Numerical Study on Onset of Turbulence using Interaction between Streaky Structure and Jet

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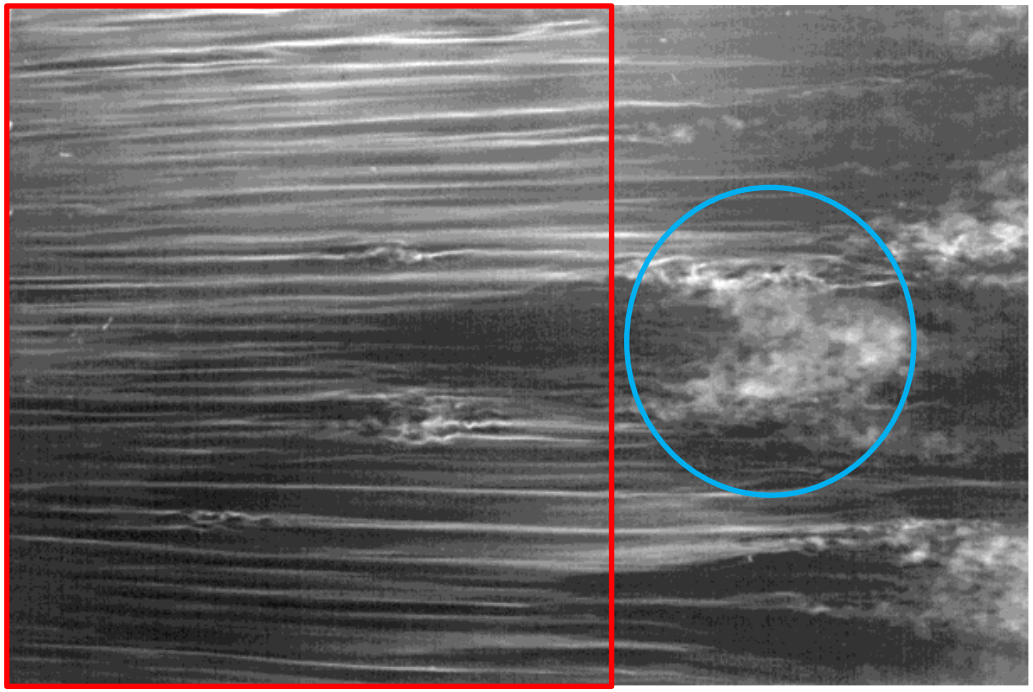
Introduction

Bypass transition (Tu >1%)

Streaky structures
develops in L.B.L.

Turbulent spots
randomly appear.

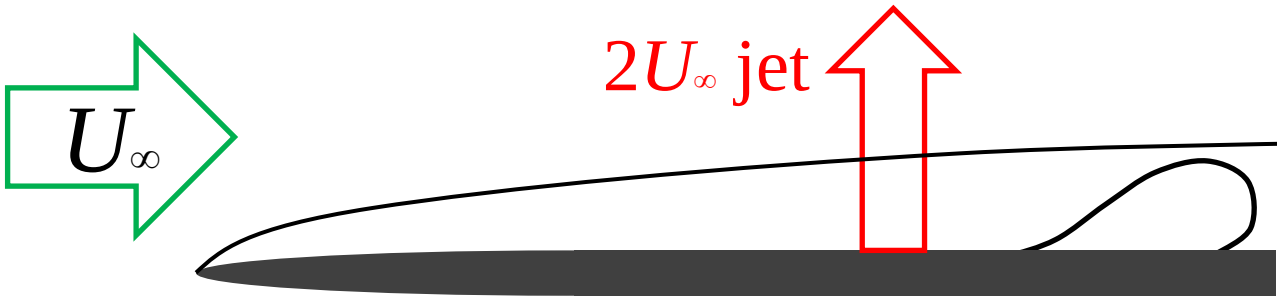
Turbulent spots fill the B.L. → End of Transition



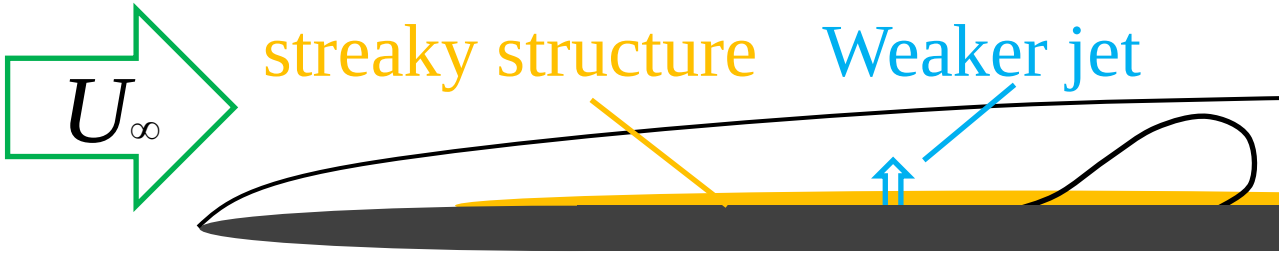
Matsubara et al. (2001)

Turbulent spots could be artifitially generated

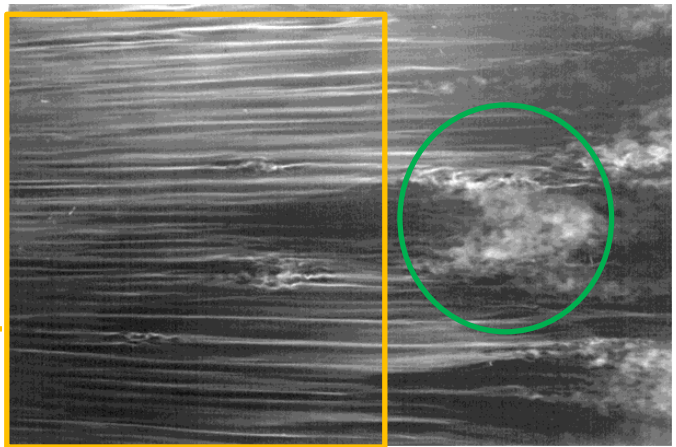
General method



This study



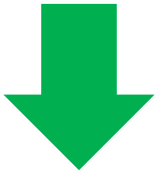
A weaker jet is introduced to the low speed streak.



Matsubara et al. (2005)

Objective

To understand the mechanism that leads to the onset of turbulence.



How the flow field changes downstream of jet is studied using numerical simulation.

Computational method

Governing equations

- 3-dimensional incompressible Navier-Stokes equations

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

- Continuity equation

$$\nabla \cdot \boldsymbol{u} = 0$$

Computational algorithm

- MAC method

Discretization

- Time ——— 2nd-order Crank-Nicolson method
- Space —— Multi-directional difference scheme
  - conv. : 3rd-order upwind difference scheme
  - others : 2nd-order central difference scheme

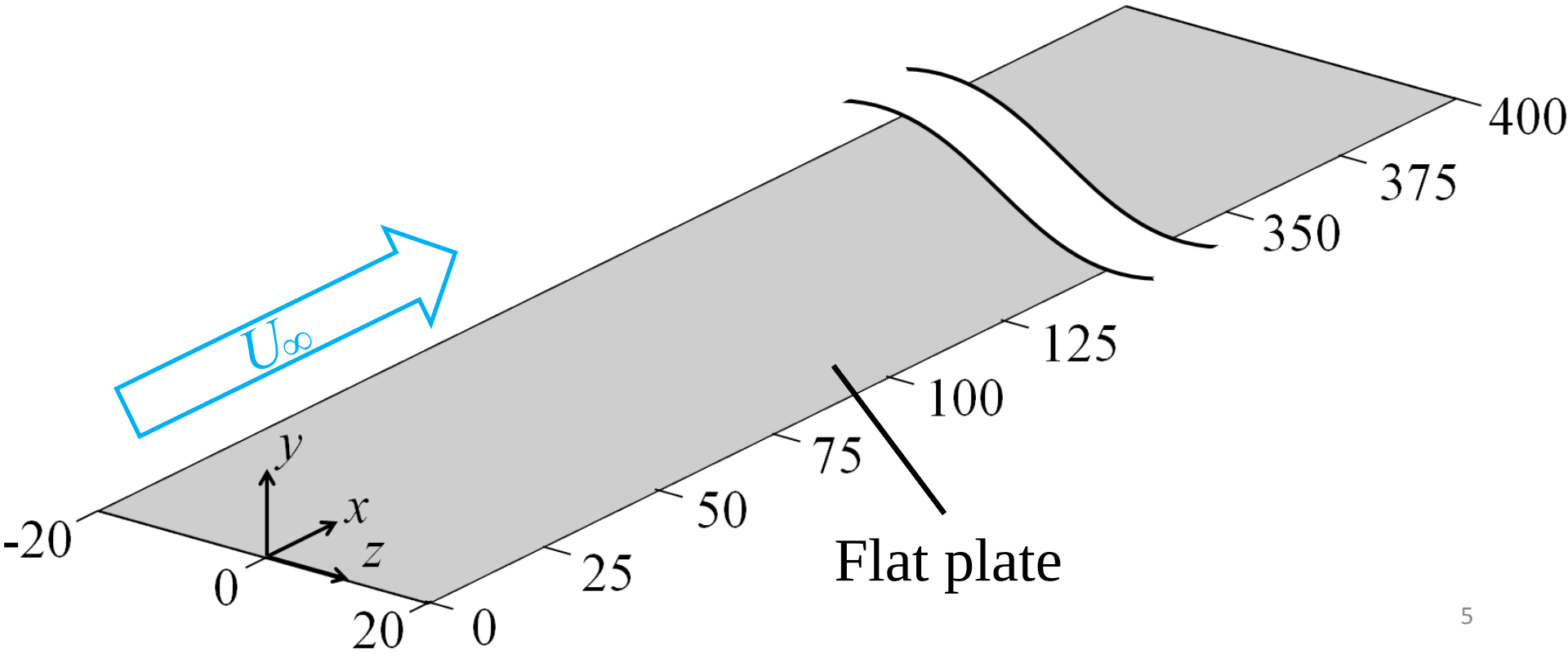
- Only the difference from the Blasius profile is computed.

Preliminary computation

Grid number : $2001 \times 101 \times 201$

Characteristic velocity U_∞ : Uniform velocity

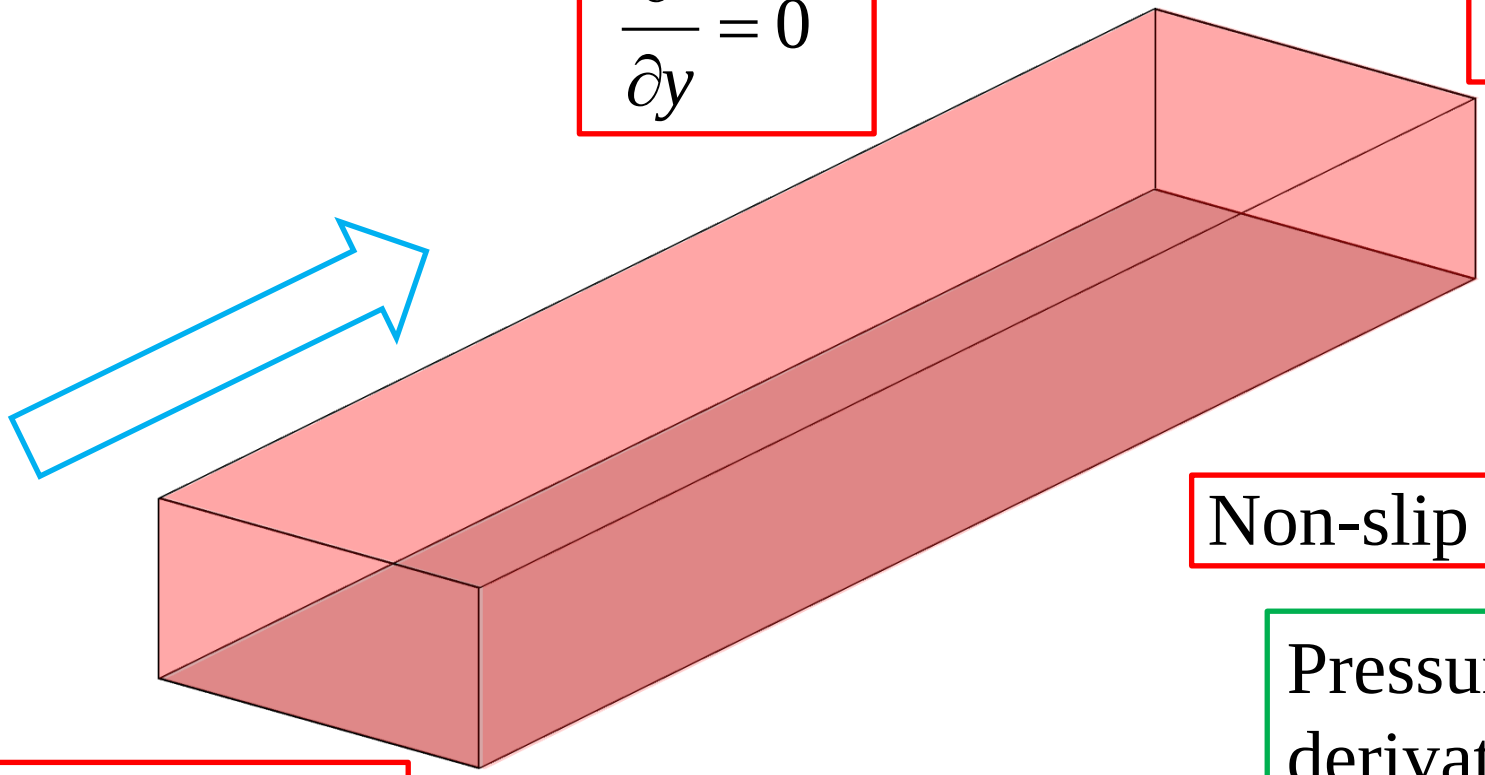
Characteristic length δ_0^* : Displacement thickness at inlet



