Modelling solar and stellar activity driven by turbulent dynamo effects and Helicity

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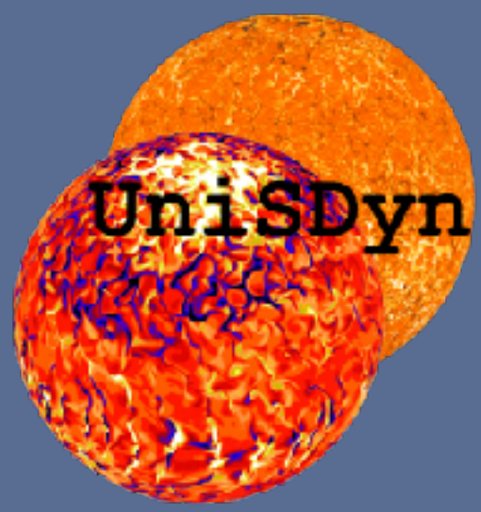
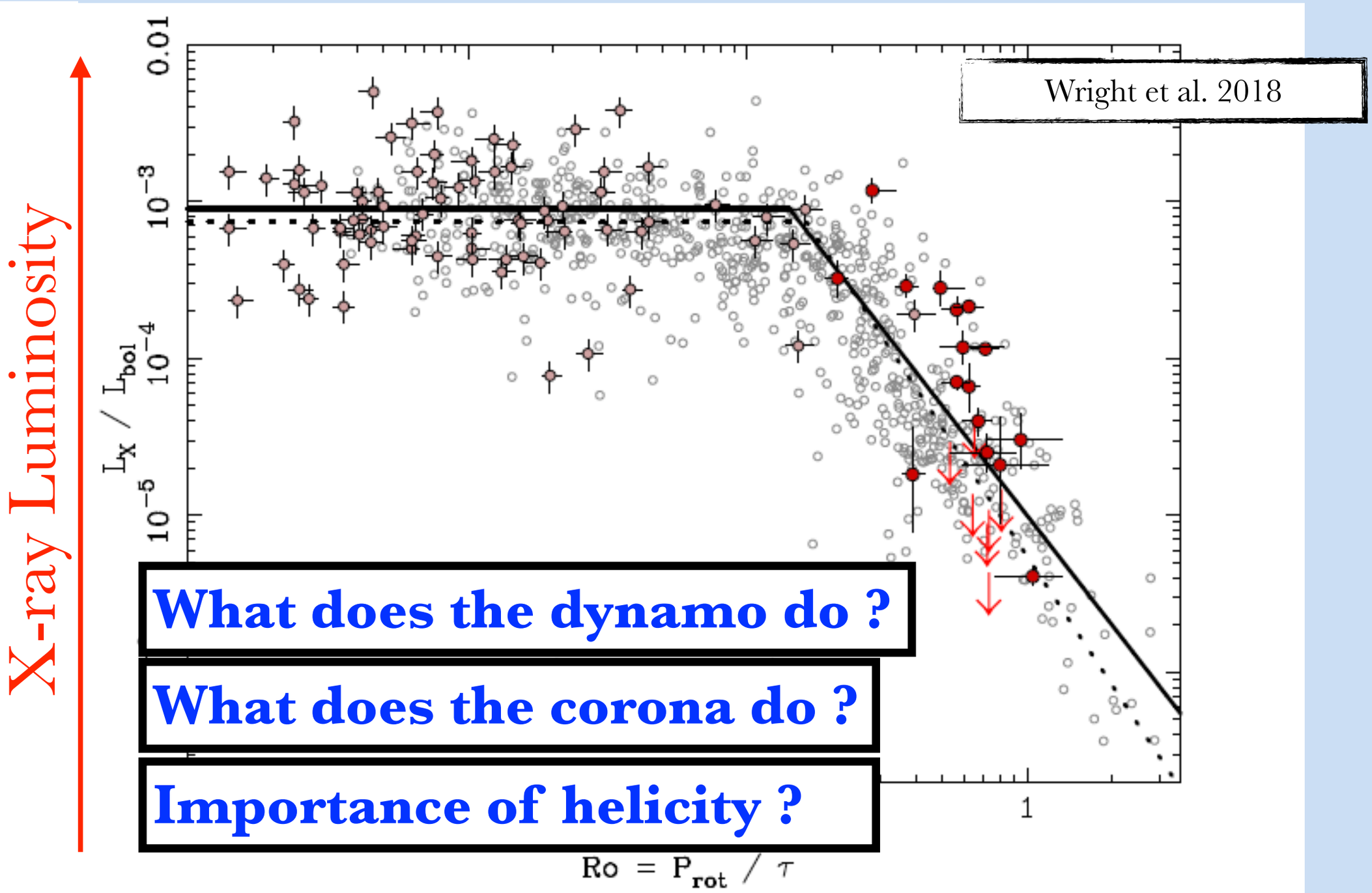


Rotation-Activity Relation



What does the dynamo do ?

What does the corona do ?

Importance of helicity ?

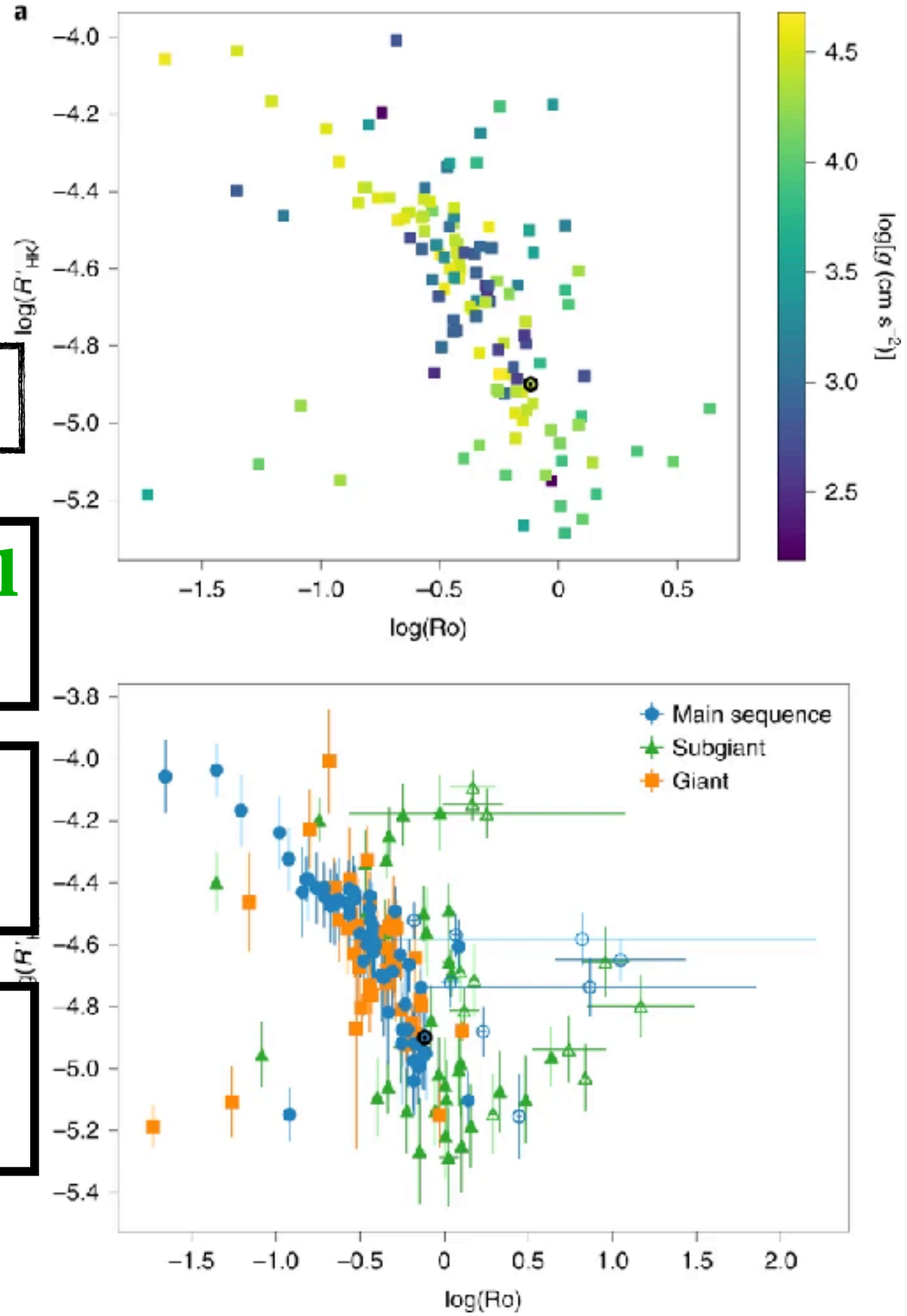
Rotation-Activity Relation II

Lehtinen et al. 2020
Nature Astronomy

MS stars and Giants fall on top of each other

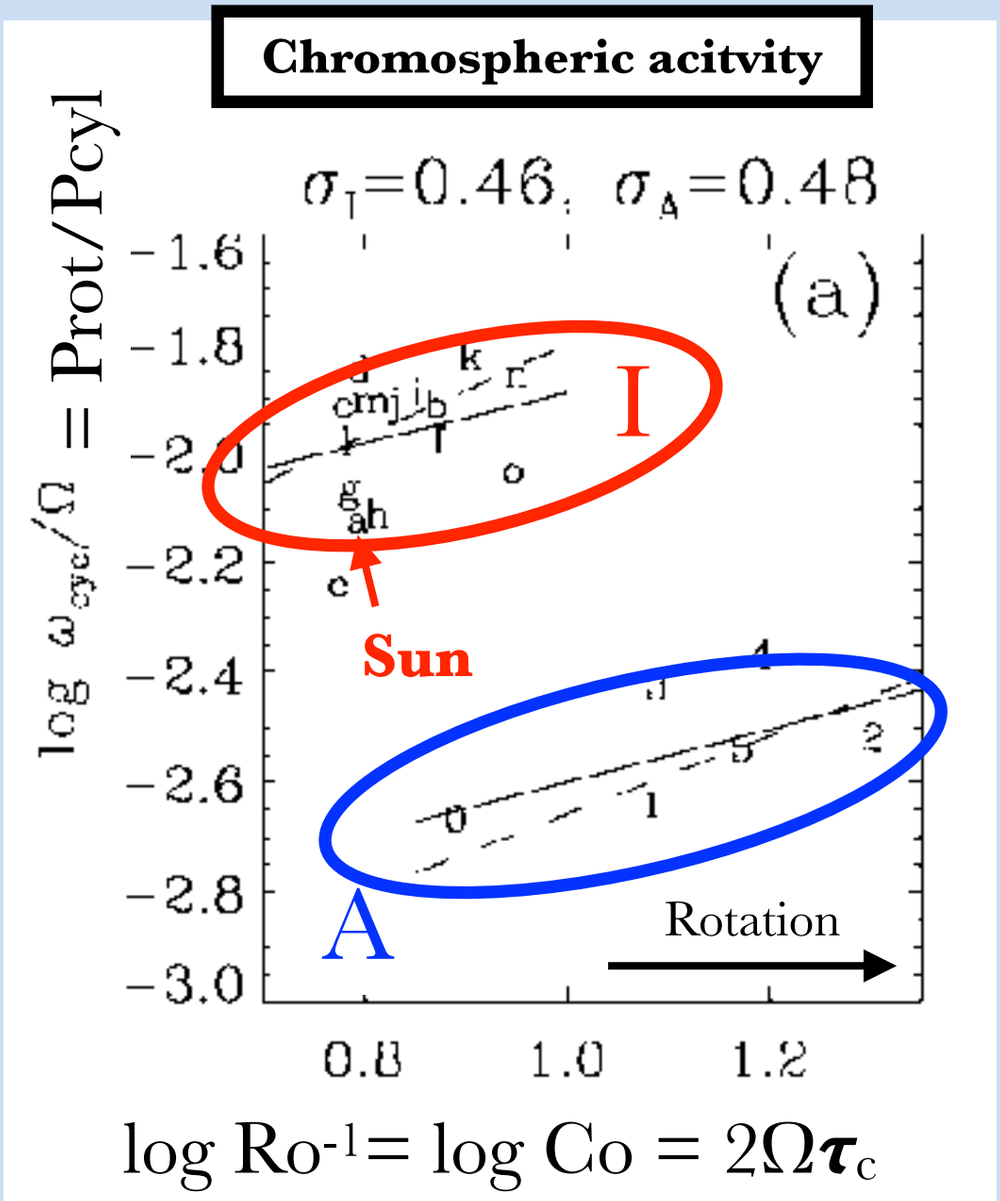
Rossby number the crucial parameter

Convective turbulence important for Dynamo



Activity Cycles

Chromospheric acitvity



Brandenburg, Saar & Turpin, 1998

Active branch under debate

(e.g. Distefano et al. 2017, Brandenburg et al. 2017, Reinhold et al. 2017, Boro Saikia et al. 2018)

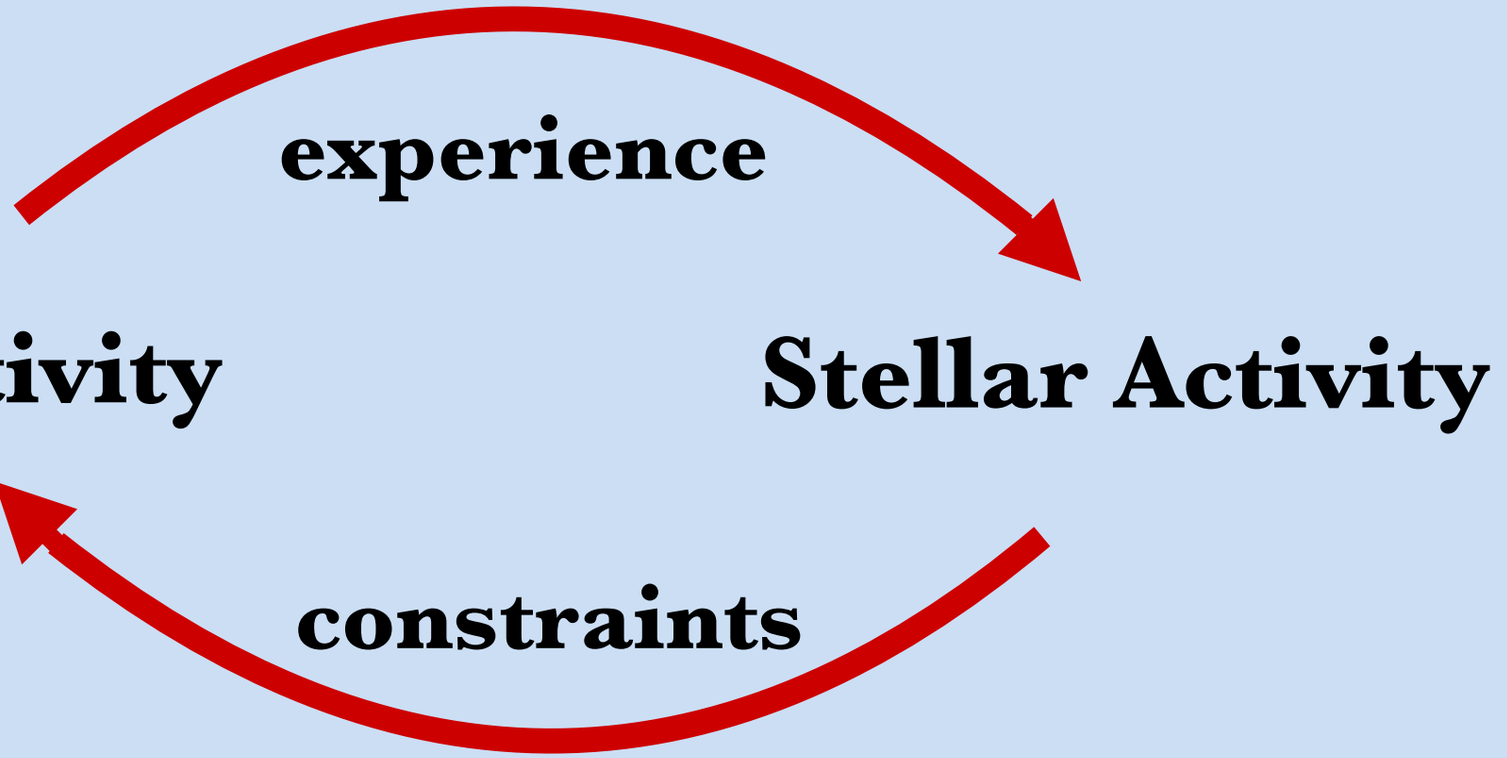
Inactive branch prevails

(e.g. Olperts et al. 2018)

Prot/Pcyl ~ Co$^{0.5}$ → Pcyl ~ Co$^{-1.5}$

Strong constrains on the solar dynamo

- **Modelling of dynamos, sunspots and the corona**
- **High-resolution and long-term observation**



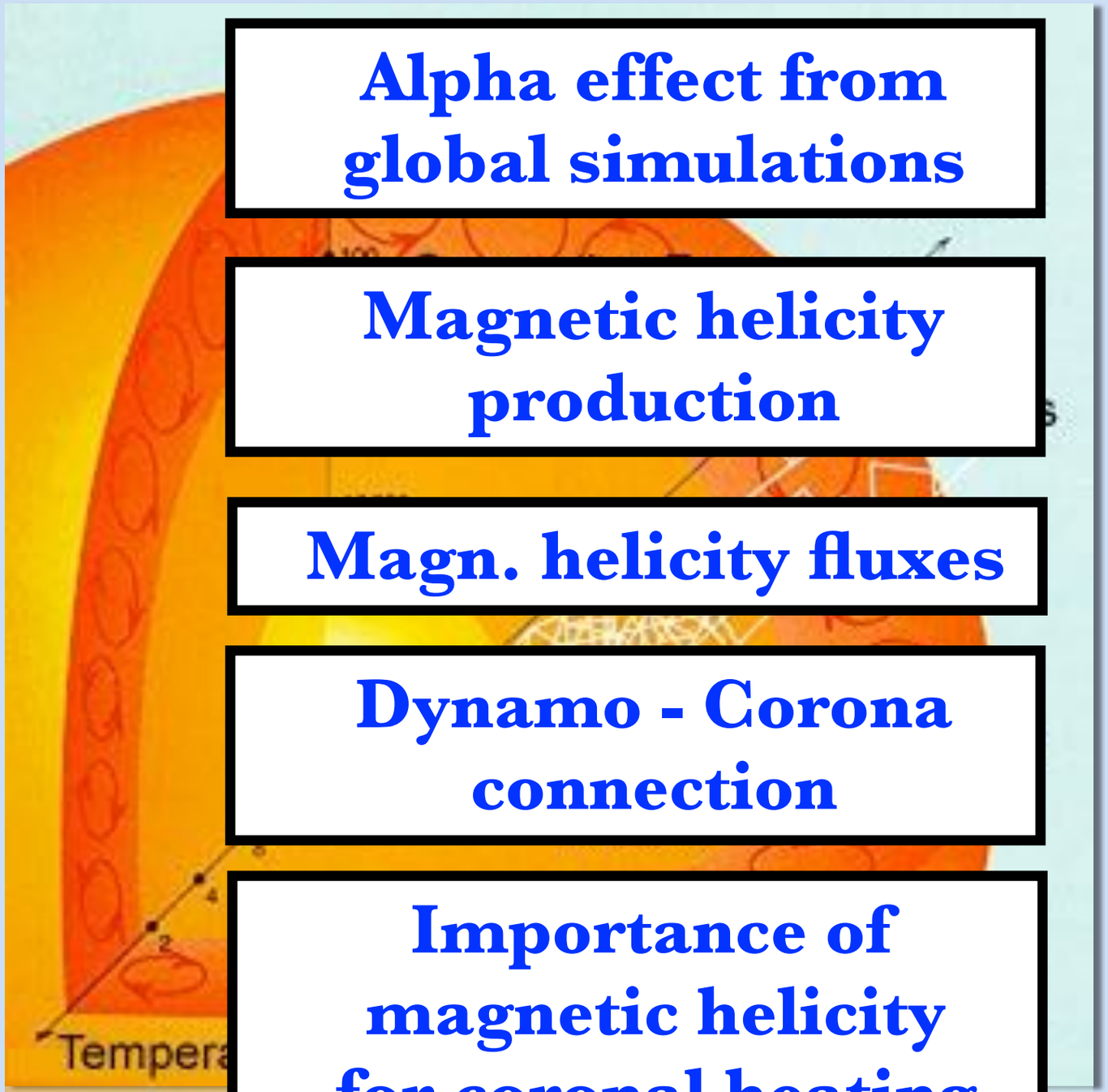
Solar Activity **Stellar Activity**

- **Rotational dependence of cycles & X-rays**
- **Size and distribution of star spots**
- **Dependence on stellar parameters**

