Magnetic flux emergence and stellar dynamo models

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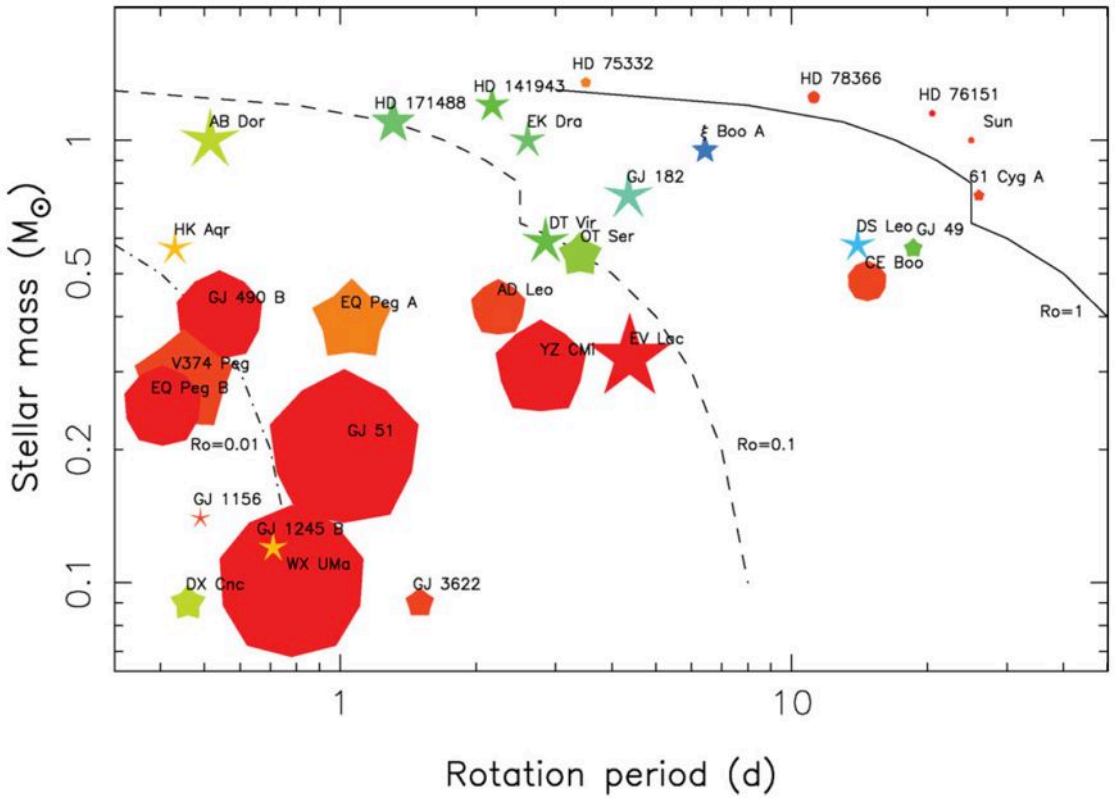
B Cool meeting, Montpellier, July 2017

Magnetic fields in cool MS stars

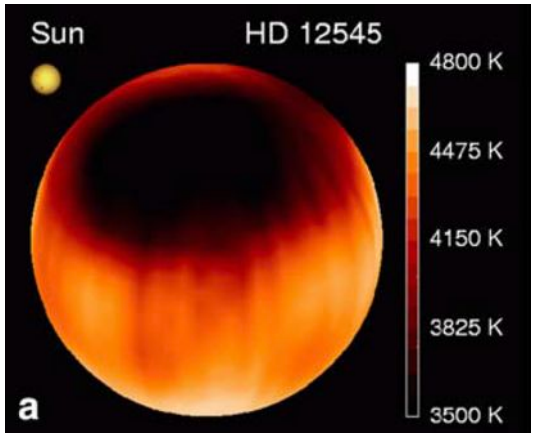
Morin, Donati et al. (2008-2010), Folsom et al. 2016



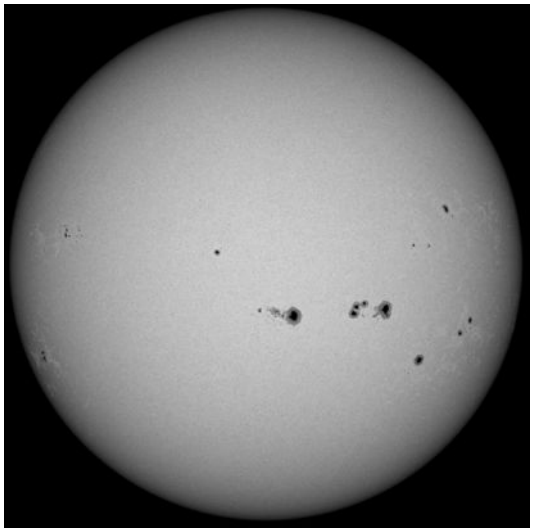
- ❑ Mostly multipolar for $M_\odot > 0.35$
- ❑ Mostly dipolar for $M_\odot < 0.35$
- ❑ Bistability for $M_\odot < 0.2$
- ❑ Field strength increases with rotation
- ❑ More and more toroidal with rotation

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

Strassmeier (1999)



SDO data (July 2014)

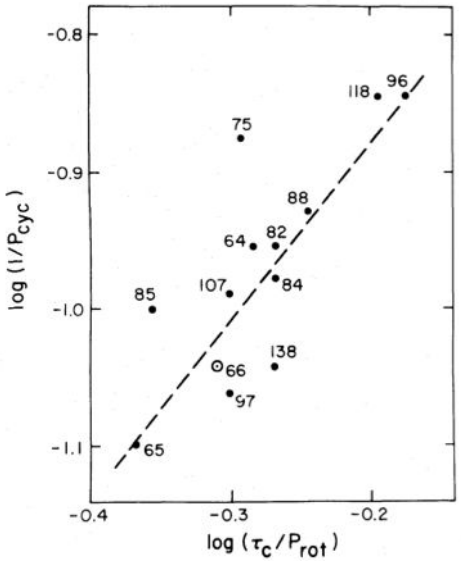


- ❑ In stars cooler than the Sun:

Polar spots with large coverage

Observations of magnetic cycles?

