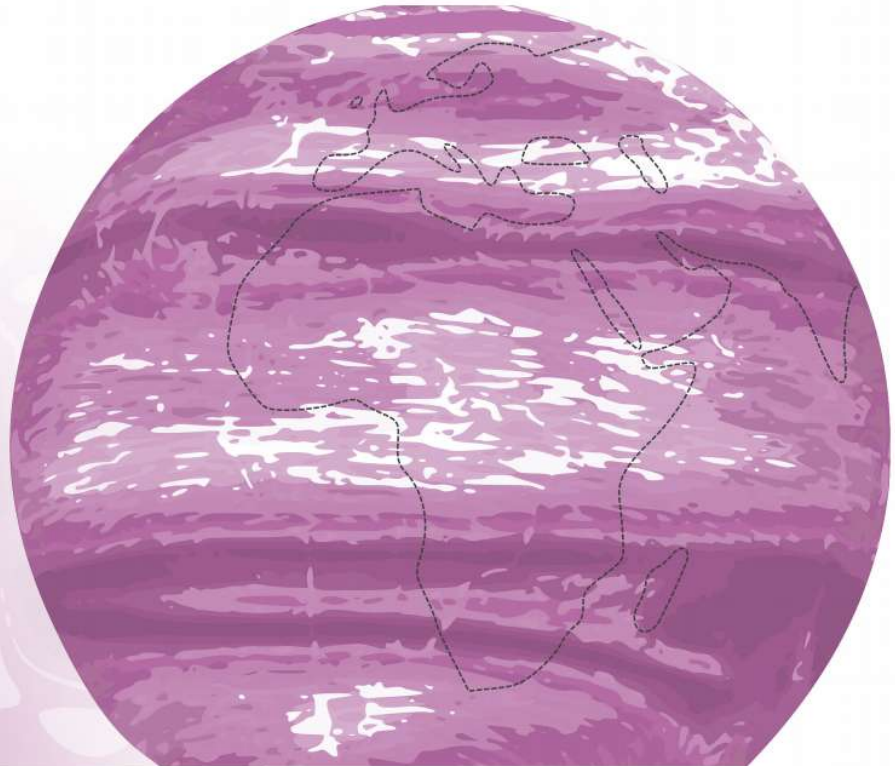
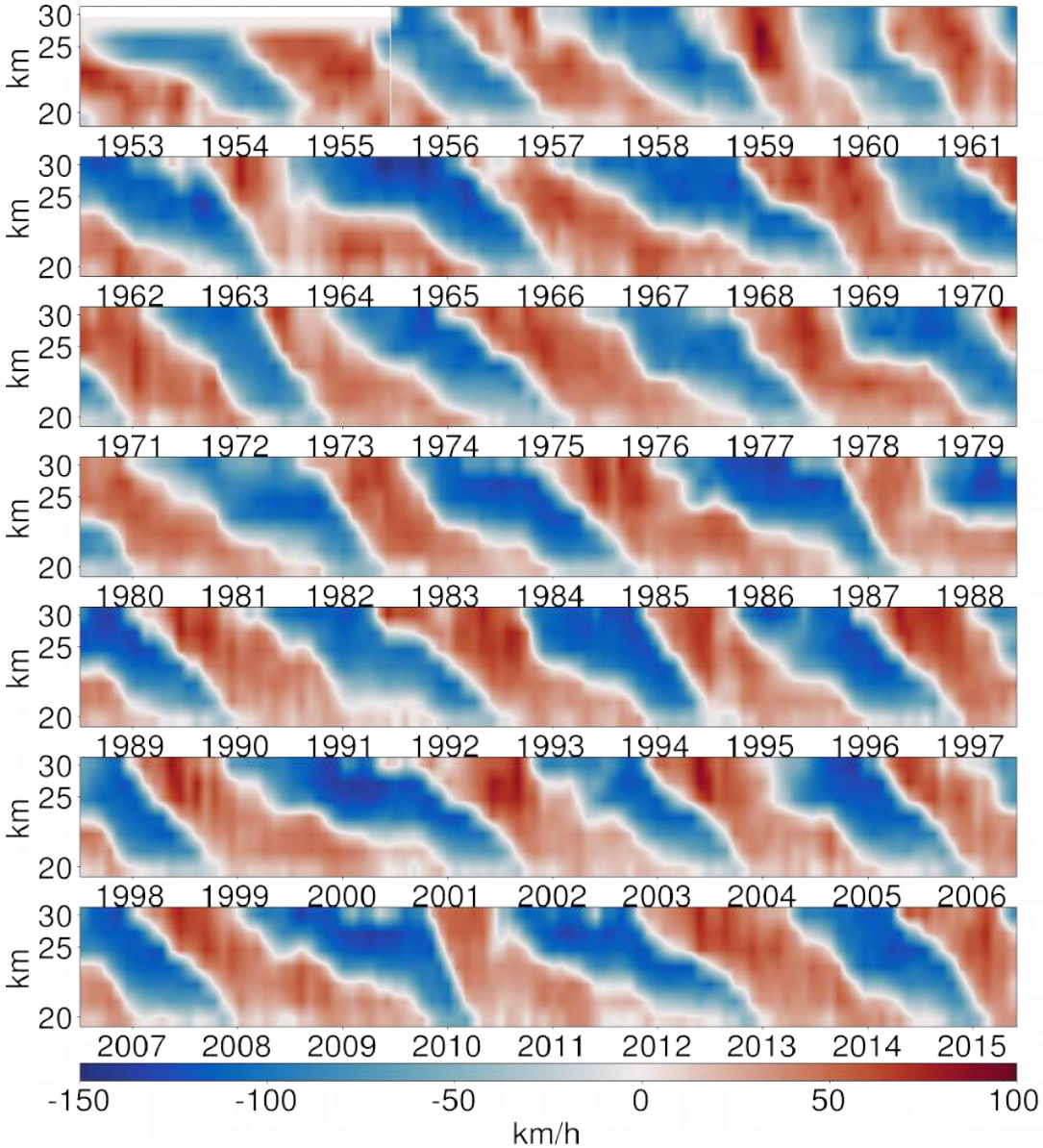
Periodicity disruptions in models of the Quasi-Biennial Oscillation

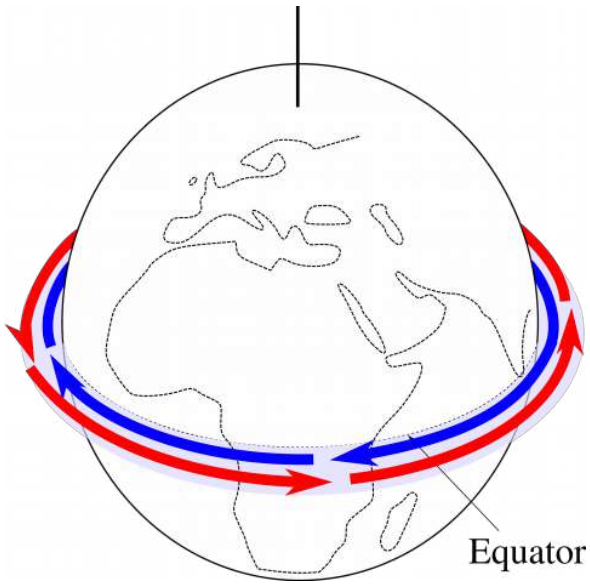
A. Renaud, A. Venaille[1] and L.P. Nadeau[2]

1 ENS, Lyon (France)
2 Ismer, Rimousky (Quebec)



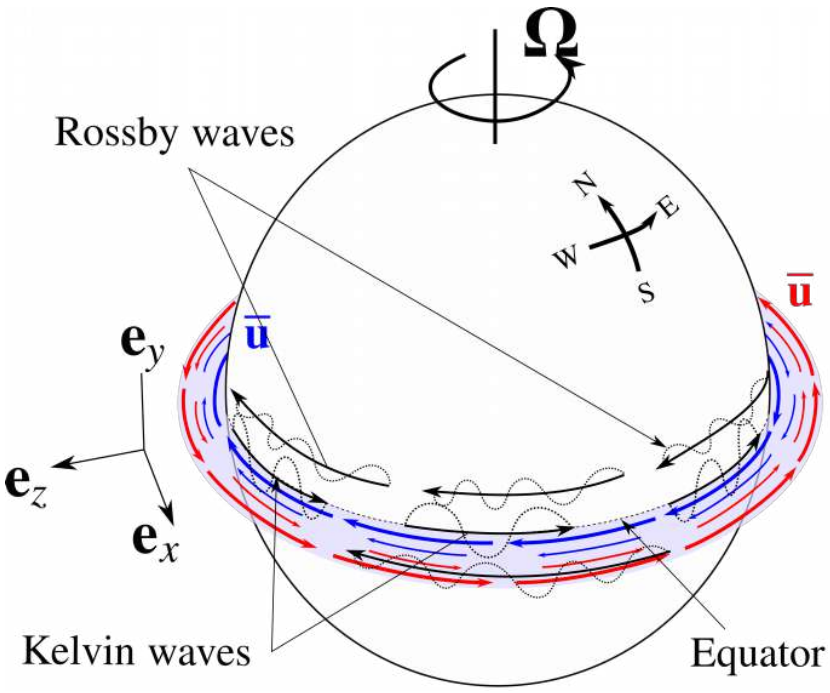
Reminder: What is the QBO?

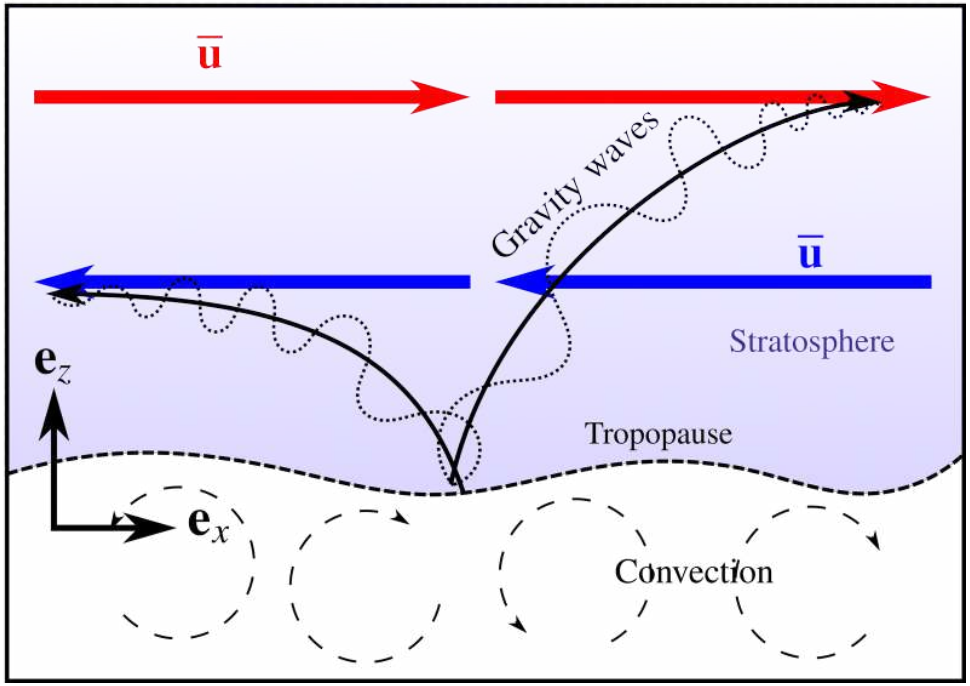




Baldwin *et al.* (2011)

