Towards Skin Friction Drag Reduction via Active Control of the Turbulent Boundary Layer

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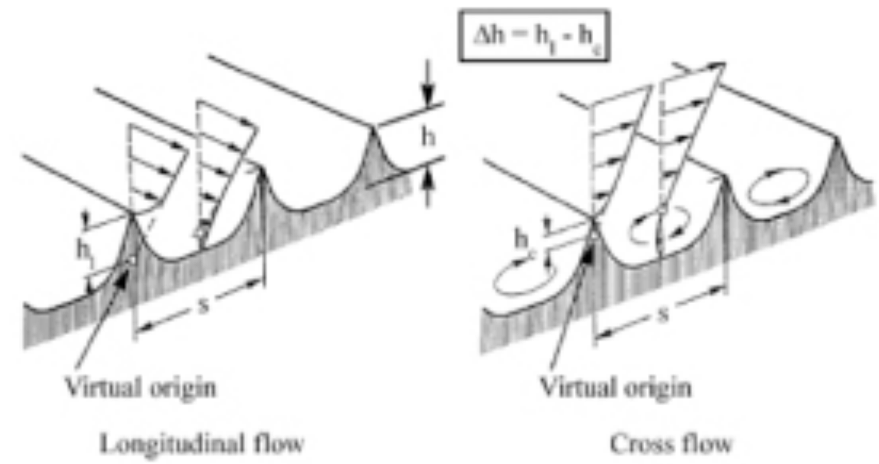
Skin Friction Drag Reduction

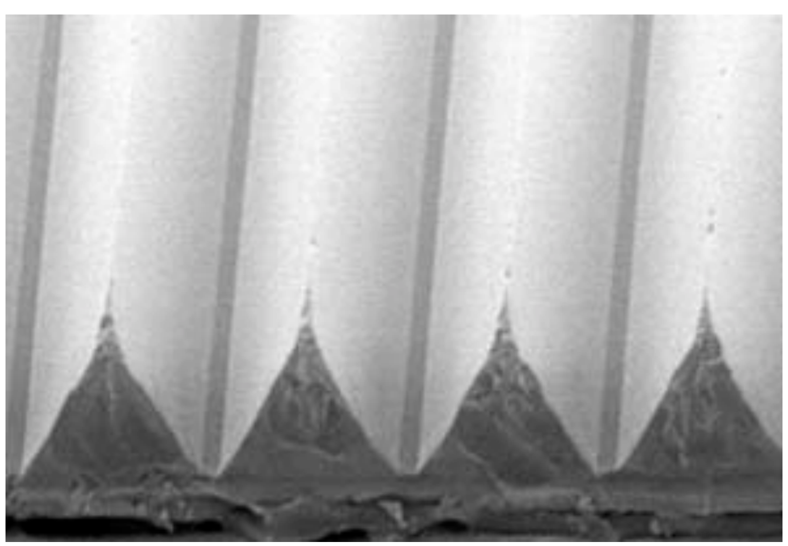
- At cruise, 40%-50% of drag on airplane from skin friction
- Can be reduced by
  - delaying transition
  - control/reduce level of turbulence

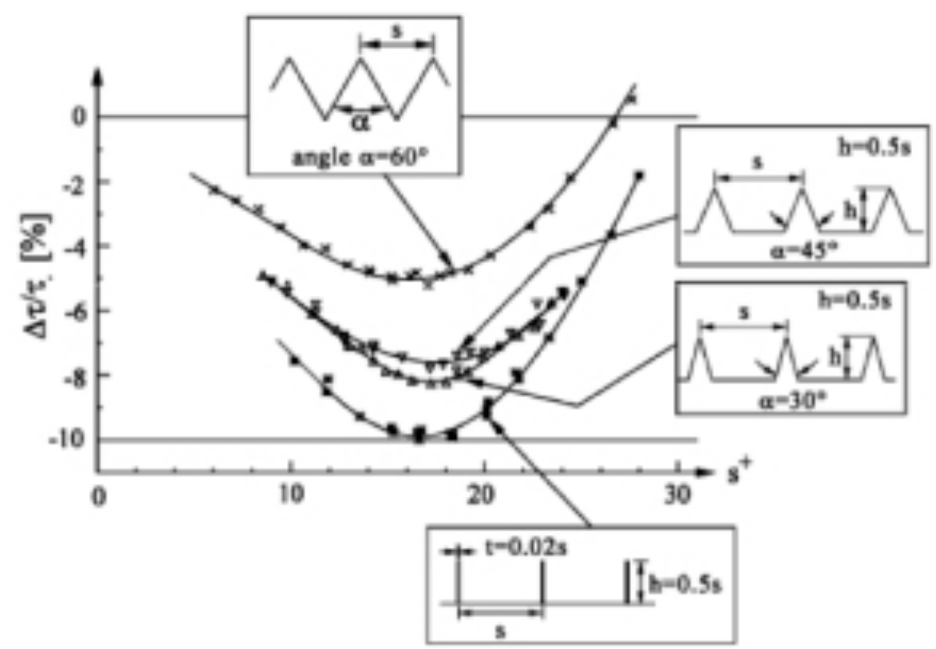
Image source http://comercialaircraft.bombardier.com/en/crj/Technology.html

Turbulent Boundary Layer Control

- Approaches based on changing mean flow have not proven energy effective
    - boundary layer suction
- More sophisticated methods rely on subtle manipulations of flow structures and/or instabilities
    - Classic example are riblets







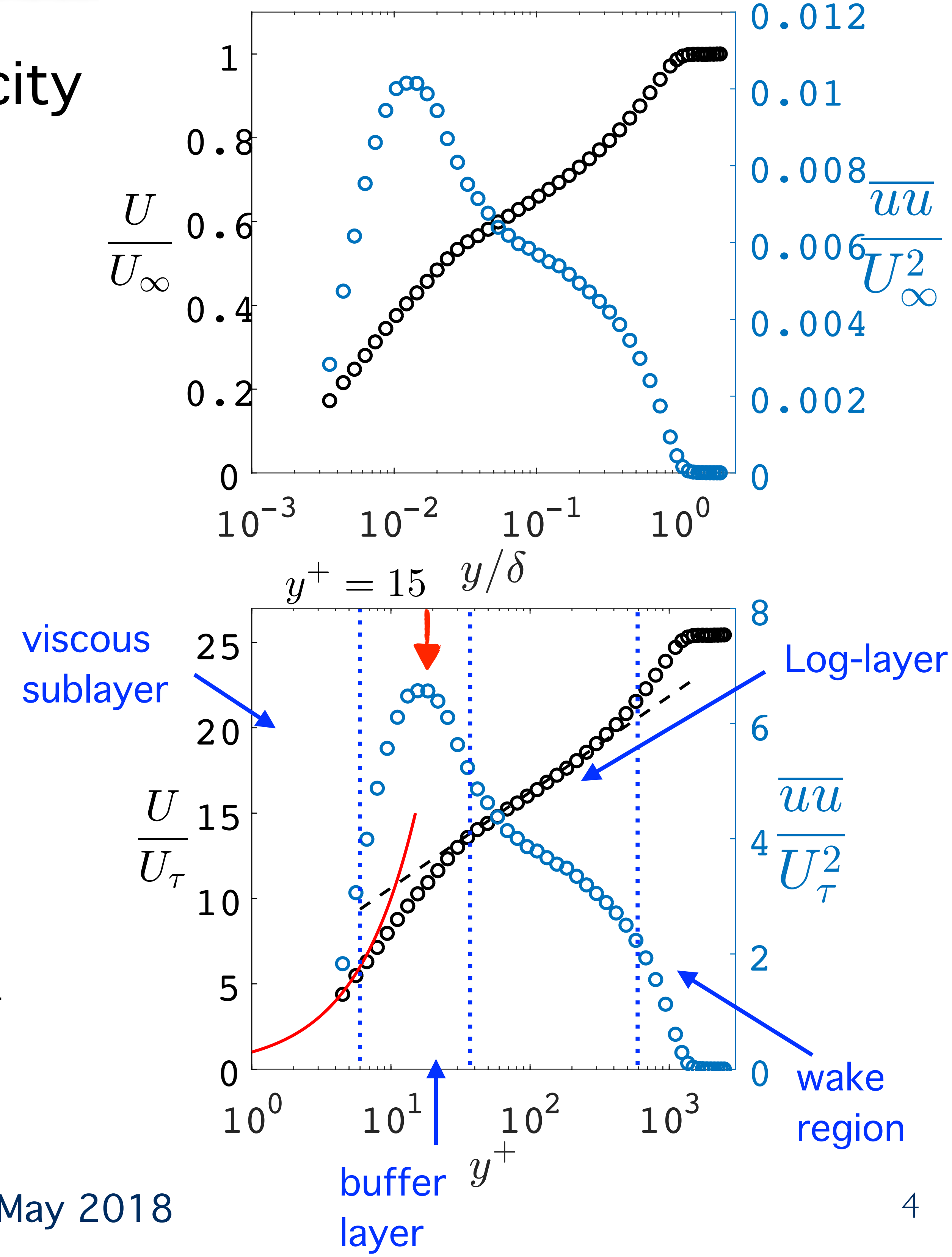
Turbulent Boundary Layer 101

- Characteristic mean profile of velocity and streamwise turbulent velocity

- Two normalizations of interest
  - Outer variables
  - Inner variables

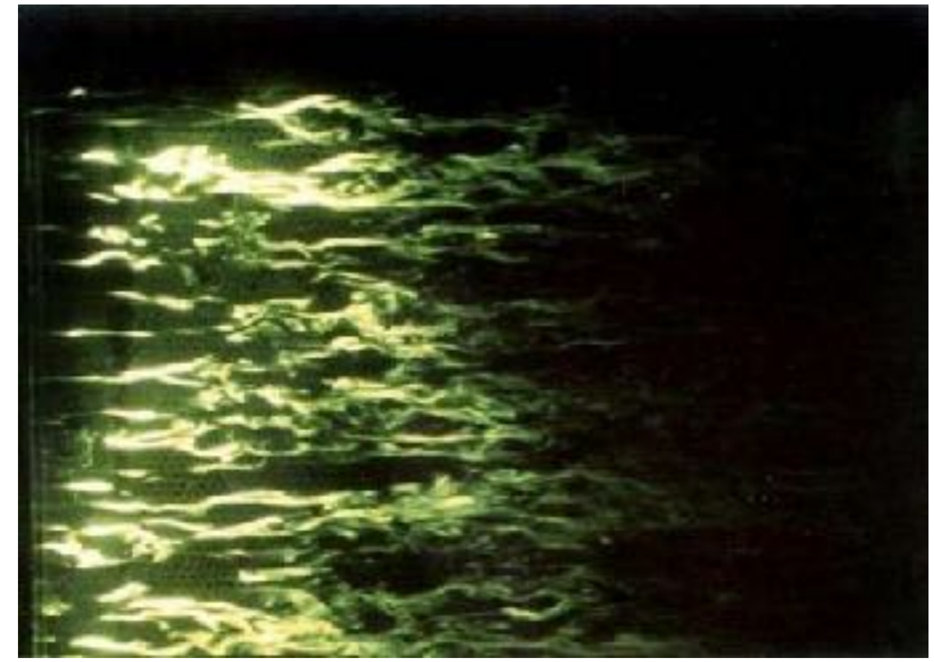
Friction velocity $u_\tau = \sqrt{\dfrac{\tau_w}{\rho}}$

