Unsteady Analysis Using Large Computational Datasets

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Integrity ★ Service ★ Excellence

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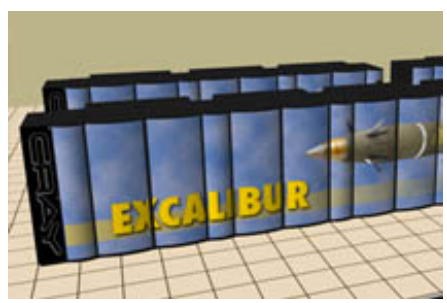
HPCMP Frontier Project

FY	CPU-Hrs (millions)
2014	90
2015	160
2016	**210**
2017	890*
2018	890*

AFRL **Lightning** : Cray XC30



ARL **Excalibur** : Cray XC40

ERDC **Topaz** : SGI ICE X

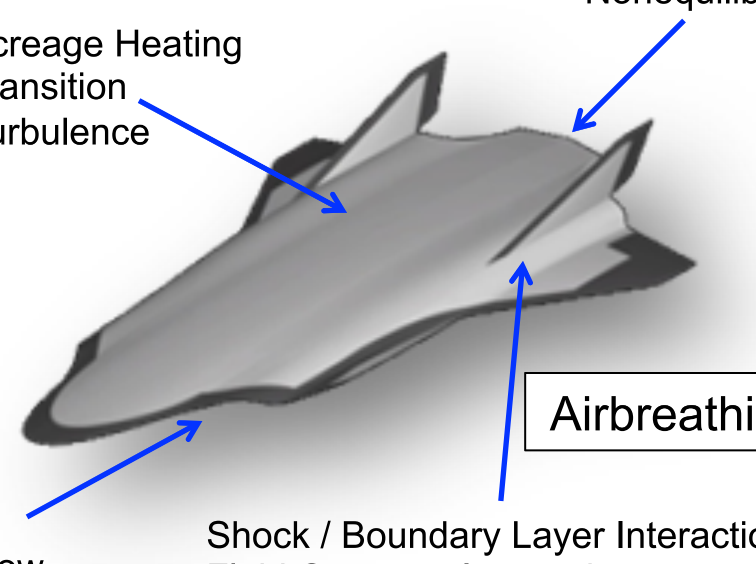
Outline

- Motivation / Background
- CFD with Big Data
  - 24-deg compression ramp
  - Reattaching shear layer
  - HIFiRE – 6
- Conclusions
- Lessons Learned

Research Challenges in Hypersonic Technology

Gliding

Airbreathing



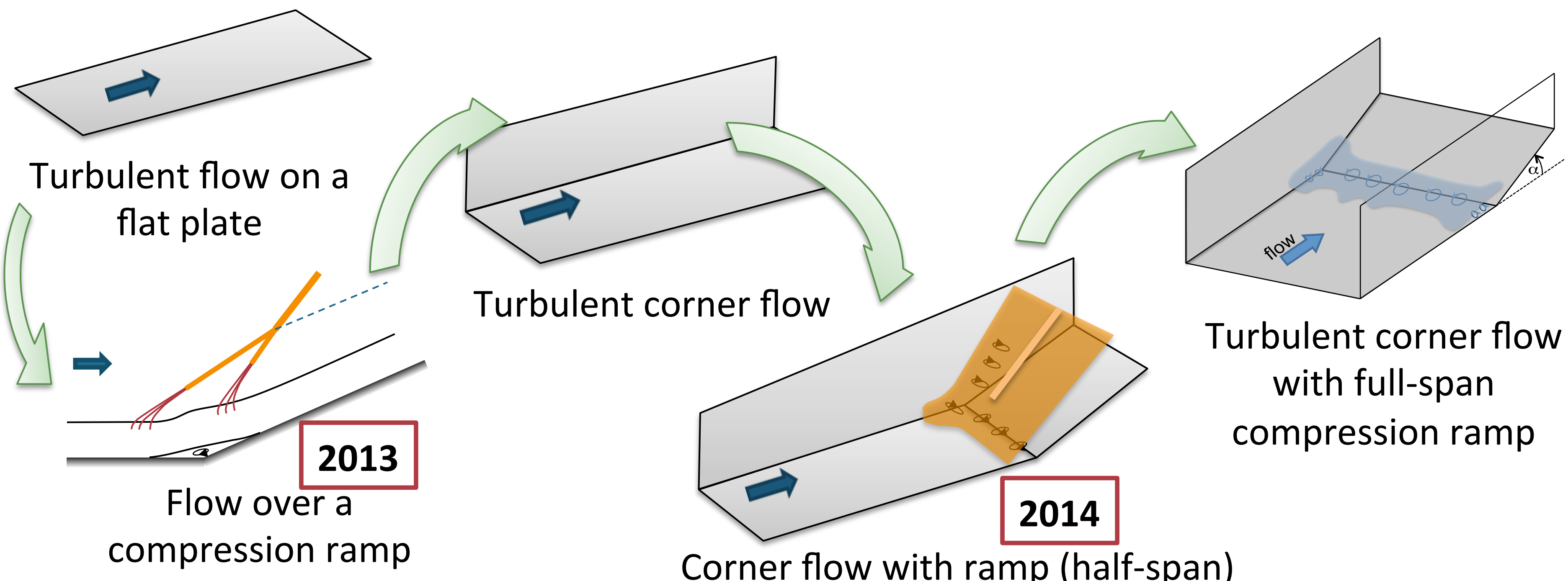
- Multidisciplinary physics
- Disparate scales

Computational Hypersonics

- **Problem:** quantify hypersonic flight environment
- **Importance:** prediction uncertainty leads to conservative design
- **Challenges:** multi-disciplinary physics, disparate space and time scales
- **Approach:** high-fidelity physical models and supercomputer resources

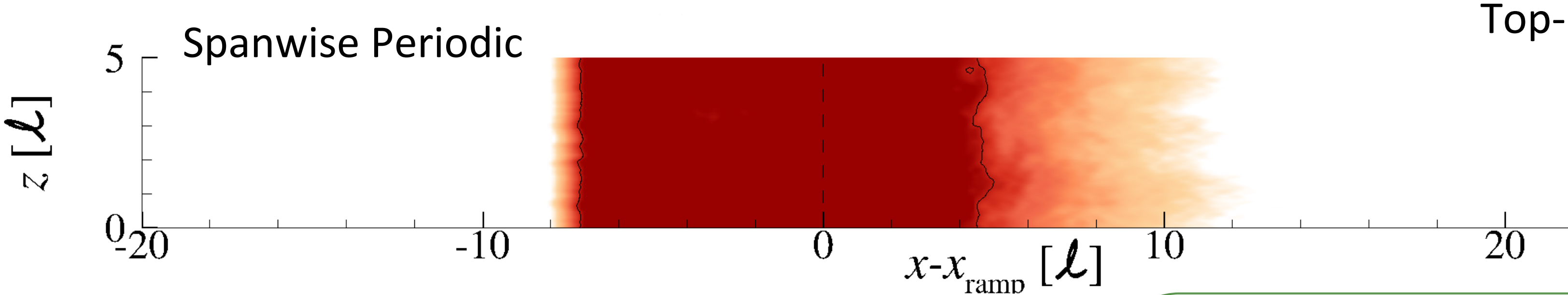
Towards Turbulent Shock Boundary-Layer Interaction (SBLI)

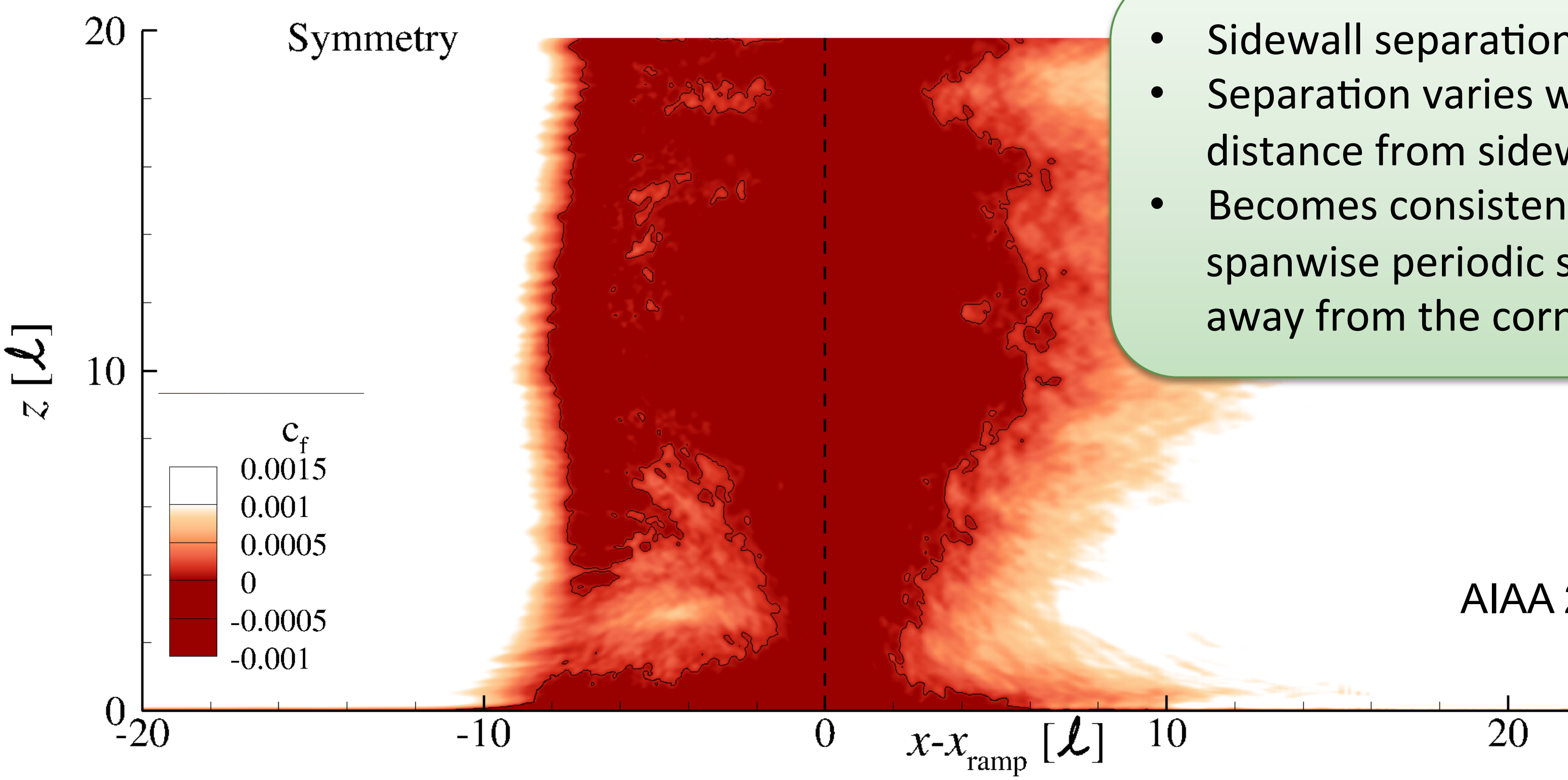
- **Exists in practical situations (i.e., supersonic inlet)**
  - **Low frequency oscillations of separation leads to fatigue loading**
  - **Increased BL thickness decreases internal inviscid cross-section**
  - **Localized heating**
  - **Separation acts as broadband amplifier**



