What do numerical simulations tell us about solar/stellar dynamos?

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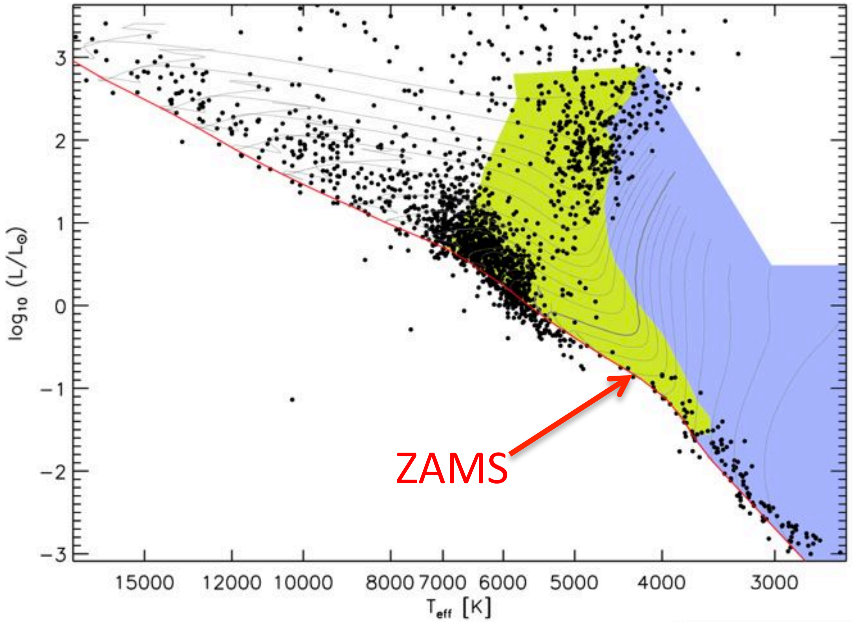
Cool Stars 2016-Uppsala

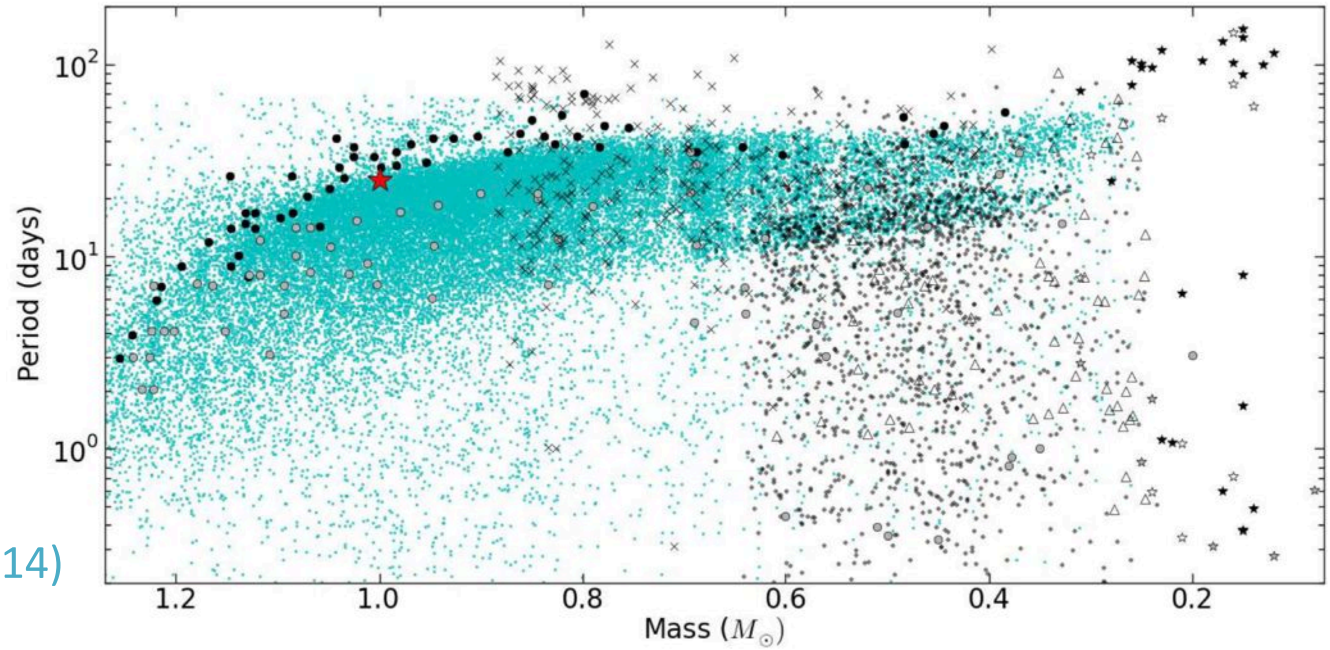
Rotation and convection in cool MS stars



Reiners (2008), Siess et al. (2000)

- On the MS:
  - Fully convective stars below $M_\odot < 0.35$
  - Convective envelope for $0.35 < M_\odot < 1.4$

