Interaction between a synthetic jet and turbulent boundary layers

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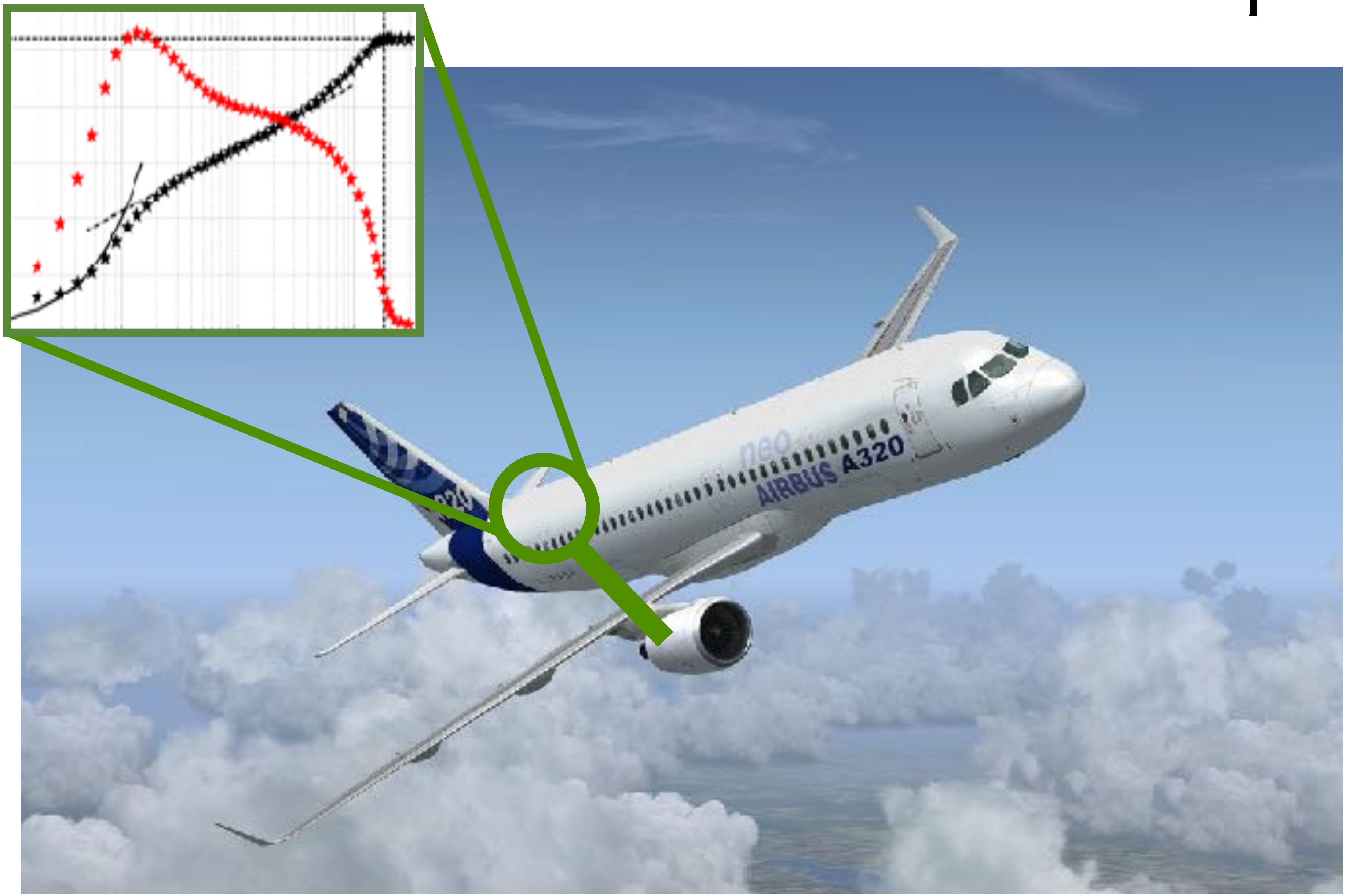
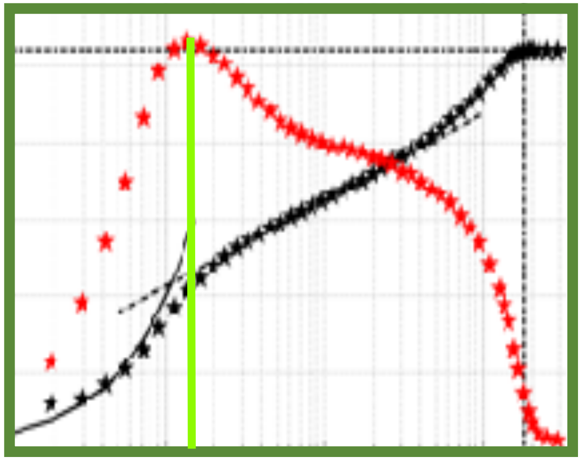
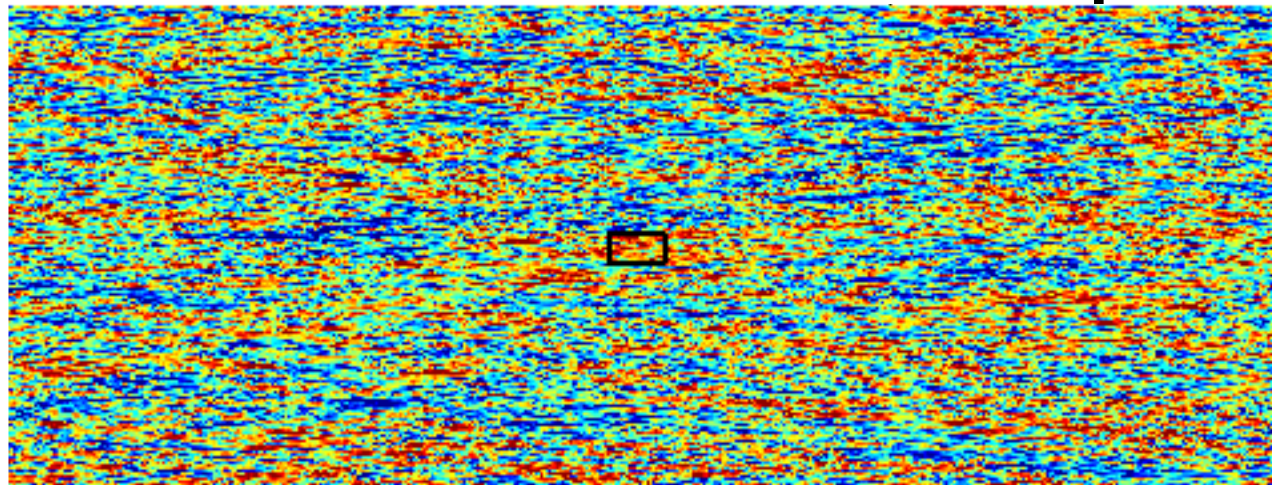
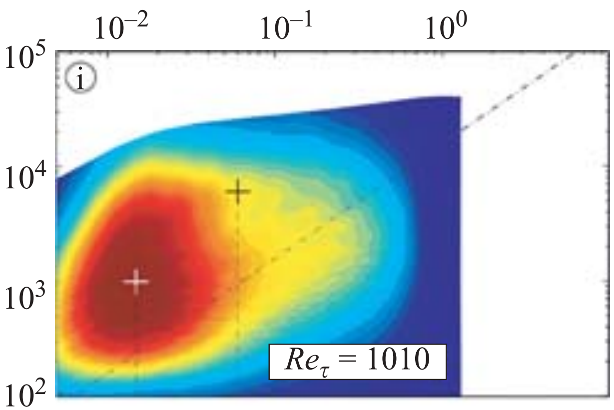

AIRBUS A320

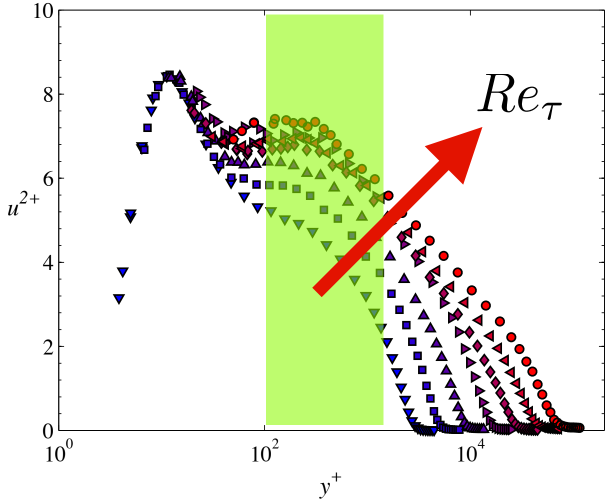


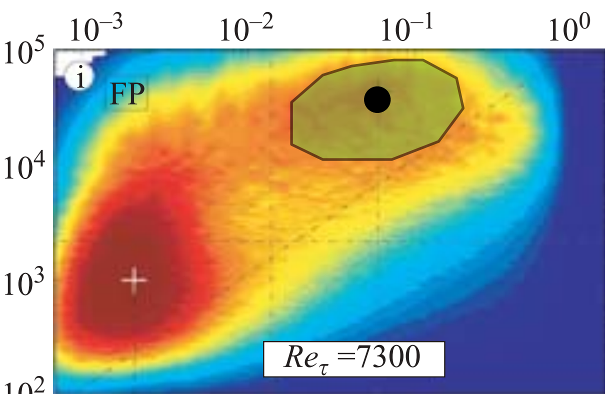




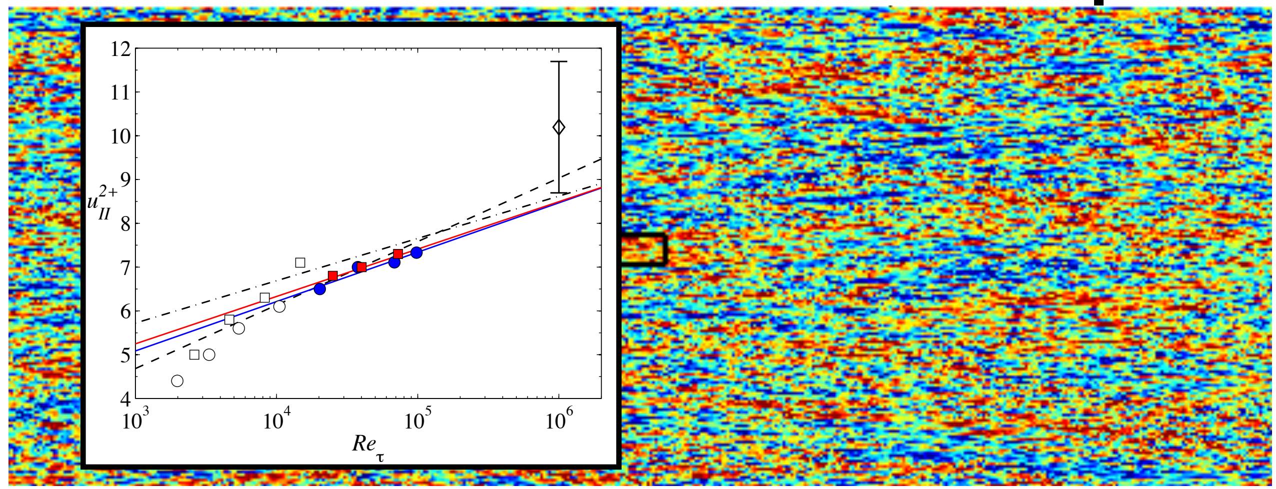
Near-wall control is the only demonstrated strategy

