Wall Modeled Lattice Boltzmann and Navier-Stokes Approaches for Selected RCA Cases

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AIAA SciTech Forum, Gaylord Palms, Kissimmee Florida
8-12 January, 2018

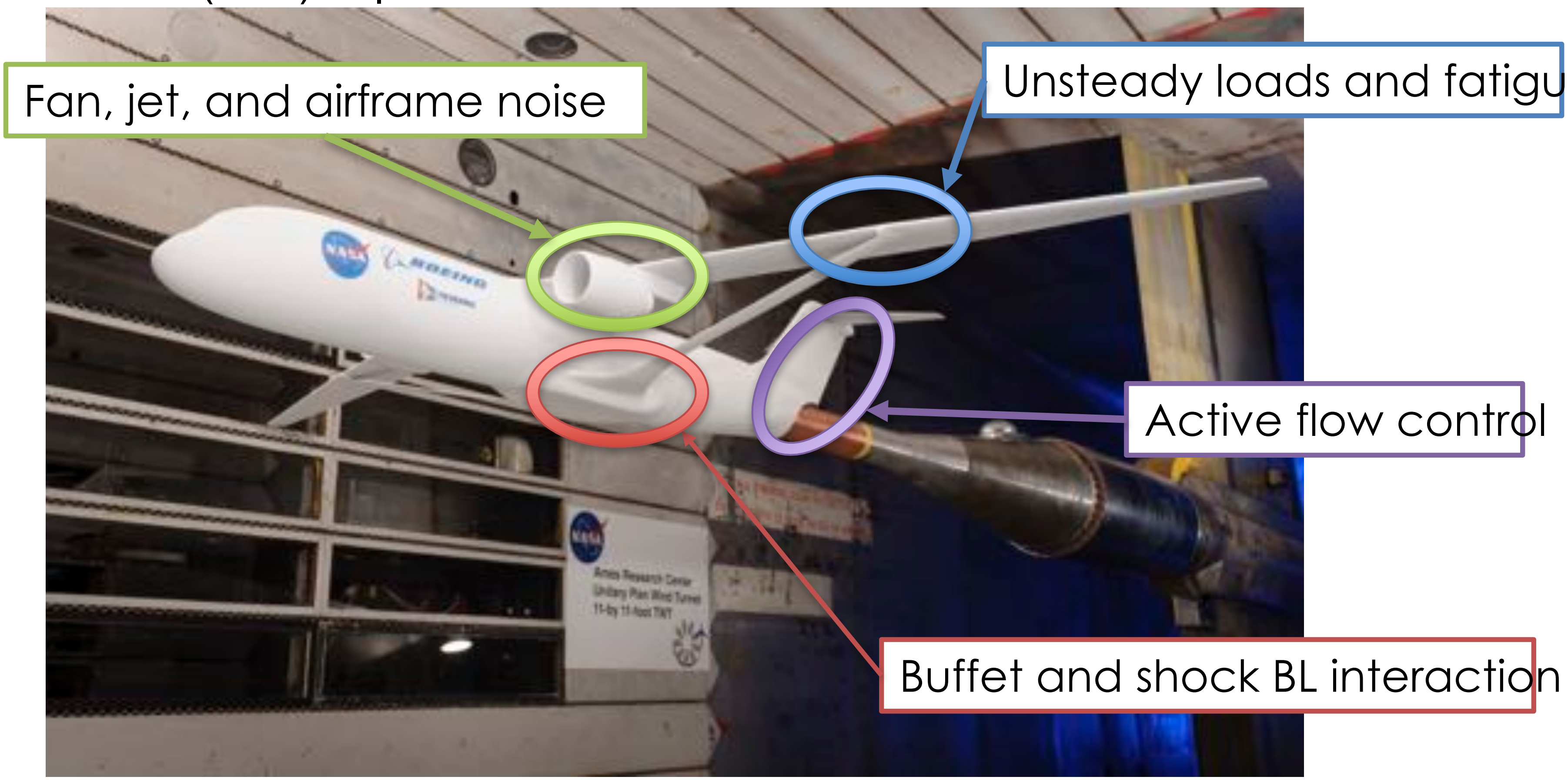
Outline

- ✓ **Motivation**
- ✓ **Computational Methodology and Framework**
  - Structured Overset Curvilinear
    - Hybrid RANS/LES; DDES, ZDES Mode 3
  - Cartesian Lattice Boltzmann Method (LBM)
- ✓ **NASA RCA separated flow case**
  - 2-D NASA Hump
    - RANS
    - Detached Delayed Eddy Simulation
    - Zonal DES Mode 3
    - Lattice Boltzmann Method
- ✓ **Summary and Future Work**

Motivation

✓ **Increase predictive use of computational aerosciences capabilities for next generation aviation and space vehicle concepts.**

- The next frontier is to use wall modeled and/or wall resolved large-eddy simulation (LES) to predict:



Motivation

- ✓ **NASA's CFD Vision 2030 Study[✝].**
  - Report from Important Industry and Academic Partners (Boeing, Lockheed, Stanford, MIT,..) on the future of CFD.
- ✓ **Revolutionary Computational Aerosciences (RCA) Technical Challenge[*].**
  - Identify and down-select critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware.
- ✓ **Hybrid RANS-LES and wall-modeled LES most promising**
- ✓ **Contribution of the Lattice Boltzmann Method**

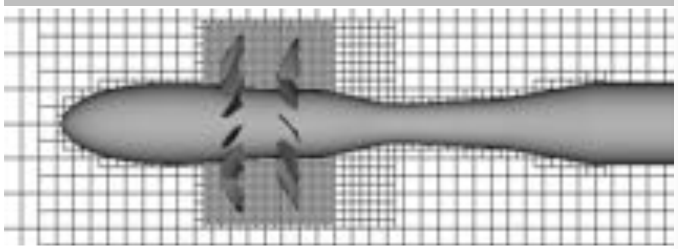
✝NASA/CR-2014-218178

* https://turbmodels.larc.nasa.gov/StandardTestCasesFinal6.pdf

Computational Grid Paradigms

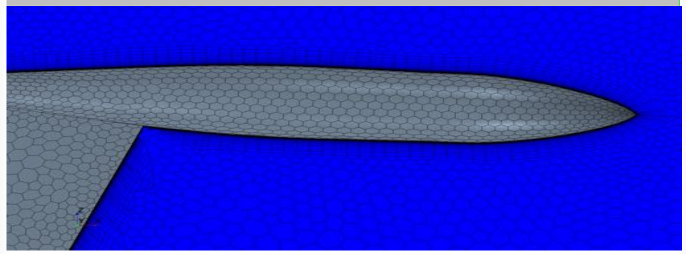
Not ALL Grid Paradigms are Ideal for EACH Problem!

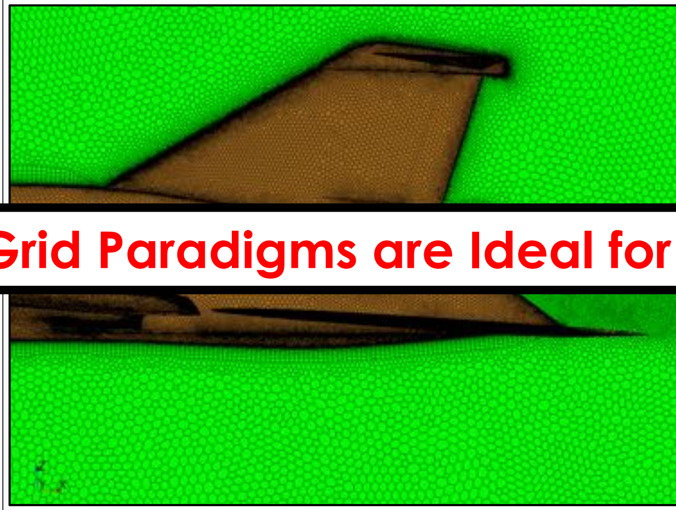
Structured Cartesian AMR



- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

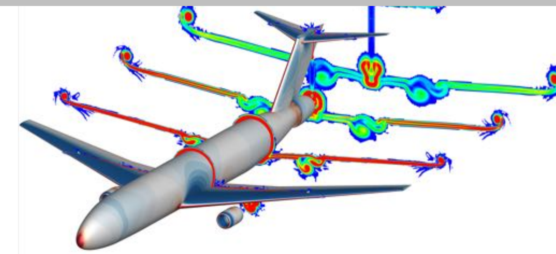
Unstructured Arbitrary Polyhedral

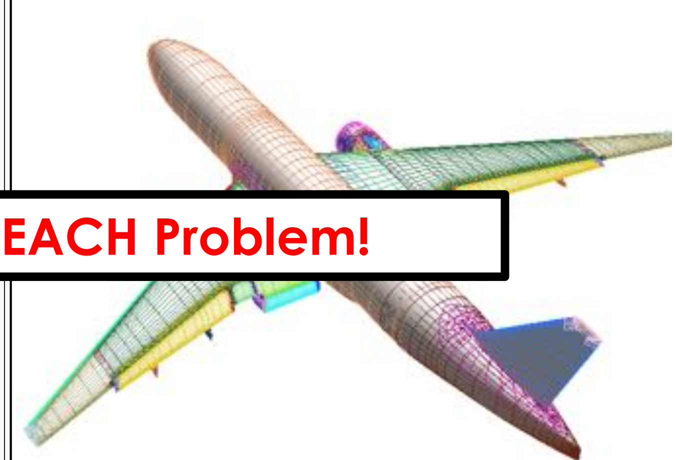




- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

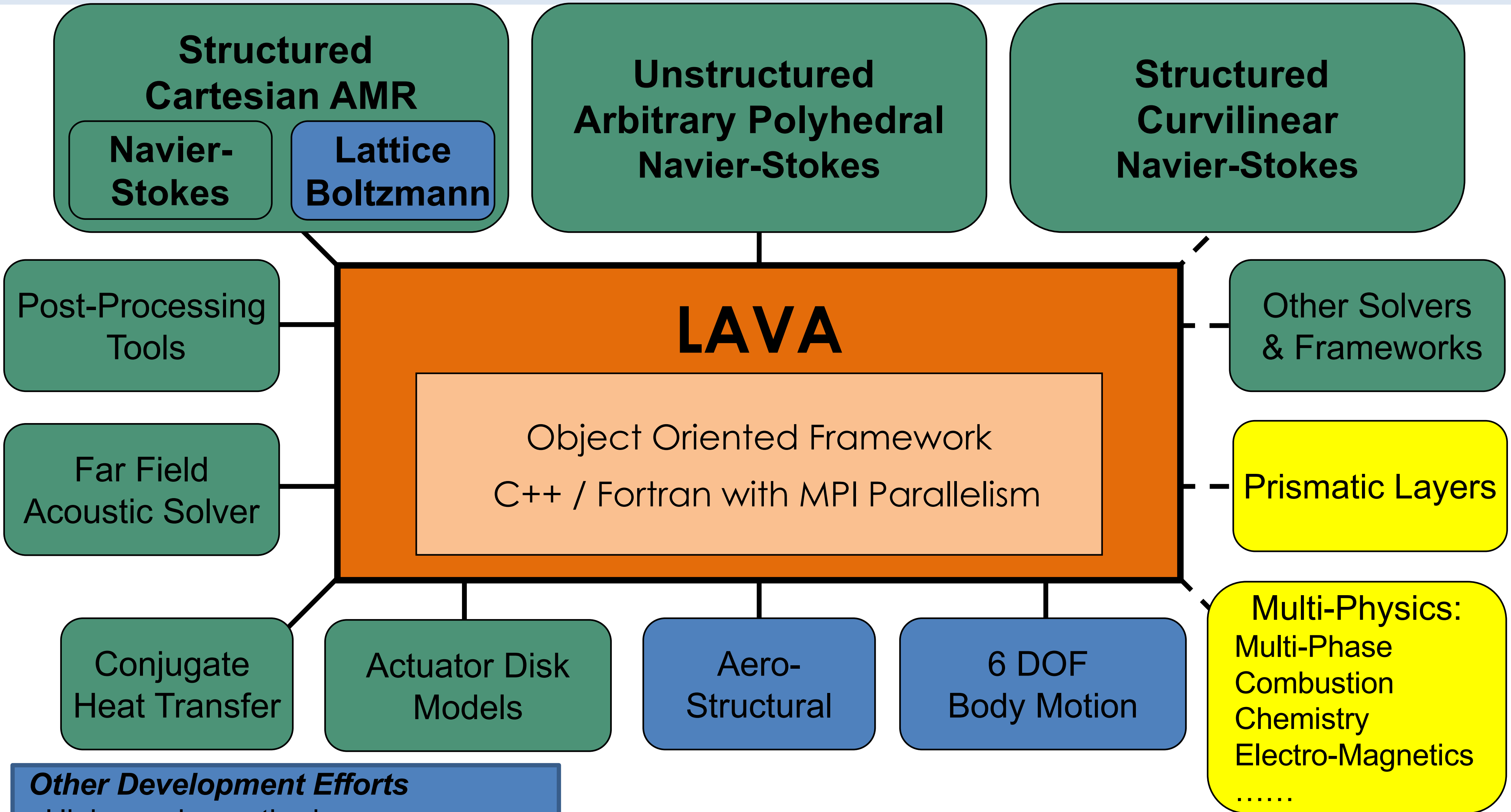
Structured Curvilinear



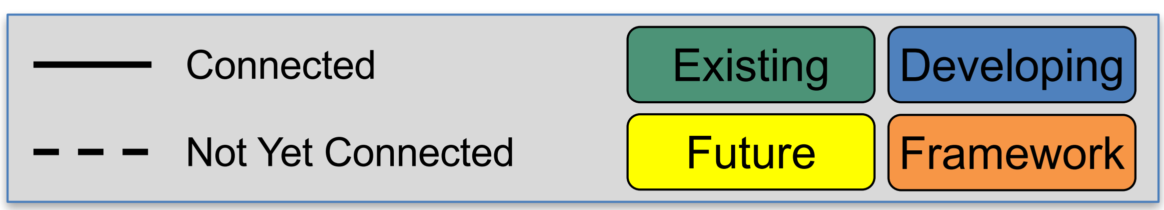


- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



Other Development Efforts
- Higher order methods
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)



Kiris at al. AST-2016 and AIAA-2014-0070

Computational Methodology: Structured Curvilinear Overset

3-D Structured Curvilinear Overset Grid Solver

- ✓ Spalart-Allmaras turbulence model (baseline turbulence model)

Low-Dissipation Finite Difference Method *(Housman et al. AIAA-2016-2963)*

- ✓ 4th-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS)
- ✓ Numerical flux is a modified Roe scheme
- ✓ $4^{th}/3^{rd}$-order blended central/upwind biased left and right state interpolation
- ✓ 2^{nd}-order accurate differencing used for time and viscous flux discretization

Hybrid RANS/LES Models

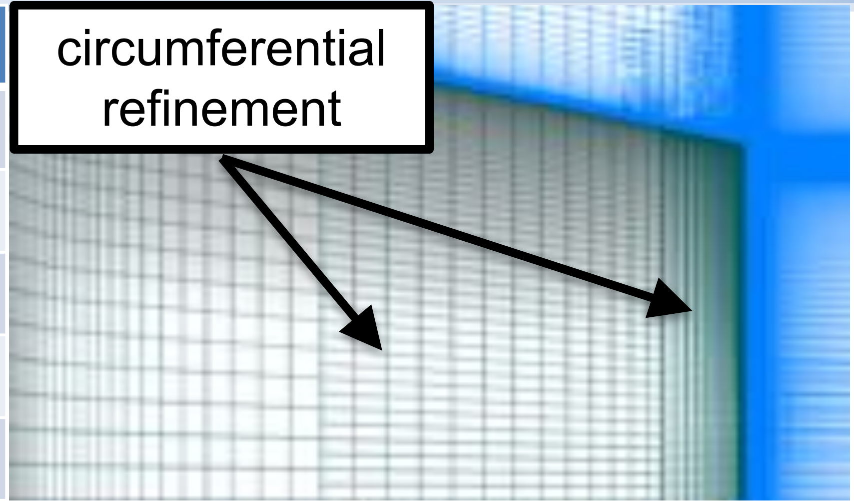
- ✓ Delayed Detached Eddy Simulation (DDES) model with modified length scale *(Chauvet at al. AIAA J. 2007, Shur et al. 2015, Housman et al. AIAA-2017-0640)*
- ✓ Zonal Detached Eddy Simulation (ZDES-Mode3) with user selected RANS, LES, and Hybrid RANS LES zones. *(Deck, S. Theor. Comput. Fluid Dyn. 2012)*

Synthetic Eddy Method

- ✓ *Coupling Methodology between RANS and LES to introduce realistic turbulent eddies* *(Jarrin et al. Int. Journal of Heat and Fluid Flow 30)*

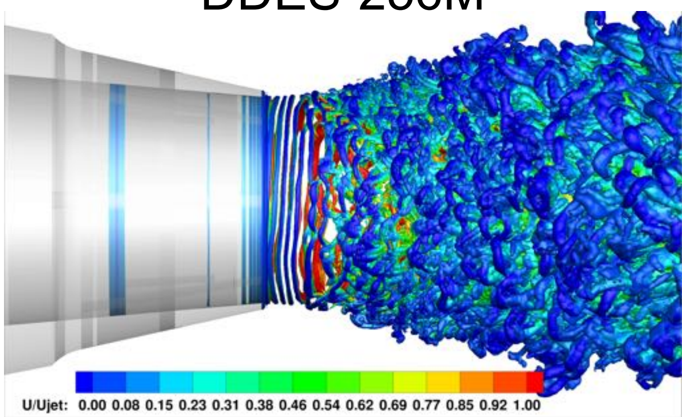
Recent LAVA Overset Structured Curvilinear Success: Round Jet SP 7 – RCA Propulsion Test Case