- Relatively fast rotation but large spread

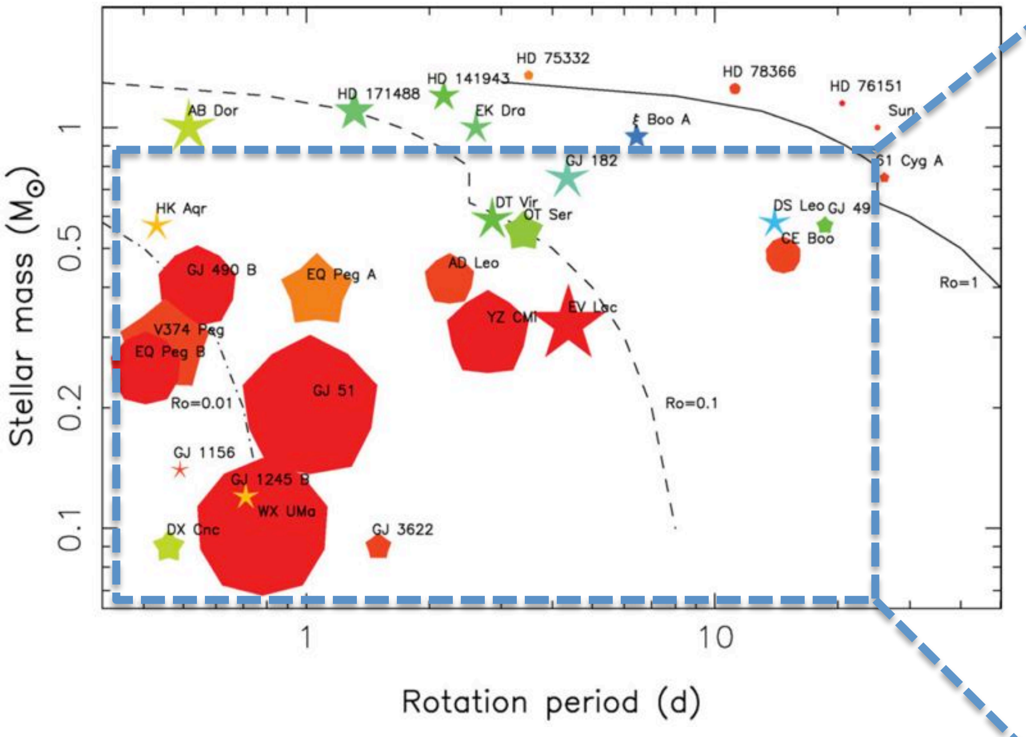


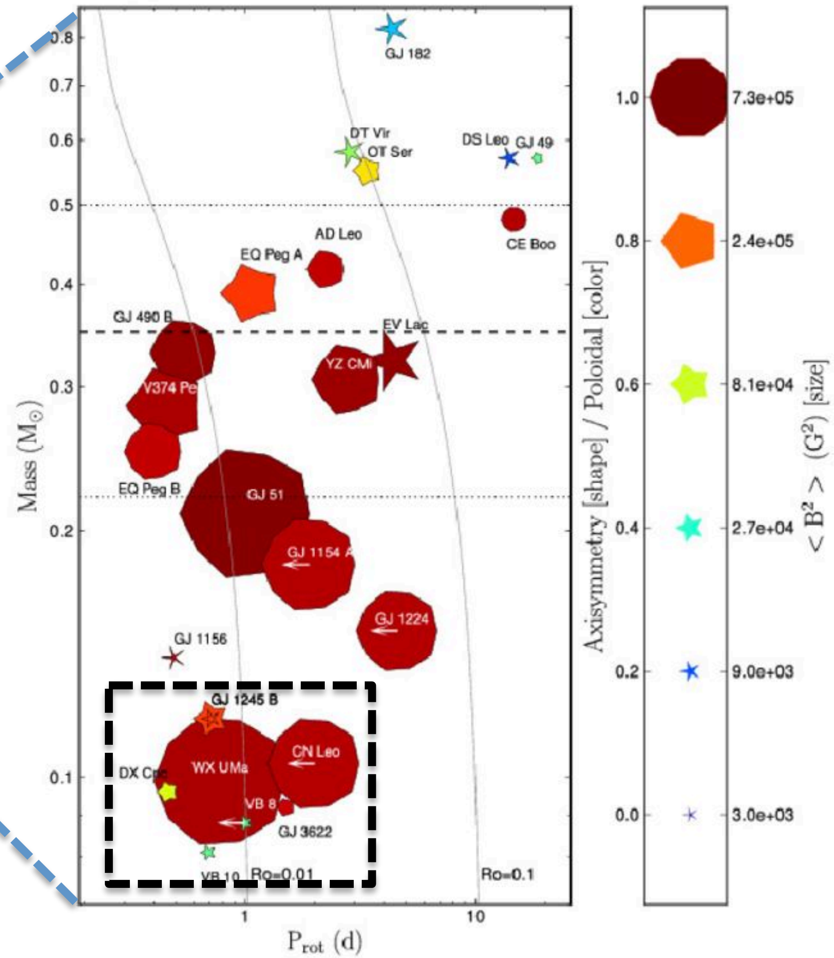
McQuillan et al. (2014)

Magnetic fields in cool MS stars

Morin, Donati et al. (2008-2010)

Donati (2011)



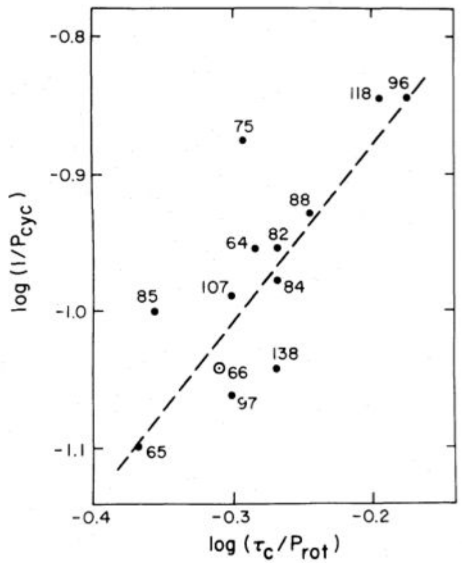


- ❑ Mostly multipolar for $M_\odot > 0.35$
- ❑ Mostly dipolar for $M_\odot < 0.35$
- ❑ Bistability for $M_\odot < 0.2$
- ❑ Field strength increases with rotation
- ❑ More and more toroidal with rotation

Petit et al. 2008, S. Marsden's talk

Observations of magnetic cycles?

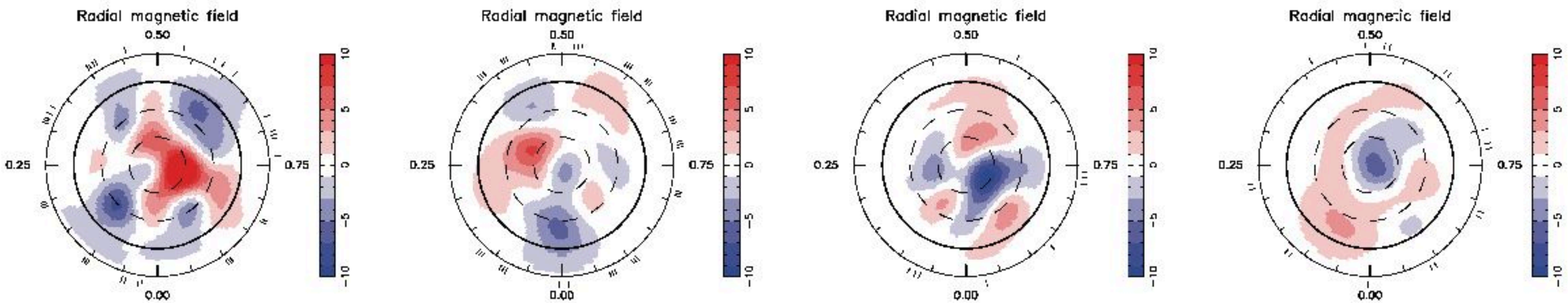
Noyes et al. 1984



Chromospheric activity (Mount Wilson data, Ca II HK lines):
$P_{cyc}=(1/Ro)^{1.28+/-0.48}$

where the Rossby number $Ro=P_{rot}/\tau$

Donati et al 2008, Fares et al 2009, Mengel et al 2016: τ boo: 2 years



Petit et al 2009, Morgenthaler et al 2011: HD 190771 (complex variability)

Garcia et al 2010: HD 49933: 120 days?

Boro-Saika et al 2016: HD 201091: 14 years

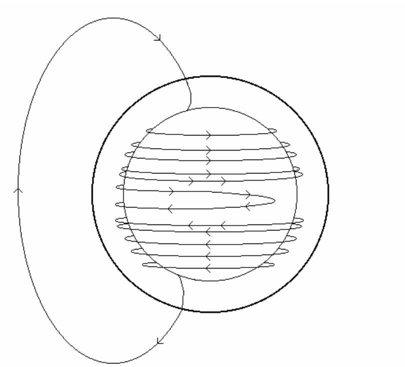
Main physical ingredients to the generation and transport of magnetic fields

Dynamo mechanism: process through which motions of a conducting fluid can permanently regenerate and maintain a magnetic field against its ohmic dissipation

