Generation of planetary core zonal flows by orbital forcings or fingering convection

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Zonal flows (ZF) generation is a **long-standing issue** in rotating fluids, possibly key for the dynamics of **planetary fluid layers** (e.g. planetary liquid cores). These flows can indeed modify angular **momentum exchanges** between liquid and solid layers[1]. Moreover, they can be **unstable**[2,3], which could sustain **space-filling turbulence** and **mixing**.

ZF of planetary liquid cores are usually studied as emerging from convection in rapidly **rotating fluid-filled spheres**. Here, we consider **two alternative origins** for such flows:

(1) Orbital forcings (e.g. tides, precession), notably through **nonlinear effects within the Ekman layer**[4]. These flows are of interest because they survive in the relevant planetary regime of both vanishing forcings and viscous effects. Their presence, and the competition with bulk driven zonal flows, are considered for various planets and moons.

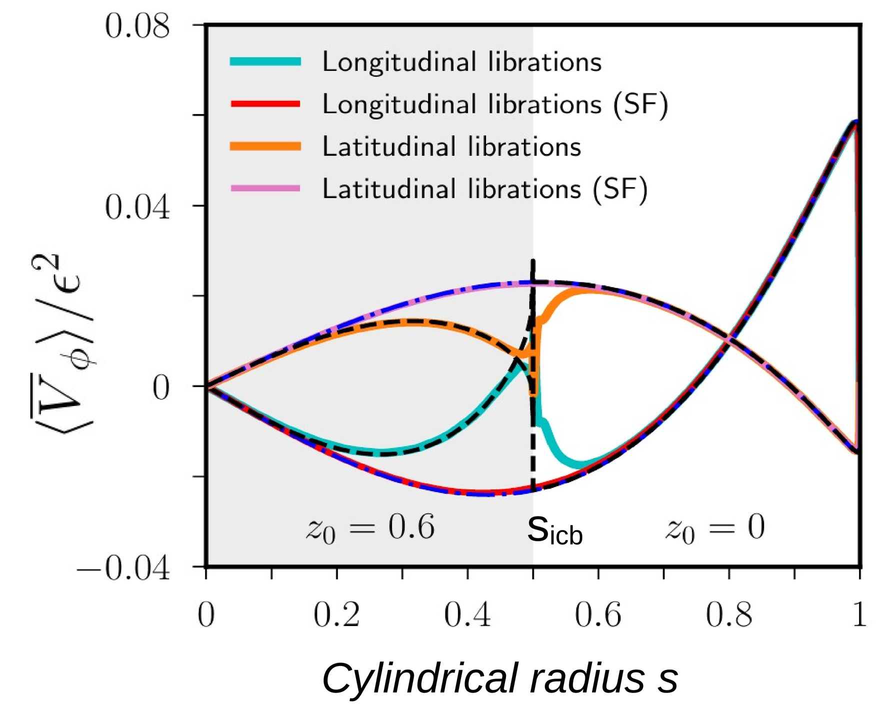
(2) Rotating double-diffusive convection (RDDC) in stably stratified planetary cores[5]. Equatorially symmetric & antisymmetric large-scale ZF are found. Considering the early Earth core, we find that double diffusion can reduce the critical Rayleigh number by **four decades**, and we suggest that it was prone to **turbulent RDDC**, with large-scale ZF.

