Magnetic flux emergence with differential rotation in compressible shells

Yori Fournier
Rainer Arlt, Klaus G. Strassmeier

Leibniz-Institut für Astrophysik Potsdam (AIP)

Description of the project

- Simulate rising magn. flux tubes for diff. type of stars.
  - compressible stratified convection zone
  - turbulent convection
  - realistic differential rotation (forced)
- First step: solar case for testing our model and compare with literature.
- Second step: to apply the model to red giants.

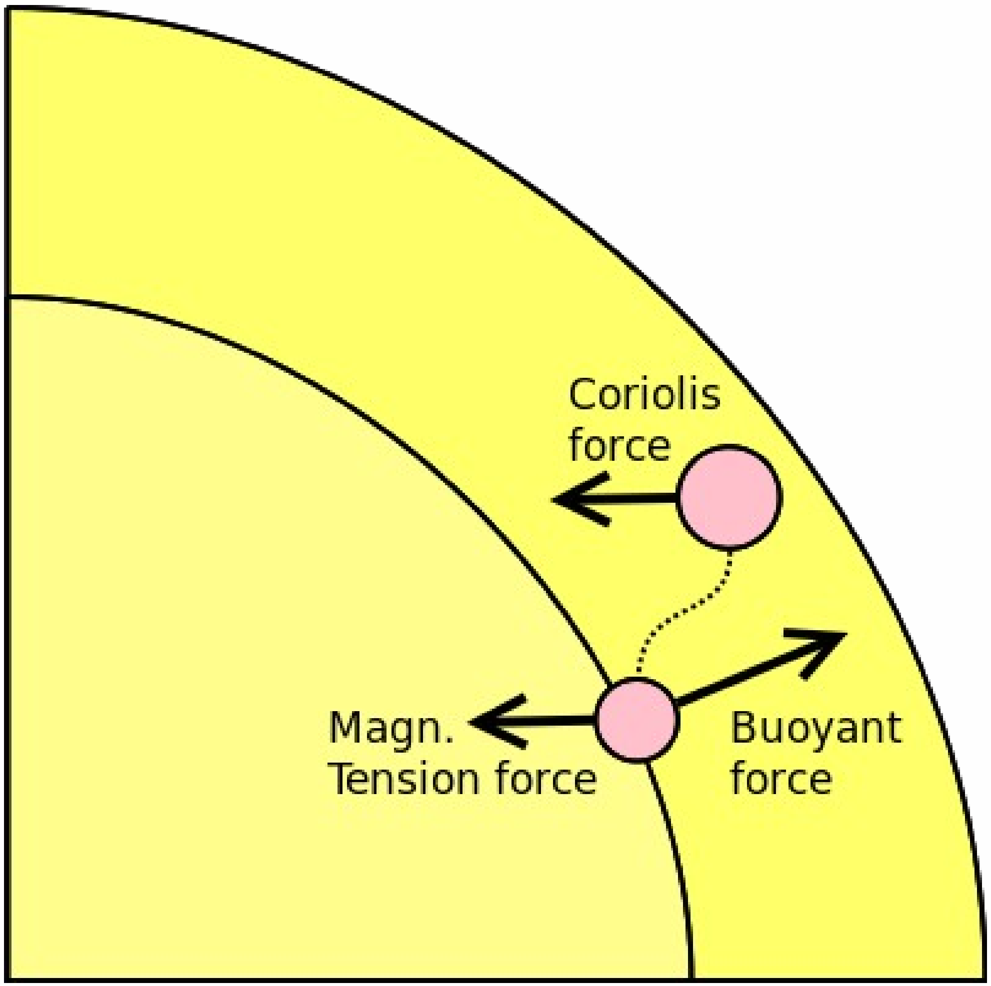
What do we need ?

- We need the following ingredients:
  - Stellar model for the *stratification*
  - A mean field model of angular momentum transport for the *realistic differential rotation*
  - A dynamo model (kinematic) for the *magn. distribution*
  - A parallel compressible MHD code with Adaptive Mesh Refinment in spherical coordinates for *convection* and the *dynamical evolution of the magn. flux*

What are we doing ?

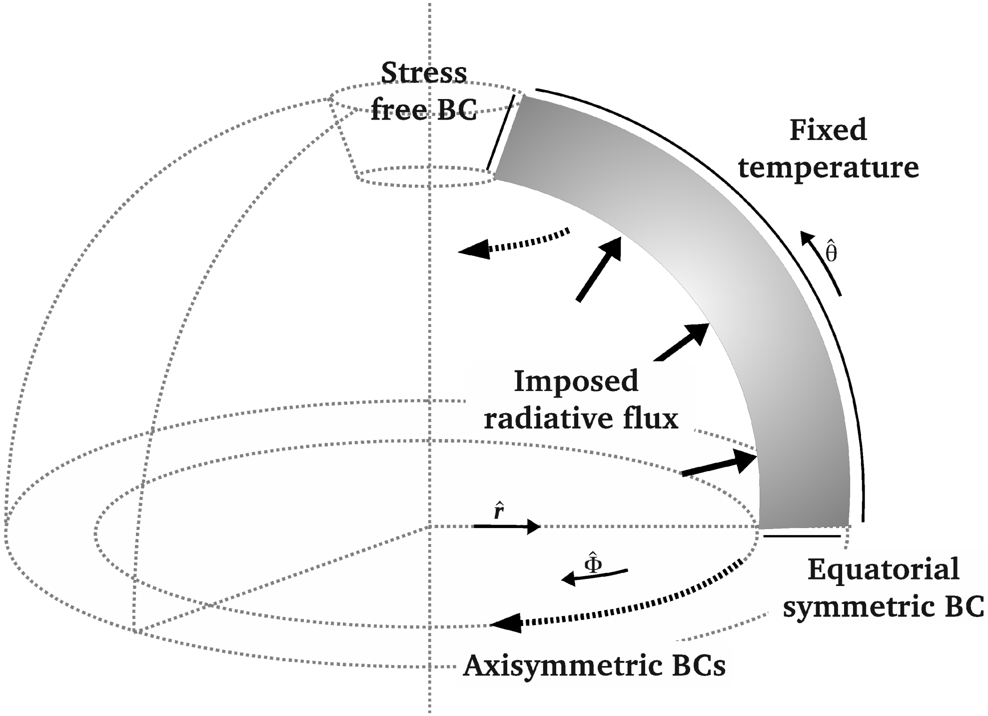
- First step:
  - 2D fully compressible MHD
  - Adiabatically stratified spherical shell
  - Forced diff. Rotation
  - Rising flux tube with AMR

