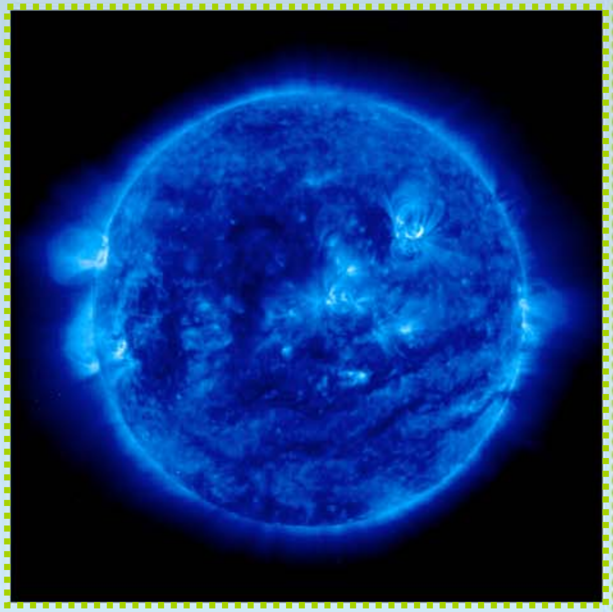
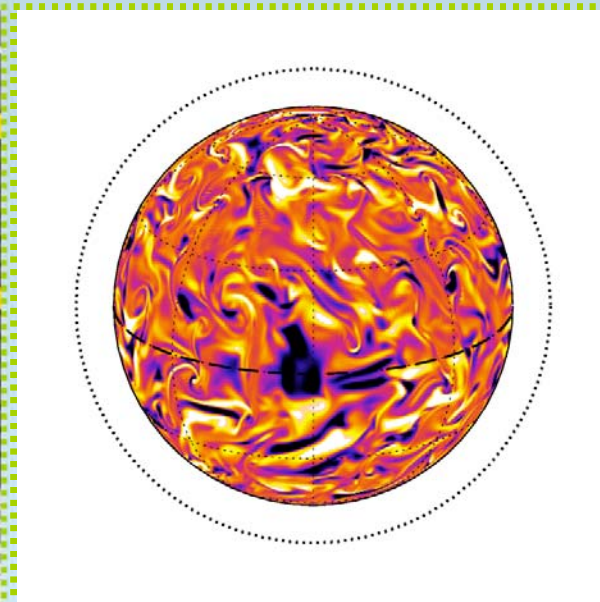
Simulations of convection and magnetism in stars



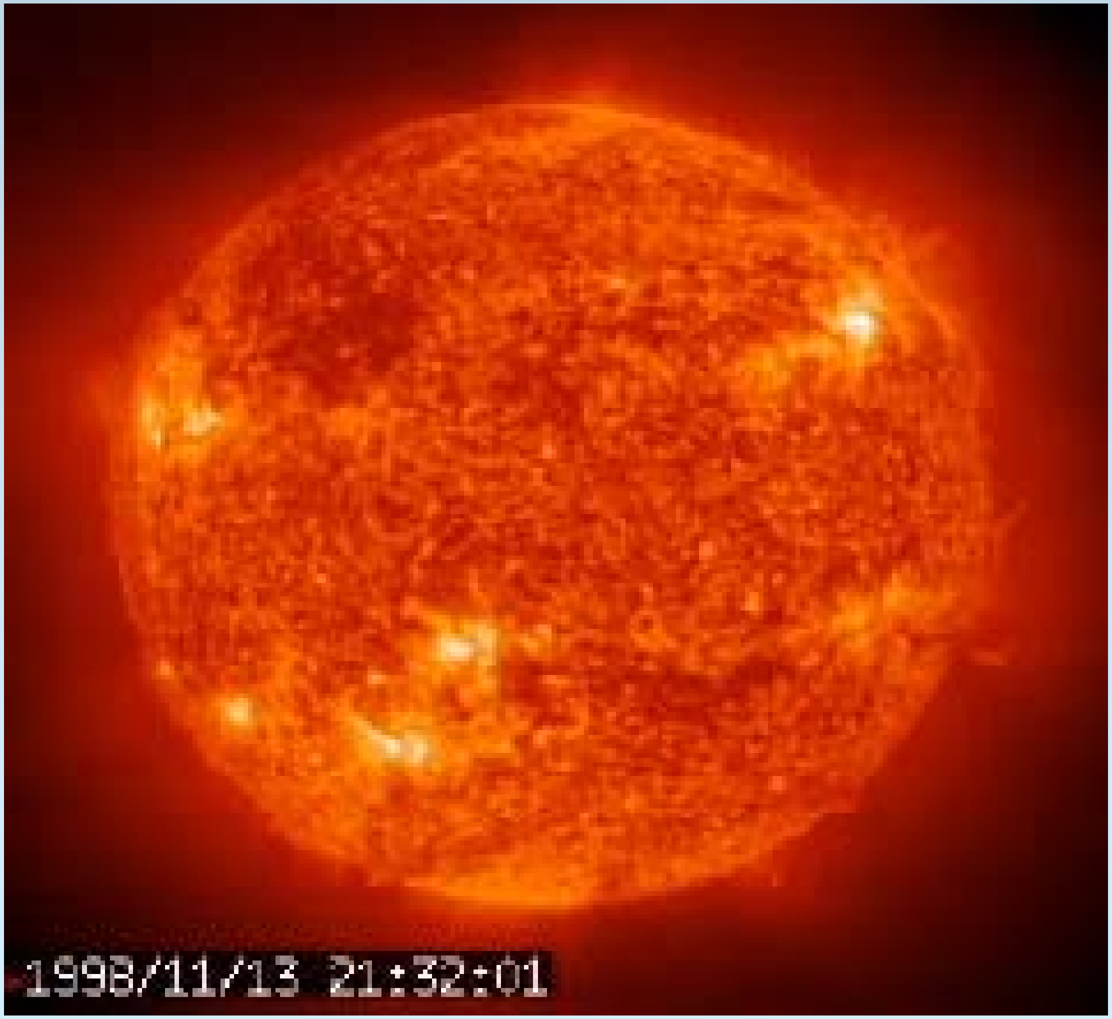


Matthew Browning (UC Berkeley)

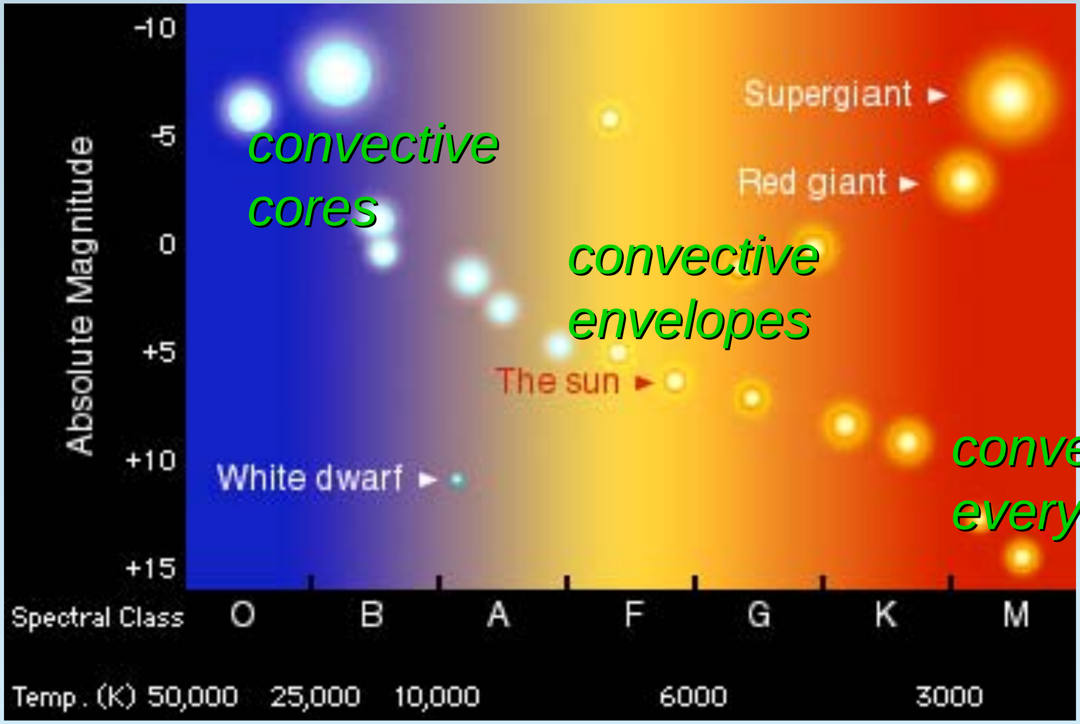
with Mark Miesch, Sacha Brun

Juri Toomre, Gibor Basri

Why study stellar dynamos?



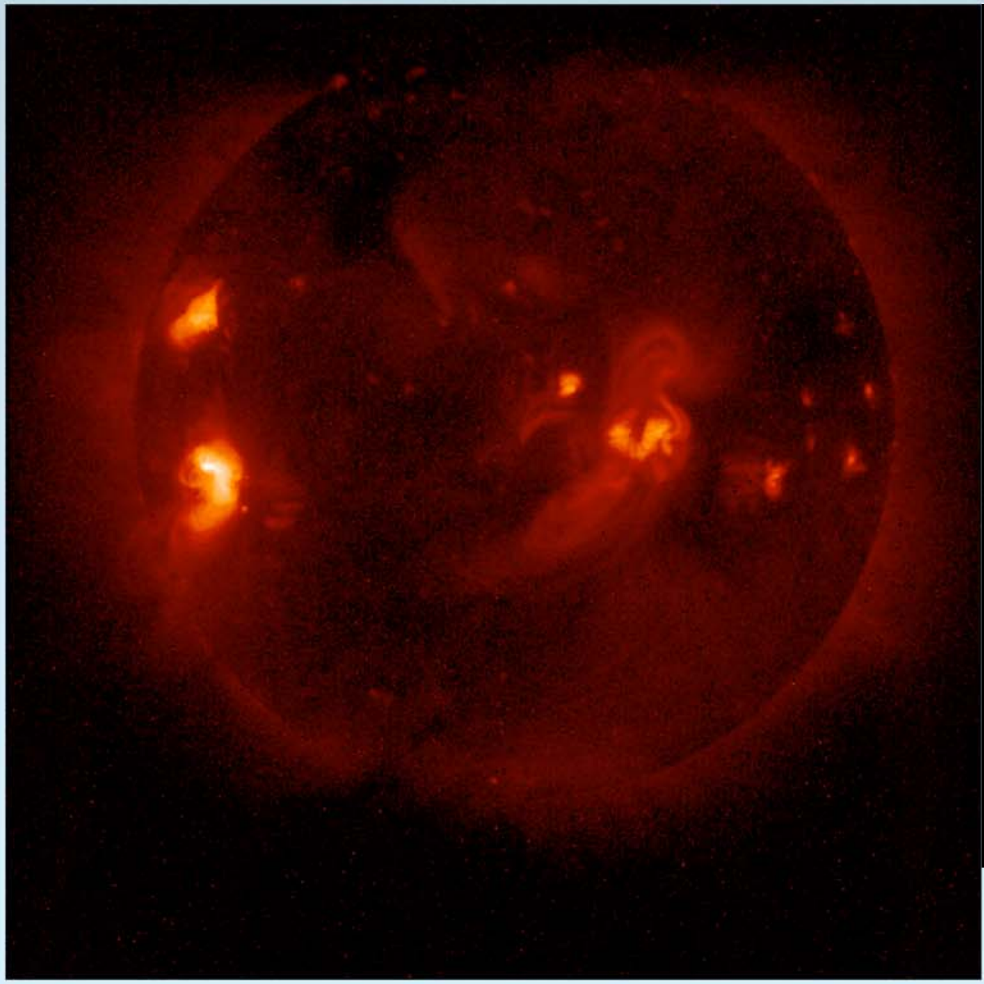
Ubiquity of convection and magnetism



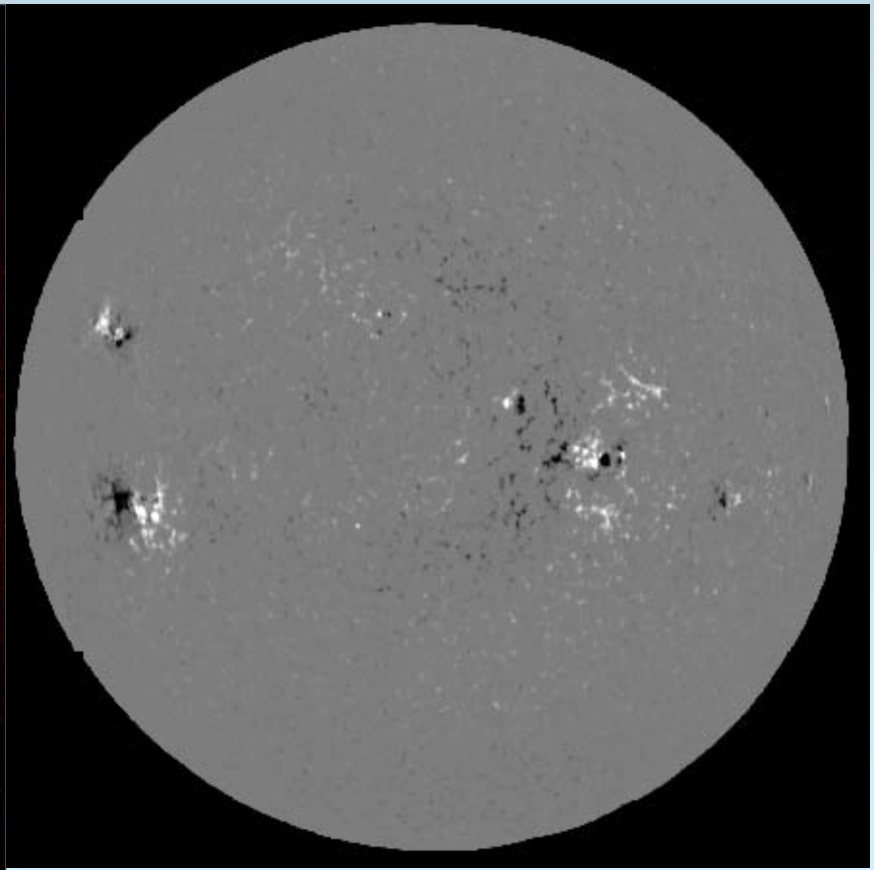
- Convection in envelopes! Cores! Full interiors!
- Connection of convection, magnetism, rotation
- Convection can build fields through dynamo action

Coronal emission as a proxy for magnetic activity

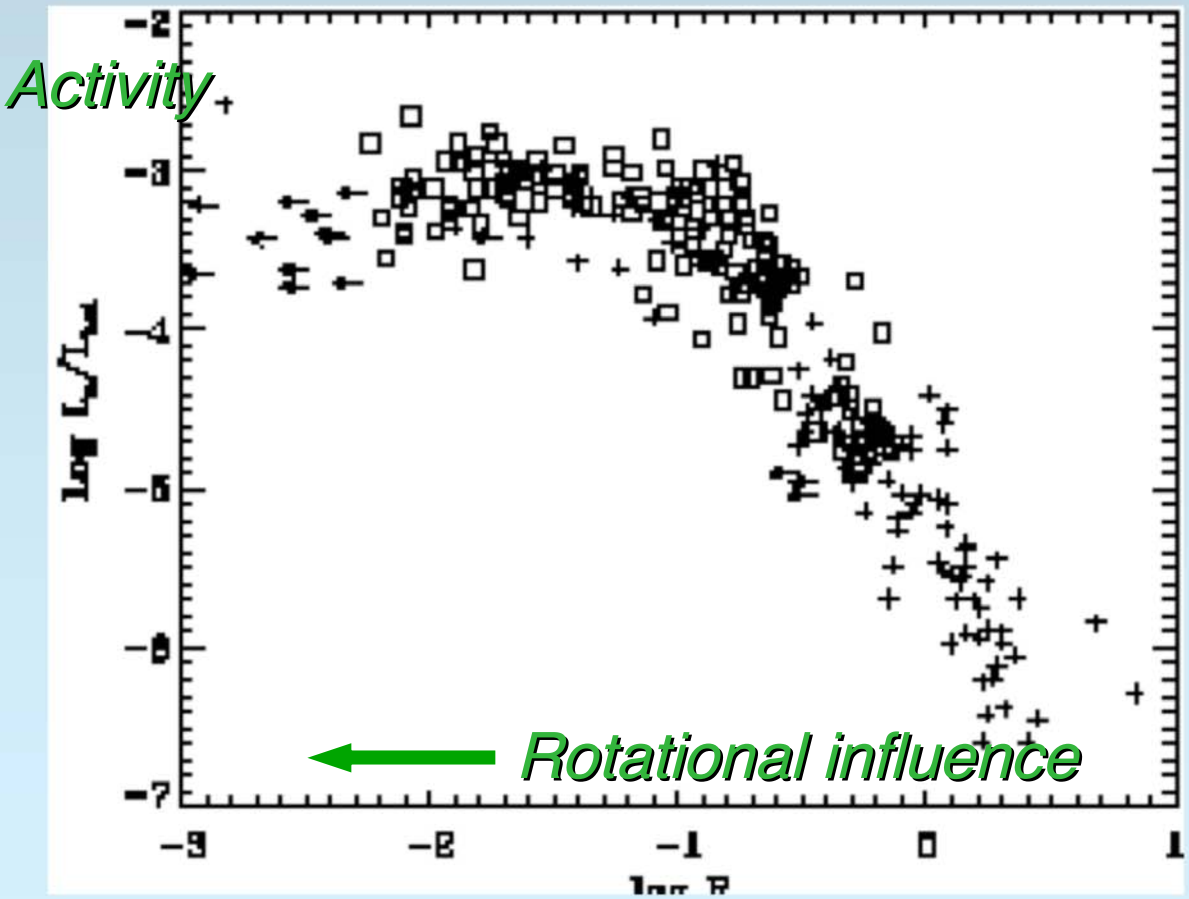
X-ray emission



Magnetogram



Magnetic activity is correlated with rotation rate

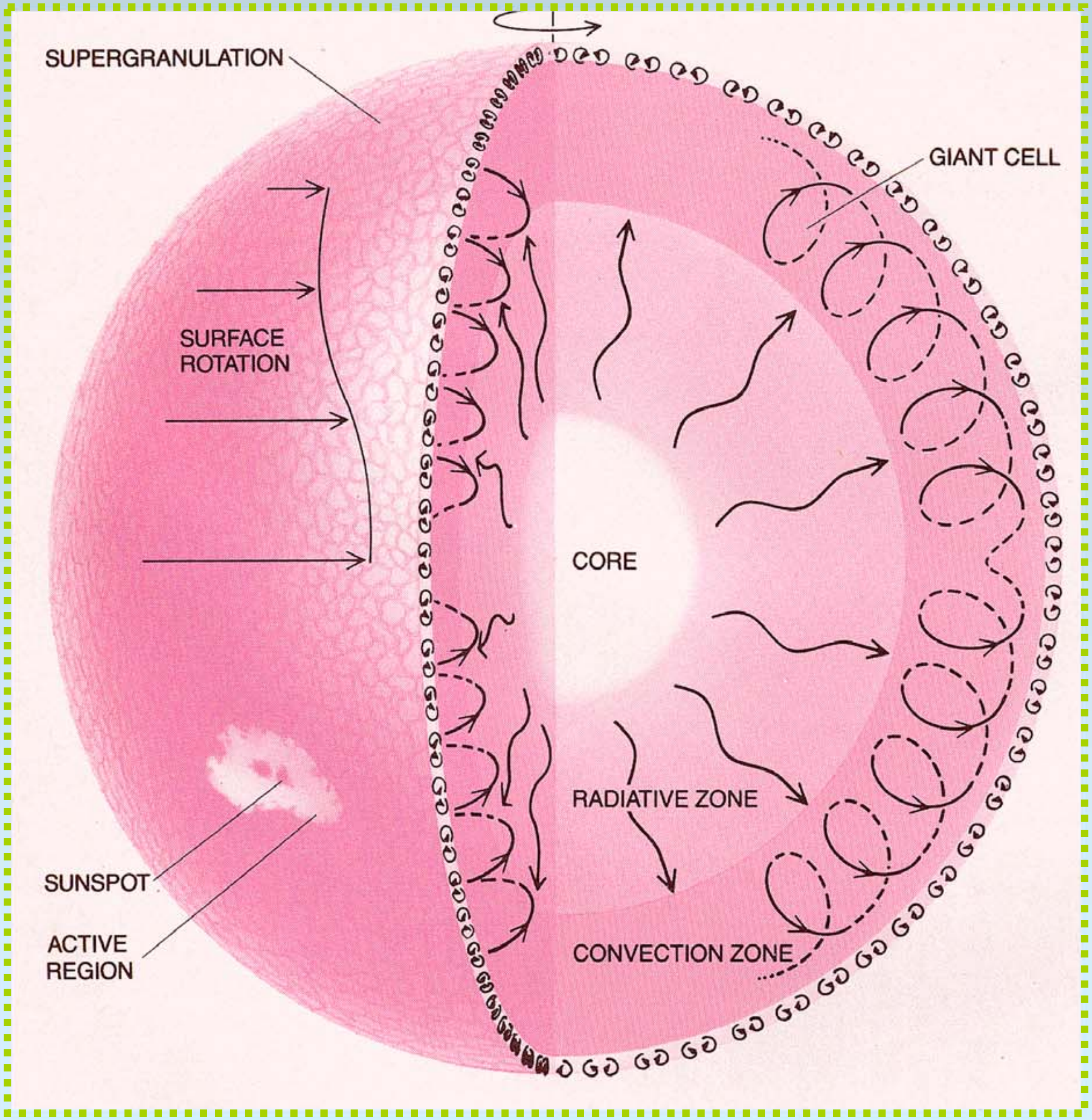


Observed from F to M

More rapid rotation = more activity (to a point)

Pizzolato et al. (2003)

