Rotating Double-Diffusive Convection: Flows and Dynamos in Stably Stratified Deep Layers of Planets

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In deep fluid layers of planets (liquid cores, gas giants, icy moons' subsurface oceans), the density depends on temperature and chemical composition, which diffuse at very different rates. **Double diffusive instabilities** can then generate **large-scale flows**. We address this problem with different approaches[1]:

1) Calculating the **instability onset** (SINGE eigensolver), showing large decreases of the critical Rayleigh numbers.
2) Performing **direct simulations** (XSHELLS code) in the **fingering regime**, showing the emergence of **strong zonal flows at a large scale**.

Considering the **early Earth**, we show that double diffusion can reduce the critical Rayleigh number by four decades, suggesting that its core was prone to **turbulent rotating double-diffusive convection** (RDDC), with **large-scale zonal flows**. Using the induction equation, we finally study the **dynamo capability** of these flows to assess their relevance for planetary dynamos (e.g. for gas giants).

Problem method & onset

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} = -\frac{2}{Ek}\mathbf{1}_z \times \boldsymbol{u} - \nabla p + \boldsymbol{\nabla}^2 \boldsymbol{u} + \left(Ra_T \Theta + Ra_C \xi \right) r \mathbf{1}_r,$$

$$\frac{\partial \Theta}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\Theta = \frac{1}{Pr} \left(2\, \boldsymbol{r} \cdot \boldsymbol{u} + \nabla^2 \Theta \right),$$

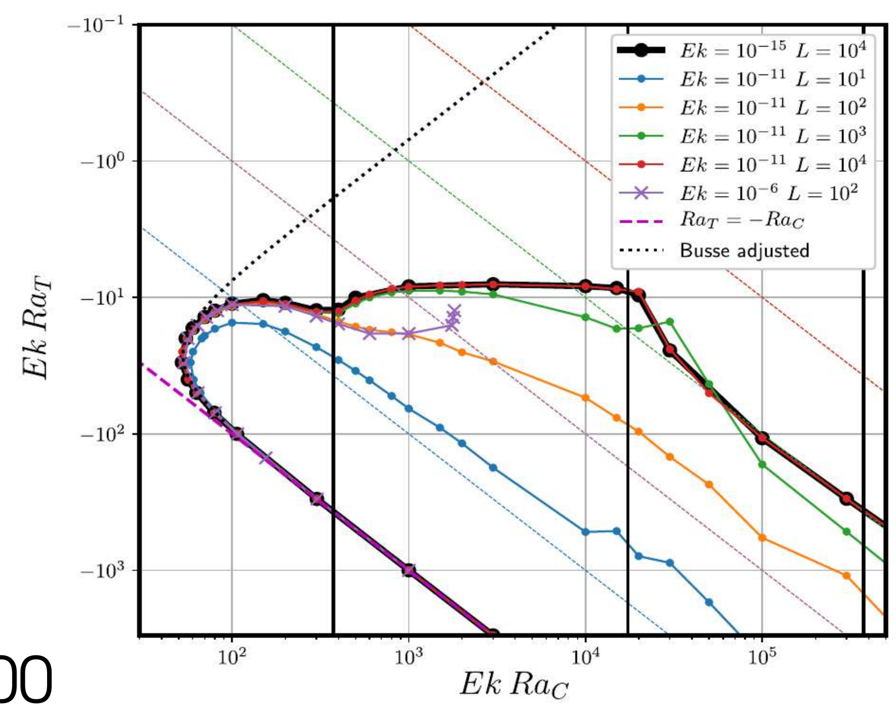
$$\frac{\partial \xi}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\xi = \frac{1}{Sc} \left(2\, \boldsymbol{r} \cdot \boldsymbol{u} + \nabla^2 \xi \right),$$

Equations of motion

- **Full sphere**, radial gravity
- **Internal** sources of **buoyancy**
- Boundary: **no-slip** & **fixed flux**
- **SINGE**[2]: linear eigensolver (onset)
- **XSHELLS**[3]: time step nonlinear equations.

Earth parameters:

