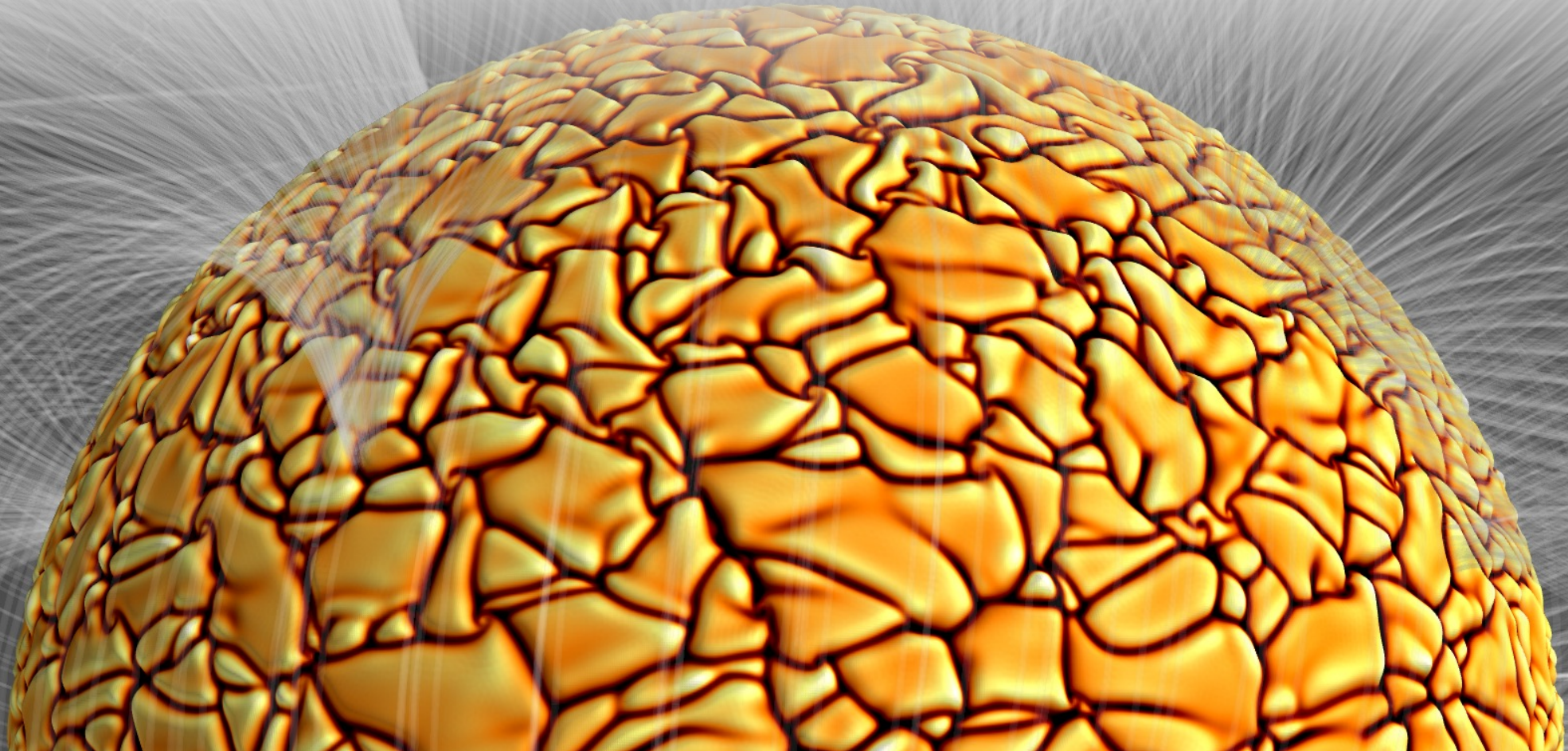
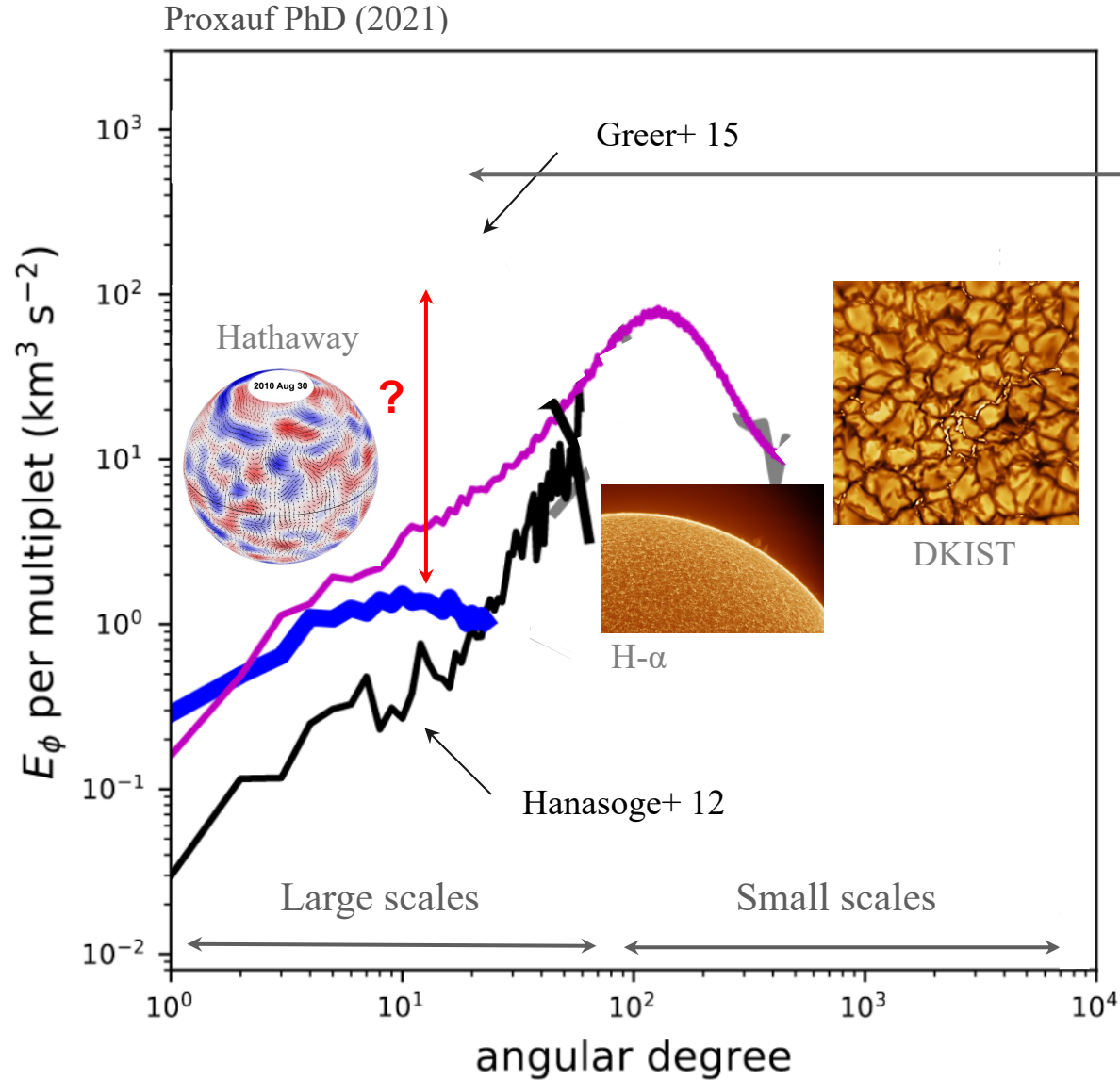


