Turbulent drag reduction by superhydrophobic surfaces

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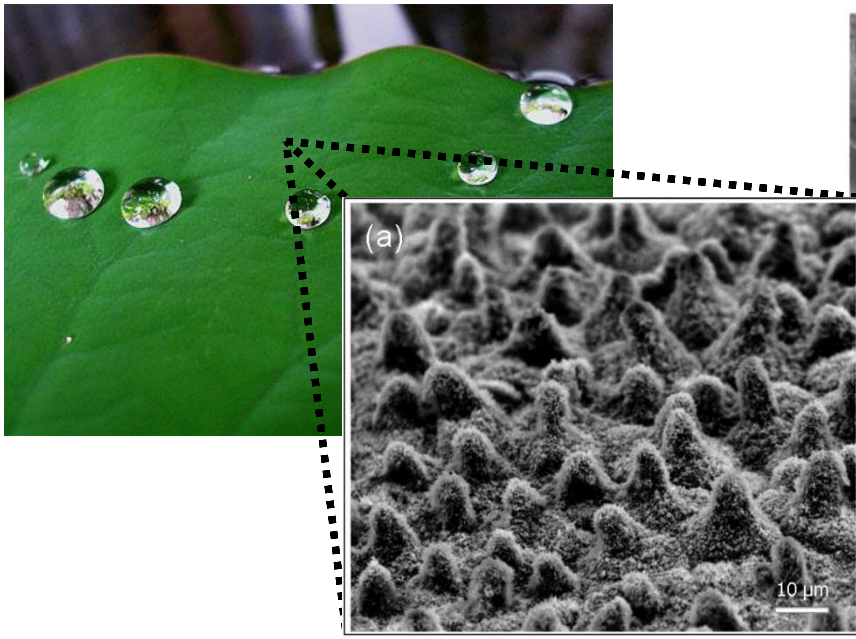
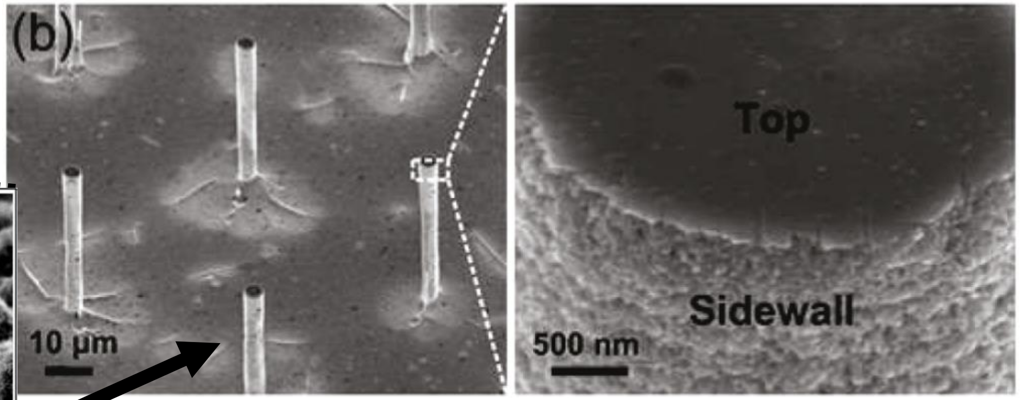
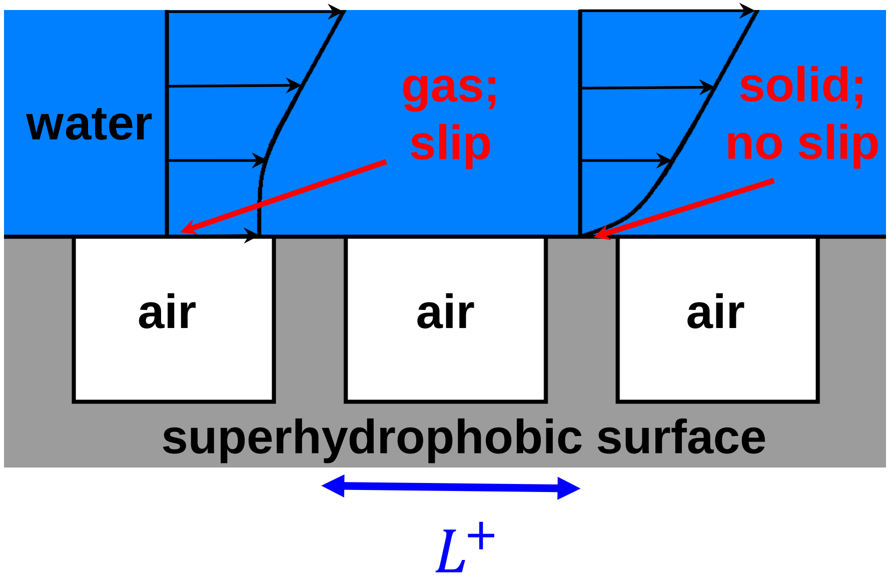
Superhydrophobic surfaces for flow control





Lee & Kim, Langmuir 2009

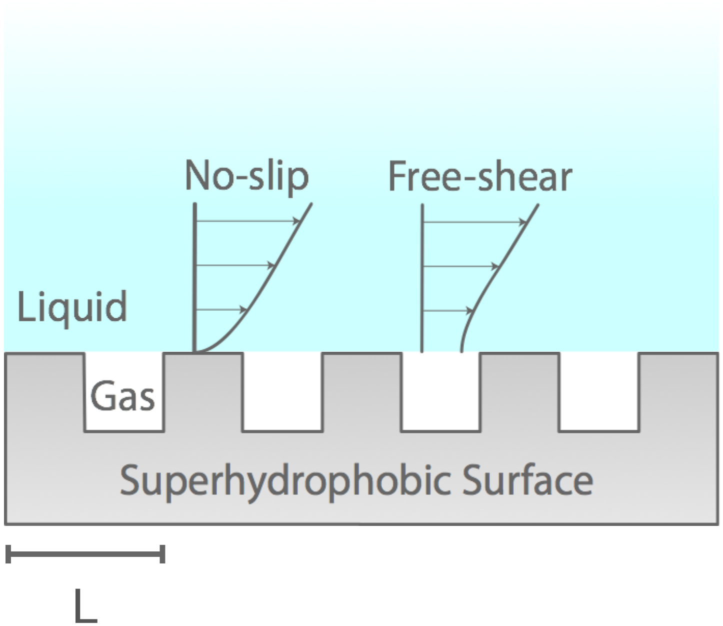
- Bio-inspired, water-repellent surface.
- When immersed in water, can entrap air bubbles, substantially reducing drag (~40%).
- Potential anti-fouling properties.
- Very small (~10μm).

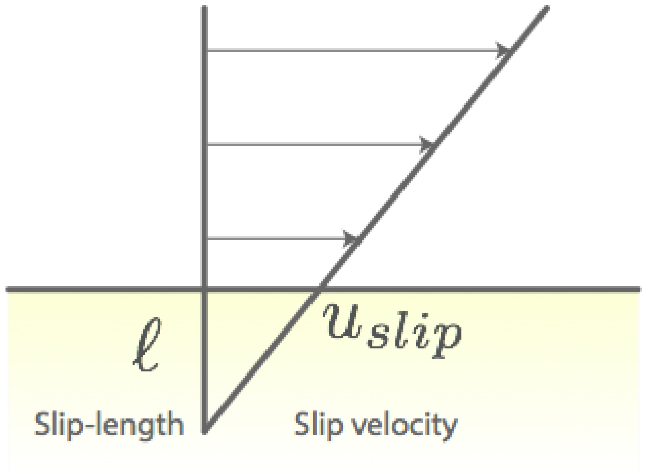


Outline

- Superhydrophobic surfaces
- Textured surfaces and slip lengths (C.T. Fairhall)
- Limits from surface tension effects (J. Seo and A. Mani)
- Summary

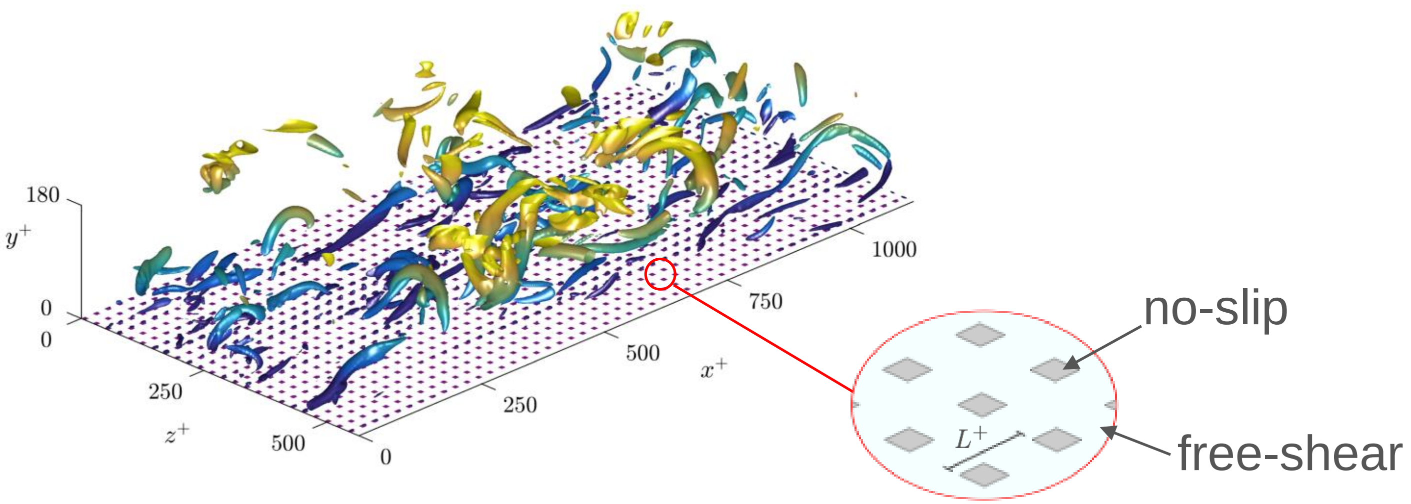
Slip by superhydrophobic surfaces





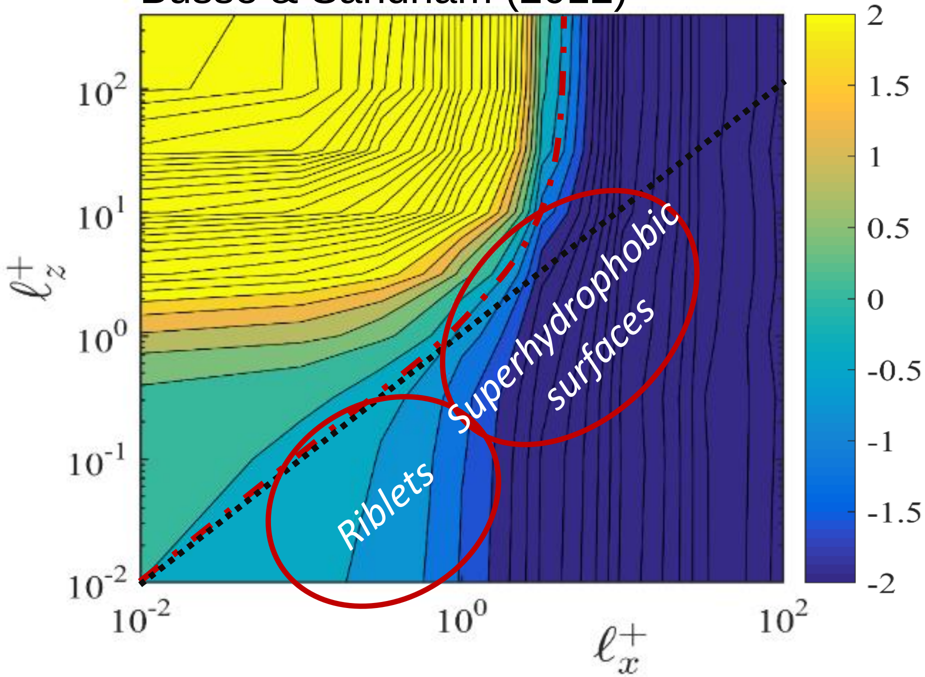
$$u_{slip} = \ell \frac{\partial u}{\partial y}\bigg|_{wall}$$

