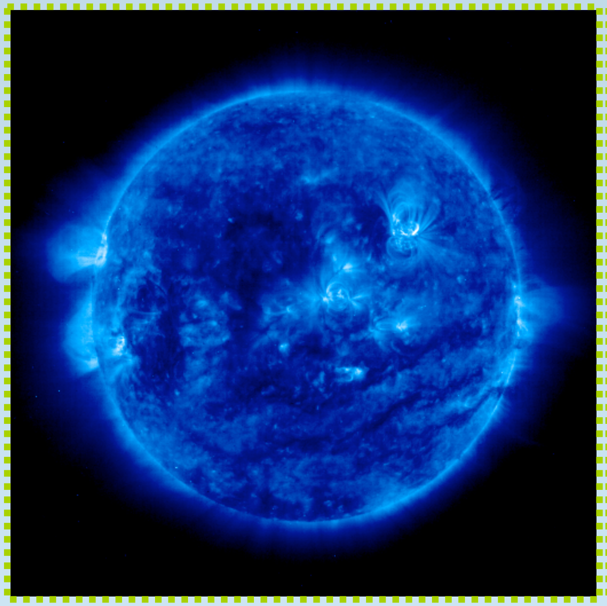
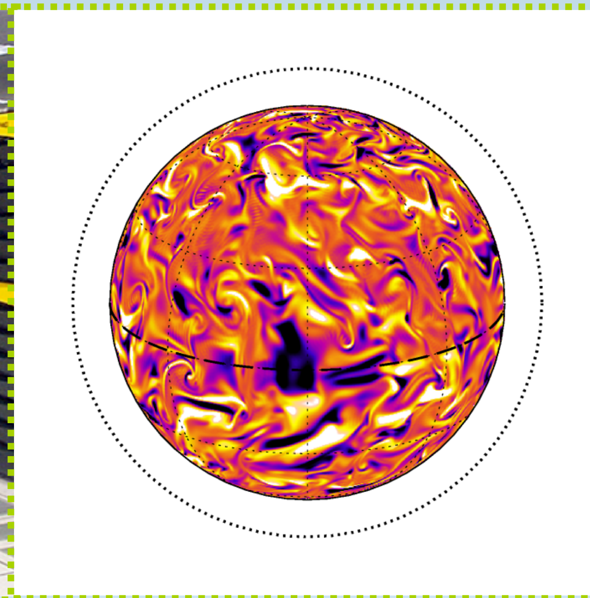
Momentum transport in stars



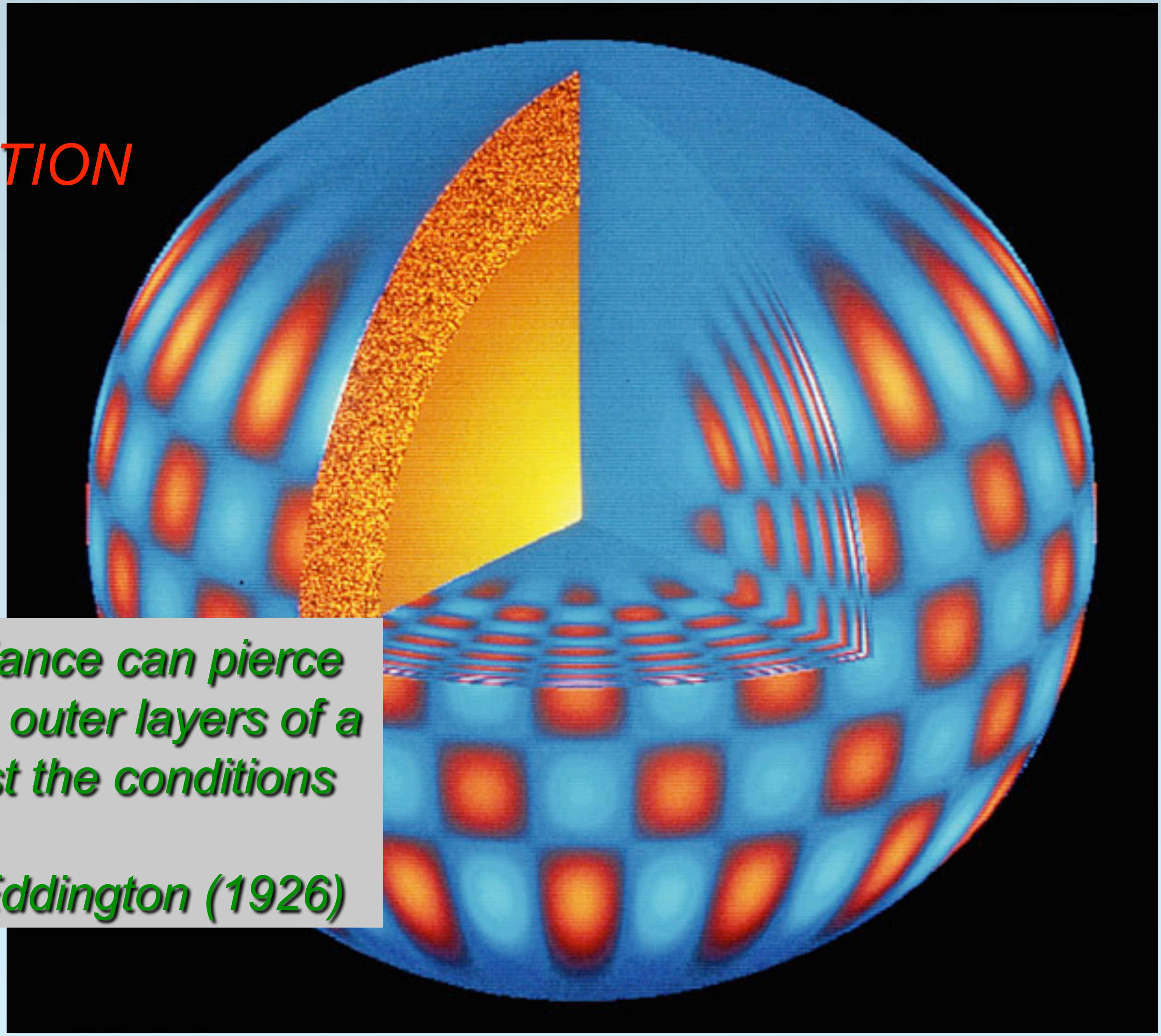


Matthew Browning

with work from Mark Miesch, Sacha Brun

Juri Toomre, Gibor Basri, Ben Brown

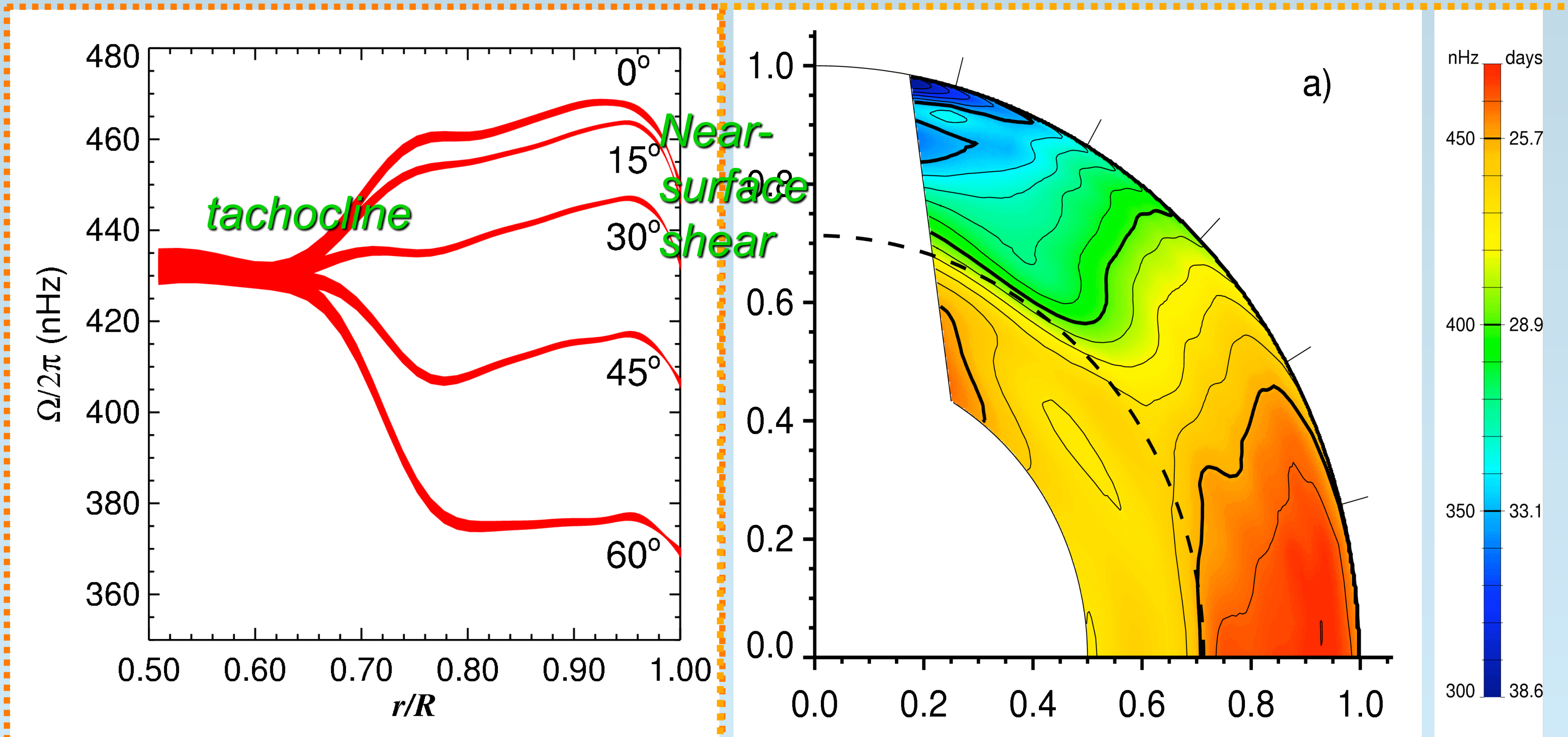
SOLAR OSCILLATION MODE



"What appliance can pierce through the outer layers of a star and test the conditions within?"