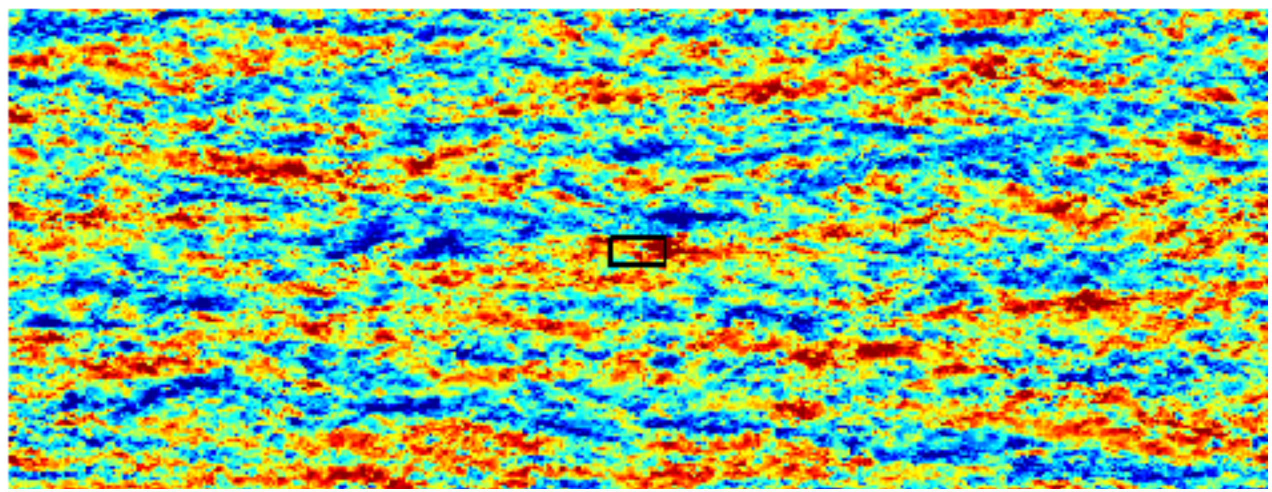
Valikivi, Hultmark & Smits (2015)





Hutchins & Marusic (2007)

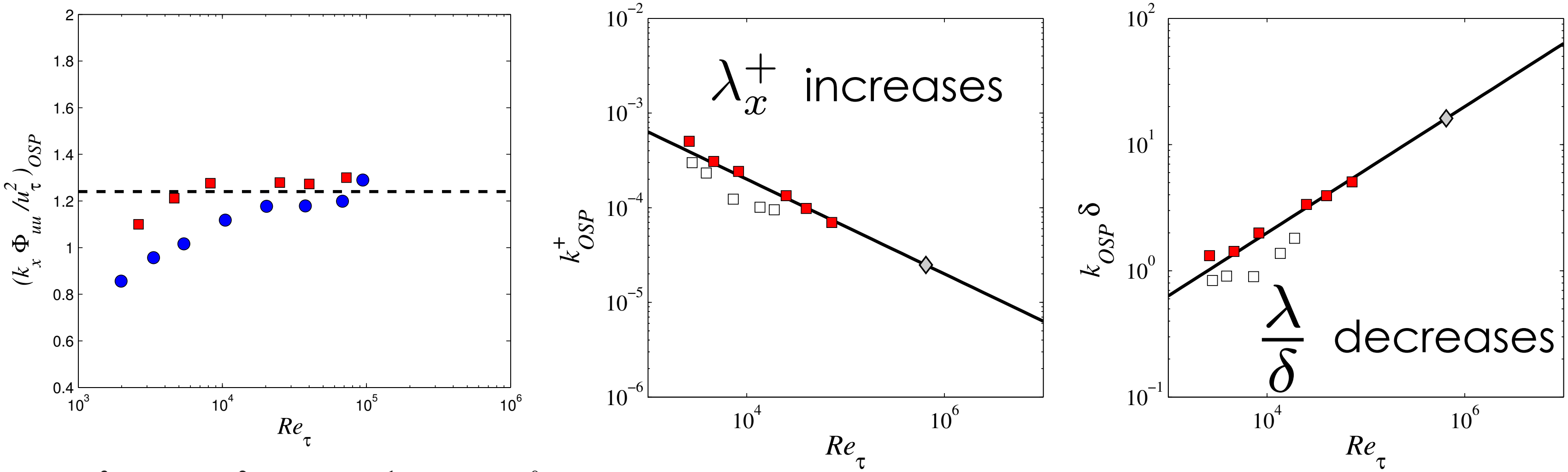


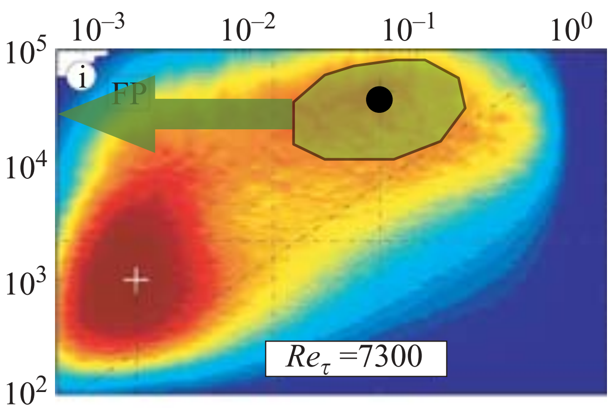


$\lambda^+_{SS} \approx 1000 \qquad \lambda_{LS} \approx \delta$

$$Re_\tau = \frac{\delta U_\tau}{\nu} \qquad Re_\tau \approx 1000,\ \frac{\lambda_{LS}}{\lambda_{SS}} \approx 1 \qquad Re_\tau \approx 5000,\ \frac{\lambda_{LS}}{\lambda_{SS}} \approx 5$$

Valikivi, Ganapathisubramani & Smits (2015)





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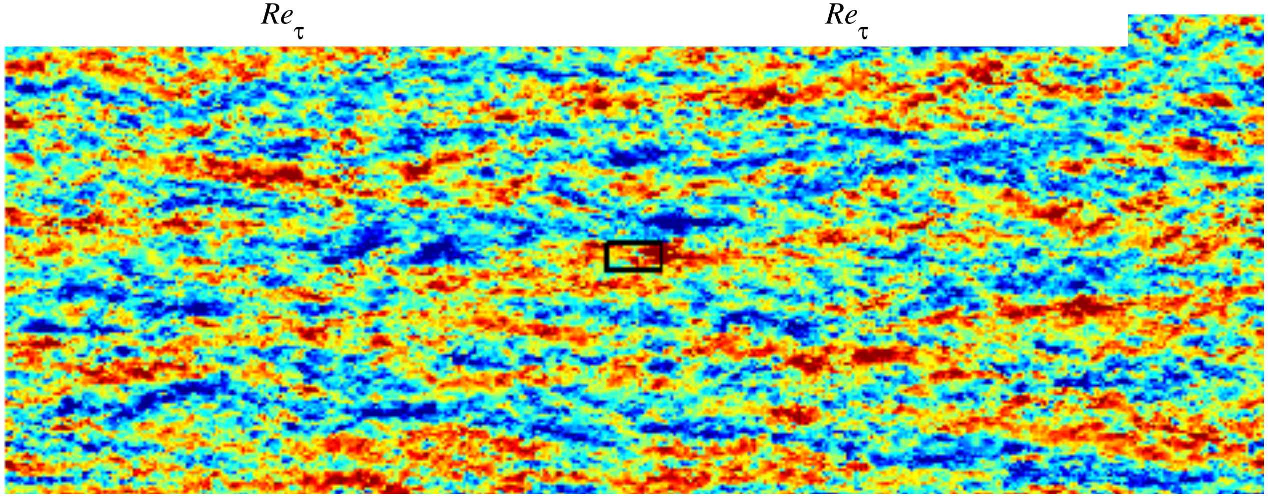

Can we control this footprint to reduce drag?

If so, what are the actuator requirements?

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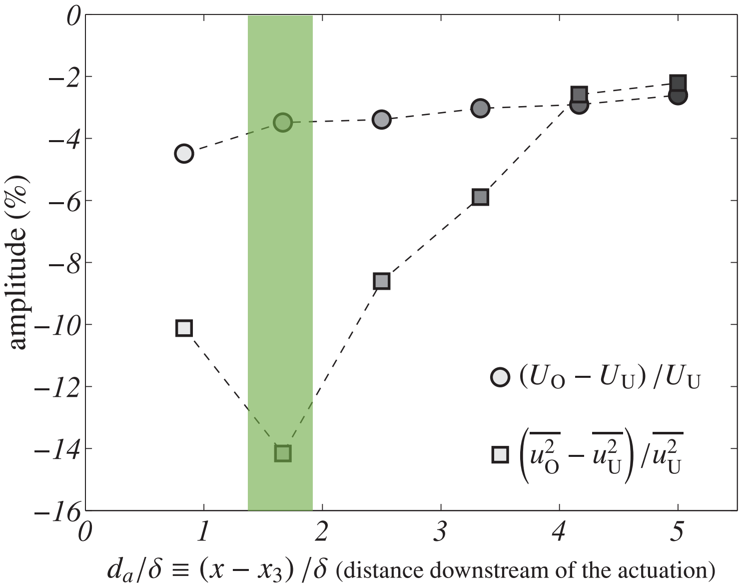
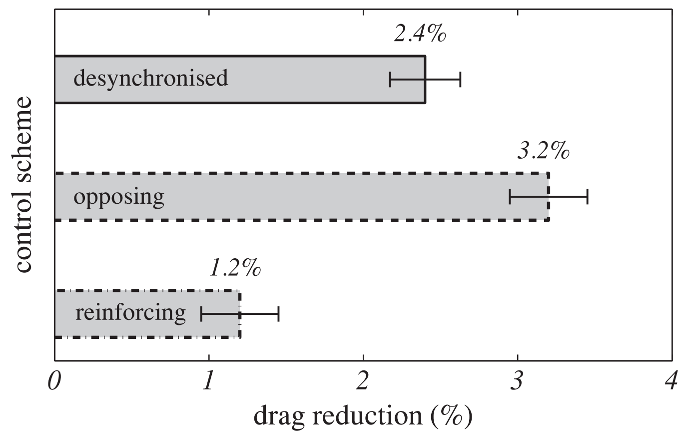
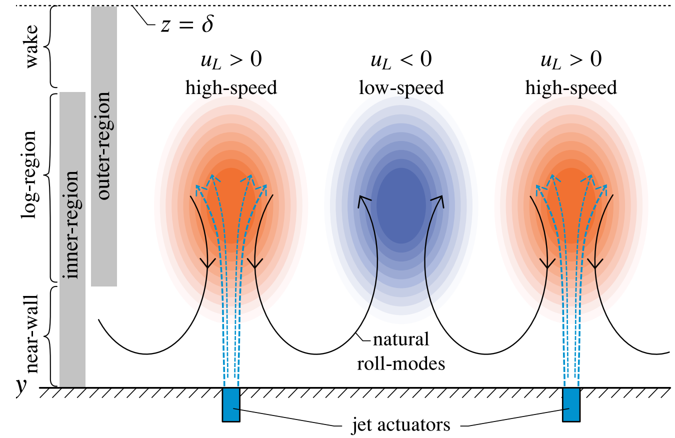
Skin-friction drag reduction in a high-Reynolds-number turbulent boundary layer via real-time control of large-scale structures

M.R. Abbassi, W.J. Baars*, N. Hutchins, I. Marusic

Department of Mechanical Engineering, The University of Melbourne, Melbourne 3010, Victoria, Australia







Effectiveness:
- **jet trajectory**
- **jet decay**

Can we control this footprint to reduce drag?

If so, what are the actuator requirements?

How does a synthetic/pulsed jet evolve in a turbulent boundary layer?

