What do numerical simulations tell us about solar/stellar magnetic fields?

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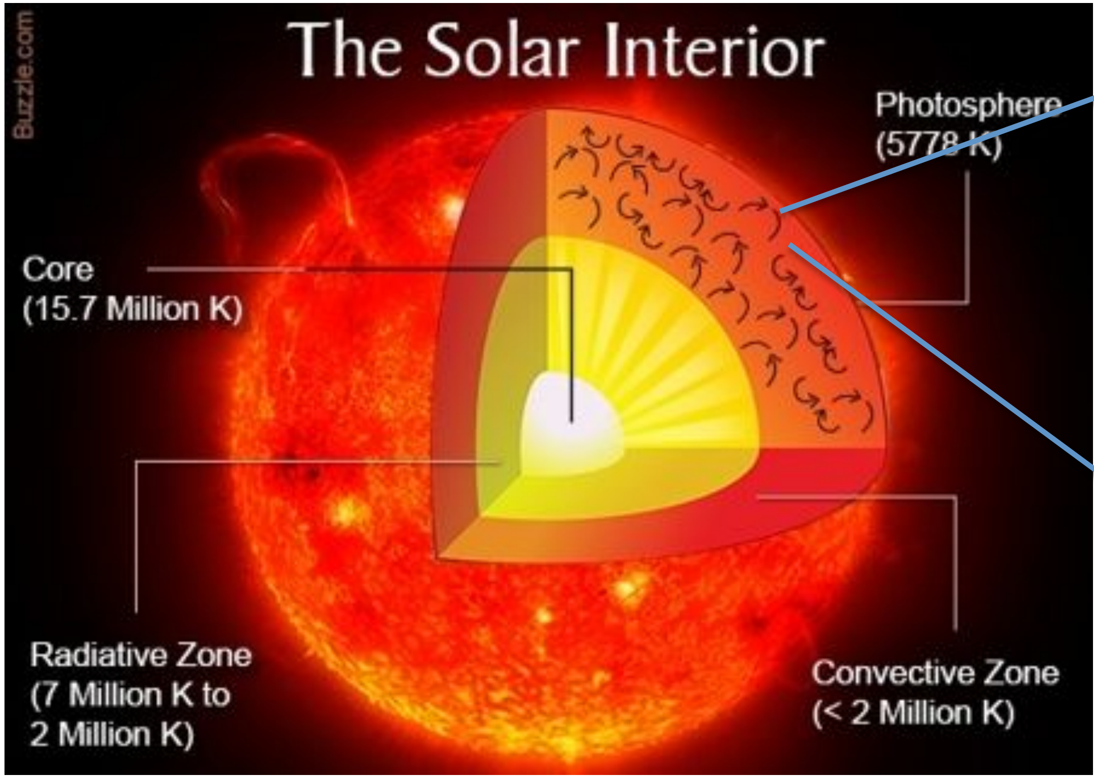
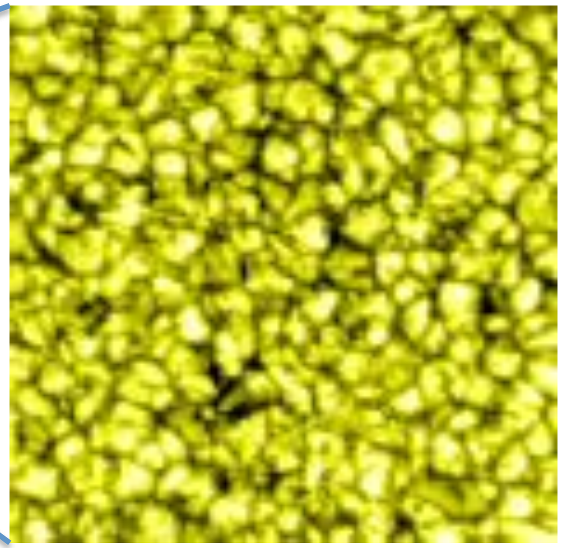
IAS, 23 November 2017

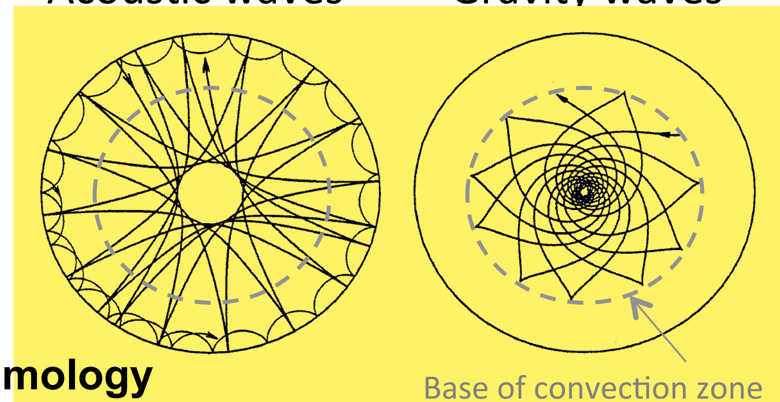
Solar interior and plasma flows



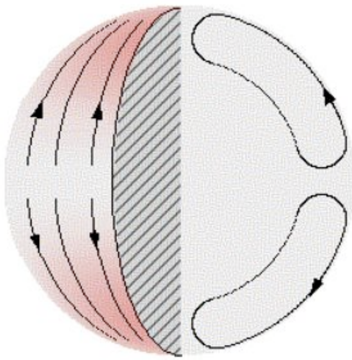
❑ Granulation (surface convection)



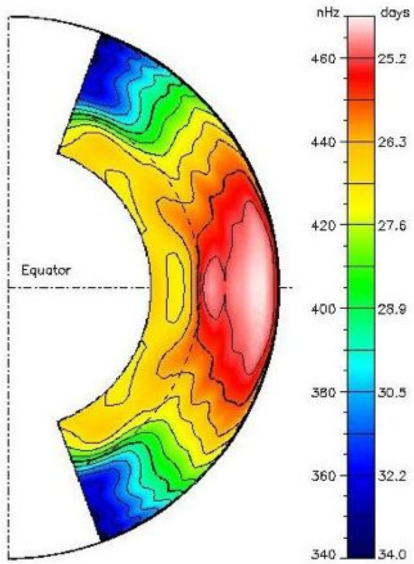
Acoustic waves Gravity waves



Helioseismology

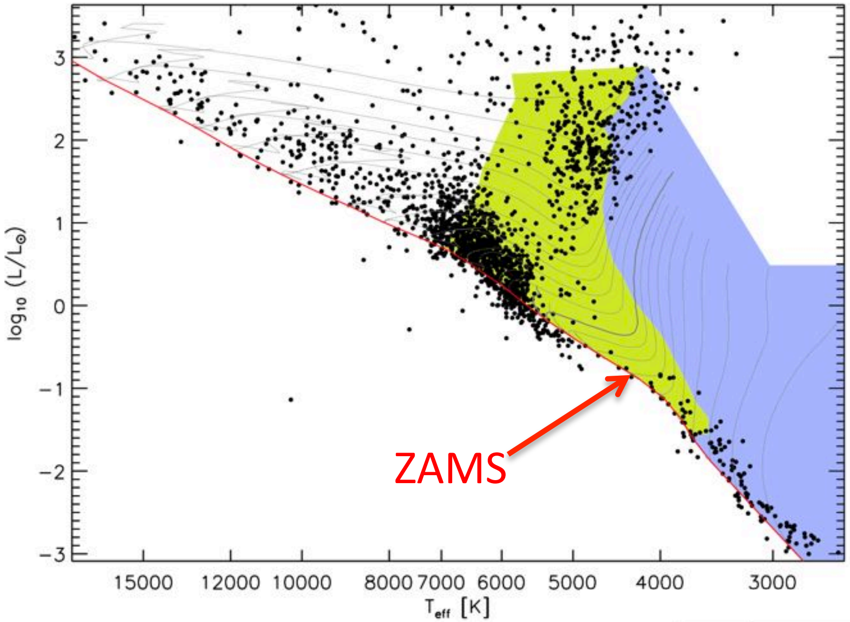


❑ Meridional flow



❑ Rotation

Rotation and convection in cool MS stars

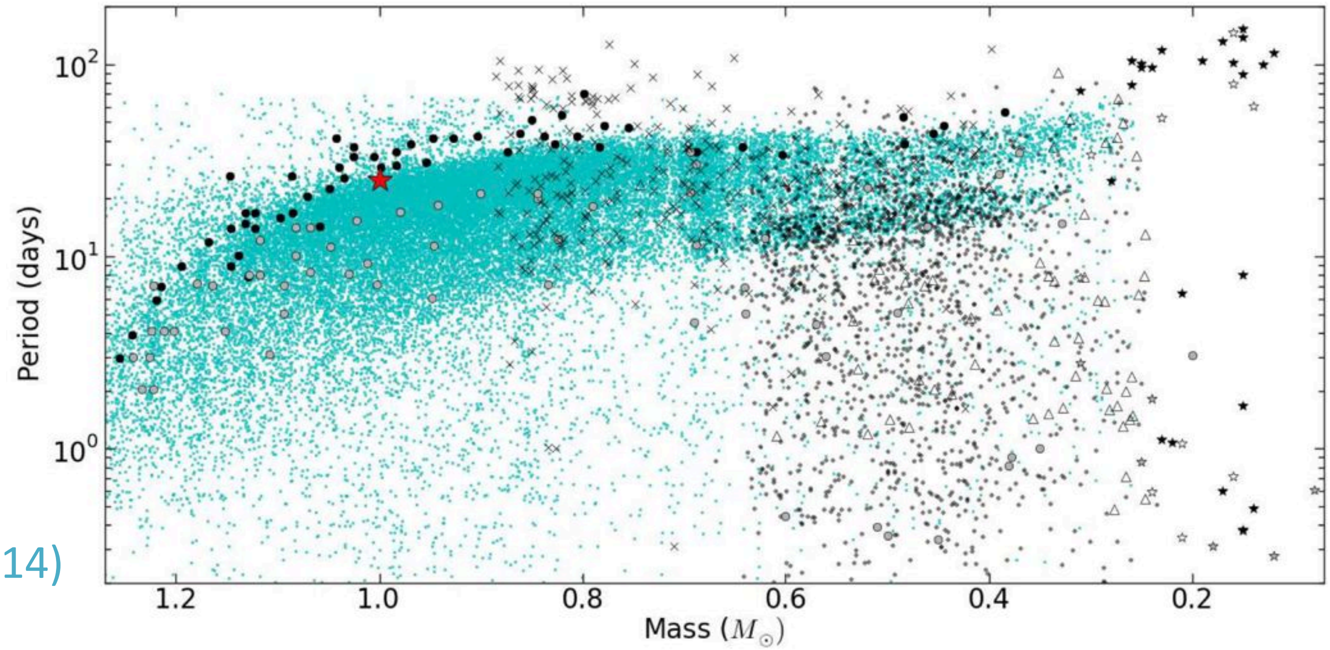


- On the MS:
  - Fully convective stars below $M_\odot < 0.35$
  - Convective envelope for $0.35 < M_\odot < 1.4$

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

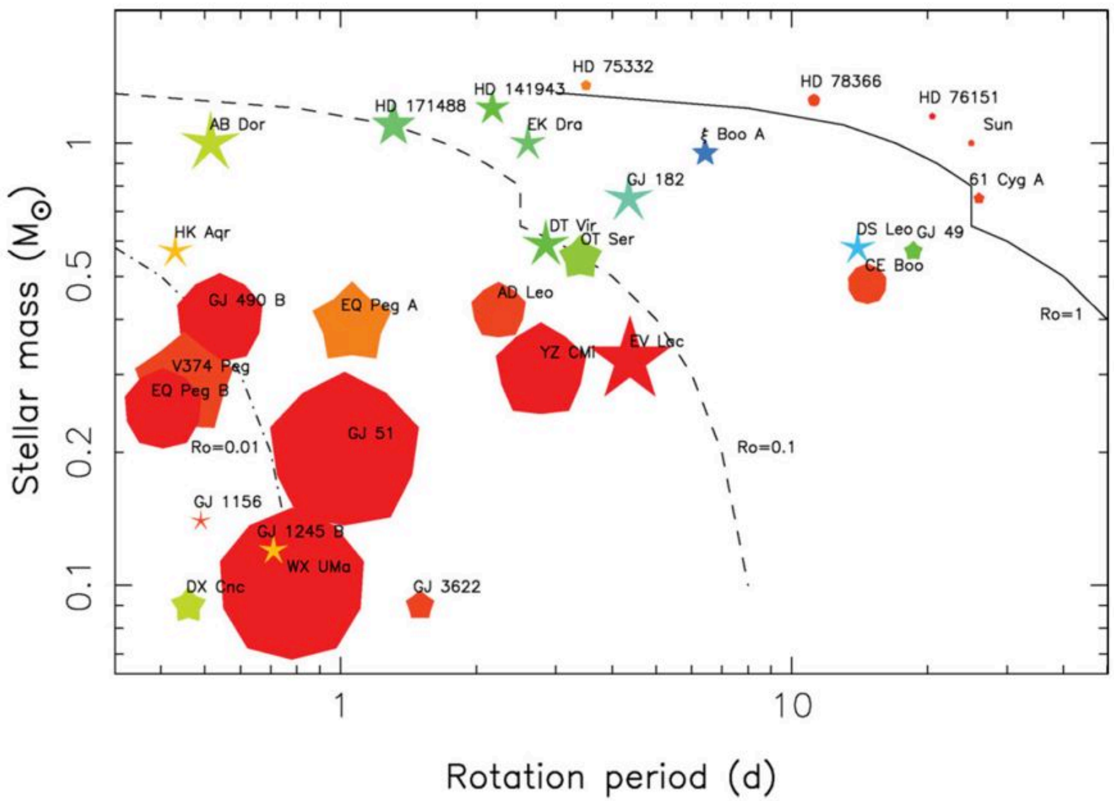
- Relatively fast rotation but large spread

