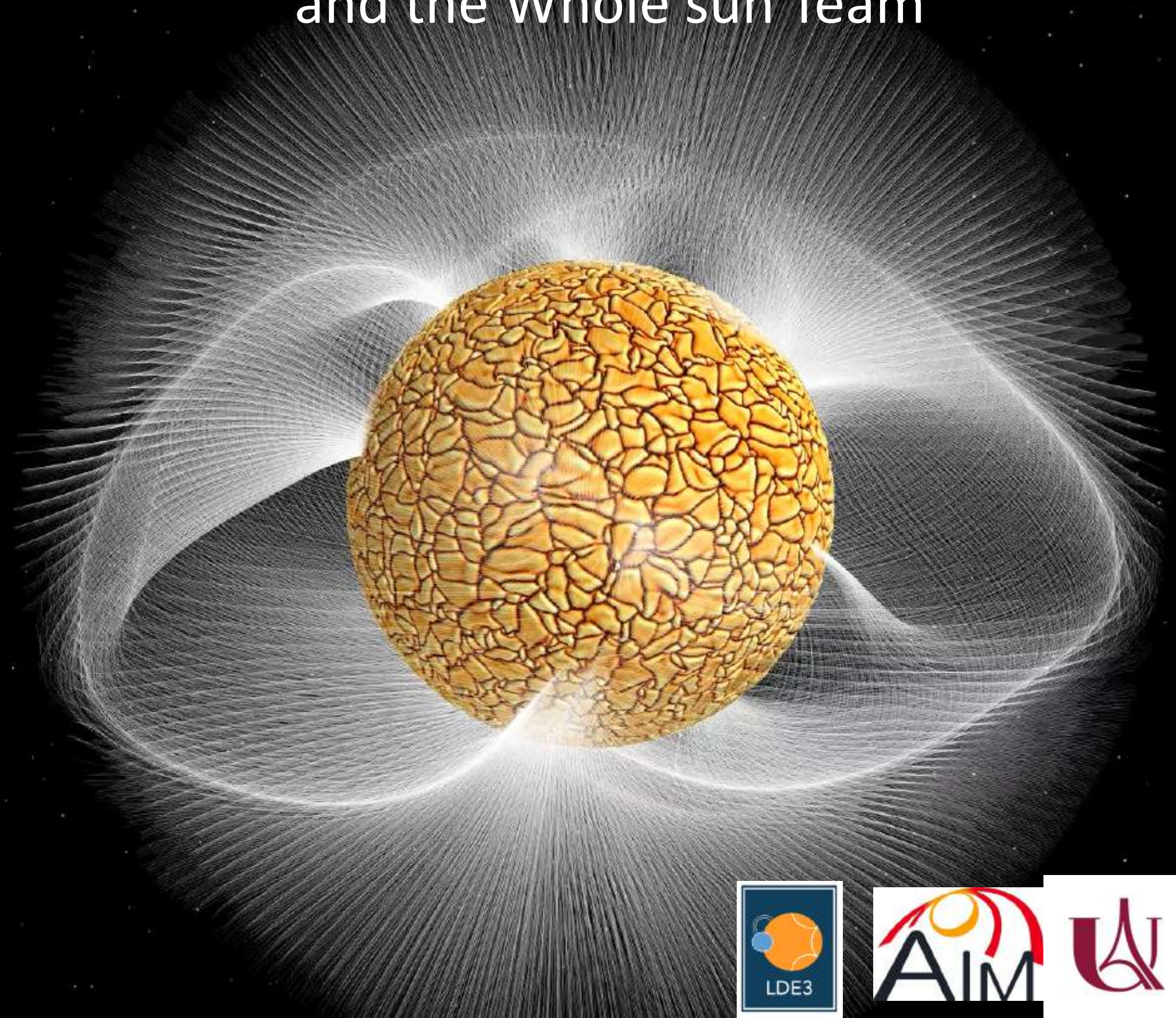
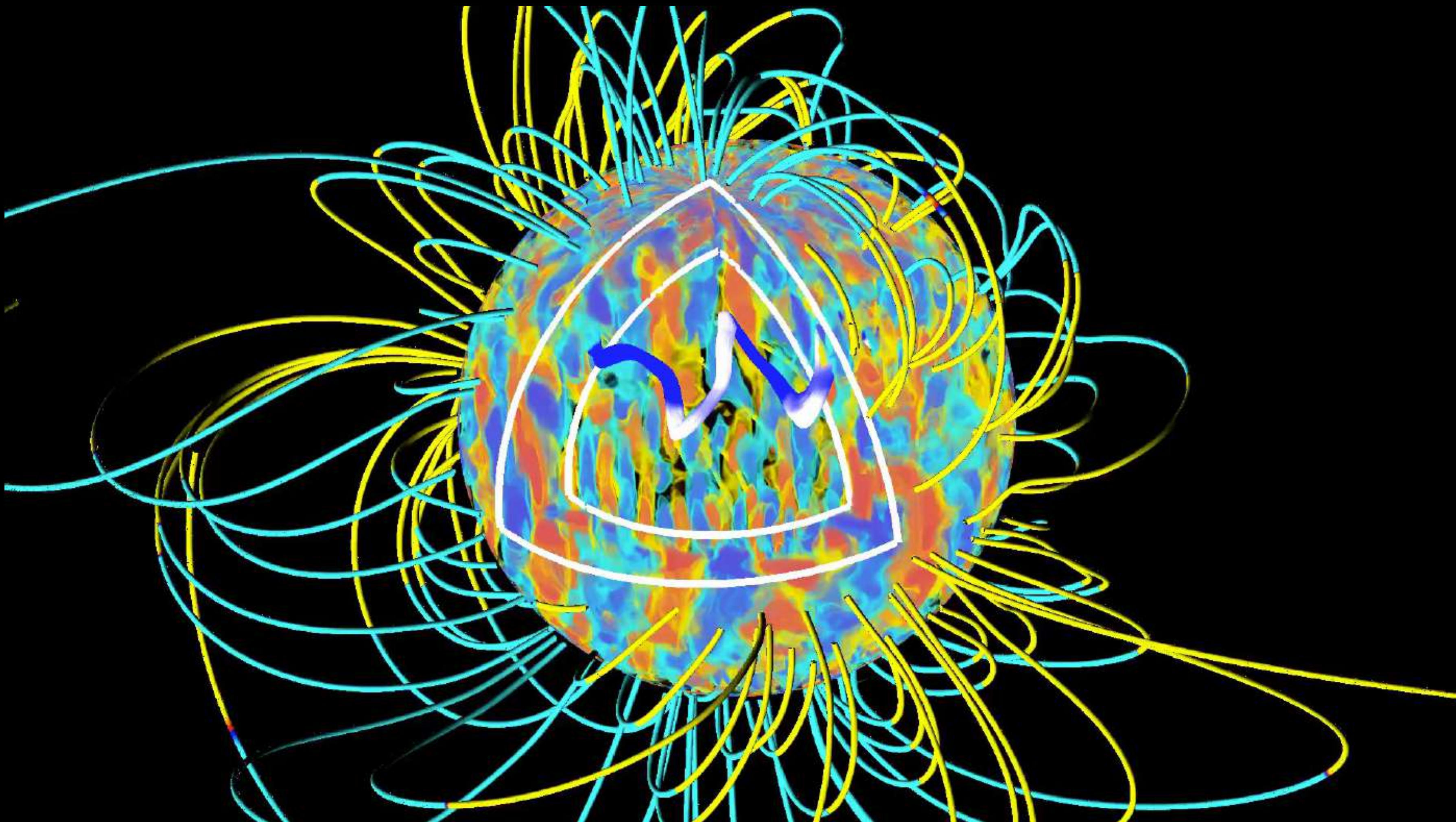
Magnetochronology of solar-type stars and the Convective Conundrum:

a path theory to study global solar magnetized convection

Allan Sacha Brun (CEA Paris-Saclay/ISEE Nagoya)
and the Whole sun Team

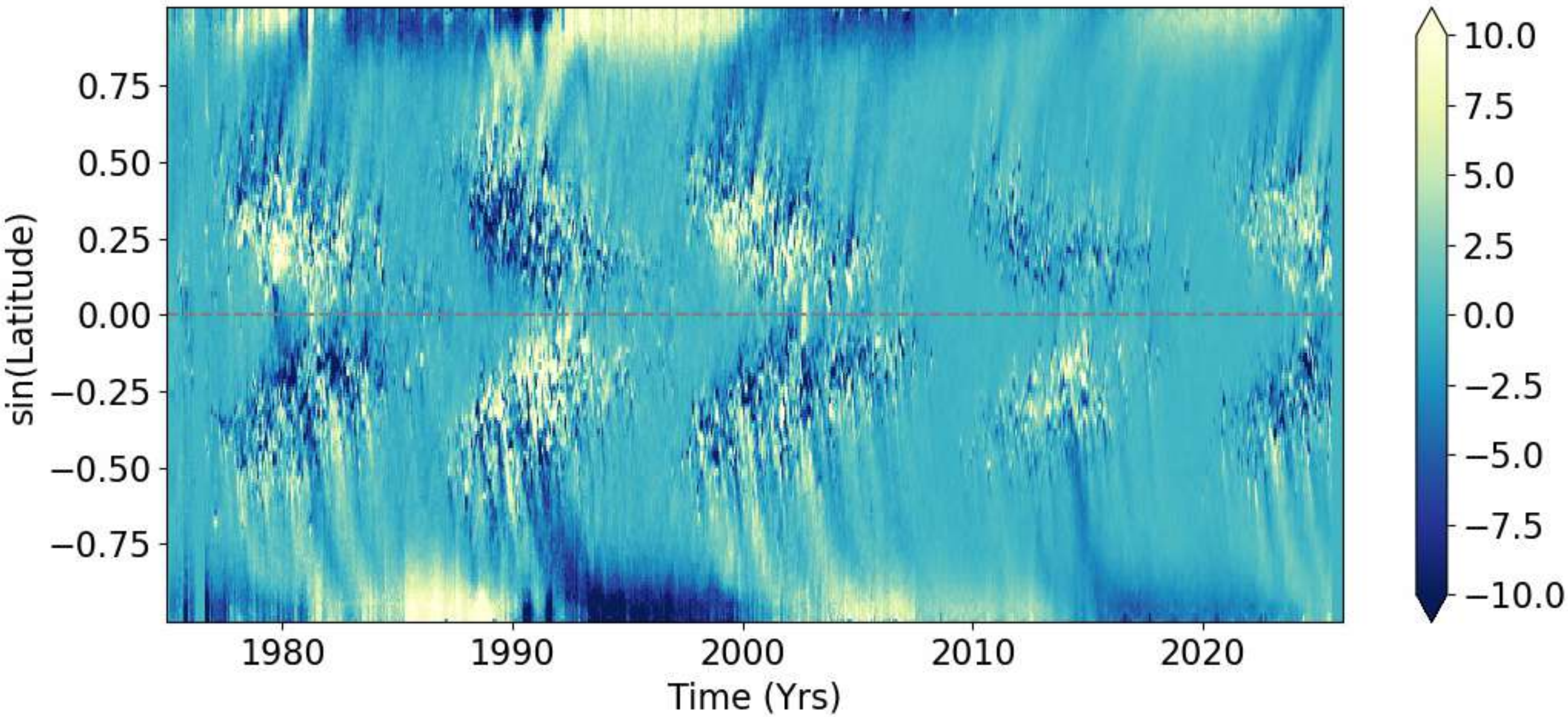


An exemple of cyclic dynamo action



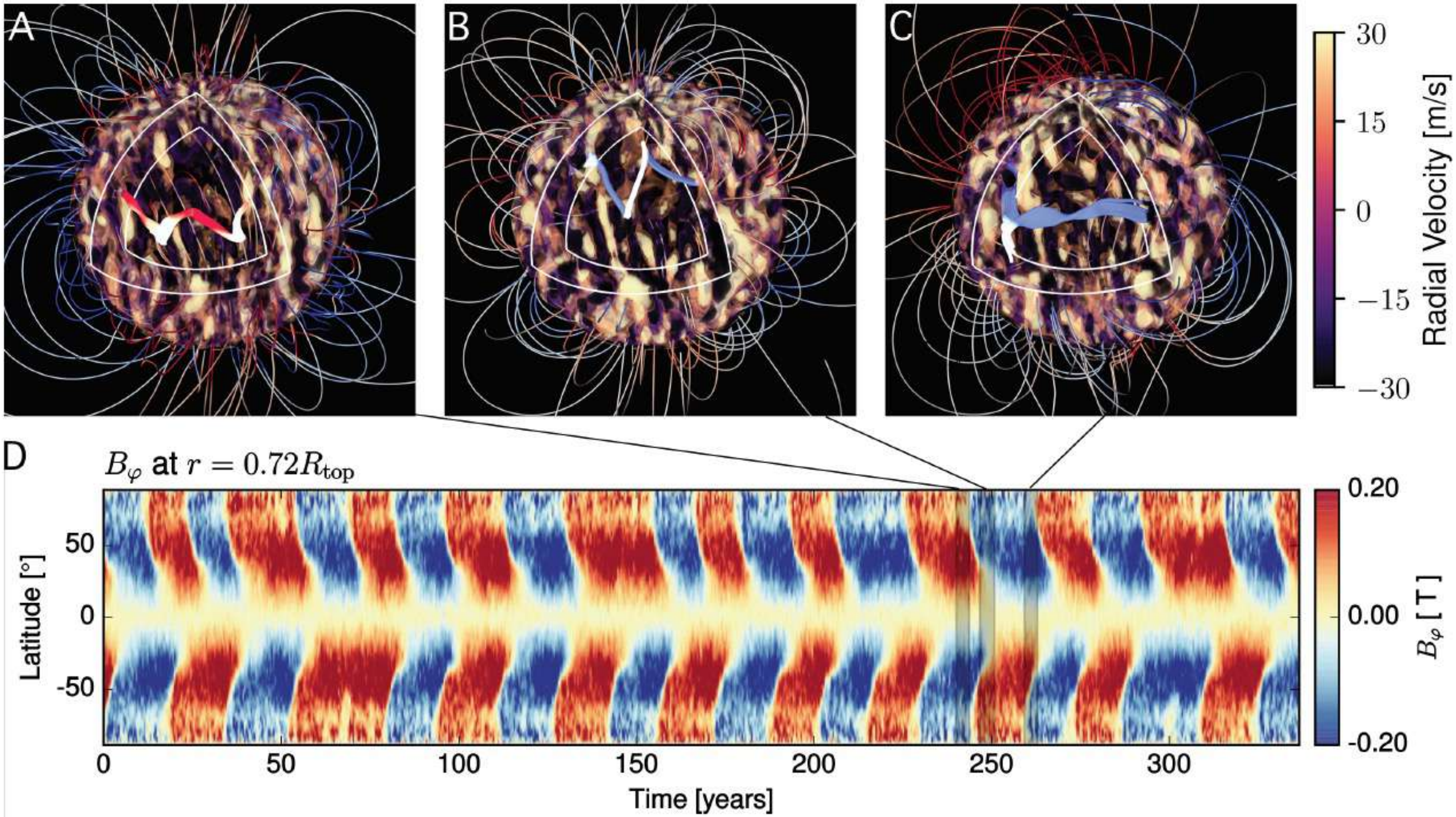
Strugarek et al. 2017, 2018

Solar buttefly Diagram



Butterfly diagram: sunspot migration towards equator during 11 yr cycle

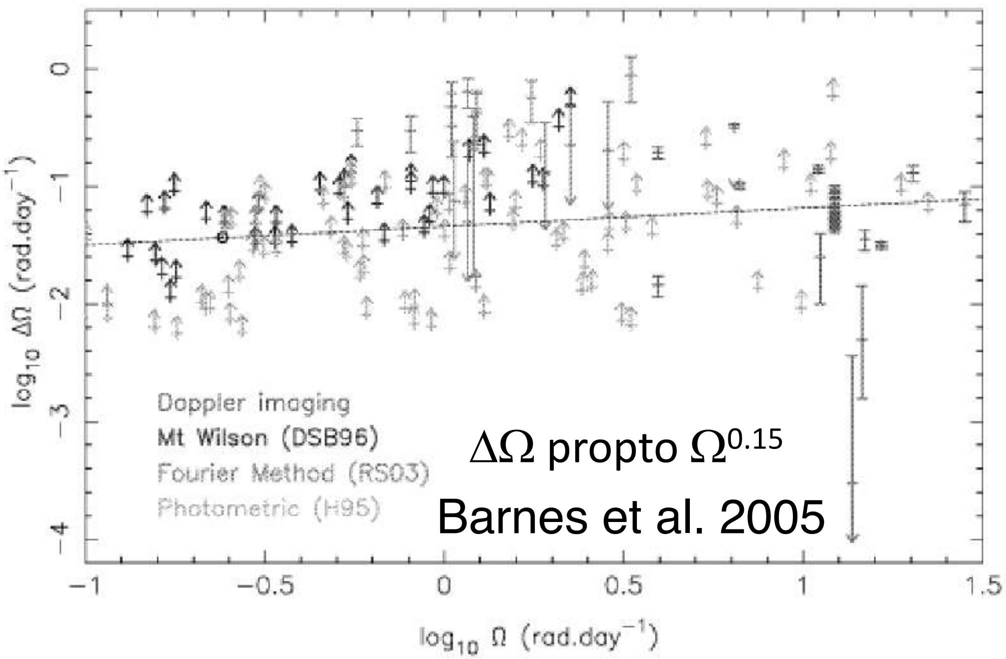
Succesful Cyclic Dynamo with long cycle period



Strugarek et al. 2017, 2018

Trends in Differential Rotation with Ω & Mass (Teff)

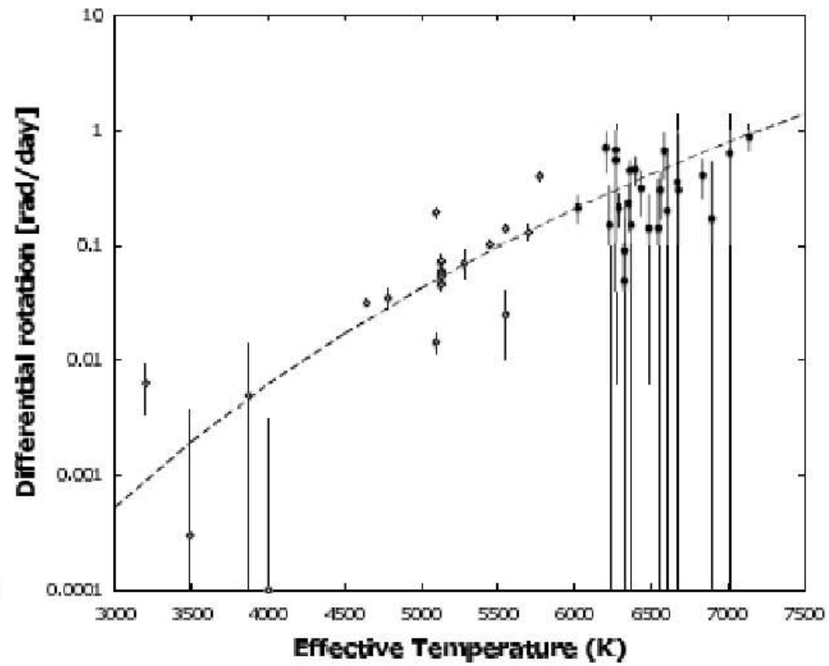
Weak trend with Ω



$\Delta\Omega$ propto $\Omega^{0.15}$

Barnes et al. 2005

$\Delta\Omega$ increases with M_*



Collier-Cameron 2007

In Donahue et al. 1996: $\Delta\Omega$ propto $\Omega^{0.7}$

So currently exponent n in $\Delta\Omega$ propto Ω^{n} ranges [0.15, 0.7]

Confirming these observational scaling is key

Solar Type Stars (late F, G and early K-type)

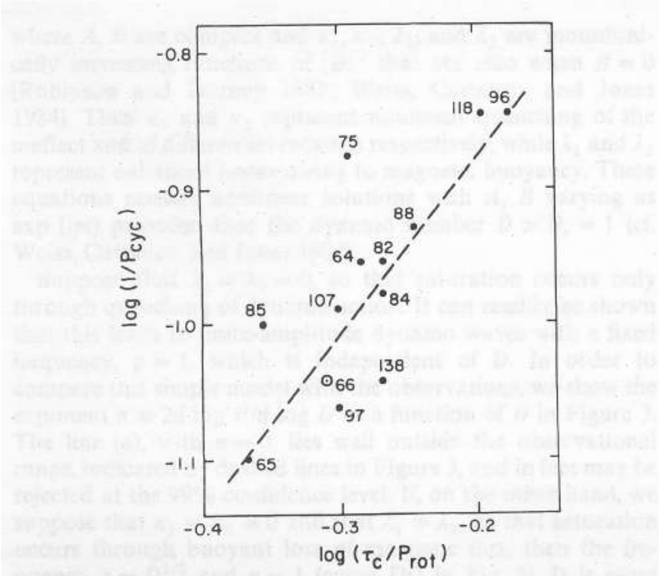
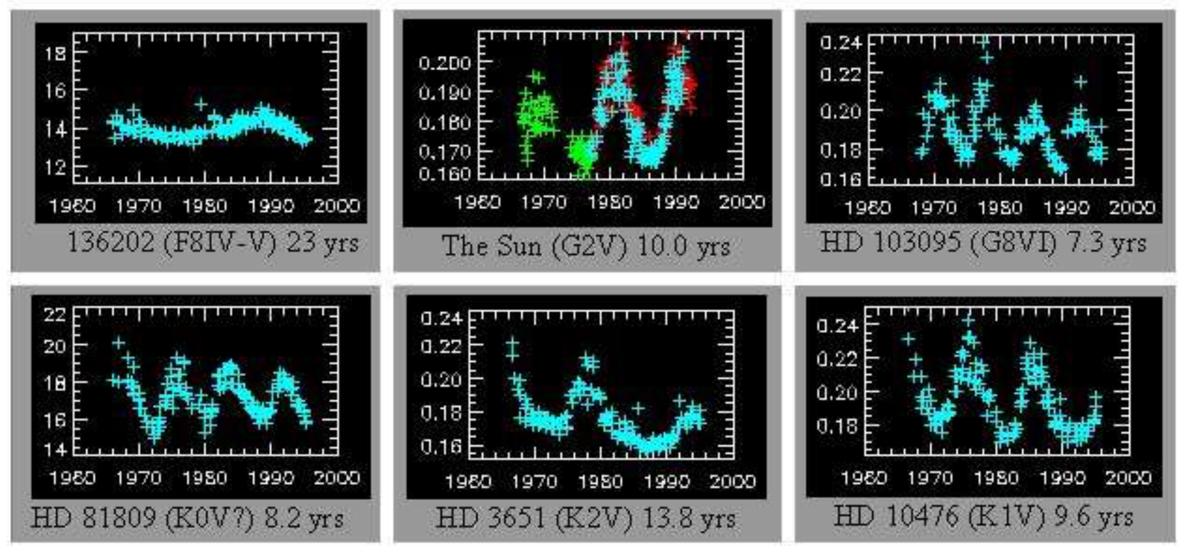


FIG. 2.—Log $(1/P_{cyc})$ vs. log (τ_c/P_{rot}) for the stars of Table 1. The dashed line is a linear least squares fit to the data.

