Bistability and transitions induced by topography in a laboratory model of a geostrophic jet

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Generic features of geophysical turbulence

- Shallow-water flows dominated by rotation - predominantly two-dimensional
- Organization into large-scale structures like jets, vortices

- Abrupt qualitative changes in these large-scale structures

- Atmospheric blocking (Weeks *et al.* 1997)

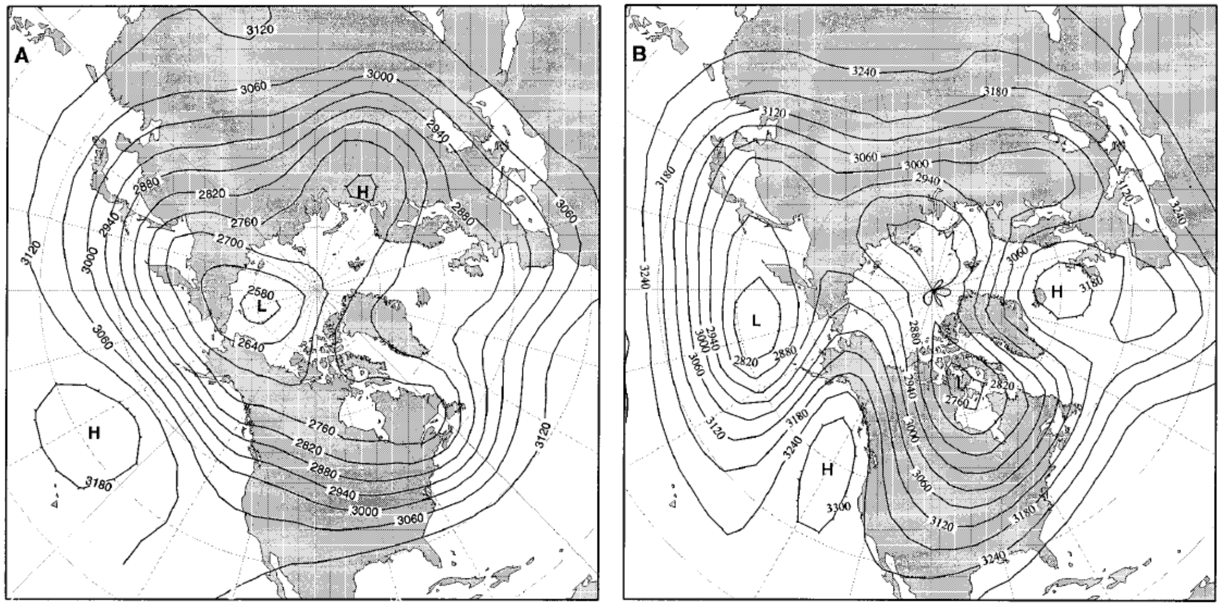
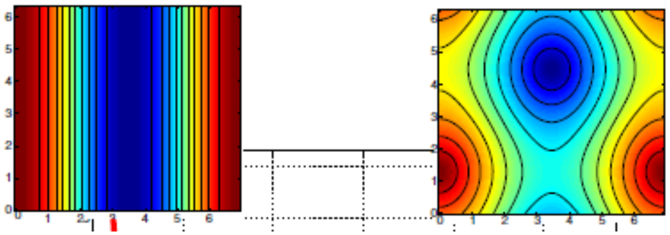


Fig. 1. Atmospheric pictures of (**A**) zonal and (**B**) blocked flow, showing contour plots of the height (m) of the 700-hPa (700 mbar) surface, with a contour interval of 60 m for both panels. The plots were obtained by averaging 10 days of twice-daily data for (A) 13 to 22 December 1978 and (B) 10 to 19 January 1963; the data are from the National Oceanic and Atmospheric Administration's Climate Analysis Center. The nearly zonal flow of (A) includes quasi-stationary, small-amplitude waves (*32*). Blocked flow advects cold Arctic air southward over eastern North America or Europe, while decreasing precipitation in the continent's western part (*26*).

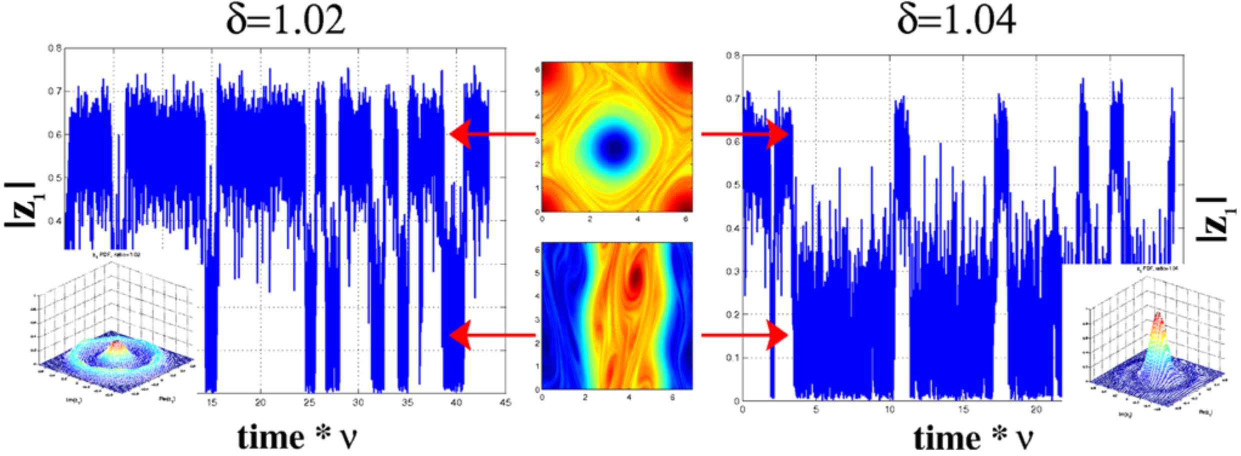
2D NS Equations (Bouchet & Simmonet 2009)

- 2D Euler equations on a doubly periodic domain

  - Equilibrium statistical mechanics predicts a 2nd order phase transition between unidirectional and dipole flows



- Adding stochastic forcing and dissipation takes the system away from equilibrium – 1st order phase transition - bistability



- 2D NS equations are structurally similar to more realistic models (quasi-geostrophic) of geophysical flows

Bistability of the Kuroshio Current

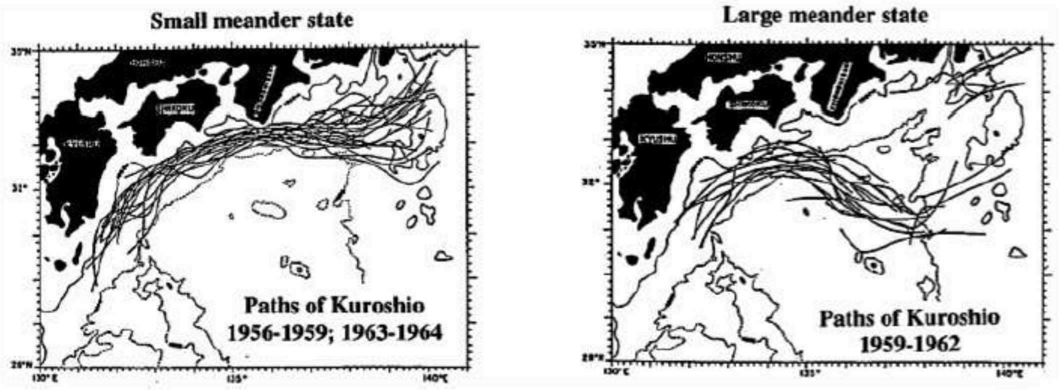


Figure 3: Bistability of the paths of the Kuroshio during the 1956-1962 period : paths of the Kuroshio in (left) its small meander state and (right) its large meander state. The 1000-m (solid) and 4000-m (dotted) contours are also shown. (figure from Schmeits and Dijkstraa [47], adapted from Taft 1972.)