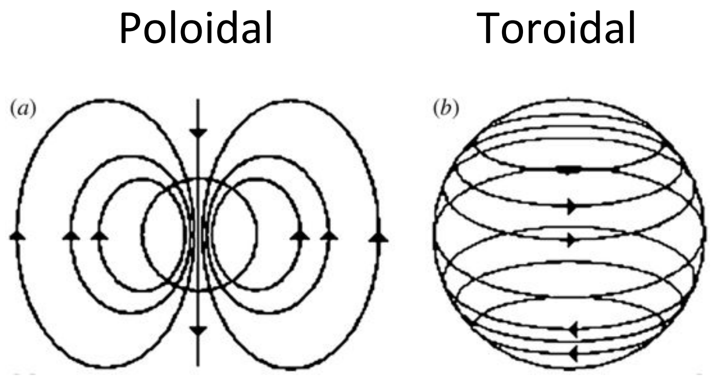
McQuillan et al. (2014)



Magnetic fields in cool stars

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

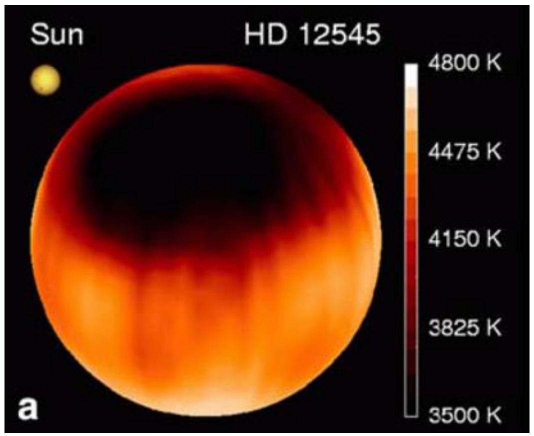




- ❑ Mostly multipolar for $M_\odot > 0.35$
- ❑ Mostly dipolar for $M_\odot < 0.35$
- ❑ Bistability for $M_\odot < 0.2$
- ❑ Field strength increases with rotation
- ❑ More and more toroidal with rotation

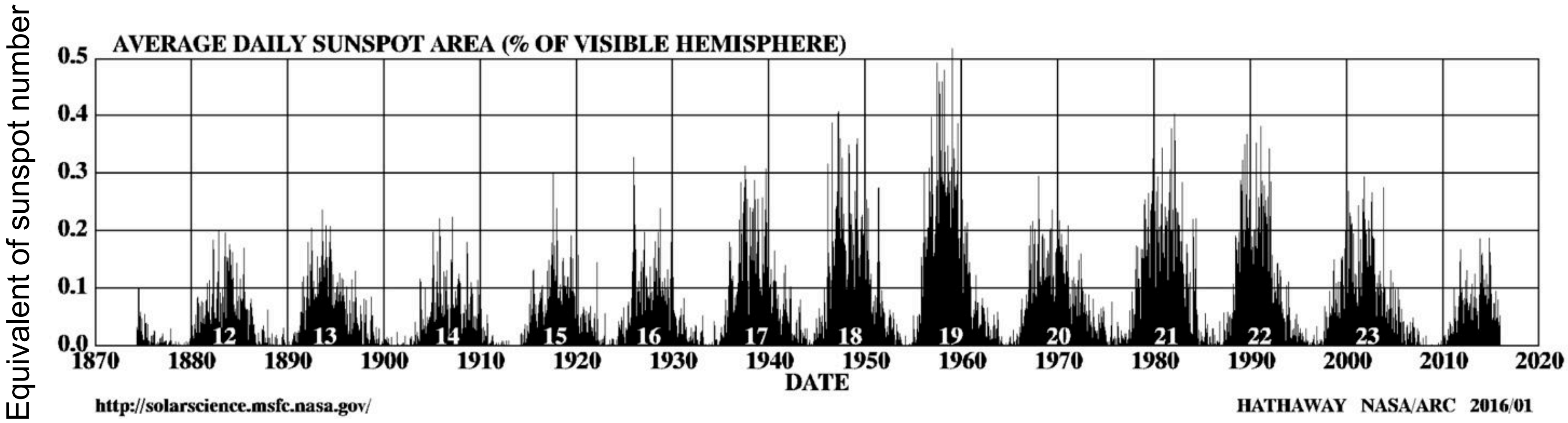
Petit et al. 2008, B cool survey (Marsden et al. 2014)

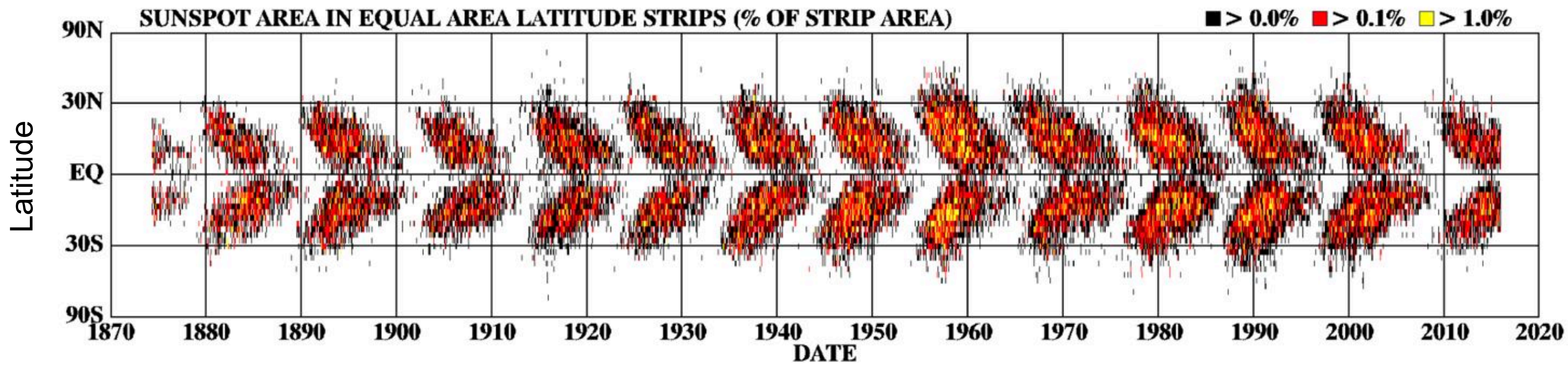
Strassmeier (1999)



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

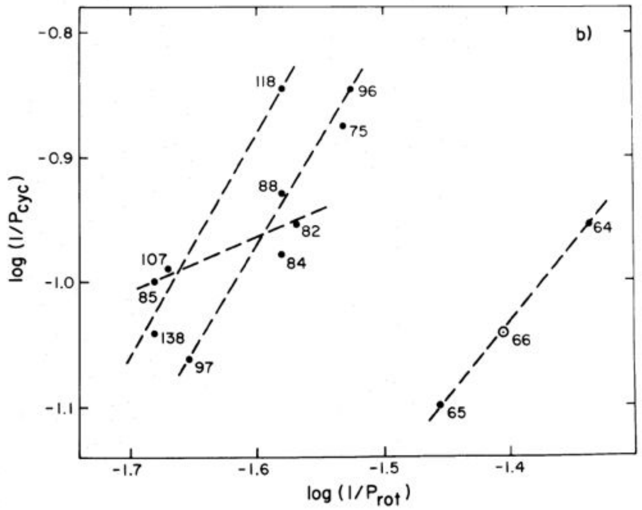
The solar magnetic cycle: sunspot evolution



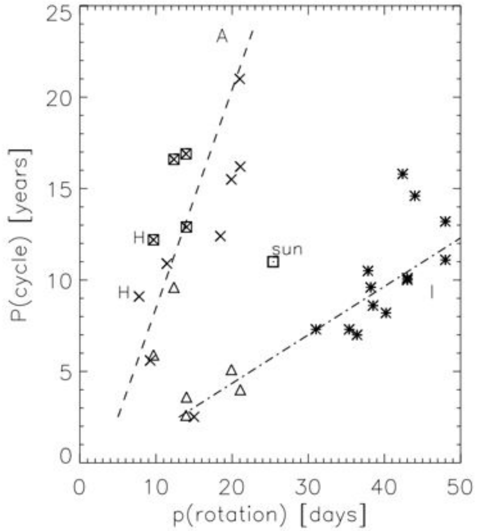


Observations of magnetic cycles?

Noyes et al. 1984



Böhm-Vitense 2007



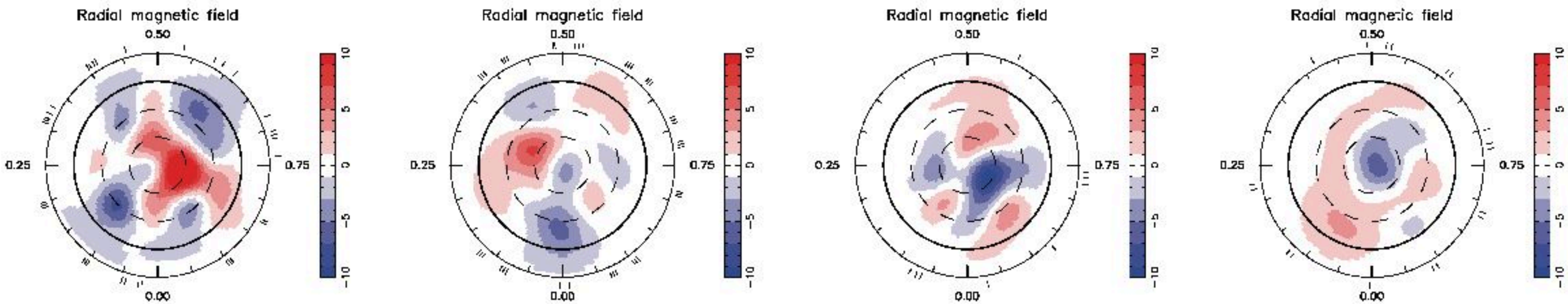
Chromospheric activity (Mount Wilson data, Ca II HK lines):

- 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, T.Lüftinger talk (complex variability)

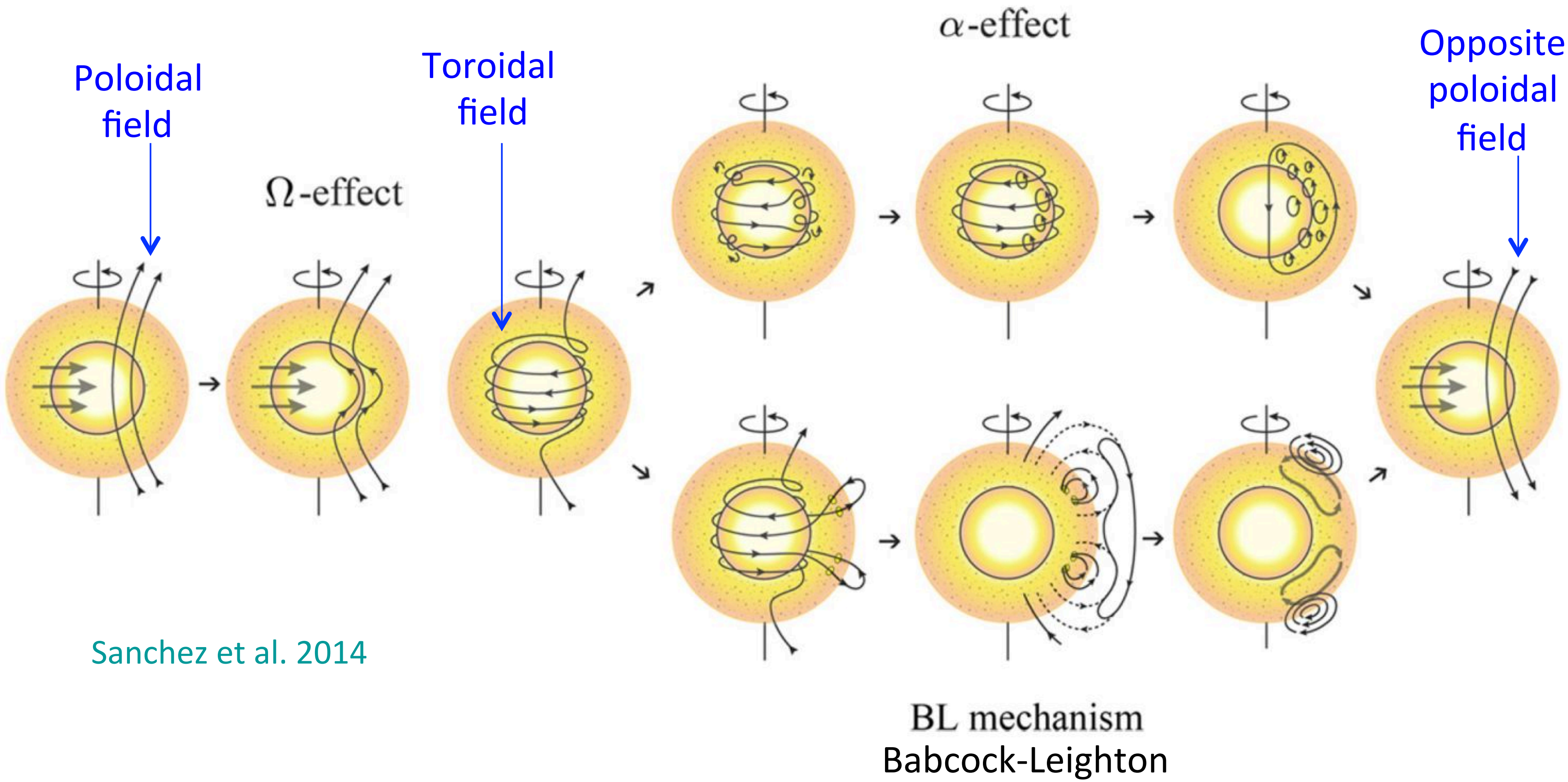
Boro-Saika et al 2016: 61 Cyg A: 14 years

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

Our Sun

Basic solar dynamo ingredients (kinematic dynamo)

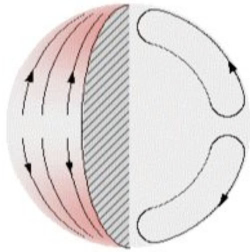
The solar dynamo: process through which the motions of a conducting fluid permanently regenerates a magnetic field