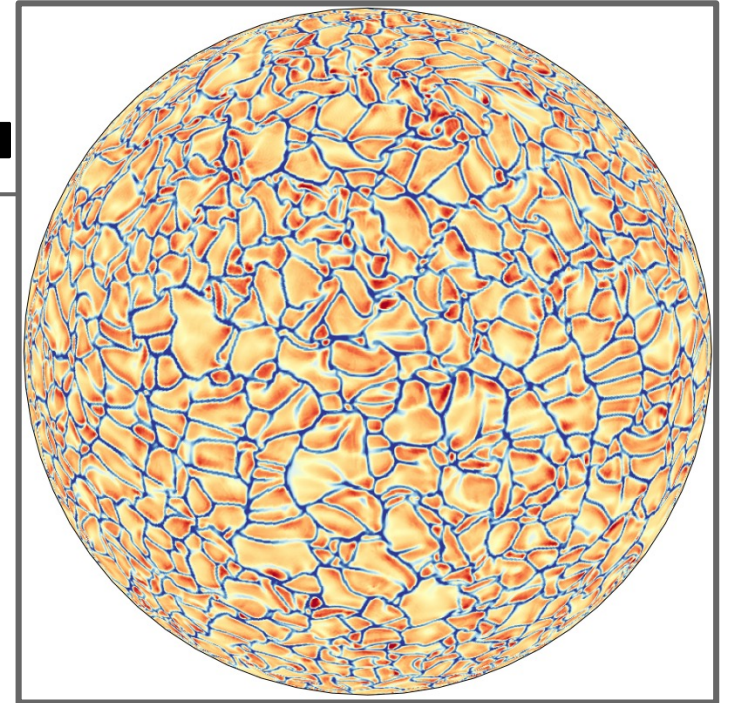
Impact of the Nusselt number on the energy distribution among solar convection scales



Solar convective conundrum : Spectrum



- Numerical simulations as a tool to modelize the process → challenge to reach realistic solar parameter regimes

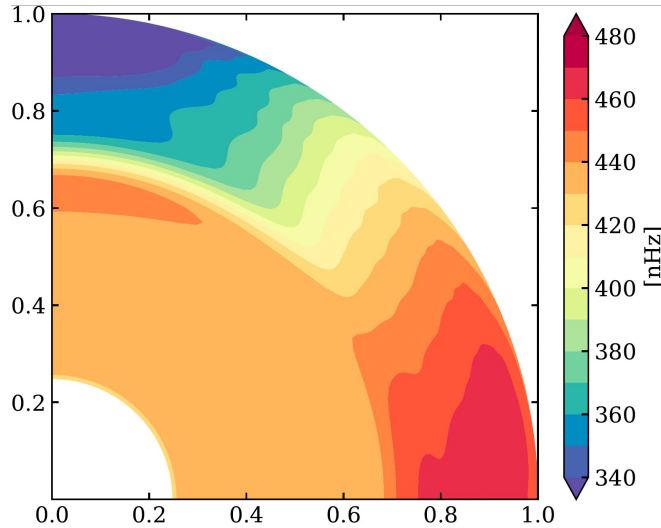


- Actual mismatch between observational results concerning the large scales contribution



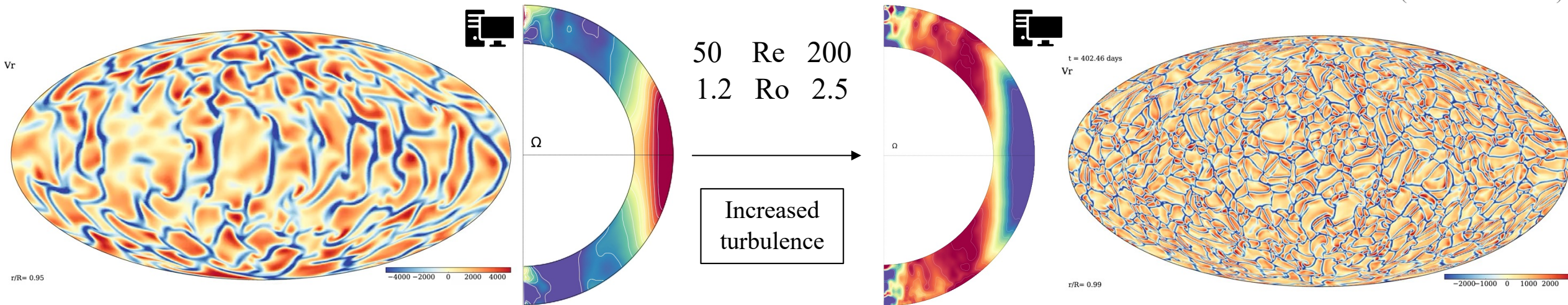
Solar convective conundrum : Differential Rotation (DR)

Larson & Schou (2018)
Thompson et al. (2003)



- Current over-estimation of the large-scale velocities came when reaching higher degree of turbulence
- **Overestimates the Rossby number**
→ reversal of the **differential rotation (DR)** profile

Code ASH (Brun et al. 2004)



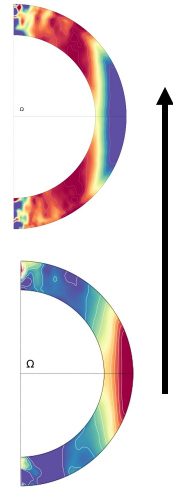
Which scales are important for constructing the DR?

How can solar models be calibrated ?

Solar DR calibration

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

(see Gilman 77,
Käpylä et al. 22,
Hotta et al. 22)



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

Reduced total Luminosity,
(e.g. Hotta et al. 2014 $\rightarrow L_*/18$)
Increased thermal cond.
(direct impact on scale distrib.
of the dynamic)

Increased Rotation rate
(Emeriau-Viard PhD 2017,
Hotta et al. 2018)

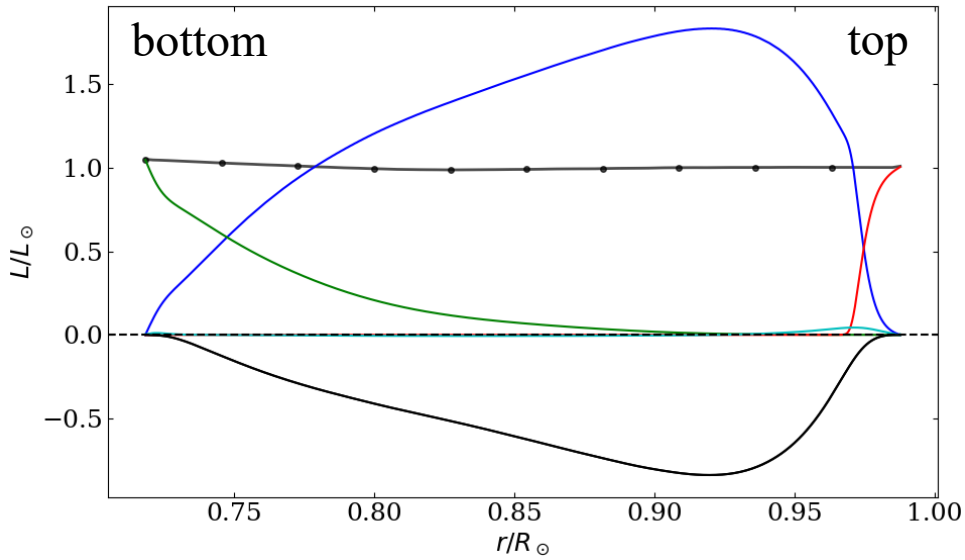
- Recent highlight of **magnetic contribution** (Hotta et al. 22, 23) :
 - needs **significant amount of numerical resources**
 - still needs numerical convergence

- We here follow a **controlled path of the parameter space, constraining Ro , L^* and Ω^* ,** while increasing the Reynolds number Re

$$Ro \propto \nu \propto \sqrt[3]{L_{\text{conv}}} / \nu^\alpha$$

How much energy does the convection transport?