The model



The model

- Domain, boundary conditions, and initial conditions



Hydrostatic Equilibrium

$$\frac{\partial P}{\partial r}\hat{\boldsymbol{r}} = -\rho \boldsymbol{g}$$

$$\frac{\partial T}{\partial r}\hat{\boldsymbol{r}} = -\frac{\boldsymbol{F}_{\rm rad}}{\kappa}$$

Definition of gravity and radiative flux

$$\boldsymbol{g} = -\frac{GM_\odot}{r^2}\hat{\boldsymbol{r}} \;, \qquad \boldsymbol{F}_{\rm rad} = \frac{L_\odot}{4\pi r^2}\hat{\boldsymbol{r}} \;.$$

The model

- Compressible MHD equations

$$\partial_t(\rho) + \nabla\cdot(\rho\boldsymbol{u}) = 0,$$

$$\partial_t(\boldsymbol{m}) + \nabla\cdot\left[\rho\boldsymbol{v}\boldsymbol{v} + P_{\rm tot}I - \frac{1}{\mu_0}\boldsymbol{B}\boldsymbol{B}\right] = -\rho\boldsymbol{g} + \boldsymbol{f}_{cc} + \boldsymbol{f}_{dr}$$

$$\partial_t(e) + \nabla\cdot\left[(e + P_{\rm tot})\,\boldsymbol{v} - \frac{1}{\mu_0}(\boldsymbol{v}\cdot\boldsymbol{B})\,\boldsymbol{B}\right] = (-\rho\boldsymbol{g} + \boldsymbol{f}_{CC} + \boldsymbol{f}_{DR})\boldsymbol{v} - \boldsymbol{F}_{\rm rad}$$

$$\partial_t(\boldsymbol{B}) - \nabla\times(\boldsymbol{u}\times\boldsymbol{B}) = 0,$$

- Dimensionless system (Käpylä et al. 2010a)

$$\tilde{\rho}_{\rm top} = G\tilde{M}_\odot = \tilde{R}_\odot = \tilde{cp} = 1$$

The model

- Forcing term
  - We do not simulate self consistently diff. Rotation.
  - We add a force in the φ direction which enforce the diff. rotation profile.

$$f_{DR} = -\frac{(< v_\phi > - v_{\mathrm{diff}})}{\tau_{\mathrm{relaxation}}}$$