-Eddington (1926)

Internal rotation profile revealed

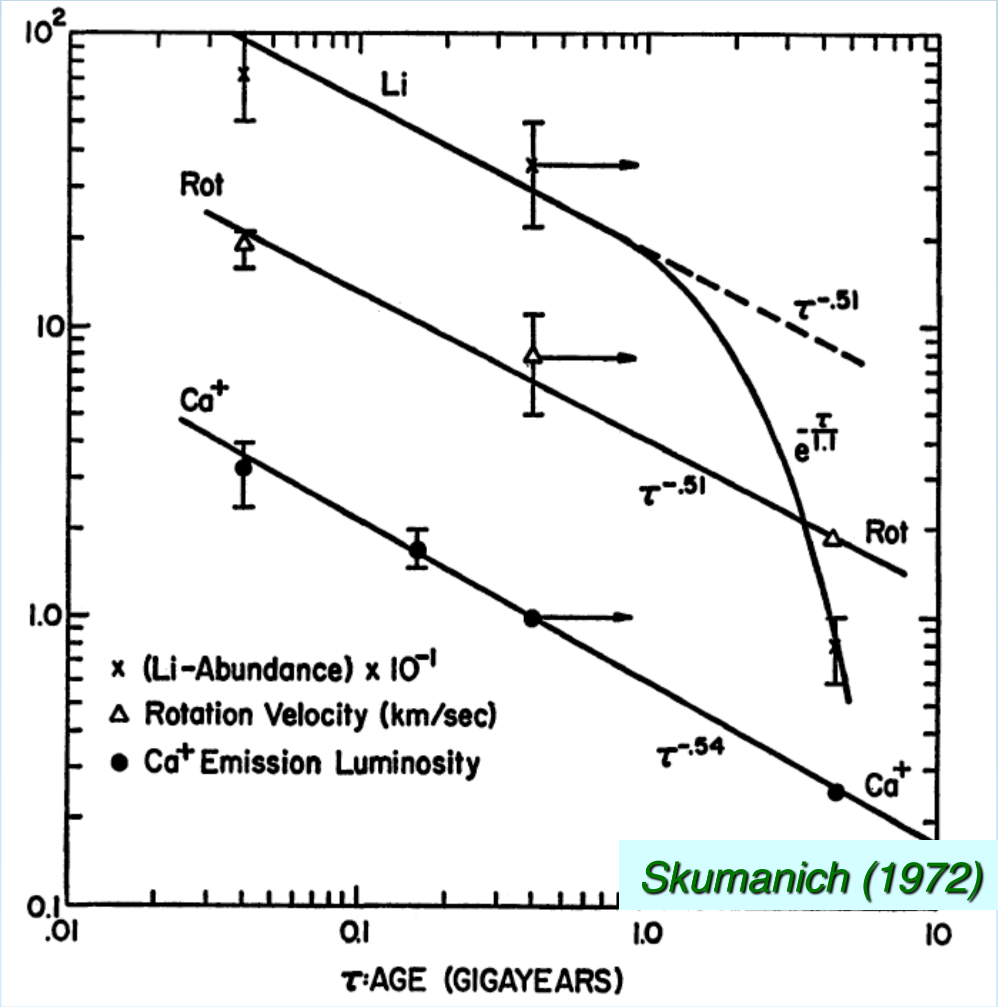


- Tachocline of rotational shear at base of CZ probably plays crucial role in solar dynamo

Rotational braking

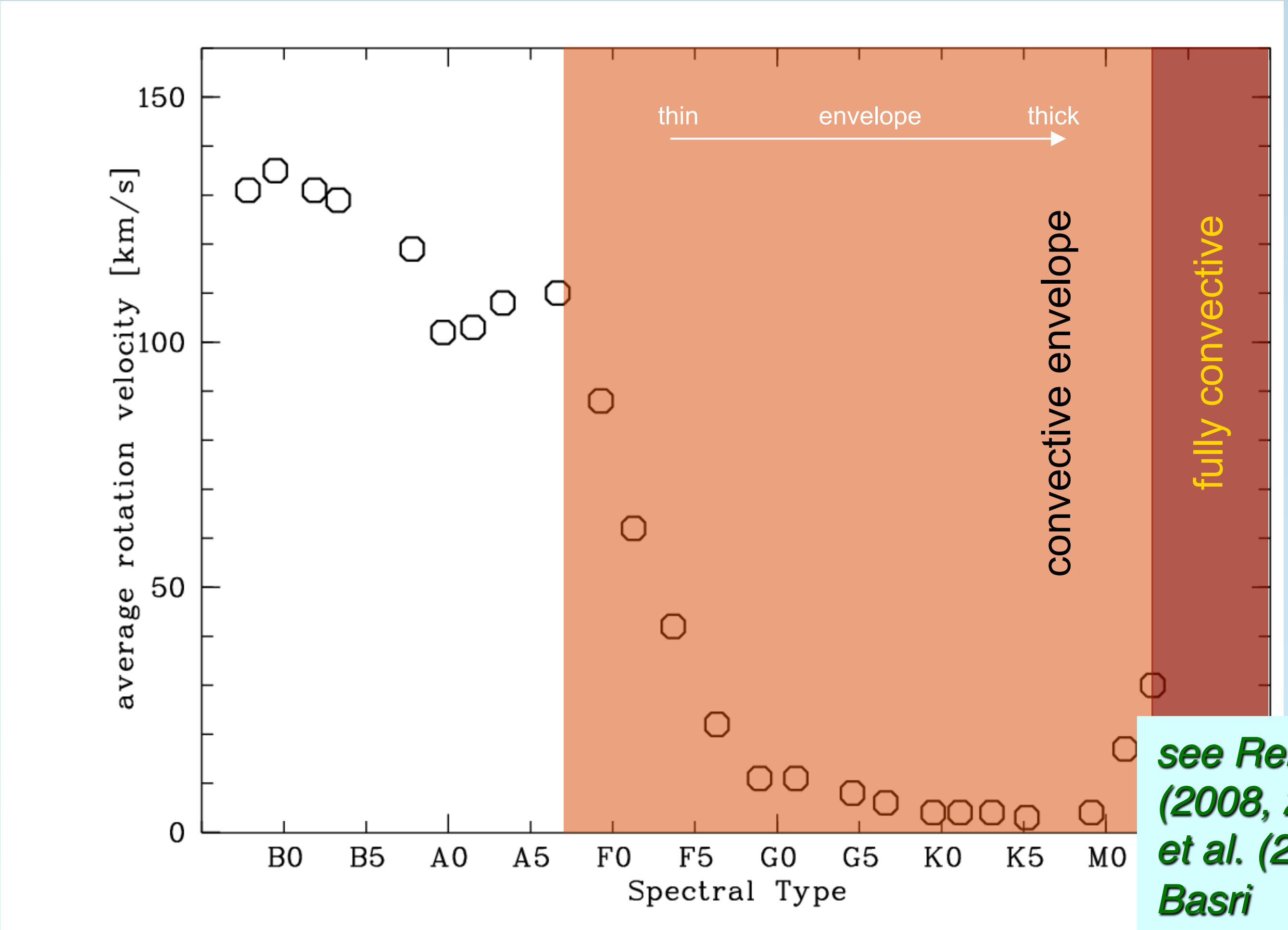
Stars spin down over time

As angular momentum is lost to magnetized wind



Skumanich (1972)

