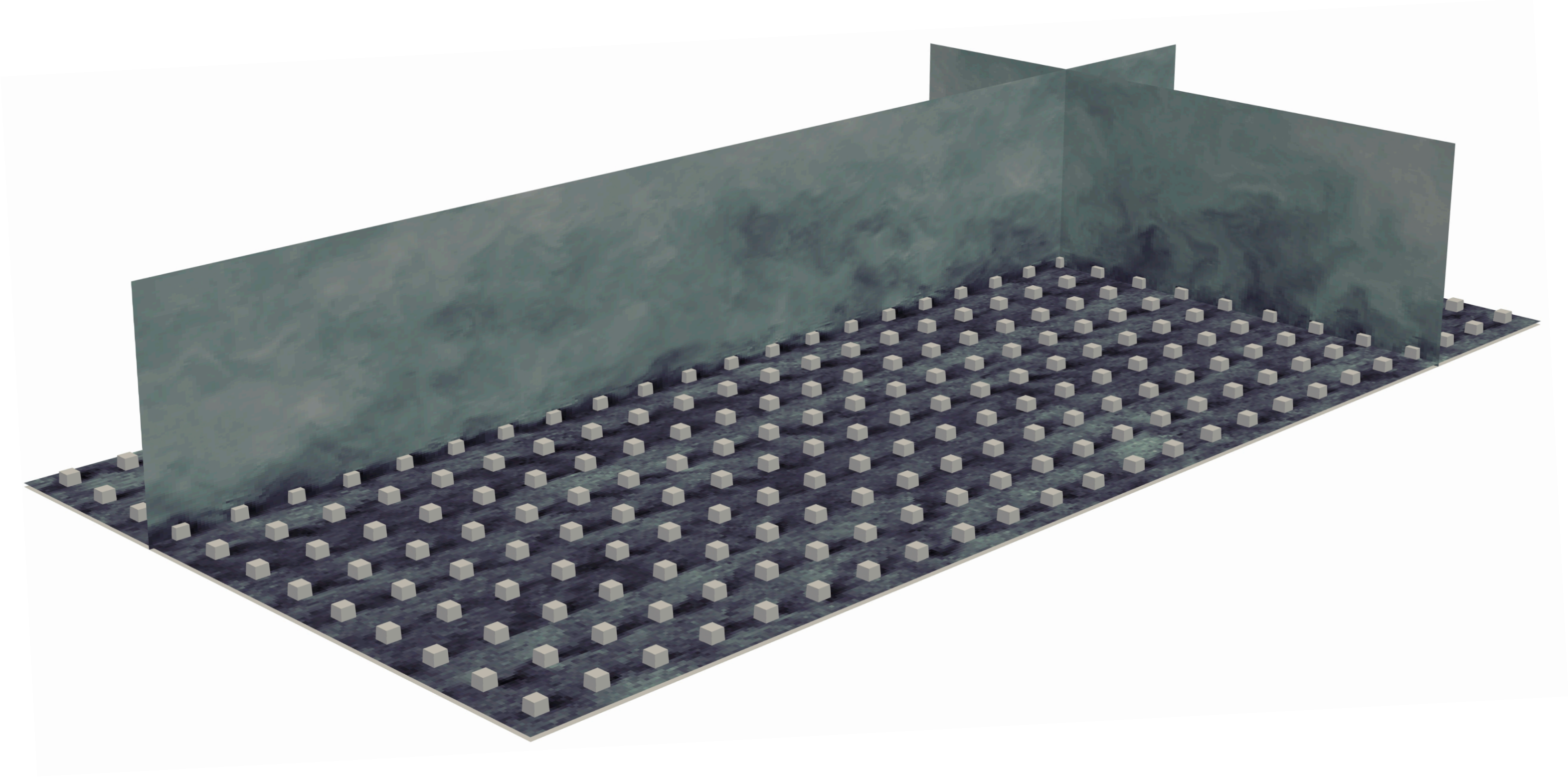
Impact of numerical domain on turbulent flow statistics: scalings and considerations for canopy flows



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Examples of different domains in the literature.

Claus et al. (2012):
$L_z/h = 4$
$L_x : L_y : L_z = 2 : 2 : 1$

Coceal et al. (2006):
$L_z/h = 4$
$L_x : L_y : L_z = 1 : 1 : 1$

Schmid et al. (2019):
$L_z/h = 4$
$L_x : L_y : L_z = 1.5 : 1.5 : 1$

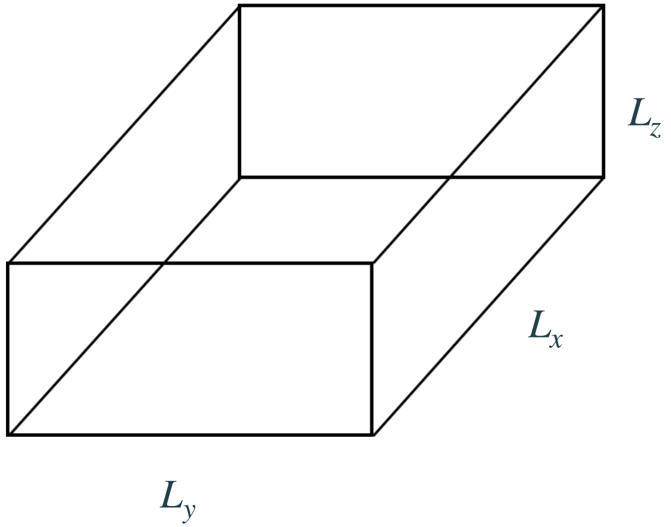
Xie and Castro (2006):
$L_z/h = 10$
$L_x : L_y : L_z = 1.6 : 1.6 : 1$

