Workshop jointly organised by Airbus and UKFN SIG on turbulent skin friction drag reduction
Imperial College London, 4-5 December 2017

Turbulent skin-friction reduction by oblique wavy surfaces

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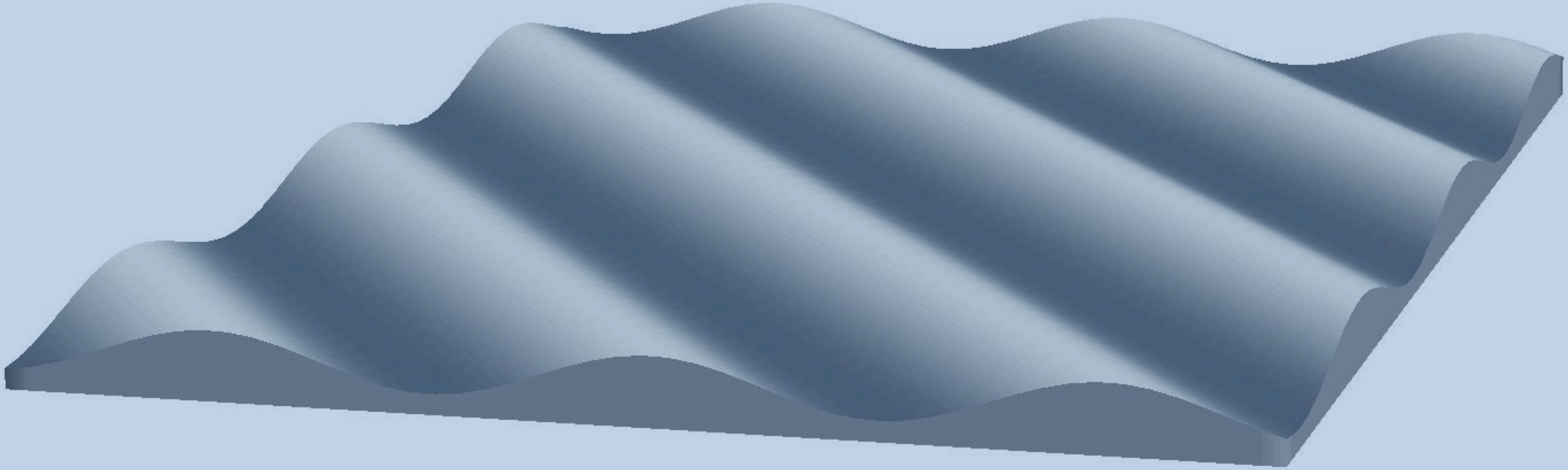
Imperial College London



It started 7 years ago …

3rd Review meeting, 18.04.2011. Airbus, Filton

Imperial College London

There is a chance. Should we try?

A question (in confidence)

by Sergei Chernyshenko

to all involved in the EPSRC/Airbus/EADS project

Investigation of alternative drag-reduction strategies in turbulent boundary layers by using wall forcing

People: Michael A. Leschziner (ICL, Principal investigator),
Sergei Chernyshenko (ICL), Sylvain Lardeau (ICL),
Emile Touber (ICL), Olivier Blesbois (ICL),
Duncan Lockerby (Warwick), Yongmann Chung (Warwick),
Faisal Baig (Warwick), Edward Hurst (Warwick),
Carlos Duque-Daza (Warwick)
Christopher Davies (Cardiff), Michael Togneri (Cardiff),
Jeremy Benton (Airbus), Stephen Rolston (EADS IW),
Jan Meyer (EADS IW), Richard Ashworth (EADS IW)

