

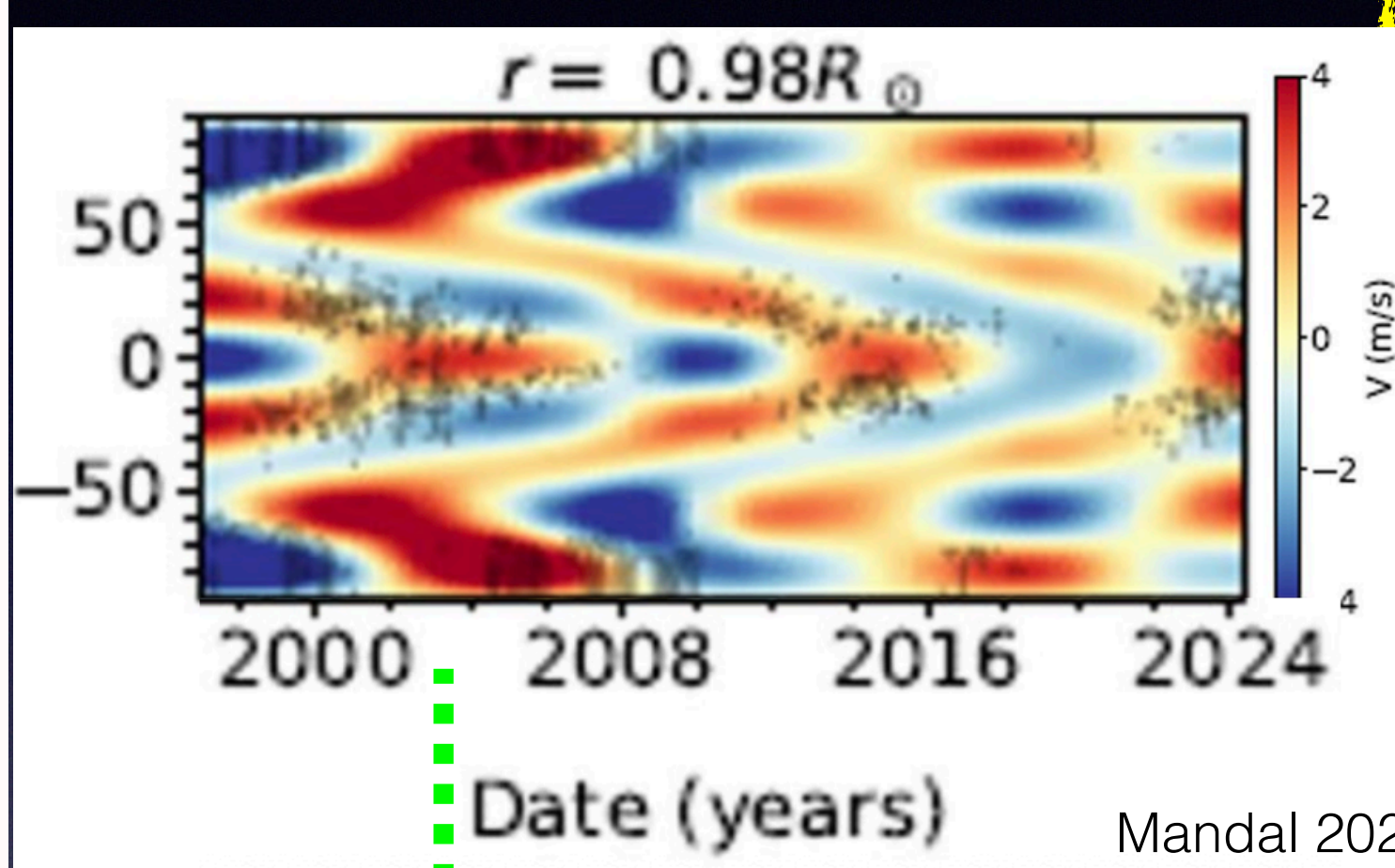
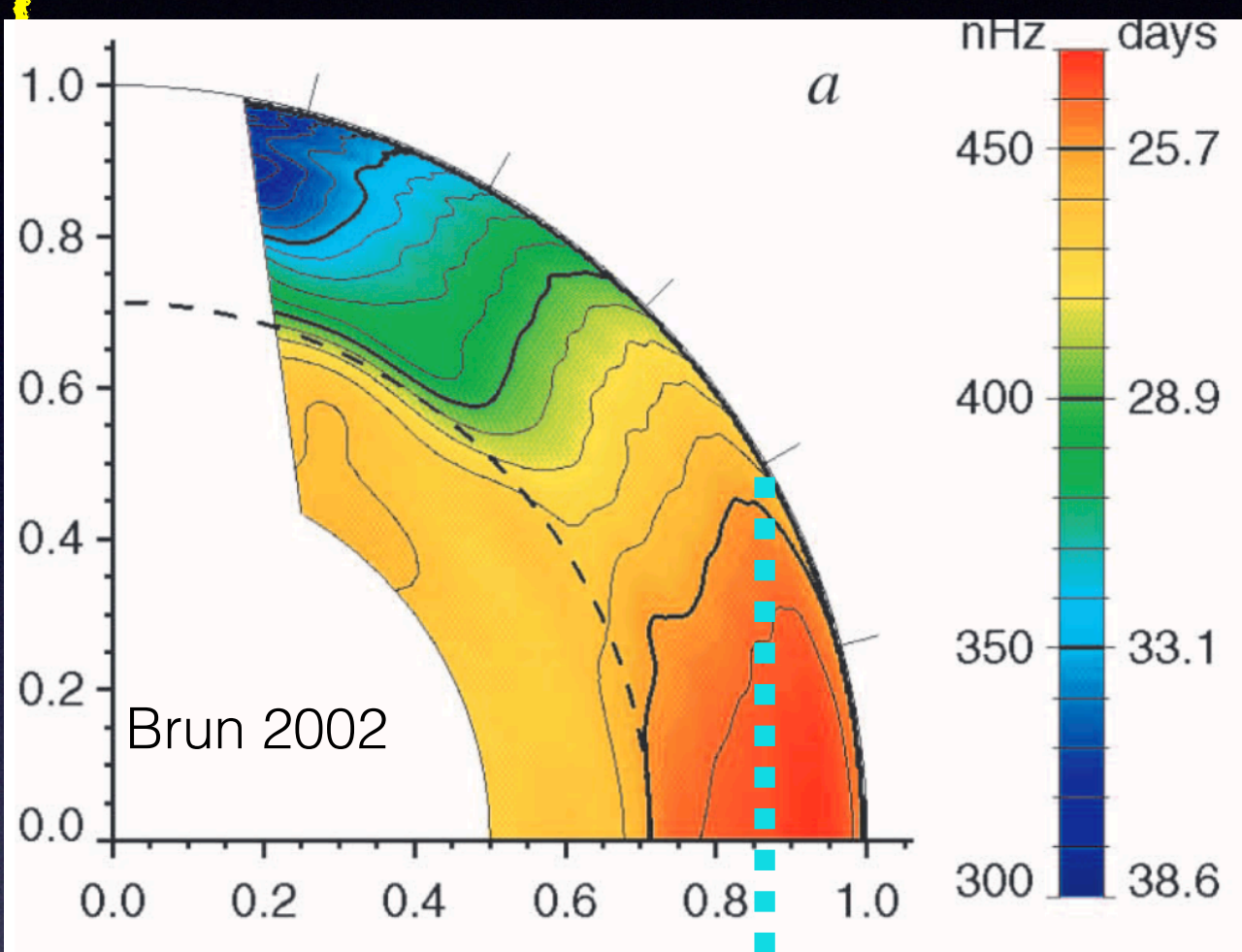
Systematic study of the low mass stars' rotation profiles

