Large-scale Dynamics of the Solar Interior

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&

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- Jon Aurnou (UCLA)
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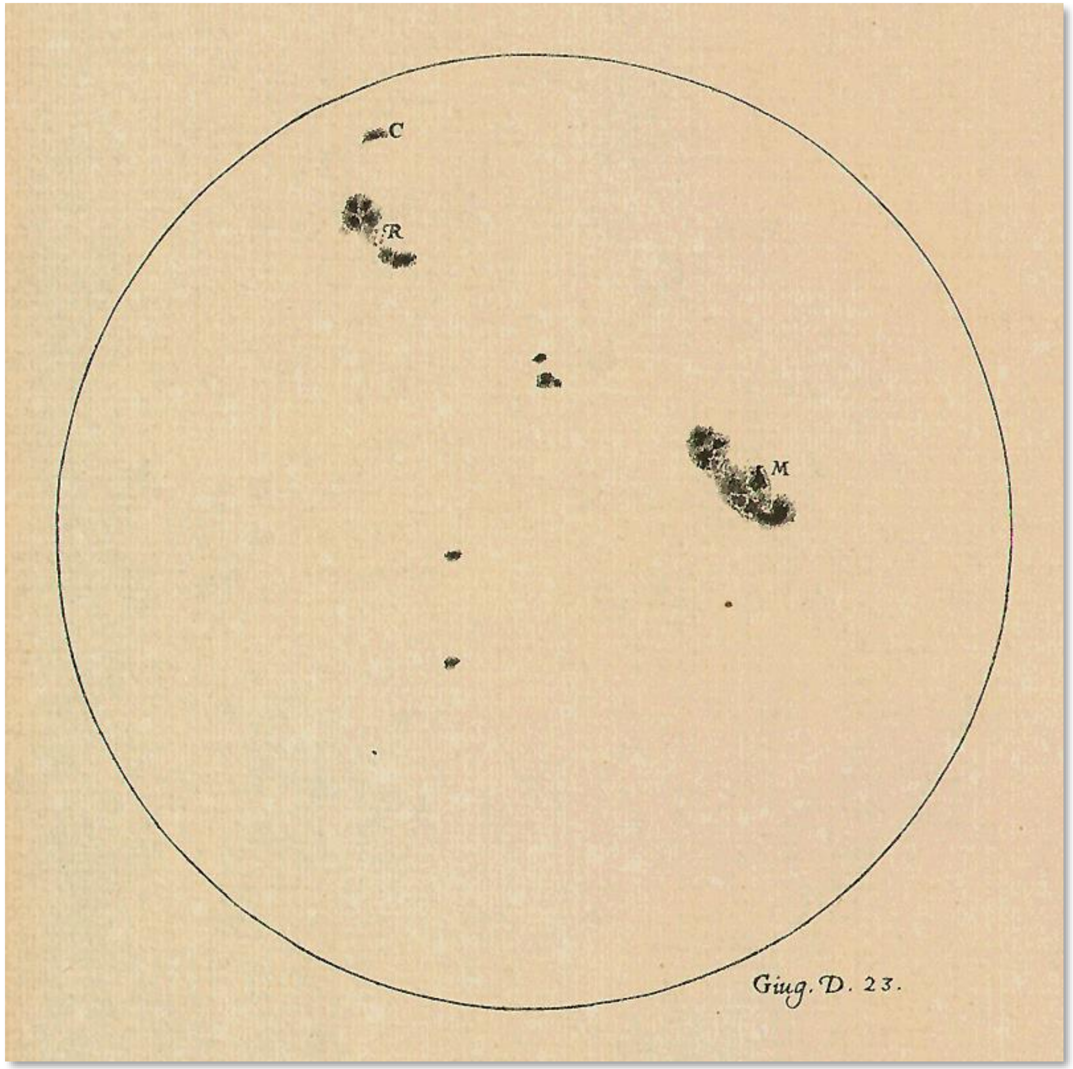
Who are we?   Why are we here?

The operation of the solar dynamo remains an outstanding problem in astrophysics.

This presentation will provide an introduction to the study of solar interior dynamics, and in particular to outstanding questions regarding the Sun’s interior convection, which underpins the dynamo.

Outline

Motivation

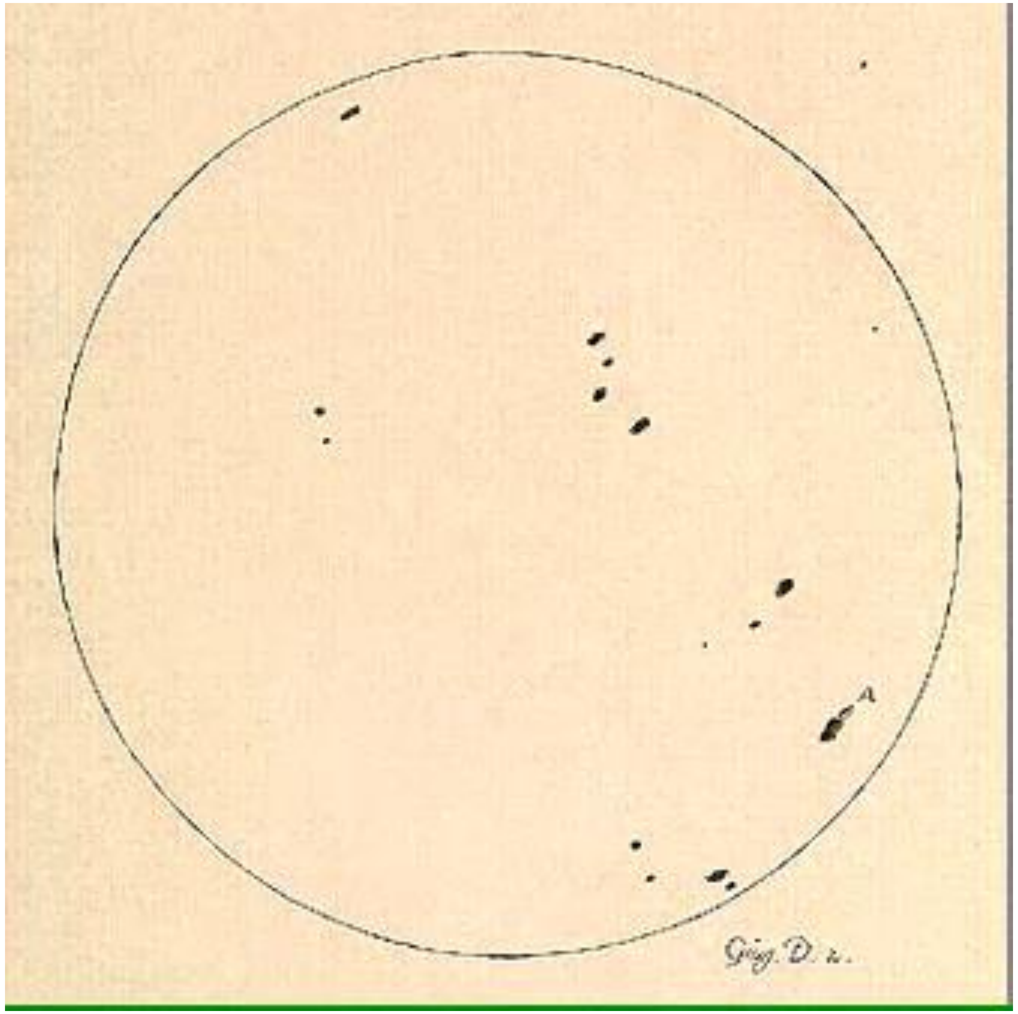


Detailed sunspot records from 1600s onward
(Galileo Galilei, 1612)

Naked-eye observations from China since 23 BCE

The Galileo Project

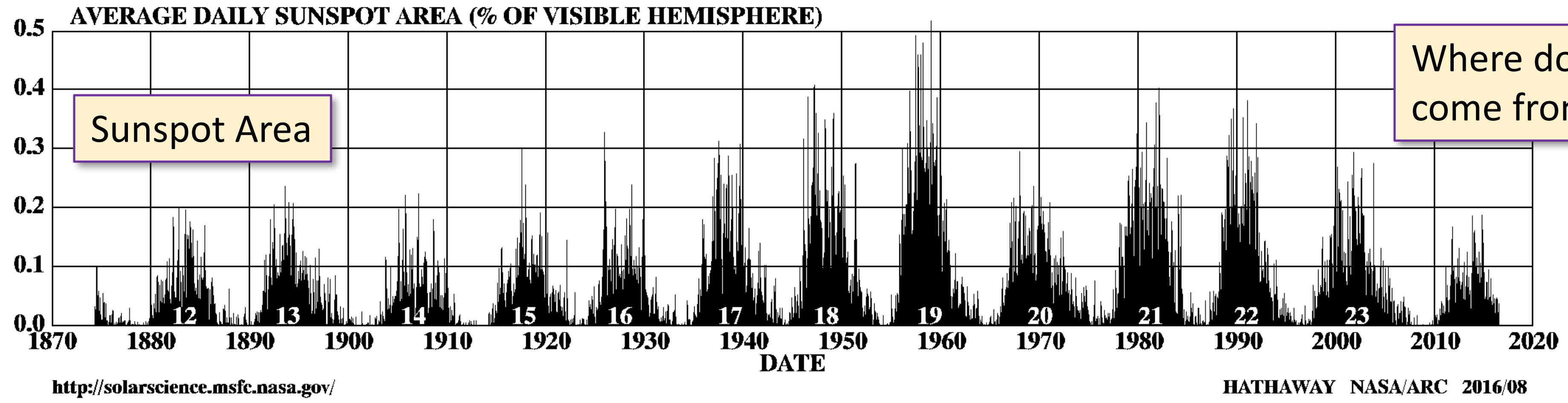
Rice Univ.



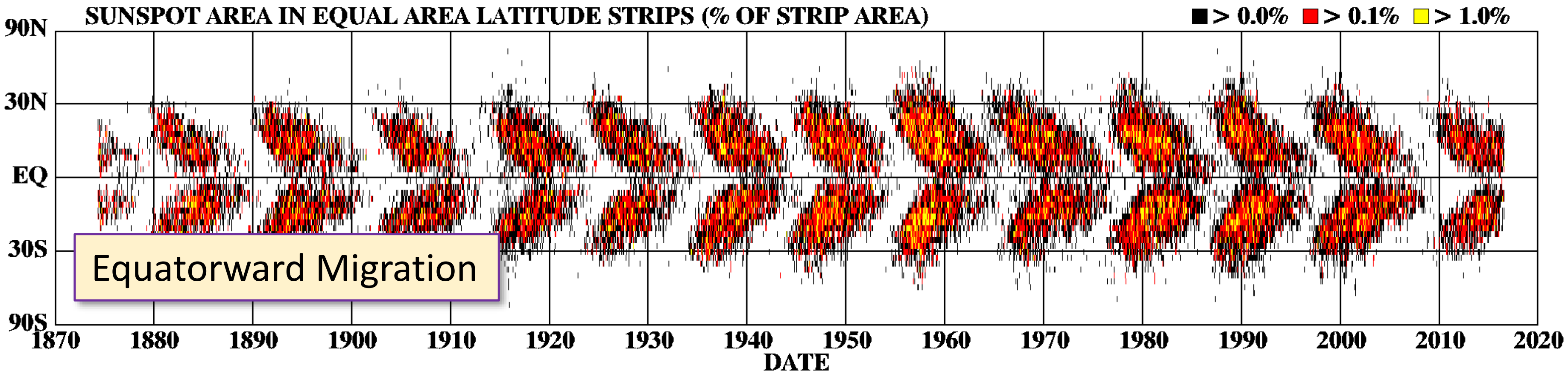
Detailed sunspot records from 1600s onward
(Galileo Galilei, 1612)

Naked-eye observations from China since 23 BCE

The Sun's Magnetic Cycle

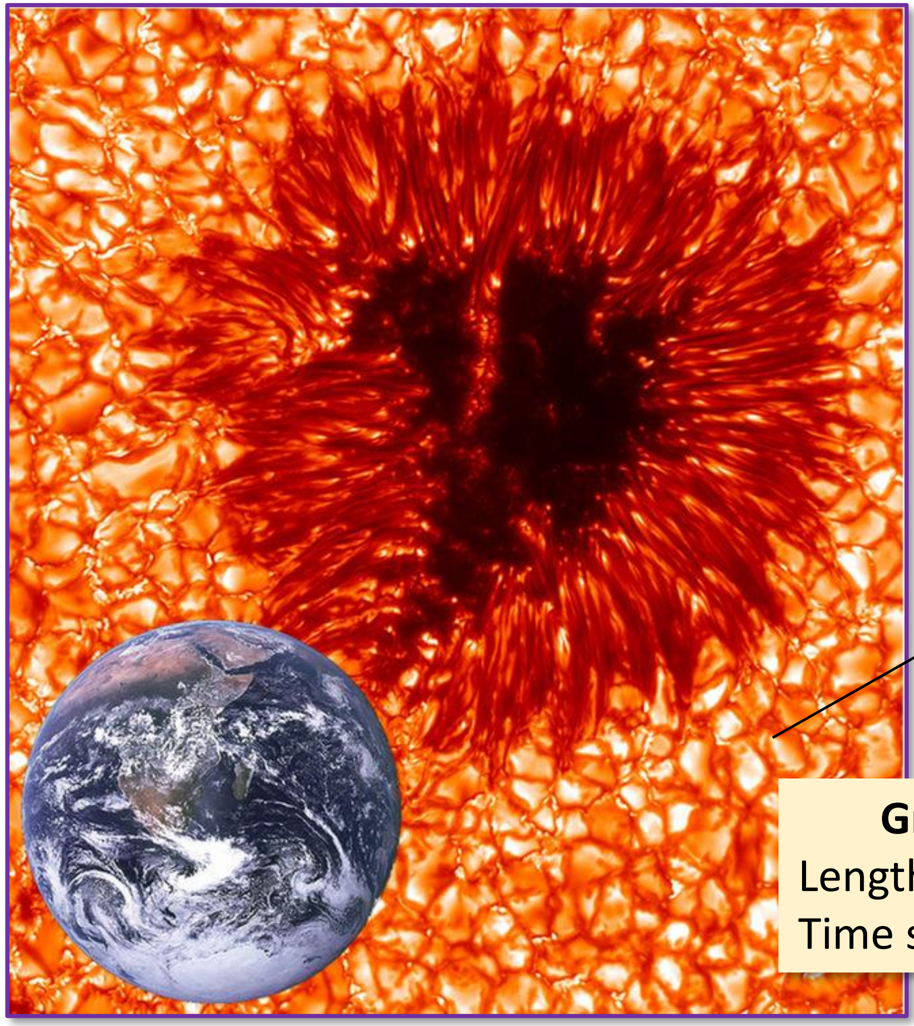


Where does all this magnetism come from?



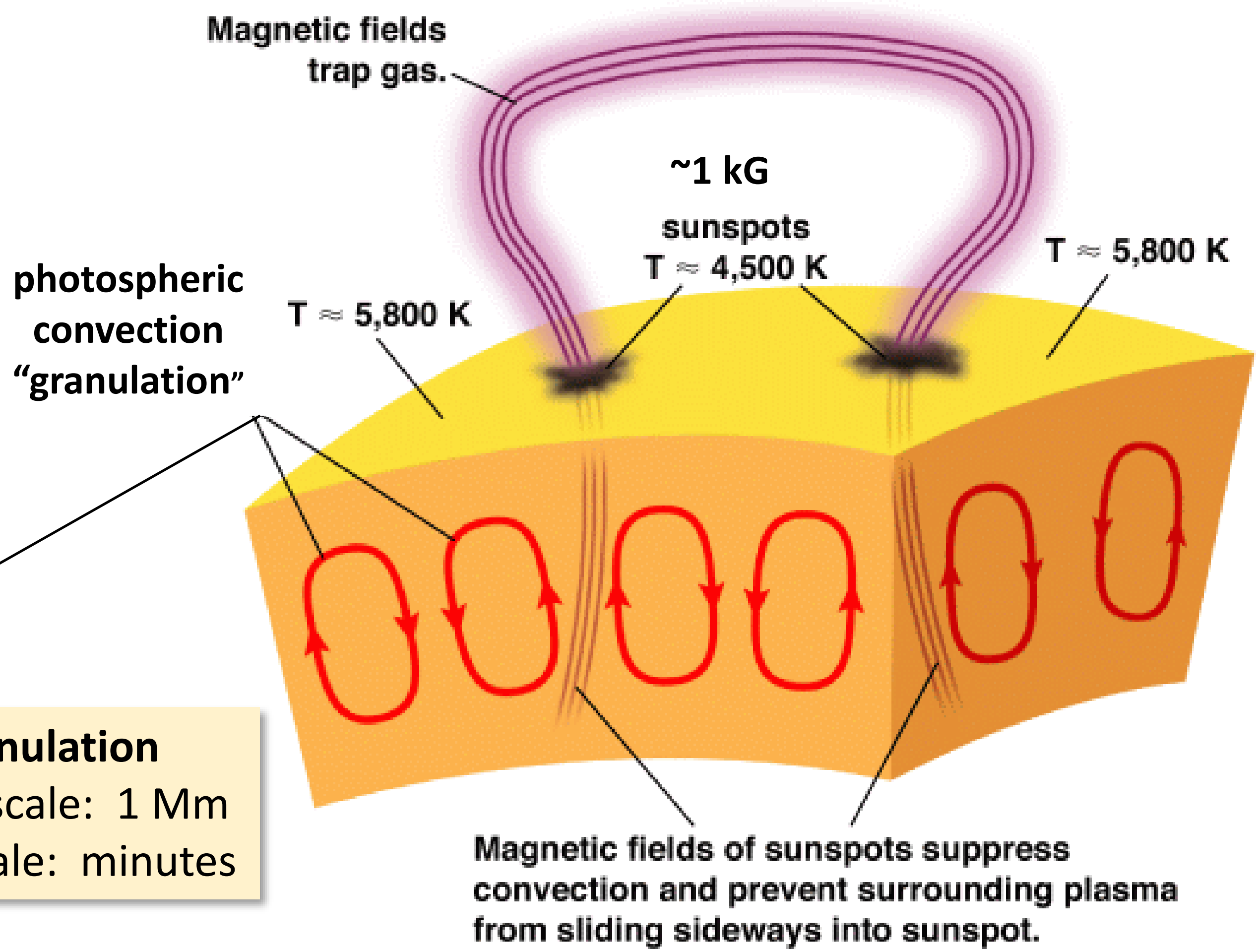
- Magnetic activity increases with sunspot area
- Mean magnetic polarity reverses every 11 years

Sunspots: A Closer Look



Granulation
Length scale: 1 Mm
Time scale: minutes

Swedish Solar Telescope (visible; 430 nm)



Cosmic Perspective, 3rd Ed.

MHD Induction: What is v?

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

compression

shear production

advection

diffusion

Rotation

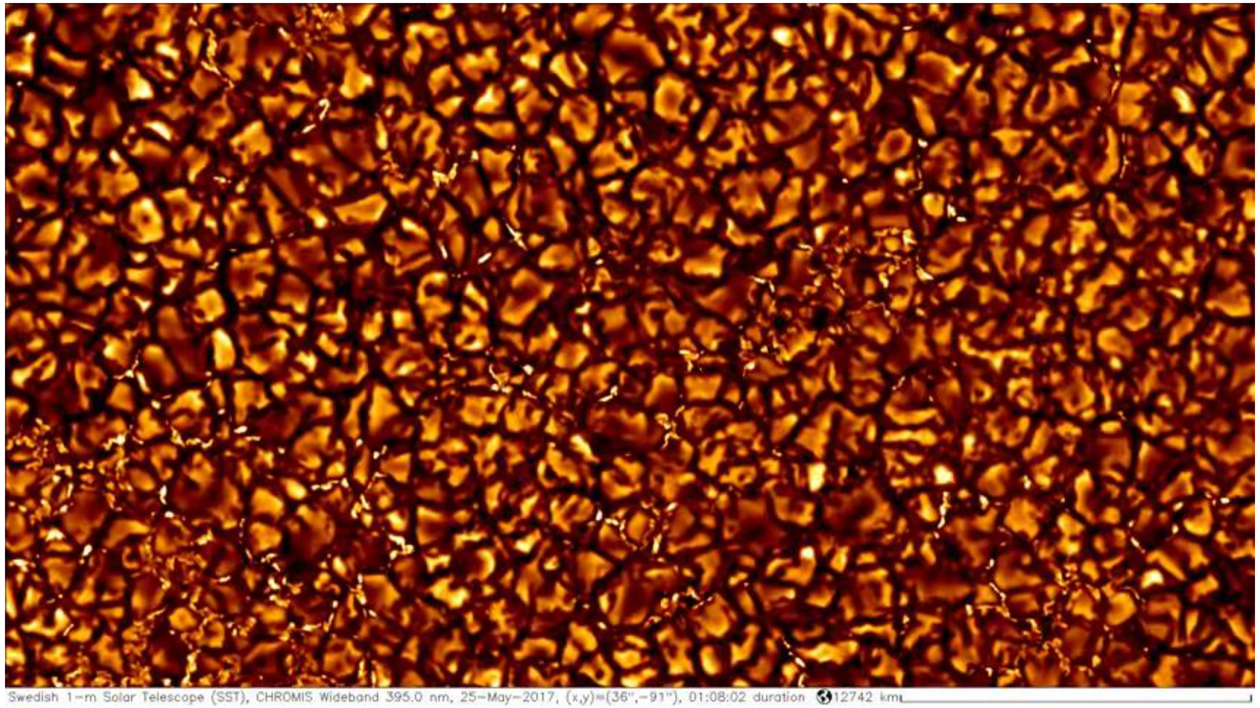
Large-Scale Shear
(differential rotation)

Small-Scale Shear
(helical rolls; α-effect)

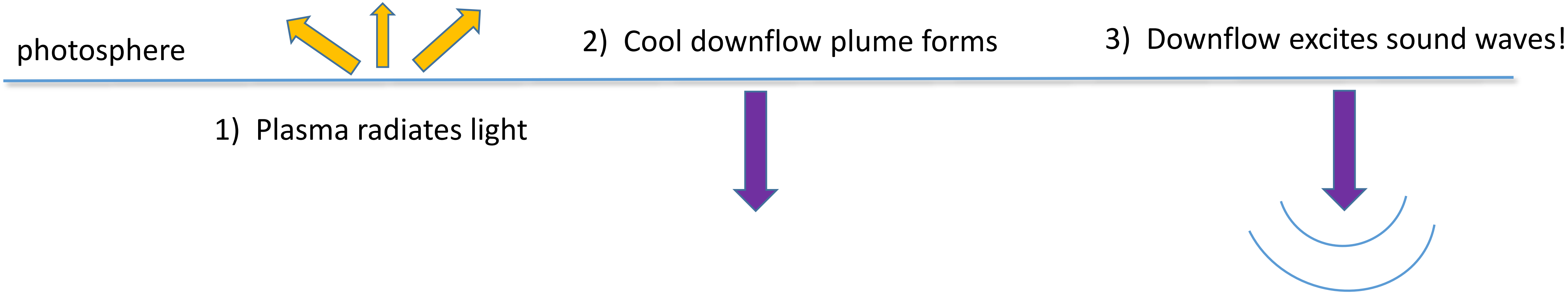
To understand **B**, we must understand **v** and how it interacts with rotation!

Helioseismology

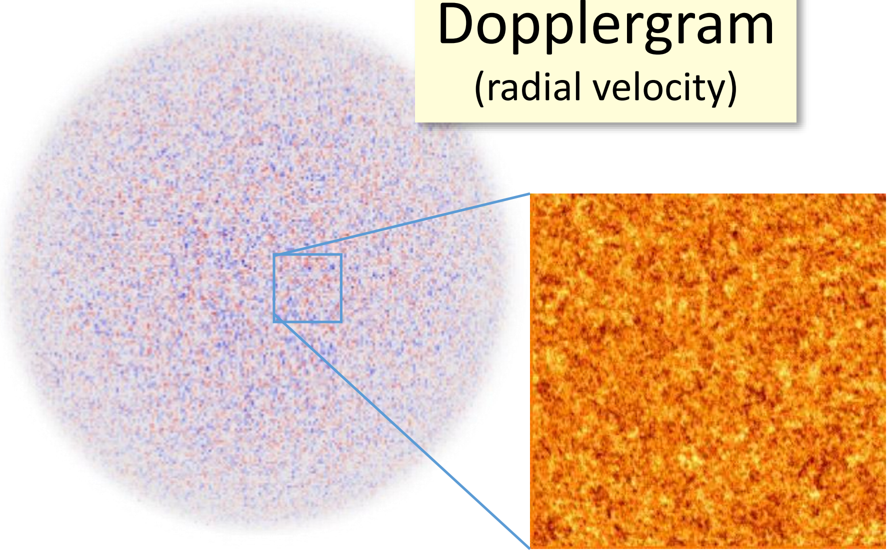
The Sound of Granulation



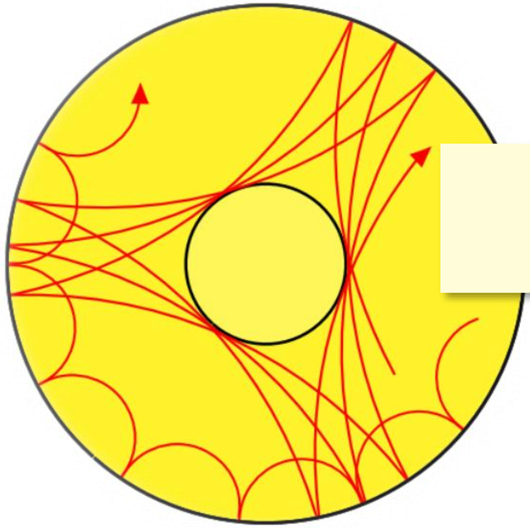
Solar Granulation Movie
Swedish Solar Telescope
Wavelength: 395 nm
Duration: 1 hour



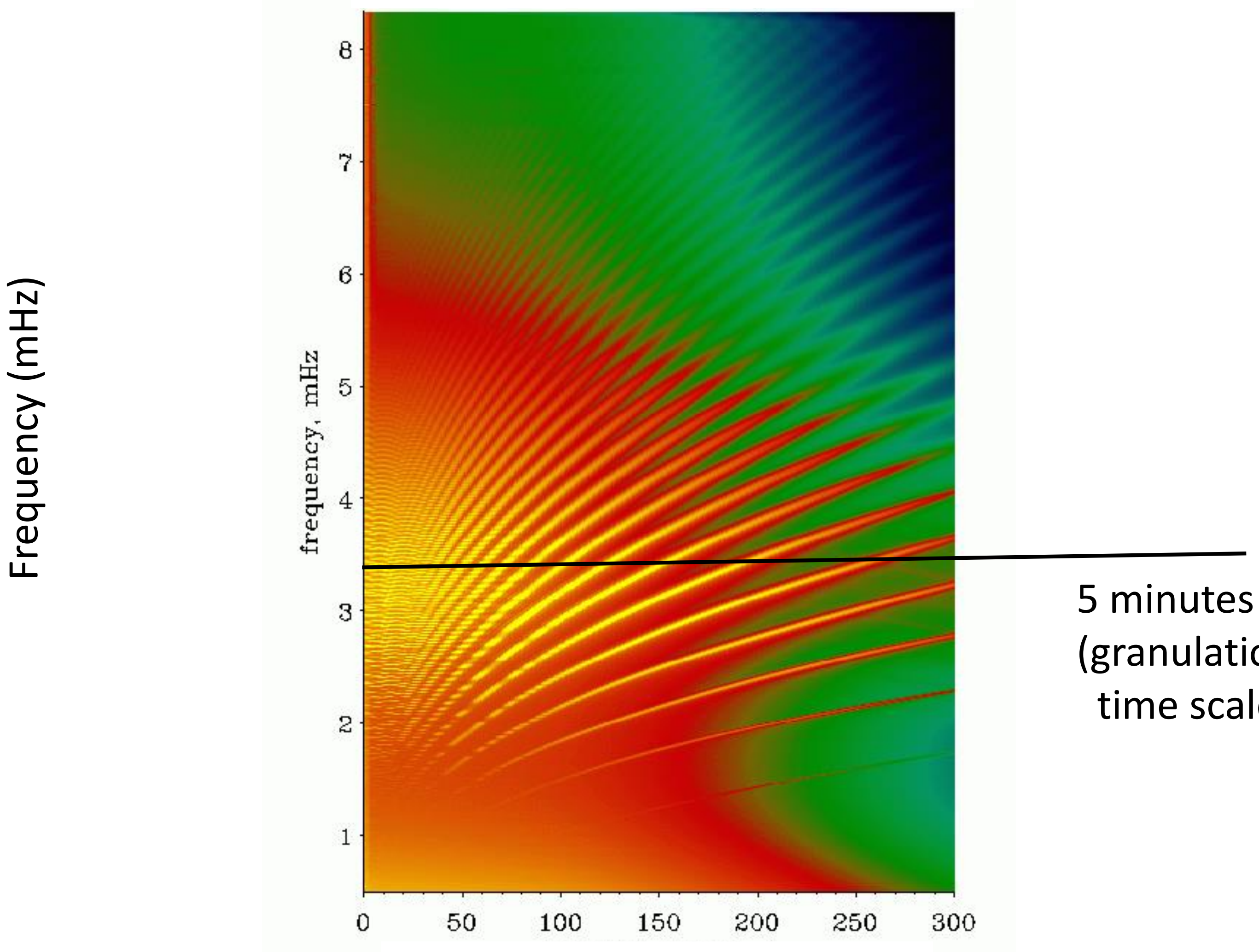
What Lies Beneath?
Solar Helioseismology



MDI



MDI Medium-ℓ Power Spectrum

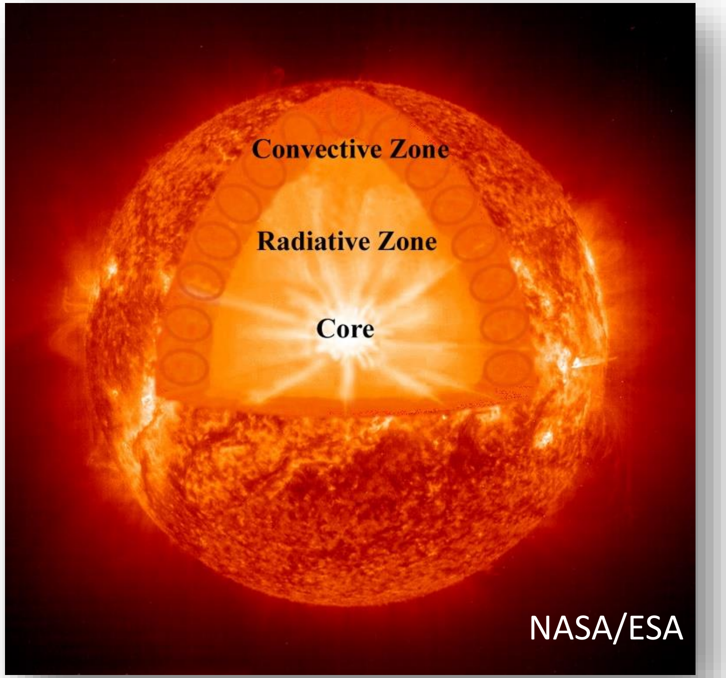


Spherical Harmonic Degree ℓ

5 minutes
(granulation
time scale)

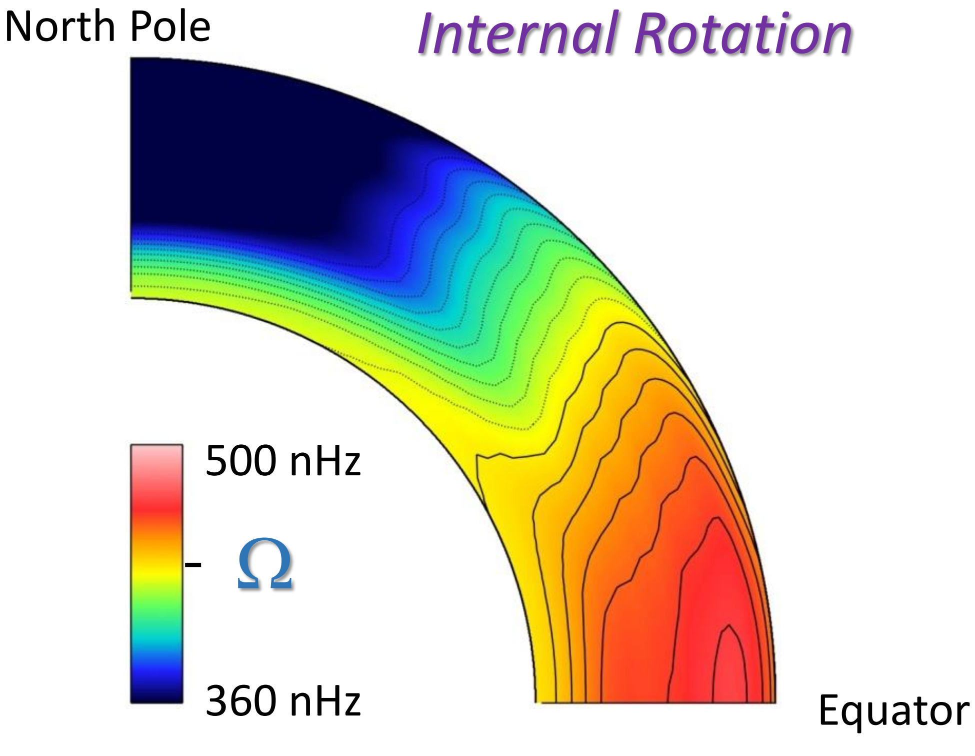
Helioseismology: Key Results

Solar Structure



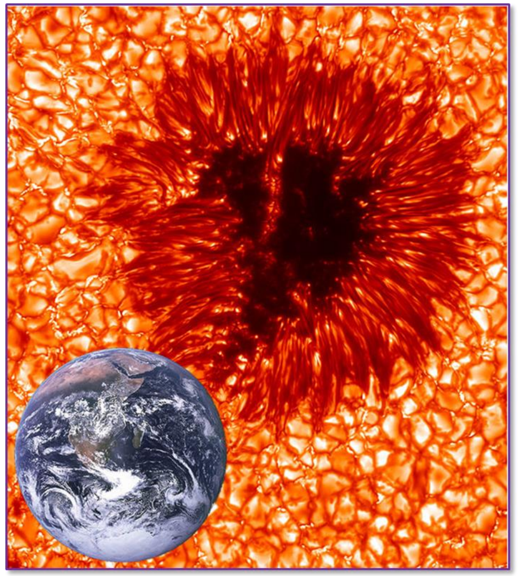
- Radiative Interior
- Outer 1/3 is convecting (2 x 10^6 K temperature contrast)
- Home to the dynamo?