Magnetic Helicity

The glue that connects dynamos and coronae of the Sun and stars

Helicity in the Sun and Stars



Alpha effect from global simulations

Magnetic helicity production

Magn. helicity fluxes

Dynamo - Corona connection

Importance of magnetic helicity for coronal heating and X-ray emission

Nonalignment of rotation and gravity

↓

Kinetic helicity

↓

Alpha-effect

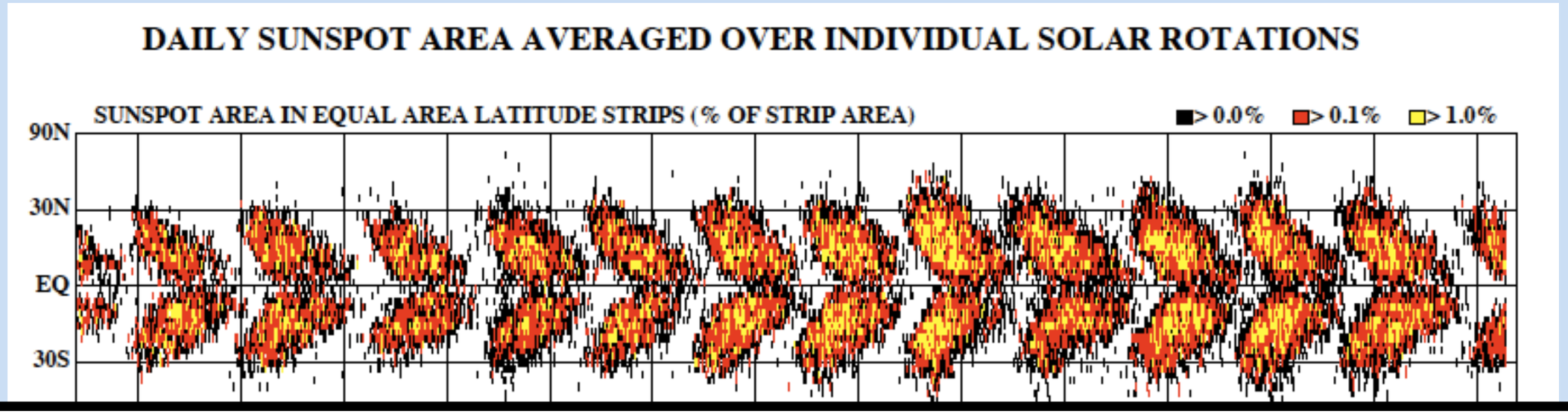
↓

Magnetic helicity + catastr. quenching

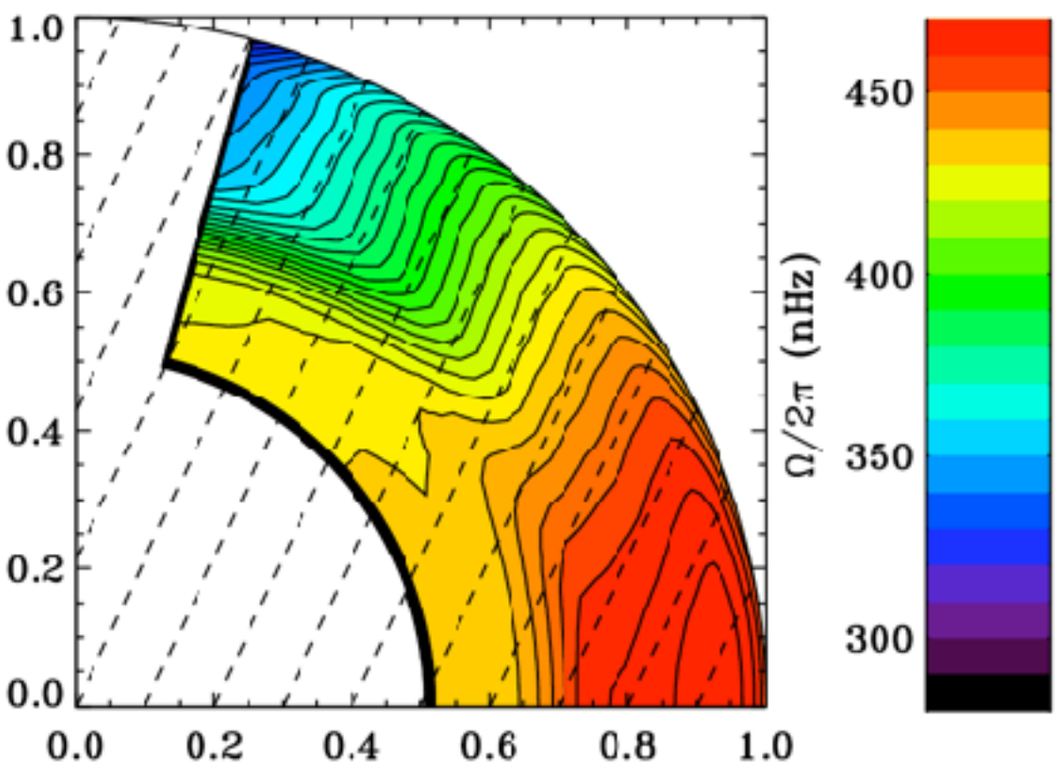
↓

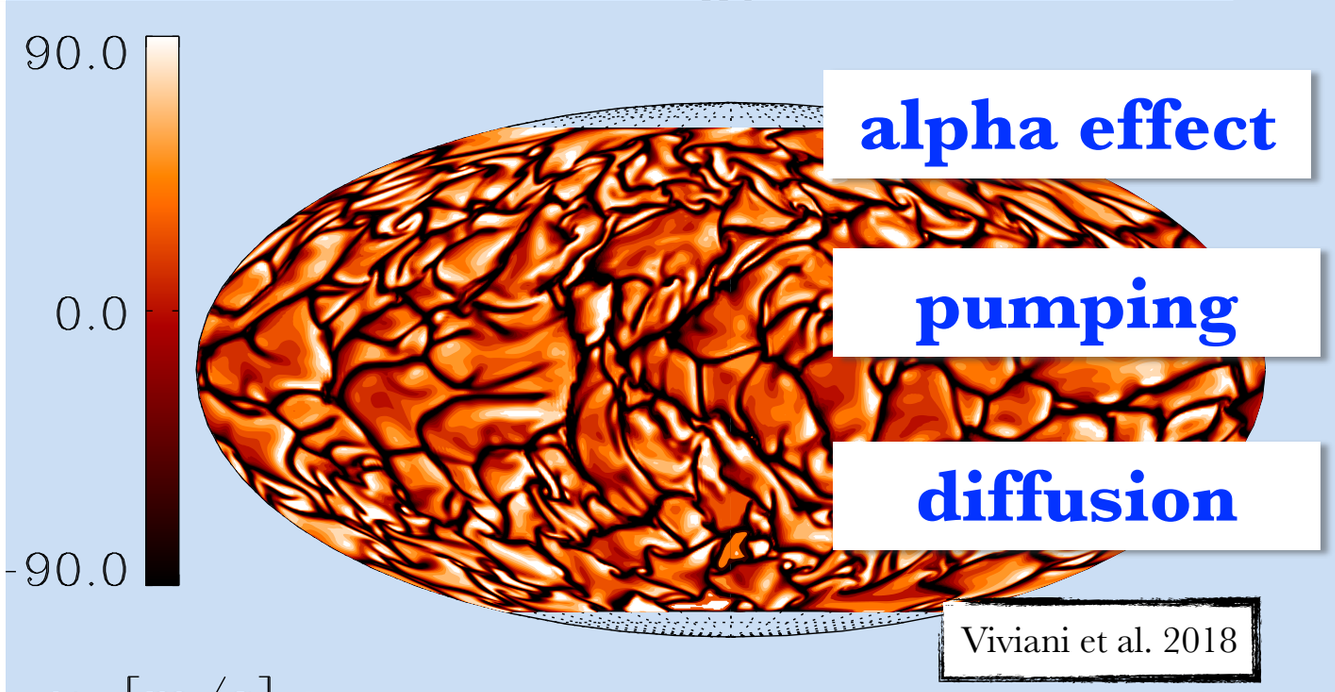
Space weather coronal heating

Solar and Stellar Dynamos



We can use numerical simulations to determine turbulent effects.





no direct measurements

Dynamo theory

$$\frac{\partial B}{\partial t} = \nabla \times (u \times B) - \nabla \times \eta J$$

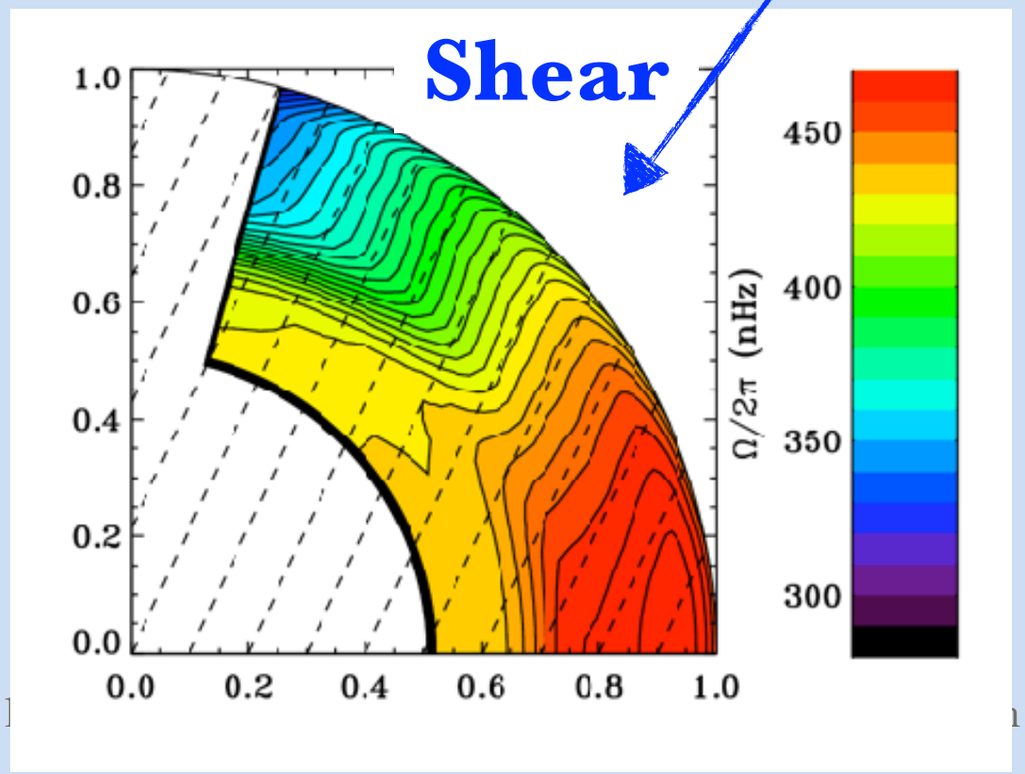
$$B = \overline{B} + b'$$

Electromotive force: Turbulent dynamo effects

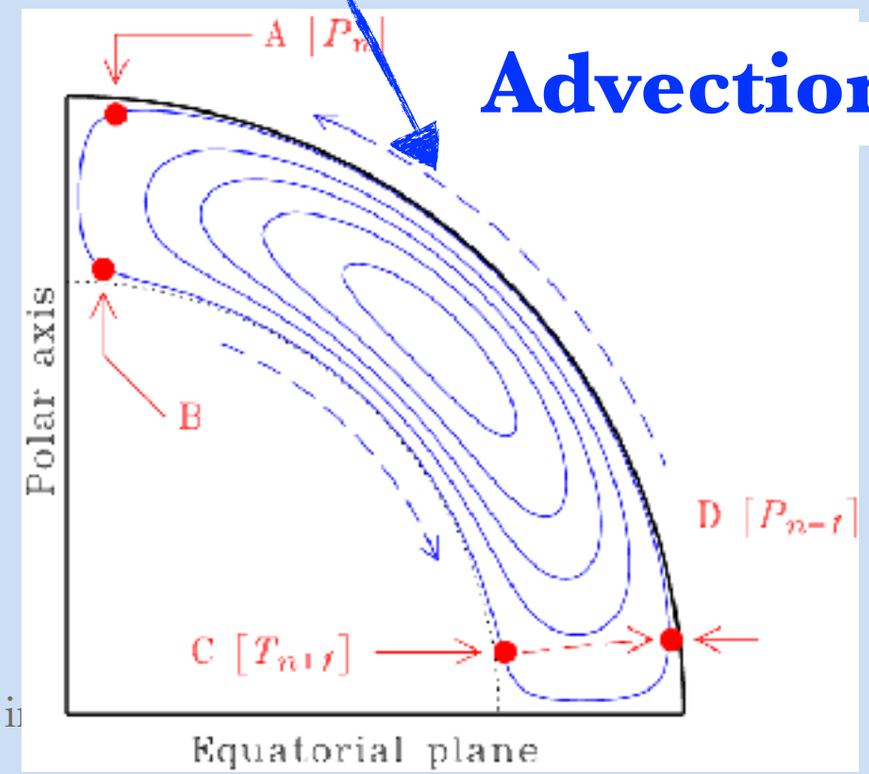
$$\frac{\partial \overline{B}}{\partial t} = \nabla \times (\overline{U} \times \overline{B} + \overline{u' \times b'}) - \nabla \times \eta \overline{J}$$

$$\nabla \times (\overline{U} \times \overline{B}) = (\overline{B} \cdot \nabla)\overline{U} - \overline{B}(\nabla \cdot \overline{U}) - (\overline{U} \cdot \nabla)\overline{B}$$

Shear



Advection



Electromotive force I

$$\mathcal{E} = \boldsymbol{a} \cdot \overline{\boldsymbol{B}} + \boldsymbol{b} \cdot \boldsymbol{\nabla} \overline{\boldsymbol{B}} + \ldots$$

$$\mathcal{E}_i = a_{ij} \overline{B}_j + b_{ijk} \partial_j \overline{B}_k + \ldots$$

$$\boldsymbol{\mathcal{E}} = \boldsymbol{\alpha} \cdot \overline{\boldsymbol{B}} + \boldsymbol{\gamma} \times \overline{\boldsymbol{B}} - \boldsymbol{\beta} \cdot (\boldsymbol{\nabla} \times \overline{\boldsymbol{B}}) - \boldsymbol{\delta} \times (\boldsymbol{\nabla} \times \overline{\boldsymbol{B}}) - \boldsymbol{\kappa} \cdot (\boldsymbol{\nabla} \overline{\boldsymbol{B}})^{(S)}$$

Alpha effect

Turbulent pumping

Turbulent diffusion

Rädler effect

Electromotive force II

Contributions:	„Easy“ approach
Alpha effect: amplificati	scalar, only acts on toroidal field
Turbulent pumping: t	radial, tuned to fit the Sun
Turbulent diffusion: d	scalar, tuned to fit the Sun
Rädler effect: delta effe	Not considered
+ **Additional turbulen**	Not considered

Schrinner et al. 2005, 2007, 2012

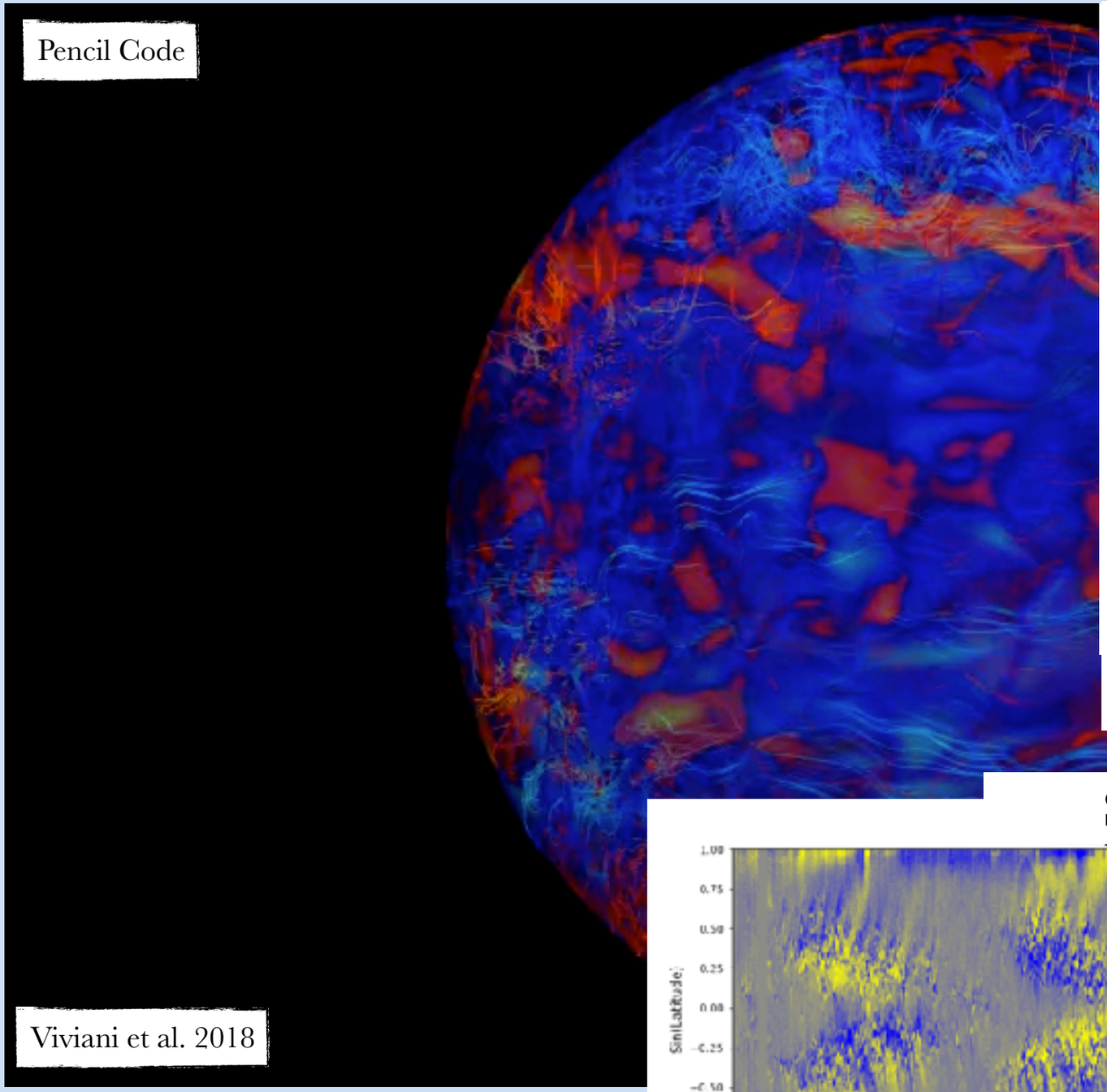
Test-field method: Measuring turbulent dynamo effects

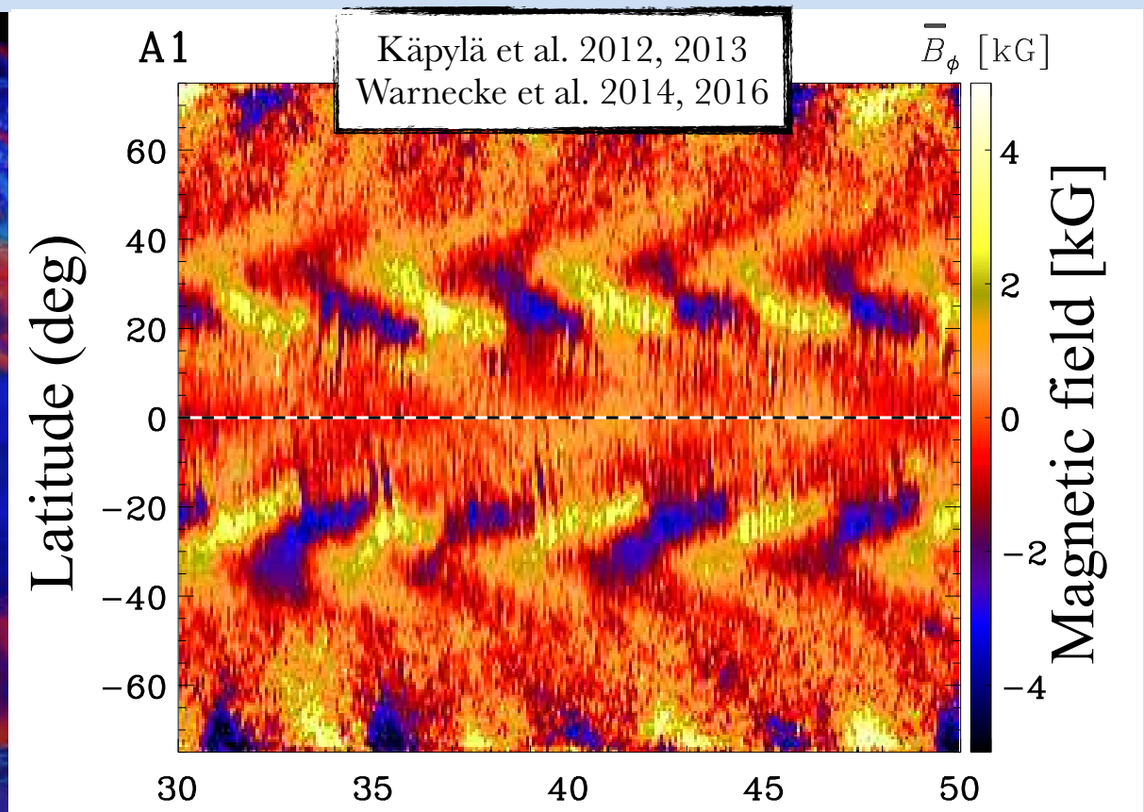
Applying 9 linear independent test-fields, no back reaction

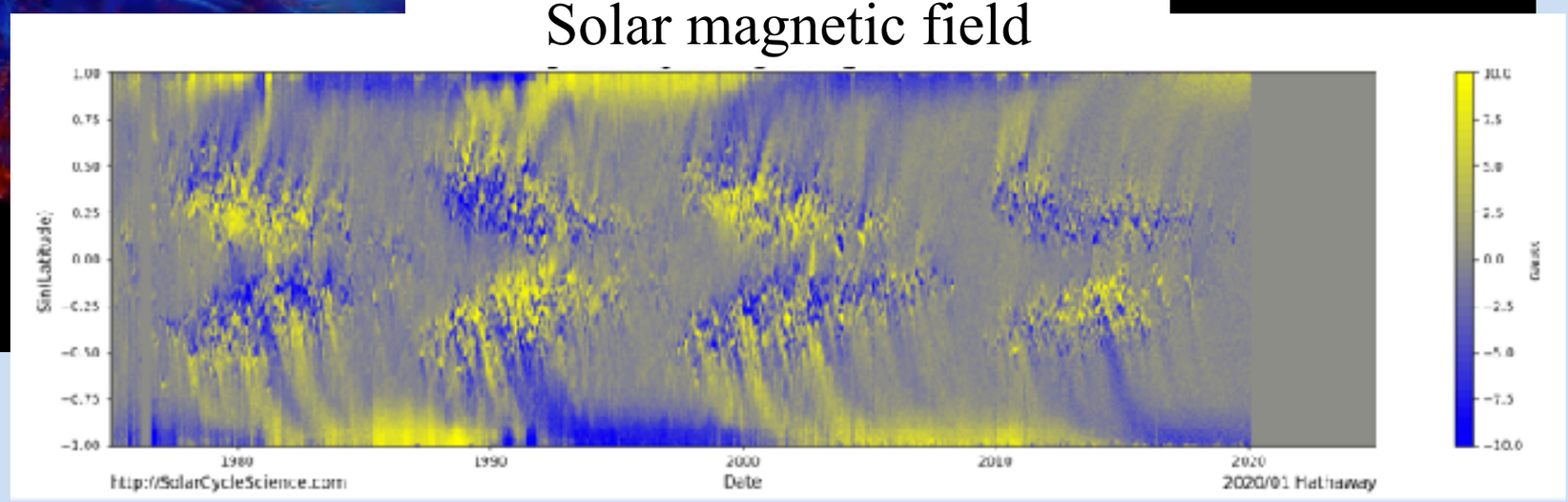
Calculating corresponding electromotive force

