A systematic experimental study of spherical shell rotating convection in water and liquid gallium.

velocity measurements, scaling relationships, flow structure (with the help of numerical simulation).

Julien Aubert, Daniel Brito, Henri-Claude Nataf, Philippe Cardin and Jean-Paul Masson.

Laboratoire de Géophysique Interne et Tectonophysique, Grenoble, France.

1– Flow in the Earth's Core

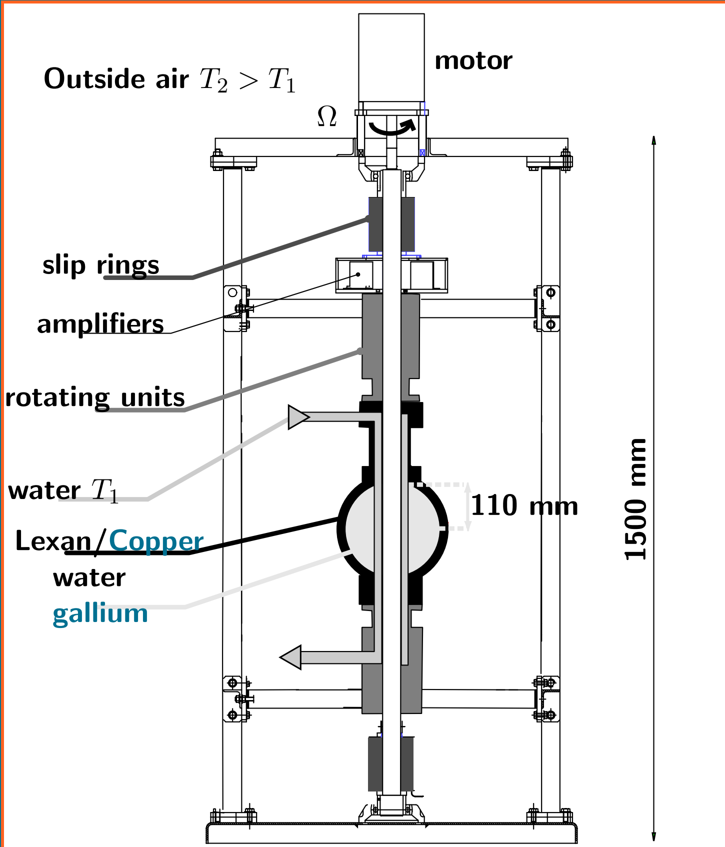
The existence of a dynamo requires the magnetic Reynolds number $Re_m = UD/\lambda$ to be of order 100.

With an usual ratio of kinematic over magnetic diffusivity of 10^6, this implies a kinematic Reynolds number of order $Re = 10^8$, i.e. an highly turbulent flow.

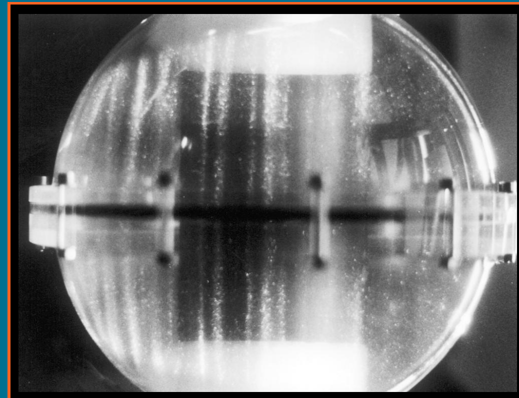
With typical values of the Ekman number of $E = 10^{-14}$ flow is also highly constrained by the Coriolis force.

Laboratory experiments allow to reach closer to these conditions, and calibrate numerical models.

