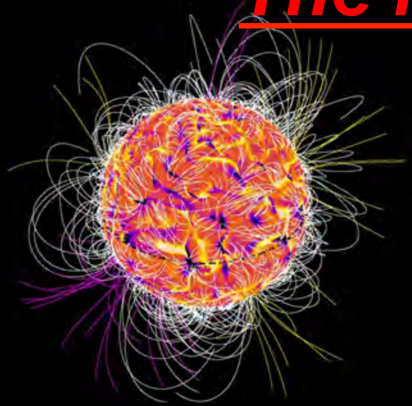
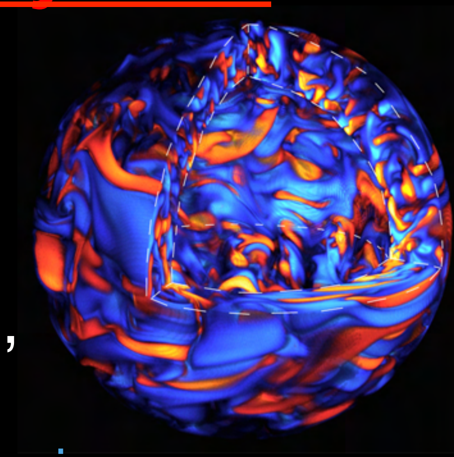
The New Concept of Stellar Spot Dynamo





Allan Sacha Brun

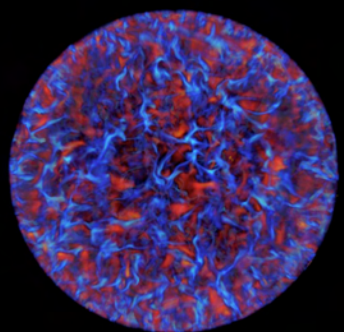
Service d’Astrophysique/UMR AIM,

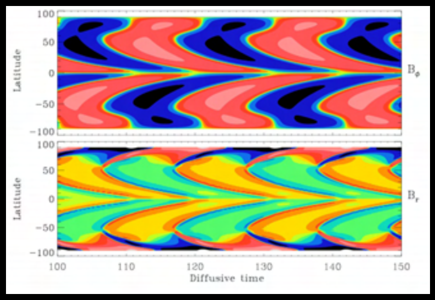
CEA-Saclay

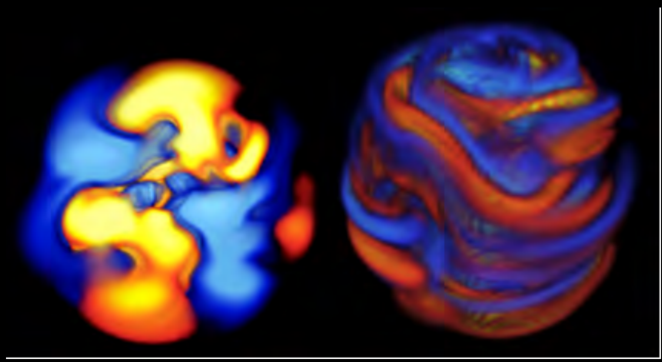
with J. Toomre, M.S. Miesch, B. Brown, M. Browning,

L. Jouve, K. Augustson, A. Strugarek, C. Emeriau and the STARS2 Team

- Observational evidence of stellar rotation/magnetism
- 3-D simulations of solar-like stars