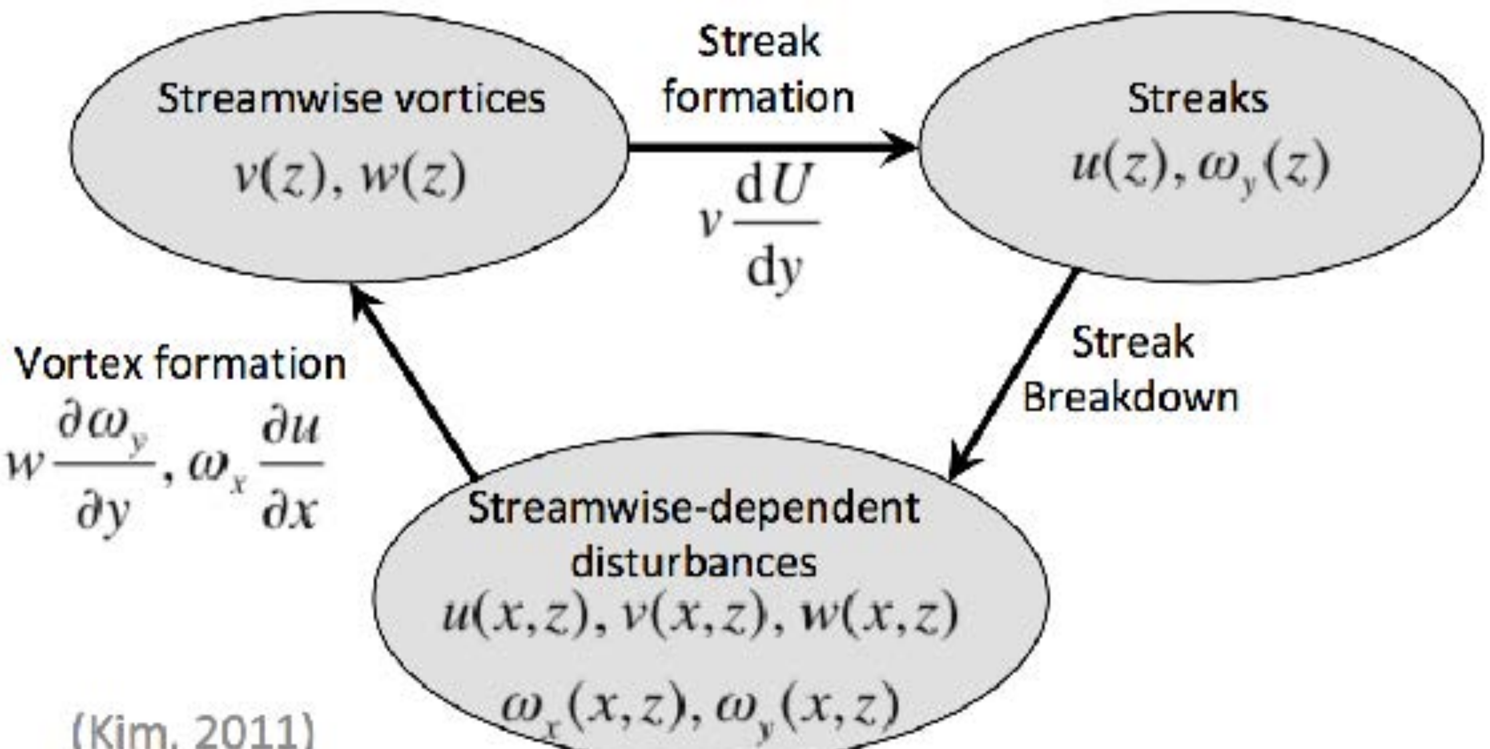
$$y^+ = \frac{y\, u_\tau}{\nu} \qquad Re_\tau = \frac{\delta u_\tau}{\nu}$$



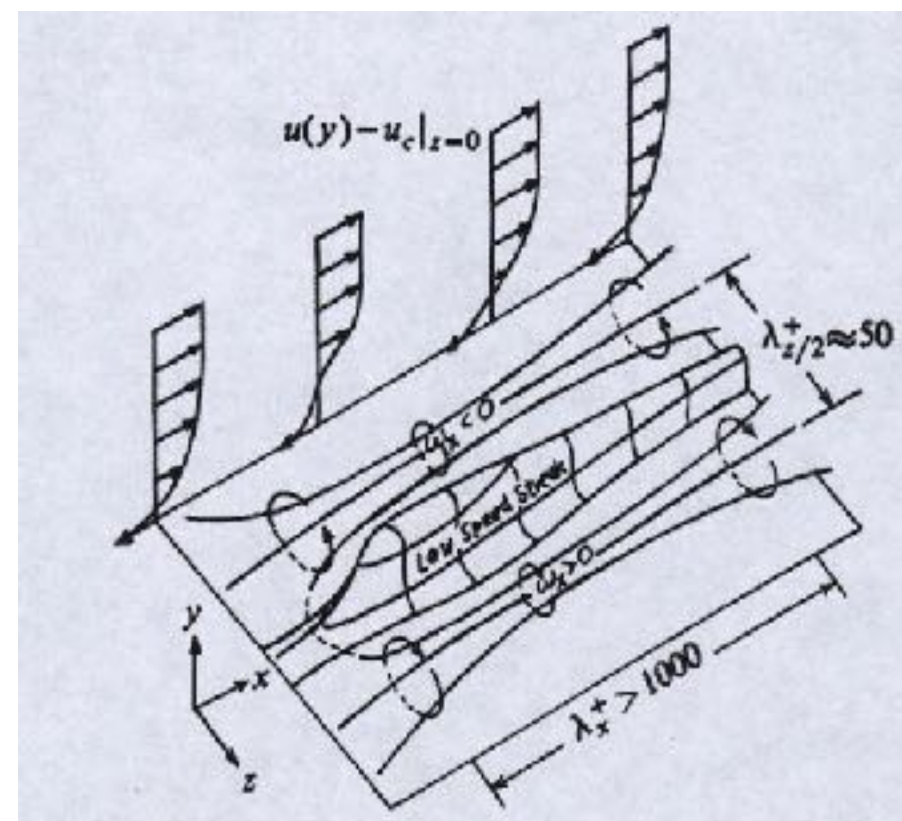
Self-sustaining Mechanism of Turbulence

- Coherent structures in the boundary layer play an important role in the self-sustaining mechanisms in wall-bounded flows *(Panton, 2001)*
- New methods attempt to disrupt or stabilize this mechanism





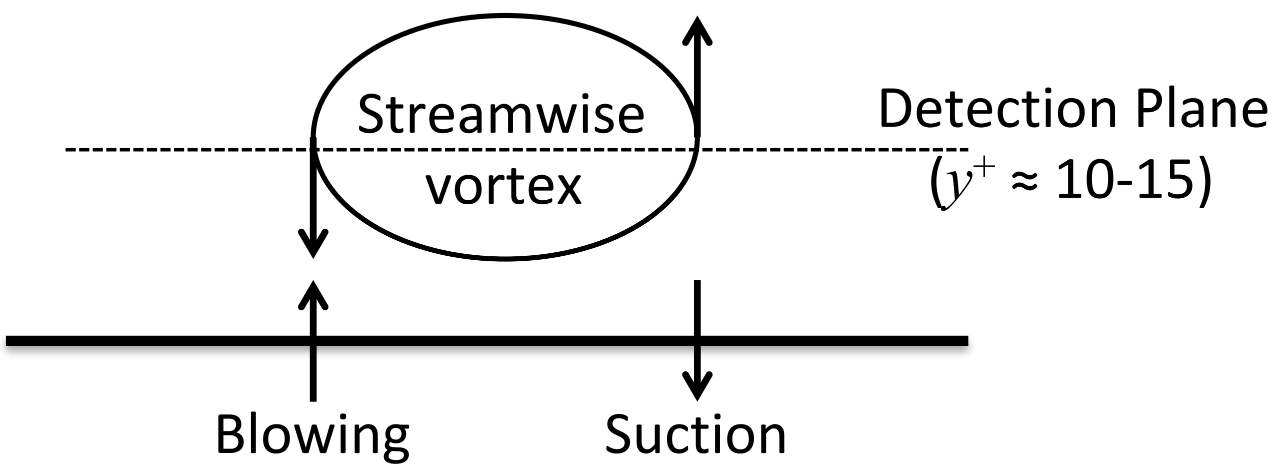
(Kim, 2011)

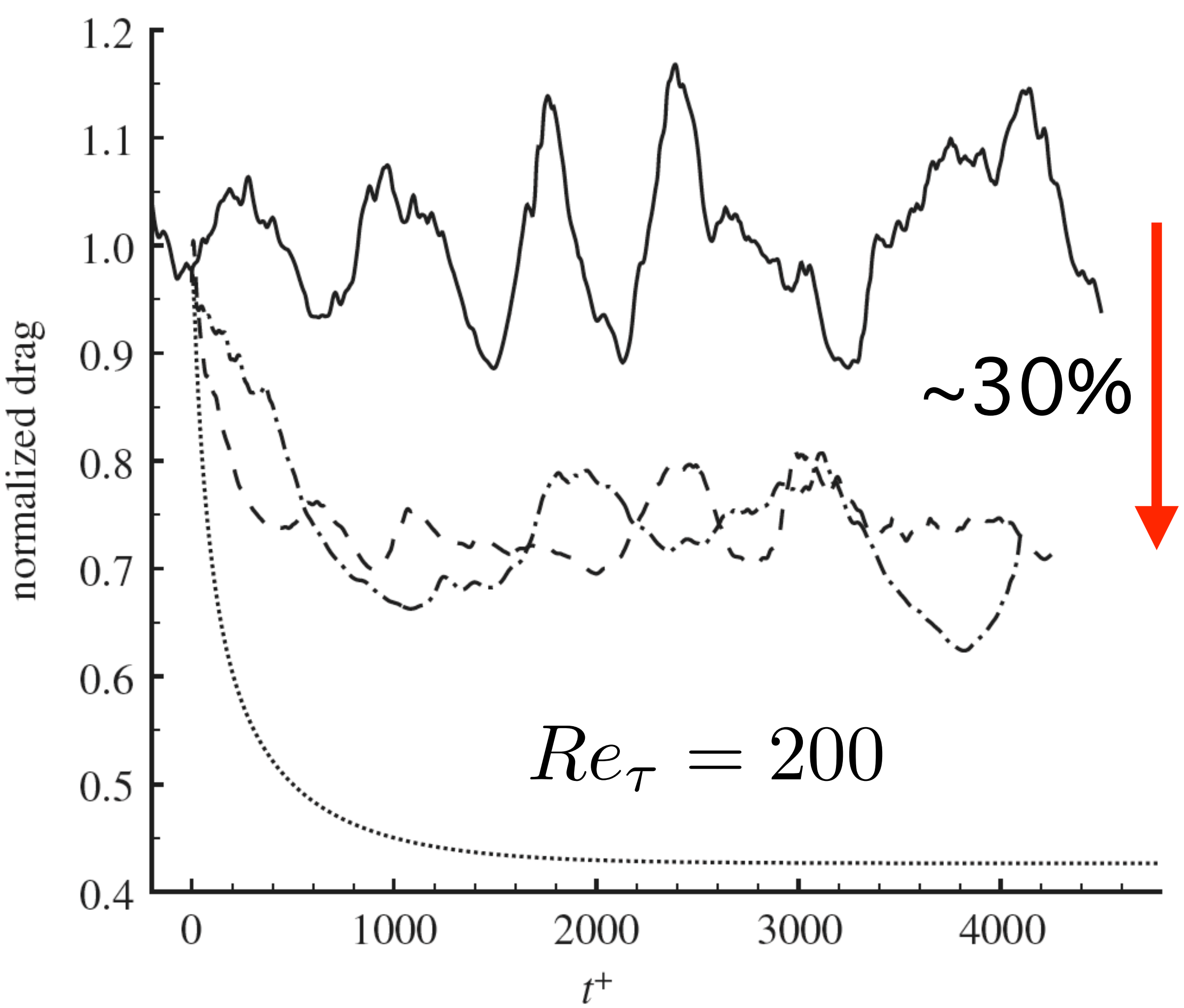


(Blackwelder, 1978)

