The state of turbulence in a pipe flow with drag reduction

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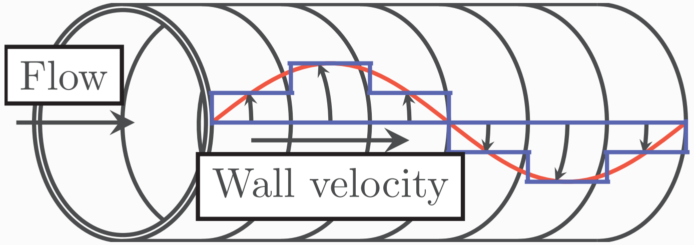
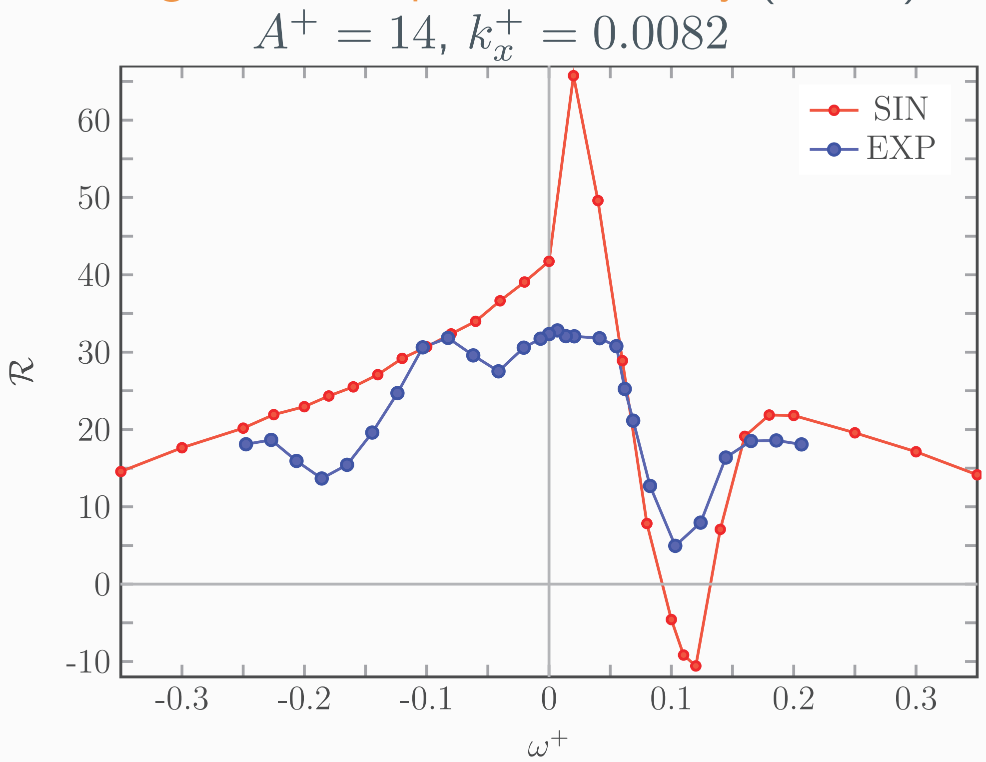
Background[1]

Experiment of Auteri et al, PoF 2010, streamwise traveling waves of spanwise velocity (StTW):

- Pipe flow ($Re_b = 4900$, $Re_\tau = 175$);
- StTW: $w(x) = A \sin(k_x x - \omega t)$;
- StTW discretized with s rotating slabs, Discrete Traveling Waves (DTW).





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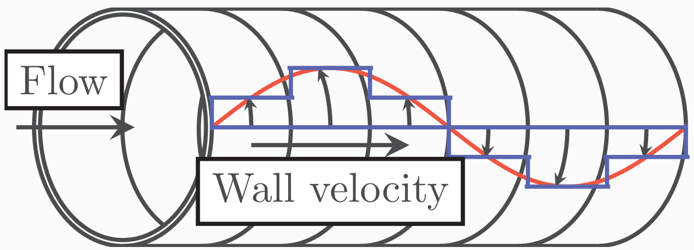

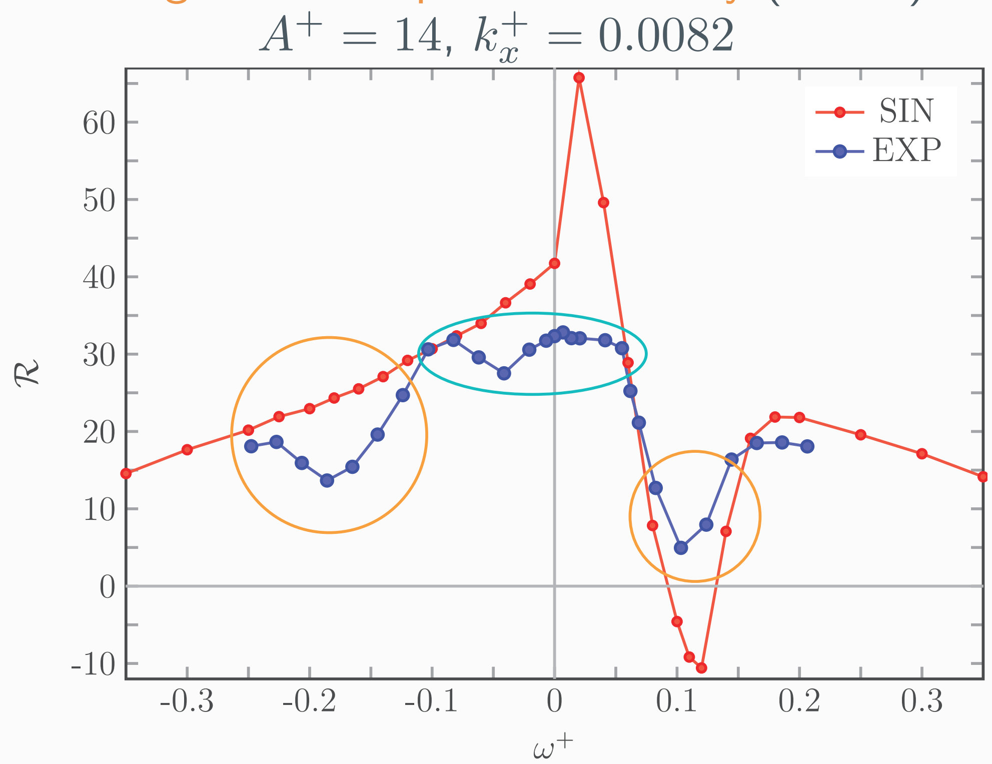

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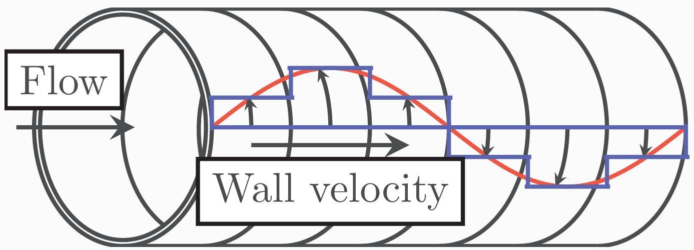