Boundary conditions

$$\frac{\partial}{\partial y} = 0$$

$$\frac{\partial}{\partial x} = 0$$



Non-slip condition

Pressure : derivative is 0

Blasius profile

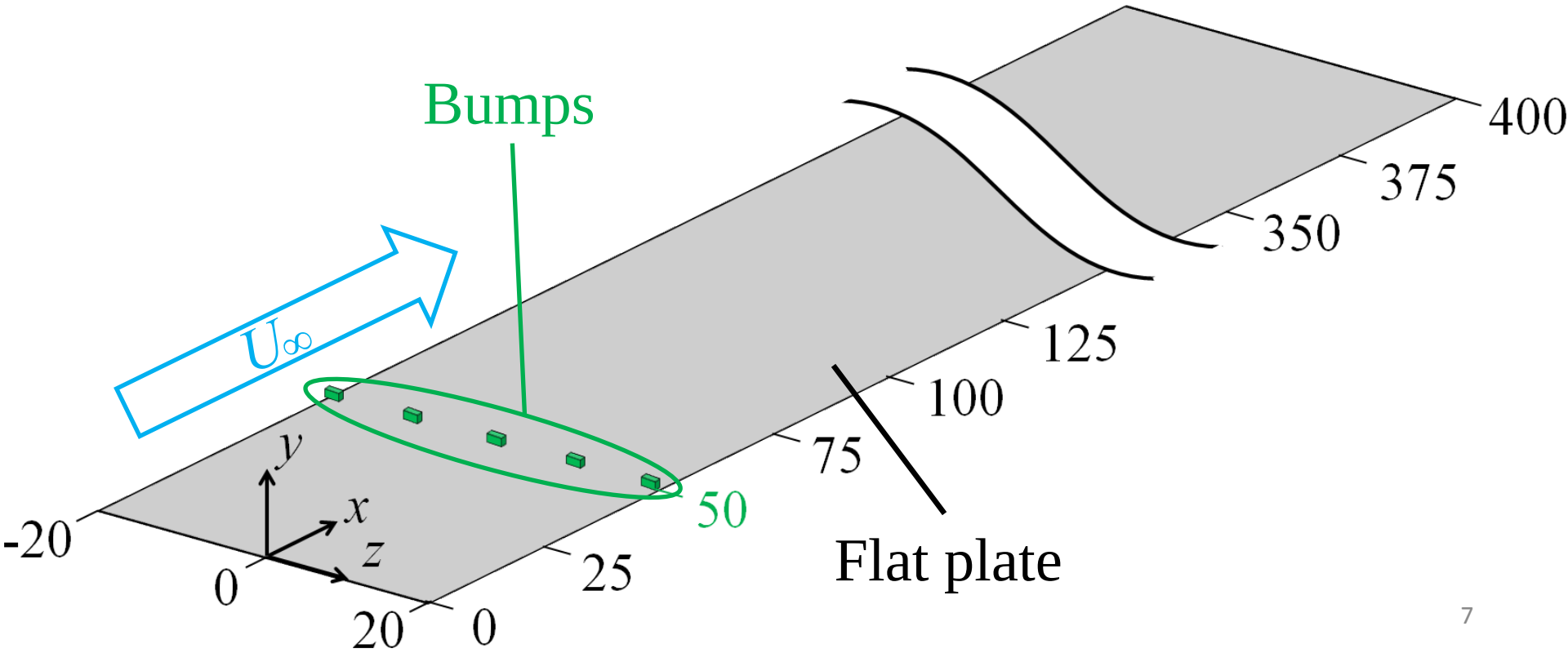
- Periodic condition is imposed in the spanwise direction.

$$Re_{\delta_0^*} = U\delta_0^* / \nu = 530$$

Preliminary computation

Grid number : $2001 \times 101 \times 201$

Bumps are installed in a Blasius boundary layer.



Preliminary computation

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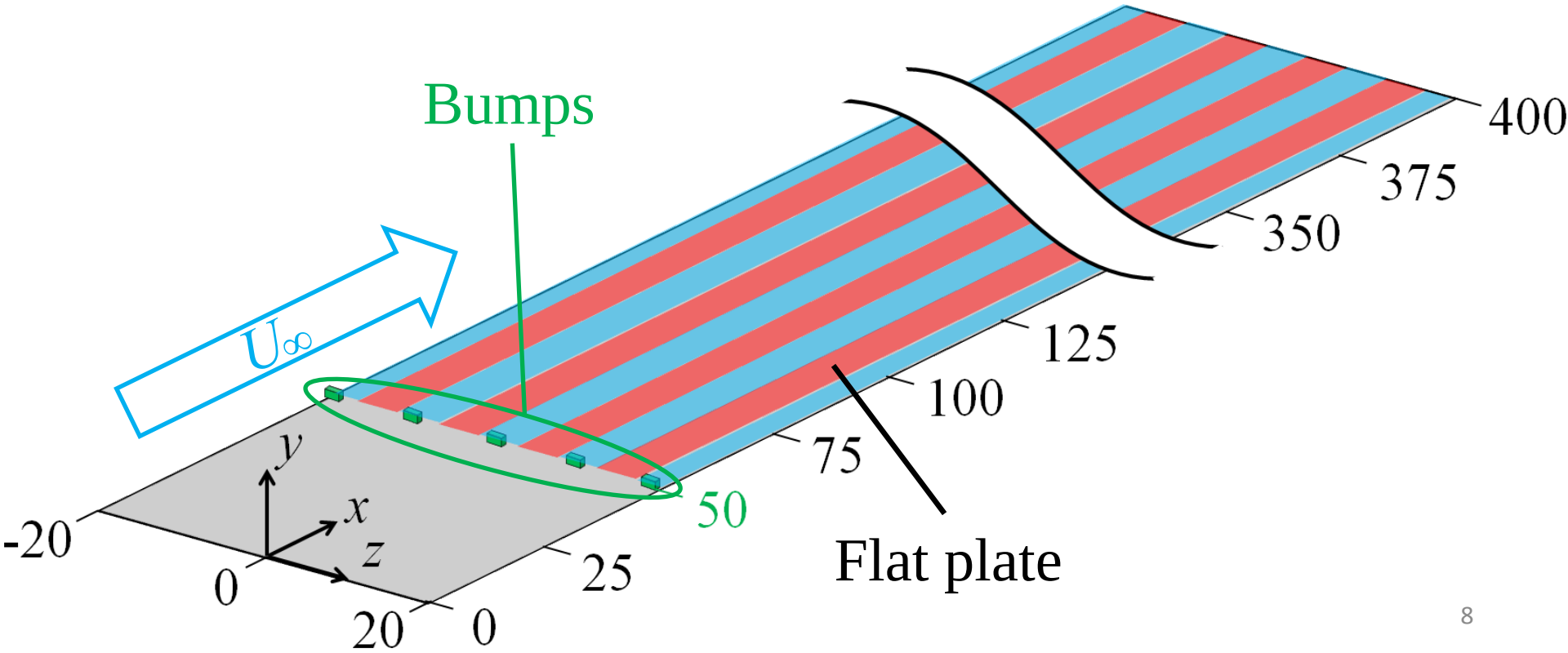

Preliminary computation

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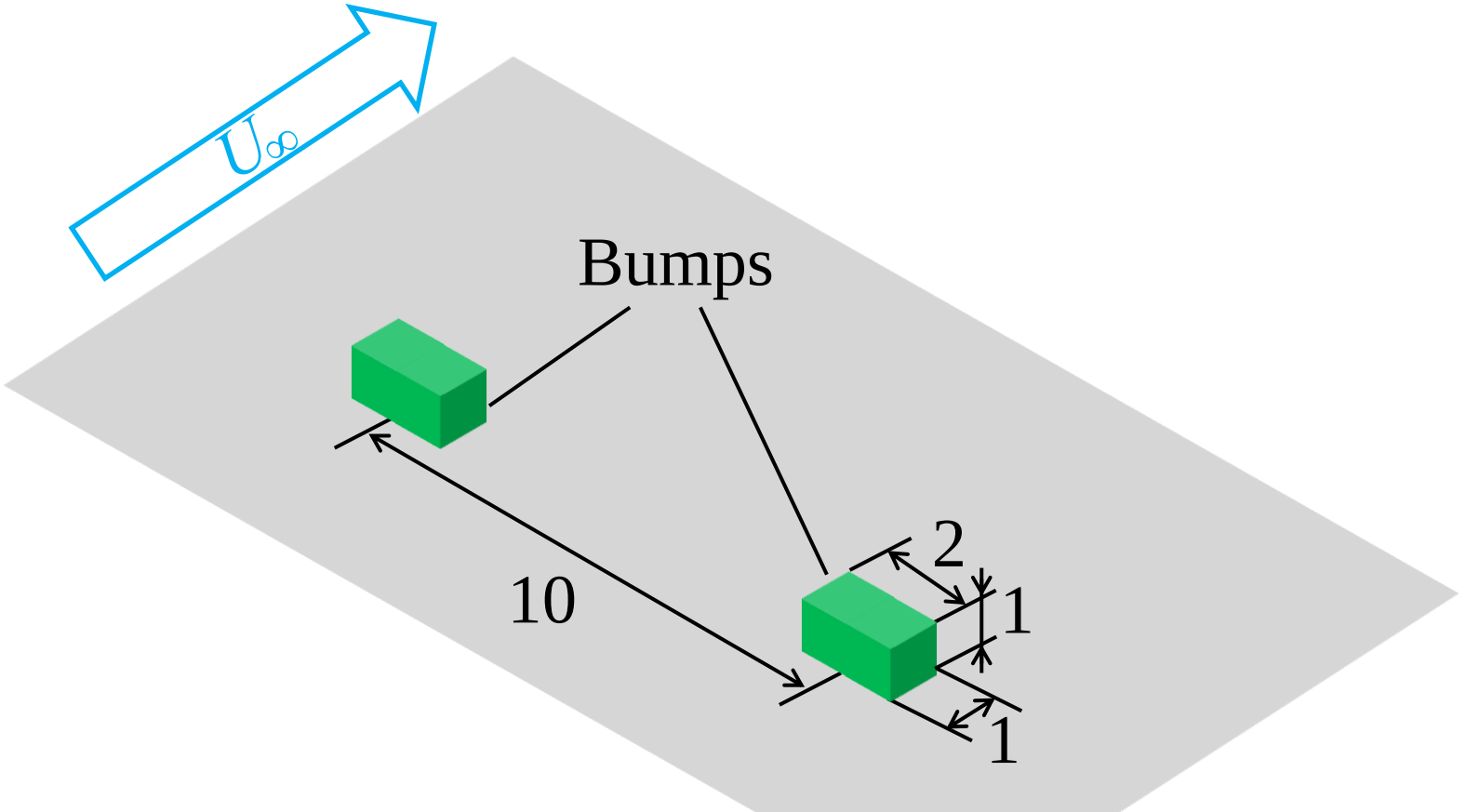
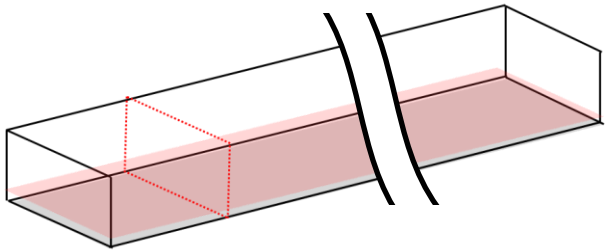
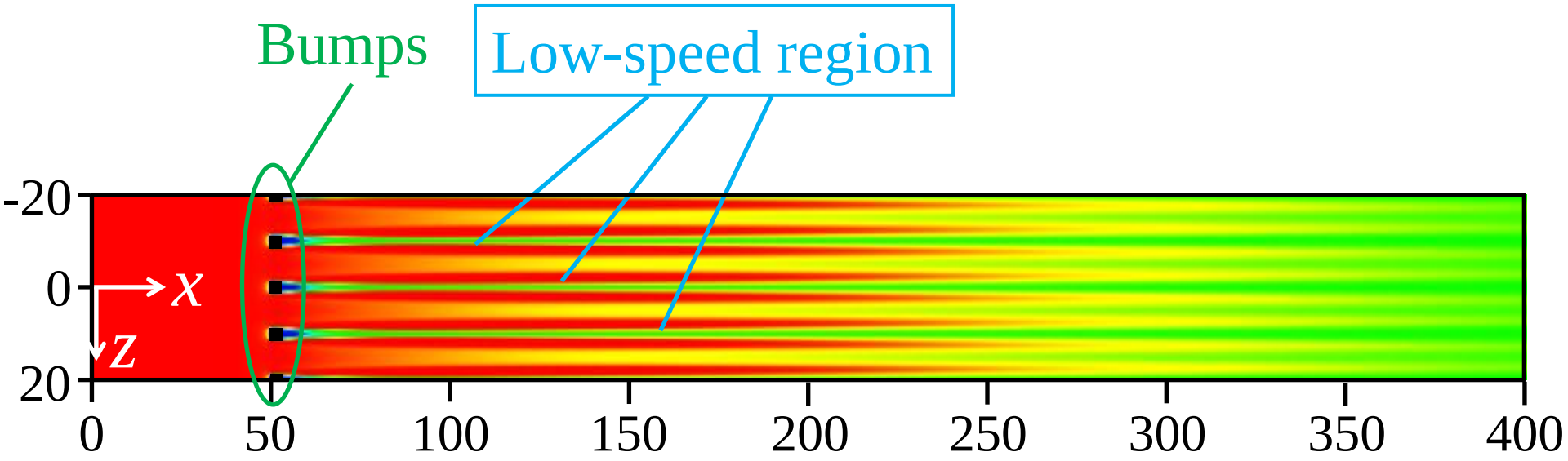


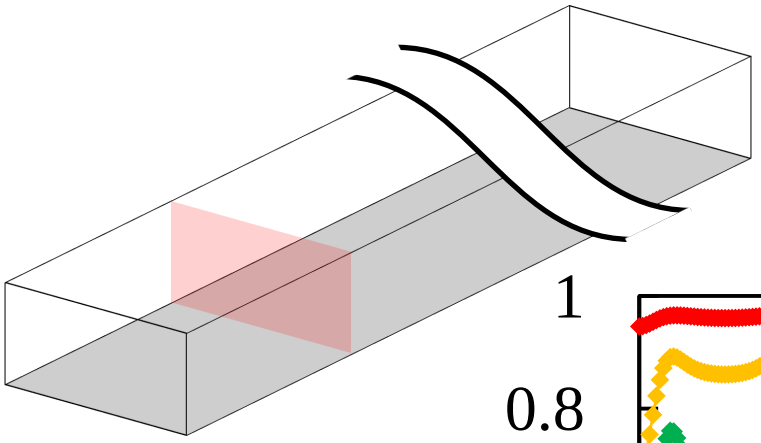
u distribution in a *xz*-plane(*y*=1)