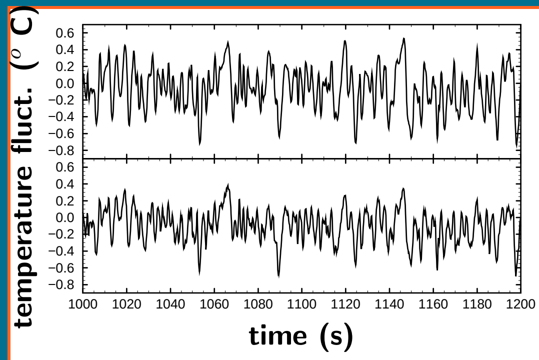
2– Rotating convection experiment



Water



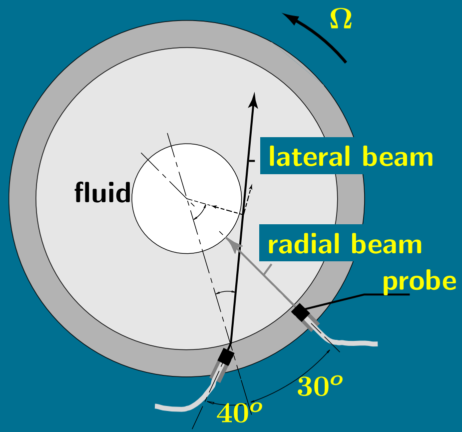
Gallium

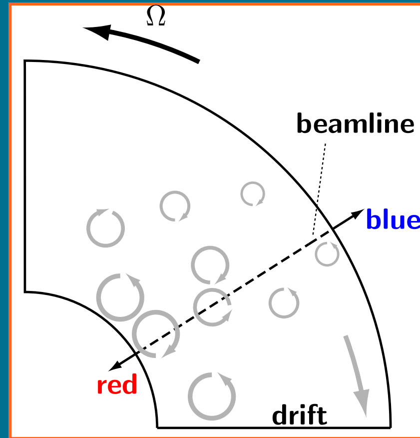


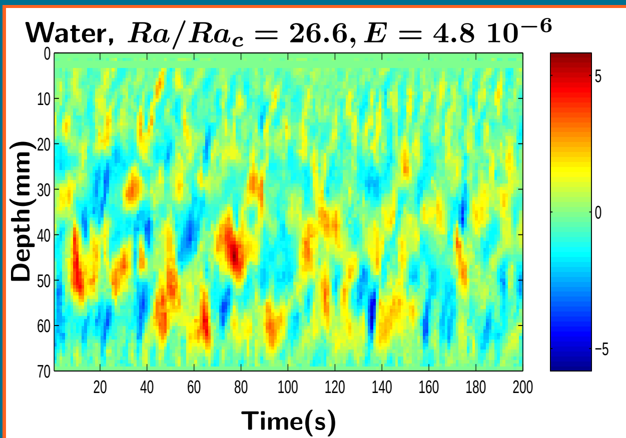
3– Parameter space

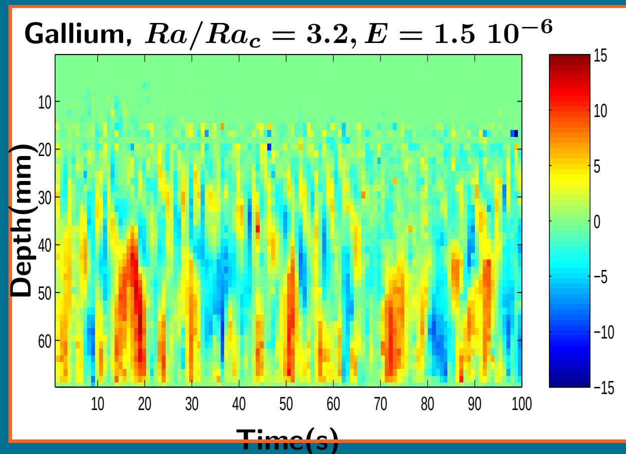
- The **Ekman** number $E = 10^{-6} - 10^{-7}$.
- The **Rayleigh** number $Ra = 2 - 100$ times the critical value.
- The **Prandtl** number $P = \begin{cases} 7 & \text{water} \\ 0.025 & \text{liquid gallium.} \end{cases}$

