Oscillation Control of Compressible Channel Flow Using Direct Numerical Simulations

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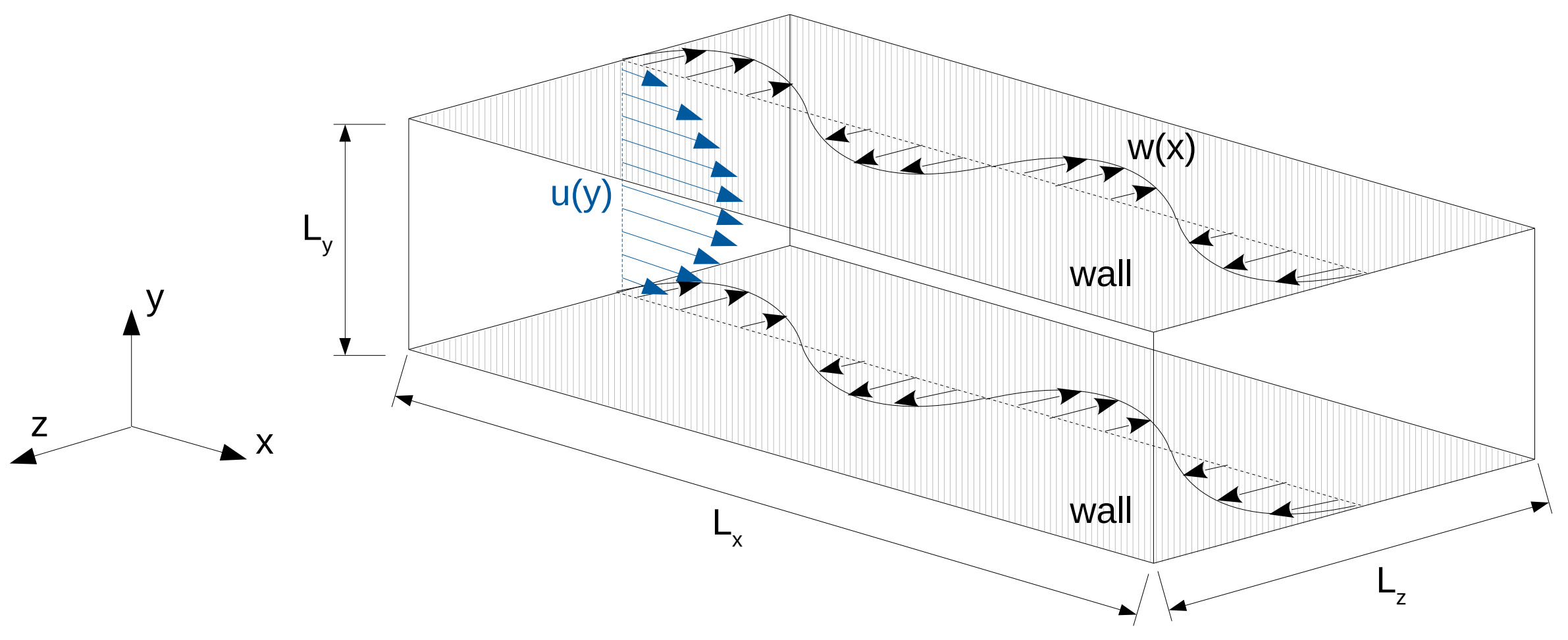
Motivation: An active oscillatory turbulence control technique has been implemented with the aim of obtaining lower turbulence intensity and thus friction drag. The achieved alterations outweigh the required input power yielding large positive net power reductions throughout the range of investigated parameters. Here, the specific control method is applied to supersonic flow as well. Particular attention is directed to characteristics purely associated with compressible flow and interactions of the control method with the latter. Published in M. Ruby & H. Foysi (2022) [1]

Flow configuration

- Compressible, turbulent channel flow
- Rectangular flow domain confined by the top and bottom walls
- x and z represent the homogeneous streamwise and spanwise directions, respectively, with periodic boundary conditions
- Controlled case:
  Temporal, spanwise wall movement transformed into pure space dependent velocity distribution [2] at the walls:

$$w(x) = A\sin\left(\frac{2\pi}{\lambda_x}x\right),\ A:\ \text{oscillation amplitude},\ \lambda_x:\ \text{wavelength}$$