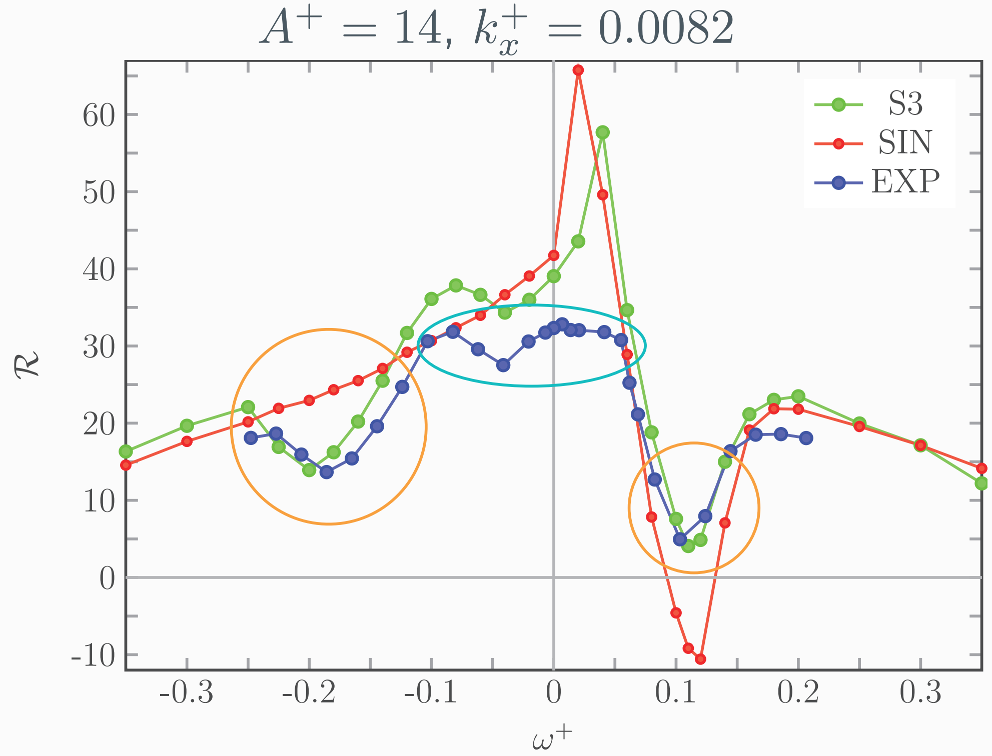

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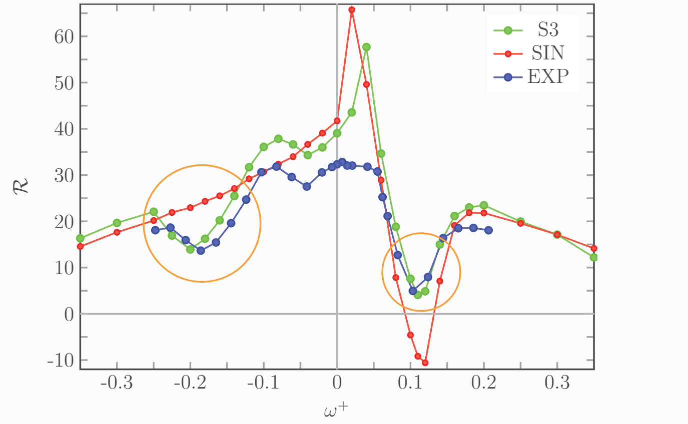
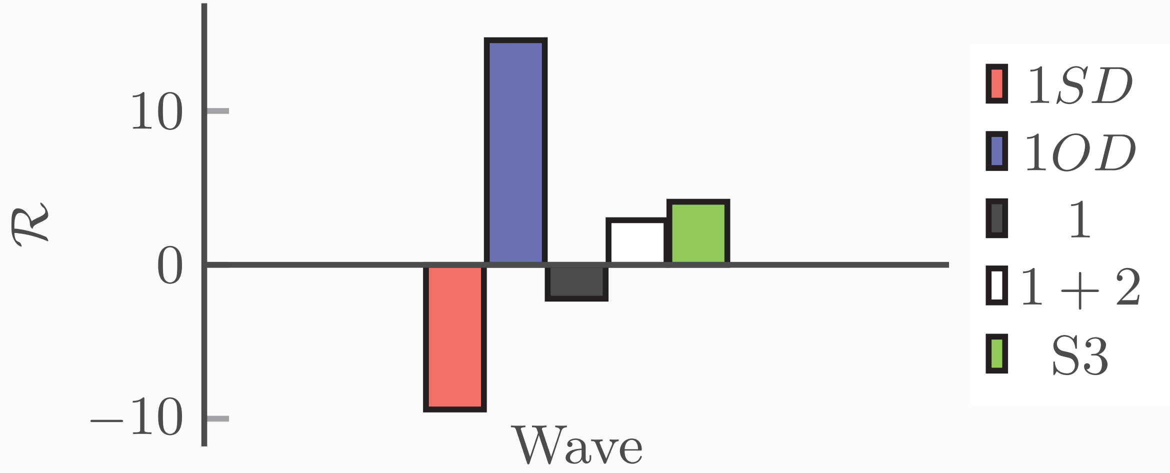
Fourier series expansion of DTW

For $s = 3$ ($S3$):

$$w = \frac{3\sqrt{3}}{2\pi} A \left[\underbrace{\sin(\omega t - \kappa_x x)}_{1SD} + \underbrace{\frac{1}{2}\sin(\omega t + 2\kappa_x x)}_{1OD} - \underbrace{\frac{1}{4}\sin(\omega t - 4\kappa_x x)}_{2SD} - \underbrace{\frac{1}{5}\sin(\omega t + 5\kappa_x x)}_{2OD} \right]$$

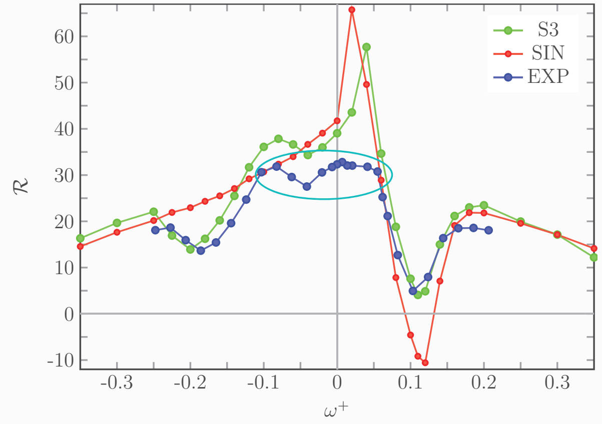


$$A^+ = 14,\ \omega^+ = 0.11,\ k_x^+ = 0.0082$$



Localized turbulence

- For high $\mathcal{R}$ $\rightarrow$ Localized turbulence;
- Could explain high $\mathcal{R}$ peaks;
- Complex experimental setup $\rightarrow$ impossible to control perturbations.



Ref

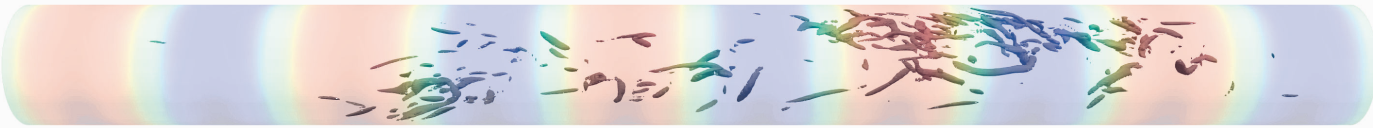
$\omega^+ = -0.02$

Localized turbulence?

Localized turbulence (puff, slugs) is common in pipe flow transition.