Nairabeze Alexandre*, Petitdemange Ludovic*, Belkacem Kevin*;

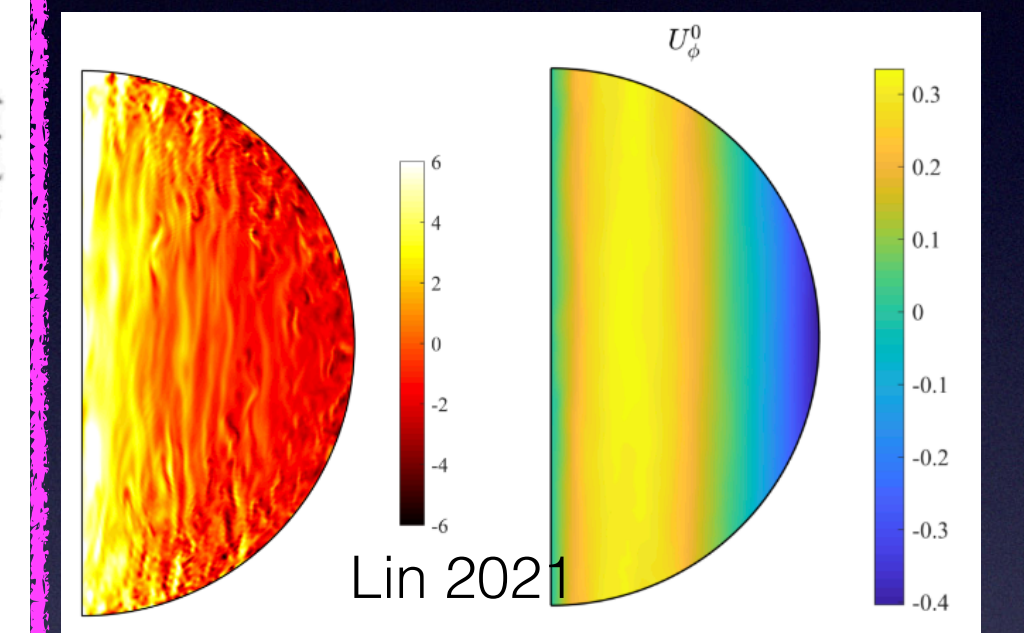
24th June 2026, SF2A 2026, Grenoble



Sun's internal/surface rotation profile observed



Correlation between the heat flux and the zonal wind in a 3D hydrodynamical rotating Boussinesq full sphere of gas



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Systematic study of the low mass stars' rotation profiles

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Aims

- Unveiling the rotation profile during the transition from a (SL) to an (AS) rotation profile at the end of the low mass star Main Sequence (MS).
- How the heat is transported before, during and after the transition?

0. Introduction

2 rotation profiles observed/expected for the low mass stars:

- Solar-Like (SL): equator rotates faster than the poles; **Not observed yet with certainty** for $Ro_c > 1$.
- Anti-Solar (AS): equator rotates slower than the poles; **Not observed yet with certainty** for $Ro_c < 1$.

II. Towards stellar parameters show some limits of the previous studies

Amplitude of the zonal flow at the equator's surface vs $\sqrt{Ro_c}$

- Reproduction of the 2 rotation profiles as in the literature: a (SL) rotation profile for $Ro_c < 1$ and an (AS) rotation profile even at $Pr = 1 \Rightarrow$ The Ro_c and Pr which are independent of the diffusivities do not catch properly the transition.
- The coefficient of variation of the axisymmetric heat flux $C_v = \sigma(Nu)/\langle Nu \rangle_c$ shows the same trend when the Ro_c is < 1 .
- The simulations with a high Nu_c at $Ro_c = 1$ are in **transition** and present 2 new rotation profiles: 3 different regimes for the heat flux distribution at the surface: Uniform (U), Poles hotter than the equator (PH), Equator hotter than the poles (EH).
- (U) (EH) $\xrightarrow{Ro_c < 1}$ (PH) $\xrightarrow{Ro_c < 1}$ (U) $\xrightarrow{Ro_c < 1}$ (EH) $\xrightarrow{Ro_c < 1}$ (U) $\xrightarrow{Ro_c < 1}$ (PH)
- The 2 last regimes are reached only at $Nu_c = 2$ due to the high level of turbulences.