Convection Zone and Radiative Interior



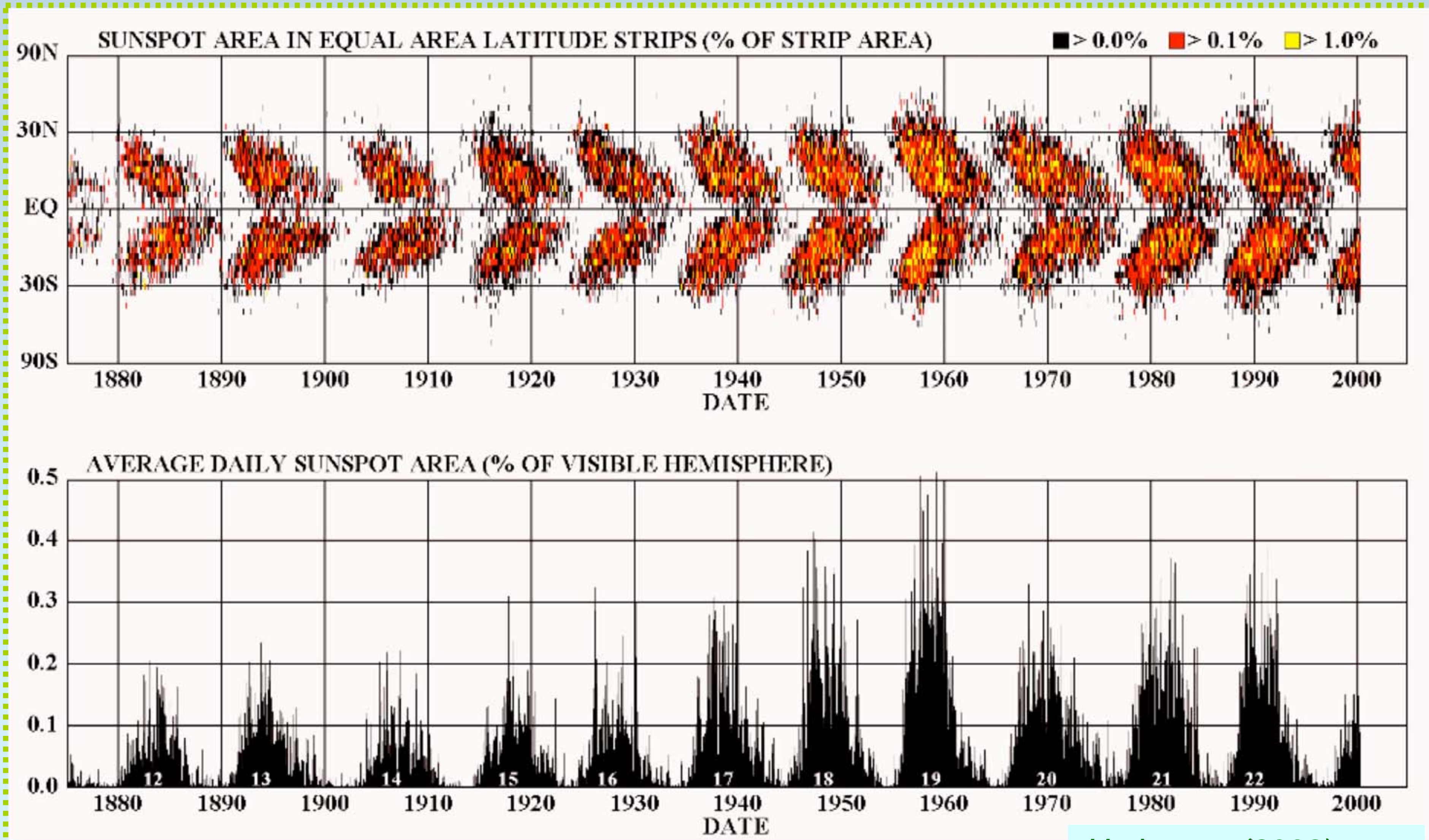
DEEP SHELL
VERY TURBULENT CONVECTION
(200 Mm)

DRIVES STRONG DIFFERENTIAL ROTATION

VAST RANGE OF DYNAMICAL SCALES

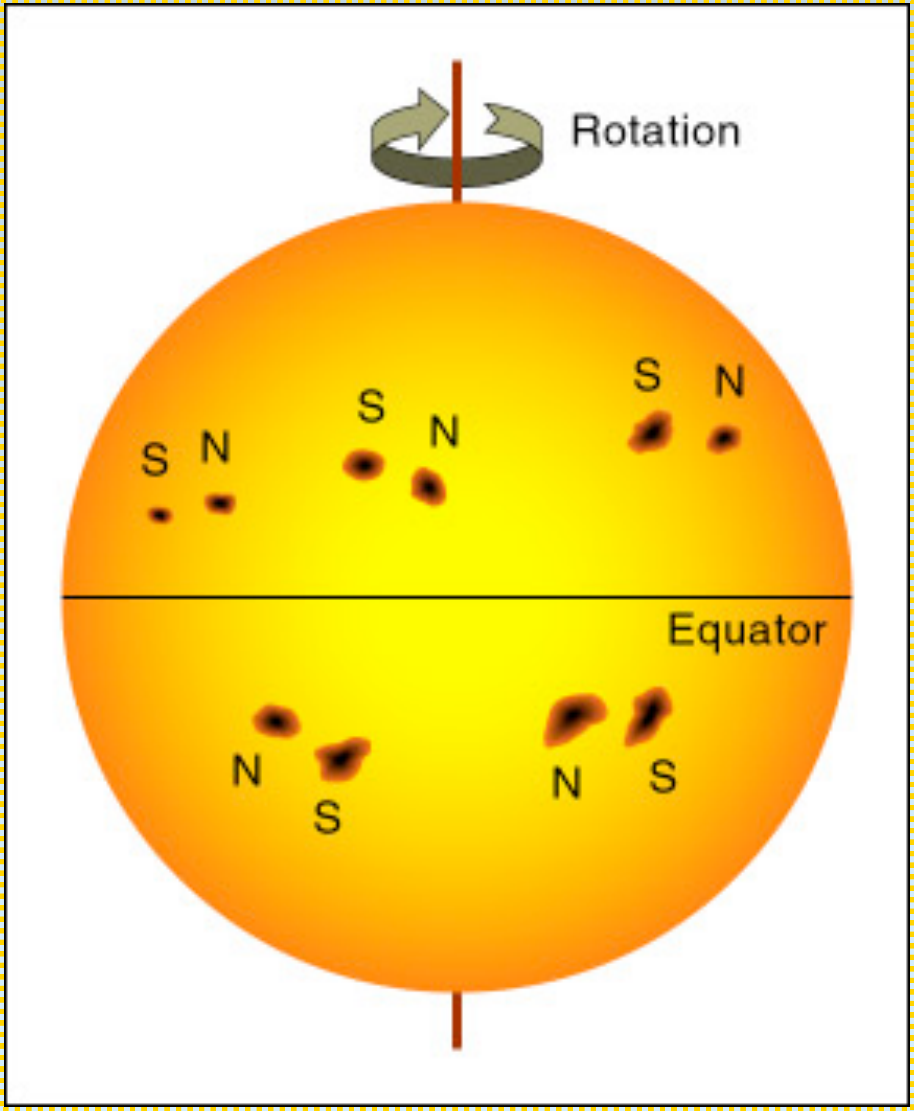
GRANULES ~1 Mm
MESOGRANULES ~5 Mm
SUPERGRANULES ~20 Mm
GIANT CELLS ~200+ Mm

Orderly Solar Magnetism

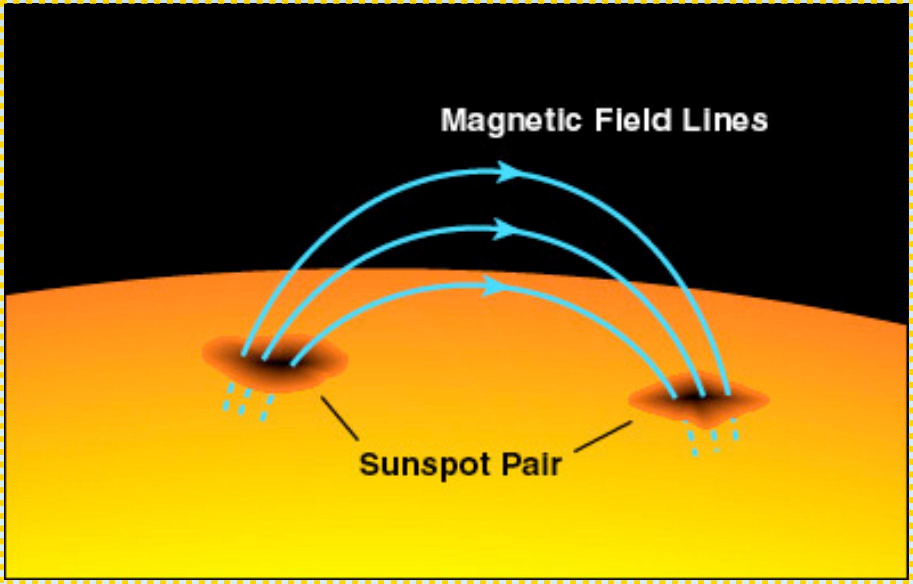


Hathaway (2003)

Sunspots: on closer look

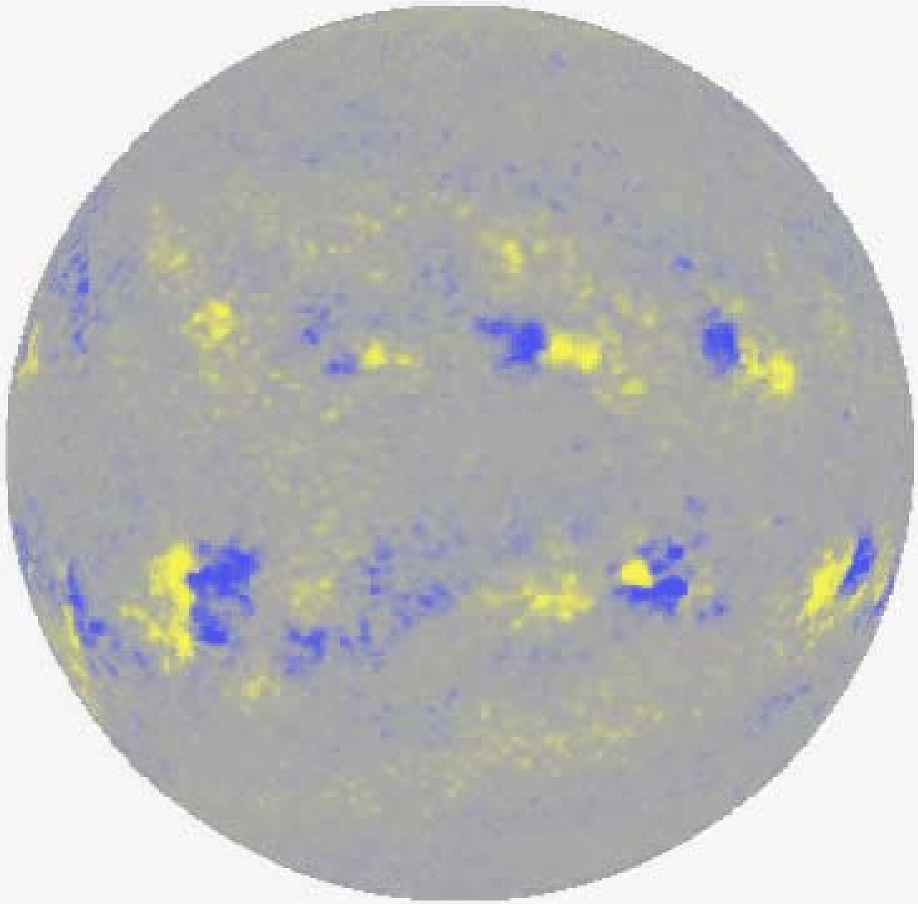


Sunspots in one hemisphere share common orientation



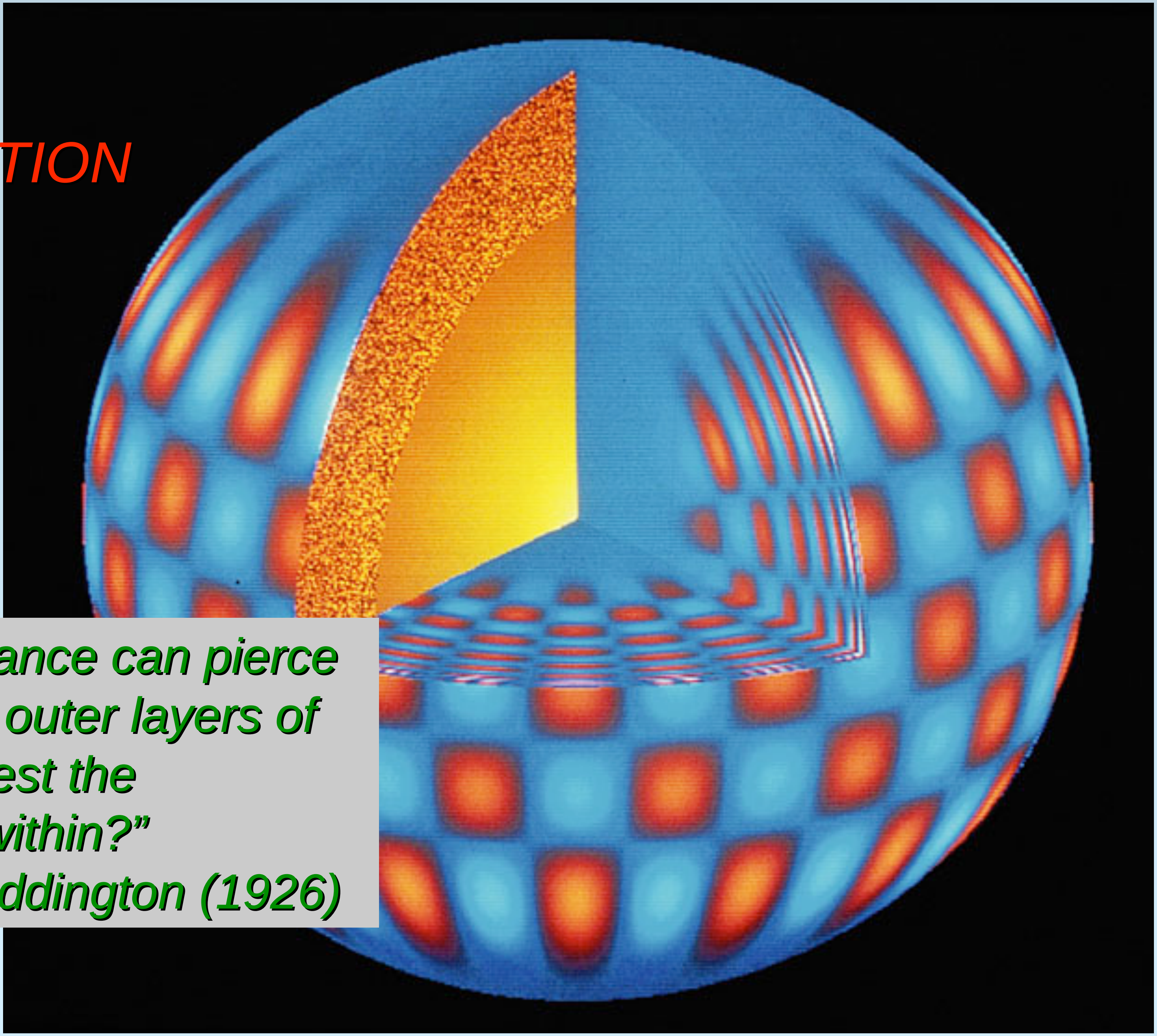
Figures: HK Space Museum

Orderly Solar Magnetism



Hathaway (2003)

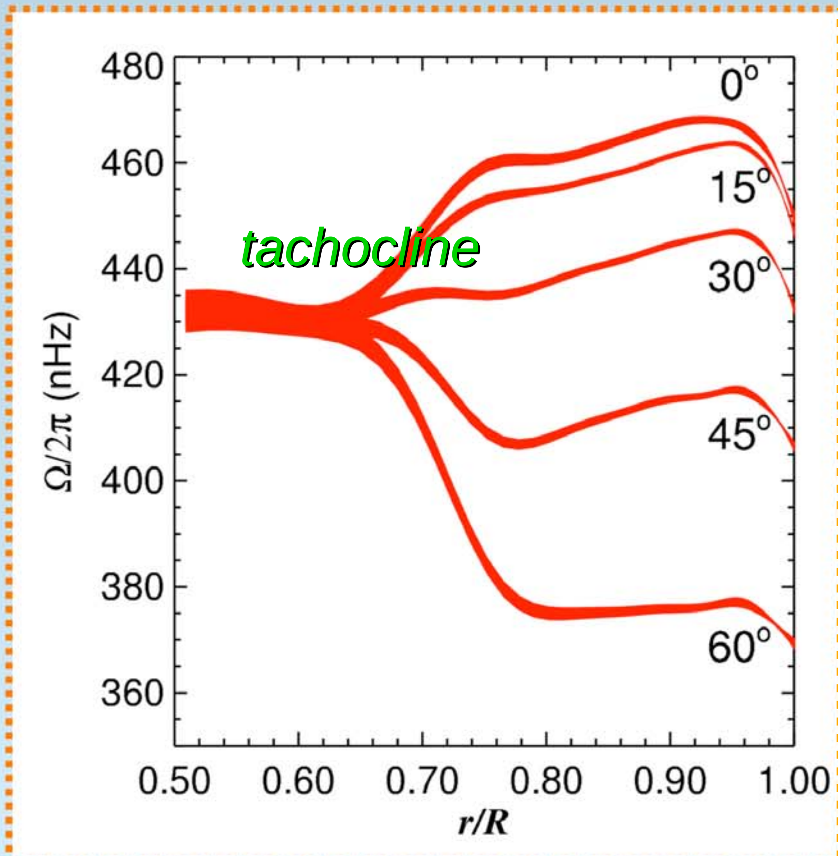
SOLAR OSCILLATION MODE

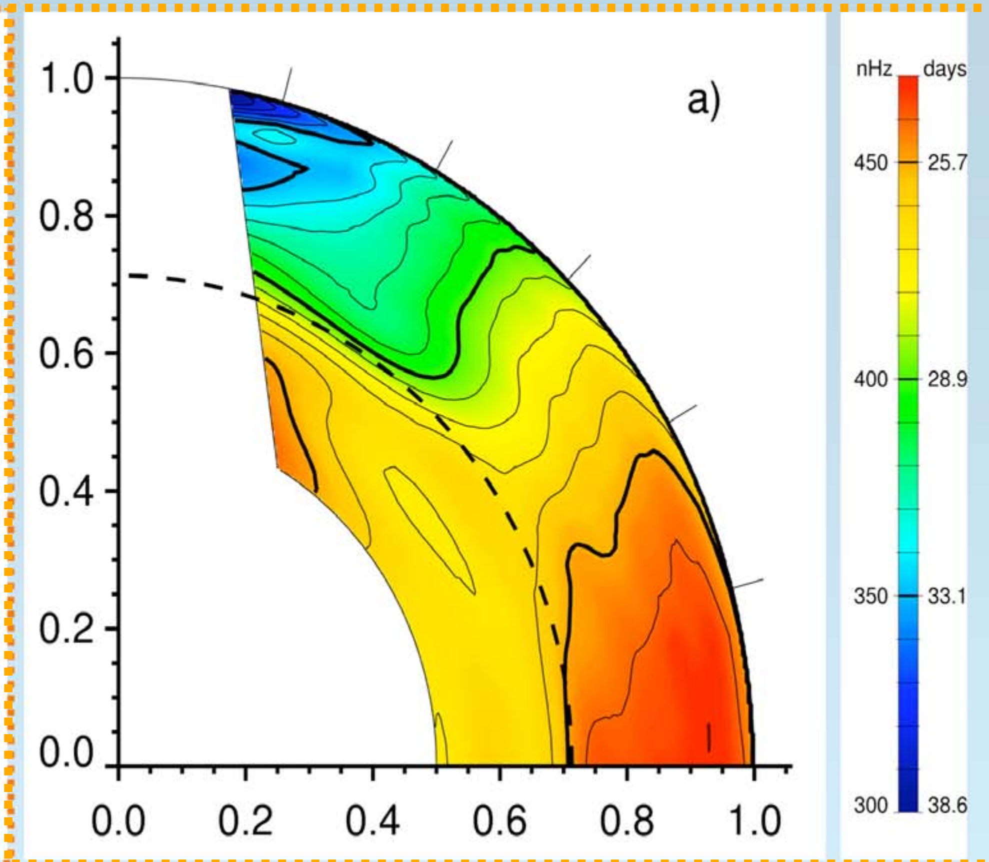


"What appliance can pierce through the outer layers of a star and test the conditions within?"

-Eddington (1926)

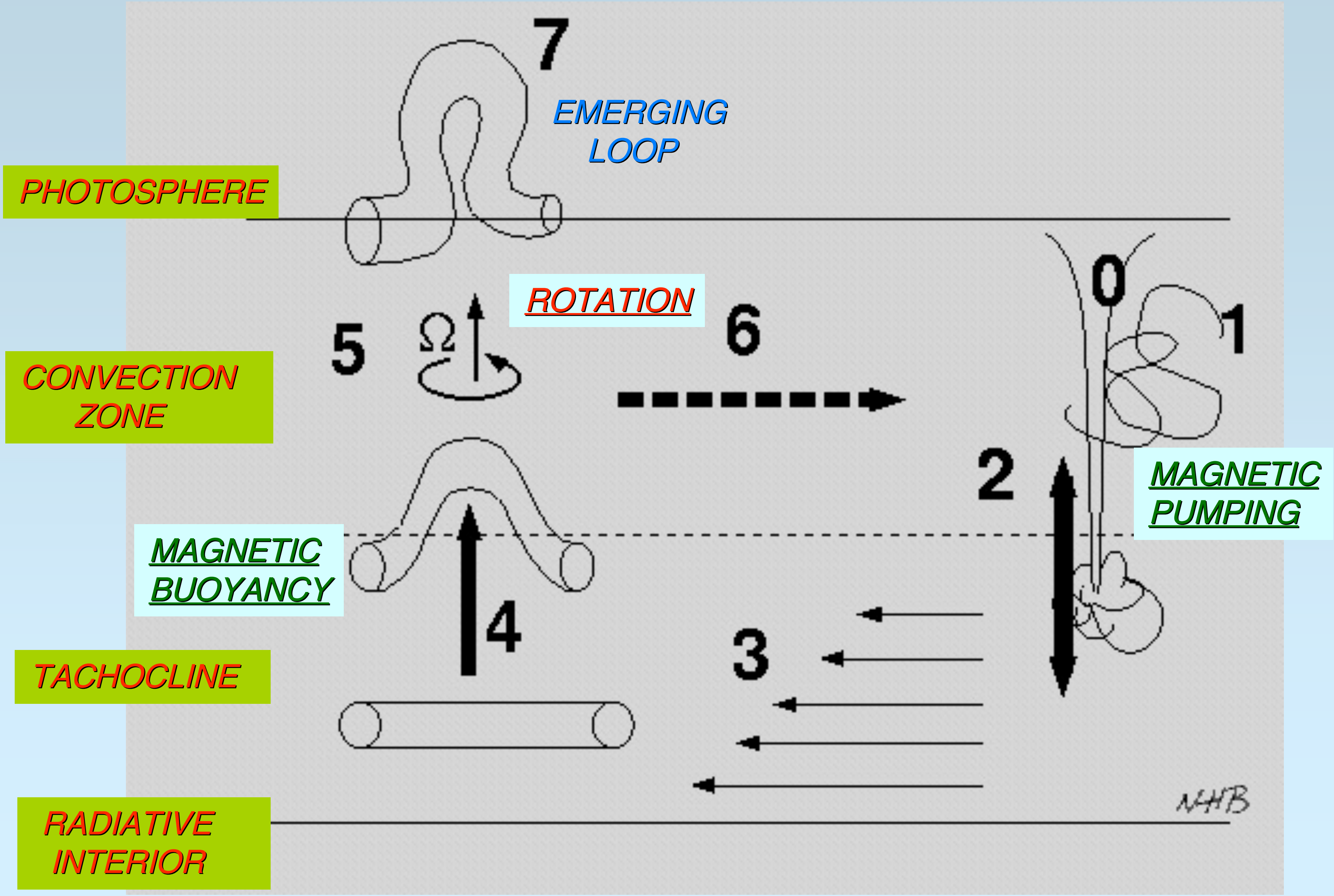
Clues provided by helioseismology

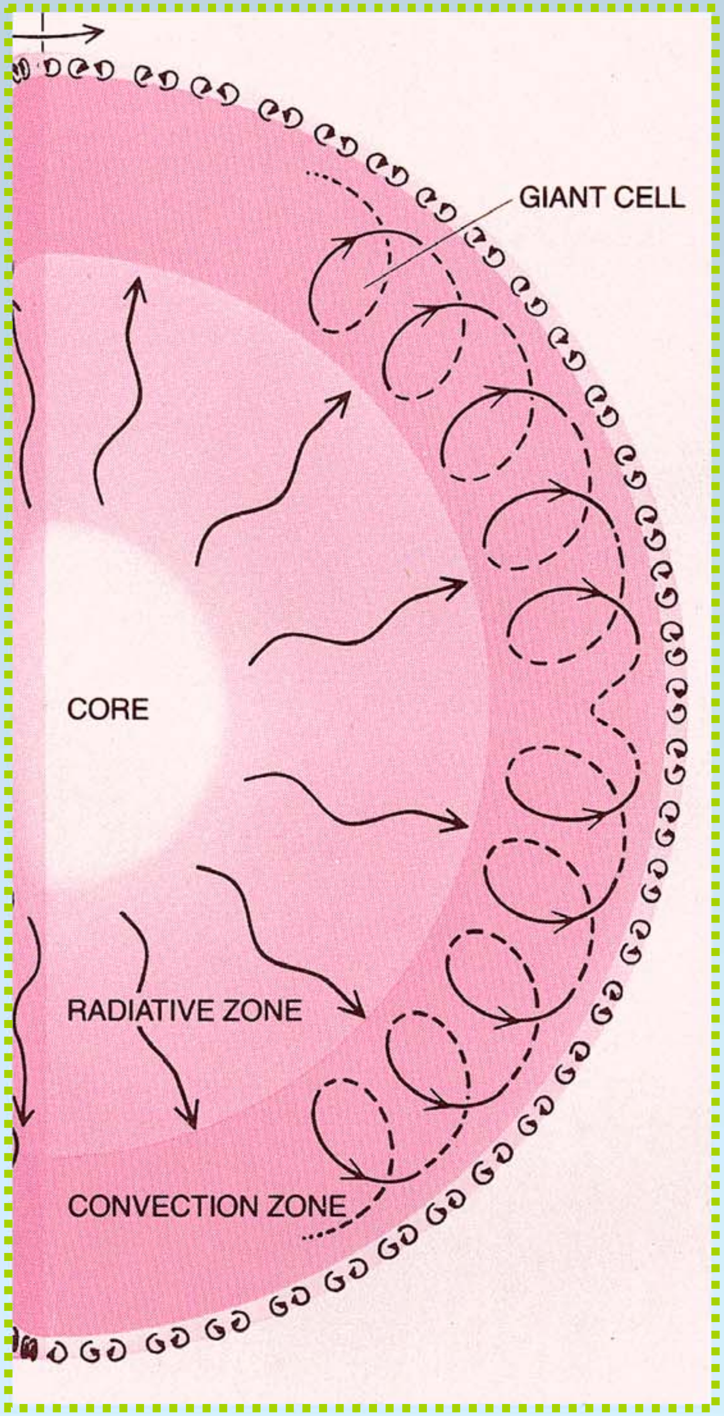




- Tachocline of rotational shear at base of CZ probably stretches toroidal field
- Helical convection in CZ likely also plays role