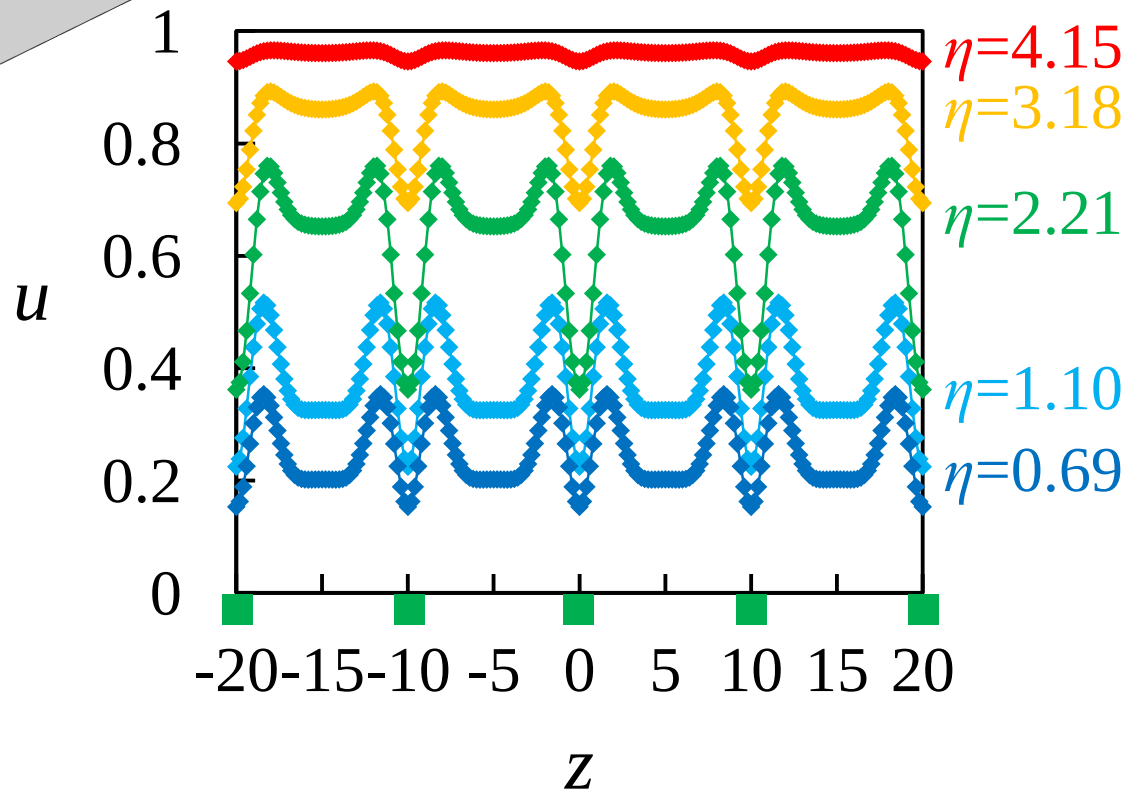




Low-speed streaks are aligned in the spanwise direction.

Streamwise velocity profile at x=100

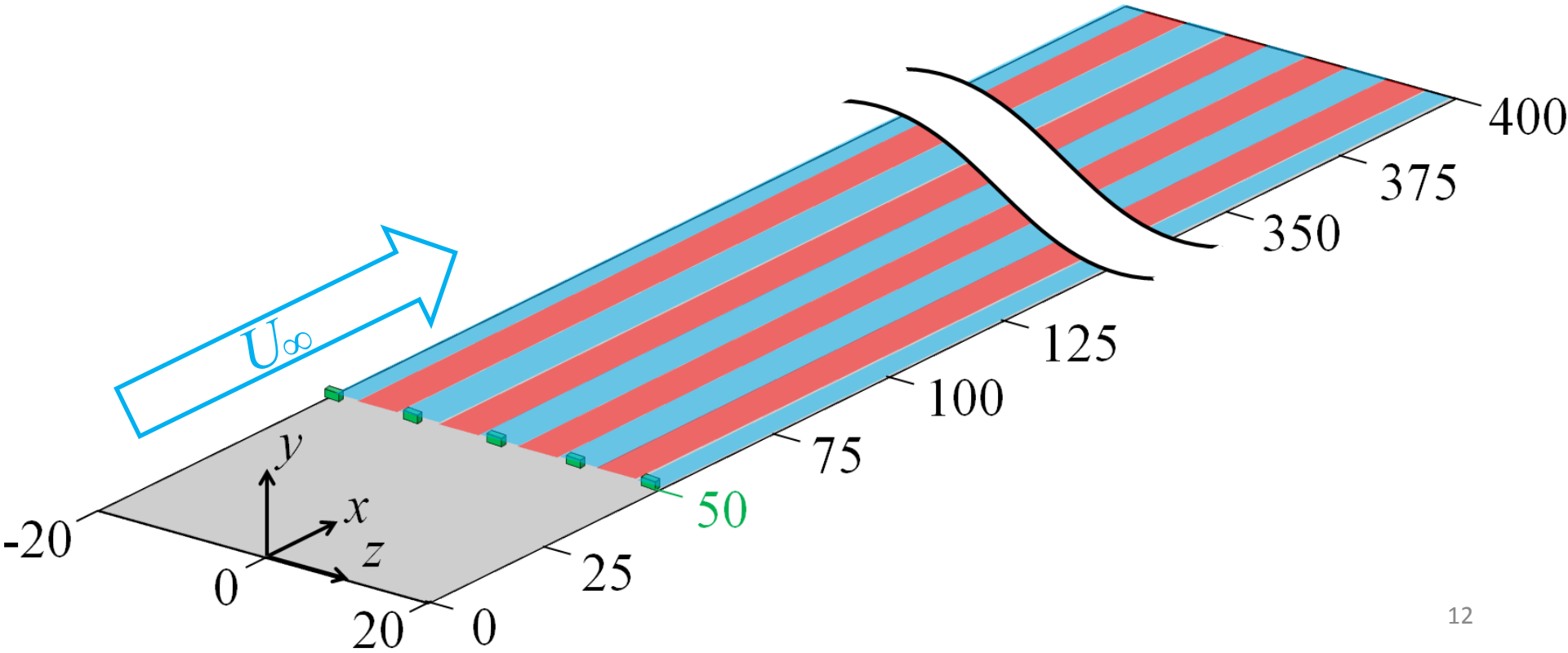




Low-speed streaks are formed.

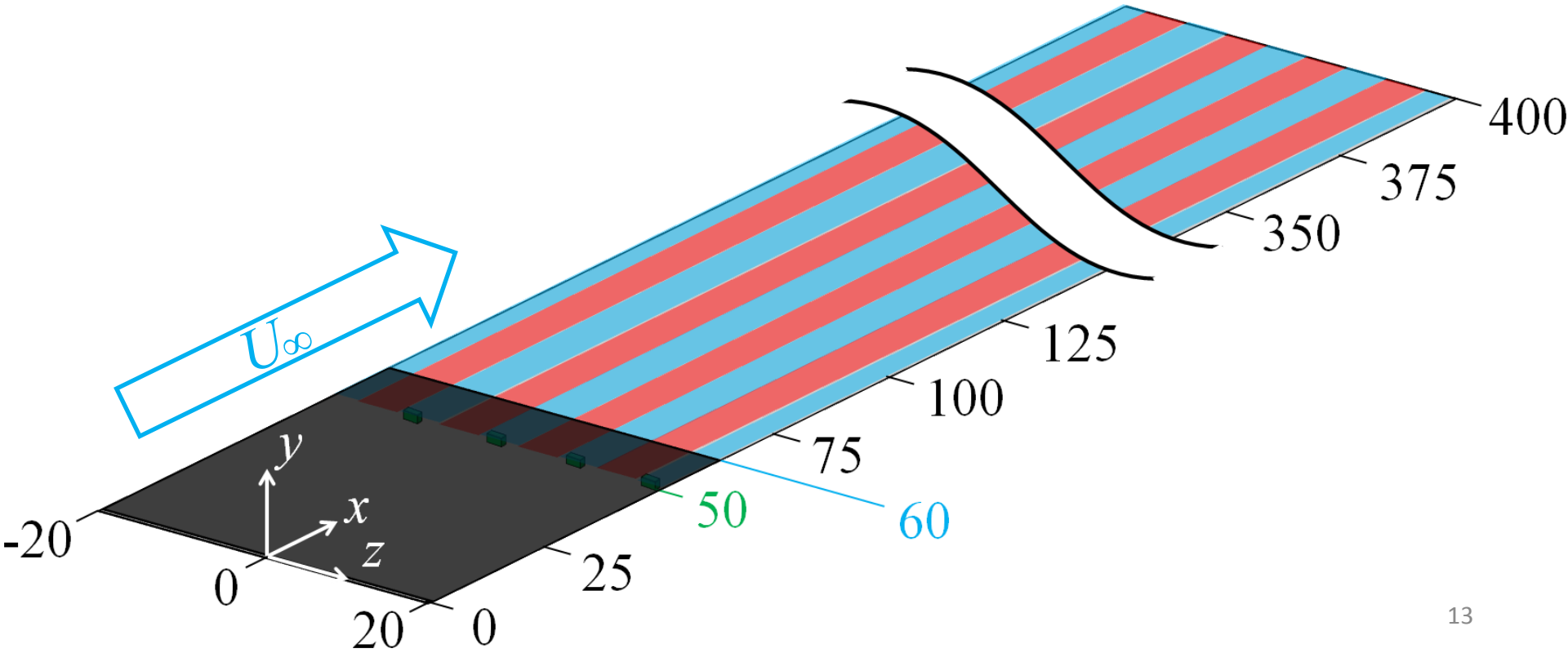
Main computation

Grid number : 2001 × 101 × 201



Main computation

Grid number : $2001 \times 101 \times 201 \rightarrow 1701 \times 101 \times 201$



Boundary conditions

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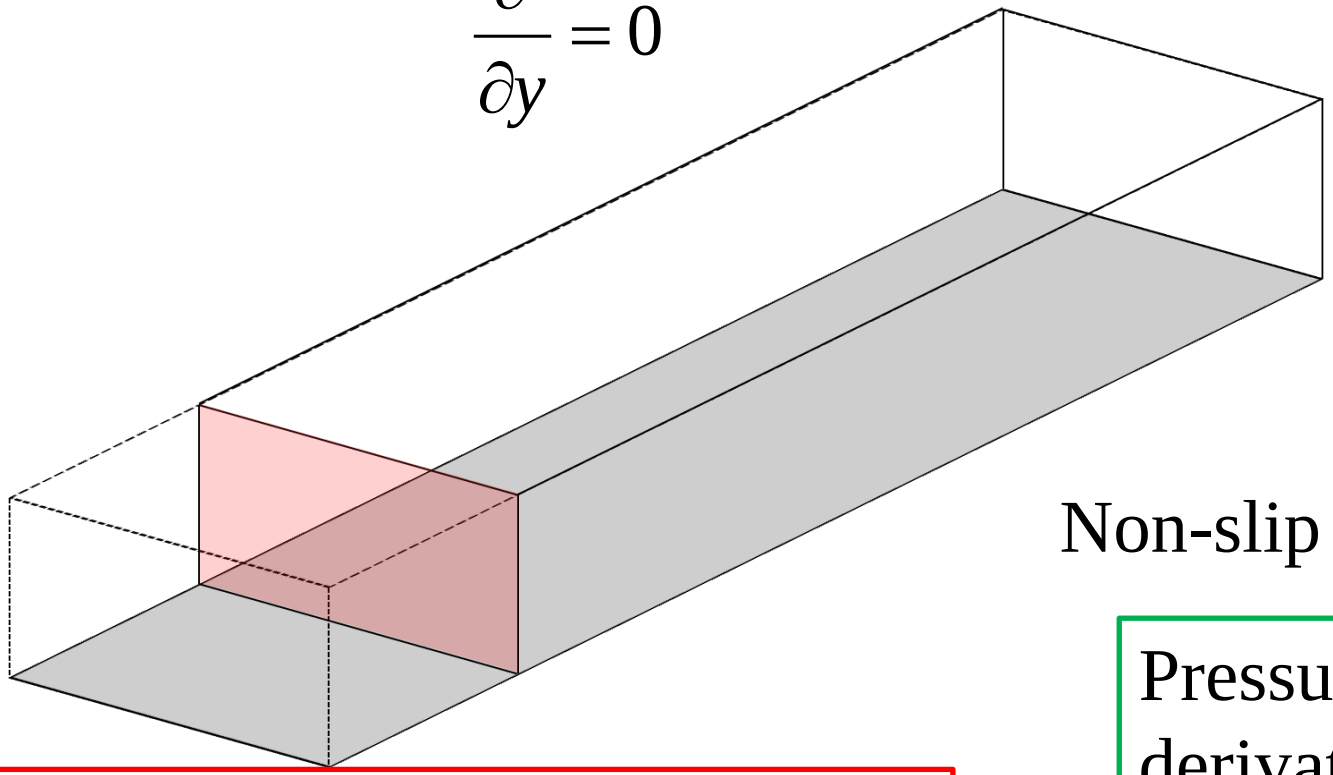
$$\frac{\partial}{\partial x} = 0$$



