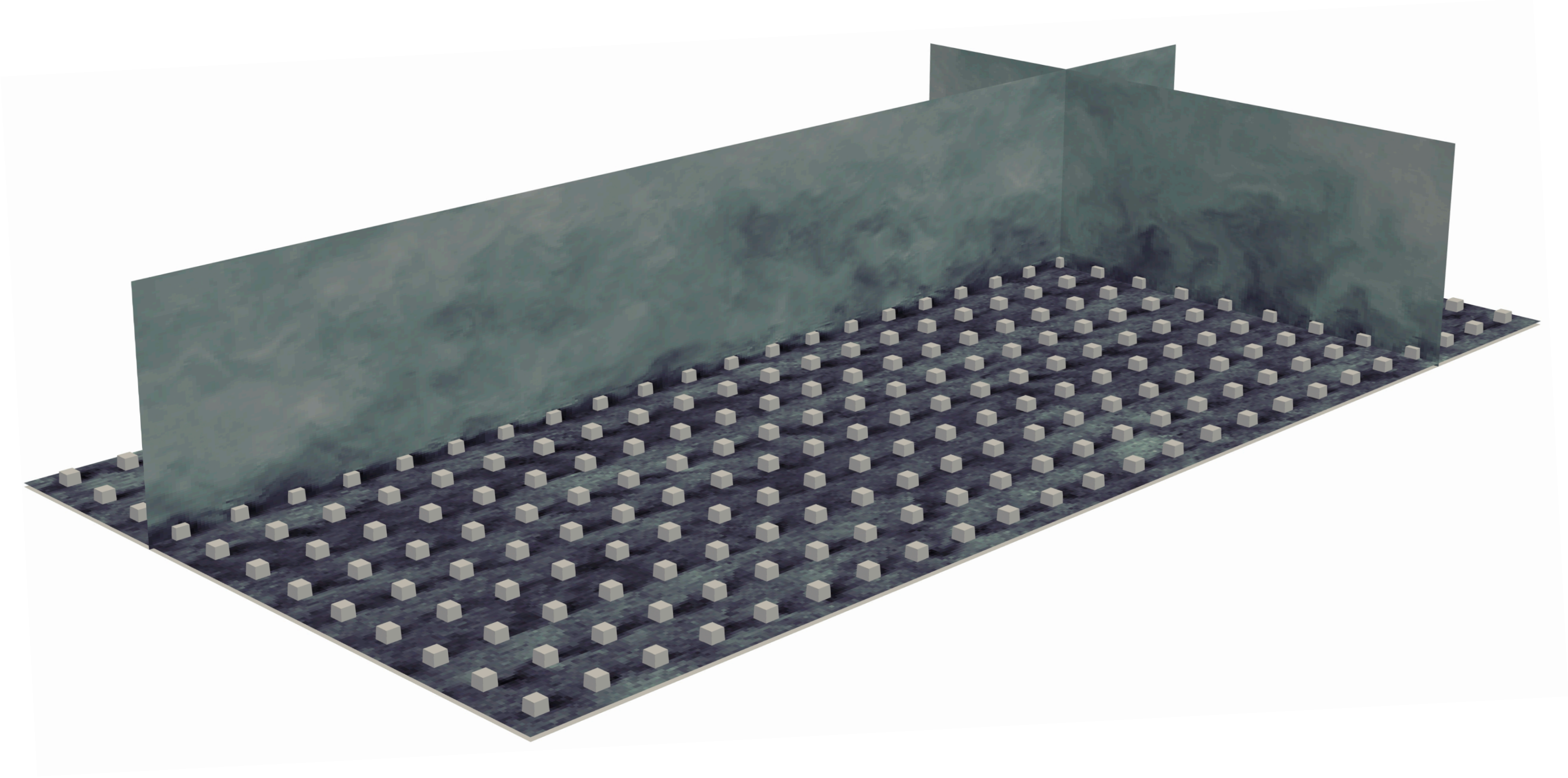
Impact of numerical domain on turbulent flow statistics: scalings and considerations for canopy flows



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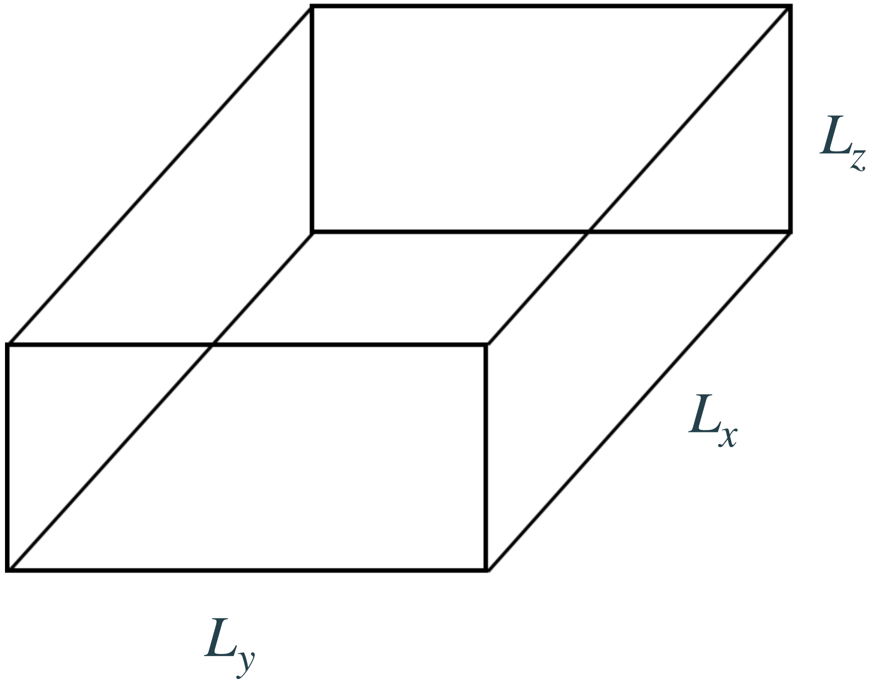
Examples of different domains in the literature.



