Turbulence: V&V and UQ Analysis of a Multi-scale Complex System

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Abstract

- Turbulent motions are ubiquitous and impact almost every aspect of our life, from the formation of hurricanes to the mixing of a cappuccino. The mathematical description of turbulent flows is established, and in the last four decades computational tools have been used extensively to increase our understanding of the basic physical processes as well as to improve the design of engineering devices. The multiscale nature of turbulence creates unique challenges for numerical simulations. Discretization methods must preserve the physical processes, reducing or eliminating artificial dissipation and dispersion. Moreover, the extreme computational effort required to capture all the temporal and spatial scales of motion leads to the introduction of physical models for unresolved features. How do you establish confidence in the numerical simulations of turbulent flows? The talk will describe how the concepts of verification, validation and uncertainty quantification are developed and used in the framework of turbulence simulations. Several applications of turbulent flow simulations will also be described ranging from turbulent combustion in jet engines to aero-acoustics.

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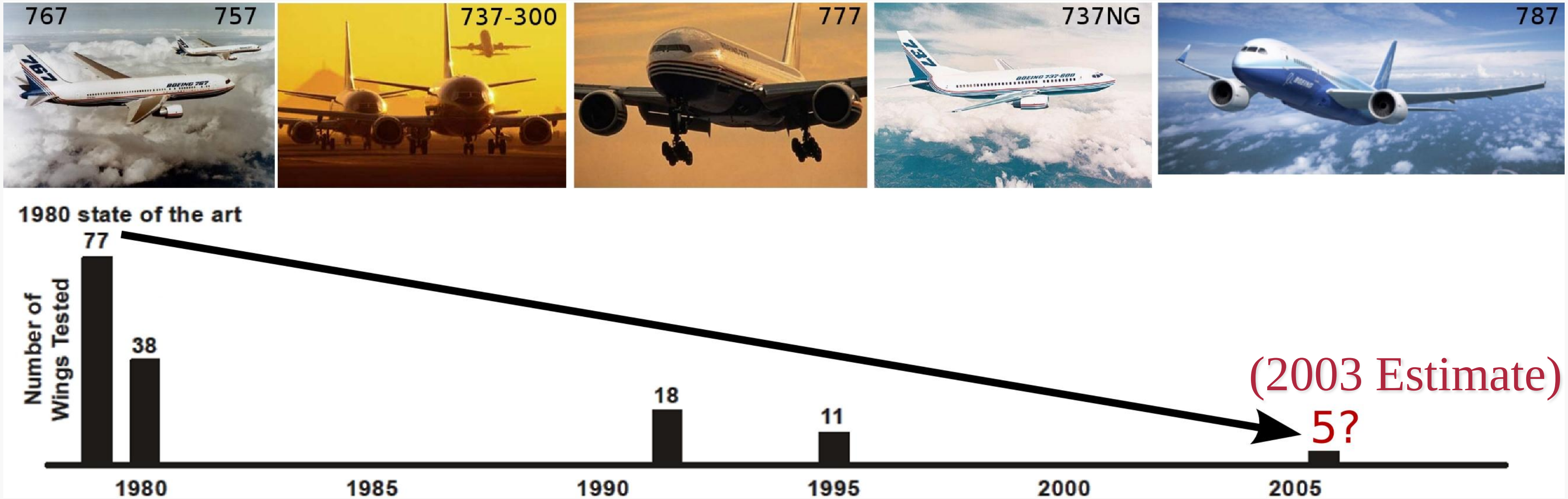
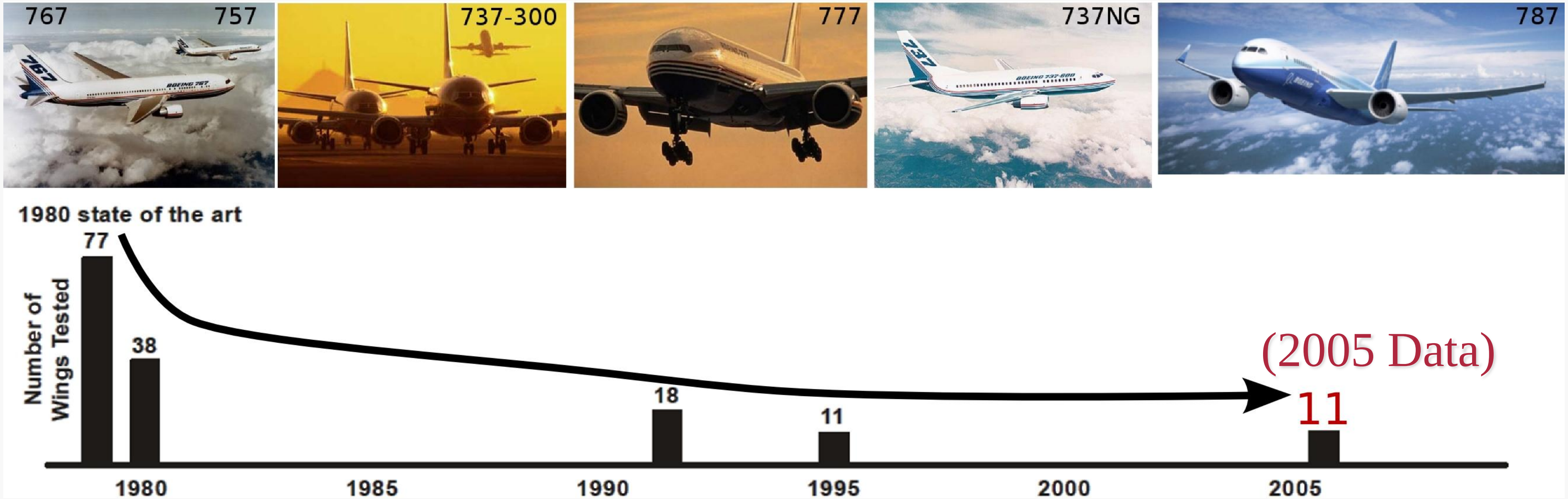
Part 1
Turbulence

CFD’s value for Boeing



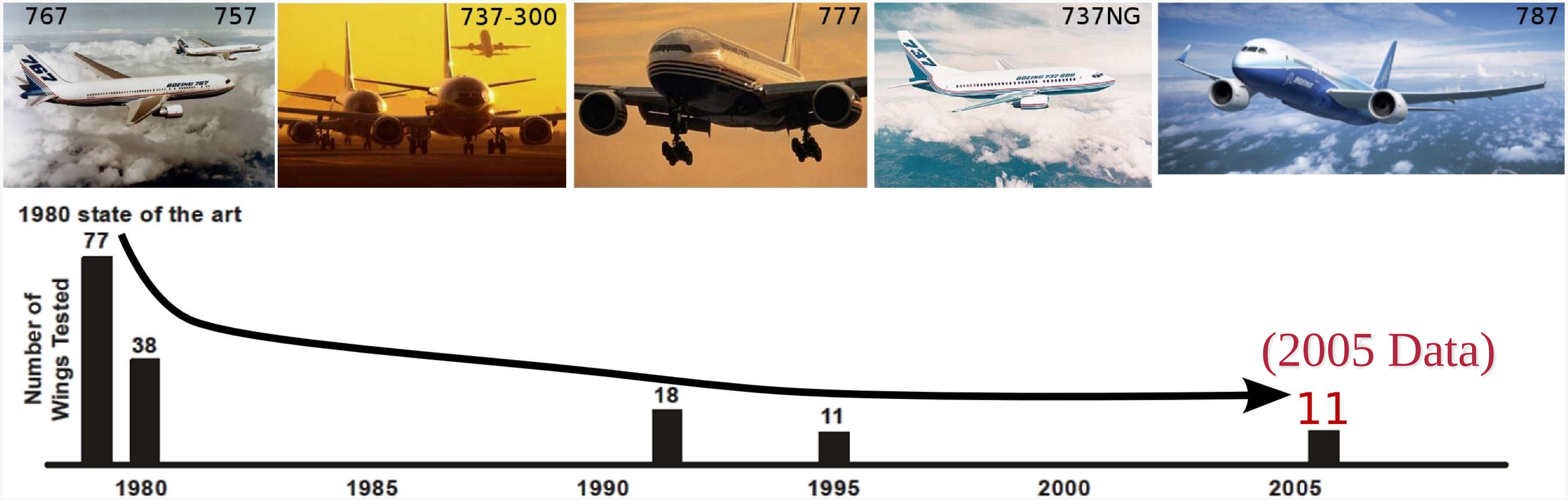
The CFD Bottleneck in Industry



More Computer Power, But # of Required Tests Plateaued.

Why?

Back to CFD Bottleneck in Industry



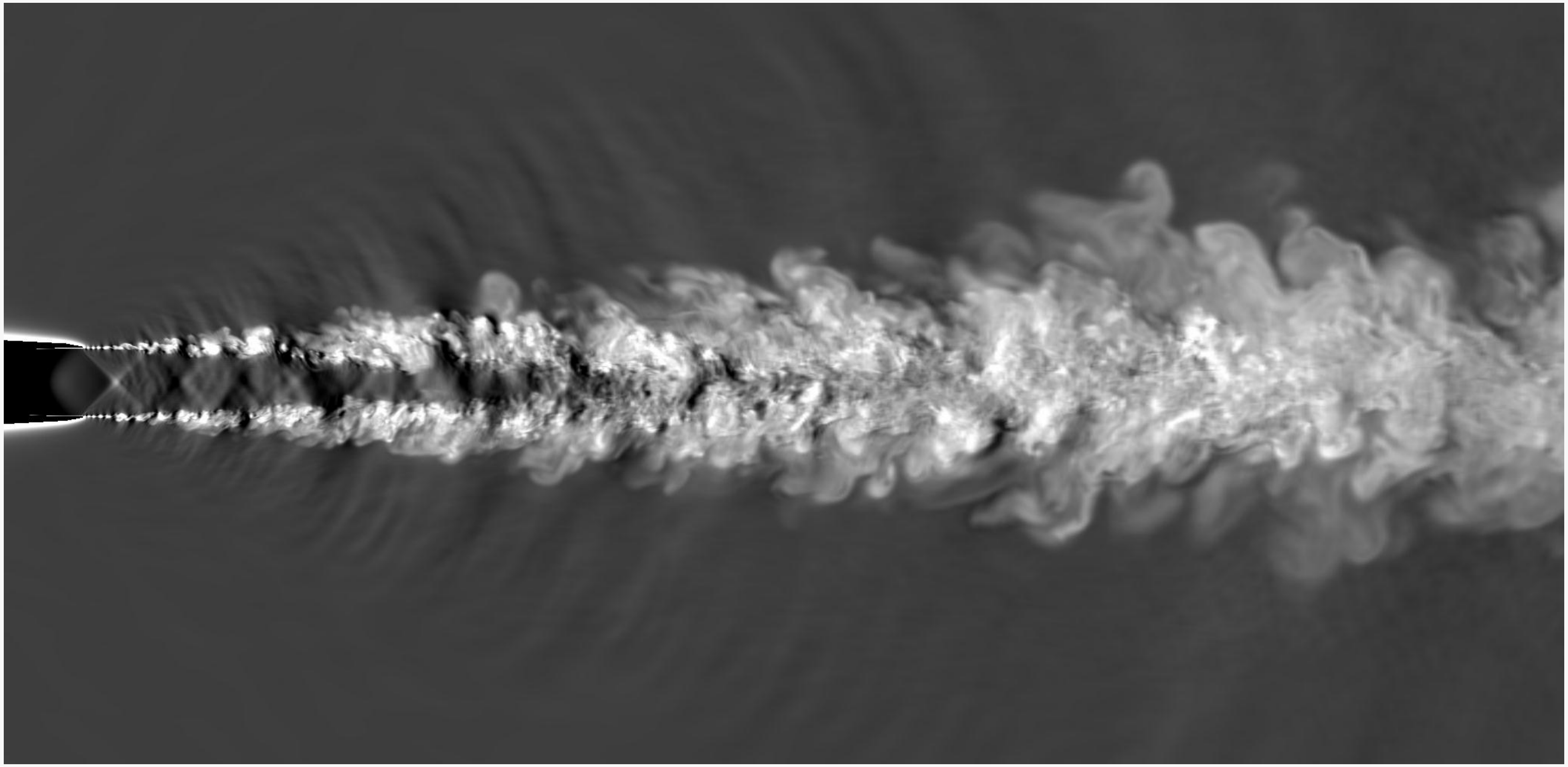
More Computer Power, But # of Required Tests Plateaued.