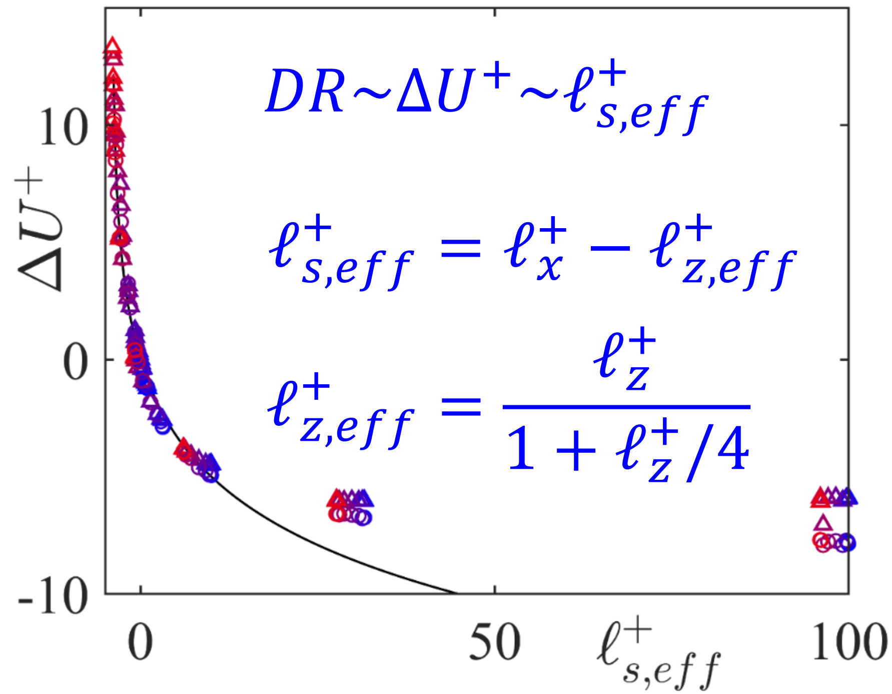
$$u^+_{slip} = \ell^+$$

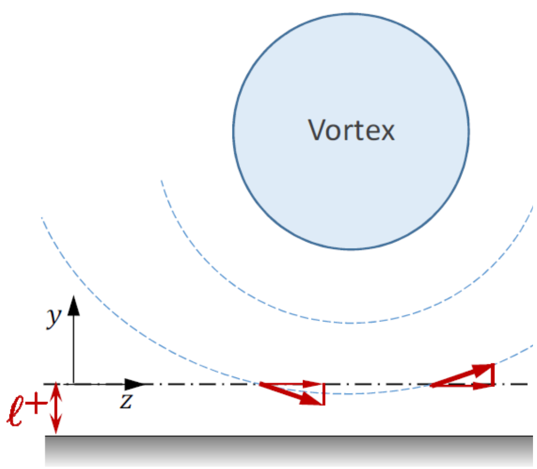


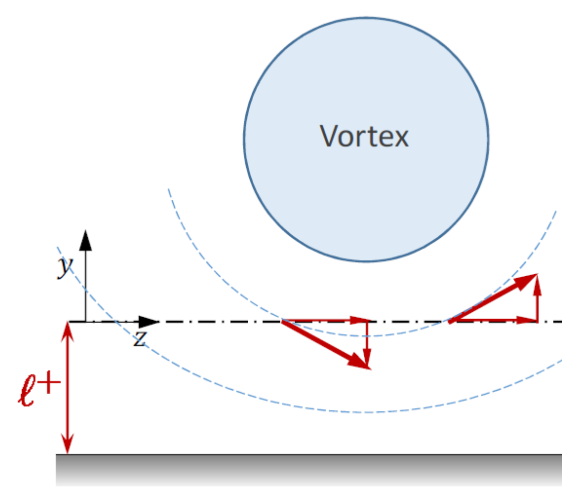
Limits to the linear slip theory

Busse & Sandham (2012)