Opposition Control of Turbulent BL

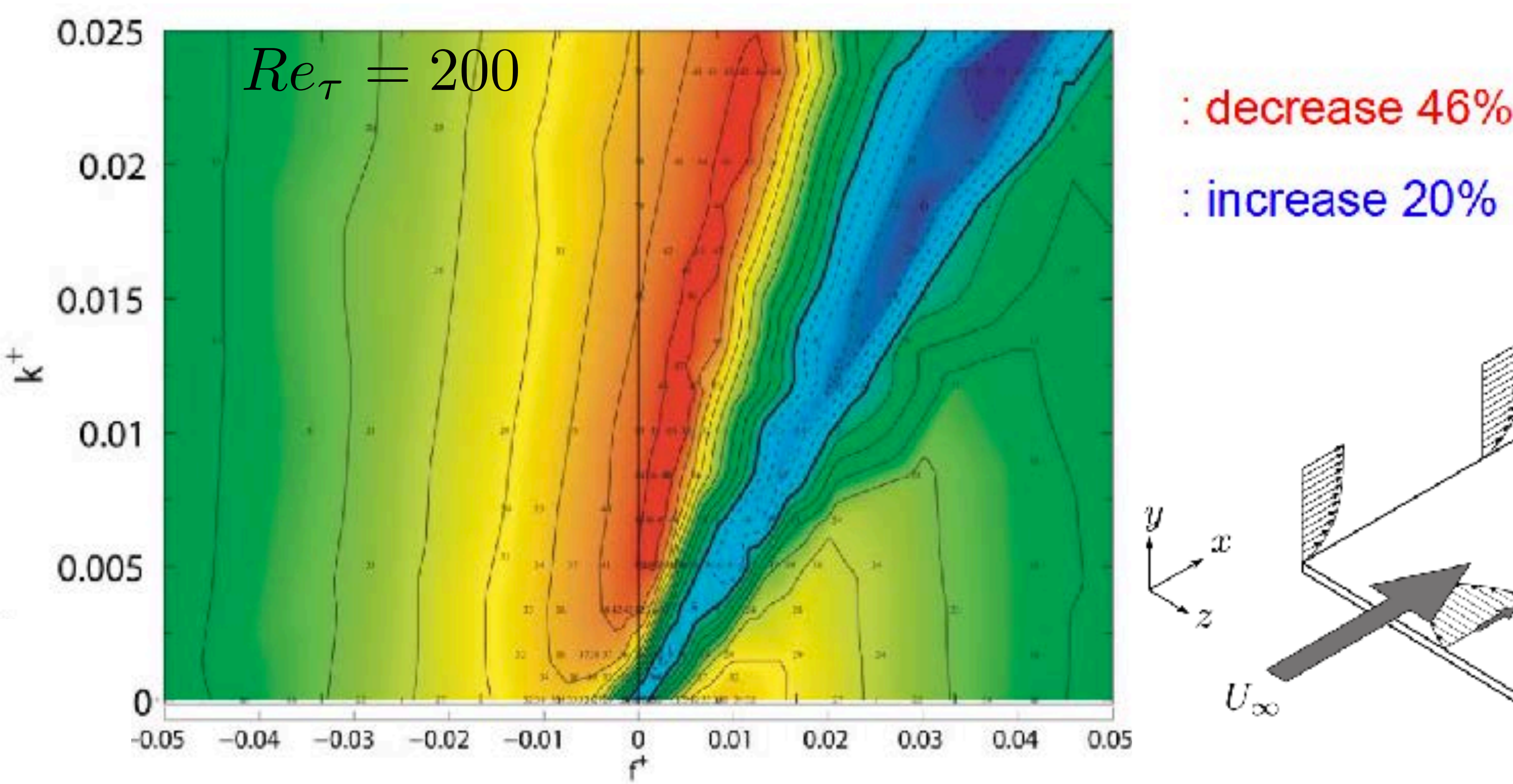
- Choi, Moin & Kim (1994) introduced concept of opposition control using DNS of channel flow
- Effective drag reduction via control of turbulence using active blowing and suction in DNS (Kim 2003 & 2011)

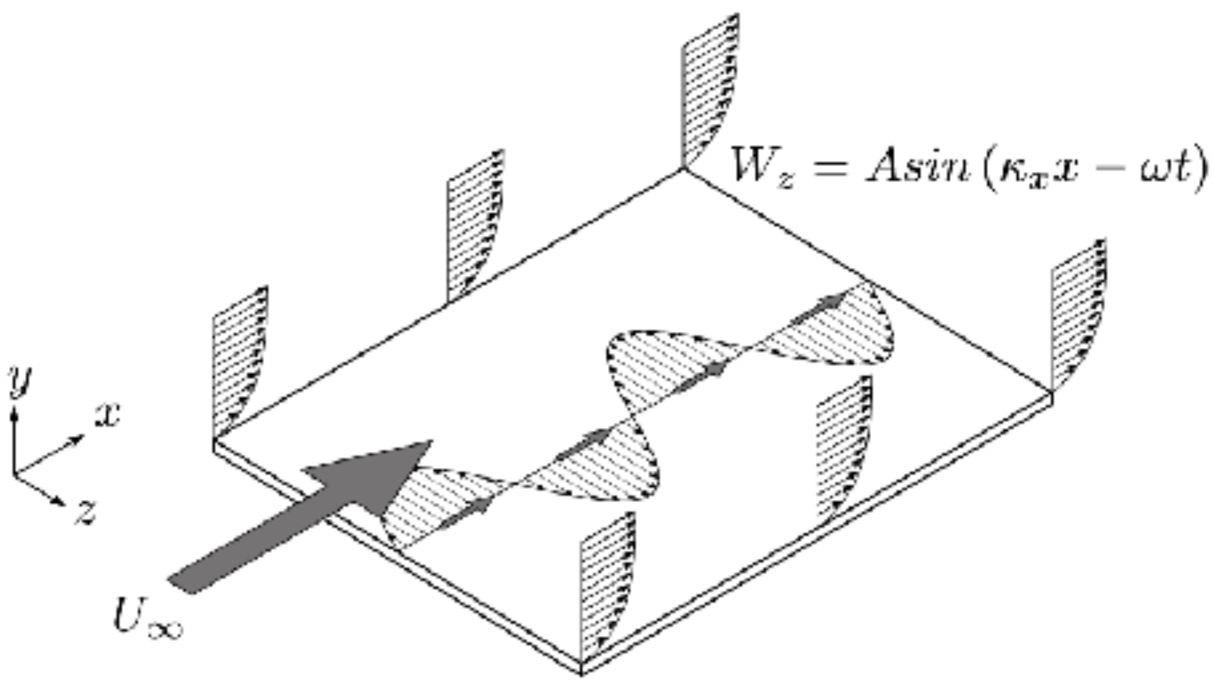




Spanwise Wall Oscillation

- Spanwise wall oscillations and traveling waves stabilize near wall flow
- Drag reduction of the order of 30-40% demonstrated numerically



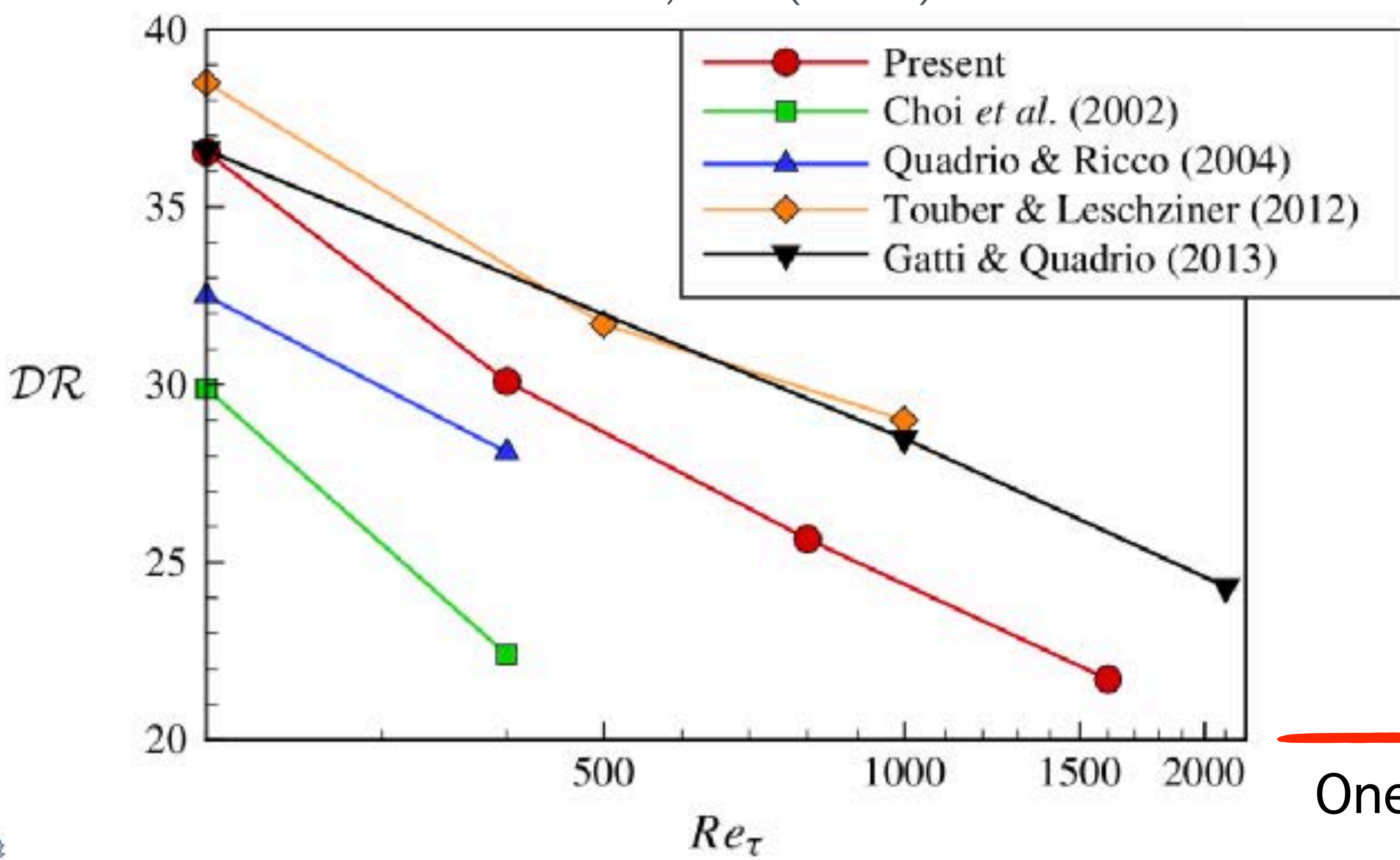


Quadrio et al. (2009)

Practical Issues

- Two key issues for implementation of these
  - physical scales at flight Reynolds numbers are very small
  - Reynolds number scaling

Hurst et al, JFM (2014)



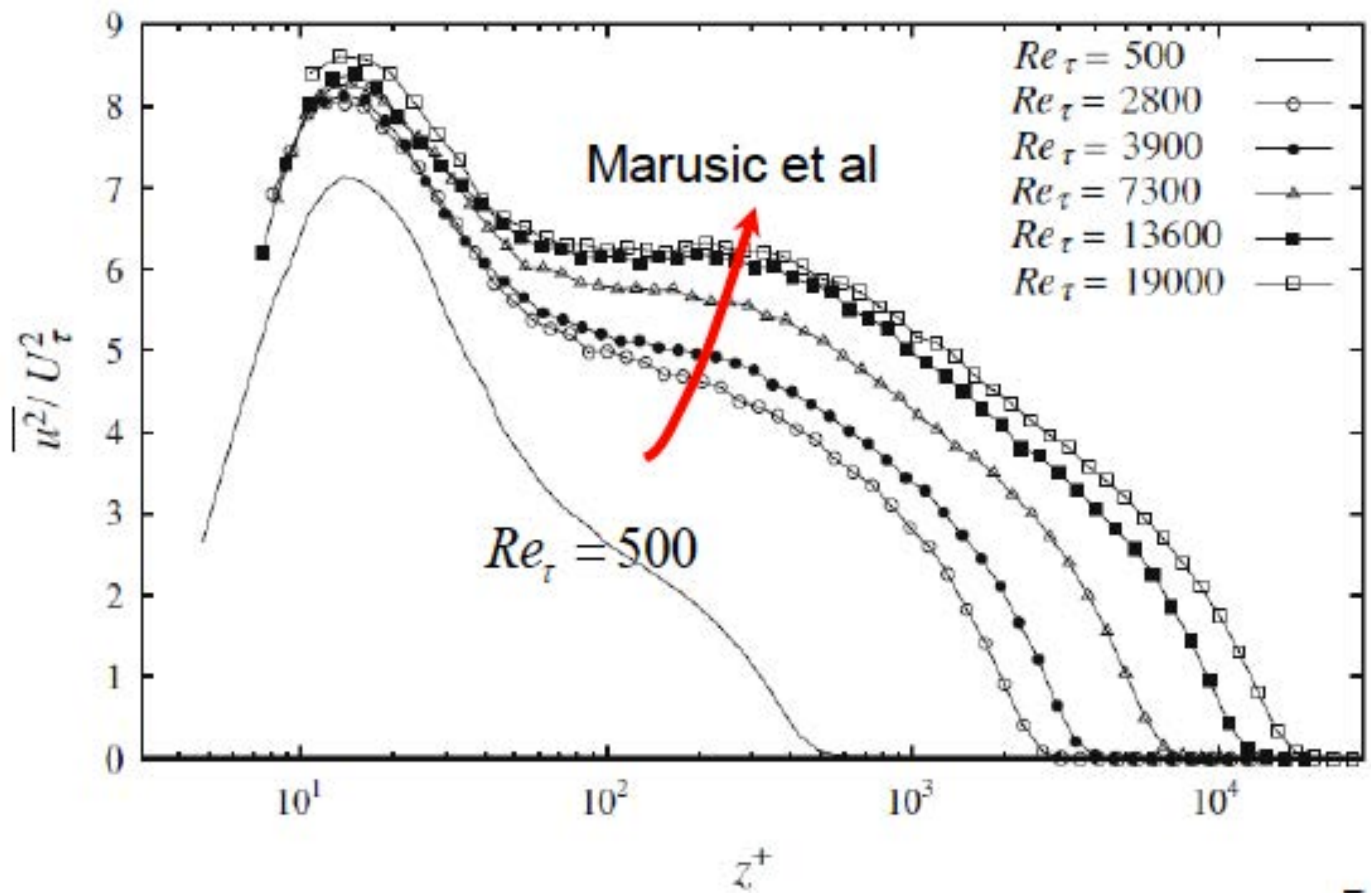
For commercial flight,

$$Re_\tau \sim 10^5$$

One more decade that way...