Bridges et. al.	Set Point 7
U_{jet}/c_∞	0.9
T_e/T_∞	0.835
p_t/p_∞	1.861
D	0.0508 m
Re_D	1 Million

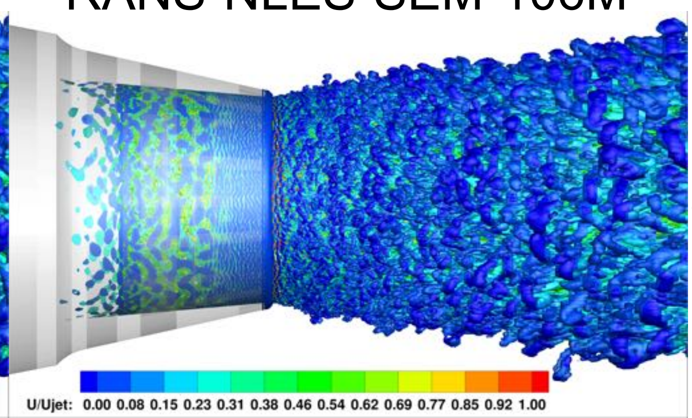


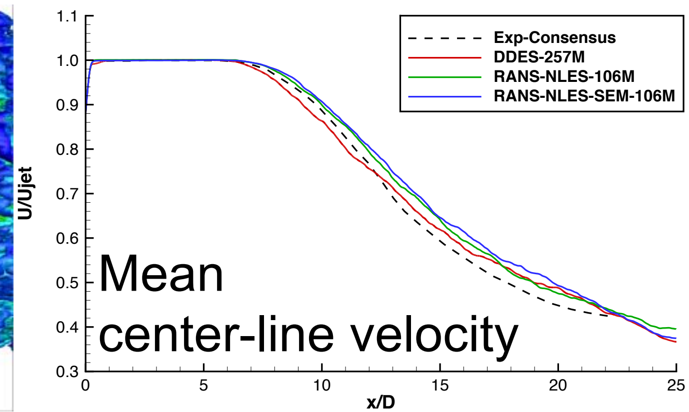
Hybrid RANS/LES technology in LAVA was successfully applied to jet-noise simulations, *Housman et al.* AIAA-2017-3213

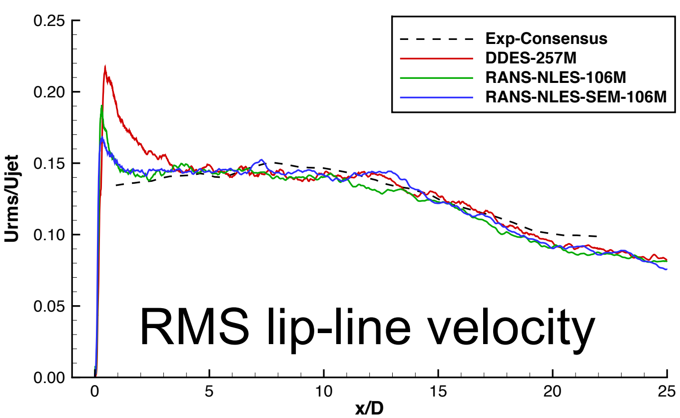
DDES-256M

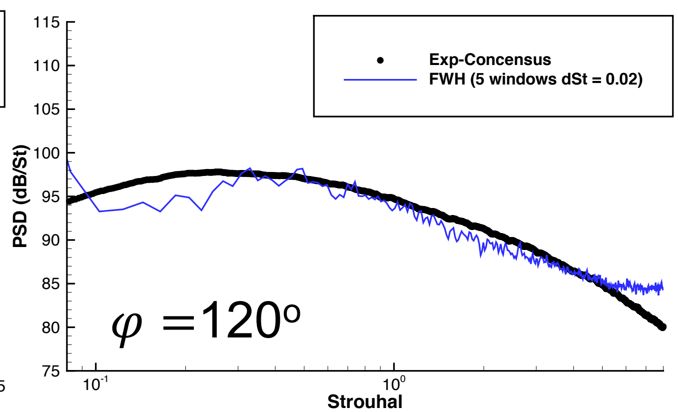


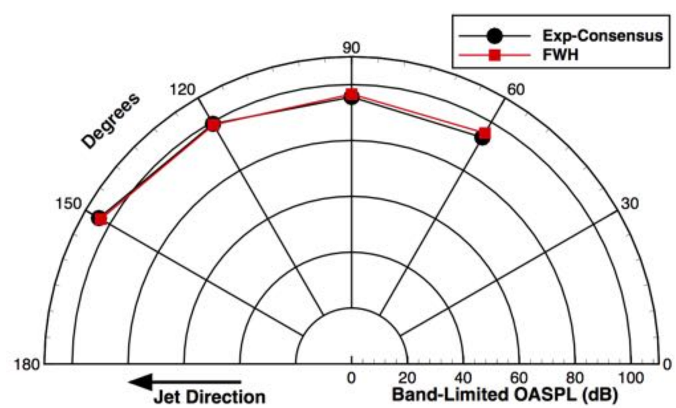
RANS-NLES-SEM-106M





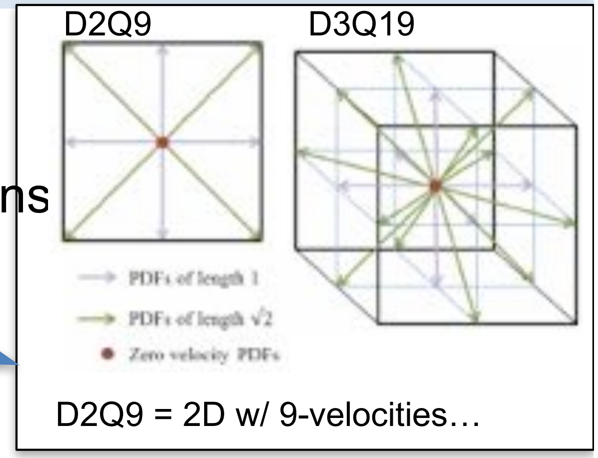




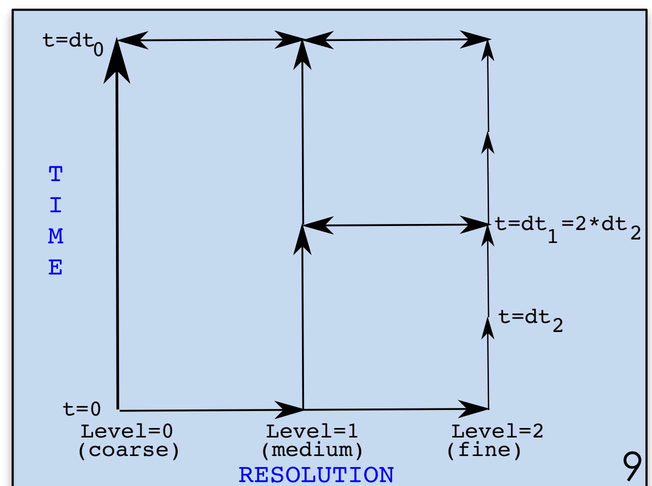


Computational Methodology:
Lattice Boltzmann Method – Current Status

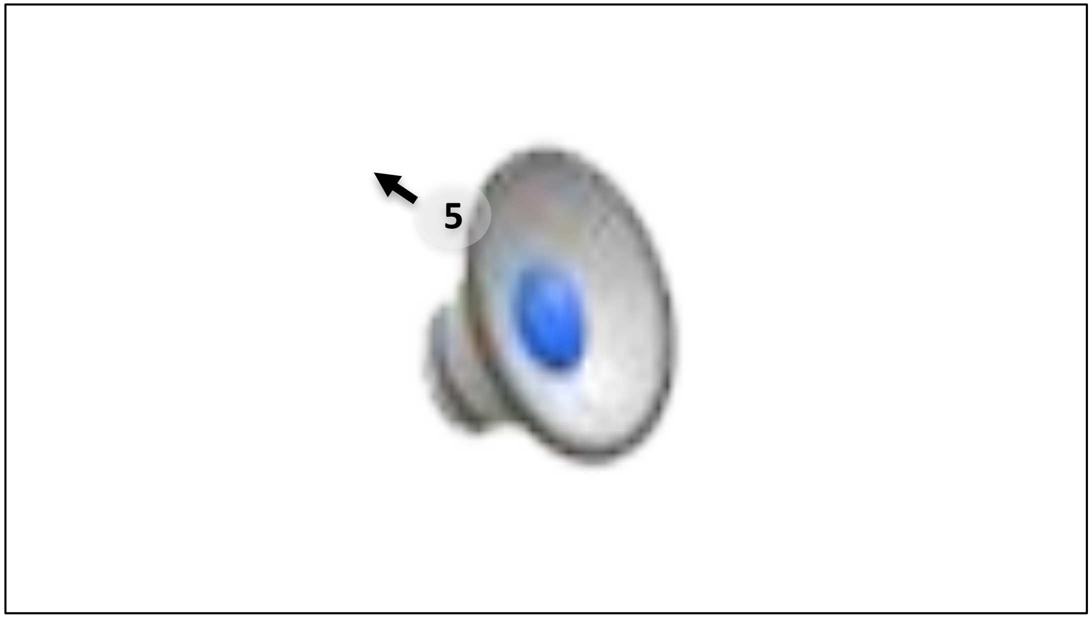
$$\underbrace{f_i(\vec{x} + c\vec{e}_i\Delta t, t + \Delta t) - f_i(\vec{x}, t)}_{\text{Streaming}} = \underbrace{\frac{1}{\tau}(f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t))}_{\text{Collision}}$$



- Governs space time evolution of Density Distribution Functions
- **Lattices**: including D2Q9, D3Q15, D3Q19, D3Q27, D3Q39 …
- **Collision Models**:
  - Bhatnagar-Gross-Krook (BGK)
  - Multi-Relaxation Time (MRT)
  - Entropic and positivity preserving variants of BGK
  - Entropic Multi-Relaxation Time (EMRT)
  - Regularized BGK
- **LES Model**: Smagorinsky sub-grid-scale
- **Wall Models:** Tamm-Mott-Smith boundary condition, filter-based slip wall model, or traditional equilibrium wall stress model
- **Parallelization**:
  - Structured adaptive mesh refinement
    - Fine-fine for communication within levels
    - Coarse-fine for communication across levels
    - Efficient parallel I/O
- **Multi-Resolution with Recursive Sub-Cycling**
- **Boundary Conditions**:
  - No-slip and slip bounce back walls
  - Accurate and robust curved walls
  - Inflow/outflow, and periodic



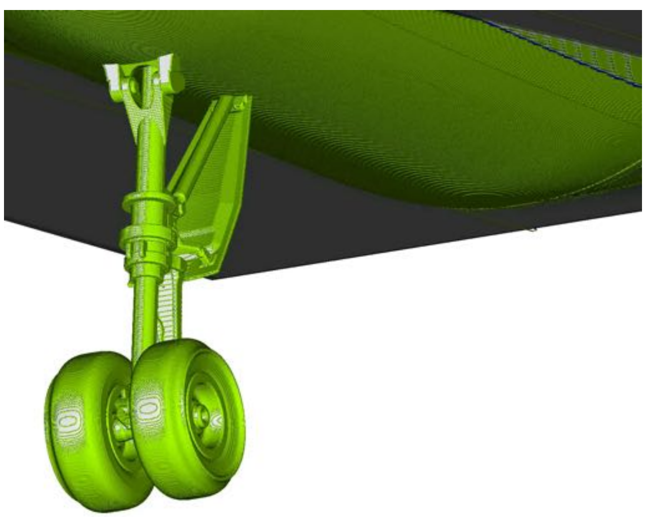
Recent LAVA Cartesian Lattice-Boltzmann Success: Landing Gear from AIAA BANCIII Workshop (problem 4)



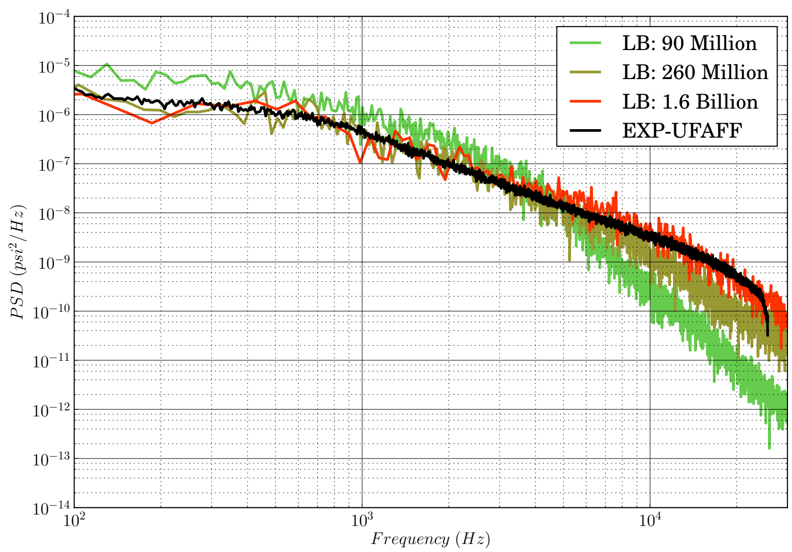
LBM @ 1.6 billion – Velocity Magnitude at Centerline

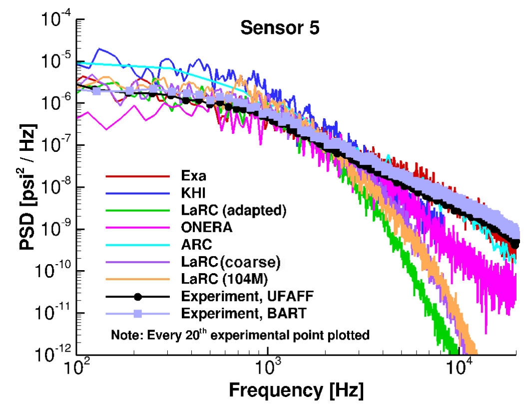
"Lattice Boltzmann and Navier-Stokes Cartesian CFD Approaches for Airframe Noise Predictions", Barad, Kocheemoolayil, Kiris, AIAA 2017-4404

Mach = 0.166
Re = 66423 ($D=D_{strut}$)
U_{ref} = 58.32 m/s
T_{ref} = 307.05 K
P_{ref} = 98605 Pa



Near Field PSD Channel 5

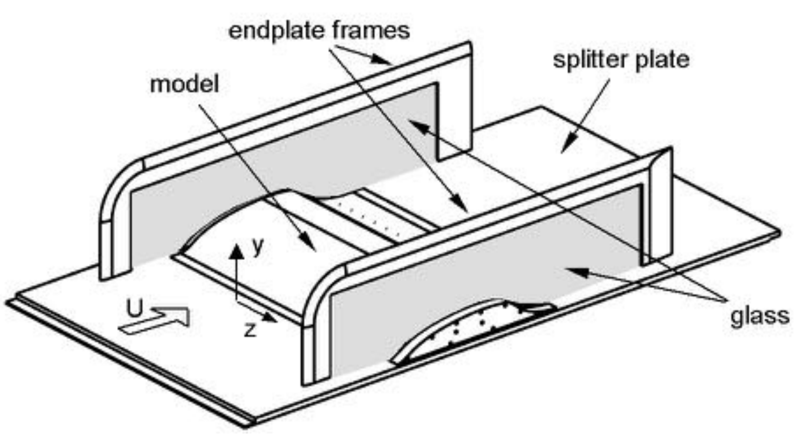




https://info.aiaa.org/tac/ASG/FDTC/DG/BECAN_files_/BANCIII.htm

NASA 2-D Hump – Experimental Setup

✓ Assess ability of CFD solvers to predict flow separation from a smooth body (caused by adverse pressure gradient) as well as subsequent reattachment and boundary layer recovery.



✓ Experiments described in Detail in Greenblatt[1] and NASA CFDVAL 2004 Workshop[2,3].

✓ RANS known to perform poorly.

✓ Eddy-resolving methods have been successfully applied.

