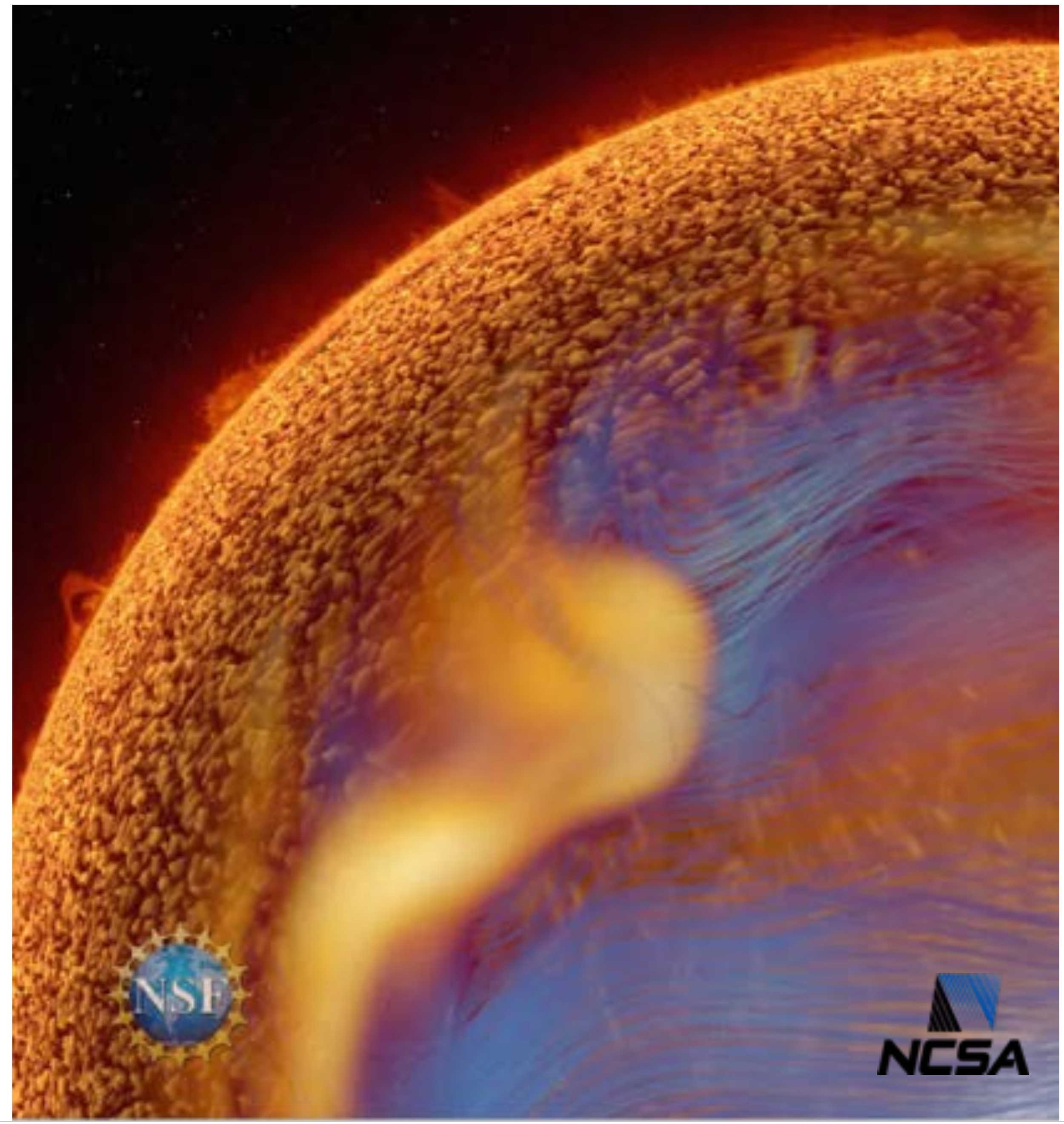
Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

The Convection Conundrum: Mystery and Intrigue Below the Solar Surface

Mark Miesch
HAO/NCAR

Our Mysterious Sun:
Magnetic Coupling Between the Solar Interior and Atmosphere
Tbilisi, Georgia
25-29 Sept., 2017



Outline

- The Convection Conundrum
  - More to it than helioseismology
- What are we missing?
  - Of plumes and rain
  - Blame it on magnetism?
  - Or rotation?
- Summary and Outlook

The Convection Conundrum

Statement of the problem

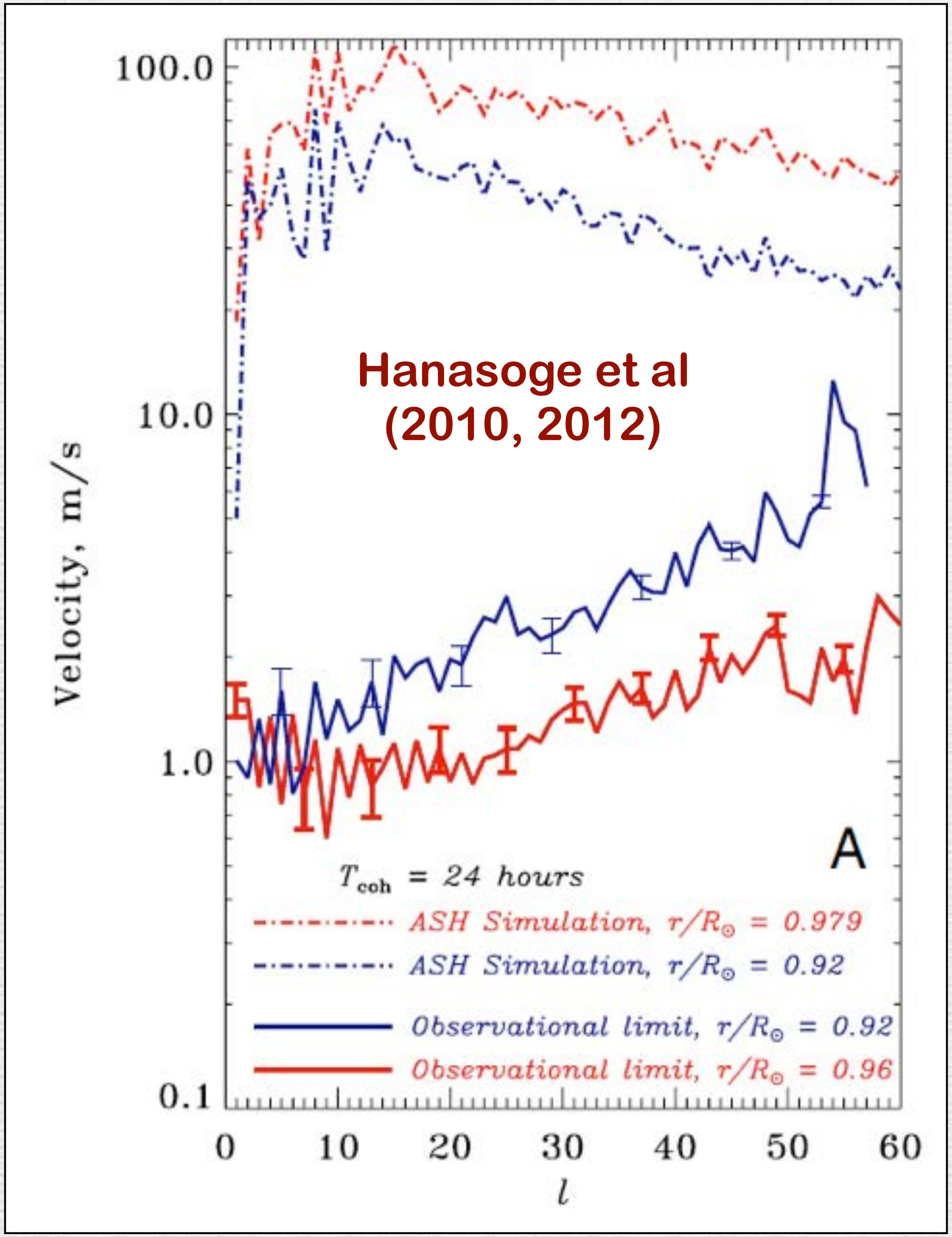
3 independent lines of evidence

(Exhibits A, B, C)

suggest that models may
be over-estimating the
amplitude
of large-scale
convective velocities
in the
deep solar interior

But if so,
How does the Sun shine?
Why does it rotate
differentially?

Exhibit A: Helioseismic Sounding



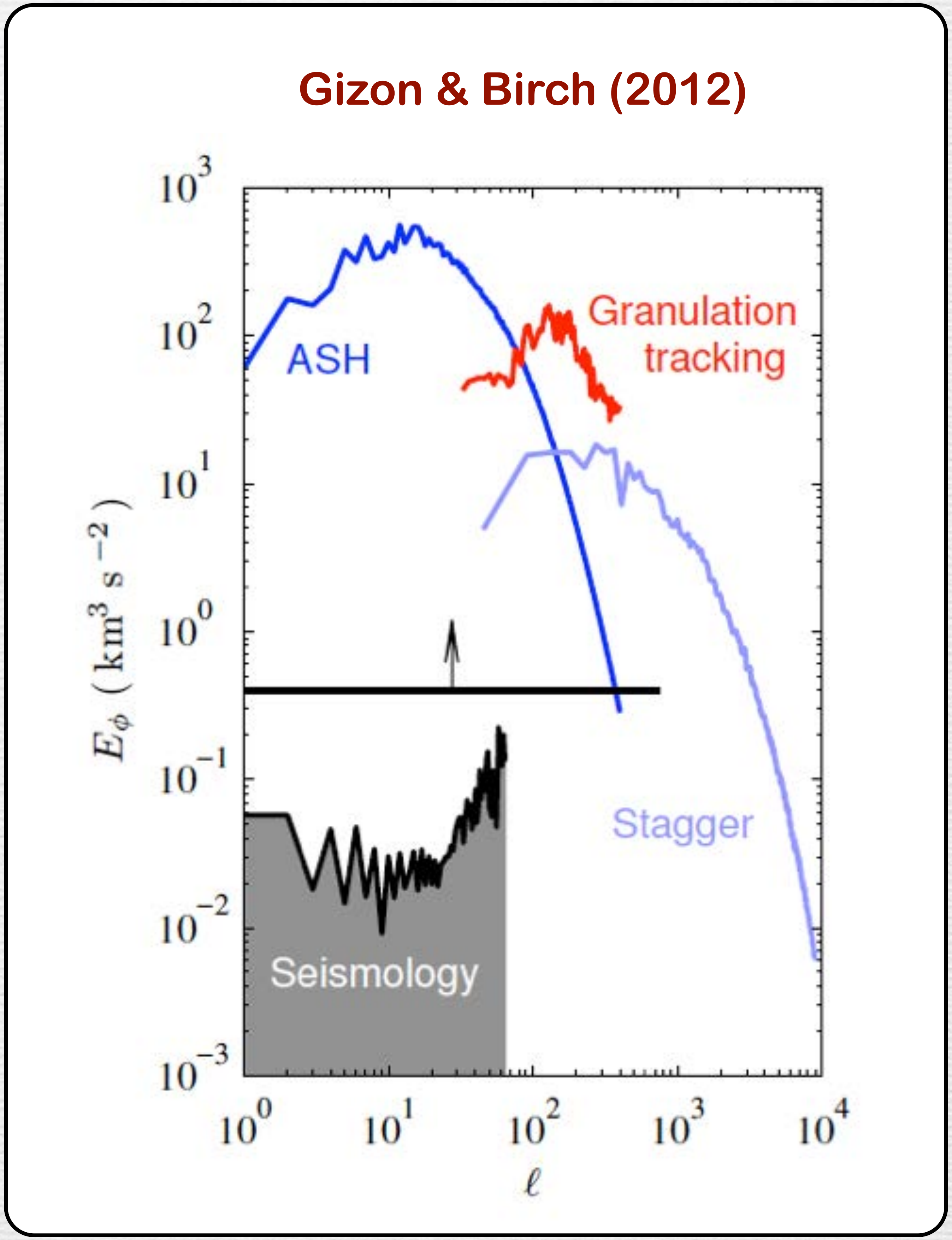
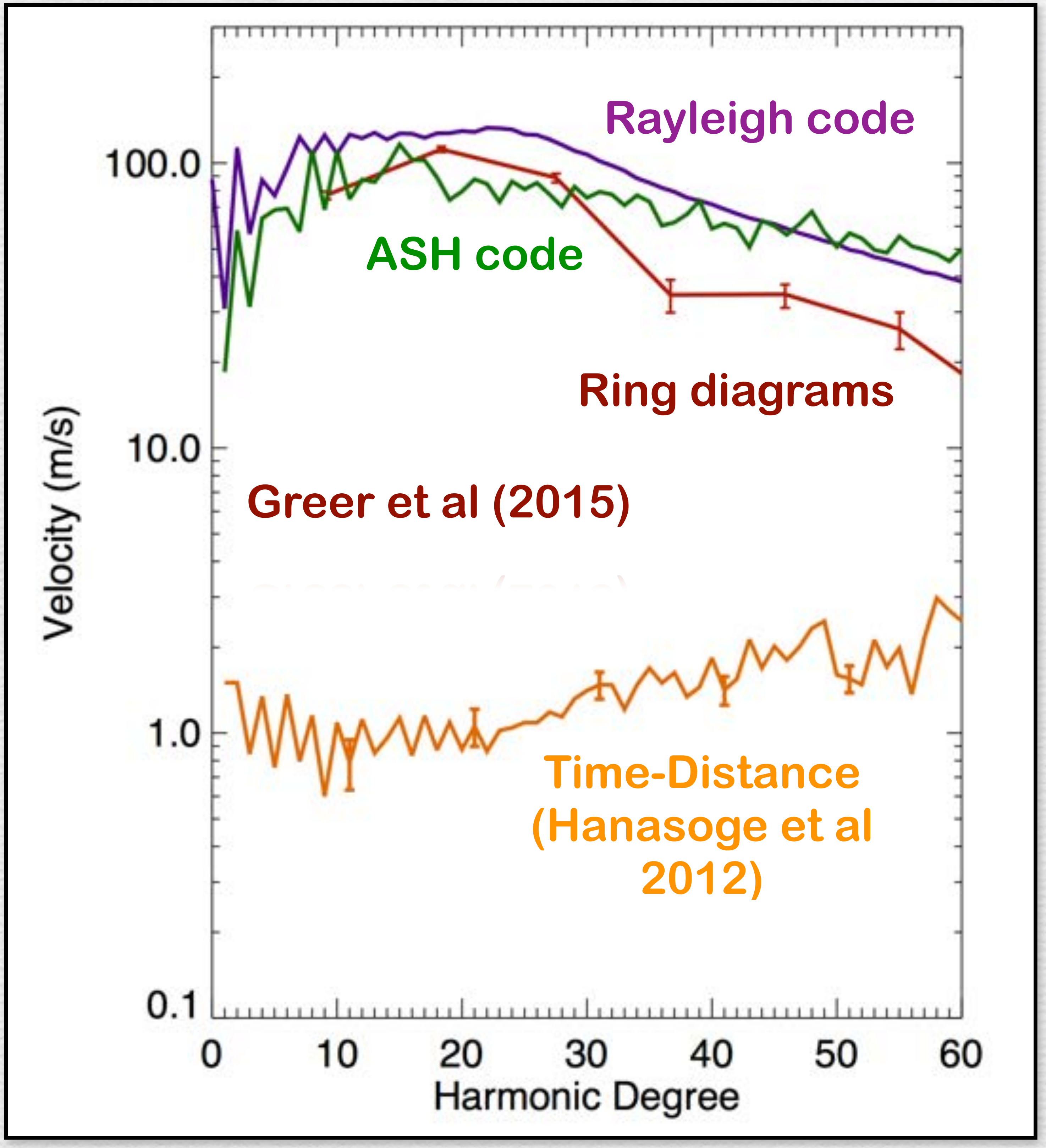
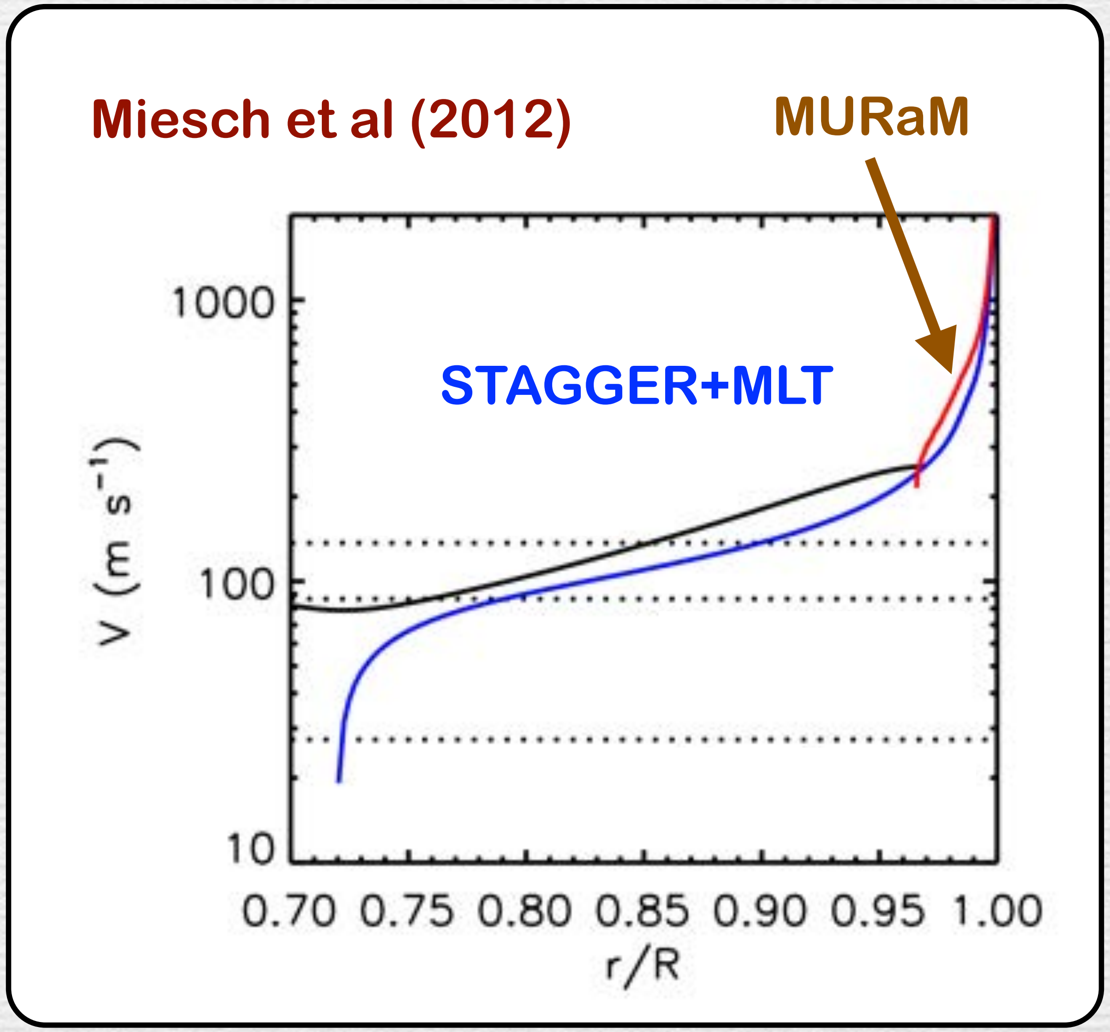