4– Ultrasonic Doppler Velocimetry

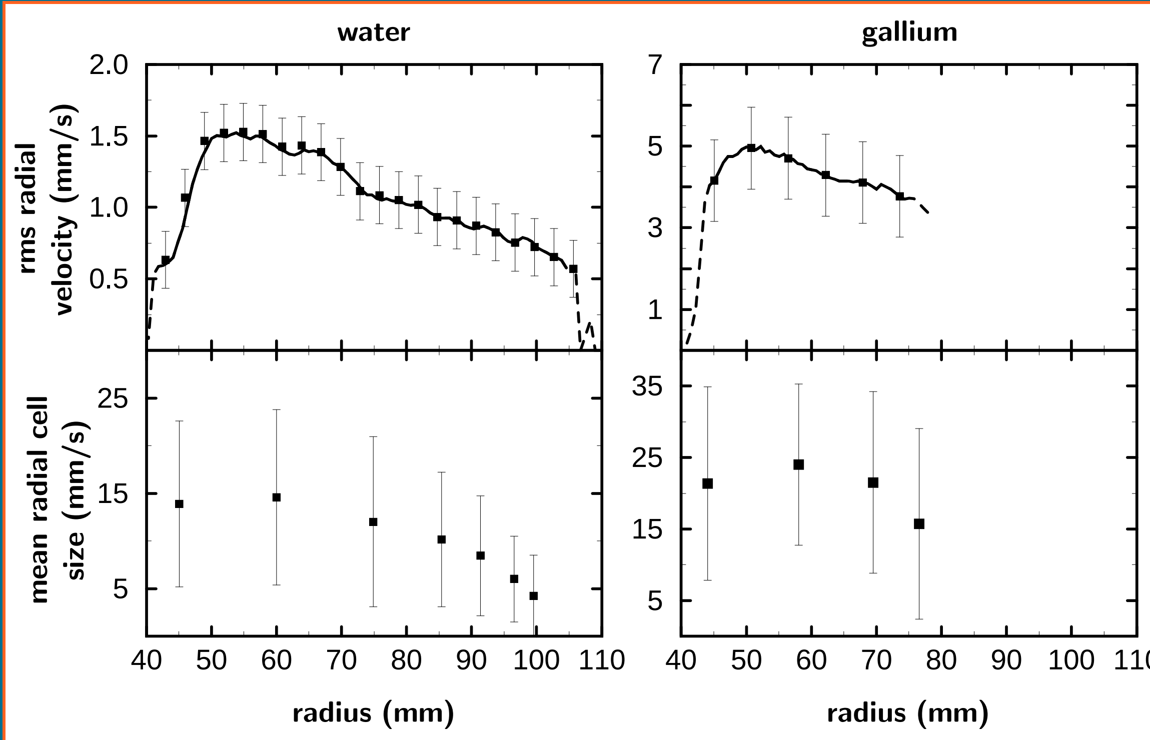




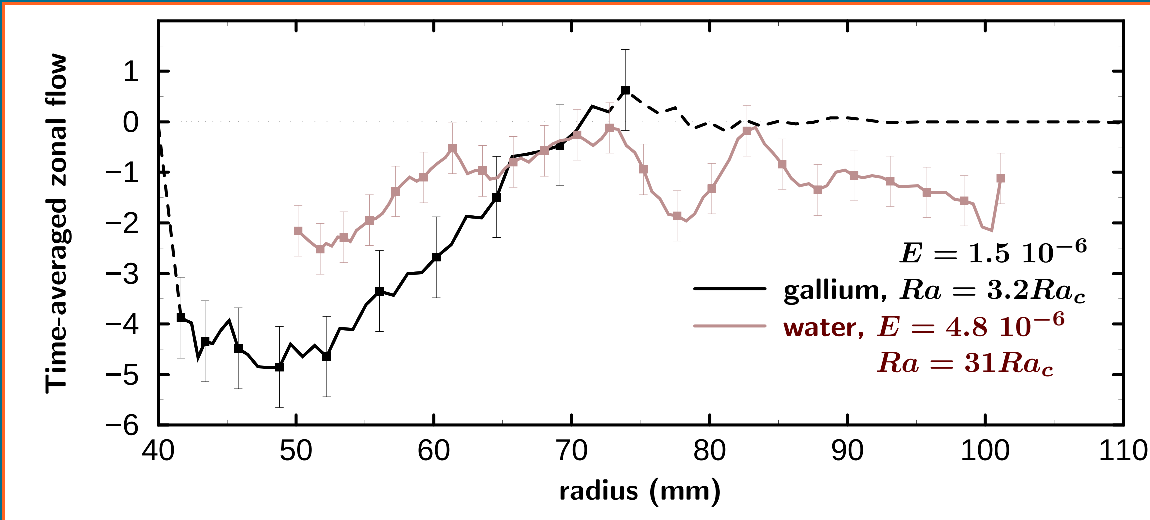




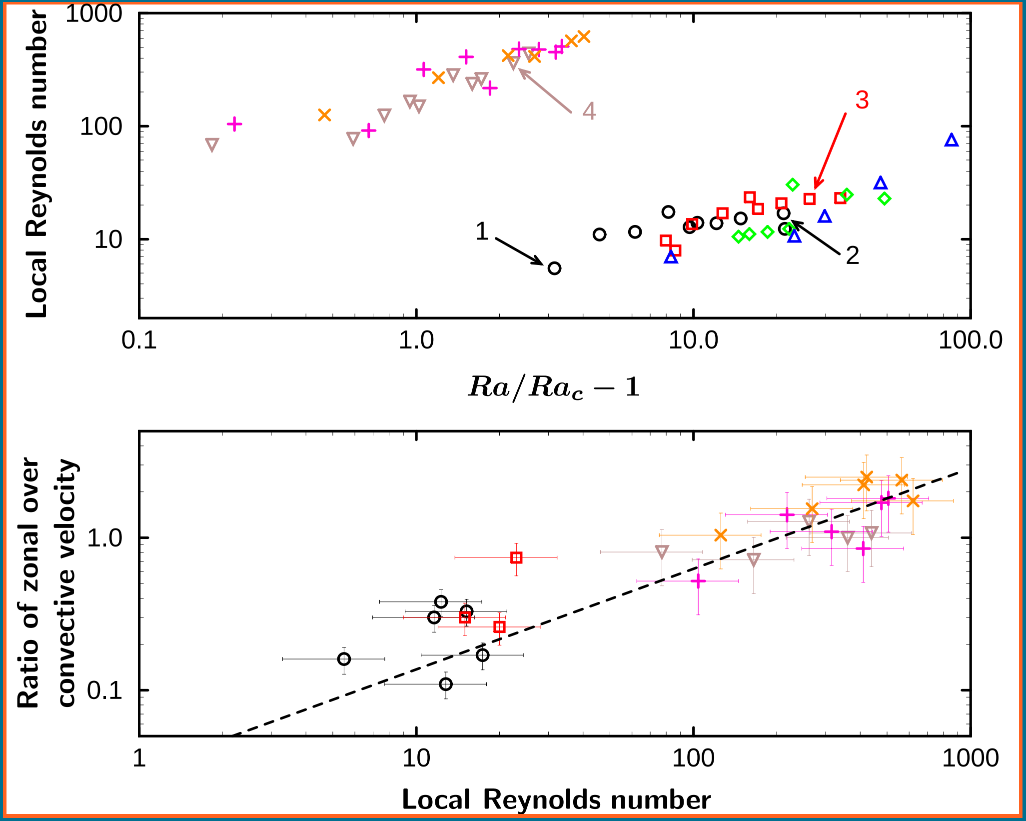
5– Mean properties of the flow: radial structure



6– Mean properties of the flow: lateral structure



7– Energy transfer mechanism



