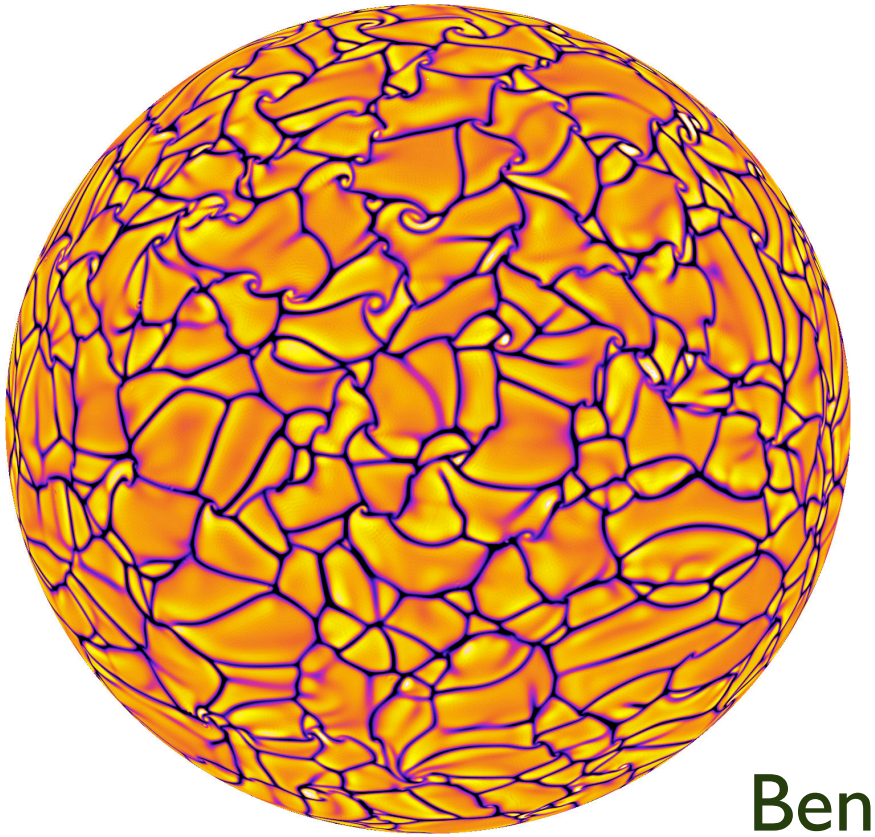
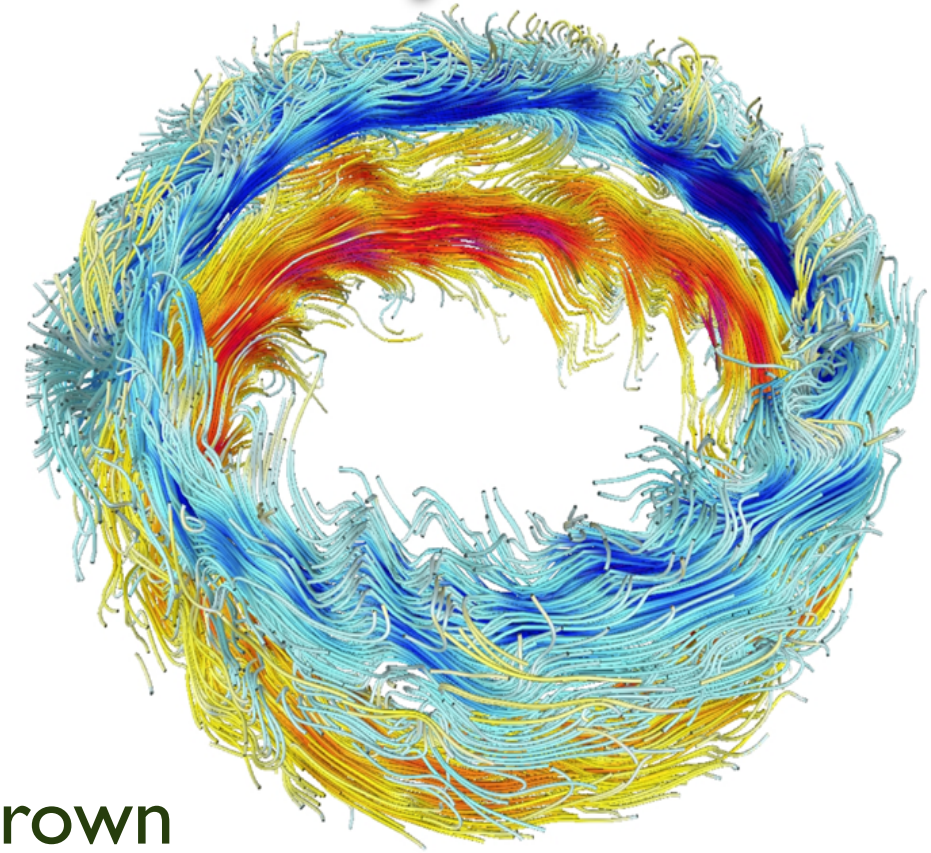
Dynamos in Stellar Convection Zones: of Wreaths and Cycles





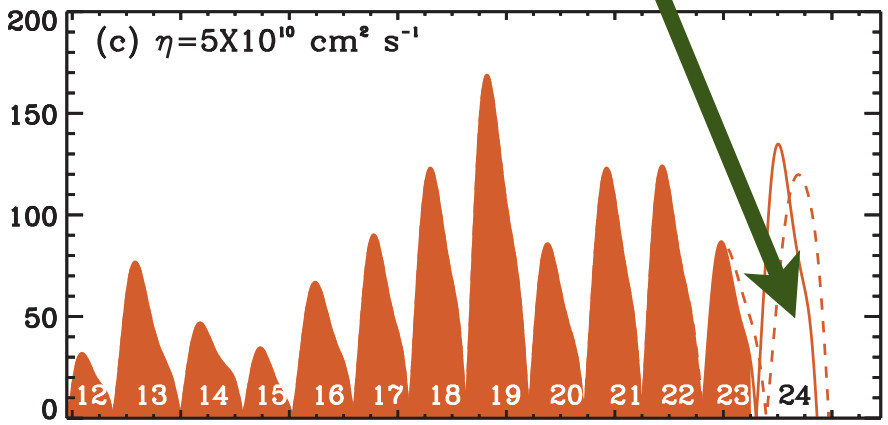
Ben Brown
Univ. Wisconsin Madison

Dynamo Modeling

(Hathaway June 2010)

2D: Mean-field models

- $\alpha-\Omega$ type
- interface dynamos
- flux-transport and many variants (e.g. Babcock-Leighton)

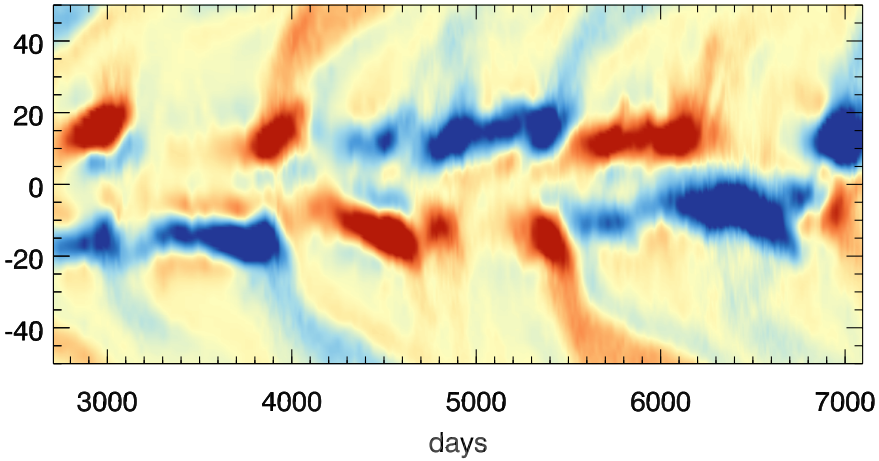


(Dikpati & Gilman 2006)

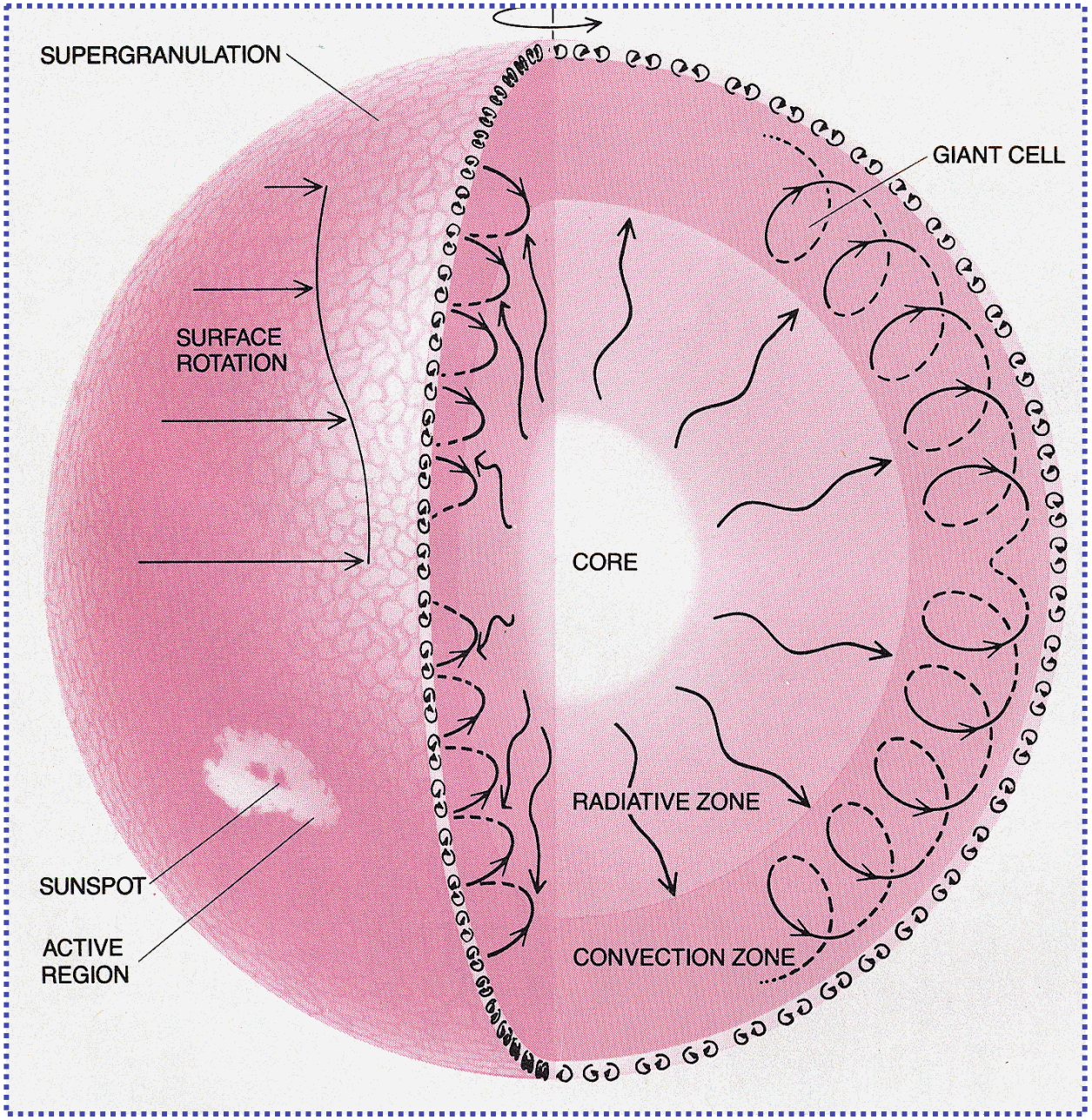
Computationally inexpensive: simulate many cycles, try many ideas
In a position to try solar predictions (but many problems)

3D: Convection, Rotation & Magnetism

- global-scale flows, magnetism, coupling from first principles
- now achieving cyclic behavior



