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

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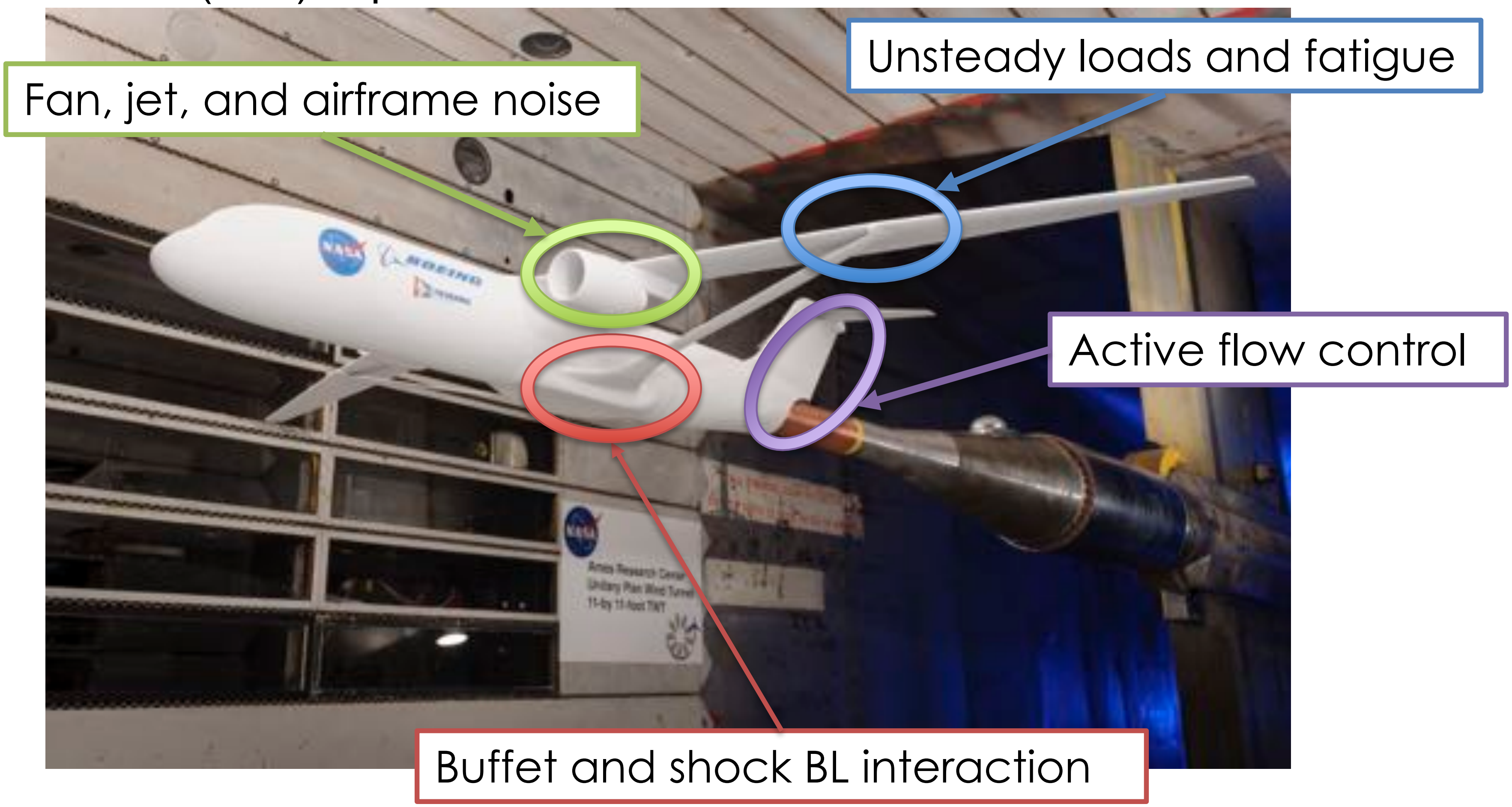
Outline

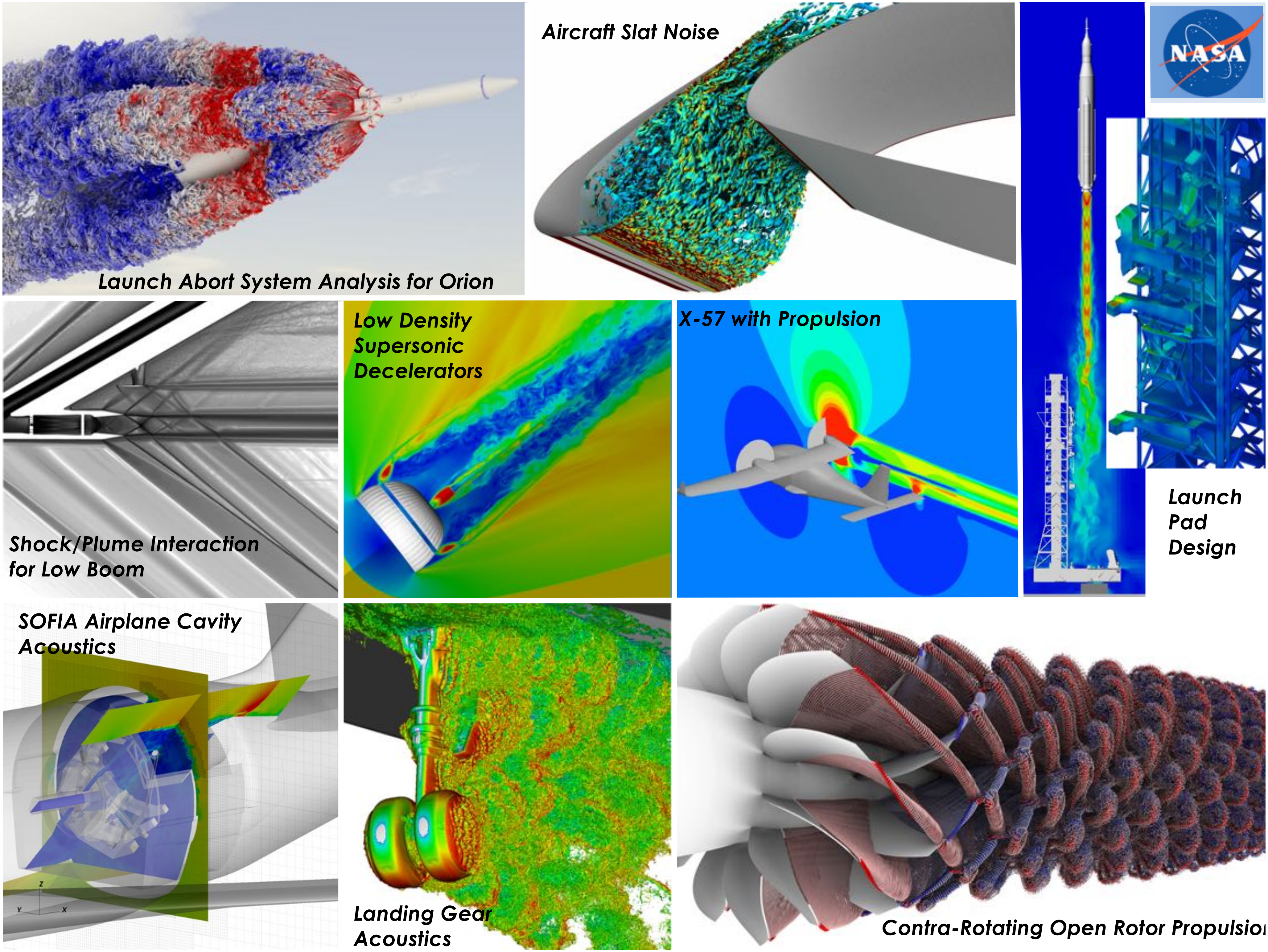
- ✓ **Motivation**
- ✓ **Computational Methodology and Framework**
  - Structured Overset Curvilinear
    - Hybrid RANS/NLES, DDES, ZDES Mode 3
  - Cartesian Lattice Boltzmann Method (LBM)
- ✓ **NASA RCA propulsion case**
  - Round Jet SP7
    - uRANS, DDES, Hybrid RANS/NLES
- ✓ **NASA RCA separated flow case**
  - 2-D NASA Hump
    - RANS, DDES, 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.**

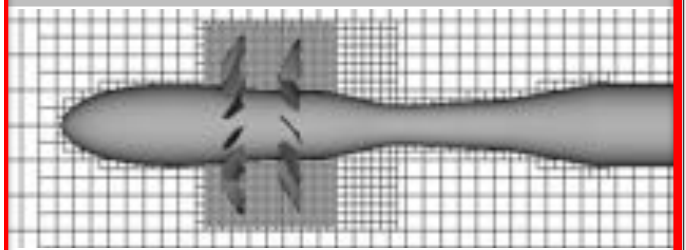
- The next frontier is to use wall modeled and/or wall resolved large-eddy simulation (LES) to predict:




Launch Abort System Analysis for Orion
Aircraft Slat Noise
NASA
Launch Pad Design
Shock/Plume Interaction for Low Boom
Low Density Supersonic Decelerators
X-57 with Propulsion
SOFIA Airplane Cavity Acoustics
Landing Gear Acoustics
Contra-Rotating Open Rotor Propulsio

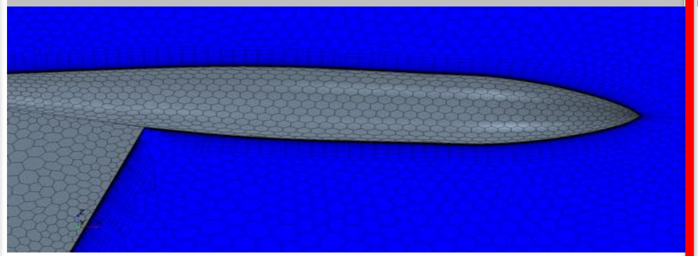
Computational Grid Paradigms

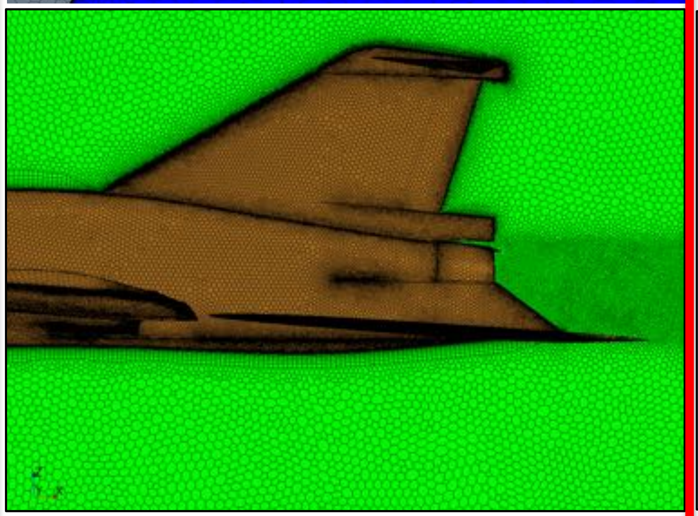
Structured Cartesian AMR



- 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

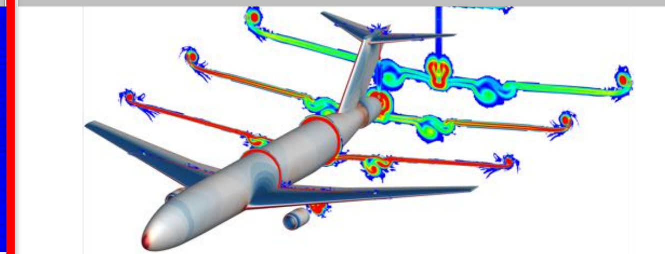
Unstructured Arbitrary Polyhedral

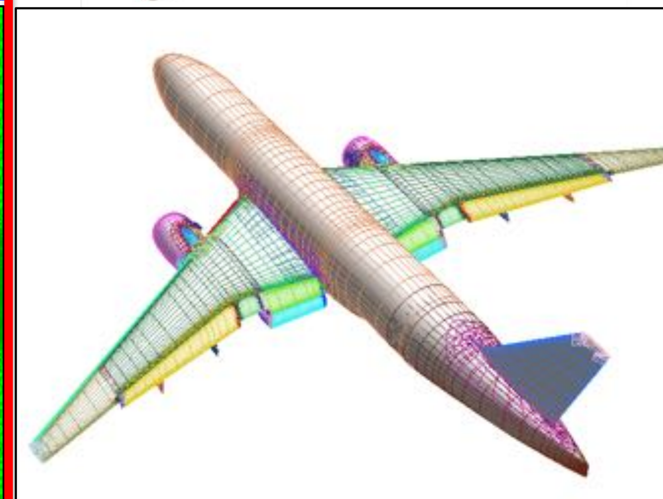




- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

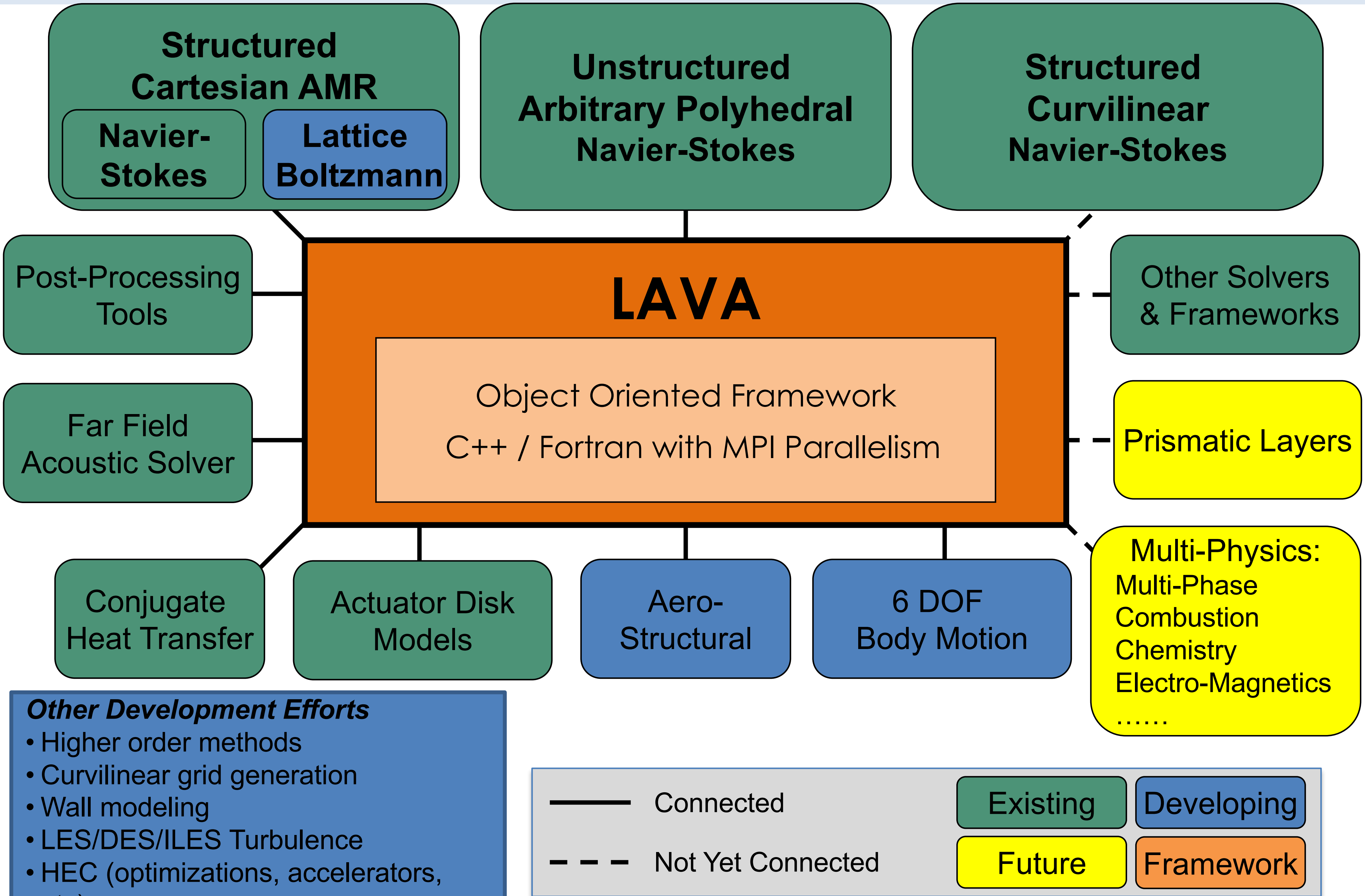
Structured Curvilinear





- 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



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

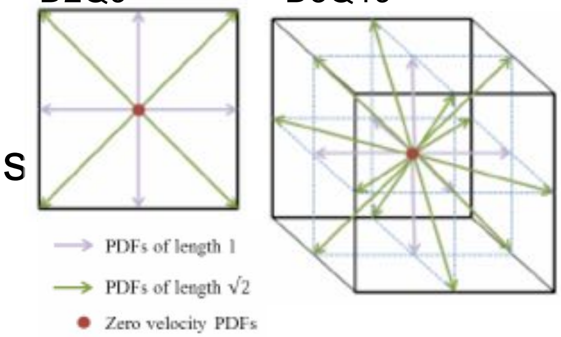
Hybrid RANS/LES Models

- ✓ 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)*
- ✓ Zonal RANS-NLES (numerical LES) with user selected zones of URANS, NLES, and wall-distance based hybrid RANS-NLES *(Housman et al. AIAA-2017-3213)*

Synthetic Eddy Method (SEM) *(Jarrin et al. Int. Journal of Heat and Fluid Flow 30)*

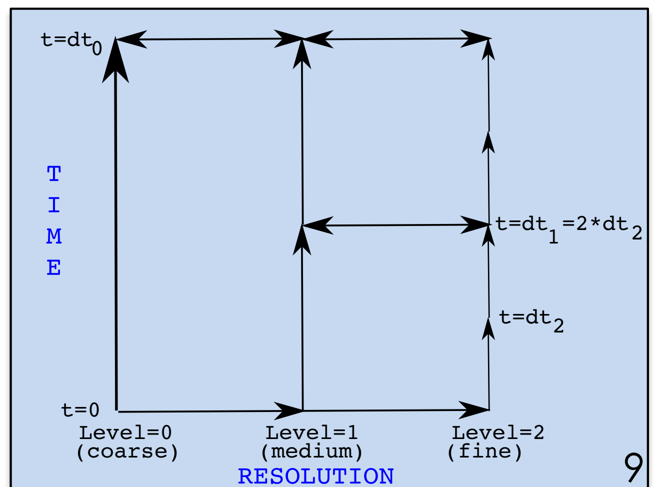
Computational Methodology: Lattice Boltzmann Method – Current Status