Exhibit A: Helioseismic Sounding



It's not just ASH
(Rayleigh, Amateras, FSAM, MLT)



Ring diagrams not yet consistent with Time-Distance

Exhibit B: Surface Measurements and Simulations

Nordlund, Stein & Asplund (2009)

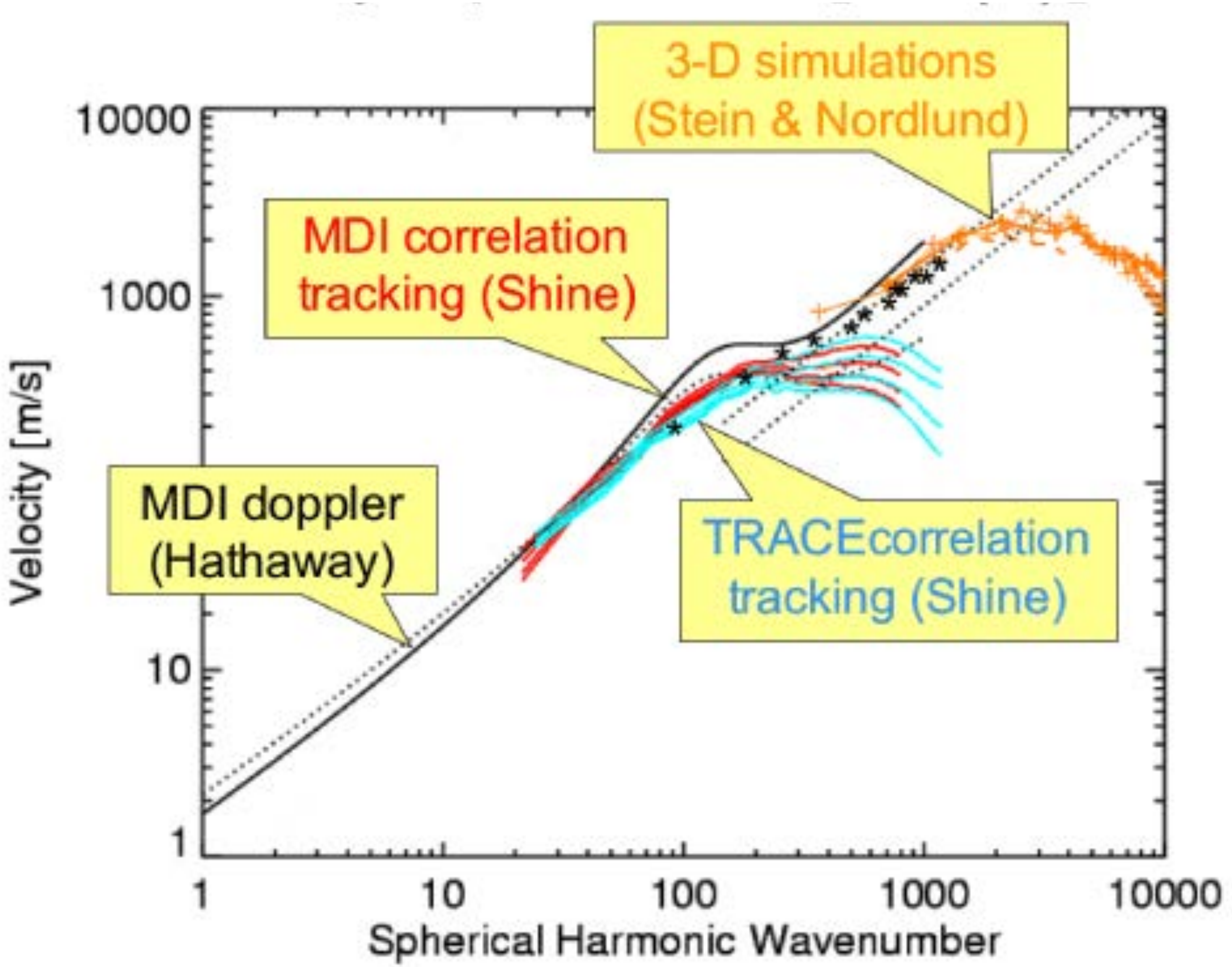
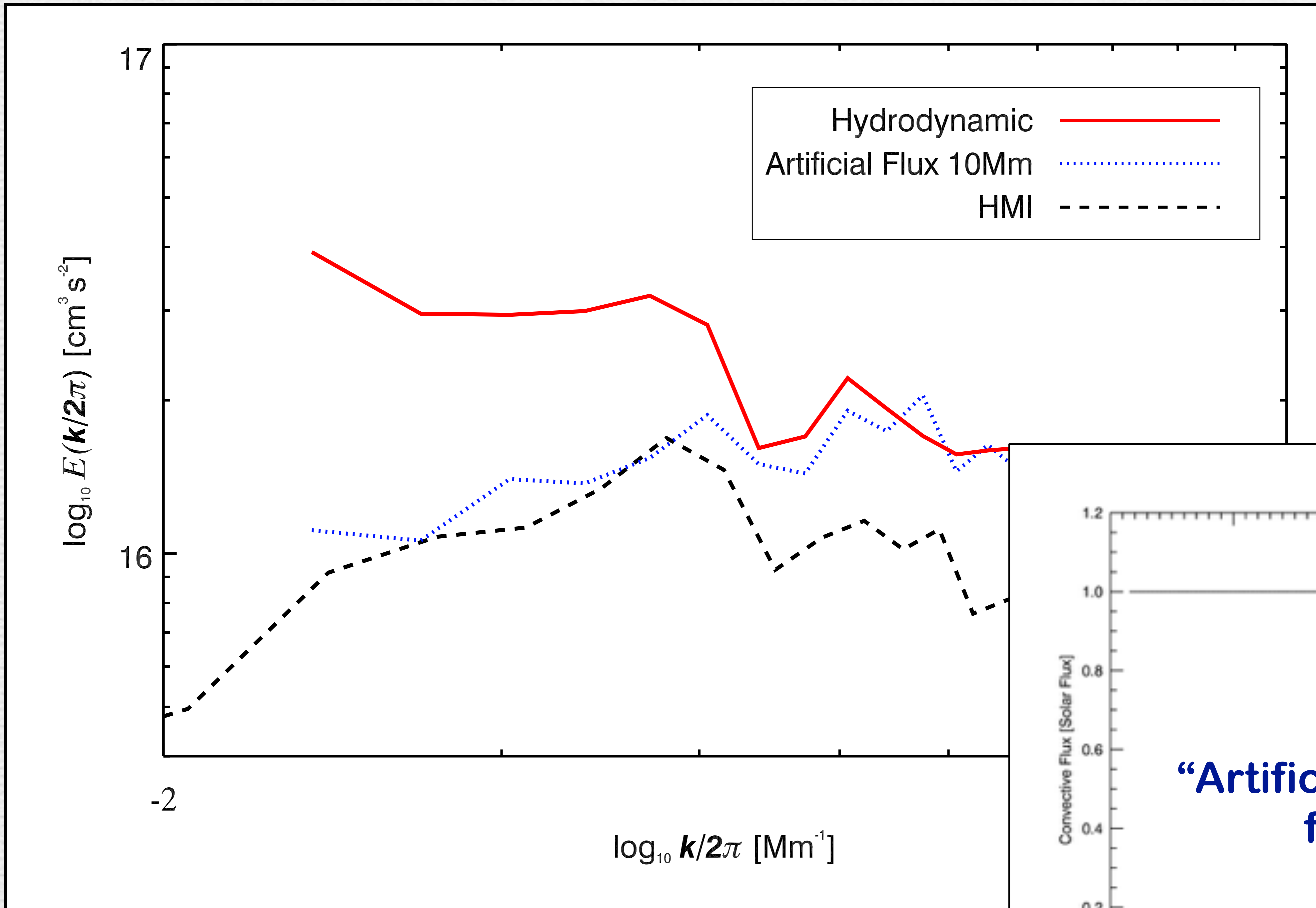


Exhibit B: Surface Measurements and Simulations

Lord et al (2014)

Depth 50 Mm (0.93 R)



Horizonal velocity spectra obtained by correlation tracking

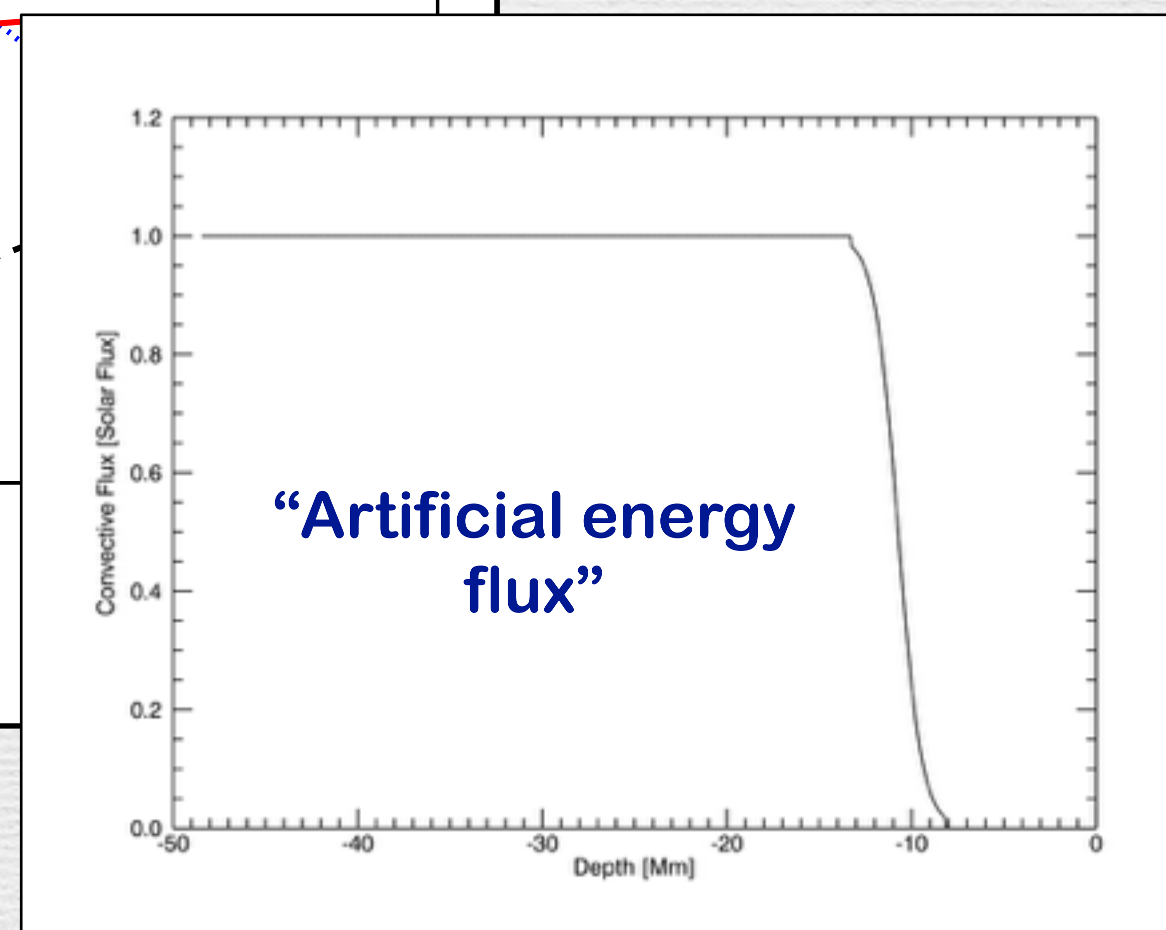
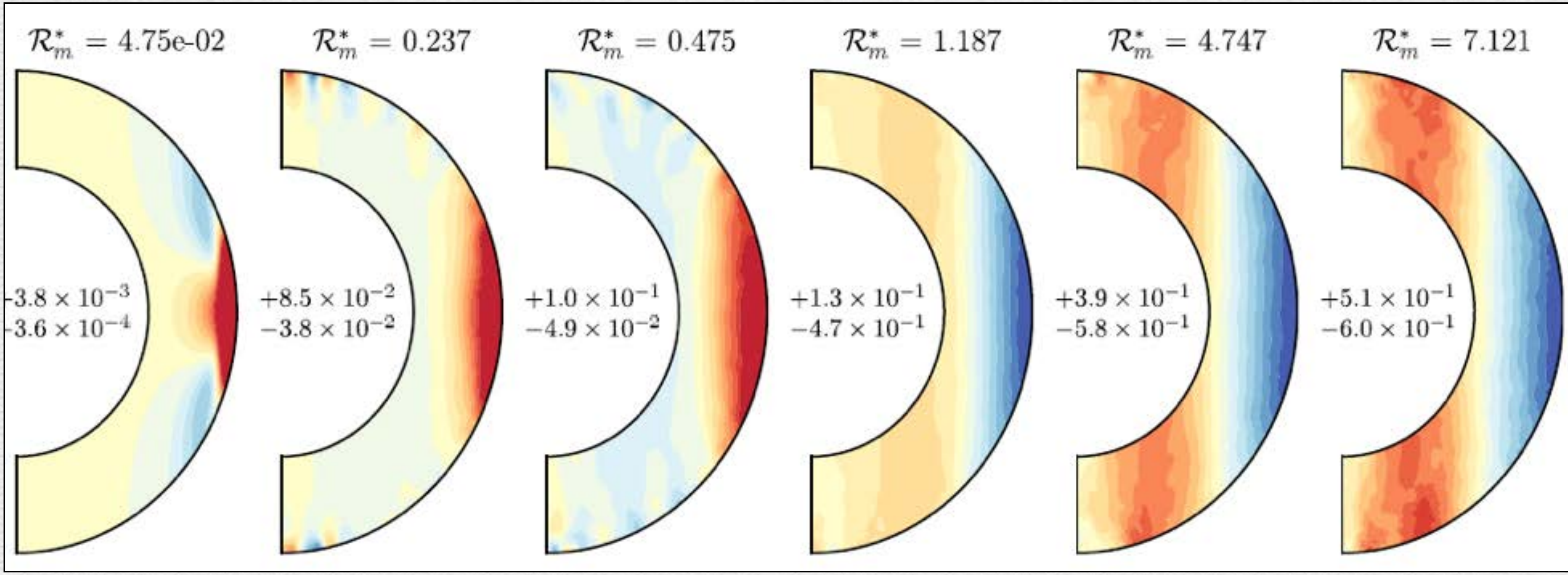