Zonal flows due to orbital forcings[4]

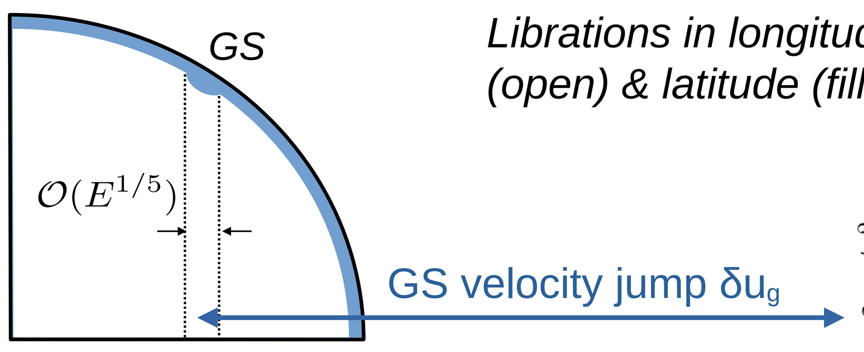
Method : theory & simulations

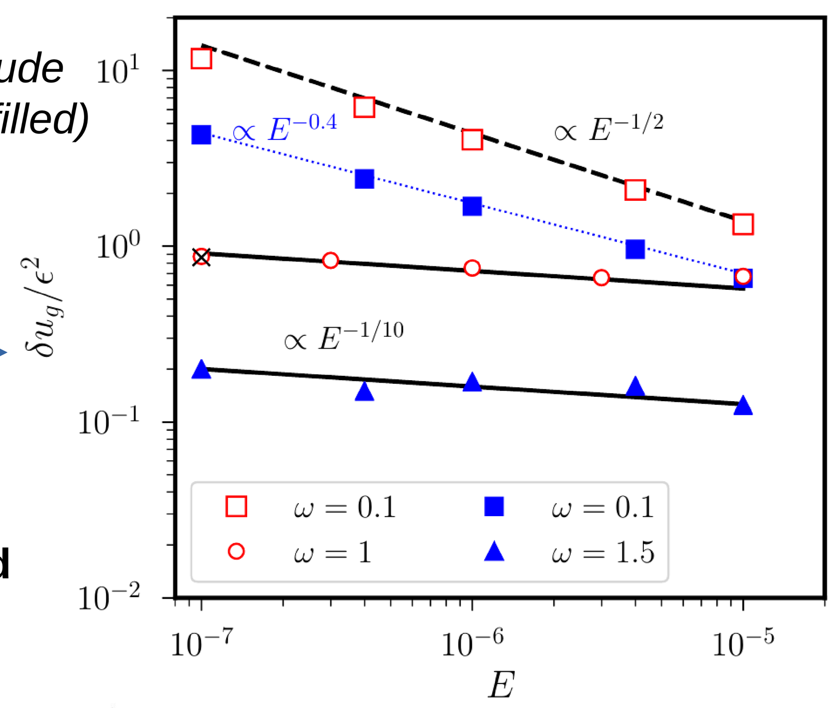
- **Boundary-layer theory**
- **Weakly nonlinear** effects
- **Spatial & temporal** perturbations
- Extended to **spheroids**
- Validation: **XSHELLS** & **NEK5000**

=> **Good agreement,** even with
- **spheroidal shell** geometries
- **different** inner & outer **flattenings**
- **different** inner & outer **forcings**