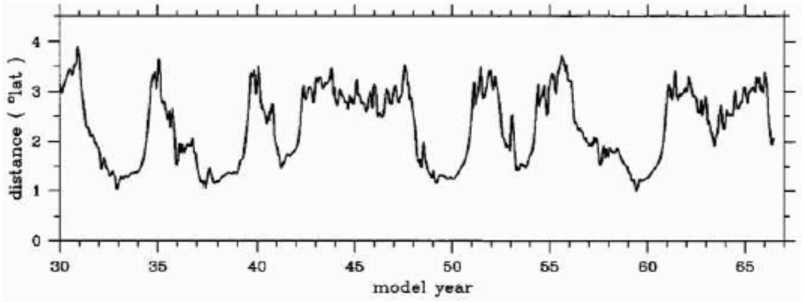
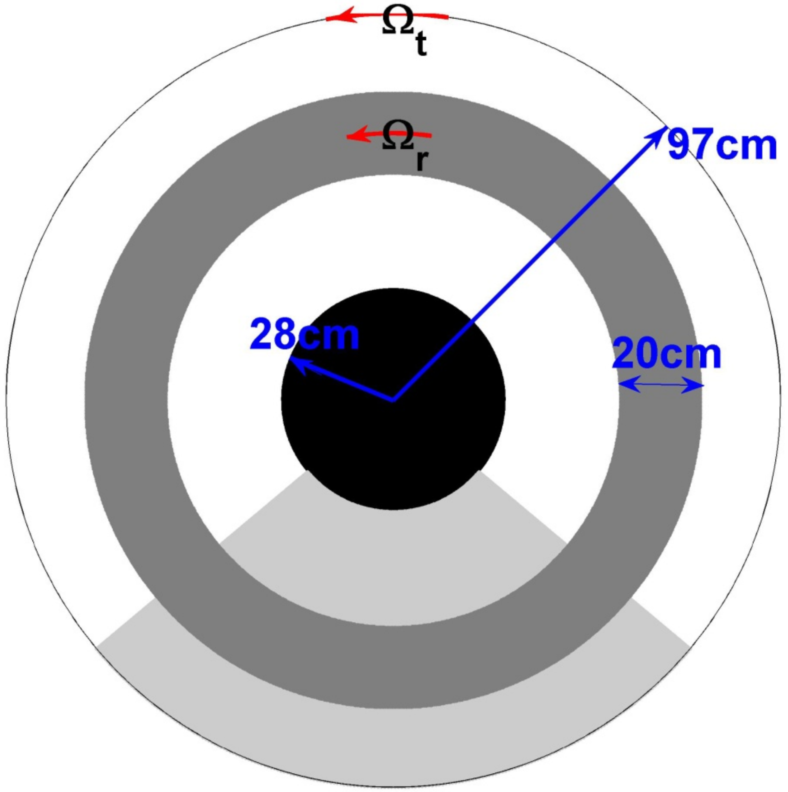


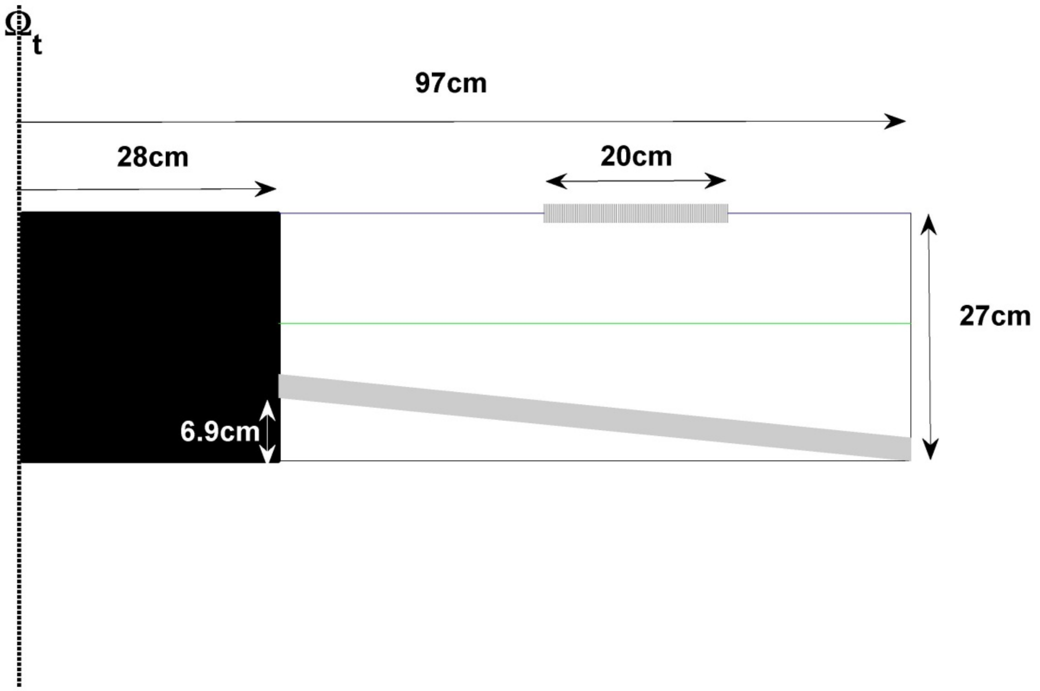
Figure 4: Bistability of the paths of the Kuroshio, from Qiu and Miao [41] : timeseries of the distance of the Kuroshio jet axes from the coast, averaged other the part of the coast between 132°-140°E, from a numerical simulation using a two layer primitive equation model.

Experimental Set-up - Schematic

Top View



Side View



Typical Values:

$$\Omega_t \approx 0.4 - 0.6\ rad/s$$

$$\Omega_r \approx 0.78\ rad/s$$

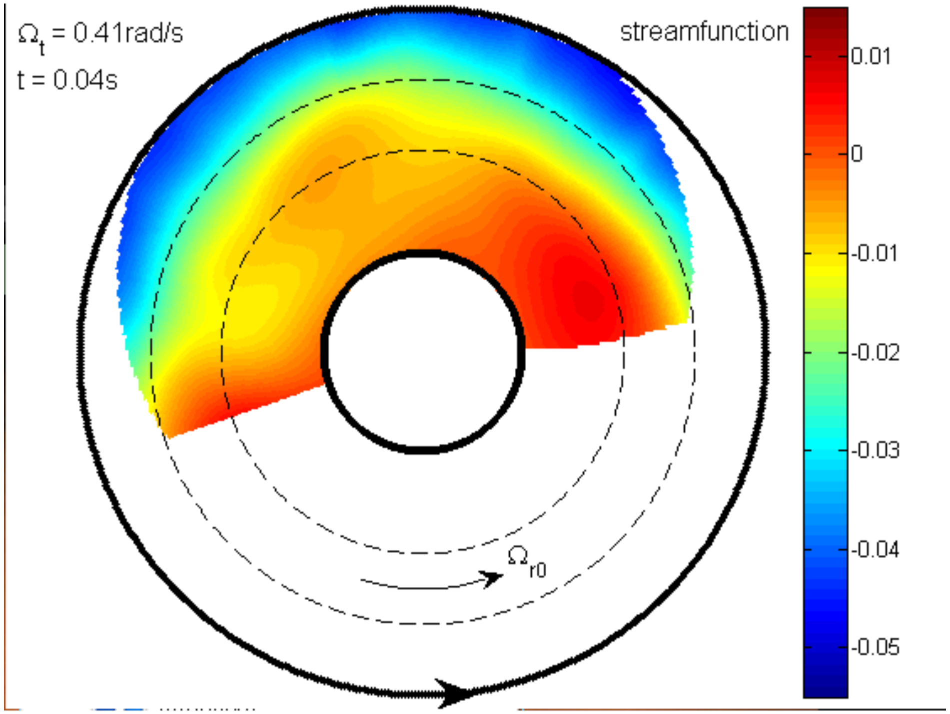
$$\beta = \frac{2\Omega_t s}{H} \approx 0.37\ rad/s/m$$

