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Collaborative Research: Effects of wall curvature on hypersonic turbulent spatially-developing boundary layers

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14. ABSTRACT
Summary: Study concave/convex wall curvature on supersonic/hypersonic SDTBL (Mach numbers up to 5) in a suite of high spatial/temporal resolution Direct Numerical Simulation (DNS) as well as Implicit Wall Resolved Large Eddy Simulation (iLES) at high Reynolds numbers. Research Objectives: 1) Evaluate the effect of: (i) wall-curvature driven pressure gradient, (ii) flow compressibility, (iii) Reynolds number dependency, and (iv) wall temperature on low/high-order statistics of the flow and turbulent structures based on high fidelity DNS. 2) Explore iLES's performance in complex flows. Highlights of Approach: Highly scalable finite-element flow solver PHASTA (Parallel Hierarchic Adaptive Stabilized Transient Analysis)1 Turbulent compressible inflow generation via the Dynamic Multi-scale Approach (DMA)2 Efficient and speedy post-processing library for large scale CFD systems.

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2022 AFOSR/ONR/HVSI Annual High-Speed Aerodynamics Portfolio Review

Drs. Sarah Popkin, Eric Marineau; Russ Cummings | July 18-22, 2022 | Caltech, CA - hybrid

University of Colorado Boulder

Effects of wall curvature on hypersonic turbulent spatially-developing boundary layers

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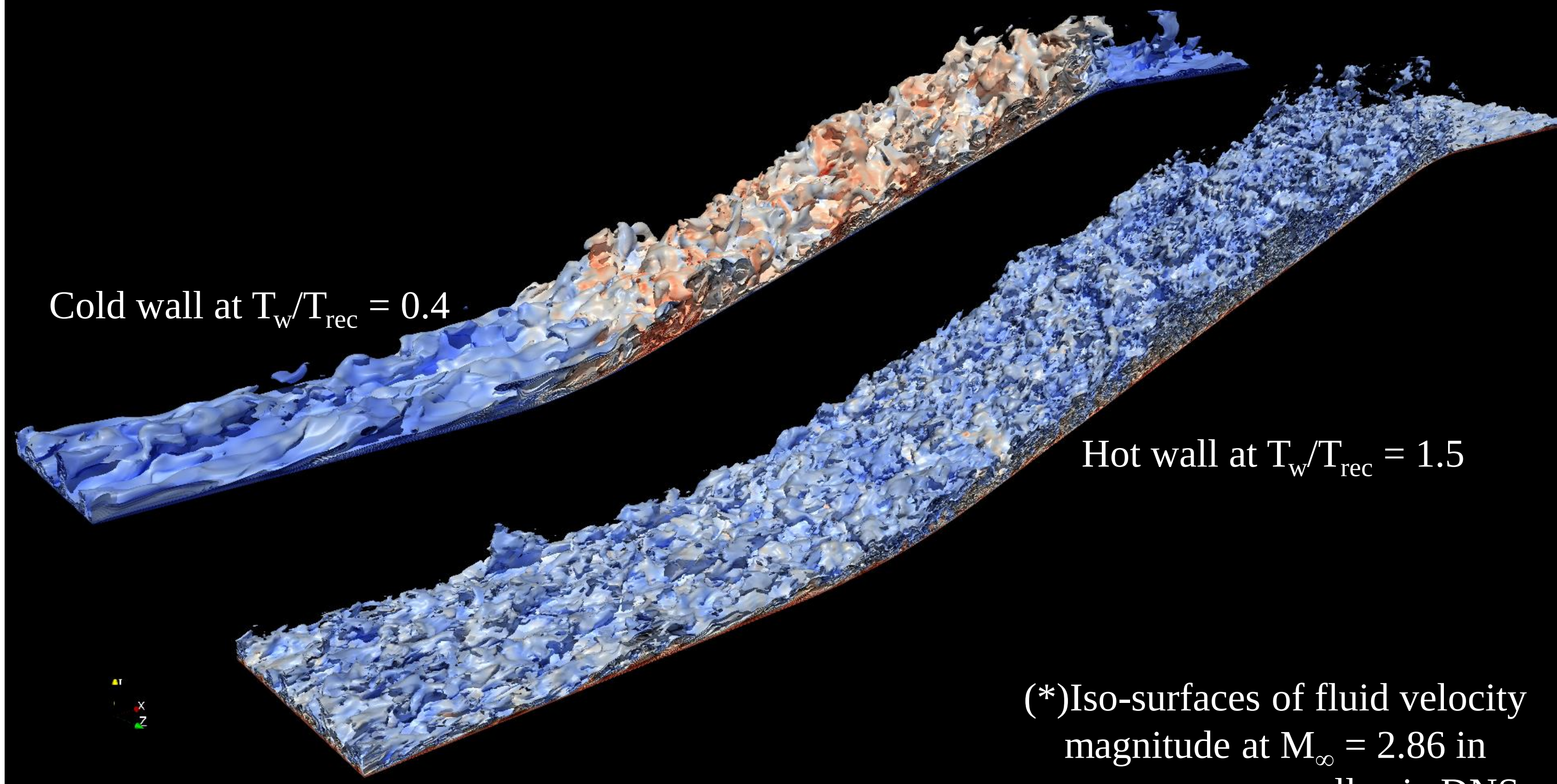
Award #FA9550-17-1-0051
Program Manager: Dr. Sarah Popkin



(*)Iso-surfaces of fluid velocity magnitude at $M_\infty = 2.86$ in concave-convex walls via DNS.

Effects of wall curvature on hypersonic turbulent spatially-developing boundary layers

Summary: Study concave/convex wall curvature on supersonic/hypersonic SDTBL (Mach numbers up to 5) in a suite of high spatial/temporal resolution Direct Numerical Simulation (DNS) as well as Implicit Wall Resolved Large Eddy Simulation (iLES) at *high Reynolds numbers*.

Research Objectives: 1) Evaluate the effect of: **(i) wall-curvature driven pressure gradient, (ii) flow compressibility, (iii) Reynolds number dependency, and (iv) wall temperature** on low/high-order statistics of the flow and **turbulent structures** based on high fidelity DNS. 2) Explore iLES's performance in complex flows.

Highlights of Approach:

- Highly scalable finite-element flow solver PHASTA (**P**arallel **H**ierarchic **A**daptive **S**tabilized **T**ransient **A**nalysis)[1]
- Turbulent compressible inflow generation via the Dynamic Multi-scale Approach (DMA)[2]
- Efficient and speedy post-processing library for large scale CFD systems (AQUILA)[3]

Expected breakthroughs:

- *"Push the envelope"* of DNS at higher Reynolds numbers in concave and convex walls ($\delta^+ = \delta\, u_\tau / \upsilon_w$ > 1,000 von Karman number) via CPU and GPU capabilities.

[1] M. Rasquin, C. Smith, K. Chitale, E. S. Seol, B. A. Matthews, J. L. Martin, O. Sahni, R. M. Loy, M. S. Shephard, and K. Jansen, *Scalable implicit flow solver for realistic wing simulations with flow control*, Computing in Science & Engineering, vol. 16, no. 6, pp. 13-21, 2014.

[2] Araya G. and Lagares C., *Implicit subgrid-scale modeling of a Mach-2.5 spatially-developing turbulent boundary layer*. Entropy 2022, 24, 555. https://doi.org/10.3390/e24040555

[3] Lagares C., Rivera W. and Araya G., *Scalable Post-Processing of Large-Scale Numerical Simulations of Turbulent Fluid Flows*. Symmetry 2022, 14, 823. https://doi.org/10.3390/sym14040823

S: Spring Sum: Summer F: Fall

Project Roadmap

Overall Timeline

S2017/Sum2017/F2017/S2018/Sum2018/F2018

S2019/Sum2019/F2019/S2020/Sum2020/F2020/ S2021/Sum2021

F2021/S2022/Sum 2022

PHASTA Flow Solver and pre-processing tools

DNS at low Reynolds numbers

- Meshing tool development.
- Turbulent inflow condition.
- Zero-pressure gradient precursor.
- Testing and validation up to Mach-7.87.
- Thorough understanding of:
  - Scaling laws for compressible flows and recycling technique.
  - Compressibility effects.
  - Wall temperature influence.