Stroh et al. (2020):
$L_z/h = 23.25$
$L_x : L_y : L_z = 8 : 4 : 1$

Yang and Anderson (2017):
$L_z/h = 15$
$L_x : L_y : L_z = \pi : \pi : 1$

Cheng and Porte-Agel (2015):
$L_z/h = 14$
$L_x : L_y : L_z = 2.28 : 0.85 : 1$

Leonardi and Castro (2010):
$L_z/h = 8$
$L_x : L_y : L_z = 1 : 0.75 : 1$

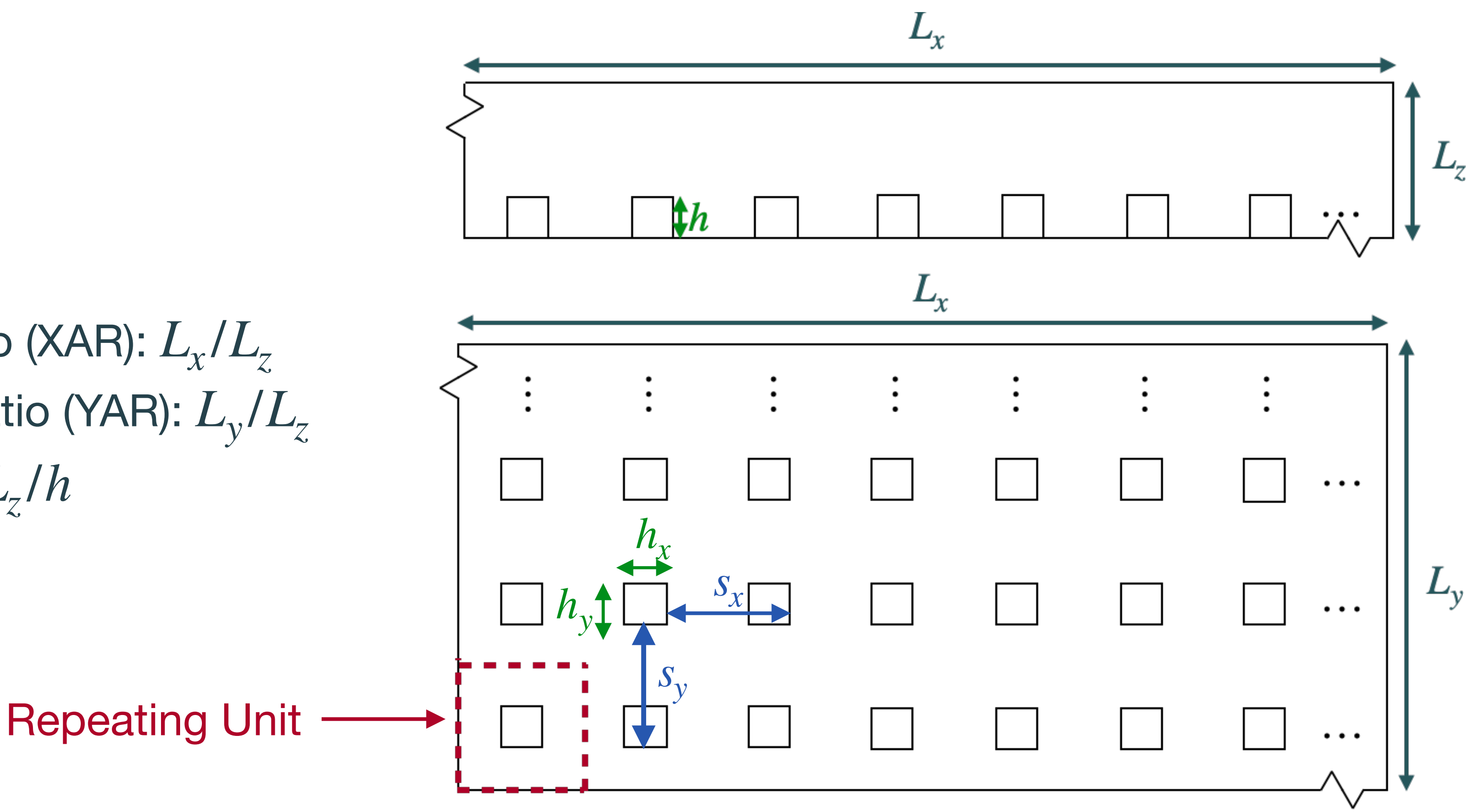


Surface geometry consists of cuboids arranged in square configuration.

Streamwise Aspect ratio (XAR): L_x/L_z

Cross-stream Aspect ratio (YAR): L_y/L_z

Scale separation (SS): L_z/h



Surface geometry consists of cuboids arranged in square configuration.