Internal Rotation



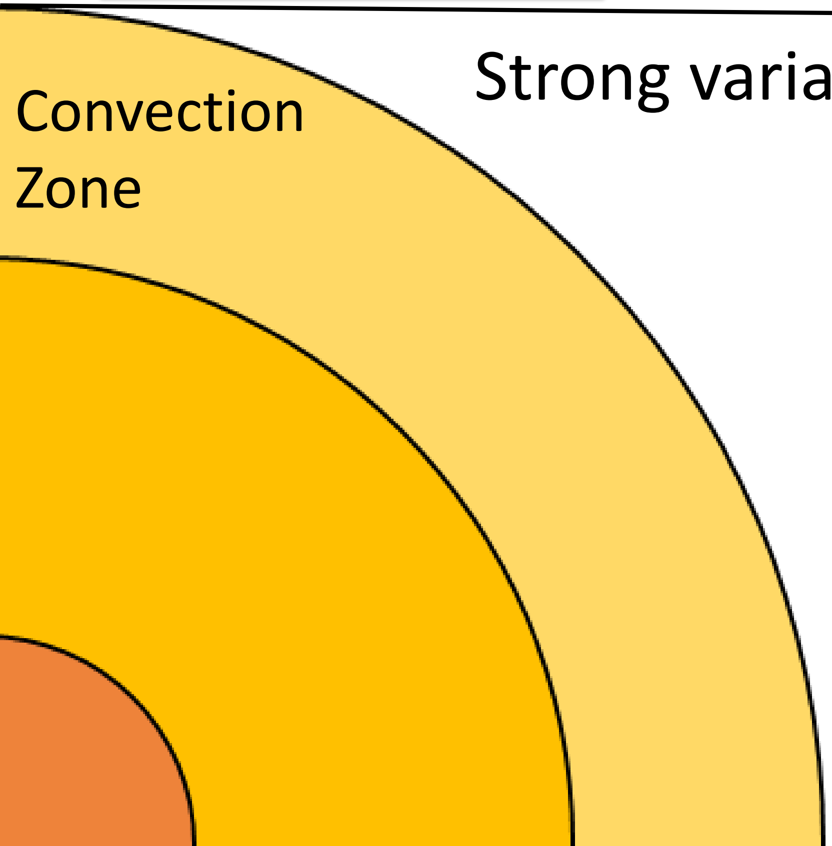
Howe et al. 2000; Schou et al. 2002

- Rotates differentially
- 24-day period equator
- 30-day period poles



Note:

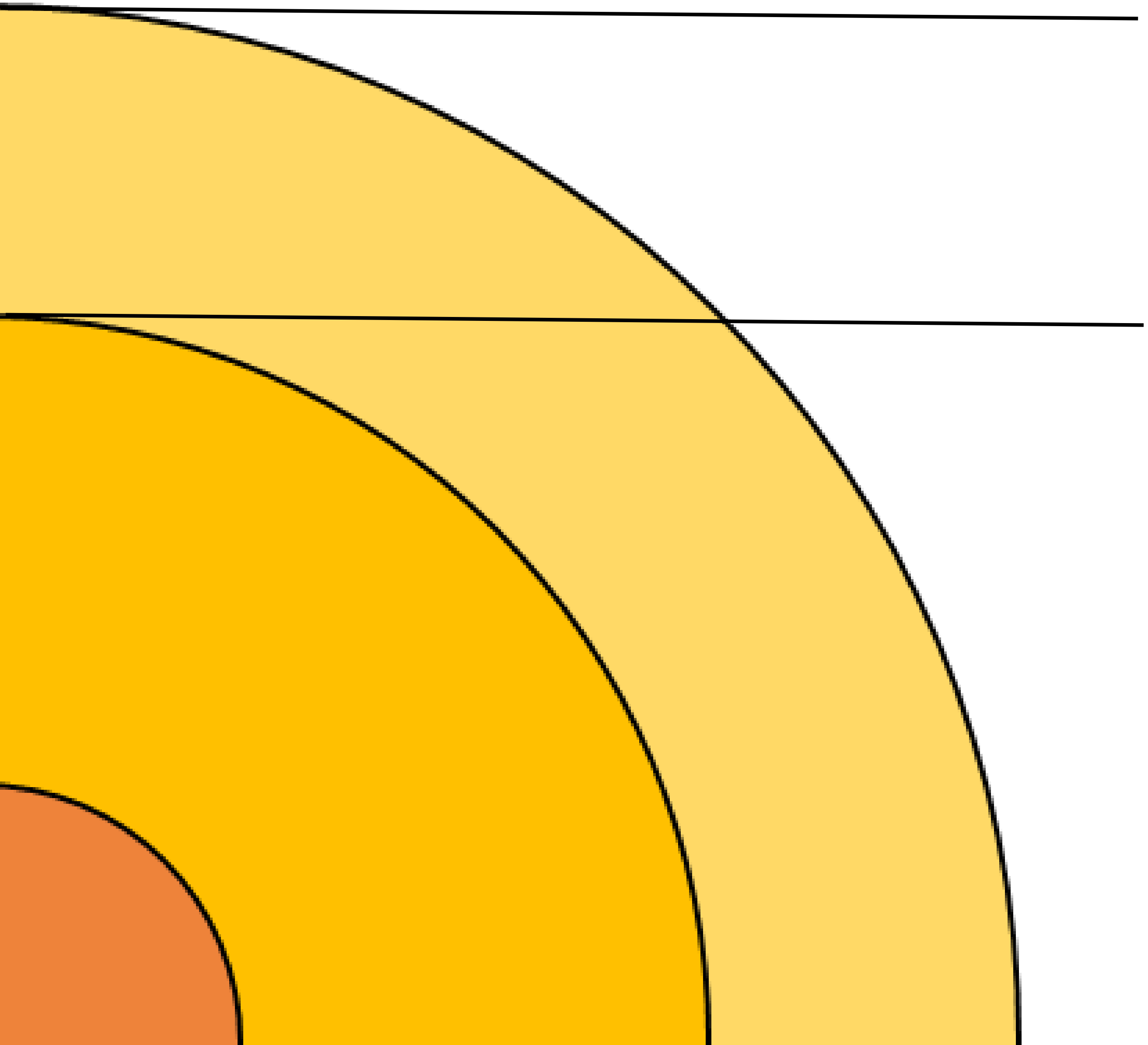
Photospheric motions that we observe occur in a region thinner than the width of this line (about 1,000 km in depth)



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

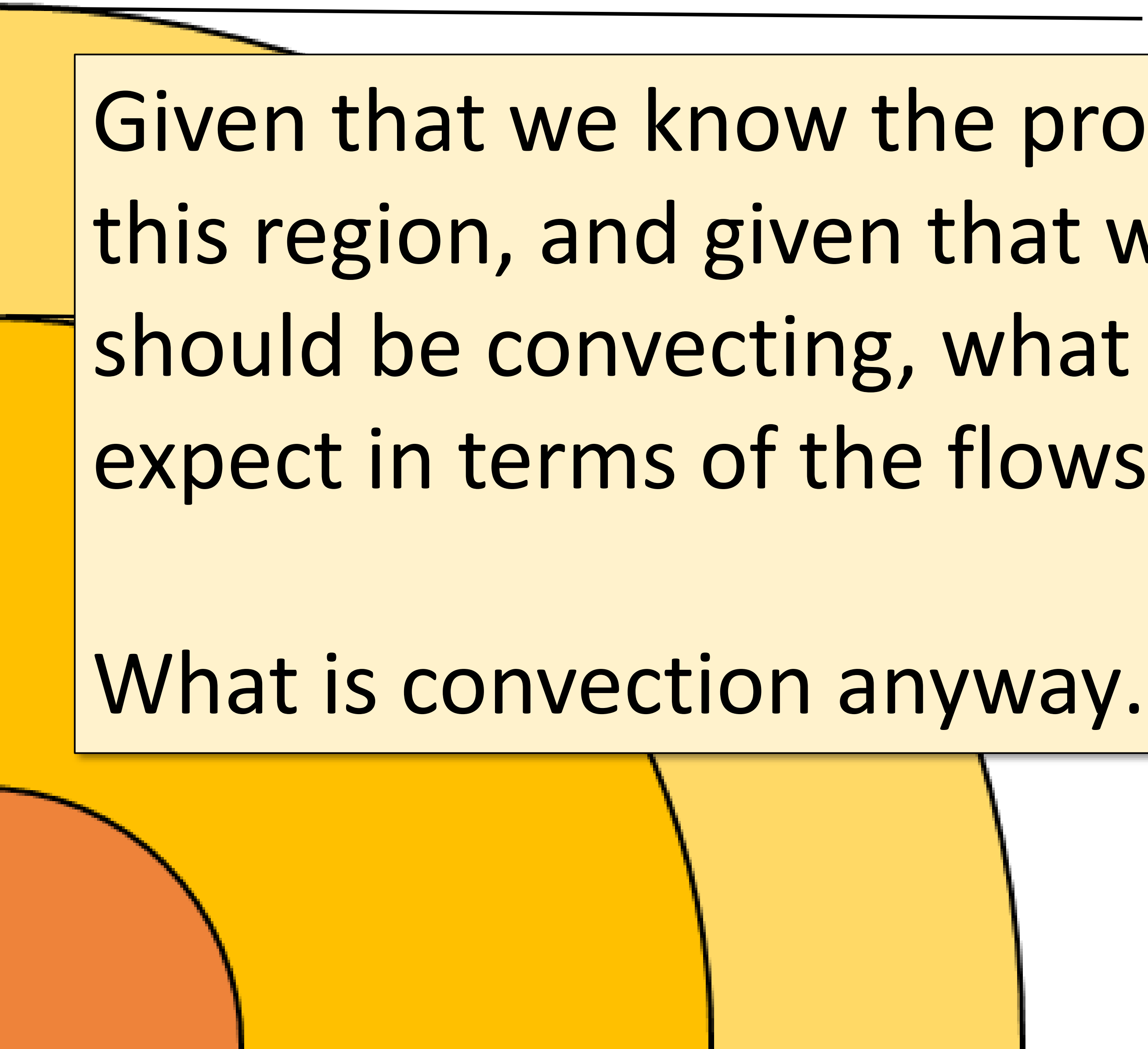


Temperature: 14,400K
Density: 2×10^{-6} g cm^{-3}

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 $\approx 10^{-15}$

Convection Zone Bulk



Given that we know the properties of this region, and given that we know it should be convecting, what might we expect in terms of the flows?

What is convection anyway….?

Temperature: 14,400K

2×10^{-6} g cm^{-3}

2.3 million K

0.2 g cm^{-3}

scaleheights

scaleheights

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A Few Convection Fundamentals

Convection 101

Caution: abbreviated fluid equations

Density

$$\rho = \rho' + \rho_0$$

Pressure

$$P = P' + P_0$$

$$\rho_0 \boldsymbol{g} = \boldsymbol{\nabla} P_0$$

Hydrostatic Background

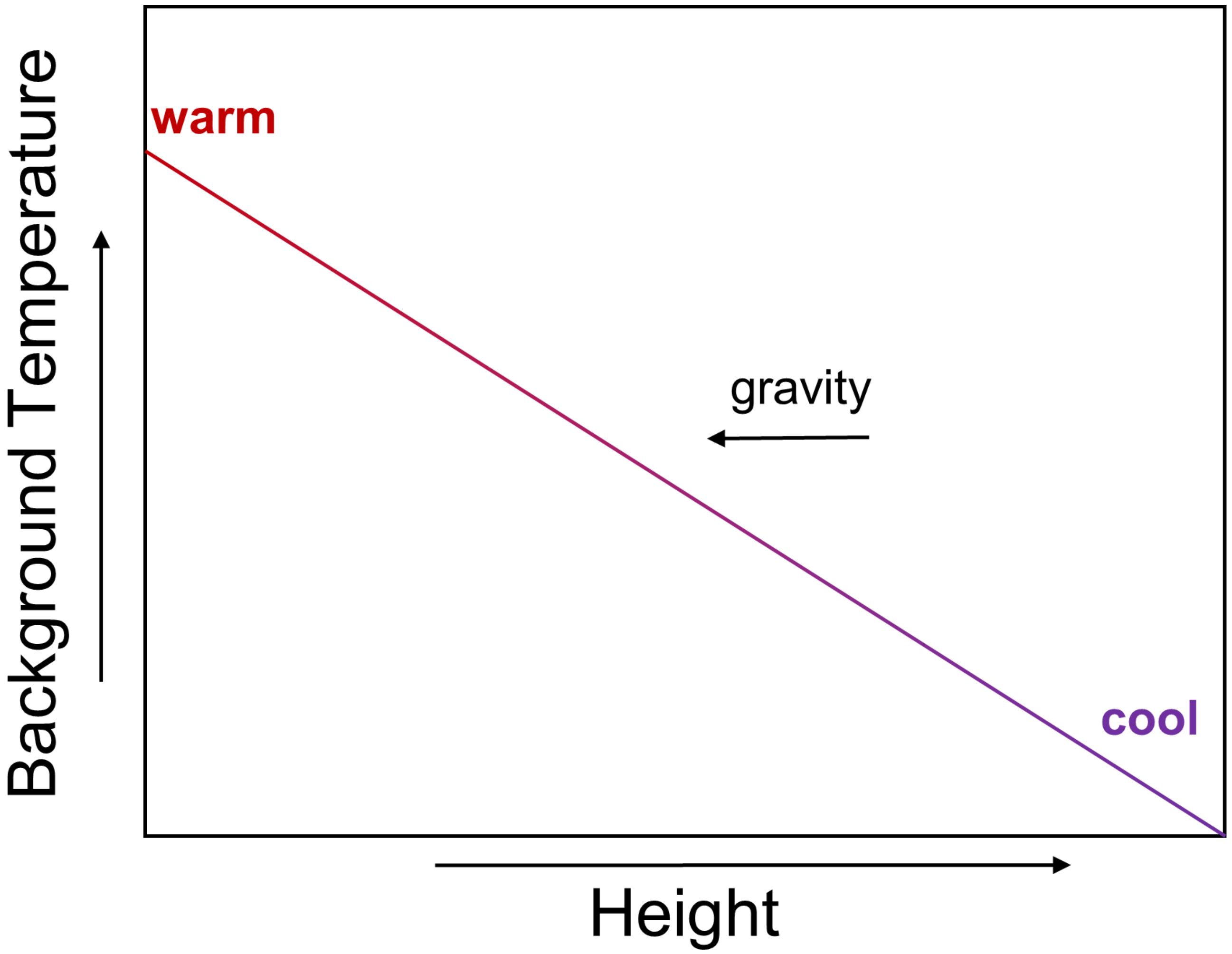
$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \boldsymbol{\nabla} \boldsymbol{v} = -\boldsymbol{\nabla} P' - \frac{\rho'}{\rho_0} g \hat{\boldsymbol{r}} + \nu \boldsymbol{\nabla}^2 v$$

perturbations drive *dynamics*

Buoyancy

$$\frac{\rho'}{\rho_0} \approx -\frac{T'}{T_0}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = -\frac{\rho'}{\rho_0} g\hat{\boldsymbol{r}} \approx \frac{T'}{T_0} g\hat{\boldsymbol{r}}$$



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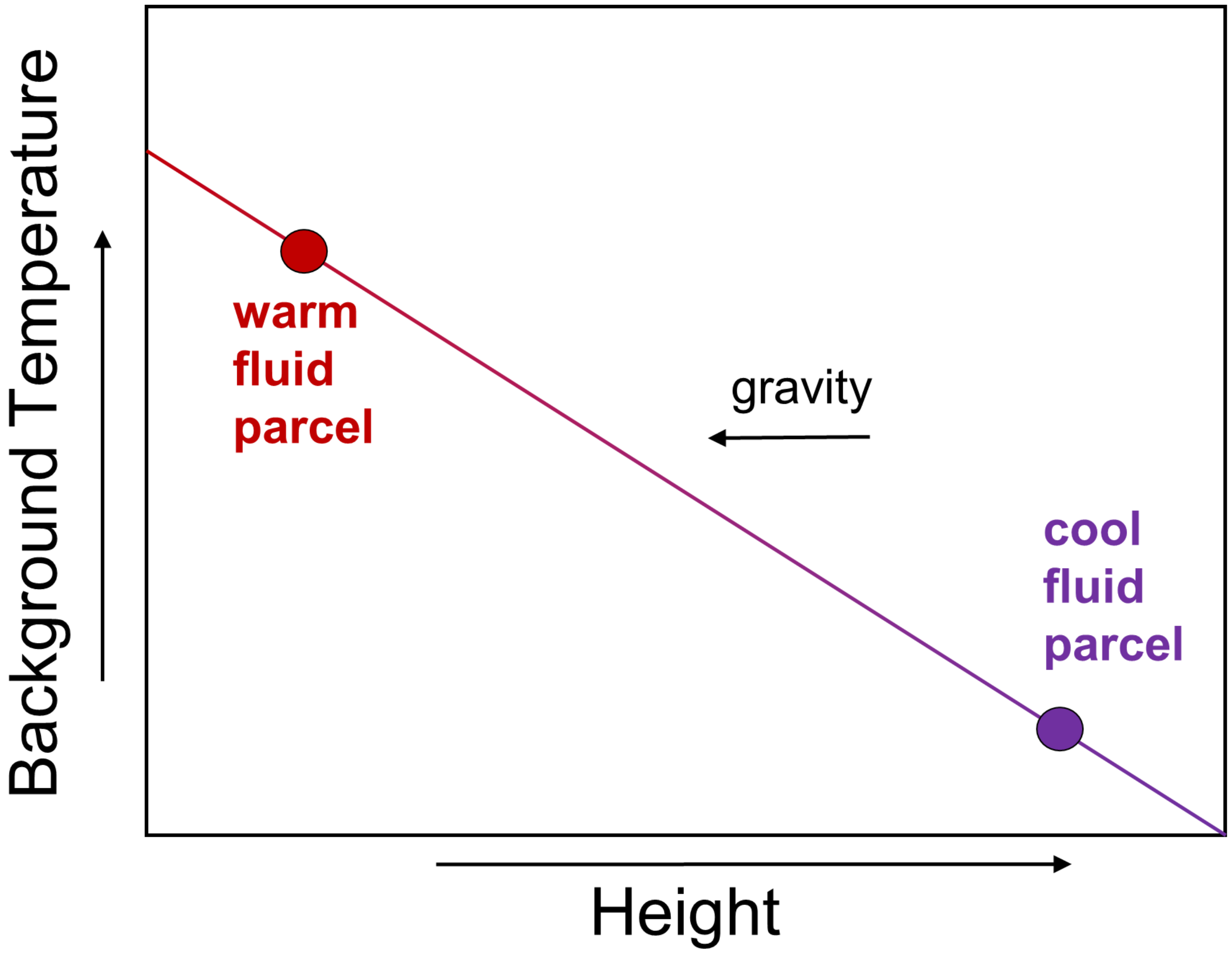

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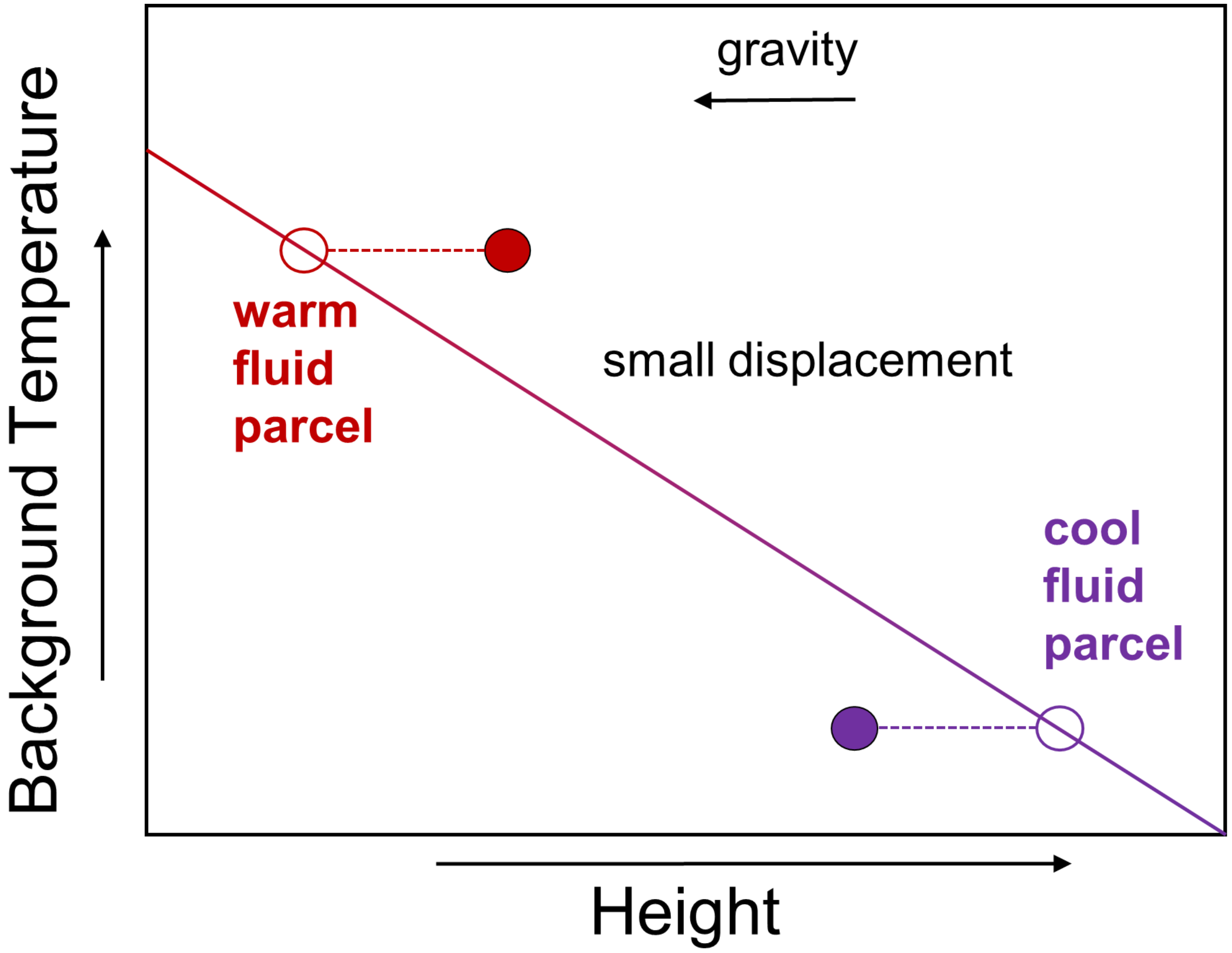

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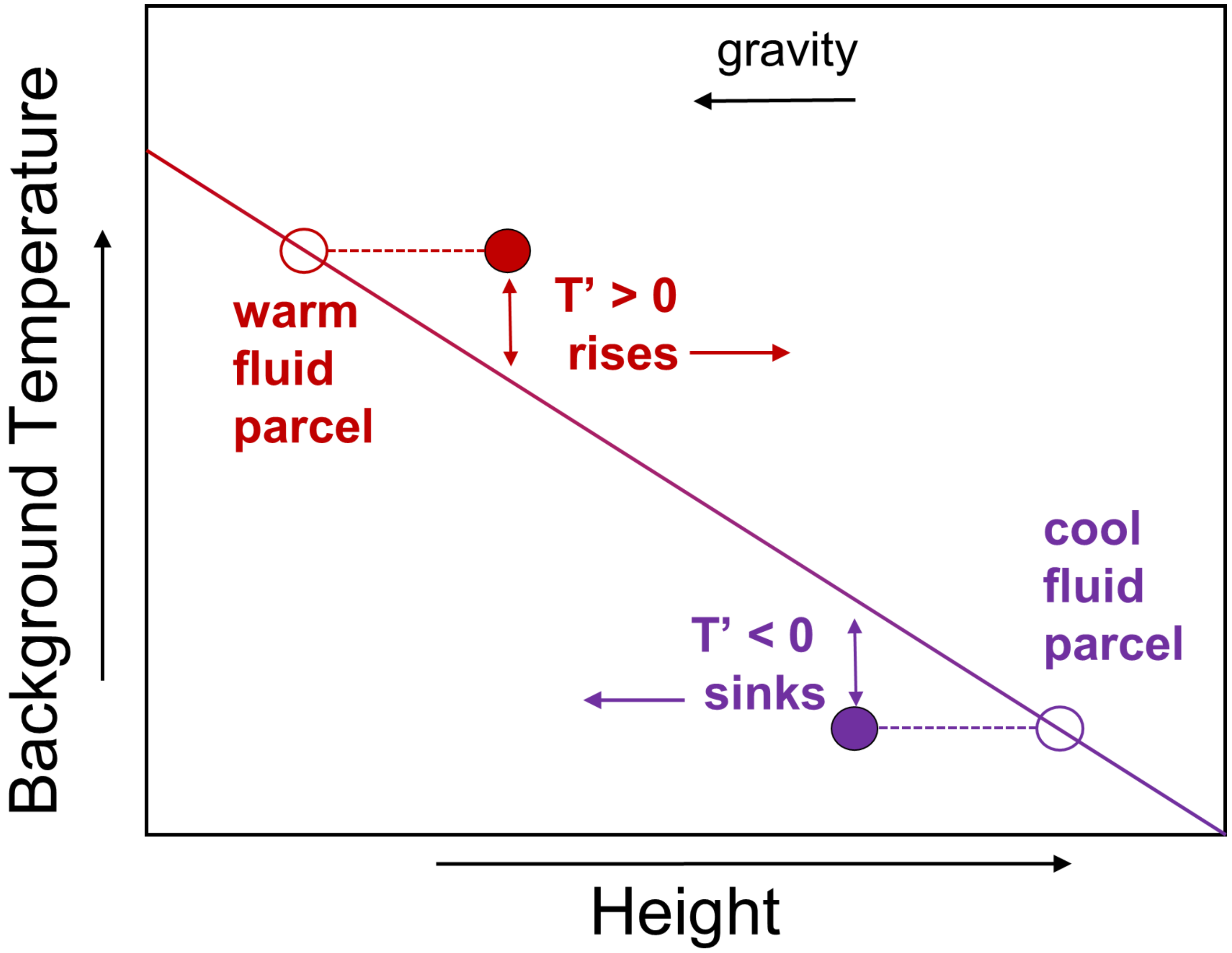
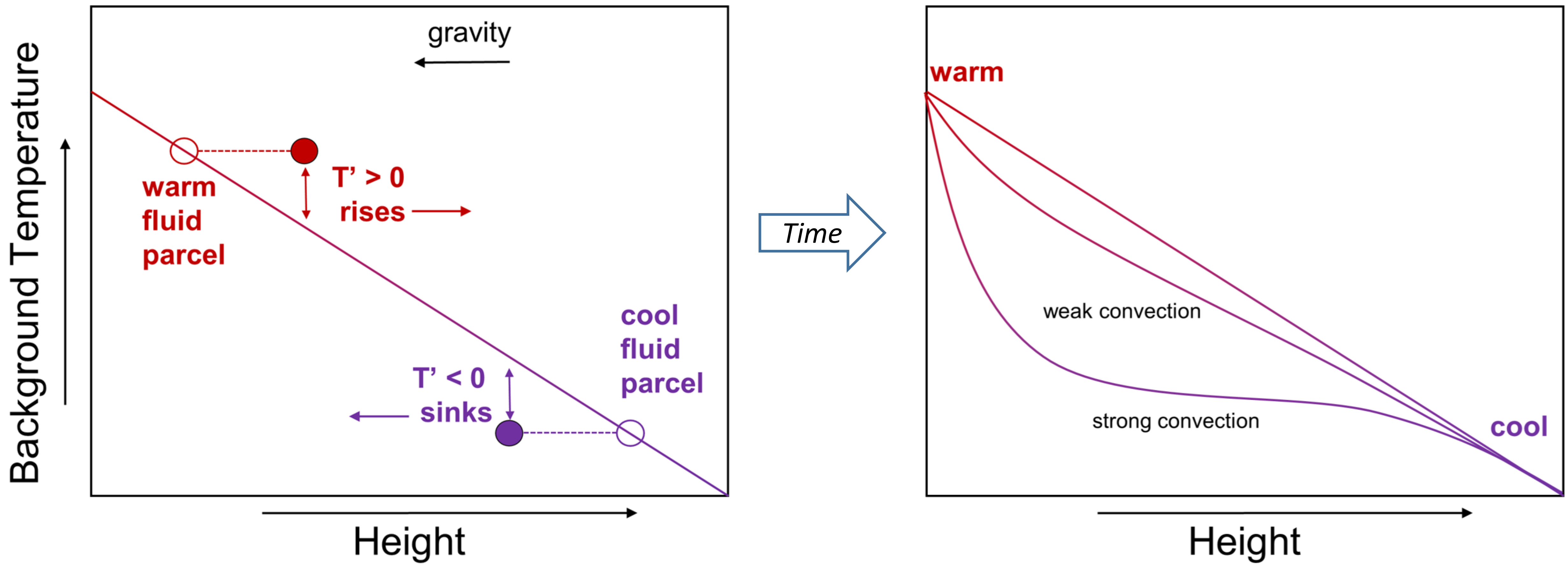


Convective Mixing



- As fluid rises and sinks, the tendency is to mix temperature (or entropy)
- Efficient convection can modify the background thermal profile
- What determines the efficiency?

