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

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

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

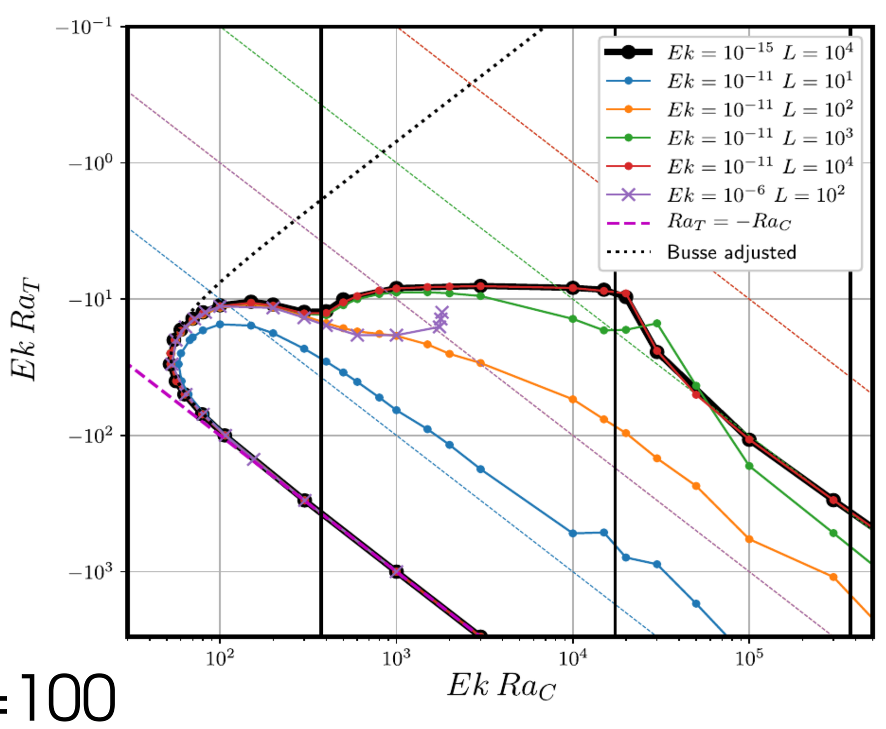
$$\frac{\partial \xi}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\xi = \frac{1}{Sc}\left(2\,\boldsymbol{r}\cdot\boldsymbol{u} + \nabla^2\xi\right),$$

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}

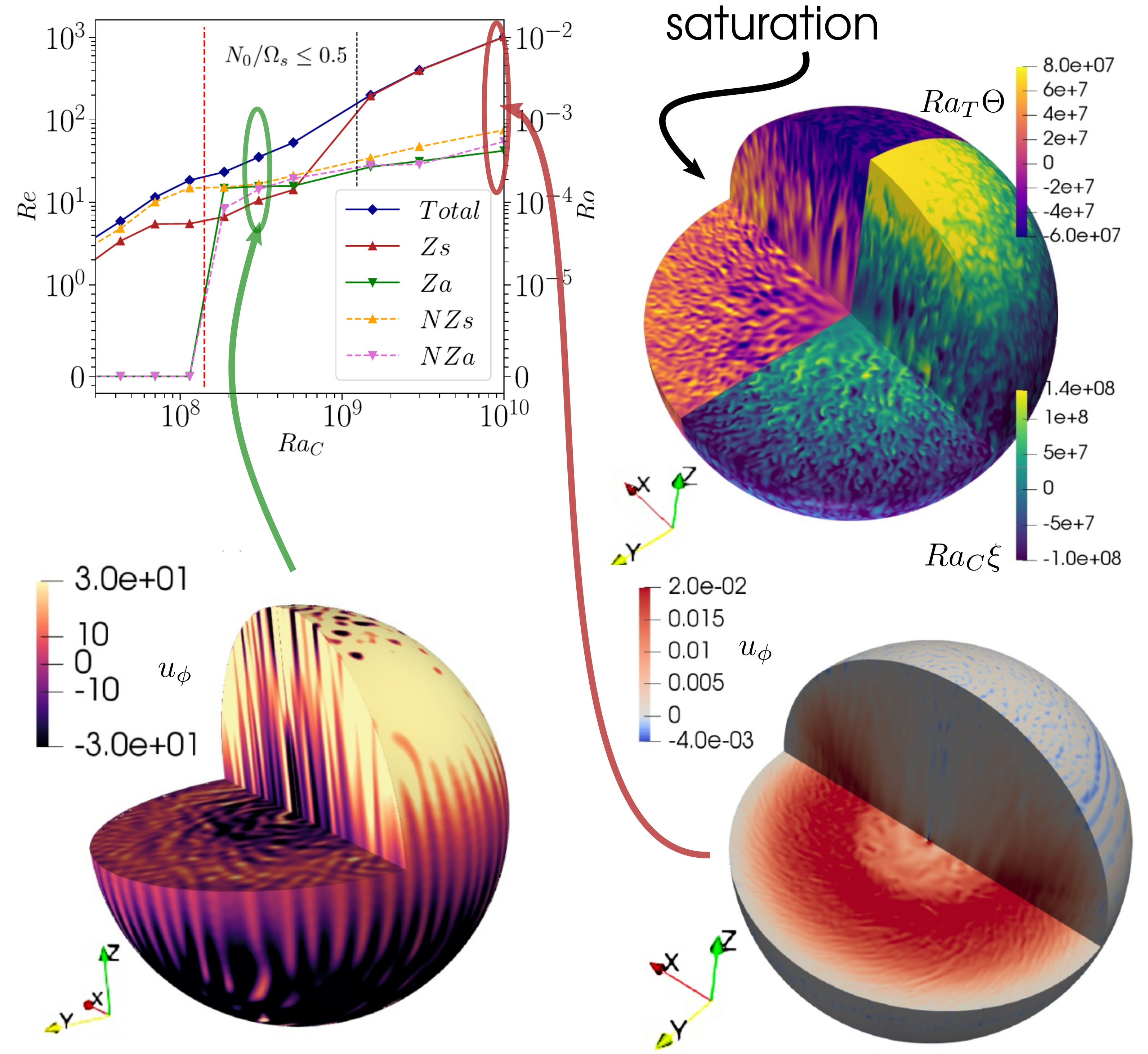


m=1 (onset), Sc=100

Reach Earth's core parameters!

