Modélisation du magnétisme solaire et stellaire

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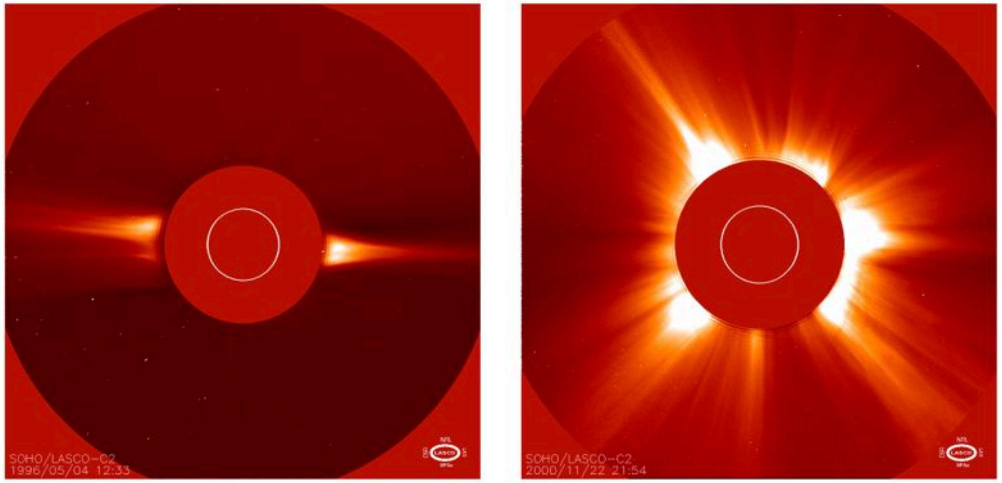
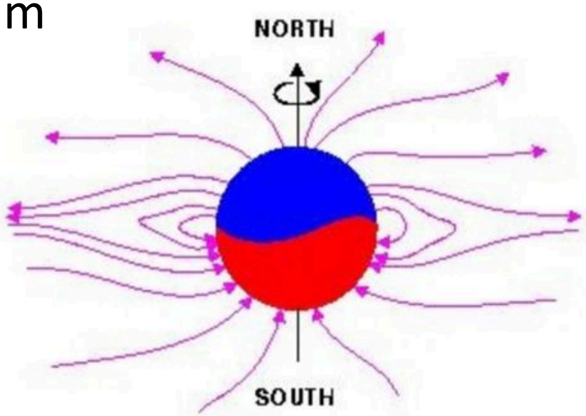
Global topology of the Sun's magnetic field

Main properties:

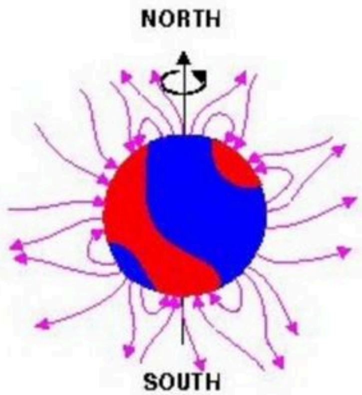
- ❑ Mean B of a few Gauss
- ❑ Mainly dipolar at solar minimum
- ❑ More complex at solar maximum (presence of spots -kG fields-)
- ❑ Polarity inversion at each 11yr sunspot cycle
  => 22yr magnetic cycle

LASCO coronograph images





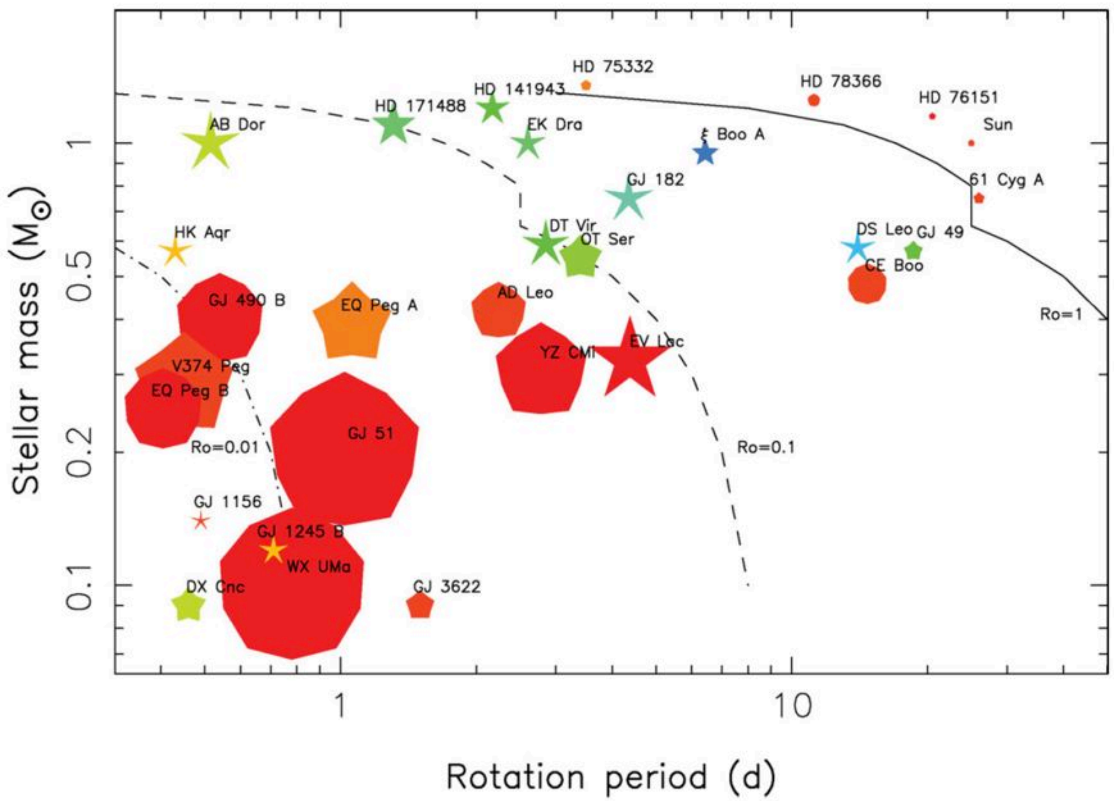
CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY



CORONAL MAGNETIC FIELD LINES AT SOLAR MAXIMUM ACTIVITY

Magnetic fields in cool MS stars

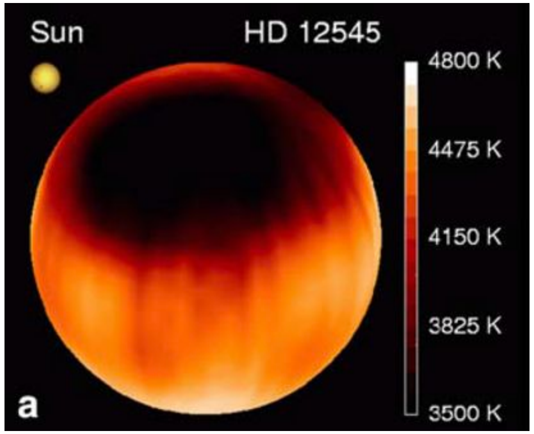
Morin, Donati et al. (2008-2010), Folsom et al. 2016



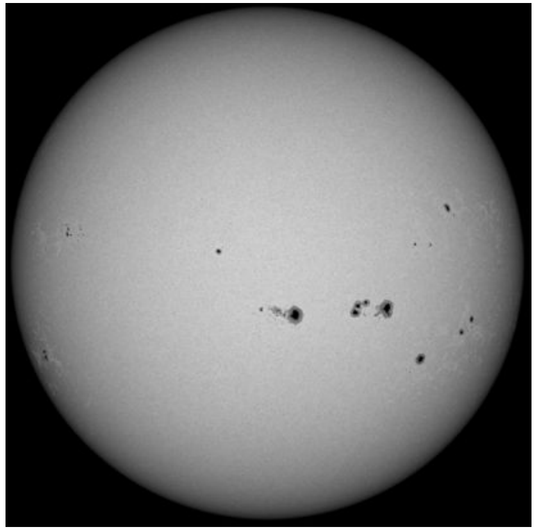
- ❑ Mostly multipolar for $M_\odot > 0.35$
- ❑ Mostly dipolar for $M_\odot < 0.35$
- ❑ Field strength increases with rotation
- ❑ More and more toroidal with rotation

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

Strassmeier (1999)