Computationally expensive
Solar parameters well out of reach



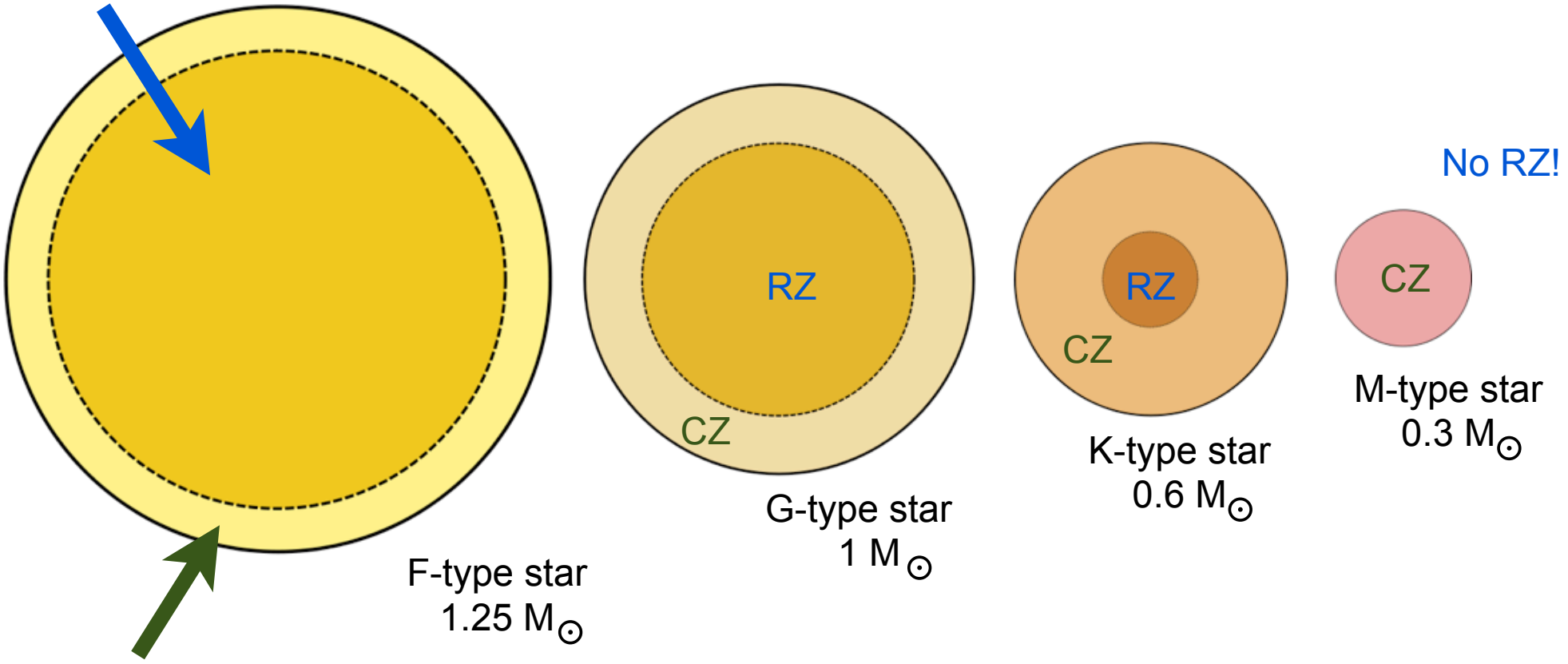
Inside The Sun

CONVECTION ZONE
VERY TURBULENT
(depth of 200 Mm)
Re ~ 10^{15}

Broad range of spatial scales

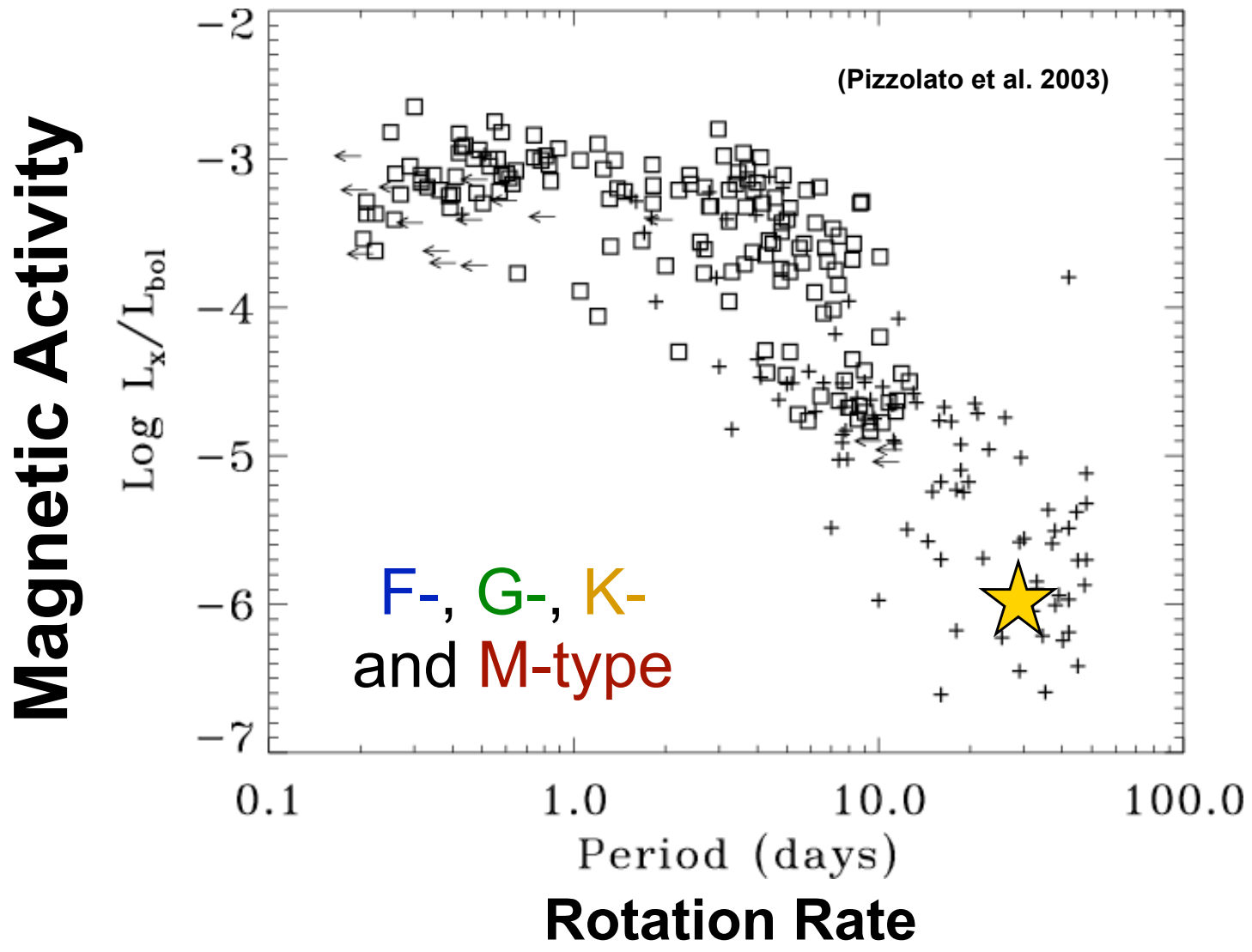
Stratified, Rotating and Magnetic

Stellar Convection Zones in Solar-like Stars

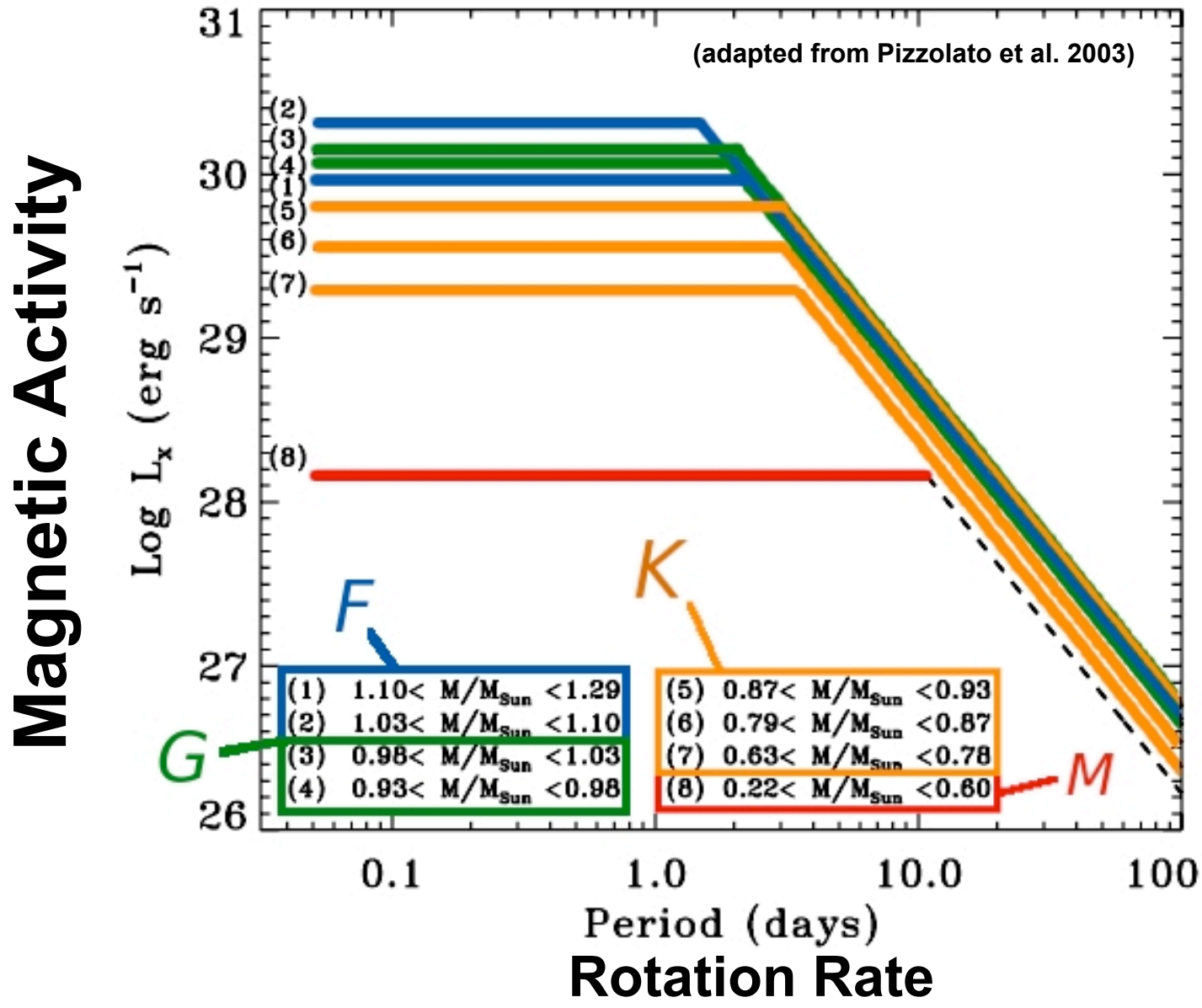


All magnetically active

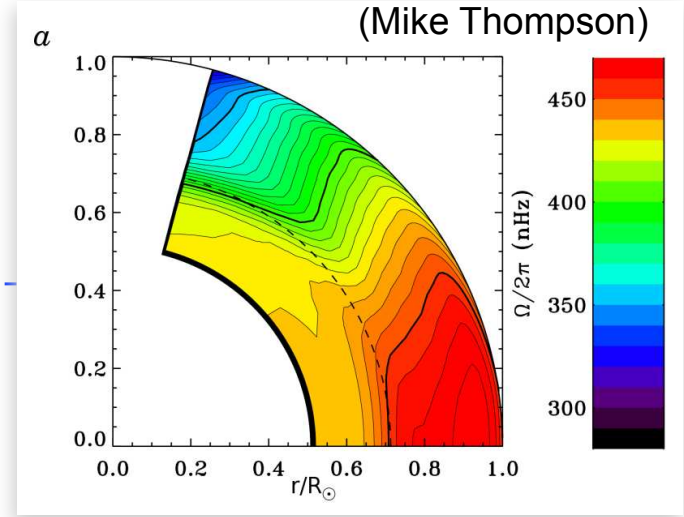
Activity in Other Suns



All dwarf stars are similar



Cartoon Solar Dynamo



PHOTOSPHERE

CONVECTION ZONE

TACHOCLINE

RADIATIVE INTERIOR

Photosphere

EMERGING LOOP

Convection zone

Ω

(4) LOCAL DYNAMO

(1)

ROTATION

BUOYANCY

(3)

Tachocline

(2) PUMPING

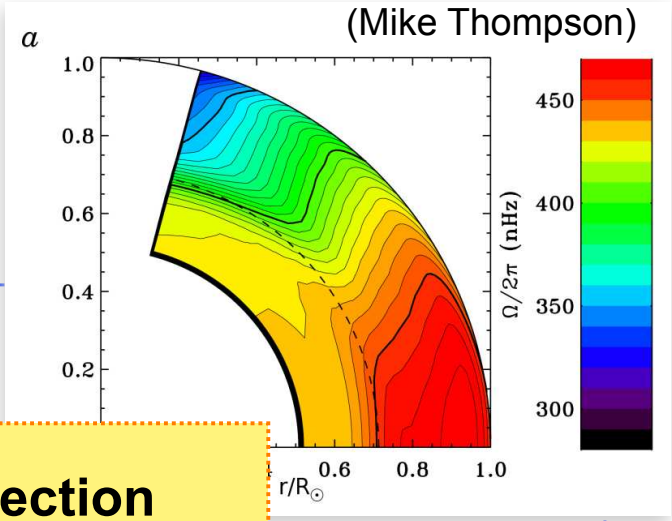
Radiative core

GLOBAL DYNAMO

NHB

(Nic Brummell)

Cartoon Solar Dynamo



PHOTOSPHERE

CONVECTION ZONE

TACHOCLINE

RADIATIVE INTERIOR

Photosphere

Convection zone

Tachocline

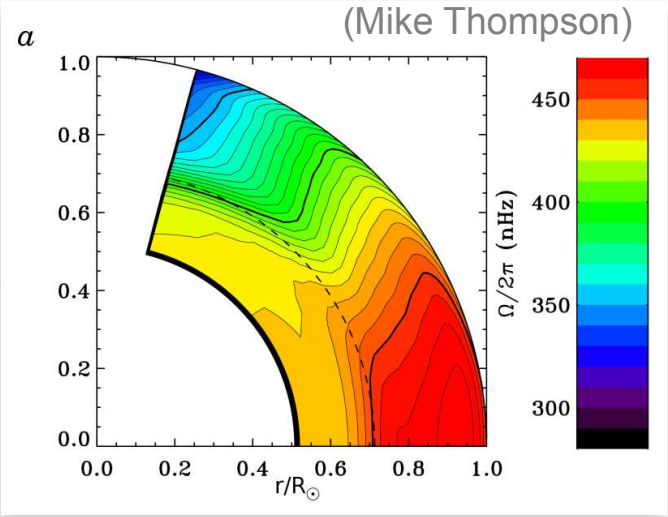
Radiative core

convection (α-effect) builds poloidal field

Shear builds (Ω-effect) toroidal field

(Nic Brummell)

Cartoon Solar Dynamo



PHOTOSPHERE

Photosphere

CONVECTION ZONE

Convection zone

Ω

(α-effect)

(Ω-effect)

GLOBAL DYNAMO

(3)

(2)

PUMPING

TACHOCLINE

Tachocline

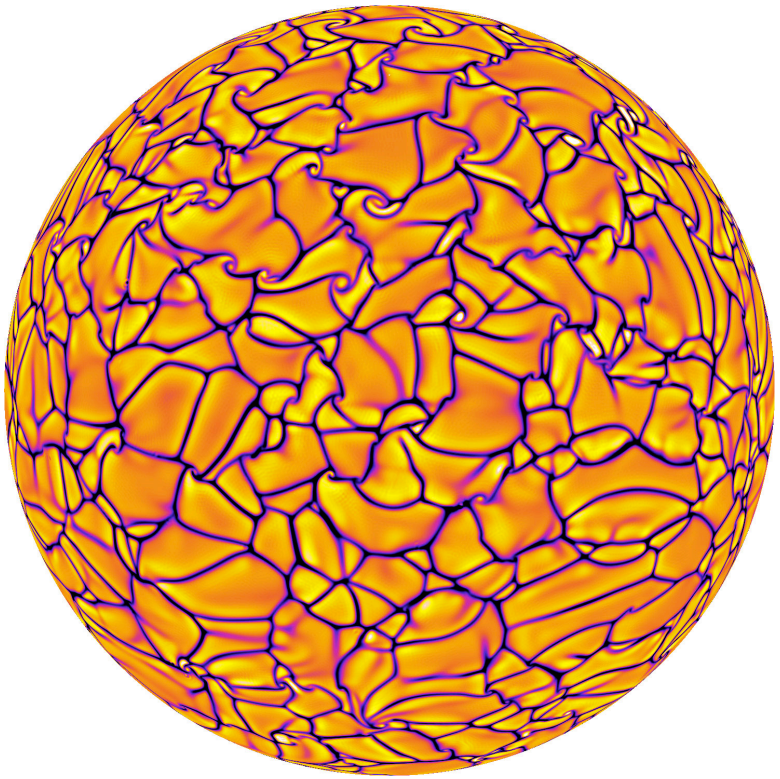
RADIATIVE INTERIOR

Radiative core

NHB

(Nic Brummell)

