Re-dependence of drag reduction by wall actuation

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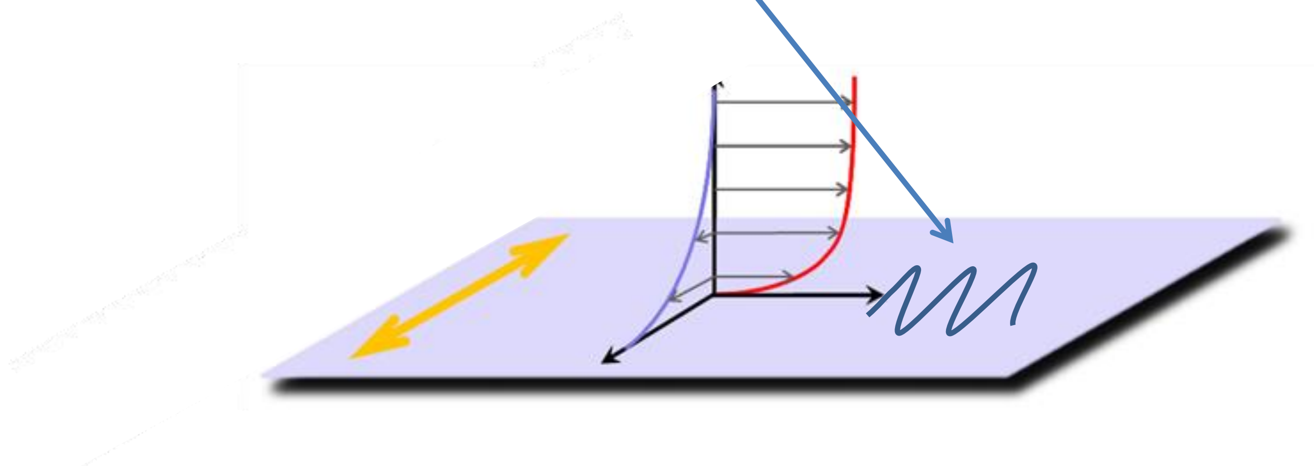
Context

- Active drag reduction by in-plane wall motion
  - Combination of oscillatory spanwise motion and streamwise waves

$$W(x,t) = W_m \cos\left(2\pi \frac{t}{T} + 2\pi \frac{x}{\lambda} \right)$$



$$W_m^+ = \frac{W_m}{u_\tau} \qquad T^+ = \frac{u_\tau^2}{\nu} T \qquad \lambda^+ = \frac{u_\tau}{\nu} \lambda$$

- Methodology applies to any other drag-reduction scenarios

Motivation

- DNS shows significant decline of drag-reduction effectiveness with *Re*

- For given actuation parameters log-law appears to asymptote to a near-constant upward shift

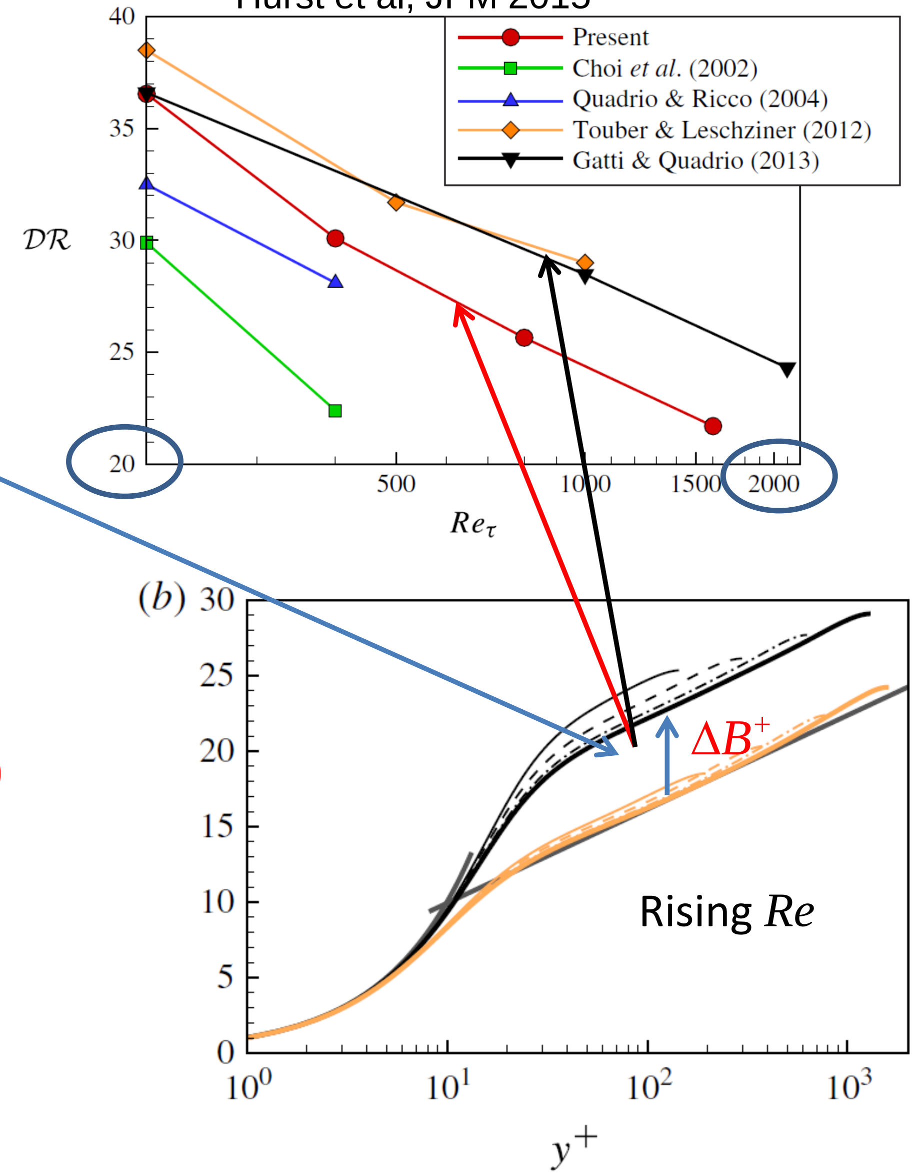
$$\Delta B^{+} \rightarrow const \qquad \neq f\,(Re)$$

- log-law can be manipulated (Gatti & Quadrio, 2017) to give:

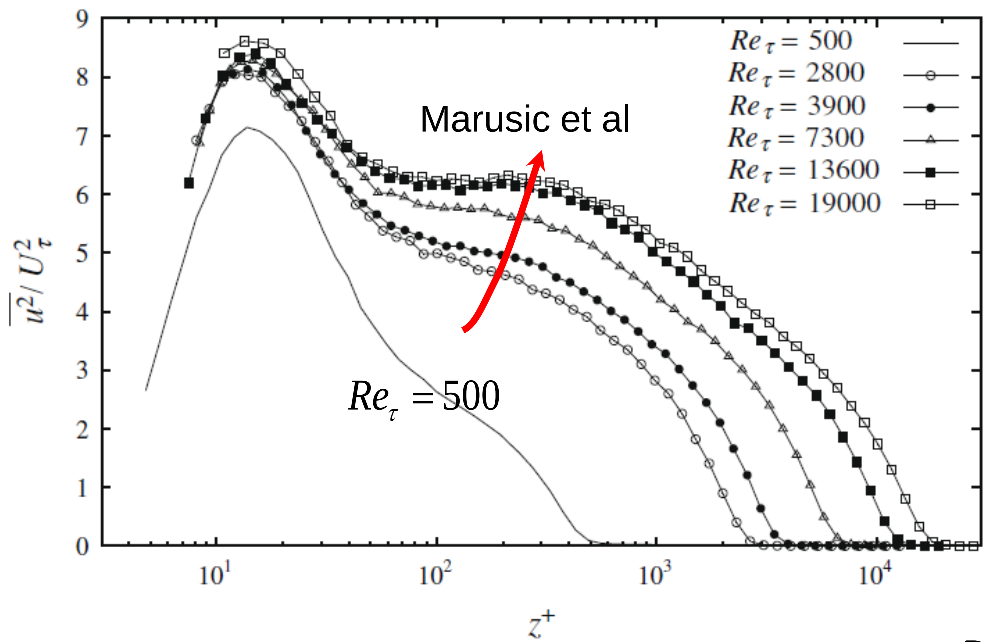
$$DR = f\,(Cf_o, \Delta B^{+}), \ \text{but} \ Cf_o = f\,(Re)$$