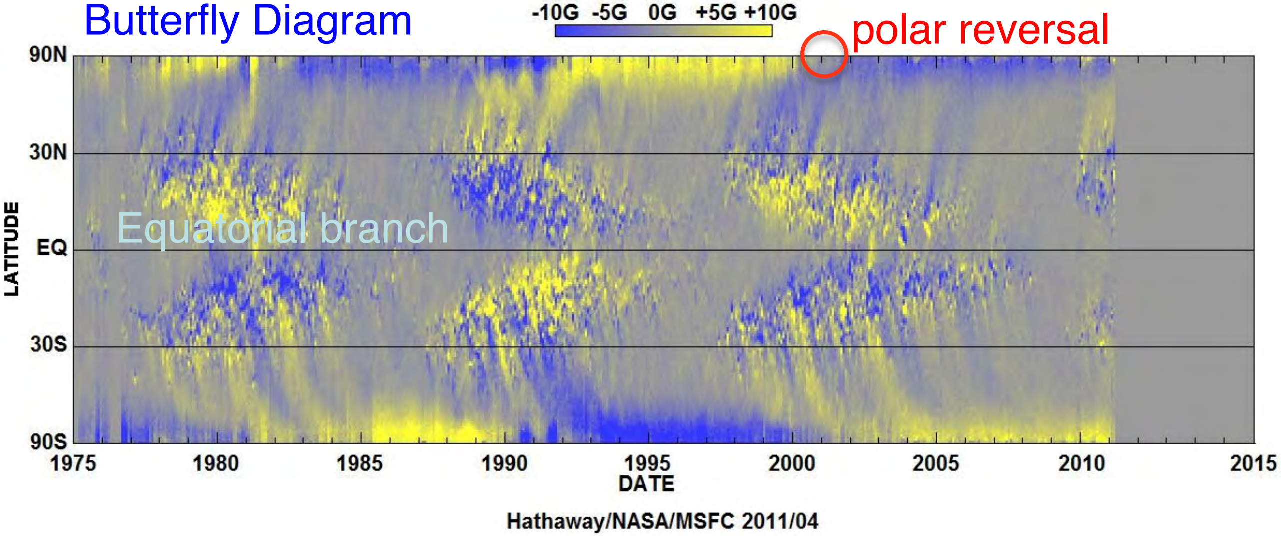


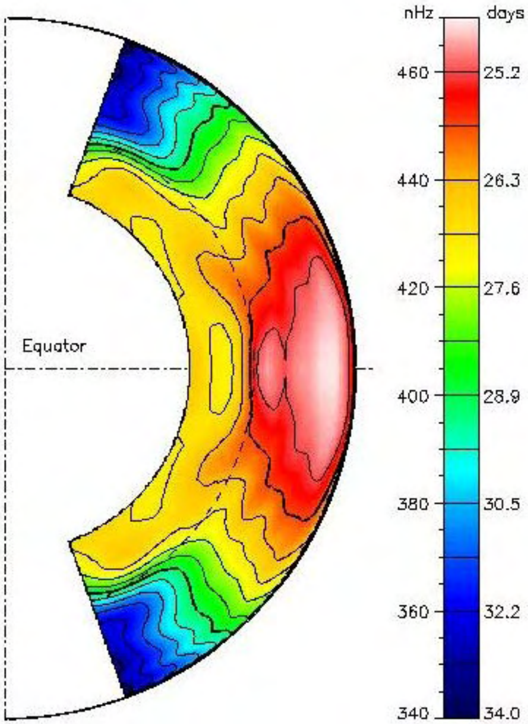




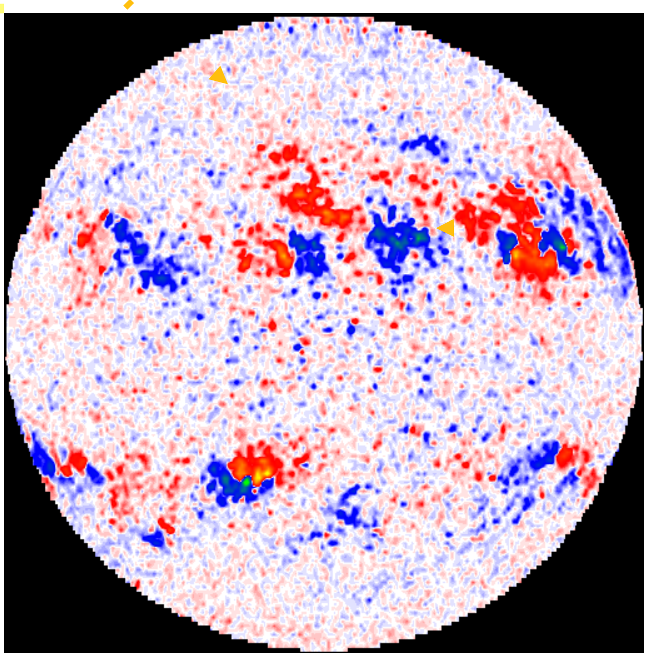
Solar Cycle and Rotation

Butterfly Diagram



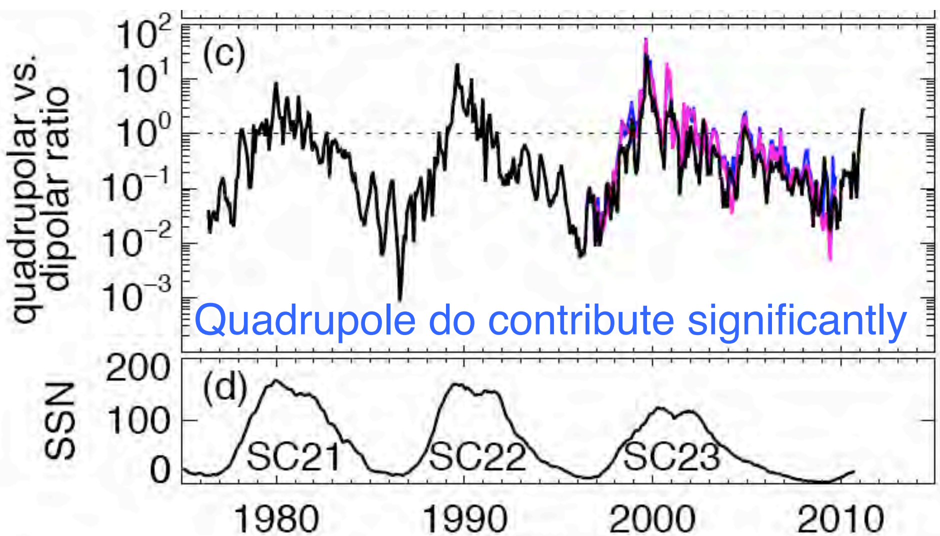


Quiet



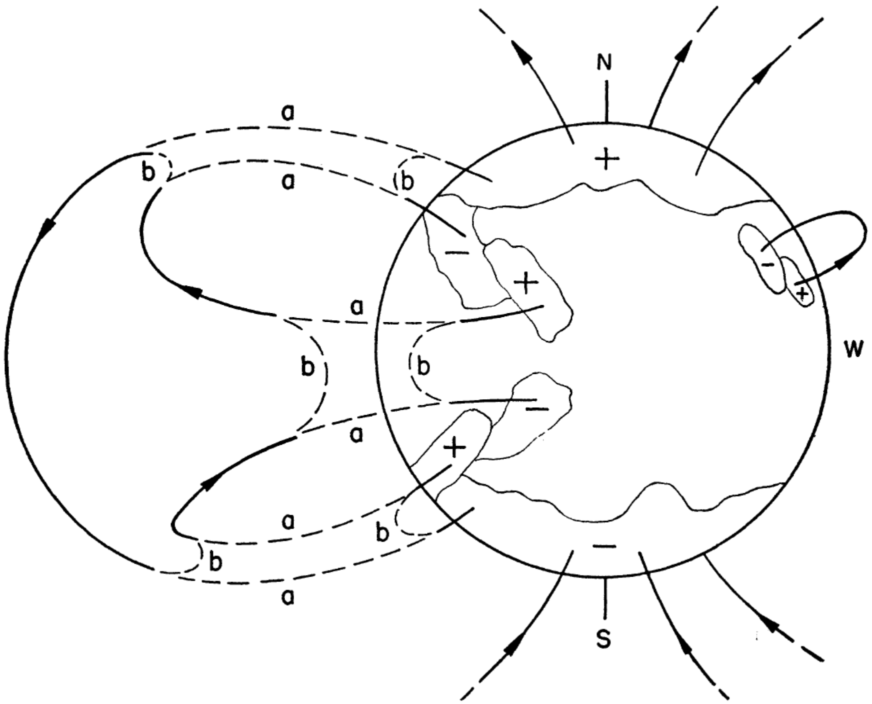
Small vs Large Scale Dynamos

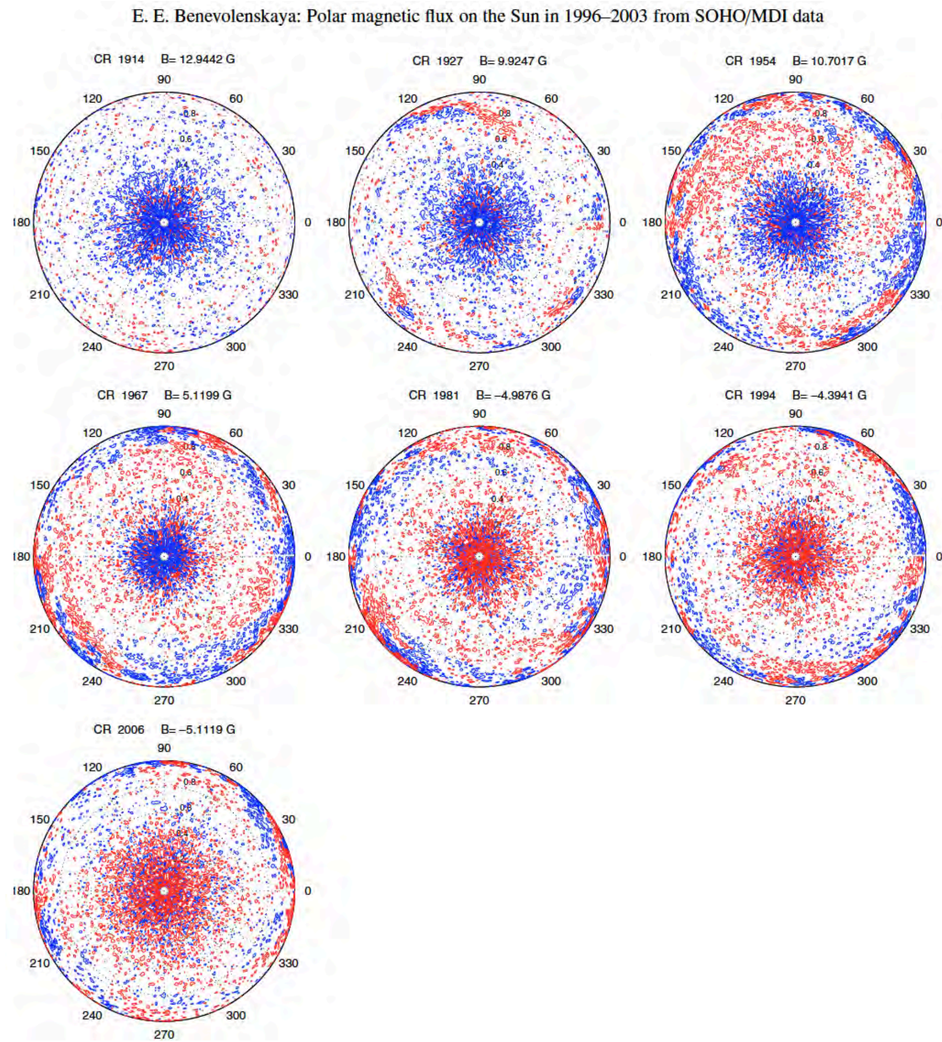
Active

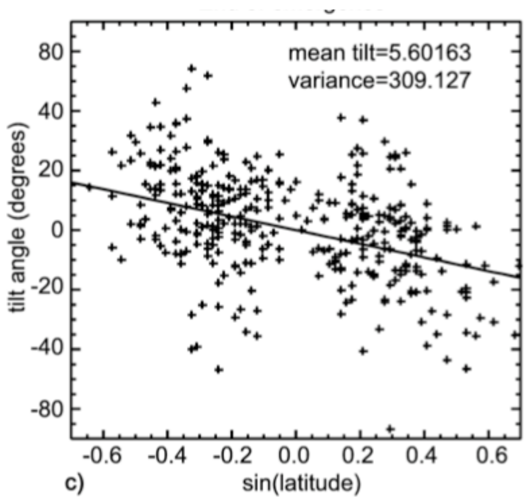


Derosa, Brun, Hoesema 2012

Babcock-Leighton Mechanism and Polar Cap Reversal







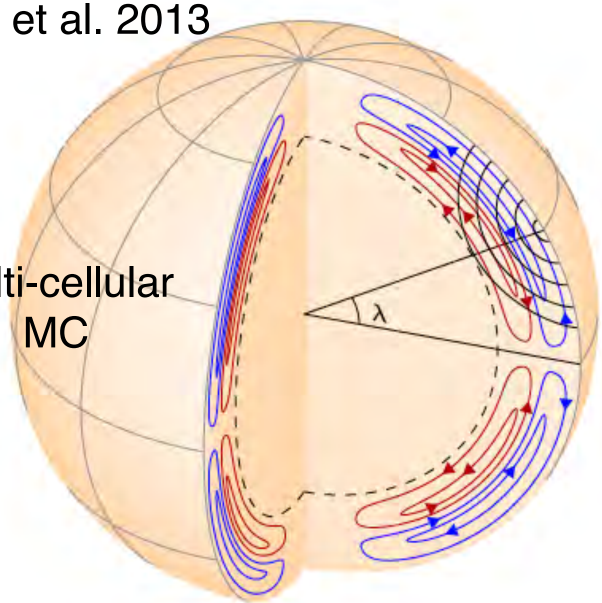
Joy's Law
Tilt of AR

How important is it to get the 11yr dynamo?

Meridional Circulation

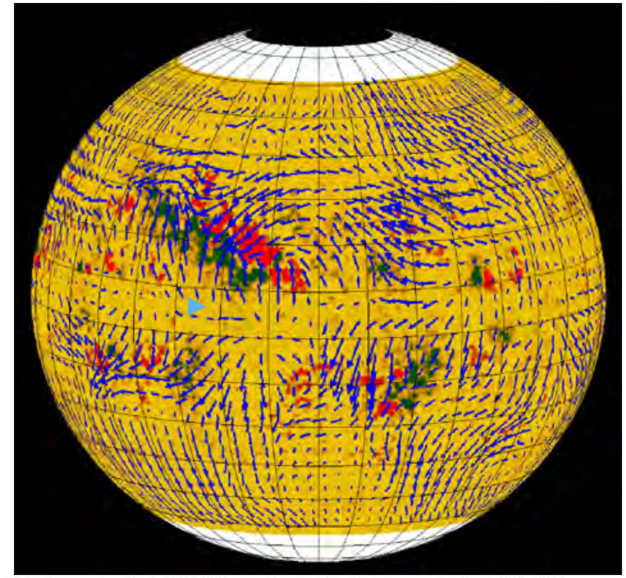
More & more evidence for multi cellular MC

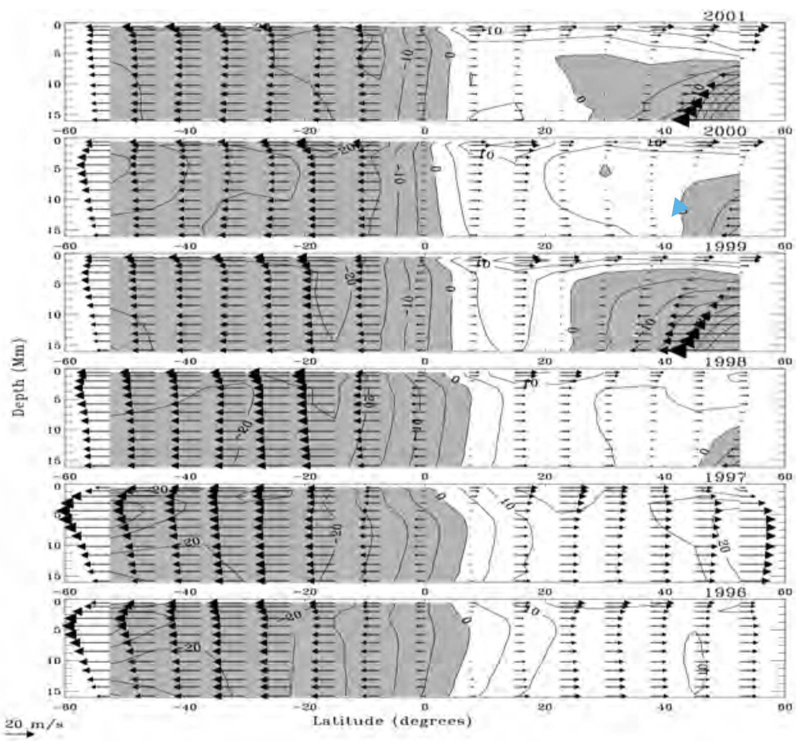
Zhao et al. 2013



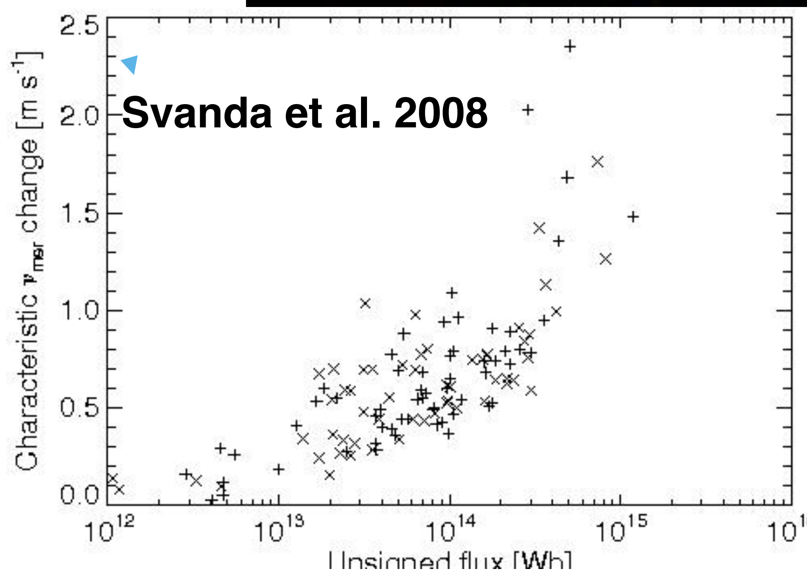
Influence of B (active region) on MC

. . .





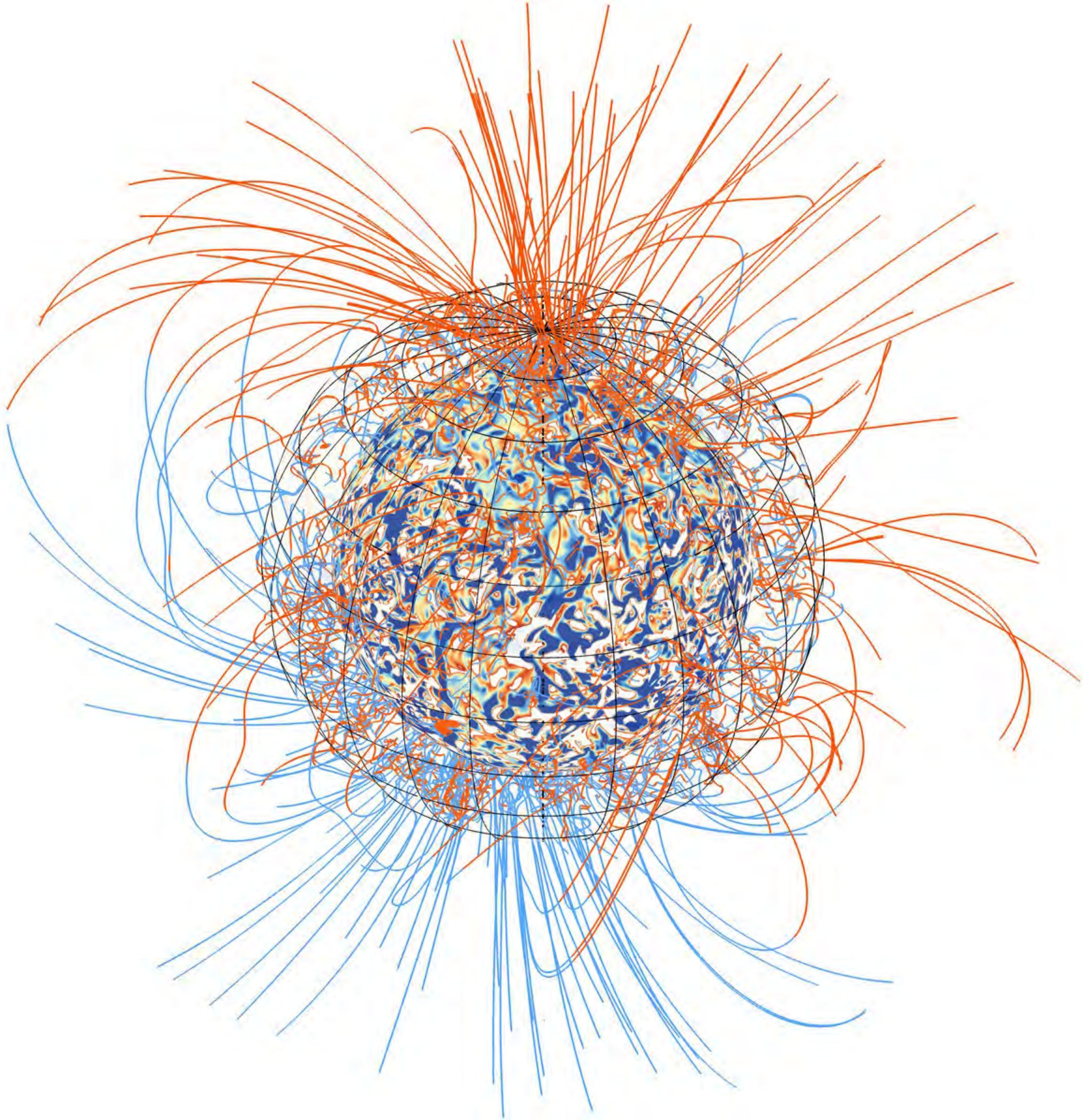
(Haber et al. 2002)



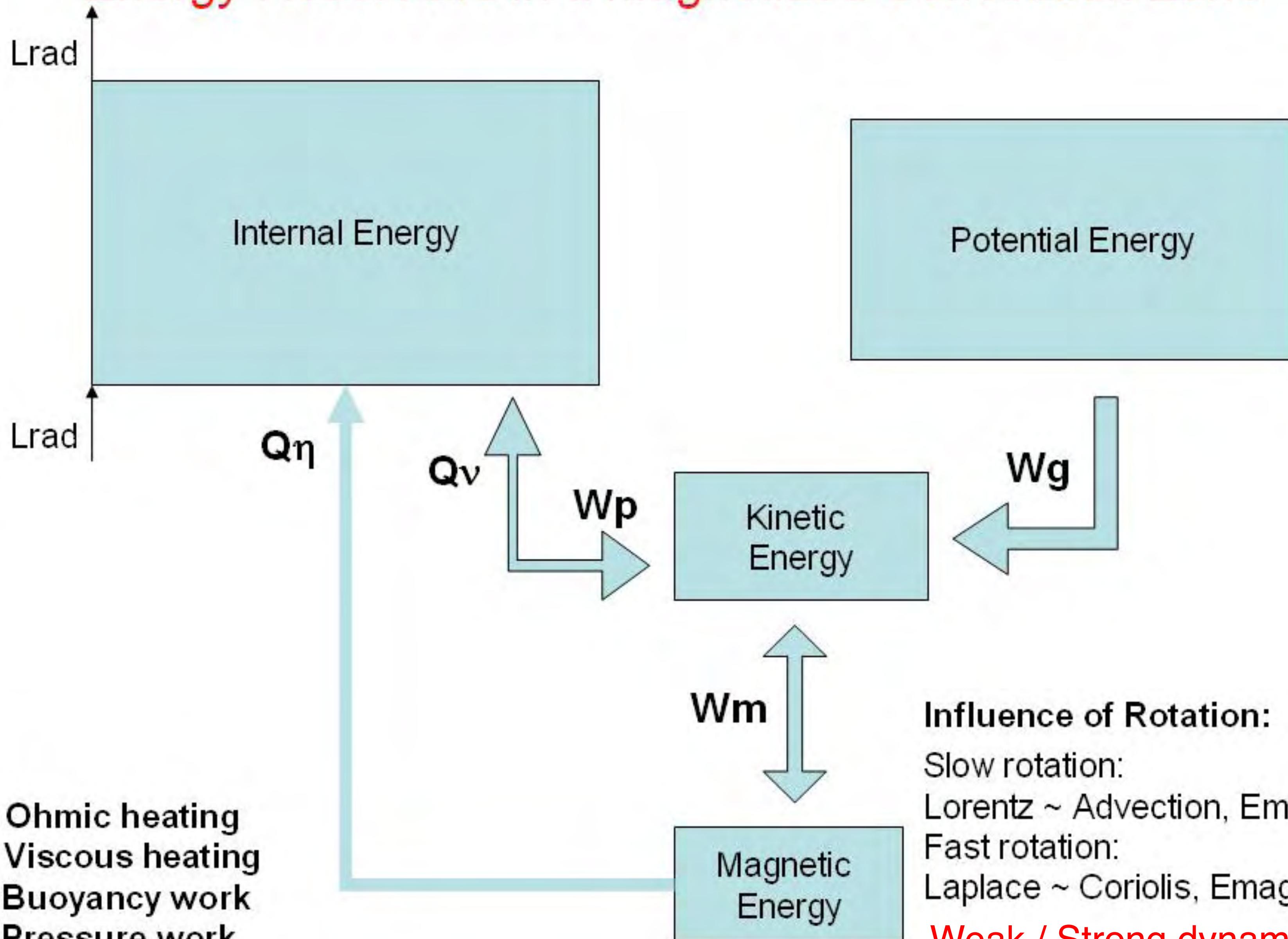
See also Hathaway et al. 1996, Gizon 2004, Zhao & Kosovichev 2004, etc…