It consists of the regeneration of both poloidal and toroidal fields

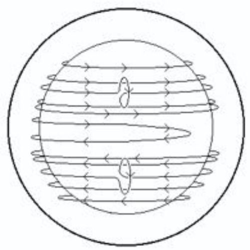
Sources of magnetic field

Poloidal → Toroidal

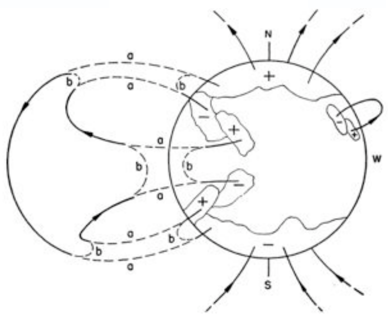


✓ Ω effect

Toroidal → Poloidal



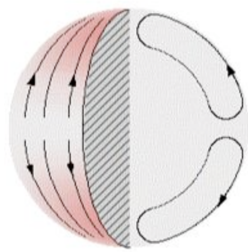
✓ α effect



✓ Babcock-Leighton effect

Transport of magnetic field

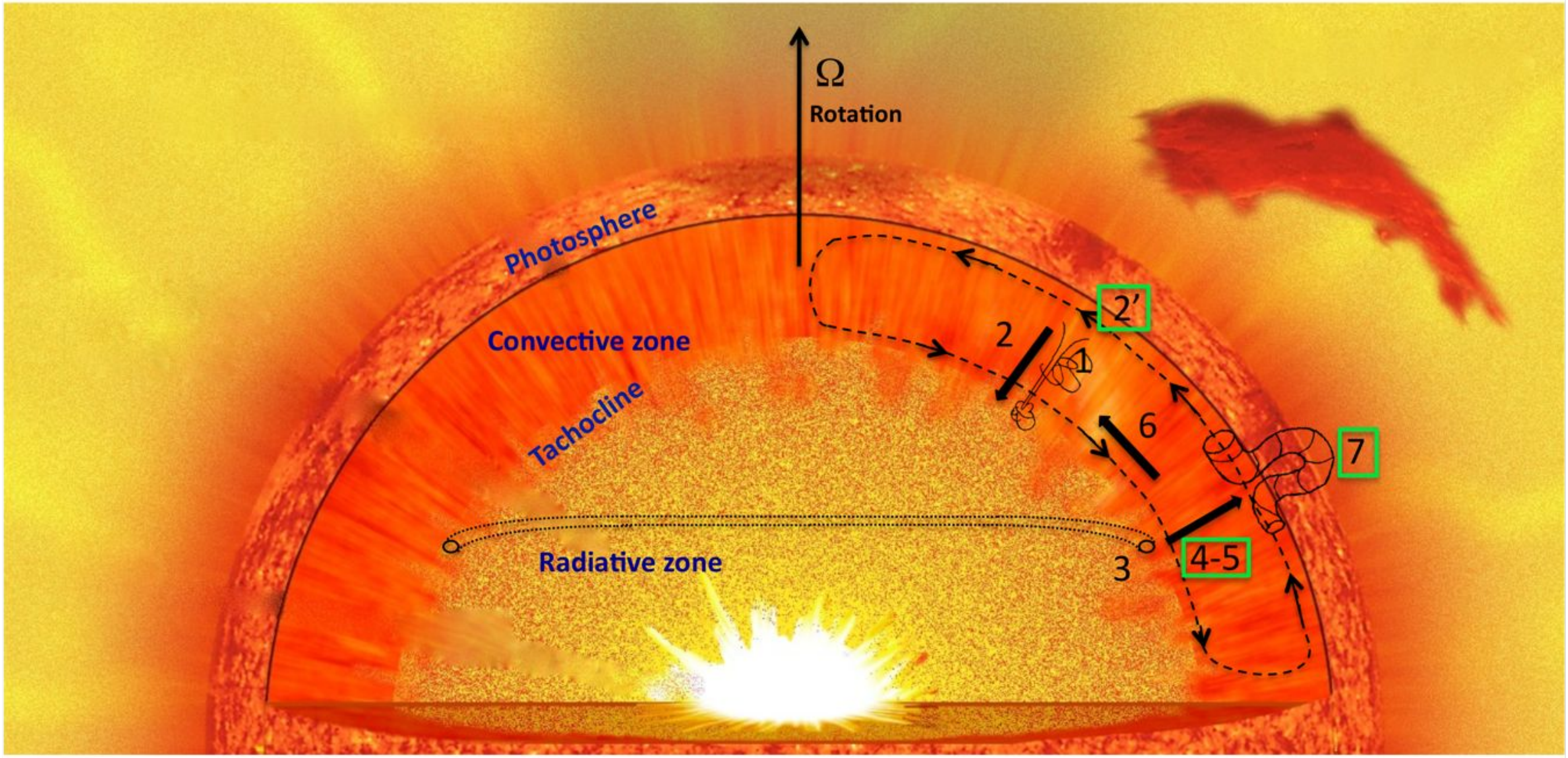
✓ Large-scale flows (meridional circulation)



✓ Downward pumping by penetrative convection

✓ Transport from the base of the convection zone to the surface (magnetic buoyancy)

Schematic theoretical view of the magnetic cycle in solar-like stars



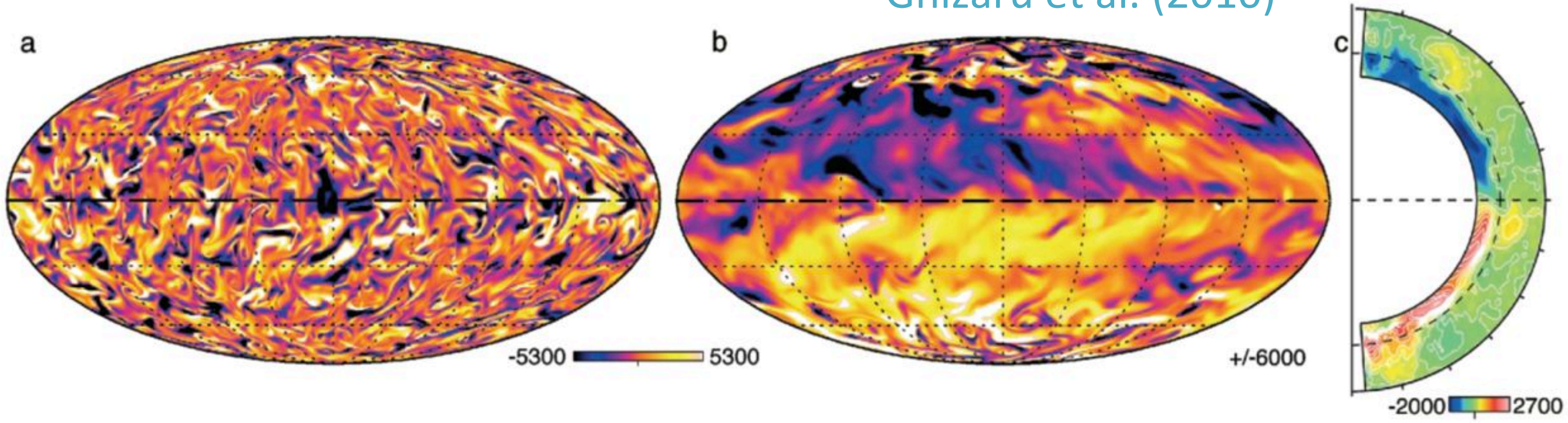
1: magnetic field generation, self-induction
2: pumping of mag. field
or
2': transport by meridional flow
3: stretching of field lines through Ω-effect

4: Parker instability
5: emergence+rotation
6: recycling through α−effect or
7: emergence of twisted bipolar structures at the surface

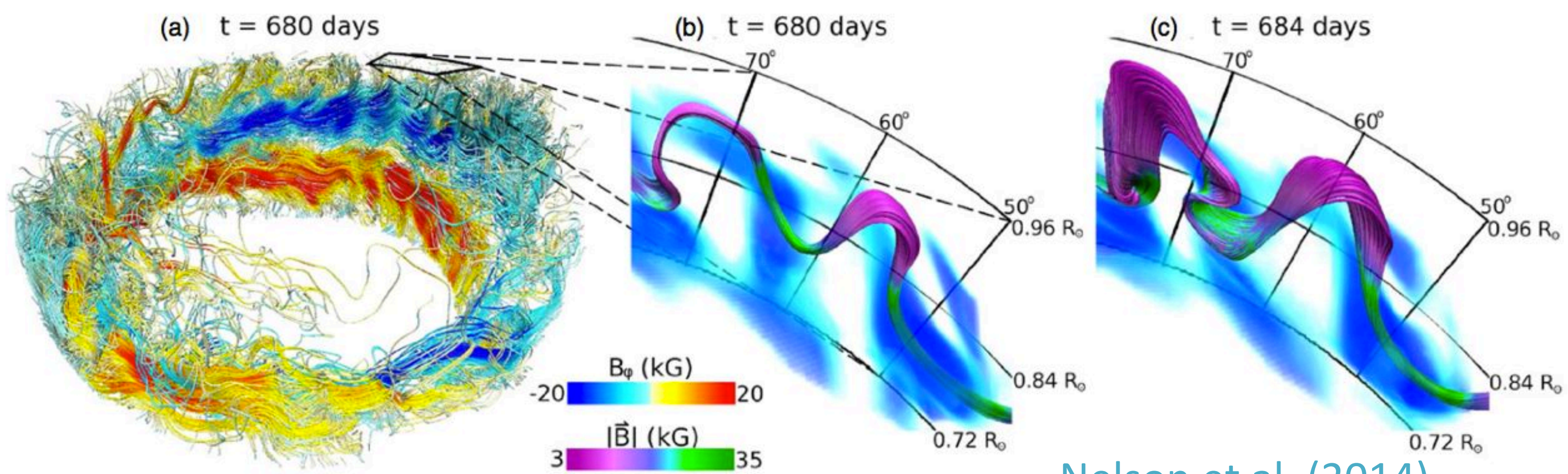
Solar-like stars: role of the the tachocline?