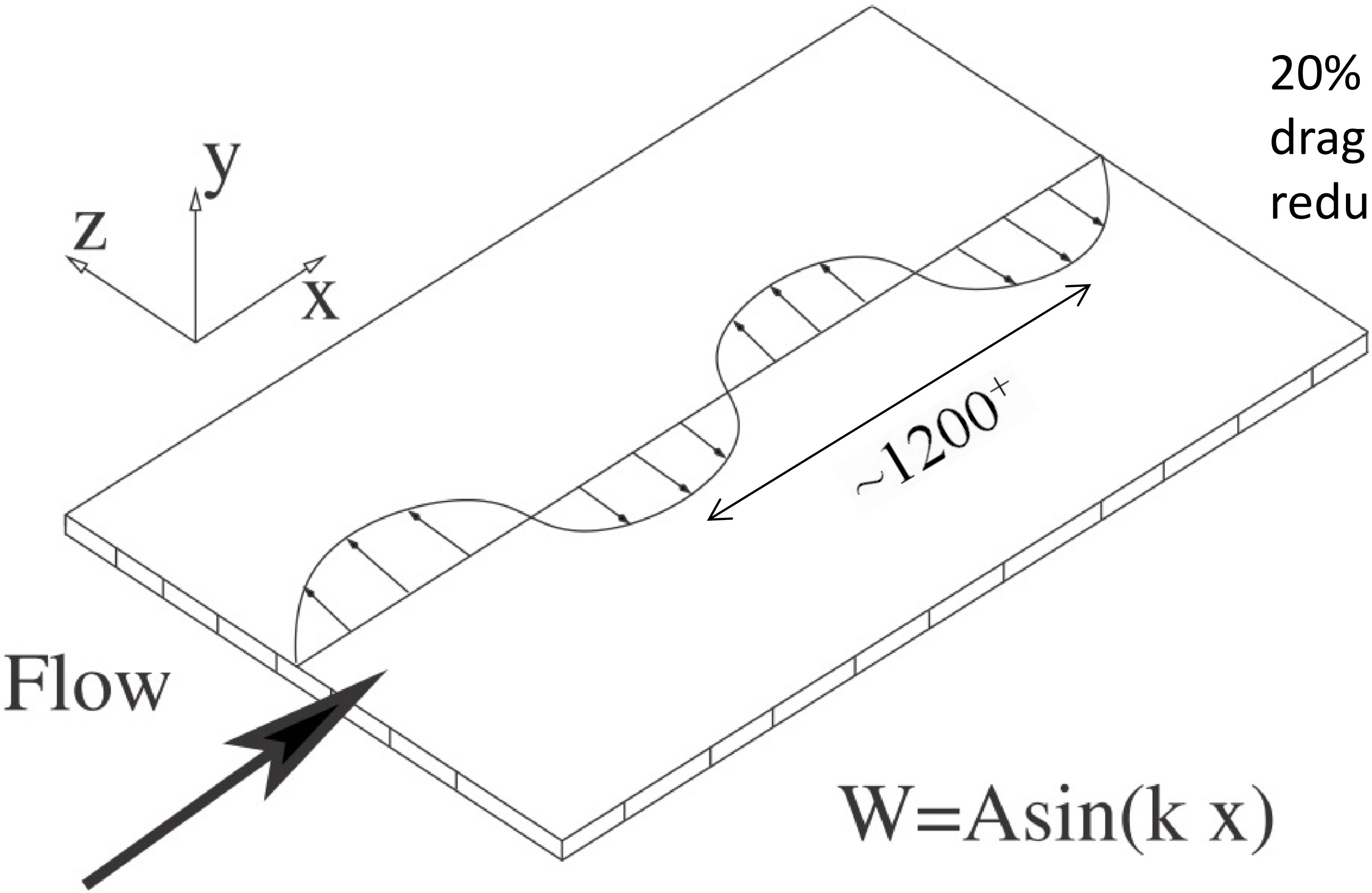
1. The idea
2. Semi-empirical theory
3. Main effects
4. DNS
5. What next

S.Chernyshenko. Drag reduction by a solid wall emulating spanwise oscillations. Part 1. arXiv:1304.4638 (2013)

Funding from Innovate UK (Technology Strategy Board), as part of the ALFET project, Project Reference No. 113022, and computing resources from the UK Turbulence Consortium (UKTC) EPSRC Grant No. EP/L000261/1.

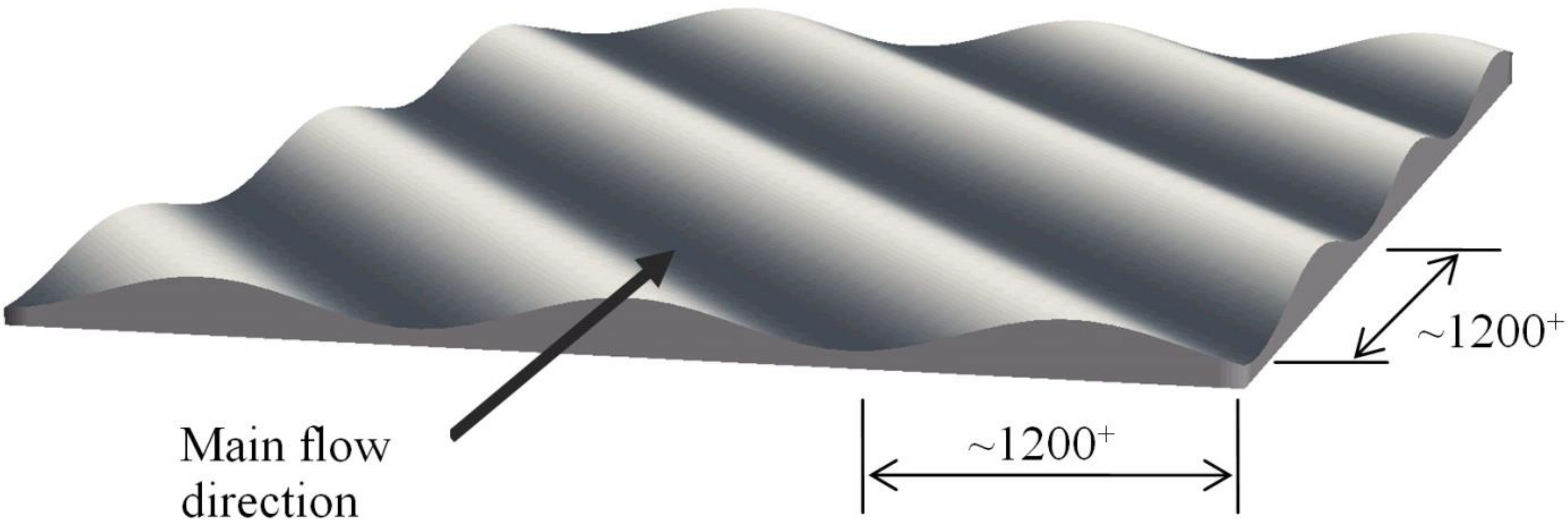
S.Ghebali, S.Chernyshenko, & M. Leschziner
Can large-scale oblique undulations on a solid wall reduce the turbulent drag? Phys. Fluids 29, 105102 (2017)

How to replace the steady Stokes layer (SSL) with something feasible?