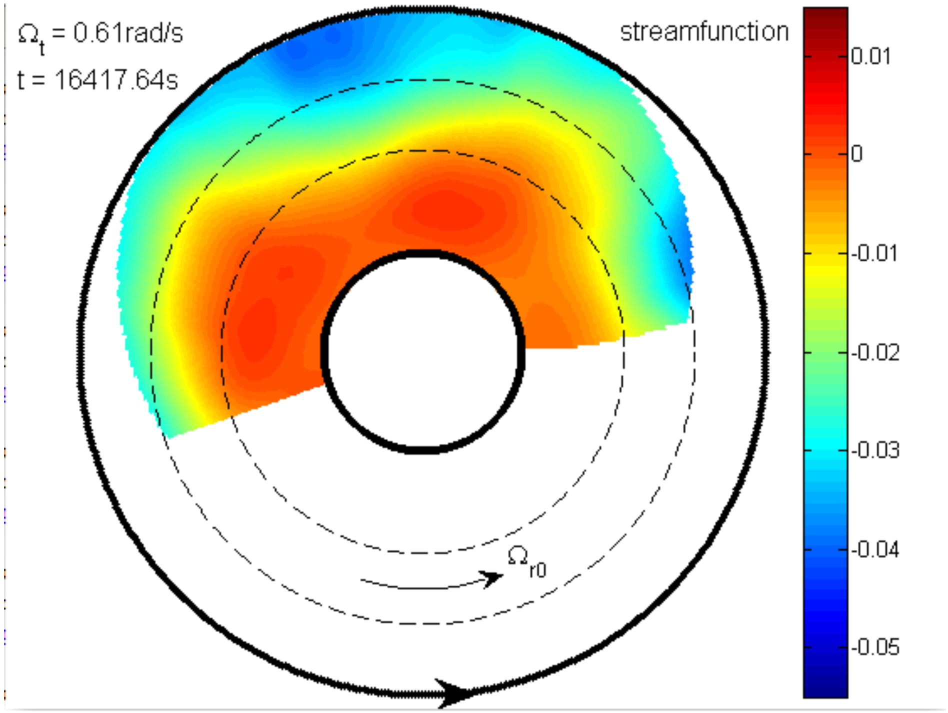
$$Ro = \frac{U}{2\Omega_t L} \approx 2.6$$

$$Ek = (4\pi/H)^2(\nu/\Omega_t) \approx 0.0043$$

$$L_R = \frac{(gH)^{1/2}}{2\Omega_t} \approx 1.63m$$

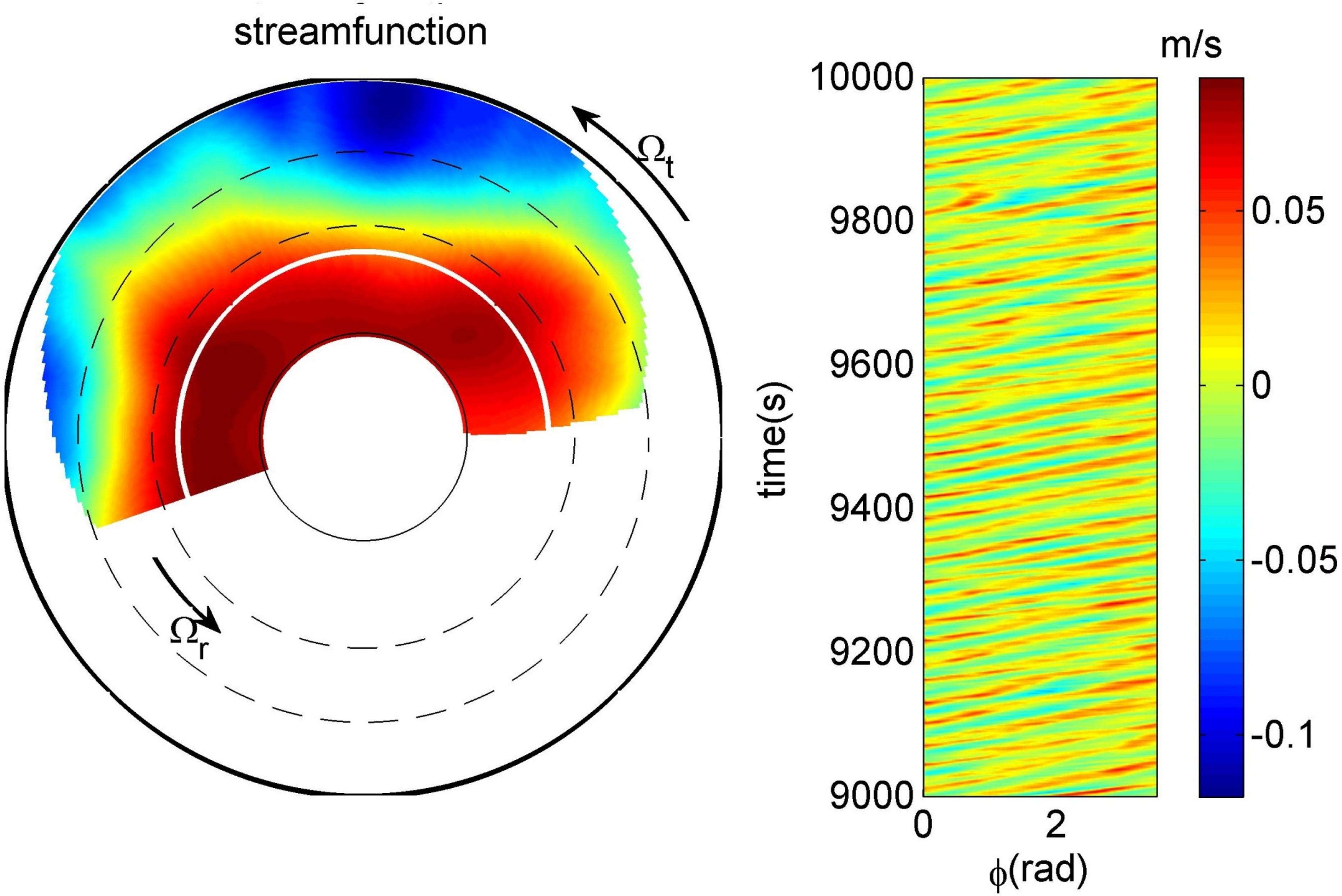
NO TOPOGRAPHY



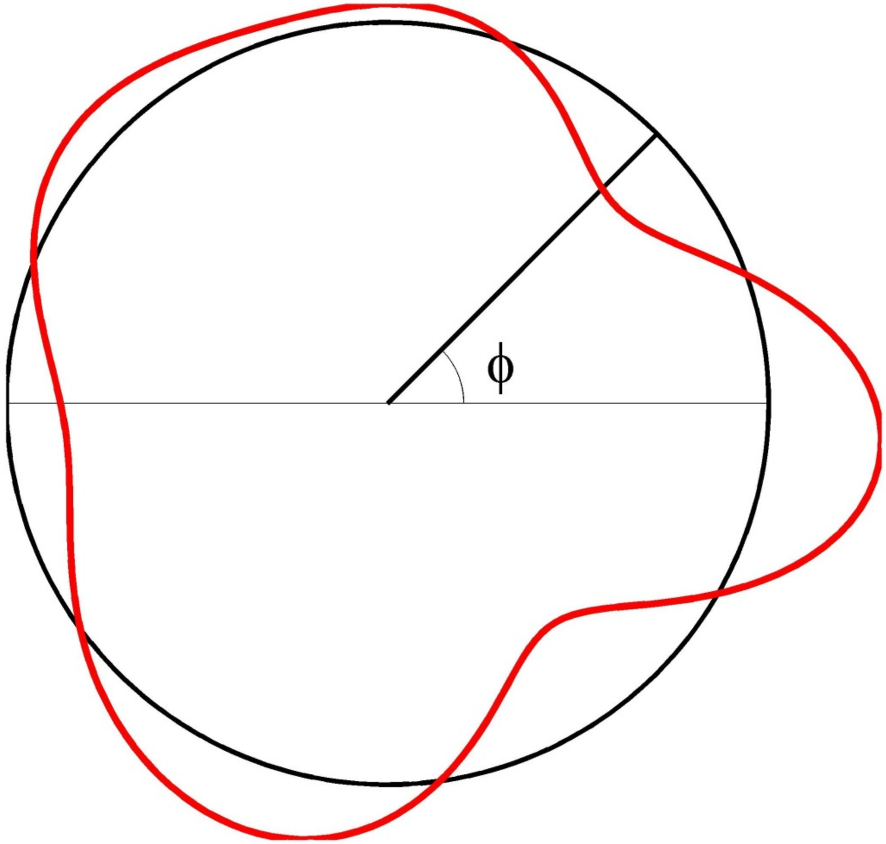


- Axi-symmetry broken by a barotropic instability of the jet
- Propagating waves evident in both the scenarios
- What does a sweep over the entire range of Ω_t give ?

