Wall-Resolved Large Eddy Simulations of Separated Flows

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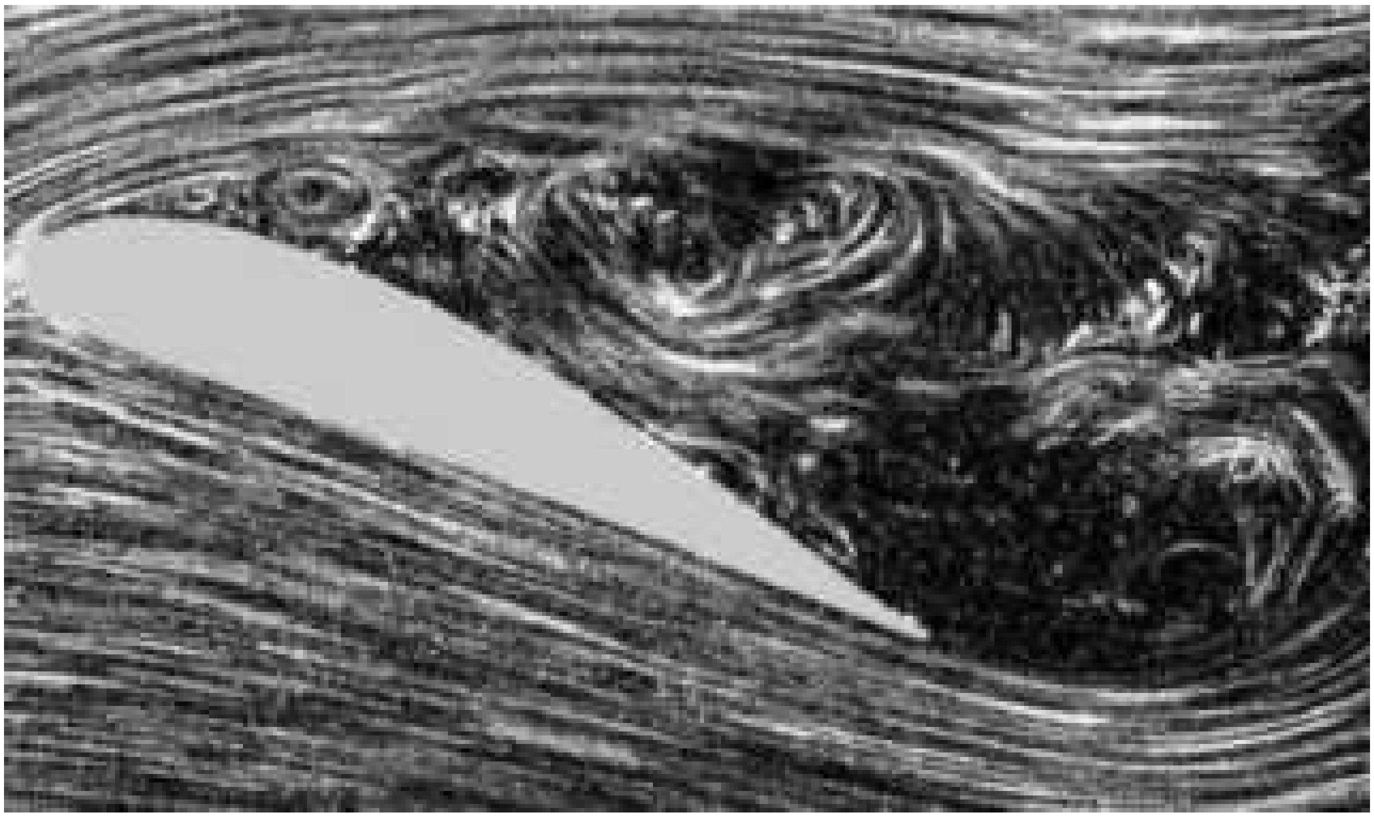
Work performed in collaboration with Dr. Mujeeb Malik

Motivation

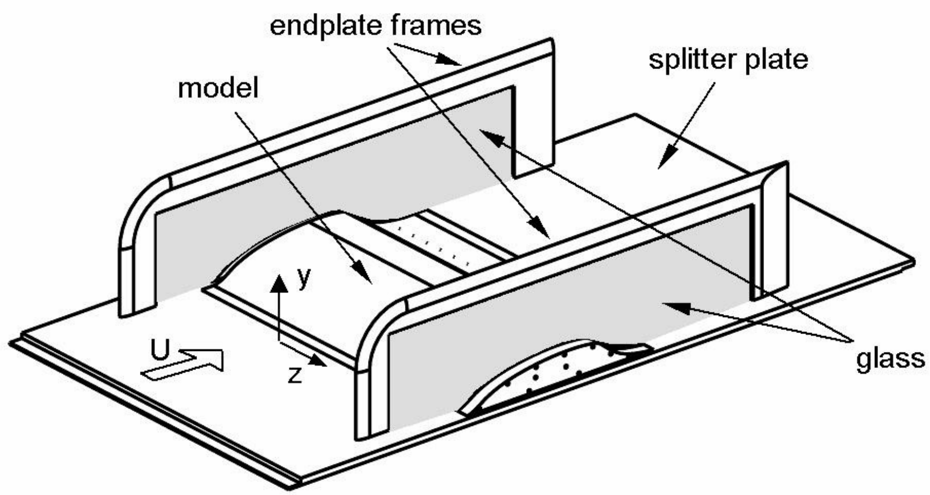
- **Flow separation is an important problem**

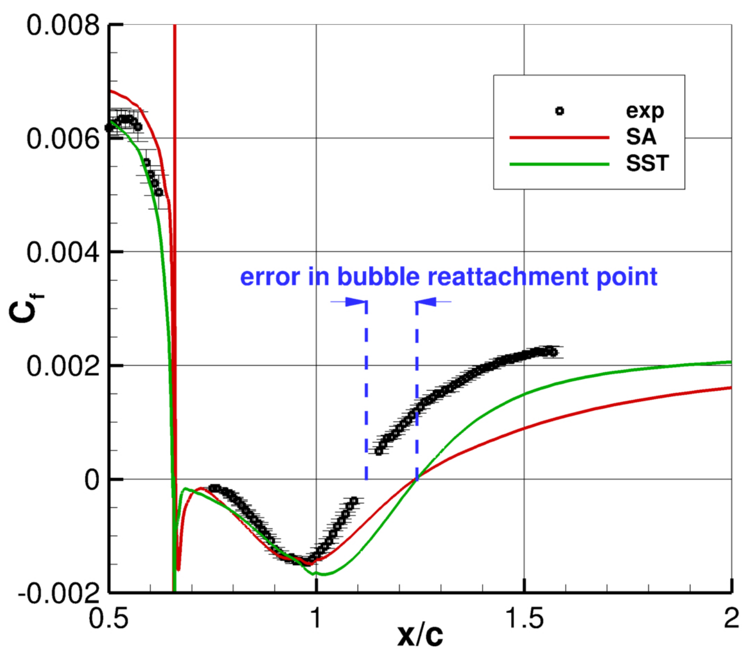


- **Separation leads to increased drag, stall and system performance loss**
- **Separated flows are very difficult to predict**

Motivation

- NASA wall-mounted hump problem shows the failure of Reynolds-Averaged Navier-Stokes (RANS) turbulence models in separated flows





Motivation

- **LES or DNS are of higher fidelity than RANS but very challenging at high Reynolds numbers**
- **A viable strategy for high Reynolds numbers is the wall-modeled LES (WMLES) approach**
- **WMLES attempts to model the near-wall region to ease the computational cost**
- **WMLES has shown mixed success so far**
- **Success/failure of WMLES strongly depends on the robustness of wall model**
- **Hard to assess the true performance of some wall models available in literature**
- **Critical information, such as skin friction predicted by WMLES, is not always provided**

Motivation

- We have been working on wall-resolved LES (i.e. no wall model) at high Reynolds numbers
- Such simulations are very rare
- Our goal is to obtain good-quality reliable data
- Such data can guide the development of improved/new wall models for WMLES
- Improved WMLES with better wall models can provide predictions with much faster turnaround
- Have encountered some issues along the way
- Will discuss those issues today
- Will also show results from the completed LES

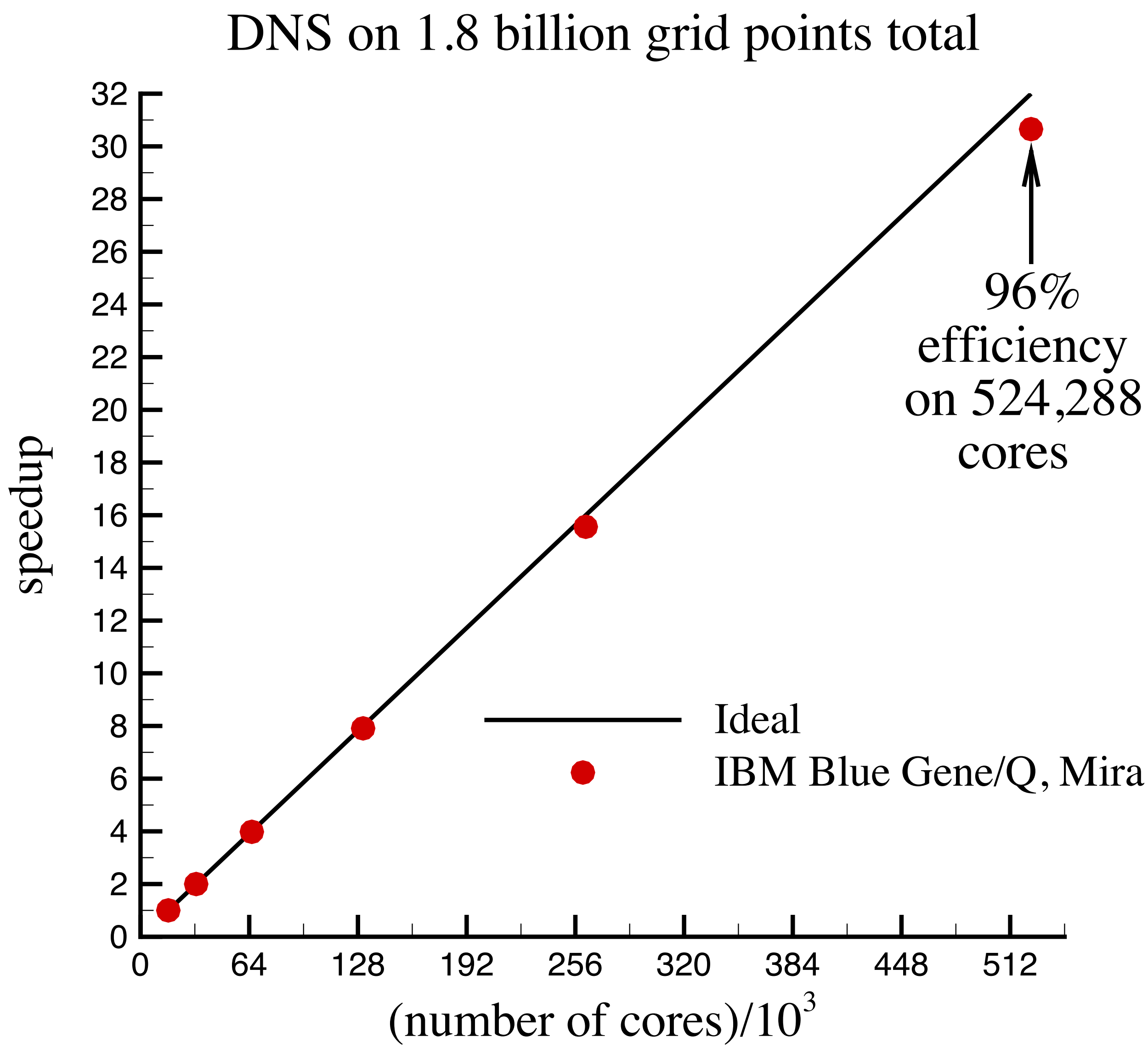
What is wall-resolved LES?

- **A wall-resolved LES is a turbulence simulation whose grid resolution *approaches* DNS-level grid resolution in the near-wall region**
- **For example, for a flat-plate turbulent boundary layer, typical DNS resolutions in wall units are:**
  - **Streamwise resolution:** $\Delta_x^+ \approx 10 - 15$
  - **Spanwise resolution:** $\Delta_z^+ \approx 5 - 10$
  - **Wall-normal resolution on the wall:** $\Delta_y^+ \leq 1$
- **For wall-resolved LES:**
  - **Near-wall Δ_x^+, Δ_z^+ can be a factor of about 2 coarser than DNS**
  - $\Delta_y^+ \approx 1$ **on the wall**

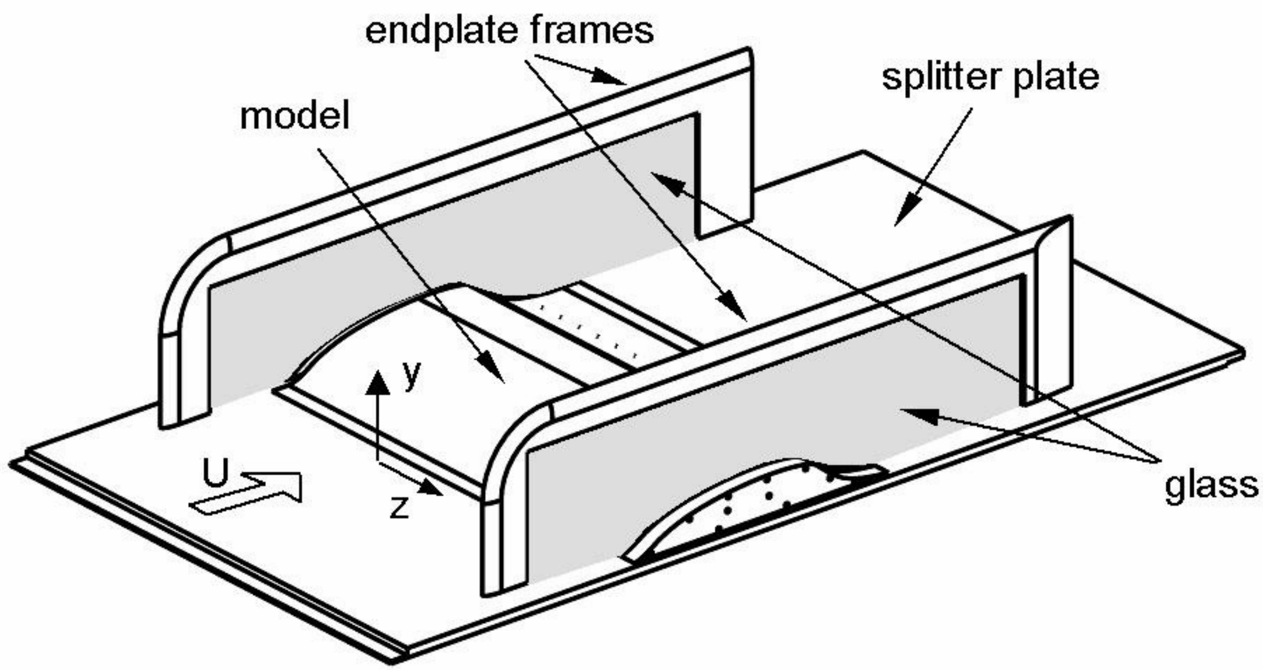
Numerical Methods for LES Flow Solver

- Discretized compressible Navier-Stokes equations in generalized curvilinear coordinates
- High-order compact finite difference schemes
- High-order spatial filtering for numerical stability
- Explicit and implicit time advancement schemes
- Multi-block and overset grid capability to handle complex geometry
- Parallelization based on domain-decomposition
- Artificial dissipation for shock-capturing
- Can be run in Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) modes
- Implicit or explicit subgrid-scale (SGS) models
- Methodology in development for over a decade