Unactuated skin friction

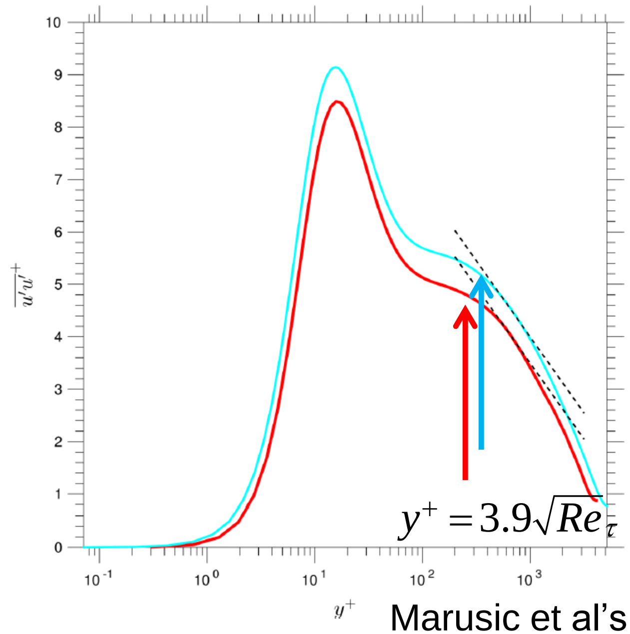
Hurst et al, JFM 2015



Motivation



Experiment: $Re_\tau = 2800 - 19000$



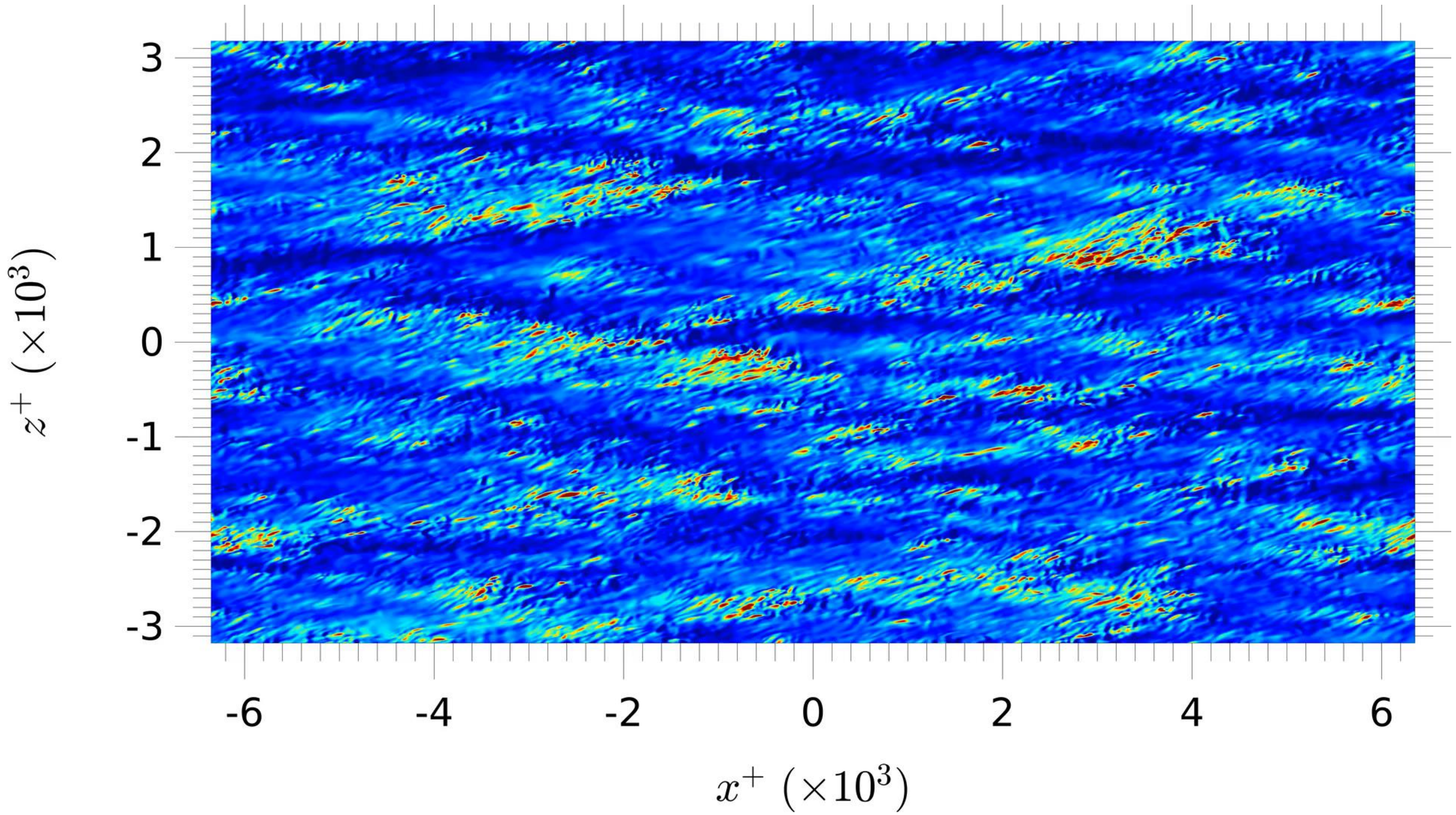
DNS: $Re_\tau = 4200, 5300$

Marusic et al's correlation of location of structures

- Streamwise energy has outer peak
- Energy increases progressively with Reynolds number
- Suggests presence of energetic outer structures

Do these distort Cf and DR ?

Effects of outer structures on skin friction



- Key question: What is the role of energetic outer structures
  - In distorting turbulence in viscous wall layer?
  - in reducing effectiveness of actuation?

Conceptual representation of LS-SS interaction

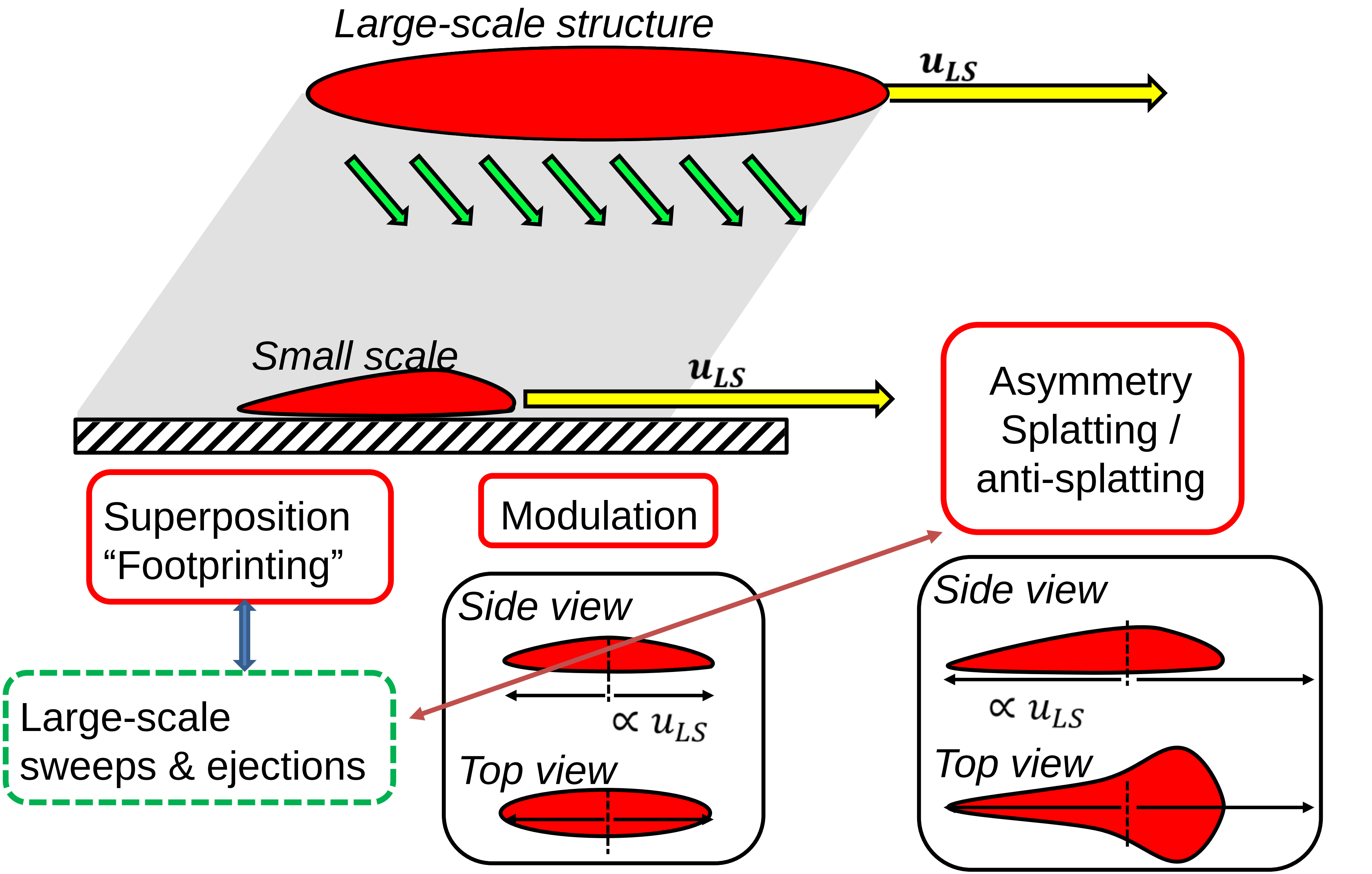
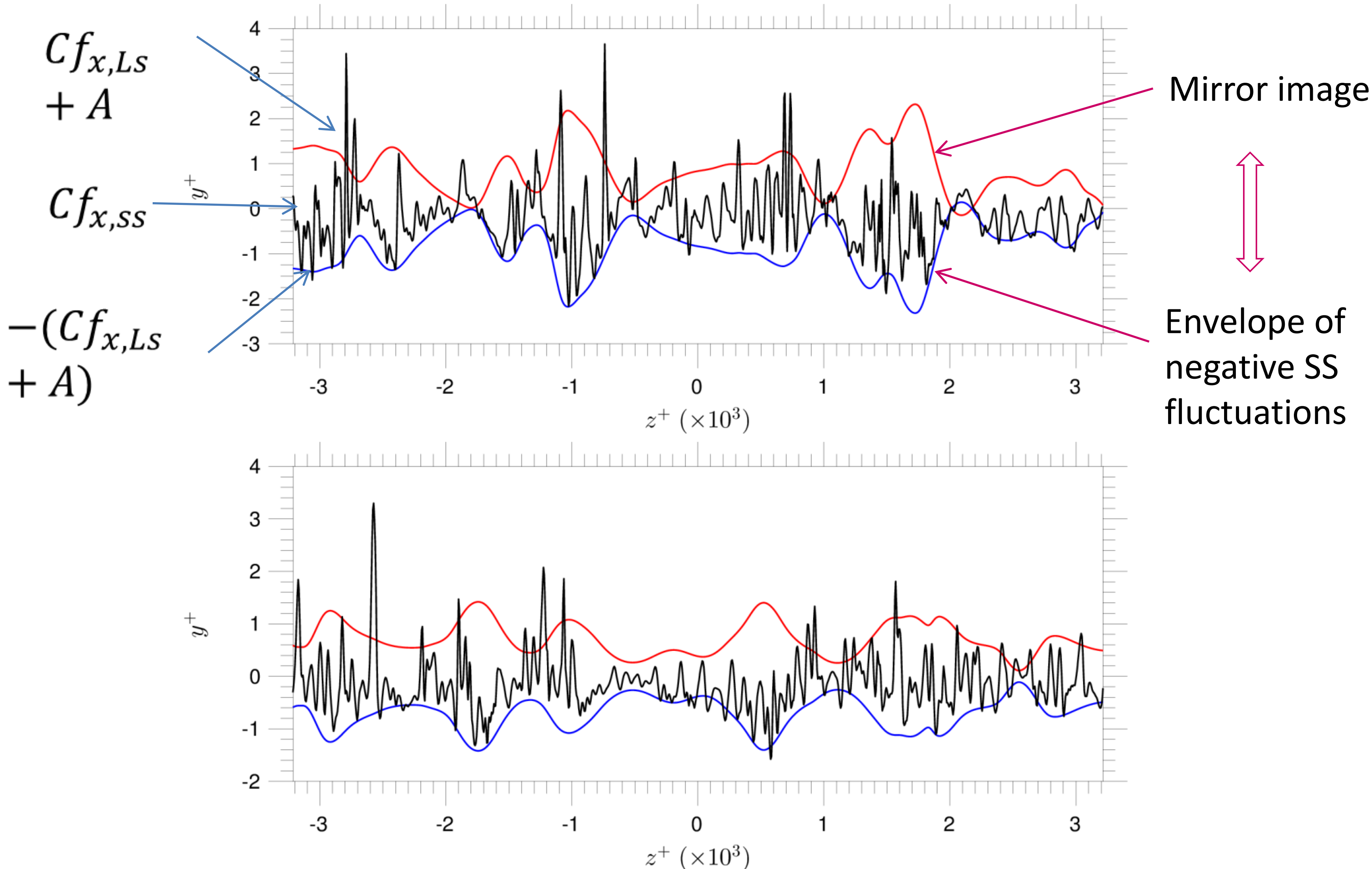