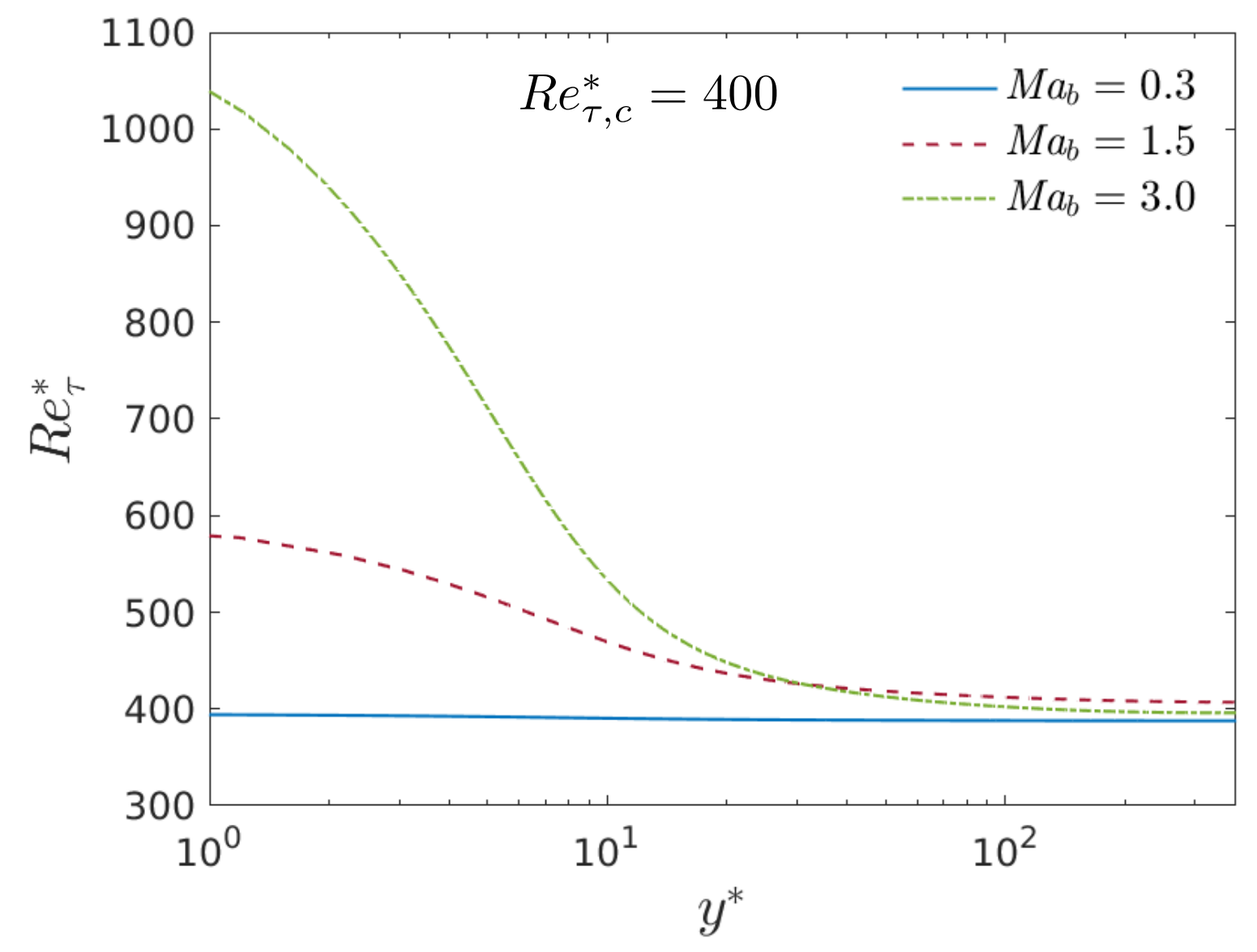


Sketch of the controlled channel flow configuration along with corresponding dimensions, directions and velocity distributions.