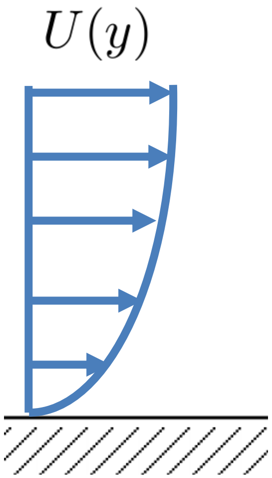


20% net drag reduction

The idea: a rigid oblique wavy wall, much smoother and with much larger wavelength than riblets



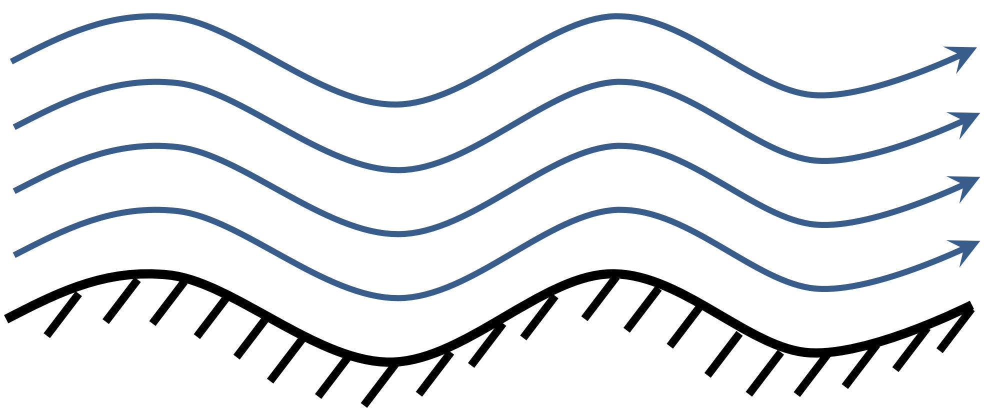
The wavy wall will need only a gentle slope due to the triple-deck interaction mechanism



$$\Delta p \sim U \Delta U$$

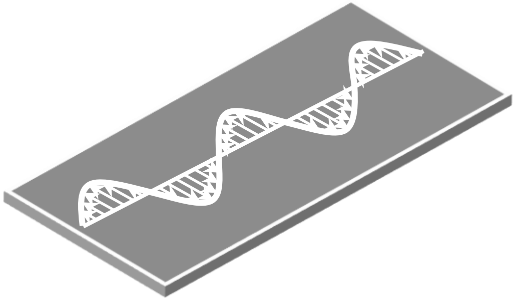
$$\Delta p \sim u \Delta u$$

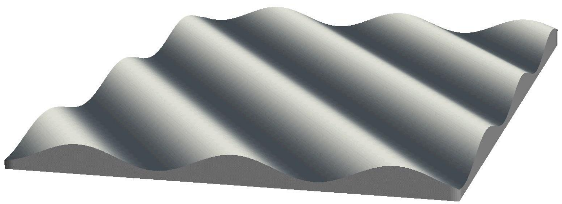
$$\Rightarrow \quad \Delta u \sim \frac{U}{u} \Delta U \gg \Delta U$$



Talk by Sergei Chernyshenko

A match between wavy wall and SSL by the spanwise shear





$$w_{\mathrm{w}} = \hat{w}_{\mathrm{w}} \sin(k_x x)$$

$$p = \hat{p} \sin(k_x x + k_z z)$$

$$w_{\mathrm{ssl}} = \hat{w}_{\mathrm{ssl}}(y) \sin(k_x x)$$

$$w_{\mathrm{ww}} = \hat{w}_{\mathrm{ww}}(y) \sin(k_x x + k_z z + C)$$

$$\frac{dw_{\mathrm{ssl}}}{dy} \approx \frac{dw_{\mathrm{ww}}}{dy}$$

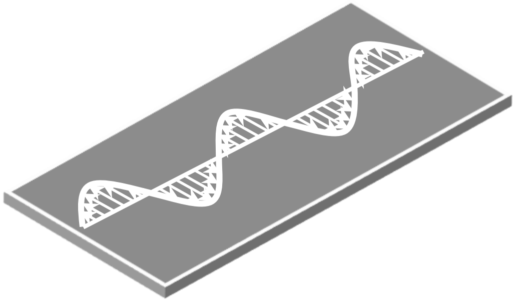
arXiv:1304.4638 →

$$\hat{p} \approx 0.9 \hat{w}_{\mathrm{w}} k_z^{2/3} / k_x$$

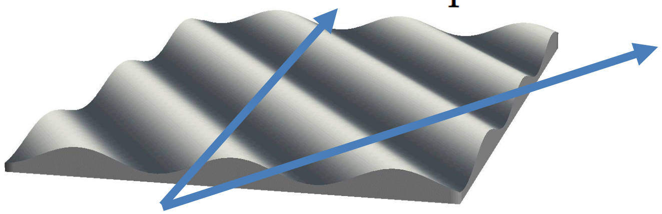
* Phase shift between SSL and WW is ignored in this presentation, and wall units used

