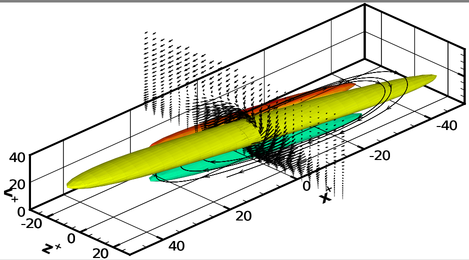
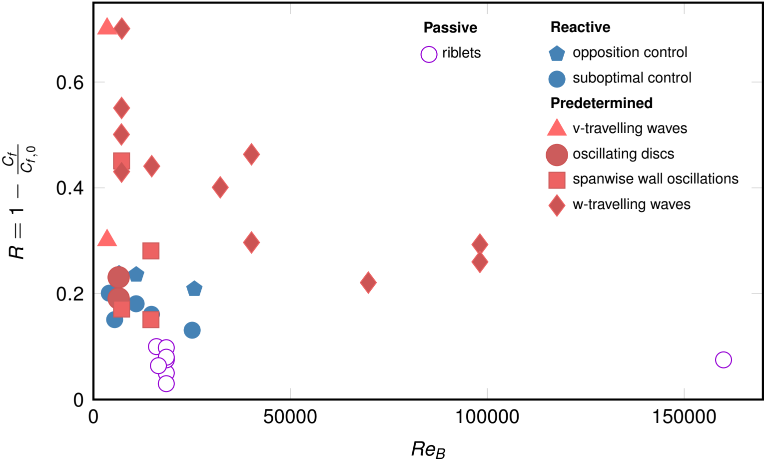
Reynolds number effect on turbulent drag reduction

Davide Gatti, M. Quadrio, B. Frohnapfel | August 26, 2015

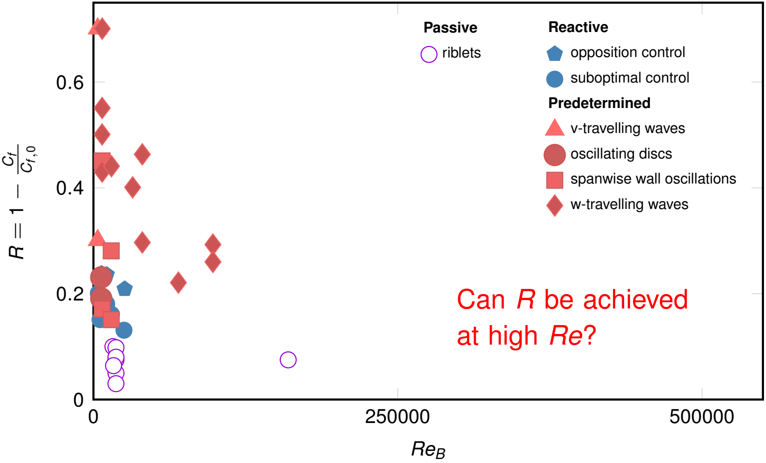
15TH EUROPEAN TURBULENCE CONFERENCE, DELFT, NETHERLANDS



Drag reduction and *Re*

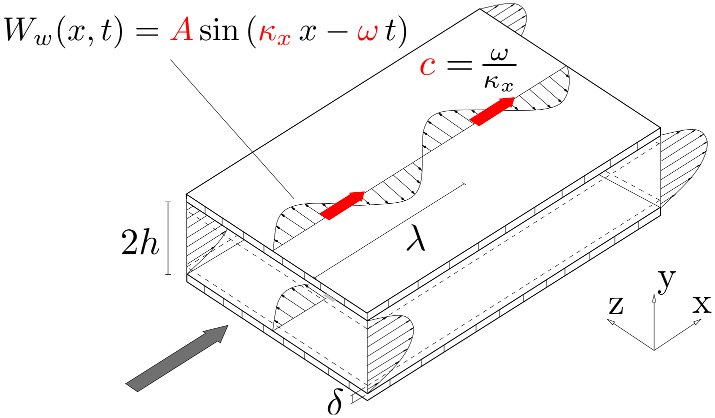


Drag reduction and *Re*



Can R be achieved at high Re?

Today's model control strategy



Quadrio, Ricco & Viotti, JFM 2009

Building a new database

large, reliable, complete

- DNS of turbulent channel flow at CFR
- $Re_\tau = 200$ and $Re_\tau = 1000$
- Many simulations with modest domain size ($L_x^+ = 1300$, $L_z^+ = 650$)
- Some simulations with full domain size ($L_x = 4\pi h$, $L_z = 2\pi h$)

Large!

- More than 4,000 DNS datapoints

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Reliable!