Building blocks of dynamo action

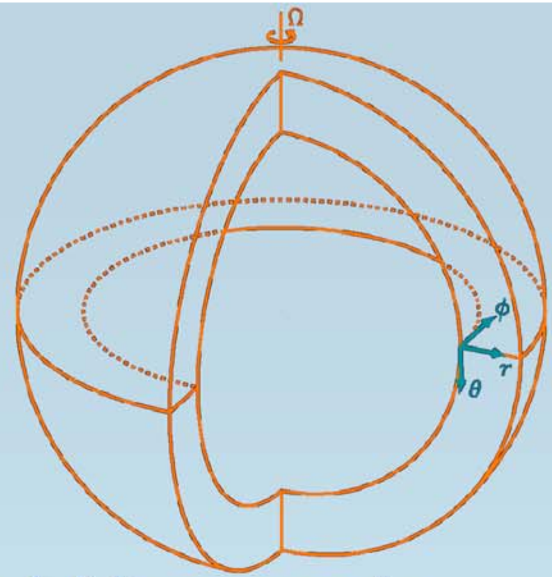




Motivating issues for 3-D simulations

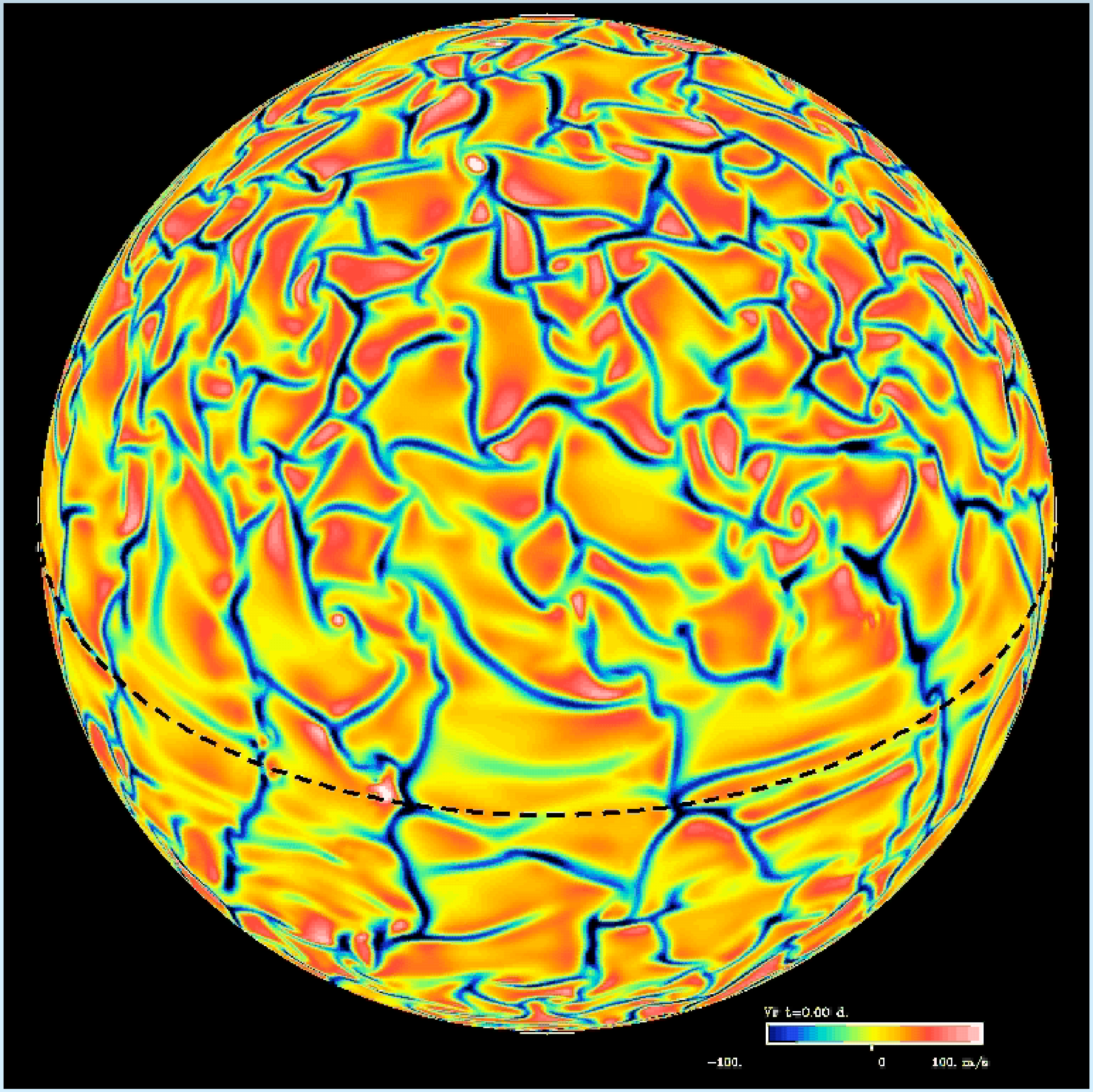
- How does convection establish strong differential rotation?
- What are the roles of convection and differential rotation in building observed magnetism?

Computational Approach for 3-D Simulations



- Utilize 3-D *Anelastic Spherical Harmonic* (ASH) code in full spherical geometry
- Realistic stratification, radiative opacity
- Simplified physics: perfect gas, subgrid turbulent transport
- Pre-2006: model bulk of CZ (0.72-0.97R)
- Latest models: include tachocline below

Vigorous and evolving convection

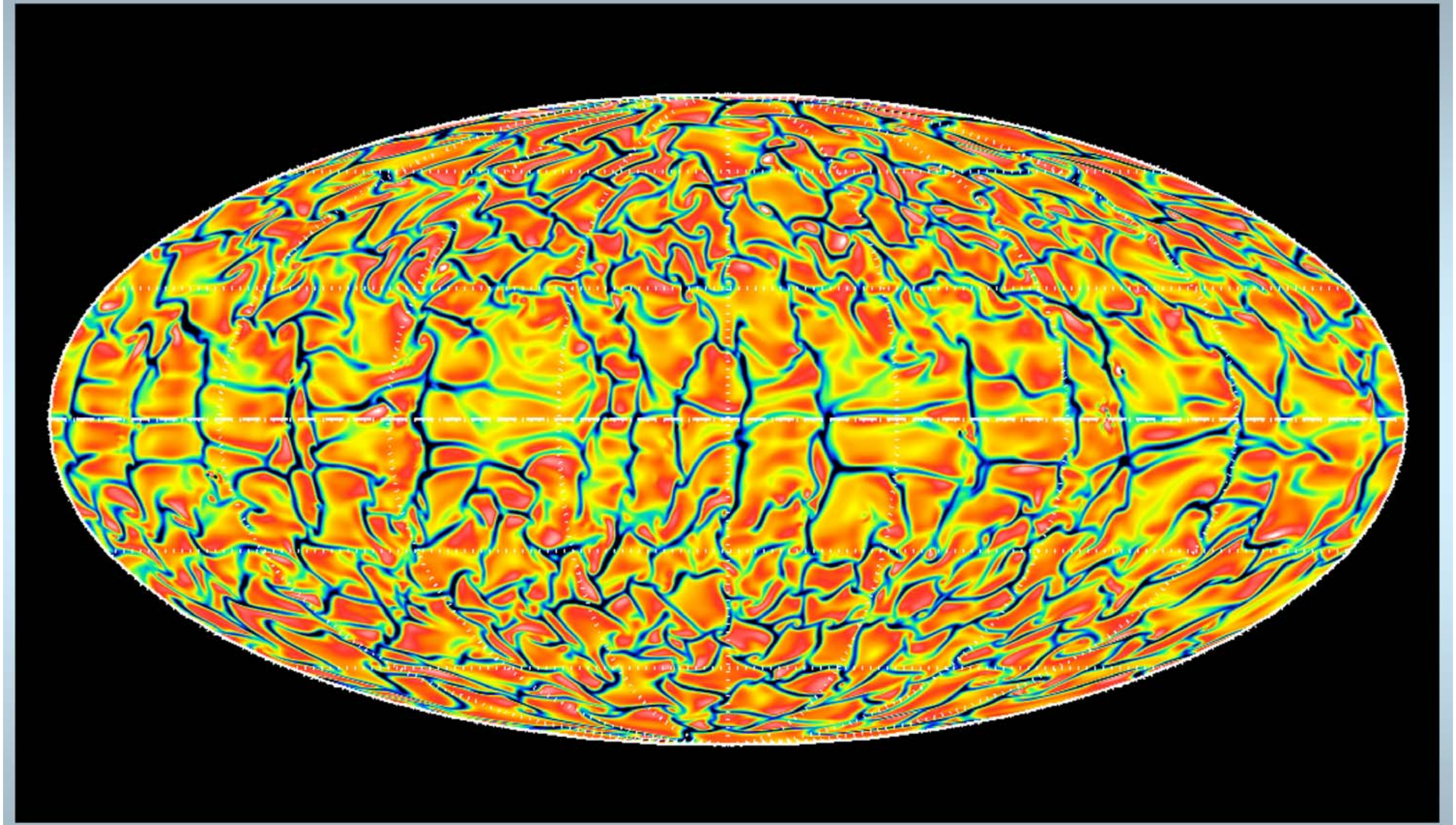


Radial velocity V_r
near top of CZ

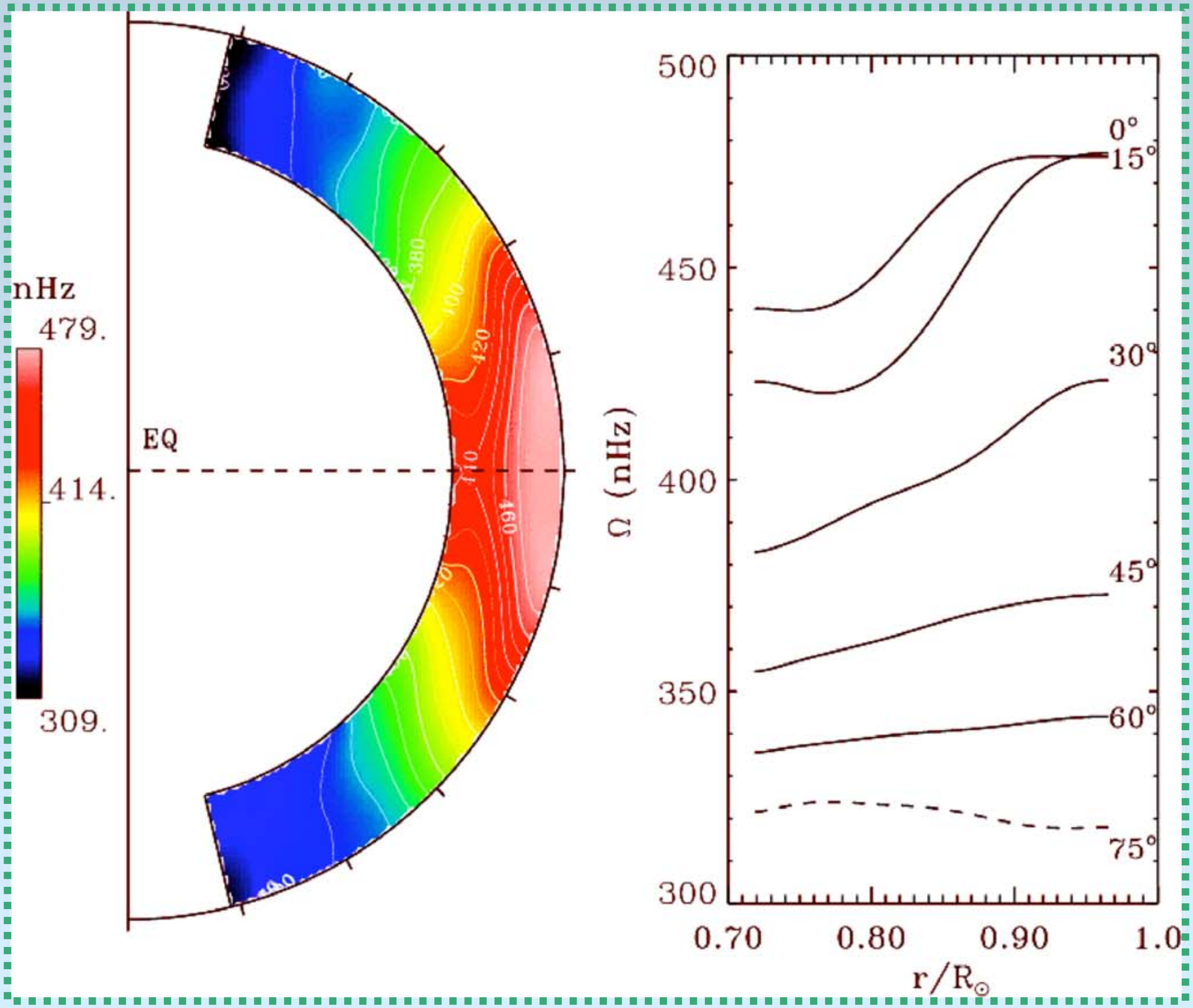
Broad upflows,
narrow downflows

Case E, Brun et al.

