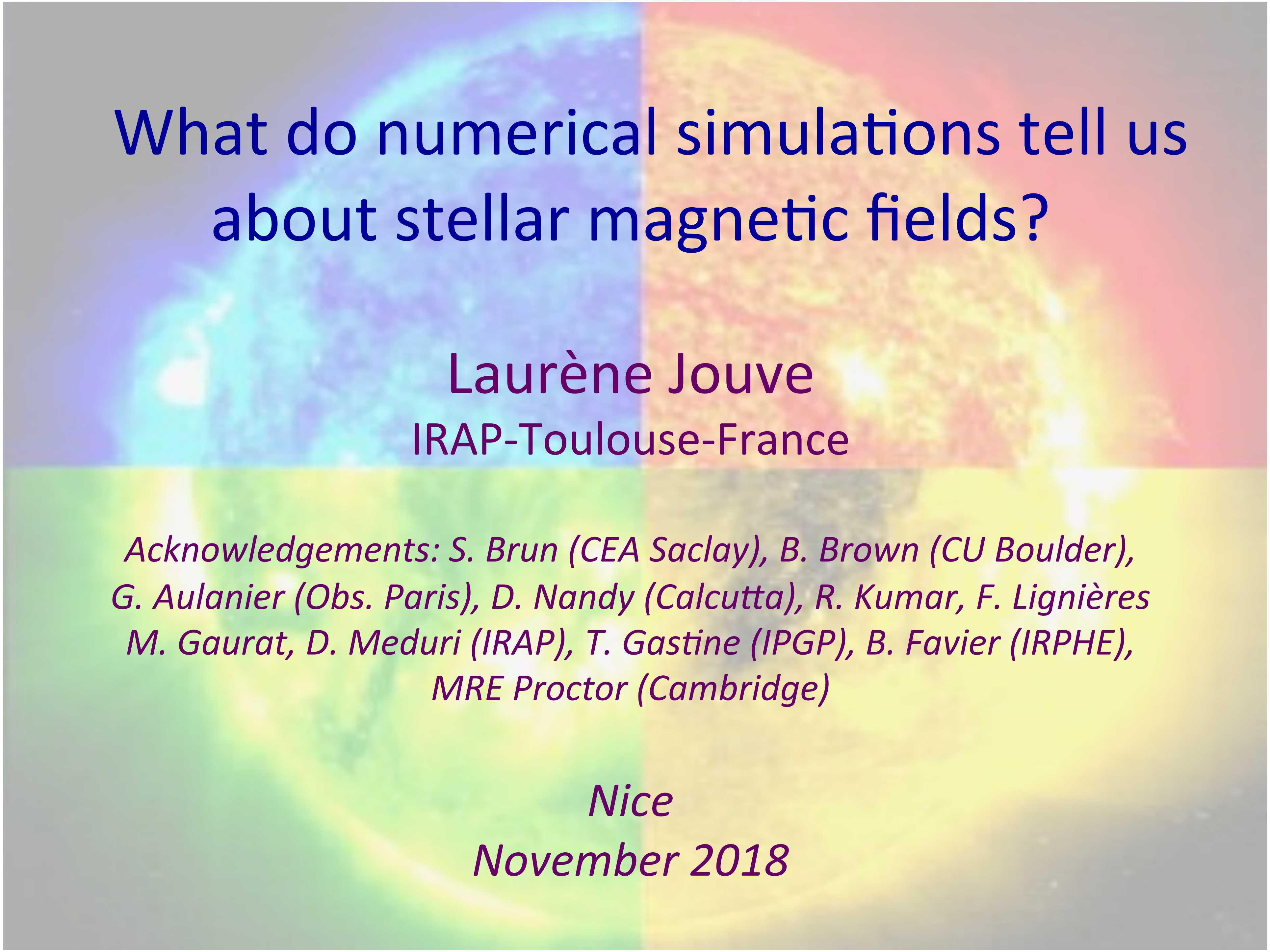


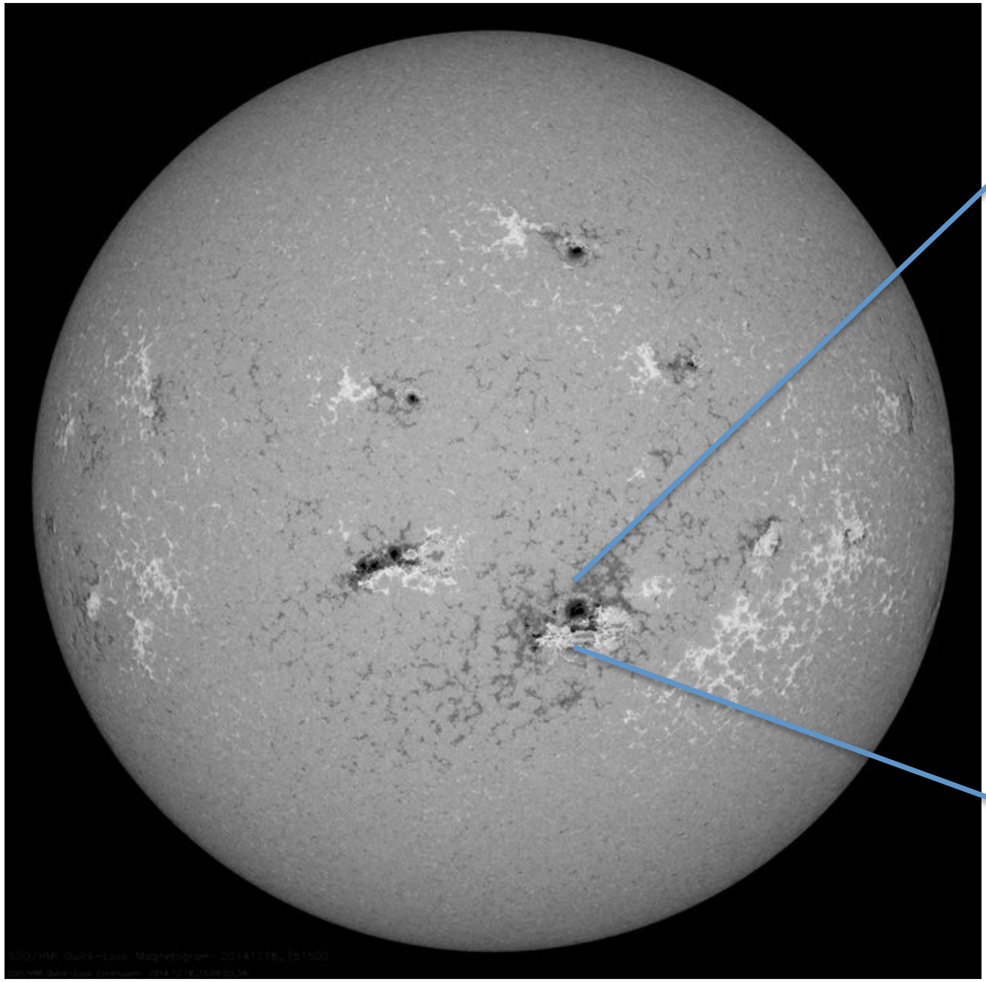
What do numerical simulations tell us about stellar magnetic fields?

Laurène Jouve
IRAP-Toulouse-France

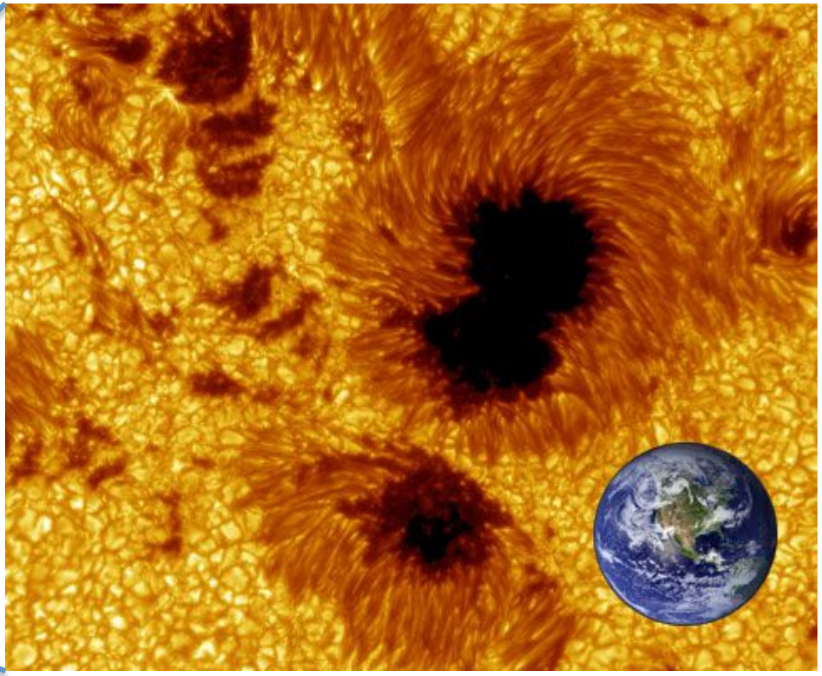
Acknowledgements: S. Brun (CEA Saclay), B. Brown (CU Boulder), G. Aulanier (Obs. Paris), D. Nandy (Calcutta), R. Kumar, F. Lignières M. Gaurat, D. Meduri (IRAP), T. Gastine (IPGP), B. Favier (IRPHE), MRE Proctor (Cambridge)