- Relaxation time

$$\tau_{\mathrm{relaxation}} = \tau_0[1 + \alpha\beta]$$

Physically motivated by the fact that magn. Field suppresses Reynolds stress

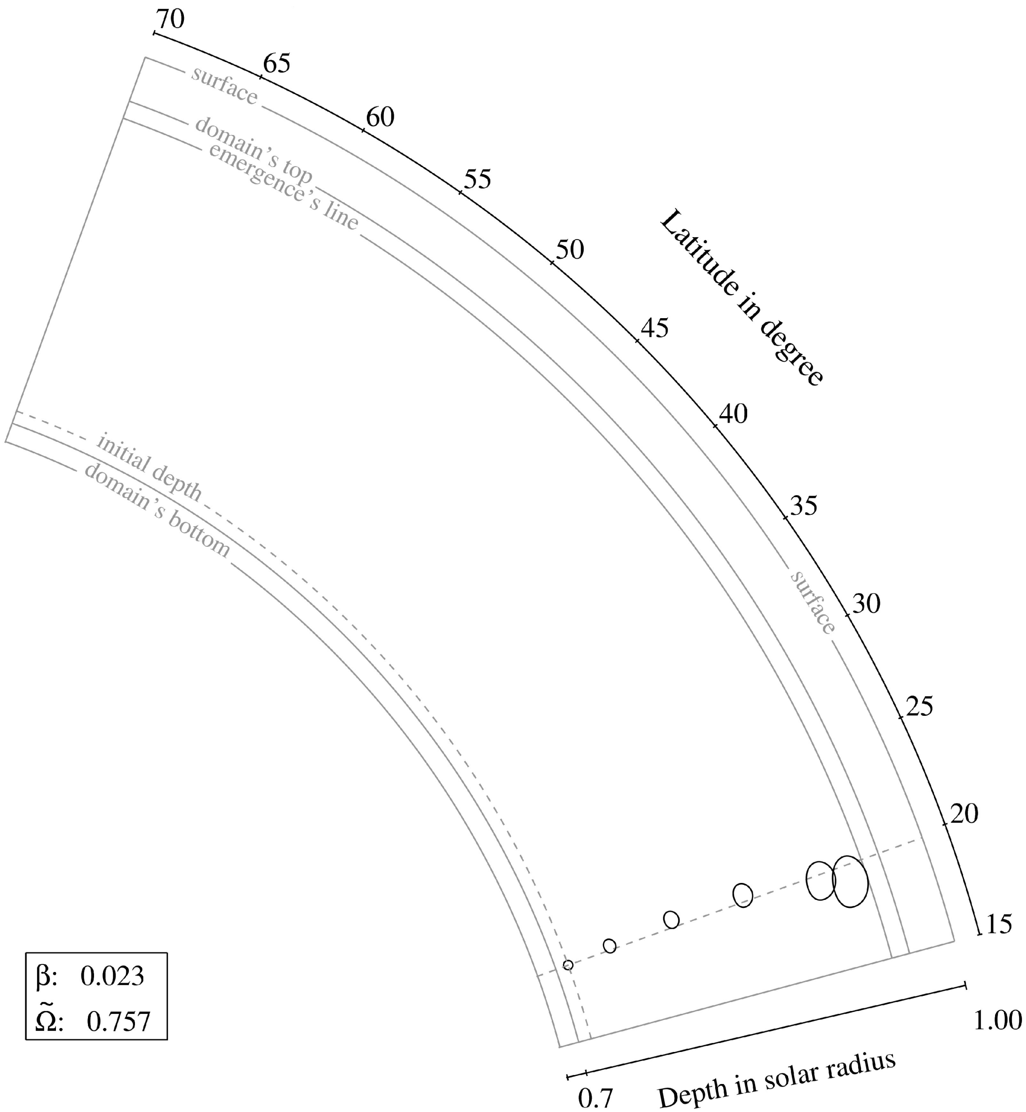
Results

- The path of thought:

Simulation	Buoy.	Magn. T.	Cor. F.	Solar DF	Cyl. DF
Without rotation	x	x			
With solid body rotation	x	x	x		
With enforced solid body rotation	x	x	x		
With solar-like diff. rotation	x	x	x	x	
With cylindrical diff. rotation	x	x	x		x