Talk by Sergei Chernyshenko

A wavy wall is a few times more energy expensive than a moving wall



$$\Theta_{\mathrm{opt}} = 52.56^\circ$$



$$w_{\mathrm{ssl}} = \hat{w}_{\mathrm{ssl}}(y)\sin(k_x x) \qquad w_{\mathrm{ww}} = \hat{w}_{\mathrm{ww}}(y)\sin(k_x x + k_z z + C)$$

$$u_{\mathrm{ssl}} = U(y) \qquad u_{\mathrm{ww}} = U(y) + \hat{u}_{\mathrm{ww}}(y)\sin(k_x x + k_z z + C)$$

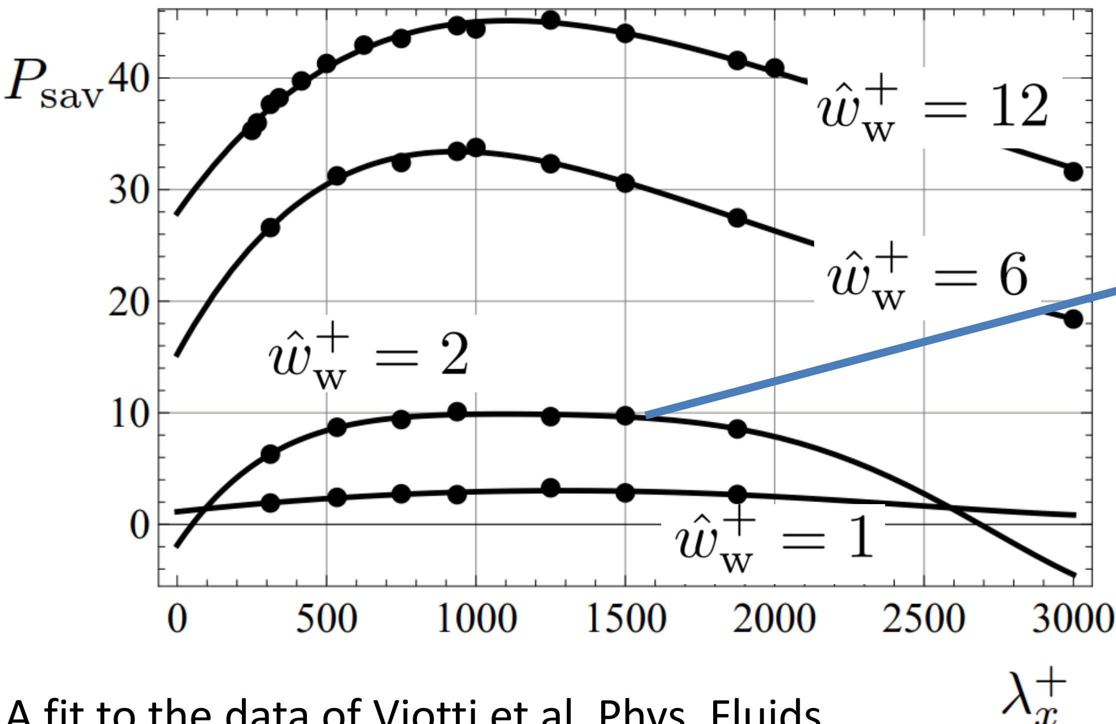
$$r = \frac{\text{energy dissipated due to wall motion}}{\text{energy dissipated due to wall waves}}$$

$$r = 3.122 + 2.323\frac{k_x^2}{k_z^2} + 0.7986\frac{k_z^2}{k_x^2} \qquad \left.\frac{k_x}{k_z}\right|_{\mathrm{opt}} = 0.7657$$

$$\boxed{r_{\min} = 5.846}$$

Talk by Sergei Chernyshenko

An assumption: when SSL and wavy wall match, the power saved by supressing turbulence is the same reduction by wavy wall → 2.4% drag