Parallel Speedup on IBM Blue Gene/Q (Fixed Total Problem Size)



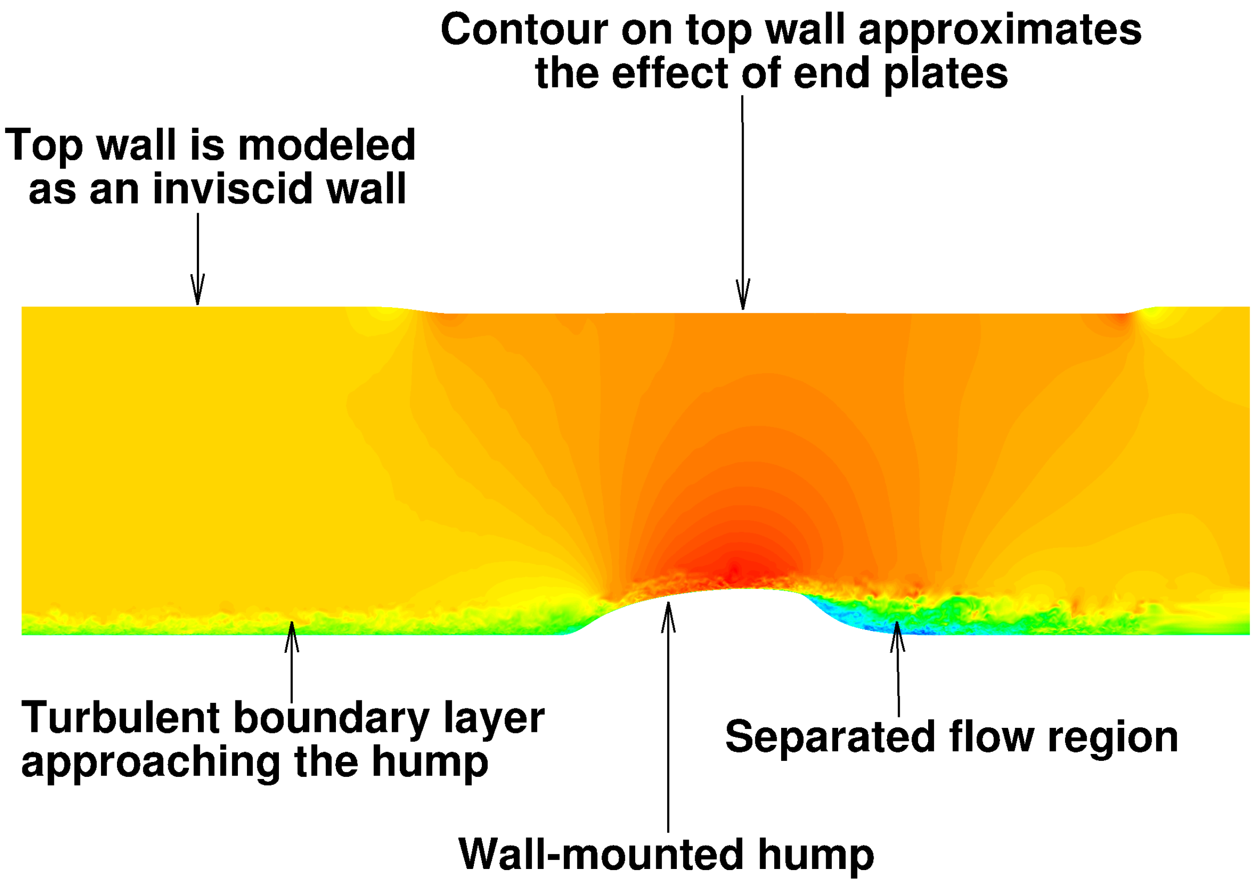
Problem of Interest:
Flow Separation over Wall Hump



- End plates are used to improve two-dimensionality
- End plates also create a blockage effect

Spanwise-Periodic LES Schematic

- LES does not include end plates but assumes spanwise periodicity instead

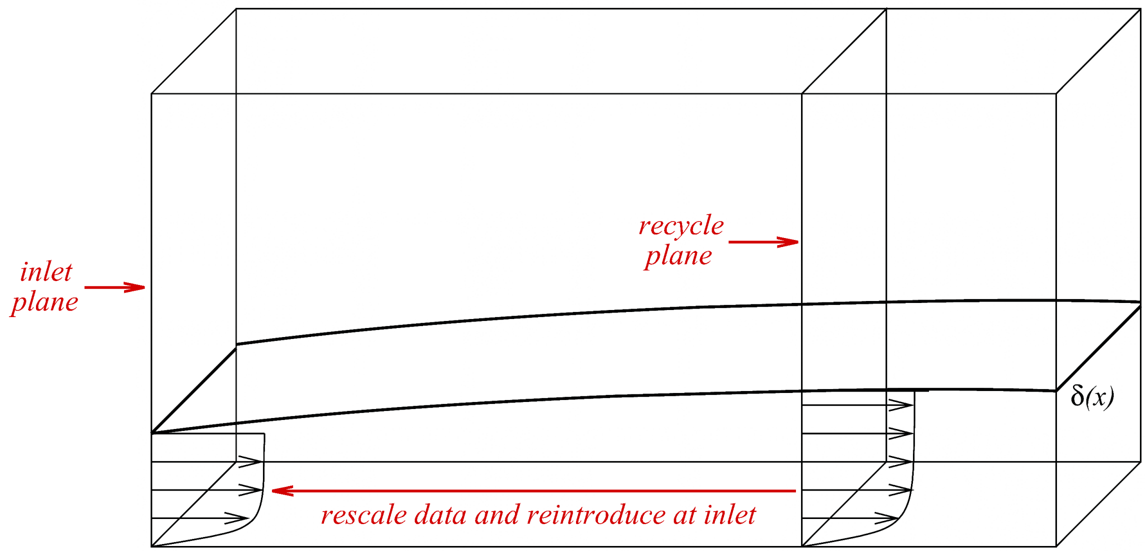


Issues Encountered

- Three important issues were encountered:
- Turbulent inflow generation upstream of the hump does not work well
- Reynolds number is quite high: Significant grid resolution is needed in order to perform a proper wall-resolved LES
- Uncertainty in experimental inflow conditions:
  - Experimental upstream skin friction does not match the value corresponding to the stated inflow Re_θ (momentum thickness Reynolds number)

First Issue: Turbulent Inflow Generation

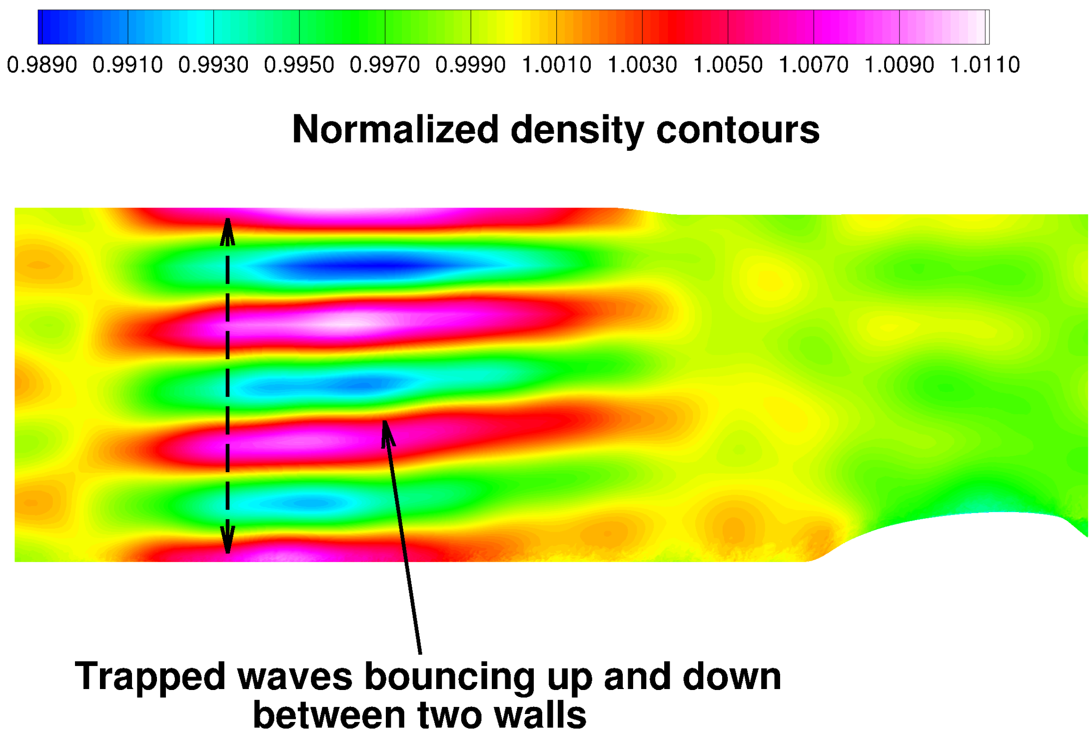
- **Inflow generation technique is based on the rescaling-recycling technique**
- **This method assumes zero pressure-gradient**



- **The zero-pressure-gradient assumption turns out to be invalid upstream of the hump**

First Issue: Turbulent Inflow Generation

- **The figure below shows some trapped waves in front of the hump, which bounce up and down**



- **Wave impingement on lower wall creates local adverse/favorable pressure gradients, violating the zero-pressure-gradient assumption**

First Issue: Turbulent Inflow Generation

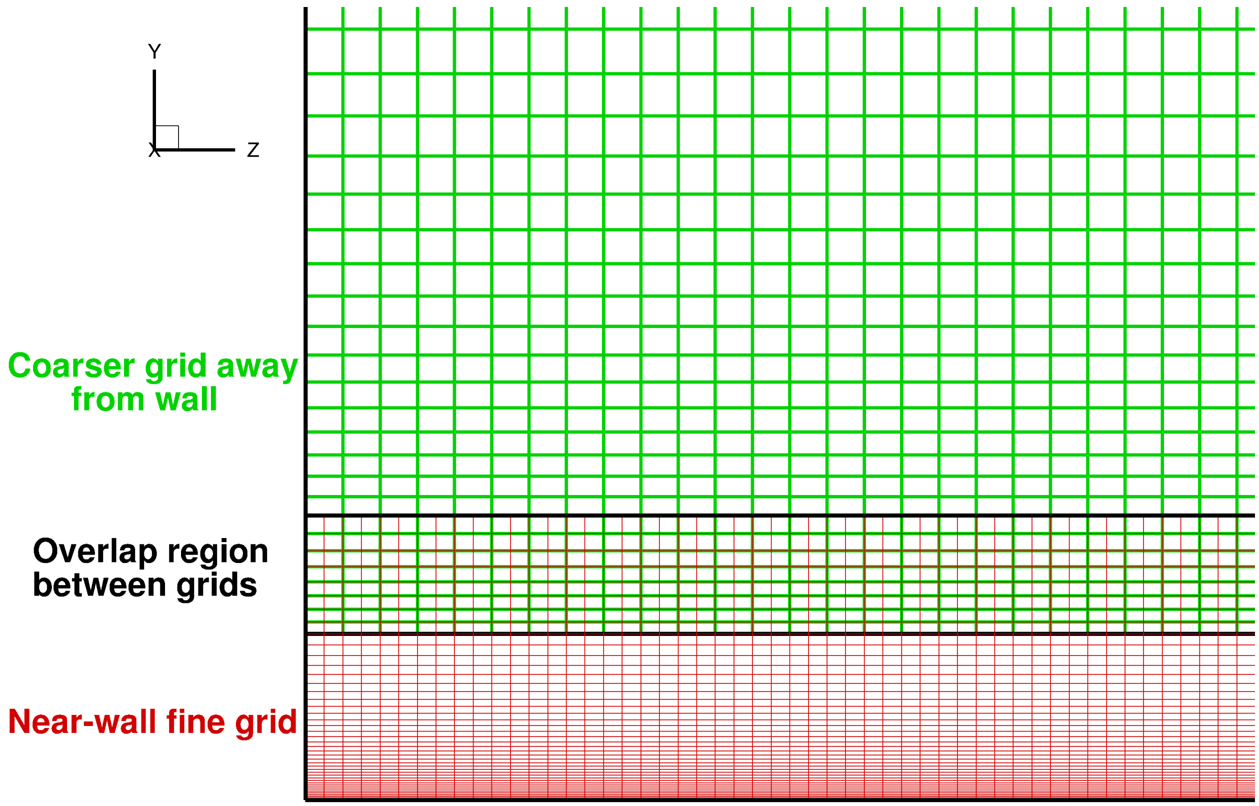
- **To get around this issue, we run the LES simultaneously in two zones:**
- **Zone 1: Turbulent boundary layer developing on a flat plate under zero-pressure gradient**
- **Zone 2: Flow over wall-mounted hump**
- **Zone 1 is completely indepedent of Zone 2**
- **An instantaneous plane extracted from Zone 1 is introduced as the inflow condition for Zone 2**
- **Turbulent boundary layer injection is done at about 2 chord lengths upstream of the hump**