Jet trajectory: Facility

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High-Reynolds number boundary layer wind tunnel

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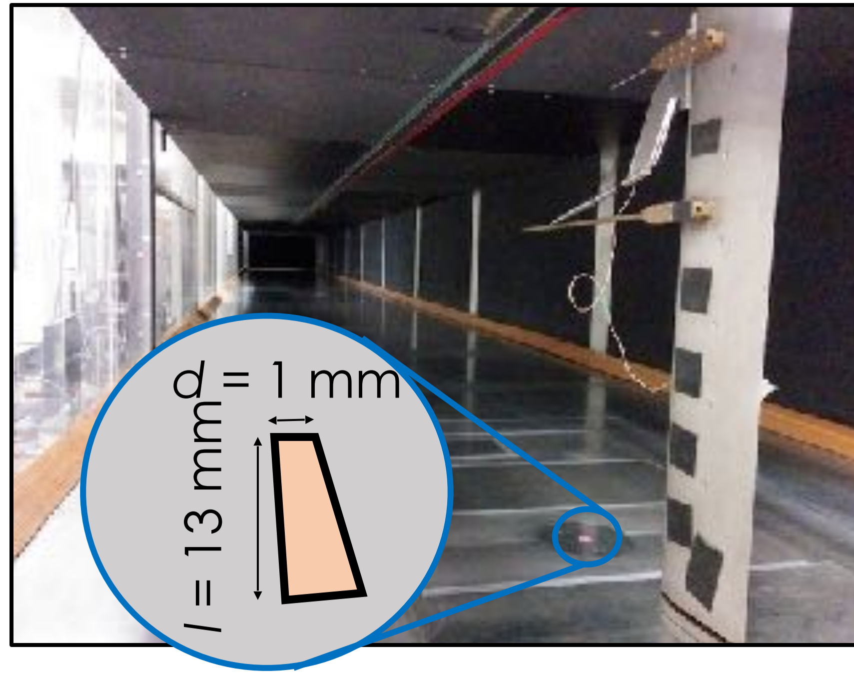
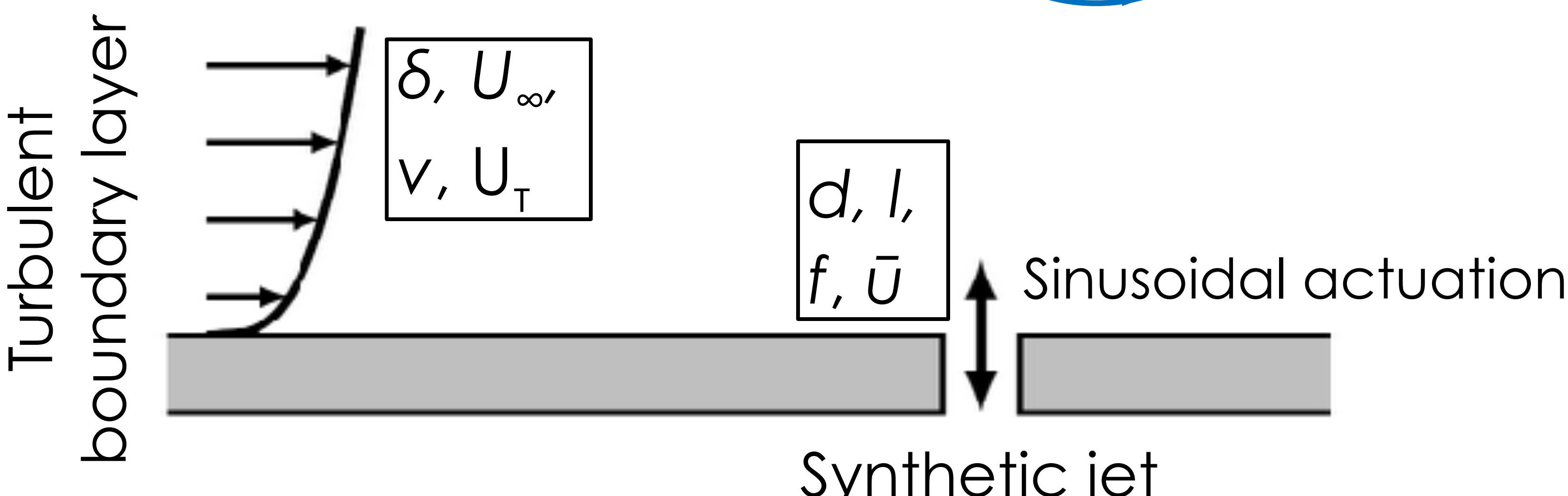
0.9 m x 1.9 m x 27 m

Re_τ: 1000 - 25000





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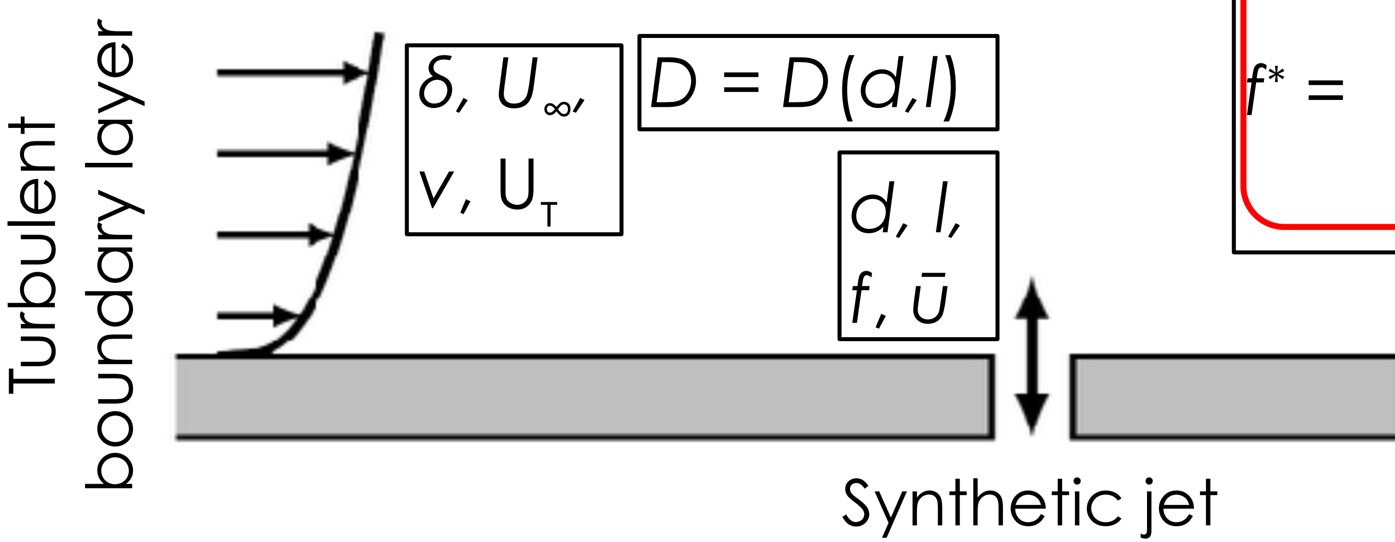
Jet trajectory

Important parameters

Proper scaling of f?

Variation of trajectory with f^*, r and Re_τ?



TBL:

$Re_\tau = U_\tau \, \delta / \nu$

Synthetic jet:

$AR = l/d = 13$

Interaction:

$r = \bar{u}/U_\infty$

$$f^* = \begin{cases} f\,\delta/U_\infty \\ f\,\nu/U_\tau^2 \\ f\,D/U_\infty \end{cases}$$

Experiments

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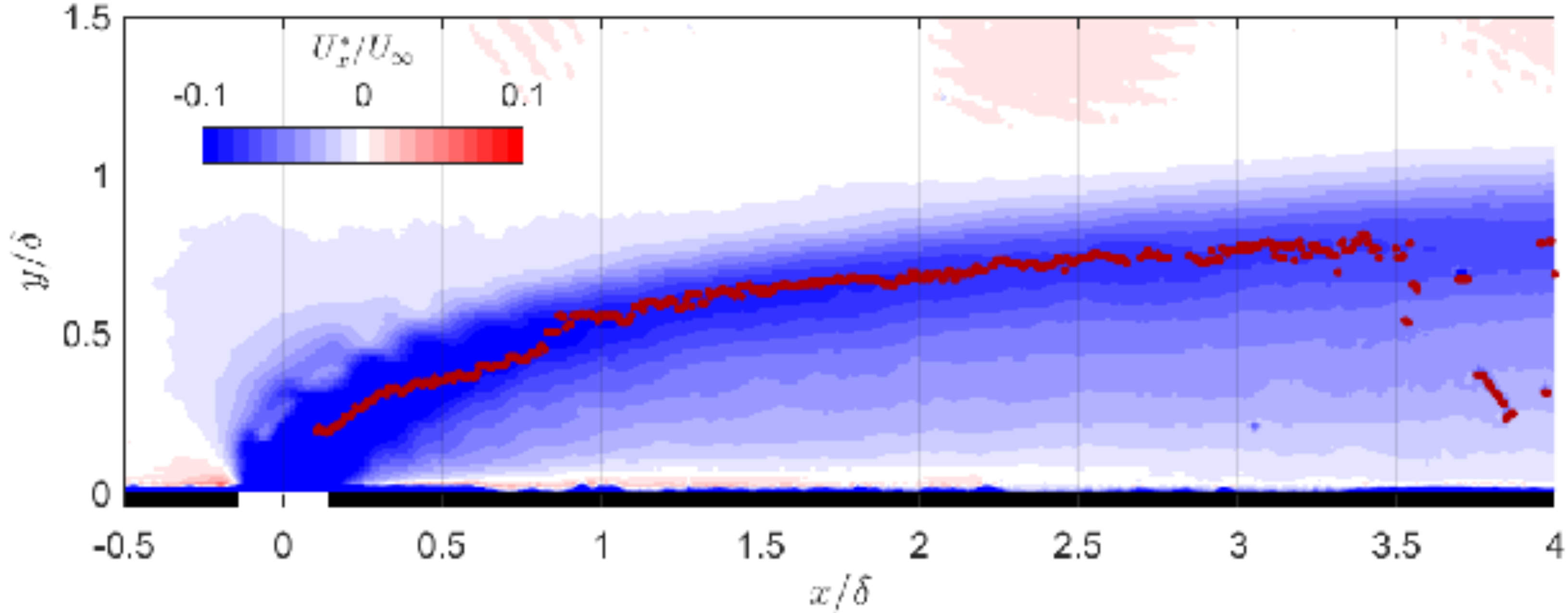
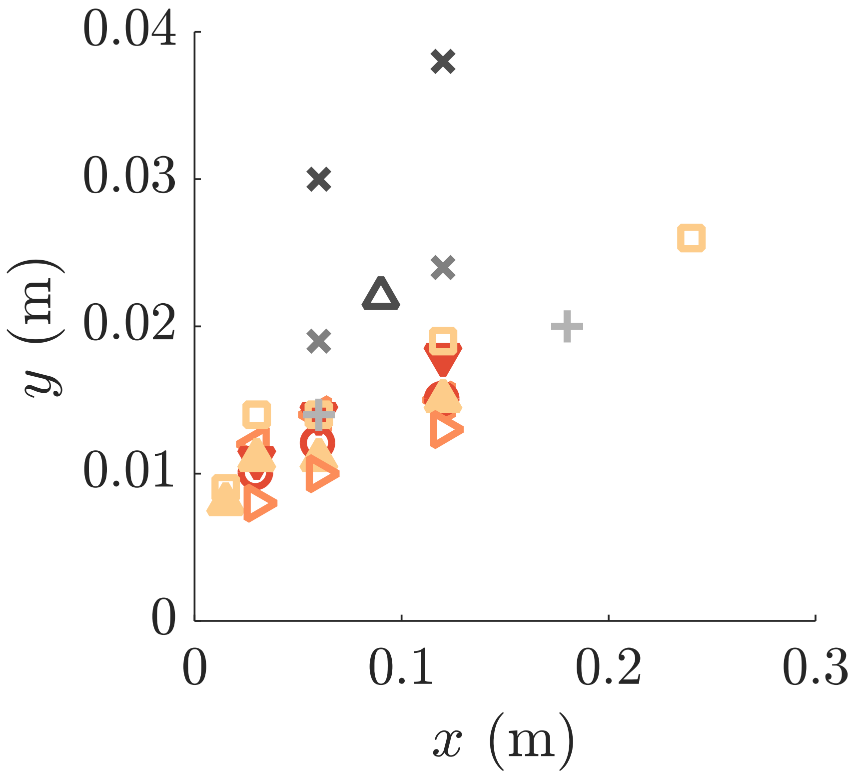