Geostrophic shear (GS) at critical latitudes

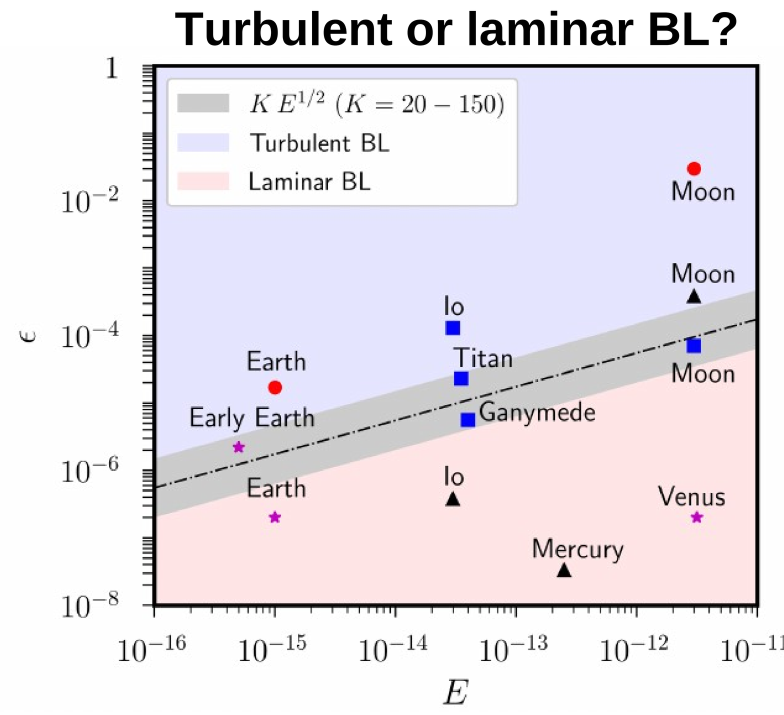


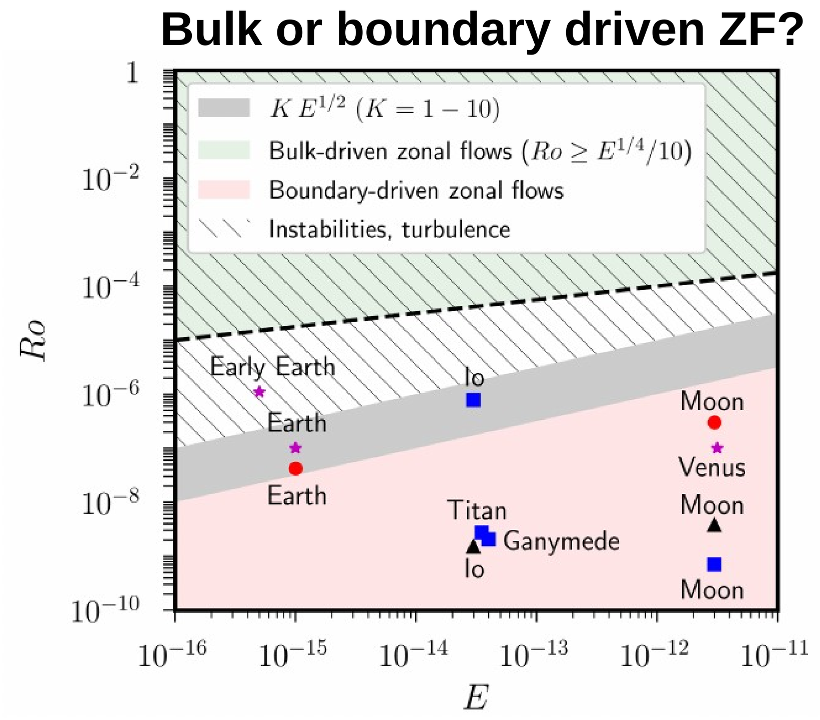


- **$E^{-1/2}$ scaling** when the **GS** enters the **Ekman** layer (at **s~1, for ω~0**)
- **Previously proposed**[6] $E^{-1/10}$ scaling **valid** for various **frequencies & forcings**

But for precession $\delta u_g/\epsilon^2 \propto E^{-3/10}$ **... Why?**

ZF in planets & moons





Red circles: precession. Blue squares: longitudinal librations. Black triangles: latitudinal librations. Magenta stars: tides. – Rossby number Ro = O(β) for tides or Ro = O(β) for precession & libration, with β the typical boundary (equatorial or polar) ellipticity.