Global view of convective patterns



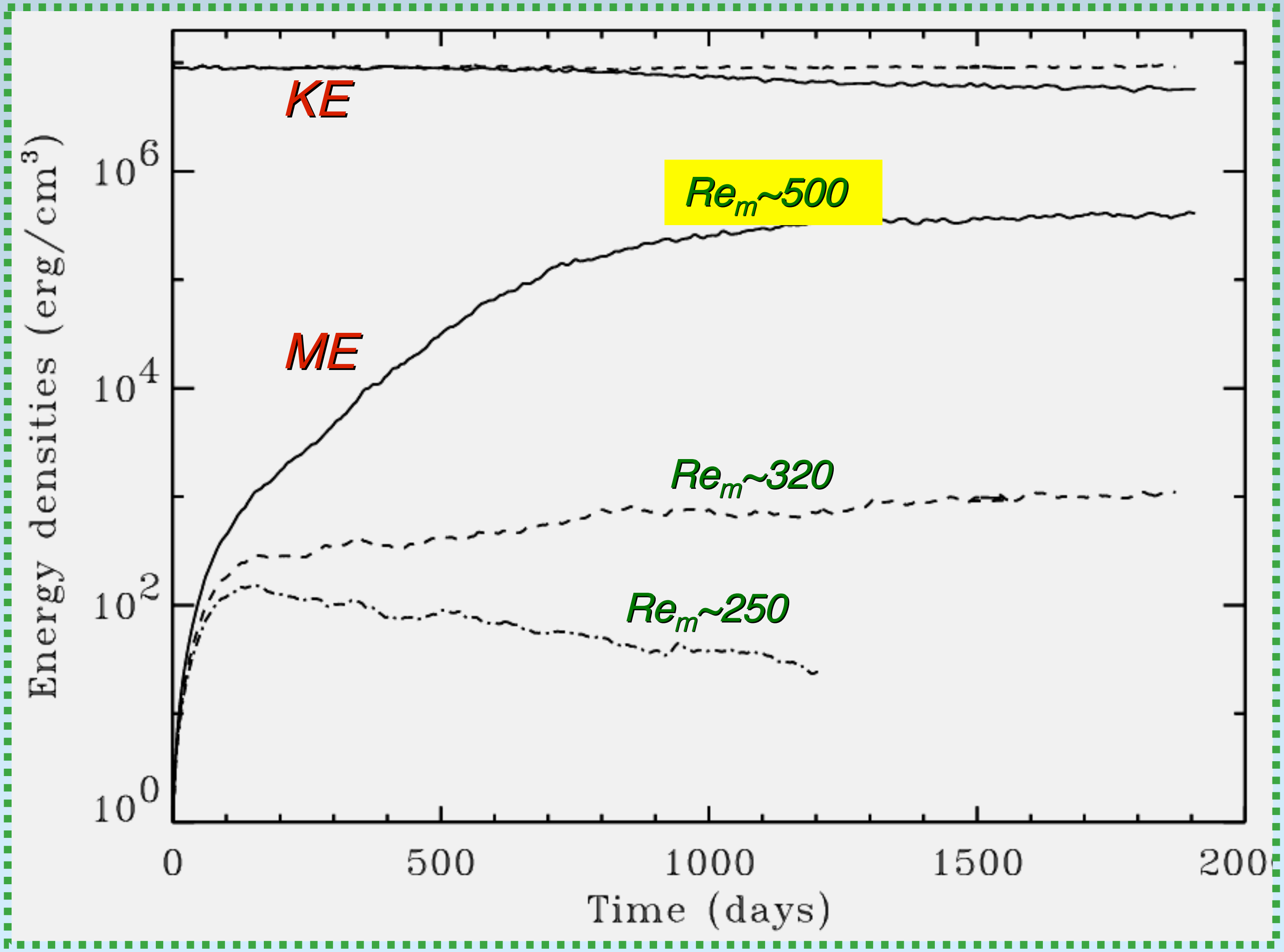
Differential rotation realized



Reasonable contact with helioseismic angular velocity

Crucial role played by Reynolds stresses

Dynamo activity in MHD models



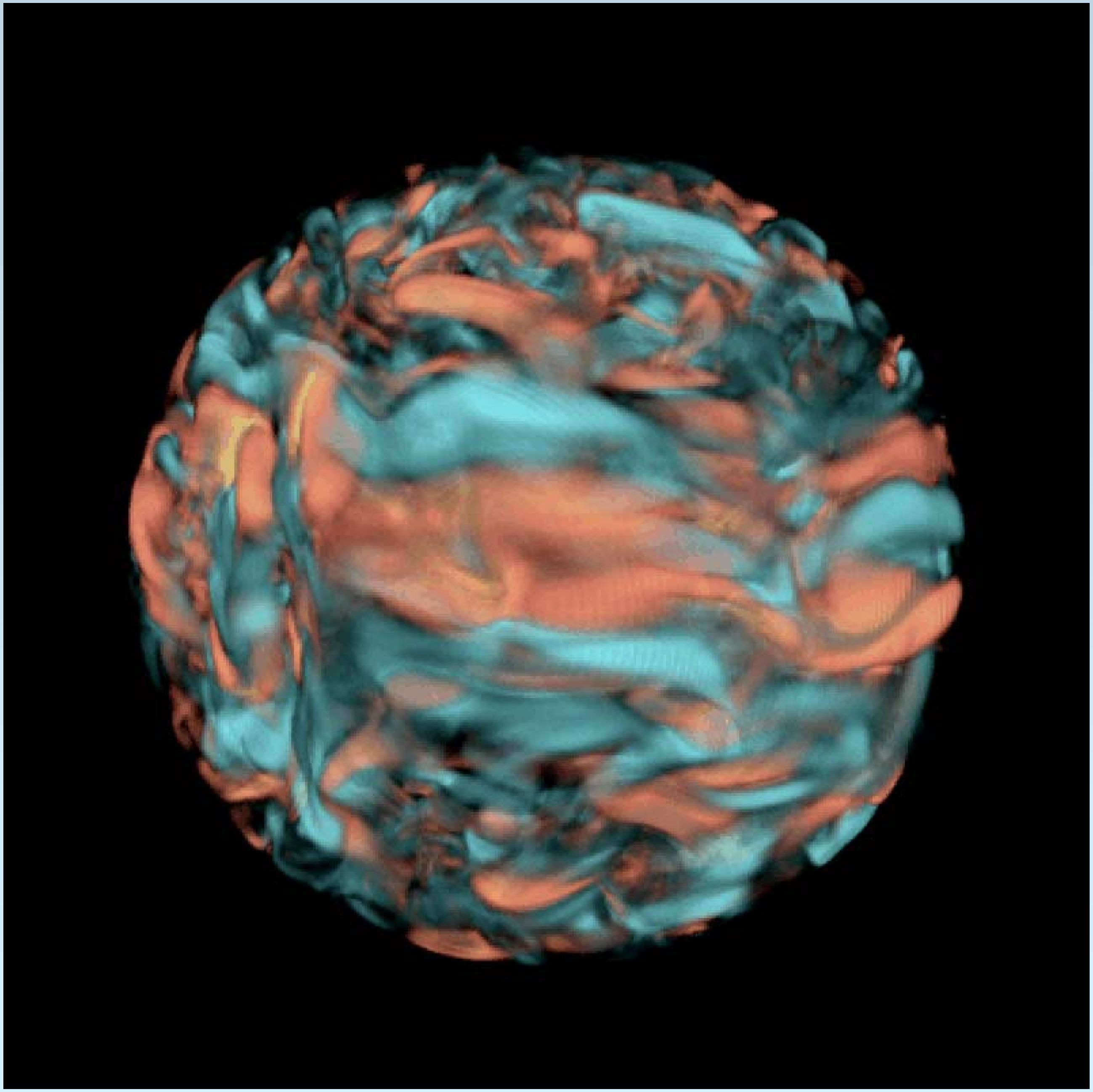
Dynamo Threshold
Near Re_m~300

With increasing ME, drop in KE

Final ME ~8% KE

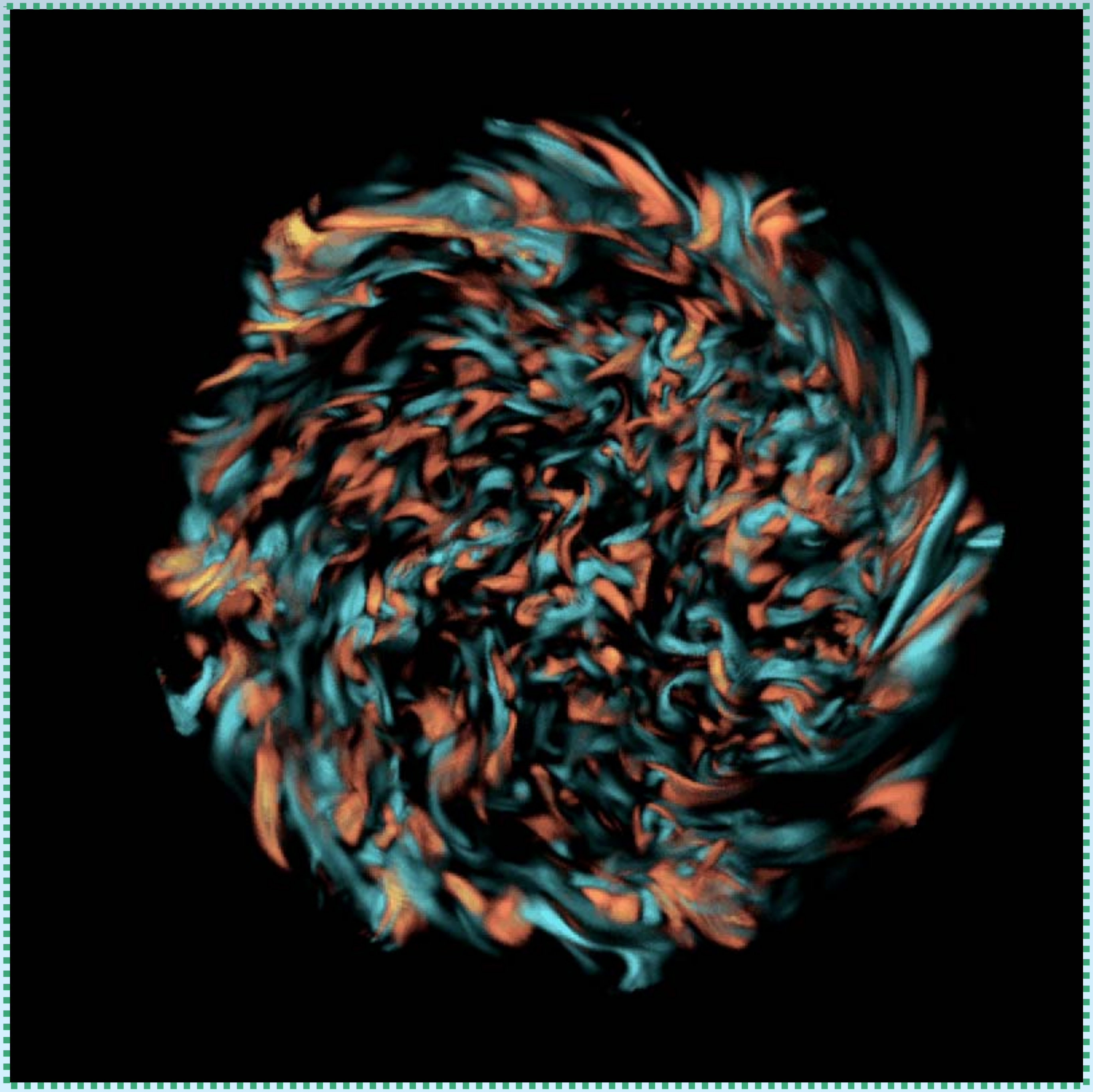
Still solar-like diff. rotn

Convective motions amplify a tiny seed field by several orders of magnitude



Intricate magnetic field

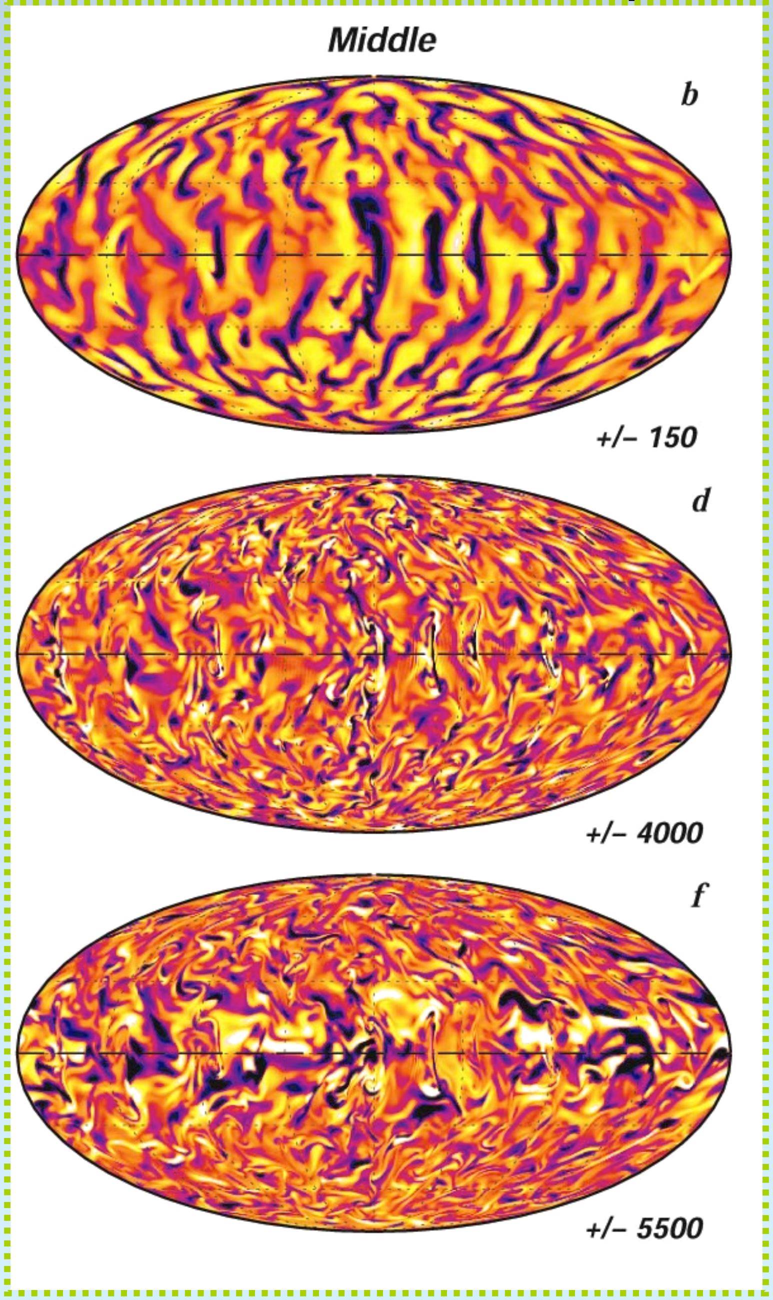
Evolving banded azimuthal field



Radial field in cutaway

Complexity in interleaved radial fields

Global views of complex flows and fields



V_r

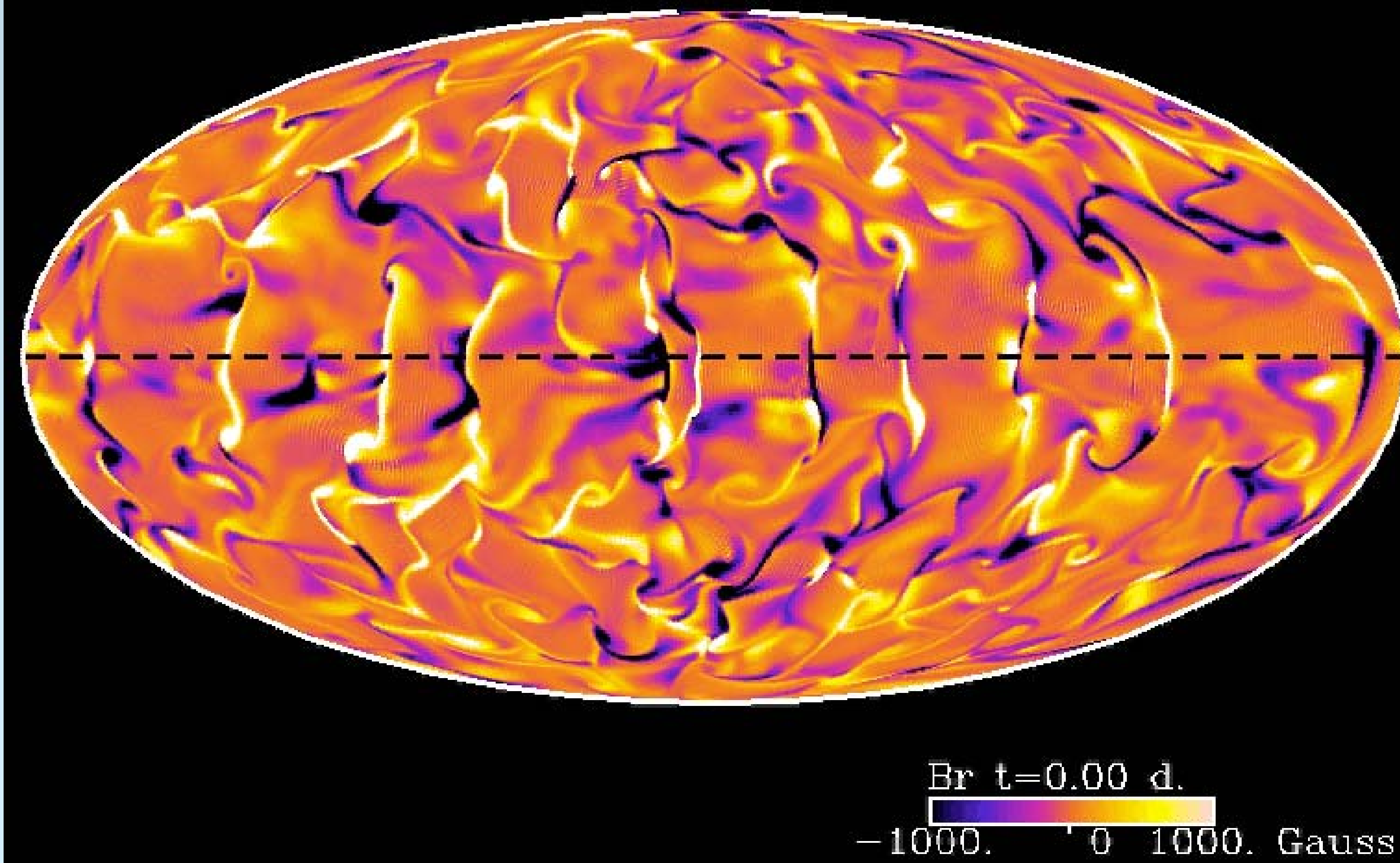
Field mainly on smaller scales than flow (Pm >1)

B_r

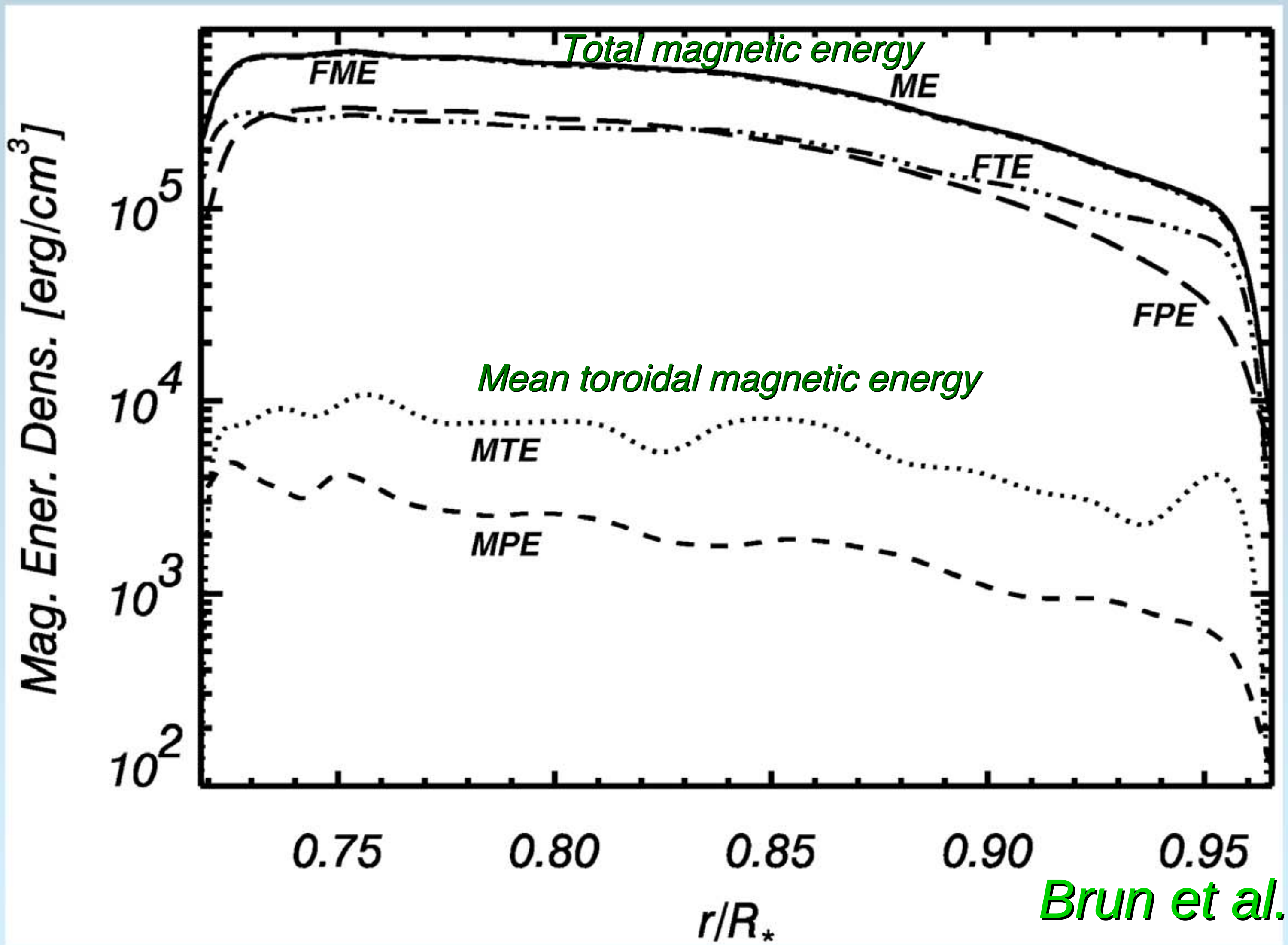
Strongest radial fields found in downflows

B_φ

Evolving radial magnetic field



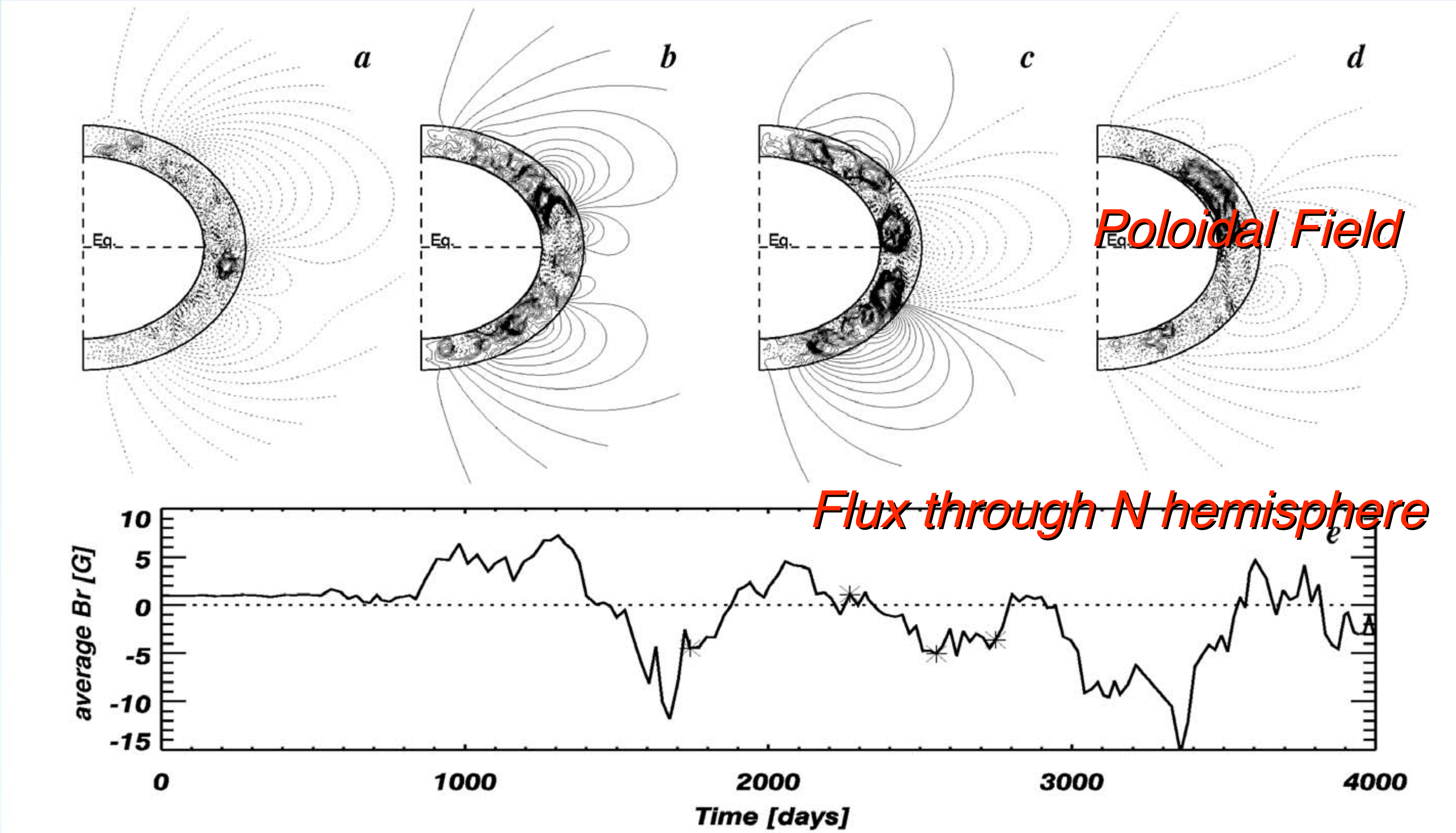
Fluctuating magnetism dominates



Brun et al. 2004

Fluctuating fields much stronger than mean fields

Frequent polarity reversals



Polarity flips at irregular intervals of <600 days

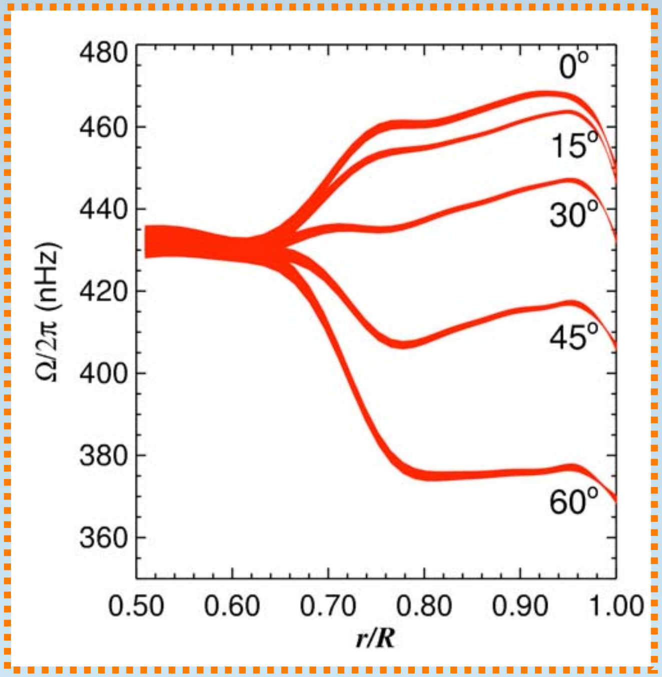
The story so far (pre-2006)

- Simulations that model bulk of CZ get reasonable differential rotation *(good)*
- Strong dynamo action is realized without diminishing that differential rotation, *(good)* BUT…
- Magnetic fields are mostly fluctuating, and exhibit frequent polarity reversals *(not so good)*

Missing crucial "building block" of global dynamo:

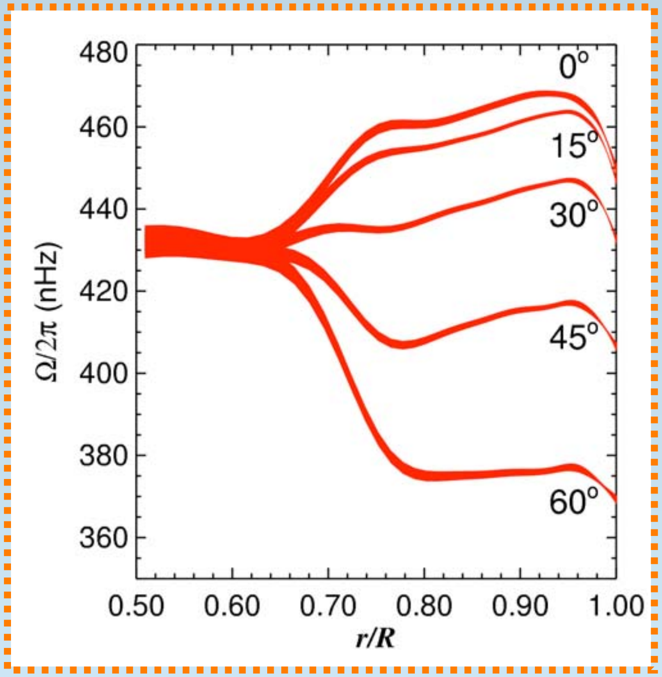
Organizing shear of tachocline

Why (do we want) a tachocline?



- Strongest radial shear
- Radiative zones are handy: magnetic buoyancy held in check (to a point)
- Other considerations from mean-field theory

Why (does the Sun have) a tachocline?