Claus et al. (2012):

$L_z/h = 4$

$L_z : L_y : L_x = 1 : 2 : 2$

Xie and Castro (2006):

$L_z/h = 10$

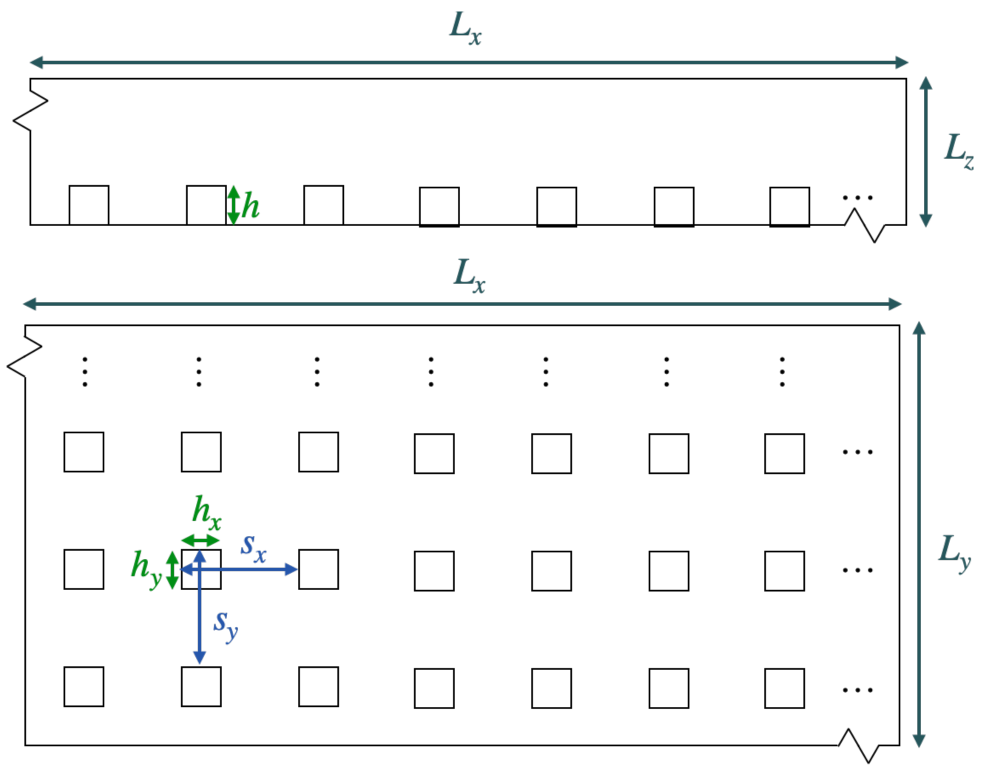
$L_z : L_y : L_x = 1 : 1.6 : 1.6$

Cheng and Porte-Agel (2015):

$L_z/h = 14$

$L_z : L_y : L_x = 1 : 0.85 : 2.28$

Impact of 8 length scales and 1 velocity scale are considered on flow statistics.



Velocity scale:

$u_\tau \longleftarrow$ Friction Velocity

Height of the canopy (h) and friction velocity (u_τ) are chosen as the repeating parameters.

$$U/u_\tau = f\left(\frac{L_z}{h}, \frac{L_y}{h}, \frac{L_x}{h}, \frac{h_y}{h}, \frac{h_x}{h}, \frac{s_y}{h}, \frac{s_x}{h}, \frac{z}{h}\right)$$

Rearranging Pi groups

$$U/u_\tau = f\left(\frac{L_z}{h}, \boxed{\frac{L_y}{L_z}}, \boxed{\frac{L_x}{L_z}}, \frac{h_y}{h}, \frac{h_x}{h}, \frac{s_y}{h}, \frac{s_x}{h}, \frac{z}{h}\right)$$

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Rearranging Pi groups

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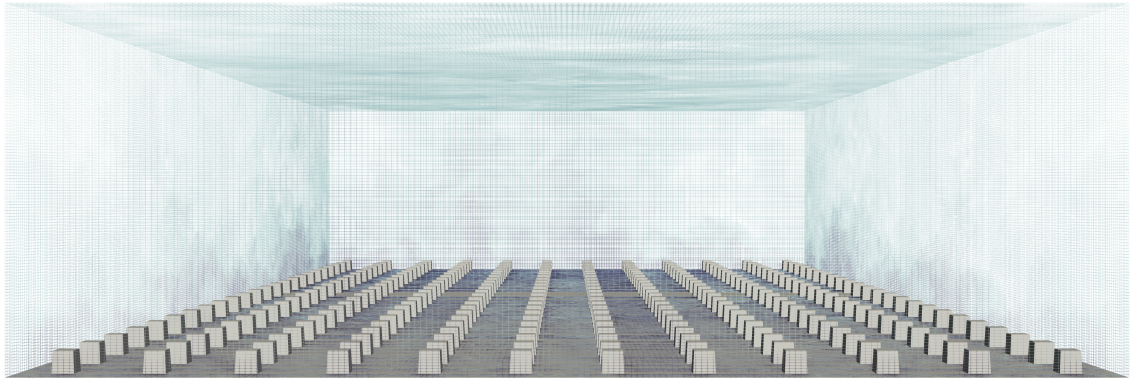
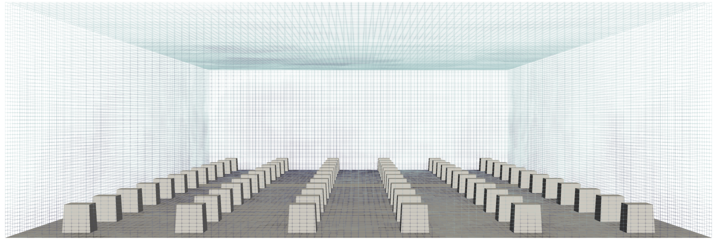
Only L_z/h is varied while keeping all other Pi groups constant.

$$U/u_\tau = f\left(\boxed{\frac{L_z}{h}}, \frac{L_y}{L_z}, \frac{L_x}{L_z}, \frac{h_y}{h}, \frac{h_x}{h}, \frac{s_y}{h}, \frac{s_x}{h}, \frac{z}{h}\right) = f\left(\boxed{\frac{L_z}{h}}, 3, 6, 1, 1, 4, 4, \frac{z}{h}\right)$$