- Control simulations (CFR, CPG) with larger domains
- Uncertainty

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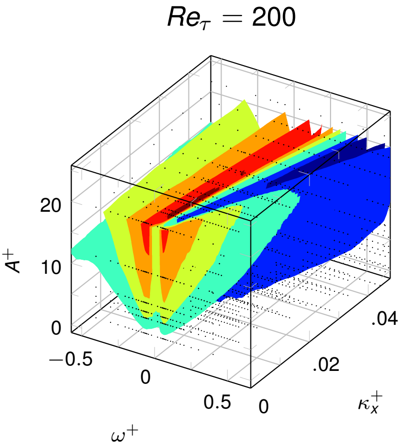
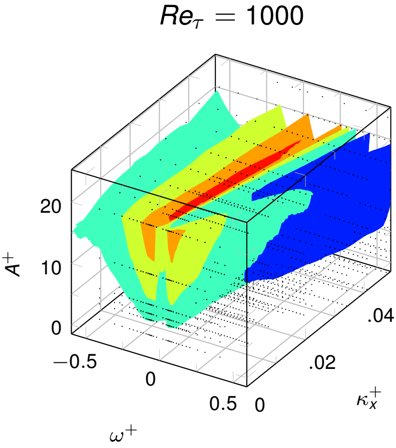
Complete!

- 3-parameter study (*A* considered for the first time)

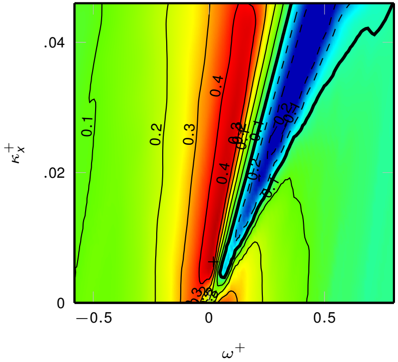
Drag reduction: global view





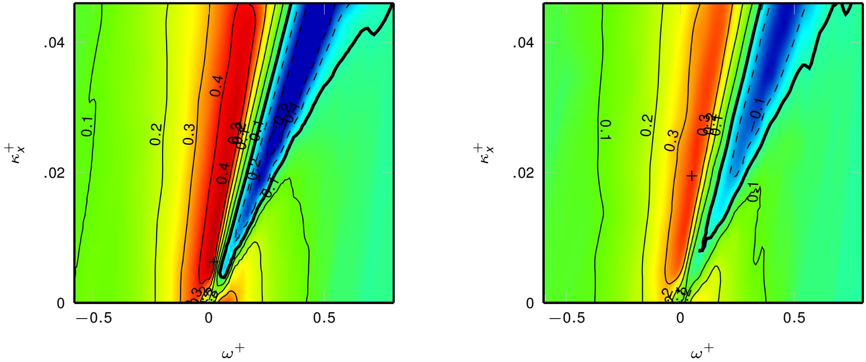
Drag reduction at $A^+ = 12$

$Re_\tau = 200$



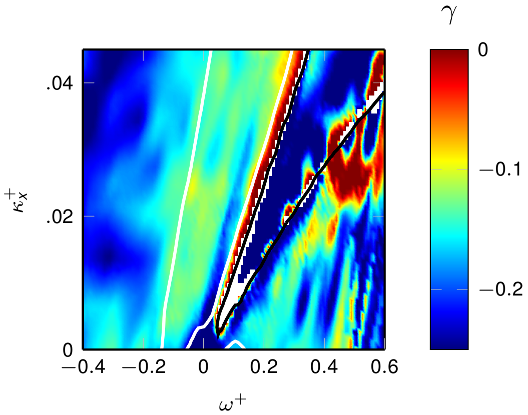
Drag reduction at $A^+ = 12$

$Re_\tau = 200$ $\quad$ $Re_\tau = 1000$



What about *Re* effect?

γ not the best figure to describe it



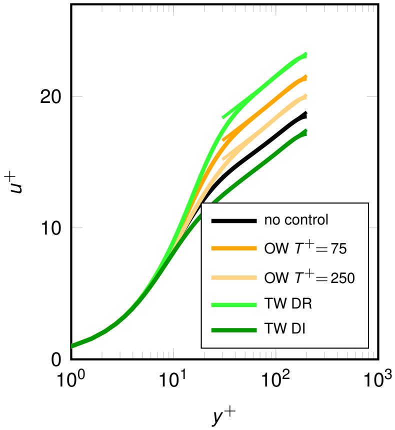
Traditionally described as $R \sim Re_\tau^{\gamma}$

- Early studies: $\gamma \approx -0.2$
- Recent evidence: $\gamma = \gamma\,(Re, A, \kappa_x, \omega)$