DNS/iLES1 at low to moderate Reynolds numbers

- Mesh design/generation in large scale complex systems.
- RANS analysis for concave/convex geometries.
- Acquired knowledge of:
  - Reynolds number dependency.
  - Compression waves.
  - Pressure gradient effect by wall-curvature (concave/convex).
  - Coherent structures
- Post-processing analysis in Aquila-CFD and HDF5 Reader.
- Scientific visualization: flow animation and virtual/augmented reality

What we have achieved since last portfolio…

- 3D Lagrangian Coherent Structures (LCS) analysis
- Post-processing numerical tool enrichment (up to **105,820 CPU cores in Onyx** and **64 V100 GPUs in Narwhal**)
- Big data storage: lossy compression
- Ending iLES2/DNS of curved walls in high-speed turbulent boundary layers at high Reynolds numbers, i.e. δ^+ = **900 to 2,600 (from 1,920 to 37K cores in Narwhal)**

Dissemination

Journal (6) Conference (6) Oral/Visual Presentations (10)

Journal (6) Conference (9) Oral/Visual Presentations (20)

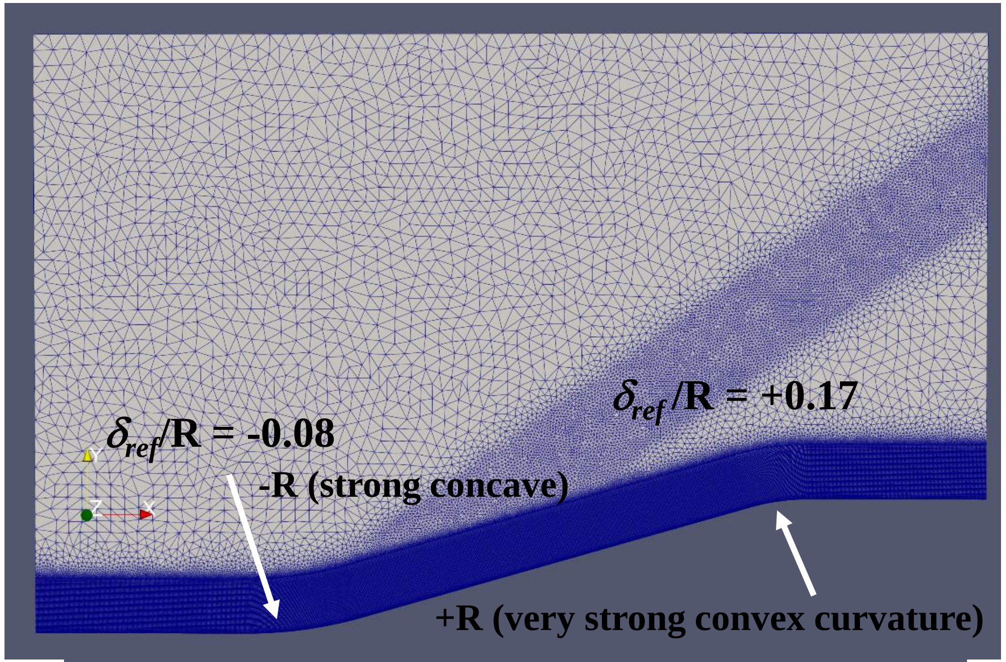
Journal (3) Conference (5) Oral/Visual Presentations (10)

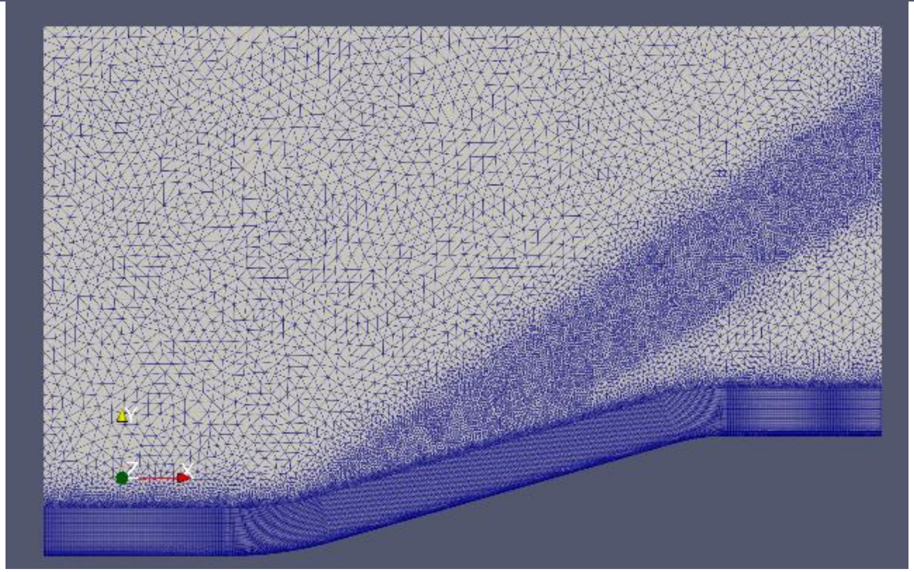
* planned

Higher Reynolds numbers (more recent)

Approach	DNS (3) Cold /**Q-Adiabatic** /Hot	iLES1 **Q-Adiabatic**	iLES2 **Q-Adiabatic**	DNS **Q-Adiabatic**
Mach	2.86	2.86	2.86	2.86
T_w/T_r	0.4/1.04/1.5	1.04	1.04	1.04
Completion percentage	100%	100%	90%	60%
Reynolds range (δ^+)	226-679 239-676 214-684	755-2160	920-2550	900-2600
$L_x L_y L_z$	$(27\times17\times3)\ \delta_{ref}$		$(27.2\times17\times3)\ \delta_{ref}$	
N° of cells	10M	10M	10.6M	385M
Δx^+**(Q-Adiab)**	8	42	40	7
$\Delta y^+_{min/\,max}$ **(Q-Adiab)**	0.2 / 10	0.72 / 36	1 / 28	0.2 / 10
Δz^+**(Q-Adiab)**	8	25	20	5
Cores	**1440**	**1440**	**1920**	***37,120**
Sample time (δ/U_∞)	270-300	274	345	*270
Sample size	**736GB (4K fields)**	**736GB (4K fields)**	**800GB (4K fields)**	***28TB(6.2 K fields)**

DNS/iLES of Concave-Convex Wall Curvature

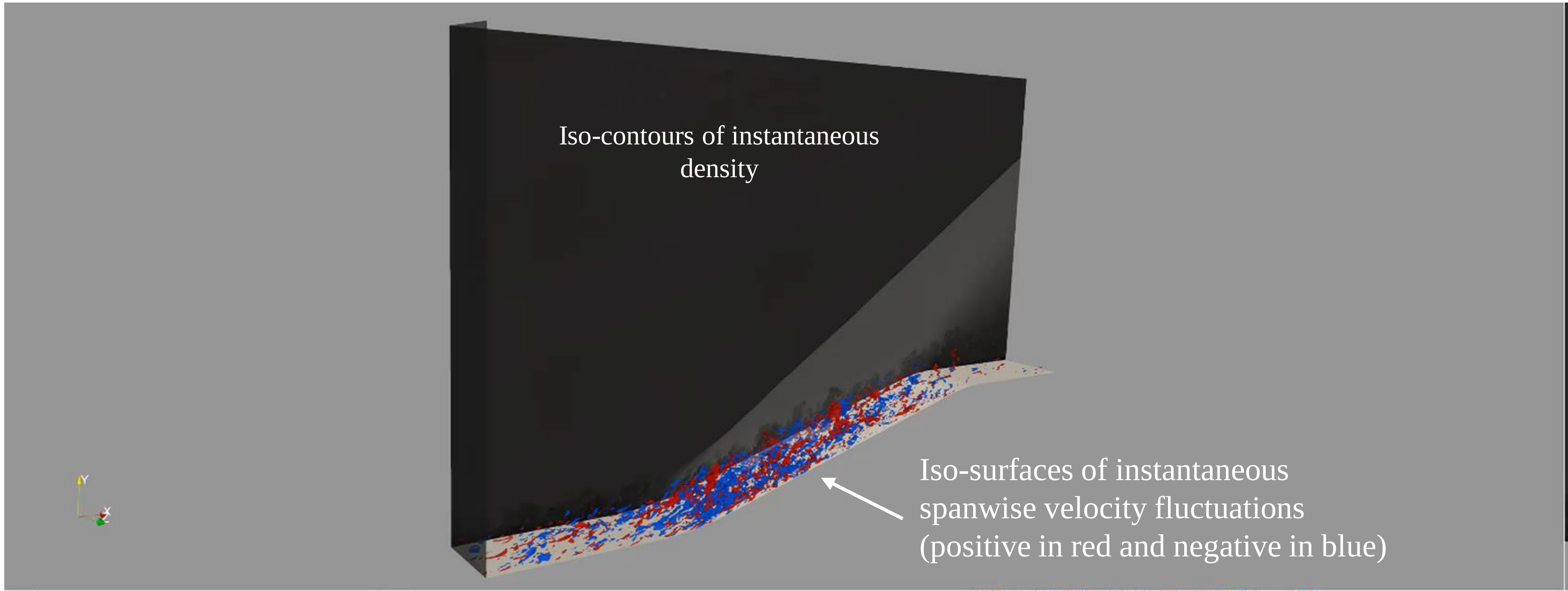




Schematics of the DNS (top) and iLES2 mesh (bottom)

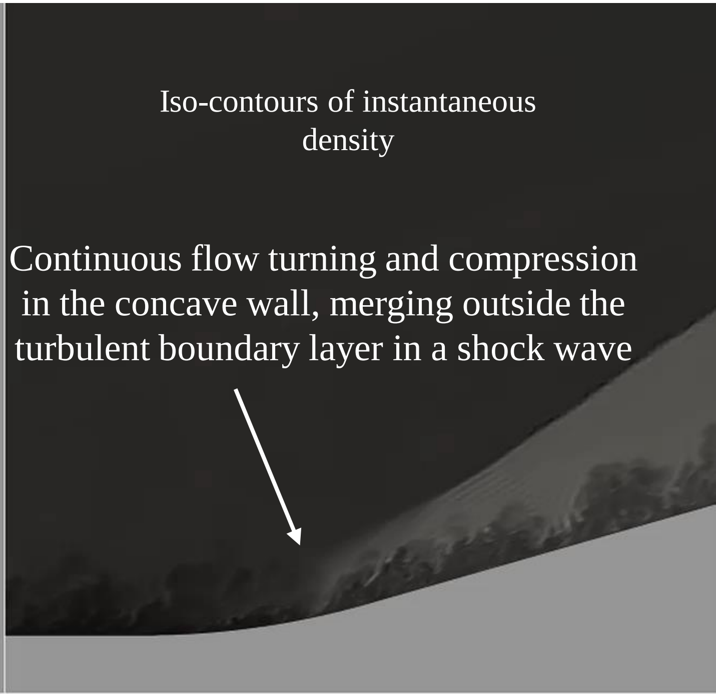
According to Simpson. (Ann. Rev. Fluid Mechanics, 21, 205-234, 1989.), **wall curvatures around** **|δ/R| ≈ 0.1** are considered strong.