Going 3-D: nonlinear convection dynamo MHD simulations

Magnetic field in a solar-like star dynamo



Energy Reservoirs in a Magnetized Convection Zone



Qη: Ohmic heating
Qν: Viscous heating
Wg:Buoyancy work
Wp:Pressure work
Wm: Lorentz force work

Influence of Rotation:

Slow rotation:
Lorentz ~ Advection, Emag ~ Eke
Fast rotation:
Laplace ~ Coriolis, Emag > Eke

Weak / Strong dynamo regime

(Brandenburg et al. 1996, Brun et al. 2004) Simitev & Busse 2009

Various Dynamo Regimes and Scalings

Equilibrium field : $B_{eq} \sim \mathrm{sqrt}(8\pi\, P_{gaz}) \sim \mathrm{sqrt}(\rho_*)$

If magnetic Reynolds number Rm ~1 , $v = \eta/L$, then

Laminar (weak) scaling: Lorentz ~ diffusion =>

$$B^2_{weak} \sim \rho\nu\eta/L^2$$

Turbulent (equipartition) scaling: Lorentz ~ advection =>

$$B^2_{turb} \sim \rho v^2 \sim \rho\eta^2/L^2 \Leftrightarrow |B_{weak}| \sim |B_{turb}|\, P_m^{1/2}$$

Magnetostrophic (strong) scaling: Lorentz ~ Coriolis =>

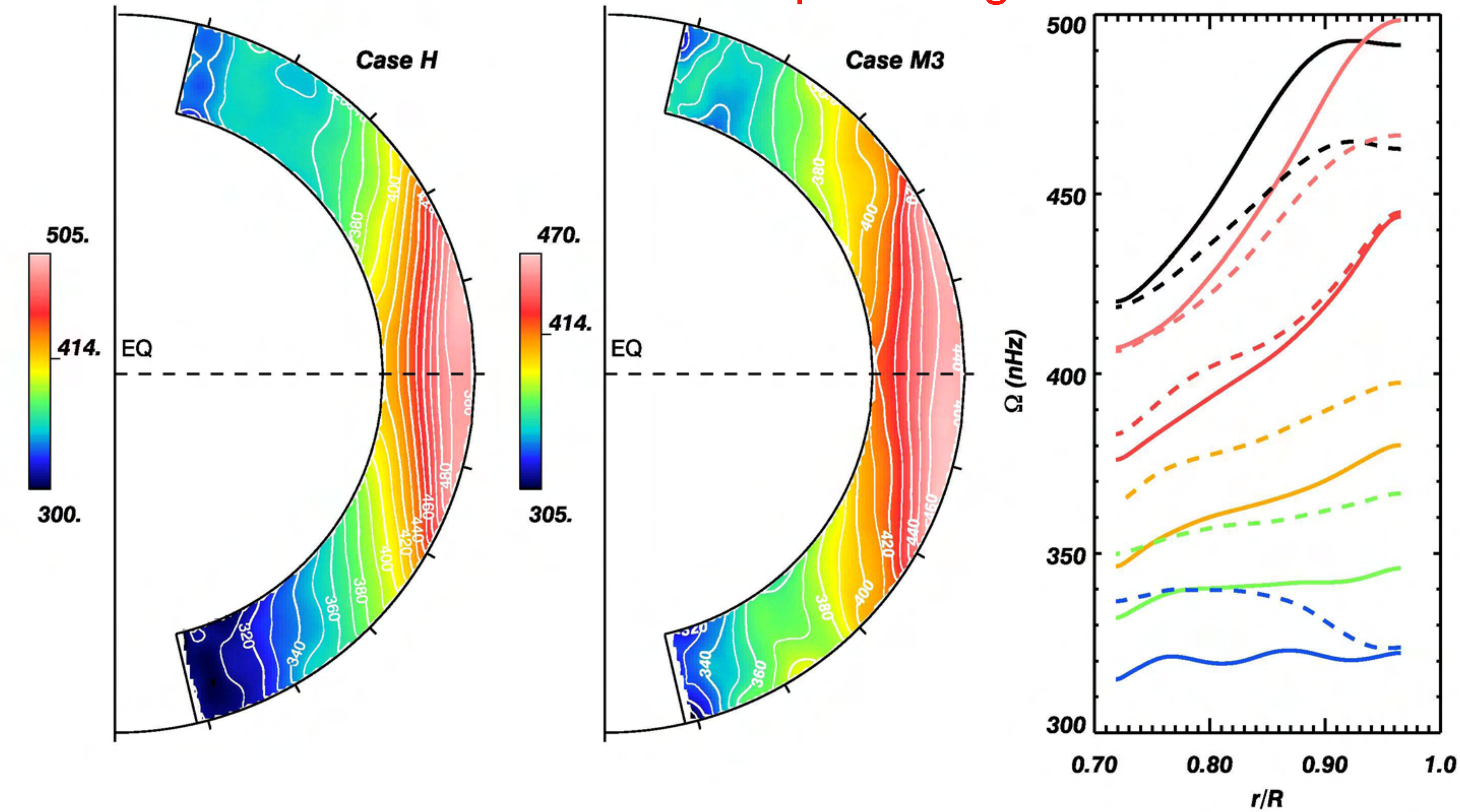
$$B^2_{strong} \sim \rho\Omega\eta$$

With ρ density, ν kinematic viscosity, η magnetic diffusivity, Ω rotation rate, v, L characteristic velocity & length scales, $P_m = \nu/\eta$ the magnetic Prandtl nb

Fauve et al. 2010, Christensen 2010, Brun et al. 2013

Mean Angular Velocity Ω

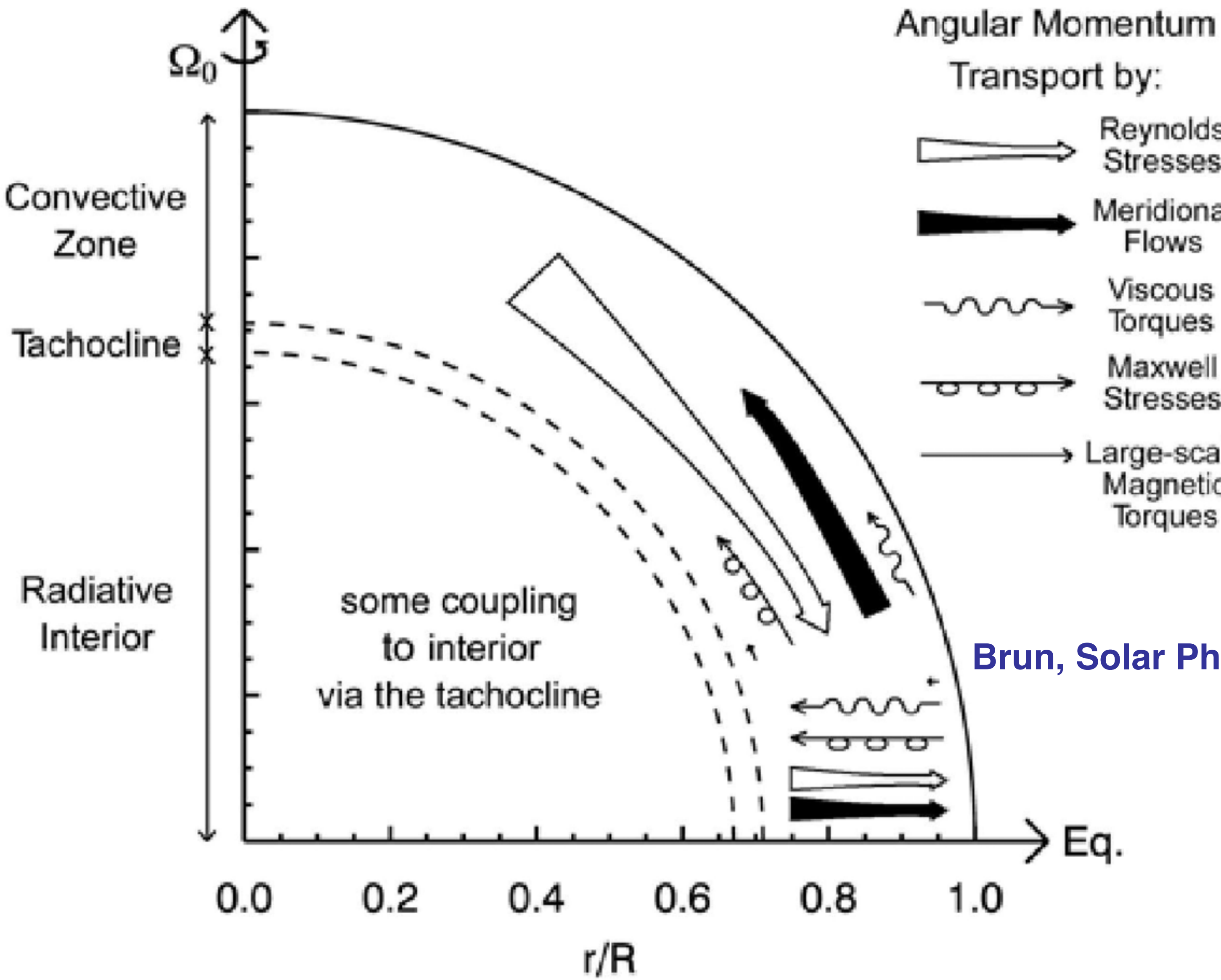
Ω quenching!



Initial state of differential rotation

Evolved state of differential rotation under the influence of the Lorentz force

Angular Momentum Balance in Presence of B

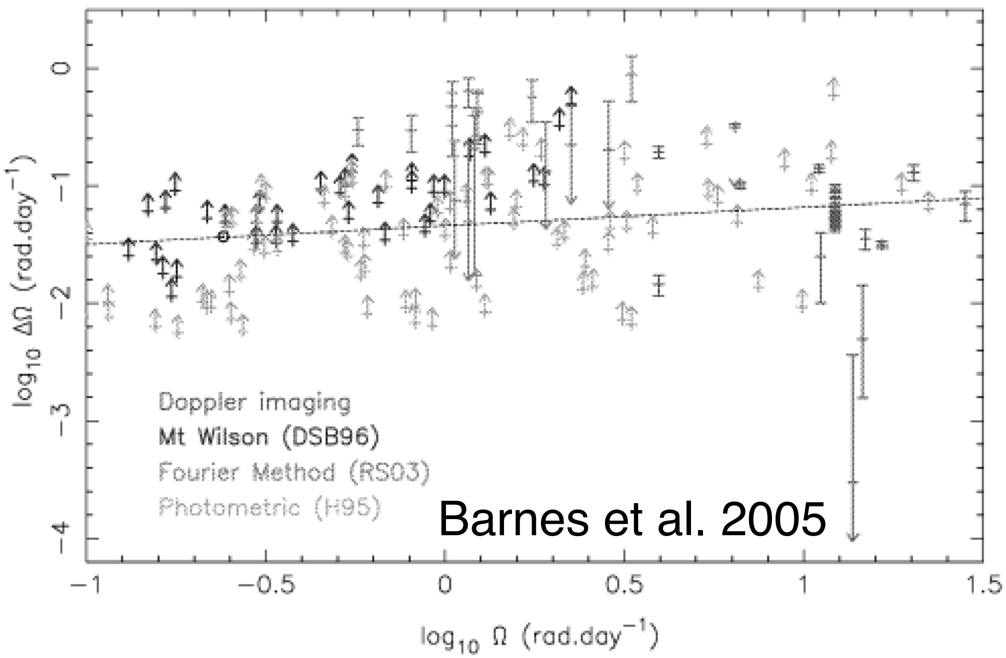


Brun, Solar Physics, 2004

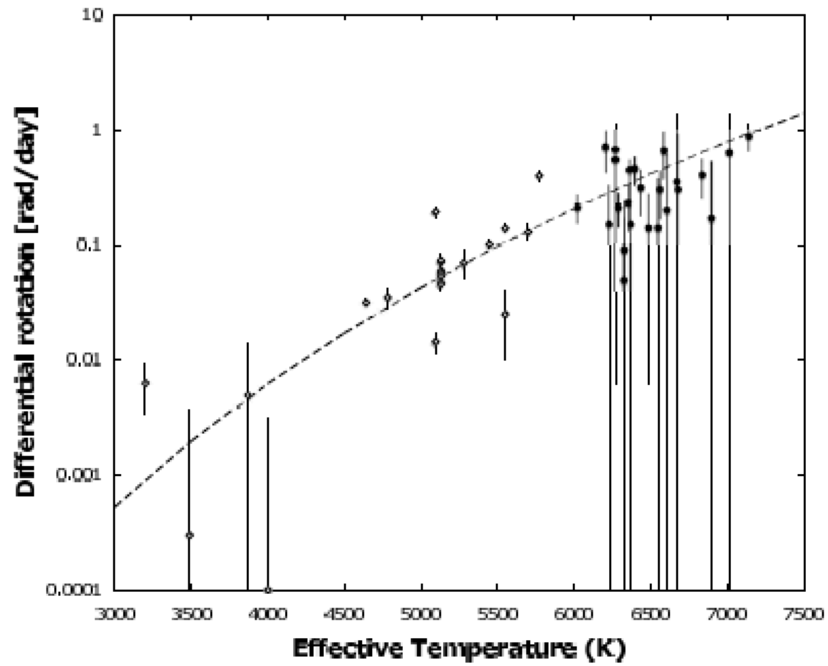
The transport of angular momentum by the Reynolds stresses remains at the origin of the equatorial acceleration. The Maxwell stresses seeks to speed up the poles.