Reminder: Underlying mechanism





Key ingredients:

- Periodic geometry
- Internal gravity wave streaming (stratification + damping)
- Doppler shift
- Counter-propagating waves

Holton-Lindzen-Plumb model
A 1D quasilinear model

Mean-flow equation:

$$\partial_t \overline{u} - \nu \partial_{zz} \overline{u} = -\partial_z \left(\overline{u'w'}_+ + \overline{u'w'}_- \right)$$

WKB momentum flux closure:

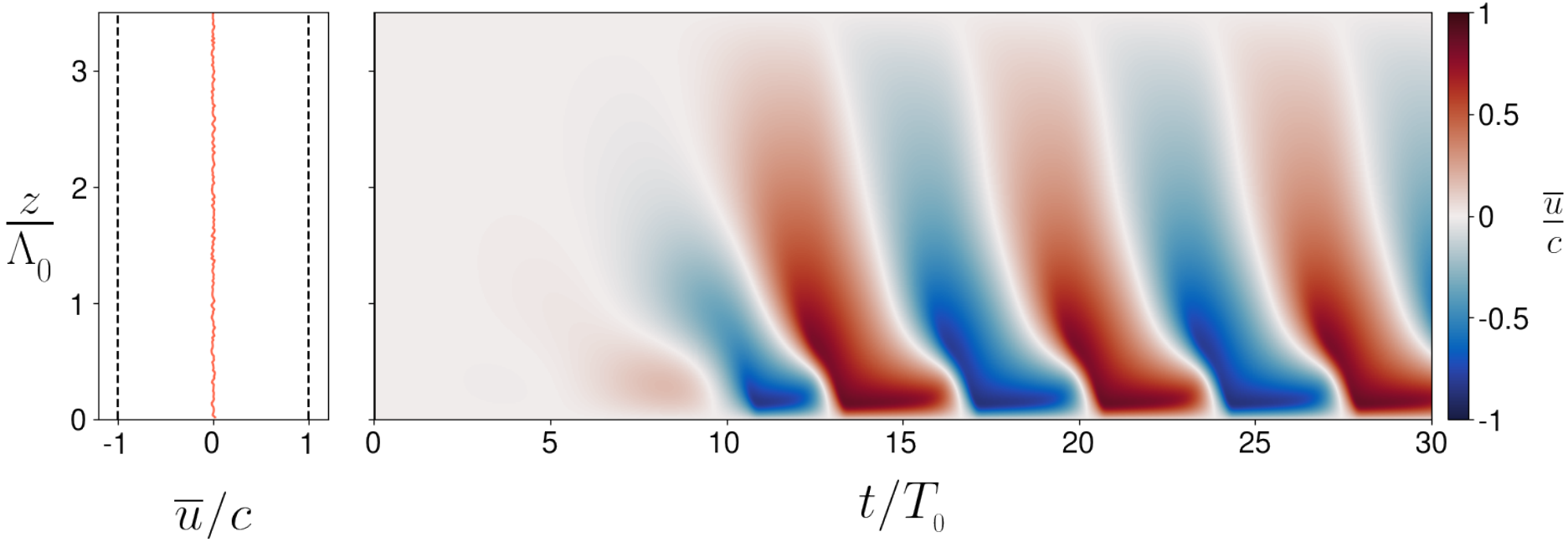
$$\begin{cases} \overline{u'w'}_+ = \quad F \exp\left\{ -\dfrac{1}{\Lambda} \displaystyle\int_0^z \dfrac{\mathrm{d}z'}{(1 - \overline{u}(z')/c)^2} \right\} \\ \overline{u'w'}_- = -F \exp\left\{ -\dfrac{1}{\Lambda} \displaystyle\int_0^z \dfrac{\mathrm{d}z'}{(1 + \overline{u}(z')/c)^2} \right\} \end{cases}$$

Key parameter – the Reynolds number:

$$Re = \frac{F\Lambda}{\nu c}$$

HLP-model in the QBO regime

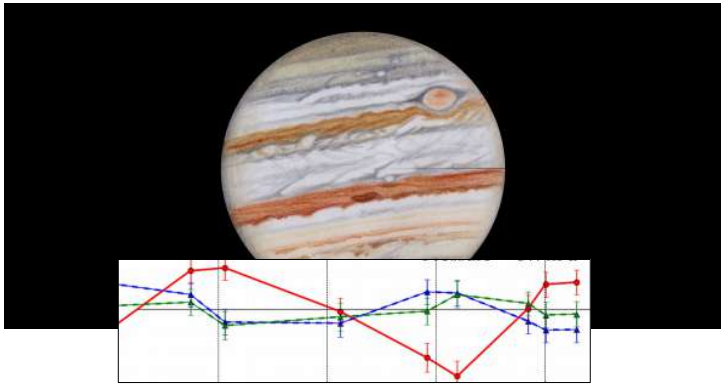
$$\partial_t \overline{u} - \nu \partial_{zz} \overline{u} = -\partial_z \overline{u'w'}_+ - \partial_z \overline{u'w'}_-$$



$$Re = 20$$

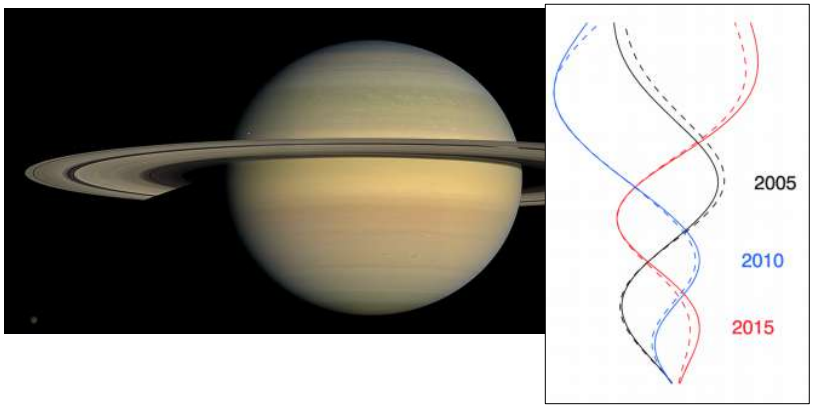
The QBO dynamical system beyond Earth

Jupiter



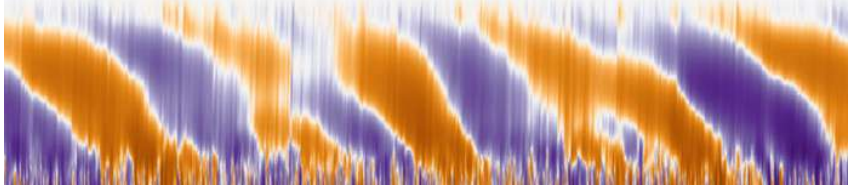
Cosentino *et al.* 2017

Saturn



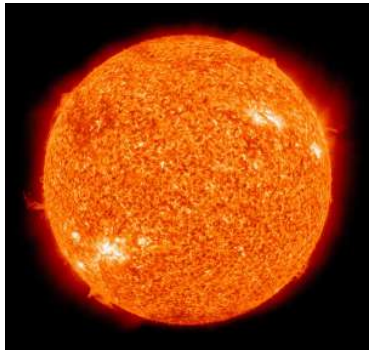
Guerlet *et al.* 2018

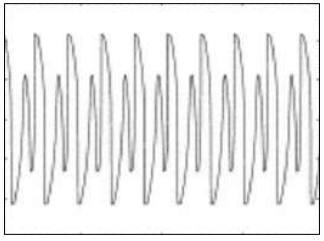
Numerical simulations and laboratory experiments



Couston *et al.* 2018
Plumb & McEwan 1978
Sémin *et al.* 2018

Stellar tachoclines





Kim & McGregor 2011

Large-scales governed by small scales

The **QBO** is a **large-scale** phenomenon
governed by **small-scale** **internal gravity waves**

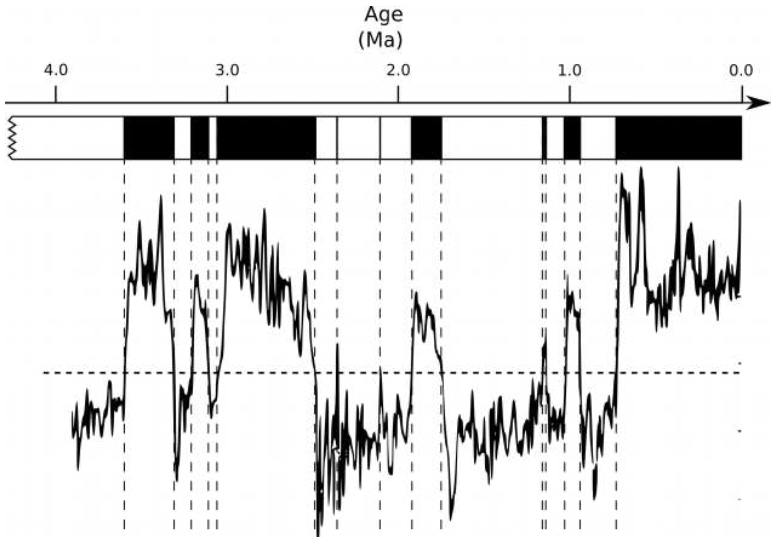
This a **very common** feature in
geophysical fluid dynamics

Low-frequency variability governed by small scales

Jupiter's Great Red Spot

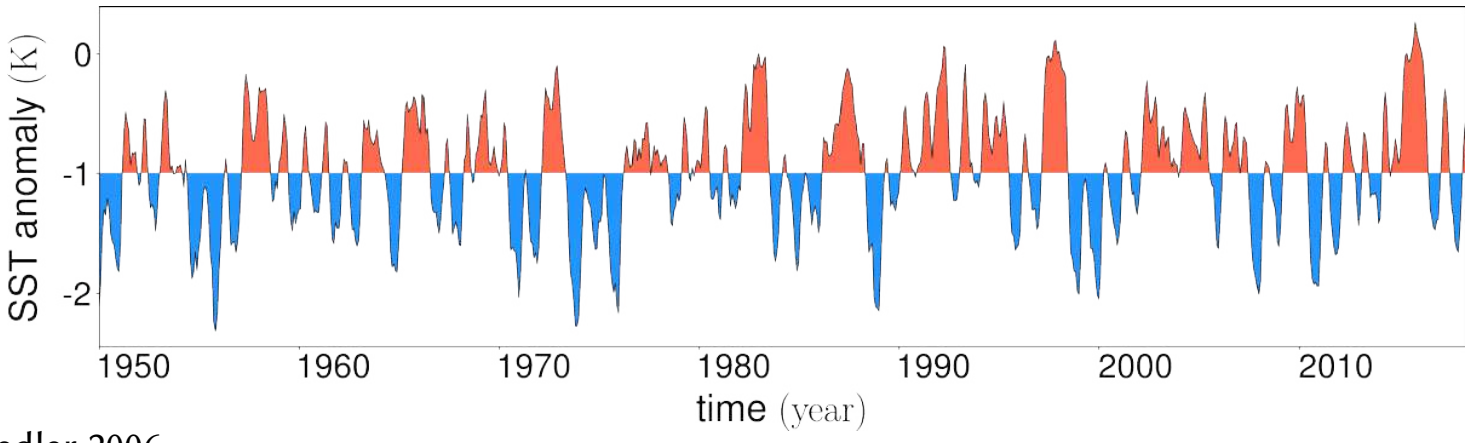
Nasa (Juno)