Illustration of skewness of small-scale fluctuations

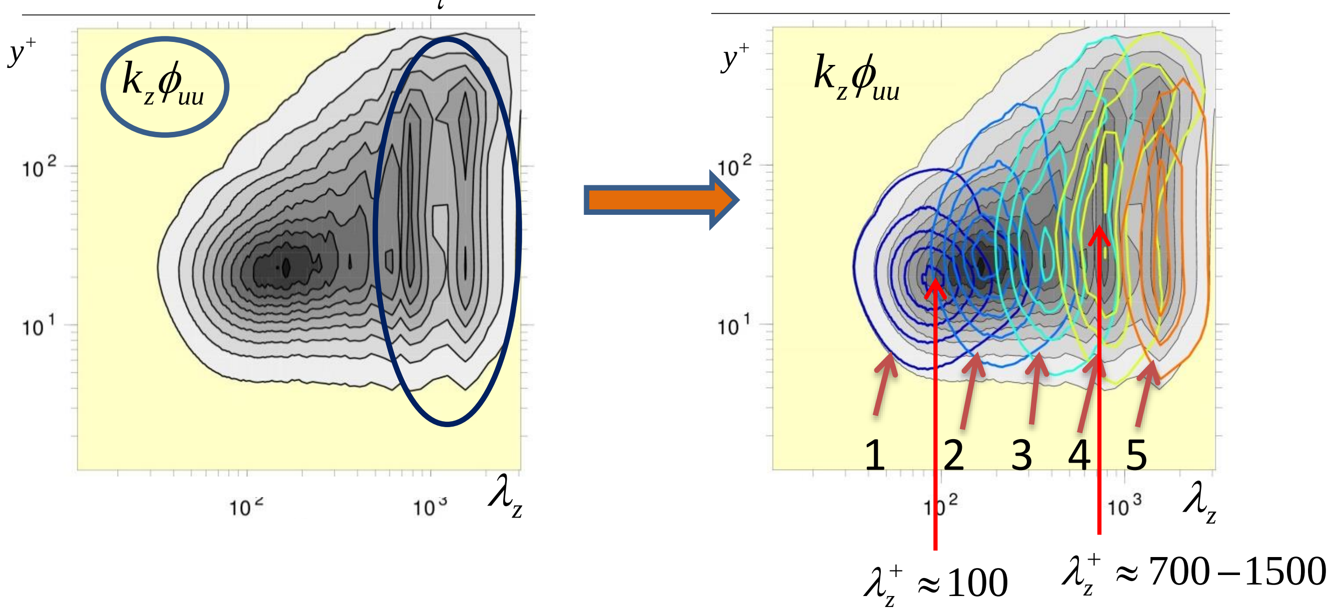
- Two instantaneous spanwise snapshots of "small-scale" skin friction
- Envelope of magnitude determined with Hilbert transform



Large-scale/small-scale splitting

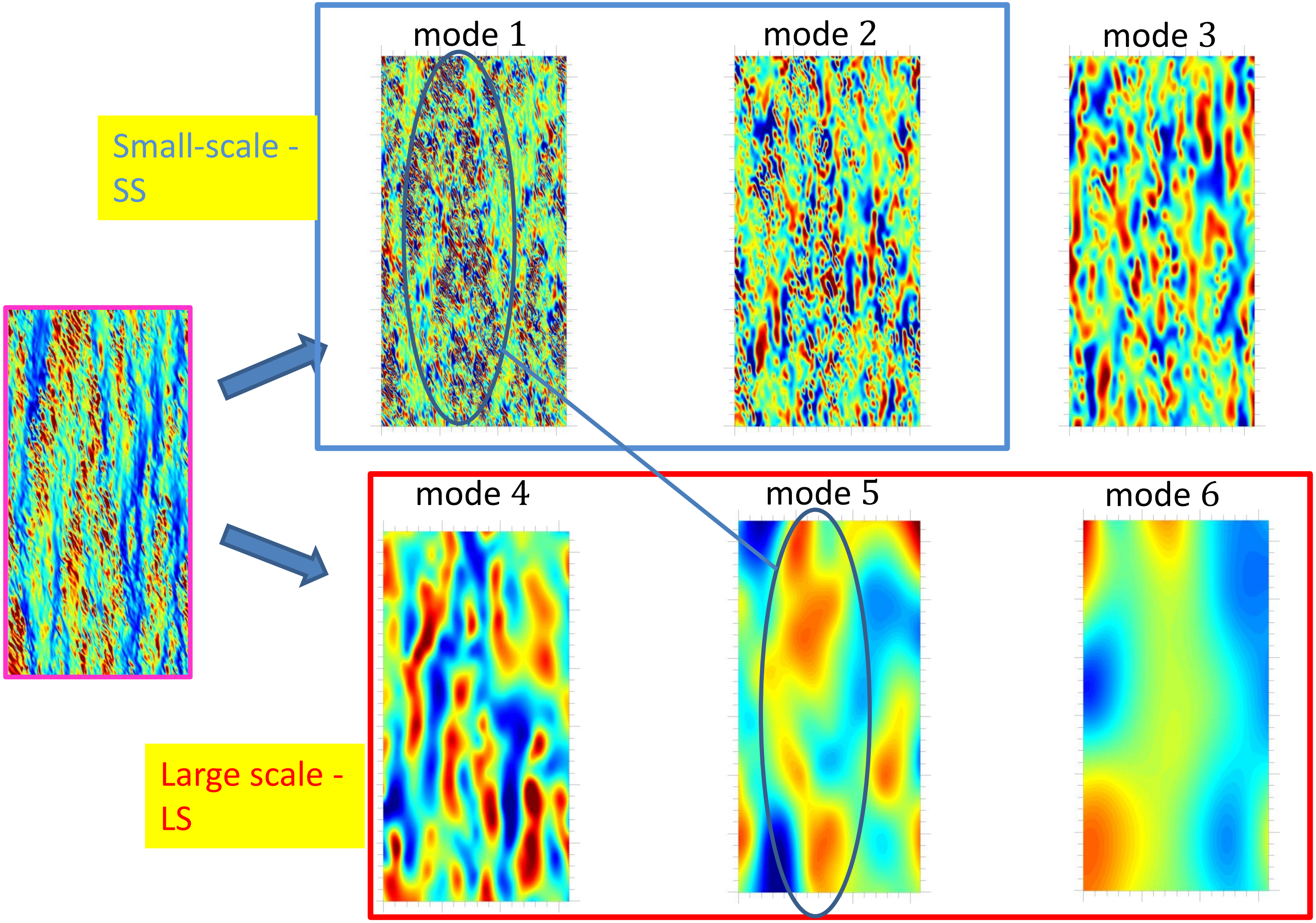
- Hilbert-Huang *Empirical Mode Decomposition (EMD) – 2D spatial implementation*
- Splits signal into chosen number of *Intrinsic Modes*
- No Fourier cut-offs or explicit filtering; energy conserving
- Mode-wise split of pre-multiplied spanwise spectra of streamwise velocity fluctuations; 6 modes

$Re_\tau = 1020 \quad T^+ = 100$

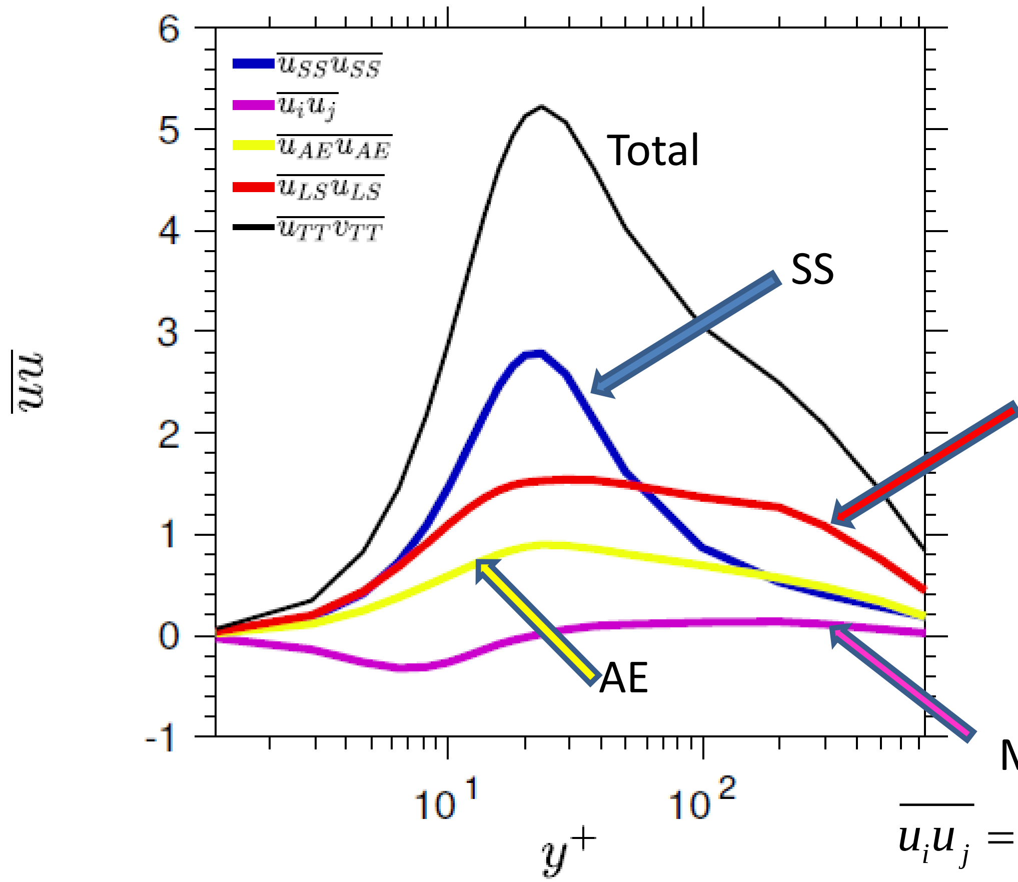


Large-scale/small-scale splitting

- Modal decomposition of streamwise energy at $y^{+} = 13$



Contributions of modes to streamwise energy



$$\overline{u_i u_j} = 2\overline{u_{SS}u_{LS}} + 2\overline{u_{SS}u_{AE}} + 2\overline{u_{LS}u_{AE}}$$