Nice
November 2018

The Sun: a magnetic star

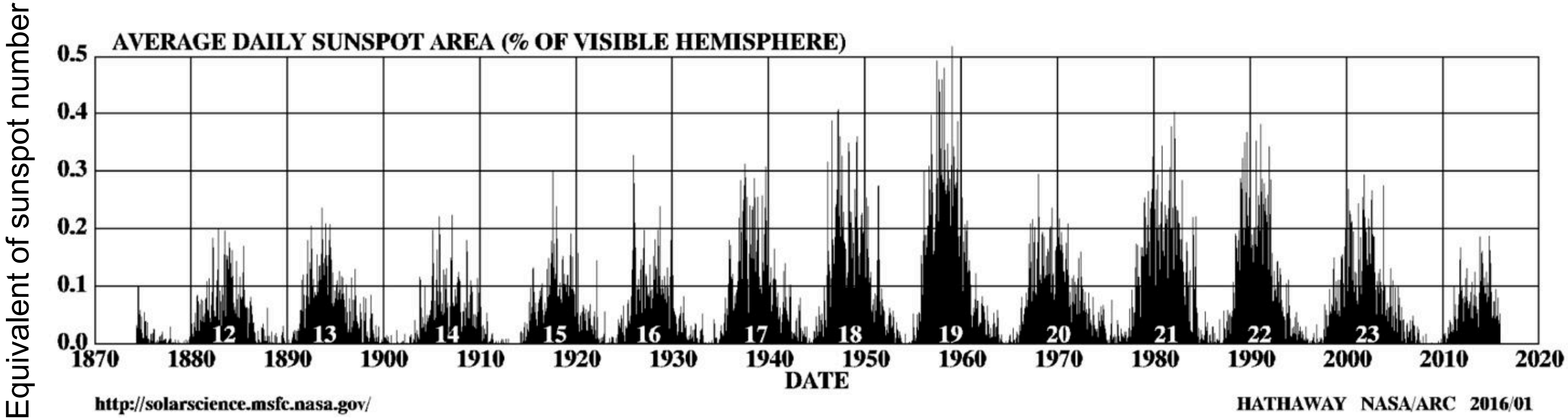


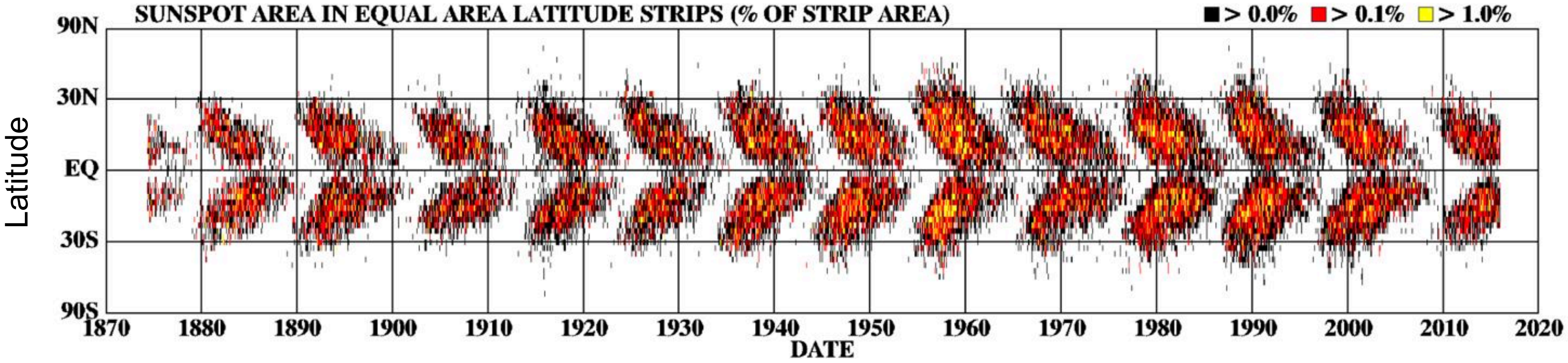
The Sun in 2014



Zoom on a sunspot group

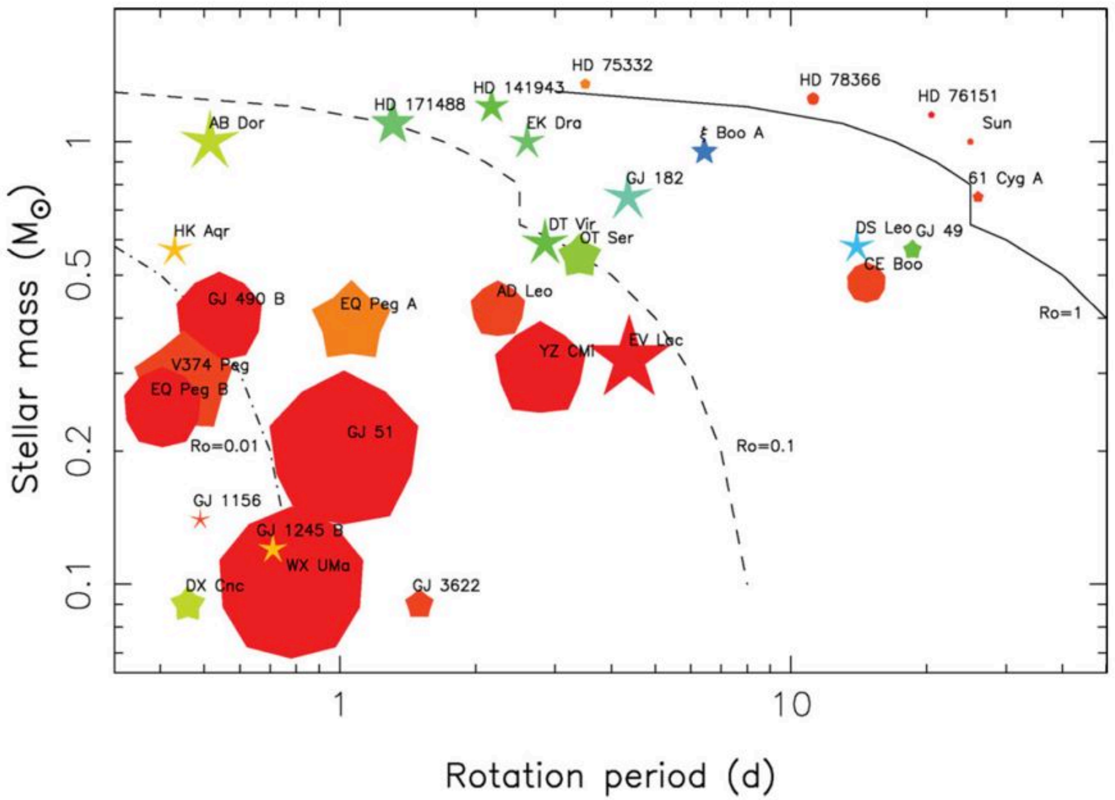
Sunspots: temporal evolution





Magnetic fields in cool MS stars

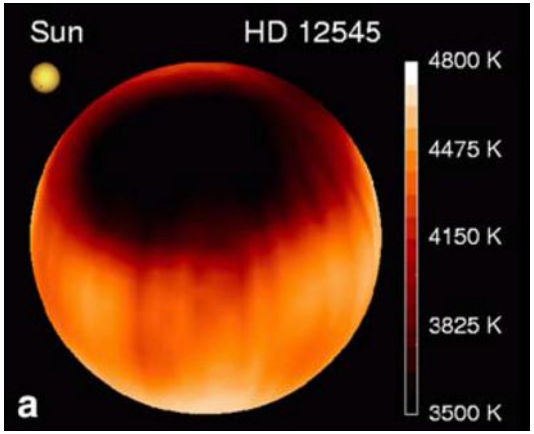
Morin, Donati et al. (2008-2010), Folsom et al. 2016



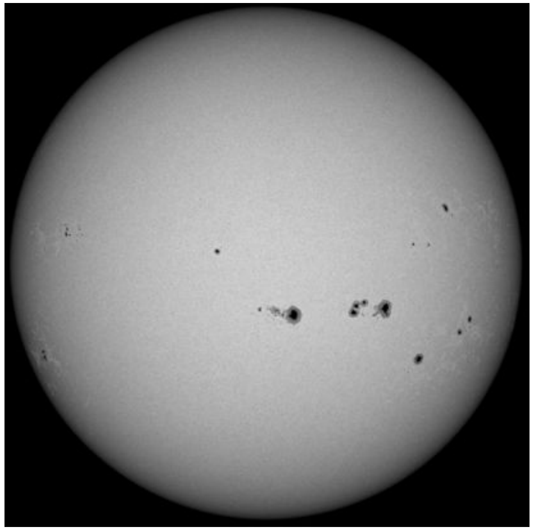
- ☐ Mostly multipolar for $M_\odot > 0.35$
- ☐ Mostly dipolar for $M_\odot < 0.35$
- ☐ Bistability for $M_\odot < 0.2$
- ☐ Field strength increases with rotation
- ☐ More and more toroidal with rotation

Petit et al. 2008, B cool survey (Marsden et al. 2014)

Strassmeier (1999)



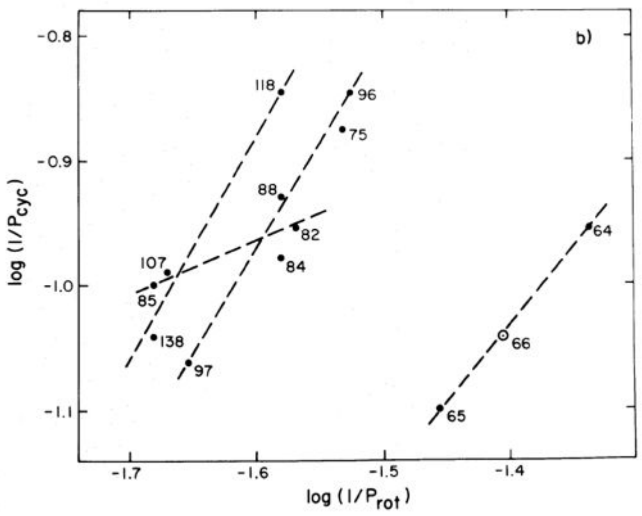
SDO data (July 2014)



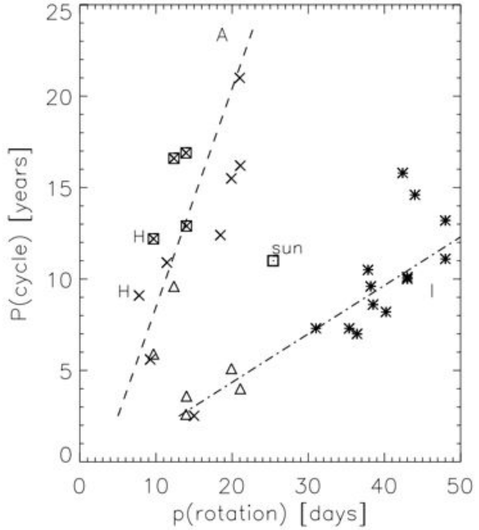
☐ In stars cooler than the Sun: Polar spots with large coverage

Observations of magnetic cycles?

Noyes et al. 1984



Böhm-Vitense 2007



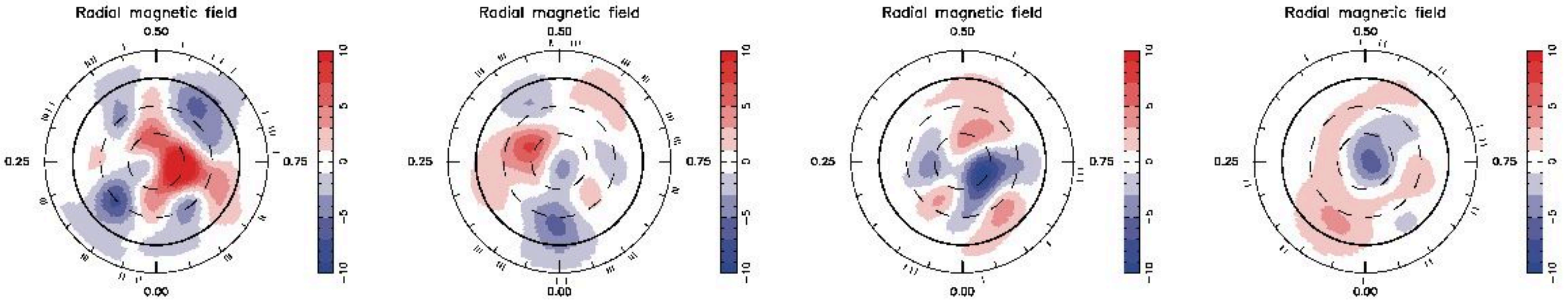
Chromospheric activity (Mount Wilson data, Ca II HK lines):

- P_{cyc} increases with P_{rot}

- Different branches

Do new obs. confirm?

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

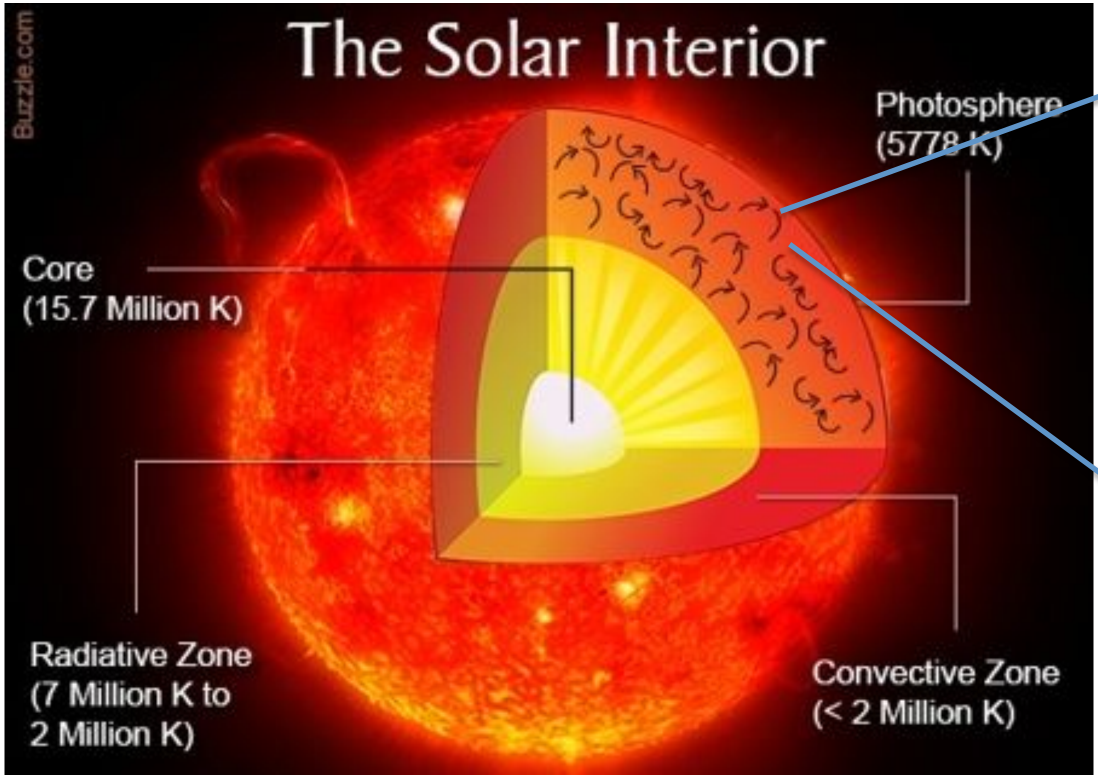


Petit et al 2009, Morgenthaler et al 2011: complex variability

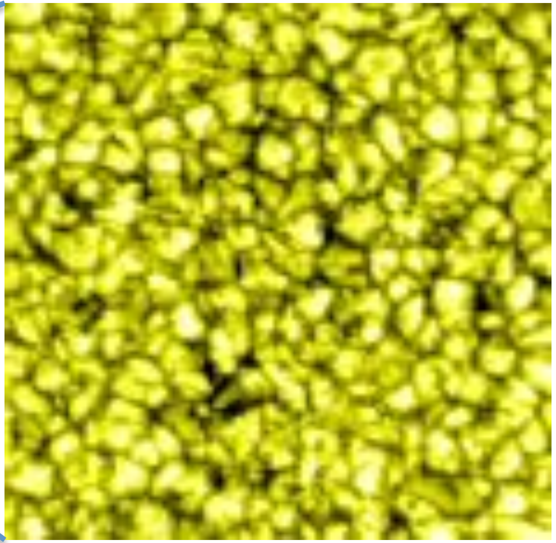
Boro-Saika et al 2016: 61 Cyg A: 14 years

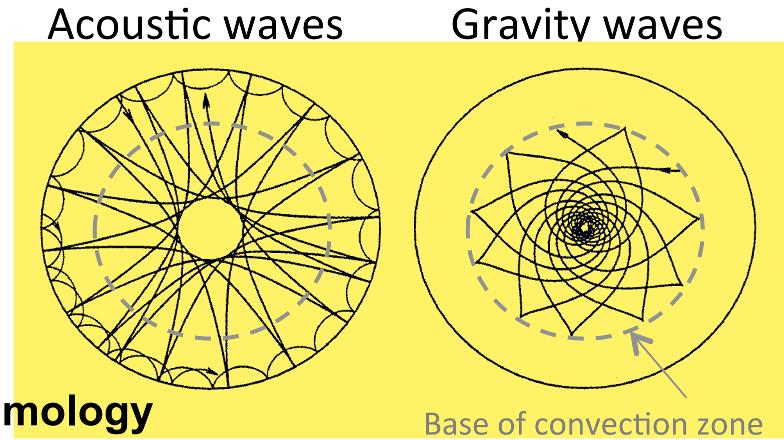
Garcia et al 2010, Salabert et al. 2016, Kiefer et al. 2017: asteroseismic signatures

Solar interior and plasma flows

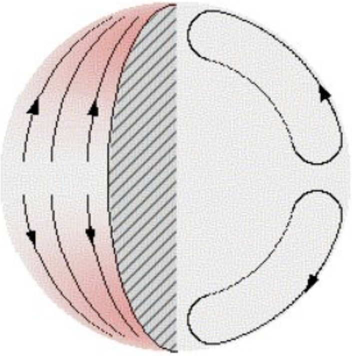


☐ Granulation (surface convection)