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

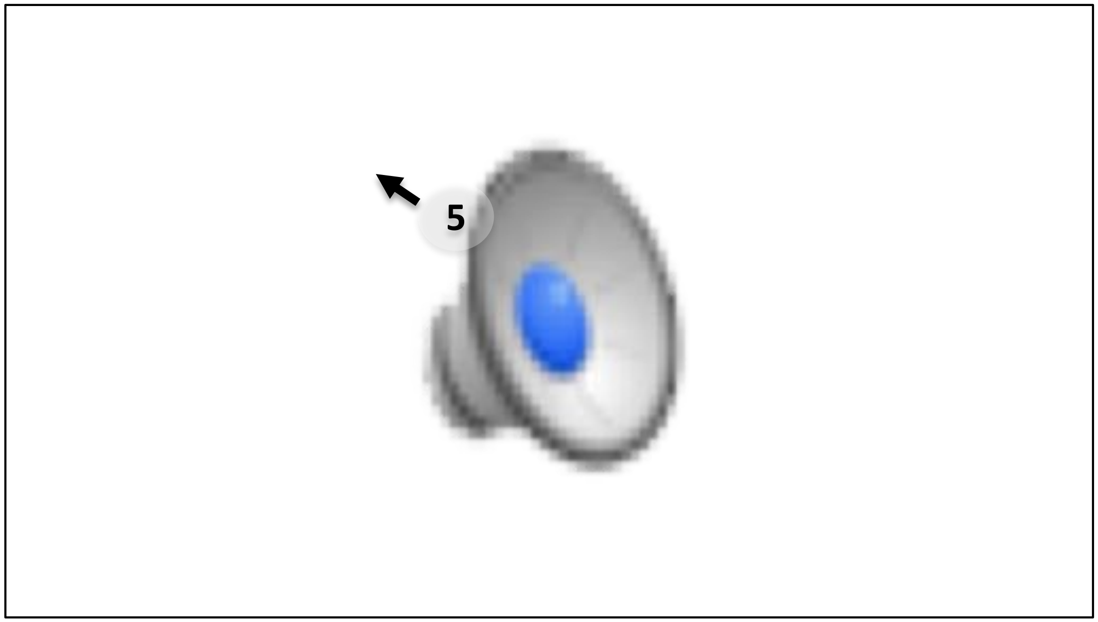


D2Q9 = 2D w/ 9-velocities…

- 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)

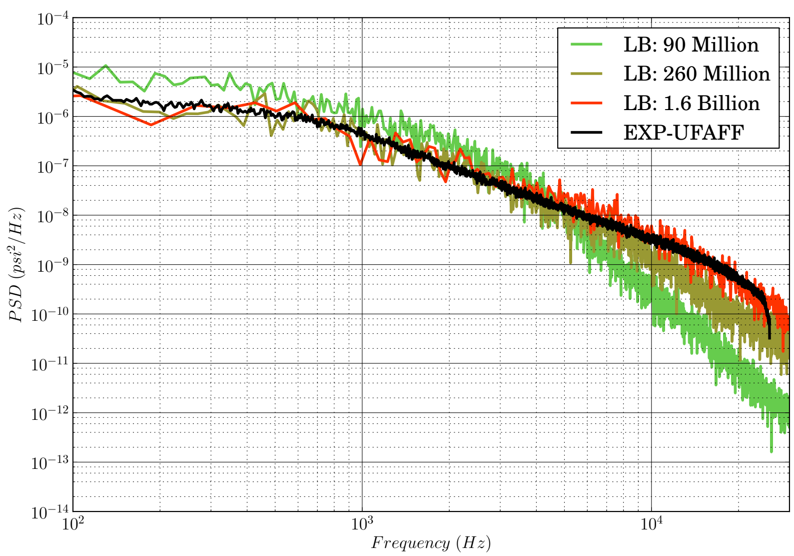


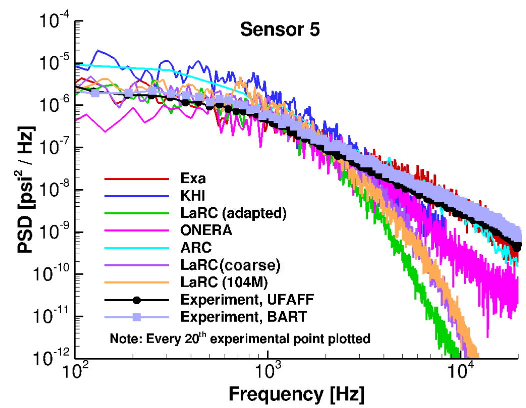
LBM @ 1.6 billion – Velocity Magnitude at Centerline

"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





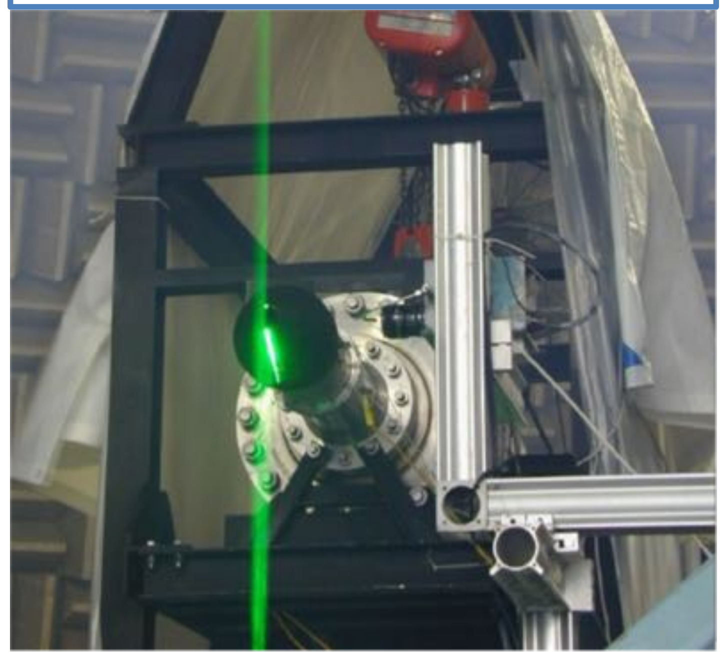
https://info.aiaa.org/tac/ASG/FDTC/DG/BECAN_files_/BANCIII.htm

Round Jet – Experimental Setup SP7

- ✓ Experiment performed by Bridges and Wernet using the Small Hot Jet Acoustic Rig (SHJAR) at NASA Glenn
- ✓ Baseline axisymmetric convergent Small Metal Chevron (SMC000) nozzle at Set Point 7 (SP7)
- ✓ Nozzle axis in downstream flow direction is marked as 180°

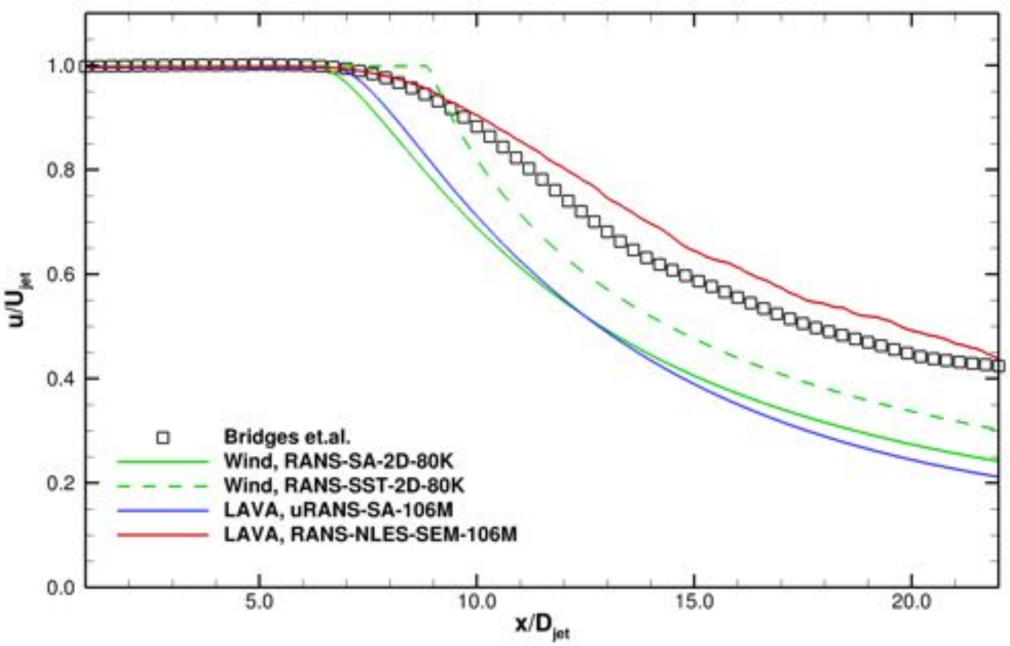
Bridges et. al. (NASA-TM-2011-216807)	**SP7**
Acoustic Mach number U_{jet}/c_{∞}	0.9
Jet temperature ratio T_e/T_{∞}	0.835
Nozzle pressure ratio p_t/p_{∞}	1.861
Nozzle Diameter D	0.0508 [m] 2.0 [inch]
Reynold number Re_D	1 Million
Reynolds number Re_{τ}	800
Boundary layer thickness	0.0128 D

PIV measurement device



Similar conditions were analyzed in Bres *et. al.* AIAA-2015-2535, but the boundary layer thickness is 5.5 times smaller in this study

Round Jet - Objective & Metrics



solver	x/D_j [-]	Error [%]
Bridges & Wernet	7.8	-
Wind, RANS-SA-2D	6.84	-12.3
Wind, RANS-SST-2D	9.01	15.5
LAVA, uRANS-SA-3D	7.22	-7.5
LAVA, RANS-NLES-SEM-3D	**7.90**	**1.2**

89.6% improvement

Objective:

- ✓ Improvements in prediction of jets (including developing region, the effect of compressibility, and the effect of temperature).

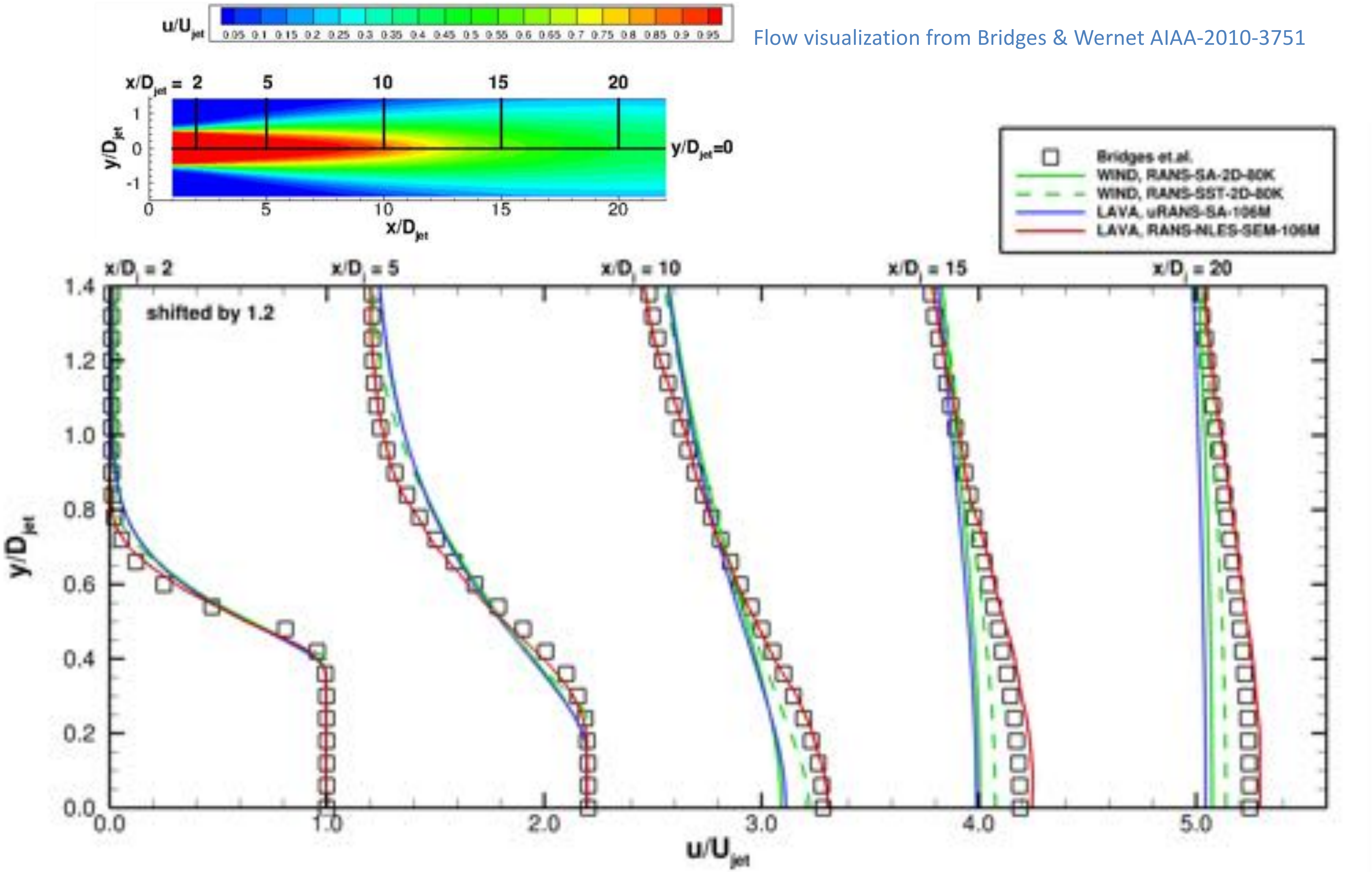
Metrics:

- ✓ Length of the potential core (where $u/U_{jet} = 0.98$)
- ✓ Value and location of the peak turbulent kinetic energy on c
- ✓ M s
- ✓ Reynolds stress fields

[1] Wind Data, Objectives and Metrics from NASA Turbulence Modeling Resource (TMR) website: https://turbmodels.larc.nasa.gov