Flow parameters

Dimensionsless parameters characterising the flow:

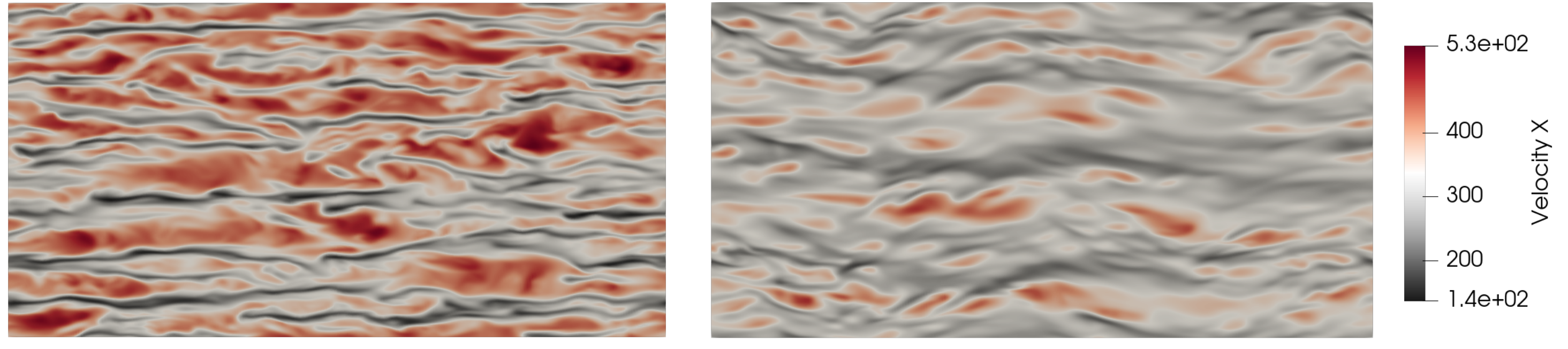
- Bulk mach number $M_b = \frac{U_b}{c_w}$
- Friction Reynolds number $Re_\tau = \frac{\rho_w u_\tau h}{\mu_w}$
- Semi-local Reynolds number $Re_\tau^* = Re_\tau \sqrt{\frac{<\rho>}{<\rho_w>}}\frac{<\mu>}{<\mu_w>}$



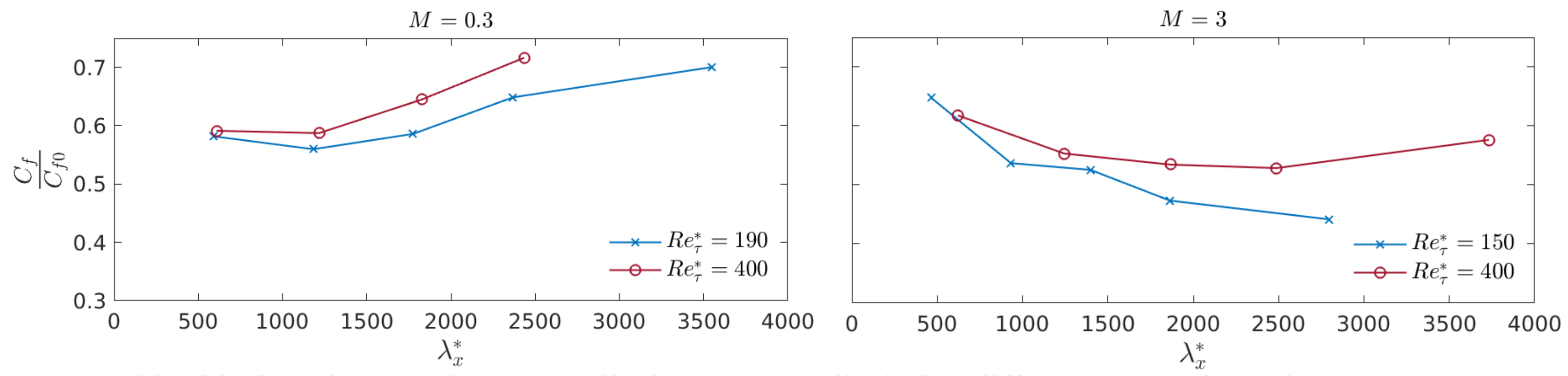
U_b : velocity averaged over whole domain
c : speed of sound
ρ : density
u_τ : friction velocity $u_\tau = (\tau_w/\rho_w)^{1/2}$
h : channel half-height
μ : viscosity
$(\cdot)_w$: value at the wall
$< \cdot >$: averaging over homogeneous directions

Semi-local Reynolds number for different Mach numbers dependent on the semi-local wall coordinate.