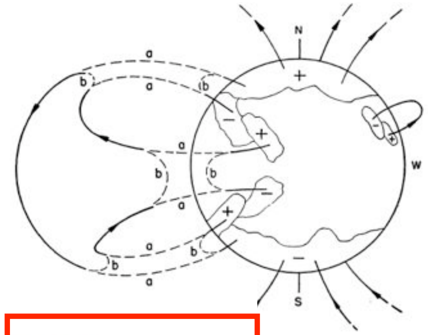


Sanchez et al. 2014

Magnetic cycles in 2D models

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

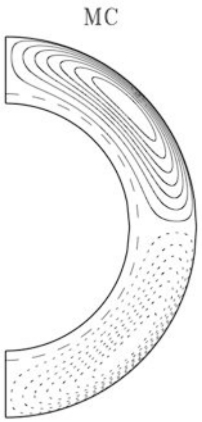




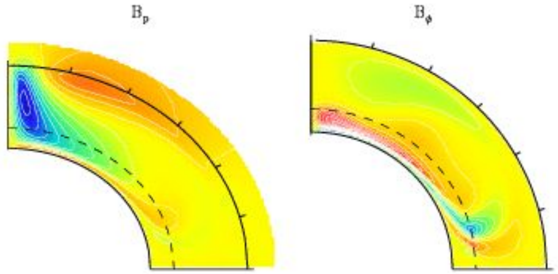
$$\frac{\partial A_\phi}{\partial t} = \frac{\eta}{\eta_t}(\nabla^2 - \frac{1}{\varpi^2})A_\phi - R_e \frac{\mathbf{u}_p}{\varpi}\cdot\nabla(\varpi A_\phi) + C_\alpha \alpha B_\phi + C_s S(r,\theta,B_\phi)$$

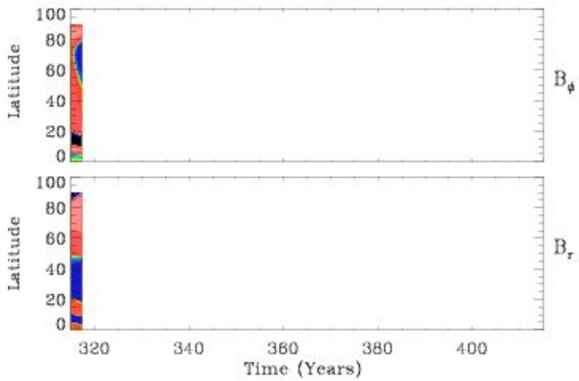
$$\frac{\partial B_\phi}{\partial t} = \frac{\eta}{\eta_t}(\nabla^2 - \frac{1}{\varpi^2})B_\phi + \frac{1}{\varpi}\frac{\partial(\varpi B_\phi)}{\partial r}\frac{\partial(\eta/\eta_t)}{\partial r} - R_e \varpi \mathbf{u}_p \cdot \nabla(\frac{B_\phi}{\varpi}) - R_e B_\phi \nabla\cdot\mathbf{u}_p + C_\Omega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

Standard model:
single-celled
meridional
circulation



Dikpati & Charbonneau 1999
Jouve & Brun 2007





- Cyclic field
- Butterfly diagram

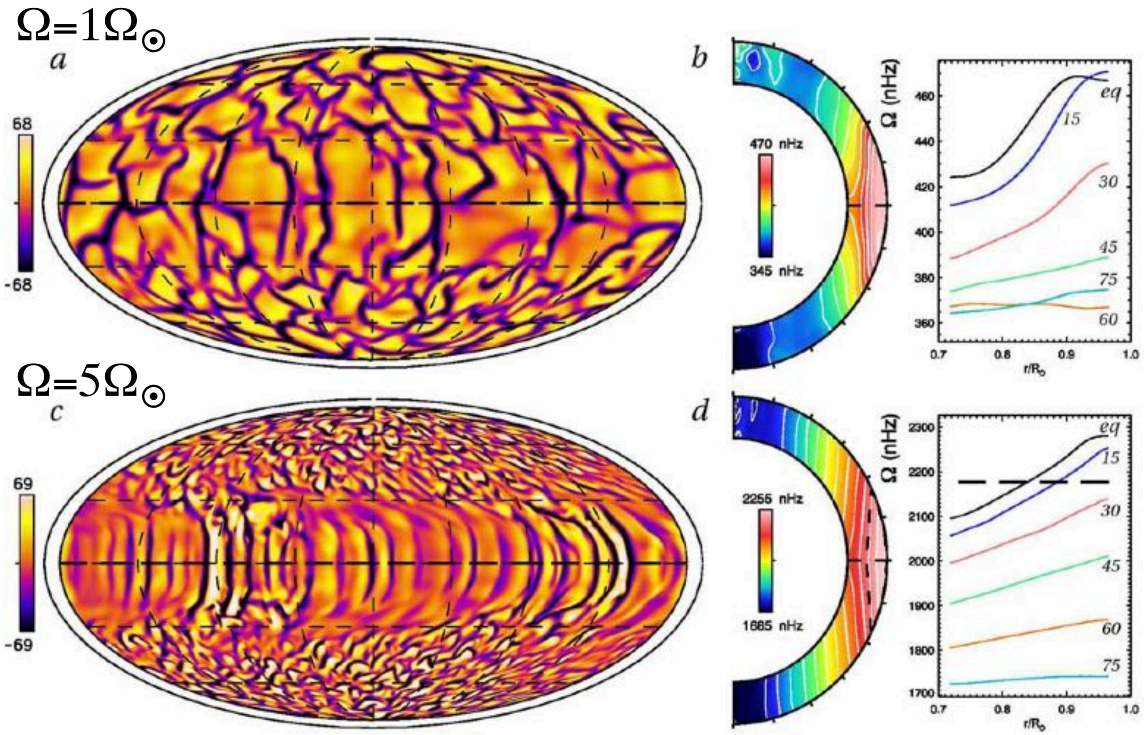
ok with observations

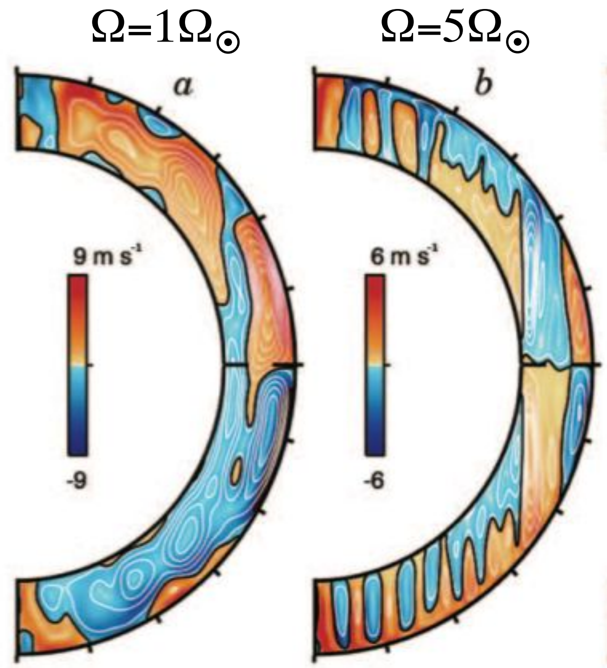
- Very strong dependence of cycle period on MC amplitude

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

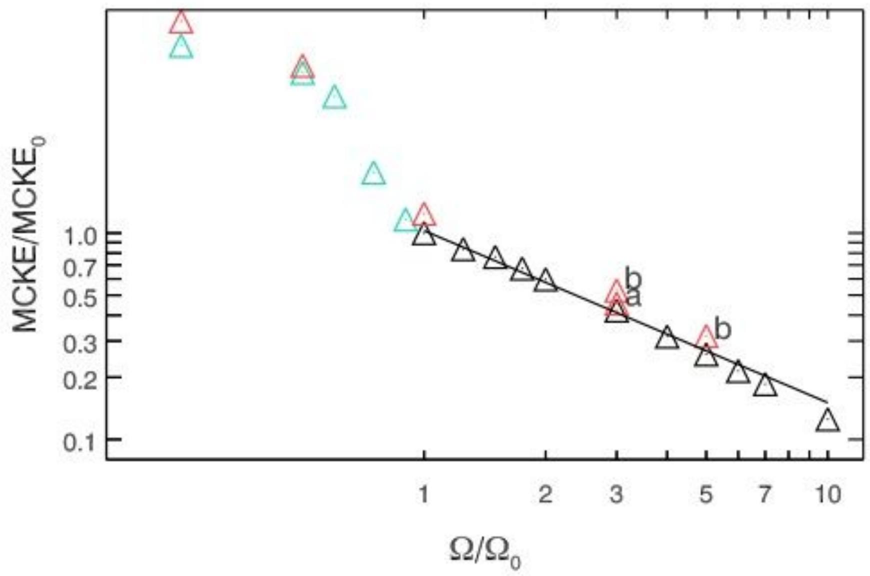
Is this solar model applicable for rapidly-rotating solar-like stars?

Prescriptions from 3D models





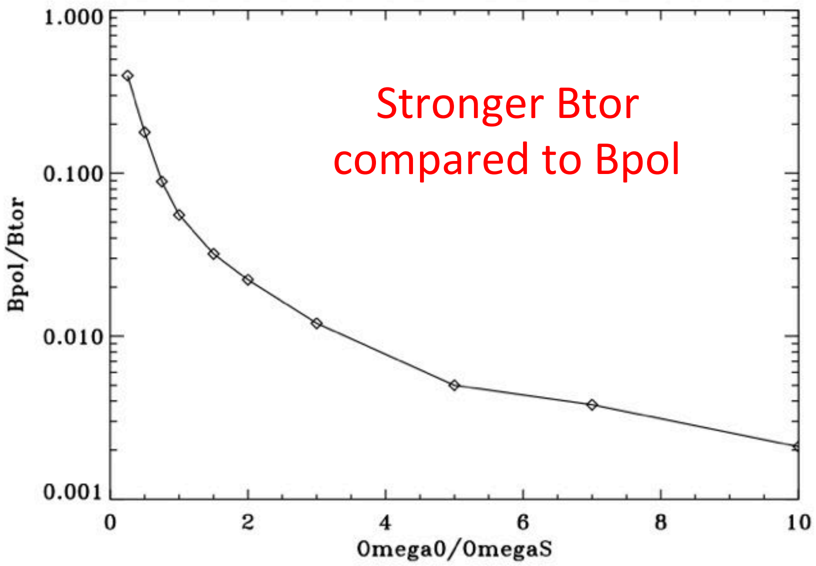
ASH Code (spectral 3D MHD)
(Miesch et al. 2000, Brun et al 2004)

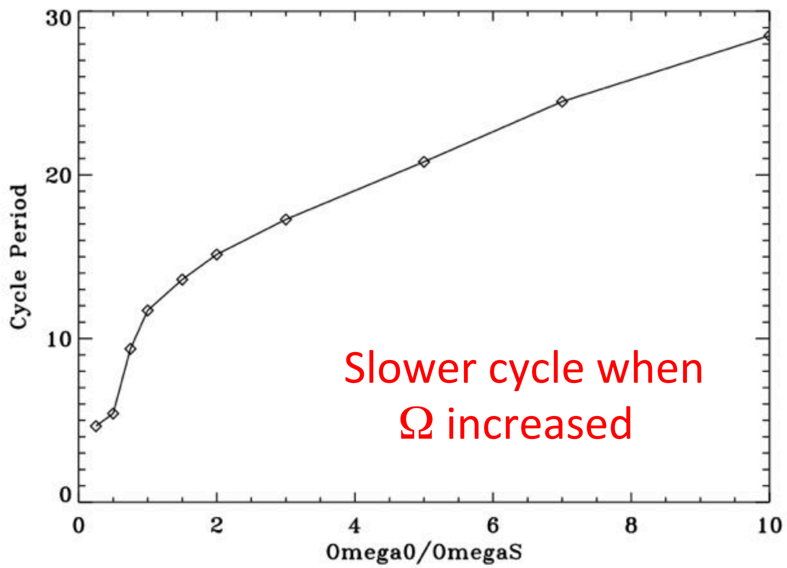


Scaling of MC deduced from
Brown et al. 2008: Vp α $\Omega^{-0.9}$

$\Delta\Omega$ increases with Ω

Applying solar models to other stars

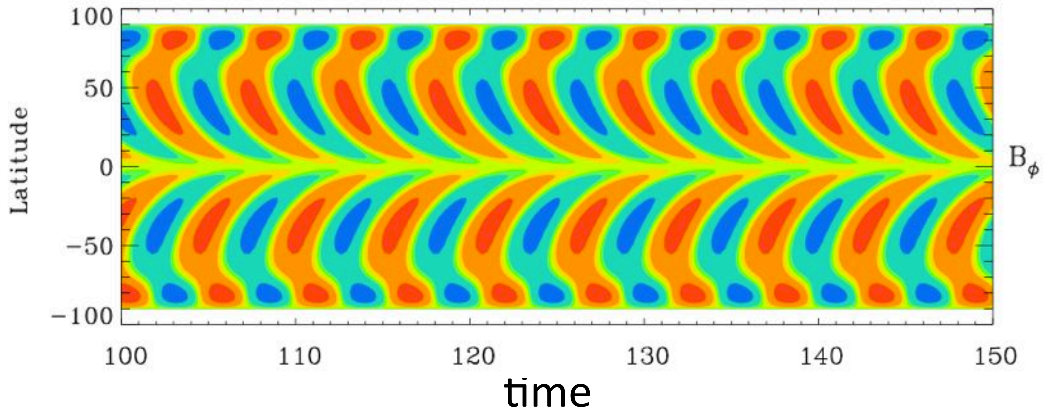




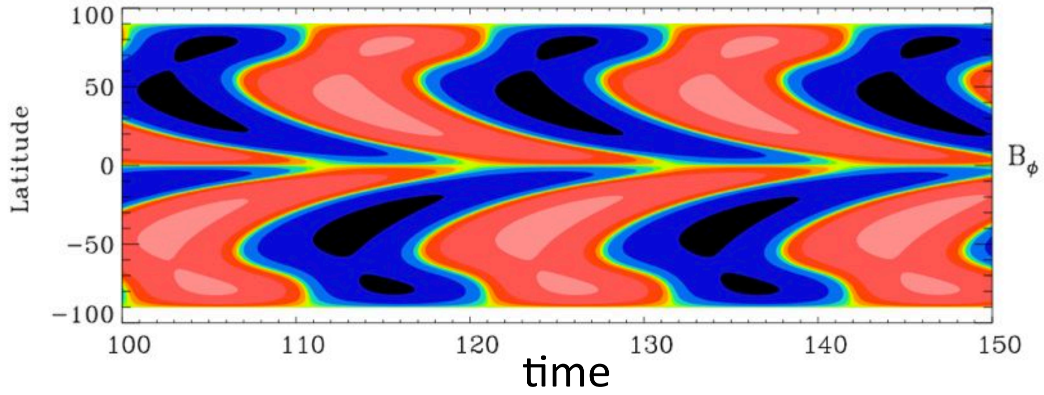
Jouve, Brown, Brun 2010

STELEM Code (finite-element 2D MHD)
Charbonneau & MacGregor 1992,
Jouve et al. 2008