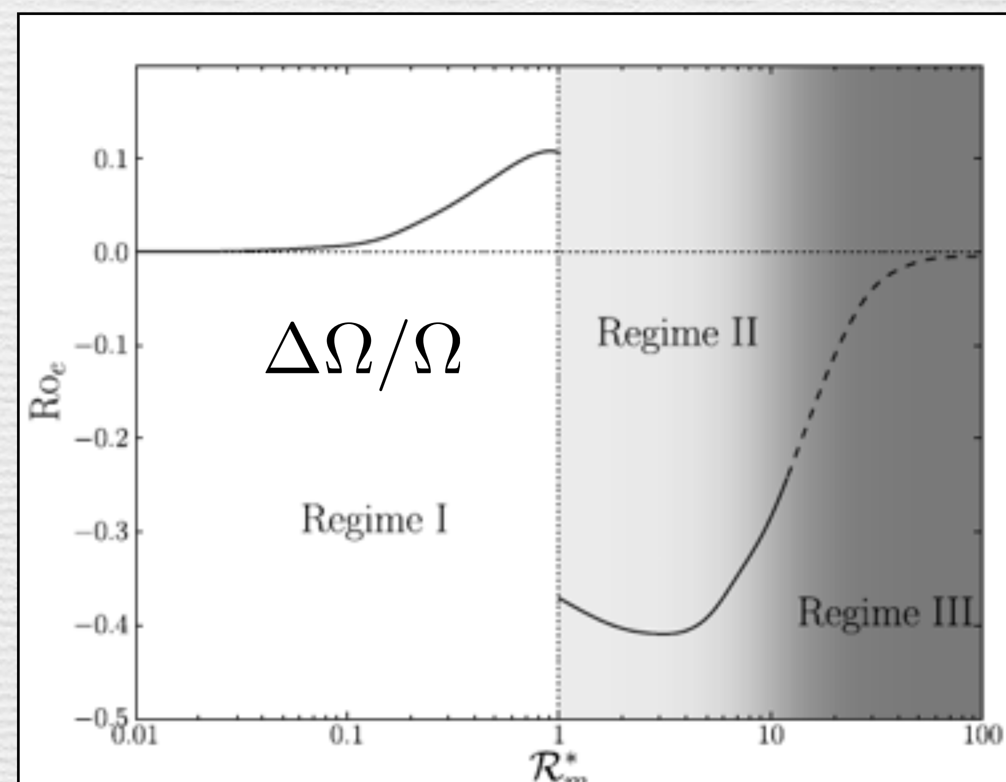
Exhibit C: Two Mean Flow Regimes



Ω

$$R_o = \frac{\omega_{rms}}{2\Omega}$$

Gastine, Wicht & Aurnou (2013)



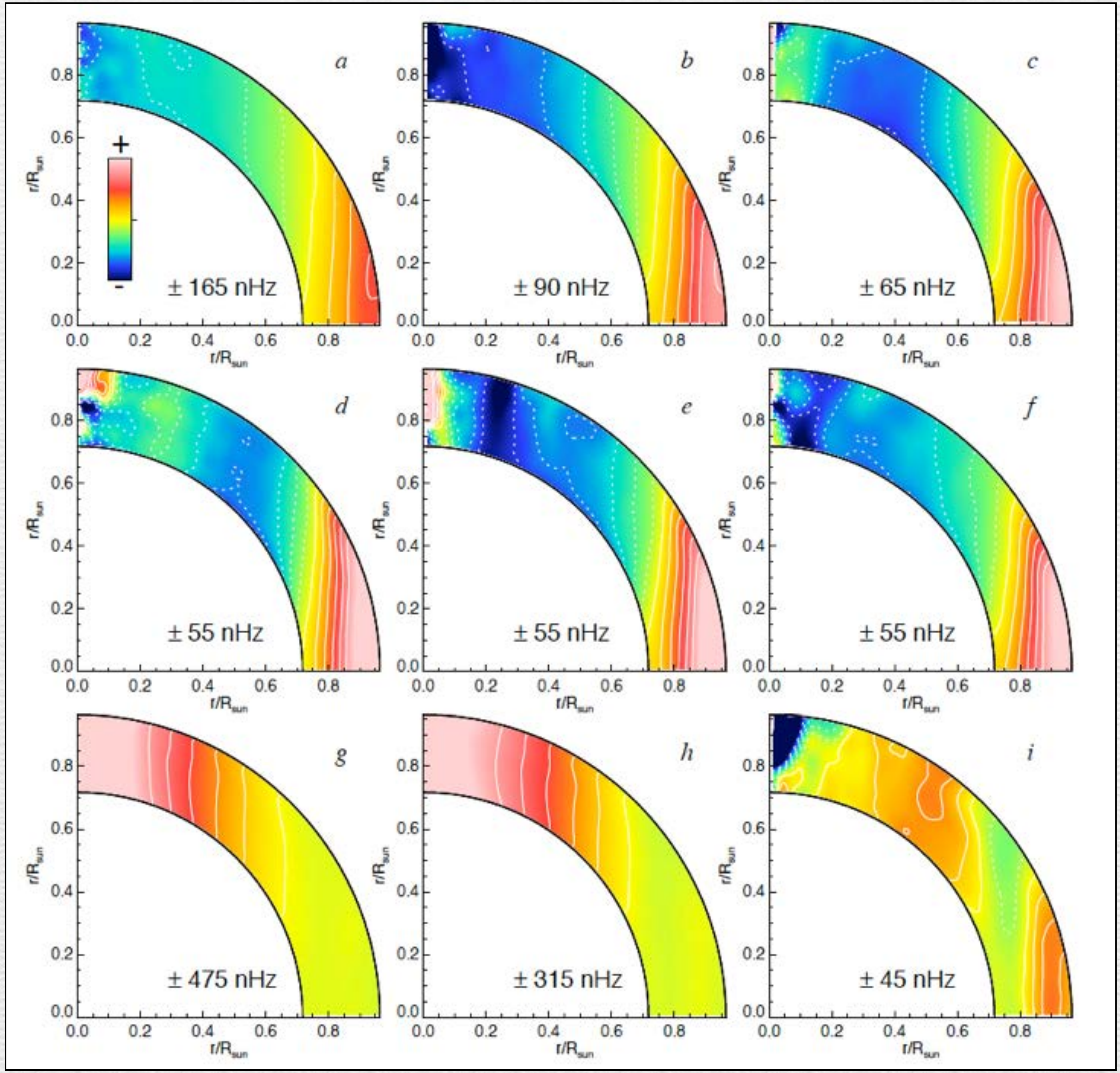
See also Gilman (1977), DeRosa et al (2002), Aurnou et al (2007), Augustson et al (2011), Kapyla et al (2011), Guerrero eta al (2013), Featherstone & Miesch (2015)

Regimes can be achieved by varying Ω or by varying dissipation

ν and κ

ν →

κ ↑



Featherstone & Miesch (2015)

Does not bode well for the Sun!

$$R_o = \frac{\omega_{rms}}{2\Omega}$$

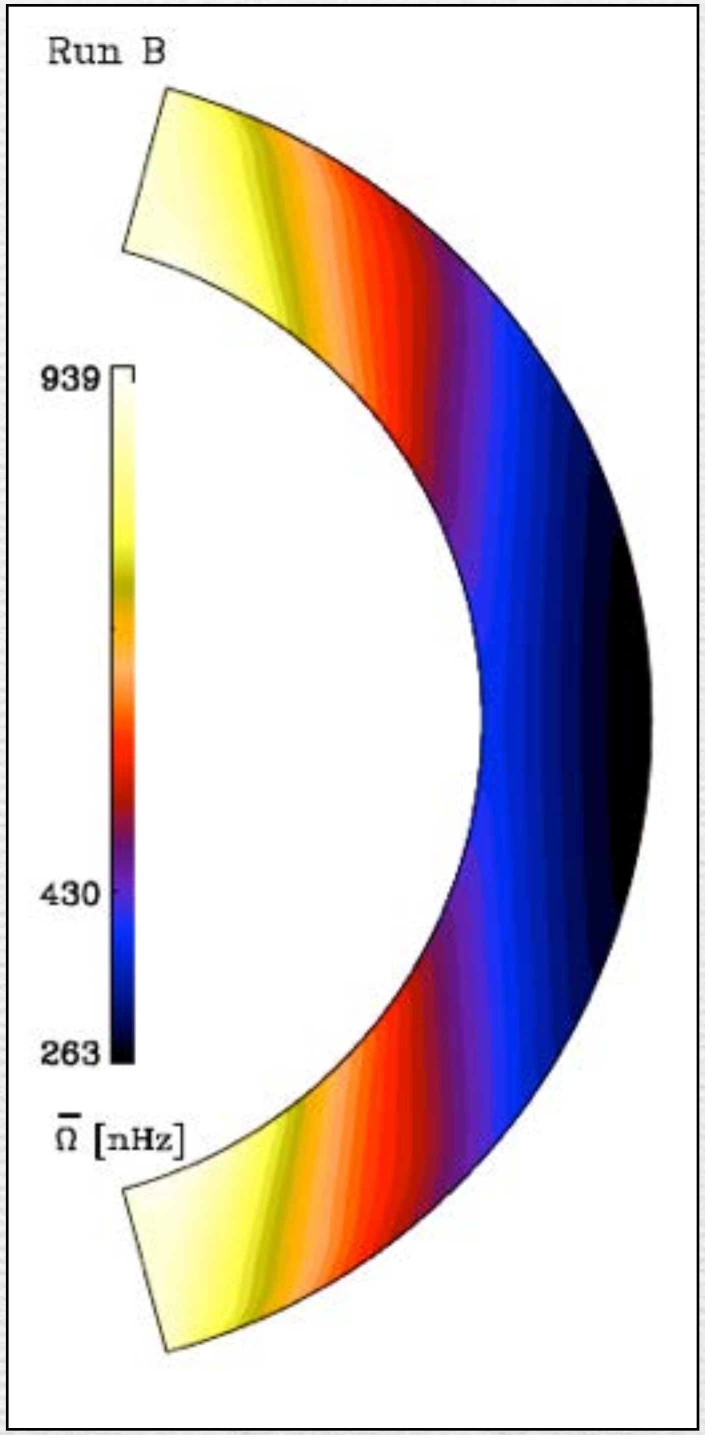
Exhibit C: Two Mean Flow Regimes

Current simulations use “tricks” to keep the Rossby number small (solar-like rotation regime)

- Increase
  - ASH
    2013a,b; Augustson et al 2014)
  - Pencil
- Decrease (resolved) Luminosity
  - EULAG
    Guerrero et al 2014)
  - AMaTeRAS
  - FSAM
  - Rayleigh

$$R_o = \frac{\omega_{rms}}{2\Omega}$$

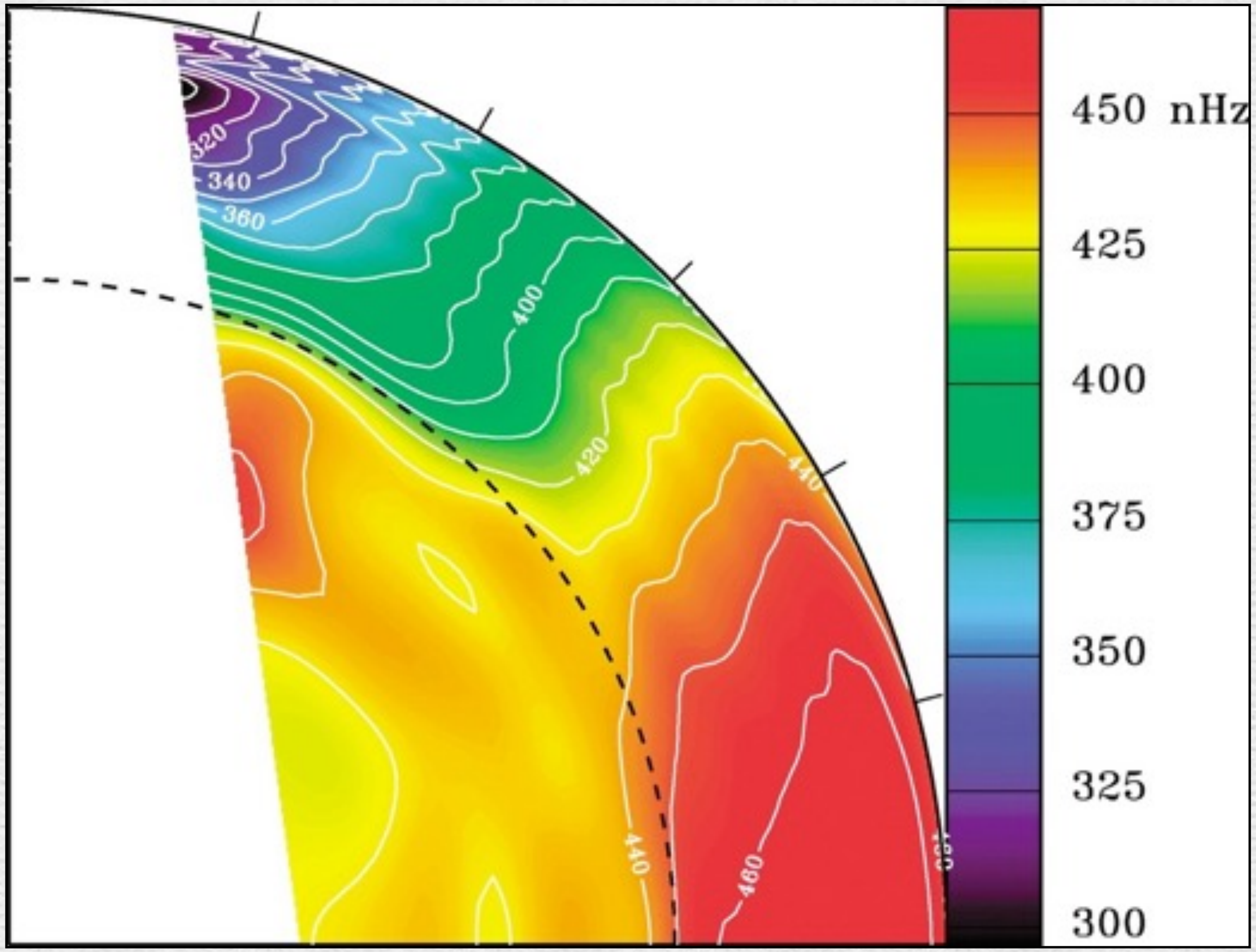
Kapyla et al (2014)



So deep convection models appear to be overestimating the convective velocity amplitude on large scales

Why is this a conundrum?