Anelastic Spherical Harmonic (ASH) Simulations

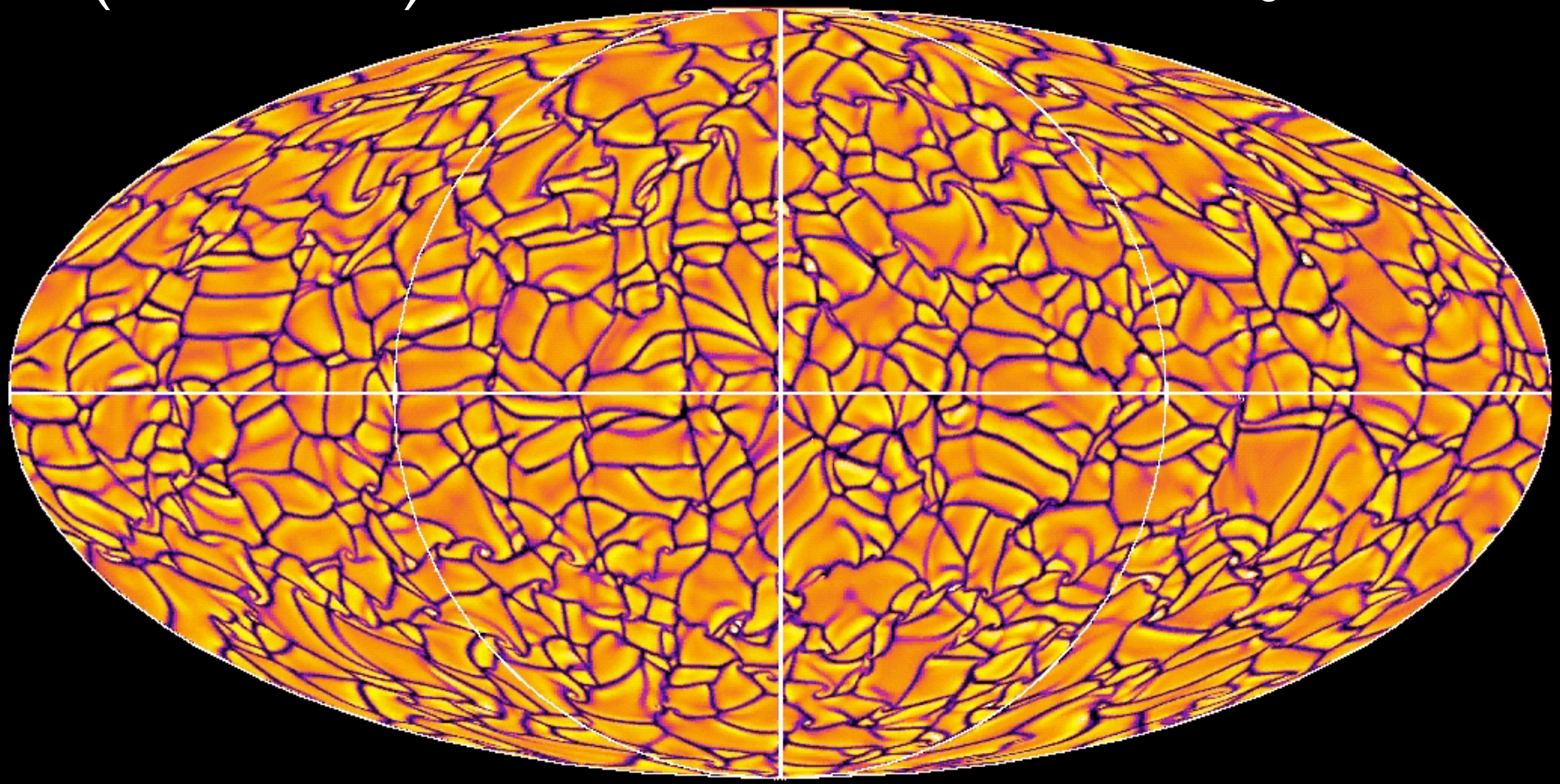


Solar convection
(Miesch et al. 2008)

- Capture 3-D MHD convection at high resolution on massively-parallel supercomputers
- Study turbulent convection interacting with rotation in bulk of solar CZ: 0.72 *R* - 0.97 *R*
- Realistic solar mean stratification
- Simplified physics: perfect gas, radiative diffusivity, compressible, subgrid transport, MHD
- Correct global spherical geometry

Radial Velocities in a solar simulation (Sun's view)

Global Mollweide view near the surface (2%), rotating with the Sun



0.0

Swirling, vortical convection near polar region

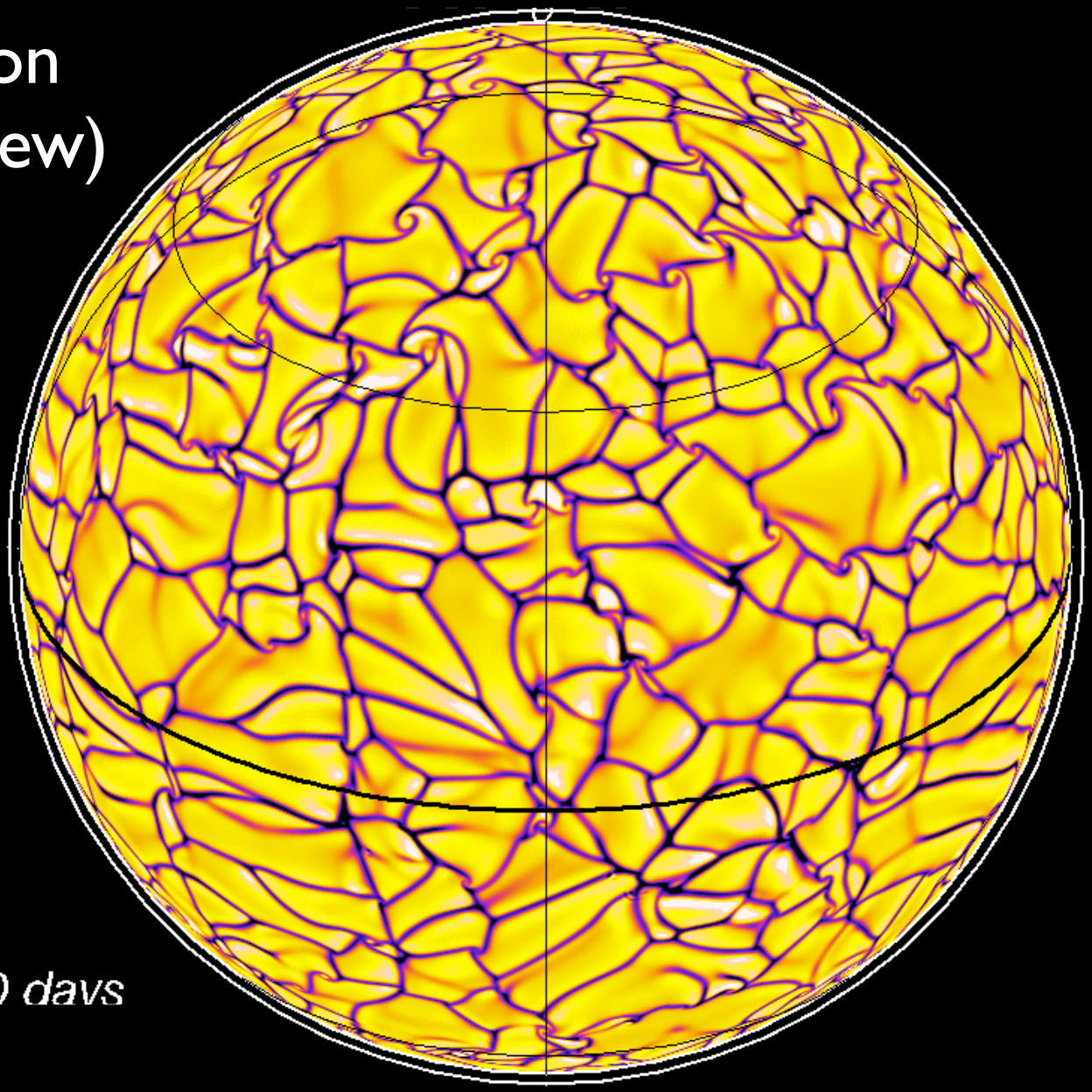
Sweeping cells near equator

(Miesch et al. 2008)

Radial Velocities in a solar simulation (Solar-C's 30N view)

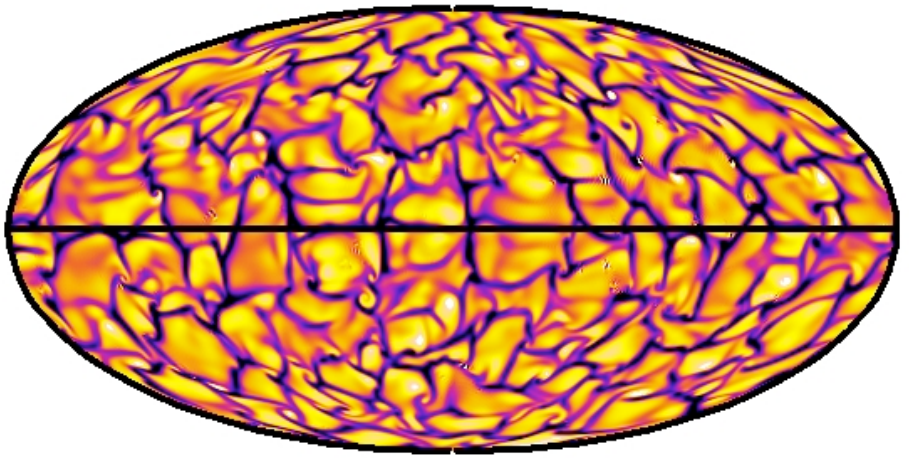
Swirling, vortical convection near polar region

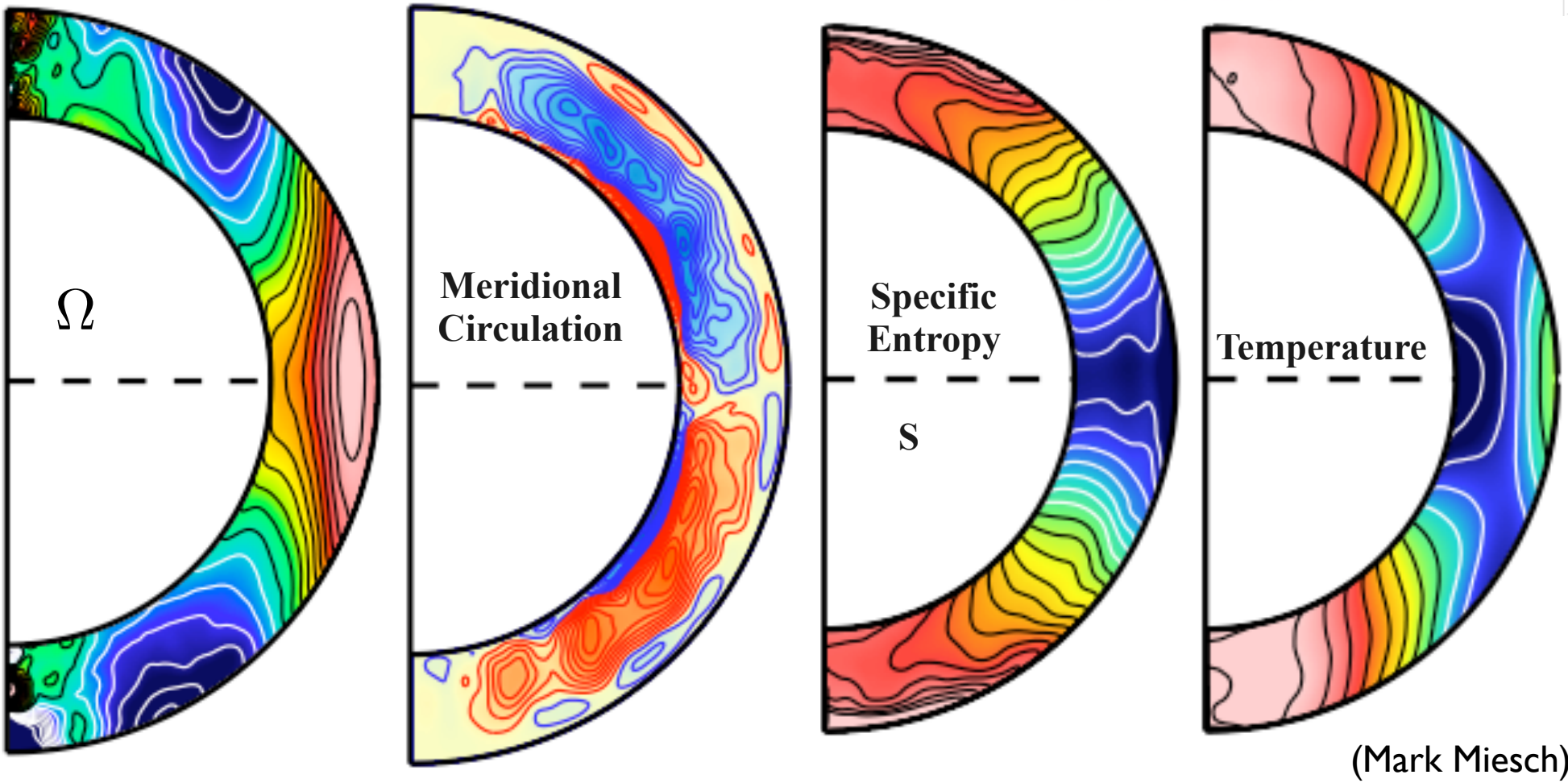
Sweeping cells near equator, only briefly in view



Near the surface (2%)