Trends in Differential Rotation with Ω & Mass (Teff)

Weak trend with Ω



ΔΩ increases with M_*



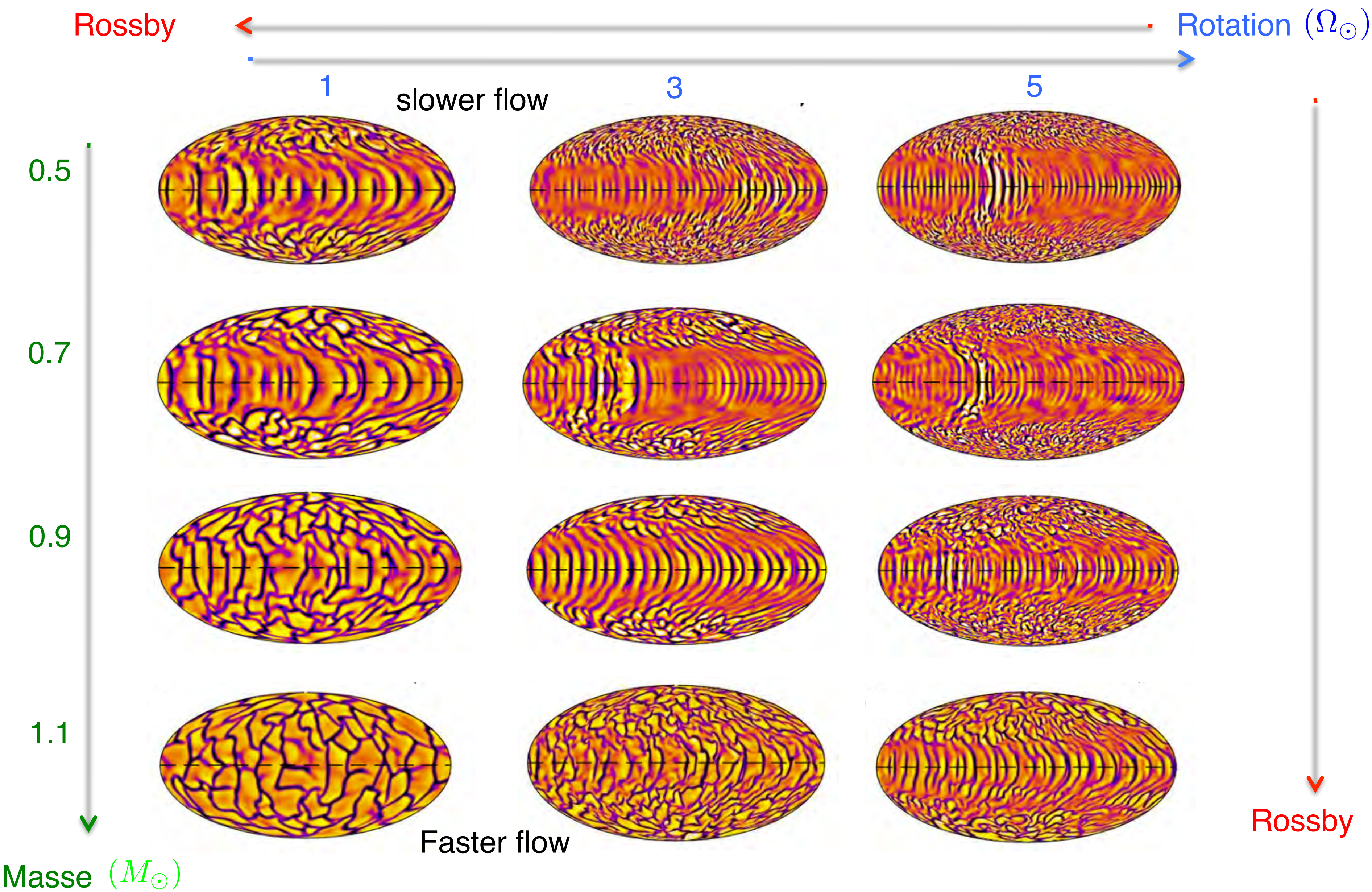
Collier-Cameron 2007

In Donahue et al. 1996: ΔΩ propto $\Omega^{0.7}$

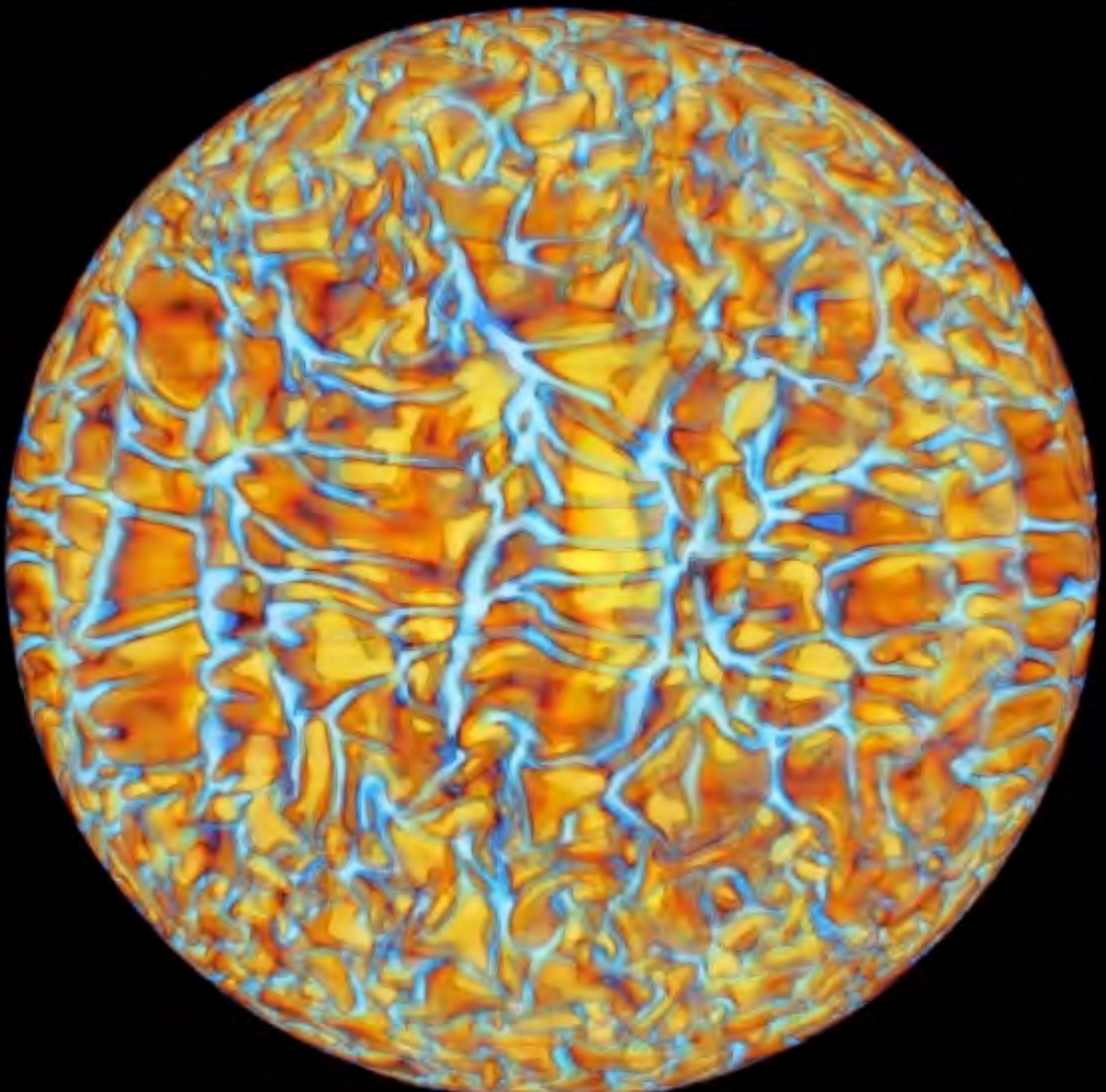
Confirming these observational scaling is key