Mass-dependence of braking



see Reiners et al. (2008, 2009); Browning et al. (2009); Reiners & Basri

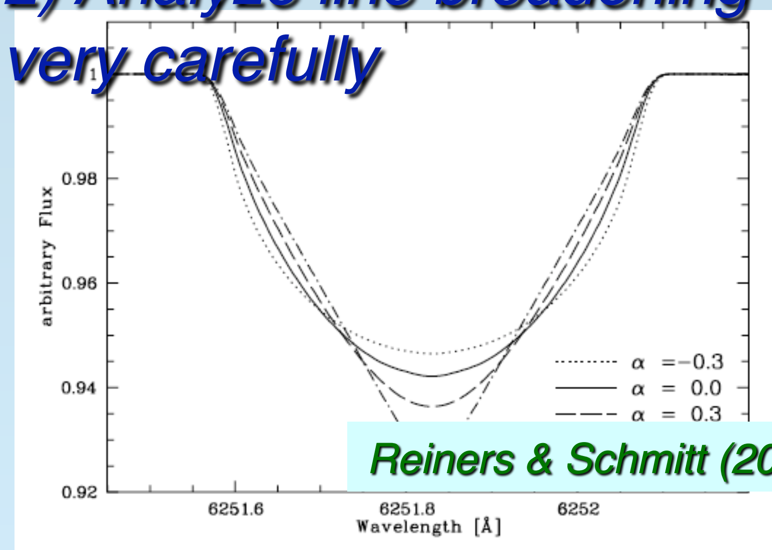
Timescale for braking depends on stellar mass

Core-envelope coupling poorly understood

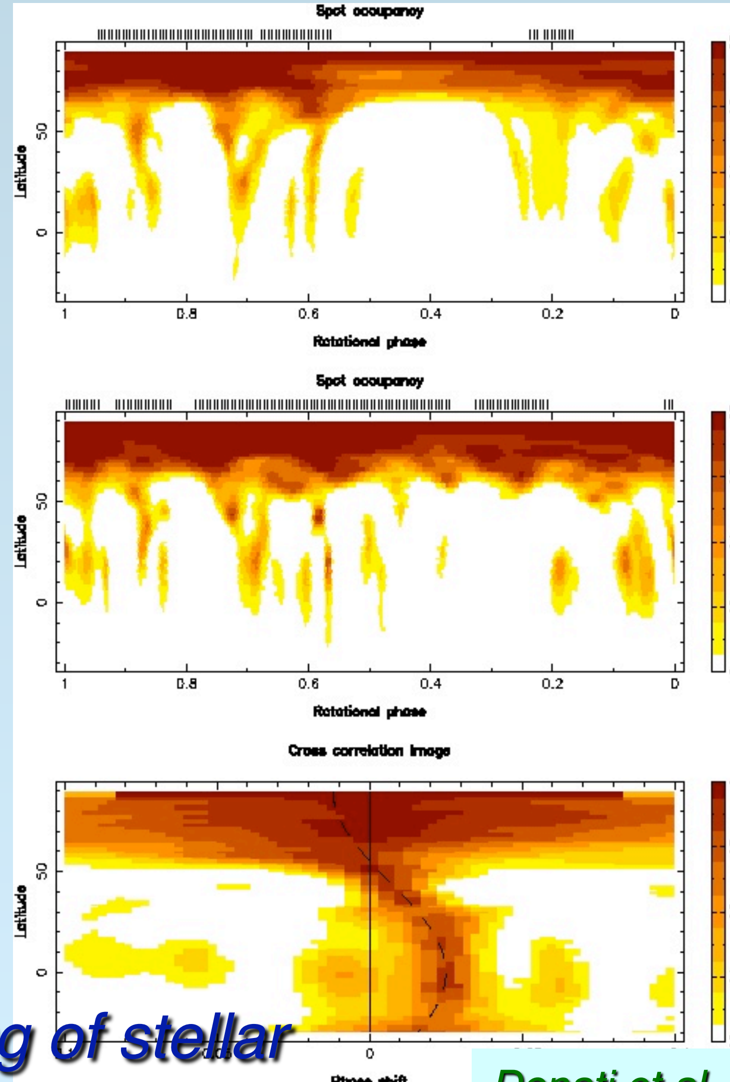
Differential rotation on other stars?

Methods. 1) measure rotation period variation for years

2) Analyze line broadening very carefully

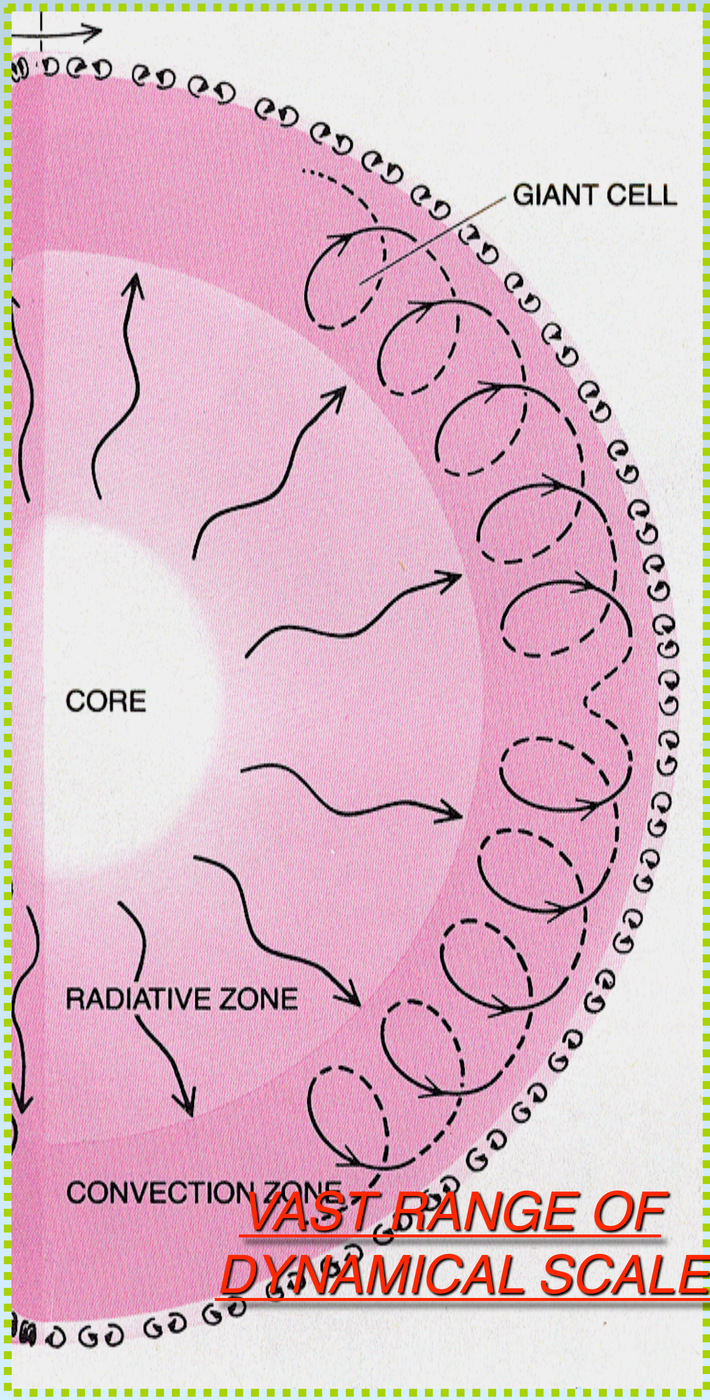


Reiners & Schmitt (2002)



Donati et al.

3) Doppler imaging of stellar surface (+ x-corl in time)

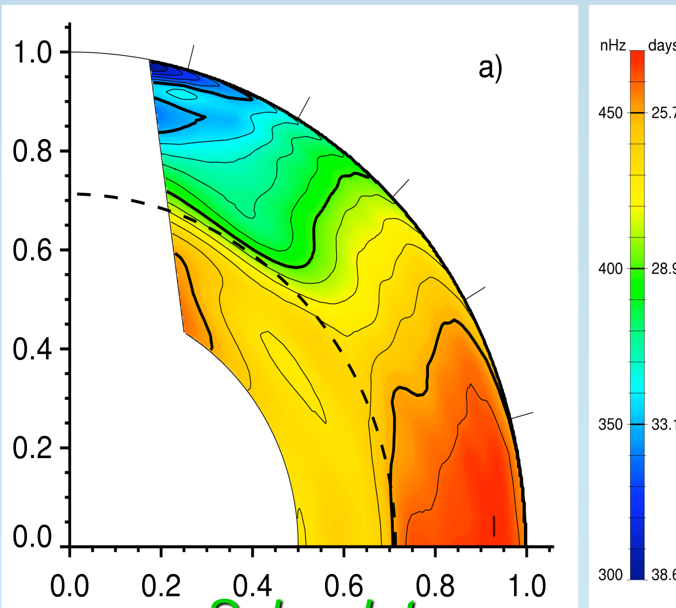


VAST RANGE OF DYNAMICAL SCALES

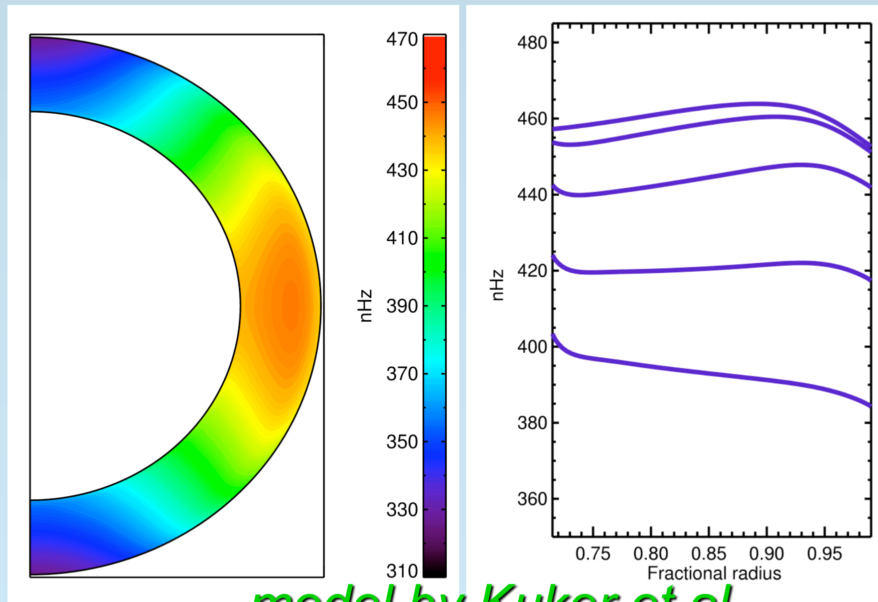
Motivating questions: order amidst chaos

- How does convection establish strong differential rotation?
- Is this process generic in stars? (How does it depend on mass, rotation, etc?)