- Industry standard RANS model predictions do not improve with more FLOPS or memory beyond 1990's levels.
- Constrained by model form
- High-fidelity first principles approaches, e.g. Large-Eddy Simulation (LES), provide a path to prediction

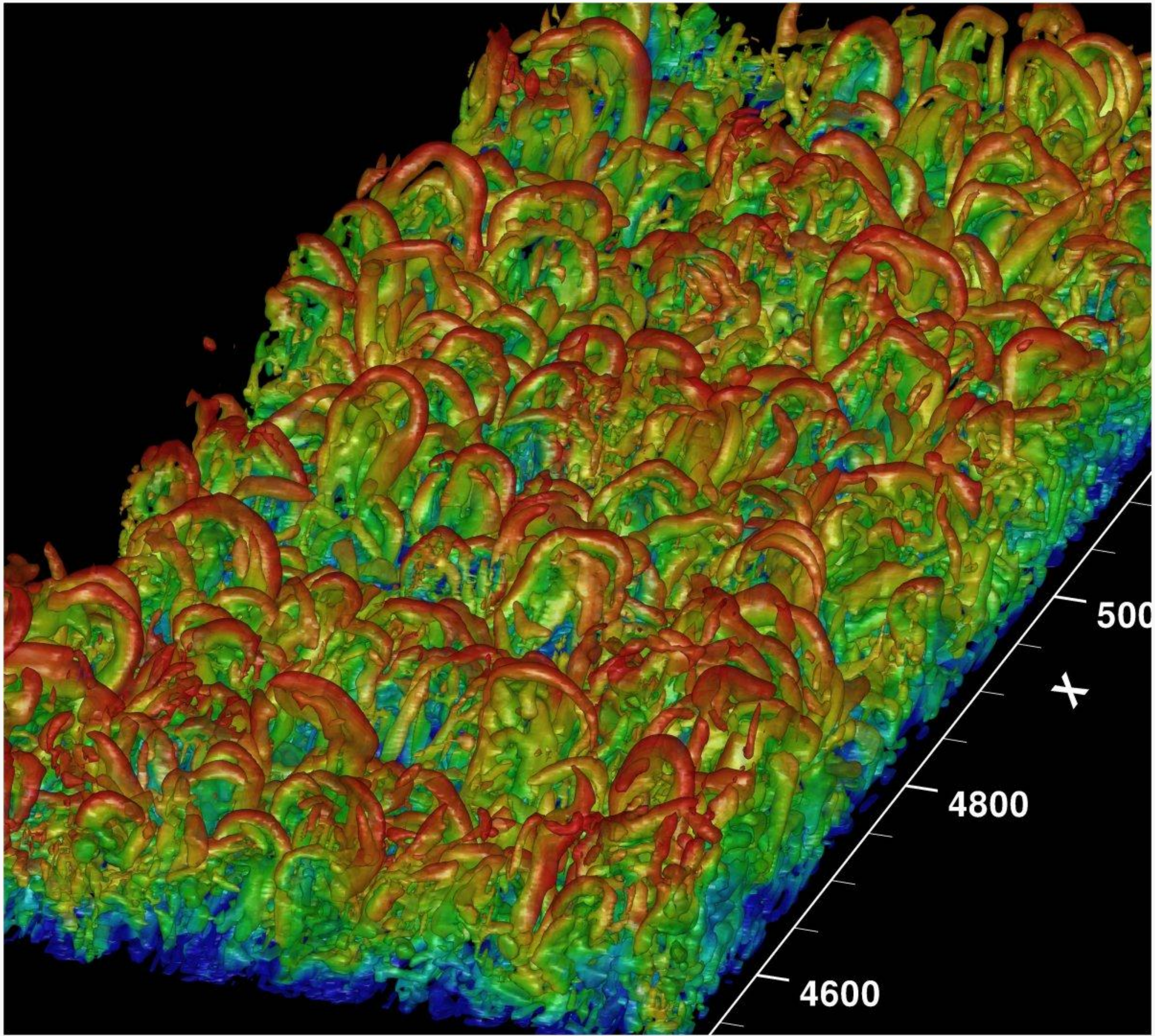
Turbulence

Turbulence is the chaotic state of fluid motion that arises when the flow speed is higher than just the creeping motion

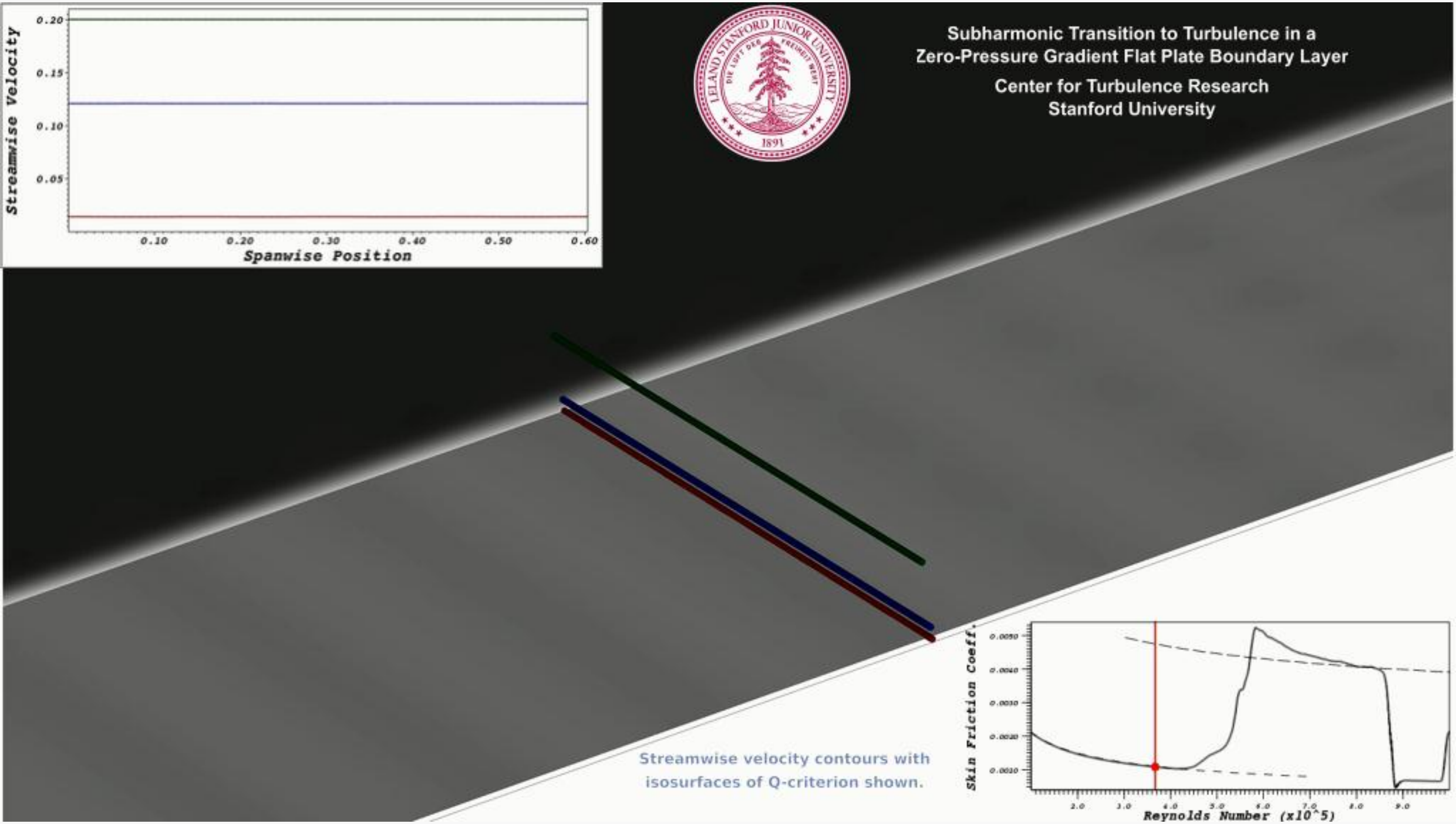
It is the rule, not the exception, in fluid dynamics



The Structure of Turbulence



Transition to Turbulence



Subharmonic Transition to Turbulence in a Zero-Pressure Gradient Flat Plate Boundary Layer

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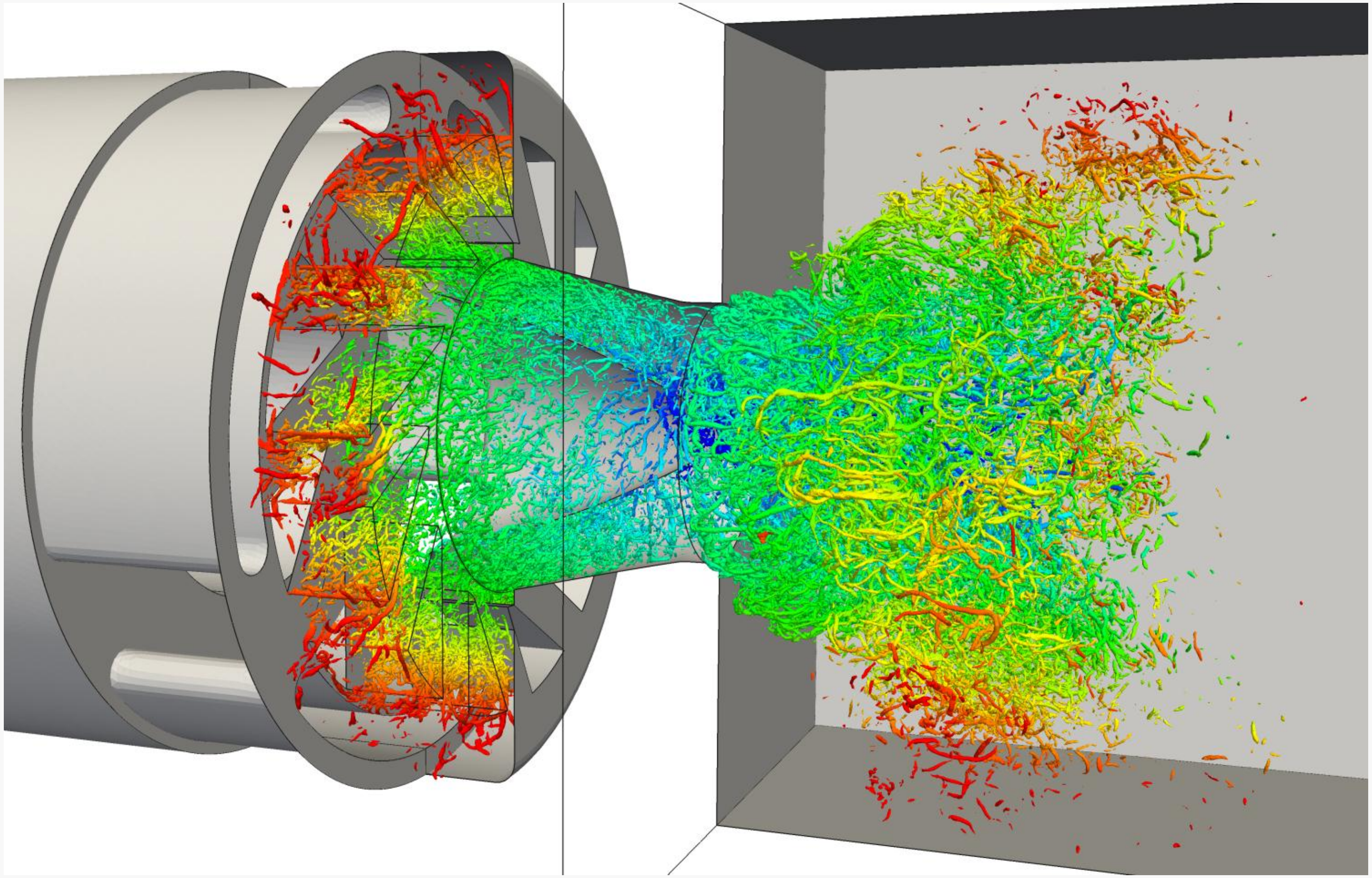
Streamwise velocity contours with isosurfaces of Q-criterion shown.