Flow visualization of DNS at $\delta^+ = 239$ to 676 (low Reynolds numbers). Wall Q-adiabatic conditions



Iso-contours of instantaneous density

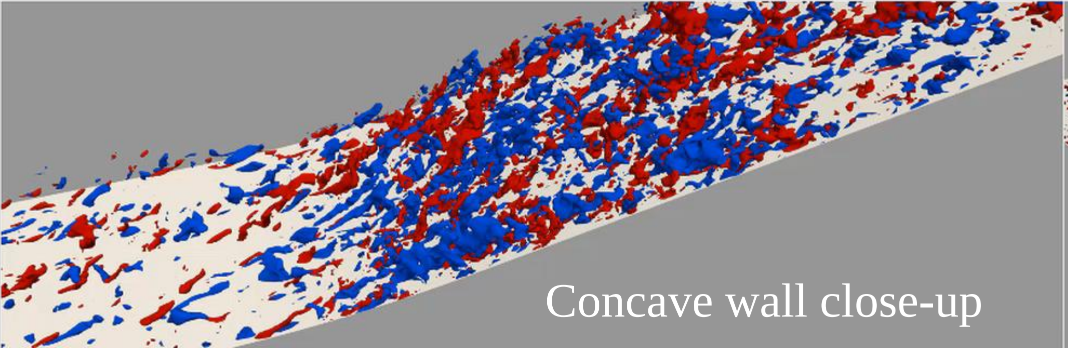
Iso-surfaces of instantaneous spanwise velocity fluctuations (positive in red and negative in blue)



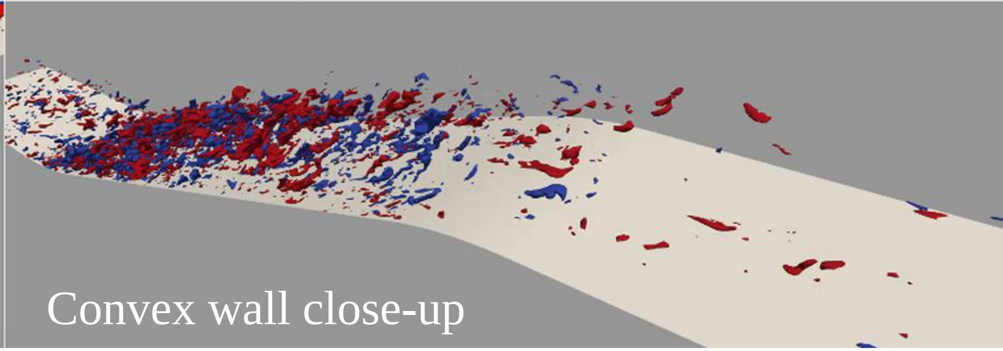
Iso-contours of instantaneous density

Continuous flow turning and compression in the concave wall, merging outside the turbulent boundary layer in a shock wave

Inflow close-up



Concave wall close-up



Convex wall close-up

Turbulent conditions were generated via an asynchronous flat-plate precursor (iso-contours of instantaneous density)

Enhancement of spanwise velocity fluctuations at the turbulent concave wall is caused by large-scale roll cells. These roll cells are generated by unsteady **"Taylor-Gortler-like" vortices** via similar centrifugal instability mechanisms as in laminar concave flows(*). **No spanwise inhomogeneity has been observed in time-averaged flow statistics**.

(*) Barlow and Johnston (JFM, 191, 137-176, 1988)

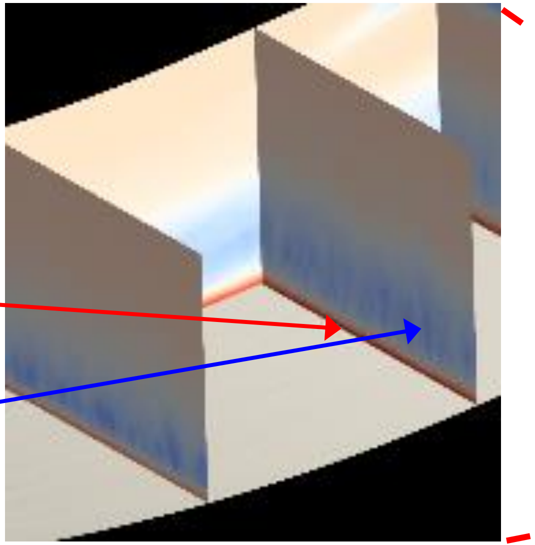
The very strong favorable pressure gradient (FPG) induced by the convex surface stabilizes and quasi-laminarizes the flow, which remains two-dimensional.

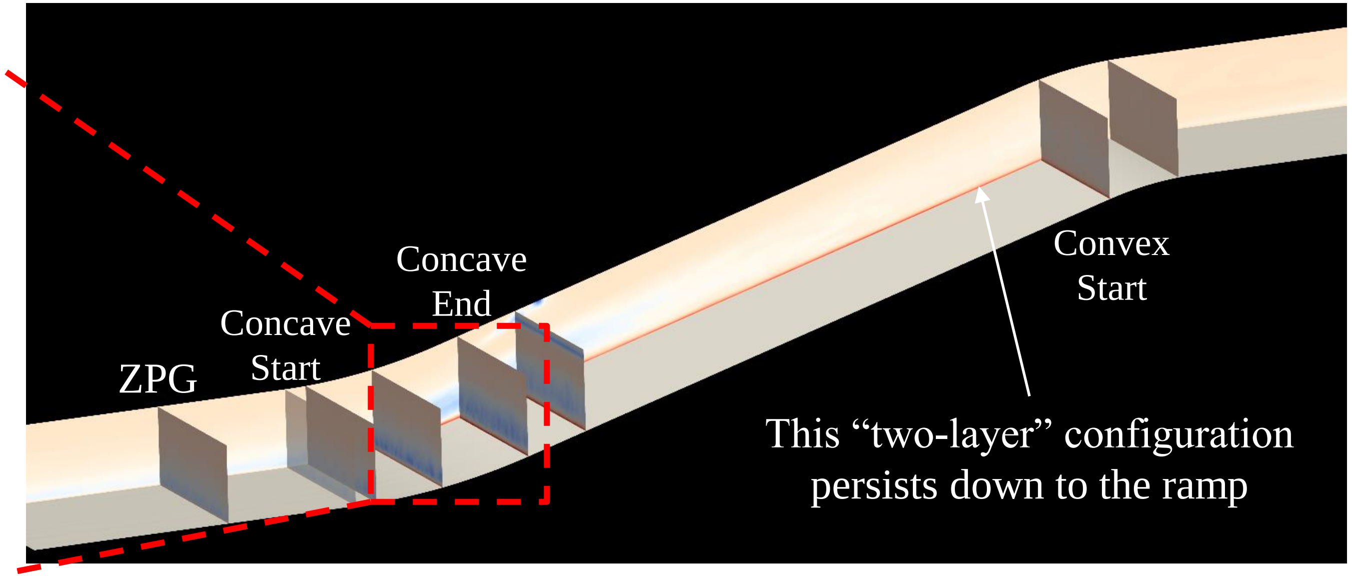
Quadrant analysis over Reynolds shear stresses $\langle u'v' \rangle^+$

Two “clearcut” layers:

-inner layer where $\langle u'v' \rangle^+ > 0$

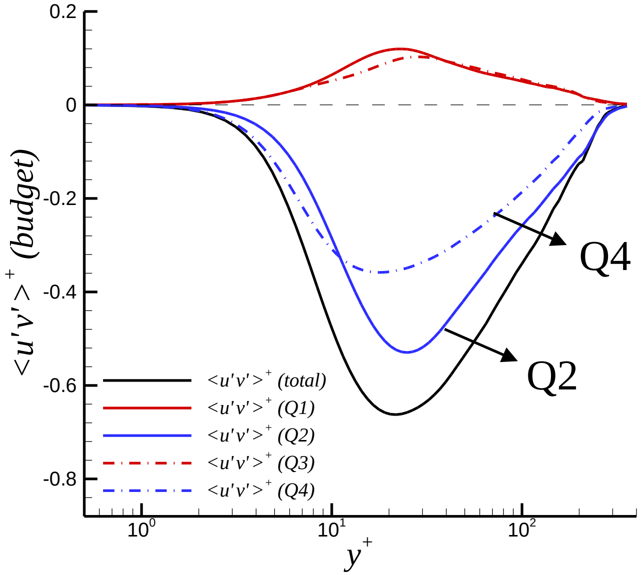
-outer layer where $\langle u'v' \rangle^+ < 0$



