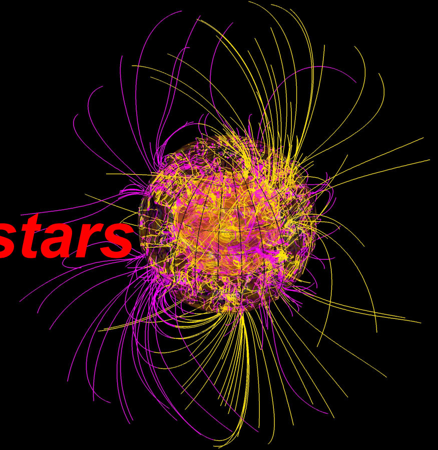
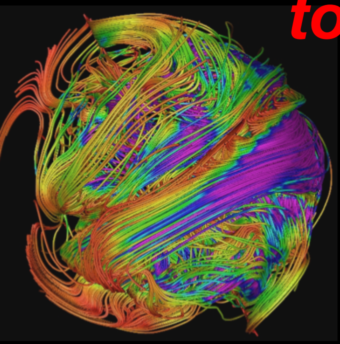


Towards getting spot-dynamos to explain the magnetism of solar-like stars

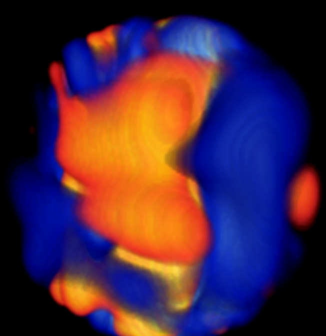


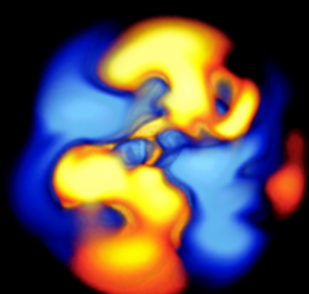
Allan Sacha Brun

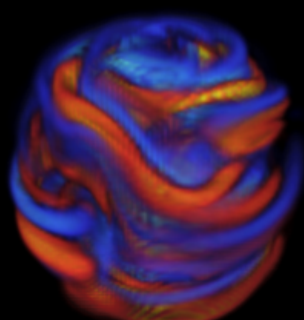
Service d'Astrophysique/UMR AIM,
CEA-Saclay
Visiting Professor @ RIMS, Univ of Kyoto

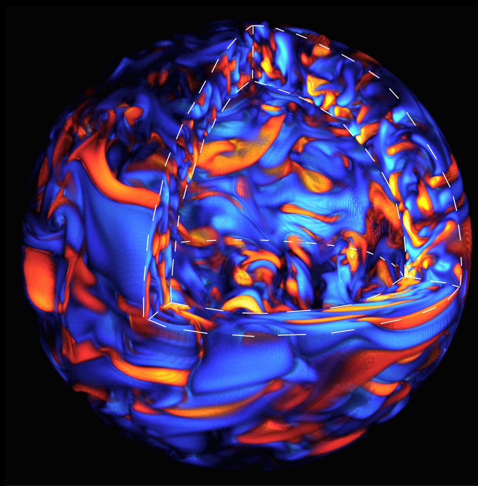
with J. Toomre, M. Miesch, K. Augustson, B. Brown, A. Strugarek, L. Jouve, N. Nelson