Turbulence downstream of a swirler



2.6 billion grid cells

Why is turbulence a stumbling block for CFD?

The range of scales or eddy sizes in a turbulent flow increases with Reynolds number, $N \sim Re^{9/4}$

The computational grid should resolve the small eddies and should encompass the entire device

For a transport airplane with a wing cord length of 5m, a 50m fuselage cruising at 250m/sec at an altitude of 10km, about 10^{16} points are required to capture the turbulence near the surface.

With a peta-flop machine, it would take several years to compute the flow for one second of flight time!

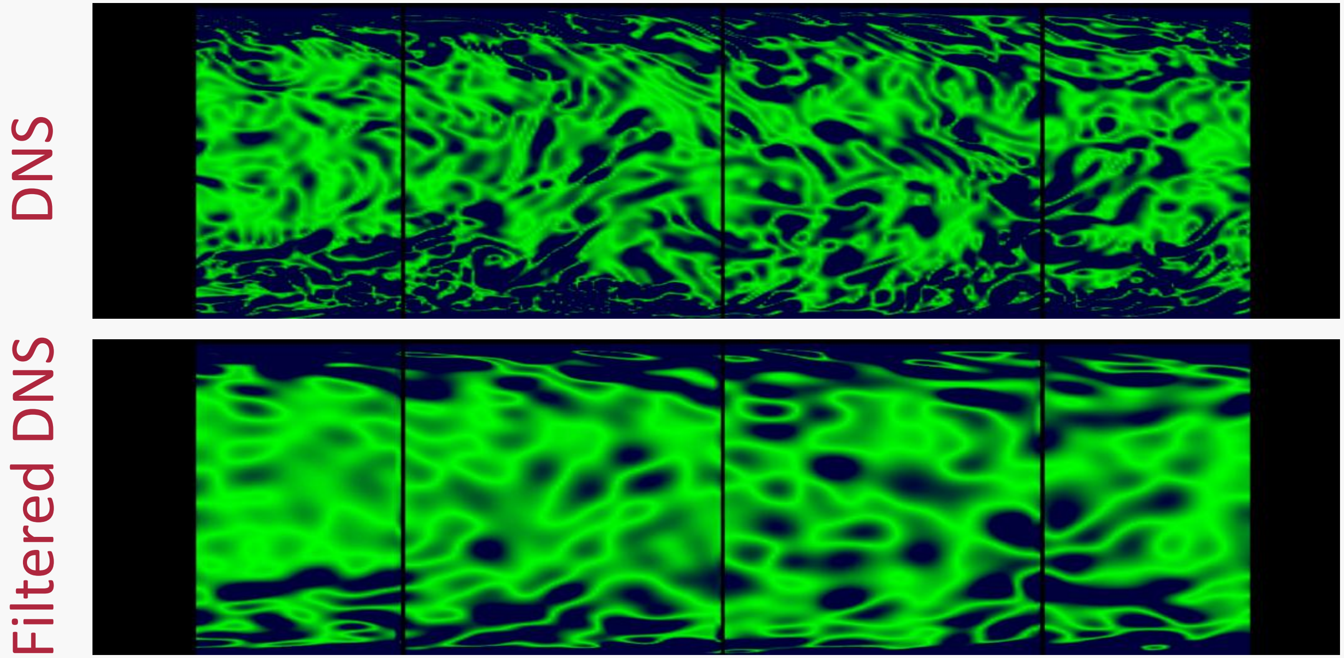
Large Eddy Simulation

- Effectiveness of the prevalent engineering tool for CFD (RANS) has reached a plateau
- RANS performance does not improve with more computational power and more grid points
- LES: Resolve the large scale motions and model the small ones
- Direct path to first principles (more computer power, higher accuracy)
- Must Contend With Greater Memory and I/O Requirements

LES and Filtering

- Formally solve for large-scale motions by applying low-pass filter to Navier-Stokes

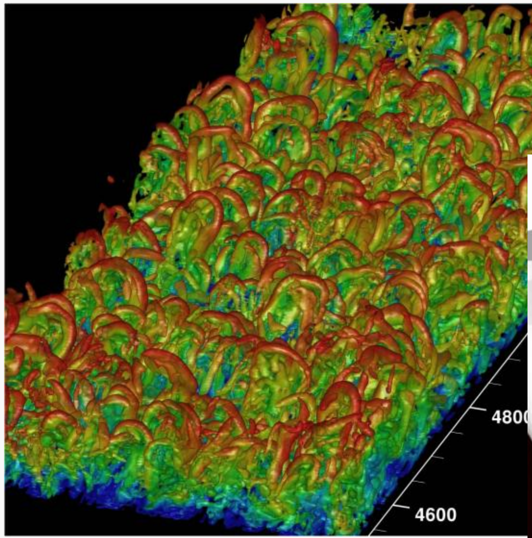
$$\bar{u}_i = \int_{\Omega} G(x, x', \Delta) u_i(x') dx'$$



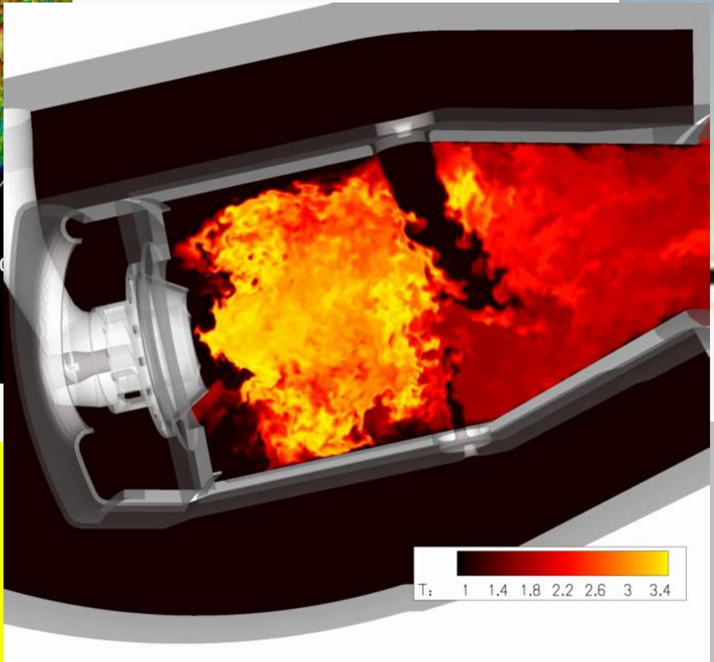
Spanwise vorticity mag., Re_τ =395 channel flow

Part 2
Success Stories

Some Examples



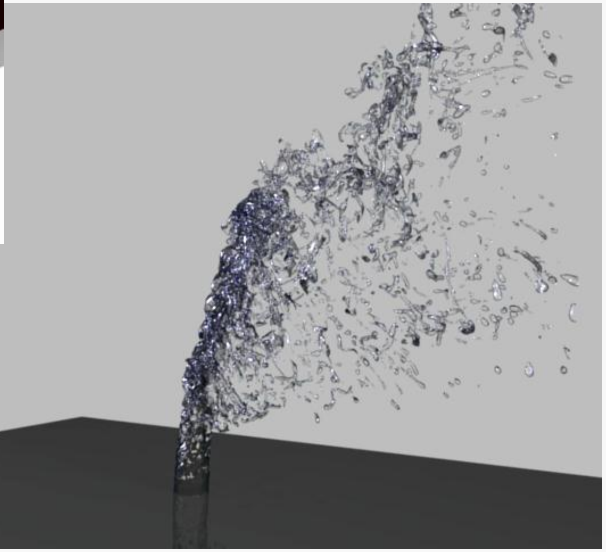
Transition



Reacting Flows in real geometries

Rotorcraft Dynamics

Flow Control



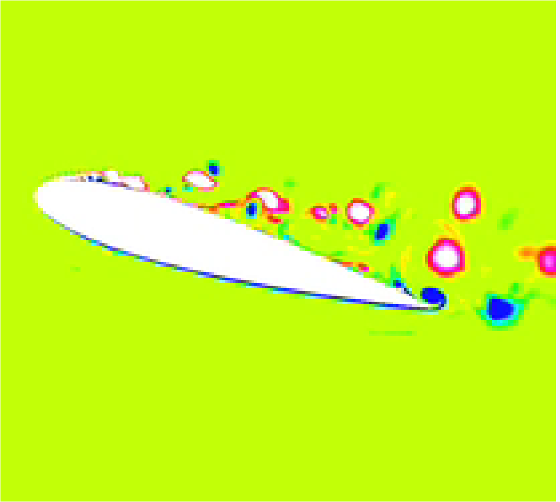
Multiphase flows


Time = 0.00

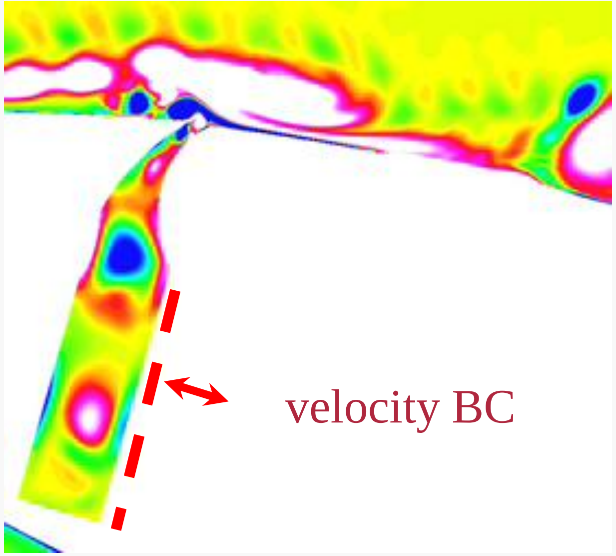
Flow Separation Control

- Control with synthetic jet actuator
- CDP's unstructured grid capability
- Spanwise vorticity ($\Omega_z C/U_\infty = -50 \sim 60$)