Inverting for turbulent dynamo effects

Global stellar dynamo simulations







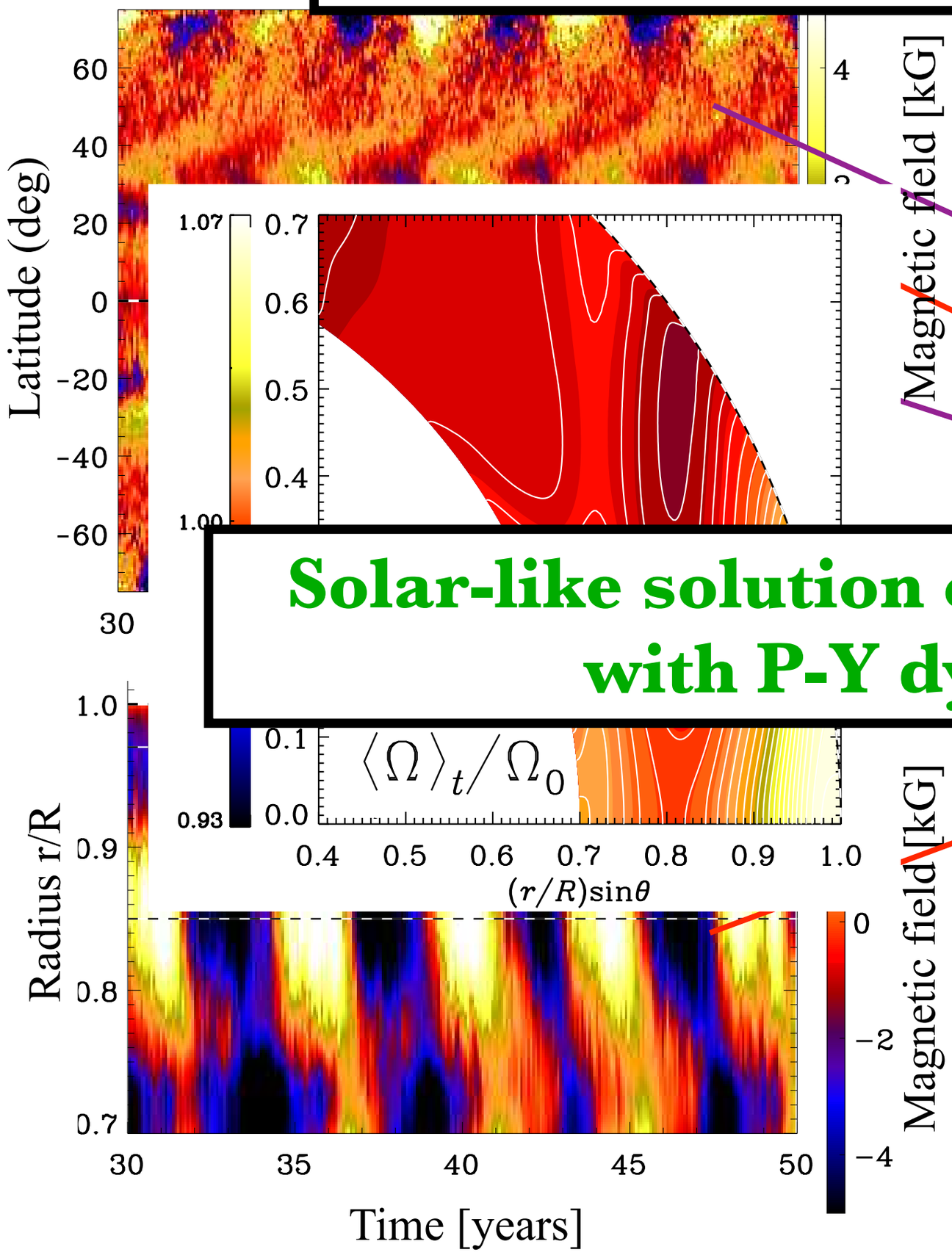
Parker—Yoshimura Rule

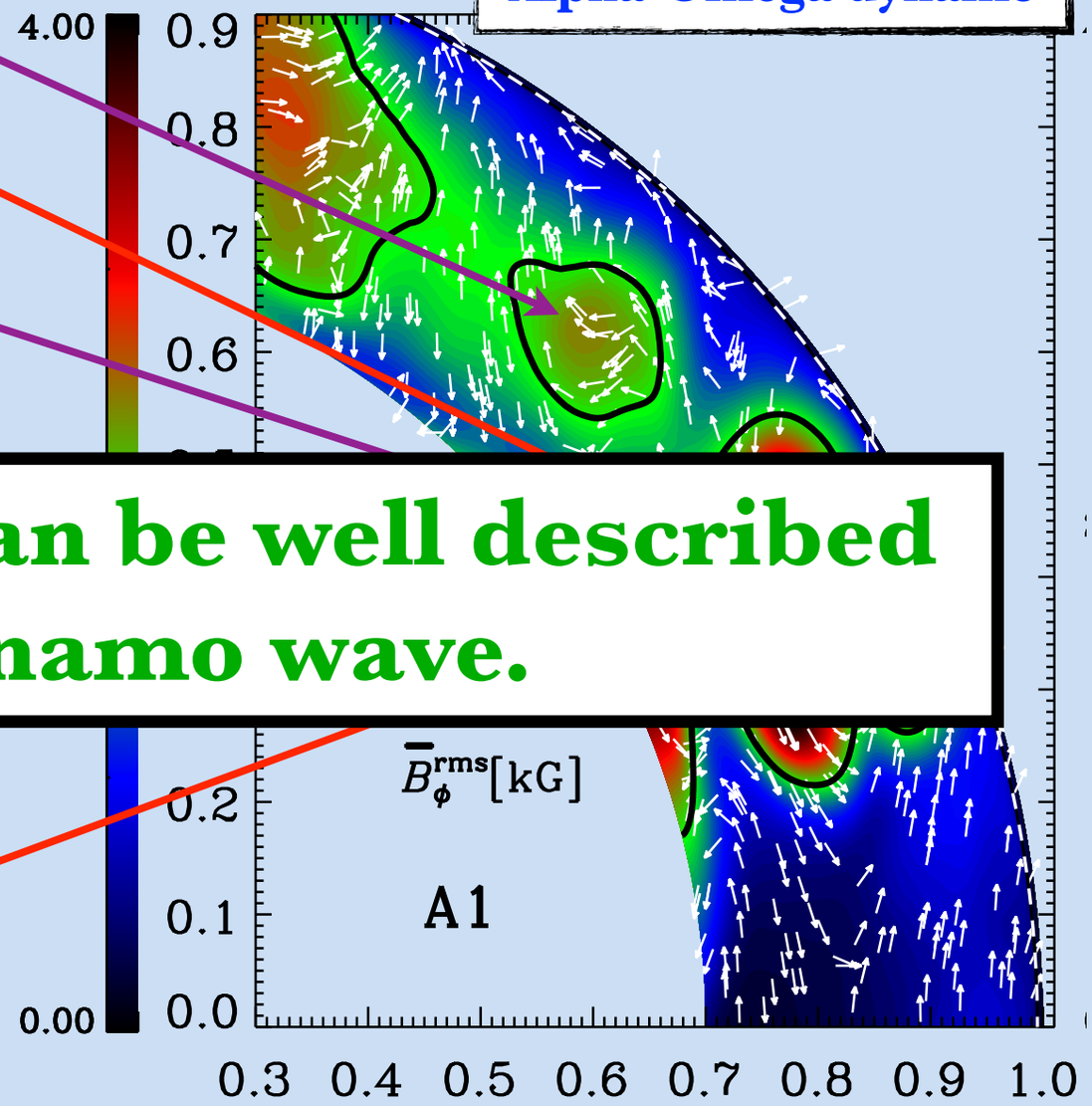
Parker 1955
Yoshimura 1975

$$\boldsymbol{s}_{\rm mig}(r,\theta) = -\alpha \hat{\boldsymbol{e}}_\phi \times \boldsymbol{\nabla}\Omega,$$

Alpha-Omega dynamo

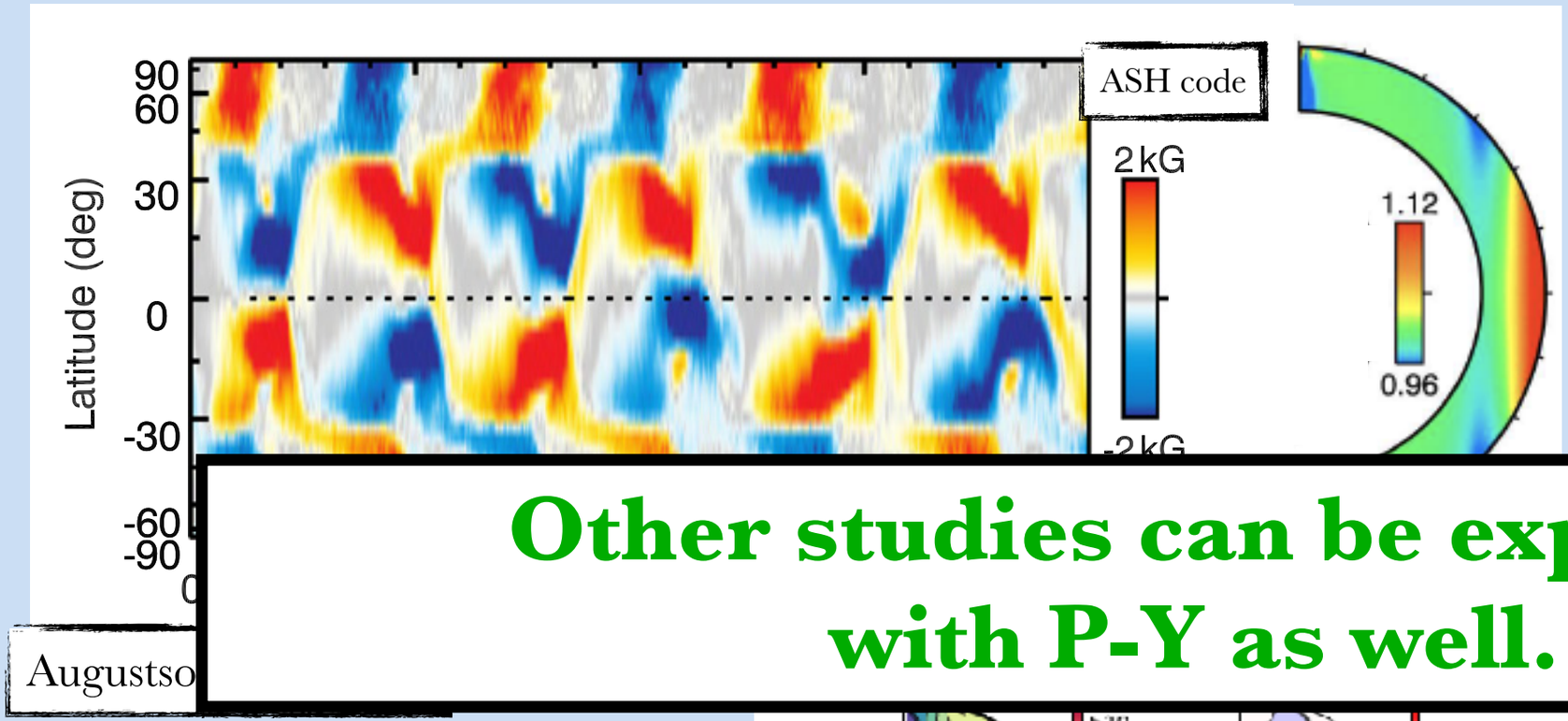
Solar-like solution can be well described with P-Y dynamo wave.



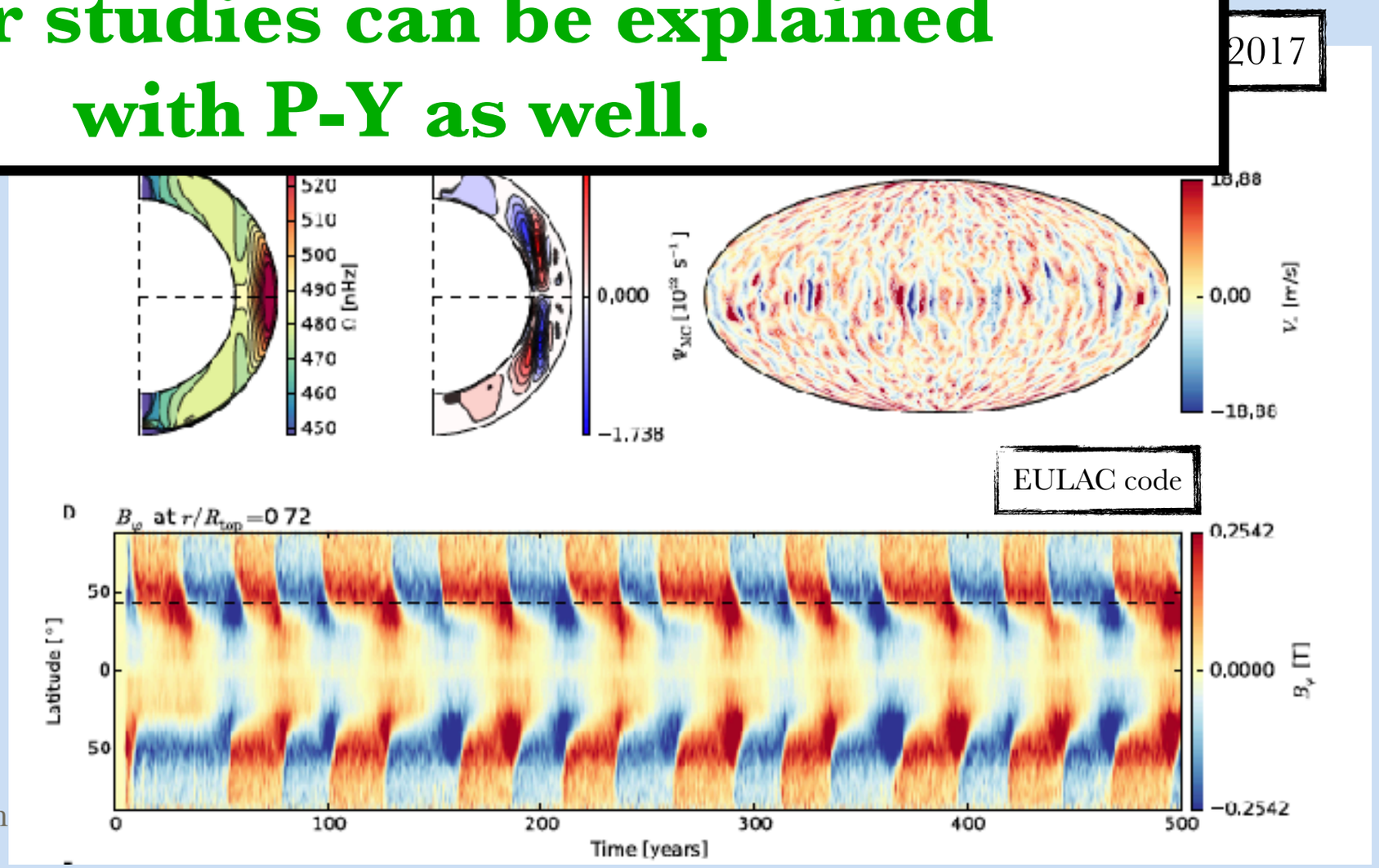


Warnecke et al. 2014, 2018

Dynamo cycles of other authors



Other studies can be explained with P-Y as well.

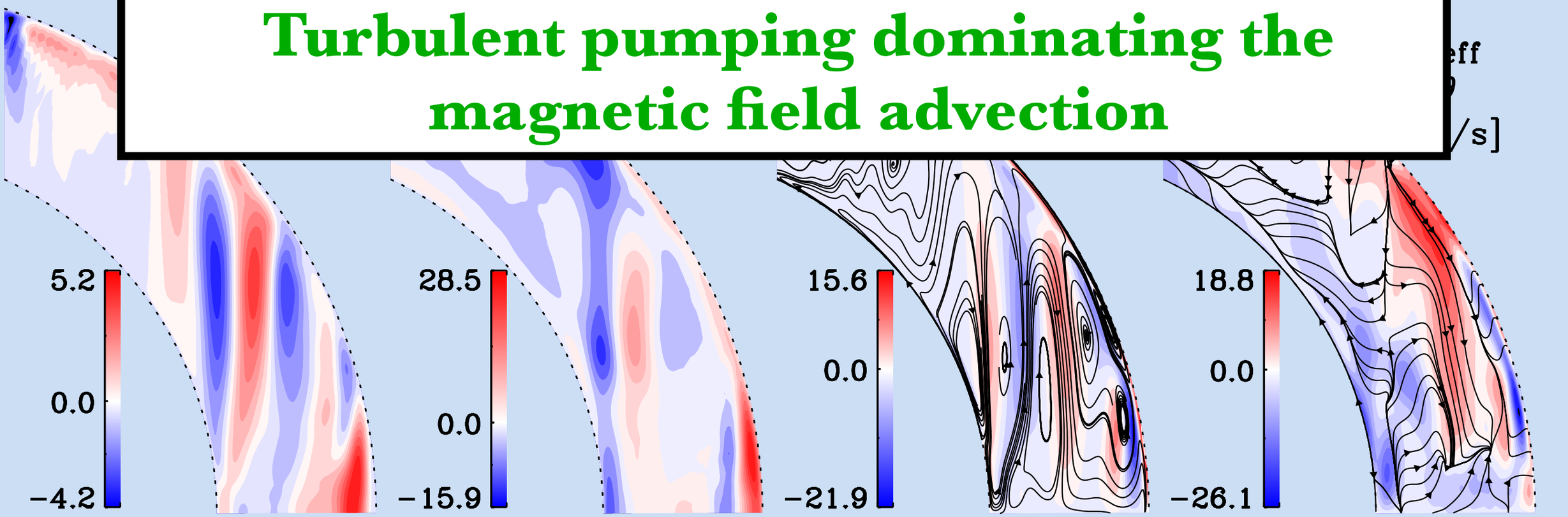


Turbulent pumping

Mean magnetic field only „sees" the sum of flow and pumping

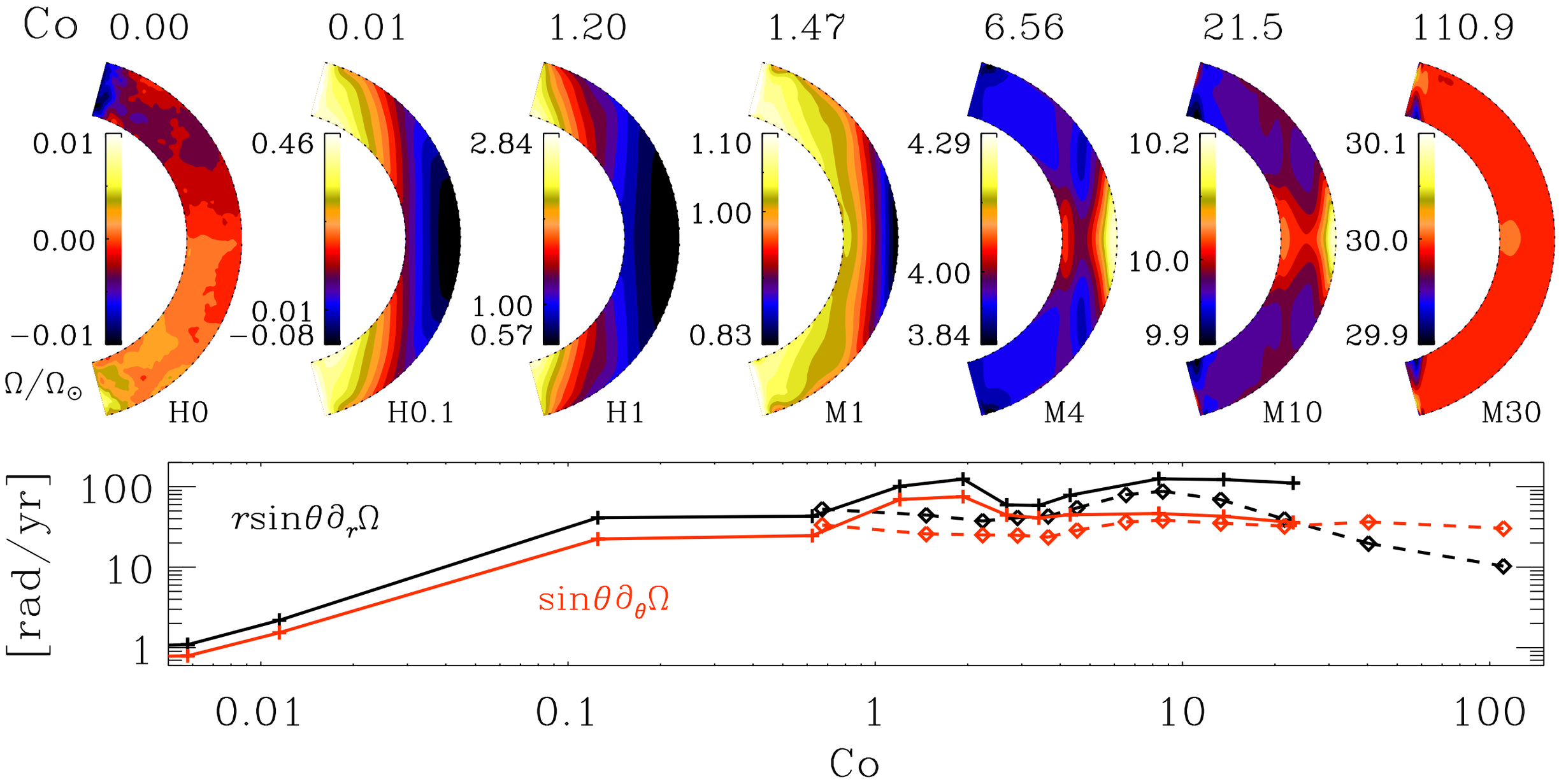
$$\overline{U}_{\mathrm{eff}} = \overline{U} + \boldsymbol{\gamma}$$

Turbulent pumping dominating the magnetic field advection



Warnecke et al. 2018

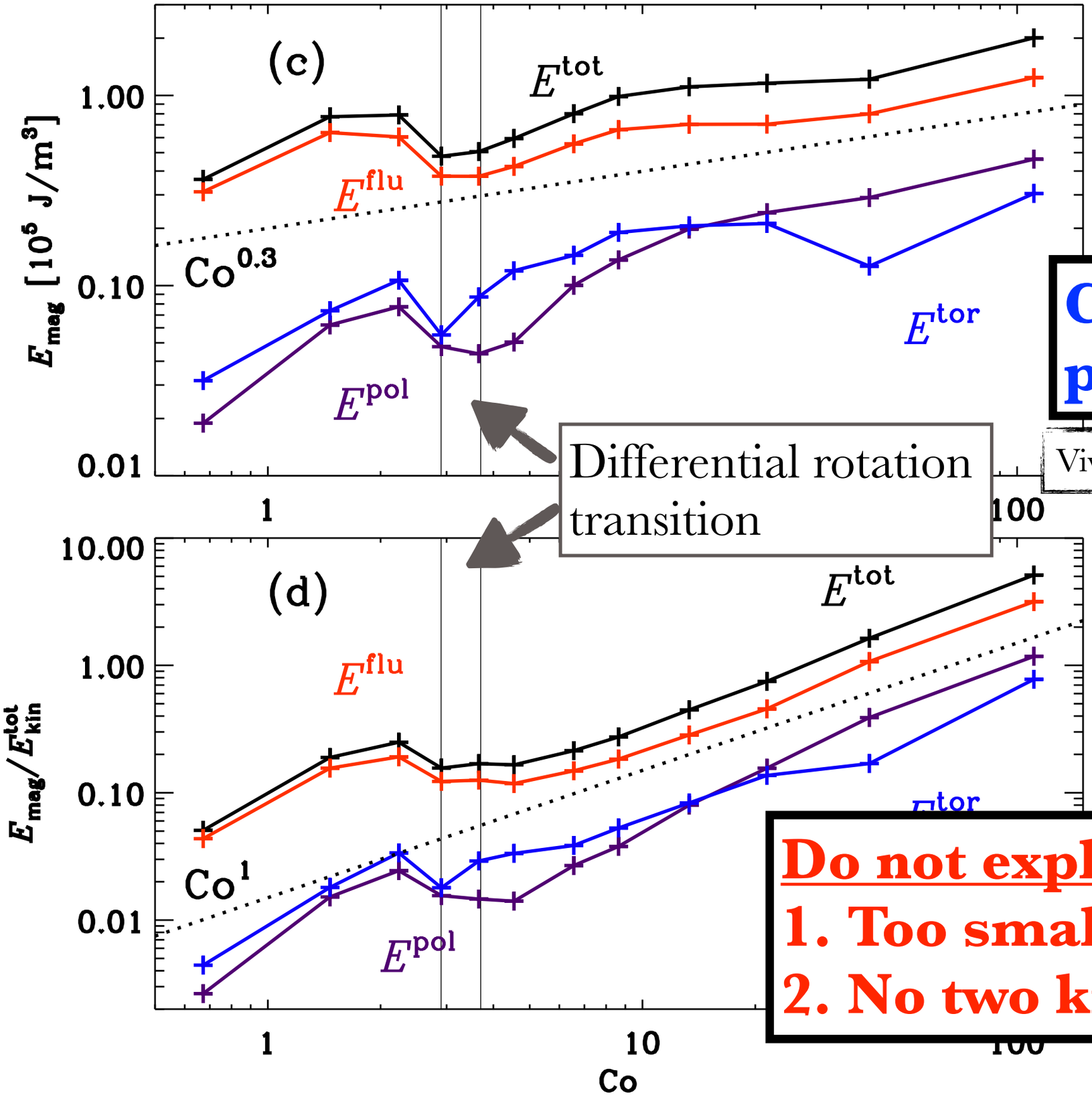
Dynamo simulations - increasing rotation