- ❑ Organize field at large scales

Browning et al. (2006)
Ghizaru et al. (2010)



- ❑ From these concentrations of toroidal field, buoyant loops can emerge

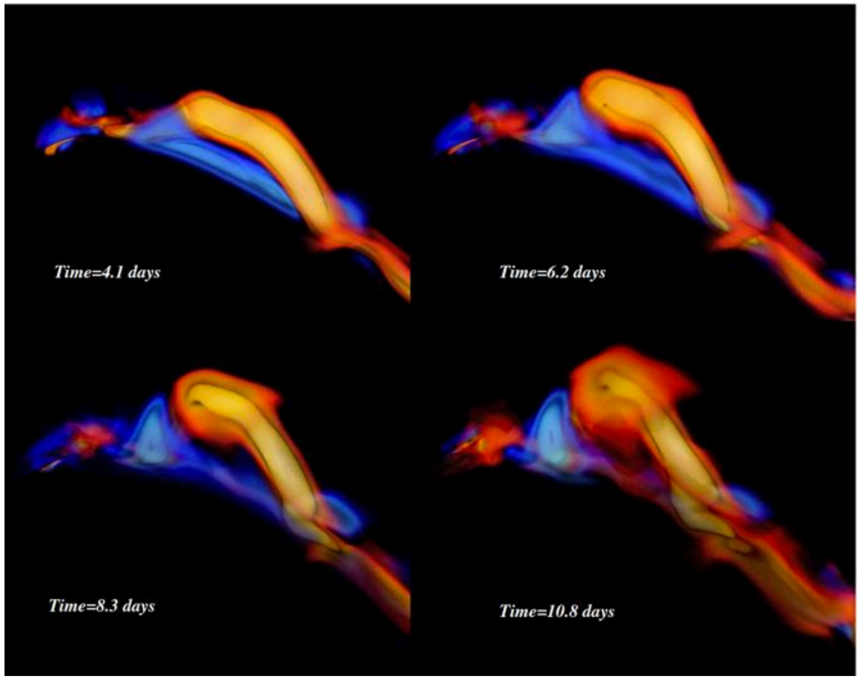


Nelson et al. (2014)

- ❑ They do not rise to the surface to create well defined spots yet, this has to be modeled independently

Solar-like stars: buoyant loops rise

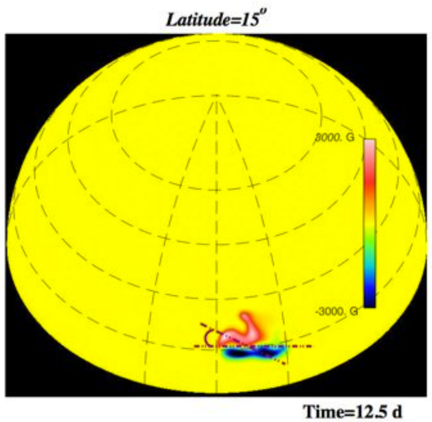
- ❑ Toroidal flux tube introduced at the base of the convection zone

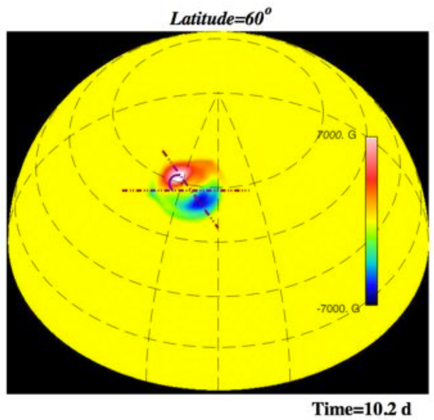


- ❑ Influence of the Coriolis force and convection introduce asymetries and modulation in longitude

Jouve et al. 2013

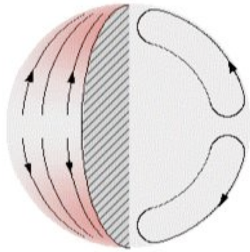
- ❑ Bipolar magnetic regions emerge, with properties close to the observed ones

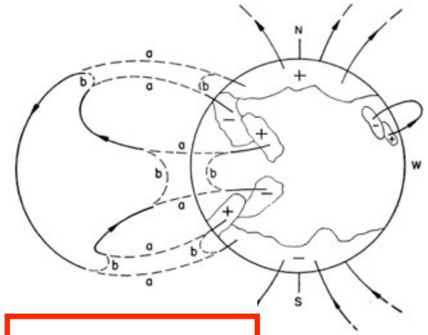




Solar-like stars: magnetic cycles, 2D models

- Mean-field induction equation only





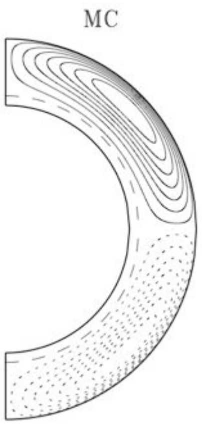
- Babcock-Leighton dynamo model

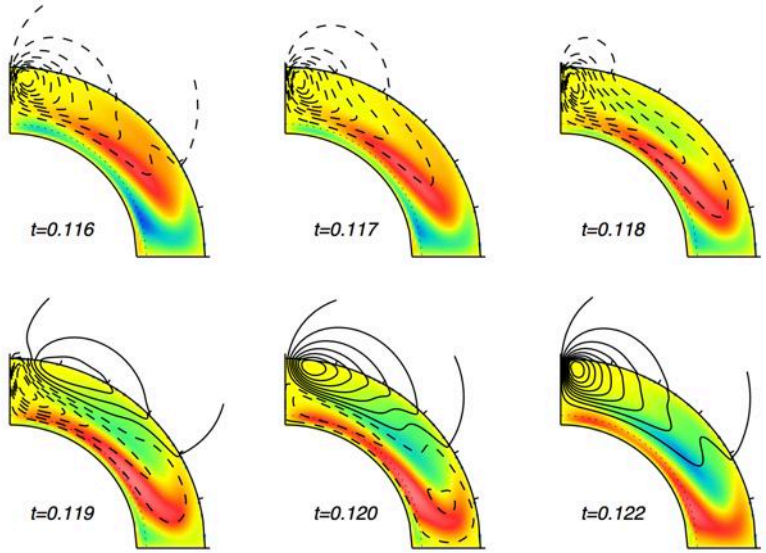
- 2 coupled PDEs

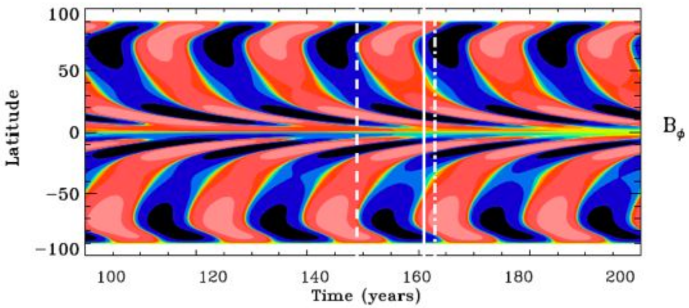
$$\frac{\partial A_\phi}{\partial t} = \frac{\eta}{\eta_t}(\nabla^2 - \frac{1}{\varpi^2})A_\phi - R_e\frac{\mathbf{u}_p}{\varpi}\cdot\nabla(\varpi A_\phi) + \cancel{C_\alpha \alpha} B_\phi + \boxed{C_s S(r,\theta,B_\phi)}$$

$$\frac{\partial B_\phi}{\partial t} = \frac{\eta}{\eta_t}(\nabla^2 - \frac{1}{\varpi^2})B_\phi + \frac{1}{\varpi}\frac{\partial(\varpi B_\phi)}{\partial r}\frac{\partial(\eta/\eta_t)}{\partial r} - R_e\varpi\mathbf{u}_p\cdot\nabla(\frac{B_\phi}{\varpi}) - R_e B_\phi \nabla\cdot\mathbf{u}_p + C_\Omega\varpi(\nabla\times(\varpi A_\phi\hat{\mathbf{e}}_\phi))\cdot\nabla\Omega$$