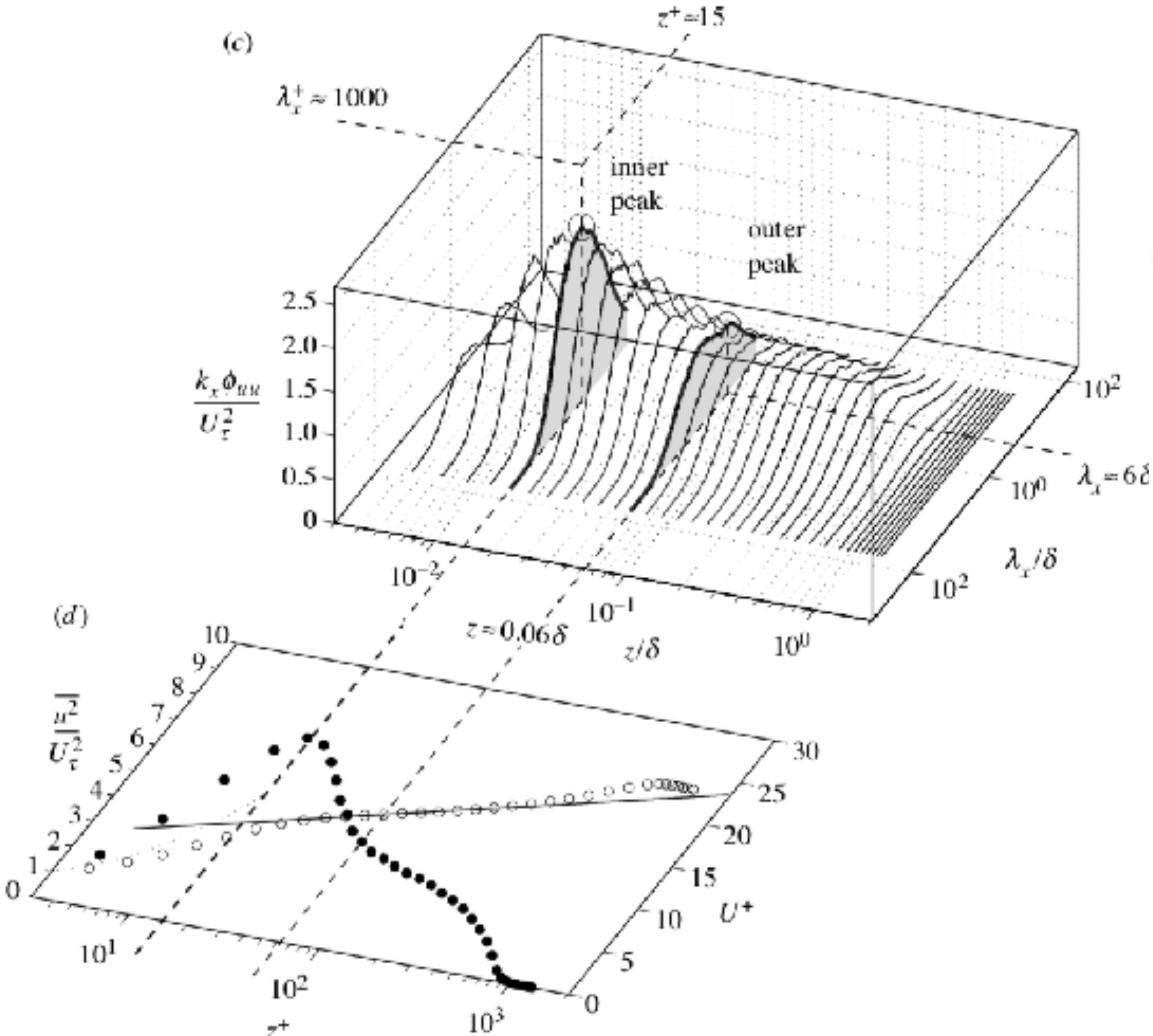
What is Changing?

- Energy content in boundary layer changes with Reynolds number
- Near-wall control might not work for high Re...

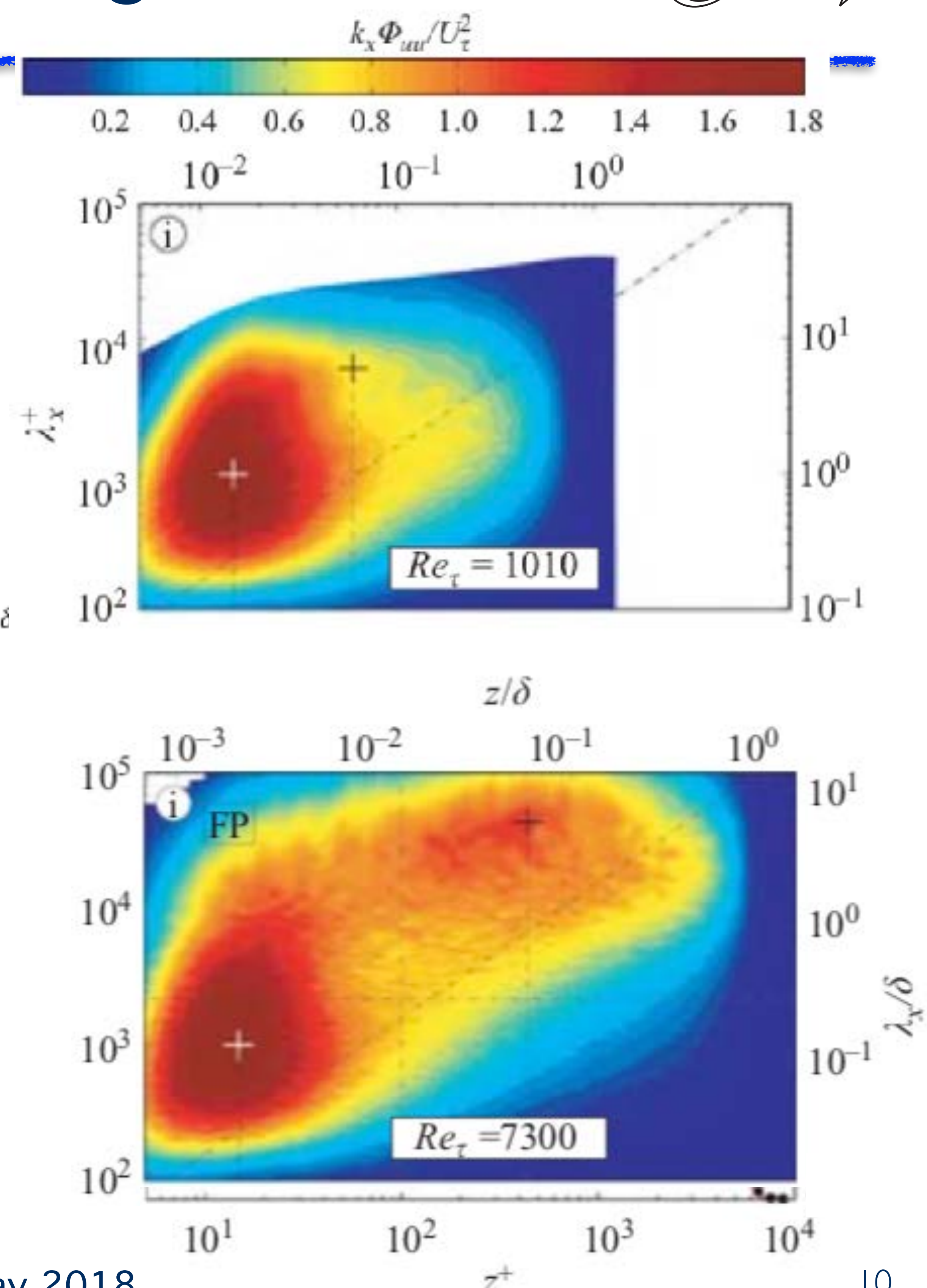


Increasing Importance of Large Scales

$Re_\tau = 1060$



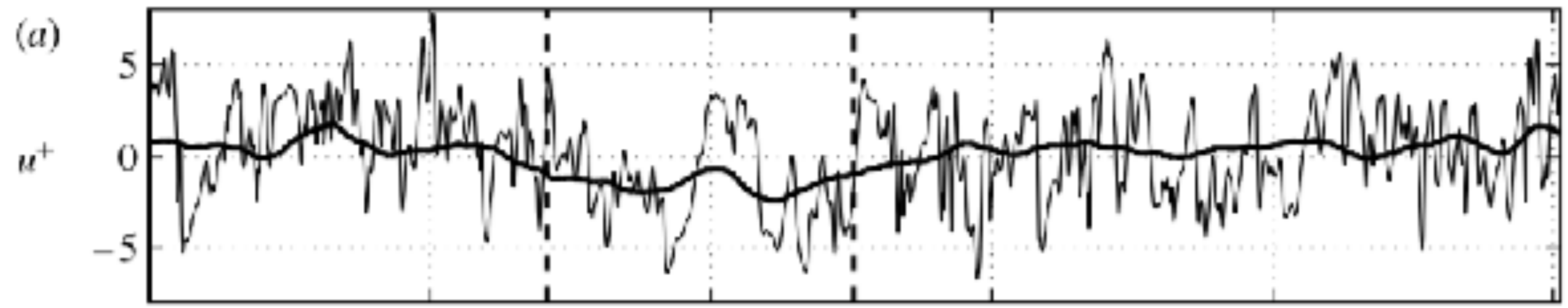
Hutchins & Marusic, Phil. Trans. R. Soc. A (2007)



Hutchins & Marusic, JFM (2007)

Top Down Interactions

$Re_\tau = 7030$

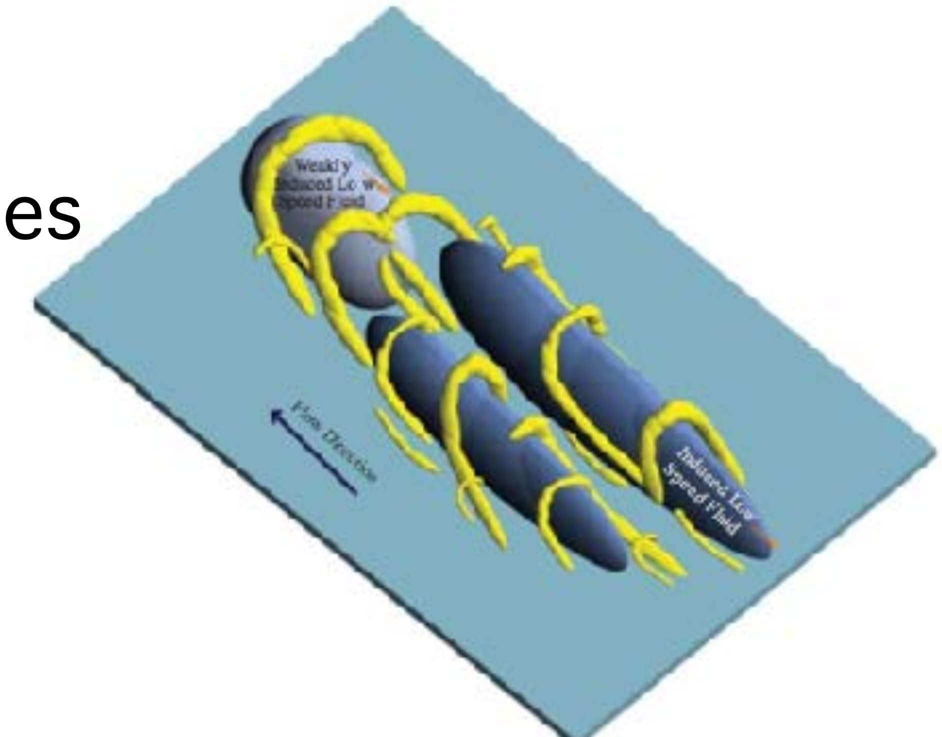


Presence of large scale structure in log-layer modulates small scale dynamics near the wall