Methods of attack 1: mean-field/closure models



Solar data



model by Kuker et al.

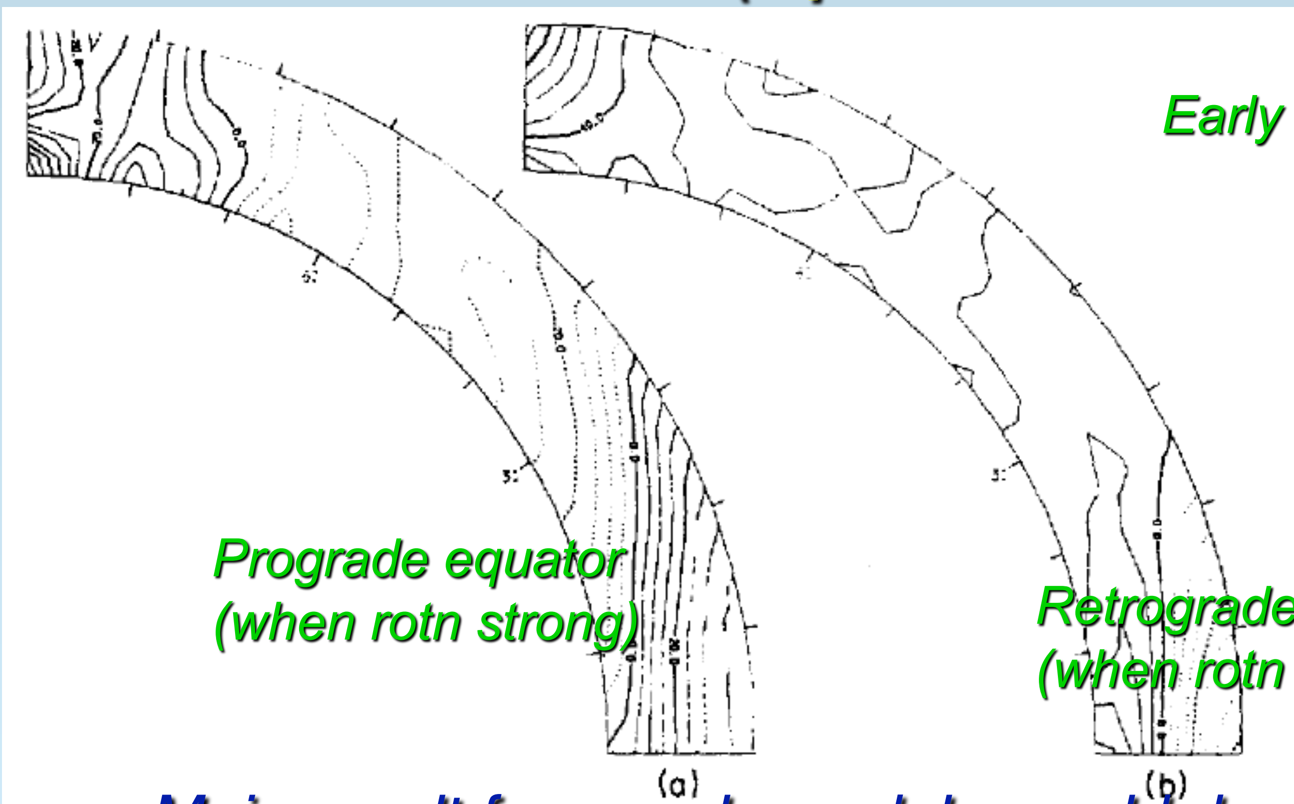
Idea: adopt some prescription for Reynolds stresses, etc -- classic turbulent closure problem

Can essentially duplicate solar rotation profile, but have some "free" parameters

(predictions for other stars are not yet clear)

Methods of attack 2:
3-D simulations (spherical or otherwise)

Early work by Gilman (1979)



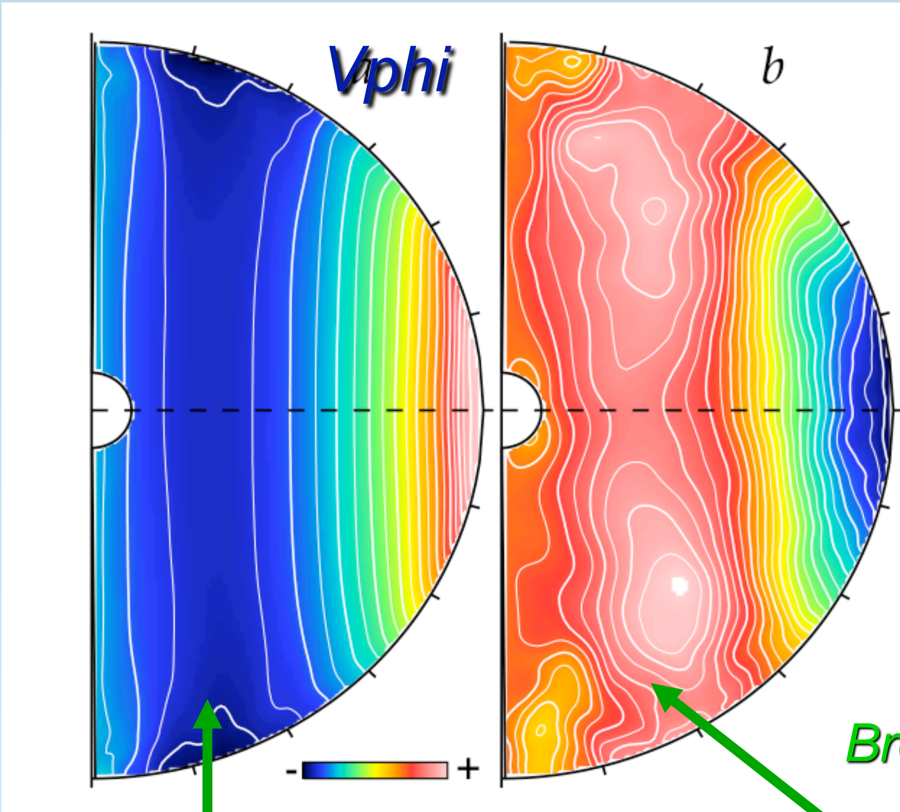
Prograde equator (when rotn strong)

Retrograde equator (when rotn weak)

Main result from early models: could duplicate solar EQ speedup, but interior angular velocity nearly constant on cylinders (Proudman-Taylor)

NB also: direction of transport different in slow/fast rotators

Equatorial speedup or slowdown



"Solar-like" surface differential rotation generically realized when rotation strong(ish)