Mach 2.25 flow over 24° Ramp
Half-span & Spanwise Periodic

Top-down view



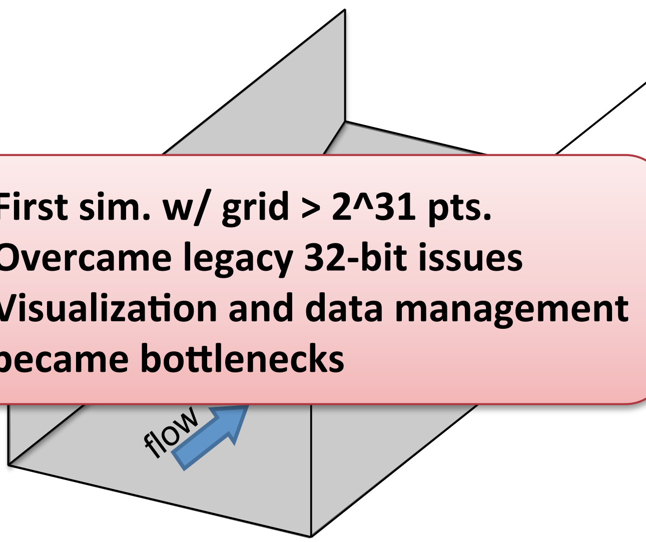


- Sidewall separation vortex
- Separation varies with distance from sidewall
- Becomes consistent with spanwise periodic scenario away from the corner!

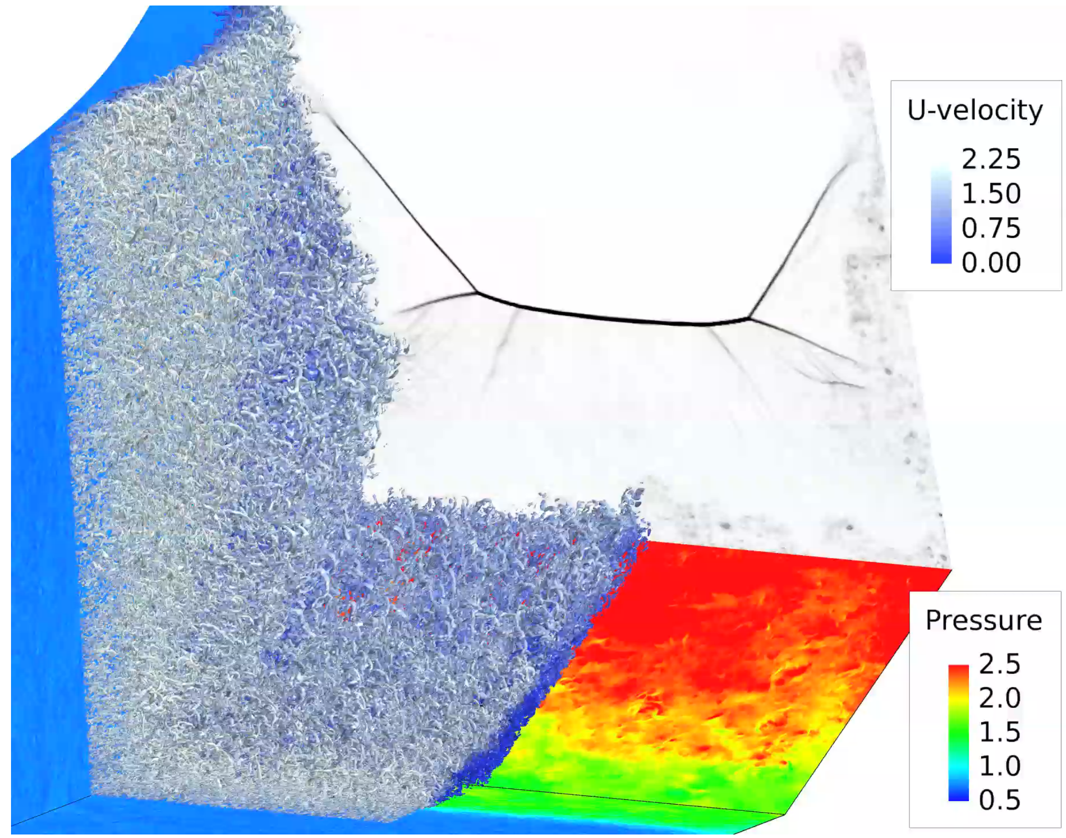
AIAA 2014-3335

Large-Scale Three-Dimensionality: 24° ramp with both sidewalls

$M_\infty = 2.25$
$T_w = 1.95 = T_{aw}$
$L_{sep} / \delta = 8$, $w / \delta = 10$
$Re = 15{,}240$



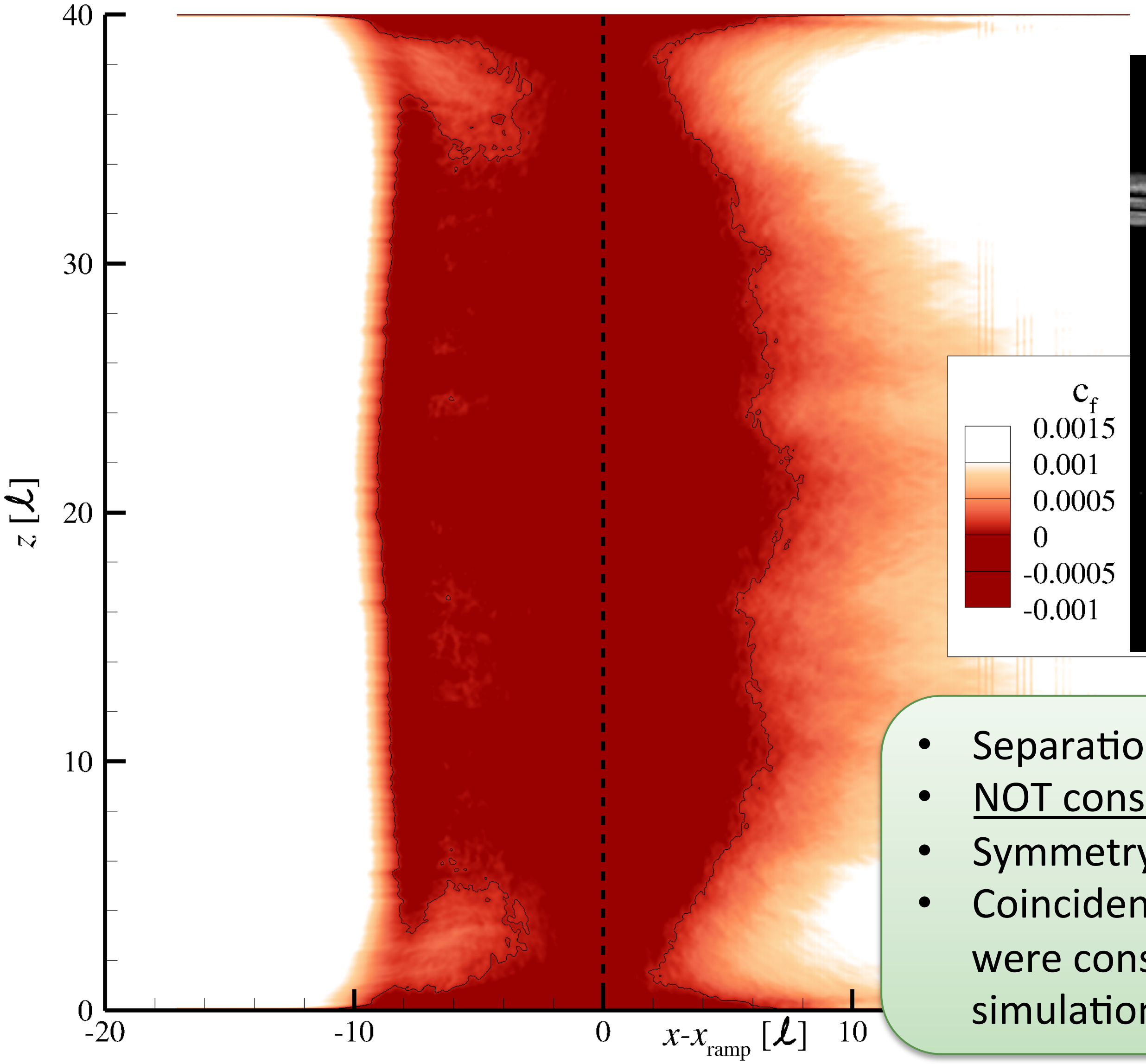
- **First sim. w/ grid > 2^31 pts.**
- **Overcame legacy 32-bit issues**
- **Visualization and data management became bottlenecks**



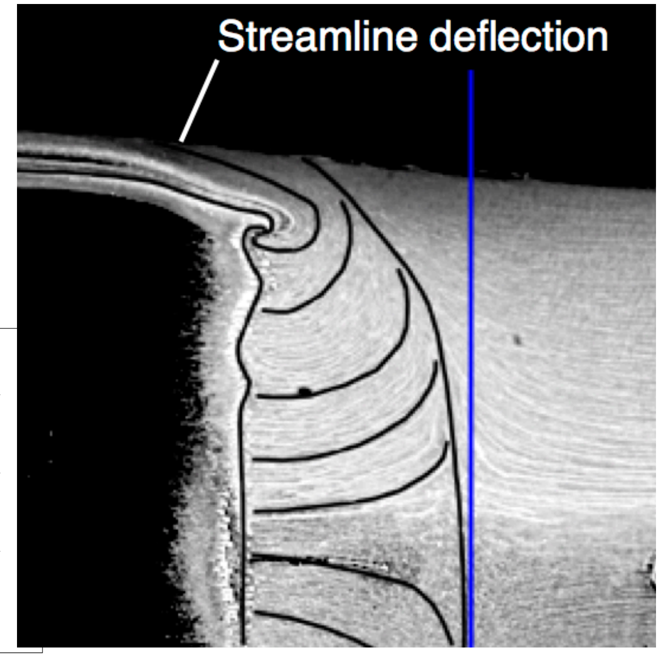
AIAA 2015-1976

- Significant interaction of corner flows and unsteadiness
- Periodic boundary conditions omit essential physics
- Enablers: large computing resources and new visualization tools

Skin-Friction (top-down view)