[1] Greenblatt et. Al. "Experimental Investigation of Separation Control Part 1: Baseline and Steady Suction". AIAA Journal, vol 44, no. 12, pp. 2820-2830, 2006
[2] Rumsey C, "Turbulence Modeling Resource", https://turbmodels.larc.nasa.gov
[3] Rumsey C, "CFD Validation of Synthetic Jets and Turbulent Separation Control", http://cfdval2004.larc.nasa.gov

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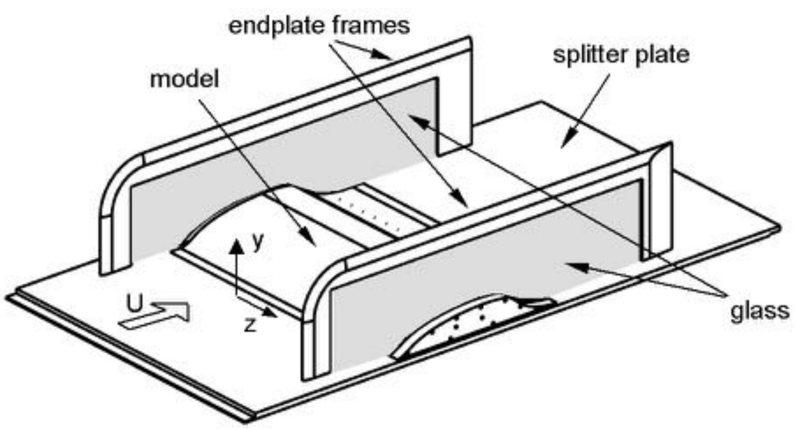

Wall-resolved LES:

✓ Uzun, A. and Malik, M. (AIAA 2017-5308)

Wall-modeled LES:

✓ Iyer, P. and Malik, M. (AIAA 2016-3186)

Lattice Boltzmann Methos:

✓ Duda, B. and Fares, E. (AIAA 2016-1836)

[1] Greenblatt et. Al. "Experimental Investigation of Separation Control Part 1: Baseline and Steady Suction". AIAA Journal, vol 44, no. 12, pp. 2820-2830, 2006
[2] Rumsey C, "Turbulence Modeling Resource", https://turbmodels.larc.nasa.gov
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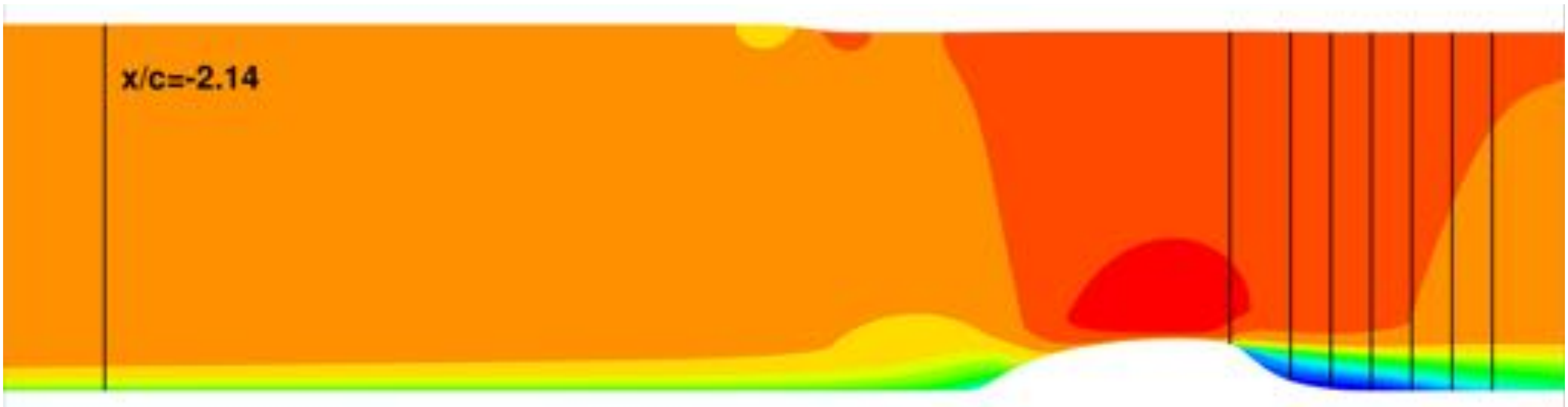
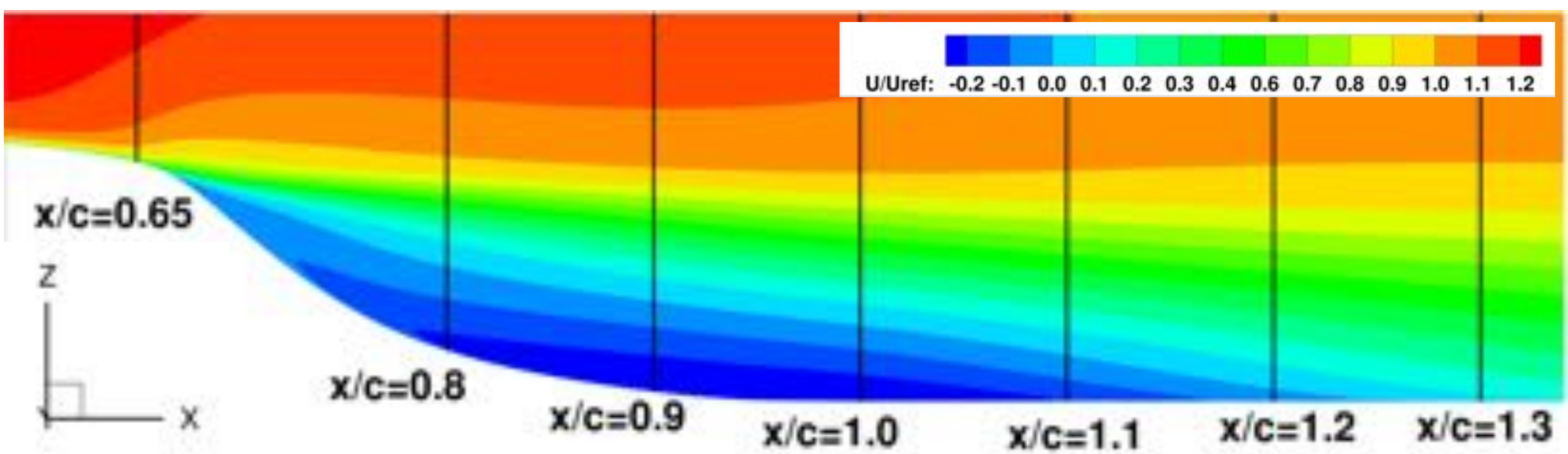
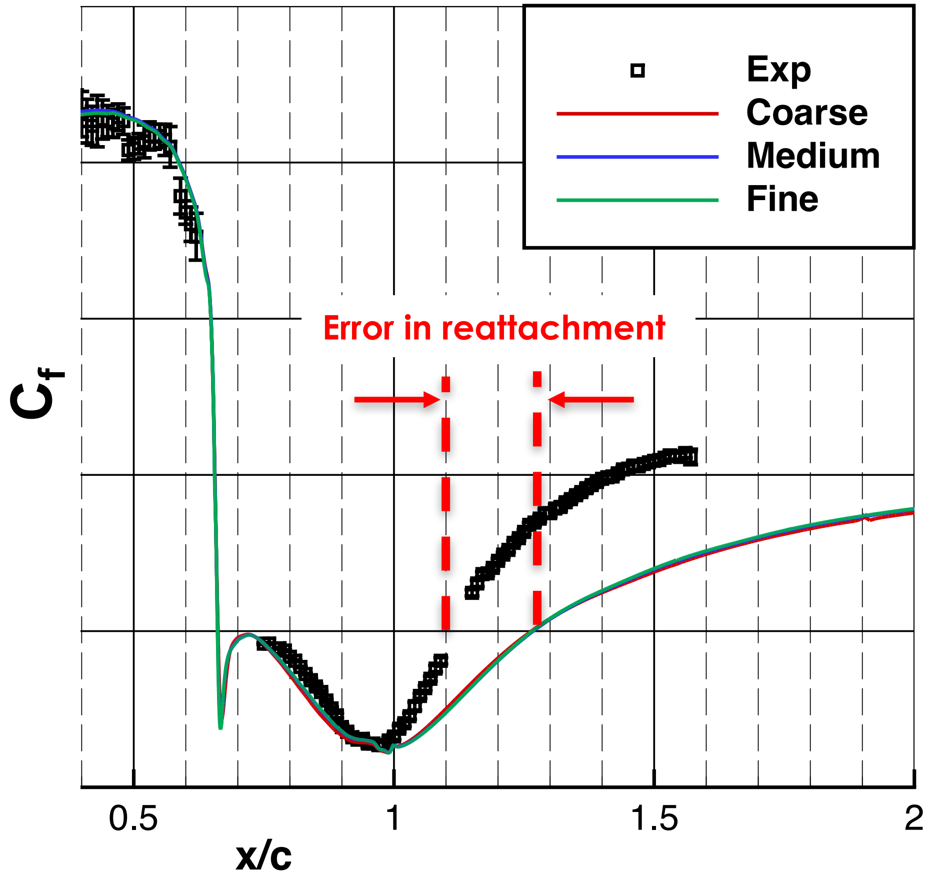
NASA 2-D Hump

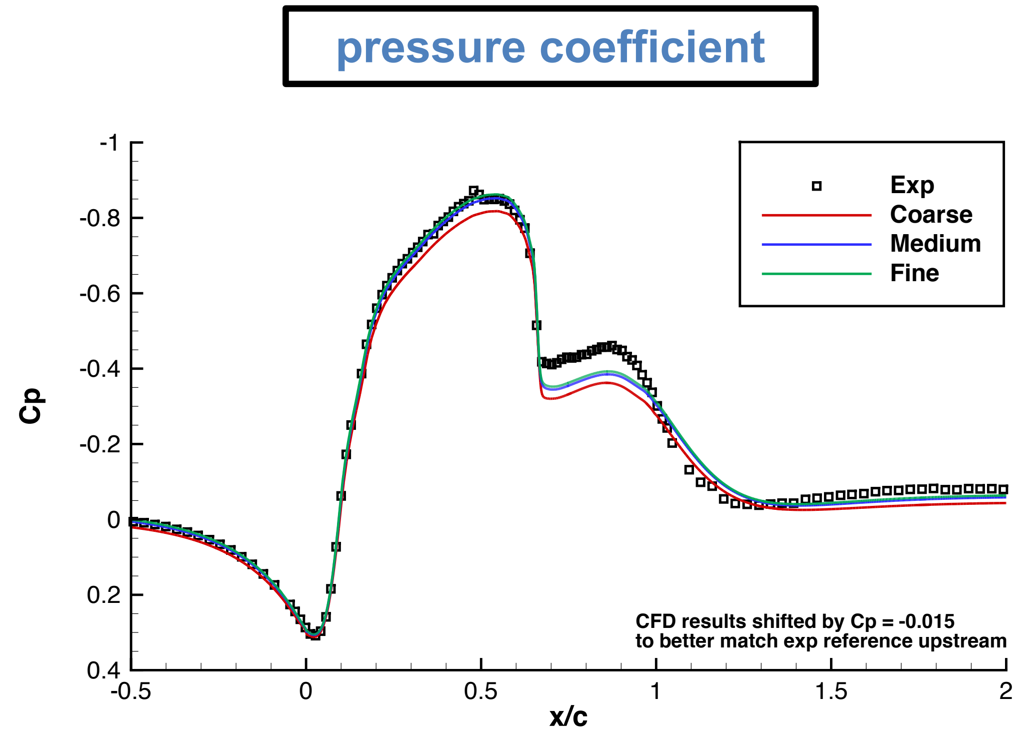
- ✓ Mach = 0.1 ; chord C = 0.42 [m] ; Re_C = 936,000 ; T_{ref} = 298.3 [K]
- ✓ Top wall contoured to mimic side-wall effect
- ✓ Experimental data at locations marked below available





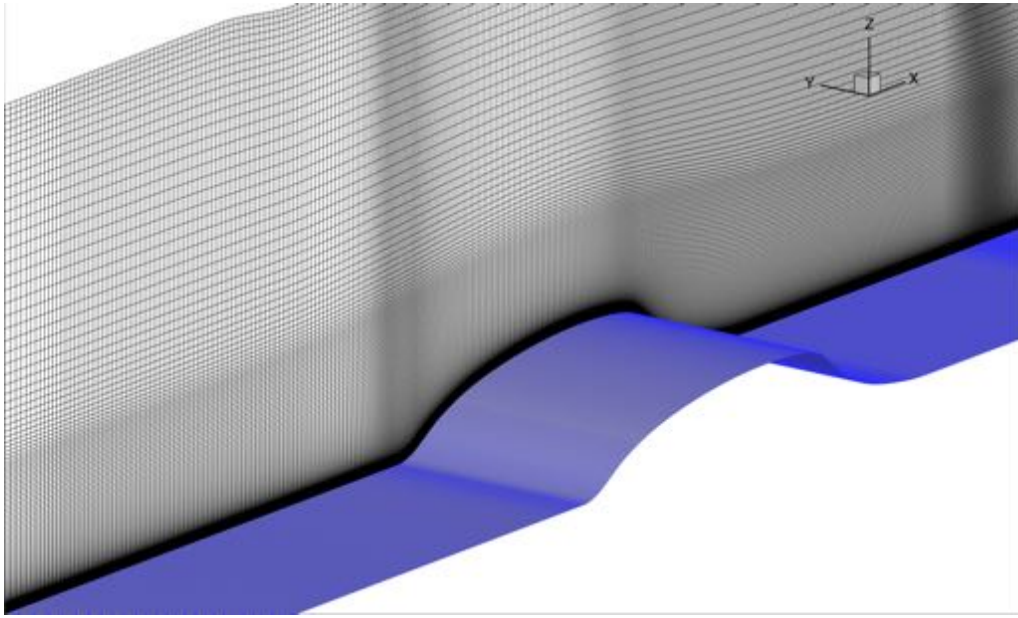
NASA 2-D Hump – LAVA RANS Validation

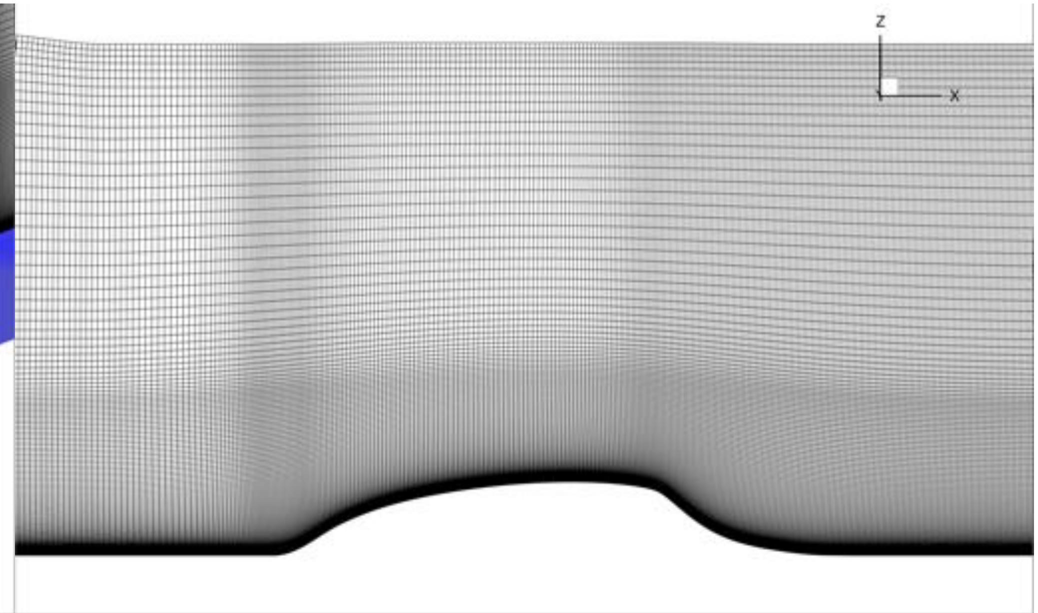


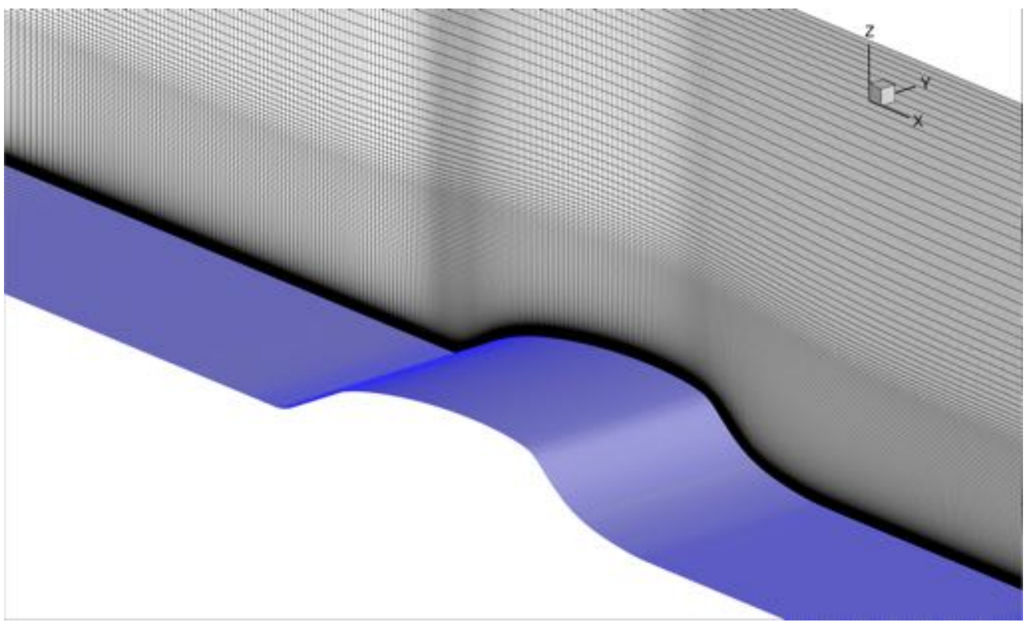


- ✓ Consistent convergence to a mesh refined solution is observed in each of the quantities
- ✓ Under prediction of C_p in the separated flow region and over prediction of the reattachment length is consistent with the SA results for CFL3D, FUN3D, and OVERFLOW (reported on the TMR)
- ✓ RANS solvers typically over predict bubble size by 35%