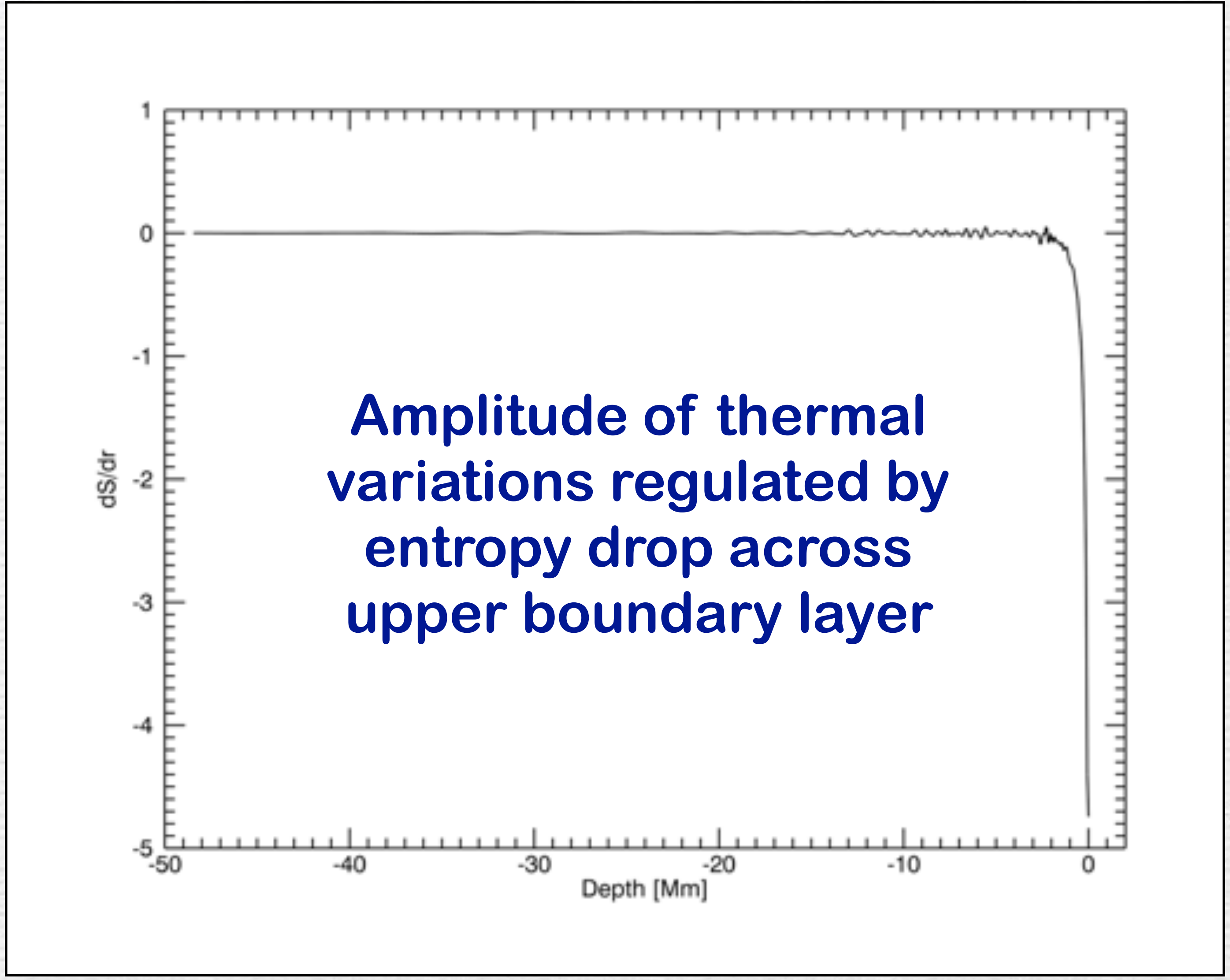
Maybe the models are just wrong…

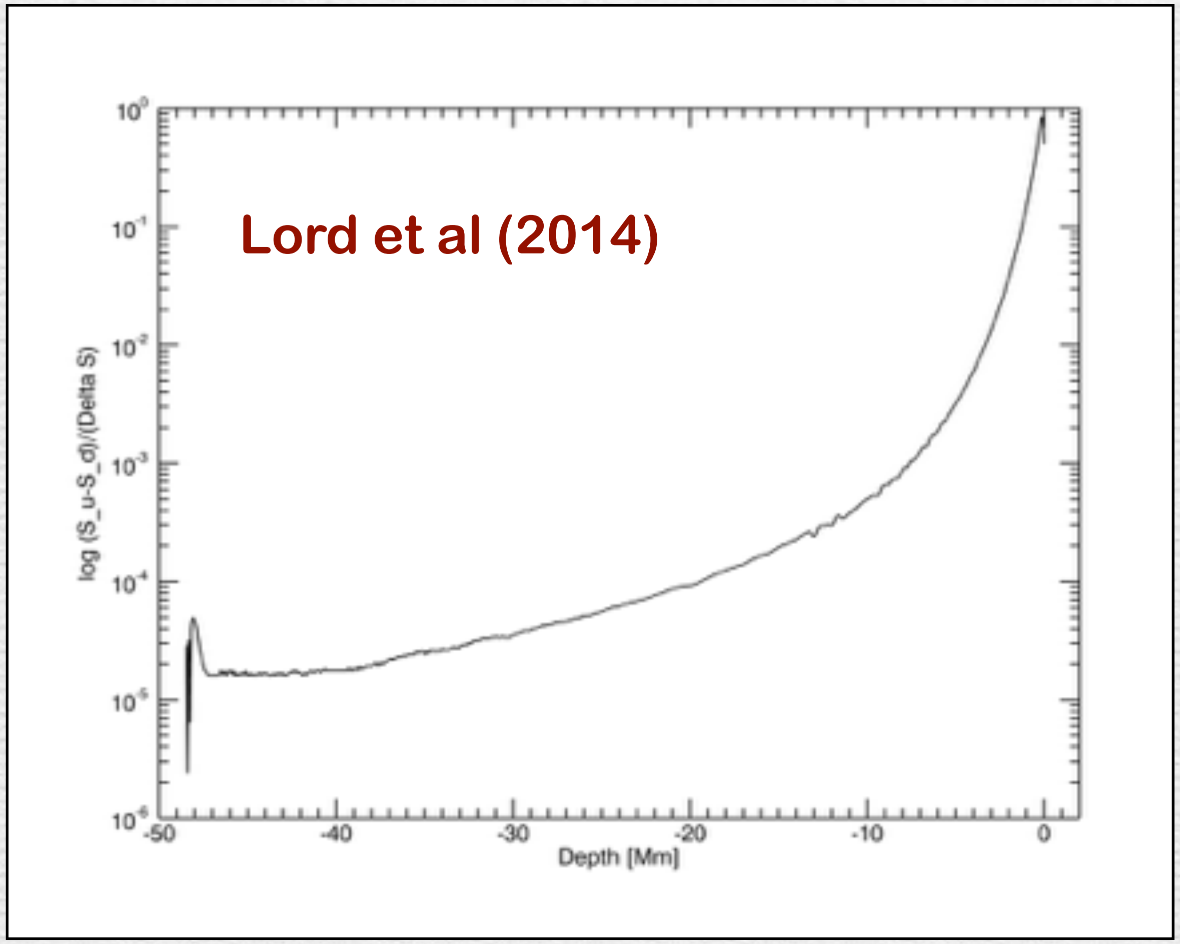


Convective amplitude required to carry solar luminosity

$$F_e = \rho C_P T v_r \sim \xi \, \frac{L}{4\pi r^2}$$

$$v_r \sim \frac{L}{4\pi \overline{\rho} C_P r^2} \left(\frac{\xi}{T'} \right)$$





$$\frac{T'}{\overline{T}} \lesssim \chi^{-1} \, \frac{\Delta S}{C_P} \qquad \chi = \frac{\overline{\rho}}{\rho_0}$$

$$v_r \gtrsim 5.7 \left(\frac{\xi}{1.2} \right) \left(\frac{\chi}{4.3 \times 10^4} \right) \ \mathrm{m\ s^{-1}}$$

Convective Amplitude required to maintain mean flows

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

Angular momentum transport by the Convective Reynolds stress must balance advection by the meridional flow

$$\mathcal{F} \sim -\boldsymbol{\nabla} \cdot \langle \rho \lambda \mathbf{v}'_m v'_\phi \rangle \sim \frac{\epsilon}{\delta} \rho V_c^2$$

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

$$\mathcal{L} = \lambda^2 \Omega$$

Where ε is an efficiency factor (0 < ε < 1) ***and***

$$V_c \gtrsim \left(\delta V_m |\boldsymbol{\nabla} \mathcal{L}|\right)^{1/2}$$

$$\delta = \frac{L_t}{\lambda} \sim \sqrt{2} \, \frac{L_t}{R_0}$$

$$V_c \gtrsim \sqrt{V_m \, V_\Omega}$$

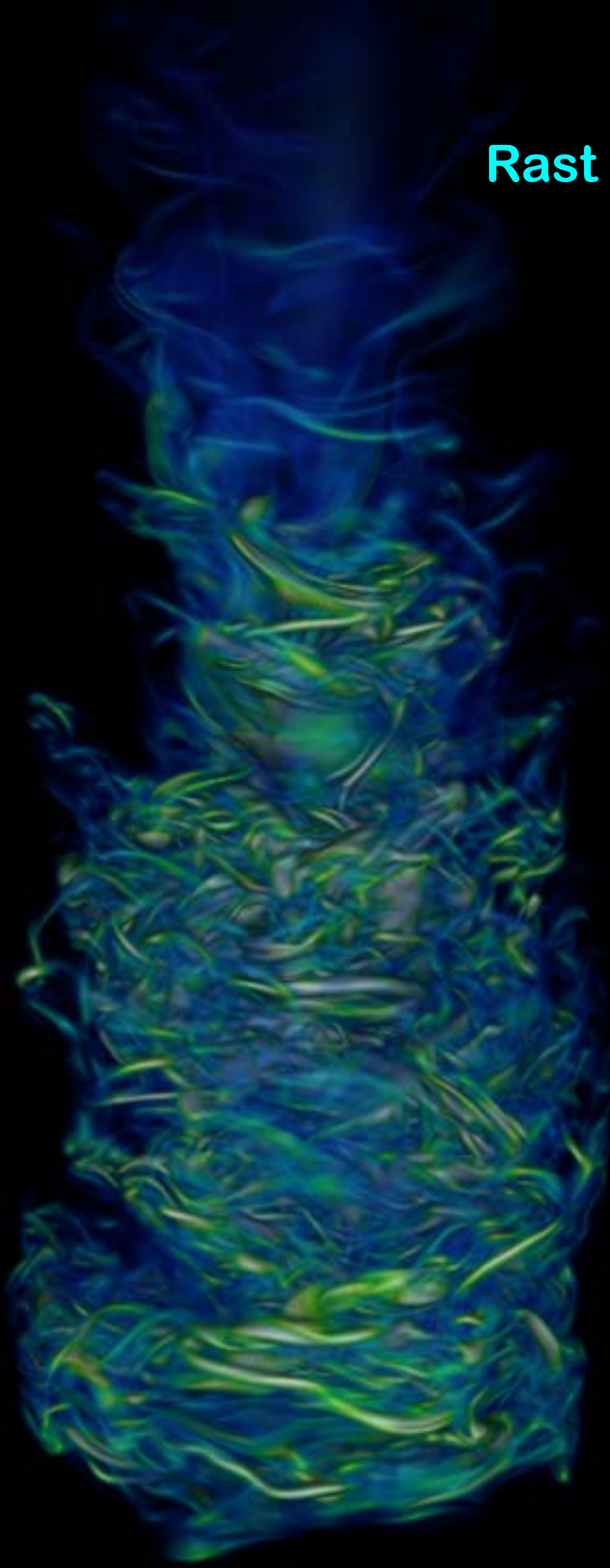
$$V_\Omega = \lambda \Omega \sim 1.1 \quad \mathrm{km\ s^{-1}}$$

Miesch et al (2012)

To sustain a meridional flow of ~ 2 m/s you need a convective velocity of at least 30 m/s

(5.8 m/s spread over = 1-60)

So what are deep convection models missing?



The answer may lie with convective plumes

Solar Convection is Surface-Driven

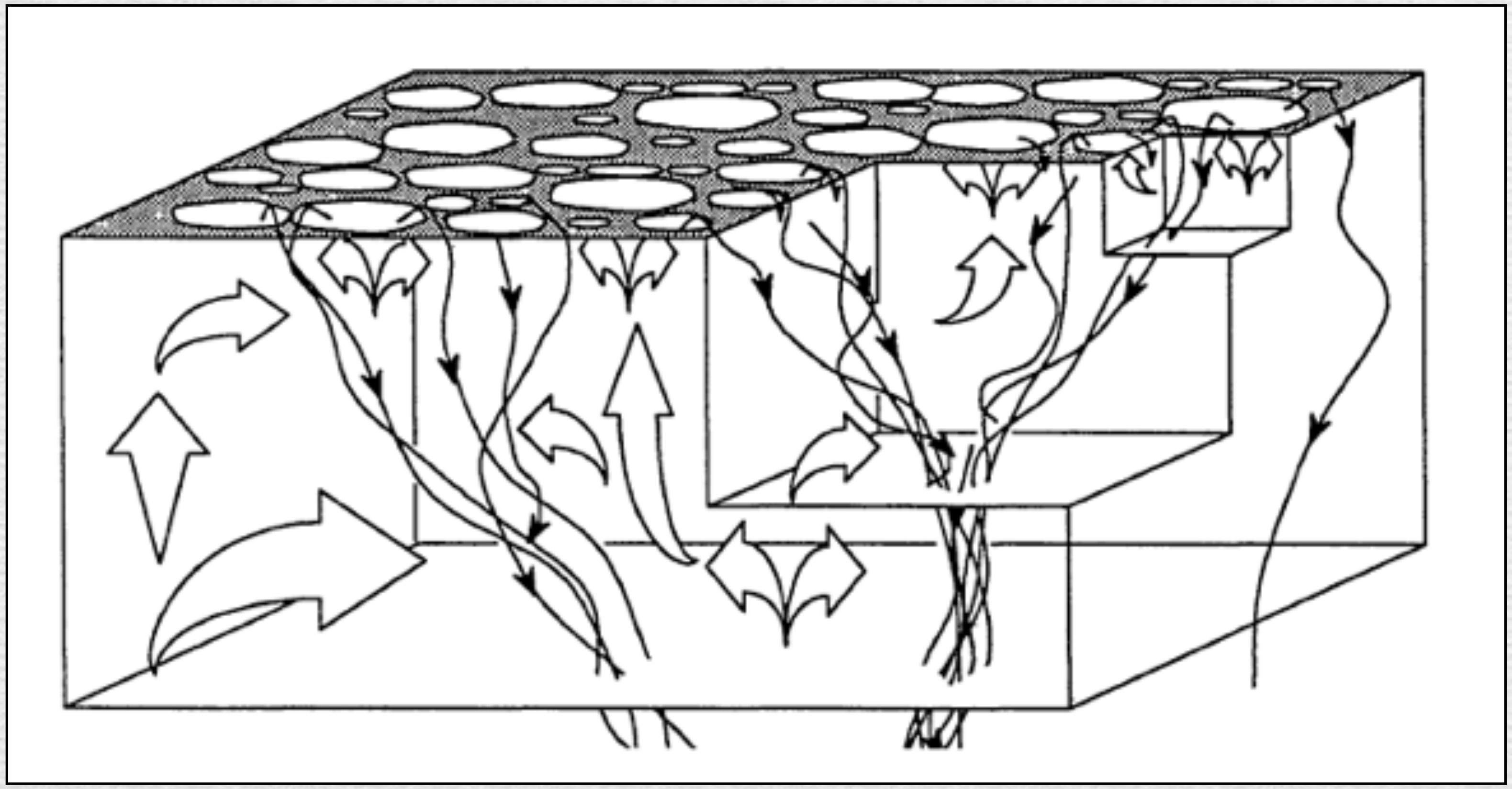
In the Sun, radiative cooling at the surface is much more efficient than radiative heating at the base of the CZ