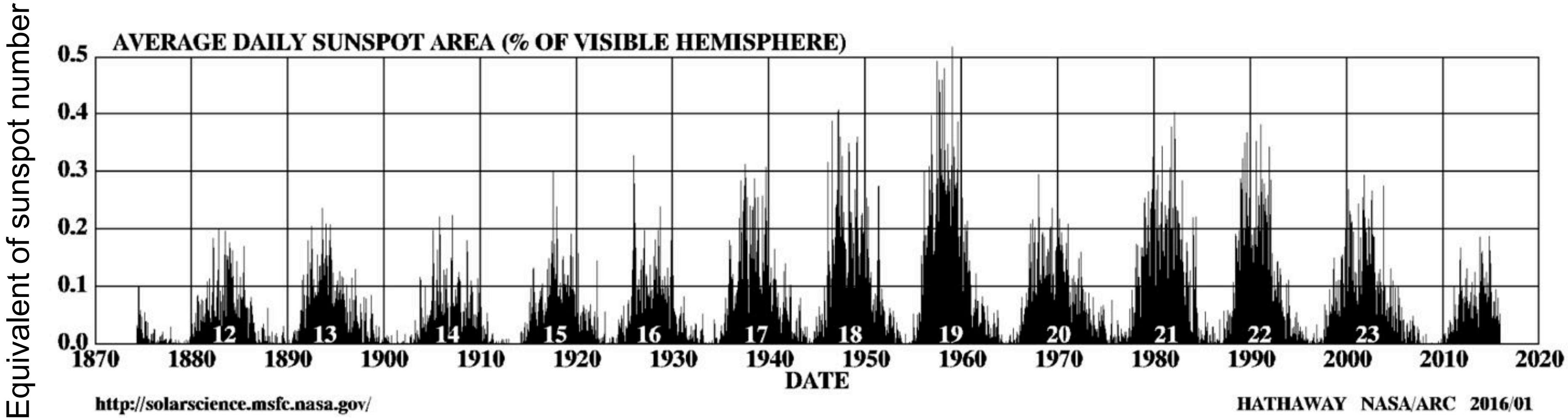


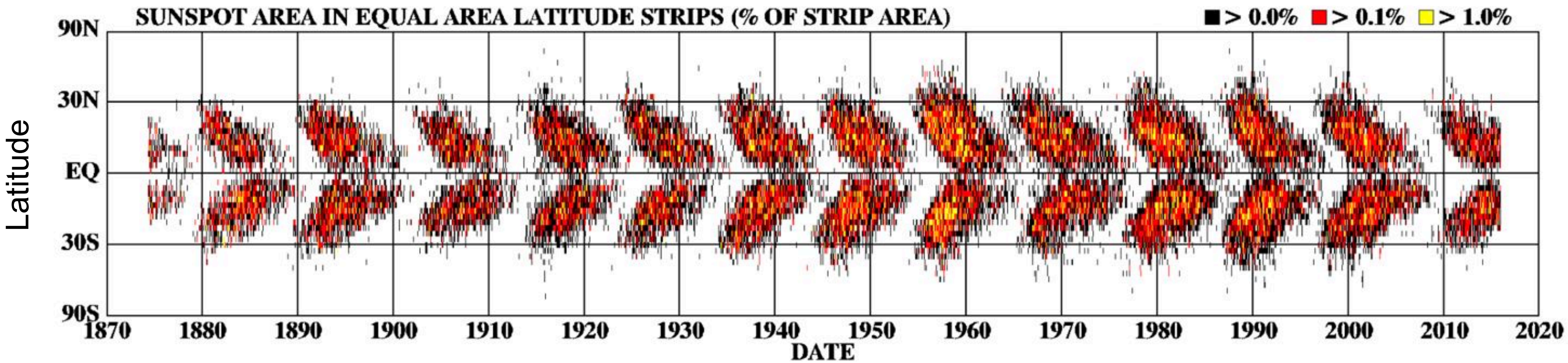
SDO data (July 2014)



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

Sunspots: temporal evolution

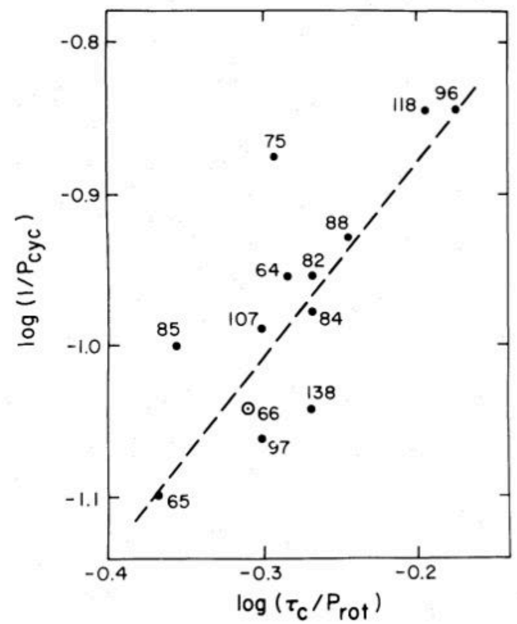




Observations of magnetic cycles on other stars

❑ **Indirect measurements**: chromospheric activity

Noyes et al. 1984



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

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

=> P_{cyc} increases with P_{rot}

❑ **Recent direct measurements**: magnetic field

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

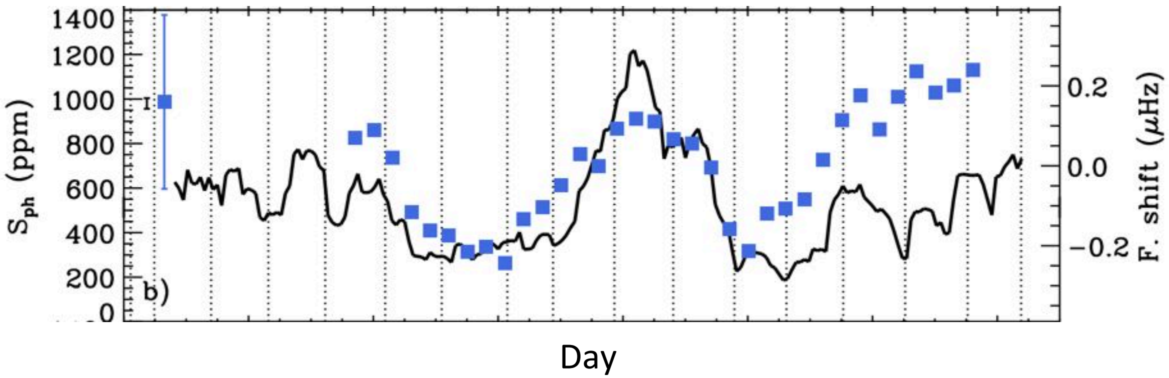
Petit et al 2009, Morgenthaler et al 2011: HD 190771 (complex variability)

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

Boro-Saika et al 2016: 61 Cyg A (solar twin): 14 years

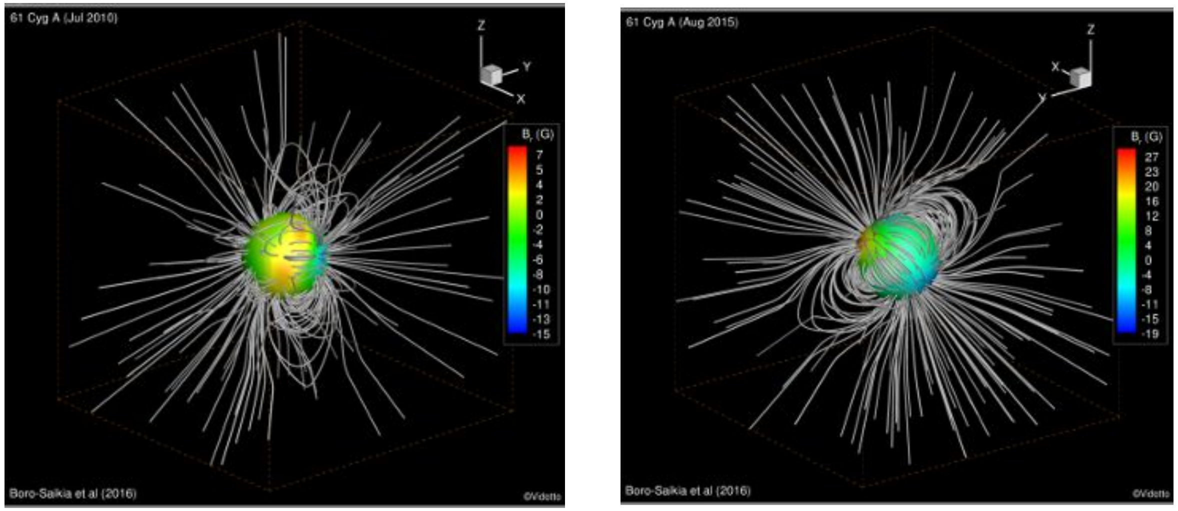
Magnetic cycles on other stars: examples

- Activity cycles detected through asteroseismology (solar-type Kepler stars)



Salabert et al. 2016

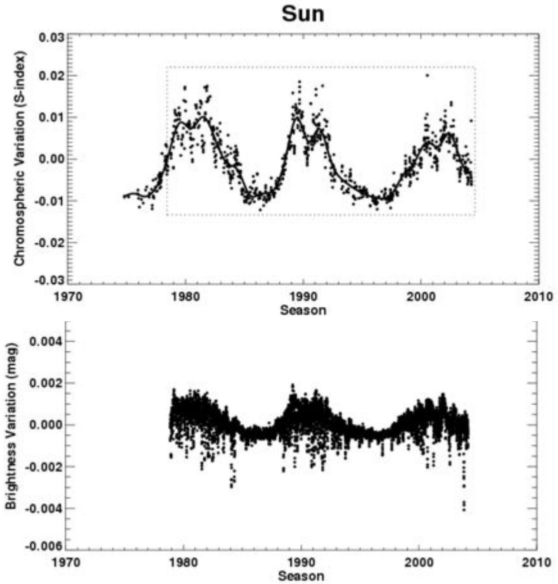
- 1st detection of a magnetic cycle analogue to the solar cycle on the K5 mature dwarf 61 Cyg A (Boro Saika et al. 2016)