NASA 2-D Hump – Application of Delayed DES (SA)

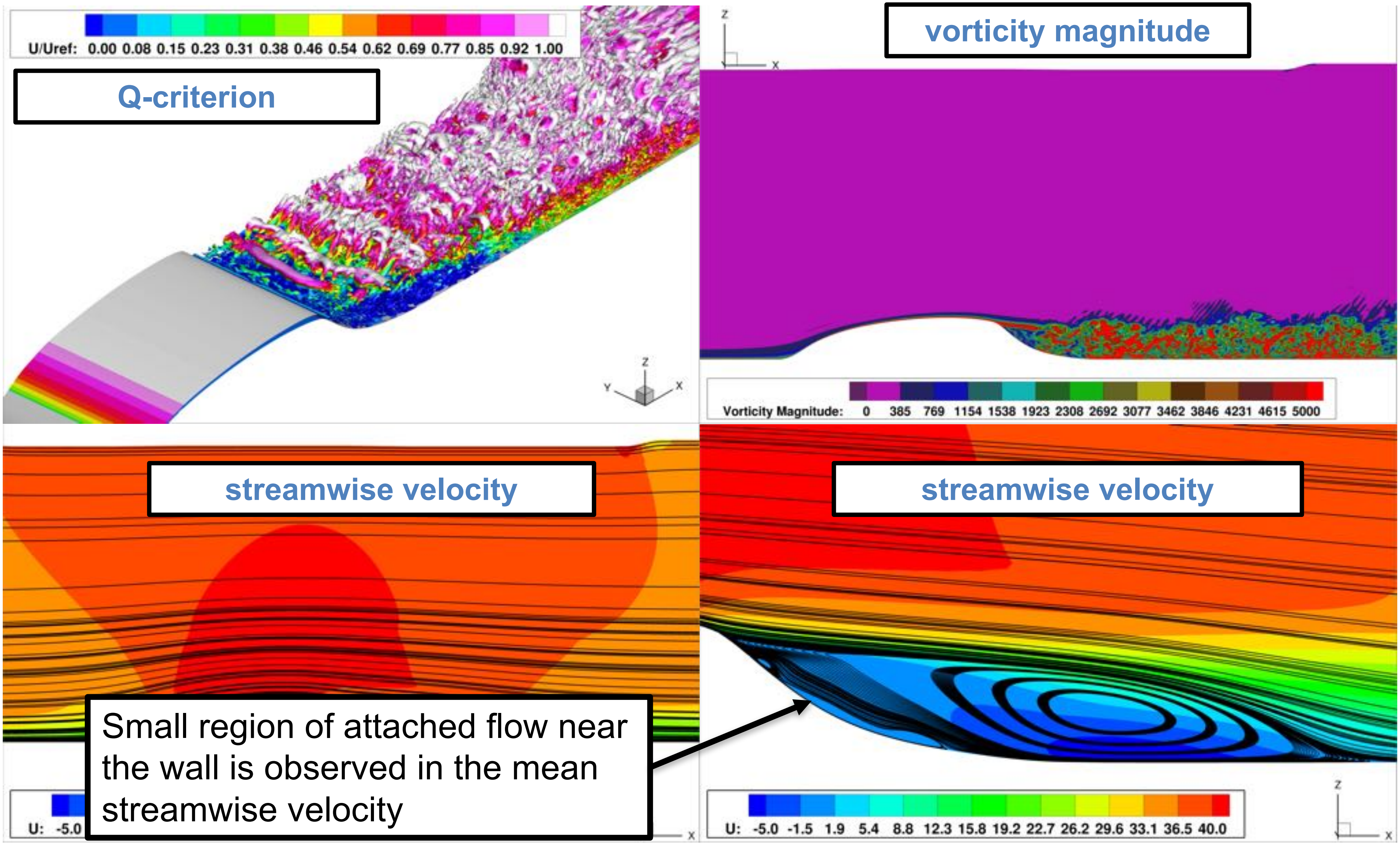






- ✓ Based on RANS mesh refinement study and DES meshing guidelines a 3D structured grid was generated
- ✓ A total of 11 million grid points are used with 81 points over the 0.4c span
- ✓ Nearly uniform spacing is used in the separated flow region were the LES model is being used

NASA 2-D Hump – Application of Delayed DES (SA)



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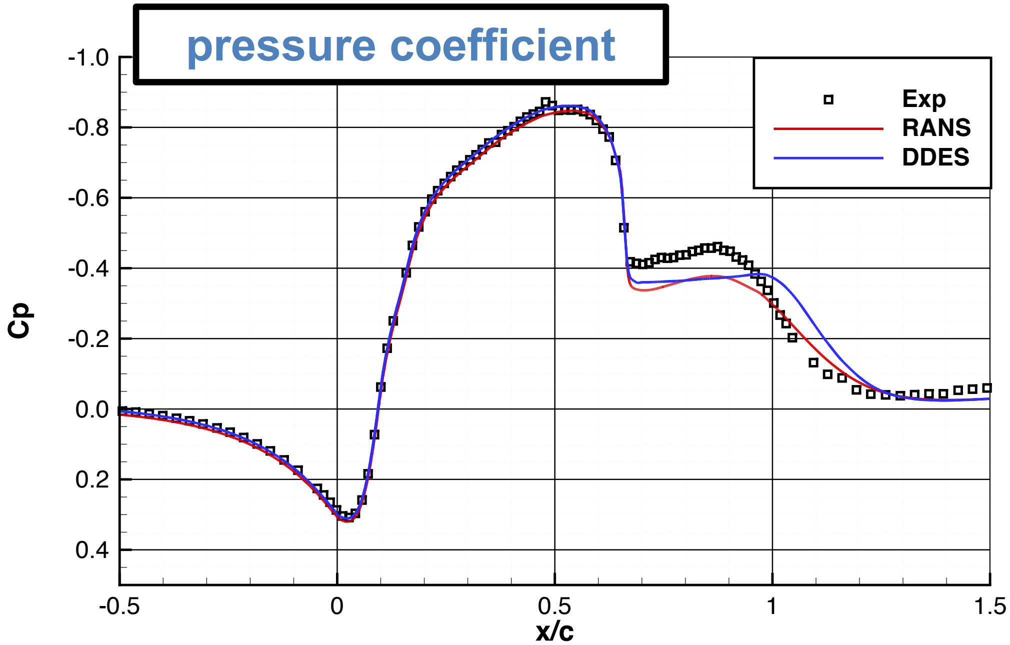
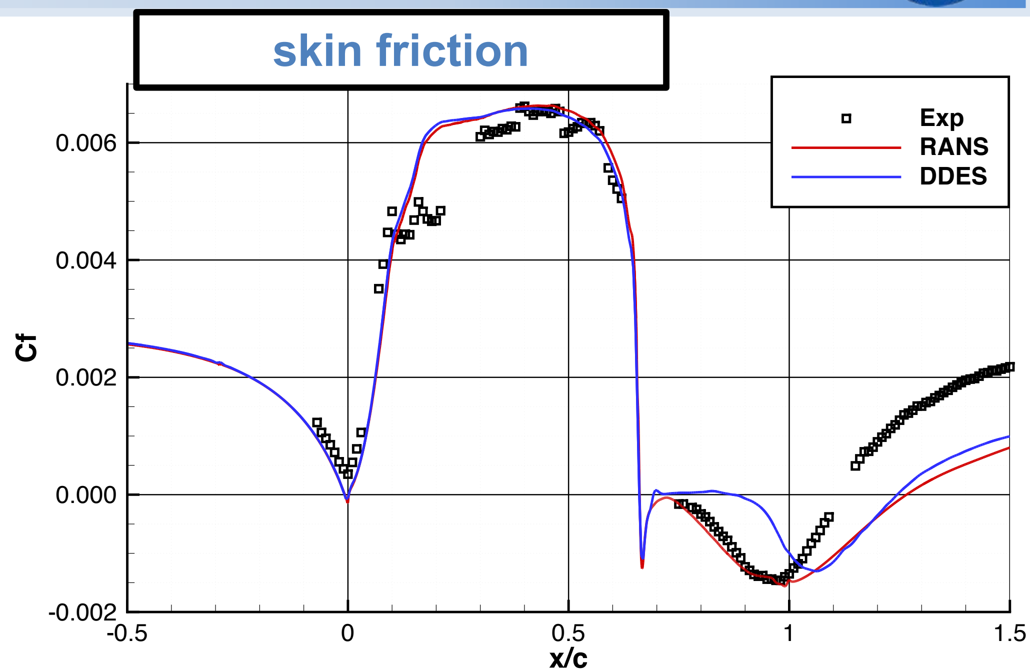
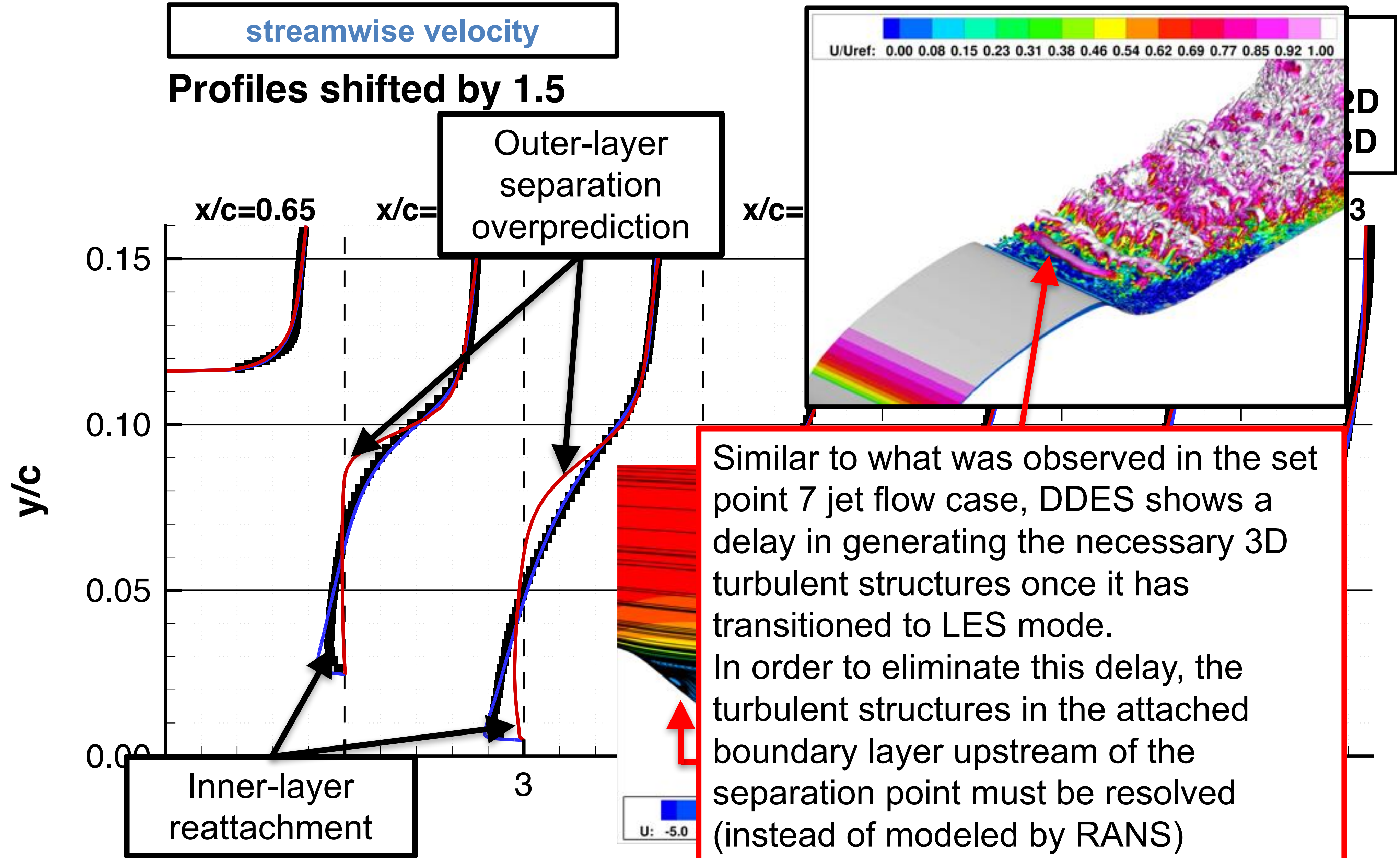




- ✓ Upstream of the separation point the SA-DDES results fall on-top of the SA-RANS results indicating the attached boundary layer is staying in RANS mode as expected
- ✓ Downstream of the separation point the flow reattaches near the wall creating a bifurcated separation flow pattern that is qualitatively different than what is observed in both the experiment and the RANS simulation
- ✓ The inner layer reattachment ends at about x/c = 0.9 and outer layer separation region reattaches in nearly the same location as the RANS

NASA 2-D Hump – Application of Delayed DES (SA)



Similar to what was observed in the set point 7 jet flow case, DDES shows a delay in generating the necessary 3D turbulent structures once it has transitioned to LES mode.

In order to eliminate this delay, the turbulent structures in the attached boundary layer upstream of the separation point must be resolved (instead of modeled by RANS)

NASA 2-D Hump – Application of Delayed DES (SA)

SA-DDES

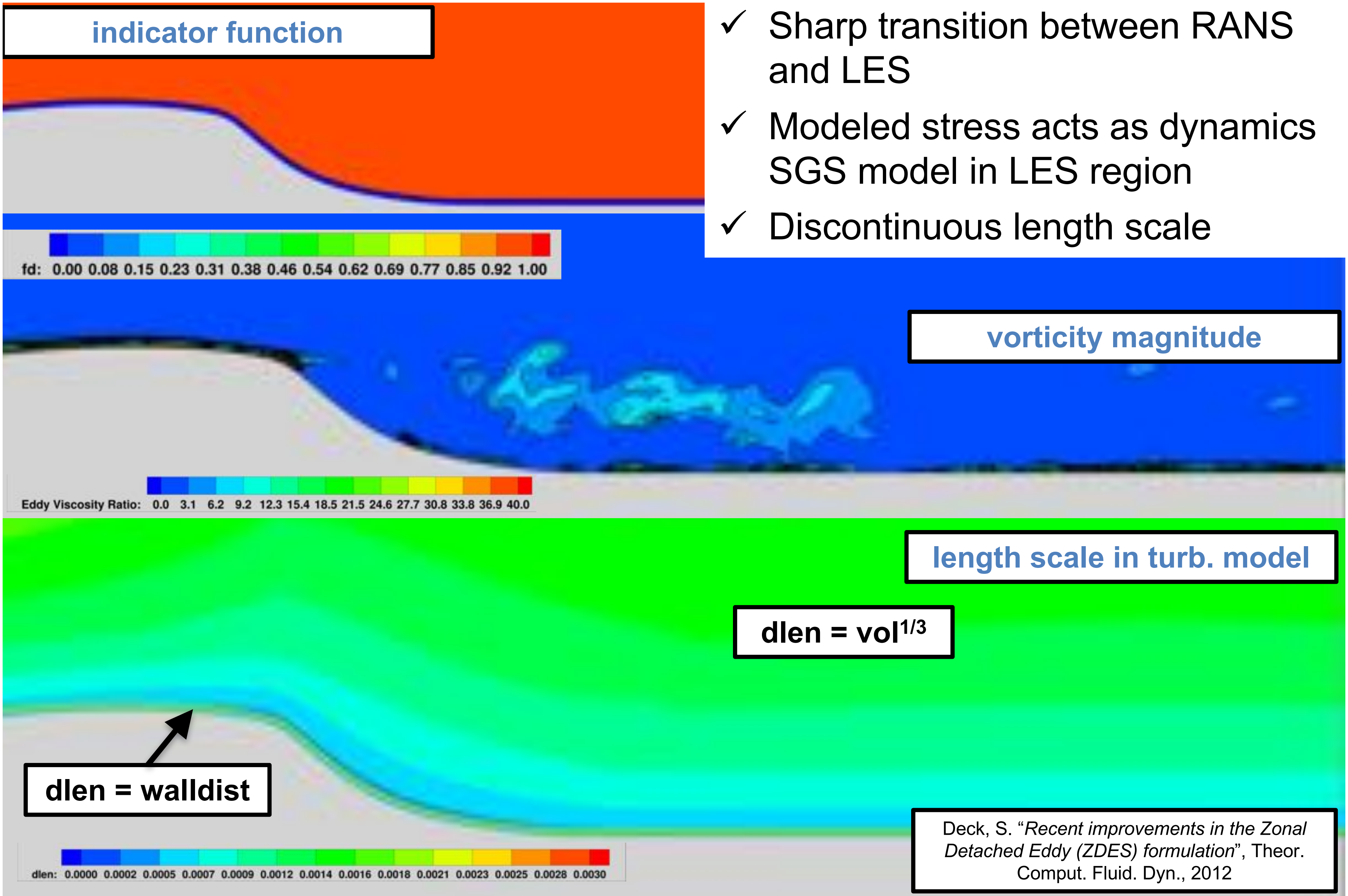
- ✅ Showed good match to experiment (and the RANS) upstream of separation point
- ❌ Failed to generate 3D turbulent structures fast enough in the separated flow region
- ❌ Over-predicted the shear-layer and created an inner-layer of attached flow in the separated flow region