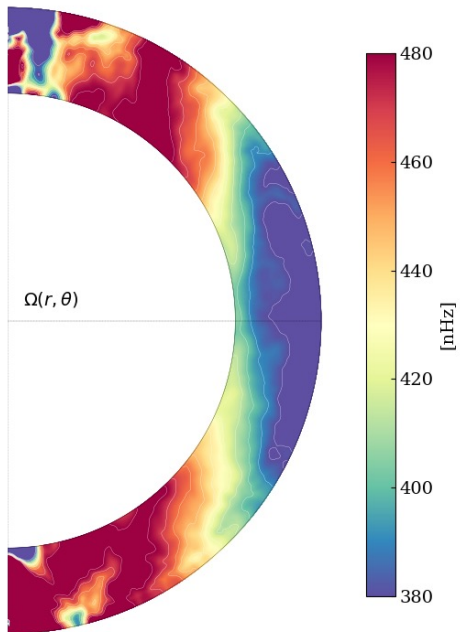
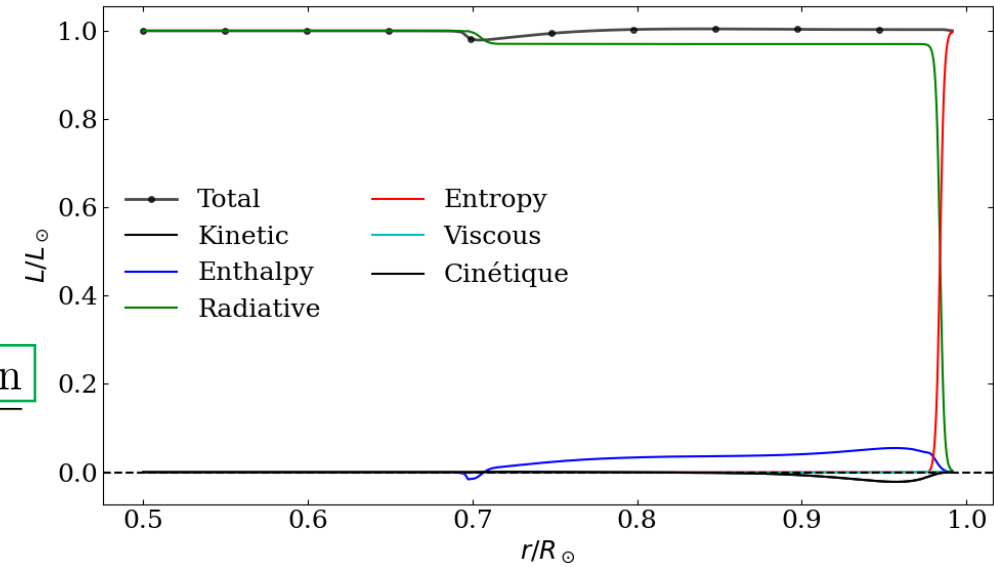
Control of the Nusselt number : increasing the radiative flux



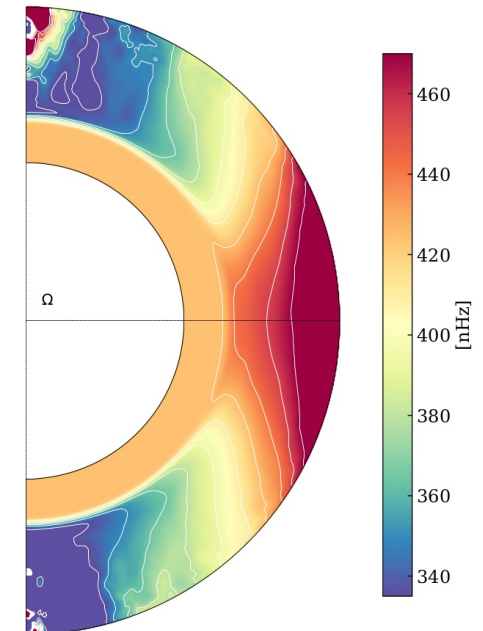
Noraz 2022 (PhD)

200	Re	270
2.5	Ro	1
25	Nu	1.04

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



- Even **higher turbulence degree**
- Rossby is limited
-> The **solar DR profile is back**