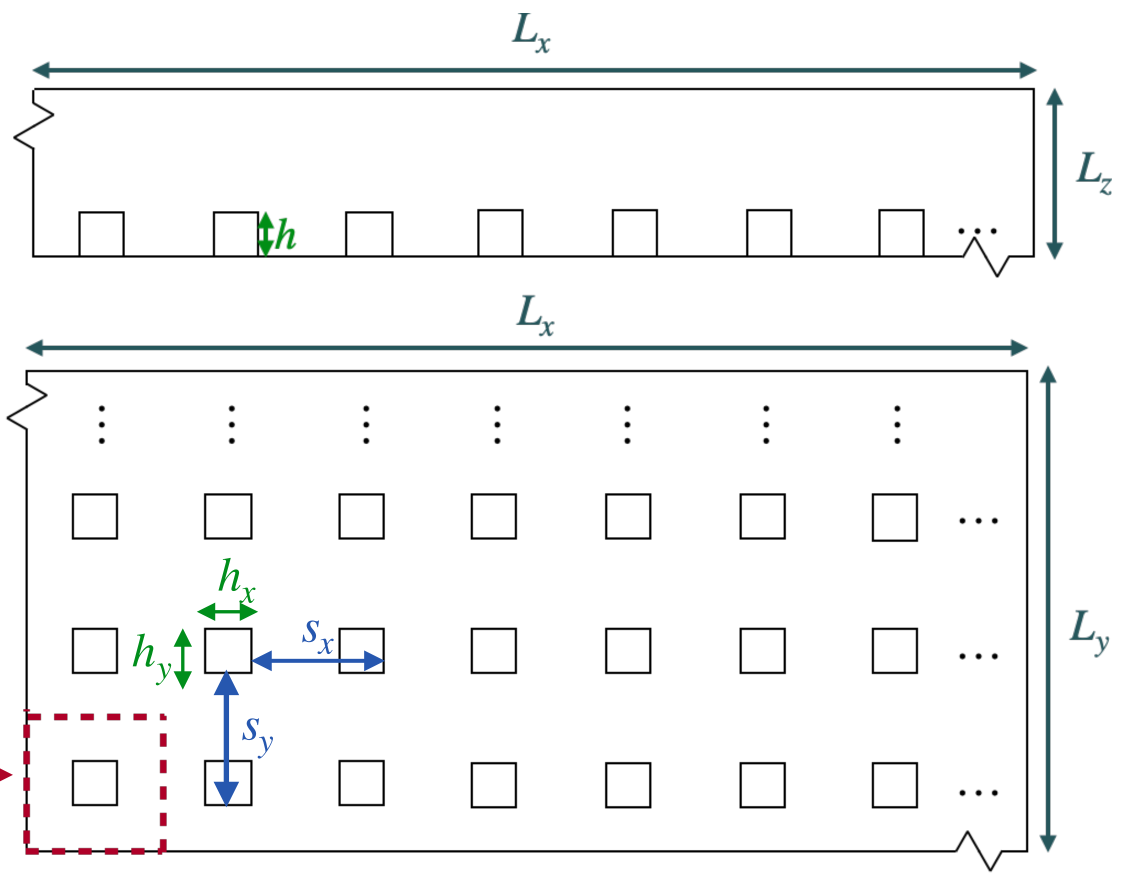
Streamwise Aspect ratio (XAR): L_x/L_z

Cross-stream Aspect ratio (YAR): L_y/L_z

Scale separation (SS): L_z/h

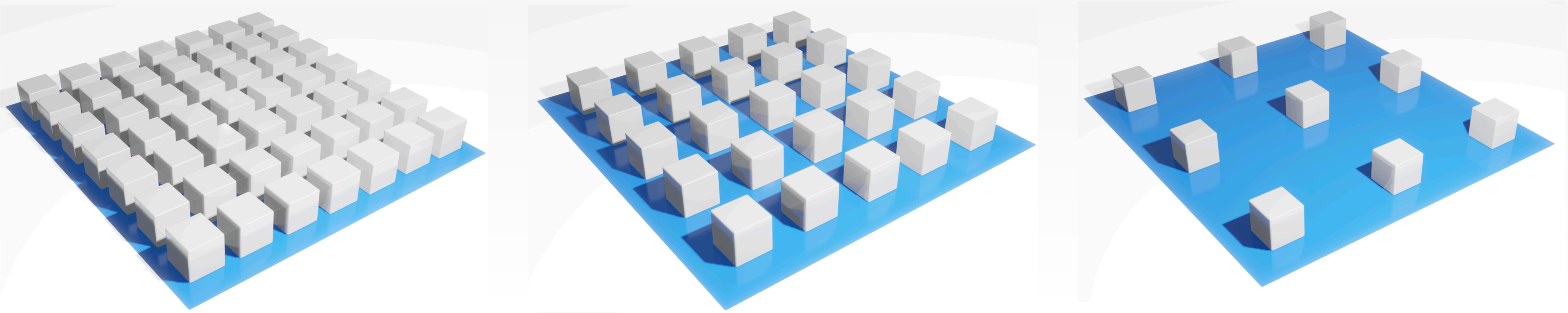
4, 8, 12 and 16

Repeating Unit

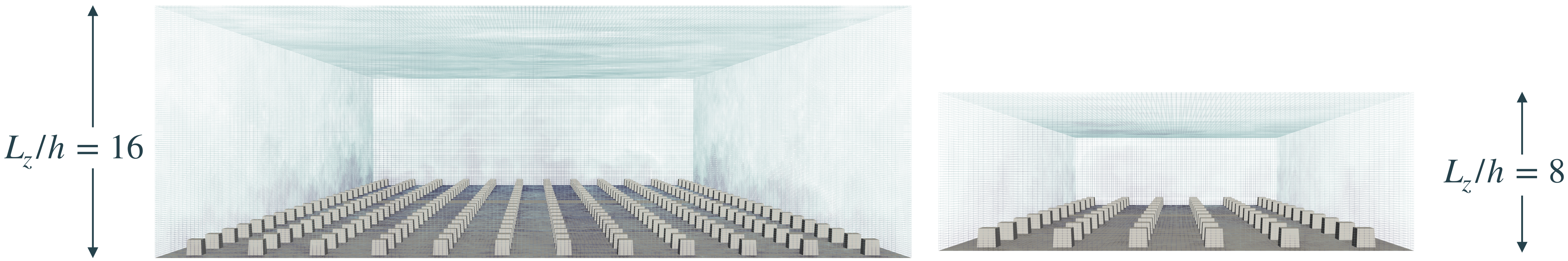


Packing density of the surface is systematically varied.

Decreasing packing density (λ)



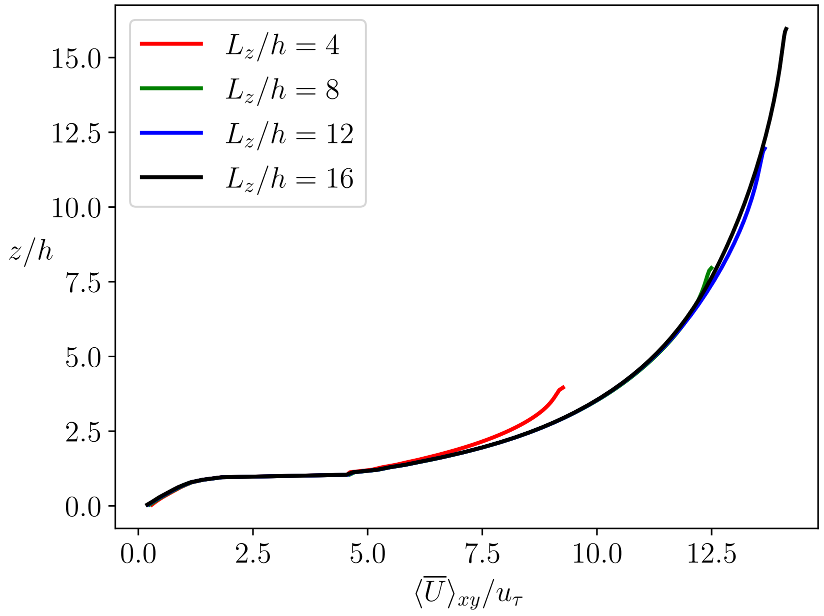
Visualization of cases with different scale separations.



Streamwise and cross-stream aspect ratio are kept constant at 6 and 3 respectively.

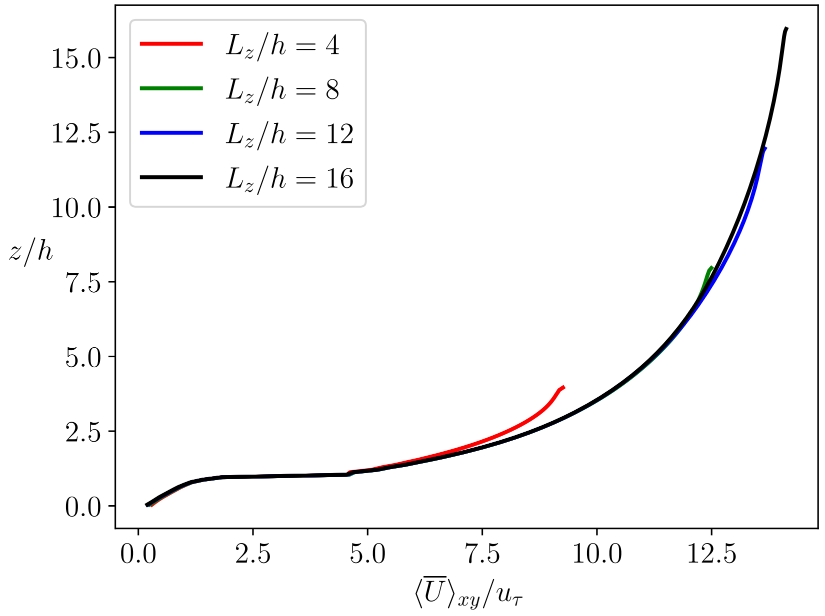
Collapse for mean streamwise velocity is observed for dense configuration;

Dense, $\lambda = 0.25$

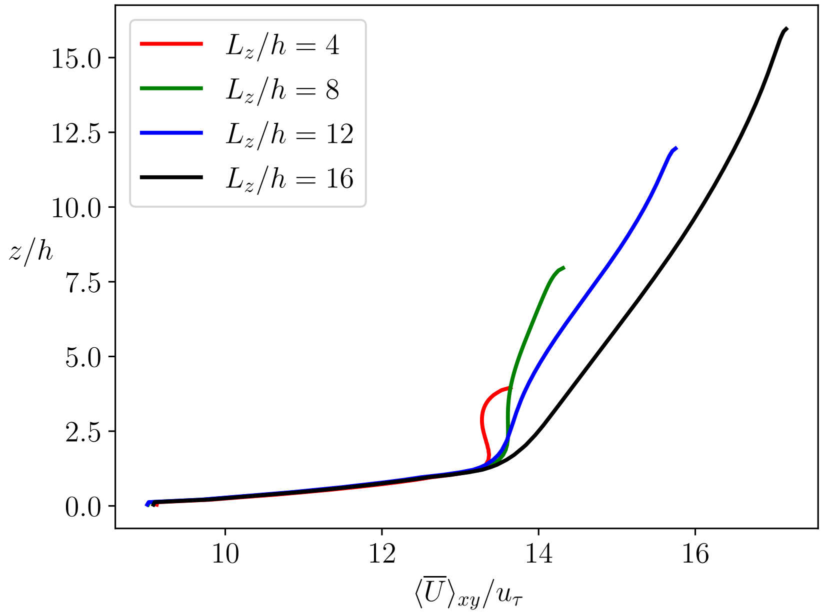


Collapse for mean streamwise velocity is observed for dense configuration; but not for sparse?