Zonal DES in “Mode 3”

- RANS model acts like a WM in the inner part of the attached BL, the outer part is resolved in LES
- Sharp user specified transition between two regions at fixed y^+

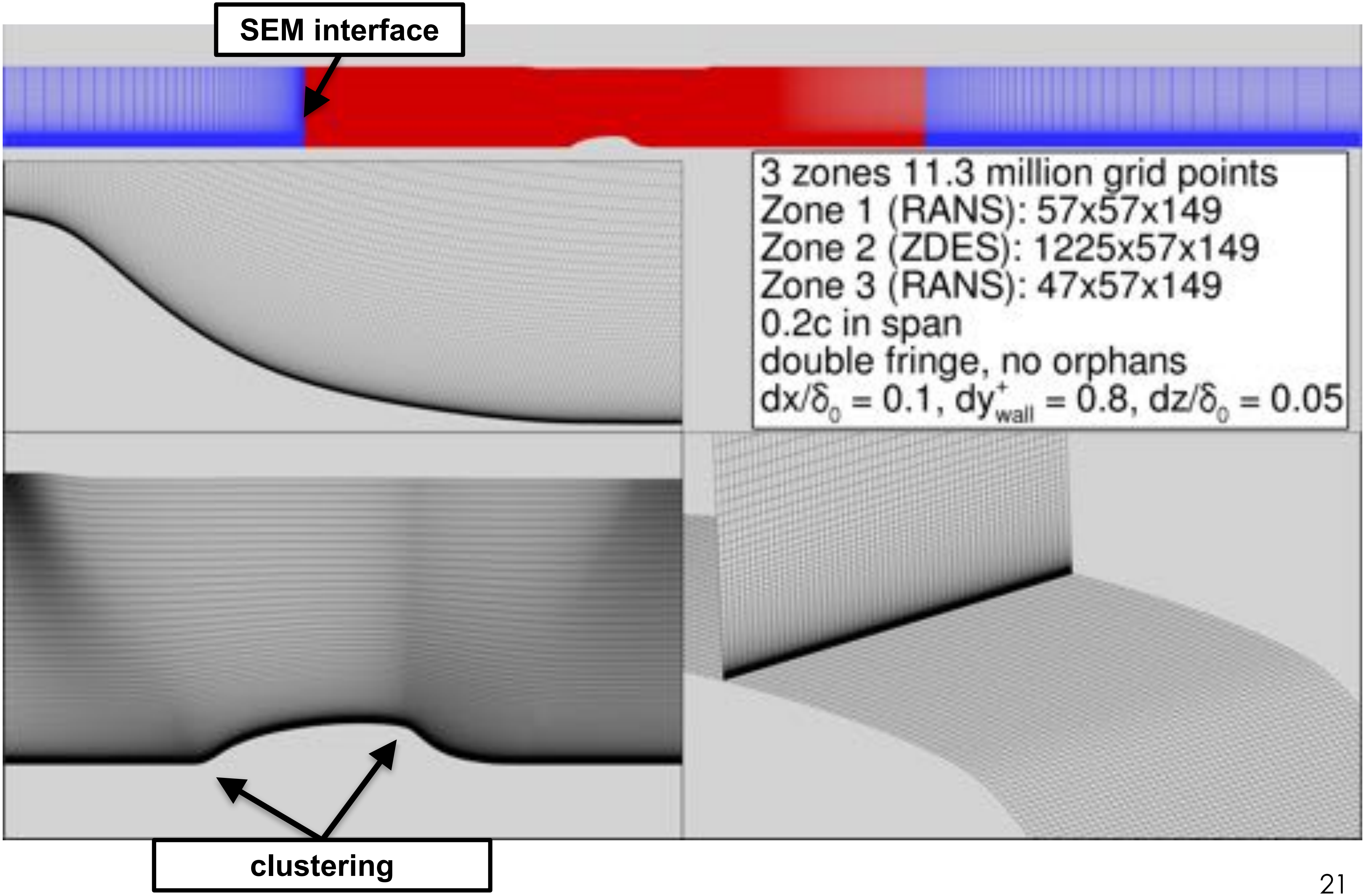
NASA 2-D Hump – Application of Zonal DES

- ✓ Sharp transition between RANS and LES
- ✓ Modeled stress acts as dynamics SGS model in LES region
- ✓ Discontinuous length scale

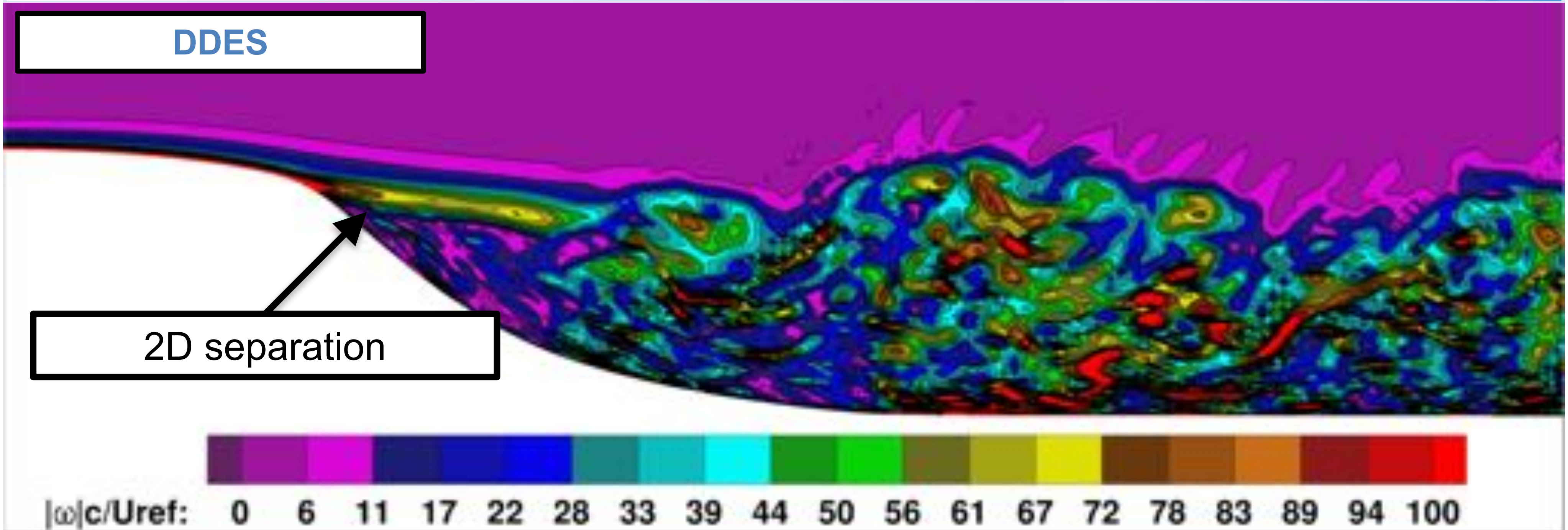


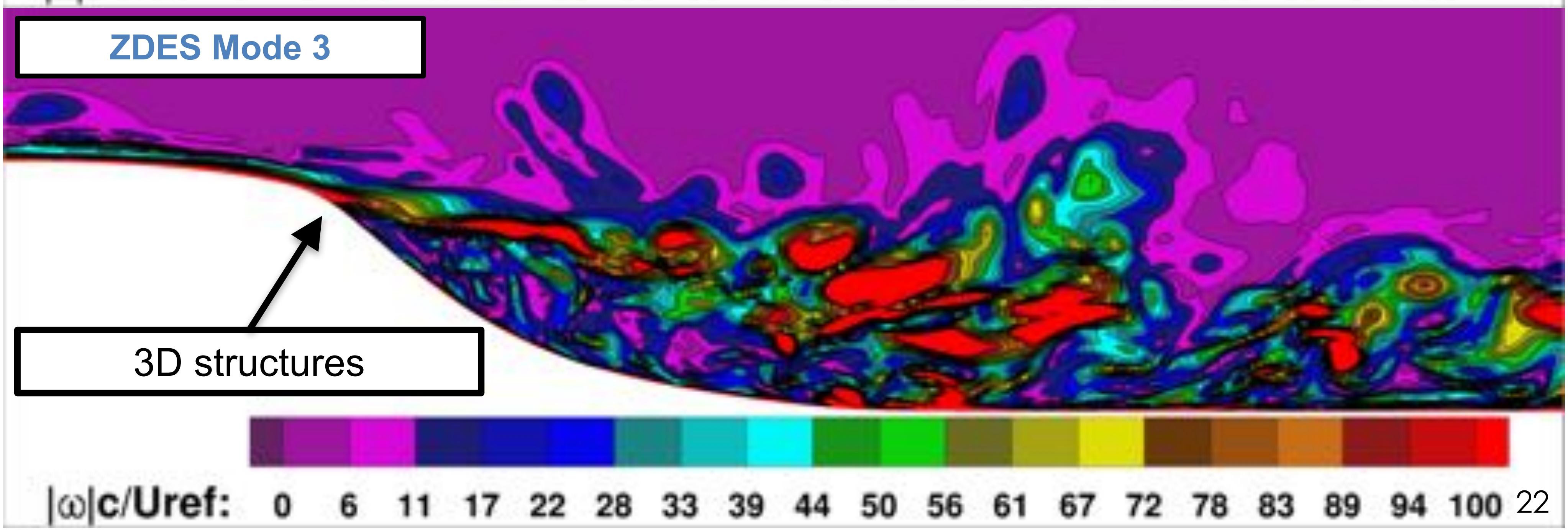
Deck, S. "*Recent improvements in the Zonal Detached Eddy (ZDES) formulation*", Theor. Comput. Fluid. Dyn., 2012

NASA 2-D Hump – Application of Zonal DES

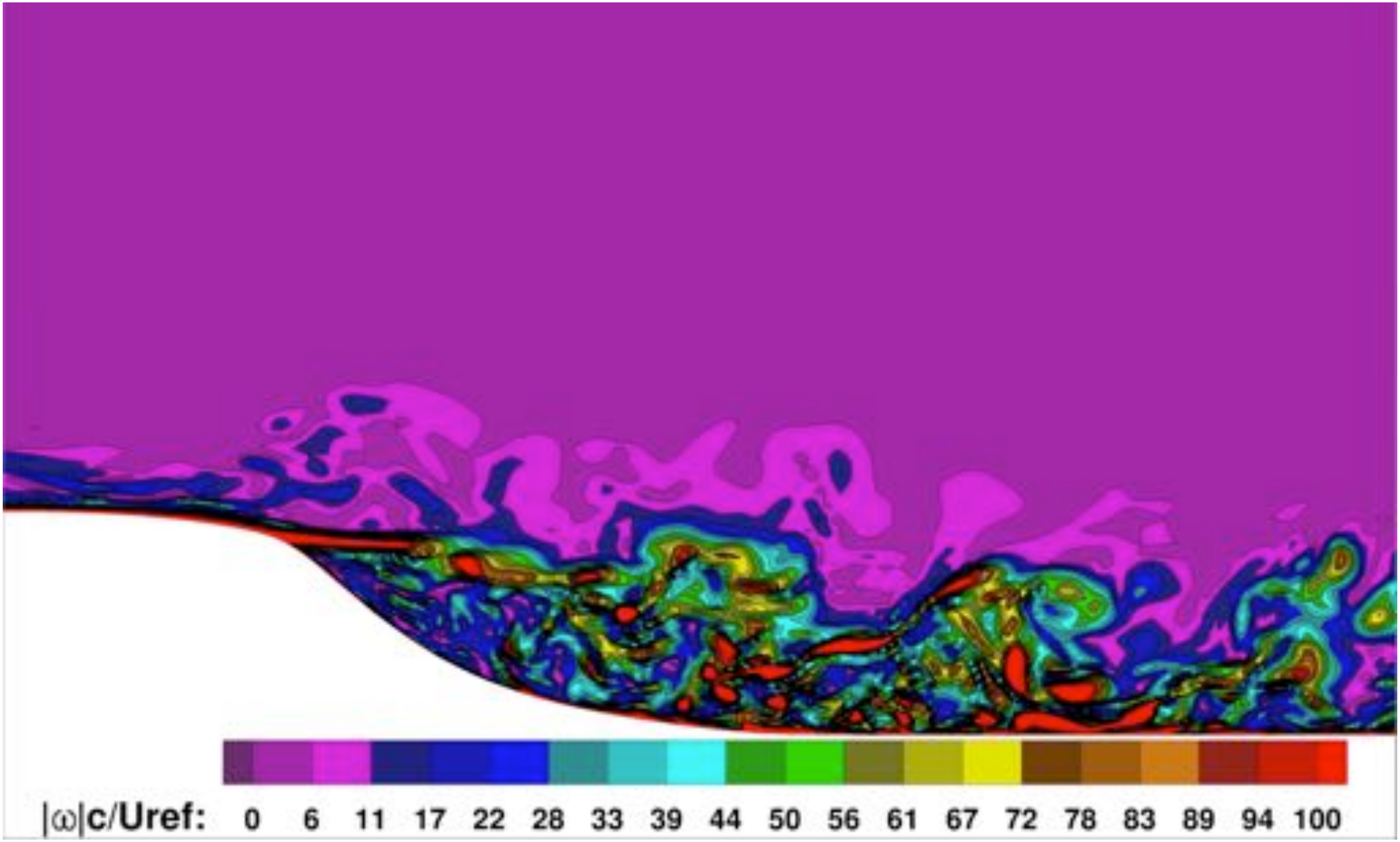


NASA 2-D Hump – Application of Zonal DES



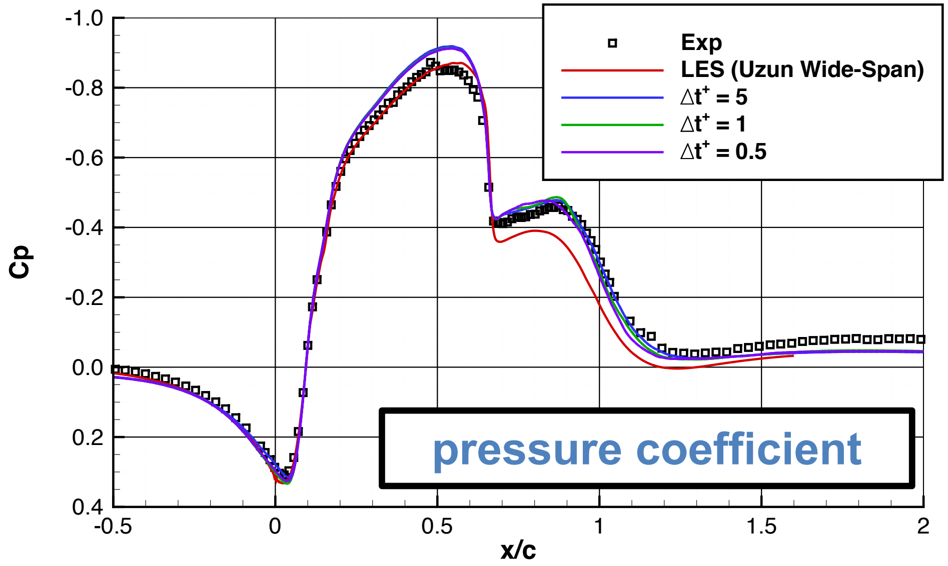


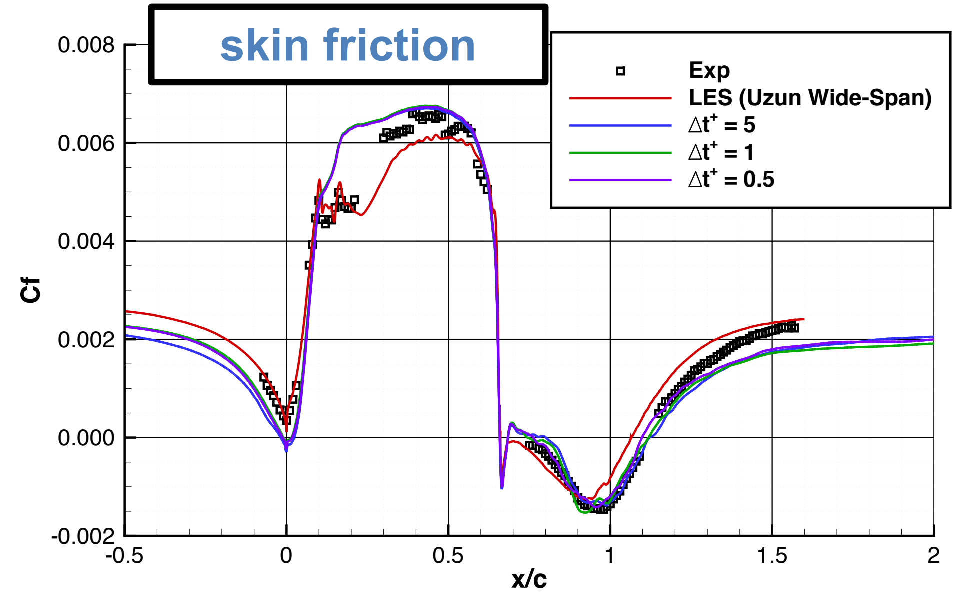
NASA 2-D Hump – Application of Zonal DES