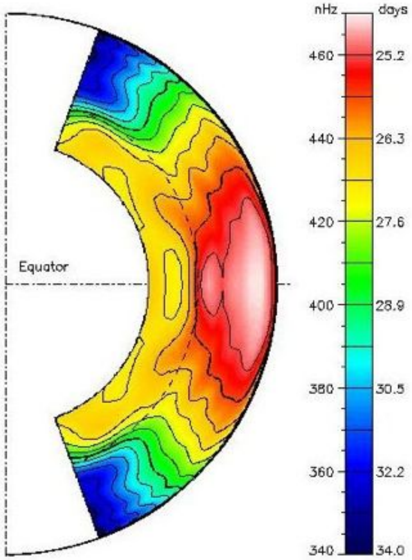




Helioseismology



☐ Meridional flow

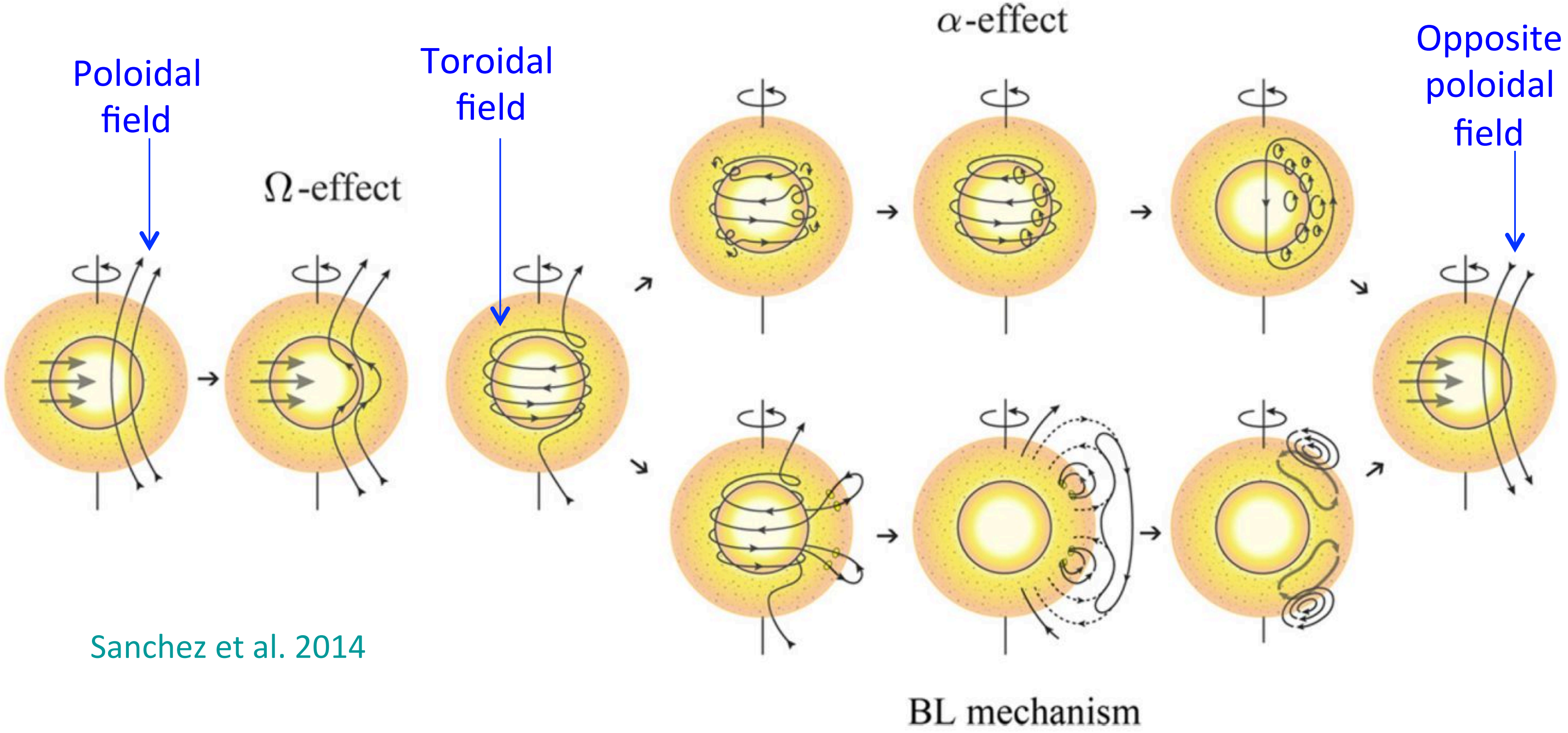


☐ Rotation

Kinematic dynamo ingredients

Basic solar dynamo ingredients (kinematic dynamo)

The solar dynamo: **process through which the motions of a conducting fluid permanently regenerates a magnetic field**

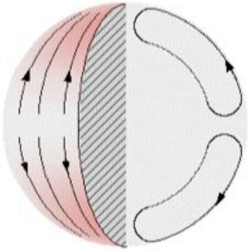


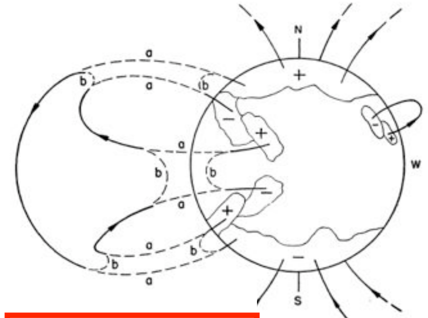
Sanchez et al. 2014

Babcock-Leighton

Magnetic cycles in 2D models

- Mean-field induction equation only
- Babcock-Leighton dynamo model
- 2 coupled PDEs

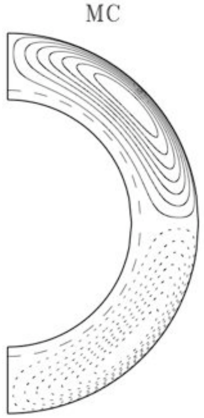




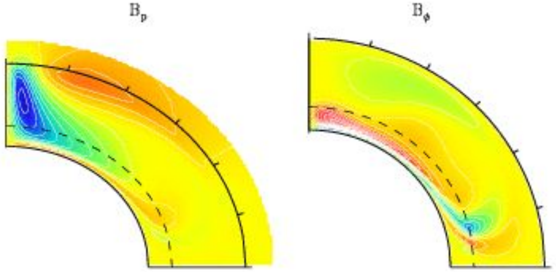
$$\frac{\partial A_{\phi}}{\partial t} = \frac{\eta}{\eta_{\mathrm{t}}}(\nabla^2 - \frac{1}{\varpi^2})A_{\phi} - R_{\mathrm{e}}\frac{\mathbf{u}_{\mathrm{p}}}{\varpi}\cdot\nabla(\varpi A_{\phi}) + \xcancel{C_{\alpha}\alpha} B_{\phi} + \boxed{C_{\mathrm{s}}S(r,\theta,B_{\phi})}$$

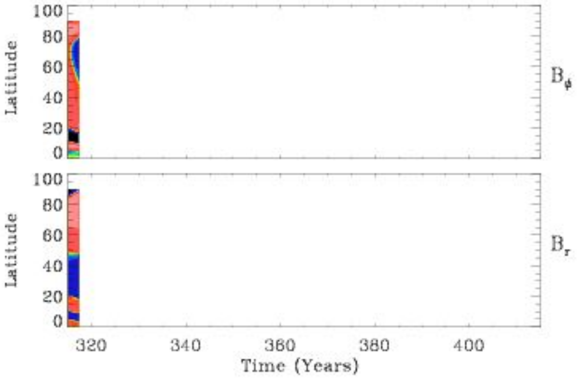
$$\frac{\partial B_{\phi}}{\partial t} = \frac{\eta}{\eta_{\mathrm{t}}}(\nabla^2 - \frac{1}{\varpi^2})B_{\phi} + \frac{1}{\varpi}\frac{\partial(\varpi B_{\phi})}{\partial r}\frac{\partial(\eta/\eta_{\mathrm{t}})}{\partial r} - R_{\mathrm{e}}\varpi\mathbf{u}_{\mathrm{p}}\cdot\nabla(\frac{B_{\phi}}{\varpi})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

Standard model:
single-celled
meridional
circulation



Dikpati & Charbonneau 1999
Jouve & Brun 2007





- Cyclic field
- Butterfly diagram

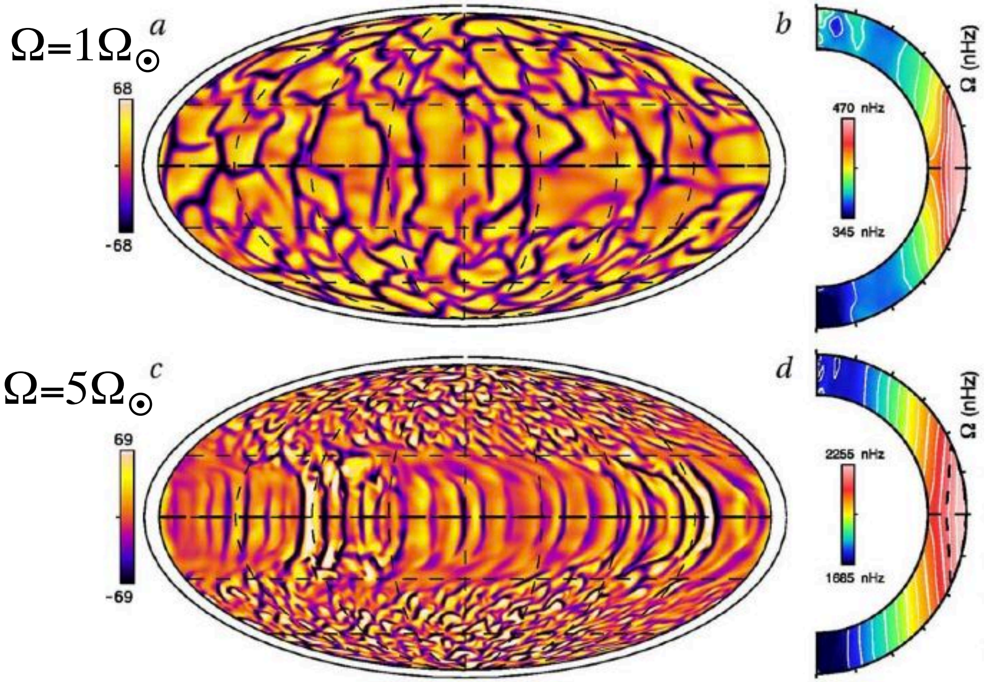
ok with observations

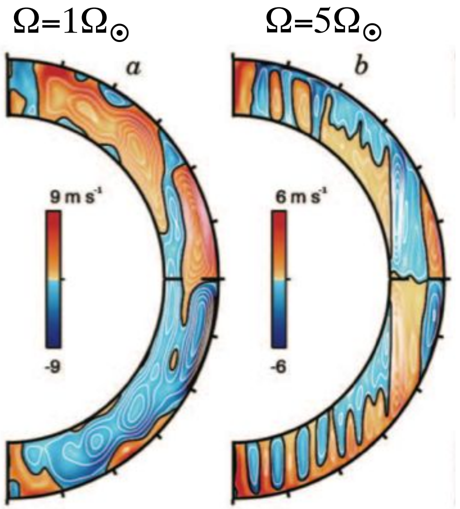
- Very strong dependence of cycle period on MC amplitude

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

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

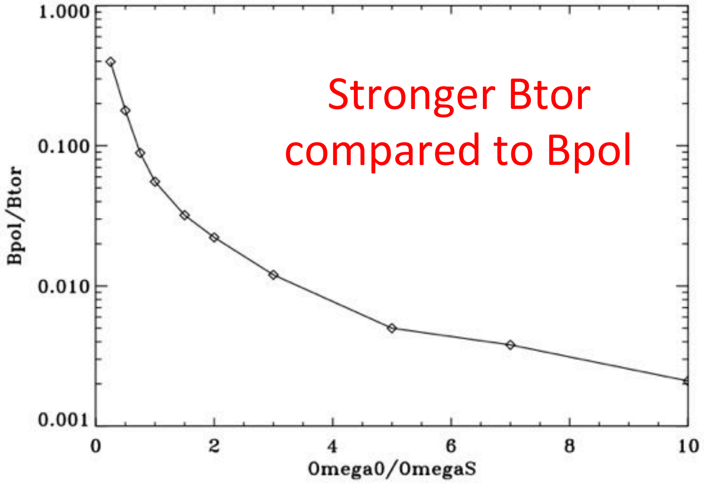
Prescriptions from 3D models



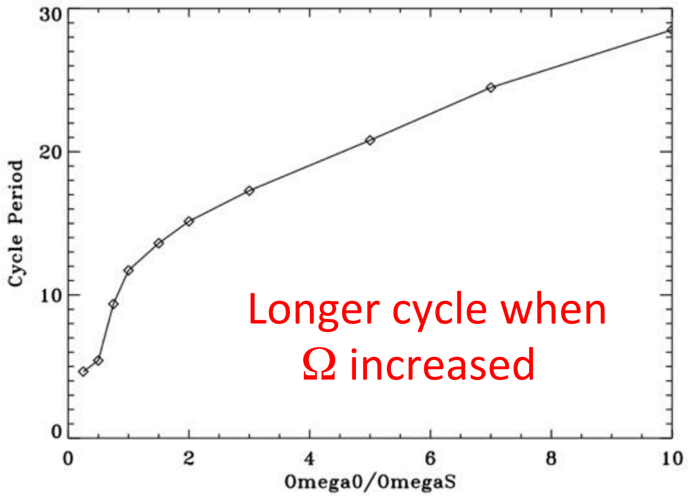


Prescriptions from Brown et al. 2008:

- Vp α $\Omega^{-0.9}$
- ΔΩ increases with Ω



Stronger Btor compared to Bpol



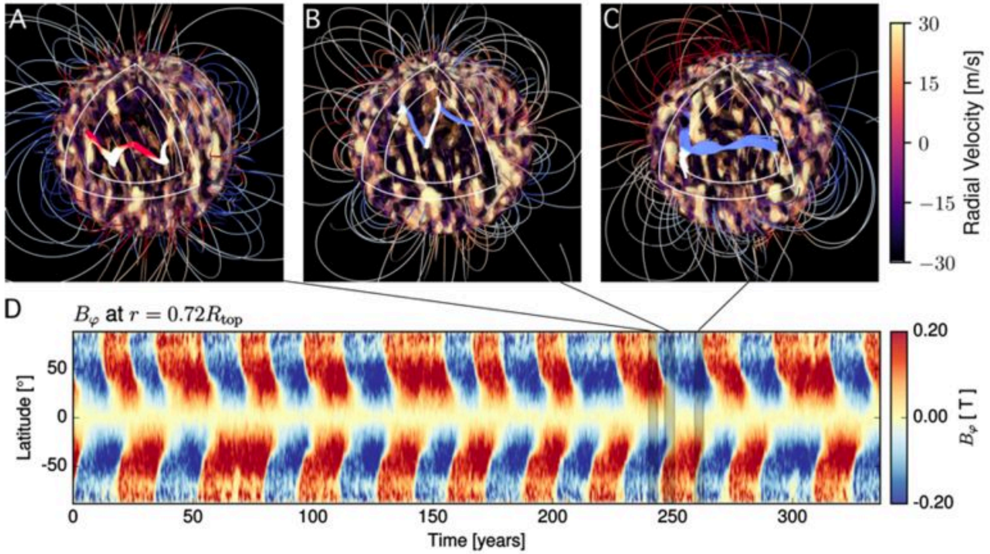
Longer cycle when Ω increased

Jouve et al. 2010

The MC profile needs to be modified to reconcile models and observations

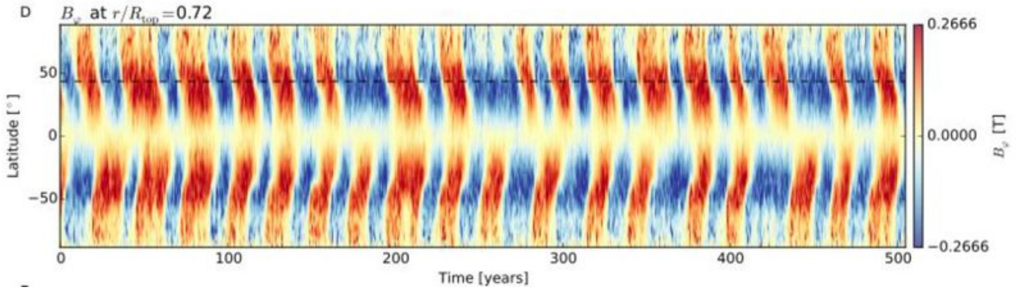
Applying solar models to other stars: more realistic models