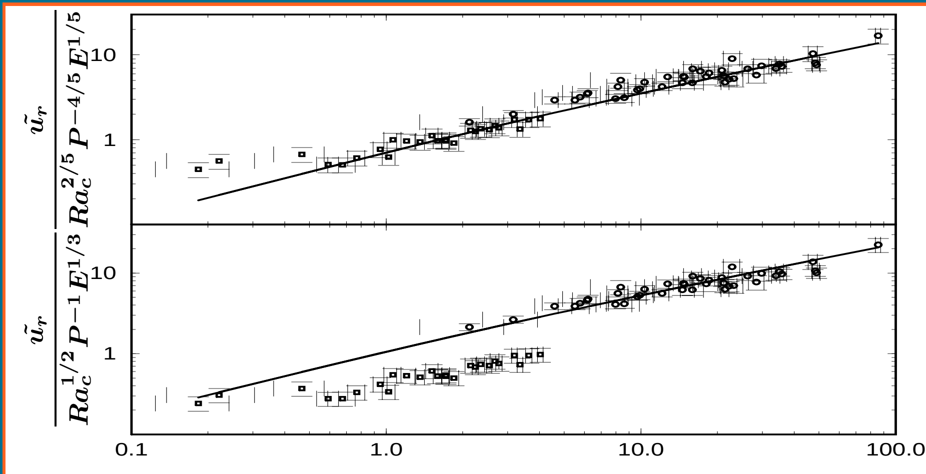
8– Scaling analysis

Depending on the Reynolds number, we propose two sets of scaling relations:

- $Re_l \sim 1$: Kinetic energy is created on the convective scale, and dissipates on the same scale. We equate buoyancy, viscous dissipation, and Coriolis force.