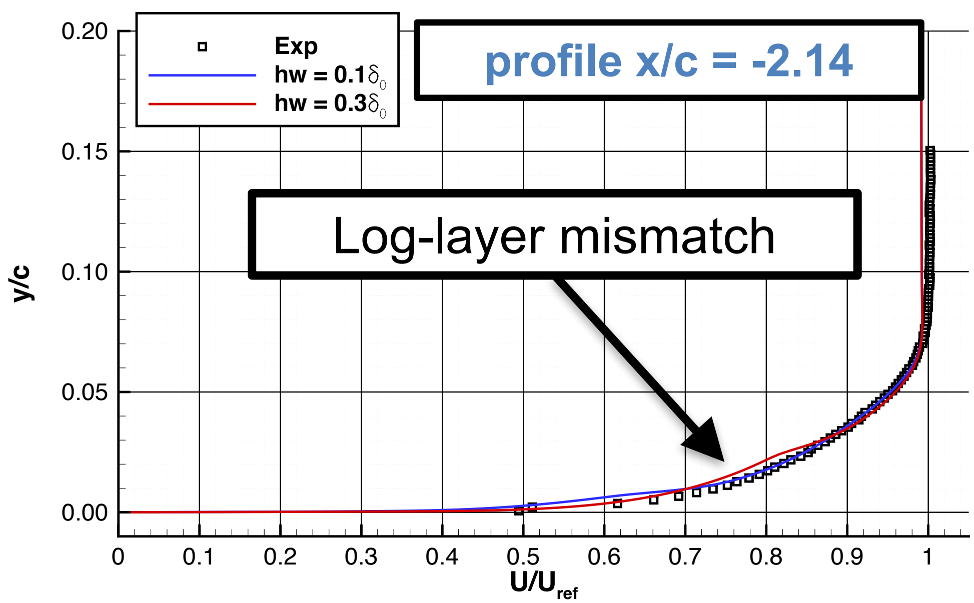


NASA 2-D Hump – Application of Zonal DES

[1] Uzun, A. : https://turbmodels.larc.nasa.gov/Other_LES_Data/nasa_hump_uzun_2017.html



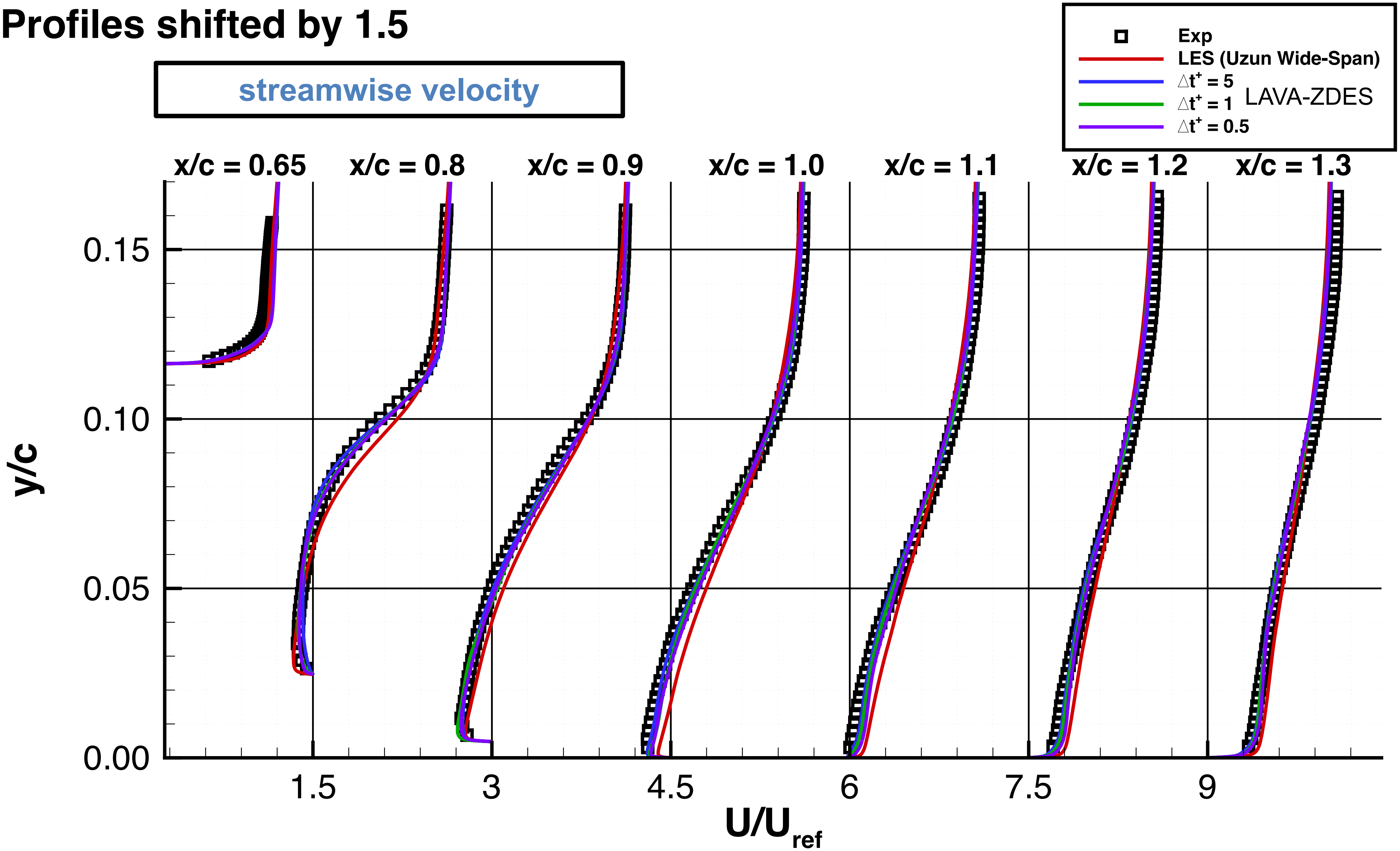




- ✓ ZDES (11.3m) compares well with wall resolved LES[1] (420m) and experiment .
- ✓ The skin-friction is under-predicted in the upstream attached BL
- ✓ Very good agreement in the re-attachment location
- ✓ Noticeable log-layer mismatch in the upstream BL profile

NASA 2-D Hump – Application of Zonal DES

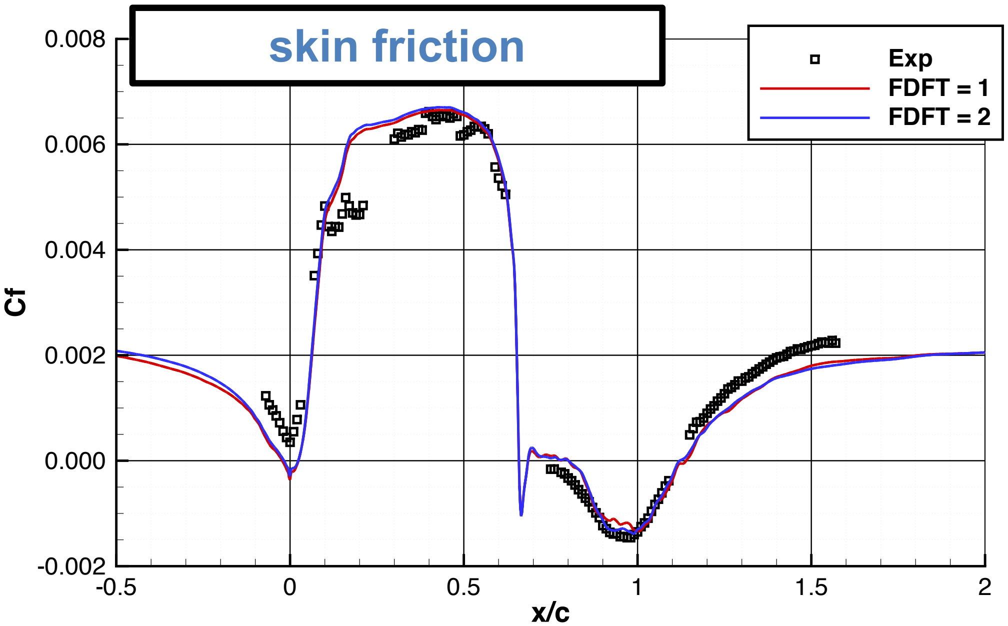
Profiles shifted by 1.5



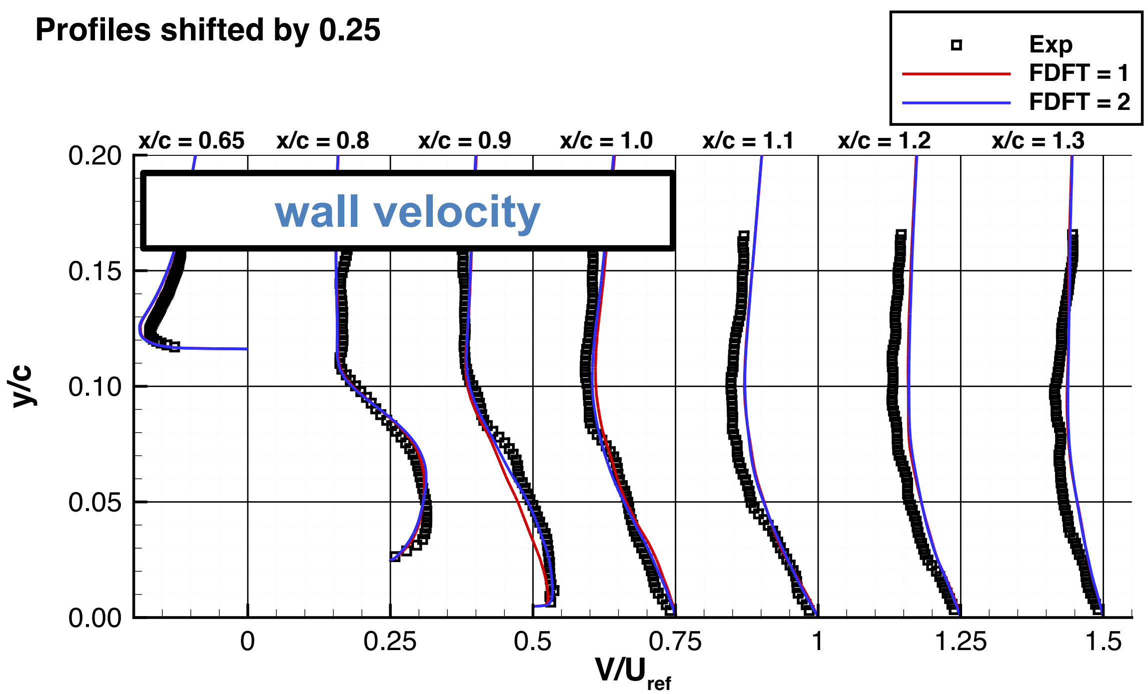
✓ Wall resolved LES mesh has 420m points, ZDES 11.3m points

[1] Uzun, A. and Malik, M., "Wall-Resolved Large-Eddy Simulation of Flow Separation Over NASA Wall-Mounted Hump", AIAA SciTech, 2017

NASA 2-D Hump – Application of Zonal DES



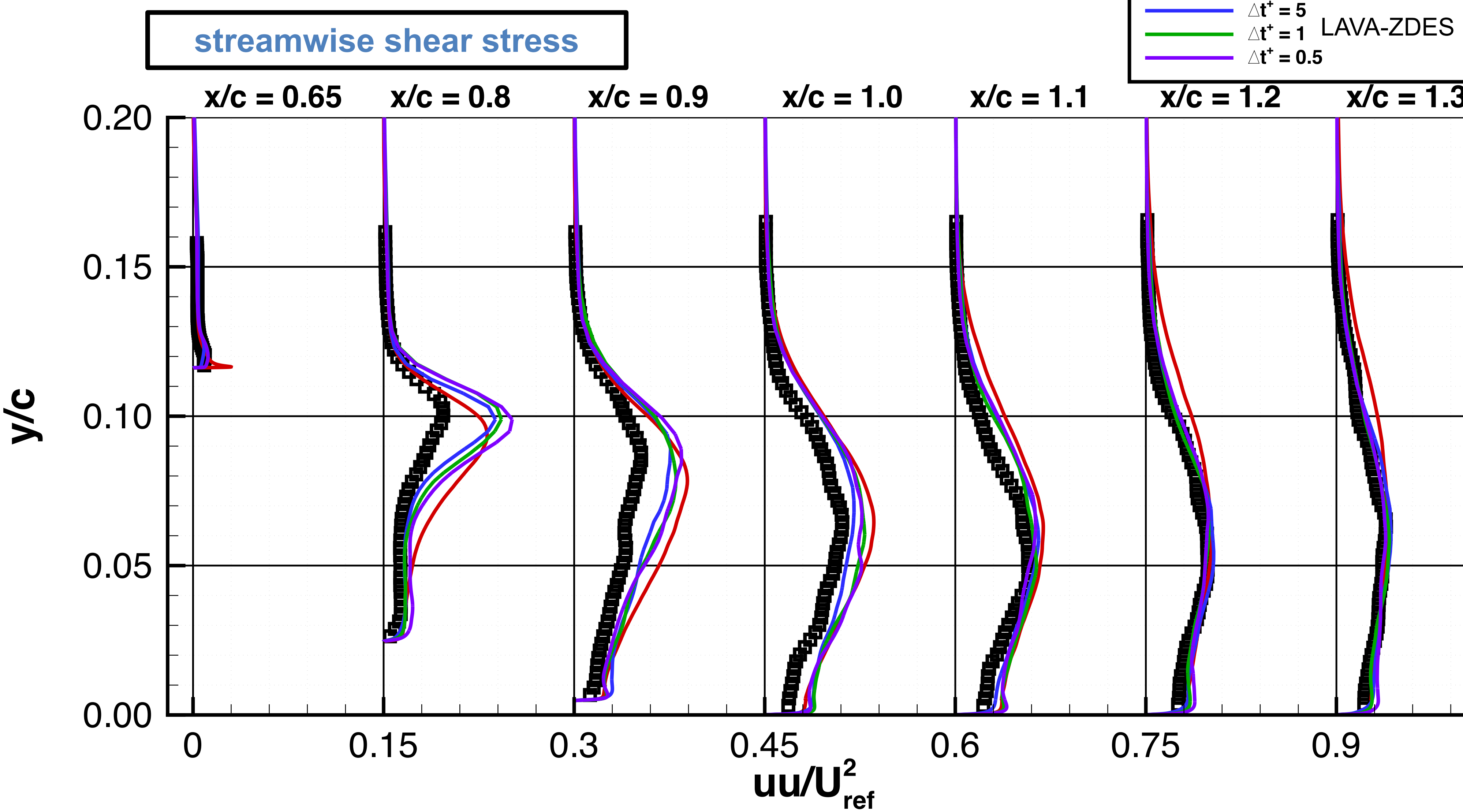
- ✓ 1 Full Domain Flow Through (FDFT) equals 7 convective FT
- ✓ Marginal difference between FDFT1 and FDFT2
- ✓ Overall Surface C_f is well-predicted
- ✓ C_f slightly under predicted in region upstream of hump



- ✓ Similar behavior for velocity component
- ✓ Of all compared quantities V-velocity has largest deviation between FDFT1 & FDFT2

NASA 2-D Hump – Application of Zonal DES

Profiles shifted by 0.15



[1] Uzun, A. and Malik, M., "Wall-Resolved Large-Eddy Simulation of Flow Separation Over NASA Wall-Mounted Hump", AIAA SciTech, 2017

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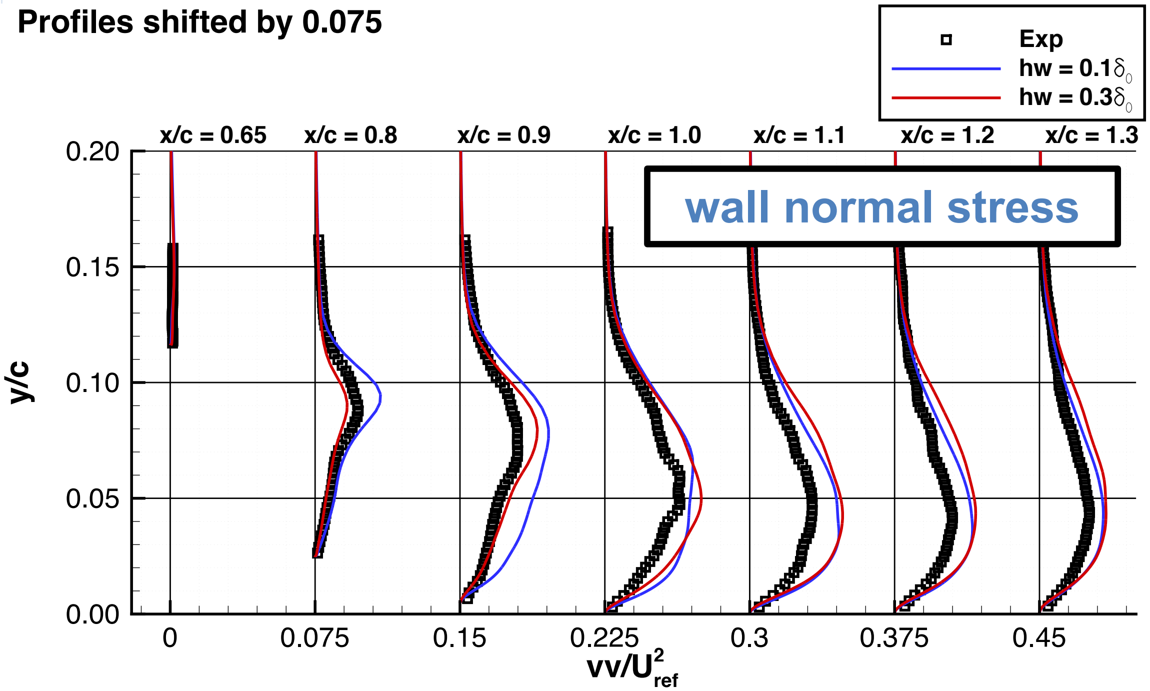

