Towards the control of transitional flows

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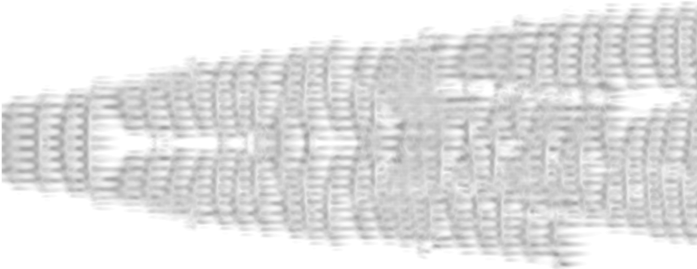
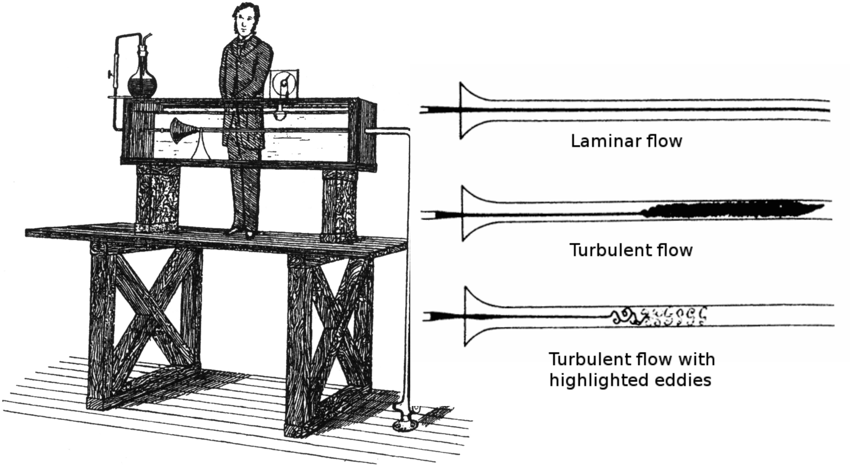


Reynolds experiment



Reynolds, Phil. Trans. R. Soc. London, 174 (1884)

Plane Couette flow

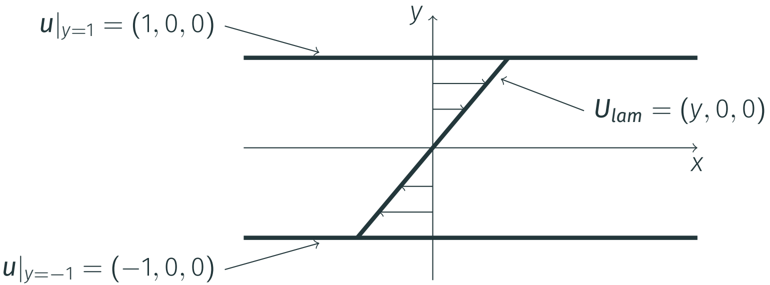
Navier–Stokes equation:

$$\partial_t \boldsymbol{u} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla p + \frac{1}{Re}\nabla^2 \boldsymbol{u}$$

Incompressibility condition: $\nabla \cdot \boldsymbol{u} = 0$

Streamwise and spanwise directions: periodic BCs

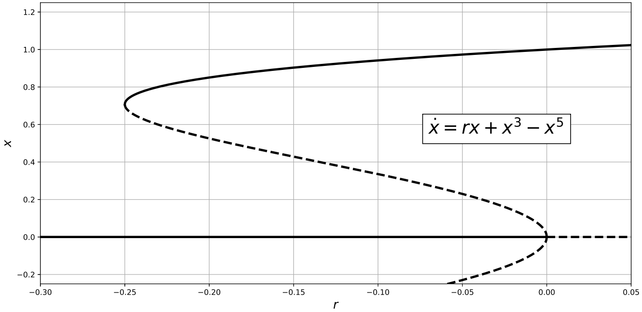
Wall-normal direction: no-slip BCs



Subcritical transitional flows

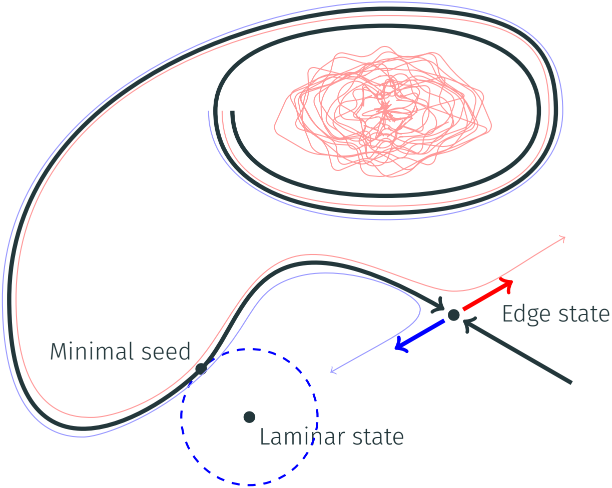
	Linearly stable laminar state	Sustained turbulence
Plane Couette flow	all Re	$Re \gtrsim 325$
Pipe flow	all Re	$Re \gtrsim 2040$
Plane Poiseuille flow	$Re \lesssim 5772$	$Re \gtrsim 840$