The Competition: Diffusion

- The momentum equation has a diffusion term:

$$\frac{\partial \boldsymbol{v}}{\partial t} = \cdots + \upsilon \nabla^2 \boldsymbol{v}$$

"nu" : kinematic *viscosity*

- … as does the temperature equation:

$$\frac{\partial T}{\partial t} = -\boldsymbol{v} \cdot \boldsymbol{\nabla} T + \kappa \nabla^2 T$$

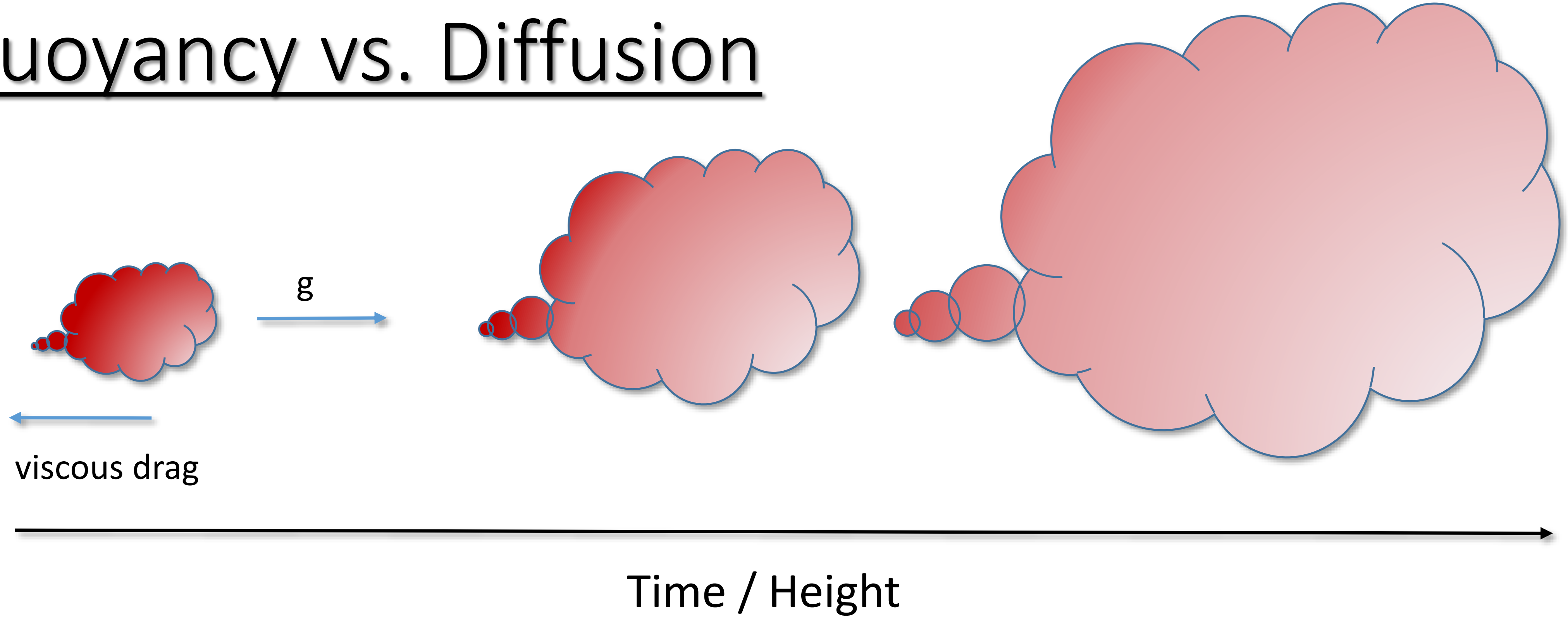
thermal diffusivity

- … as does the induction equation:

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

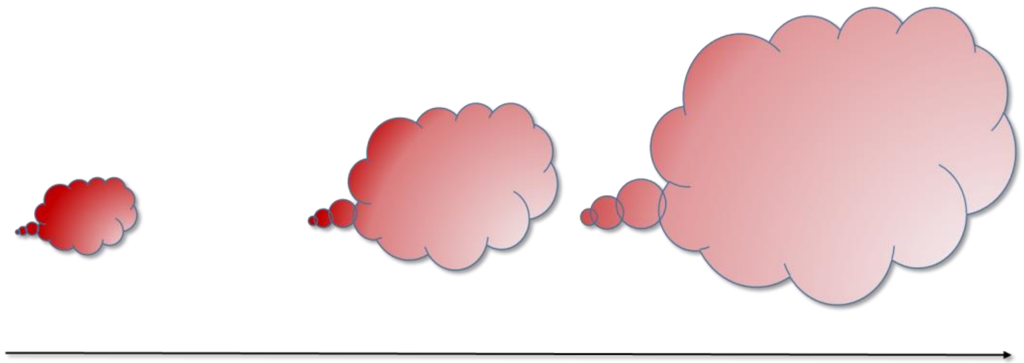
magnetic diffusivity

Buoyancy vs. Diffusion



- As a warm parcel rises, it mixes with its surroundings via diffusion:
  - Momentum → slows down
  - Temperature → cools down / weakens buoyancy
- Relative timescale of buoyancy vs. diffusion determines efficiency

Buoyancy vs. Diffusion



- Competition between buoyancy and diffusion characterized via Rayleigh number Ra:

$$\mathrm{Ra} = \left(\frac{\text{viscous diffusion time across layer}}{\text{freefall time across layer}}\right)\left(\frac{\text{thermal diffusion time across layer}}{\text{freefall time across layer}}\right)$$

- High Ra: Fluid moves across domain before diffusion has time to act.
- Low Ra: Diffusion slows rise/fall and prevents efficient transport of heat

- Convection sets in around Ra = 1,000
- What is Ra for the Solar convection zone? Let's estimate it.

Convection in the Sun

Exercise 1: The Diffusive Timescale

- Consider the 1-D diffusion equation:

$$\frac{\partial v}{\partial t} = \upsilon \frac{\partial^2 v}{\partial x^2}$$

- Seek a solution of the form:

$$T = Ae^{t/\tau}\sin(kx)$$

- What is τ ? Is it positive or negative?

Exercise 1: The Diffusive Timescale

- I find that:

$$\tau_{visc} = -\frac{1}{\upsilon k^2} \approx -\frac{\lambda^2}{\upsilon}$$

- For the solar convection zone:

$$\upsilon \approx 1\ \mathrm{cm^2 s^{-1}} \qquad \tau_{visc} \approx 4 \times 10^{20} s\ (\text{about } 10^{13}\ yr)$$

$$\lambda \approx 2 \times\ 10^{10}\ \mathrm{cm}\ \ (\text{CZ depth})$$

- Thermal Diffusion Time:

$$\kappa \approx 10^{7}\ \mathrm{cm^2 s^{-1}} \qquad \tau_{thermal} \approx 10^{6}\ yr$$

Exercise 2: The Freefall Timescale

$$\frac{\partial^2 x}{\partial t^2} = \tilde{g}$$

$$\tilde{g} \equiv \frac{T'}{T_0} g$$

Estimate the time for cool plasma to fall from the top of the convection zone to the bottom.

Typical convection zone values:

$T' \approx 1\mathrm{K}\,?^{*}$

$\mathrm{Depth} \approx 2 \times 10^8 \mathrm{m}$

$T_0 \approx 10^6 \mathrm{K}$

$g \approx 368\, m\, s^{-2}$

$$\tau_{freefall} = \sqrt{\frac{2 \times Depth}{\tilde{g}}} \approx 10^6 s \;\; \text{(or about 12 days)}$$

*Rast et al., 2008, ApJ, 673, 1209
*Kuhn et al., 1998, Nat. Lett., 392, 155

In Summary

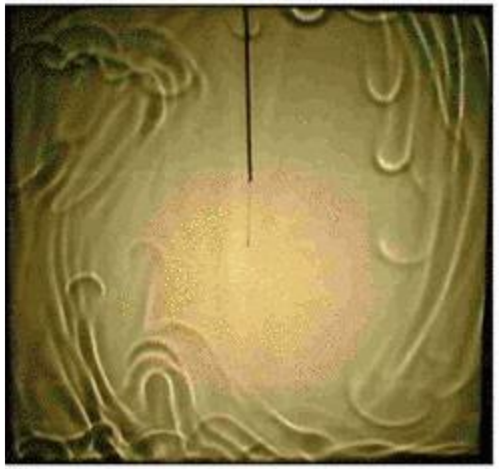
$$\mathrm{Ra} = \left(\frac{\tau_{viscous}}{\tau_{freefall}}\right)\left(\frac{\tau_{thermal}}{\tau_{freefall}}\right) = \left(\frac{4 \times 10^{20}\ s}{10^{6}\ s}\right)\left(\frac{4 \times 10^{13}\ s}{10^{6}\ s}\right) \approx 10^{22}$$

- This is well above 1,000, so diffusive effects are minimal globally
- On small enough spatial scales, they WILL matter on the freefall timescale
- Estimate:

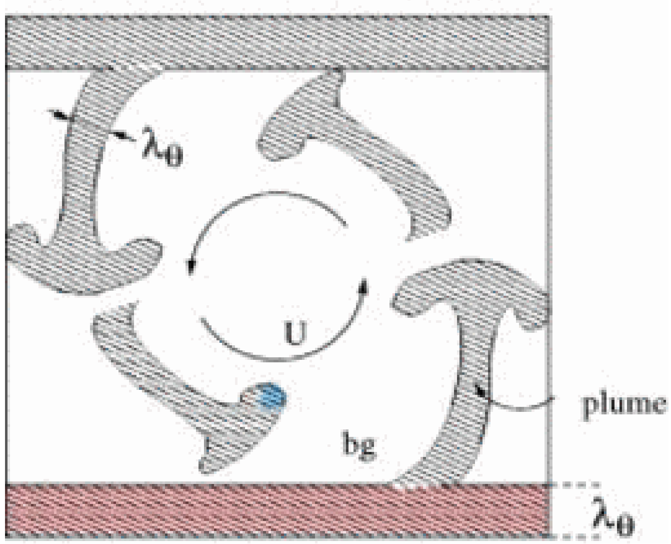
$$\tau_{freefall} = \frac{\lambda^2}{\upsilon} \rightarrow \lambda \approx 10\ m$$

On par with the length of a typical room in your home.

What Might we See: Canonical Picture

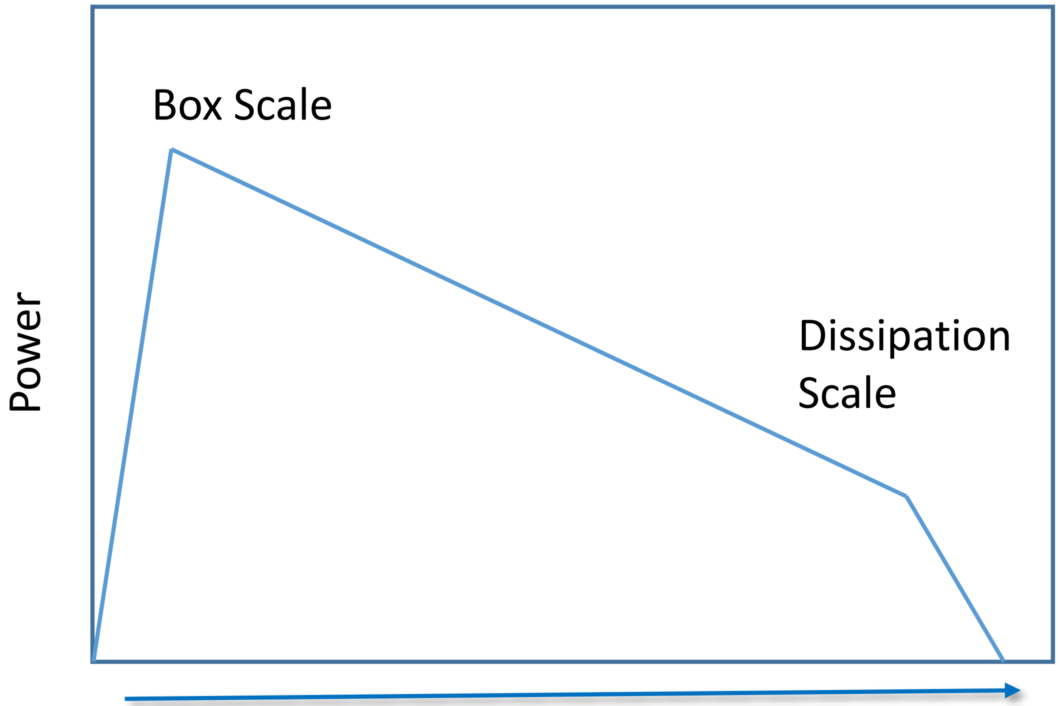


(a)

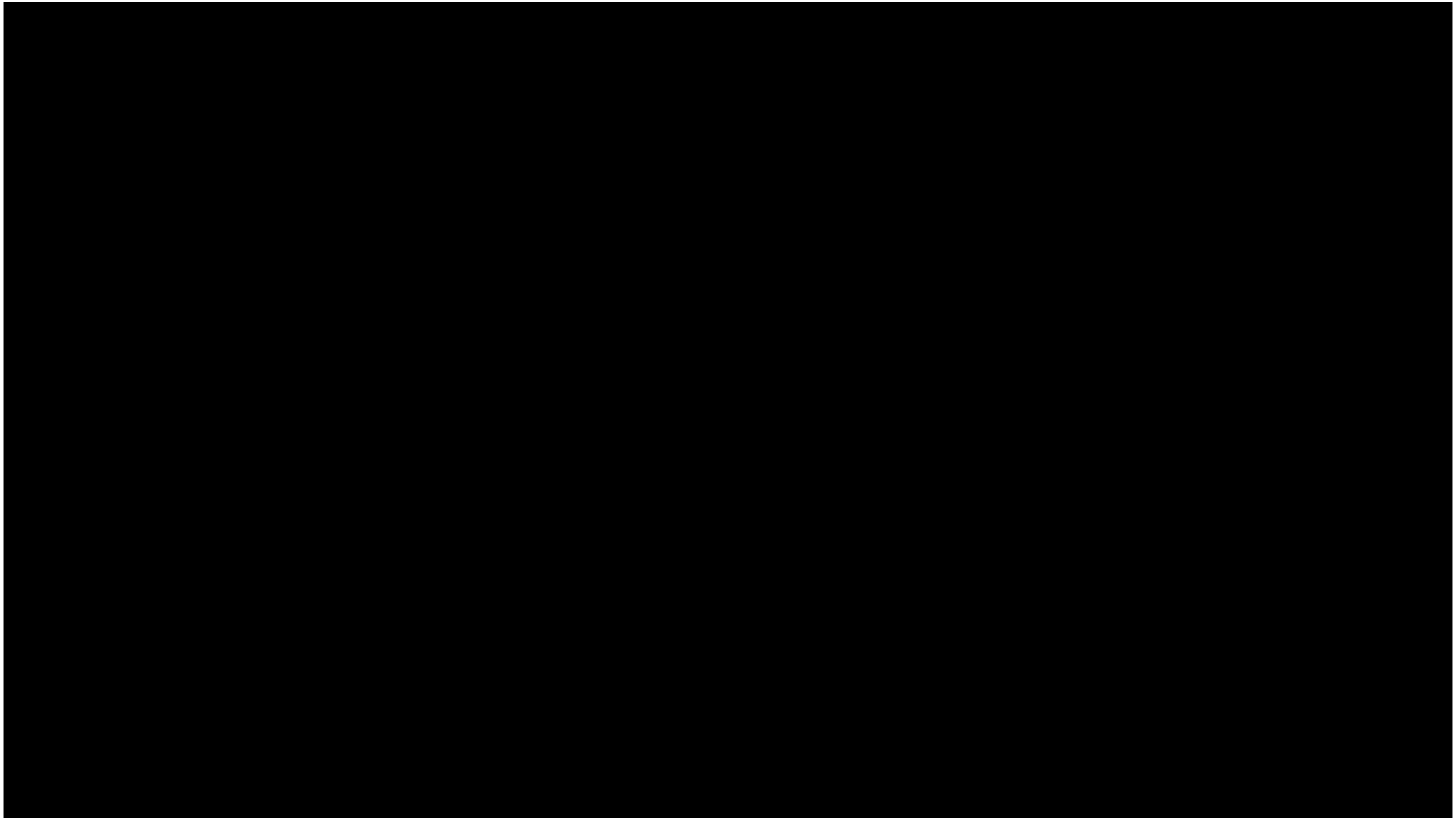


Ahlers, Grossman & Lohse,
2009, Rev. Mod. Phys., 81, 503

Schematic Power Spectrum



Increasing Wavenumber/
Decreasing length scale

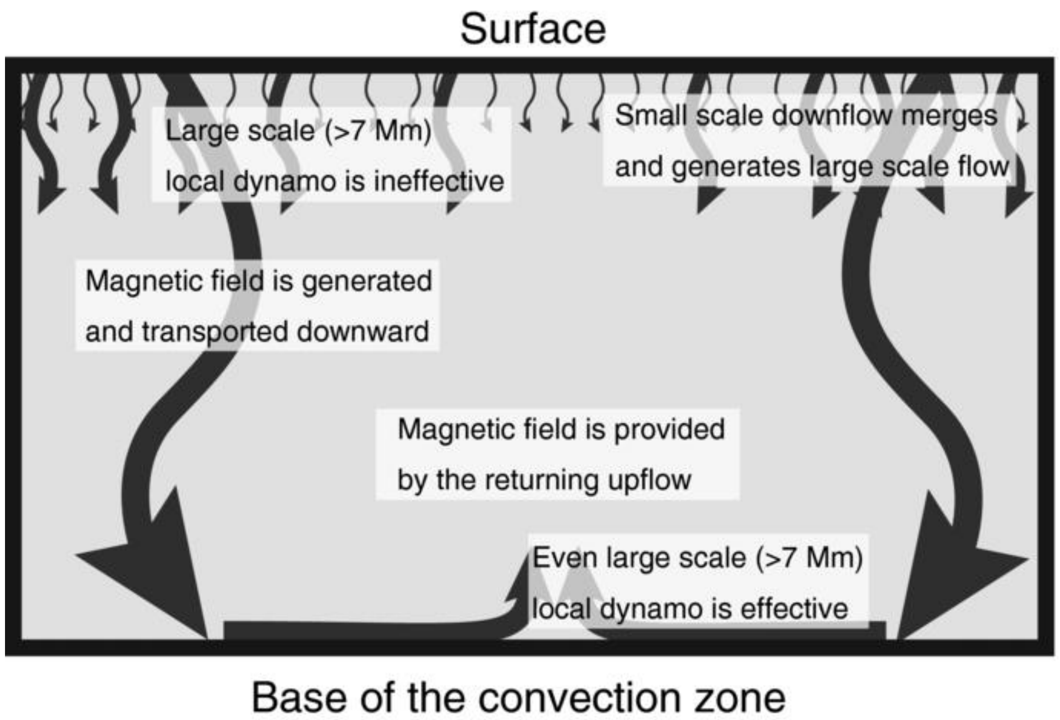


https://youtu.be/OM0l2YPVMf8

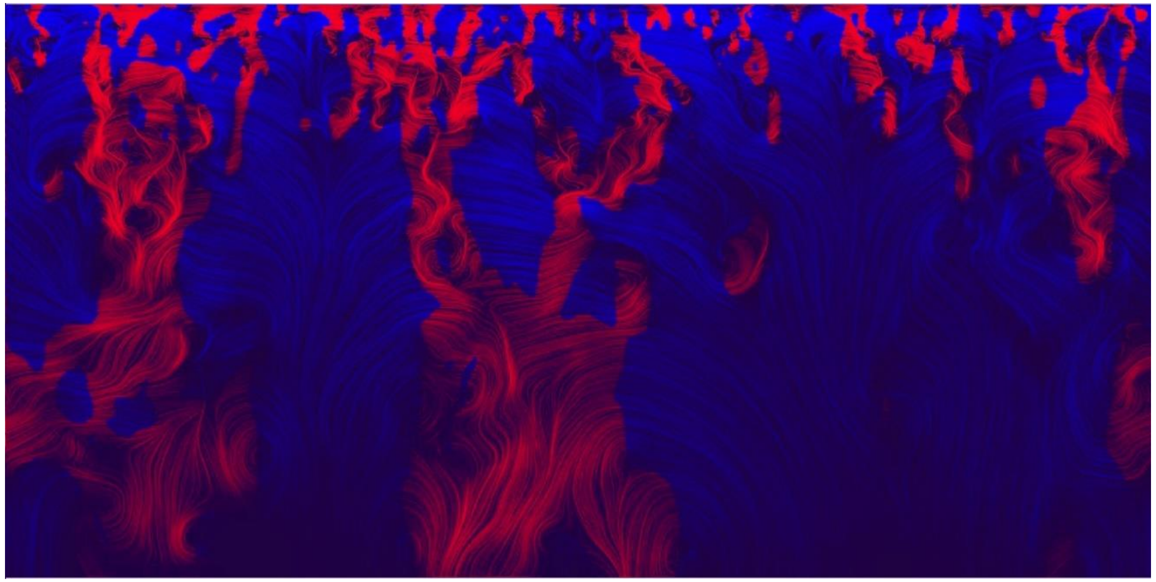
Ra = 10^{13}

What About in a System like the Sun?

- Density scale height acts like box scale:
  - Compressibility → Small structure near surface
  - Large structure throughout
  - Density scale height O(100) Mm at CZ base



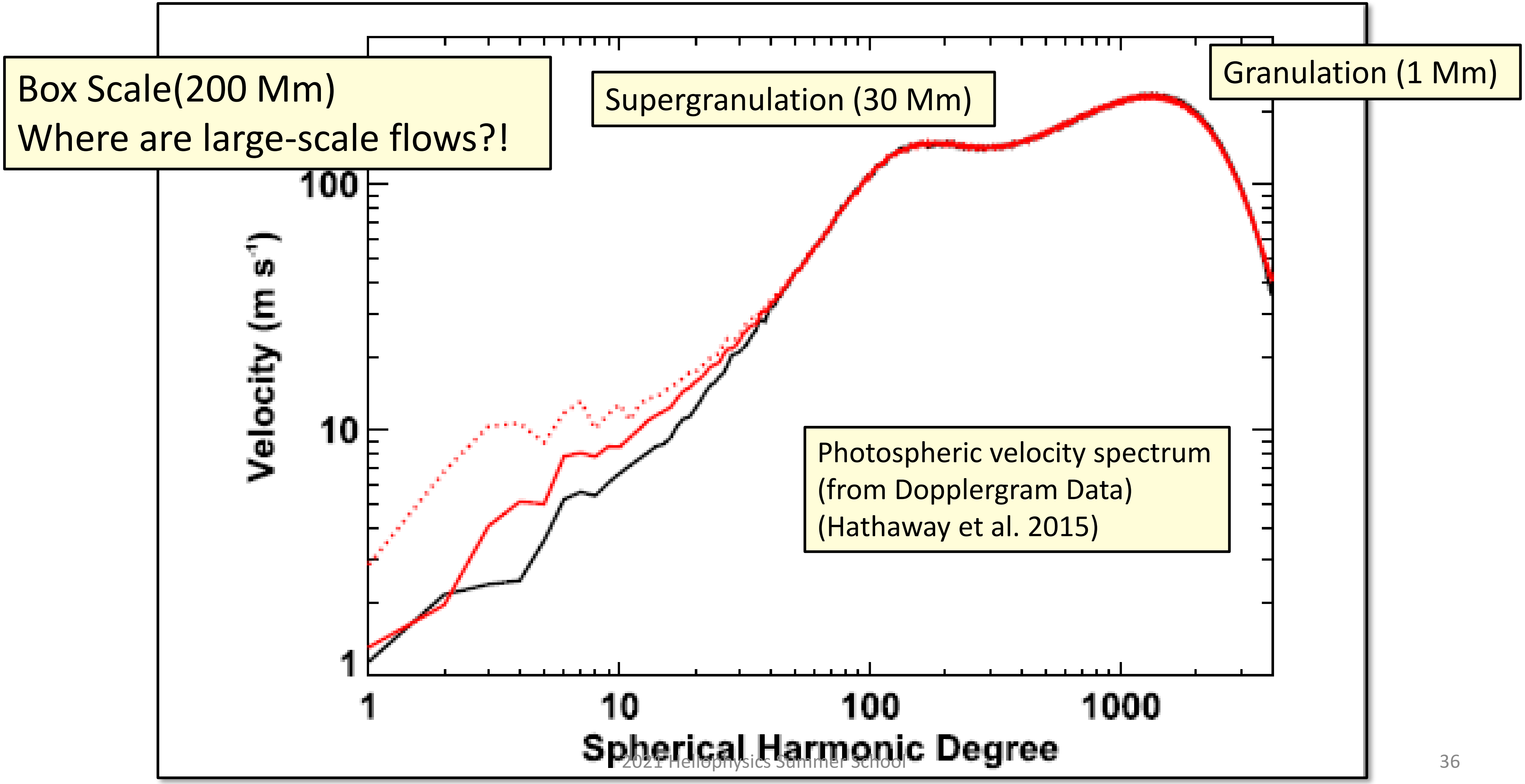
Hotta et al., 2014, ApJ, 786, 24



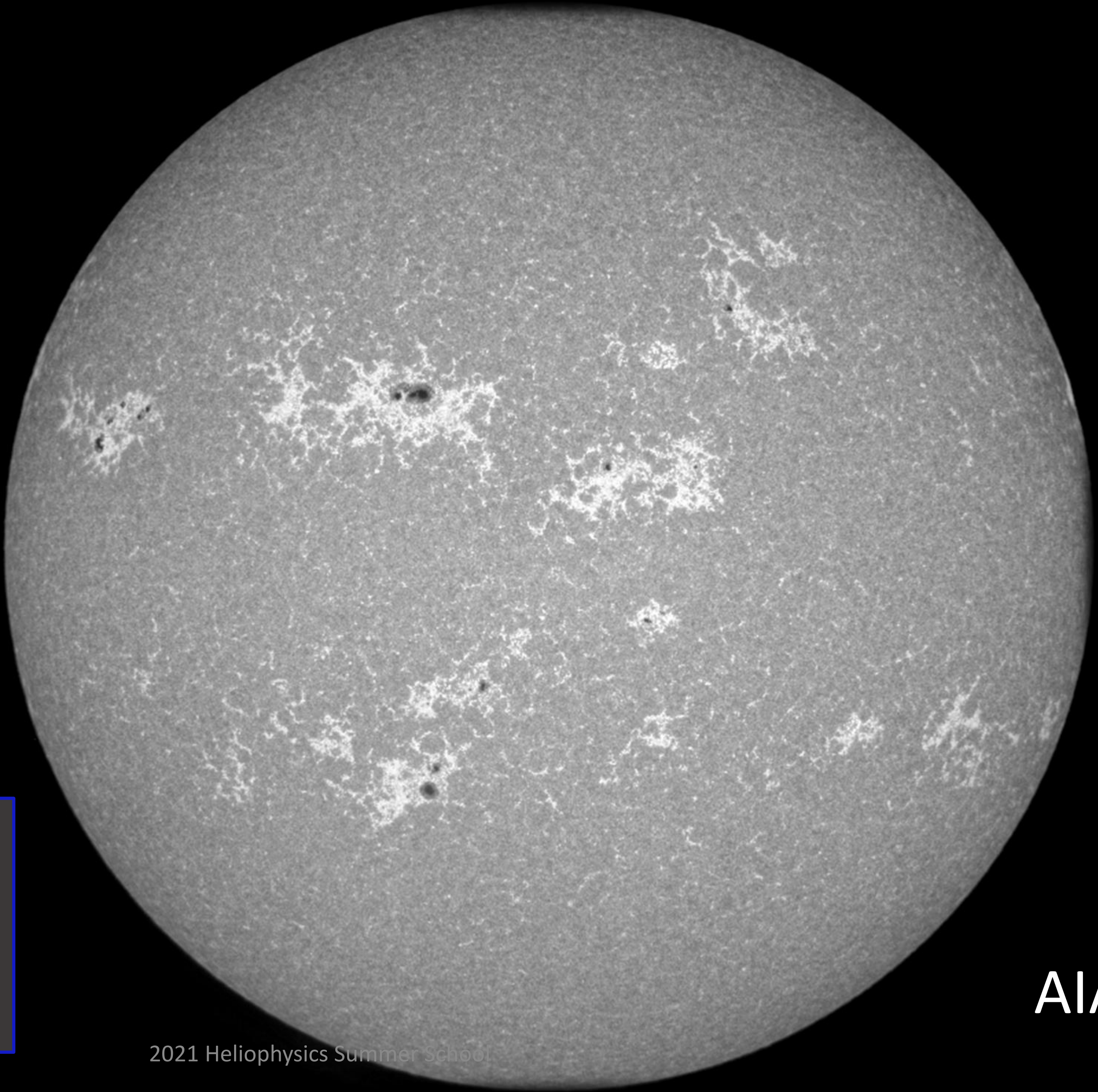
Red Downflow / Blue Upflow

Image Credit: Bob Stein (MSU)
Chris Henze (NASA)
https://web.pa.msu.edu/people/steinr/research.html

What do we see on the Sun? Surface Convective Spectrum



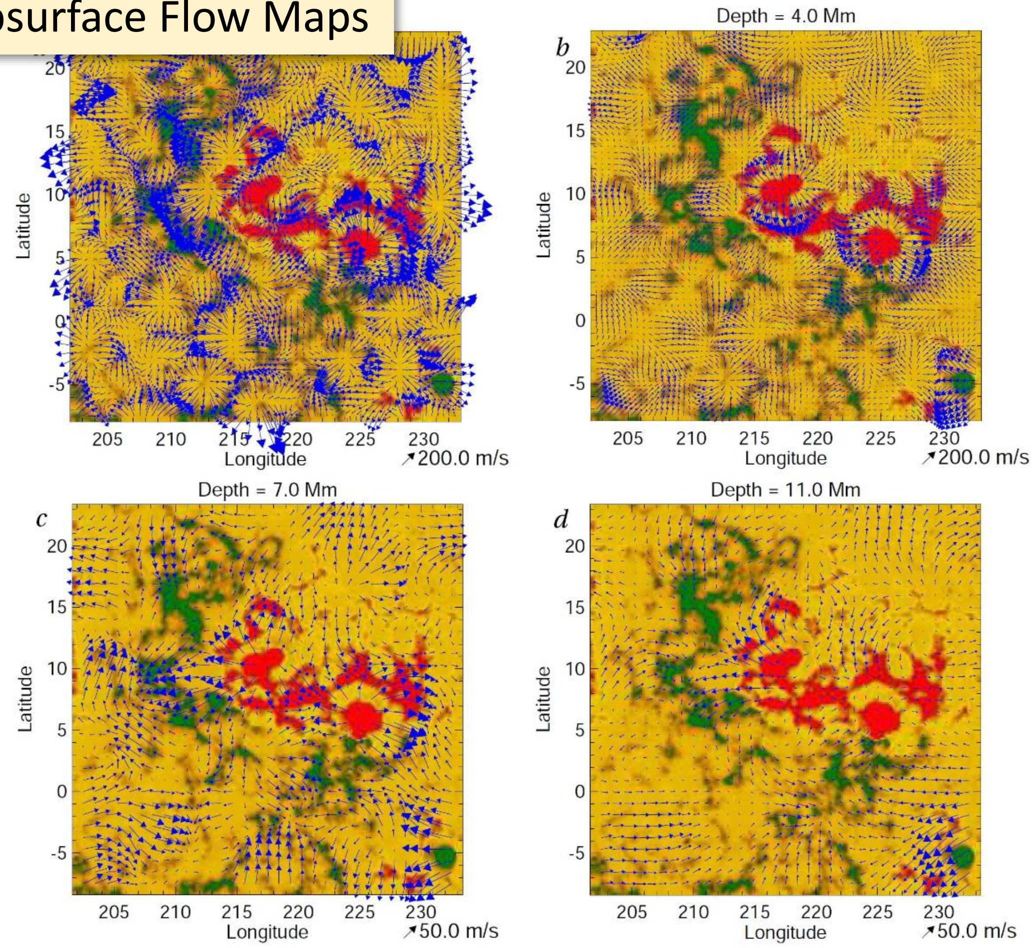
Supergranulation



L ≈ 30 Mm
Harmonic Degree 100
U ≈ 400 m s^{-1}

Probing Deeper: Local Helioseismology

Subsurface Flow Maps

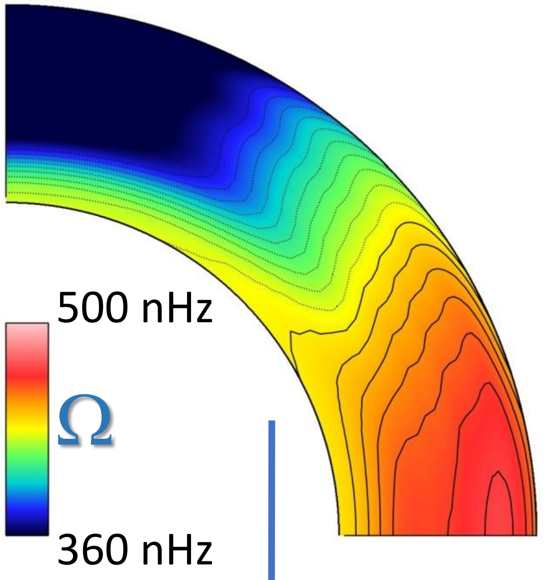


Featherstone et al., 2010

- Using helioseismology, we can also measure convective flows below the surface.
- Are large-scale flows possibly visible there?