Examples of the results for $Nu_c = 4, Pr = 1$:

- Correlation between Nu_c and v_z : $Ra < Ra_c$
- Anti-correlation between Nu_c and v_z : Coriolis regime: $Ro_c < 1$
- Any correlation between Nu_c and v_z : Coriolis -buoyancy regime: $Ro_c \approx 1$
- Anti-correlation between Nu_c and v_z : Buoyancy regime: $Ro_c > 1$

III. 2 new rotation profiles at $Ro_c = 1$ and 1 new convective regime

I. (a) Toward the (NSL) when a more realistic Nu_c is imposed?

I. (b) A cyclic inversion of the rotation profile between the (SL) and (AS) regimes like the (TO) in the Sun without θ (preliminary results)

2 regimes coexist simultaneously: Coriolis with the buoyancy and the Reynolds stress outside the (TC)

- The system is balanced between the meridional circulation and the Reynolds stress
- The inversion is due to lack of vigor of the imposed buoyancy and the Reynolds stress at mid-depth in a steady state
- Reason: A single large scale vortex is located along the rotation axis [14]

I. Star considered, its numerical model [1] and equations [11]

Low mass stars: Radiative core (ignored) and convective envelope:

- Using the Boussinesq approximation with a thick convective shell ($r \in [0.35, 1]r_s$)

Parameter	Ratio	IRL	Simu
Prandtl	$Pr = \frac{\nu}{\kappa}$	10^{-3}	0.1
Rayleigh	$Ra = \frac{g \alpha \Delta T r^3}{\nu \kappa}$	10^{20}	$10^5 - 10^7$
Ekman	$Ek = \frac{U \tau}{\rho \nu}$	10^{15}	$3 \cdot 10^4$
Polytropic index	$n = \log(\rho/\rho_0) / \log(r/r_0)$	12	4.5, 6
Nusselt	$Nu = 1 + \frac{q_{conv}}{q_{rad}}$	/	/
Conv. Rossby	$Ro_c = \frac{U_{eq} r_{eq}}{\nu}$	/	/
Ra mid-depth	$Ra_{mid} = Ro_c \sqrt{g \alpha \Delta T} / \nu$	/	/

Navier-Stokes, mass, energy, anelastic approximation:

- Navier-Stokes: $\rho \frac{Dv}{Dt} = -\nabla p + \nabla \cdot \mathbb{S} + \rho \mathbf{g}$
- Where \mathbb{S} is the Strain tensor
- Mass conservation: $\nabla \cdot (\rho \mathbf{v}) = 0$
- Energy (Entropy form): $\rho \frac{D\theta}{Dt} = \nabla \cdot (\mathbb{K} \cdot \nabla \theta) + \rho \mathbf{v} \cdot \nabla \theta$

Adiabatic backgrounds for the density, the gravity and the conductive entropy (gradient)