Earth magnetic field reversals



Pelletier 1998

El Niño southern oscillation



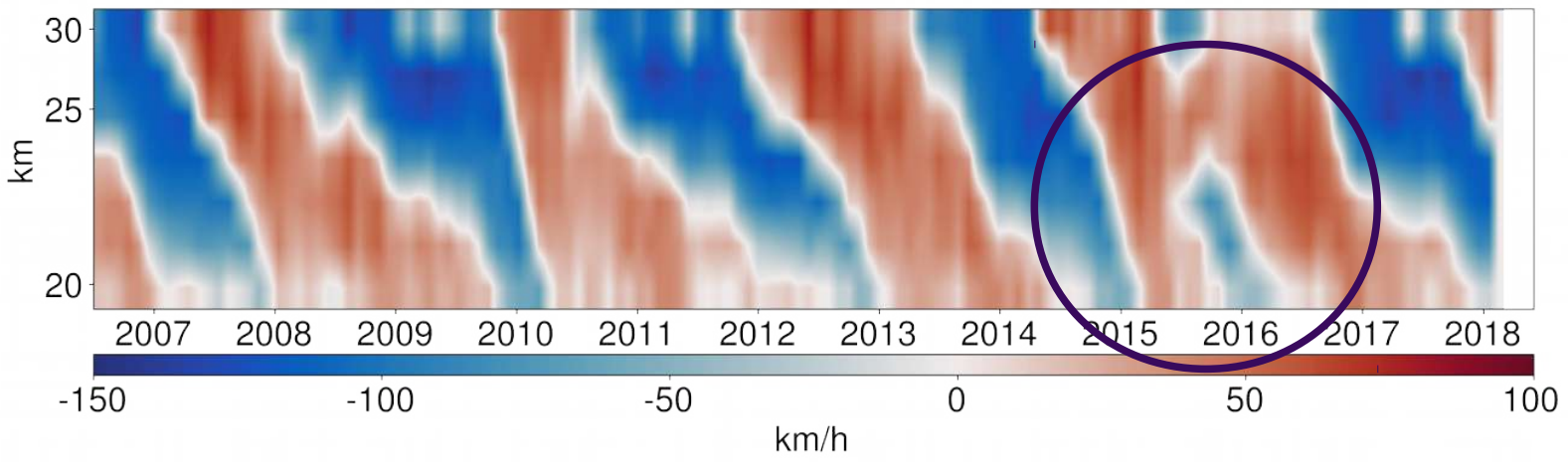
Wang & Fiedler 2006

Low-frequency variability of the QBO

→ **Quasiperiodic** : 24 months $\leq T_{\mathrm{qbo}} \leq$ 30 months

→ **Unexpected** periodicity **disruption** in 2016

Osprey et al 2016



NATURE WORLD NEWS

Scientists Baffled by Strange Disruption of Wind Pattern in Earth's Stratosphere

france culture

"Un contresens dans la stratosphère"
08/09/2016

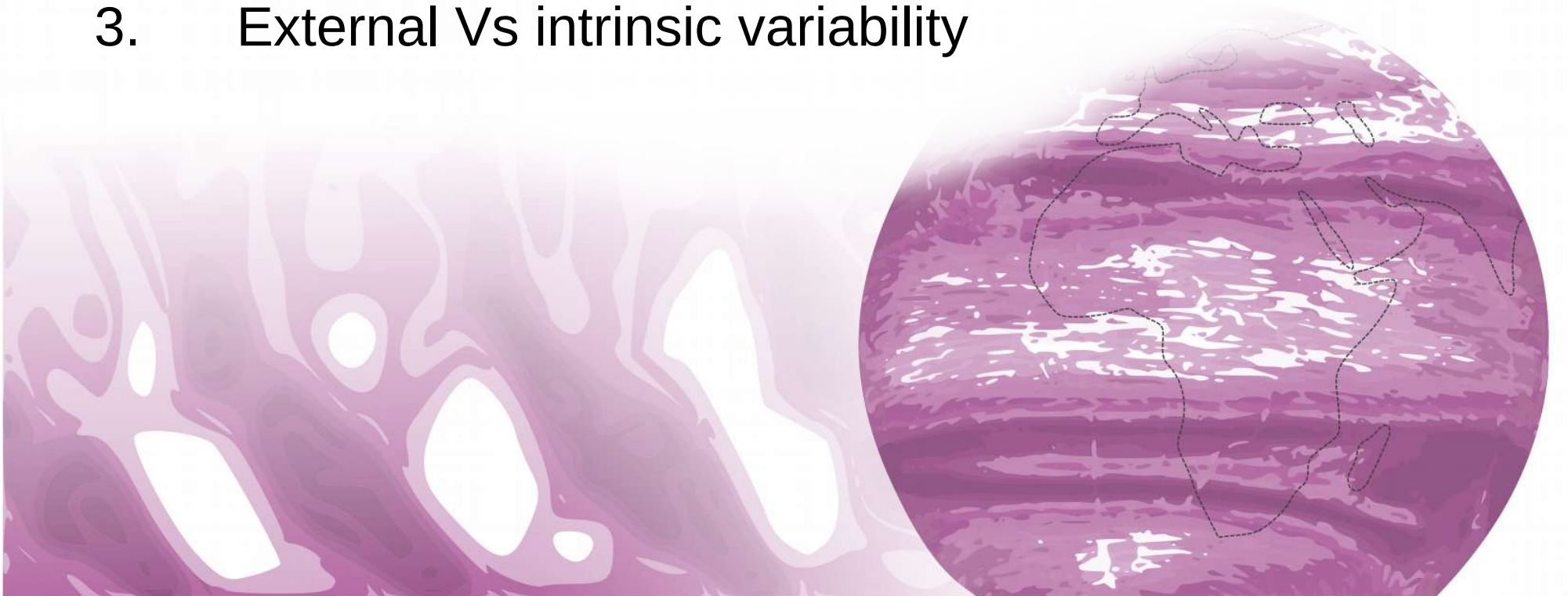
Beyond the periodic regime in idealised models of the QBO

→ Is there other **non-periodic regimes** ?

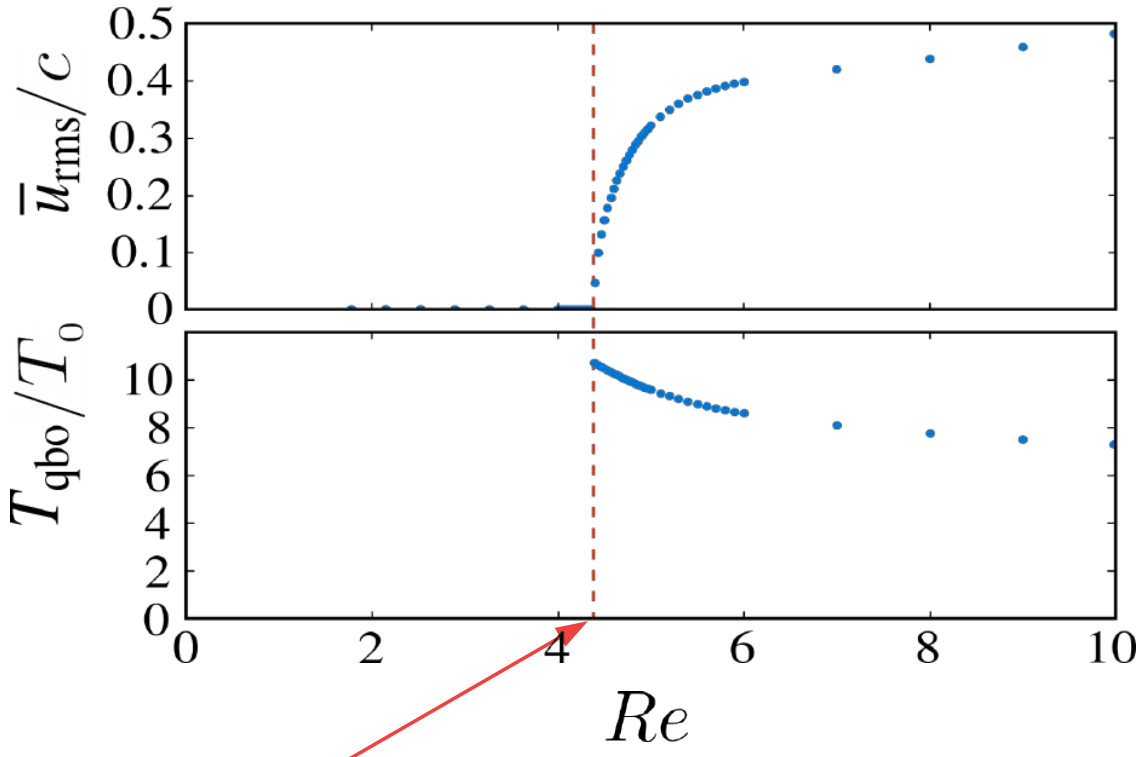
→ What is at the origin of the QBO **variability ?**

Route to chaos in equatorial wind reversals

1. **The QBO bifurcation**
2. A quasiperiodic route to chaos
3. External Vs intrinsic variability



Yoden & Holton (1988)