- Dynamo action in solar/stellar convection envelopes
- Solar-stellar connection



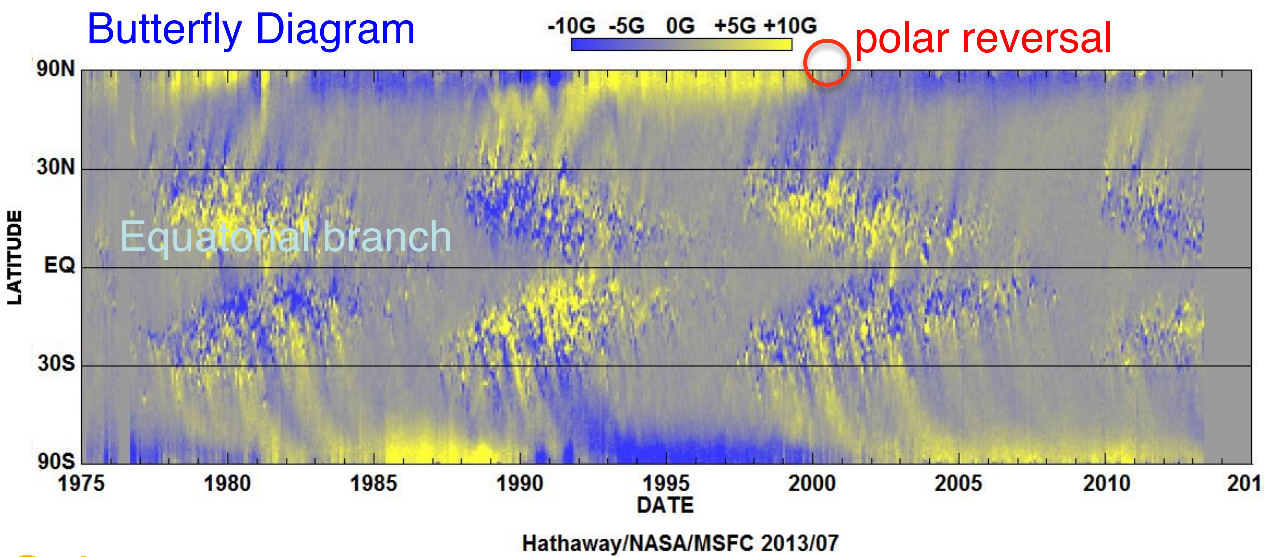


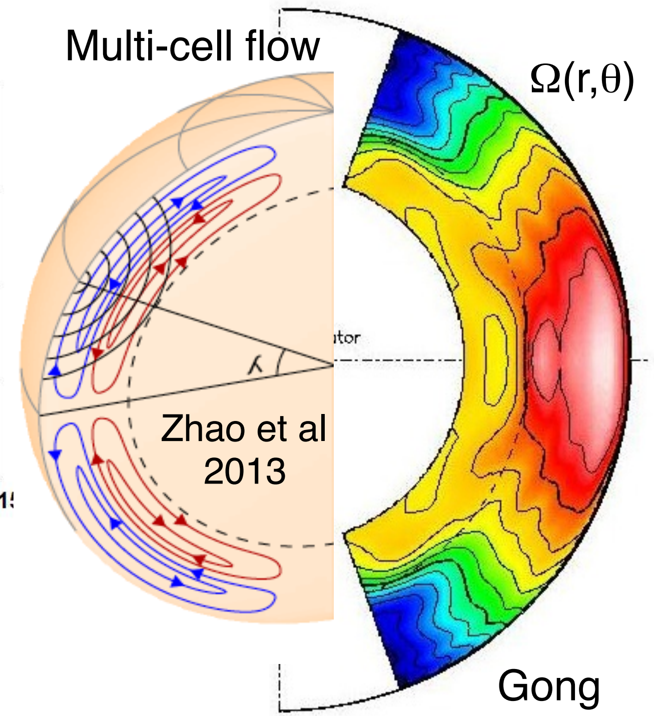


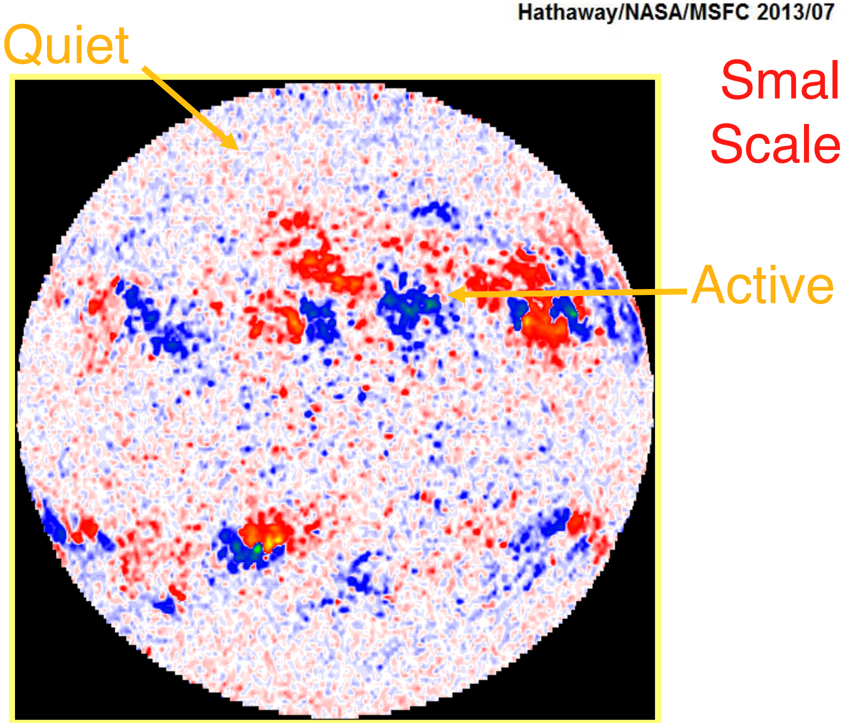


The Sun: the closest magnetic star

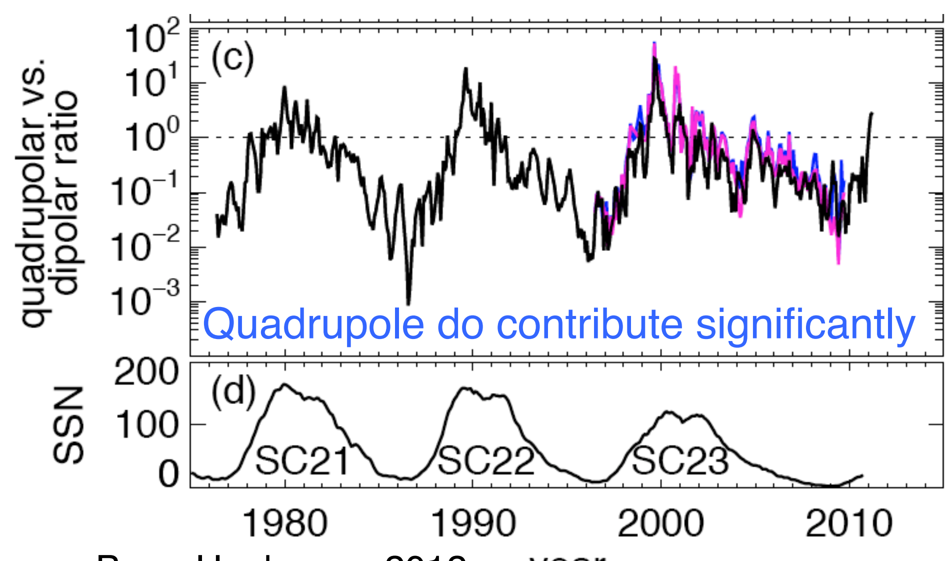
Solar Cycle and Rotation







Small vs Large Scale Dynamos



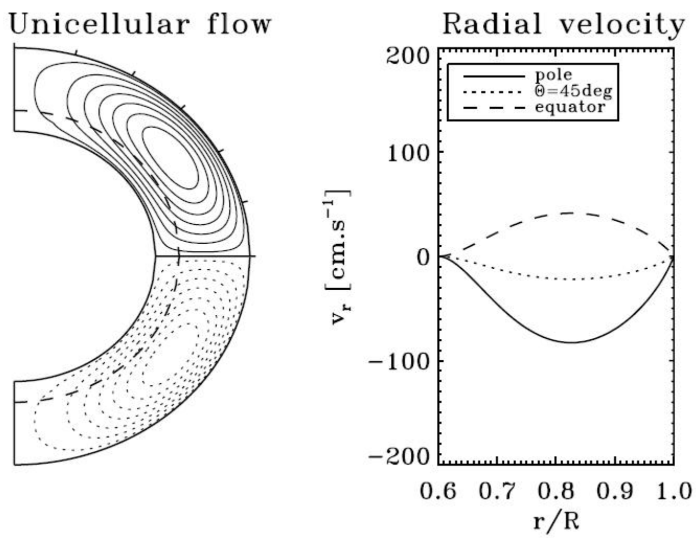
Derosa, Brun, Hoeksema 2012

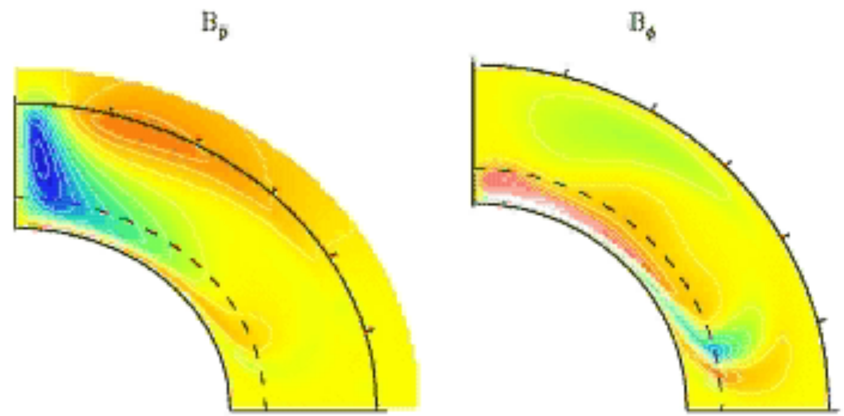
Magnetic Field Generation & Dynamo

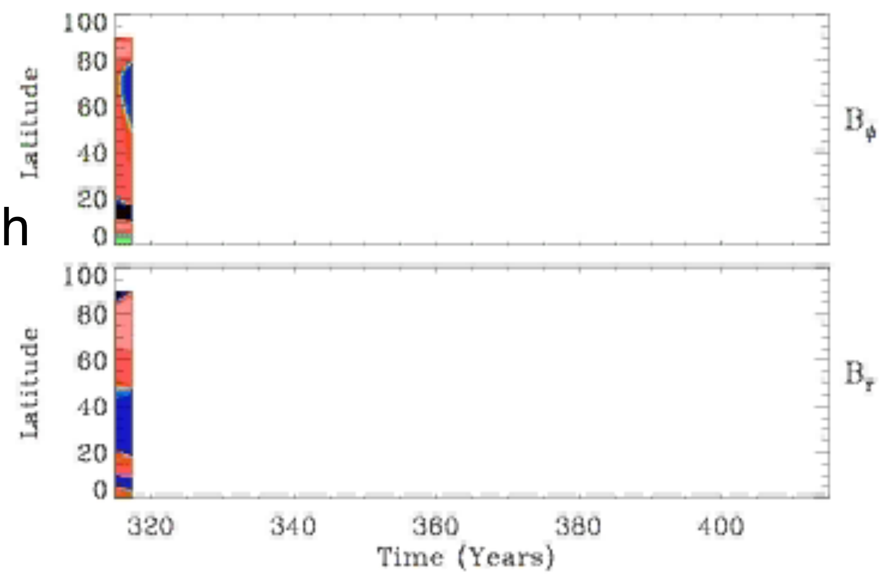
- Simple 2-D mean field dynamo models
- Nonlinear 3-D dynamo models

Simpler 2D Mean Field models: Babcock-Leighton

Present standard model: 1 cell per hemisphere







If fine tune =>
Period = 22 yr and equatorward branch

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

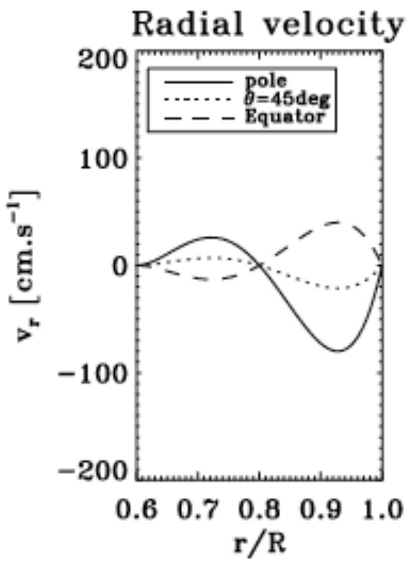
Strong dependence on MC amplitude

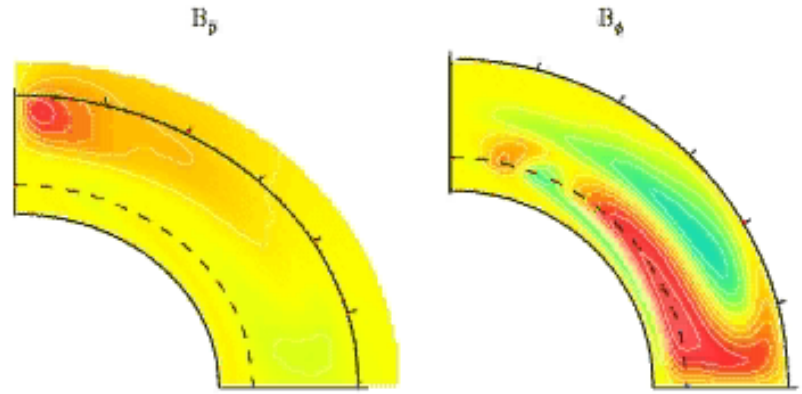
Jouve & Brun, 2007 A&A, 474, 239

Check international Benchmark: Jouve et al. 2008, A&A

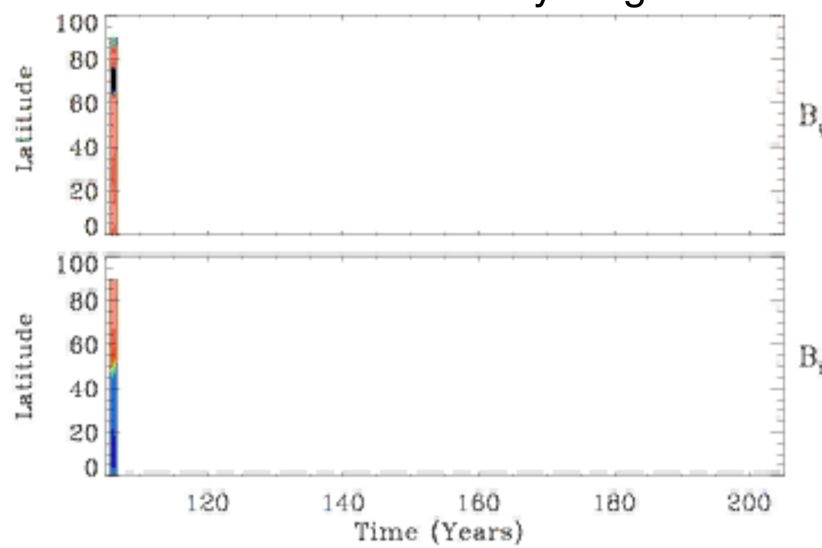
Simpler 2D Mean Field models: Babcock-Leighton

2 cells in radius per hemisphere





Incorrect Butterfly diagram



For parameter values identical to 1 cell case, find P=84 yr instead of 22yr,
Big change can lead to 22yr

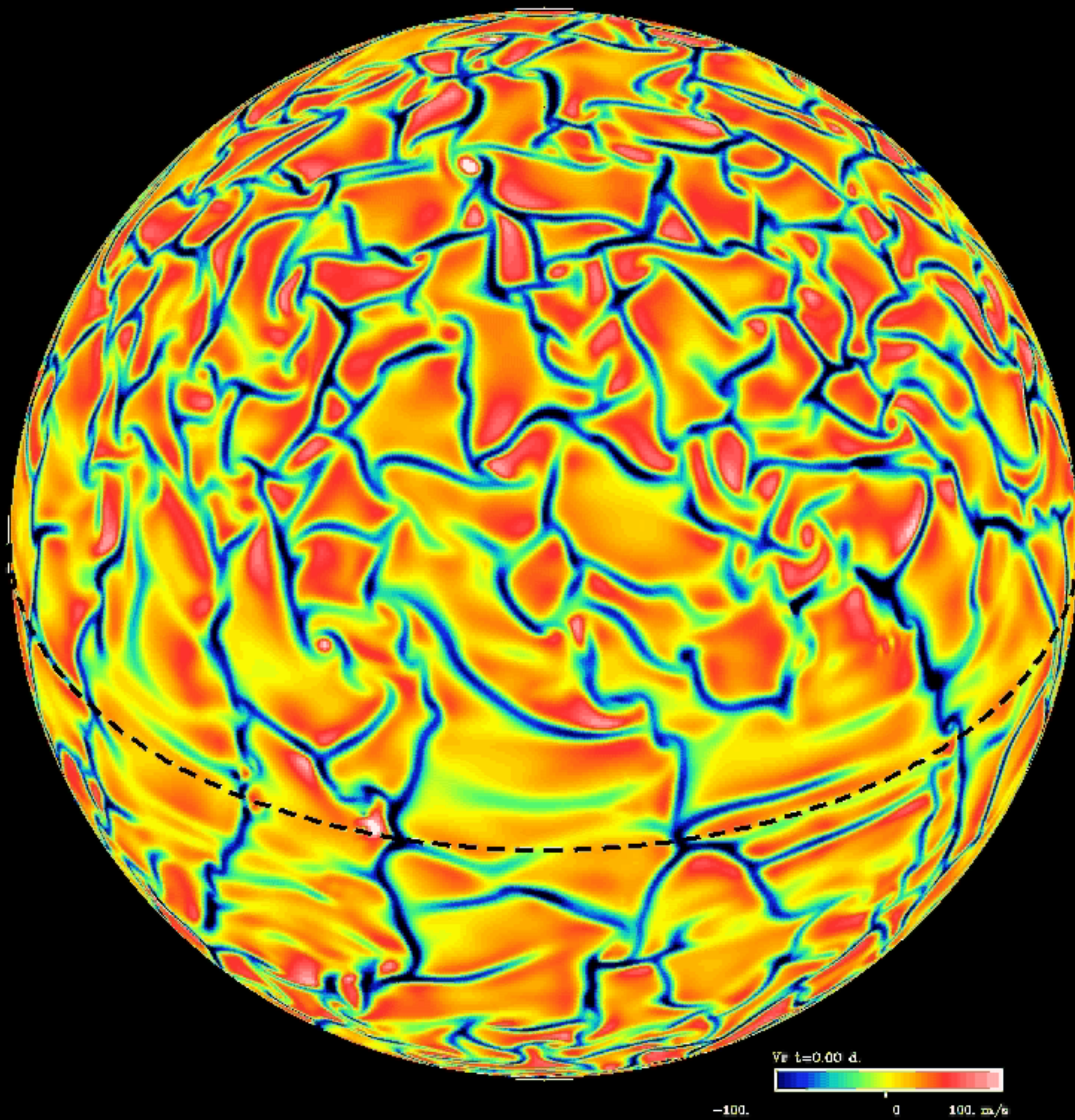
Slow down cycle period:
$P \sim v_0^{-0.35} \eta_t^{-0.4} s_0^{0.05}$