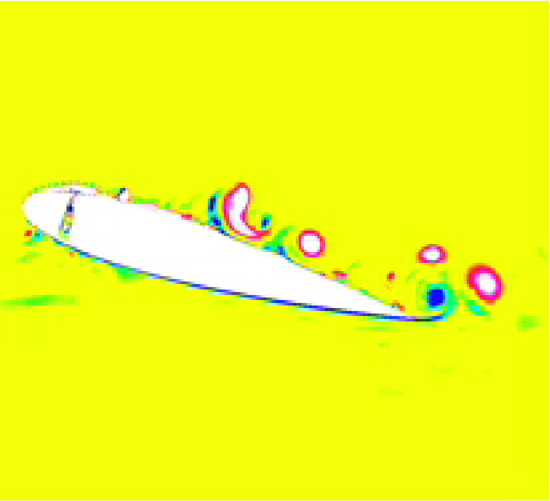
uncontrolled



synthetic jet actuator

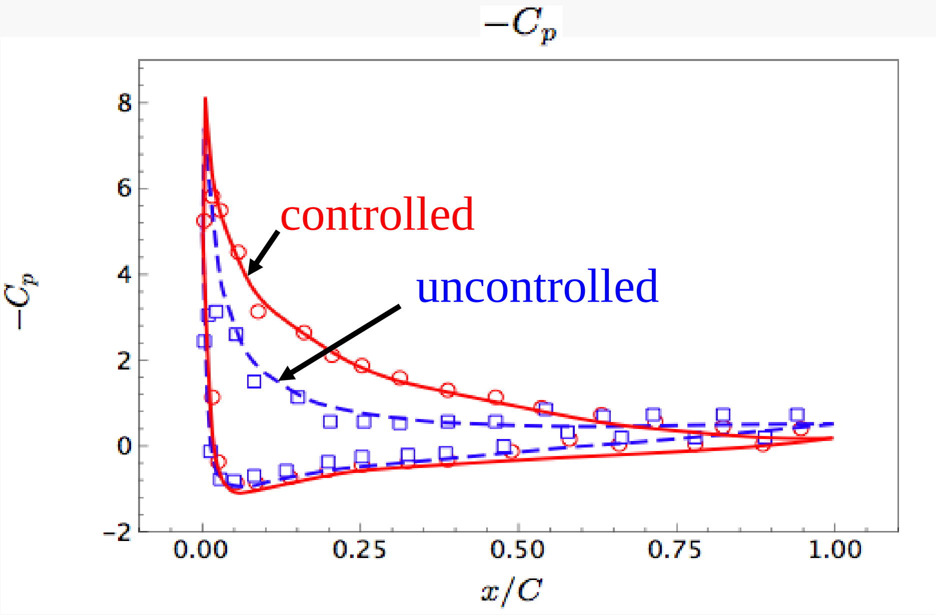


controlled

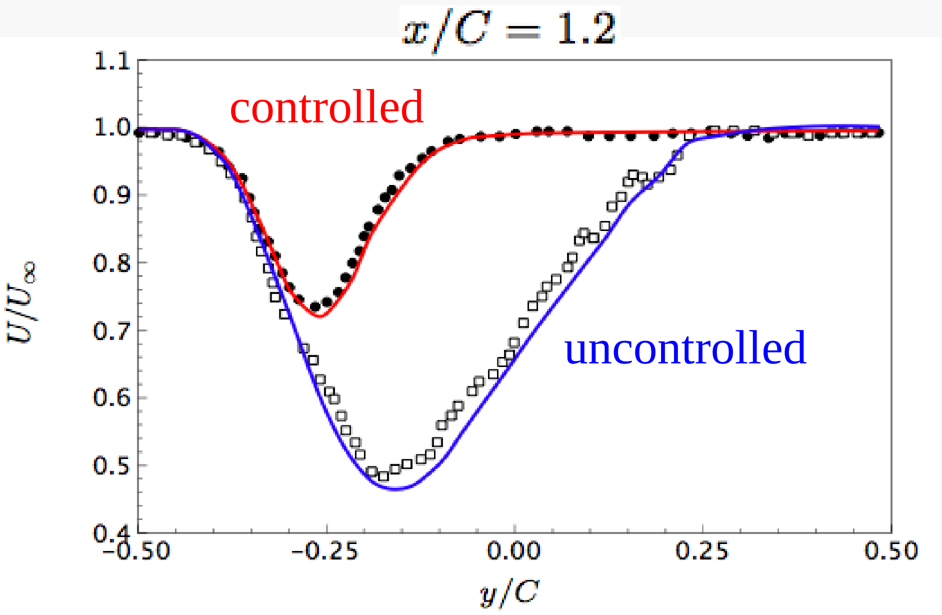


Flow Separation Control

Surface pressure



Velocity in the wake

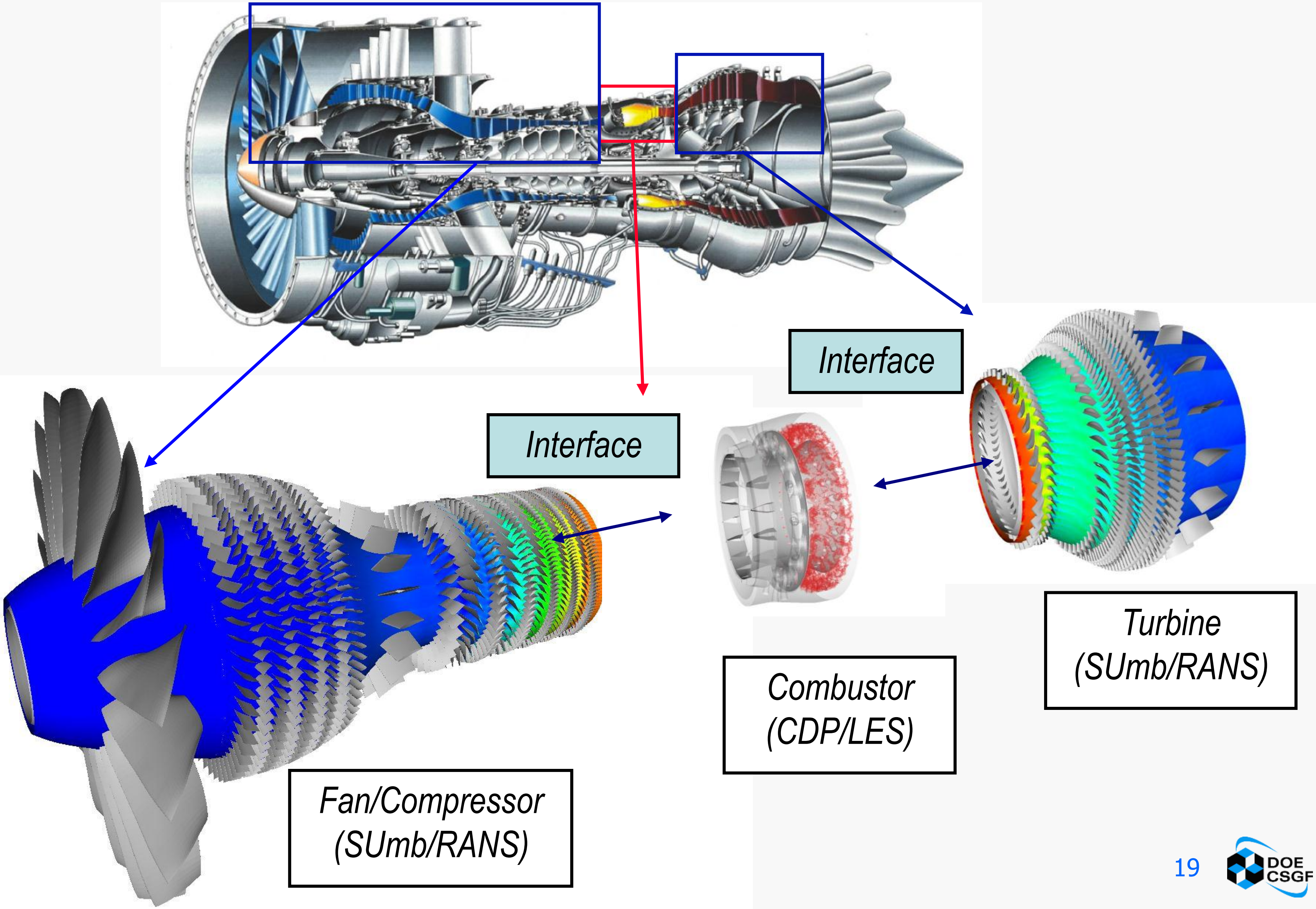


Lift coefficient

	Uncontrolled	Controlled
LES	0.83	1.43
EXP	0.82	1.41

Lines: LES
Symbols: Experiments (Gilarranz *et al*., *JFE*, ’05)

Integrated Jet Engine Simulations



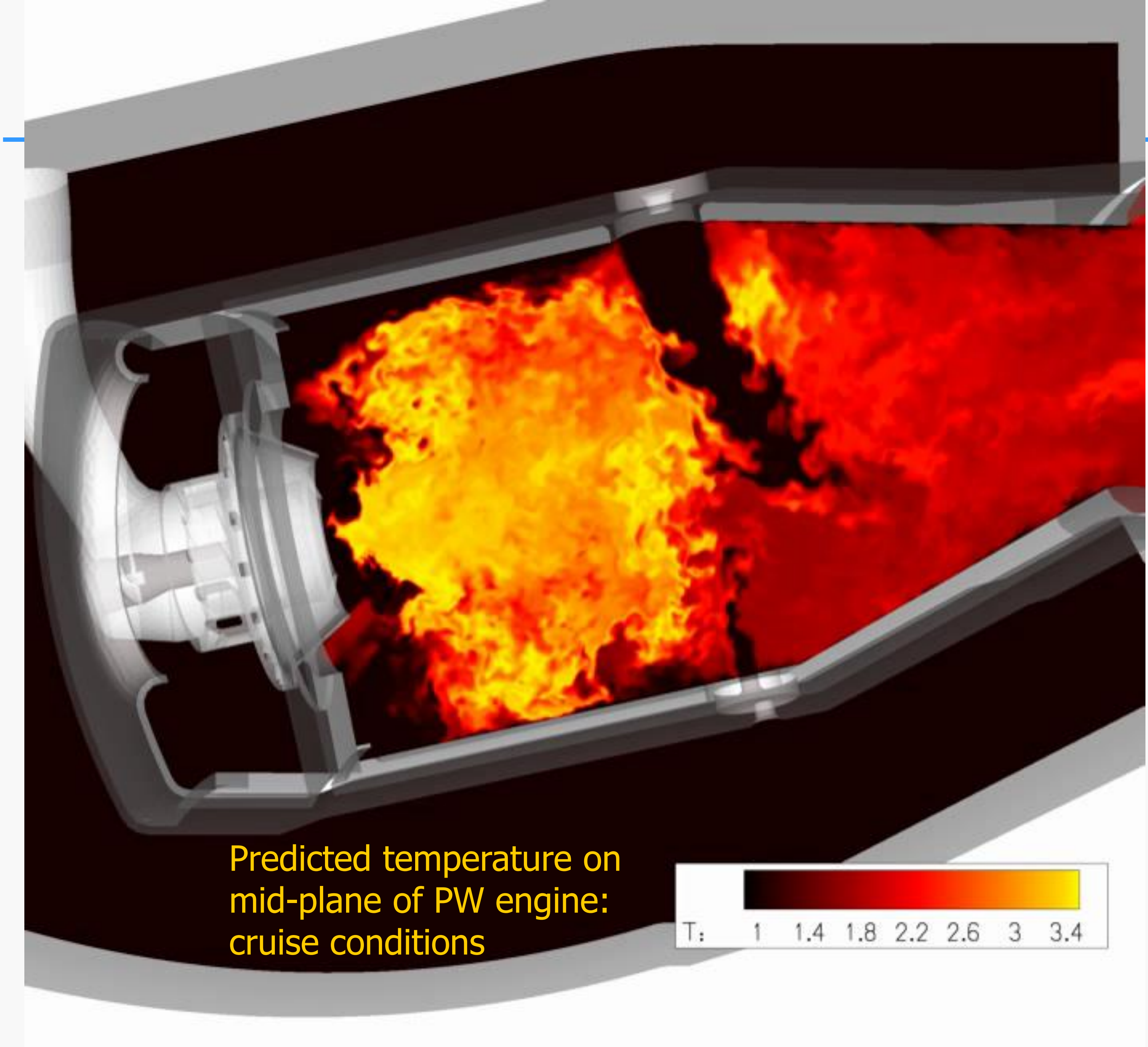
Interface

Interface

Fan/Compressor
(SUmb/RANS)