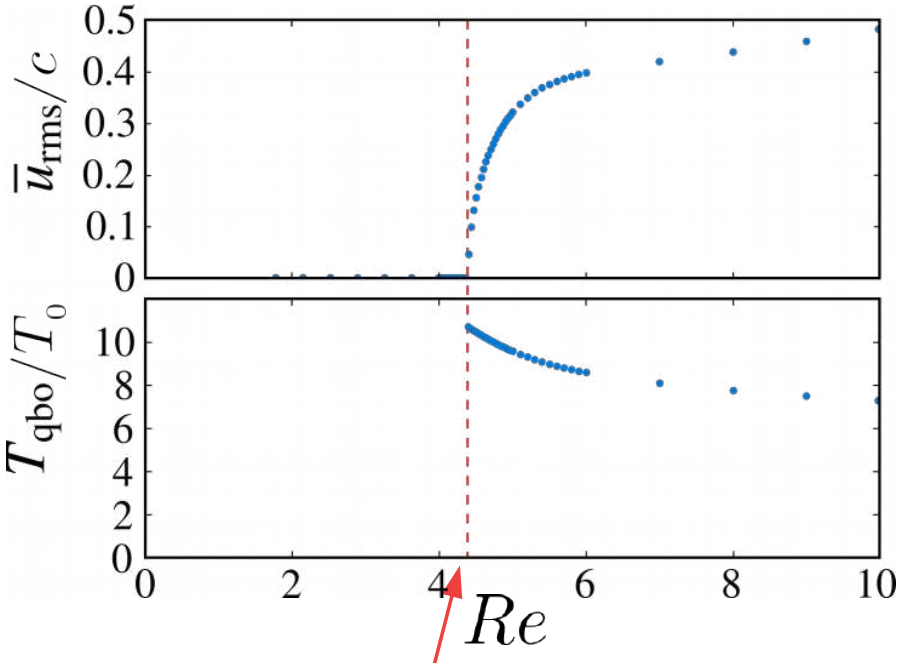


$Re_c \approx 4.25$

A Hopf bifurcation

Importance of the bottom boundary condition

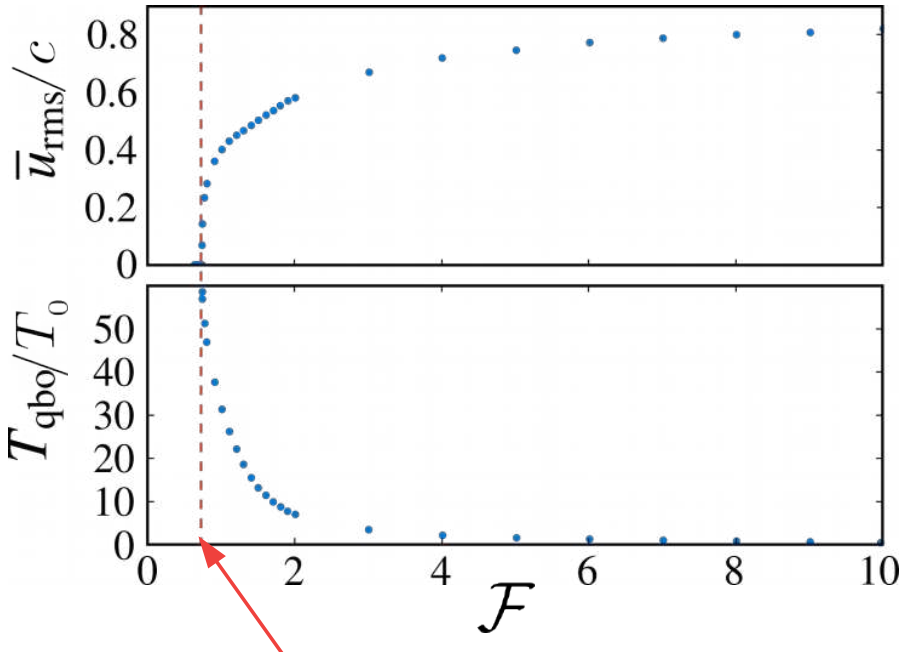
No-slip $\overline{u}|_{z=0} = 0$



$Re_c \approx 4.25$

Yoden & Holton (1988)

Free-slip $(\partial_z \overline{u})|_{z=0} = 0$



$$Re_c = \frac{j_{0,1}^2}{16} \approx 0.36$$

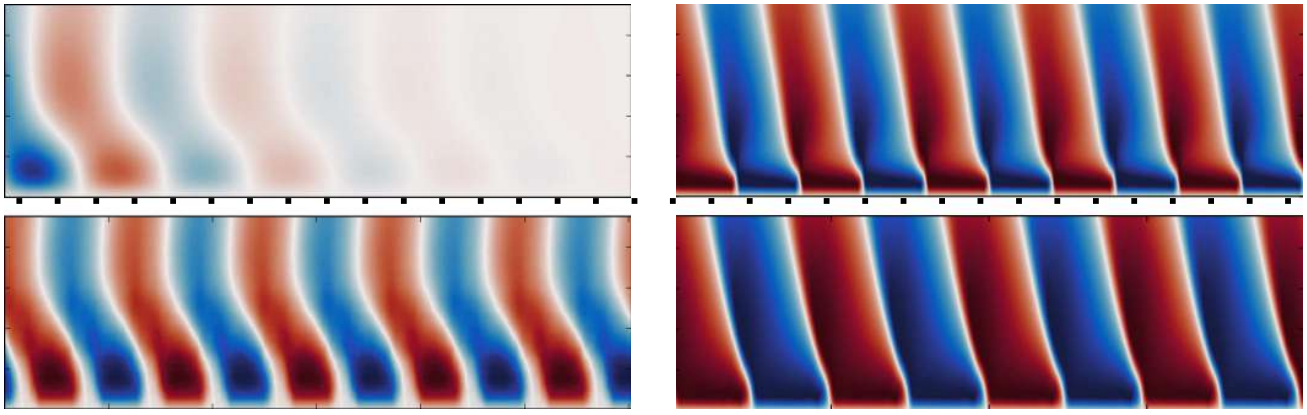
Analytical result

Effect of boundary streaming

Wave viscous boundary layers → **Boundary streaming**

With boundary streaming

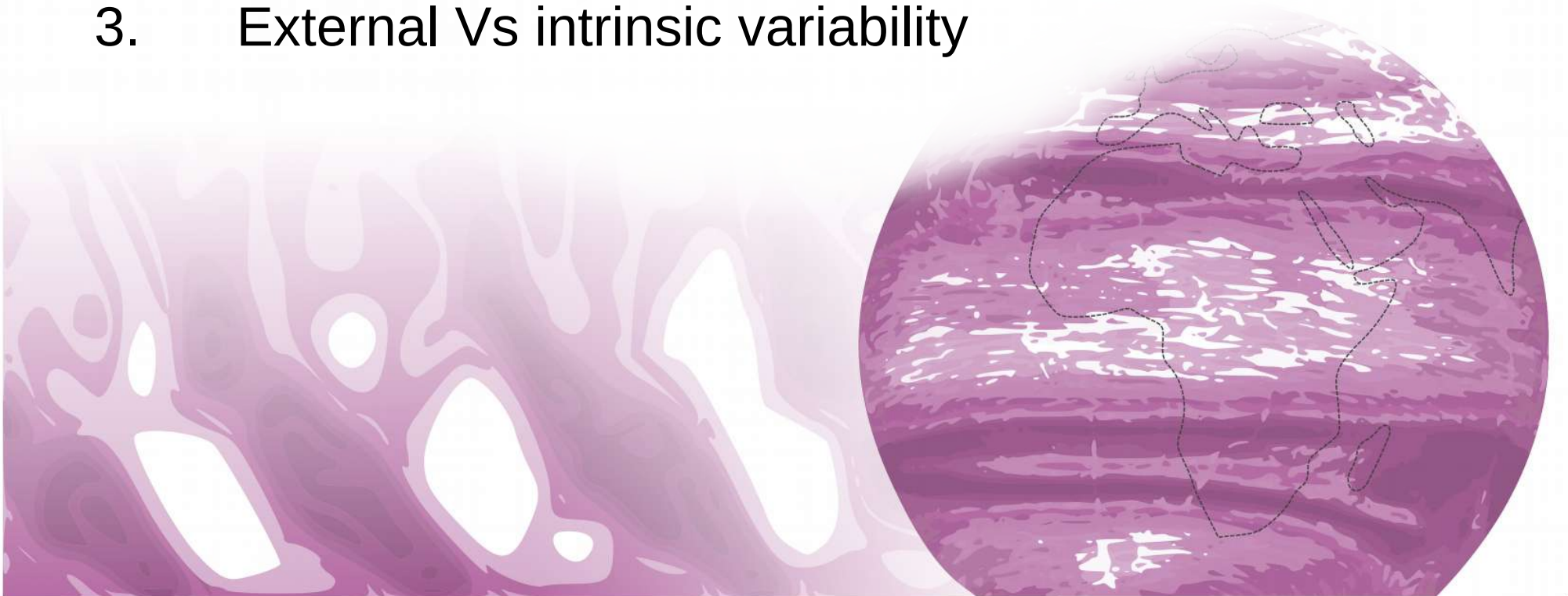
Without boundary streaming



Renaud & Venaille, *JFM* 2018

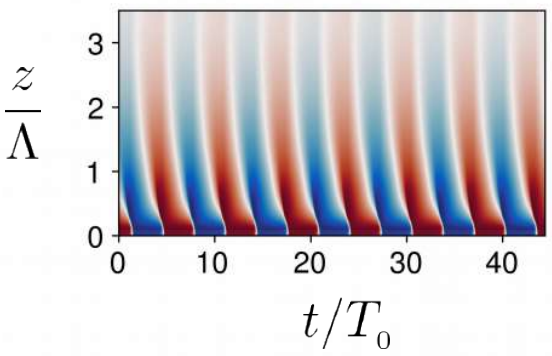
Route to chaos in equatorial wind reversals

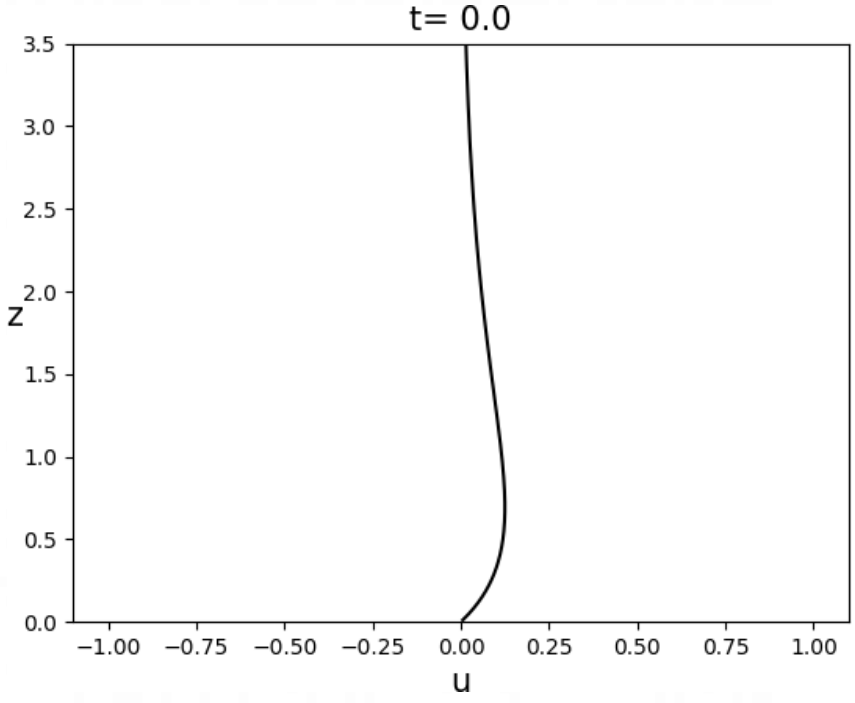
1. The QBO bifurcation
2. **A quasiperiodic route to chaos**
3. External Vs intrinsic variability