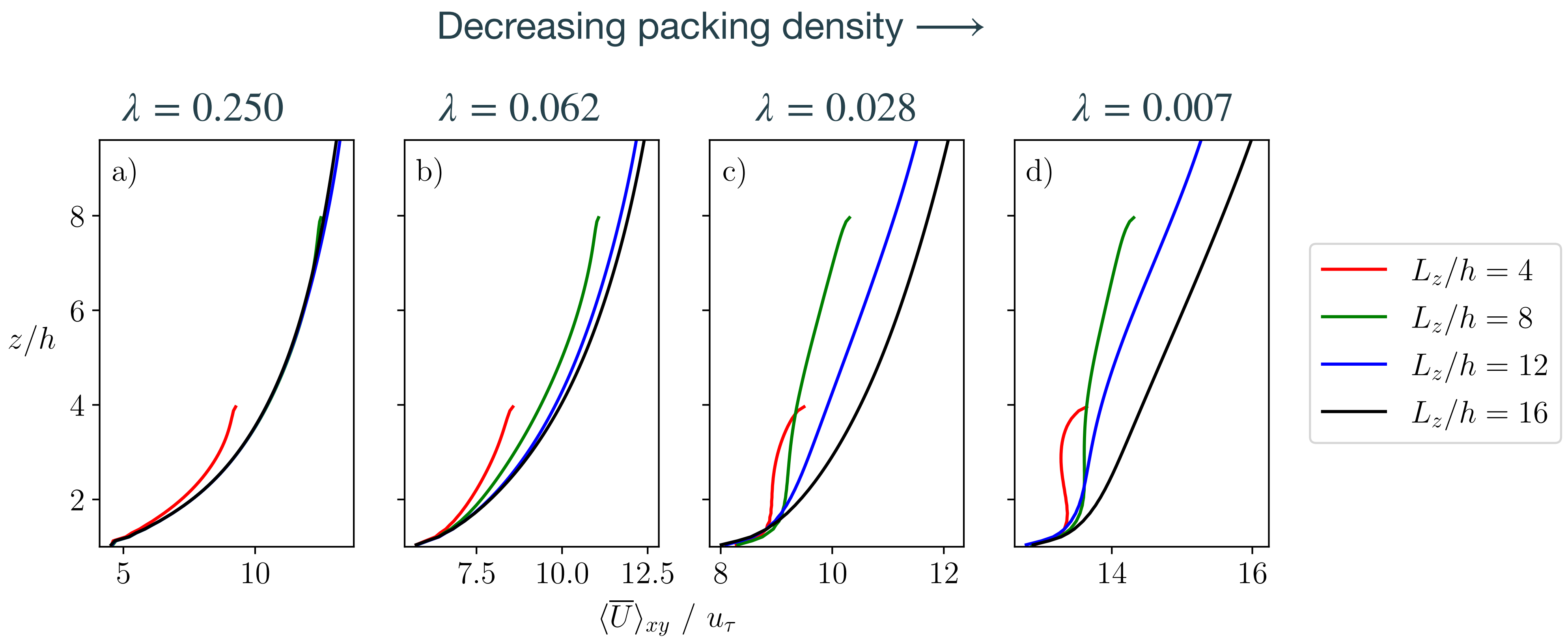
Dense, $\lambda = 0.25$



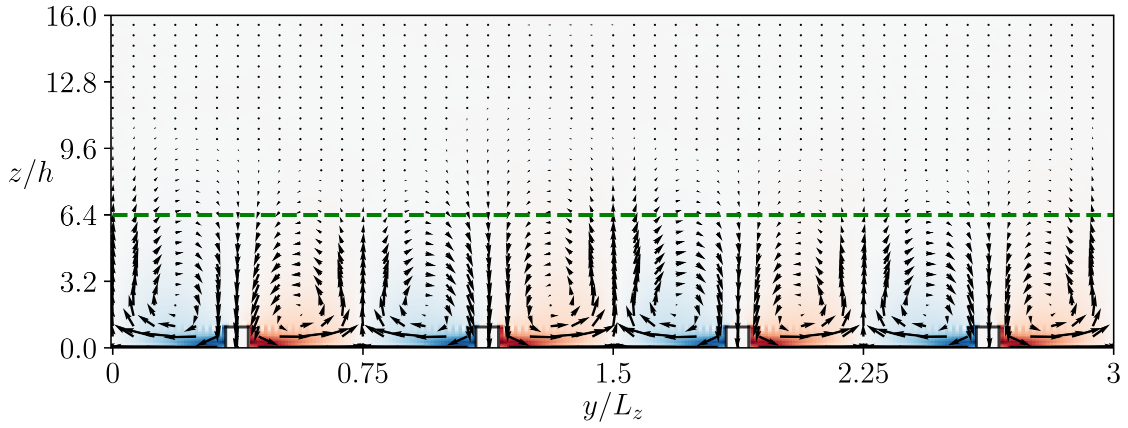
Sparse, $\lambda = 0.007$



Mean streamwise velocity profiles gradually diverge with decreasing packing density.