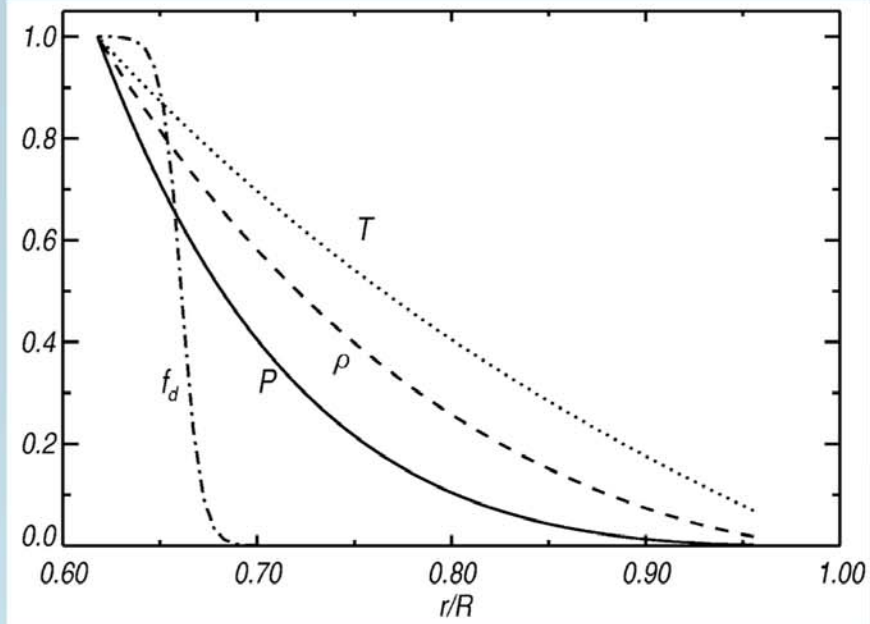


- A: I don't know (and neither do others)
- Alternate A: Elves

  (aka magnetic fields, gravity waves, anisotropic turbulence, instabilities …)

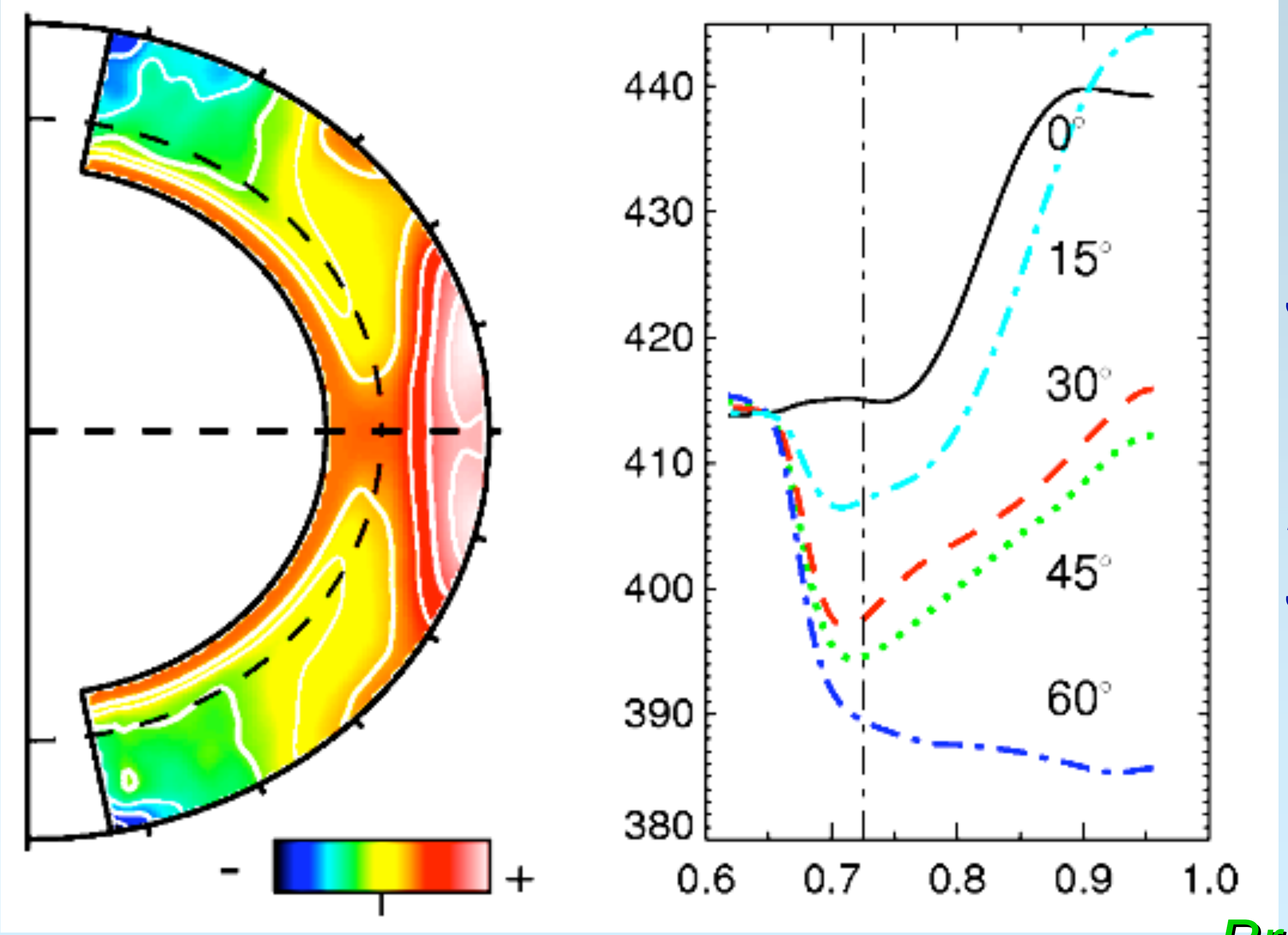
But it's there anyway

Solar dynamo with overshooting and shear



- Aim to capture key element of *overshooting* into underlying stable region
- Emulate tachocline by imposing drag and small entropy variations in radiative zone
- Seek to quantify role of penetration and shear in generating magnetism

A pseudo-tachocline of rotational shear



Weaker angular velocity contrasts than Sun, but still solar-like

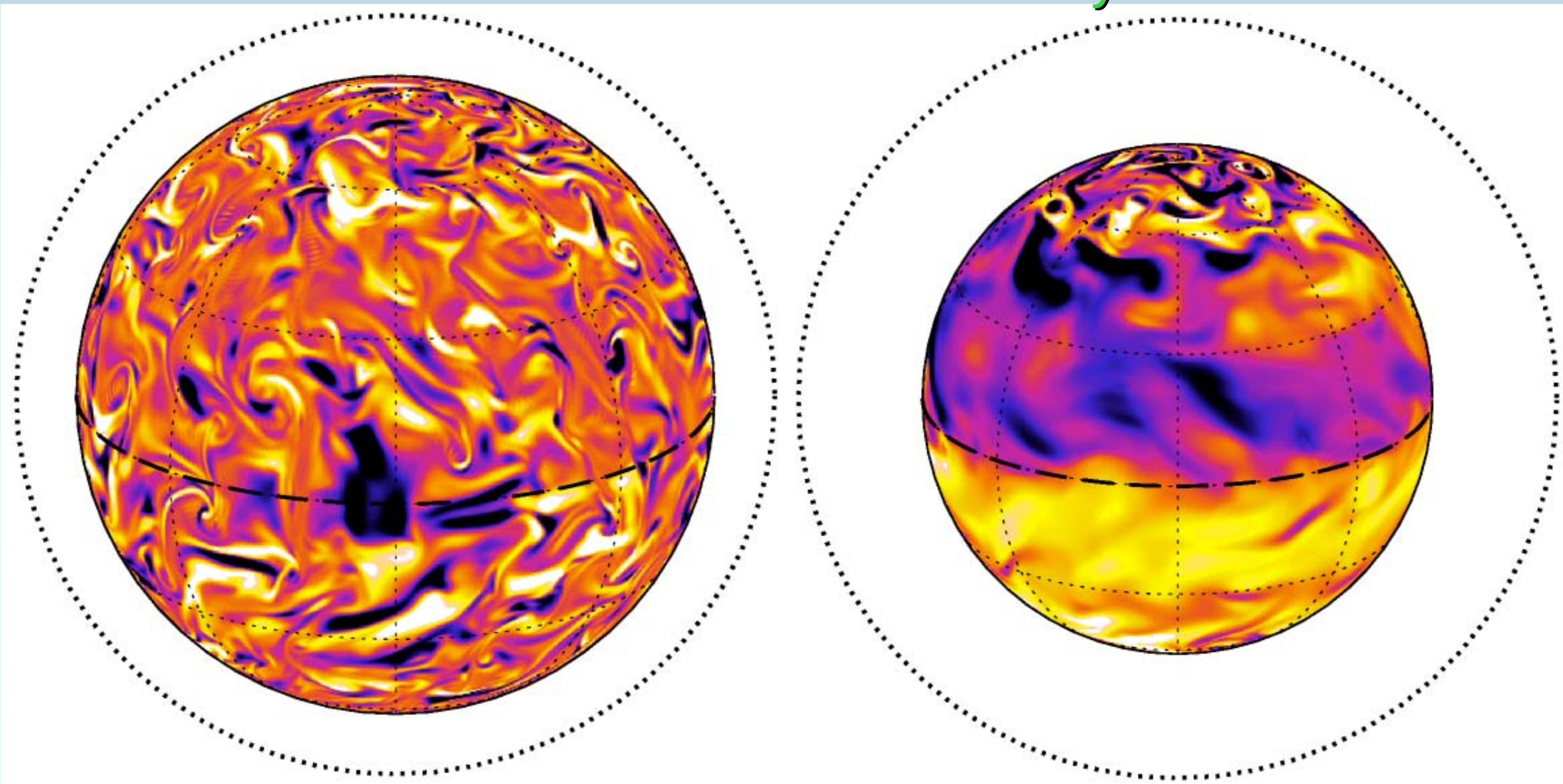
Region of strong shear at base of CZ

Browning et al. 2006, ApJL, 648, 157

Pumping, Amplification, and Organization of Toroidal Magnetic Fields

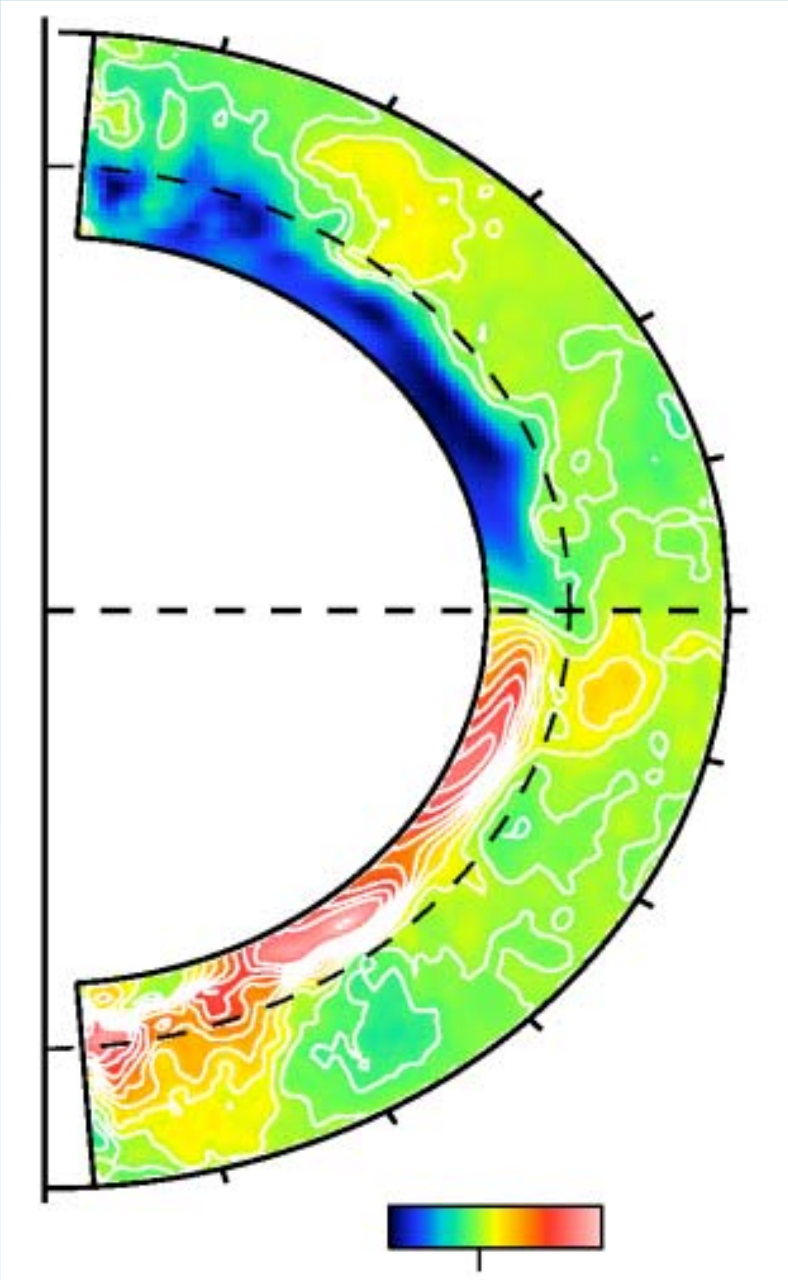
In bulk of CZ

In stably stratified zone



Toroidal fields in radiative zone are mostly axisymmetric, and exhibit stable antisymmetric parity

Strongest mean fields below convection zone

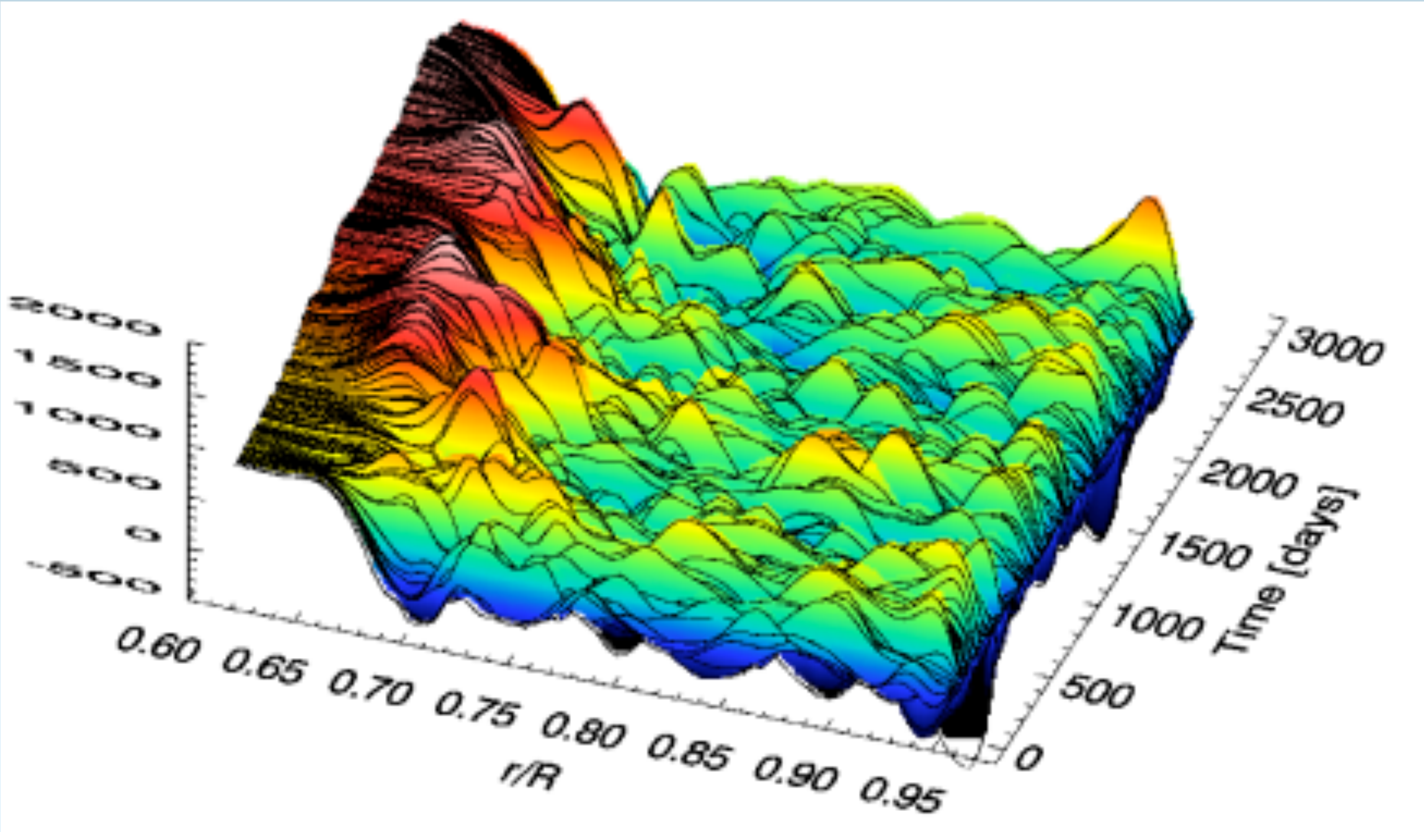


Typical mean toroidal field strengths in CZ: ~300 G

Mean toroidal field strengths in stable region: ~3000 G

Mean toroidal field is dominant contributor to total ME below CZ (unlike in CZ where fluctuating fields dominate)

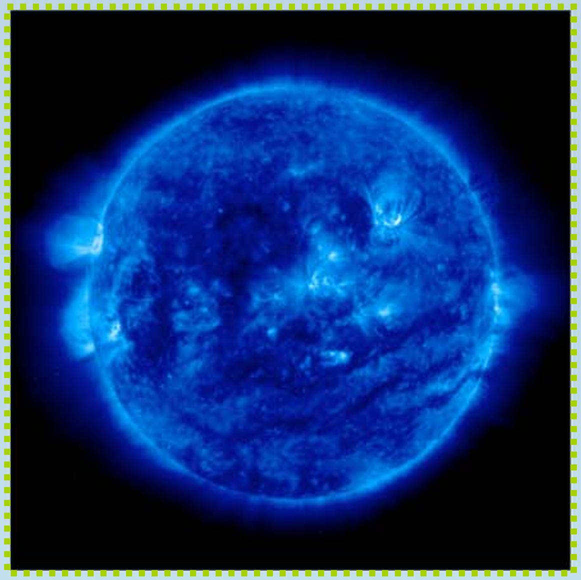
Persistence of Field Polarity



Toroidal field at single latitude

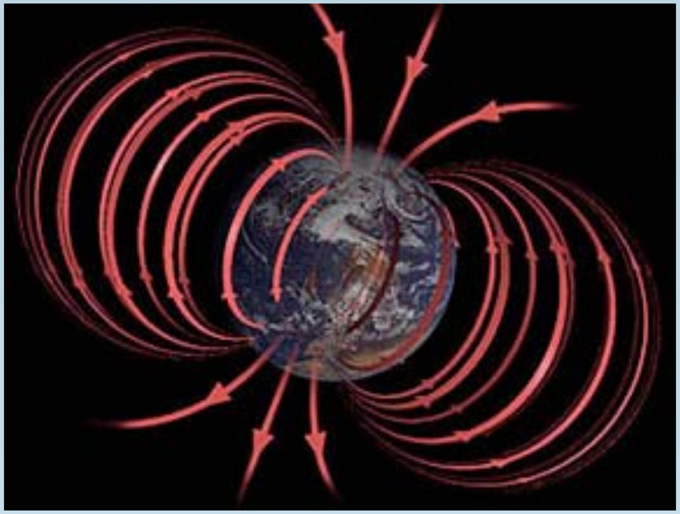
Polarity of overall dipole field component has not flipped in ~9 years of simulated evolution

Summary of solar magnetism simulations



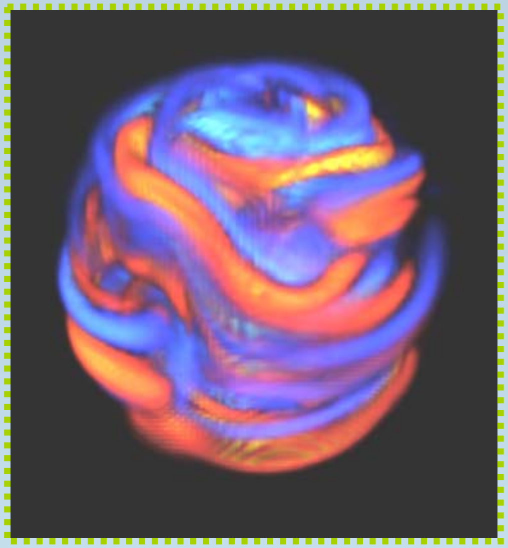
- Simulations with a forced tachocline yield magnetism with several striking properties: *predominantly mean fields below CZ, antisymmetric parity of B_{Φ}, persistence of single polarity*
- Impact of simplifications (large diffusive terms, wide tachocline) remains uncertain: field strength? latitudinal propagation?

Puzzles of A-type Stars



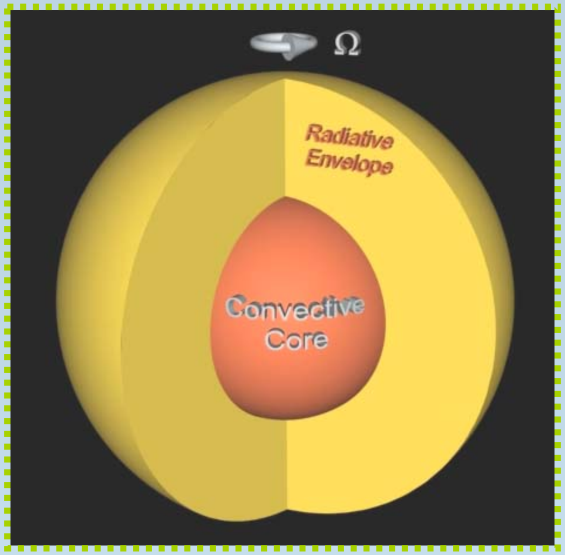
- Strong (kG) surface magnetic fields
- Fields are steady in rotating frame
- "Oblique dipole" geometry
- Central question: *what is the origin of the magnetism?*
- Two main contenders: fossil and dynamo

Motivating issues for 3-D simulations



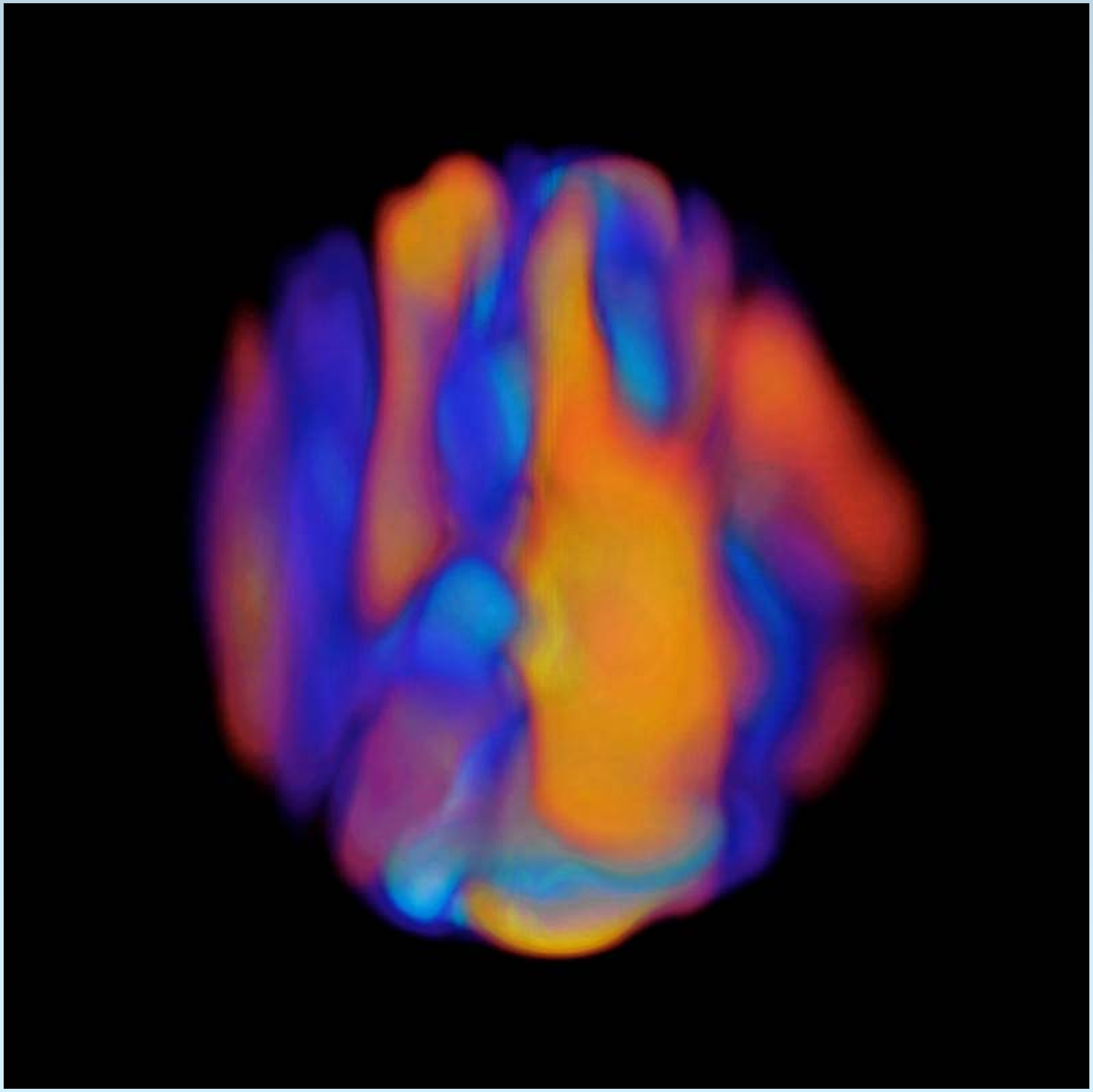
- What is nature of penetration and overshooting from convective cores?
- Does the convection drive differential rotation within the core, and in what manner?
- Is magnetic dynamo action realized?
- If so, what are the properties of the magnetism, and in what way does it feed back upon the flows?