$\Omega=\Omega_\odot$

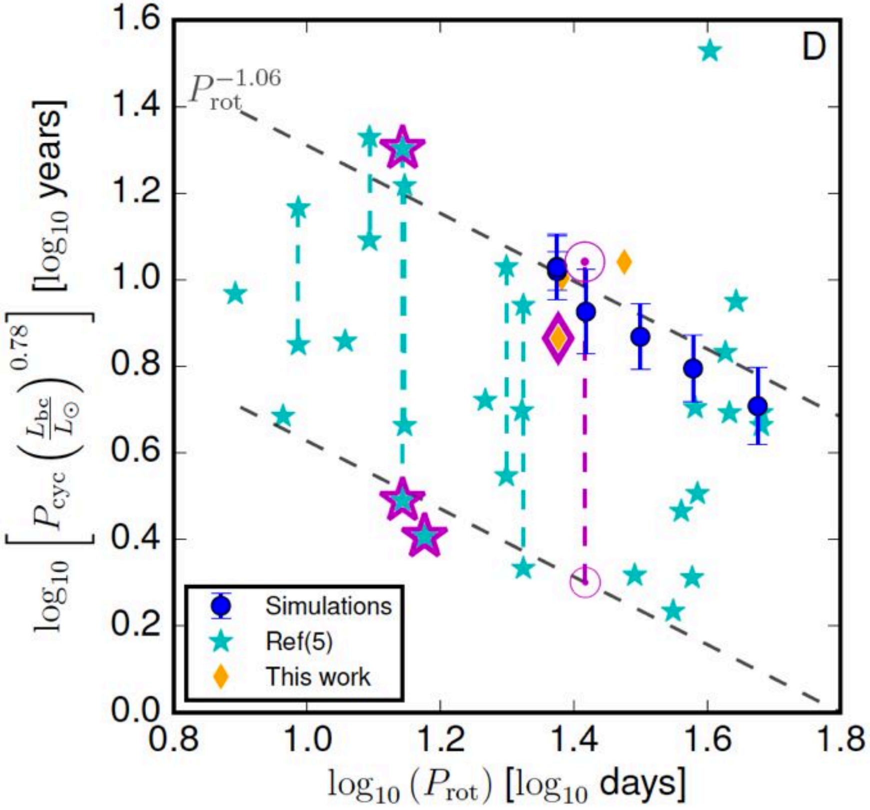


At fixed luminosity, slower rotation produces shorter magnetic cycles!

$\Omega=0.6\Omega_\odot$



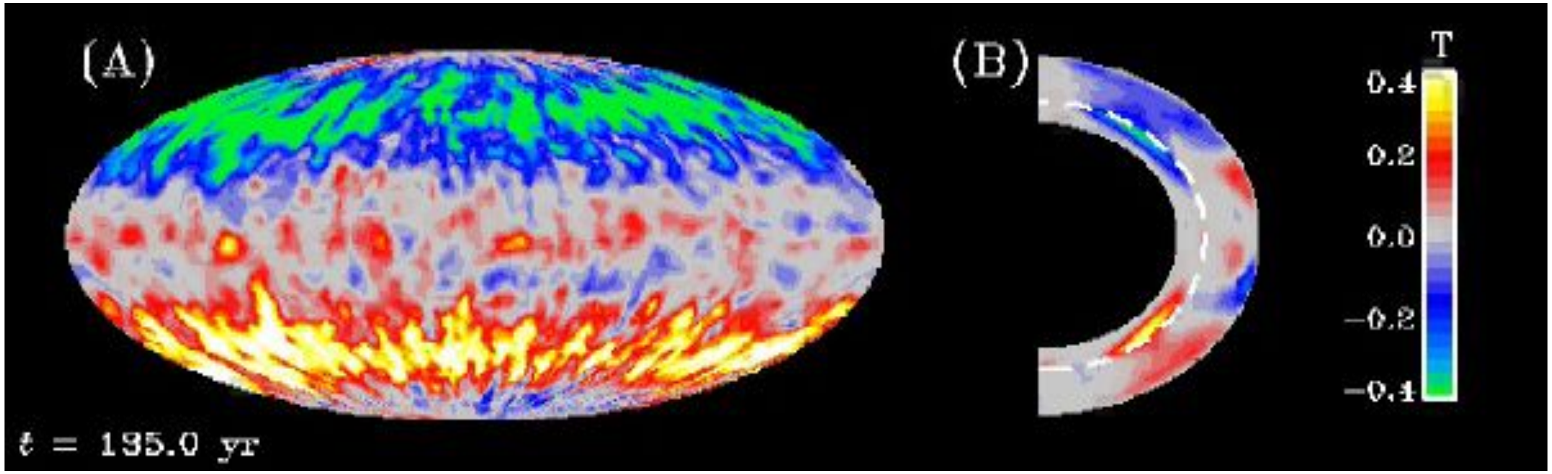
Strugarek et al. 2017



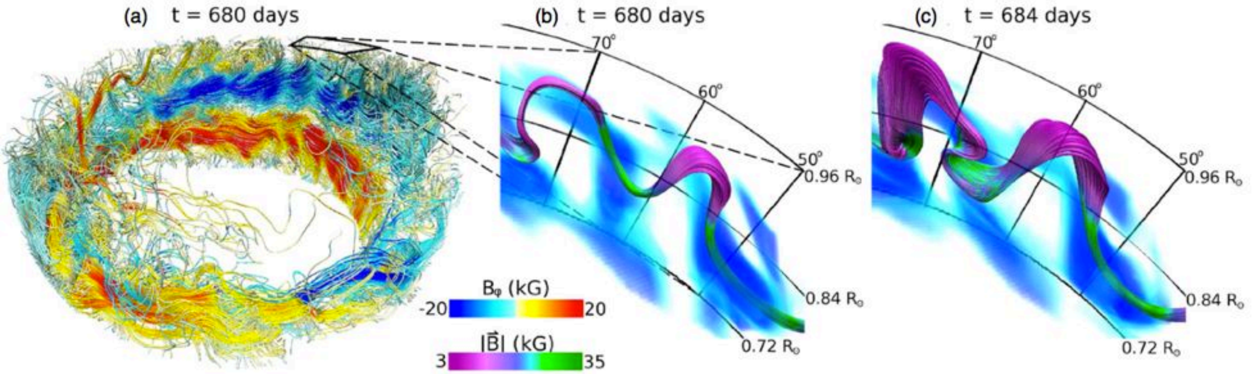
- ☐ Corrected P_{cyc} scales with P_{rot}^{-1}
- ☐ Not in disagreement with obs
- ☐ Not an $\alpha\Omega$ nor a BL dynamo

Spots in 3D models?

- 3D models produce magnetic cycles **without producing spots** and meridional circulation does not seem to set up the cycle period (Brown et al. 2011, Ghizaru et al. 2010, Nelson et al. 2013, Käpylä et al. 2013, Augustson et al. 2015, Hotta et al. 2016)



- Strong concentrations of toroidal field can still be built but buoyant structures do not make it to the top to produce spots!

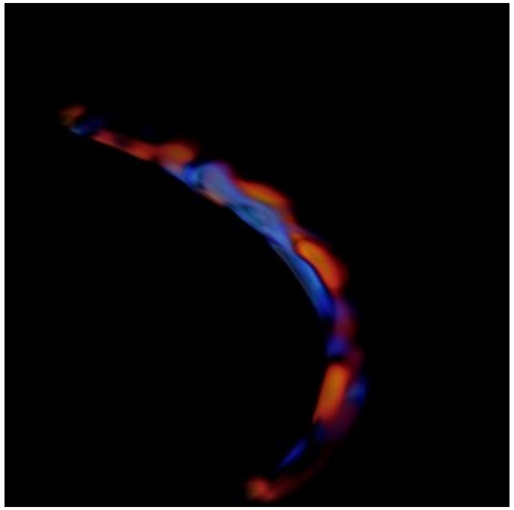


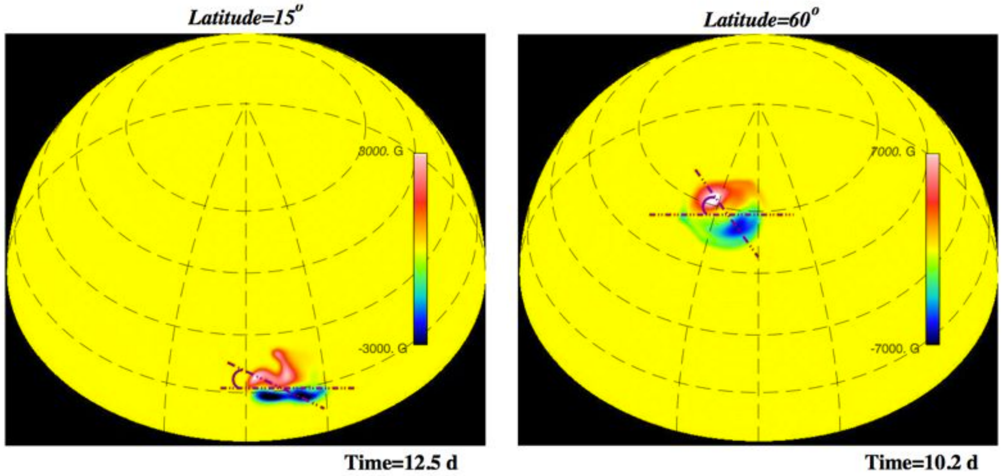
Nelson et al. (2011, 2014)

Simulation of buoyant loop rise and sunspots

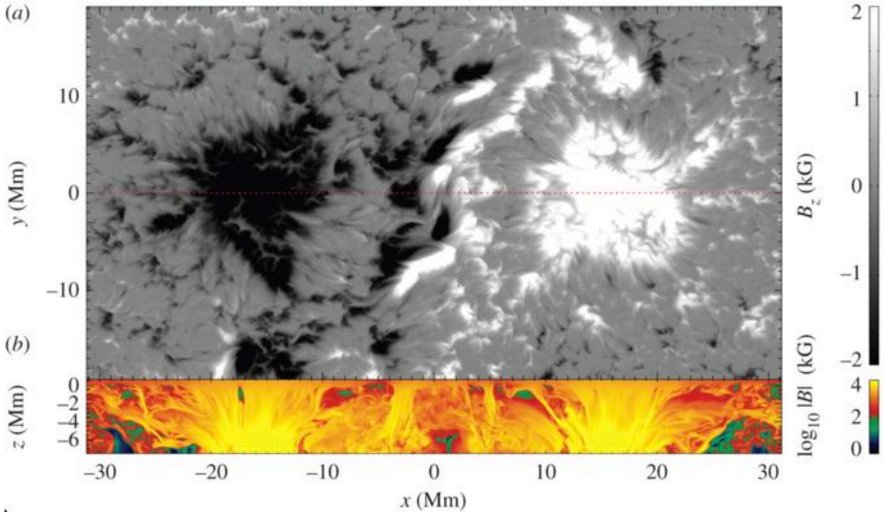
- ☐ The buoyant rise has to be modeled independently: **toroidal flux tube introduced at the base of the CZ in a convective layer**

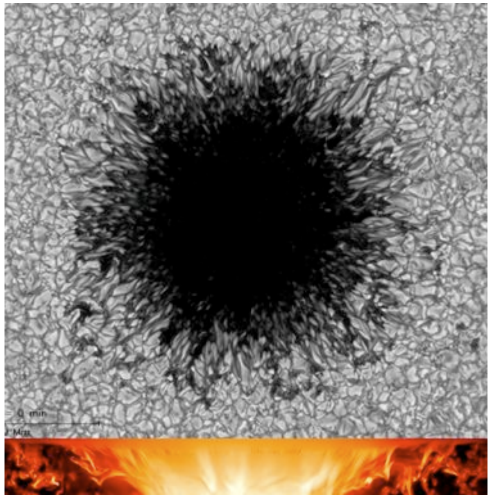
Jouve et al. 2013





- ☐ Or individual sunspots can be modeled in **radiative MHD codes (only upper CZ and atmosphere)**