- Critical Re_C is around $Re_C = 2000$ (Faisst and Eckhardt, *JFM* 2004: $Re_C = 2250$; Willis and Kerswell, *PRL* 2007 $Re_C = 1870$);
- Our simulations are well beyond Re_C ($Re_b = 4900$);
- What produces localized turbulence? Re_b? Re_τ?

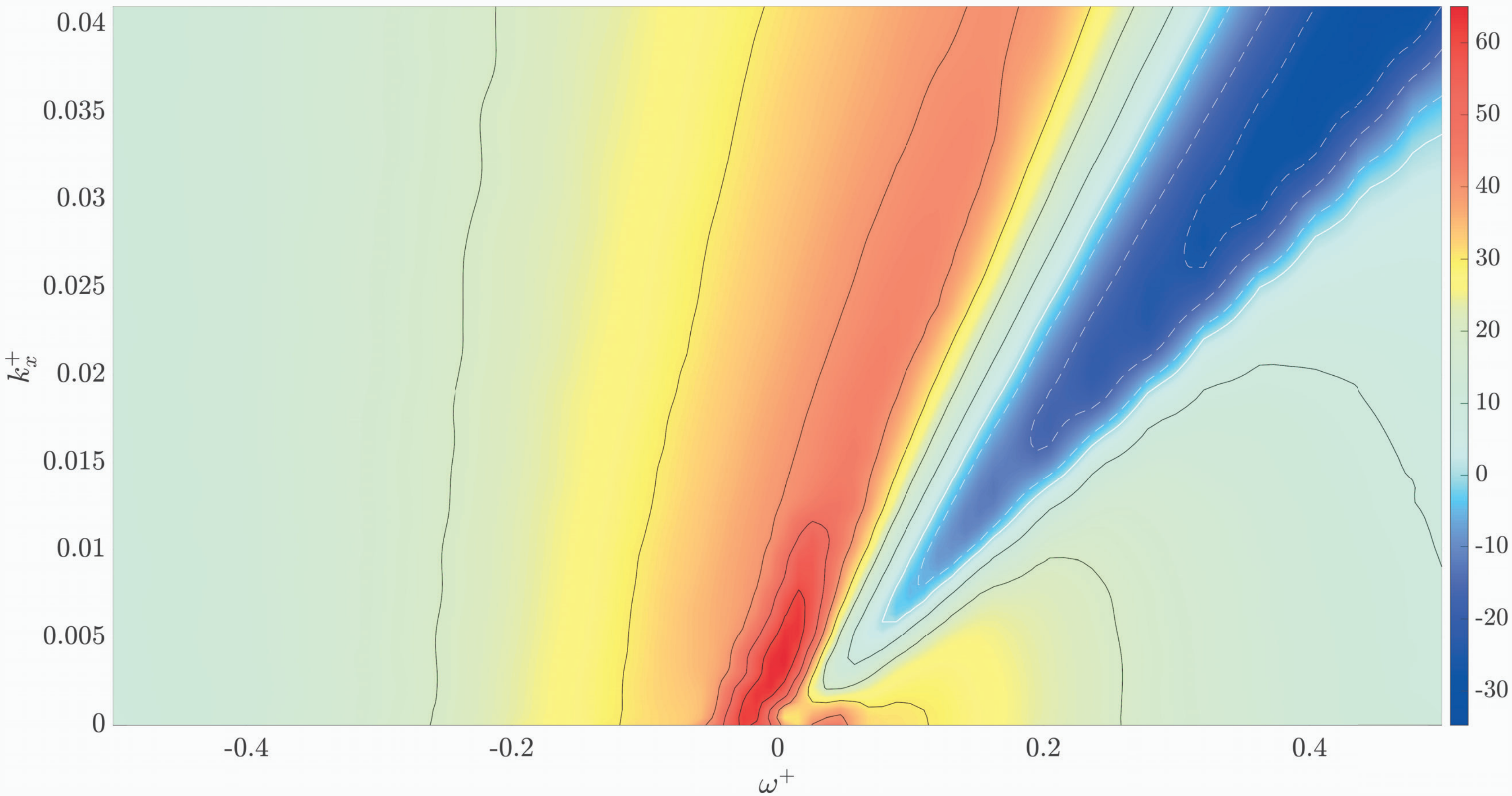
$$k_x^+ = 0.0082,\ \omega^+ = 0$$



A complete dataset for StTW in the pipe

$\mathcal{R}$ map for the pipe, 1184 simulations.

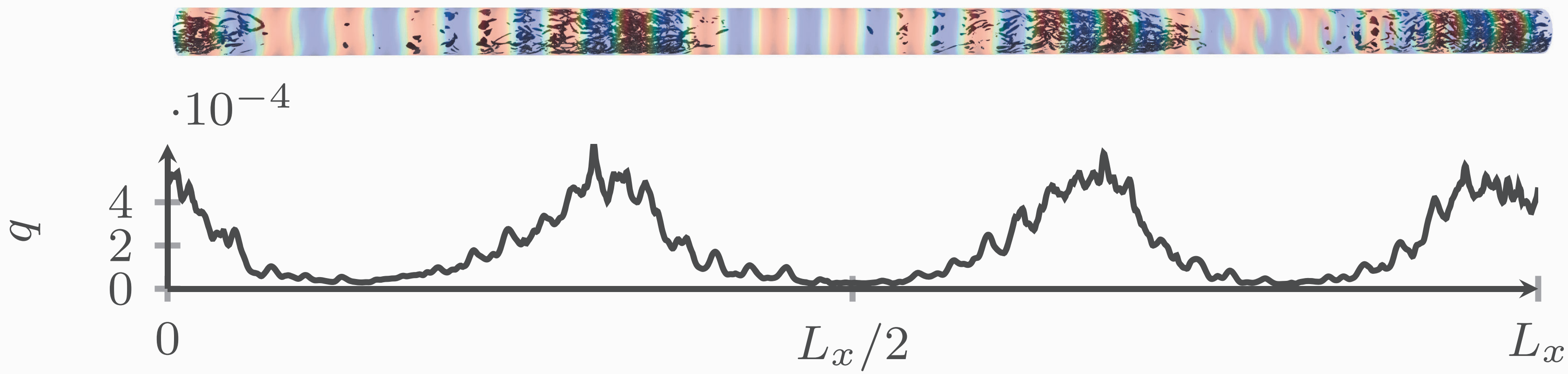
$L_x = 30D$ to catch the presence of transition phenomena.