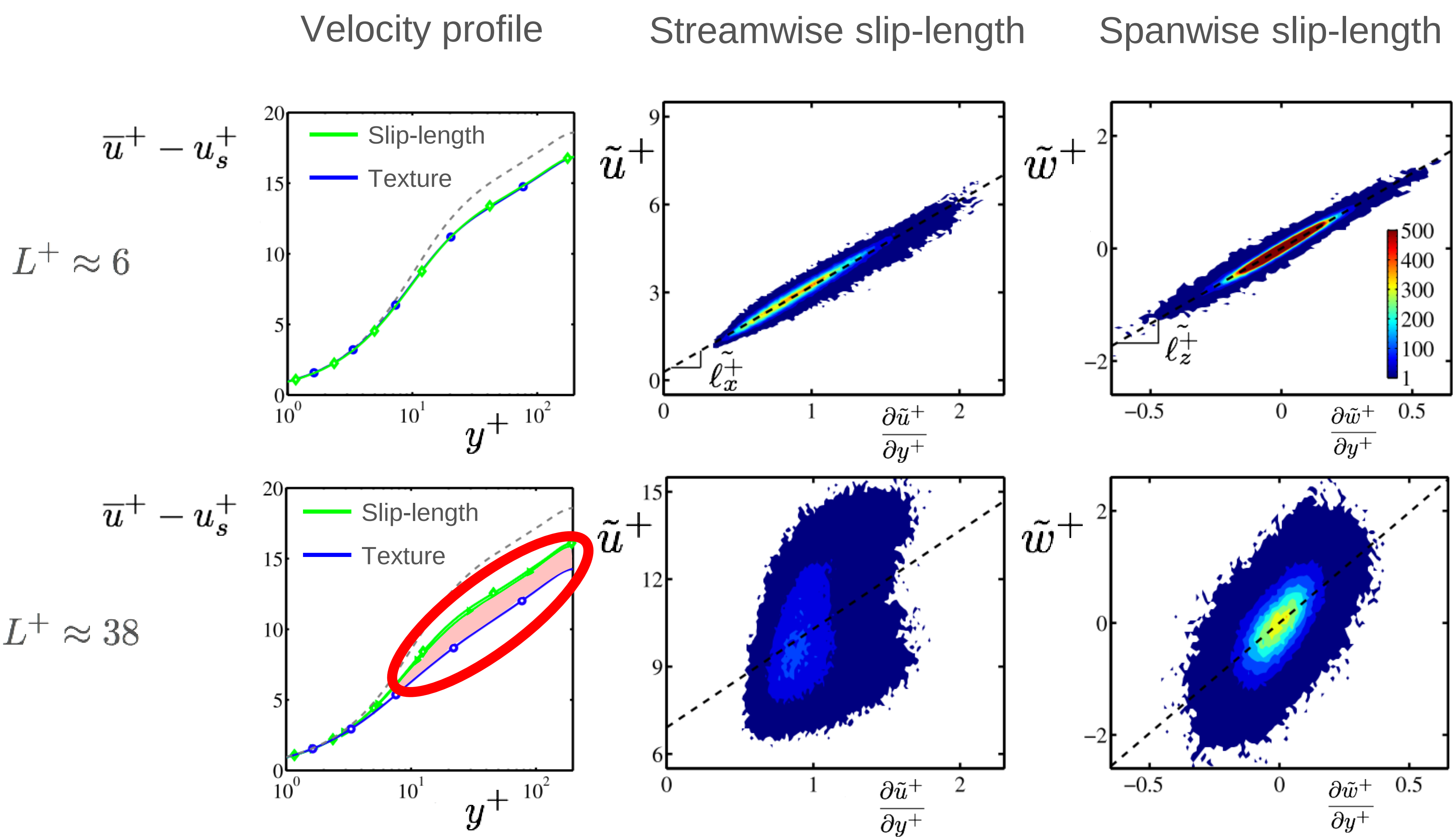






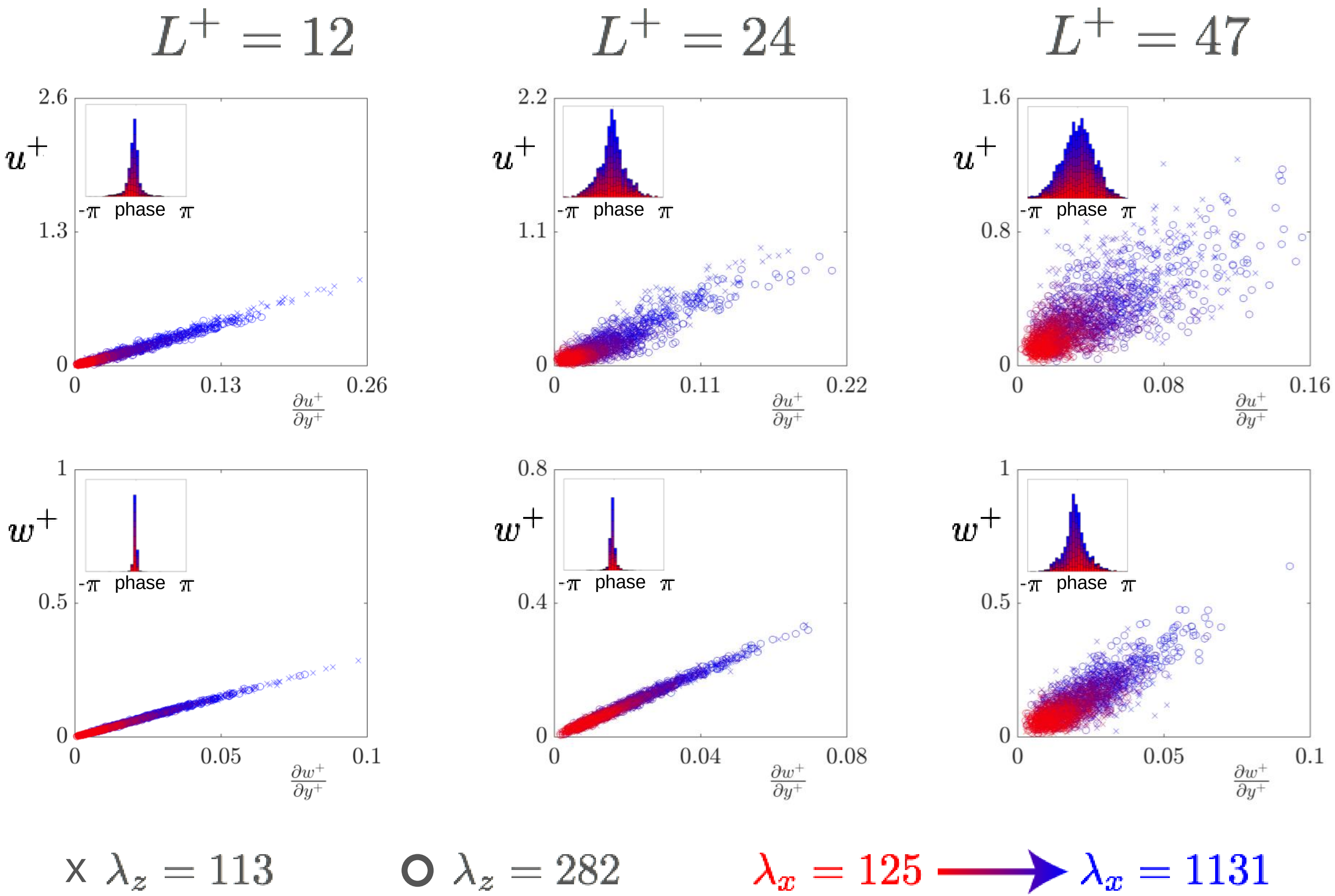


Validity of homogenous slip-lengths



Seo & Mani 2016

Wavelength spectrum of the slip lengths



Textured-coherent vs. background flow

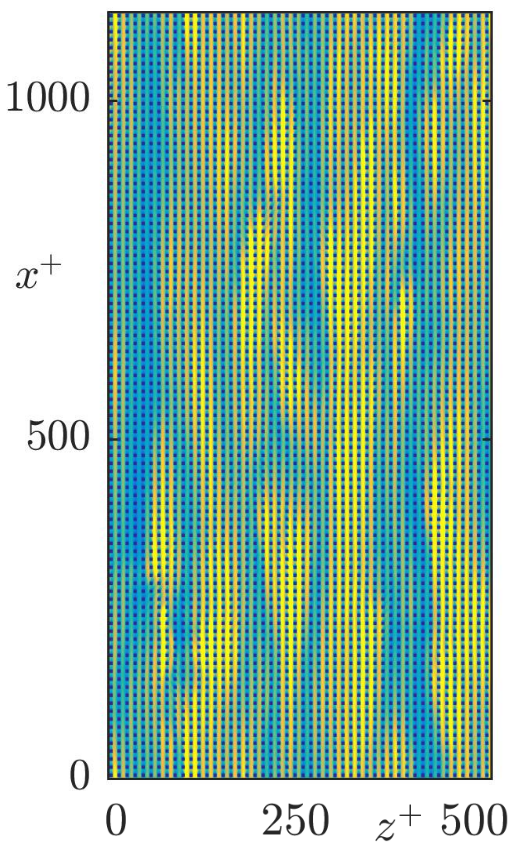
$$u = \overline{u} + \widetilde{u}_u + u_T \quad \left(\frac{\overline{u} + u_T}{\overline{u}} \right)$$

(Reynolds & Hussain 1972)

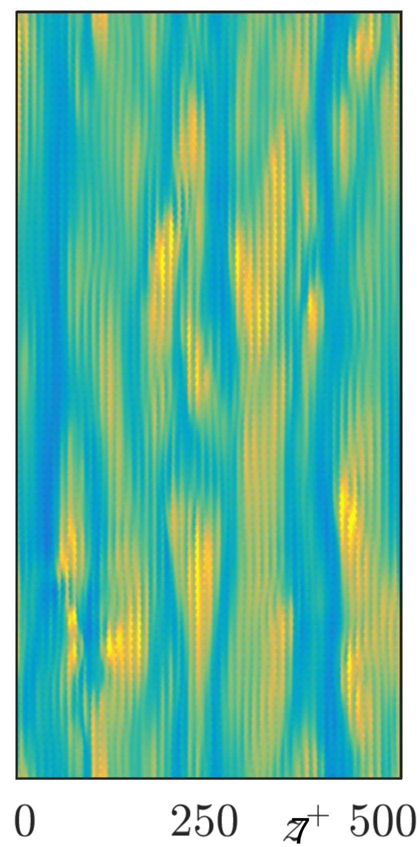
(Abderrahaman-Elena & GM 2016)

Mean   Coherent   'Turbulent'