Hutchins & Marusic, Phil. Trans. R. Soc. A (2007)

Skin Friction Reduction via Log-layer

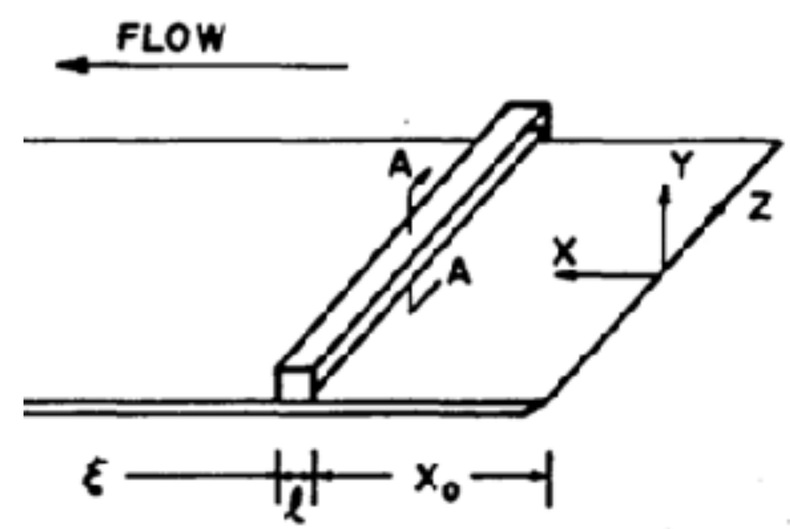
- Hairpin packets also important in log-layer
  - Might be easier to control - larger scales



Tomkins & Adrian, JFM, 2003

- Previous attempts at modifying these with physical obstacles have demonstrated persistent effects (order of 100 δ)

- So-called "Large-eddy break up" (LEBU) devices have shown net skin friction drag reduction of order 10-20% at the wall...
  - not enough to overcome drag of LEBU and effect of thickened boundary layer



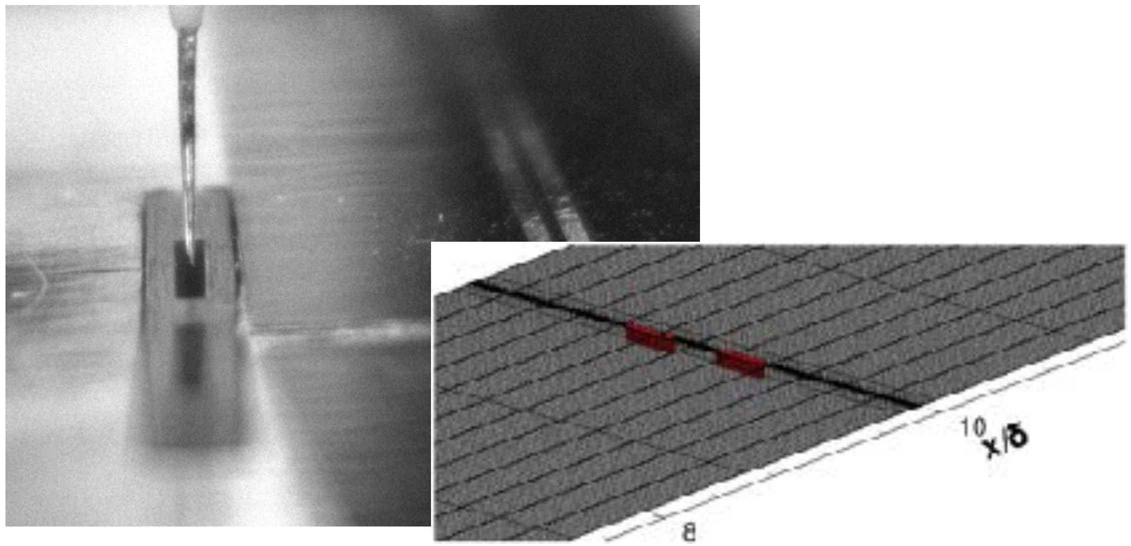
Corke et al., NASA Report (1981)

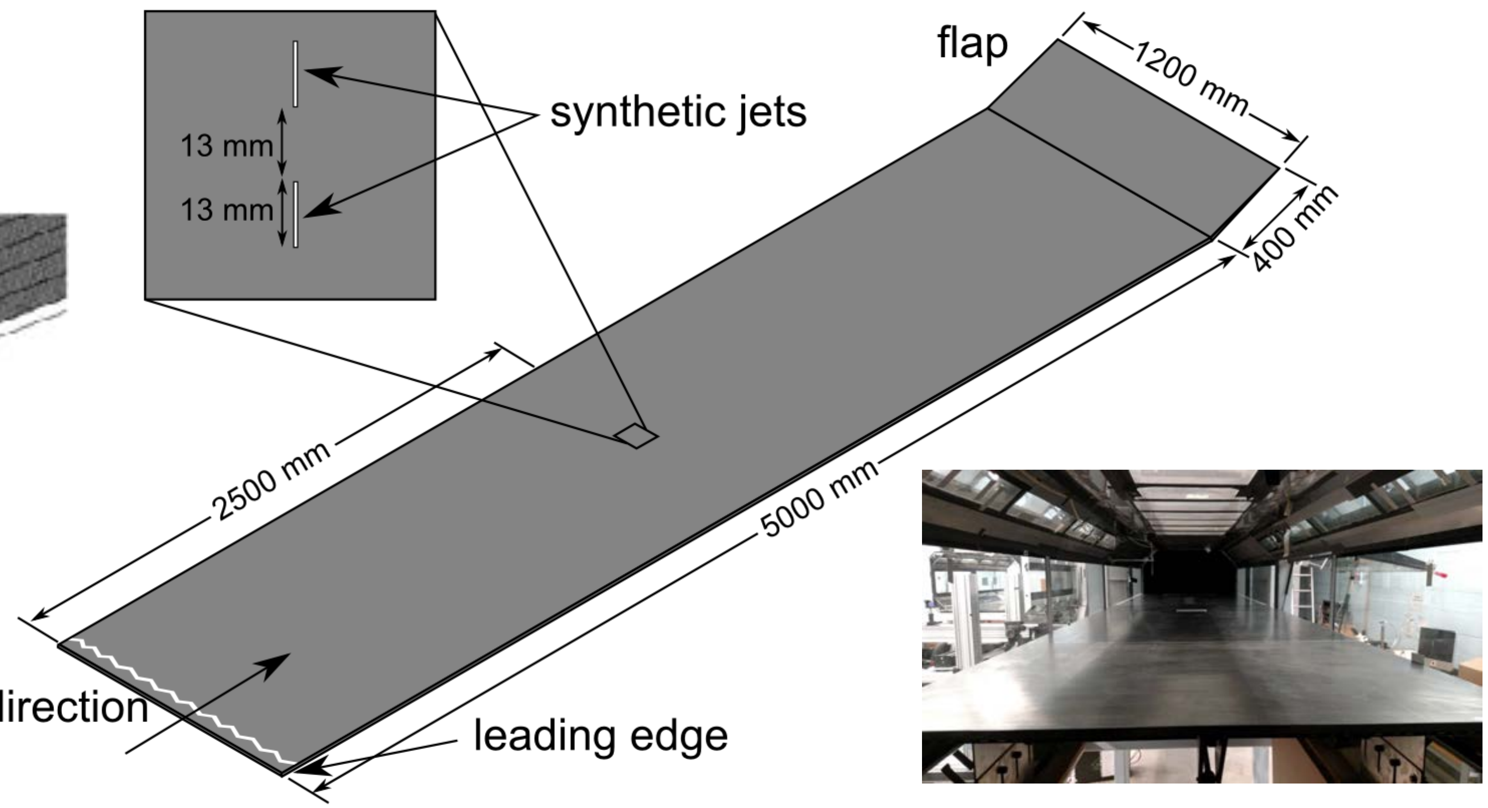
Beyond Steady Forcing

- Recent efforts at manipulating vortex packets using physical obstacles - this time 3D (e.g., humps, cylinders; in isolation or array)
- Steady forcing from physical objects limiting - missing time scale, lack of flexibility for changes in conditions

- Our current work aims to manipulate vortex packets in the log-layer using an array of synthetic jets
- Combined experimental and numerical techniques used to approach problem

Base Flow Conditions





Base flow

$$U_\infty = 10 \text{ m/s} \quad Re_\tau = 1070$$

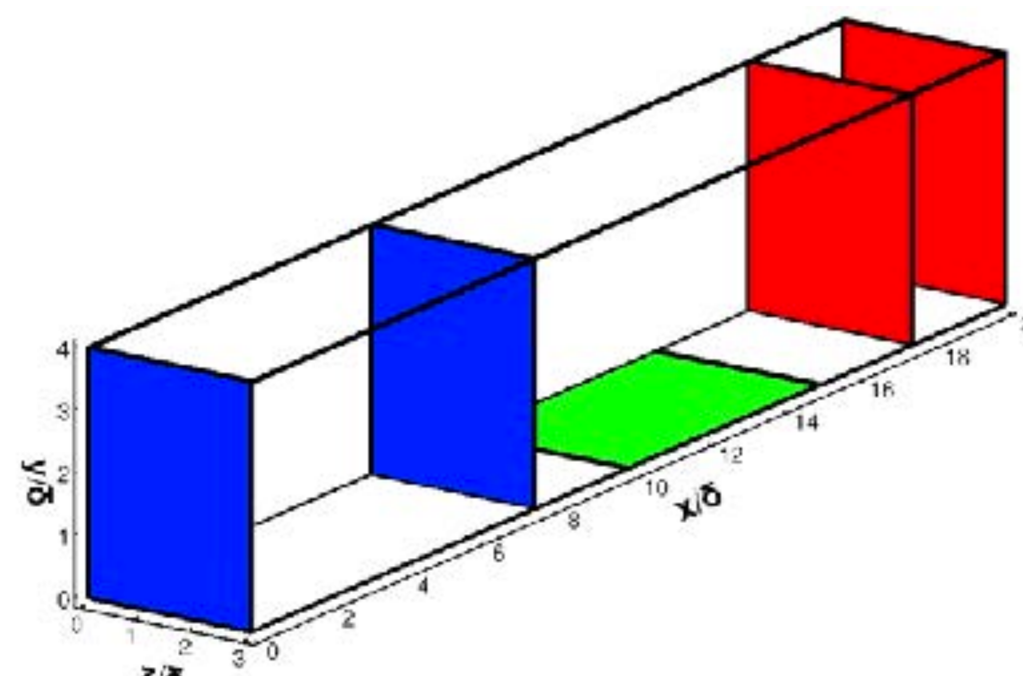
$$\delta = 42.5 \text{ mm}$$

Forcing parameters

$St = \frac{f\delta}{U_\infty}$ blowing frequency

$r = \frac{U_j}{U_\infty}$ blowing ratio

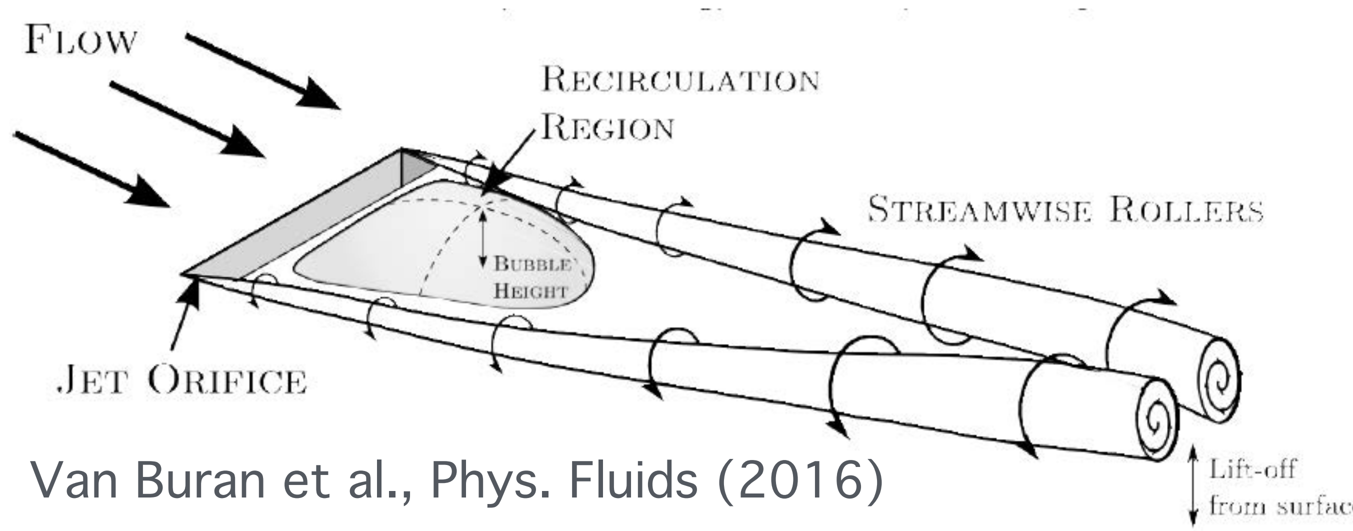
$\Delta z = 0.3\delta$ actuators spacing