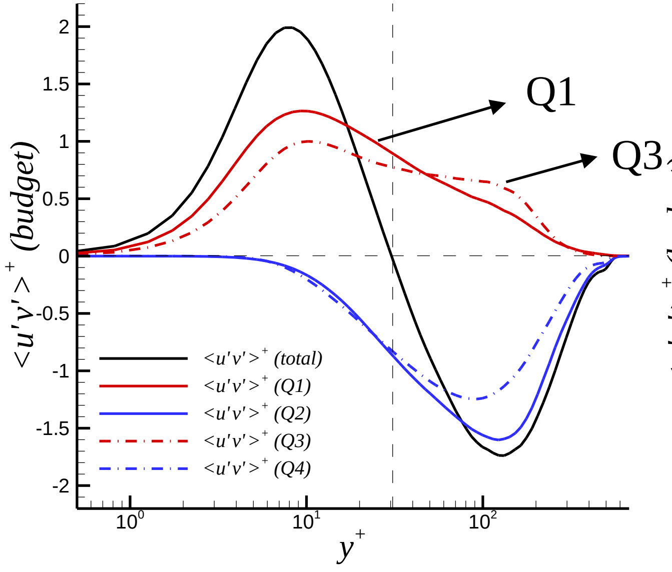


This “two-layer” configuration persists down to the ramp

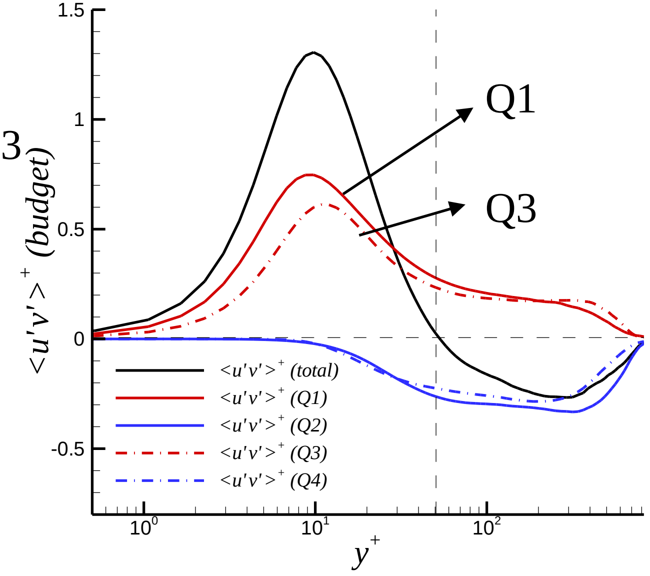
DNS at low Reynolds numbers and wall Q-adiabatic conditions (structured part)



Incoming flow (ZPG region)



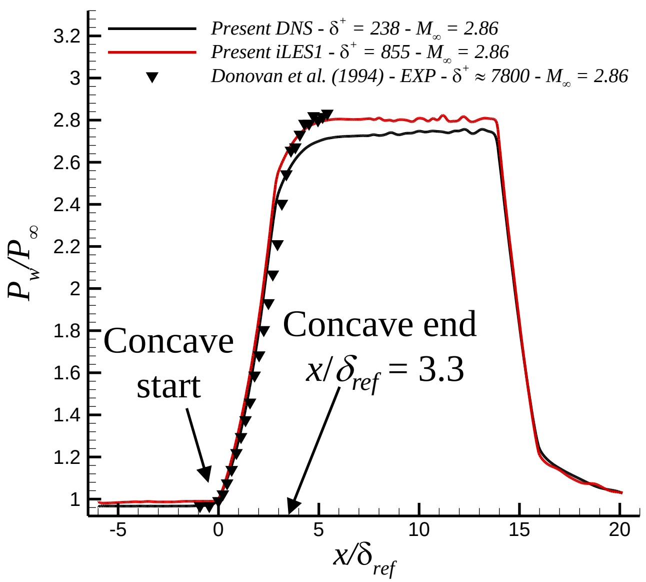
Concave End region



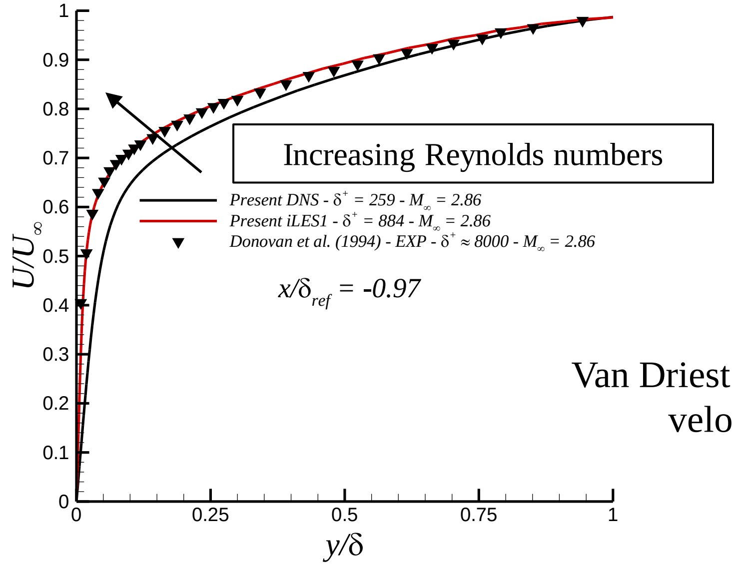
Convex Start region

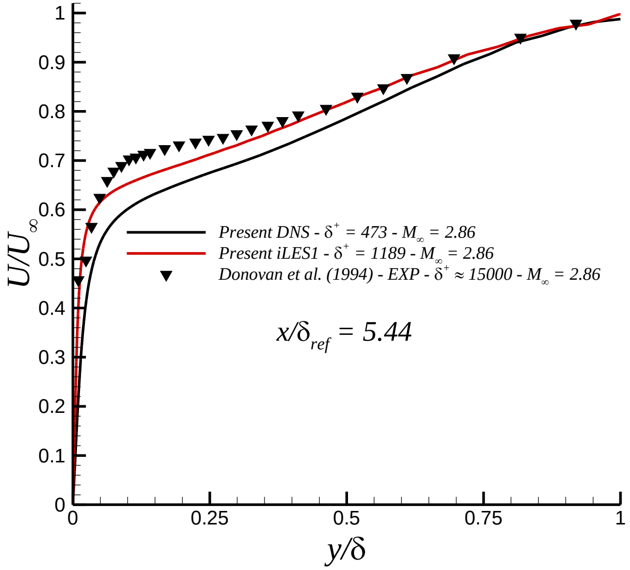
Q1: outward interactions
Q2: ejections
Q3: inward interactions
Q4: sweeps

Statistics comparison with wind tunnel experiments by Donovan et al (JFM, 259, 1994)