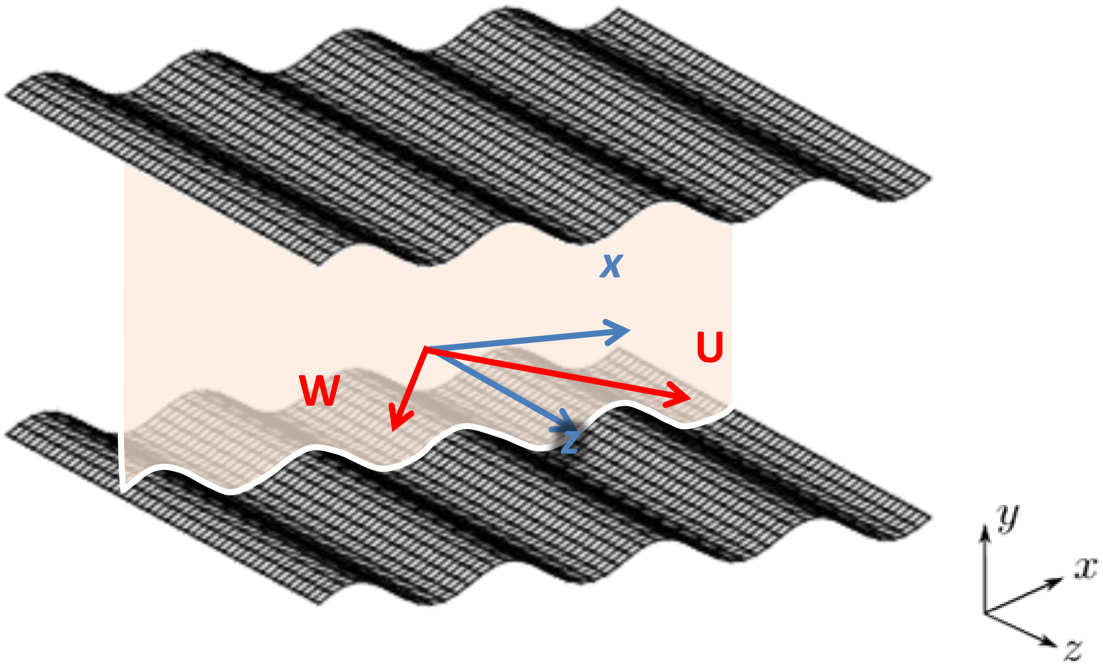


2.4% drag reduction at

$$k_x^+ = 2\pi/\lambda_x^+ \approx 2\pi/1520$$

A fit to the data of Viotti et al. Phys. Fluids, 21(11):1–9, 2009

DNS – Skewed flow



$$\Delta x^+ = \Delta z^+ < 2$$

$$\Delta y^+ \in [0.6, 4.5]$$

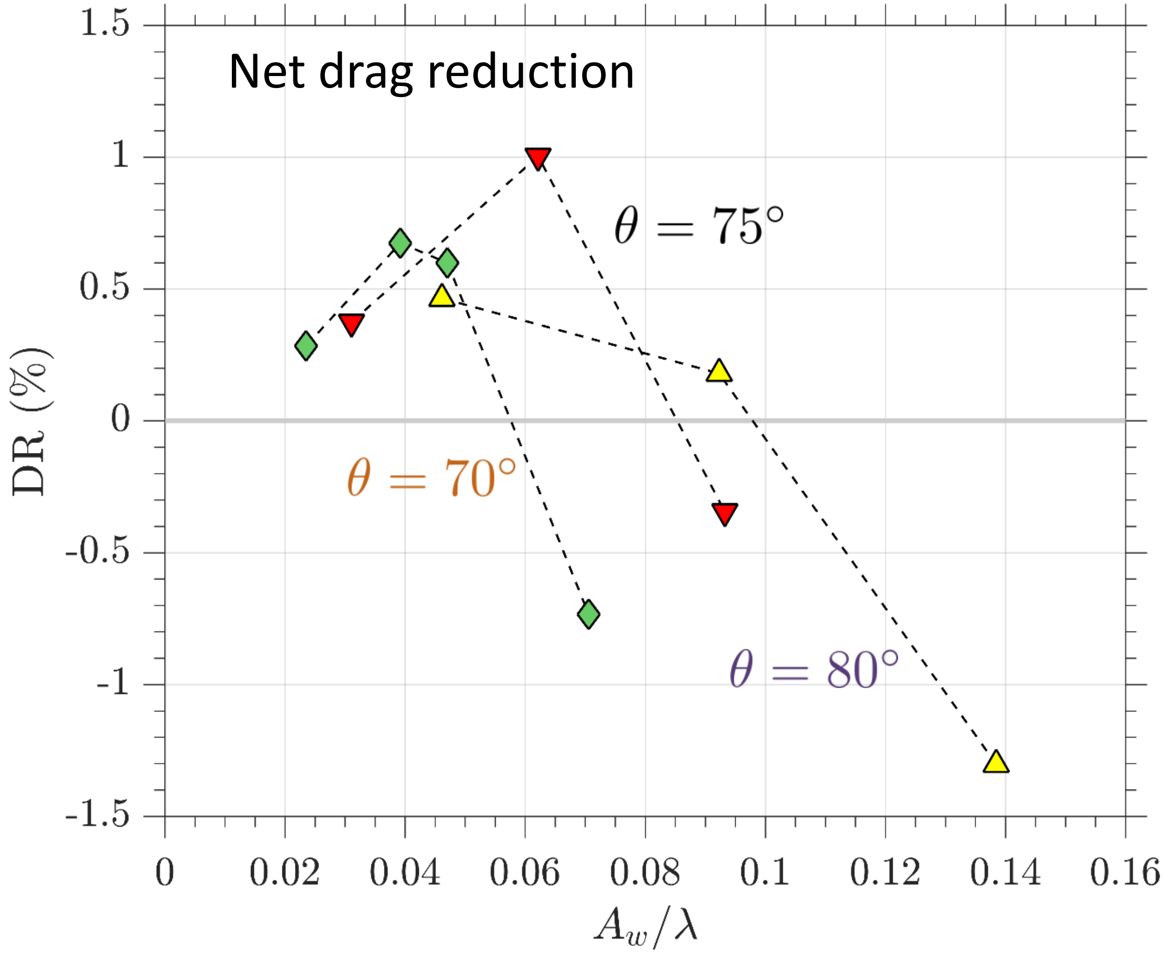
$$L_x^+ \times L_z^+ \approx 1900 \times 3700$$