Noyes et al. 1984

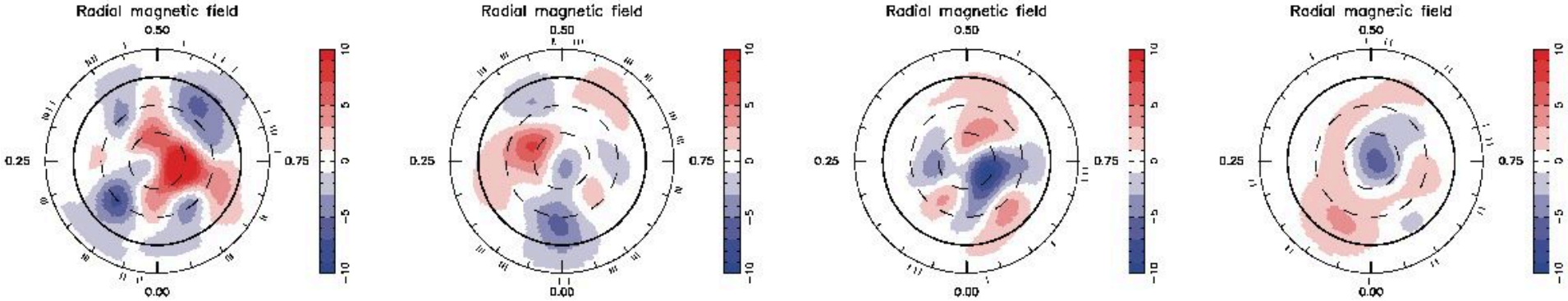


Chromospheric activity (Mount Wilson data, Ca II HK lines):
$P_{cyc}=Ro^{1.28+/-0.48}$

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

Do news 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: HD 190771 (complex variability)

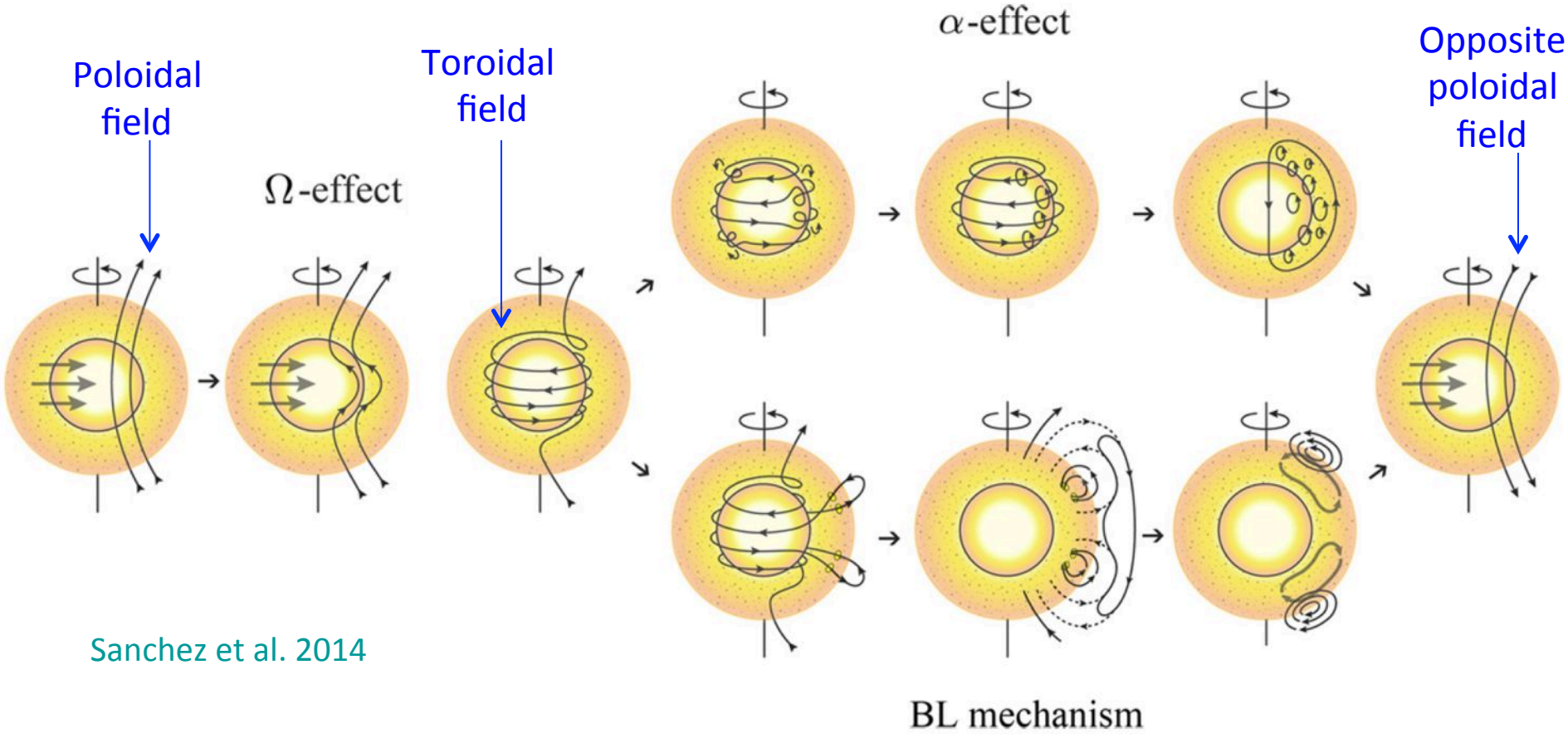
Garcia et al 2010: HD 49933: 120 days?