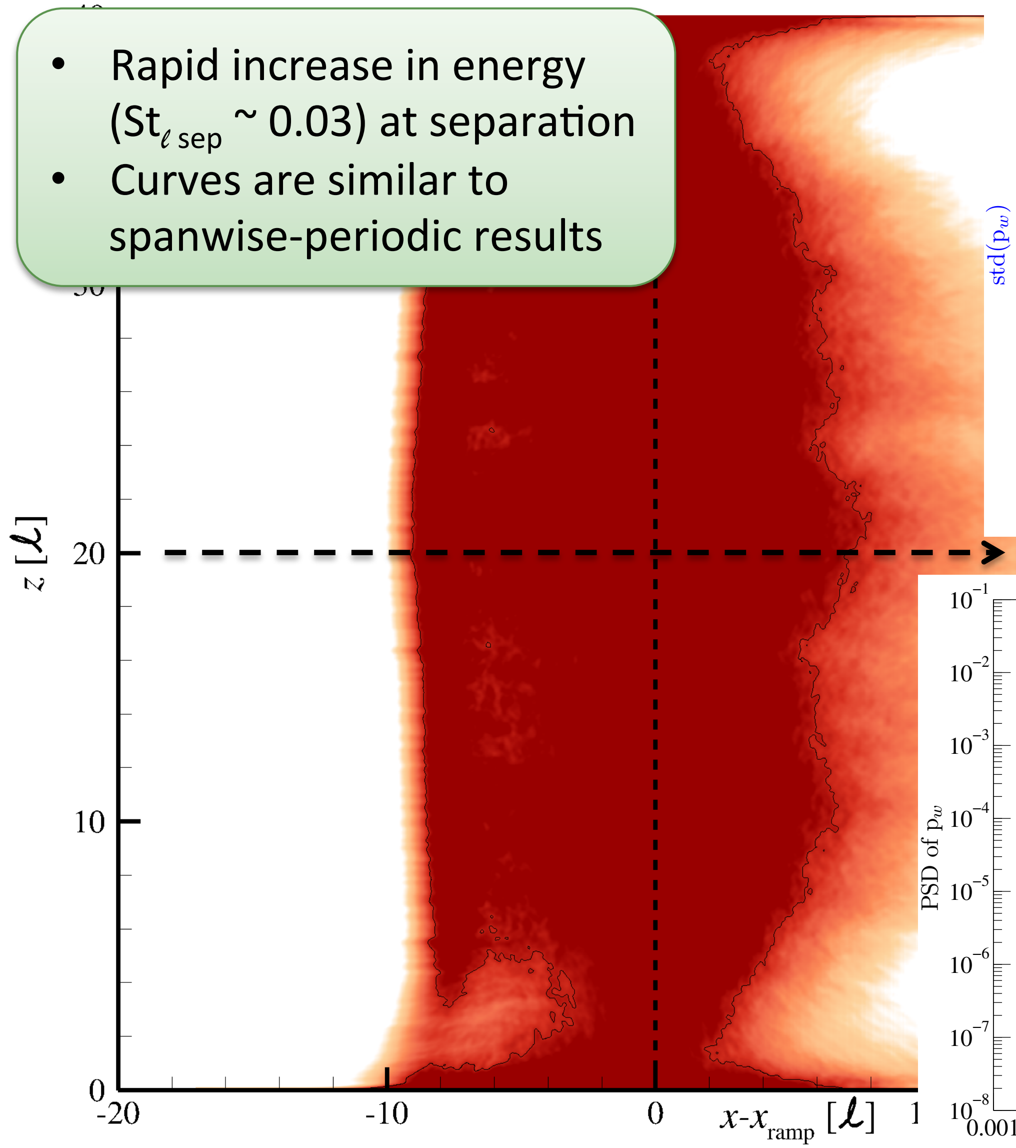
Babinsky, et al., AIAA 2013-859

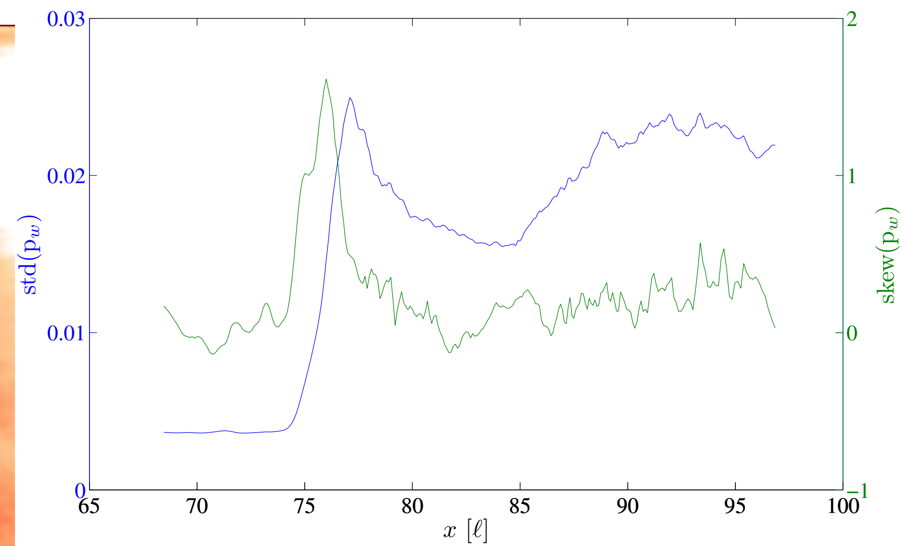


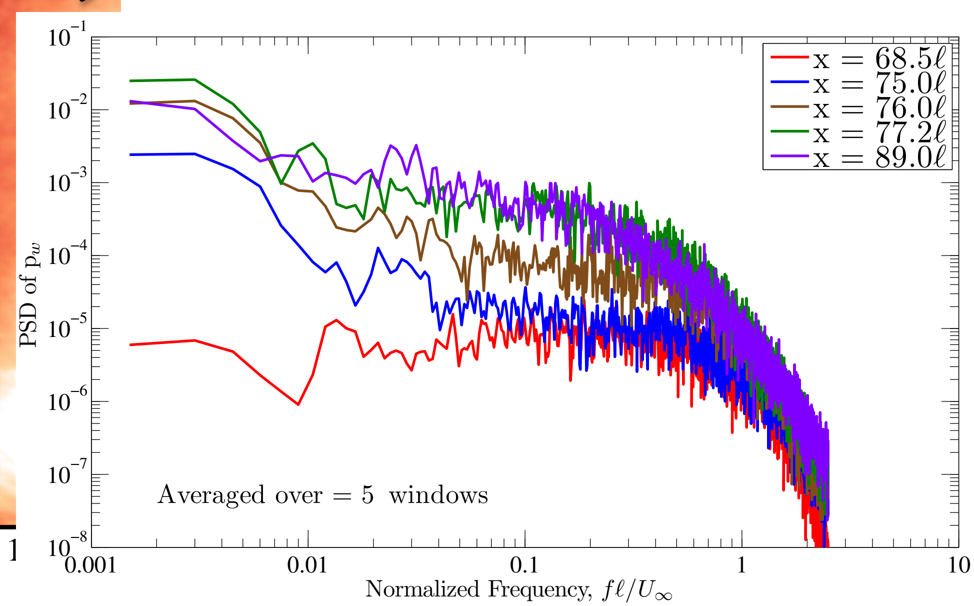
- Separation grows to the midspan
- NOT consistent with previous results
- Symmetry BC provided fuller profile
- Coincidence that the half-span results were consistent with the periodic simulation at the midspan

Unsteady SBLI

- Rapid increase in energy ($St_{\ell\ sep}$ ~ 0.03) at separation
- Curves are similar to spanwise-periodic results