Full velocity field

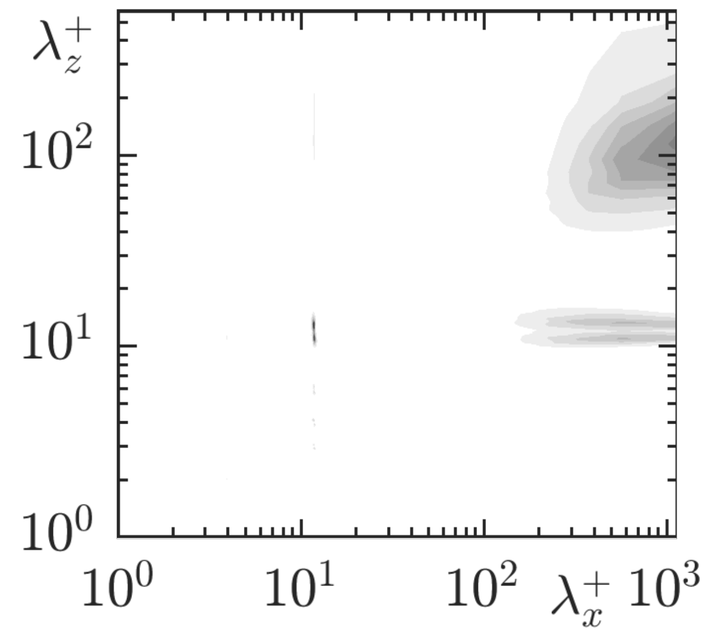


'Turbulent' component

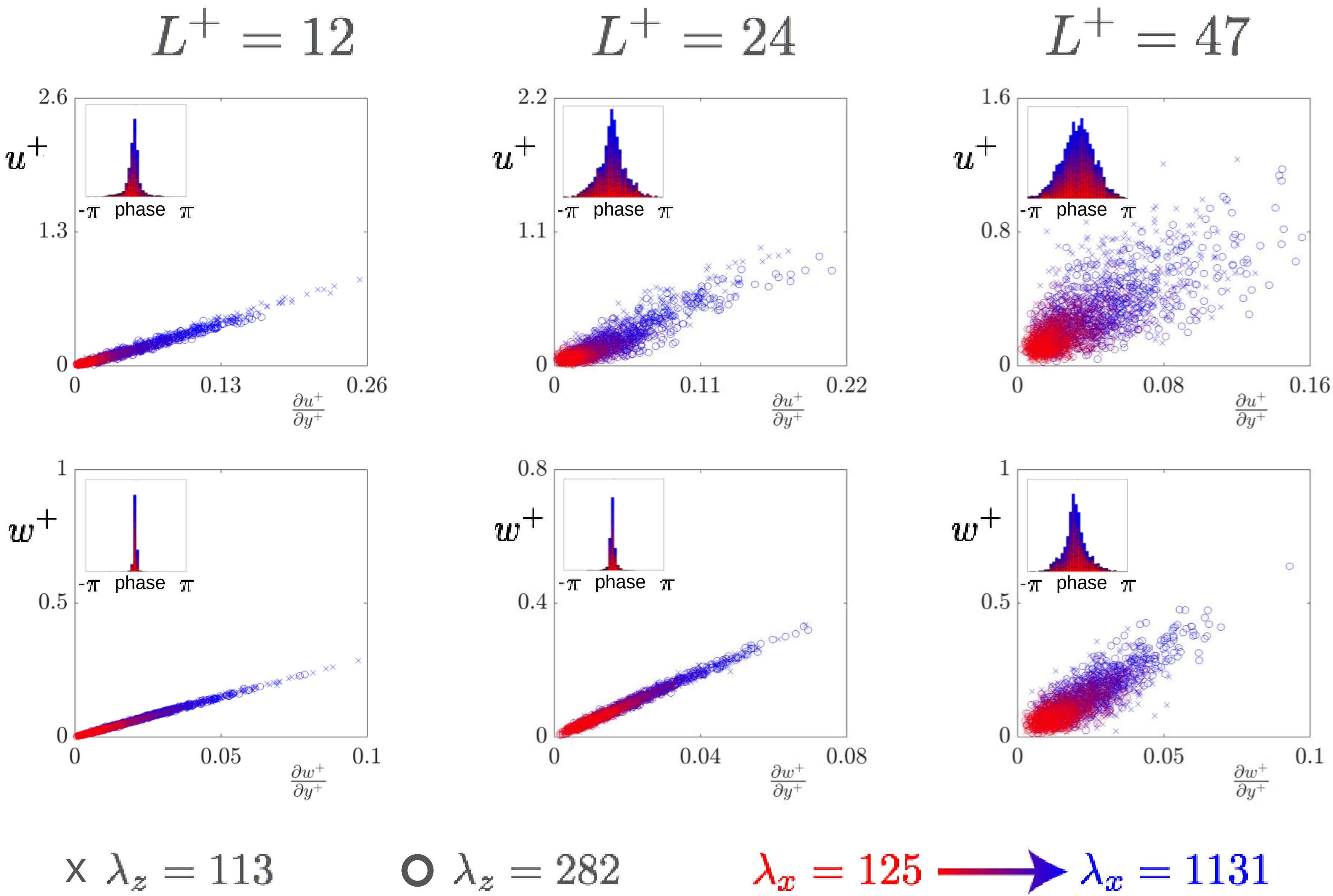


'Turbulent' component spectra

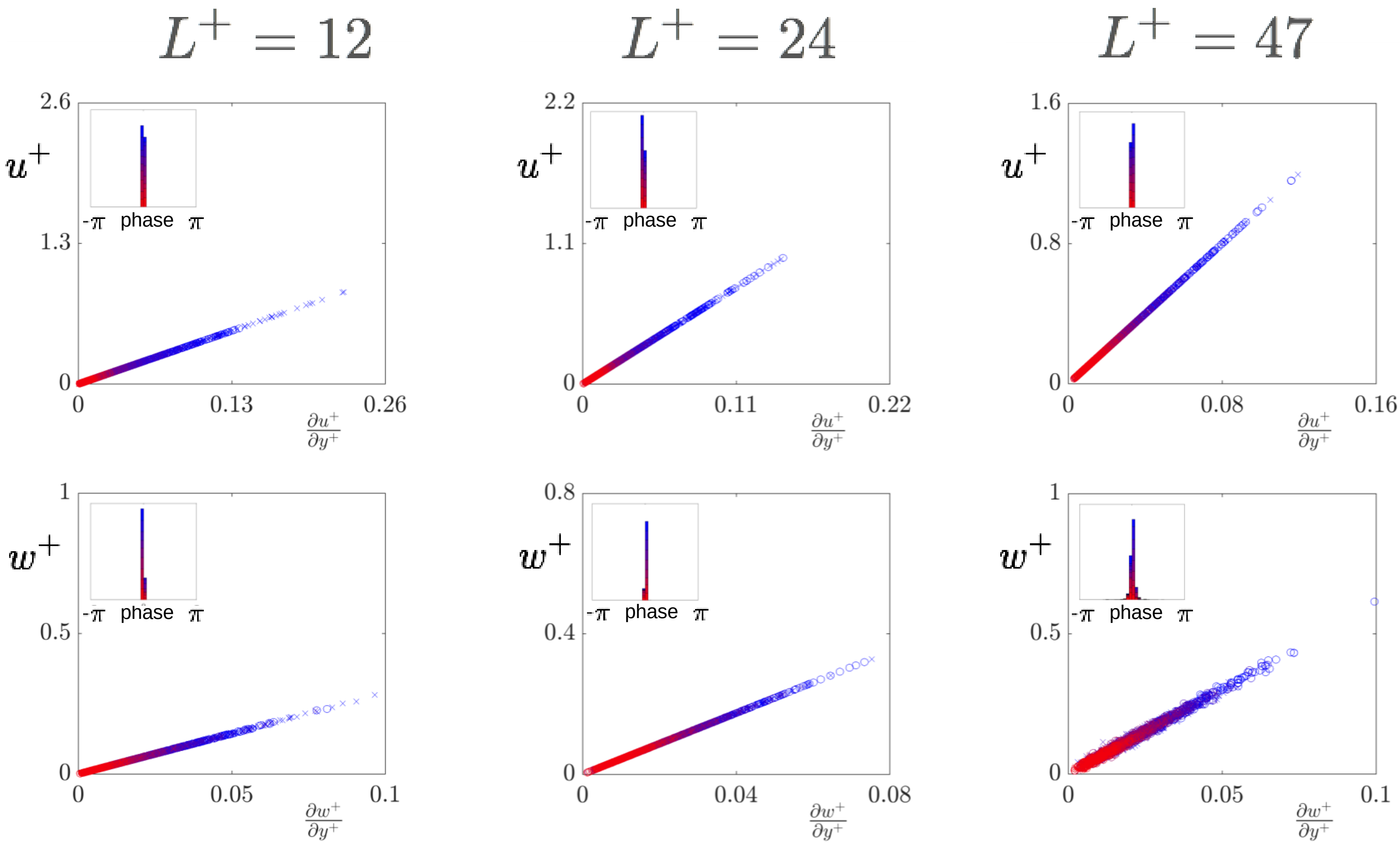
Full velocity spectra



Wavelength spectrum of the slip lengths



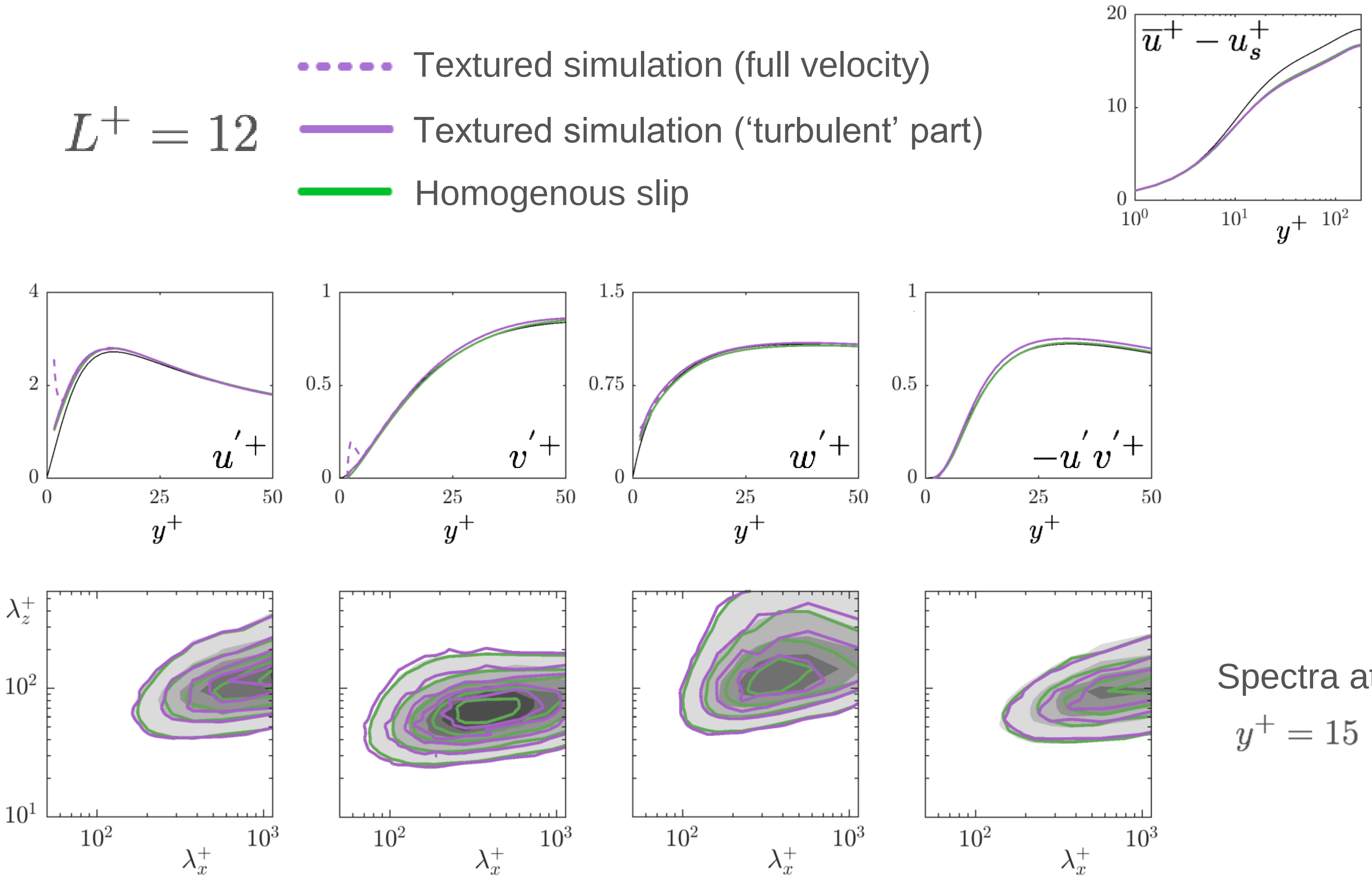
Wavelength spectrum of the slip lengths



x $\lambda_z = 113$ o $\lambda_z = 282$ $\lambda_x = 125$ → $\lambda_x = 1131$

Textured vs. homogeneous slip DNSs

$L^+ = 12$



Spectra at $y^+ = 15$

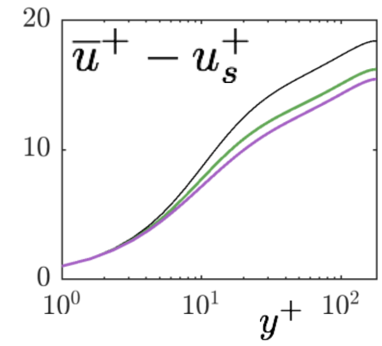
Textured vs. homogeneous slip DNSs

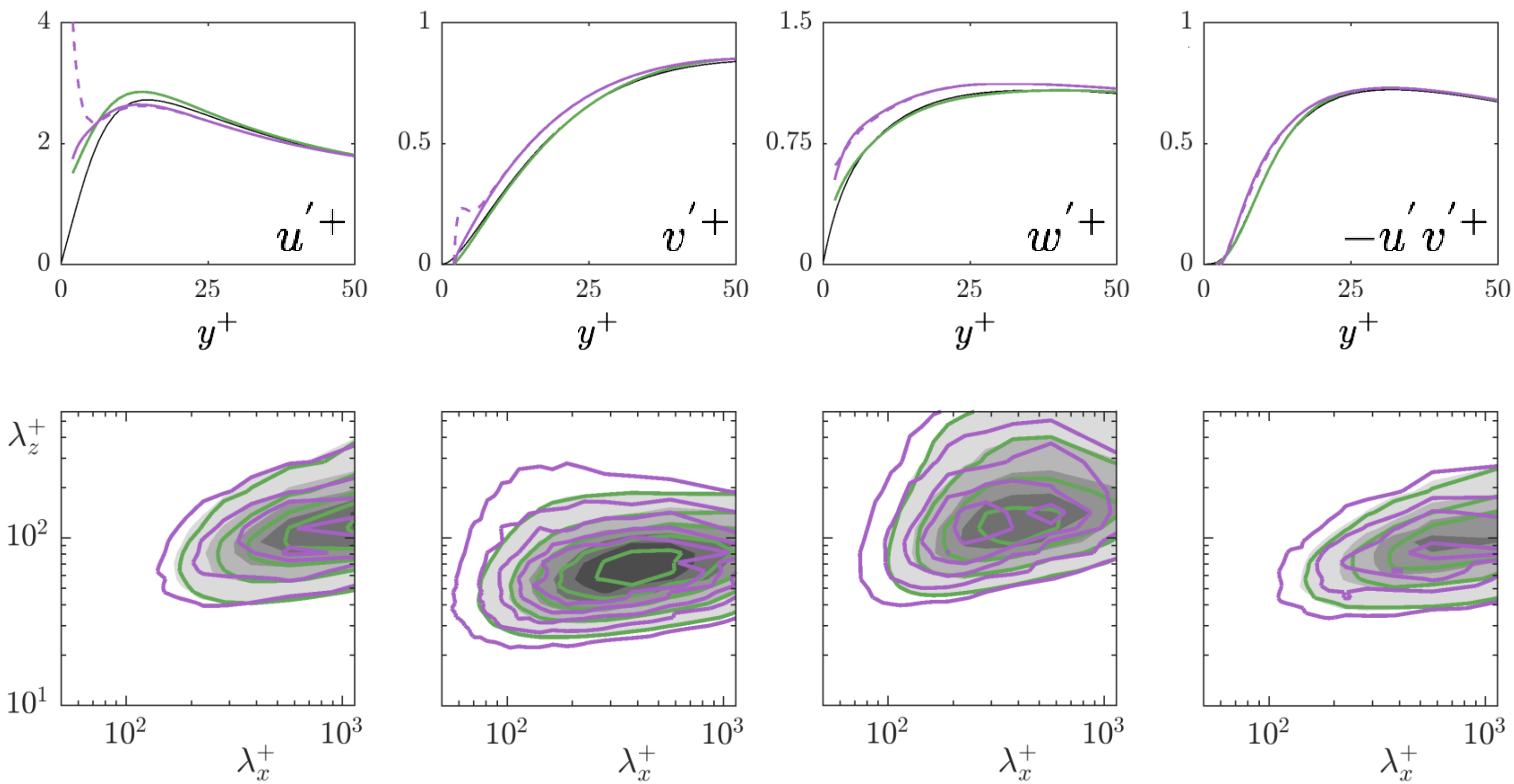
$L^+ = 24$

Textured simulation (full velocity)

Textured simulation (‘turbulent’ part)