Trajectory measured from hot-wire measurements matches PIV

Results



Re_τ	r	$f\delta/U_\infty$	$f\nu/U_\tau^2$	fD/U_∞	
3200	0.3	1.8	0.016	13.0	▲
6350	0.3	1.8	0.008	13.6	▷
6350	0.3	1.8	0.009	6.2	◁
12800	0.3	2.3	0.004	6.8	▼
3200	0.3	1.0	0.009	6.9	□
6350	0.3	1.8	0.008	13.6	▷
6350	0.3	1.8	0.009	6.2	◁
12800	0.3	4.1	0.010	16.2	○
3200	0.6	1.8	0.016	13.0	×
3200	0.9	1.8	0.016	13.0	×
6350	0.45	1.8	0.008	13.6	+
3200	0.9	5.4	0.049	39.0	△

A wide range of cases over variation in Reynolds number, frequency and velocity ratio

Effect of velocity ratio

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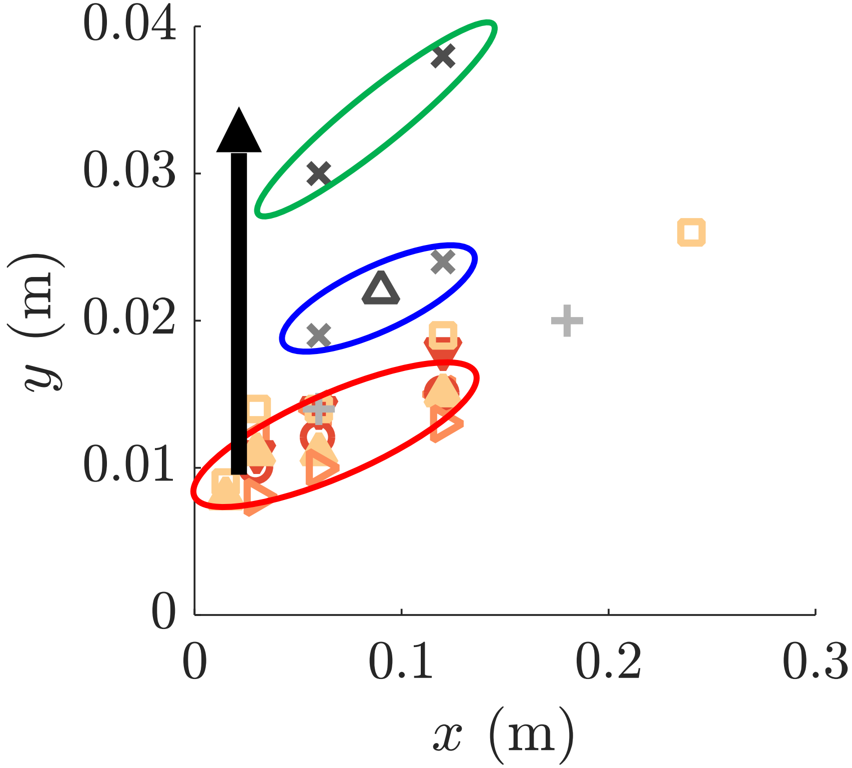

Re_τ	r	$f\delta/U_\infty$	$f\nu/U_\tau^2$	fD/U_∞	
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Wall-normal penetration increases with velocity ratio

Effect of frequency

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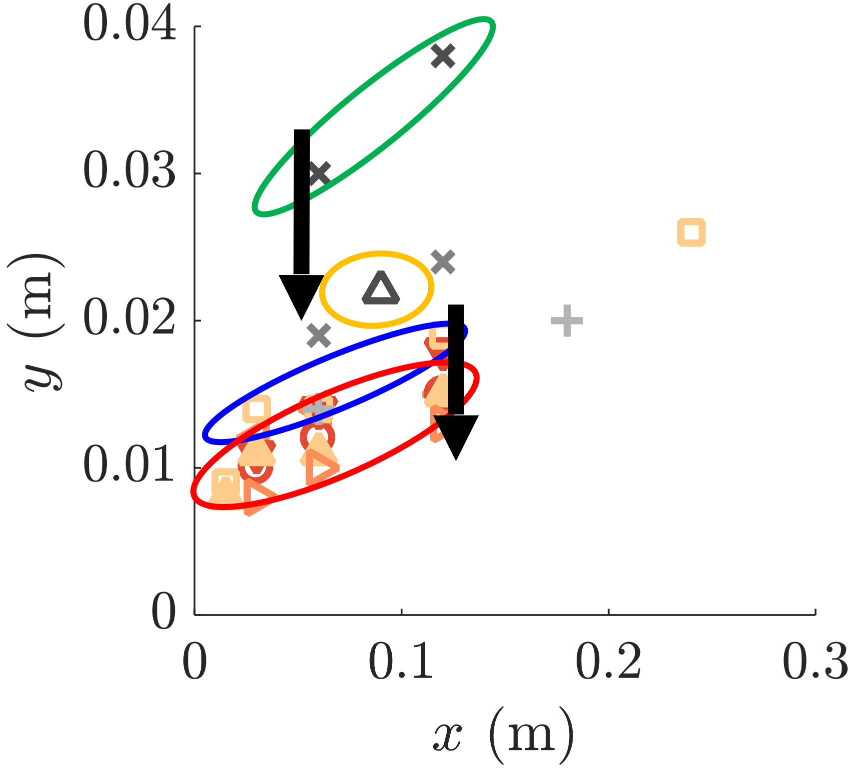

Re_τ	r	$f\delta/U_\infty$	$f\nu/U_\tau^2$	fD/U_∞	
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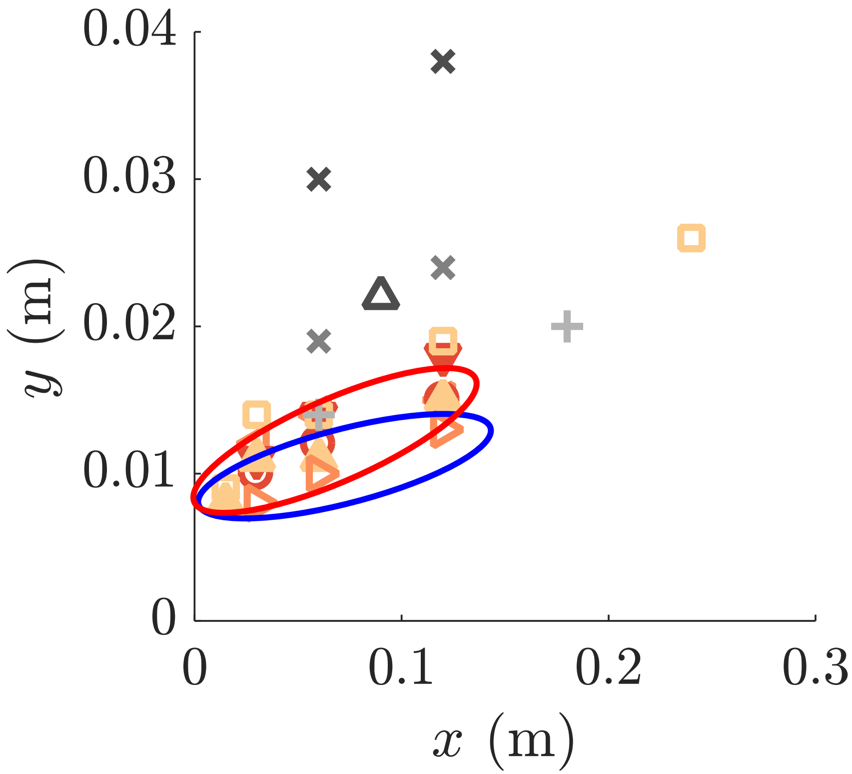
6350	0.45	1.8	0.008	13.6	+
3200	0.9	5.4	0.049	39.0	△

Wall-normal penetration decreases with frequency

Effect of Reynolds number



Re_τ	r	$f\delta/U_\infty$	$f\nu/U_\tau^2$	fD/U_∞	
3200	0.3	1.8	0.016	13.0	▲
6350	0.3	1.8	0.008	13.6	▷
6350	0.3	1.8	0.009	6.2	◁
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6350	0.45	1.8	0.008	13.6	+
3200	0.9	5.4	0.049	39.0	△

Reynolds number has a minor effect on trajectory

Jet trajectory: Empirical model

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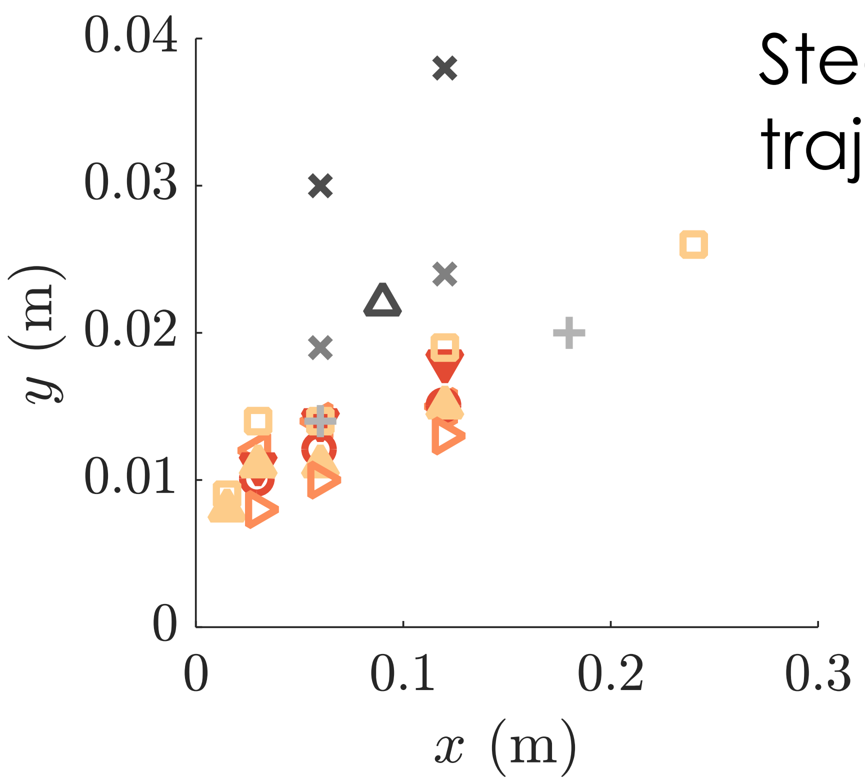

Steady-jet trajectory: $\frac{y/D}{r^c} = A\left(\frac{x/D}{r^c}\right)^B$

$$\frac{y/D}{g(\ldots)} = A\left(\frac{x/D}{g(\ldots)}\right)^B$$

$$g(\ldots) \propto \overline{U}^{c_1} f^{c_2} U_\infty^{c_3} \delta^{c_4}$$

Fit:

$$g(\ldots) \propto \overline{U}^{1.2} f^{-0.6} U_\infty^{-0.8} \delta^{-0.1}$$

$$g(\ldots) \propto r^{1.2} (U_\infty/(fD))^{0.6}$$

Velocity scaling

Frequency scaling

Reynolds number scaling

Jet trajectory: Empirical model

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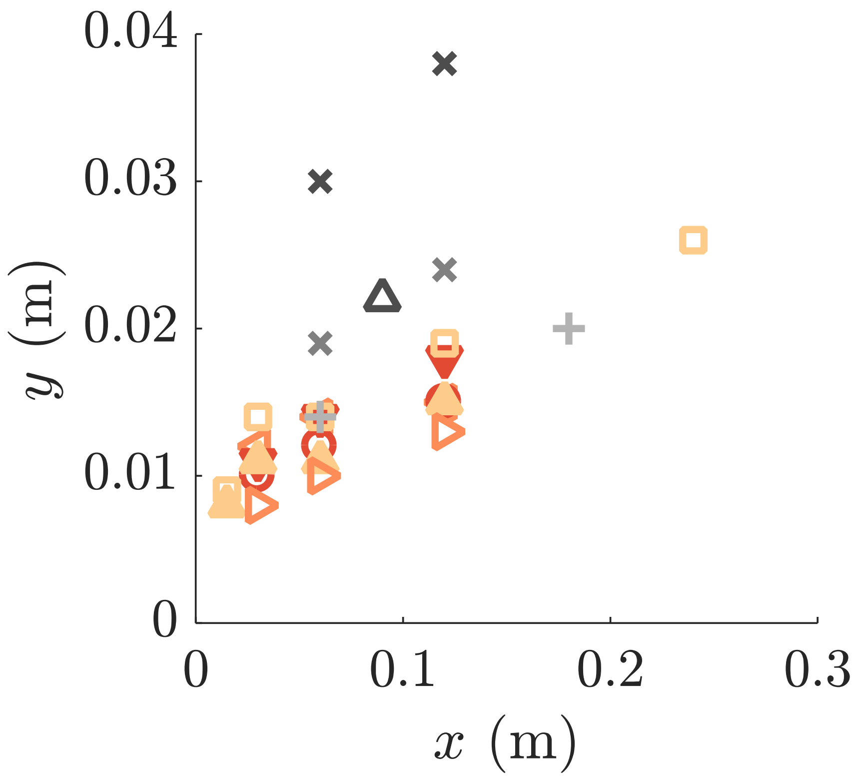
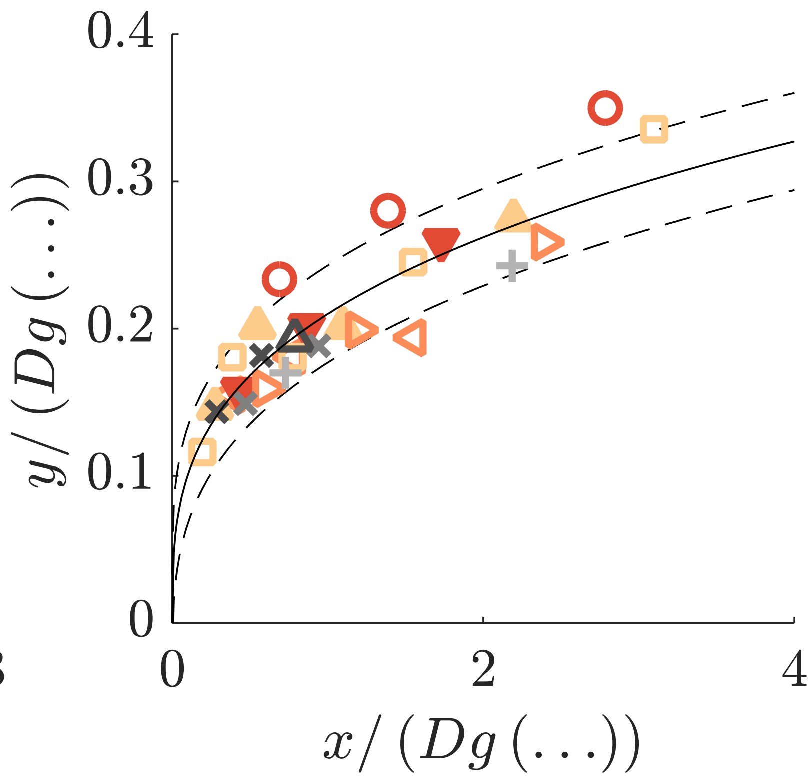




$$\frac{y/D}{r^{1.2}(U_\infty/(fD))^{0.6}} = A \left(\frac{x/D}{r^{1.2}(U_\infty/(fD))^{0.6}}\right)^B$$

Jet trajectory: Empirical model

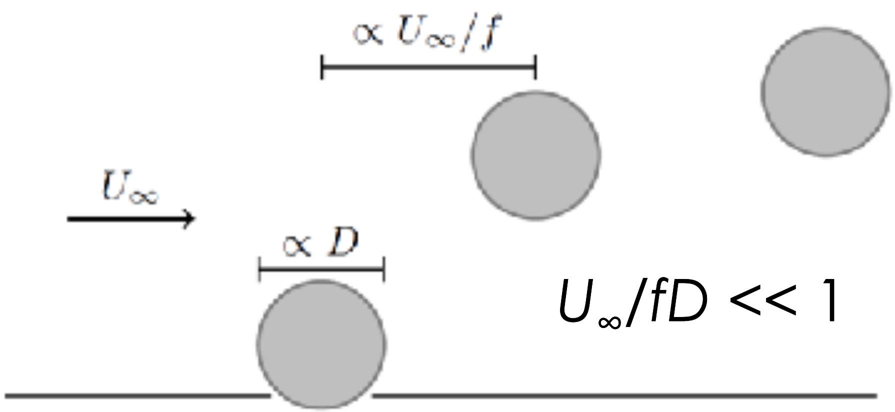
Synthetic-jet trajectory:

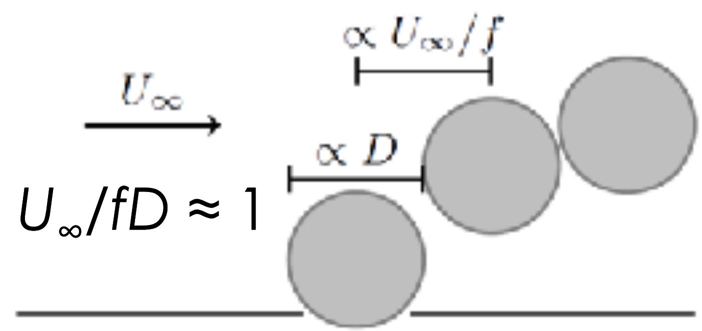
$$\frac{y/D}{r^{1.2}\boxed{(U_\infty/(fD))^{0.6}}} = A\left(\frac{x/D}{r^{1.2}\boxed{(U_\infty/(fD))^{0.6}}}\right)^B$$

Steady-jet trajectory:

$$\frac{y/D}{r^c} = A\left(\frac{x/D}{r^c}\right)^B$$

In the limit of a steady jet the original power-law scaling is recovered!





How does the jet strength decay with downstream distance? We could explore this in moderate Reynolds number facilities

Jet decay: Facility

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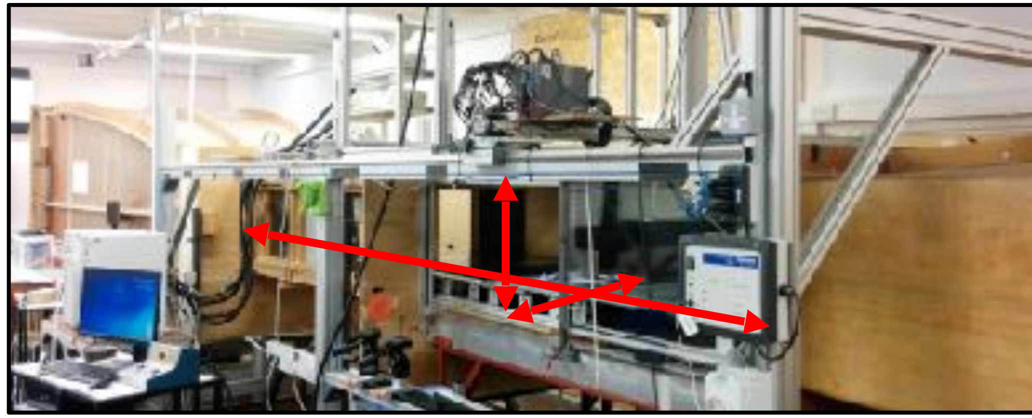
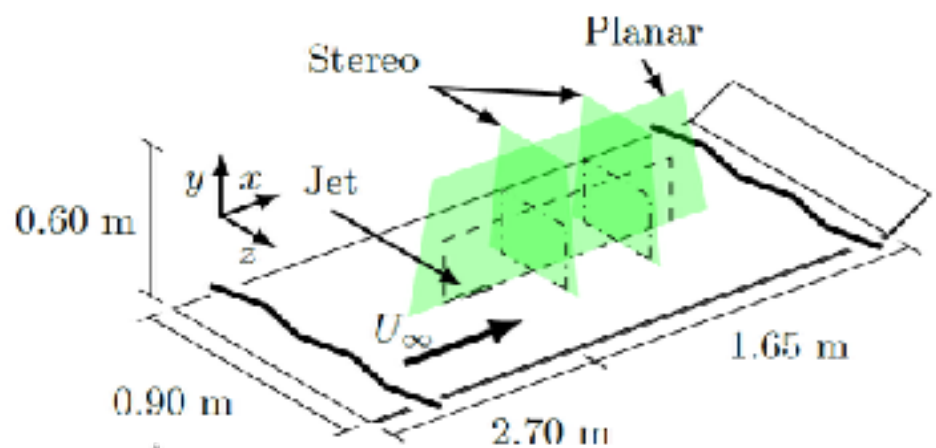
3’ x 2’ turbulent boundary layer wind tunnel