Non-slip condition

Pressure : derivative is 0

Velocity profile with streaky structure

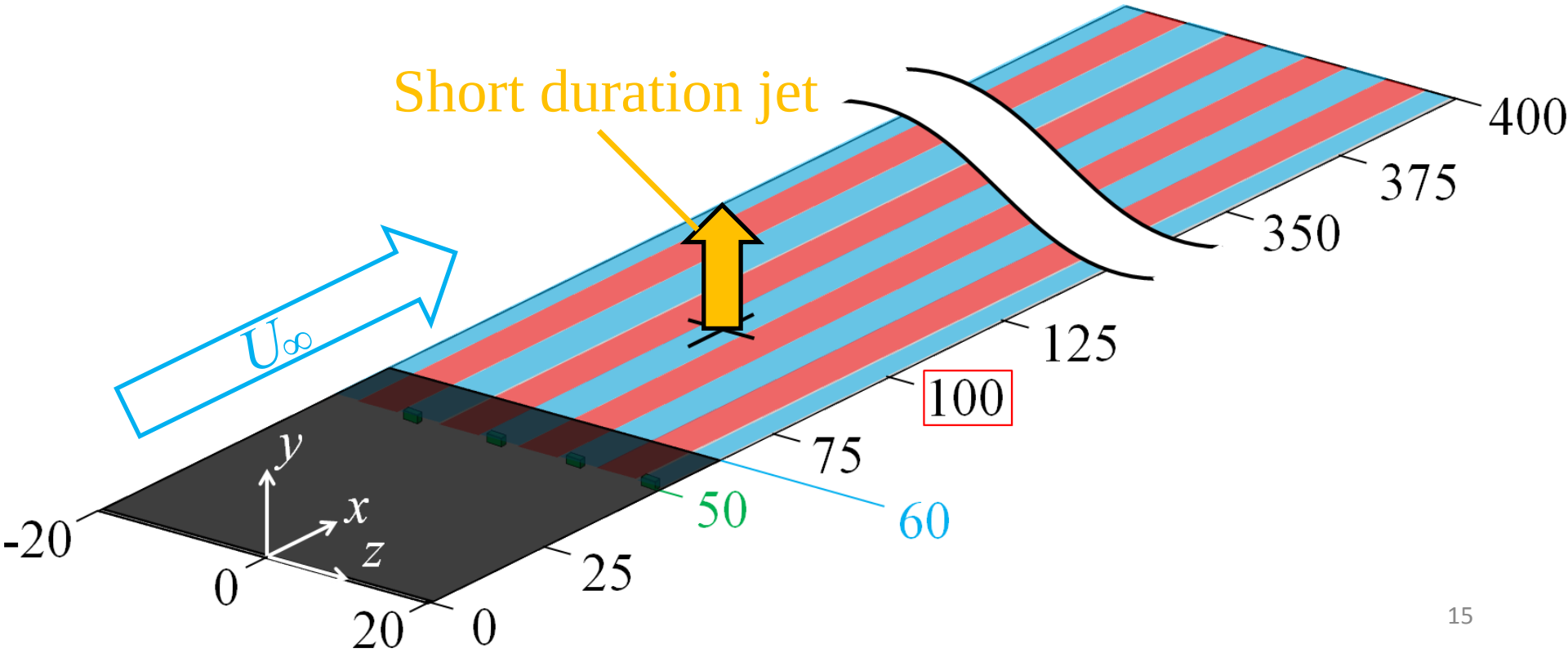
- Periodic condition is imposed in the spanwise direction.

$$Re_{\delta_0^*} = U\delta_0^* / \nu = 530$$

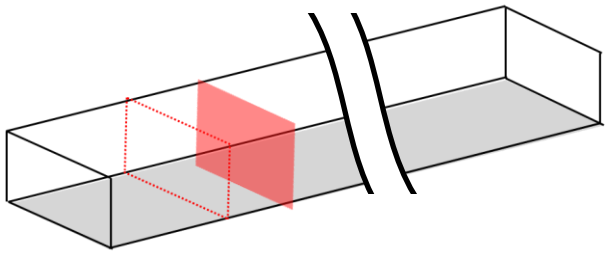
Main computation

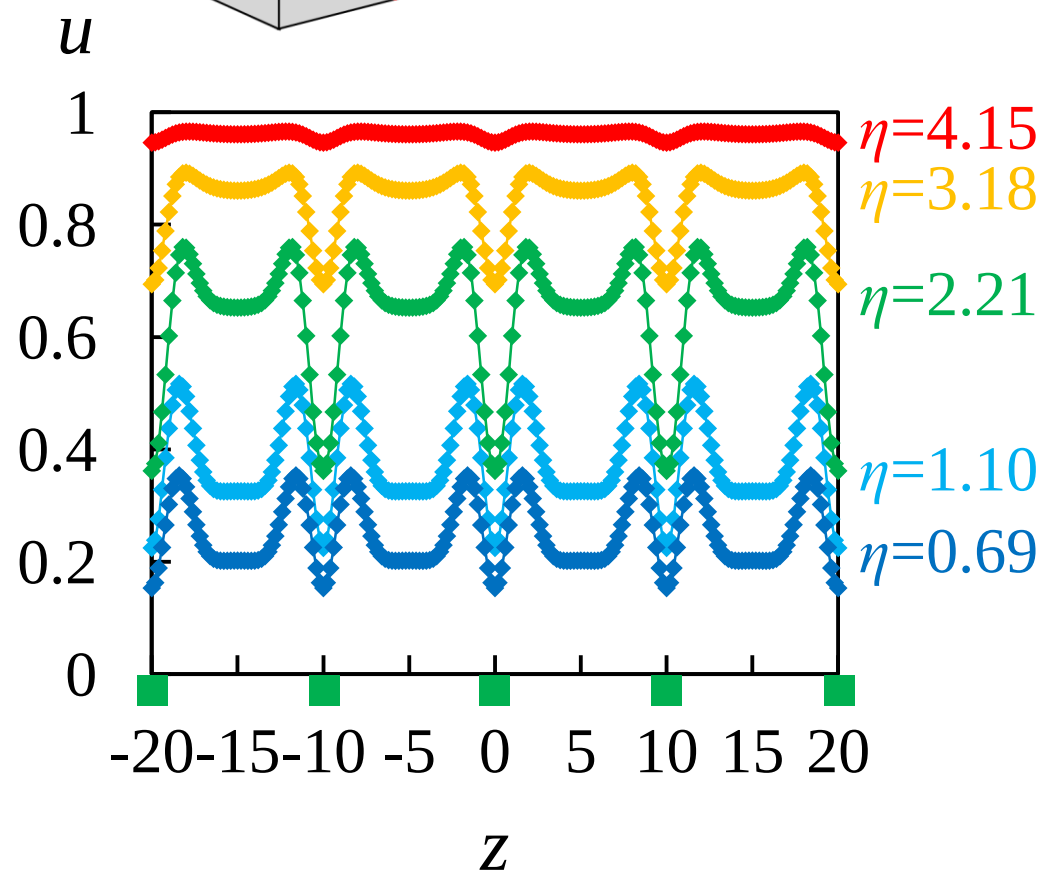
Grid number : $2001 \times 101 \times 201 \rightarrow 1701 \times 101 \times 201$

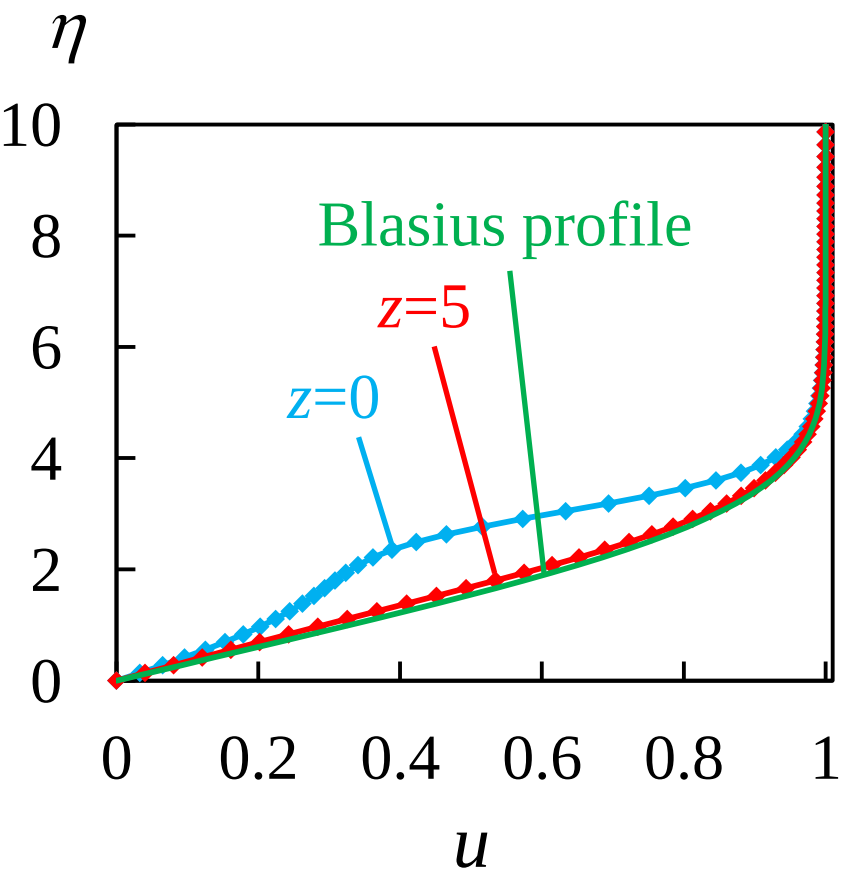
Short duration jet is introduced into a low-speed streak.



u profile at the jet location(*x*=100)



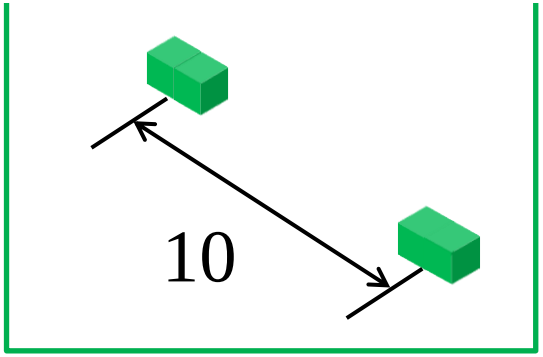


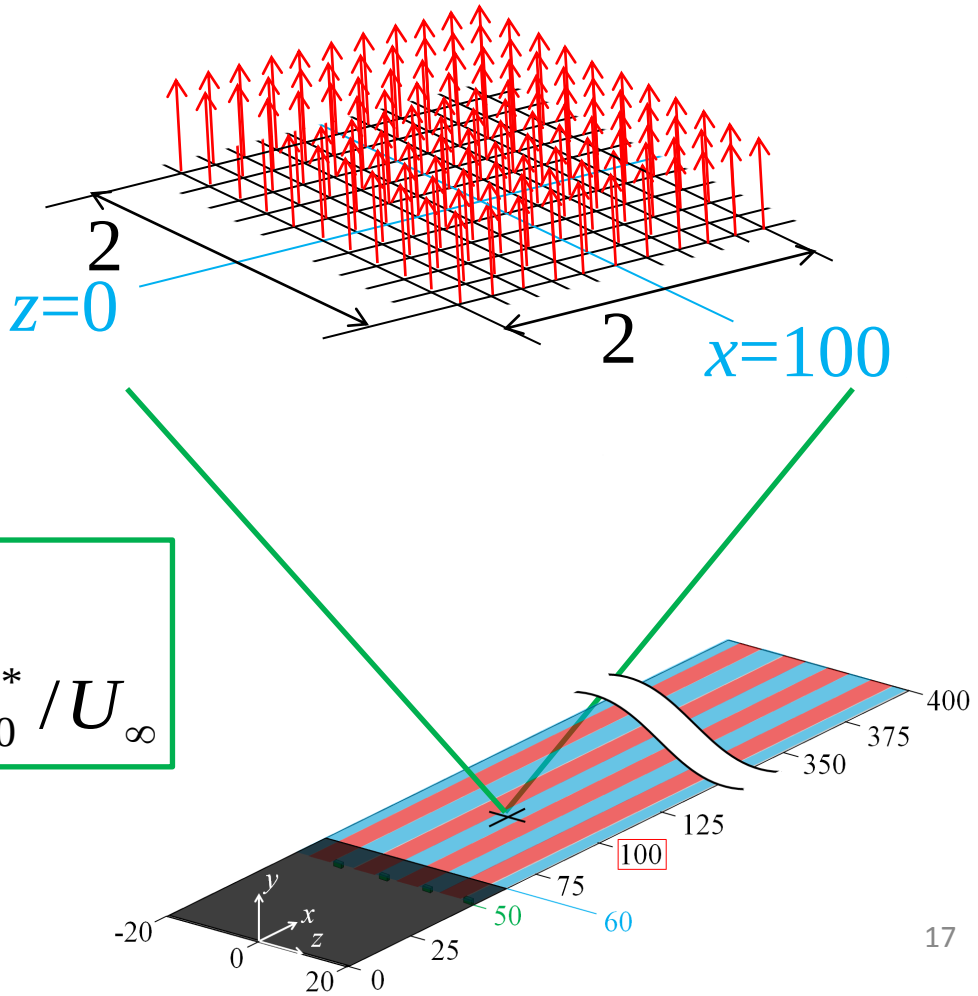


It is confirmed that streaky structures are formed.