Structure of Induced Flow

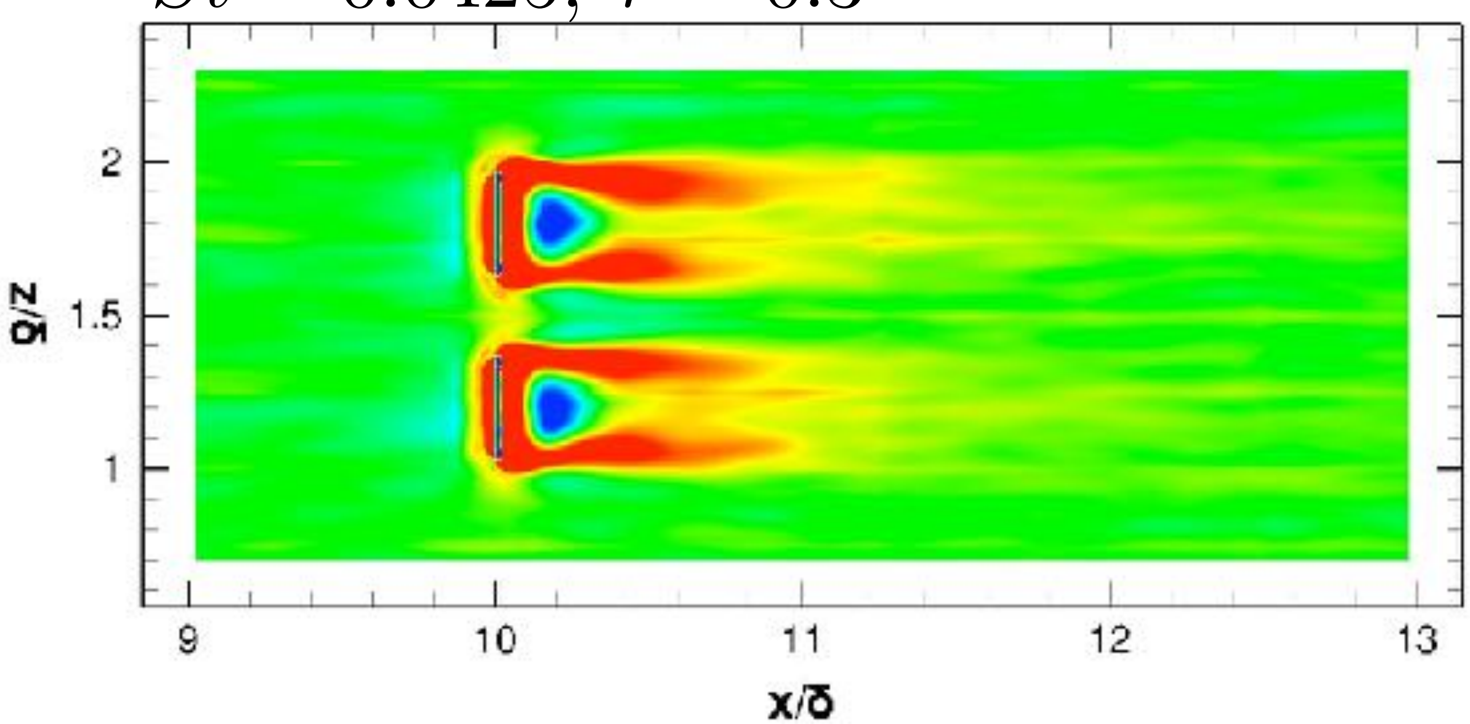
Mean flow structure induced by the jet include:

- counter rotating vortices from nozzle edge
- recirculating bubble (sometimes)



Van Buran et al., Phys. Fluids (2016)

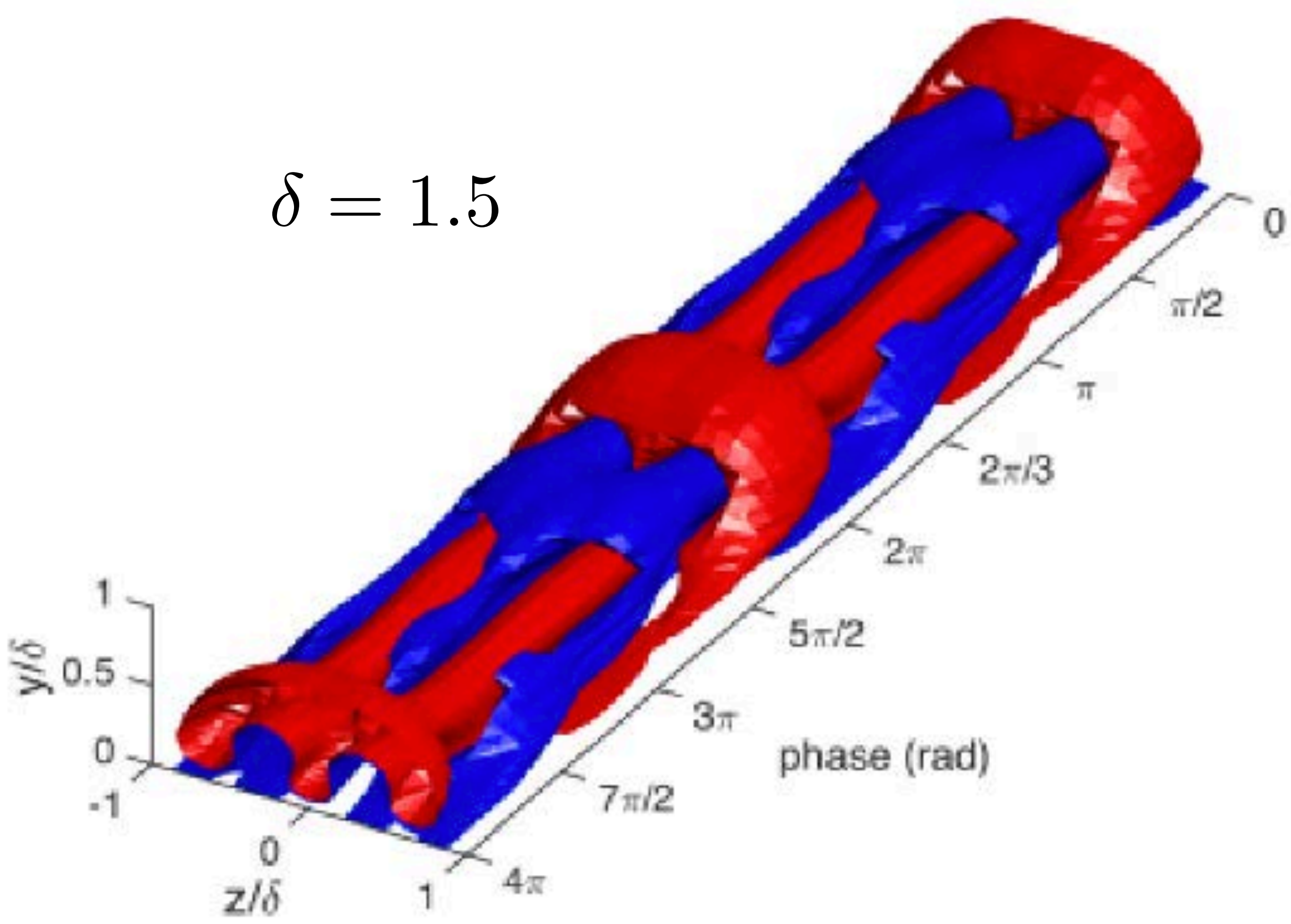
$St = 0.0425,\ r = 0.3$



Time Dependence of Forcing

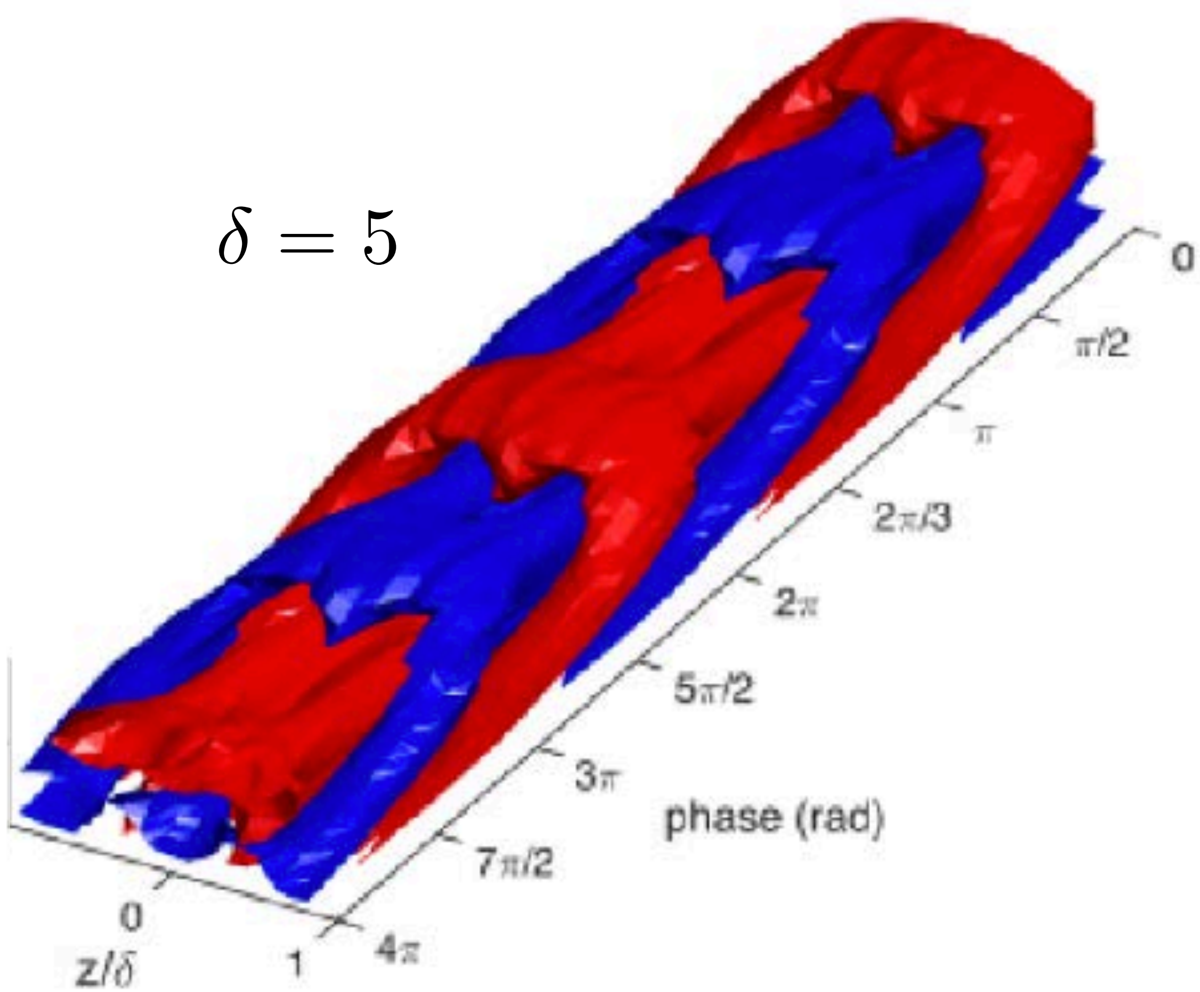
Similar structure from the mean, plus a leading high speed pocket

$\delta = 1.5$



(a) $St = 0.5$, $r = 0.88$.