Identify the localized turbulence

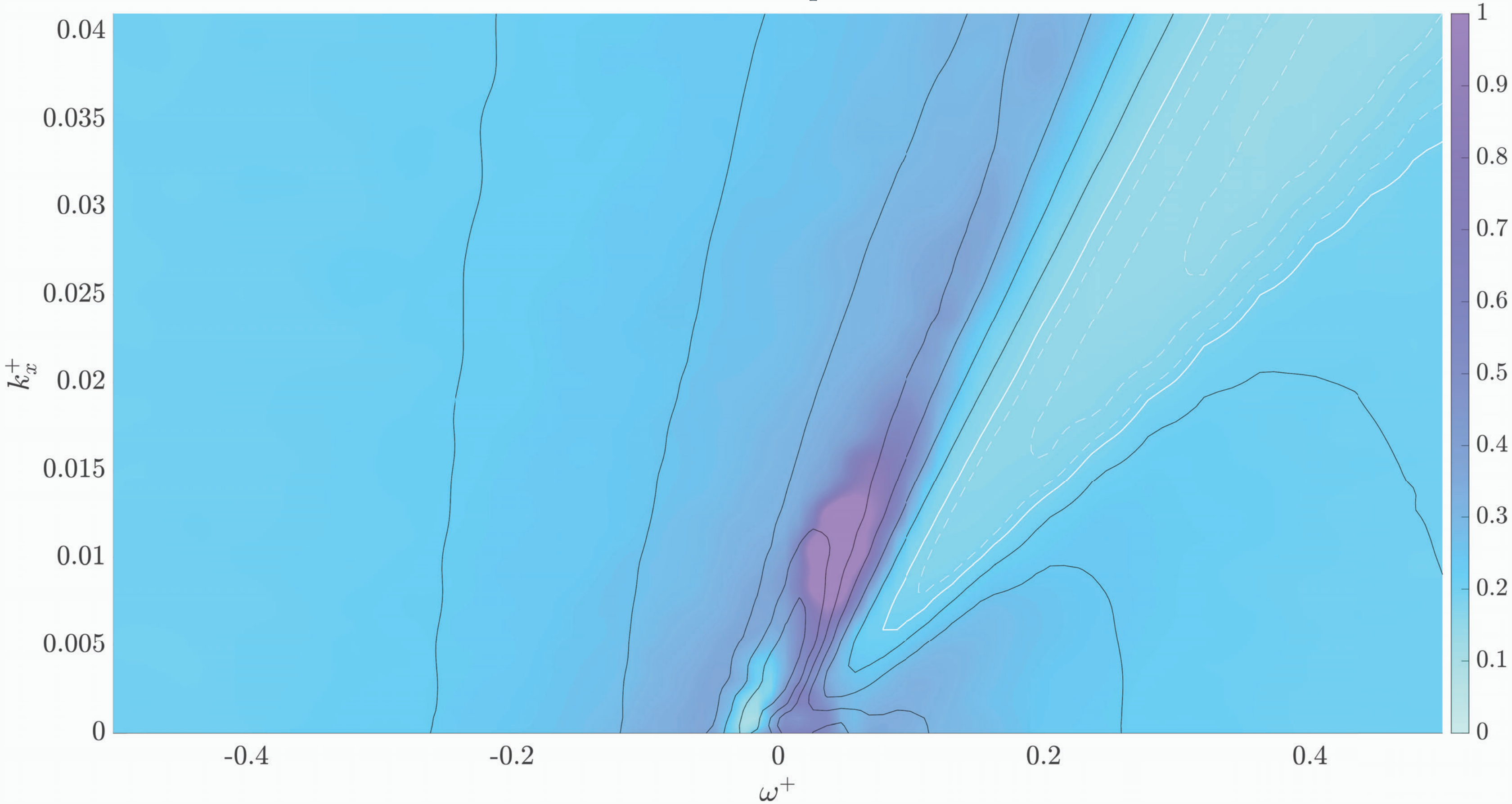
$$q(x,t) = \frac{\int (u_r^2 + u_\theta^2)\; dA}{AU_b^2}$$

$$k_x^+ = 0.00126,\ \omega^+ = 0.08,\ \lambda_2^* = 0.03$$



Localized turbulence in $\omega - k_x$ map

$$\mathcal{I} = \frac{\sigma_q}{\mu_q}$$

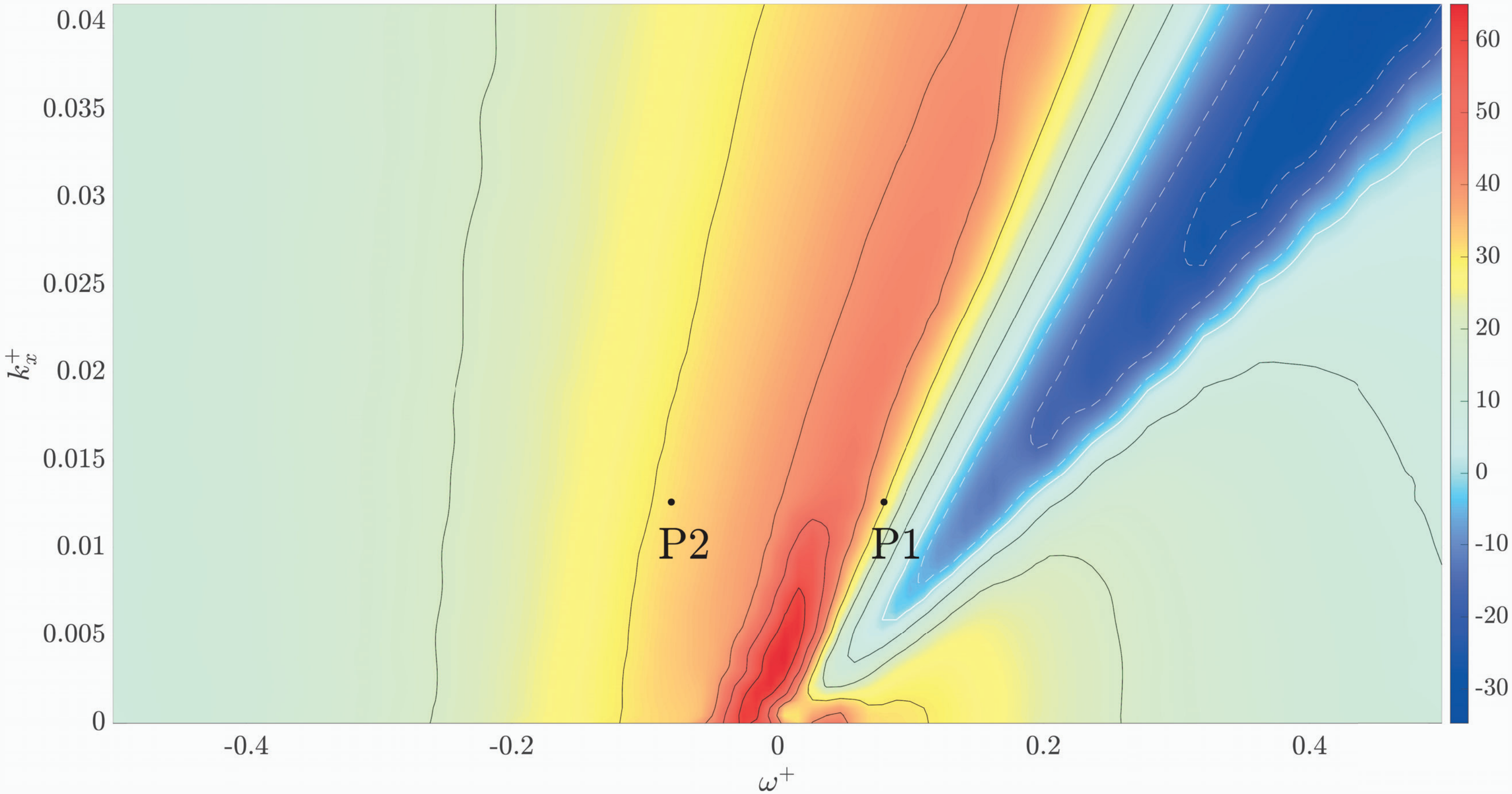


What determines turbulence state?

Re_b is not critical for the turbulence state. Maybe friction (Re_τ)?

