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Inlet boundary conditions for Hybrid LES-RANS (Davidson, 2007a, 2007b, 2007c)

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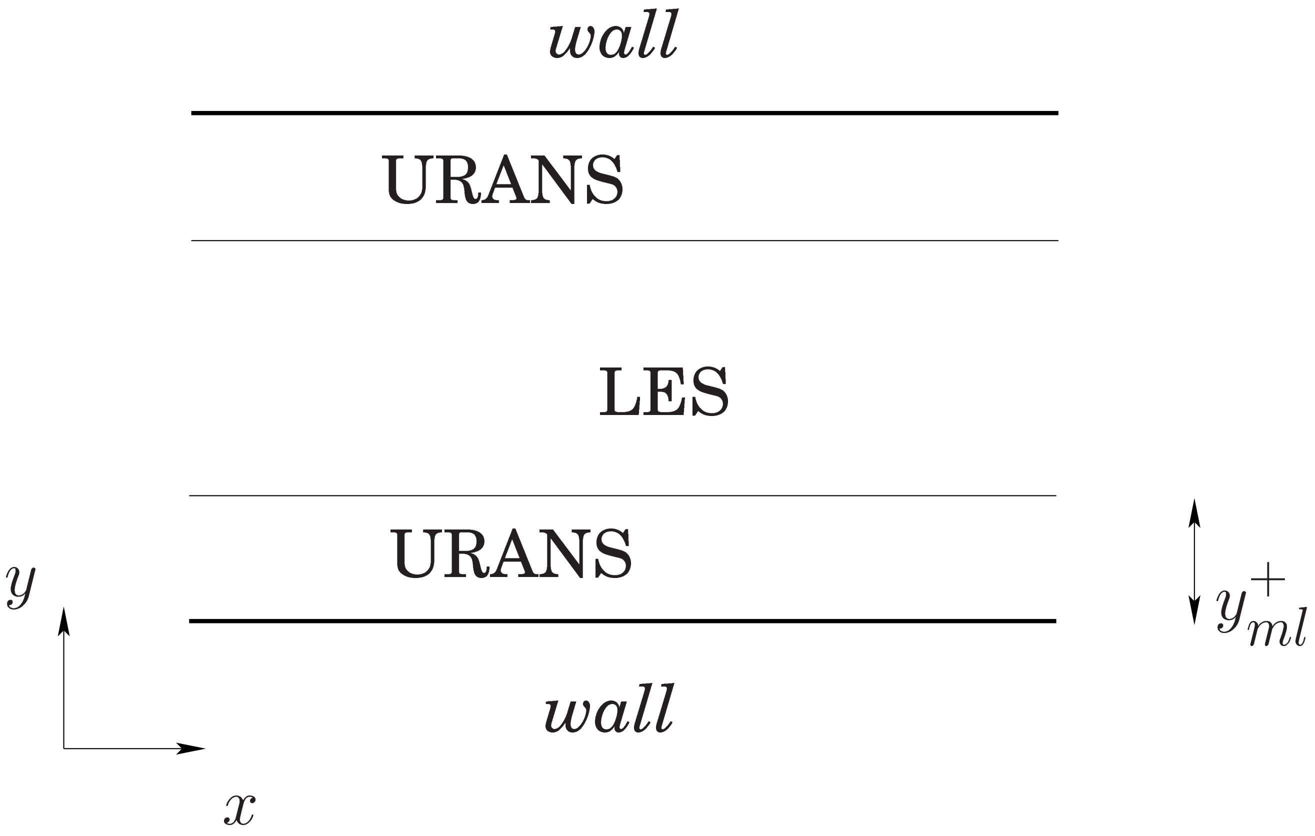
HYBRID LES-RANS

Near walls: a RANS one-eq. k model.

In core region: a LES one-eq. k_{SGS} model.



wall

URANS

LES

URANS

wall

y_{ml}^{+}

y

x

MOMENTUM EQUATIONS

- The Navier-Stokes, time-averaged in the near-wall regions and filtered in the core region, reads

$$\frac{\partial \bar{U}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{U}_i \bar{U}_j\right) = \beta\delta_{1i} - \frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_T)\frac{\partial \bar{U}_i}{\partial x_j}\right]$$

$$\nu_T = \nu_t, y \le y_{ml}; \nu_T = \nu_{sgs}, y \ge y_{ml}$$

TURBULENCE MODEL

- Use one-equation model in both URANS region and LES region.

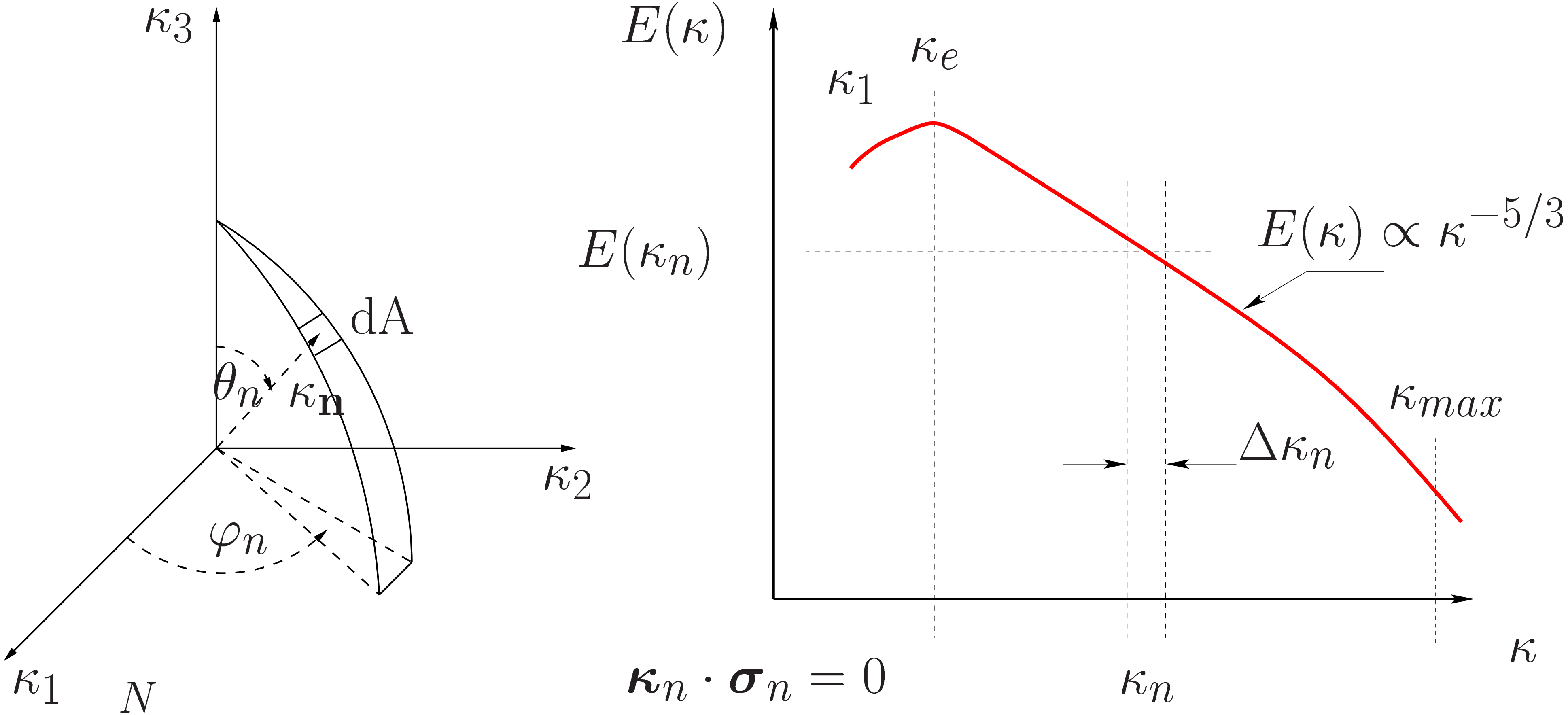
$$\frac{\partial k_T}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_j k_T) = \frac{\partial}{\partial x_j}\left[(\nu + \nu_T)\frac{\partial k_T}{\partial x_j}\right] + P_{k_T} - C_\varepsilon \frac{k_T^{3/2}}{\ell}$$

$$P_{k_T} = 2\nu_T \bar{S}_{ij}\bar{S}_{ij},\ \nu_T = C_k \ell k_T^{1/2}$$

LES-region: $k_T = k_{sgs}$, $\nu_T = \nu_{sgs}$, $\ell = \Delta = (\delta V)^{1/3}$

URANS-region: $k_T = k$, $\nu_T = \nu_t$, $\ell \propto y$, Chen-Patel model (AIAA J. 1988)

SYNTHESIZED ISOTROPIC TURBULENCE



$\boldsymbol{\kappa}_n \cdot \boldsymbol{\sigma}_n = 0$

$$\mathbf{u}_t(\mathbf{x}) = 2\sum_{n=1}^{N} \hat{u}_n \cos(\boldsymbol{\kappa}_n \cdot \mathbf{x} + \psi_n)\boldsymbol{\sigma}_n, \quad N = 150, \quad \hat{u}_n = \sqrt{E(\kappa_n)\Delta\kappa_n}, \quad \kappa_n = |\boldsymbol{\kappa}_n|$$

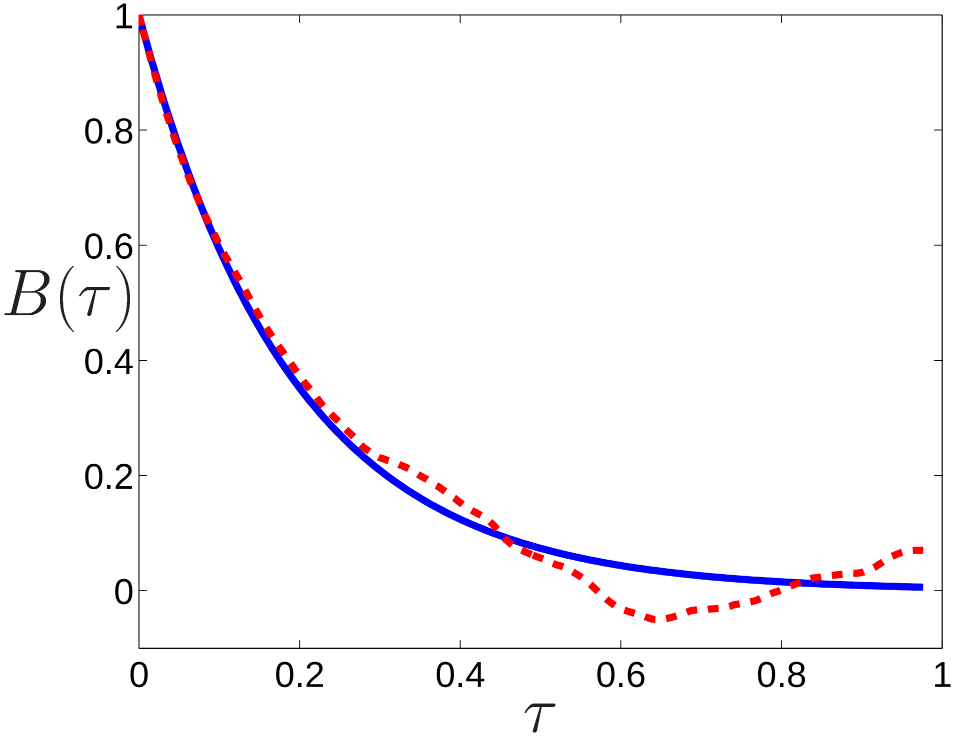
- $\kappa_e = 13\pi/(55L_t)$, $L_t = k^{3/2}/\varepsilon$ **At high κ, $E(\kappa)$ is a function of ν**
- $[\kappa_1, \kappa_{max}]$ **divided into N modes,** $\kappa_{max} = \frac{\pi}{\min\{\Delta x, \Delta y, \Delta z\}}$, $\kappa_1 = \kappa_e/2$