0.6 m x 0.9 m x 4.5 m

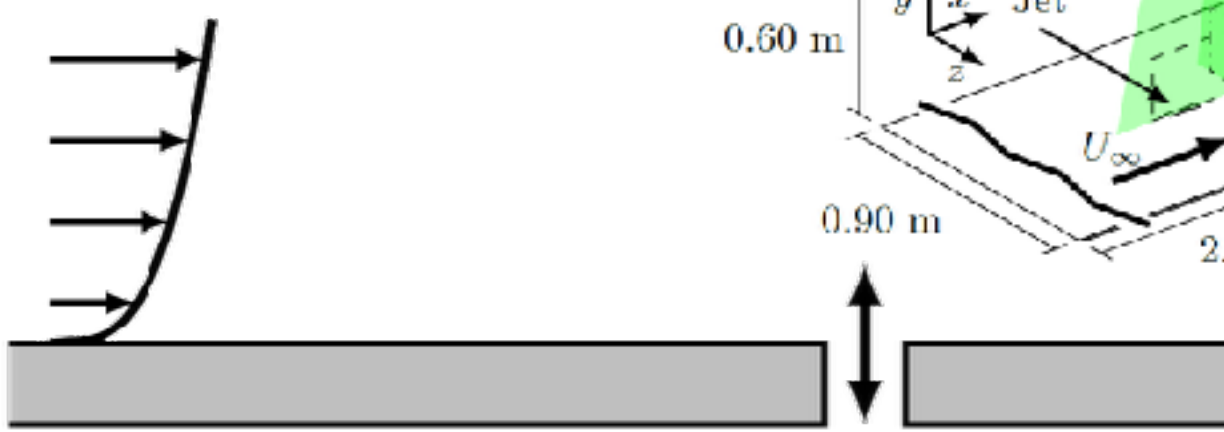
$Re_\tau = 1250$

$\delta = 0.05$ m





Turbulent boundary layer



Synthetic jet

Jet decay

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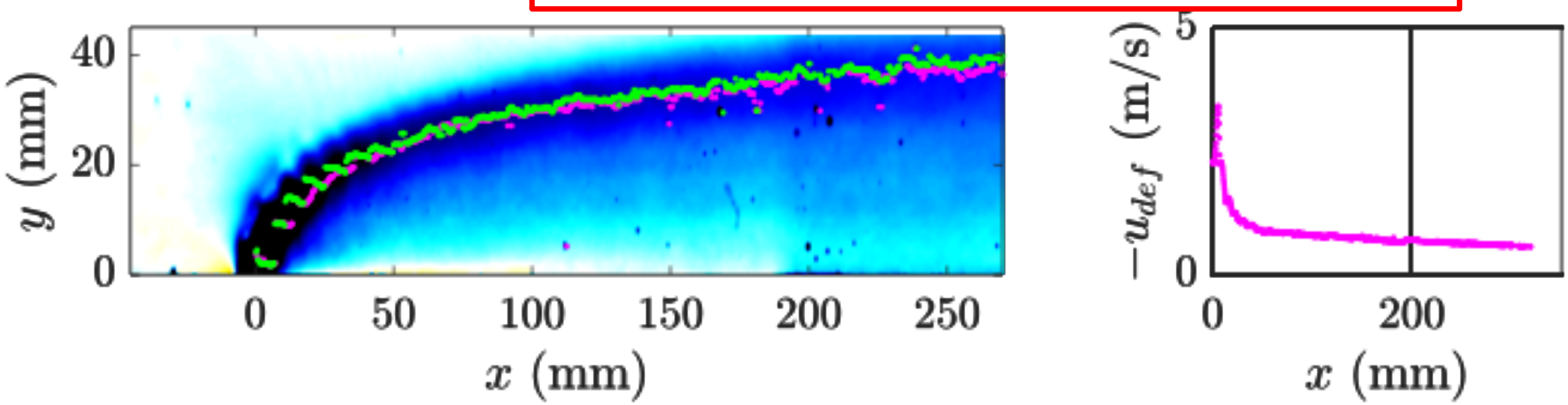
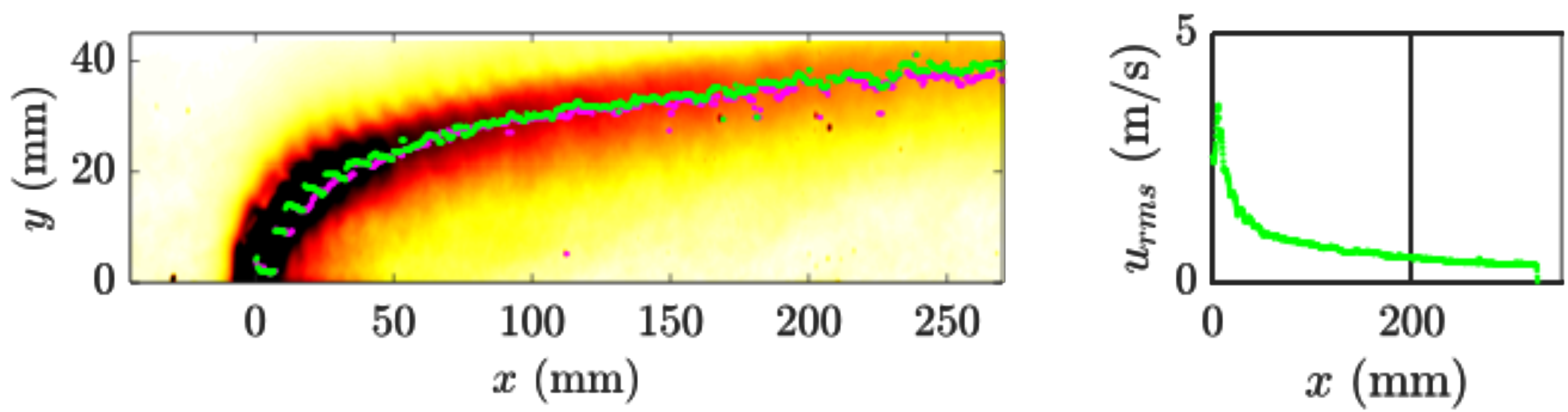
Velocity deficit:

Both methods give very similar results



Velocity rms:



Jet decay

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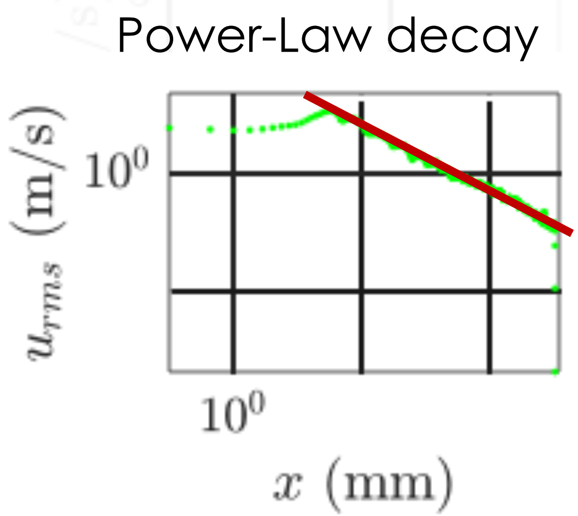
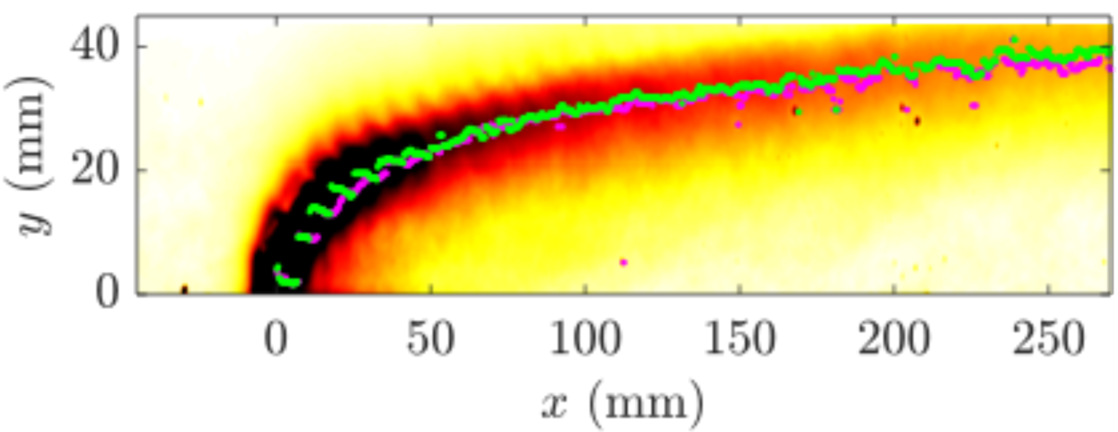
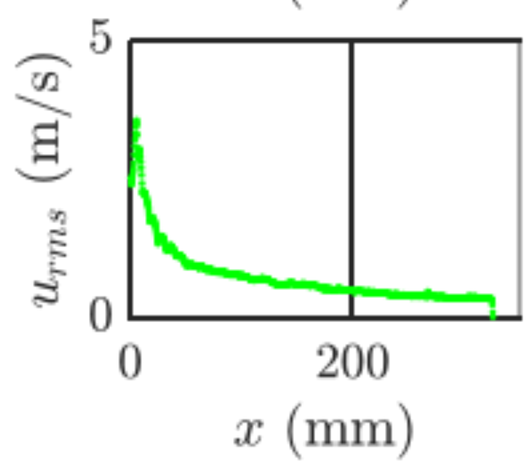
Velocity deficit: Both methods give very similar results

- RMS only depends on the local velocity signal
- The velocity deficit compares the perturbed with the unperturbed velocity, leading to larger uncertainties for hot-wire measurements



Velocity rms:





Jet decay

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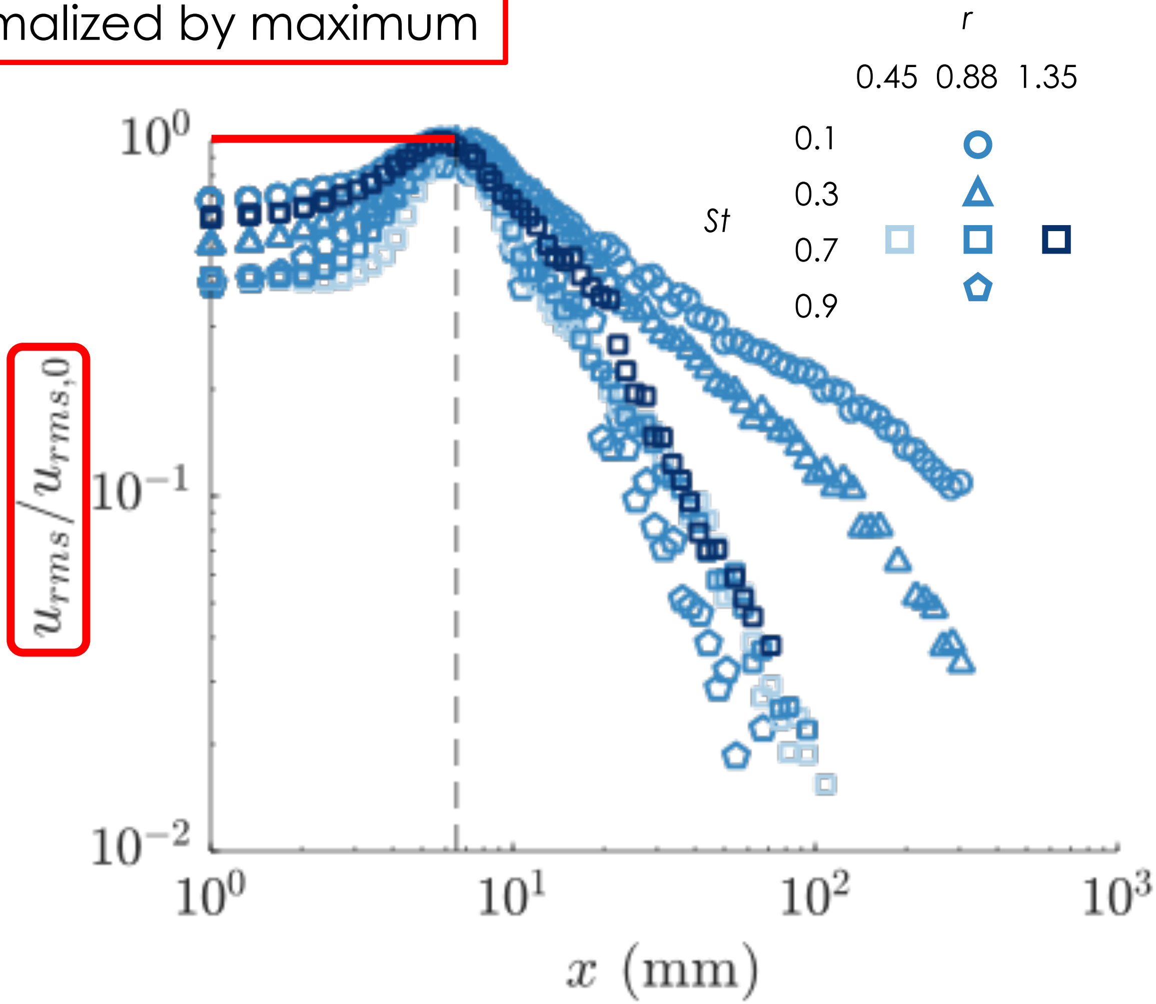
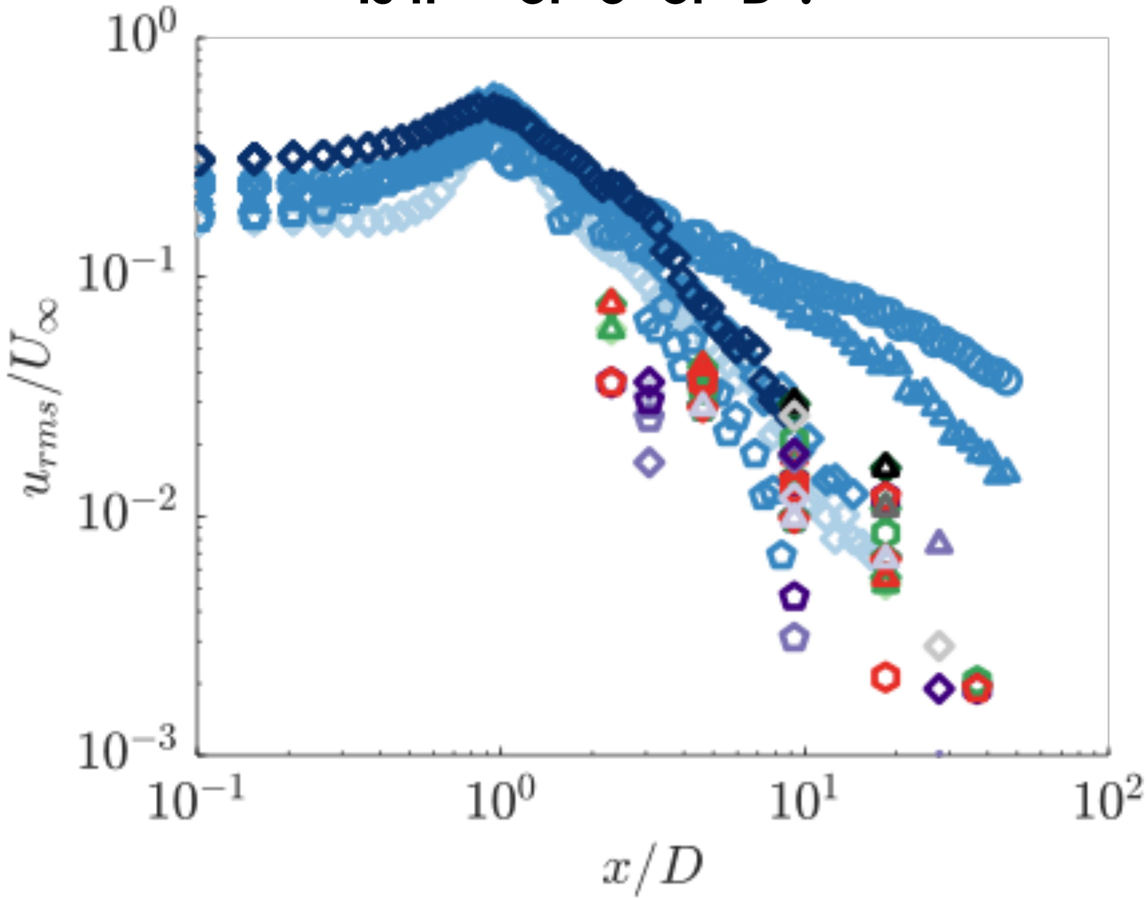
RMS is normalized by maximum

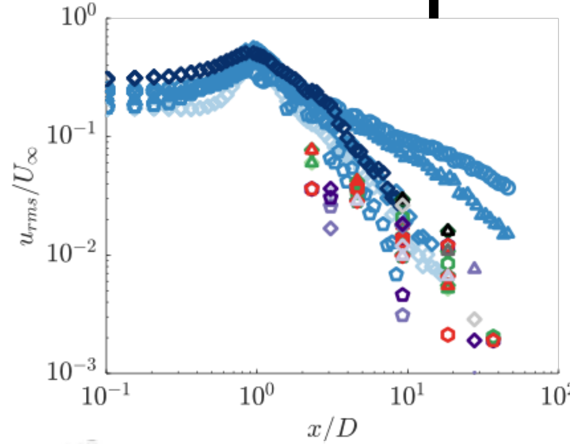


Jet decay

This data can be used to examine scaling:
Is it '+'or 'δ' or 'D'?