How Deep Can We Go?

- Axisymmetric flows imaged throughout convection zone.
- Other flow measurements confined to upper 15% …
- Not all observations agree…



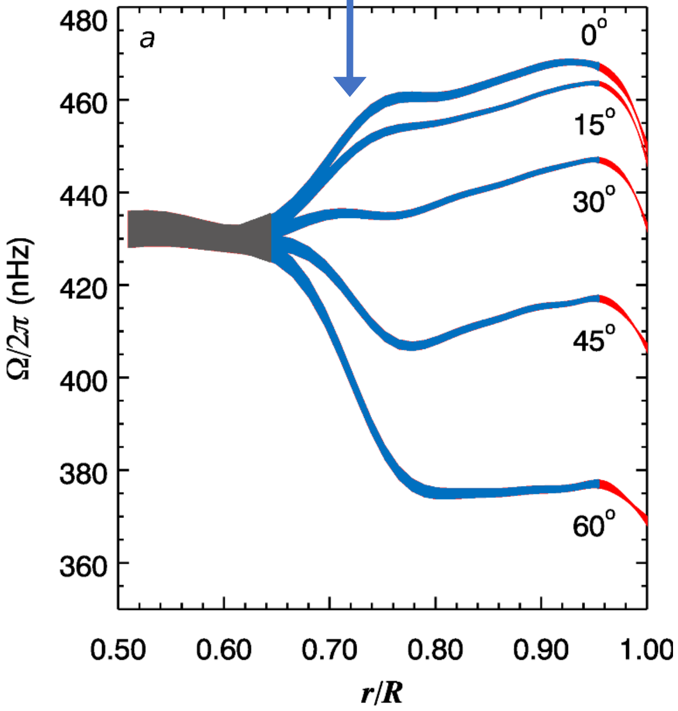
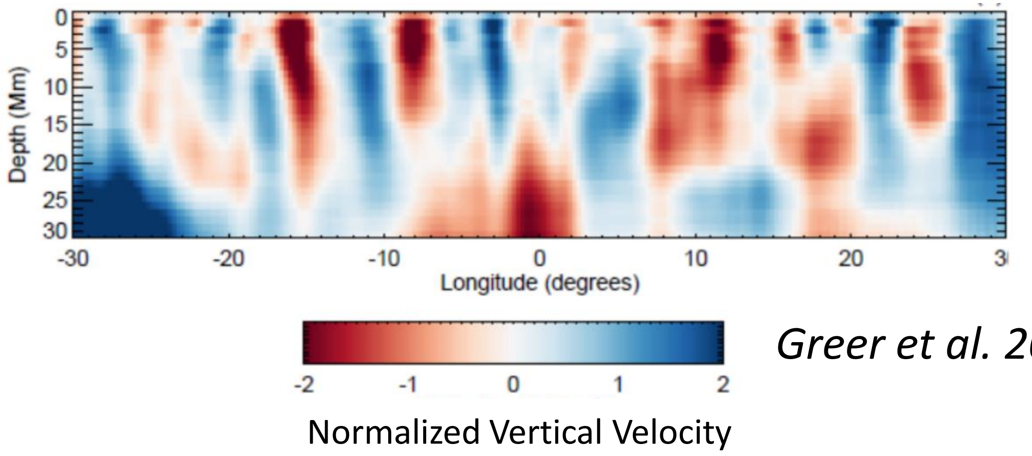
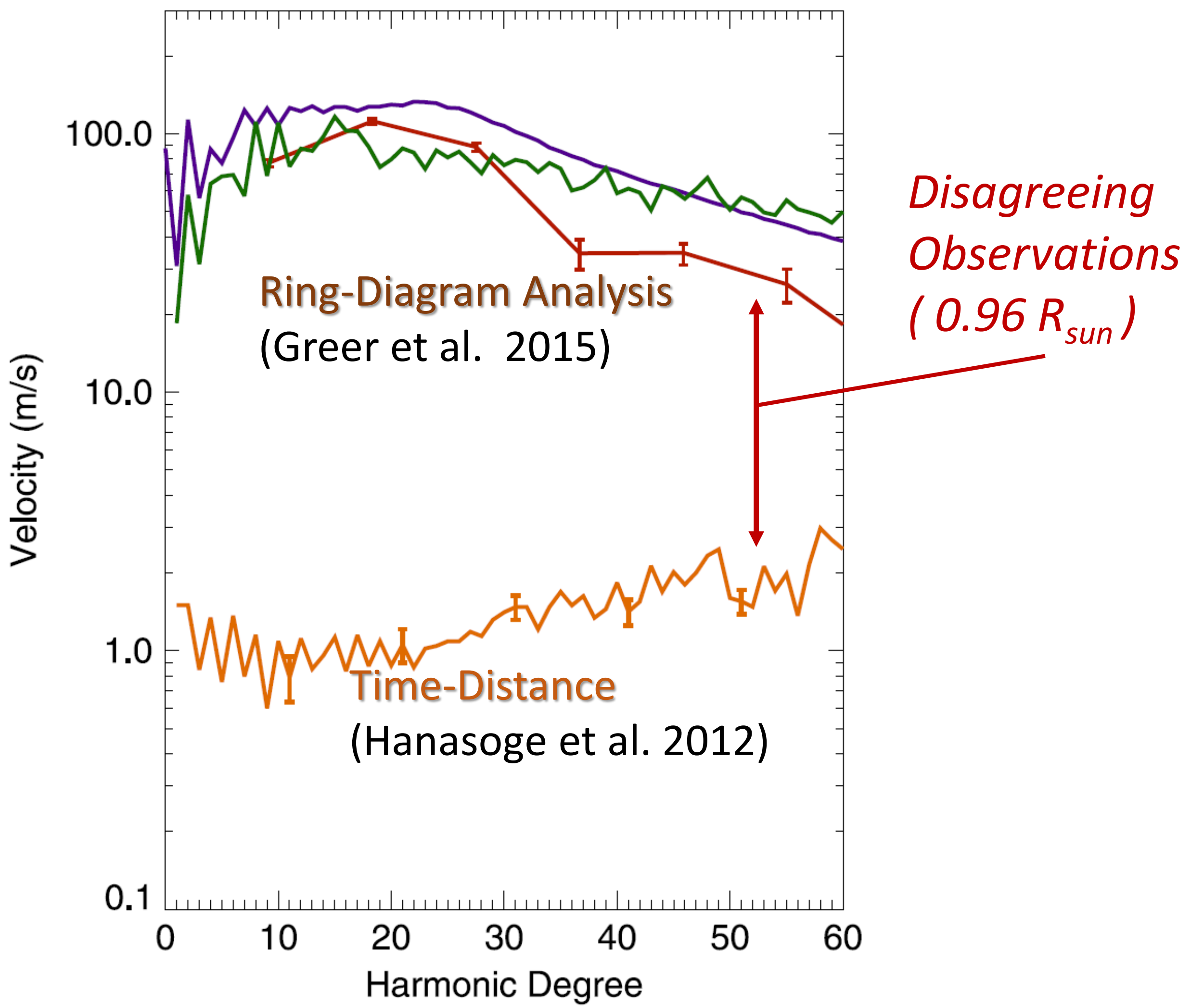


Image credit: NSO (adapted)



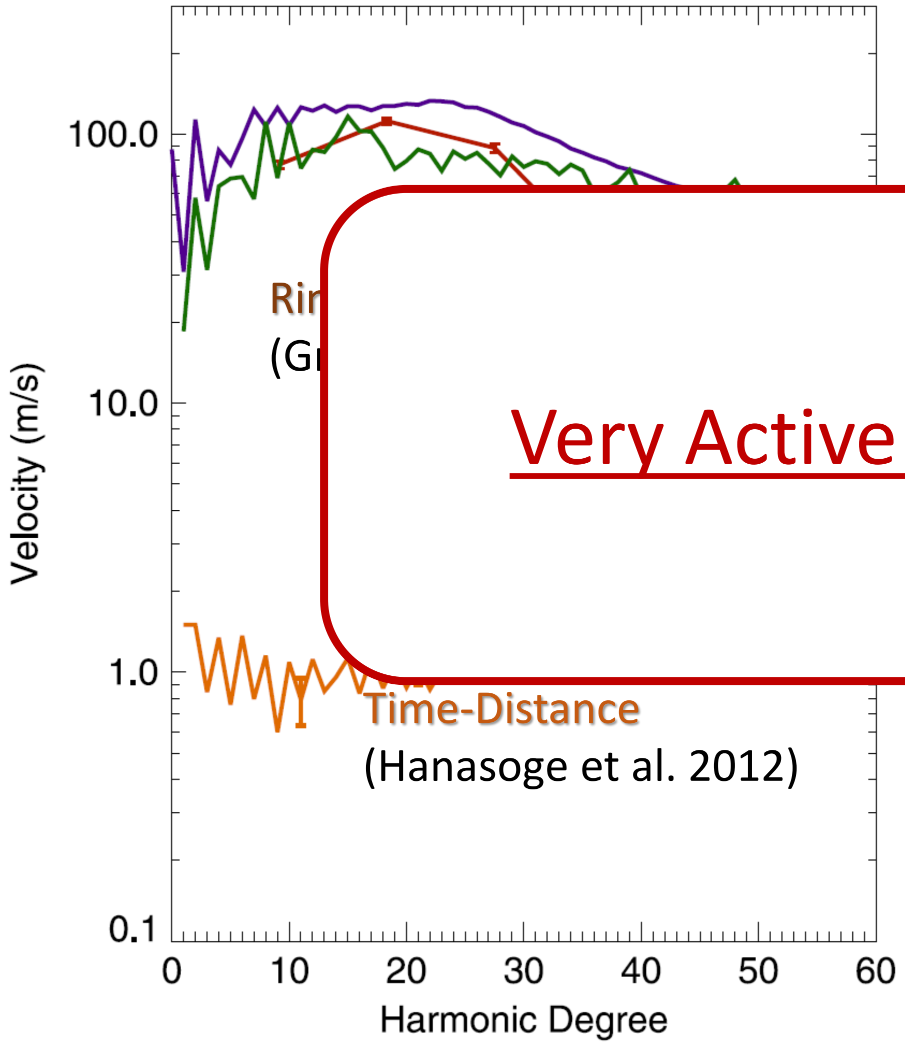
Greer et al. 2016

The Convective Conundrum



- Large-scale power appears to be missing or very weak
- Disagreement between helioseismic analyses
- Where does supergranulation come from?
- How does Sun transport its heat with such weak flows?

The Convective Conundrum



- Large-scale power appears to be missing or very weak
- ween
- ses
- come from?
- How does Sun transport its heat with such weak flows?

Very Active Area of Research Right Now

The Effect of Rotation

Rotating Convection

- The Sun rotates once every 27 days.
- Rotation changes the picture drastically.
- Rotational influence on flow traditionally characterized in two ways
- The first is via the Ekman number Ek:

$$\mathrm{Ek} \equiv \frac{\text{rotation period}}{\text{viscous timescale}} \approx 10^{-15} \text{ in the Sun}$$

- This tells us that relative to rotational effects, viscous diffusion is very weak.
- Unsurprising given our earlier analyses and the fact that the Sun rotates every 27 days.

The Rossby Number (this is important)

- The other way we quantify the effect of rotation on convection is through a Rossby number Ro.
- Different ways to define, but all have the same flavor:

$$\mathrm{Ro} \equiv \frac{\text{rotation period}}{\text{convective timescale}}$$

- High Ro → weak rotational influence
- Low Ro → strong rotational influence
- How/why?

The Coriolis Force (still important)

- Two important effects arise from the Coriolis force:
  1. Strong Coriolis force implies invariance of convective structure with rotation axis (Taylor Proudman effect; stated without proof)
  2. Fluid motions become curved…
- Coriolis force given by:

$$\boldsymbol{F_C} = -2m\boldsymbol{\Omega} \times \boldsymbol{v}$$

- Mathematically similar to Lorentz force, so we define a gyro radius:

$$r_{gyro} = \frac{v}{2\Omega}$$

The Gyro Radius and Rossby Number (still important…almost there)

- Let's look more closely at this.
- Let L be convection zone depth.   Multiply by one…

$$r_{gyro} = \frac{v}{2\Omega} = \frac{L}{L}\frac{v}{2\Omega} = L\left(\frac{1}{2\Omega}\right)\left(\frac{v}{L}\right)$$

$$r_{gyro} \approx L\left(\frac{rotation\ period}{1}\right)\left(\frac{1}{convective\ overturning\ time}\right)$$

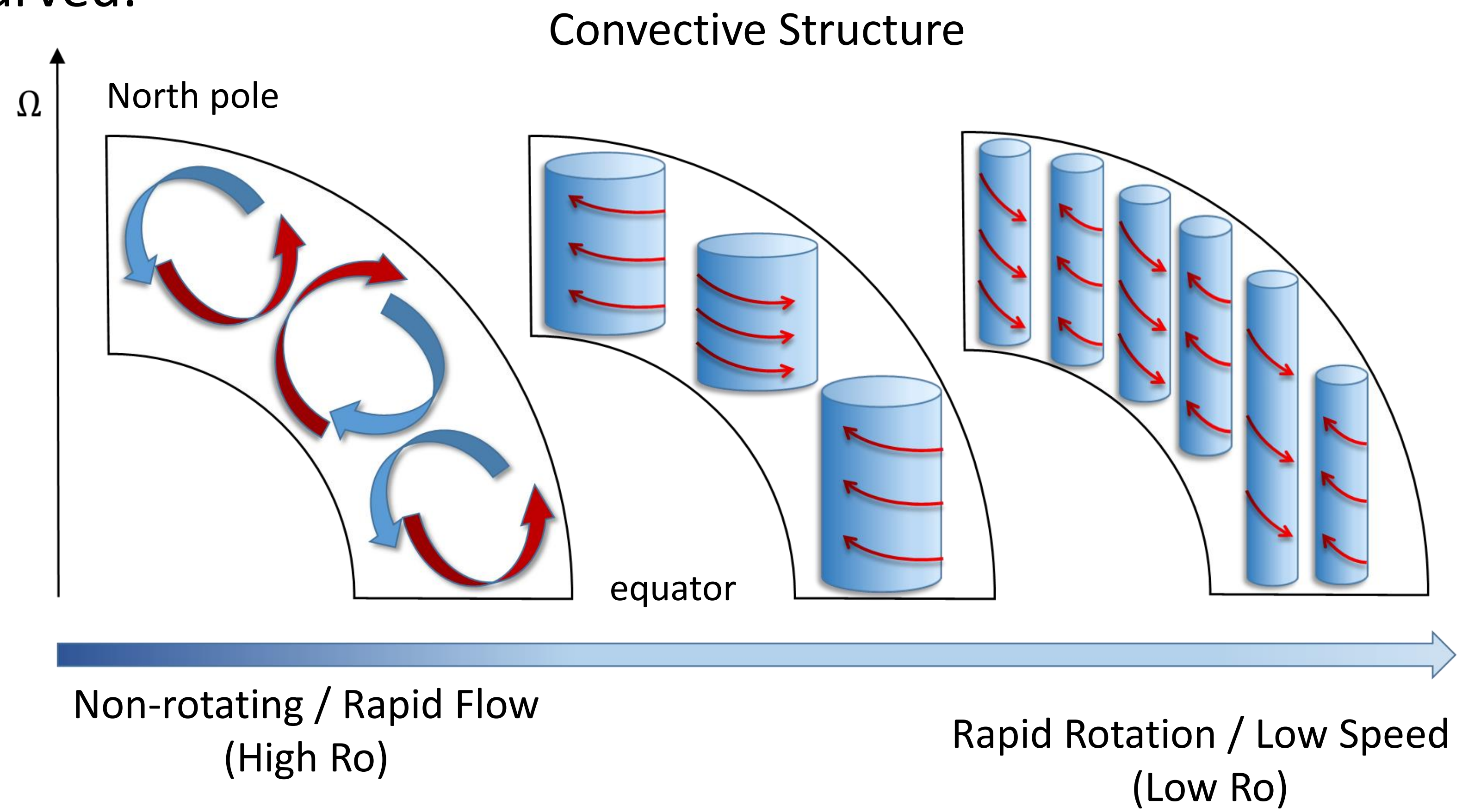
$$r_{gyro} \approx L\ Ro$$

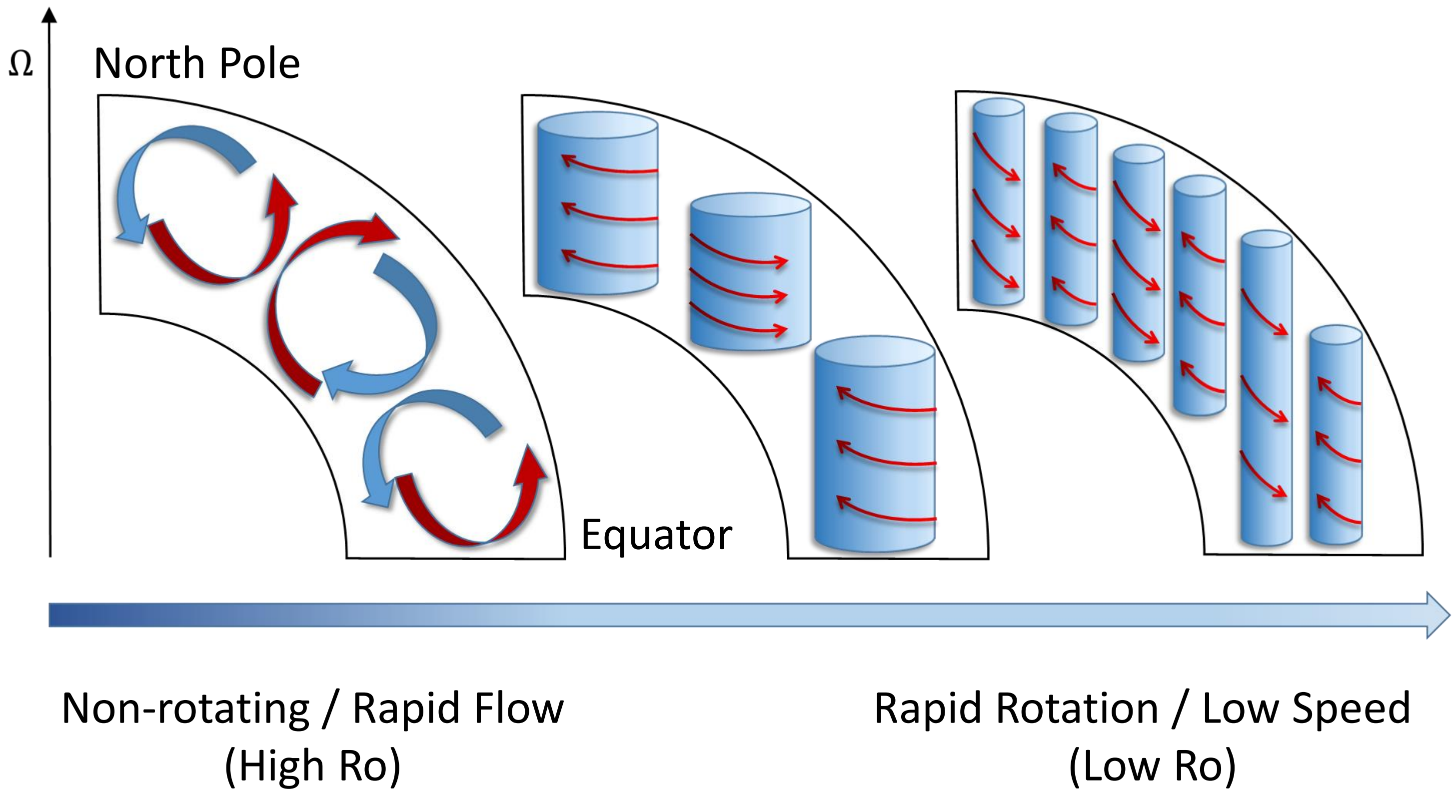
The Coriolis Force, the Rossby Number & Everything

- Two important effects :
  1. Structures align with rotation axis
  2. Fluid motions become curved:

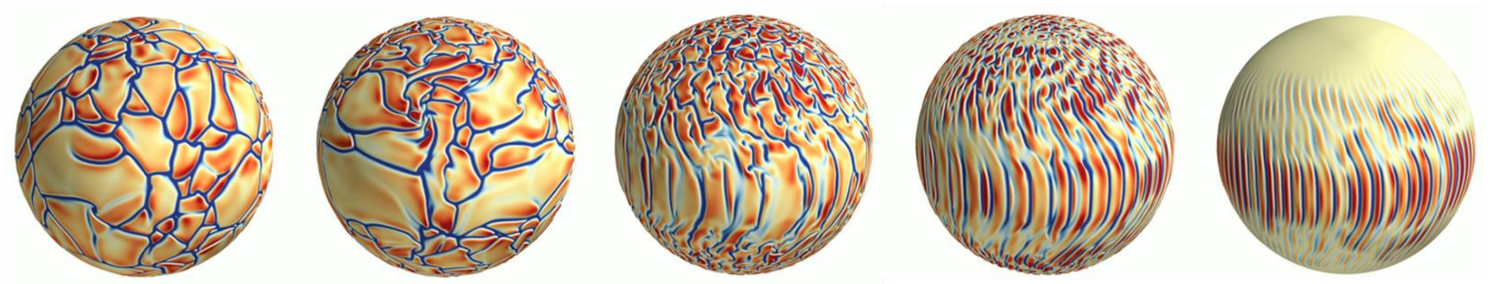
$$r_{gyro} = \frac{v}{2\Omega} \approx L\, Ro$$

- So what do we expect?



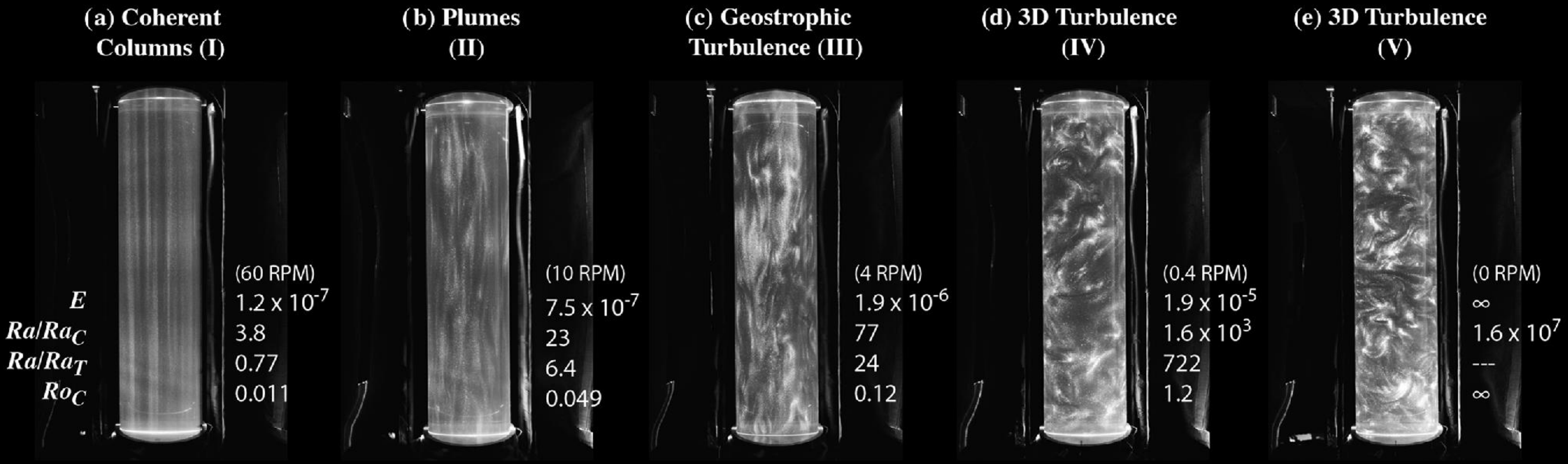


OK, but wasn't this really just a bunch of "twiddle algebra?"



Fully 3-D, nonlinear numerical models bear this out.

Not Just Theoretical Musing!   Experimental Results...

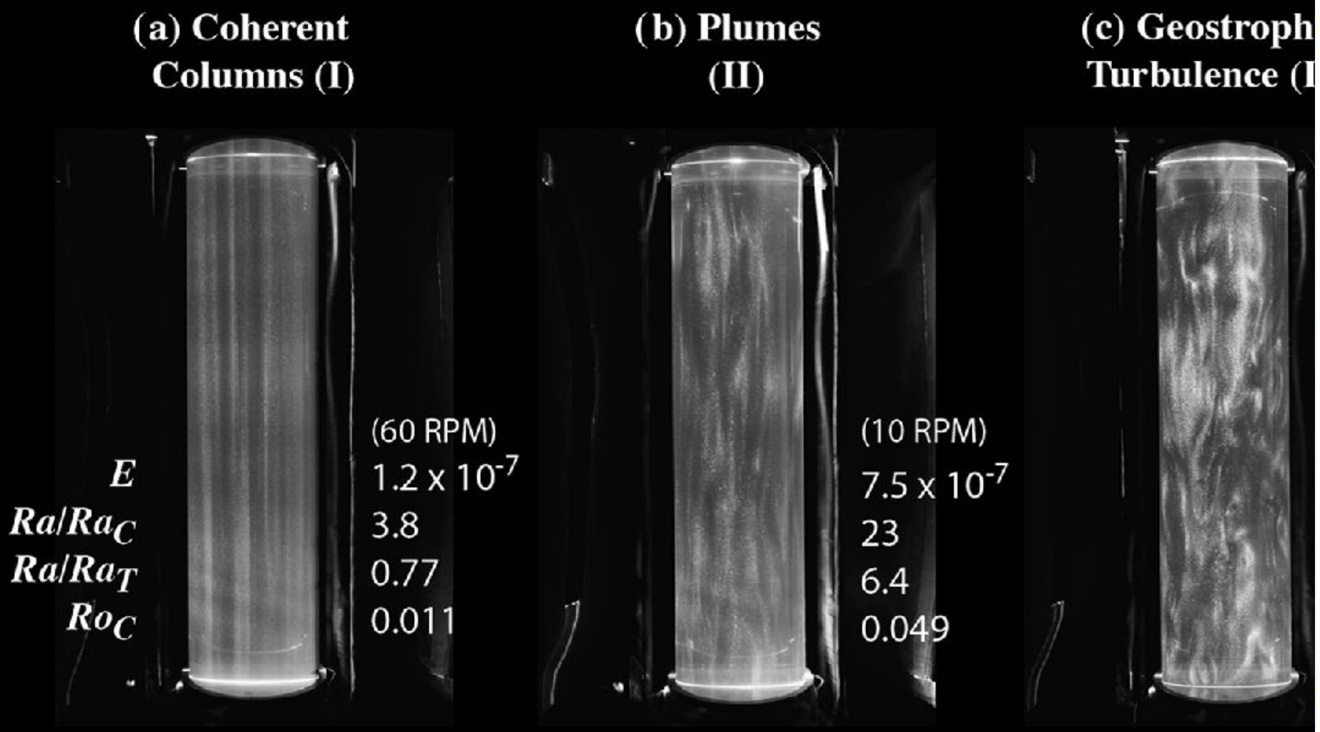


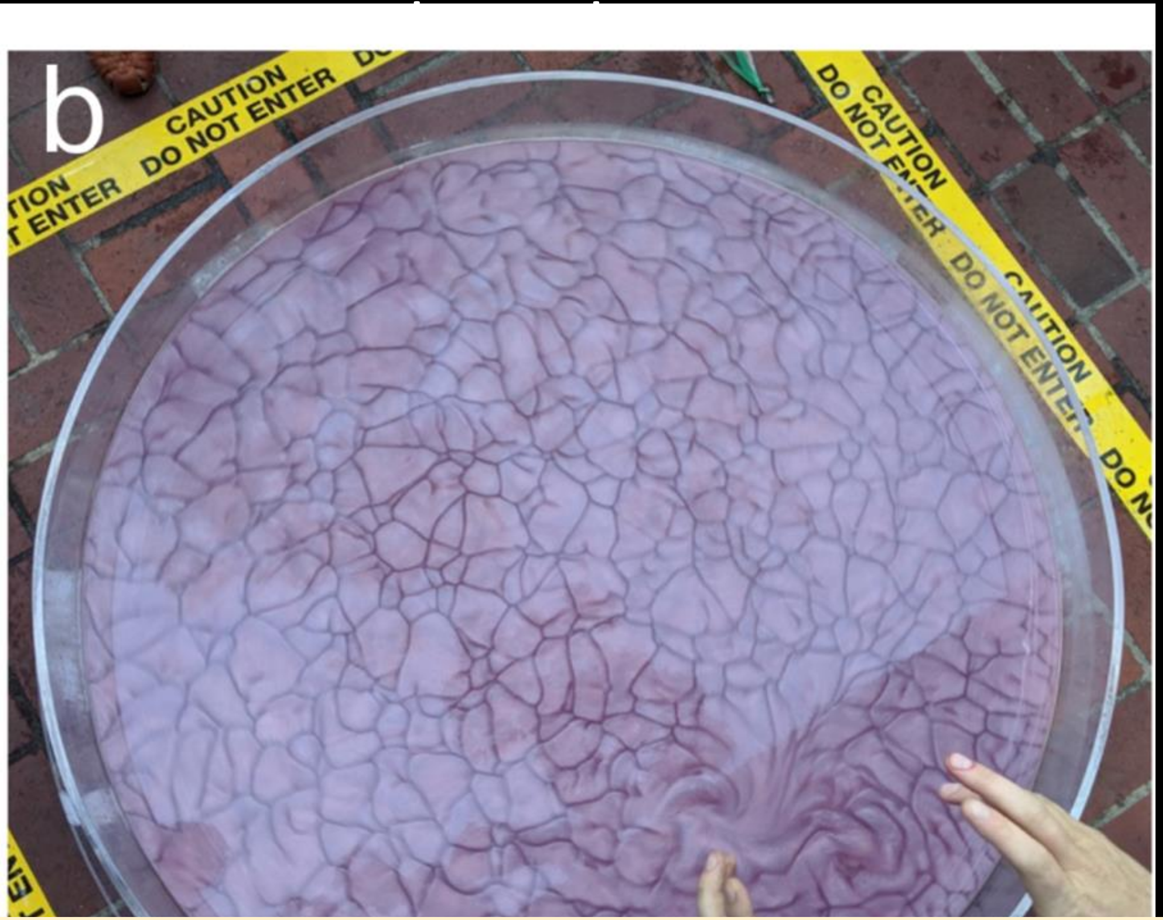
Cheng et al., 2015, GJI, 201,1   NoMag Experiment, SpinLab UCLA

rapid rotation / columnar cells

no rotation / Isotropic turbulence

Not Just Theoretical Musing!