Second Issue: Grid Resolution

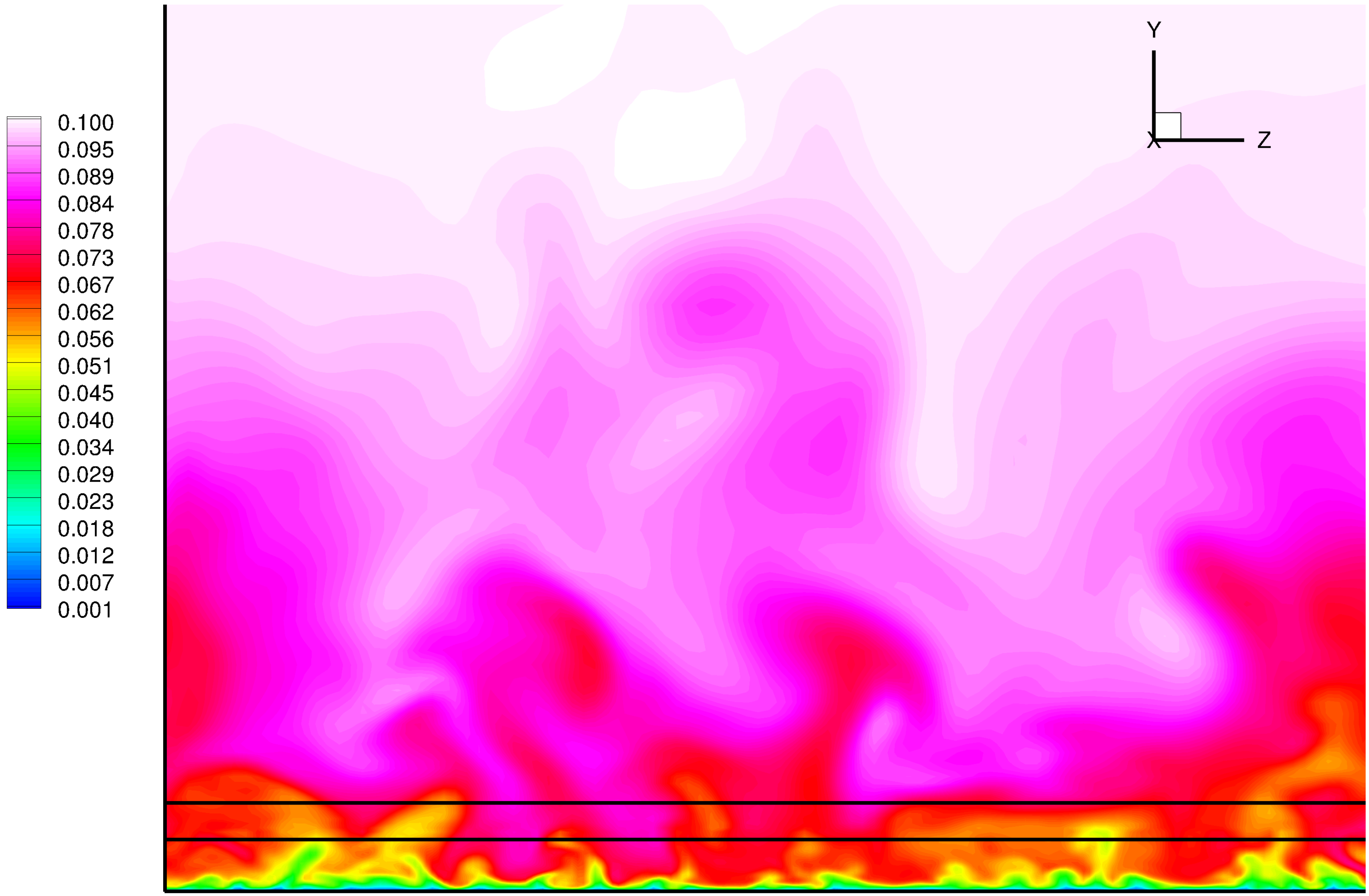
- **A proper wall-resolved LES requires significant number of points at high Reynolds number**
- **Near-wall grid resolution is very important for getting the correct skin friction**
- **To get the skin friction right for the flat plate, the code needs:** $\Delta_x^+ \approx 25$**,** $\Delta_z^+ \approx 12.5$**,** $\Delta_y^+ \approx 1$
- **DNS-level resolution:** $\Delta_x^+ \approx 10 - 15$**,** $\Delta_z^+ \approx 5 - 10$
- **Coarser resolutions under-predict skin friction**
- **It is prohibitively expensive to maintain these** Δ_x^+ **and** Δ_z^+ **until the boundary layer edge**
- **A reasonable compromise is to use a fine resolution grid near the wall and switch to a coarser grid away from the wall**

Second Issue: Grid Resolution

- **We keep $\Delta_x^+ \approx 25$, $\Delta_z^+ \approx 12.5$ until $y^+ \approx 200$ and then coarsen the grid by a factor of 2 in both streamwise and spanwise directions**
- **We use overset grids for this purpose**

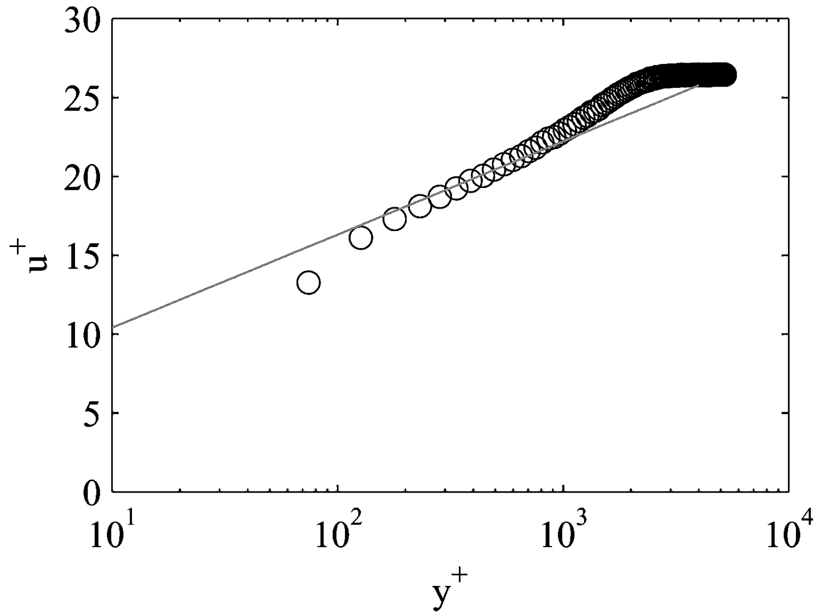


Snapshot of Turbulent Boundary Layer on Overset Grids



Third Issue: Inflow Conditions

- **In related papers, experimentalists state that: inflow** $Re_\theta \approx 6800 - 7200$ **at** $x/c \approx -2.14$
- **The following figure is from the skin friction measurement paper (by Naughton, Viken and Greenblatt, *AIAA Journal*, 2006):**



- **From this figure,** $u_\infty/u_\tau \approx 26.431$ **or** $u_\tau/u_\infty \approx 0.0378$**: This corresponds to** $Re_\theta \approx 5000$

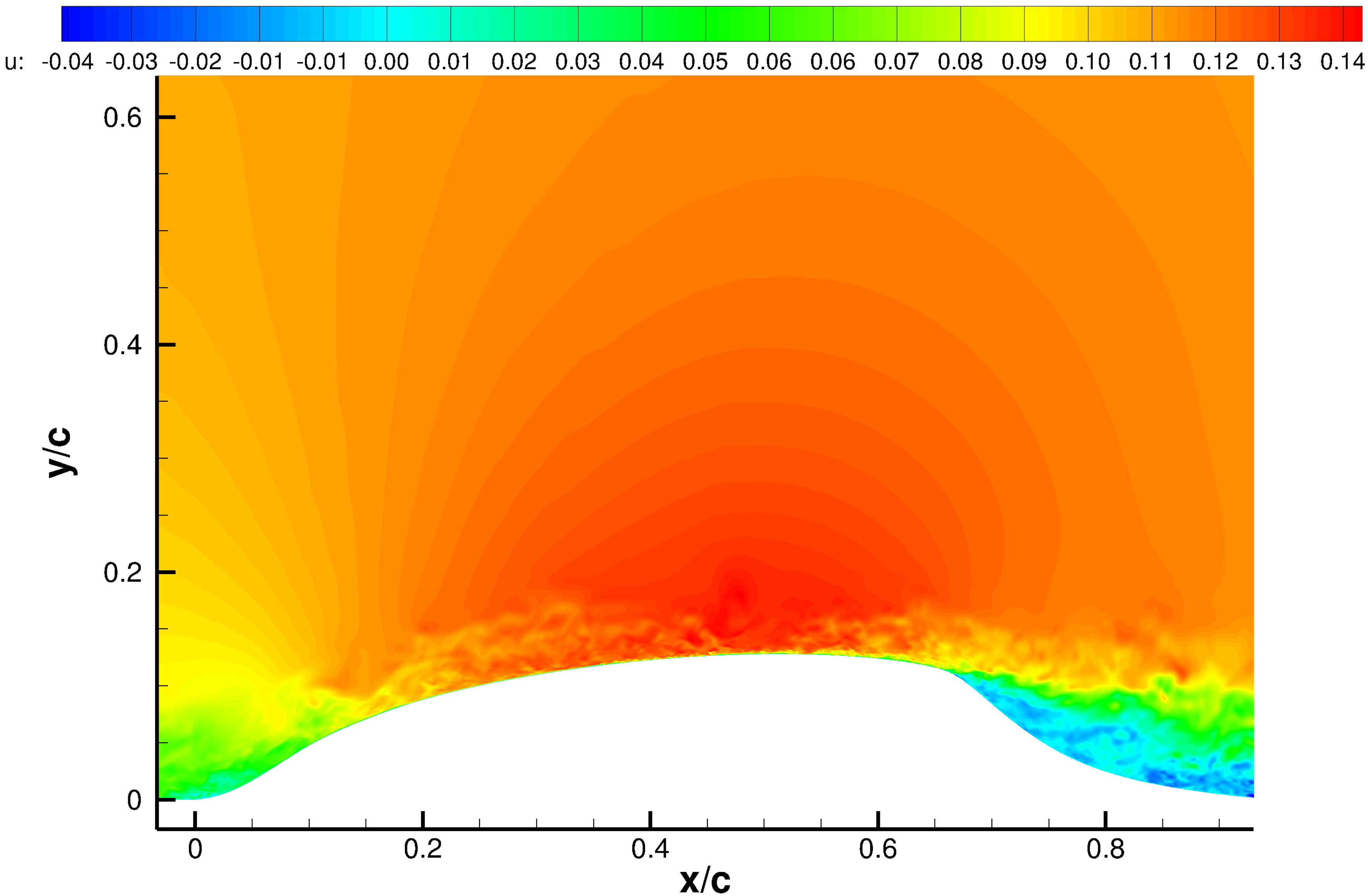
Wall-Resolved LES Details

- **Wall-resolved LES with 300 million point total**
- $Re_c = 936,000$**, Mach number** $= 0.1$
- **Spanwise-periodic domain with a size of** $0.2c$
- **Flat-plate grid resolution on the wall:** $\Delta_x^+ \approx 25$**,** $\Delta_z^+ \approx 12.5$**,** $\Delta_y^+ \approx 1$
- Δ_x^+ **and** Δ_z^+ **are coarsened by a factor of** 2 **at around** $y^+ \approx 200$ **on the flat plate**
- **Similar grid strategy applied for the hump**
- **Vreman's constant-coefficient SGS model**
- **A turbulent boundary layer at** $Re_\theta \approx 5000$ **is injected upstream of the hump**
- $\Delta t u_\infty / c = 2.5 \times 10^{-5}$ **with a max CFL of** 16.5
- **Gathered time-averaged data over** $10c/u_\infty$

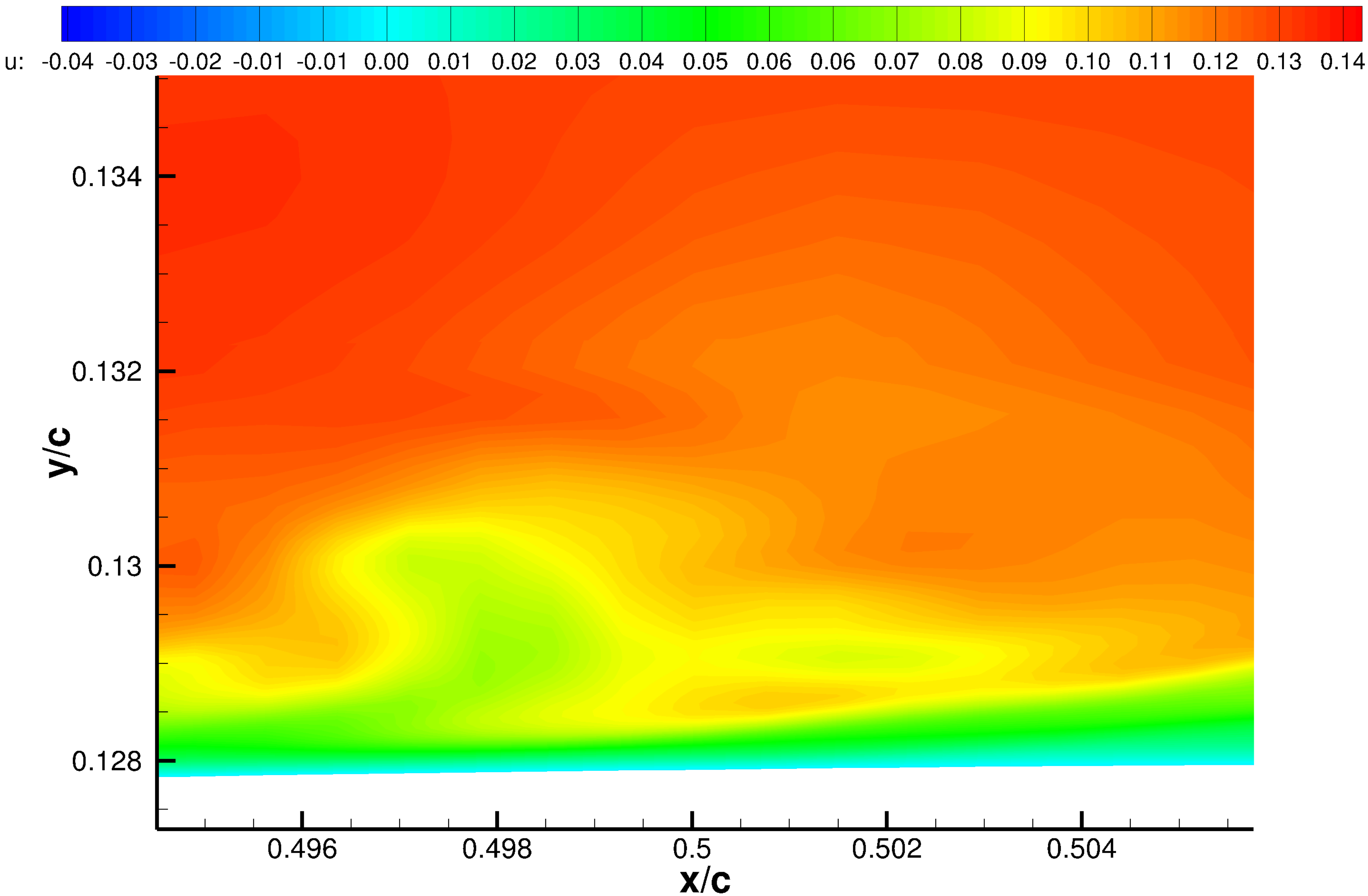
Simulation Run Time

- **Using 7200 "dedicated" Intel Ivy Bridge cores on NAS Pleiades, the simulation would take about 7.5 days to compute $20c/u_\infty$**
- **Note that we have a compressible flow solver and the Mach number is 0.1**
- **If the Mach number was 0.3, the simulation would take $7.5/3 = 2.5$ days**
- **Because of heavy load on NAS, the simulation is performed as multiple consecutive runs using fewer core counts**