NO TOPOGRAPHY - Ω_t↑



ANALYSIS METHOD



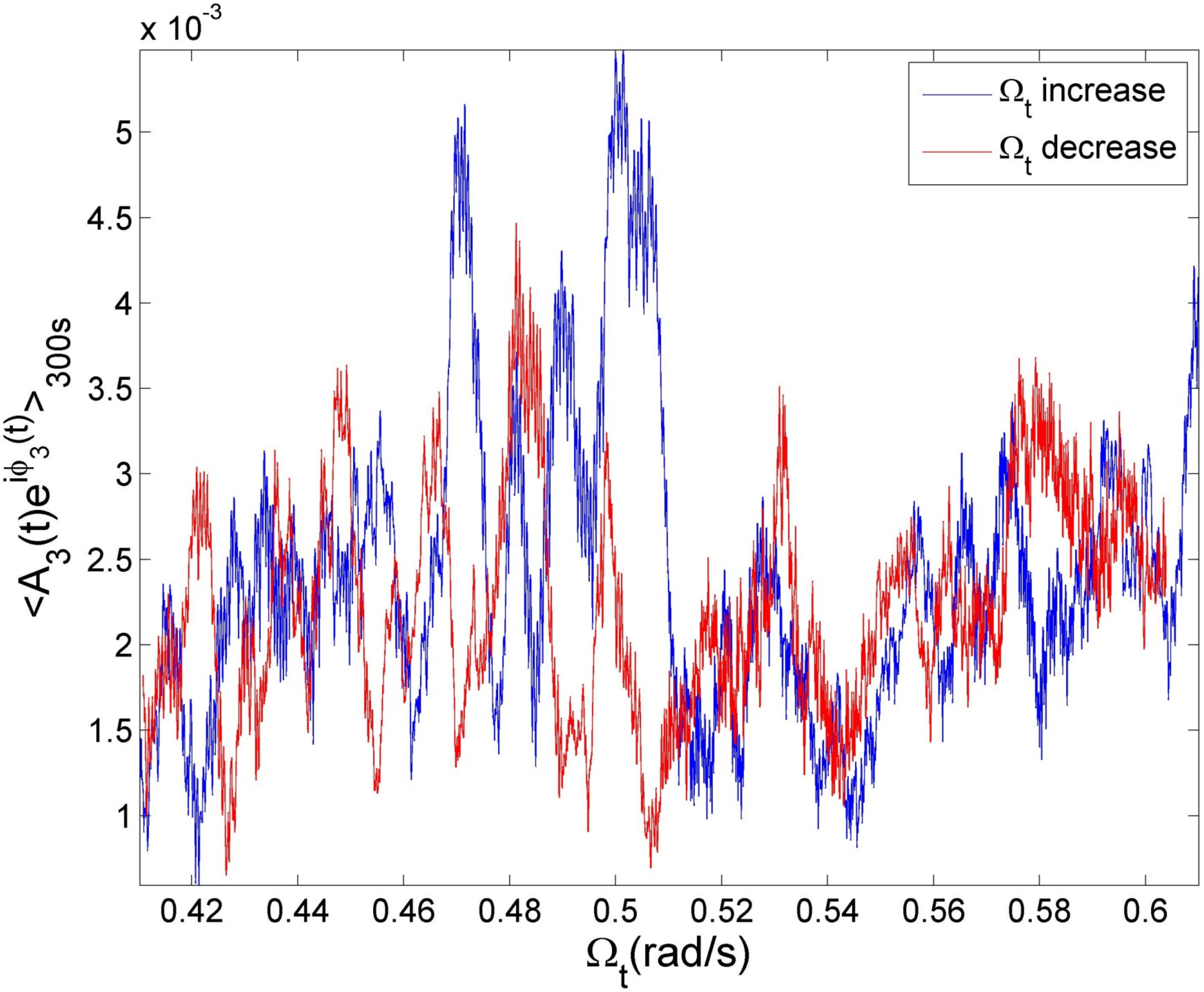
$$f(\phi) = A_1 e^{i\phi_1} e^{i\phi} + A_2 e^{i\phi_2} e^{2i\phi} + A_3 e^{i\phi_3} e^{3i\phi} + \ldots\ldots$$

$$f(\phi, t) = A_1(t) e^{i\phi_1(t)} e^{i\phi} + A_2(t) e^{i\phi_2(t)} e^{2i\phi} + A_3(t) e^{i\phi_3(t)} e^{3i\phi} + \ldots\ldots$$

purely propagating mode-3 wave: $< A_3(t) e^{i\phi_3(t)} > \; = \; 0$

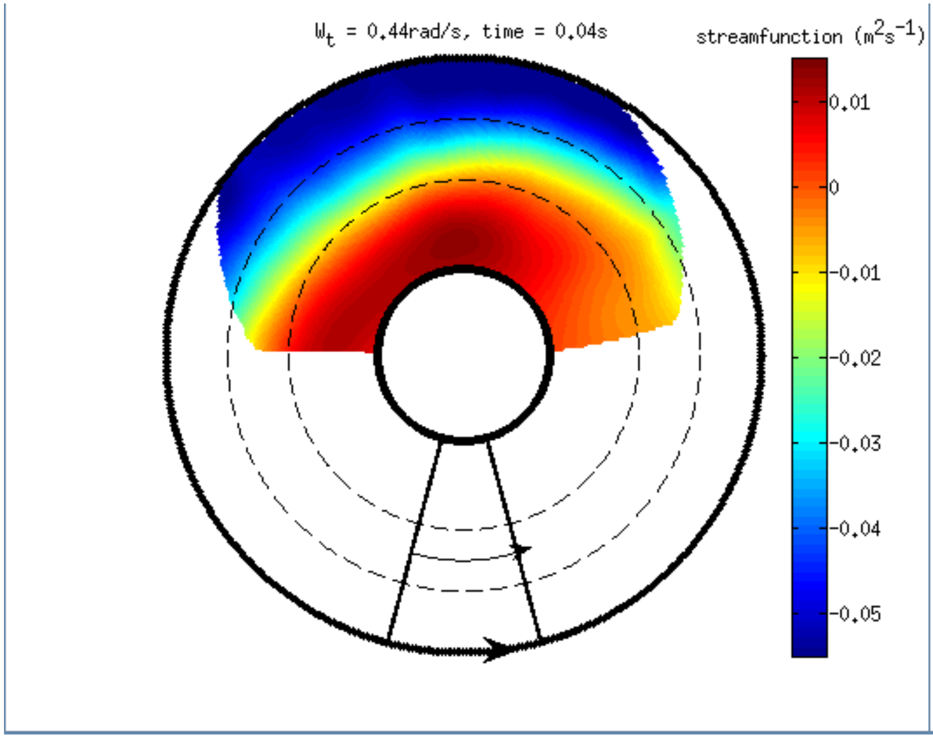
standing mode-3 wave: $< A_3(t) e^{i\phi_3(t)} > \; = \; c_0$