$\boxed{L_z/h = 16}$

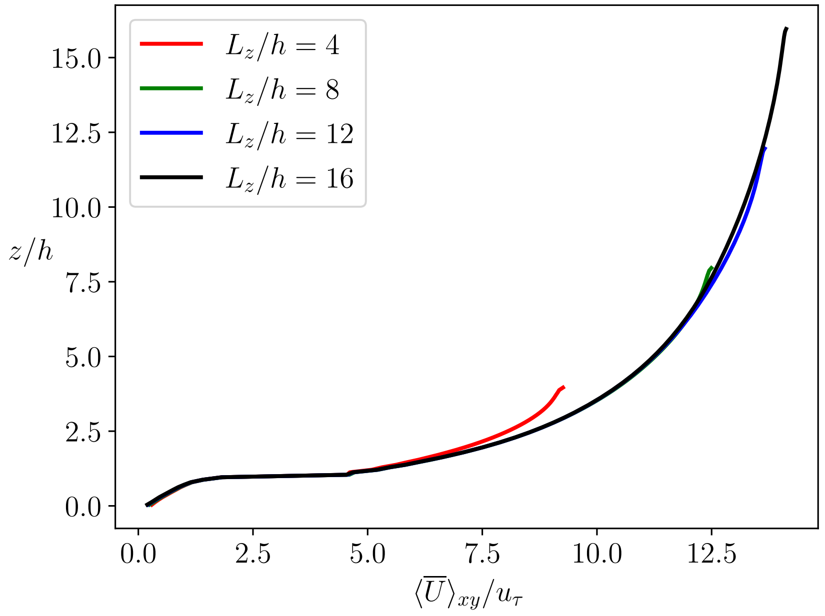


$\boxed{L_z/h = 8}$



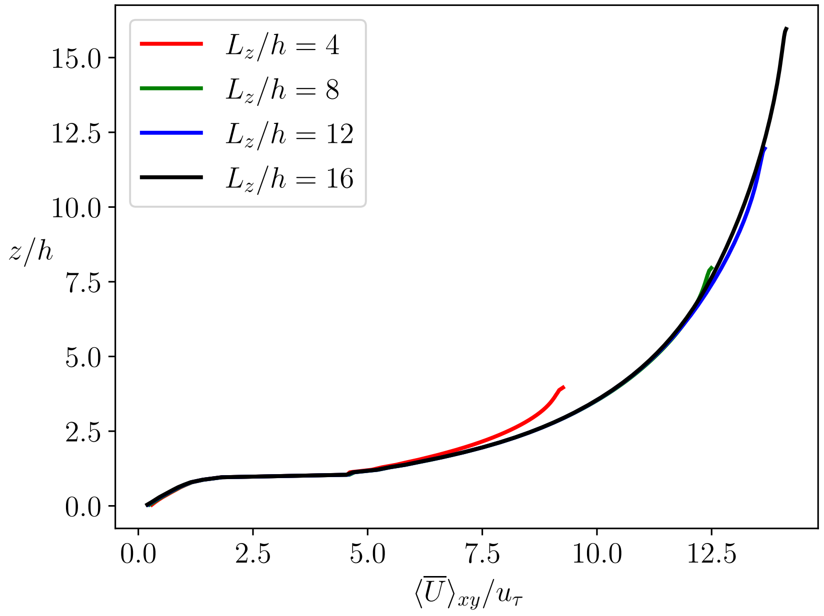
Collapse for mean streamwise velocity is observed for dense configuration;

Dense, $\lambda_p = \lambda_f = 0.25$

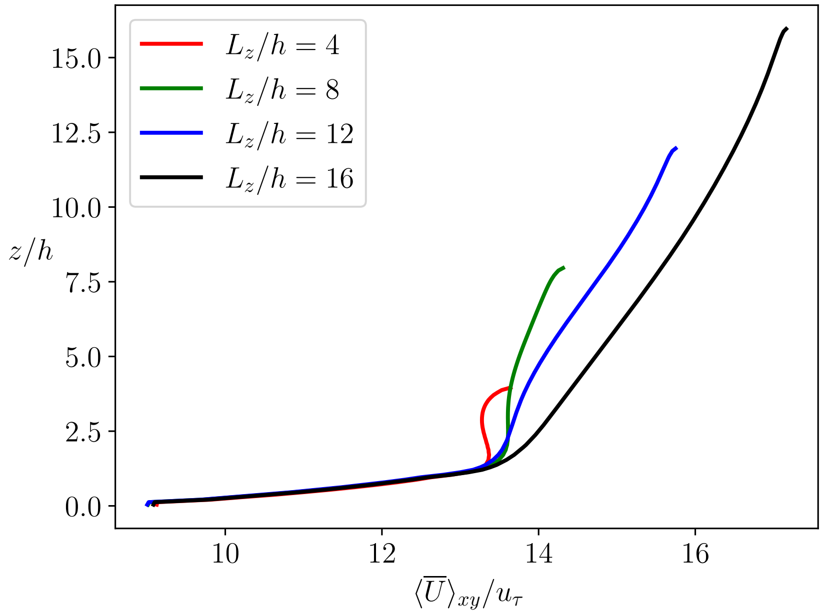


Collapse for mean streamwise velocity is observed for dense configuration; but not for sparse?