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

Our Sun

Basic solar dynamo ingredients

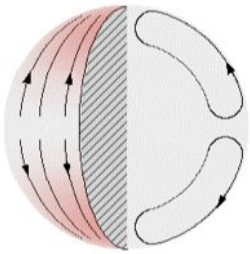
The solar dynamo: process through which the motions of a conducting fluid permanently regenerates a magnetic field

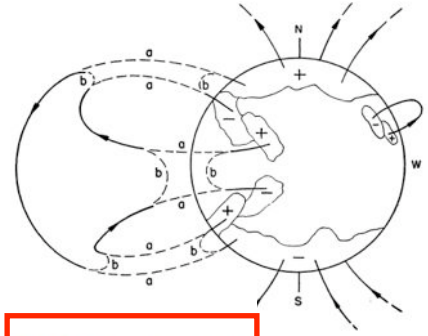


Sanchez et al. 2014

Magnetic cycles in 2D models

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

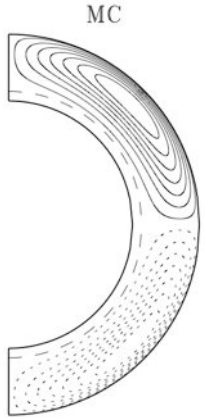




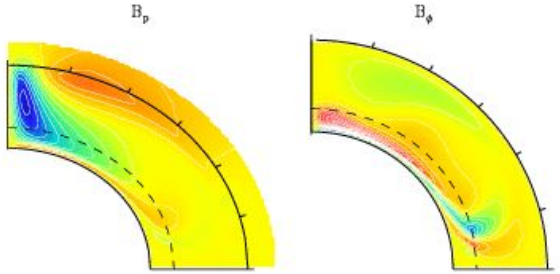
$$\frac{\partial A_\phi}{\partial t} = \frac{\eta}{\eta_t}(\nabla^2 - \frac{1}{\varpi^2})A_\phi - R_e \frac{\mathbf{u}_p}{\varpi}\cdot\nabla(\varpi A_\phi) + C_\alpha \alpha B_\phi + C_s S(r,\theta,B_\phi)$$

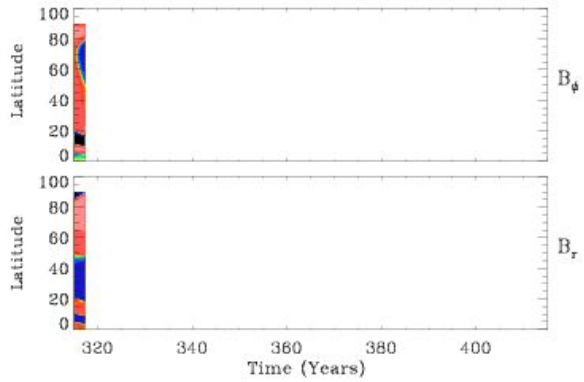
$$\frac{\partial B_\phi}{\partial t} = \frac{\eta}{\eta_t}(\nabla^2 - \frac{1}{\varpi^2})B_\phi + \frac{1}{\varpi}\frac{\partial(\varpi B_\phi)}{\partial r}\frac{\partial(\eta/\eta_t)}{\partial r} - R_e \varpi \mathbf{u}_p \cdot \nabla(\frac{B_\phi}{\varpi}) - R_e B_\phi \nabla\cdot\mathbf{u}_p + C_\Omega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