0.5 Ωsol

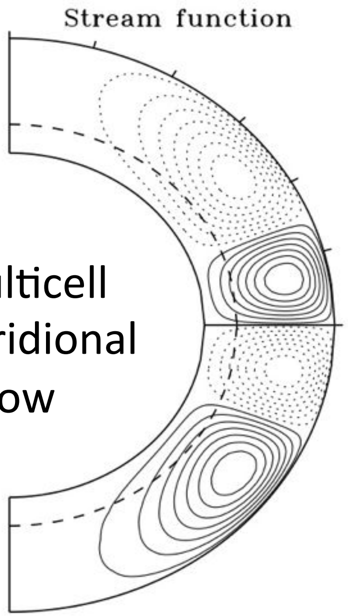


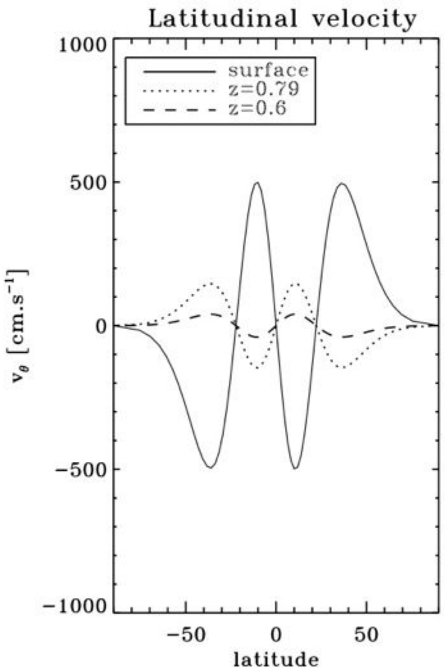
5 Ωsol Pcyc = 20 yr



Applying solar models to other stars

Multicell meridional flow

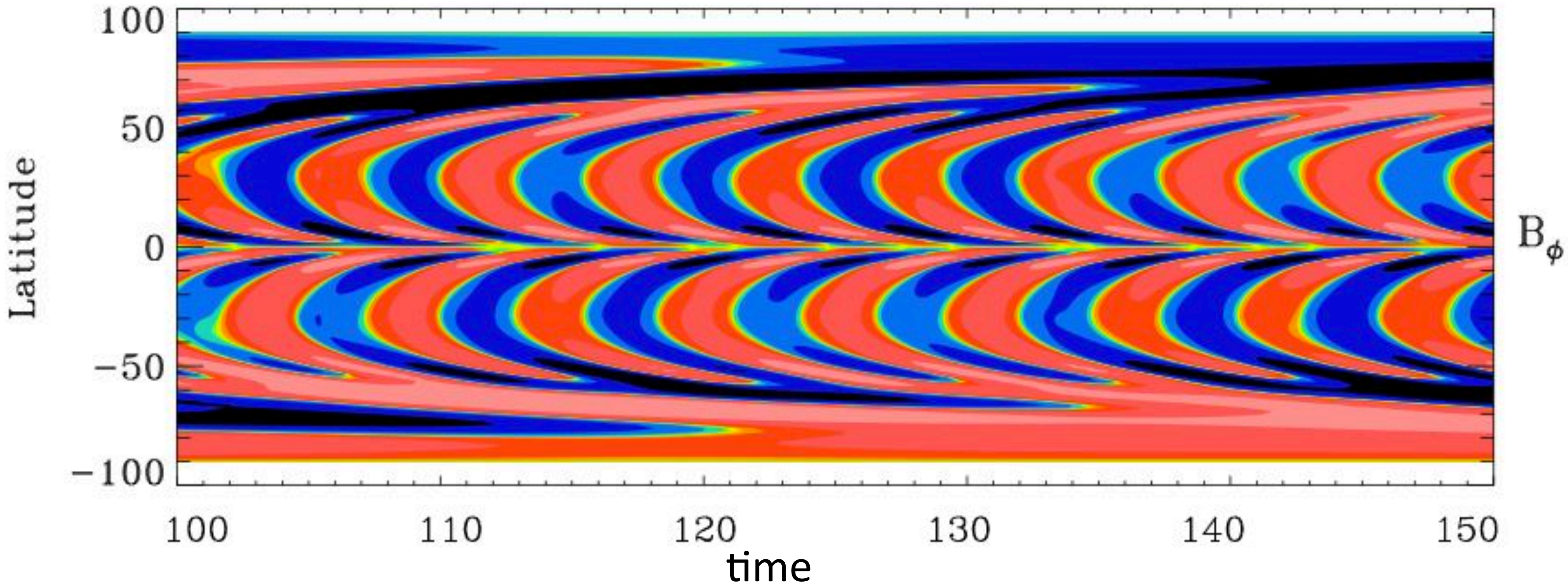




Can we reconcile this model with stellar data using a more complex MC?

Jouve, Brown, Brun 2010

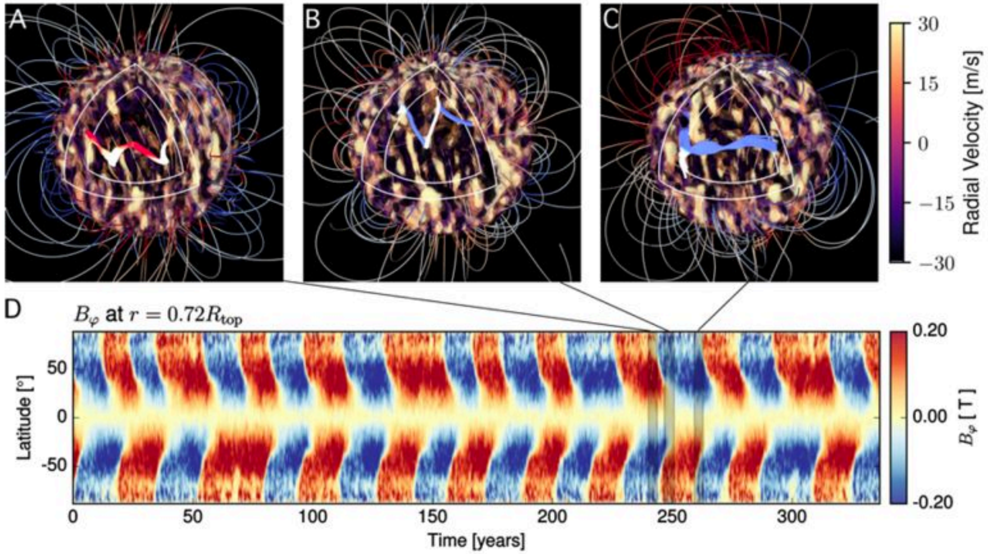
5 Ωsol, Pcyc = 5.2 yr, better agreement



Applying solar models to other stars: more realistic models

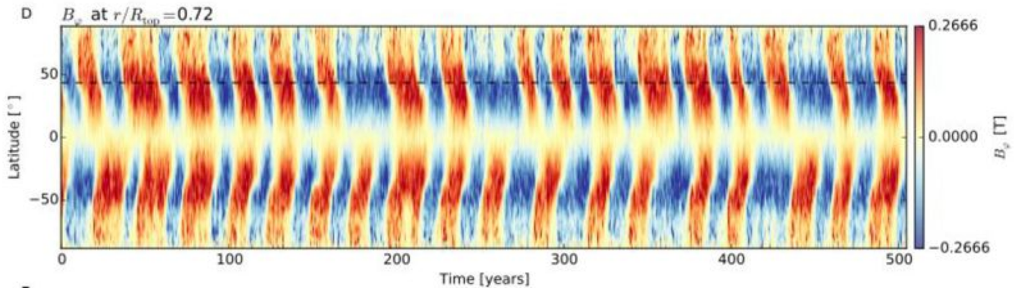
Strugarek et al. 2017

$\Omega = \Omega_\odot$

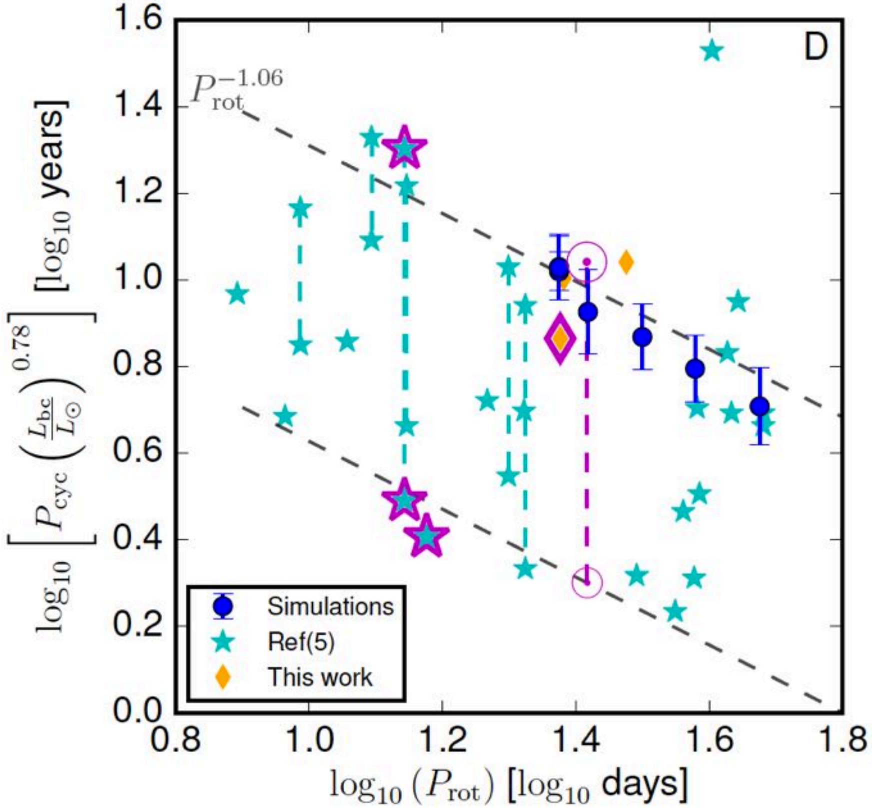


At fixed luminosity, slower rotation produces shorter magnetic cycles!

$\Omega = 0.6\Omega_\odot$



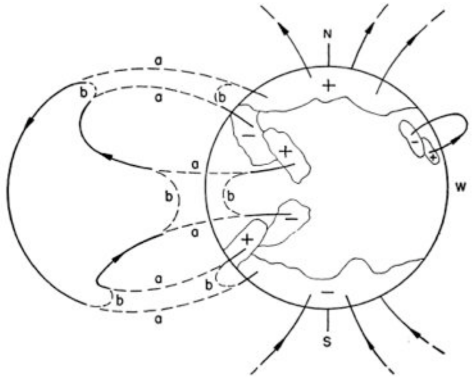
EULAG Code (ILES 3D MHD)
(Smolarkiewicz et al. 2013)

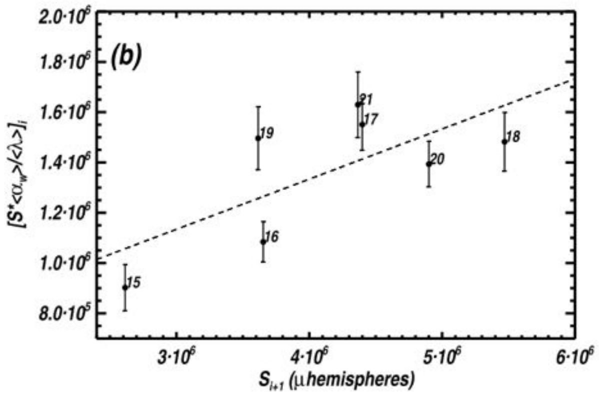


- ❑ Corrected P_{cyc} scales with P_{rot}^{-1}
- ❑ Not in disagreement with obs
- ❑ Not a kinematic dynamo

Crucial role of spots? What about 3D models?

- ❑ Babcock-Leighton model relies on spot decay to reverse polar field



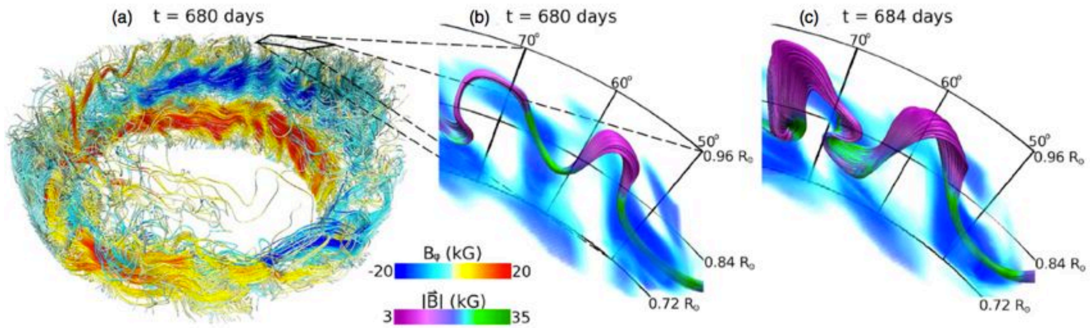


Dasi-Espuig et al. 2010

- ❑ 3D models produce magnetic cycles without producing spots

(Brown et al. 2011, Ghizaru et al. 2010, Käpylä et al. 2013, Augustson et al. 2015, Hotta et al. 2016, Strugarek et al. 2017)

- ❑ Strong concentrations of toroidal field from which buoyant loops can emerge.