Computational Approach for A-star Simulations



- Simulate 2 solar mass stars, at 1 to 4 times solar rotation rate
- Model dynamics of inner 30% of star (CZ + portion of RZ), excluding innermost 3%
- Simplified physics: perfect gas, subgrid turbulent transport, T^8 energy generation

Vigorous convection in the core

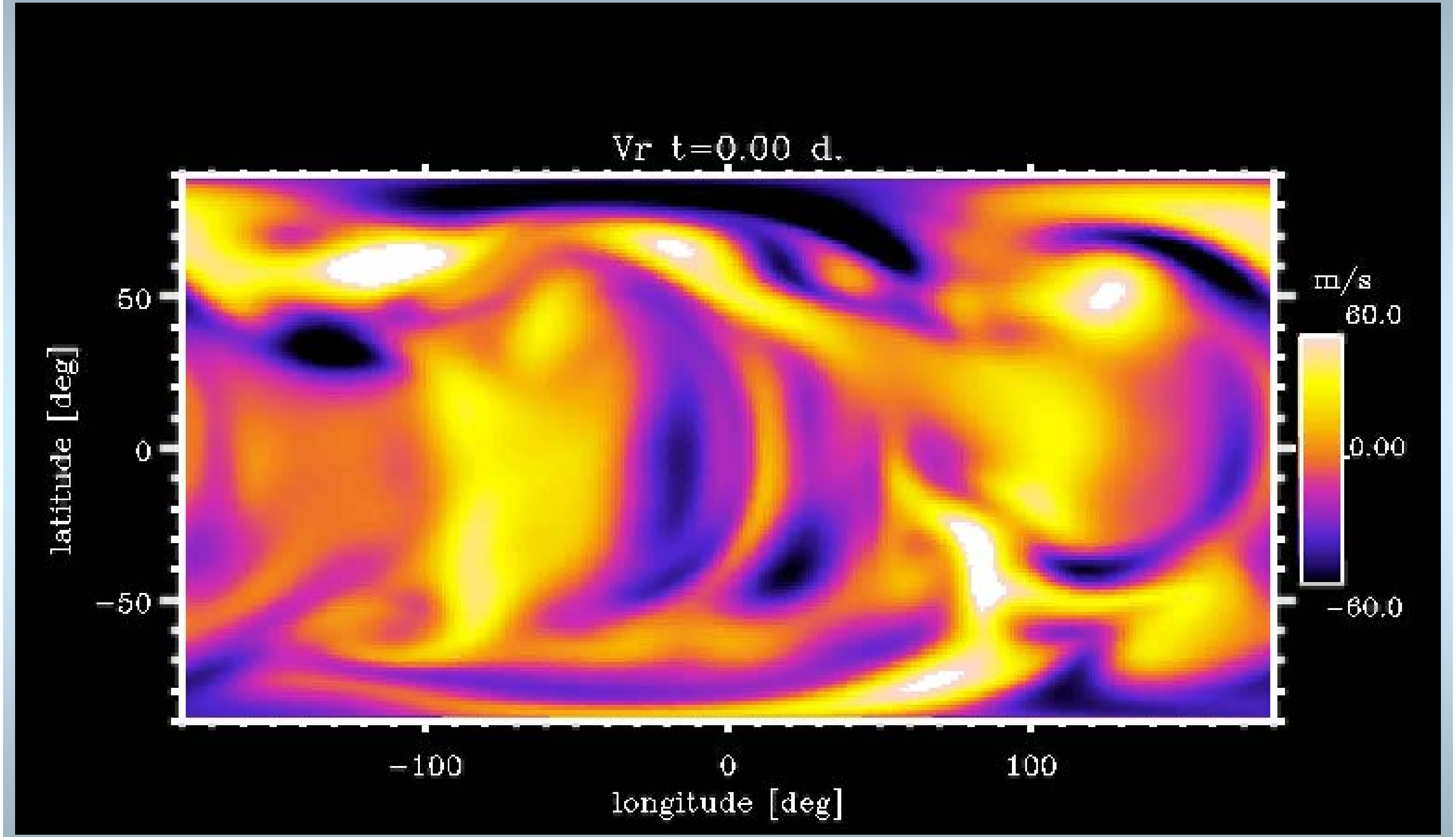


Radial velocity V_r at mid-core in hydro simulations

Broad, sweeping flows that evolve

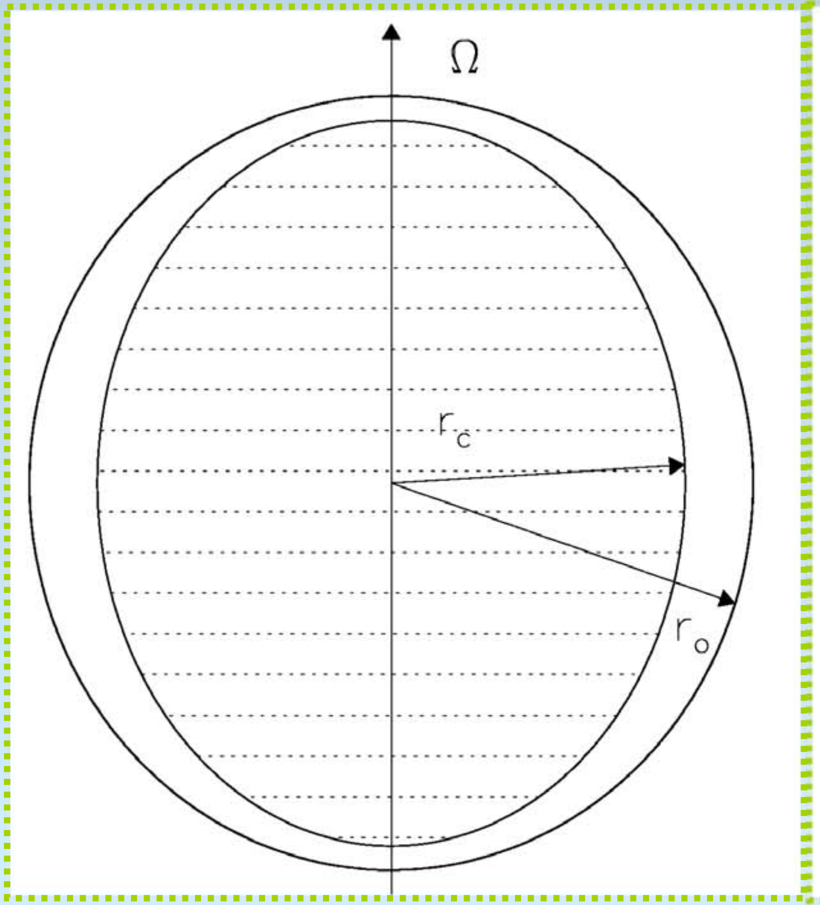
Browning, Brun & Toomre (2004), ApJ v. 601, 512

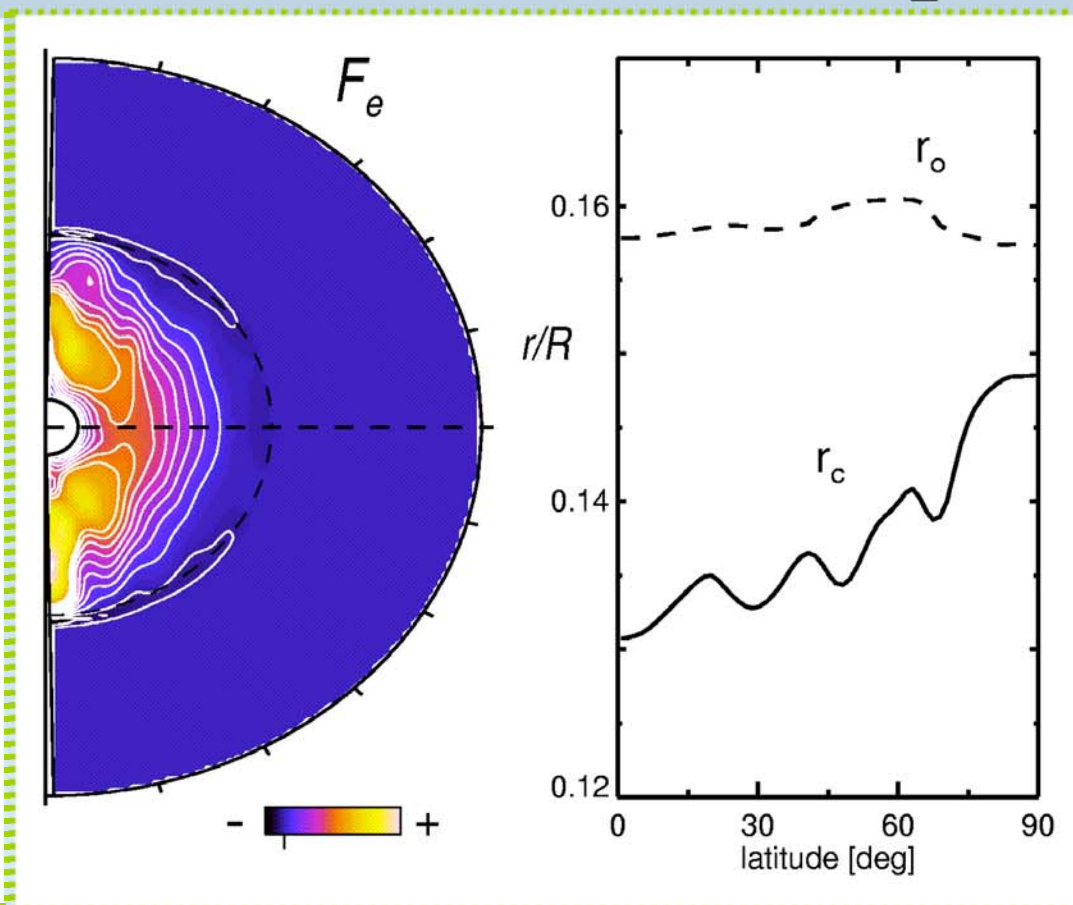
Evolution of convective patterns



Radial velocity in longitude-latitude mapping

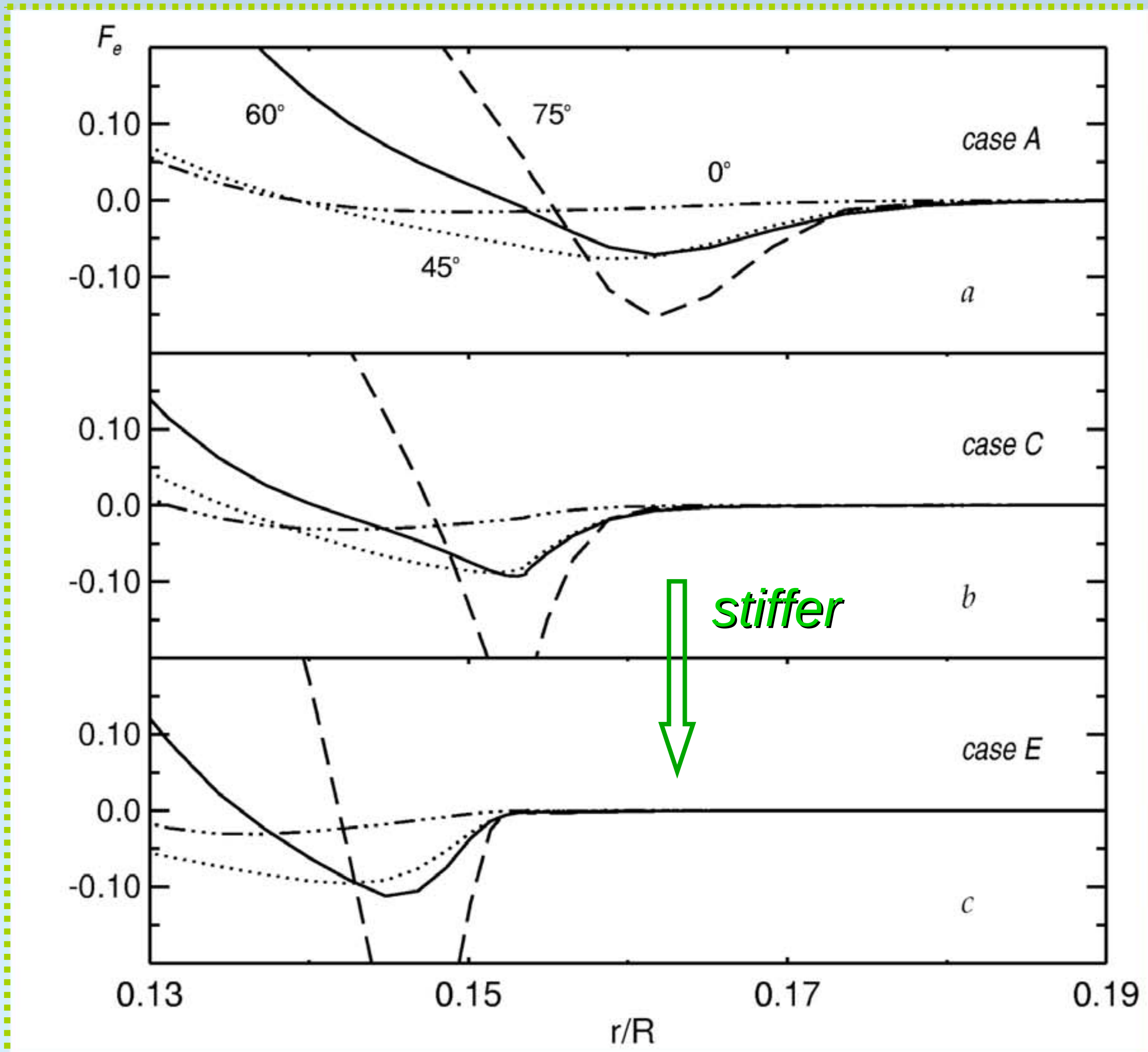
Penetration into radiative envelope





Prolate convective core, spherical overshooting region

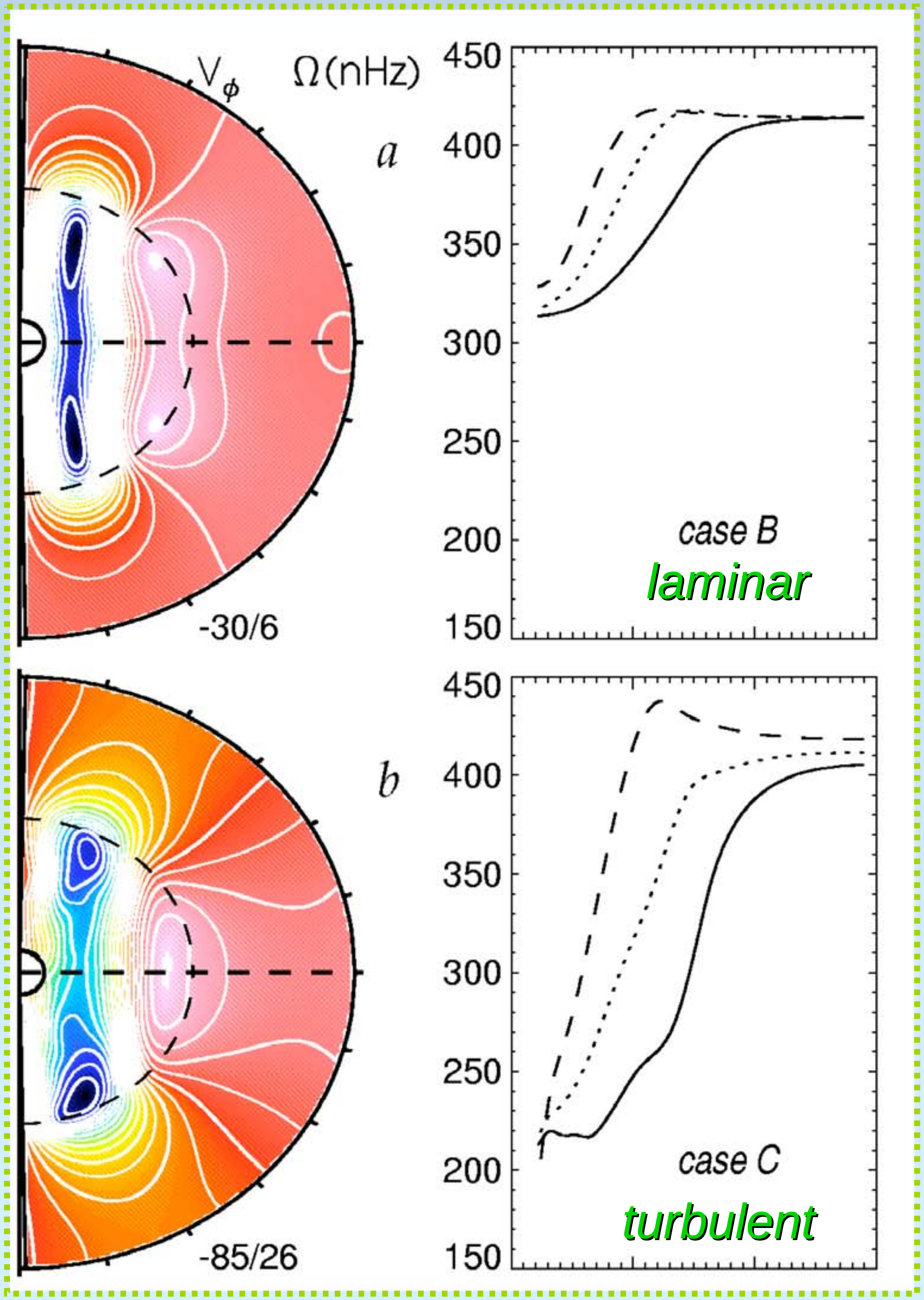
Variation of penetration with radiative zone stiffness



- Simulations provide *upper bound* to extent of overshooting
- In stiffest, most turbulent case:

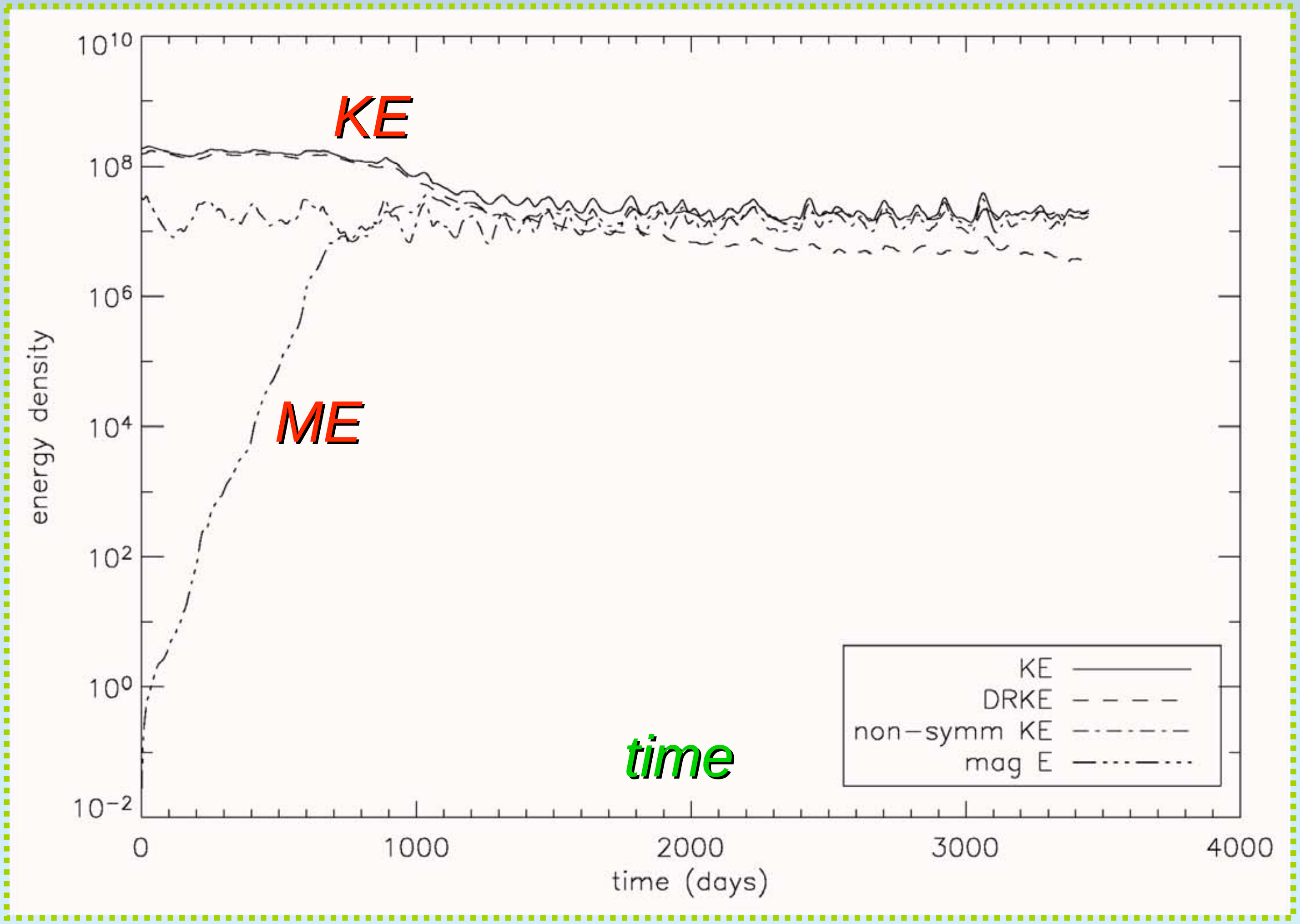
$d_{ov} \sim 0.21_{+/-\ 0.05}\ H_p$

Character of differential rotation



- Central columns of slow rotation
- More turbulent flows yield greater angular velocity contrasts
- When influence of rotation very weak, central column of fast rotation arises