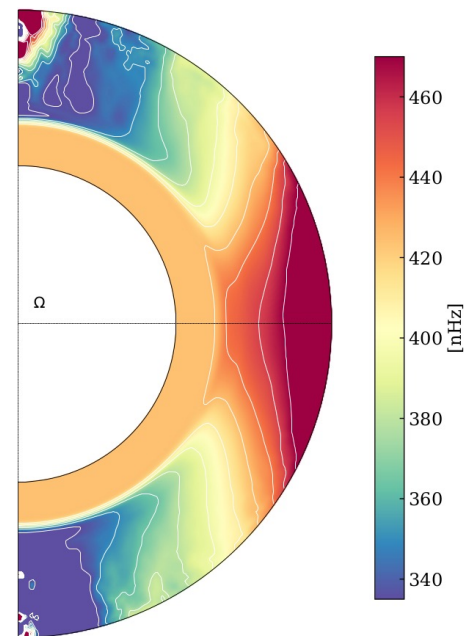
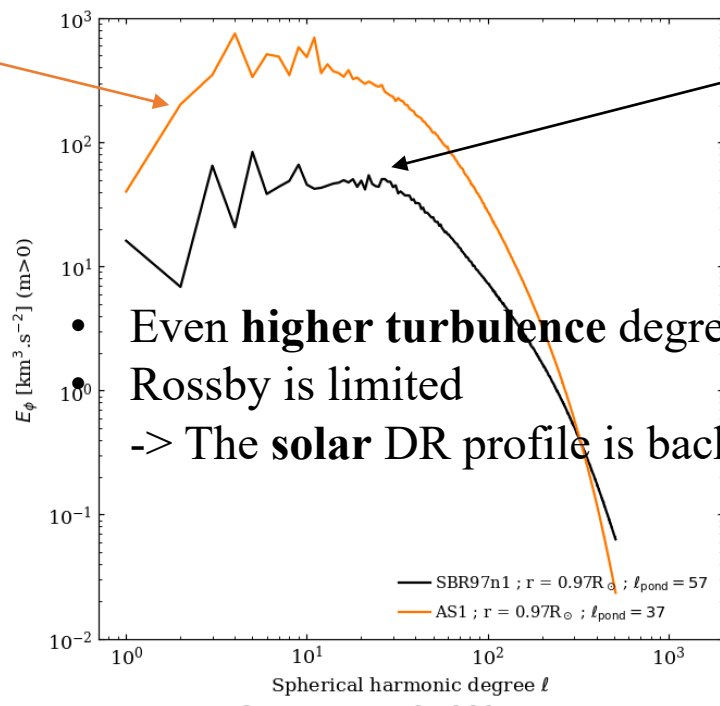
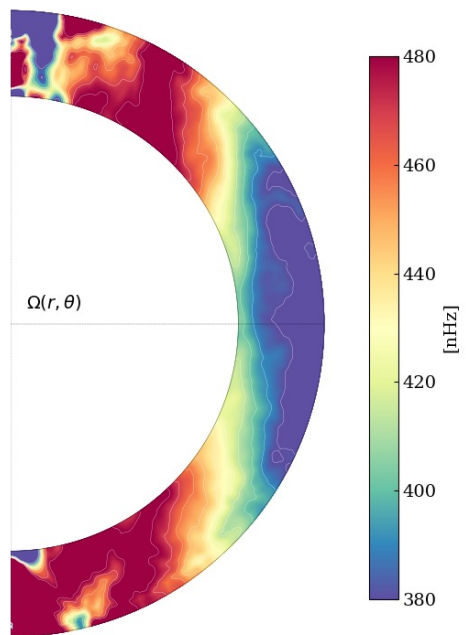
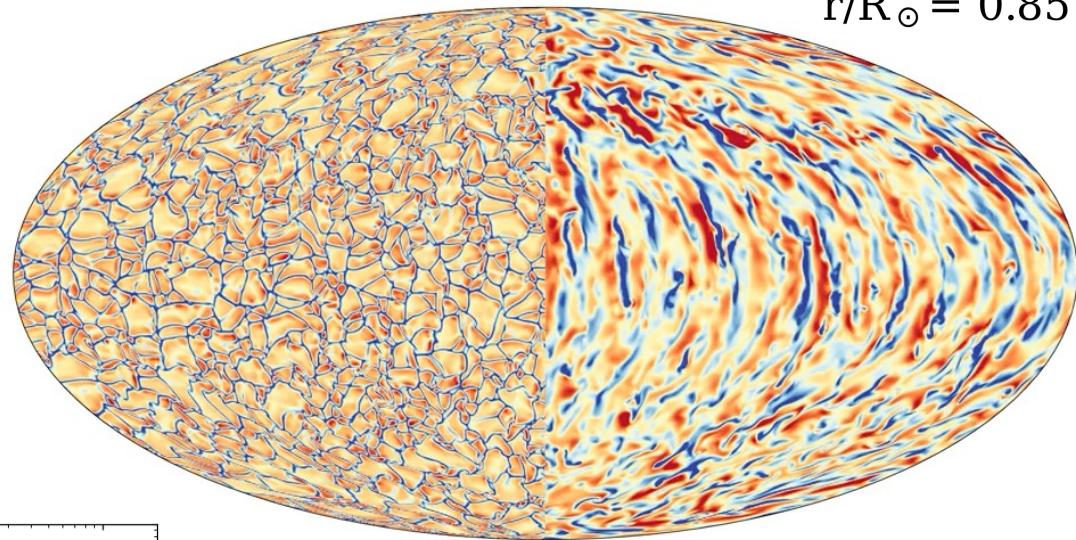
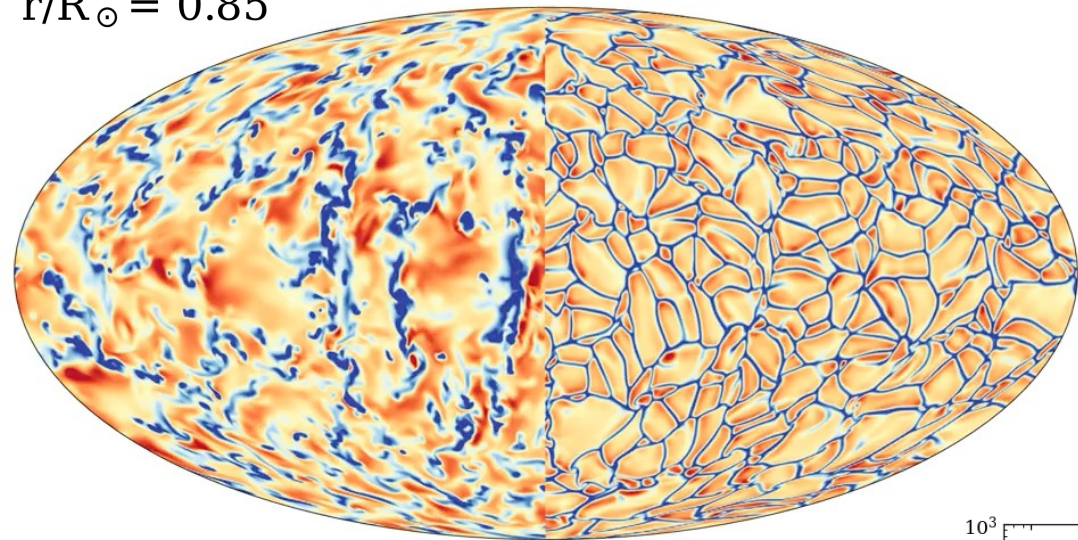
Control of the Nusselt number : large-scales amplitude

$r/R_{\odot} = 0.85$

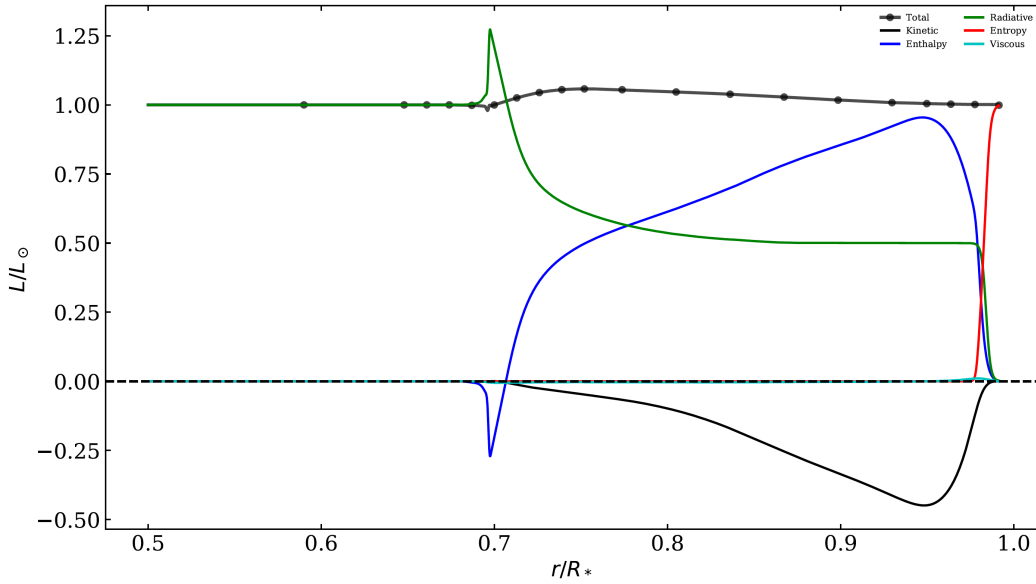
Noraz 2022 (PhD)