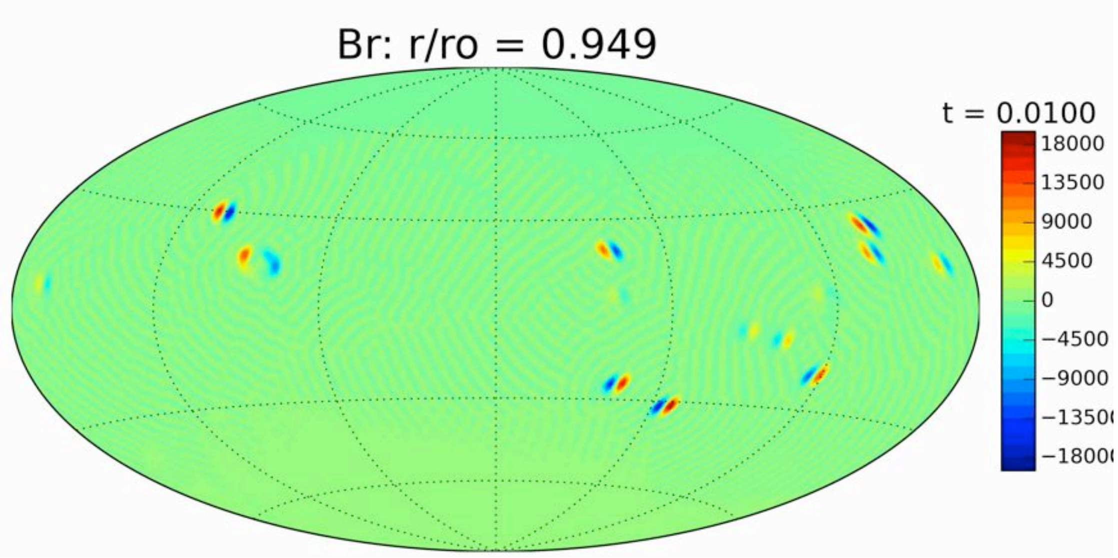


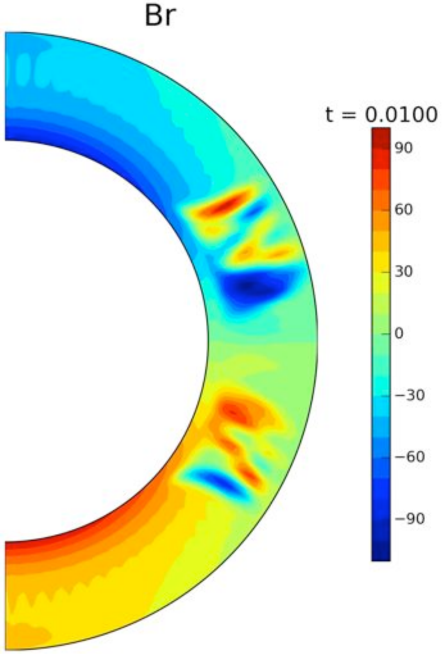


Rempel et al. 2009, 2014

3D kinematic models: combining approaches

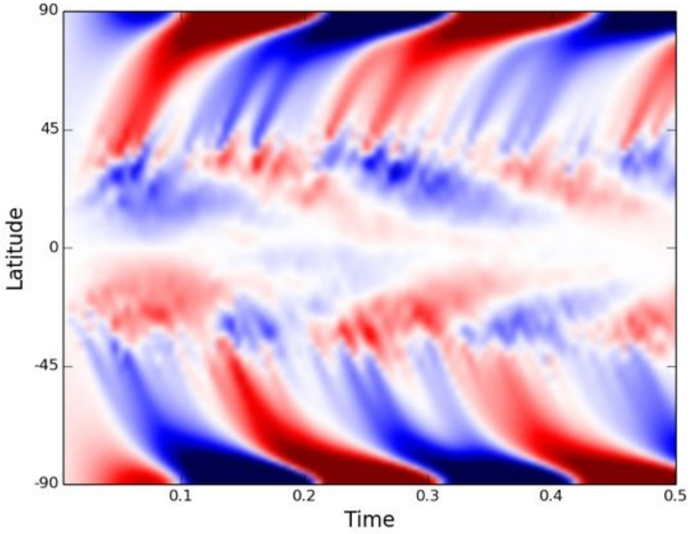
- Mean-field dynamo models + 3D flux emergence and spot formation (Yeates & Munoz Jaramillo 2013, Miesch & Dikpati 2014, Miesch & Teweldebirhan 2016, Kumar, Jouve, Pinto & Rouillard 2018)





CEFIPRA Project
(D. Nandy & L. Jouve)

Self-consistent butterfly diagrams



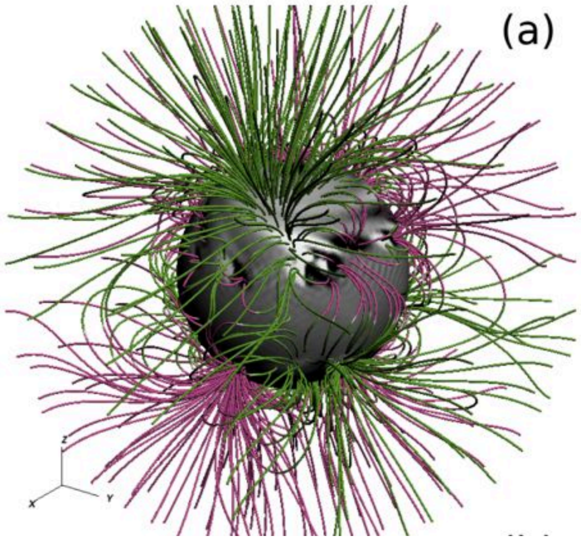
Kumar, Jouve, Pinto & Rouillard , 2018

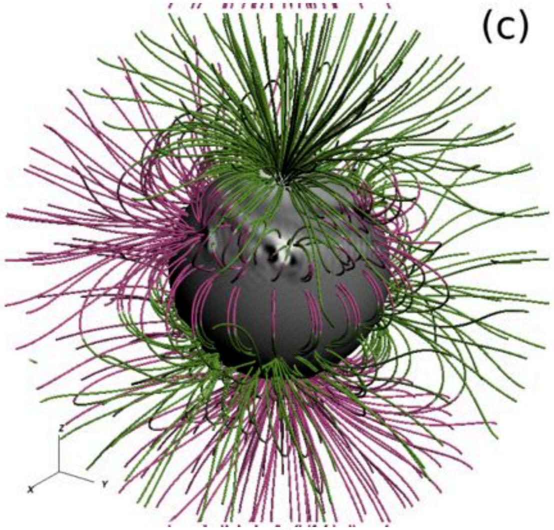
Kumar, Jouve & Nandy, submitted (parametric study)

3D kinematic models: combining approaches

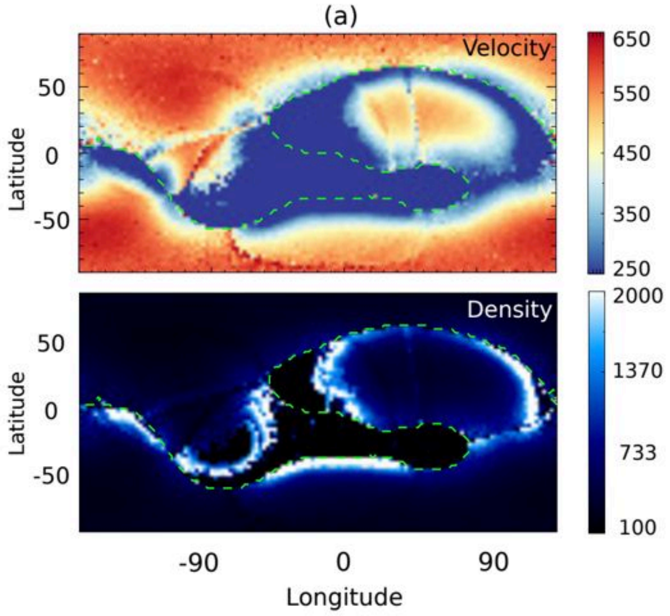
- ❑ Coronal fiel reconstruction and solar wind solutions

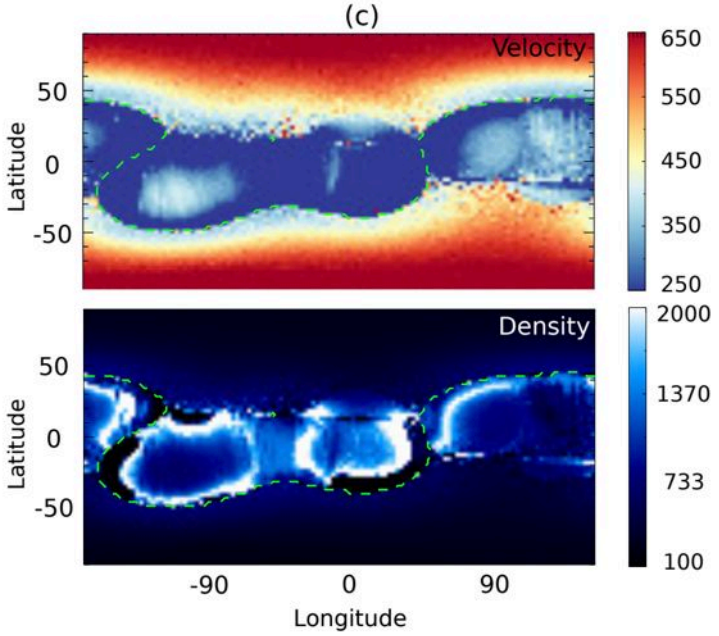
PFSS
reconstruction





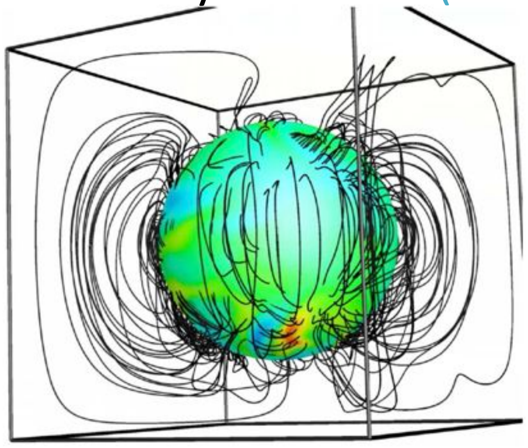
At r=21.5 R





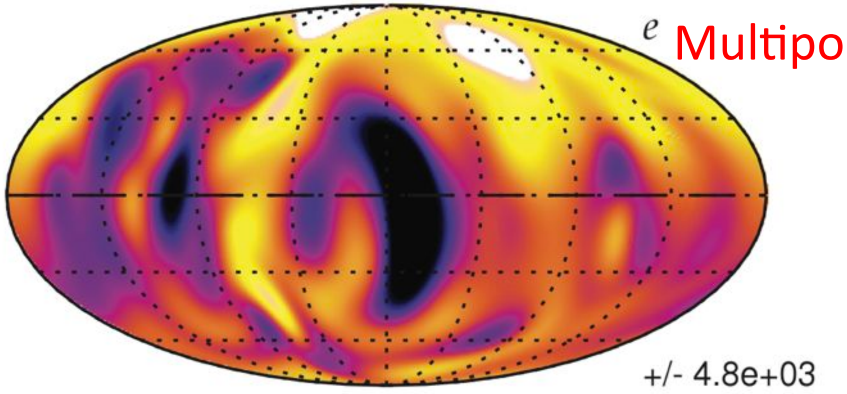
Dynamo models of fully convective stars

☐ Weakly stratified (Dobler 2005)



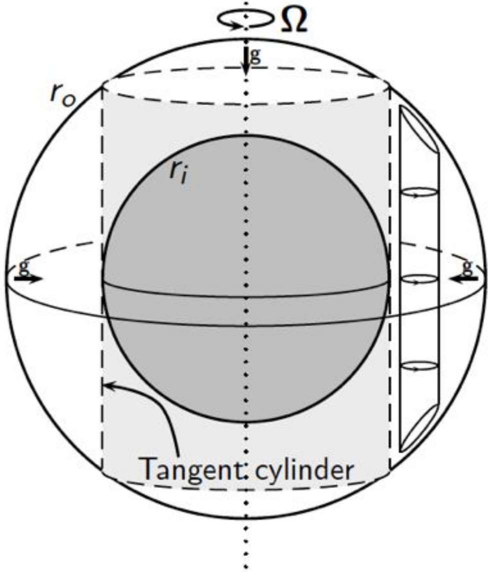
Dipolar

☐ More strongly stratified (Browning 2008)



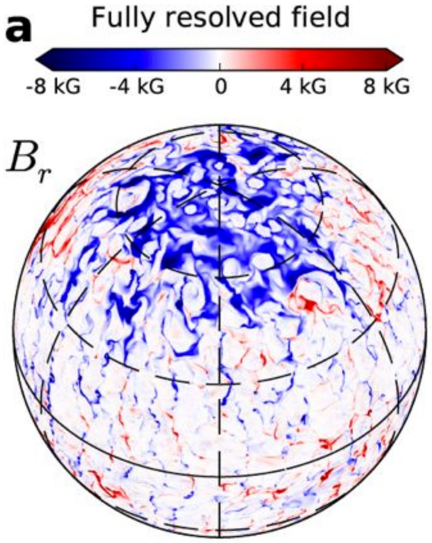
Multipolar

☐ Systematic study (Gastine et al. 2012)



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

☐ Most recent (Yadav et al. 2015, 2016)



Small and large scales coexist

Fully convective stars: Rossby and bistability

- Change in Rossby (inertia/Coriolis) (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

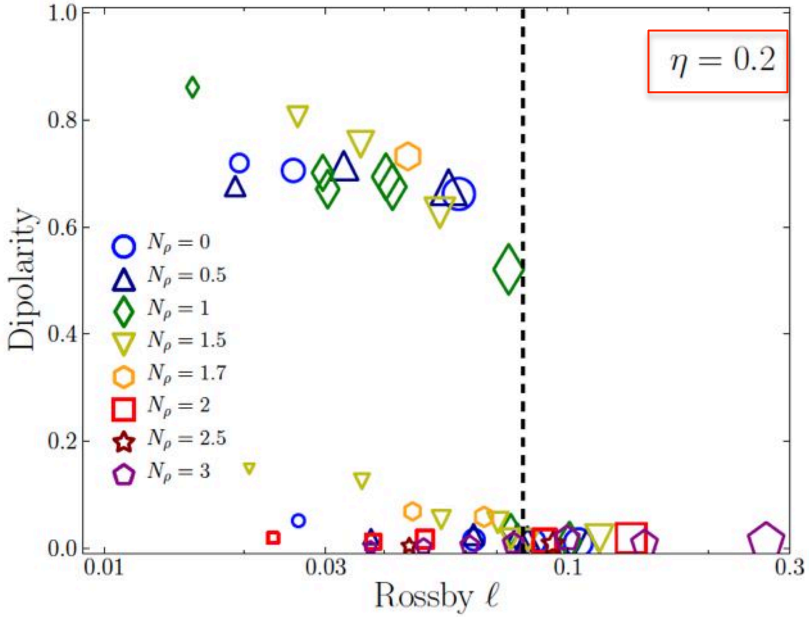
    (no role of shear in dynamo)

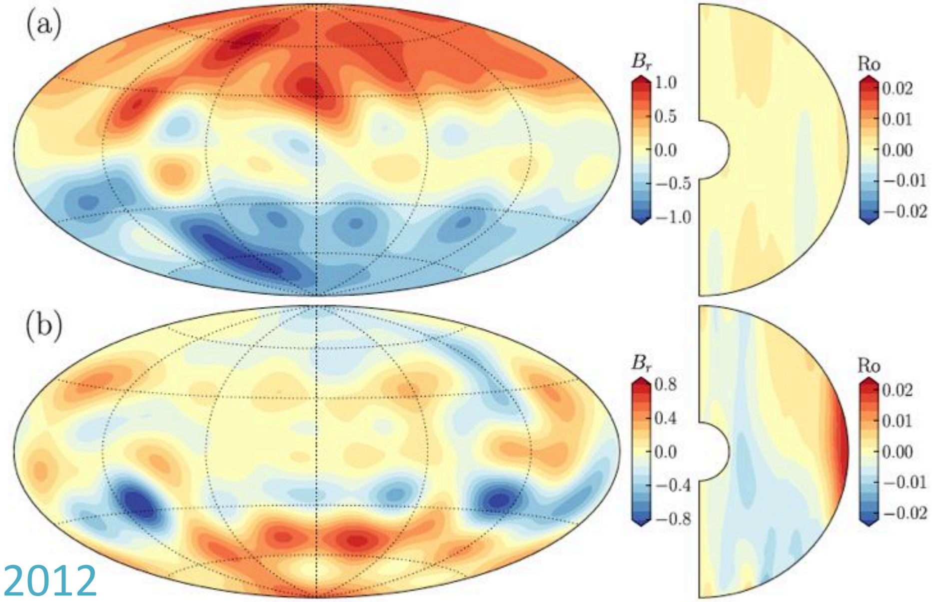
    $\Lambda = 1$ (magnetostrophic?)
  - Weak initial field=shear

    (shear plays a role: Parker waves?)