Short duration jet

Interval of bumps

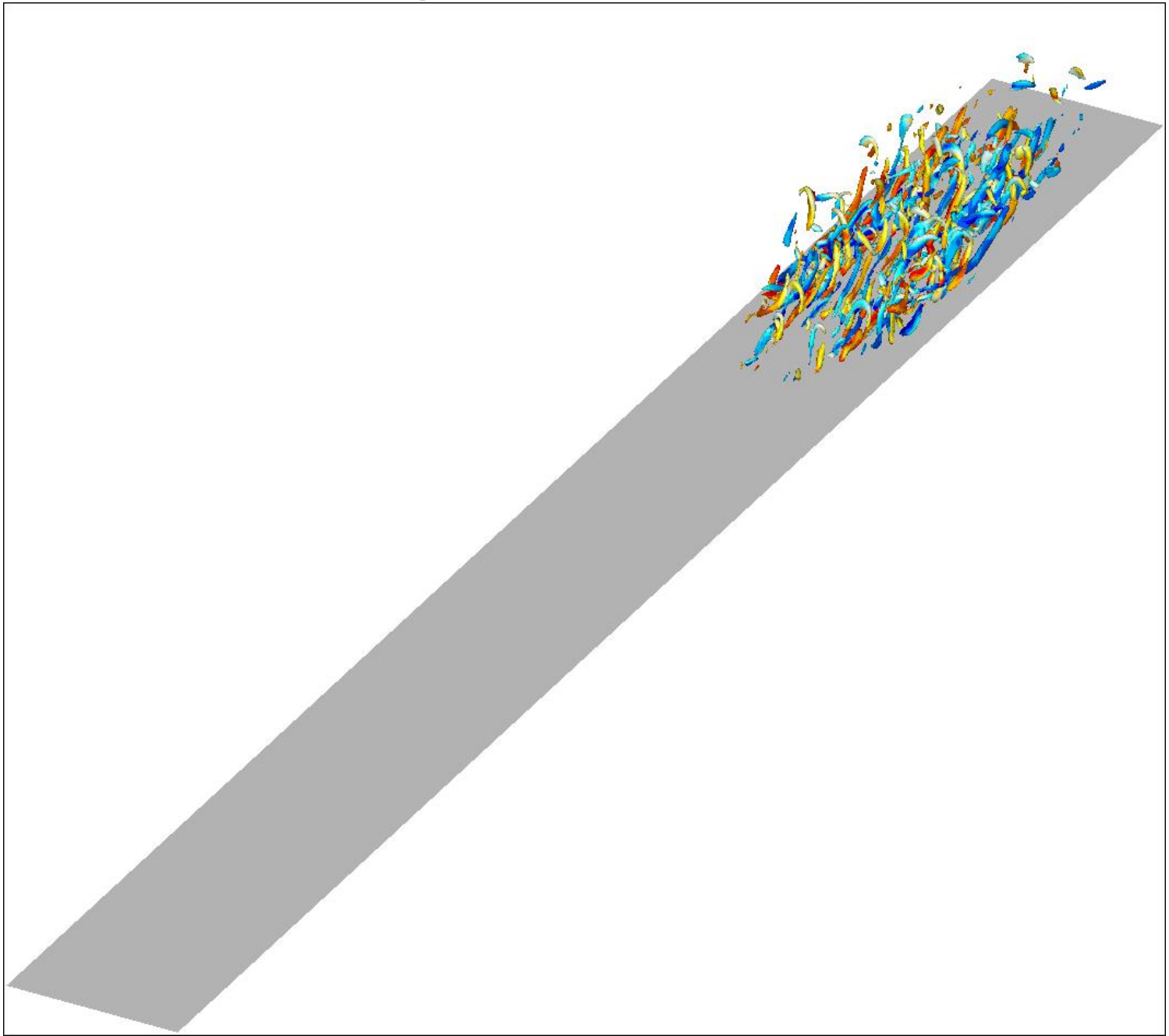




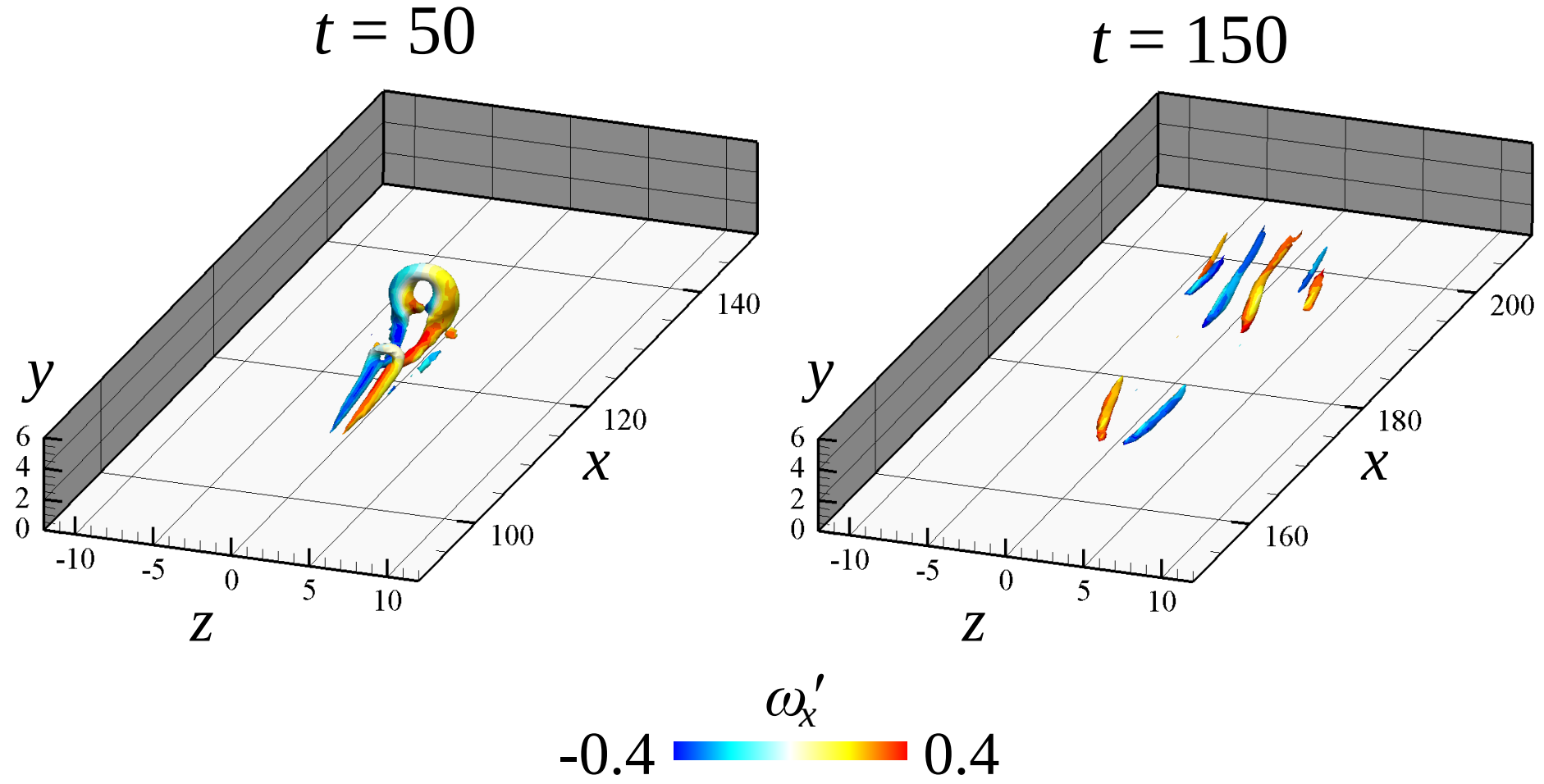
Jet velocity : $0.3U_\infty$

Introducing duration : $15\delta_0^* / U_\infty$

Movie showing vortex structures(Q=0.025)

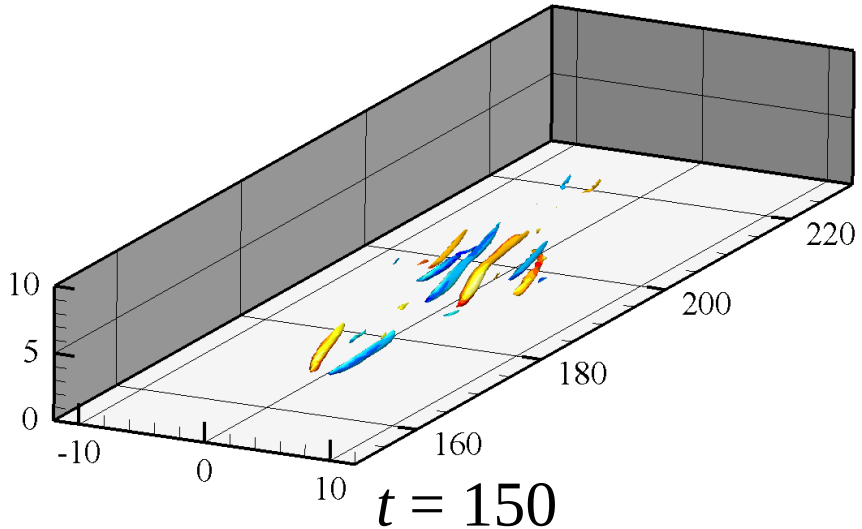


Vortex structures introduced into the boundary layer. (Q=0.025)

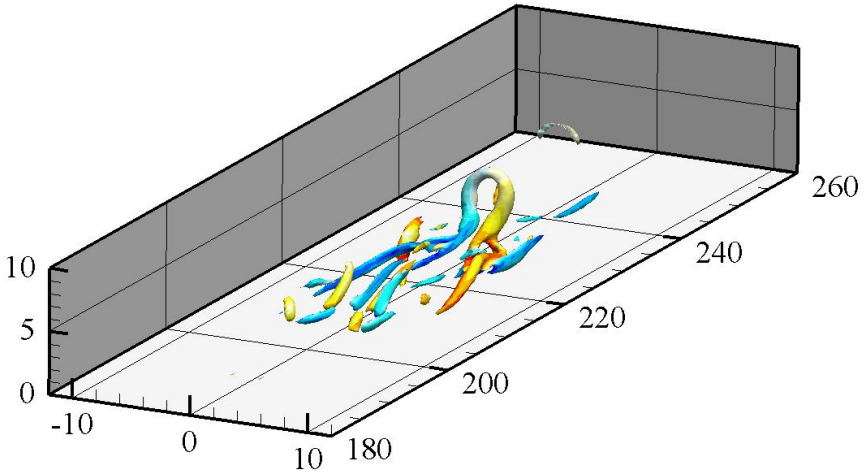


The initial vortex structures decay.

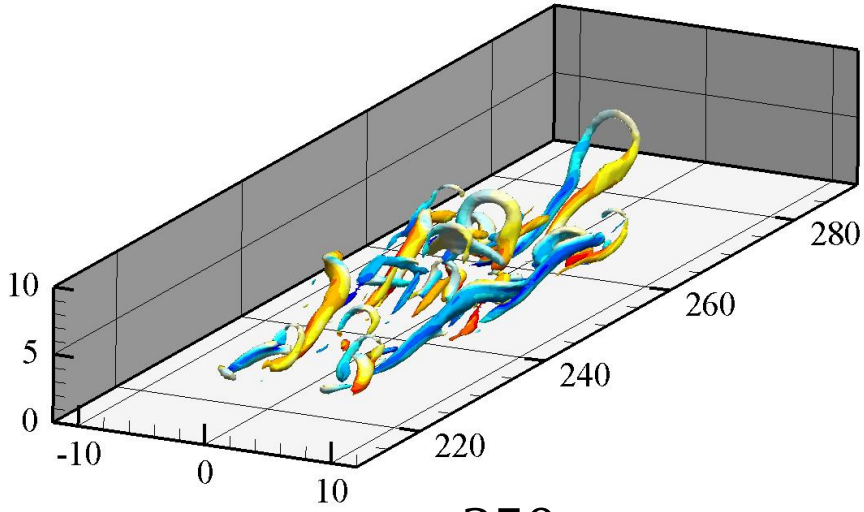
Revival of vortex structures (Q=0.025)



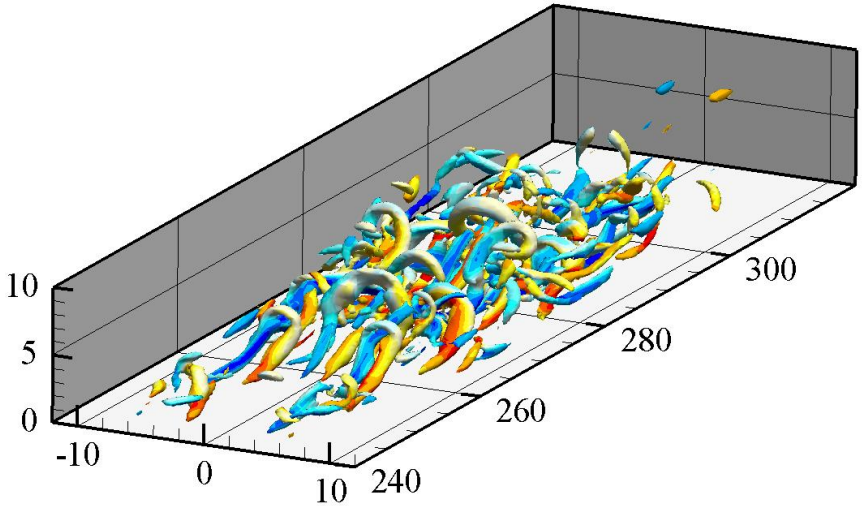
t = 150



t = 200



t = 250



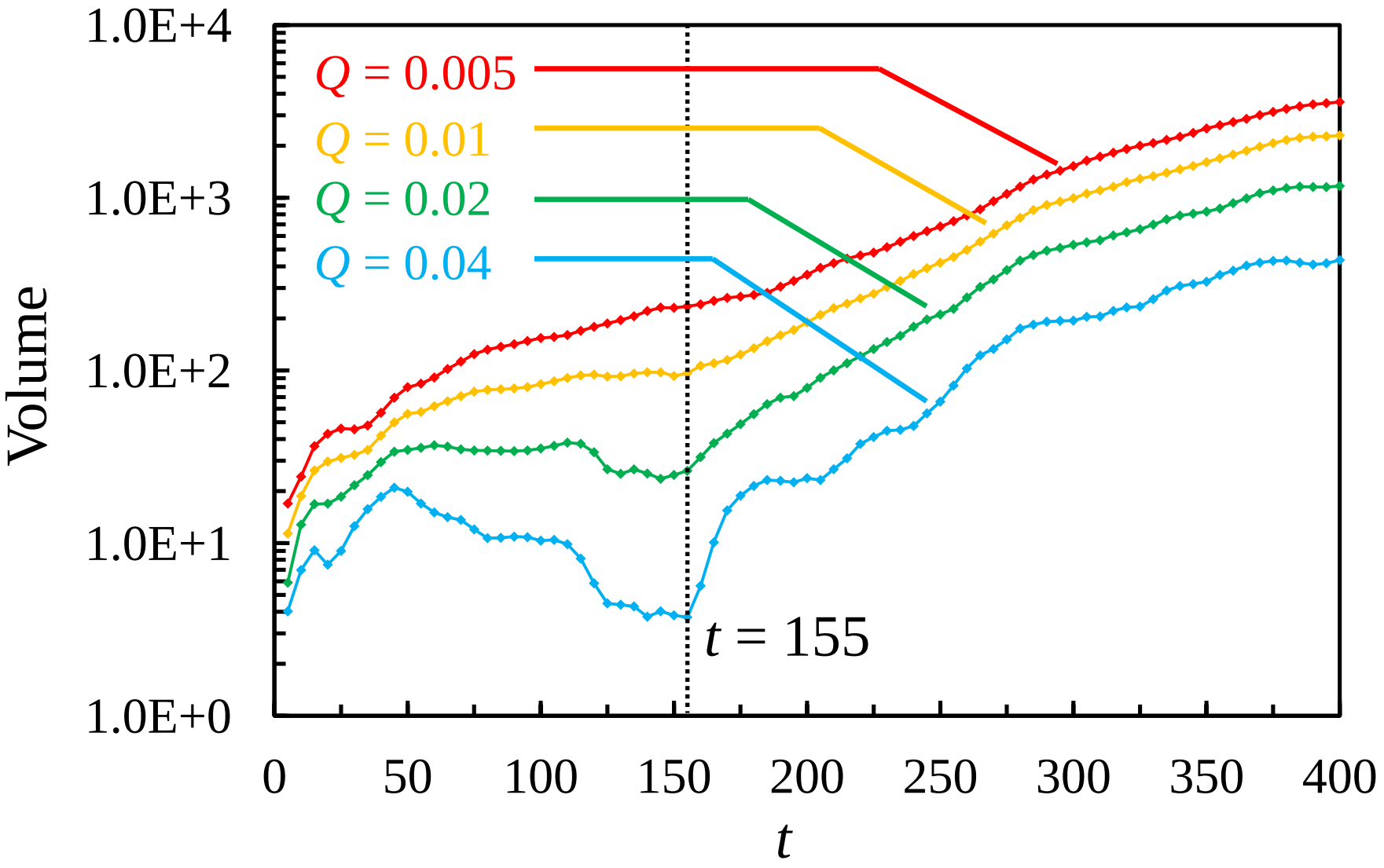
t = 300

Number of vortex structures increase.