Global-Scale Flows in a Solar Simulation

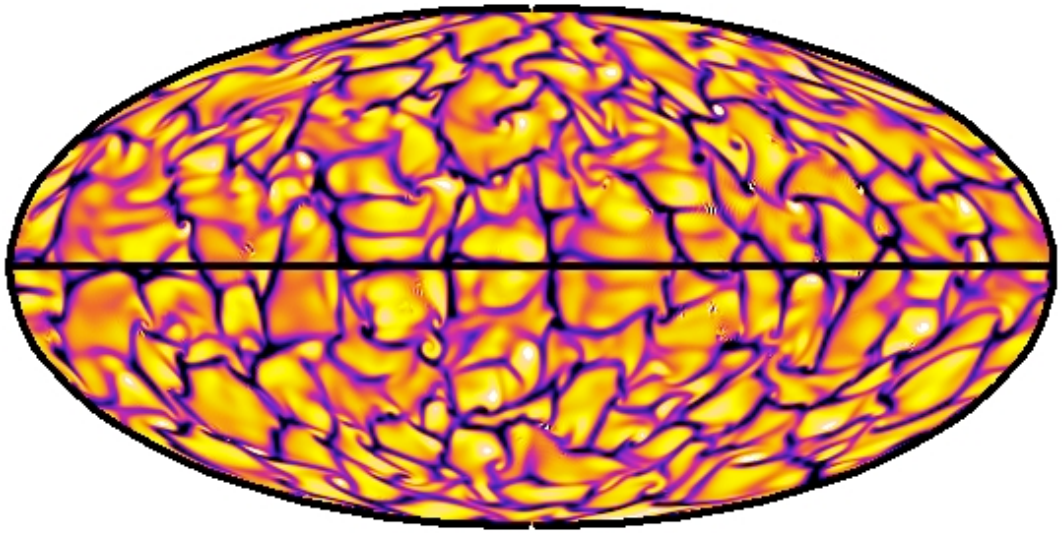


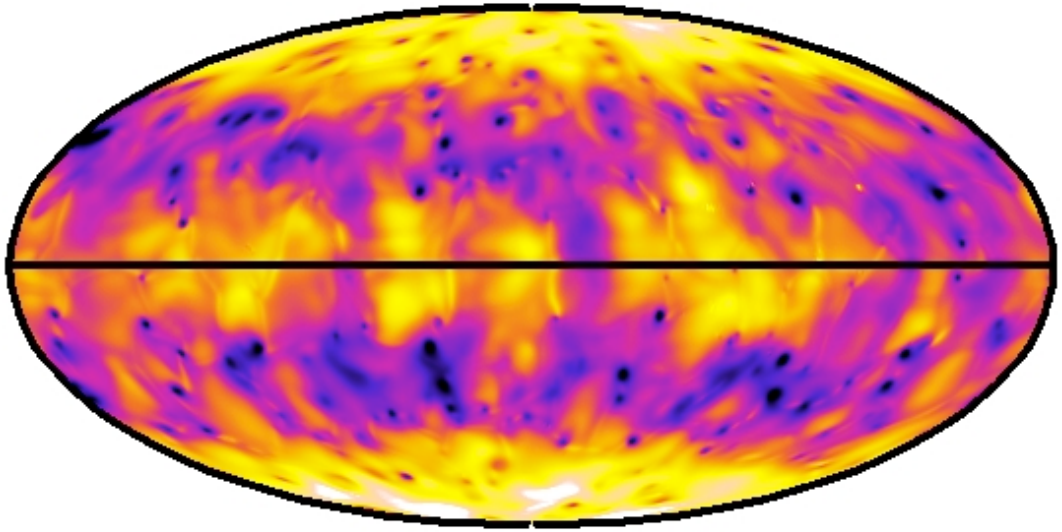


(Mark Miesch)

Thermal Winds

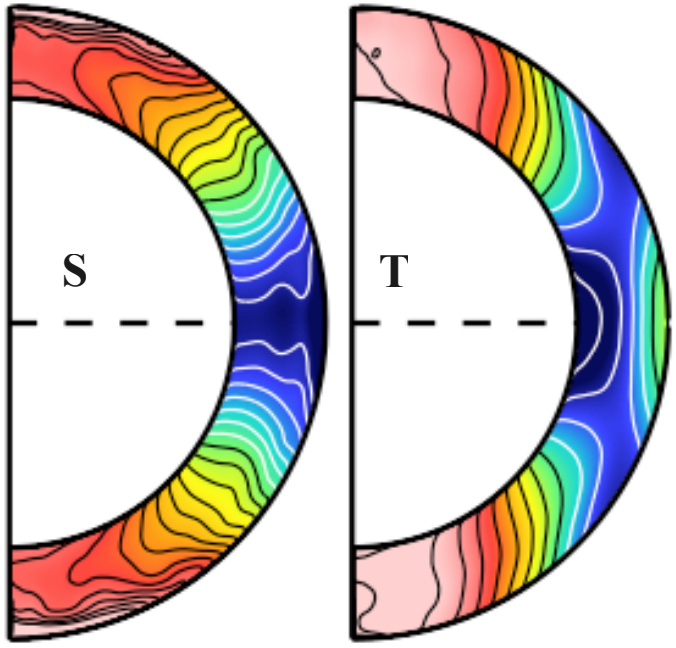
radial velocity, r = 0.96R





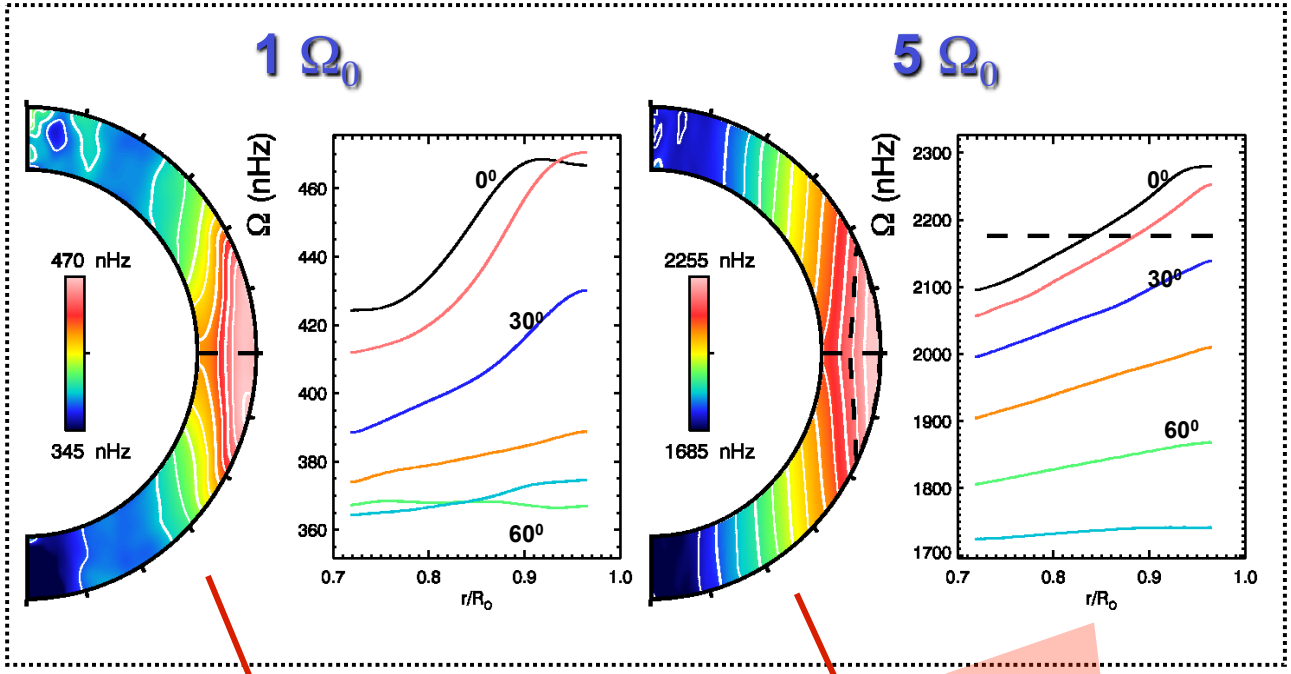
Temperature, r = 0.96R

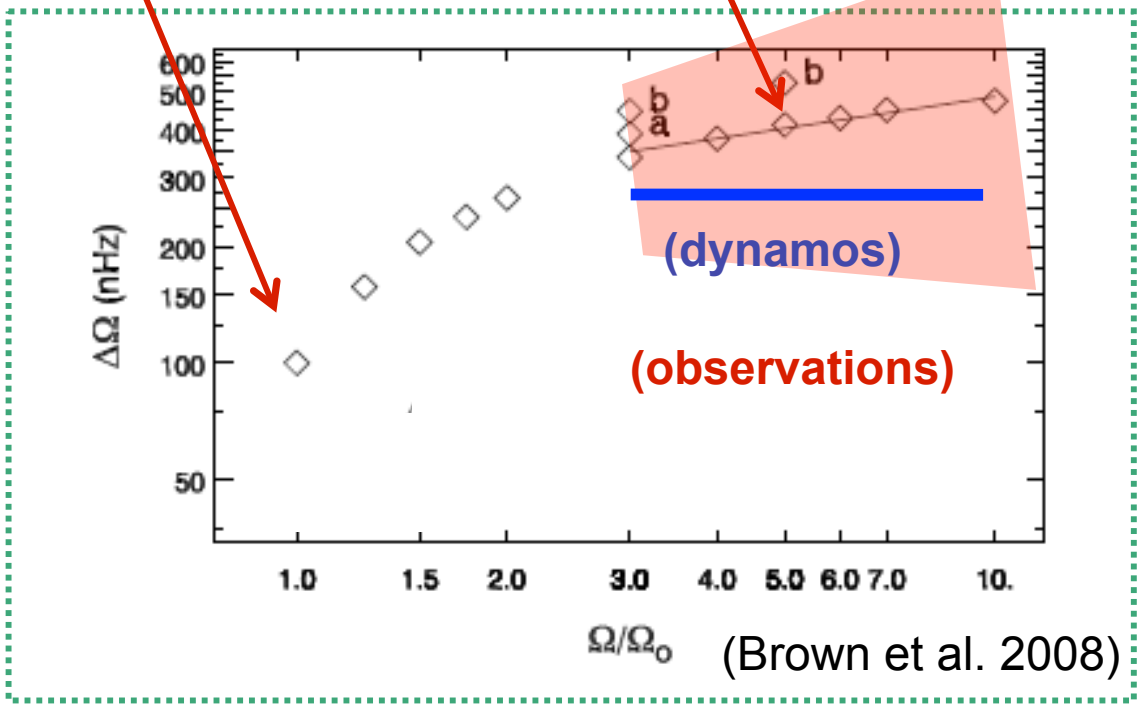
Persistent, global latitudinal gradients comparable in amplitude (~10K) to transient temperature fluctuations associated with convection
(lifetime several days to several months)



(Mark Miesch)