NO TOPOGRAPHY – SWEEP OVER Ω_t

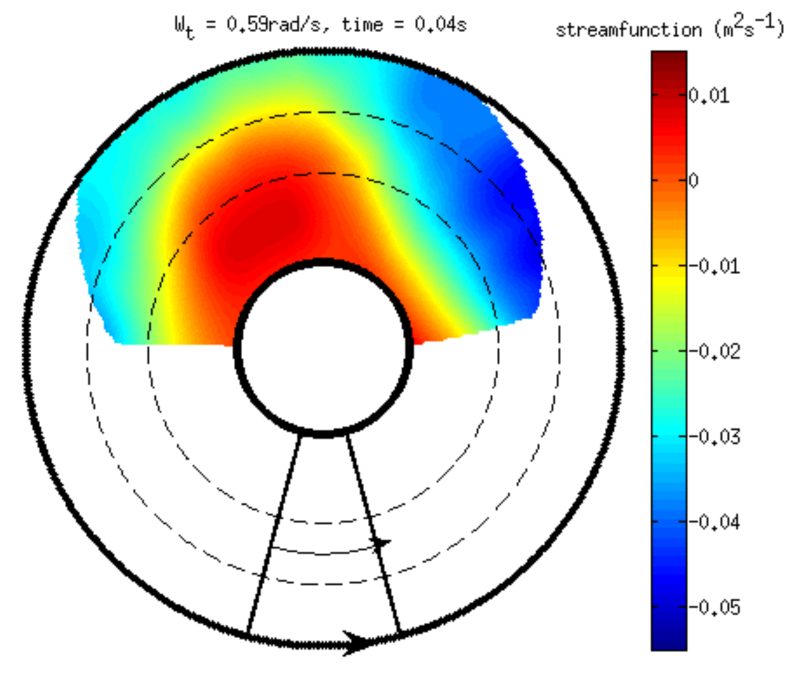


WITH TOPOGRAPHY – SWEEP OVER Ω_t

Ω_t increase

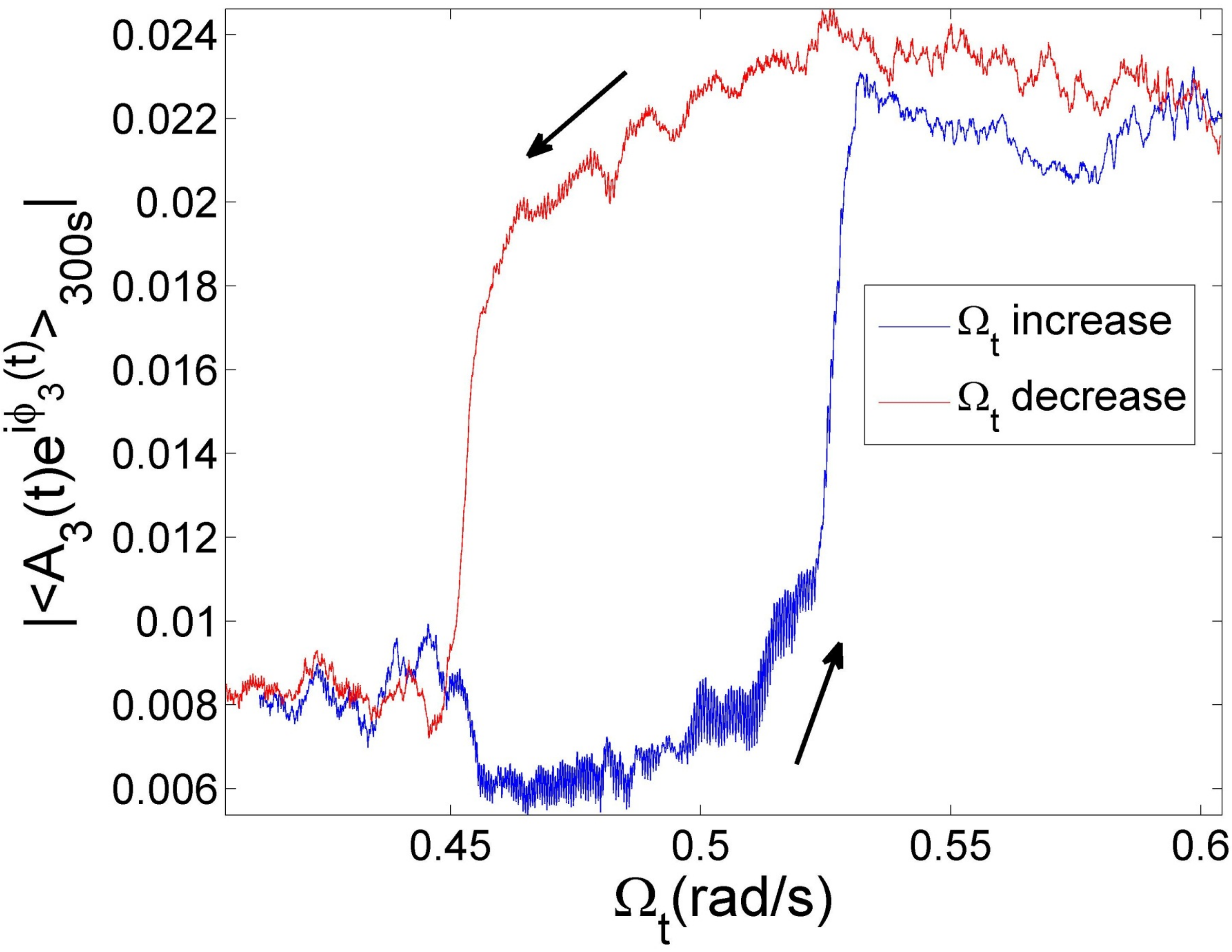


Ω_t decrease

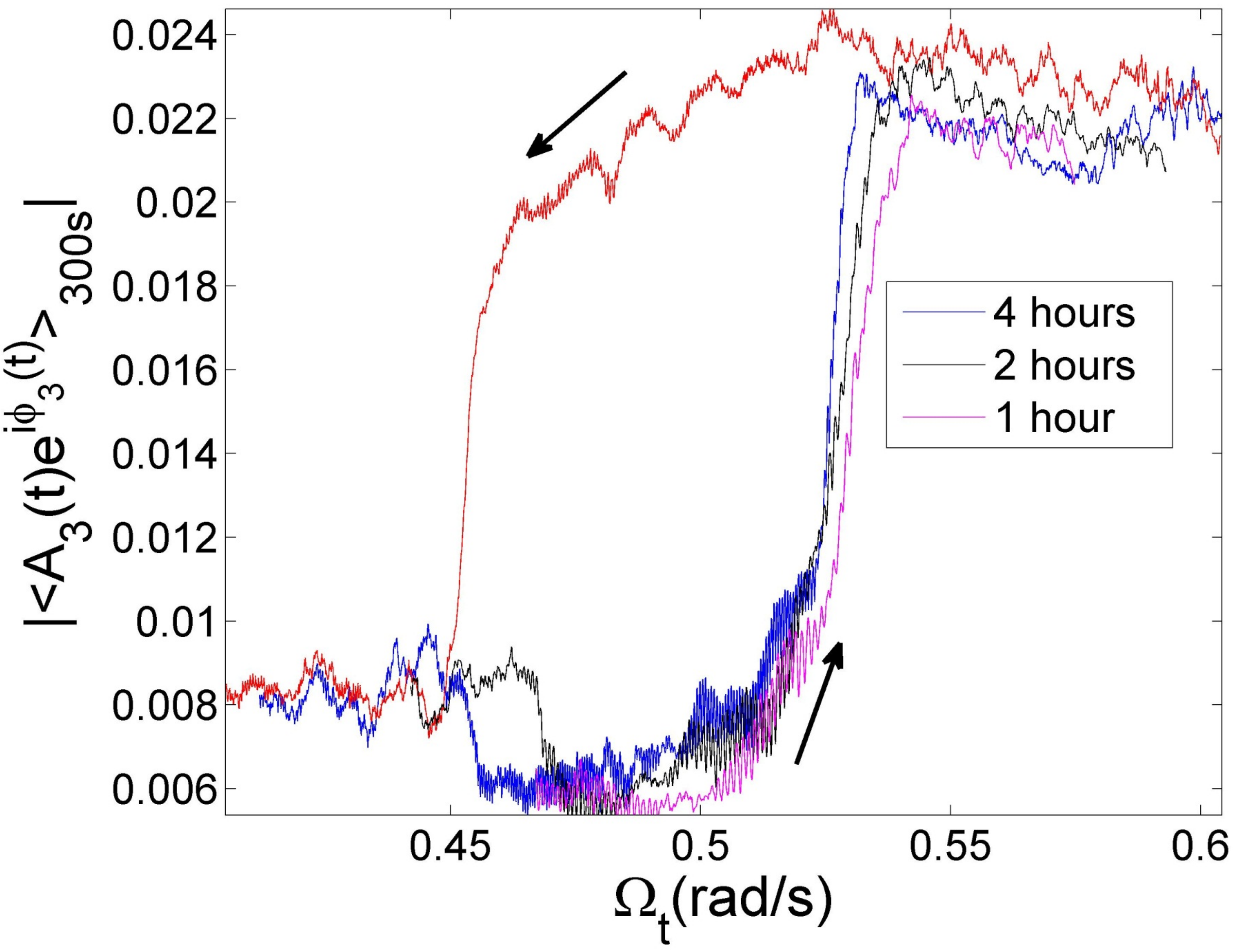


- Transitions occur at different points in the two experiments