Anti-solar rotation realized in very slow rotators

Big caveat: magnetic fields

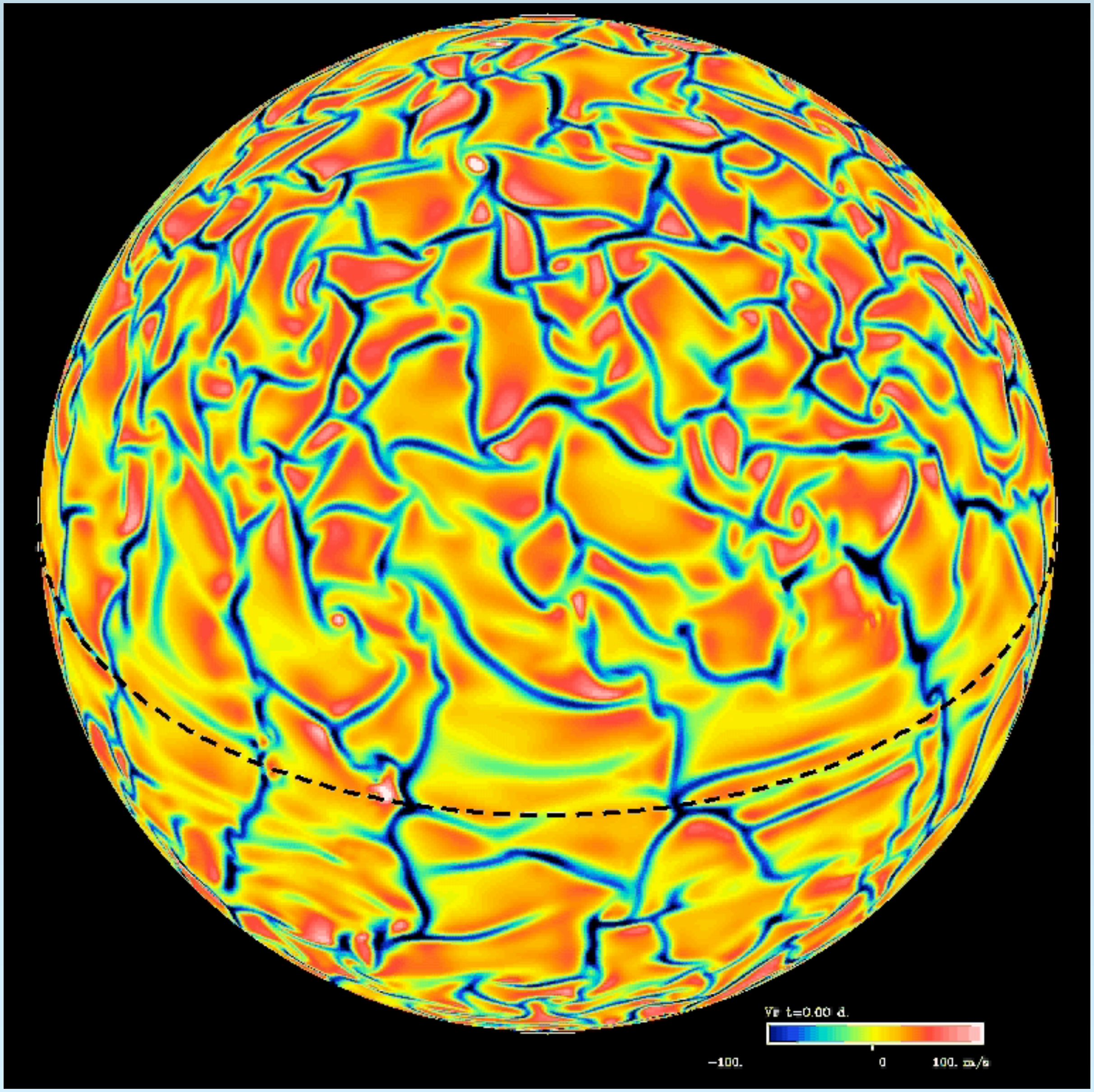
Browning (2010)

Rotating at solar angular velocity (Ro~0.2)

Rotating ten times slower

Clear observational prediction (not yet tested)

Vigorous and evolving convection



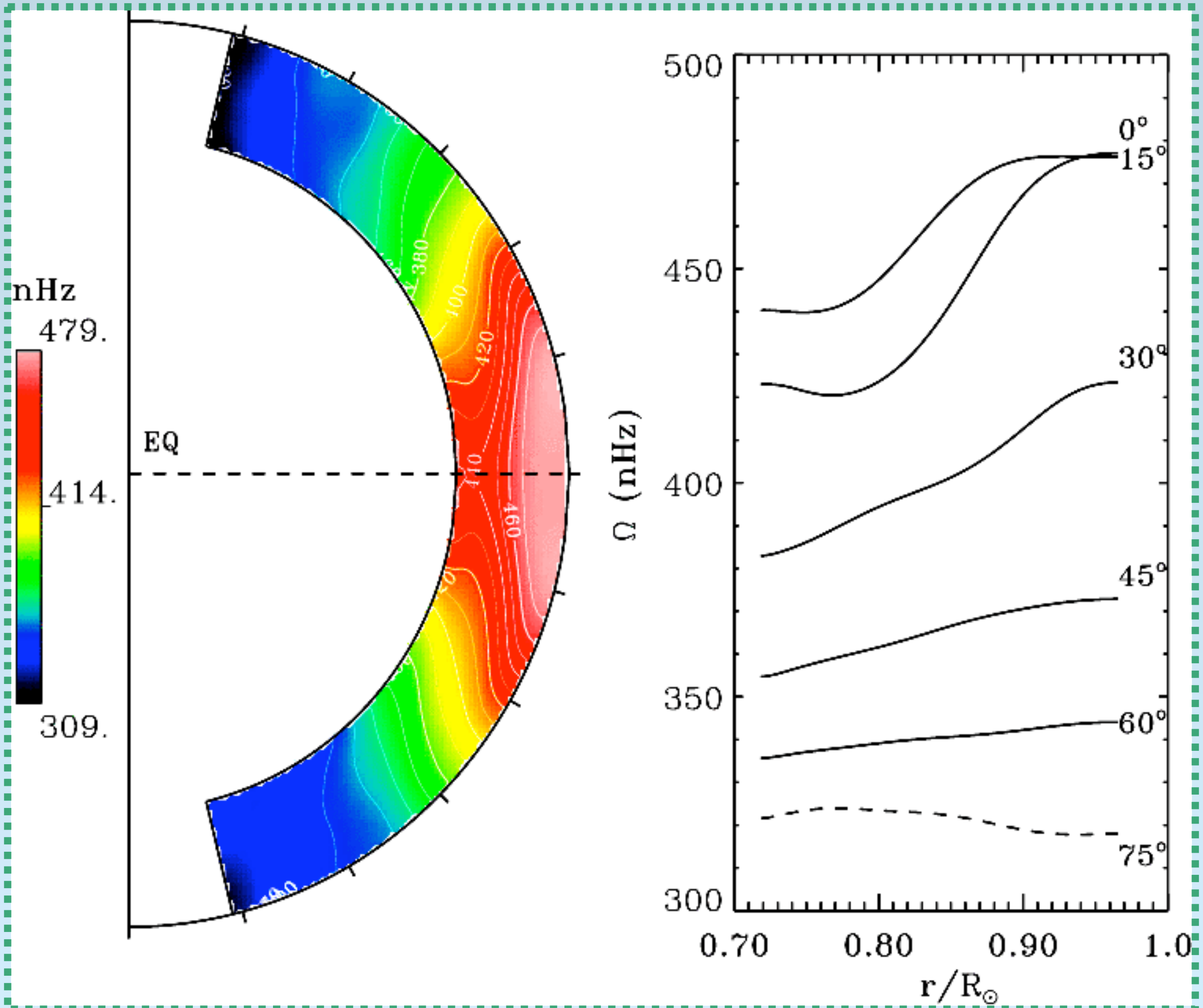
Radial velocity V_r near top of "solar" CZ

Broad upflows, narrow downflows

Coherent structures that persist

Case E, Brun et al.