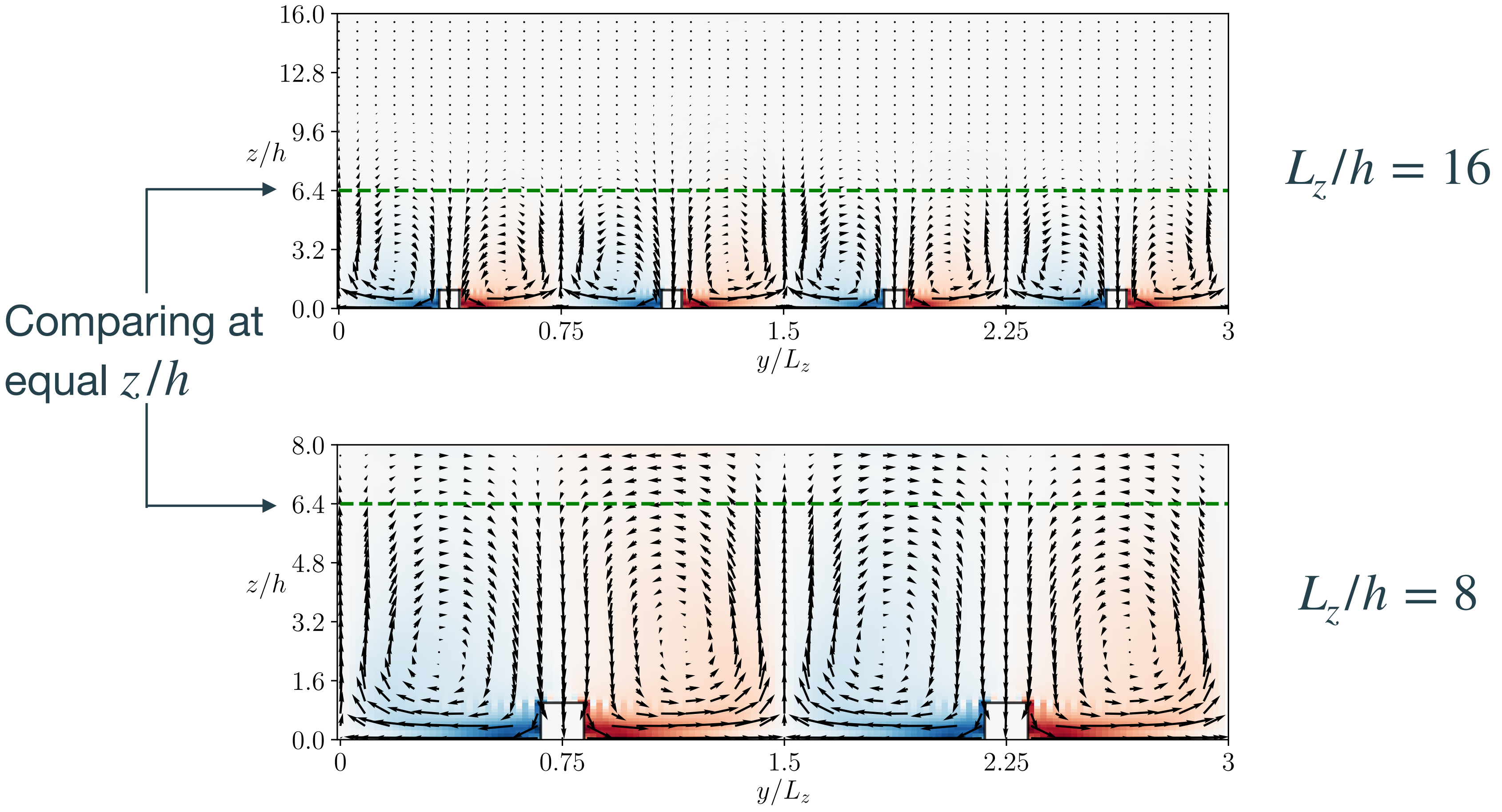


As we change the scale separation for sparse configuration, the size and strength of secondary flows changes.

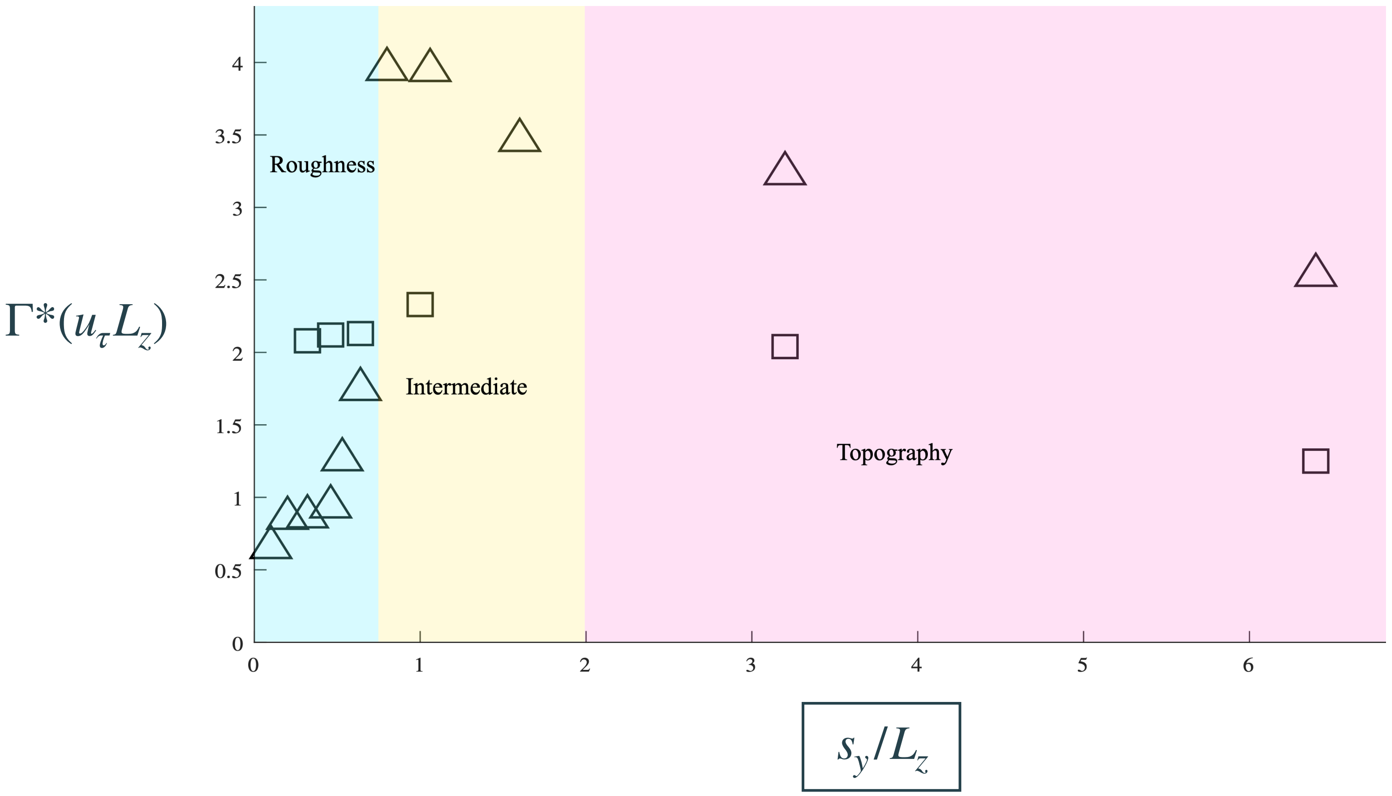


$L_z/h = 16$

As we change the scale separation for sparse configuration, the size and strength of secondary flows changes.