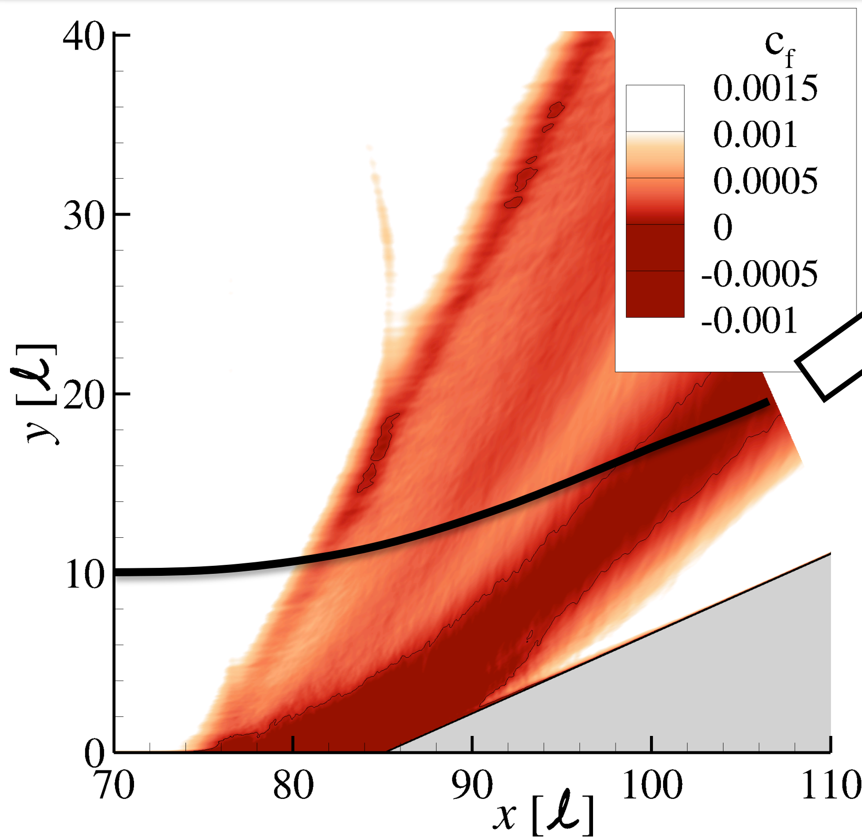


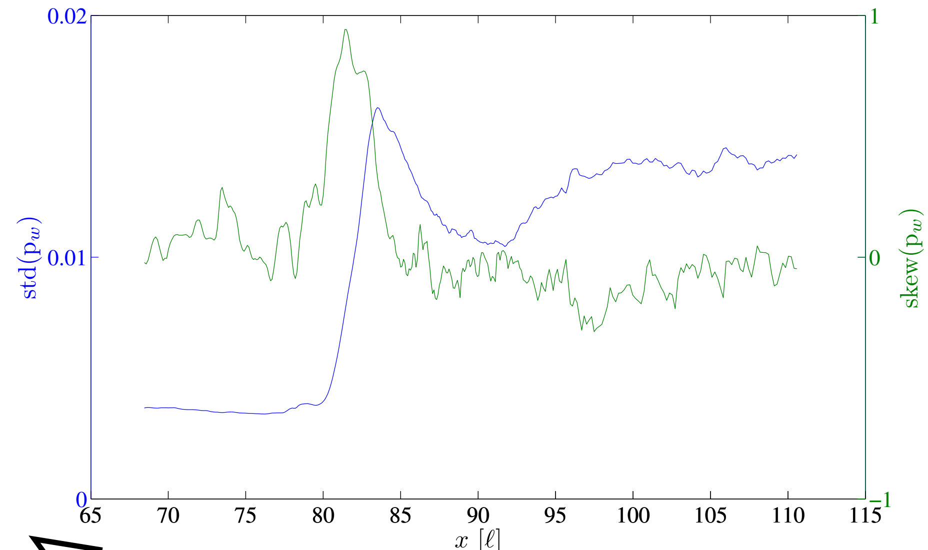


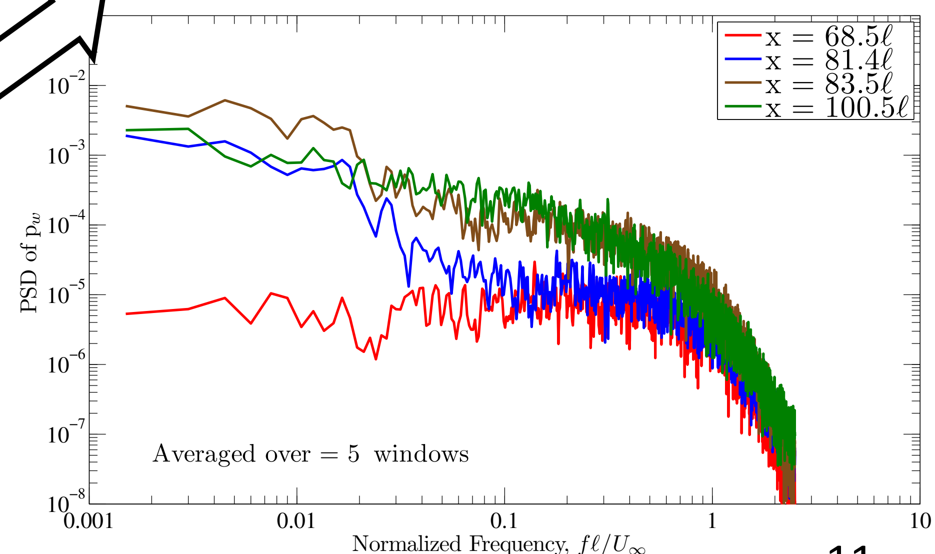


Sidewall Glancing SBLI

- Flow did not separate at the leading foot of the glancing SBLI, but still displayed unsteady low-frequency content consistent with typical SBLI
- Flow at separation (due to the separation vortex), did not show the low frequency



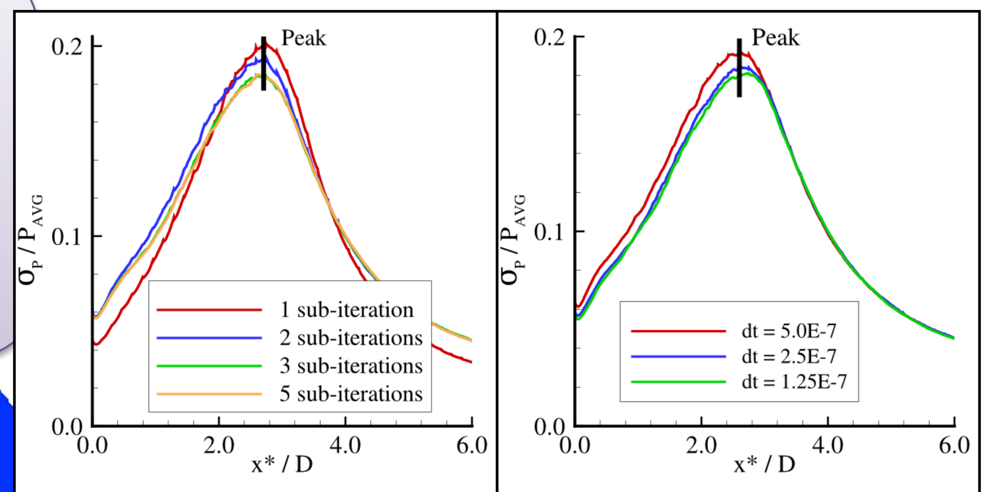


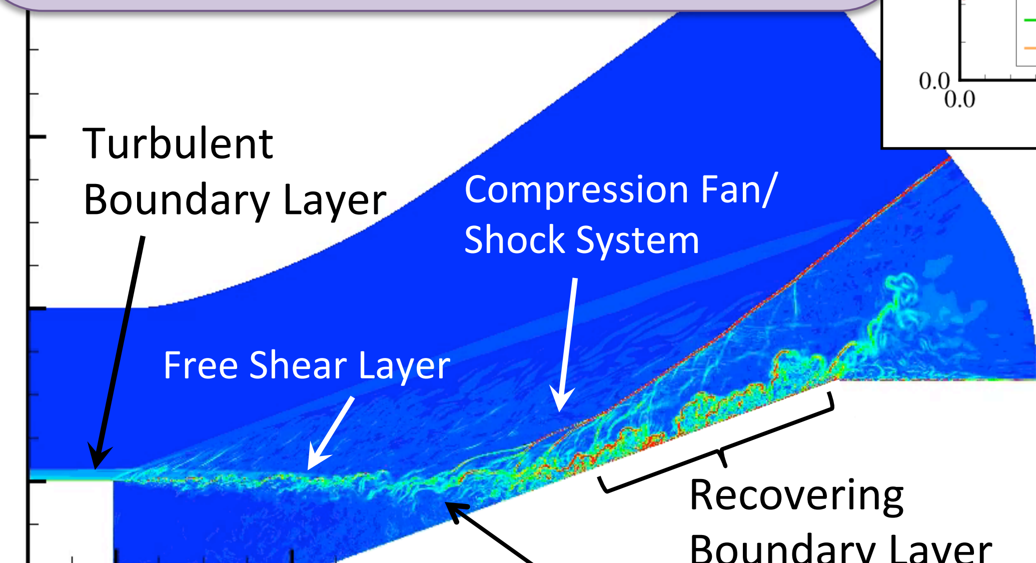


Reattaching Shear Layer

Mach 2.9 flow with a 20-deg ramp

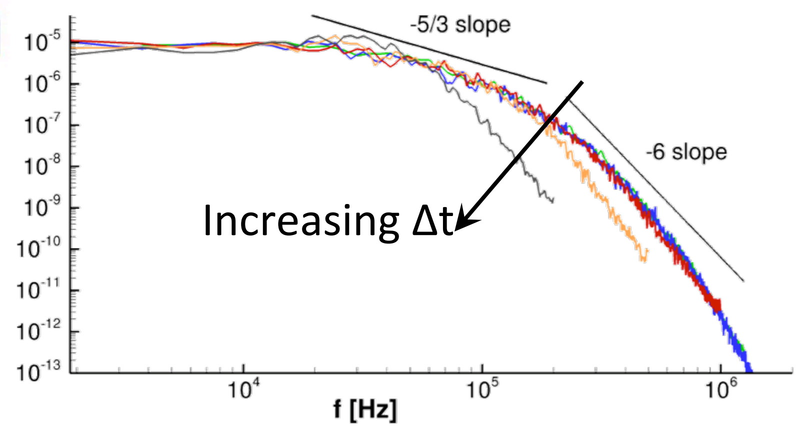
- Long time-histories (seconds) are needed to couple multidisciplinary engineering analysis (thermal/structural response)
- DES / wall-modeled LES enables:
  - ✧ DES Δt >> LES Δt
  - ✧ Actual Reynolds number
  - ✧ Δt & sub-iterations affect predictions





Density-gradient contours

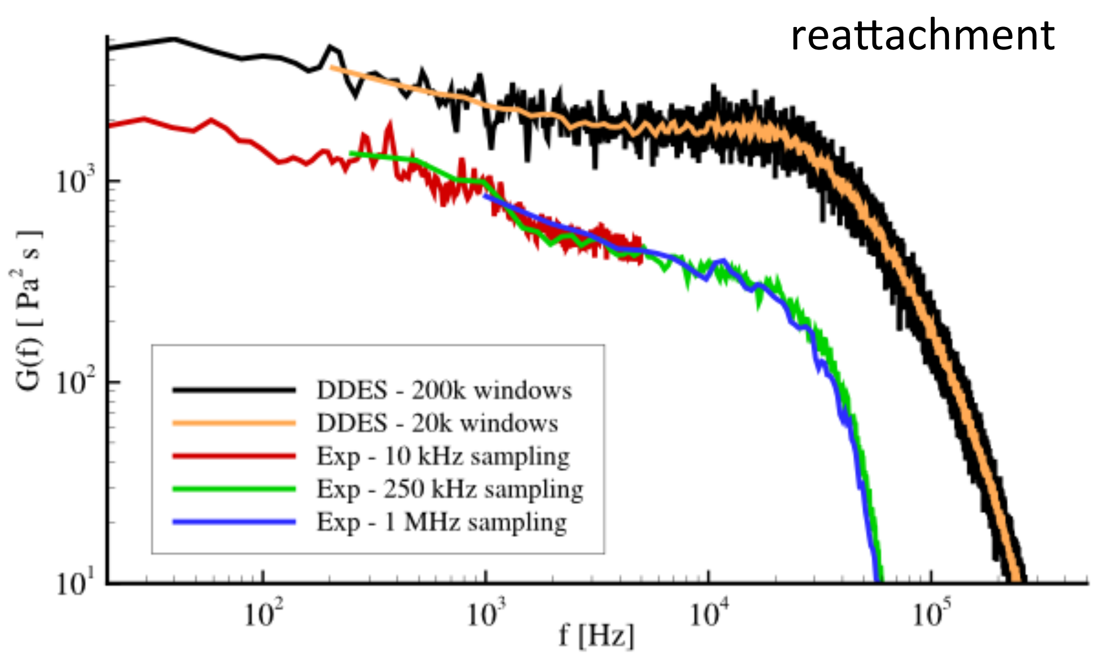
Spectral analysis

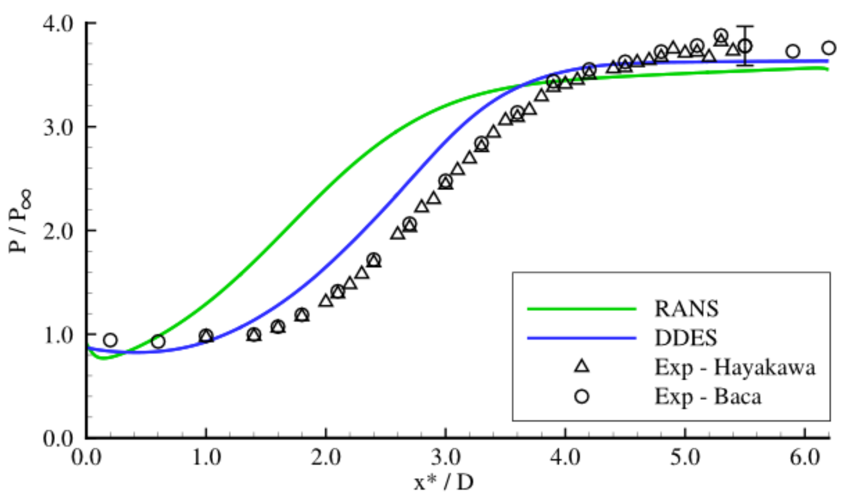


Leger & Bisek

Reattaching Shear Layer (part 2)

- ***O***(1 sec) data needed to explore low frequency flapping of shear layer
- Long time series (<u>months of wall time</u>), drove need for automated processing of intermediate data





- **File system issues and mean time to failure are still lingering problems**
- Need for better node health checking
- Need for AI to process intermediate data (help decide what info to save & study)