Transition is complicated by the coexistence of two attractive states:



Edge of chaos

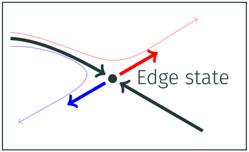
Edge of chaos is wrapped up around the turbulent saddle[1]

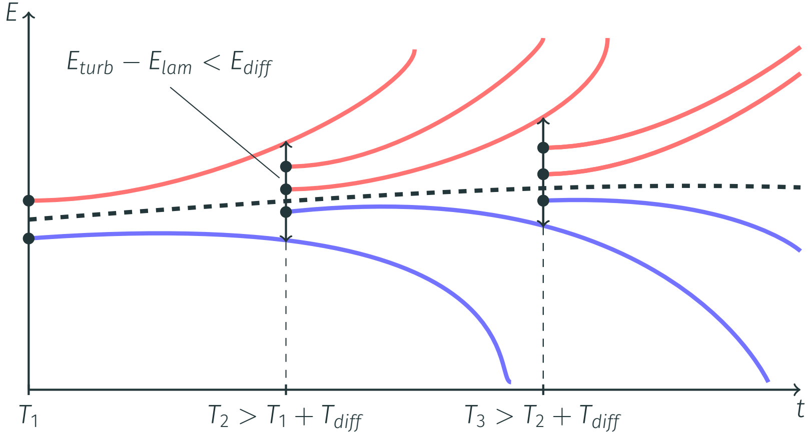


[1] Chantry *et al.*, J. Fluid Mech. **747** (2014)

Edge tracking

Edge tracking allows to compute edge states

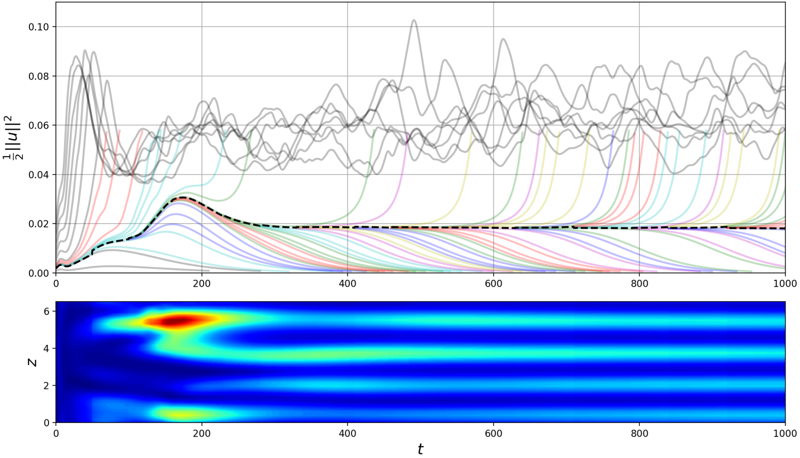




Transition and control in a small domain

Edge states in plane Couette flow

Edge states are equilibria in small domains:[2]



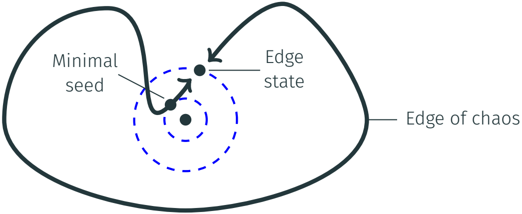
Top plot: initial trajectories (gray), following iterations (color) and edge trajectory (dashed).
Bottom plot: edge trajectory represented via *xy*-averaged kinetic energy.

[2]Schneider *et al.*, Phys. Rev. E, 76, 016301 (2007)

How robust is the laminar state to perturbations?