Differential Rotation in Other Suns



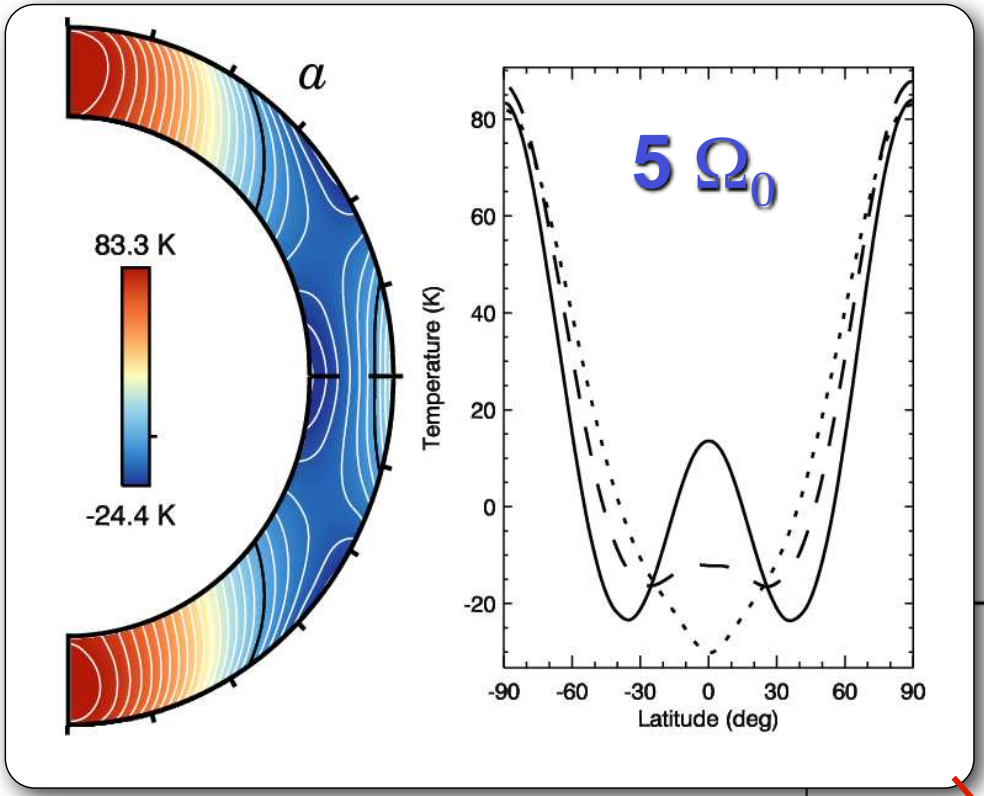


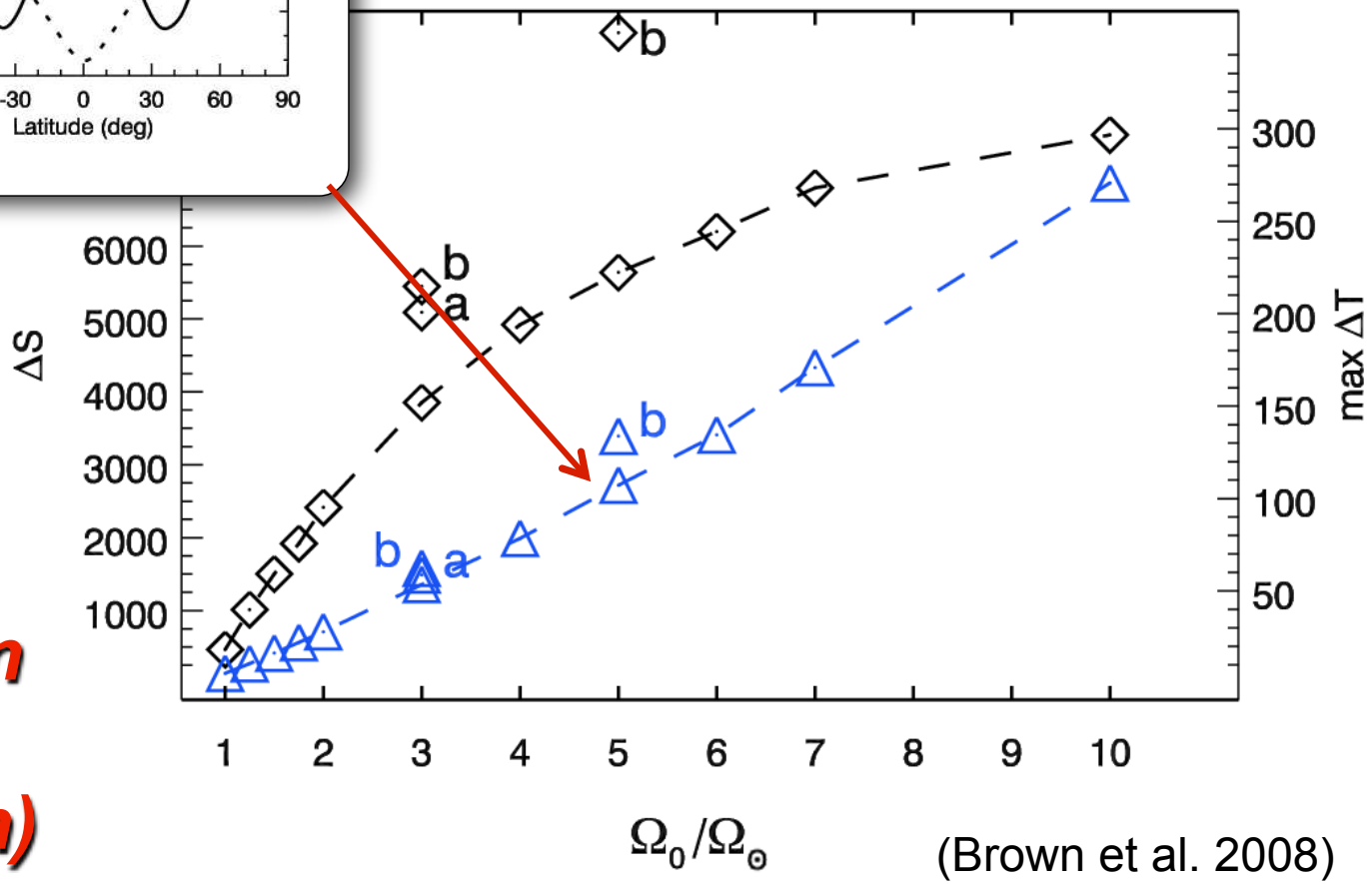
(Brown et al. 2008)

More rapidly rotating suns look much like the Sun, but with stronger overall DR contrast

Decent agreement with observations

Pole-to-Equator Temperature: Thermal Wind



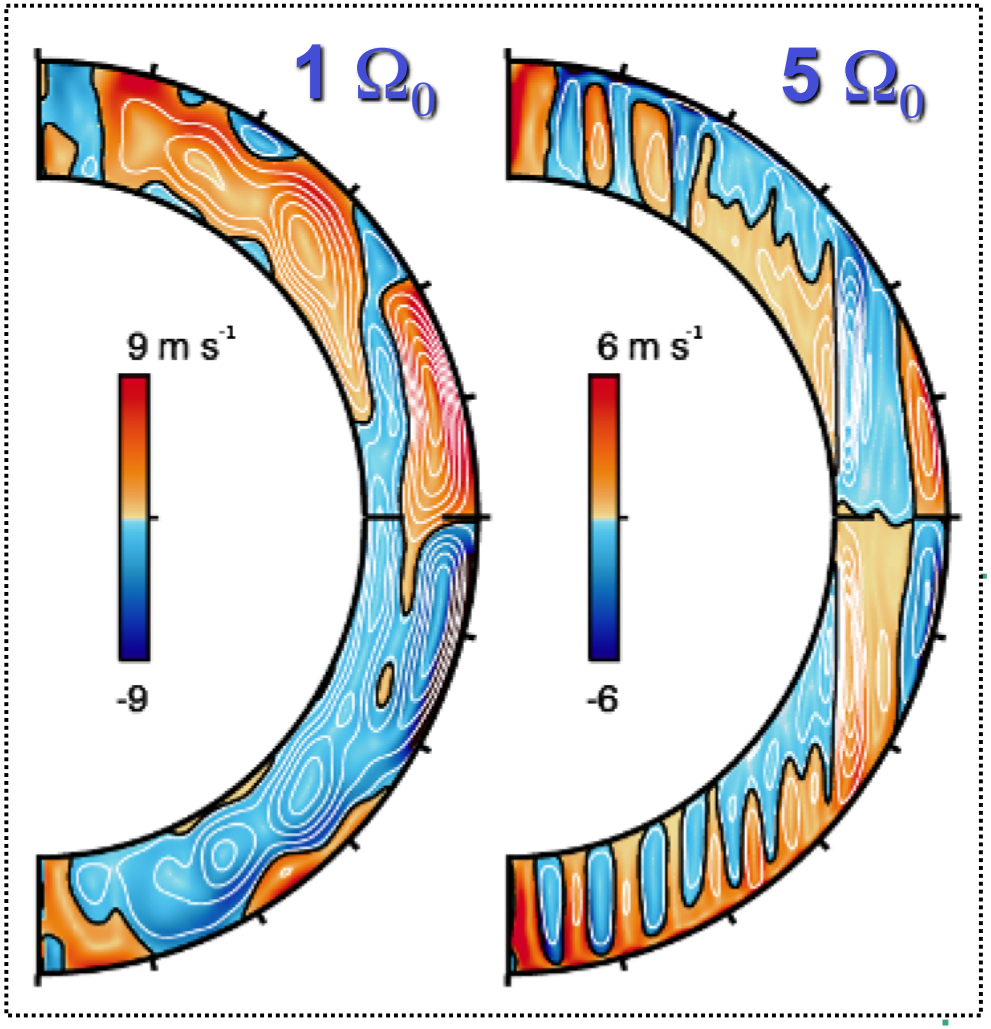


Temperature contrast in latitude grows substantially with fast rotation

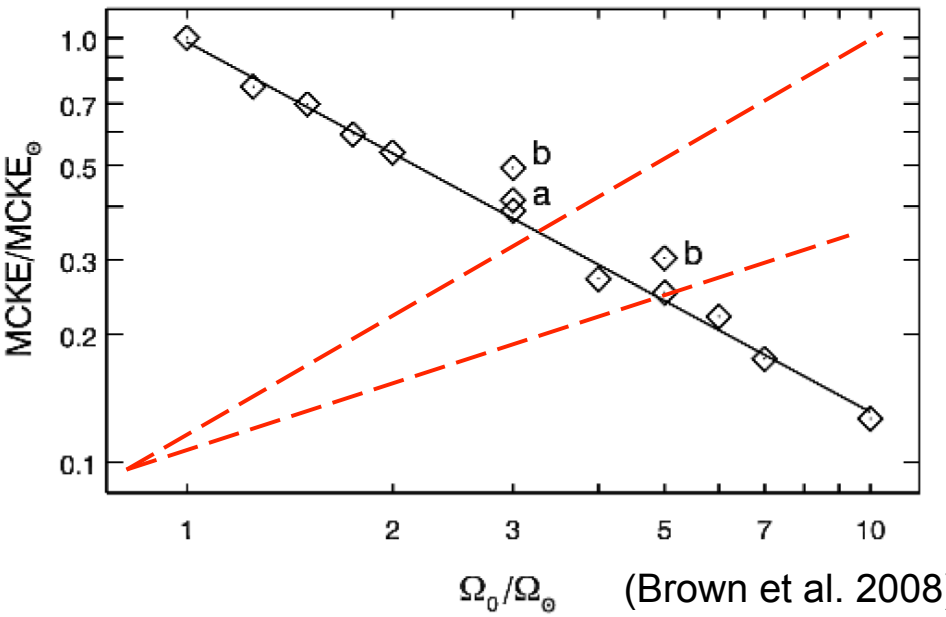
(few K in the Sun)

(Brown et al. 2008)

Meridional Circulations



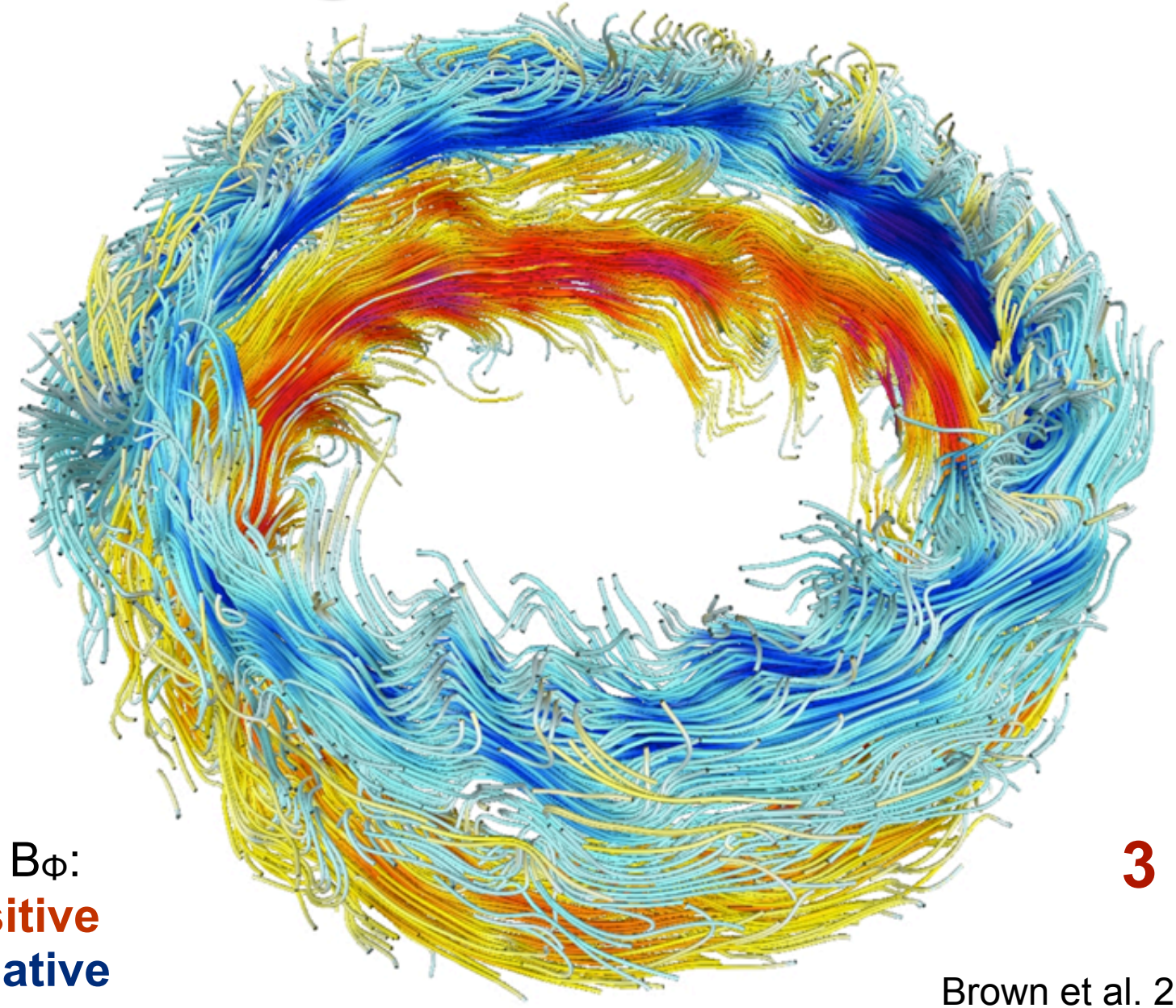
In contrast, meridional circulations are weaker and mutli-celled



(Brown et al. 2008)