DOD HPC Frontier Project

- <u>Awarded First Place Out of 60</u>
- <u>First-ever award</u>

DOD HPC MODERNIZATION PROGRAM

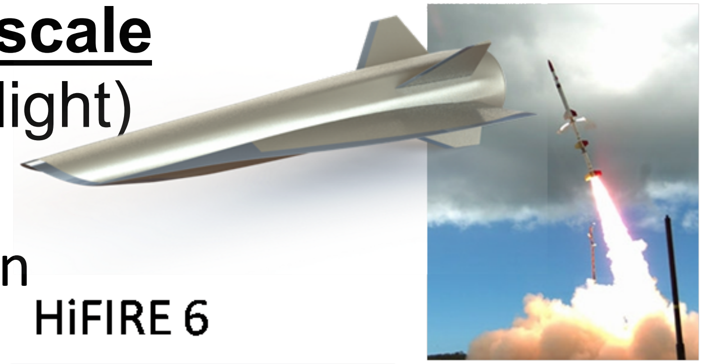
- Push 6.1 LES/DNS CFD capability into 6.2/6.3 T&E environment
- Gosse, Bisek (co-PI's)

- <u>Why?</u>
  - Understand Unsteady Load Environment for Aero-Thermal-Structural Interactions
  - Full Vehicle Scale Experimental Limitations
    - $5M/fight (1x), $75M/flight (10x), $???M/flight (100x)
    - Wind Tunnel only up to ~3x full vehicle scale
  - ILES Computational Simulation
    - Time accurate, full physics, full scale
    - Currently possible up to 10x

<u>LES vehicle scale</u>

(CPUH/min flight)

0.1x
200M/min



HiFIRE 6

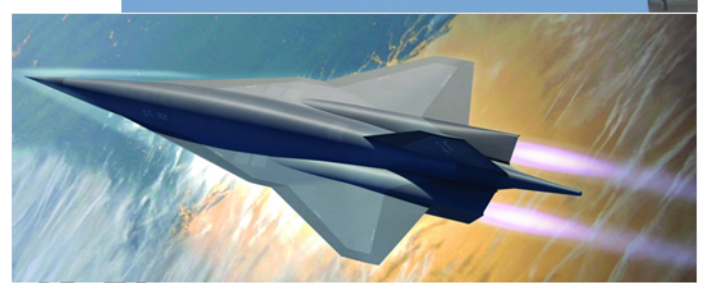
↓

1x
10B/min

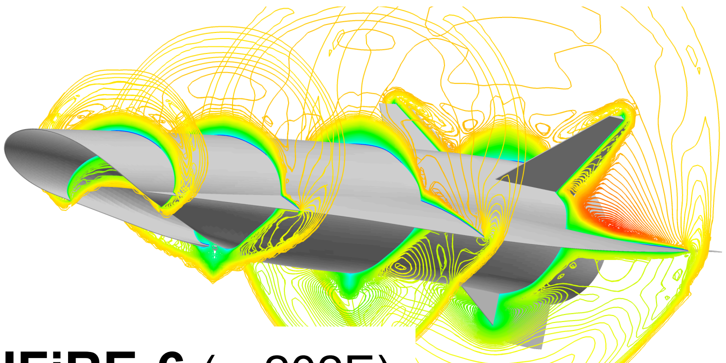
X-51

↓

10x
4T/min

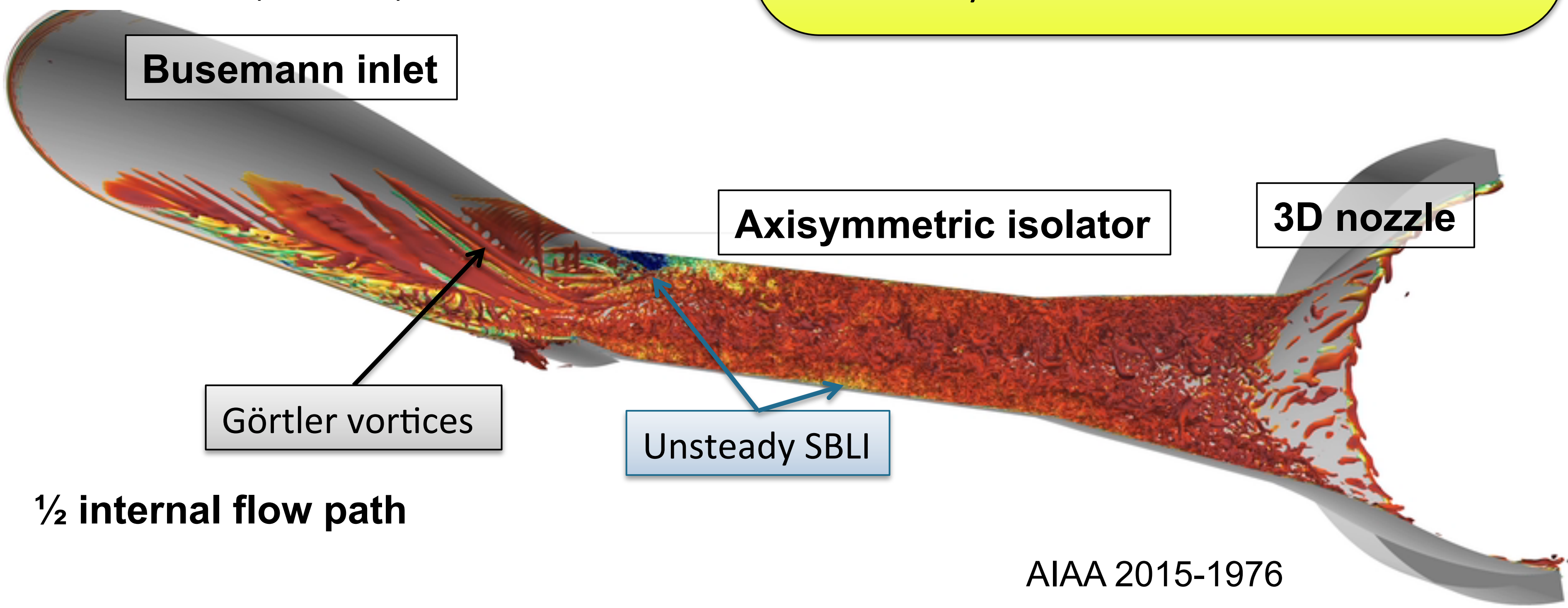


6.1 CFD on a 6.2 Vehicle



HIFiRE-6 (v. 202E)

- Large core count enables LES for engineering analysis
- LES at true scale and flight conditions
  - ✧ First for a hypersonic vehicle
  - ✧ Near limit of current supercomputers
  - ✧ Grid generation and data challenges
  - ✧ Quantify differences between RANS & LES



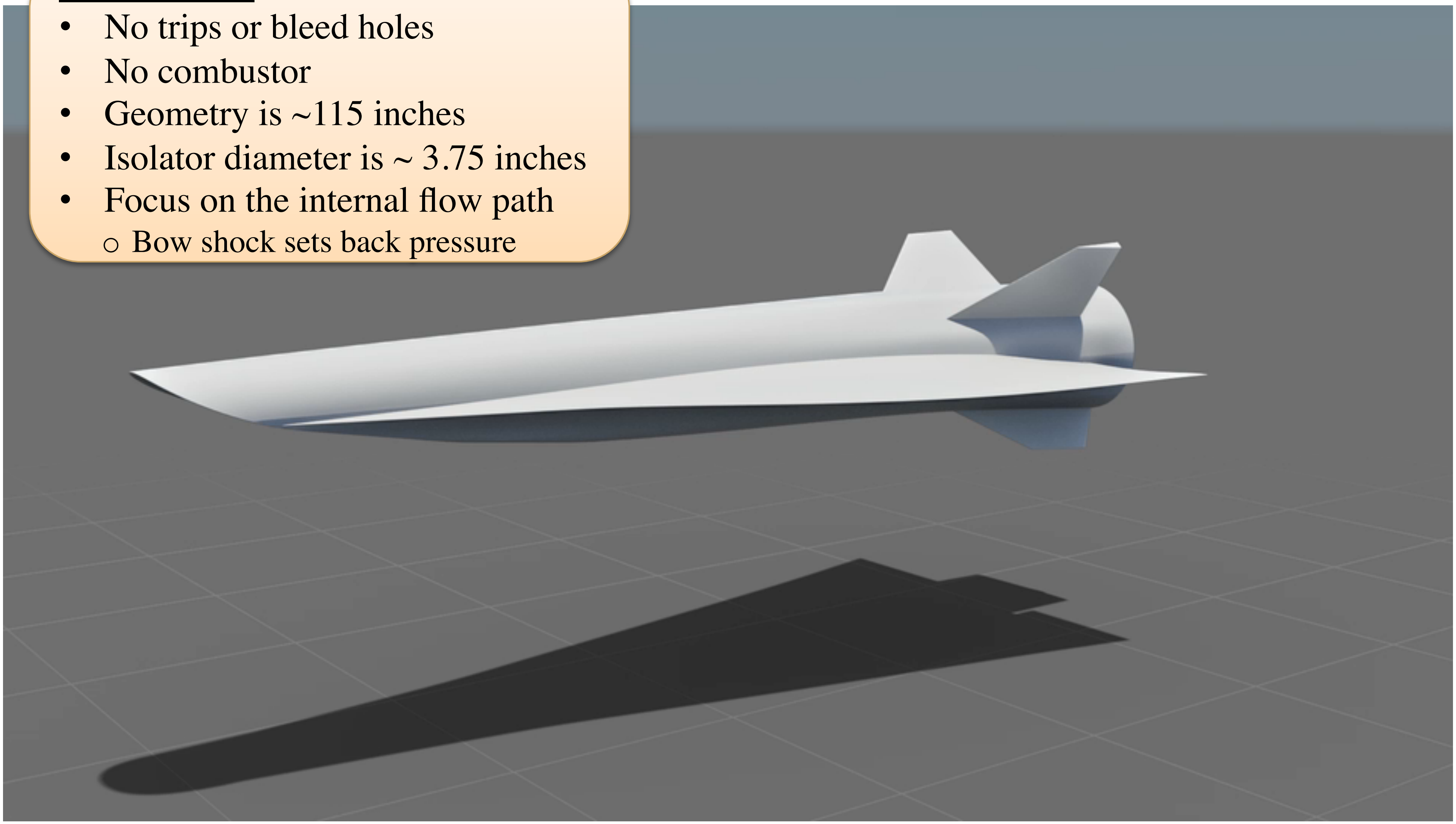
½ internal flow path

AIAA 2015-1976

HIFiRE-6

Version 202E

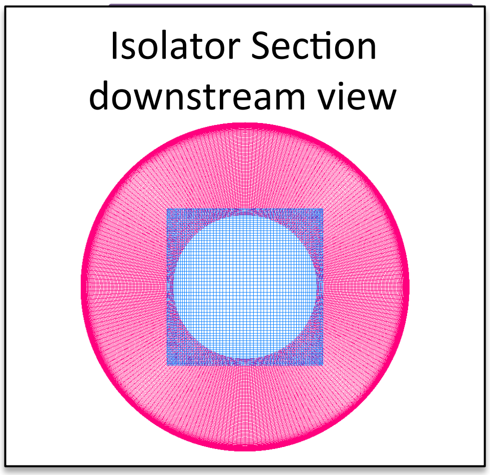
- No trips or bleed holes
- No combustor
- Geometry is ~115 inches
- Isolator diameter is ~ 3.75 inches
- Focus on the internal flow path
  - Bow shock sets back pressure