- Both **laminar** & **turbulent** boundary layers (**BL**) can be expected
- **Bulk-driven** ZF are likely **irrelevant**

=> **Our** theoretical **ZF** (based on laminar BL) **is expected in several bodies**

Zonal flows due to fingering convection[5]

Problem, method & onset

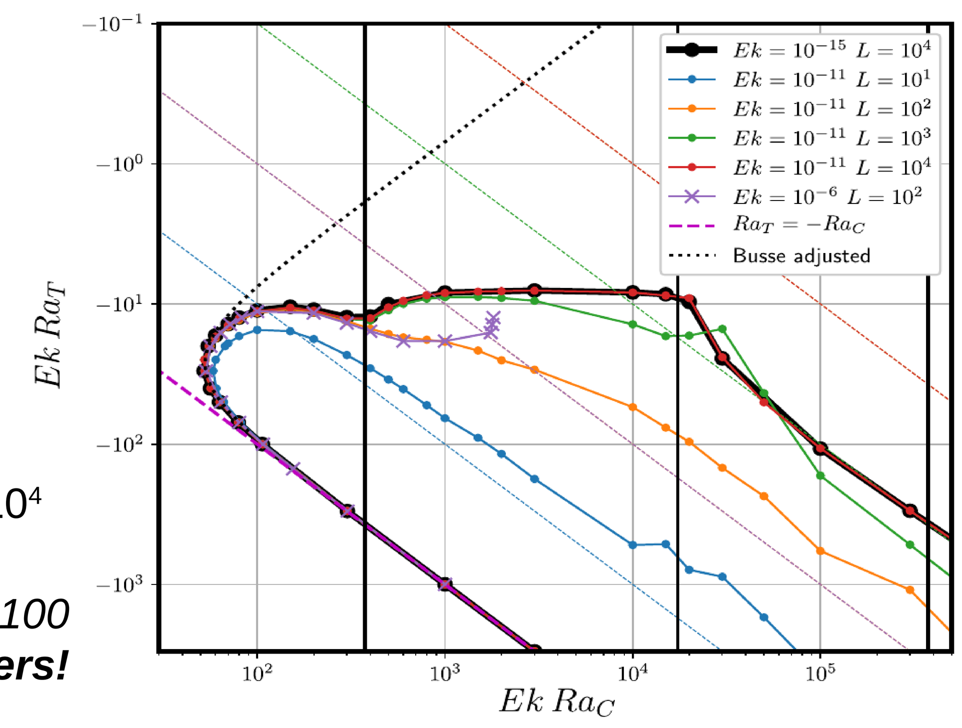
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} = -\frac{2}{Ek}\boldsymbol{1}_z \times \boldsymbol{u} - \nabla p + \boldsymbol{\nabla}^2\boldsymbol{u} + (Ra_T\,\Theta + Ra_C\,\xi)\; r\boldsymbol{1}_r,$$

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

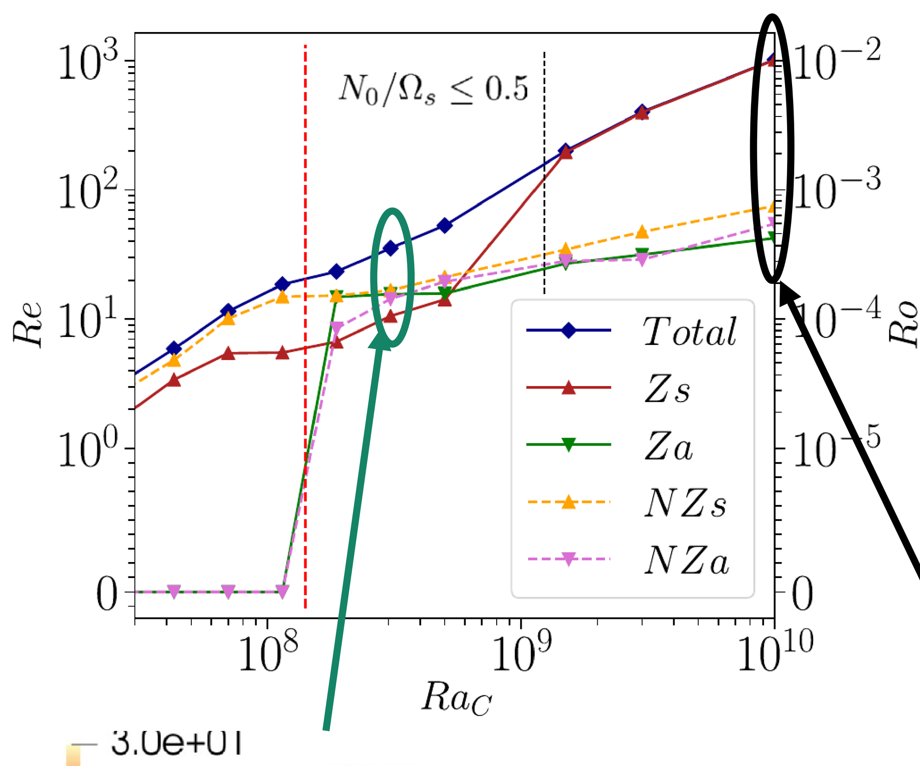
$$\frac{\partial \xi}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\xi = \frac{1}{Sc}\left(2\,\boldsymbol{r}\cdot\boldsymbol{u} + \nabla^2\xi\right),$$