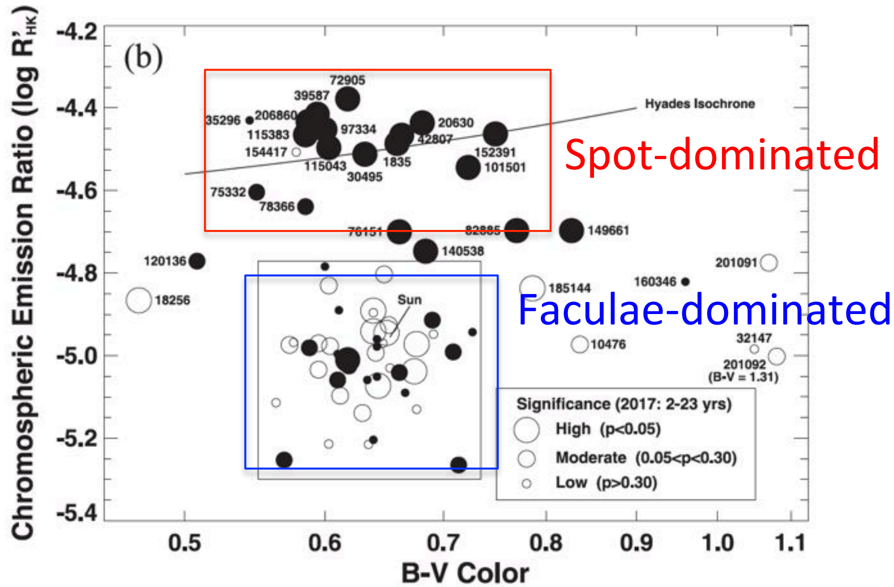


Activity proxies of Sun-like stars

- ❑ Chromospheric activity and photometric variability: spots vs faculae

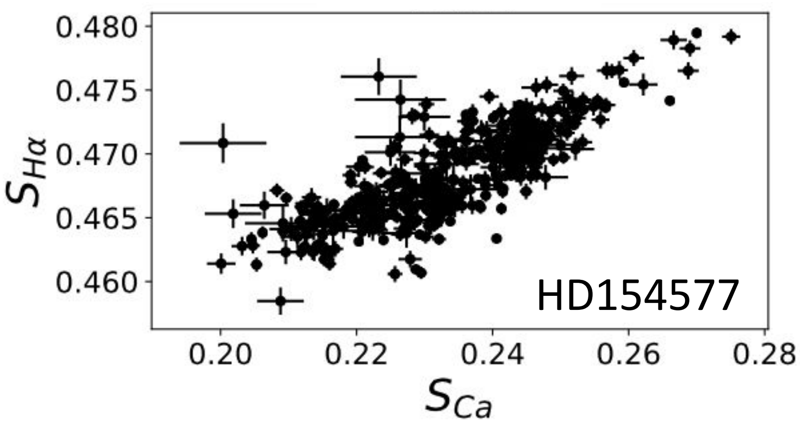
Radick et al. 2018



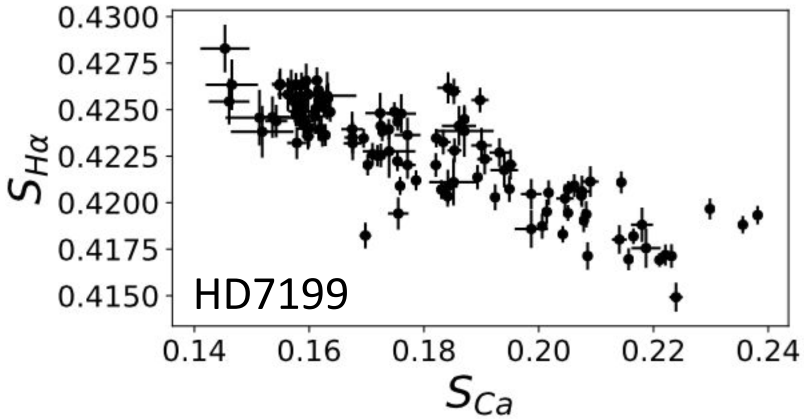


- ❑ Chromospheric activity: link with the Sun (Harps obs. of 465 stars)

Solar like correlation

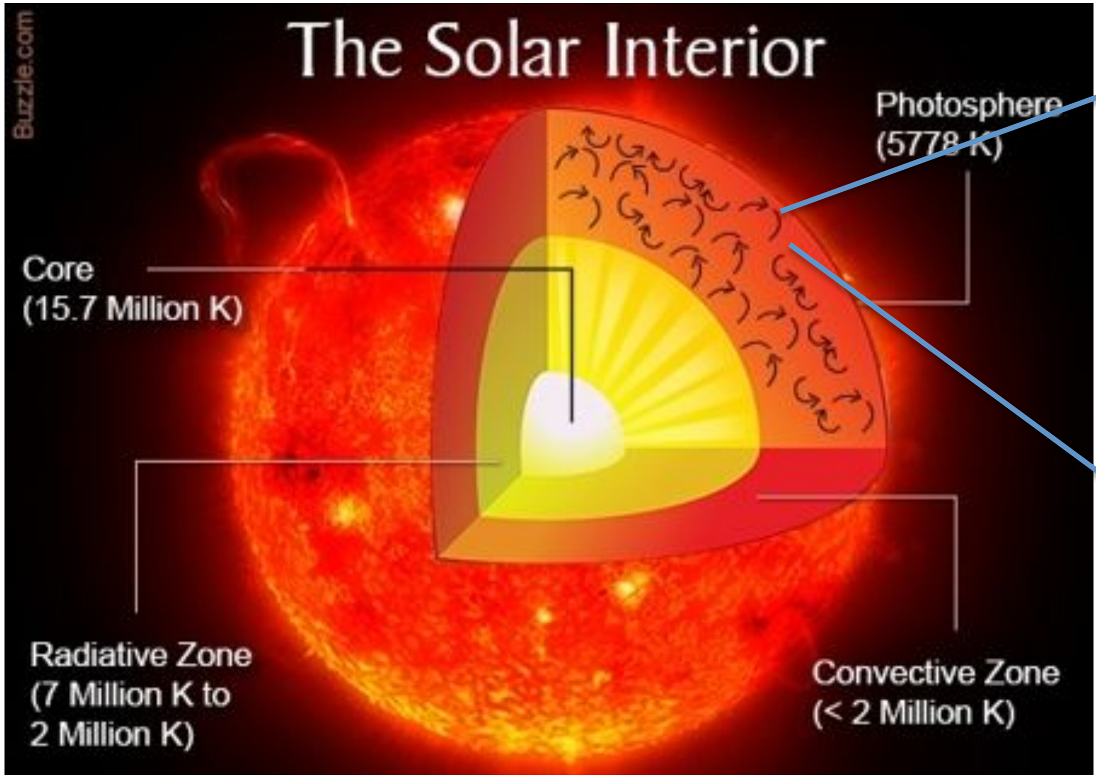


Anti correlation: filaments ? (hyp)

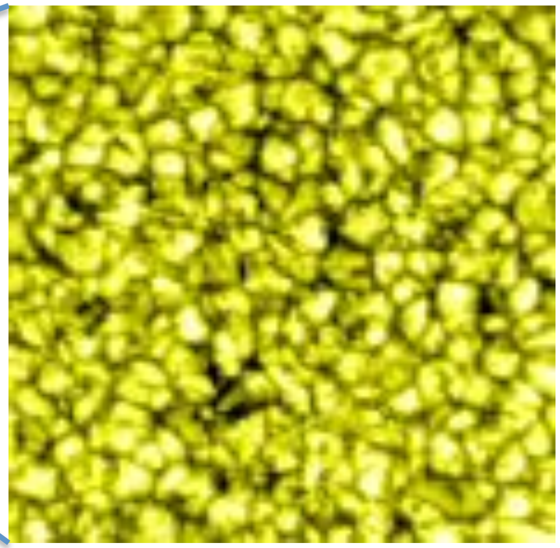


Meunier, Kretzschmar et al., ongoing

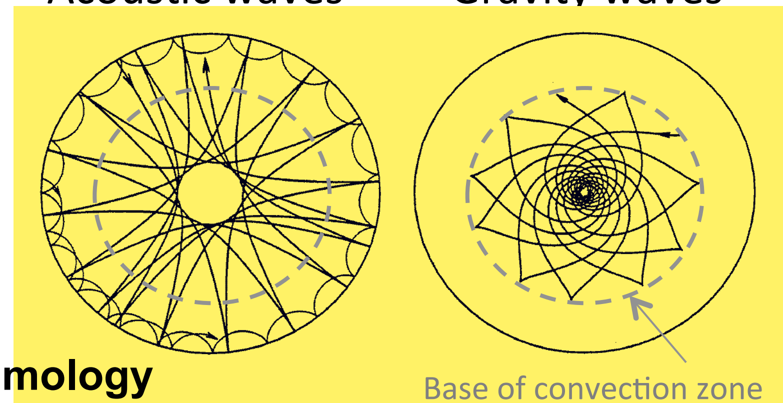
Solar interior and plasma flows



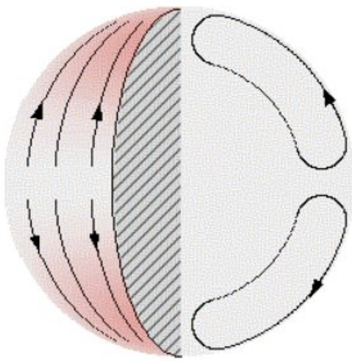
- Granulation (surface convection)