Homogenous slip



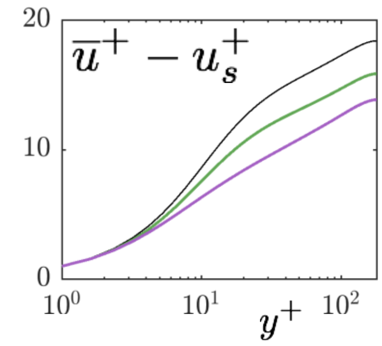


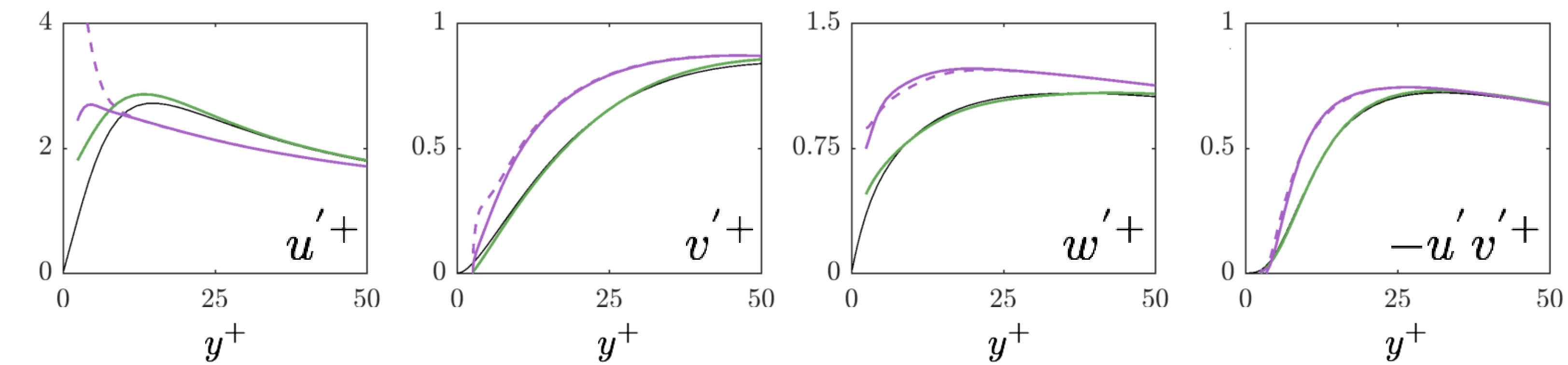
Spectra at $y^+ = 15$

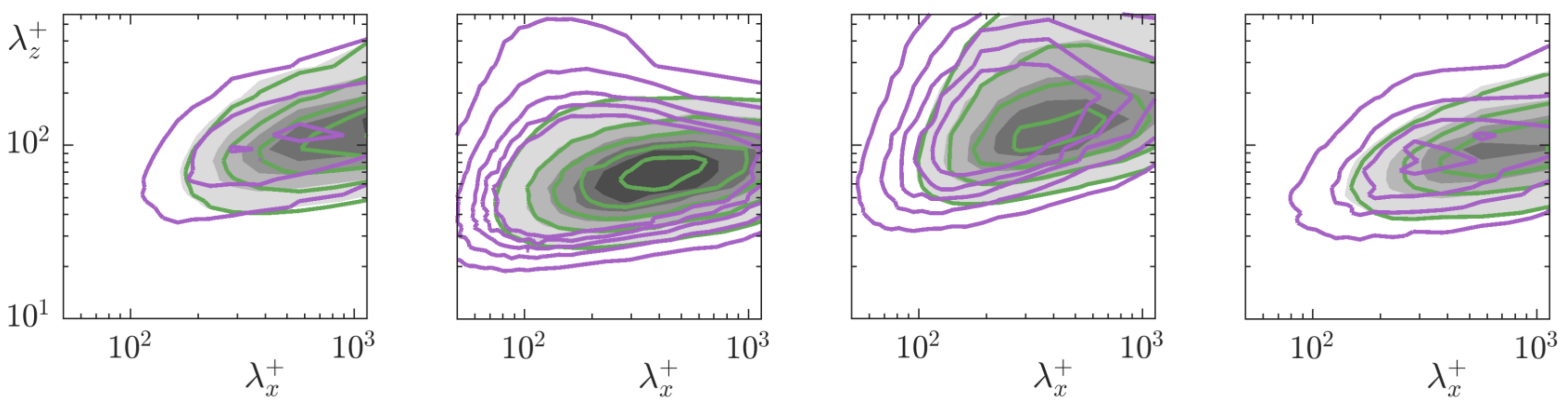
Textured vs. homogeneous slip DNSs

$L^+ = 47$

- Textured simulation (full velocity)
- Textured simulation (‘turbulent’ part)
- Homogenous slip

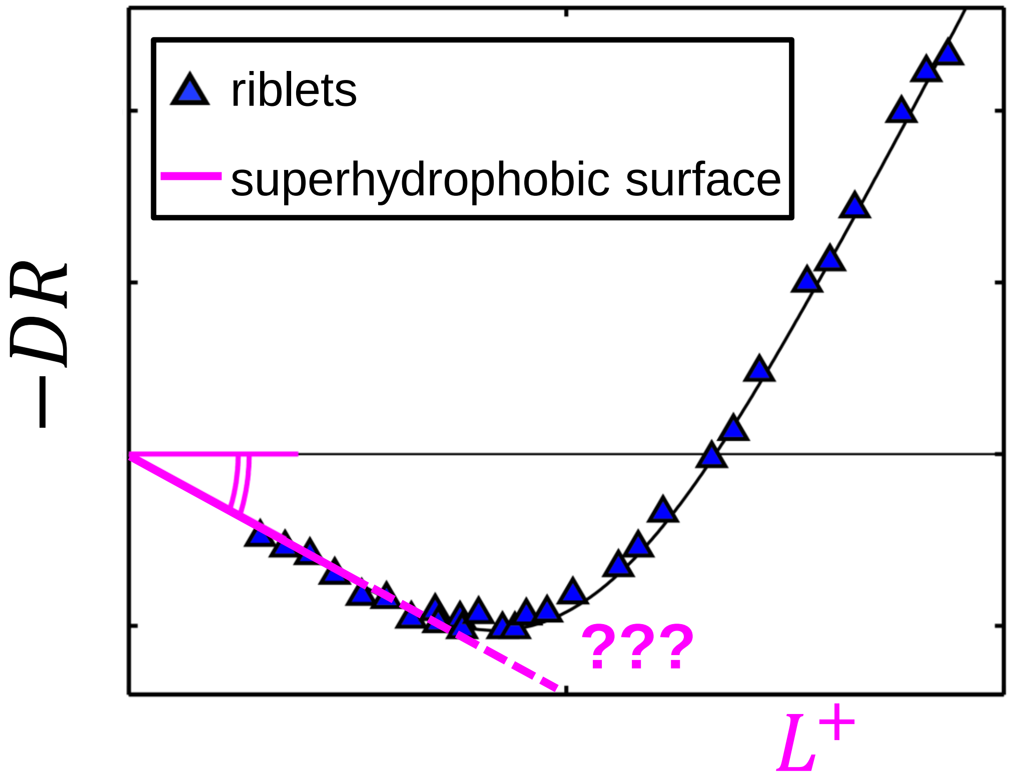




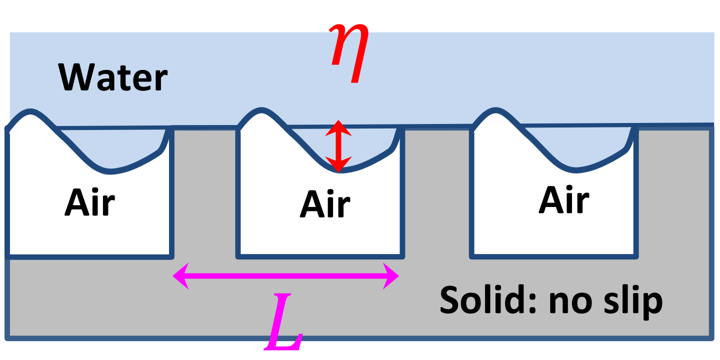


Spectra at $y^+ = 15$

Limitations from surface tension effects



- For large L^+, air bubbles are depleted, and superhydrophobic character is lost
- The degradation/depletion mechanisms are unknown



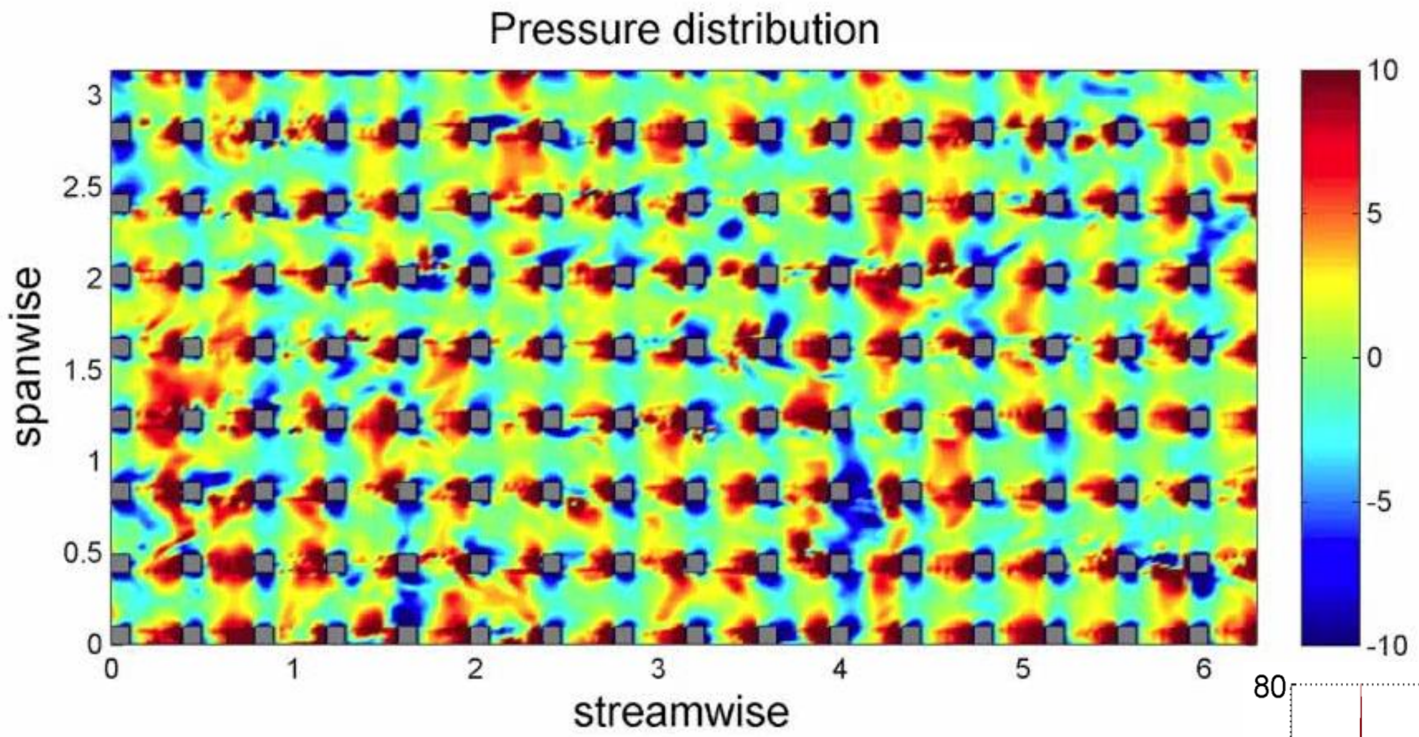
Interface deformation:

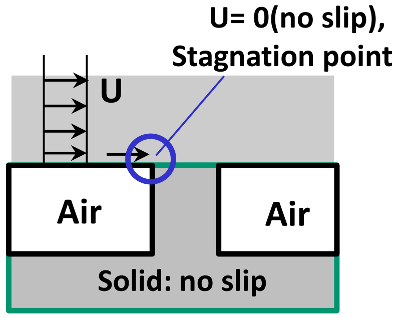
$$\nabla^2 \eta \approx \frac{\Delta p}{\sigma}$$