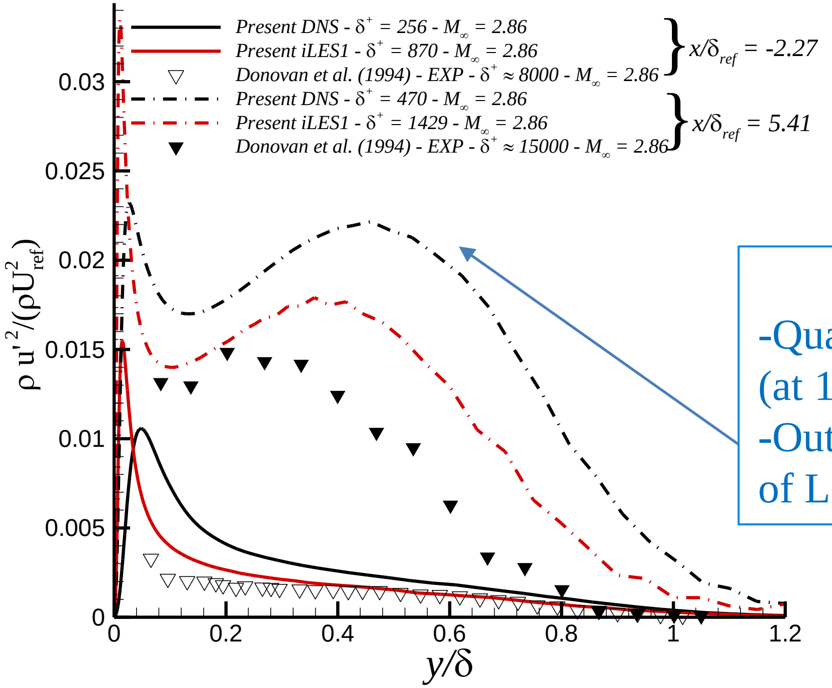


Wall pressure normalized by freestream pressure





Van Driest transformed mean velocity profiles



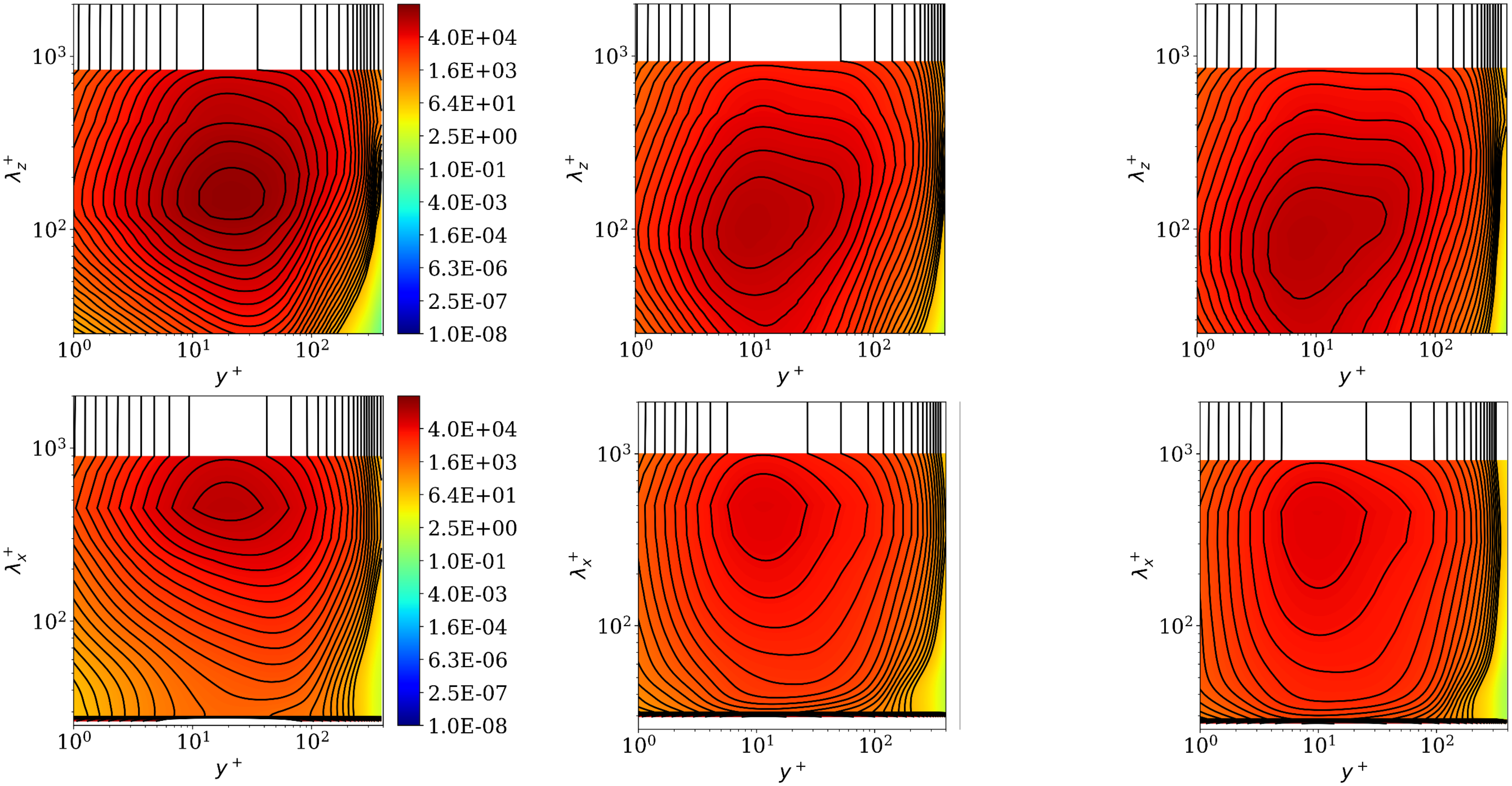
Streamwise Reynolds normal stresses

Lessons learned:

-Qualitative agreement of iLES and DNS with experiments (at 10X and 30X times lower δ+, respectively)

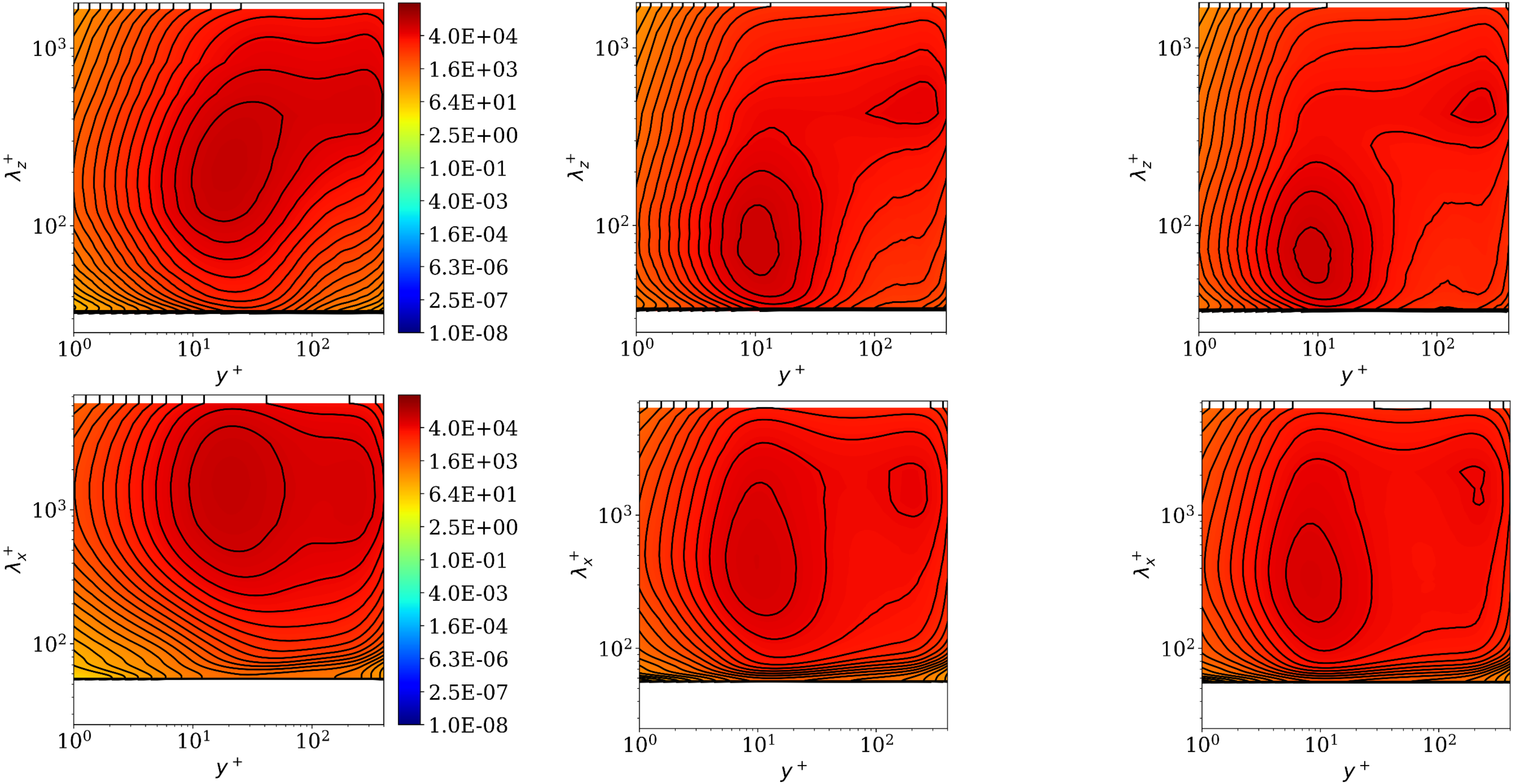
-Outer secondary peaks on *u*’ caused by the enhancement of LSM due to adverse pressure gradient

Middle Concave Wall: Normalized, 2D pre-multiplied spectra, $kE_{u'u'}$



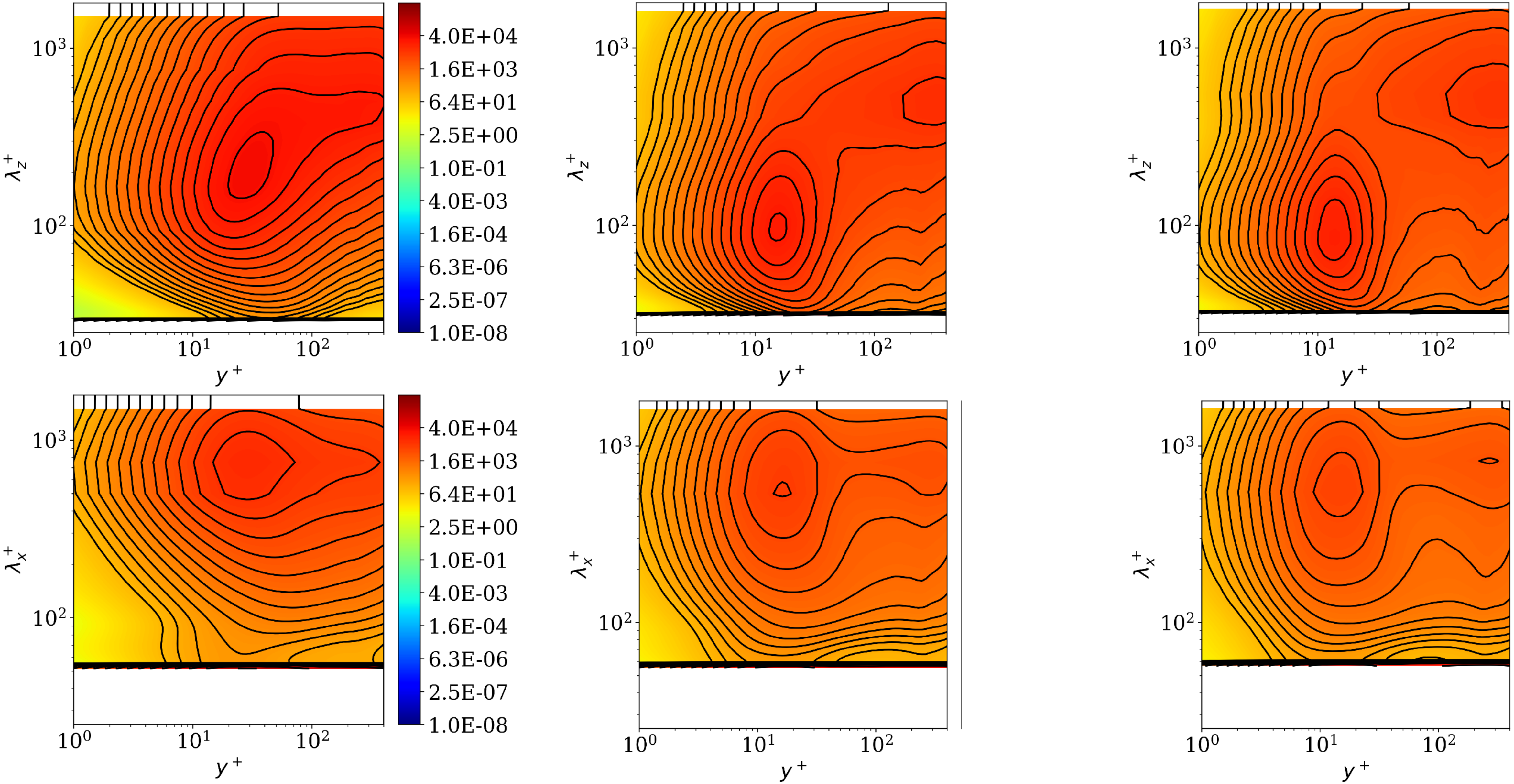
(Top) Spanwise; (Bottom) Streamwise; & Cold, Q-Adiabatic and Hot from Left to Right, respectively. DNS at low Reynolds numbers.