TIME SCALES

- M independent realizations $\mathbf{u}_t(\mathbf{x})$ are created. Thus no time correlation. A time correlation is introduced by

$$(\mathcal{U}')^m = a(\mathcal{U}')^{m-1} + b(\mathbf{u}_t(\mathbf{x}))^m, m = \text{time step}$$

autocorrelation $B(\tau)$



- The autocorrelation is prescribed by setting $a = \exp(-\Delta t/\mathcal{T})$, $b = (1-a^2)^{1/2}$

CHANNEL WITH INLET-OUTLET

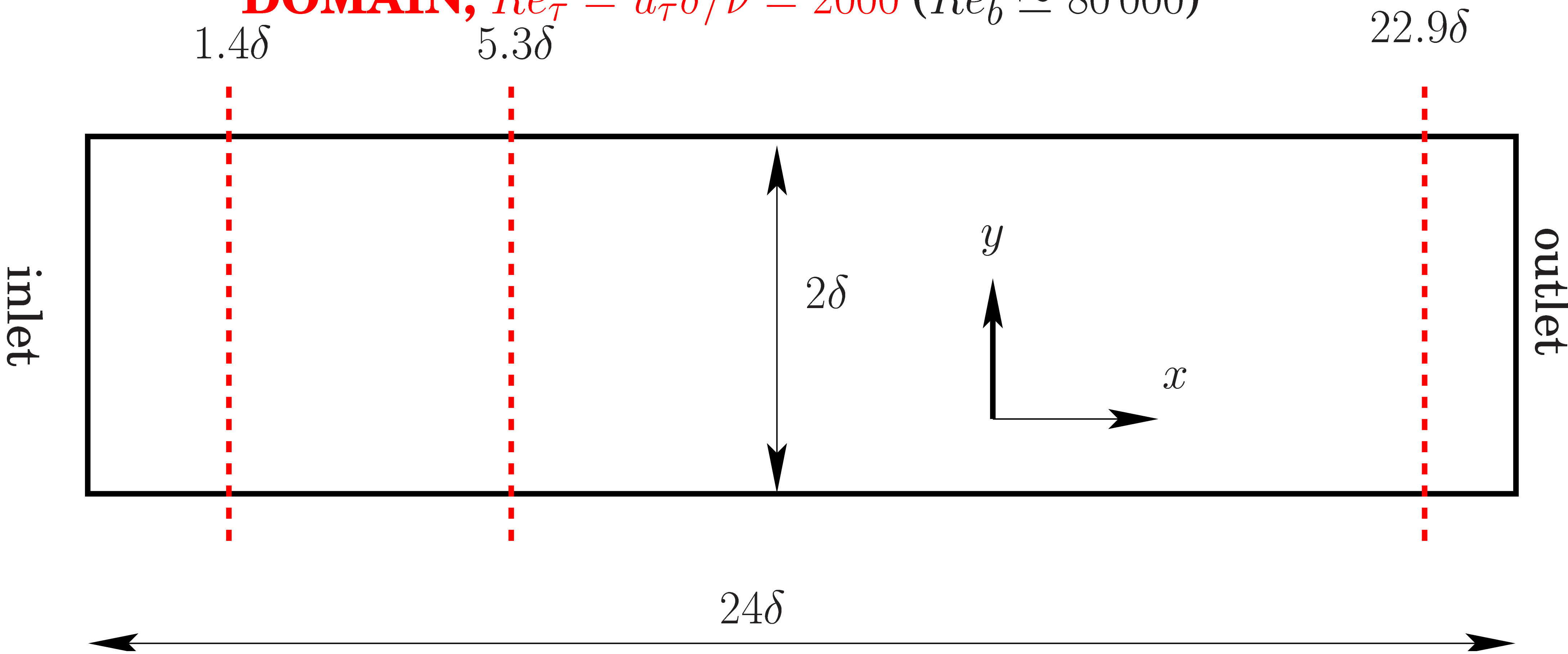
- Inlet fluctuations are set as $(\mathcal{U}')^m$, $(\mathcal{V}')^m$, $(\mathcal{W}')^m$.

- The streamwise fluctuations are superimposed to the mean profile

$$U_{in}^+ = \begin{cases} y^+ & y^+ \leq 5 \\ -3.05 + 5\ln(y^+) & 5 < y^+ < 30 \\ \frac{1}{\kappa}\ln(y^+) + B & y^+ \geq 30 \end{cases}$$

where $\kappa = 0.4$ and $B = 5.2$

DOMAIN, $Re_\tau = u_\tau\delta/\nu = 2000$ ($Re_b \simeq 80\,000$)



- $64 \times 64 \times 32$ (x, y, z) **cells.** $z_{max} = 6.3\delta$, $\Delta x^+ \simeq 785$, $\Delta z^+ \simeq 393$.
- $\delta/\Delta z \simeq 5$, $\delta/\Delta x \simeq 2.5$
- **The location of the matching plane at** $y = 0.075$ ($y^+ = 150$)

TEST CASES

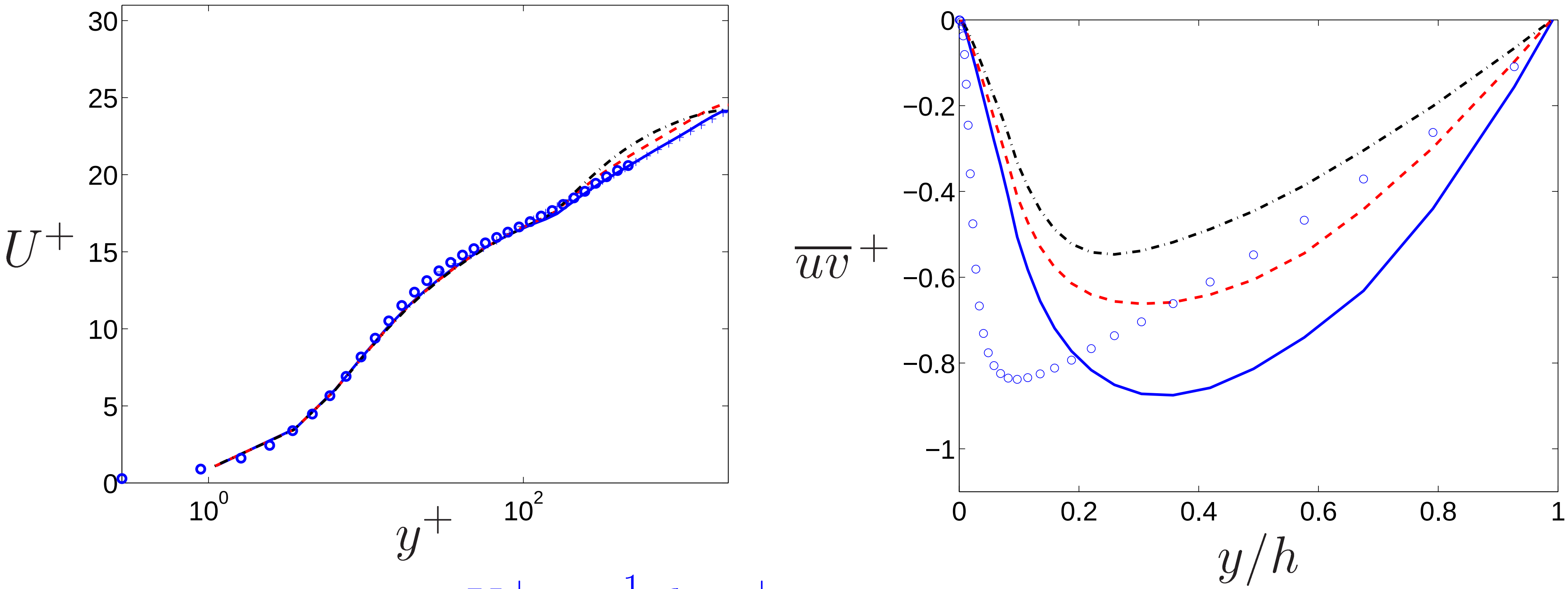
- Different inlet turbulent length and time scales have been used

- Using $k = 4$, $\varepsilon = 70$ (scaled with u_τ and δ), the baseline scales were set to:

Length scale: $L_t = k^{3/2}/\varepsilon = \mathcal{L}_1 = 0.11\delta$

Time scale: $\tau_t = 4k/\varepsilon = \mathcal{T}_1 = 0.22\delta/u_\tau$

Time scale $\mathcal{T}_1$ and length scale $\mathcal{L}_1$



+: $U^+ = \frac{1}{0.4} \ln y^+ + 5.2$

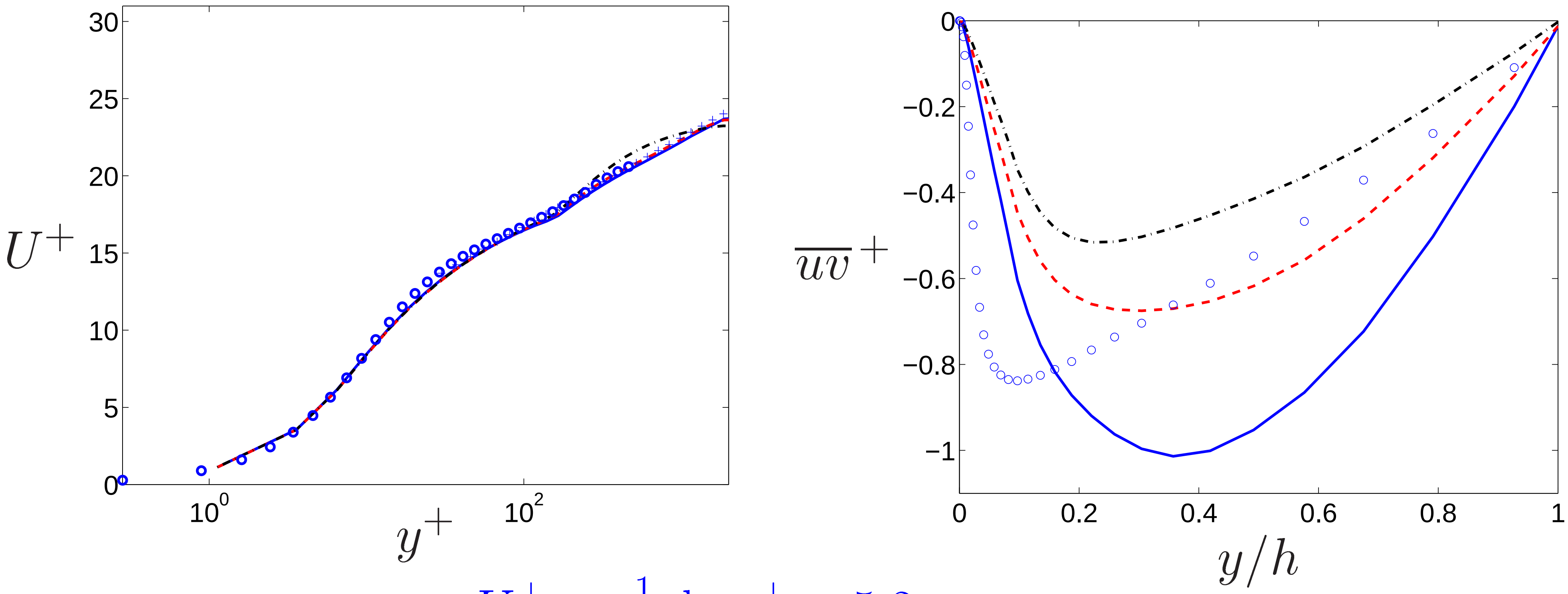
circles: **DNS at** $Re_\tau = 500$

solid lines: $x/\delta = 1.4$

dashed lines: $x/\delta = 5.3$

dash-dotted lines: $x/\delta = 22.9$

Time scale $\mathcal{T}_1$ and length scale $2\mathcal{L}_1$



+: $U^+ = \frac{1}{0.4}\ln y^+ + 5.2$

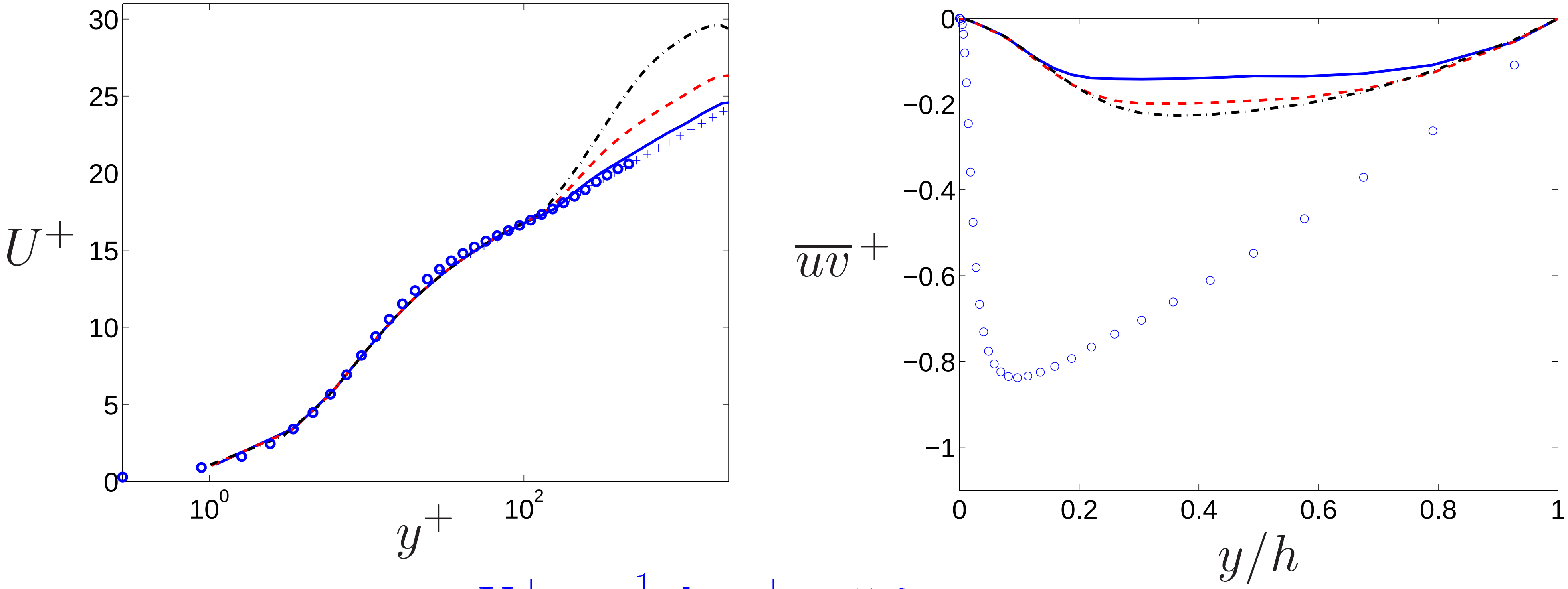
circles: **DNS at** $Re_\tau = 500$

solid lines: $x/\delta = 1.4$

dashed lines: $x/\delta = 5.3$

dash-dotted lines: $x/\delta = 22.9$

Time scale $\mathcal{T}_1$ and length scale $L_t = 0$



+: $U^+ = \frac{1}{0.4}\ln y^+ + 5.2$

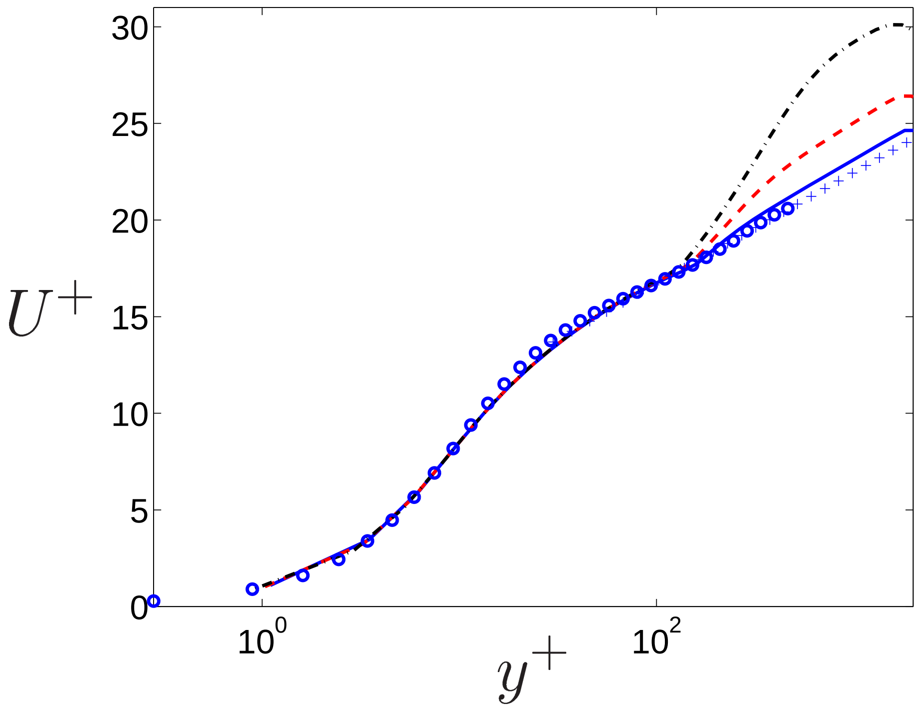
circles: **DNS at** $Re_\tau = 500$

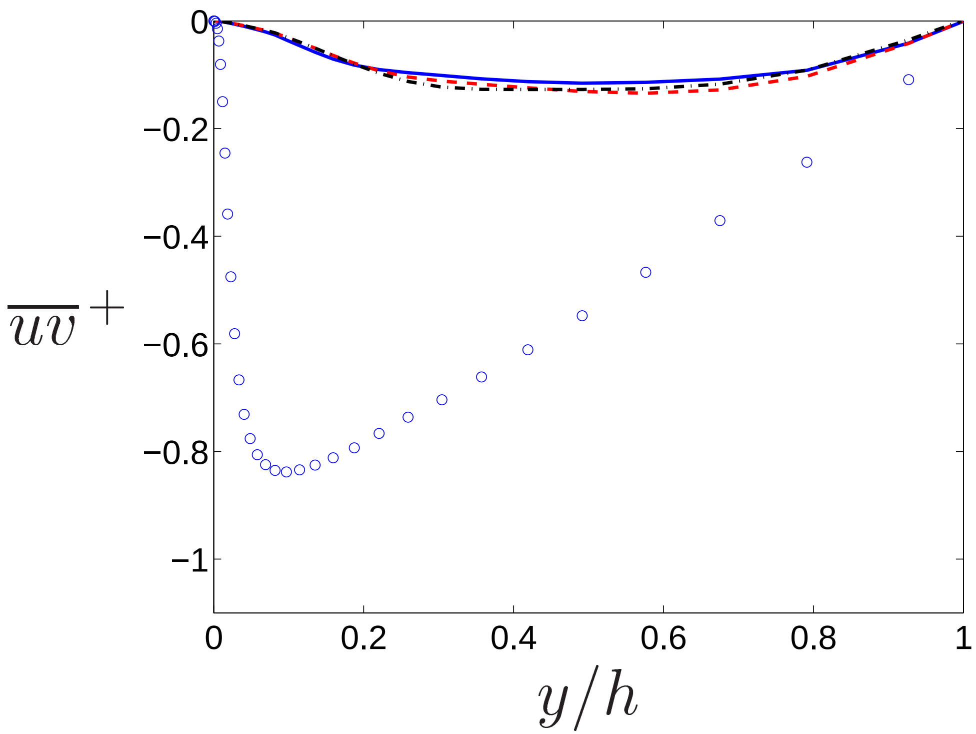
solid lines: $x/\delta = 1.4$

dashed lines: $x/\delta = 5.3$