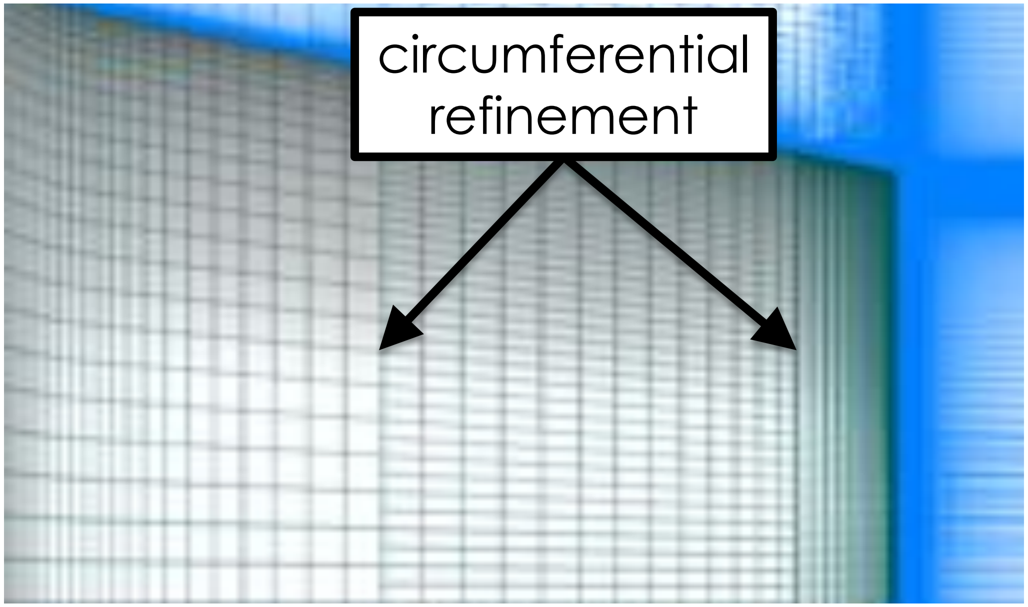
Round Jet - Objective & Metrics

Flow visualization from Bridges & Wernet AIAA-2010-3751

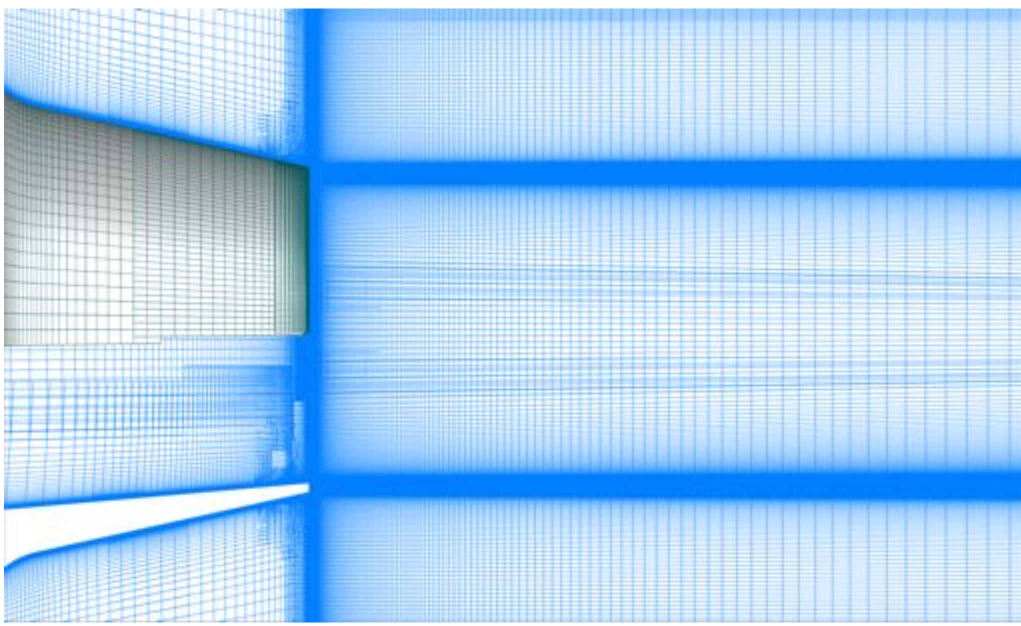


✓ Mean velocity field at locations downstream of nozzle exit shifted by 1.2

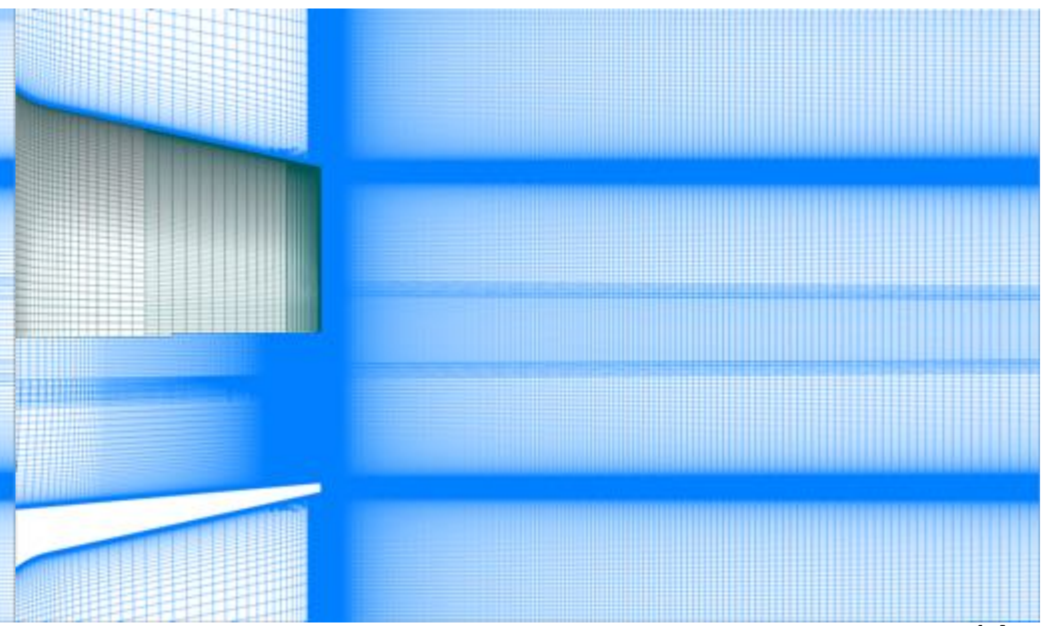
Round Jet – Structured Overset Grid



- ✓ Coarse (28 M) and Refined (106 M) grid point meshes were generated
- ✓ Seven point overlap
- ✓ No orphan points
- ✓ Minimum stencil quality 0.9
- ✓ Localized circumferential refinement at specified axial and radial locations

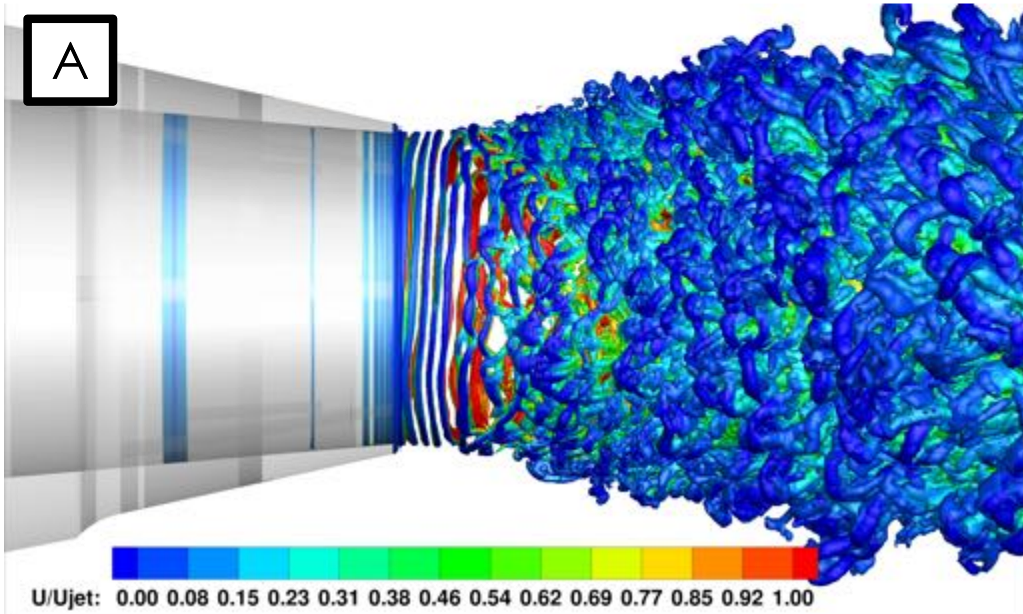


Coarse (28 M)

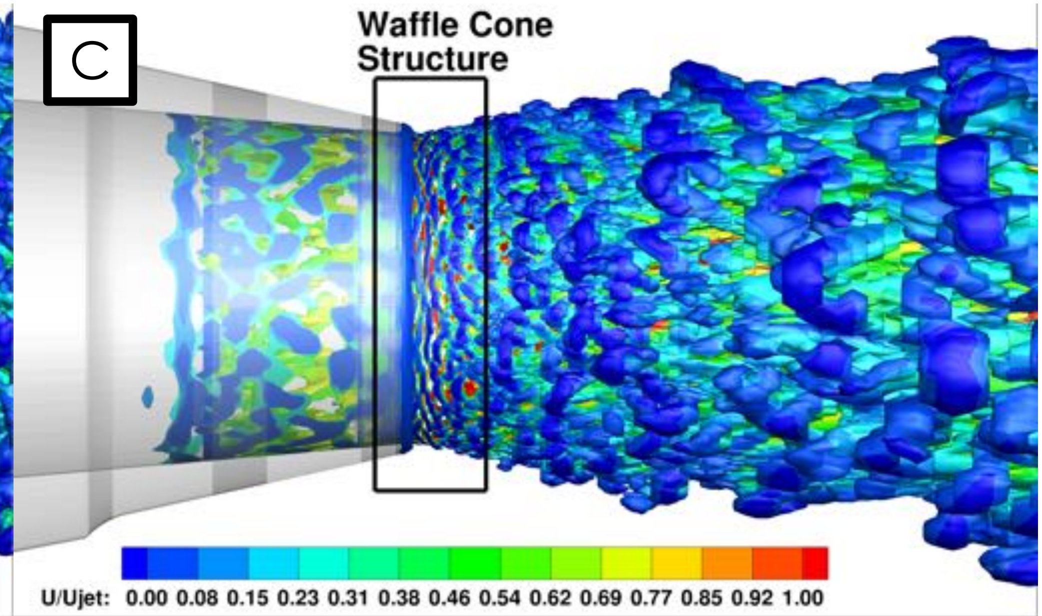


Refined (106 M)