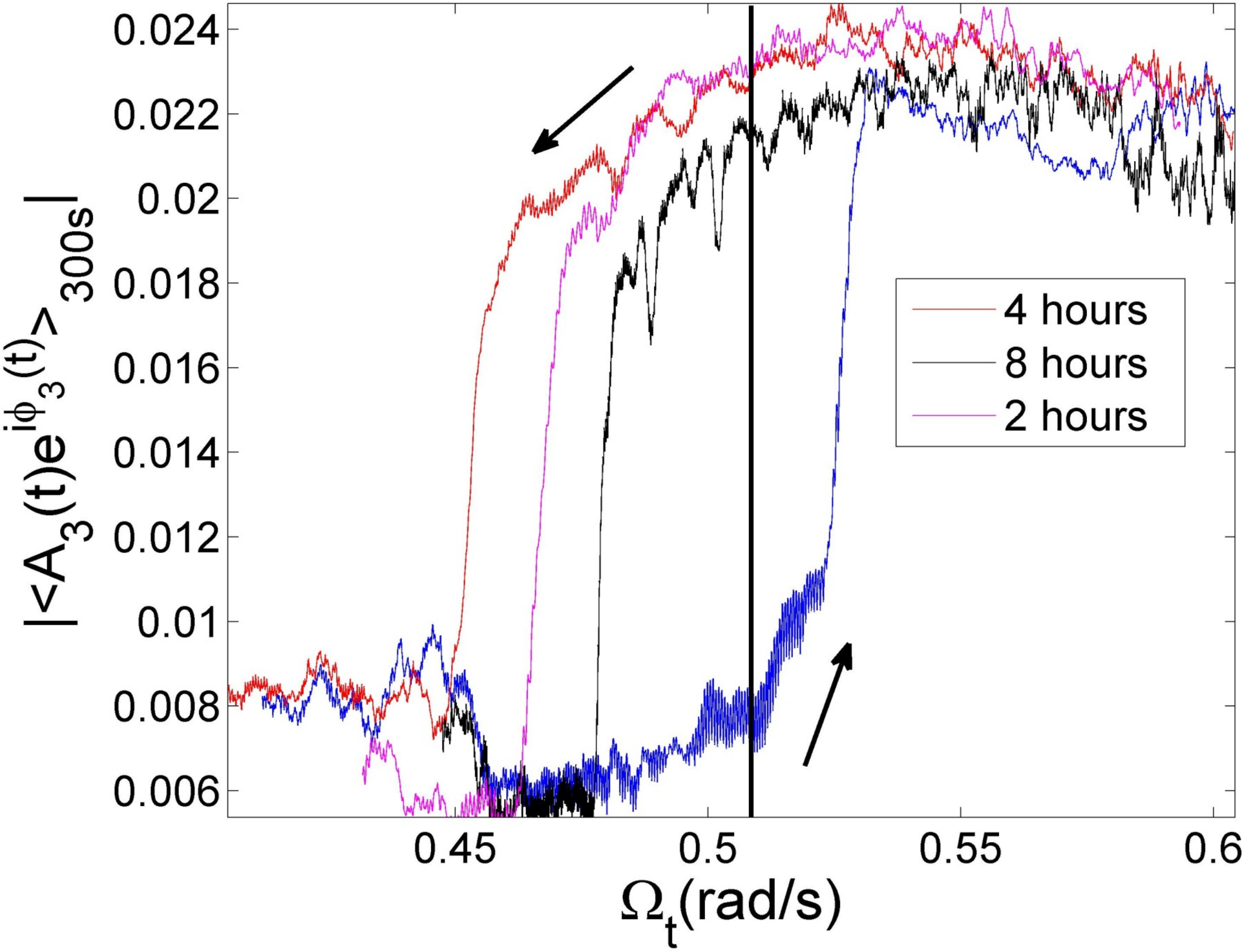
WITH TOPOGRAPHY – SWEEP OVER Ω_t



WITH TOPOGRAPHY – SWEEP OVER Ω_t

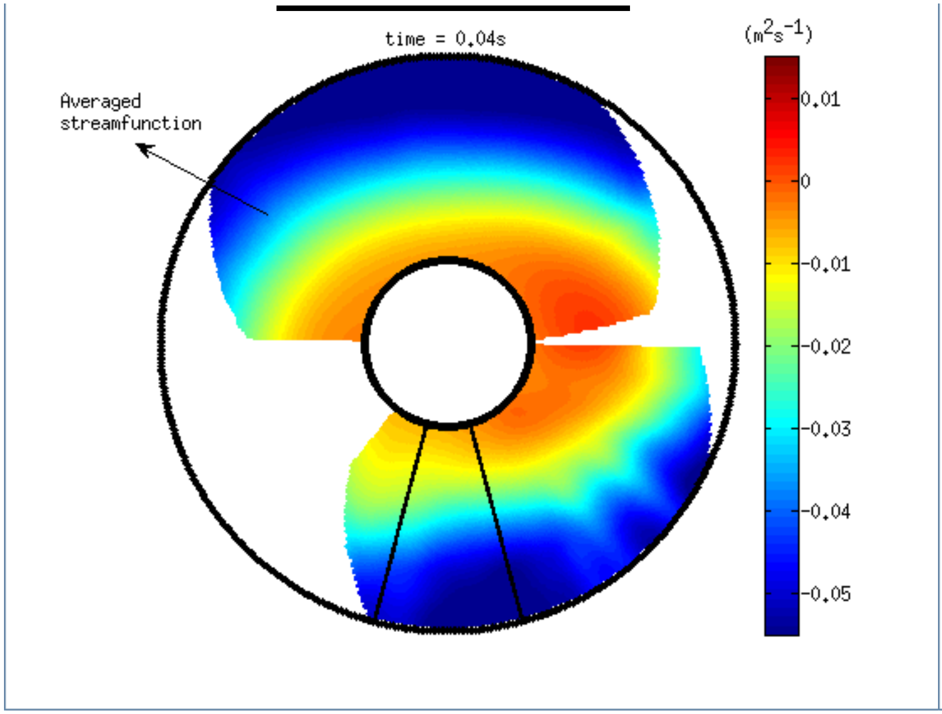


WITH TOPOGRAPHY – SWEEP OVER Ω_t

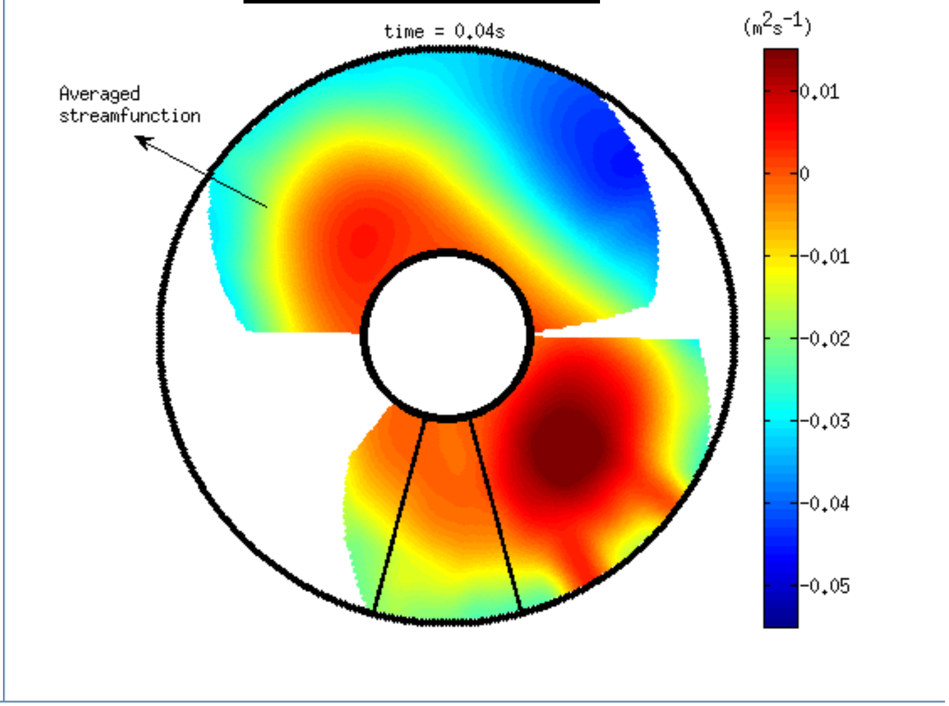