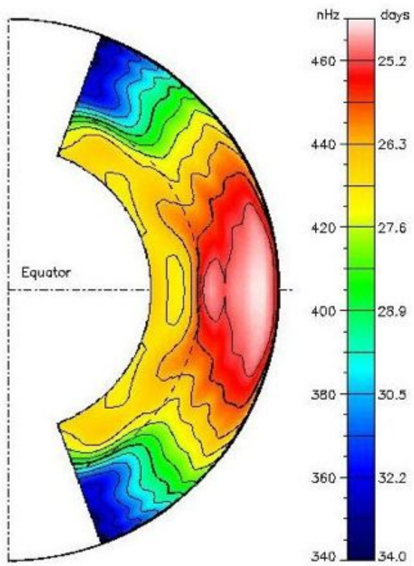
Acoustic waves Gravity waves



Helioseismology



- Meridional flow

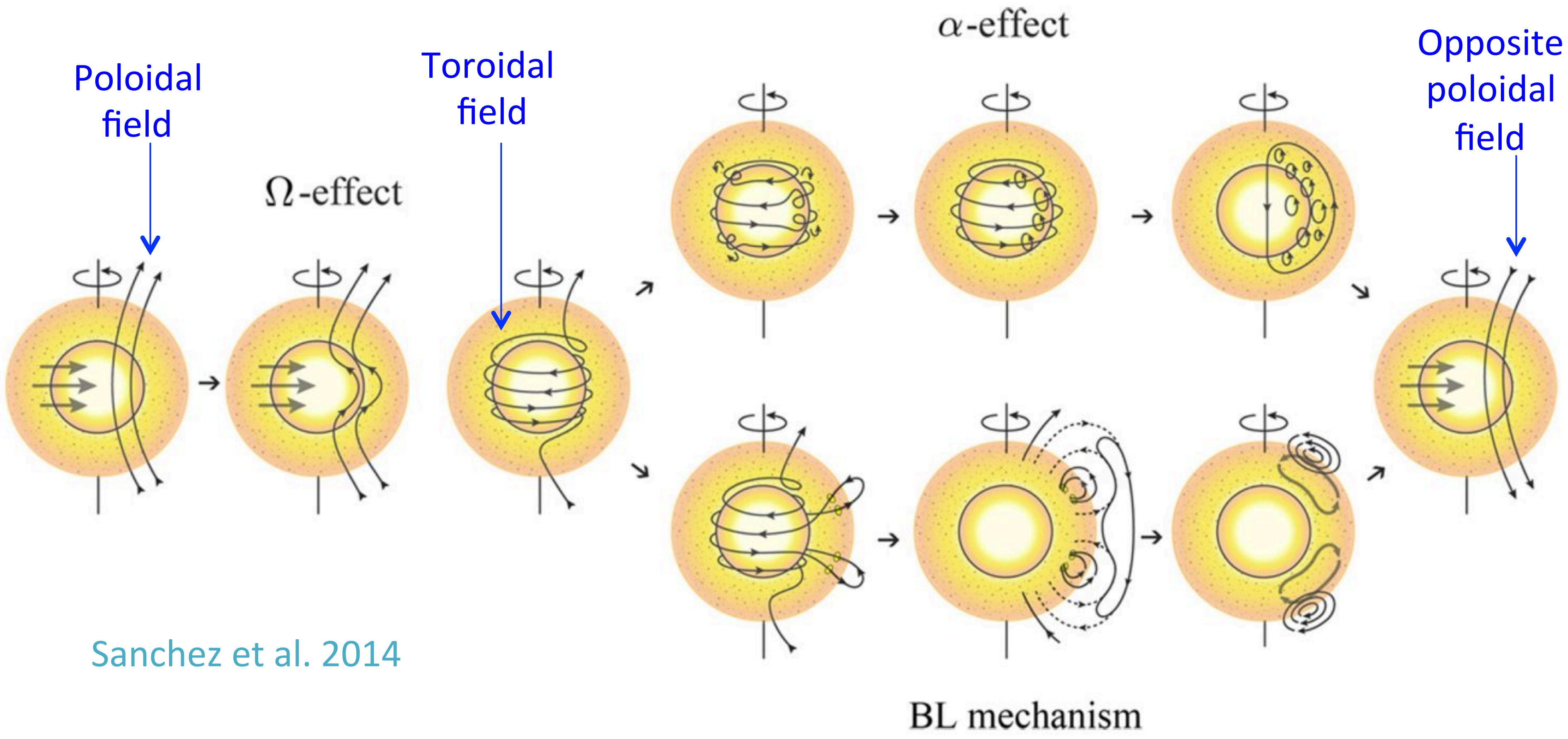


- Rotation

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

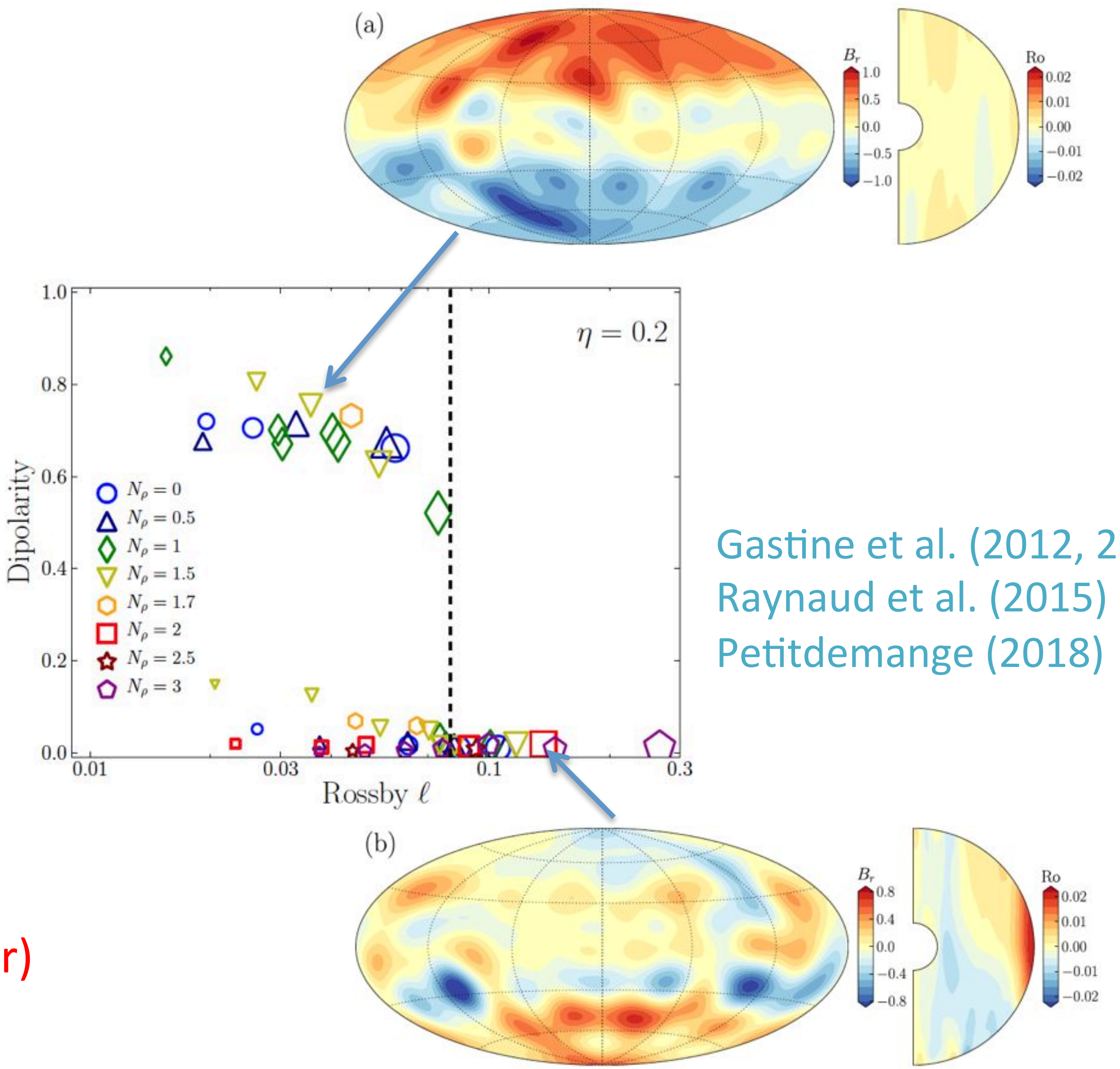
Magnetic topology: influence of the Rossby number

- Change in Rossby
  Ro=inertia/Coriolis

(also seen in planetary dynamos: Christensen & Aubert 2006)

- Small Ro:
  Ordering role of Coriolis=dipolar (no role of shear)

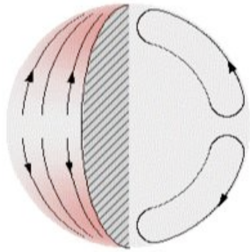
- Large Ro:
  Inertia becomes dominant=multipolar (important role of shear)

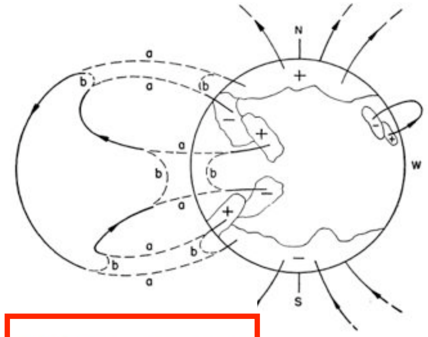


Gastine et al. (2012, 2013)
Raynaud et al. (2015)
Petitdemange (2018)