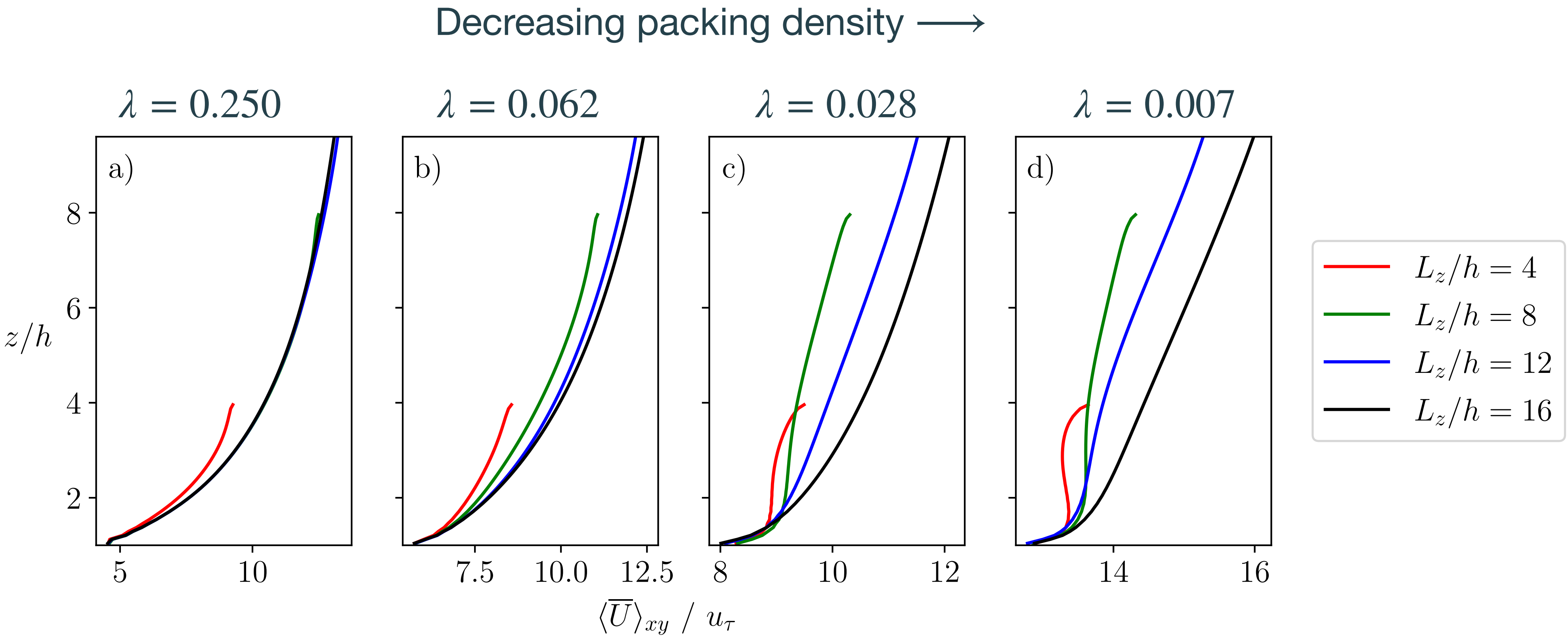
Dense, $\lambda_p = \lambda_f = 0.25$



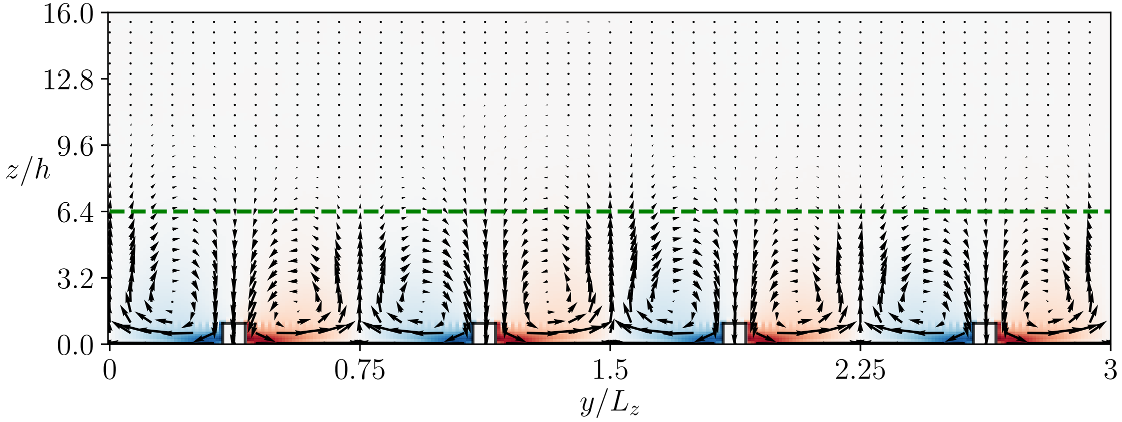
Sparse, $\lambda_p = \lambda_f = 0.007$



Mean streamwise velocity profiles gradually diverge with decreasing packing density.



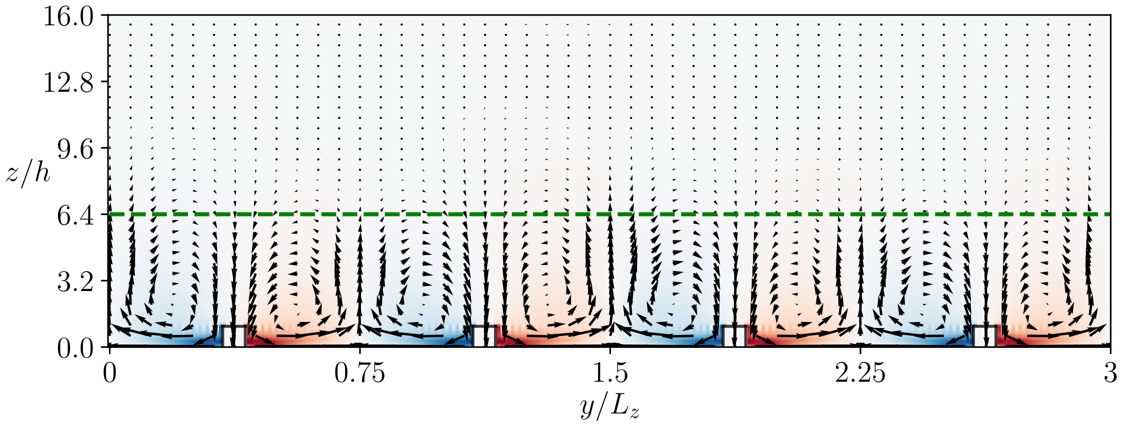
Changing L_z/h while keeping s_y/h constant changes a key parameter s_y/L_z which controls the size and strength of secondary flows.



$L_z/h = 16,\ s_y/h = 12$
$\Rightarrow s_y/L_z = 0.75$

$L_z/h = 8,\ s_y/h = 12$
$\Rightarrow s_y/L_z = 1.5$

Changing L_z/h while keeping s_y/h constant changes a key parameter s_y/L_z which controls the size and strength of secondary flows.