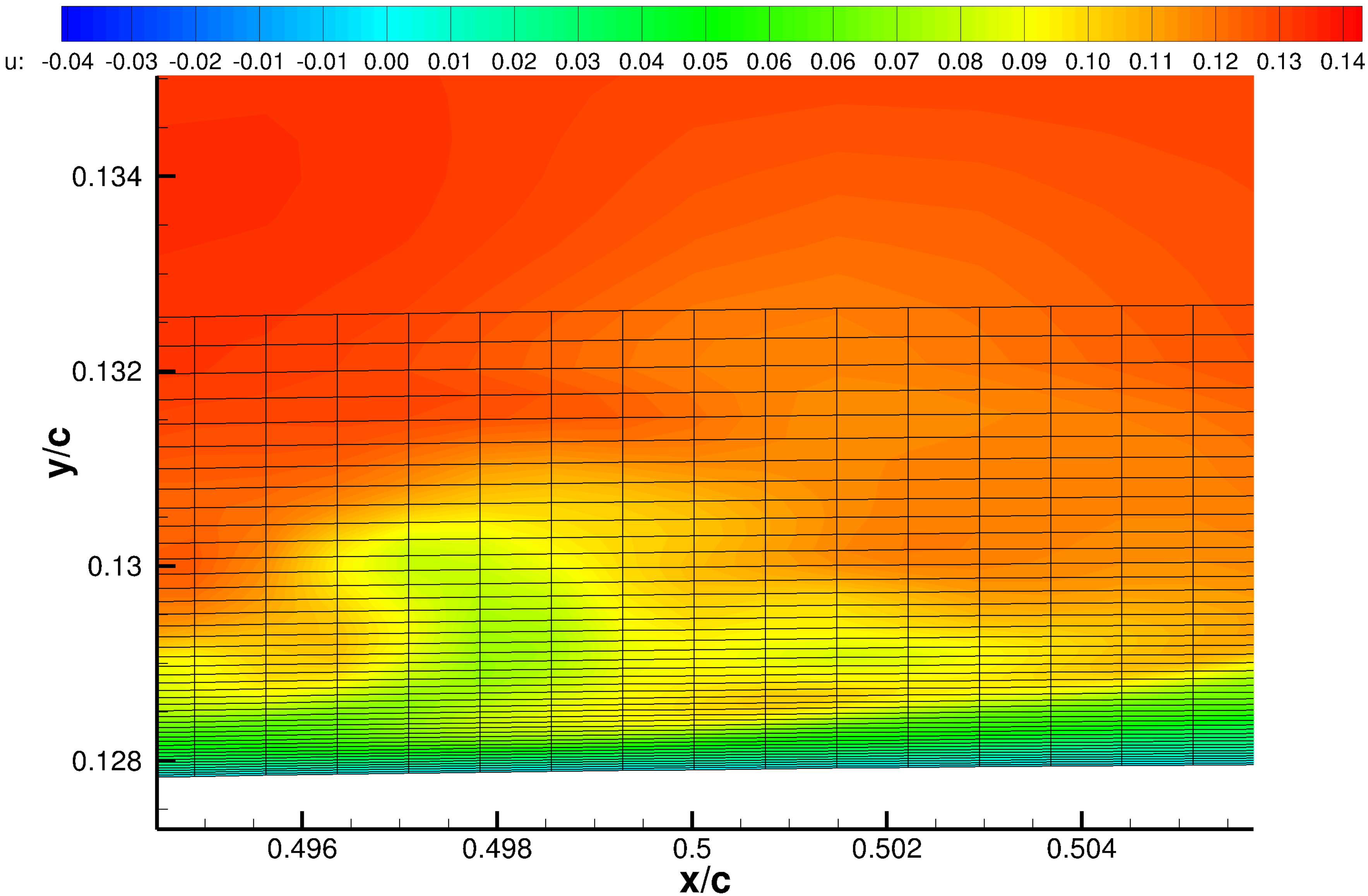
Thinning of Boundary Layer Over Hump



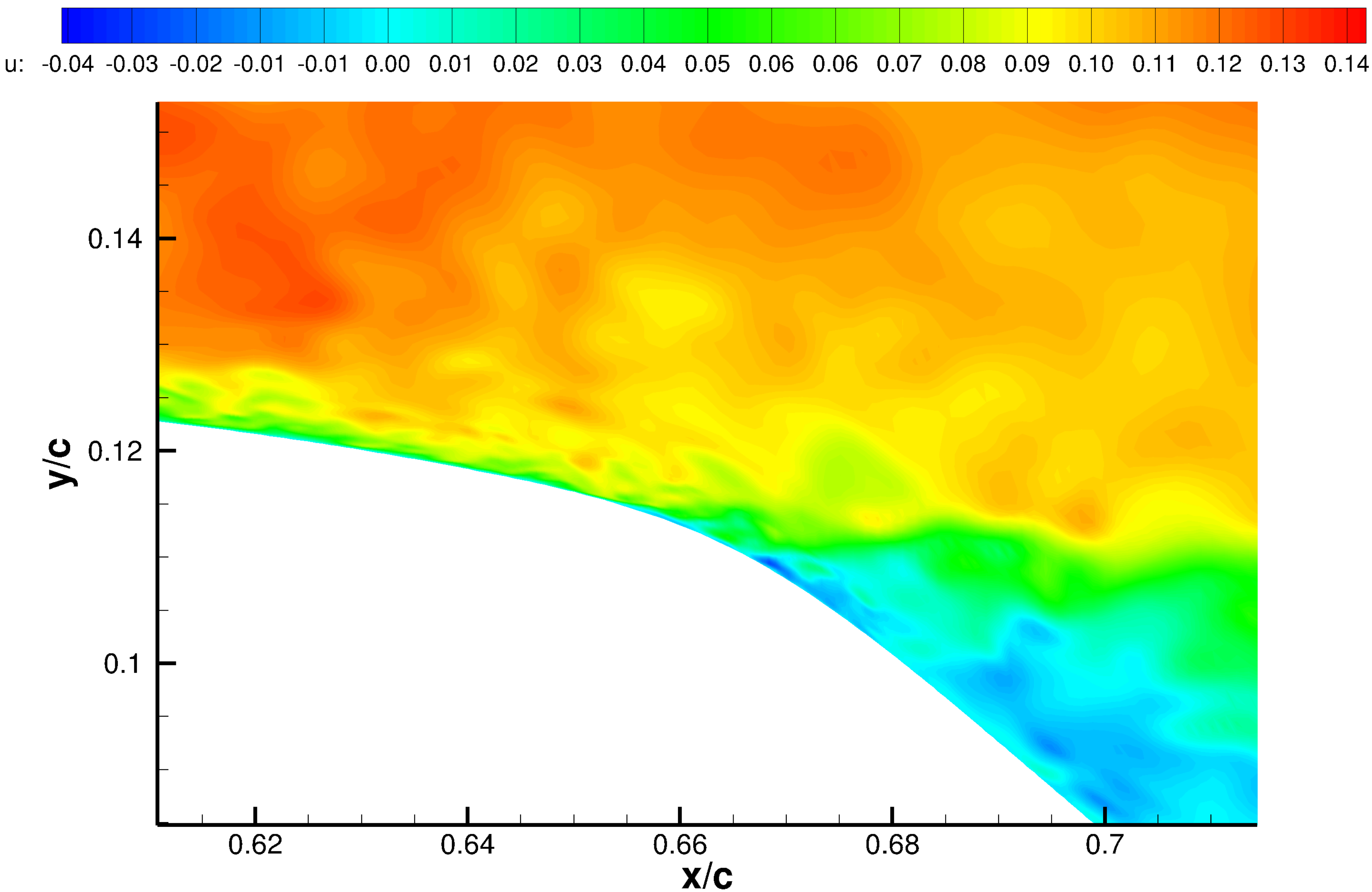
Thin Boundary Layer at around $x/c = 0.5$