P1: $\omega^+ = +0.08$, $k_x^+ = 0.0126$, $R = 31\%$

P2: $\omega^+ = -0.08$, $k_x^+ = 0.0126$, $R = 31\%$



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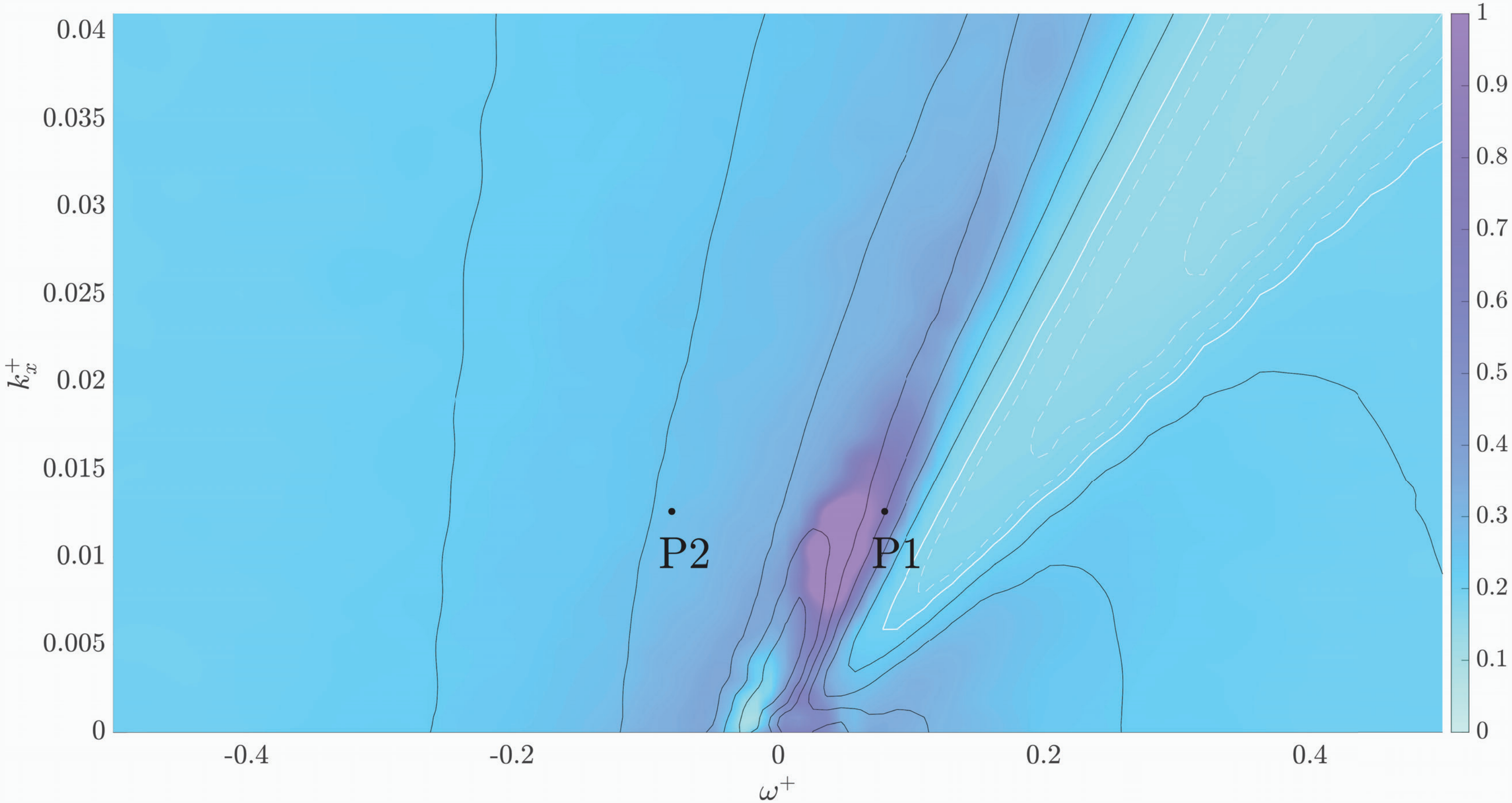

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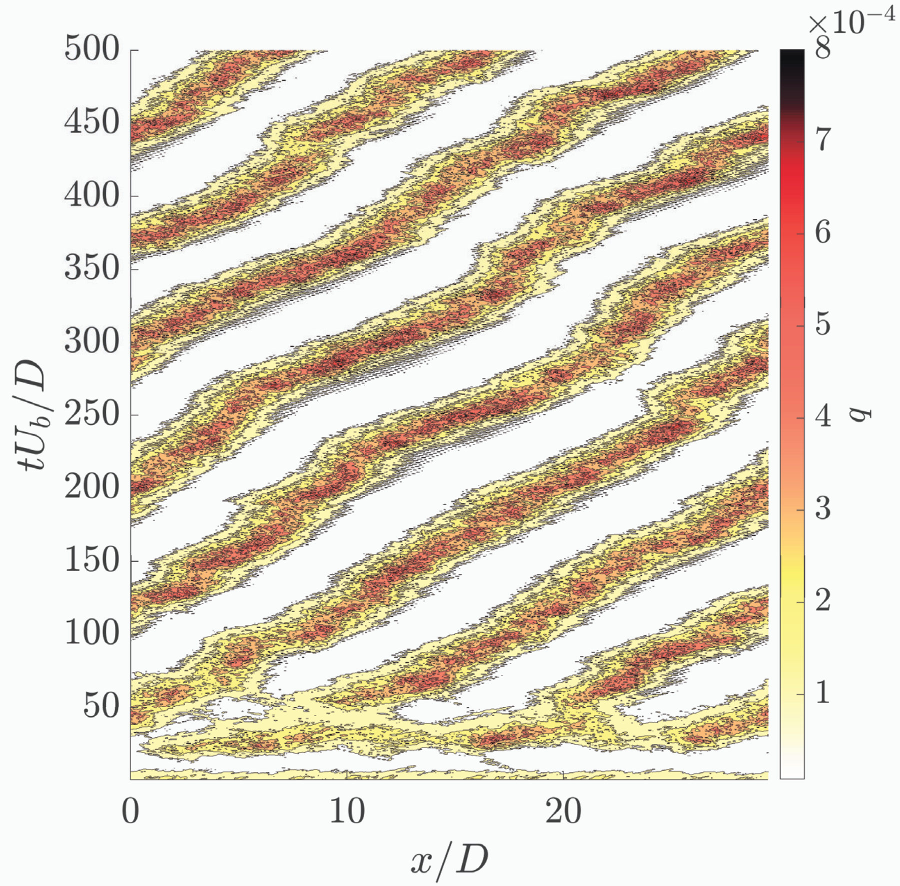
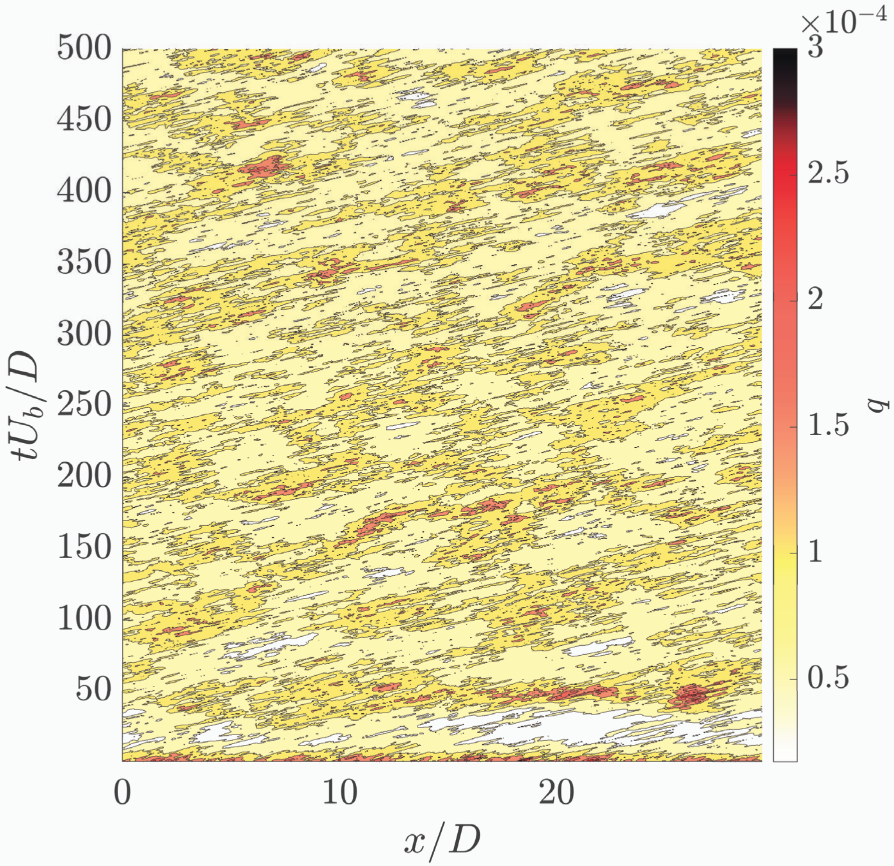