$L_z/h = 16,\ s_y/h = 12$
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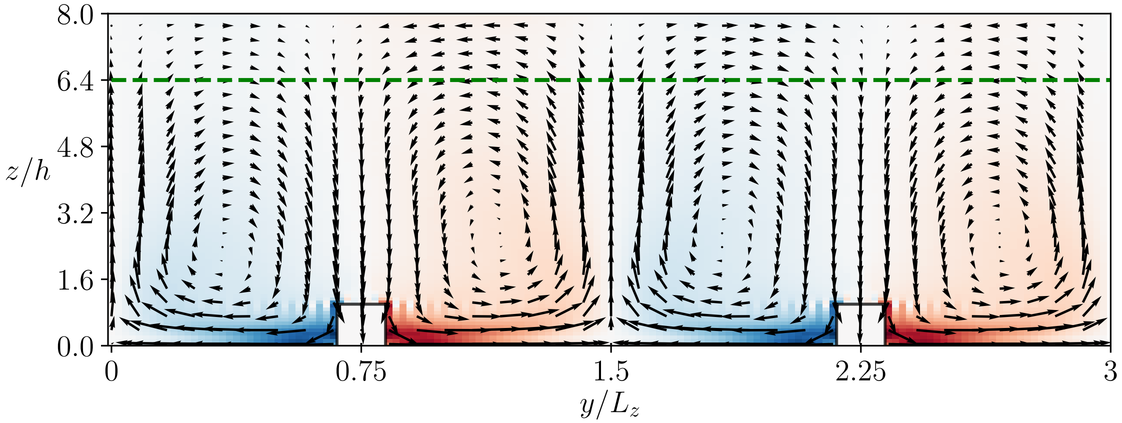
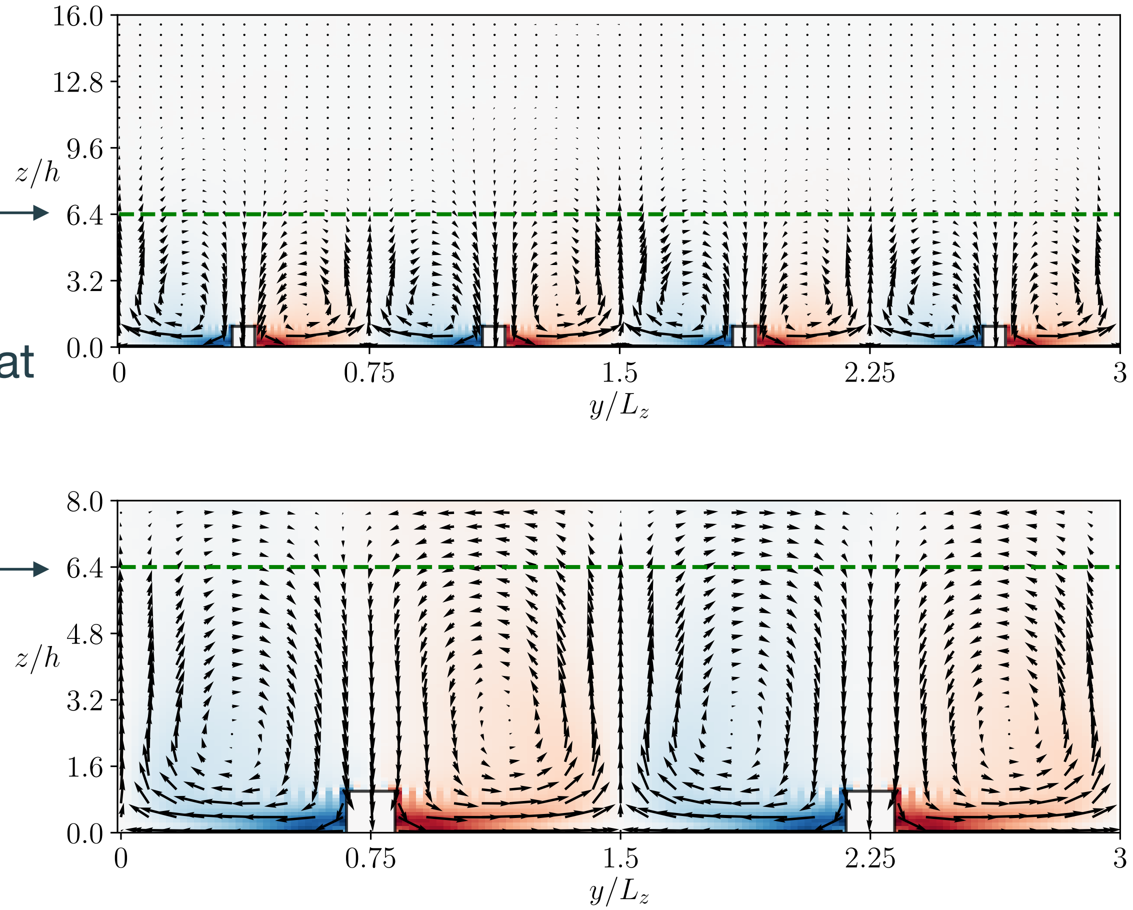


$L_z/h = 8,\ s_y/h = 12$
$\Rightarrow s_y/L_z = 1.5$

Changing L_z/h while keeping s_y/h constant changes a key parameter s_y/L_z which controls the size and strength of secondary flows.



Comparing at equal z/h

$L_z/h = 16,\ s_y/h = 12$
$\Rightarrow s_y/L_z = 0.75$

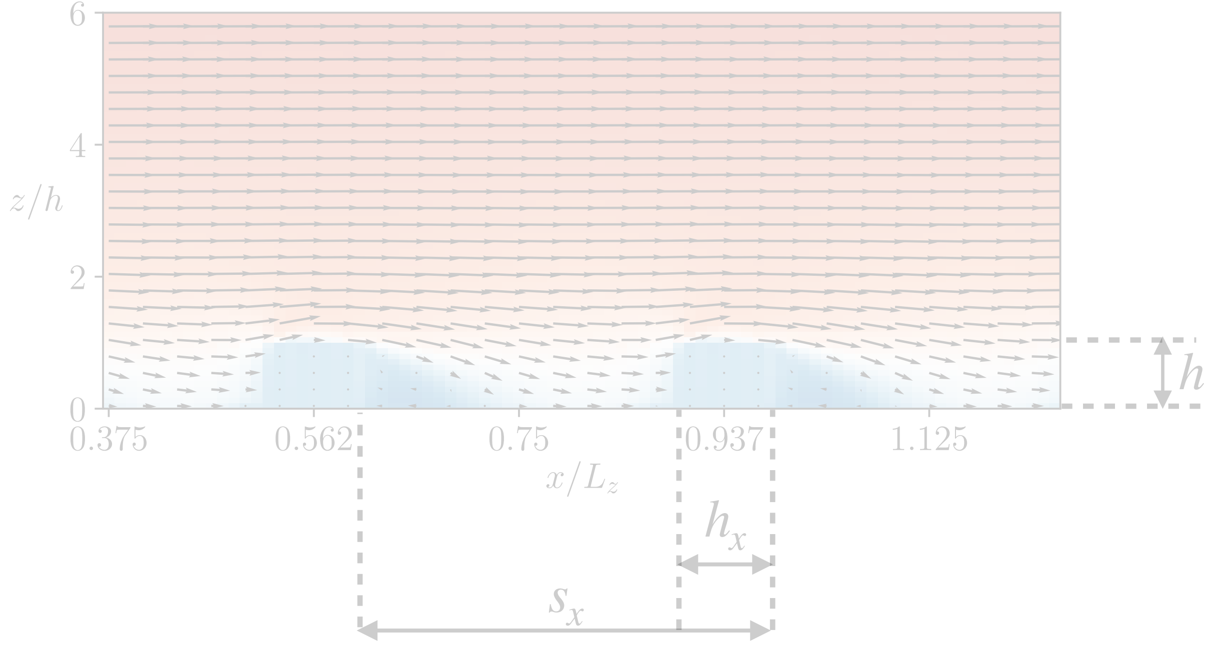
$L_z/h = 8,\ s_y/h = 12$
$\Rightarrow s_y/L_z = 1.5$

Height of the half-channel (L_z) and friction velocity (u_τ) are chosen as new repeating parameters.

$$U/u_\tau = f\left(\frac{L_z}{h}, \frac{L_y}{L_z}, \frac{L_x}{L_z}, \frac{s_y}{L_z}, \frac{s_x}{L_z}, \frac{h_y}{L_z}, \frac{h_x}{L_z}, \frac{z}{L_z}\right)$$