Disagreement with expectations

Magnetic Wreaths

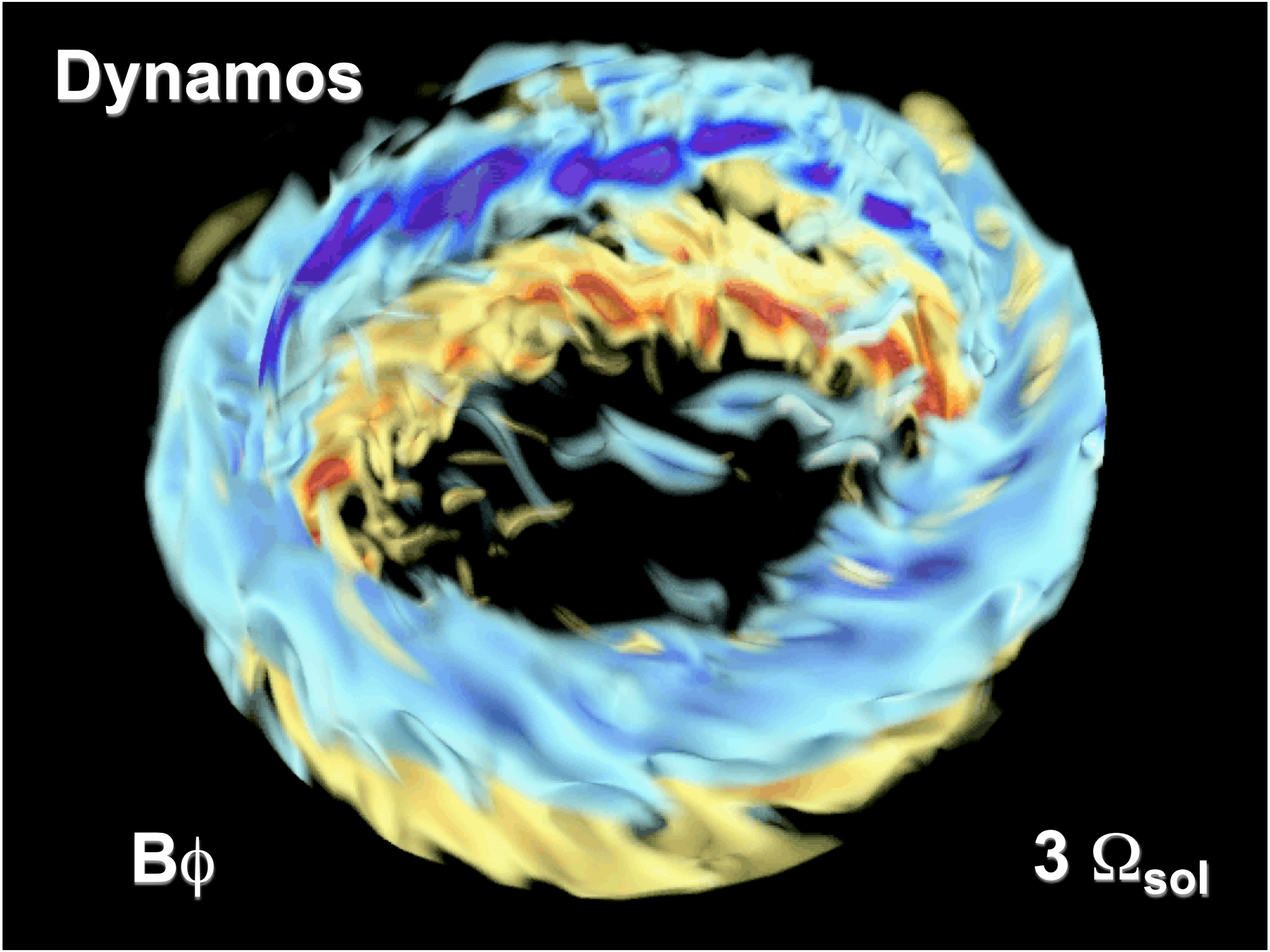


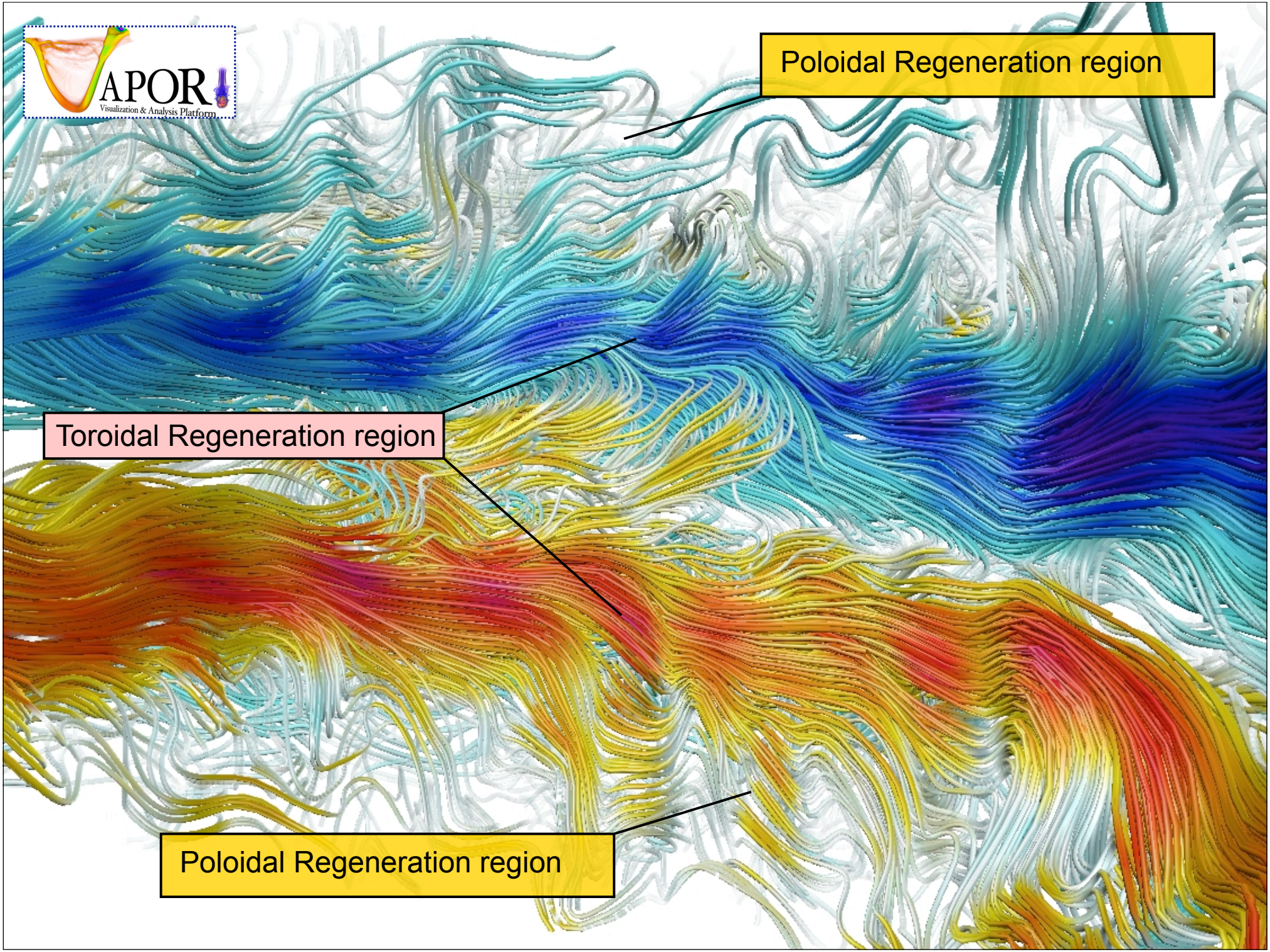
Polarity B_Φ:
red positive
blue negative

3 Ω_0

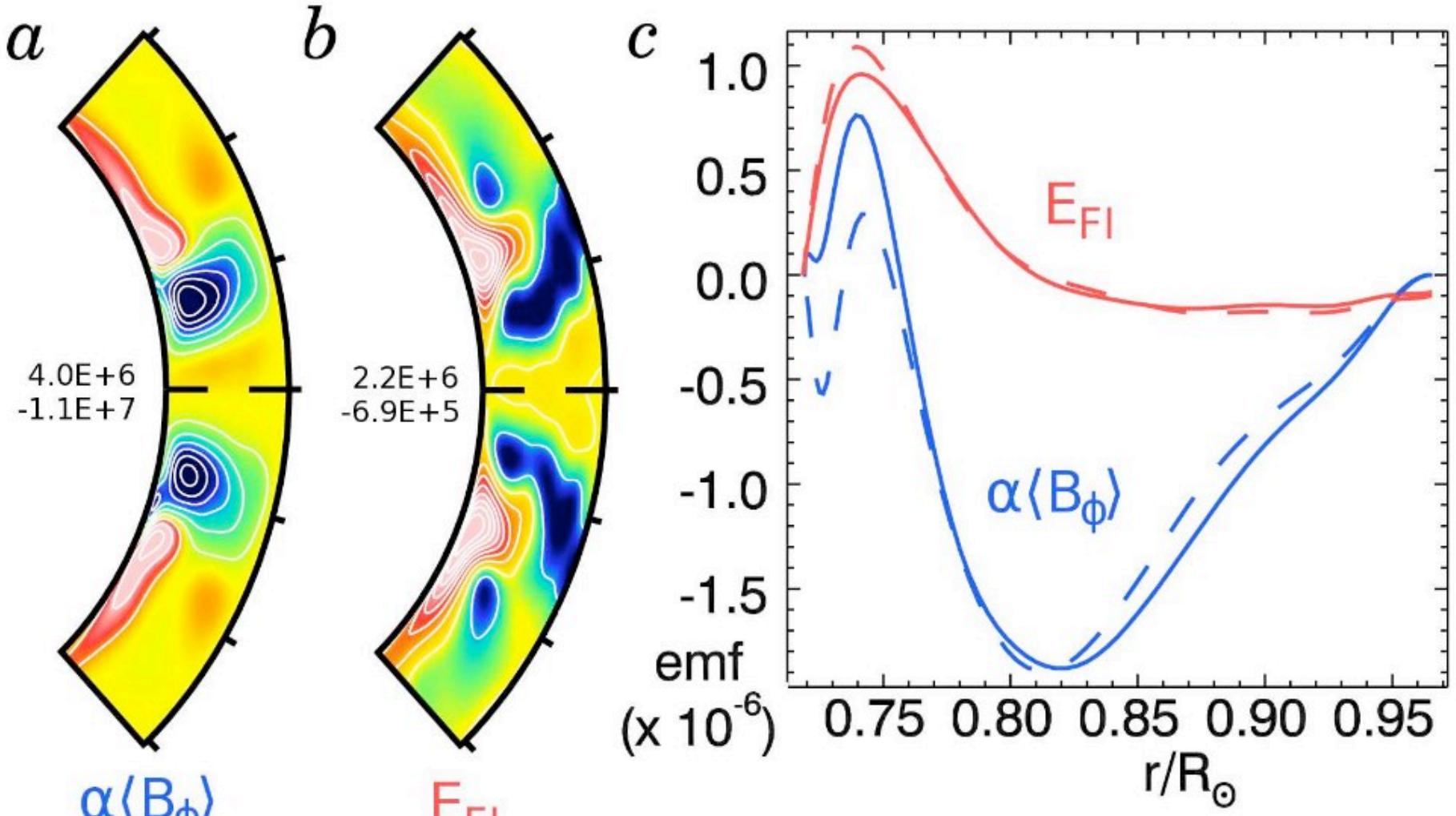
Brown et al. 2010, ApJ

Dynamos




VAPOR
Visualization & Analysis Platform
Poloidal Regeneration region
Toroidal Regeneration region
Poloidal Regeneration region

Simple α-effect: Poor match to 3D



Simple α-effect

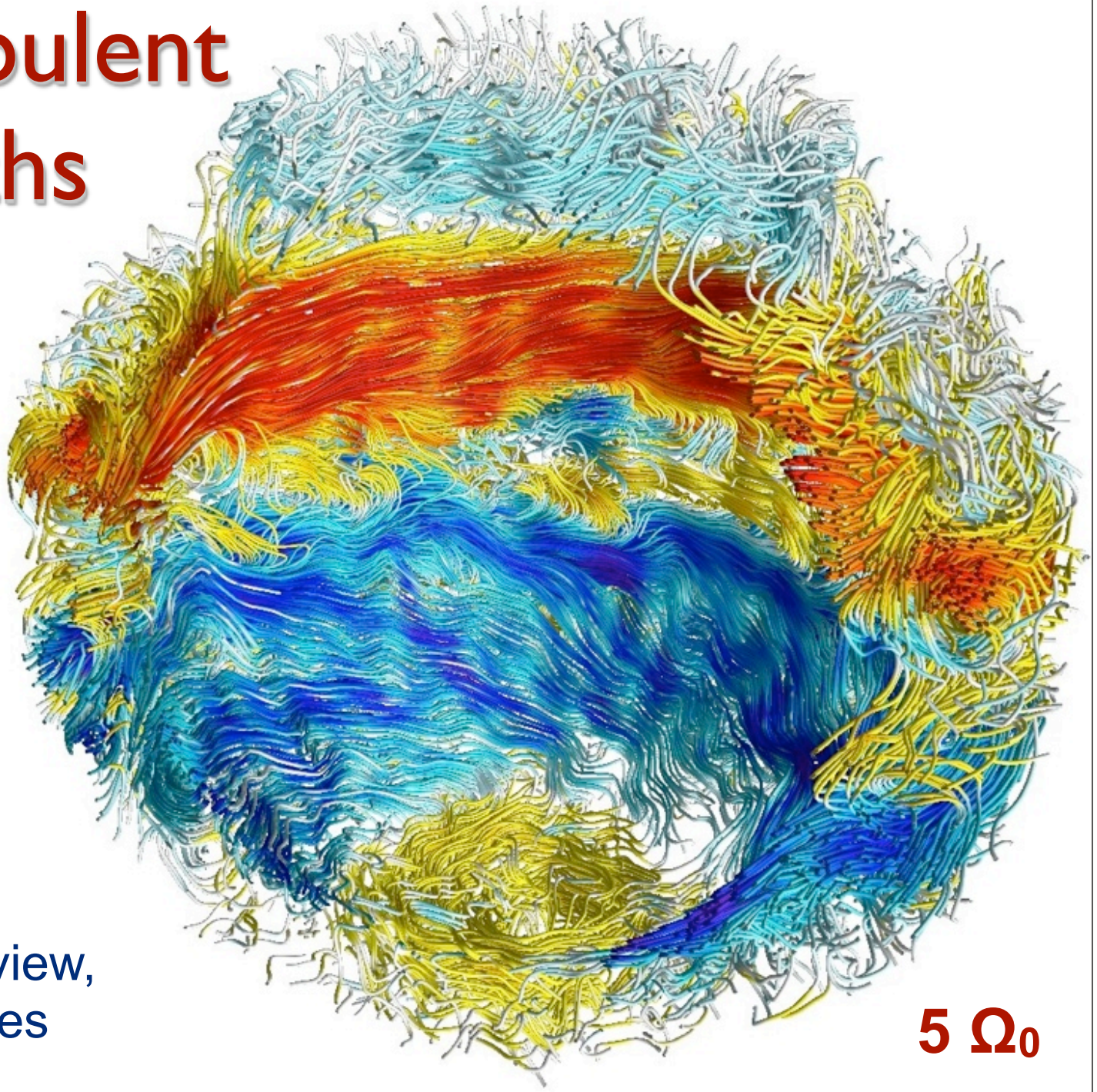
fluctuating EMF (real)