Noyes et al. 1984



In stars activity depends on rotation & convective overturning time via Rossby nb $Ro=P_{rot}/\tau$

$<R'_{HK}> = Ro^{-1}$, $P_{cyc}=P_{rot}^{1.25+/-0.5}$

Wilson 1978

Baliunas et al. 1995

CaII H & K lines , $<R'_{HK}>$

Over 111 stars in HK project (F2-M2):

31 flat or linear signal

29 irregular variables

51 + Sun possess magnetic cycle

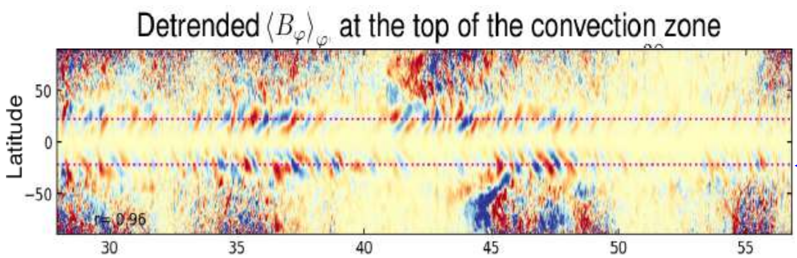
=> Much more coming in Asteroseismology Era (Mike's talk)

Quid of Star-Planet Interaction and cyclic activity?

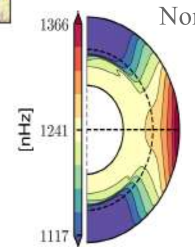
Magnetic cycles of the planet-hosting star τ Bootis

J.-F. Donati,[1★] C. Moutou,[2★] R. Farès,[1★] D. Bohlender,[3★] C. Catala,[4★] M. Deleuil,[2★] E. Shkolnik,[5★] A. C. Cameron,[6★] M. M. Jardine[6★] and G. A. H. Walker[7★]

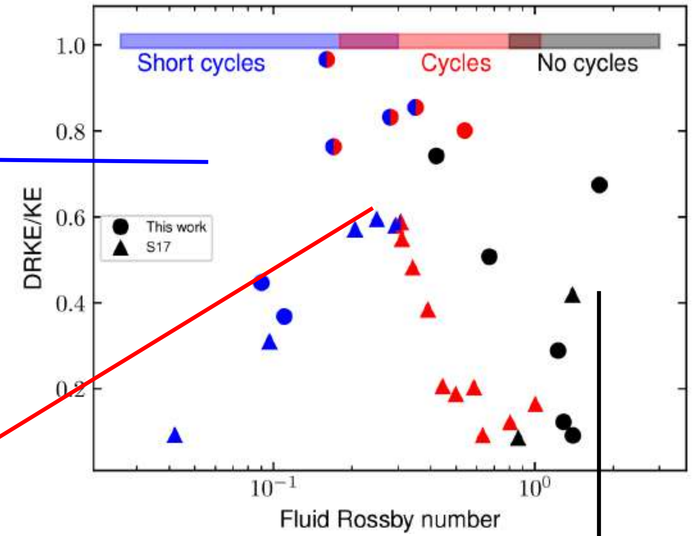
Rotational and magnetic transitions

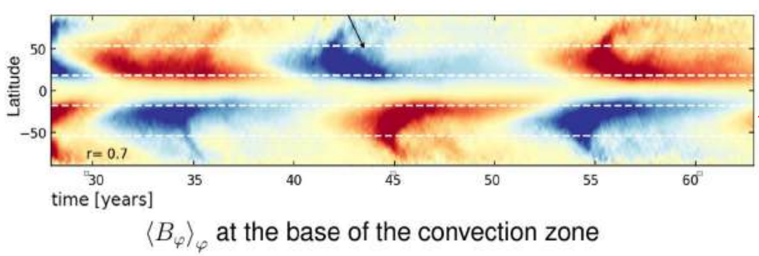


- short cycles (~year) ; **quasi-biennial oscillations ?**
- surface dynamo
- Parker-Yoshimura type (αΩ)



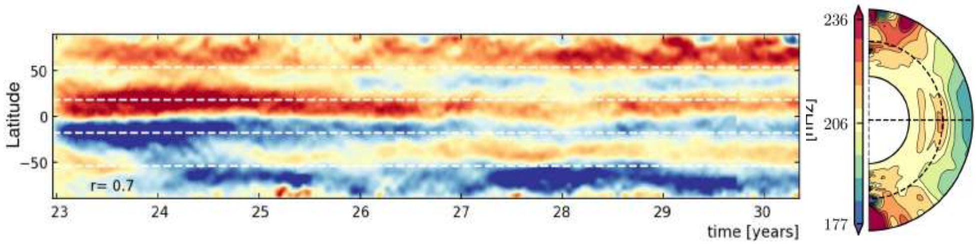
Brun, Strugarek, Noraz+ 22





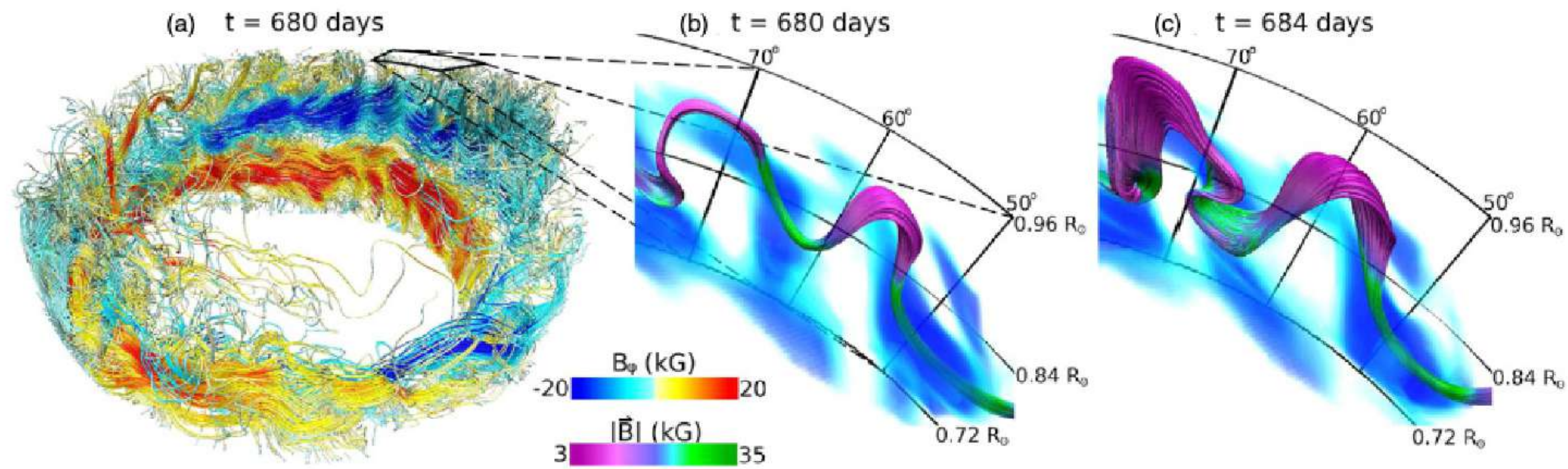
- long cycles (**decadal solar-like**)
- deeper dynamo
- non-linear retroaction

- **Stationnay** dynamo
- hemispherical toroidal field



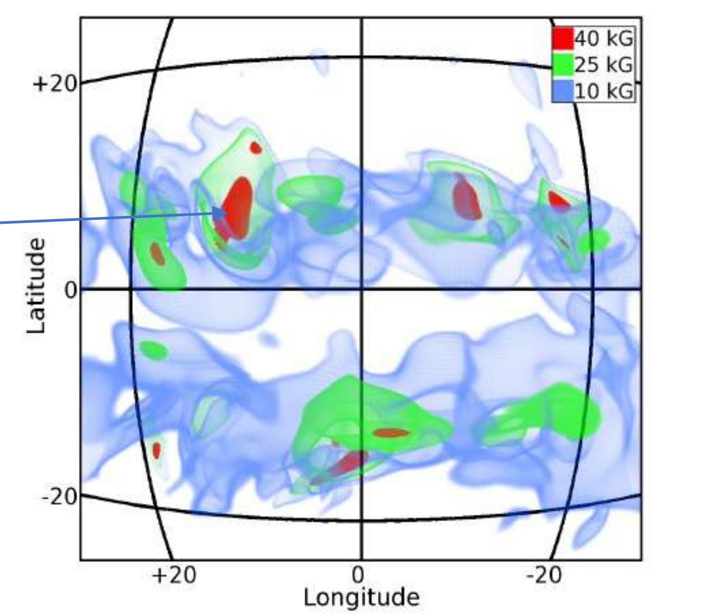
Brun et al. 2017, 2022

Going Beyond the introduction of flux tube:
Self-consistent buoyant Loops generations



We have Omega-loops
but no atmosphere to
See sunspot formation.
What are their role?

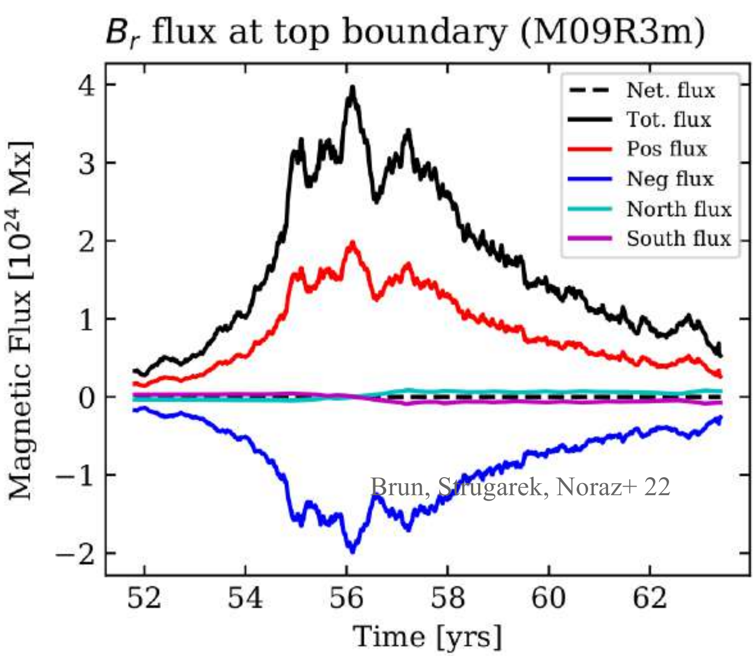
Magnetic seeds



Nelson et al. 2011, 2013a, 2013b,
Strugarek et al. 2017, 2018
Brun et al. 2015, 2022, Brun & Browning 2017
See also Fan & Fang 2014

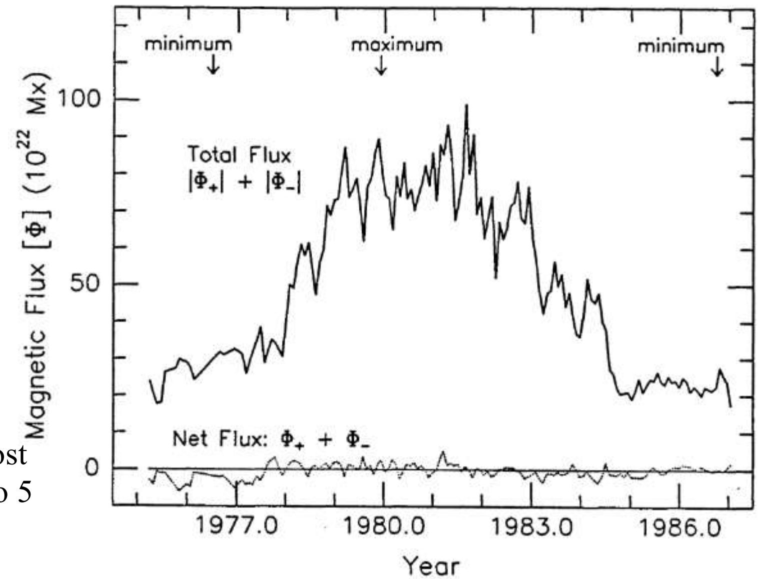
Magnetic Flux in long cyclic case: comparison with observations

Magnetic fluxes **from 10^{24} to 10^{25} Mx**, in good agreement with values observed on the Sun.



$$\Phi = \int_S \boldsymbol{B}\,\mathrm{d}\boldsymbol{S}$$

Modulation reaches almost a factor of 8 (compared to 5 for the Sun).



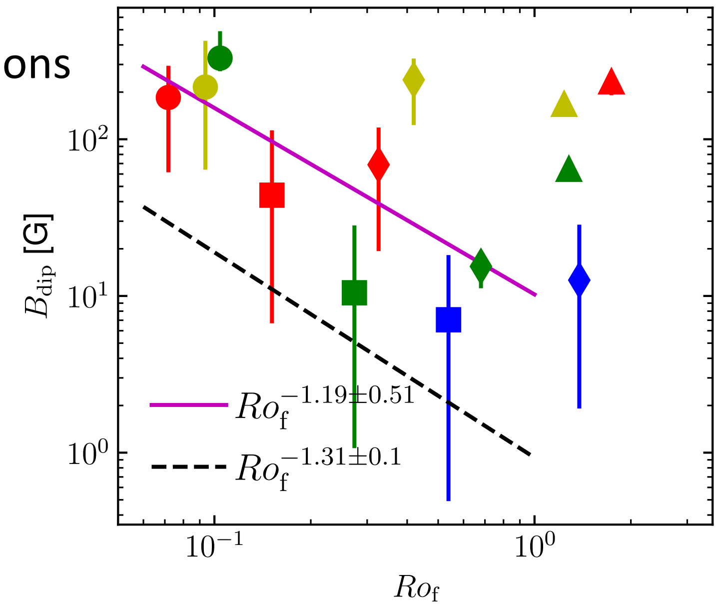
Magnetochronology of Solar-type Stars

=> good qualitative agreement with observations

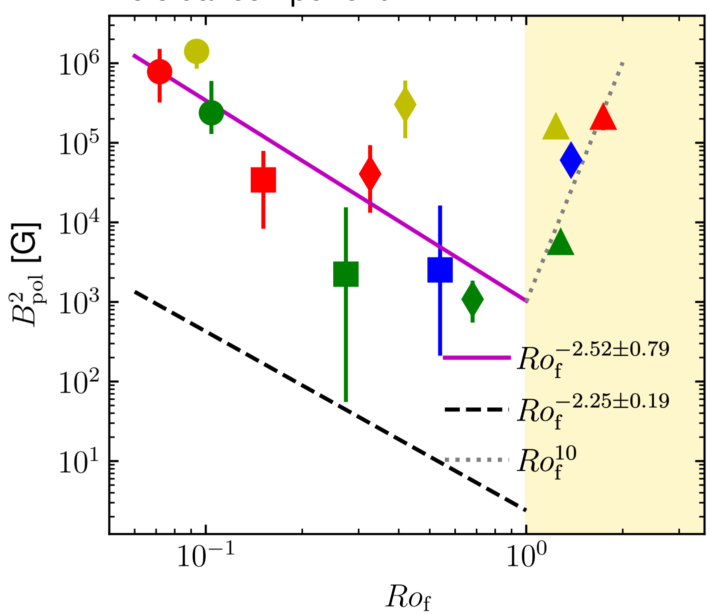
See et al. 2015, 2019
Vidotto et al. 2014

Noraz, Brun et al. 2024, A&A

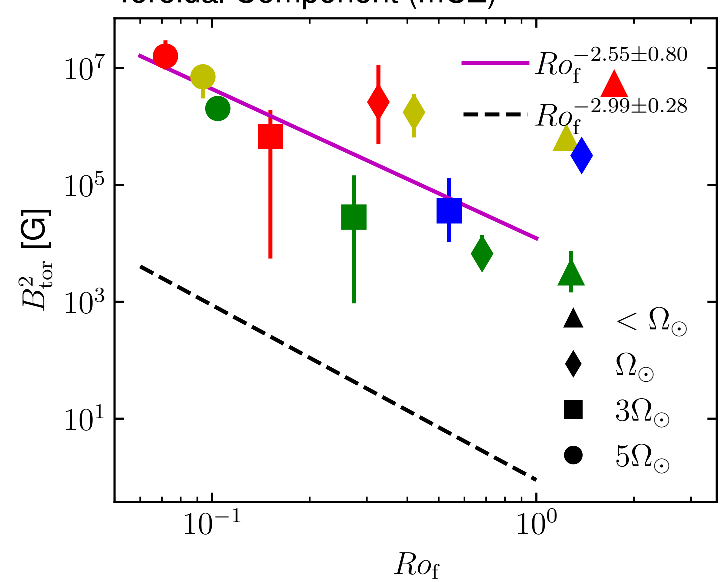
Magnetic Dipole ($\ell = 1$)



Poloidal component



Toroidal Component (mCZ)