dash-dotted lines: $x/\delta = 22.9$

Time scale $\tau = 0$ and length scale $\mathcal{L}_1$





+: $U^+ = \frac{1}{0.4}\ln y^+ + 5.2$

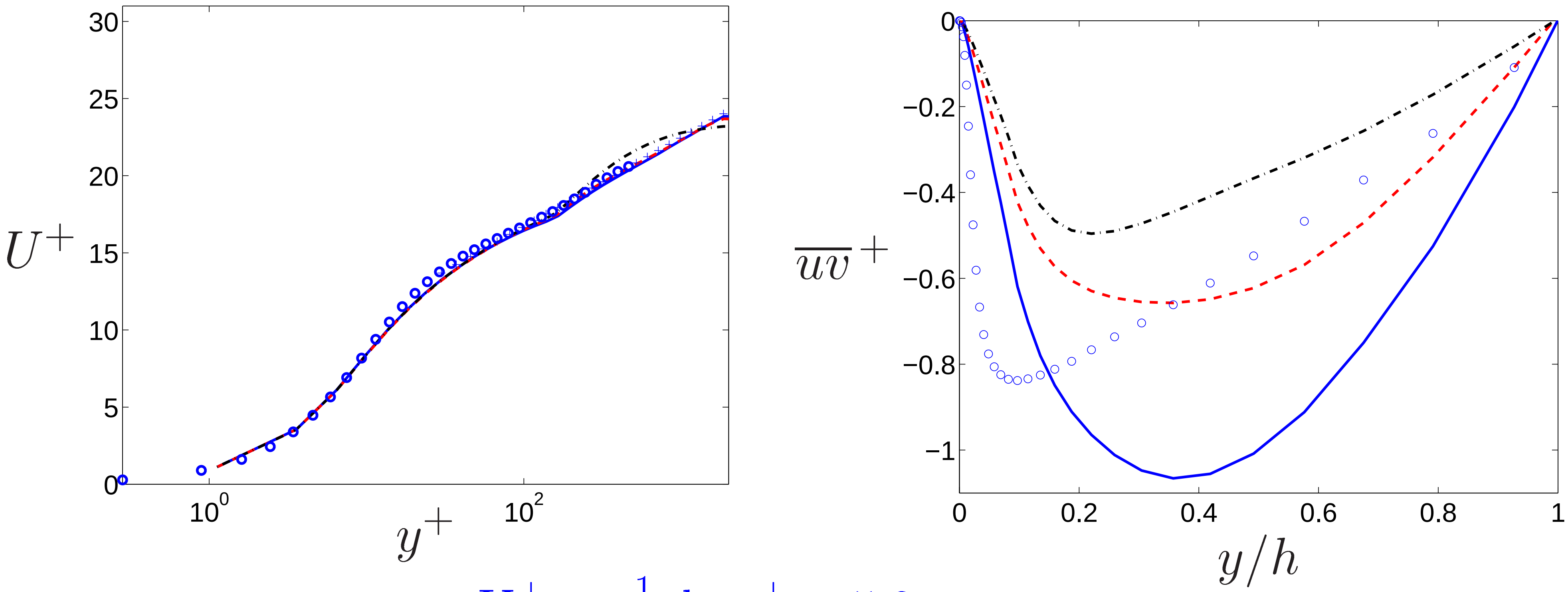
circles: **DNS at** $Re_\tau = 500$

solid lines: $x/\delta = 1.4$

dashed lines: $x/\delta = 5.3$

dash-dotted lines: $x/\delta = 22.9$

Time scale $0.25\mathcal{T}_1$ and length scale $\mathcal{L}_1$



+: $U^+ = \frac{1}{0.4}\ln y^+ + 5.2$

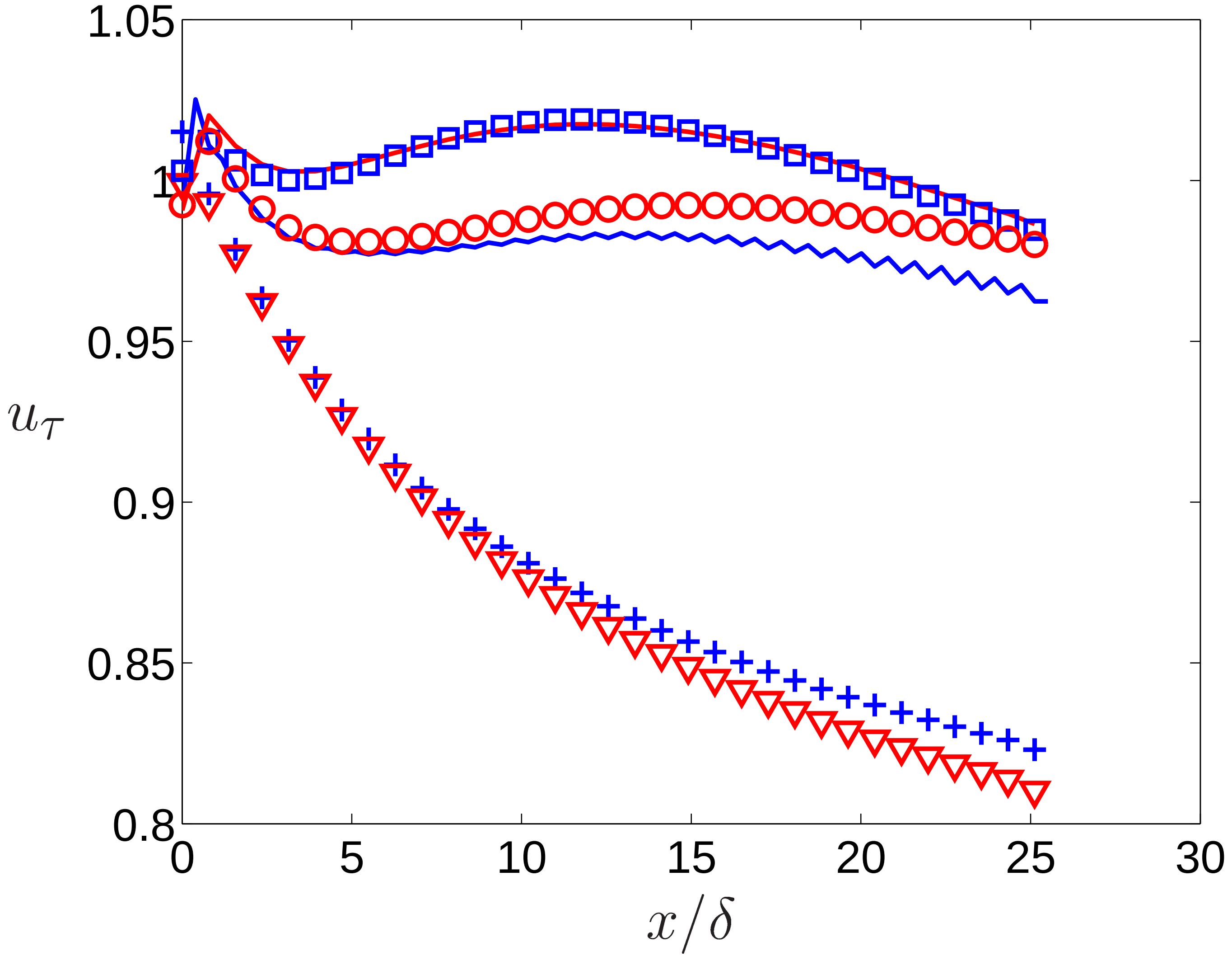
circles: DNS at $Re_\tau = 500$

solid lines: $x/\delta = 1.4$

dashed lines: $x/\delta = 5.3$

dash-dotted lines: $x/\delta = 22.9$

FRICTION VELOCITIES



— $\mathcal{T}_1,\ \mathcal{L}_1$

— $\mathcal{T}_1,\ 2\mathcal{L}_1$

$\square$: $0.25\mathcal{T}_1,\ \mathcal{L}_1$

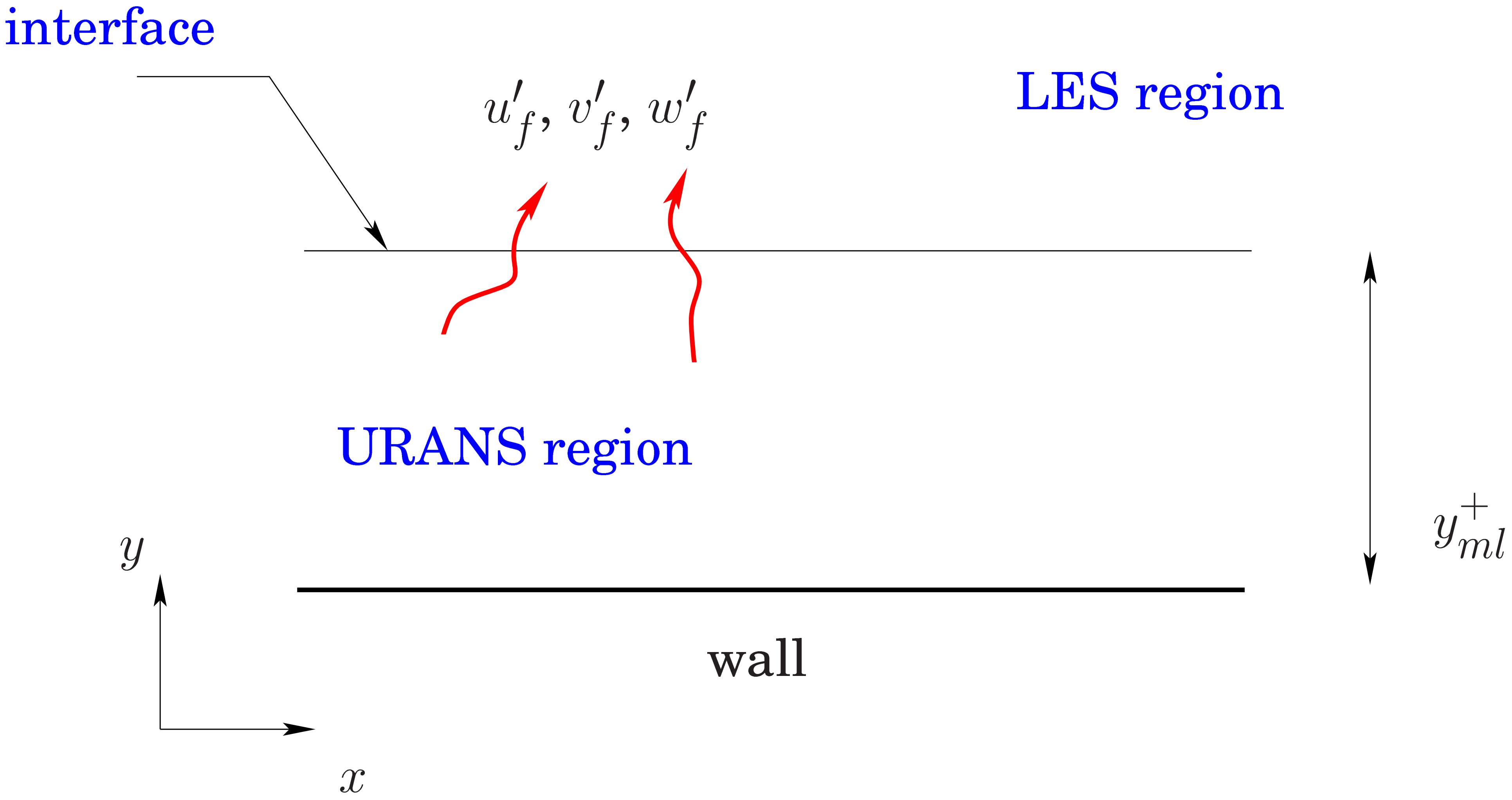
$\bigtriangledown$: $\mathcal{T}=0,\ \mathcal{L}_1$

$+$: $\mathcal{T}_1,\ \mathcal{L}=0$

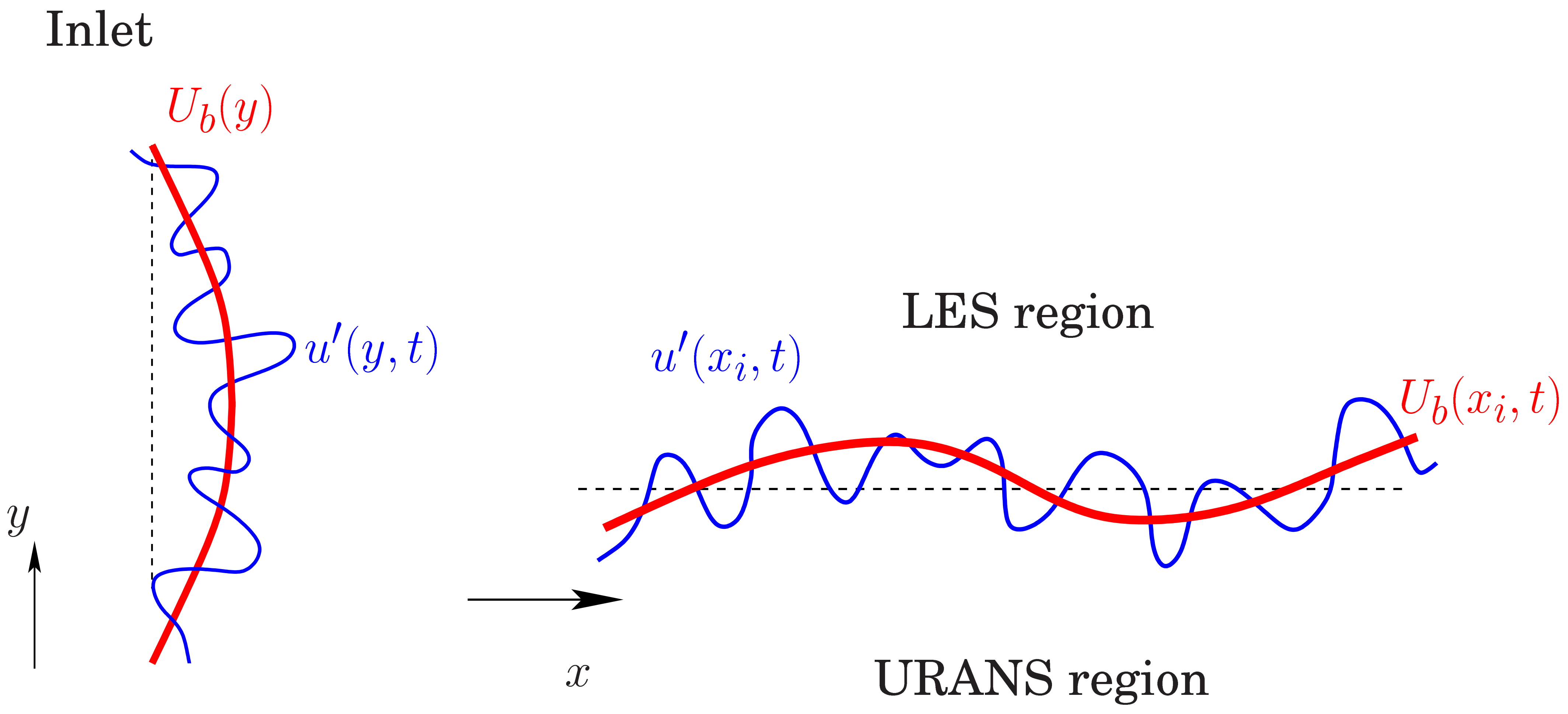
$\circ$: $\mathcal{T}_1,\ \mathcal{L}_1$ **forcing**