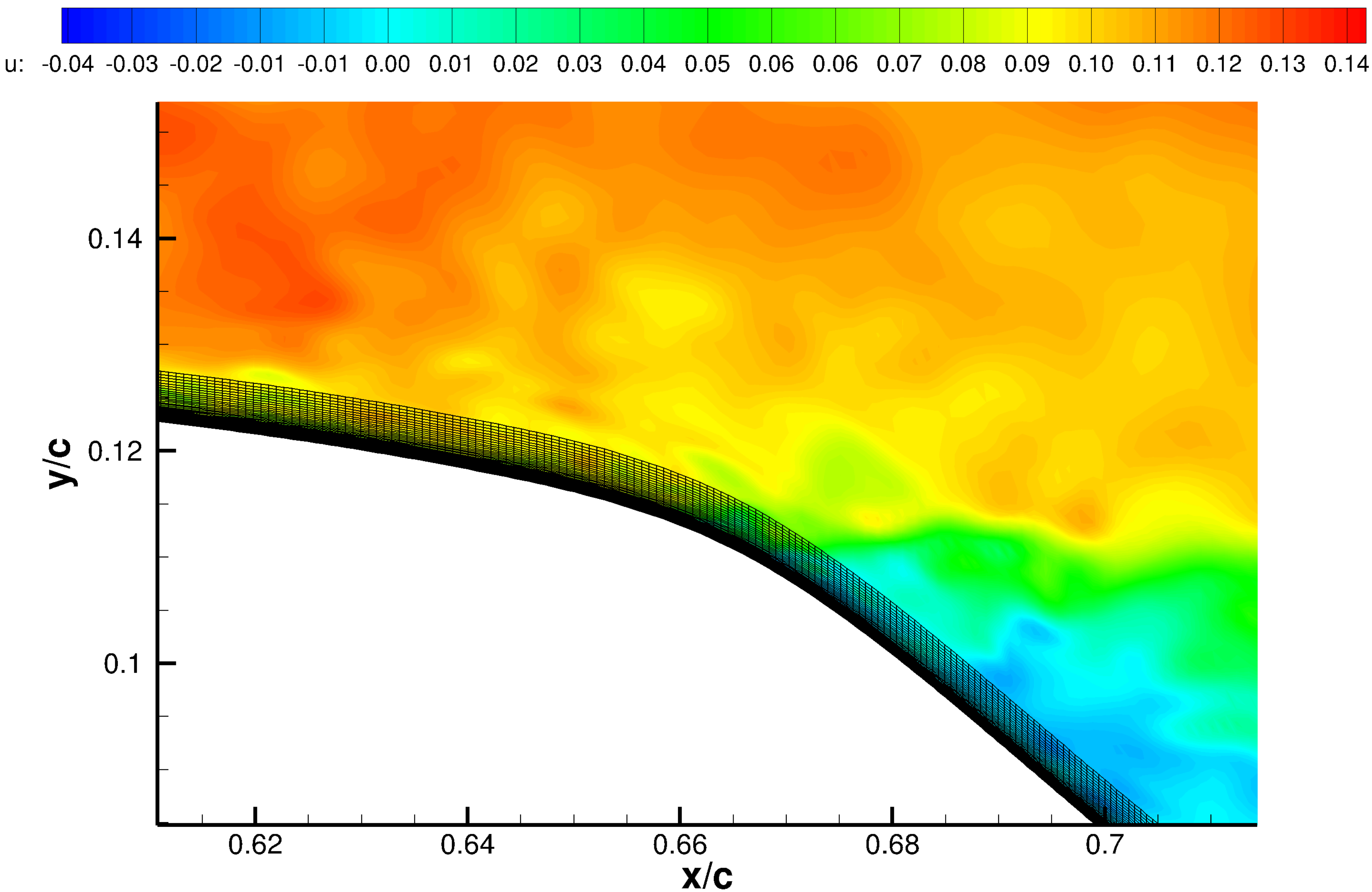
Near-Wall Grid at around $x/c = 0.5$



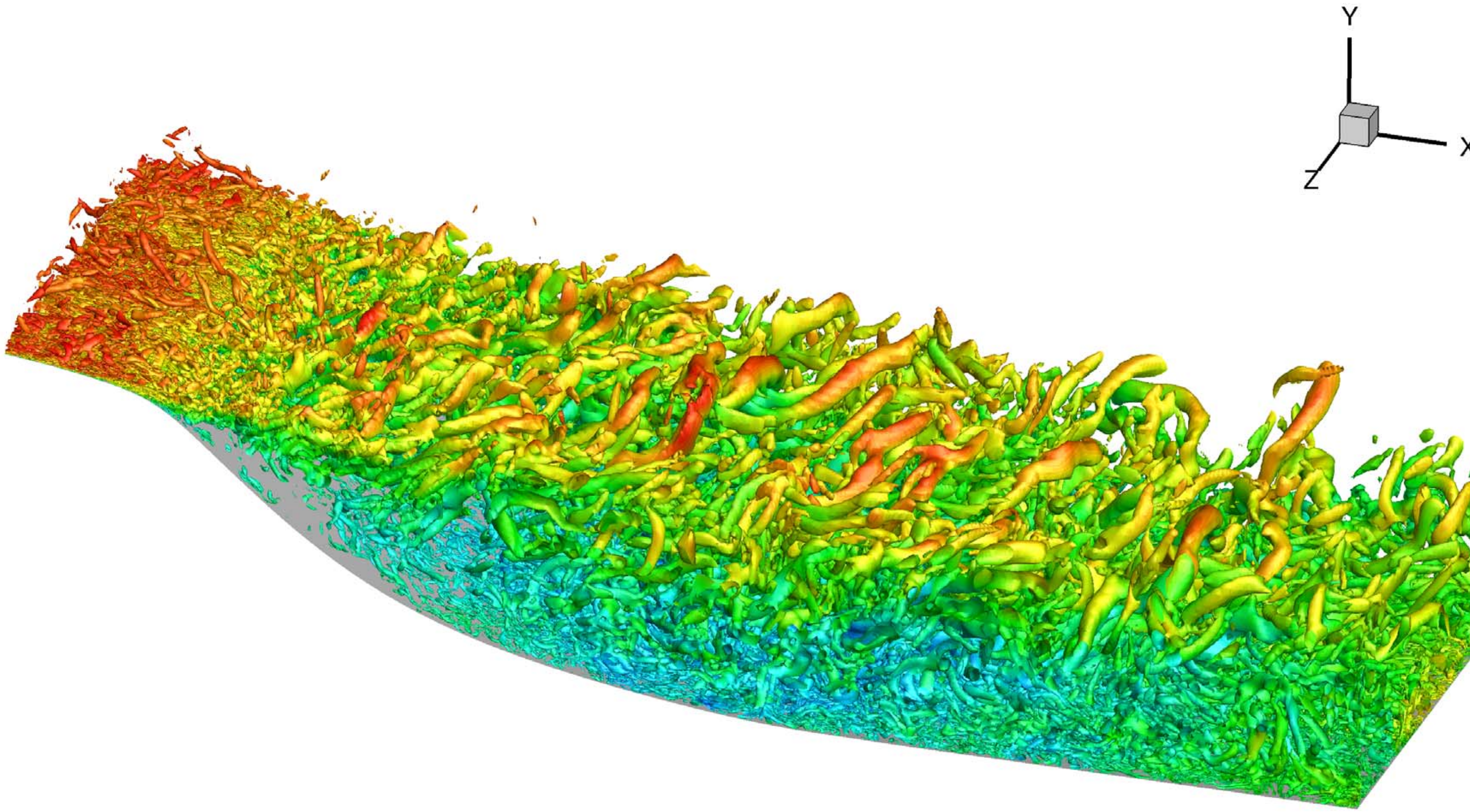
Boundary Layer Separation on Hump



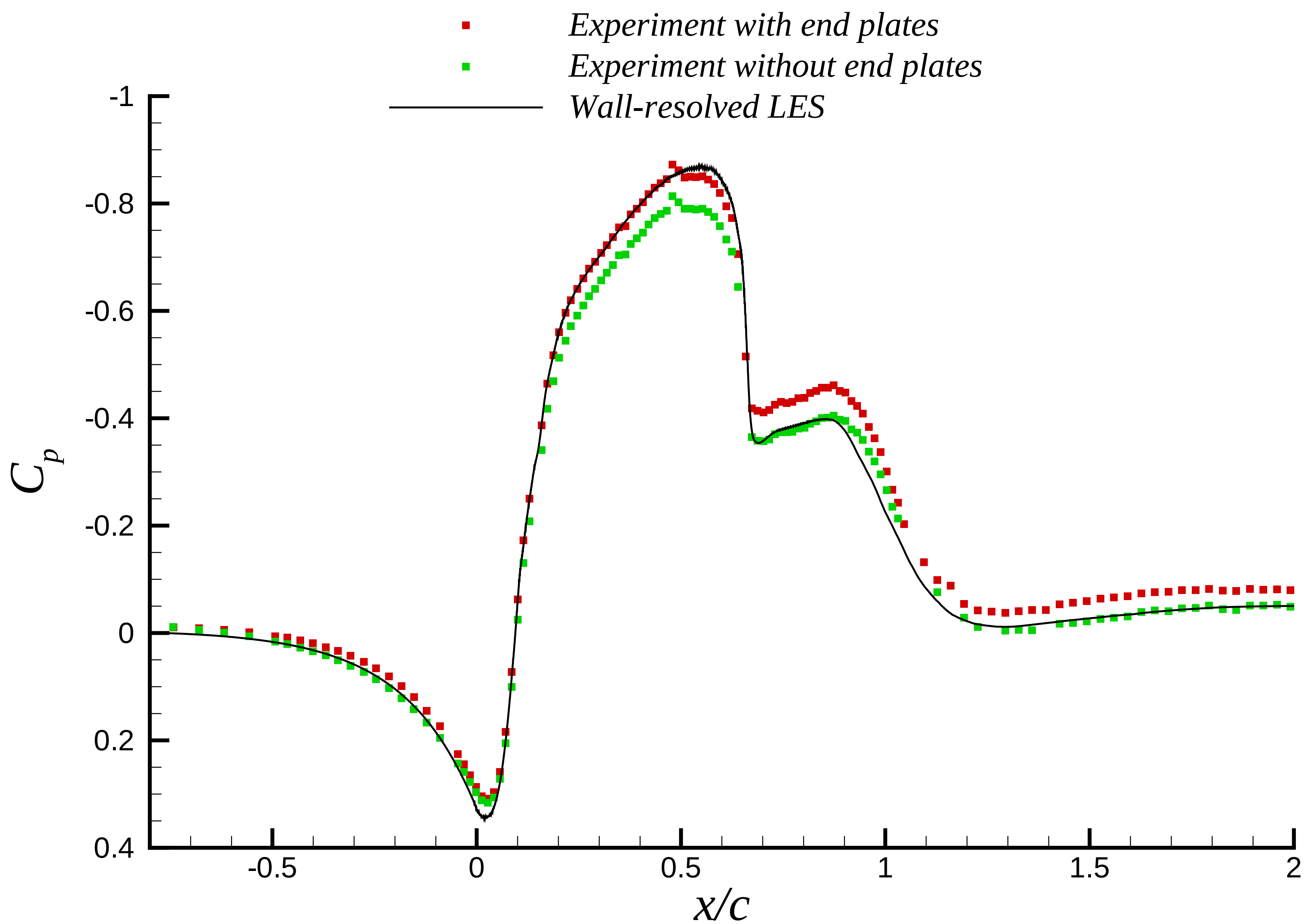
Near-Wall Grid in Separated Region



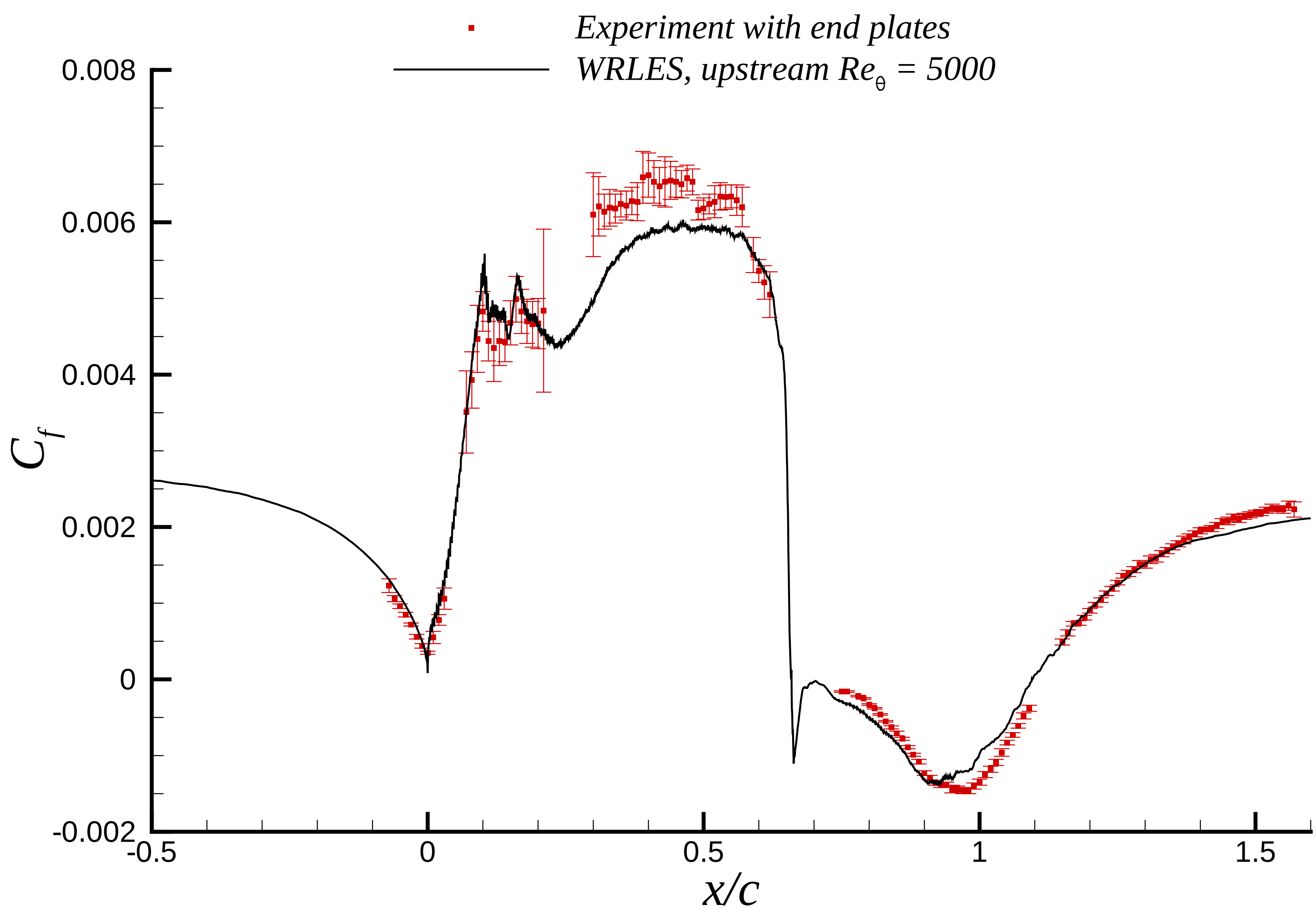
Complex Structure of Separated Flow



Pressure Coefficient Distribution



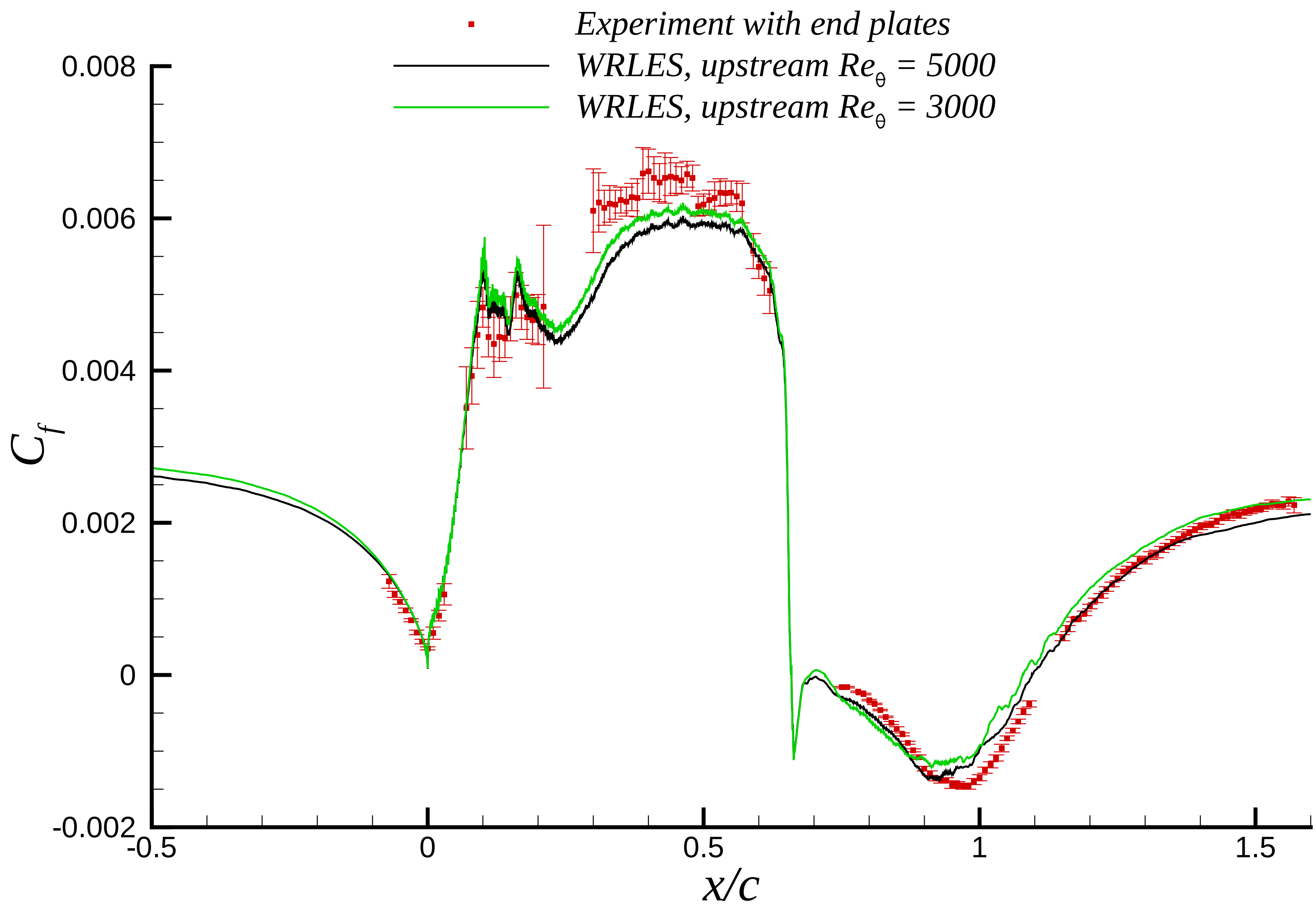
Skin Friction Coefficient Distribution



Observations from C_f Plot

- **Reasonable agreement with experiment**
- **The peak C_f region in the LES seems a bit under-predicted relative to the experiment**
- **Differences may possibly arise from:**
  - **Uncertainty in upstream conditions**
  - **End-plate effects which cannot be captured in a spanwise-periodic calculation**
- **To see the effect of the upstream Re_θ on the peak C_f region and separated flow, LES was repeated with an upstream $Re_\theta \approx 3000$**
- **The upstream Re_θ is lowered to 3000 in order to increase the upstream skin friction**
- **Same grid and time step as before**
- **Gathered time-averaged data over $10c/u_\infty$**