    $\Lambda < 1$ (geostrophic?)

- Strong stratification leads to multipolar fields

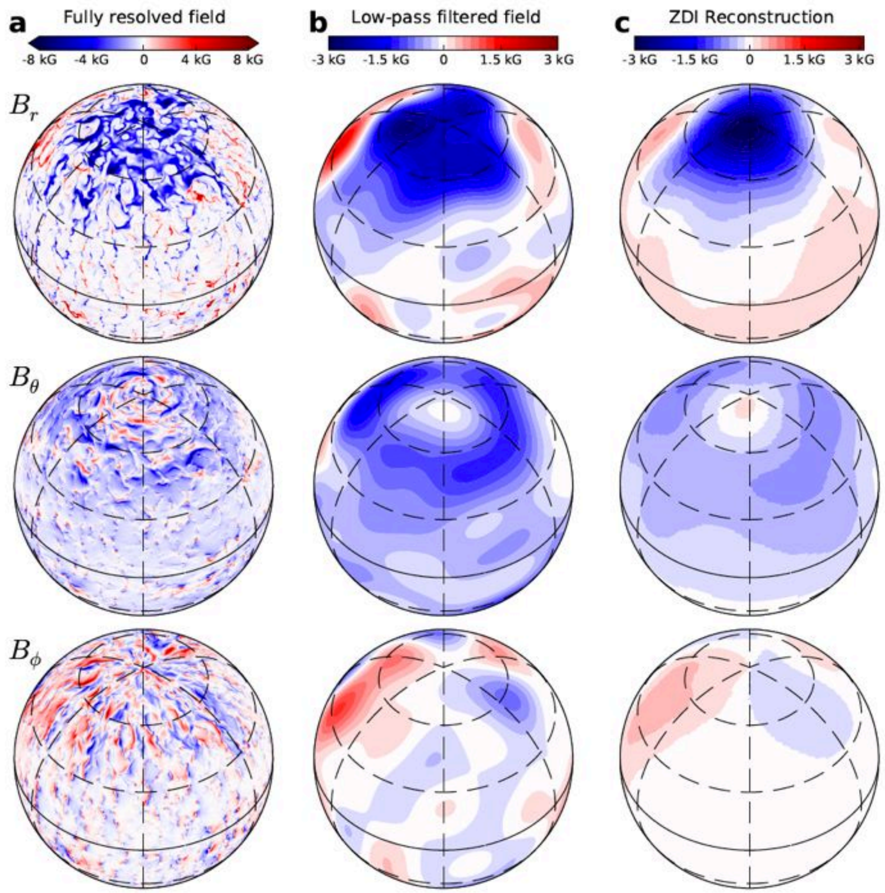




Gastine et al. 2012

Fully convective stars: influence of Rossby number

Yadav et al. (2015): small Ro

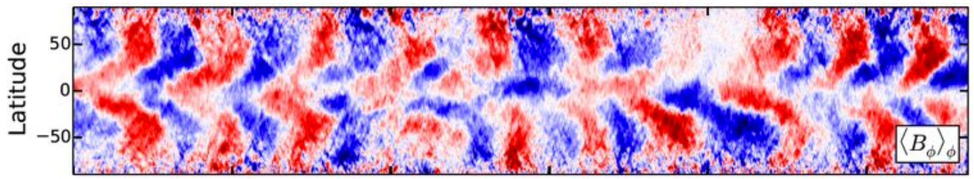


☐ Small and large scales coexist
(even though strong stratification Nrho=5)

☐ ZDI reconstruction:

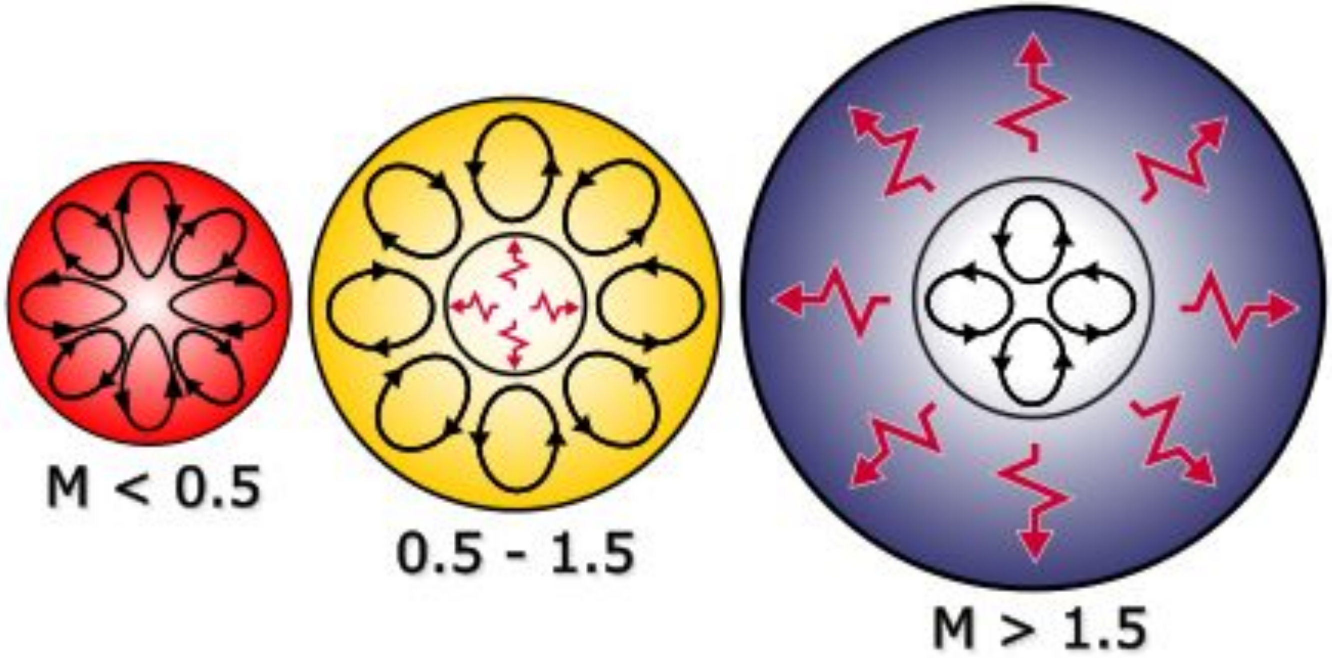
- Field geometry recovered (large-scale only)
- Field strength underestimated

Yadav et al. (2016): larger Ro



☐ Magnetic cycle on a modeled slowly-rotating fully convective star

Magnetism of more massive stars



❑ **In more massive stars (with radiative envelopes)**

- Only 5 to 10% are found to possess a strong magnetic field, they are Ap/Bp stars
- Magnetic field starts to be detected on non-Ap stars: much weaker and complex

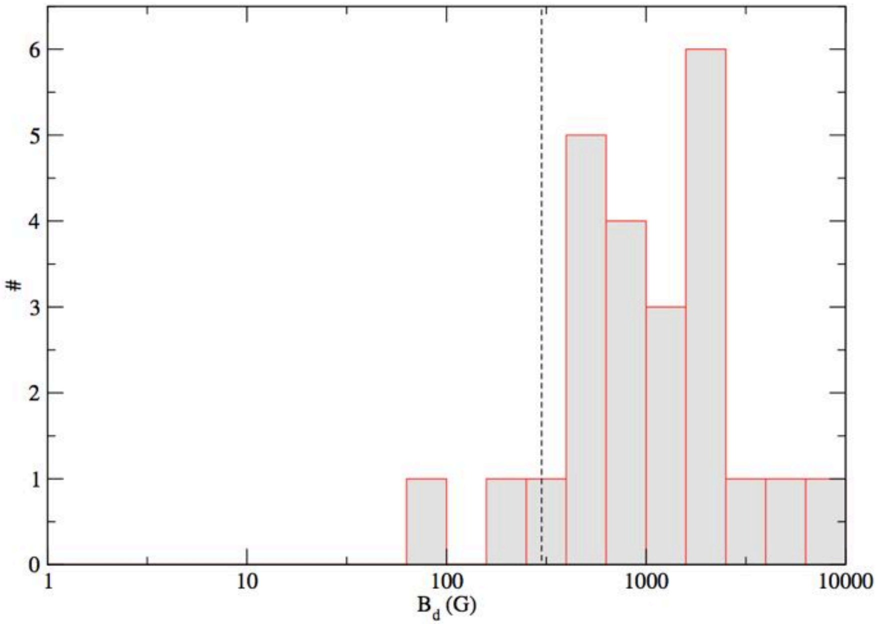
Ap/Bp stars magnetism

❑ Field configuration: inclined dipole (Lüftinger et al 2010)

❑ Field intensity: either strong fields (B > 300 G) or no field (Aurière et al. 2007)

❑ No detection on large sample of Am or HgMn stars (Aurière et al. 2010)

Musicos + NARVAL



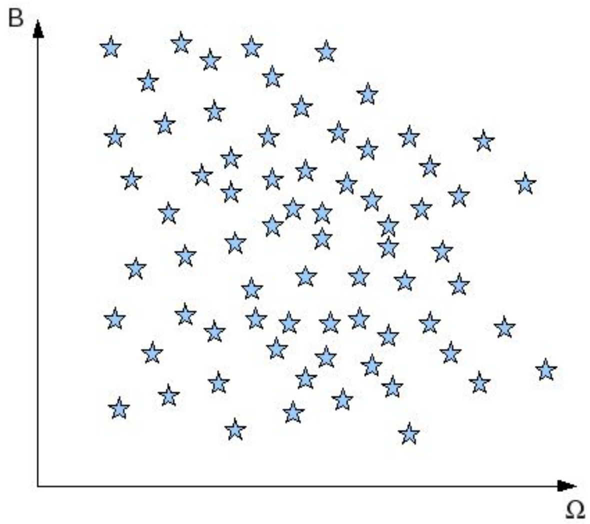
❑ **Why such a threshold?** (Aurière et al. 2007)

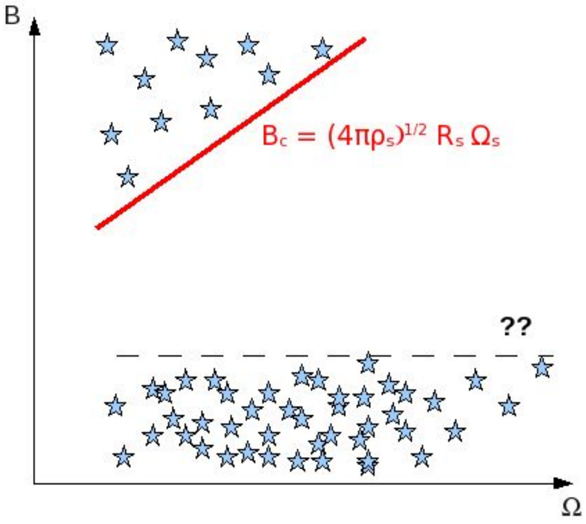
- Strong poloidal field → Differential rotation suppressed → Strong measured Bl
- Weak poloidal field → Strong Bphi → Instabilities (Tayler 73) → Small horizontal scales Weak measured Bl

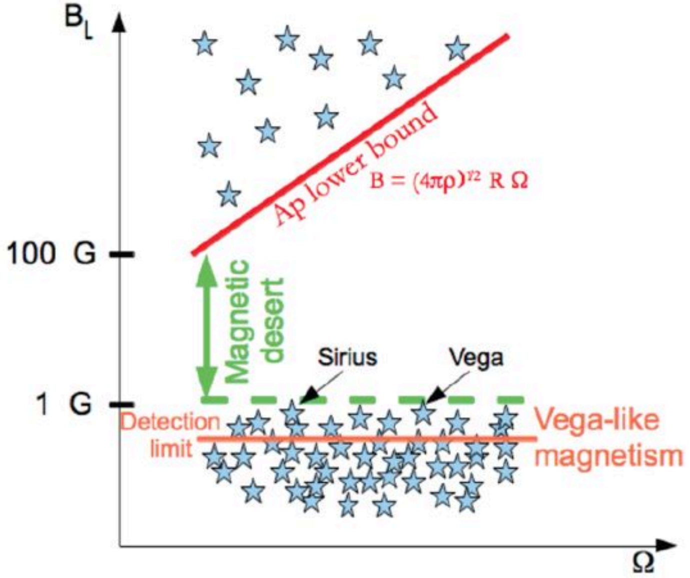
- Structure dominated by toroidal field when $\boxed{Max\left(\frac{B_\phi}{B_p}\right) \approx r\sin\theta\frac{\sqrt{4\pi\rho}\;\Omega}{B_p} \geq \alpha}$
- Possible instabilities for $\boxed{Bp < Bc = r\sin\theta\sqrt{4\pi\rho}\Omega}$