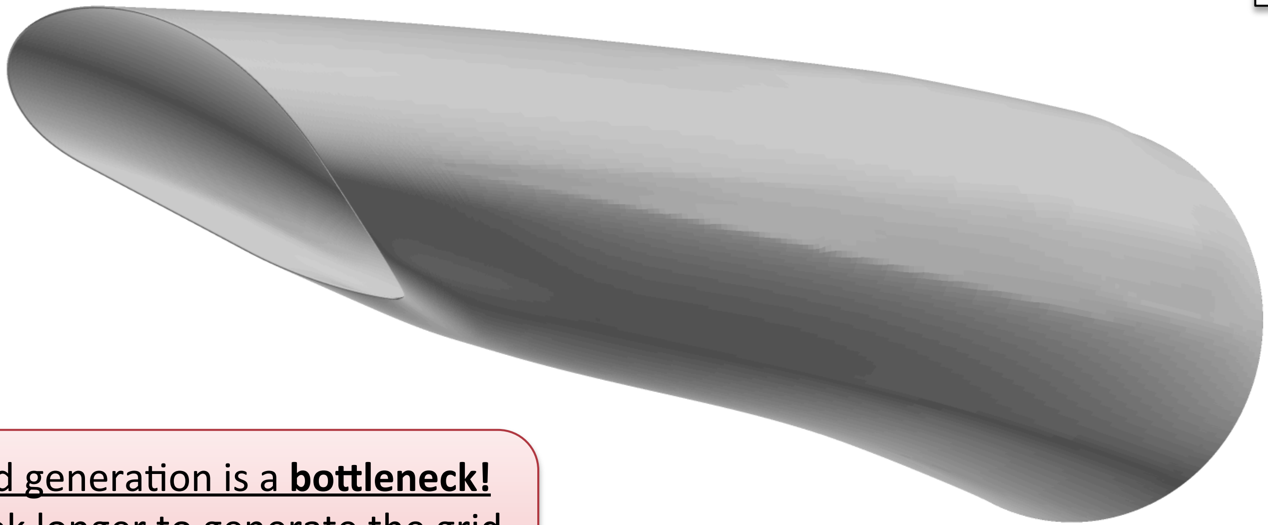


Semi-Automatic Grid System Generation

<u>4 systems of grids:</u>

- Coarse, 23 grids (64^3) → 55M pts
- Medium, 23 grids (96^3) → 150M pts
- Fine, 32 grids (128^3) → **640M pts**
- Very Fine, 89 grids (128^3) → 3.5B pts





- <u>Grid generation is a **bottleneck!**</u>
- Took longer to generate the grid system (**months**), then it took to perform the simulation (**weeks**).

Time-Accurate CFD = *Big Data*

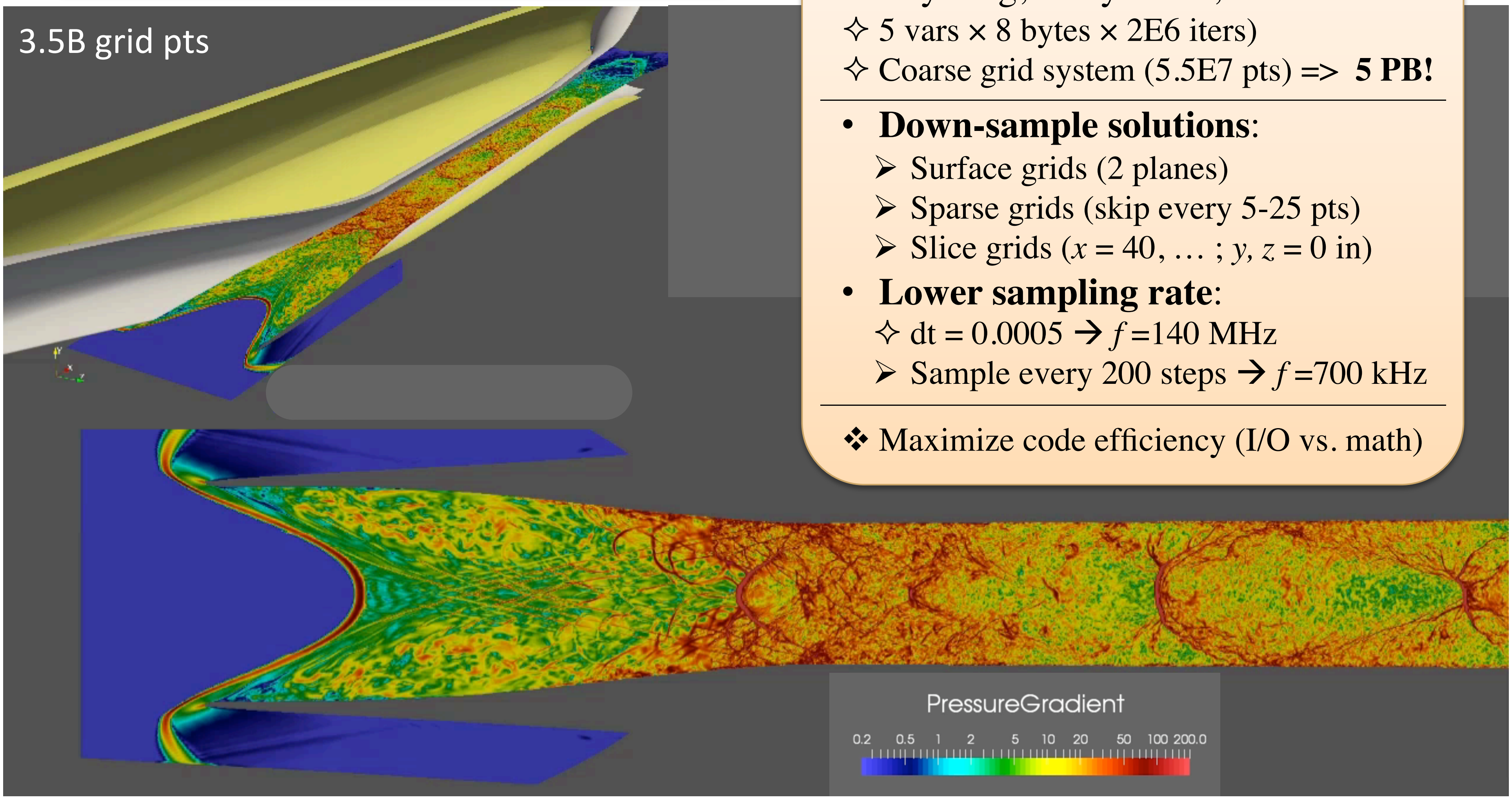
- Data management is not a bottleneck … **yet** ☺
- Does need upfront planning and coordination

Computations are too large to collect everything, everywhere, all the time:

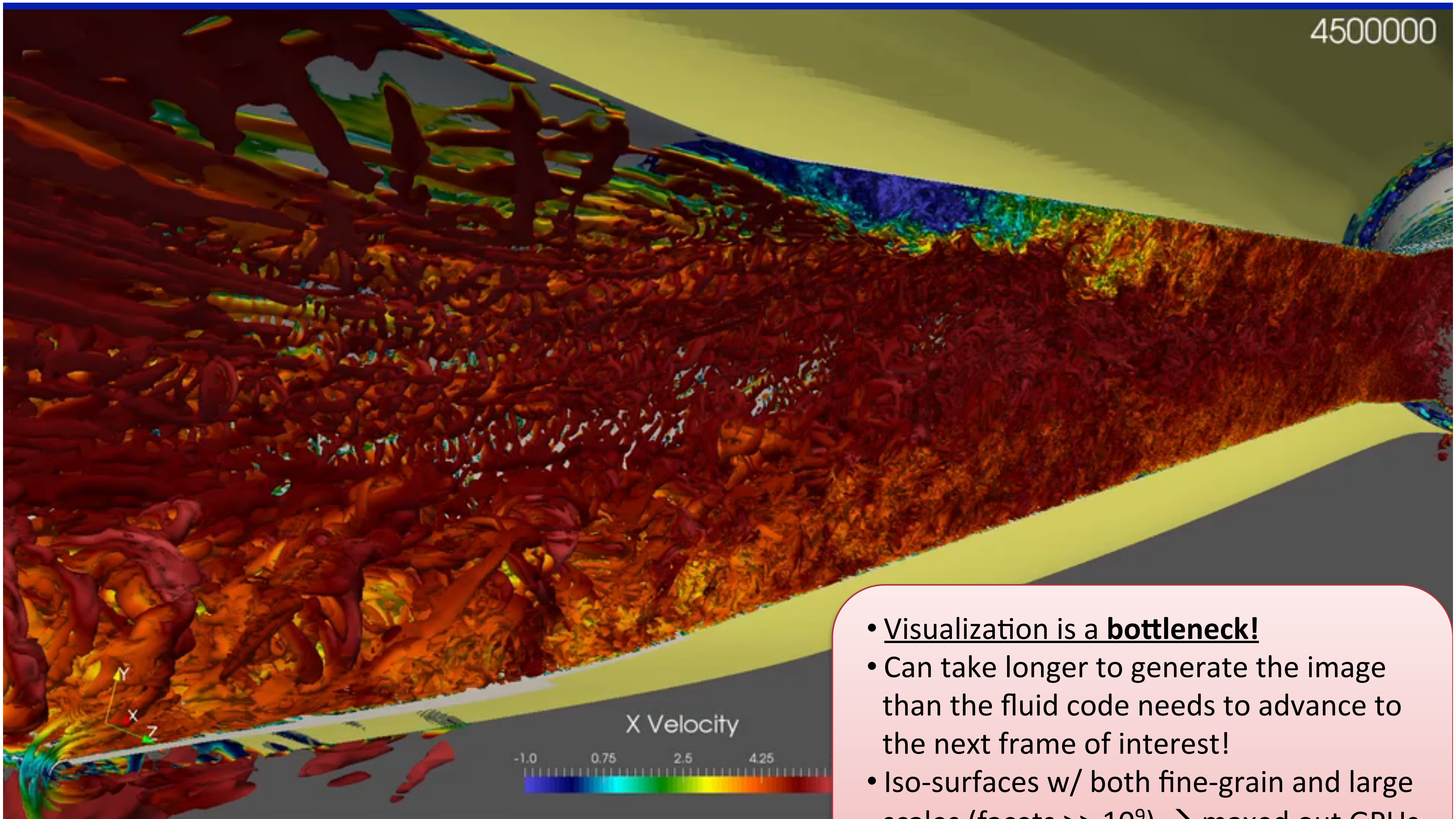
✧ 5 vars × 8 bytes × 2E6 iters)
✧ Coarse grid system (5.5E7 pts) => **5 PB!**

- **Down-sample solutions**:
  - ➢ Surface grids (2 planes)
  - ➢ Sparse grids (skip every 5-25 pts)
  - ➢ Slice grids ($x = 40, \ldots; y, z = 0$ in)
- **Lower sampling rate**:
  - ✧ dt = 0.0005 → f =140 MHz
  - ➢ Sample every 200 steps → f =700 kHz