$\delta = 5$



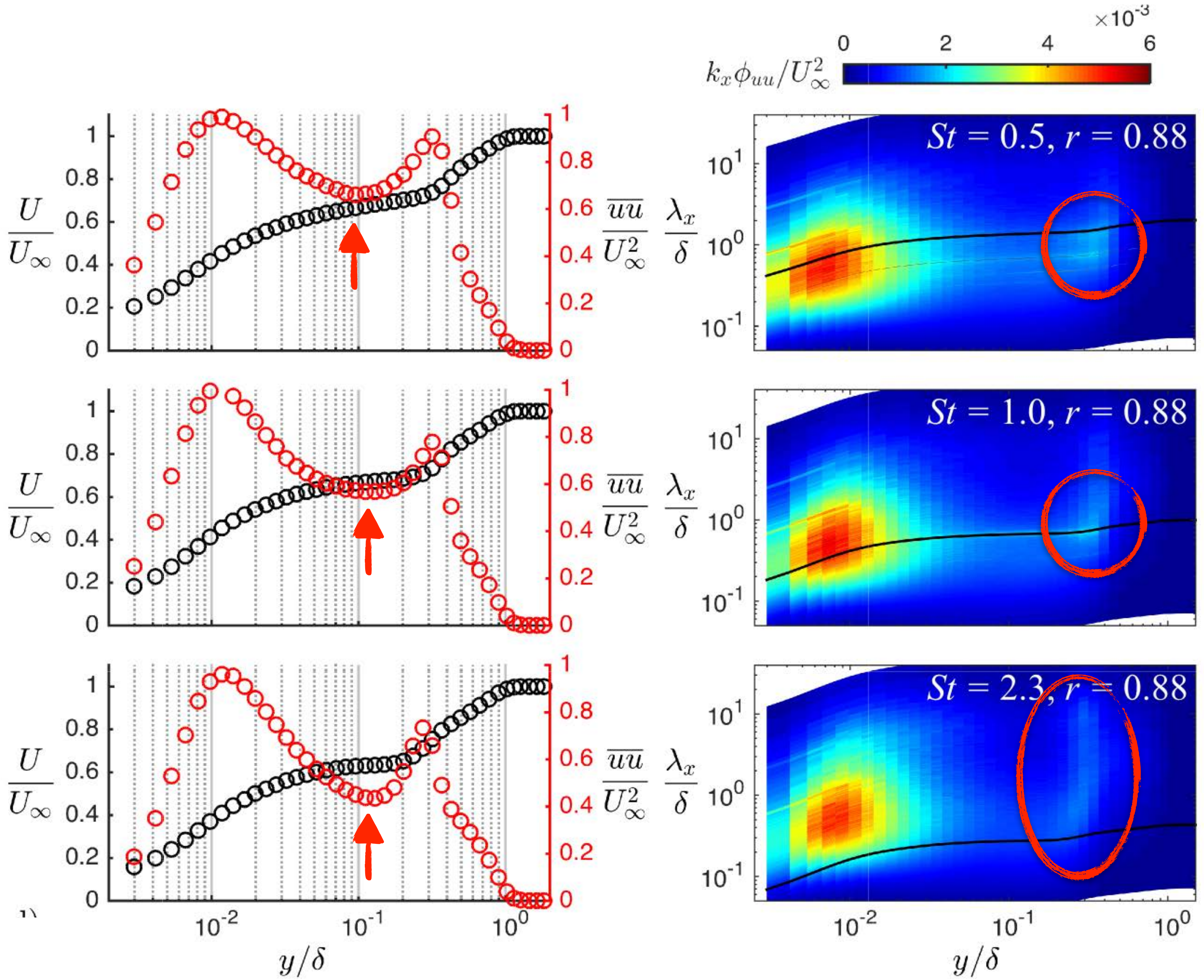
(a) $St = 0.5$, $r = 0.88$.