$r/R_{\odot} = 0.85$

$r/R_{\odot} = 0.99$

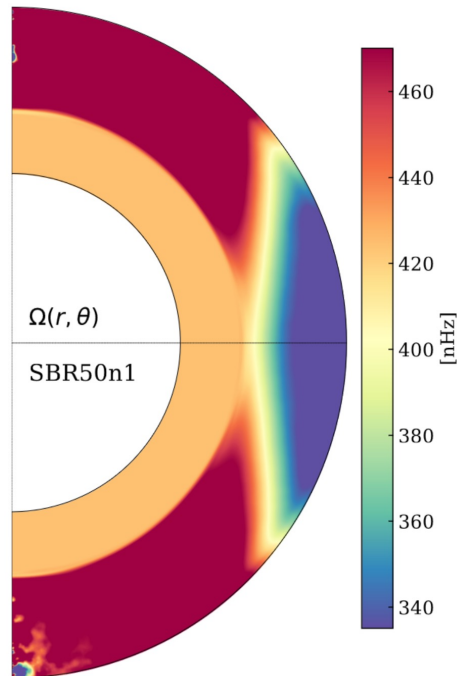
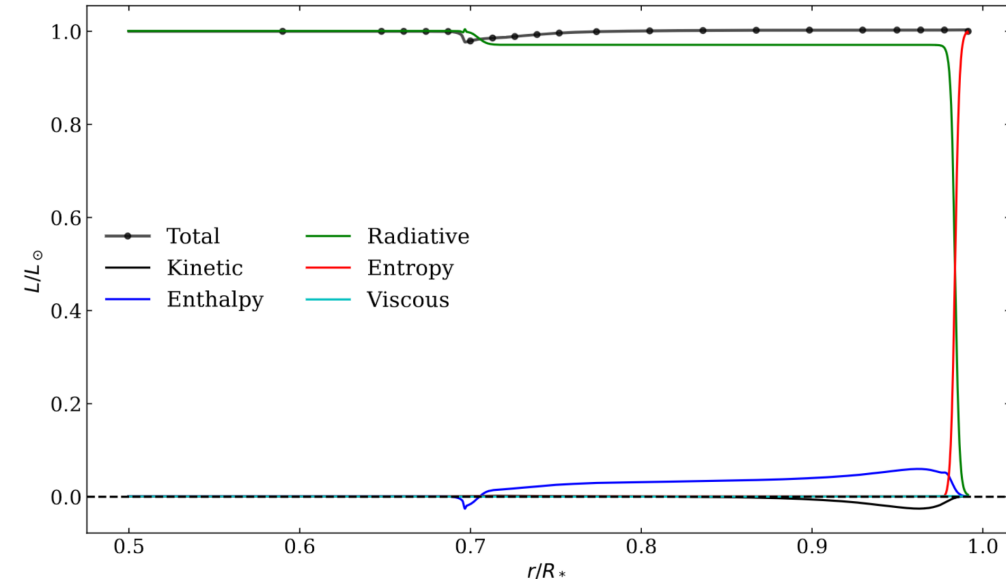


Control of the Nusselt number : increasing the turbulence degree

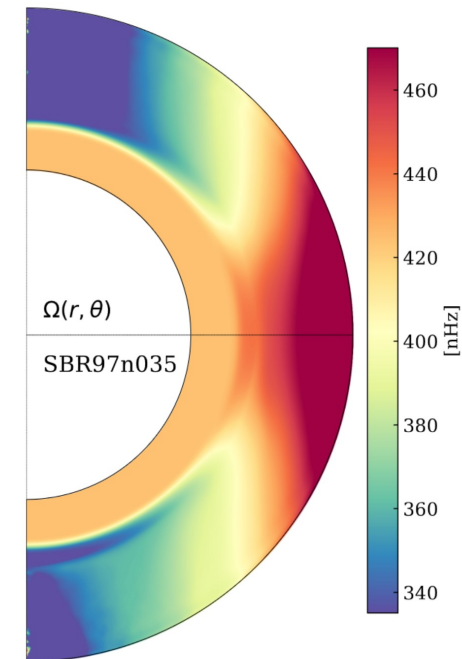


Noraz et al. (in prep)

860	Re	810
4	Ro	1.5
2.5	Nu	1.04

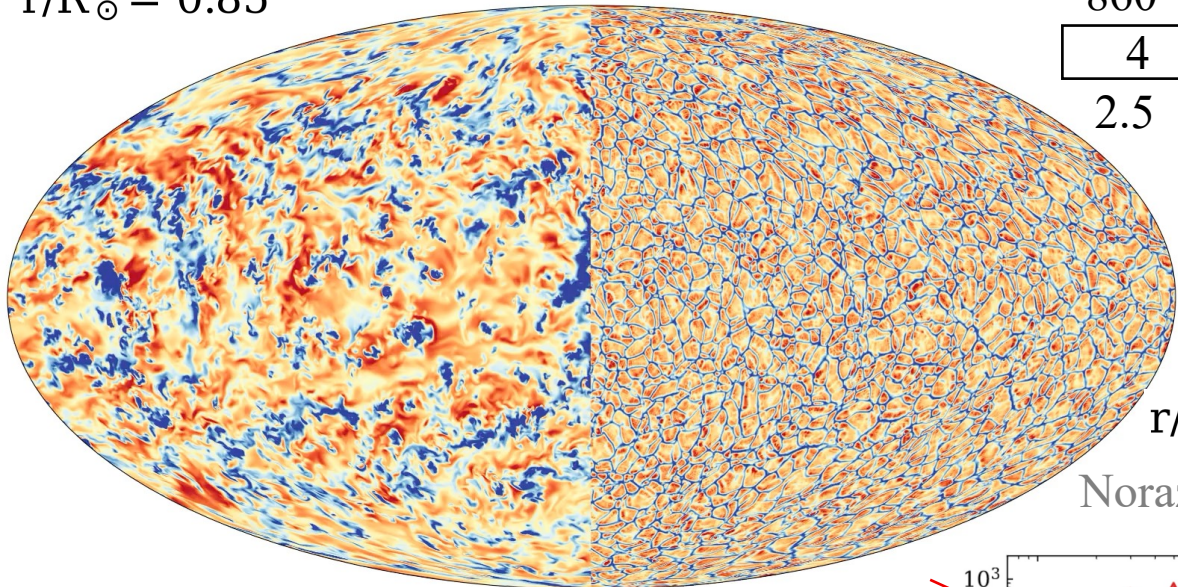


- We continue the path aiming a **higher turbulence degree**
- We construct a anti-solar case with similar Reynolds
-> **What is important in the dynamics to get the solar DR?**



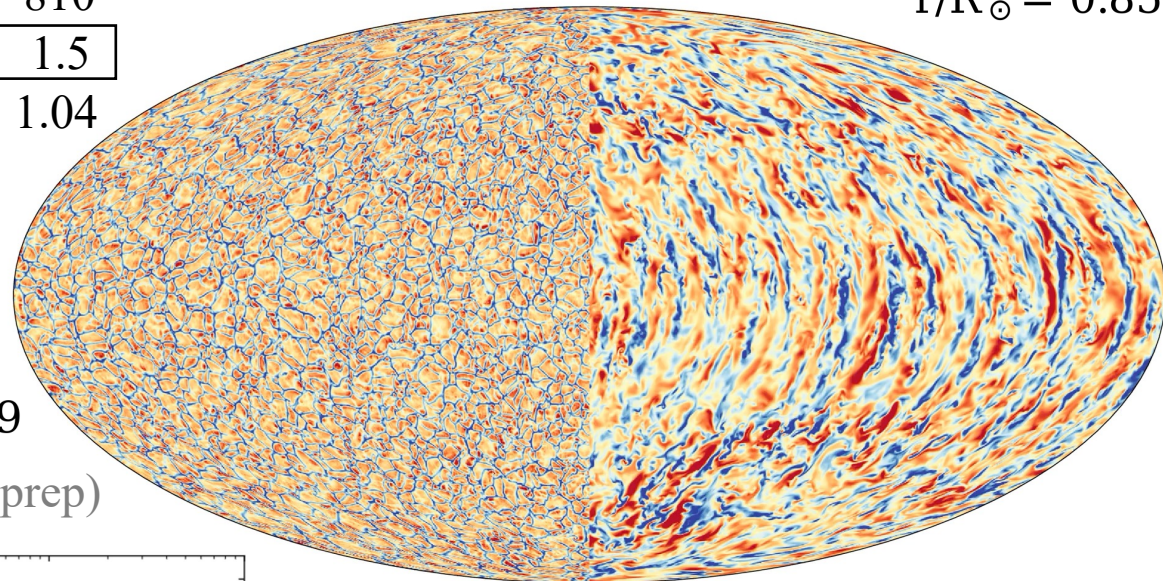
Control of the Nusselt number : surface imprint of the internal dynamics