Indicators of stability:

- Infinitesimal perturbations $\Longrightarrow$ linear growth rate
- Finite-amplitude perturbations $\Longrightarrow$ the size of the basin of attraction

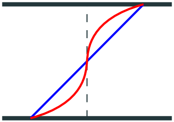


Laminarisation probability $P_{lam}(E)$ is the probability
that a random finite perturbation of energy E laminarises

Random perturbation:

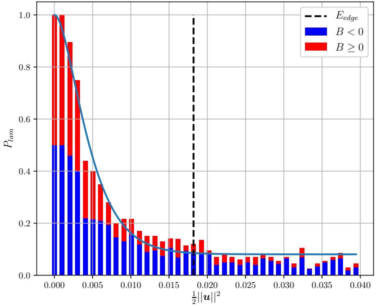
$$\boldsymbol{u} = A\boldsymbol{u}_\perp + B\boldsymbol{U}_{lam},$$

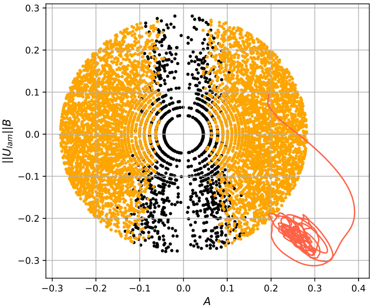
where $A, B, \boldsymbol{u}_\perp$ are generated randomly and $\langle \boldsymbol{u}_\perp, \boldsymbol{U}_{lam} \rangle = 0$



Laminarisation probability

- $P_{lam}(E)$ approximates the size of the basin of attraction
- Laminarisation probability fitting: $p(E) = 1 - (1 - a)\gamma(\alpha, \beta E)$
- Control strategies can be assessed by comparing $P_{lam}(E)$





Left: laminarisation probability for perturbations with energies between 0 and $2E_{edge}$
Right: random perturbations classified as laminarising (black) and transitioning (yellow)

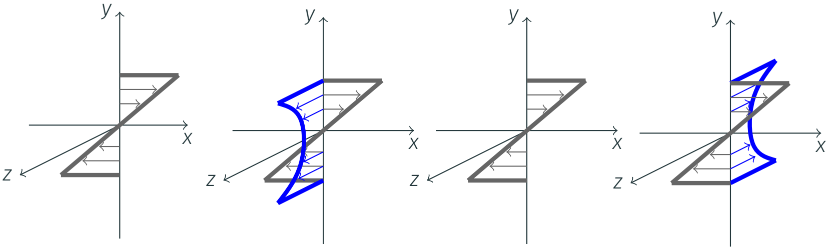
Control strategy: wall oscillations

We impose in-phase oscillations on the walls[3]:

$$\boldsymbol{u}(x, \pm 1, z, t) = \pm \boldsymbol{e_x} + A\sin(\omega t)\boldsymbol{e_z}$$

$$\implies \quad \boldsymbol{U_{lam}} = y\boldsymbol{e_x} + W(y, t)\boldsymbol{e_z}.$$

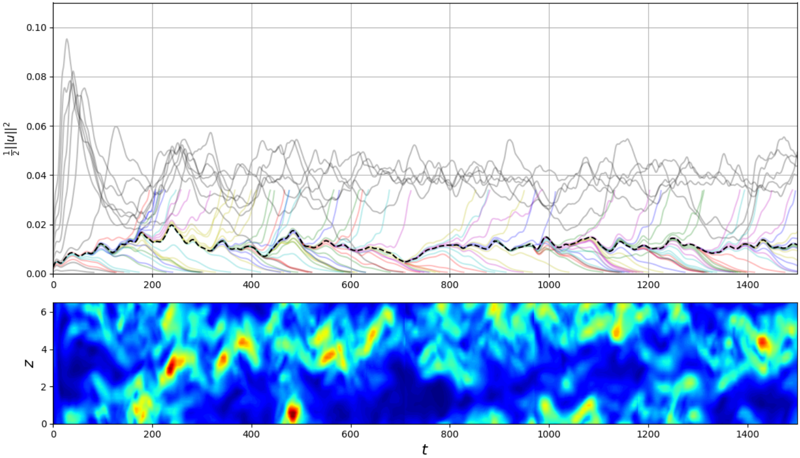
(a) $t = 0$: (b) $t = \frac{\pi}{2\omega}$: (c) $t = \frac{\pi}{\omega}$: (d) $t = \frac{3\pi}{2\omega}$:



[3] Motivated by Rabin *et al.*, J. Fluid Mech. **738** (2014)

Edge state for wall-oscillated flow

- Consider $A = 0.3$ and $\omega = 1/16 \implies$ the edge state is chaotic
- The average E_{edge} is decreased by approximately 37%



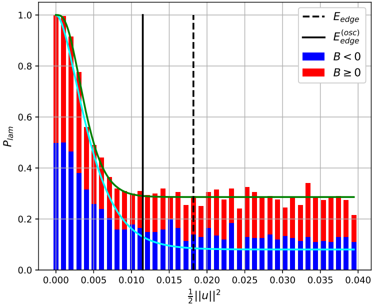
Top plot: initial trajectories (gray), following iterations (color) and edge trajectory (dashed).
Bottom plot: edge trajectory represented via xy-averaged kinetic energy.