Periodic state

25





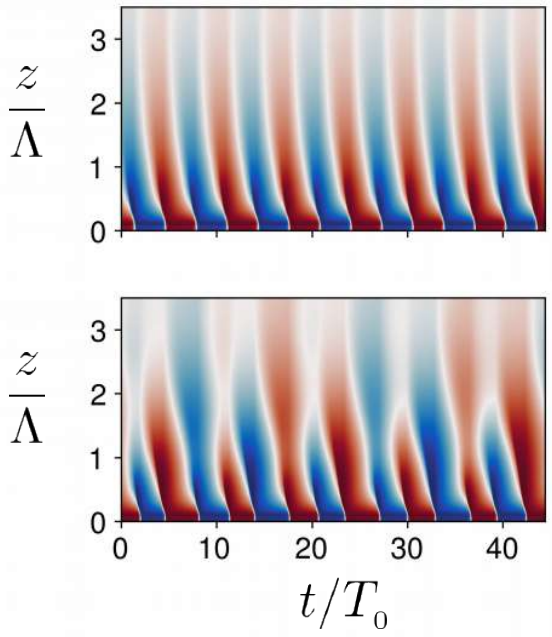
Re

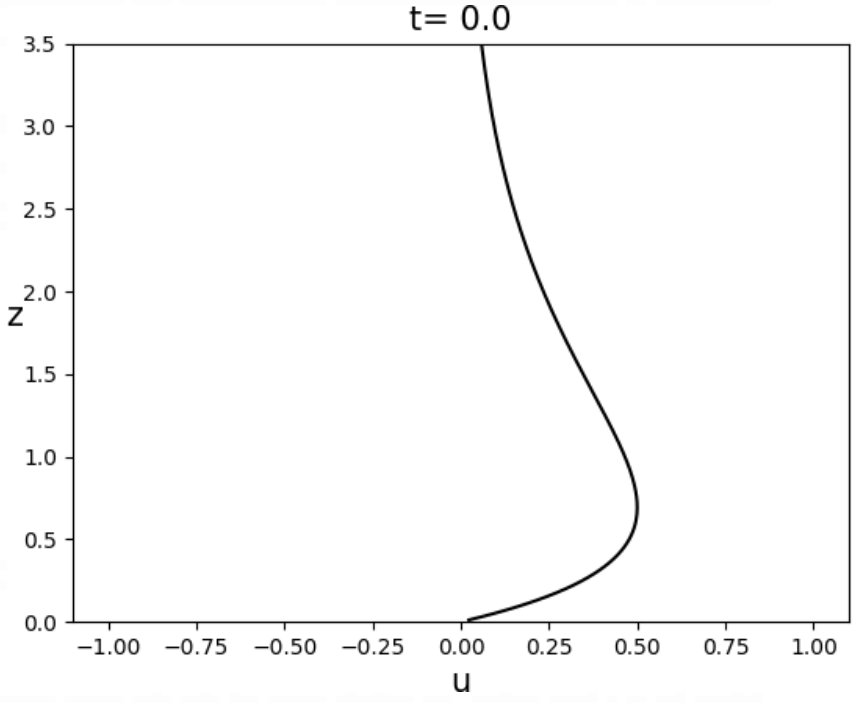
Quasiperiodic state

25

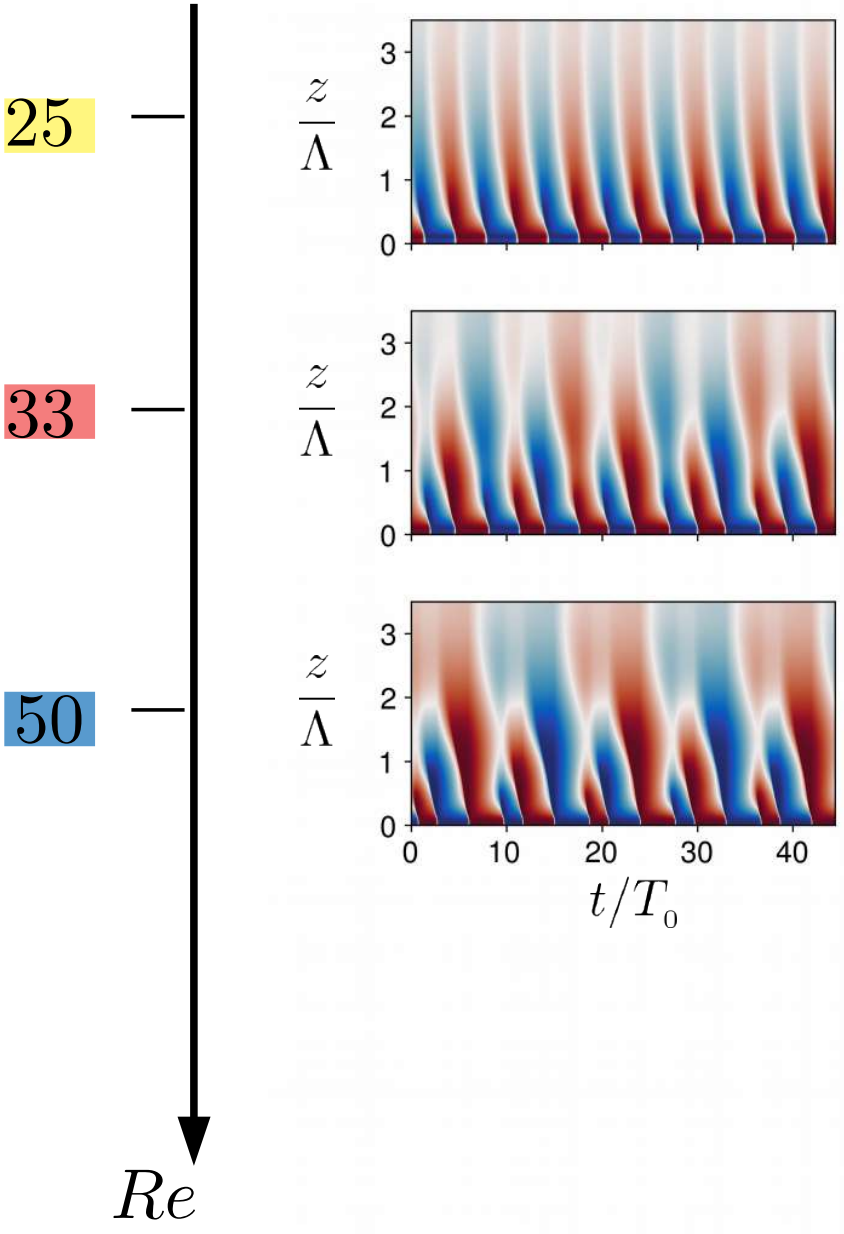
33

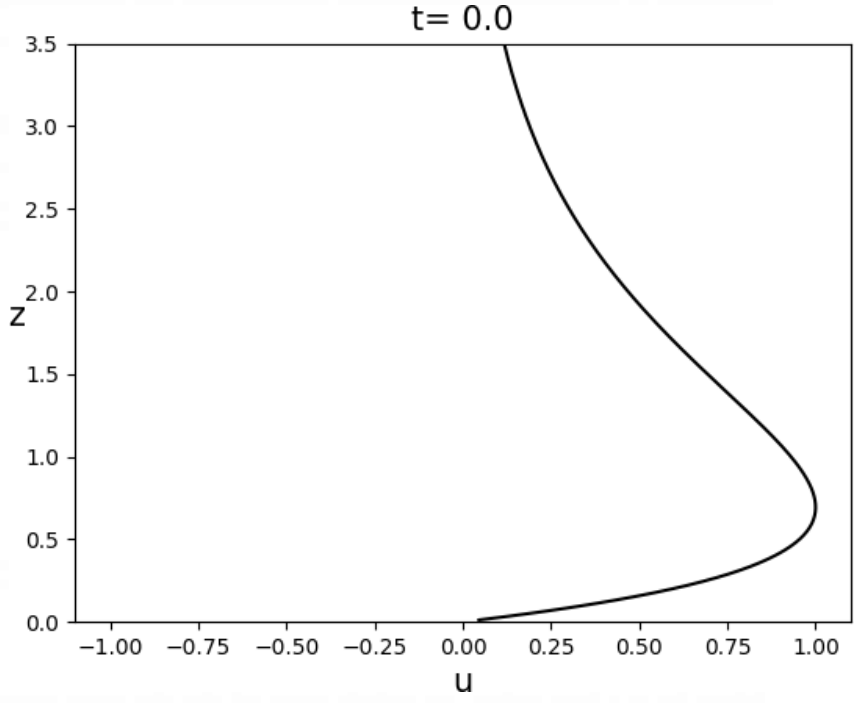
Re



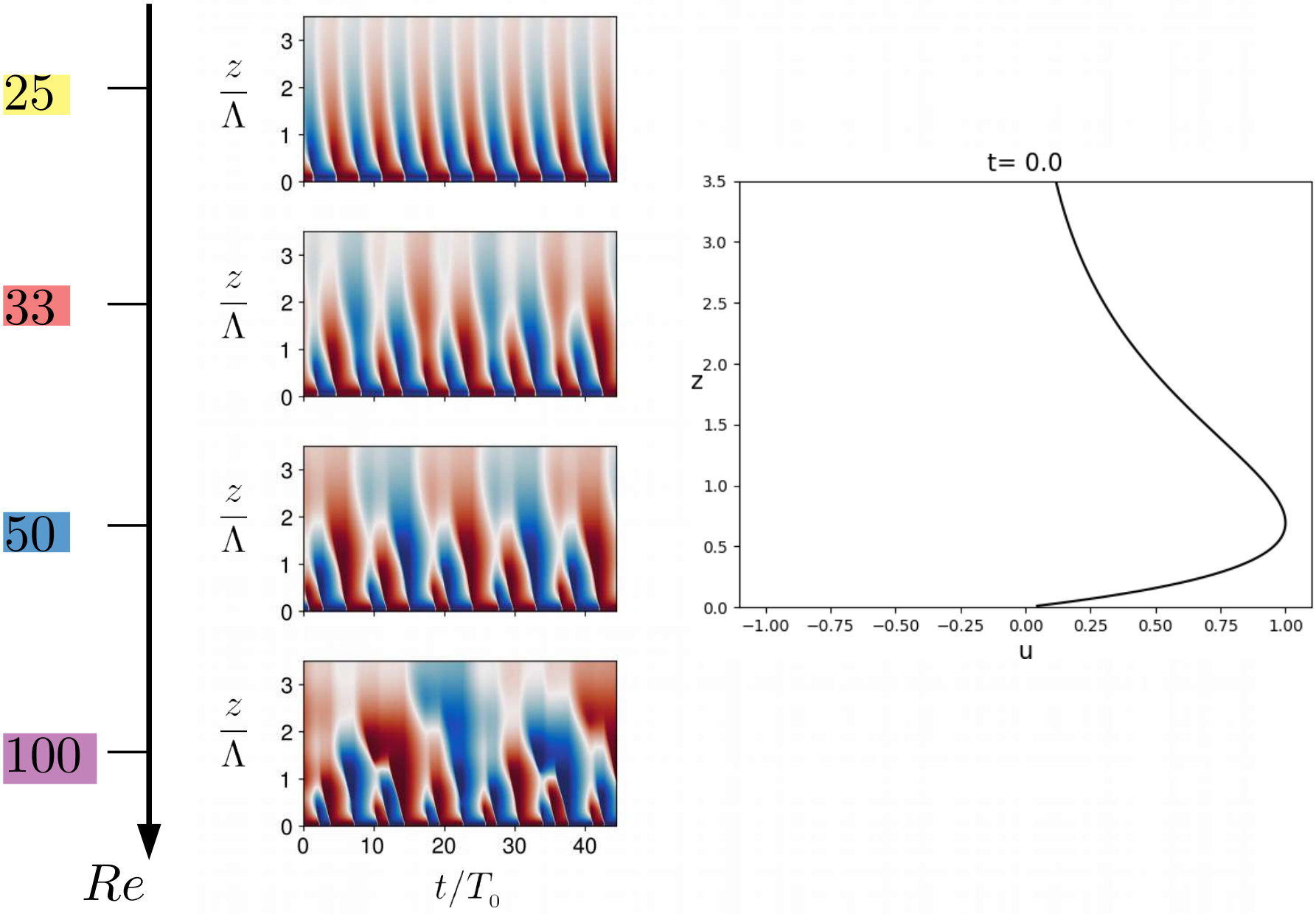


Frequency locked state

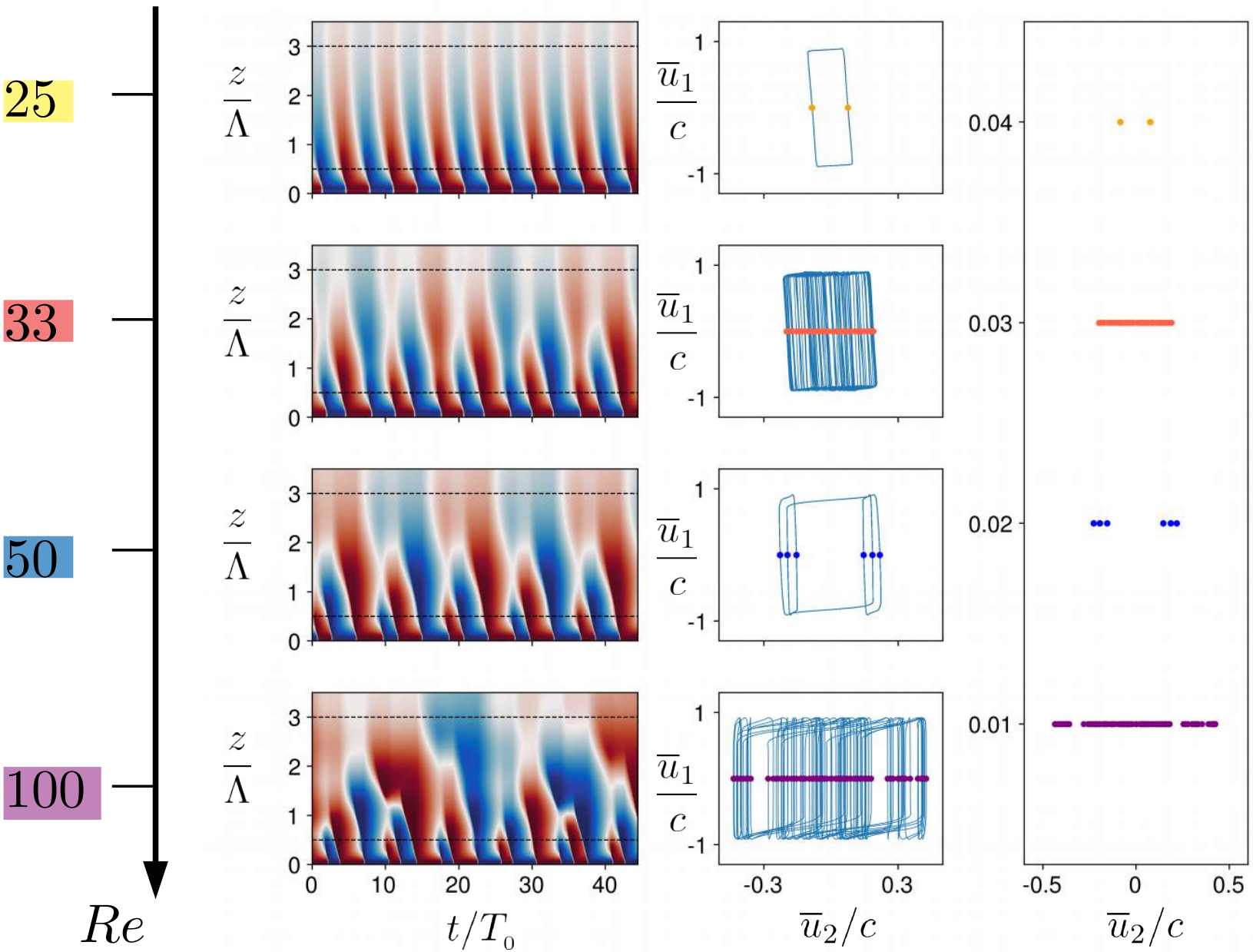




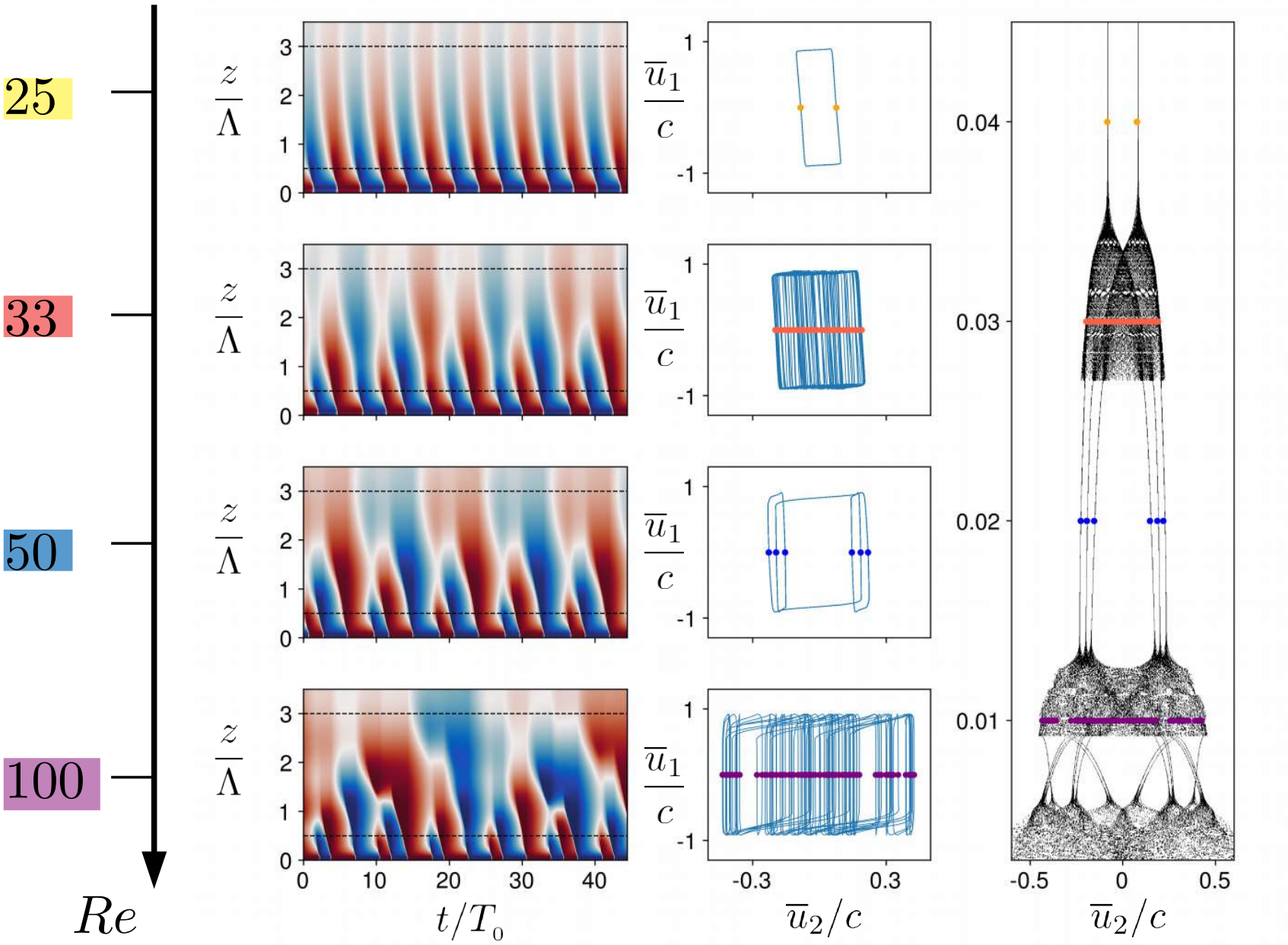
Chaotic state



Bifurcation diagram



Bifurcation diagram



Additional “damping type” parameter

2 damping process: Newtonian Cooling and (effective) viscosity

$$\frac{1}{\Lambda} = \frac{1}{\Lambda_{\mathrm{NC}}} + \frac{1}{\Lambda_{\nu}} \qquad \textbf{with} \qquad \begin{cases} \Lambda_{\mathrm{NC}} \propto \omega^2 \\ \Lambda_{\nu} \propto \omega^4 \end{cases}$$

Additional “damping type” parameter

2 damping process: Newtonian Cooling and (effective) viscosity