Standard model: single-celled meridional circulation



Dikpati & Charbonneau 1999
Jouve & Brun 2007



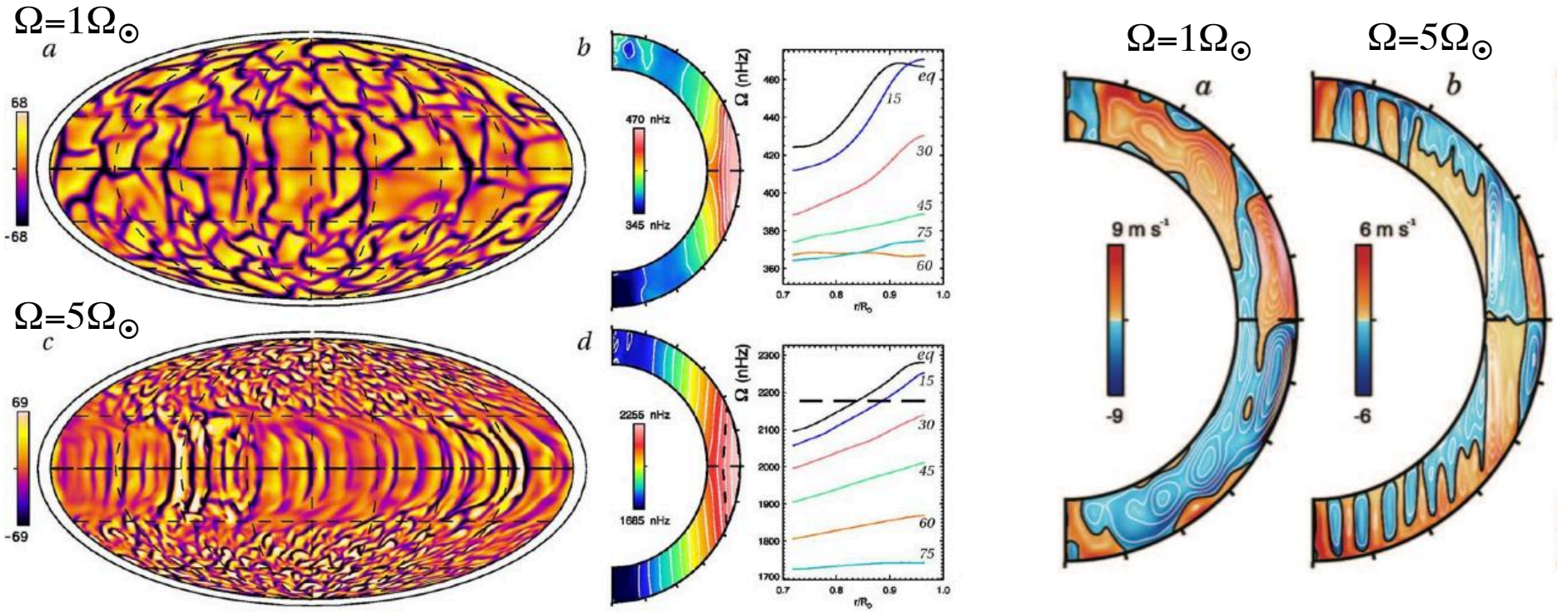


- Cyclic field
- Butterfly diagram ok with observations
- Very strong dependence of cycle period on MC amplitude

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

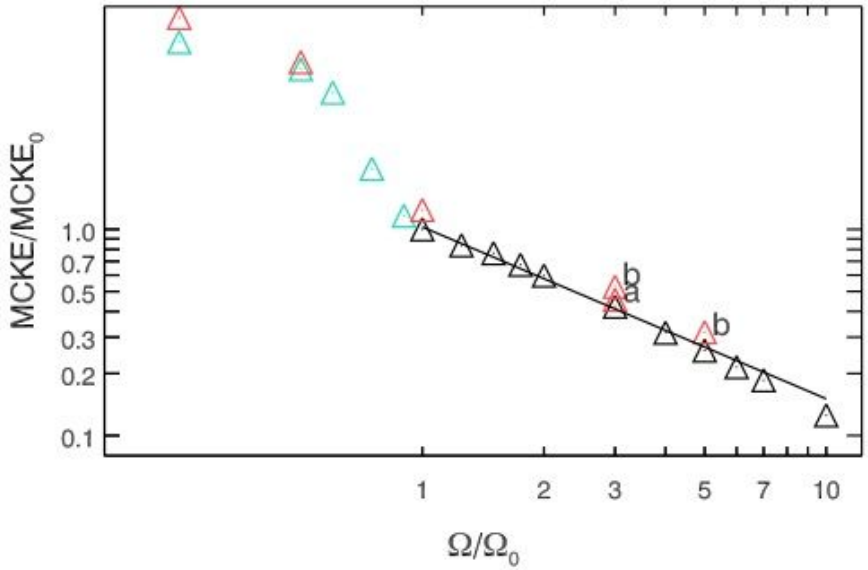
Is this solar model applicable for rapidly-rotating solar-like stars?

Prescriptions from 3D models

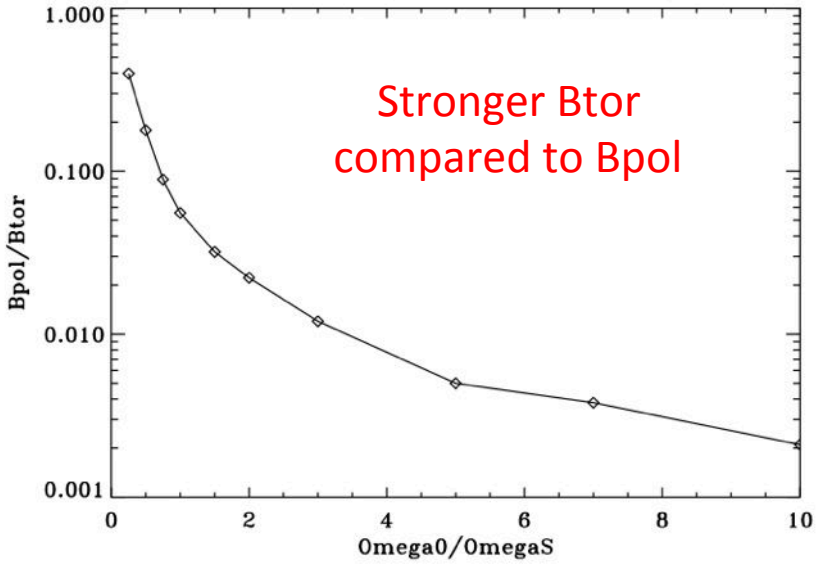


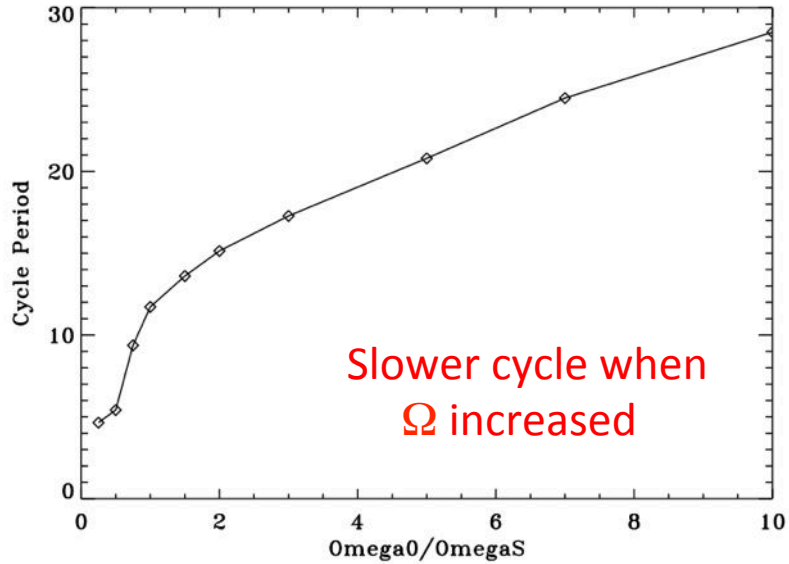
Scaling of MC deduced from Brown et al. 2008: Vp α $\Omega^{-0.9}$