Effect of Rotation on Convection

Matt, DoCao, Brun et al. 2011, 2013



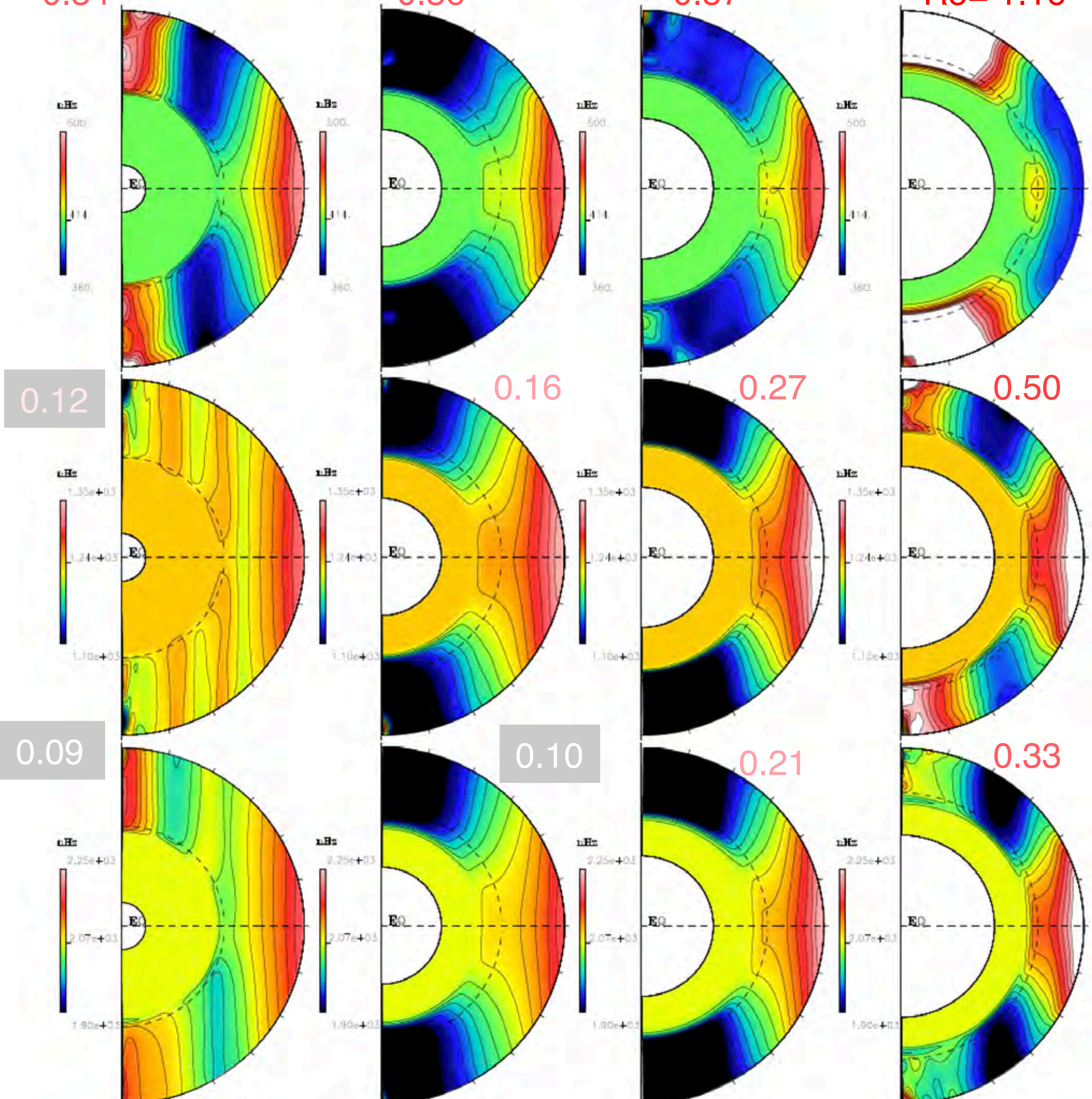
Turbulent Convection in Stars



Bessolaz & Brun 2011

Mass increases ->

Differential Rotation In G & K stars



Ω

Matt et al. 2011
Brun et al. 2014

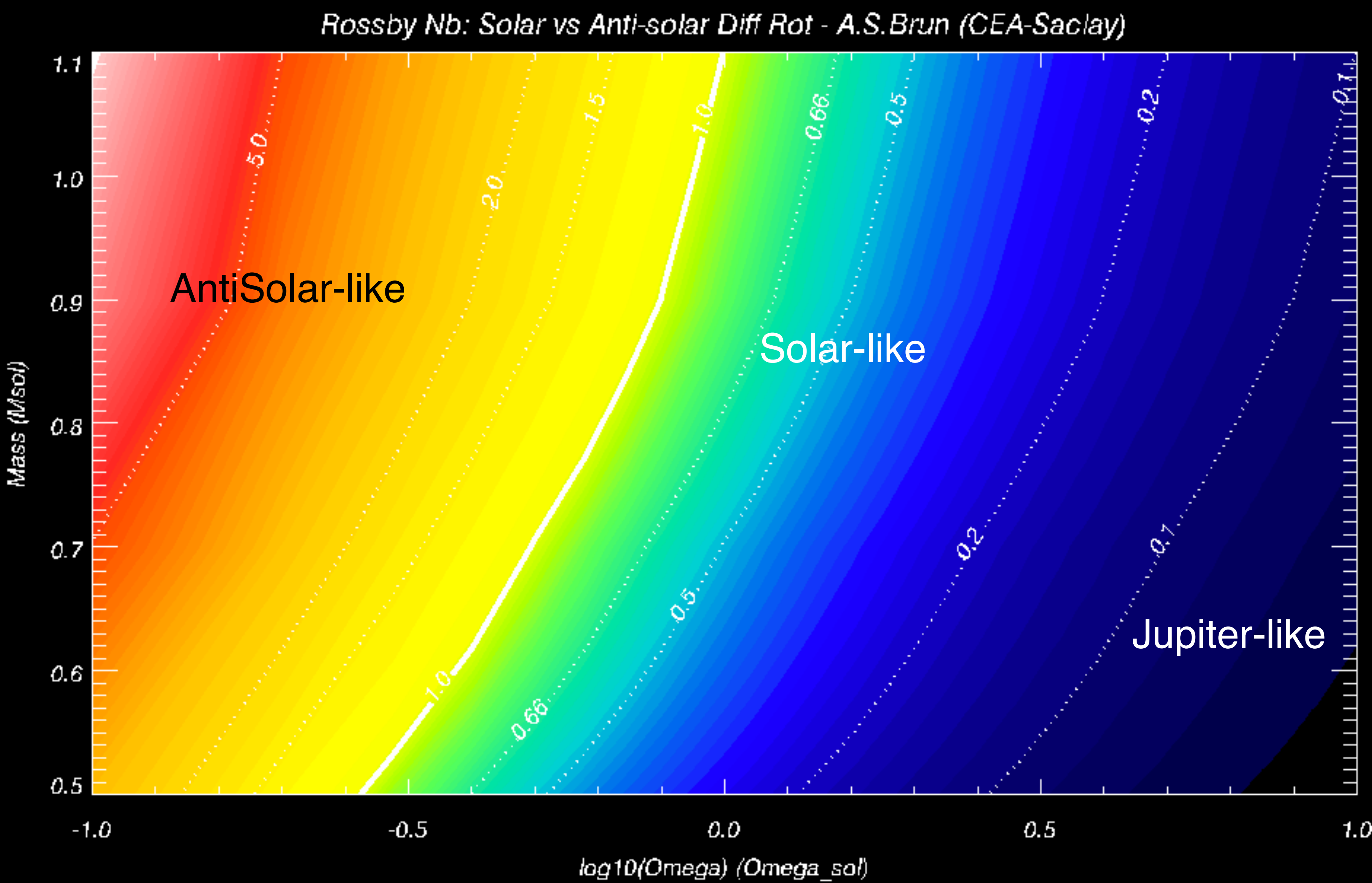
Rotation Increases

Rossby nb
$Ro=\omega/2\Omega_*$

5 Ω

See also: Gastine et al. 2014
Kapyla et al. 2013

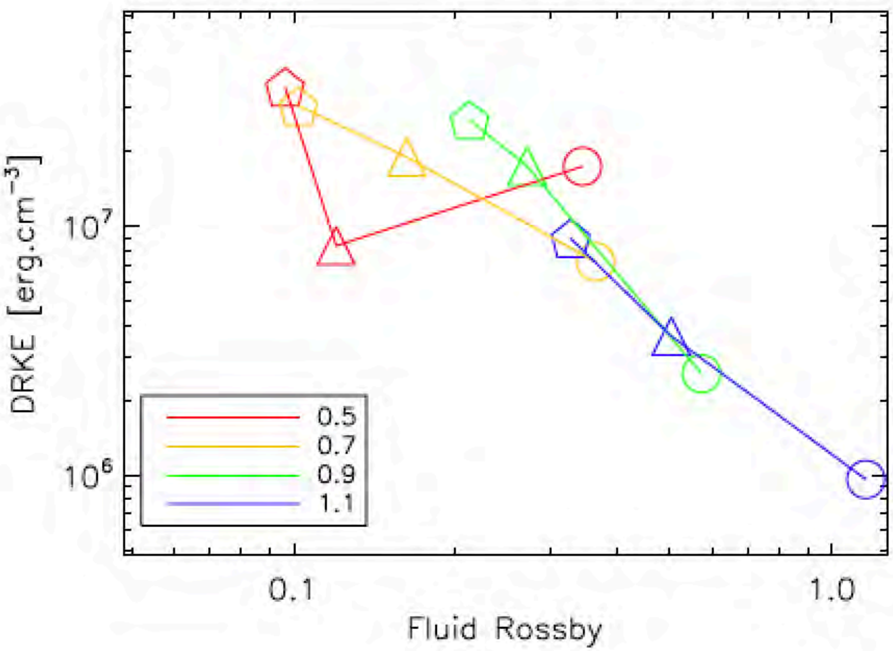
Rossby Number vs Stellar Mass and Rotation

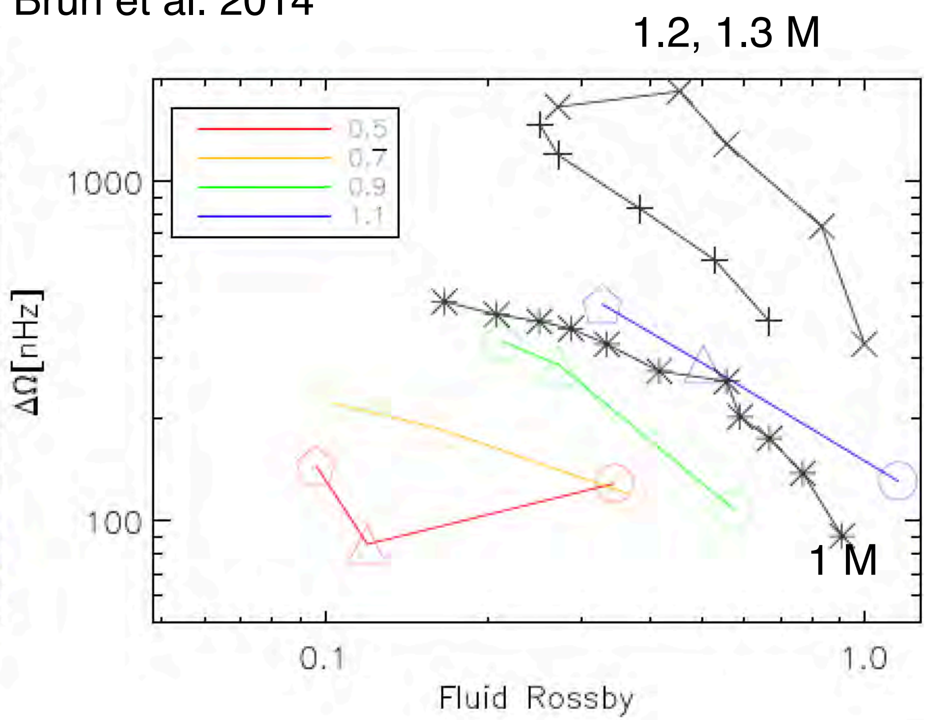


Brun et al. 2014, 2015

Scaling Law for $\Delta\Omega$

Matt et al. 2011, Brun et al. 2014





Brown et al. 2008
Augustson et al. 2012

$$\Delta\Omega = 156.0\ \mathrm{nHz}\left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^{1.0}\left(\frac{\Omega_0}{\Omega_\odot}\right)^{0.47}$$
$$= 150.3\ \mathrm{nHz}\left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^{1.85}\mathrm{R}_{\mathrm{of}}^{-0.52}$$

Smaller $\Delta\Omega$ with smaller Mass

Guessing a scaling with rotation of meridional flows

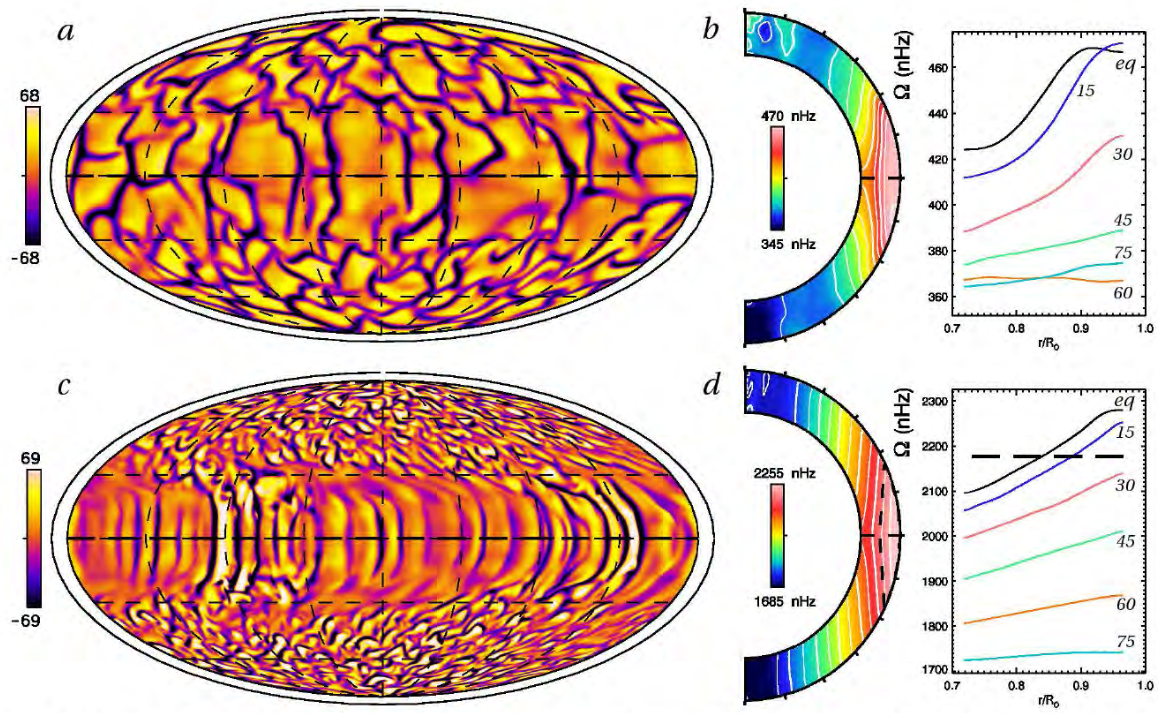
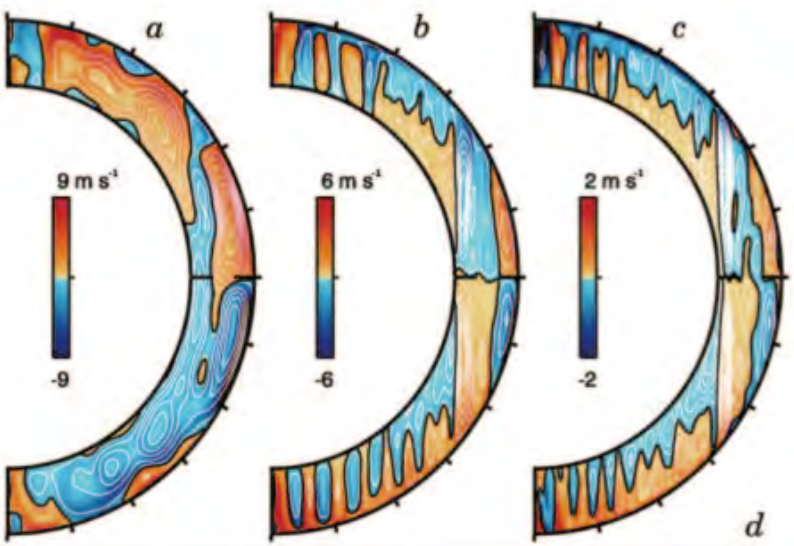
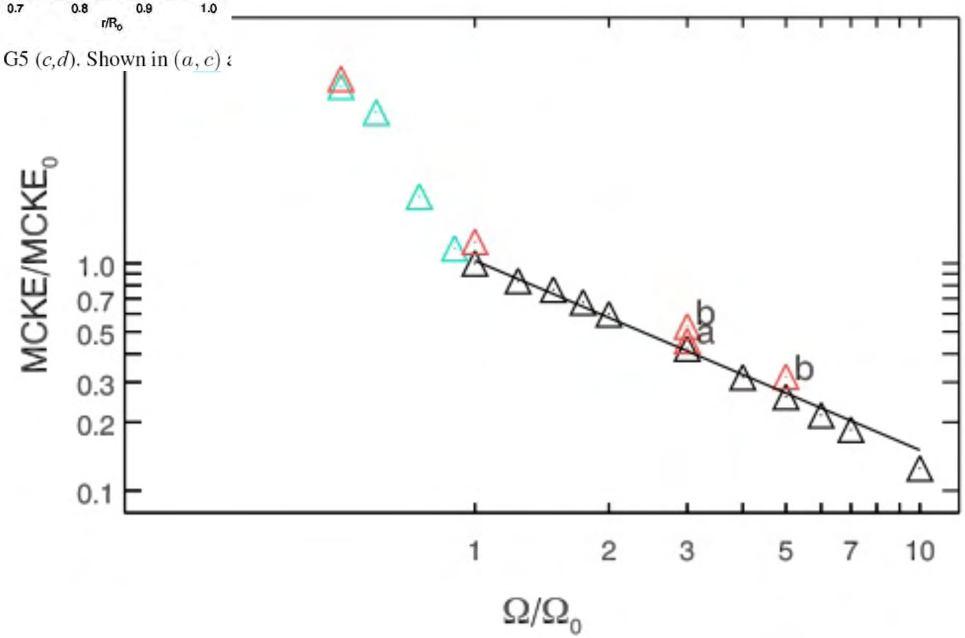


Fig. 1 Evolution of global-scale convective flows with increasing rotation rate for case G1 (a,b) and case G5 (c,d). Shown in (a, c)

Dikpati et al. 2001 assumed Vp $\sim\Omega$
Charbonneau & Saar 2001 assumed Vp $\sim\Omega$ or $\log(\Omega)$

Scaling of MC deduced from Brown et al. 2008





Stellar Magnetism: observations and models

Solar Type Stars (late F, G and early K-type)

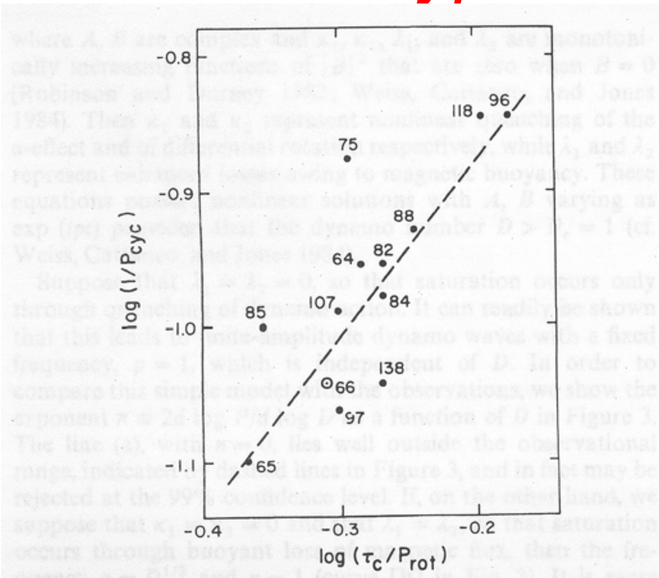
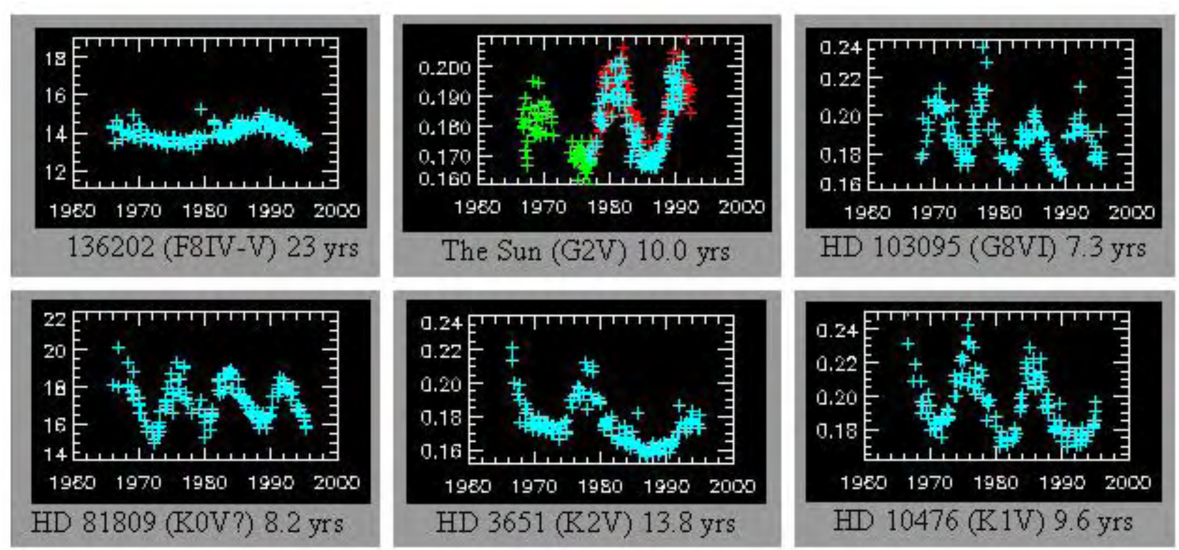


FIG. 2.—Log ($1/P_{cyc}$) vs. log (τ_c/P_{rot}) for the stars of Table 1. The dashed line is a linear least squares fit to the data.