Results

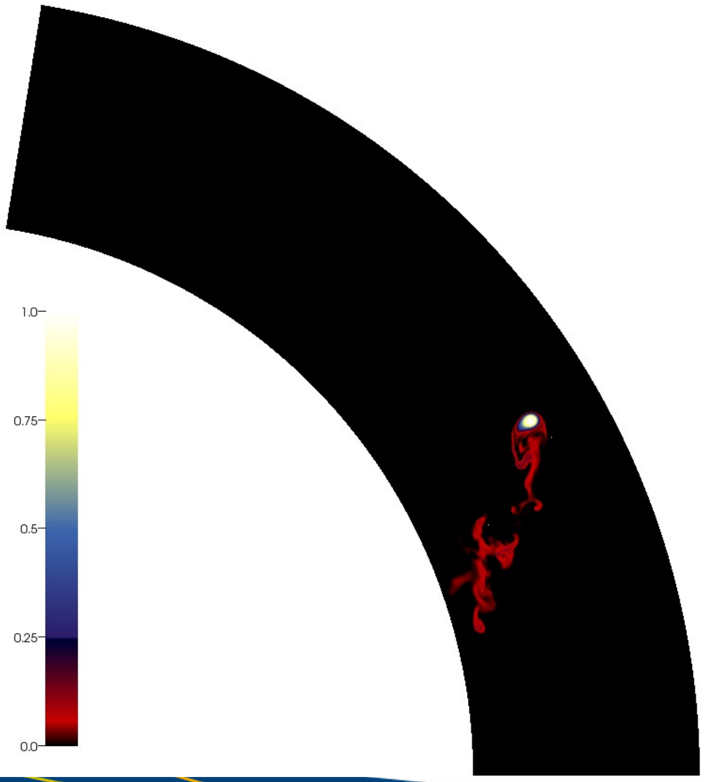
- Without rotation

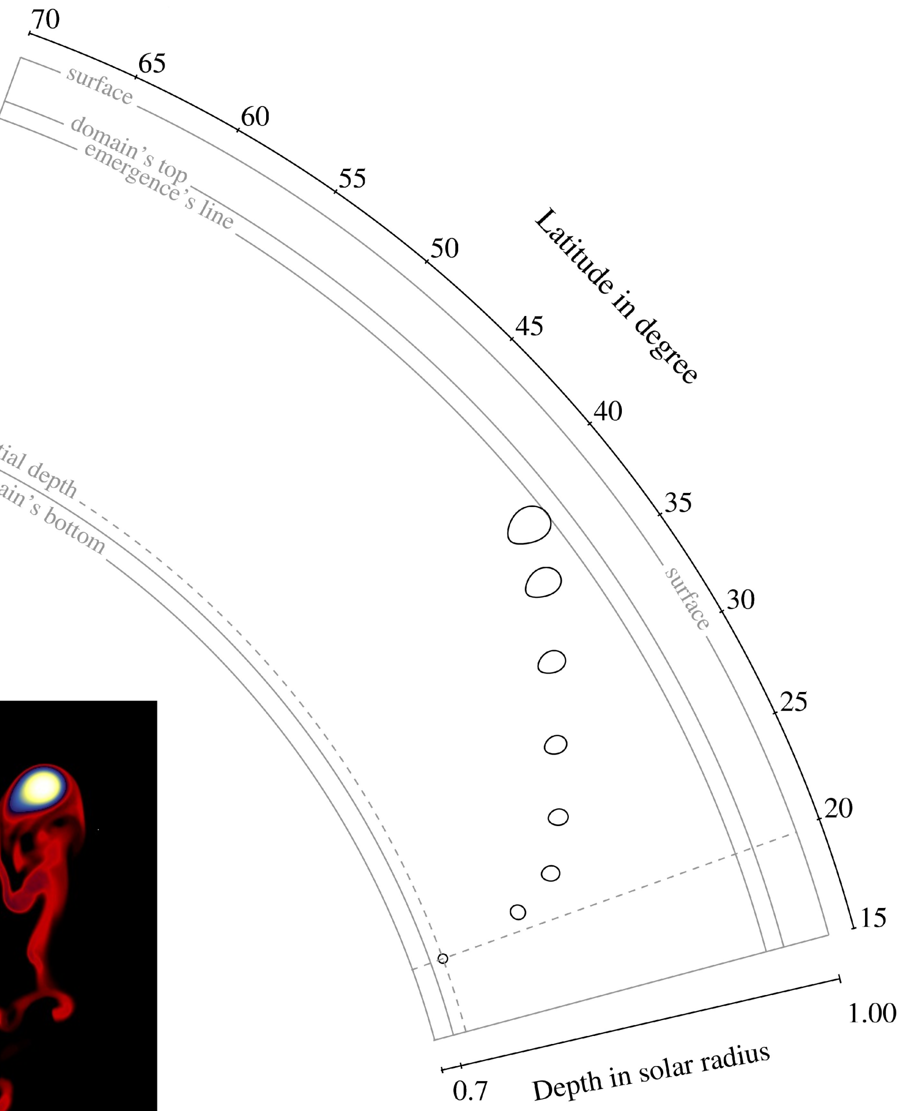


Agrees with
Choudhuri, & Gilman, 1987

Results

- Solid Body rotation

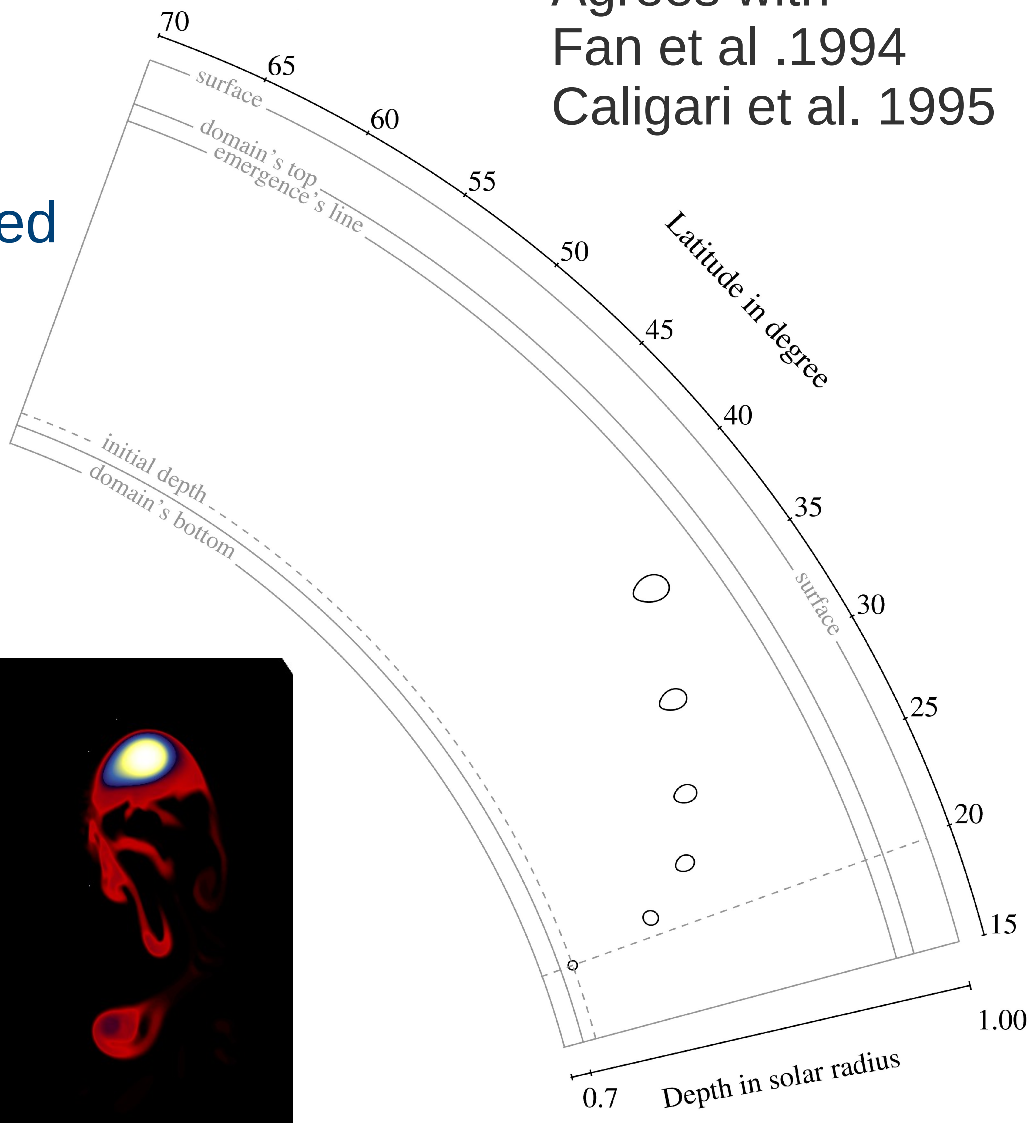