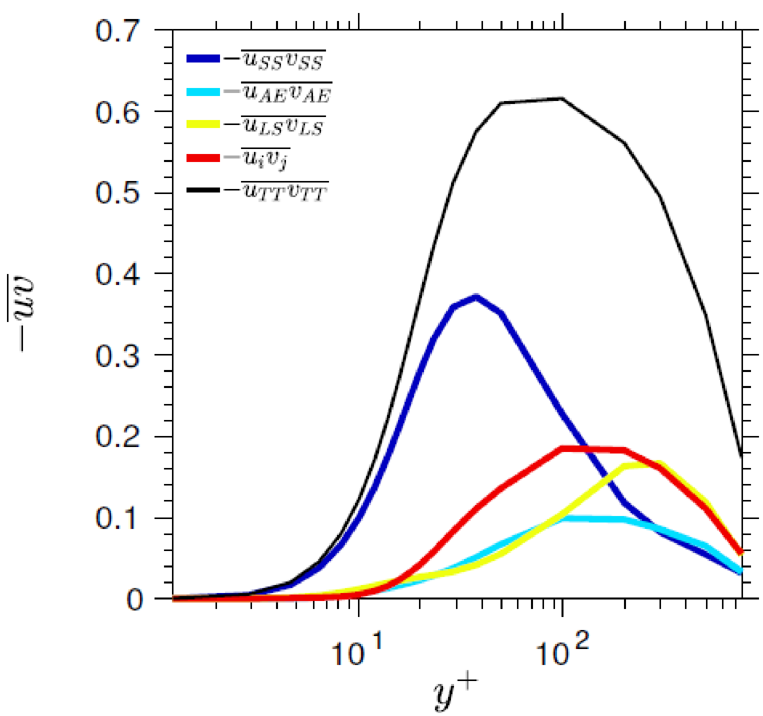
- Mixed-mode contributions weak
- $\sum$ modal contributions = total

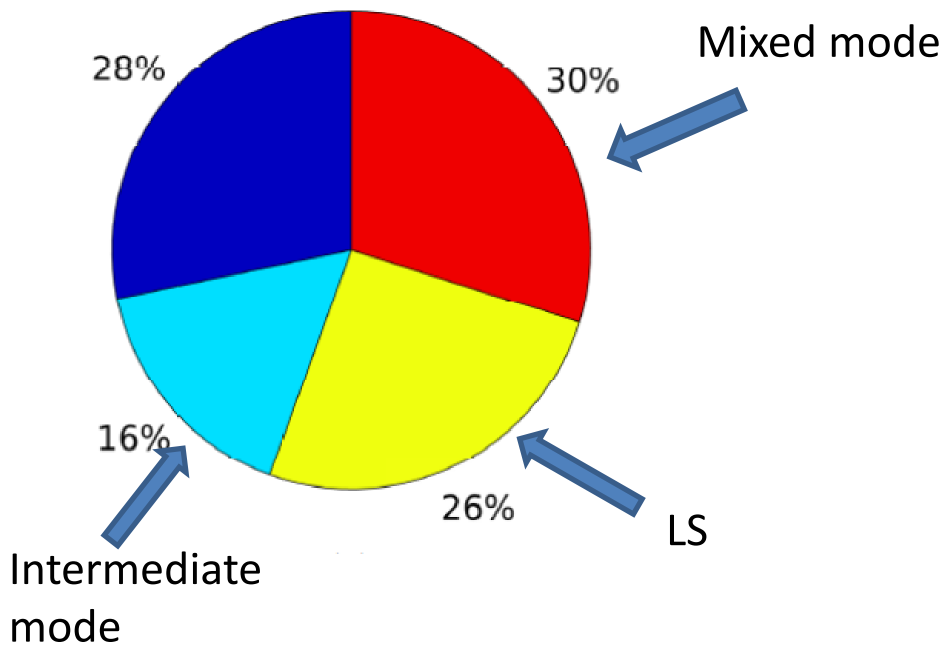
Contributions of modes to shear stress and skin friction

- Contribution of turbulent shear stress to C_f (Fukagata-Iwamoto-Kasagi relation)

$$C_f = \frac{12}{Re_b} + 12\int_0^1 2\left(1-\frac{y}{h}\right)\left(-\frac{\overline{uv}}{4U_b^2}\right)d\left(\frac{y}{h}\right)$$

$$\overline{u_i v_j} = \begin{vmatrix} \overline{u_{SS}v_{SS}} & \overline{u_{SS}v_{AE}} & \overline{u_{SS}v_{LS}} \\ \overline{u_{AE}v_{SS}} & \overline{u_{AE}v_{AE}} & \overline{u_{AE}v_{LS}} \\ \overline{u_{LS}v_{SS}} & \overline{u_{LS}v_{AE}} & \overline{u_{LS}v_{LS}} \end{vmatrix}$$