Noyes et al. 1984



In stars activity depends on rotation & convective overturning time via Rossby nb $Ro=P_{rot}/\tau$

$\langle R'_{HK}\rangle = Ro^{-1}$, $P_{cyc}=P_{rot}^{1.25+/-0.5}$

Wilson 1978

Baliunas et al. 1995

CaII H & K lines , $\langle R'_{HK}\rangle$

<u>Over 111 stars in HK project (F2-M2):</u>

31 flat or linear signal

29 irregular variables

51 + Sun possess magnetic cycle

=> Much more coming in Asteroseismology Era (Mike's talk)

Quid of Star-Planet Interaction and cyclic activity?

Magnetic cycles of the planet-hosting star τ Bootis

J.-F. Donati,[1★] C. Moutou,[2★] R. Farès,[1★] D. Bohlender,[3★] C. Catala,[4★] M. Deleuil,[2★] E. Shkolnik,[5★] A. C. Cameron,[6★] M. M. Jardine[6★] and G. A. H. Walker[7★]

Solar Analogs

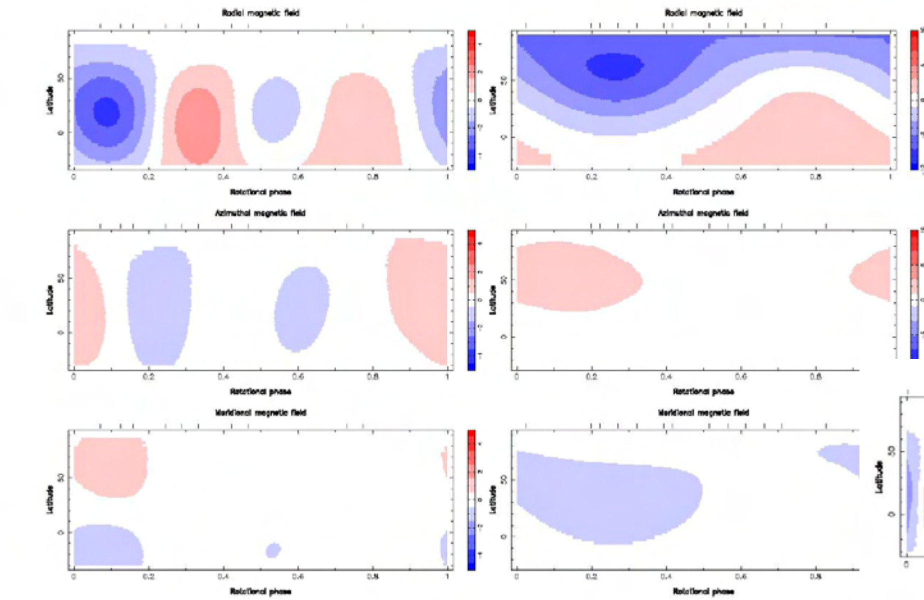


Figure 4. Magnetic maps of HD 146233 and HD 76151 (left and right panel, respectively). Each chart illustrates the onto one axis of the spherical coordinate frame. The magnetic field strength is expressed in Gauss. Vertical ticks above the the observed rotational phases. Note that color scales are not the same for every star.

Faster the solar analogs rotate more toroidal Field contribution they possess.

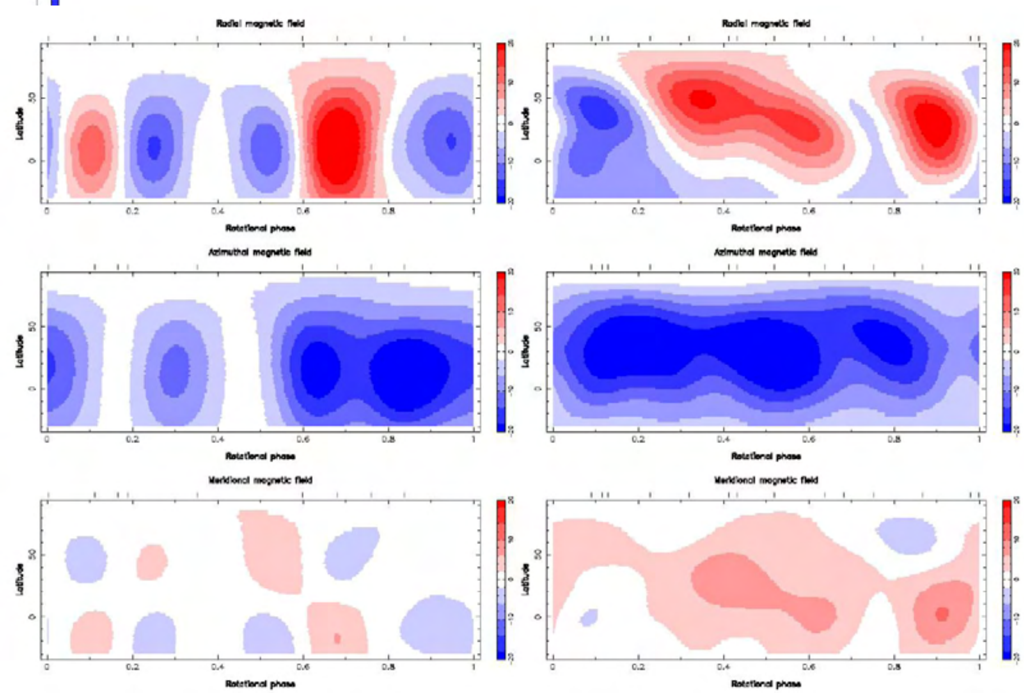


Figure 5. Same as Fig. 4, for HD 73350 (left panel) and HD 190771 (right panel).

Petit et al. 2008, MNRAS

ESPADON/NARVAL

Stellar Magnetism vs Stellar Dynamo

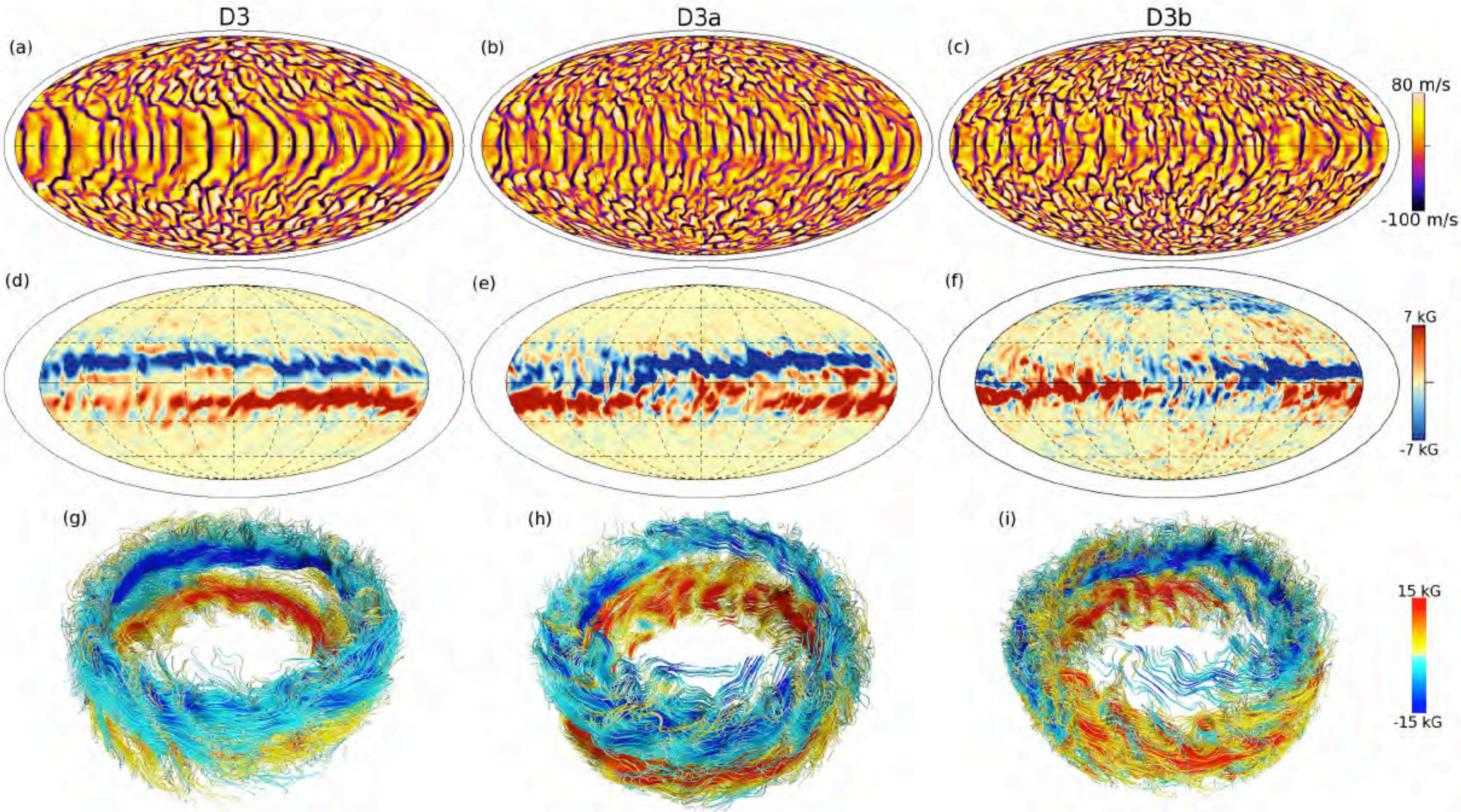
- Source of variability (chaos, intermittency,…)
- Existence of starspot and sensitivity to stellar parameters
- Can we reproduce the trend $P_{cyc} \sim P_{rot}^{n}$ (with n ~1+/-0.2)
- Can we reproduce the rise of the toroidal vs poloidal field
- What can we do about MC flow profile and amplitude?
- Which « solar model» is best to explain stellar data?

BL mean field models

$$P_{cyc} = v_0^{-0.91} s_0^{-0.013} \eta^{-0.075} \Omega_0^{-0.014}$$

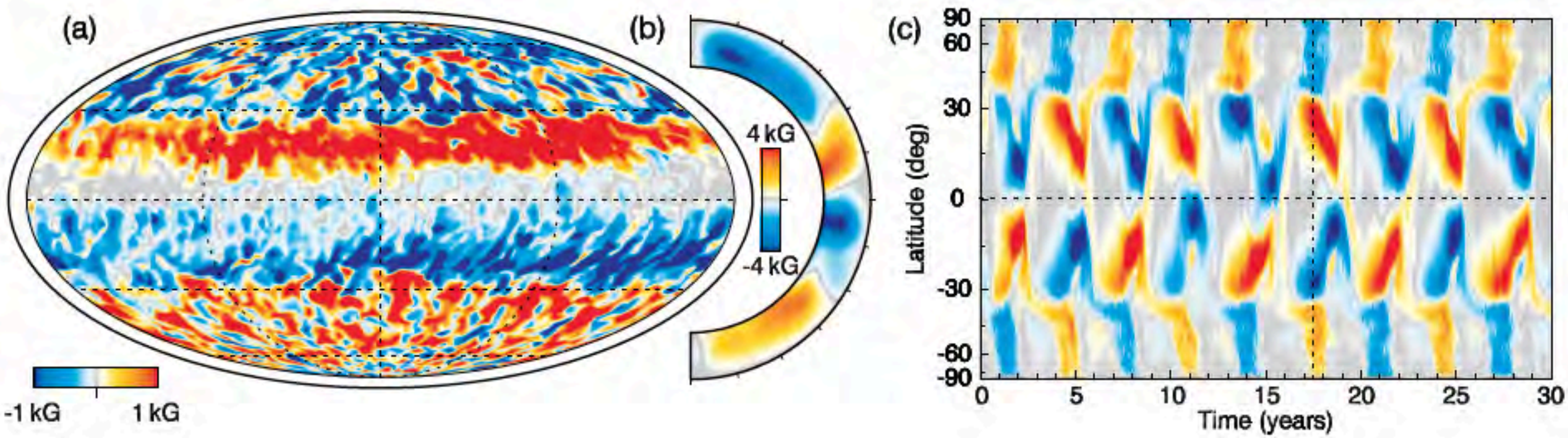
Strong dependancy on meridional flow amplitude

Magnetic Wreaths vs Turbulence



Nelson et al. 2013a

Latest solar-like case D3: getting cycle and equatorward branch

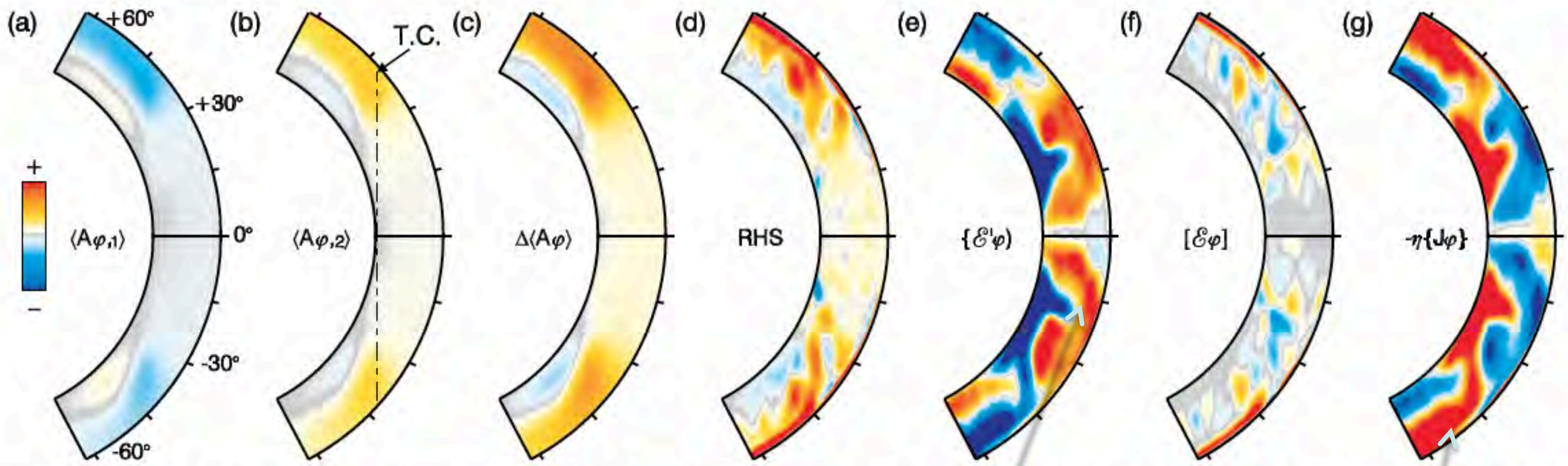


Reducing nu even further nu by using SLD scheme makes the simulation develop a more regular cyclic behavior