Ω_t = 0.51 rad/s

Lower Branch



Upper Branch

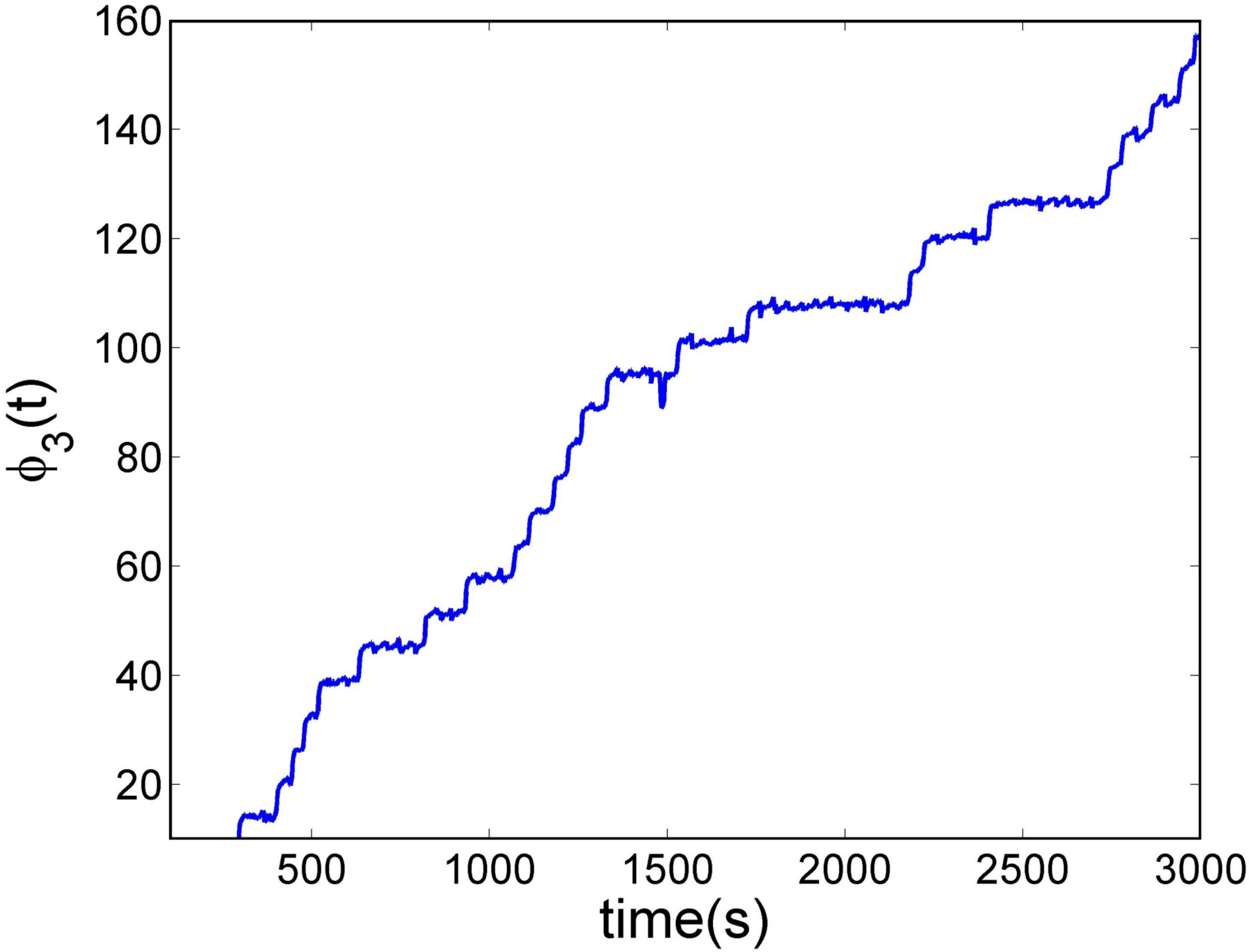


- Lower branch exhibits propagating features

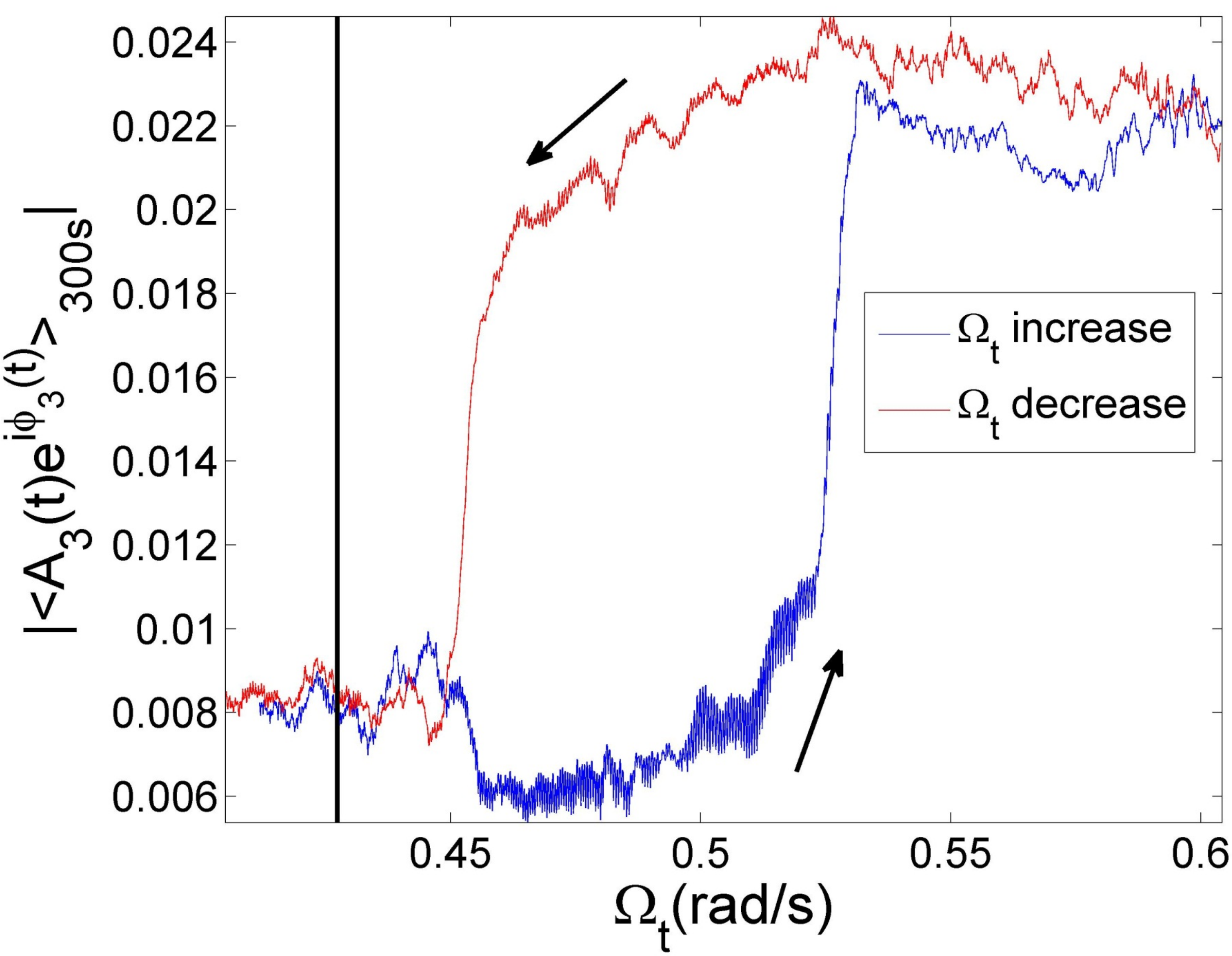
- Upper branch characterized by a strong cyclonic vortex downstream of the topography