Vertical shift of the mean velocity profile

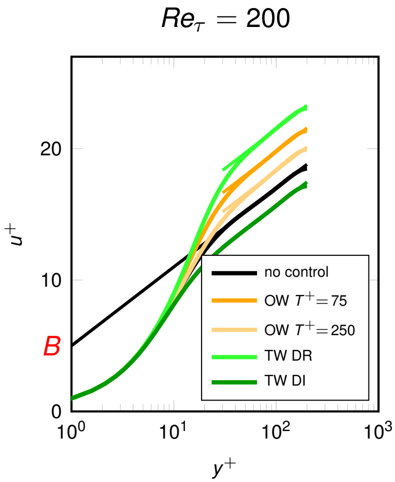
large-scale simulations

$Re_\tau = 200$



Vertical shift of the mean velocity profile

large-scale simulations



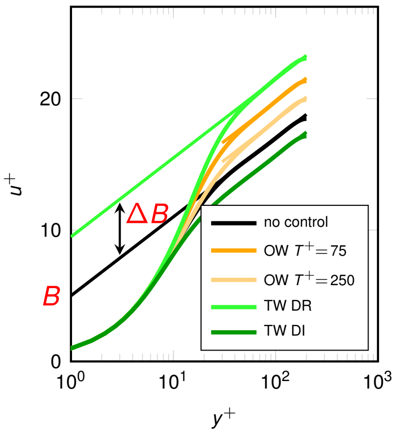
Log law:

$$u^+ = \frac{1}{\kappa} \log y^+ + B$$

Vertical shift of the mean velocity profile

large-scale simulations

$Re_\tau = 200$



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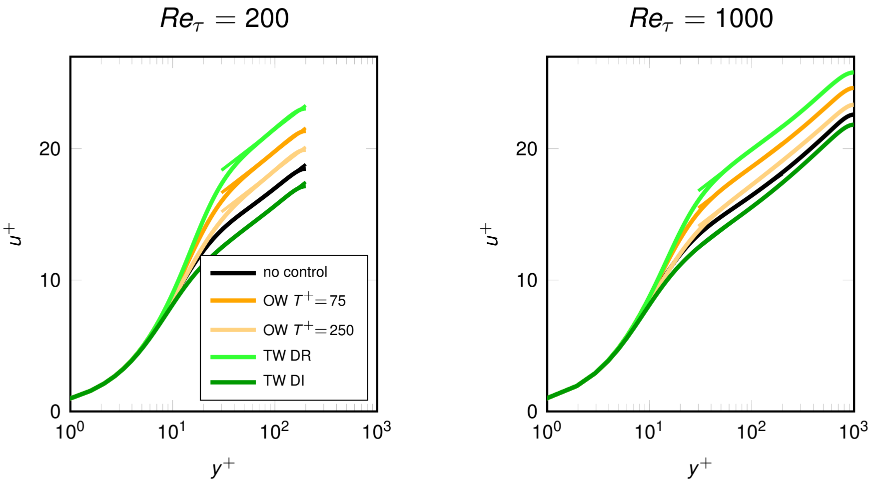
Vertical shift of the mean velocity profile

large-scale simulations



The Prandtl – von Kármán friction law

Log law:

$$u^+ = \frac{1}{\kappa} \ln\left(\frac{y}{\delta_\nu}\right) + B$$

Defect law:

$$U_c^+ - u^+ = \frac{1}{\kappa} \ln\left(\frac{y}{\delta}\right) + B_1$$

Adding together and using $U_c^+ = U_b^+ + 1/\kappa$:

$$\sqrt{\frac{2}{C_f}} = \frac{1}{\kappa} \ln Re_\tau + B + B_1 - \frac{1}{\kappa}$$

A simple subtraction

writing P-vK for flow with/without control

$Re_{\tau,0}$ and $C_{f,0}$ without control, Re_τ and C_f with control

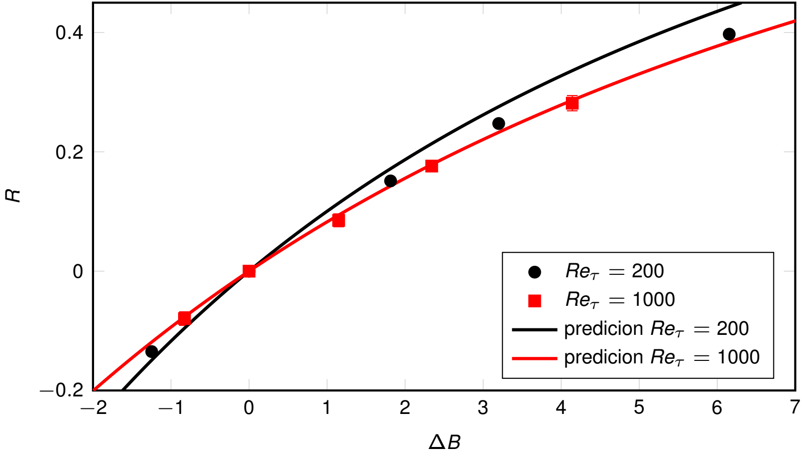
$$\sqrt{\frac{2}{C_f}} - \sqrt{\frac{2}{C_{f,0}}} = \frac{1}{\kappa} \ln \frac{Re_\tau}{Re_{\tau,0}} + \Delta B + \cancel{\Delta B_1}$$