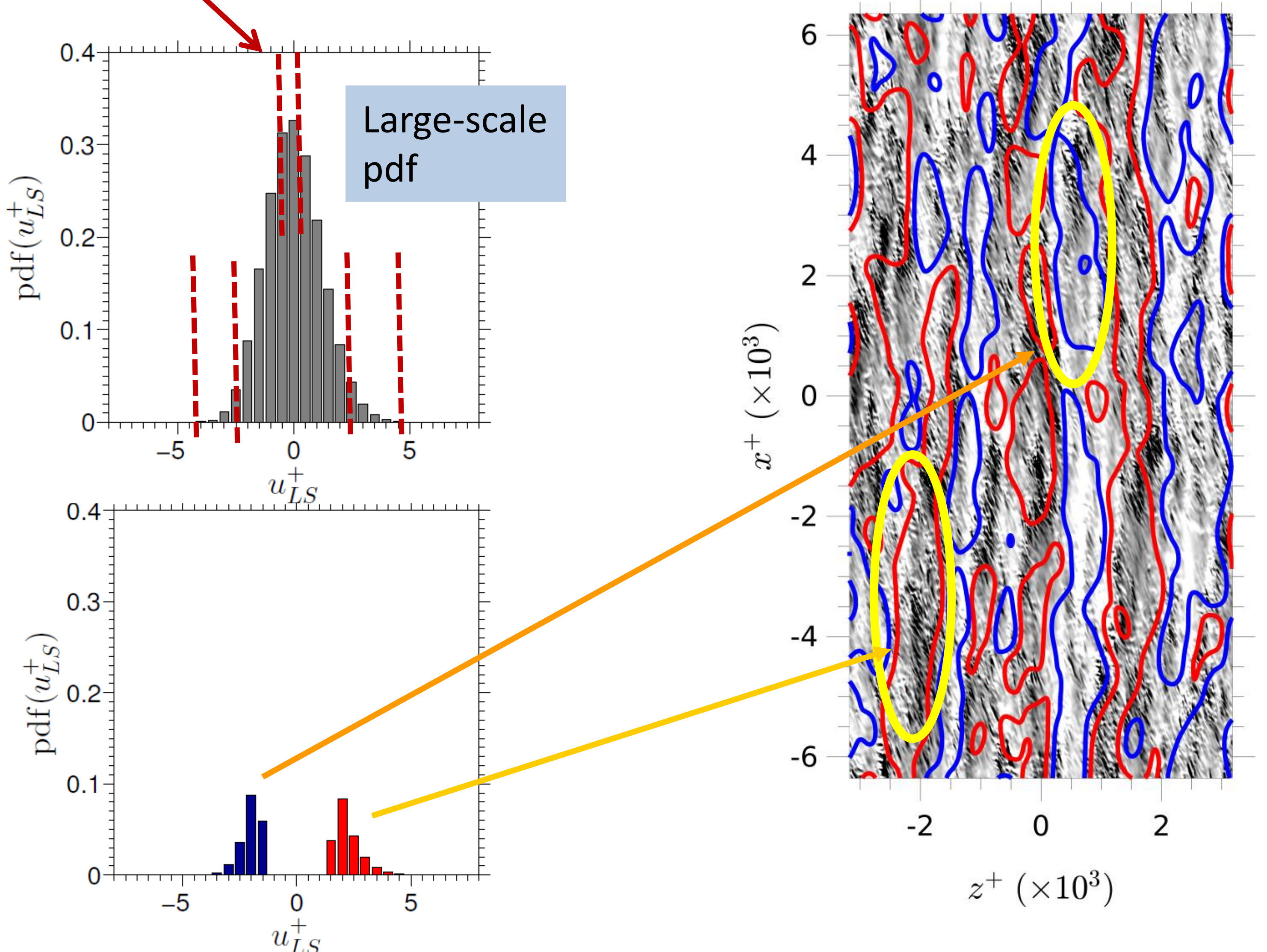




→ But contributions do not reflect indirect modulation interactions

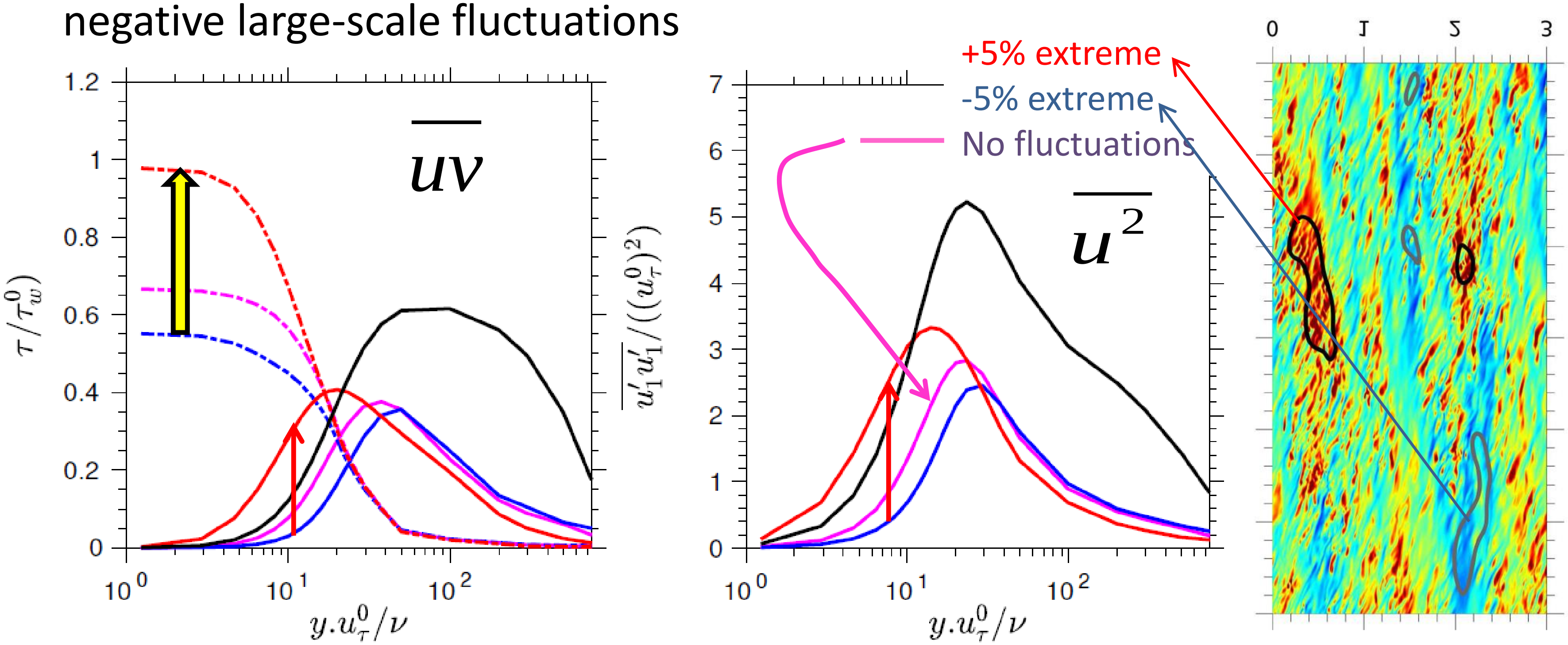
Conditional statistics

- Focus on 5%.... 50% sub-ranges of extreme events in large-scales PDF
- Addition of central band of PDF – absence of large-scale motions



Small-scale stress profiles

- Effect on small-scale shear and normal stress in extreme 5% positive and negative large-scale fluctuations

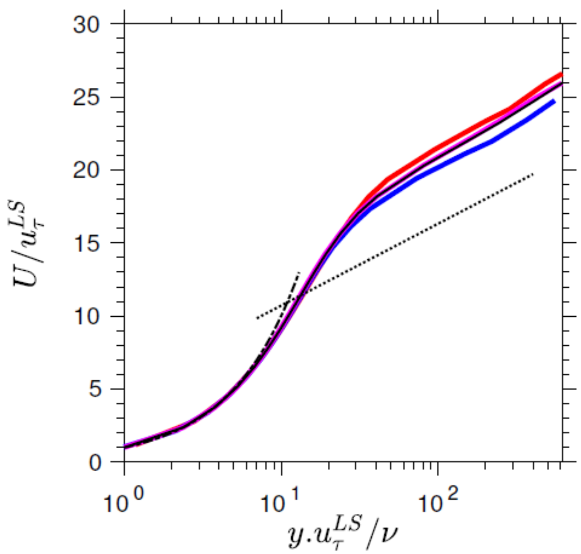


- Large positive LS fluctuations:
  - **thin** viscous sublayer & **increase** viscous stress
  - **Increase** turbulent SS stress near the wall
- Large negative LS fluctuations:
  - **thicken** viscous sublayer & **reduce** viscous stress
  - **reduce** turbulent SS stress near the wall

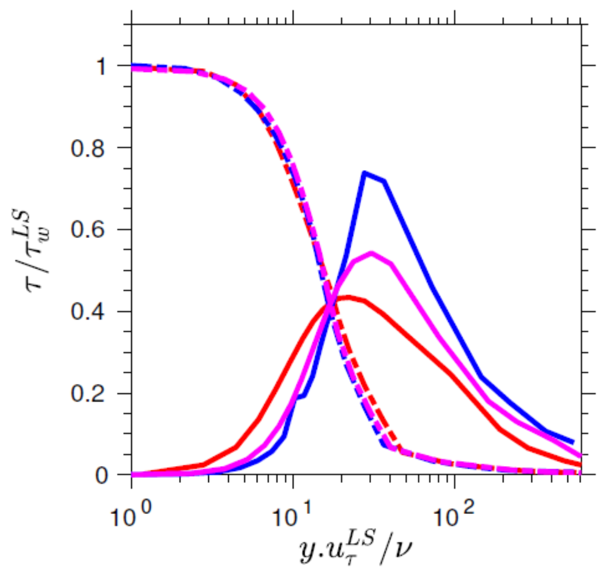
Effect asymmetric!

Quasi-steady representation

- Normalisation by LS-modified skin friction



$\overline{uv}$



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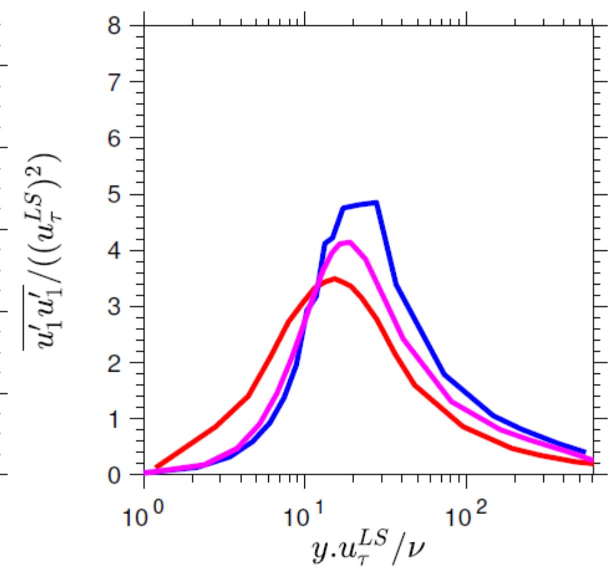
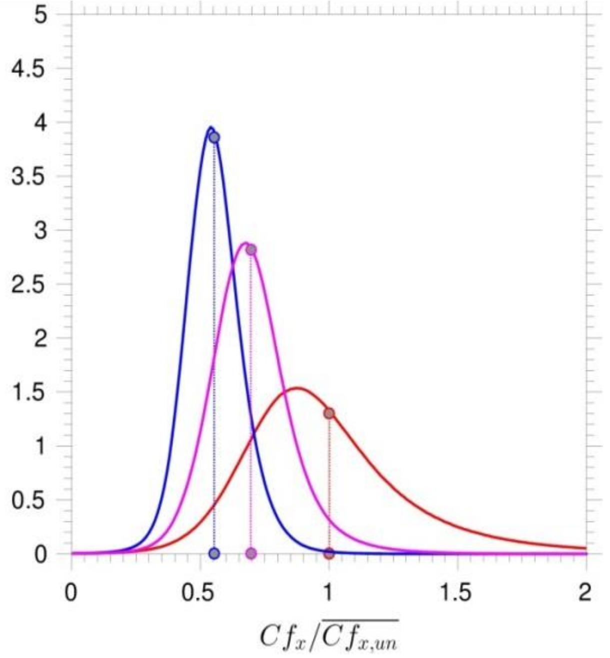


Conditional PDFs of Cf_x fluctuations

- Conditional sampling of SS skin-friction fluctuations within

  - 5% weakest LS events
  - 5% strongest LS events
  - 5% "no" LS events



- Strongly asymmetric modulation
- Positive LS motions cause much strongest modulation (large variance of PDF)
- Negative LS motions cause weaker modulation