- Wrong spatial structure
- Wrong sign in core of wreathes

Brown et al. 2010, ApJ

More Turbulent Wreaths

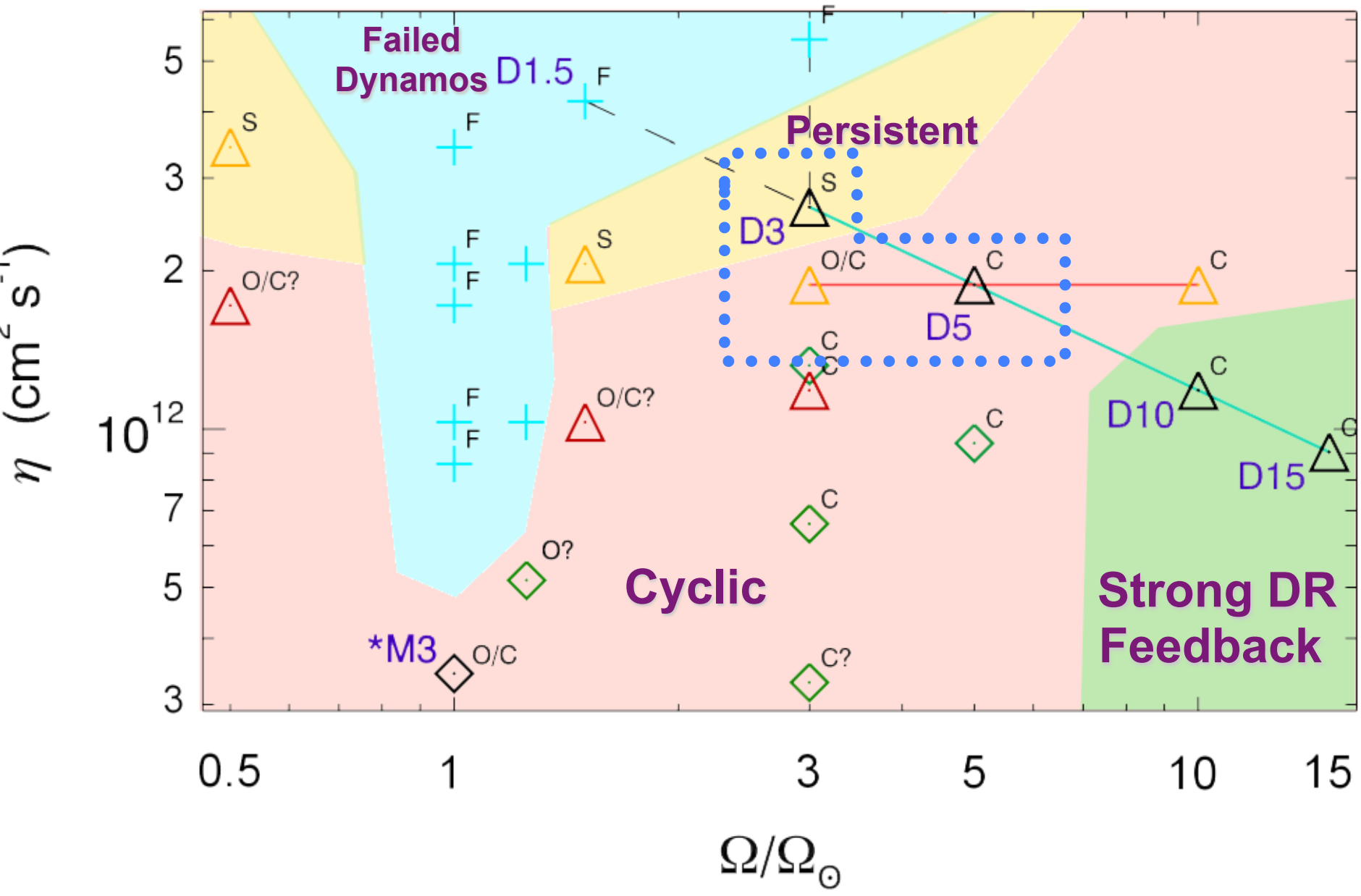
- Volume-filling
- cross-equator connectivity
- cyclic!



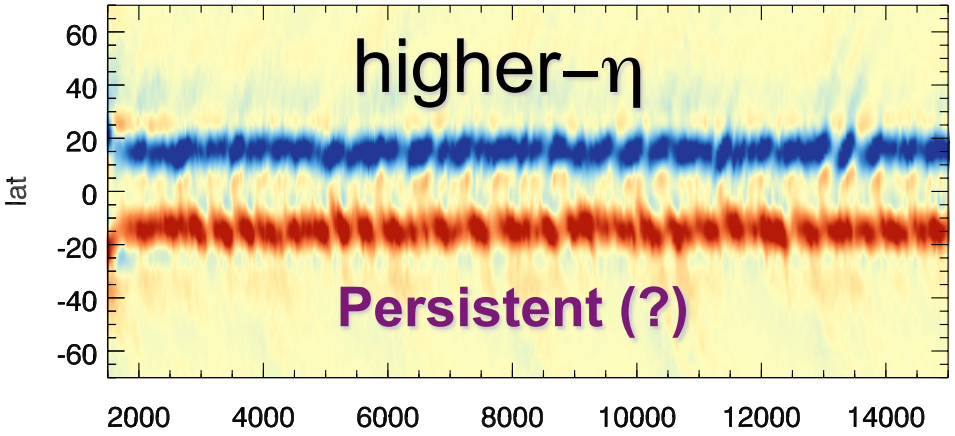
Hemisphere view, with both poles

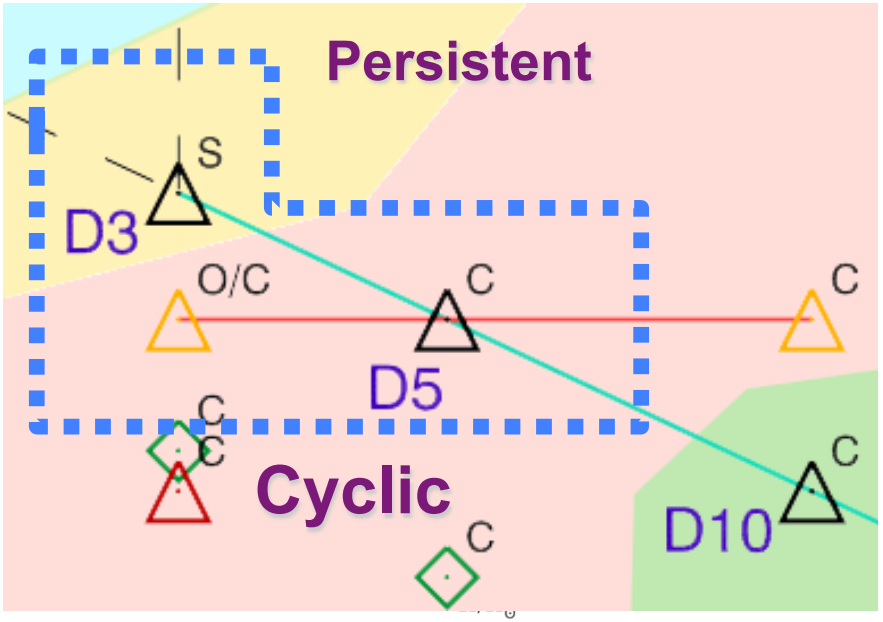
$5\ \Omega_0$

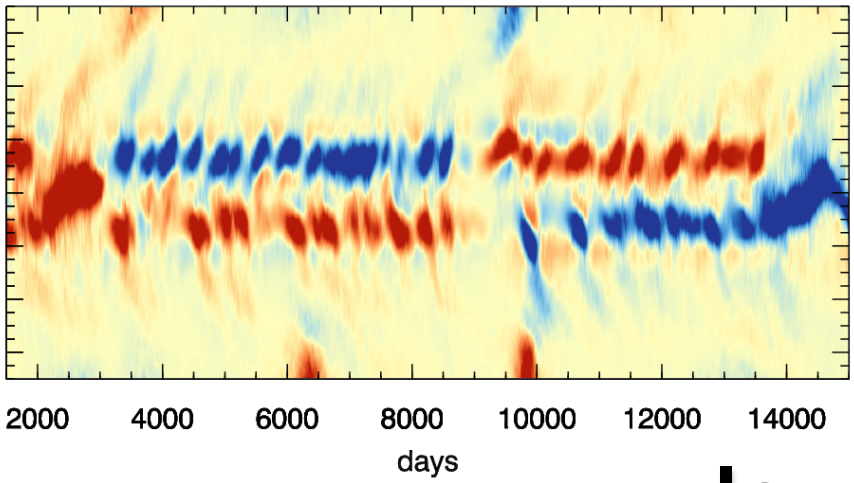
Cyclic Activity: Nearly Ubiquitous

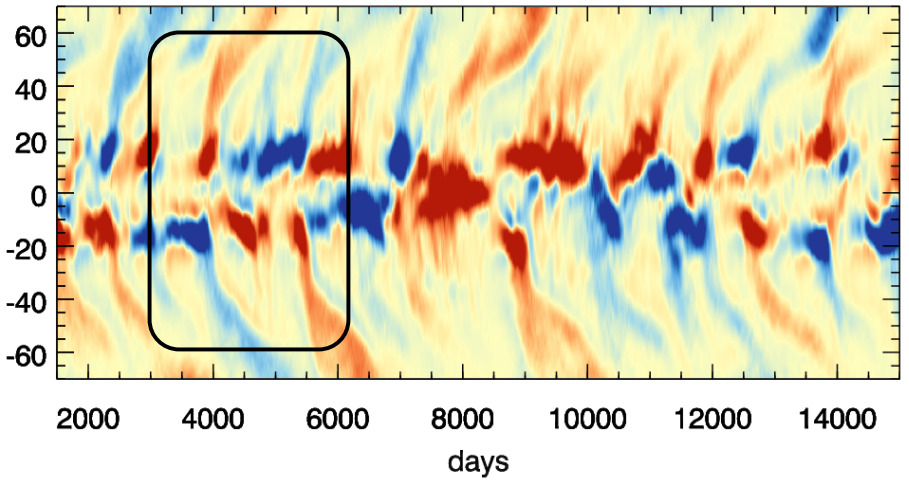


Rotation and Turbulence









3 Ω

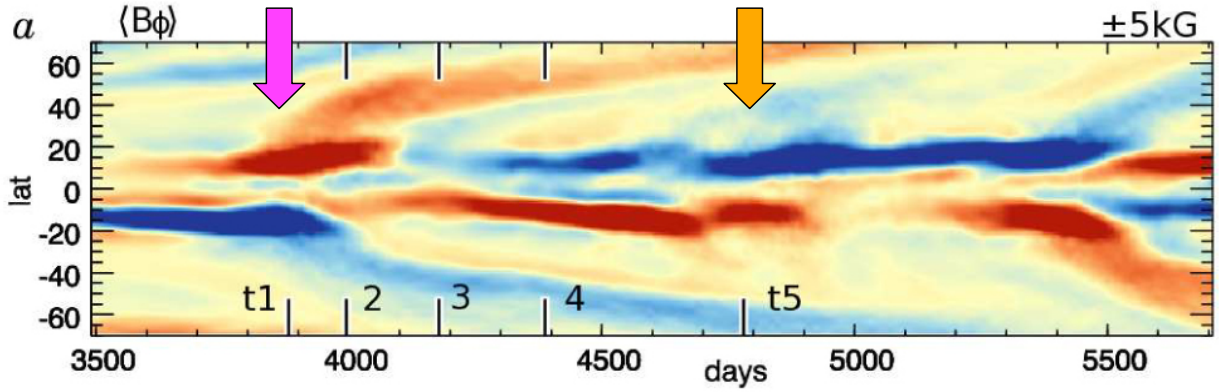
lower–η

Cyclic

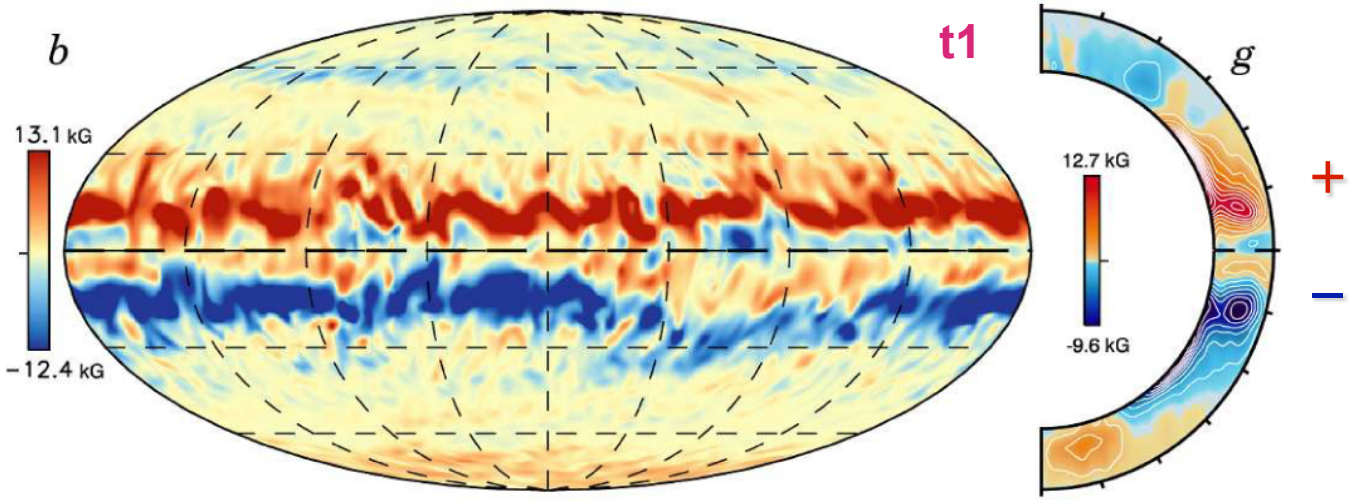
5 Ω

5 Ω

Time-latitude map of Bϕ

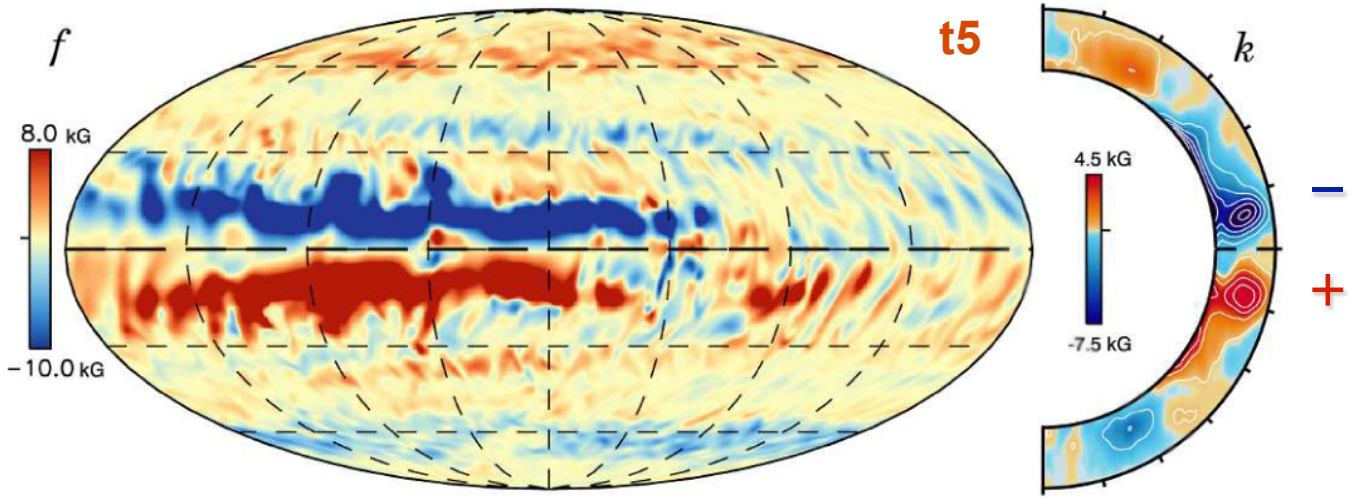


Torroidal field …



flips!