$\Delta\Omega$ increases with Ω



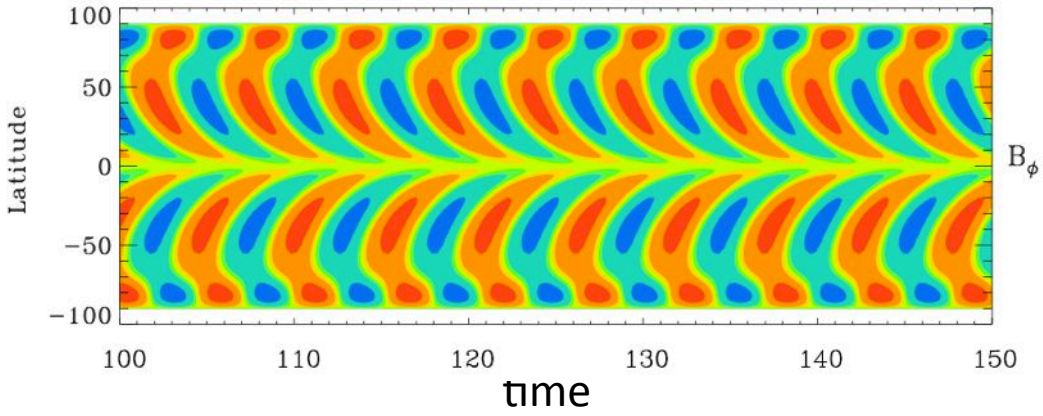
Applying solar models to other stars



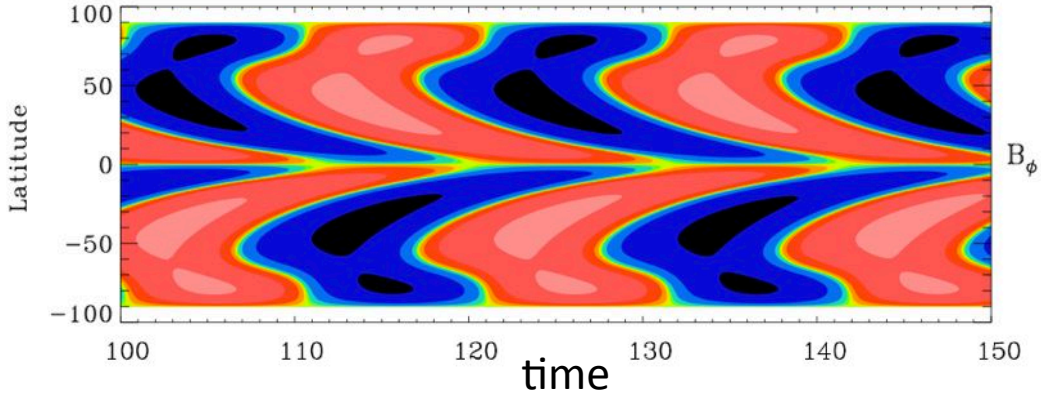


Jouve et al. 2010

0.5 Ωsol



5 Ωsol Pcyc = 20 yr

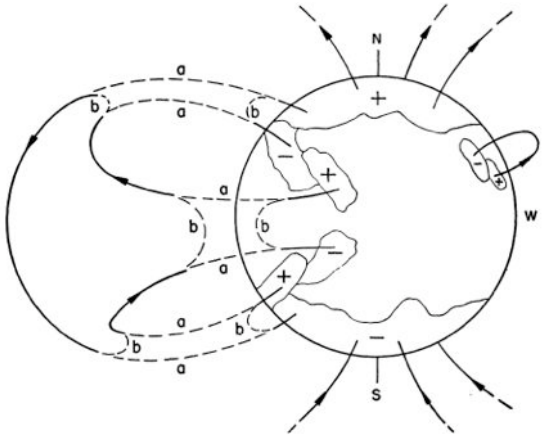


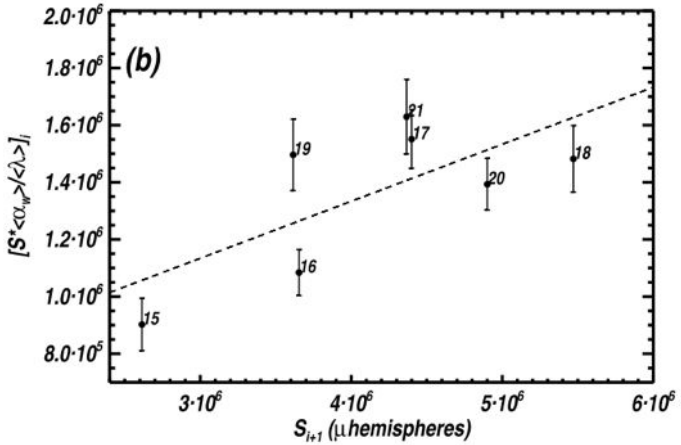
The MC profile needs to be modified to reconcile models and observations

But other more realistic models also find the opposite trend (Strugarek et al. 2017, in press)

Crucial role of spots? What about 3D models?