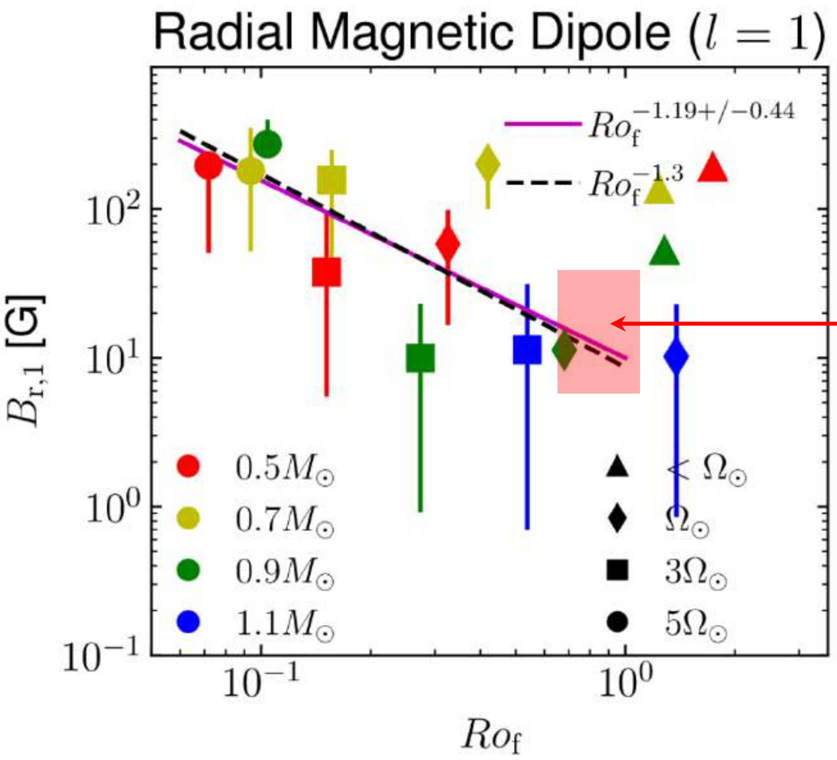


Augustson et al. 2019: $B_{\rm bulk}$ ~ Ro^-0.5

Large scale field does not follow same trends

Recovering Observational Trends

Brun, Strugarek, Noraz+ 22



- The dipole decreases but does not disappear

However, there may be a minimum around the solar Rossby value

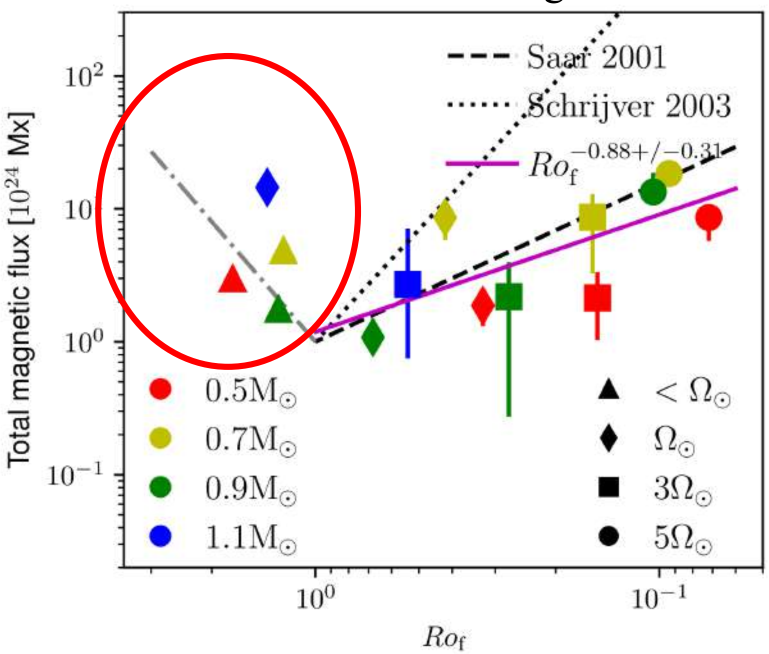
- Can a star be trapped in this regime by a **combination of magnetism and mass loss rate?**

$$\dot{J} \propto \dot{M}\Omega_* \langle r_A \rangle^2$$

Larger global field in slowly rotating stars?

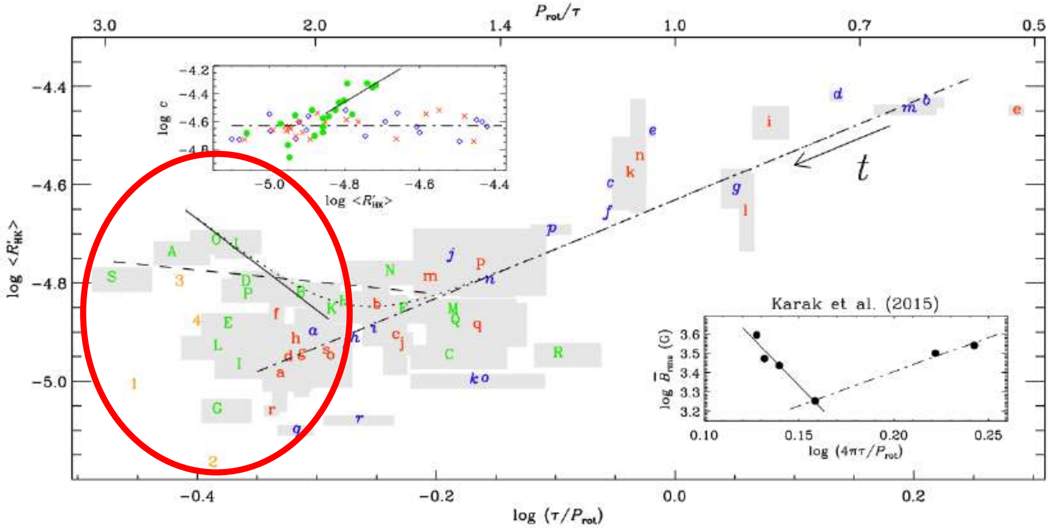
Brun, Strugarek, Noraz+ 22

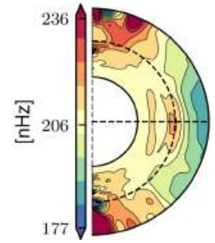
Possible increase of the magnetic flux



Brandenburg & Giampapa 18

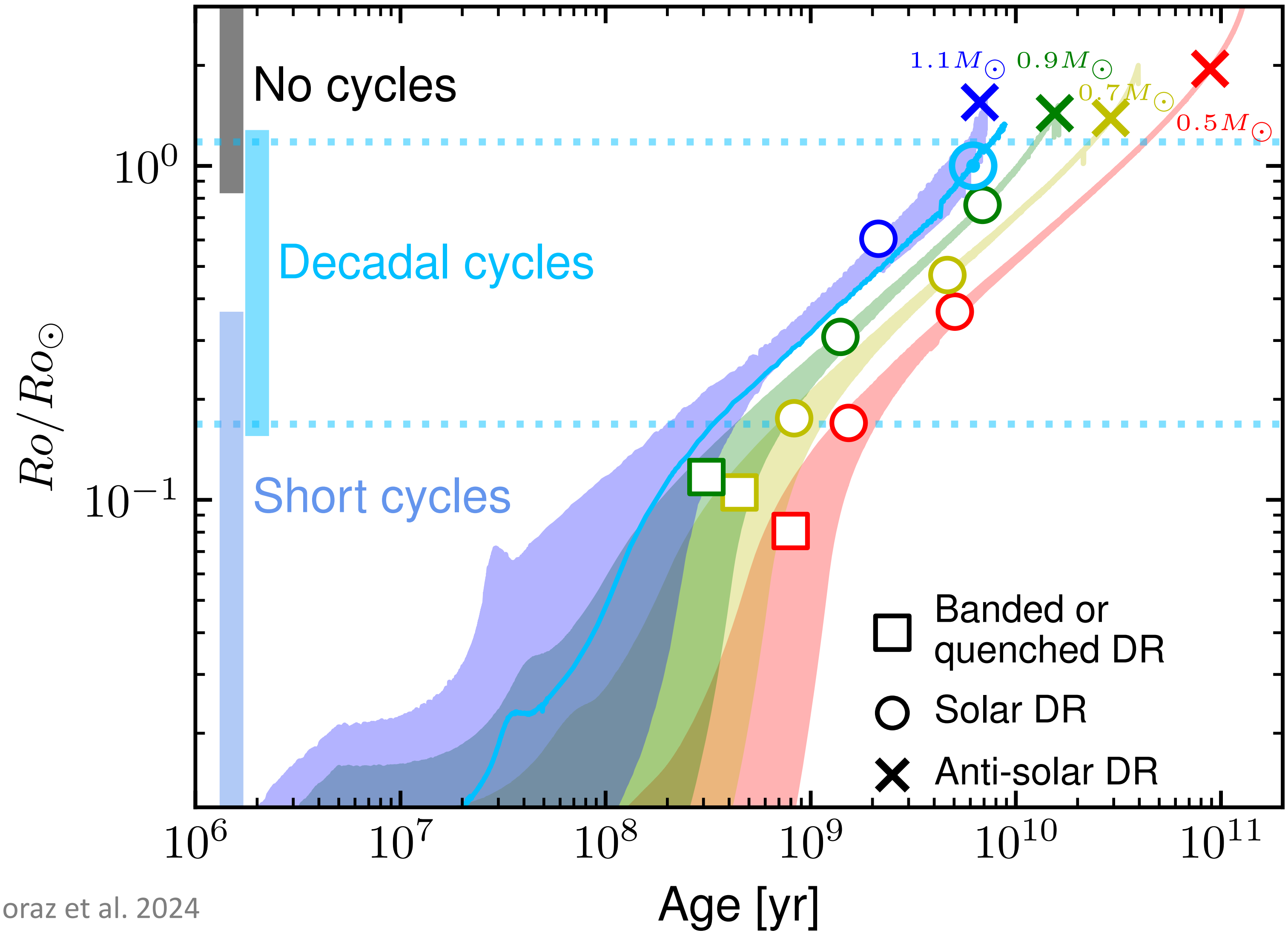
Possible enhancement of the activity





- Need **theoretical** and **observational constraints** to enlighten what occurs in the anti-solar regime

A plausible « Sun in time » story



Noraz et al. 2024

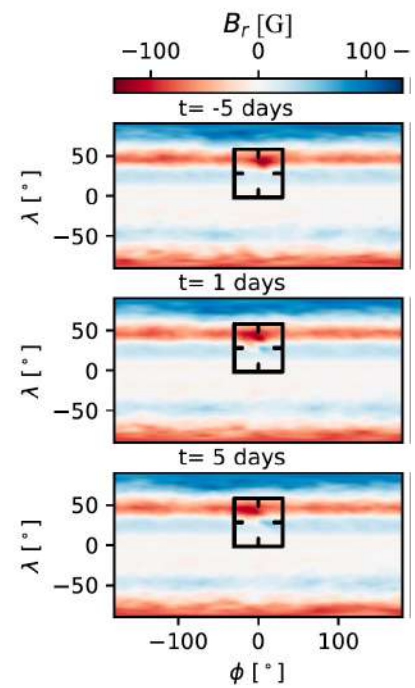
Trends of the stellar dynamo simulation are qualitatively correct,

But the solar case is shifted in parameter space

⇒ Convective conundrum

+ The stellar convective dynamo solutions do not exhibit sunspot/starspots…. Where are they, are they needed?

Note: In Cameron, Schunker, Brun et al. 2025, we have made a first analysis of flux emergence events in such convective dynamo and have found Interesting bipolar events but not strong enough to perturb convection and lead to progenitor sunspot/starspot.



A&A, 701, A277 (2025)
https://doi.org/10.1051/0004-6361/202553844

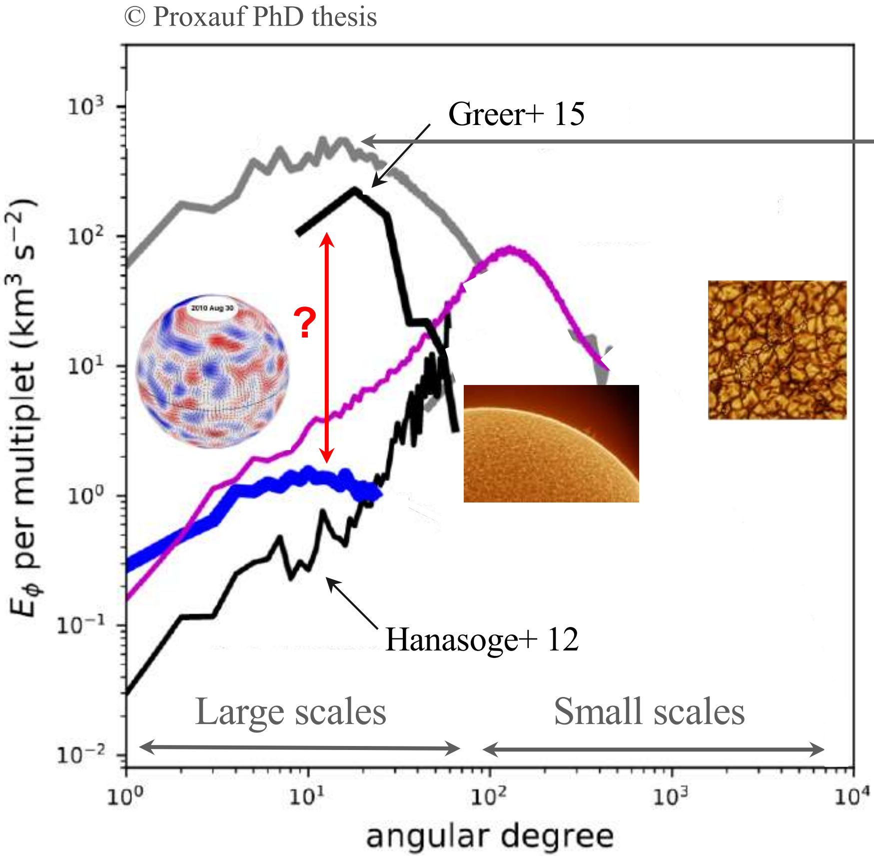
Astronomy & Astrophysics

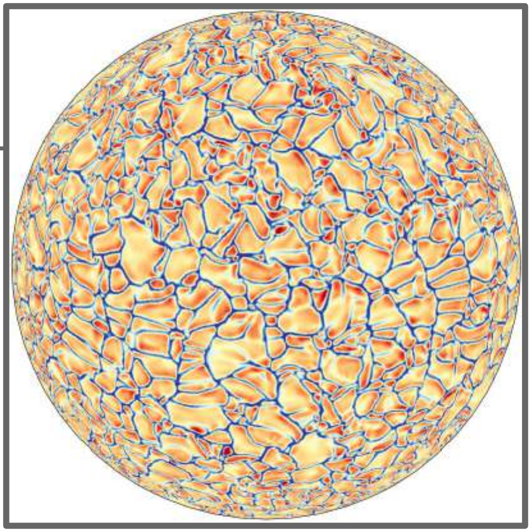
Closing the solar dynamo loop: Poloidal field generated at the surface by plasma flows

R. H. Cameron[1,4,*], H. Schunker[2], A. S. Brun[3], A. Strugarek[3], A. J. Finley[3], W. Roland-Batty[2], A. C. Birch[1], and L. Gizon[1,4]

Convective Conundrum

Solar case is qualitatively correct, but slightly misplaced in parameter space. Effective Rossby too high.



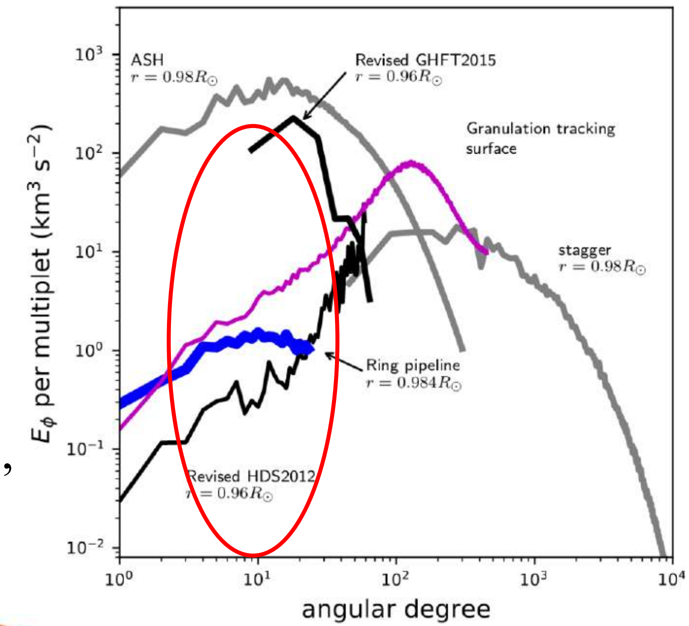


- **Numerical simulations** as a tool to modelize the process → challenge to reach realistic solar parameter regimes
- Actual mismatch between observational results concerning the large scales contribution

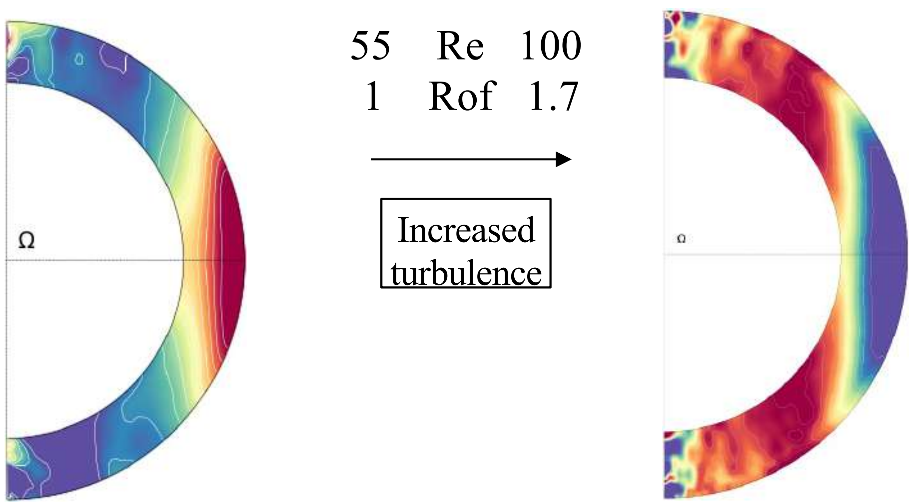
How can solar convection models be calibrated to study stellar convection?

Convective Conundrum

- Current mismatch between **global models** and **helioseismic inversion** regarding giant convective cells

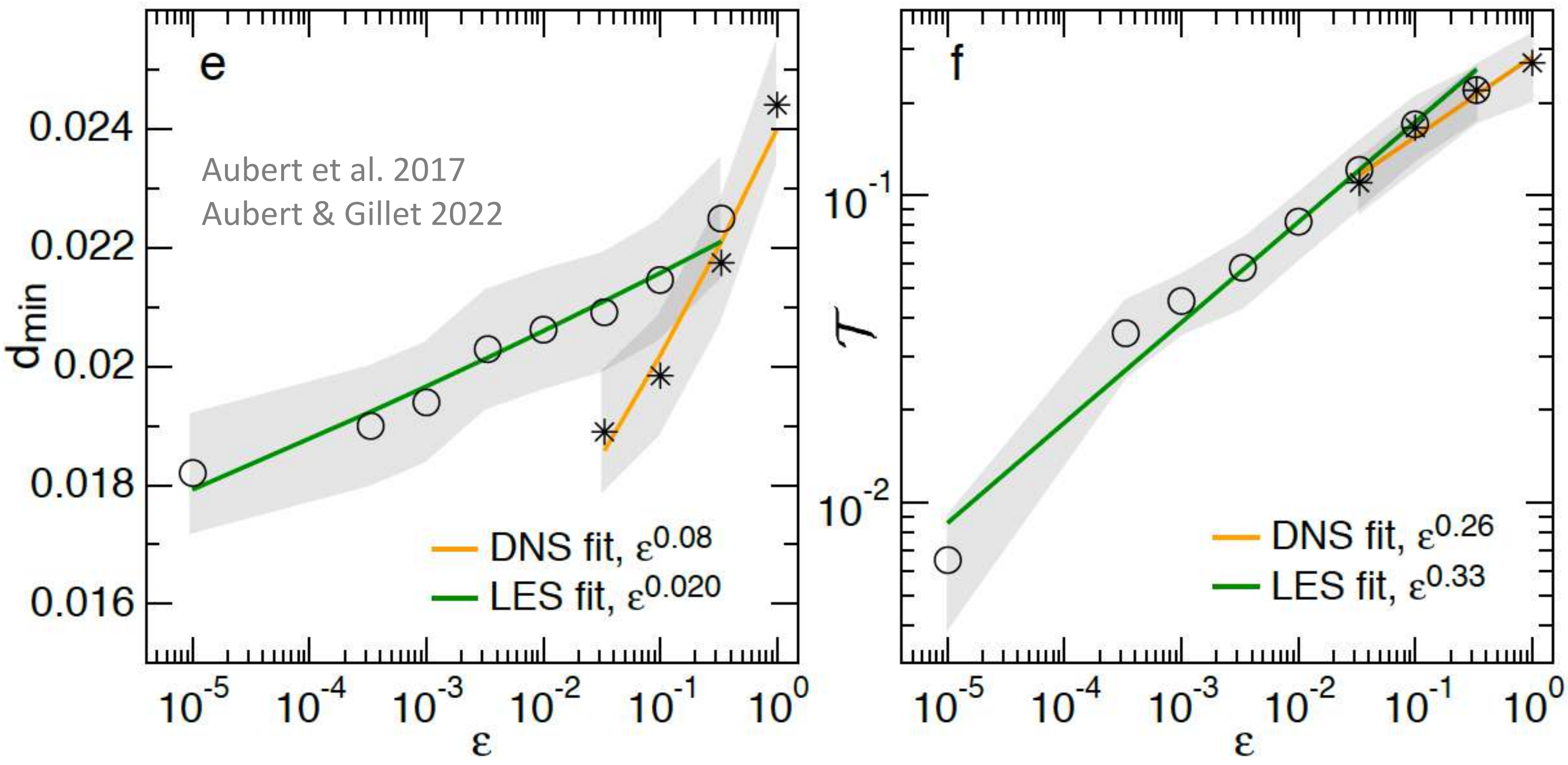


- **Overestimation of the Rossby number** in global models,
  - establishing **anti-solar** DR in turbulent solar models



Path parameter approach: The geodynamo case

Path theory in the Earth convection setup:
The calculations do not represent a systematic sampling of the parameter space, but are rather chosen to follow a path connecting the classical numerical models such as the original CE dynamo (Aubert et al. 2013) to Earth's core conditions ($\varepsilon = 10^{-7}$)



Shown are results from hyperdiffusive solutions along the path (LES or large-eddy-simulations) up to 71 percent of the path ($\varepsilon = 10^{-5}$), and the direct numerical simulations (DNS) up to 21 percent of the path ($\varepsilon = 3.3\ 10^{-2}$). (fixed Rm and Re, decreasing Ekman number).