(shown here at mid-CZ)



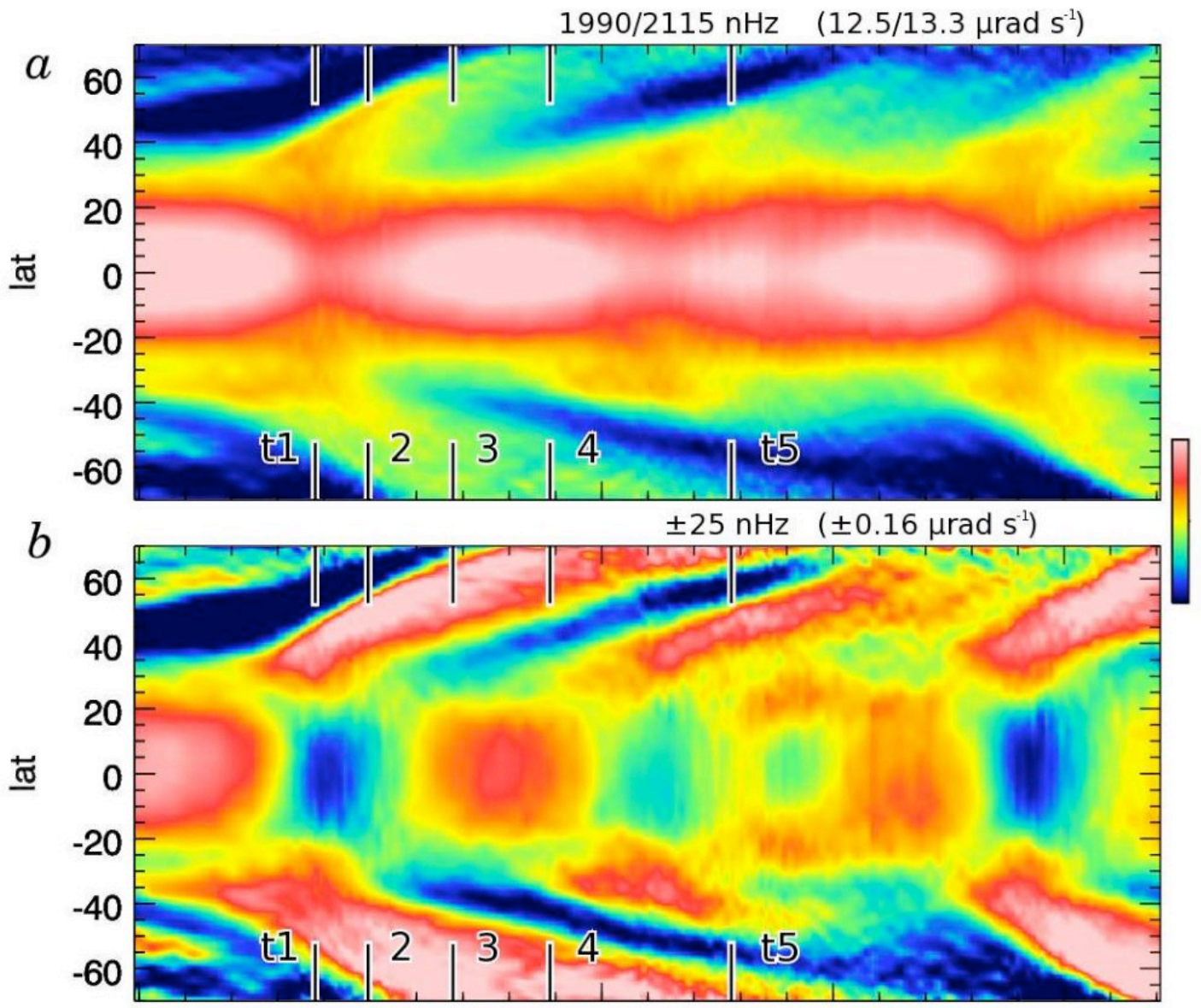
Changes in Differential Rotation Ω

5 Ω

Ω at mid-CZ

Ω' at mid-CZ, with time-avg removed

Polar branch of torsional oscillations?



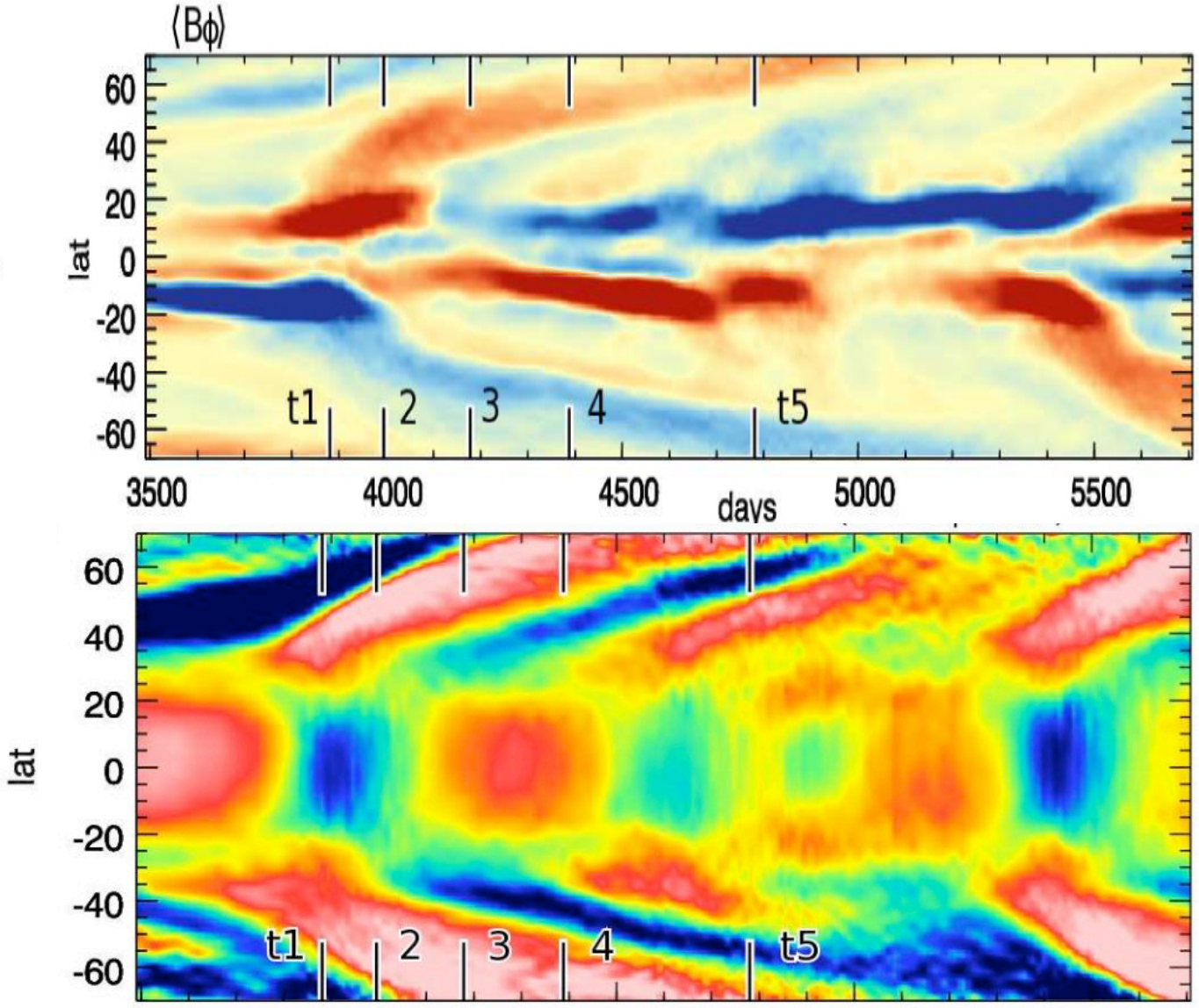
Changes in Differential Rotation Ω

5 Ω

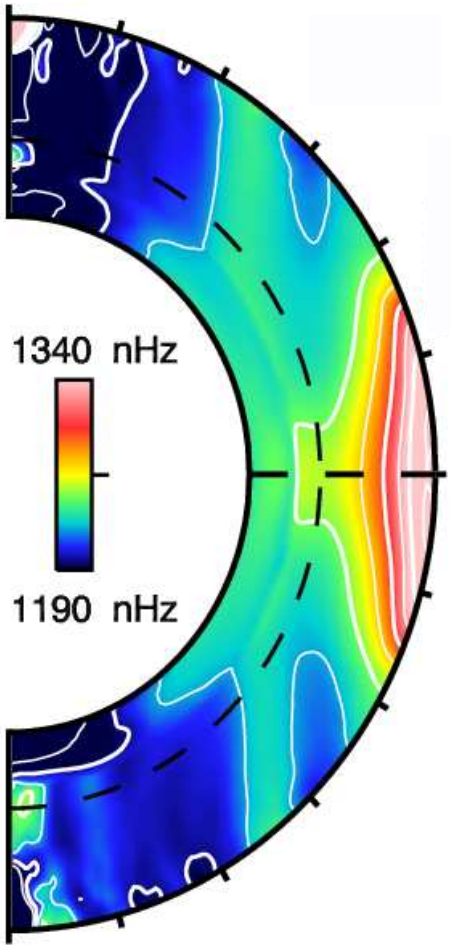
Toroidal field at mid-CZ

Ω' at mid-CZ, with time-avg removed

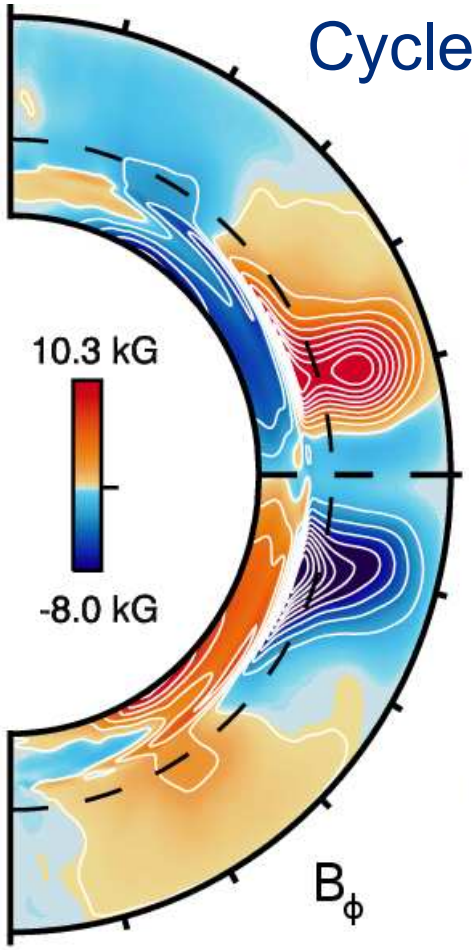
Polar branch of torsional oscillations?

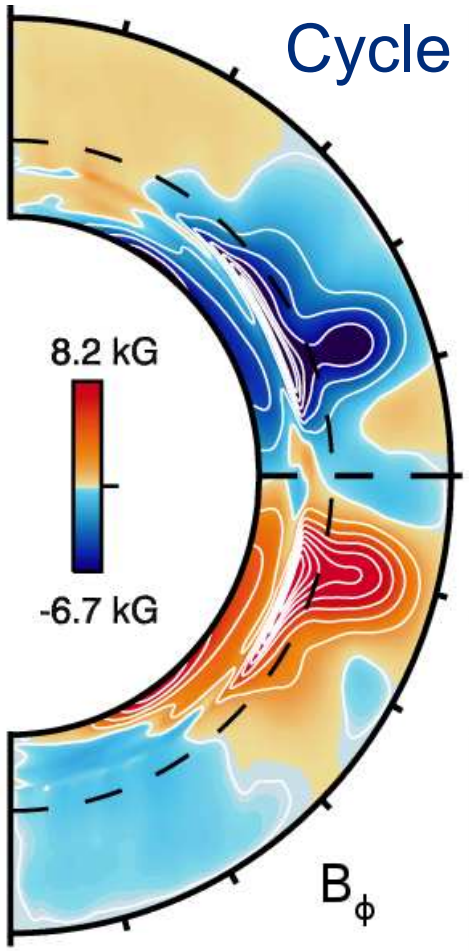


Wreaths Above a Tachocline



Differential Rotation



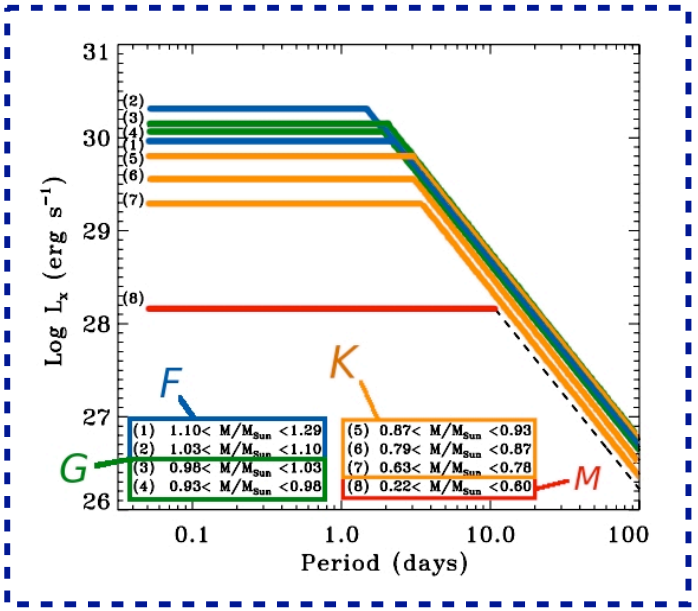


Cyclic magnetism

Observational Questions

Our Sun

- What is the nature of deep meridional circulation?
- Where are the giant cells?
- Can we see the thermal wind?



The Distant Stars

- How does activity scale with surface differential rotation?
- Do stellar dynamos depend on stellar mass? How?
- Is our Sun a typical star?