Jouve & Brun, 2007 A&A, 474, 239

Convective Motions in a Spherical Shell

Resolution~ 1000^3
Re=VrmsD/**n~**800
Pr=0.25

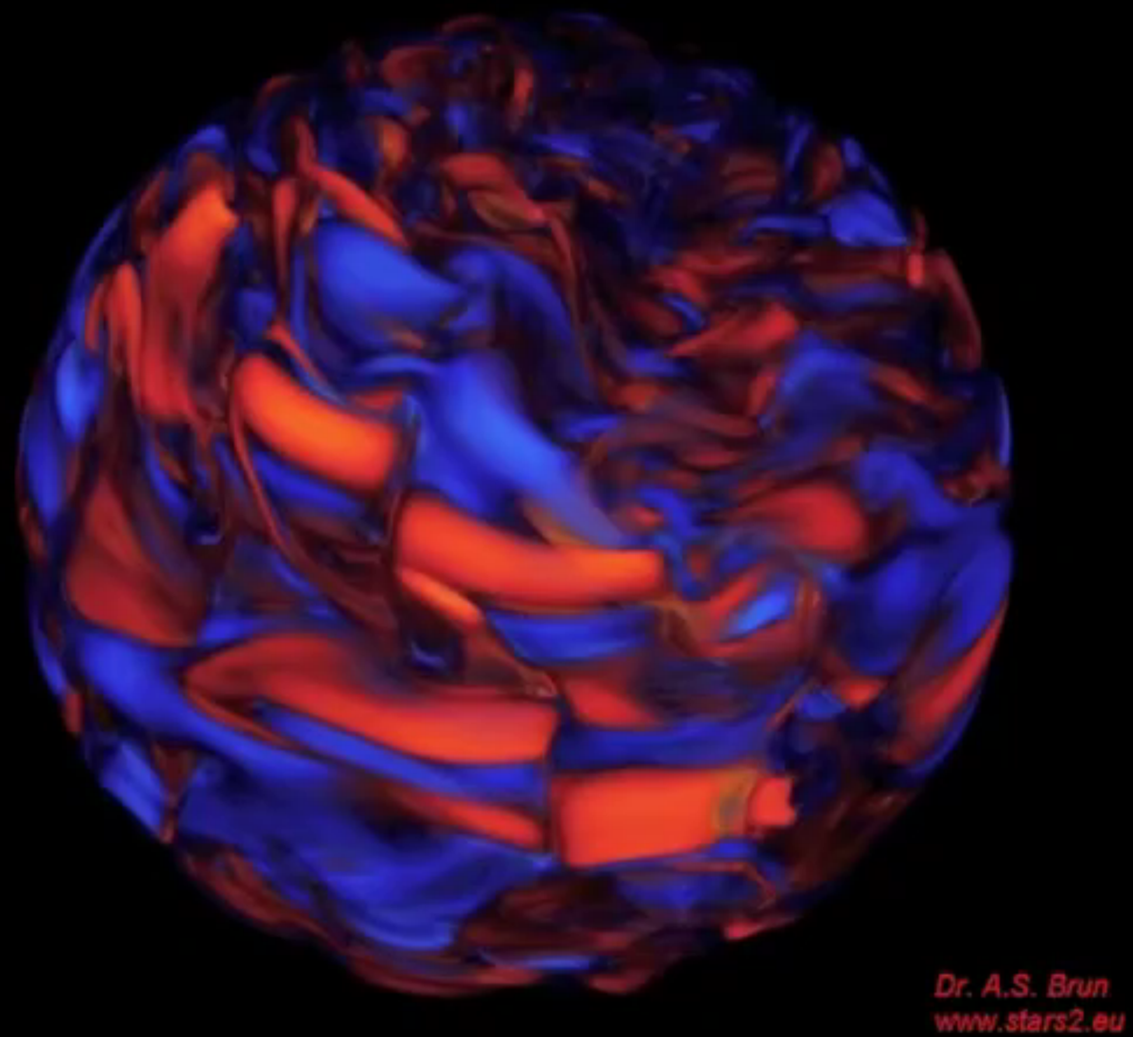
depth=0.96 R



(Brun & Toomre,
2002, ApJ, 570, 865
Miesch et al. 2008, ApJ)

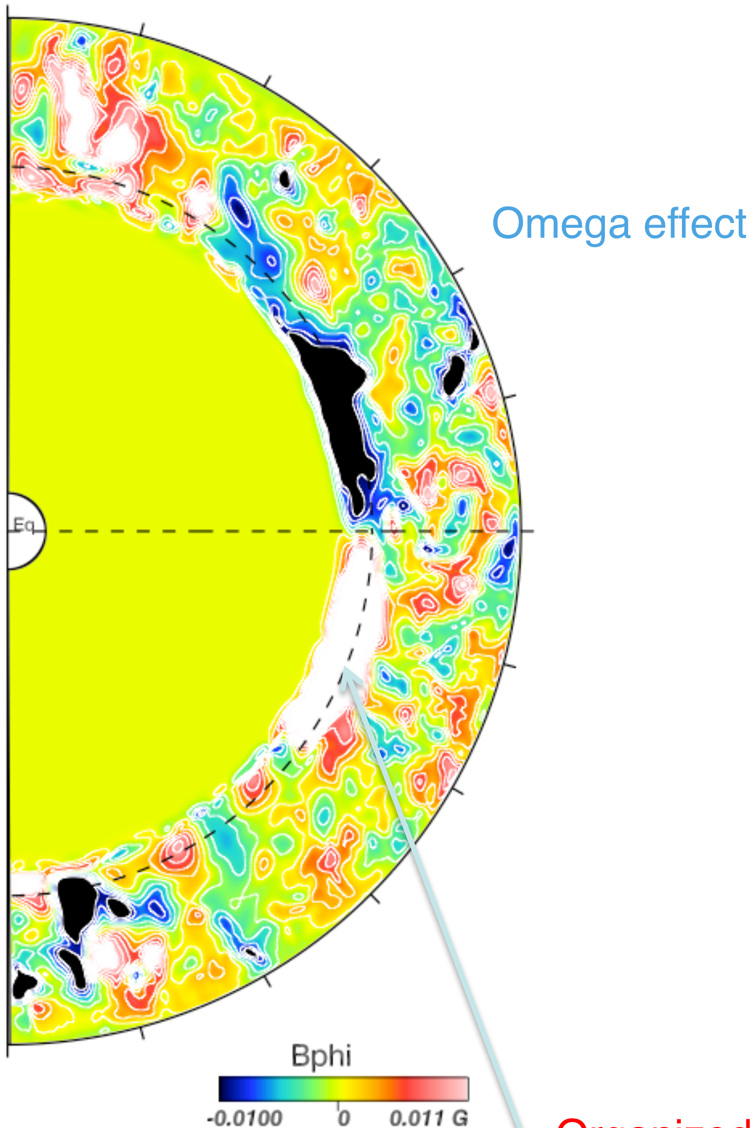
Remember Hotta's talk

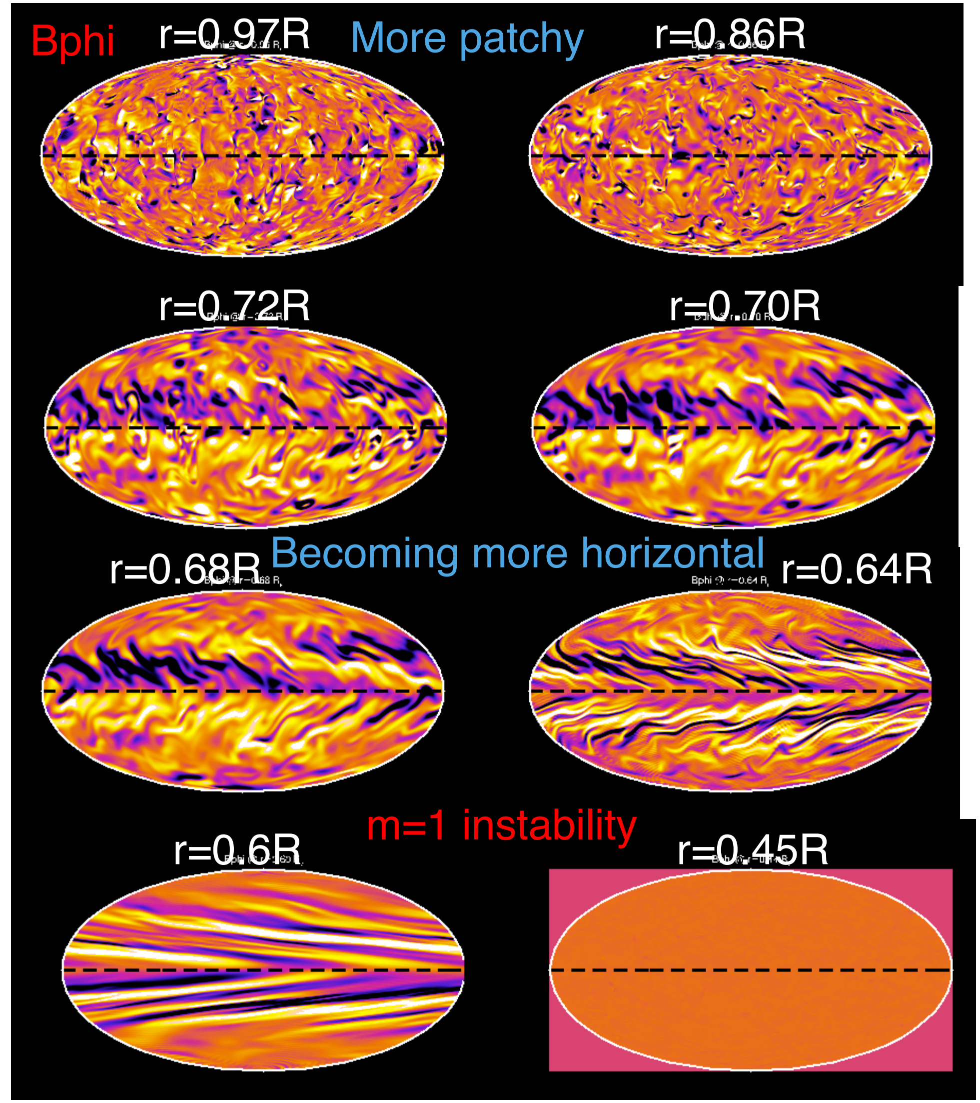
3-D Nonlinear Convective Dynamo
(adding B seed field and letting it grow)



see also Browning et al. 2006, Brown et al. 2011, Racine et al. 2011, Kapyla et al 2013

Dynamo Action in Whole Sun Models





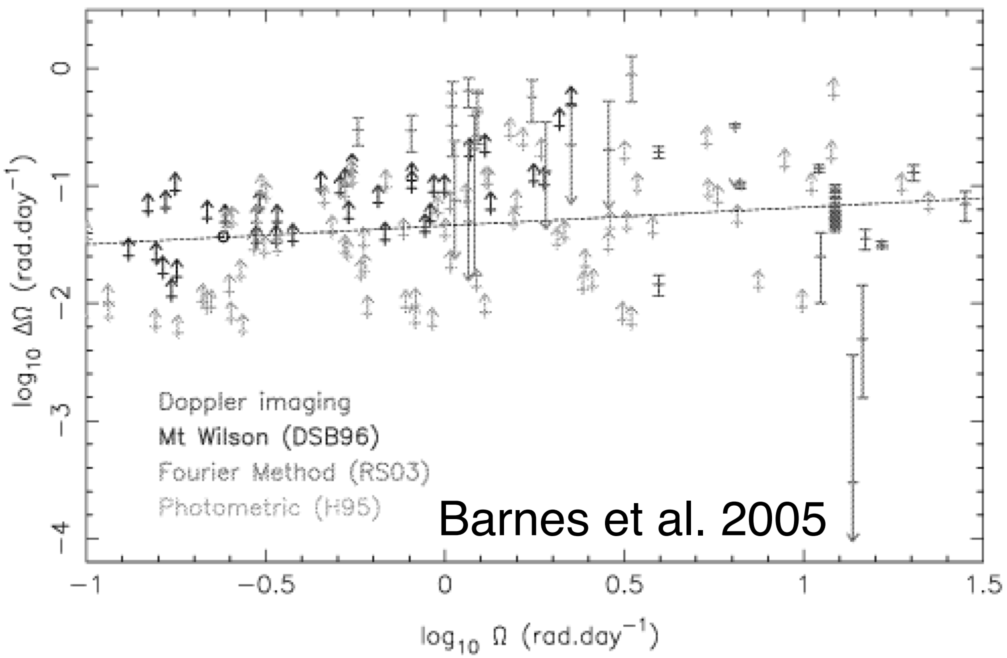
Organized (antisymmetric) magnetic layer in formation
But field highly non axisym in CZ and dominated by m=1 @ bcz