Augustson, Brun et al. 2013, ApJL, submitted

Origin of Poloidal Field Reversal

$$\Delta\langle A_\varphi\rangle = \langle A_{\varphi,2}\rangle - \langle A_{\varphi,1}\rangle = \{\mathcal{E}'_\varphi\} + [\mathcal{E}_\varphi] + \eta\{J_\varphi\}$$
$$= \int_{t_1}^{t_2} dt\,\hat{\varphi}\cdot\langle\mathbf{v}'\times\mathbf{B}'\rangle + \int_{t_1}^{t_2} dt\,\hat{\varphi}\cdot(\langle\mathbf{v}\rangle\times\langle\mathbf{B}\rangle) - \int_{t_1}^{t_2} dt\,\eta\langle J_\varphi\rangle.$$



Fluctuating Emf key term

some contribution
from diffusion term
at high latitudes

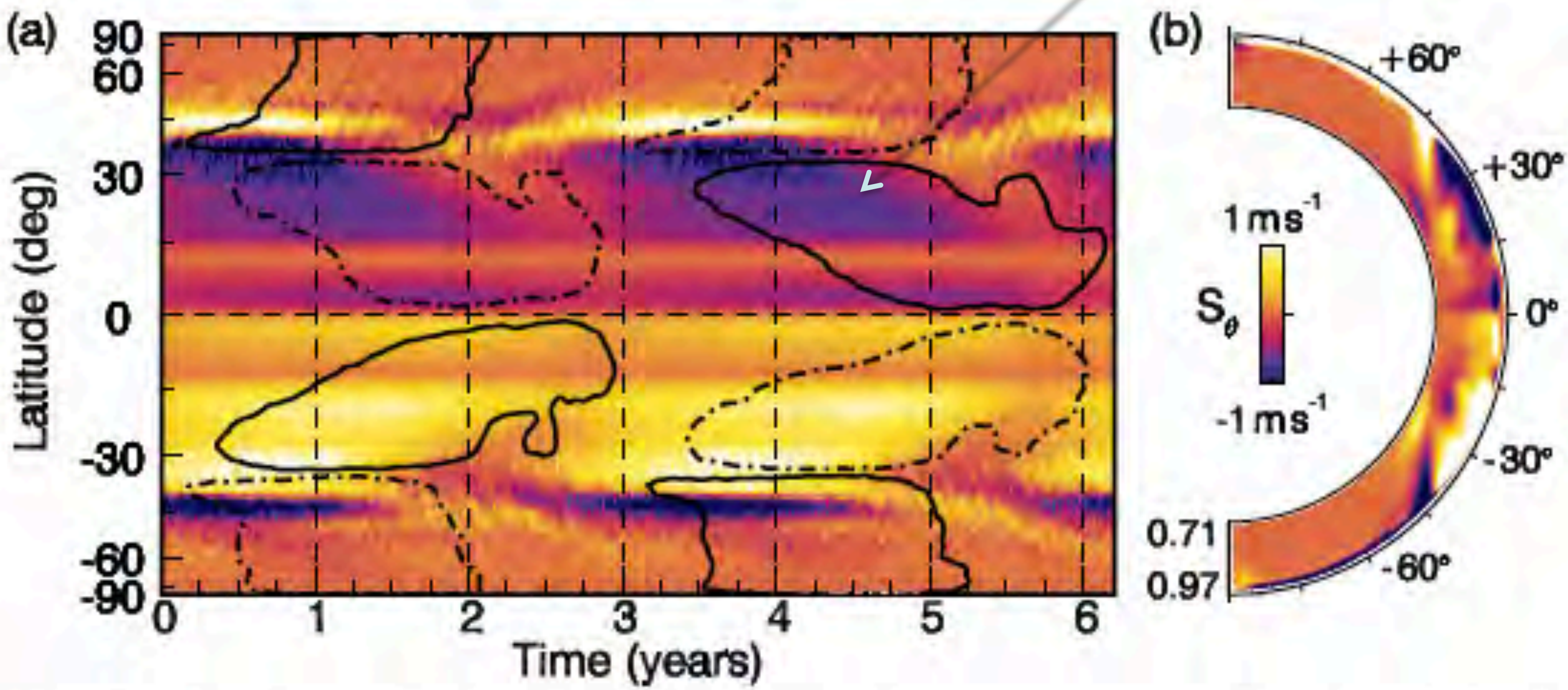
In kinematic theory the propagation direction of such a wave is given by the Parker-Yoshimura rule (e.g., Parker 1955; Yoshimura 1975) as

$$\mathbf{S} = -\lambda\overline{\alpha}\hat{\varphi} \times \boldsymbol{\nabla}\frac{\Omega}{\Omega_0}, \tag{19}$$

where $\lambda = r\sin\theta$ and $\overline{\alpha} = -\tau_o\langle\mathbf{v}'\cdot\boldsymbol{\omega}'\rangle/3$. Thus $\overline{\alpha}$ depends on the convective overturning time τ_o and the kinetic helicity.

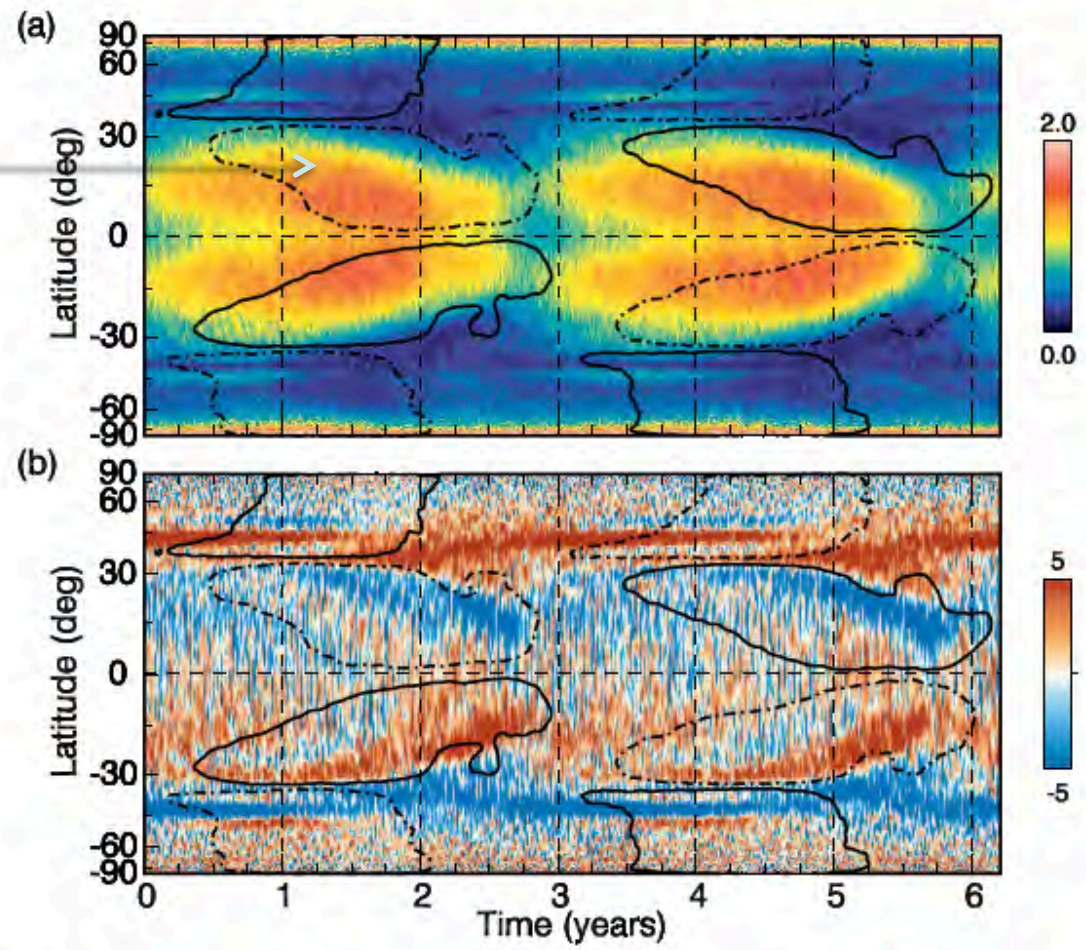
Parker-Yoshimura Rule

uncorrect sign



Non-linear dynamo wave

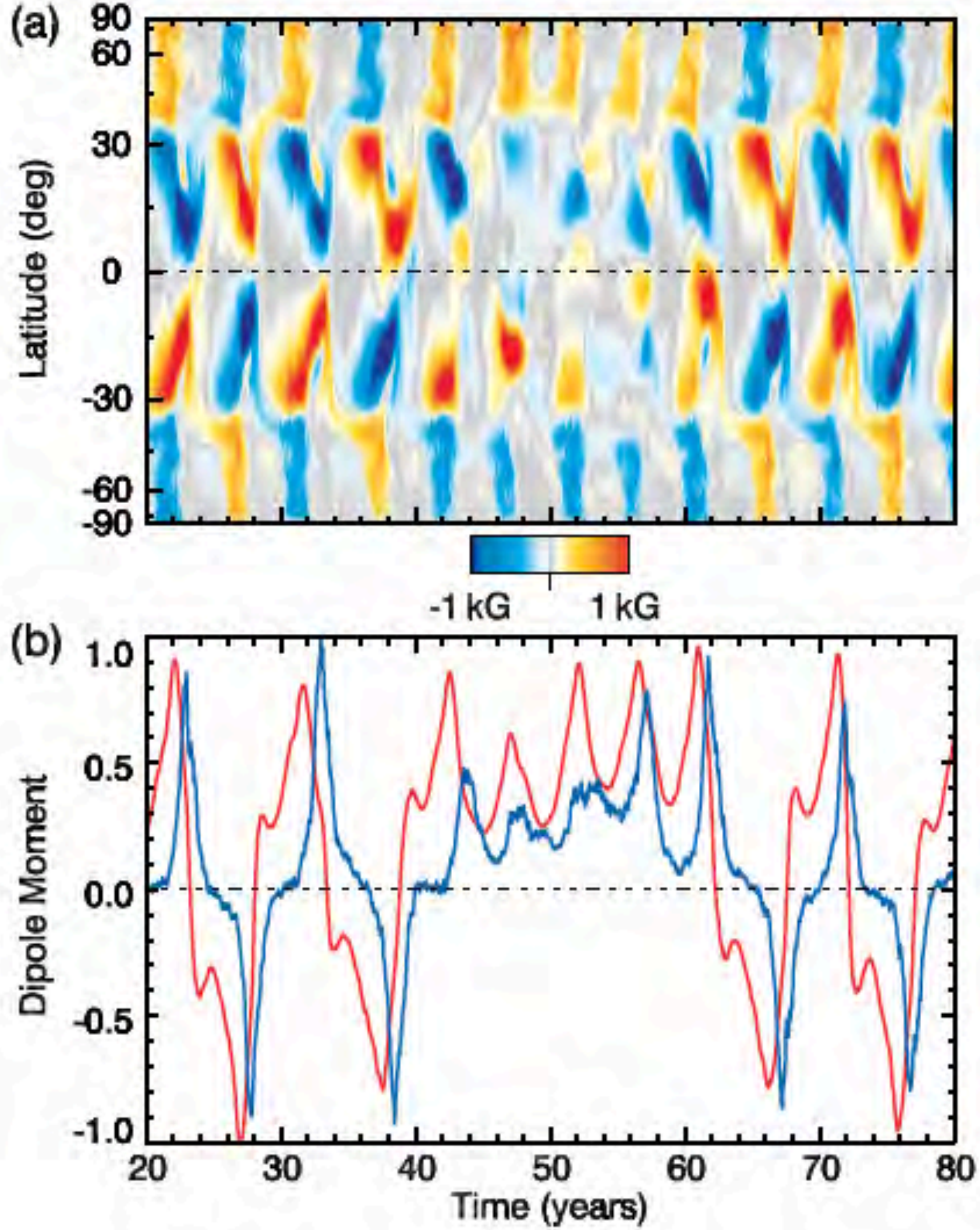
Correct sign



Interaction between Shear and Bphi

Figure 11. Coevolution of the mean toroidal magnetic field $\langle B_\varphi \rangle$ at $0.92\,R_\odot$ over the average magnetic polarity cycle with (a) the magnitude of the mean angular velocity gradient $R_\odot |\nabla\Omega| / \Omega_0$ and (b) latitudinal velocity $\langle v_\theta \rangle$ of the evolving meridional circulation in units of $\mathrm{m\,s^{-1}}$. Here $\langle B_\varphi \rangle$ is overlain with positive magnetic field as solid lines and negative field as dashed lines, with the contours corresponding to a 1 kG strength field.