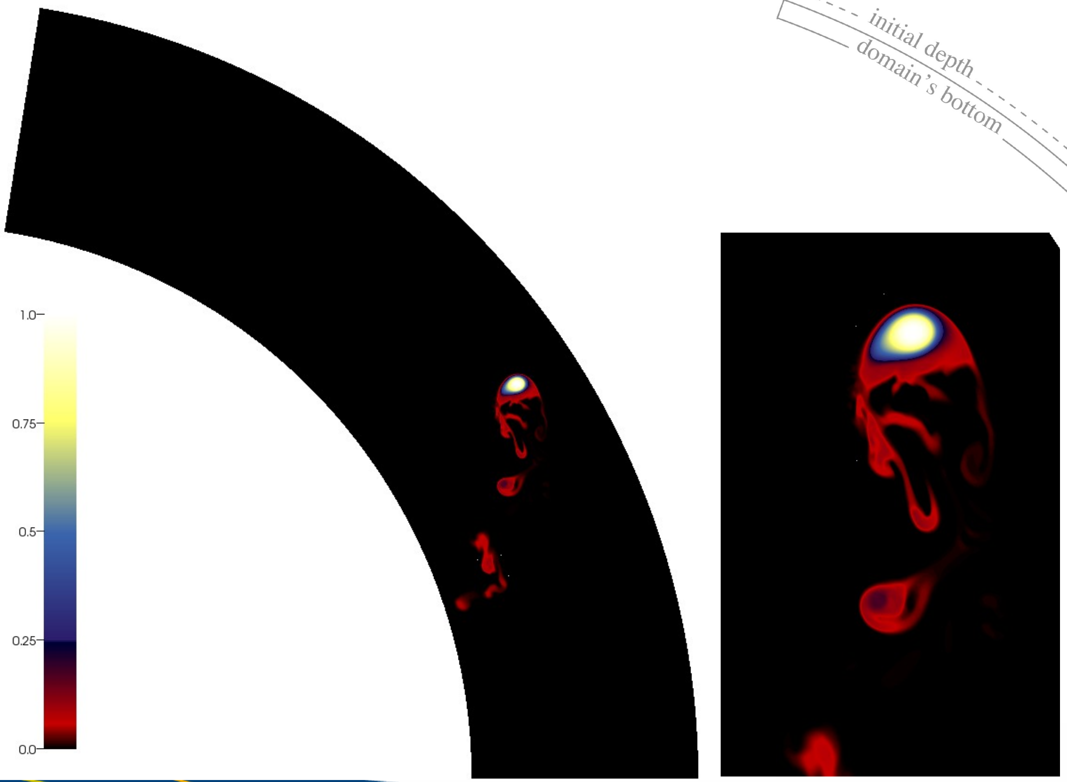


Results

- Solid body rotation enforced by the forcing term

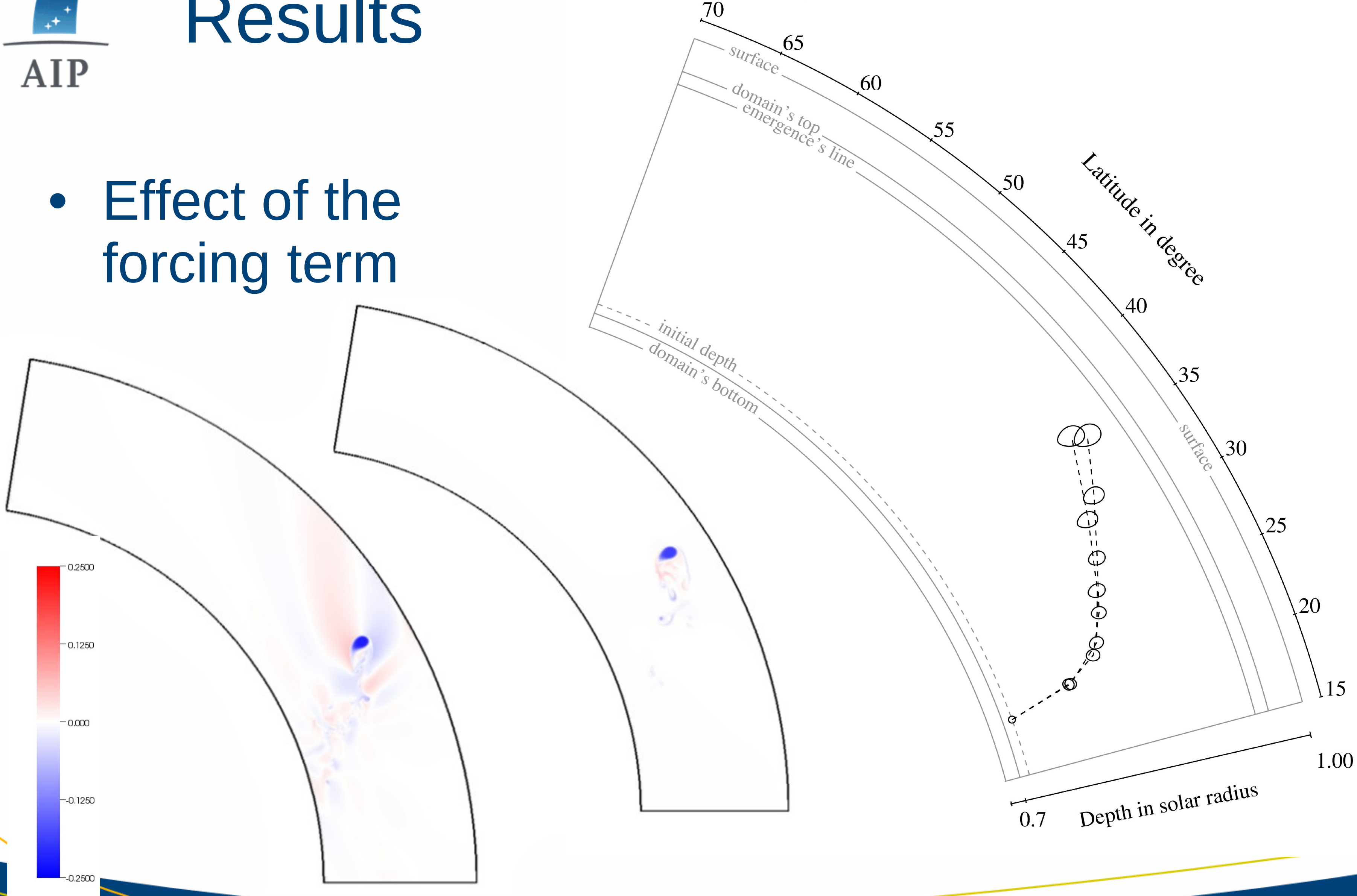
Agrees with
Fan et al .1994
Caligari et al. 1995