Differential rotation realized

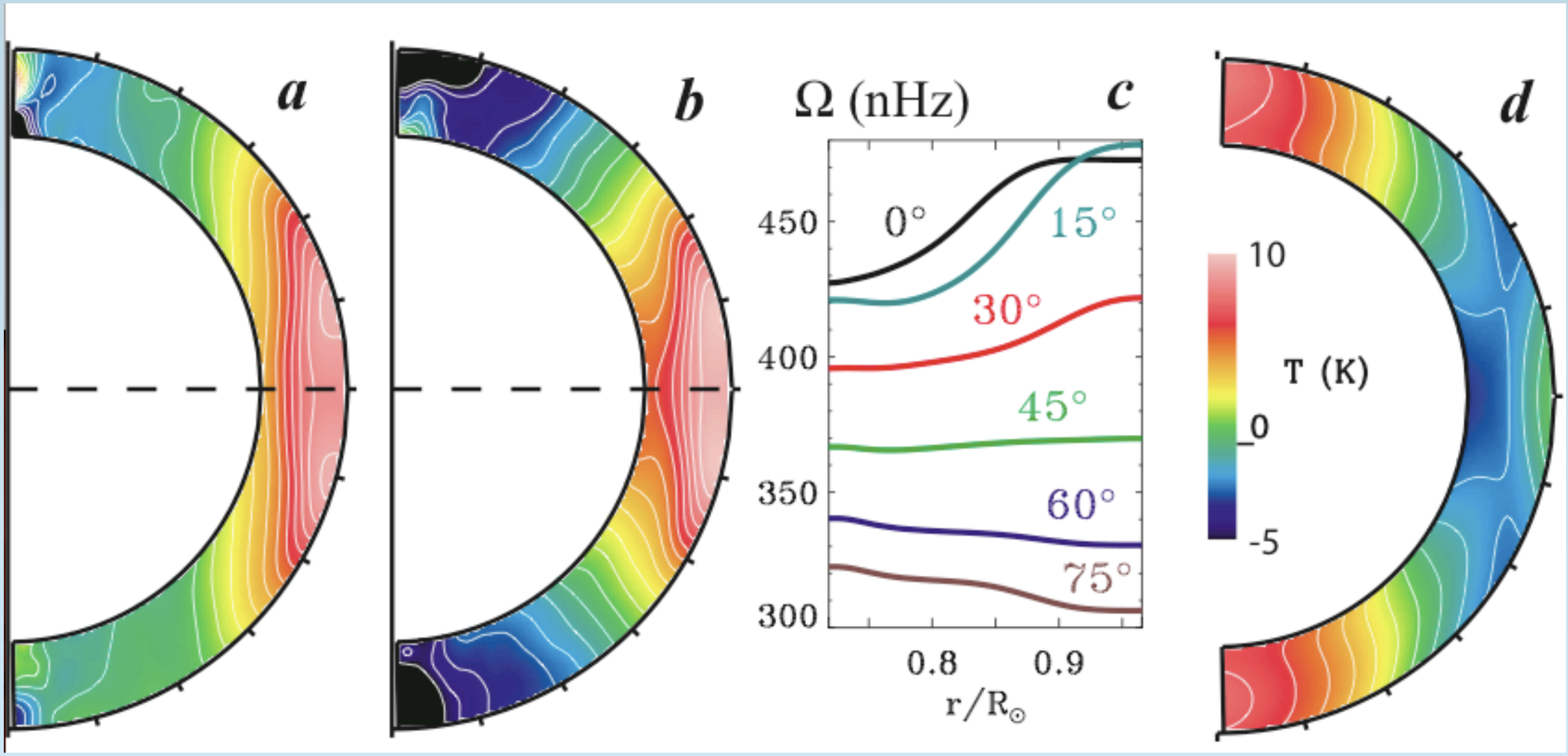


Reasonable contact with helioseismic angular velocity

(but still typically too cylindrical)

Important role played by Reynolds stresses

Breaking Taylor-Proudman constraint



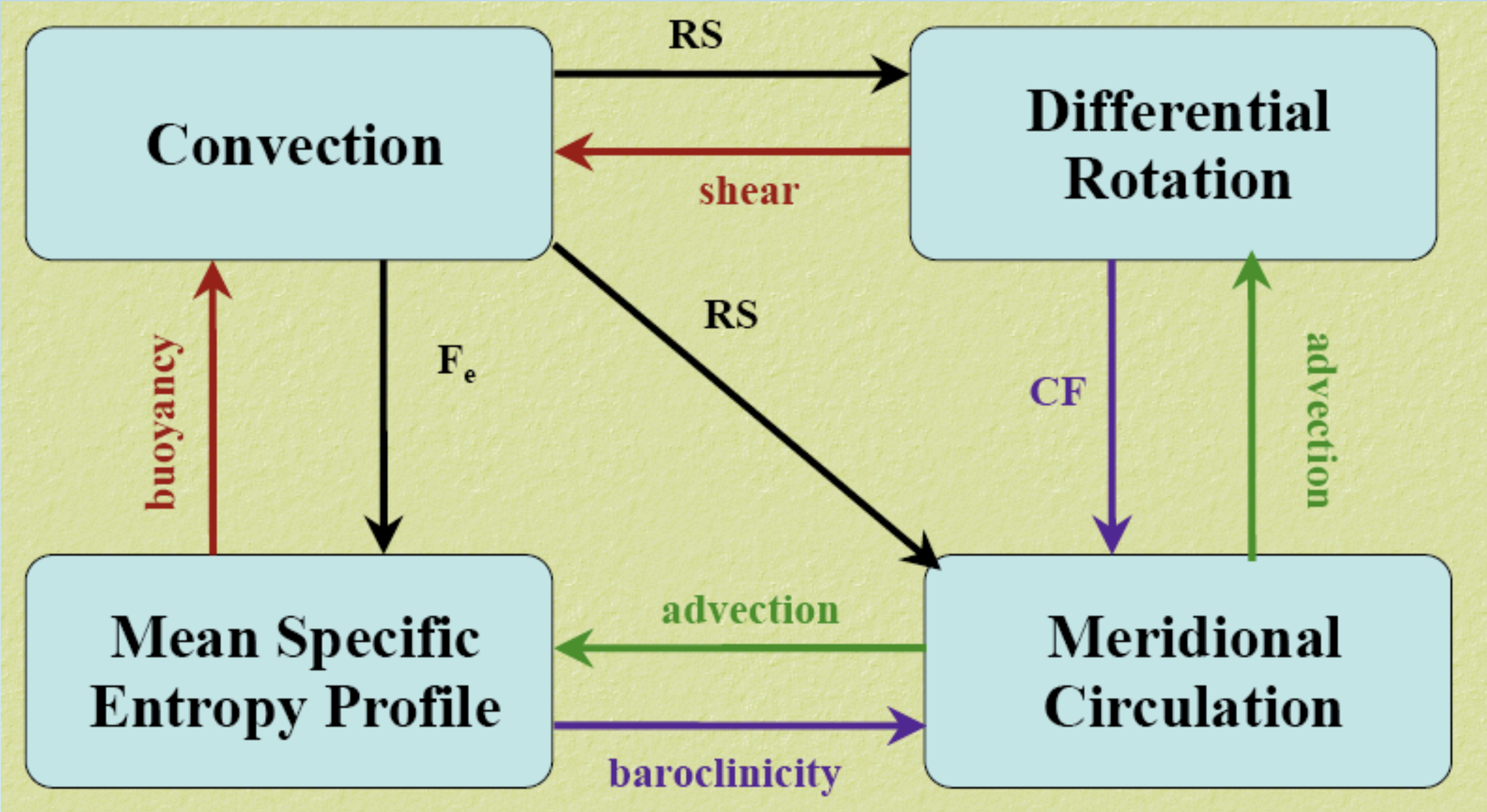
Miesch et al. (2006)

Impose latitude-dependent bottom temperature BC

Warm poles, cool equator

Conical profile maintained by baroclinic effects

Zoo of Stellar Momentum Transport



Miesch et al. (2009)

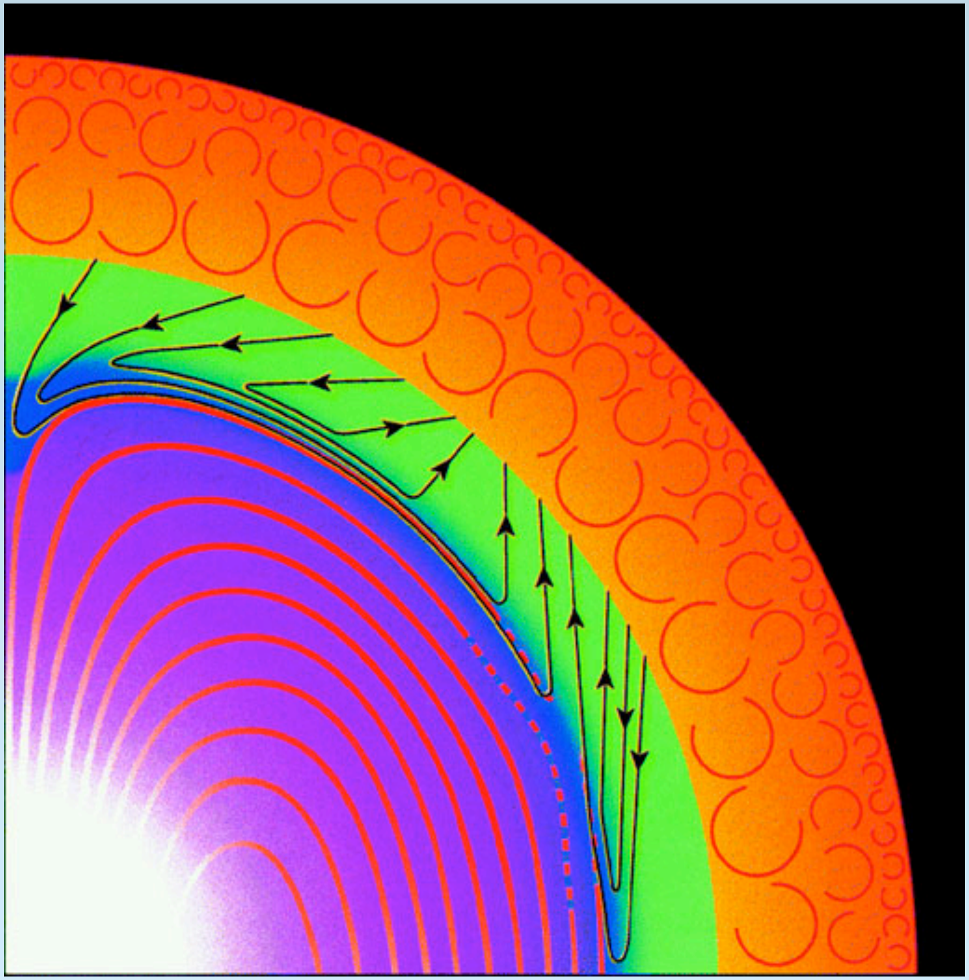
… plus magnetic fields (alas)

Why a tachocline?