→ streaks are already weak due to actuation

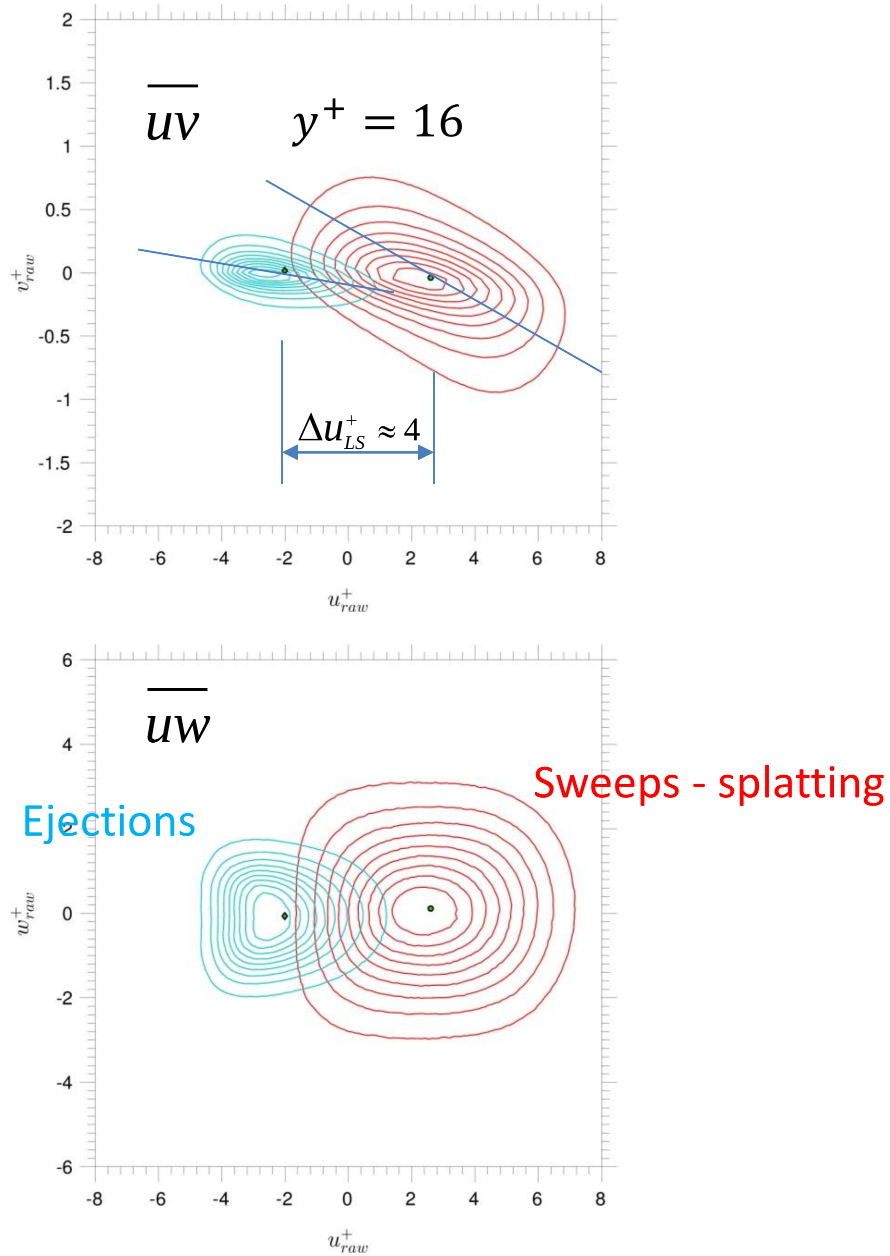
Joint PDFs of small-scale motions

- Conditional sampling within

  — 5% weakest LS events

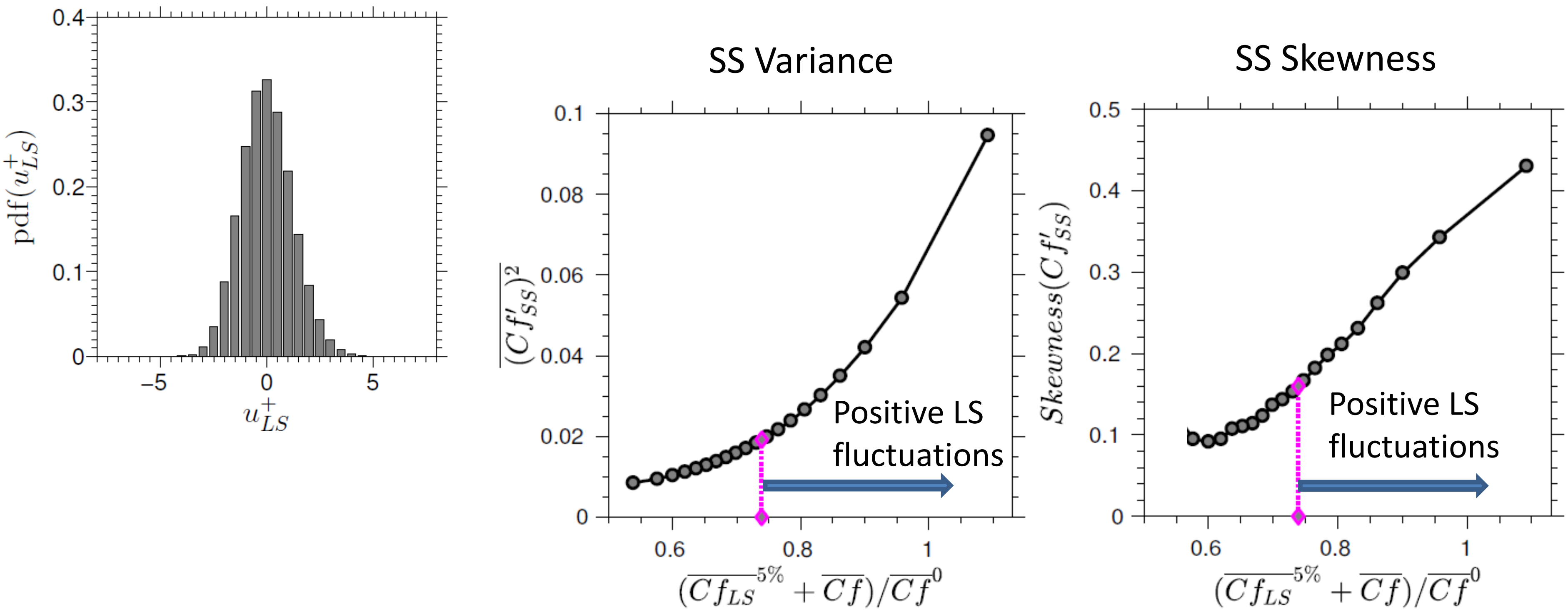
  — 5% strongest LS events

- Drastic differences in
  - intensity
  - correlation



Conditional sampling of Cf_x fluctuations

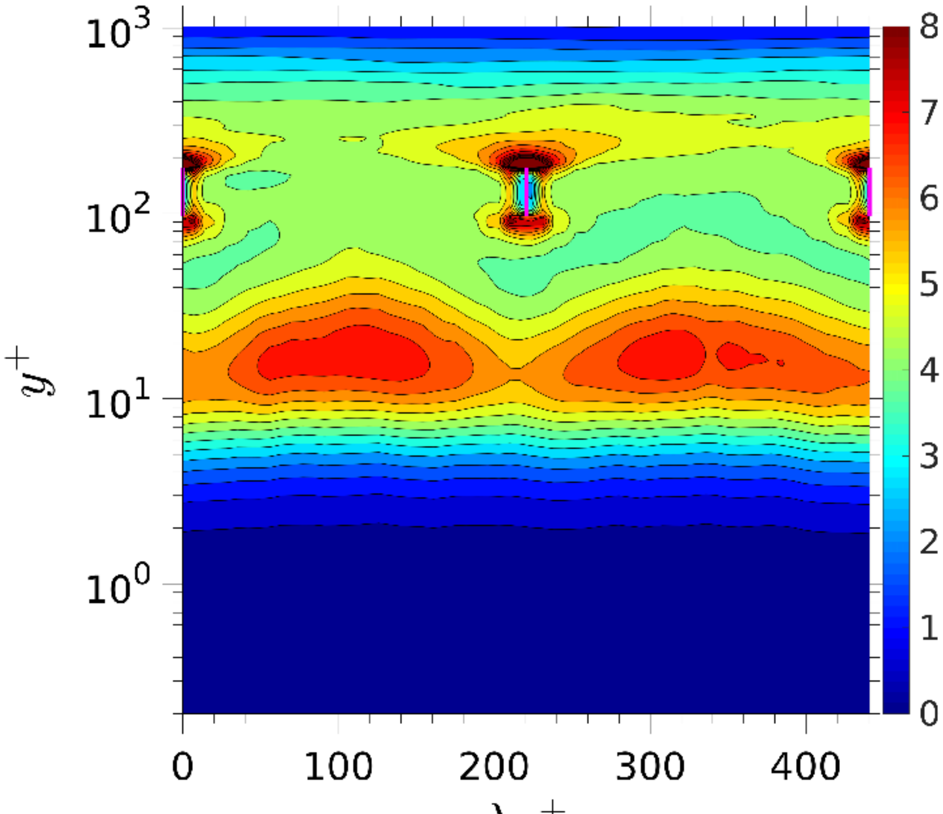
- Conditional SS PDFs within 5% segments of LS PDF



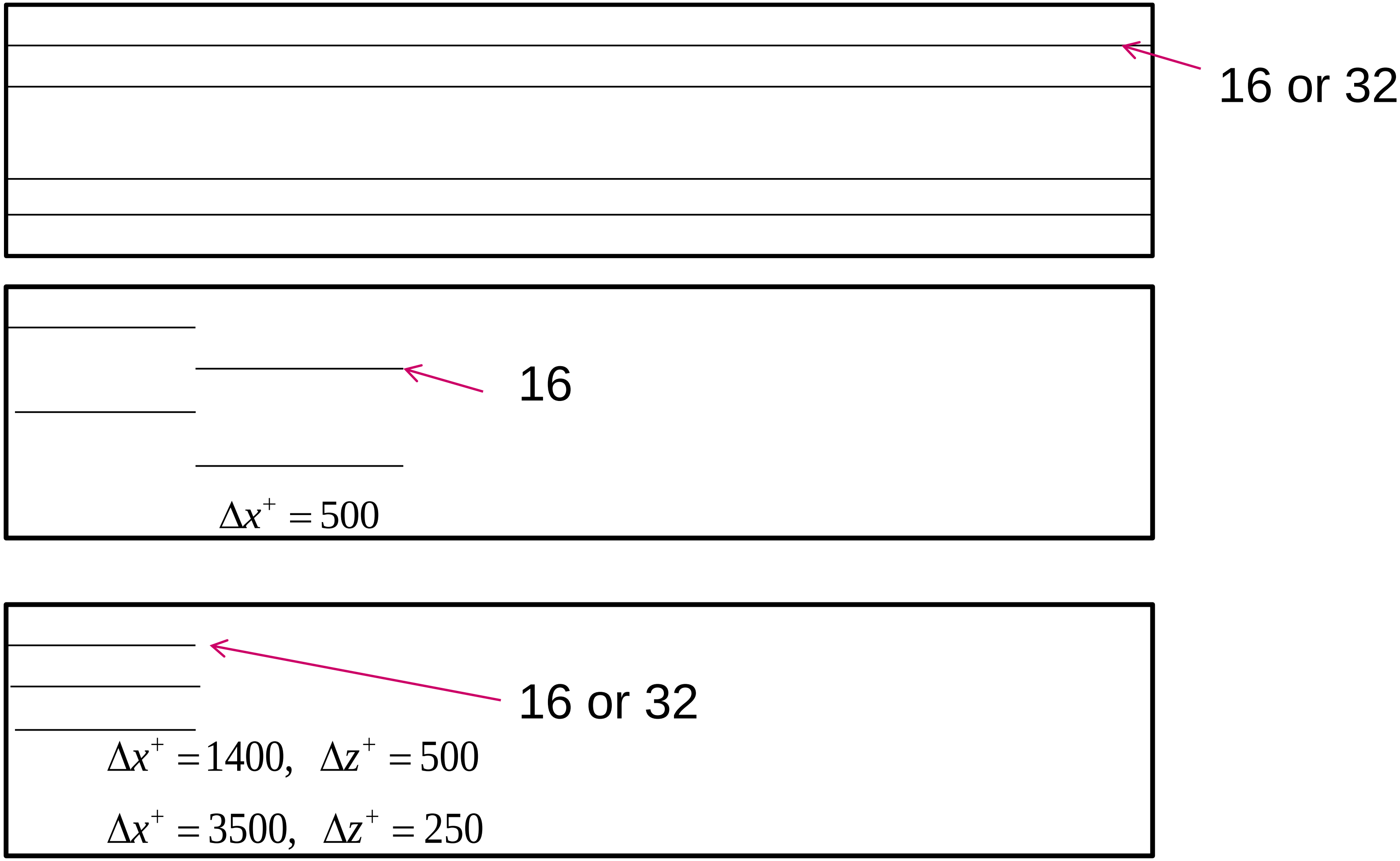
- Strongly asymmetric modulation
- Positive LS motions cause strongest modulation
  - large variance
  - Large skewness ⟶ Modulation cannot be described by variance alone!