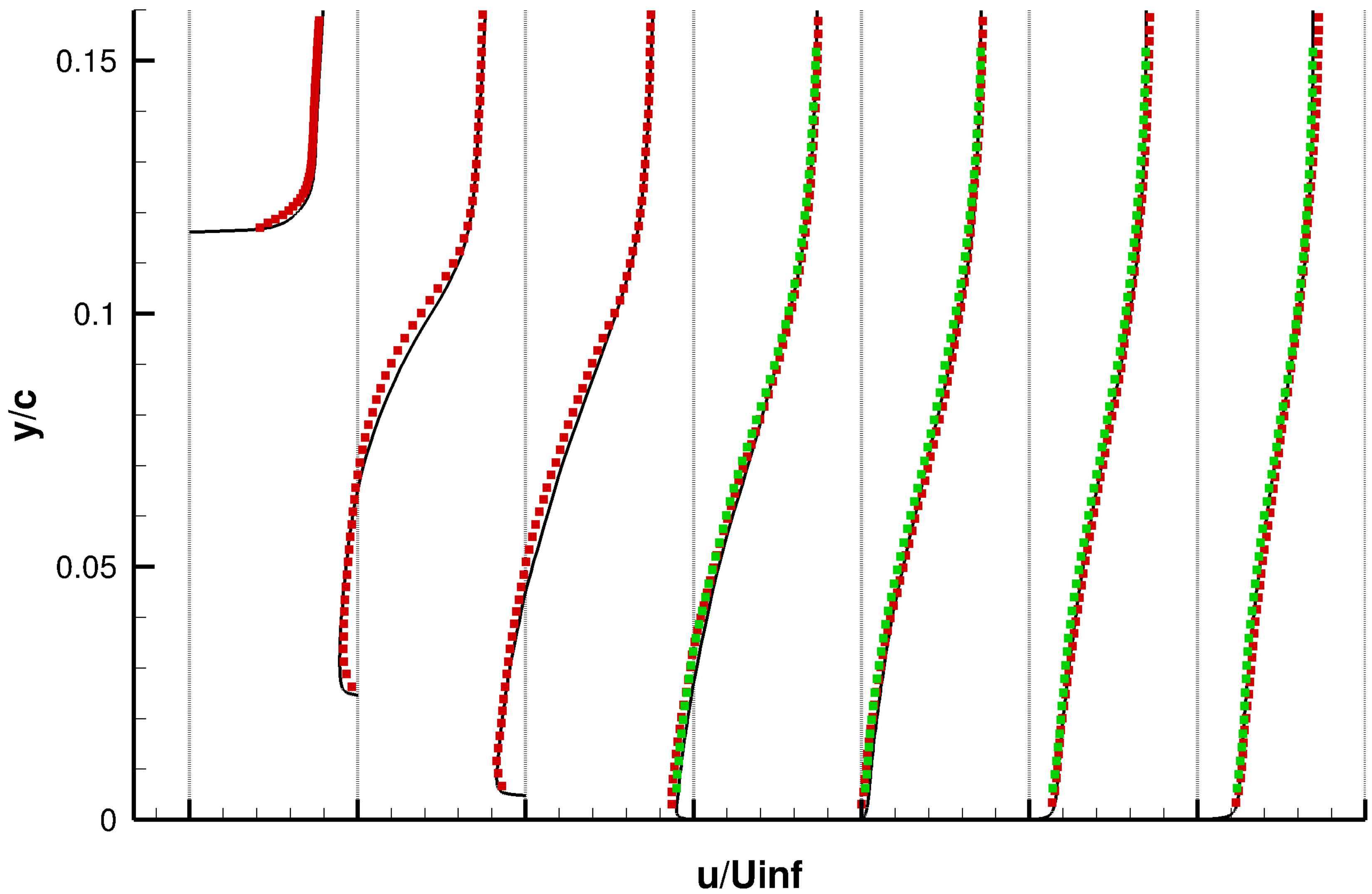
Effect of Upstream Re_θ on C_f



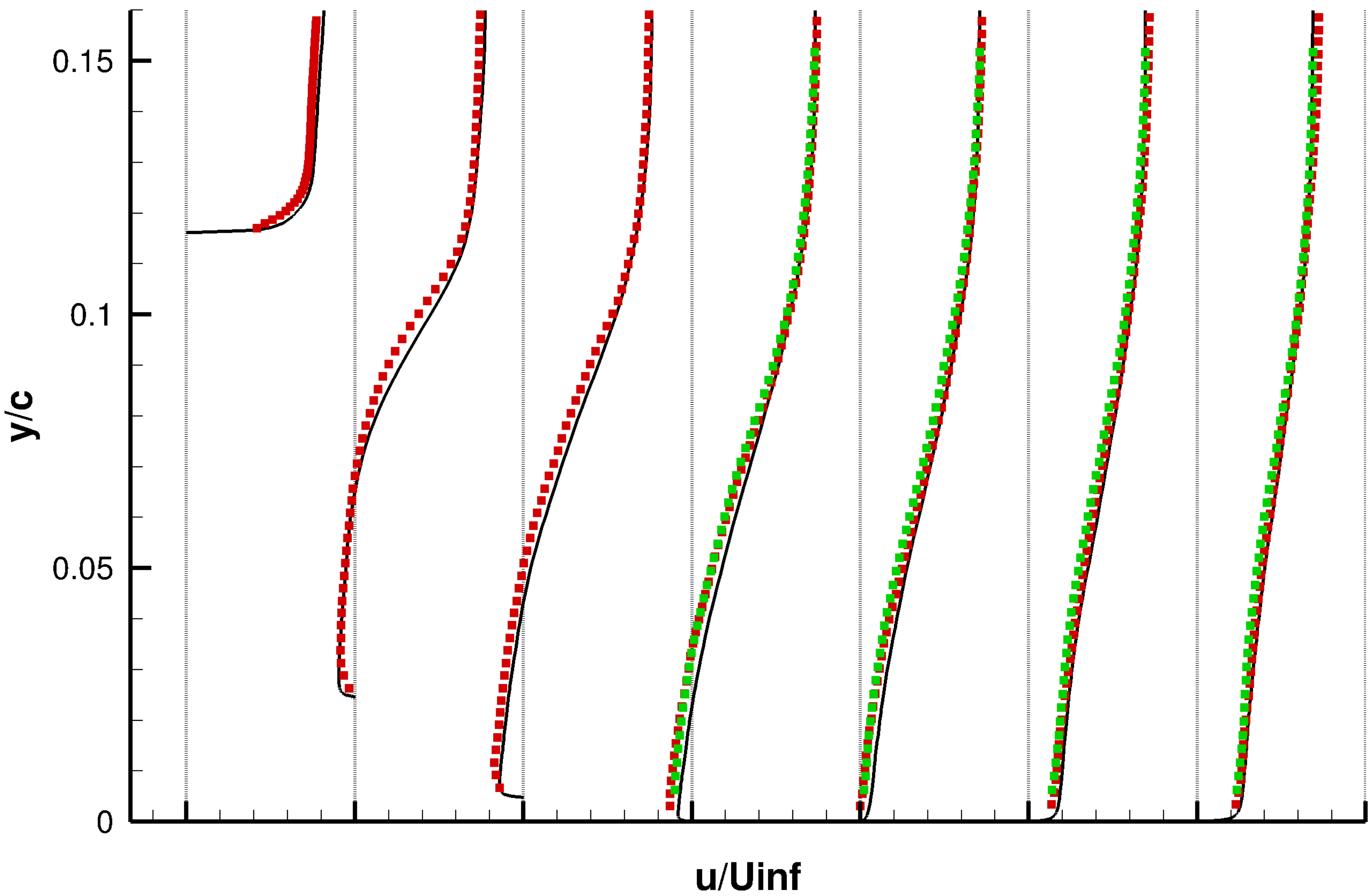
Flow Separation and Reattachment

- **With $Re_\theta = 3000$, the peak C_f region moves closer to the experiment, but there is greater discrepancy in the separated region**
- **In the experiment:**
  - **Flow separates at $x/c \approx 0.665$**
  - **Flow reattaches at $x/c \approx 1.110$**
- **In the LES:**
  - **Both Re_θ cases separate at $x/c \approx 0.659$**
  - **For $Re_\theta = 5000$, flow reattaches at $x/c \approx 1.095$**
  - **For $Re_\theta = 3000$, flow reattaches at $x/c \approx 1.078$**
- **Next slides provide mean velocity and Reynolds stress profiles at $x/c = 0.65, 0.8, 0.9, 1, 1.1, 1.2, 1.3$**

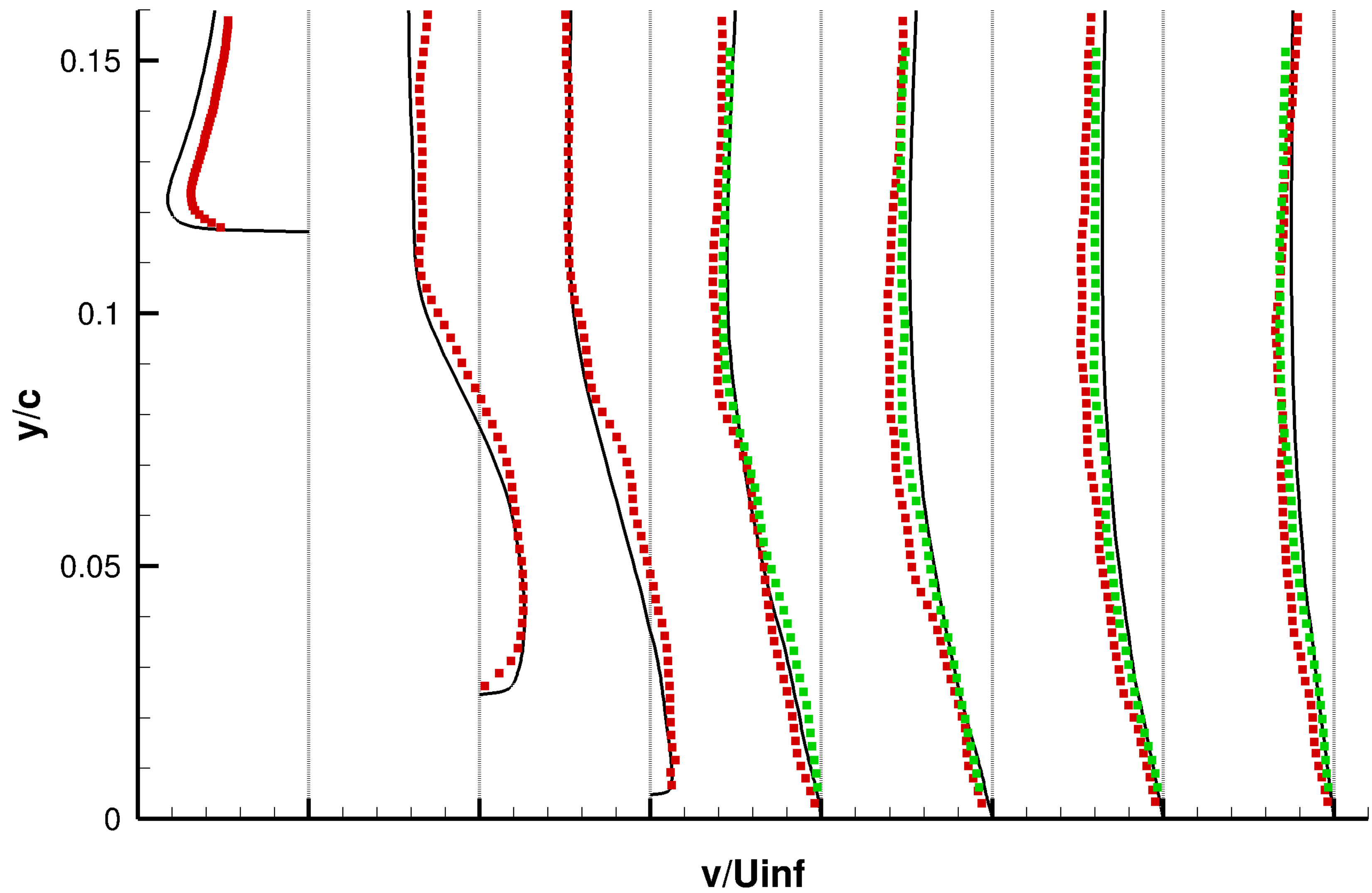
Streamwise Velocity with $Re_\theta = 5000$