FORCING FLUCTUATIONS ADDED AT THE INTERFACE

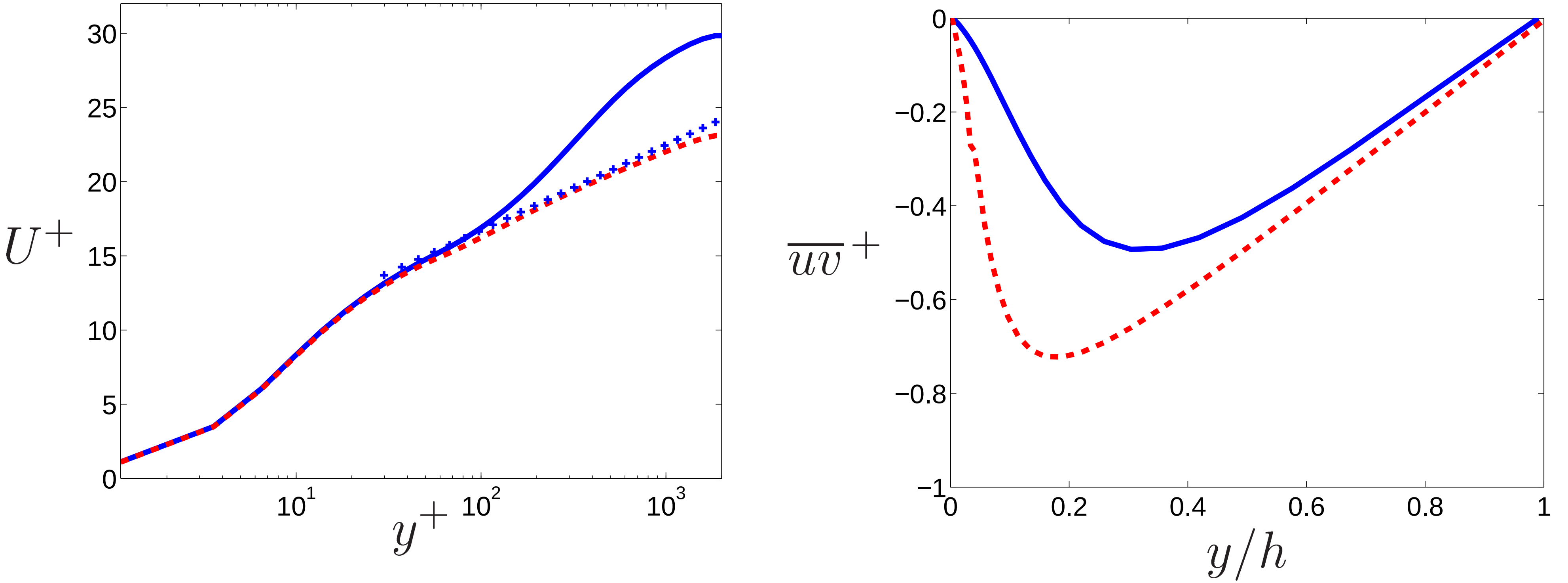
- Object: to trig the momentum equations into resolving large-scale turbulence



INLET BOUNDARY CONDITIONS vs. FORCING



FULLY DEVELOPED CHANNEL FLOW (periodic in x)



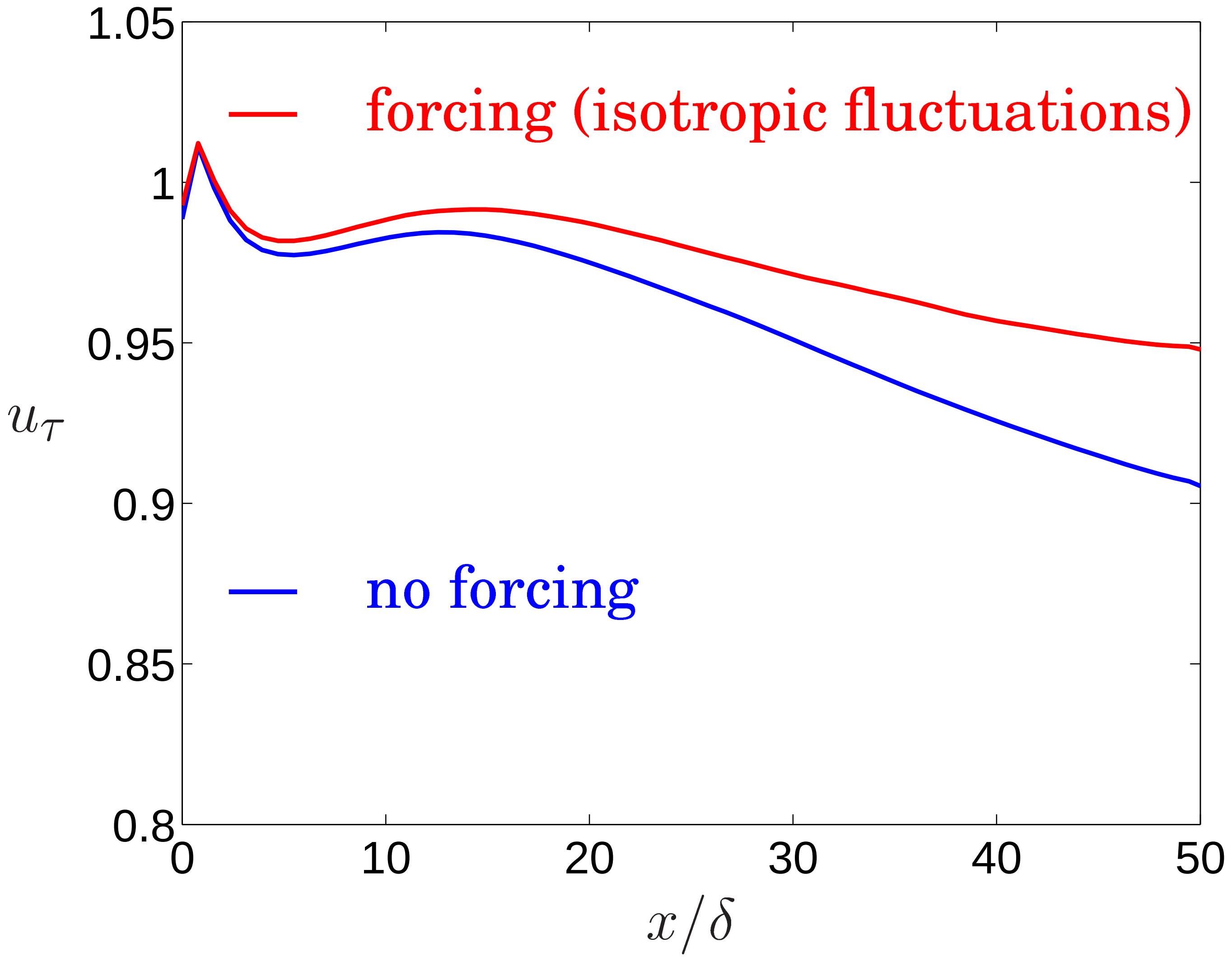
+: $U^+ = \frac{1}{0.4}\ln y^+ + 5.2$

— **no forcing**

---- forcing (isotropic fluctuations)