Magnetic cycles in 2D models

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

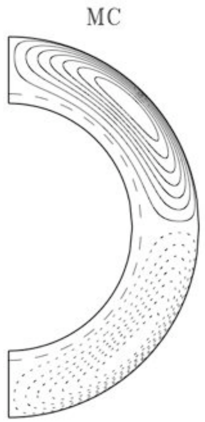




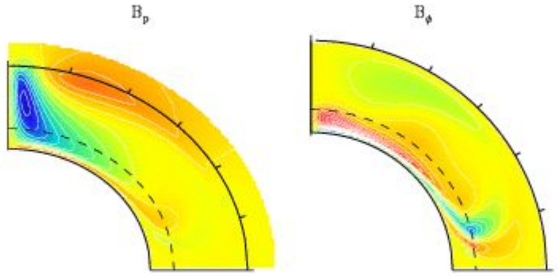
$$\frac{\partial A_\phi}{\partial t} = \frac{\eta}{\eta_t}(\nabla^2 - \frac{1}{\varpi^2})A_\phi - R_e \frac{\mathbf{u}_p}{\varpi}\cdot\nabla(\varpi A_\phi) + \cancel{C_\alpha \alpha} B_\phi + \boxed{C_s S(r,\theta,B_\phi)}$$

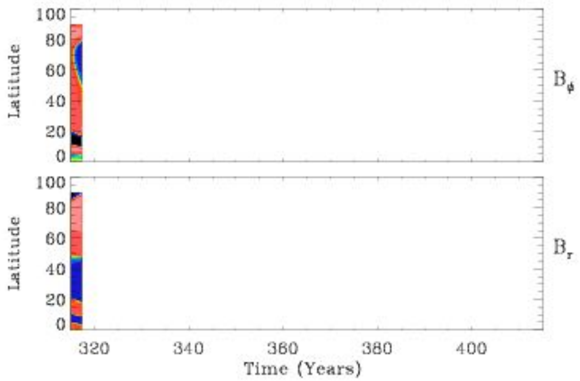
$$\frac{\partial B_\phi}{\partial t} = \frac{\eta}{\eta_t}(\nabla^2 - \frac{1}{\varpi^2})B_\phi + \frac{1}{\varpi}\frac{\partial(\varpi B_\phi)}{\partial r}\frac{\partial(\eta/\eta_t)}{\partial r} - R_e \varpi \mathbf{u}_p \cdot \nabla(\frac{B_\phi}{\varpi}) - R_e B_\phi \nabla \cdot \mathbf{u}_p + C_\Omega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

Standard model: single-celled meridional circulation



Dikpati & Charbonneau 1999
Jouve & Brun 2007



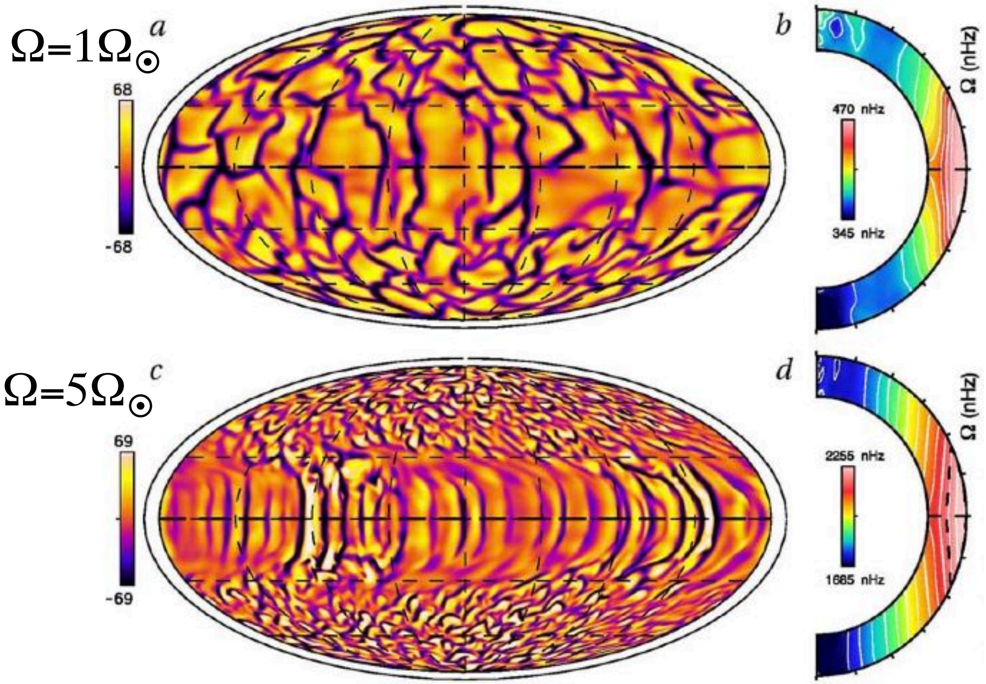


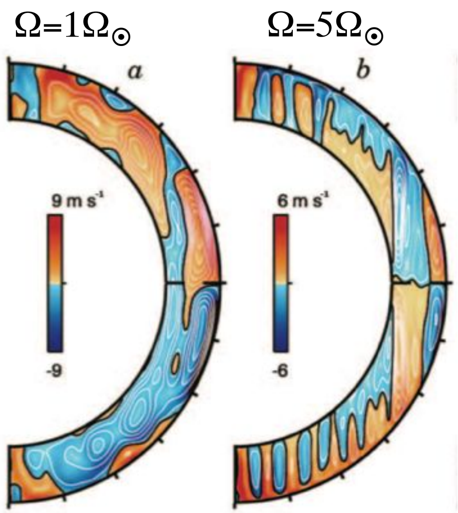
- Cyclic field
- Butterfly diagram
ok with observations
- Very strong dependence of cycle period on MC amplitude

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

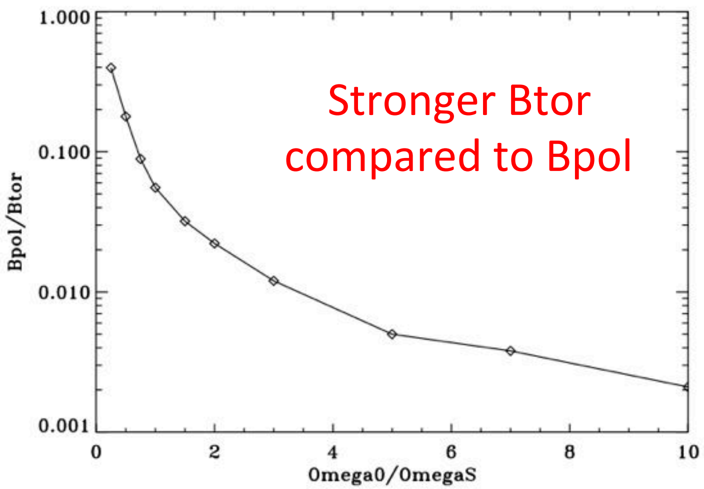
Is this solar model applicable for rapidly-rotating solar-like stars?

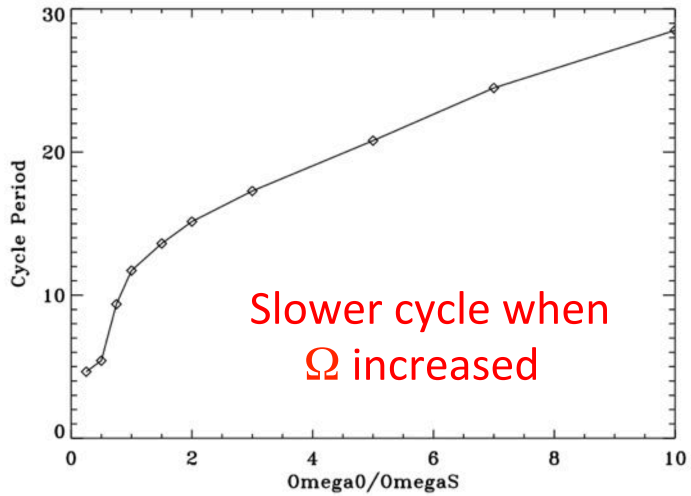
Applications to young Suns





- Prescriptions from 3D models (Brown et al. 2008):
  - Vp α $\Omega^{-0.9}$
  - $\Delta\Omega$ increases with Ω