Rearranging Pi groups

$$U/u_\tau = f\left(\boxed{\frac{L_z}{h}}, \frac{L_y}{L_z}, \frac{L_x}{L_z}, \frac{s_y}{L_z}, \boxed{\frac{s_x}{h}}, \frac{h_y}{L_z}, \boxed{\frac{h_x}{h}}, \frac{z}{L_z}\right)$$

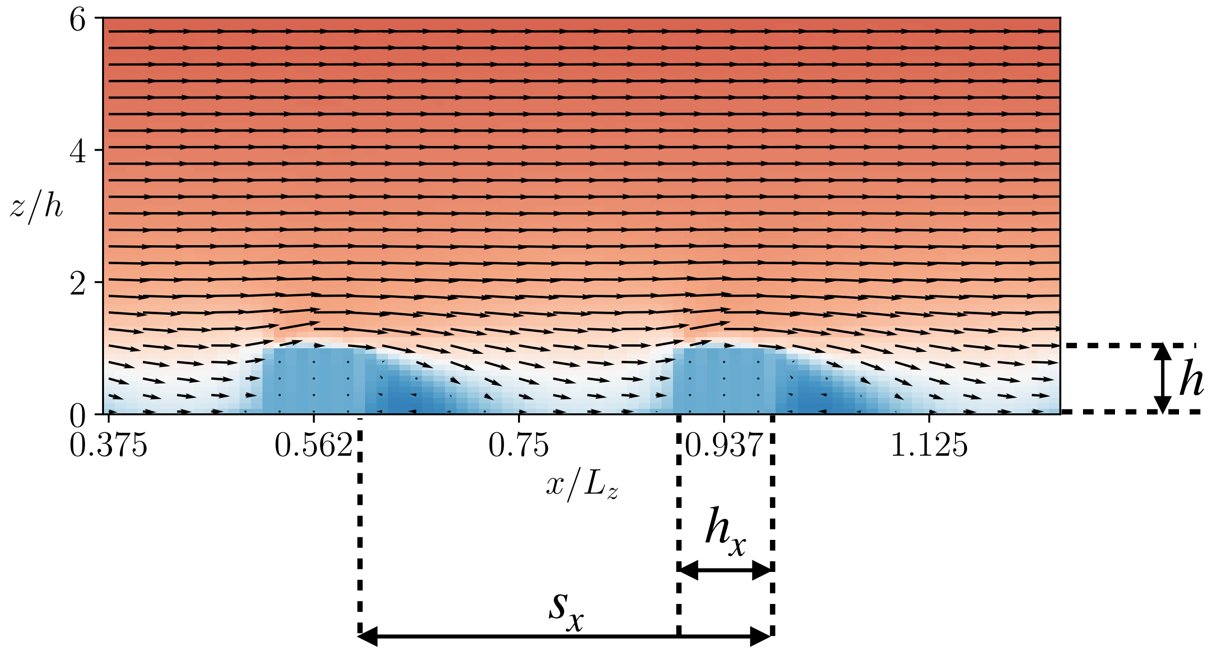


Height of the half-channel (L_z) and friction velocity (u_τ) are chosen as new repeating parameters.

$$U/u_\tau = f\left(\frac{L_z}{h}, \frac{L_y}{L_z}, \frac{L_x}{L_z}, \frac{s_y}{L_z}, \boxed{\frac{s_x}{L_z}}, \frac{h_y}{L_z}, \boxed{\frac{h_x}{L_z}}, \frac{z}{L_z}\right)$$

Rearranging Pi groups

$$U/u_\tau = f\left(\boxed{\frac{L_z}{h}}, \frac{L_y}{L_z}, \frac{L_x}{L_z}, \frac{s_y}{L_z}, \frac{s_x}{h}, \frac{h_y}{L_z}, \frac{h_x}{h}, \frac{z}{L_z}\right)$$