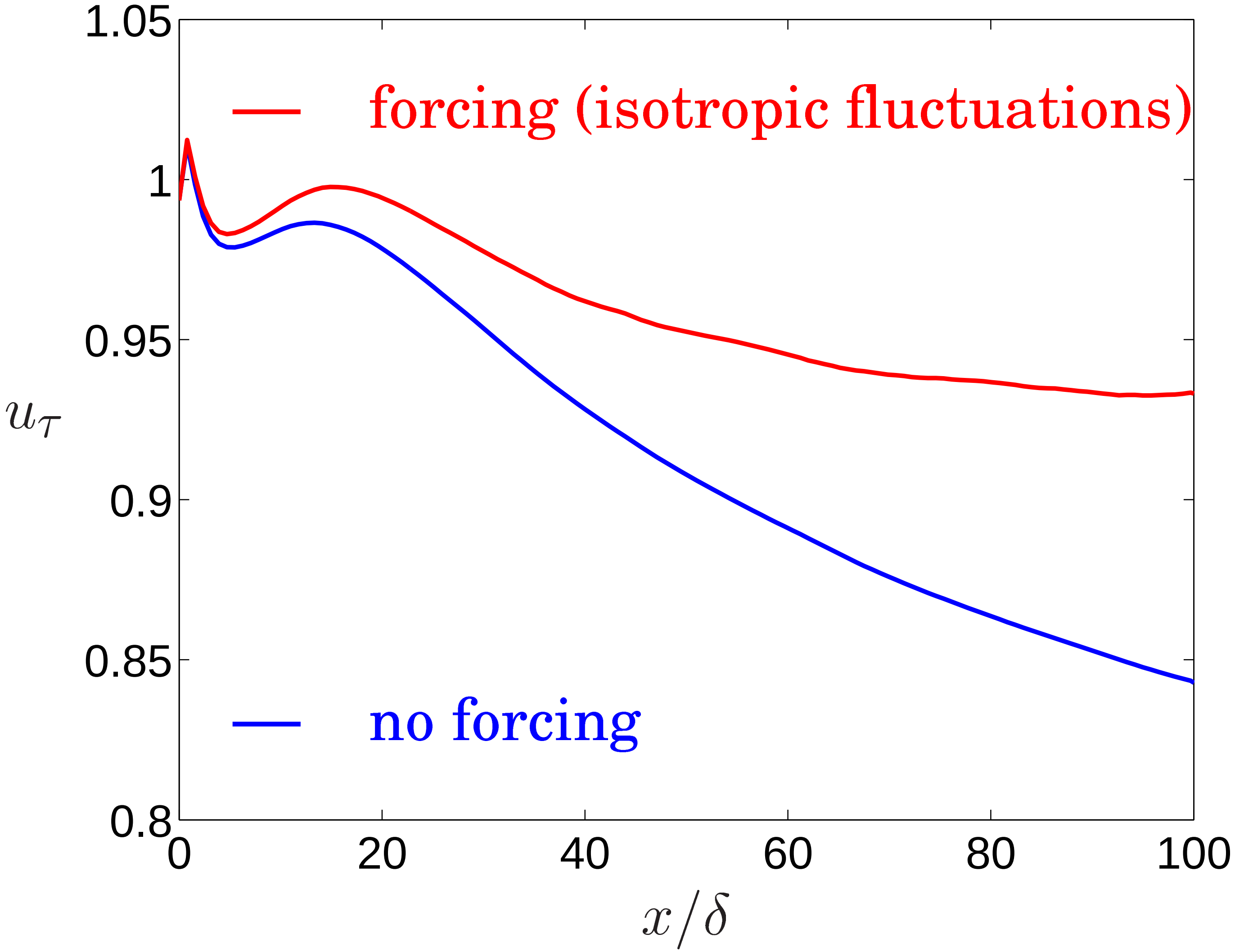
FRICTION VELOCITIES, LONG CHANNEL

- $\mathcal{T}_1$, $\mathcal{L}_1$



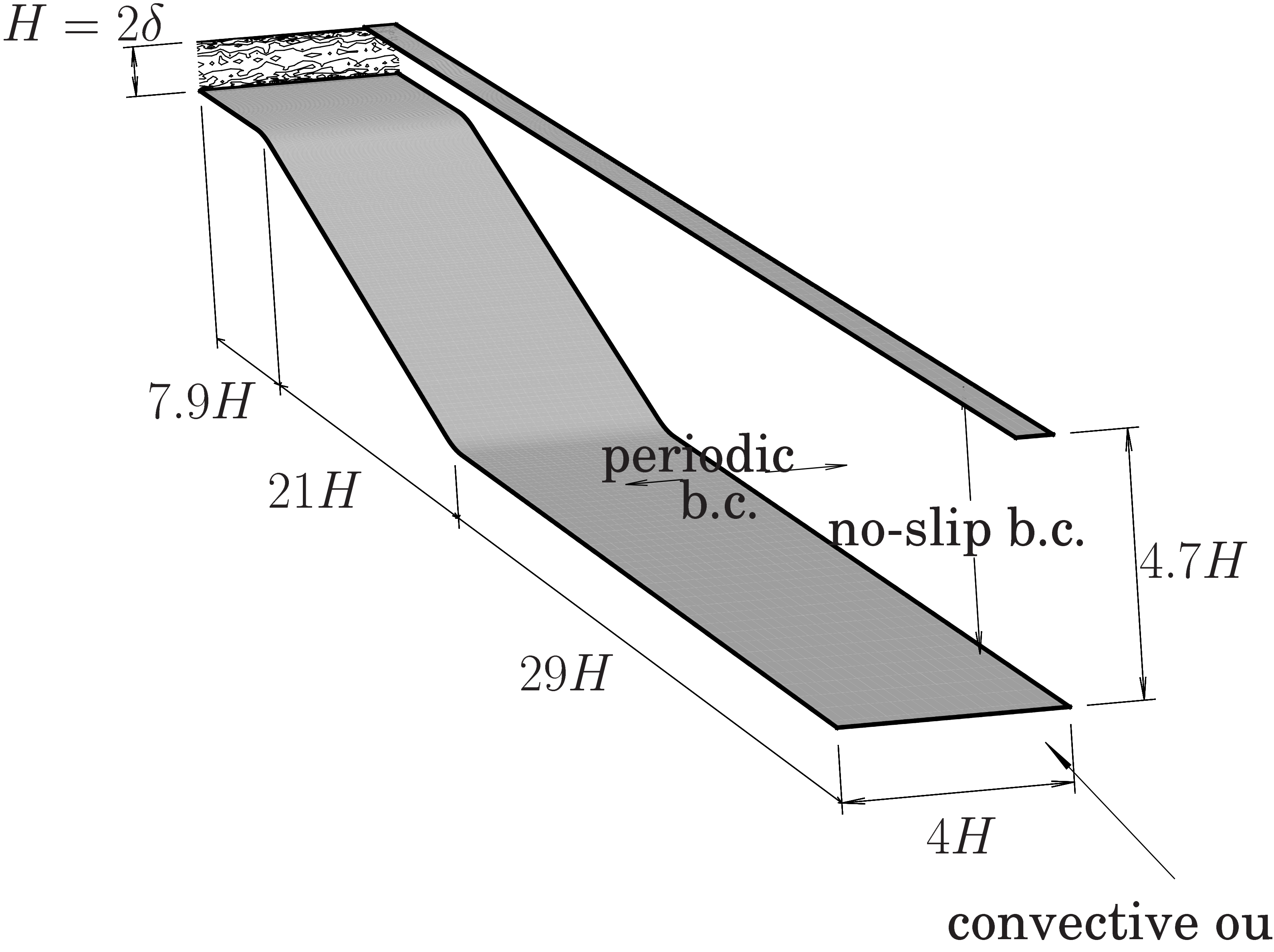
FRICTION VELOCITIES, X-LONG CHANNEL

- $\mathcal{T}_1$, $\mathcal{L}_1$

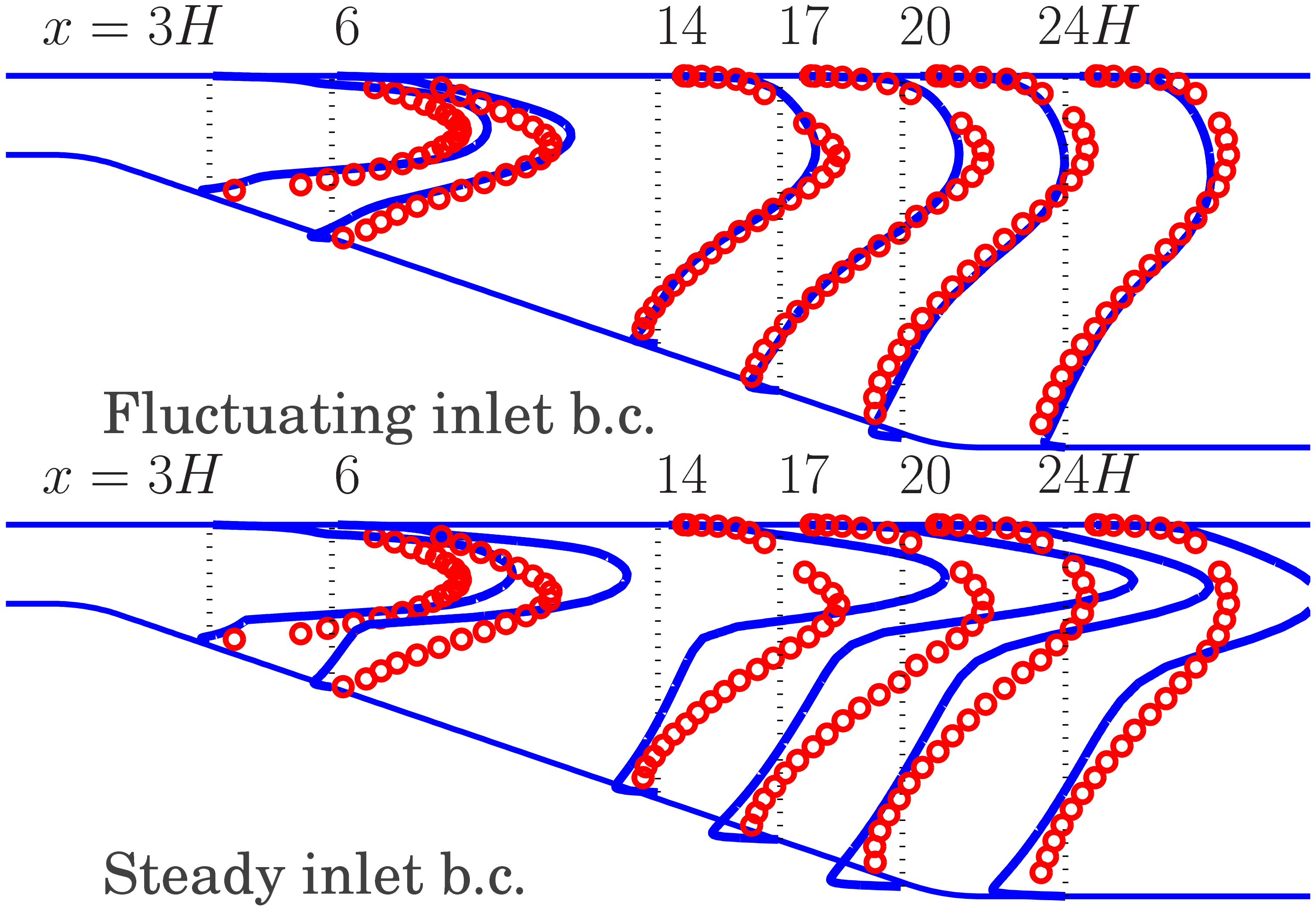


DIFFUSER GEOMETRY. $Re = U_{in}H/\nu = 18\,000$, angle 10^o

Hybrid LES-RANS, Dahlström & Davidson (2005a)