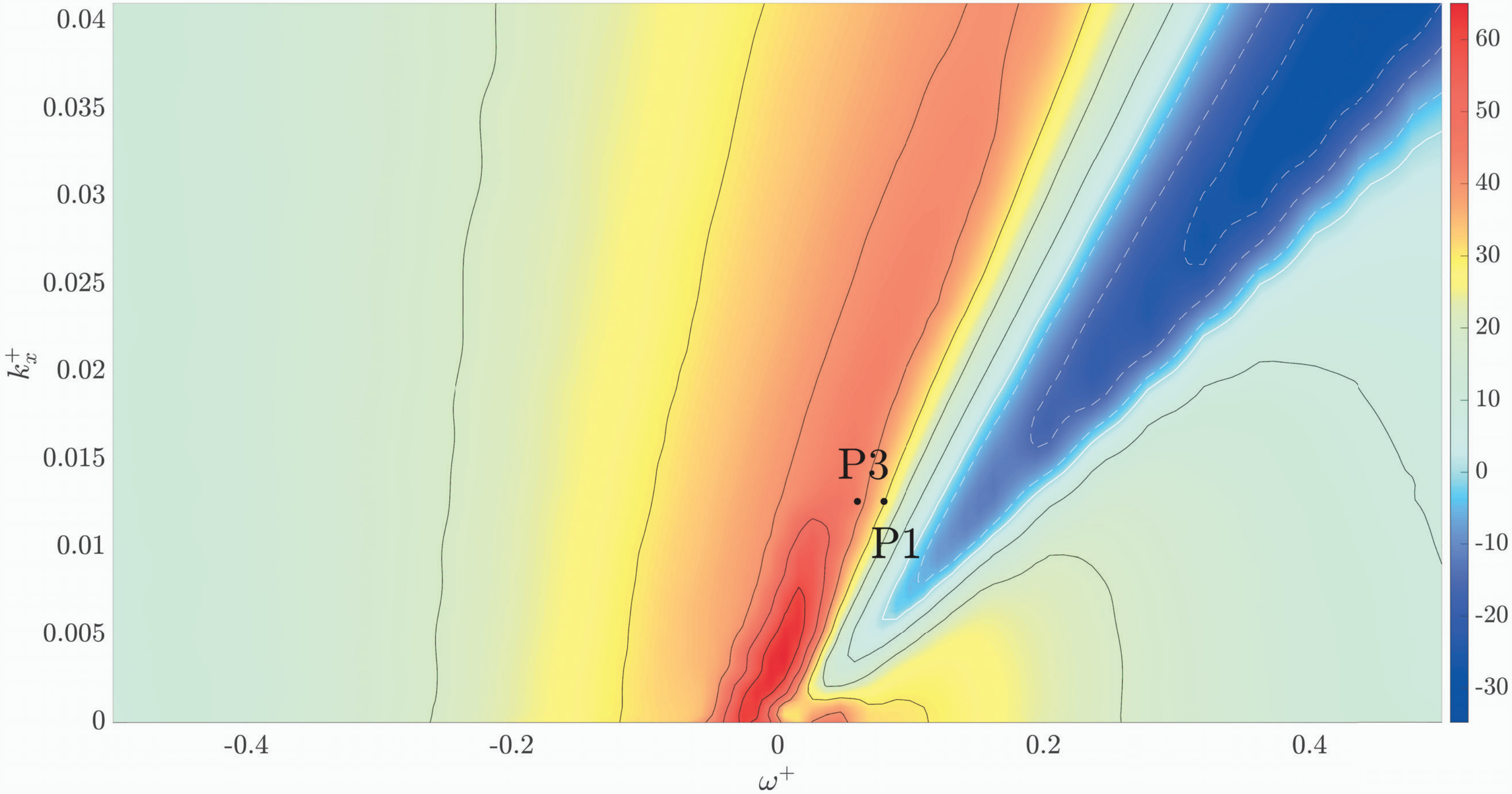
P2



What determines turbulence state?