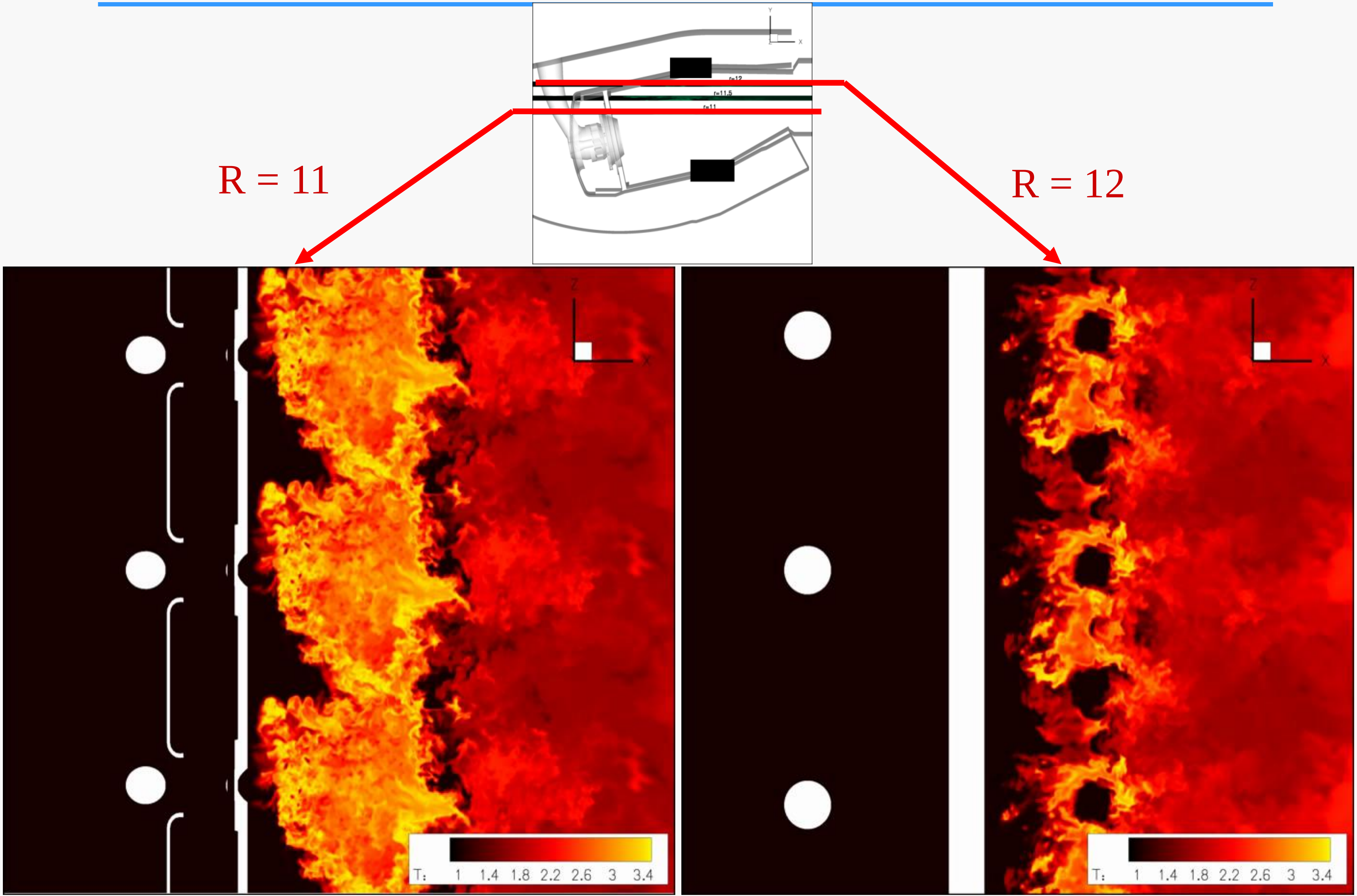
Combustor
(CDP/LES)

Turbine
(SUmb/RANS)



Predicted temperature on mid-plane of PW engine: cruise conditions

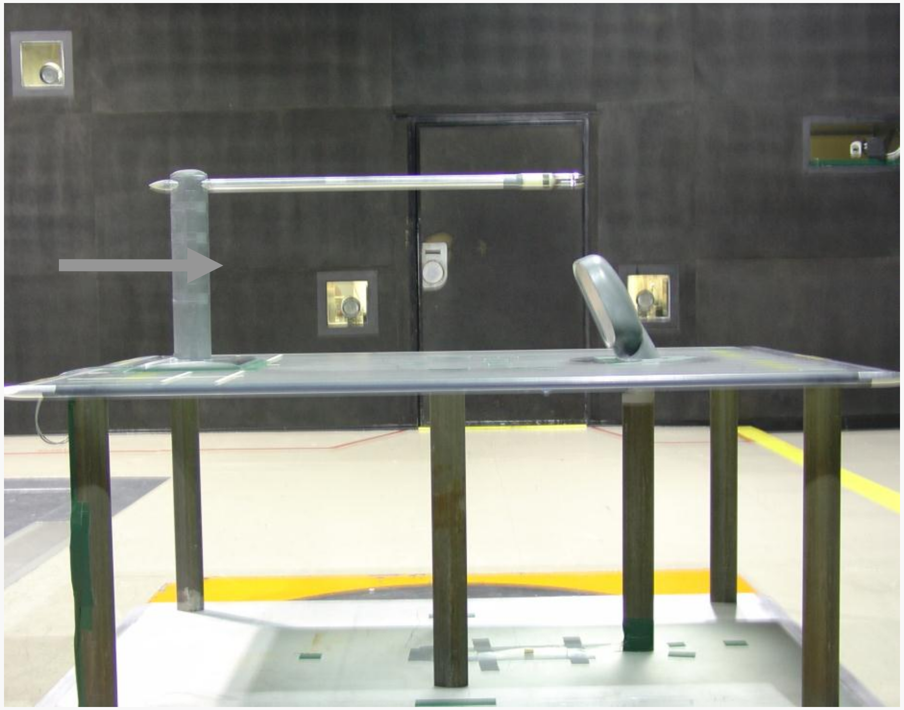
Temperature Inside the Combustor at 2 Different Radial Locations