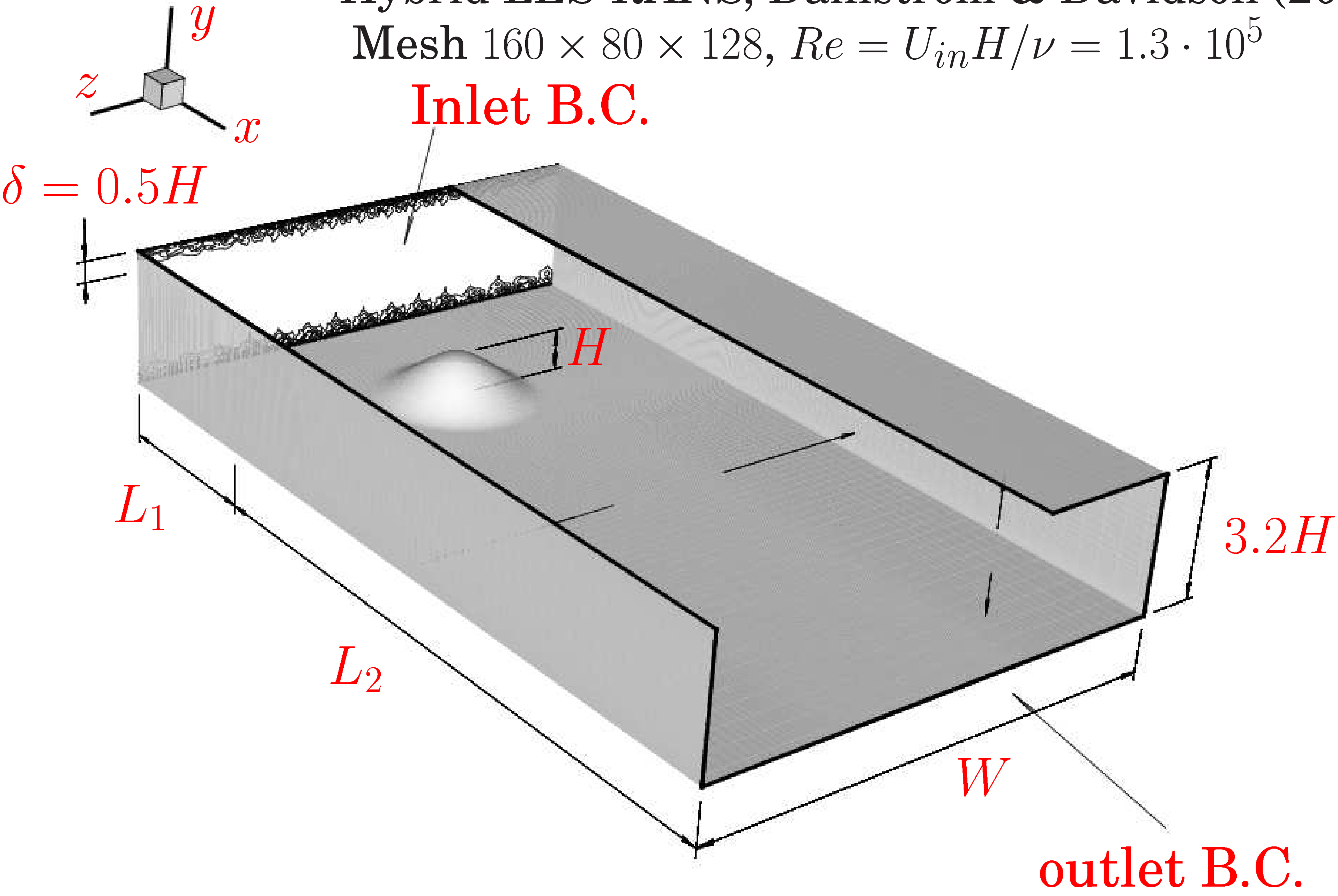
DIFFUSER



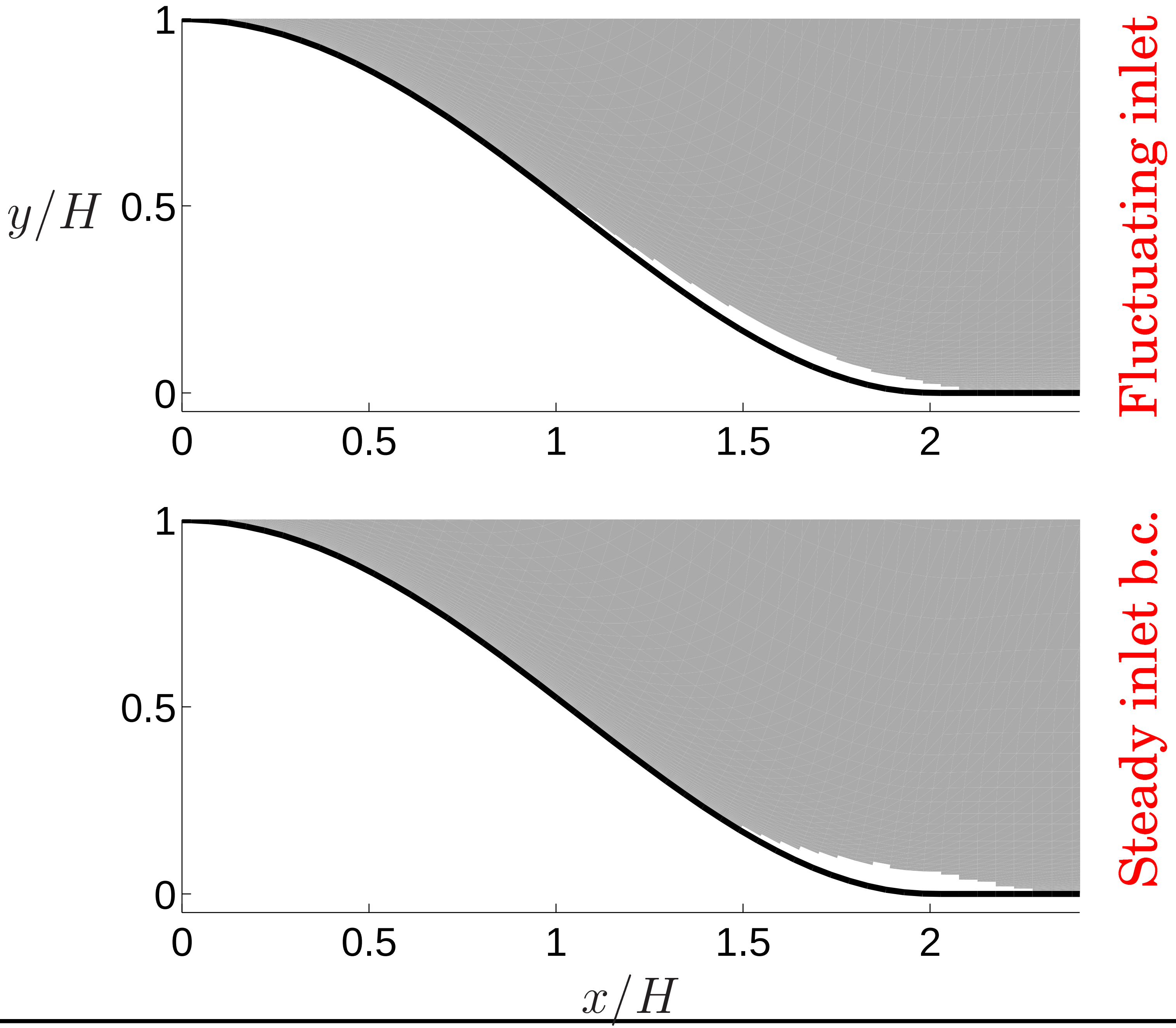
- Velocities

Hybrid LES-RANS, Dahlström & Davidson (2005b)

Mesh $160 \times 80 \times 128$, $Re = U_{in}H/\nu = 1.3 \cdot 10^5$



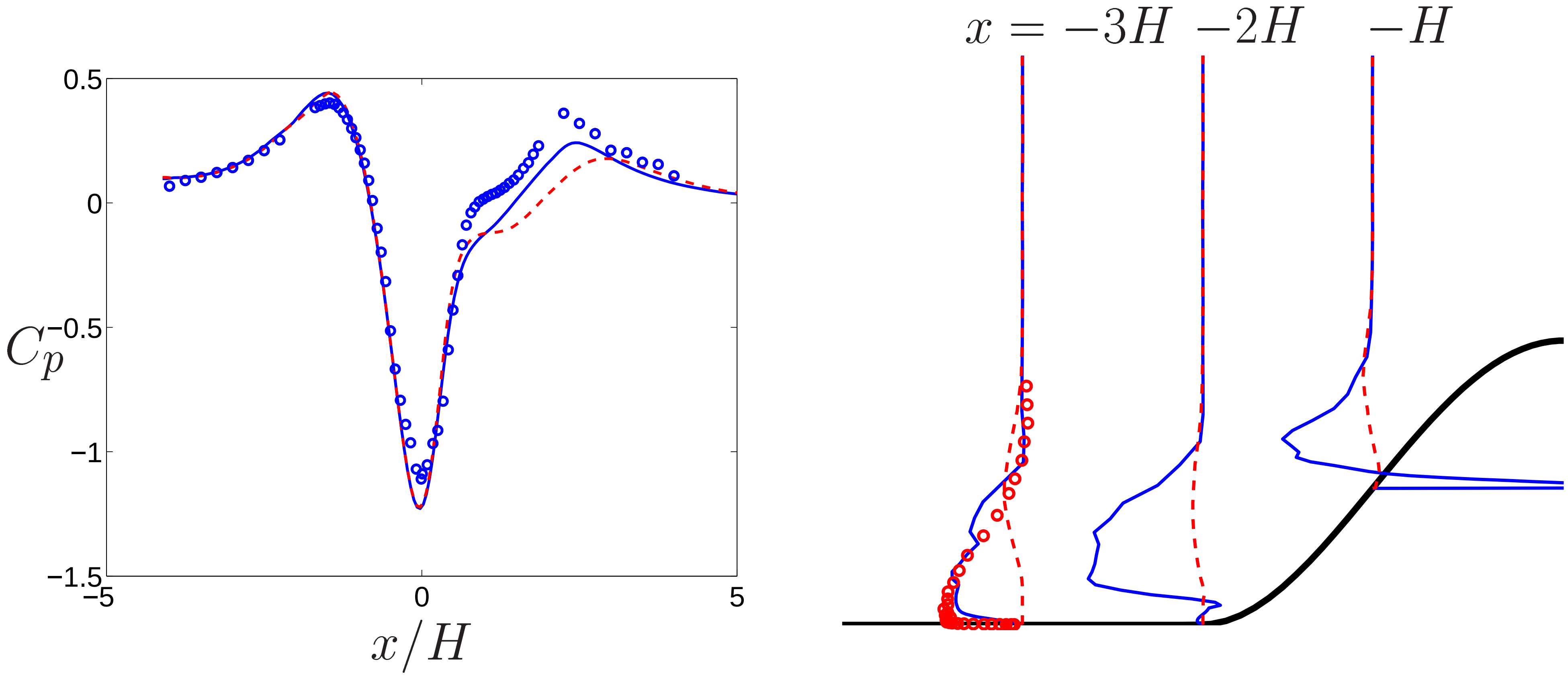
3D HILL: white region is backflow. $z = 0$



Fluctuating inlet b.c.

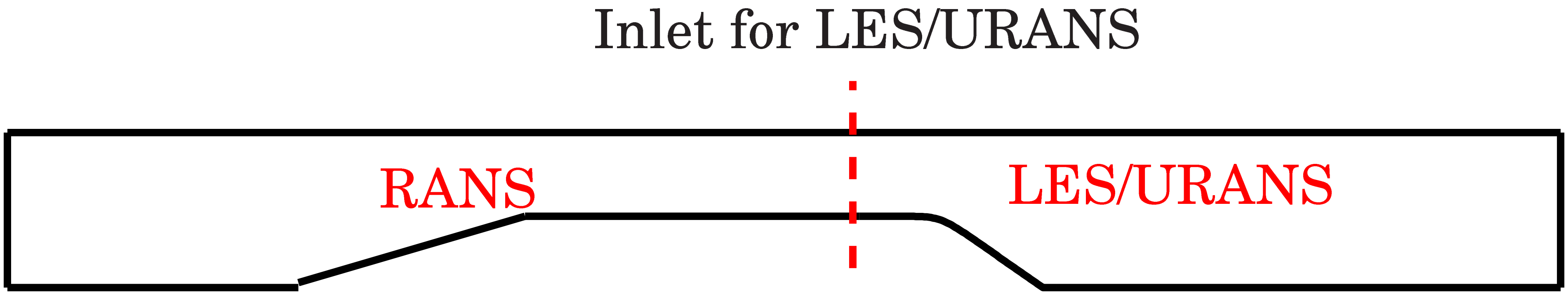
Steady inlet b.c.

3D HILL



—— fluctating inlet b.c. - - - - - - steady inlet b.c.

EMBEDDED LES



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1. Do a RANS simulation of the entire domain
2. Do an unsteady LES/RANS simulation of the right part of the domain

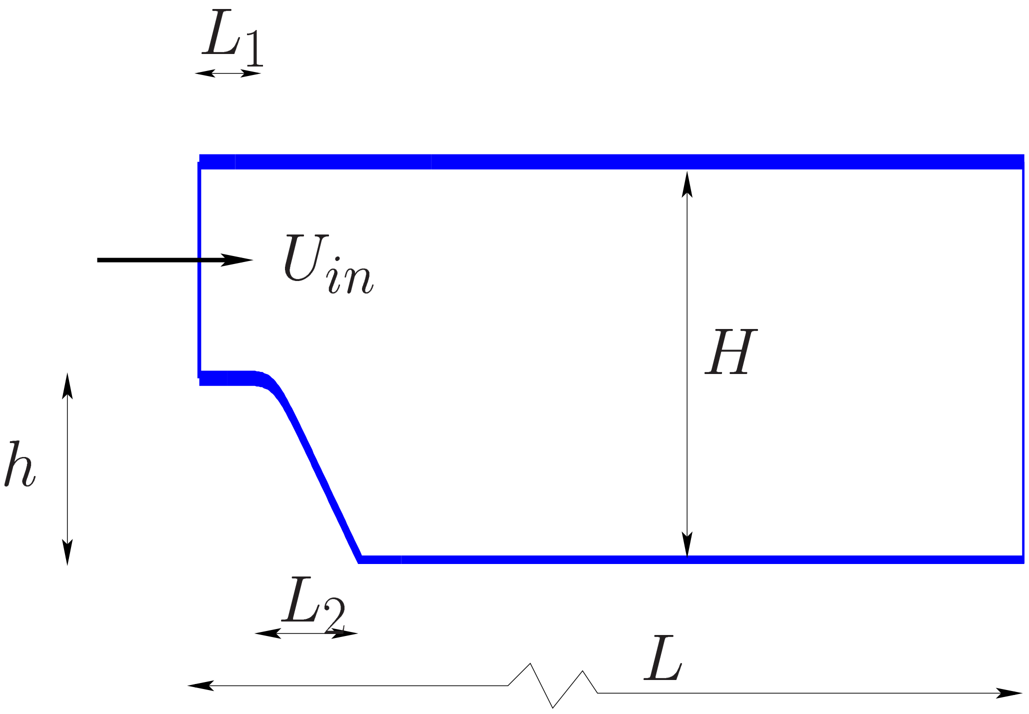
- At stage 2, fluctuating inlet boundary conditions needed