On Rossby and Nusselt numbers

- Two solutions are commonly used by the community to recover the solar DR:

$$\boldsymbol{Ro} = \frac{\text{Advection}}{\text{Coriolis}} \sim \frac{v}{2\Omega R_*}$$

→ **Reduced Luminosity**
[e.g. Hotta+ 14] → $L_*/18$

→ **Increased Rotation rate**
Emeriau-Viard & Brun 17
Hotta+ 18

- Recent highlight of **magnetic contribution**:
- →significant retroaction of the small-scale dynamo (Hotta+ 22)

- We propose to **control the Nusselt number** *Nu* and to keep L_{sun} & Ω_{sun} ! (Noraz et al. 2025)
  → How much energy does the convection transport?

$$Nu = \frac{\text{Convection + Radiation}}{\text{Radiation}}$$

(see also Kapyla+ 17, 19)

A Nusselt controlled Path
at fixed Rossby Ro nb and increasing turbulence Reynolds Re nb

$\tau_\Omega = 1/2\Omega$
$\tau_u = L/u$
$\tau_\nu = L^2/\nu$

Ro= τ_Ω/τ_u we want that number fixed

Re = τ_ν/τ_u we want that number Big

In today's achievable parameter regime, if you reduce viscosity to increase Re, you get an increase of u and hence a decrease of τ_u and you change Ro! not good => convective conundrum

So we need to control the amplitude of u as we increase Re by lowering the viscosity ν

Noraz, Brun, Strugarek 2025: arXiv:2501.13169 **(ApJ in press)**

A Nusselt controlled Path
at fixed Rossby Ro nb and increasing turbulence Reynolds Re nb

We need to control u .....
but u is mostly controlled by the imposed luminosity: $u \sim L_{conv}^{1/3}$
and in non diffusion free limit also by ν

$$\Rightarrow u \sim L_{conv}^{1/3} \nu^{-\alpha}$$

($\alpha \sim 0.2$ – exact value depends on stratification N_ρ)

So in order to compensate for ν, one needs to adapt L_{conv}

One way is to control the Nusselt nb: $Nu = (L_{conv} + L_{diff})/L_{diff}$

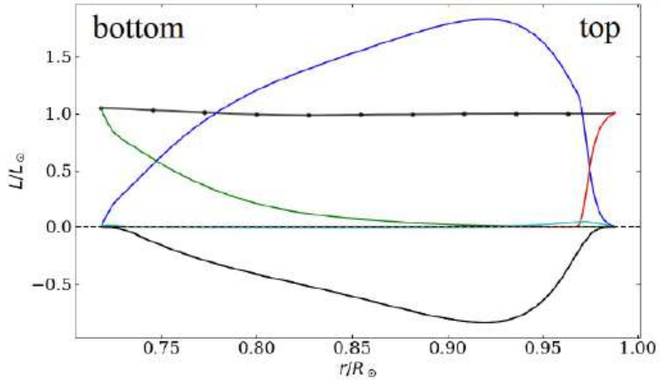
We will follow that numerical path as a fluid mechanics experiment

$L_{conv} = \varepsilon L_{sun}$, $\tau_\nu = \varepsilon^{-\beta} \tau_{\nu 0}$, $\tau_u = \tau_{u0}$, $\tau_\Omega = \tau_{\Omega 0}$, $R_e = \varepsilon^{-\beta} R_{e0}$, $L_{diff} = (1-\varepsilon) L_{sun}$

a priori $\beta = 3\alpha$

$$\tau_\Omega = 1/2\Omega;\ \tau_u = L/u;\ \tau_\nu = L^2/\nu$$

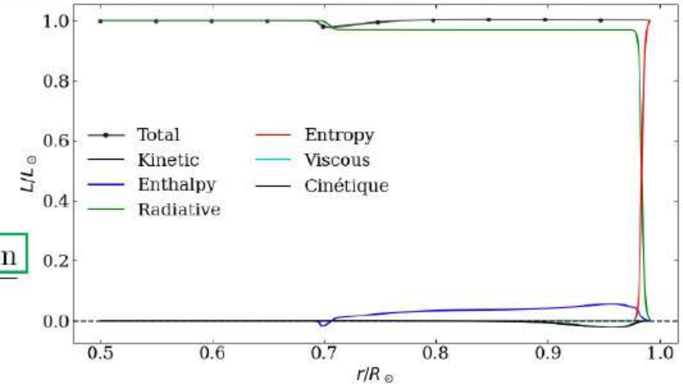
Nusselt Controlled Experiment: Re~200+

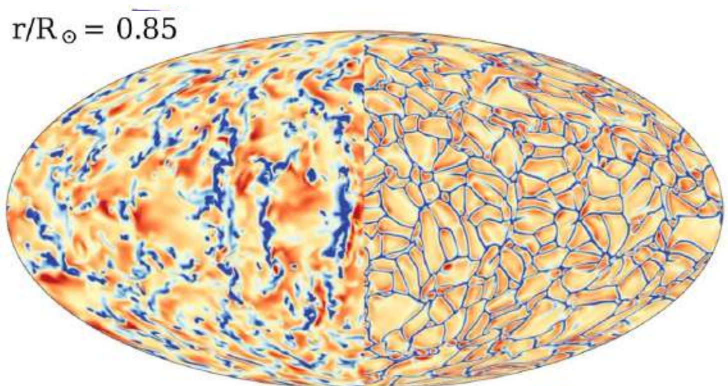


Noraz+22 (PhD)

205	Re	270
2.53	Ro	0.9
26	Nu	1.04

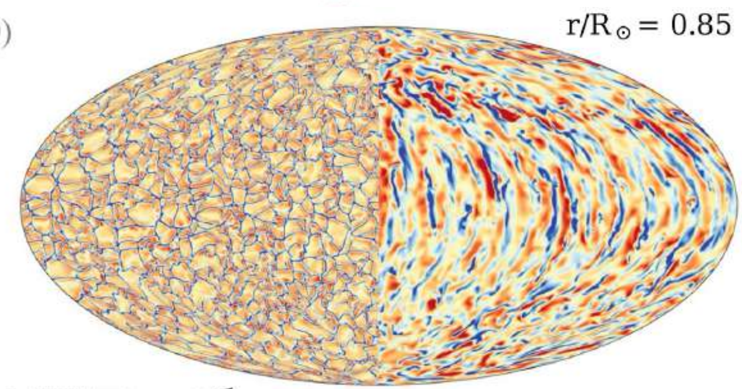
$$Nu = \frac{\text{Convection} - \text{Radiation}}{\text{Radiation}}$$

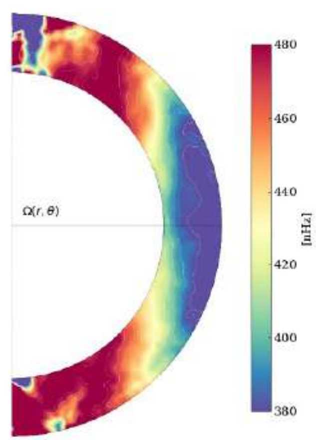


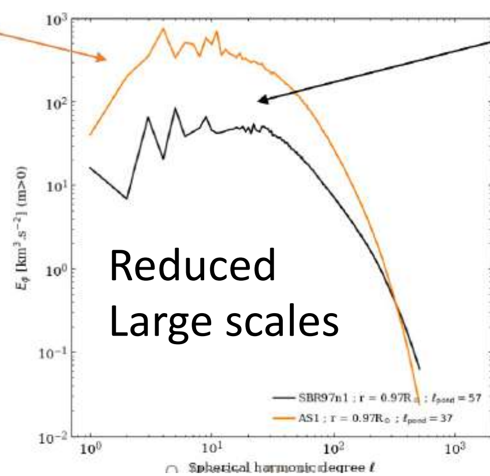


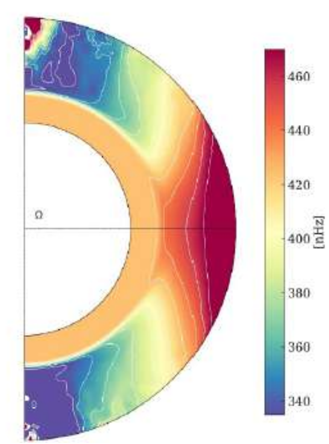
Noraz+22 (PhD)

$r/R_\odot = 0.99$

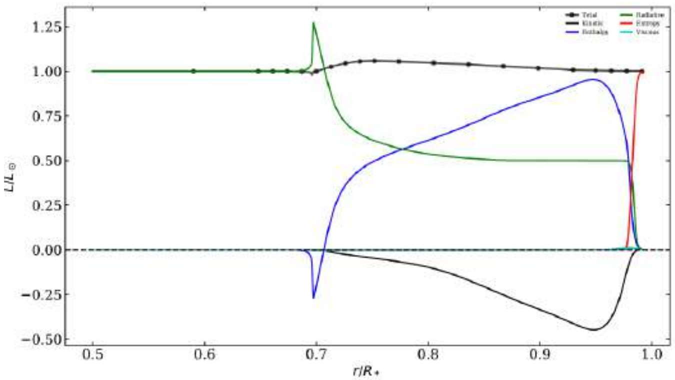






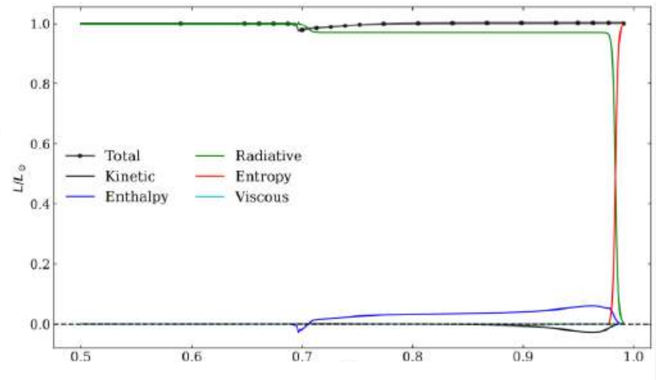


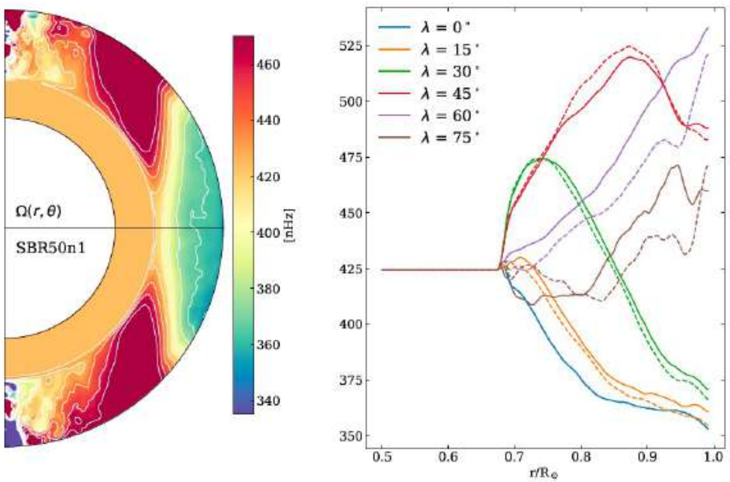
Higher Reynolds Number cases Re ~800+

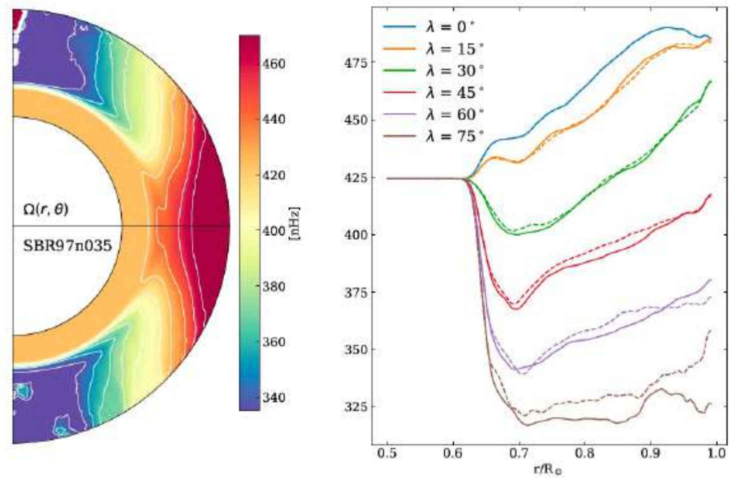


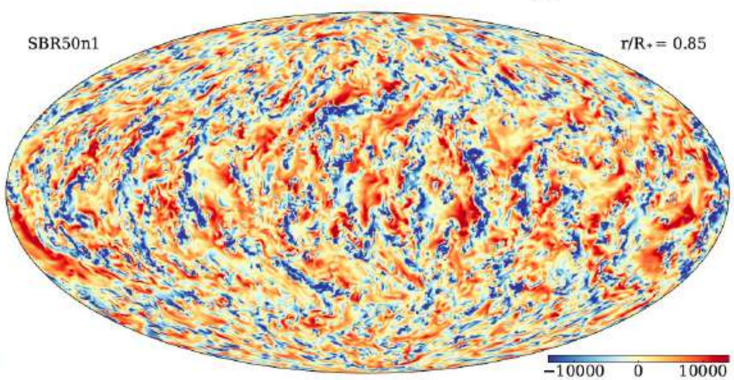
Noraz+22 (PhD)