Mean and turbulent wall pressure signals

$\mathrm{Re}_\tau \approx 400, L^+ \approx 150, \mathrm{We} = 0$

Seo et al. JFM 2015

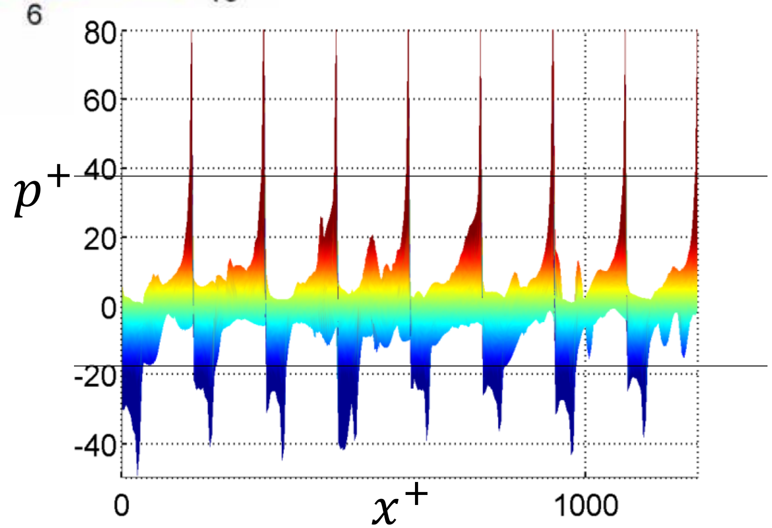




rms of total pressure: $p'^+ \approx 8$

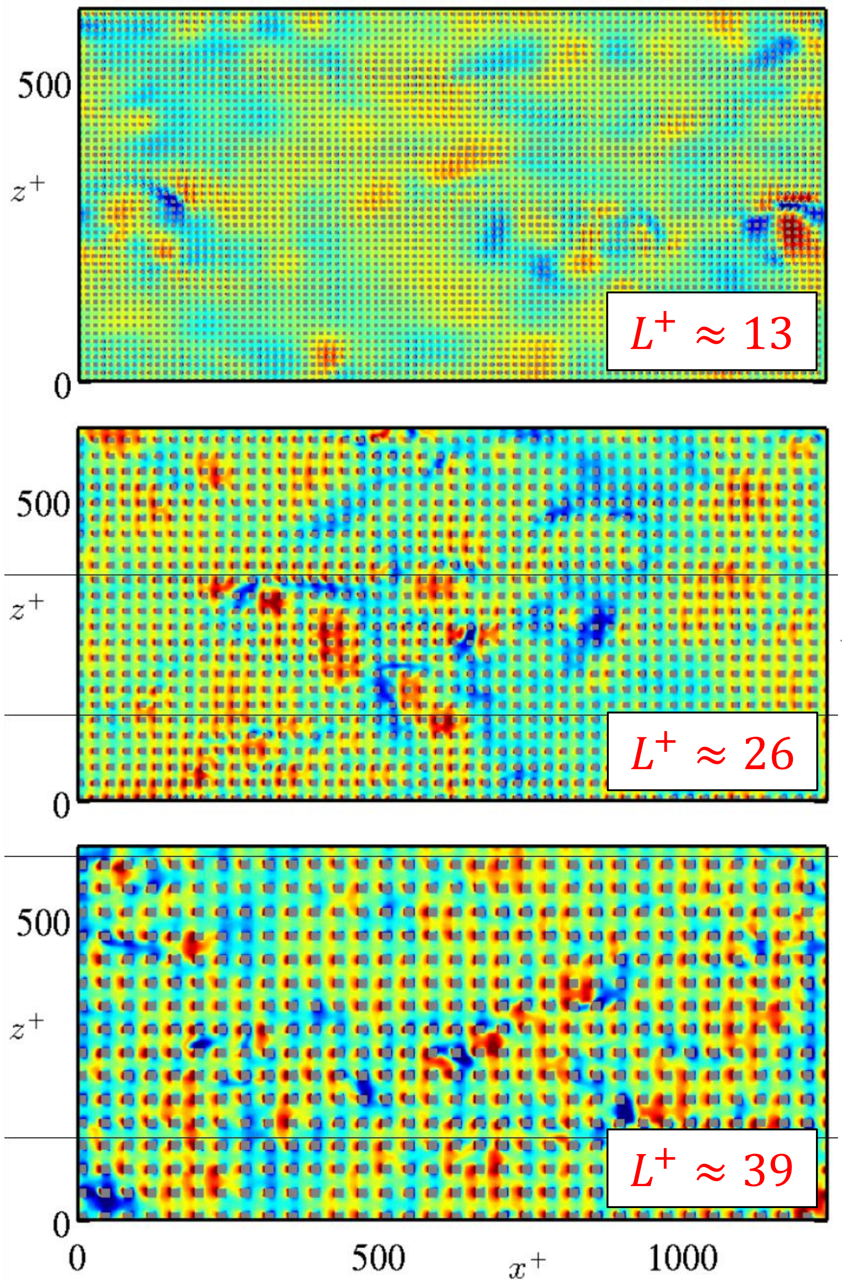
rms of turbulent component: $p''^+ \approx 3$

max of total pressure: $p^+_{max} \approx 80$

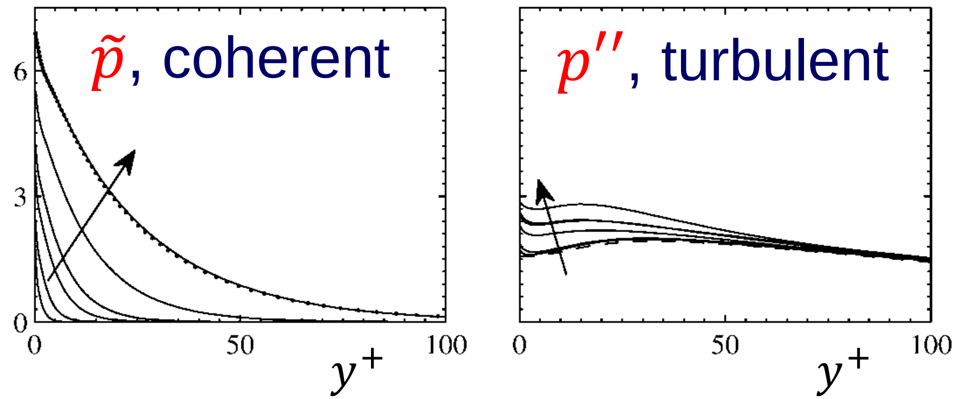


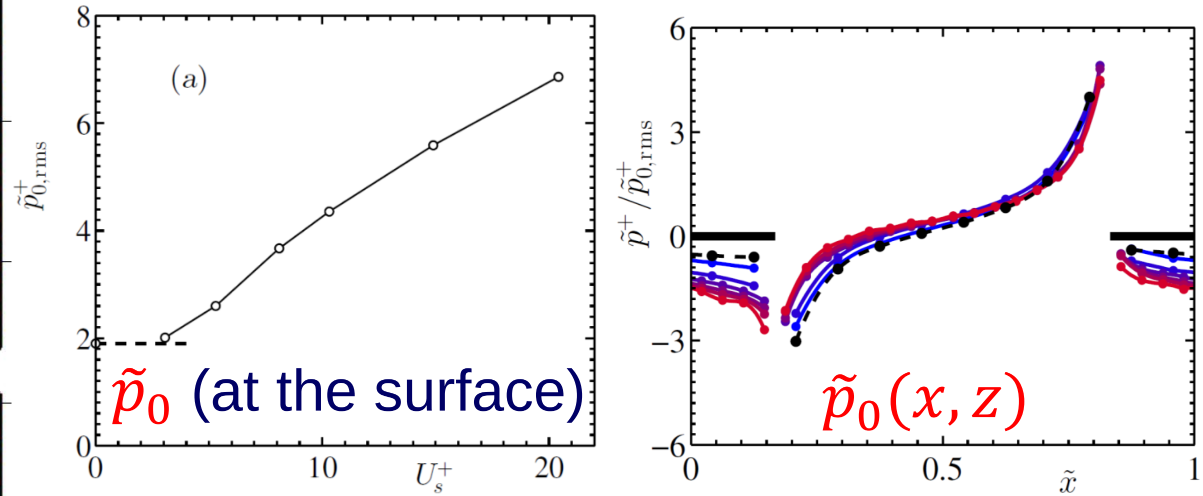
Scaling of pressure components

Seo et al. JFM 2015



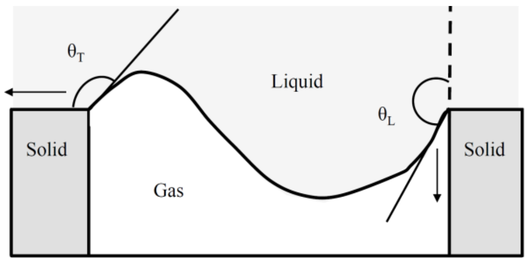
$L^+ = 6, 13, 26, 39, 78, 155$

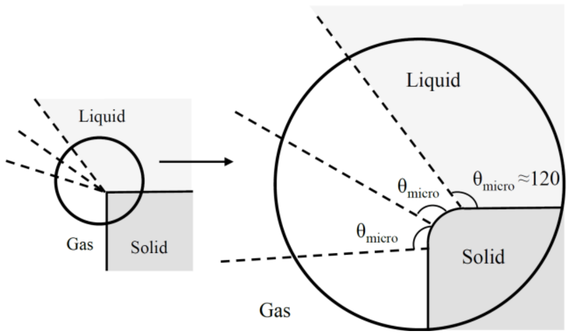




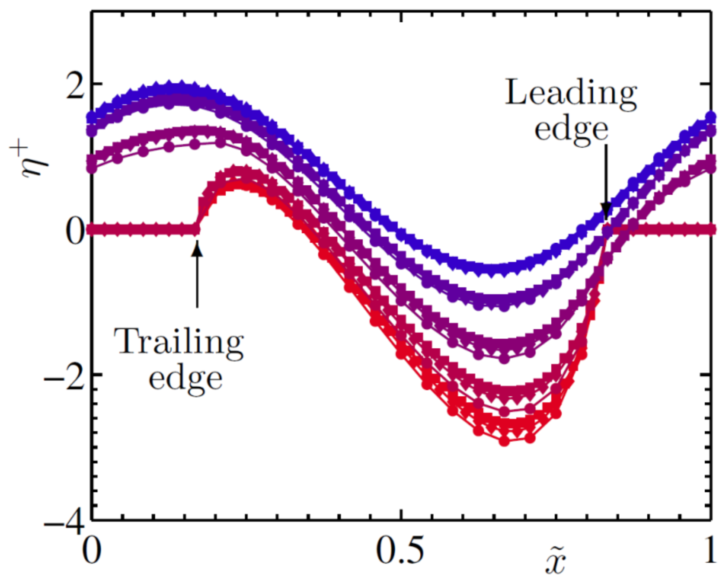
- p'' remains close to smooth-wall case, and $\tilde{p}$ dominates for large textures
- $\tilde{p}_0$ x-z distribution is self similar across whole L^+ range