Data on ZENODO:
DOI: 10.5281/zenodo.3629665

Warnecke and Käpylä, 2020

Magnetic energy



Differential rotation transition

Consistent with previous simulations

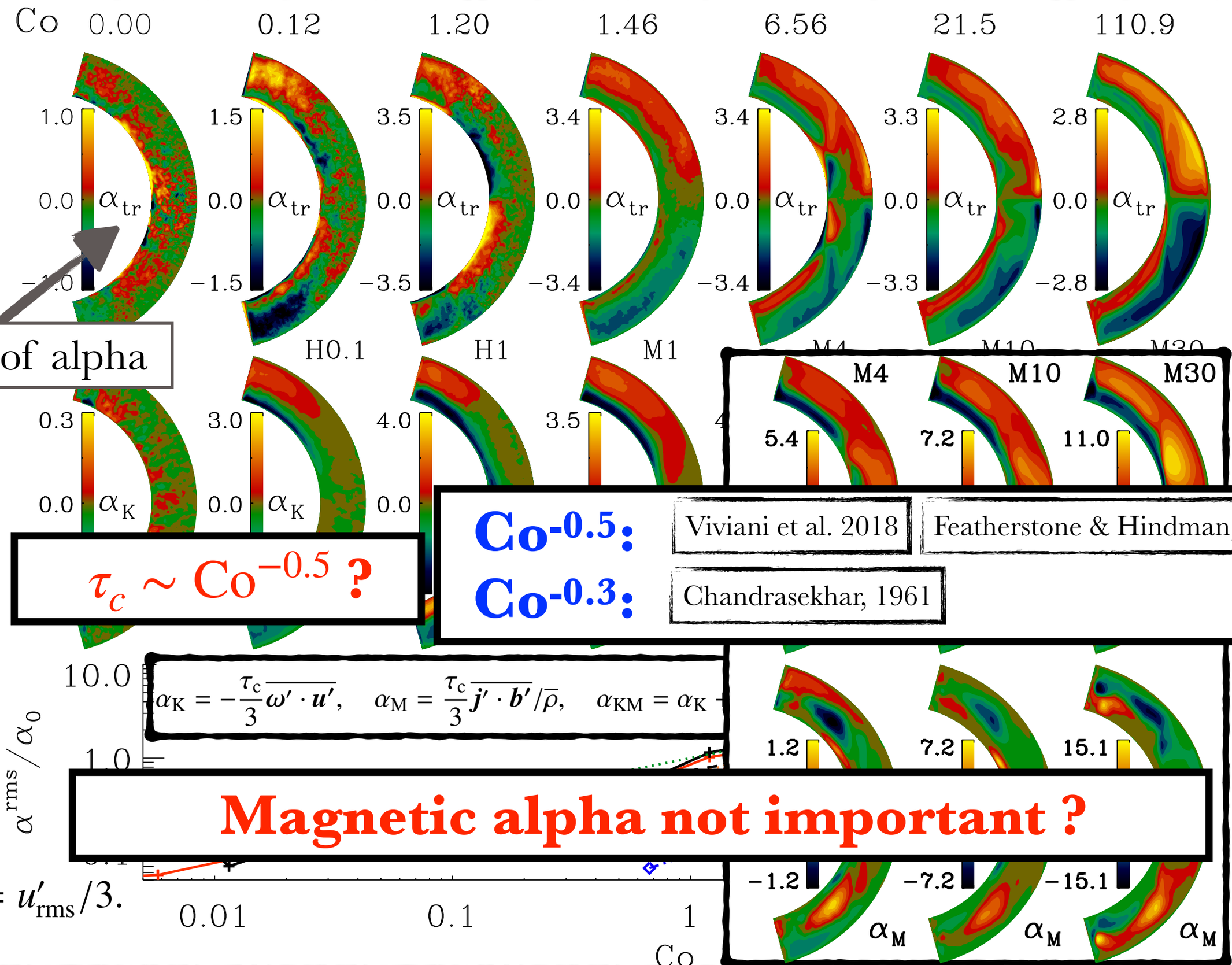
Viviani et al. 2018 | Augustson et al. 2019

Do not explain observations:

1. Too small slope

2. No two kinds of dependency

Turbulent transport coefficients: alpha



Trace of alpha

$\tau_c \sim \mathrm{Co}^{-0.5}$?

Co$^{-0.5}$: Viviani et al. 2018; Featherstone & Hindman, 2016

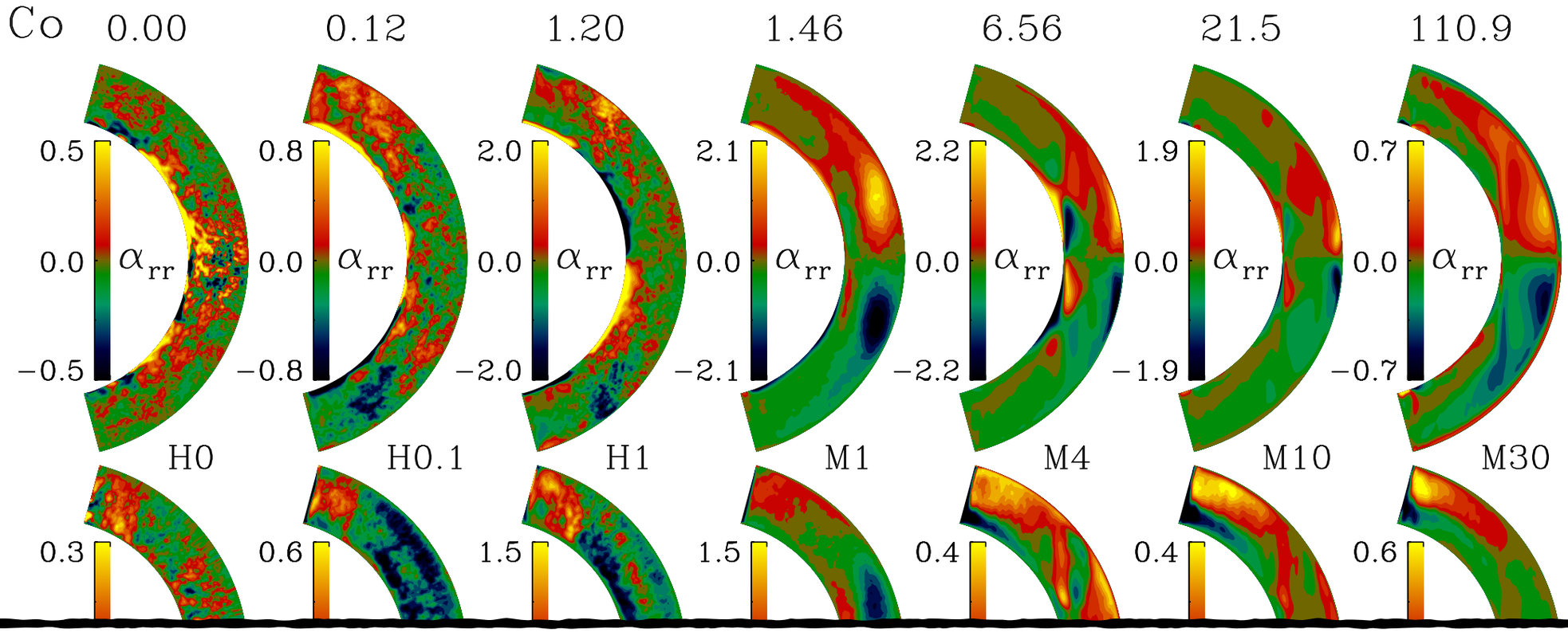
Co$^{-0.3}$: Chandrasekhar, 1961

$$\alpha_K = -\frac{\tau_c}{3}\overline{\boldsymbol{\omega}' \cdot \boldsymbol{u}'}, \quad \alpha_M = \frac{\tau_c}{3}\overline{\boldsymbol{j}' \cdot \boldsymbol{b}'}/\overline{\rho}, \quad \alpha_{KM} = \alpha_K +$$

$\alpha_0 = u'_{rms}/3.$

Magnetic alpha not important ?

Turbulent transport coefficients: alpha

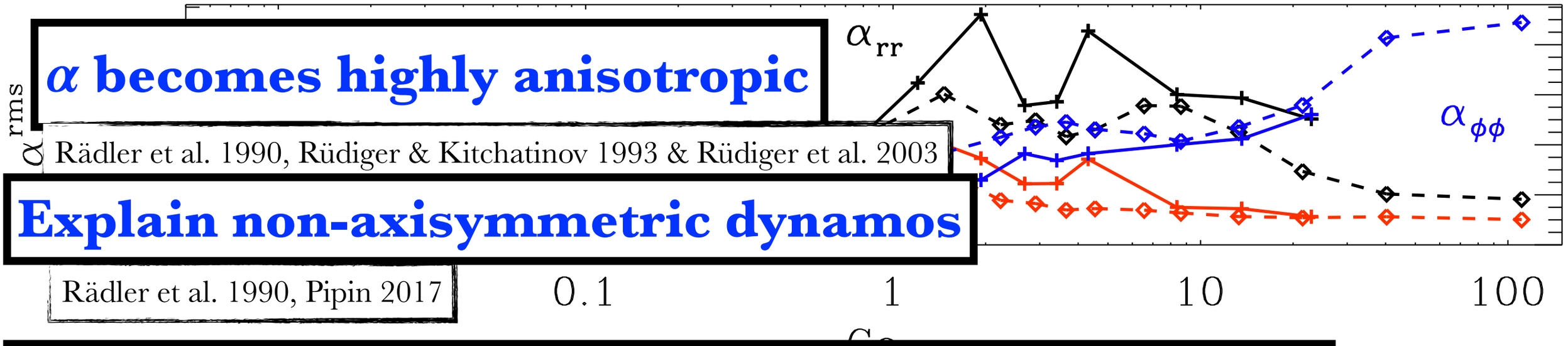


α becomes highly anisotropic

Rädler et al. 1990, Rüdiger & Kitchatinov 1993 & Rüdiger et al. 2003

Explain non-axisymmetric dynamos

Rädler et al. 1990, Pipin 2017

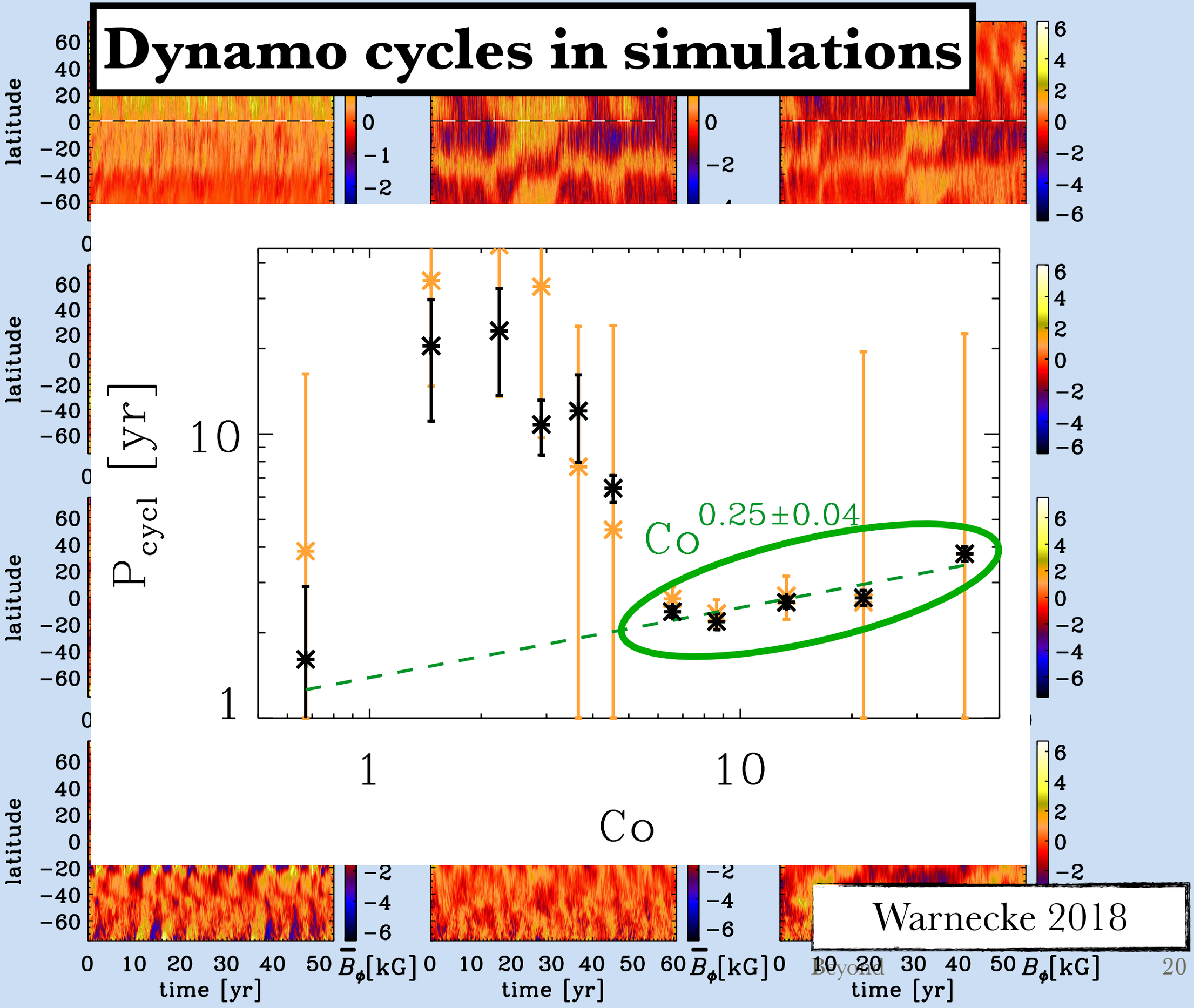


Found in observations and simulations

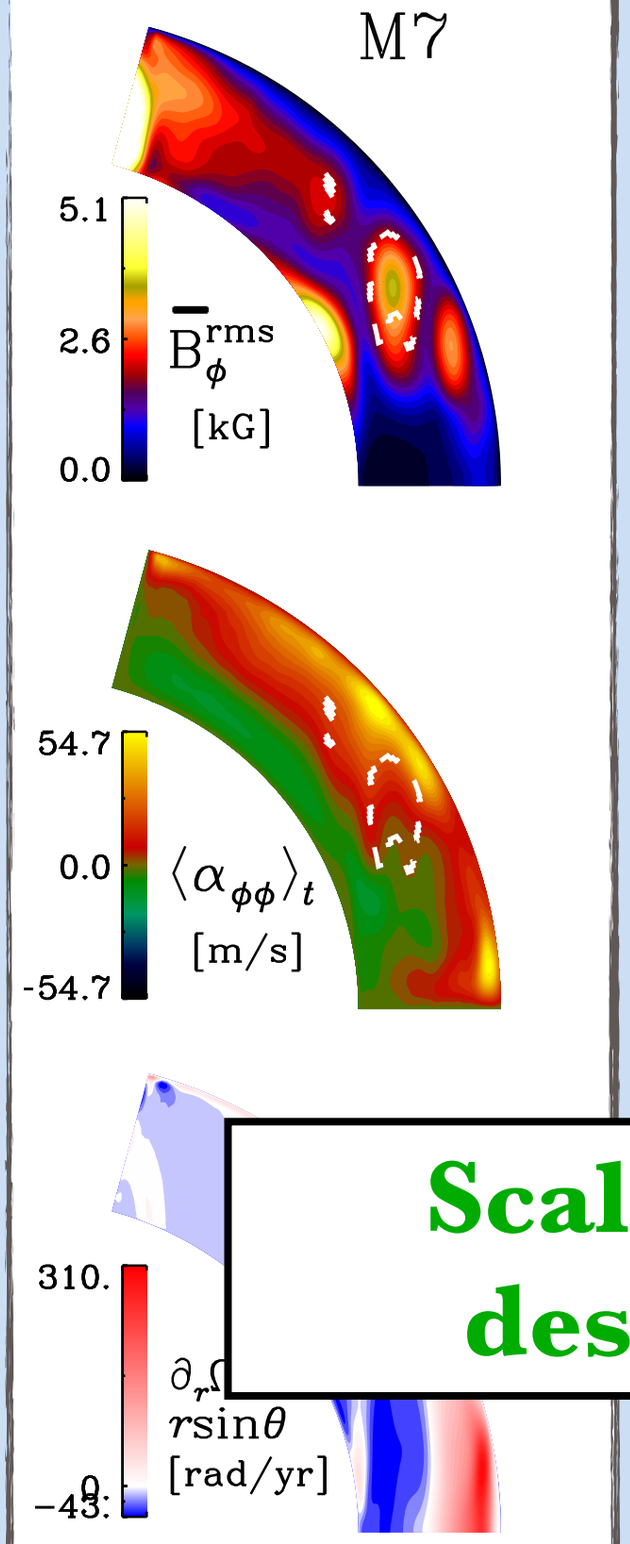
Berdyugina & Tuominen, 1998 & Lehtinen et al 2018

Viviani et al. 2018

Dynamo cycles in simulations

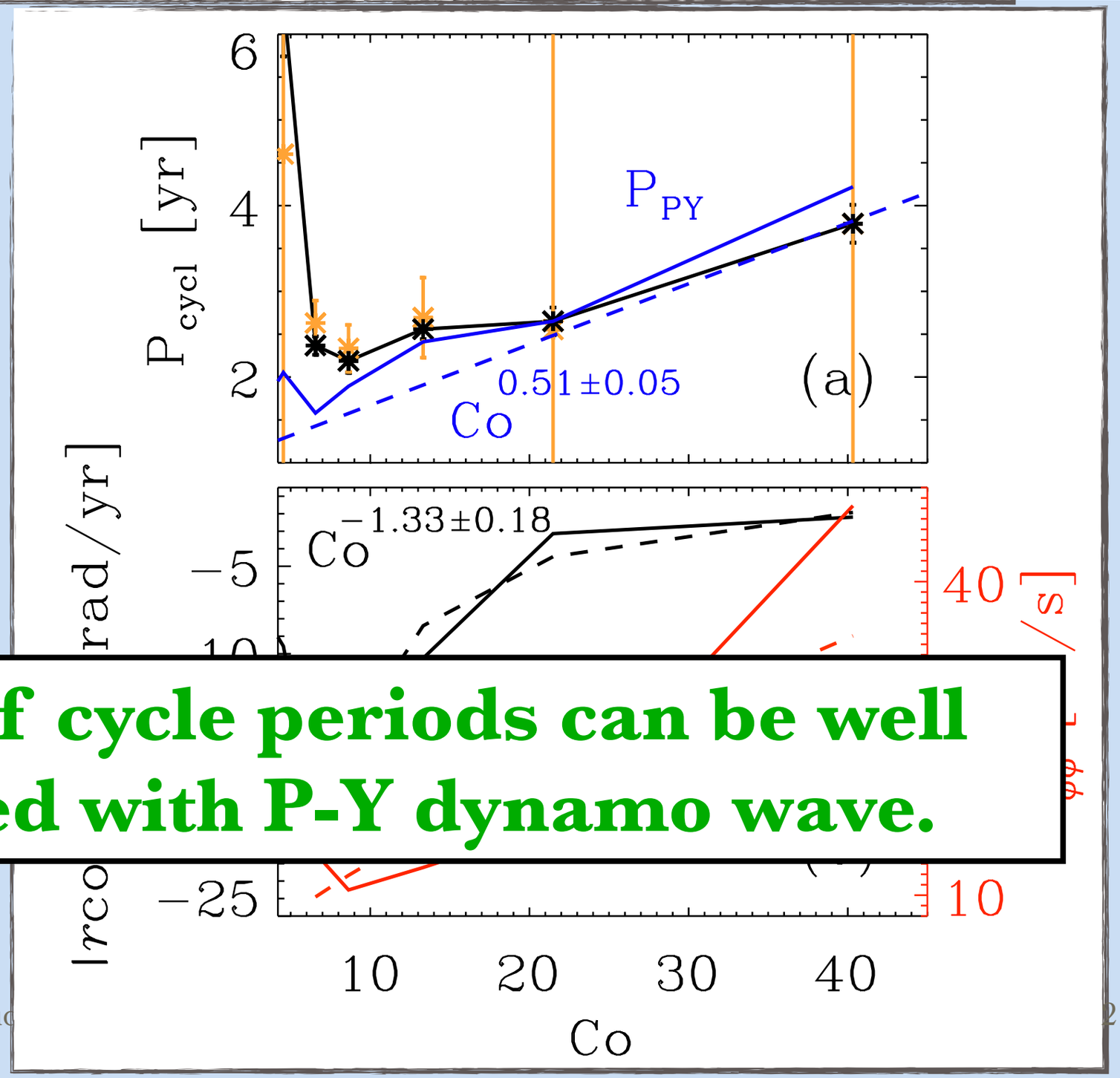


Dynamo cycles in simulations II



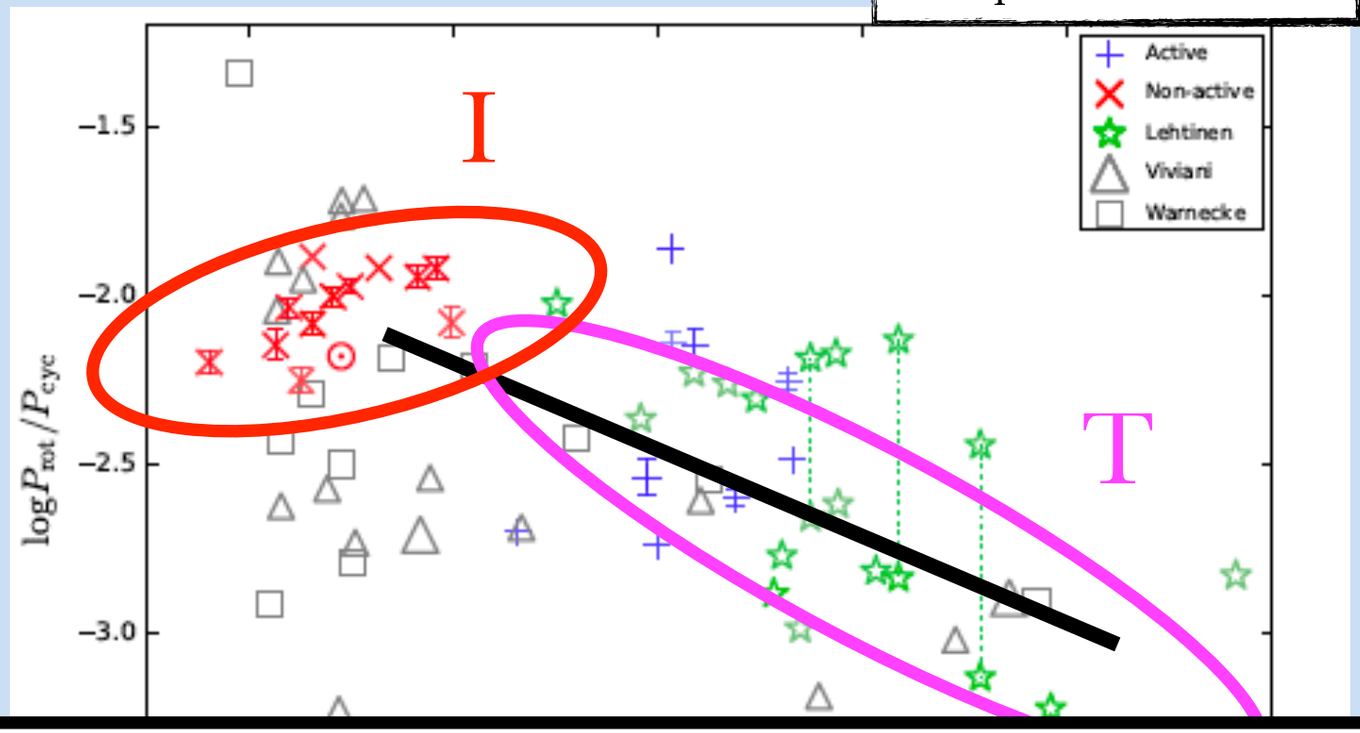
$$\omega_{\rm PY} = \left| \frac{\alpha_{\phi\phi}\, k_\theta}{2} r \cos\theta \frac{\partial \Omega}{\partial r} \right|^{1/2}$$

Parker-Yoshimura



Scaling of cycle periods can be well described with P-Y dynamo wave.