Jon Aurnou
UCLA/SpinLab
https://www.youtube.com/user/spinlabucla

Cheng et al., 2015, GJI, 201,1

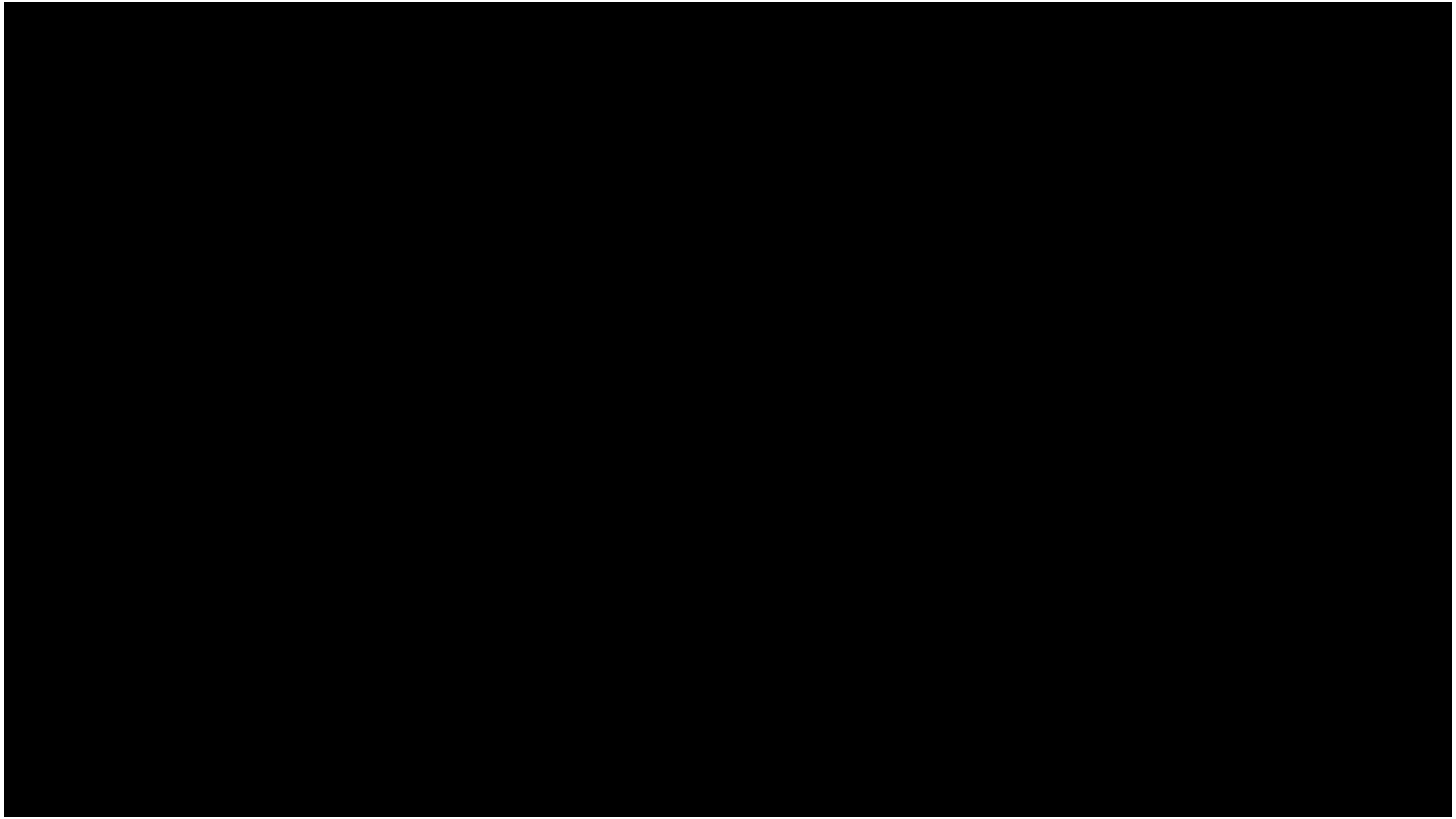
rapid rotation / columnar cells

no rotation / Isotropic turbulence

Flow Patterns at Different Rotation Rates (red upflow, blue downflow)

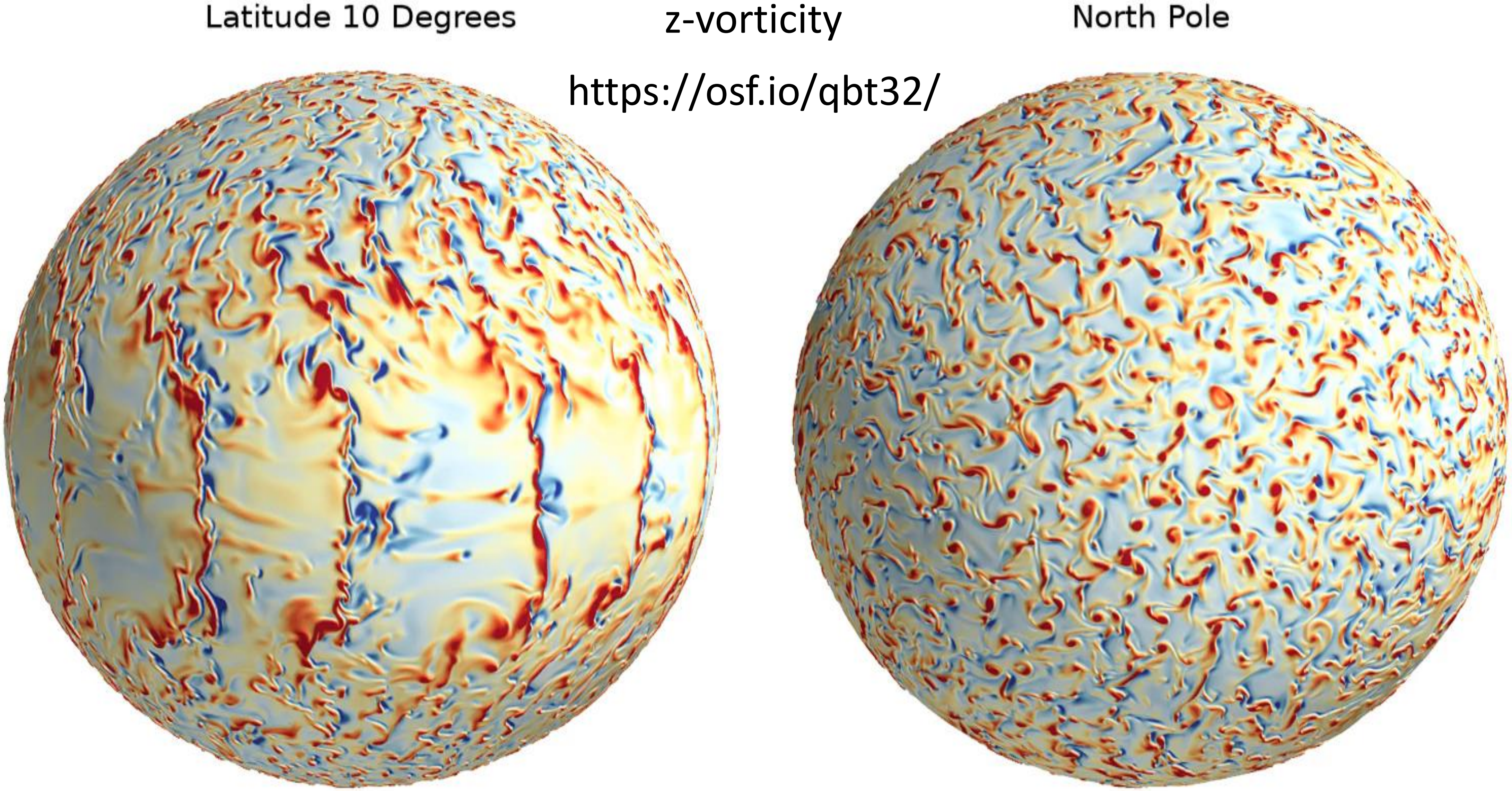
"Giant Cells"

"Banana Cells"



https://youtu.be/3iRggdo3i0I (www.youtube.com/feathern24) z-vorticity

https://osf.io/qbt32/



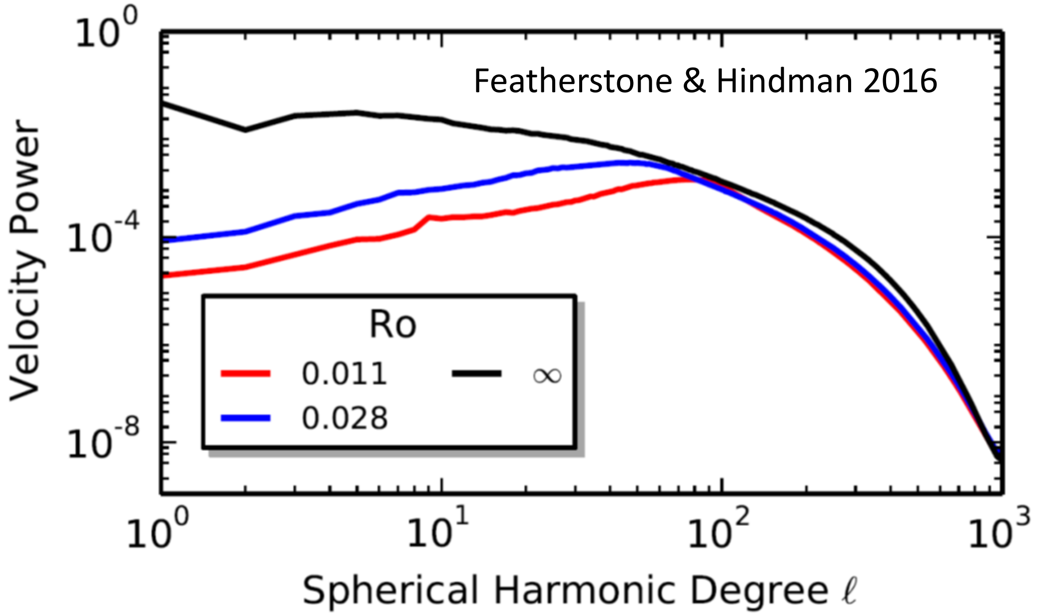
Hindman et al. 2020
Model #47
Antisolar/Polar Plumes

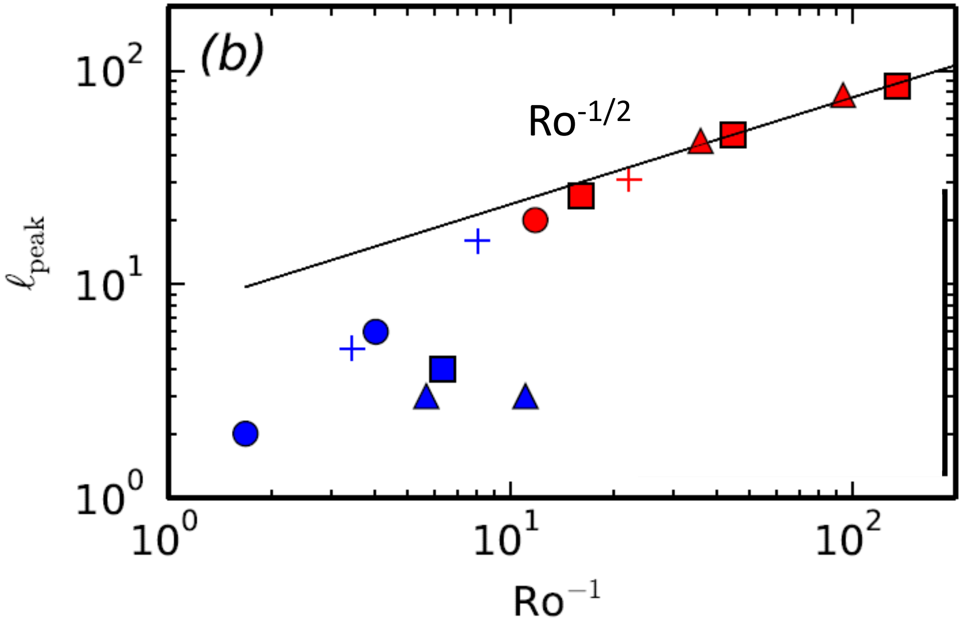
Rayleigh Number = 1.63×10^{7}
Ekman Number = 3.46×10^{-4}
Rossby Number = 4.62×10^{-2}

CCW — Clockwise

$r/r_{top} = 0.967$

Scaling of Spectral Peak

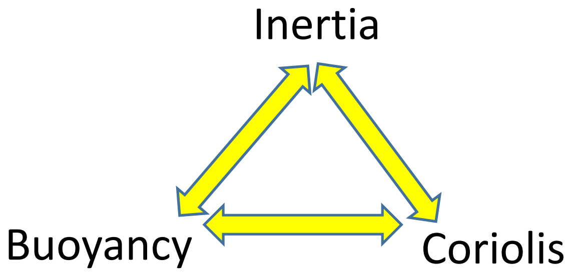




- Change in spatial scale apparent in spectra
- Ro dependent
- Look at peak spectral power vs. Ro

$Ro^{-1/2}$ Scaling:

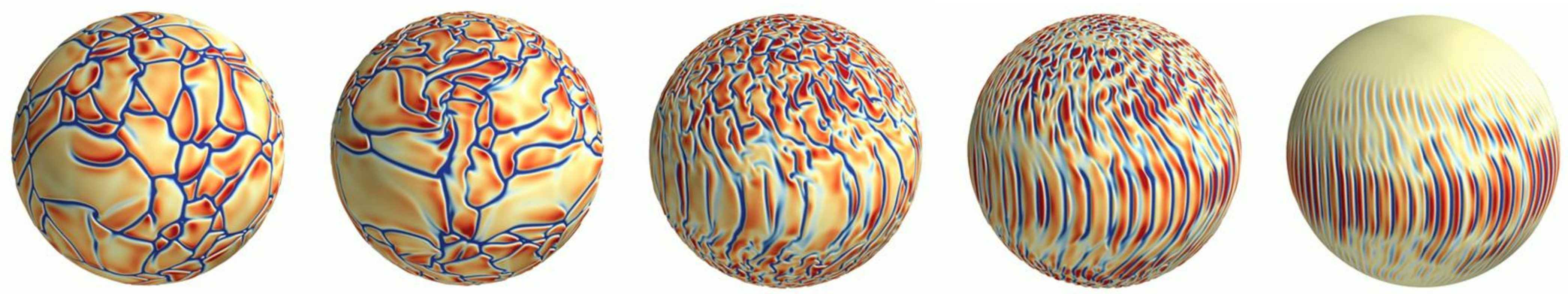
- Triple Force Balance
- Non-diffusive



Where is the Sun on this Spectrum of Behavior?

Non-rotating / High Ro

Rapidly-rotating / Low Ro



Estimate the Rossby Number:

mean rotation period: 27 days

convective turnover time?

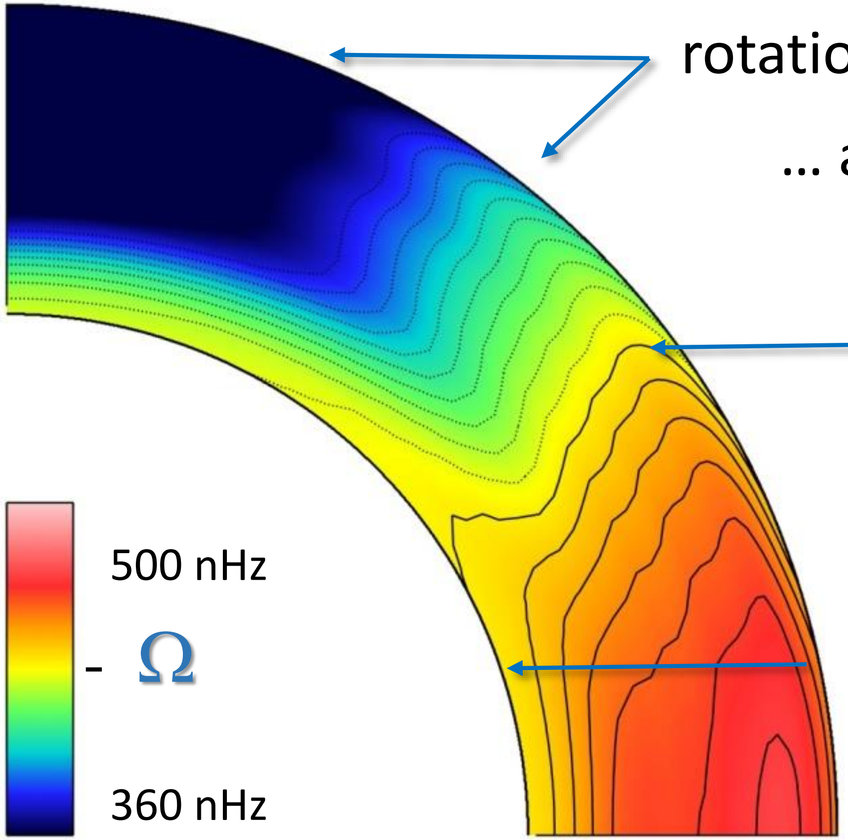
$$\tau_{conv} \approx 2\tau_{freefall} \approx 24\ days$$

$$Ro \approx 1$$

- Ballpark estimate only – lots of assumptions
- Still, rotation matters – Sun not at extrema
- Probably more to the right than the left
- ....Why?

Solar Differential Rotation

North Pole
(30 days)



rotation rate varies in latitude…

… and also in radius

near surface shear layer
(differential rotation weakens near photosphere)

Tachocline
(transition to solid-body interior in radiative zone)

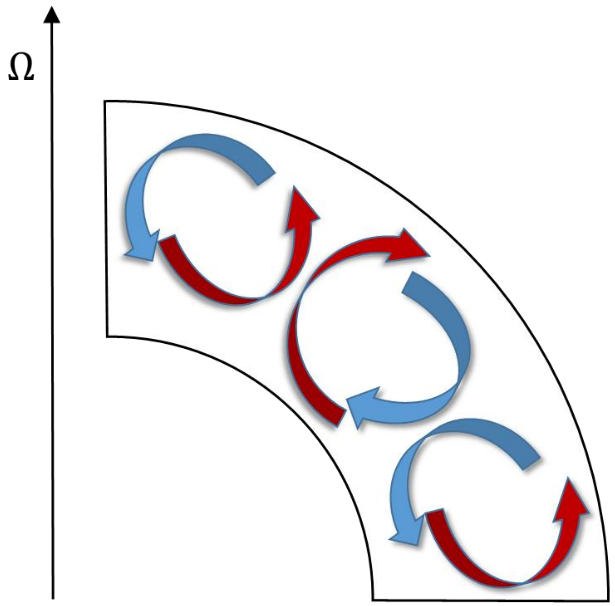
Equator
(24 days)

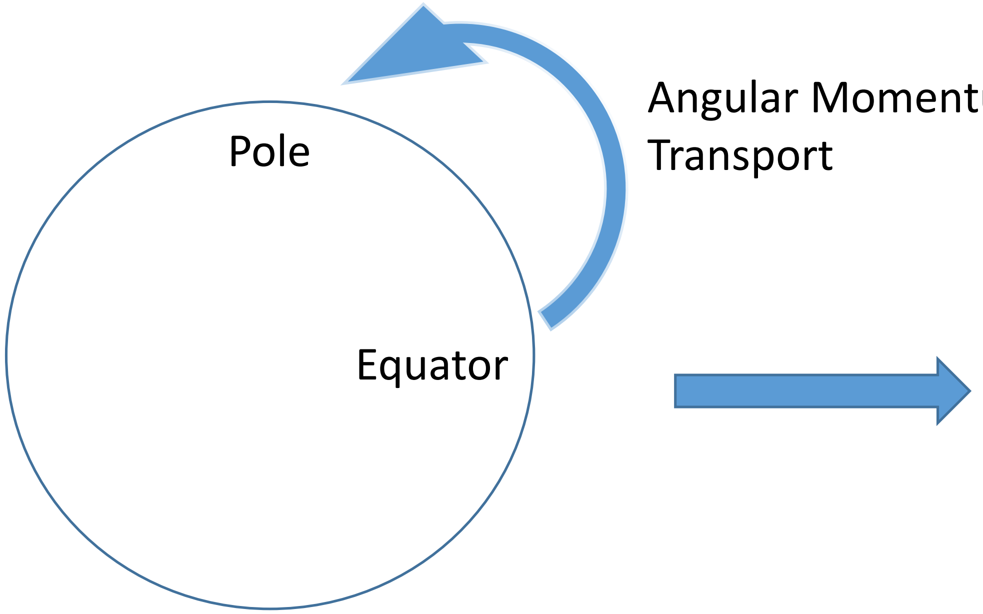
Howe et al. 2000;
Schou et al. 2002

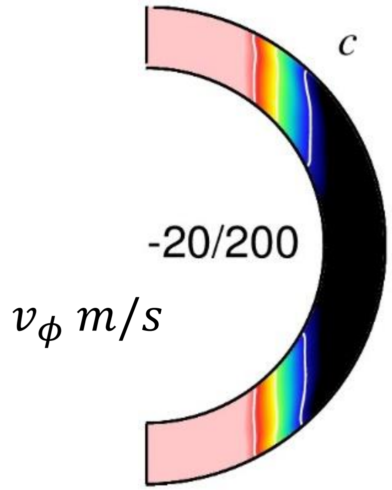
Opposite of what is expected if Coriolis force is weak (high Ro) … why?

Antisolar Differential Rotation

- Isotropic convection will try to mix (homogenize) angular momentum
- Star with solid-body rotation.
- Angular momentum is highest at the equator. Lowest at pole.
- Poles spin up. Equator spins down.
- Need a source of anisotropic transport to break this pattern.



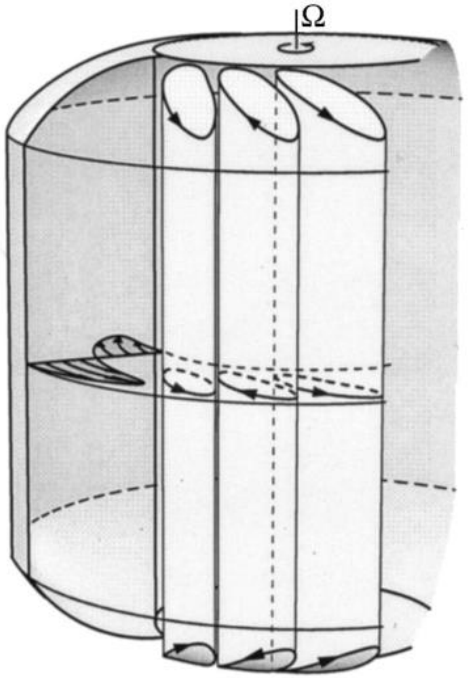




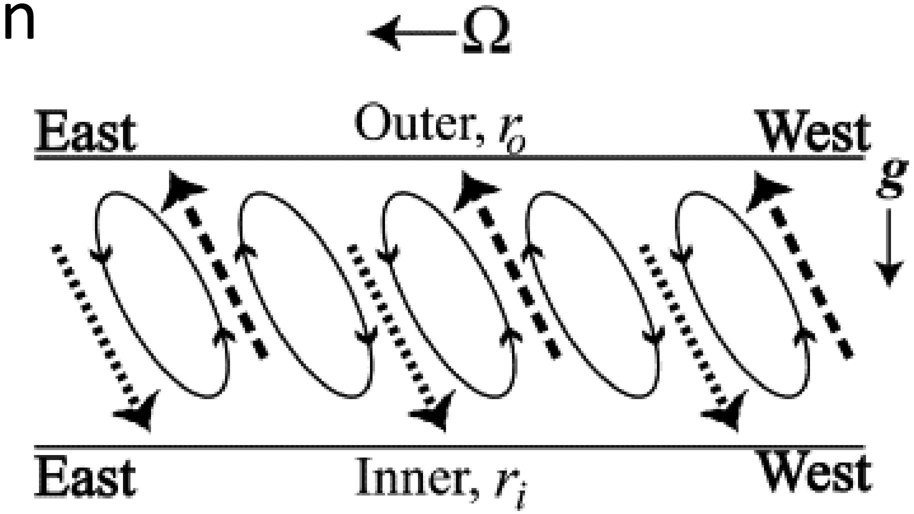
Rotating Frame

Solar-like Differential Rotation

- In this state, angular momentum IS NOT homogenized.
- At low Ro, convection takes on columnar aspect.
- Columns drift and tilt in prograde sense.
- Transfers angular momentum away from rotation axis.
- From this, we infer that Coriolis forces impact solar convection

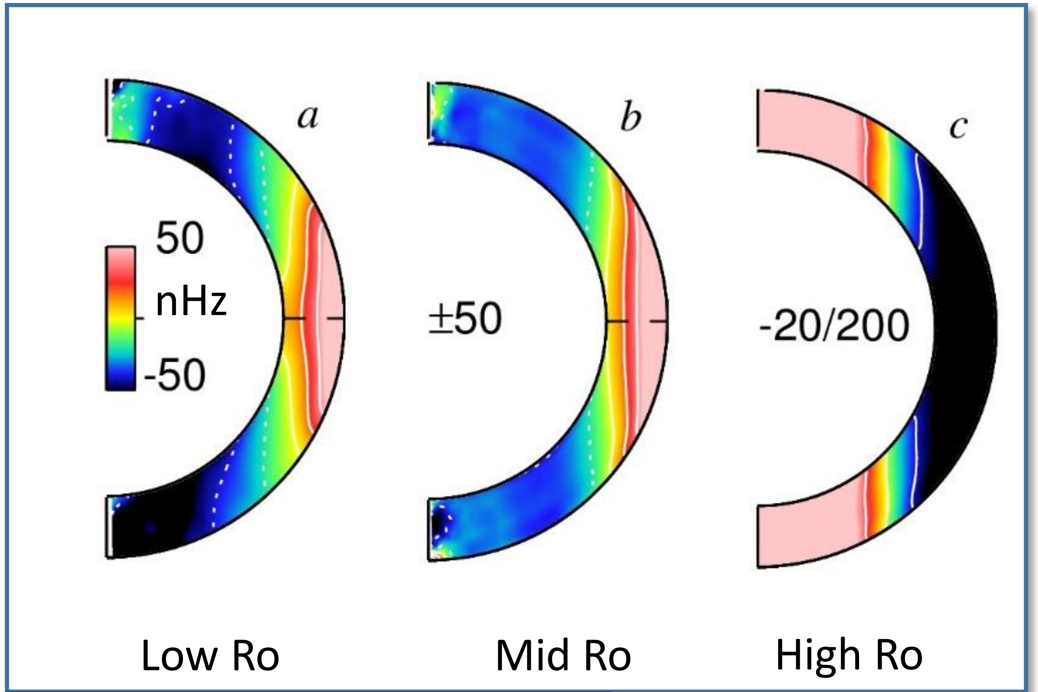


Busse, F.H., 2002, Physics of Fluids **14**, 1301



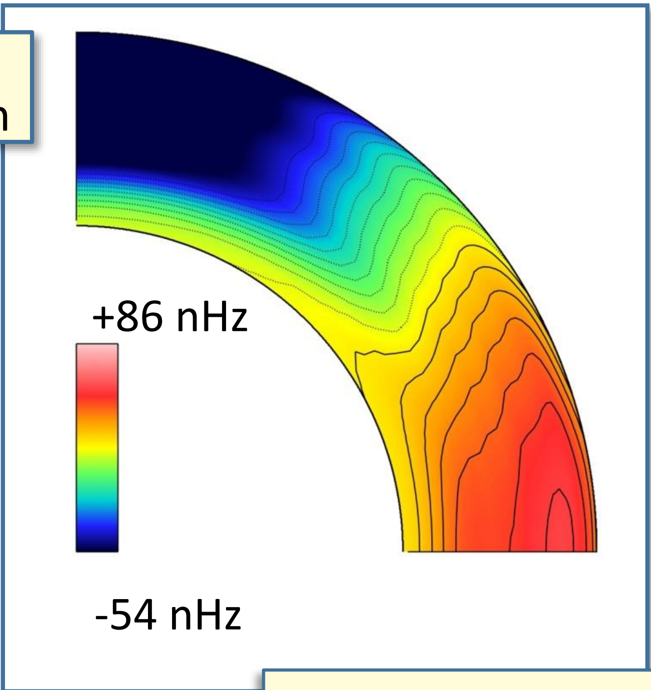
Aurnou et al. 2007, Icarus, 190, 110

Differential Rotation and Rossby Number



Models
Featherstone & Miesch 2015

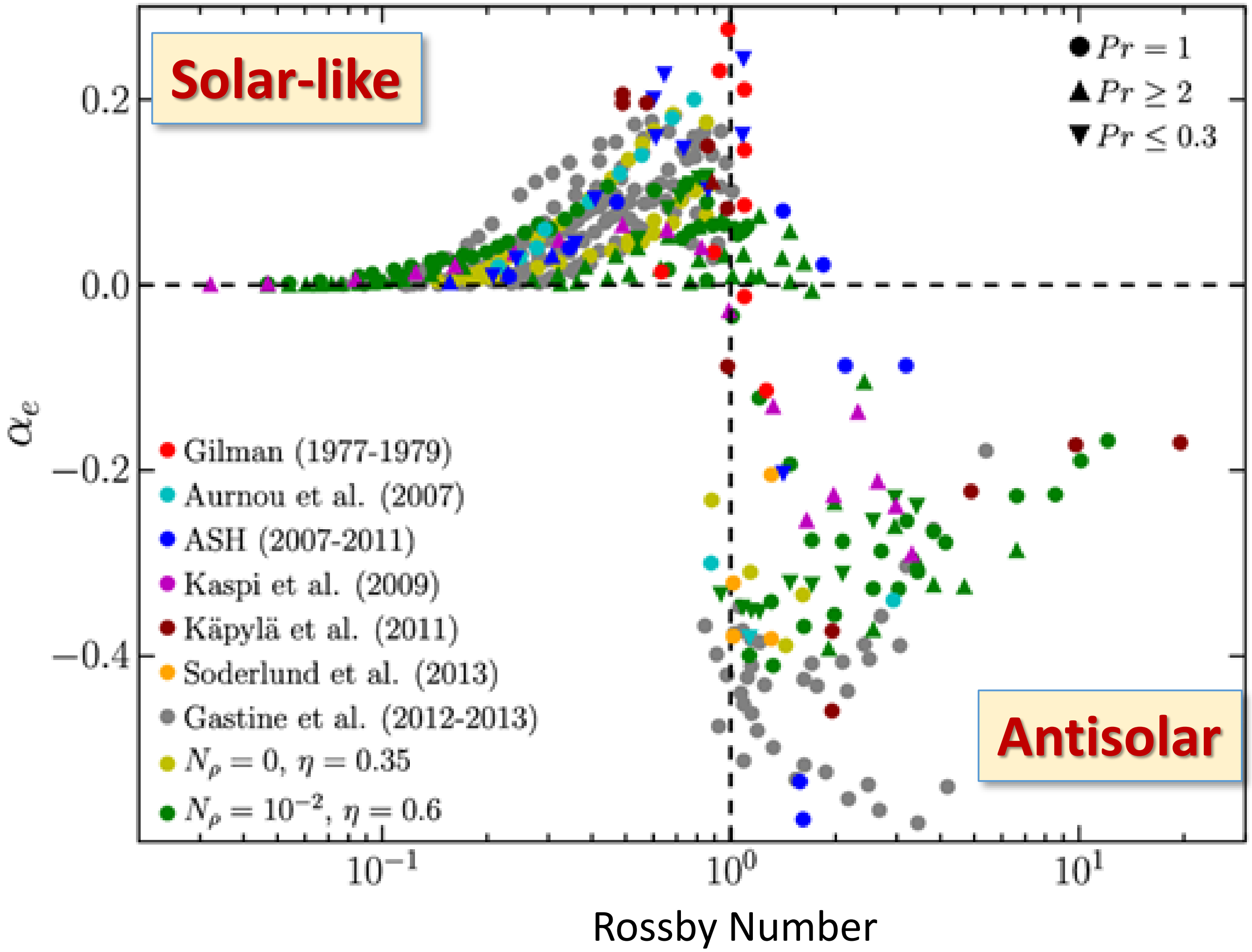
$\Omega - \Omega_{sun}$



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 …

Robust, Systematic Trend



Ro = 1 delineates a clear transition in behavior.