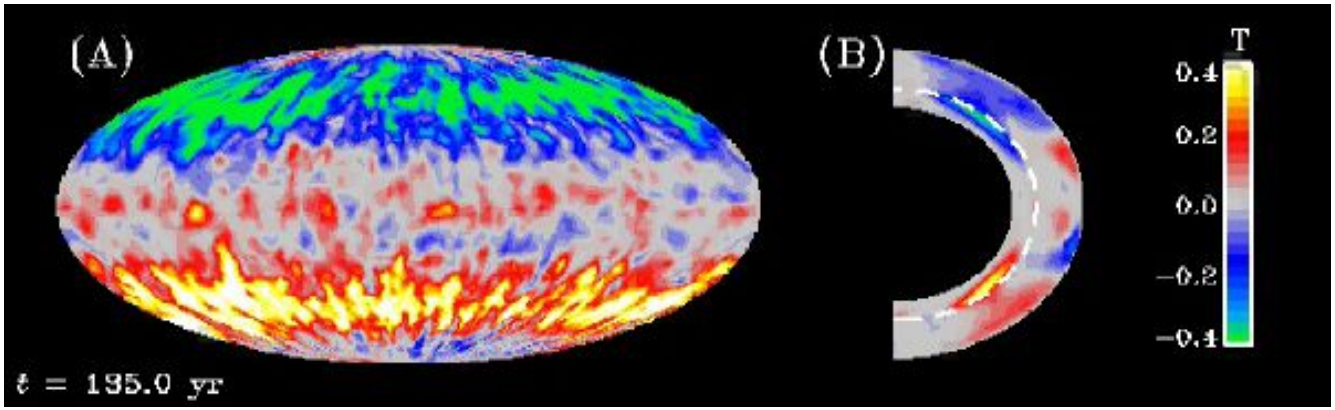
- Babcock-Leighton models relies on spot decay to reverse polar field





Dasi-Espuig et al. 2010

- 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)

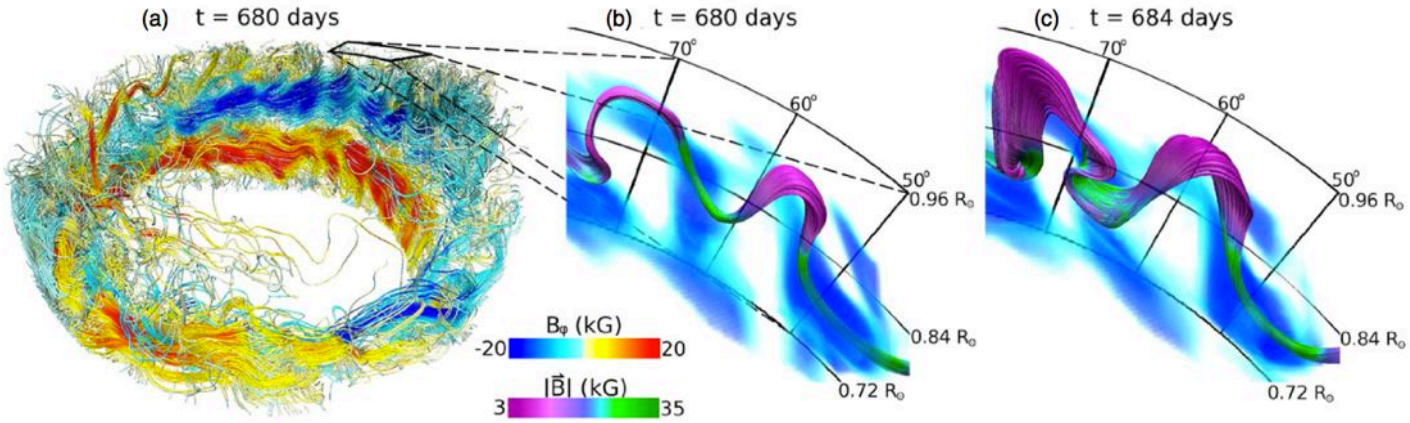


Ghizaru et al. (2010)

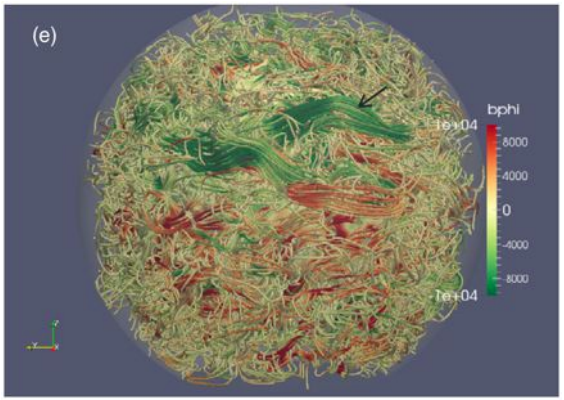
3D models do produce buoyant structures

- Strong concentrations of toroidal field (without the need of a tachocline) from which buoyant loops can emerge. Diffusion has to be treated carefully.

Nelson et al. (2011, 2014)



Fan & Fang (2014)



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

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)

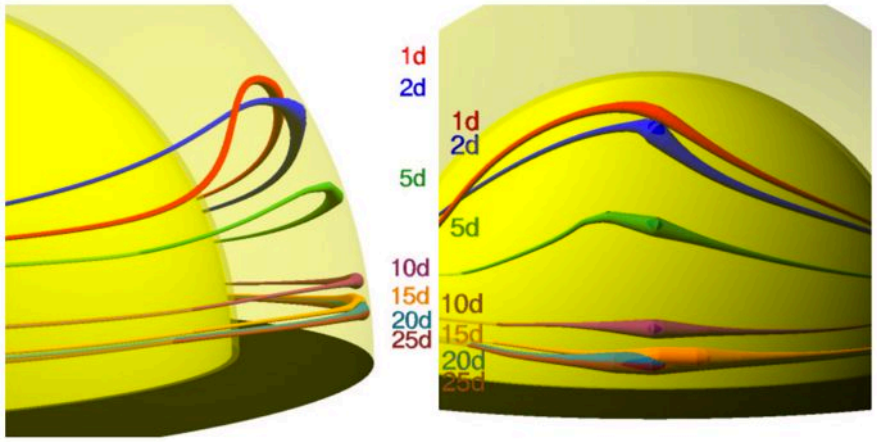
- Latitude of emergence related to buoyancy VS Coriolis
- Rise time depends on field strength
- Tilt angle depends on field strength and latitude
- Effect of convection and (differential) rotation
- Twist of the field lines is necessary (and observed)
- Reconnection needed for emergence in the stably 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)