Length scale for flux convergence ~ 100 Mm

Length scale for flux divergence ~ 100 km

Amplified by density contrast of ~ 10^6

Entropy variations in the solar convection zone originate at the upper thermal boundary layer



Spruit, Nordlund & Title (1990)

Upflows are isentropic and a response to downflows

Length, time scales increase with depth

Entropy Rain

Spruit (1997)

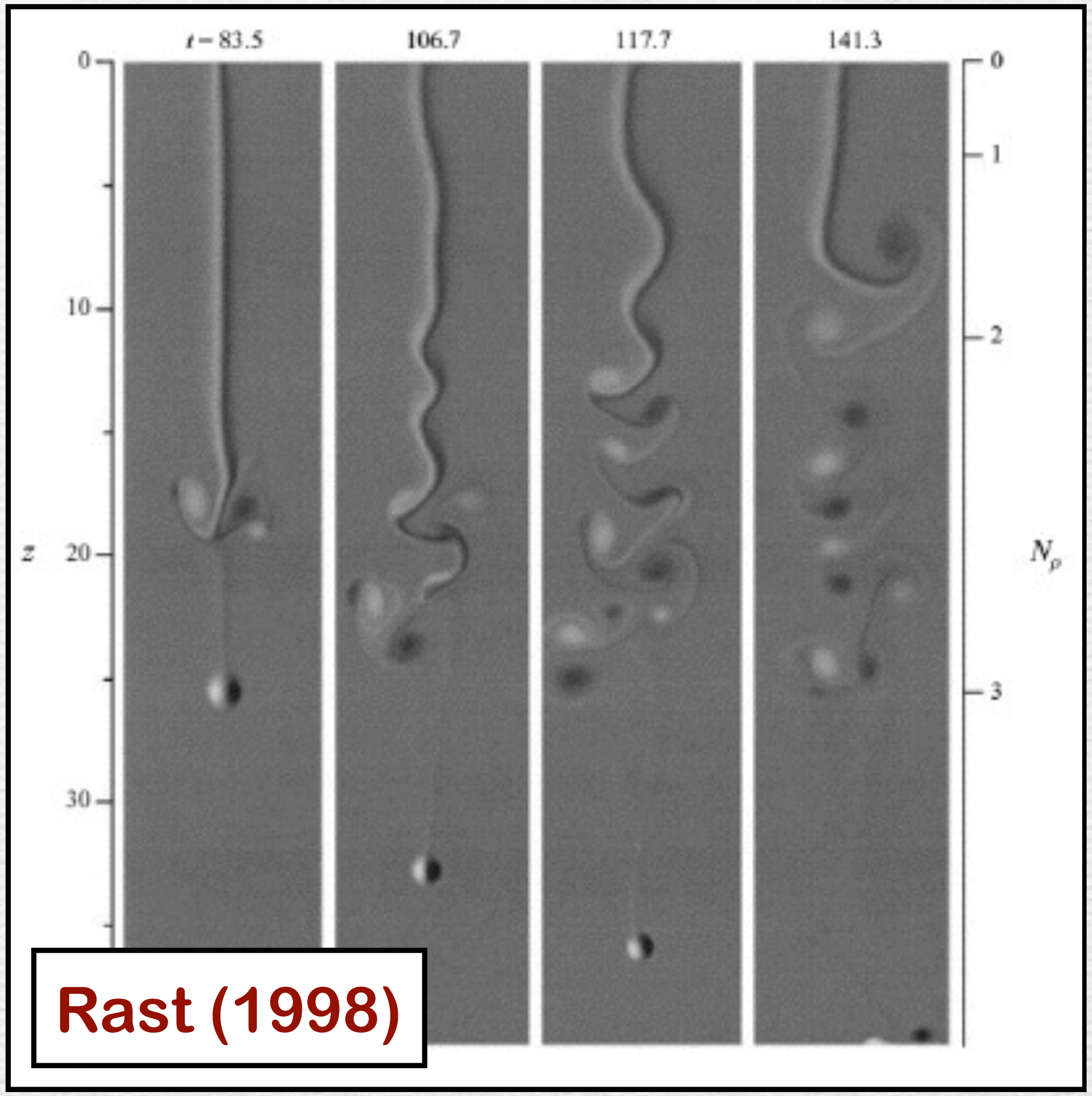
Heat transport dominated by threads of low-entropy fluid that drop down through the CZ

Even if they break up and get caught up in giant cells, the gravitational settling of droplets will still transport heat outward

High Peclet Number key to retaining a large thermal contrast

If bouyant acceleration is offset by thermal dissipative losses this leads to the Deardorff Flux (Brandenburg 2016)

$$\mathbf{F}_D = -\overline{s^2}\ \left(\tau\overline{\rho}\overline{T}/C_P\right)\ \mathbf{g}$$



Rast (1998)

$$\mathrm{Pe} = \frac{UL}{\kappa}$$

Global Simulations:

$\kappa \sim 10^{11}$-10^{12} cm^2 s^{-1}

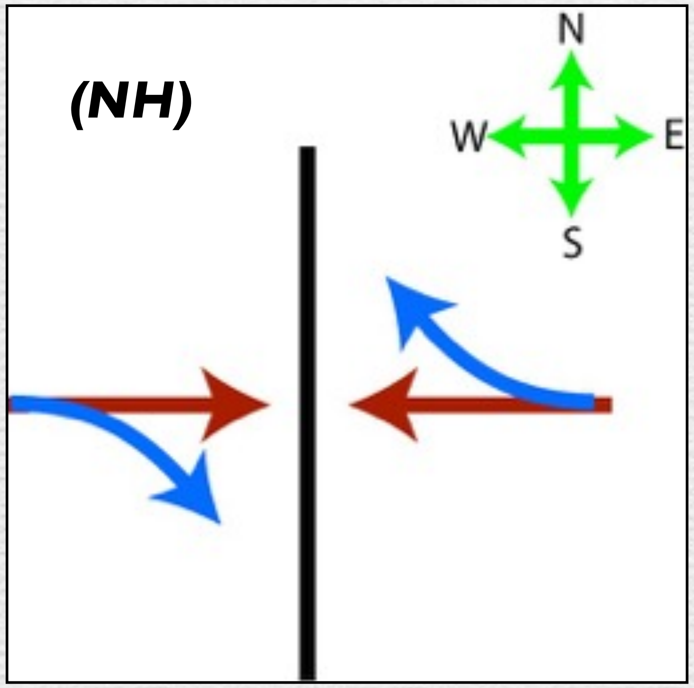
Sun:

$\kappa \sim 10^{7}$ cm^2 s^{-1}

But what about the differential rotation?

Equatorward angular momentum transport requires
Banana Cells

Giant cells big enough and slow enough to feel the Coriolis Force



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

$$R_o = \frac{\omega_{rms}}{2\Omega}$$

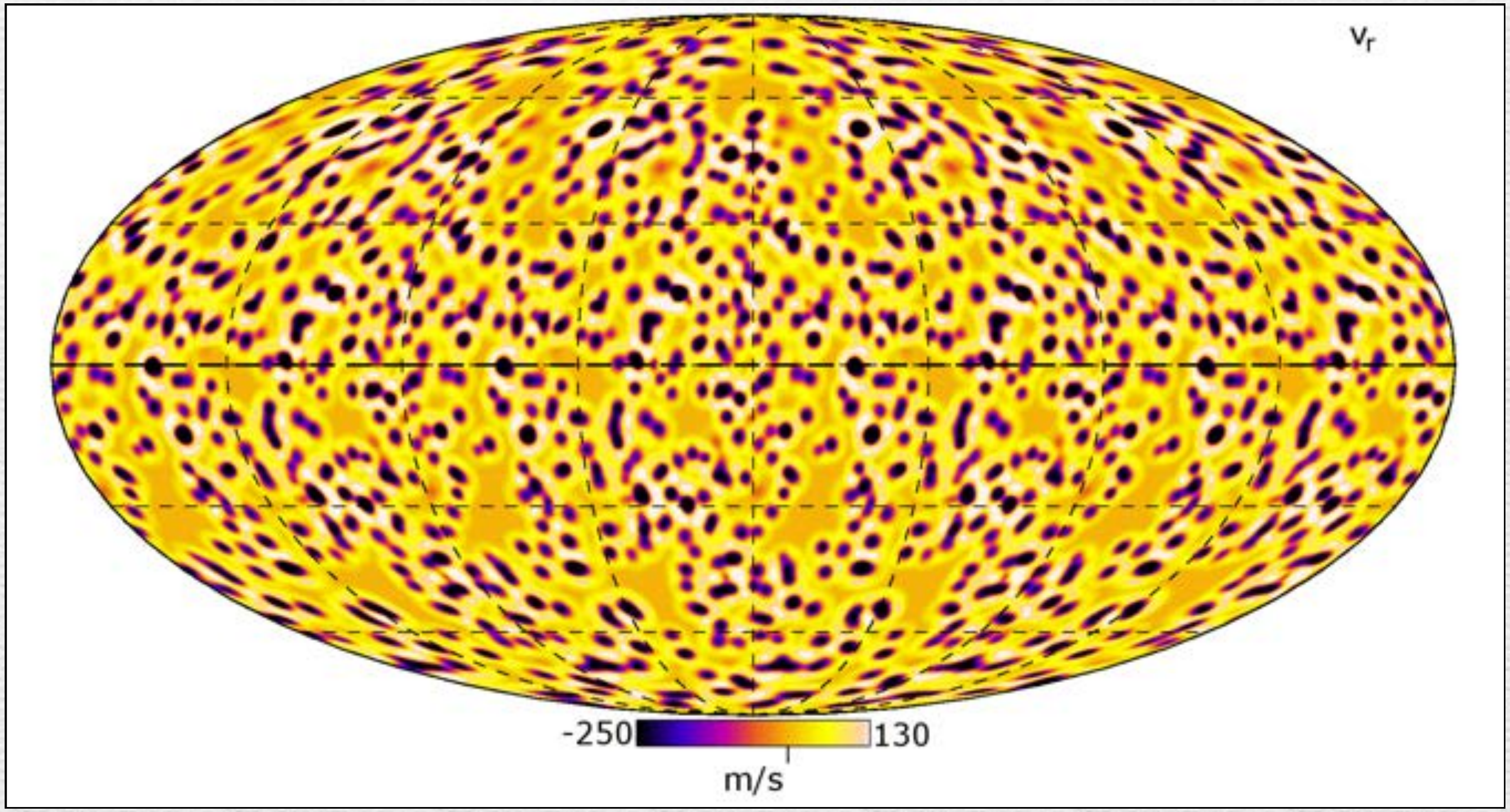
Featherstone (2016)

Suggests Possible Scale Separation

- ***Heat transport on small scales***
- ***Angular Momentum transport on large scales***

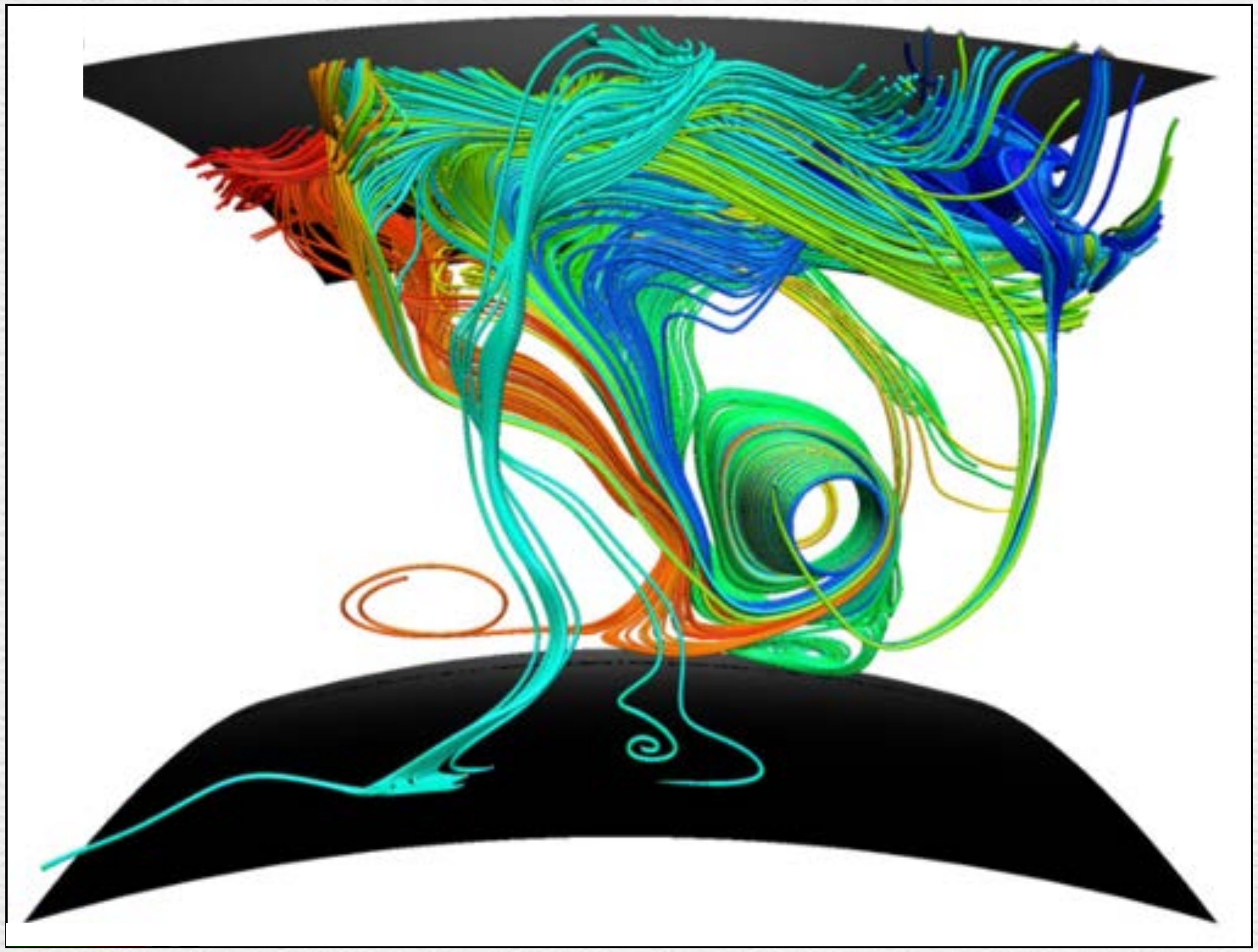
Plausibility test:

Replace homogeneous boundary condition in global convection simulations with small-scale plumes



Nelson et al (2017)

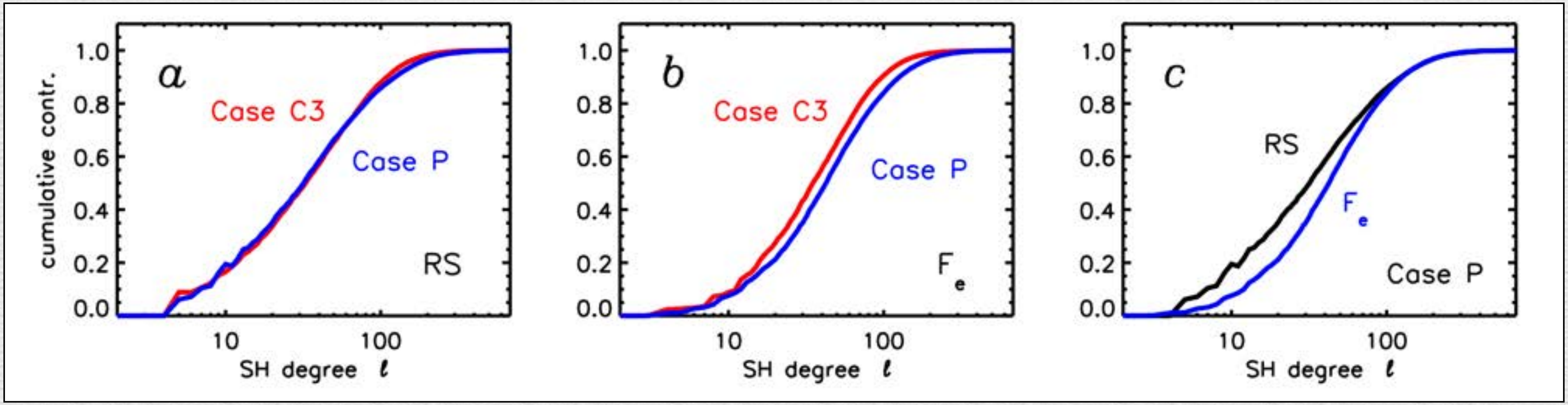
Plumes Imposed at Upper Boundary



Nelson et al (2017)