Solar-Stellar connection

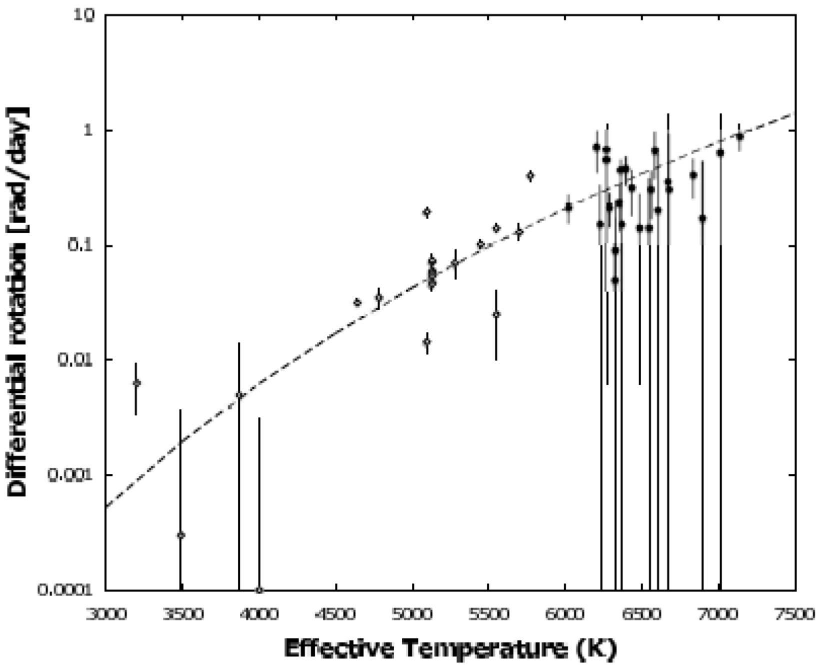
- Convection
- Differential Rotation & Meridional Circulation
- Dynamo and cycles – Spot-dynamo

Trends in Differential Rotation with Ω & Mass (Teff)

Weak trend with Ω



ΔΩ increases with M_*

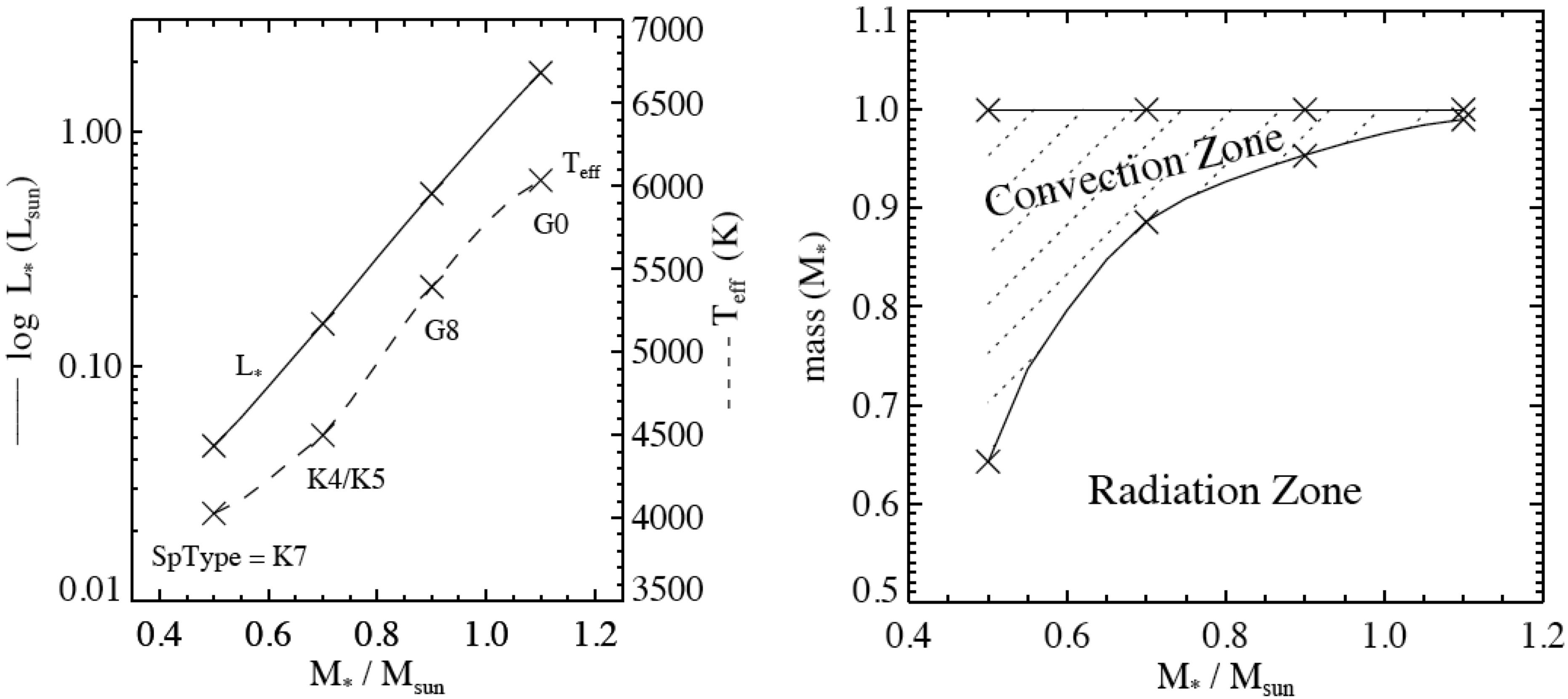


Collier-Cameron 2007

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

Confirming these observational scaling is key

Our G & K star Models

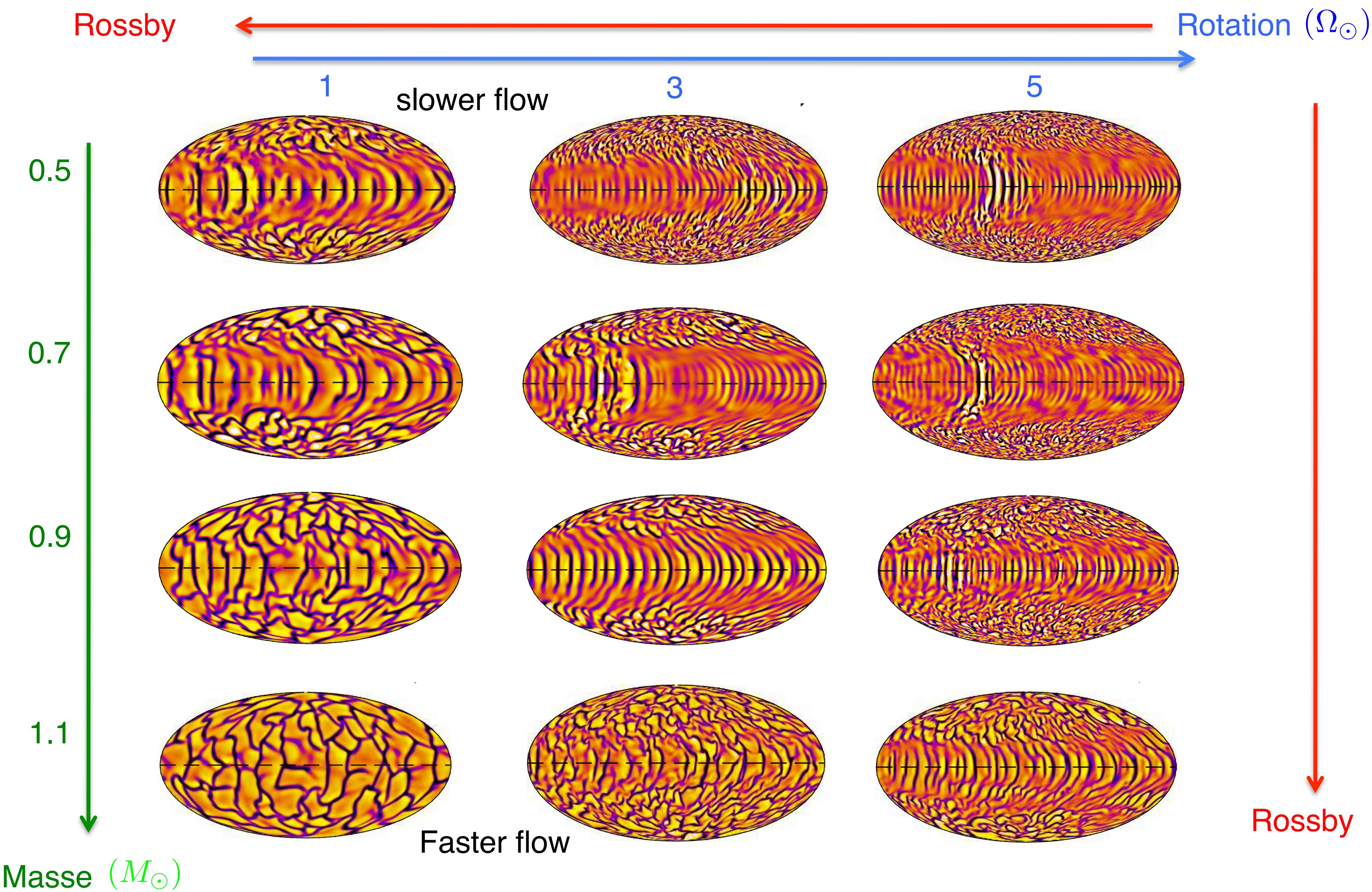


Mass ($M_\odot$)	Radius ($R_\odot$)	L_* ($L_\odot$)	$T_{\rm eff}$ (K)	SpT	$M_{\rm cz}$ ($M_\odot$, M_*)	$R_{\rm cz}$ ($R_\odot$, R_*)
0.5	0.44	0.046	4030	K7	0.18, 0.36	0.25, 0.56
0.7	0.64	0.15	4500	K4/K5	0.079, 0.11	0.42, 0.66
0.9	0.85	0.55	5390	G8	0.042, 0.046	0.59, 0.69
1.1	1.23	1.79	6030	G0	0.011, 0.0100	0.92, 0.75