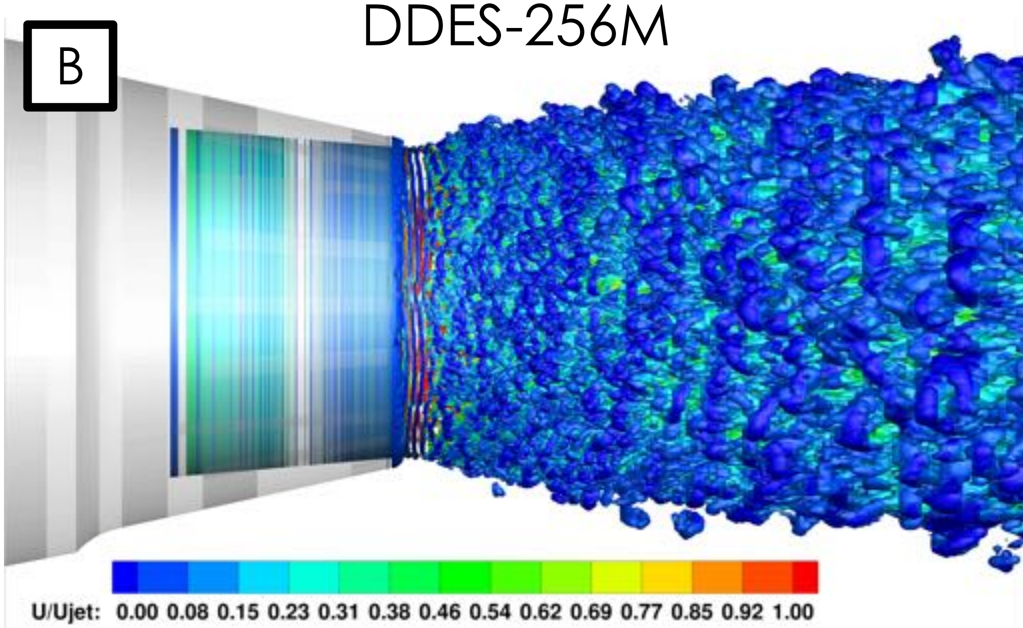
Round Jet - Computational Results



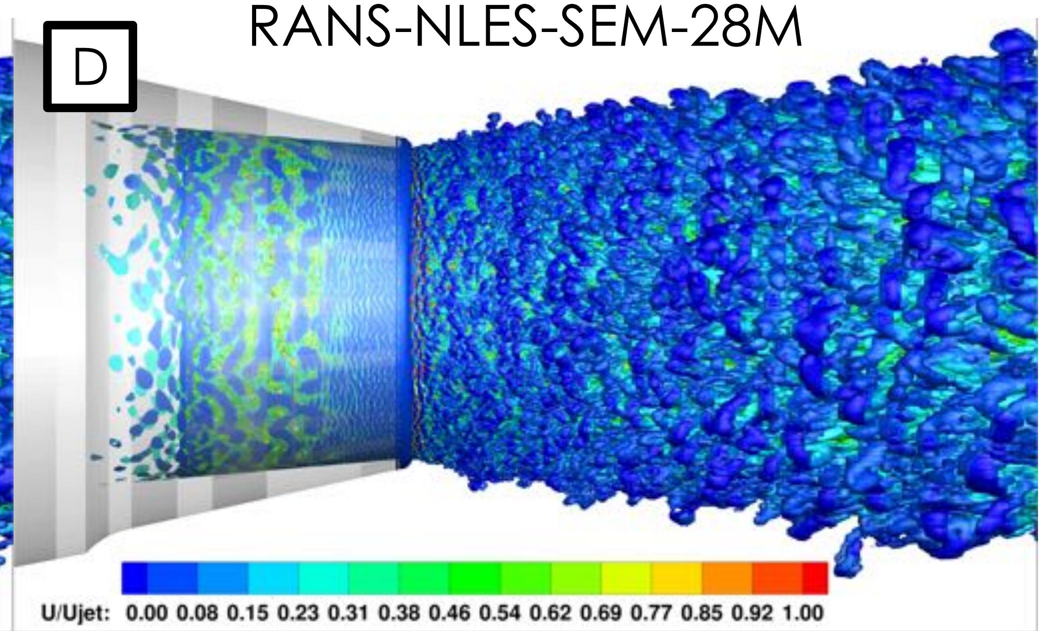
DDES-256M



RANS-NLES-SEM-28M



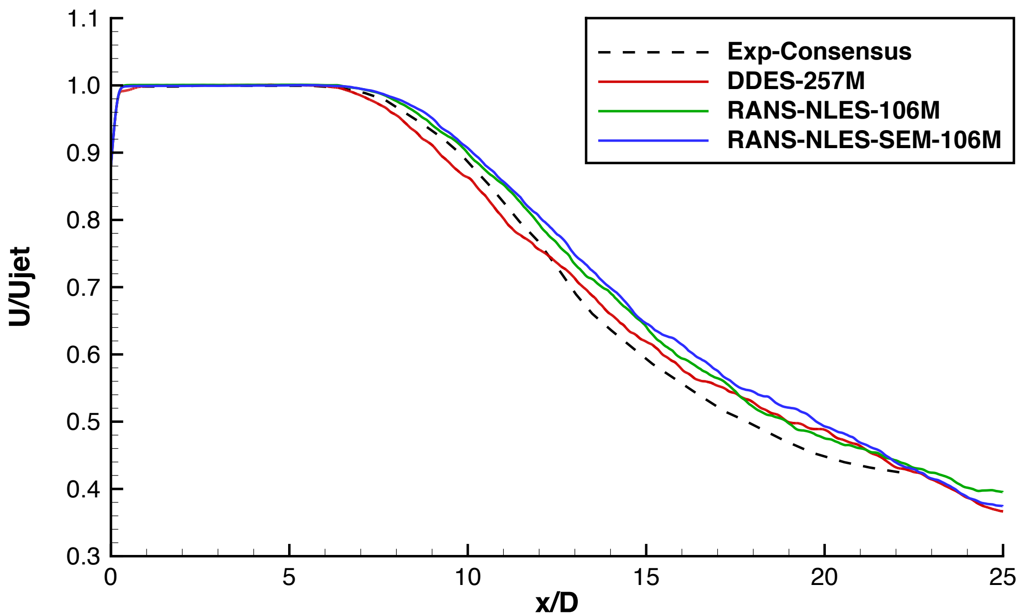
RANS-NLES-106M



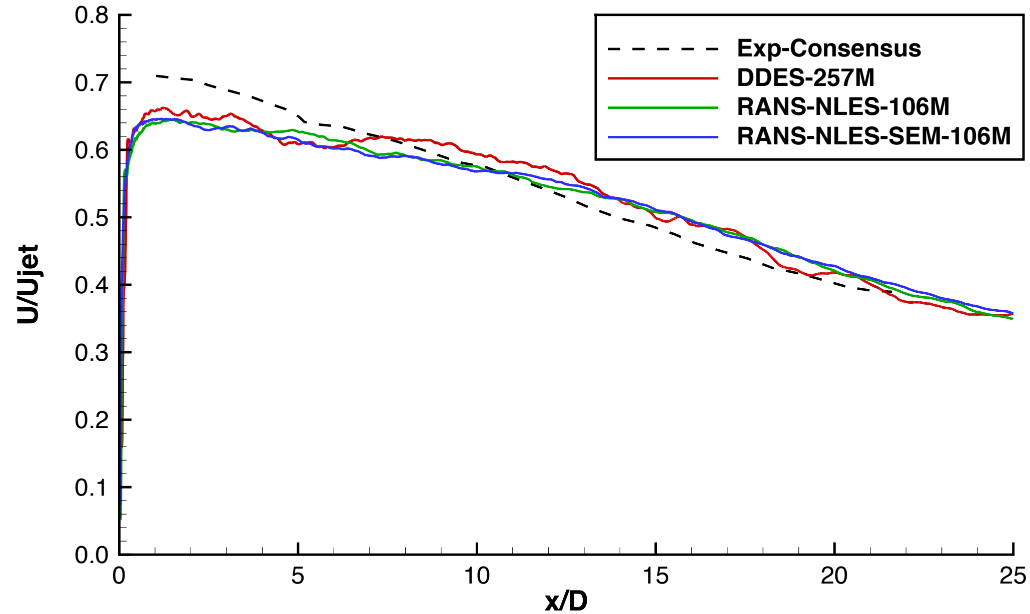
RANS-NLES-SEM-106M

Round Jet – Near-Field Results

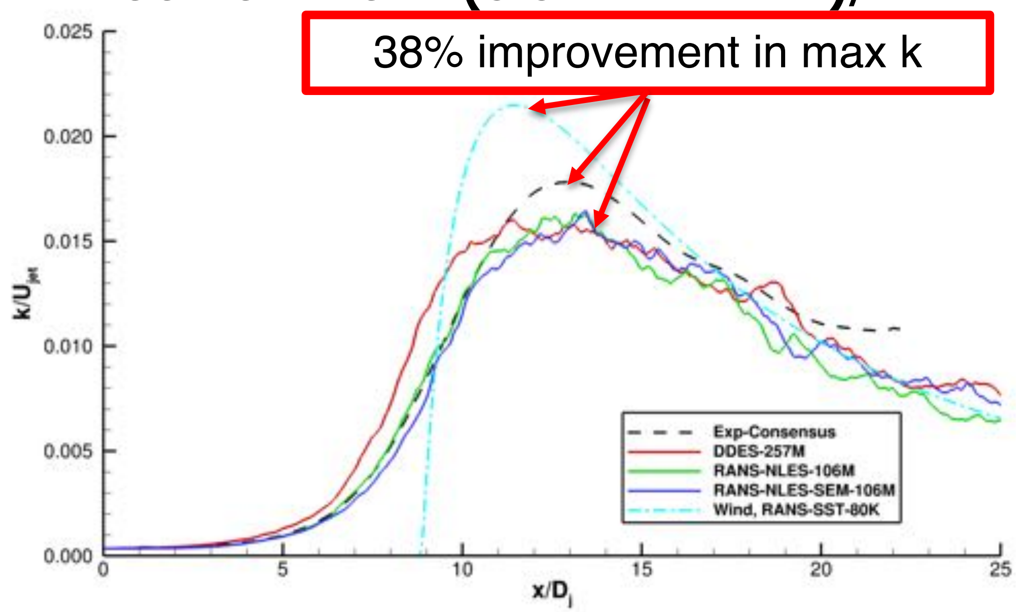
Time-averaged center-line velocity



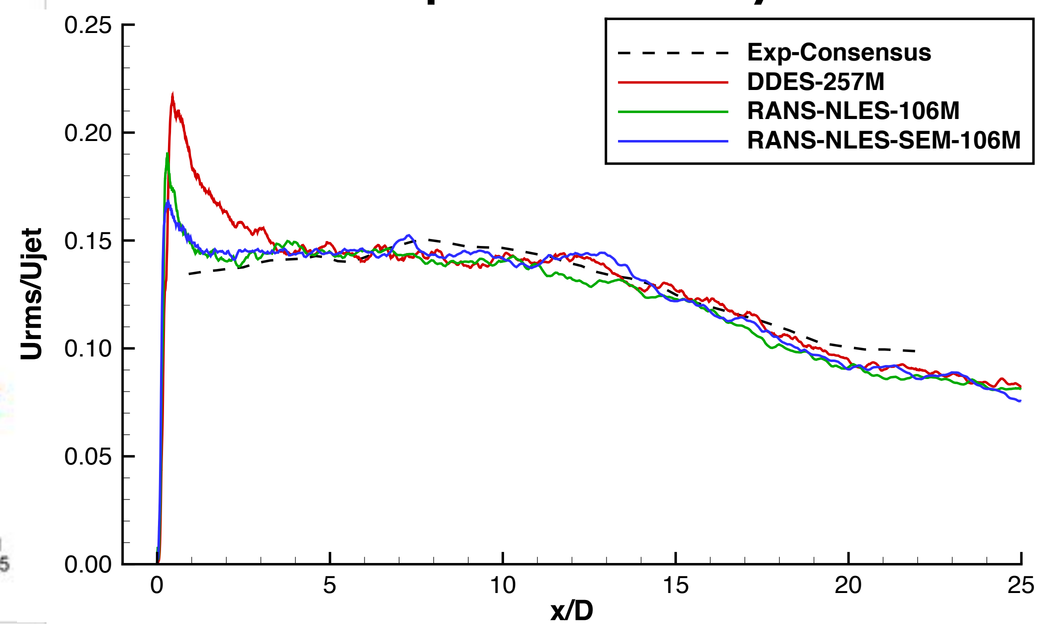
Time-averaged lip-line velocity



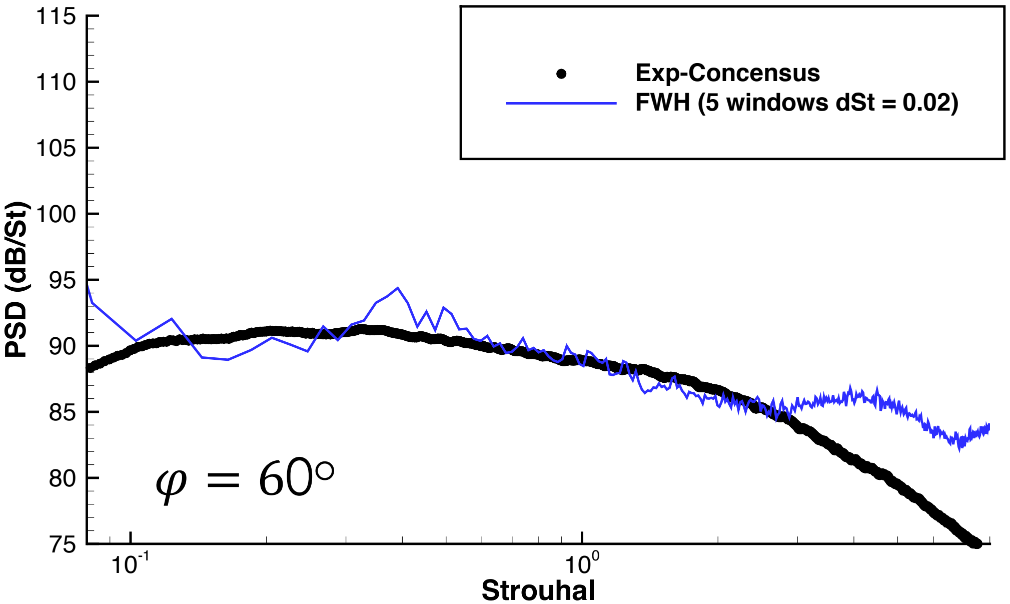
center-line k=(u'u'+v'v'+w'w')/2

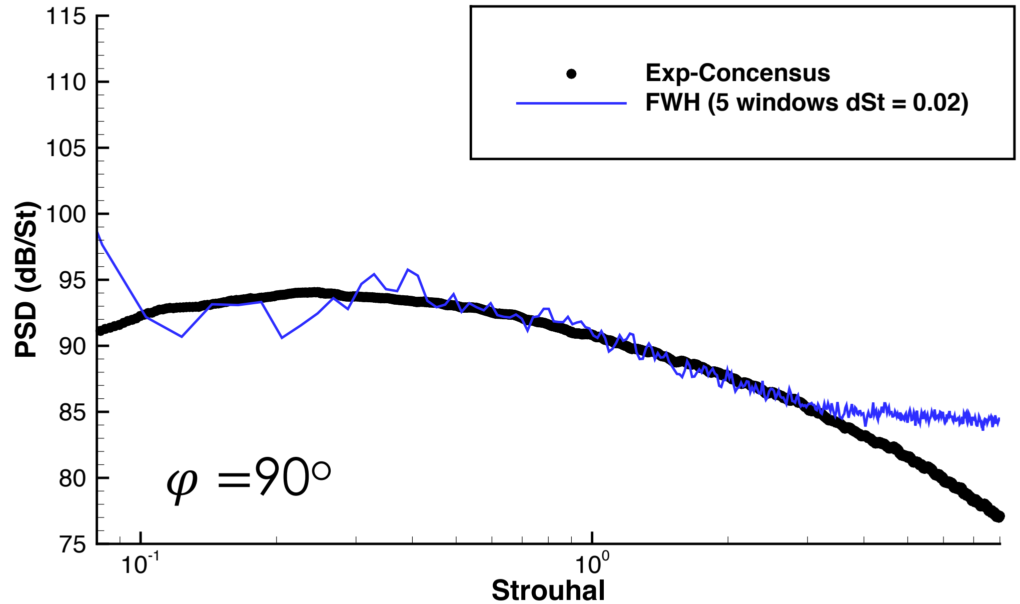


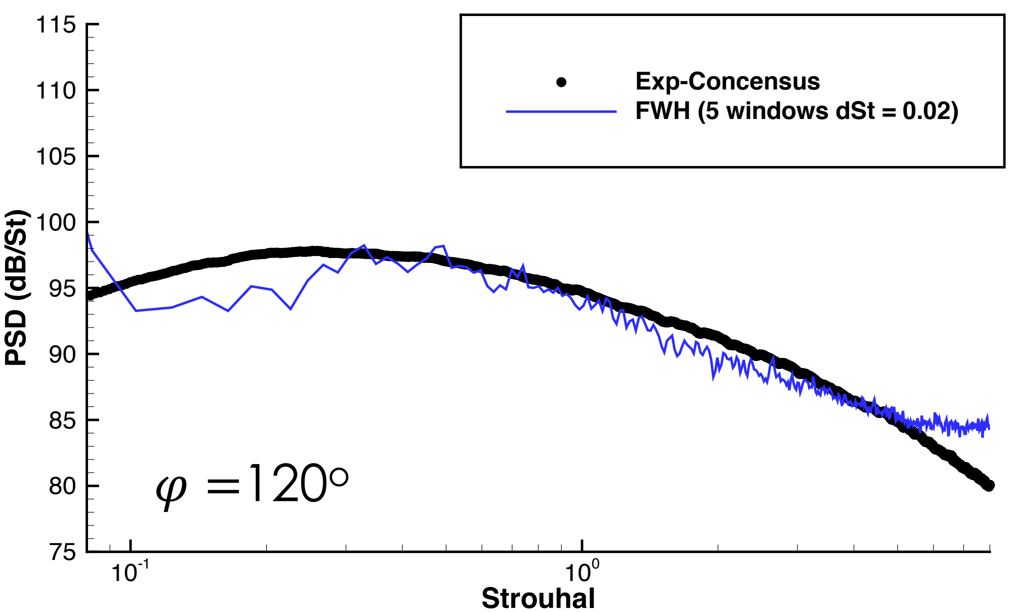
RMS lip-line velocity

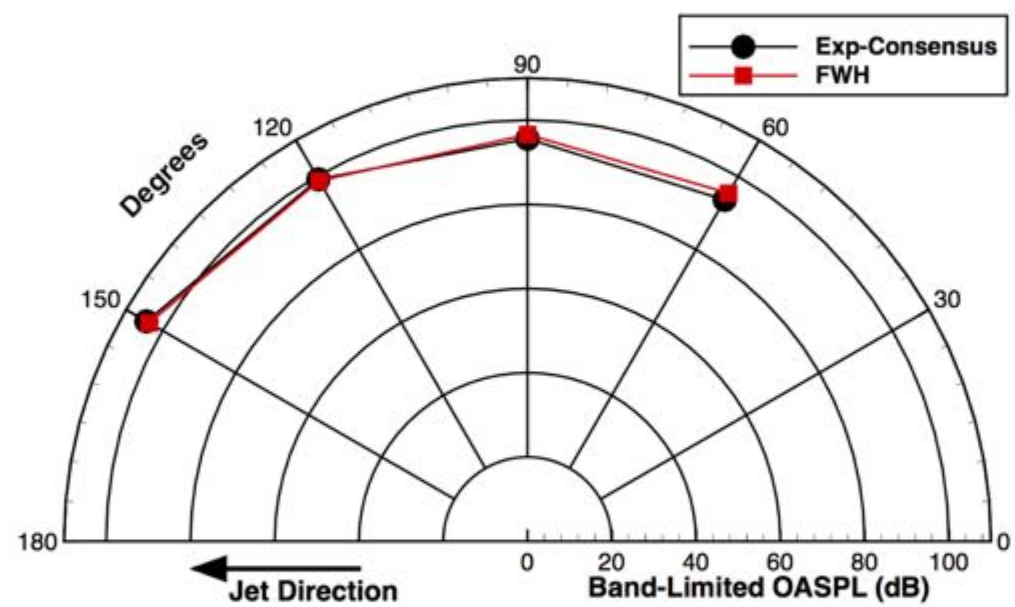


Round Jet – Far Field at 100D



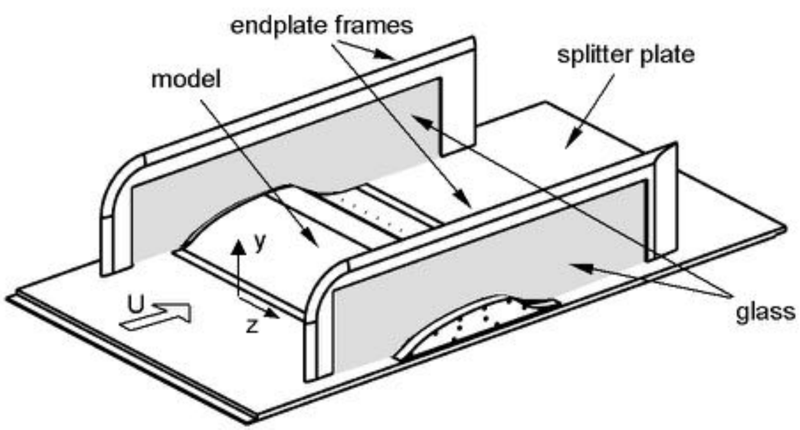






NASA 2-D Hump – Experimental Setup

- ✓ 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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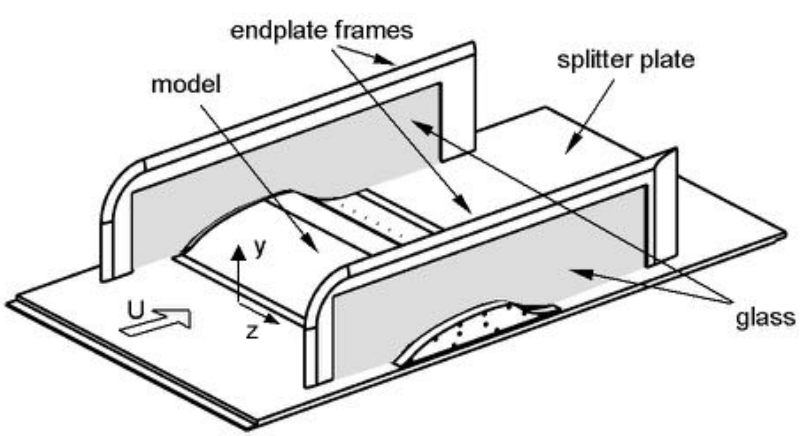


Wall-resolved LES:

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

Wall-modeled LES:

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

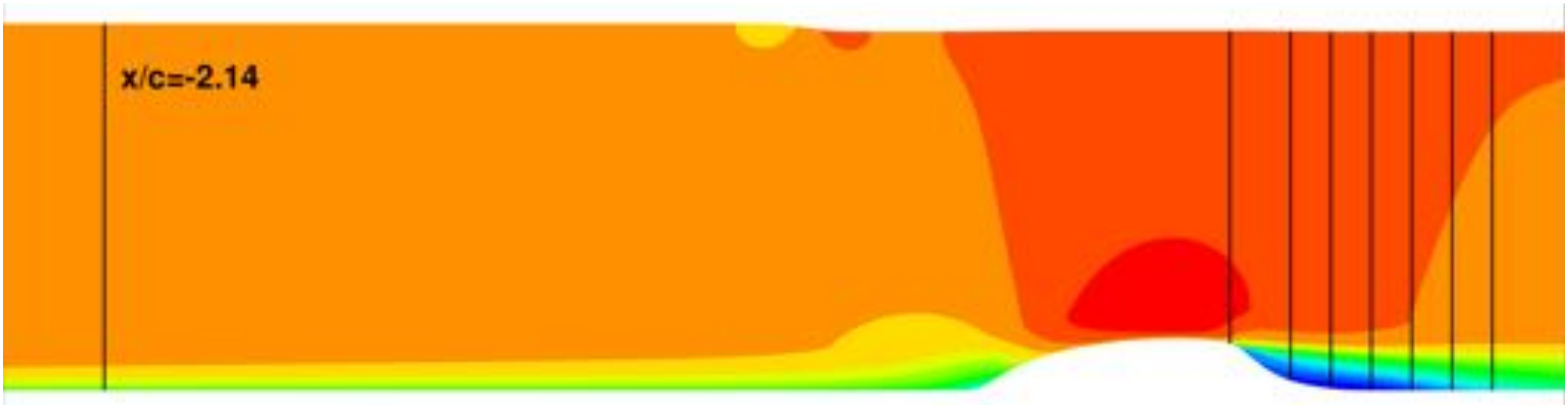
Lattice Boltzmann Methods:

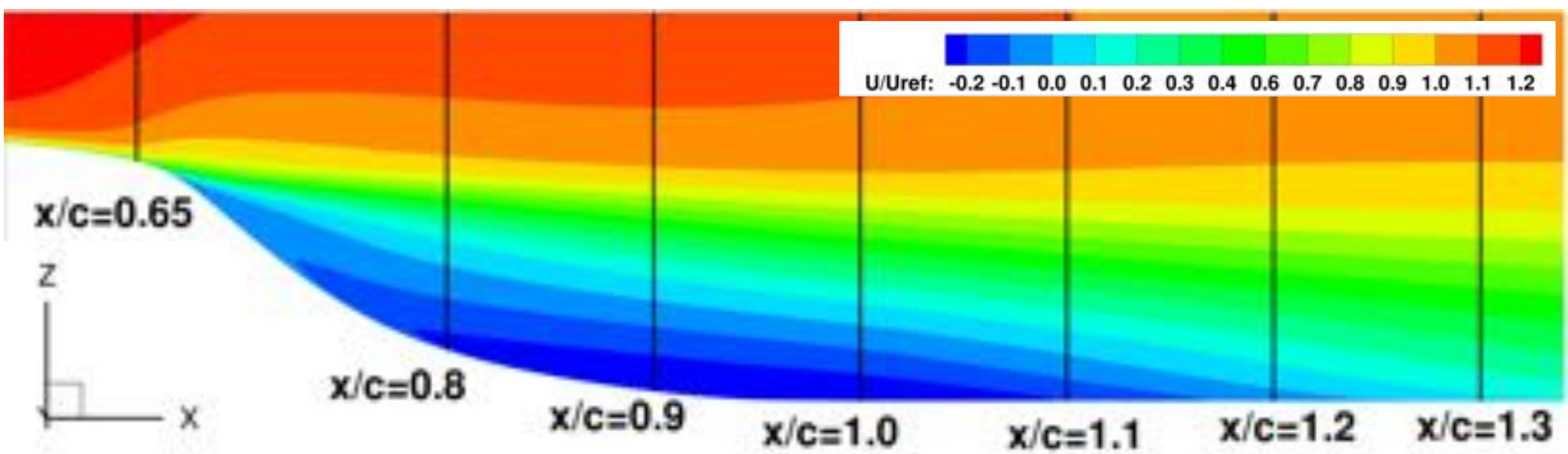
✓ Duda, B. and Fares, E. (AIAA 2016-1836)

[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
[3] Rumsey C, "CFD Validation of Synthetic Jets and Turbulent Separation Control", http://cfdval2004.larc.nasa.gov