$r/R_{\odot} = 0.85$



860	Re	810
4	Ro	1.5
2.5	Nu	1.04

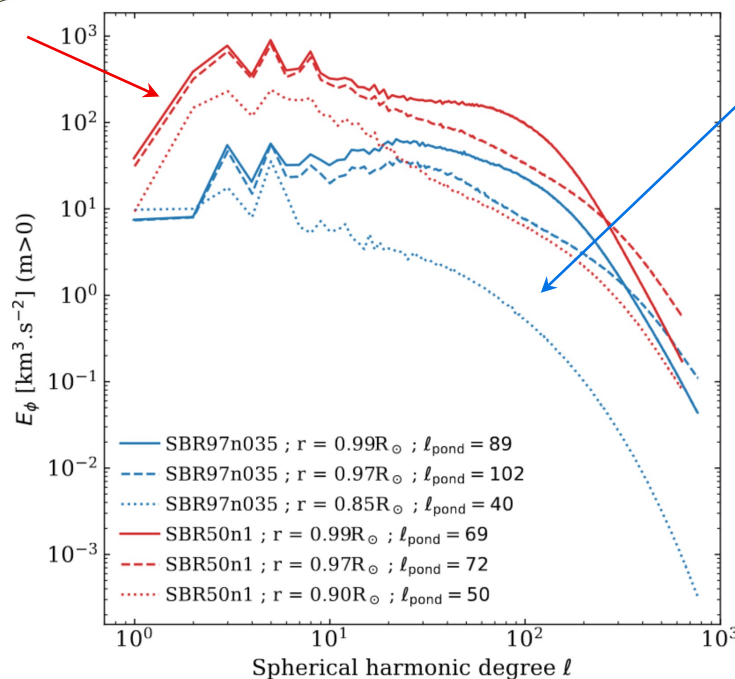
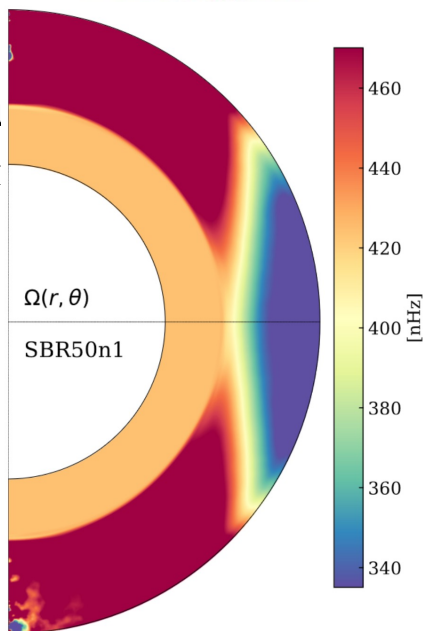
$r/R_{\odot} = 0.85$



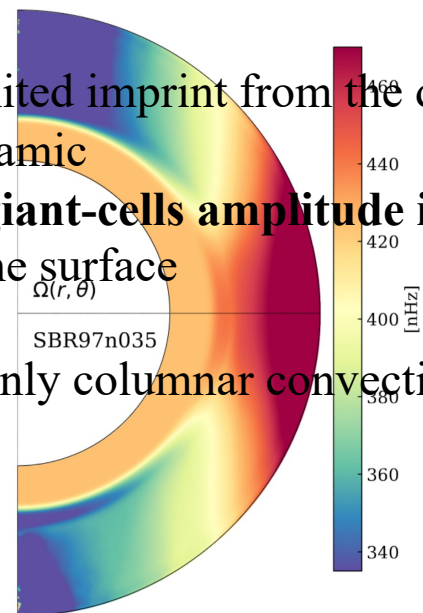
$r/R_{\odot} = 0.99$

Noraz et al. (in prep)

- Giant structure which imprints

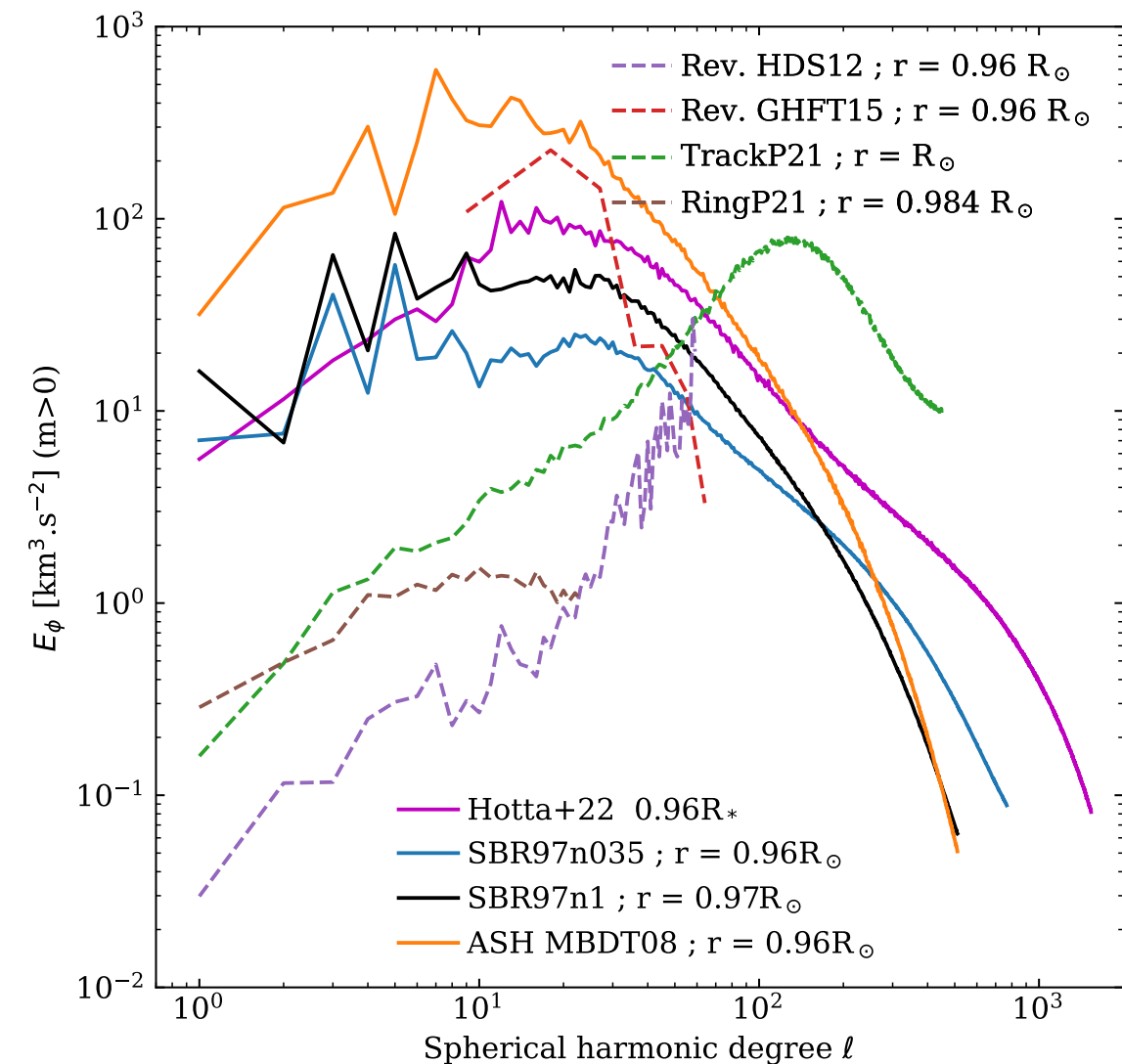


- Limited imprint from the deeper dynamic
 -> **giant-cells amplitude is limited at the surface**
- Mainly columnar convection



Which scales are important for the establishment of the solar DR?