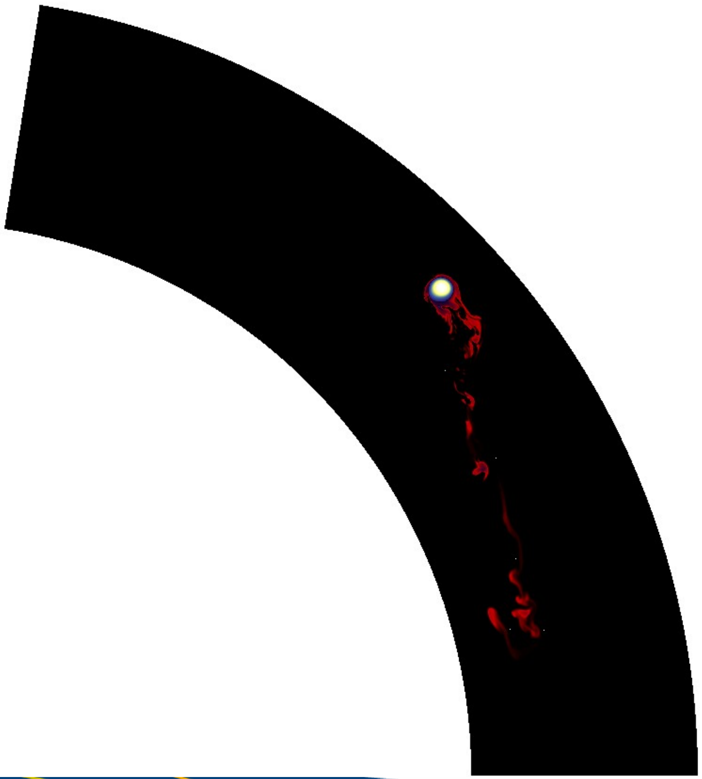
Results

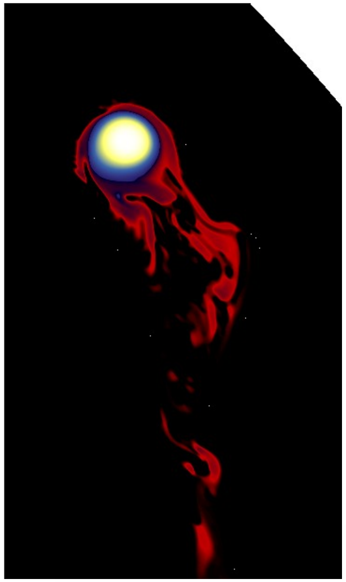
- Effect of the forcing term

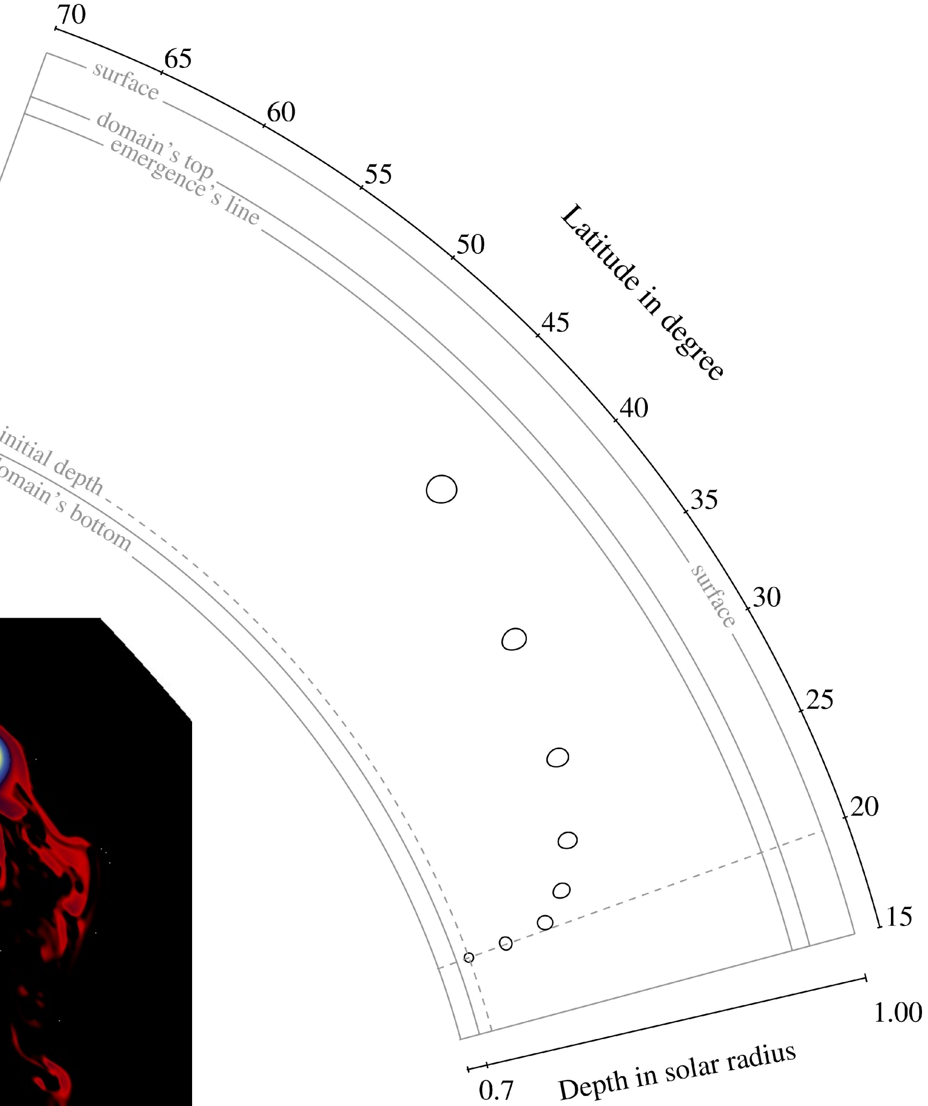


Results

- Solar-like diff. rotation

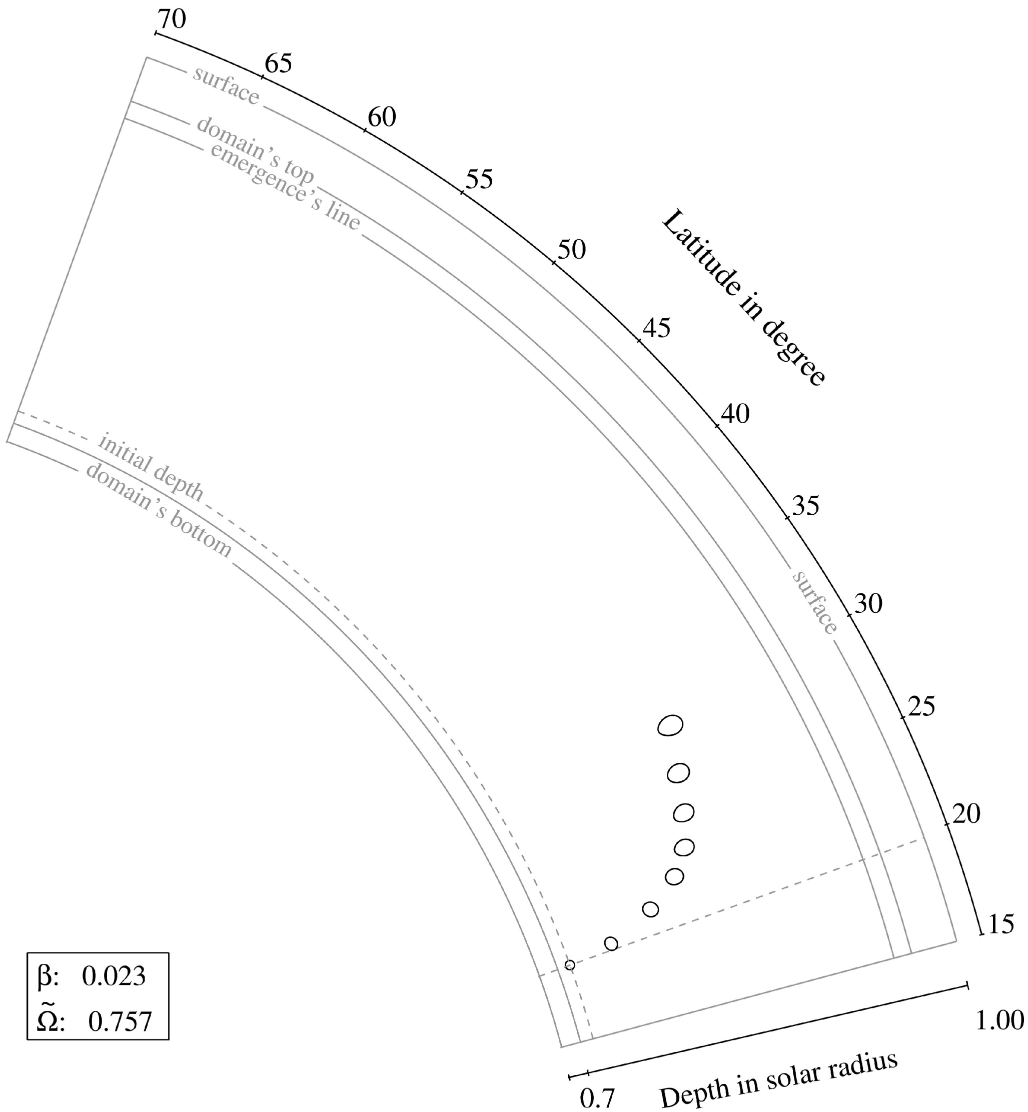






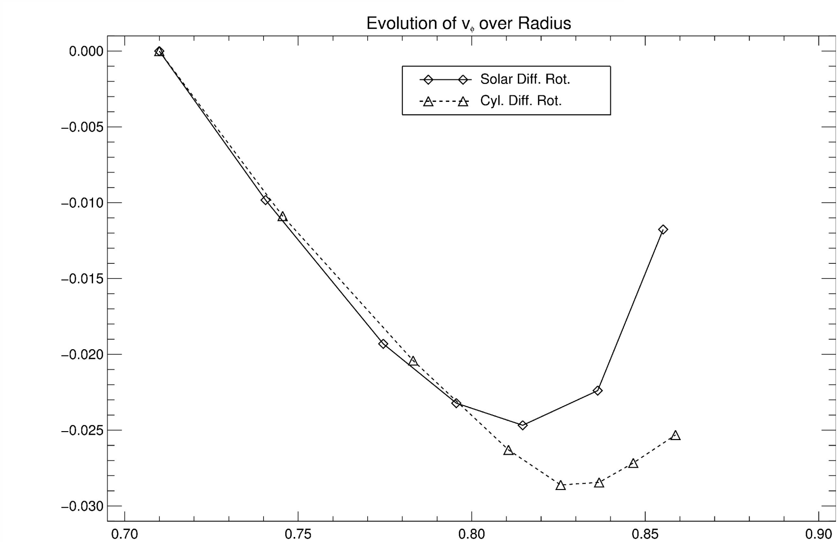
Results

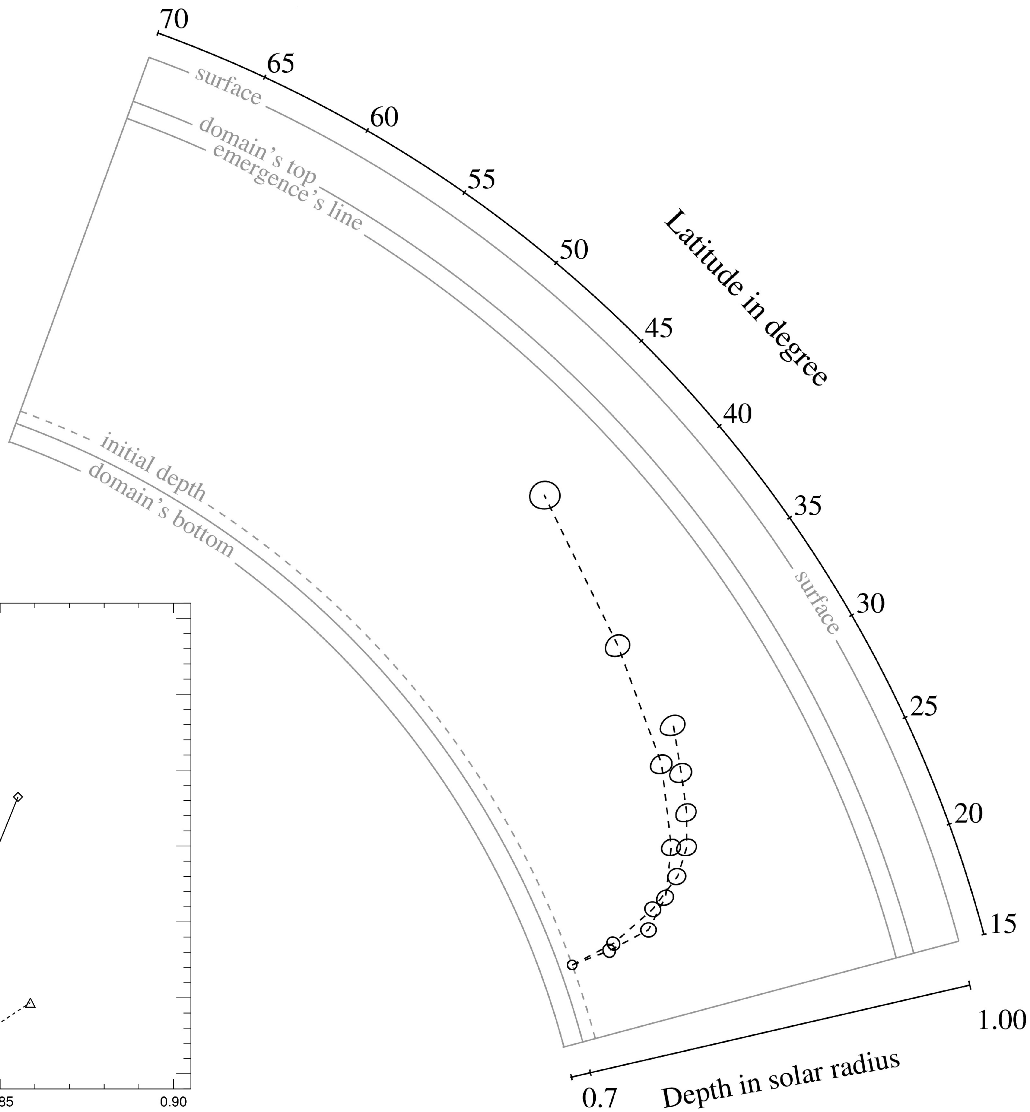
- With Cylindrical dif



Results

- Effect of diff. Rotat





Discussion

- These are just preliminary work
  - Parameter study for different initial latitudes and magn. field strength.
  - Apply this model on Giants