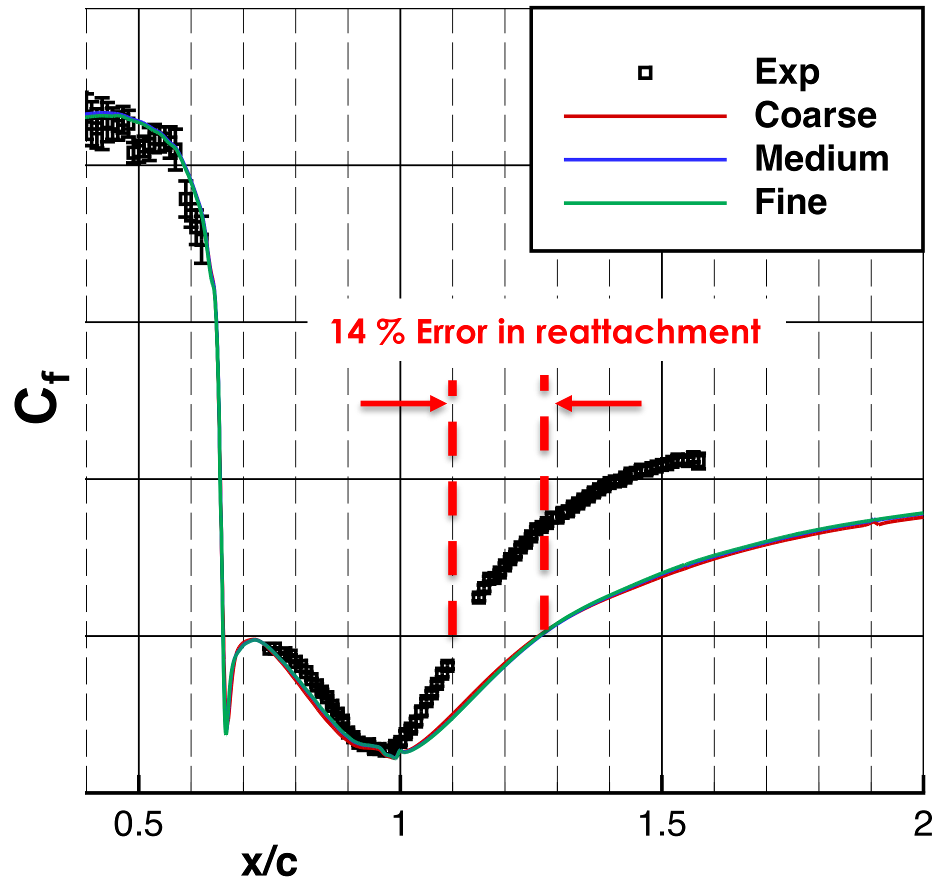
NASA 2-D Hump

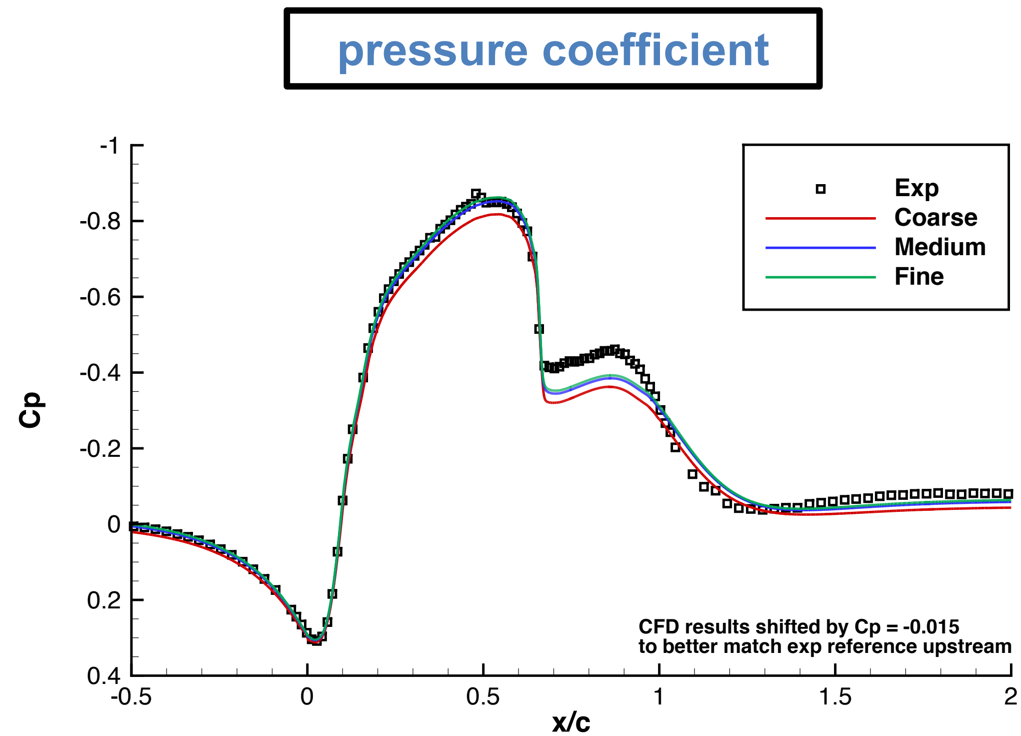
- ✓ Mach = 0.1 ; chord C = 0.42 [m] ; Re_C = 936,000 ; T_{ref} = 298.3 [K]
- ✓ Top wall contoured to mimic side-wall effect
- ✓ Experimental data at locations marked below available





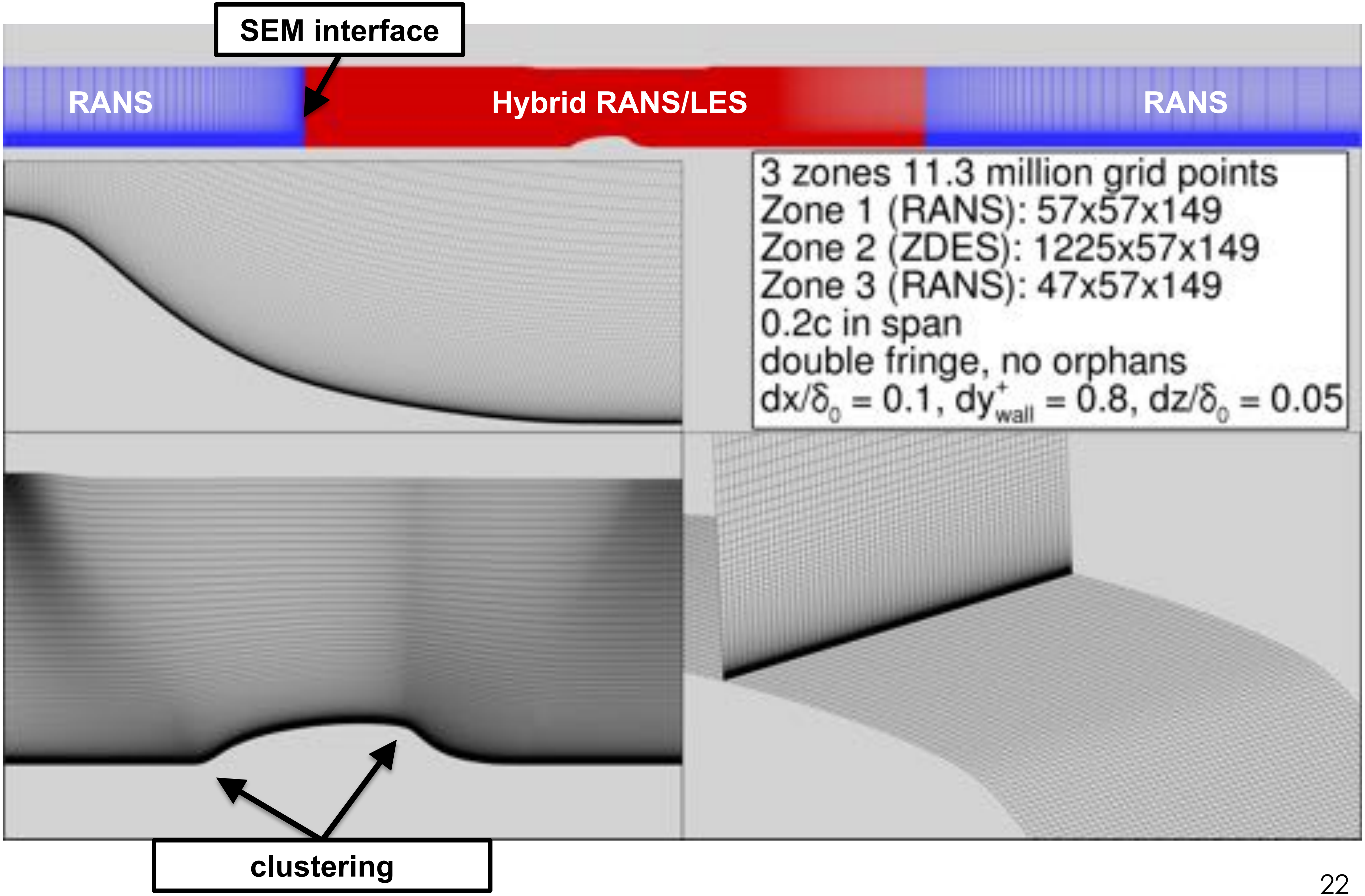
NASA 2-D Hump – LAVA RANS Validation



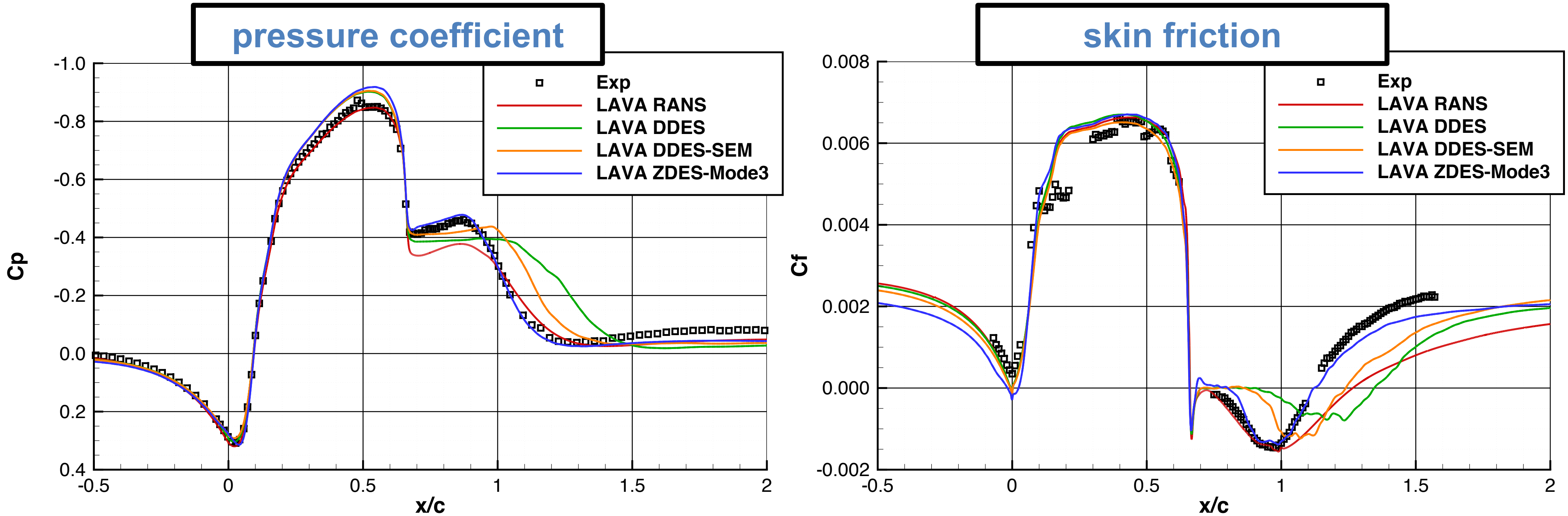


- ✓ Consistent convergence to a mesh refined solution is observed in each of the quantities
- ✓ Under prediction of C_p in the separated flow region and over prediction of the reattachment length is consistent with the SA results for CFL3D, FUN3D, and OVERFLOW (reported on the TMR)
- ✓ RANS solvers typically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

NASA 2-D Hump – Application of Zonal DES

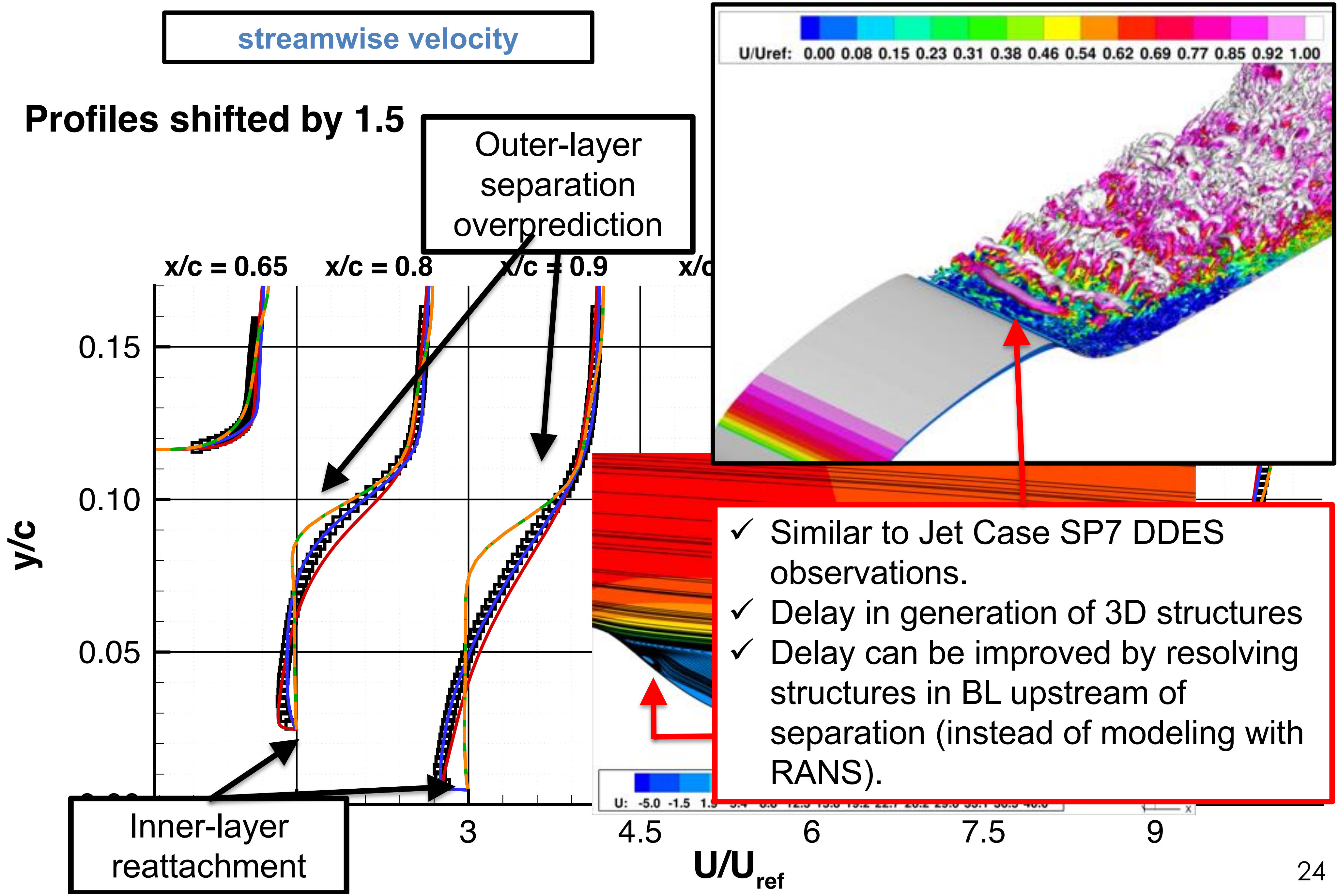


NASA 2-D Hump – Application of Delayed DES (SA)



- ✓ 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.
- ✓ SA-ZDES-Mode3 shows slightly lower skin friction upstream of the bump
- ✓ Downstream of the separation point SA-DDES shows a shallow reattachment region with the larger separated flow region reattaching near the SA-RANS result.
- ✓ The separated flow region is very well-predicted using the SA-ZDES-Mode3 with almost no difference between the experiment and the computation

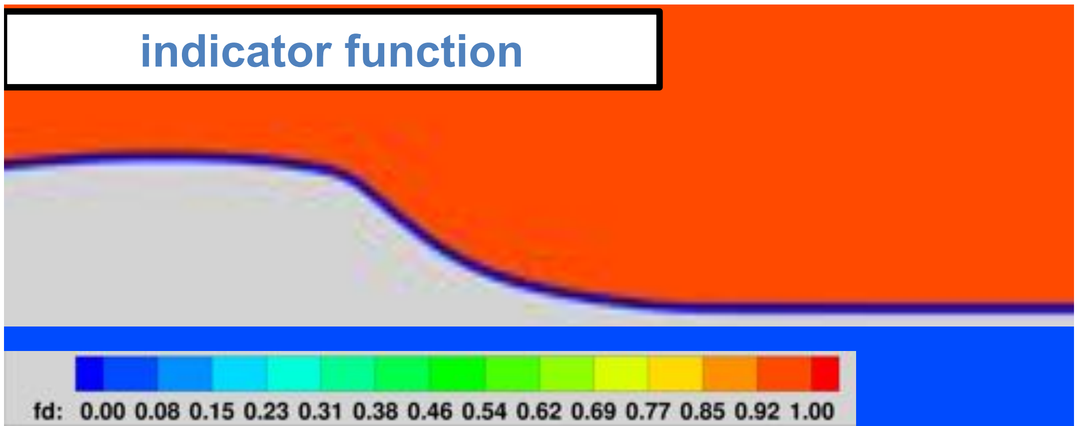
NASA 2-D Hump – Application of Delayed DES (SA)

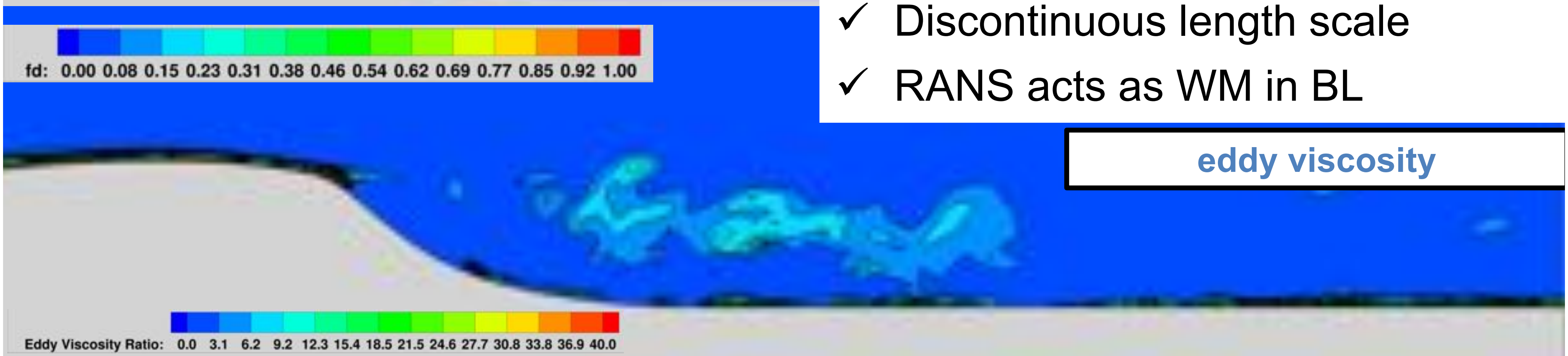


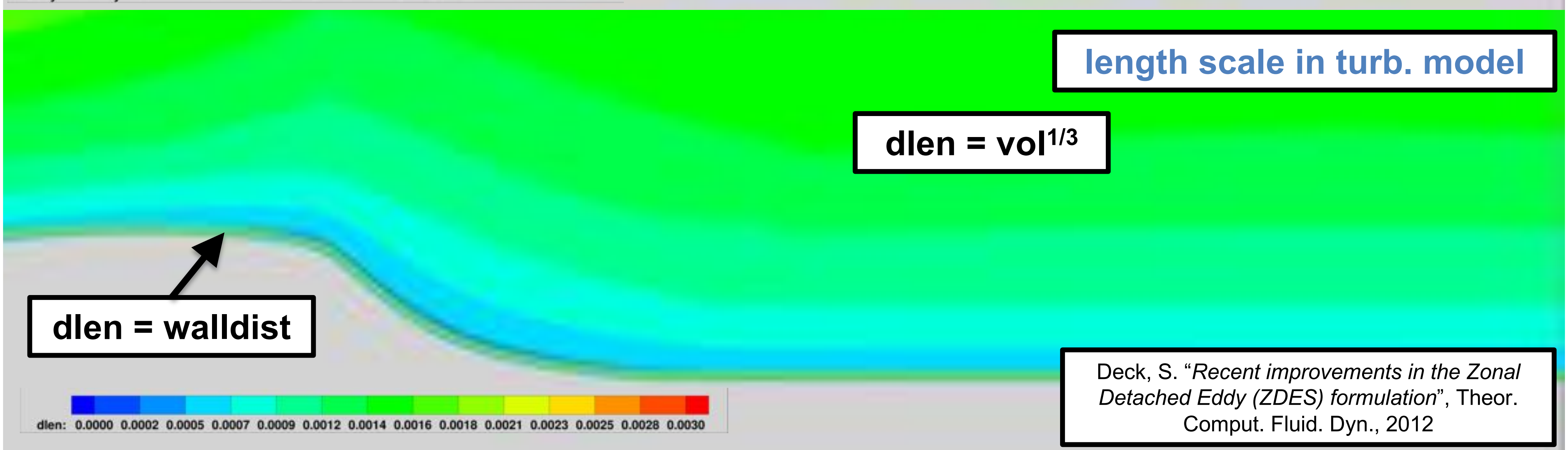
- ✓ Similar to Jet Case SP7 DDES observations.
- ✓ Delay in generation of 3D structures
- ✓ Delay can be improved by resolving structures in BL upstream of separation (instead of modeling with RANS).