Middle Ramp: Normalized, 2D pre-multiplied spectra, $kE_{u'u'}$



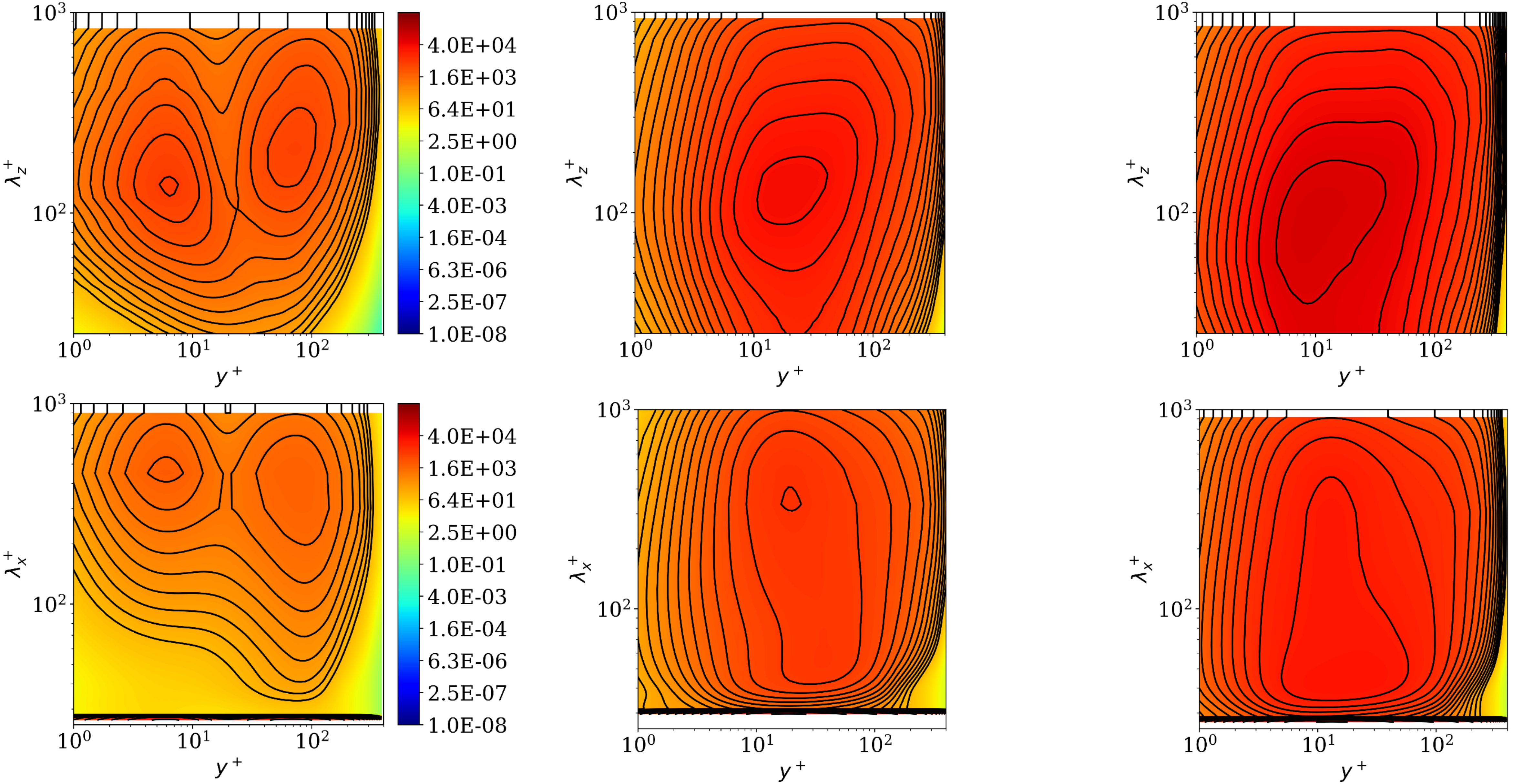
(Top) Spanwise; (Bottom) Streamwise; & Cold, Q-Adiabatic and Hot from Left to Right, respectively

Middle Convex Wall: Normalized, 2D pre-multiplied spectra, $kE_{u'u'}$



(Top) Spanwise; (Bottom) Streamwise; & Cold, Q-Adiabatic and Hot from Left to Right, respectively

Middle Concave Wall: Normalized, 2D pre-multiplied spectra, $k\mathrm{E}_{t't'}$



(Top) Spanwise; (Bottom) Streamwise; & Cold, Q-Adiabatic and Hot from Left to Right, respectively

Lagrangian Coherent Structures (LCS)

- Two main approaches to identifying coherent structures are Eulerian Coherent Structures (ECS) and Lagrangian Coherent Structures (LCS).
- **ECS** are scalars calculated at each grid point using the instantaneous (or time averaged) velocity field and its gradient (e.g., Q-criterion, λ_2, λ_{ci})
- **LCS** are surfaces formed by particle trajectories that organize the flow into ordered patterns (Haller 2015). These surfaces are **stable or unstable** manifolds which cause particle **attraction or repulsion**, respectively. One of the most popular methods of finding LCS is to calculate the Finite-Time Lyapunov Exponent (FTLE):

$$FTLE(\boldsymbol{x},t) = \frac{1}{|\tau|} \ln \sqrt{\lambda_{max}(C_t^{t+\tau}(\boldsymbol{x}))}$$

$C_t^{t+\tau}$: Cauchy-Green strain tensor
λ_{max}: maximum deformation eigenvalue
τ: integration time.