❖ Maximize code efficiency (I/O vs. math)



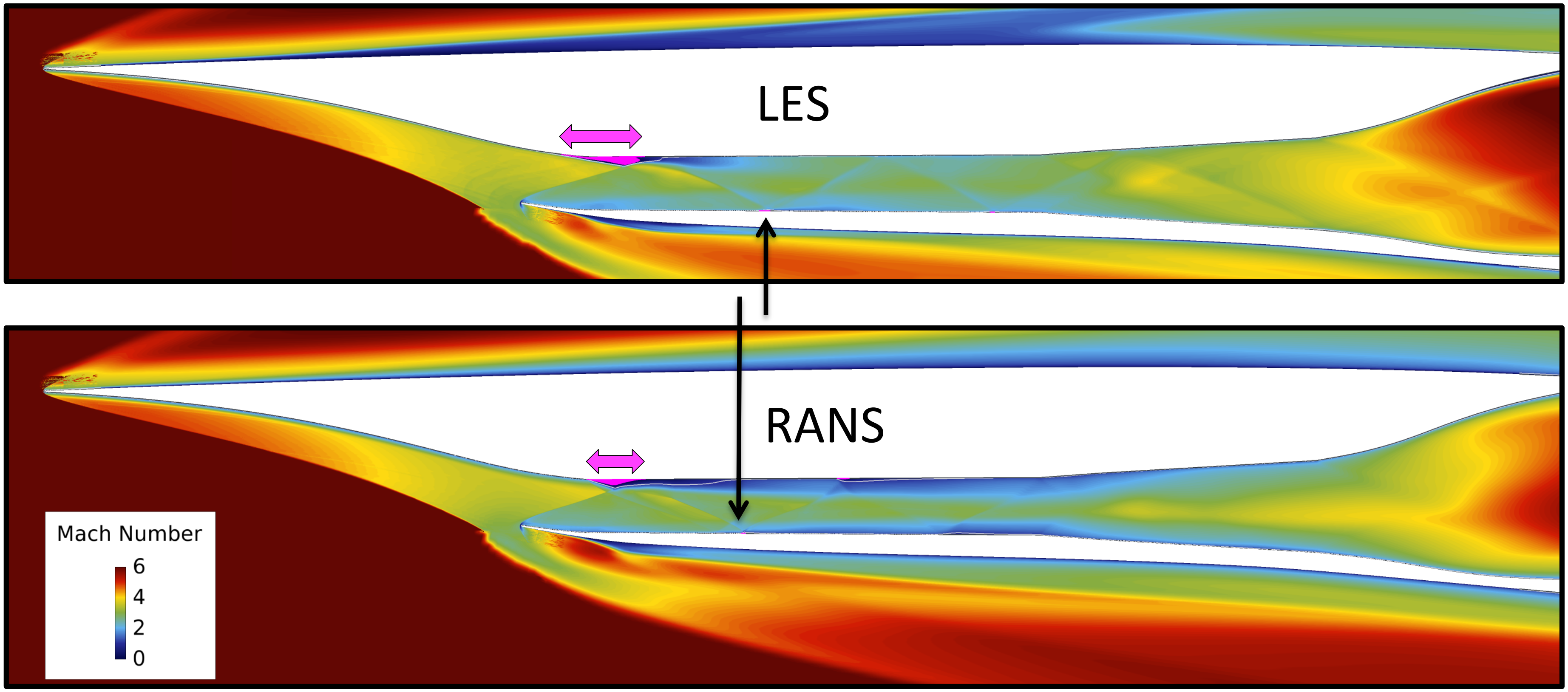
Visualizing Large Eddy Simulations



Q-criterion near inlet/isolator junction

- <u>Visualization is a **bottleneck!**</u>
- Can take longer to generate the image than the fluid code needs to advance to the next frame of interest!
- Iso-surfaces w/ both fine-grain and large scales (facets >> 10^9) → maxed out GPUs
- Even 4K resolution can be inadequate!

Time-Mean Mach Contours



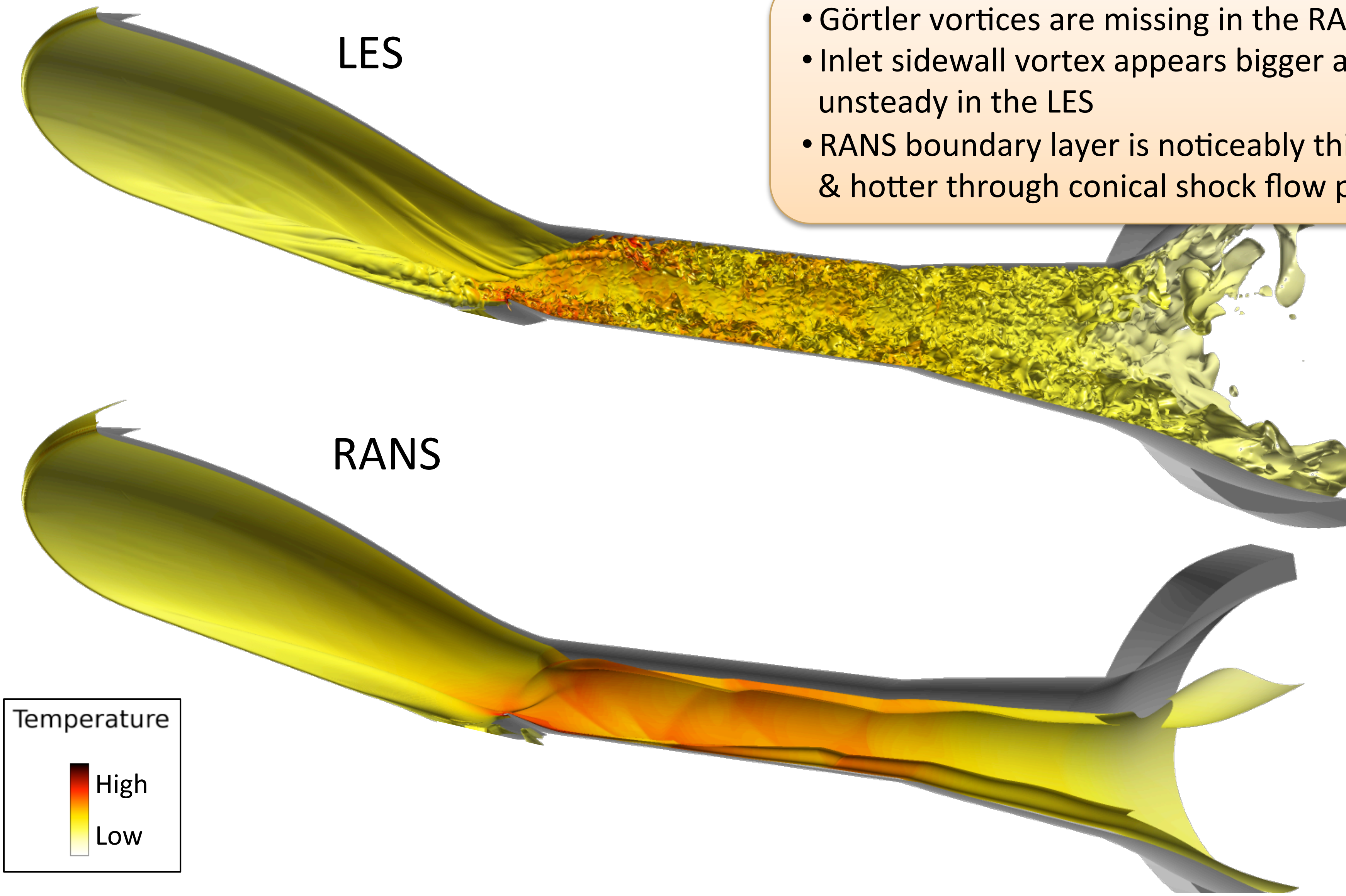
- LES has a thinner boundary layer
- λ-shock feet are farther apart
- Separation size for 1st SBLI is 2X bigger
- 2nd SBLI occurs occurs several inches farther downstream
- Large differences seen in the nozzle

Midspan (z = 0)

Mach 6, 88 kft
$\alpha = 4°$

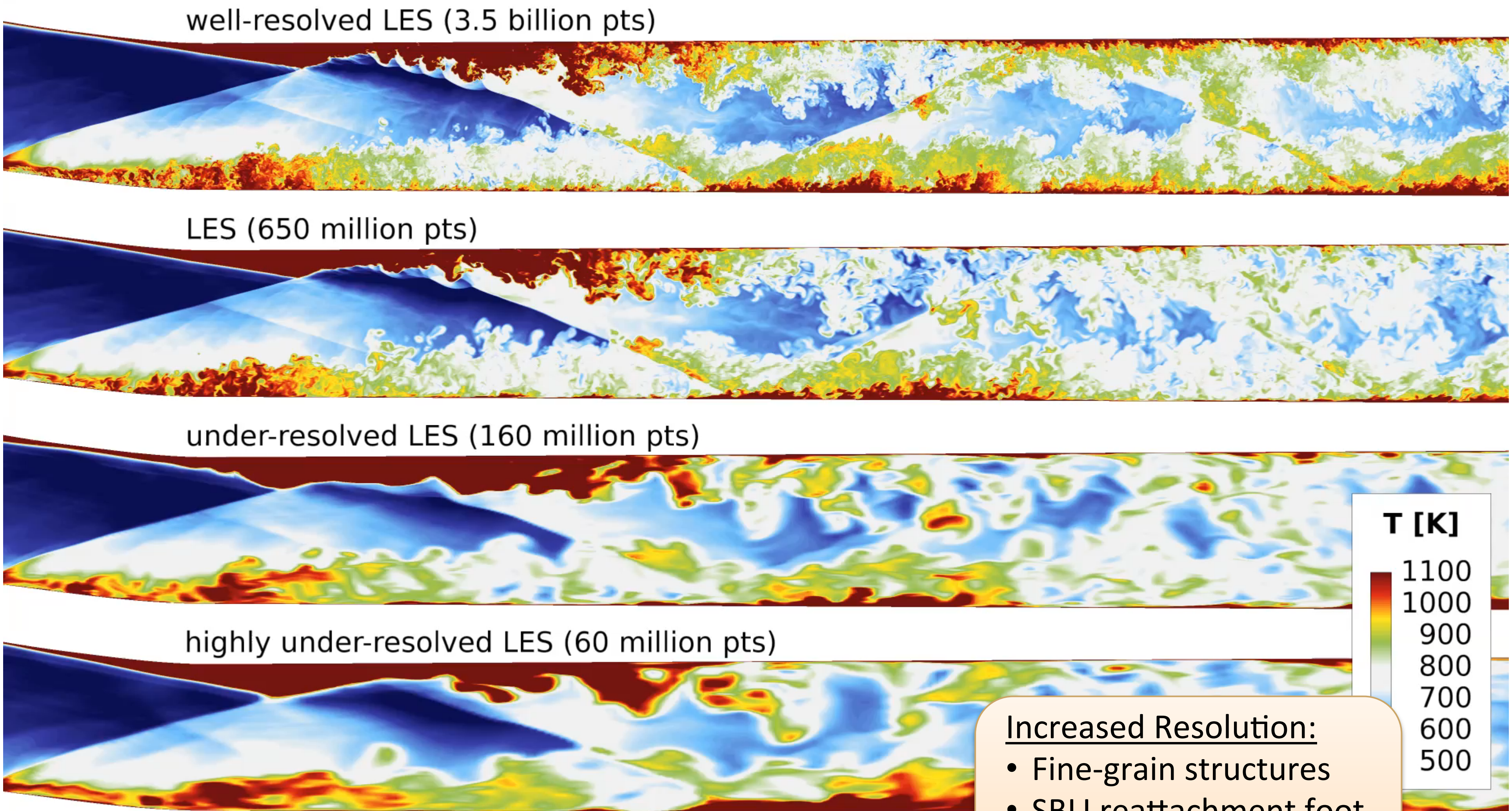
Iso-surfaces of Stagnation Pressure

- Görtler vortices are missing in the RANS
- Inlet sidewall vortex appears bigger and unsteady in the LES
- RANS boundary layer is noticeably thicker & hotter through conical shock flow path