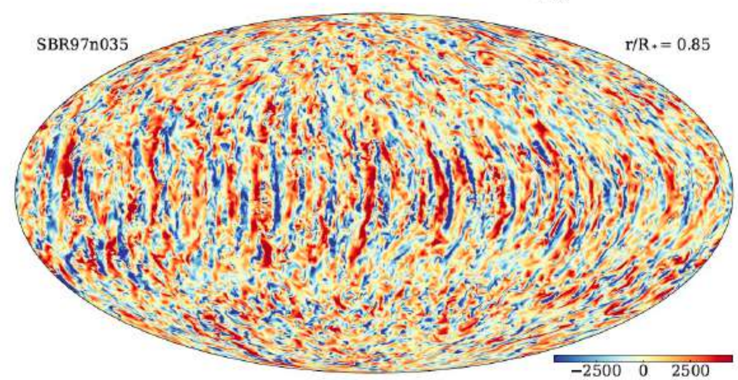
860	Re	811
4	Ro	1.49
2.45	Nu	1.04





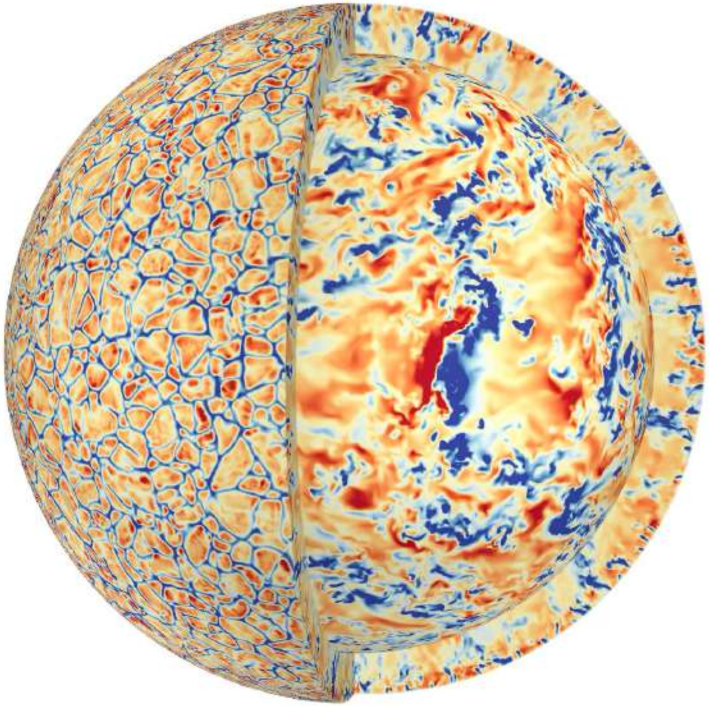




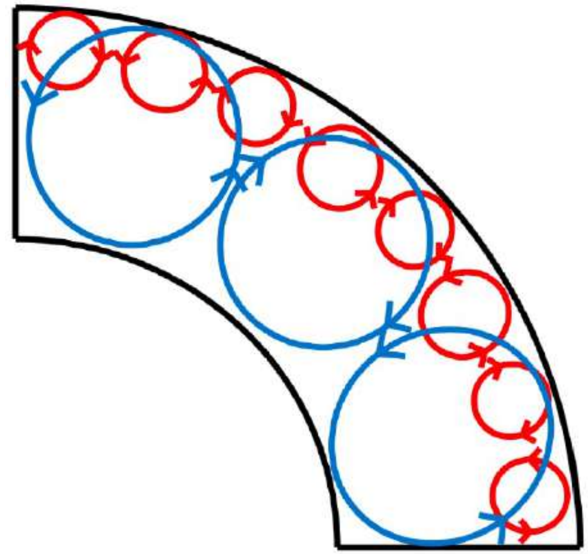


Noraz, Brun, Strugarek 2025, ApJ

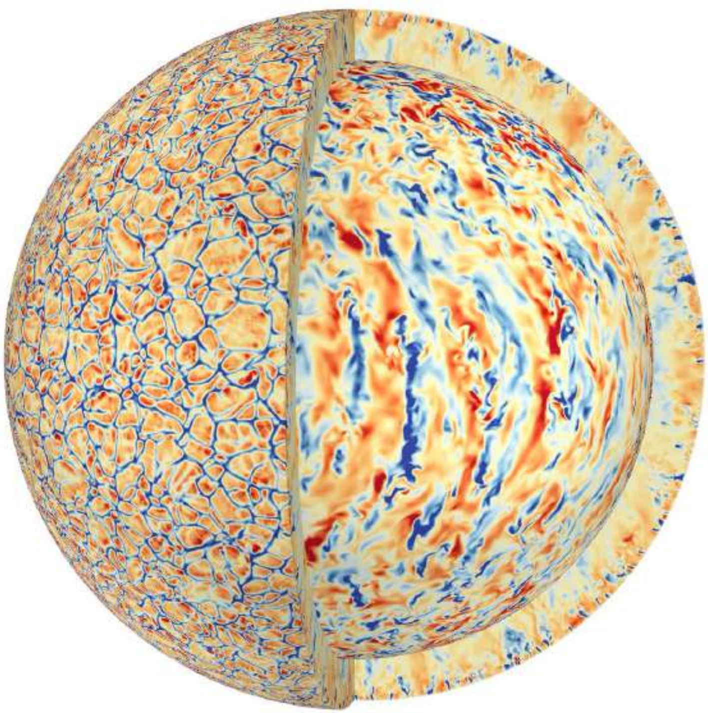
Convection Dynamics



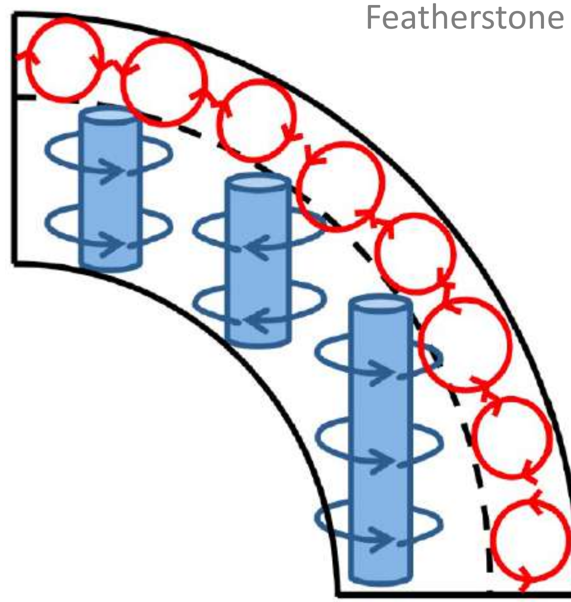
Anti-
Solar



Featherstone & Hindman 2016

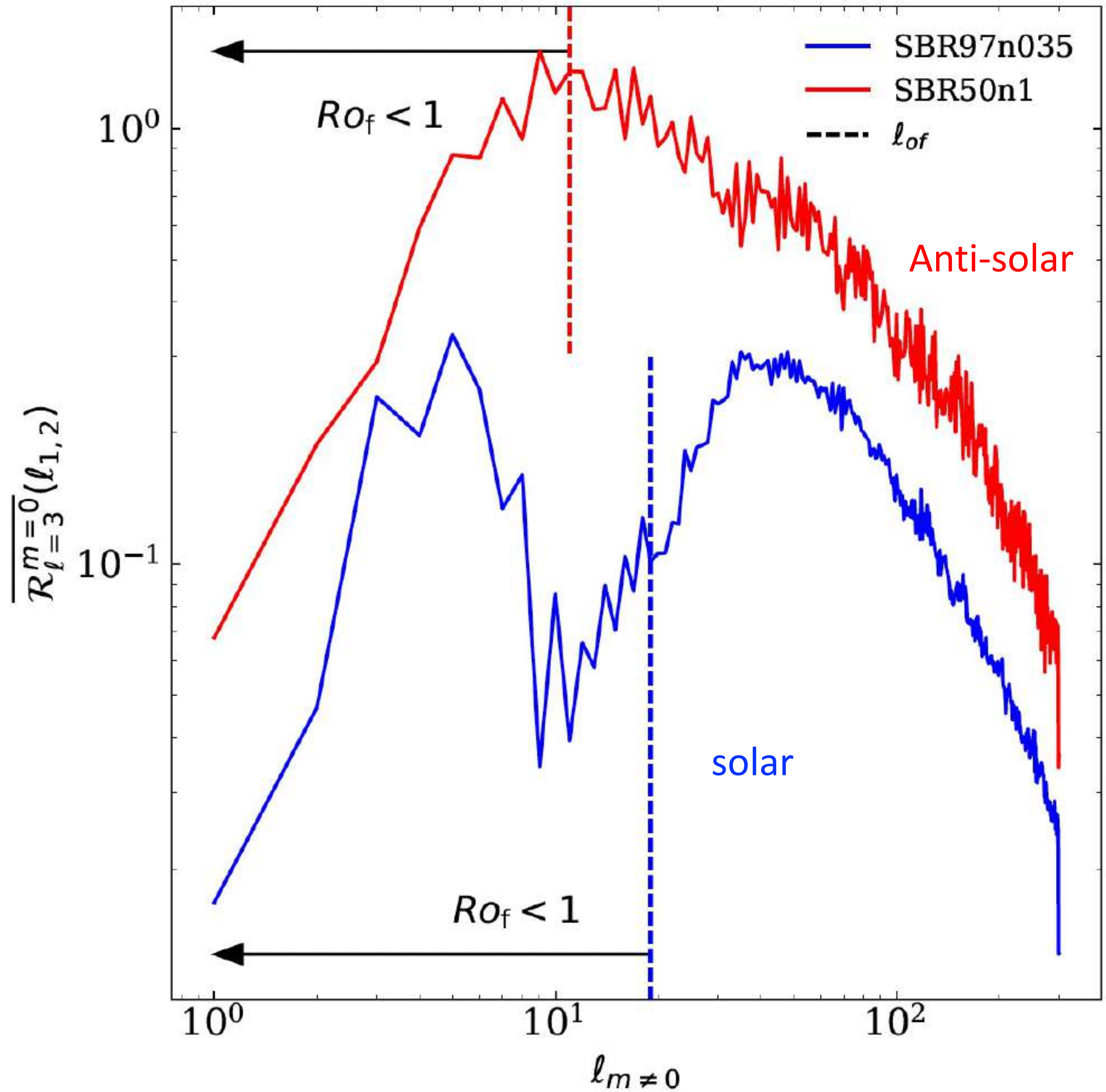


Solar



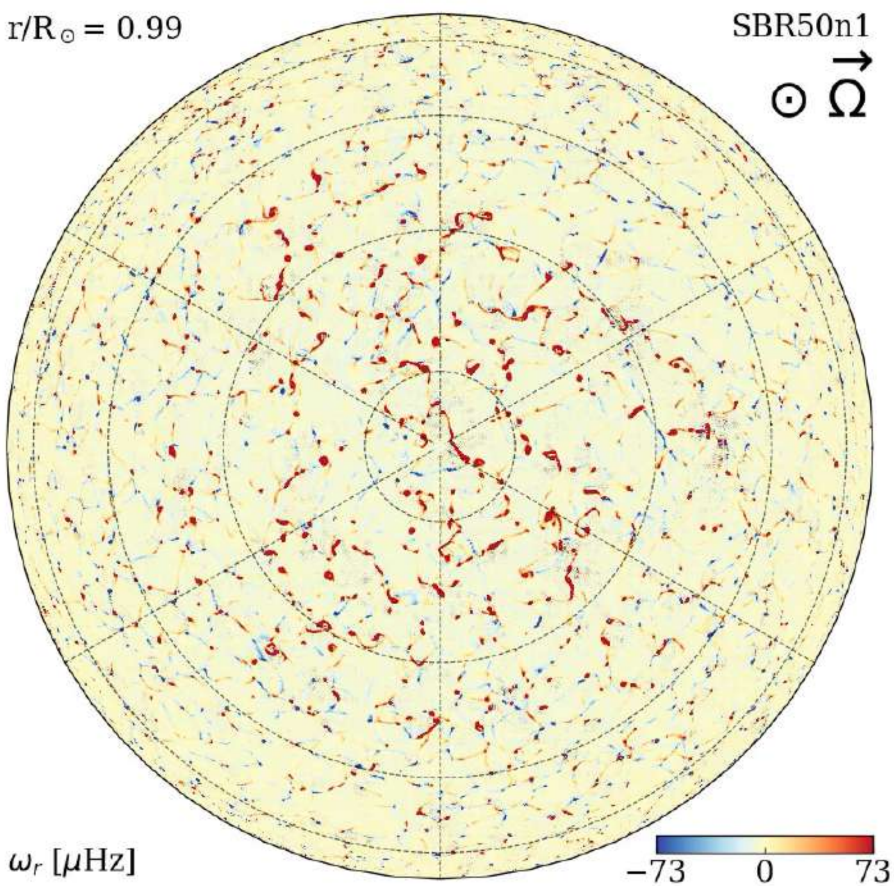
Noraz et al. 2025, ApJ. **(arXiv:2501.13169)**

Angular momentum spectral transfers via Reynolds stresses

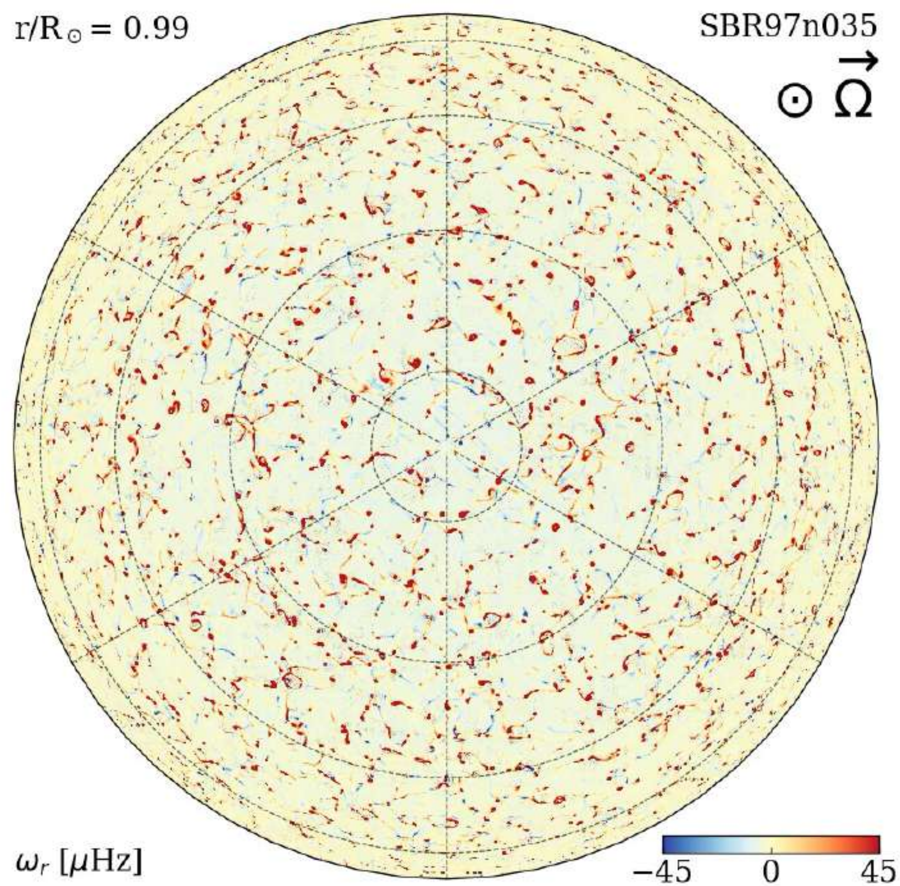


Polar View

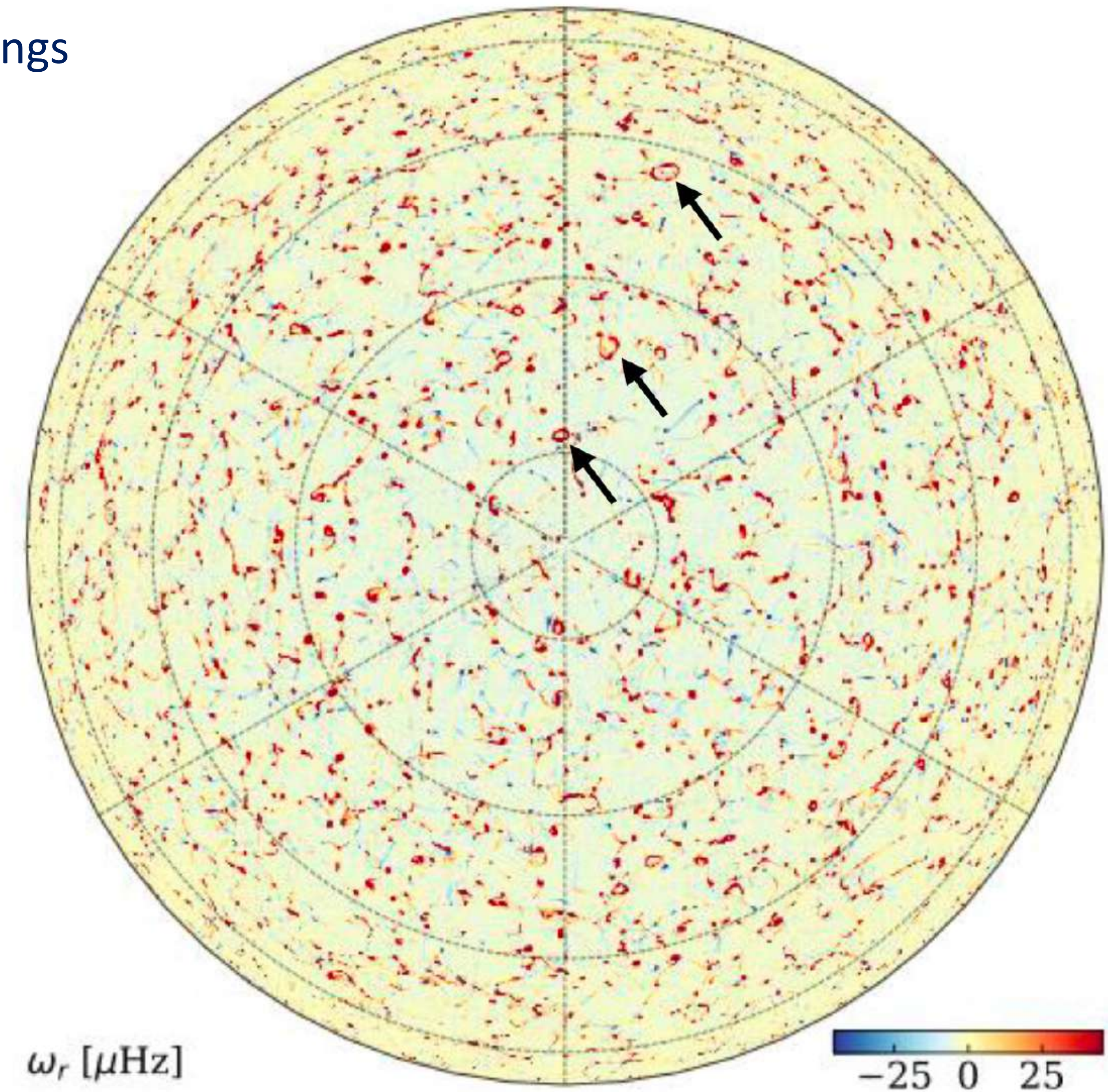
Anti-Solar



Solar

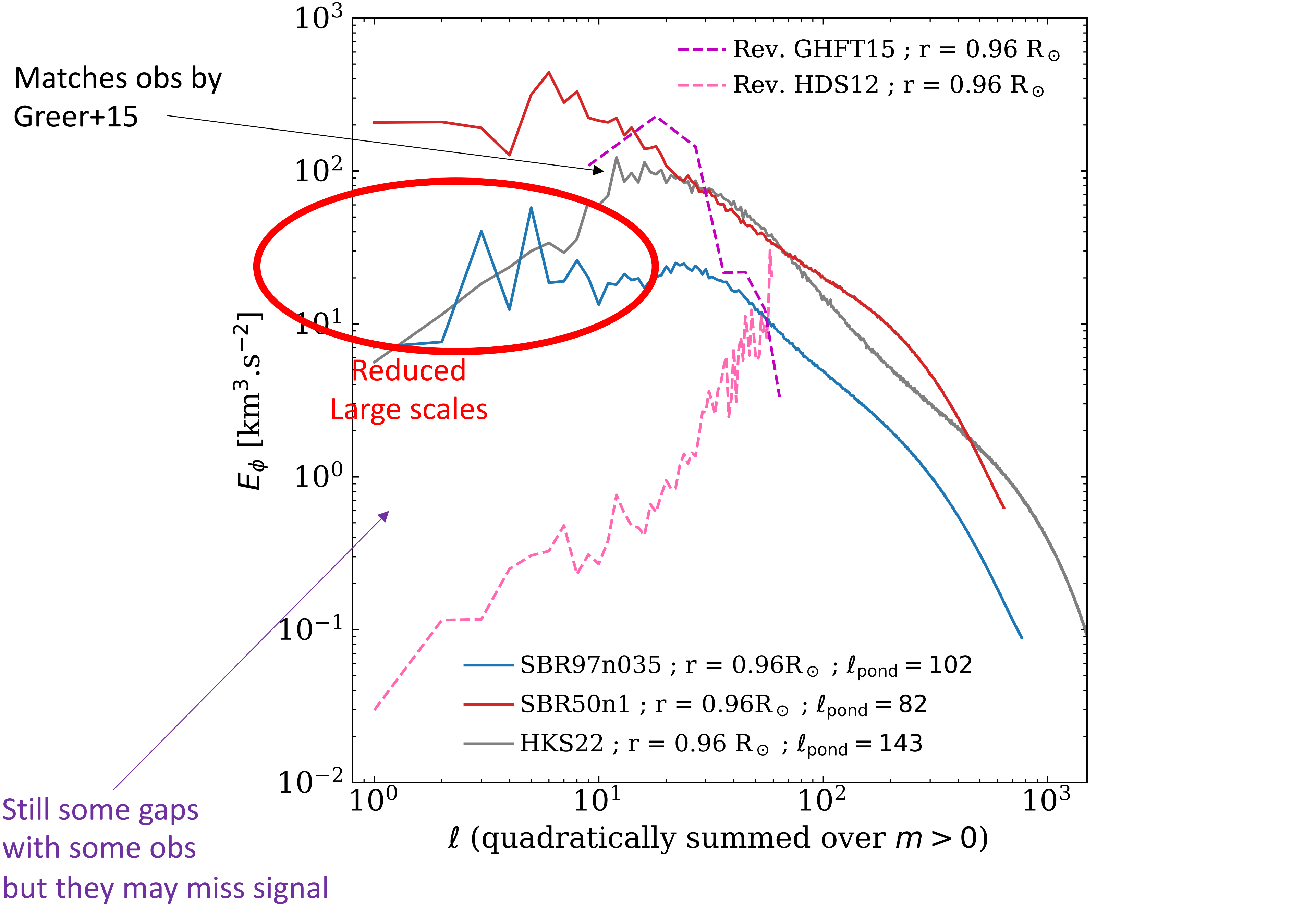


Polar Rings



Confronting simulations to observational (SDO) constraints

- Spectra
- m=1 Rossby mode
- Adiabaticity



Matches obs by
Greer+15
Rev. GHFT15 ; r = 0.96 R$_\odot$
Rev. HDS12 ; r = 0.96 R$_\odot$
Reduced
Large scales
SBR97n035 ; r = 0.96R$_\odot$; $\ell_{pond} = 102$
SBR50n1 ; r = 0.96R$_\odot$; $\ell_{pond} = 82$
HKS22 ; r = 0.96 R$_\odot$; $\ell_{pond} = 143$
E_ϕ [km^3.s^{-2}]
ℓ (quadratically summed over $m > 0$)
Still some gaps
with some obs
but they may miss signal