Selected Results



Near-wall streak modification through the control method (right) compared to the unaffected reference flow (left).



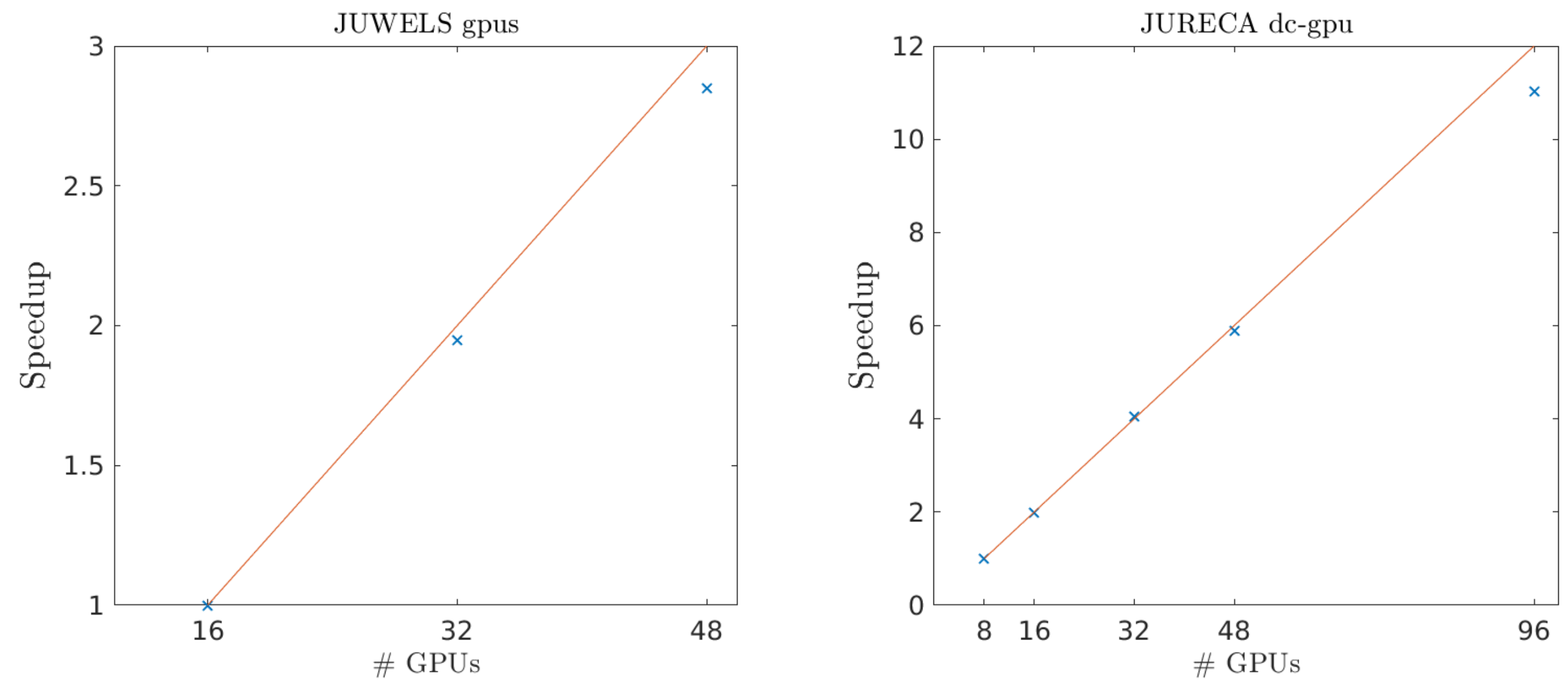
Skin friction drag ratio (controlled / uncontrolled) for different wavelengths.
Left: nearly incompressible condition, right: supersonic flow.