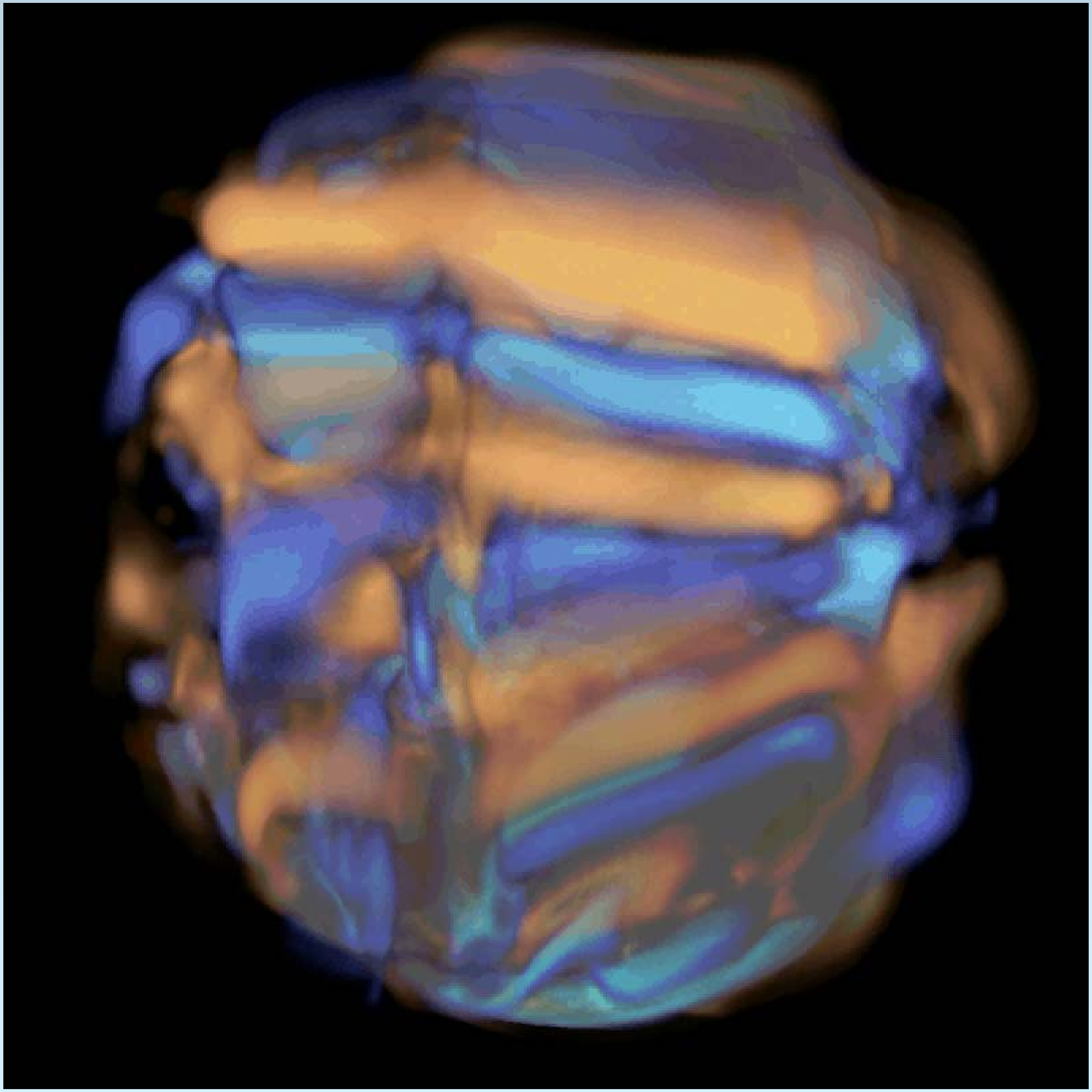
Dynamo activity in MHD models



With increasing ME, drop in KE

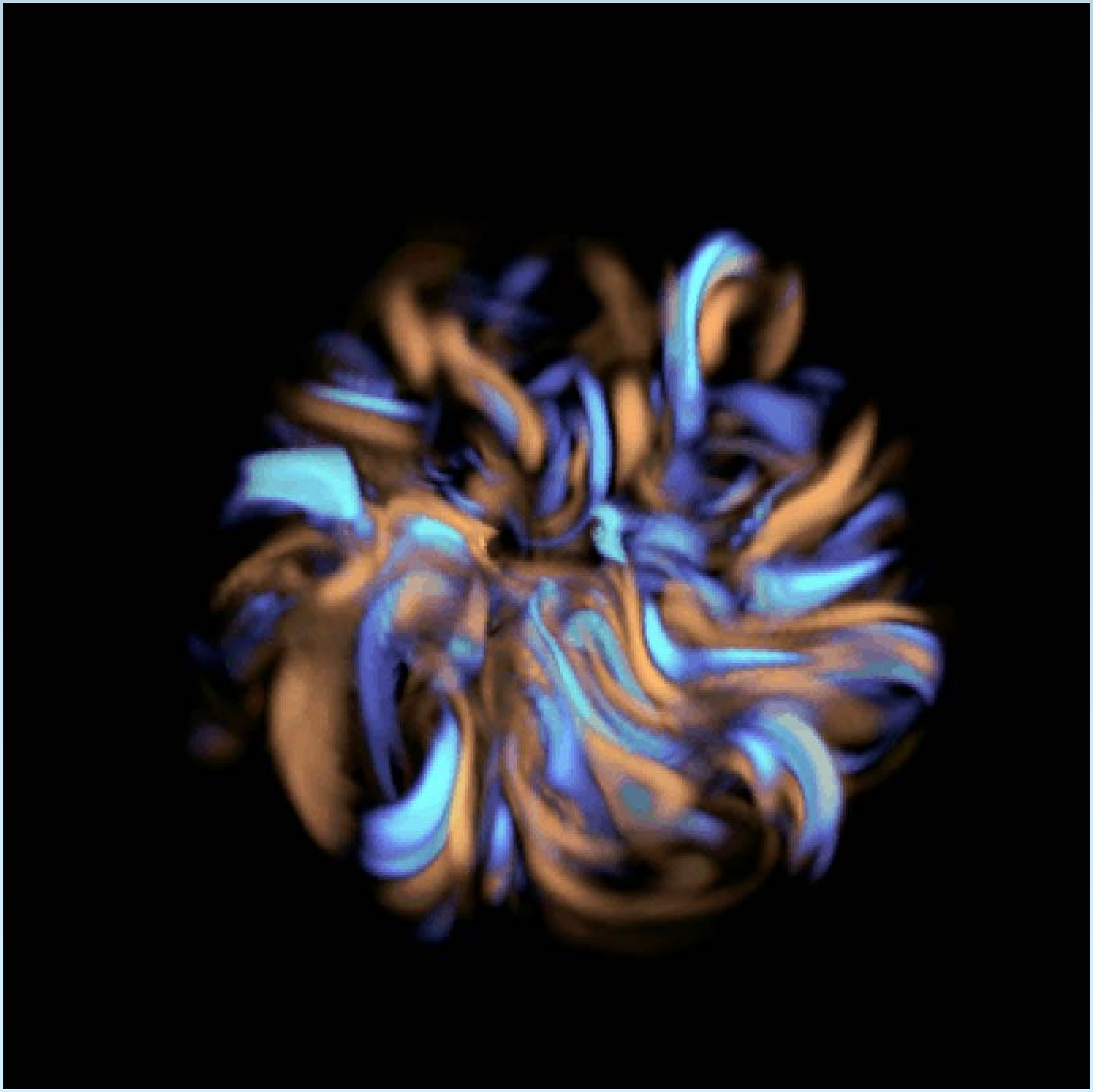
Final ME ~ 90% KE

Convective motions amplify a tiny seed field by many orders of magnitude



Intricate magnetic field

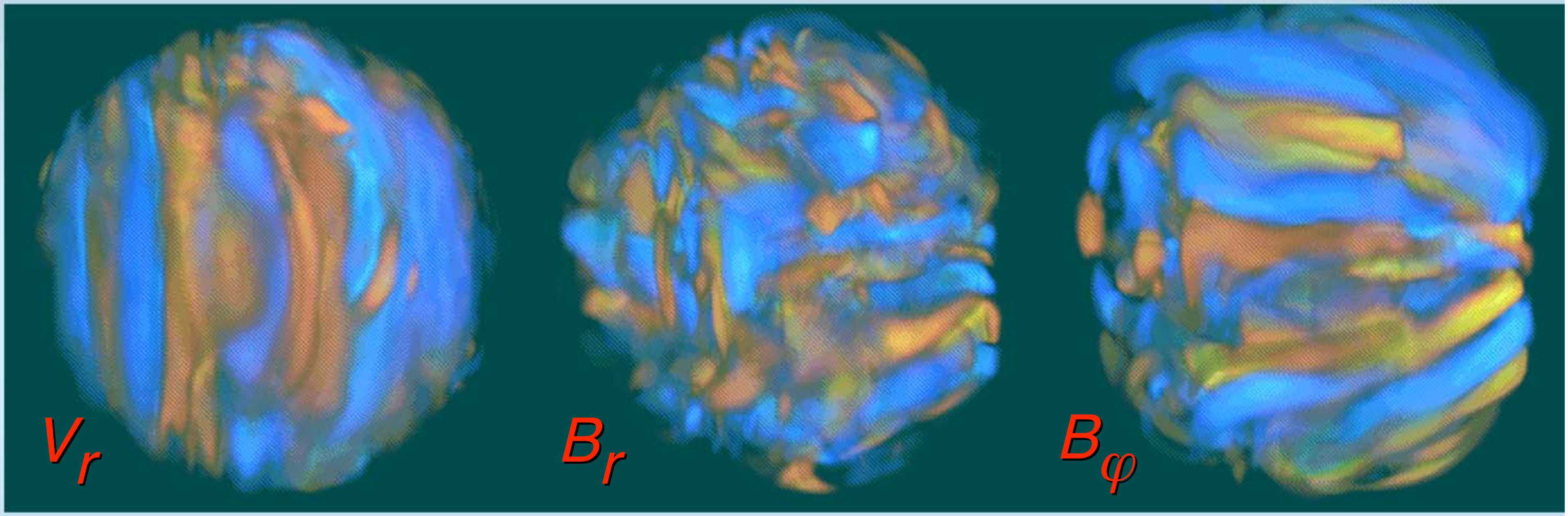
Evolving banded azimuthal field



Radial field in cutaway

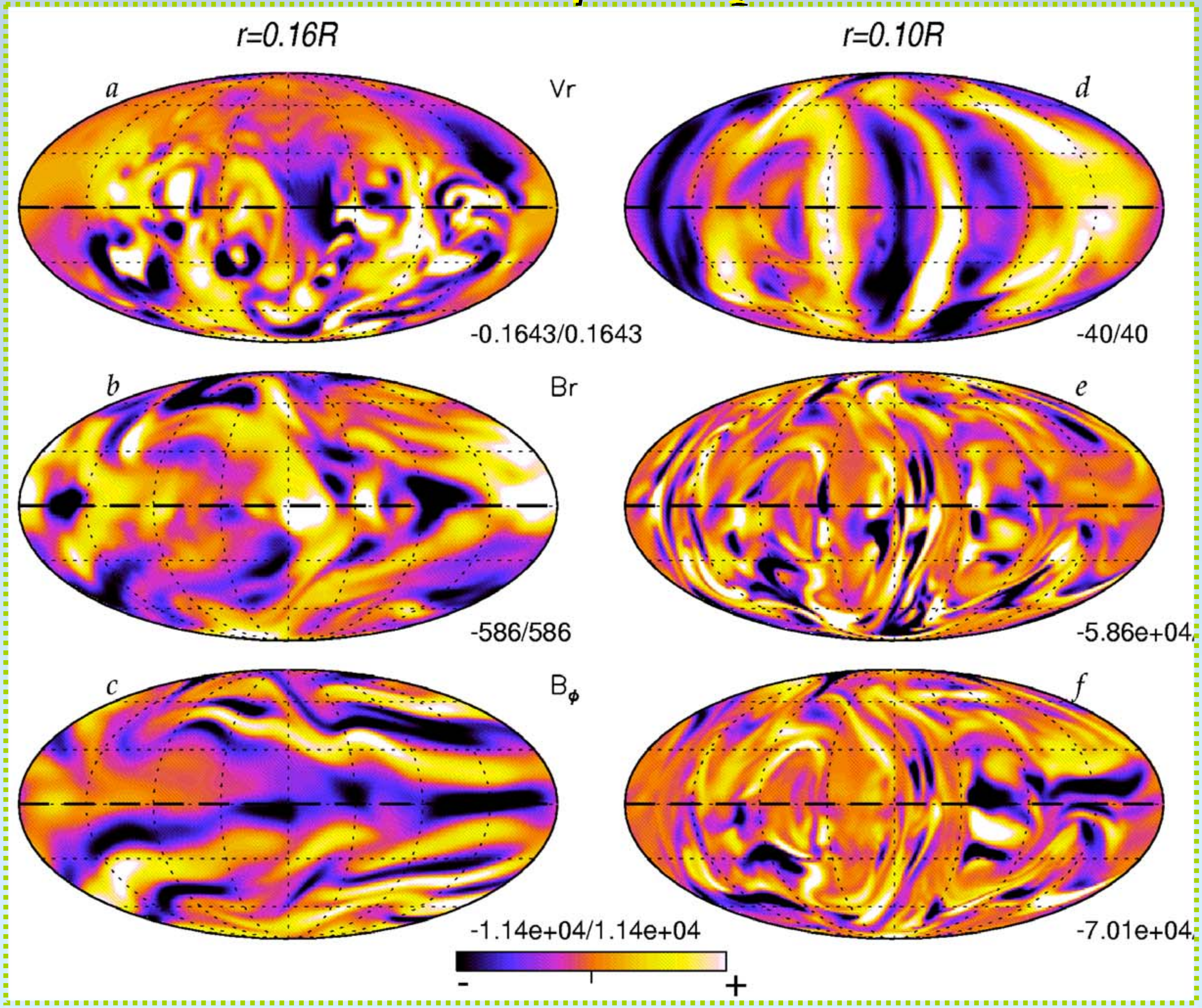
Complexity in interleaved radial fields

Topology of core magnetism



- Field on finer scales than flow ($P_m > 1$)
- Tangled radial field, but B_φ partly organized into ribbon-like structures

Global views of complex structures

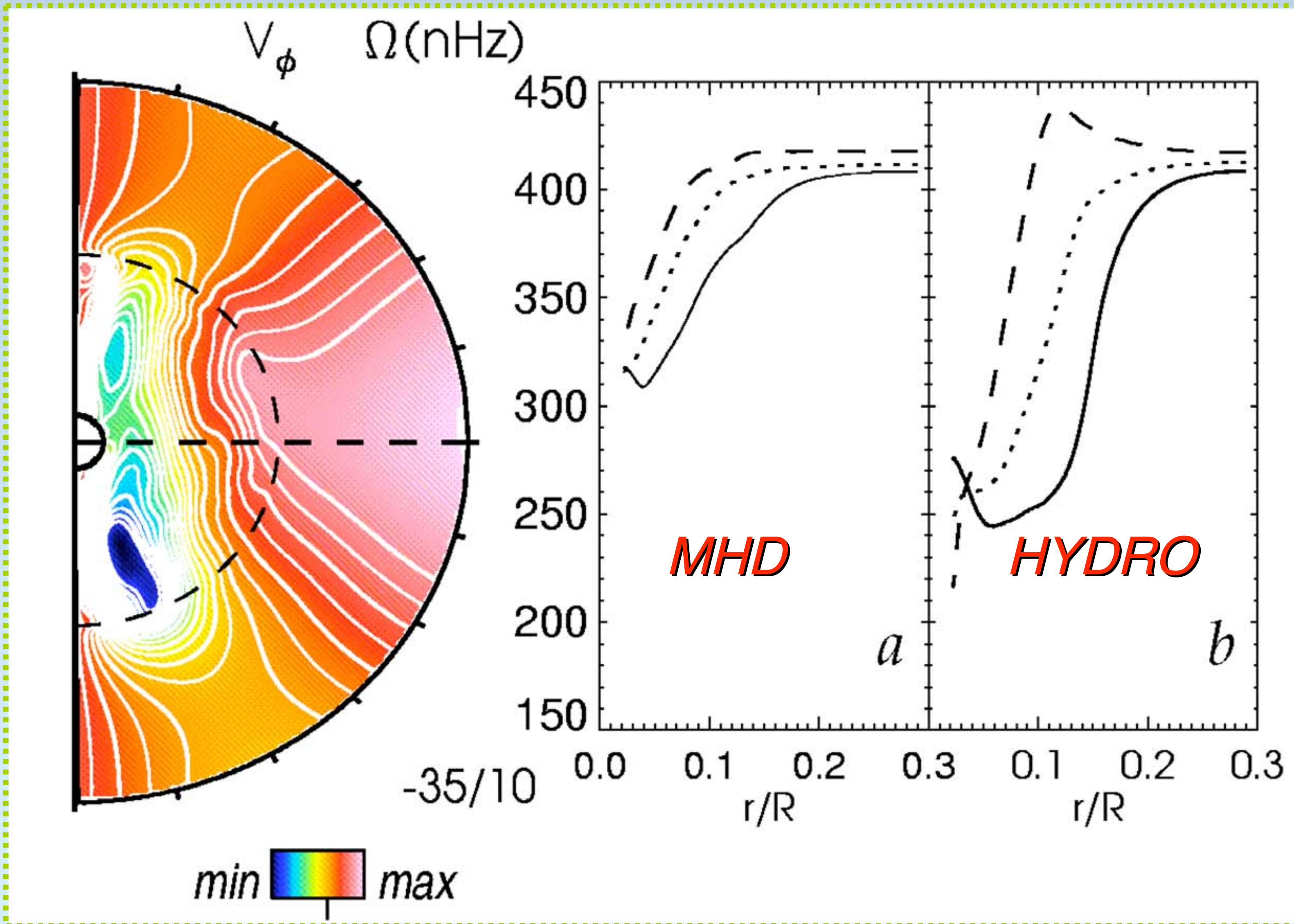


V_r

B_r

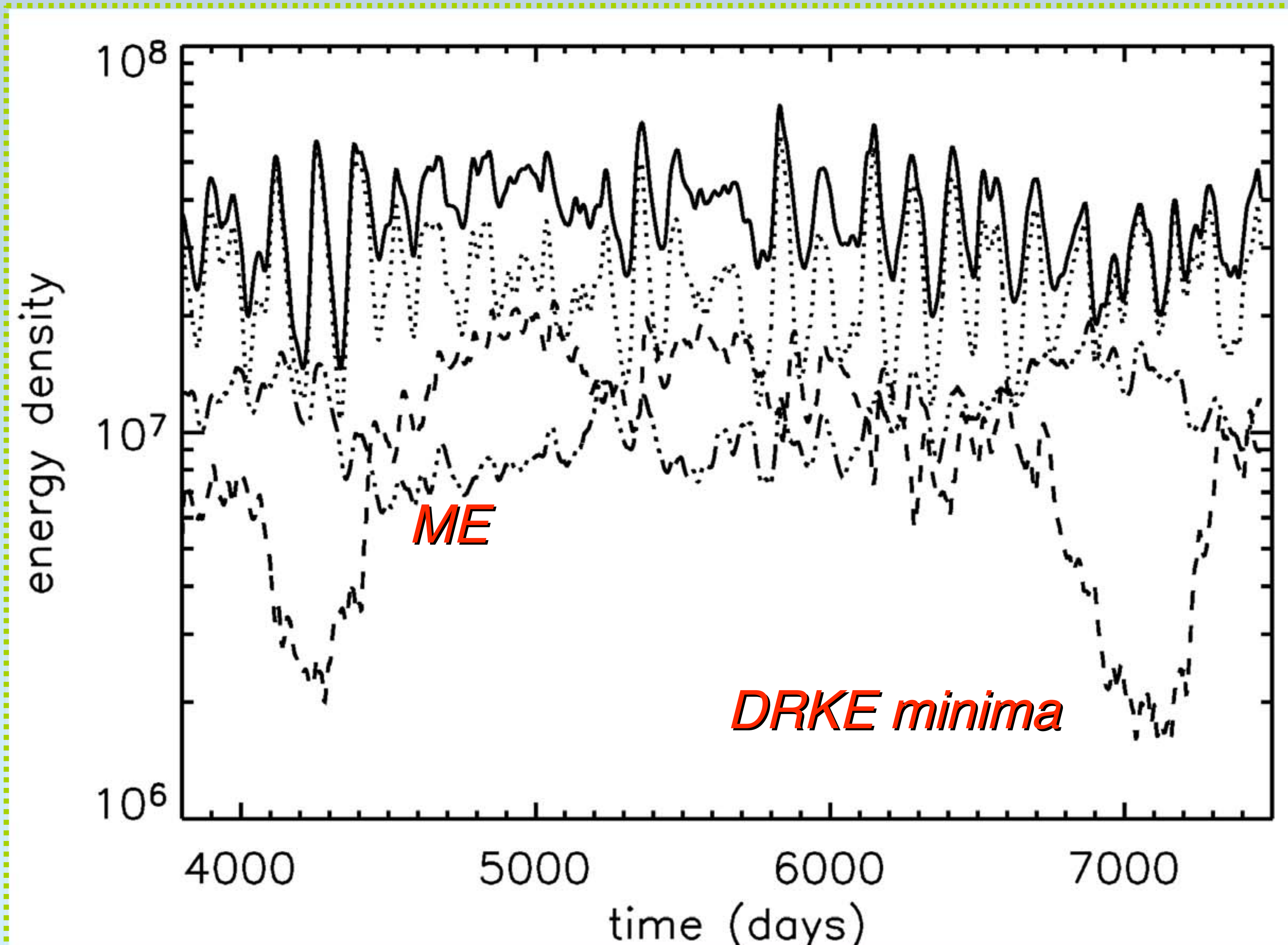
B_φ

Magnetism reduces differential rotation



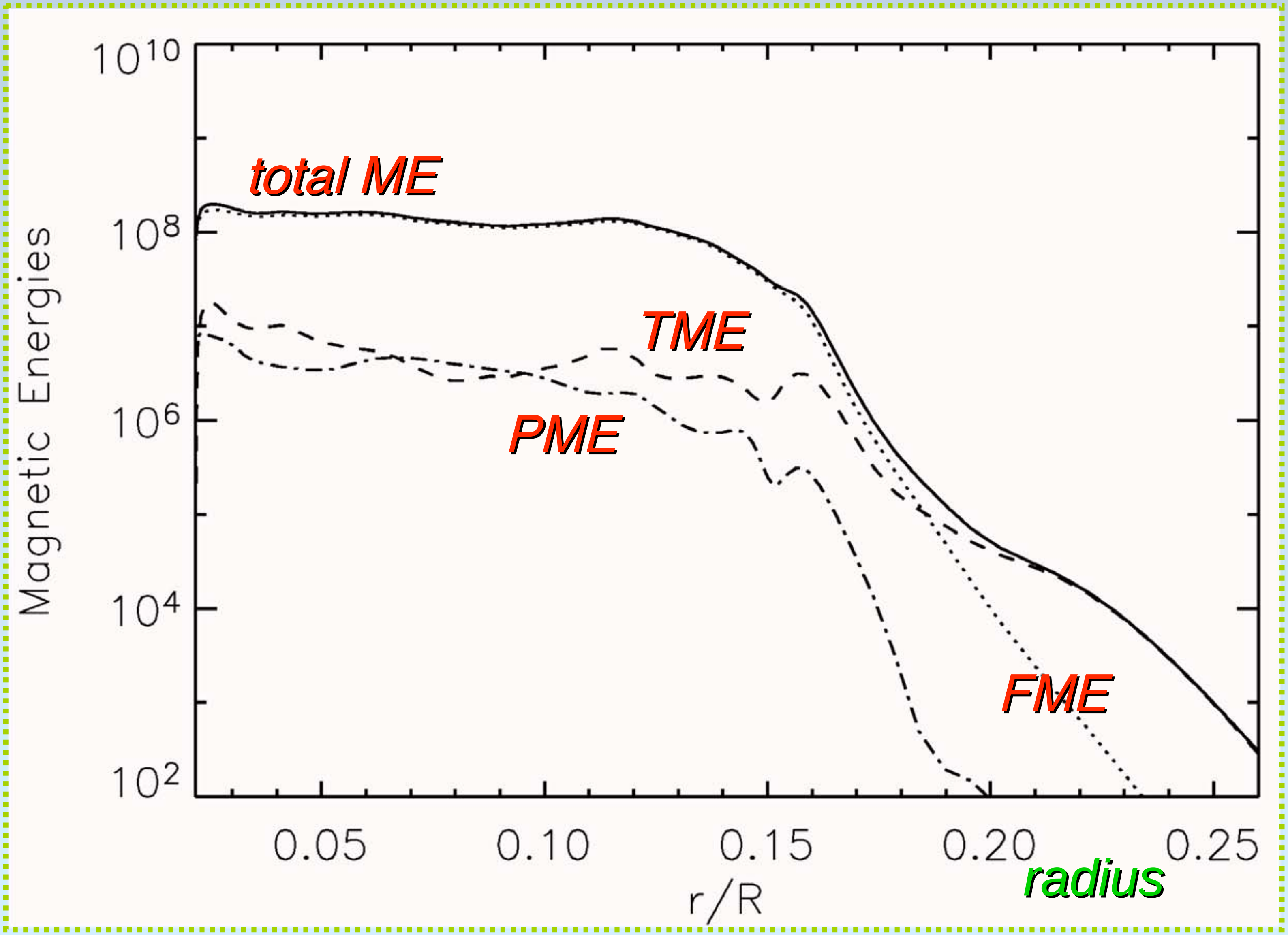
Angular velocity contrasts lessened by magnetic field