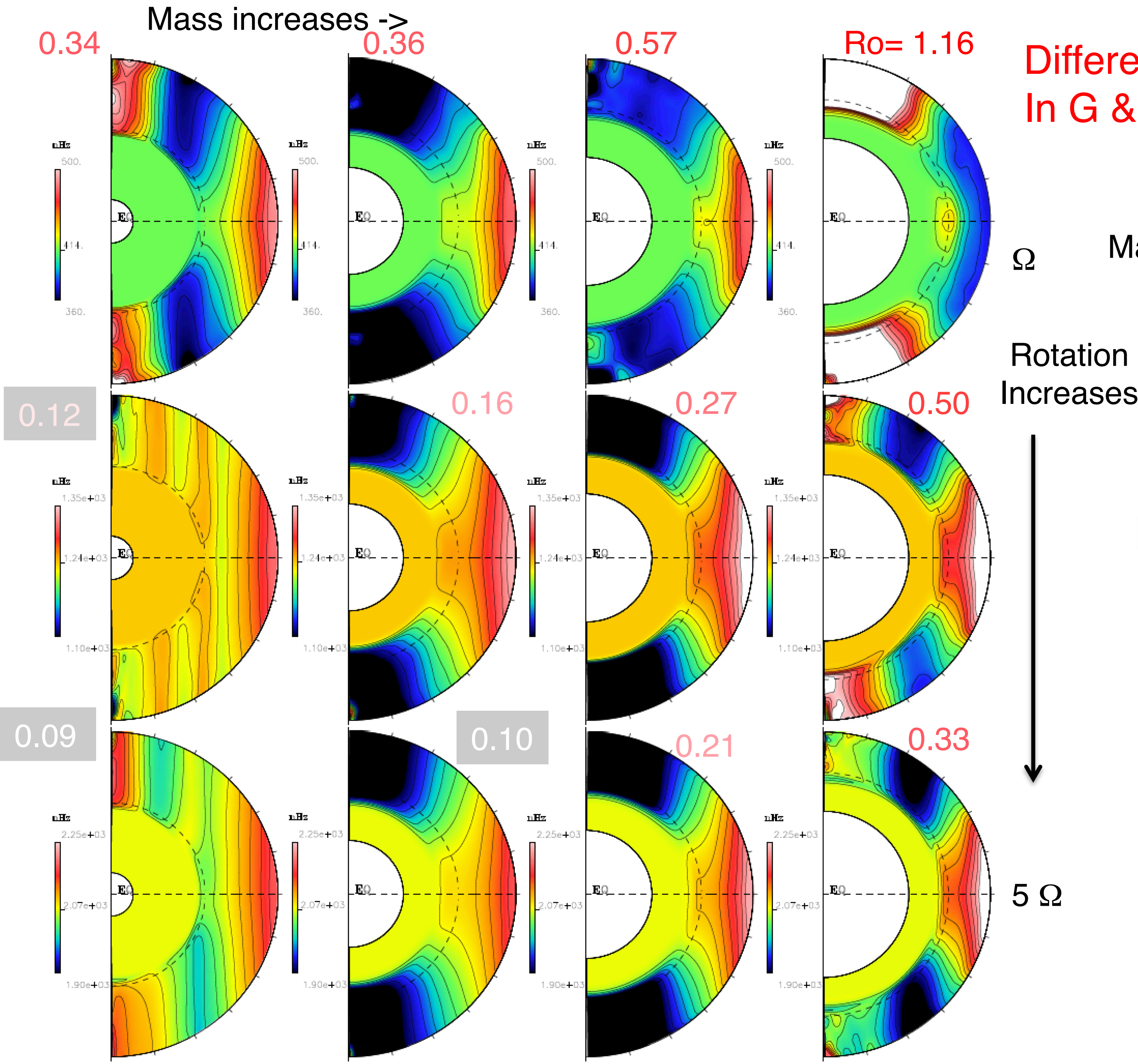
Matt et al. 2011, 2013

Effect of Rotation on Convection

Matt, DoCao, Brun et al. 2011, 2013



Differential Rotation In G & K stars



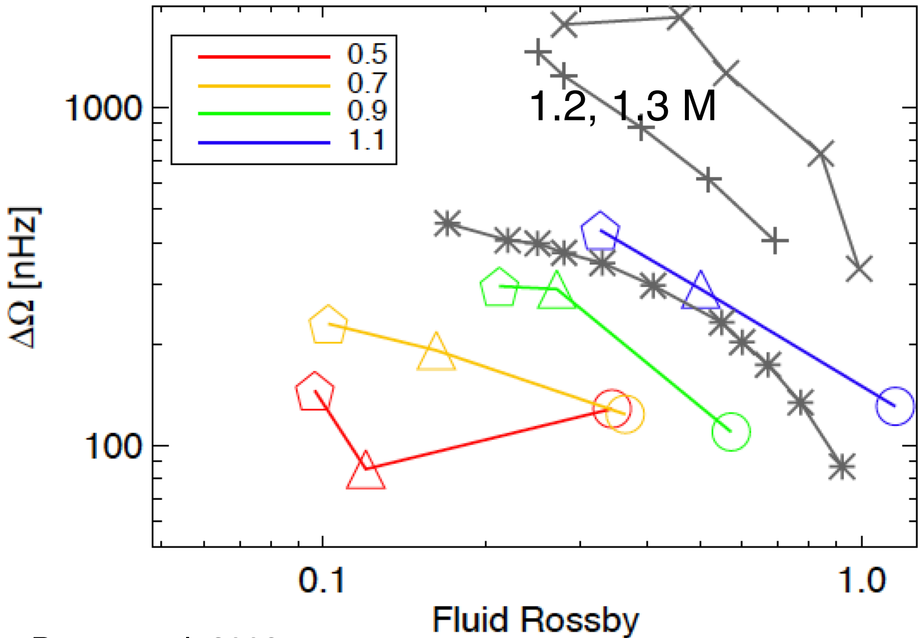
Matt et al. 2011, 2013

Rossby nb

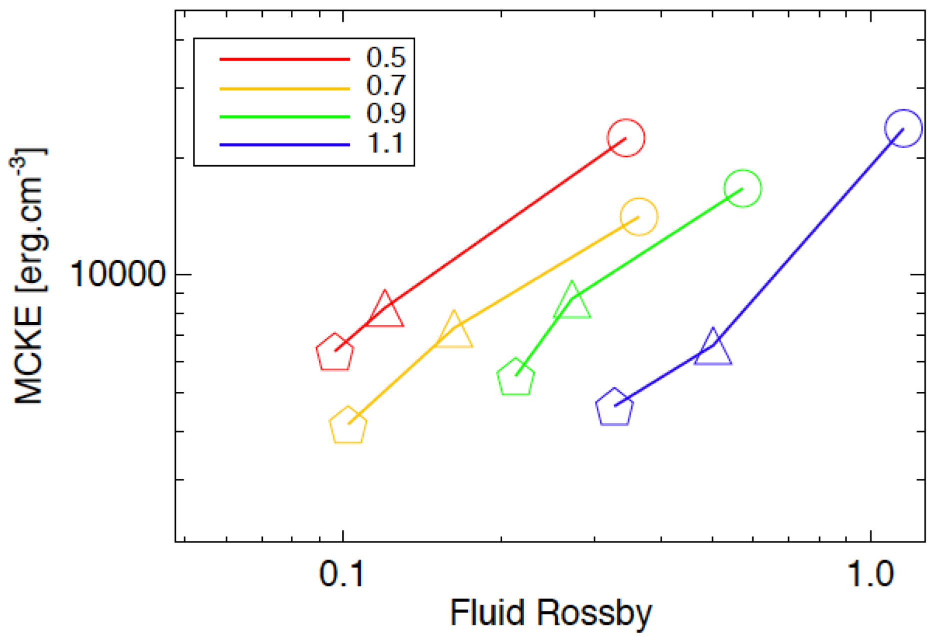
$Ro=\omega/2\Omega_*$

Recovering Scaling Law for ΔΩ & Meridional Flows

Smaller ΔΩ with smaller Mass,
Larger ΔΩ with faster rotation



Weaker flow for faster rotating stars



Brown et al. 2008
Augustson et al. 2012

$$\Delta\Omega = 156.0\ \mathrm{nHz}\left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^{1.0}\left(\frac{\Omega_0}{\Omega_\odot}\right)^{0.47}$$

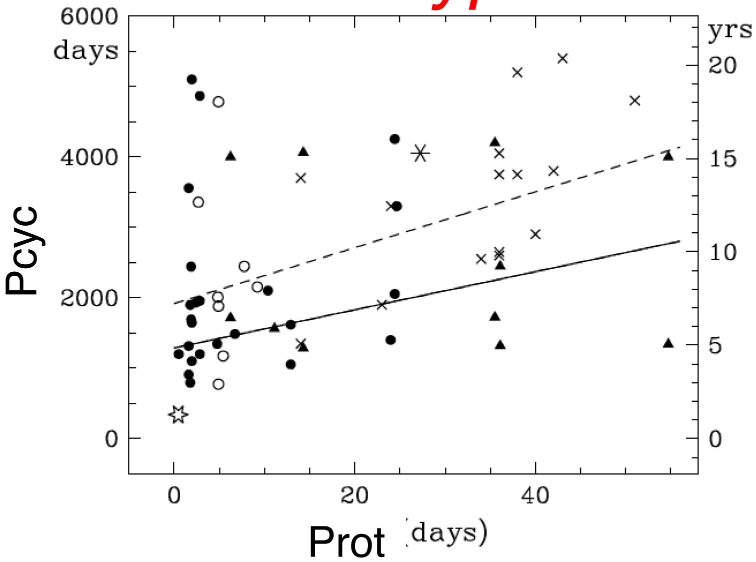
$$= 150.3\ \mathrm{nHz}\left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^{1.85}\mathrm{R}_{\mathrm{of}}^{-0.52}$$

$$\mathrm{MCKE} = 1.8\times10^4\ \mathrm{erg.cm}^{-3}\left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^{-0.14}\left(\frac{\Omega_0}{\Omega_\odot}\right)^{-0.8}$$

$$= 2.1\times10^4\ \mathrm{erg.cm}^{-3}\left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^{-1.8}\mathrm{R}_{\mathrm{of}}^{1.0}$$

Matt, Brun et al. 2011, 2013

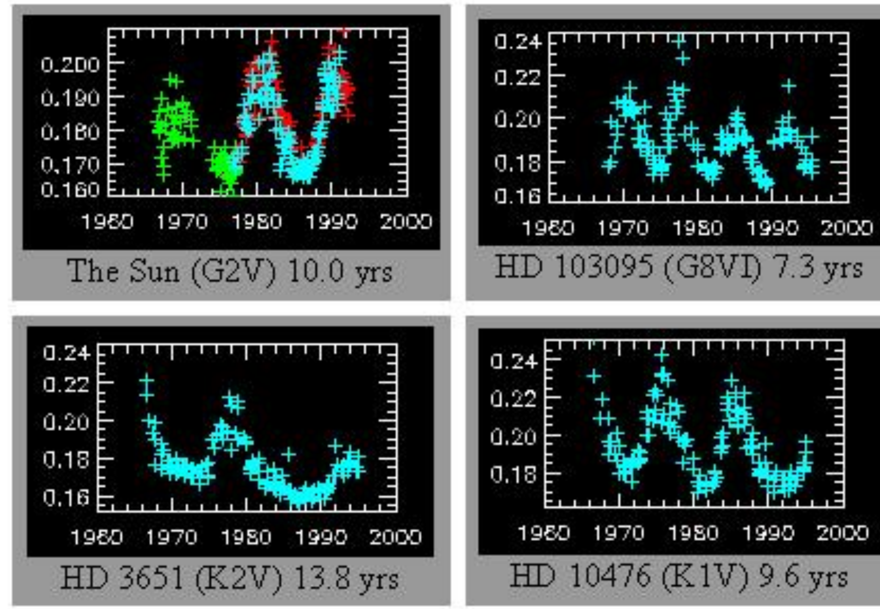
Solar Type Stars (late F, G and early K-type)



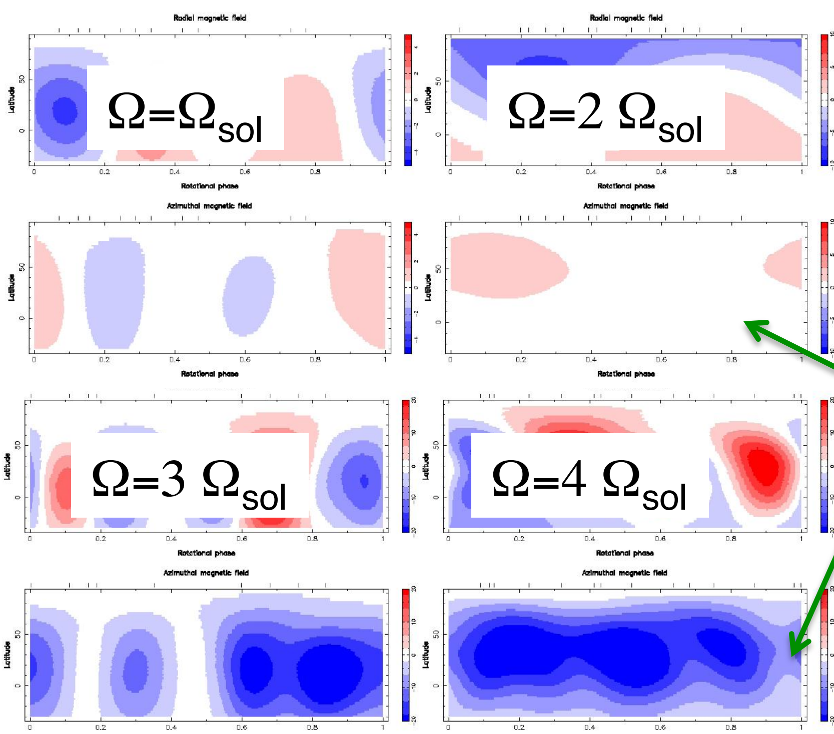
Olah et al. 2009

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

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



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



Toroidal field stronger vs Ω

Petit et al. 2008

Over 111 stars in HK project (F2-M2):