$$\frac{1}{\Lambda} = \frac{1}{\Lambda_{\mathrm{NC}}} + \frac{1}{\Lambda_{\nu}} \qquad \textbf{with} \qquad \begin{cases} \Lambda_{\mathrm{NC}} \propto \omega^2 \\ \\ \Lambda_{\nu} \propto \omega^4 \end{cases}$$

Momentum flux:

$$\overline{u'w'}_{+}(z) = F_0 \exp\left\{ -\frac{1}{\Lambda_0} \int_0^z \mathrm{d}z' \left(\frac{1-\alpha}{\left(1-\overline{u}(z')/c\right)^2} + |\frac{\alpha}{\left(1-\overline{u}(z')/c\right)^4} \right) \right\}$$

Additional “damping type” parameter

2 damping process: Newtonian Cooling and (effective) viscosity

$$\frac{1}{\Lambda} = \frac{1}{\Lambda_{\mathrm{NC}}} + \frac{1}{\Lambda_{\nu}} \qquad \textbf{with} \qquad \begin{cases} \Lambda_{\mathrm{NC}} \propto \omega^2 \\ \Lambda_{\nu} \propto \omega^4 \end{cases}$$

Momentum flux:

$$\overline{u'w'}_{+}(z) = F \exp\left\{ -\frac{1}{\Lambda} \int_0^z \mathrm{d}z' \left(\frac{1-\alpha}{(1-\overline{u}(z')/c)^2} + | \frac{\alpha}{(1-\overline{u}(z')/c)^4} \right) \right\}$$