Proxauf (PhD), Noraz 22 (PhD)

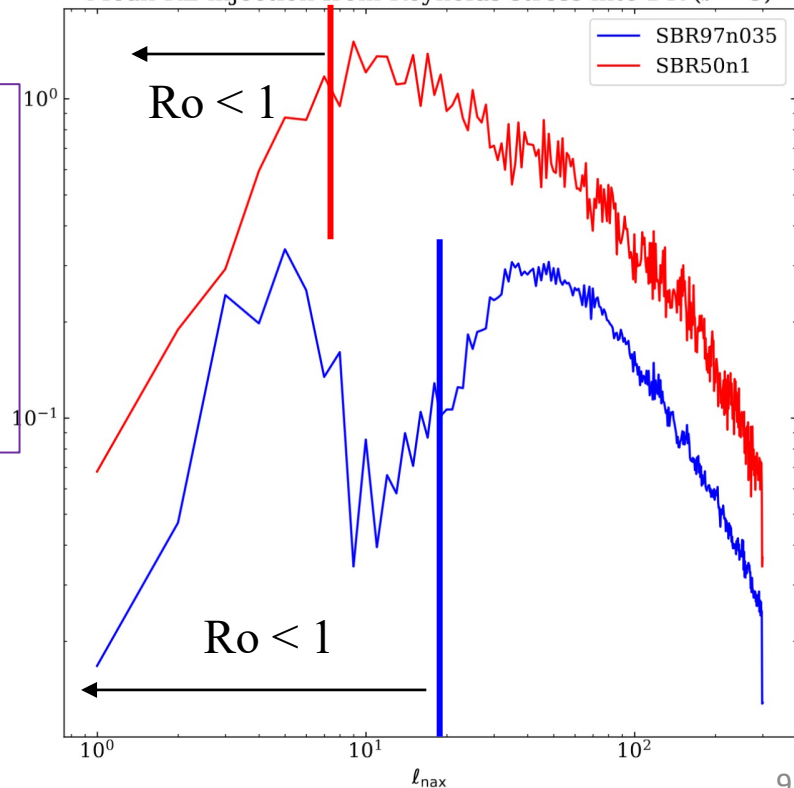


$$\partial_t E_\ell^K = \underbrace{\sum_{\substack{\ell_1, \ell_2 \\ \ell_{1,2} \geq |\ell_1 - \ell_2| \\ \ell_{1,2} \leq \ell_1 + \ell_2}} [\mathcal{R}_\ell(\ell_1, \ell_2)]}_{\text{Reynolds stress}} + \underbrace{C_\ell(\ell - 1, \ell + 1)}_{\text{Coriolis force}} - \underbrace{\mathcal{H}_\ell}_{\text{Pressure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

The scales contributing the most to energy transfer towards differential rotation have changed and are the one influenced by Coriolis force

Noraz et al. (in prep)

Mean KE injection from Reynolds stress into DR ($\ell = 3$)

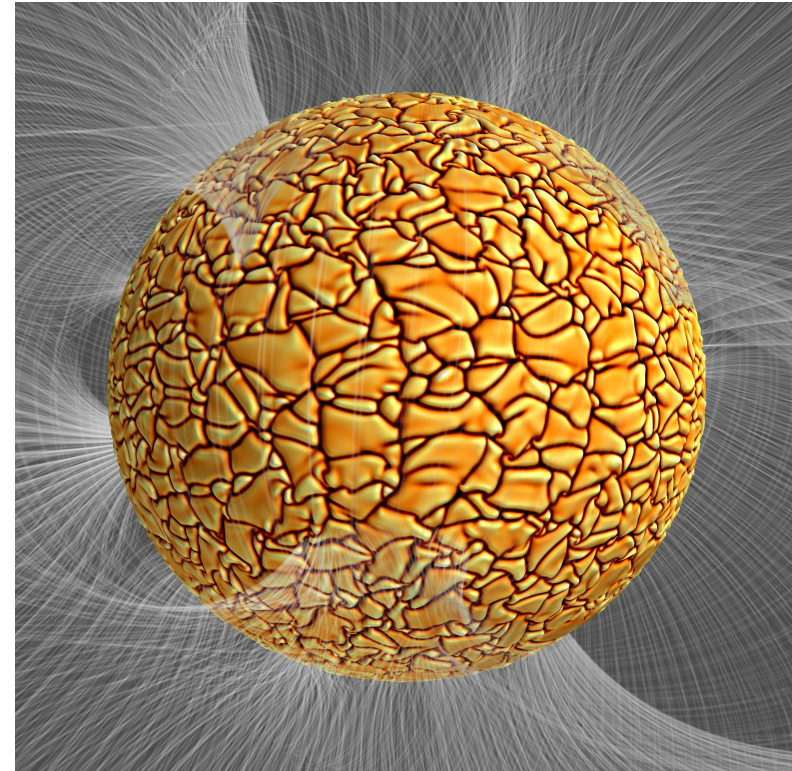


Conclusion & Take home messages

- 1) We are able to reproduce and maintain **solar-like differential rotation** at **high Reynolds number Re , L_{\odot} and Ω_{\odot}**
- 2) **Large-scales amplitudes decreased**, are still high compare to helio-sismic inversions, but seems to converge,
- 3) Convective **scales injecting energy into DR** are larger in solar cases, and **more influenced by Coriolis force**,
- 4) Effect seen on the spectral diagnostic **holds for different turbulence degrees (Re)** -> but still far from solar regime,

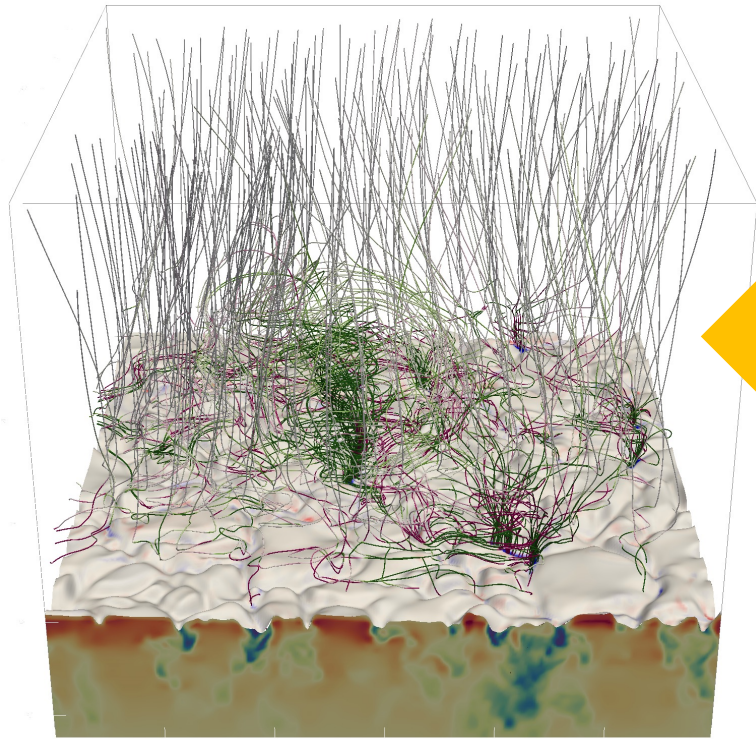
→ Noraz 2022 (PhD), Noraz et al. (in prep.)
(see also Hotta et al. 2023 review)