Reasonable collapse of jet decay



Jet decay

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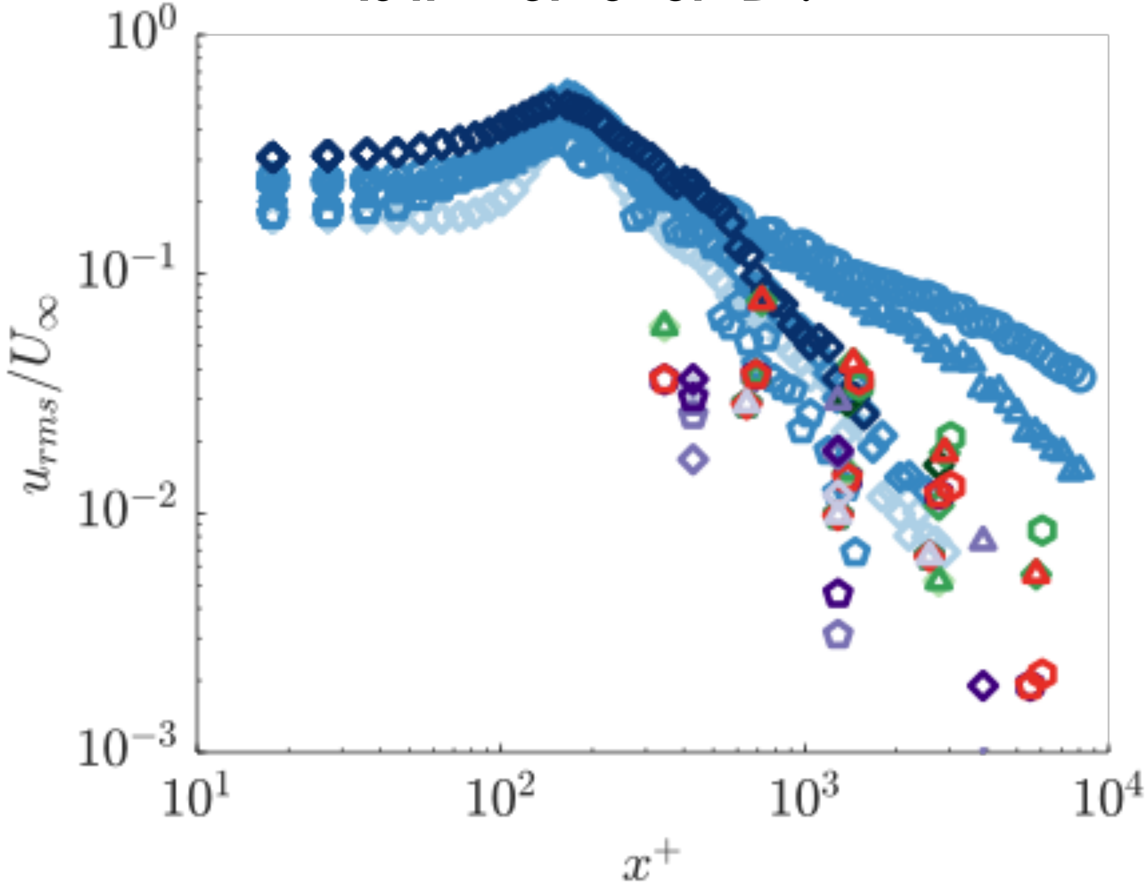

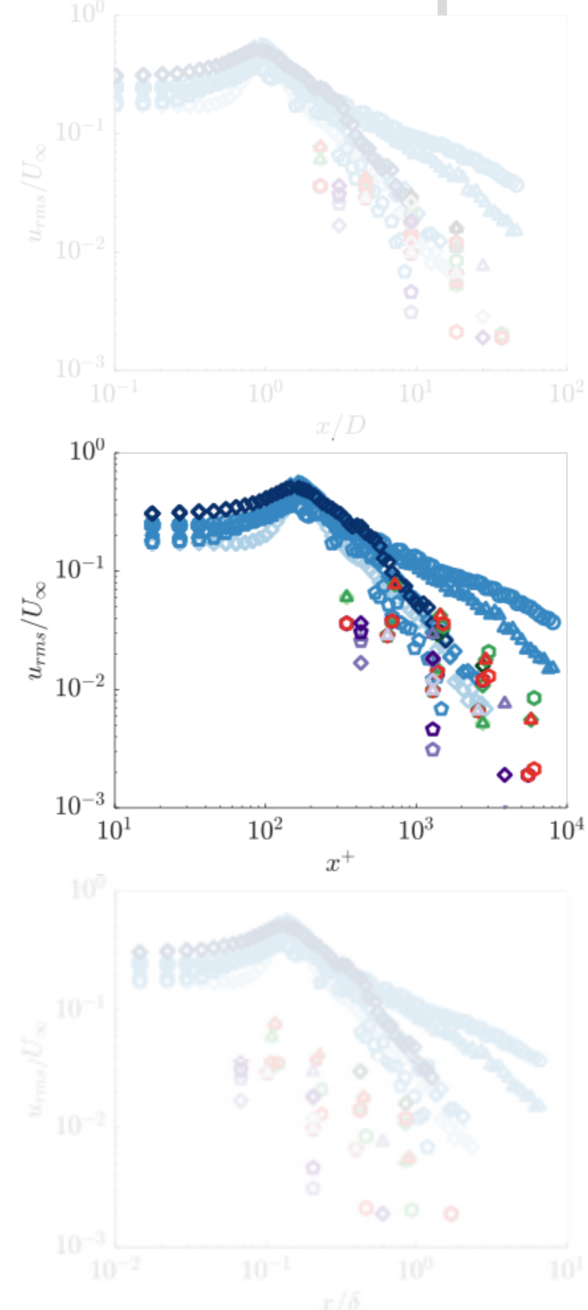

x^+ shows a slightly larger spread of the data

Jet decay

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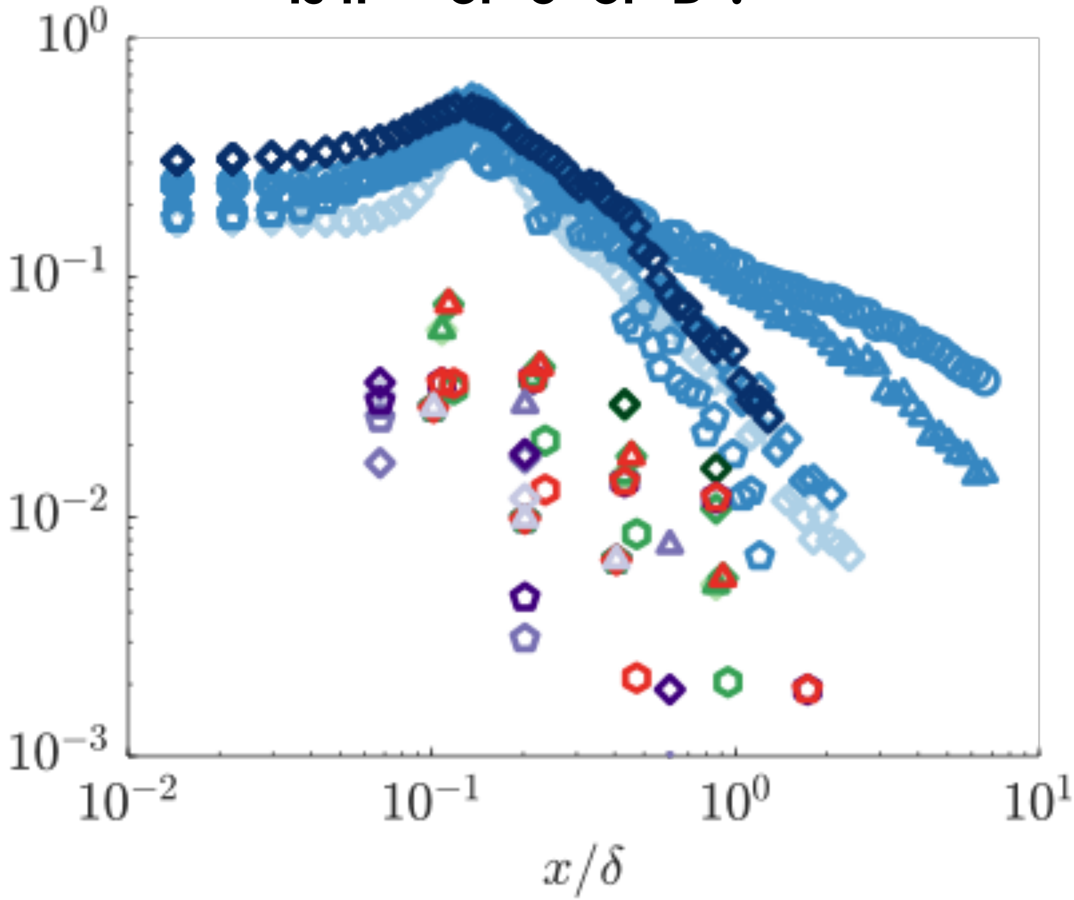
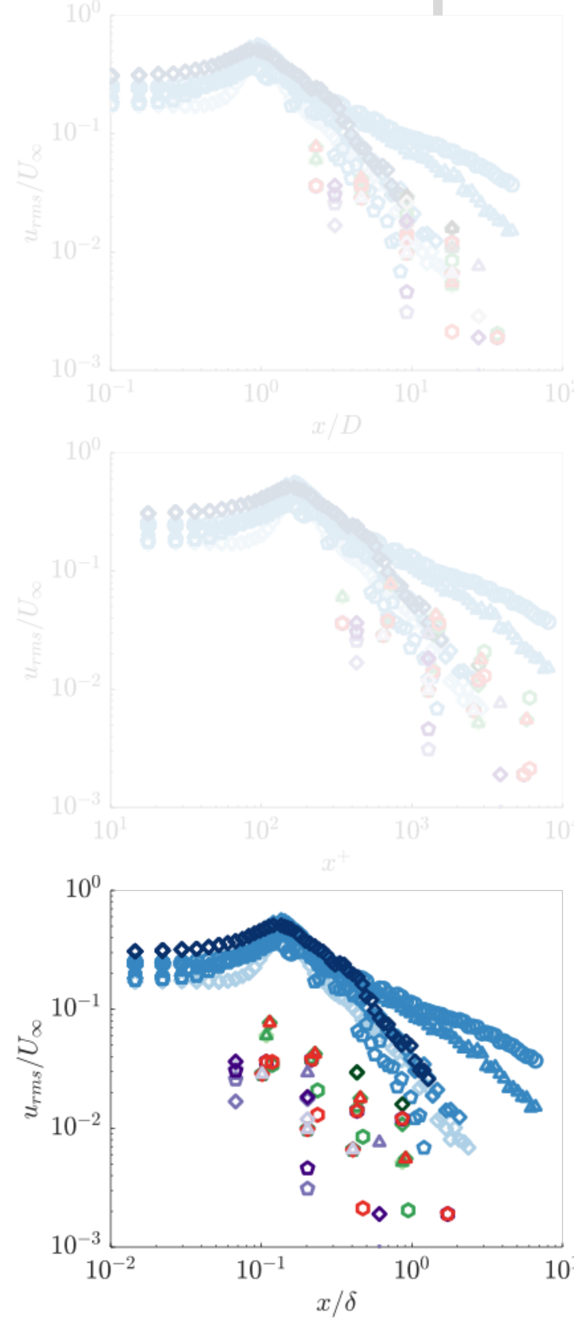
This data can be used to examine scaling:
Is it ‘+’or ‘δ’ or ‘D’?