Theoretical argument

Courtesy: François Lignières

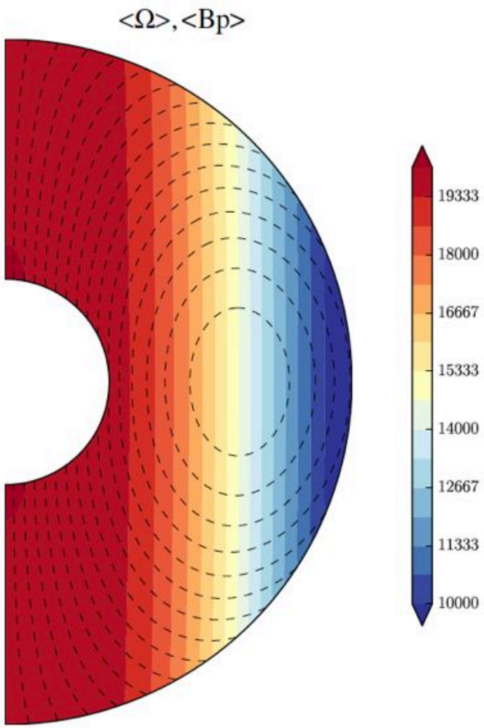


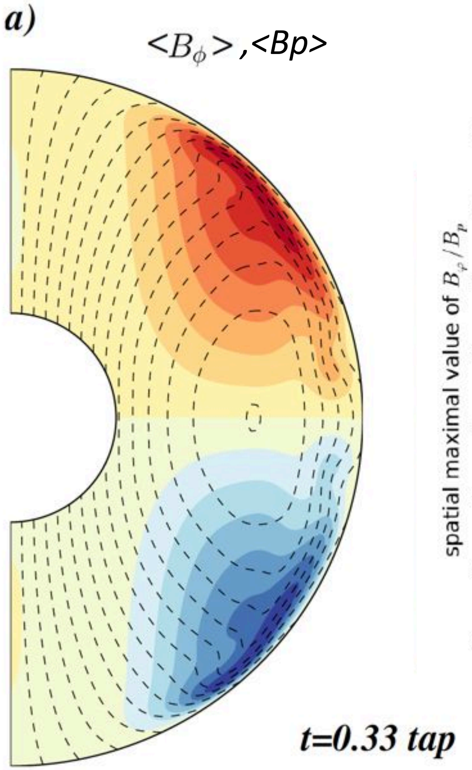


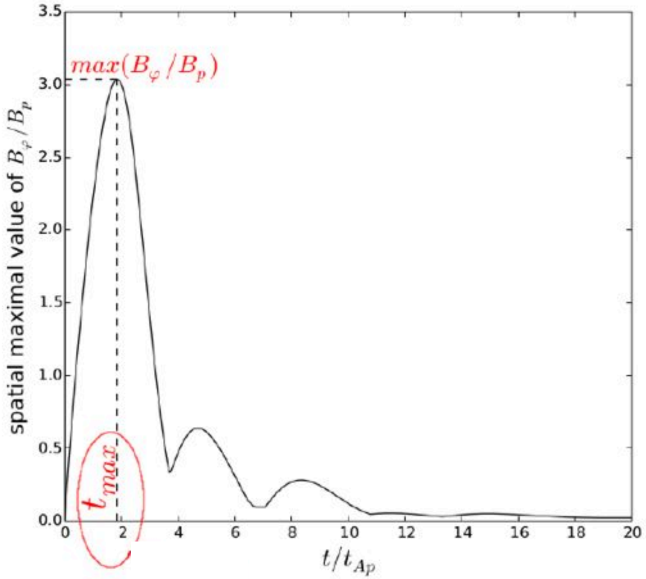


- Stellar formation: Fossil fields of variable intensities Bp, various rotation rates (and diff.rot.)
- For Bp < Bc → instabilities → Small longitudinal field (below detection limit).
- For Bp > Bc → Stable dipolar configurations (detected in Ap stars).

Numerical approach: 3D simulations







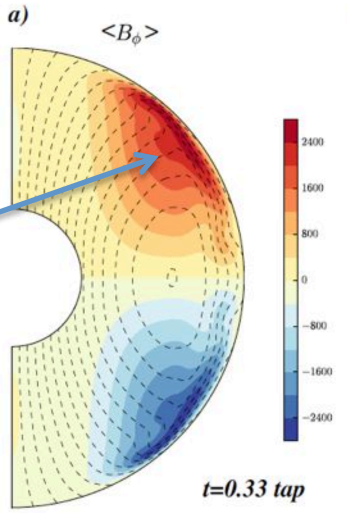
- Initial conditions: poloidal field (Lu) wound-up by cylindrical differential rotation (Re)

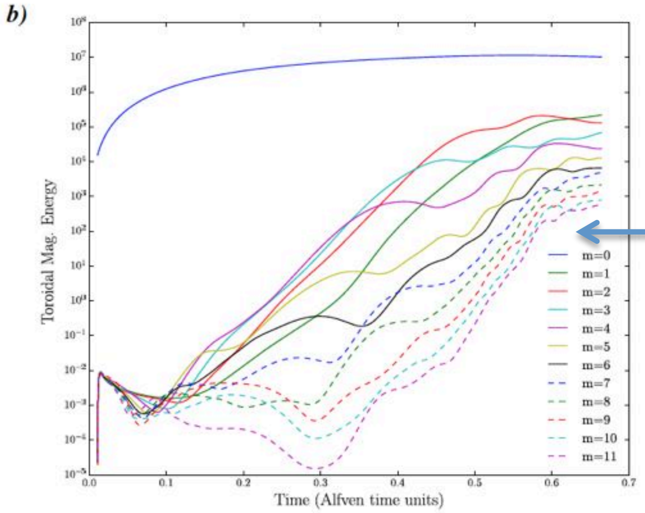
- A toroidal field is built which will then back-react on the differential rotation:
  - Is this configuration unstable?
  - Under which conditions is it triggered?
  - What are the consequences of this instability?

Evidence for an instability

❑ Typical case: Lu=60, Re=2 x 10^4: instability sets in around t=0.1 tap

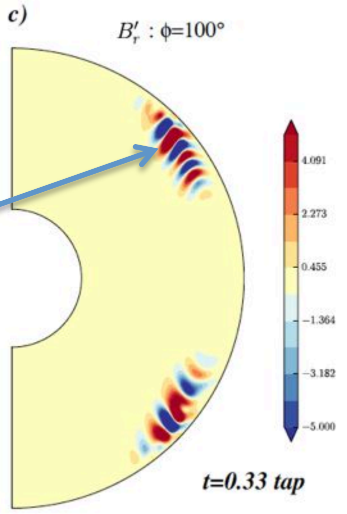
- Strong toroidal field, antisymmetric, close to the surface

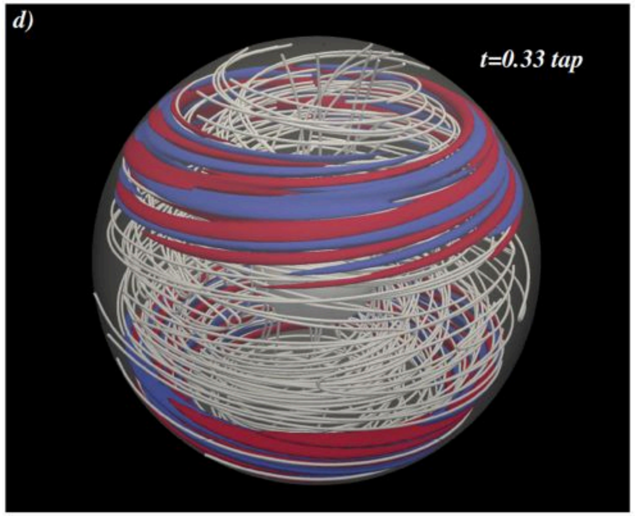




- Favored modes: m=4, 5 and 6

- Instability around the regions of strong toroidal field



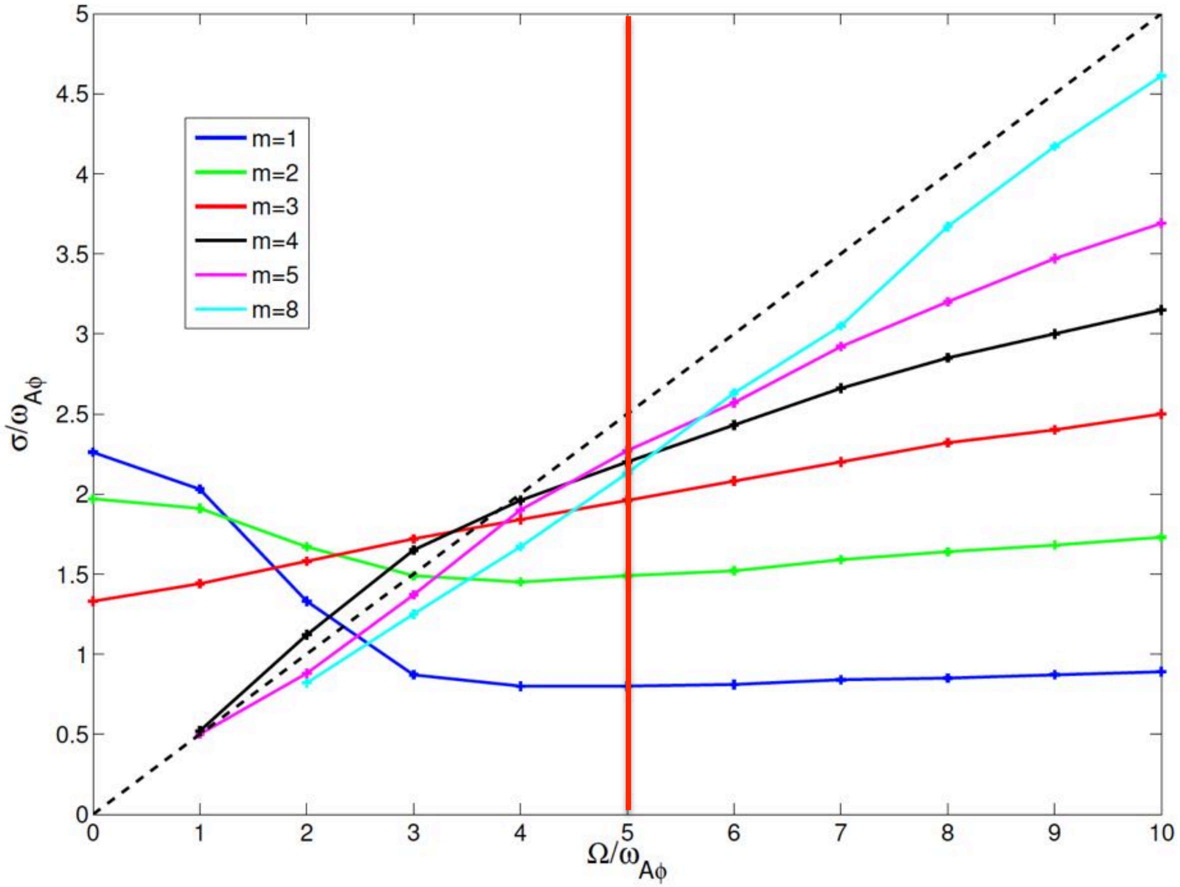


Jouve, Gastine Lignières 2015

What is the nature of this instability?

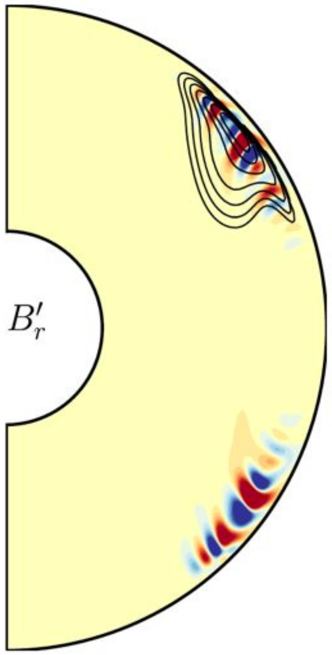
☐ MRI vs TI: importance of rotation rate to toroidal Alfvén frequency ratio: Ogilvie (2007)

$$\left[\omega^2-\frac{m^2B^2}{s^2}-2\boxed{\left(\frac{\Omega_0}{\omega_{A_{\phi 0}}}\right)^2} s\,\Omega\,\mathbf{e_s}\cdot\nabla\Omega+2\,B\,\mathbf{e_s}\cdot\nabla\left(\frac{B}{s}\right)\right]\times\left[\omega^2-\frac{m^2B^2}{s^2}\right]=\left[2\boxed{\left(\frac{\Omega_0}{\omega_{A_{\phi 0}}}\right)}\omega\,\Omega+\frac{2mB^2}{s^2}\right]^2$$



In all our cases, the instability sets in when $\boxed{\Omega/\omega_{A\varphi}\approx 5}$

→ MRI regime

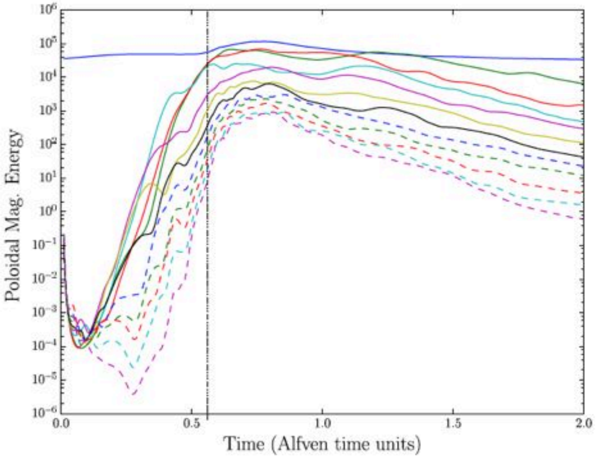


What distinguishes between stable and unstable cases?