51 + Sun possess magnetic cycle

More coming in Asteroseismology Era

Noyes et al. 1984, Wilson 1978, Baliunas et al. 1995

Few Points We Must Address

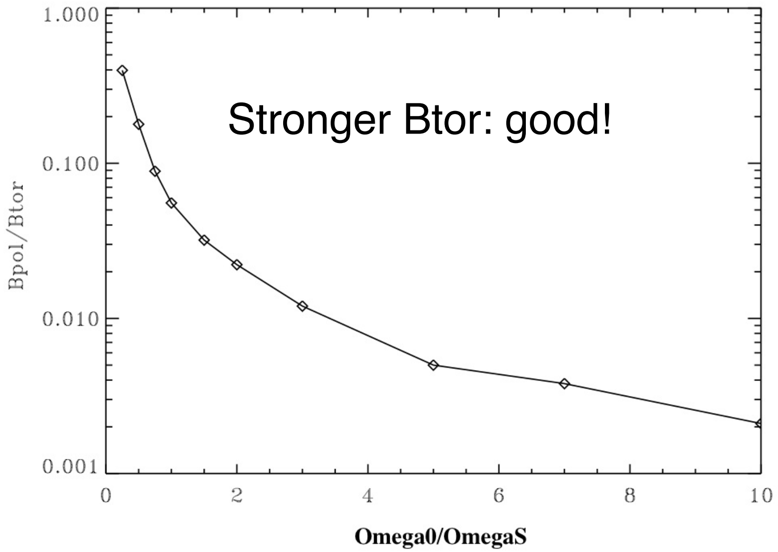
- Source of variability (chaos, intermittency,…)
- Can we reproduce the trend $P_{cyc} \sim P_{rot}^{n}$ (n ~1+/-0.2)
- Can we reproduce the increase of the toroidal vs poloidal component
- Which « solar model» is best to explain stellar data?

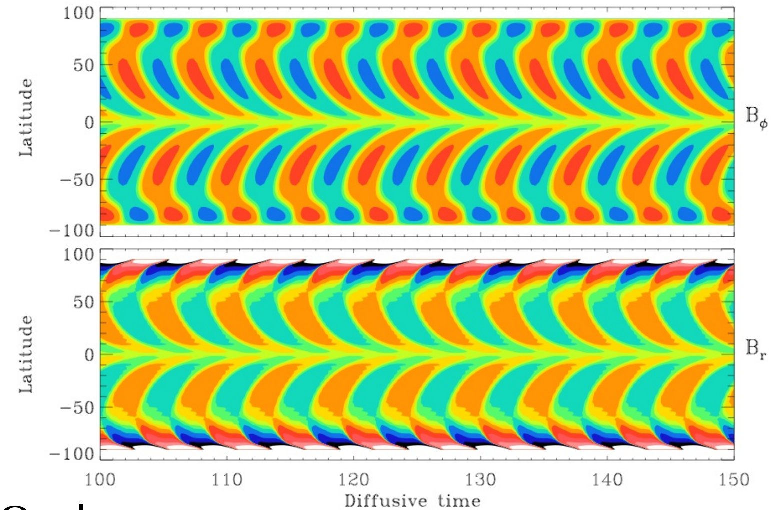
BL mean field models

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

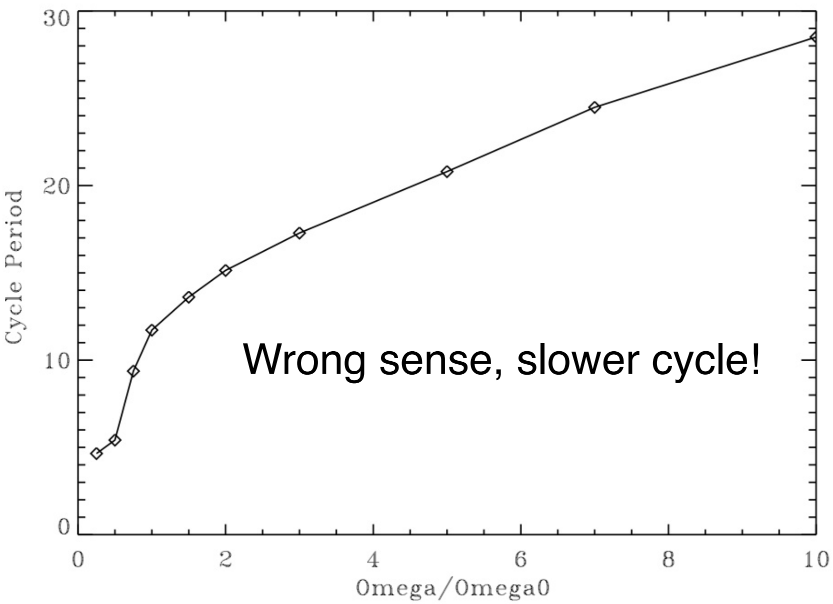
Strong dependancy on meridional flow amplitude

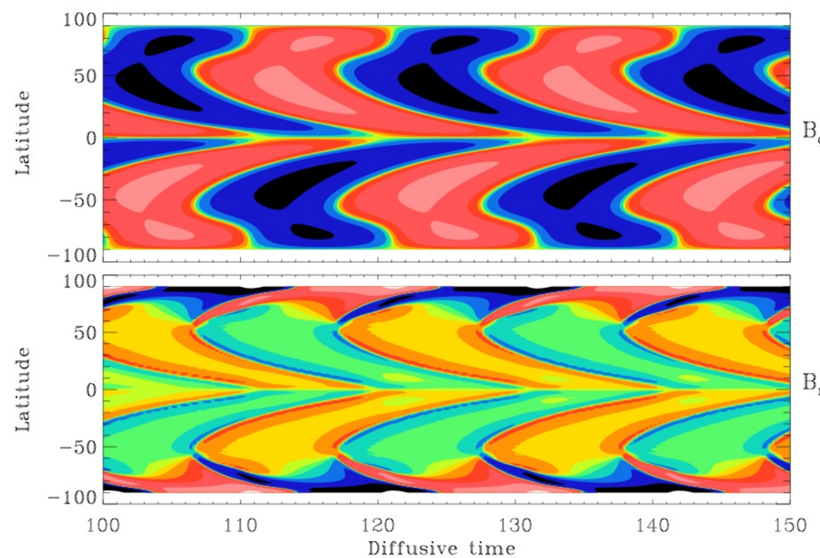
Testing Babcock-Leighton Models with Stellar Magnetism Data





0.5 Ωsol



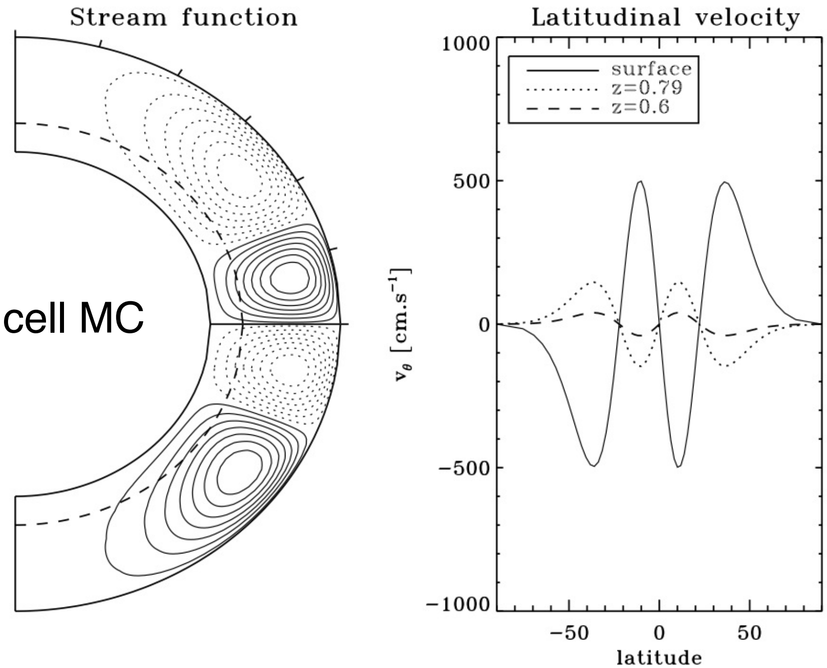


5 Ωsol

Pcyc = 20 yr!

Jouve, Brown, Brun, A&A 2010

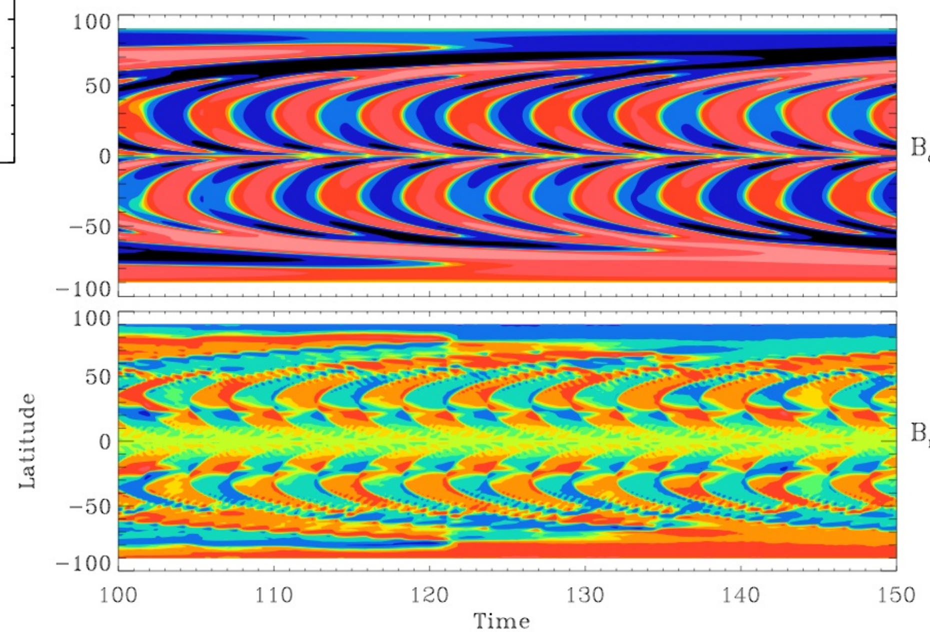
Testing Babcock-Leighton Models with Stellar Magnetism Data



Multi cell MC

We have seen in the solar case that MC profile greatly influences the cycle and butterfly diagram. Can we reconcile stellar data with more complex MC?