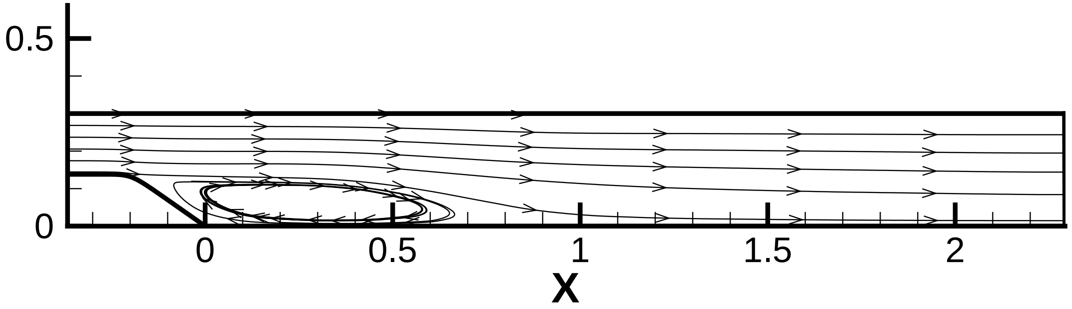
FLOW OVER a BUMP: DESider CASE

- Measurements have been carried out by ONERA. $Re_h = 2.1 \cdot 10^6$ based on the bump height. Rectangular duct.

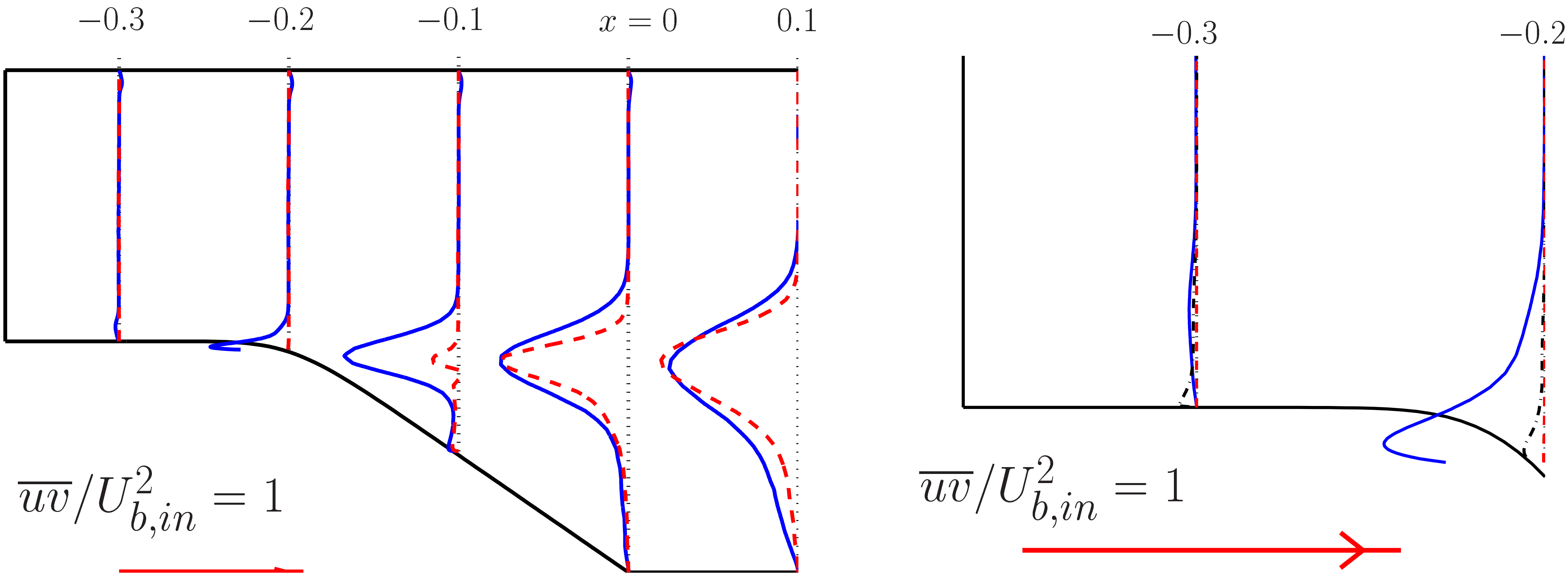
- $W/H = 1.67$, $h/H = 0.46$, $L_1/H = 0.34$, $L_2/H = 0.88$, $L/H = 7.6$, $\delta_{in}/H = 0.03$.

- Mesh: $221 \times 122 \times 32$. Note that $\delta_{in}/\Delta z \simeq 2$ and $\delta_{in}/\Delta x_{in} \simeq 3$





FLOW OVER a BUMP: shear stresses

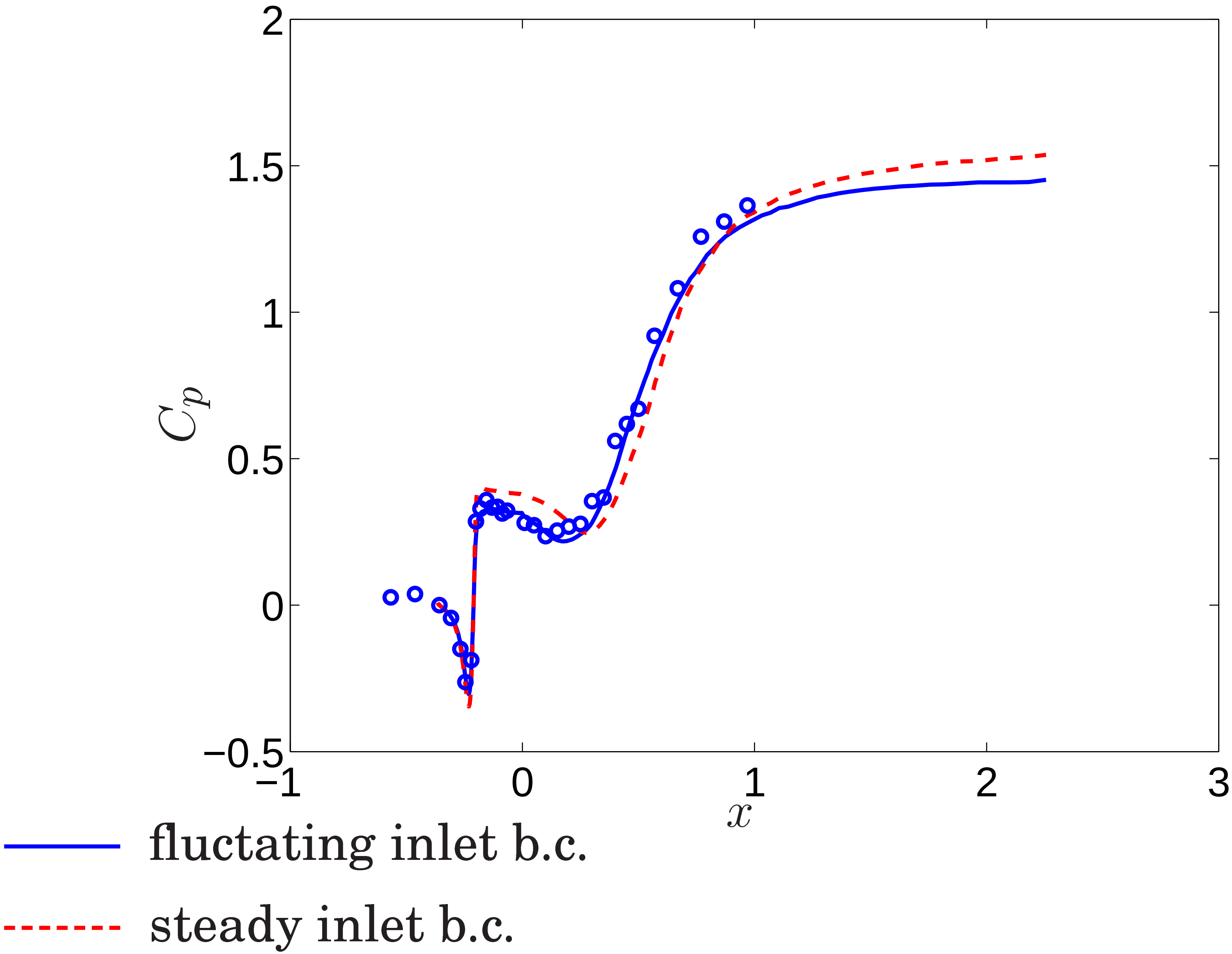


——— resolved shear stresses; fluctating inlet b.c.

- - - - - resolved shear stresses; steady inlet b.c.

–·–·– modelled shear stresses; fluctating inlet b.c.

FLOW OVER a BUMP: pressure coefficient



CONCLUSIONS

- Synthesized isotropic turbulence fluctuations have been used for prescribing fluctuating inlet velocities.
- Length scale $\mathcal{L}_1$ and time scale $\mathcal{T}$ prescribed independently
- It has been shown that both $\mathcal{L}_1$ and $\mathcal{T}$ are essential
- Far downstream the inlet, the standard hybrid LES-RANS forgets the inlet turbulence
- Hybrid LES-RANS with forcing conditions are needed for long channels
- Forcing conditions similar to inlet boundary conditions of fluctuating velocities. The object is to trig the equations into resolving turbulence.

REFERENCES

- Davidson, L., Dahlström, S. (2005a), ”Hybrid LES-RANS: An approach to make LES applicable at high Reynolds number”, International Journal of Computational Fluid Dynamics, 19(6):415–427.

- Davidson, L. and Billson, M. (2006), ”Hybrid LES/RANS: Using Synthesized Turbulence for Forcing at the Interface”, *International Journal of Heat and Fluid Flow*, Vol. 27, Number 6, pp. 1028–1042.

- Davidson, L. and Billson, M. (2004), ”Hybrid LES/RANS: Using Synthesized Turbulence for Forcing at the Interface”, *ECCOMAS 2004*, P. Neittaanmäki, T. Rossi, S. Korotov, E. Oñate and J. Périaux and D. Knörzer (eds), July 24-28, Finland.

REFERENCES

L. Davidson (2007a), ”Using Isotropic Synthetic Fluctuations as Inlet Boundary Conditions for Unsteady Simulations”, *Advances and Applications in Fluid Mechanics*, Vol. 1, Number =1, pp. 1–35.

- Davidson, L (2005). ”Hybrid LES-RANS: Inlet boundary conditions”, In *3rd National Conference on Computational Mechanics – MekIT'05 (invited paper)*, Trondheim, Norway.

- Davidson, L. and Dahlström, S. (2005b), ”Hybrid LES-RANS: Computation of the flow around a three-dimensional hill”, In W. Rodi and M. Mulas, editors, *Engineering Turbulence Modelling and Measurements 6*, pages 319–328. Elsevier.

REFERENCES

L. Davidson (2007c), ”Inlet Boundary Conditions for Embedded LES”, *First CEAS European Air and Space Conference*, 10-13 September, Berlin.

L. Davidson (2007b), ”Hybrid LES-RANS: Inlet Boundary Conditions for Flows Including Recirculation”, *5th International Symposium on Turbulence and Shear Flow Phenomena*, Vol. 2, pp. 689–694, 27-29 August, Munich, Germany.