Effects of Forcing Frequency

Larger effect on log-layer with lower Strouhal numbers

constant r

increasing St

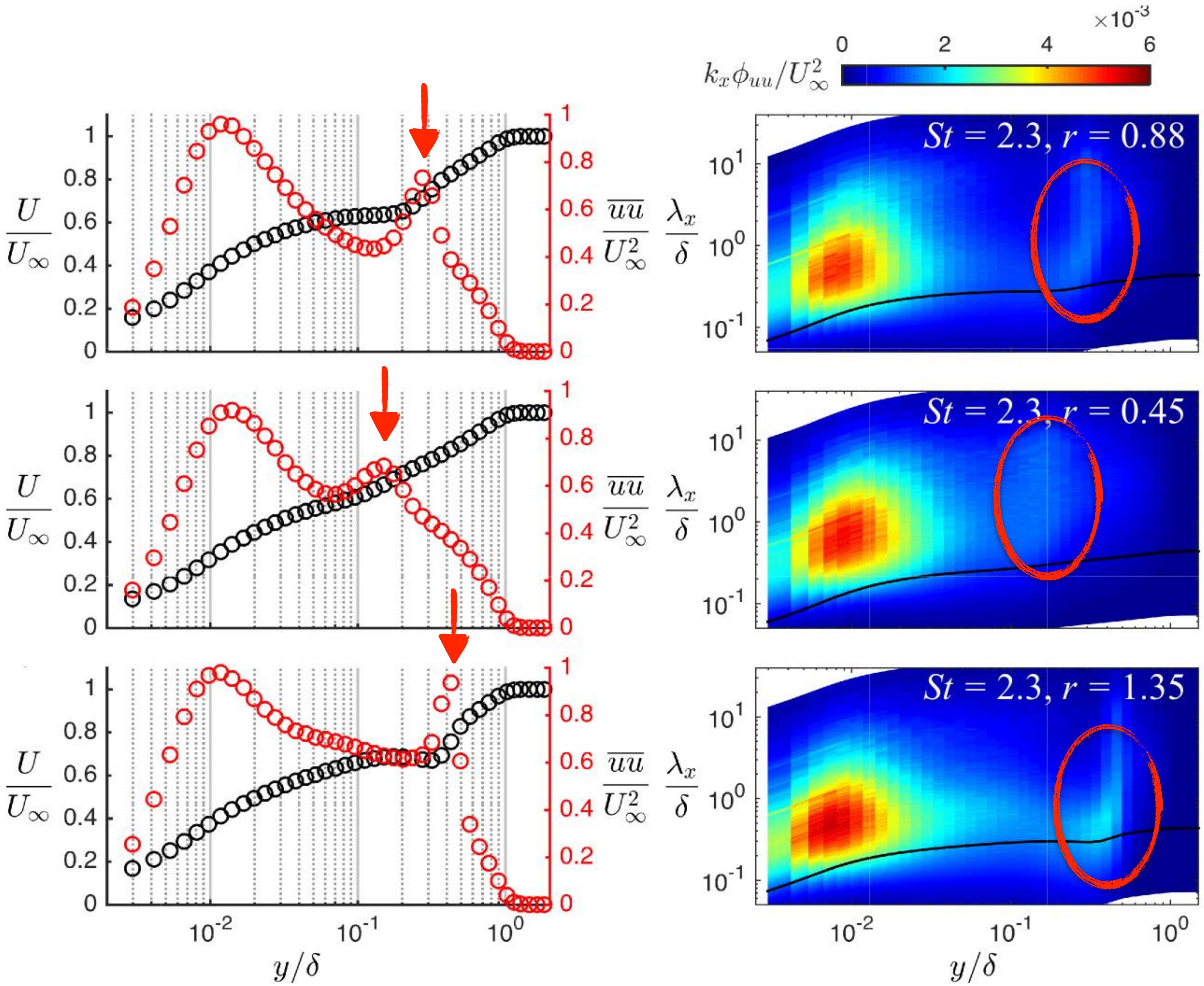


Effects of Forcing Amplitude

Increased penetration with higher blowing ratio

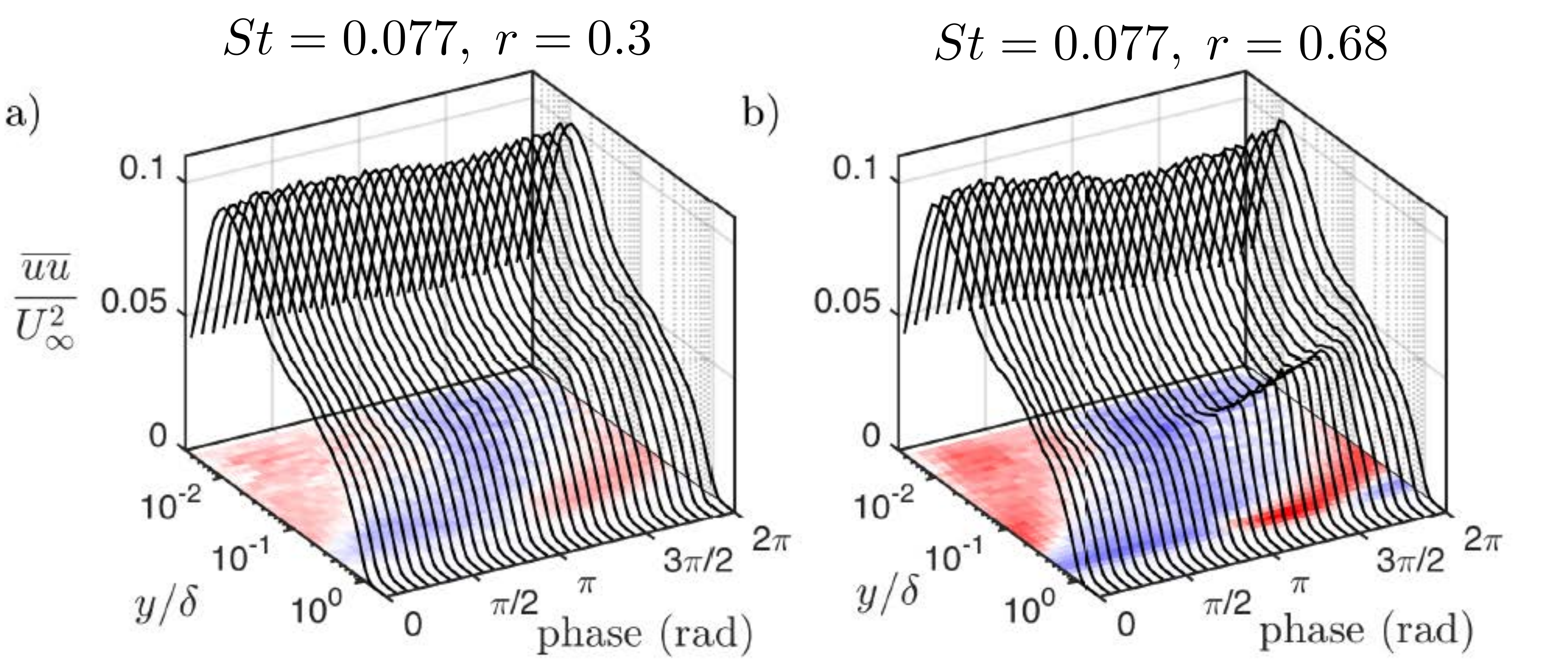
constant St

varying r



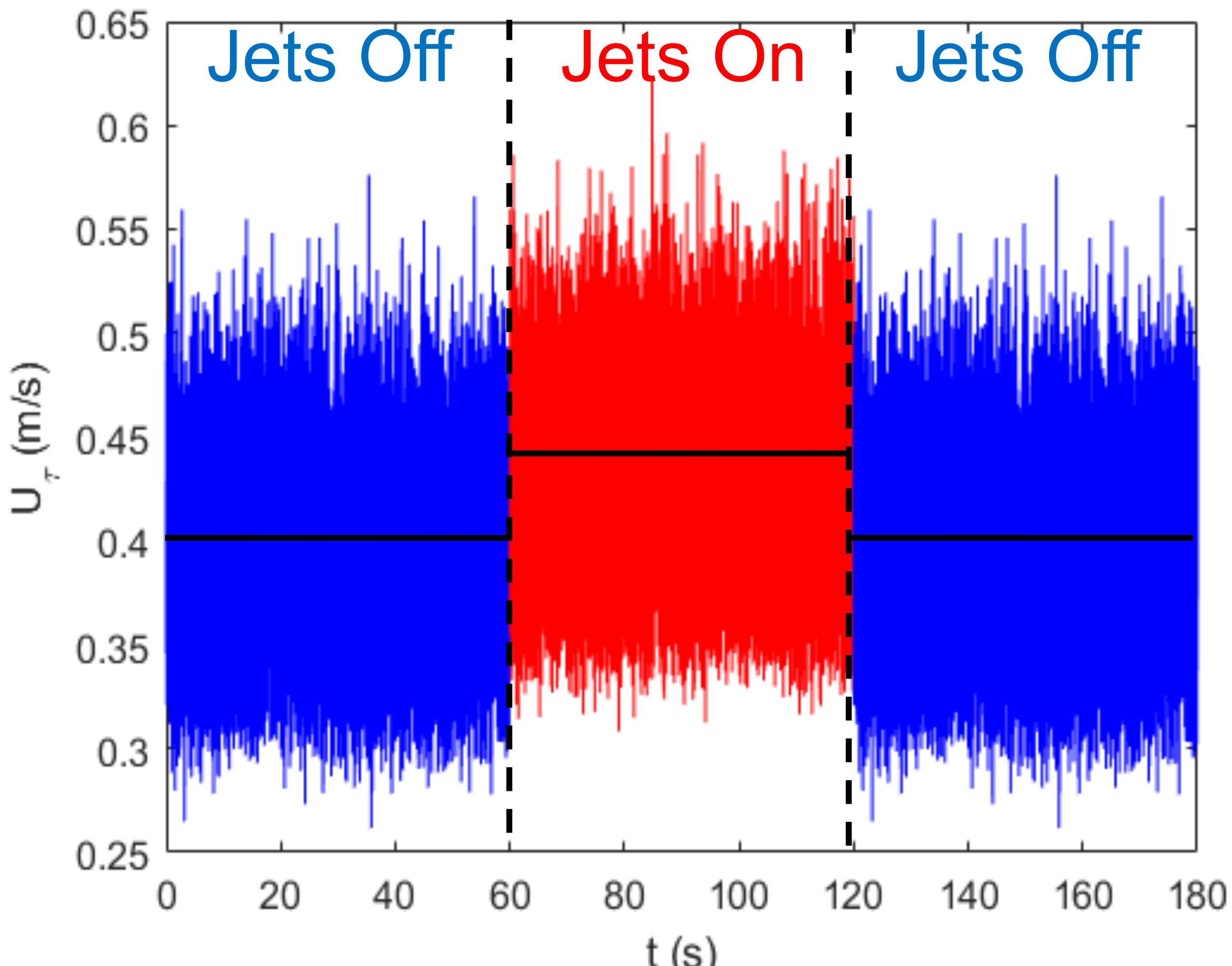
Phase Information

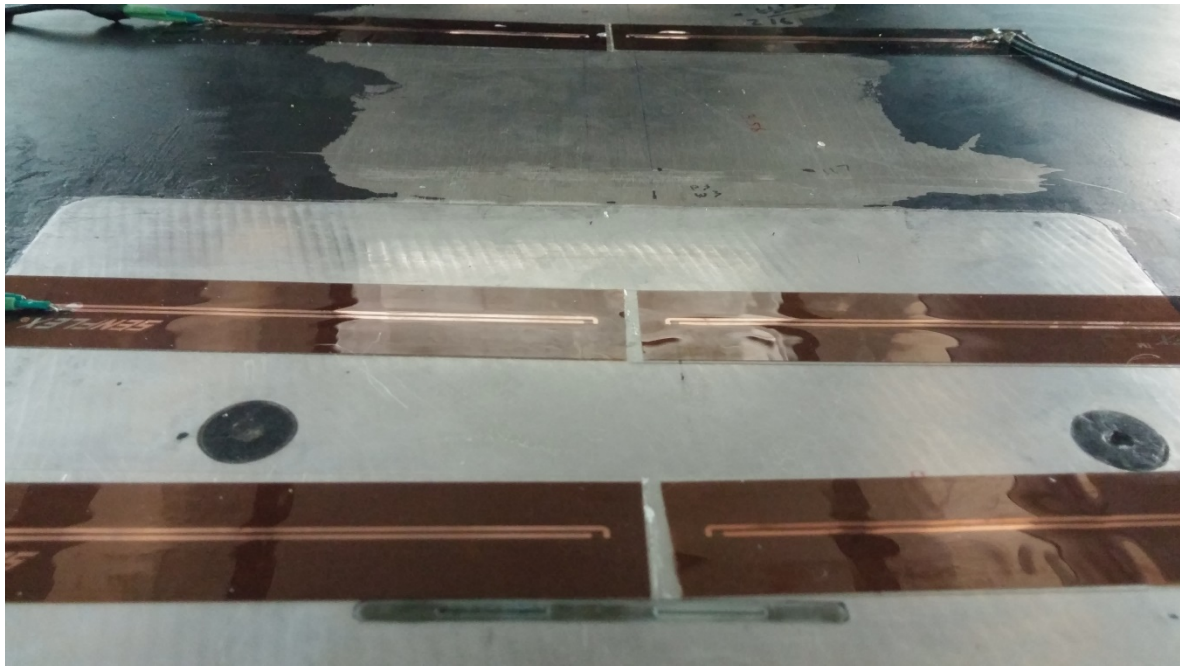
- Amplitude modulation of near-wall peak due to structures imparted by synthetic jet
- Effect increases with increasing blowing ratio

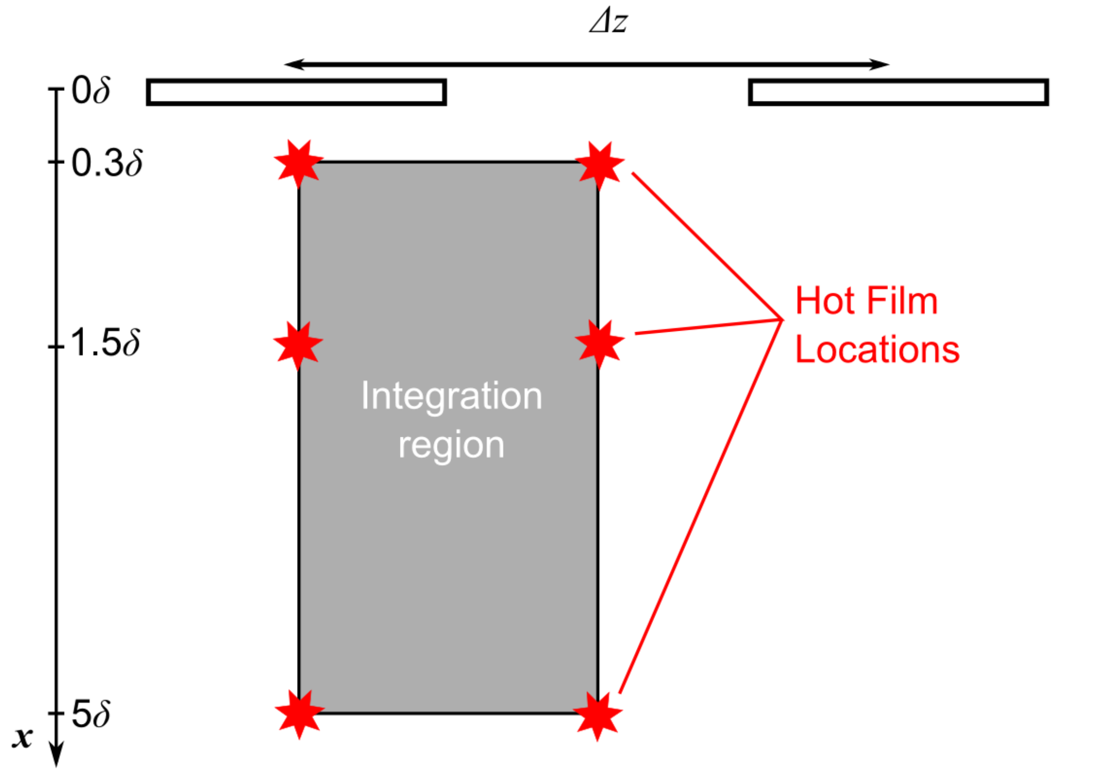


Skin Friction Measurements

- Hot-films used to measure skin friction at 6 locations
- Coarse spatial measurements for fine study of forcing parameter space





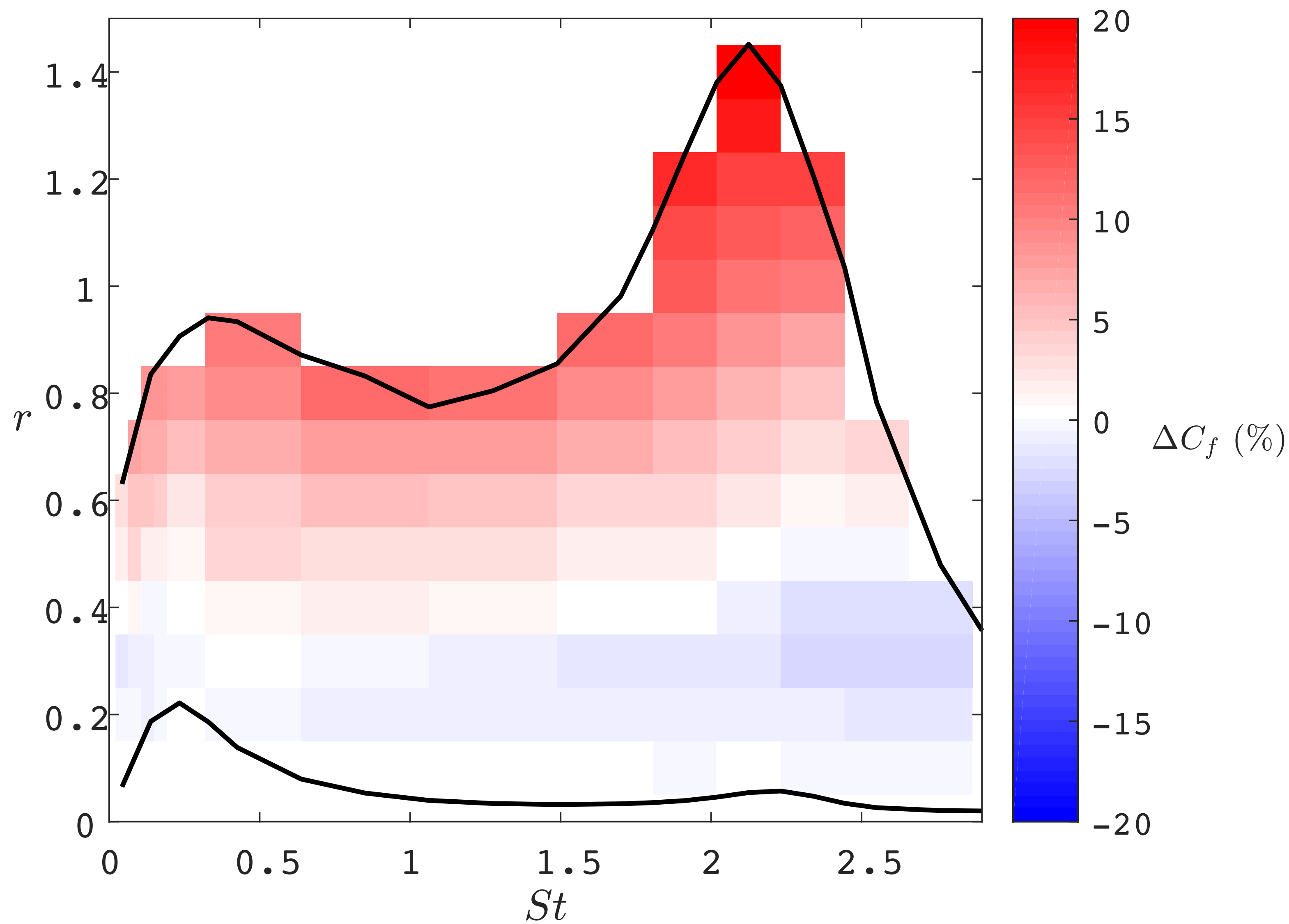


Effect of Forcing on Skin Friction

- Average of four most downstream sensors (plus some caveat)

- Region of "lower" skin friction at low forcing amplitude

- What is changing in the boundary layer dynamics?



Conclusion

- Best way to control turbulent boundary layer at flight Reynolds number might be different from low Reynolds number case
- Increasing importance of log-layer structures could provide a pathway to changing the dynamics of the boundary layer and reduce skin friction
- Synthetic jets were demonstrated to be effective at imposing a new structure to log-layer turbulence

- What is the nature of the interaction between the jet flow and turbulence?
- How to optimize this interaction for drag reduction?
- Can we be a bit smarter?
    - Would some knowledge of present structures help?

Thanks for your attention!
Questions?