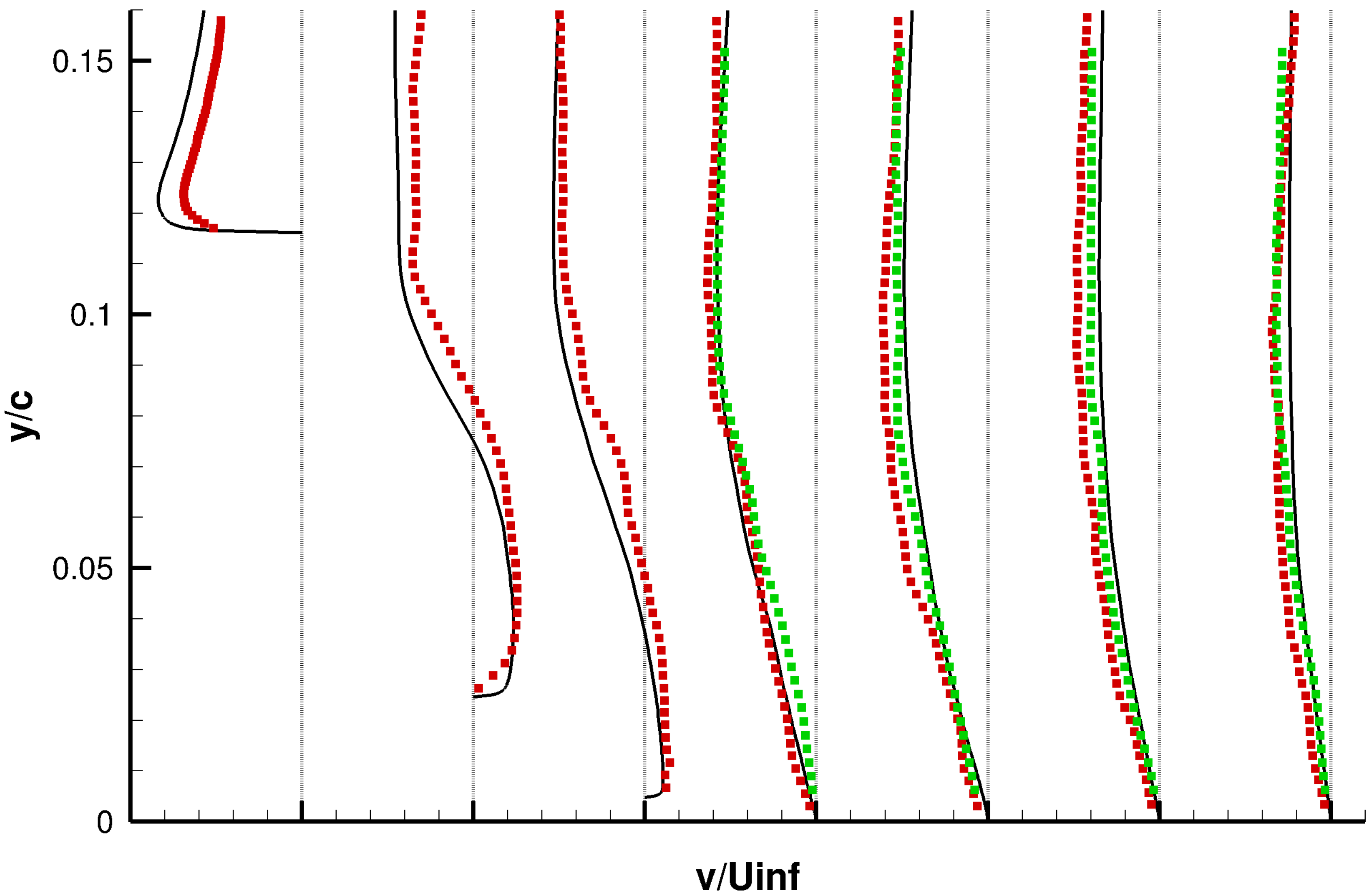
Streamwise Velocity with $Re_\theta = 3000$



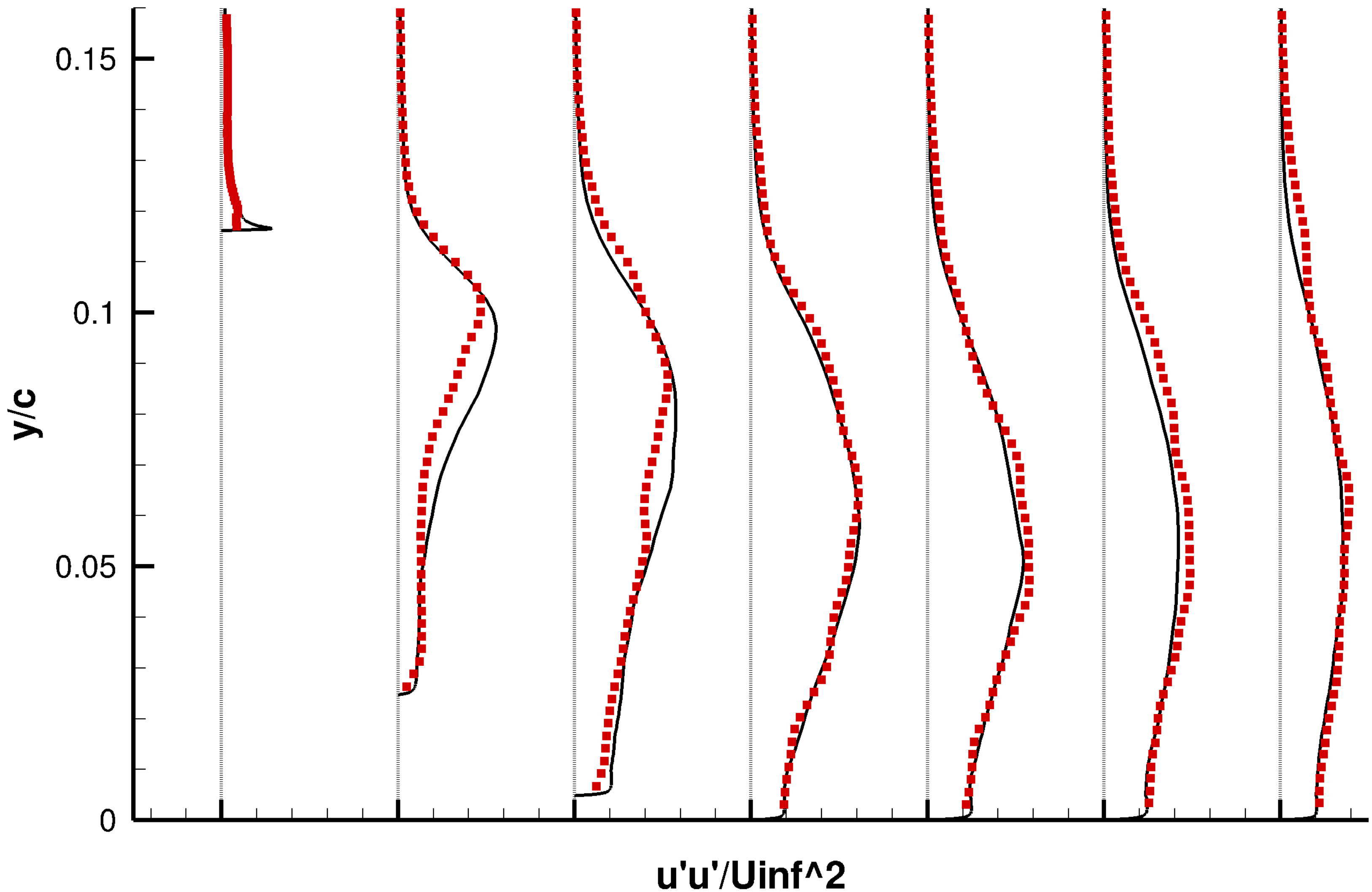
Vertical Velocity with $Re_\theta = 5000$



Vertical Velocity with $Re_\theta = 3000$



Reynolds Stress $\overline{u'u'}$ with $Re_\theta = 5000$



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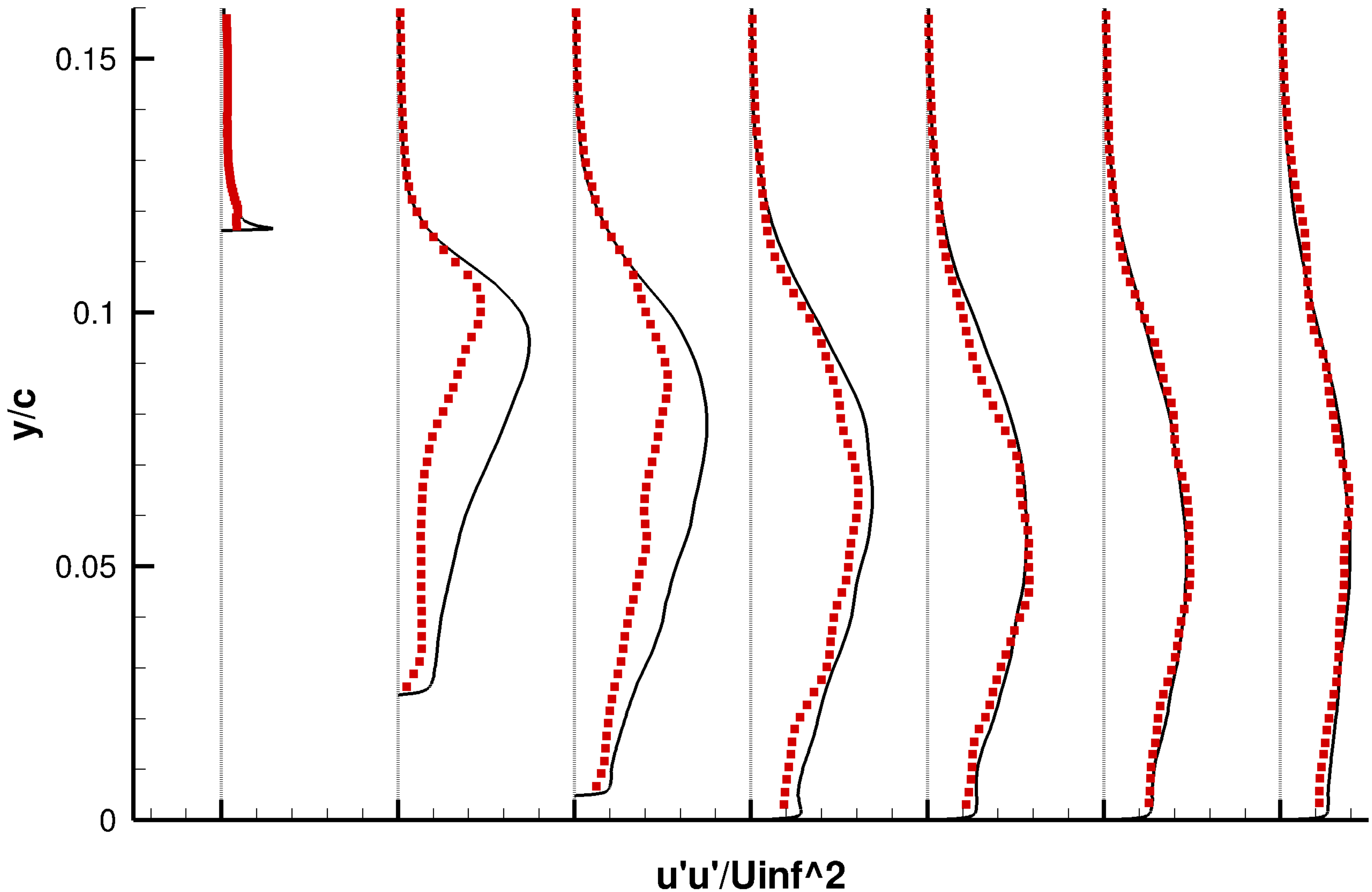
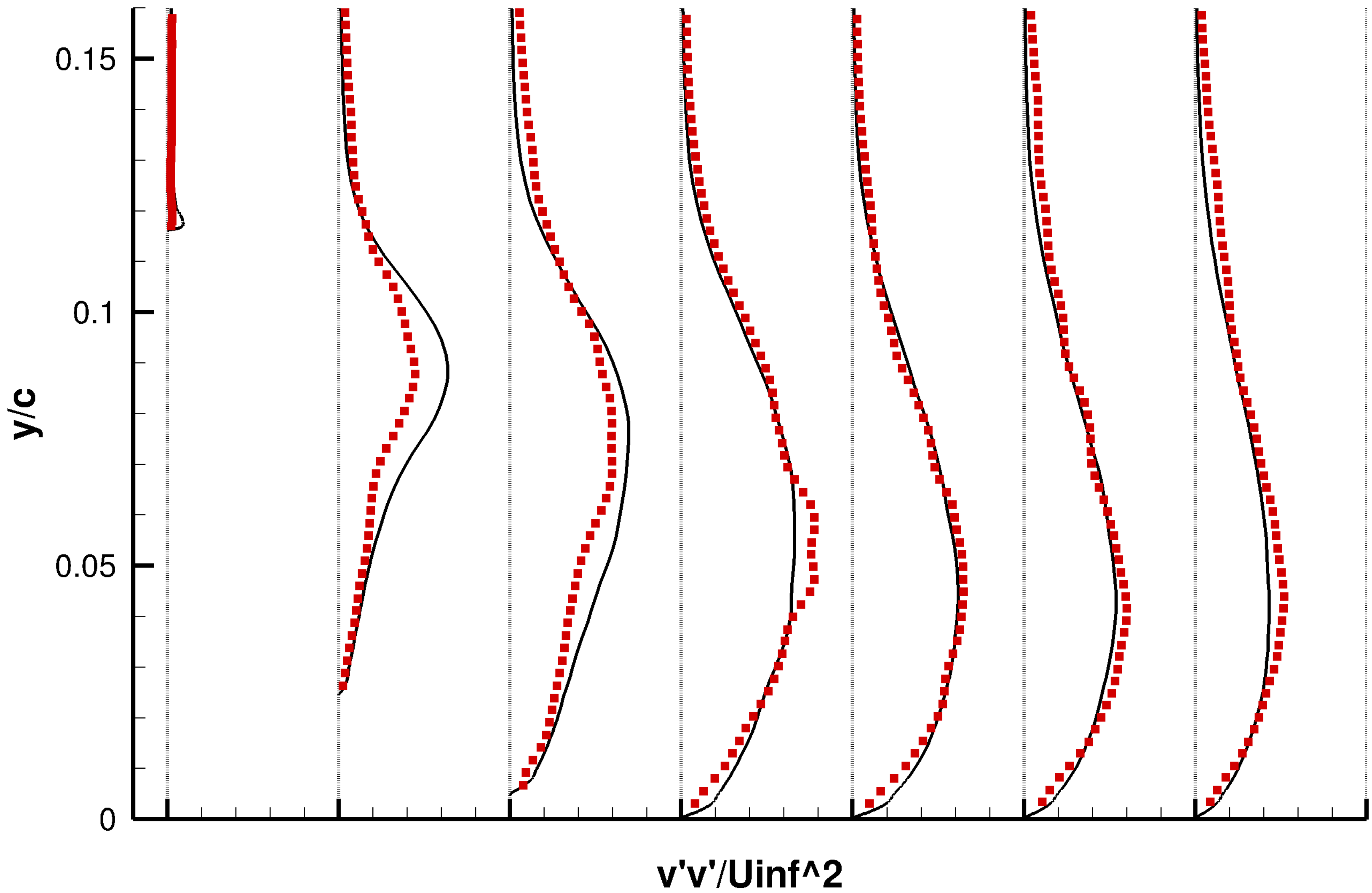
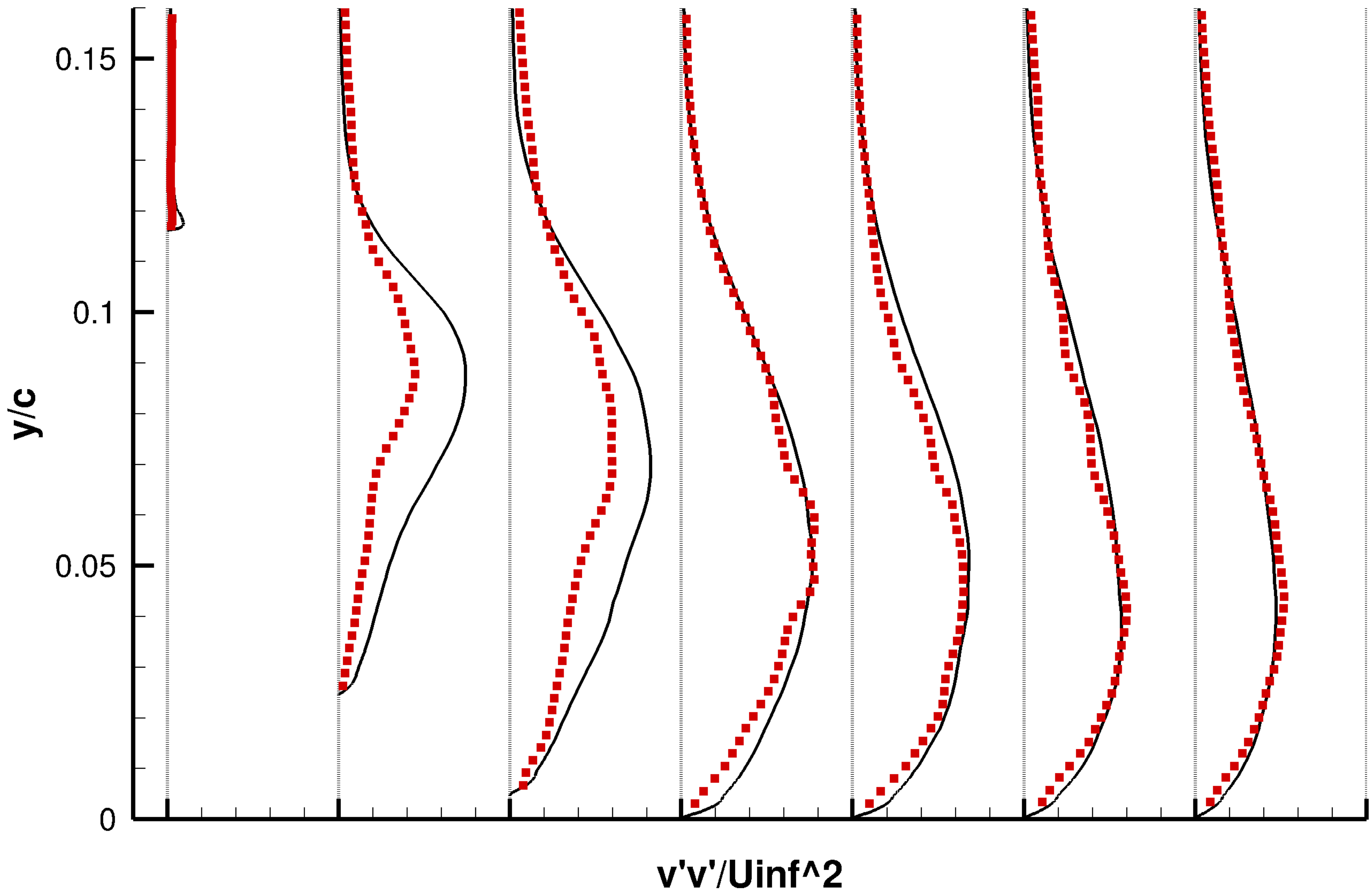