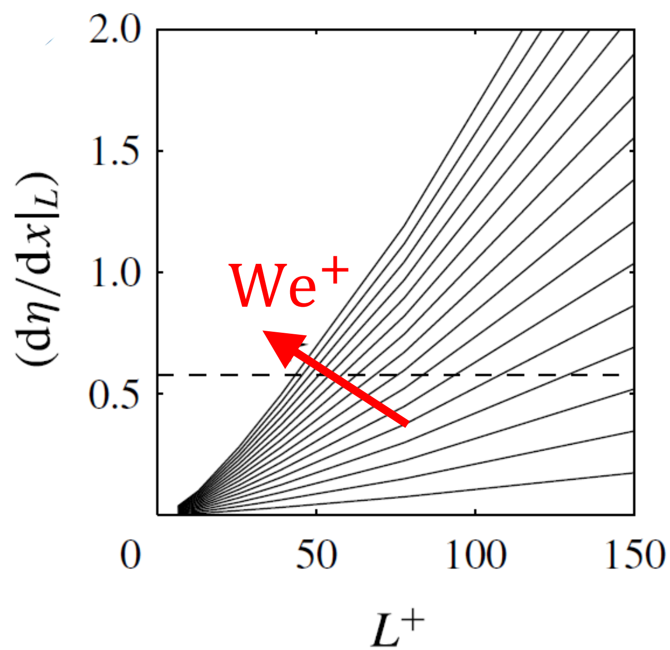
Static 1-way coupling deformation





$$\eta^+ = \mathrm{We}^+\, \nabla^{-2}(p^+)$$



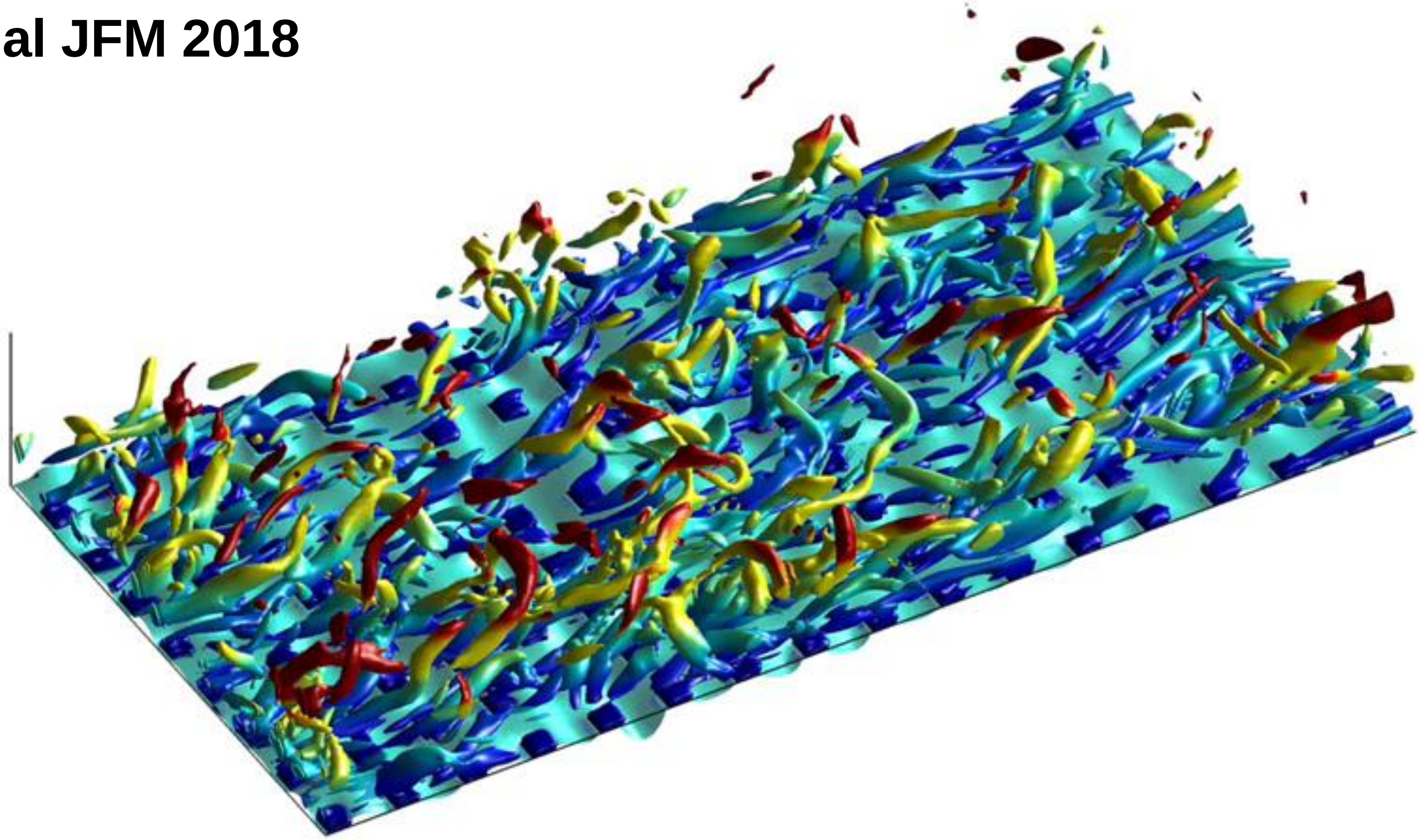


- A critical contact angle will be reached as L^+ increases

  ⇨ Upper bound for L^+

Fully coupled interface deformation

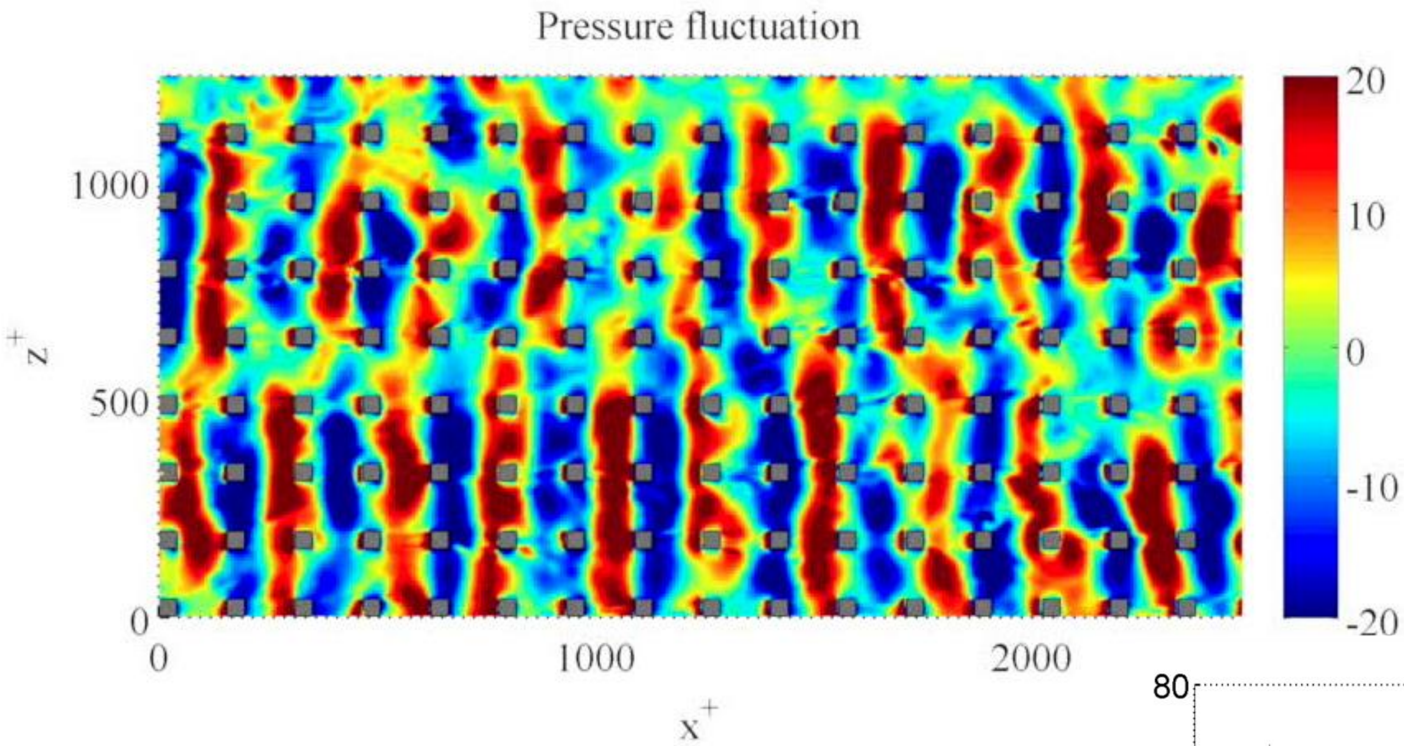
Seo et al JFM 2018



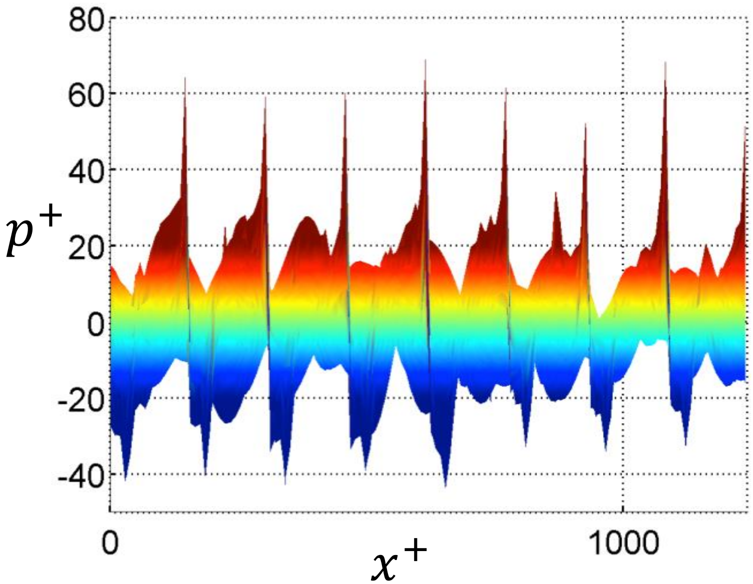
- Boundary conditions over gas-liquid interface (linearized for small deformations η):

$$\nabla^2\eta = \frac{1}{\sigma}p' \qquad v = \frac{D\eta}{Dt} \qquad \tau_{\parallel\eta} = 0$$