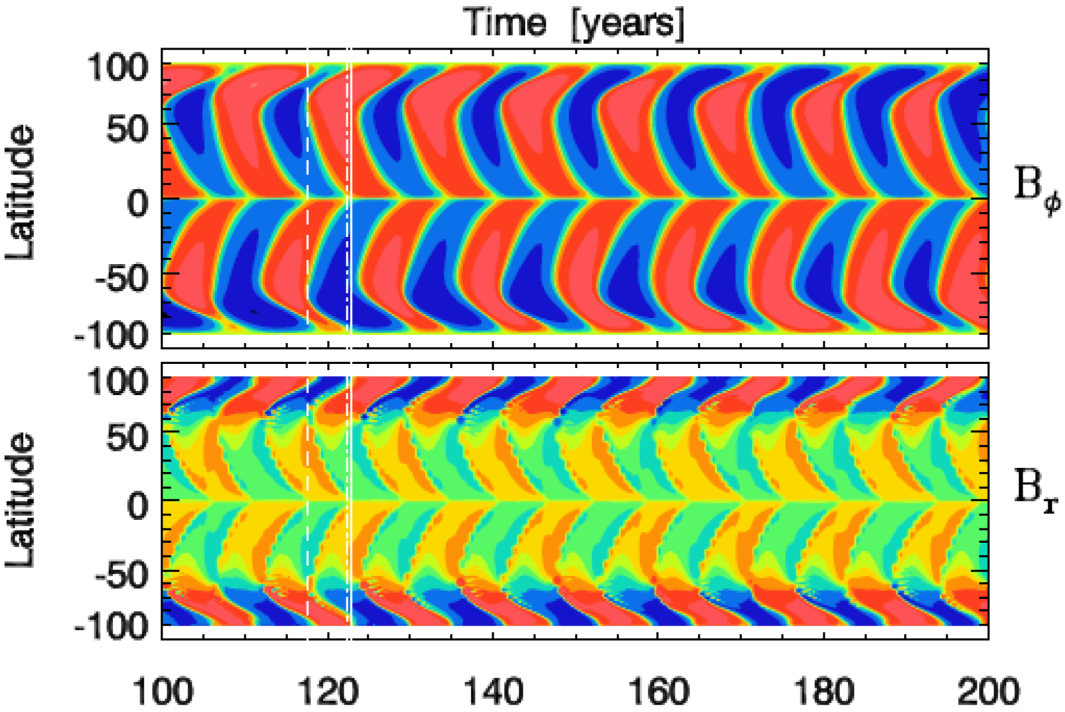
Pcyc = 5.2 yr !!!! success



See also talk
C. Dubé

Jouve, Brown, Brun, A&A 2010

5 Ωsol

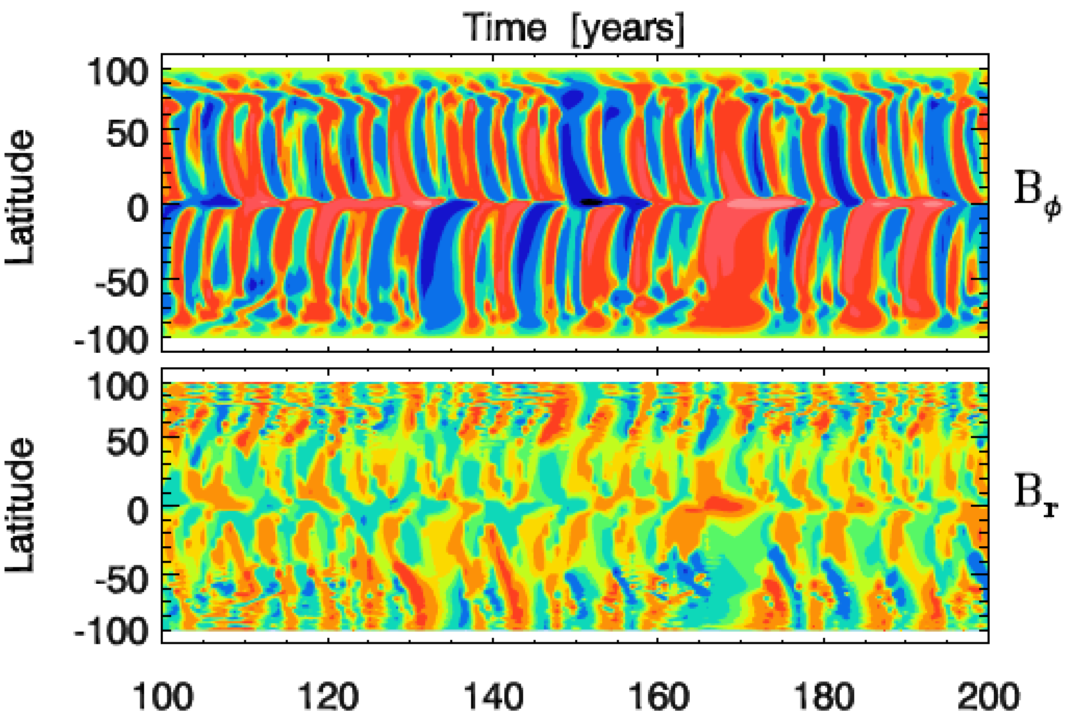


Another Option to make cycle faster:
Turbulent Pumping

$\Omega = \Omega_{sol}$

DoCao & Brun 2011

$$P_{\rm cyc} \propto v_0^{-0.40} \gamma_{r0}^{-0.30} \gamma_{\theta 0}^{-0.15}$$



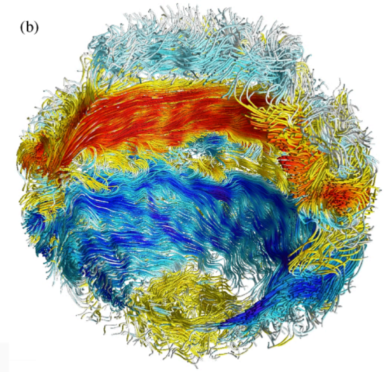
More irregular Butterfly diagram
due to offset of conveyor belt

$\Omega = 5\ \Omega_{sol}$

See also Guerrero et al. 2008

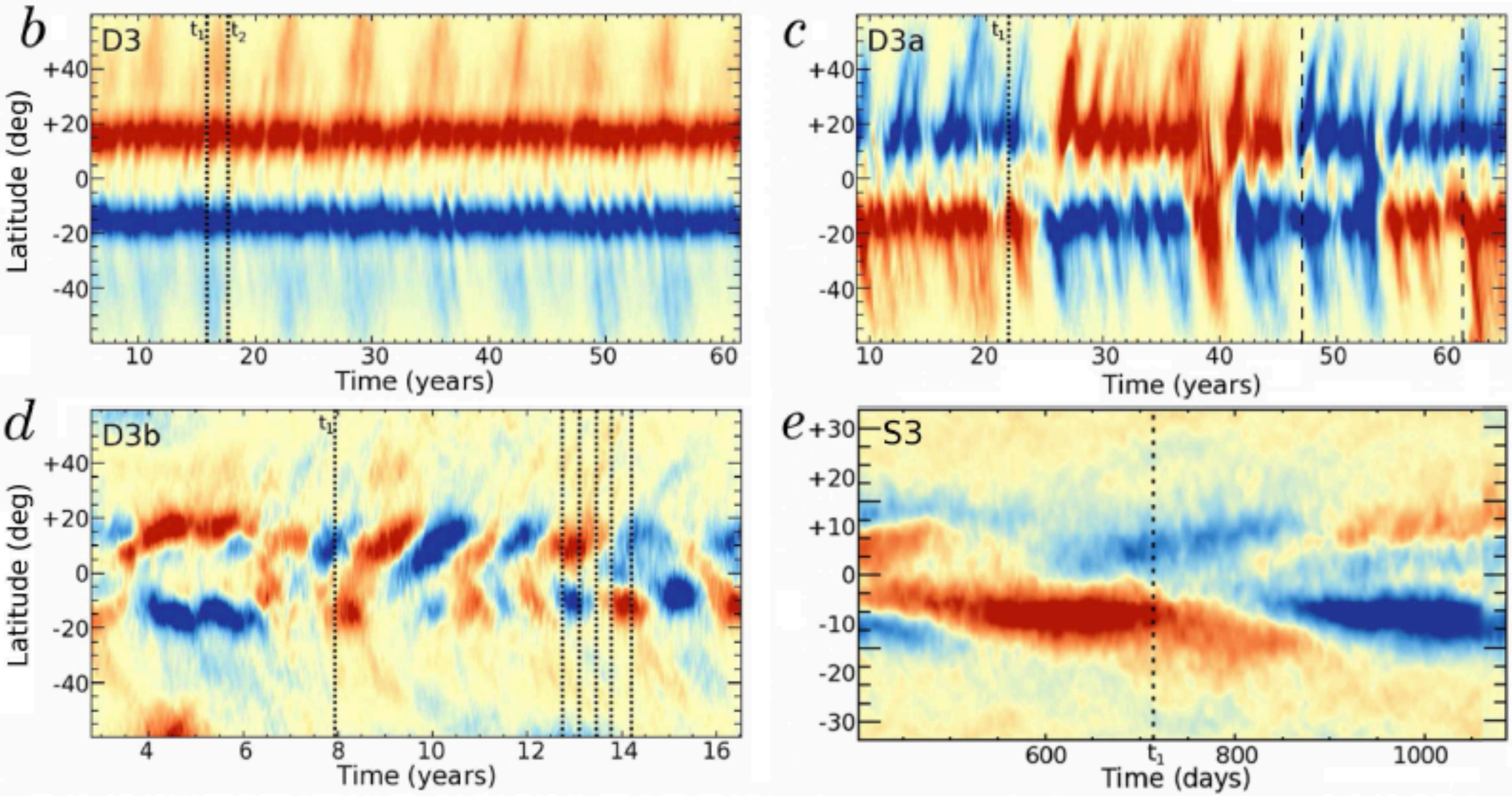
3-D stellar dynamo models:

Decreasing Magnetic Diffusion yields Cyclic Activity



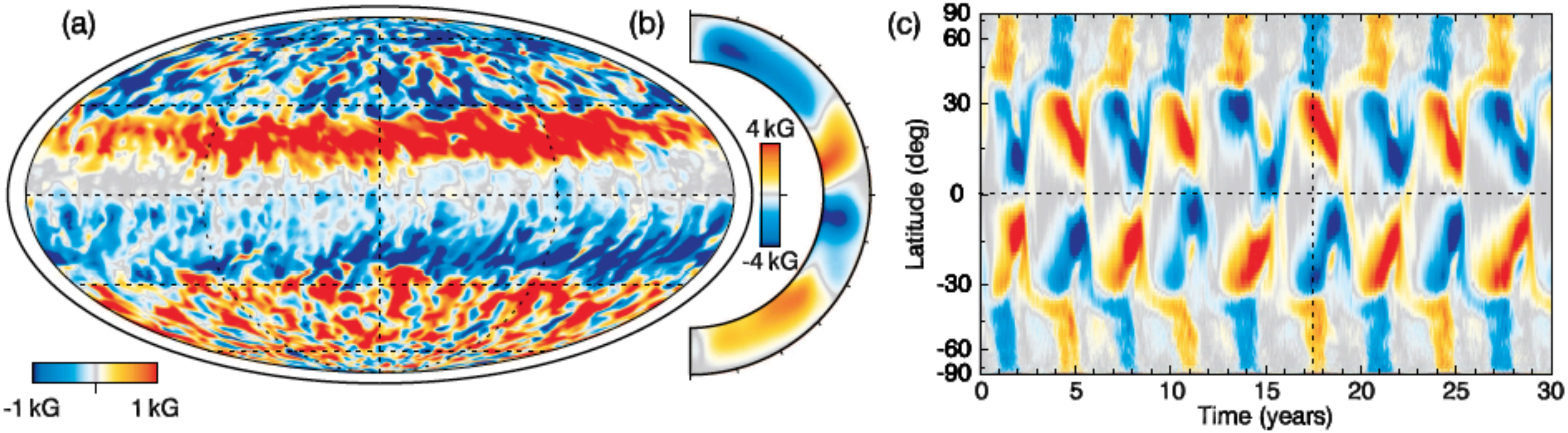
Butterfly diagrams (time-latitude plots of Bphi)