Olspert et al. 2017



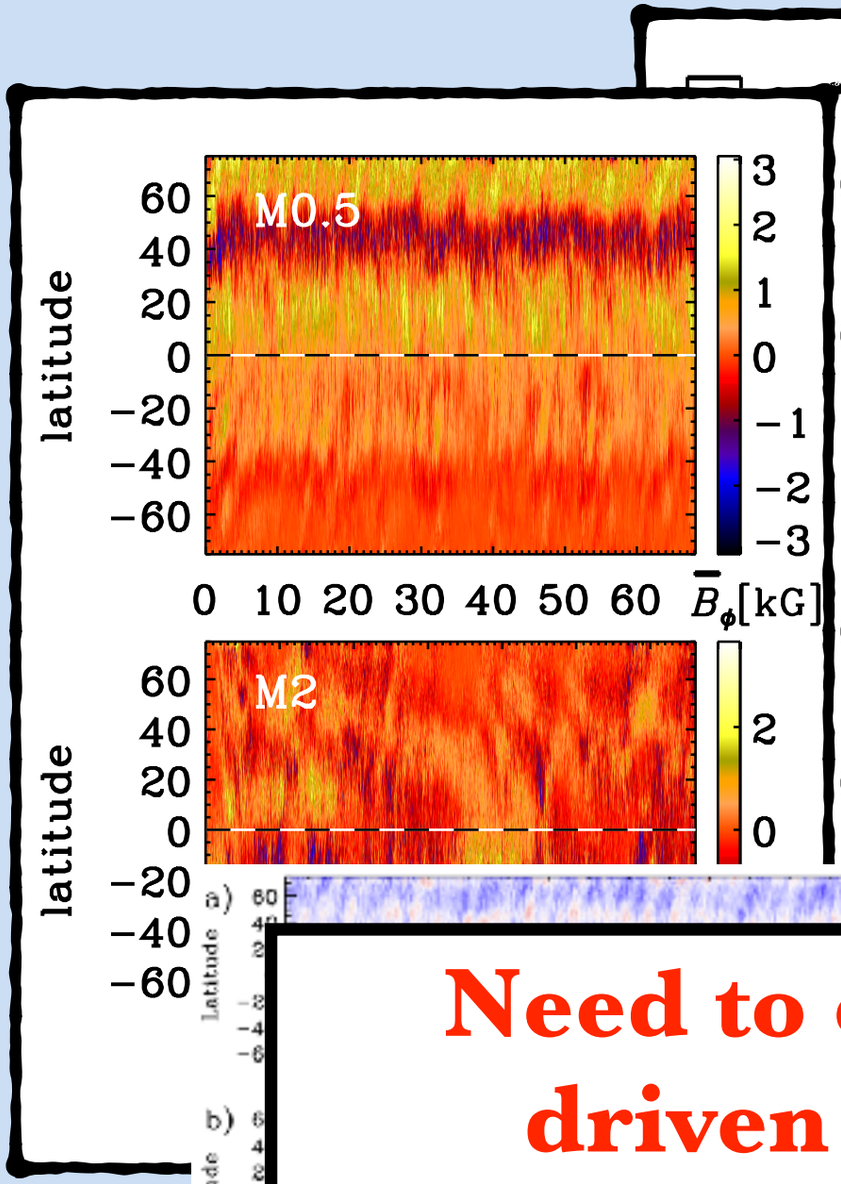
Results of simulations fit well with transitional branch

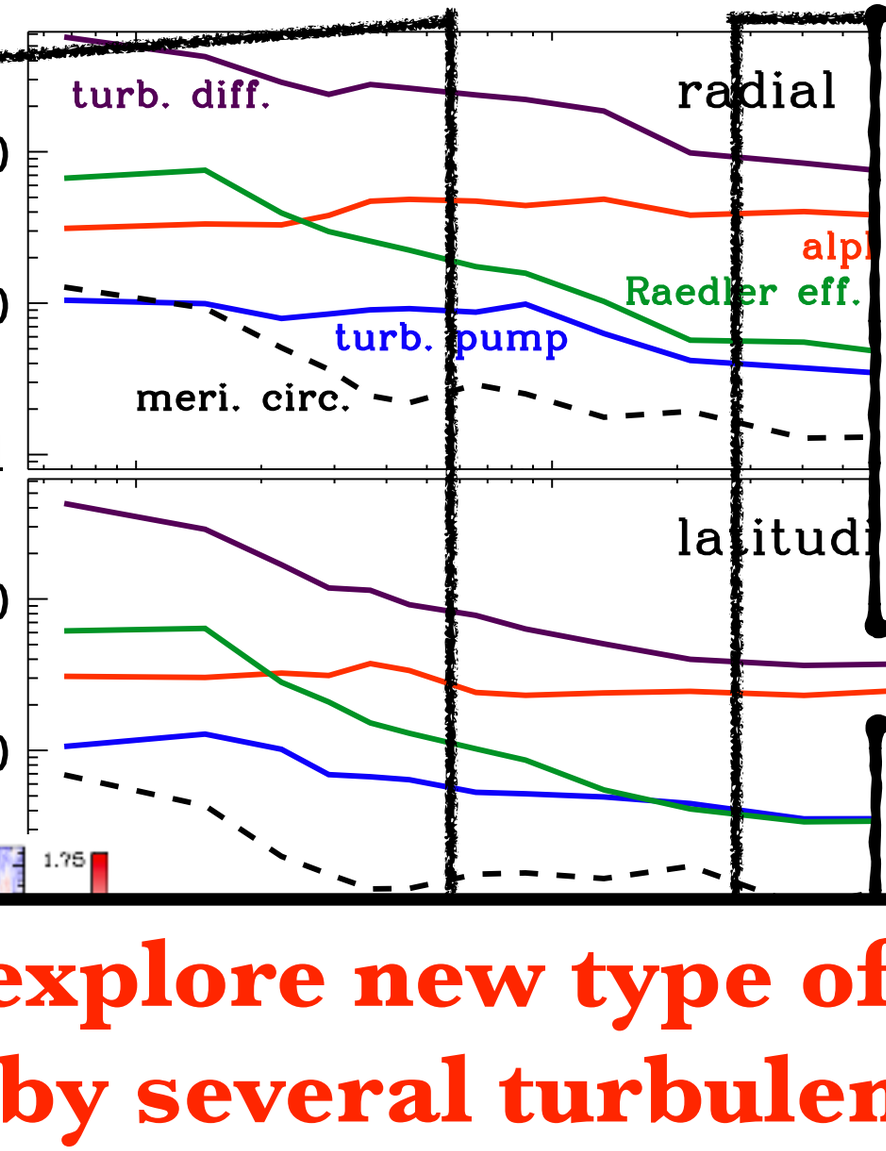
Transitional branch

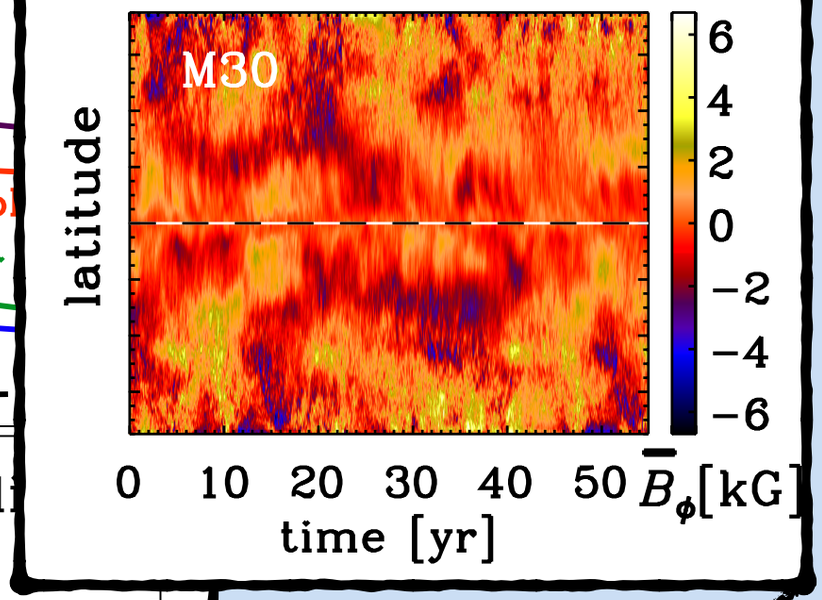
Distefano et al. 2017

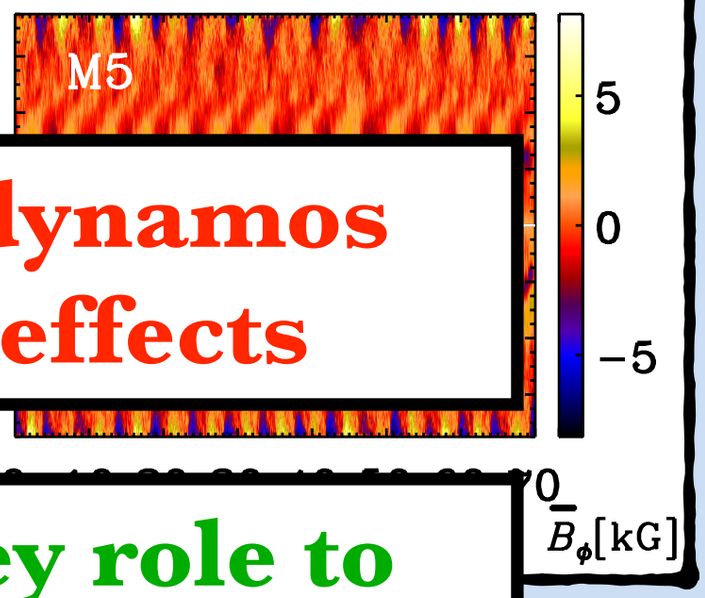
Explanation for inactive branch still missing

Turbulent dynamo effects





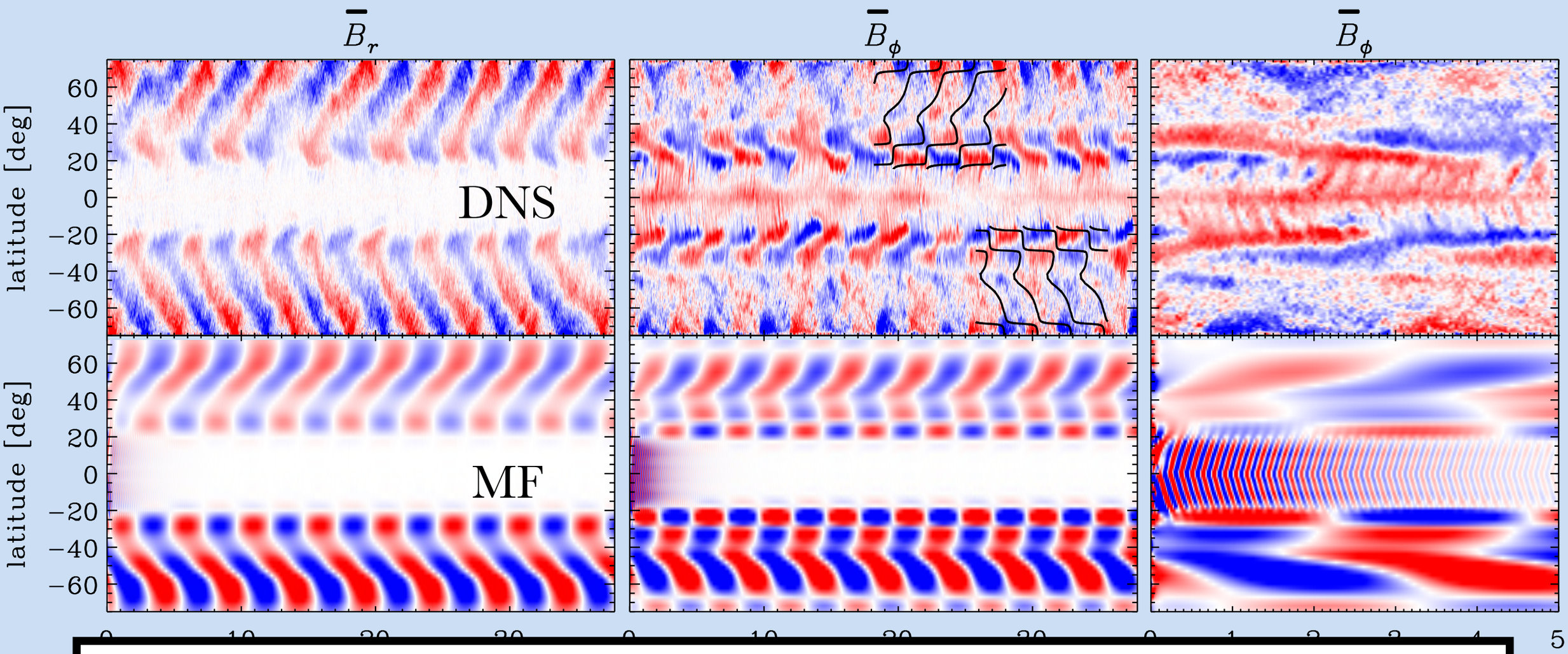




Need to explore new type of dynamos driven by several turbulent effects

Numerical simulation play key role to determine the effects now in the future

Mean-field model vs. DNS



Very good agreement of MF model with DNS: (Period and Pattern)

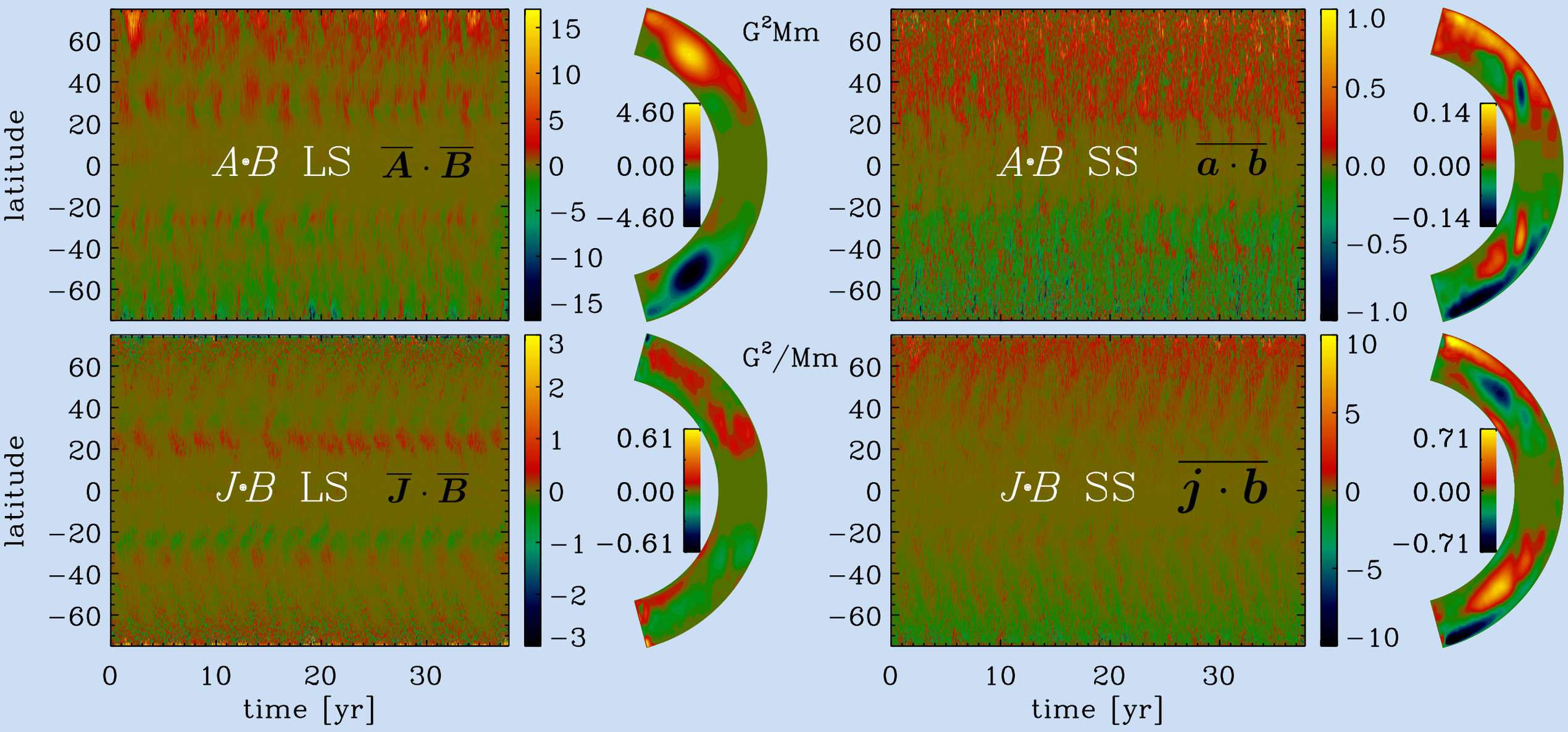
Full spectrum of effects needed

Simple dynamo models may not viable

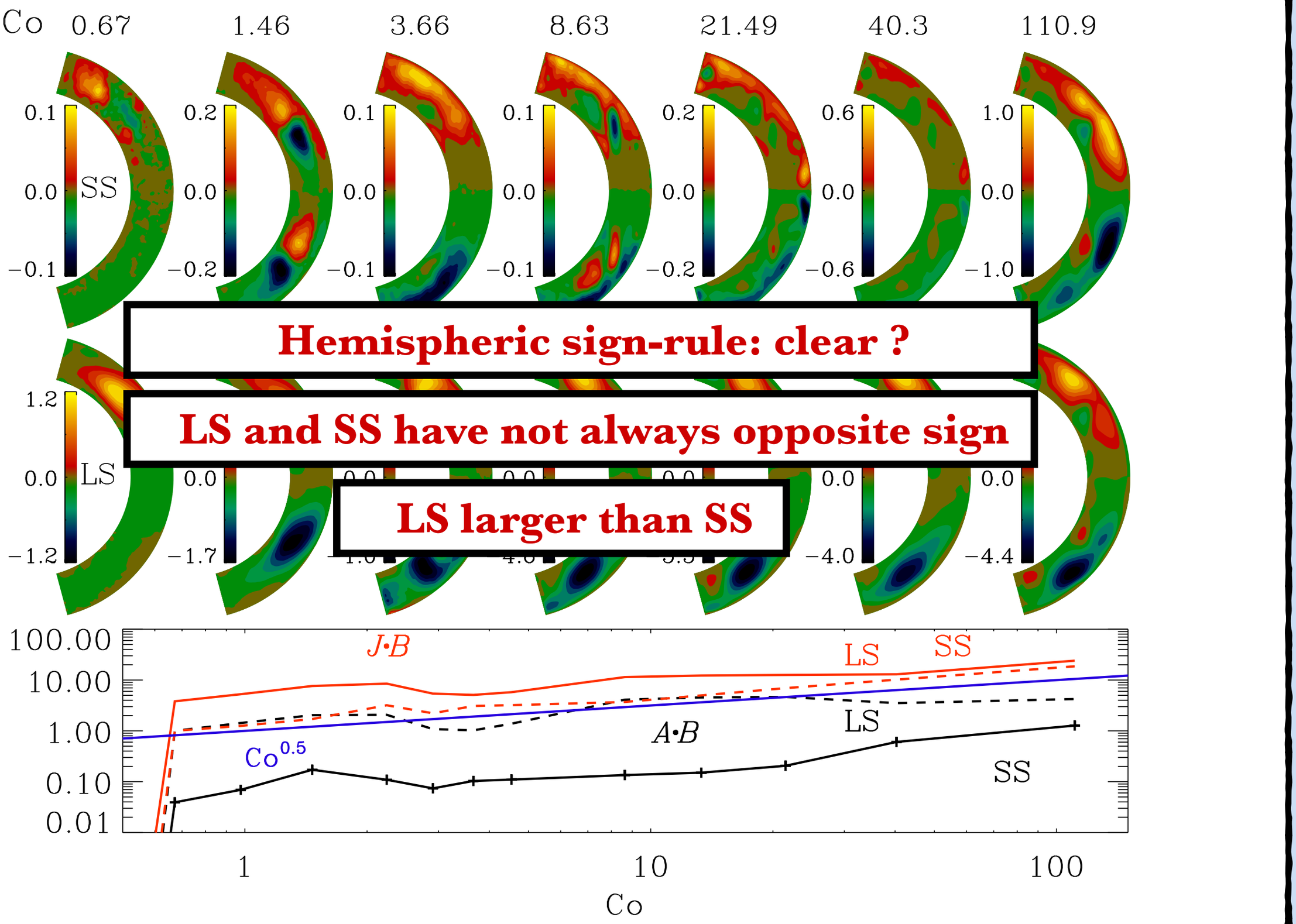
Warnecke et al. 2021
Submitted
arXiv:2105.07708

Magnetic helicity in convective dynamo simulation

M5: Co=8.63



Magnetic helicity production with increasing rotation



Magnetic helicity fluxes

$$\alpha = -\frac{1}{3}\tau_{\rm c}\overline{\boldsymbol{\omega}'\cdot\boldsymbol{u}'} + \frac{1}{3}\frac{\tau_{\rm c}}{\overline{\rho}}\overline{\boldsymbol{J}'\cdot\boldsymbol{B}'} = \alpha_{\rm K} + \alpha_{\rm M},$$