Interplay of rotation and magnetism



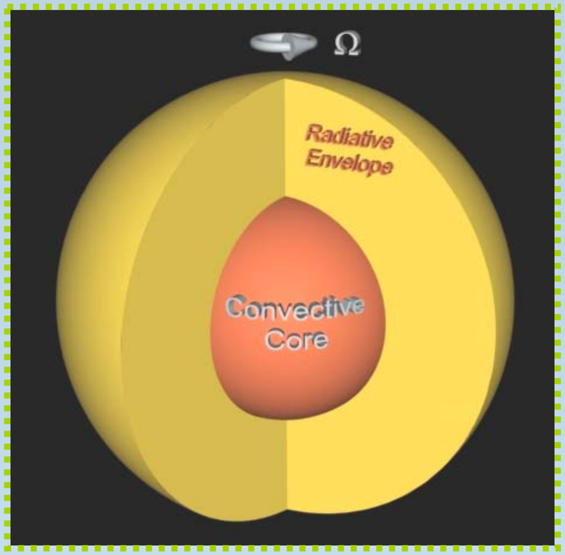
Differential rotation quenched when ME > ~ 40% KE

Fluctuating and mean magnetic fields



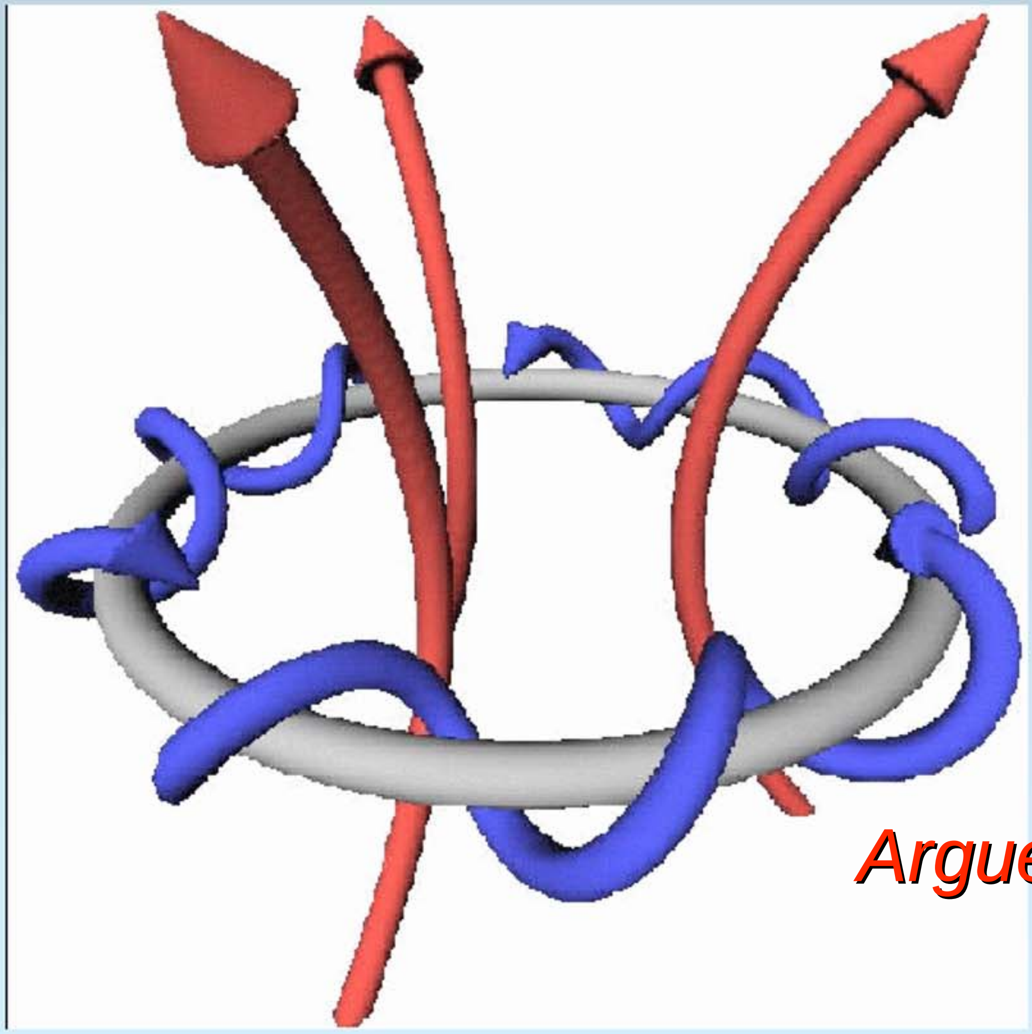
Fluctuating fields much stronger than mean fields

But can the fields get out?



- Core magnetic fields likely screened by radiative envelope
- Possibly magnetic buoyancy instability could bring fields outward, but …
- Recent modeling (MacGregor & Cassinelli; MacDonald & Mullan) suggests this process is *too slow* for fields like the ones realized here

Stable fossil field configuration



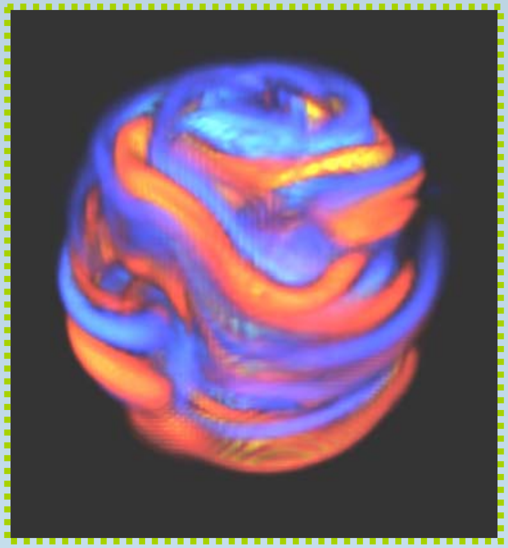
Initial arbitrary field evolves to stable field

Final stable field with mixed poloidal and toroidal components

Argues in favor of fossil field

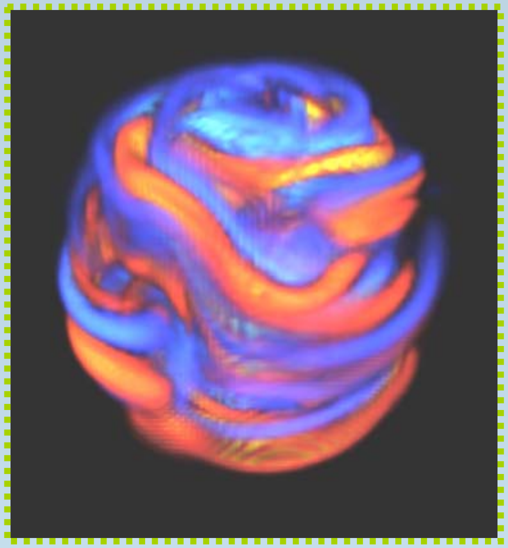
Braithwaite & Spruit, 2004 Nature

Some A-star findings



- Global simulations of magnetized core convection reveal *dynamo action, differential rotation and prolate penetration*
- Resulting complex magnetic fields weaken differential rotation
- Magnetism likely hidden from view, though magnetic buoyancy may play a role
- Stable field configurations found, so fossil field a plausible explanation

What about the rest?

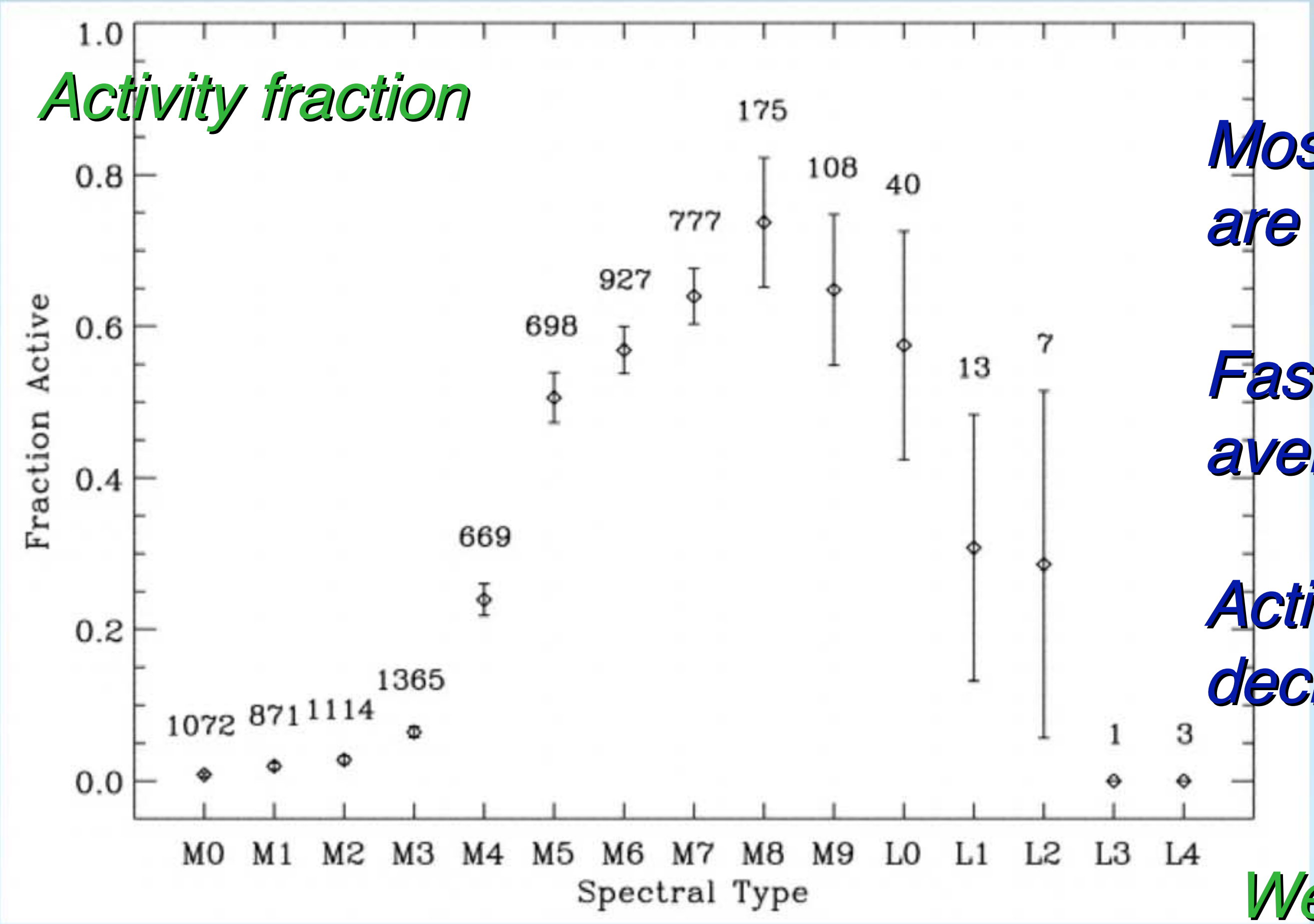


- In stars with both convective and radiative zones, *interface of shear (tachocline) seems to play major role in building fields*
- What happens in stars with no such interface?
- Low mass stars (<0.35 M) are fully convective

M-dwarfs straddle this boundary:

potential probe of dynamo physics

Fully convective stars show strong magnetic activity



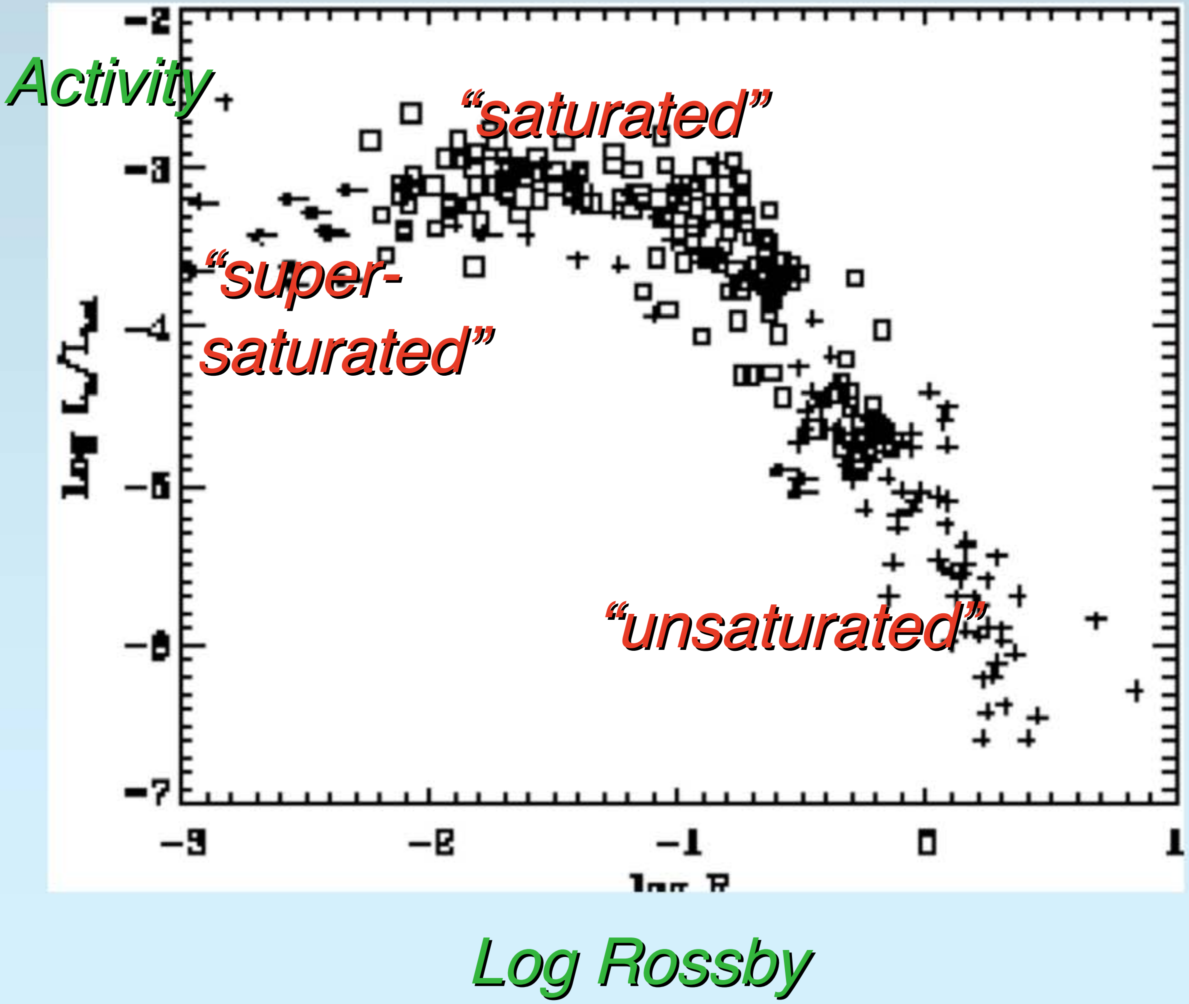
Most mid-late M-stars are active

Faster rotating on average than early-M

Activity fraction declines near M9/L0

West et al. (2004)

One probe: Rotation-activity correlation in X-rays



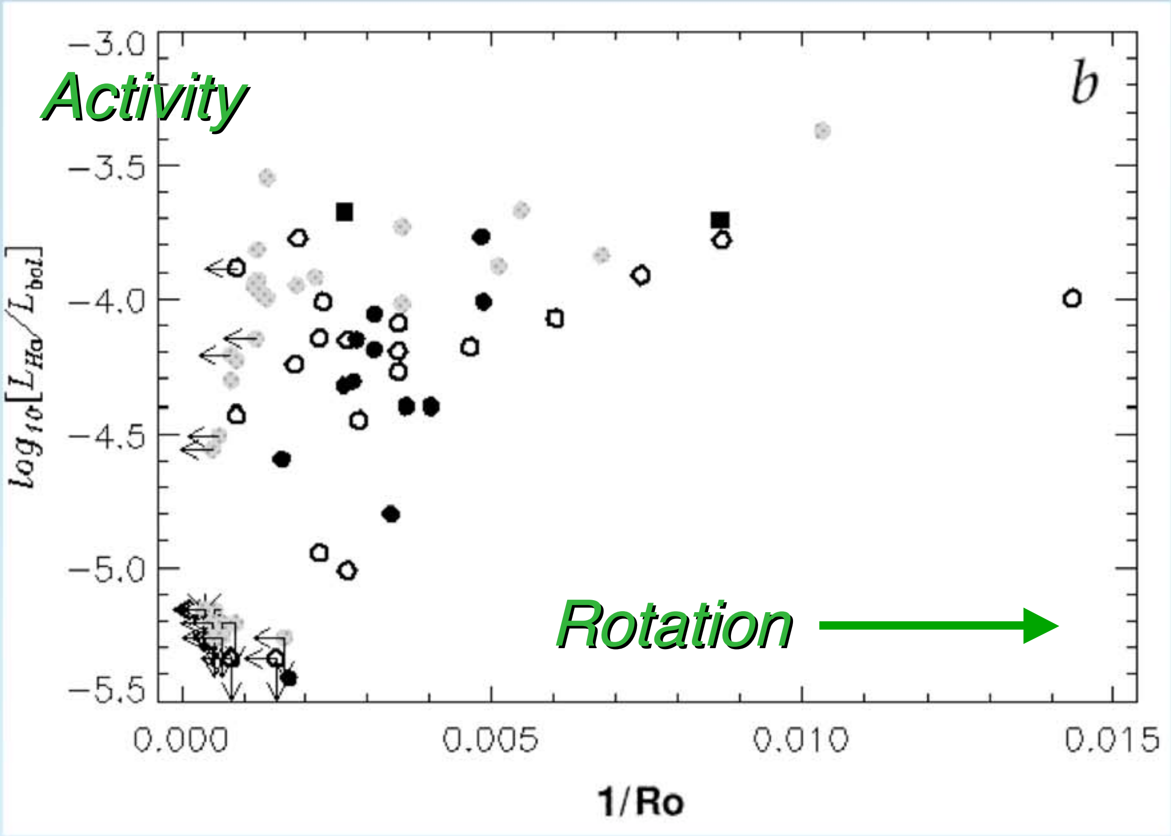
Coronal emission correlated with rotation

Saturation of emission at $L_x/L_{bol}=10^{-3}$

Observed from F to M

Pizzolato et al. (2003)

M-dwarfs also show correlation between rotation and activity

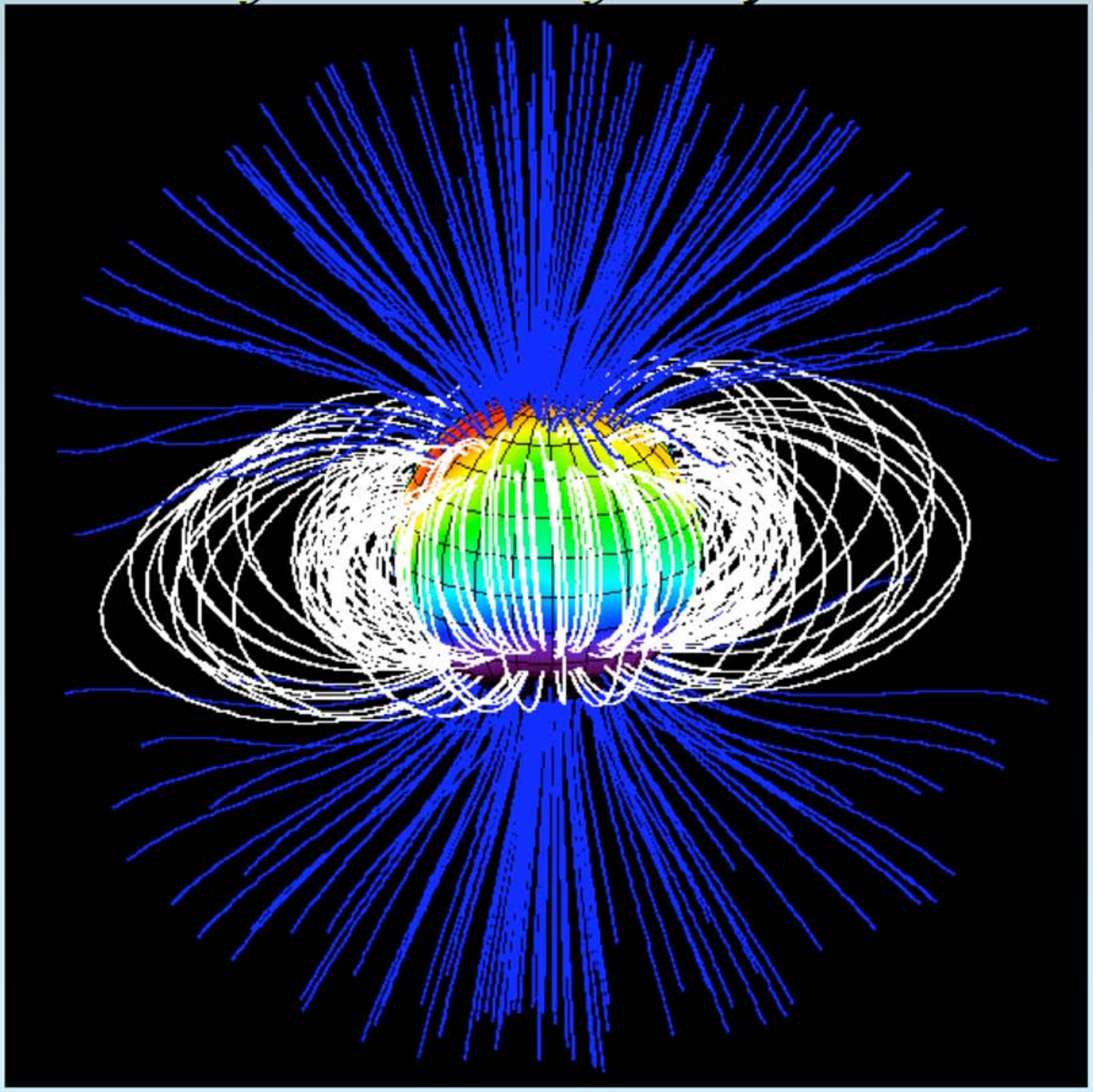


M2 and M4 stars show similar trends

I.e., no obvious break in rotation-activity relation (until late-M/early-L)

Mohanty & Basri (2003)

Observations of large-scale magnetic field in fully convective star



Rapidly rotating M-dwarf

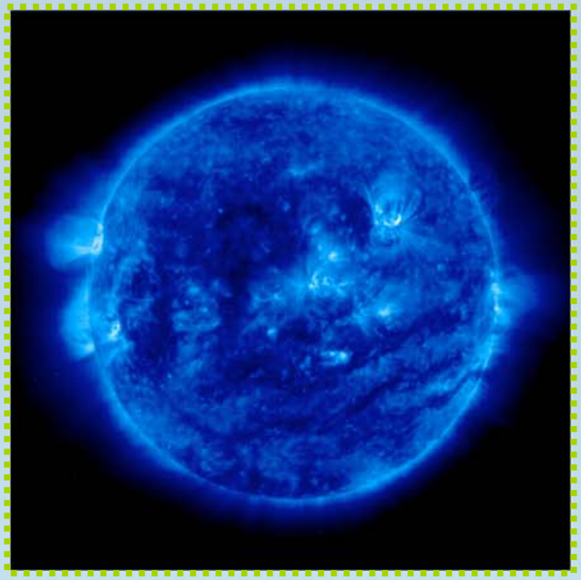
Zeeman Doppler reveals large-scale, axisymmetric field (~kG)

But no differential rotation

HOW?

Donati et al. (2006), Science

Summary and reflections



- Simulations suggest *crucial role of tachocline in building organized magnetism in Sun-like stars*
- In more massive stars, *dynamo action also realized*, but may have little effect at surface
- Major puzzles of rotation-activity correlation, especially at low mass