$$\Delta t^+ = 0.02$$

2 – 3 waves

700M cells, 1728 cores, ~ 10 days

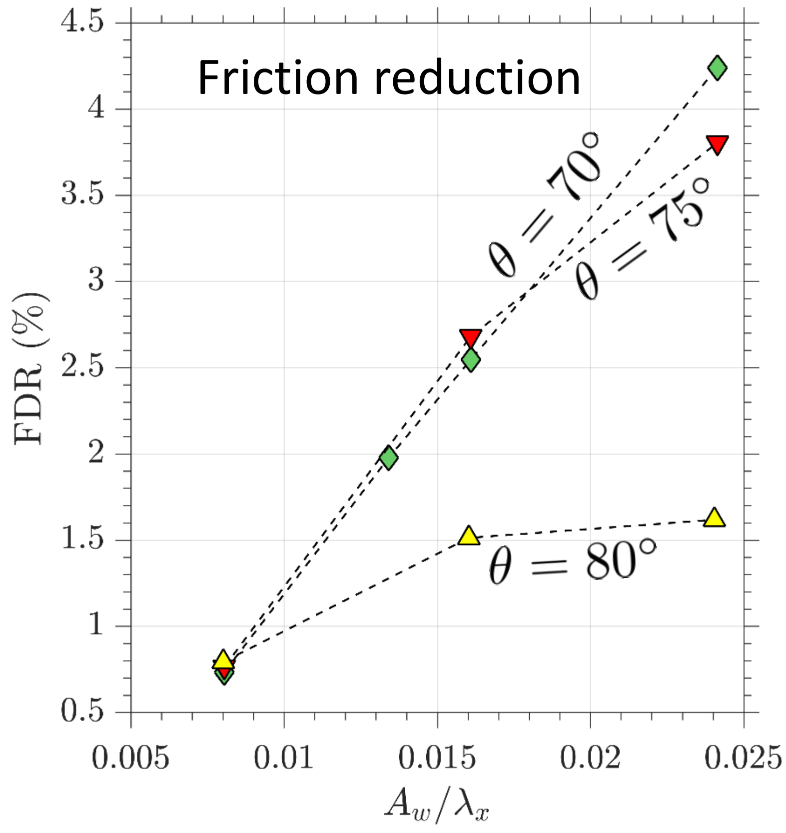
There is drag reduction, but 1% only and at a different angle and wavelength from predicted

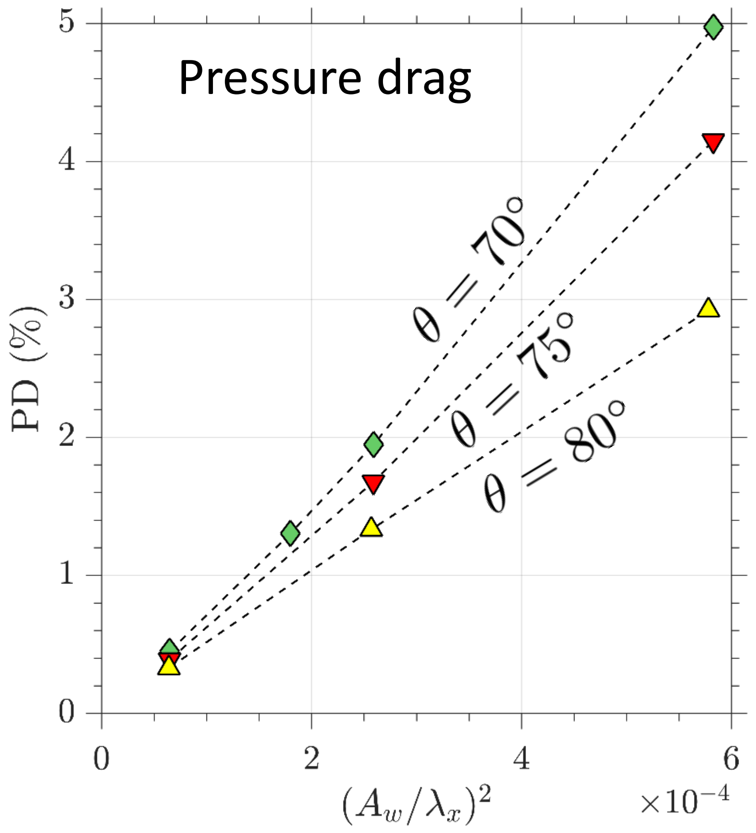


$$Re_\tau \approx 360$$

$$\lambda_x^+ \approx 2700$$

Also, the drag reduction is observed at a smaller amplitude than predicted by the theory