Nelson et al. (2011, 2014)

- ❑ The loops do not rise to the surface to create well defined spots yet, this has to be modeled independently (Living Reviews by Fan 2009 and Cheung & Isobe 2014)

Simulation of buoyant loop rise in solar-like stars

❑ In the Sun: large literature on flux emergence
(see Fan 2009 and Cheung & Isobe 2014 Living Reviews in Solar Physics)

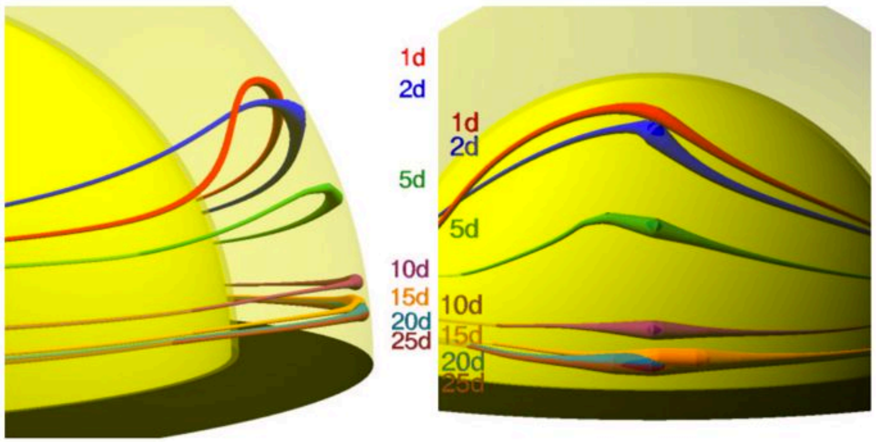
- Latitude of emergence related to buoyancy VS Coriolis
- Rise time depends on field strength
- Tilt angle depends on field strength and latitude
- Effect of convection and (differential) rotation
- Twist of the field lines is necessary (and observed)
- Reconnection needed for emergence in the stably stratified atmosphere
- Instabilities related to reconnection with coronal field => flaring activity

❑ In other stars:

- Fast rotating solar-like stars: poleward deflection

- Study of the effect of meridional flows + flux transport (Isik et al. 2011)

- Fully convective stars: Weber & Browning 2016



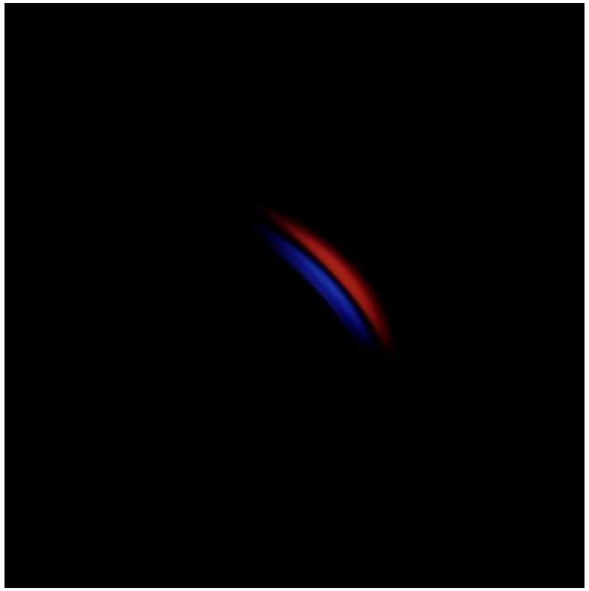
Holzwarth, 2007

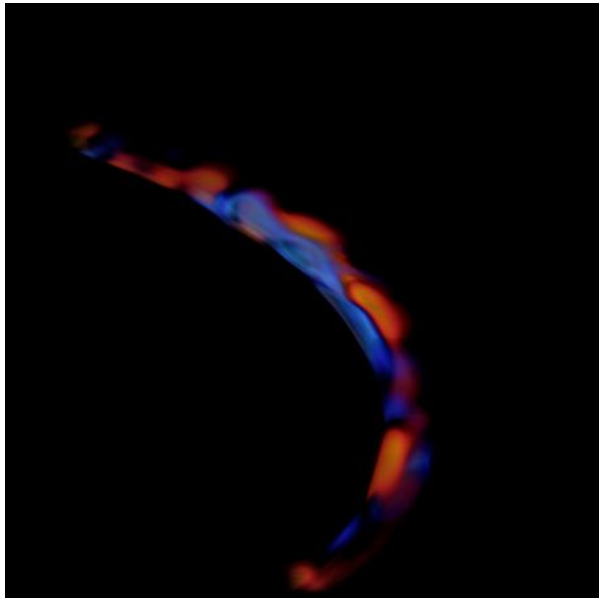
Simulation of buoyant loop rise in the Sun

- Toroidal flux tube introduced at the base of the CZ in an isentropic or convective layer

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

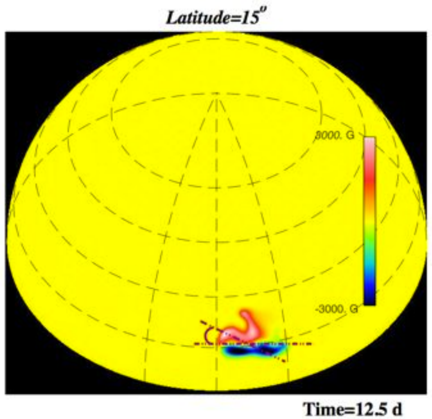
Isentropic layer

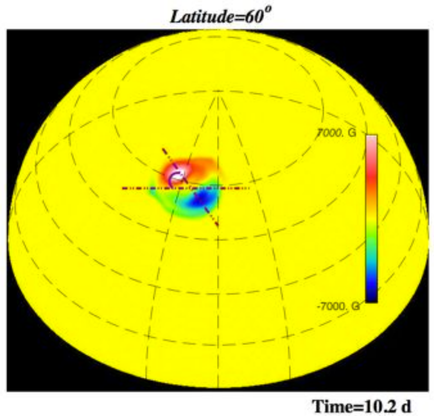




Convective layer

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

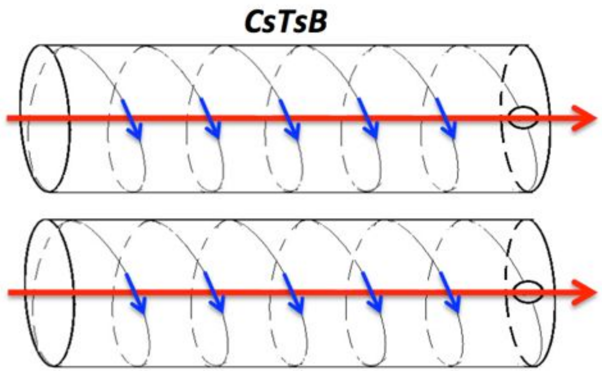




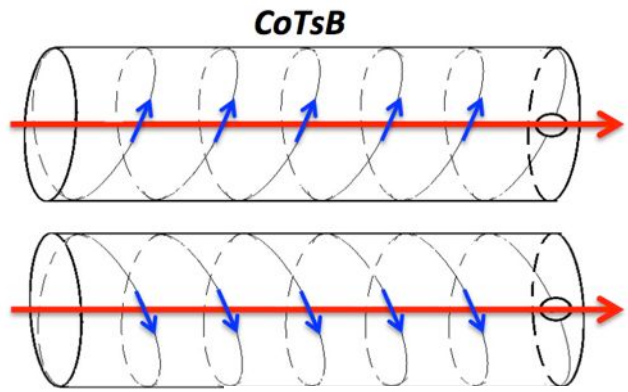
Jouve et al. 2013

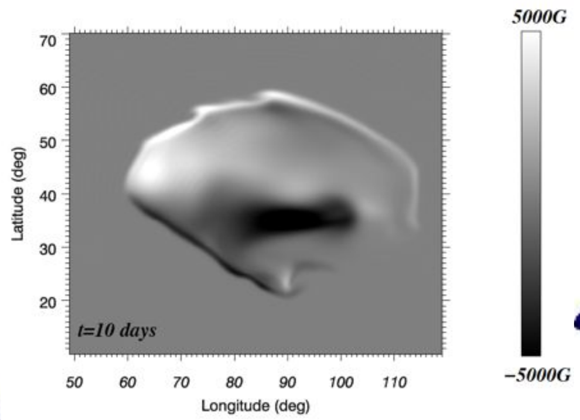
Simulation of buoyant loop rise in the Sun

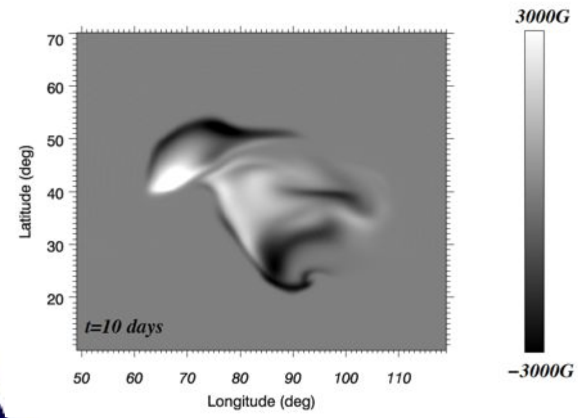
- ❑ Simulations of interacting loops to produce complex active regions

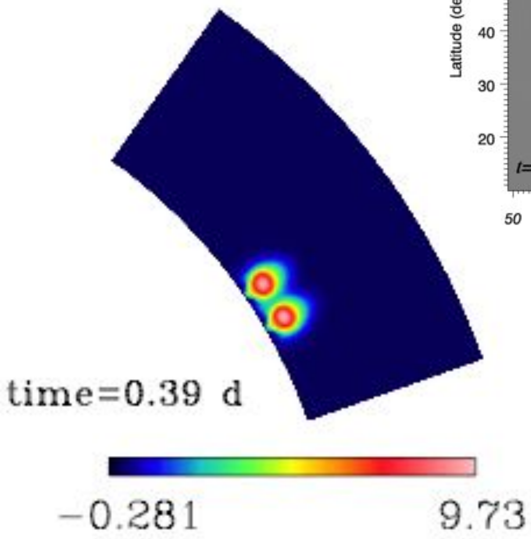


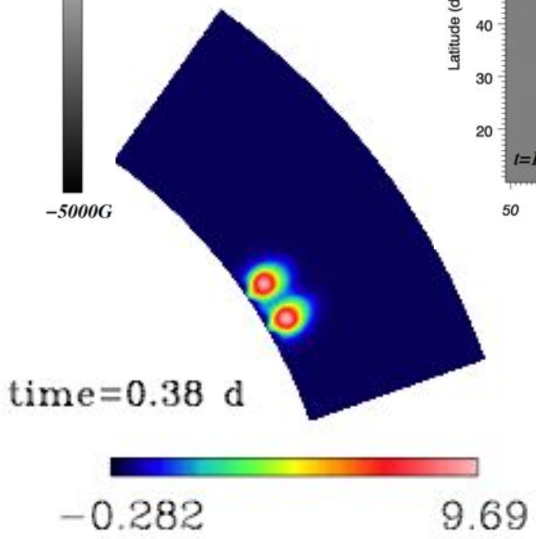
Jouve et al., submitted





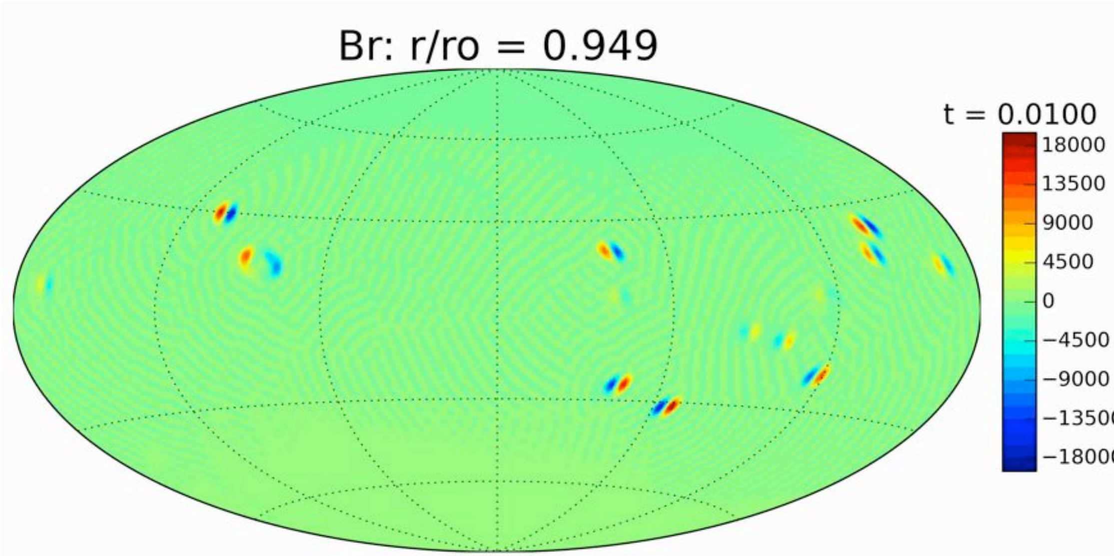


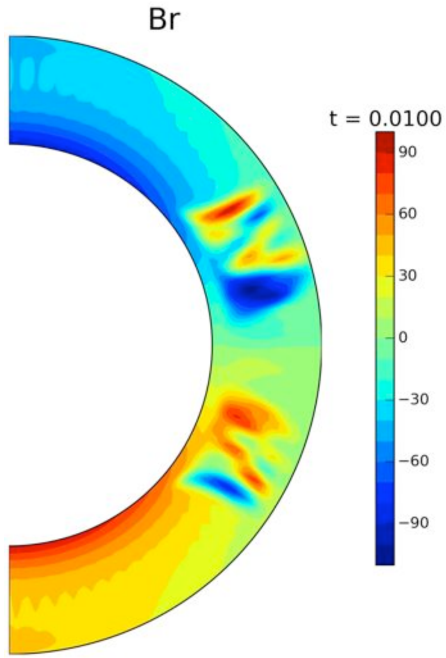




3D kinematic models: combining approaches

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

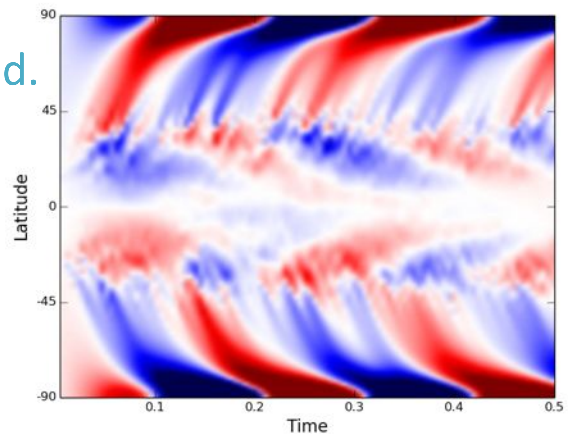


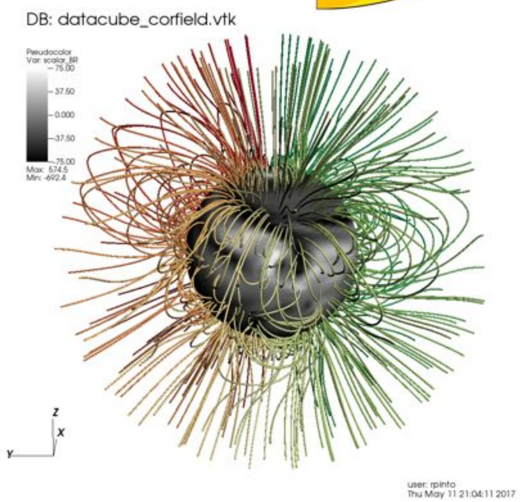


CEFIPRA Project (D. Nandy & L. Jouve)

Kumar, Jouve, Pinto & Rouillard , submitted.