Standard model: single-celled meridional circulation



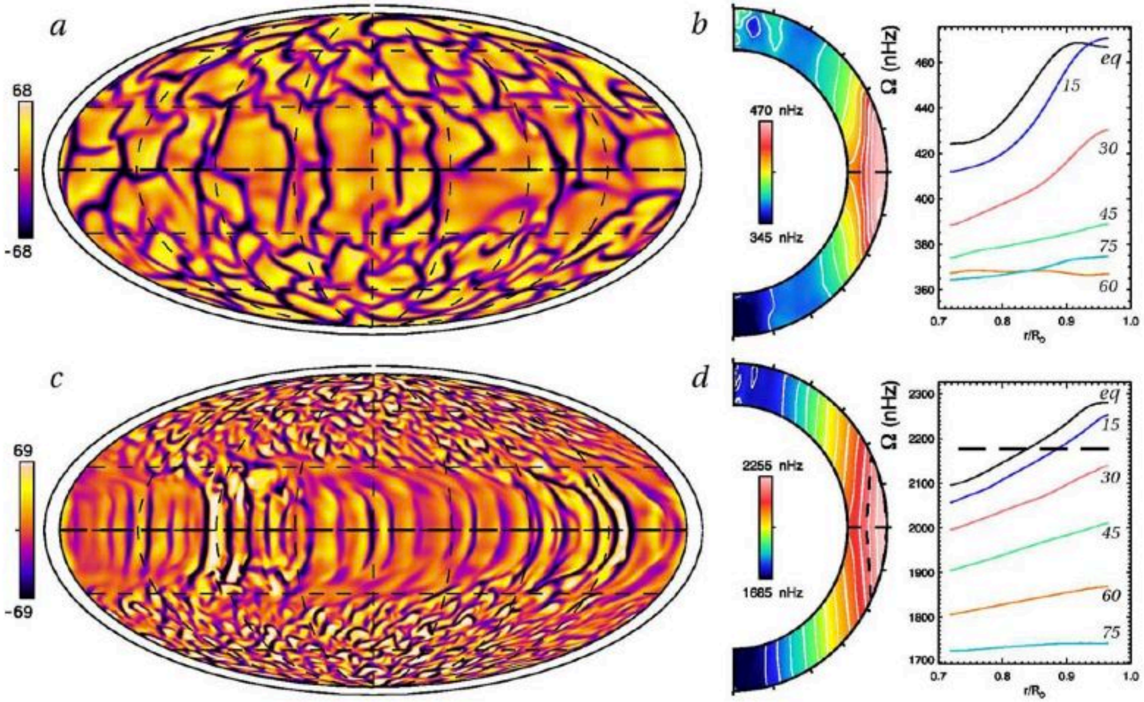


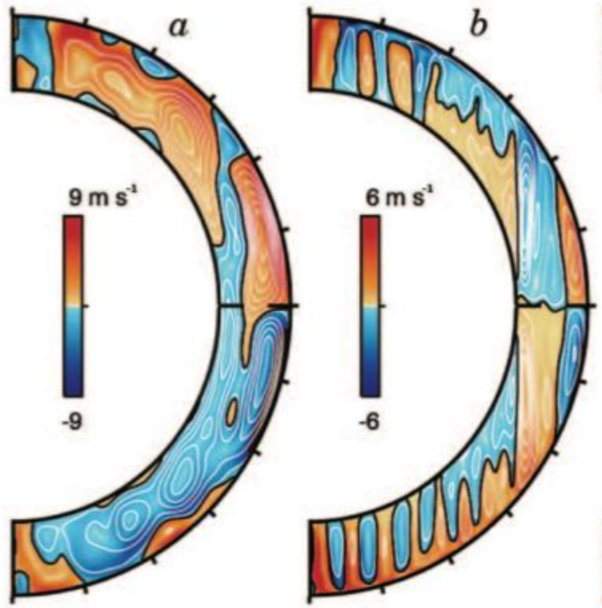


Cyclic field
Butterfly diagram close to observations

Is this solar model applicable for rapidly-rotating solar-like stars?

Solar-like stars: prescriptions from 3D models

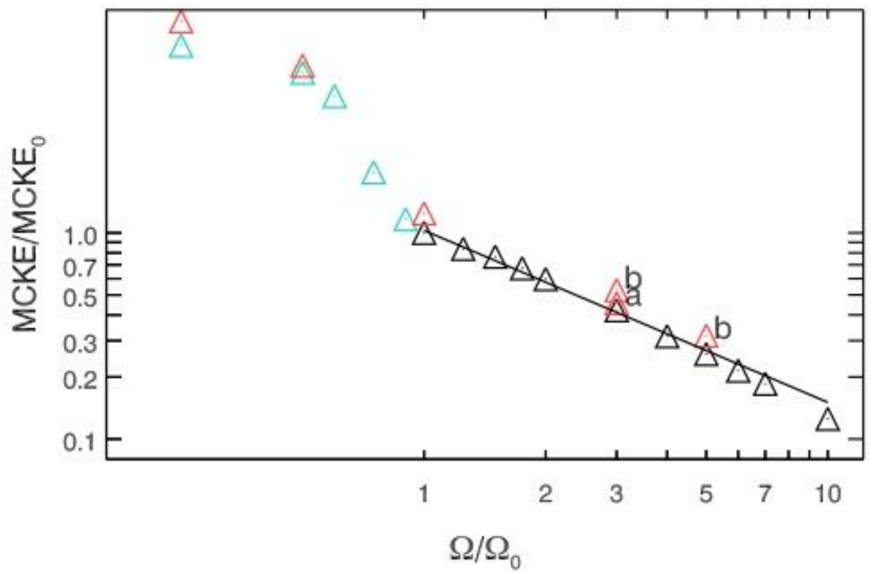




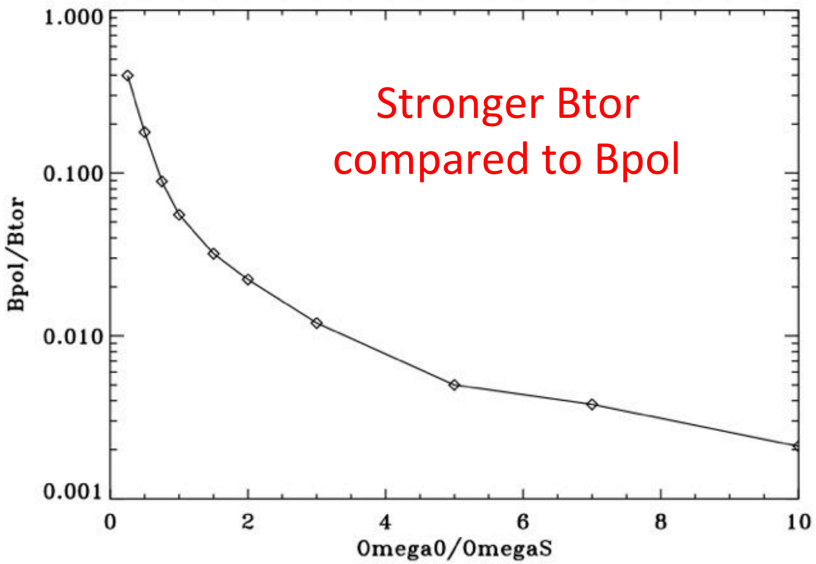
Dikpati et al. 2001 assumed Vp ~Ω
Charbonneau & Saar 2001
assumed Vp α Ω or log(Ω)