- Better performance with increasing influence of compressibility and improved power balance
- Preference of larger wavelengths in compressible conditions and extended optimum parameter range

Numerical Method

- Compressible Navier-Stokes equations provide essential conservation laws for mass, momentum and energy
- Solution vector composed of density, momentum components and total energy is obtained through the flux reconstruction approach by Huynh [3], implemented in the flow solver PyFR [4].
- A time varying external volume force in the streamwise direction ensures a constant flow rate.
- Pure MPI Parallelization using one rank per GPU was adopted.
- Utilization of up to 64 nodes of JUWELS Booster
- The different flow cases are listed in the table, below

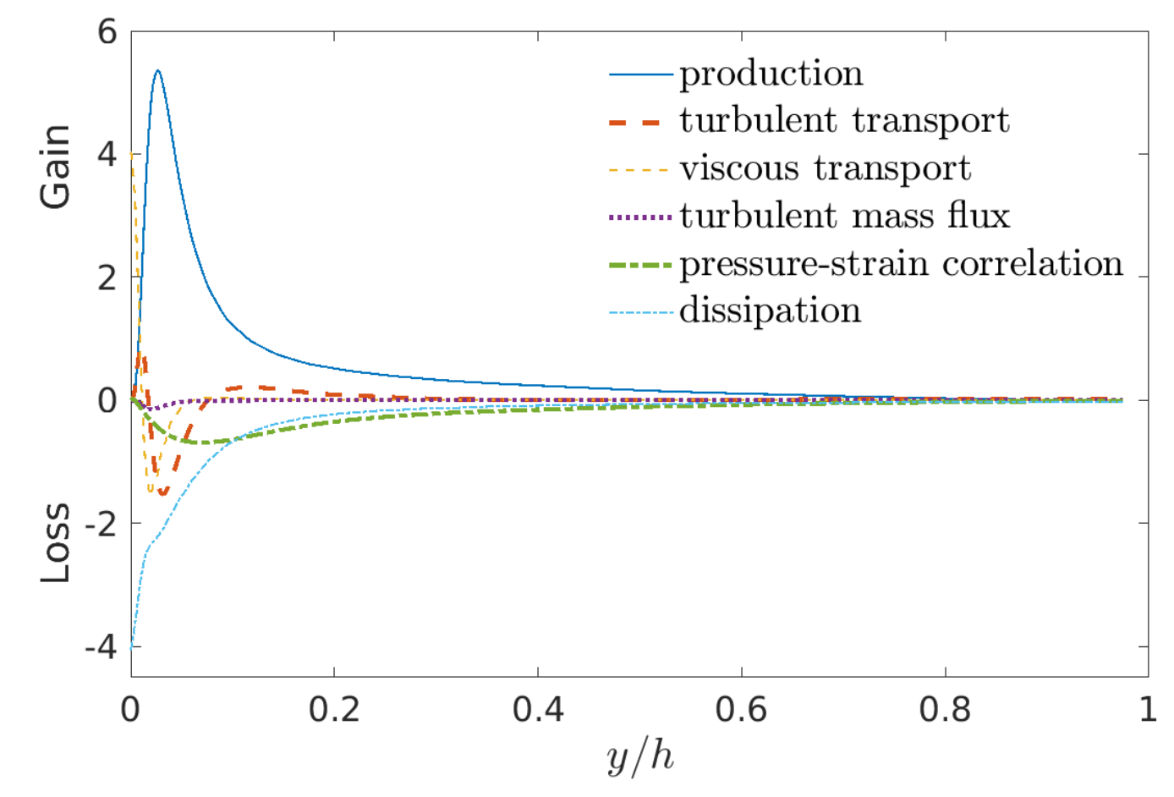
Flow conditions				computational domain		
Ma_b	Re_b	Re_τ	$Re^*_{\tau c}$	$\frac{L_x \times L_y \times L_z}{h}$	$N_x \times N_y \times N_z$	# cells [10^6]
0.3	3000	192	188	$6\pi \times 2 \times 2\pi$	$288 \times 128 \times 152$	3.7
1.5	3000	218	146	$6\pi \times 2 \times 2\pi$	$288 \times 128 \times 152$	5.6
3.0	4880	454	148	$6\pi \times 2 \times 3/2\pi$	$752 \times 224 \times 288$	48.5
0.3	6890	396	388	$3\pi \times 2 \times \pi$	$300 \times 160 \times 200$	9.6
1.5	9450	604	407	$3\pi \times 2 \times \pi$	$380 \times 200 \times 252$	19.2
3.0	14000	1150	398	$3\pi \times 2 \times \pi$	$564 \times 336 \times 375$	71.1
0.3	15400	804	784	$2\pi \times 2 \times \pi$	$400 \times 448 \times 400$	71.7
1.5	20000	1182	807	$2\pi \times 2 \times \pi$	$396 \times 336 \times 396$	52.7
3.0	33035	2522	855	$3/2\pi \times 2 \times \pi/2$	$600 \times 700 \times 400$	168