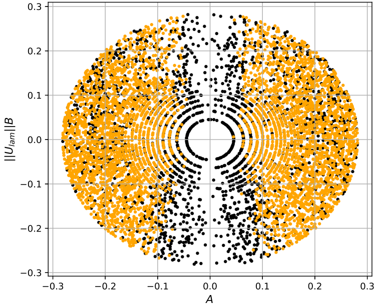
Laminarisation probability for wall-oscillated flow

- P_{lam} is significantly increased compared to the uncontrolled case
- Relative probability increase:

$$\frac{1}{2E_{edge}} \int_0^{2E_{edge}} \frac{p_{osc}(E) - p(E)}{p(E)} dE \approx 1.8$$

- Laminarising perturbations are spread all over the space $(A, ||\boldsymbol{U}_{lam}||B)$



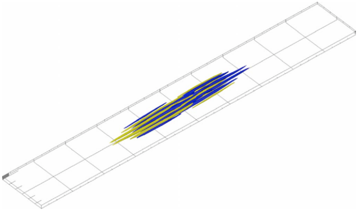


Left: laminarisation probability for perturbations with energies between 0 and $2E_{edge}$
Right: random perturbations classified as laminarising (black) and transitioning (yellow)

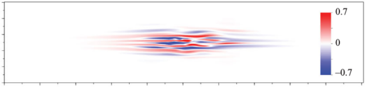
Transition to turbulence in a wide domain

Localised edge states

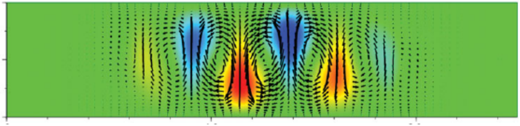
(a) $63.7\pi \times 2 \times 15.9\pi$ domain[4]:



(b) $64\pi \times 2 \times 16\pi$ domain[5]:



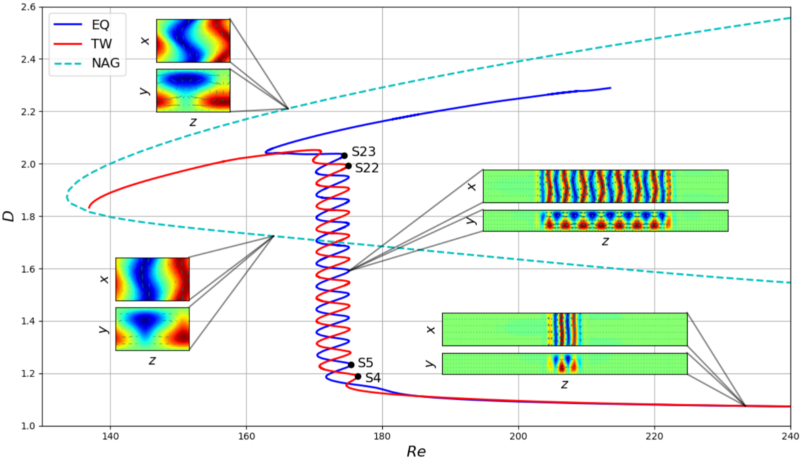
(c) $4\pi \times 2 \times 8\pi$ domain[5]:



[4] Duguet *et al.*, Phys. Fluids, 21, 111701 (2009)
[5] Schneider, *et al.*, J. Fluid Mech., 646 (2010)

Snaking in plane Couette flow ($4\pi \times 2 \times 32\pi$)

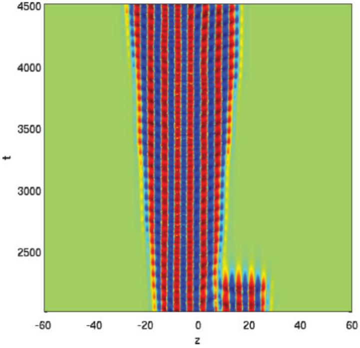
- First observed by Schneider *et al.* in 2010[6]
- Homoclinic snaking is most studied for the Swift–Hohenberg equation[7]