Inertial Waves in the Sun

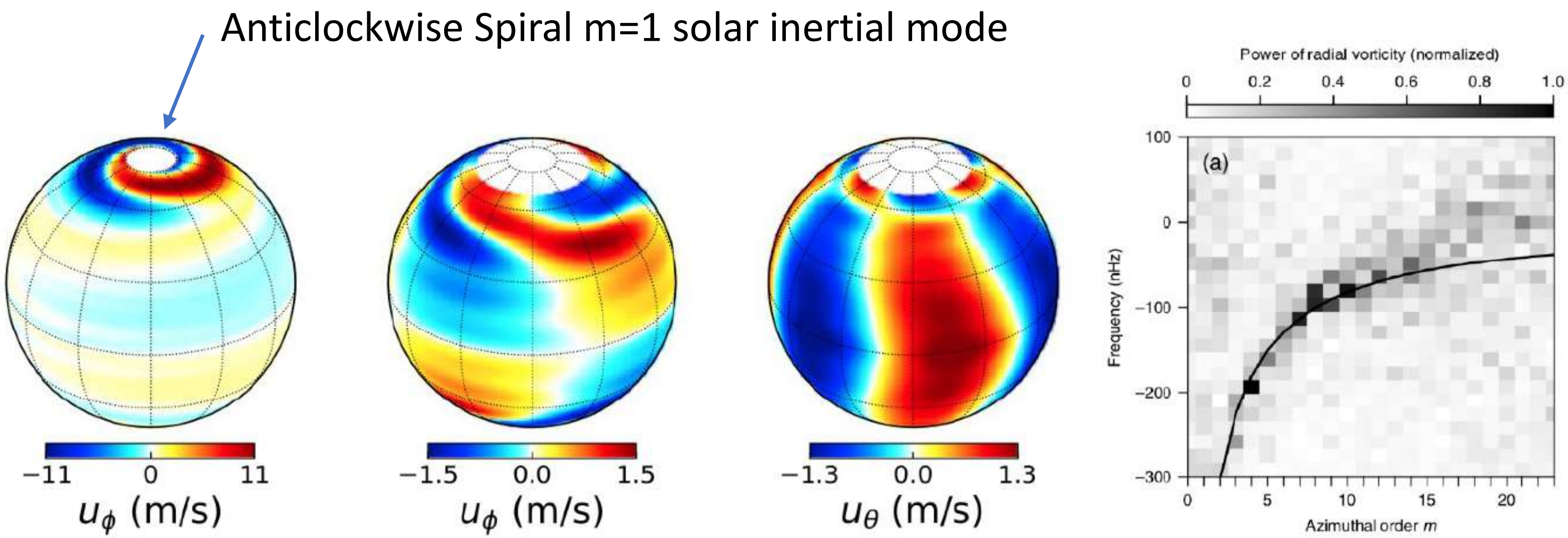
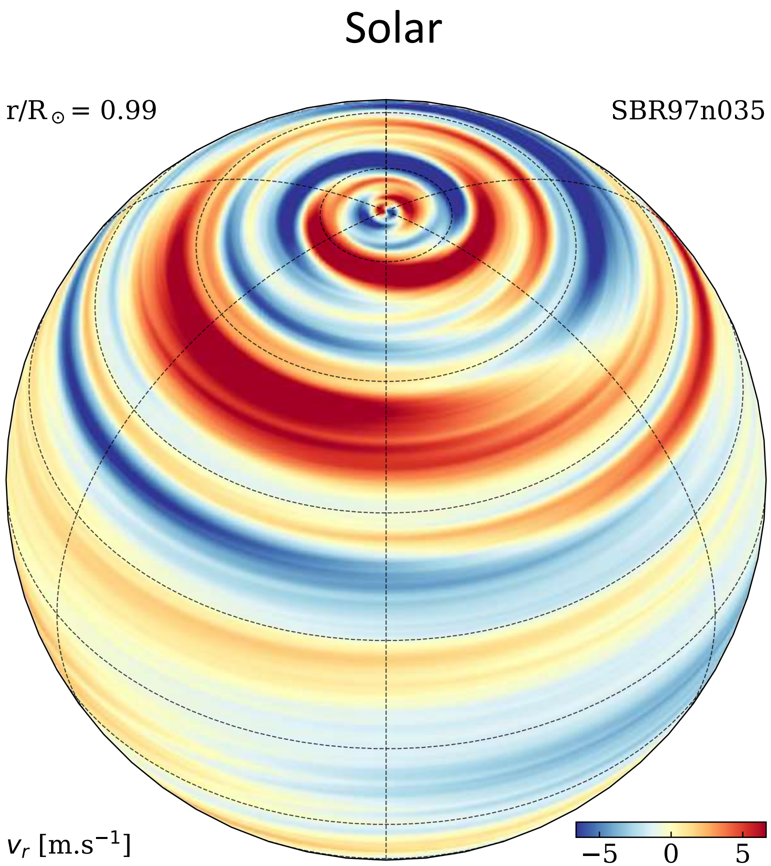
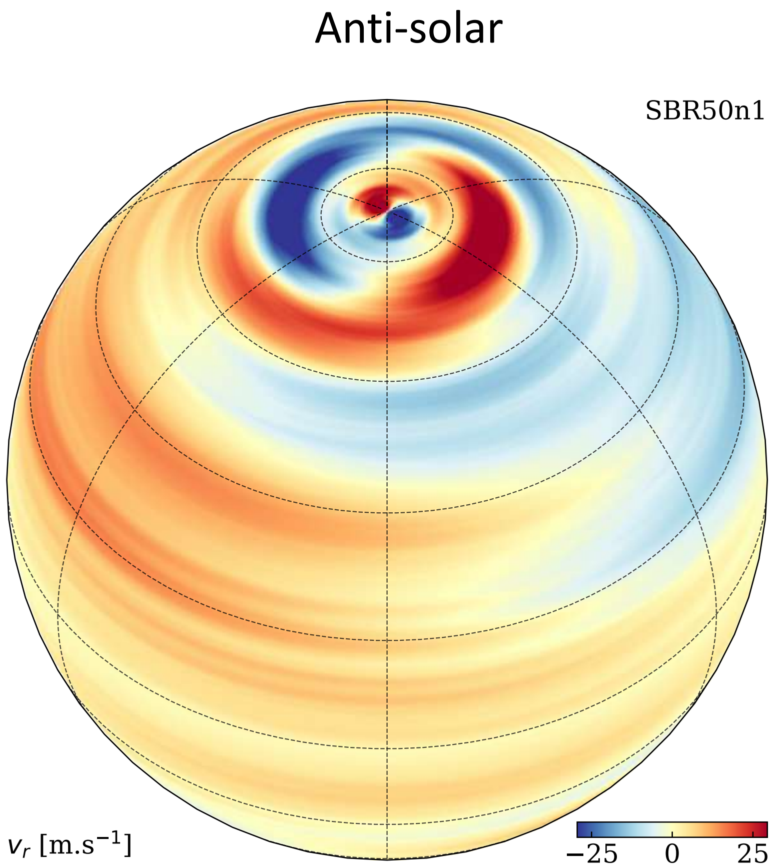


Figure 2.32 – From left to 2nd panel to the right we show: the m = 1 high-latitude spiral mode at -86 nHz, the m = 2 mid-latitude mode at -73 nHz (Gizon et al., 2021), the m = 3 equatorial (sectoral) Rossby mode at -269 nHz (Löptien et al., 2018a), adapted from (Gizon et al., 2024). Rightmost panel: Power spectrum of radial vorticity from local tracking of granulation, with the sectoral ($\ell = m$) Rossby mode dispersion relation ($\omega = -2\Omega_\odot/(m+1)$) overplotted in black (Löptien et al., 2018a).

m=1 Rossby mode

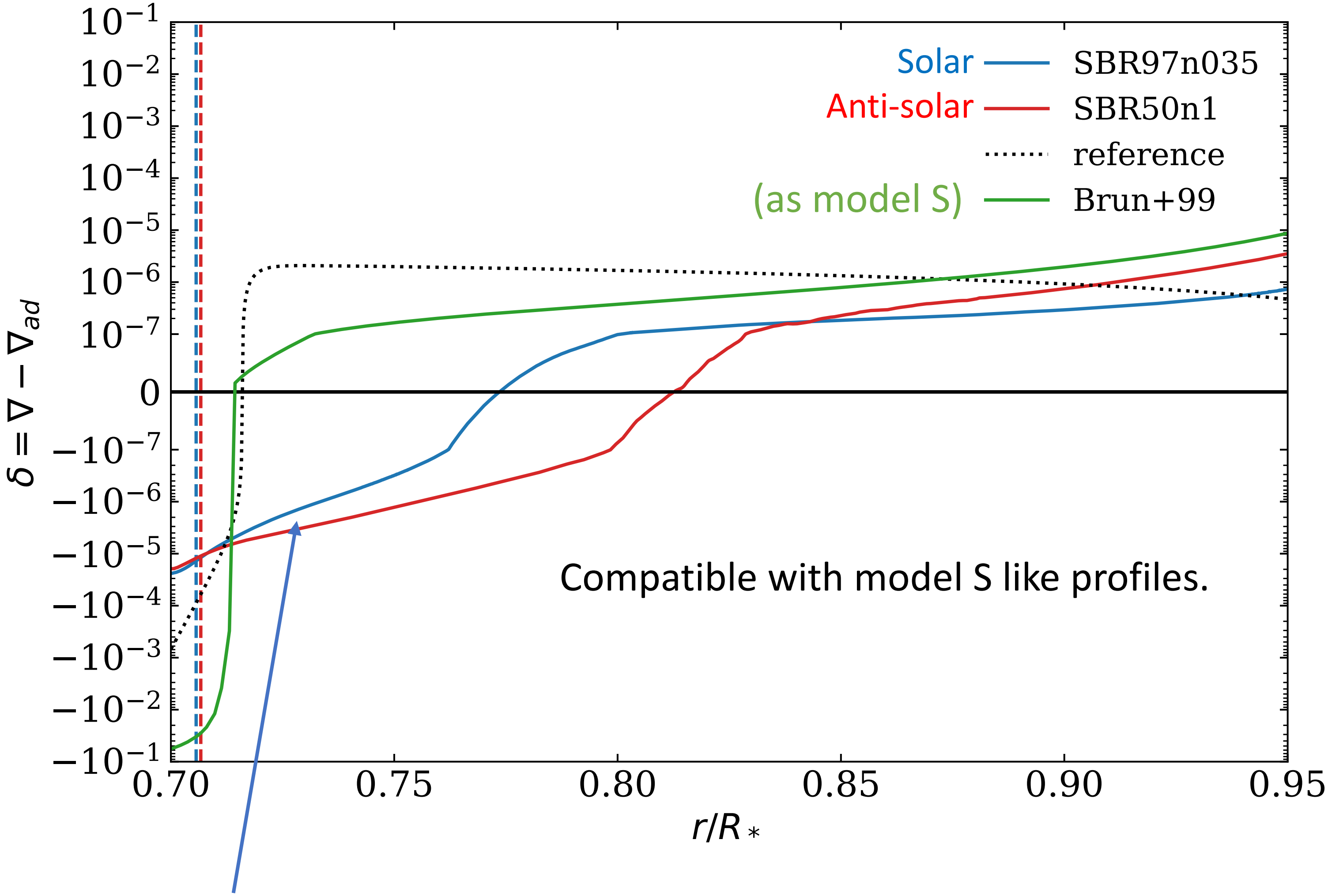




Correct sign of the spiral

uncorrect sign of the spiral

Adiabaticity Profiles in the simulations



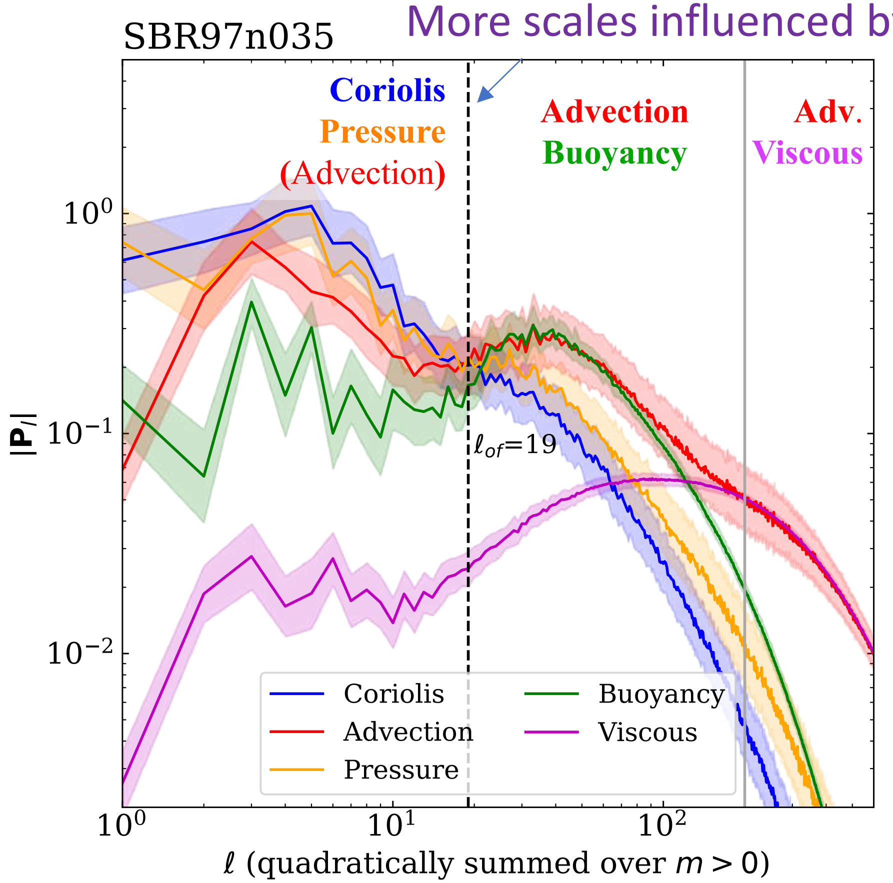
subadiabatic region in both models, unclear you can discriminate….

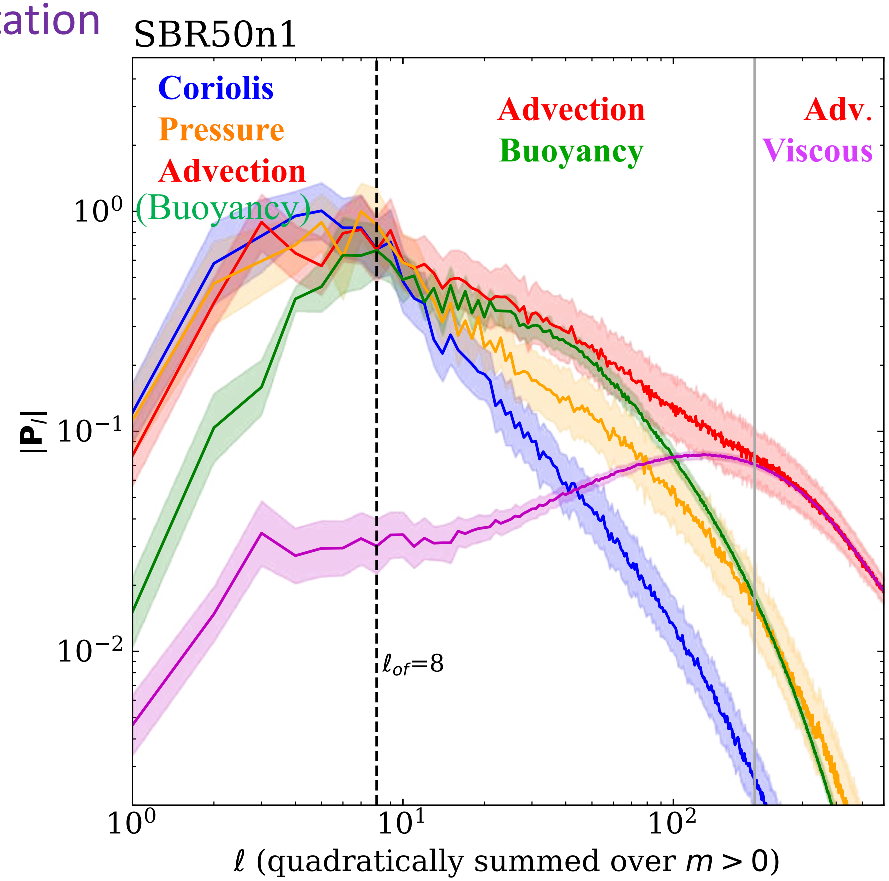
Kinetic Energy Diagnostic

Solar

Anti Solar

More scales influenced by rotation

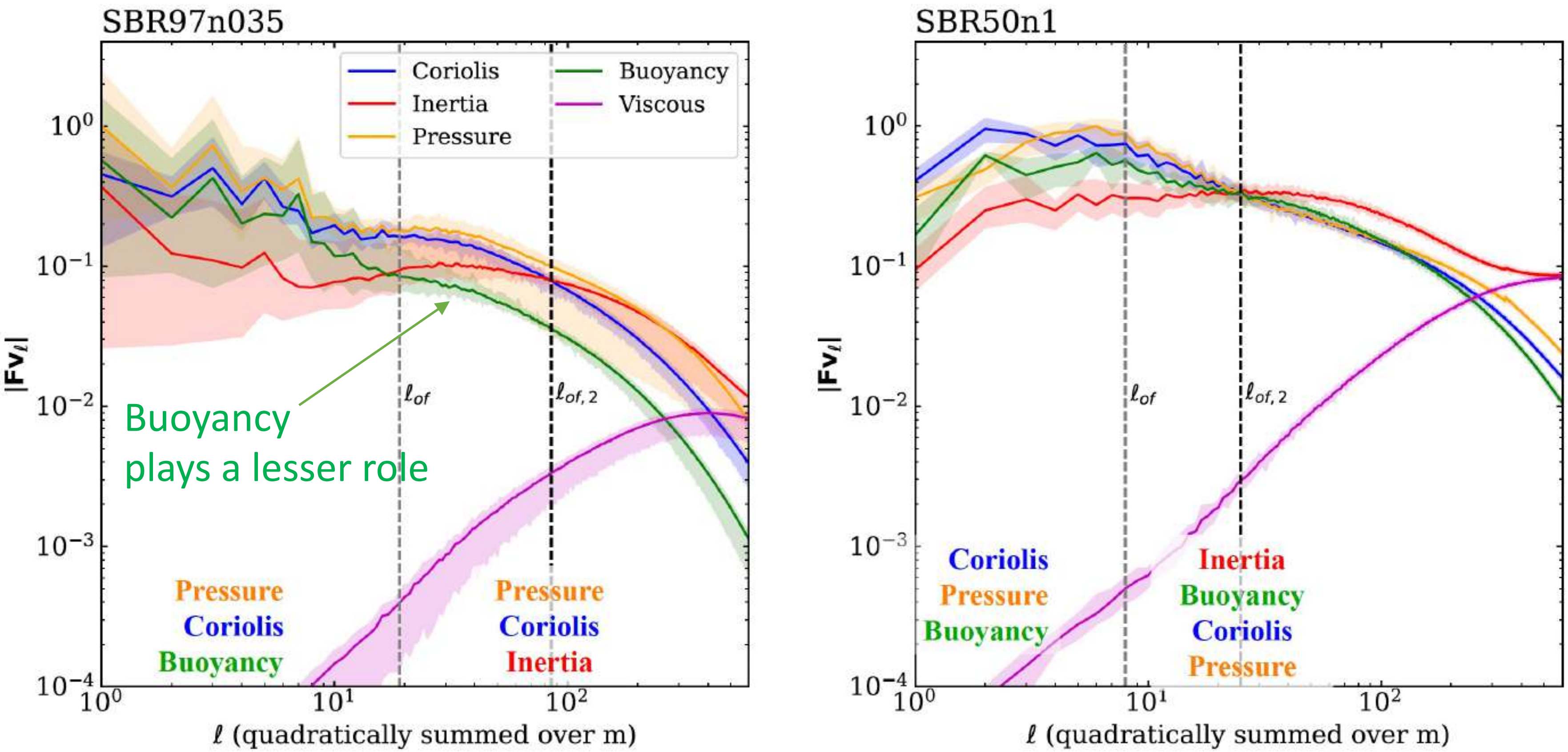




$$\partial_t E_\ell^K = \overbrace{\sum_{\substack{\ell_1,\ell_2 \\ \ell_{1,2}\geq|\ell_1-\ell_2| \\ \ell_{1,2}\leq\ell_1+\ell_2}} \left[\mathcal{R}_\ell(\ell_1,\ell_2)\right]}^{\text{Reynolds stress}} + \underbrace{\mathcal{C}_\ell(\ell-1,\ell+1)}_{\text{Coriolis force}} + \overbrace{\mathcal{H}_\ell}^{\text{Pressure work}} + \underbrace{\mathcal{B}_\ell}_{\text{Buoyancy}} + \overbrace{\mathcal{V}_\ell}^{\text{Viscosity}}$$

(Strugarek et al. 2013, Noraz et al. 2025)