Scaling of MC deduced from
Brown et al. 2008: Vp α $\Omega^{-0.9}$

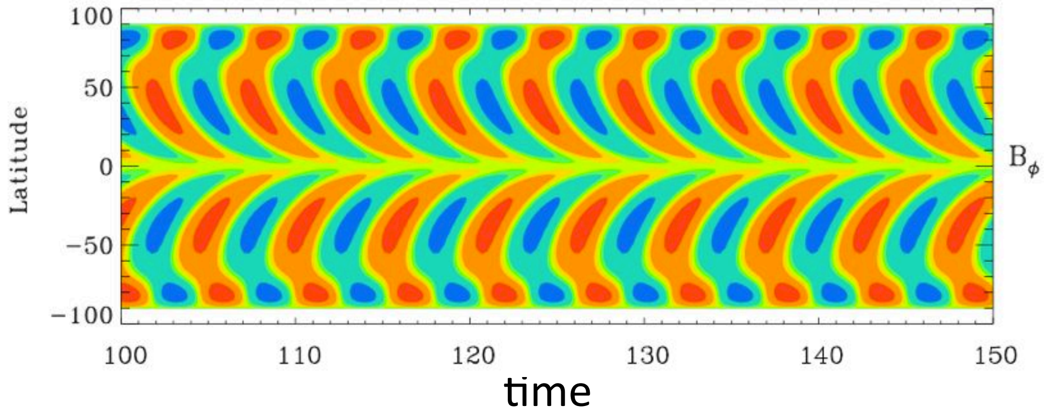
$\Delta\Omega$ increases with Ω

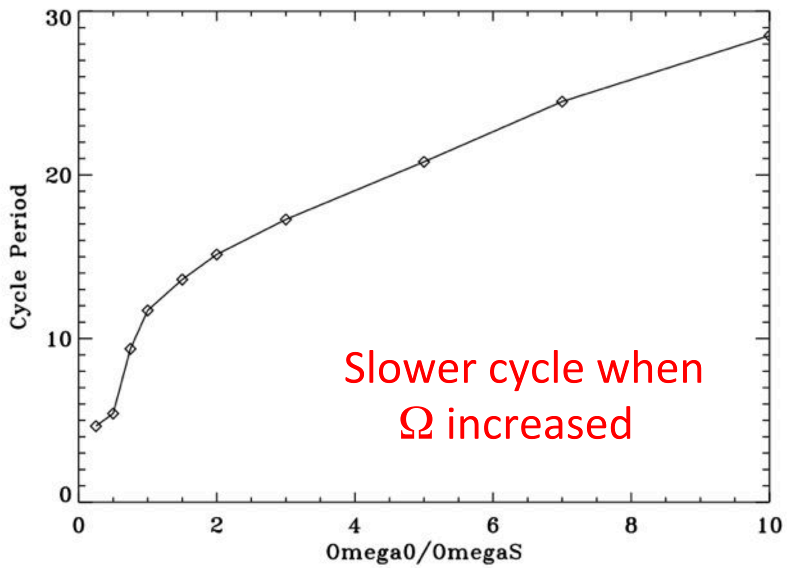


Solar-like stars: applying solar models to other stars

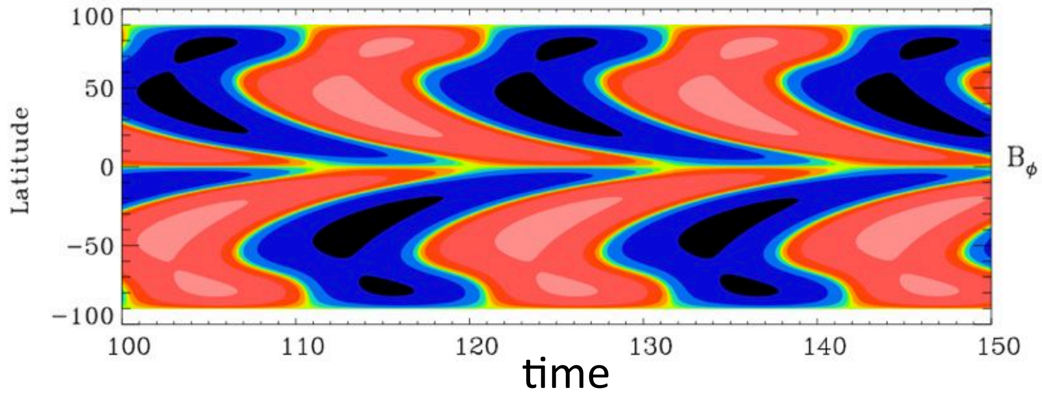


0.5 Ωsol





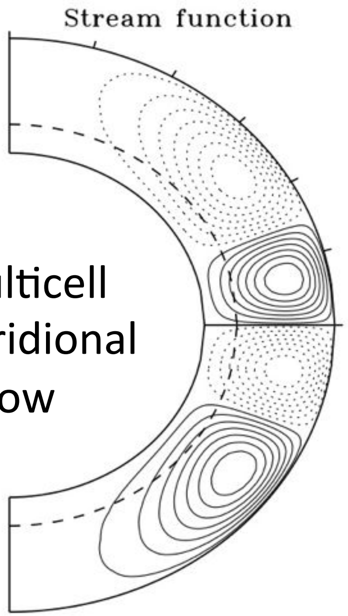
5 Ωsol Pcyc = 20 yr

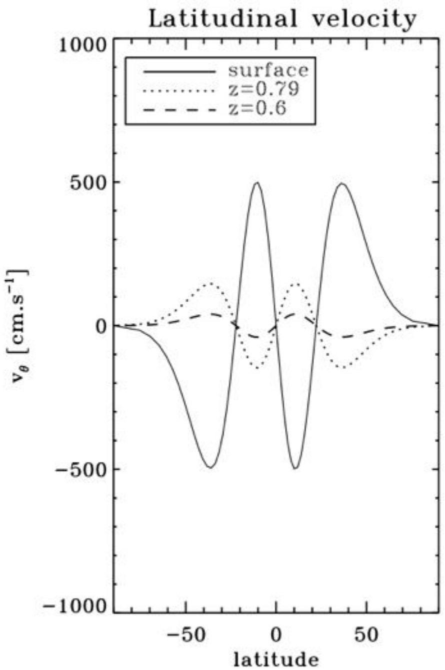


Jouve, Brown, Brun 2010

Solar-like stars: applying solar models to other stars

Multicell meridional flow

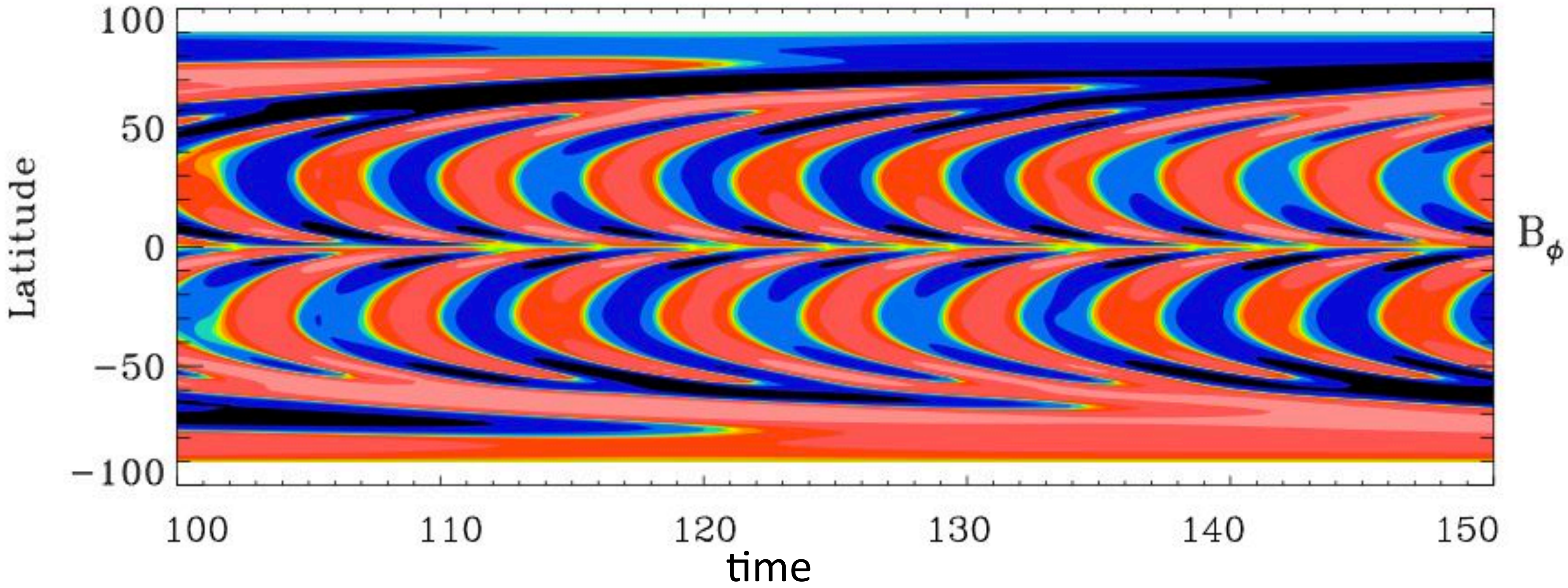




Can we reconcile this model with stellar data using a more complex MC?