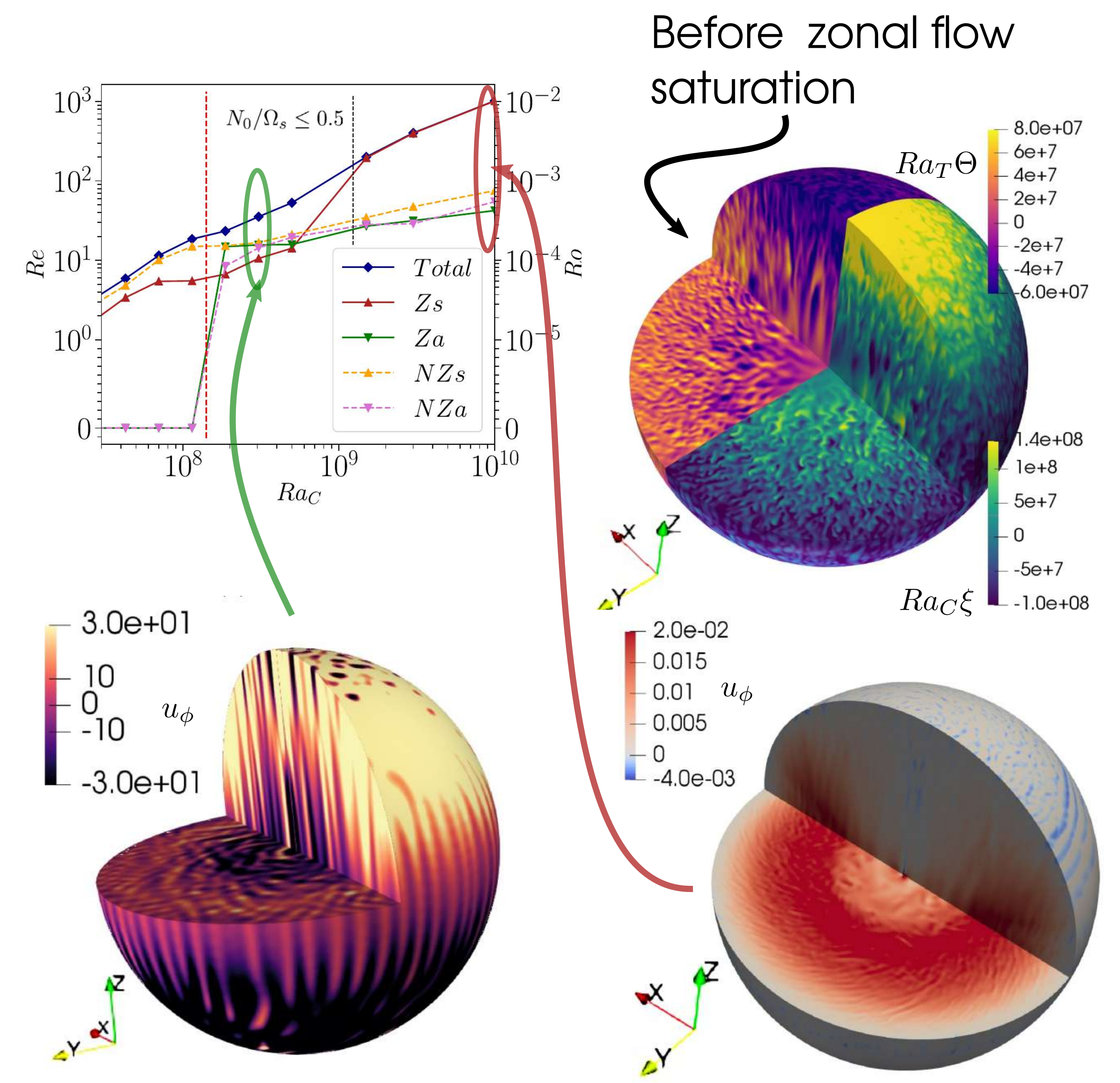
L	Lewis	κ_T/κ_C	10^4
Pr	Prandtl	ν/κ_T	0.01 - 0.1
Sc	Schmidt	ν/κ_C	$10^2 - 10^3$
Ek	Ekman	$\nu/(\Omega_s R^2)$	10^{-15}



m=1 (onset), Sc=100

Reach Earth's core parameters!