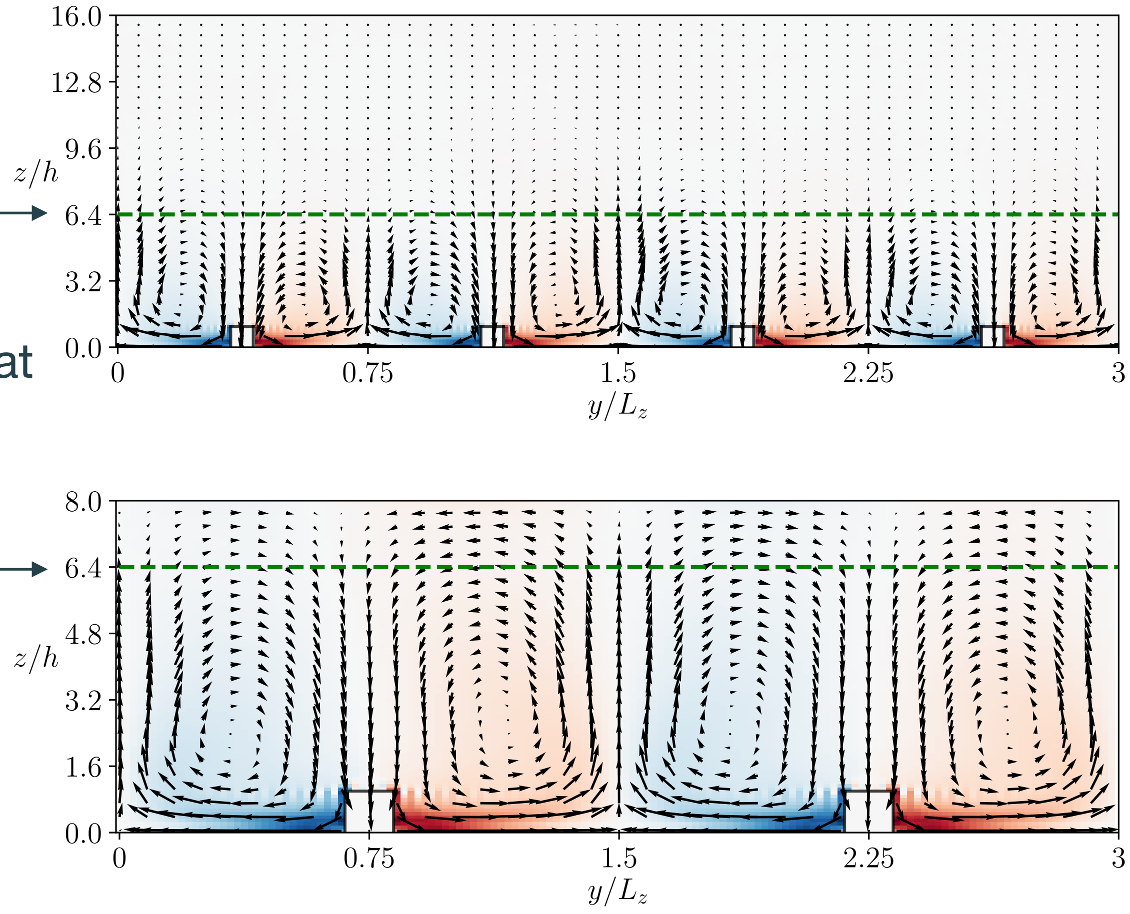


s_y/L_z is a crucial parameter that controls size and strength of secondary flows [Yang and Anderson (2017)].



When L_z/h changes from 16 to 8, s_y/L_z changes from 0.75 to 1.5.

Comparing at equal z/h



$L_z/h = 16$

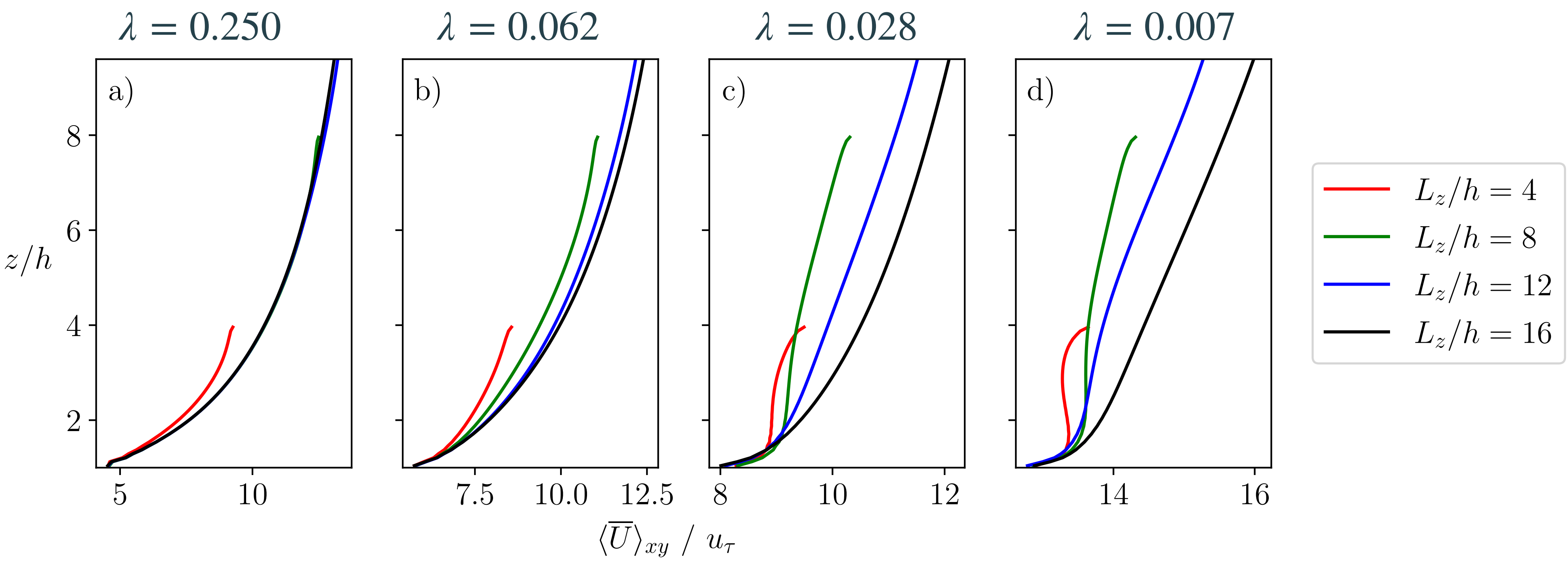
$s_y/L_z = 0.75$

$L_z/h = 8$

$s_y/L_z = 1.5$

The deviation in mean streamwise velocity for sparse configuration is not solely due to the impact of scale separation.

Decreasing packing density ⟶



To analyze the individual impact of a single parameter, we systematically adjust that particular variable while maintaining constancy in all other parameters.

$$U_1 = f(a_1, b, c, d, e, \ldots)$$

$$\downarrow$$

$$U_2 = f(a_2, b, c, d, e, \ldots)$$

← Impact of parameter a on U is isolated.

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$$U_1 = f(a_1, b, c, d, e, \ldots)$$

$$\downarrow$$

$$U_2 = f(a_2, b, c, d, e, \ldots)$$

← Impact of parameter a on U is isolated.

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

← Impact of parameter L_z/h on U/u_τ is isolated.

L: Domain length

h: Cuboid dimensions

s: Spacing between cuboids

To analyze the individual impact of a single parameter, we systematically adjust that particular variable while maintaining constancy in all other parameters.

$$U_1 = f(a_1, b, c, d, e, \ldots)$$

$$\downarrow$$

$$U_2 = f(a_2, b, c, d, e, \ldots)$$

← Impact of parameter a on U is isolated.

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

← Impact of parameter L_z/h on U/u_τ is isolated.

L: Domain length

h: Cuboid dimensions

s: Spacing between cuboids

When only L_z/h is varied while keeping s_y/h constant,
it changes the value of s_y/L_z.

This limitation can be solved by rearranging the PI groups.

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

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

s_y is adjusted when L_z/h varies, preserving the size and strength of secondary flows

This limitation can be solved by rearranging the PI groups.