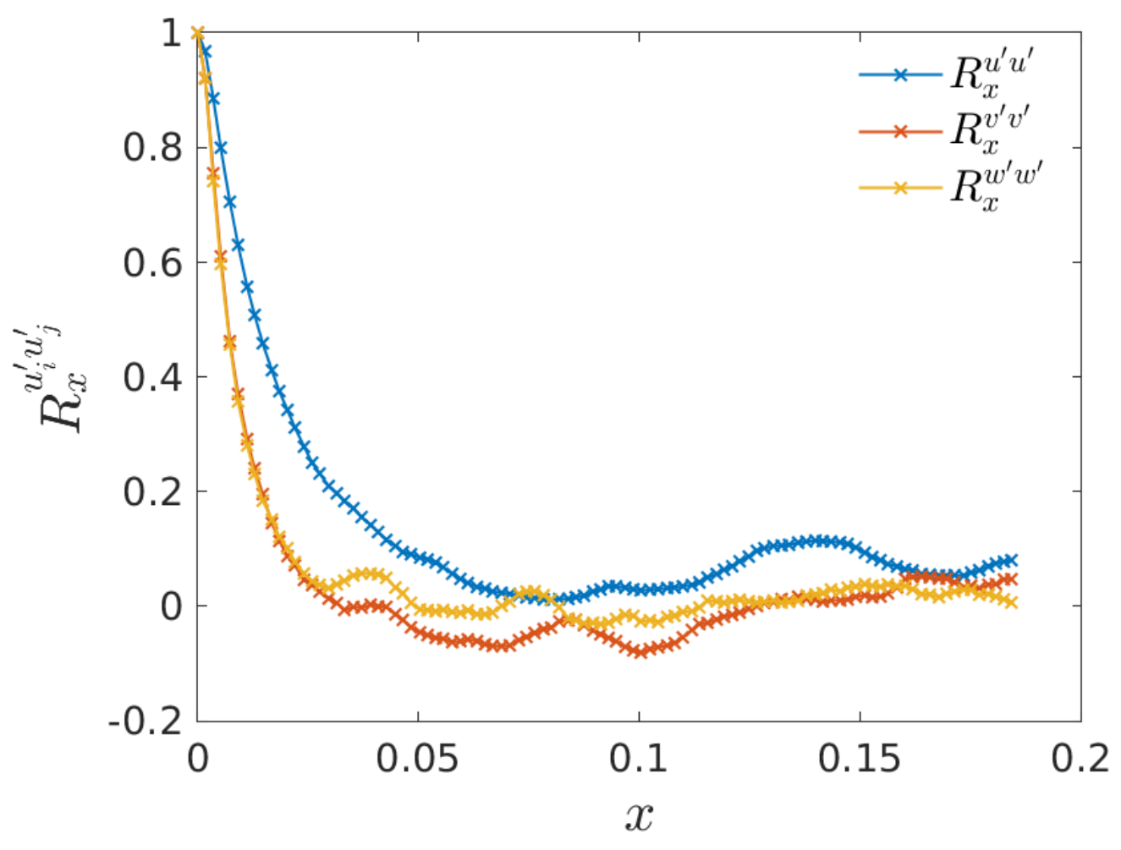
Scaling behaviour using a test case with a problem size of 112 Mio. cells.