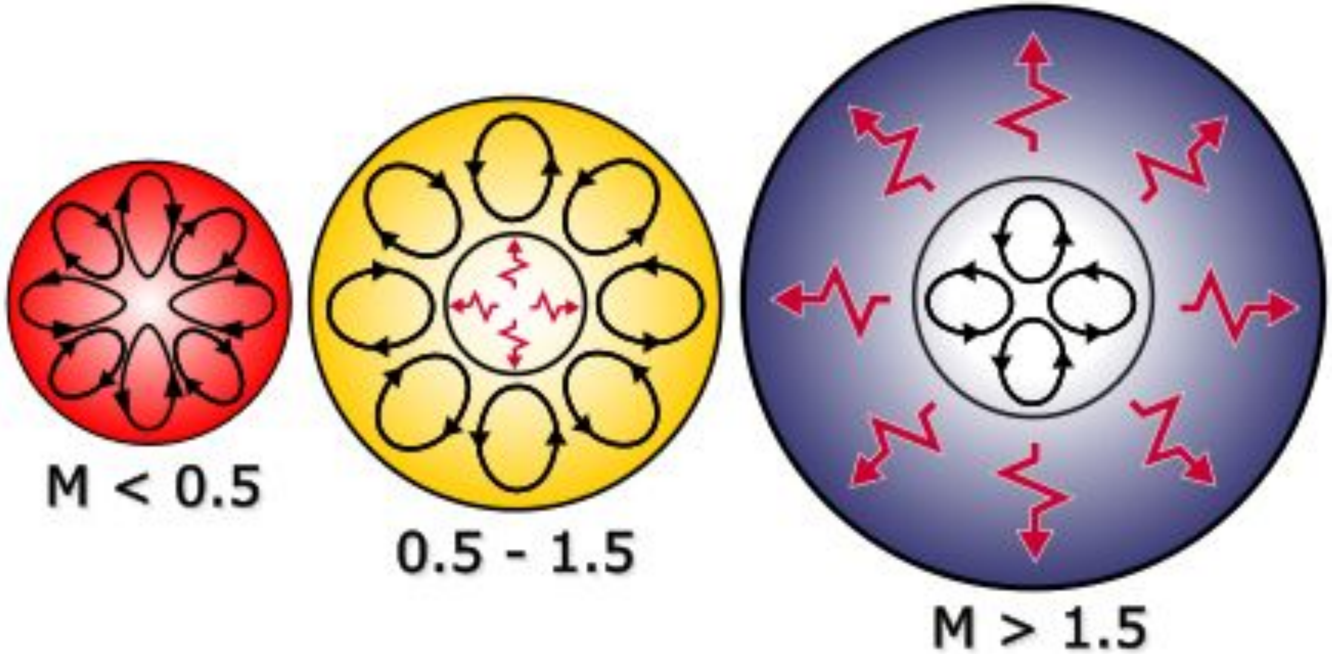
Self-consistent butterfly diagrams





Coronal field + wind solutions

Magnetism of more massive stars

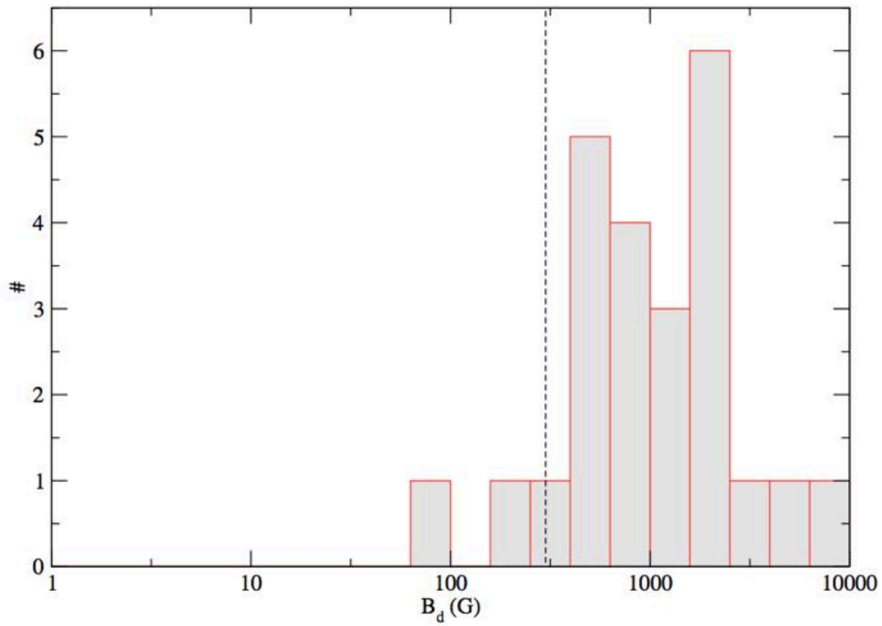


❑ **In more massive stars (with radiative envelopes)**

- 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

Musicos + NARVAL



- ❑ 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)

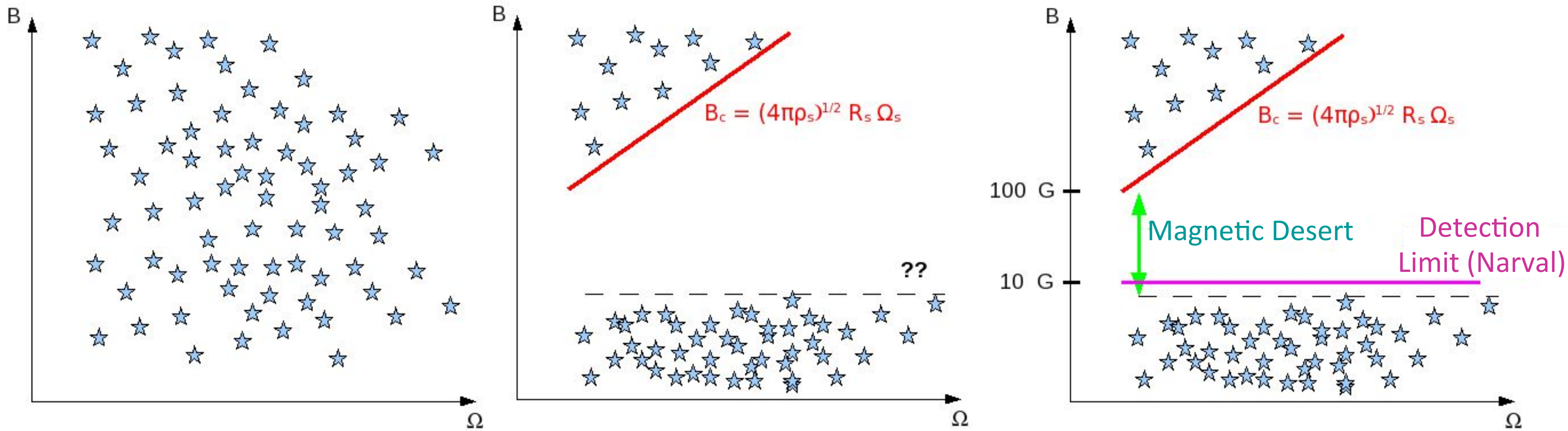
- ❑ **Why such a threshold?** (Aurière et al. 2007)
  - Strong poloidal field → Differential rotation suppressed → Strong measured Bl
  - Weak poloidal field → Strong Bphi → Instabilities (Tayler 73) → Small horizontal scales Weak measured Bl

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

- Possible instabilities for $Bp < Bc = r\sin\theta\sqrt{4\pi\rho}\Omega$

Theoretical argument

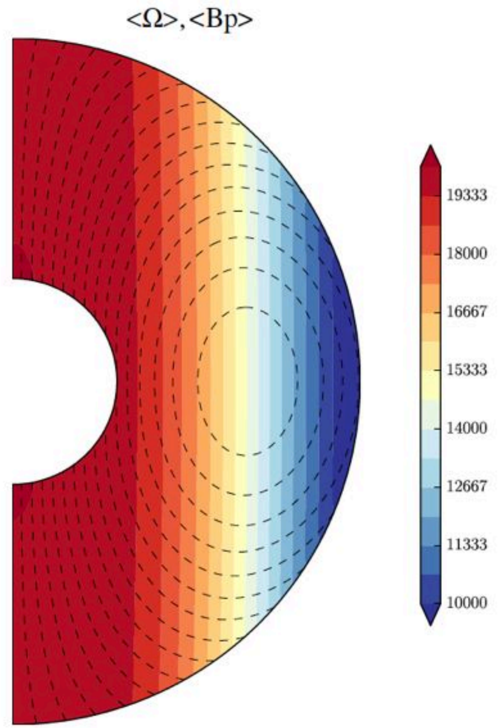
Courtesy: François Lignières

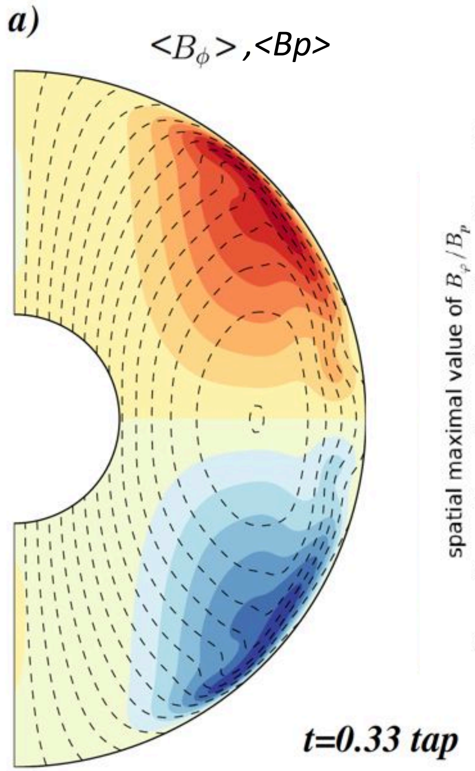


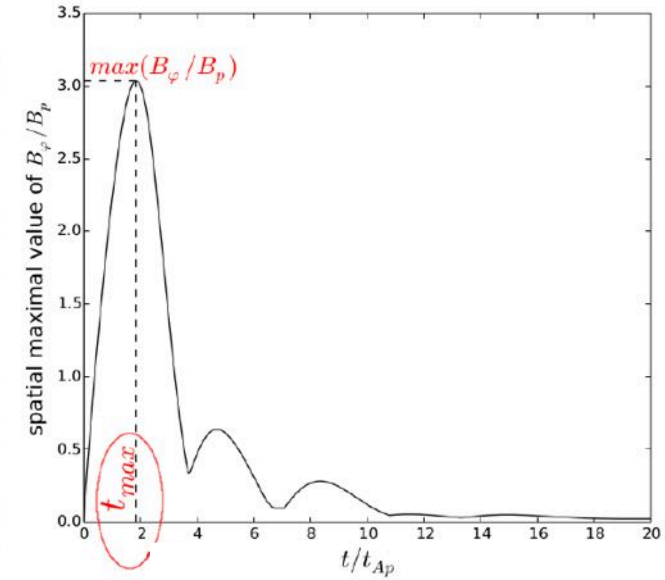
- ❑ Stellar formation: Fossil fields of variable intensities Bp, various rotation rates (and diff.rot.)
- ❑ For Bp < Bc ⟶ instabilities ⟶ Small longitudinal field (below detection limit).
- ❑ For Bp > Bc ⟶ Stable dipolar configurations (detected in Ap stars).