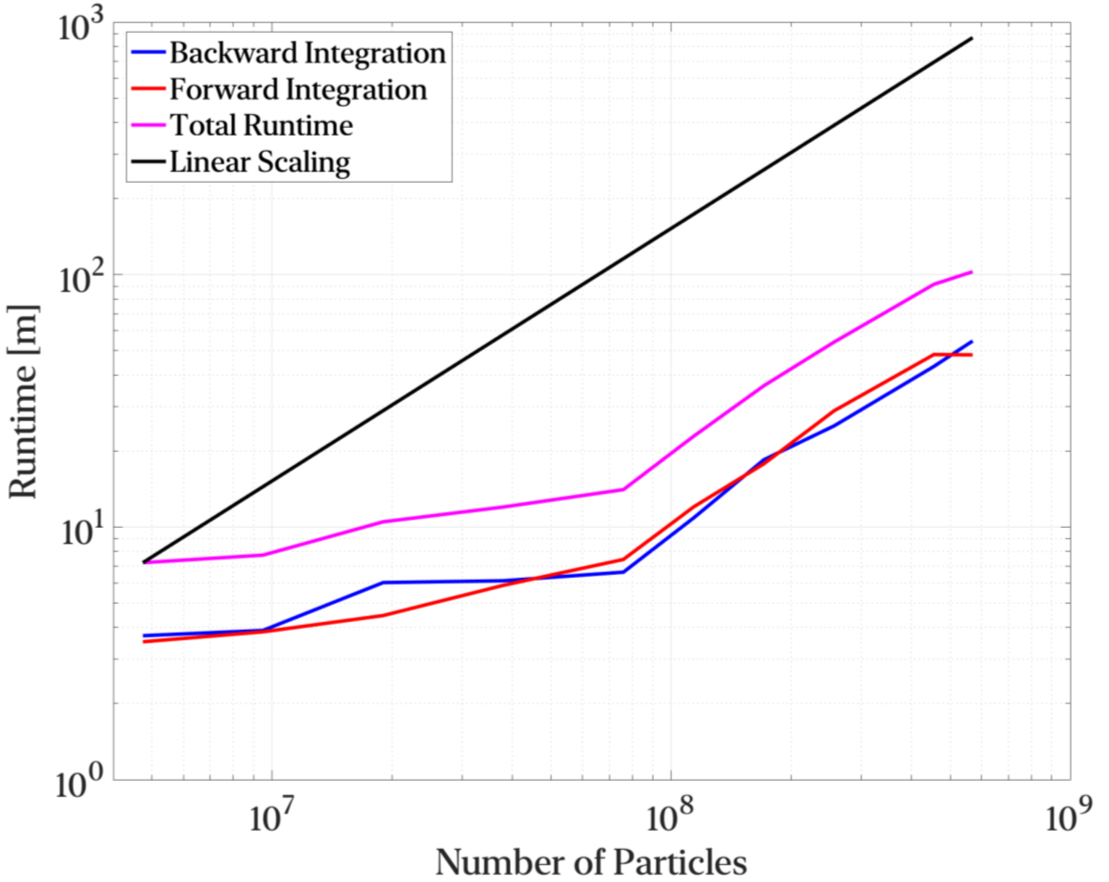
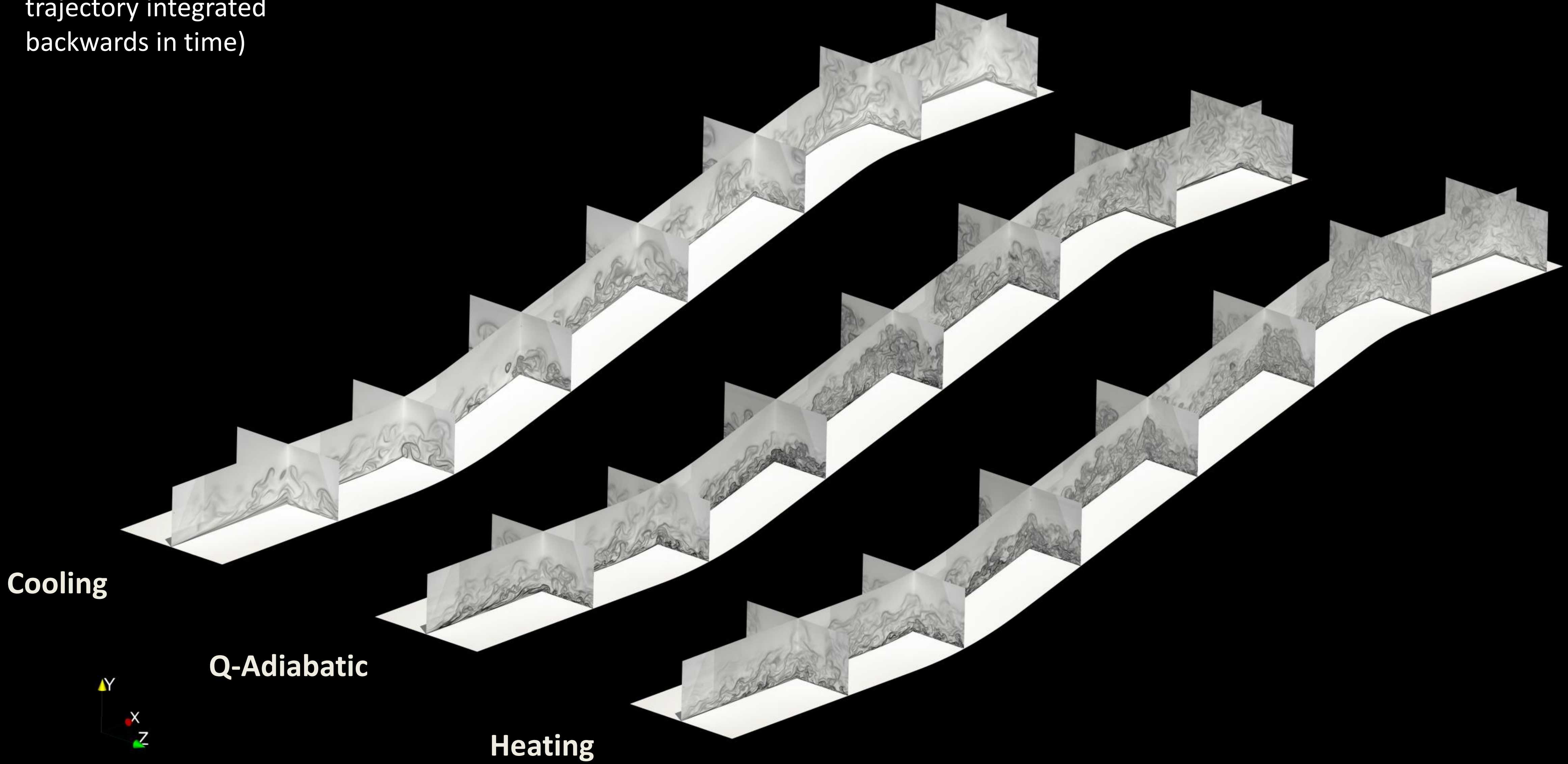


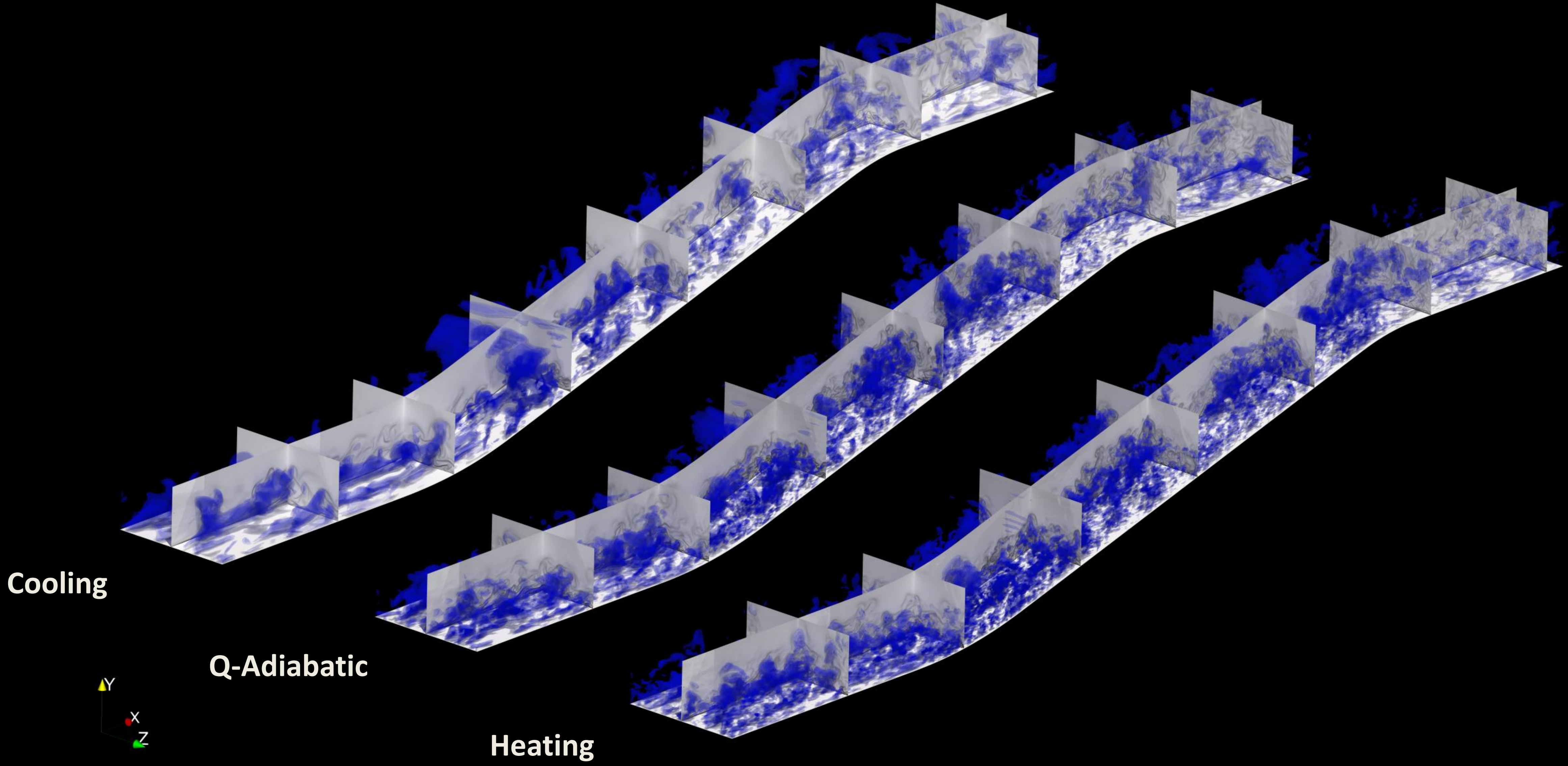
Figure: GPU scaling study for our in-house LCS code

Our **GPU-accelerated** particle tracer and LCS code exhibits super-linear scaling up to the point where the GPUs are saturated. The above study was done over the adiabatic concave-convex geometry at Mach 2.86 (DNS at low Reynolds numbers).