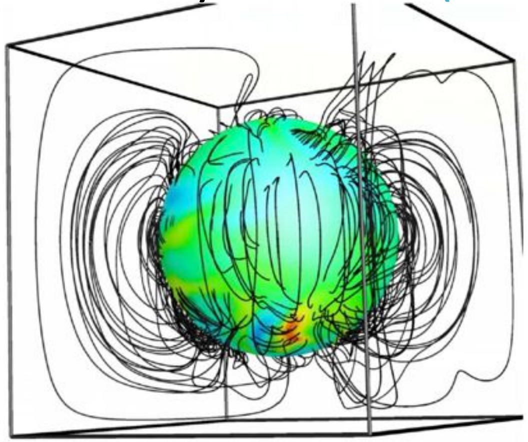
Jouve, Brown, Brun 2010

5 Ωsol, Pcyc = 5.2 yr, better agreement



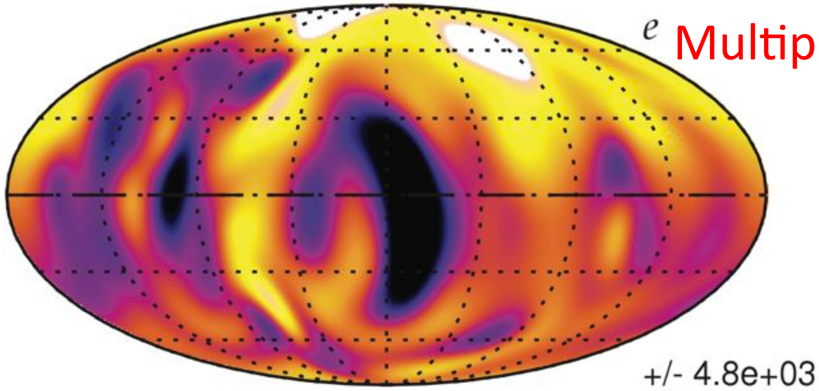
Models of fully convective stars

- Weakly stratified (Dobler 2005)



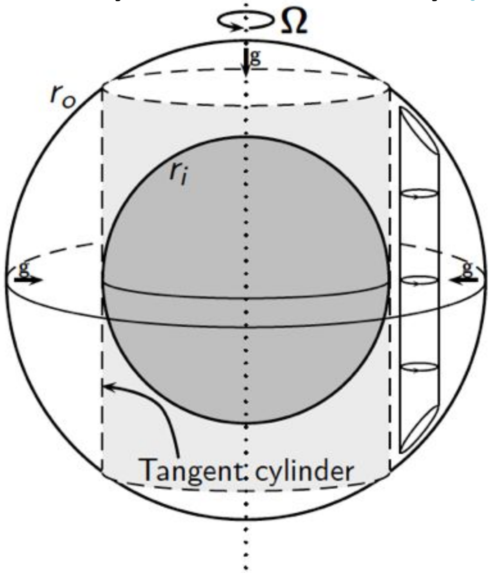
Dipolar

- More strongly stratified (Browning 2008)



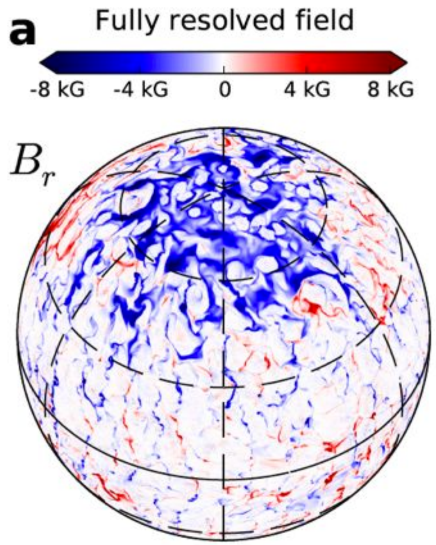
Multipolar

- Systematic study (Gastine et al. 2012)



Aspect ratio, density contrast and influence of rotation (Rossby number) varied

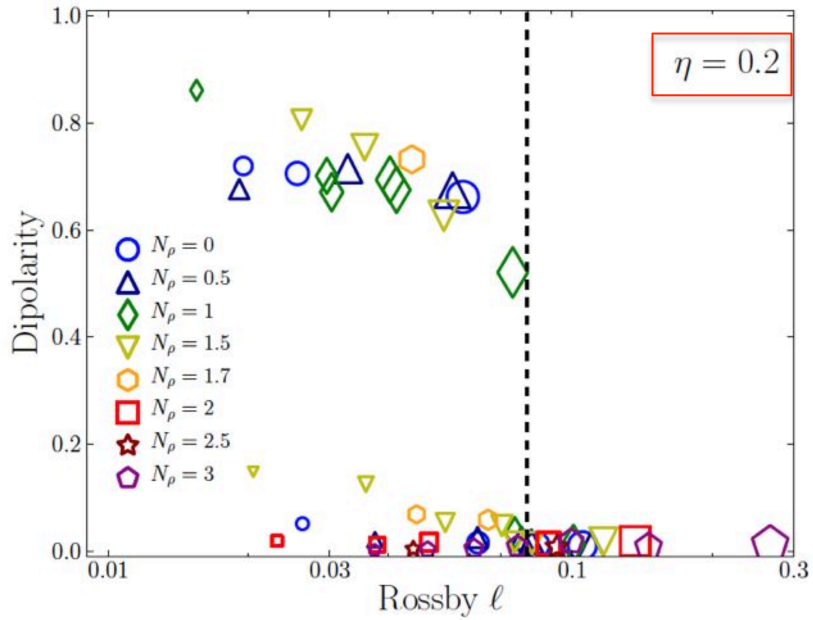
- Most recent (Yadav et al. 2015)