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

$$\downarrow$$

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

[Willingham et al. (2014)]
[Hwang and Lee (2018)]

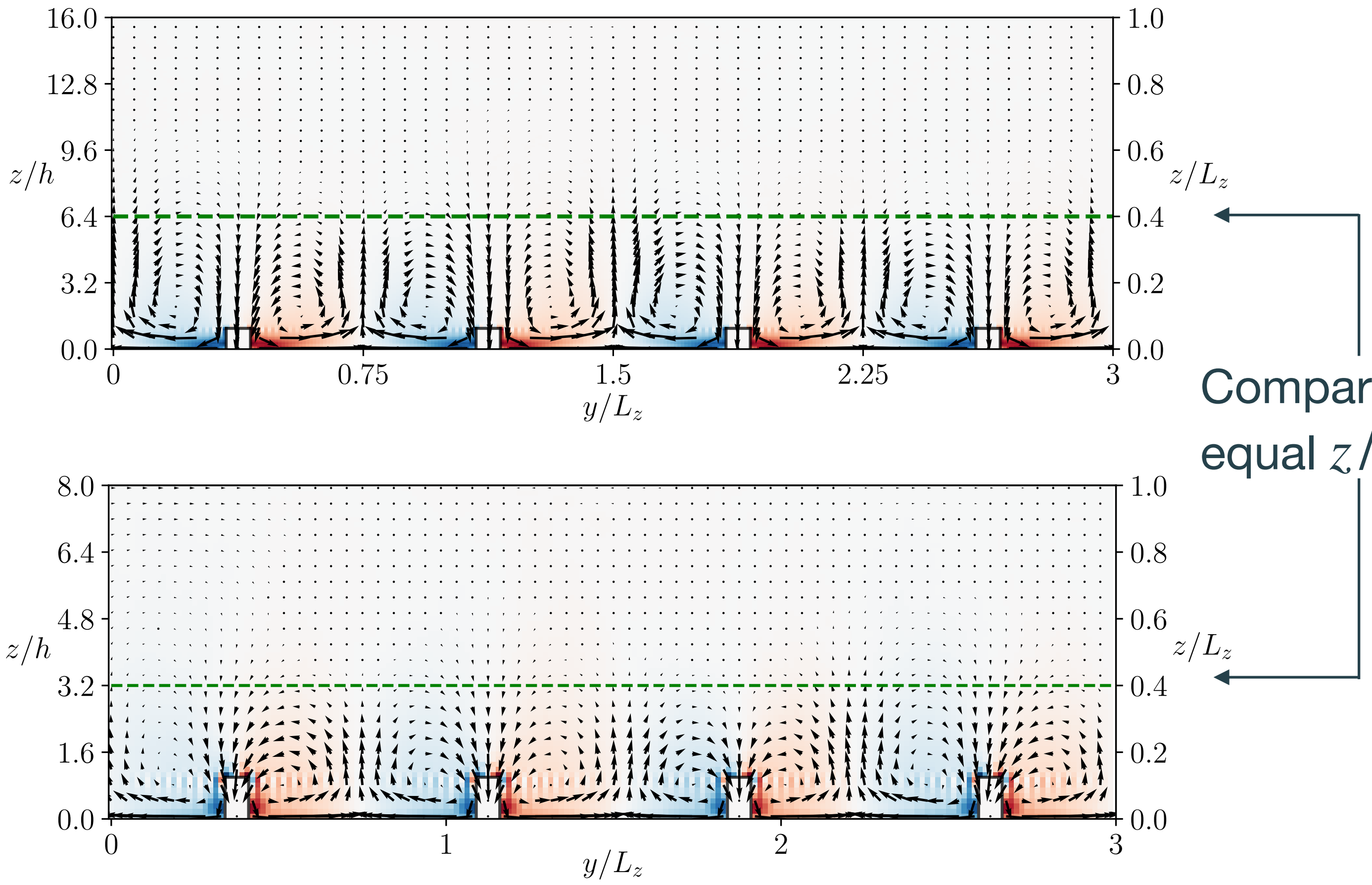
This limitation can be solved by rearranging the PI groups.