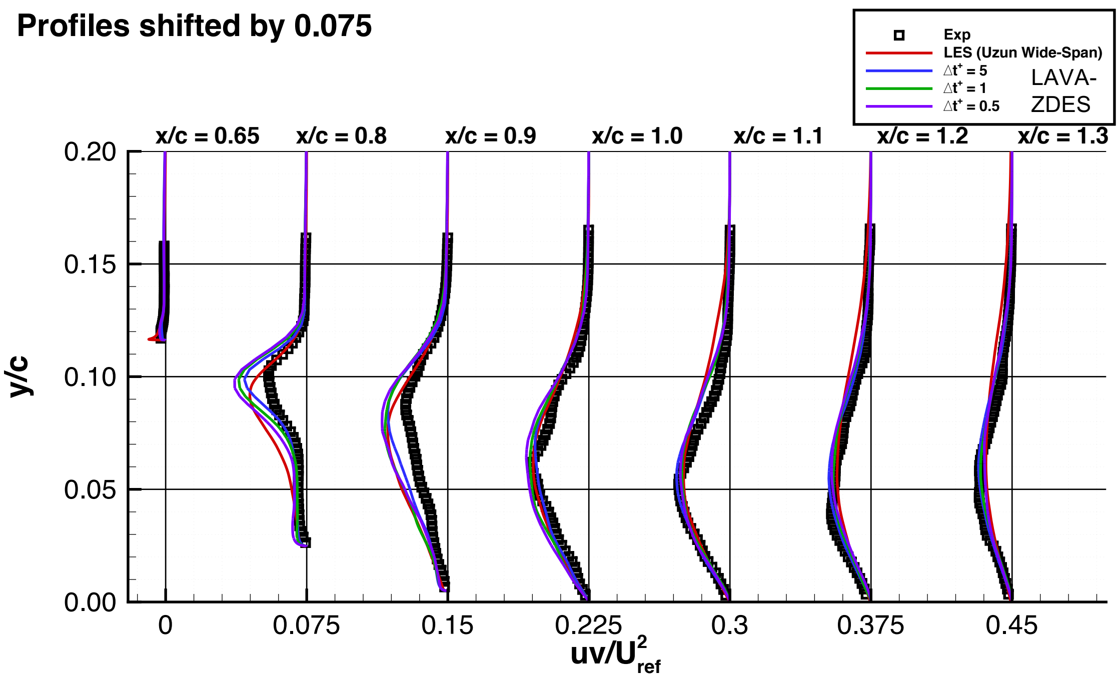

- ✓ Interface location based on BL thickness on top of hump
- ✓ Interface location constant across whole domain

Future work:

- ✓ Implement interface sensor based on local BL thickness (e.g. from vorticity magnitude)

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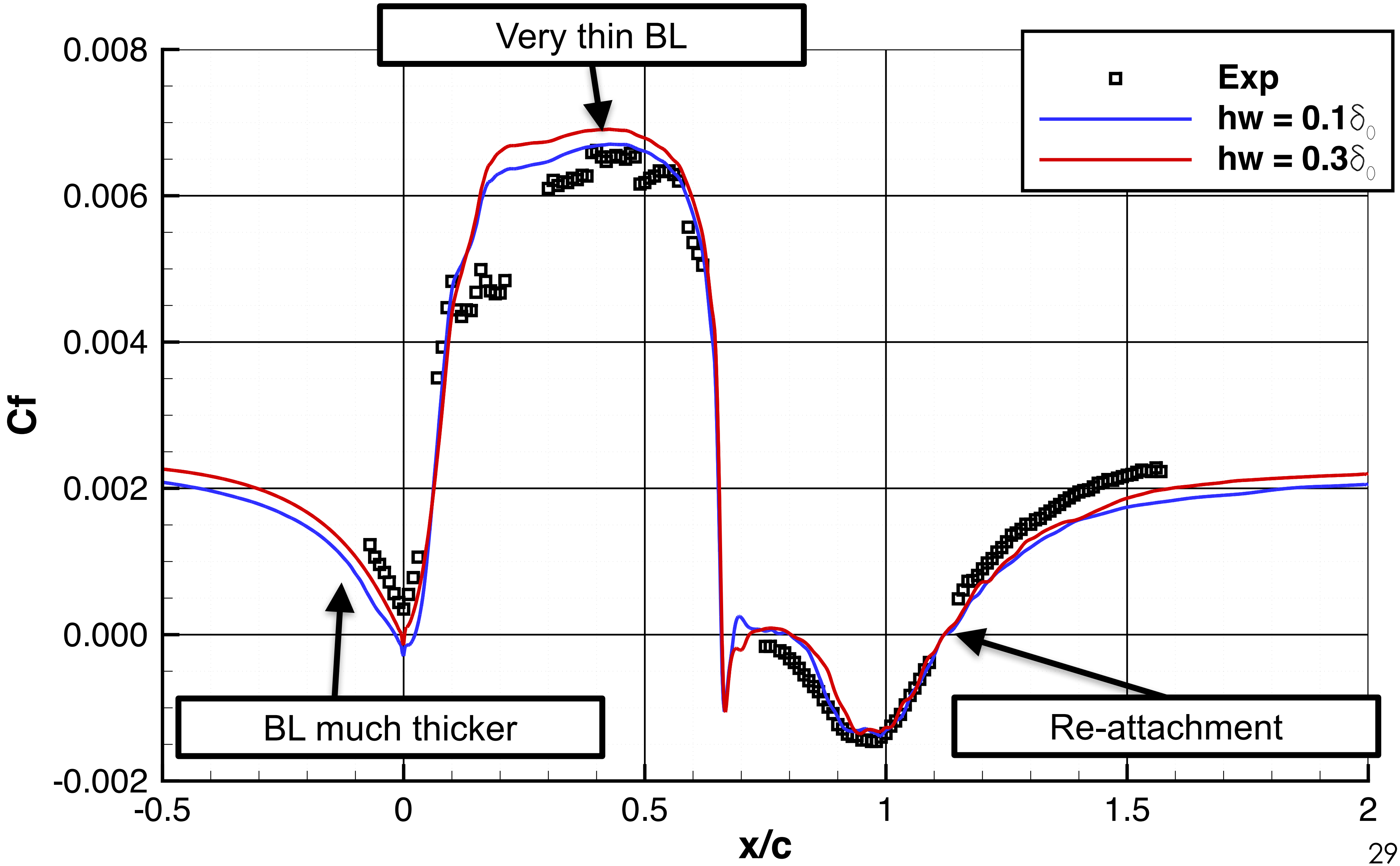
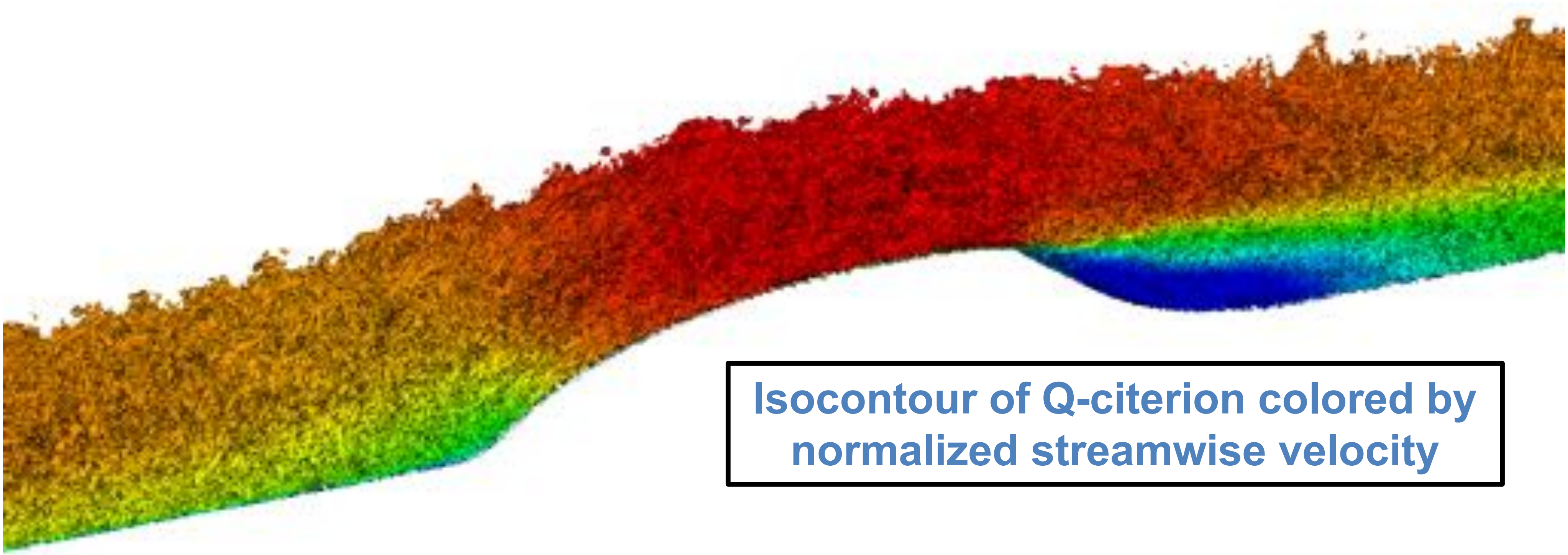
skin friction coefficient for different interface locations



NASA 2-D Hump – Application of Lattice Boltzmann

- ✓ Lattice: D3Q27
- ✓ Collision Model: ELBM
- ✓ Synthetic Eddy Method with scaled DNS Flat plate Data at x/c = -3.0

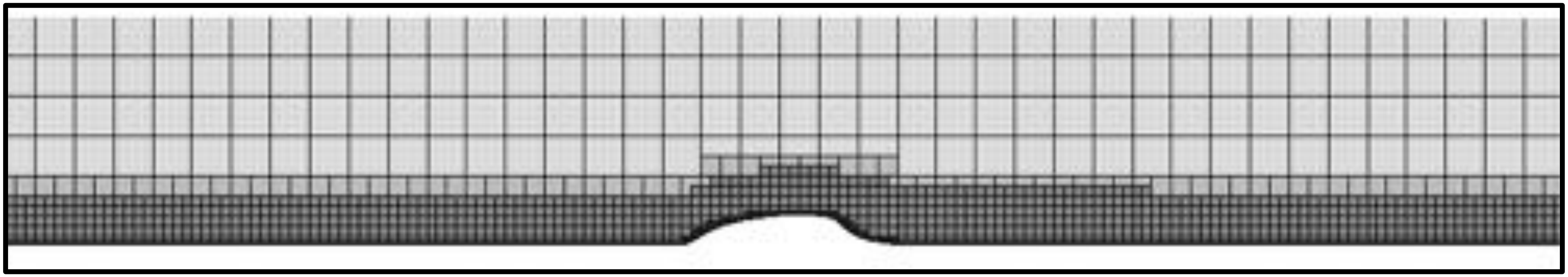
PRELIMINARY RESULTS!
EARLY STAGE!

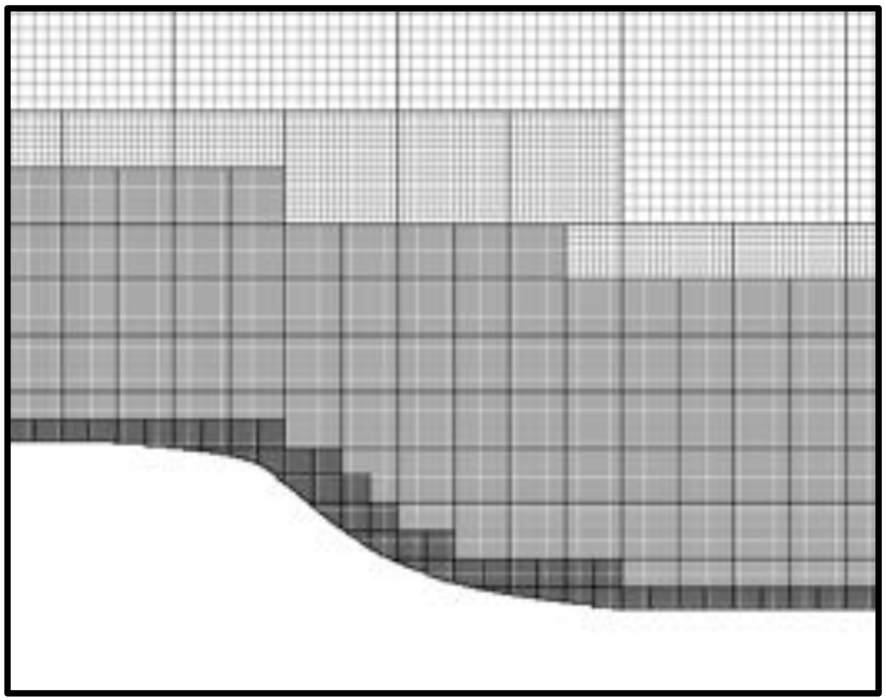


- ✓ Synthetic eddy method created realistic turbulent structures
- ✓ Initial run without included top-wall to simulate side-wall effects

NASA 2-D Hump – Application of Lattice Boltzmann

- ✓ Local as well as adaptive mesh refinement well tested in our Cartesian framework.

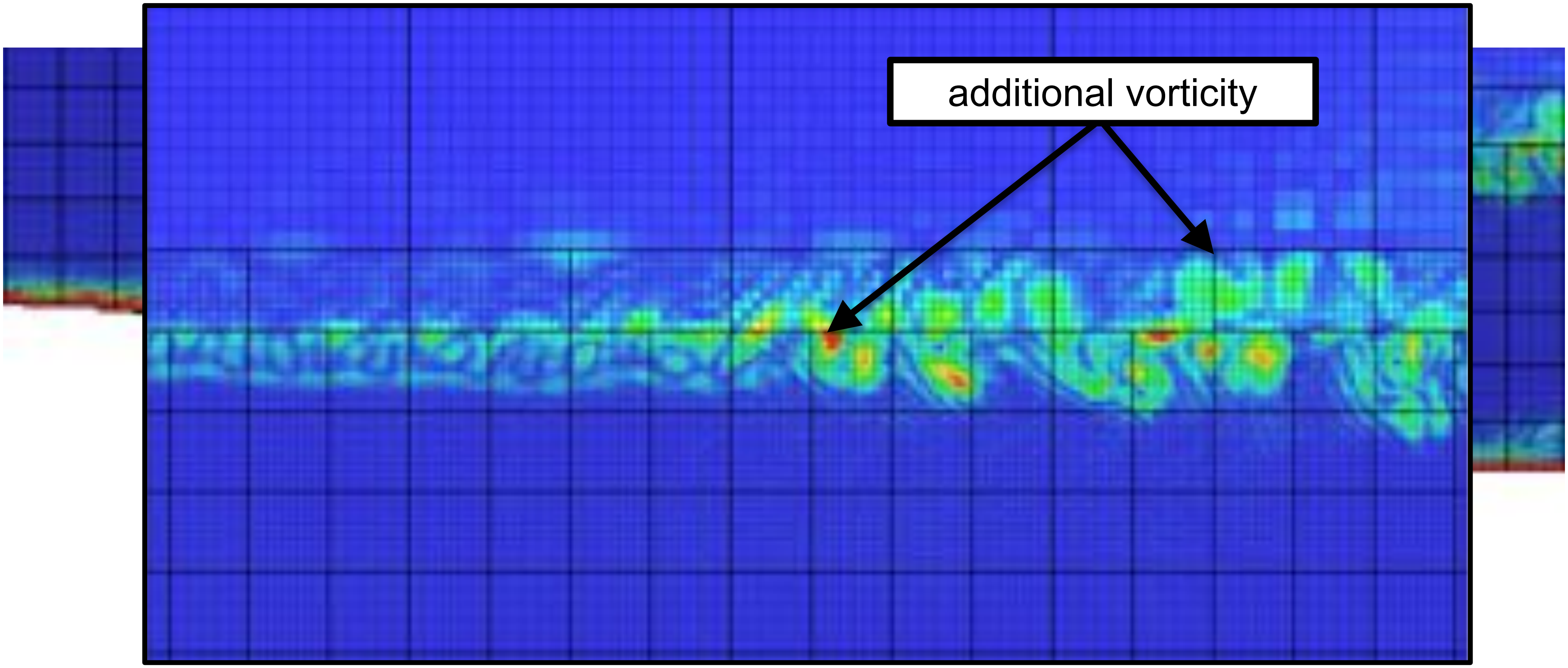




- ✓ Total of 5 Levels with
- ✓ Refinement ratio of 2
- ✓ Level 3 in regions of high vorticity
- ✓ Level 4 on all viscous walls
- ✓ Level 5 from x/c = -0.2 to 1.3
- ✓ 105 million points
- ✓ Spanwise extend 0.2 chord
- ✓ $dy^+ \approx 50$ in wall normal direction