Virtual LEBUs - overview

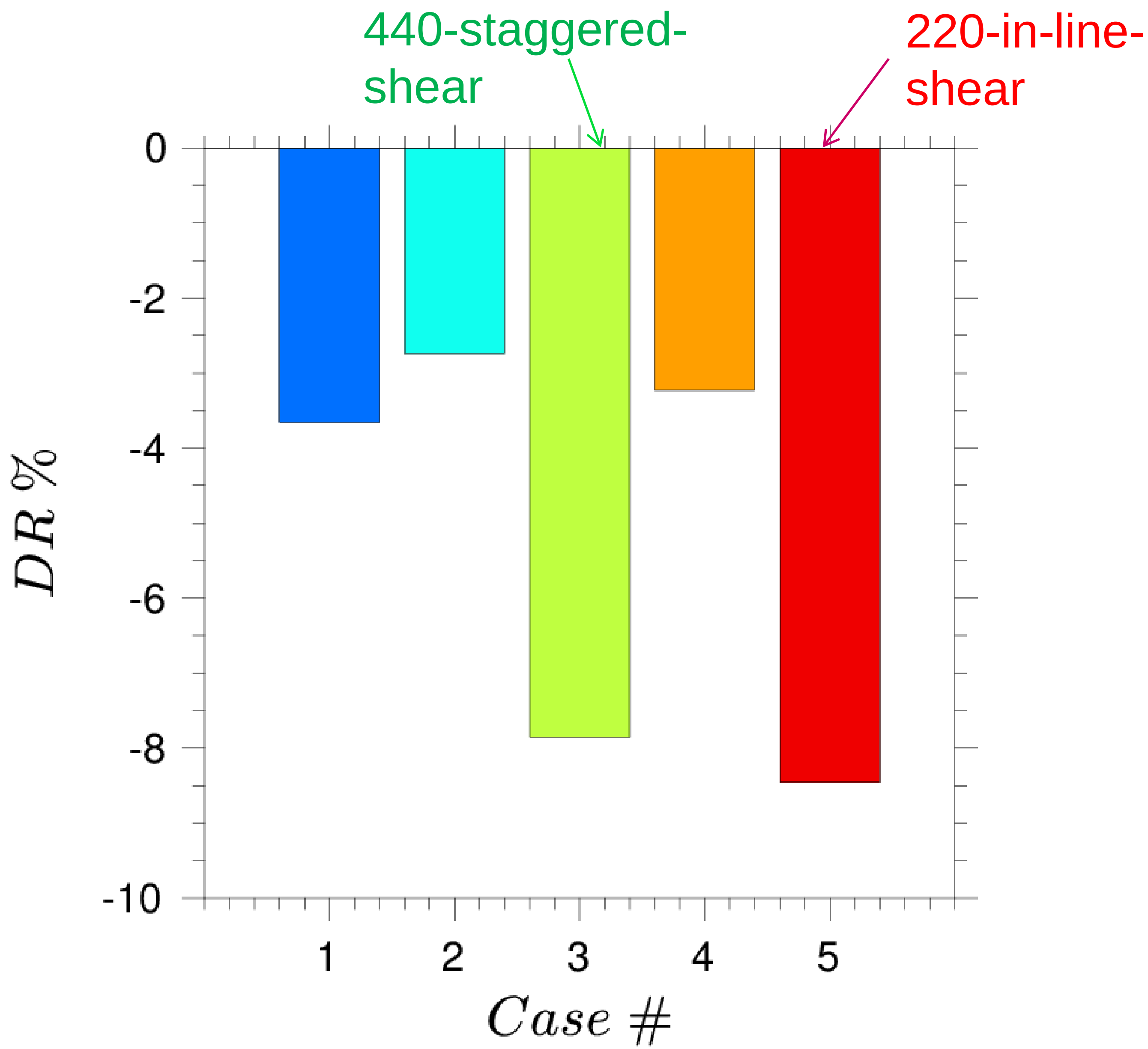
- DNS, canonical (unactuated) Channel flow $Re_\tau = 1000$
- Domain: $14h \times 7h \times 2h$ 1024x1024x512=0.5Bn nodes.
- Duration: $t^+ = 5000$
- LEBUs $y^+_{lower} = 80$ $y^+_{upper} = 200$ $\Delta z^+ = 220,\ 440$,
  in-line, z/x-wise staggered:
- LEBUs treated as real or frictionless.
- Total: 10 configurations
- Parasitic drag ignored
- Computations on ARCHER on 24000 cores, with UKTC resources