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

↓

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

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

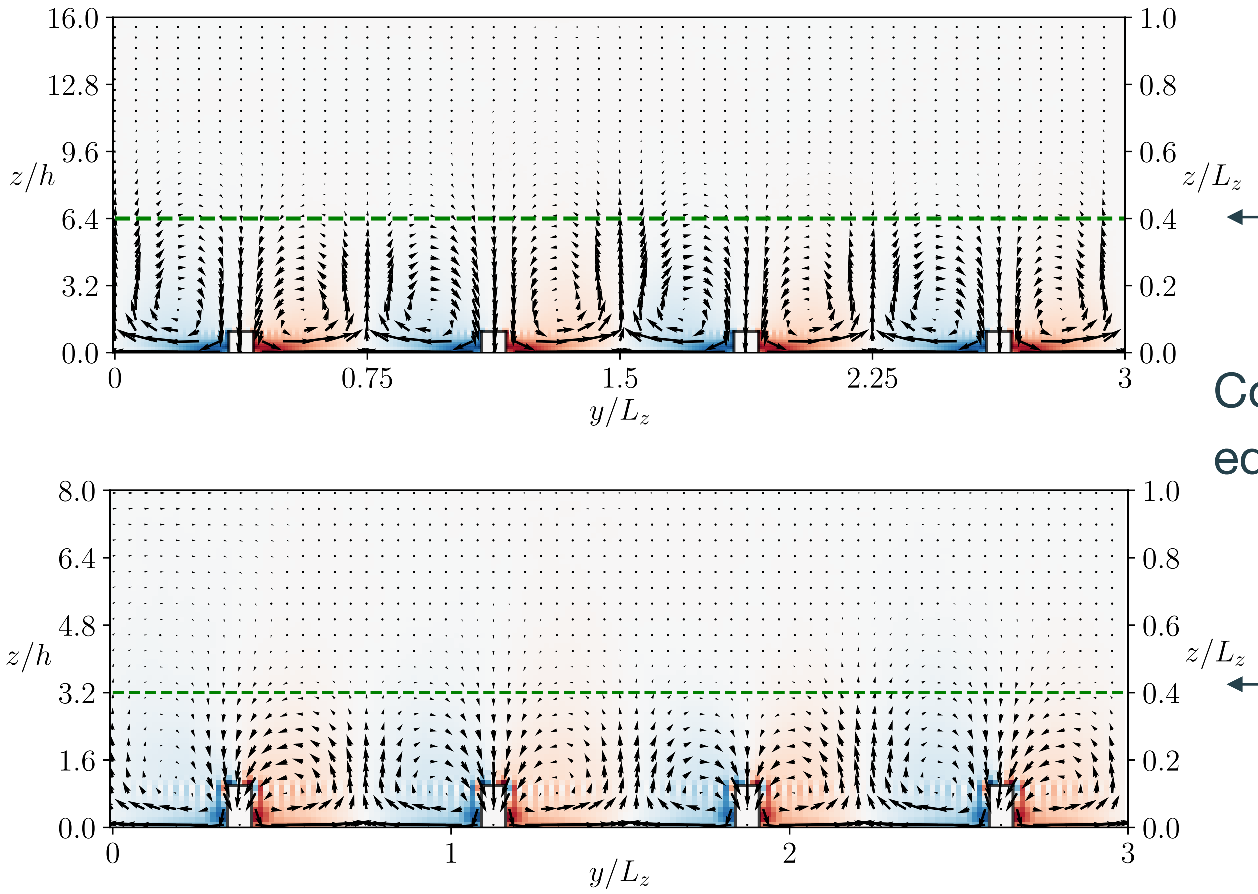


$L_z/h = 16,\ s_y/L_z = 0.75$

Comparing at equal z/L_z

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

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

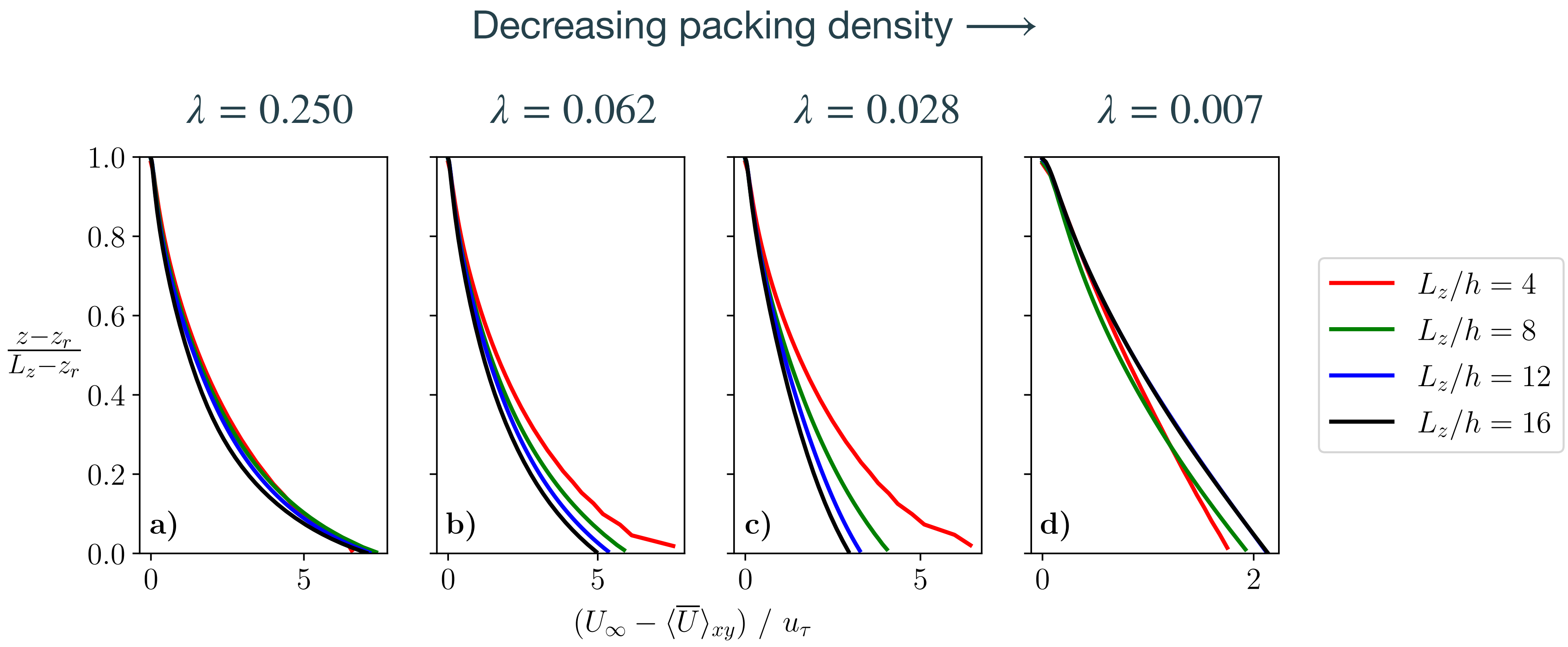
$L_z/h = 16,\ s_y/L_z = 0.75$

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

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

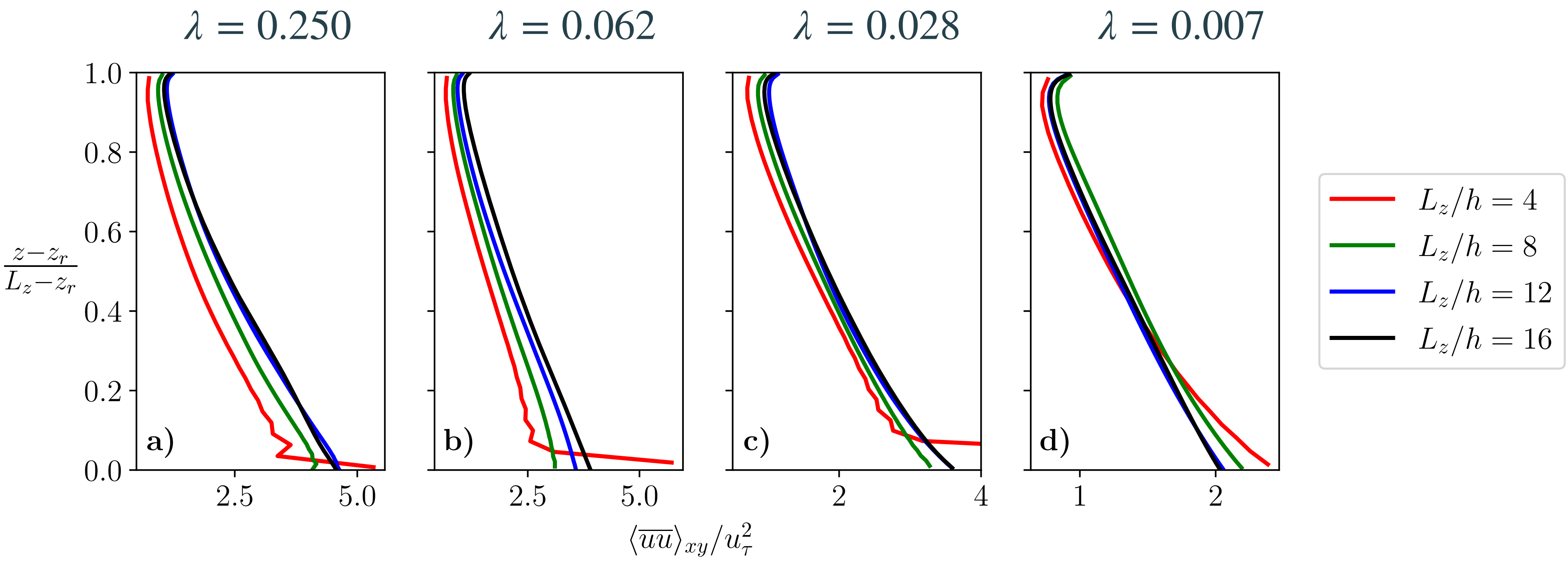
$h_y/L_z = 1/16 \longrightarrow h_y = 0.5$

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



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

Decreasing packing density ⟶



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.

Acknowledgements

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Contributions

Sathe, A., Giometto, M. G. (2023). Impact of the numerical domain on turbulent flow statistics; scalings and considerations for canopy flow. Journal of Fluid Mechanics *(under review)*

Sathe, A., Giometto, M. G. (2022), Impact of Numerical Domain on Turbulent Flow Statistics: Scalings and Considerations for Canopy Flows [Conference presentation], AGU fall meeting, Chicago, IL, United States.

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Willingham, D., Anderson, W., Christensen, K. T., & Barros, J. M. (2014). Turbulent boundary layer flow over transverse aerodynamic roughness transitions: Induced mixing and flow characterization. *Physics of Fluids*, *26*(2), 025111. https://doi.org/10.1063/1.4864105

Hwang, H. G., & Lee, J. H. (2018). Secondary flows in turbulent boundary layers over longitudinal surface roughness. *Physical Review Fluids*, *3*(1). https://doi.org/10.1103/PhysRevFluids.3.014608