Pouquet et al. 1976

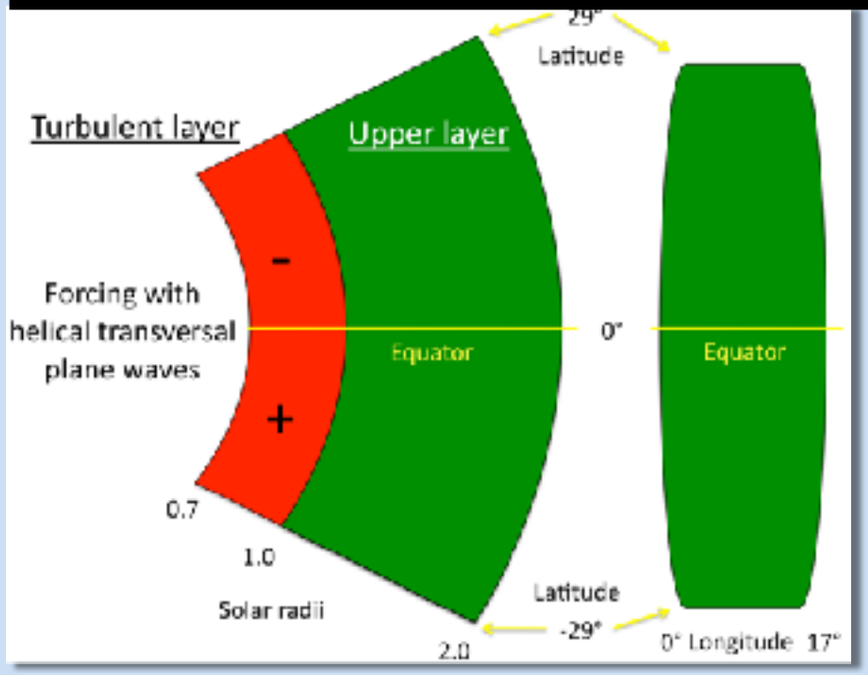
$$\alpha = \frac{\alpha_{\rm K} + {\rm Re}_{\rm M}\left(\eta_{\rm t}\overline{\boldsymbol{J}}\cdot\overline{\boldsymbol{B}} - \frac{1}{2}\boldsymbol{\nabla}\cdot\overline{\boldsymbol{\mathcal{F}}}^{f}_{h}\right)/B^2_{\rm eq}}{1 + {\rm Re}_{\rm M}\overline{\boldsymbol{B}}^2/B^2_{\rm eq}}$$

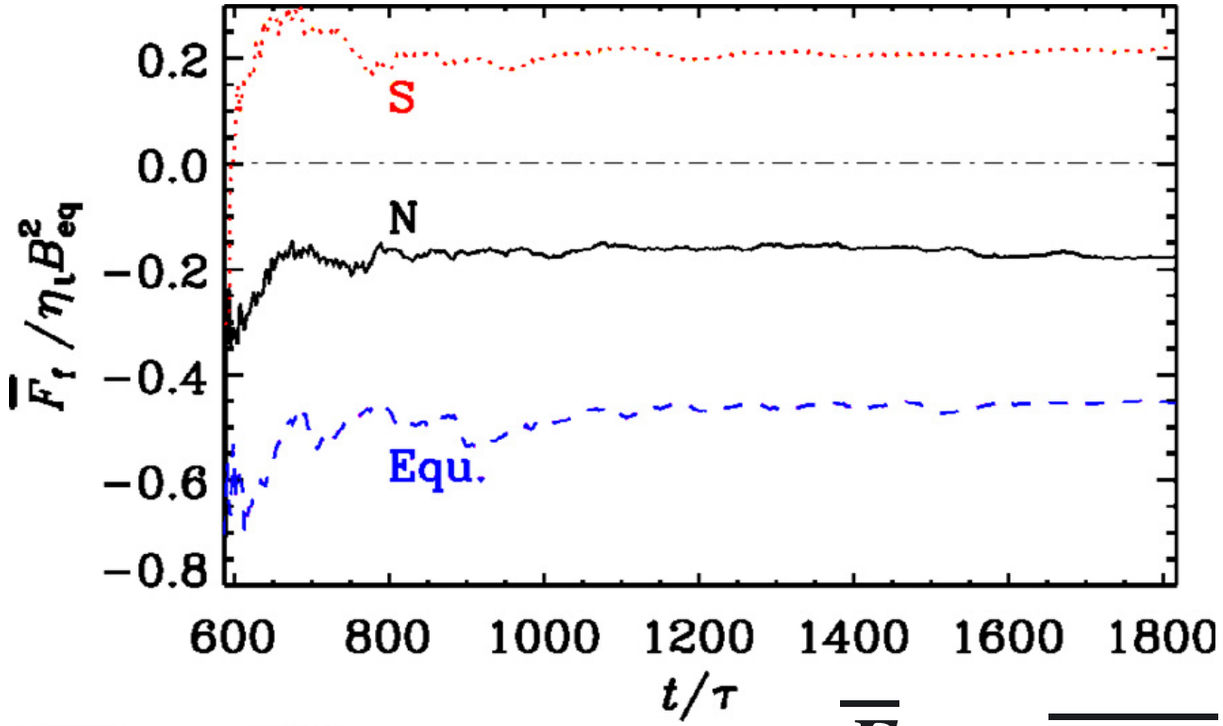
Kleeorin & Ruzmaikin 1982

Vainshtein & Cattaneo 1992

Based on assumption, which might be not true in complex systems

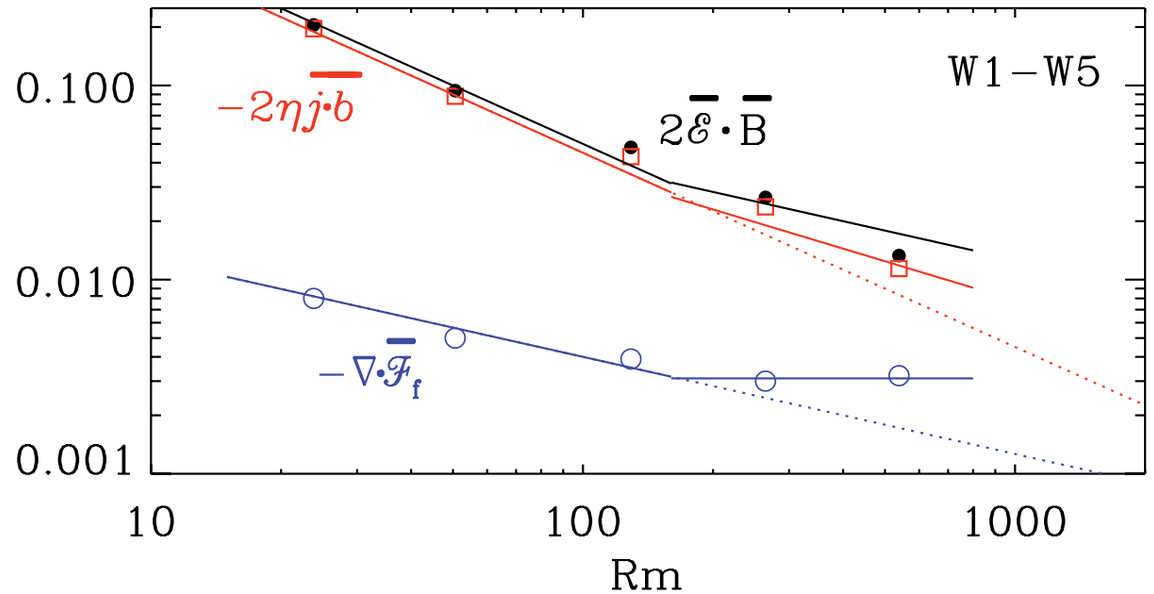
Magnetic helicity fluxes from simulations

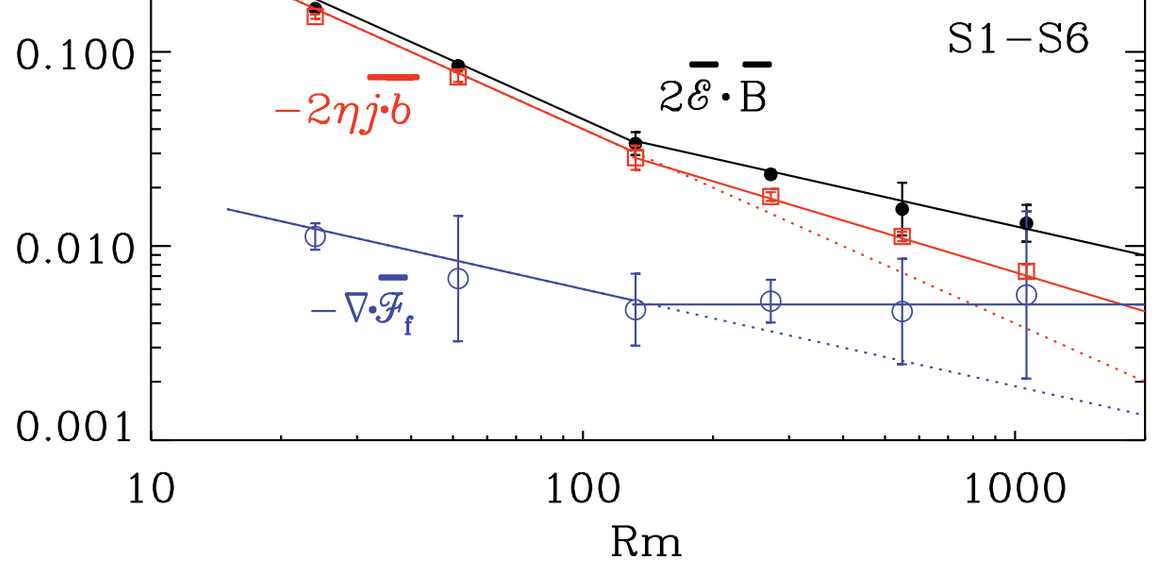




Warnecke et al. 2011

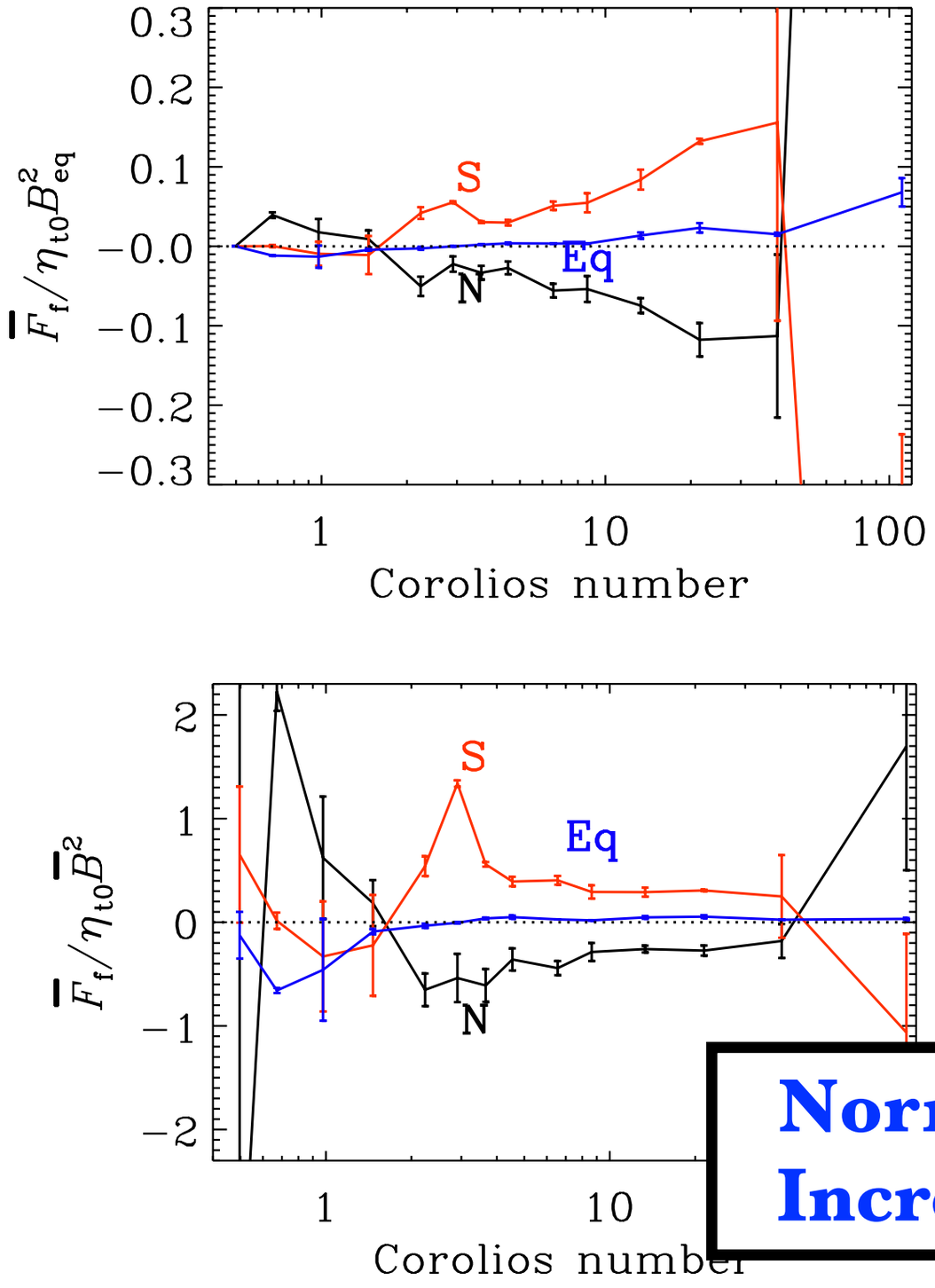
$$\overline{\boldsymbol{F}}_{\rm f} = \overline{\boldsymbol{e} \times \boldsymbol{a}}$$

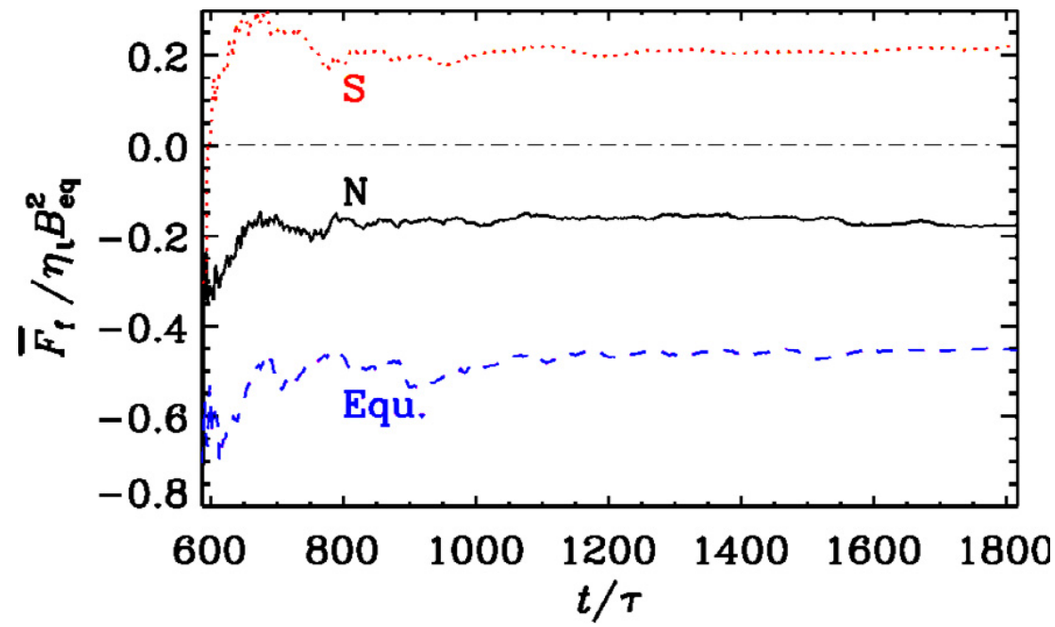




Del Sordo et al. 2013

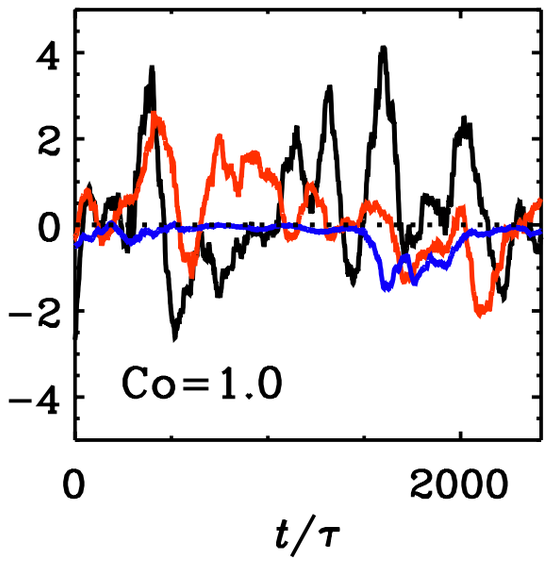
Magnetic helicity fluxes from convection simulations

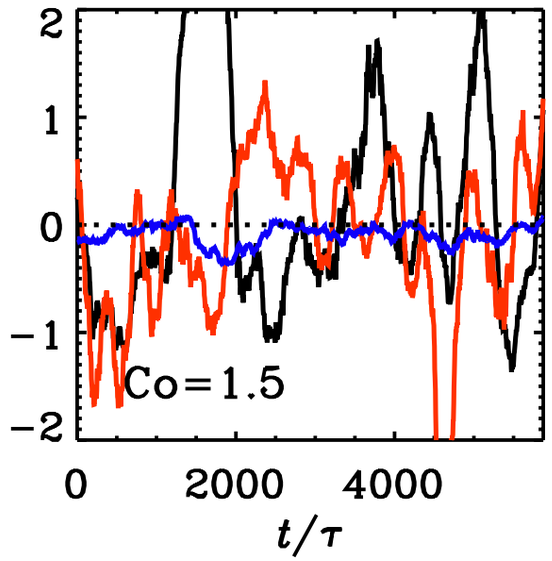


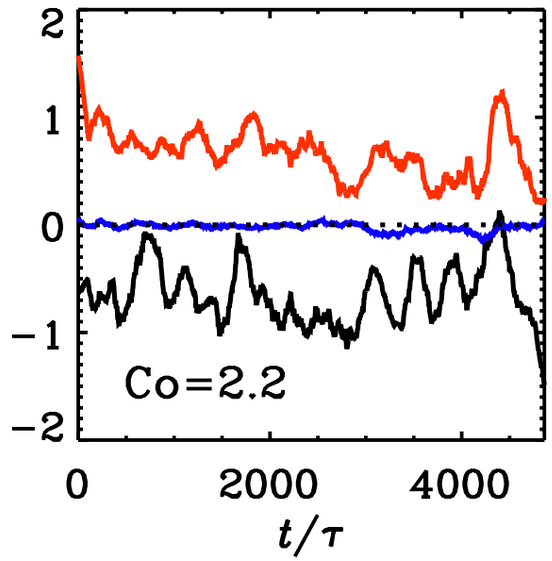


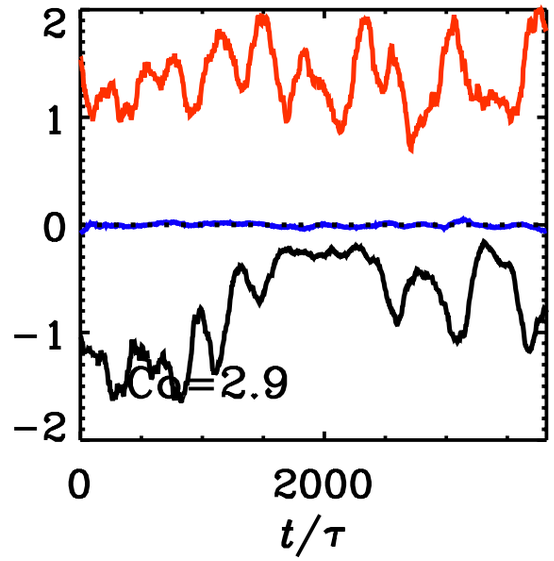
Norm. helicity fluxes stay constant
Increase due to mag. field increase