Vertical Force Balance



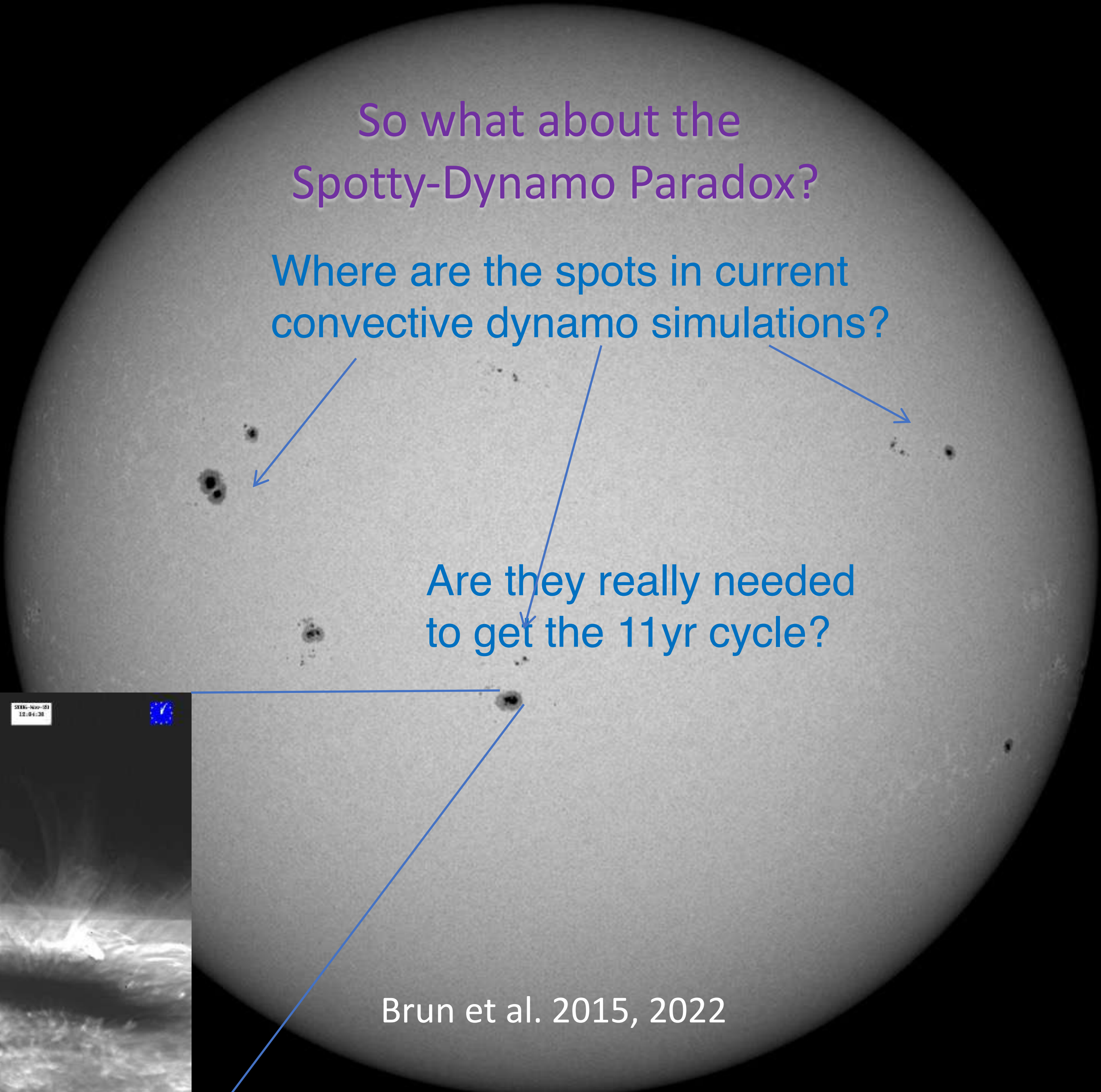
$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v} = -\boldsymbol{\nabla}\varpi - \frac{S}{c_p}\boldsymbol{g} - 2\boldsymbol{\Omega}_*\times\boldsymbol{v} - \frac{1}{\bar{\rho}}\boldsymbol{\nabla}\cdot\boldsymbol{\mathcal{D}} - [\boldsymbol{\nabla}\bar{\varpi} + \bar{\varpi}\boldsymbol{\nabla}\ln\bar{\rho} - \boldsymbol{g}],$$

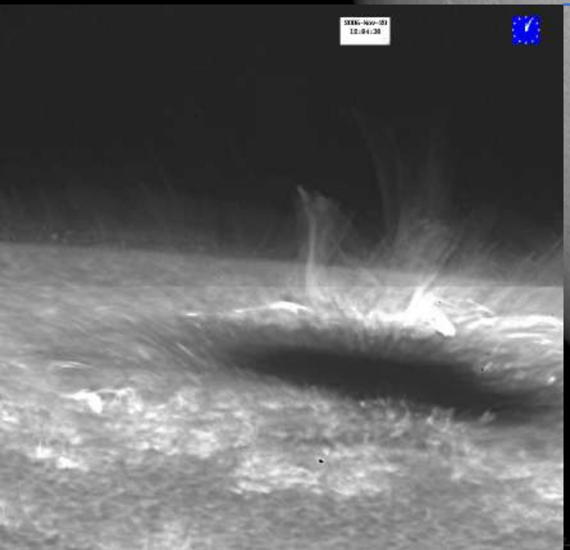
$$|\mathbf{F}_\ell| = \sqrt{\int_t\int_r \mathbf{f}_\ell^2 r^2 \mathrm{d}t\mathrm{d}r \Big/ \int_t\int_r r^2 \mathrm{d}t\mathrm{d}r}$$

So what about the Spotty-Dynamo Paradox?

Where are the spots in current convective dynamo simulations?

Are they really needed to get the 11yr cycle?



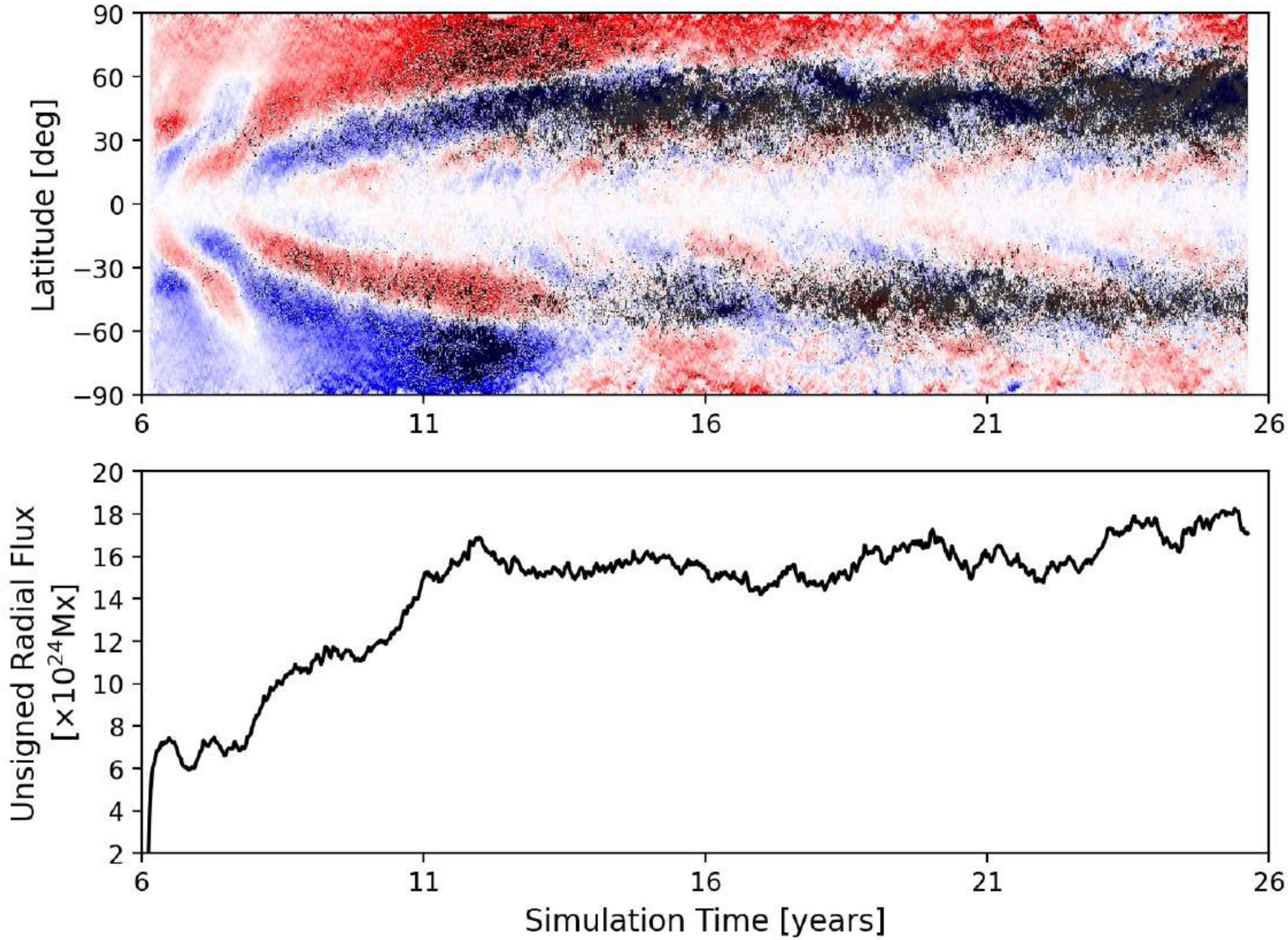


Brun et al. 2015, 2022

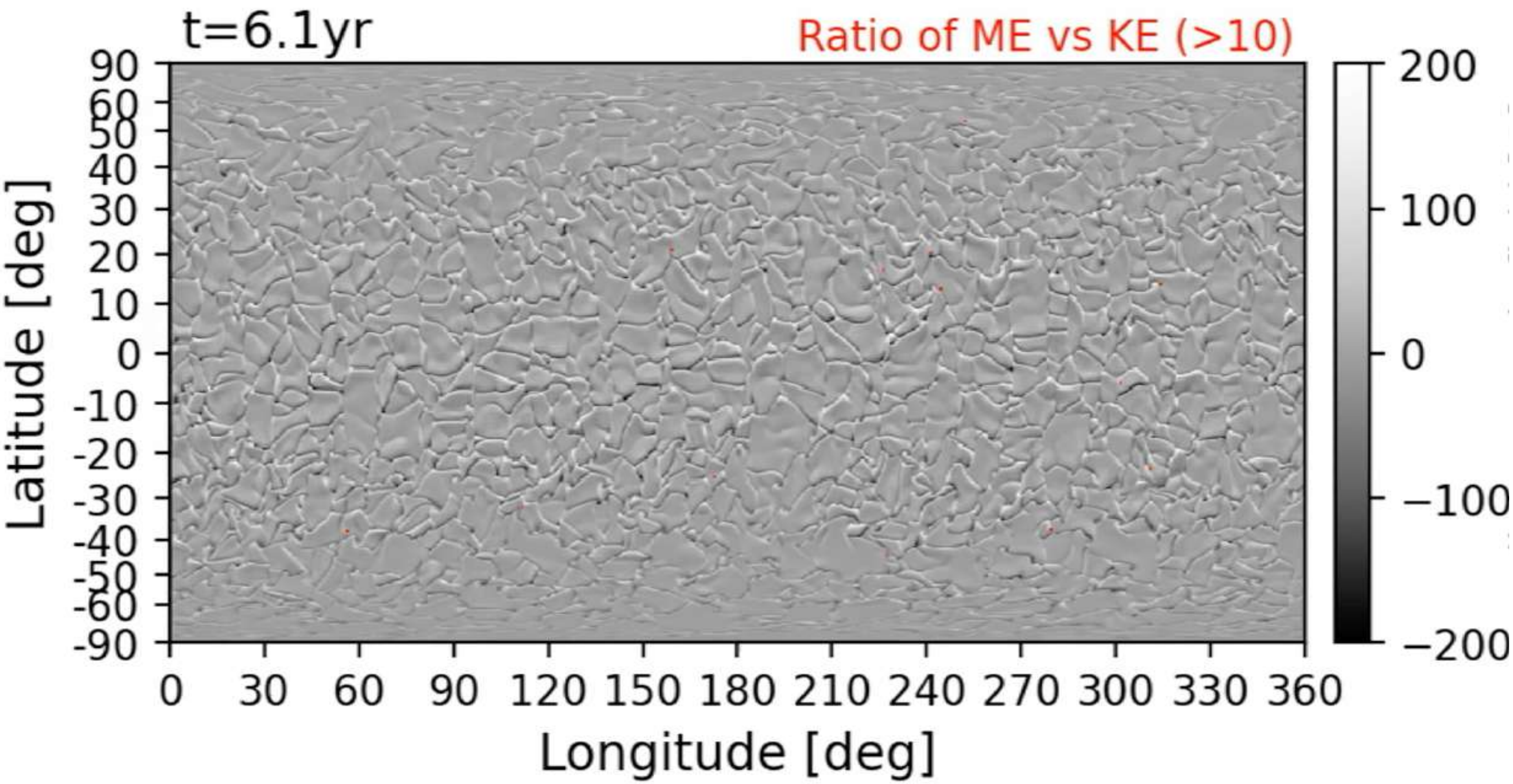
Adding Magnetic field in these Nusselt controlled experiments

Let’s see if that makes a difference about spotty dynamo paradox?

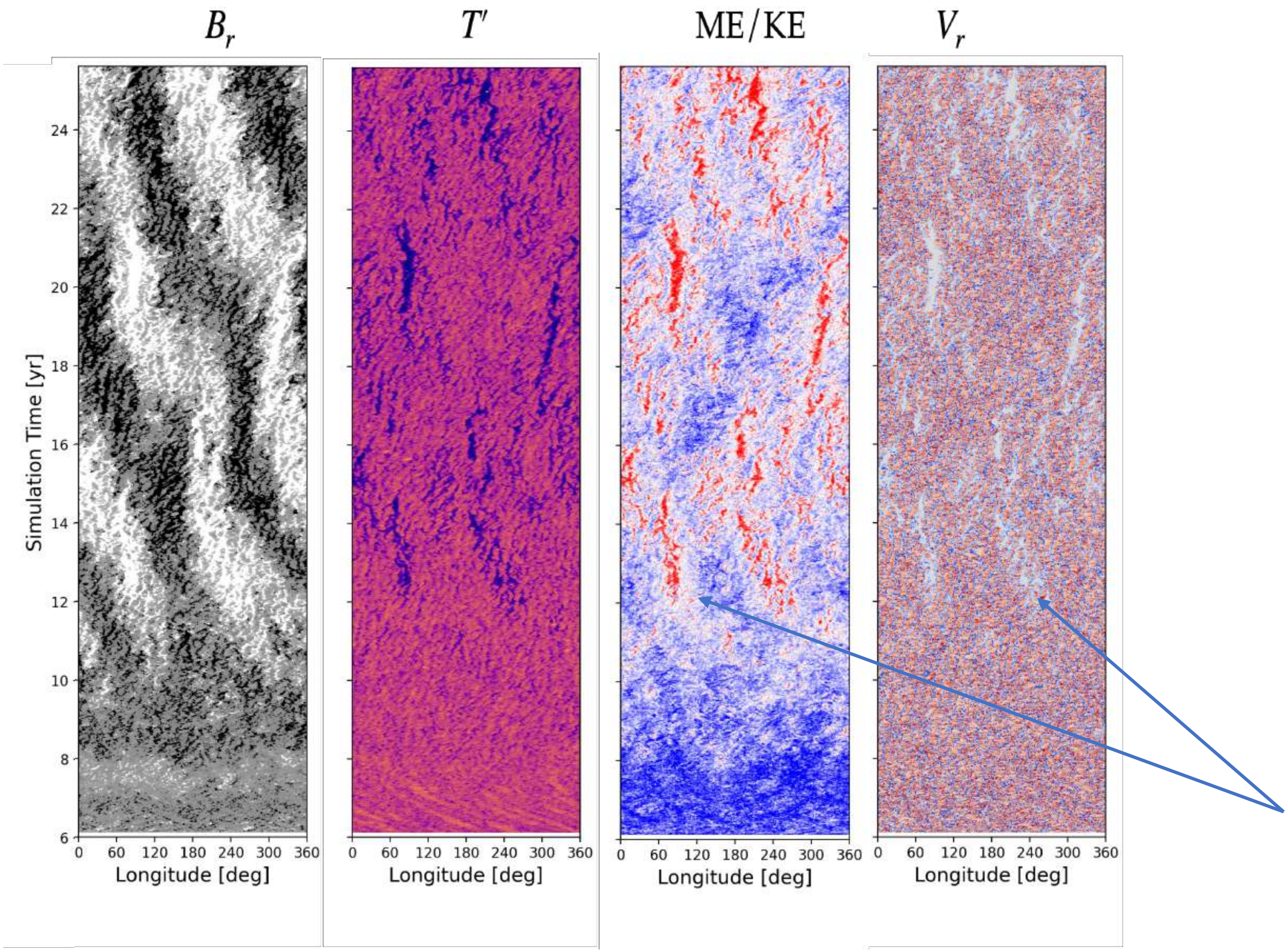
Current Evolution Stage of the dynamo solution simulation



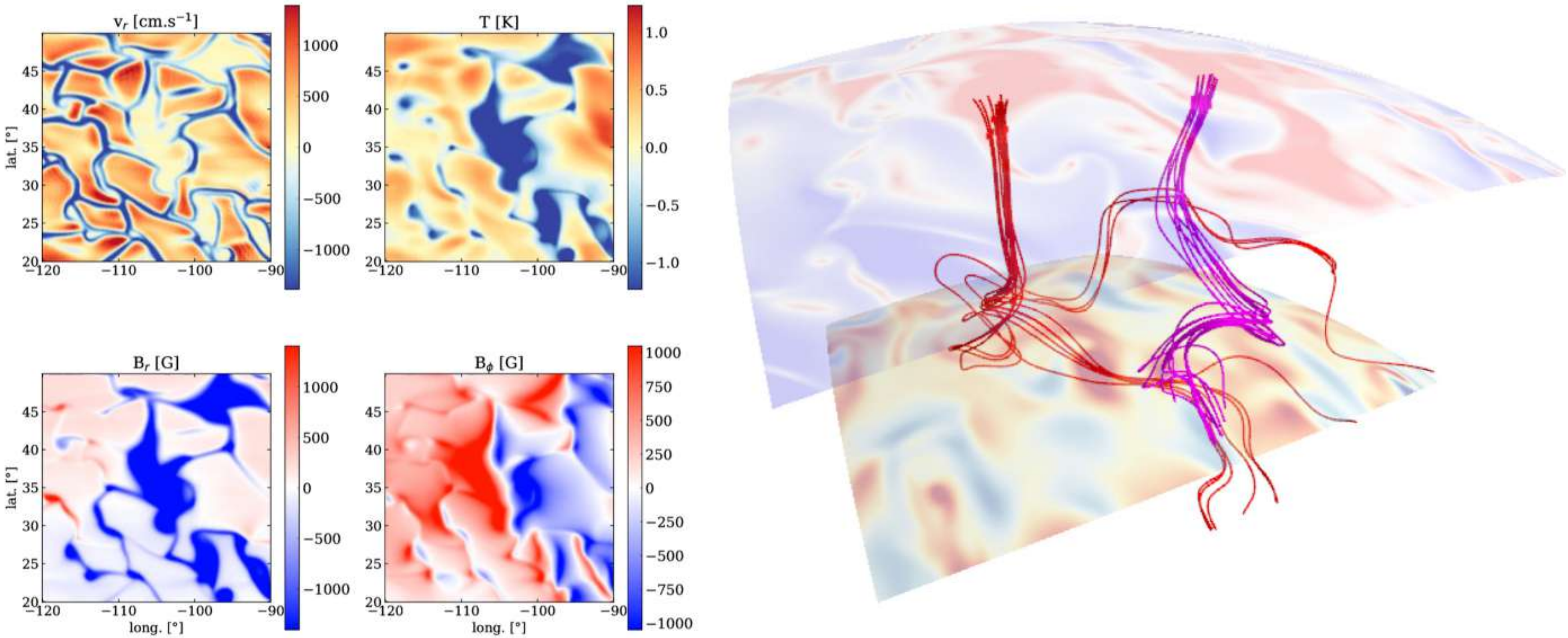
Progressive Emergence of Strong and Large Events



Time-longitude diagrams



3D view on a stronger magnetic feature



Convective inhibition by strong magnetic concentrated flux tubes
Very promising for progenitor « sunspot » formation

Noraz, Brun et al. 2026, in prep

What’s Next?

Harvesting exascale supercomputers and new numerical methods

In 2017, we (A.S. Brun, L. Gizon, M. Carlsson, V. Archontis, F. Moreno-Insertis)
Designed a synergy ERC project to attack some of these difficult solar physics pb.