NASA 2-D Hump – Application of Zonal DES

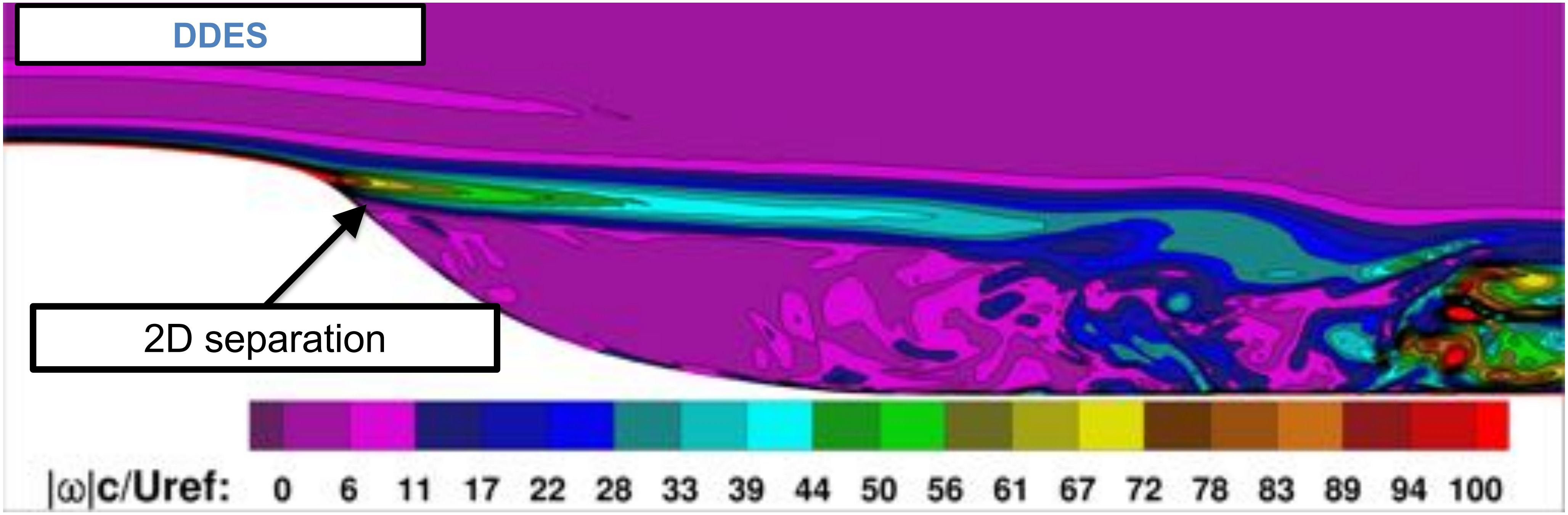
- ✓ Sharp transition between RANS and LES
- ✓ Modeled stress acts as dynamics SGS model in LES region
- ✓ Discontinuous length scale
- ✓ RANS acts as WM in BL

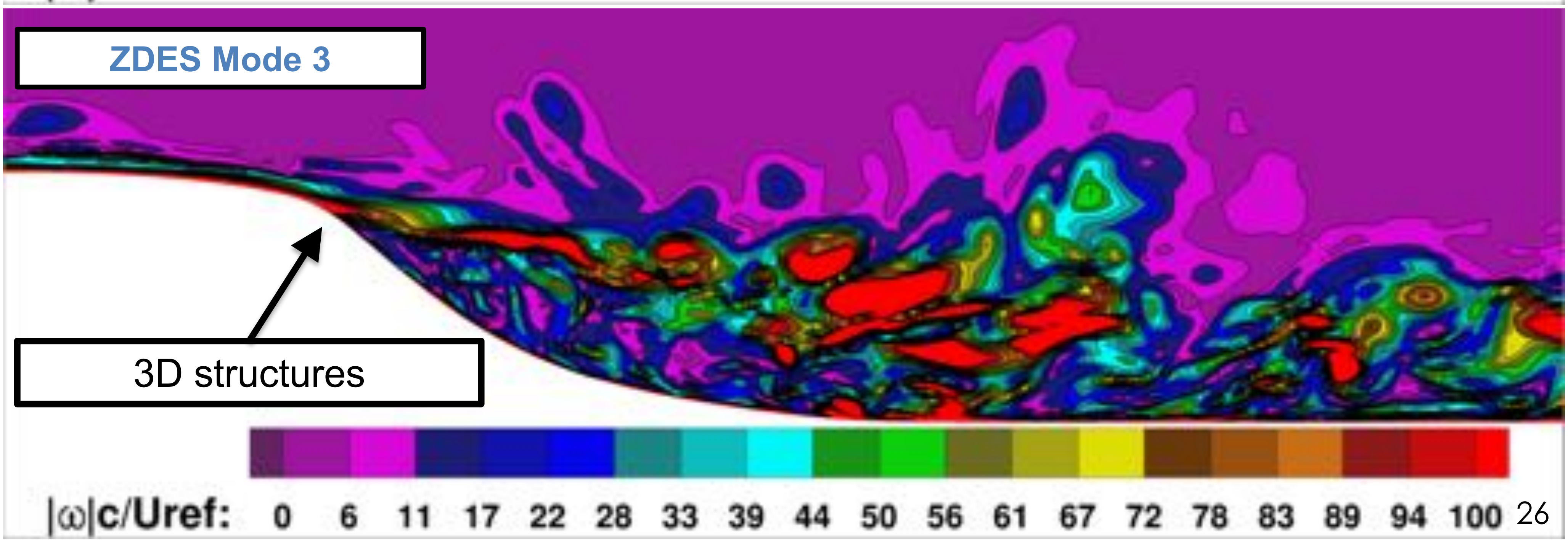






NASA 2-D Hump – Application of Zonal DES





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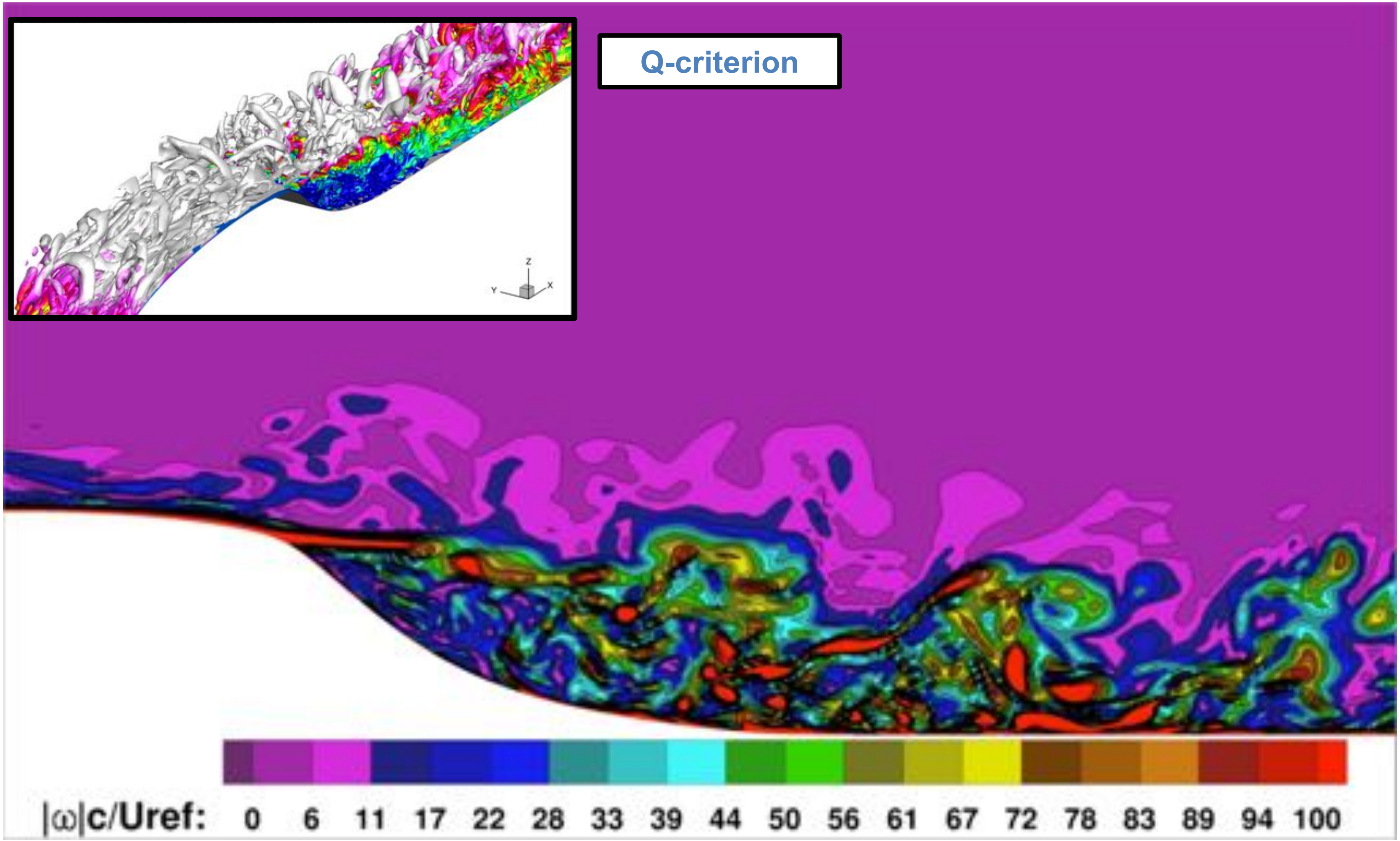
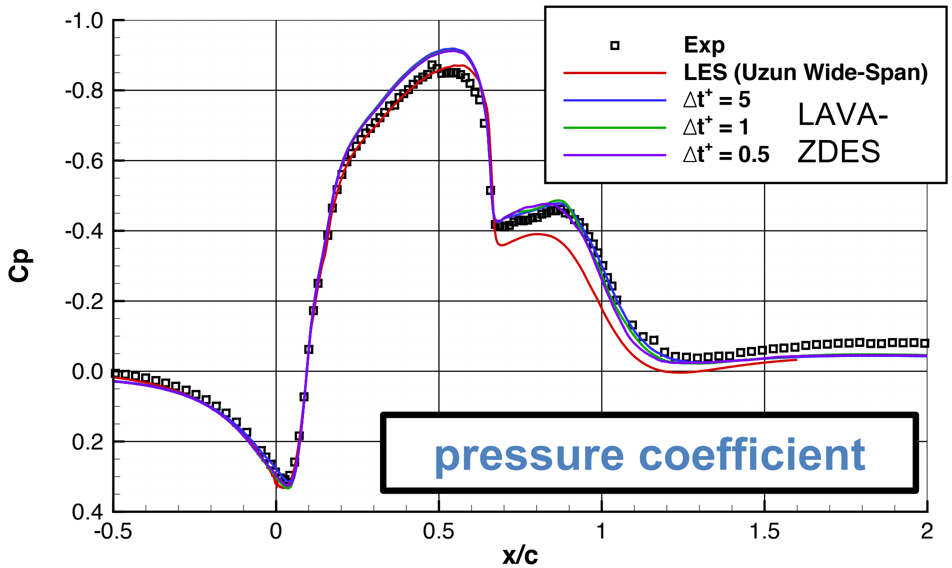
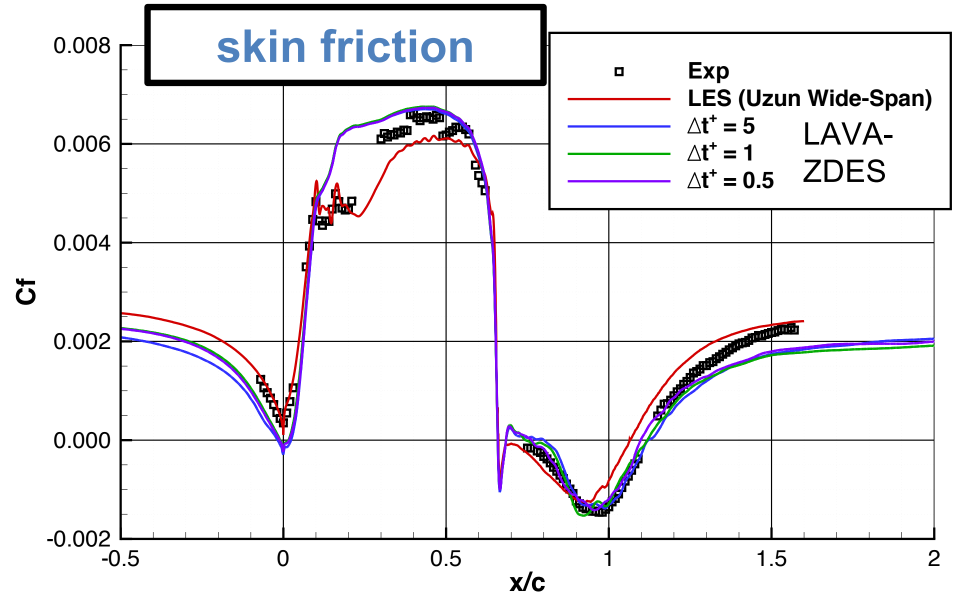
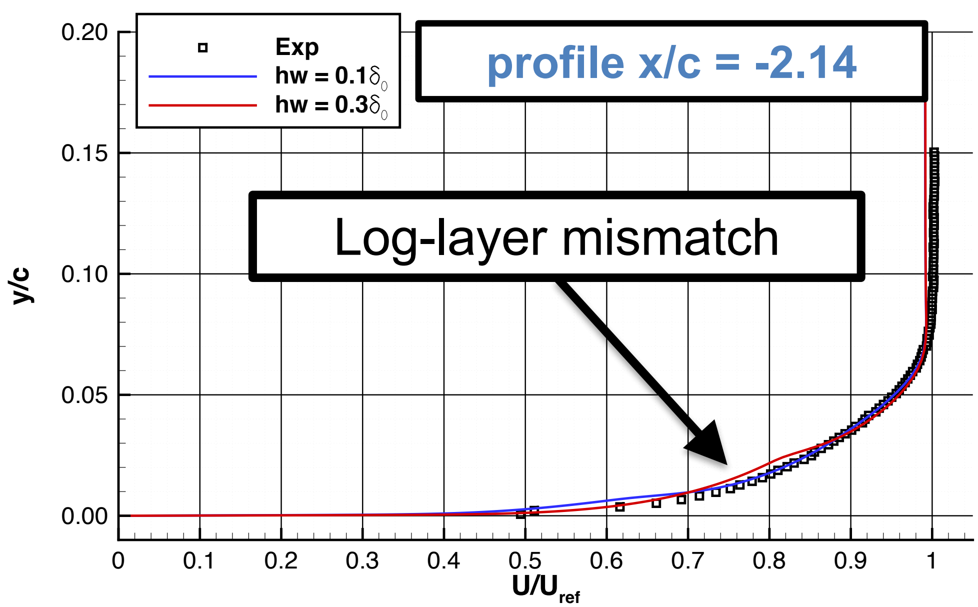