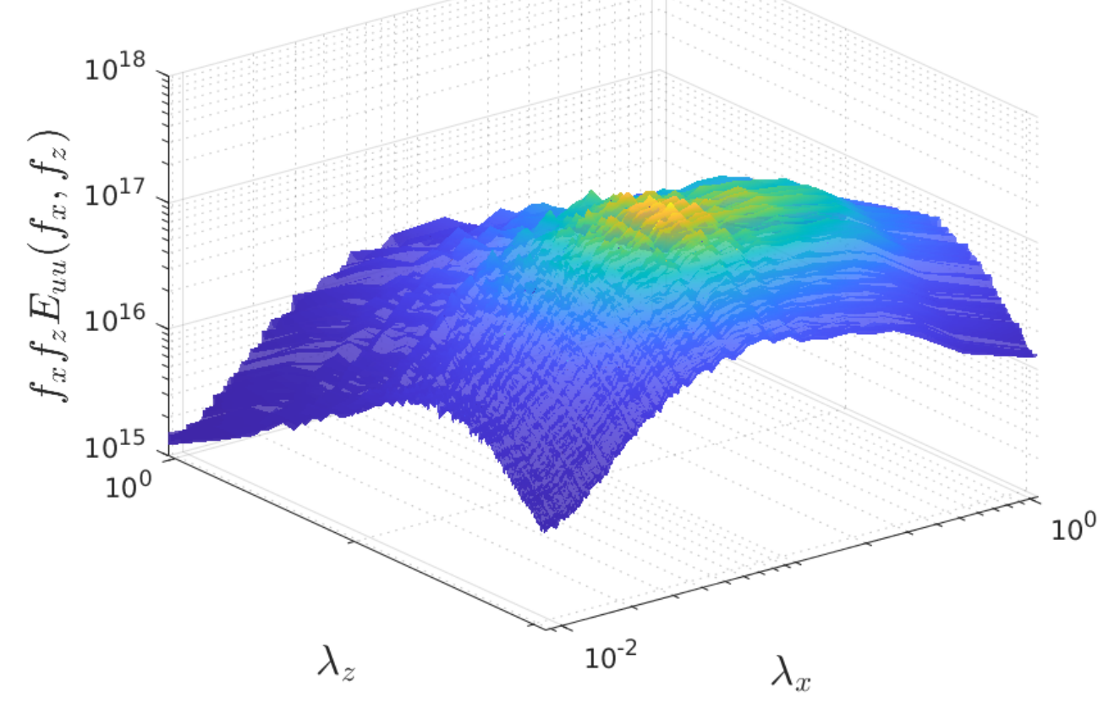
Ongoing work

- Parallel processing of arising data by running ParaView Server on in-house 32-core workstation
- Analysis of balance equations for turbulent stresses $\overline{\rho u_i'' u_j''}$



- Evaluation of two-point correlations and energy spectra





⇒ better understanding of differences in operation and length scales between different flow conditions

References

[1] M. Ruby and H. Foysi, Active control of compressible channel flow up to $Ma_b = 3$ using direct numerical simulations with spanwise velocity modulation at the walls, GAMM Mitteilungen, Special Issue: Direct Numerical Simulations of Turbulent Flows – Part I, 45 (1), 2022.
[2] C. Viotti, M. Quadrio, and P. Luchini, Streamwise oscillation of spanwise velocity at the wall of a channel for turbulent drag reduction, Physics of Fluids, 21, no. 11, 115109, 2009.
[3] H. T. Huynh, A Flux Reconstruction Approach to High-Order Schemes Including Discontinuous Galerkin Methods, AIAA Paper AIAA 20074079, 1–42, 01 2007.
[4] F. Witherden, B. C. Vermeire, and P. Vincent, Heterogeneous Computing on Mixed Unstructured Grids with PyFR, Computers & Fluids, 120, 09 2014.