P1: $\omega^+ = +0.06,\ k_x^+ = 0.0126,\ R = 31\%$

P3: $\omega^+ = +0.08,\ k_x^+ = 0.0126,\ R = 43\%$



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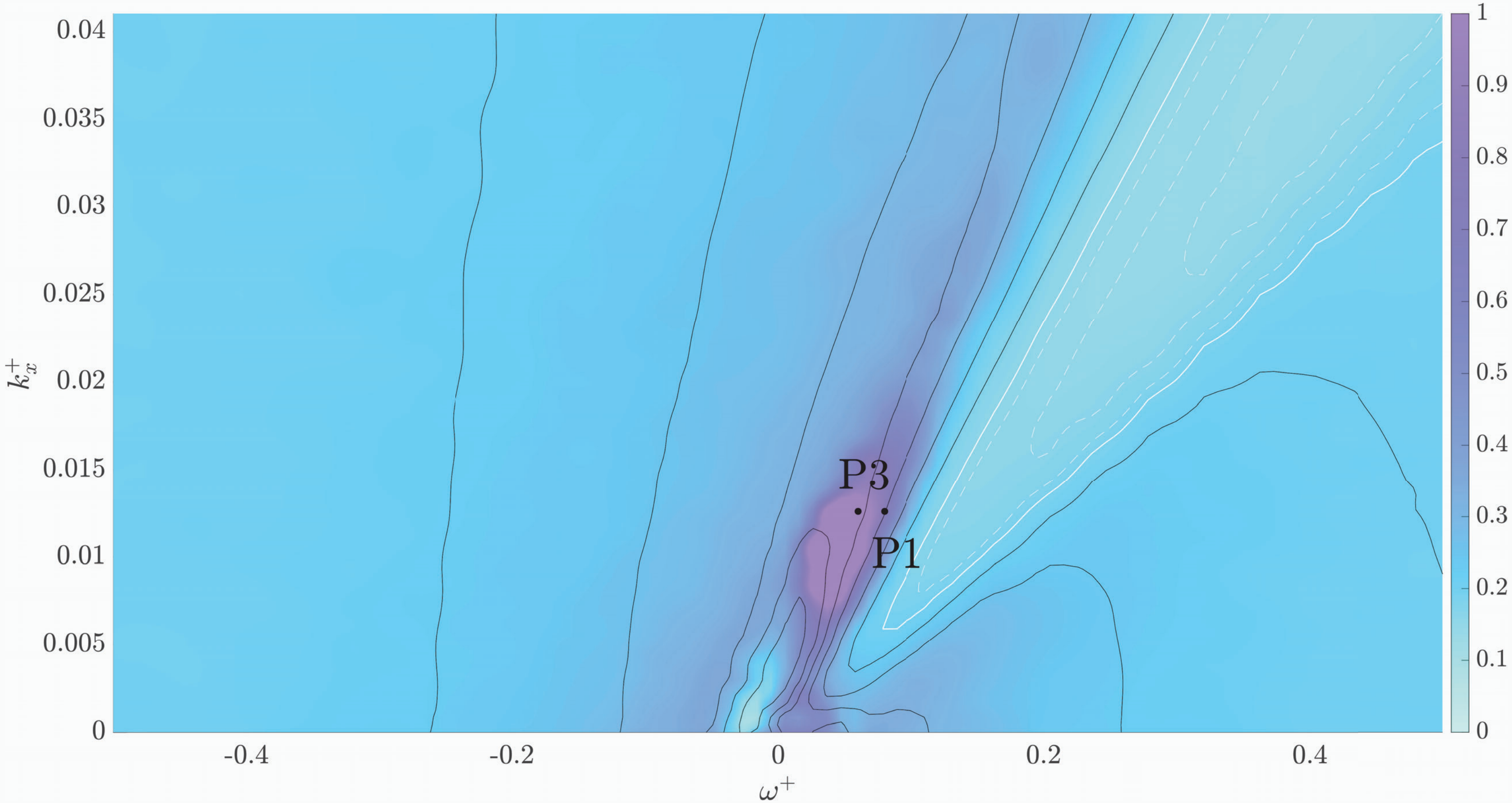
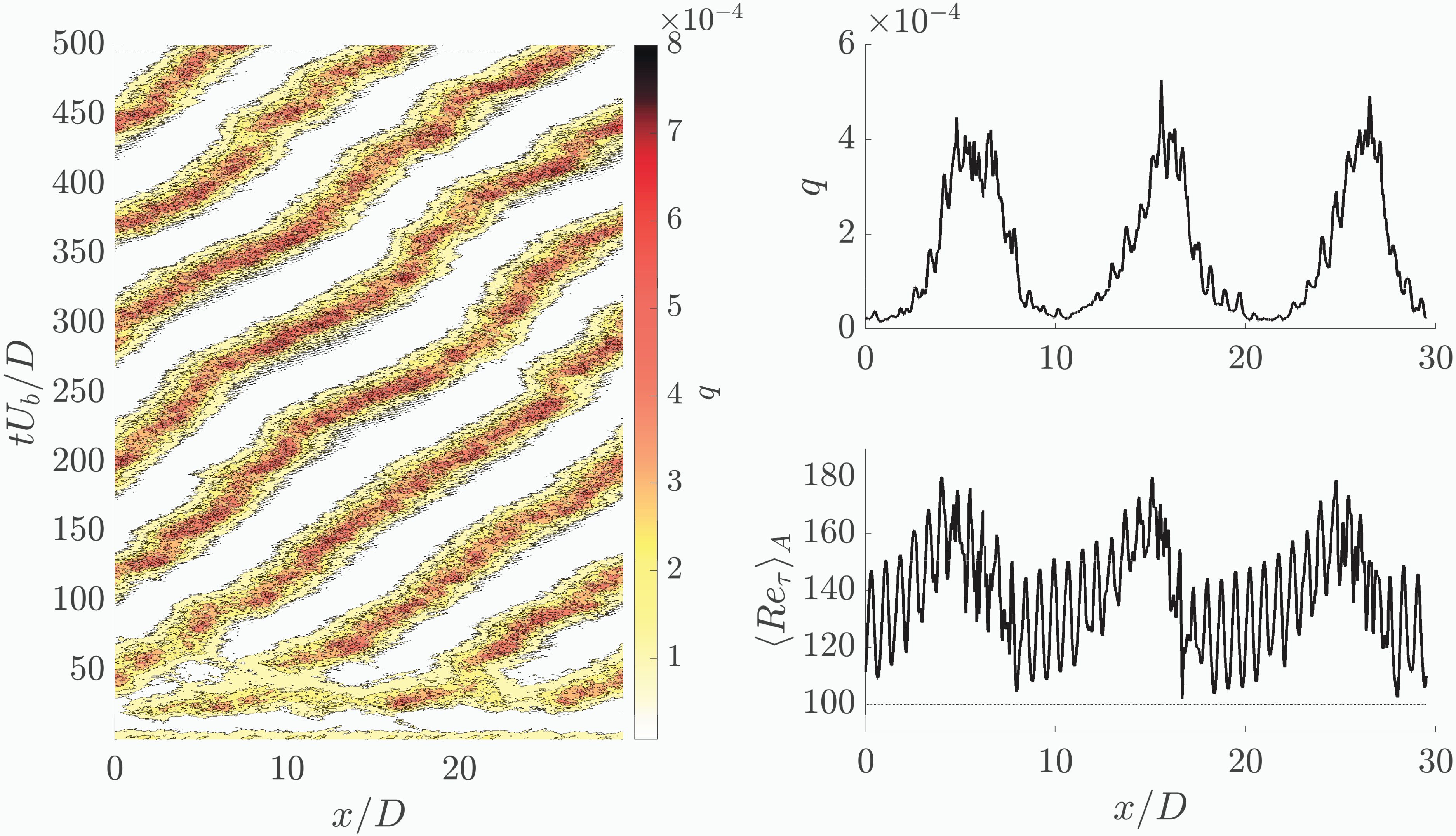
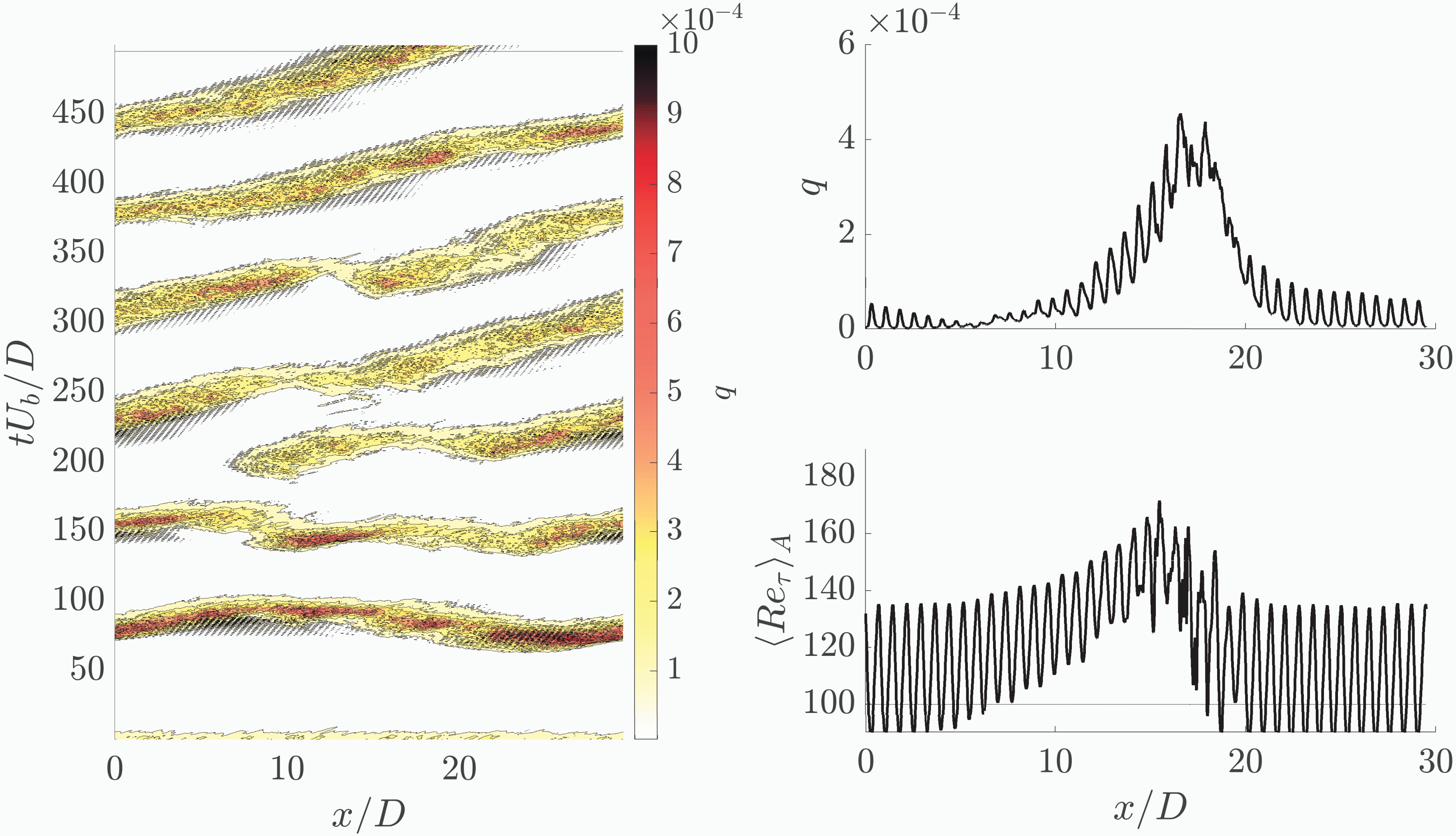