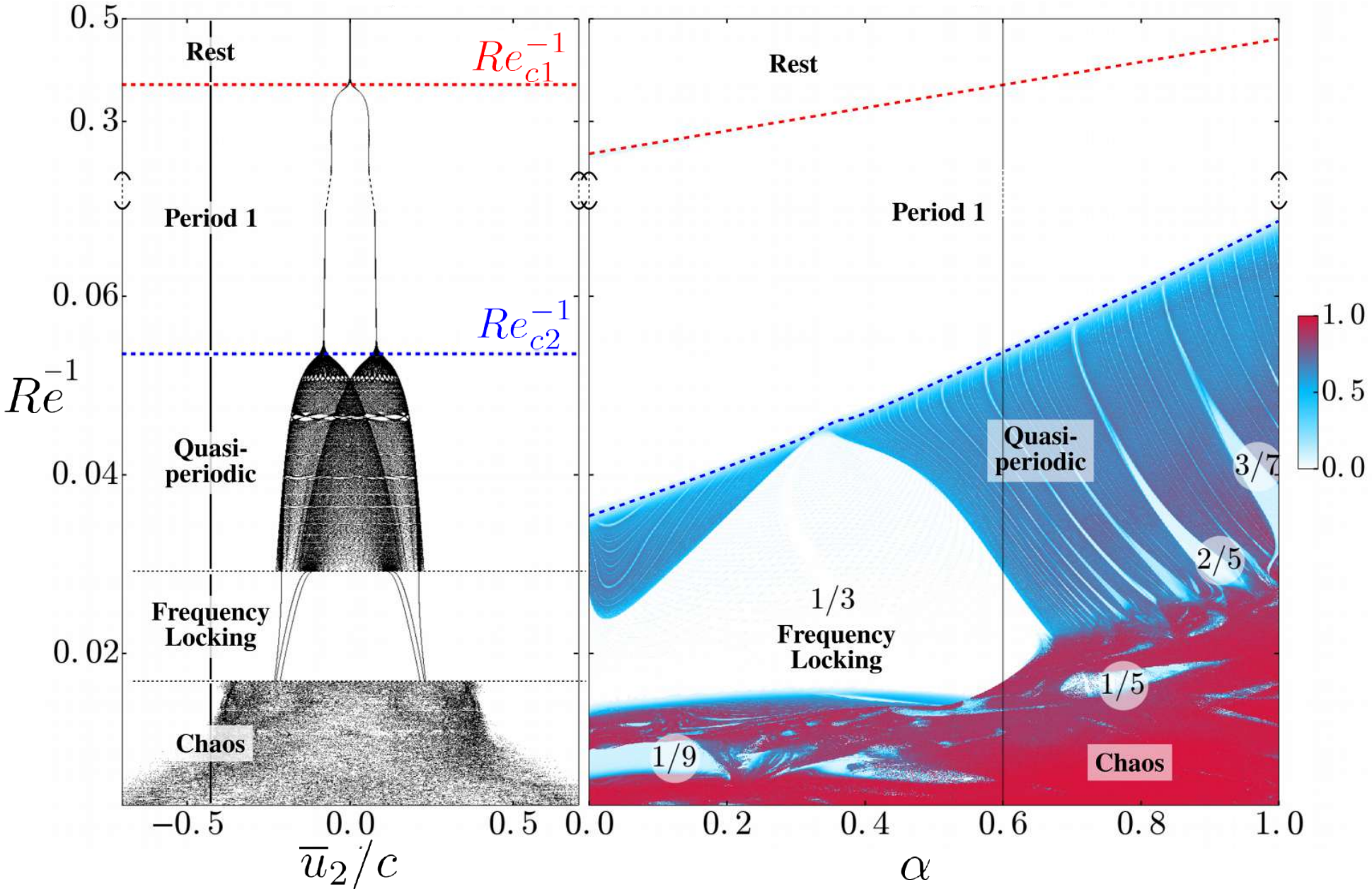
New parameter

$$0 \leq \alpha \leq 1$$

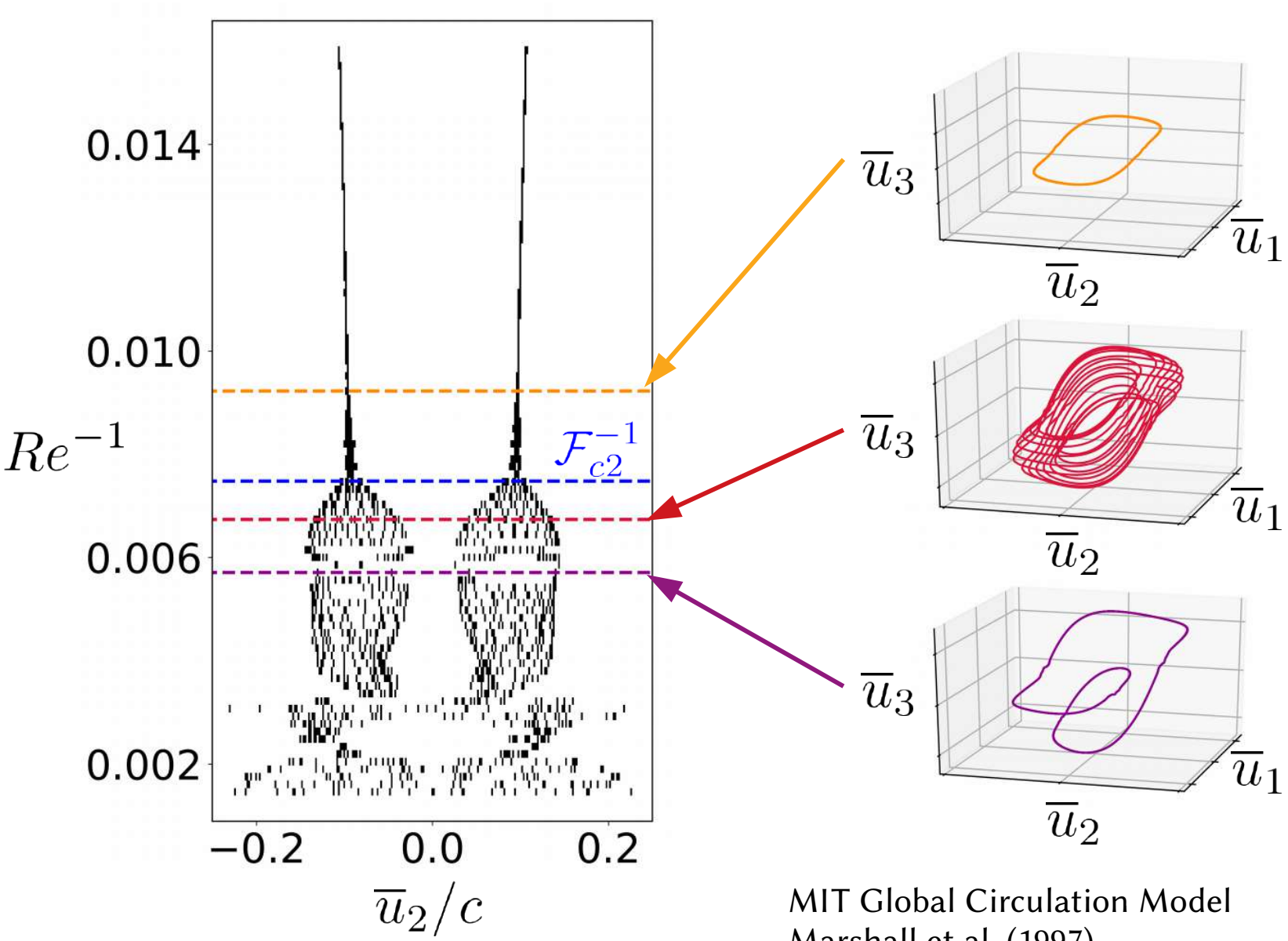
Newtonian cooling only

Viscosity only

Quasiperiodic route to chaos

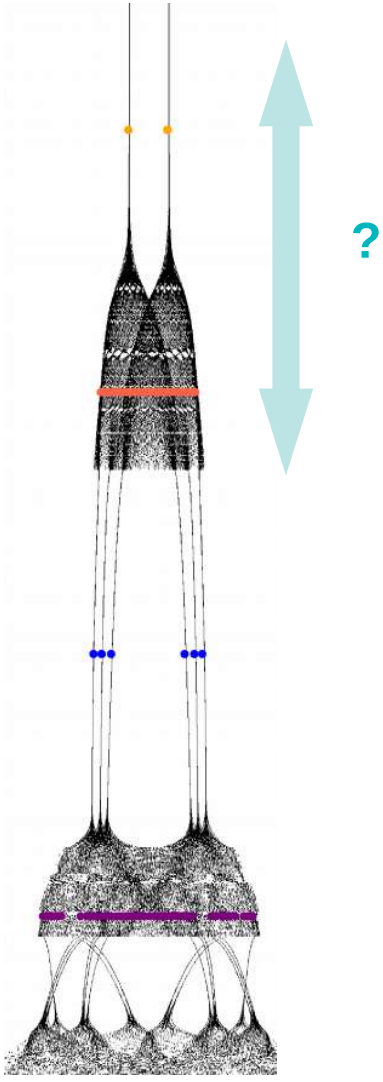


2D fully nonlinear simulations



MIT Global Circulation Model
Marshall et al. (1997)

Where is the QBO?

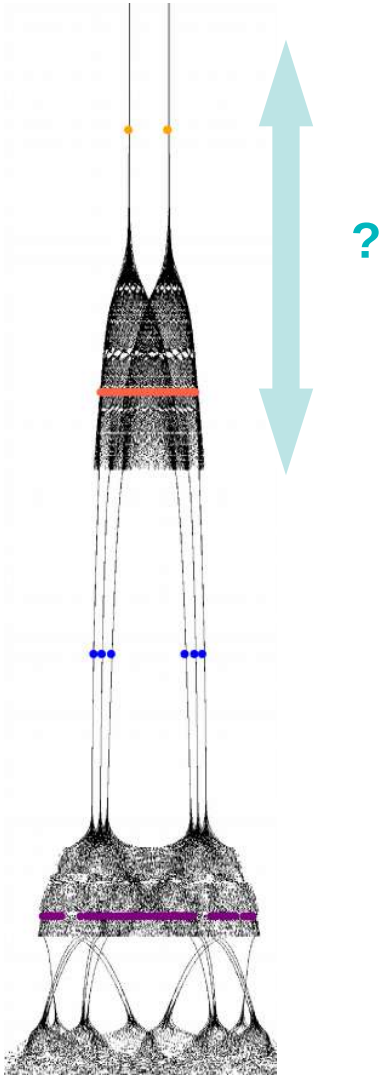


$$Re = \frac{\Lambda^2}{\nu T}$$

Turbulent (effective) viscosity

↳ **Large uncertainties !**

Where is the QBO?



$$Re = \frac{\Lambda^2}{\nu T}$$

Turbulent (effective) viscosity

Large uncertainties !