Conclusions / Perspectives

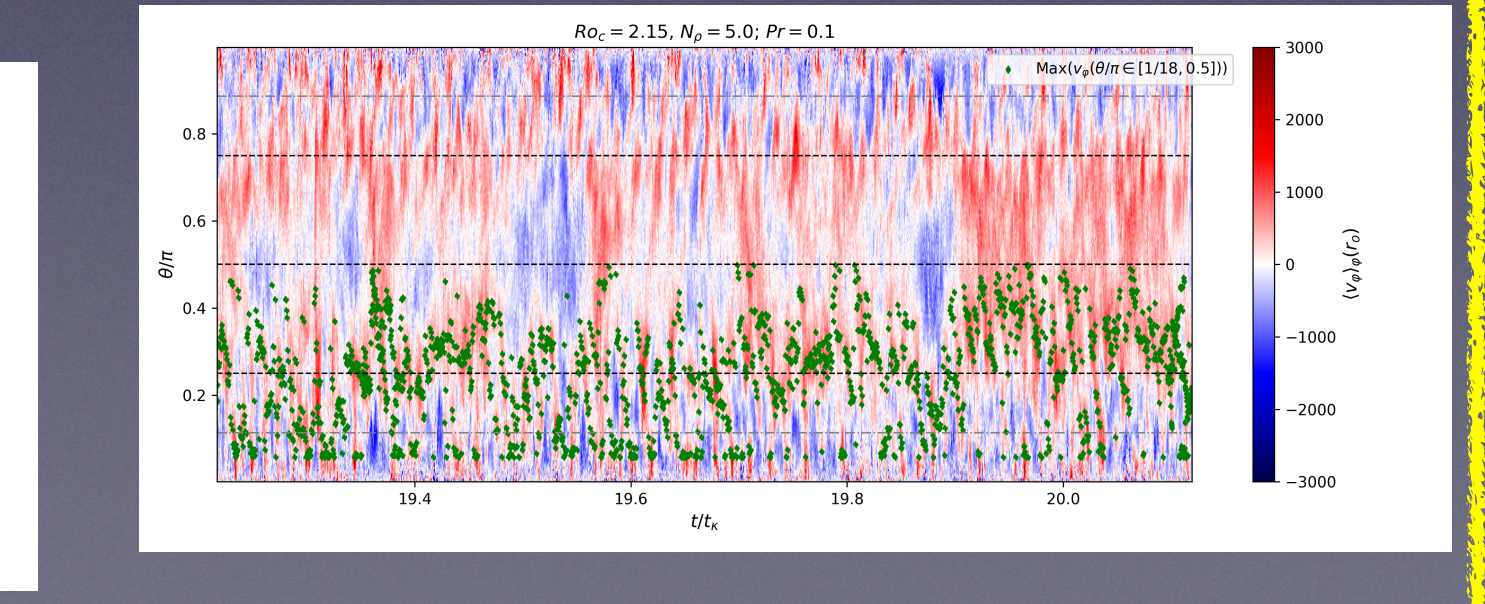
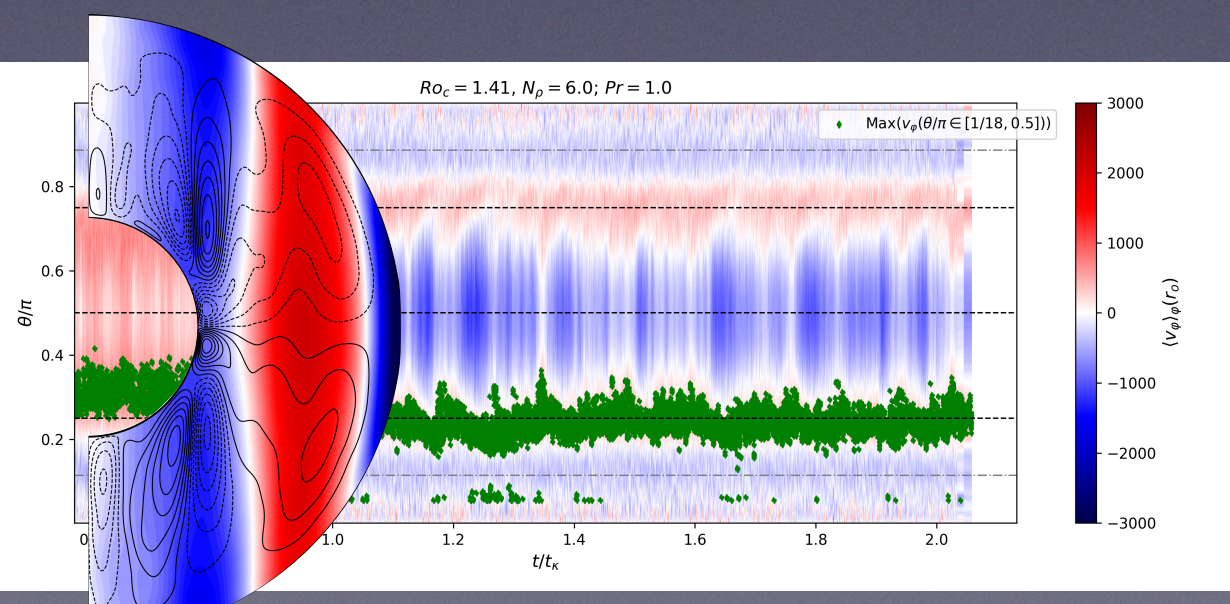
- We have seen the limits of the Ro_c for the transition (SL) (AS), and we want to improve this prescription by finding an other parameter and explain the 2 new rotation regimes.
- By adding a radiative zone (RZ) below the (CZ) in order to be closer to the reality, we want to see if we will observe the conical shape of the rotation at mid-latitude in the (SL) and (AS) low mass stars as in [12]

References

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3D hydrodynamical rotating simulations

- The Near Subsurface Shear Layer (NSSL) which reaches the mid-latitudes with some constant diffusivities?
- The Torsionnal Oscillations without a magnetic field?



3. A new convective regime with an (AS) profile in an anelastic spherical shell