P1: $R = 31\%$



tU_b/D
500
450
400
350
300
250
200
150
100
50
0
10
20
x/D
$\times 10^{-4}$
8
7
6
5
4
3
2
1
q
$\times 10^{-4}$
6
4
2
0
q
0
10
20
30
180
160
140
120
100
$\langle Re_\tau \rangle_A$
0
10
20
30
x/D

P3: $R = 43\%$



$\times 10^{-4}$
10
9
8
7
6
5
4
3
2
1
q
450
400
350
300
250
200
150
100
50
tU_b/D
0
10
20
x/D
$\times 10^{-4}$
6
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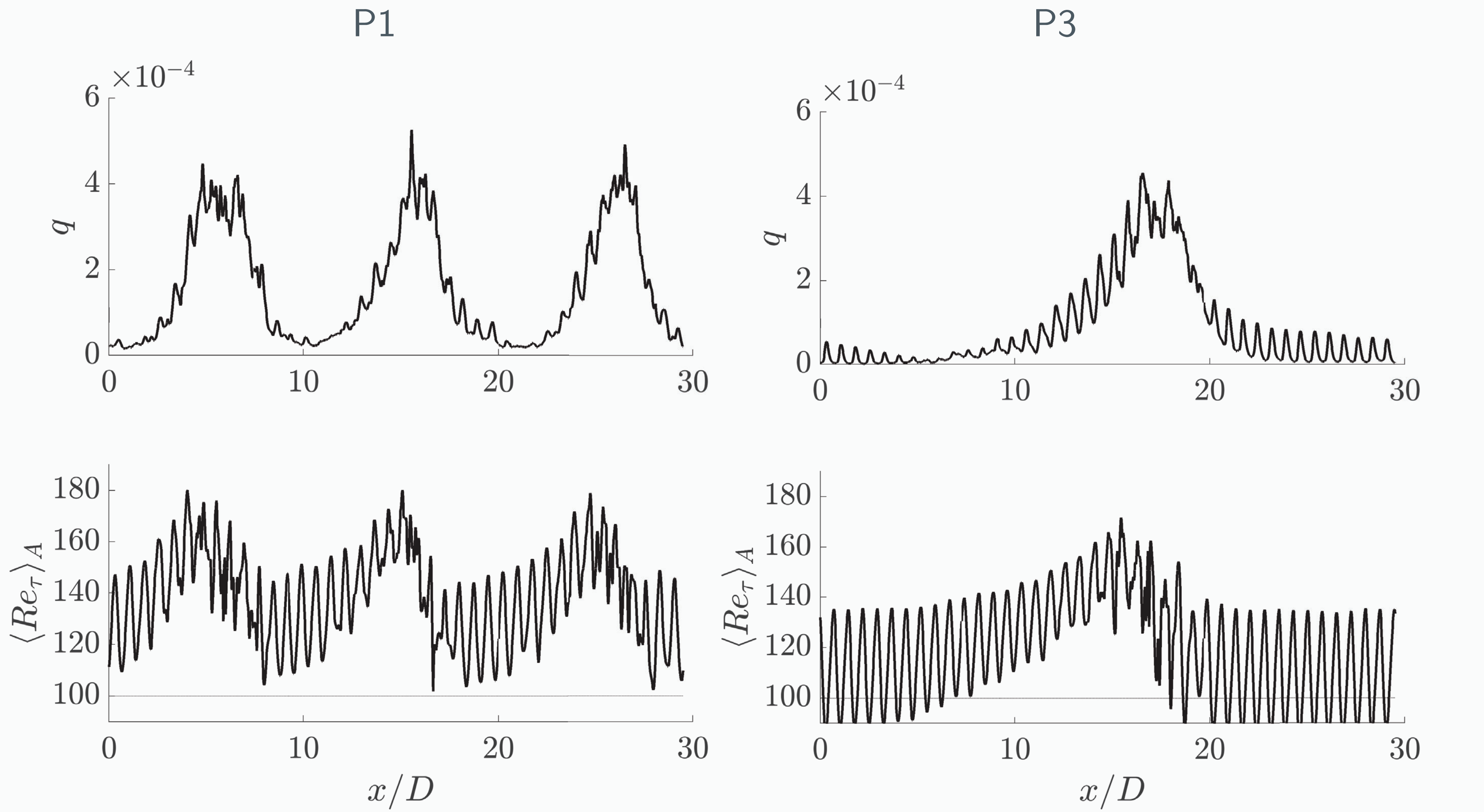

Conclusions

DNS to replicate (and expand) the experiment by Auteri et al, PoF 2010 $\rightarrow$ localized turbulence at $Re_b = 4900$

Localized turbulence at $Re_b > Re_C$? $\rightarrow$ Expand the $\omega - k_x$ space

- Presence of localized turbulence does not depend (only) on Re_b and Re_τ;
- When present, regions of localized turbulence have similar dimensions, Re_τ, q;
- Number of localized turbulence regions $\leftrightarrow$ $\mathcal{R}$ (Re_τ).