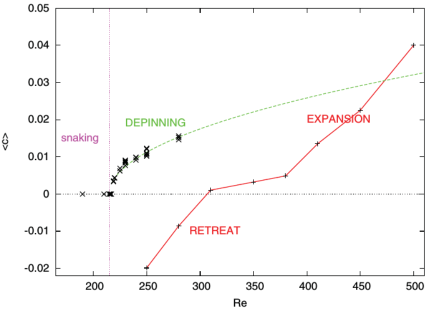


[6] Schneider *et al.*, Phys. Rev. Lett., **104** (2010)
[7] Knobloch, Annu. Rev. Condens. Matter Phys., **6** (2015)

Depinning

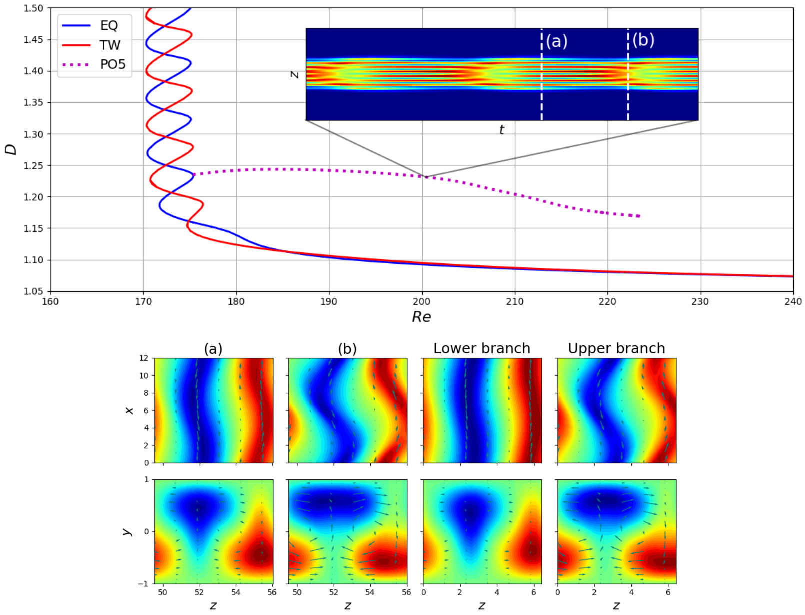
- **Depinning** is the process of expansion/collapse of the initial spatial pattern outside the snaking by nucleation/annihilation of cells
- Square-root law of the speed of fronts: $c \propto |Re - Re_s|^{1/2}$
- Depinning in plane Couette flow was witnessed by Duguet *et al.*[8]



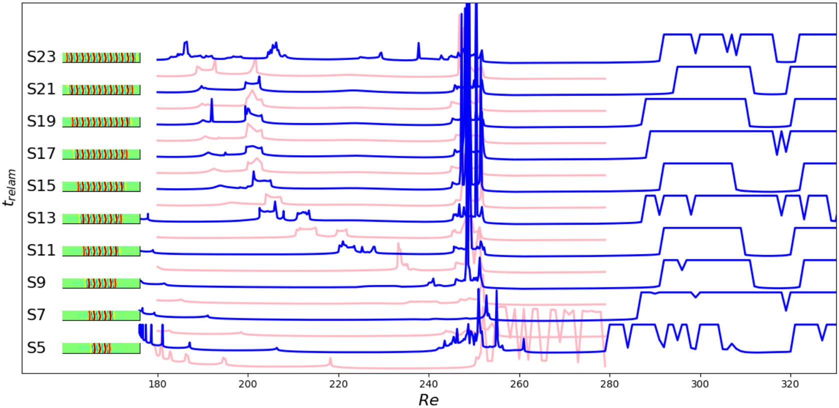


[8] Duguet *et al.*, Phys. Rev. E, 84 (2011)

Localised periodic orbit and oscillatory dynamics



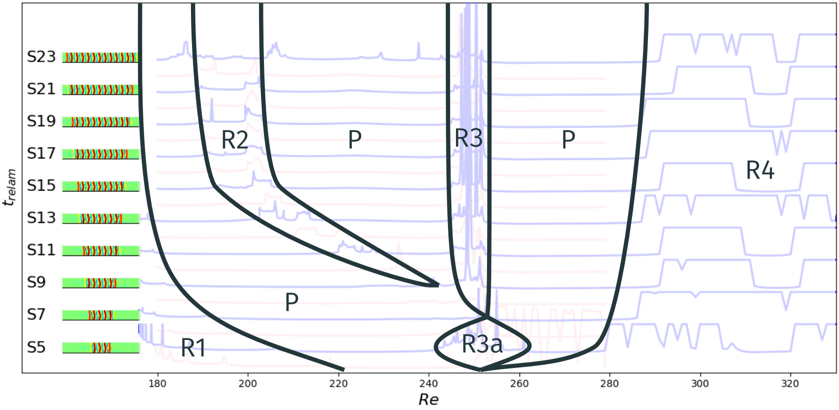
Relaminarisation times for localised states



Relaminarisation times for EQ (blue) and TW (red) saddle-node states. Midplane of streamwise velocity of EQ saddle-node states is shown on the left.