- Towards the investigation of magnetic effects

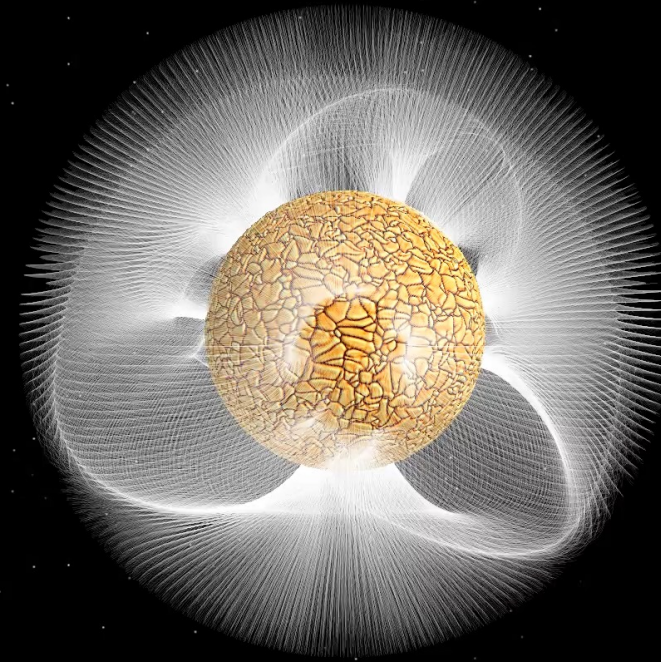


Toward a better modelling of the low solar-atmosphere

Code : Bifrost
Poster 55



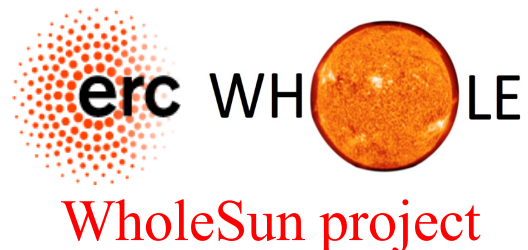
Numerical
coupling

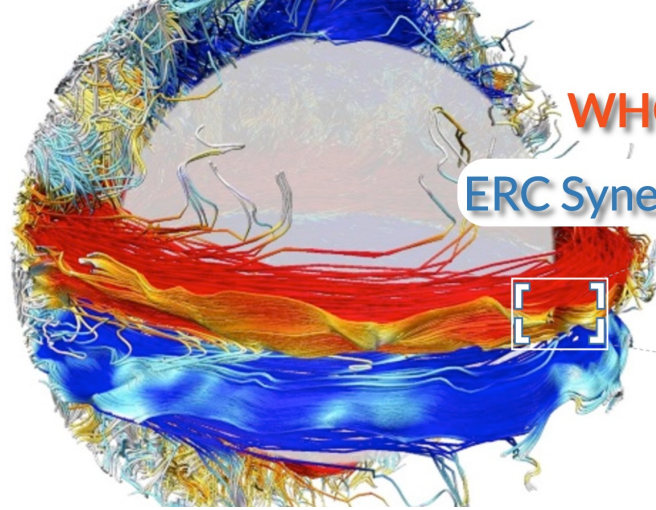


**WP4: Heating and thermo-dynamical
coupling of the solar atmosphere**

WP1: Dynamo & Convection

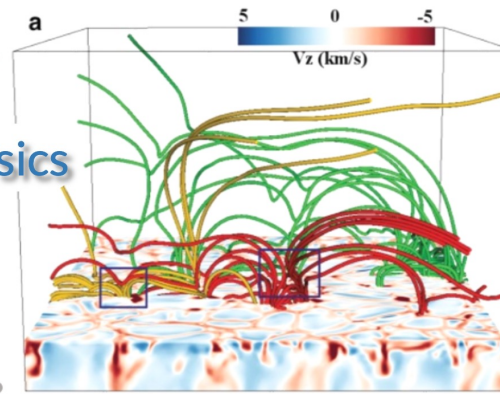
WP2: Magnetic Flux Emergence





WHOLE SUN PROJECT

ERC Synergy Grant in Astrophysics



WP1: Dynamo & Convection

WP2: Magnetic Flux Emergence

WP3: Solar eruptivity, flares and jets

WP4: Heating and thermo-dynamical coupling of the solar atmosphere

WP5: The Solar-Stellar connection

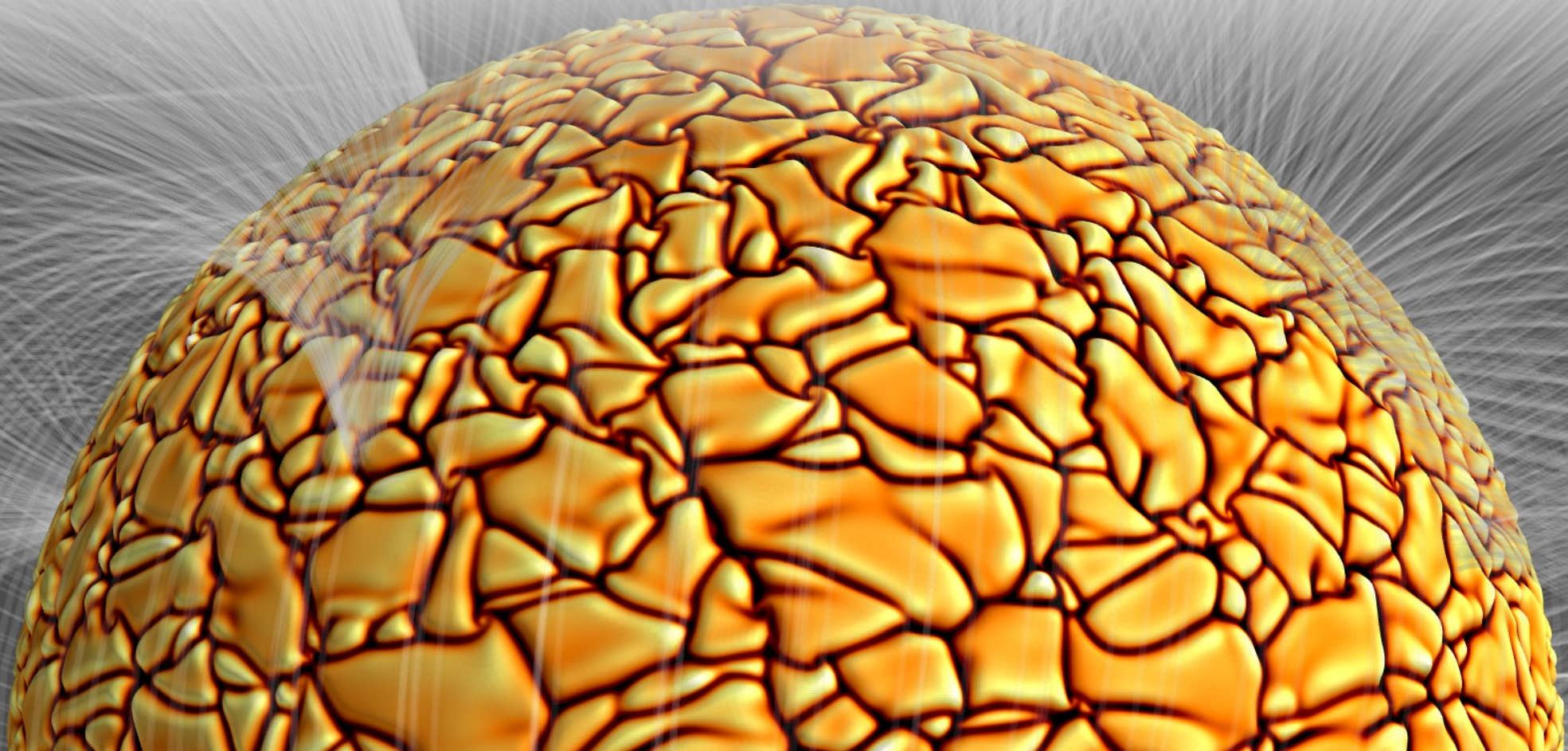
WPX: New exa-scale global solar code



3 weeks

Institut Pascal of University Paris-Saclay
from March 4 until March 22nd 2024

Thanks for you attention! Questions?



DE LA RECHERCHE À L'INDUSTRIE

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PNST 2024 - Marseille