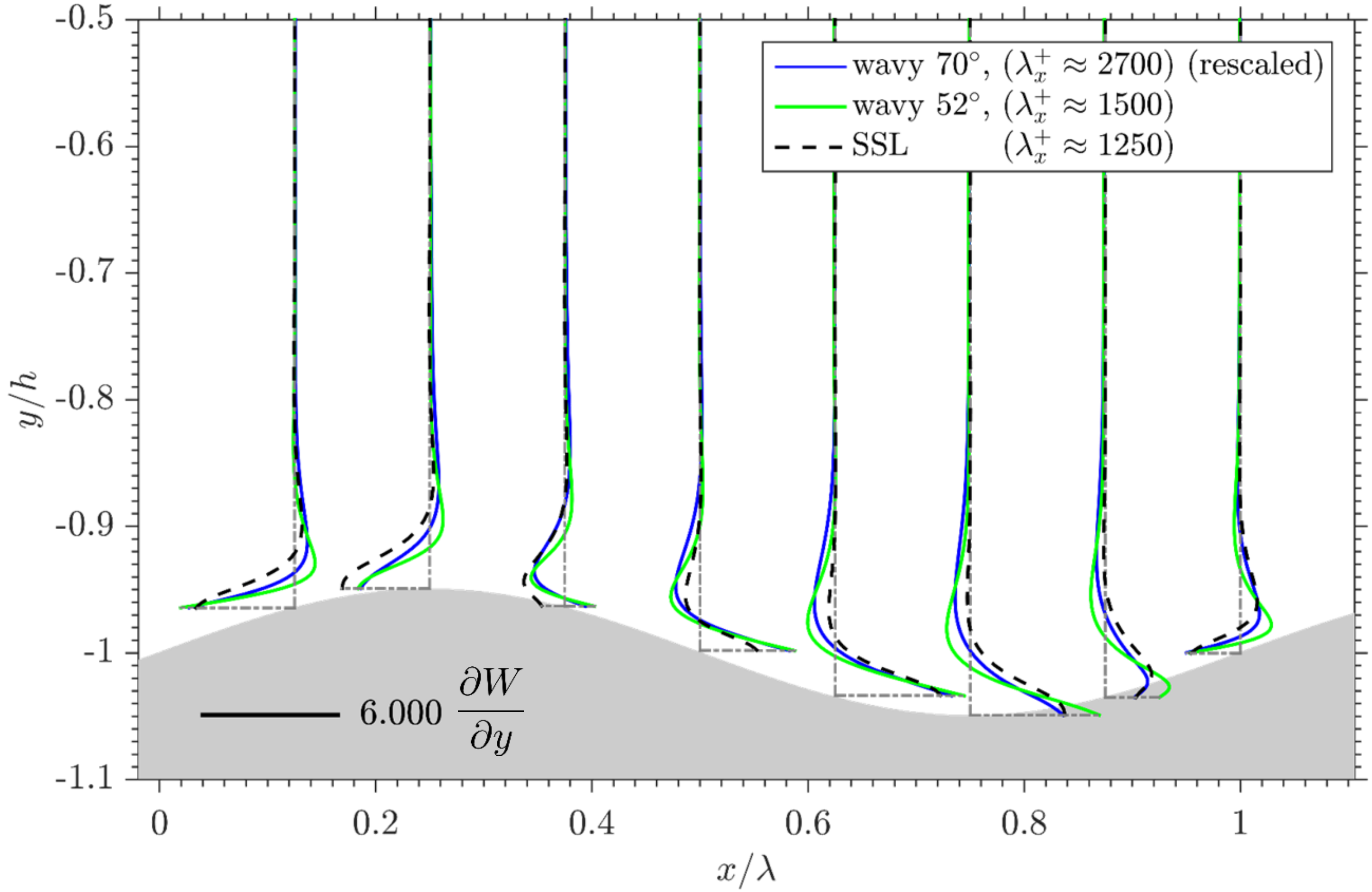




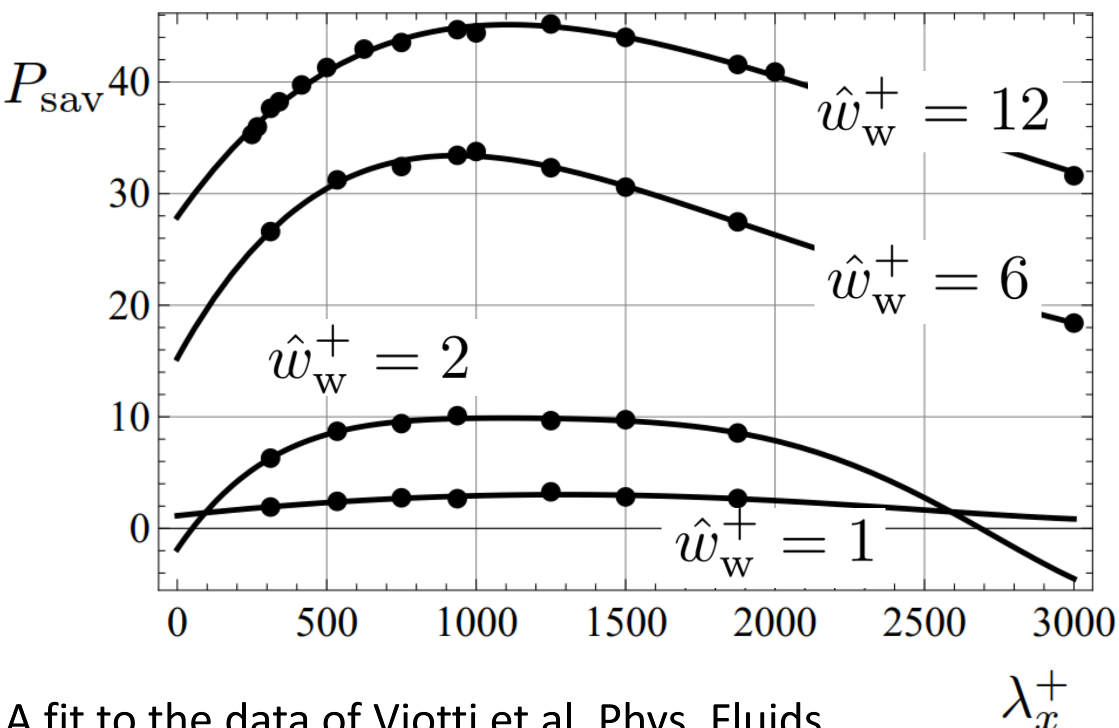
DNS: spanwise shear of SSL and a wavy wall are indeed close