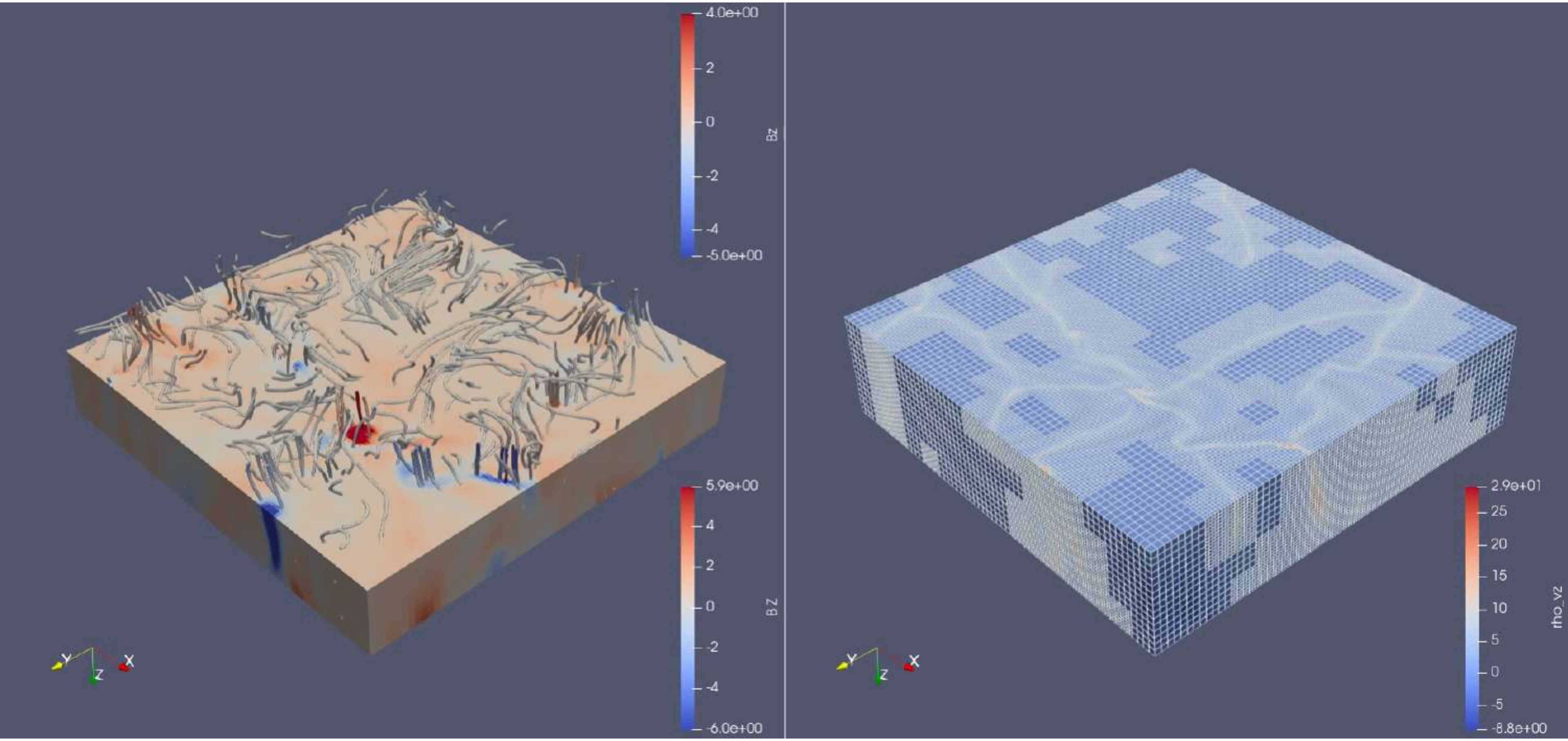
a 7 yr project

wholesun.eu

Every March since 2020 we have a 3 weeks program in Paris, contact us if you wish to attend

=> New open source Dyablo Code – some recent updates.

3D AMR Dynamo Convection simulation with Dyablo



erc WHOLE

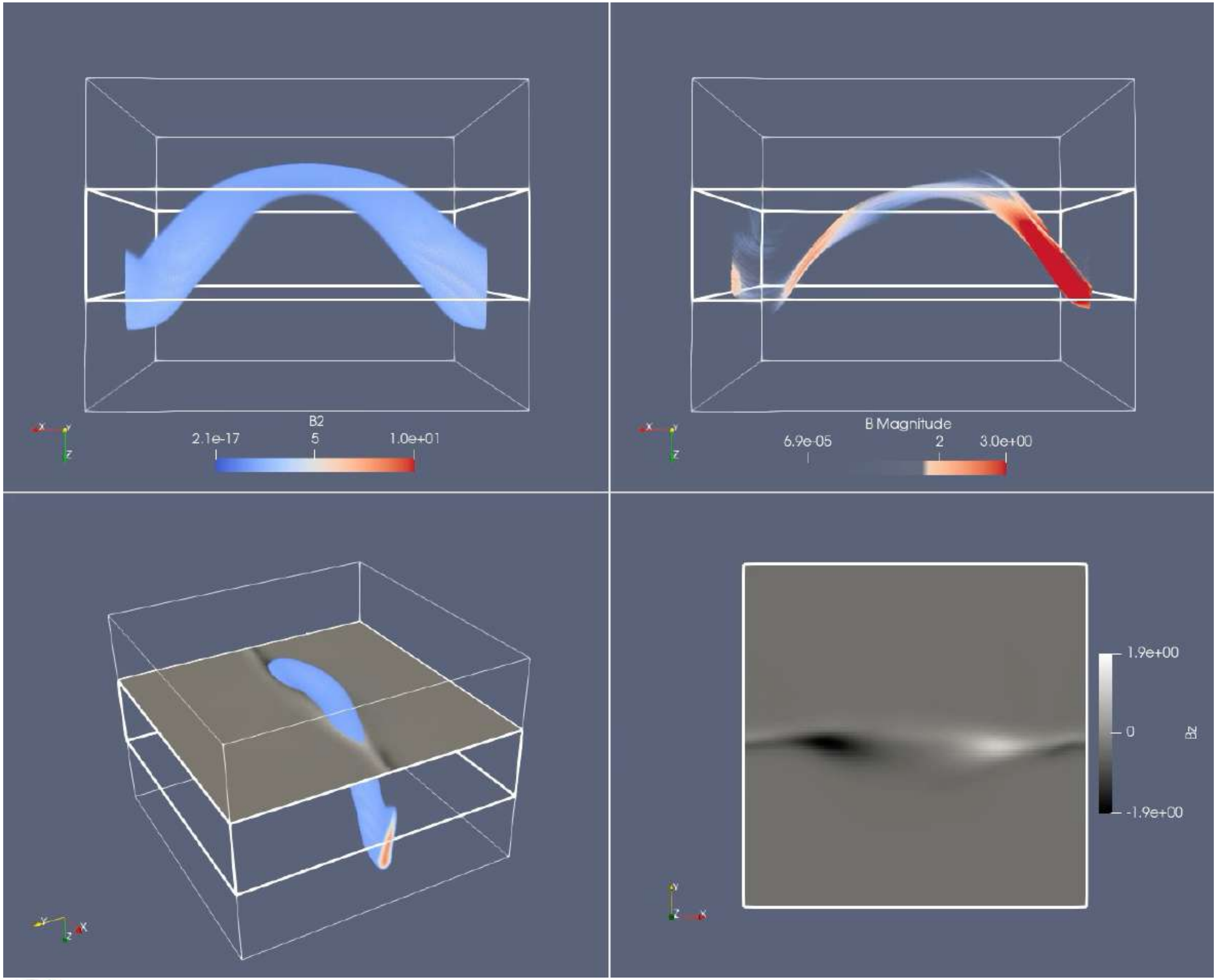
Brun et al. (work in progress)

3D Tri-layers Convection + Flux Emergence simulation with Dyablo

Stable

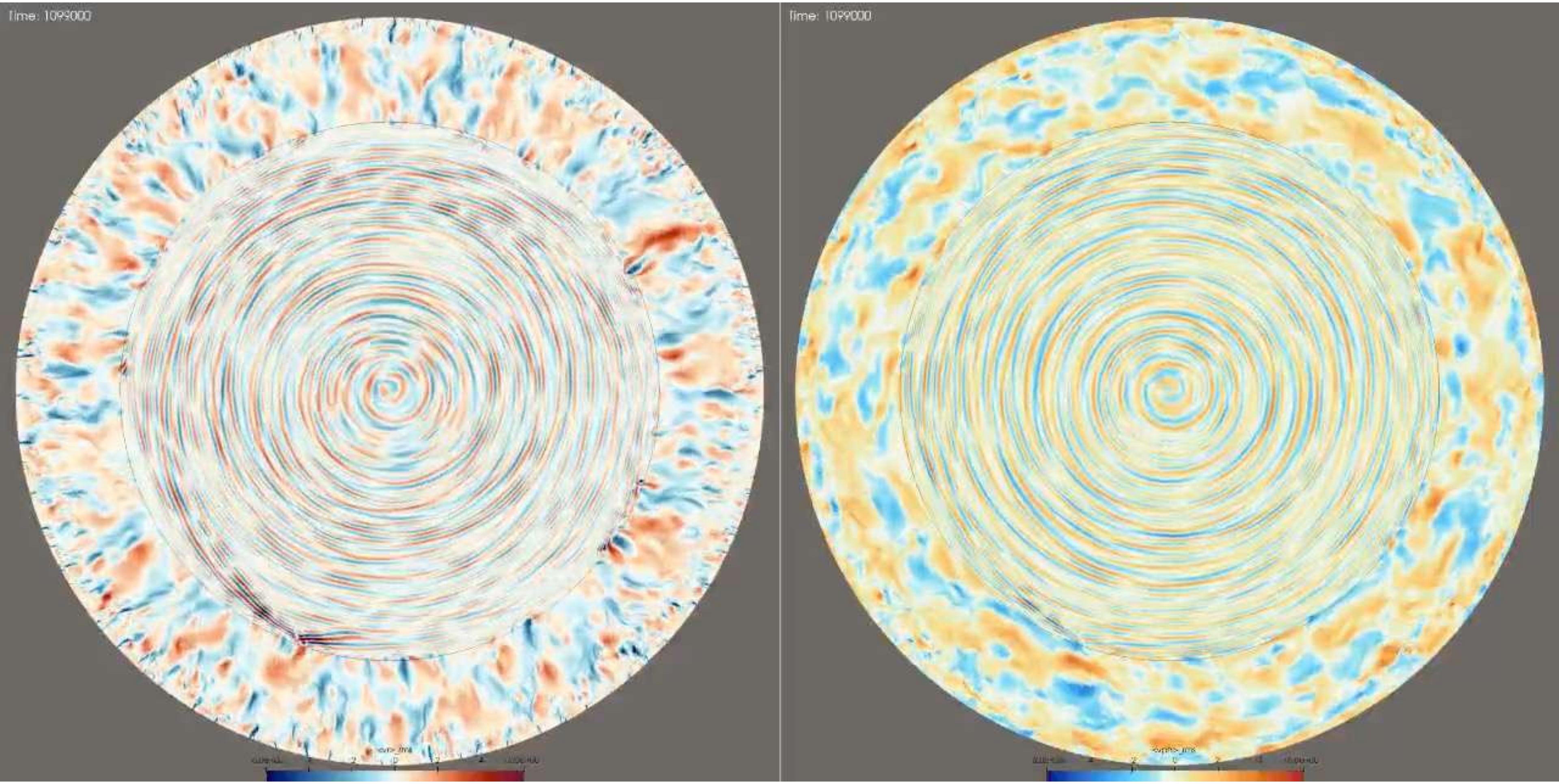
Convection

Stable



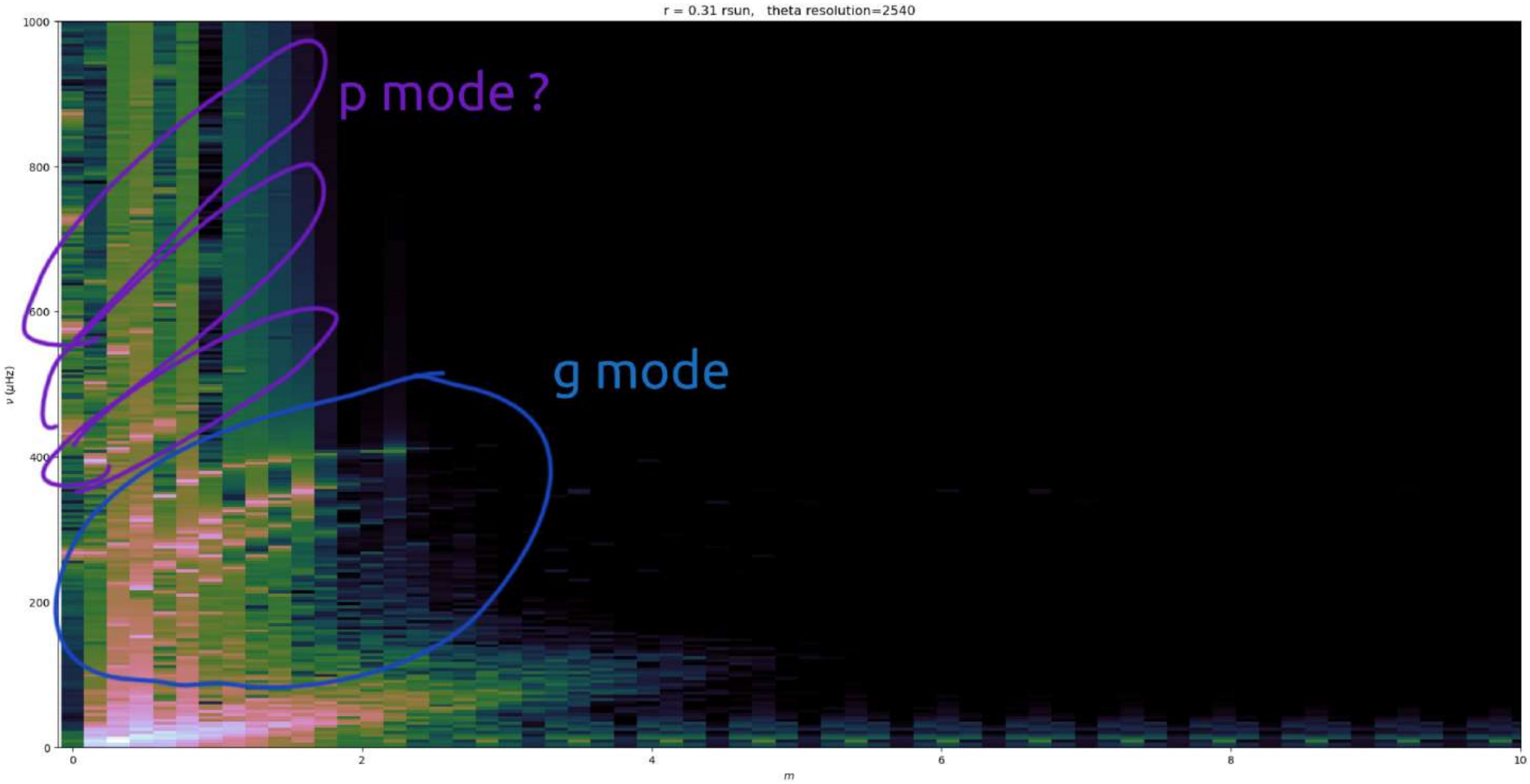
Blume, Brun, Barbier (work in progress)

Solar Convection, Gravity and Acoustic Waves in fully compressible Dyablo Whole Sun Simulations

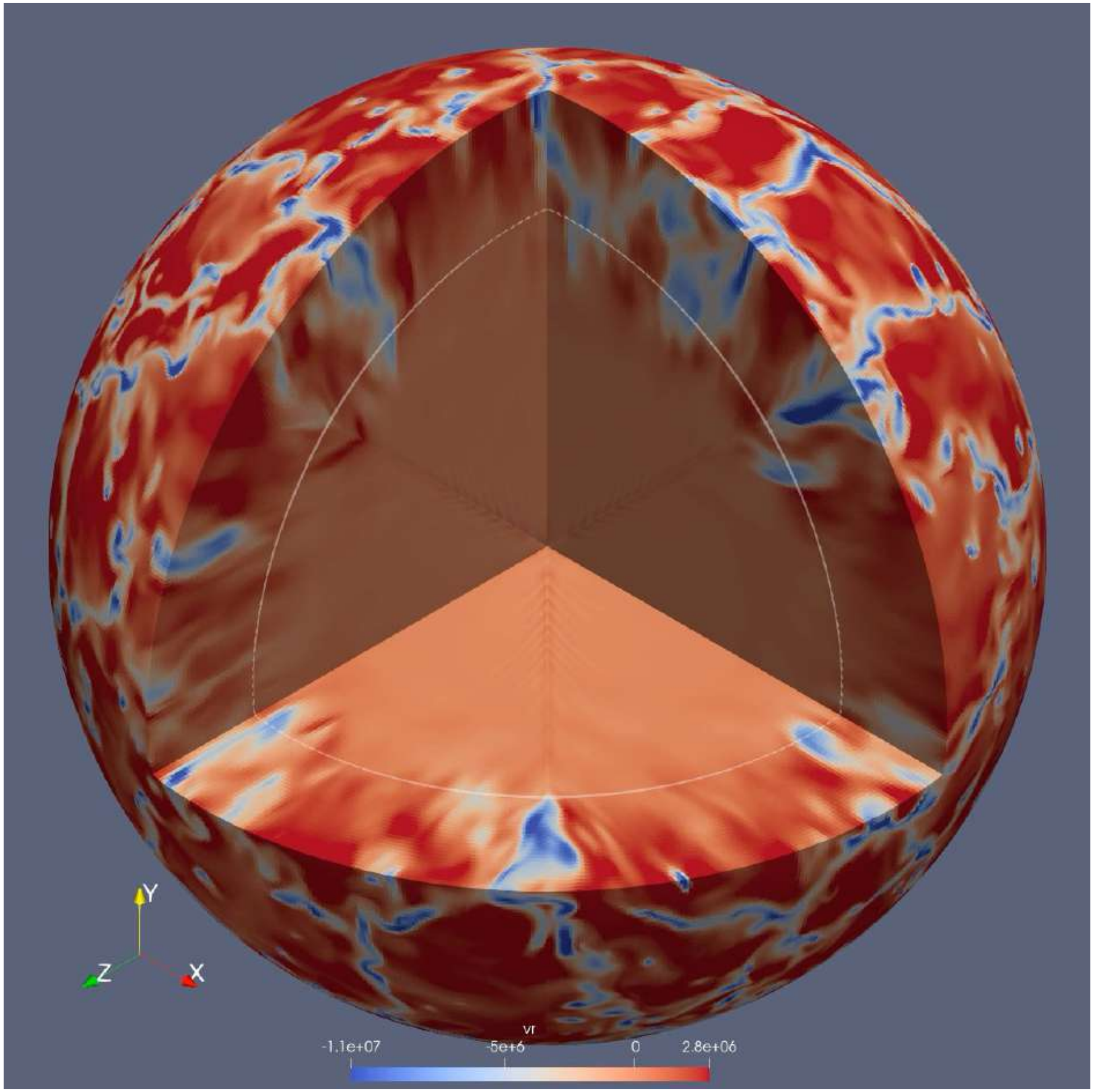


Doboele, Brun, Delorme et al. 2026, in prep

P and G modes in a Solar simulations



3D Convection spherical simulation with Dyablo



Doebele, Brun, Delorme in prep

Conclusions (I)

1) In solar/stellar dynamo we are able to get decadal long cyclic solutions, that exhibits intense Magnetic wreaths that lead to the formation of self-consistent Omega-loop formation and to Flux emergence events with interesting properties (such as tilt). They also agree with Zeeman-Doppler Imaging observational trends (B(Ro) propto $Ro^{-1.4}$).

2) A *Magnetochronology* story can be presented where yound stars have banded/cyclindrical differential rotation and short period magnetic cycles, stars like the Sun decadal long cycles and slowly old rotating stars a direc tdynamo (no cycles) and a retrograde equator (anti-solar)

3) However, these solutions do not possess sunspot/starspot though and are slightly misplaced in Rossby number parameter space.

Conclusions (II)

4) With a control of Nusselt number, we are able to reproduce (maintain) realistic solar differential rotation at high Reynolds numbers

5) We may see that the Sun is running deep a C-I balance rather than a CIA (in hydro). This may imply that in MHD case it is a MIC and not a MAC balance that dominates (work in progress)

6) In the Nusselt controlled experiement, we start seeing very interesting intense magnetic field concentration that inhibits surface convection, these new generation dynamo solution are very promising, stay tuned !!!

Reynolds stresses in spectral space

$$\mathcal{R}_\ell(r, \ell_1, \ell_2) = \bar{\rho} \int_S [\boldsymbol{v}_{\ell_1} \cdot \boldsymbol{\nabla}(\boldsymbol{v}_{\ell_2})]_\ell \cdot \boldsymbol{v}_\ell \mathrm{d}\Omega,$$

$$\overline{\mathcal{R}_{\ell=3}^{m=0}}(\ell_{1,2}) = \frac{1}{(2\ell+1)\mathcal{R}_\ell^{m>0}} \sum_{\substack{\ell_{2,1} \\ |\ell_1-\ell_2|\leq\ell\leq\ell_1+\ell_2 \\ m_1+m_2=0; m_1>0, m_2>0}} |\mathcal{R}_{\ell=3}(\ell_1, \ell_2)|,$$

$$\text{where } \mathcal{R}_\ell^{m>0} = \sum_{\substack{\ell_1,\ell_2 \\ |\ell_1-\ell_2|\leq\ell\leq\ell_1+\ell_2 \\ m_1+m_2=0; m_1>0, m_2>0}} \mathcal{R}_{\ell=3}(\ell_1, \ell_2).$$