Self-organization of near-surface plumes into banana cells

(Weak) Scale separation of heat transport & angular momentum transport



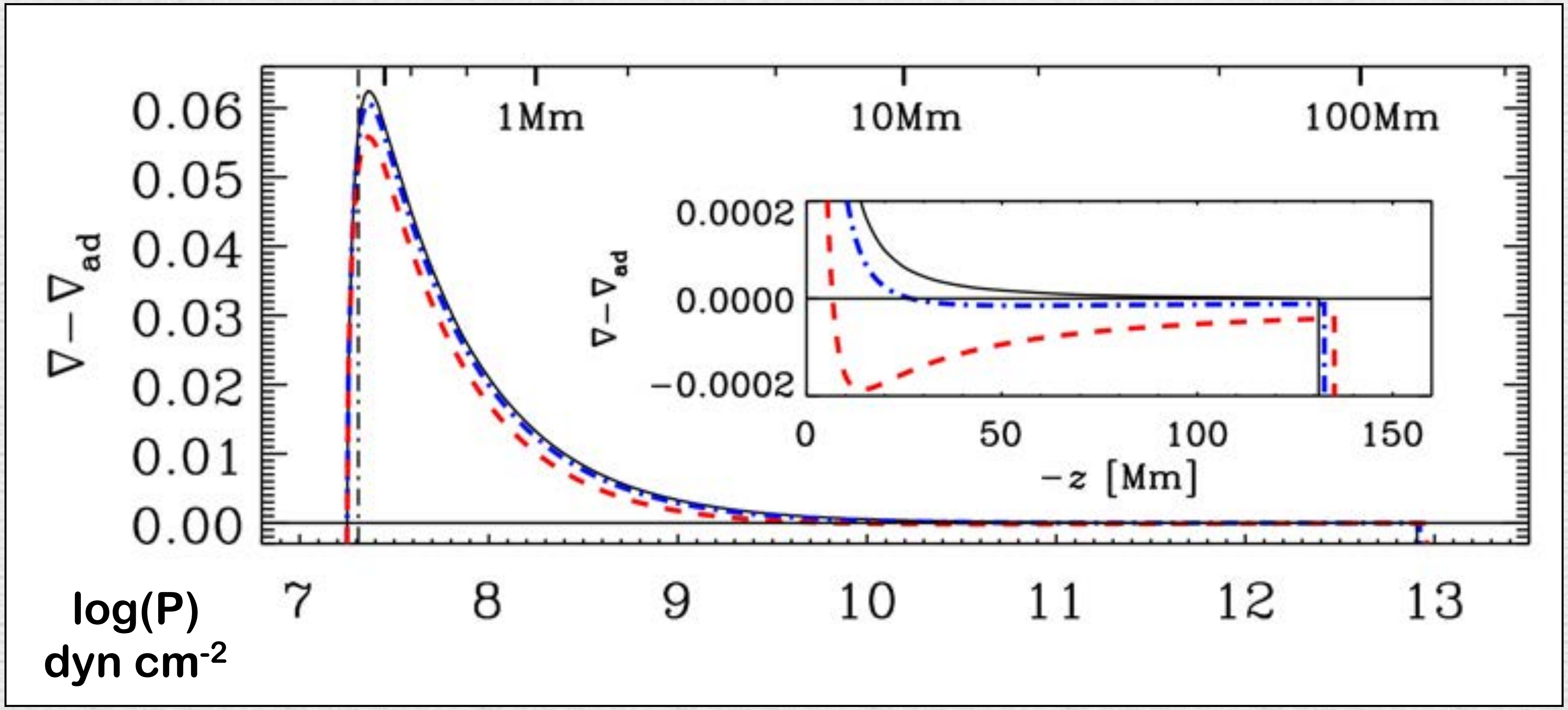
Subadiabatic Lower Convection Zone

An interesting consequence of the Deardorff flux:

$$\mathbf{F}_D = -\overline{s^2}\ \left(\tau\overline{\rho}\overline{T}/C_P\right)\ \mathbf{g}$$

It's always outward even if the stratification is subadiabtic (convectively stable)

If one includes this in MLT, one can find solutions where the stratification in much of the CZ is subadiabatic, but the heat flux is still outward



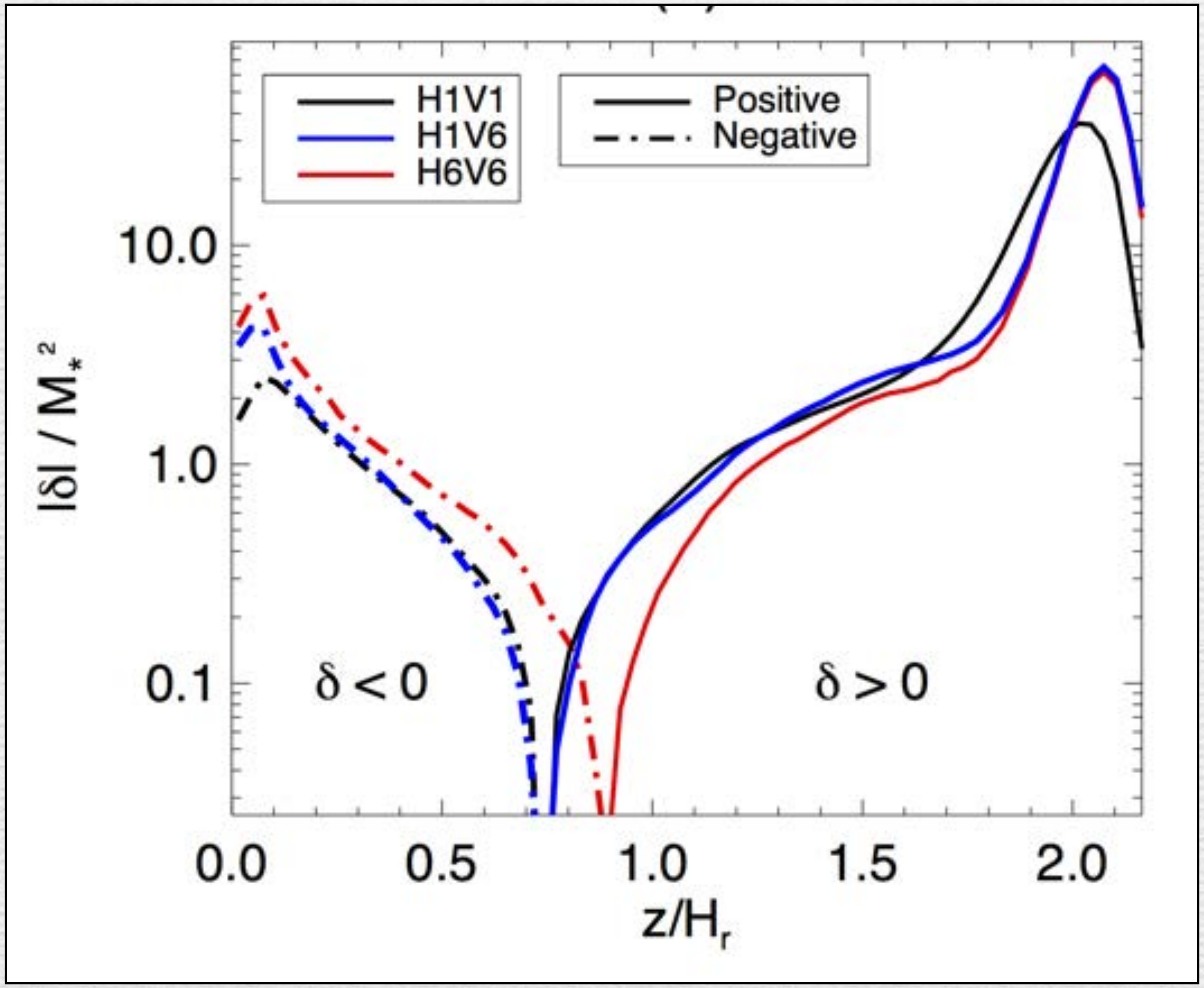
Brandenburg (2016)

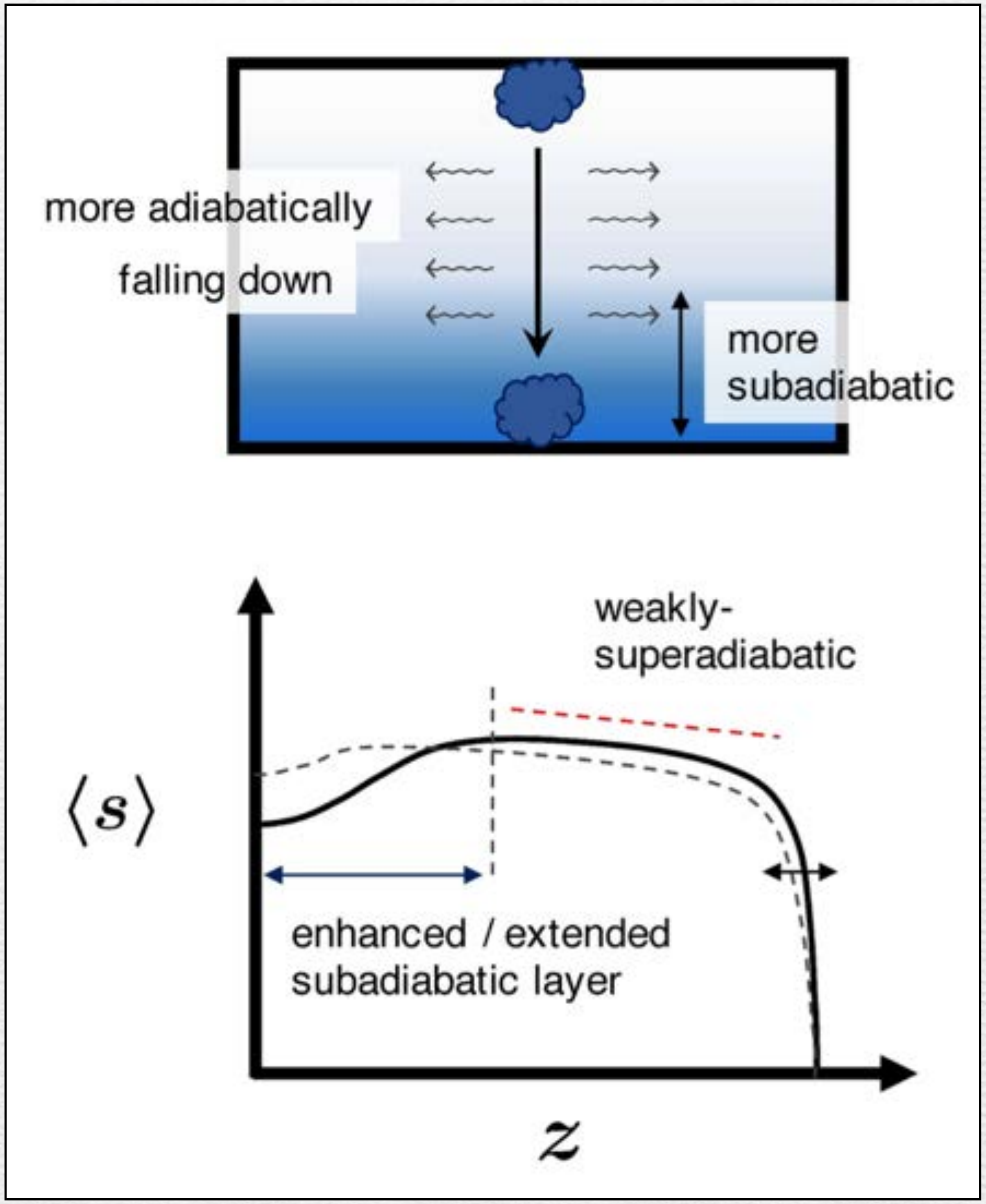
Subadiabatic Lower Convection Zone

Bekki et al (2017)

Subadiabatic stratification can arise in simulations from the accumulation of low-S fluid in the lower CZ when κ is small

(Large Pe and Pr)





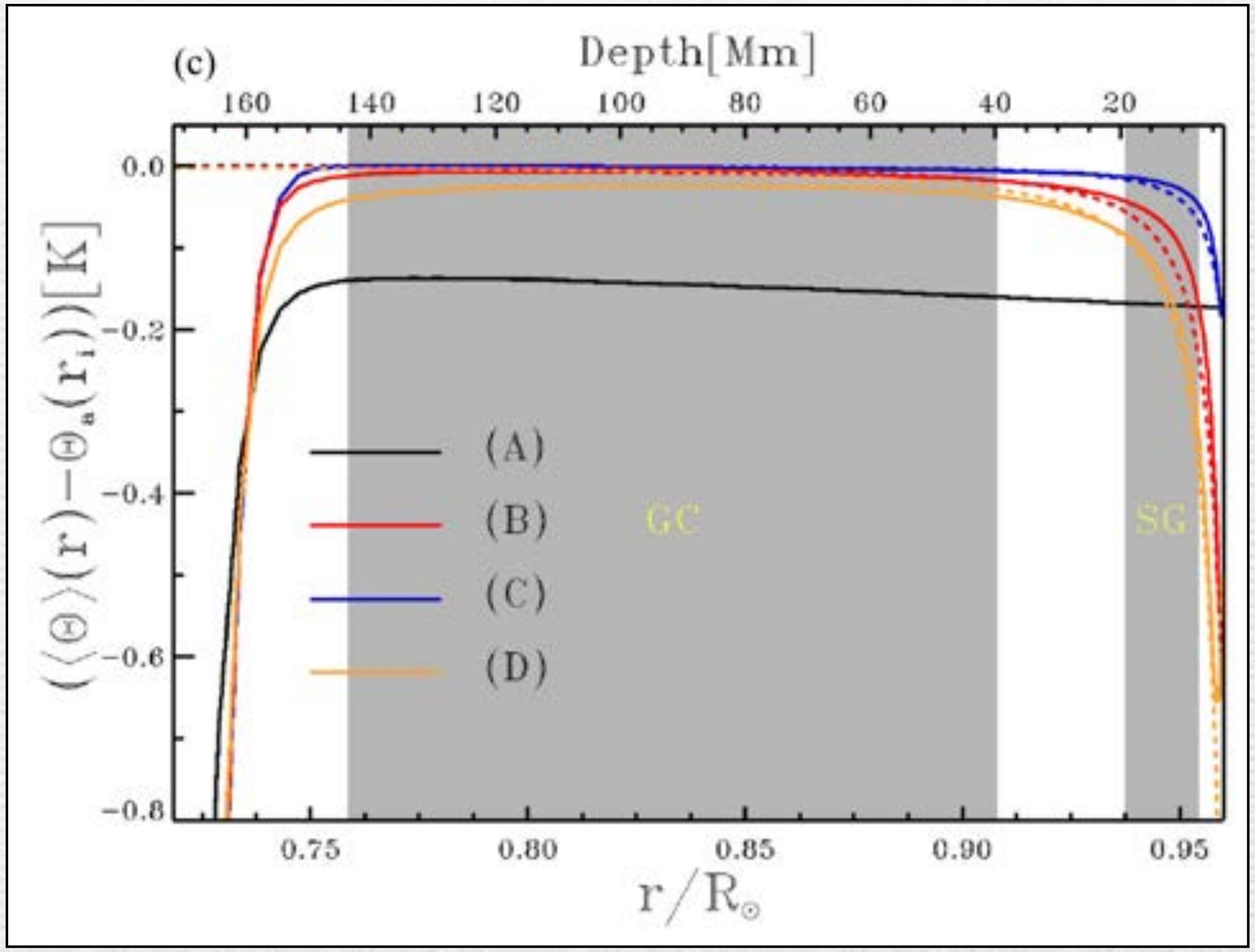
Käpylä et al (2017) emphasize Kramers opacity