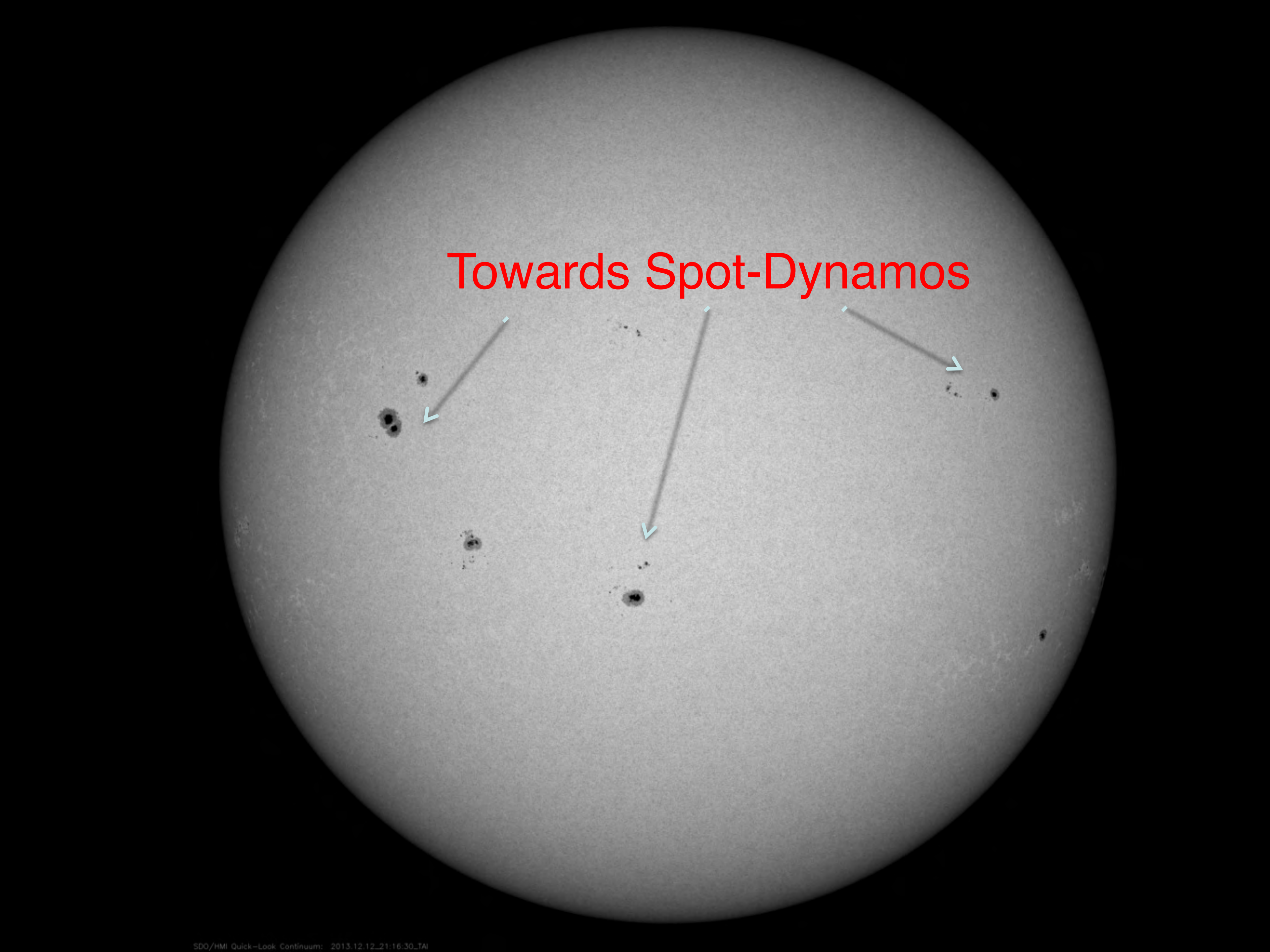
Latest solar-like case DS3:
Getting Maunder like minimun



Quadrupole dominates over Dipole during reversal and Grand minimum phase

Augustson, Brun et al. 2015, ApJ

Towards Spot-Dynamos



Magnetic Wreath and Intermittency yielding flux emergence

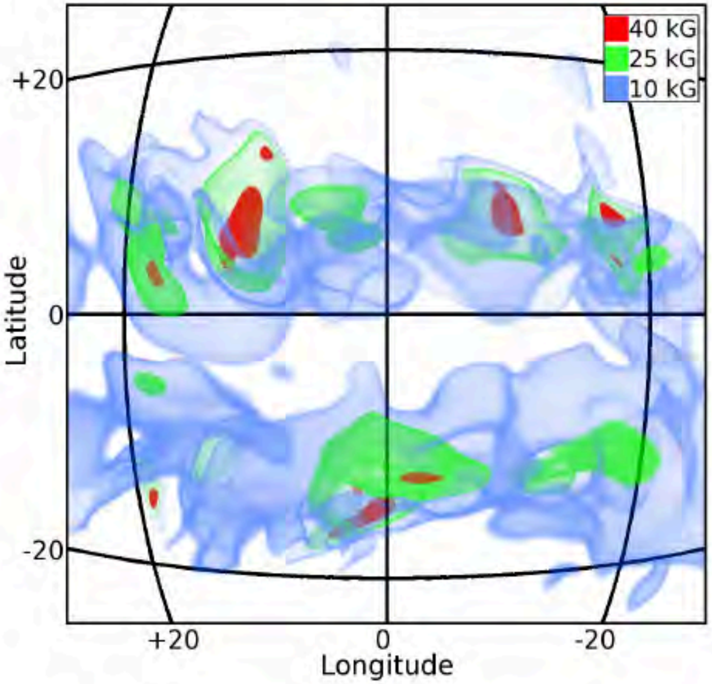


Figure 17. Three-dimensional volume renderings of isosurfaces of magnetic field amplitude in case S3. Blue surfaces have amplitudes of 10 kG, green surfaces represent 25 kG, and red surfaces indicate 40 kG fields. Grid lines indicate latitude and longitude at 0.72 $R_\odot$ as they would appear from the vantage point of the viewer. Small portions of the cores of these wreaths have been amplified to field strengths in excess of 40 kG while the majority of the wreaths exhibit fields of about 10 kG or roughly in equipartition with the mean kinetic energy density (see Figure 2).

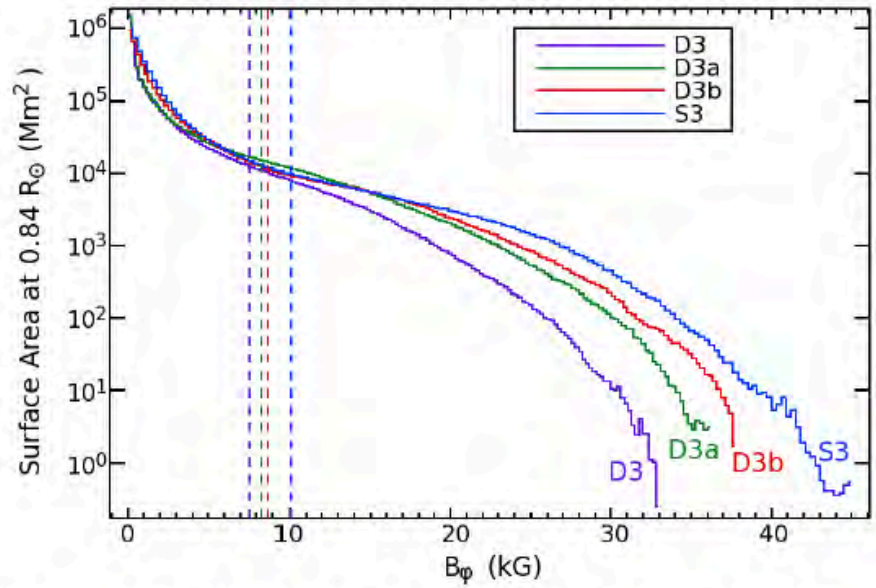
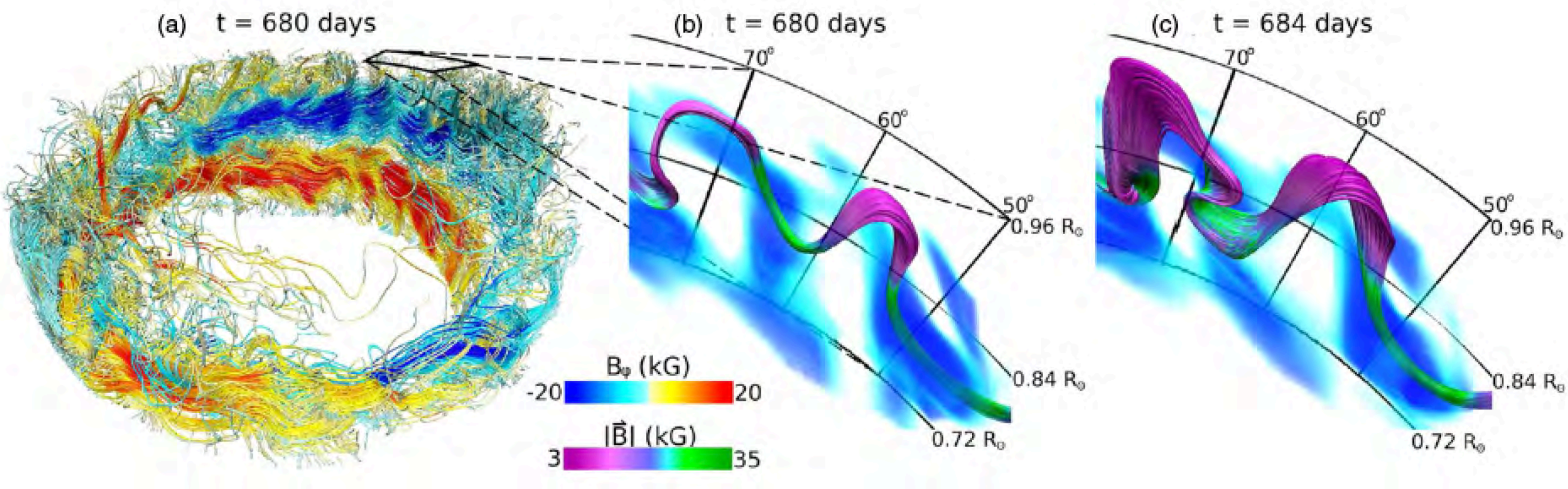


Figure 2. Probability distribution functions for unsigned B_ϕ at mid-convection zone for cases D3 (purple), D3a (green), D3b (red), and S3 (blue) showing the surface area covered by fields of a given magnitude. Distributions are averaged over about 300 days when fields are strong and as steady as possible. Dashed vertical lines show the field-strength at which equipartition is achieved with the maximum fluctuating kinetic energy (FKE) at mid-convection zone for each case. Case D3b shows a deficit of field in the 10 kG range, but an excess of surface area covered by extremely strong fields above 25 kG range, as well as higher peak field strengths. Case S3 shows significantly greater regions of fields in excess of 20 kG than all other cases.

Nelson et al. 2013, ApJ

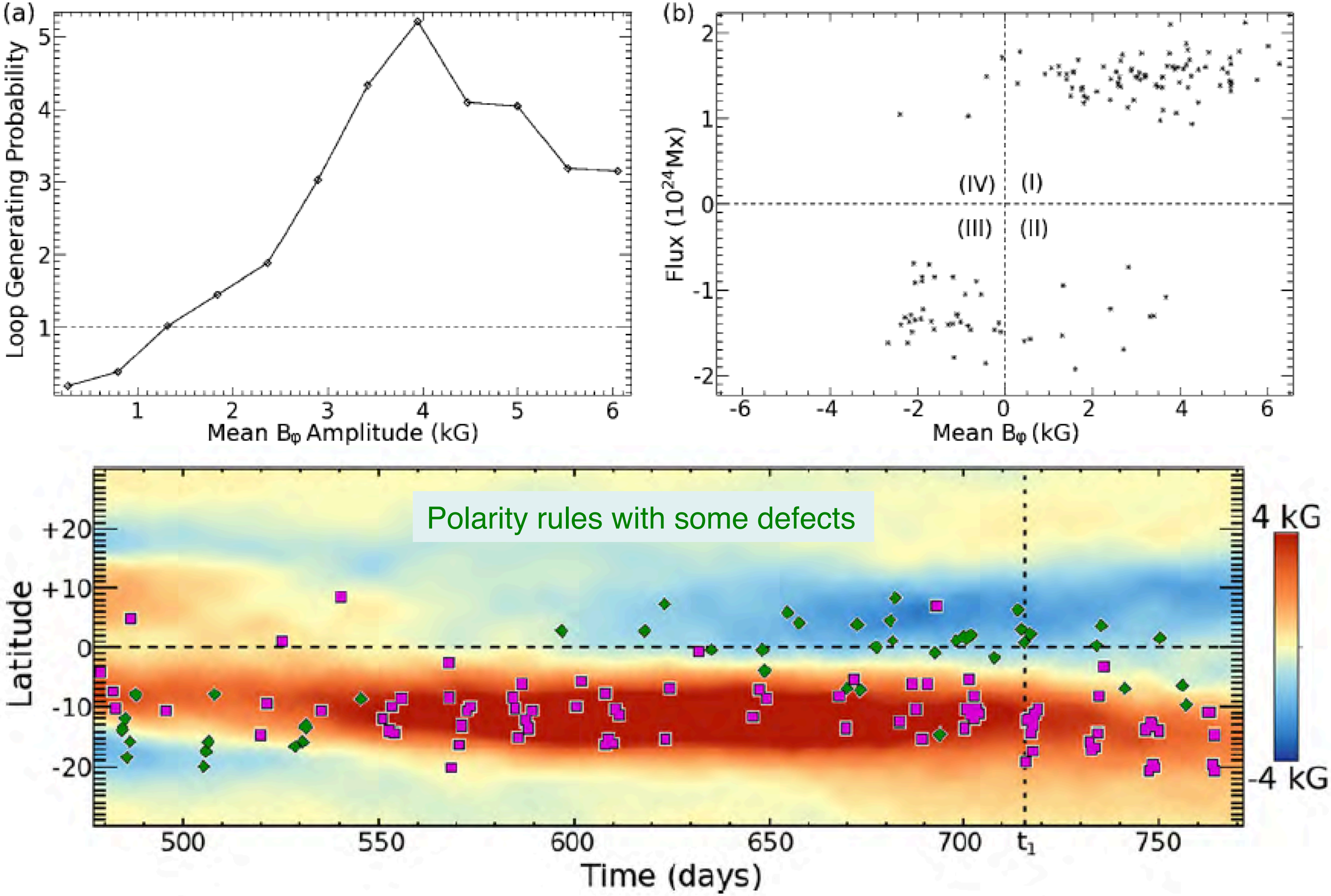
Wreaths can generate Buoyant Loops



Nelson et al. 2011, 2013a, 2013b

Towards getting first “spot-dynamos”…

Statistic of Buoyant Loops



Nelson et al. 2013b

Conclusions

Convective velocities Vr roughly scales with cubic root of $L_*/(R_*^2\rho_{meanCZ})$ (star's luminosity devided by mean density in CZ)

$\Rightarrow$ Prograde vs retrograde state changes at different Ω_0 as spectral type is changed (since $Ro=V/2\Omega_0 L$ and V changes with spectral type)

$\Rightarrow$ Cylindrical vs conical vs shellular differential profiles depends on Reynolds stresses & thermal (baroclinic) effects/tachocline

$\Rightarrow$ Magnetic field B reduces or can even supress diff rot Ω

$\Rightarrow$ at high rotation rate we get magnetic wreaths that generate omega-loops as we lower diffusivity, cyclic dynamos easier to get

$\Rightarrow$ Multipolar or Dipolar magnetic bi-stability exist but Multipolar fields seem to dominate at high stratification

$\Rightarrow$ Stratification and/or a tachocline may help getting equatorward butterfly diagram (shift location of Ω and α-like effects)