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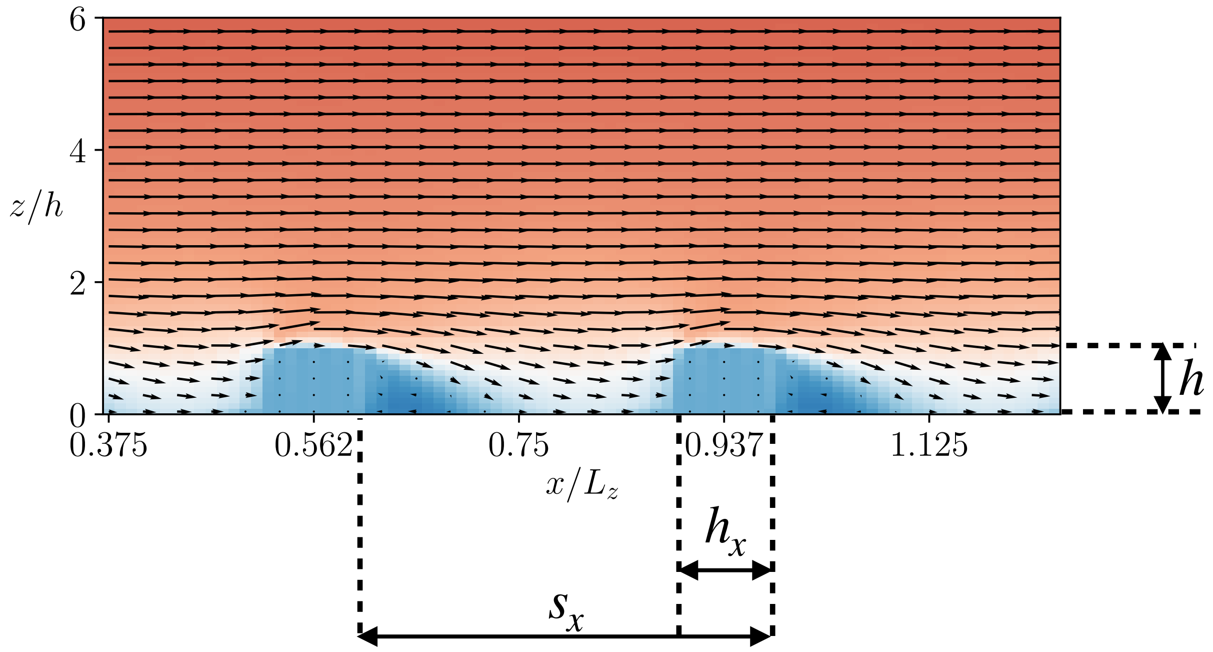
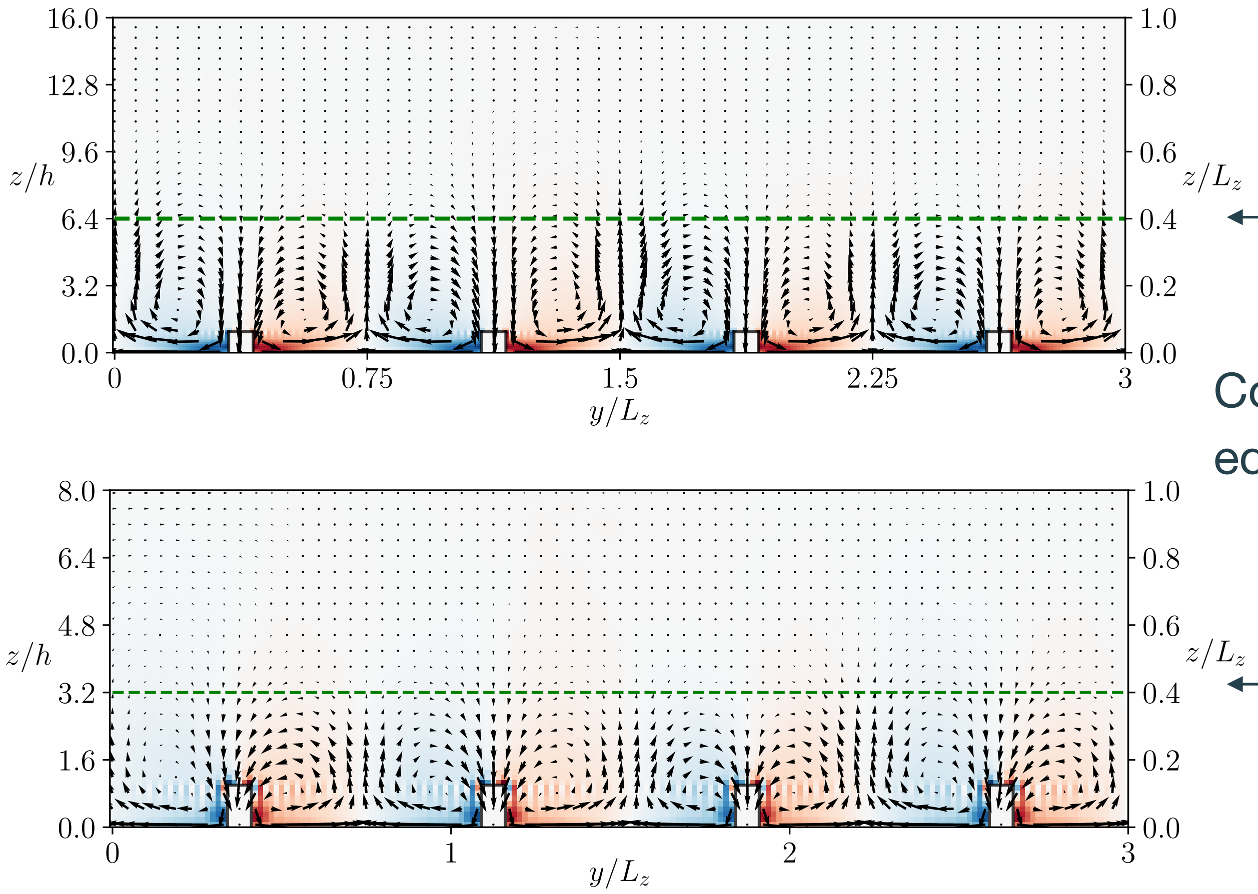
Rearranging Pi groups

$$U/u_\tau = f\left(\boxed{\frac{L_z}{h}}, \frac{L_y}{L_z}, \frac{L_x}{L_z}, \frac{s_y}{L_z}, \boxed{\frac{s_x}{h}}, \frac{h_y}{L_z}, \boxed{\frac{h_x}{h}}, \frac{z}{L_z}\right)$$



With the new set of Pi groups, s_y/L_z is preserved across the simulations, generating equivalent secondary flow configurations.