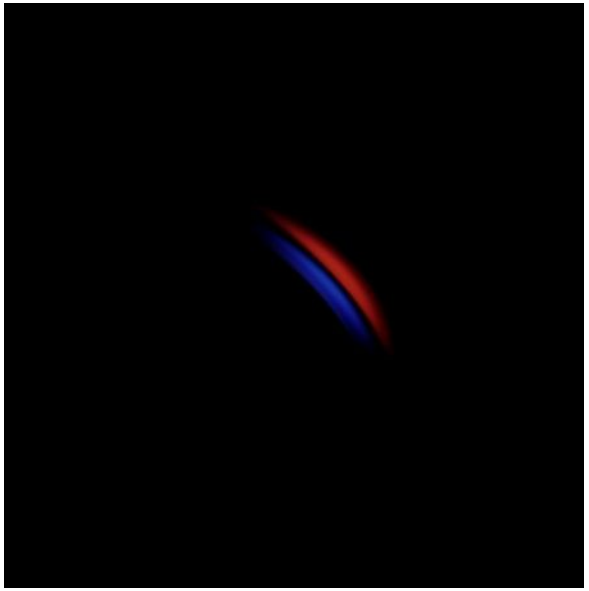


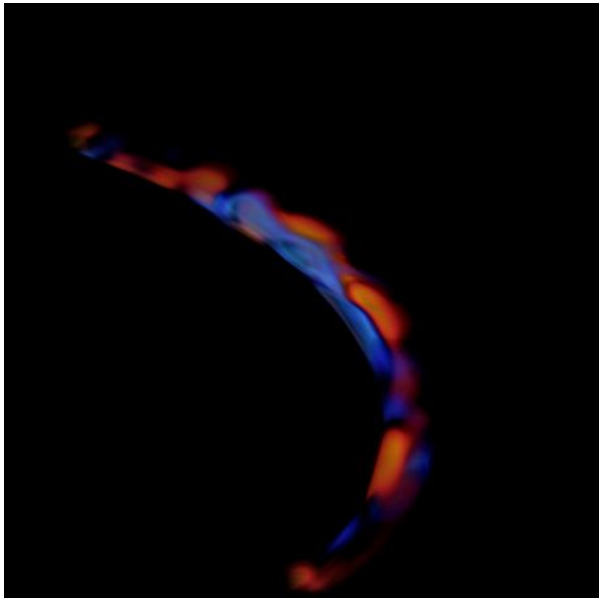
Holzwarth, 2007

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

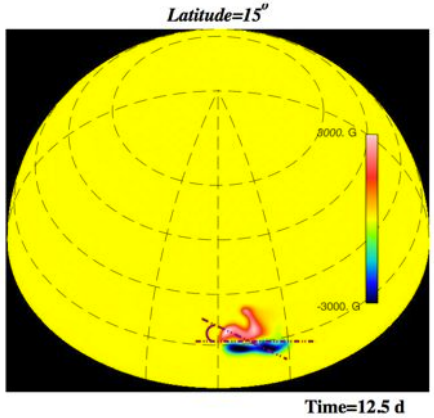
Isentropic layer

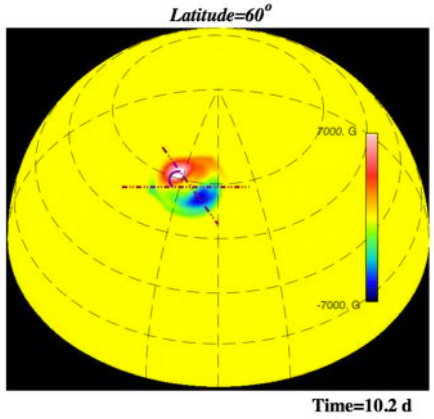




Convective layer

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





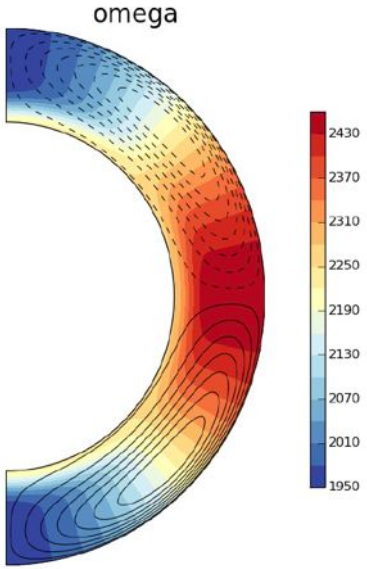
Jouve et al. 2013

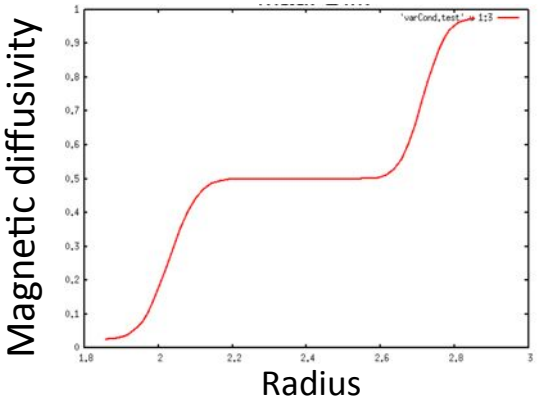
3D kinematic model: combining approaches