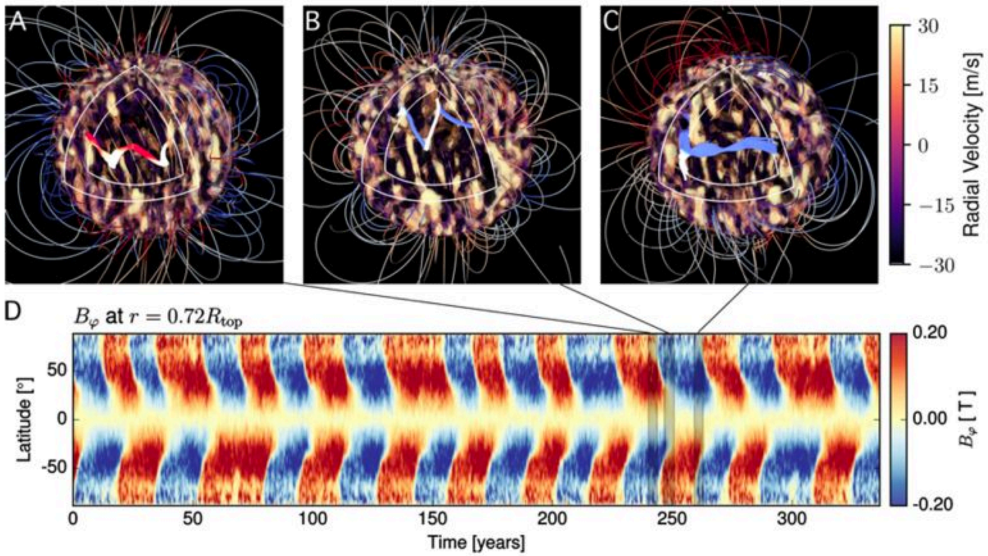


Jouve et al. 2010

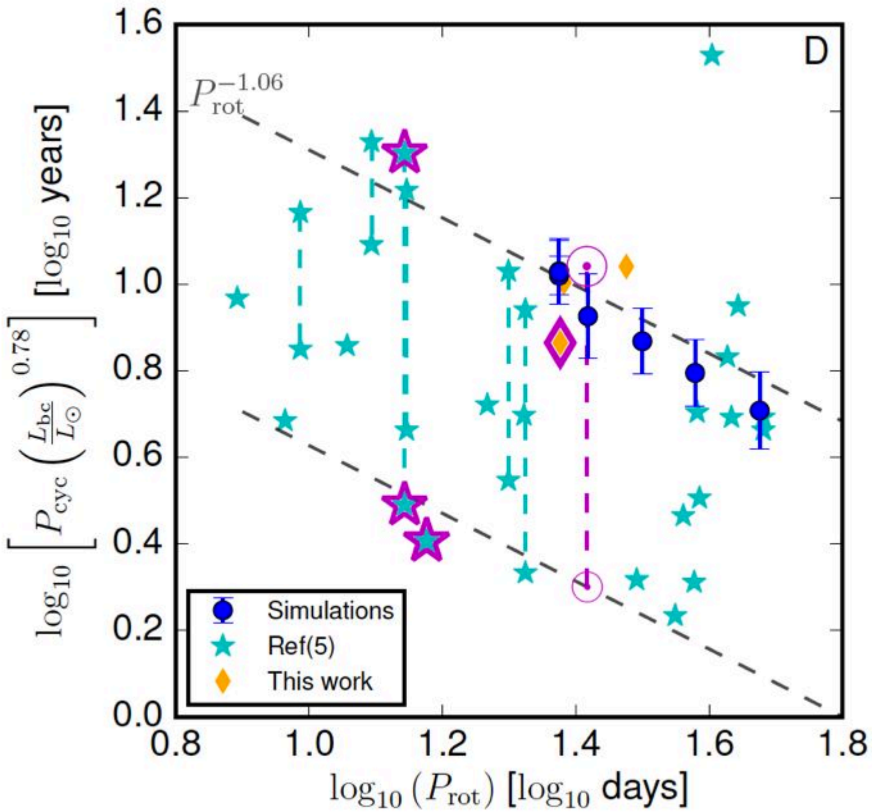
The MC profile needs to be modified to reconcile models and observations

Applying solar models to other stars: more realistic models

$\Omega = \Omega_\odot$

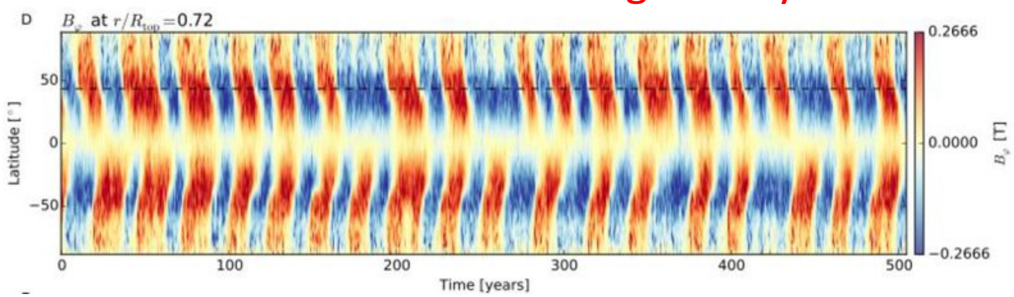


Strugarek et al. 2017



At fixed luminosity, slower rotation produces shorter magnetic cycles!

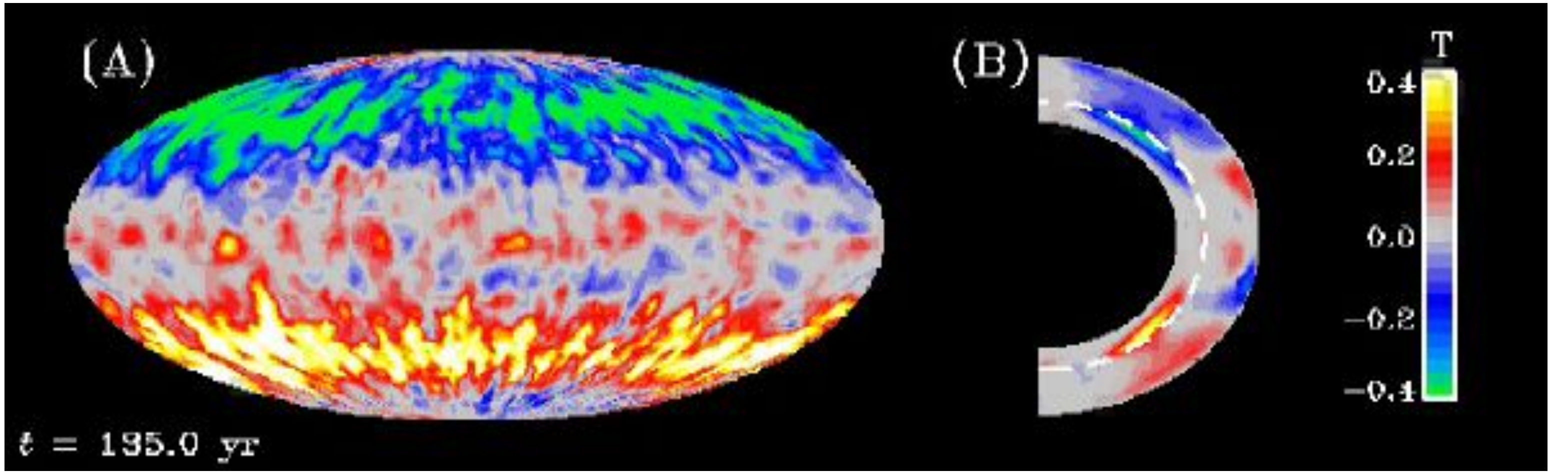
$\Omega = 0.6\Omega_\odot$



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

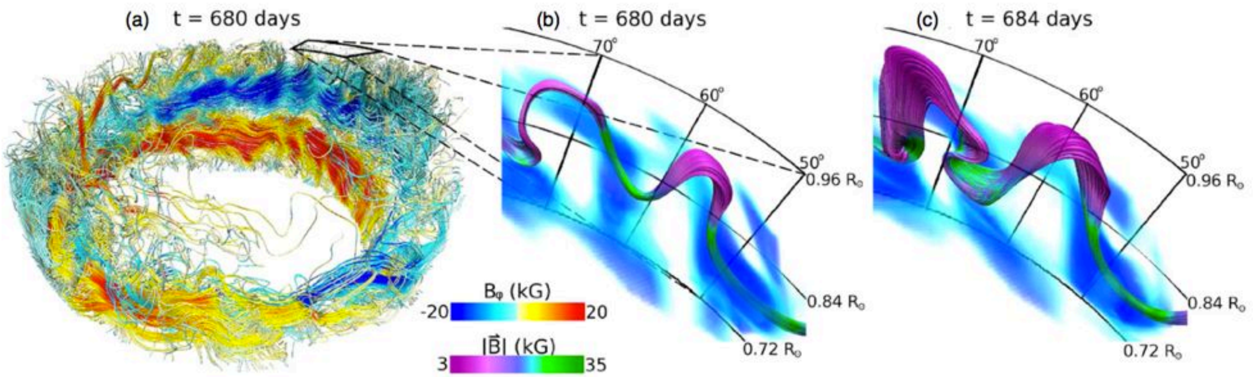
Role of spots: what about 3D models?

- 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)

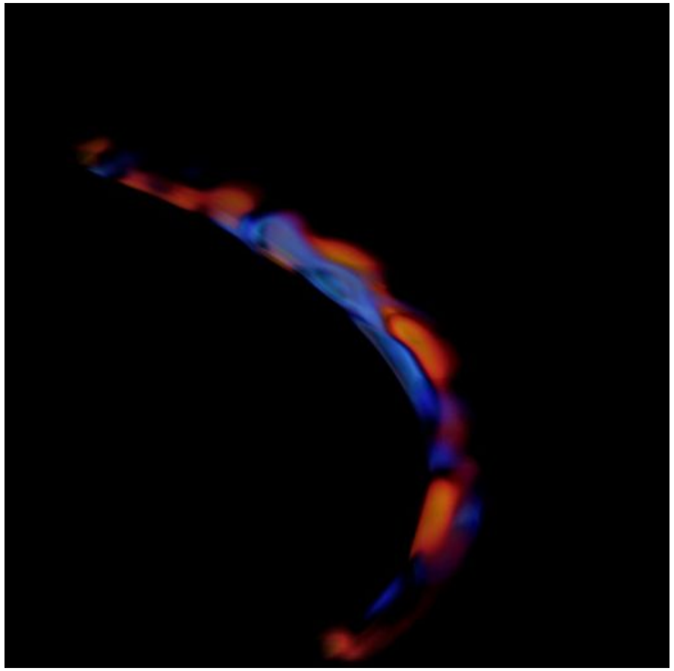


- Strong concentrations of toroidal field can still be built but buoyant structures do not make it to the top to produce spots!