Comparing at equal z/L_z

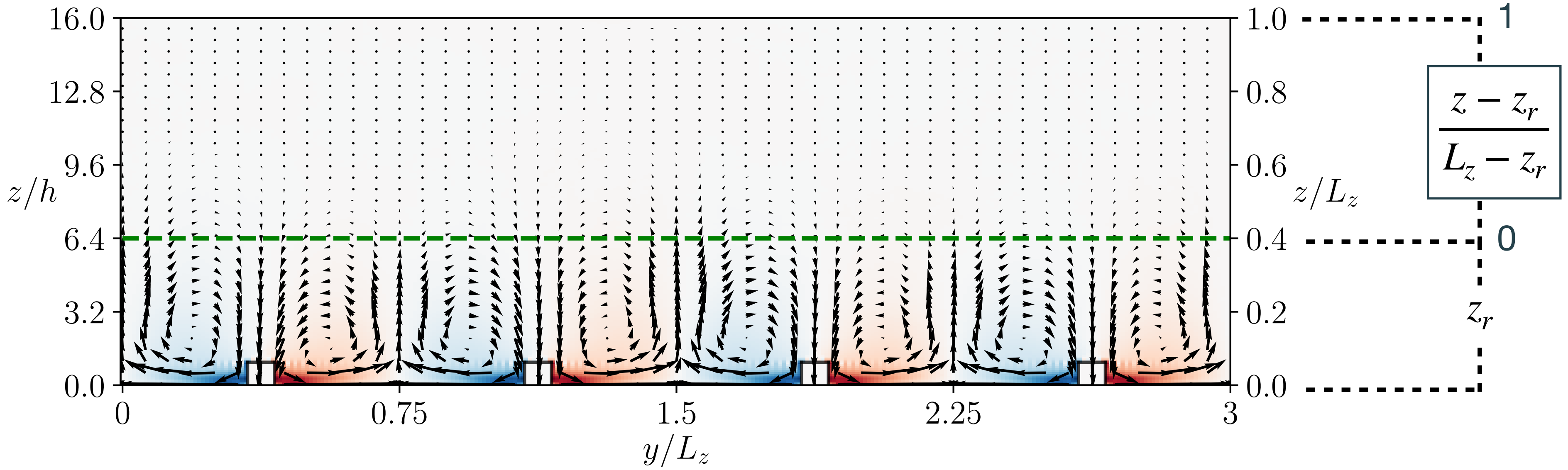
$L_z/h = 16,\ s_y/L_z = 0.75$

$h_y/L_z = 1/16 \longrightarrow h_y = 1$

$L_z/h = 8,\ s_y/L_z = 0.75$

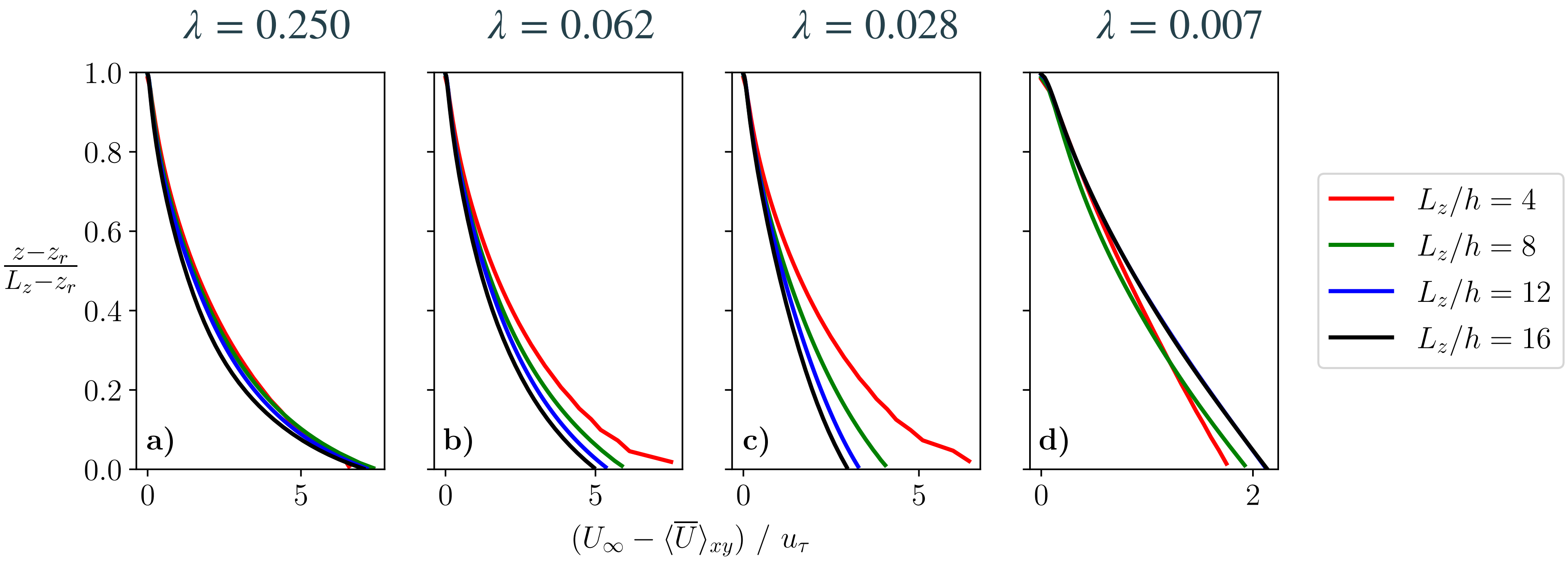
$h_y/L_z = 1/16 \longrightarrow h_y = 0.5$

A scale based on the extent of roughness sublayer is introduced to accurately compare the statistics in outer layer.

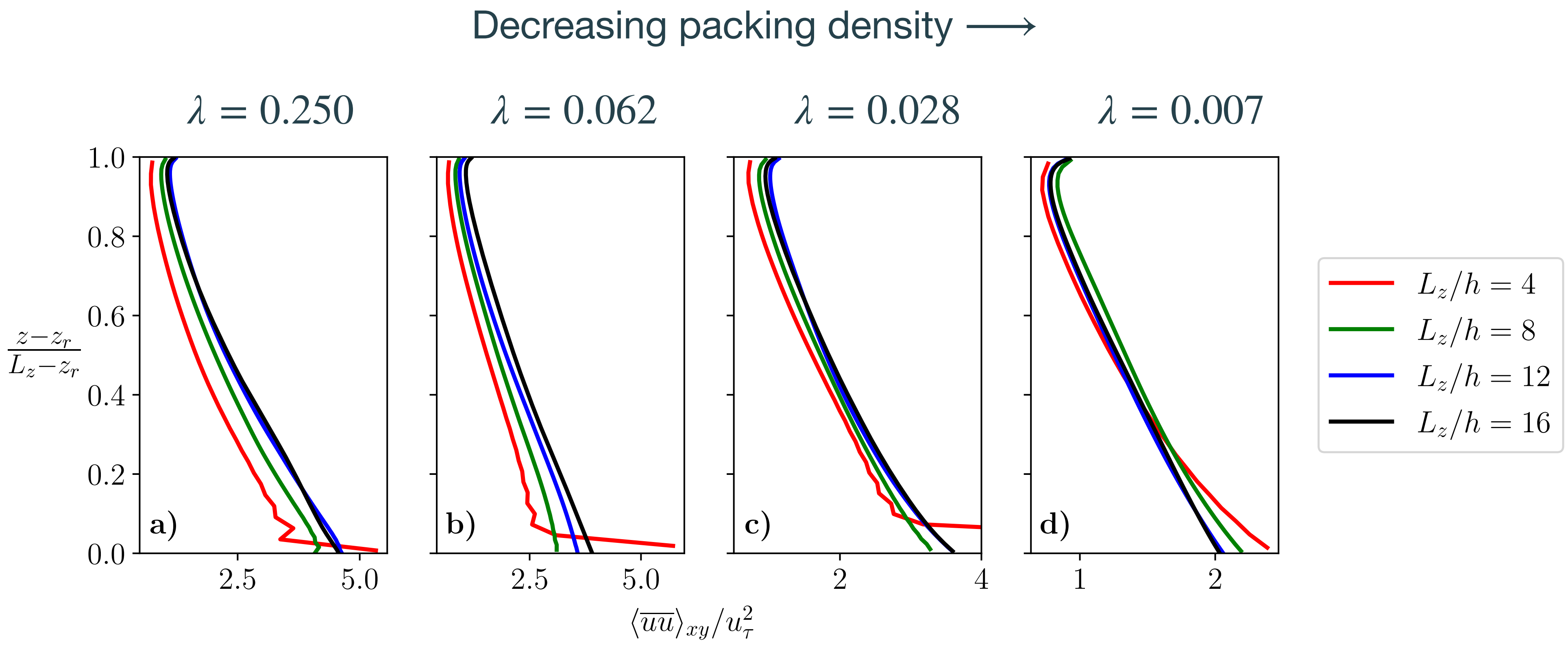


Converging trend is observed with L_z based scaling across all the packing densities.

Decreasing packing density $\longrightarrow$



Converging trend is also observed for the 2nd order statistics.



In summary, conventional method to test the impact of scale separation only works for dense configurations.

A novel approach is shown to test the impact of scale separation, which requires producing equivalent surface geometry.

With this approach, we see that the scale separation of 12 - 16 is enough for most of the applications to minimize the artificial impact of top boundary condition.