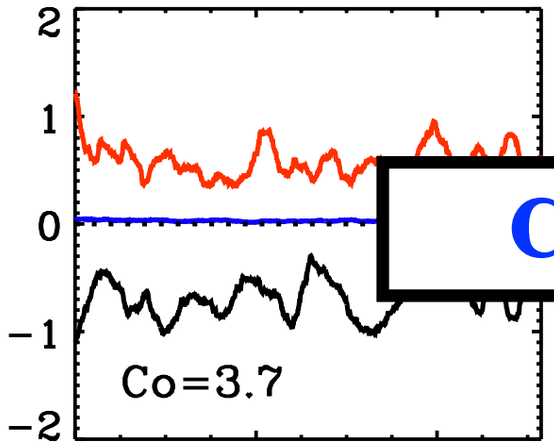
Cyclic dependency of helicity fluxes

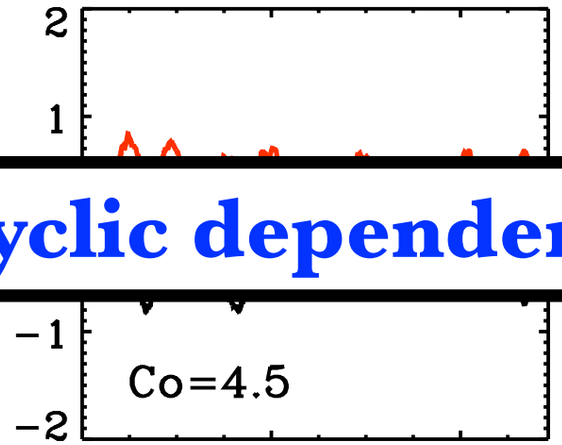


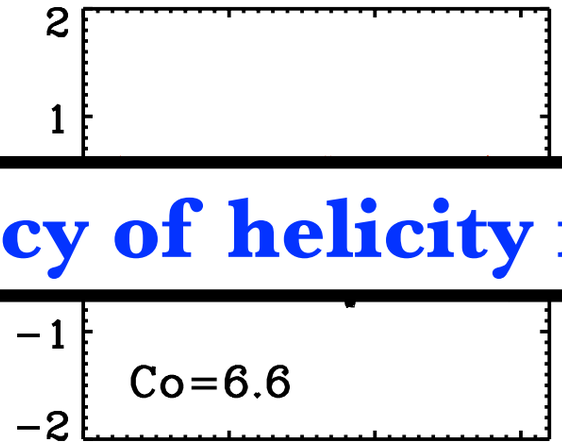


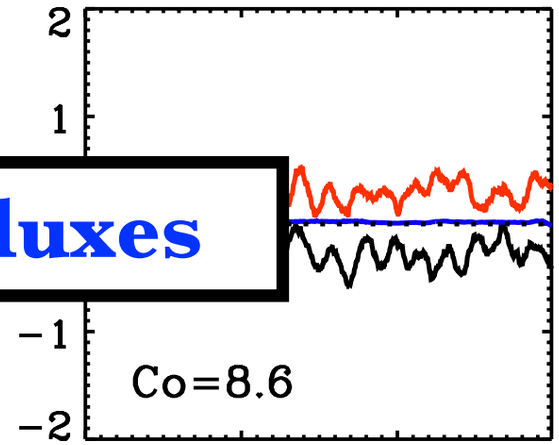


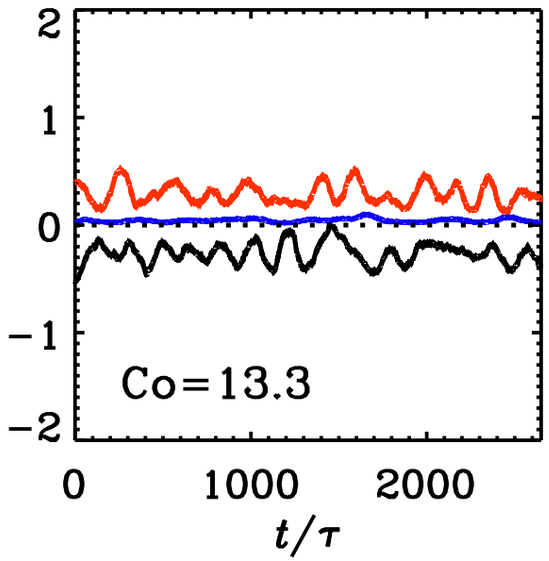


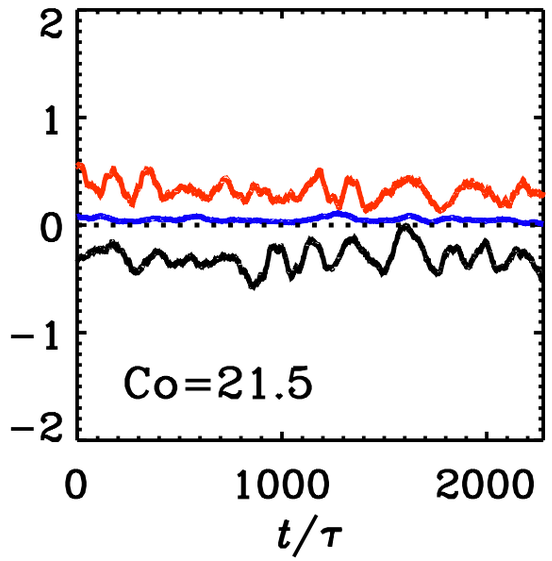


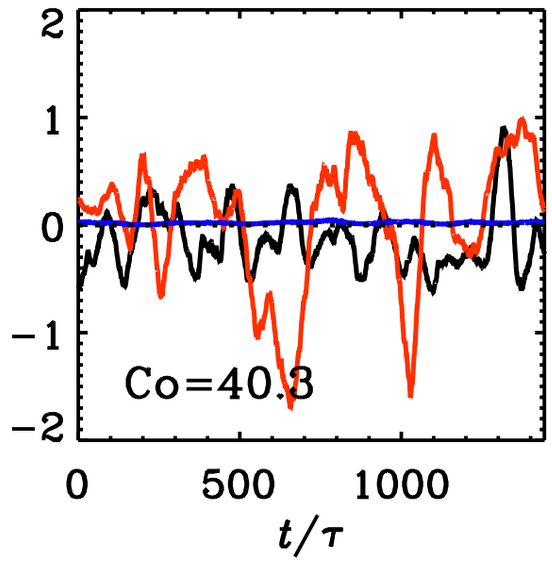


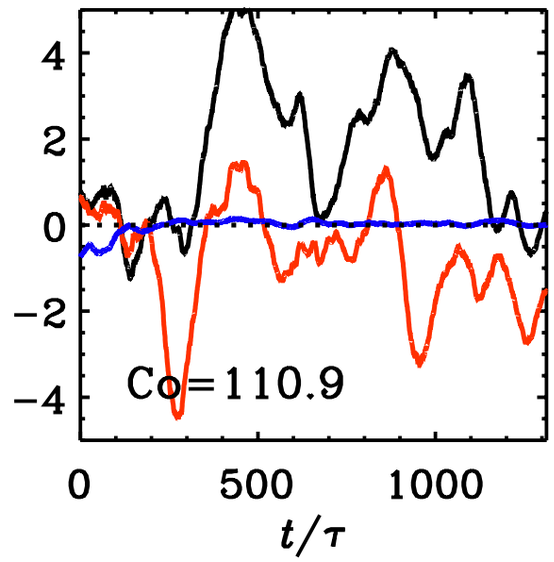




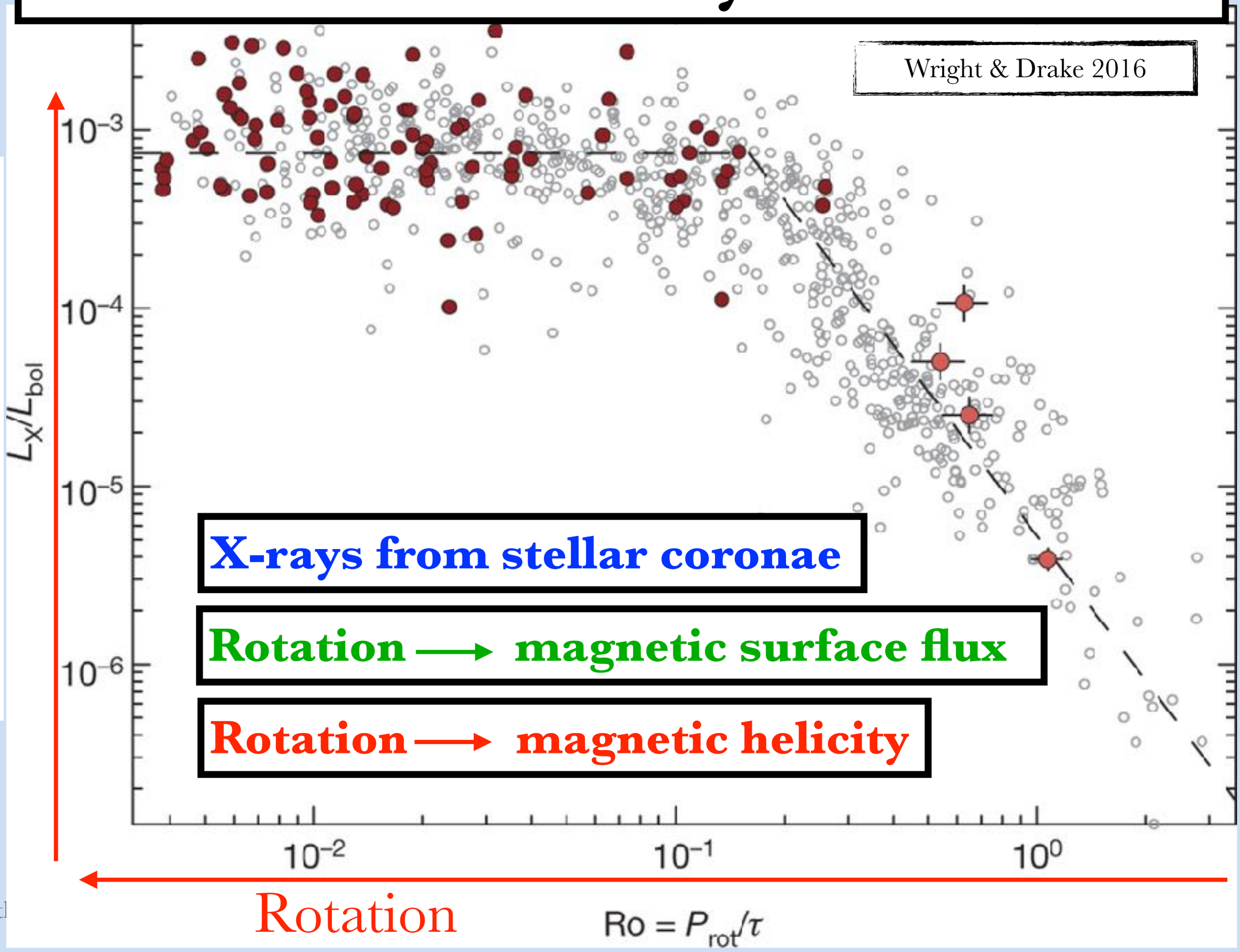




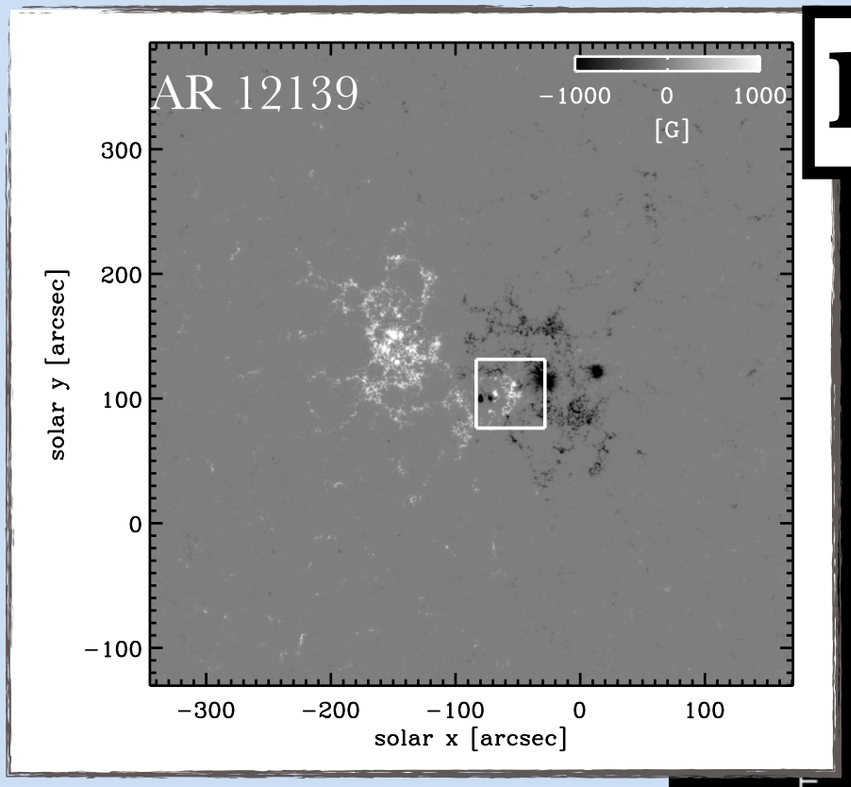




Rotation-Activity Relation



Data-driven coronal simulation



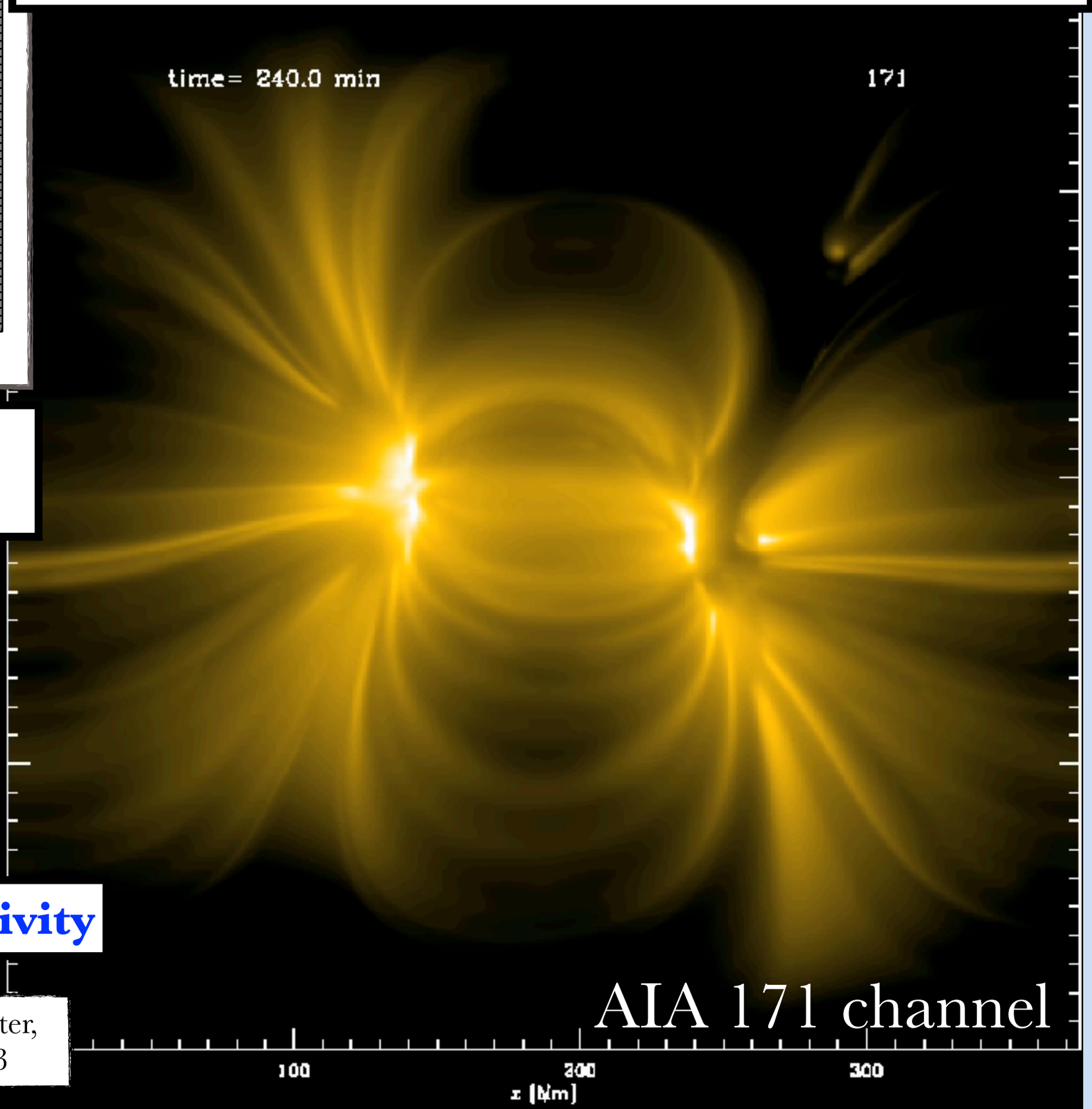
Compressible (resistive) MHD

Prescribed photospheric motions mimicking solar granulation

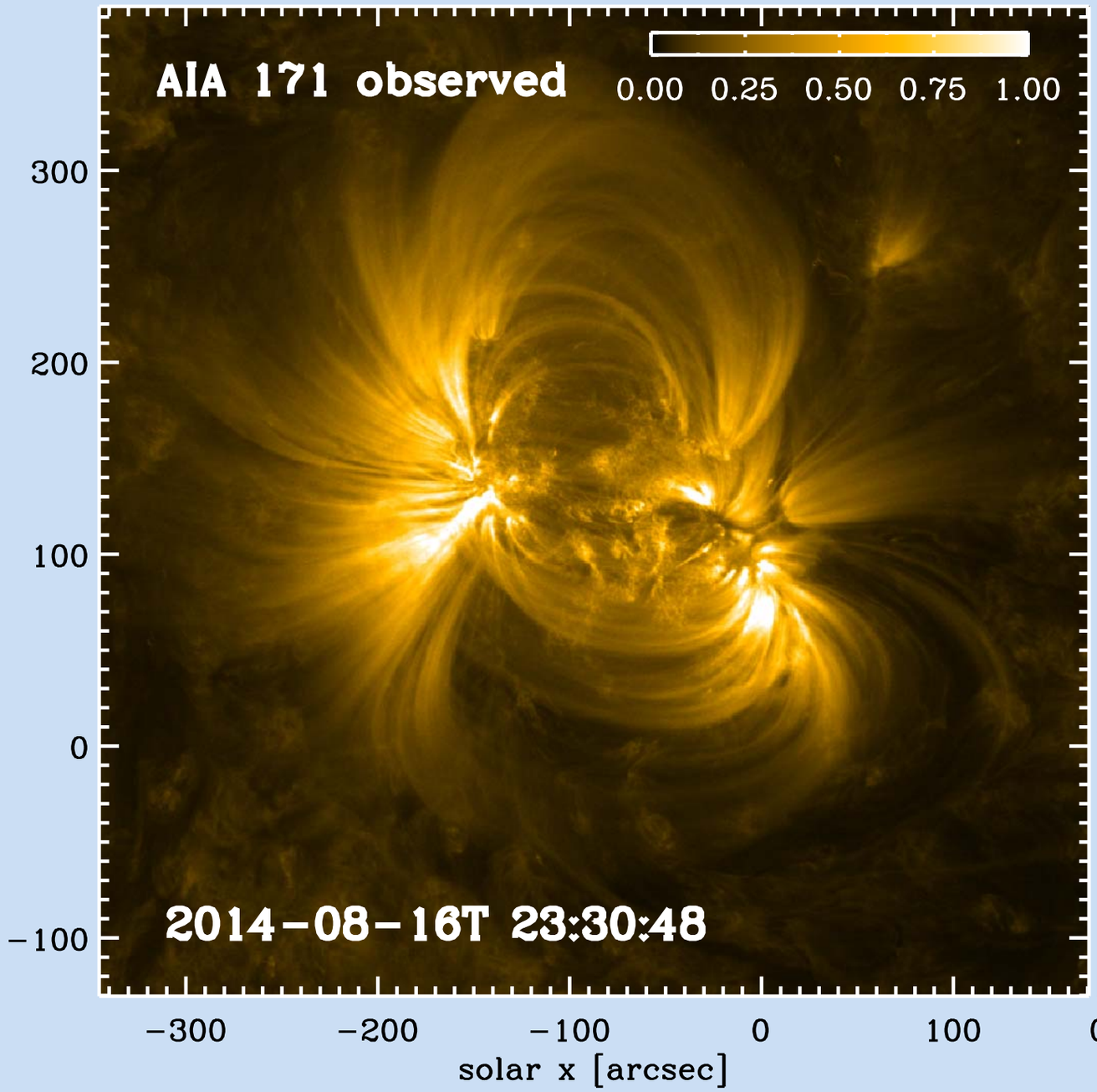
Spitzer heat conductivity

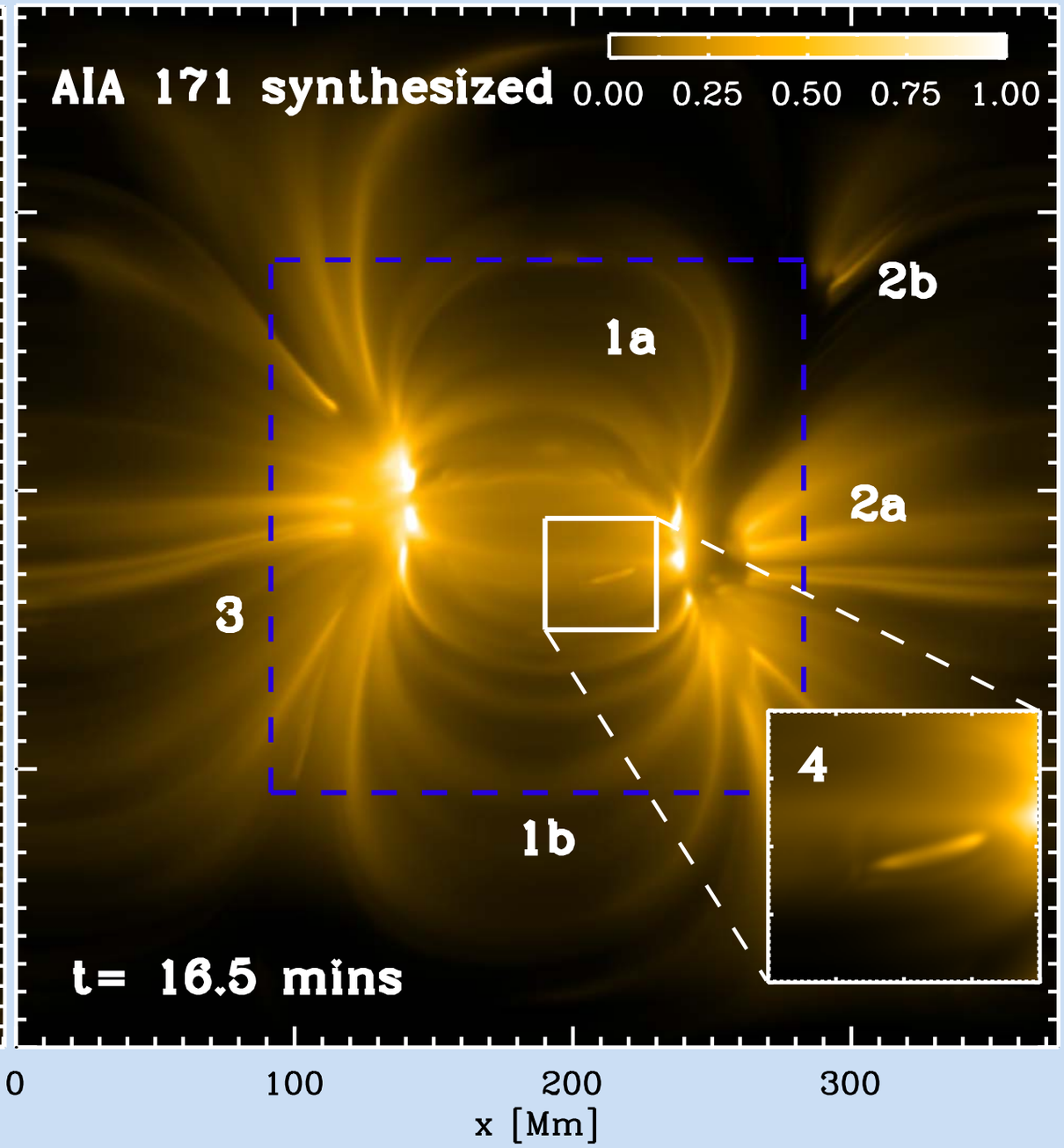
Pencil Code

Bingert & Peter, 2011, 2013



Comparison with observations

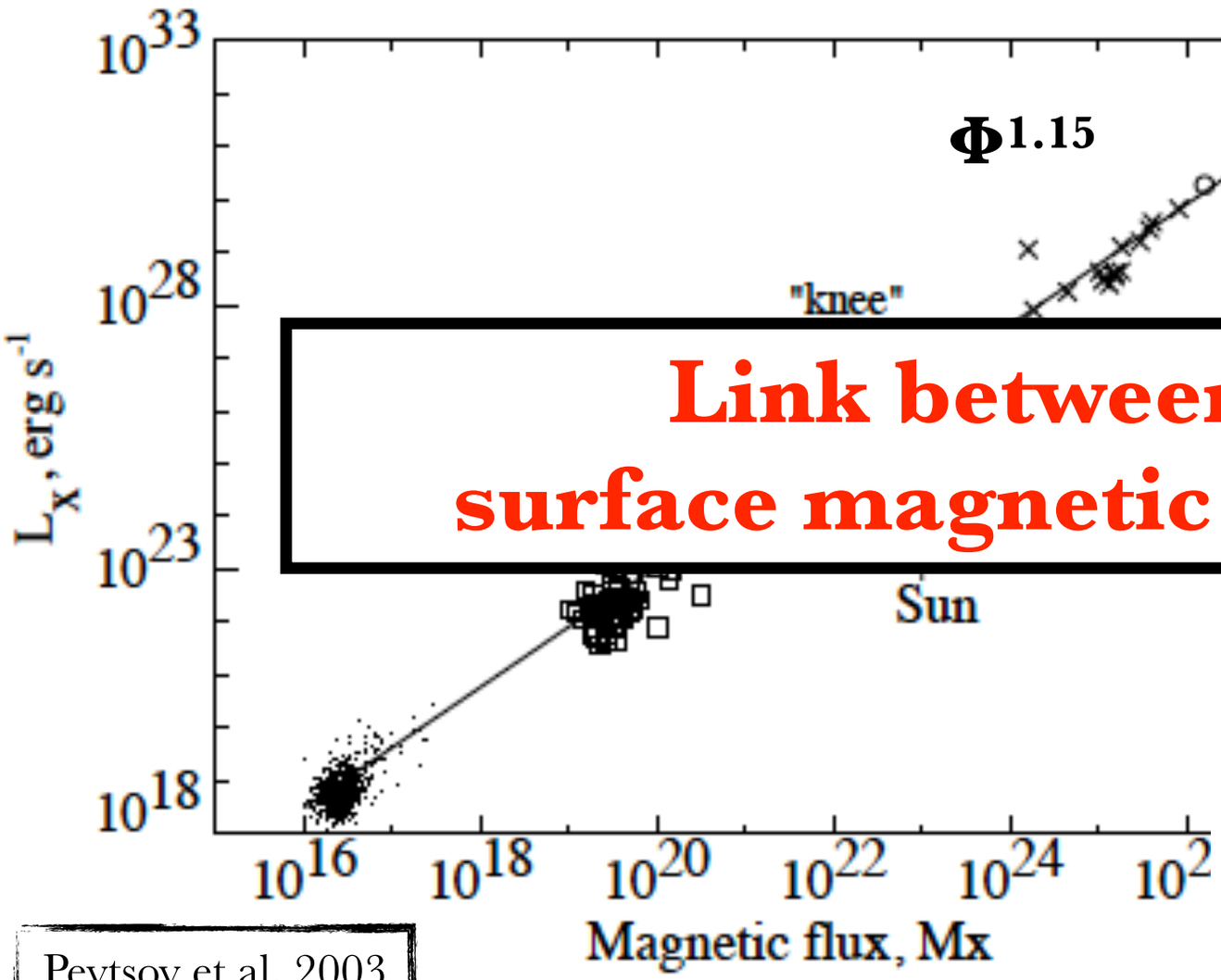




Can reproduce many observed features !