No major difference between the dynamics of EQ and TW

Relaminarisation times for localised states



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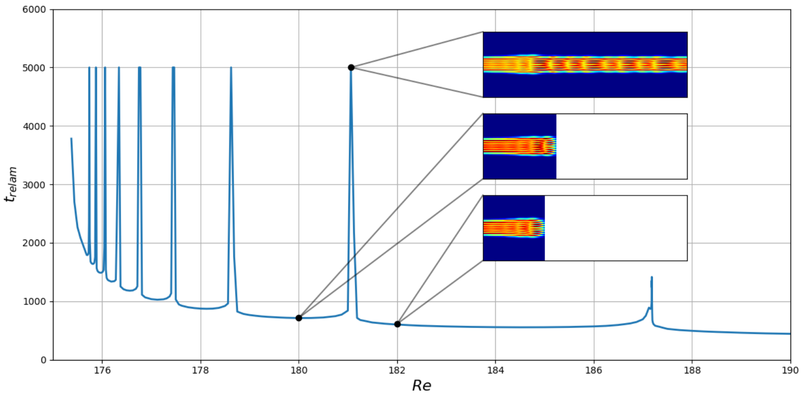
Region R1 – peaks (S5)

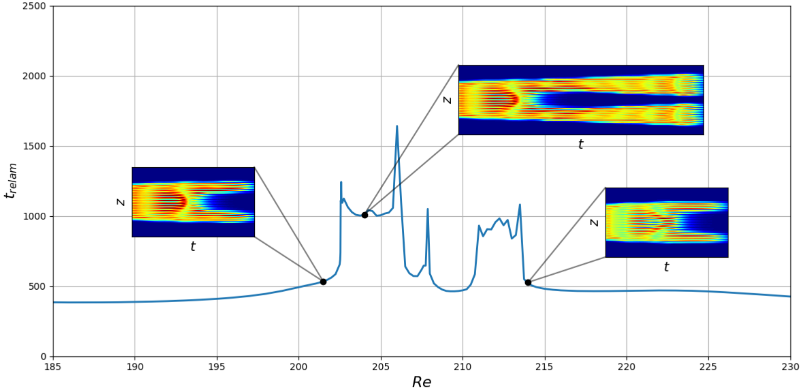


- Peaks: $Re_{n+1} - Re_s = \alpha\,(Re_n - Re_s)$
- Local minima: $t_n = t_0 + \beta n$

$$\implies \quad t_{relam} = \frac{\beta}{\ln \alpha} \ln \left[\frac{2\,(Re - Re_s)}{(1+\alpha)\,(Re_0 - Re_s)} \right] + t_0$$

Region R2 – splitting

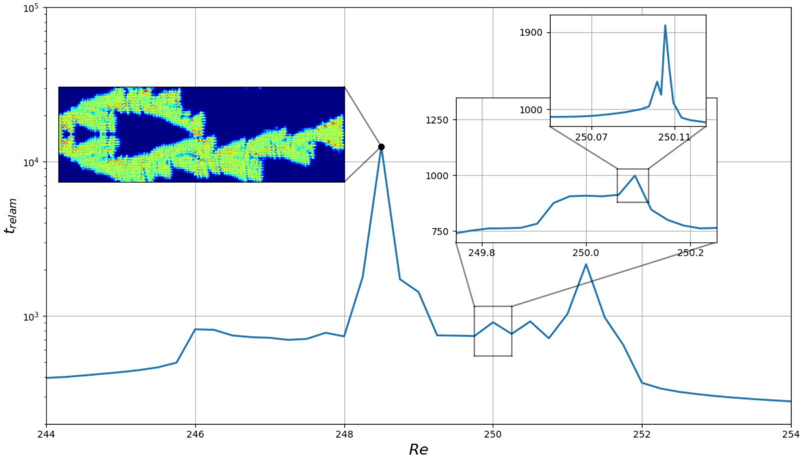
- Region R2 appears due to the creation and activation of spots
- The spot size is the same for all considered initial conditions



Relaminarisation times for S13 integrated for $Re \in [185; 230]$.