R = 11

R = 12

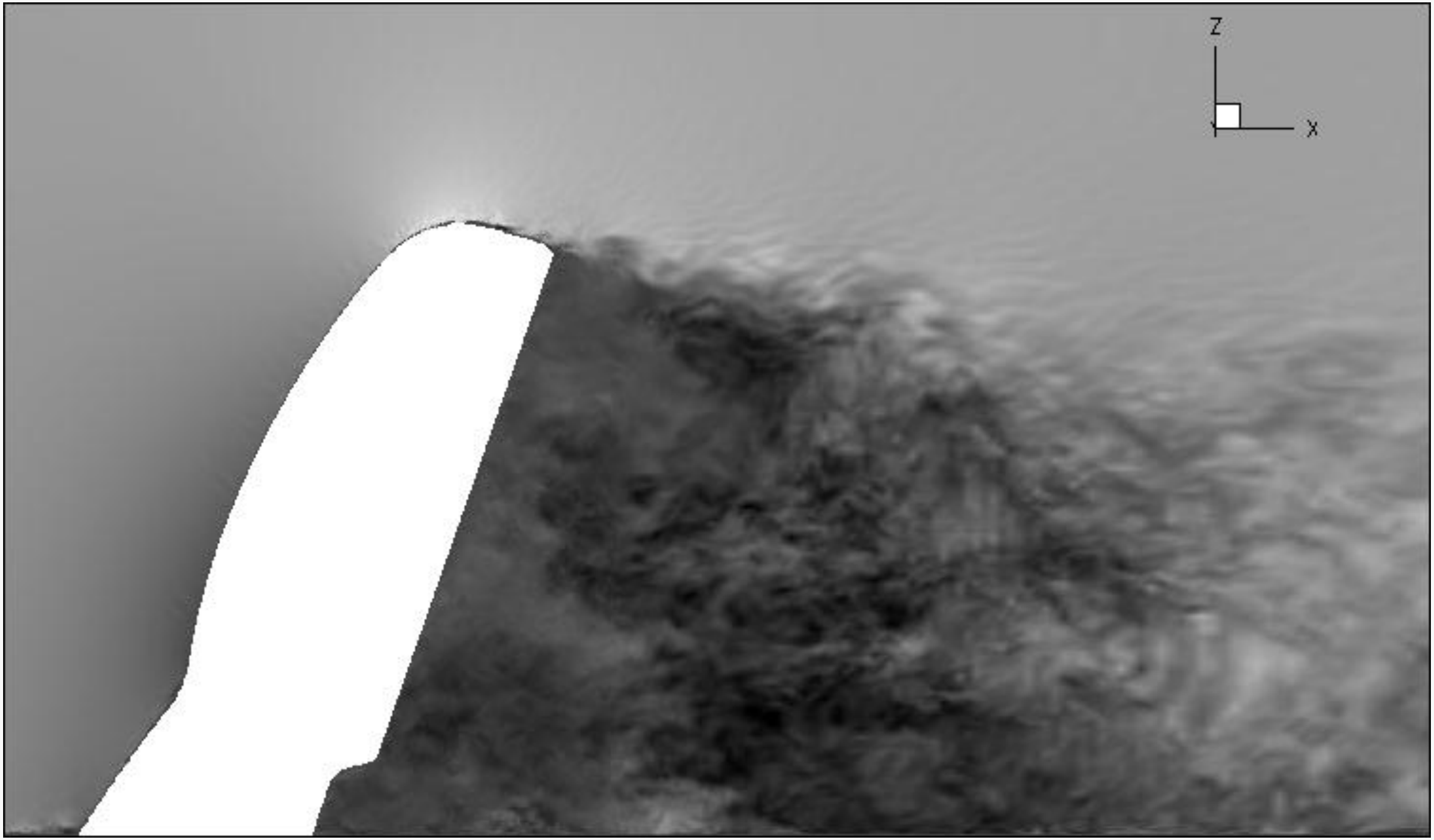
Noise Prediction for Low-Mach Flows



Side View Mirror in a Wind Tunnel

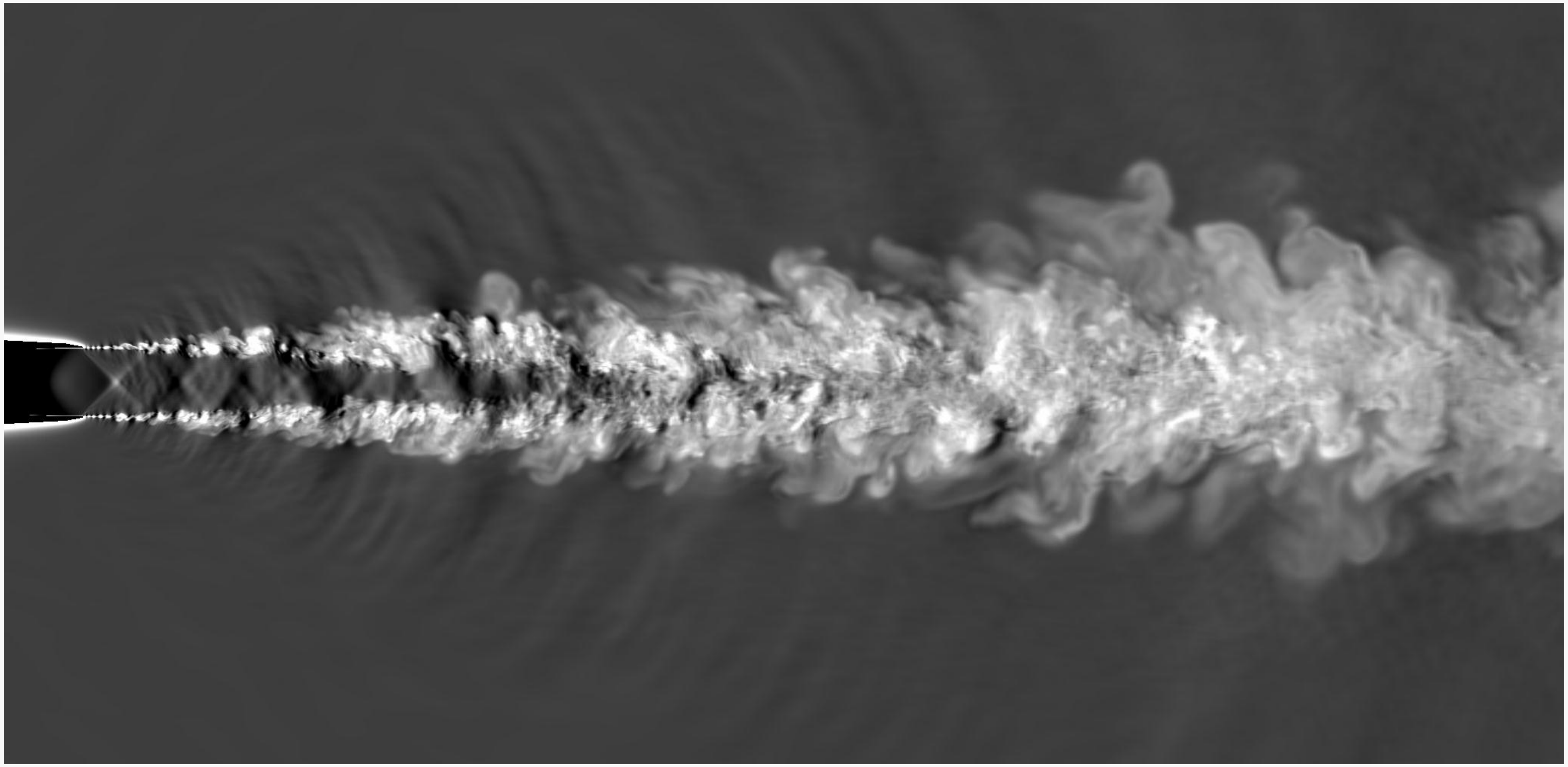
Automotive Cooling Fans

Flow visualization: Side view mirror

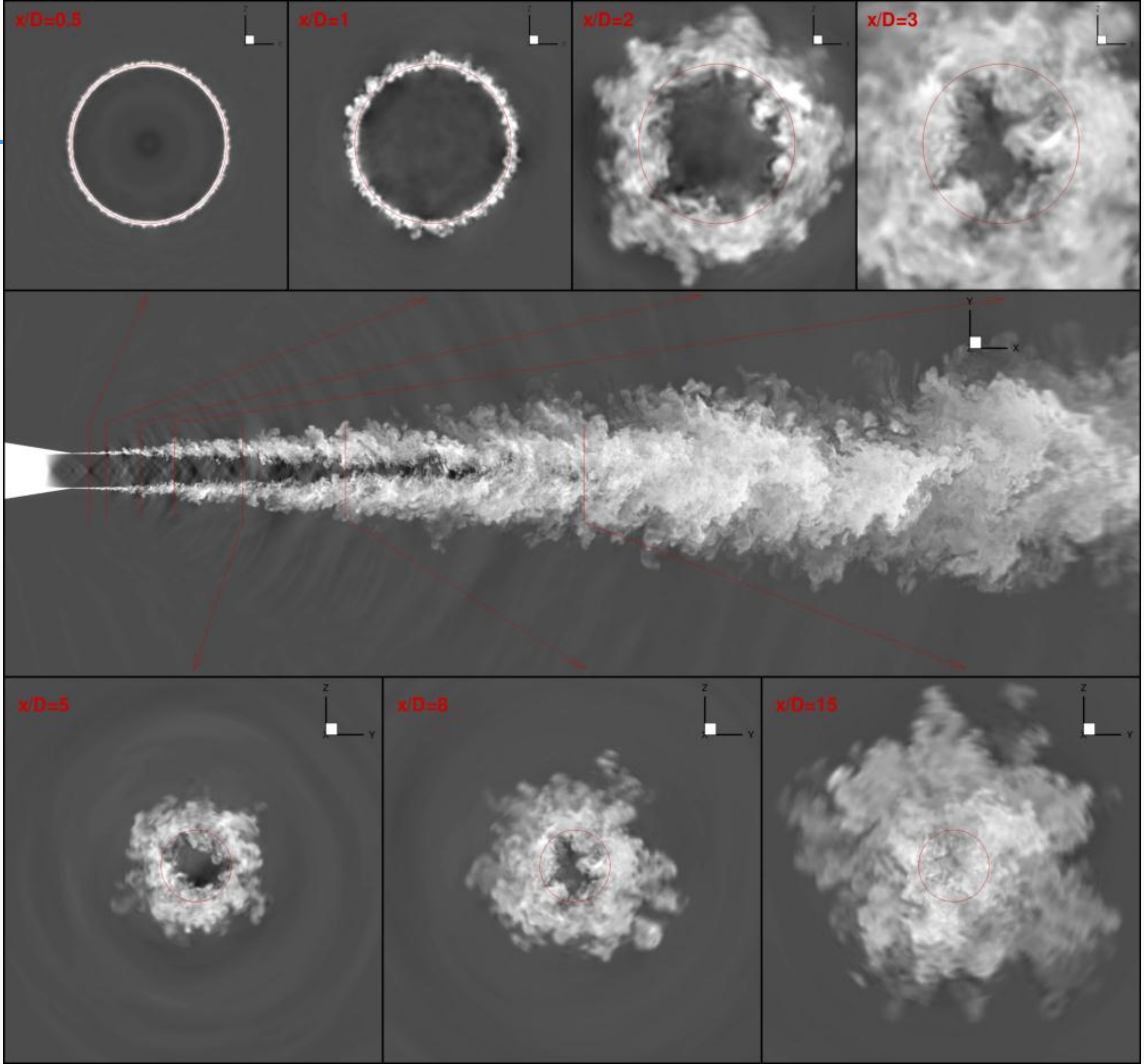


Speed = 34 mph = 55 km/h, Re = 200,000, Mesh Resolution: 25M grid cells

Supersonic Jet Noise

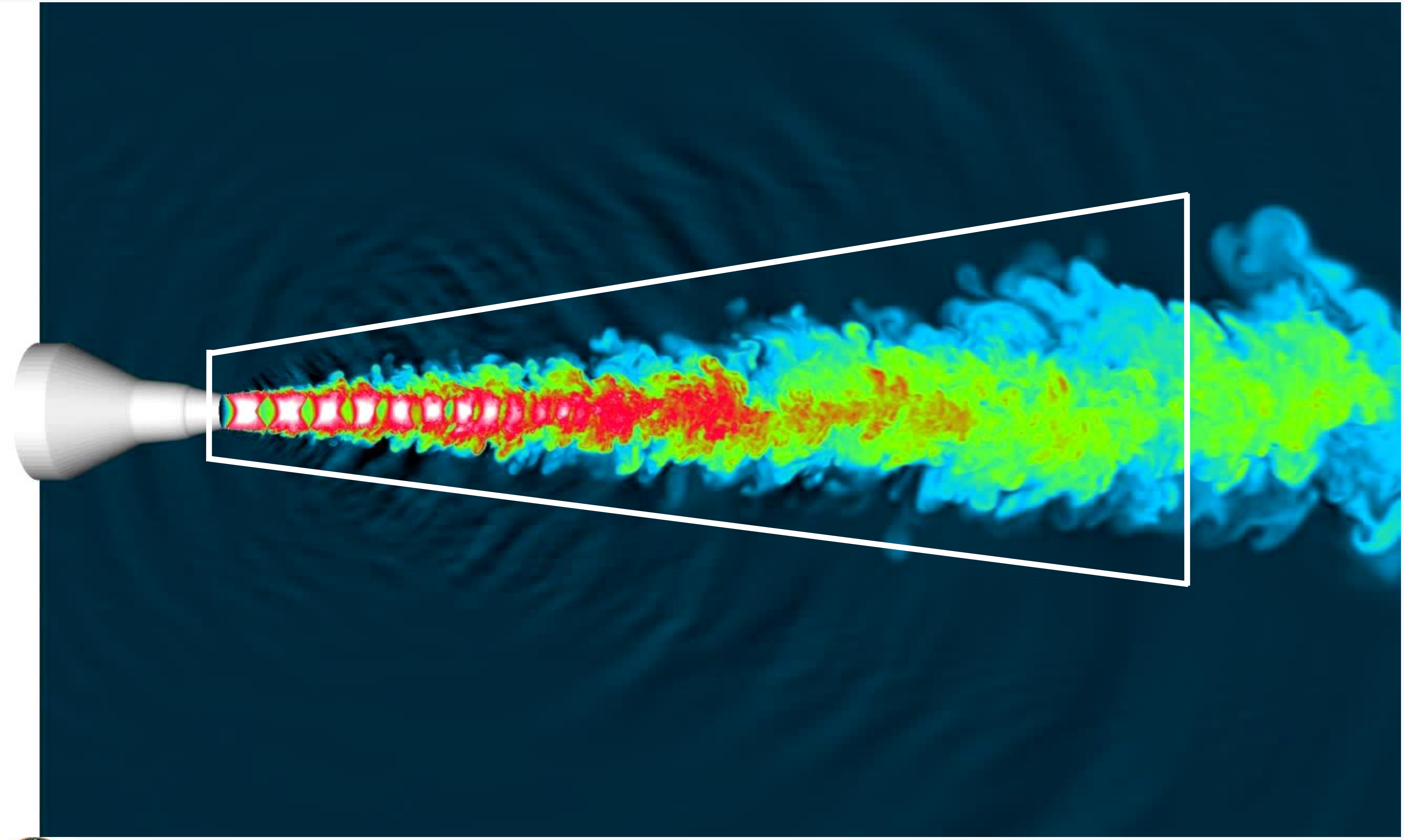


Supersonic Round Jet, Ma=1.7



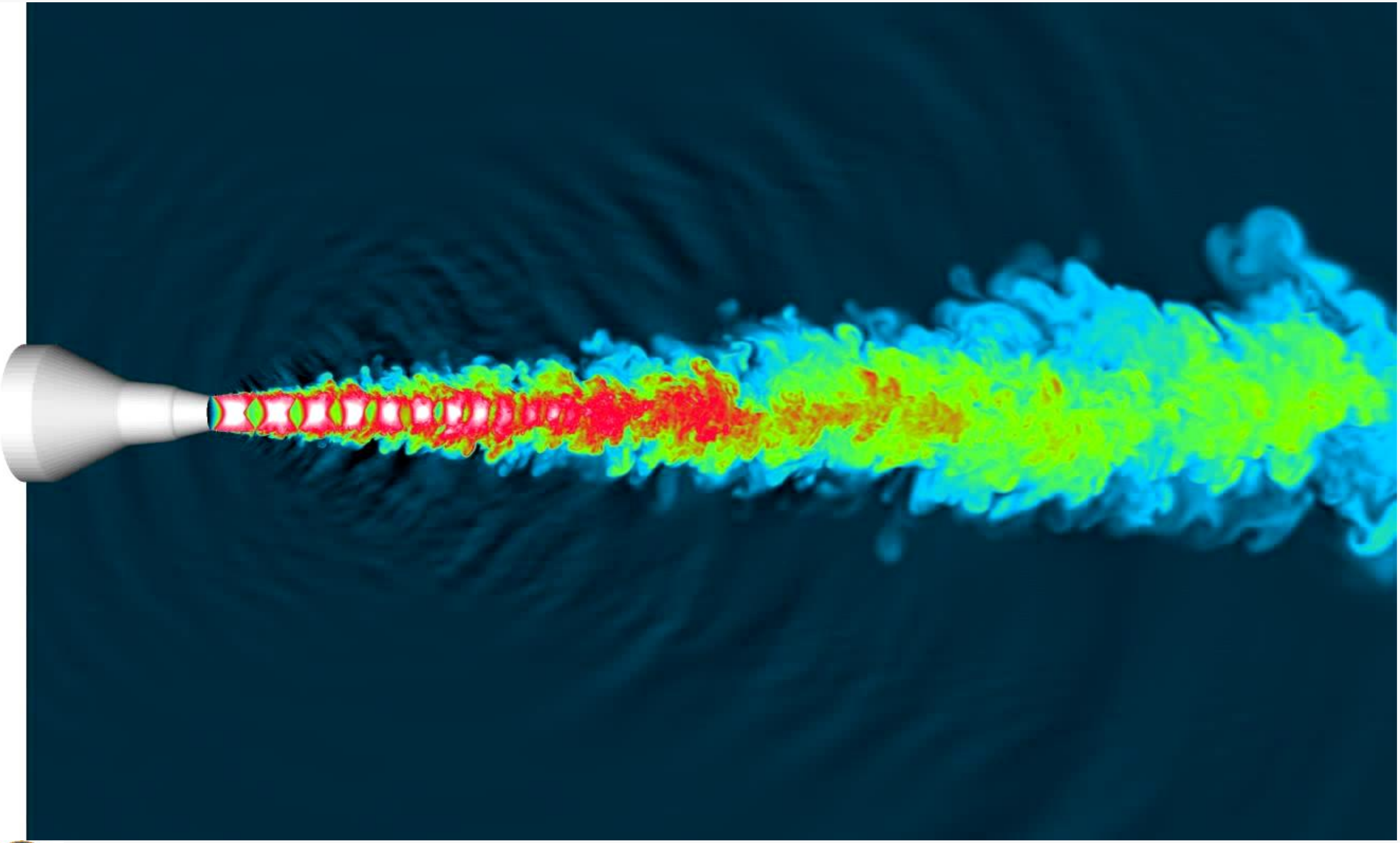
Temperature in a pressure-matched isothermal jet, Ma=1.5