Nelson et al. (2011, 2014)



Simulation of buoyant loop rise and sunspots

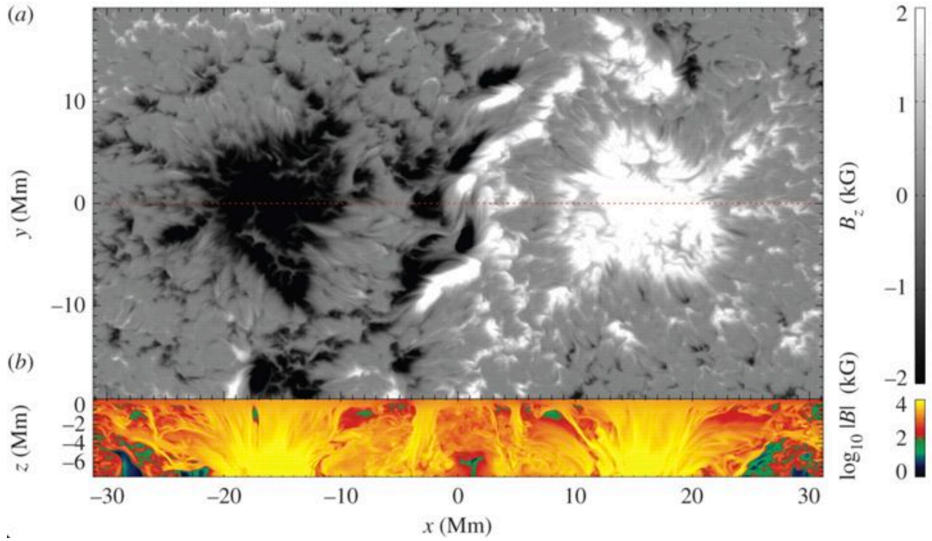


- The buoyant rise has to be modeled independently:

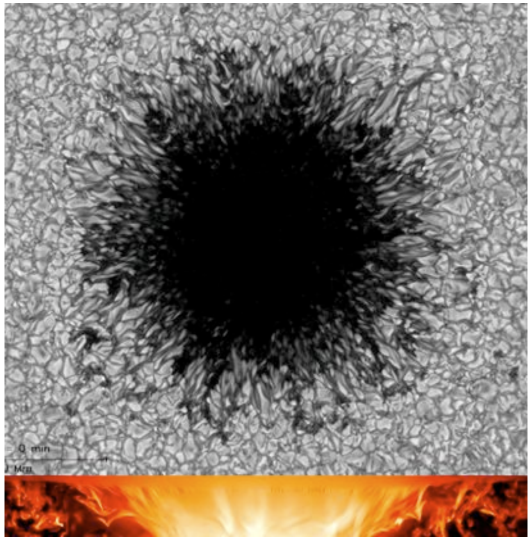
  Toroidal flux tube introduced at the base of the CZ in a convective layer

  Jouve, Brun & Aulanier 2013, 2018

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

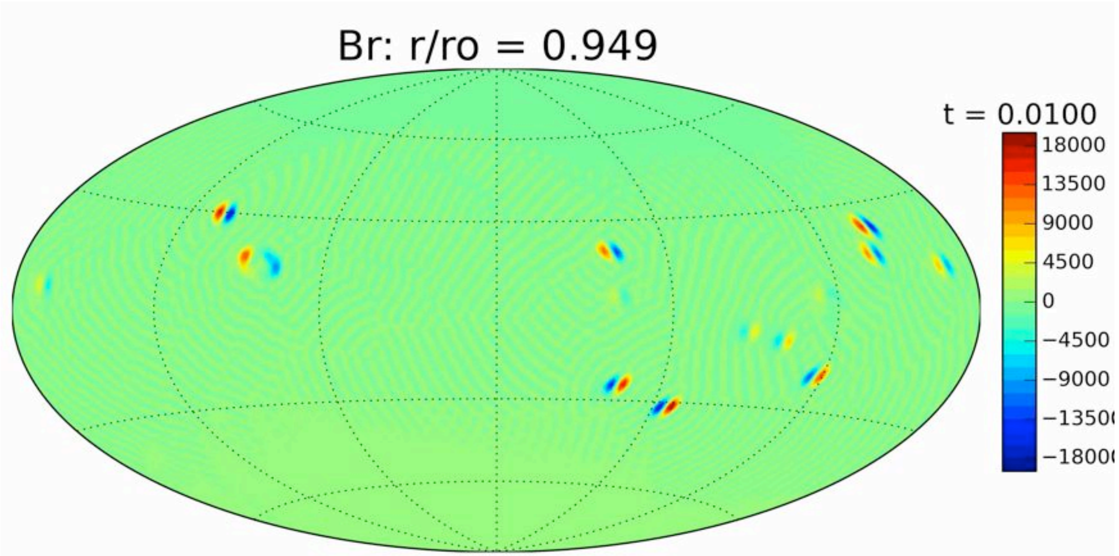


Rempel et al. 2009, 2014

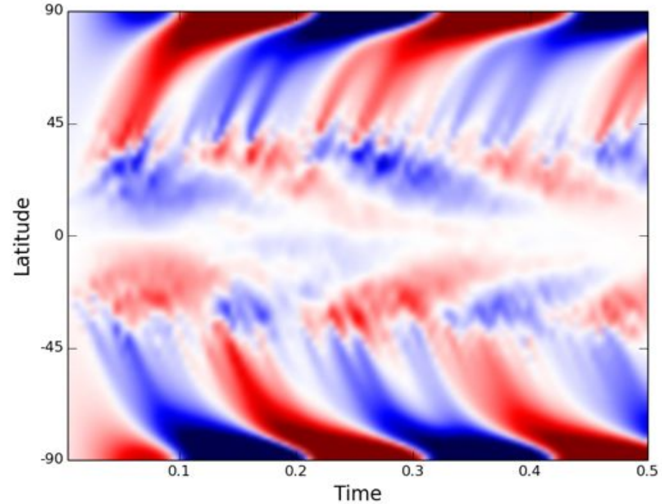


3D kinematic models: combining approaches

- 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)



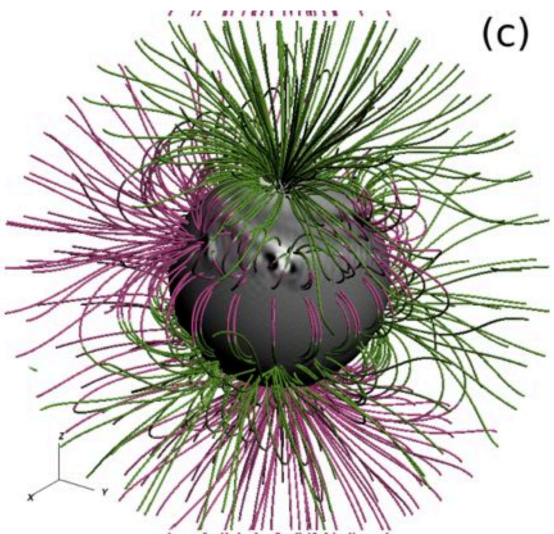
Self-consistent butterfly diagrams

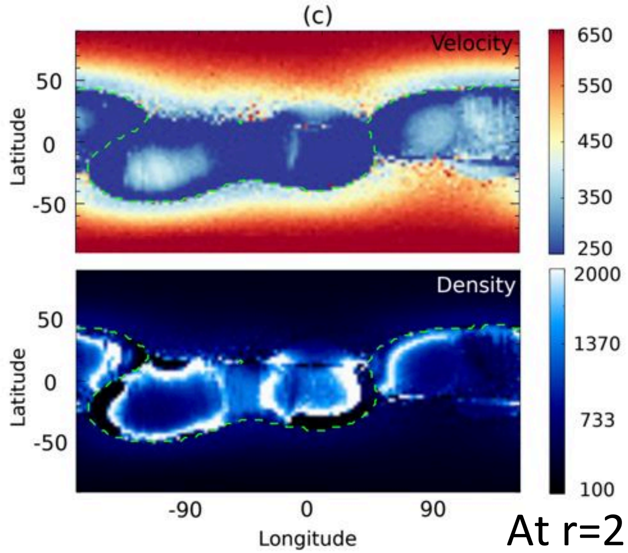


CEFIPRA Project
(D. Nandy & L. Jouve)