ω_x'

-0.4 0.4

Change in total volume of vortex structures

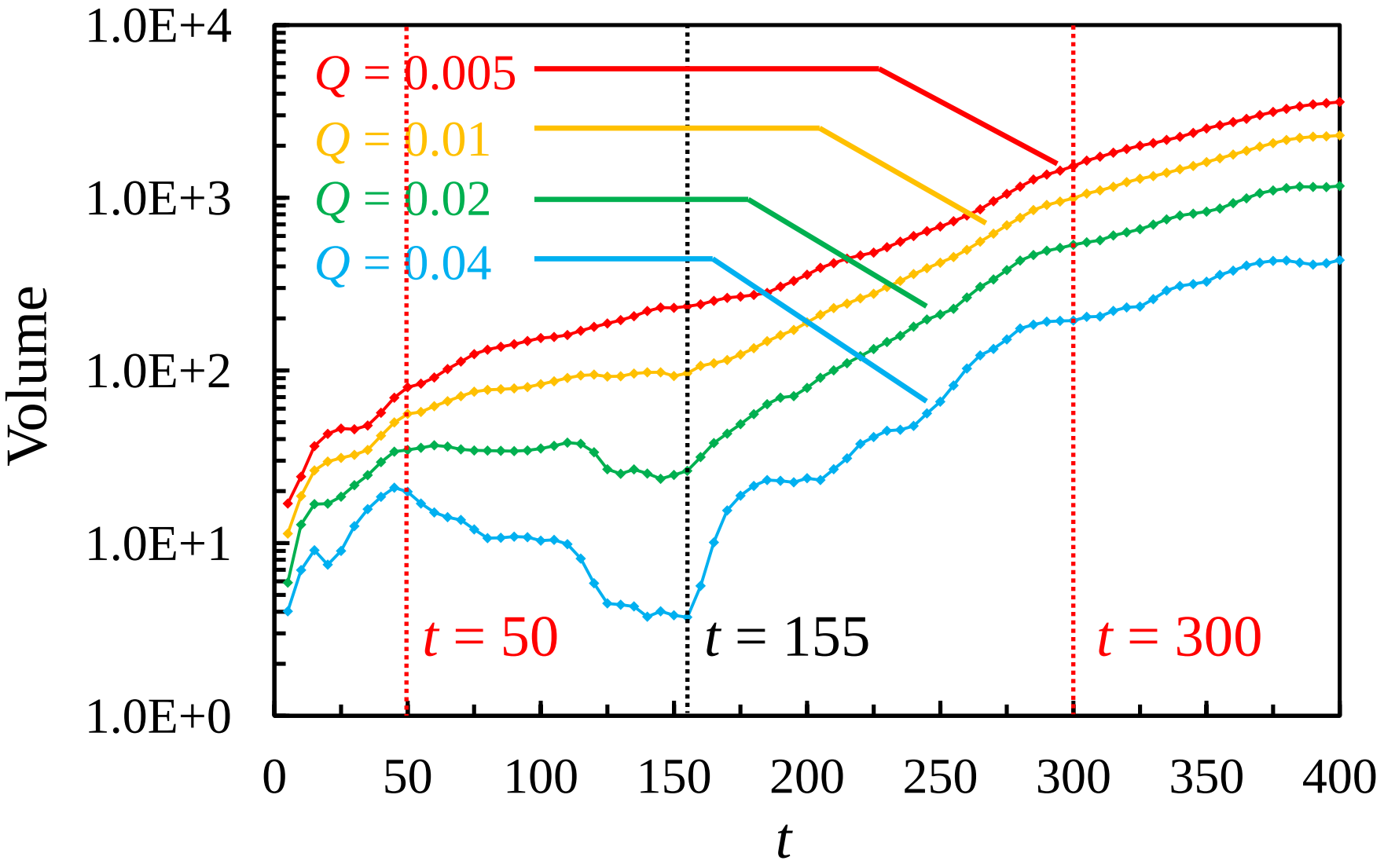


Turbulence starts around t=155.

Under what condition does the turbulence start?

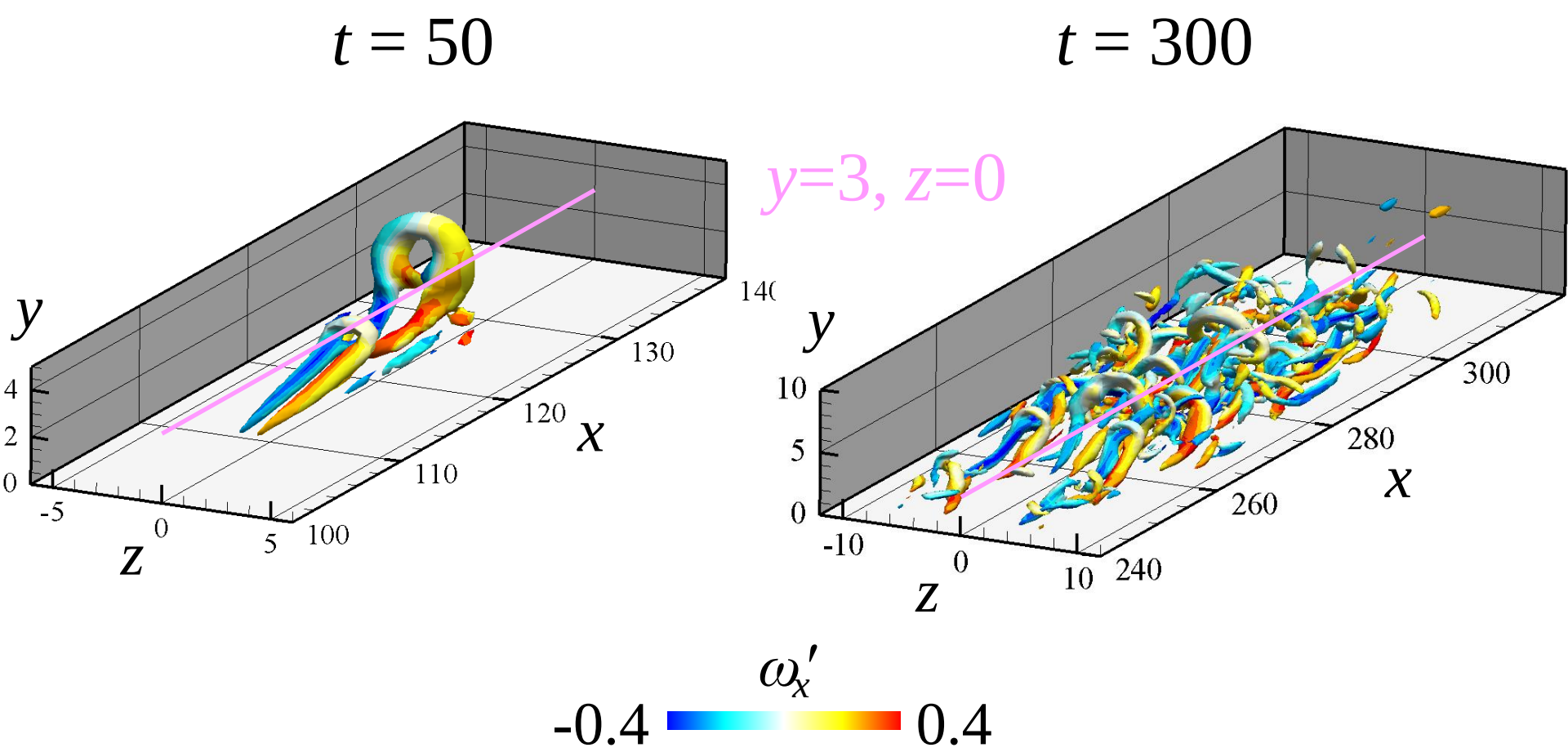
Any good way to identify the onset of turbulence ?

Time variation of total volume of vortex structures



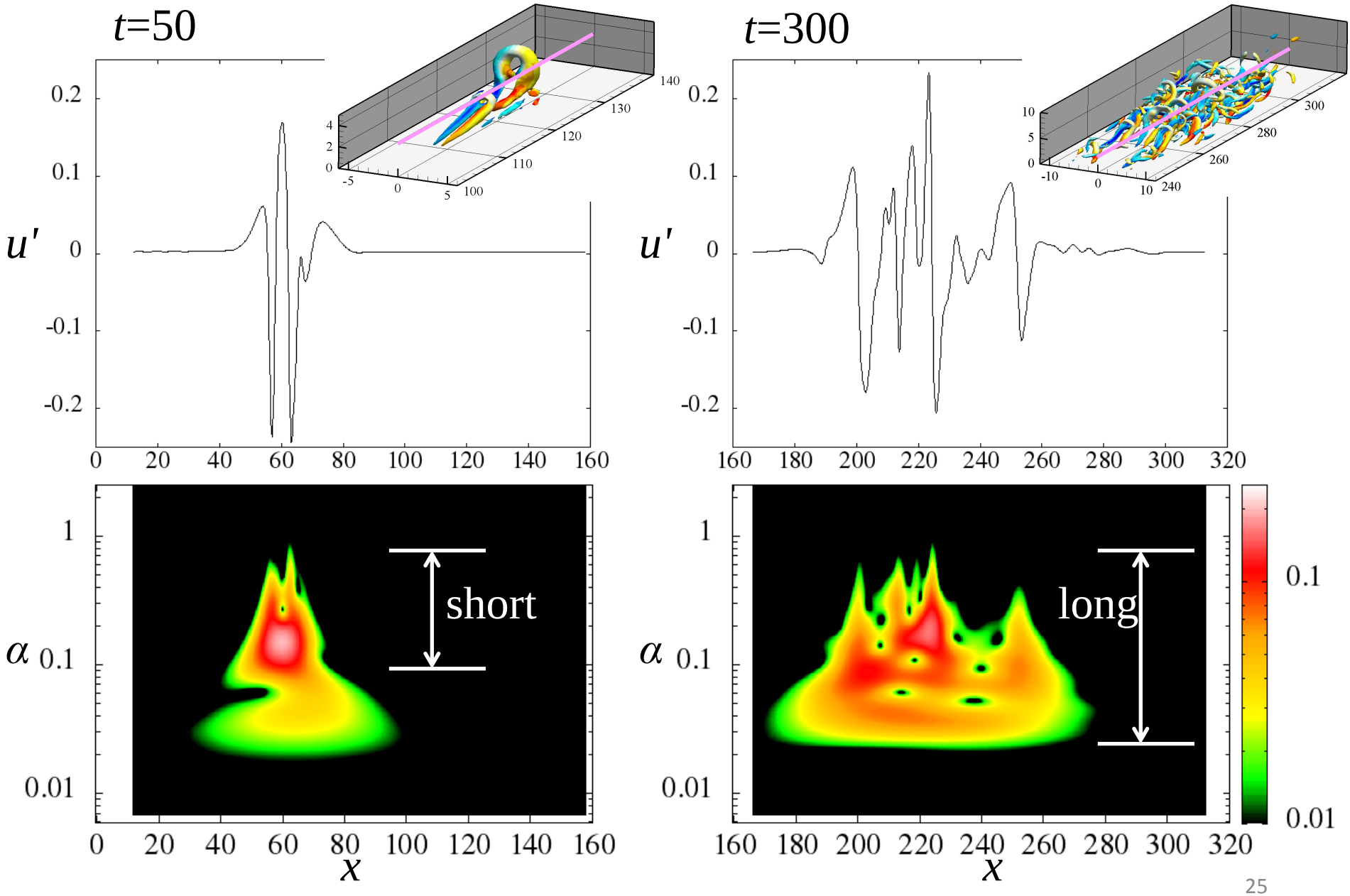
Turbulence starts around t=155.

In order to identify local turbulent regions…

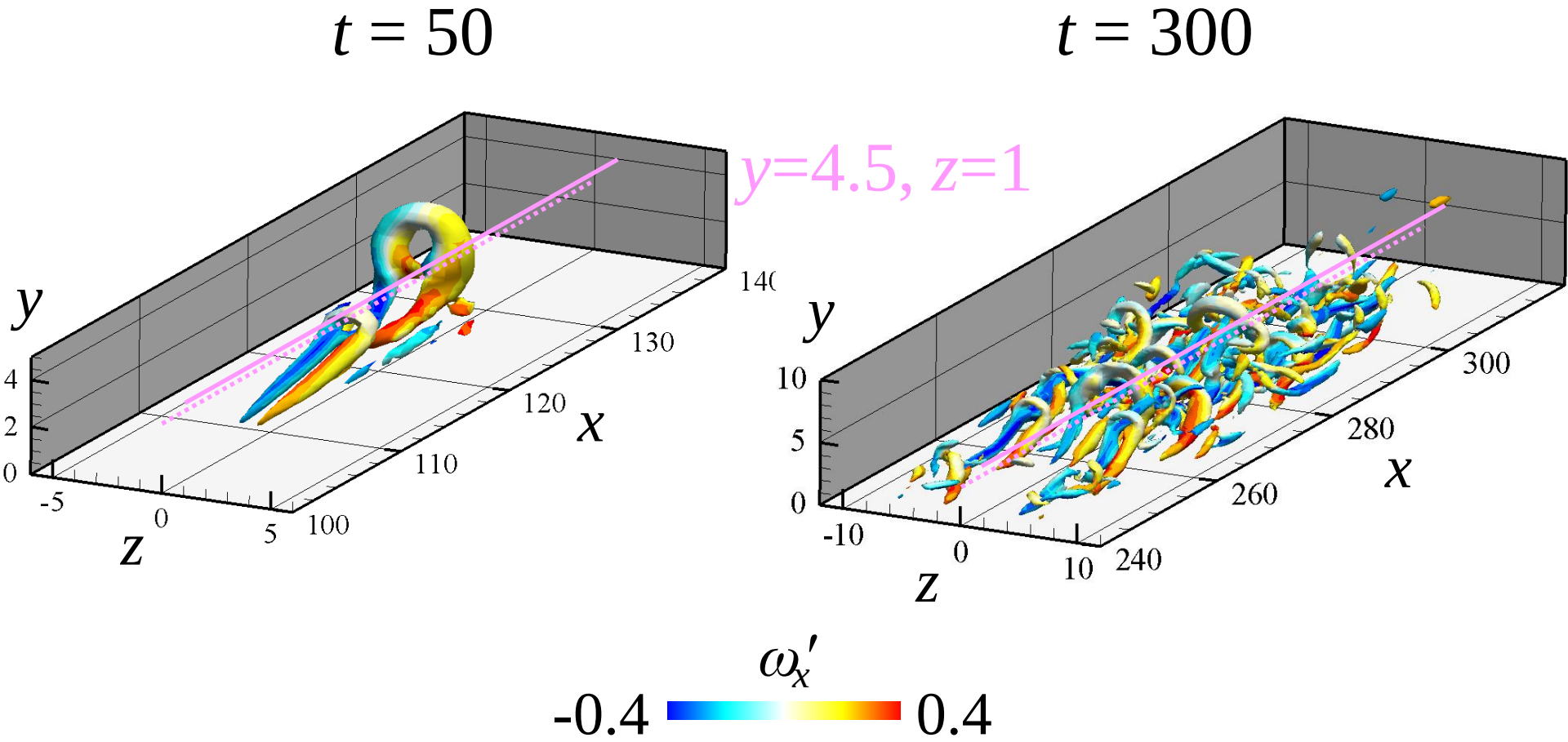


We tried to identify turbulent regions using **wavelet analysis**.