Comparison of the shear strain

$Re_\tau \approx 360$



An assumption: when SSL and wavy wall match, the power saved by supressing turbulence is the same, but the DNS says:



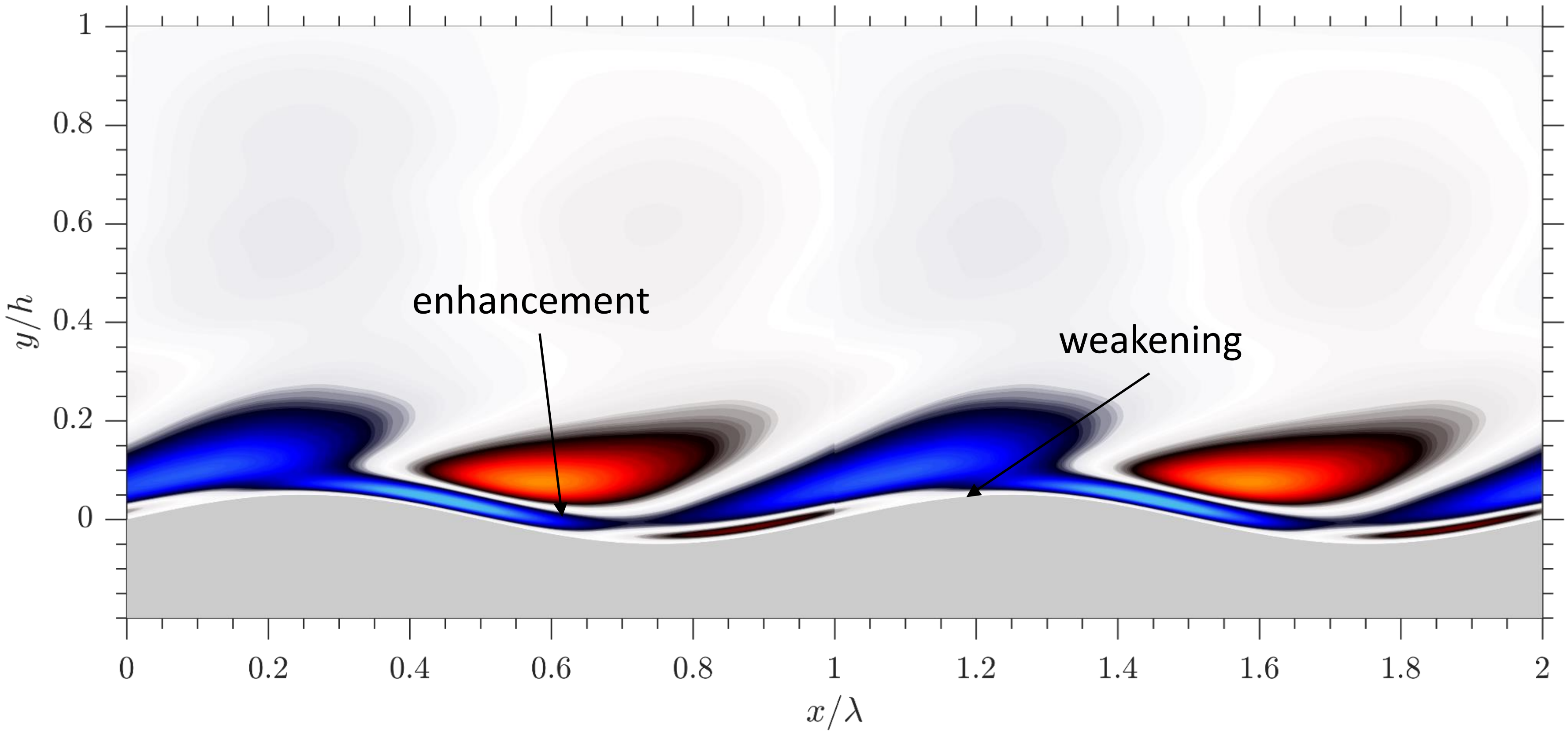
A fit to the data of Viotti et al. Phys. Fluids, 21(11):1–9, 2009

DNS: at this Re, a substantial part of the power is saved due to the change in the mean profile.

We can have the same suppression of turbulence but less power saved due to smaller change in the mean profile.

Longitudinal pressure gradient strongly affect turbulent fluctuations

Change in $\overline{u'^2}$ from the baseline



Conclusions

- ✓ The proof of concept is given: wavy wall produced drag reduction, although small (about 1%)
- ✓ The wavy wall does create a spanwise shear profile similar to that created by a steady Stokes layer
- ✓ The semi-empirical theory should be improved by taking into account the effect of wall forcing on the mean profile energy dissipation
- ✓ Drag reduction can be affected by the influence of the longitudinal pressure gradient. Hence, modifying wall shape to reduce the effect of the unfavourable pressure gradient can be beneficial
- ✓ Reducing the longitudinal component of the mean velocity induced by the waves can be beneficial