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

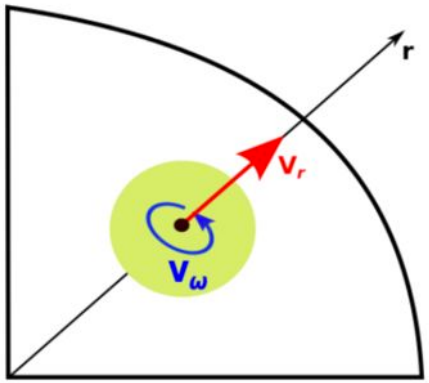
❑ In the 3D MAGIC Code:

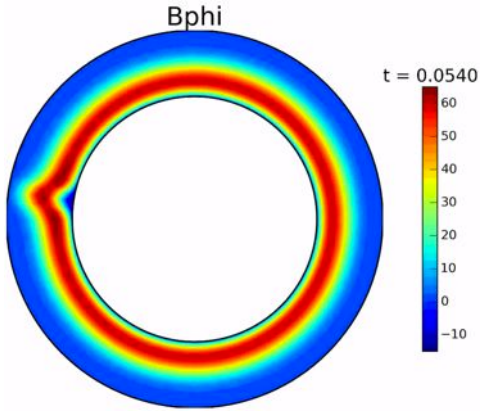
❑ Prescribed differential rotation + meridional flow + diffusivity profile

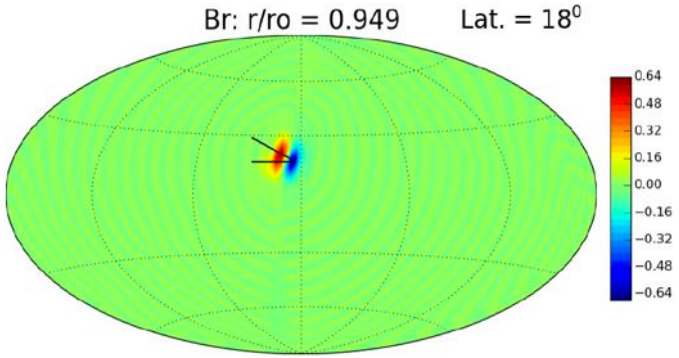




❑ Buoyancy algorithm for flux emergence





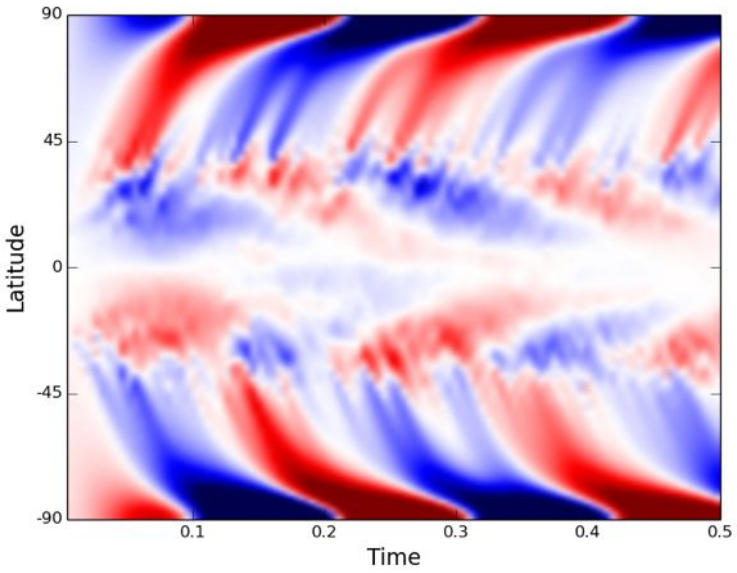


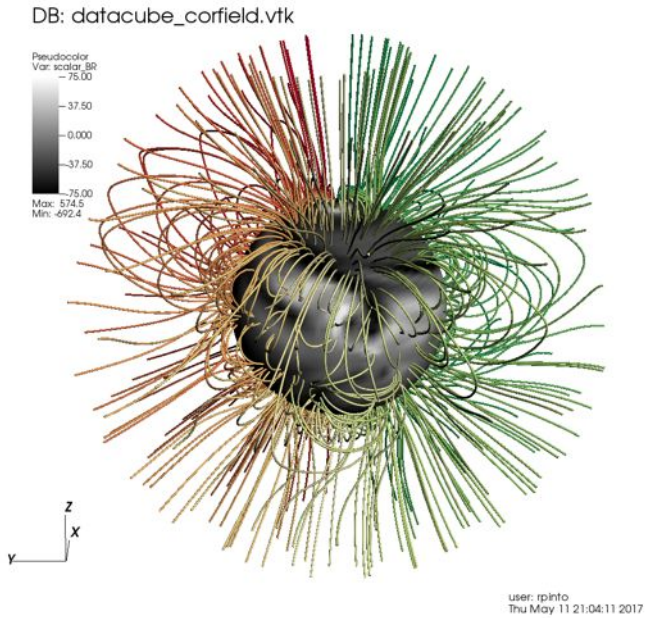
3D kinematic model: combining approaches

❑ Self-consistent butterfly diagrams + coronal field + wind solutions

Kumar, Jouve, Pinto & Rouillard , in prep.

Br Movie





❑ Applicable to other stars (adapted mean flows and flux emergence properties) + wind solutions

❑ Data-driven simulations and data assimilation easily applicable in those models (CEFIPRA Project PIs: Nandy & Jouve)

Conclusions

- Applying commonly used models for the Sun to other stars

  - BLFT dynamo model supported by solar observations
  - used for the Sun to reproduce features of the magnetic cycle
  - Very strong dependence on meridional flow
    - not seen in 3D global models
    - could be a problem when applied to other stars

- Do spots play a significant role in the dynamo process (like in BL model)?

  - 3D dynamo simulations work without spots
  - some start producing buoyant loops
  - The flux emergence step can be modelled independently
    - rise times, tilt angles, latitude of emergence can be related to initial conditions
  - 3D kinematic models can test the BL hypothesis and data can be assimilated into them