Warnecke & Peter, 2019

Scaling of X-rays with magnetic flux



Pevtsov et al. 2003

See also Vidotto et al. 2014

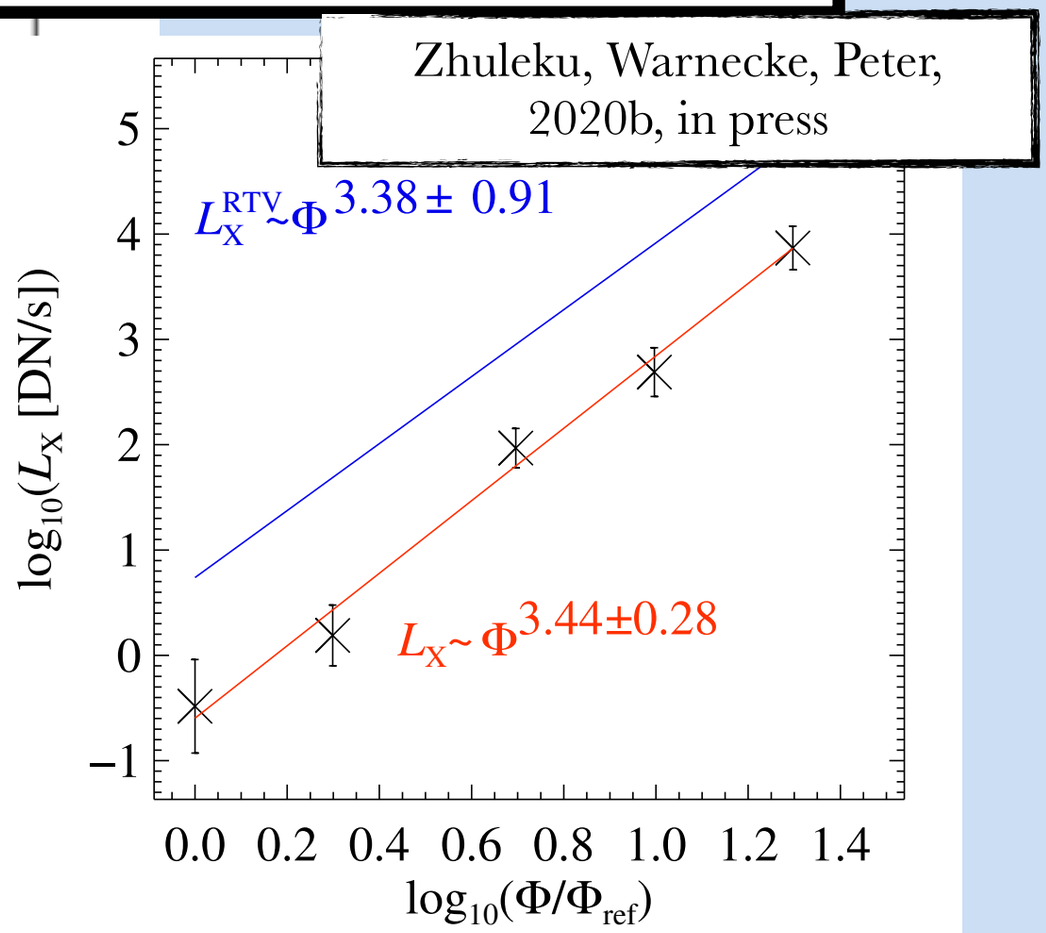
Explained by analytical model

Zhuleku, Warnecke, Peter, 2020a

Link between X-rays and surface magnetic field distribution

X-ray emission

Zhuleku, Warnecke, Peter, 2020b, in press



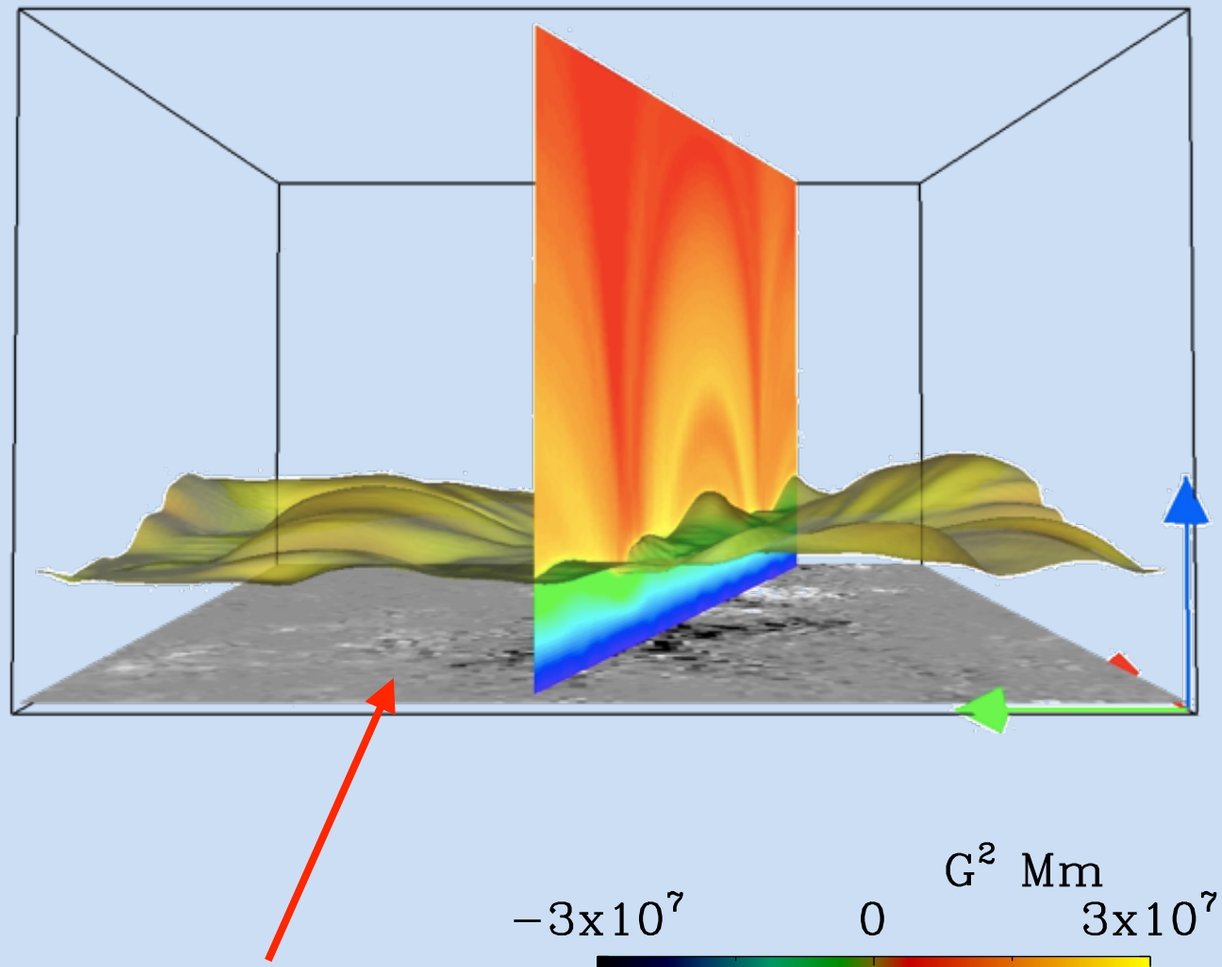
Magnetic flux log (Φ/Φ_0)

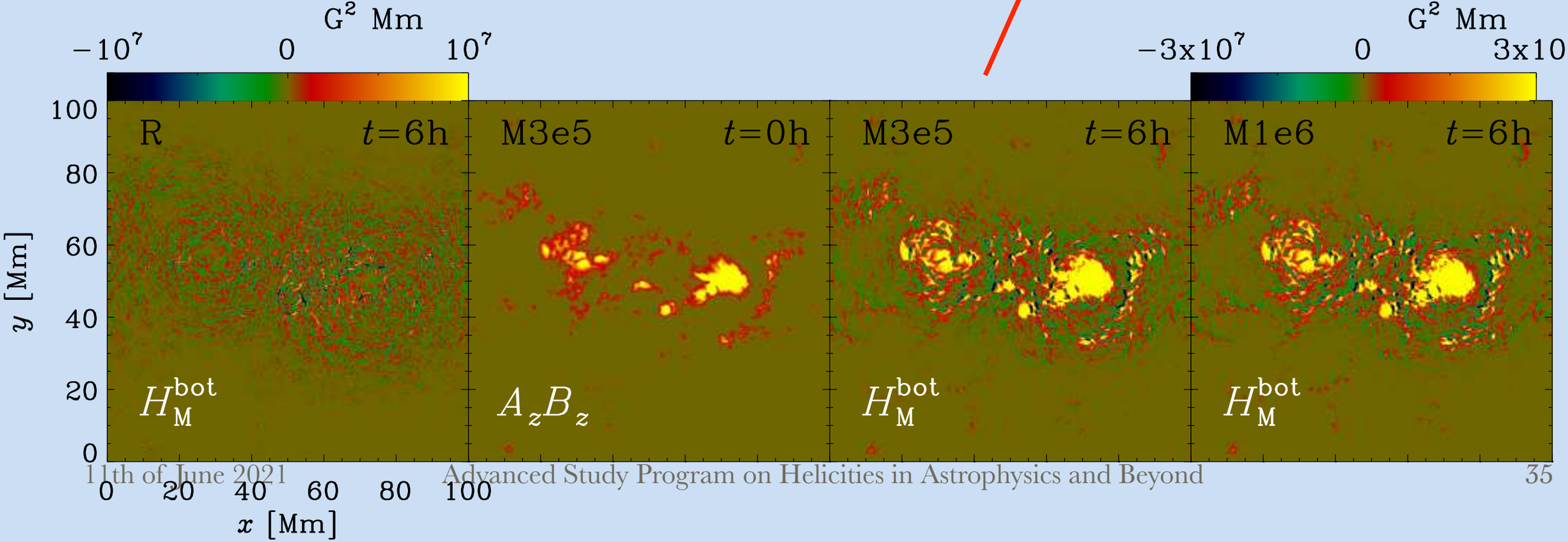
Magnetic helicity injection

Vertical photospheric field: A_x, A_y

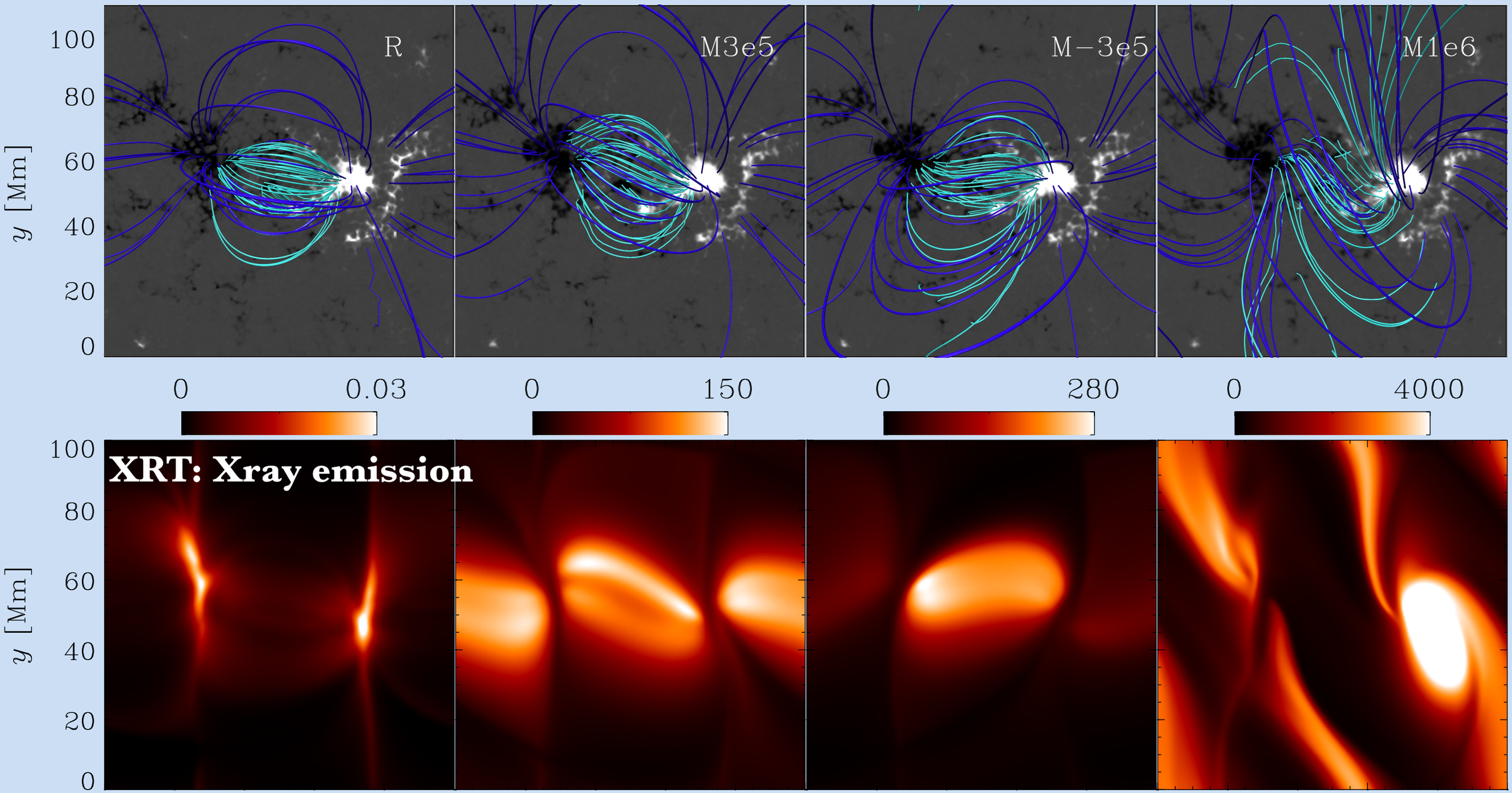
$$A_z = \frac{H_{\rm M}^{\rm in}}{< B_z^2 >_{xy}} B_z,$$

$$H_{\rm M}^{\rm bot} =< \boldsymbol{A} \cdot \boldsymbol{B} >_{xy} (z = 0).$$

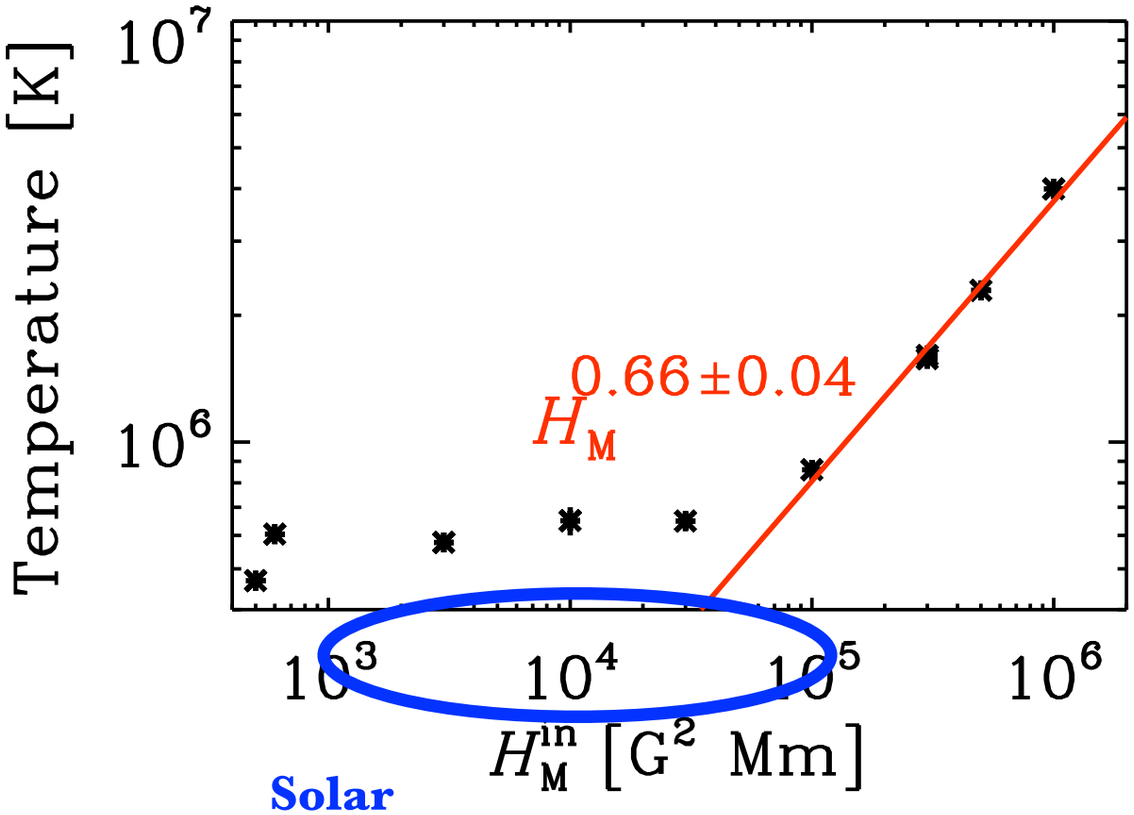


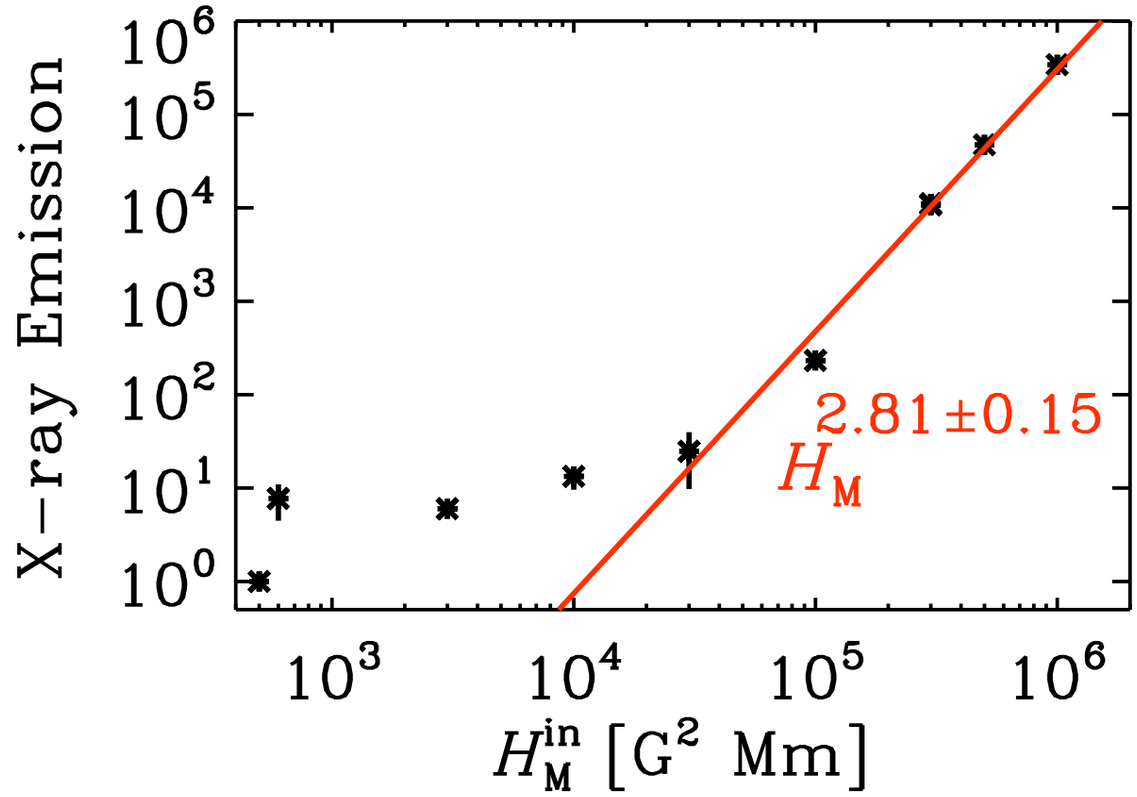


Magnetic helicity + X-ray production



Magnetic helicity enhances heating





Magnetic helicity density

Increase of X-rays with magnetic helicity is consistent with observation, if H_m increases less linearly with rotation.

Increase of X-rays with magnetic helicity provide a significant contribution to activity-rotation-relation

Conclusions

Test-field method one way to measure dynamo effects

Trace of alpha saturates for high rotation, but non-isotropic

Explanation for inactive branch still missing

Large variety of turbulent dynamo effects

Simple dynamo models may not viable

LS and SS mag. helicity no opposite sign

All helicities follow ~ $Co^{0.5}$

Norm. helicity fluxes independent of rotation

Injecting mag. helicity causes higher Xray fluxes

Significant contribution to Xray rotation relation

Helical magnetic field important role in understanding the Rotation-Activity-Relation of stars