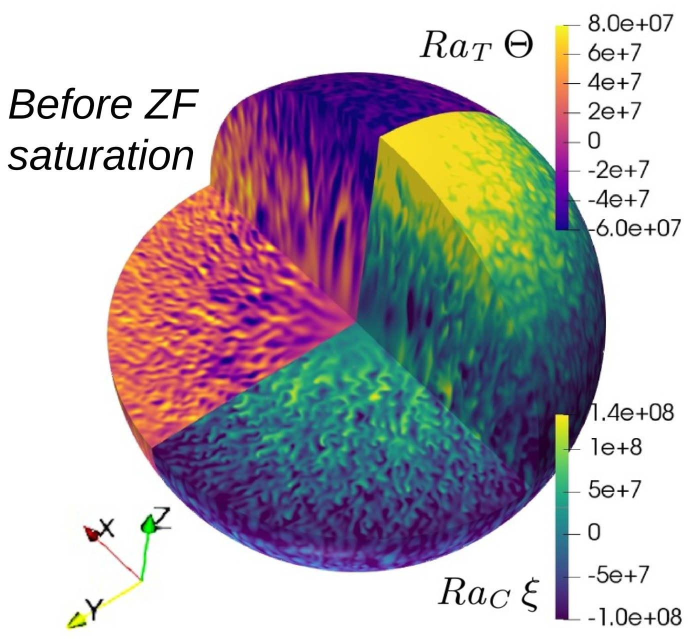
- **Full sphere**, radial gravity
- **Internal** sources of **buoyancy**
- Boundary: **no-slip** & **fixed flux**
- **SINGE**[7]: linear eigensolver (onset)
- **XSHELLS**[8]: time step nonlinear eq.
- **Earth**: Ek=10^{-15}, Sc=10^2-10^3, L=Sc/Pr=10^4

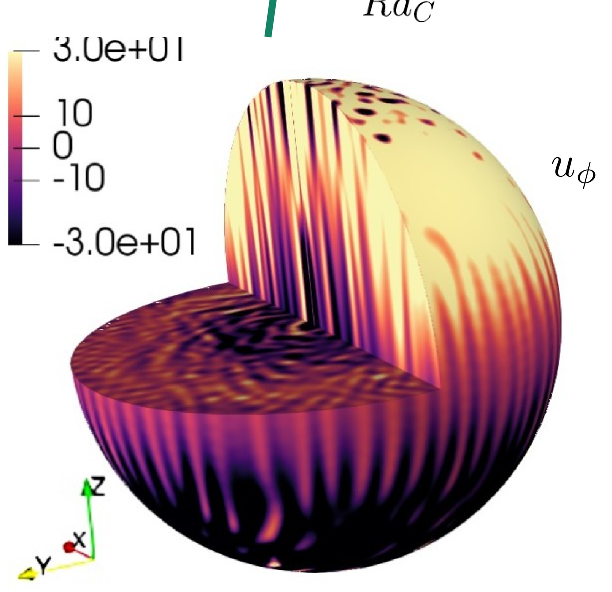
m=1 (onset), Sc=100
=> Reach Earth's core parameters!