NASA 2-D Hump – Application of Lattice Boltzmann

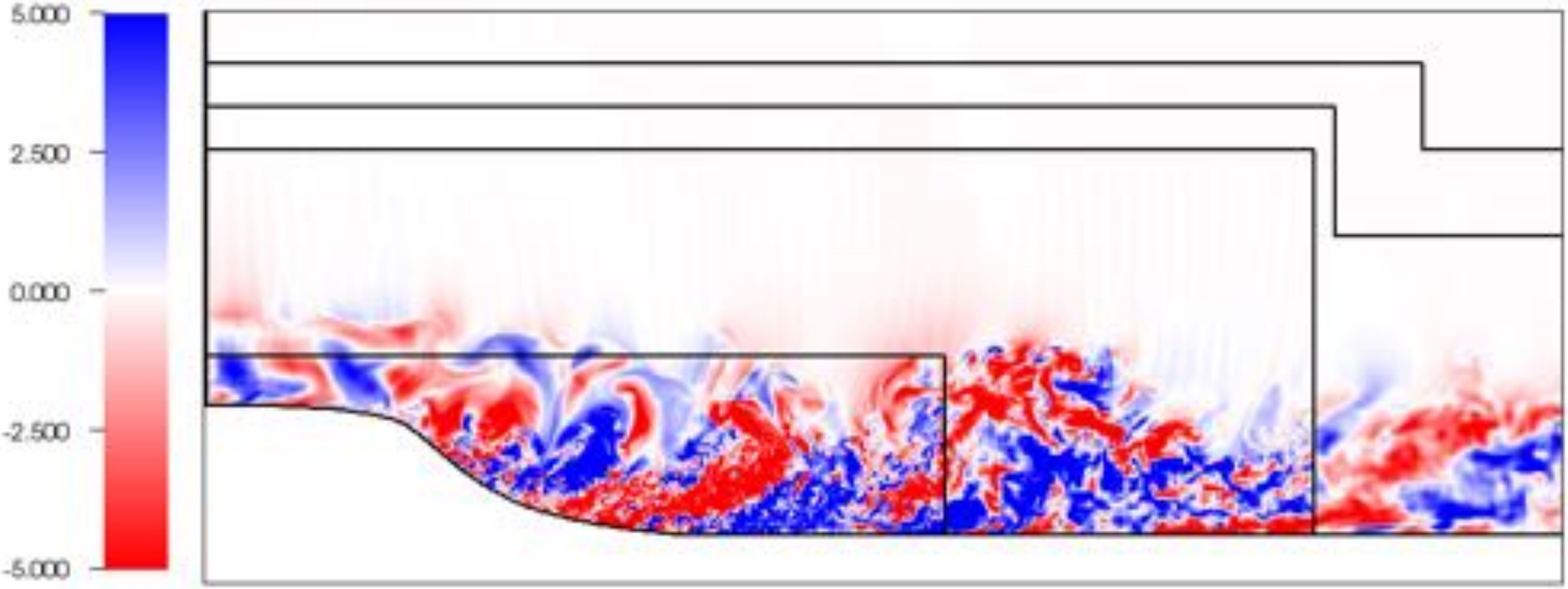
- ✓ The use of local mesh refinement has proven very challenging in Lattice-Boltzmann for higher Reynolds number cases
- ✓ Current implementation was not precisely conserving mass, momentum and energy. This has previously not been a problem



NASA 2-D Hump – Conservative Coarse Fine Algorithm

Modified algorithm based on Rhode et. al. (2006) and Schornbaum et. al. (2015)

Spanwise velocity across multiple grid interfaces

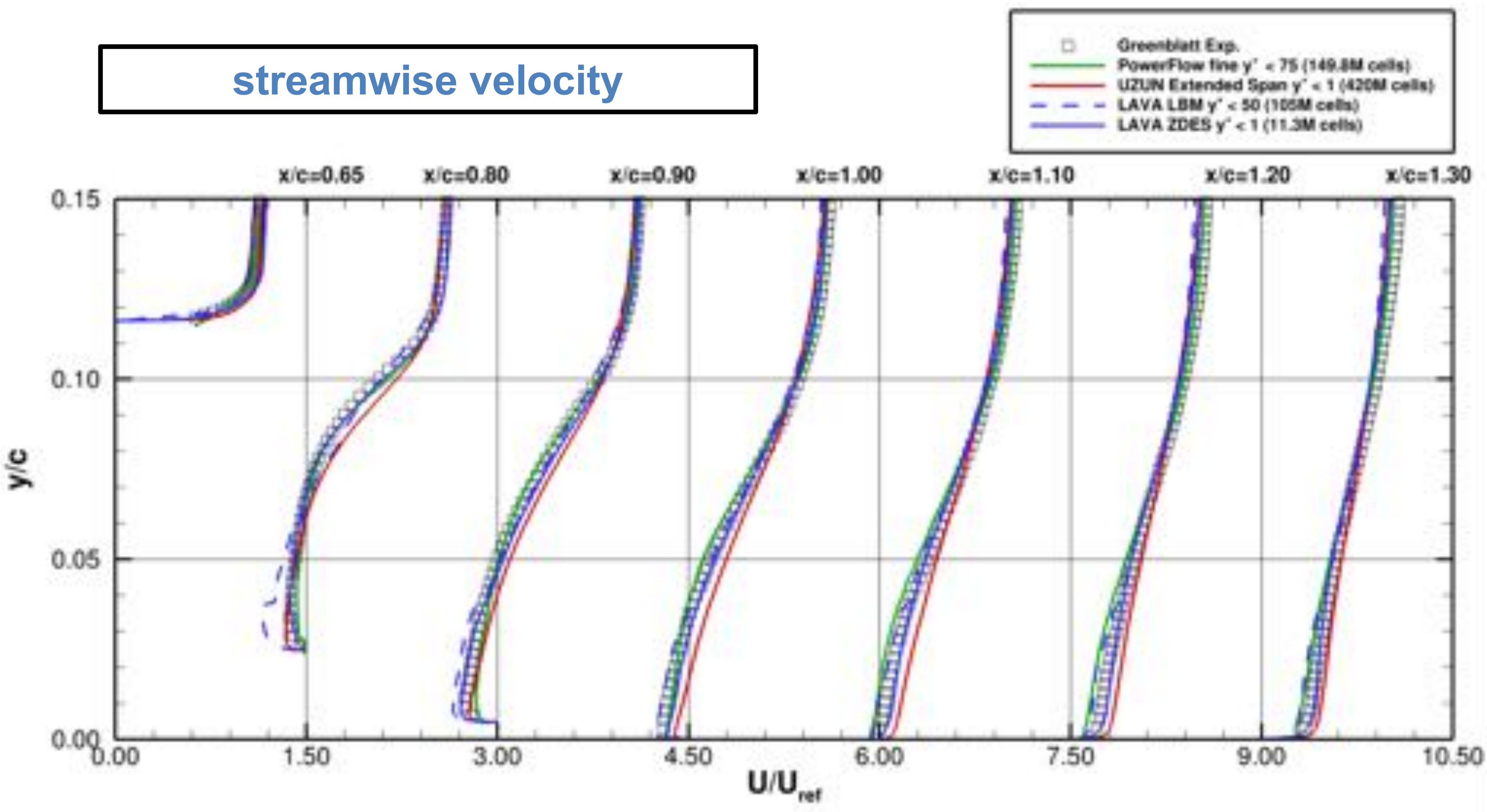


- ✓ Corse-fine inner level communication improved with discrete conservation
- ✓ No excess vorticity/velocity created at the coarse-fine interface

Future work:

- ✓ Implement higher order inter level communication

NASA 2-D Hump – Application of Lattice Boltzmann



✓ Further improvement in coarse fine interface operation necessary

Summary

Overset Curvilinear:

- ✓ Excellent agreement with state-of-the-art wall-resolved LES (Uzun) achieved with a significant smaller mesh (11.3M ZDES vs 420M WR-LES).
- ✓ DDES over-predicts the shear-layer strength and causes a spurious inner-layer attached region.
- ✓ Some sensitivity to interface height for ZDES Mode 3 has been observed.

Cartesian Lattice Boltzmann:

- ✓ Hump case has proven to be very challenging on a Cartesian mesh, accurate wall-model crucial for accuracy and efficiency.
- ✓ Coarse-Fine interface very sensitive at higher Reynolds-number, conservative interface necessary.
- ✓ Good agreement achieved once coarse-fine interface was improved and enough grid resolution was provided.

Future work:

- ✓ Add sensor to determine local boundary layer thickness for defining the interface location in ZDES Mode 3.
- ✓ Further enhance wall-models in LBM implementation for higher Reynolds-numbers, e.g. filtered wall-model and equilibrium wall model.
- ✓ Add higher order accurate coarse-fine interface operations.
- ✓ Implement a hybrid RANS-LBM model to add modeled stress in highly under resolved regions.

Acknowledgments

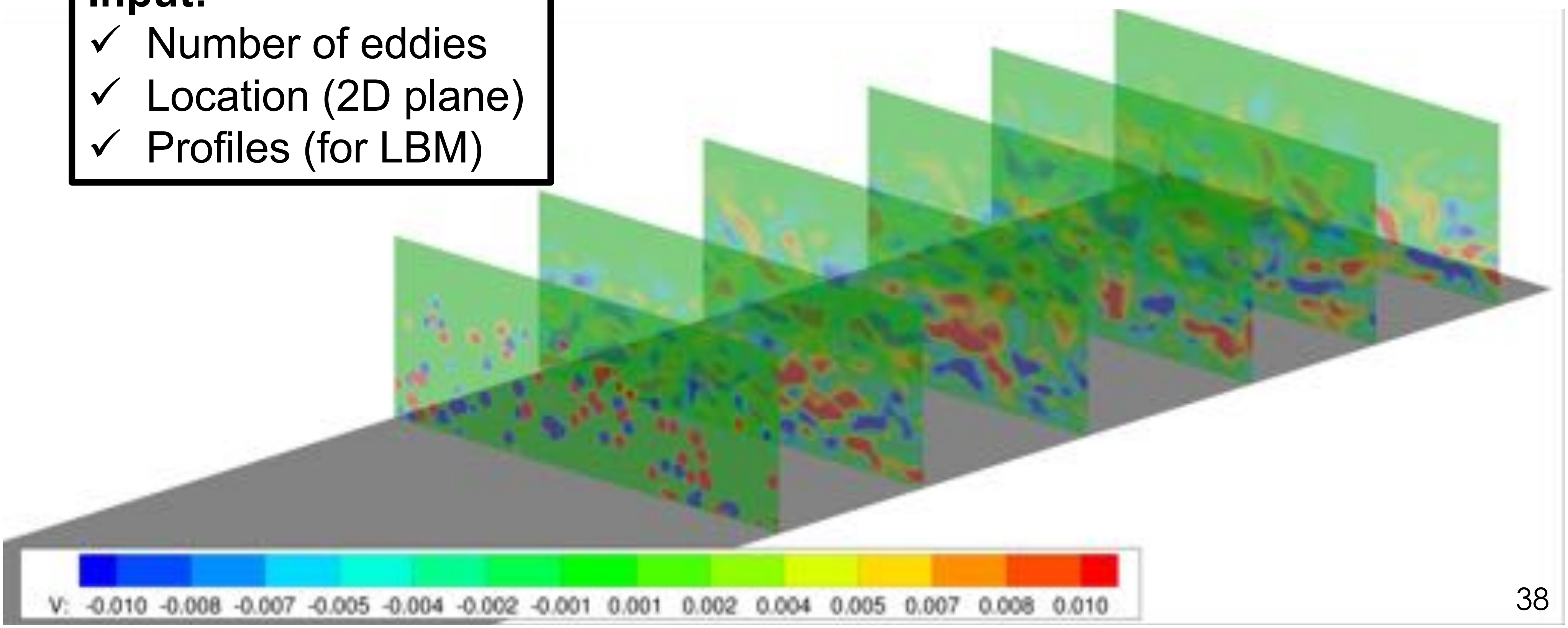
- ✓ This work was partially supported by the NASA ARMD's Transformational Tools and Technologies (T^3) and Advanced Air Transport Technology (AATT) projects
- ✓ LAVA team members in the Computational Aerosciences Branch at NASA Ames Research Center for many fruitful discussions
- ✓ Tim Sandstrom (optimized ray-tracing kernels, and particle visualizations) NASA Ames Research Center
- ✓ Computer time provided by NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center

Questions?

Computational Methodology: Synthetic Eddy Method (SEM)

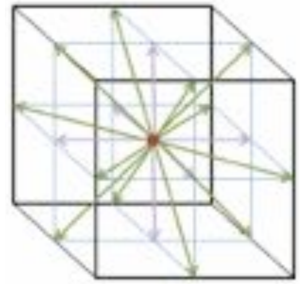
- ✓ When transitioning from RANS to LES in wall-bounded flows it is necessary to insert meaningful 3D content at the interface
- ✓ The synthetic eddy method (SEM) is one approach which adds eddies such that first and second order turbulent statistics can be recovered.
- ✓ Can also be modified to be used as a turbulent inflow condition for Lattice Boltzmann

Input:
- ✓ Number of eddies
- ✓ Location (2D plane)
- ✓ Profiles (for LBM)



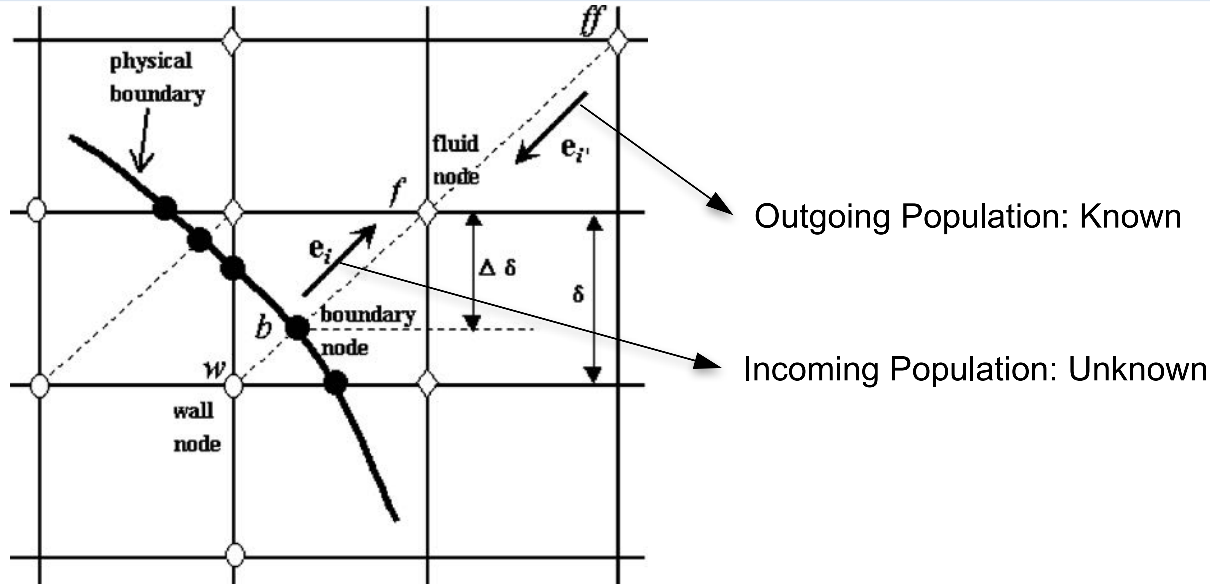
Computational Methodology:
Lattice Boltzmann Method - Governing Equations

$$\underbrace{f_i(\vec{x}+c\vec{e}_i\Delta t, t+\Delta t) - f_i(\vec{x},t)}_{\text{Streaming}} = \underbrace{\frac{1}{\tau}(f_i(\vec{x},t) - f_i^{eq}(\vec{x},t))}_{\text{Collision}}$$



- **Physics:**
  - Governs space time evolution of Density Distribution Functions
  - Equilibrium distribution functions are truncated Maxwell-Boltzmann distributions
  - Relaxation time related to kinematic viscosity
  - Pressure related to density through the isothermal ideal gas law
  - Lattice Boltzmann Equations (LBE) recover the Navier-Stokes equations in the low Mach number limit
- **Numerics:**
  - Extremely efficient 'collide at nodes and stream along links' discrete analog to the Boltzmann equation
  - Particles bound to a regularly spaced lattice collide at nodes relaxing towards the local equilibrium (RHS)
  - Post-collision distribution functions hop on to neighboring nodes along the lattice links (LHS) – Exact, dissipation-free advection from simple 'copy' operation
  - Macroscopic quantities such as density and momentum are moments of the density distribution functions in the discrete velocity space

Computational Methodology:
Lattice Boltzmann Method – Embedded Geometry



- Boundary conditions in LBM are simple rules that relate ‘incoming’ populations to ‘outgoing’ populations for lattice links intercepted by an embedded surface
- **Standard Bounce Back** (SBB): ‘Bounce-back’ rule realizes the no-slip boundary condition,` but approximates the curved geometry by a series of small steps.
- **Linear Bounce Back** (LBB): Interpolated no-slip bounce-back rules (cf. Bouzidi et al. (POF, 01)) capture the curvature in geometry more accurately. Improved prediction of surface pressure fluctuations, critical for accurate acoustic predictions.
- **Halfway Bounce Back** (HBB) rule of A. C. Ladd (JFM, 94) generalized to be second-order accurate for arbitrary geometry (stationary and moving) and adapted for wall models using a generalized slip algorithm for realizing the appropriate momentum exchange.

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