Two main classes of models for uniform rotation of solar interior:
1) Magnetic field pervading radiative zone

Weak field sufficient

Main problem is preventing "link-up" with CZ



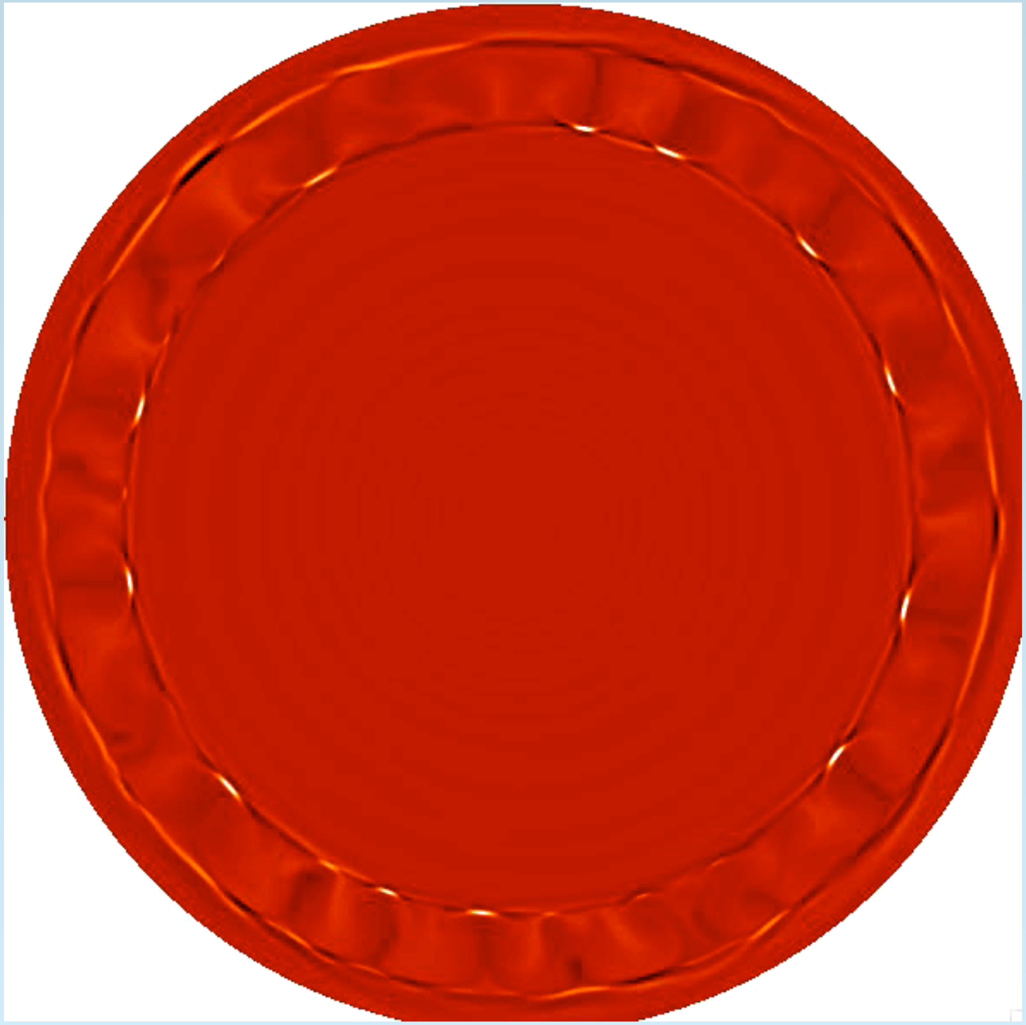
Gough & McIntyre (1998)

Why a tachocline (2) ?

2) Gravity waves might extract angular momentum from core

Only 2-D sims (or unrealistic stratifications) so far

Unclear whether this can actually lead to uniform rotation (or “shear-layer oscillations”)



Rogers \& Glatzmaier (2006+)

How can we do better?
1. Isolate pieces of physics

The Sun is a great laboratory, BUT

It is also a pain:

It has a tachocline

Rotation is “sort-of” important

We will learn a lot from study of other stars:
e.g., fully convective M-dwarfs

(This one generates strong l-s field without evident diff. rotn.)

Donati et al. 2006

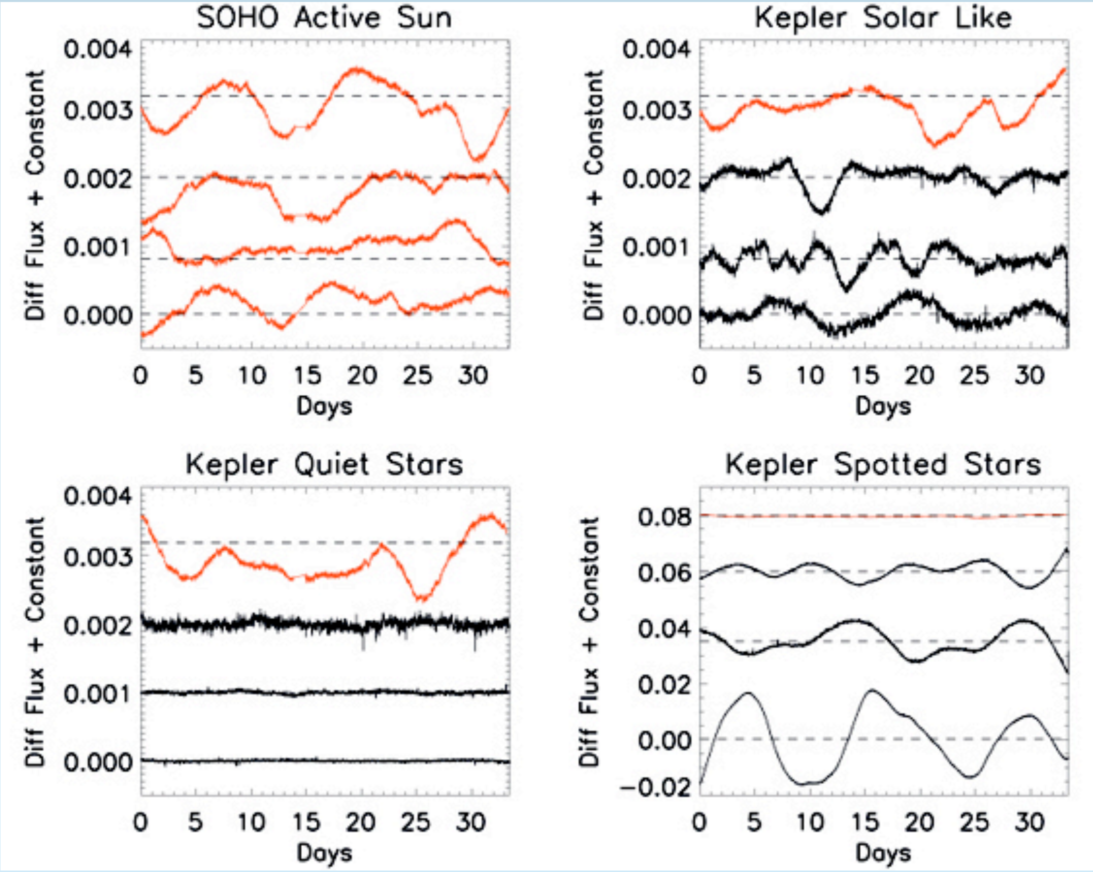
Opportunities from new observations

Kepler: monitoring photometric variability of ~150,000 stars

Mission lifetime ~years

Determine photometric rotation periods (incl. M-dwarfs!), mag cycles, …

Also some asteroseismology capability



Basri, Walkowicz et al. (2010)

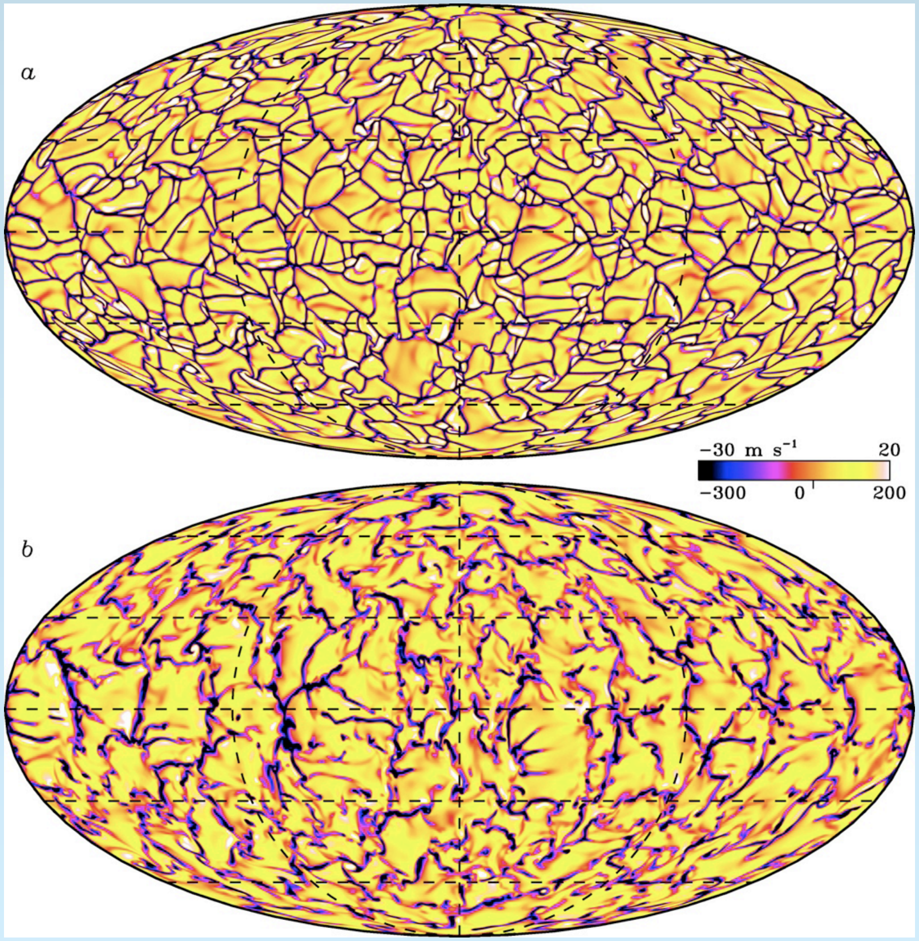
How can we do better?
2. Resolve new scales/physics