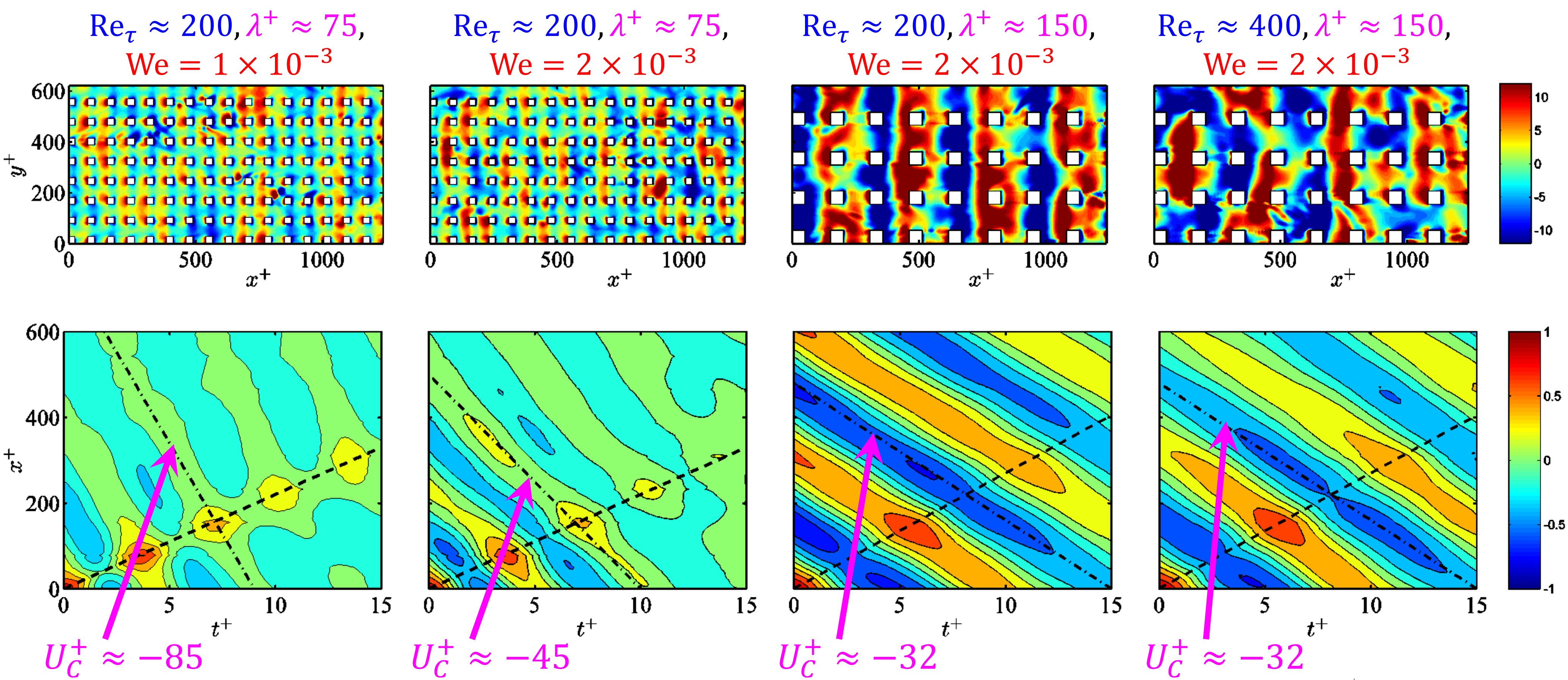
Fully coupled interface pressure



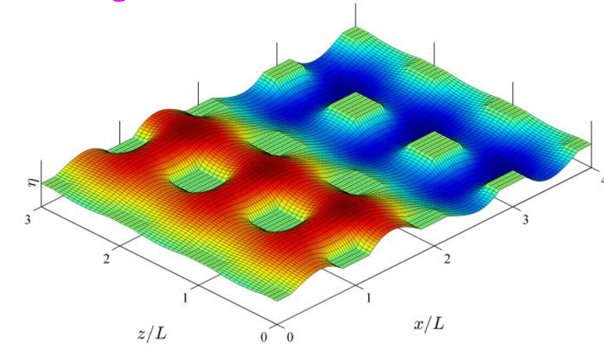
- Pressure fluctuations with upstream-traveling waves
- Can be more critical than stagnation effect



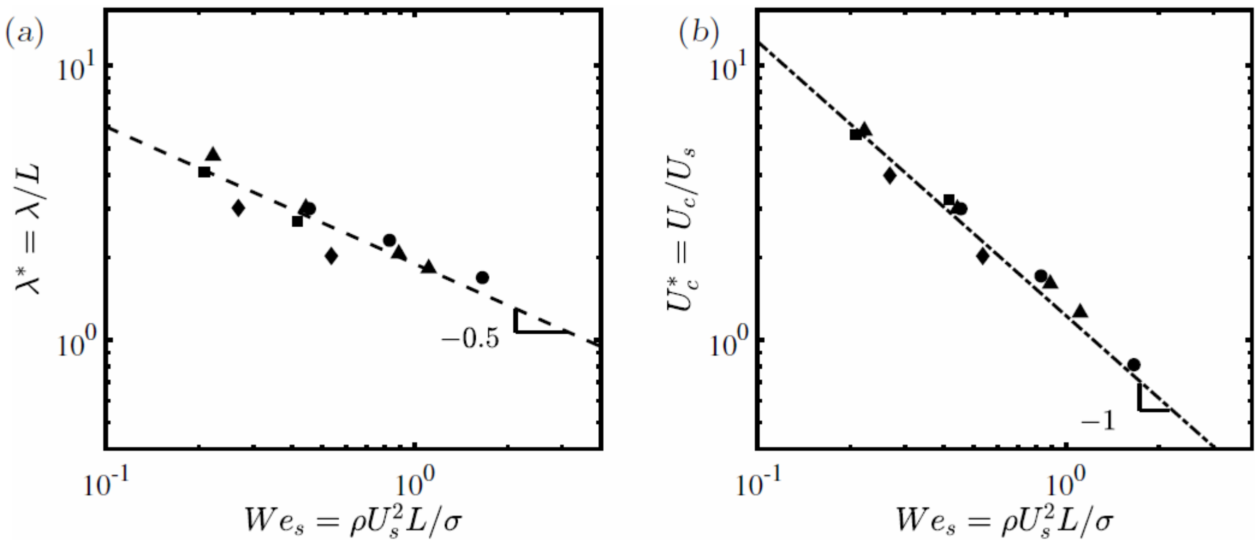
Upstream-traveling interfacial waves

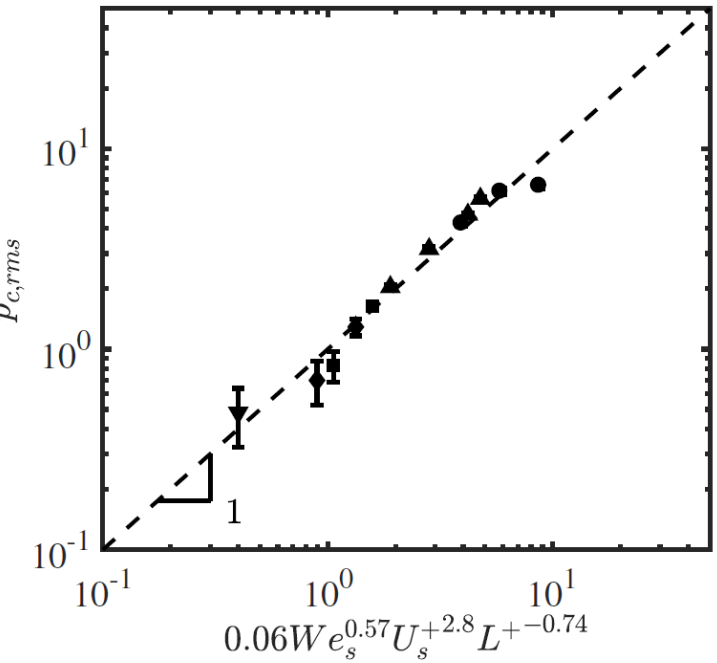


- The backward travelling waves are natural modes of the interface as a membrane (Taylor ‘59, Squire ‘53)
- An inviscid linearised model reproduces the wave dynamics



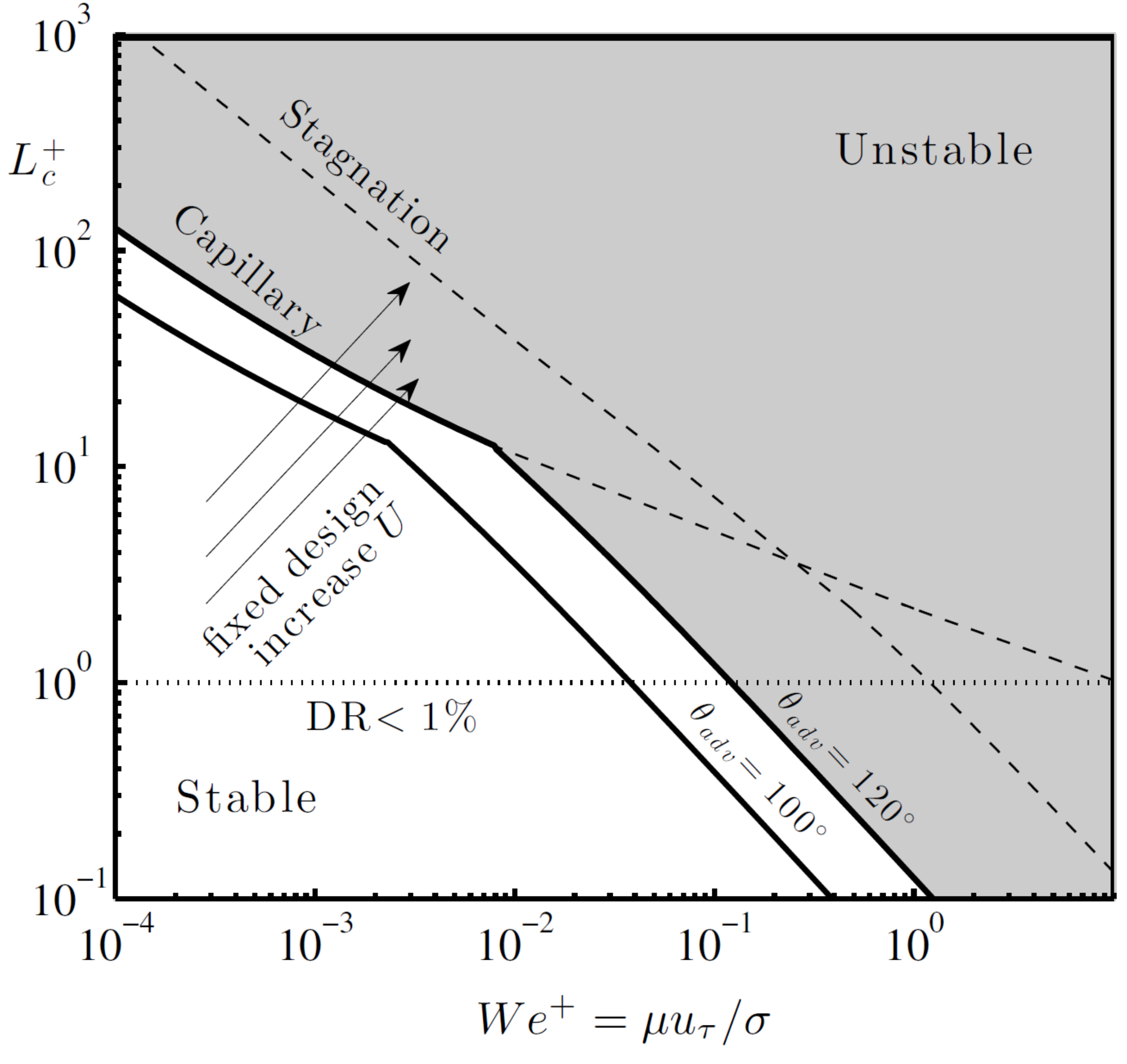
Scaling of interfacial waves





Collapse with We based on slip velocity: $We_s = \rho U_s^2 L/\sigma$

Bounds for realizable DR



Summary

- Superhydrophobic textures can produce large slip lengths and reduce drag.
- For small textures, the background turbulence remains essentially smooth-like, plus the slip-length shift.
- For larger textures, the surface modifies the background turbulence.
- The texture-coherent flow has stagnation regions that can destabilize the air/liquid interface.
- Capillary waves can also destabilize the interface.