Fingering and zonal flows

Before zonal flow saturation



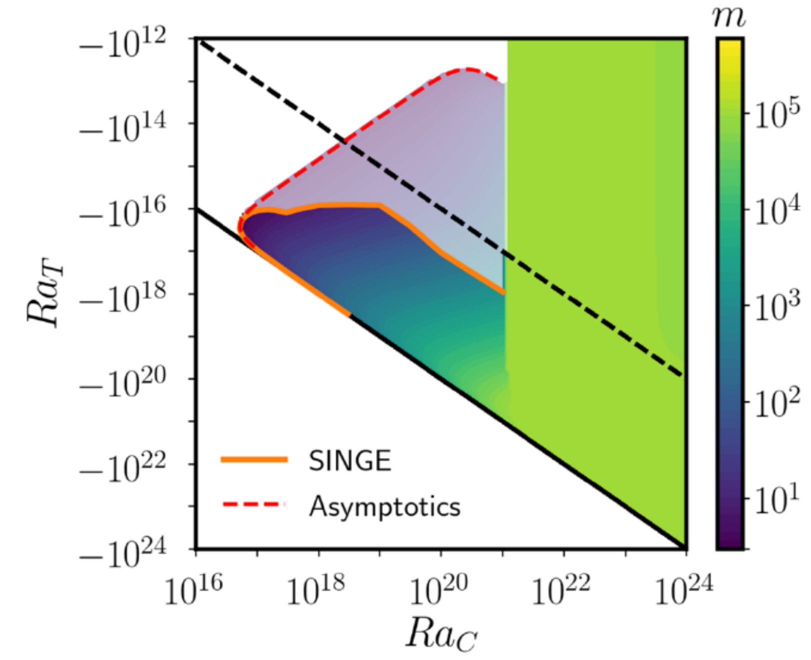
Equatorially Anti-symmetric Equatorially symmetric

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].



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.

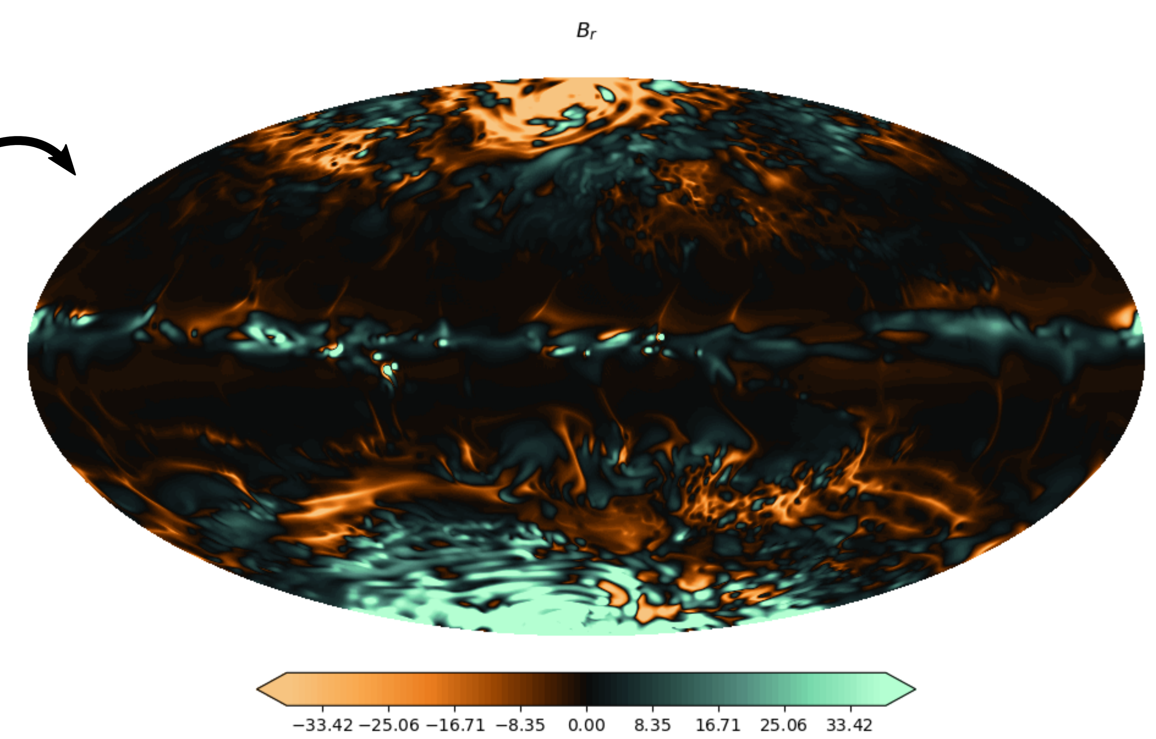
We found a parameter space which is viable to generate **dynamos in the fingering regime**, for *Pm* as low as *Pm* = 0.4.

Radial magnetic field

$Pm = 4$

$Ek = 10^{-5}$

$L = 10$



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.

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[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