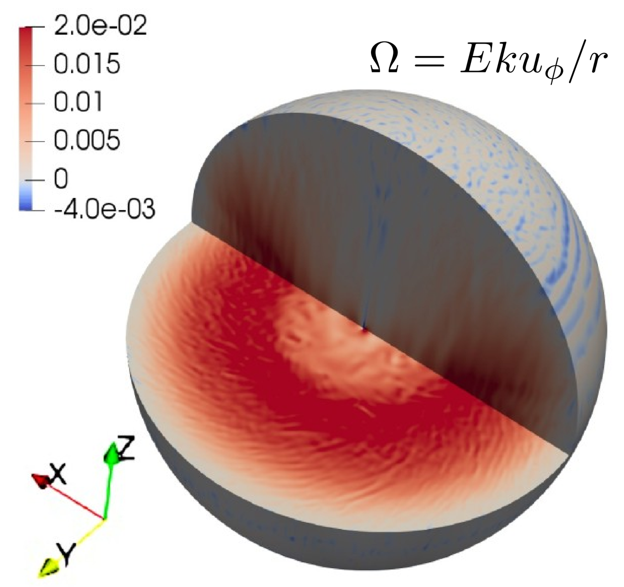
Fingering & zonal flows (ZF)







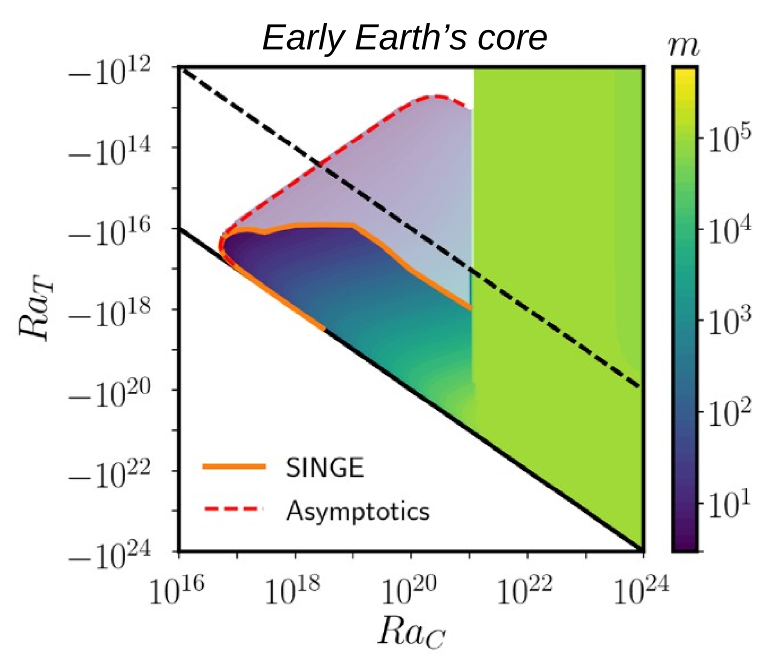
ZF: equatorial antisymmetry



ZF: equatorial symmetry

Fingering & ZF in the Early Earth's core ?

- **Double-diffusion** is only key for **Ra$_T$ ~ -Ra$_C$**
- **Early Earth's core onset** reduced from Ra_C~10^{21} to 10^{17} (by the thermal field)
- Suggest that the **early Earth core** was prone to **turbulent RDDC**, with **large-scale ZF**
- Confirmed in spherical **shells** by C. **Guervilly** (https://arxiv.org/abs/2205.01761): *ZF exceed the non-axisymmetric flow for large Ra*



=> **Perspective**: magnetic field effect?

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