Can use this to check our earlier assumptions.

From solar-like to antisolar differential rotation in cool stars

Gastine et al., 2013, MRNAS Lett. , 438, Issue 1, 11

Temperature Perturbation

- Recall that we assumed T' was roughly 1 K.
- Idea based on 1 =Ro_c as transition point
  - Measure a star's rotation rate
  - Measure a star's spectral type (to get CZ depth)
  - Classify a star's differential rotation and bound temperature fluctuations.
- EXAMPLE:
  - g at mid CZ is 379.3 m s^{-2}
  - T at mid CZ is 9.6×10^5 K (alpha = 1/T)
  - The Sun has a solar-like differential rotation.
  - Therefore:

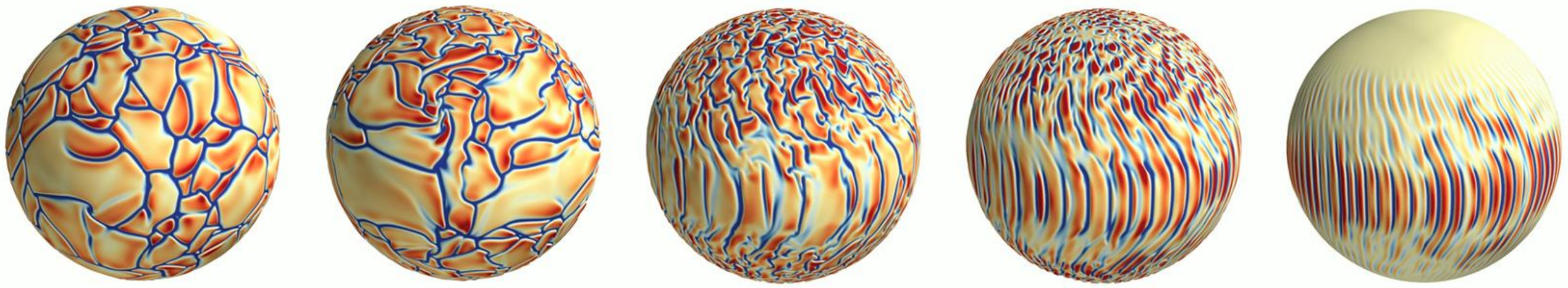
$$\frac{1}{\Omega}\sqrt{\frac{g \propto T'}{L}} \leq 1 \qquad\qquad T' \leq \frac{\Omega^2 L T}{g} \approx 3.6\ \mathrm{K}$$

Implications for the Dynamo

Where is the Sun on this Spectrum of Behavior?

Non-rotating / High Ro

Rapidly-rotating / Low Ro



... and why do we care?

The MHD Induction Equation

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

compression

shear production

advection

diffusion

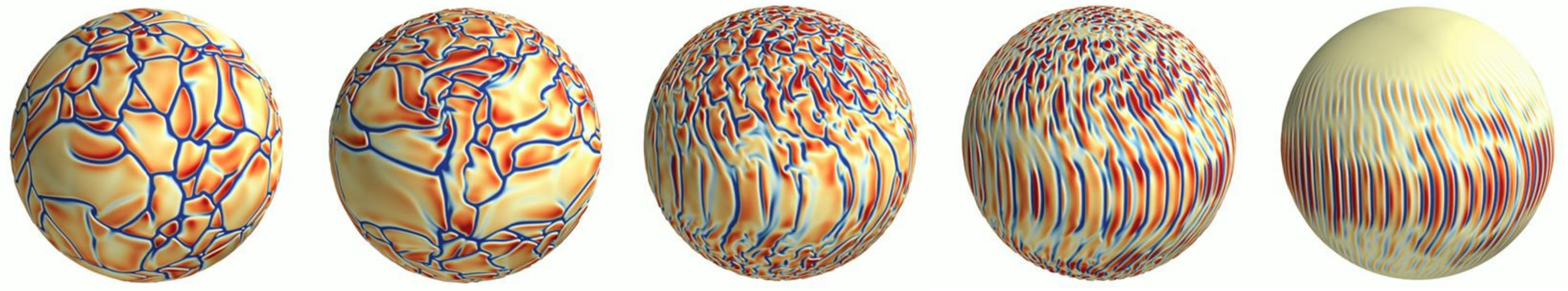
Rotation → shear production

Rotation → Large-Scale Shear (differential rotation)

Rotation → Small-Scale Shear (helical rolls)

Convection Models

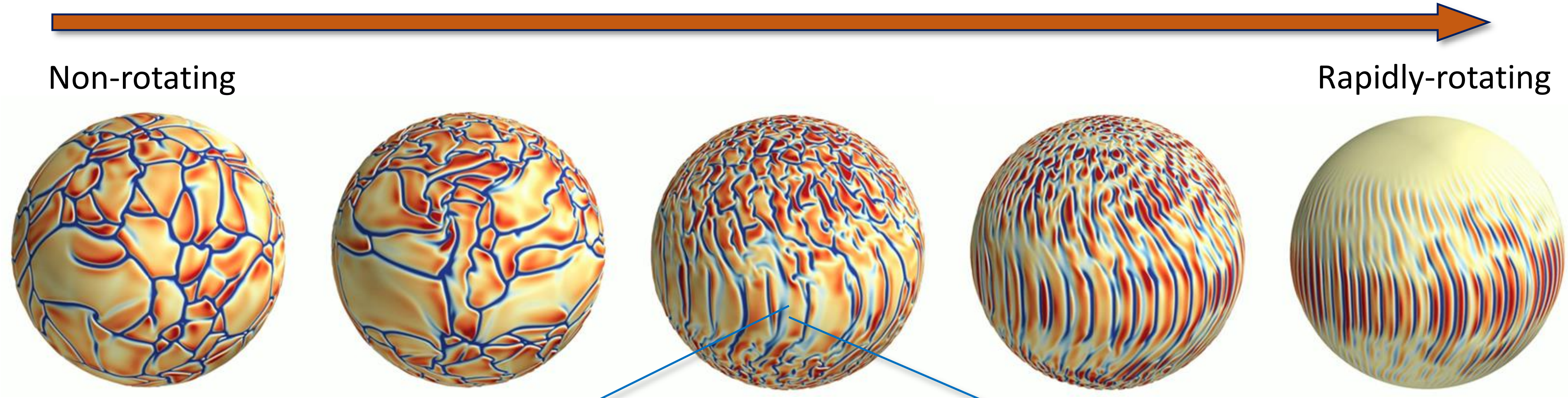
Non-rotating → Rapidly-rotating

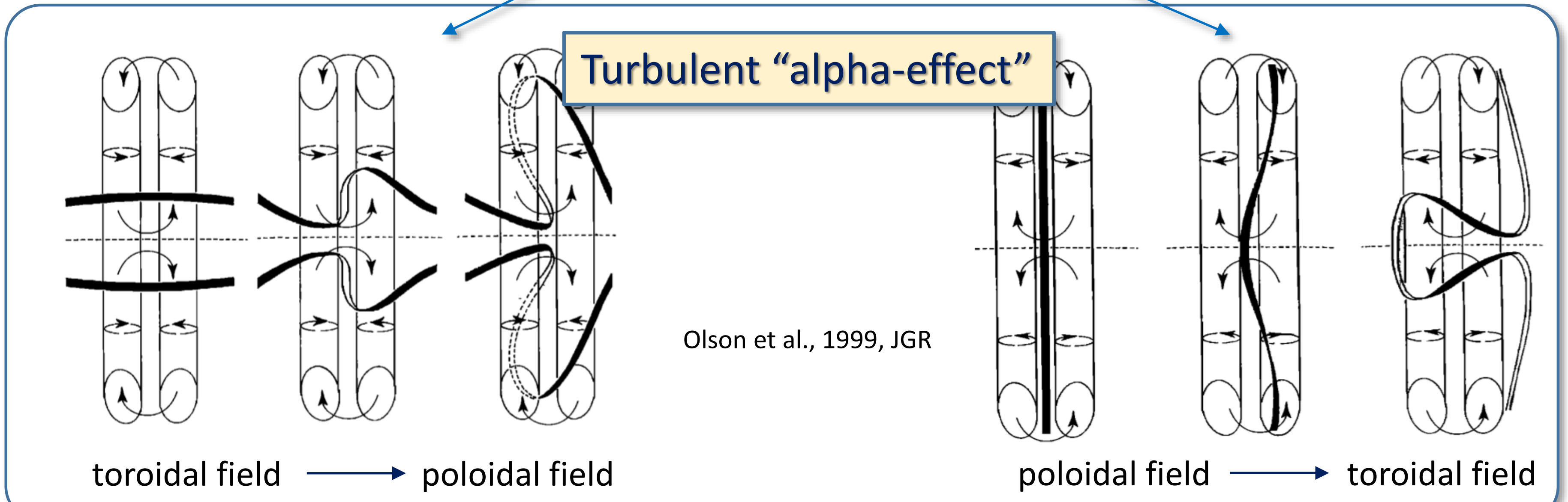


red upflow

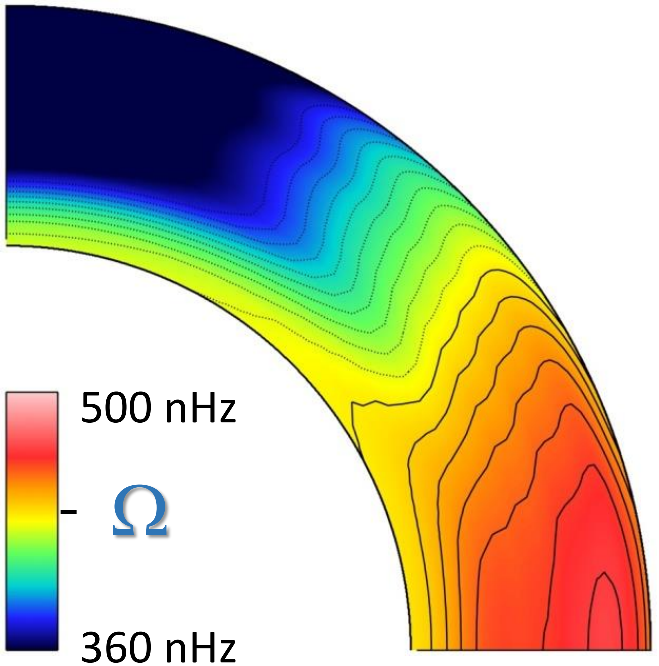
blue downflow

Rotation Yields Helical Convection



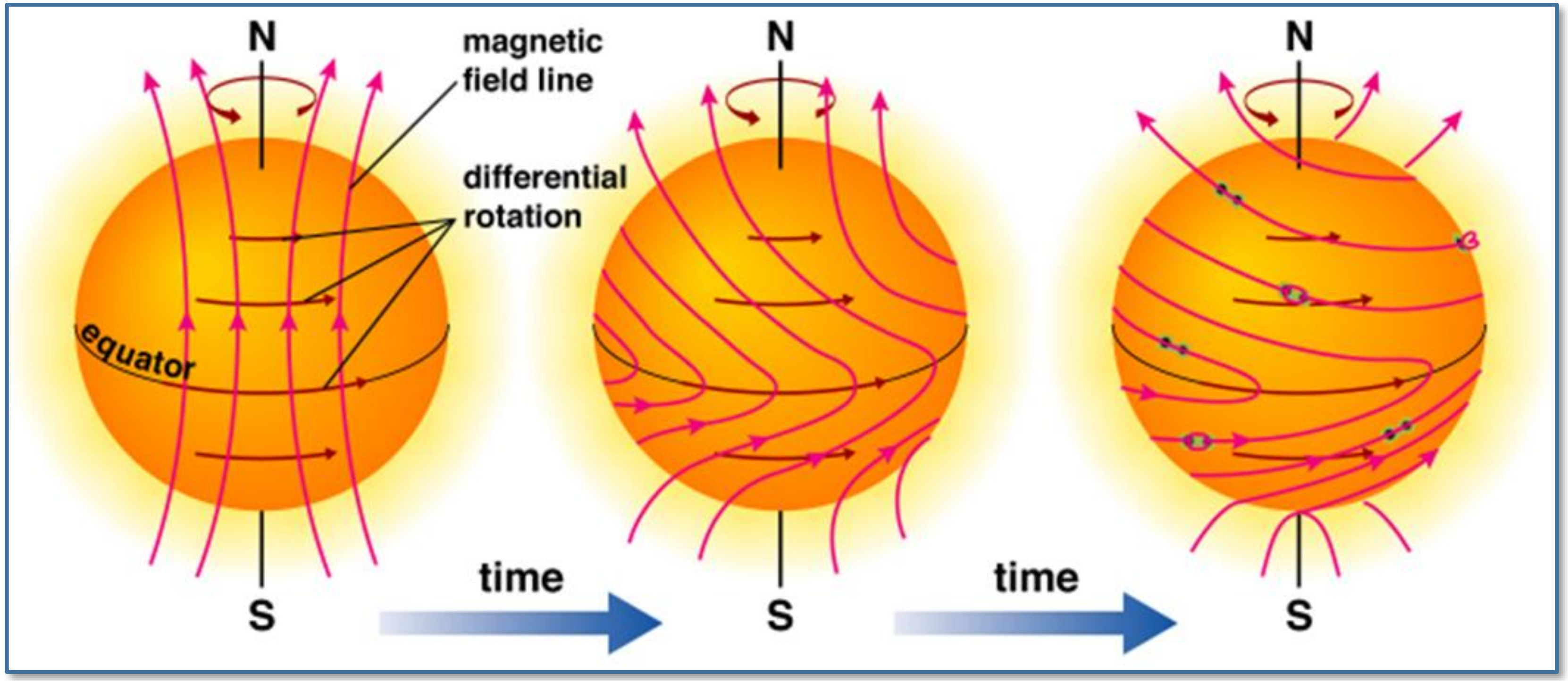


Helical Convection Yields Differential Rotation



Howe et al. 2000; Schou et al. 2002

“Omega effect”



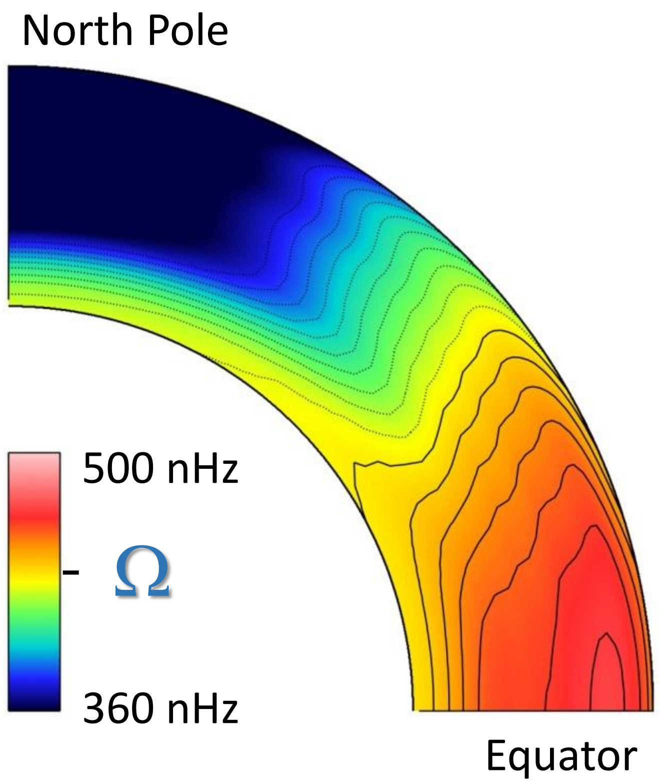
Bennett, et al. 2003

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

Shearing:

- Latitudindal
- Radial (Tachocline)

An Interface Dynamo?



Howe et al. 2000; Schou et al. 2002

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

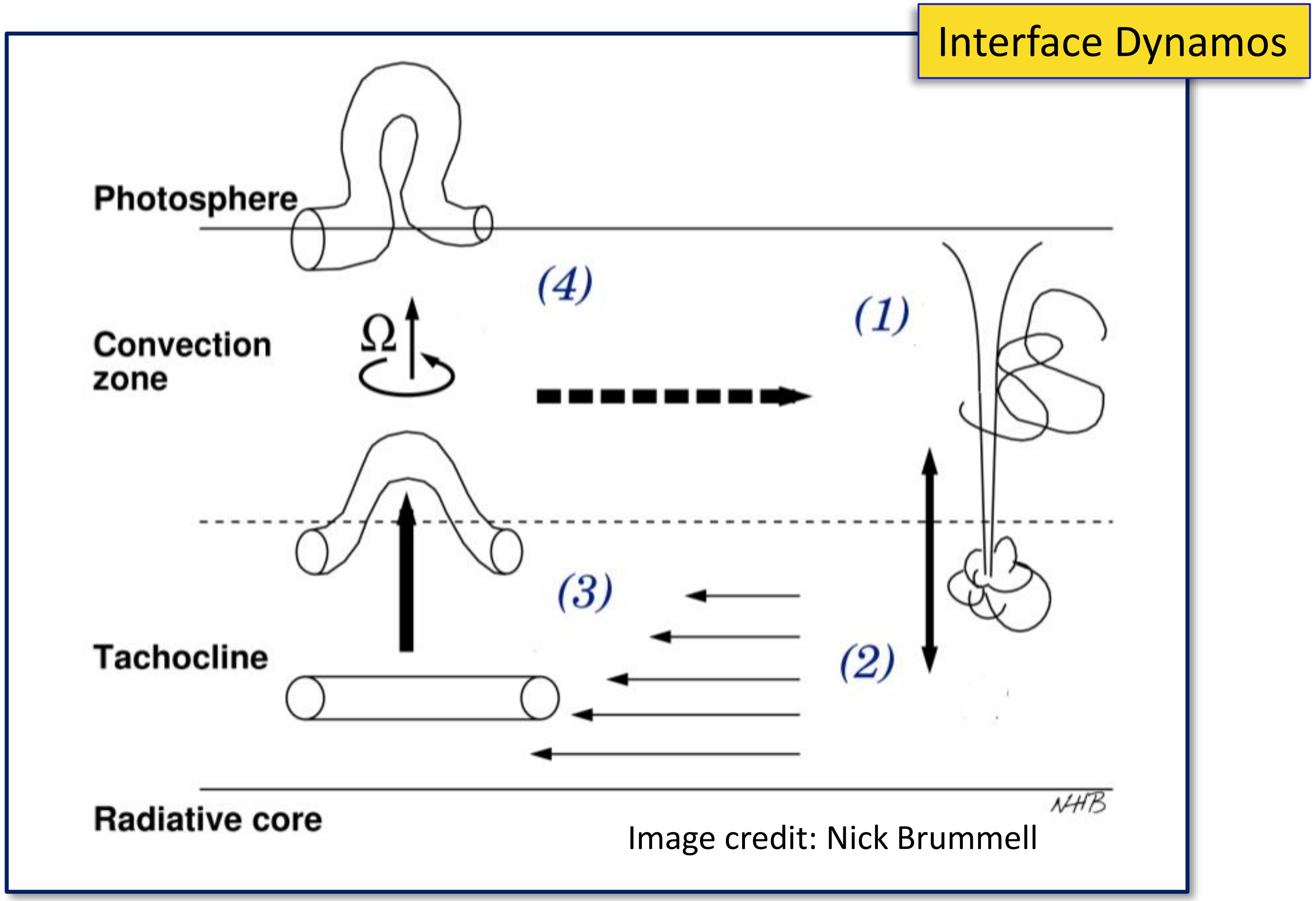
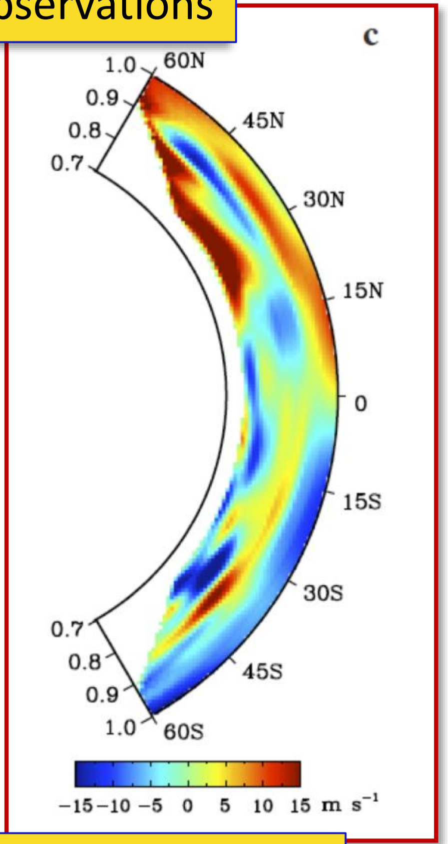


Image credit: Nick Brummell

- Does tachocline shear form the basis of the dynamo?
- Parker, 1993, ApJ, 408, 707

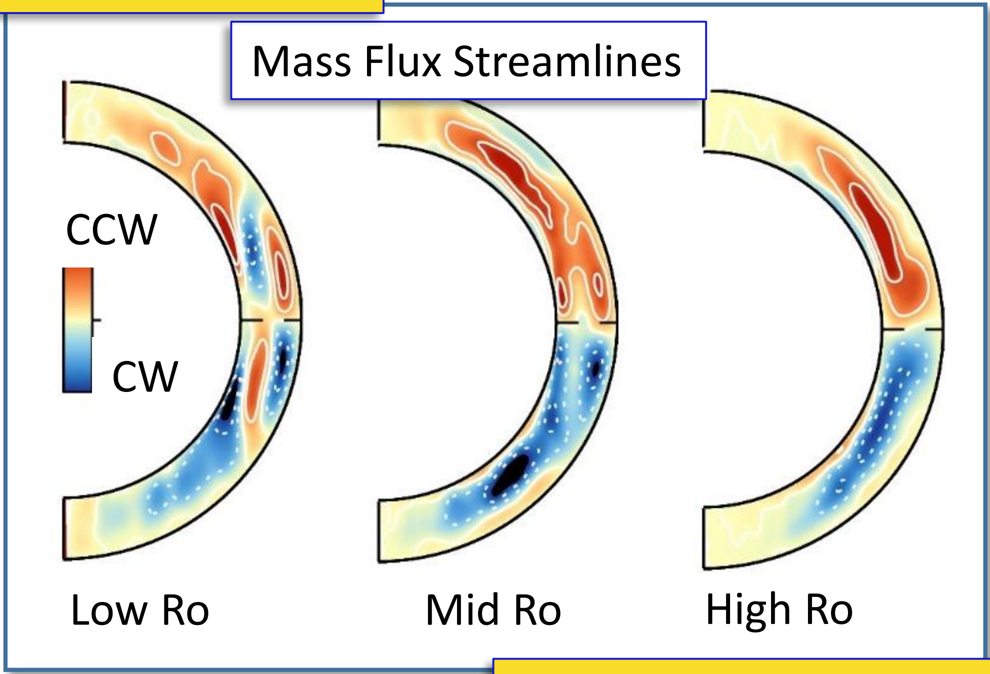
Convection Also Drives Meridional Circulation

Observations



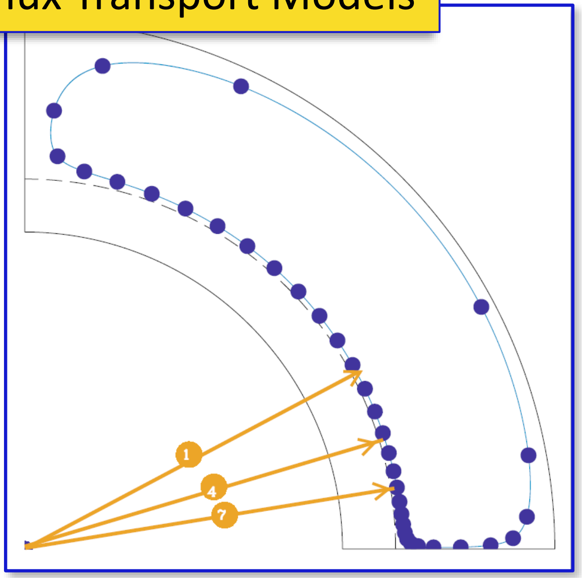
Zhao et al. 2012

Convection Models



Featherstone & Miesch 2015

Flux Transport Models

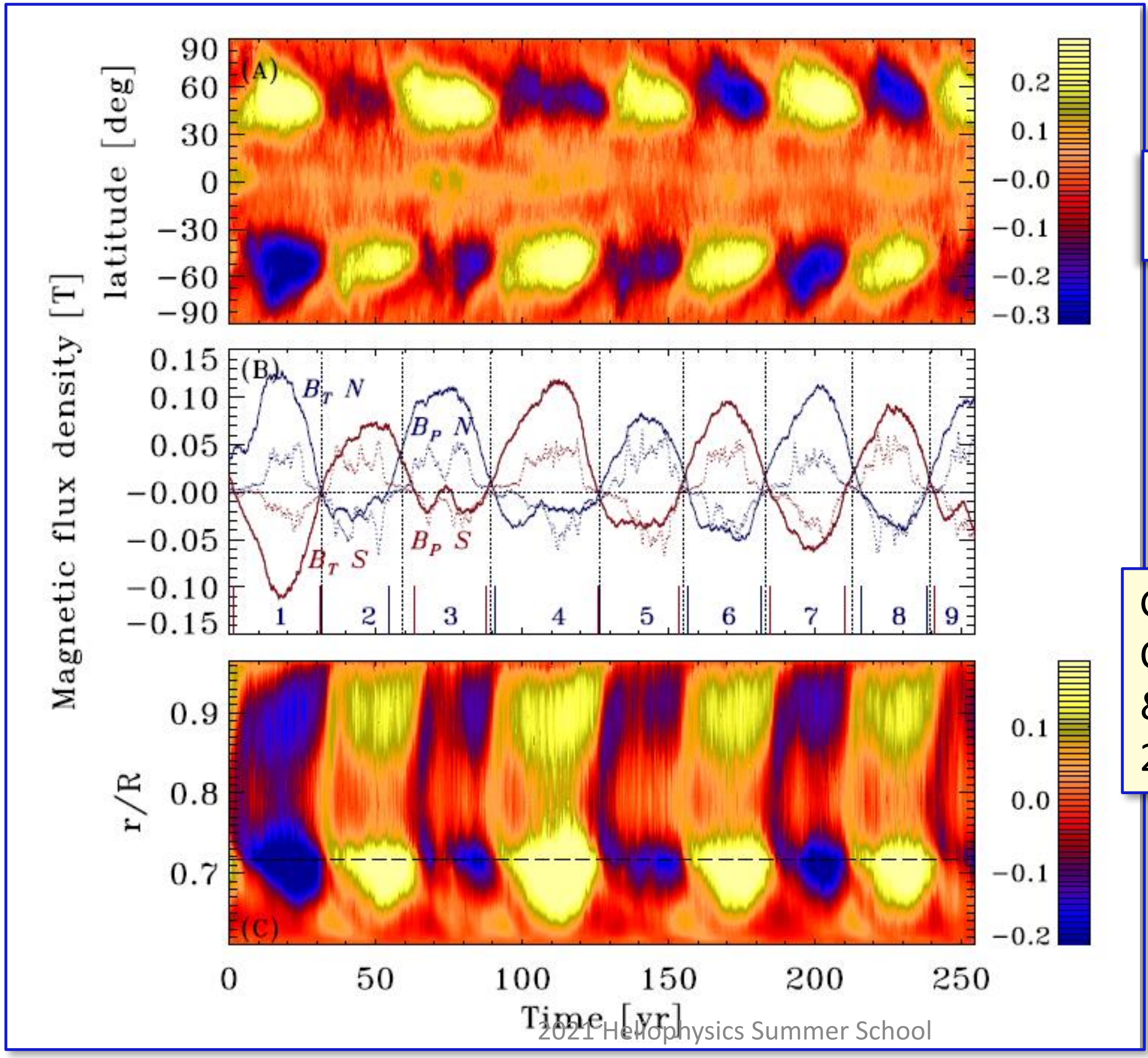


Dikpati & Gilman 2009

Cycle Timing?