Numerical approach: 3D simulations

MagIC Code
(https://magic-sph.github.io)
Wicht 2002, Gastine & Wicht 2012, Schaeffer (2013)





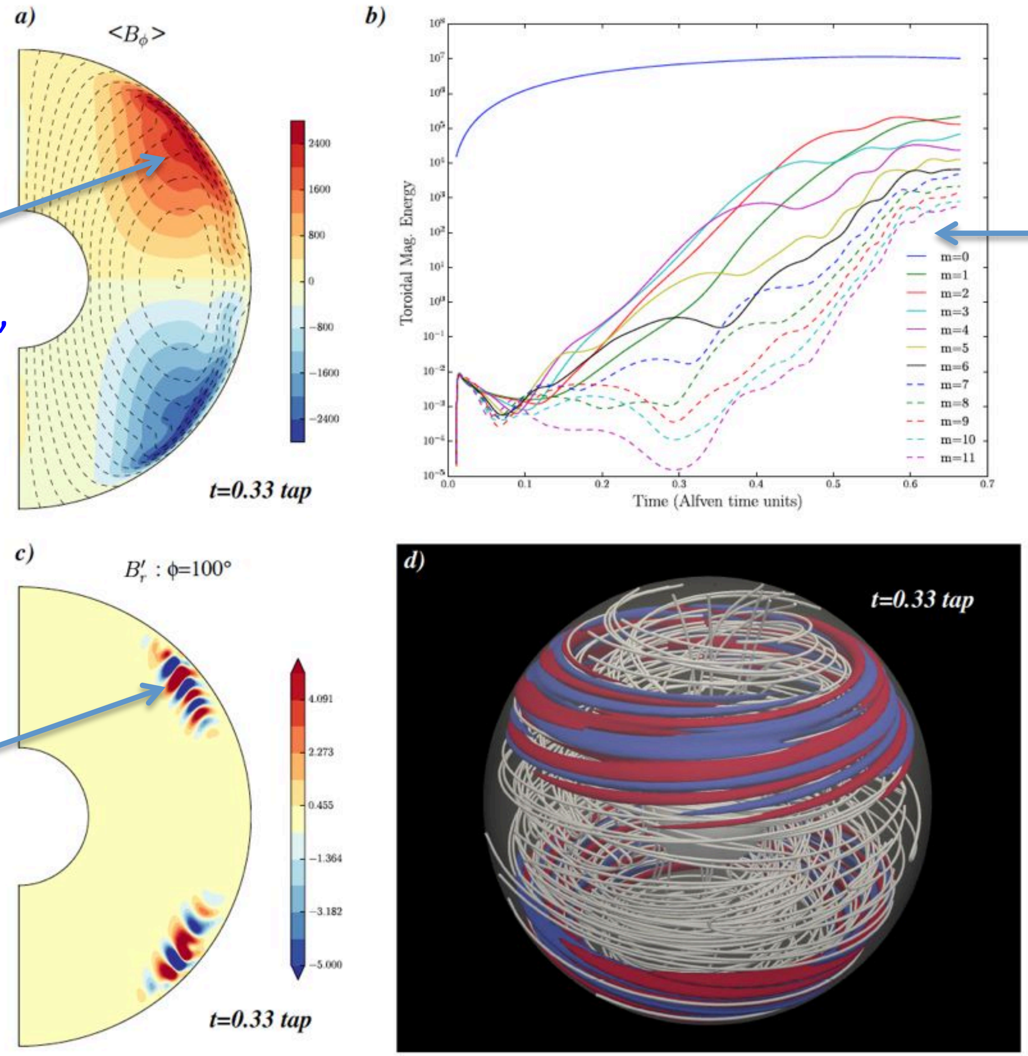


- Initial conditions: poloidal field (Lu) wound-up by cylindrical differential rotation (Re)

- 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



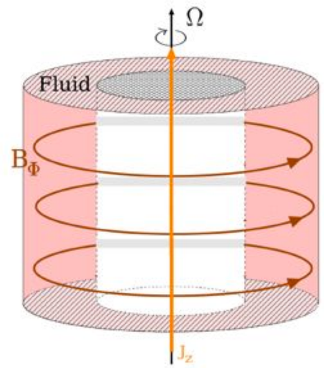
- Strong toroidal field, antisymmetric, close to the surface
- Favored modes: m=4, 5 and 6
- Instability around the regions of strong toroidal field

Jouve, Gastine Lignières 2015

What is the nature of this instability?

- **Magneto-rotational instability:**

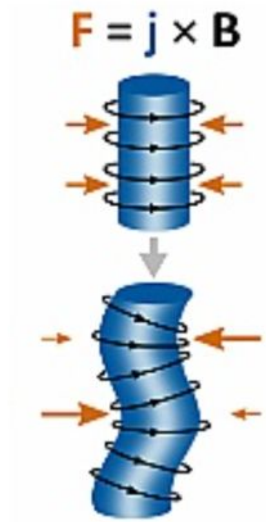
  - source of energy: kinetic energy of differential rotation (decreasing outward)
  - growth rate prop. to rotation rate and shear
  - high m's can be excited
  - necessitates weak field and strong differential rotation



Azimuthal MRI

- **Tayler instability:**

  - source of energy: magnetic energy
  - m=1 favored
  - growth rate prop. to Alfvén frequency
  - necessitates strong field and weak (differential) rotation

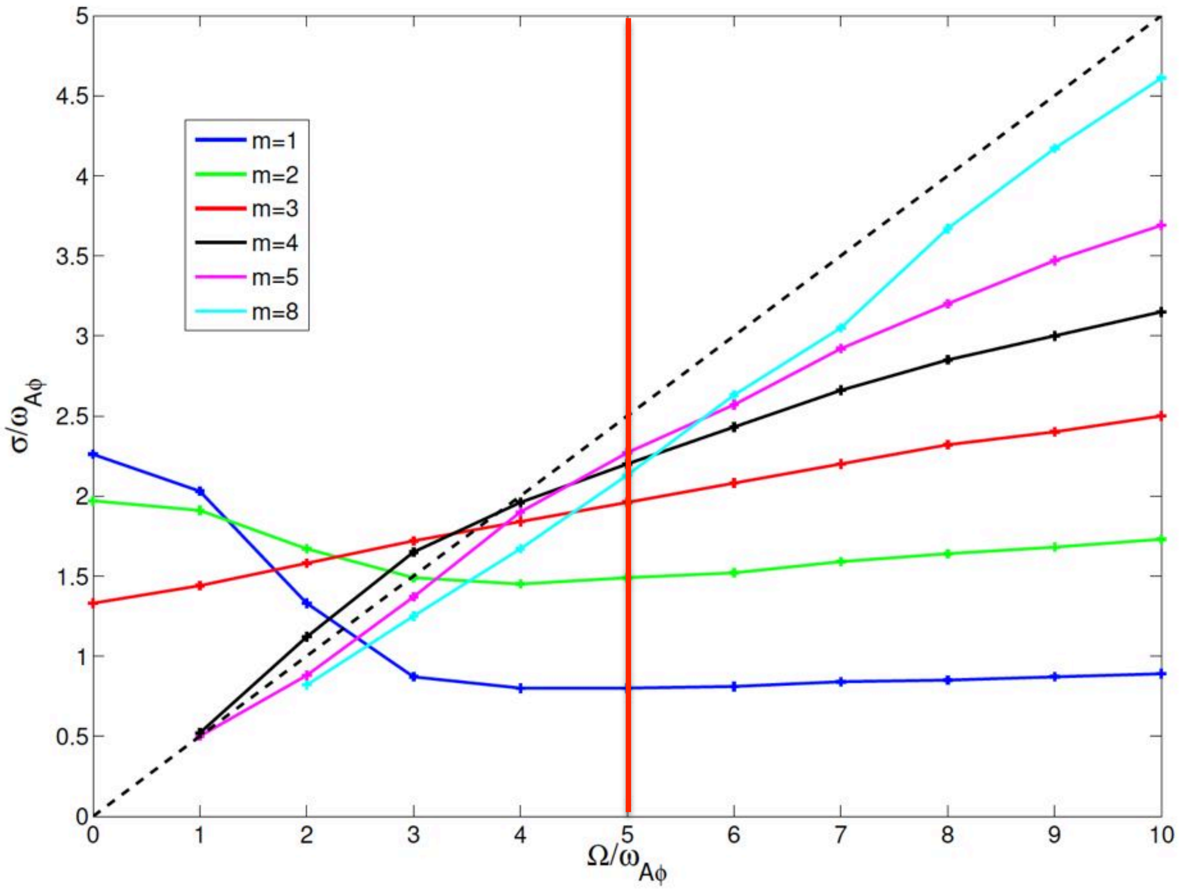


- **MRI vs TI:** importance of rotation rate (or shear) to toroidal Alfvén frequency ratio

What is the nature of this instability?

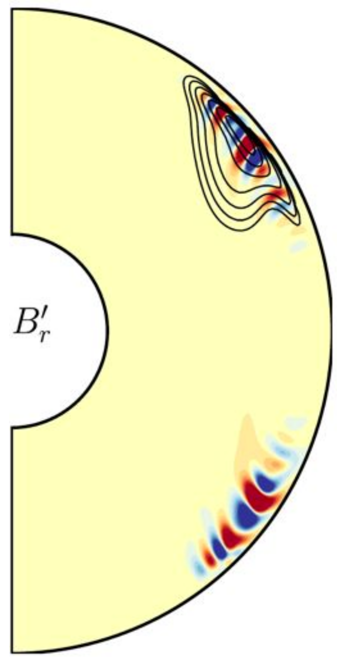
- MRI vs TI: importance of rotation rate to toroidal Alfvén frequency ratio: Ogilvie (2007)

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



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

→ MRI regime

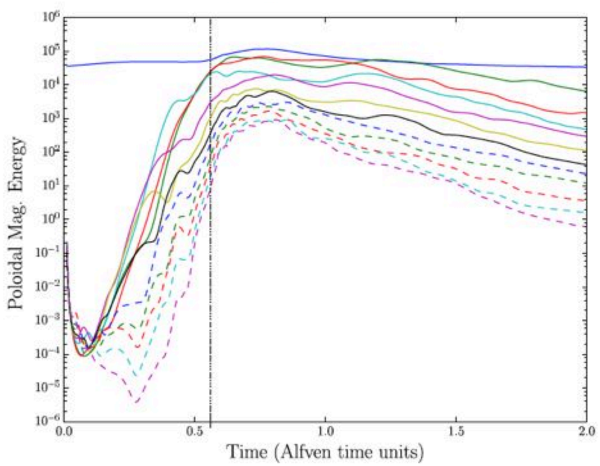


What distinguishes between stable and unstable cases?

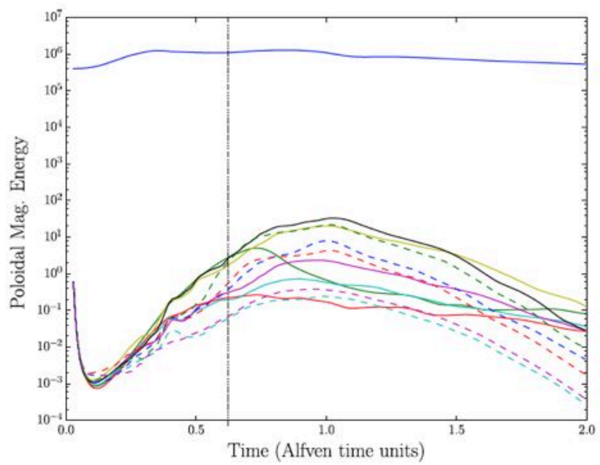
- ❑ Background field evolves on poloidal Alfvén time scale t_{ap}
- ❑ Growth time of the MRI of the order of t_{Ω} ($\sigma = q\,\Omega/2$ with q around 1 here)

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

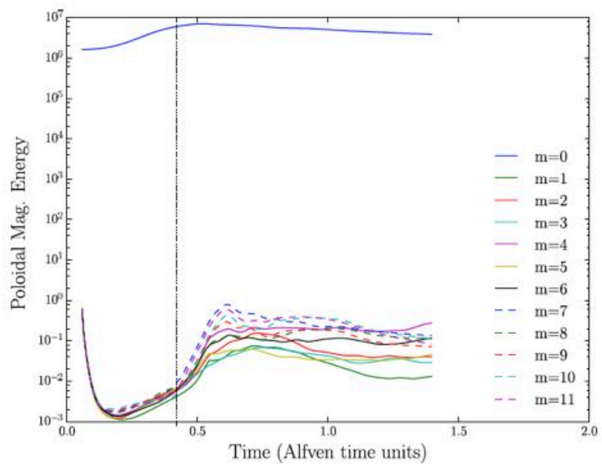
$t_{\Omega}/t_{ap} = 3.10^{-3}$



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



$t_{\Omega}/t_{ap} = 2.10^{-2}$



Effects of stable stratification

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

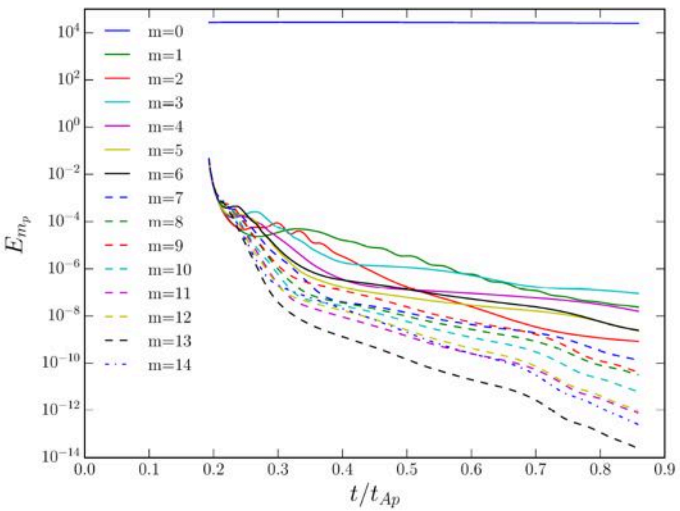
- We expect strong effects of stable stratification

- But a large thermal diffusion (small Pr) can help to reduce the effects of stratification

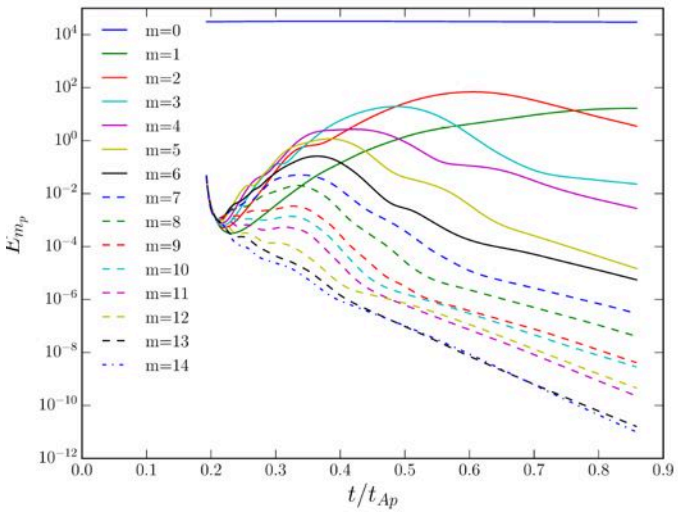
For N/Ω=5, the MRI:
- is lost for Pr=1
- recovered for Pr=10^{-2}

Gaurat et al., in prep.