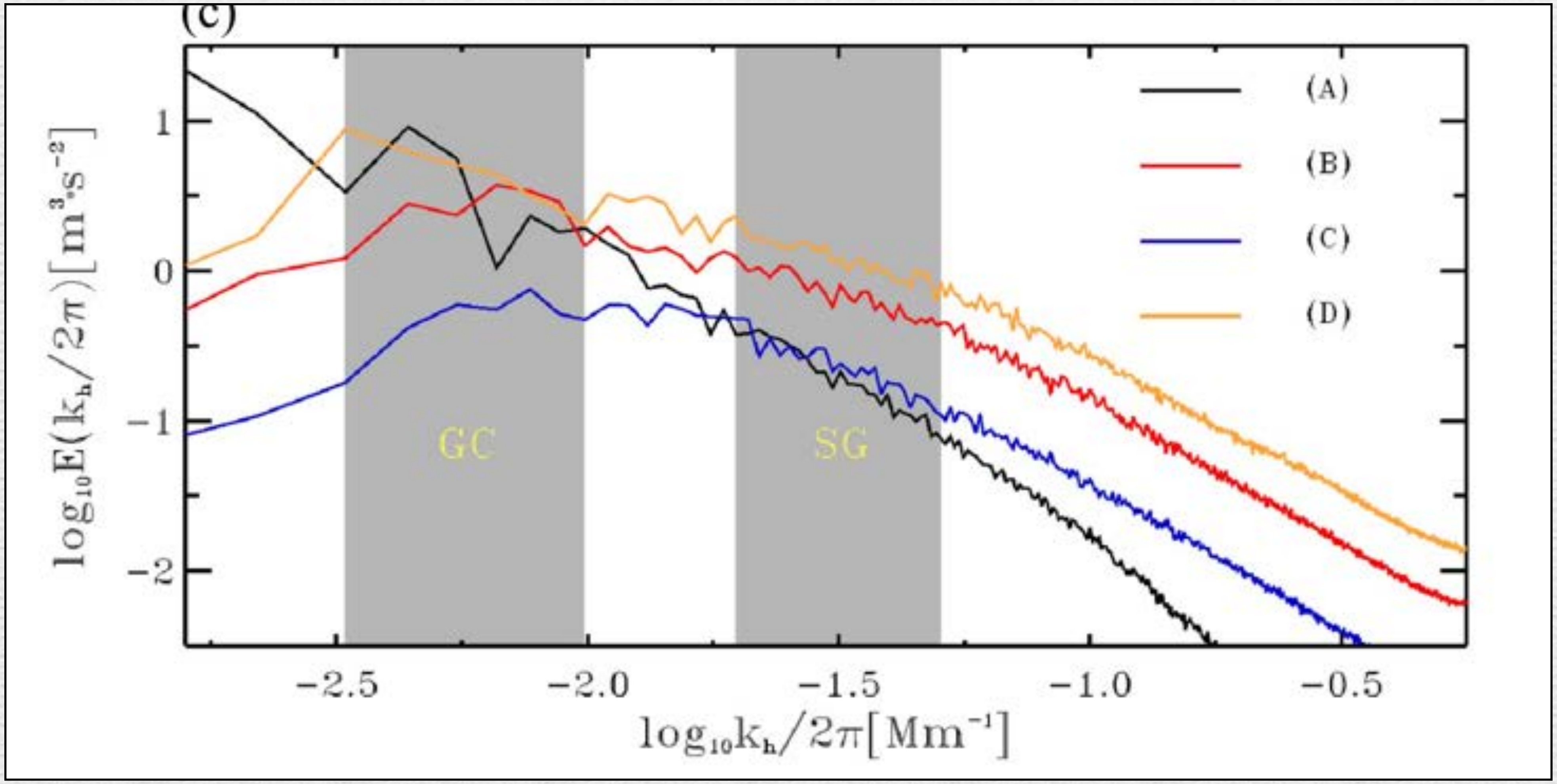
See also Hotta (2017), Korre et al (2017)

Subadiabatic Lower Convection Zone

Subadiabatic or adiabatic stratification in lower CZ suppresses large-scale power

(Stable to giant cells)





Cossette & Rast (2016)

High Prandtl Number also Helps (but maybe not enough?)

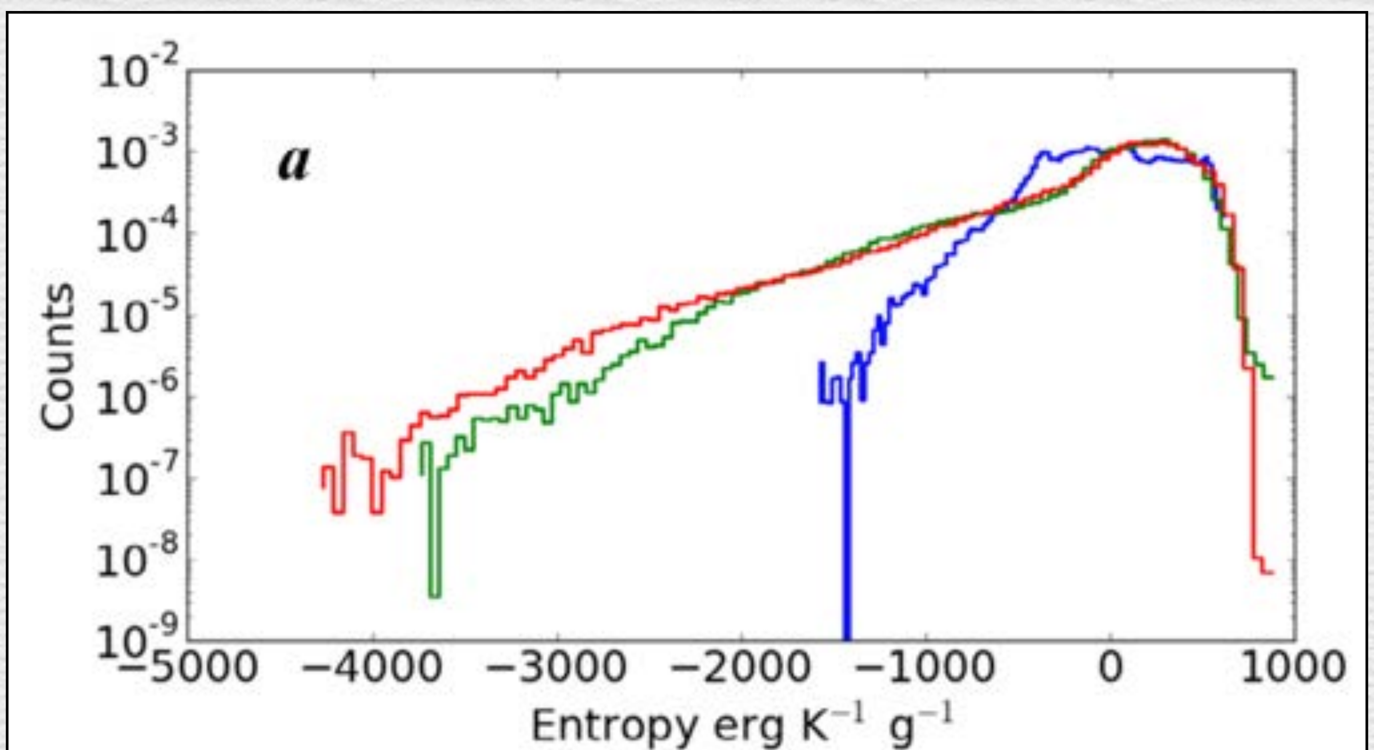
Low κ enhances thermal variations, requiring weaker velocities to carry the heat flux

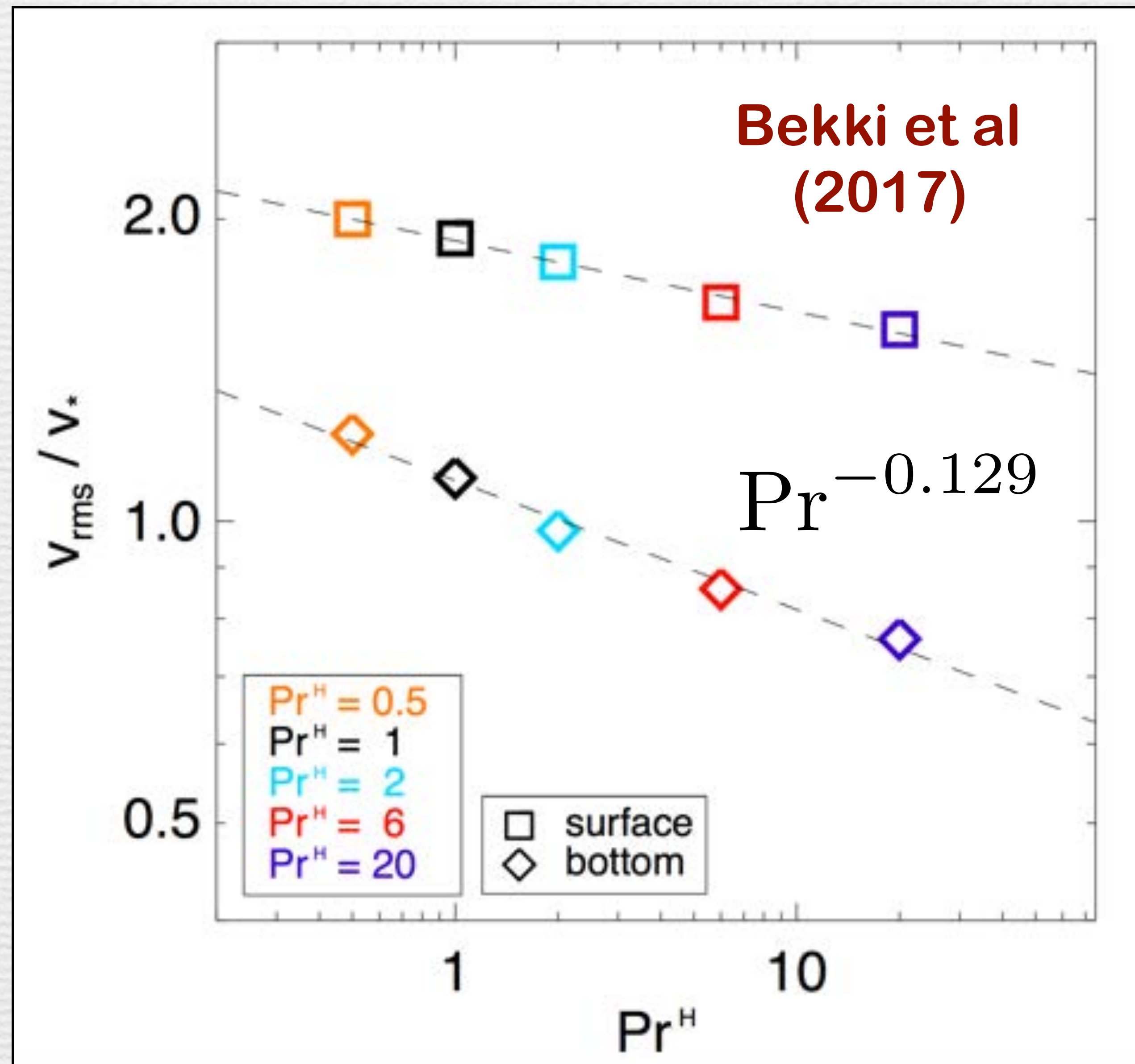
Relatively high ν promotes ⟨Tvr⟩ correlations by suppressing instabilities and turbulent mixing

O'Mara et al (2016)

$$\mathrm{Pr} = \frac{\nu}{\kappa}$$

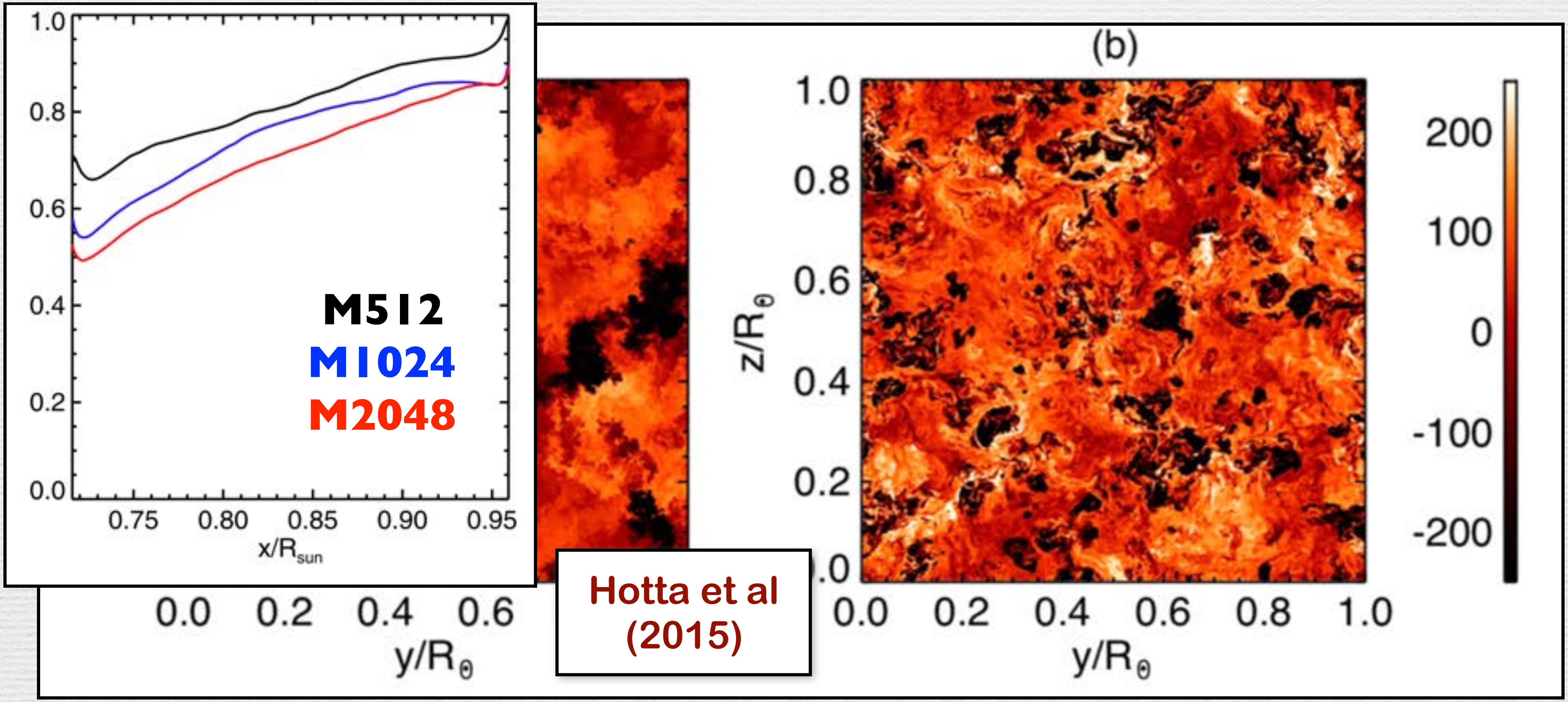
$$F_e = \rho C_P T v_r \sim \xi \, \frac{L}{4\pi r^2}$$





Why would the Sun Operate in the High Prandtl Number Regime?

Small-scale magnetism! **Can suppress horizontal mixing of thermal fluctuations (effectively increasing Pr and Pe)**



Hotta et al (2015)

Effective viscosity from magnetic fields can also act to lower V_c, shifting the solar ⇒ anti solar DR transition to lower Ω

(Fan & Fang 2014; Karak et al 2014)

Blame it on Rotation?