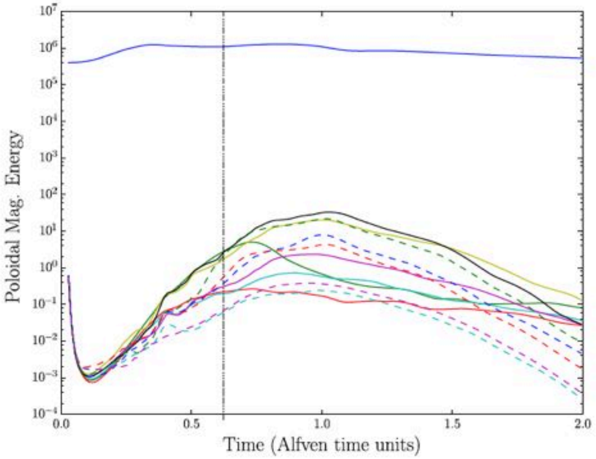
- Background field evolves on poloidal Alfvén time scale t_{ap}
- Growth time of the MRI of the order of t_{Ω} ($\sigma = q\, \Omega/2$ with q around 1 here)

Stable and unstable cases distinguished by the ratio t_{Ω}/t_{ap}

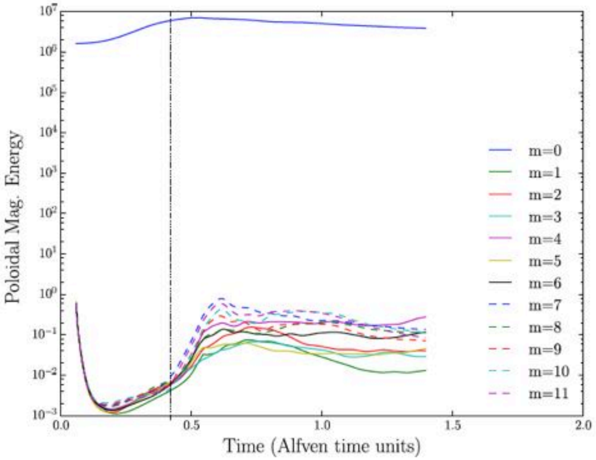
t_{Ω}/t_{ap} = 3.10^{-3}



t_{Ω}/t_{ap} = 10^{-2}



t_{Ω}/t_{ap} = 2.10^{-2}



Effects of stable stratification

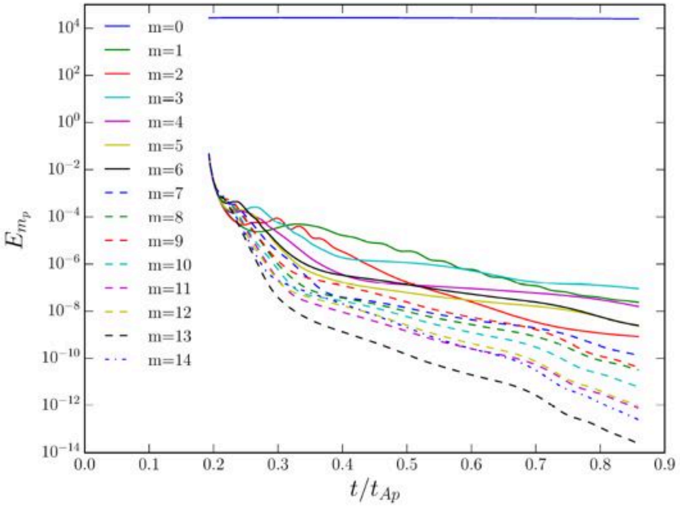
- ❑ Additional parameters:
  - ▪ degree of stratification measured by N/Ω
  - ▪ Ratio of viscosity to thermal diffusivity measured by $Pr=\nu/\kappa$
  - ▪ In stars, N/Ω is large (10^2-10^3) and Pr is small (10^{-6}-10^{-4})

- ❑ We expect strong effects of stable stratification

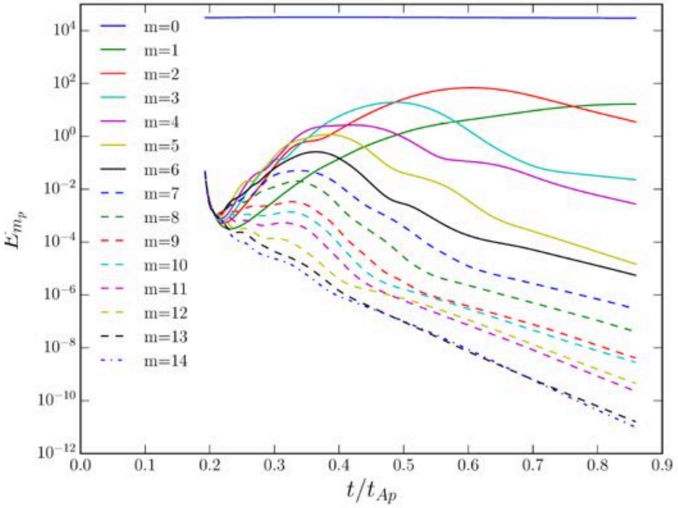
- ❑ But a large thermal diffusion (small Pr) can help to reduce the effects of stratification (our axisymmetric solutions depend only on Pr x $(N/\Omega)^2$ if Pr small enough)

For $N/\Omega=5$, the MRI:
- is lost for Pr=1
- recovered for $Pr=10^{-2}$

Gaurat, Jouve
& Lignières, in prep.



Pr=1



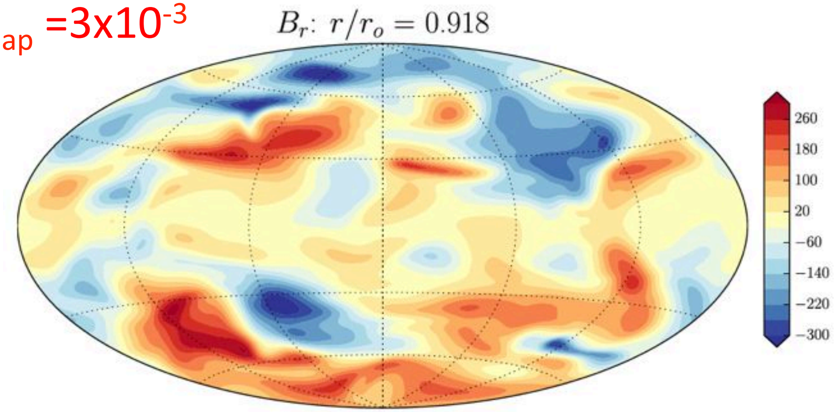
$Pr=10^{-2}$

Application to A-type stars

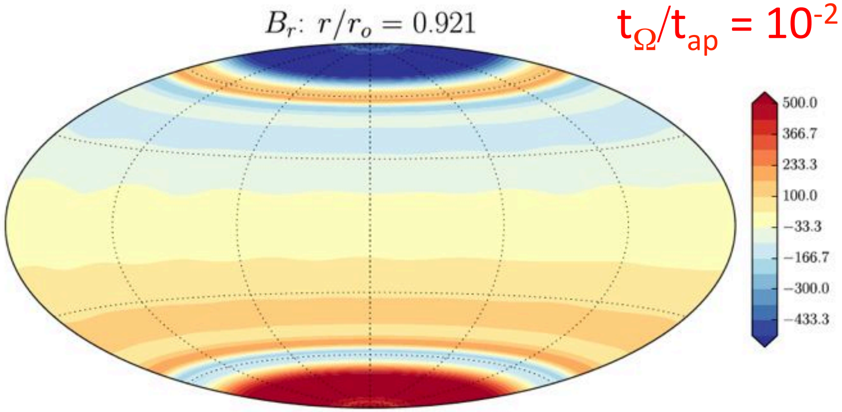
- ☐ Surface radial field: non-axisymmetric VS axisymmetric

  - Unstratified cases

$t_\Omega/t_{ap} = 3\text{x}10^{-3}$

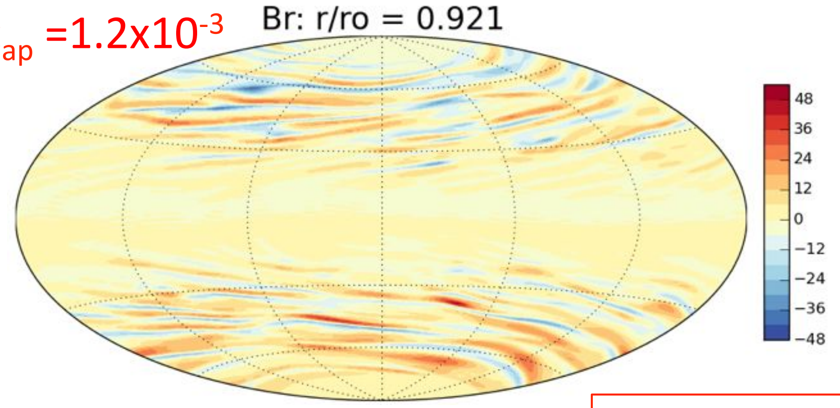


$t_\Omega/t_{ap} = 10^{-2}$

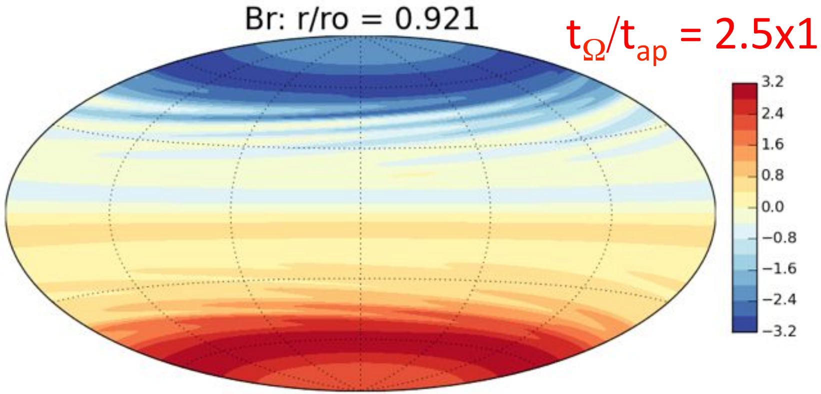


  - Stratified cases

$t_\Omega/t_{ap} = 1.2\text{x}10^{-3}$



$t_\Omega/t_{ap} = 2.5\text{x}10^{-3}$



- ☐ Estimate of threshold field:

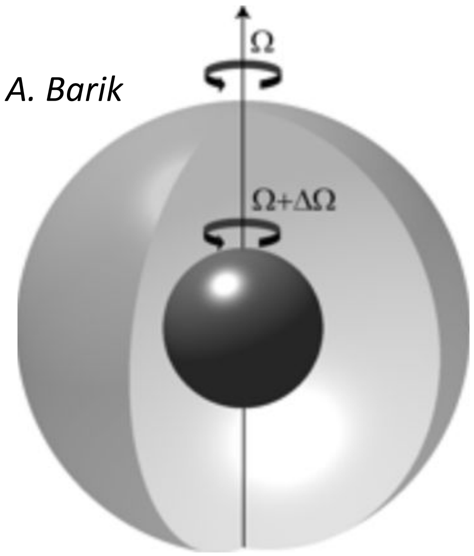
$$\boxed{B_{0_{crit}} = 10^{-2}\Omega_0 d\sqrt{\rho_0\mu_0}}$$

- ☐ Proportionality with rotation rate also seen in observations (Lignières et al. 2014)

Forced differential rotation

❑ Spherical Couette flow producing Stewartson layer and concentrated Bphi

Courtesy A. Barik

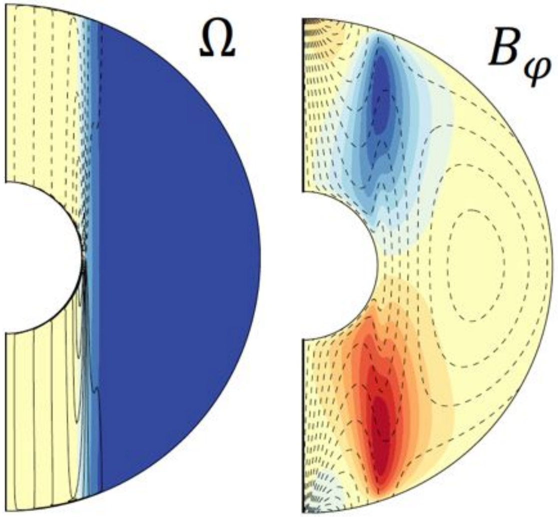


Meduri, Lignières
& Jouve, submitted

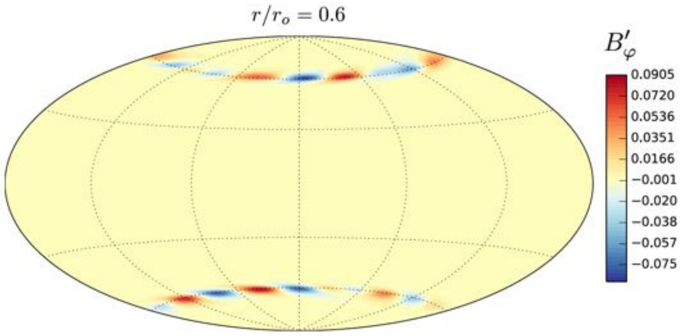
$$E = \frac{\nu}{\Omega d^2} = 10^{-5}$$

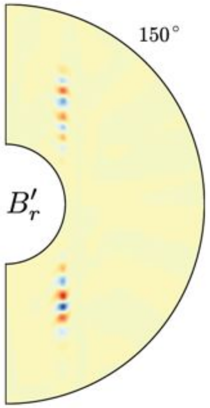
$$Ro = \frac{\Delta\Omega}{\Omega} = 0.03$$

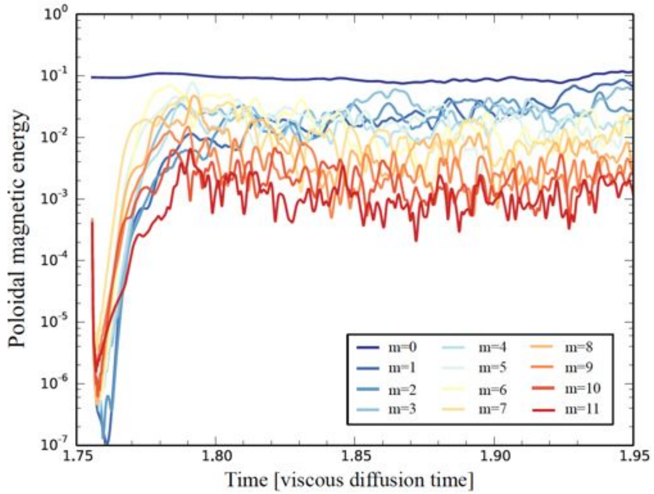
$$Rm = \frac{\Delta\Omega d^2}{\eta} = 2.10^4$$



❑ MRI and possible dynamo action?







Conclusions

- ☐ Dynamo models of solar-like stars:

  - Magnetic cycle period VS rotation period: still unclear
  - What is missing in 3D models to actually produce spots?
  - Models commonly applied to the Sun 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?

- ☐ Stellar radiative zones:

  - MRI (or TI) unstable fields if t_{Ω}/t_{ap} weak enough
  - Strong modification of surface field in unstable cases
    => Dichotomy among A-type stars ?
  - Radiative zone dynamo?
  - Angular momentum transport by magnetic fields (red giants): ANR BEAMING

- ☐ More to come with SPIROU, Solar Orbiter, PLATO