- $Re_l >> 1$: Energy is created on the convective scale, flows inertially to the scale of the container where it is dissipated by friction of zonal flow on CMB boundaries. For convective velocity we equate inertia, buoyancy and Coriolis force. For zonal flow we equate inertia and Ekman friction.

9– Validation



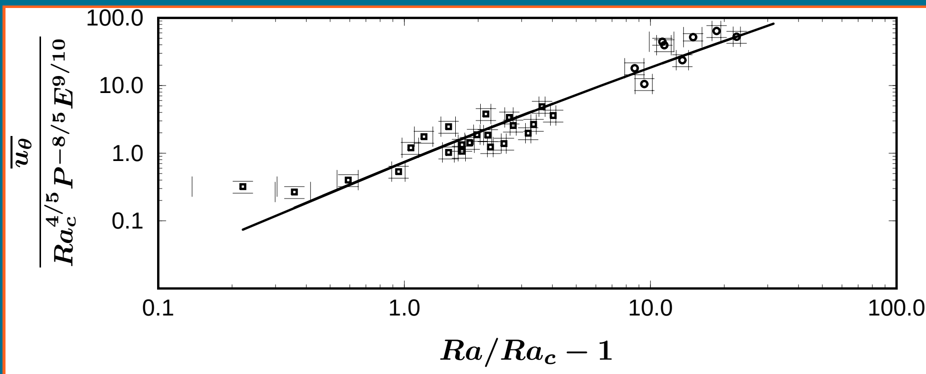
Radial velocity

"Inertial:"

$$\tilde{u_r} = \left(\frac{Ra_Q}{P^2}\right)^{2/5} E^{1/5}$$

"Viscous:"

$$\tilde{u_r} = \left(\frac{Ra_Q}{P^2}\right)^{1/2} E^{1/3}$$



Zonal velocity

"Inertial:"

$$\overline{u_\theta} = \left(\frac{Ra_Q}{P^2}\right)^{4/5} E^{9/10}.$$

10– Core conditions.

- Importance of zonal flow for ω-type dynamo action.

- Non-magnetic extrapolation: the heat-flux Rayleigh number entering the scaling relations is estimated to $Ra_Q \sim 10^{30}$, and $P = 1, E = 10^{-14}$:

– convective velocity of order 10^{-3} m/s,
– Reynolds number of order 10^{8},
– zonal flow velocity of order 10^{-2} m/s $\Rightarrow$ wiping convection ?
– Typical cell size of order 10 km.

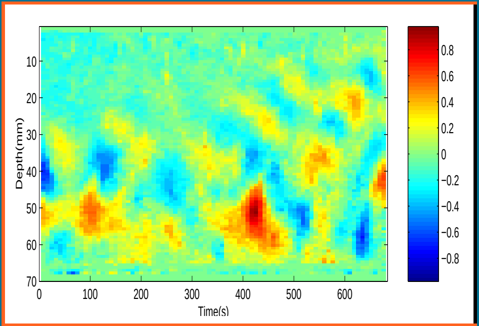
Magnetic field $\Rightarrow$ should enlarge structures and slow down zonal flow.

11– Comparison with a numerical code

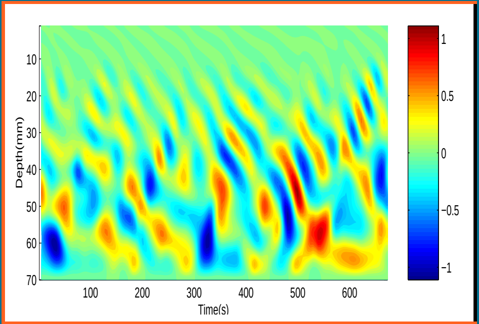
- A numerical quasigeostrophic code (of Cardin and Olson (1994) type) has been written to compare synthetic and experimental Doppler maps.
- The code has been modified somehow to take Ekman friction of zonal flow into account. The importance of this friction for zonal flow has been revealed by experiments.
- Simulations have been carried out for the exact conditions of experiments (including Prandtl number of gallium)
- Results from this code satisfy experimentally obtained scaling relations.