Sound Propagation to the Far-Field



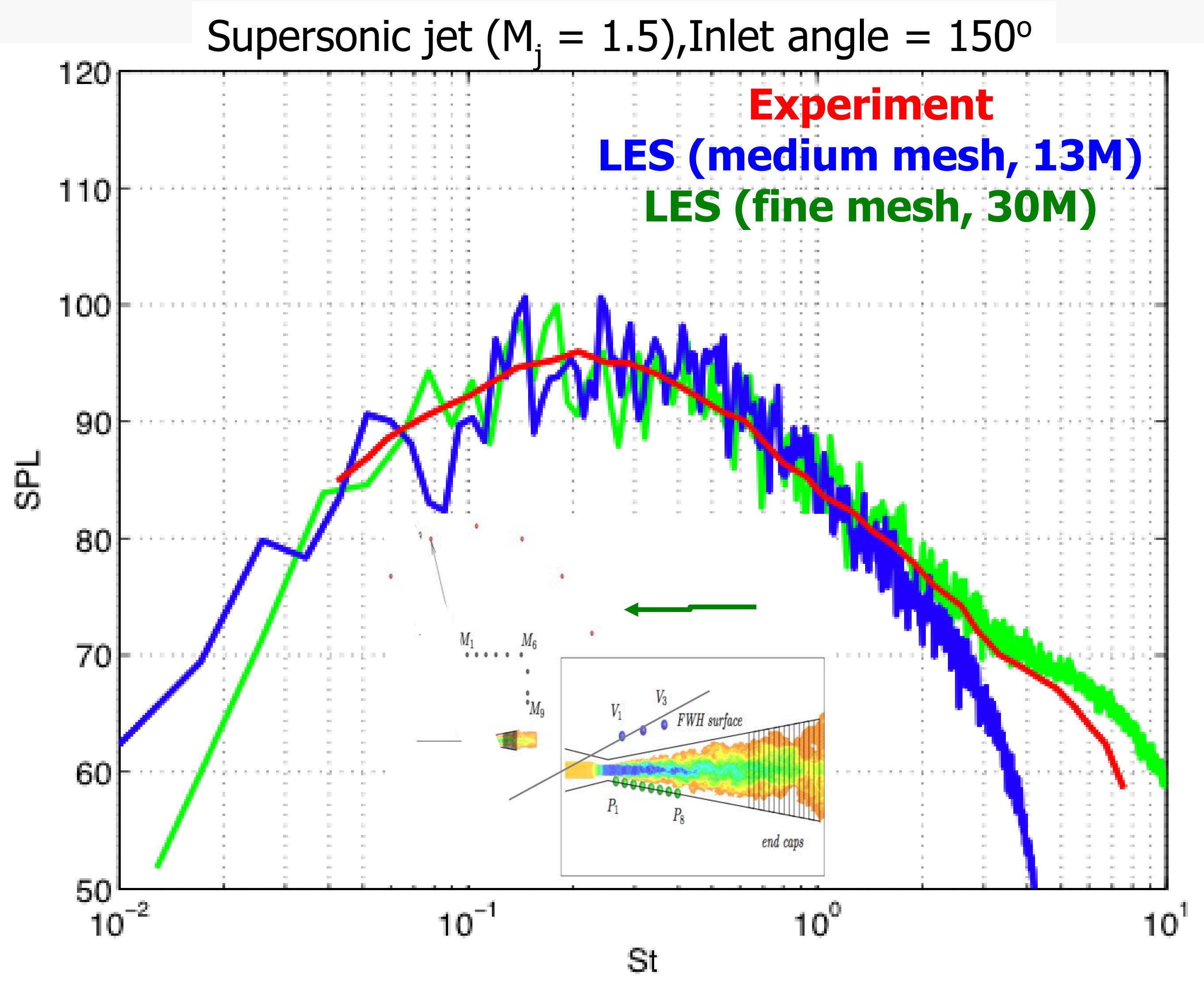
Data-Intensive Post-Processing Step (Acoustic Analogies)

Sound Propagation to the Far-Field



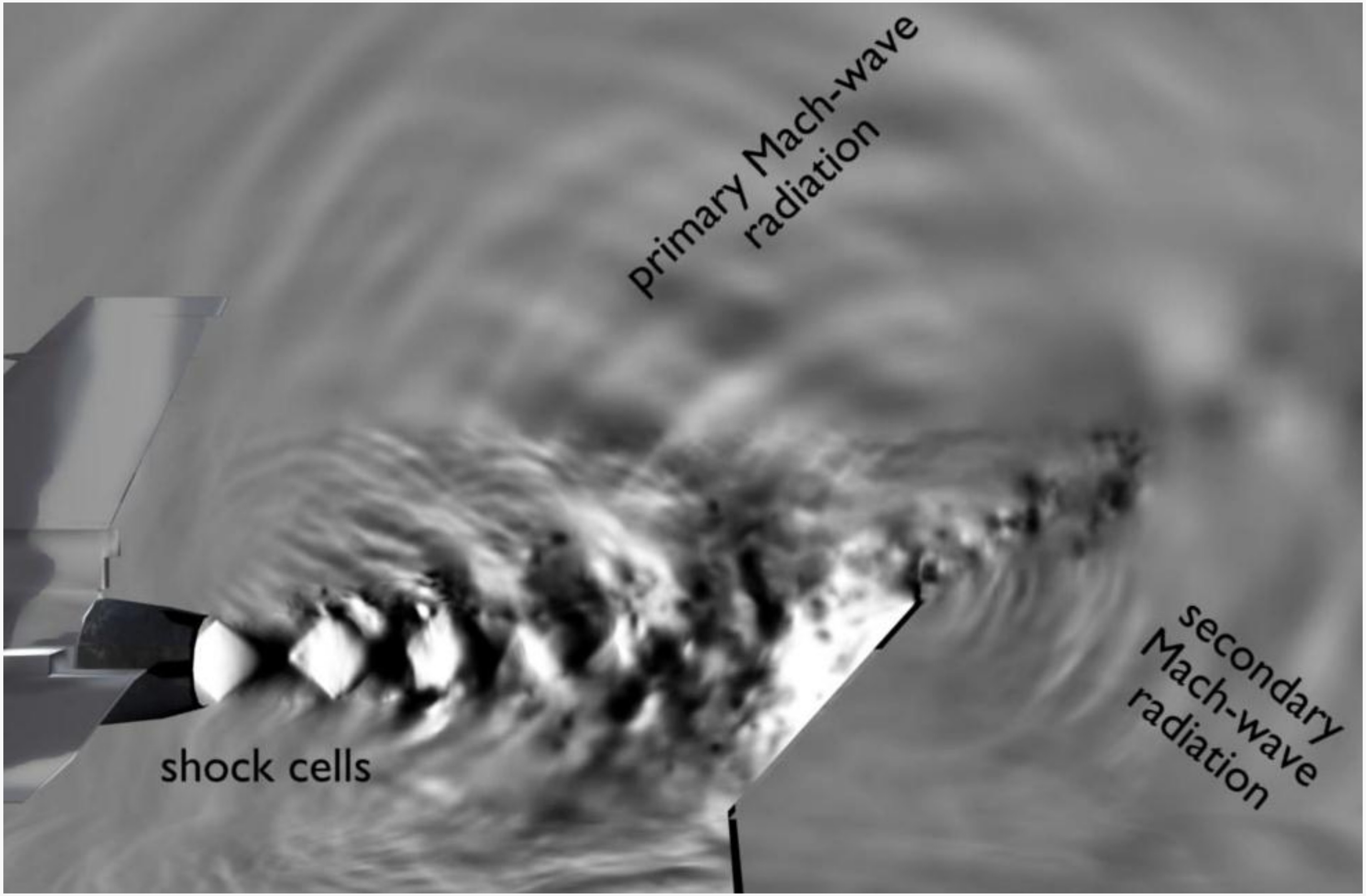
Data-Intensive Post-Processing Step (Acoustic Analogies)

Effect of mesh resolution



Supersonic jet (M_j = 1.5),Inlet angle = 150°

LES of Supersonic Jet Exhaust with Jet Blast Deflector and Carrier Deck



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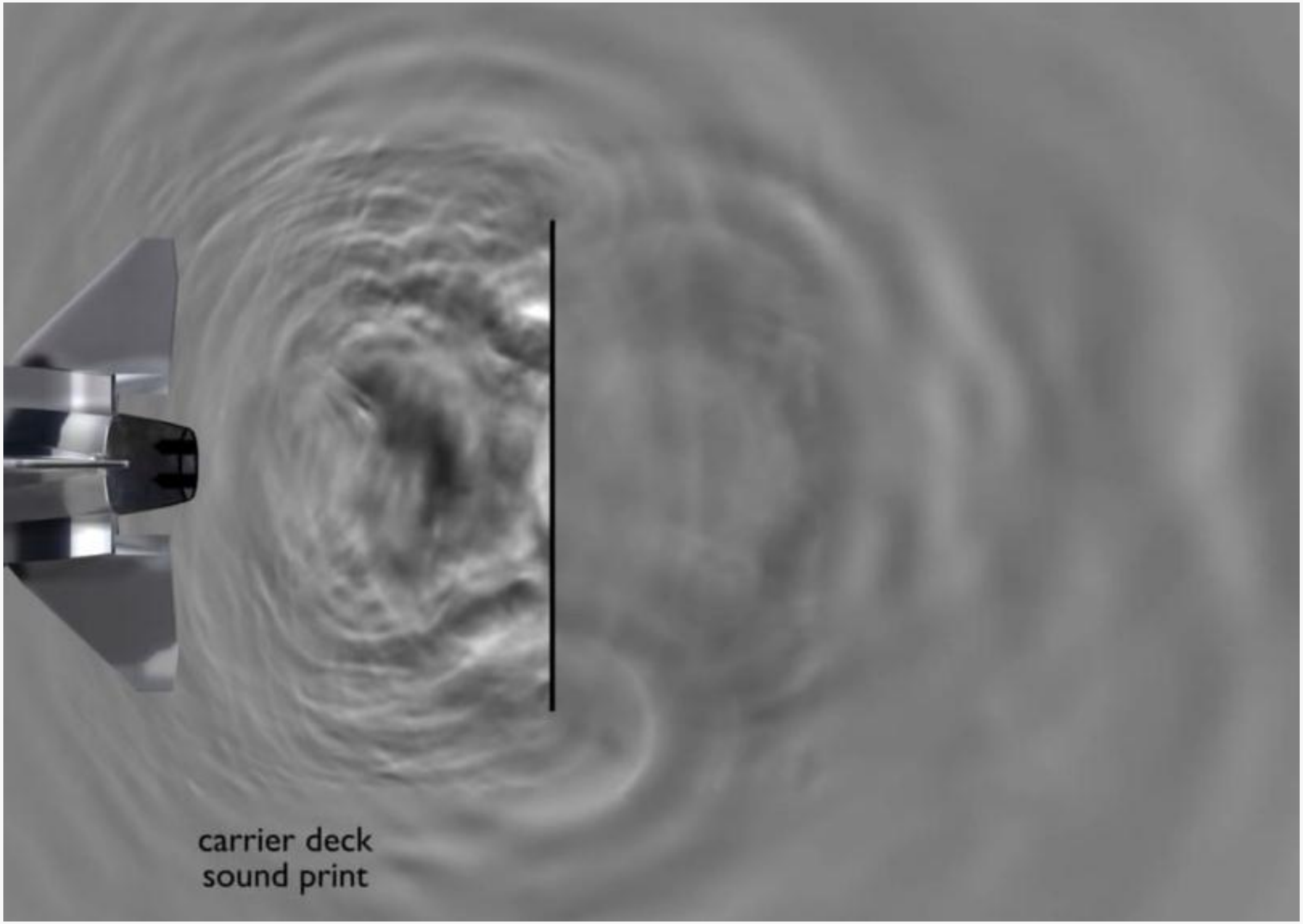