NASA 2-D Hump – Application of Zonal DES

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



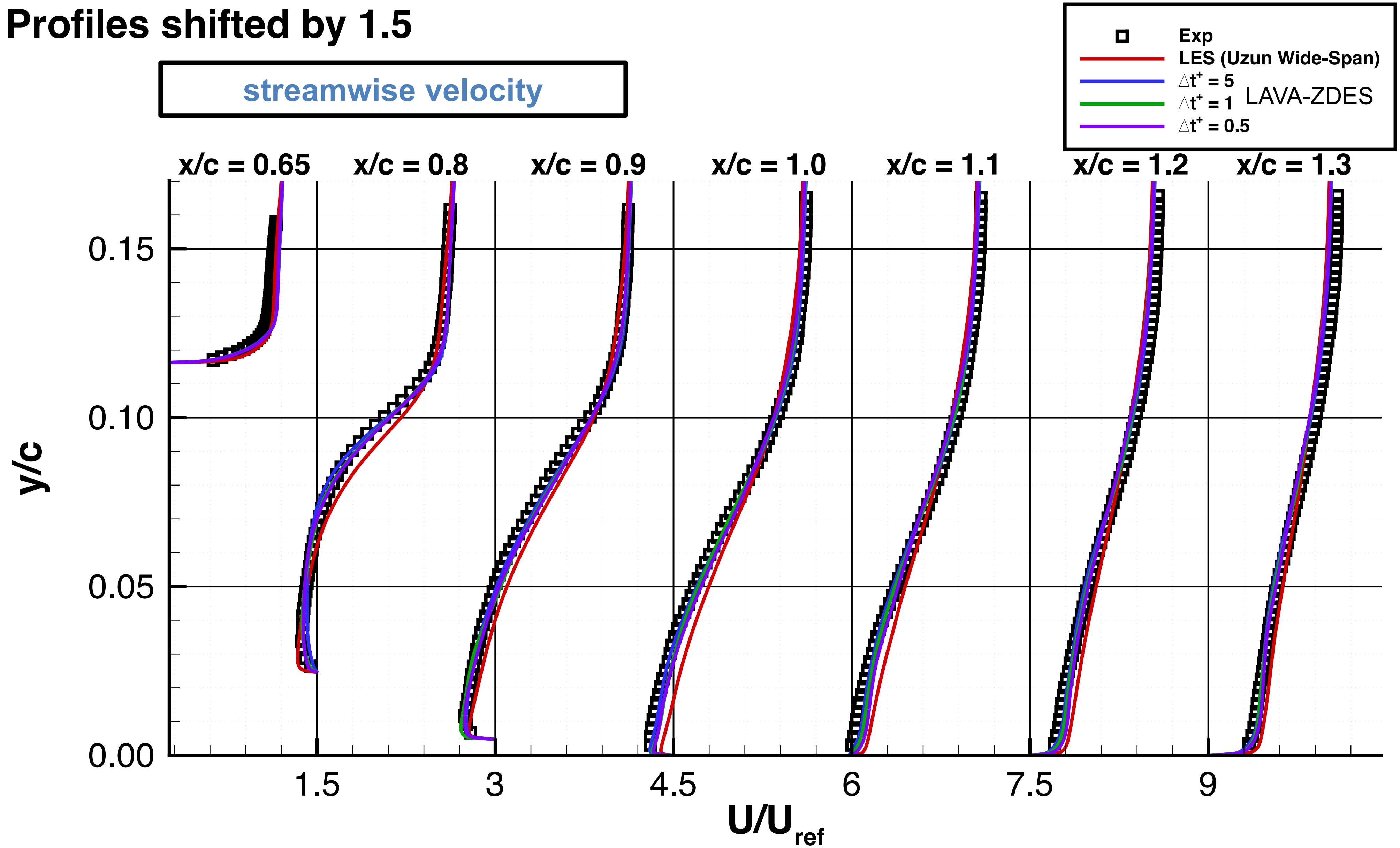




- ✓ ZDES (11.3m) compares well with wall resolved LES[1] (420m) and experiment .
- ✓ The skin-friction is under-predicted in the upstream attached BL
- ✓ Very good agreement in the re-attachment location
- ✓ Noticeable log-layer mismatch in the upstream BL profile

NASA 2-D Hump – Application of Zonal DES

Profiles shifted by 1.5



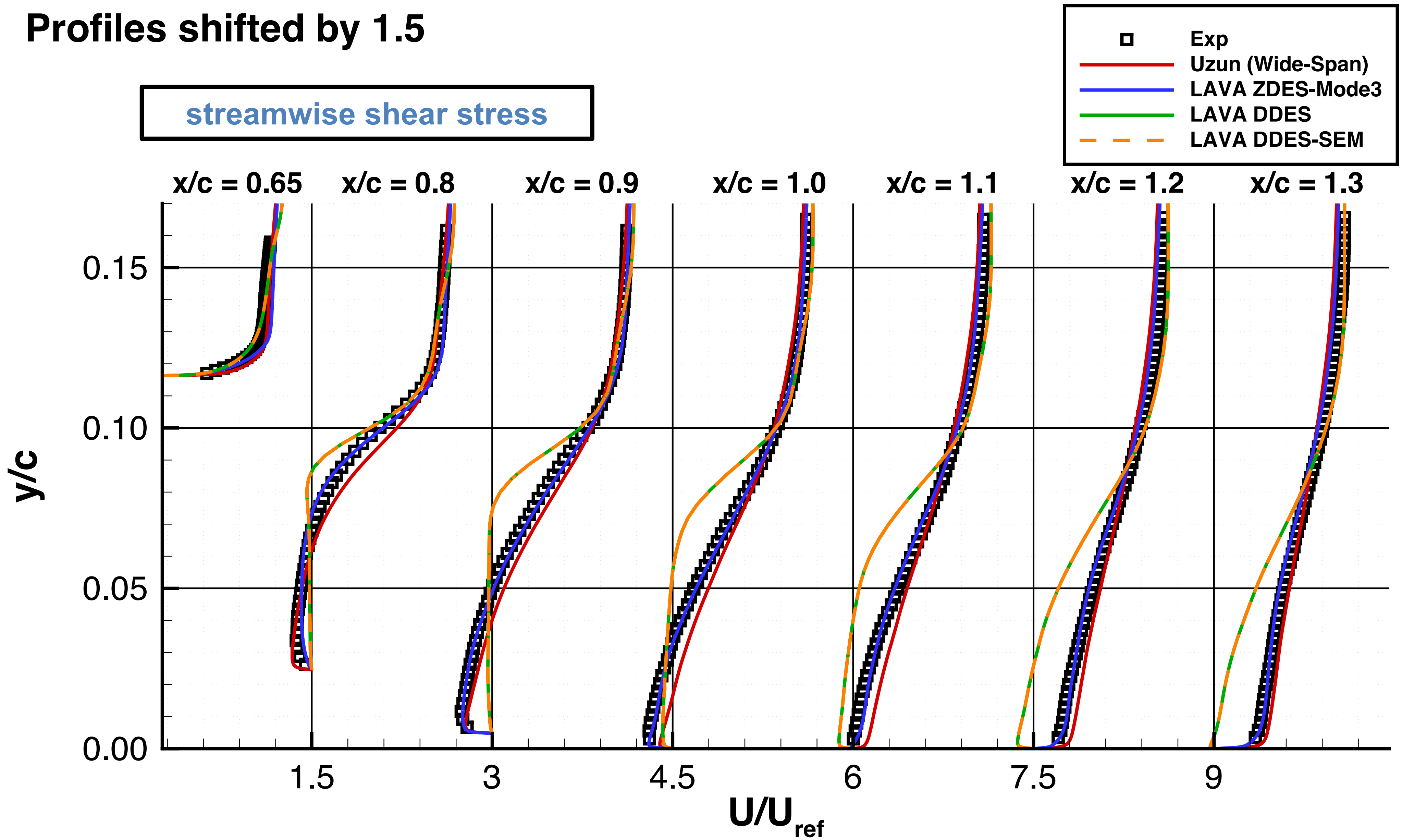
✓ Wall resolved LES mesh has 420m points, ZDES 11.3m points

[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 – Hybrid RANS-LES

Profiles shifted by 1.5

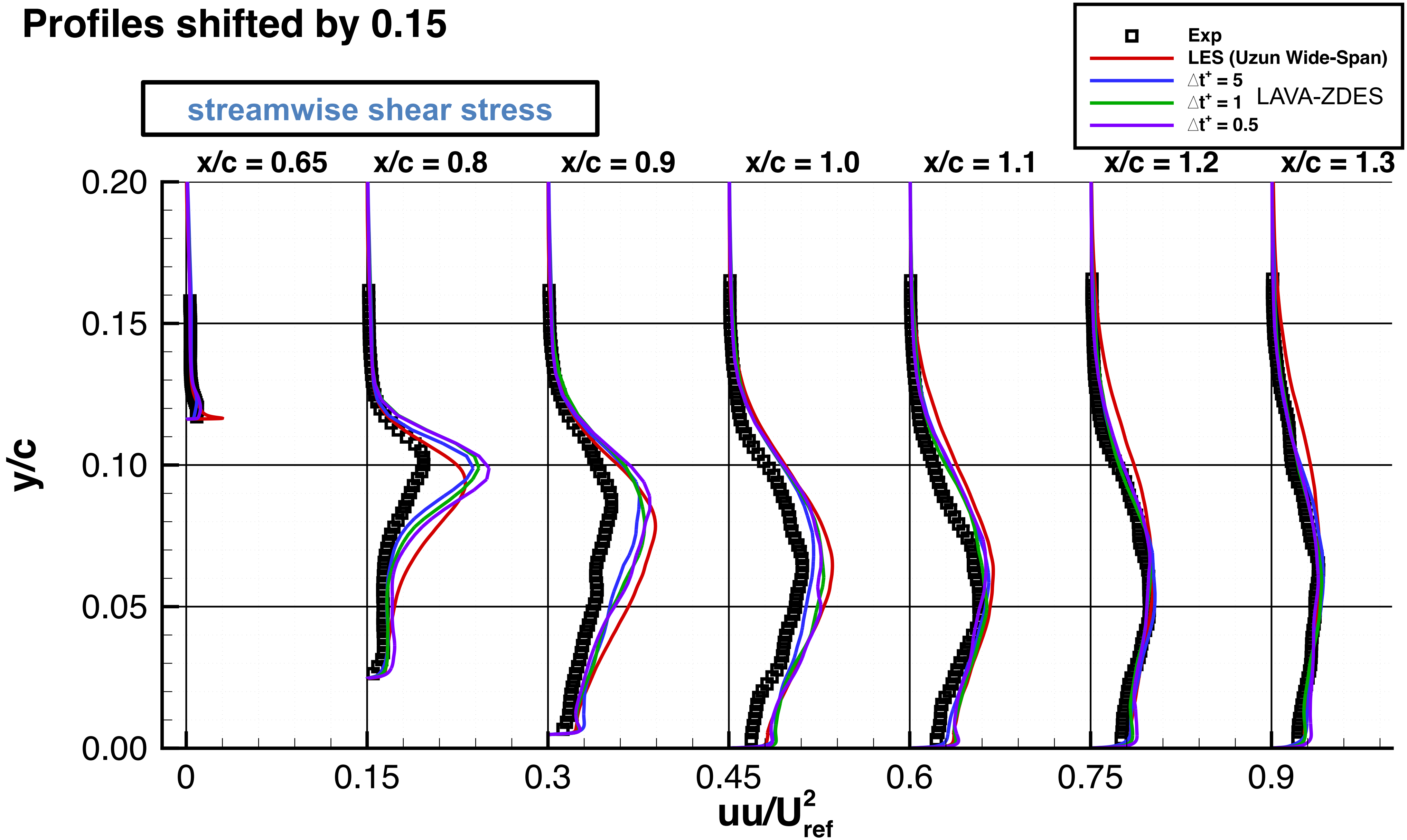
streamwise shear stress



[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

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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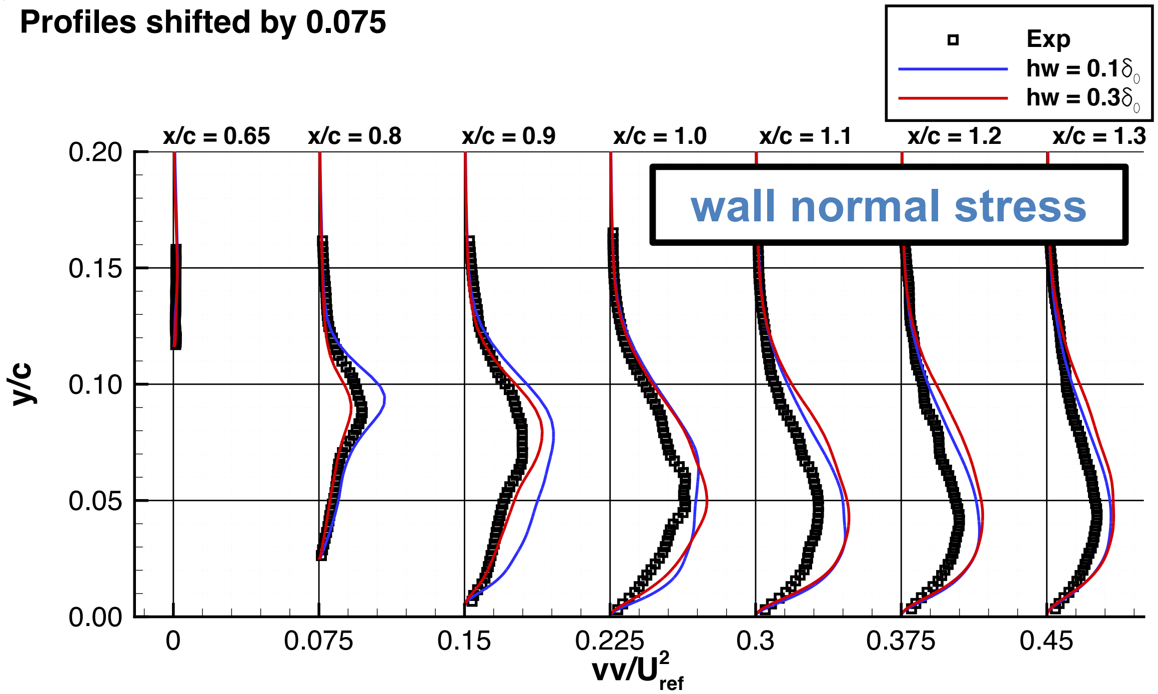
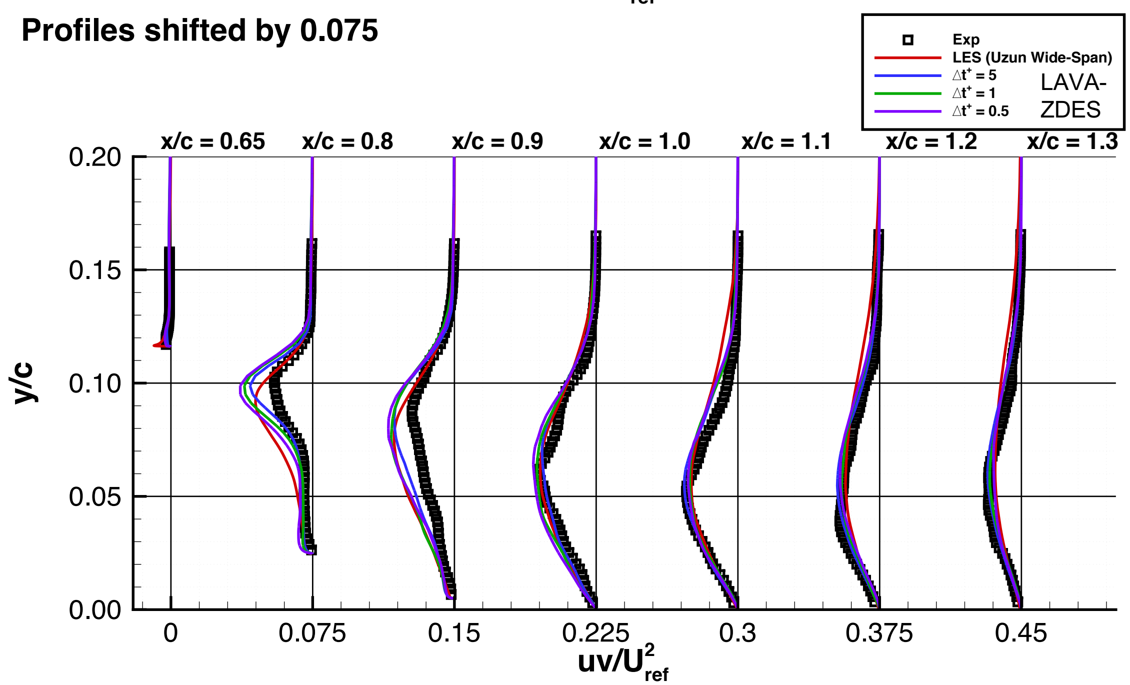
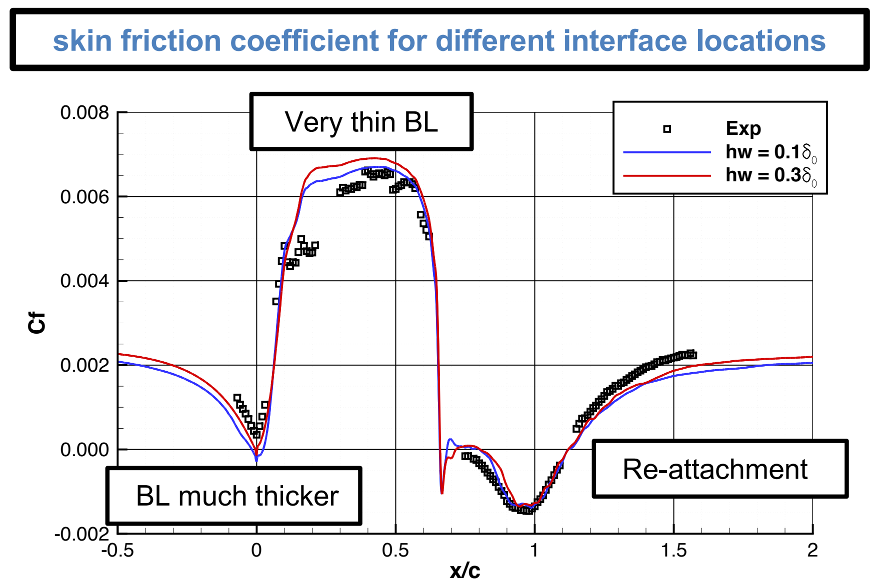




- ✓ Interface location based on BL thickness on top of hump
- ✓ Interface location constant across whole domain