More generally, the location of the Sun along the Rossby spectrum seems key to reproducing several aspects of the dynamo in models…

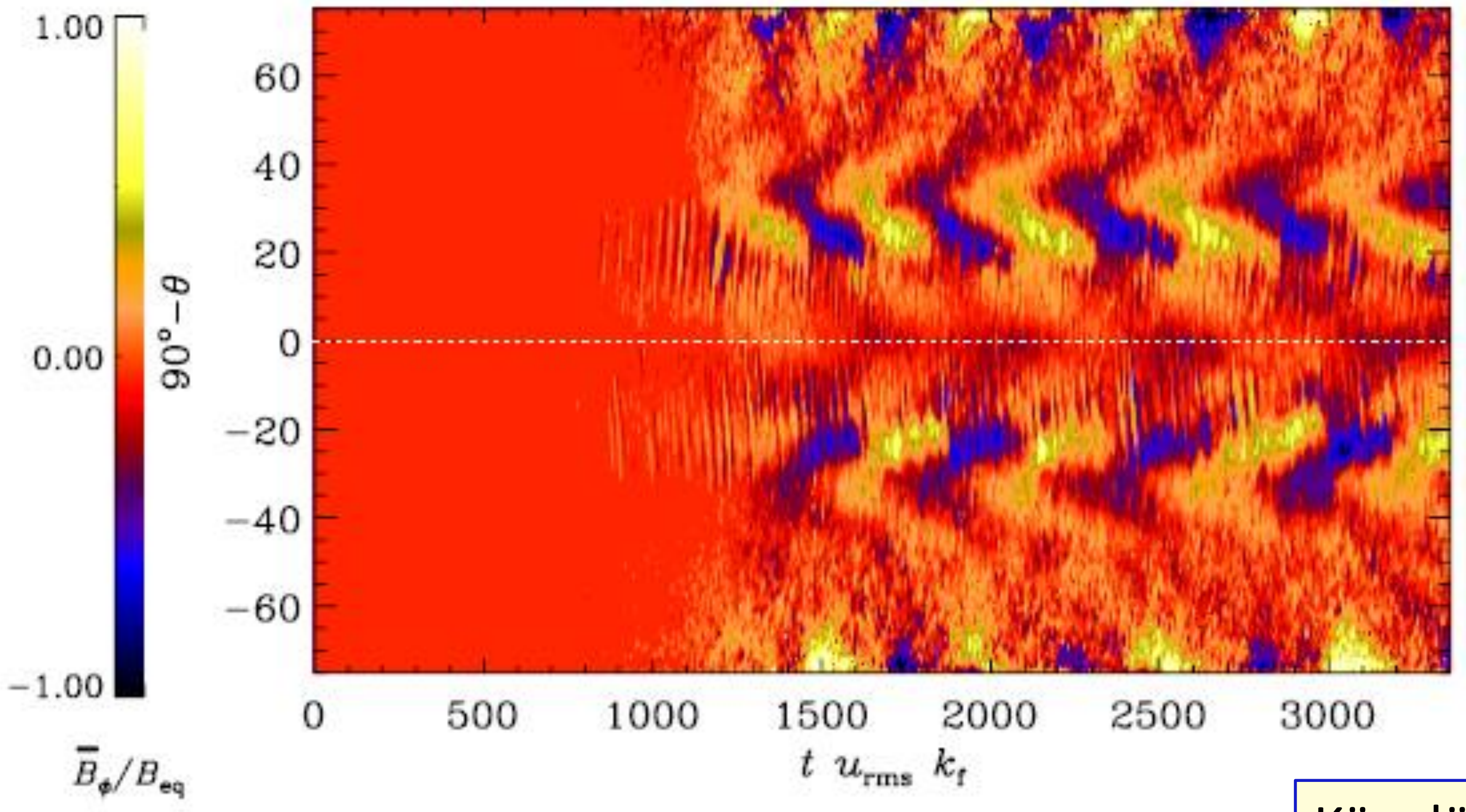
Models: Magnetic Cycles



Ro ≈ 0.01

Ghizaru, Charbonneau & Schmolarkiewicz 2010

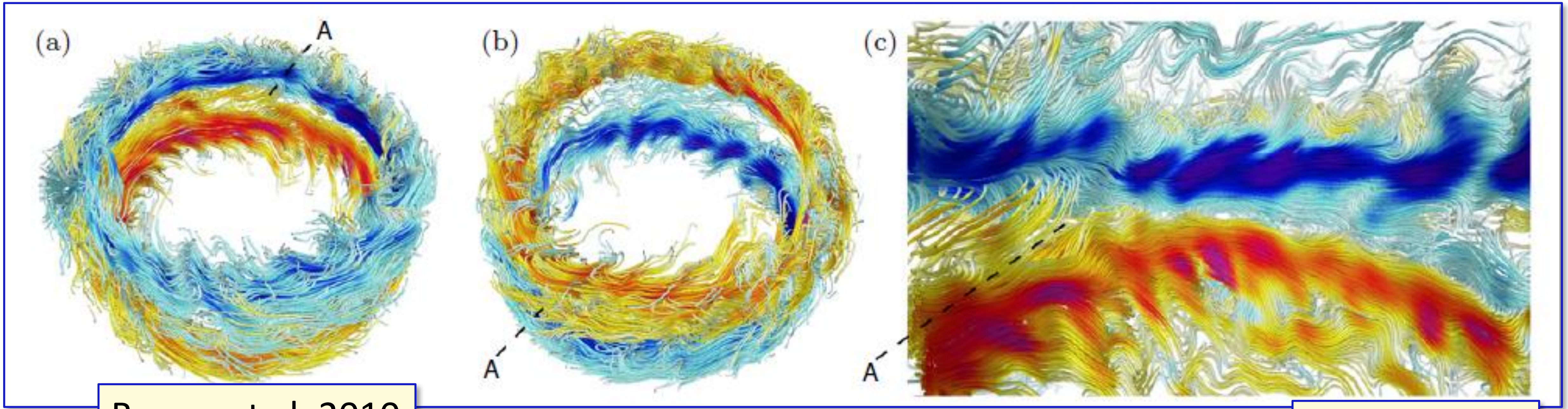
Models: Equatorward Propagation of Magnetic Features



Ro ≈ 0.02

Käpylä et al. 2013

Models: Large-Scale Magnetic Structure



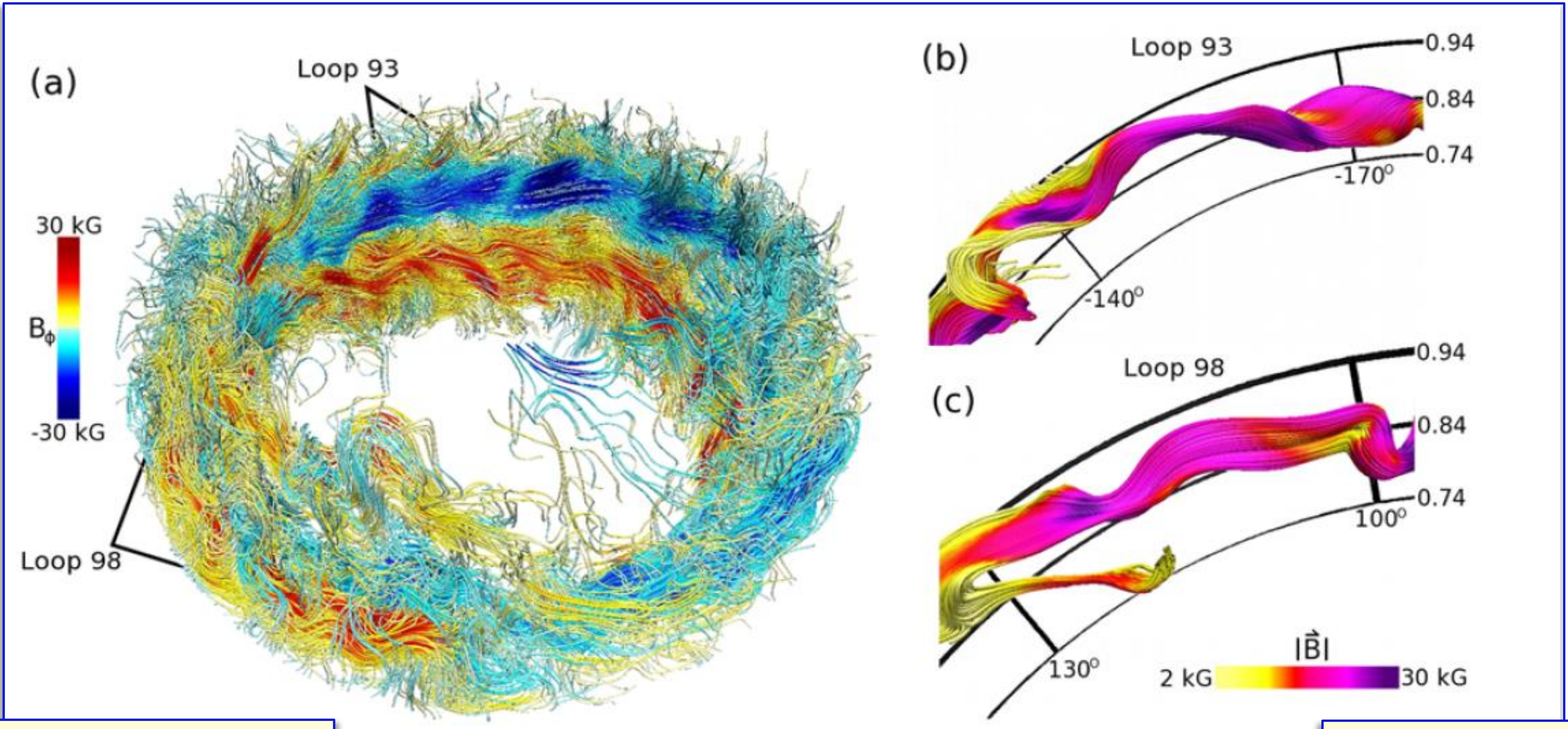
Brown et al. 2010

Ro ≈ 0.03

"wreathy" dynamos

- Possible alternative to interface dynamo?
- Possibly working in tandem?
- Driven roughly equally by Omega and turbulent alpha effects

Models: Buoyant Magnetic Loops



Nelson et al. 2014

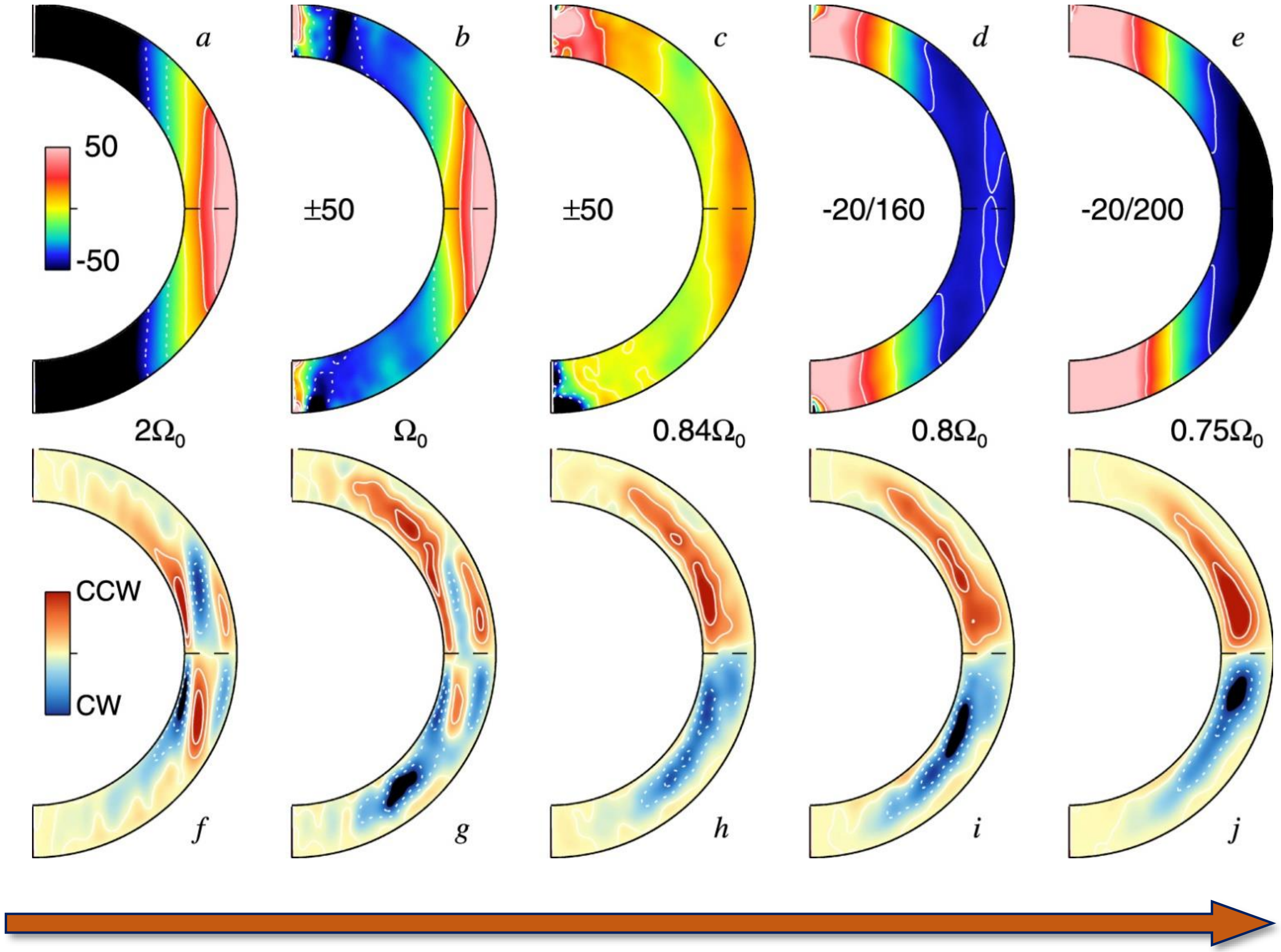
Ro ≈ 0.03

Where do we go from here?

Clues From Out of the Ecliptic?

Differential Rotation

Meridional Circulation



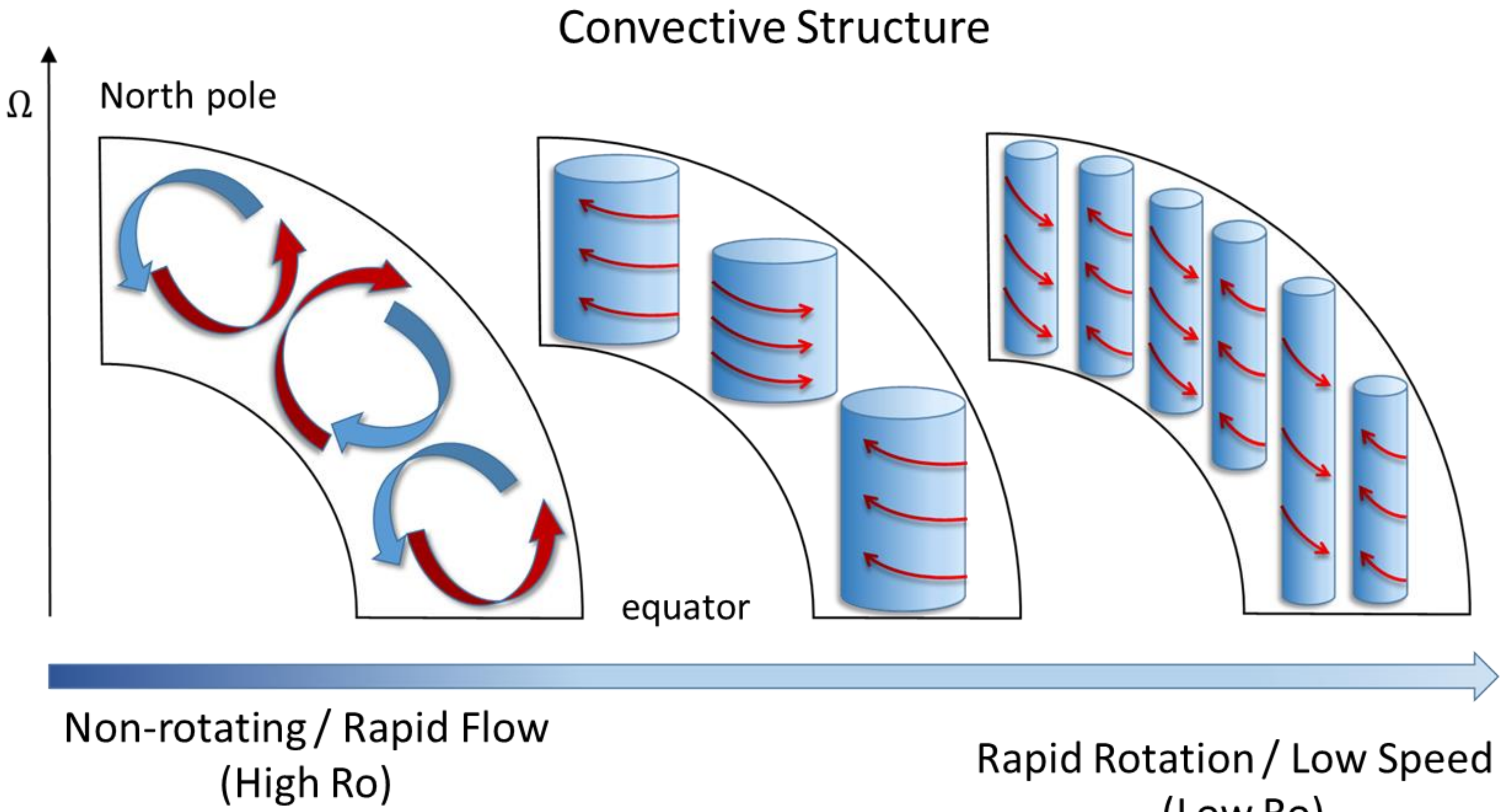
Is there a polar spinup?

What is the high-latitude structure of MC?

Rapidly rotating / low Ro

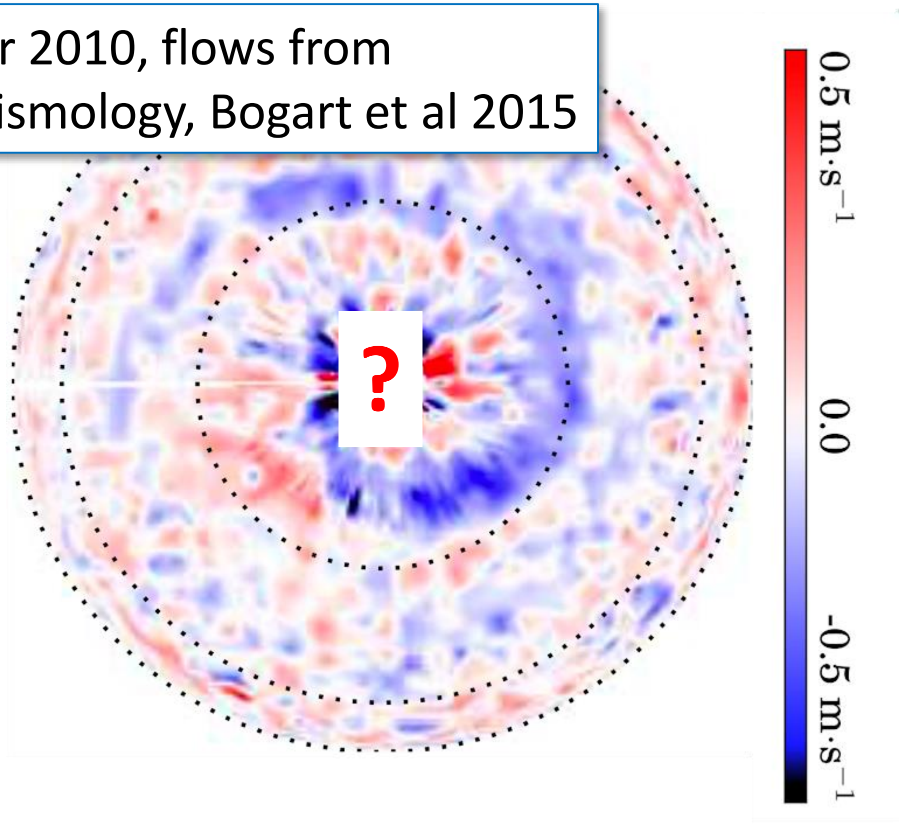
Slowly-rotating / high Ro

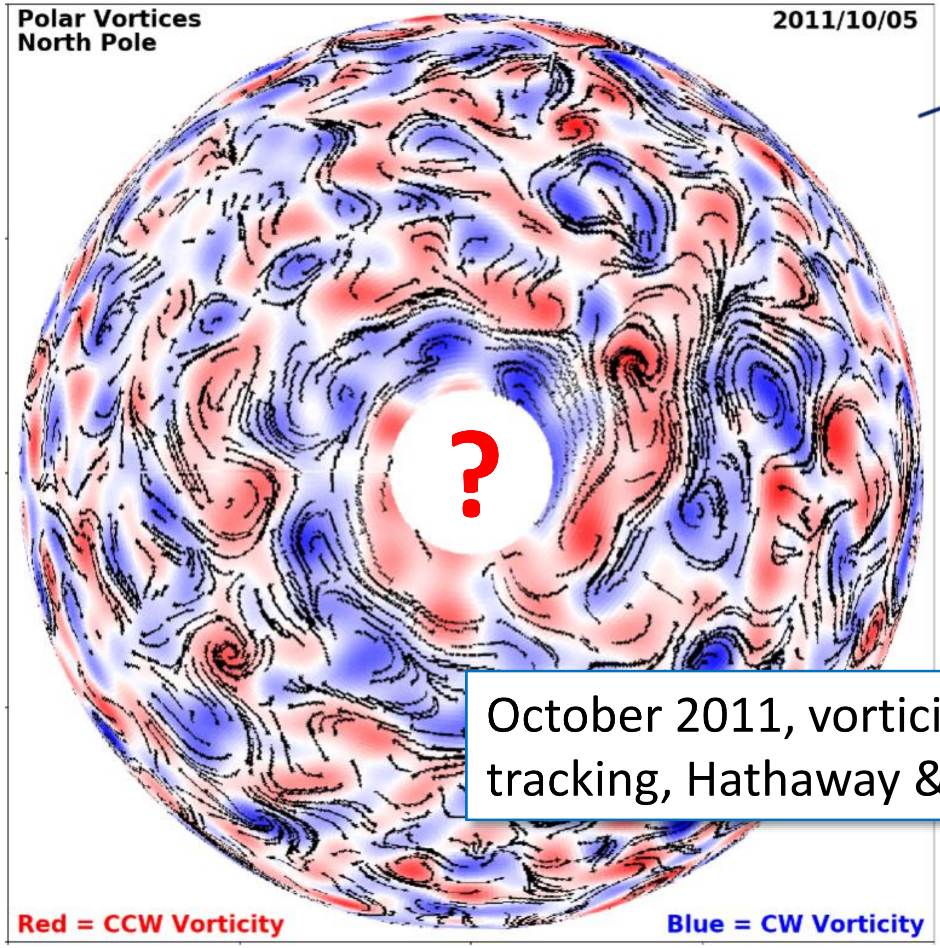
Clues From Out of the Ecliptic?



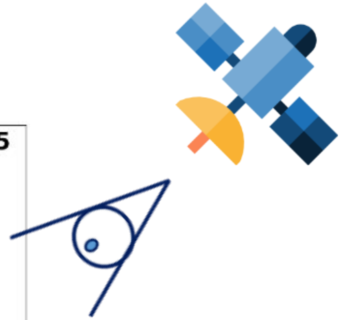
Clues From Out of the Ecliptic?

October 2010, flows from helioseismology, Bogart et al 2015





October 2011, vorticity from SG tracking, Hathaway & Upton, 2020



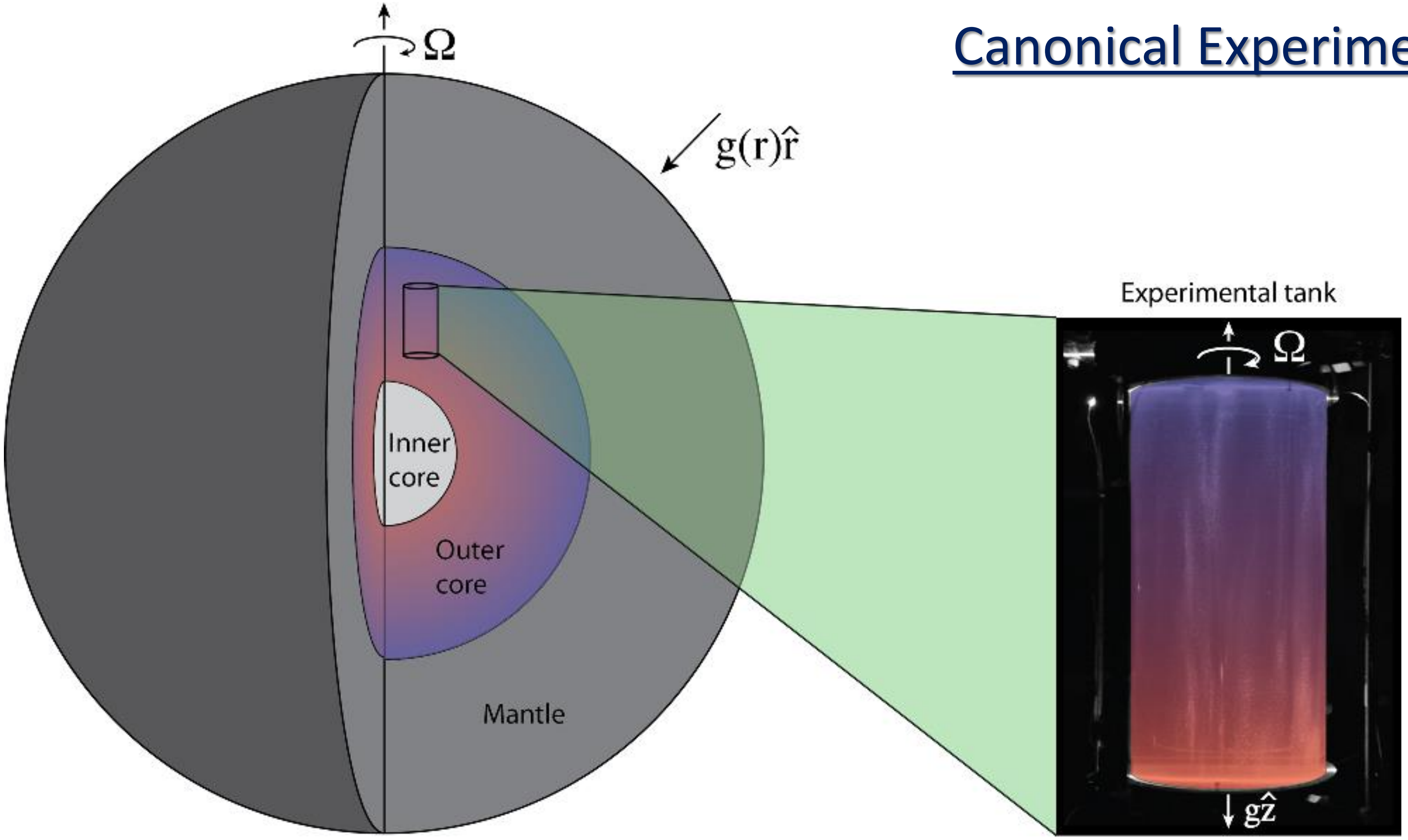
Polar View

- Clearly SOMETHING interesting at the poles
- Foreshortening effects and resolution constraints severe
- Need direct views over long periods!

Thank You!

If Time Allows: A Novel Experiment…

Canonical Experimental Setup



Cheng et al., 2015, GJI, 201,1

Primary control parameters:

- Tank depth
- Heat flux
- Rotation rate

$$E = \frac{\tau_{rotation}}{\tau_{viscous}} = \frac{\nu}{\Omega L^2}$$

- Ekman number is control parameter
- Influences Ro
- Controlled via tank height.

Some Large Rotating Convection Experiments

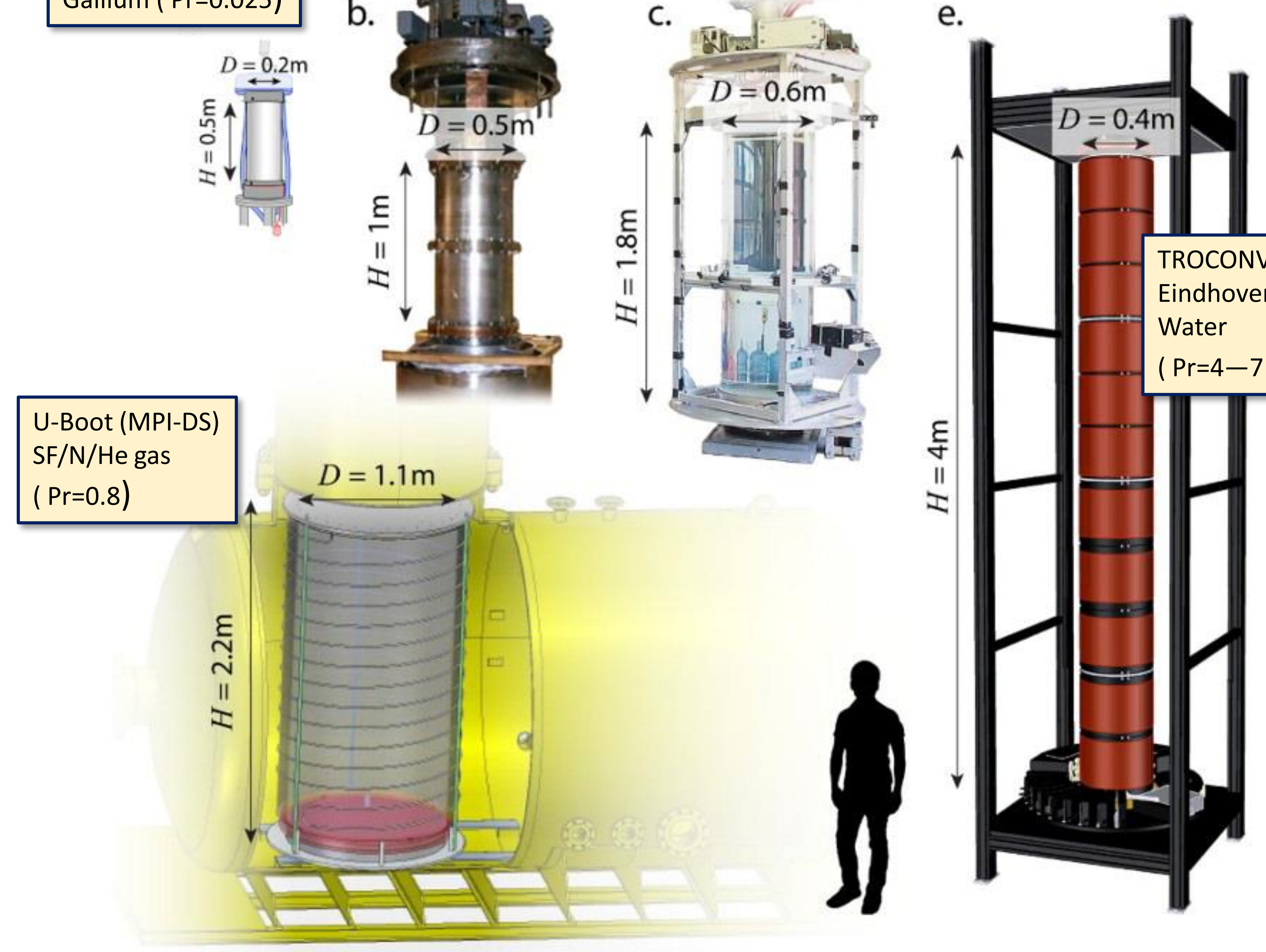
RoMag (UCLA)
Gallium (Pr=0.025)

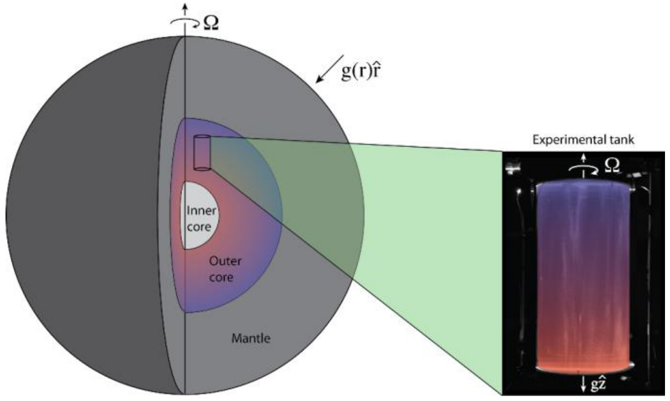
Trieste (ICTP)
Liquid He (Pr=0.7)

NoMag (UCLA)
Water (Pr= 4 –7)

TROCONVEX
Eindhoven UT
Water
(Pr=4—7)

U-Boot (MPI-DS)
SF/N/He gas
(Pr=0.8)





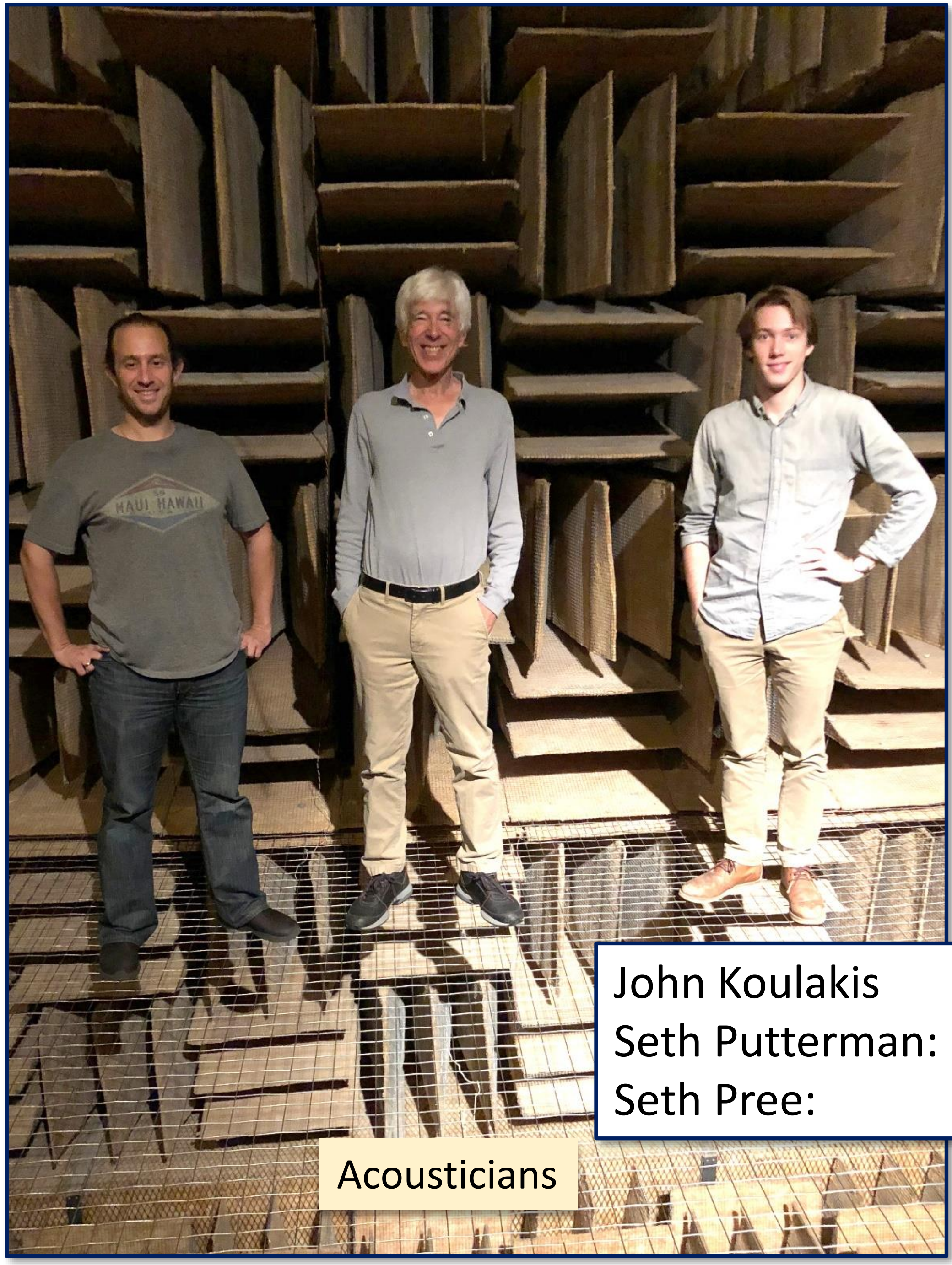
$$E = \frac{\tau_{rotation}}{\tau_{viscous}} = \frac{\nu}{\Omega L^2}$$

Image:
Cheng et al., 2018, GAFD, 112, 277

Experiments: What else do we lack?