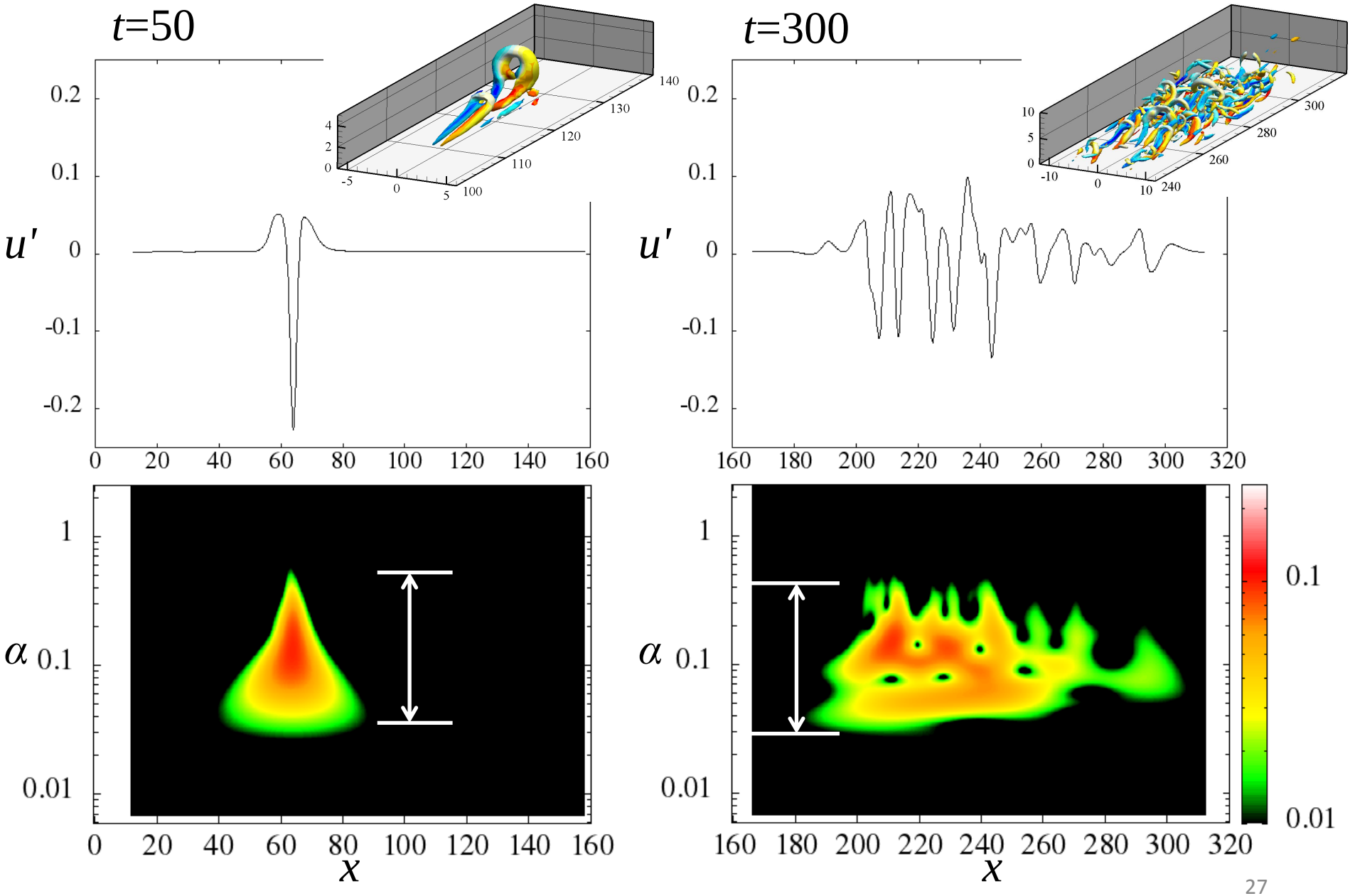
Fluctuation waves and their wavelets (y=3, z=0)



At a different location



Fluctuation waves and their wavelets (y=4.5, z=1)



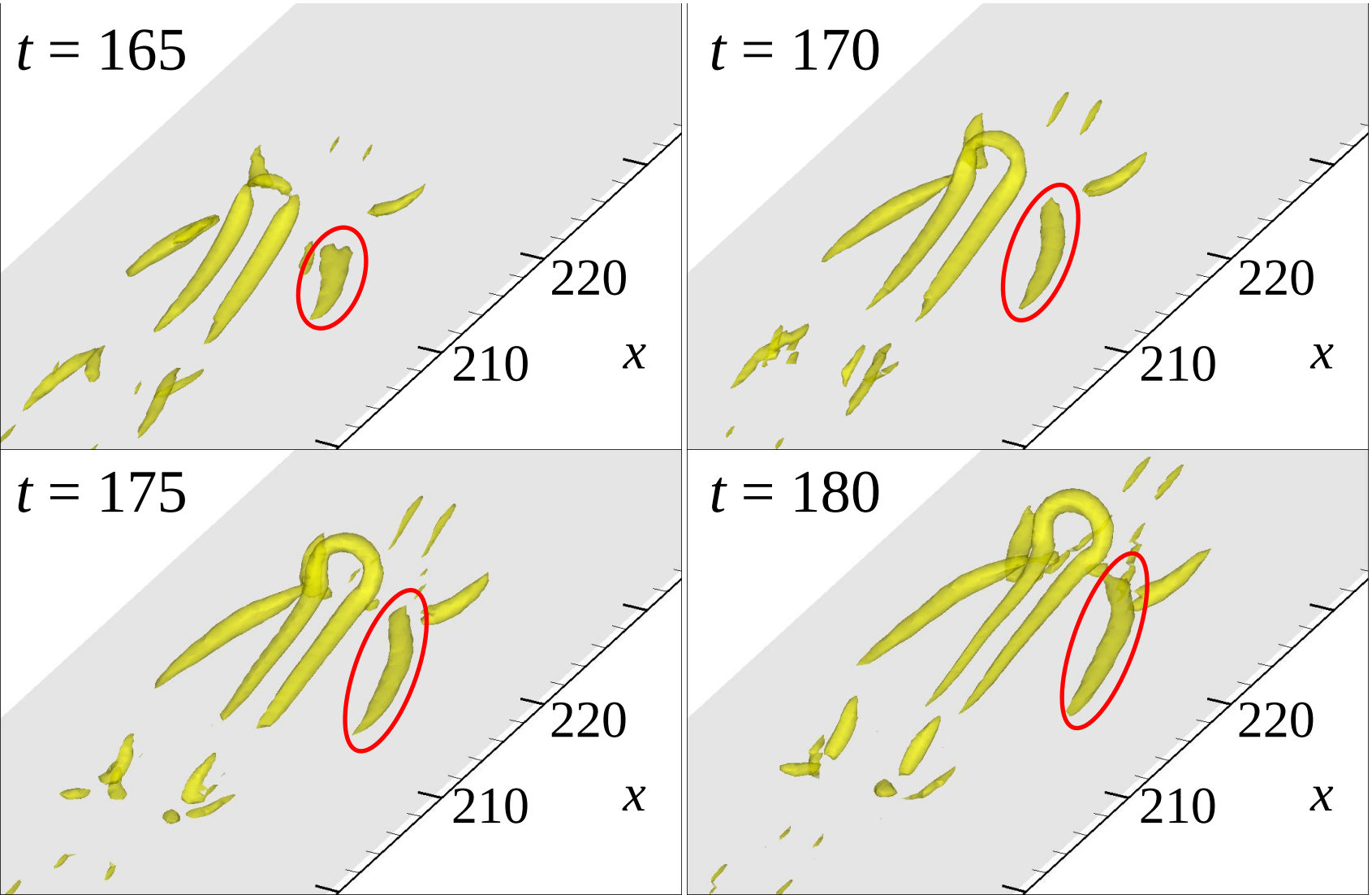
Result

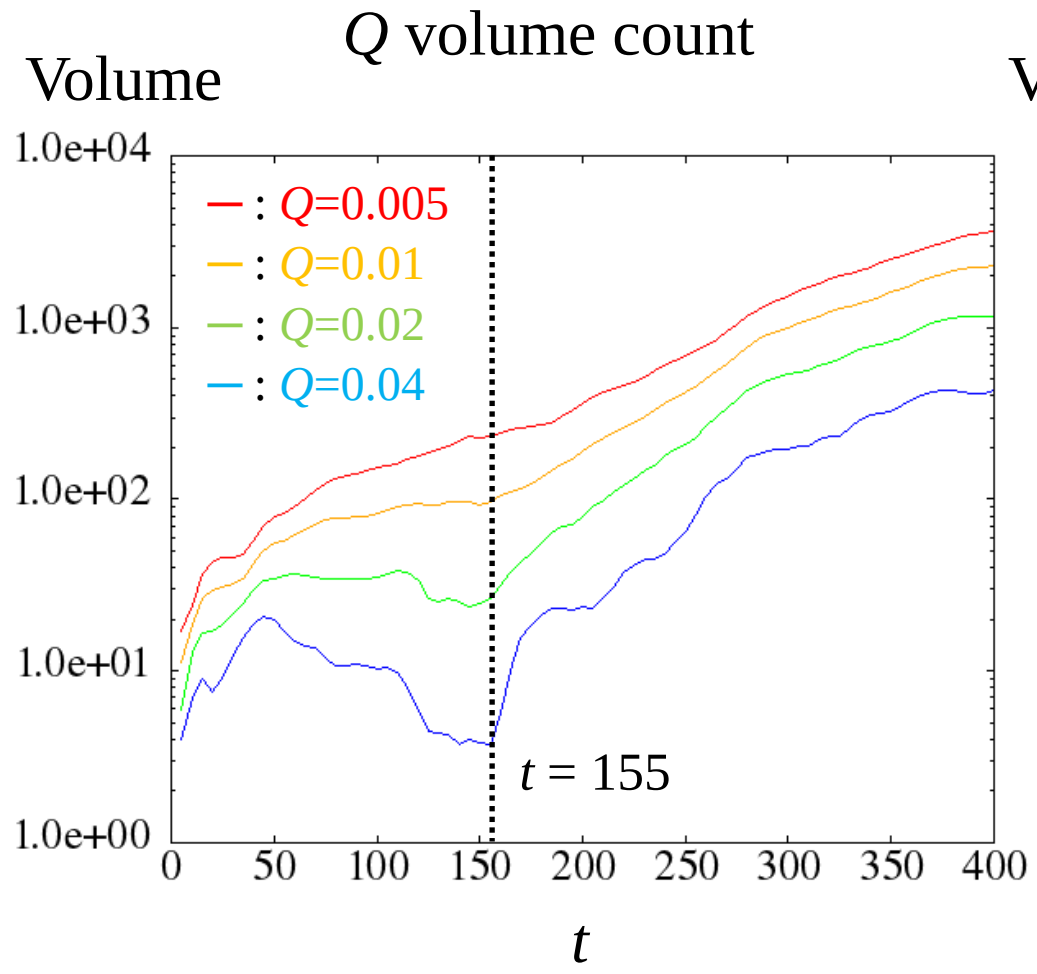
Wavelet analysis failed to distinguish.