	1D quasilinear	2D nonlinear
Re_{c1}	≈ 4	≈ 45
Re_{c2}	≈ 20	≈ 130

Hard to answer..

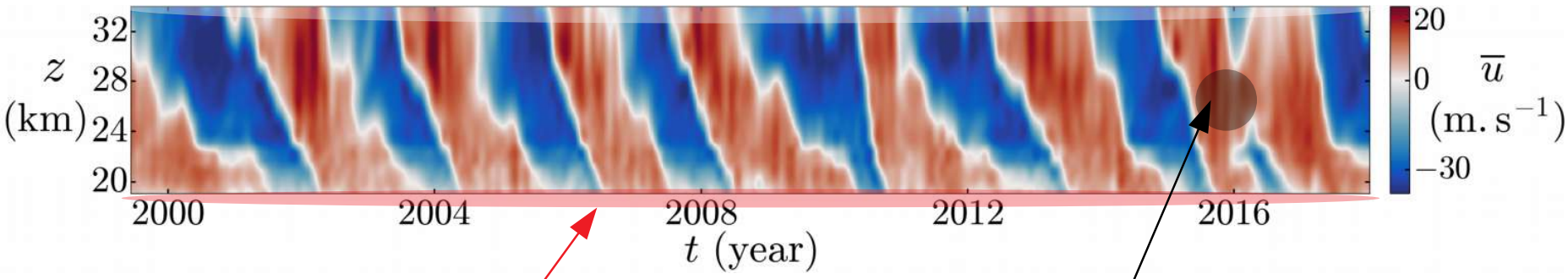
Route to chaos in equatorial wind reversals

1. The QBO bifurcation
2. A quasiperiodic route to chaos
3. **External Vs intrinsic variability**

Extrinsic variability

Seasonal cycle → **tropical up-welling**

Read & Castrejón-Pita 2012
Rajendran *et al.* 2018

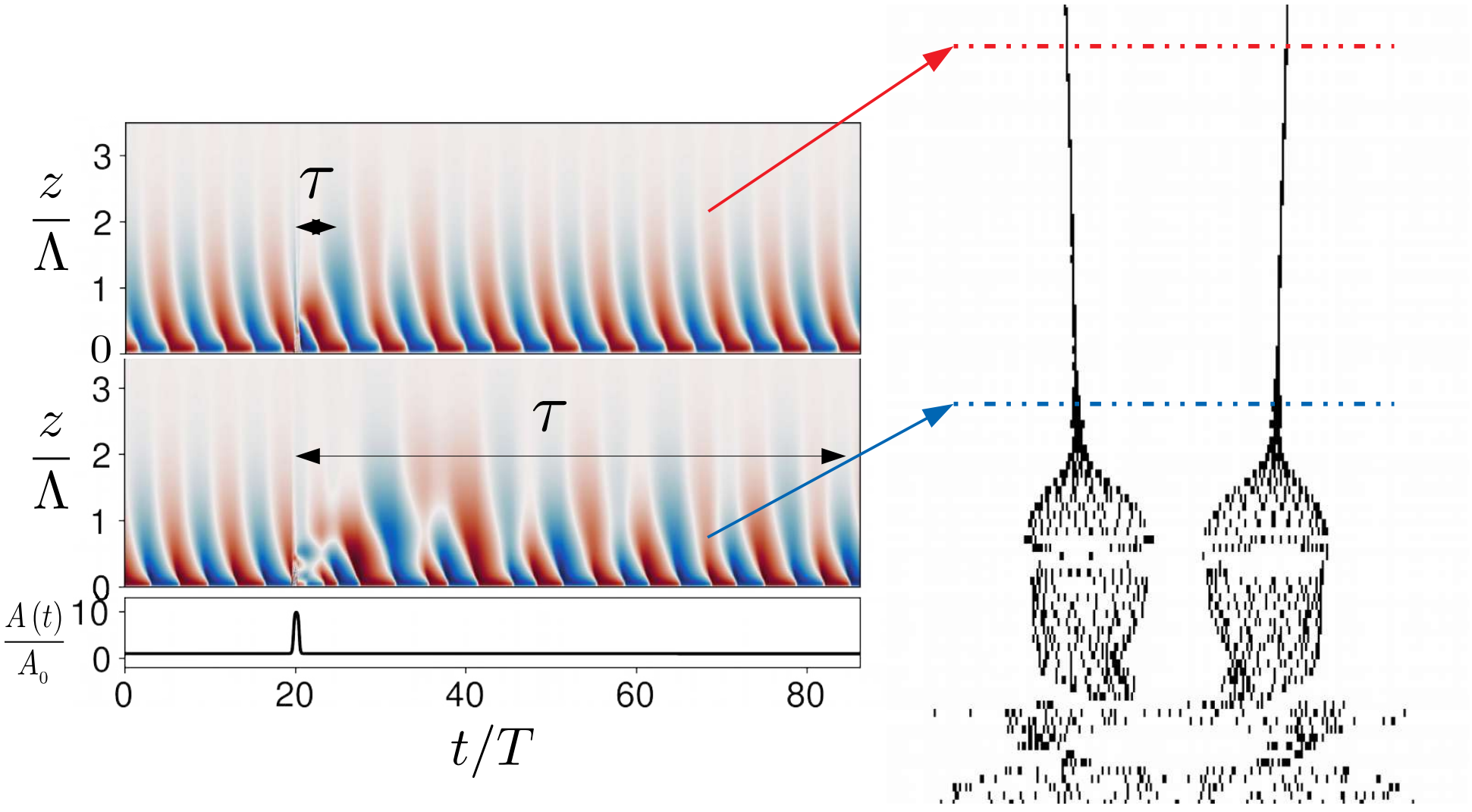


Wave-activity variability

Extra-tropical perturbations

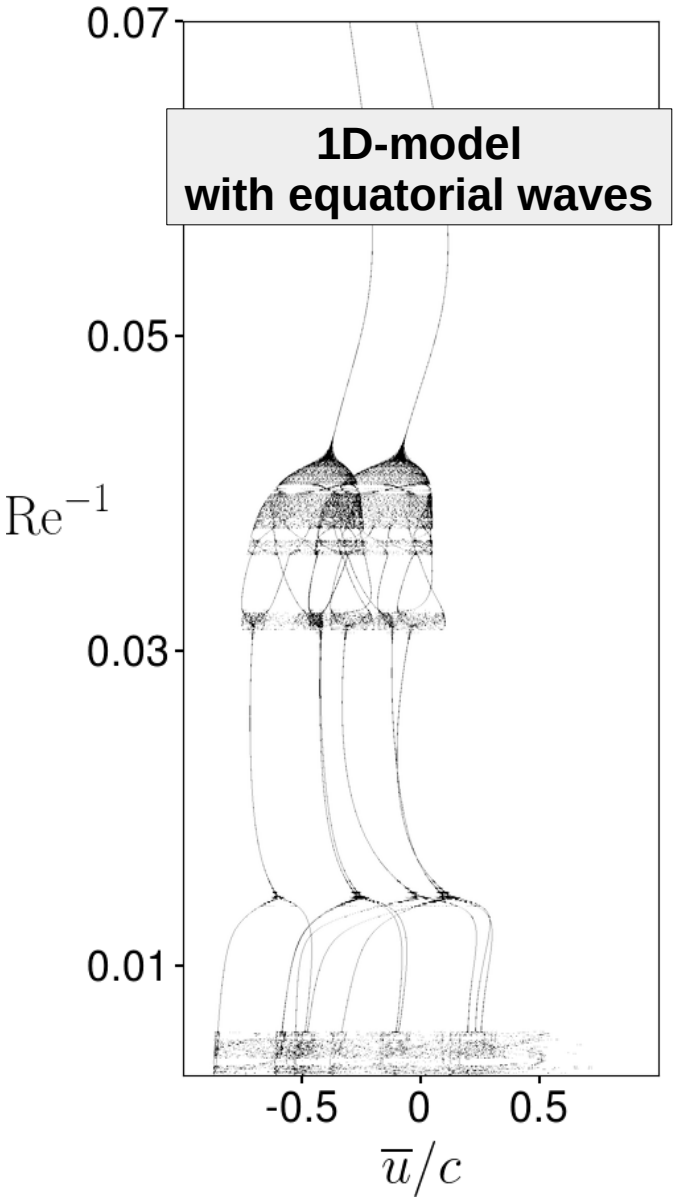
Coy *et al.* 2017
Fletcher *et al.* 2017

Coupling with internal mode of variability

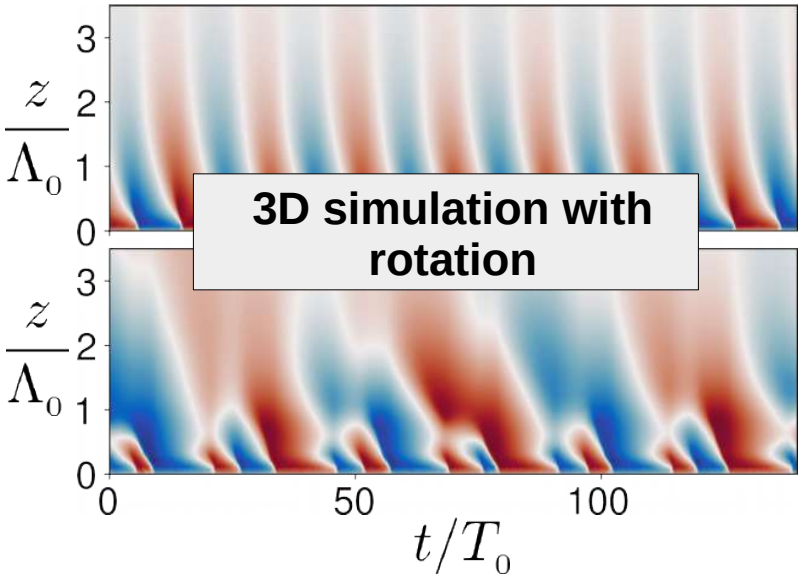


Scheffer et al. (2009)

Perspectives: Trace-up results in more realistic models



- 3D simulations
- Rotation and sphericity
- Full internal wave spectrum
- Seasonal cycle (Upwelling & SAO)
- Achievable in experimental settings ?



Additional work: existence of a distinguished limit

The assumptions made to derive the model are rarely discussed.

⟶ Quasilinear approximation, WKB asymptotics, weak damping, ...

Can we actually consider arbitrarily large Reynolds number without breaking any hypothesis?

⟶ For purely **viscous** damping, the distinguished limit imposes $Re \to 0$

Boundary streaming by internal wave,
Renaud & Venaille, JFM 2018

⟶ Where the damping is dominated by **Newtonian cooling**, we have shown the existence of a distinguished limit with $Re \sim 1$ or $Re \gg 1$

Upcoming paper

Thank you for your attention!

Renaud, Nadeau & Venaille,
Periodicity Disruption of a Model Quasibiennial Oscillation of Equatorial Winds,
PRL (2019)