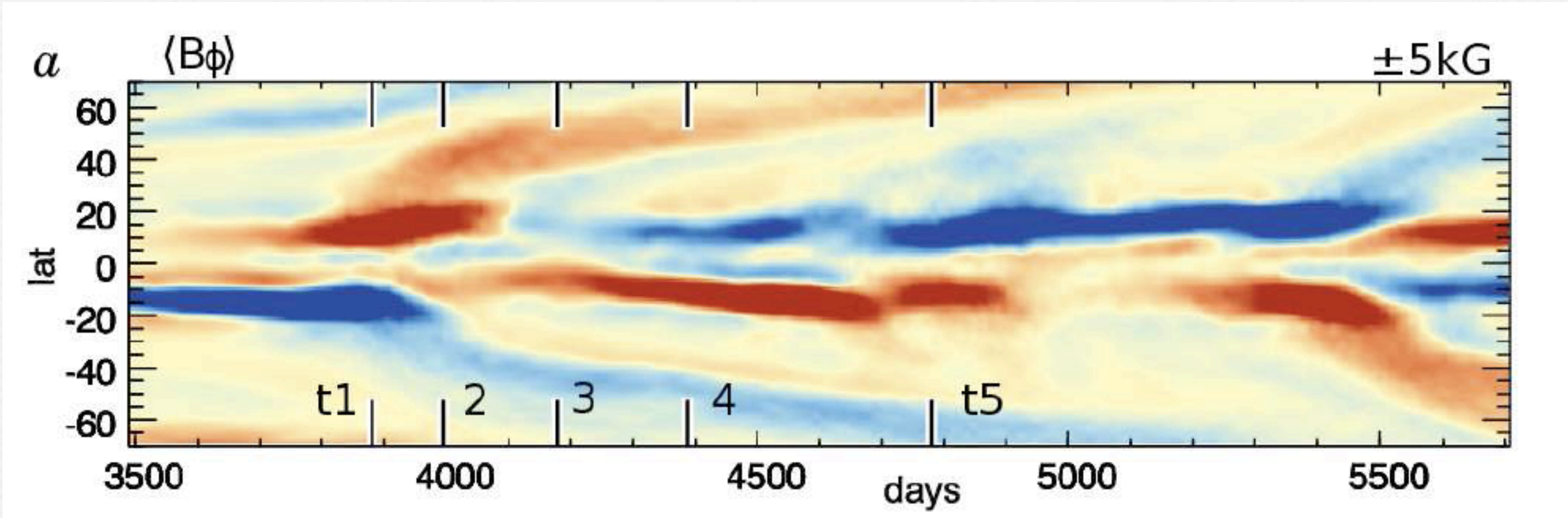
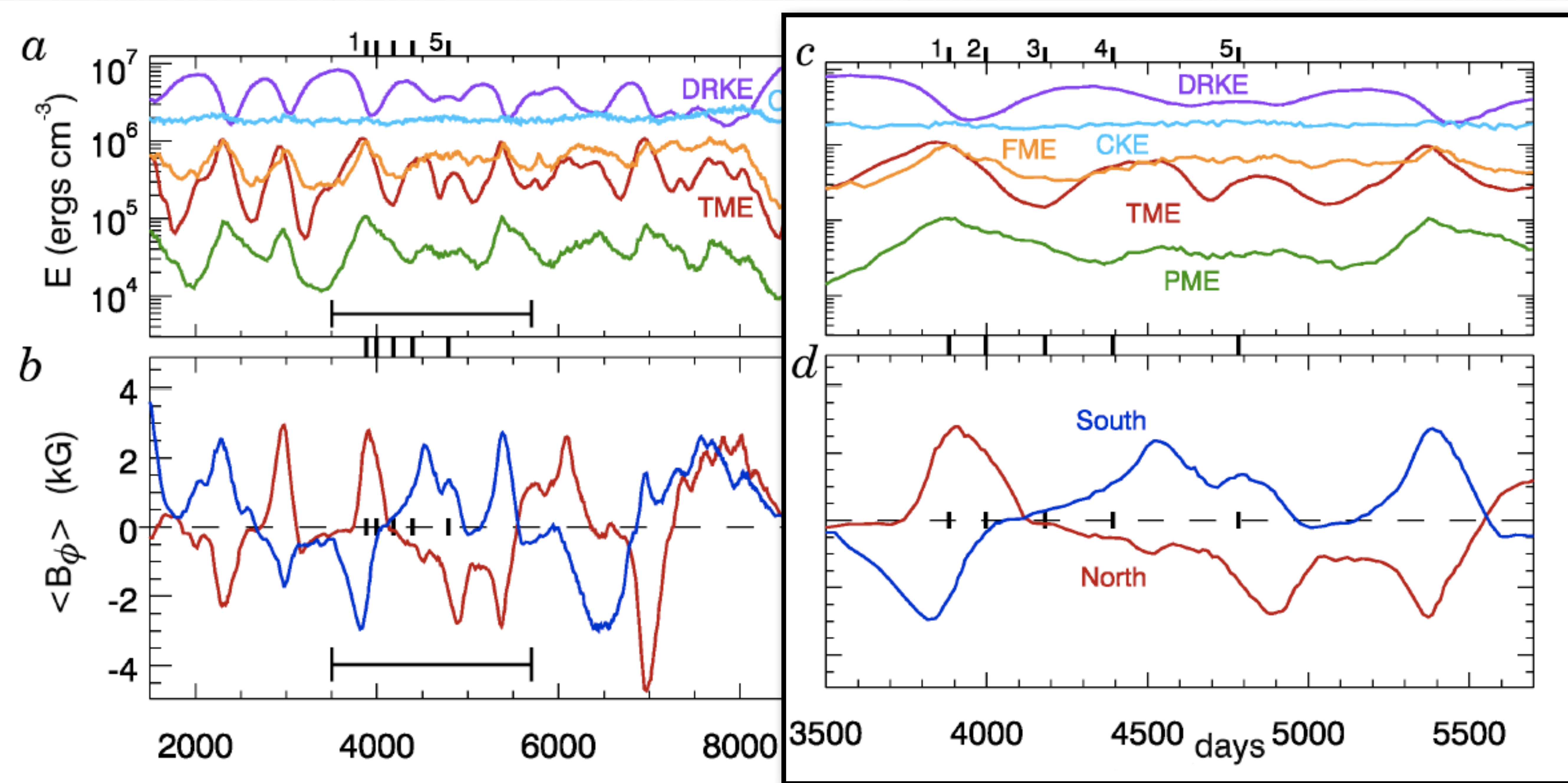
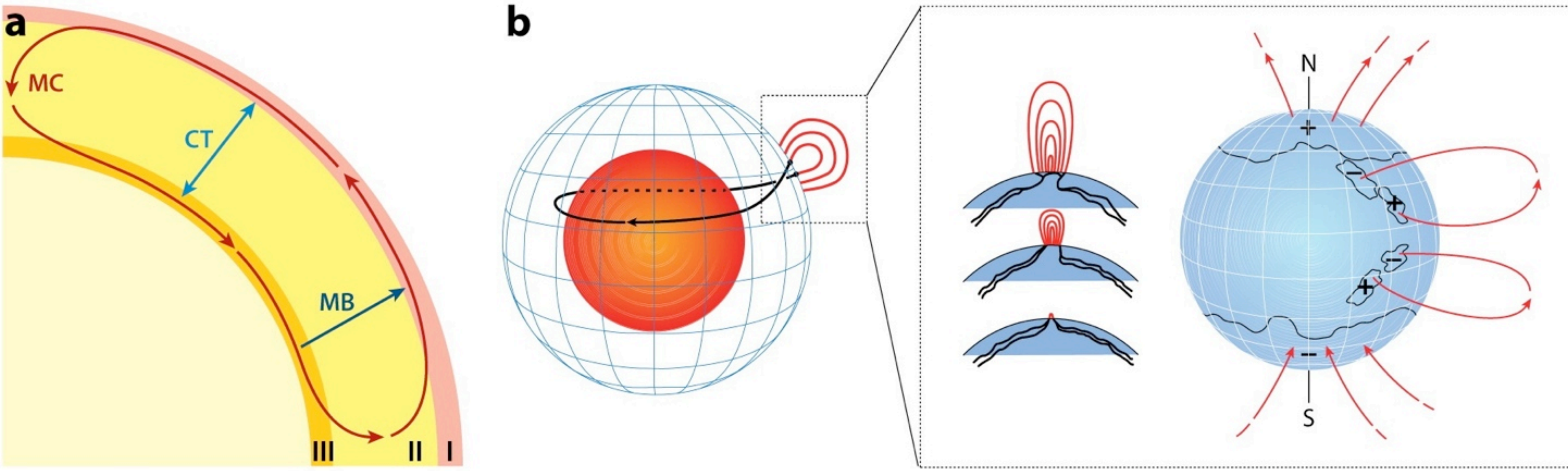
Brown et al (2009)



# The (Global) Solar Dynamo: A Boundary Layer Dynamo




Dikpati & Gilman (2006)

c Miesch & Toomre (2009)

| | 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 $\alpha$, $\Delta\,\Omega$, and $\eta_t$.

***Meridional Circulation may contribute to cyclic activity (Flux-Transport Models)***

***Breakup and dispersal of photospheric active regions may contribute to poloidal flux generation (Babcock-Leighton mechanism)***

# Summary: Convective Dynamos

- **Local Dynamos**
  - Lagrangian Chaos
  - Small-scale fields
  - Magnetic carpet
  - Strong horizontal fields near photosphere
- **Global Dynamos**
  - Rotational Shear
  - Helicity
  - Spherical Geometry
  - Meridional Circulation
  - Boundary Layers

***Solar Activity Cycle still the most pressing and formidable challenge***