  - Add more physics
    - Convection
    - 3D
    - Turbulence ?

Convection similar to Käpylä 2010a
Final simulation similar to Jouve & Brun 2006/2013

Conclusion

- We have all the ingredients we need for designing an advanced model.
- We choose not to simulate diff. rot. but to force it.
- We obtain confident results in 2D without convection.
- We are now going to study giants, to go to 3D, and add convection.

Questions, Comments, & Critics

Thanks for your attention

Conclusion

- We have all the ingredients we need for designing an advanced model and learn from it.
- We choose not to simulate diff. rot. but to force it.
- We obtain confident results in 2D without convection.
- We are now going to study giants, to go to 3D, and add convection.

References

- Cheung, Schüssler, Moreno-Insertis, 2006 ASPC
- Käpylä, Korpi, Brandenburg, Mitra, Tavakol 2010 AN
- Choudhuri, & Gilman, 1987 ApJ
- Fan, Fisher, McClymont, 1994 ApJ
- Caligari, Moreno-Insertis, Schüssler, 1995 ApJ
- Demarque, Günther,Li, Mazumdar, & Straka, 2008 ApSS
- Küker & Rüdiger 2008 J. Phys.
- Jouve, Brun, 2009 ApJ
- Weber, Fan, Miesch, 2011 ApJ