- No spontaneous transitions observed

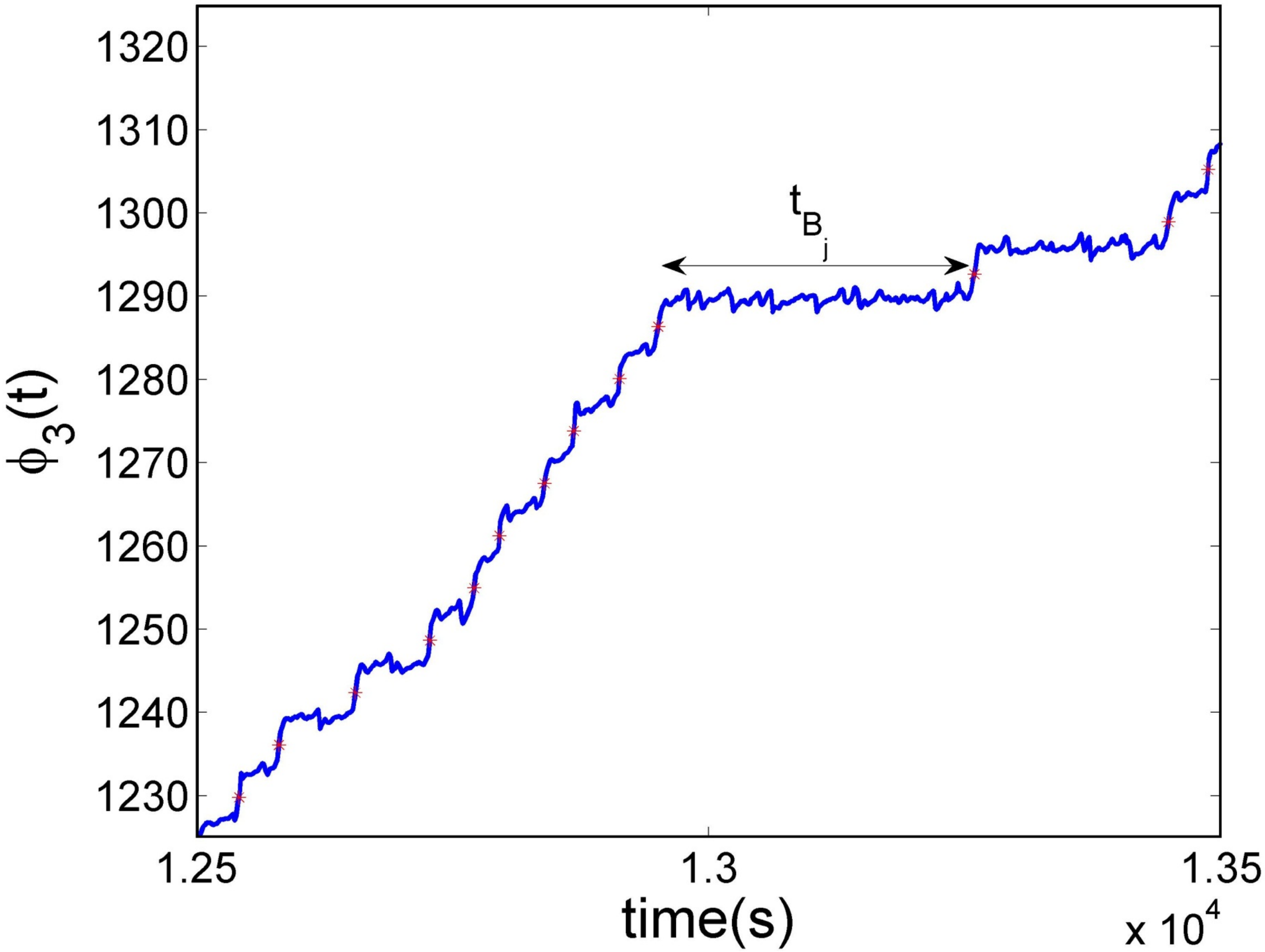
Sweep over Ω_t



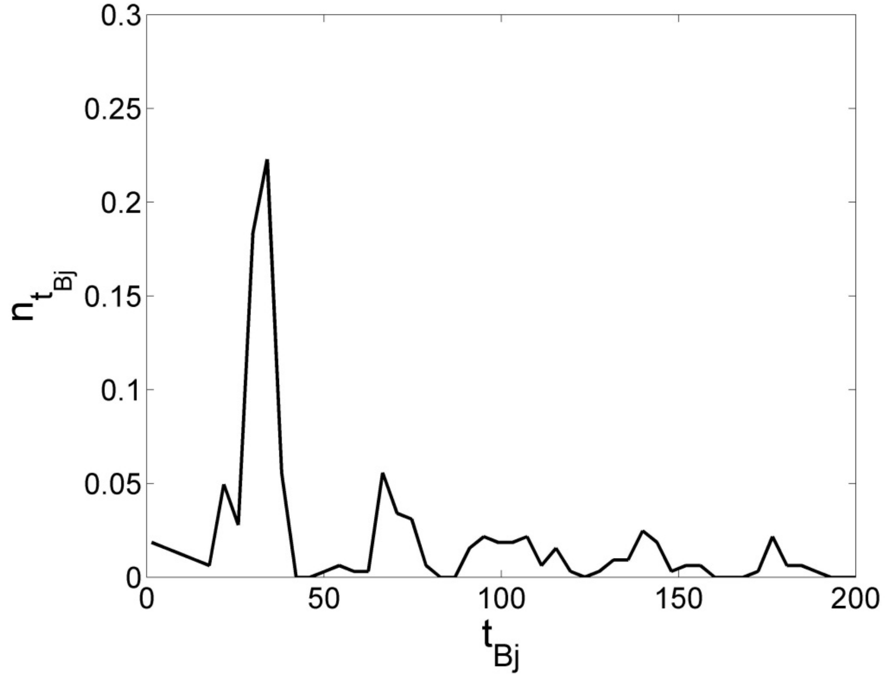
Sweep over Ω_t

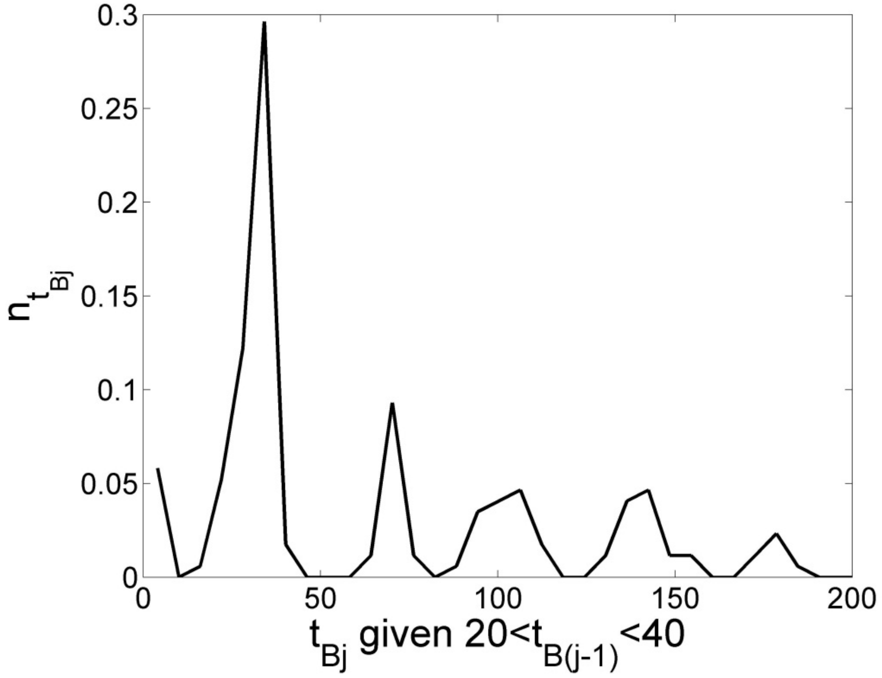


Ω_t = 0.43 rad/s



Ω_t = 0.43 rad/s





- Peaks around a specific frequency and sub-harmonics
- Conditional probability indicates memorylessness

Conclusions

- First order phase transition, and hence bistability, induced by topography in a geostrophic flow.
- Spontaneous switches not observed in the laboratory experiments. Comparisons with numerical simulations ongoing.
- “Mixed state” observed. Time spent on “blocked” state memoryless.

Thank you