Kumar, Jouve, Pinto & Rouillard , 2018

Coronal field:
PFSS reconstruction





At r=21.5 R

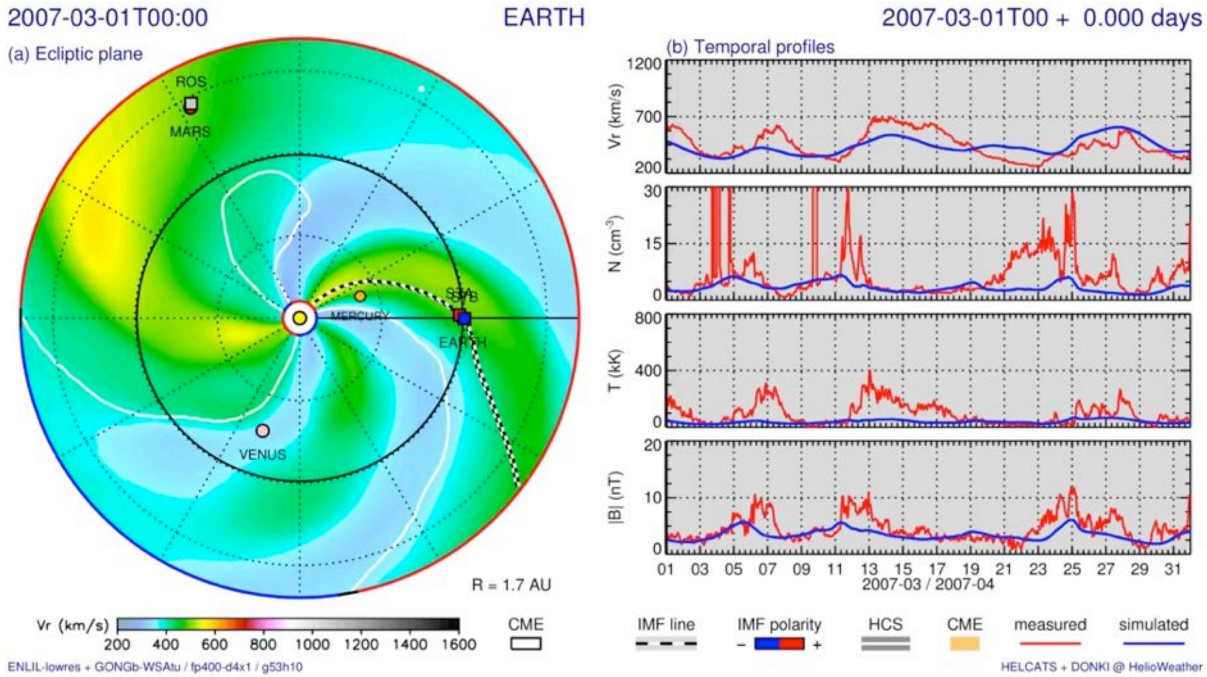
Stellar winds, CMEs and exoplanets

- ❑ In the solar system:

Multi-VP+ENLIL
Integrated in Propagation Tool
(CDPP)

Rouillard et al. 2016
Pinto & Rouillard 2017

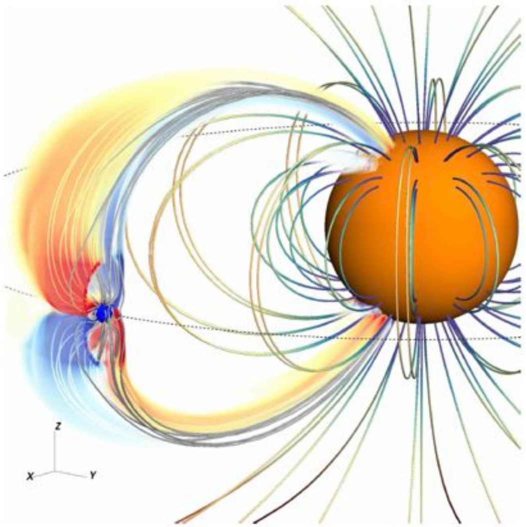
See also MAVEN results

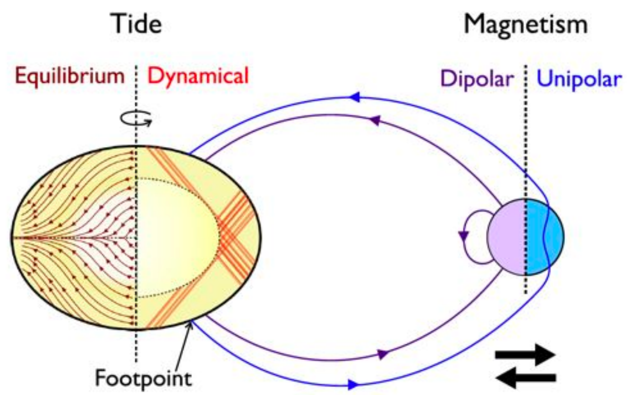


- ❑ Around other stars:

Magnetic interactions that can lead to planet migration (like tides)

Strugarek 2016
Strugarek et al. 2017

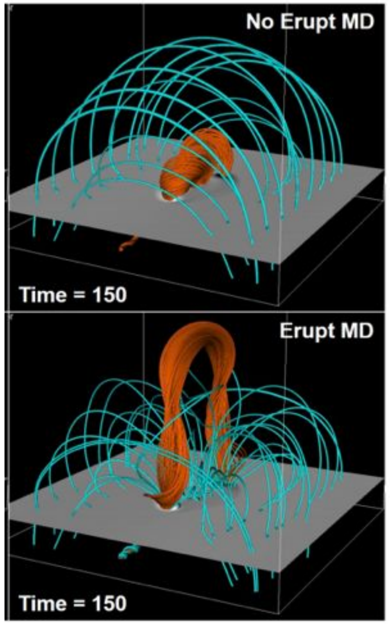


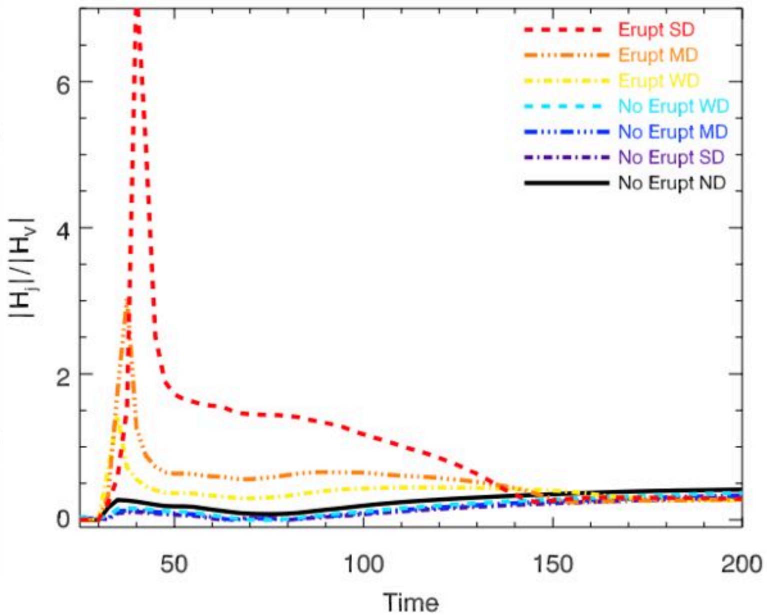


Predicting future solar activity

❑ Short term: prediction of eruptions

Pariat et al. 2017





- European effort to forecast eruptions: **Flarecast**

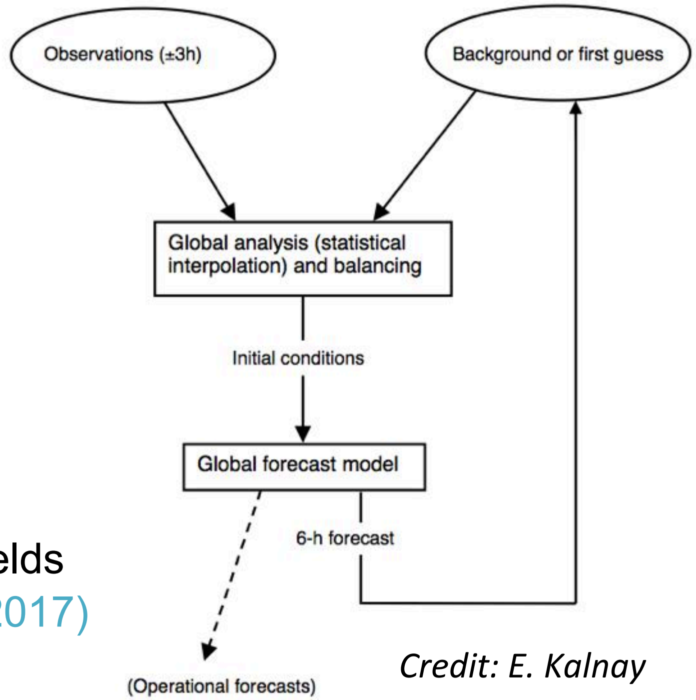
- Identification of useful criteria to distinguish between erupting and non-erupting cases => based on **helicity of non-potential field**

- See also Amari et al. 2014, 2018

❑ Long term: prediction of cycles

✓ Inspired from weather forecasting on Earth:
Physics-based models and observations combined through ***data assimilation (Solar Predict CEA, S. Brun)***

✓ Dynamo models+observations of surface flows and mag. fields (Kitiashvili et al. 2008, Jouve et al. 2010, Hung et al. 2015, 2017)



Credit: E. Kalnay

Conclusions

MHD models of stellar interiors enable to understand some aspects of stellar magnetism

- Internal magnetism of solar-like stars:

    - Dynamo action at the origin of their magnetic fields (solar models applicable to other stars?)
    - Effect of internal structure? Rotation?
    - What is missing in 3D models to actually produce spots?

- Shaping the stars' environments:

    - Stellar winds and CMEs interact with neighbouring planets (necessitates accurate wind modeling)
    - Direct magnetic interactions can modify planets' orbits (observational constraints?)

- Predicting future solar/stellar activity:

    - European effort for flare forecasting
    - Longer-term forecasting (cycles): applying data assimilation?

More to come with Parker Solar Probe, Solar orbiter, Spirou, Plato