Region R3 – chaotic transients

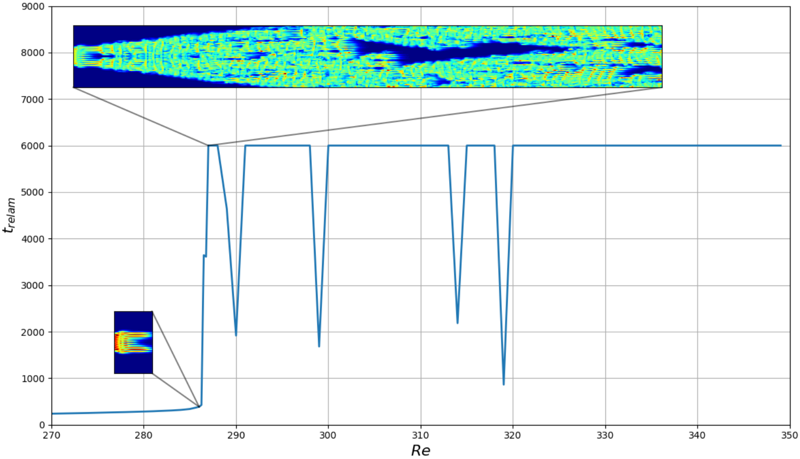
- Like R2, R3 originates from the splitting of the initial spot
- Unlike R2, R3 contains long-lasting chaotic transients ($T > 4000$)
  - Decay of roll clusters overwhelms front propagation



Relaminarisation times for S9 integrated for $Re \in [244; 254]$.

Region R4 – transition to turbulence

- Front propagation overwhelms decay of roll clusters
- Average front speed $\langle c \rangle = 0.02$ does not depend on *Re* for $Re < 350$

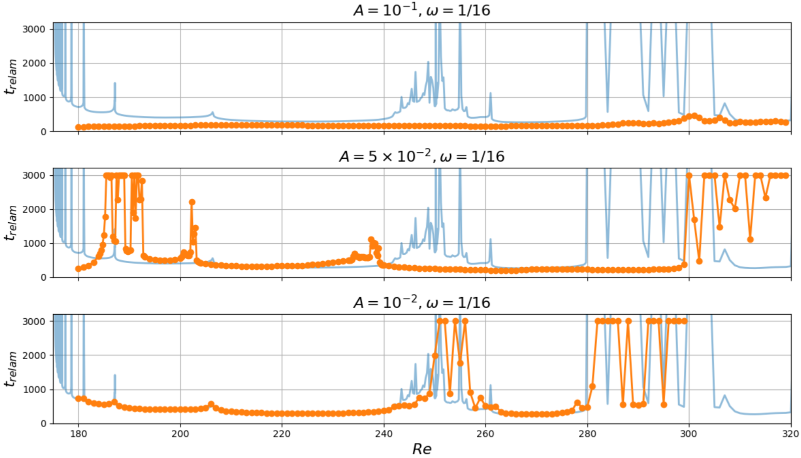


Relaminarisation times for S7 integrated for $Re \in [270; 350)$ and cut at $t_{relam} = 6000$.

Control of transition in a wide domain

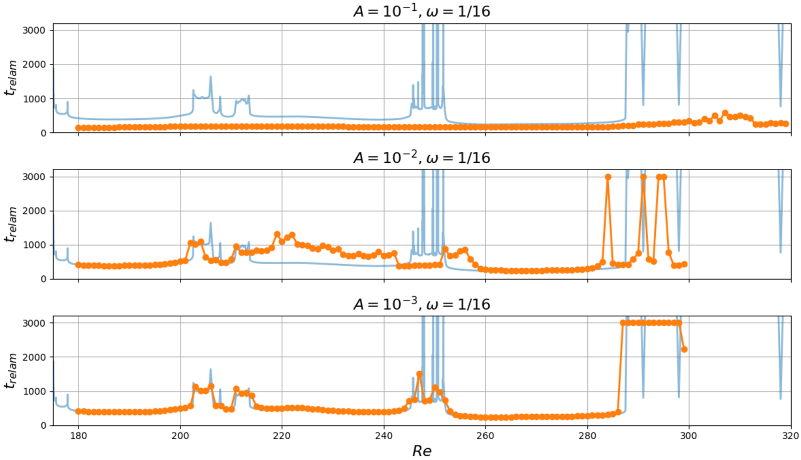
Homotopy from the uncontrolled system for S5

- Control strategies can be assessed by comparing t_{relam}
- Consider in-phase wall oscillations with $\omega = 1/16$
  - Fast relaminarization for $A \sim O(10^{-1})$
  - Original regions are recovered for $A \lesssim 10^{-2}$