Resolution, Resolution, Resolution

the three most important words in LES **– Don Rizzetta**



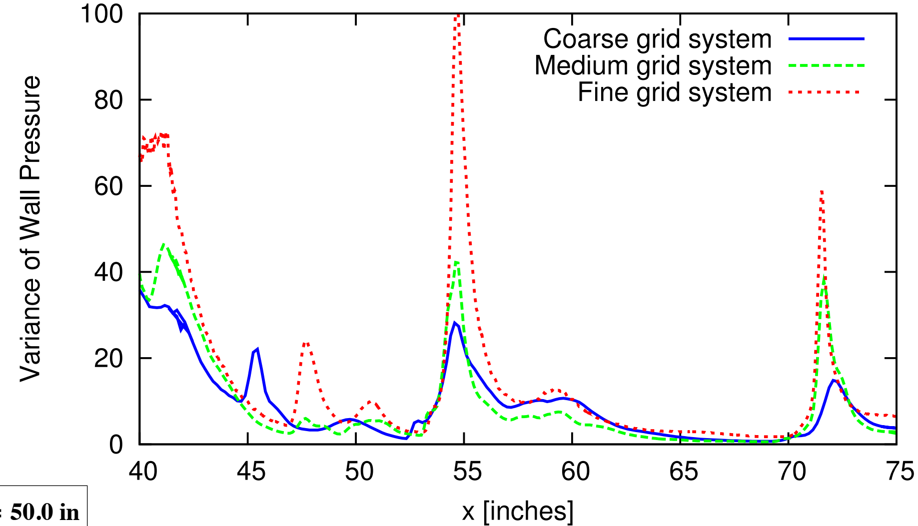
Midspan contours in the isolator [*x* = 40 to 75 inches]

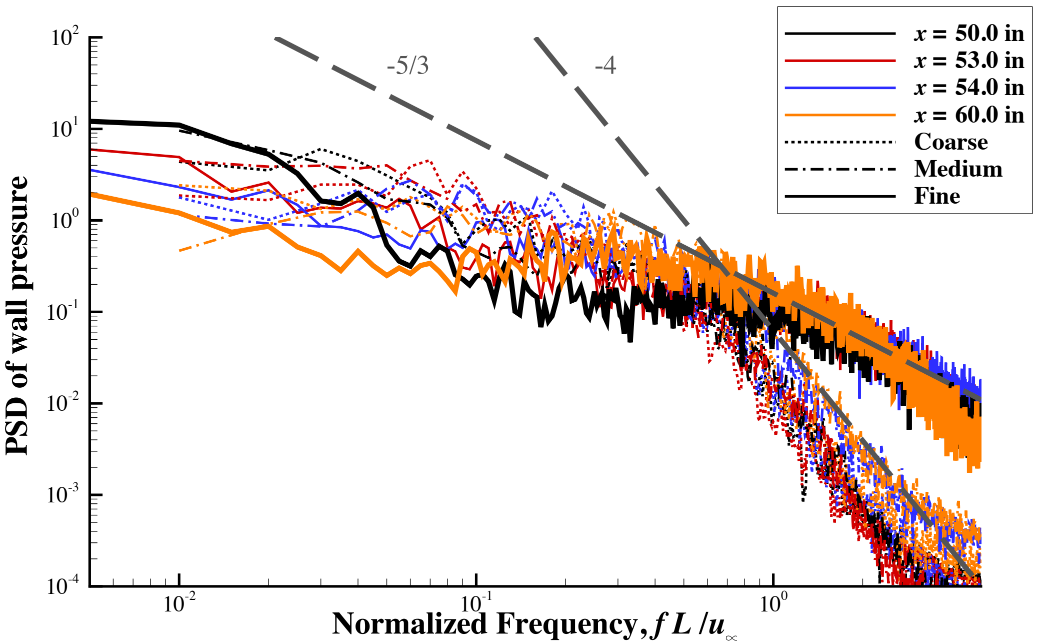
<u>Increased Resolution:</u>

- Fine-grain structures
- SBLI reattachment foot appears more dynamic
- Clearer shock train

Unsteady Surface Pressure
(bottom centerline)

- Time-mean results occur at similar locations for both the 2nd and 4th SBLIs
- Pressure fluctuations are stronger with increased resolution
- Large scale fluctuations present downstream of the saddle





- Lack of spatial resolution leads to numerically-driven dissipation at highest frequencies for Coarse and Medium grid systems
- Rapid increase in energy at low frequencies, even upstream of SBLI

Summary

- High-Fidelity **ILES** was simulated for Mach 2.25 flow over a 24^o compression corner
  - SBLI in the presence of a sidewall shows a **significantly 3D** shock structure
  - Separation length size varies significantly with distance from the sidewall
  - SBLI *was not 2D near the midspan* (inconsistent with previous conclusions)
  - Sidewall glancing SBLI exhibited low-frequency motion even though $c_f > 0$
  - Low-frequency motion not observed on at sidewall vortex-induced separation locations
- **DDES** was carried out for Mach 3 reattaching shear layer
  - Both time step size and the numbers of sub-iterations influence the predictions
  - Flapping motion consistent with Exp., even though simulation did not have a fluctuating inflow
- **ILES** for **full-scale** HIFiRE-6 flight vehicle internal full path **at flight cruise conditions**
  - 5th order WENO scheme within NASA's OVERFLOW CFD solver were used for RANS and LES
  - Overset grid systems (56M, 160M, 650M, and 3.6B grid pts.) without hole-cutting or orphans!
  - LES predicts transitional inlet flow due to cross-flow instabilities and Görtler vortices
  - RANS assumed fully turbulent inlet, which led to a thicker boundary-layers and suppressed the formation of the Görtler vortices, leading to a smaller SBLI footprints and a different flow
  - Flow path experienced a **significantly 3D unsteady** conical shock system

Large-Scale Computing: Lessons Learned

- Upfront ‘effort’ to develop the grid system with optimal decompositions & optimized thread count per MPI Rank
- Tune file system to optimize MPIIO

- Data management is not a bottleneck … **yet**
- Does need upfront planning and coordination

- <u>Grid generation is a **bottleneck!**</u>
- Took longer to generate the grid system (**months**), then it took to perform the simulation (**weeks**).

- <u>Visualization is a **bottleneck!**</u>
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- Iso-surfaces w/ both fine-grain and large scales (facets >> 10^9) → maxed out GPUs
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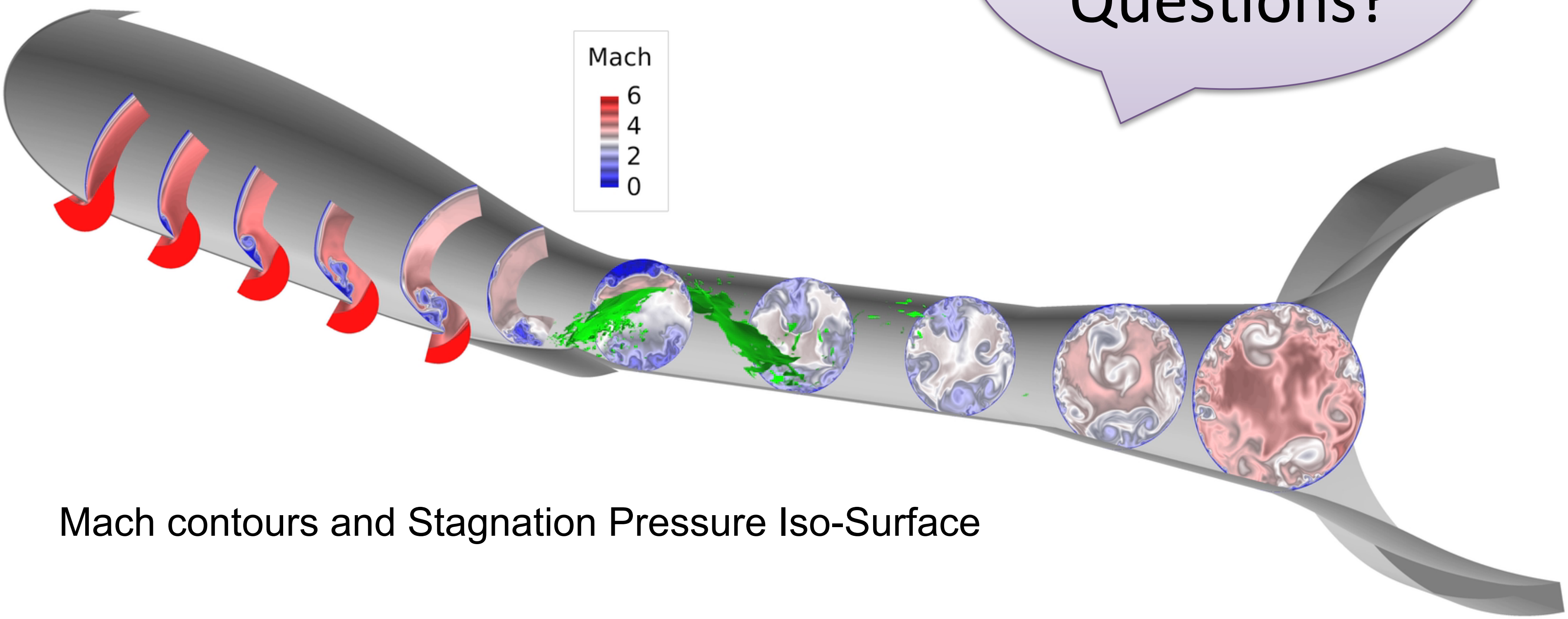
- Mean time to failure is a **bottleneck**. Must develop better system monitoring capabilities and run parallel jobs to actively monitor and sort intermediate data from the actual jobs

Grid generation, Visualization, and mean-time to compute node failure are clear bottlenecks in the process, but the Frontier Project has shown that high-fidelity unsteady simulations <u>can be used for full-scale flight vehicle predictions.</u>

Thank You

Any Questions?



Mach contours and Stagnation Pressure Iso-Surface