- Extreme parameter regimes are not the only difficulties…
- Historically, other details difficult to explore experimentally:
  - Density stratification
  - Internal radiative heating
  - Spherical geometry/central force

Something New Under the Sun



Acousticians

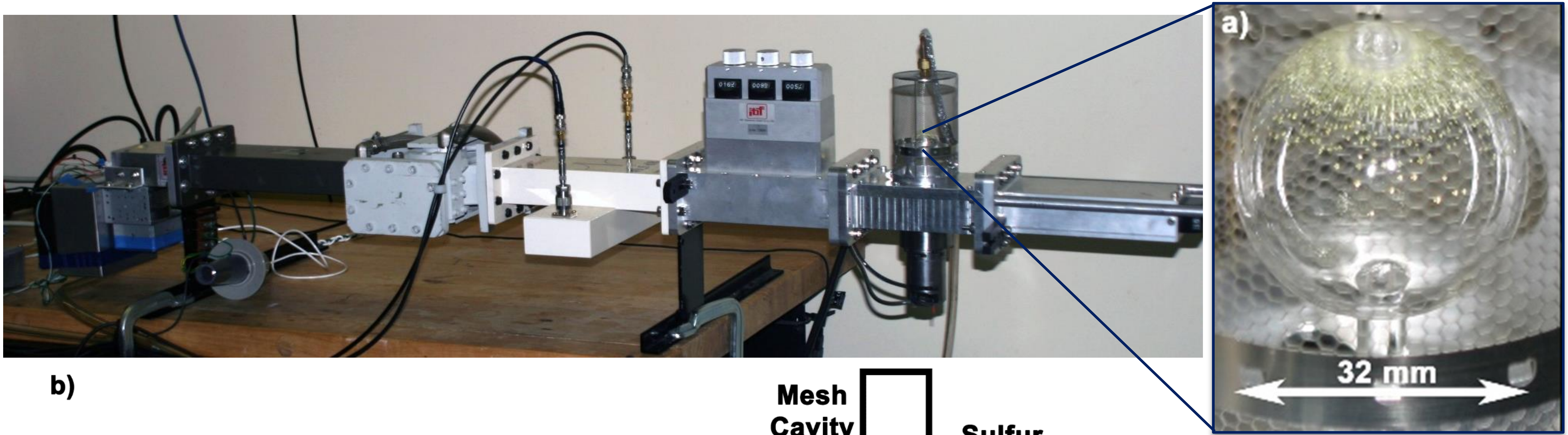
John Koulakis (Left)
Seth Putterman: (Center)
Seth Pree: (Right)

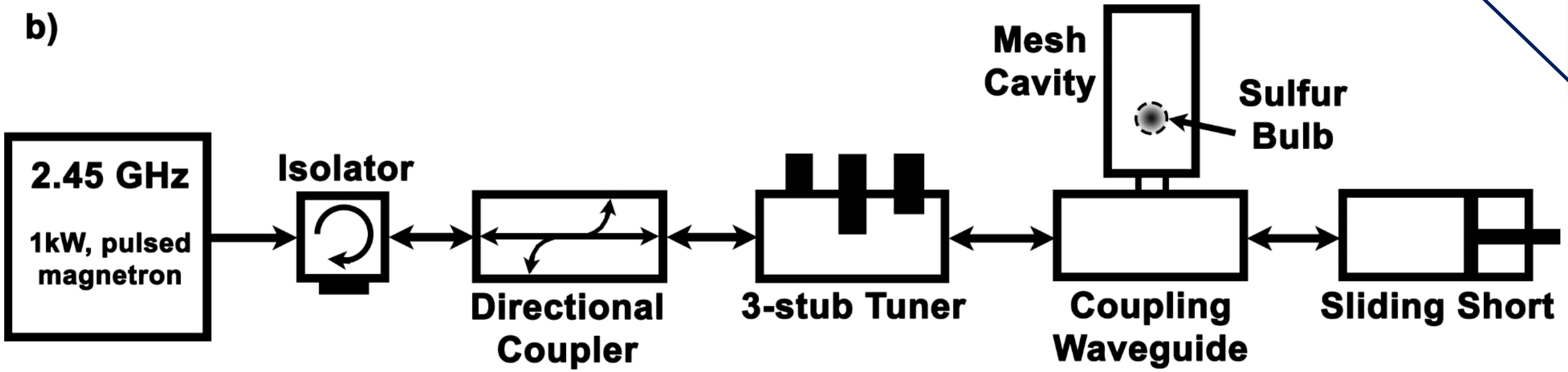
UCLA Plasma Acoustics Experiment

Cell Phone Video
(welding mask attached…)

Koulakis et al., 2018,
Phys. Rev. E, **98**, 043103

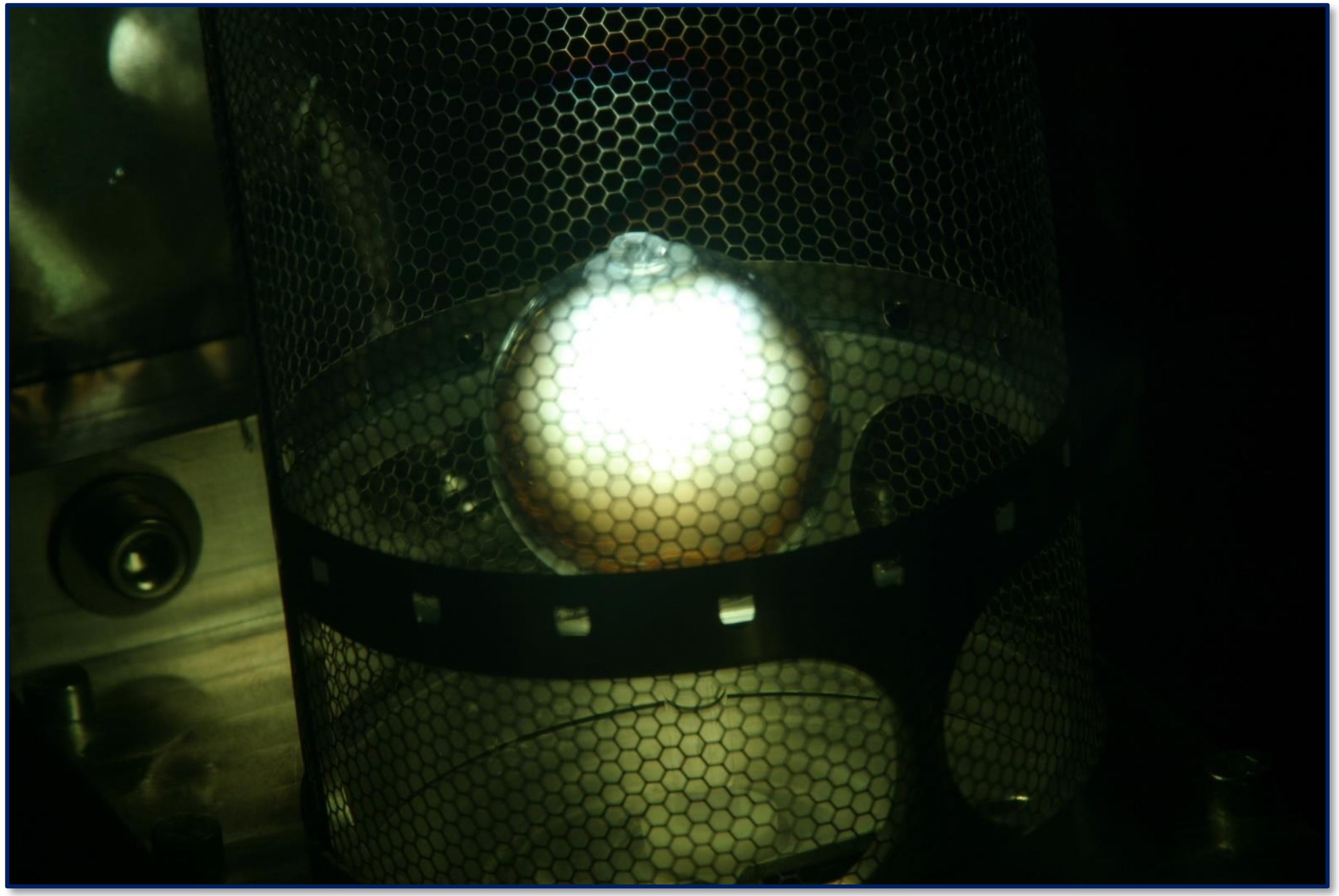
Table-Top Plasma Acoustics Experiment





Koulakis et al., 2018,
Phys. Rev. E, **98**, 043103

“Normal” State: Internally-Heated Plasma



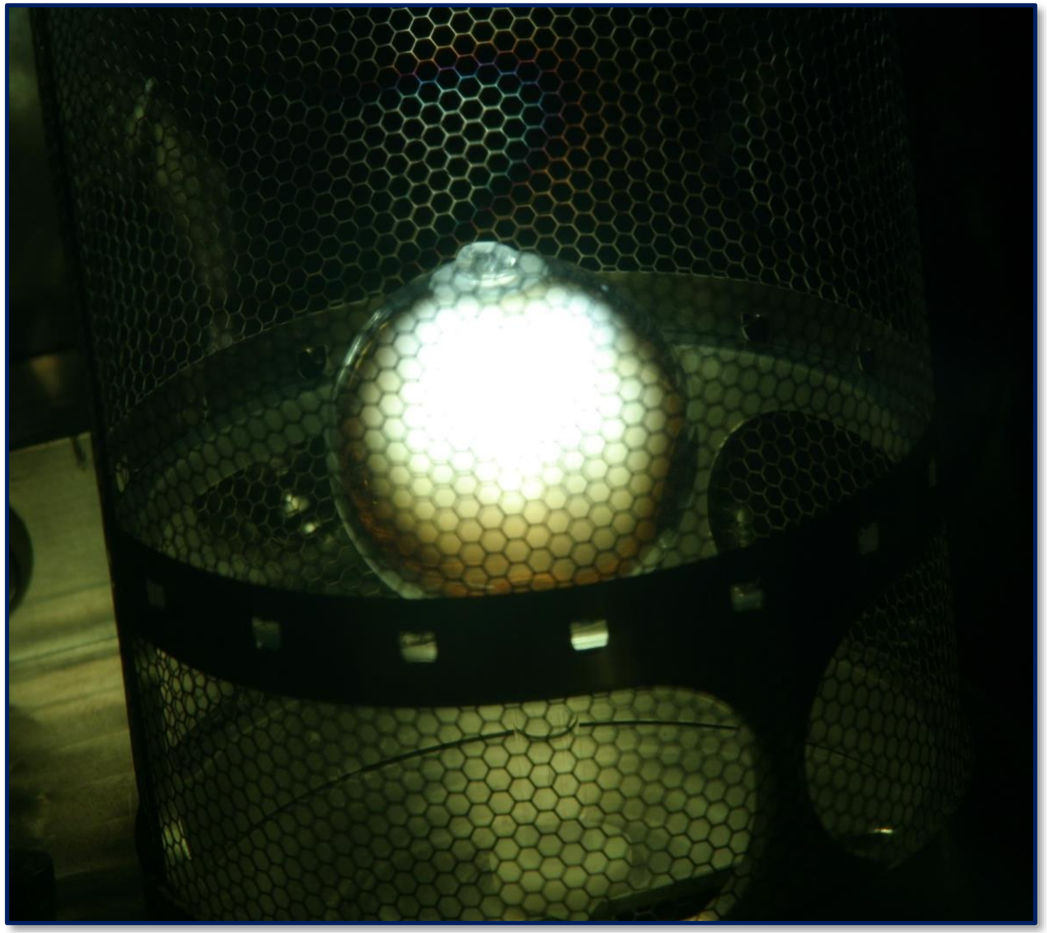
- Rotation rate: 50 Hz
- Central temperature: 4,000 K
- Outer temperature: 1,000 K
- Density: O(10^{-4}) g cm^{-3}
- Ionization Fraction: 10^{-5}

Experiment:

Pulse microwaves at resonant frequency of low-order, spherically symmetric mode.

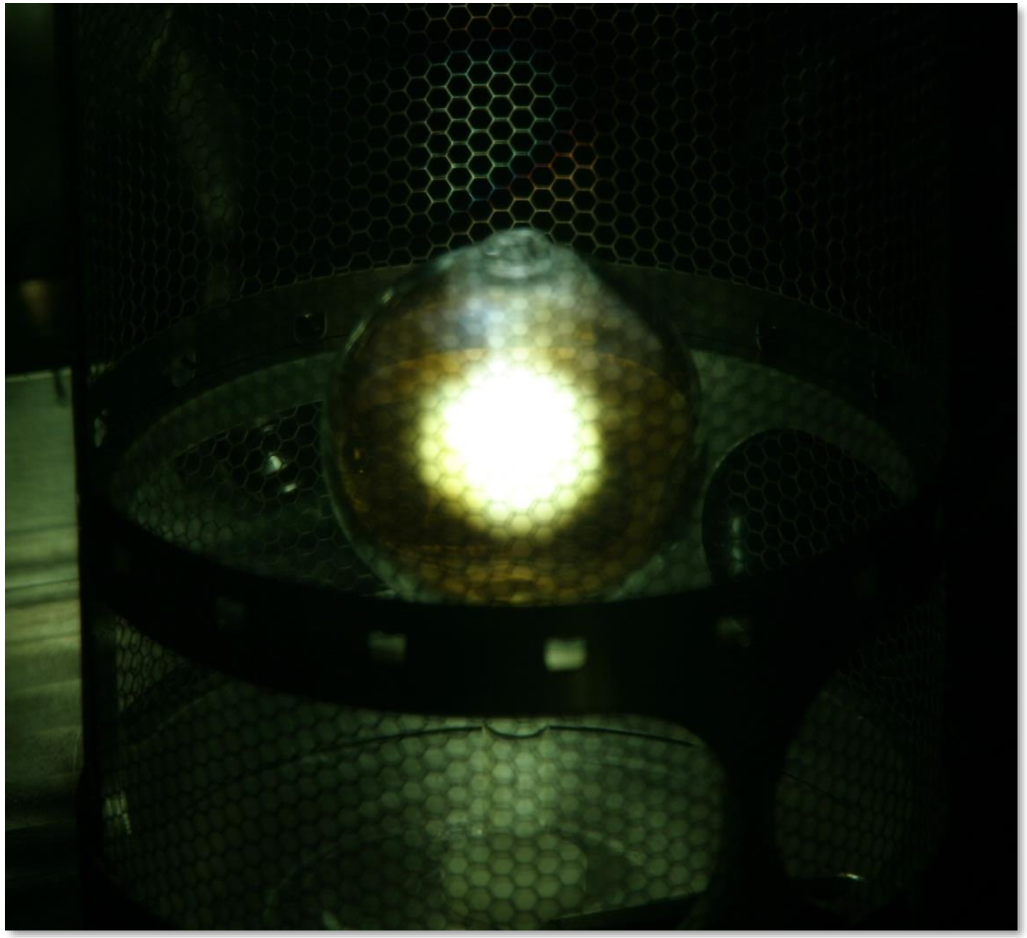
Koulakis et al., 2018,
Phys. Rev. E, **98**, 043103

Normal State



Microwaves pulsed off-resonance

Confined State



Microwaves pulsed on-resonance

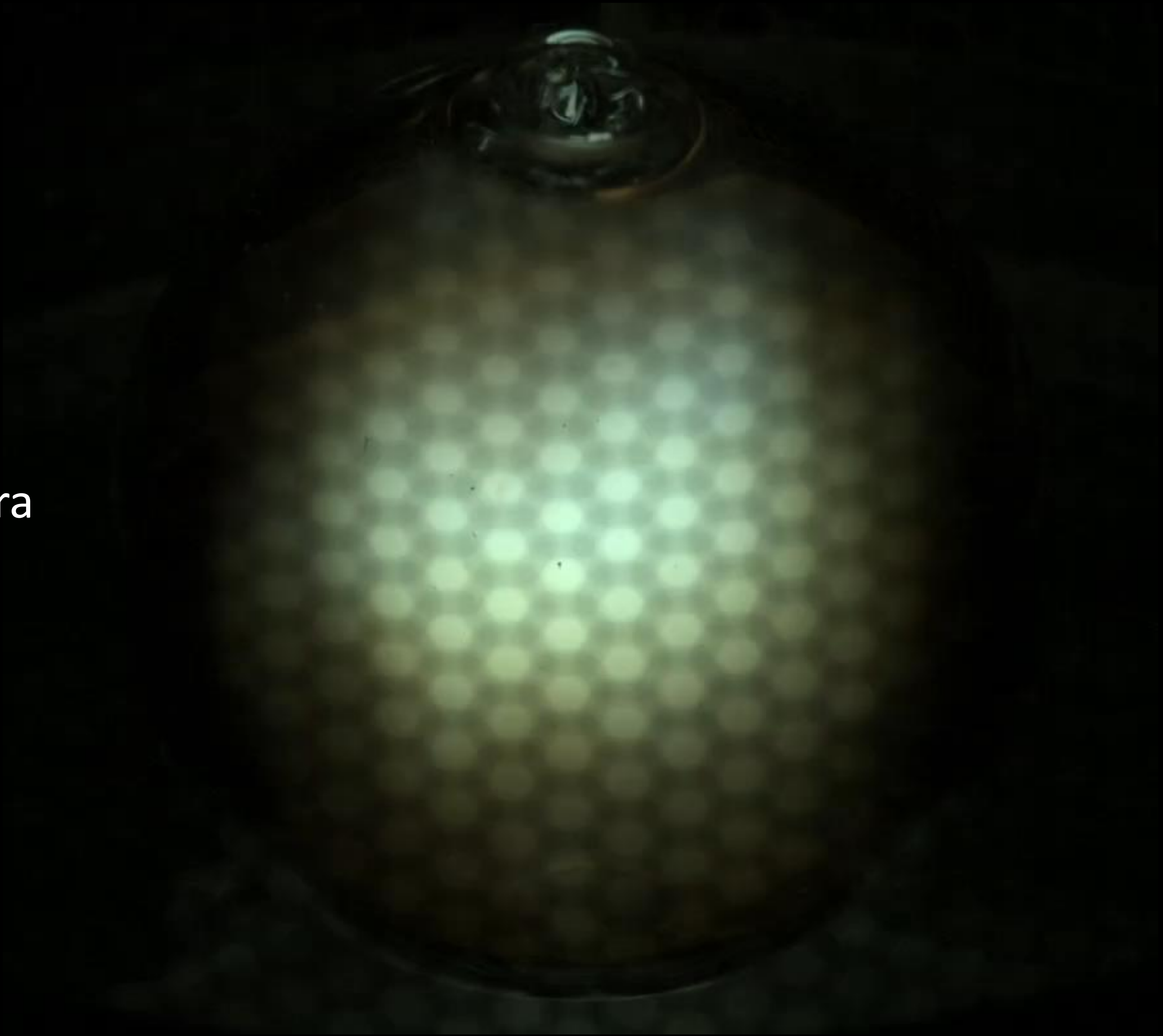
29 kHz , Q = 700 – 900, Ma = 0.03 , 180 dB

Transition:
Normal to Trapped

Rotation rate: 50 Hz

Phantom v2512 high-speed camera
(33,000 Frames per Second)

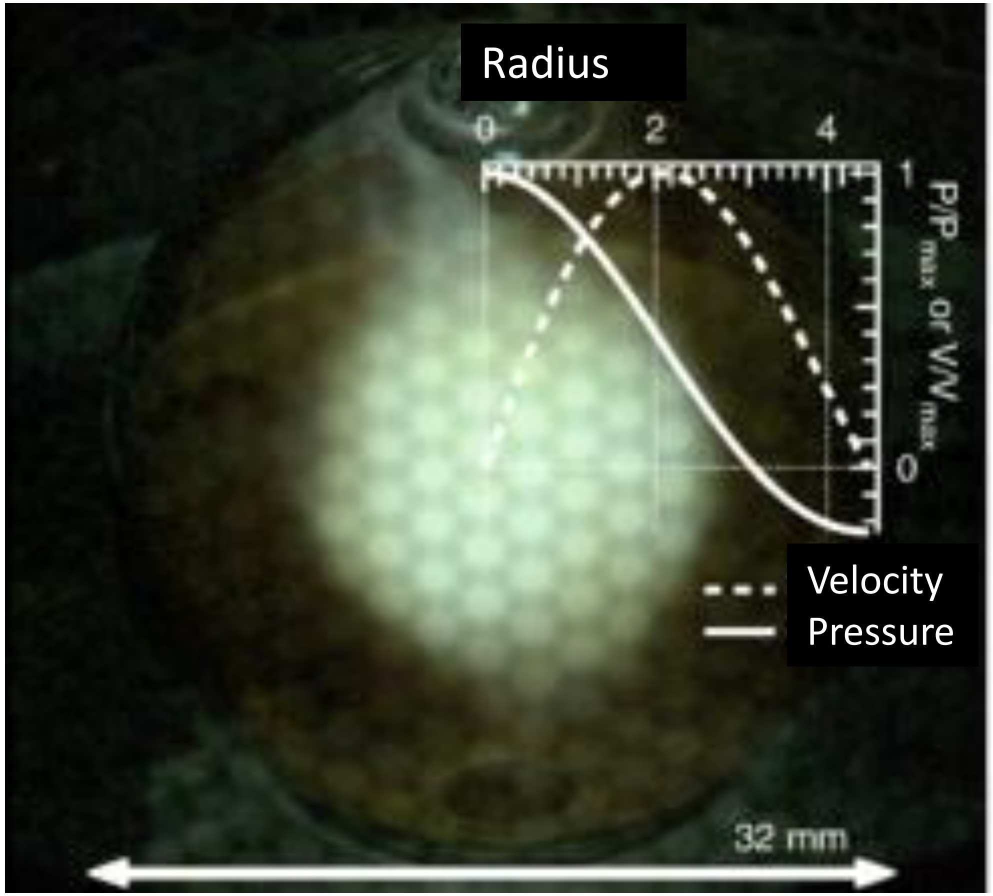
Koulakis et al., 2018,
Phys. Rev. E, **98**, 043103



Dynamics: Pycnoclinic Acoustic Effect

- Interaction of high amplitude sound w/ density gradients
- “Acoustic radiation pressure”

Koulakis et al., 2018, Phys. Rev. E, **98**, 043103



Standard Buoyancy

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} = \cdots + \alpha T' g \hat{\boldsymbol{r}} + \cdots$$

Pycnoclinic “Buoyancy”

resonant mode velocity amplitude

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} = \cdots + \frac{\alpha T'}{2} \boldsymbol{\nabla} \langle v_s^2 \rangle \; + \; \alpha \langle v_s^2 \rangle \boldsymbol{\nabla} T' \ldots$$

Dynamics!

Rotation rate: 50 Hz

(11,000 Frames per Second)

Stable, radiatively heated interior.

Convectively unstable exterior…

The beginnings of a spherical convection experiment!

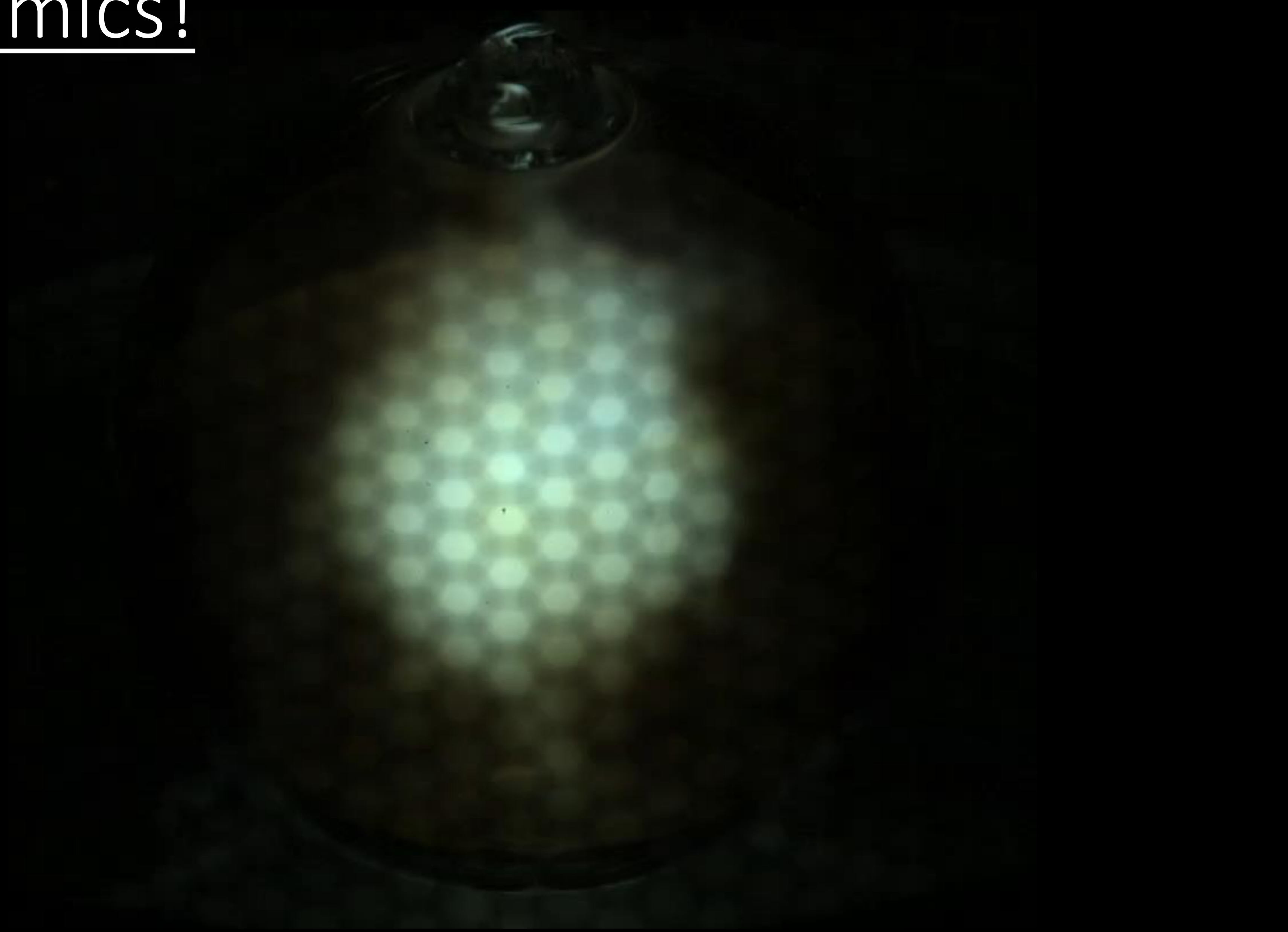


Table 1. Dimensionless parameters characterizing convection and dynamo action

parameter		measure of
$\Delta\nabla \equiv \nabla - \nabla_{\rm ad}$	superadiabaticity	Schwarzschild instability
$\mathrm{Ra} \equiv g\Delta\nabla d^4/(\nu\chi H_{\rm p})$	Rayleigh nr.	thermal instability
$\mathrm{Re} \equiv UL/\nu$	Reynolds nr.	hydrodynamic turbulence
$\mathrm{Rm} \equiv UL/\eta$	magn. Reynolds nr.	ratio of adv. to diff. of $\boldsymbol{B}$
$\mathrm{Pr} \equiv \nu/\chi$	Prandtl nr.	ratio of smallest therm. to kin. scales
$\mathrm{Pm} \equiv \nu/\eta$	magn. Prandtl nr.	ratio of smallest magn. to kin. scales
$\mathrm{Co} \equiv 2\Omega L/U$ $^{(a)}$	Coriolis nr.	rotational influence on flow
$\mathrm{Ta} \equiv (2\Omega d^2)^2/\nu^2$	Taylor nr.	(de)stabilising effect of rotation
$S \equiv U\tau_{\rm c}/L$	Strouhal nr.	ratio of corr. time to turnover time
$\mathrm{Ma} \equiv U/c_{\rm s}$	Mach nr.	ratio of flow speed to sound speed
$\beta \equiv 2\mu_0 p/B^2$	plasma β	ratio of gas to magn. pressure

(a) Identical to the inverse Rossby number. However, in some publications on stellar activity the Rossby number is defined as $P_{\rm rot}/\tau_{\rm c} = 4\pi/\mathrm{Co}$

Table 2. Representative values of dimensionless parameters in the Sun

parameter (a)	base of convection zone	photosphere
$\Delta\nabla$	$\lesssim 10^{-6}$	$\lesssim 0.5$
Ra	10^{20}	10^{16}
Re	10^{13}	10^{12}
Rm	10^{10}	10^{6}
Pr	10^{-7}	10^{-7}
Pm	10^{-3}	10^{-6}
Co	15	$2 \cdot 10^{-3} \ldots 0.4$ $^{(b)}$
Ta	10^{27}	10^{19}
Ma	10^{-4}	1
β	$10^{5} \ldots 10^{7}$ $^{(c)}$	1 $^{(d)}$

(a) Unless stated otherwise, estimated by setting $L \approx H_p$
(b) Lower value: granulation; upper value: supergranulation
(c) Magnetized plasma with $1 \lesssim B \lesssim 10$ T
(d) Sunspots and magnetic elements

Ossendrijver, M., 2003, "The Solar Dynamo," Astron Astrophys Rev, 11, 287