11– Close to onset: $E = 9.74\ 10^{-6}, P = 7, Ra/Ra_c = 5.$

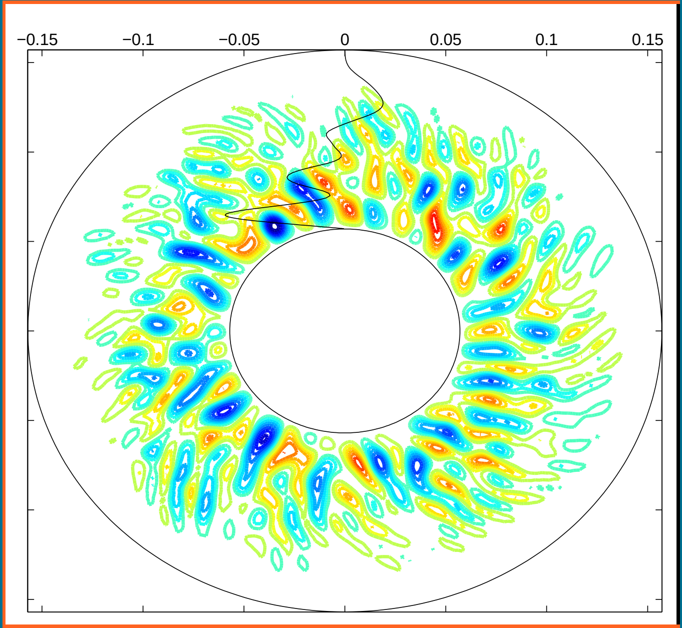
Experimental



Synthetic



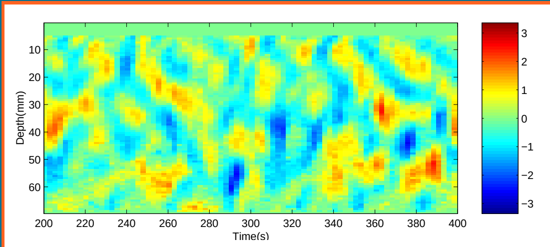
Streamfunction



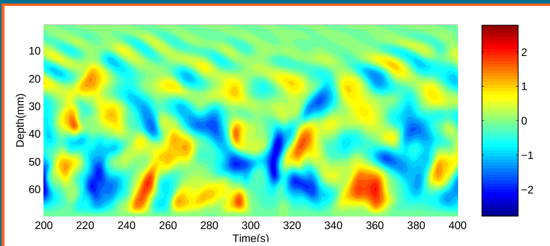
Flow is mainly a nonlinearly stable, prograde propagating Rossby wave with defects.

12– Further away from onset: $Ra/Ra_c = 22.2$.