Pr=1



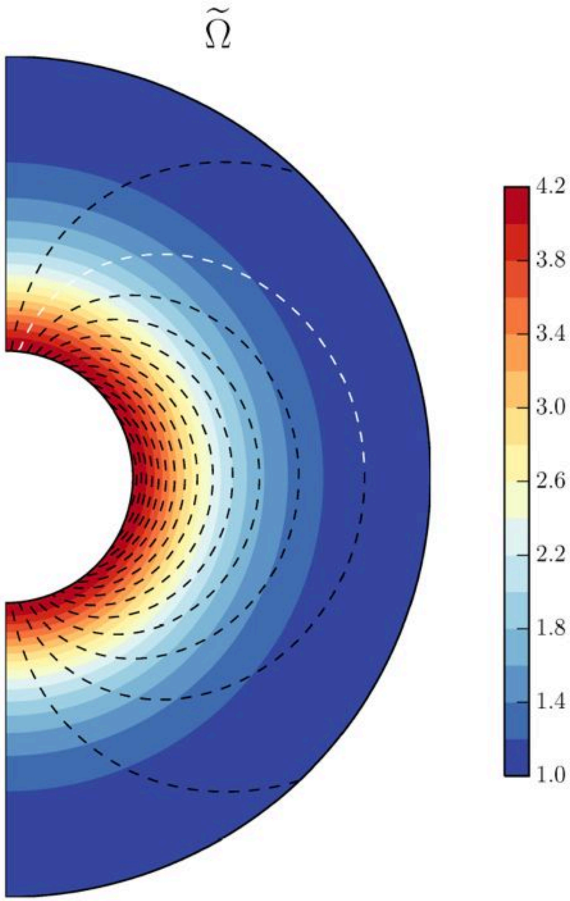
Pr=10^{-2}

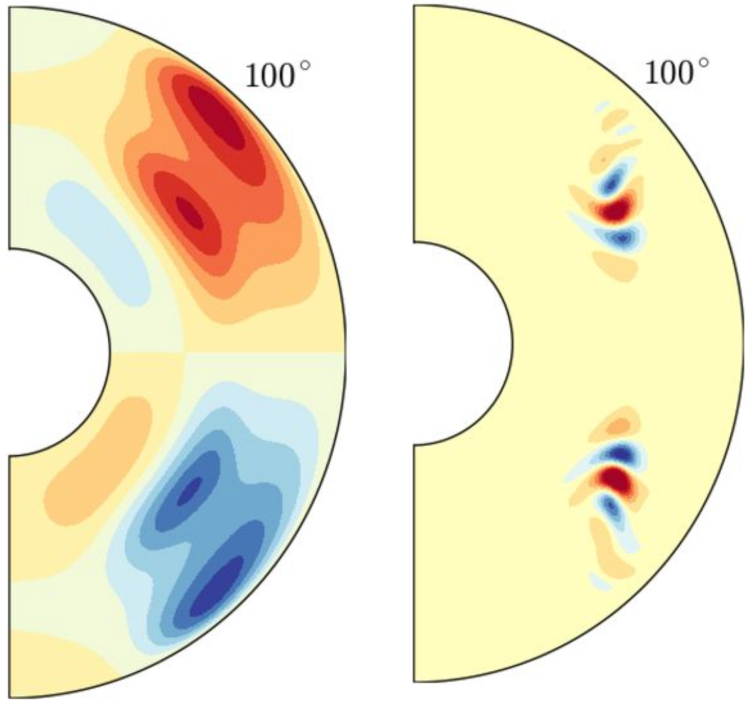


Effects of stable stratification

❑ Different initial differential rotation profile: radial (or shellular) instead of cylindrical => Tayler instability

- m=1 is favored
- Instability still present when rotation profile inverted
- Growth rate close to $\Omega_{a\phi} x\ \Omega_{a\phi}/\Omega$

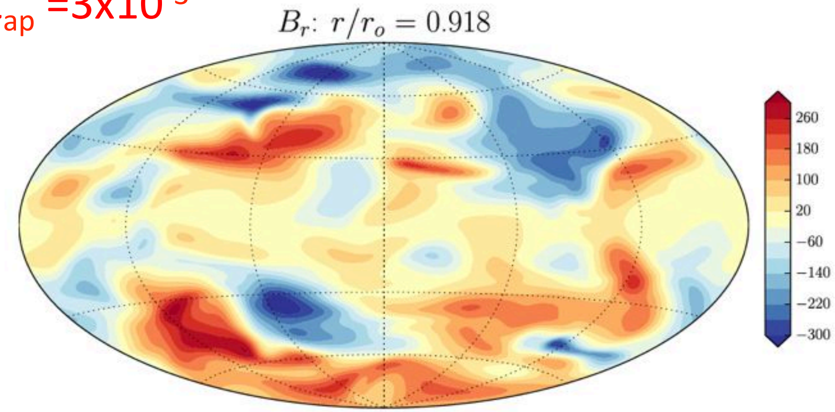




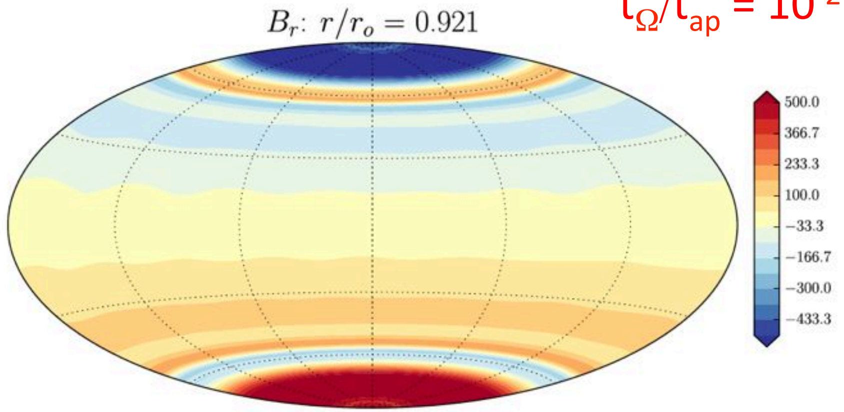
Application to A-type stars

- ❑ Surface radial field: non-axisymmetric VS axisymmetric
  - Unstratified cases

$t_\Omega/t_{ap} = 3\times10^{-3}$

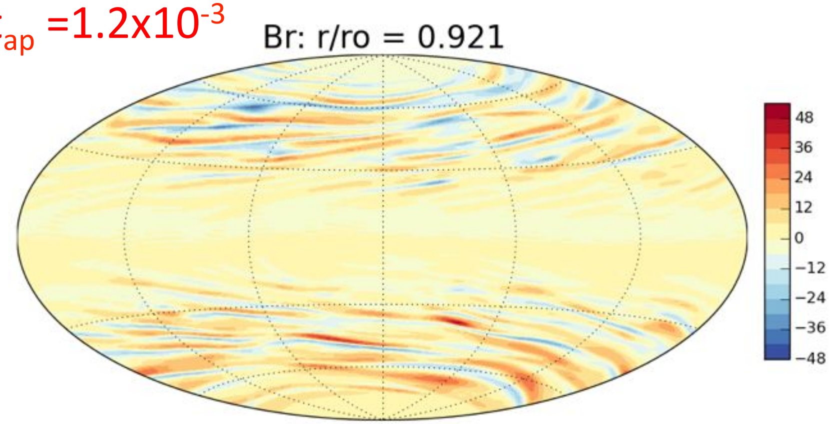


$t_\Omega/t_{ap} = 10^{-2}$

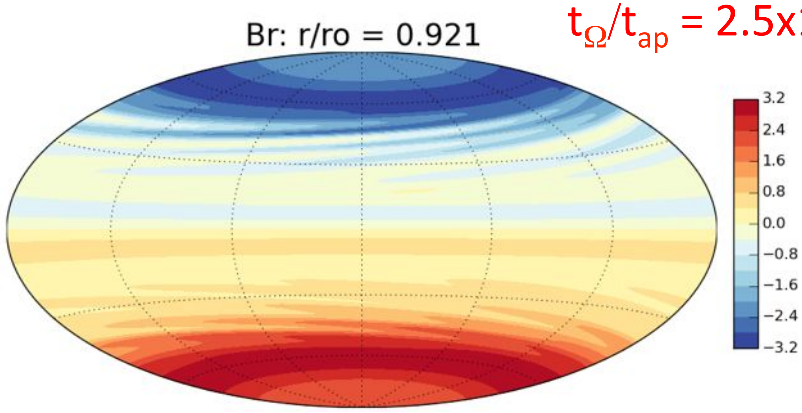


  - Stratified cases

$t_\Omega/t_{ap} = 1.2\times10^{-3}$



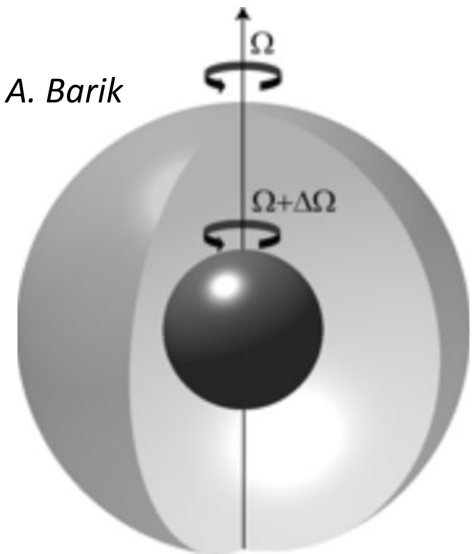
$t_\Omega/t_{ap} = 2.5\times10^{-3}$



Forced differential rotation

- Spherical Couette flow producing Stewartson layer and concentrated Bphi

Courtesy A. Barik

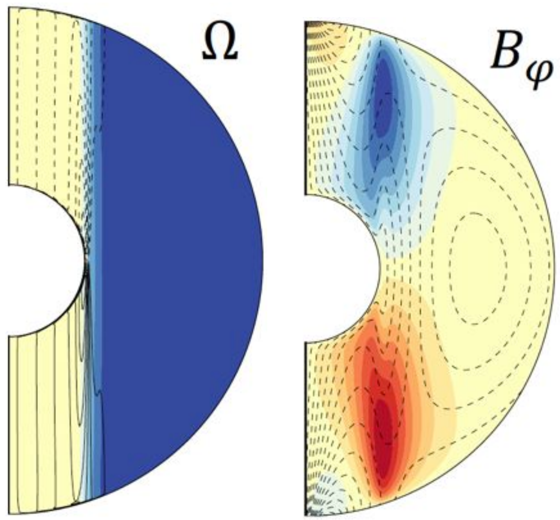


Meduri et al., in prep.

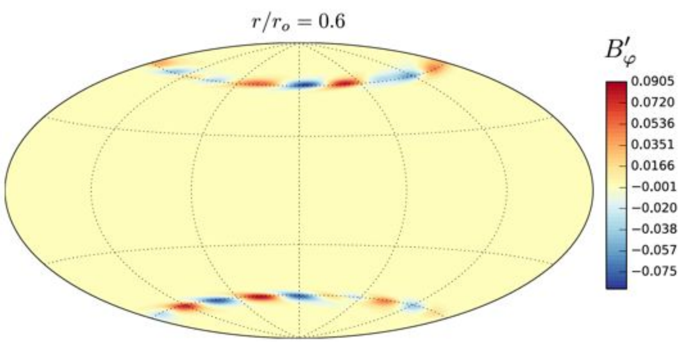
$$E = \frac{\nu}{\Omega d^2} = 10^{-5}$$

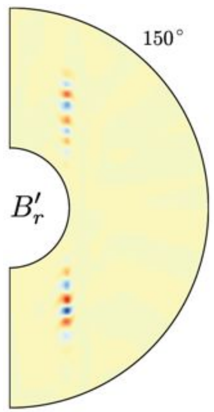
$$Ro = \frac{\Delta\Omega}{\Omega} = 0.03$$

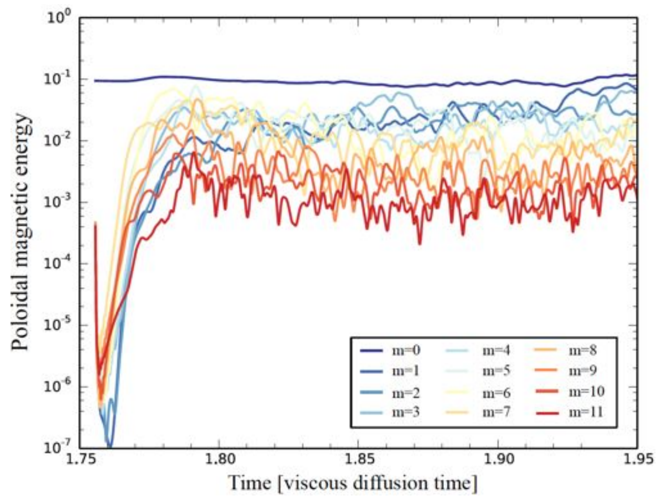
$$Rm = \frac{\Delta\Omega d^2}{\eta} = 2.10^4$$



- MRI and possible dynamo action?







Conclusions

- ❑ Dynamo models of solar-like stars:

  - 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?
  - 3D kinematic model as a combined approach
  - Models commonly applied to the Sun are challenged by other stars
  - More to come with SPIROU and Solar Orbiter!

- ❑ Magnetism of intermediate-mass stars:

  - Ratio t_{Ω}/t_{ap} distinguishes between stable and unstable cases

    ⇒ Critical poloidal field proportional to Ω ?
  - Strong modification of surface field in unstable cases

    ⇒ Dichotomy among A-type stars ?
  - Radiative zone dynamo?
  - Angular momentum transport by magnetic fields (red giants)
  - More to come with PLATO!

Ecole Connexions en Physique Solaire et Stellaire

- Où: Banyuls sur mer (66)
- Quand: 14 au 18 Mai 2018
- Thèmes abordés:
  - Activité solaire/stellaire
  - Hélio/astérosismologie
  - MHD solaire/stellaire
  - Environnements solaires/stellaires

- Cours + TP + temps pour discussions
- Inscriptions sur: *https://sunstars.sciencesconf.org*