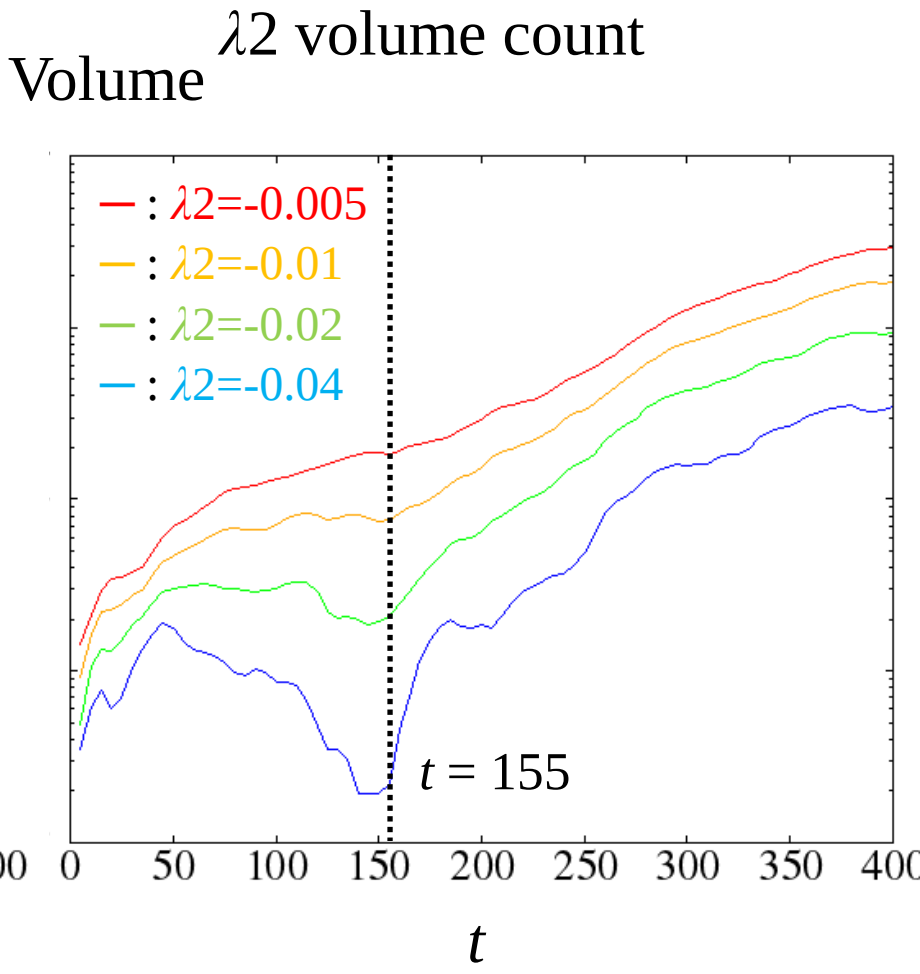
What method can?

Vortex structures soon after t=155

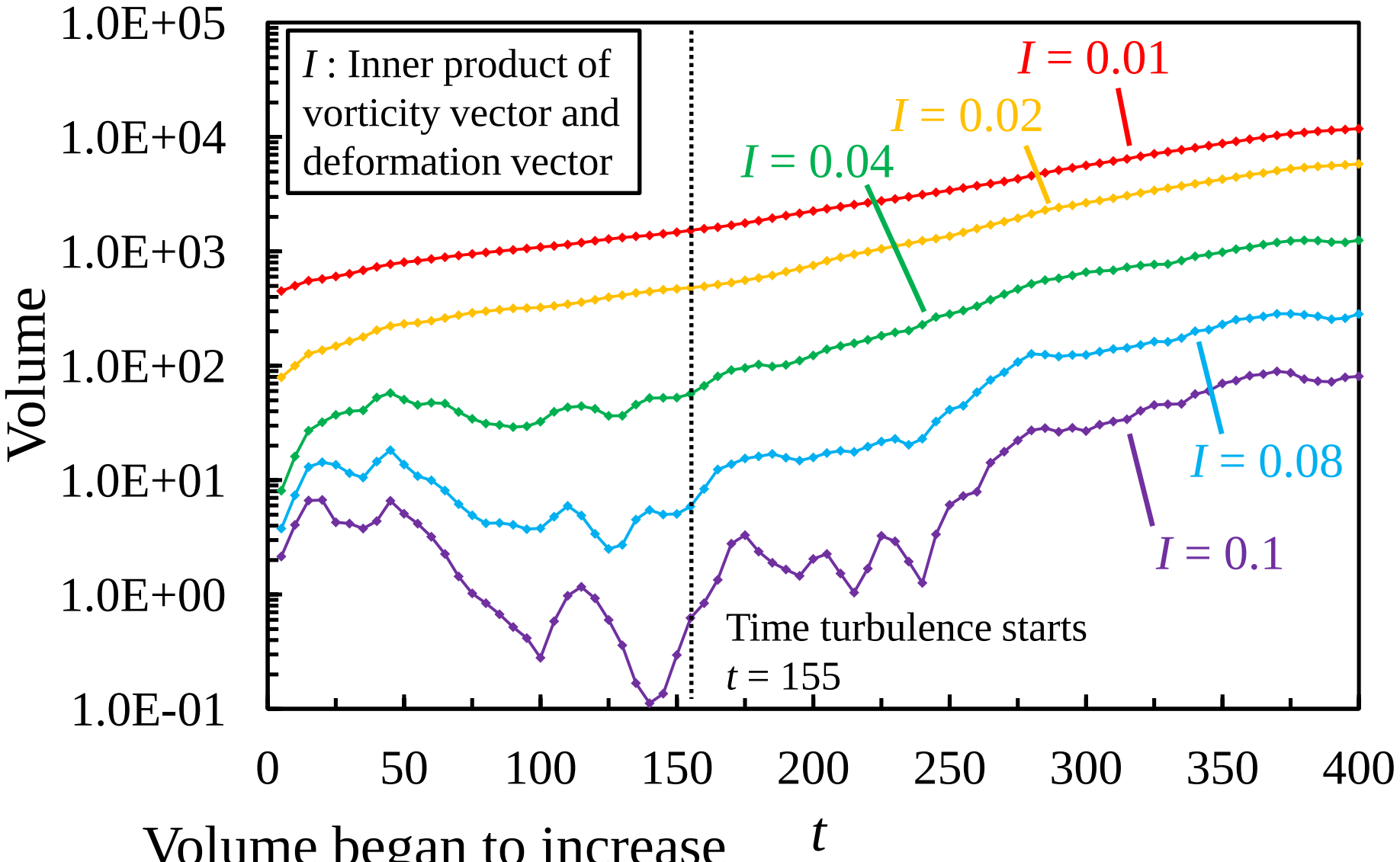
Q=0.025




Q volume count
Volume
1.0e+04
1.0e+03
1.0e+02
1.0e+01
1.0e+00
— : Q=0.005
— : Q=0.01
— : Q=0.02
— : Q=0.04
t = 155
0
50
100
150
200
250
300
350
400
t


λ2 volume count
Volume
— : λ2=-0.005
— : λ2=-0.01
— : λ2=-0.02
— : λ2=-0.04
t = 155
0
50
100
150
200
250
300
350
400
t

Time variation of volume of stretched region

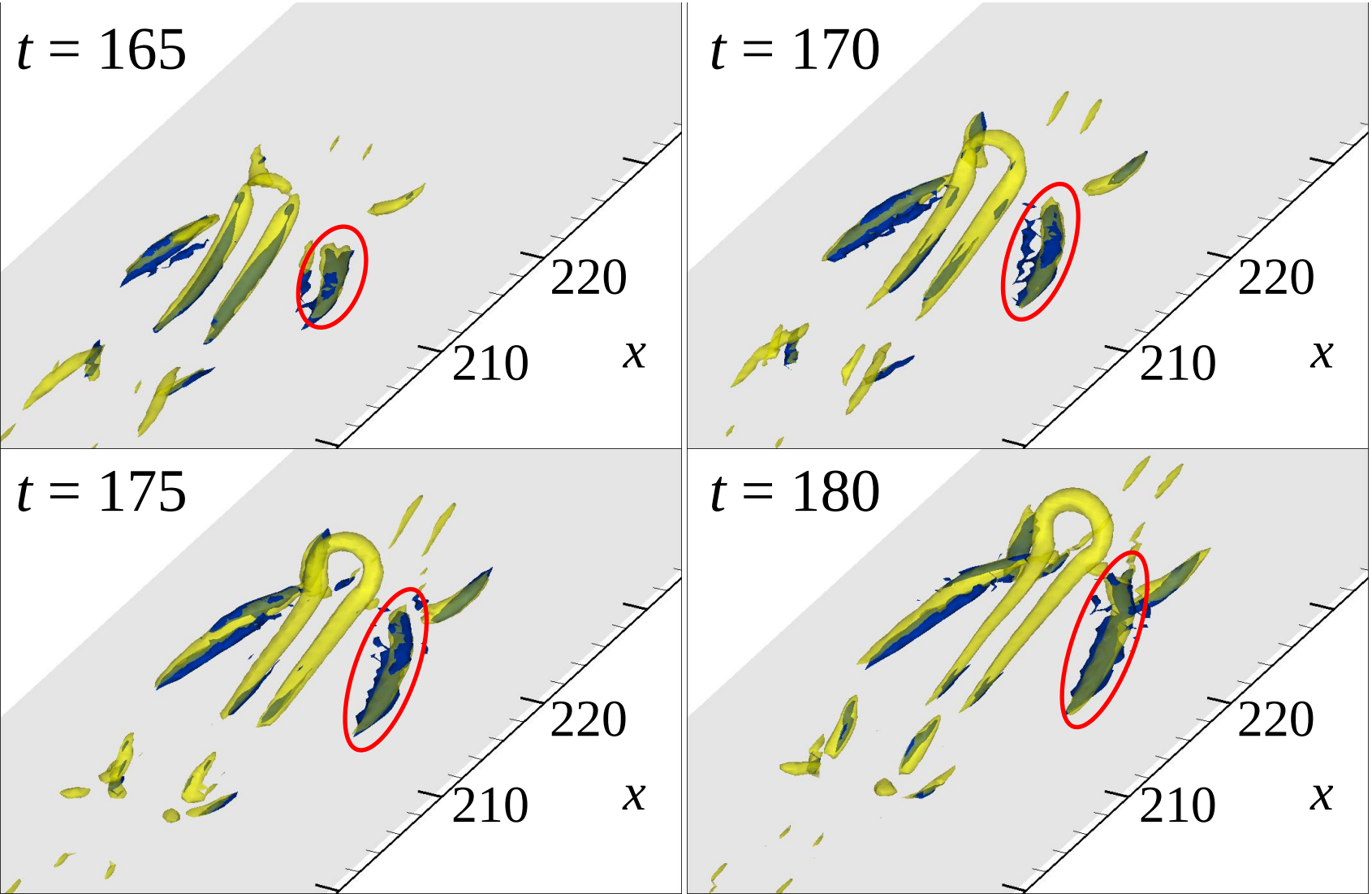


Volume began to increase a little before the turbulent onset.

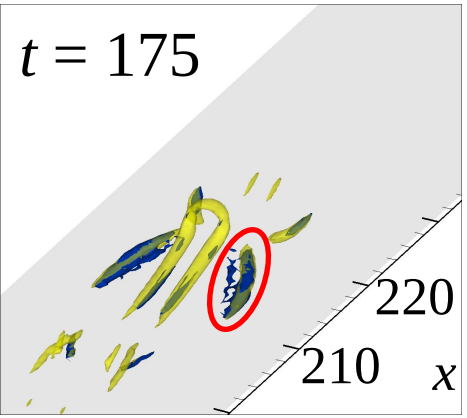
Vortex structures and stretching region

Q=0.025, I=0.06 shown together

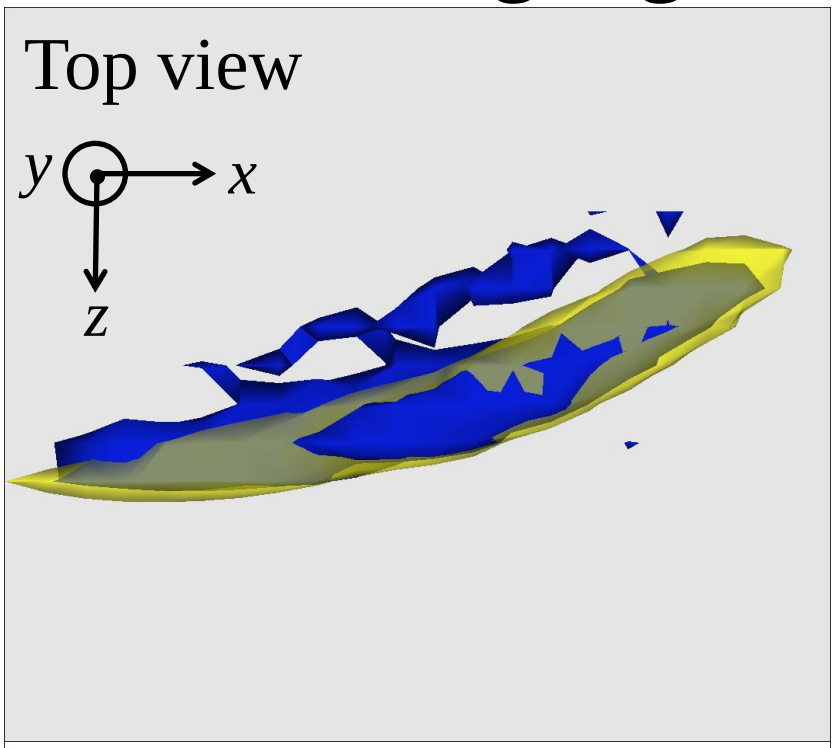
I : Inner product of vorticity vector and primary eigen vector

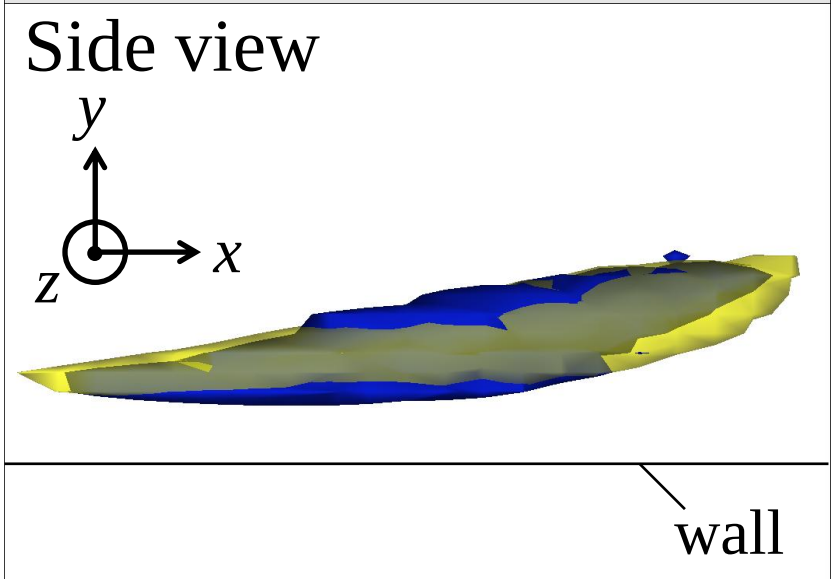


Vortex structures and stretching region



Vortex structure





Summary

Destabilization of flow by short duration jet introduced into the low-speed streak was studied using 3-dimensional numerical simulation, aimed at investigating how the turbulence starts.

We tried to identify a locally turbulent region using wavelet analysis.

Result was:

We could not distinguish turbulent region from non-turbulent region.

We are currently trying focusing on vortex stretching.

Any suggestion is welcome!