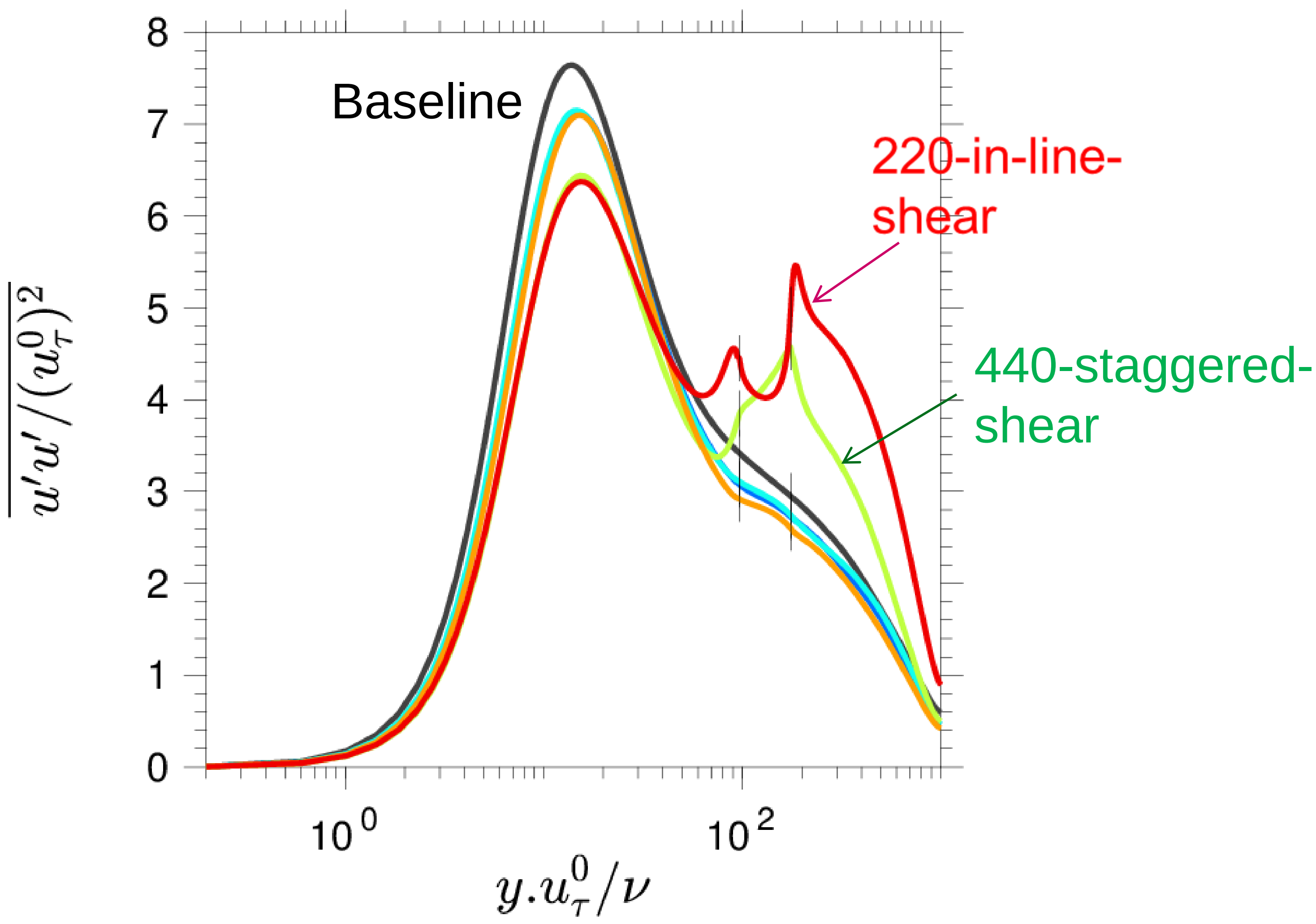
Configurations



Drag reduction



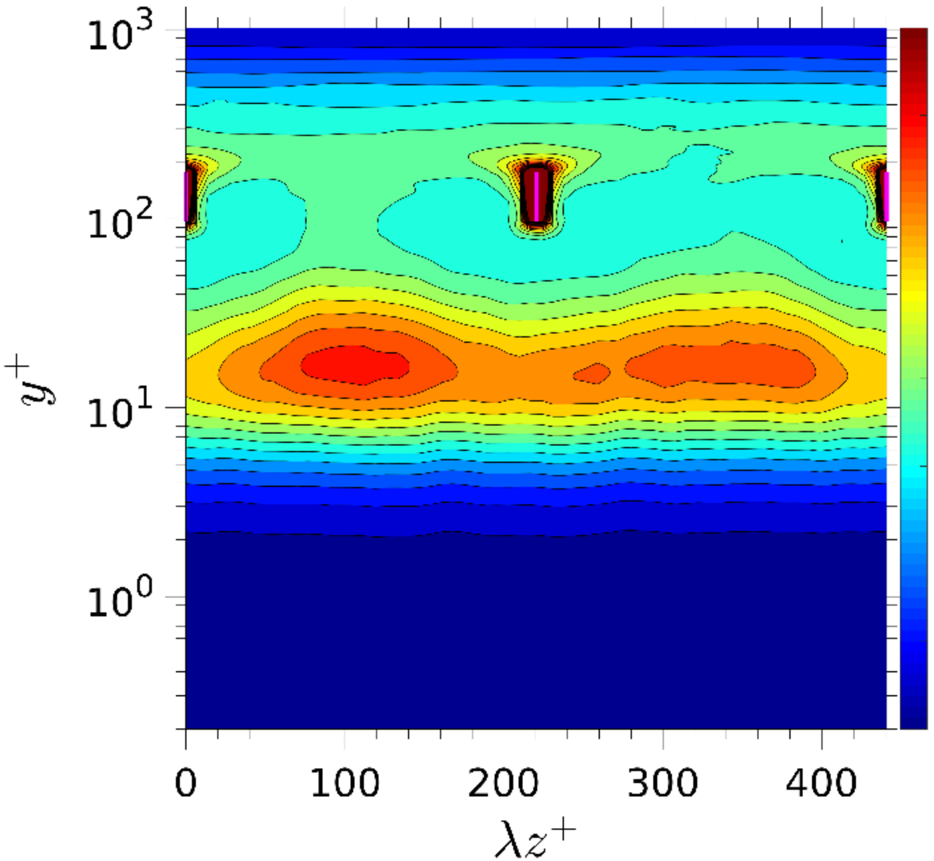
Average streamwise energy



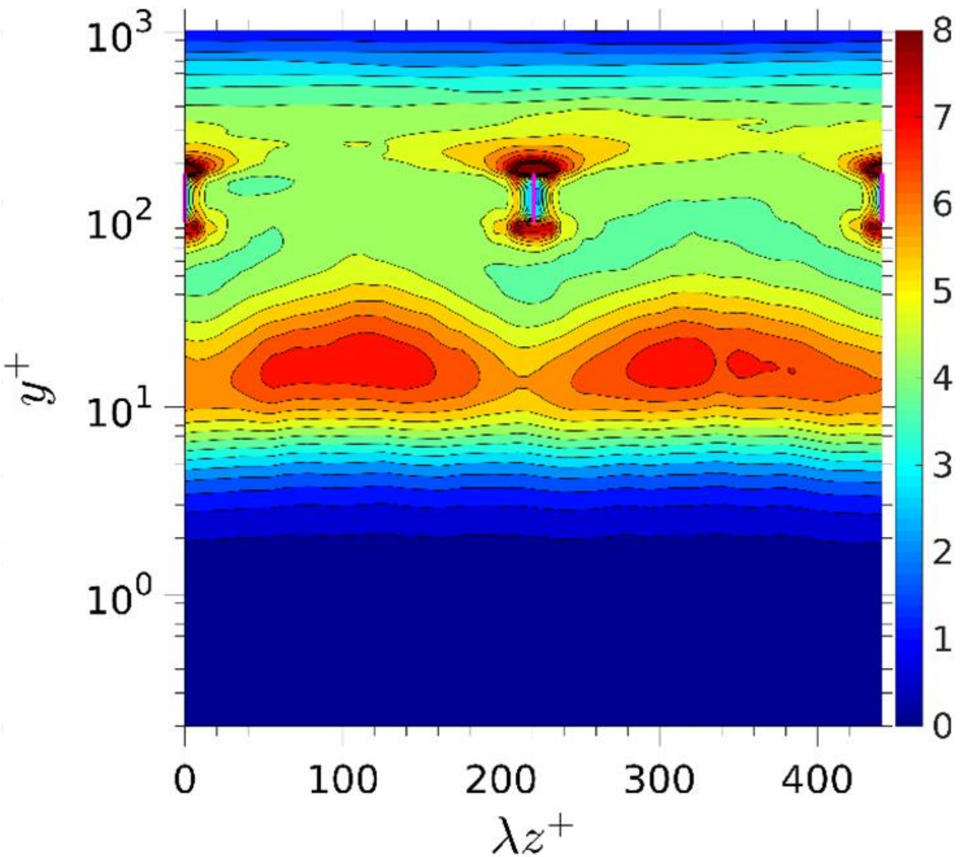
Average streamwise energy

Streamwise-
integrated !!!

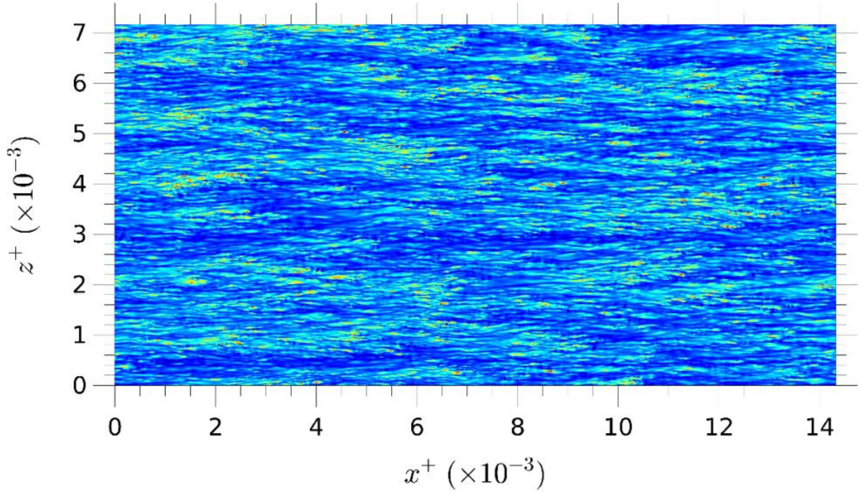
Staggered with shear



In-line with shear

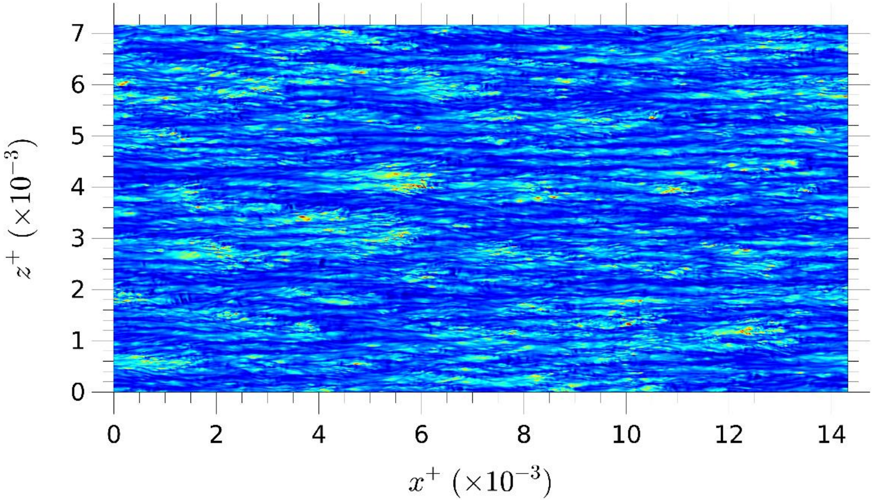


Skin friction snapshots

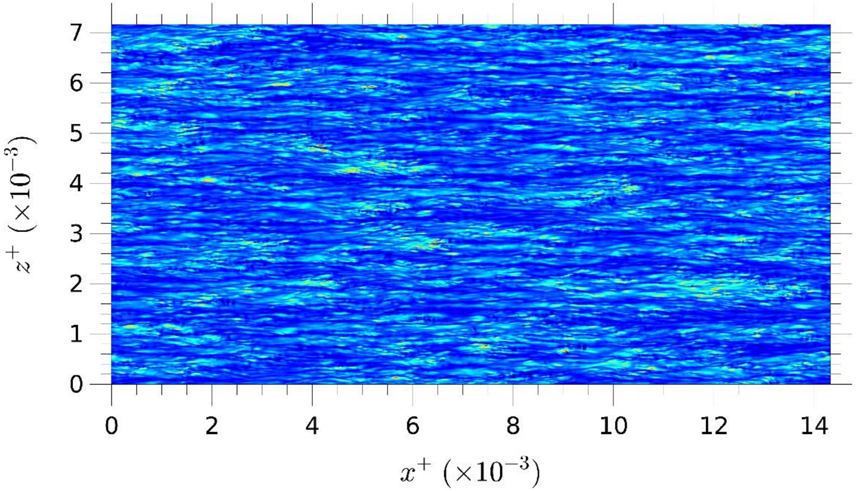


Baseline

In-line with shear



Staggered with shear



Concluding observations

Do outer-layer structures affect the Re-dependence of drag reduction by wall actuation?

No quantitative answer (yet), on contribution of modulation but…..

- Direct large-scales contribution to skin friction is order 30%
- Maximum large-scale skin-friction fluctuations around 30%
- Maximum skin-friction fluctuations around 100%
- Strong differences between effects of positive and negative large-scale footprints
- Strong modulation of near wall small-scale motions and skin friction by positive large-scale motions; much weaker modulation by negative motions
- Positive large-scale fluctuations cause strong increase in energy and shear stress close to the wall.
- Negative large-scale fluctuations cause moderate decrease in energy and shear stress.