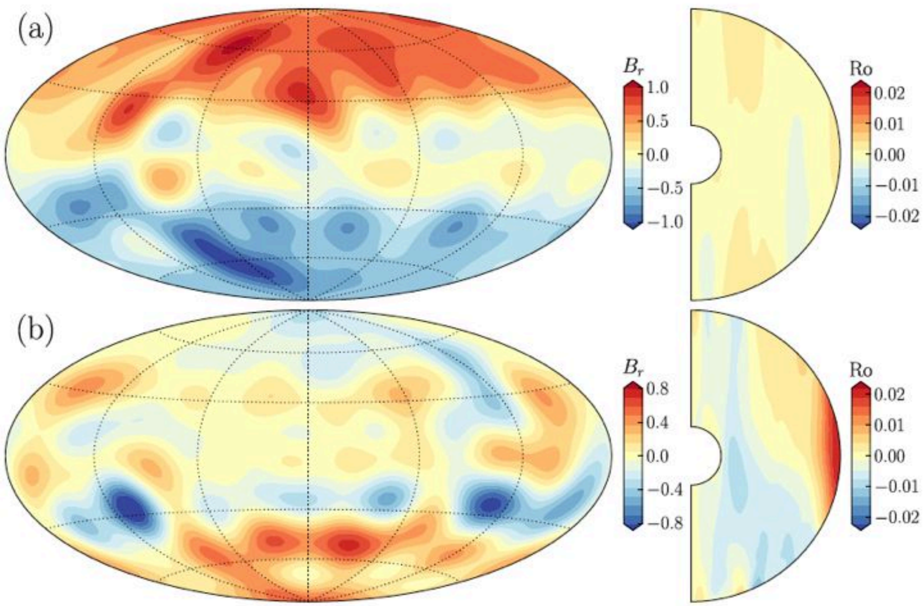
Small and large scales coexist

Fully convective stars: Rossby and bistability

- ❑ Change in Rossby
  (also seen in planetary dynamos)
  Christensen & Aubert (2006)
  - Ordering role of Coriolis=dipolar
  - Inertia becomes dominant=multipolar



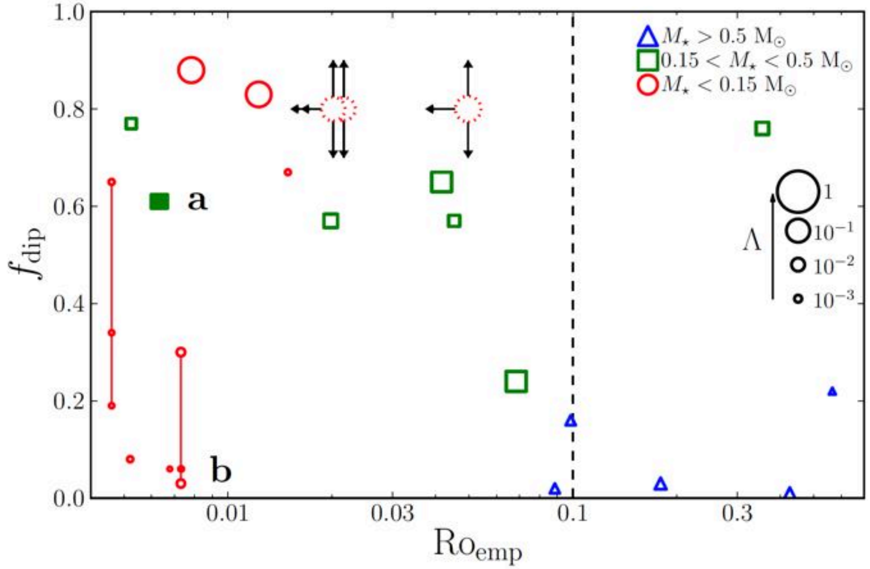
- ❑ Two regimes for low Rossby numbers
  (also seen in planetary dynamos)
  Schrinner et al. (2012)
  - Strong initial field=no shear
  (no role of shear in dynamo)
  - Weak initial field=shear
  (shear plays a role: Parker waves?)



- ❑ Strong stratification leads to multipolar fields

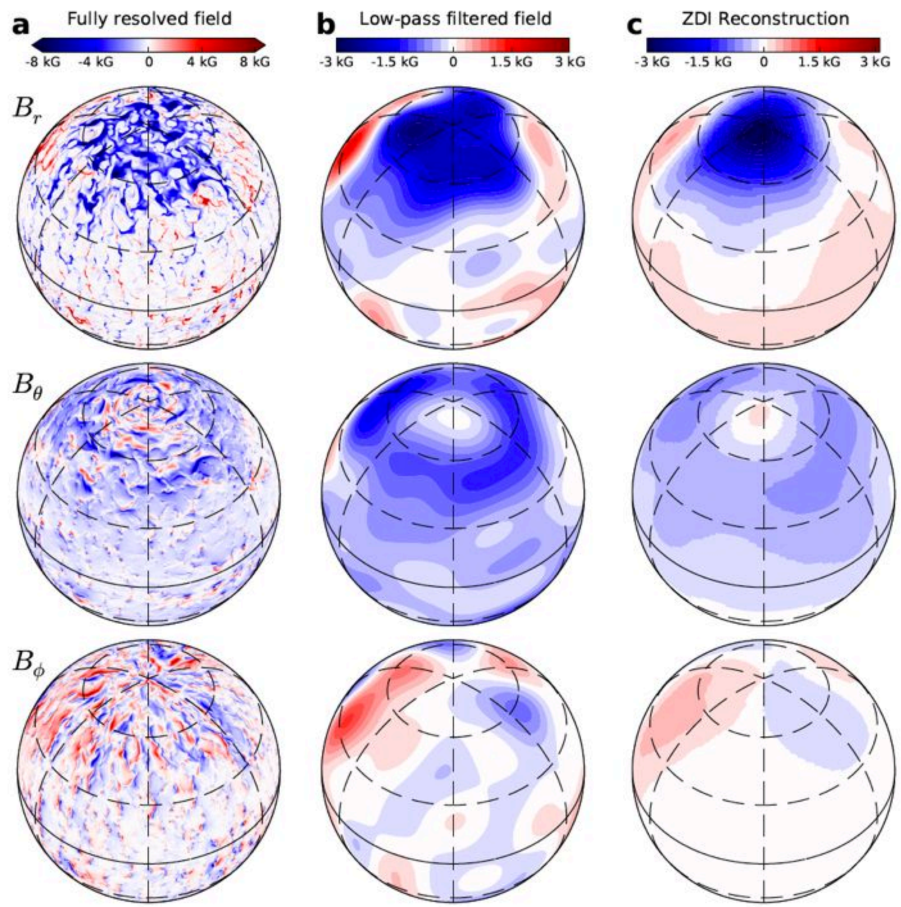
Fully convective stars: comparison to observations

Gastine et al. (2013)



- ❑ Dipolarity lost for Ro > 0.1
- ❑ Bistability for low Ro
- ❑ Variability for very low Ro: compatible with Parker waves?

Yadav et al. (2015)



❑ ZDI reconstruction:

- Field geometry recovered (large-scale only)
- Field strength underestimated

Conclusions

- Dynamo models of solar-like stars:

  - Role of the tachocline: building organised field
  - Is a tachocline necessary for buoyant loops generation?
  - What is missing in 3D models to actually produce spots?
  - Models commonly applied to the Sun are challenged by other stars

- Dynamo models of fully convective stars:

  - Change of geometry with Rossby number (or with internal structure?)
  - Bistable regime for late M
  - Temporal variability for multipolar fields?
  - Can dipoles (and thus bistability) resist strong stratifications?