CPG: $C_f = C_{f,0}\,(1 - R)$ and $Re_\tau = Re_{\tau,0}$

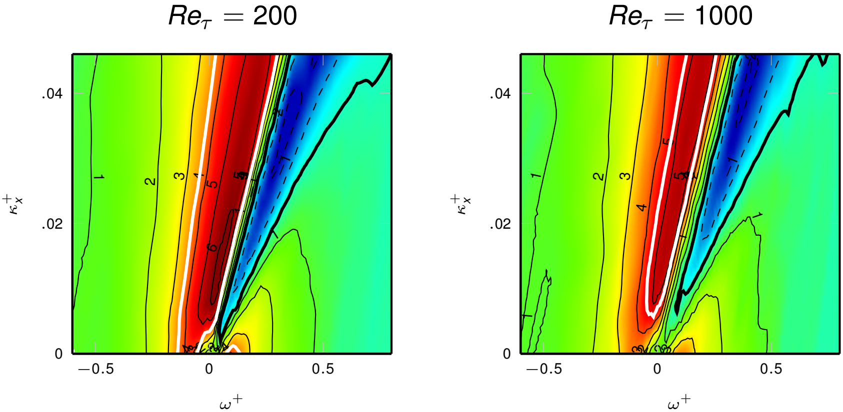
$$\boxed{\Delta B = \sqrt{\frac{2}{C_{f,0}}} \left[(1 - R)^{-1/2} - 1 \right]}$$

Relationship among ΔB, R and Re_τ

check with full-size simulations

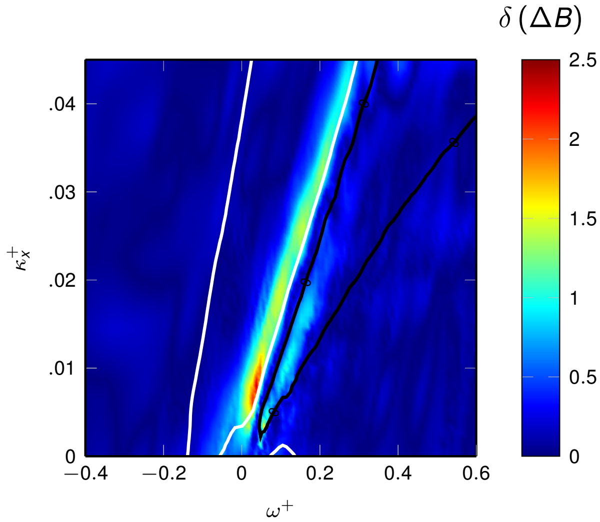


Map of ΔB



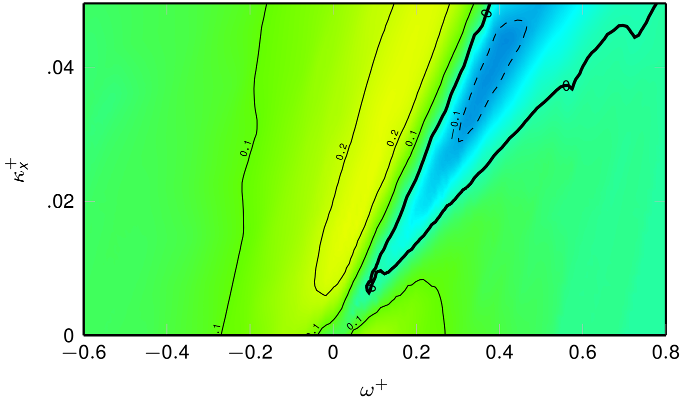
Change of ΔB

from $Re_\tau = 200$ **to** $Re_\tau = 1000$



Extrapolation to $Re_\tau = 10^5$

assumptions: ΔB **at** $Re_\tau = 1000$ **remains constant**



Conclusions

Karlsruhe Institute of Technology

- Drag reduction is not as simple as “percentage change of C_f”
- Many wall-based control scheme (as riblets)
  are characterized by their ΔB
- ΔB is constant with (not too low) Re
- No Re-effect on drag reduction!
- Extrapolation to higher Re is possible

Thanks for your kind attention!

for comments and complaints

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Figures of merit

Pumping with power P and controlling with power P_{in}

- drag reduction (rate) $$R = 1 - \frac{P}{P_0} = 1 - \frac{C_f}{C_{f,0}}$$
- net power saving (rate) $$S = R - \frac{P_{\mathrm{in}}}{P_0}$$
- gain $$G = \frac{P_0 - P}{P_{\mathrm{in}}}$$