Iso-contours of attracting material lines (particles' trajectory integrated backwards in time)

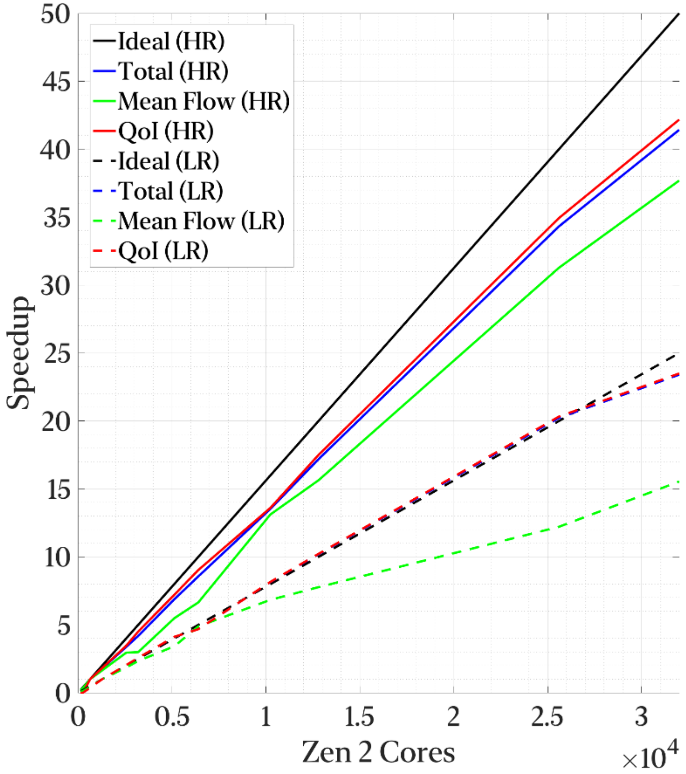


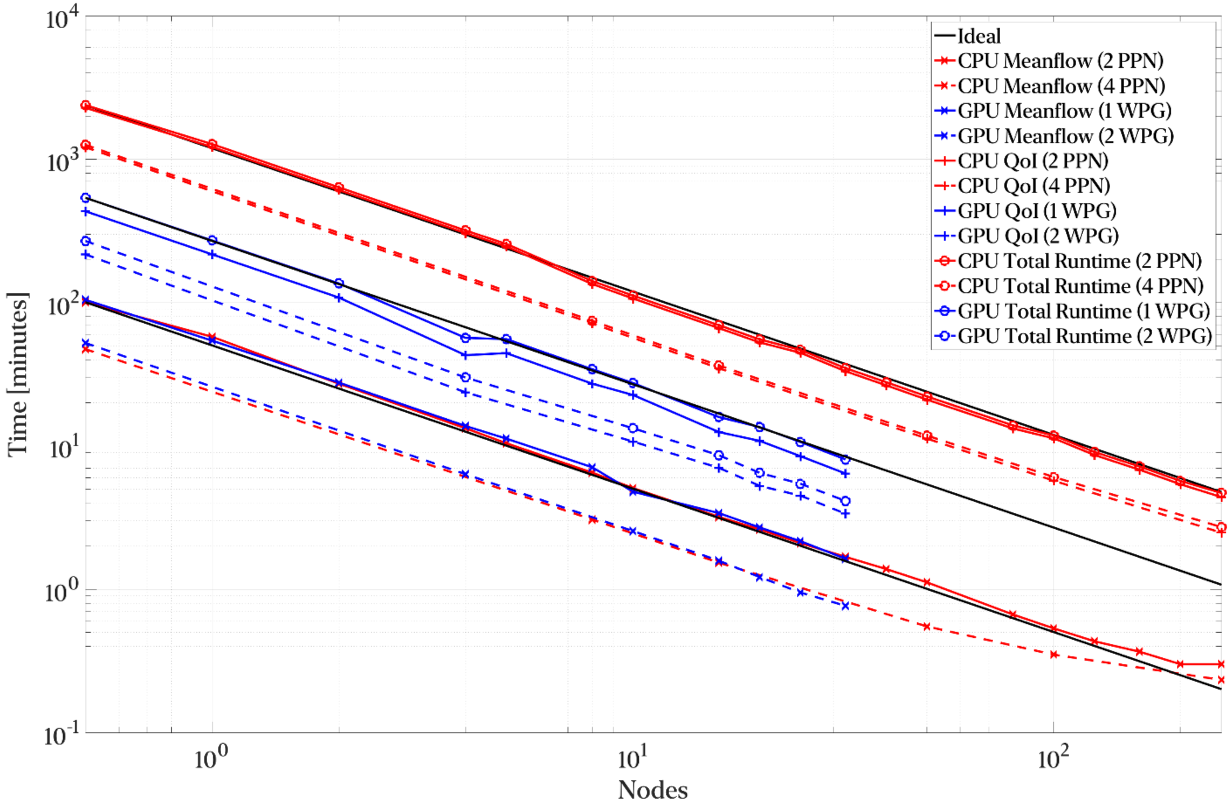
Iso-surfaces of Q2 (ejection) events in blue



Aquila – Our In-House Post-Processing Library

- Aquila-CFD is an out-of-core, CFD post-processing library scalable across CPUs and GPUs.
- Aquila also supports lossy compression via the ZFP HDF5 library plugin.
- Lossy compression becomes vital as the size of our computational domains grows to satisfy resolution requirements at higher Reynolds.





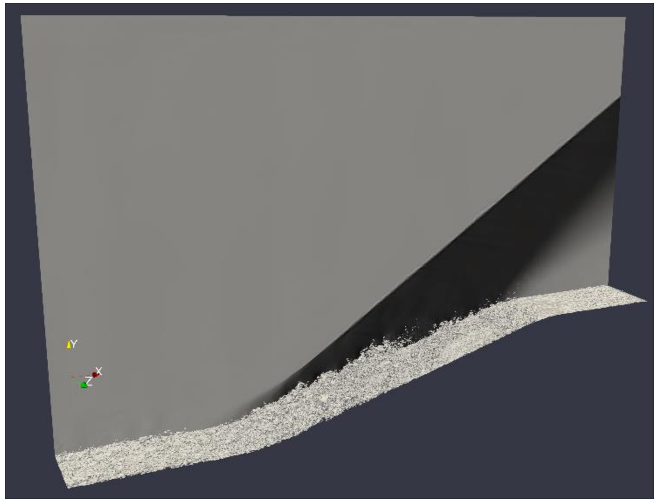
Figures: (Lower Left) CPU and GPU strong scaling performance and oversubscription impact for Aquila-CFD; (Top Right) CPU scaling performance for different datasets. Aquila has scaled to over 100K CPU cores (Onyx) and to 64 Tesla V100 GPUs (Narwhal). The above figure highlights the strong scaling performance and benefits of oversubscription for out-of-core post-processing. The calculation for the mean flow is often the bottleneck since it has a low arithmetic intensity.

Summary

- Centrifugal forces enhance spanwise flow variations and Q1/Q3 events in the supersonic concave wall and downstream in the ramp, which cause positively correlated *u*’ and *v*’ (two “clearcut” layers).
- Evident secondary peaks of streamwise velocity fluctuation ($kE_{u'u'}$) are observed in the pre-multiplied spectra at spanwise wavelengths of the order of $\lambda^+_z \approx 500$. These outer peaks are caused by adverse pressure gradient due to the concave wall and persist downstream, mostly observed in the quasi-adiabatic and hot wall conditions.
- A very strong correlation has been observed between attracting material lines and Q2 (ejections) in a three-dimensional LCS study.

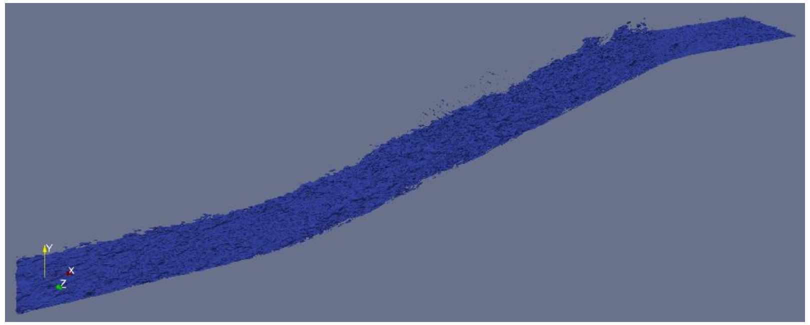
Next Steps and Technical Challenges

- Full postprocessing of the iLES2 case will be carried out, including a Lagrangian Coherent Structure (LCS) analysis.



(*) Instantaneous pressure contours at lateral plane and iso-surfaces of instantaneous temperature.

- The high Reynolds-number case for the DNS approach under combined concave/convex surface curvatures ($\delta^+_{max} \approx$ 2,600) will be finished for the supersonic regime.
- A similar geometry with combined concave/convex surface curvatures is being numerically explored at a Mach number of 5 via Implicit LES.



(*) Iso-surfaces of instantaneous streamwise velocity.

- DNS data (time-spanwise averaged) at low and high Reynolds numbers are being posted at https://www.uprm.edu/hpcvl/
- Instantaneous volumetric flow fields (snapshots) are shared upon reasonable request.

Dissemination and Acknowledgement

Highlights:

- 3 journal papers
- 5 conference papers
- 10 oral/visual presentations
- 2 PhD Dissertations in Progress

Acknowledgement:

- Dr. Sarah Popkin is acknowledged for her support.
- Students Christian Lagares/David Paeres and the University of Colorado-Boulder's team.

Questions?