Fingering and zonal flows

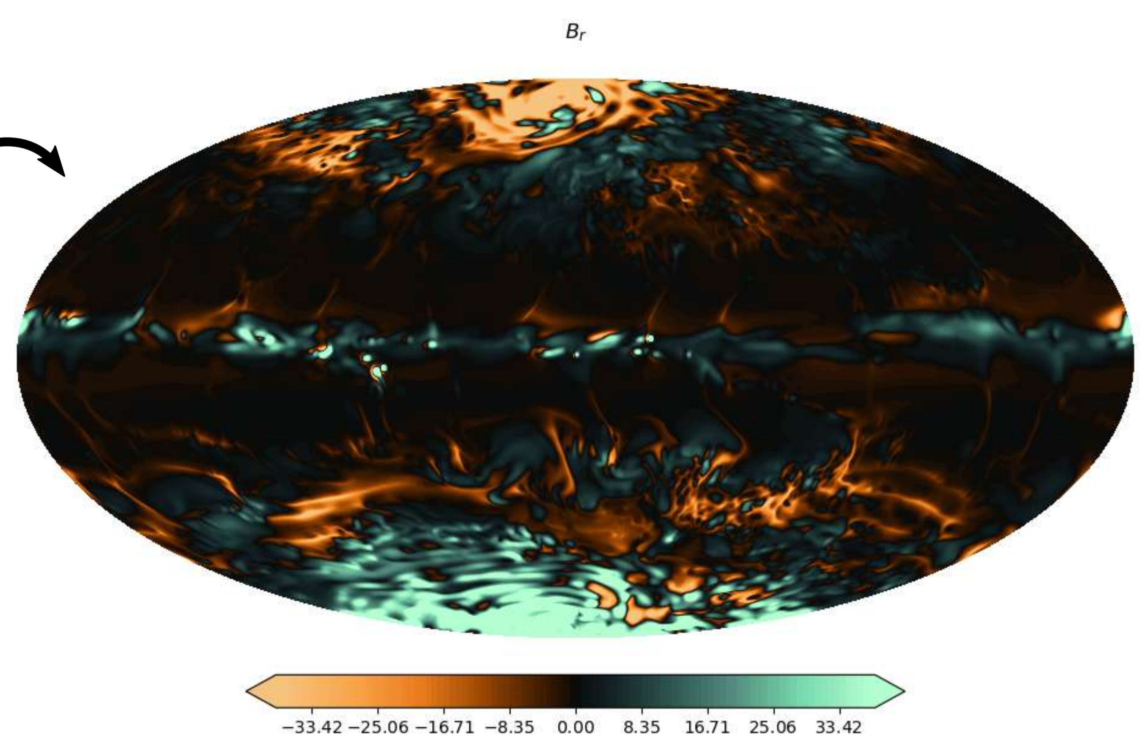


Equatorially Anti-symmetric — Equatorially symmetric

Toward a RDDC driven dynamo ?

Dynamos in RDDC have already been obtained[5] for large *Pm* (~300) in semi-convection, but not in the fingering regime.

We found a parameter space which is viable to generate **dynamos in the fingering regime**, for *Pm* as low as *Pm = 0.4*.



$Pm = 4$

$Ek = 10^{-5}$

$L = 10$

Different types of dynamos are obtained :

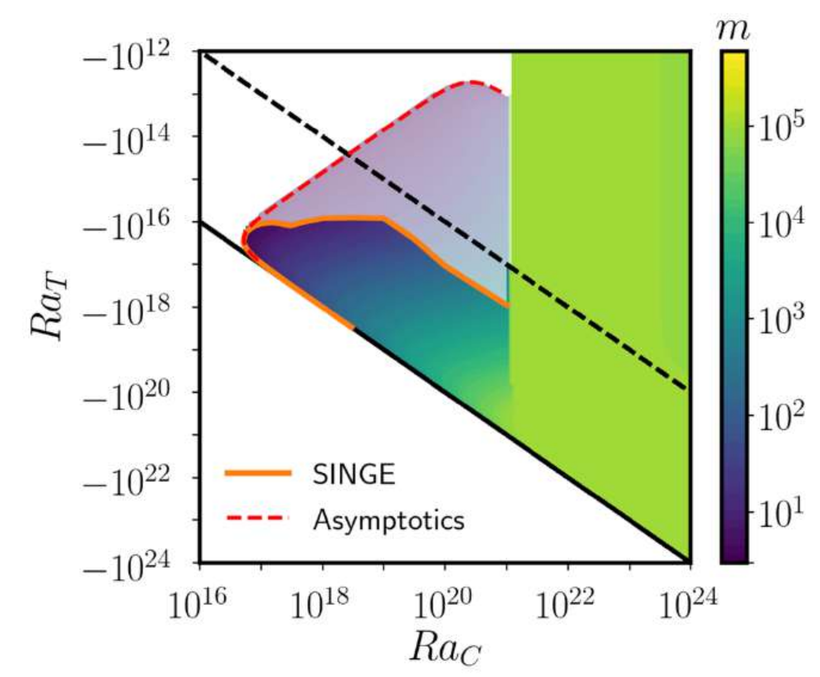
Dipolar/quadripolar, high/low field intensity

Motivated by **gas giants**, flows and dynamos in the **semi-convection** regime will be explored.

How about the early Earth core?

Early Earth core is expected to be stably stratified (below black dashed line) with uncertain parameters.
The onset is reduced from $Ra_C \sim 10^{21}$ to 10^{17} with RDDC.

Early Earth core might be prone to **turbulent RDDC**, with **large-scale zonal flows** (far from the onset).



Confirmed in **spherical shells** by C. Guervilly[4].

[1] R. Monville, J. Vidal, D. Cébron, and N. Schaeffer, "Rotating double-diffusive convection in stably stratified planetary cores," GJI 2019
[2] J. Vidal and N. Schaeffer, "Quasi-geostrophic modes in the Earth's fluid core with an outer stably stratified layer," GJI 2015.
[3] N. Schaeffer, "Efficient spherical harmonic transforms aimed at pseudospectral numerical simulations," G^3, 2013.
[4] C. Guervilly, "Fingering convection in the stably-stratified layers of planetary cores," preprint, 2022.
[5] J. F. Mather and R. D. Simitev, "Regimes of thermo-compositional convection and related dynamos in rotating spherical shells," GAFD, 2021

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