x/δ shows a much larger spread of the data

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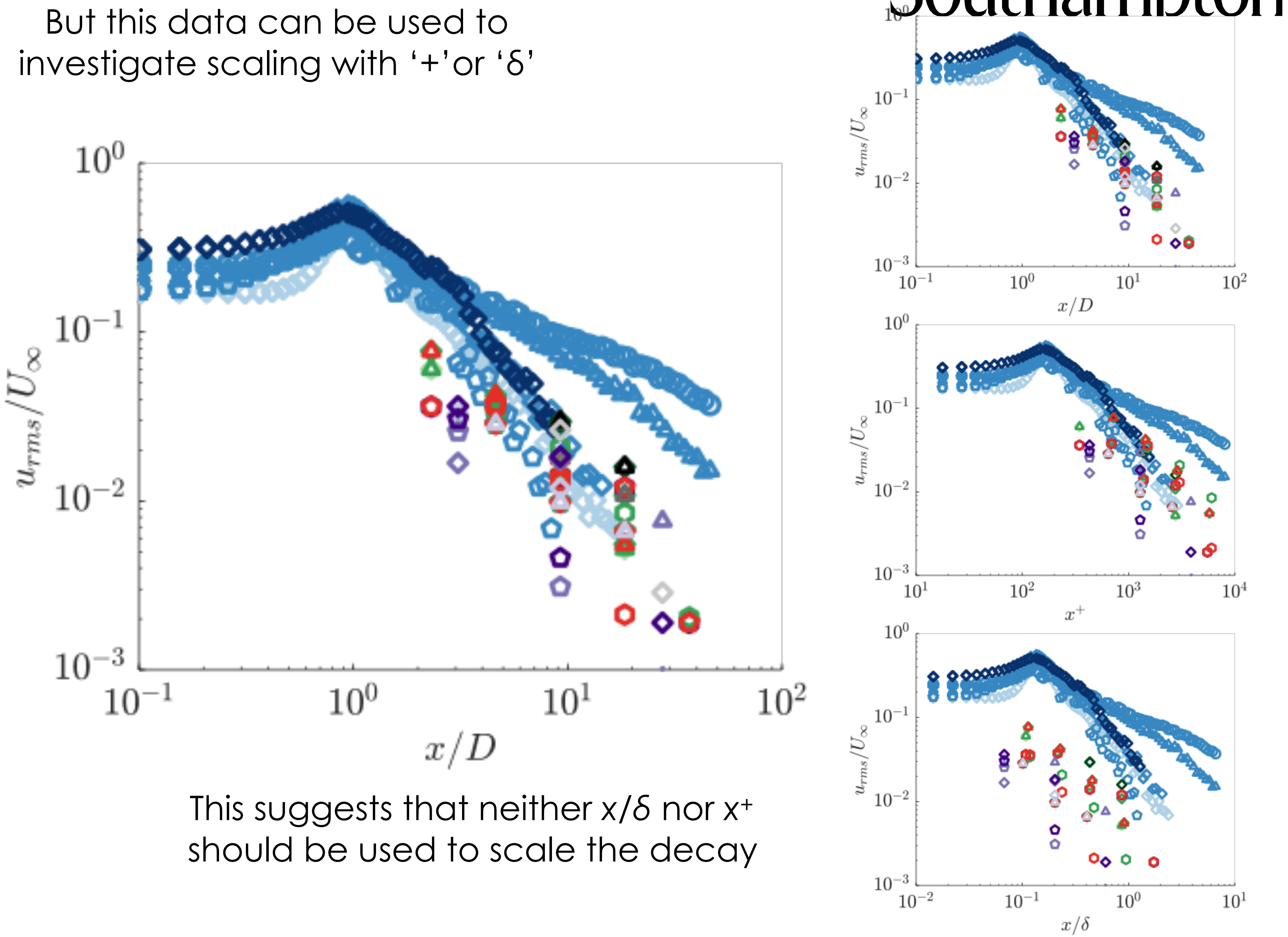
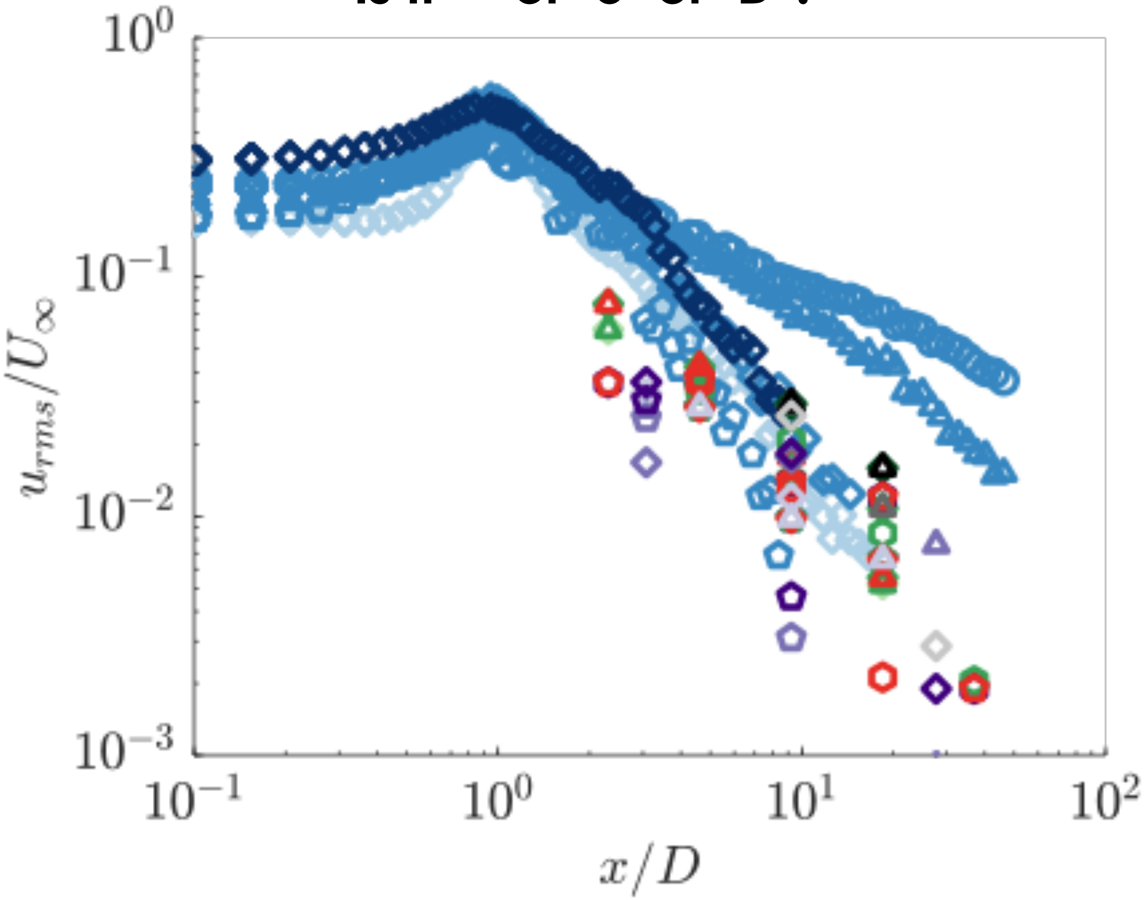
But this data can be used to investigate scaling with '+'or 'δ'



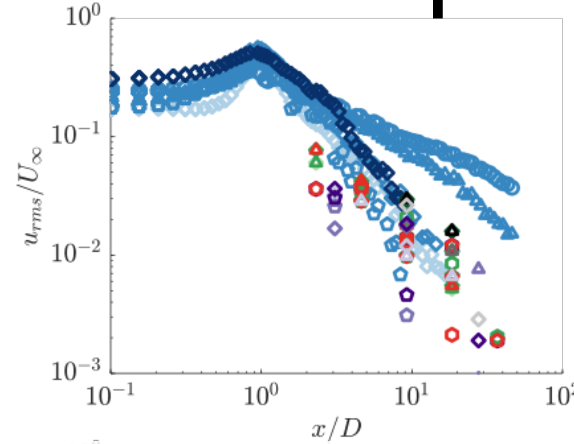
This suggests that neither x/δ nor x^+ should be used to scale the decay

Jet decay

This data can be used to examine scaling:
Is it ‘+’or ‘δ’ or ‘D’?



Reasonable collapse of jet decay
Consistent with free-wakes



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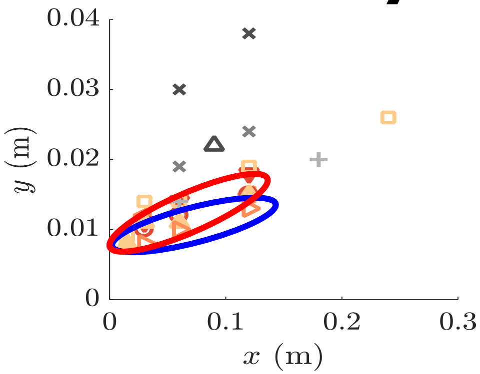
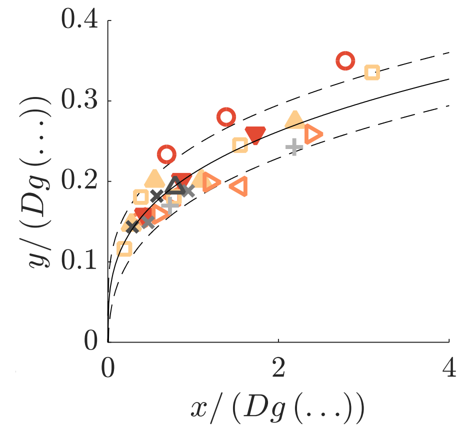
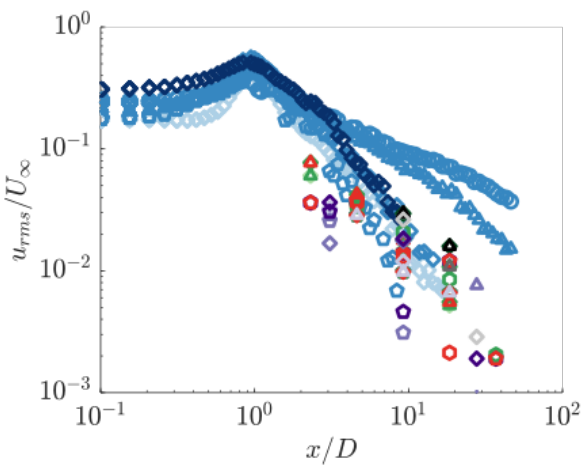
Summary



The Reynolds number only has a small influence on the trajectory of a synthetic jet



The jet trajectory follows a power-law for which an empirical scaling has been derived



Jet decay appears to scale with jet dimensions

Actuator requirements for large-scale control?

Jet frequency determined by passage of VLSMs

Determine velocity ratio based on the derived empirical scaling for the trajectory

Location of subsequent jets along streamwise direction scales with jet dimensions

Thank you!

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