More diffusive case



Less diffusive case

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

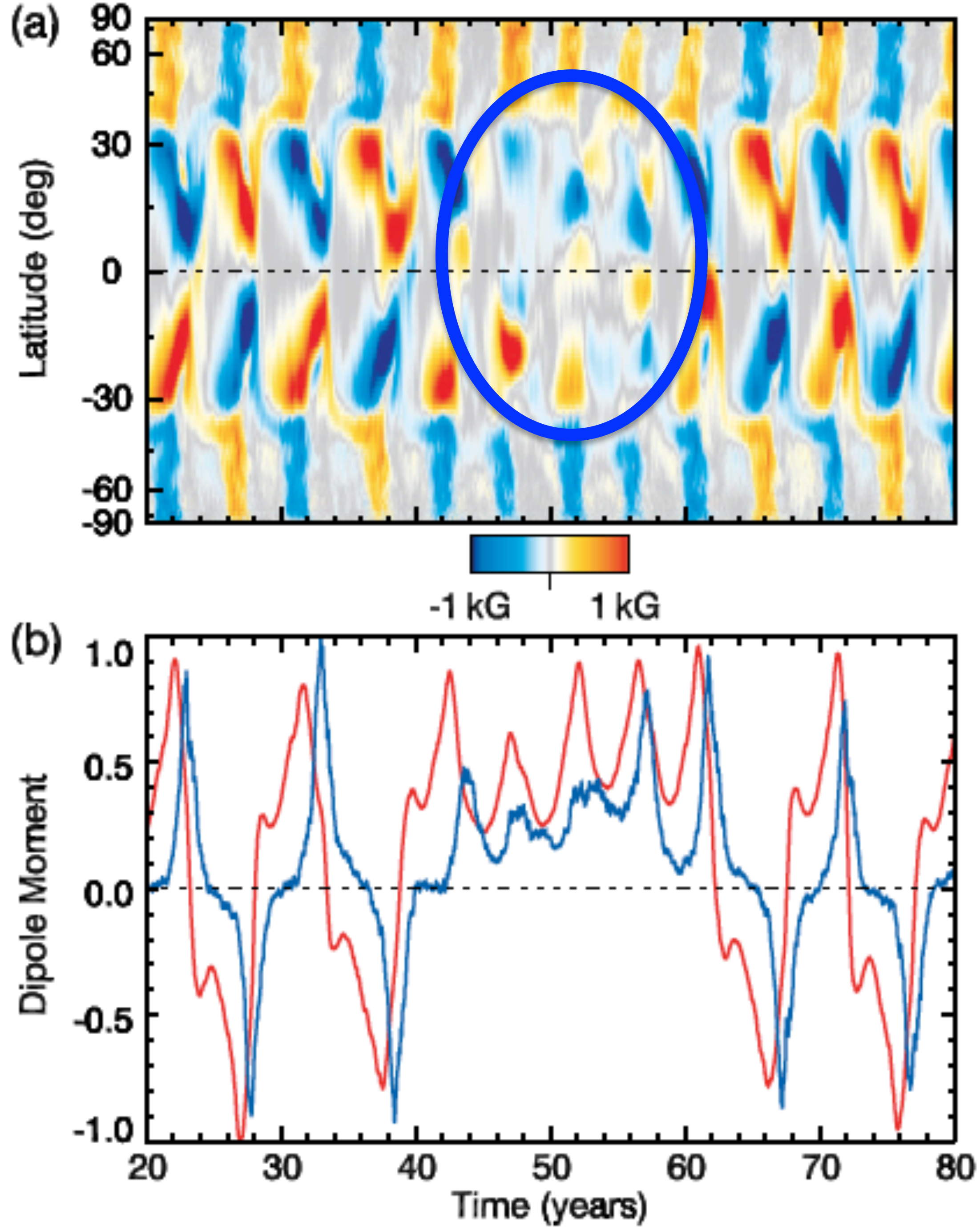


Reducing nu even further by using SLD scheme makes the simulation develop a more regular cyclic behavior

Augustson, Brun et al. 2013, ApJL, submitted

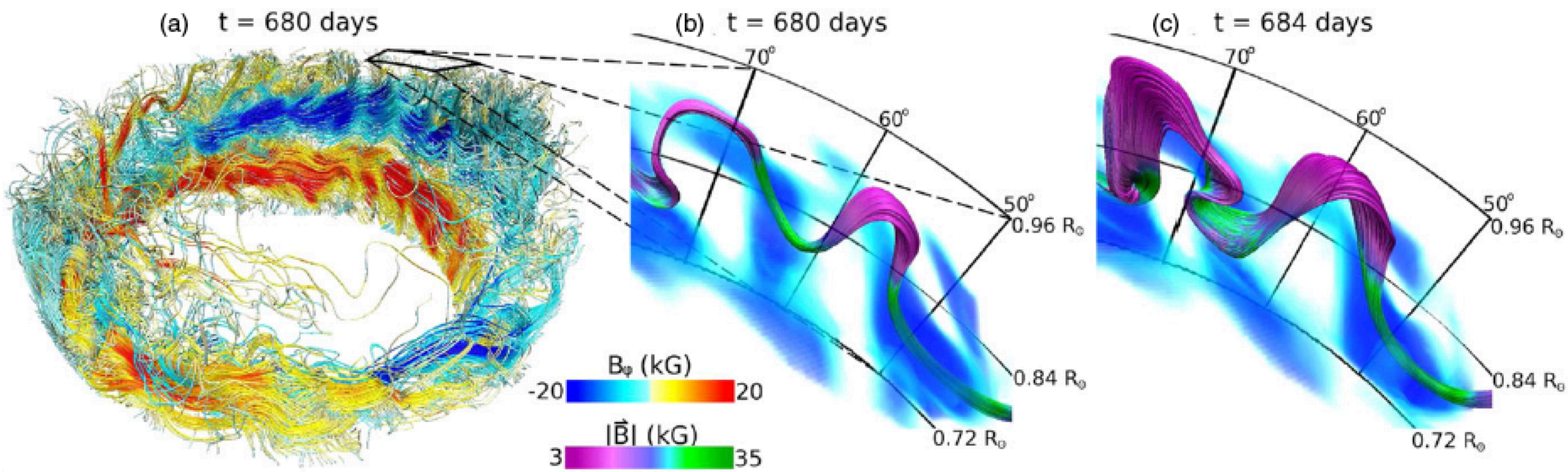
Latest solar-like case DS3:
Getting Maunder like minimun

Augustson, Brun et al. 2013, ApJL



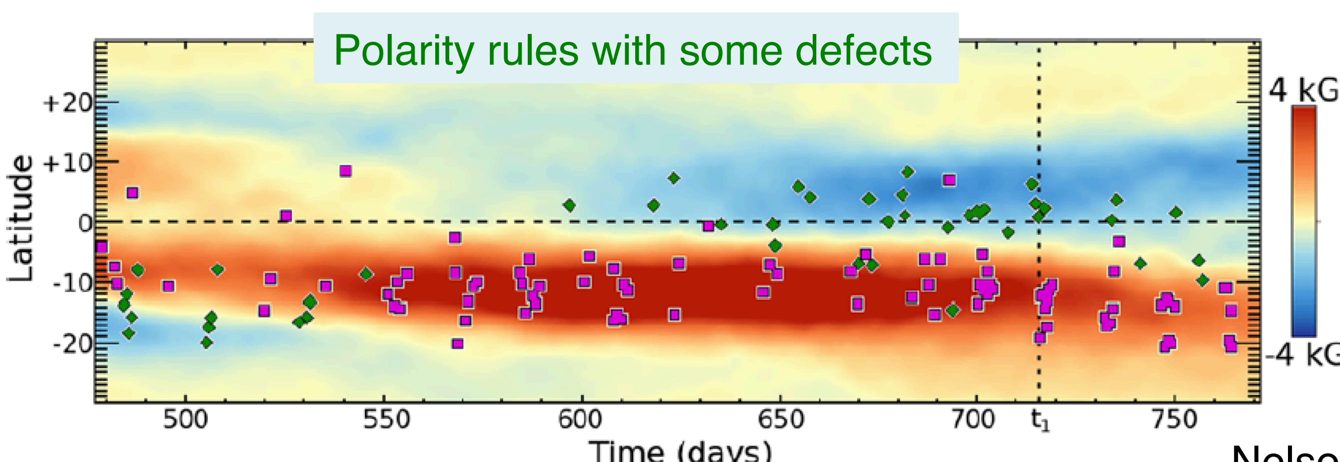
Quadrupole dominates over Dipole during reversal and Grand minimum phase as in the Sun and Earth
(Derosa, Brun, Hoeksema 2012)

Wreaths can generate Buoyant Loops



Case S3

Towards getting first "spot-dynamos"…
Brun et al. 2013, Space Sci. Rev., in press



133 loops

Nelson et al. 2011, 2013a, 2013b

Conclusions

$\Rightarrow$ Standard Babcock-Leigthon dynamo models are in difficulty!
both due to multi-cellular flows structure and with stellar data,
pumping, higher diffusion, different flow required

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

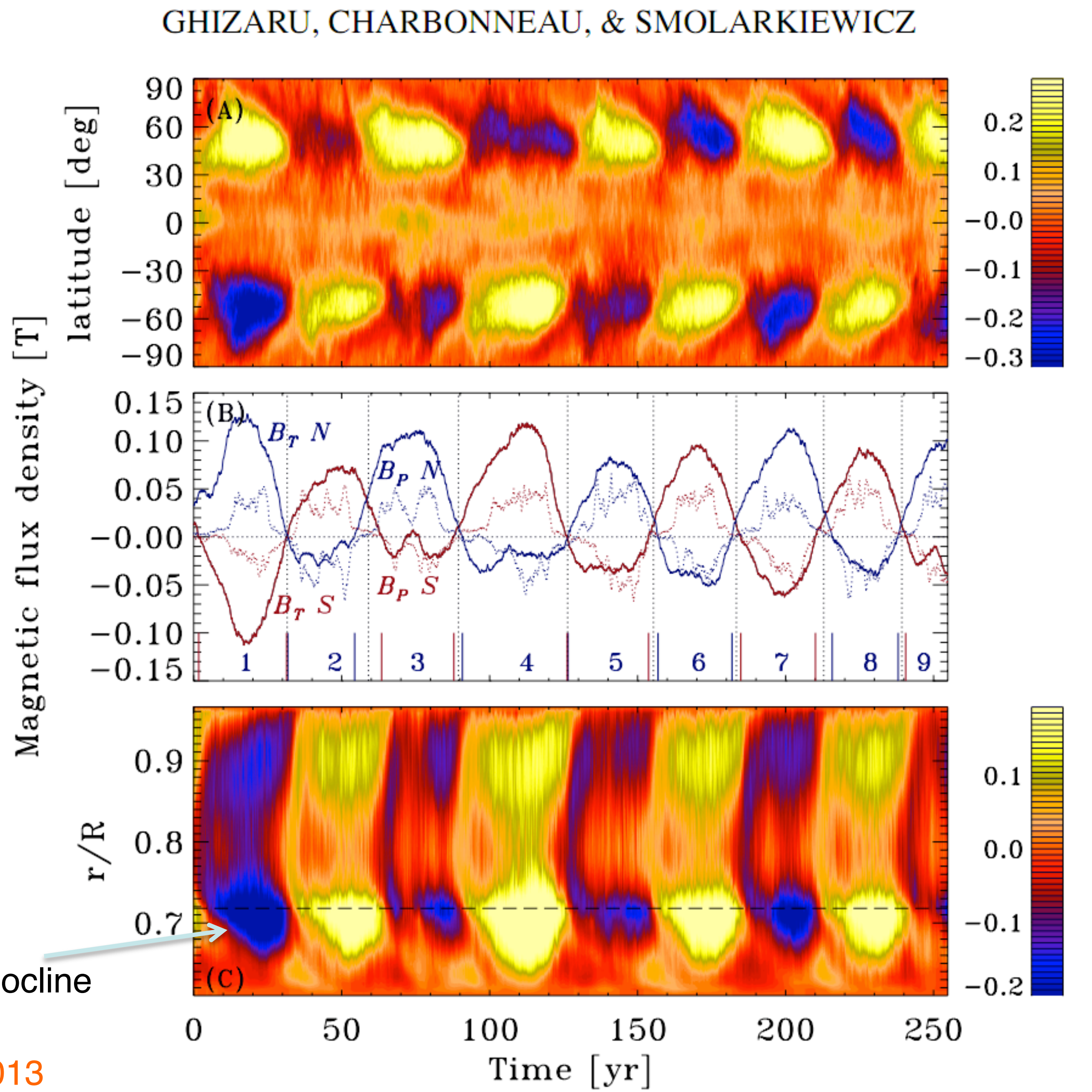
$\Rightarrow$ Self consitent buoyant loops generation possible,
may yield first « Spot-Dynamo »

Getting Cycle
in similar Models

Ghizaru et al. 2010

Model has been run
for several centuries

30 yr period



Turbulent pumping and
shearing in imposed tachocline

See also Masada et al. 2013