Reynolds Stress $\overline{v'v'}$ with $Re_\theta = 5000$



Reynolds Stress $\overline{v'v'}$ with $Re_\theta = 3000$



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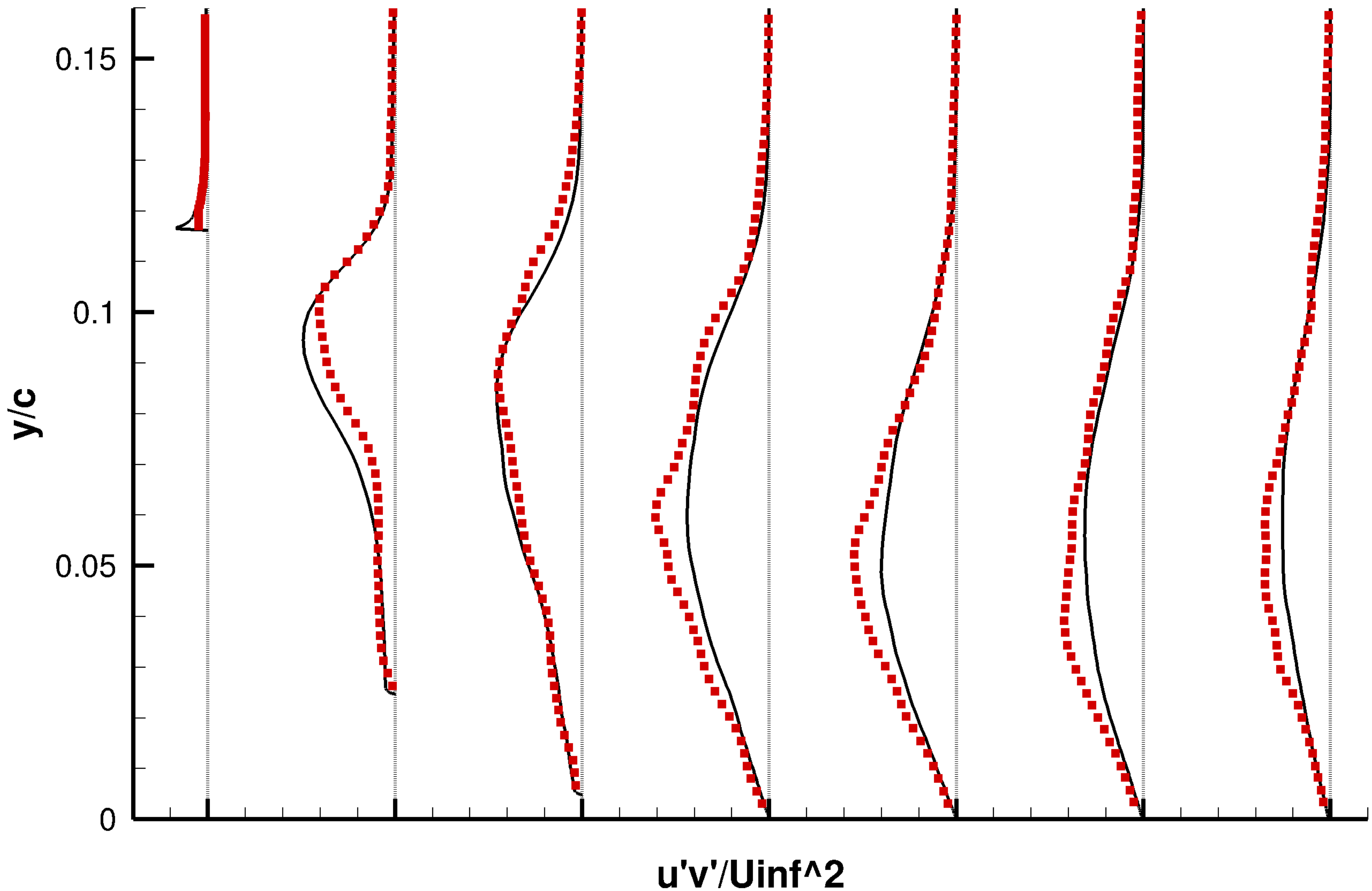
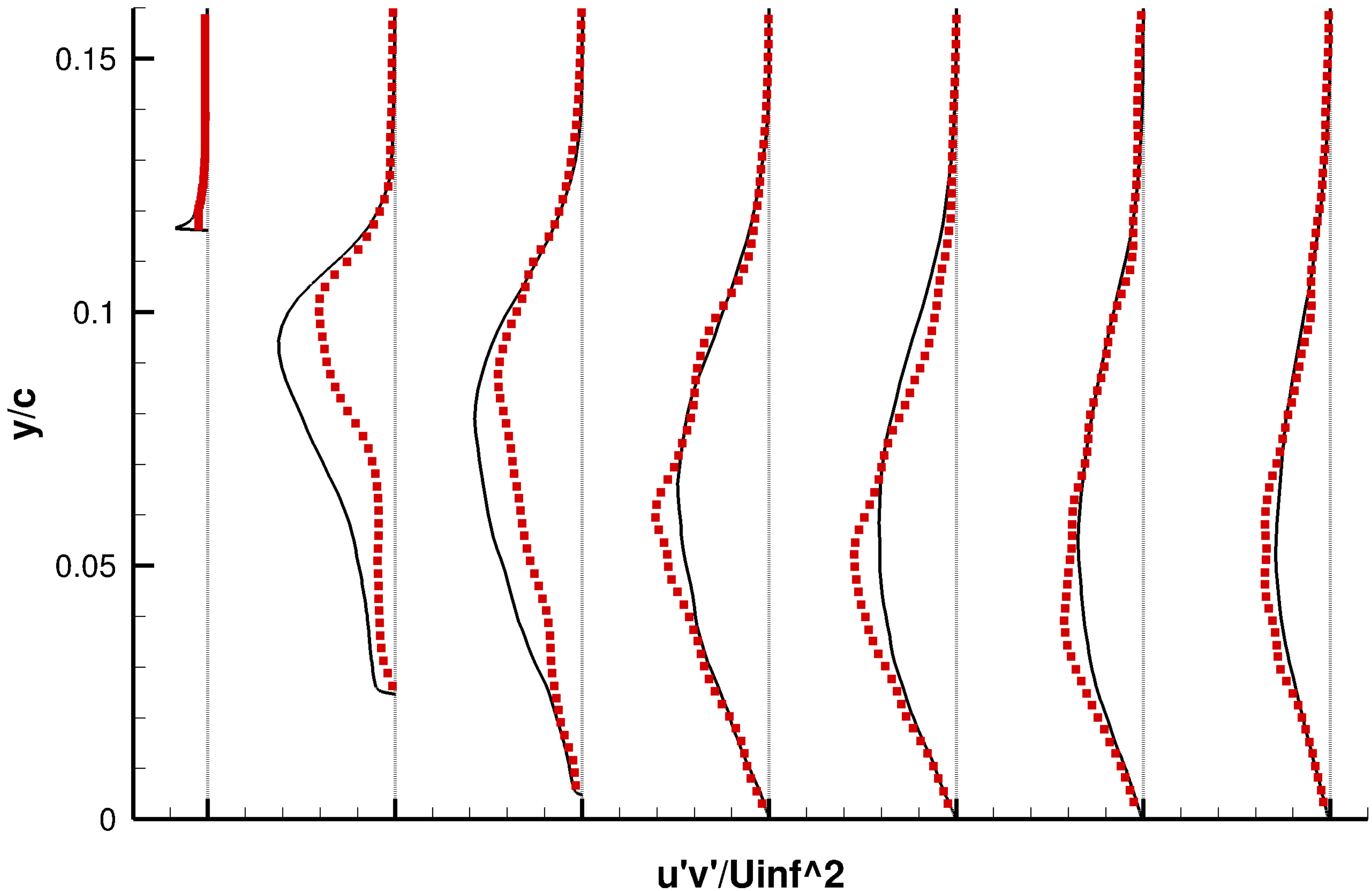


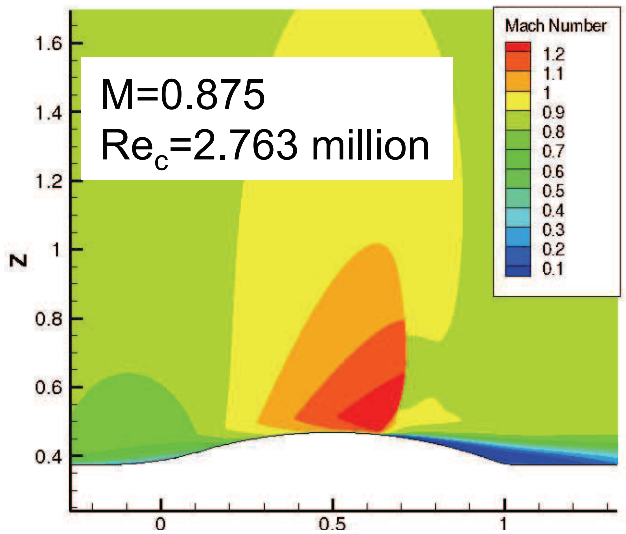
Reynolds Stress $\overline{u'v'}$ with $Re_\theta = 3000$

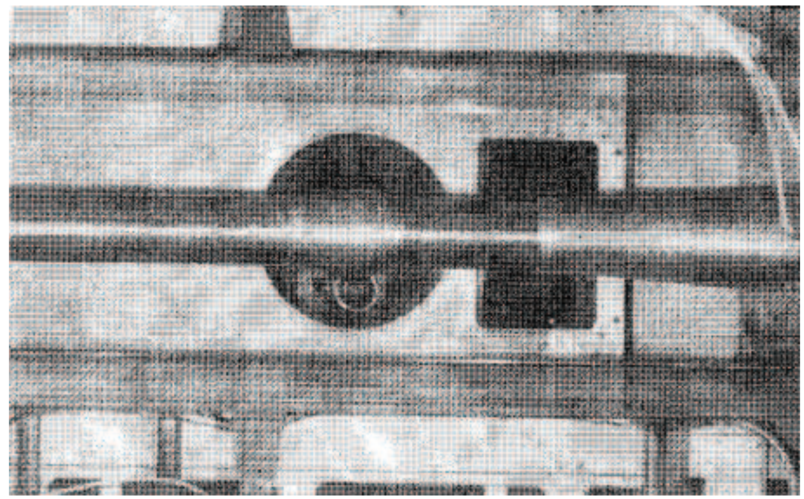


Observations and Ongoing Work

- **Upstream boundary layer has some effect on the separated flow and reattachment point**
- **Good overall agreement between the LES with** $Re_\theta = 5000$ **and experiment**
- **We are re-running the LES with upstream** $Re_\theta \approx 7000$
- **We plan to perform more detailed analysis of LES data**
- **We are exploring the use of GPUs to accelerate the computations**

Next Problem: Transonic Shock-Induced Flow Separation on Axisymmetric Bump





- **Very common problem in transonic flight**
- **We estimate 2 billion grid points for LES of the NASA experiment by Bachalo and Johnson**
- **Need $40,000$ cores for 12 days of run time**
- **Hope to access DOE computers for this work**