Homotopy from the uncontrolled system for S13

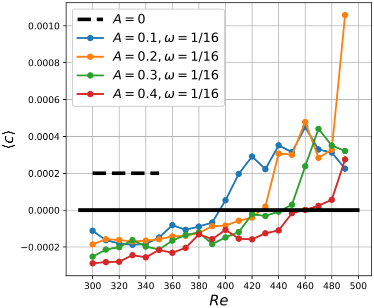
- Fast relaminarization for $A \sim O(10^{-1})$
- Original regions are recovered for $A \lesssim 10^{-3}$

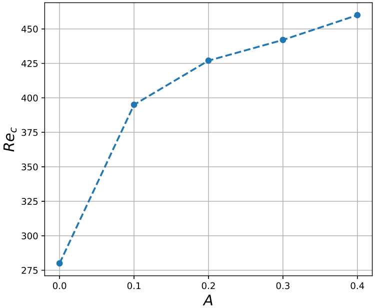


Relaminarisation times for the uncontrolled (blue) and wall-oscillated (orange) cases.

The onset of R4 for S5

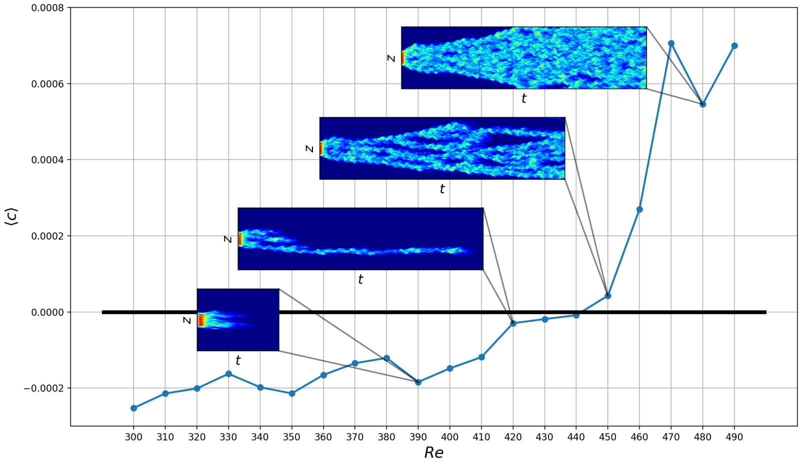
- For amplitudes $A \gtrsim 10^{-1}$, the only existing region is R4
- Increasing A delays the onset of R4





What amplitude and frequency are optimal?

Wall oscillations favour directed-percolation-like transition [9,10]:



[9] Sipos and Goldenfeld, *Phys. Rev. E* 84, 035304 (2011)

[10] Chantry *et al.*, *J. Fluid Mech.* 824, R1 (2017)

Conclusion

Laminarisation probability:

- Helps analyse finite-amplitude instabilities
- Approximates the size of the basin of attraction
- Allows to quantify and compare the efficiency of control strategies
- Minimal seeds and edge states may be misleading while designing control

Pershin, Beaume and Tobias, *submitted, arXiv:1908.03050* (2019)

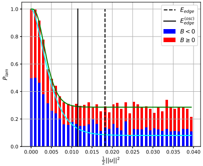
Transition in a wide domain:

- Exact solutions are reproducible initial conditions
- Characterise transitional dynamics via relaminarisation times
- Exact solutions + relaminarisation times = framework
  $\Longrightarrow$ Assessment of control strategies

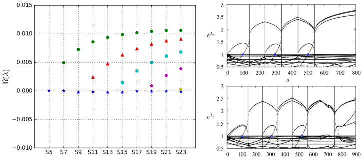
Pershin, Beaume and Tobias, *J. Fluid Mech.* **867**, 414–437 (2019)

Future work

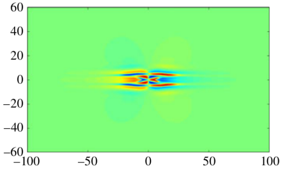
(a) Designing control using P_{lam}? Large domains?



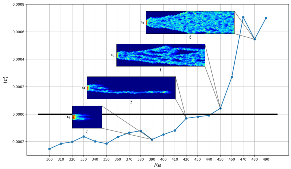
(b) Stability analysis of the snakes? compare with doubly-diffusive convection[11]



(c) Doubly localized solutions?[12]



(d) Optimal delay of transition?



[11] Beaume, *et al.*, J. Fluid Mech., **840** (2018)
[12] Brand and Gibson, J. Fluid Mech. **750**, R3 (2014)