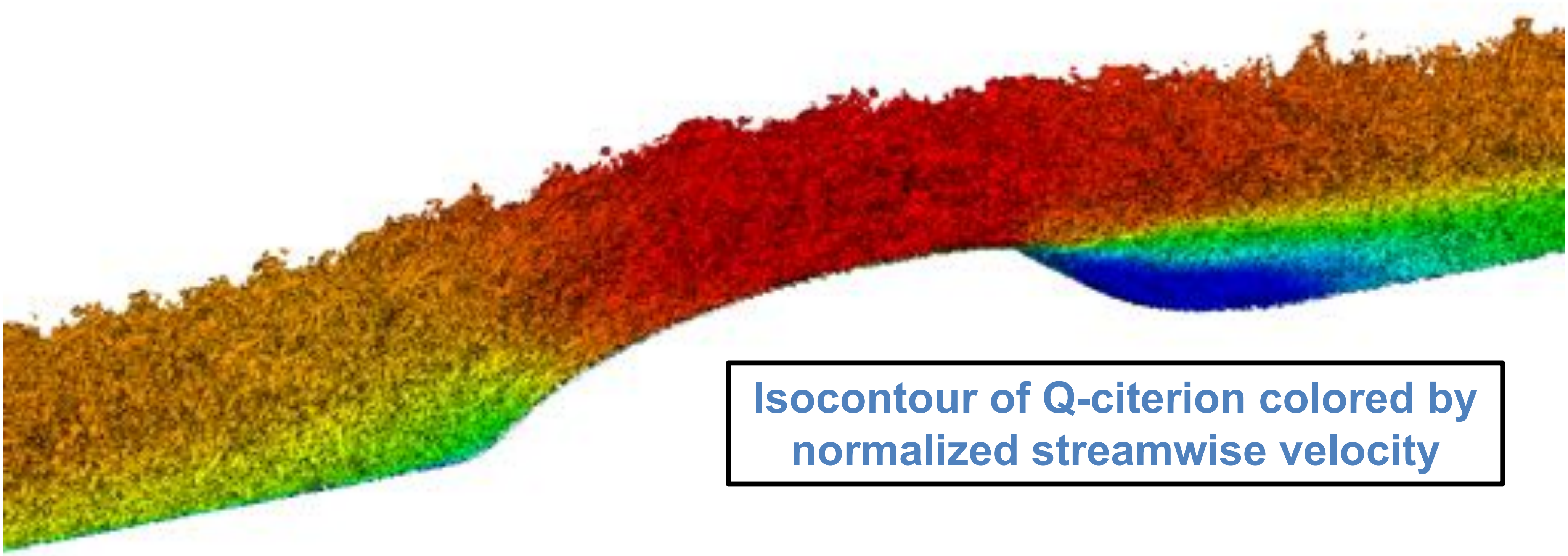


Future work:

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

NASA 2-D Hump – Application of Lattice Boltzmann

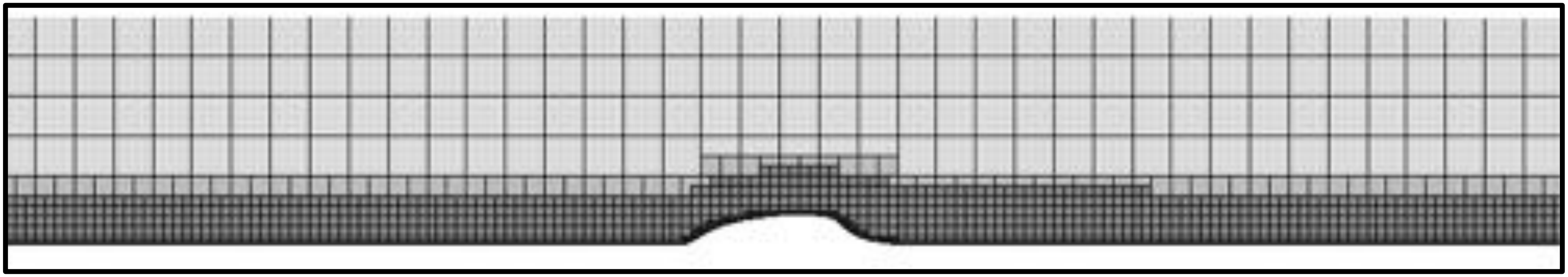
- ✓ Lattice: D3Q27
- ✓ Collision Model: EMRT
- ✓ Synthetic Eddy Method with scaled DNS Flat plate Data at x/c = -3.0

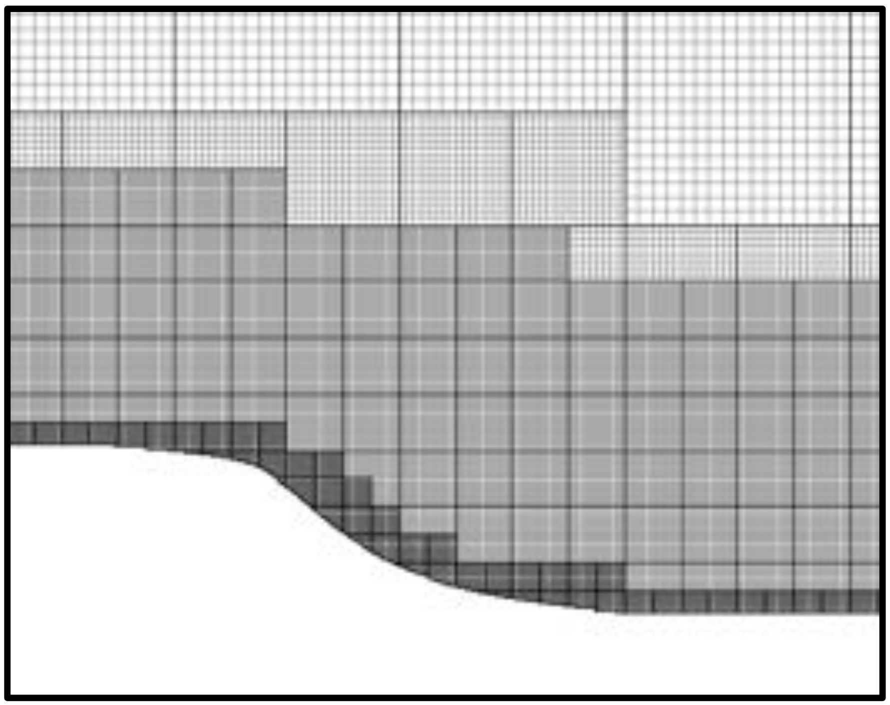


- ✓ Synthetic eddy method created realistic turbulent structures
- ✓ Initial run without included top-wall to simulate side-wall effects

NASA 2-D Hump – Application of Lattice Boltzmann

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

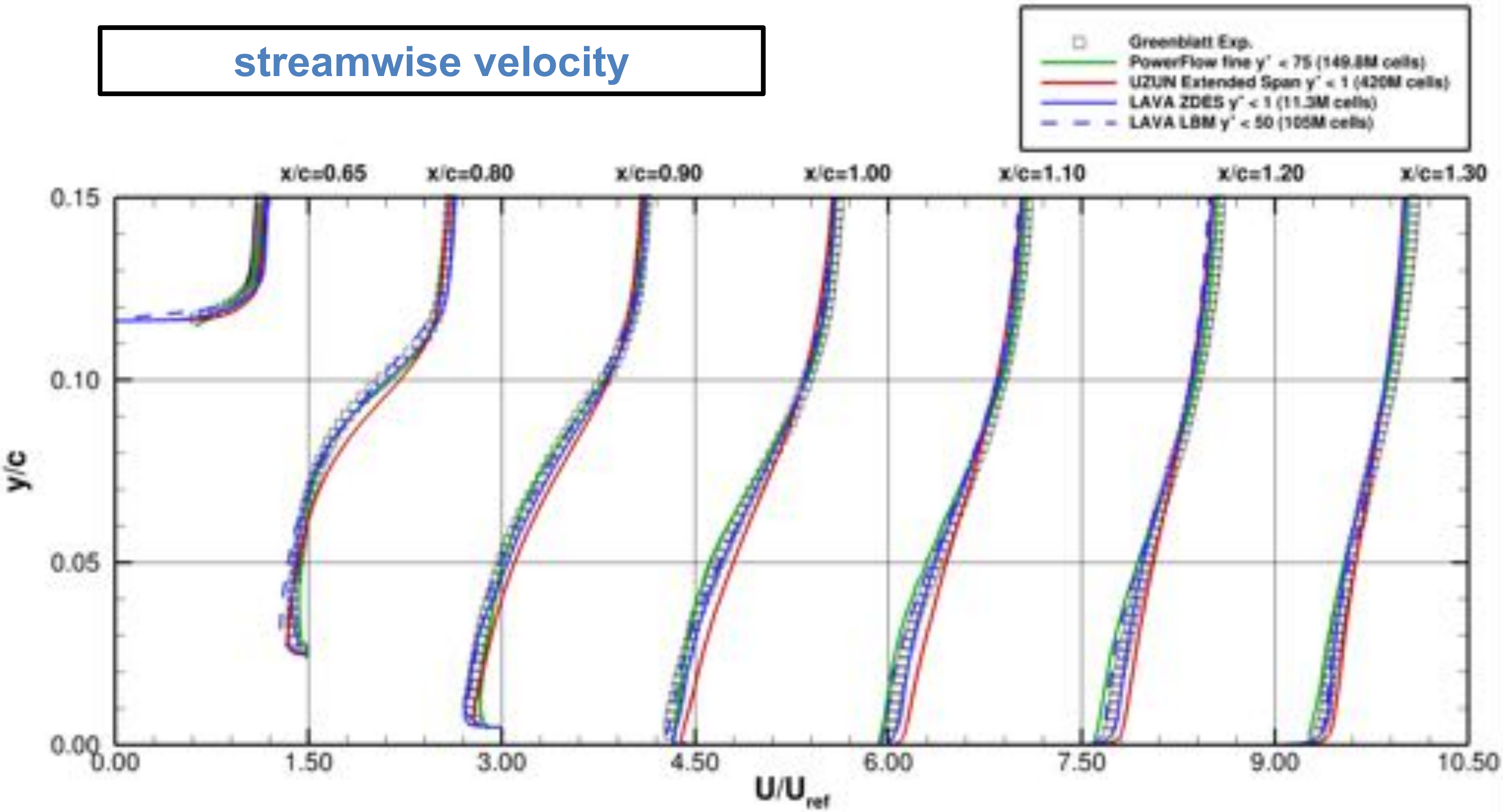




- ✓ Total of 5 Levels with
- ✓ Refinement ratio of 2
- ✓ Level 3 in regions of high vorticity
- ✓ Level 4 on all viscous walls
- ✓ Level 5 from x/c = -0.2 to 1.3
- ✓ 105 million points
- ✓ Spanwise extend 0.2 chord
- ✓ $dy^+ \approx 50$ in wall normal direction

NASA 2-D Hump – Application of Lattice Boltzmann

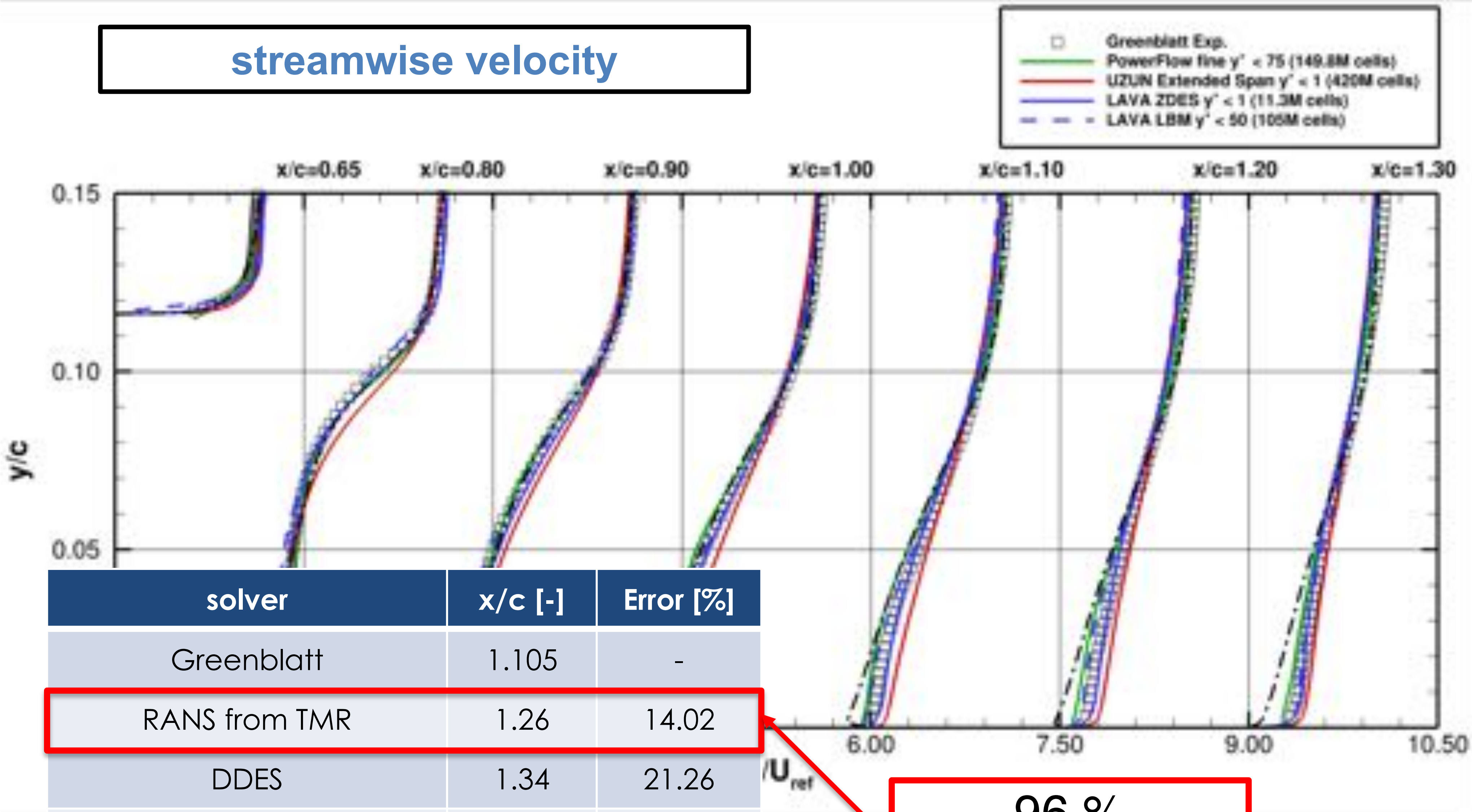
streamwise velocity



✓ Further improvement in coarse fine interface operation necessary

NASA 2-D Hump – Application of Lattice Boltzmann

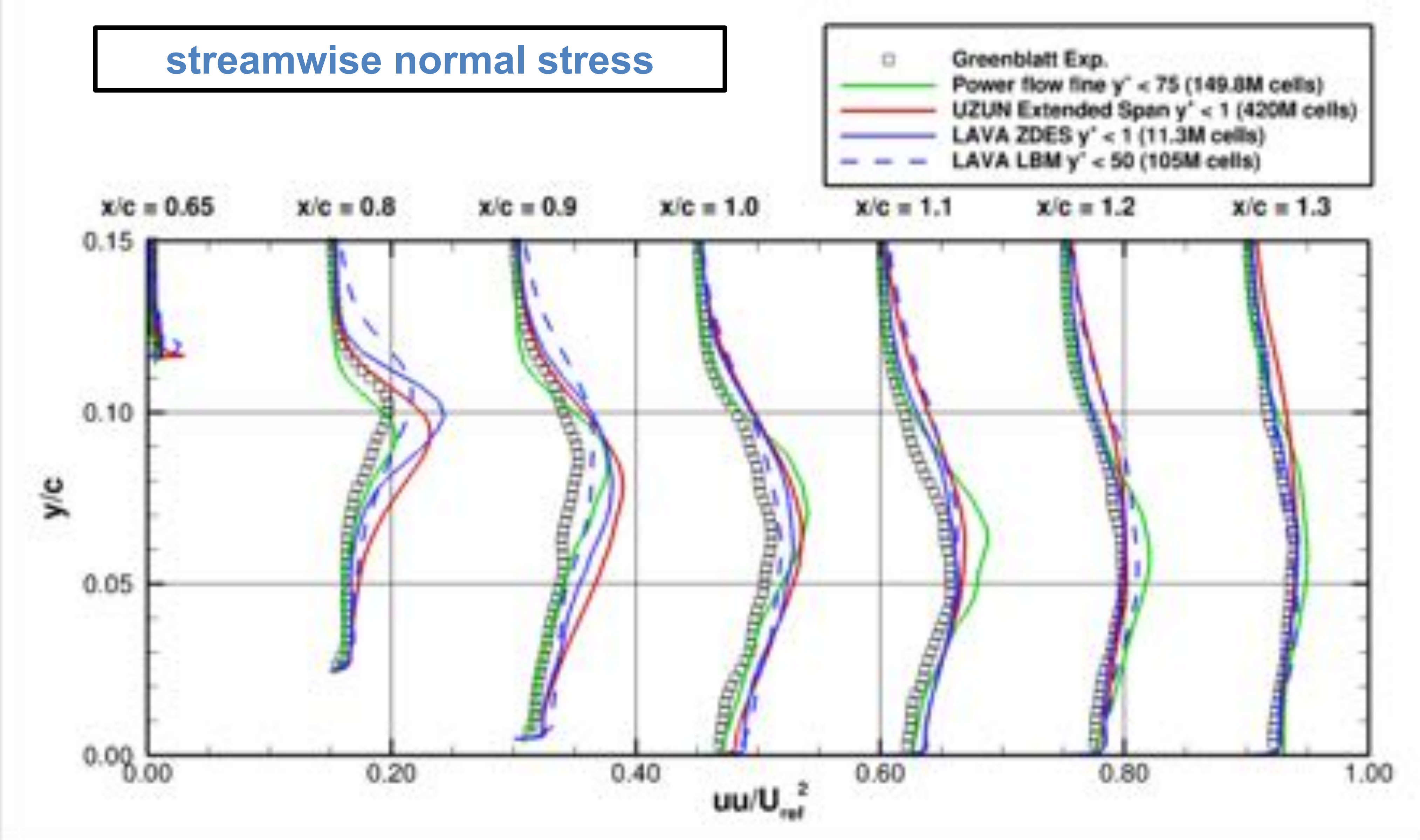
streamwise velocity



solver	x/c [-]	Error [%]
Greenblatt	1.105	-
RANS from TMR	1.26	14.02
DDES	1.34	21.26
DDES + SEM	1.23	11.31
ZDES + SEM	**1.11**	**0.45**

96 % improvement

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) for Hump 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 for Hump and delays development of 3D structures at nozzle exit.
- ✓ 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

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- ✓ Computer time provided by NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center

Questions?