Wide range of spatial and *temporal* scales

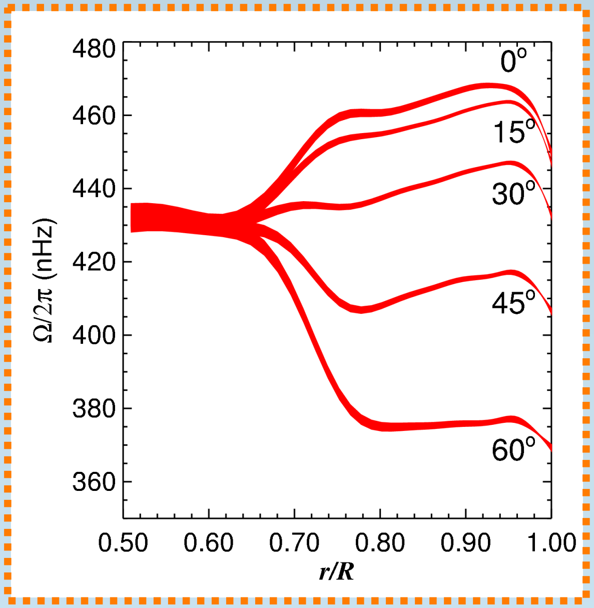
An extremely pessimistic view: Need dynamic range $>10^6$

More plausible :
Need to resolve range of scales above/below Rossby radius; also overshooting region. (g-modes? MRI?)

Timescale problem tricky: May need to couple 2-D, 3-D models



Summary and reflections

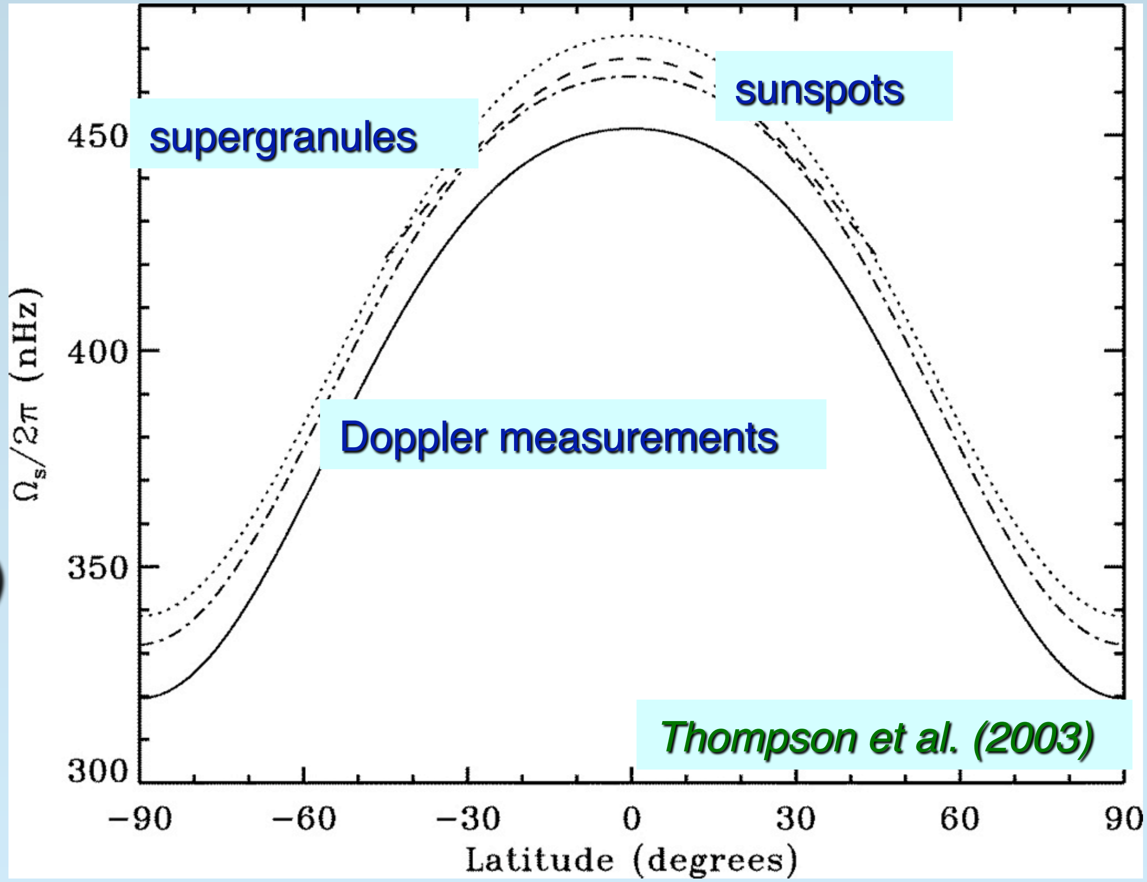


- The Sun and other stars show *persistent differential rotation*
- Some aspects understood, but many puzzles remain
- New simulations will help: resolve additional relevant physics, isolate pieces of problem
- New observations (e.g. Kepler) will constrain momentum transport on other stars
- But there is also a need for more cross-talk between theory, simulation, and observation

Using spots to infer differential rotation

Spots move faster than photosphere

Interpreted as speed-up with depth (spots anchored below surface) (Foukal 1972)



Dynamical balances in convection zone

Meridional circulations balance Reynolds stresses

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

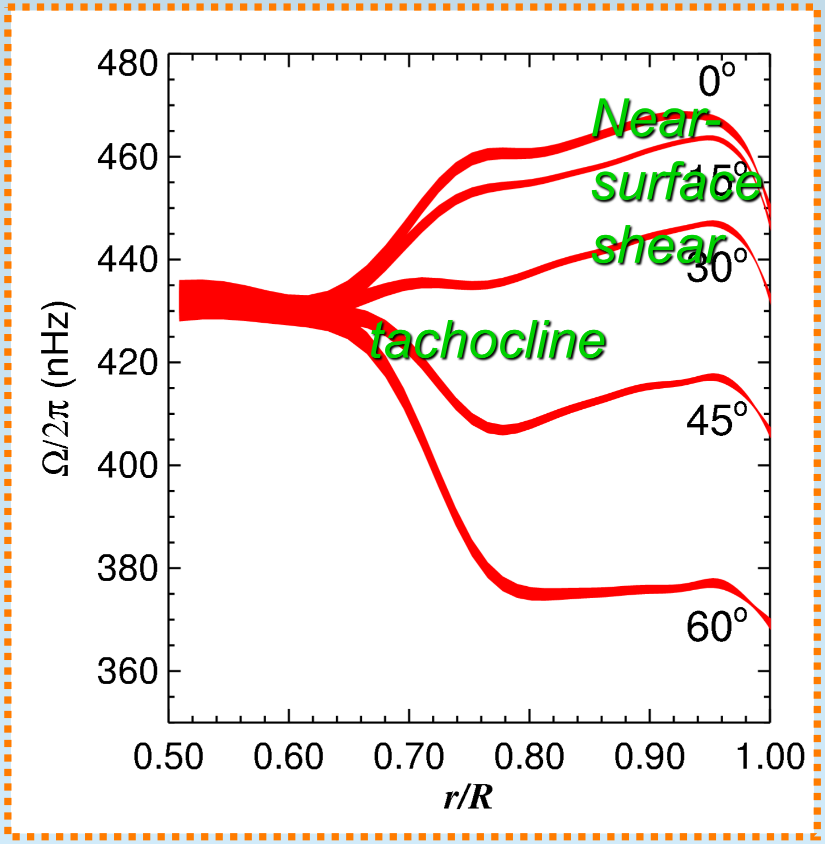
Thermal wind balance

$$\frac{\partial \Omega}{\partial z} = \frac{g}{2\Omega_0 r^2 \sin\theta C_P}\frac{\partial \left\langle S\right\rangle}{\partial \theta}$$

i.e., cylindrical symmetry broken by entropy gradients

(Supposing steady-state, non-magnetic (!), neglect viscosity; for TW: rapid rotation (Coriolis >> RS), ideal gas in hydro equilib.)

Motivating questions 2: a more detailed view



- Why a fast eq/slow pole?
- Why is rotation roughly constant on radial lines?
- Why is the interior in solid-body rotation?
- Why a near-surface shear layer?
- What is timescale for core-envelope coupling?