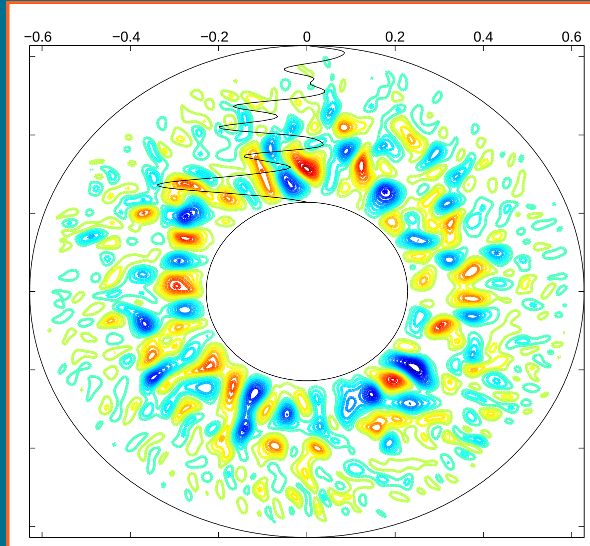
Experimental



Synthetic



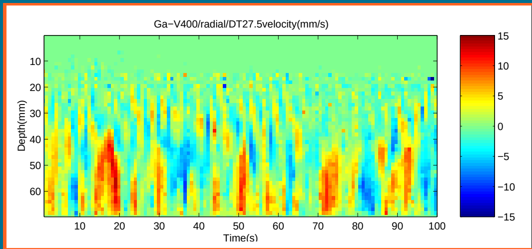
Streamfunction



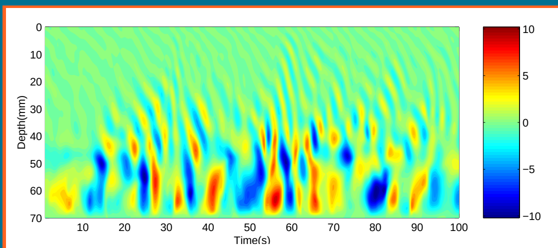
Flow near the inner cylinder is now made of size-increasing, inertially sustained structures, while weak Rossby wave survive at the exterior of the shell.

13– In liquid gallium: $P = 0.027, E = 1.46\ 10^{-6}, Ra/Ra_c = 3.2$.

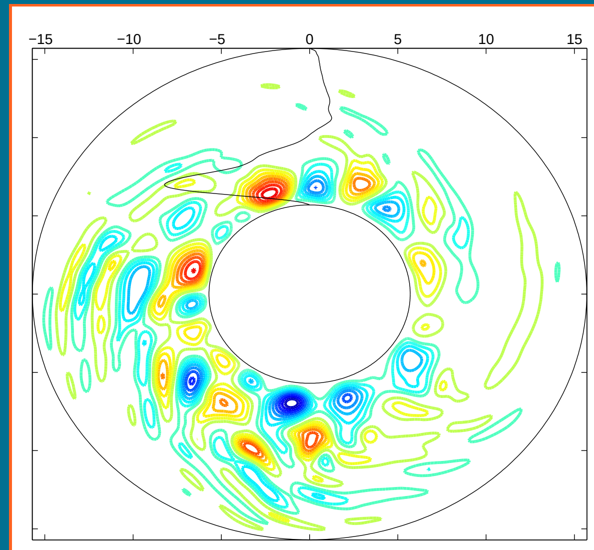
Experimental



Synthetic



Streamfunction



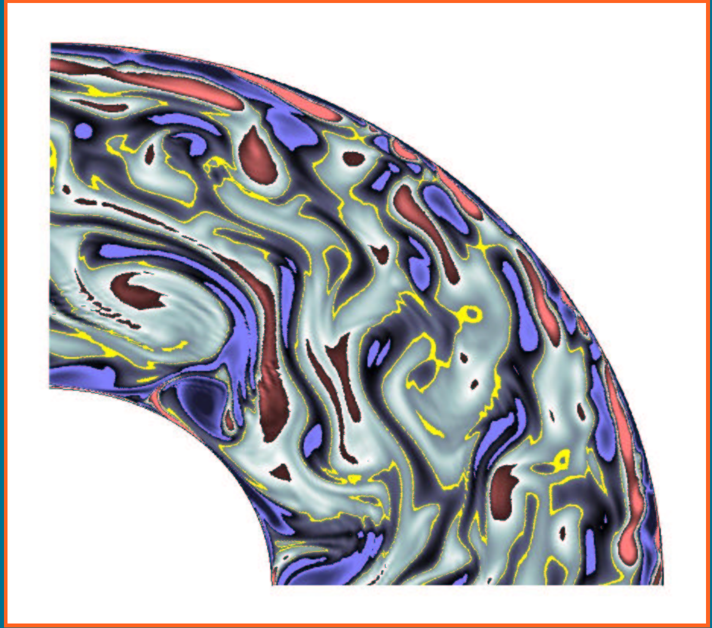
Inertial structures near the inner cylinder feed a strong retrograde zonal flow which advects them. Rossby waves at the exterior are visible.

14– Conclusions

- Experiment and code are quantitatively in agreement.
- Coherent inertial structures have been put into evidence, from scaling relations and also from structural numerical analysis. These structures coexist with Rossby waves.
- The quantitative agreement opens the way to further 2D-treatment of rotating convection equations.

15– Don't miss the poster!

More results about the quasigeostrophic convection code in the poster of J. Aubert and P. Cardin, session G1.08.



$(P = 0.025, E = 1.46\ 10^{-6}, Ra/Ra_c = 5)$