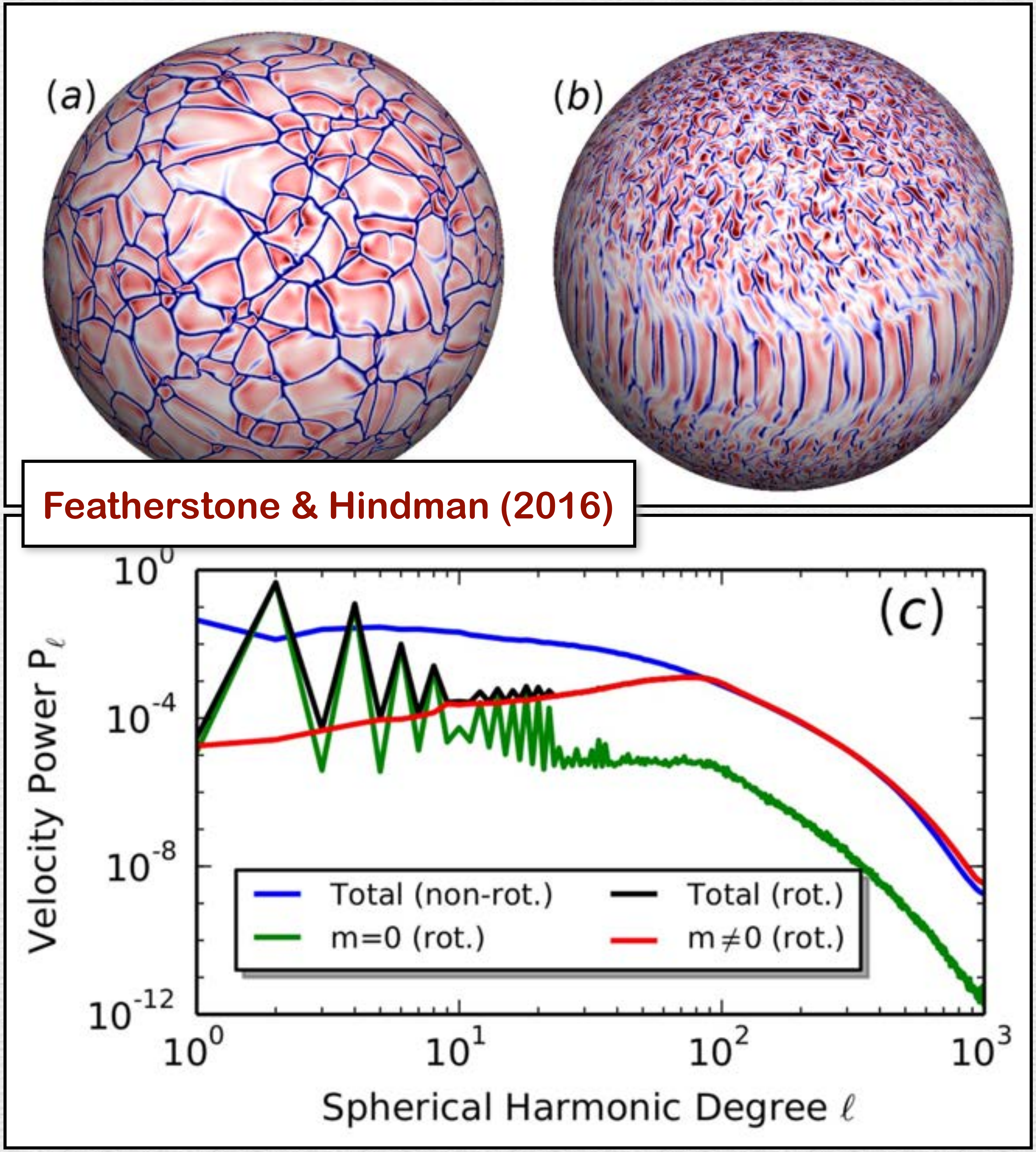
$$\mathrm{Ek} = \frac{\nu}{\Omega L^2}$$

If Ek << 1, Ro << 1

Then convection is highly rotationally constrained

Power spectrum may peak at SG scales!

Giant cells may not be so giant!



Summary and Outlook

The Convection Conundrum

- Excess convective power on large scales
- A: Helioseismic inversions (controversial)
- B: Observations & Simulations of surface convection

C: Anti-solar differential rotation in global simulations

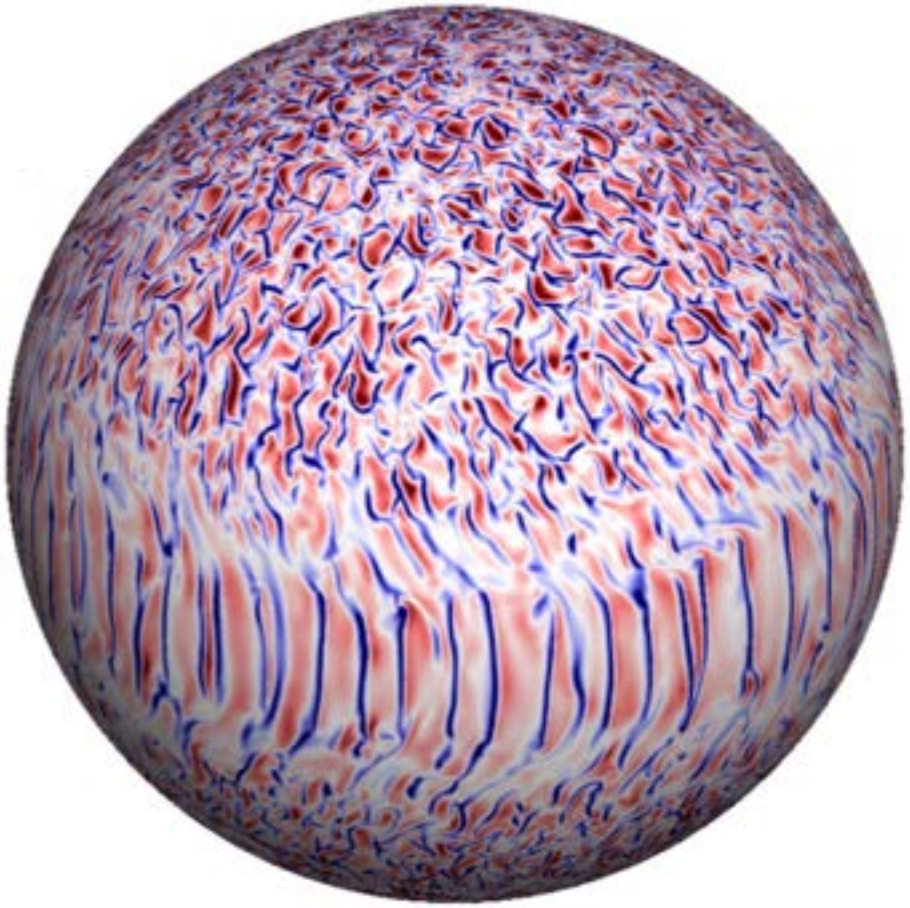
Summary: Where do We Stand?

Will any of these be enough?

Possible solutions

- **Entropy rain**
  - Scale separation between heat transport & angular momentum transport?
- **Subadiabatic stratification in lower CZ**
  - Accumulation of entropy rain
  - High Pe, Pr
  - Convective driving limited to upper CZ
  - Suppresses large-scale motions
- **Small-Scale Magnetism**
  - Suppresses shear, laminarizing flow
  - Enhances thermal variations by suppressing horizontal mixing
- **Rotation**
  - Shifts power spectrum toward small scales

Outlook: How Should we Proceed?



Featherstone & Hindman (2016)

Observations - What to look for

- Robust local inversions!
- Small Vc would imply small Ro
- NS alignment/anisotropy
- Latitude-dependent heat flux?

Modeling

- SGS modeling of entropy rain?
- Global impacts of Small-scale dynamo

Synergy of observations and modeling

- Near-surface shear layer and the transition from surface to deep convection

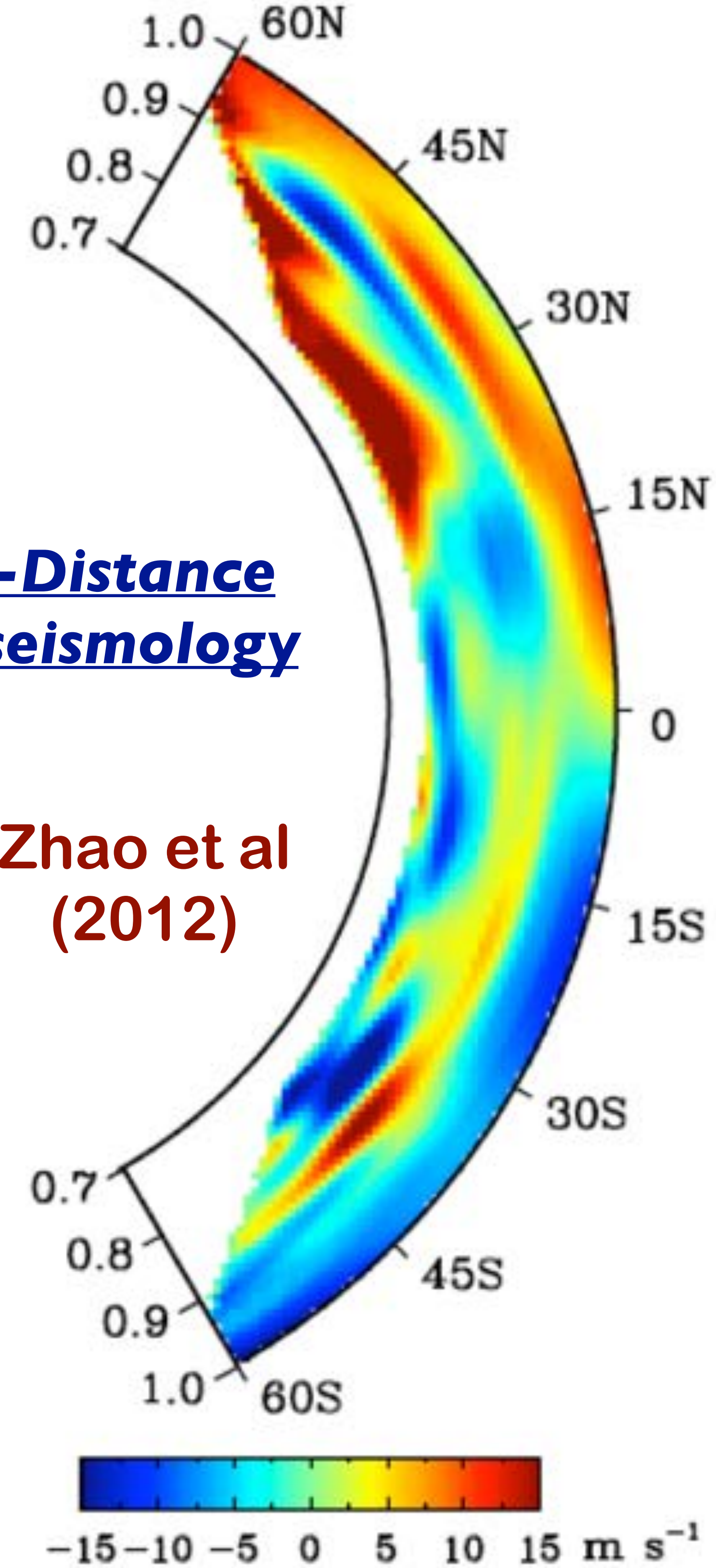
Example: Shallow Return Flow

May be established by a convergence of inward angular momentum flux

May signify the penetration depth of coherent plumes

What lies below?

- ***"Rain Droplets"?***
- ***Rapid falloff of convective power?***
- ***Subadiabatic stratification and loss of convective driving?***



Time-Distance Helioseismology

Zhao et al (2012)

Also seen in correlation tracking (Hathaway 2012)

Convective Amplitude required to maintain mean flows

An estimate of δ based solely on observables

$$\dot{M} = \rho V_m 2\pi r L_t$$

$$\delta \sim \frac{\dot{M}}{\rho V_m 2\pi r^2}$$

$$V_c \gtrsim \left(\frac{\dot{M}|\boldsymbol{\nabla}\mathcal{L}|}{2\pi r^2 \rho}\right)$$

(r ~ 0.95R)

Where $\dot{M}$ is the poleward mass flux at mid-latitudes above r ~ 0.95 R

Plugging in values deduced from helioseismology gives

V_c > 30 m/s at r ~ 0.95R

However, if ν is decreased along with κ

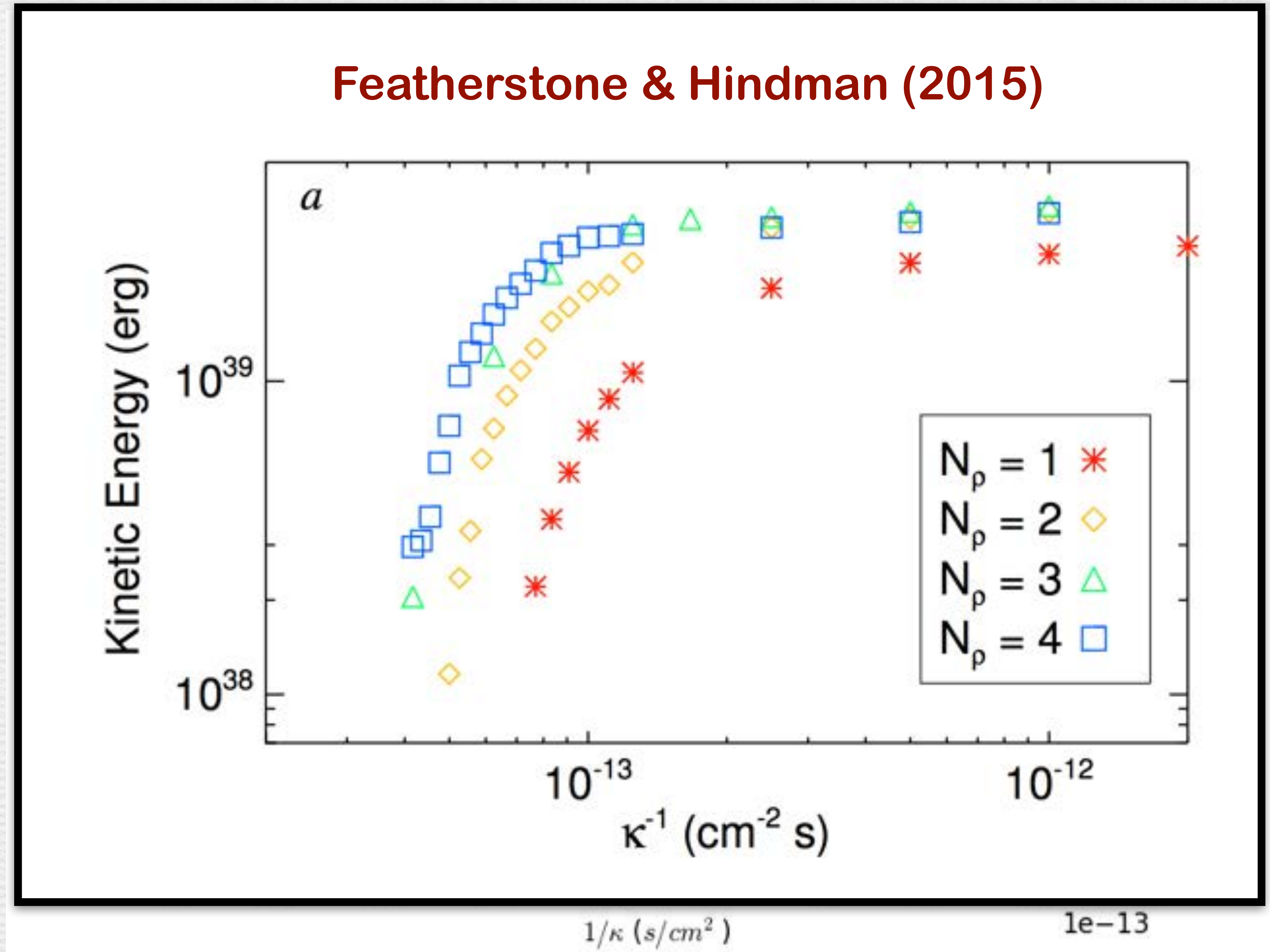
(P_r = 1)

then the effect is lost

V_c approaches a constant value with decreasing dissipation

(Featherstone & Hindman 2015)

$$\mathrm{Pr} = \frac{\nu}{\kappa}$$



Why the difference? Larger Re makes the flow more turbulent, inhibiting v_r T' correlations

V_c now determined largely by free-fall potential energy budget (FH15)