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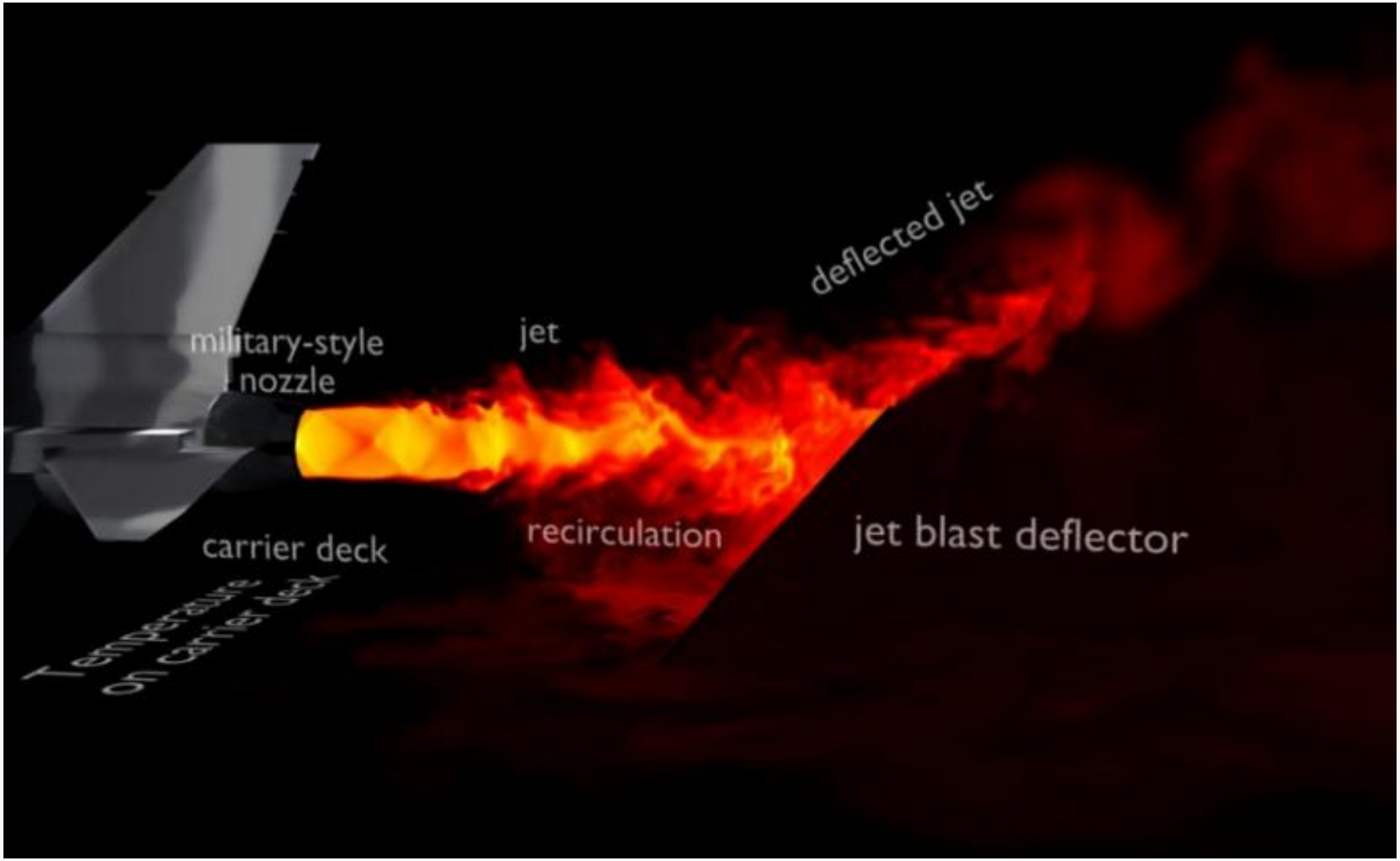


Part 3
Numerical Methods

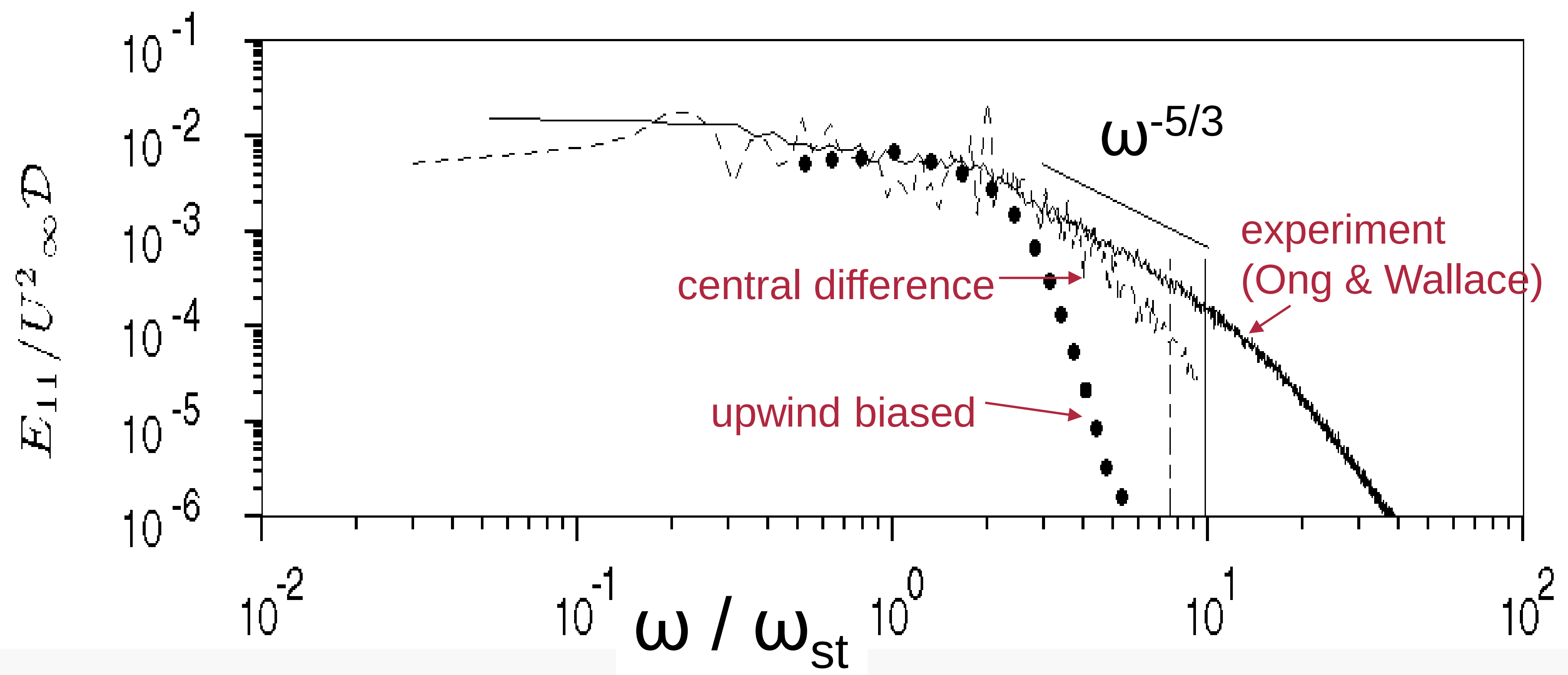
Numerical Methods for LES

- It is important for LES calculations to predict accurately the quantities that led to choosing LES in the first place (e.g., turbulent fluctuations, acoustic sources, mixing, …)
- Numerical dissipation present in most RANS codes is inadequate for LES (c.f. flow over cylinder)
- Dispersion errors important for compressible flow and prediction of aerodynamic noise

Numerical Dissipation in LES of Cylinder

$Re = 3,900$

Mittal & Moin (AIAA J., 1997)



central difference

upwind biased

experiment (Ong & Wallace)

One-dimensional streamwise velocity spectra E_{11} along the wake centerline

Vertical lines indicate the grid cutoff:

—— central difference

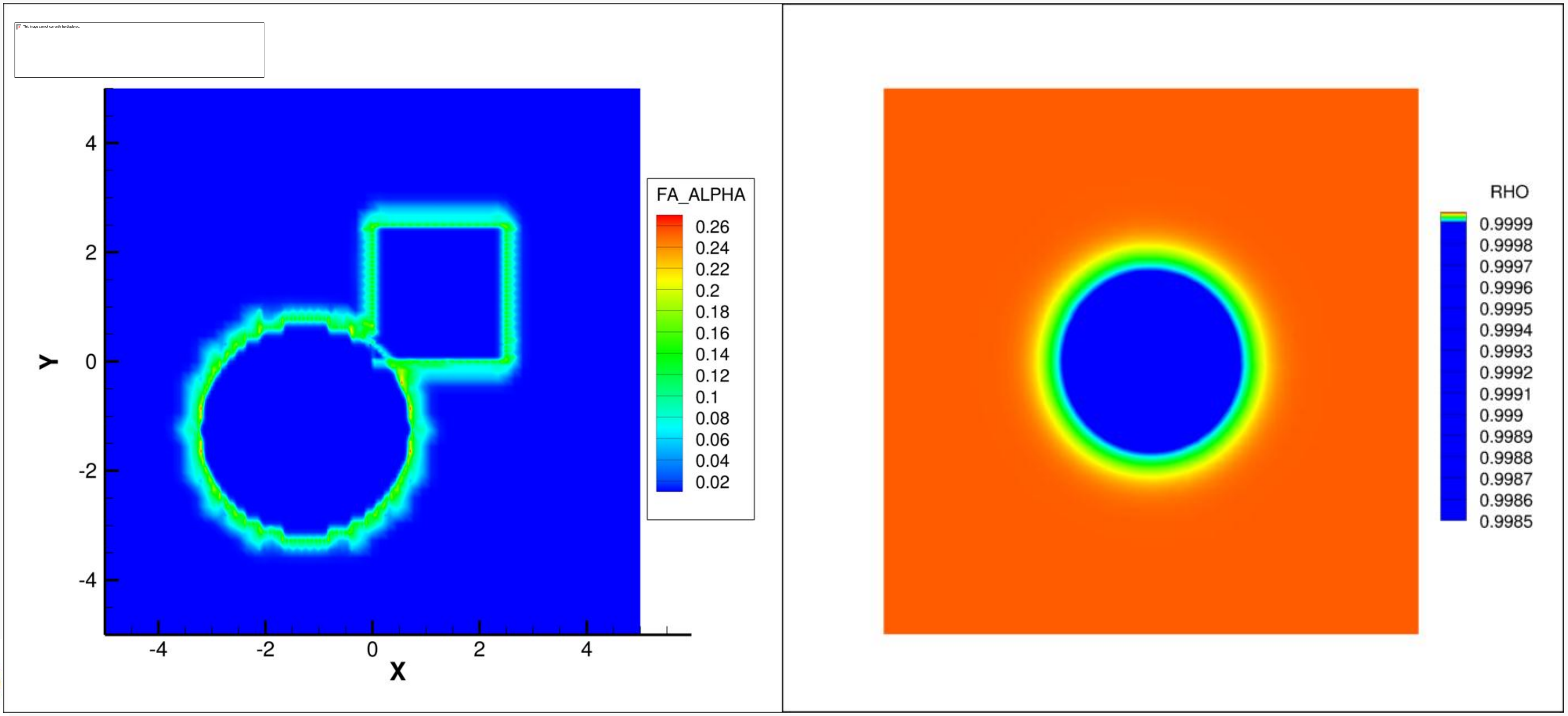
–·–·– upwind biased

Numerics: Low dissipation/dispersion grid-sensitive operators for unstructured grids

- Developed novel grid-sensitive operators for minimizing dissipation and dispersion on unstructured grids
  - Dispersion reduced by using nominally 4th-order reconstruction in the face-normal direction
  - Dissipation minimized by assessing skew-symmetry of local differencing operator and introducing local dissipation scaled by the local lack of skew-symmetry

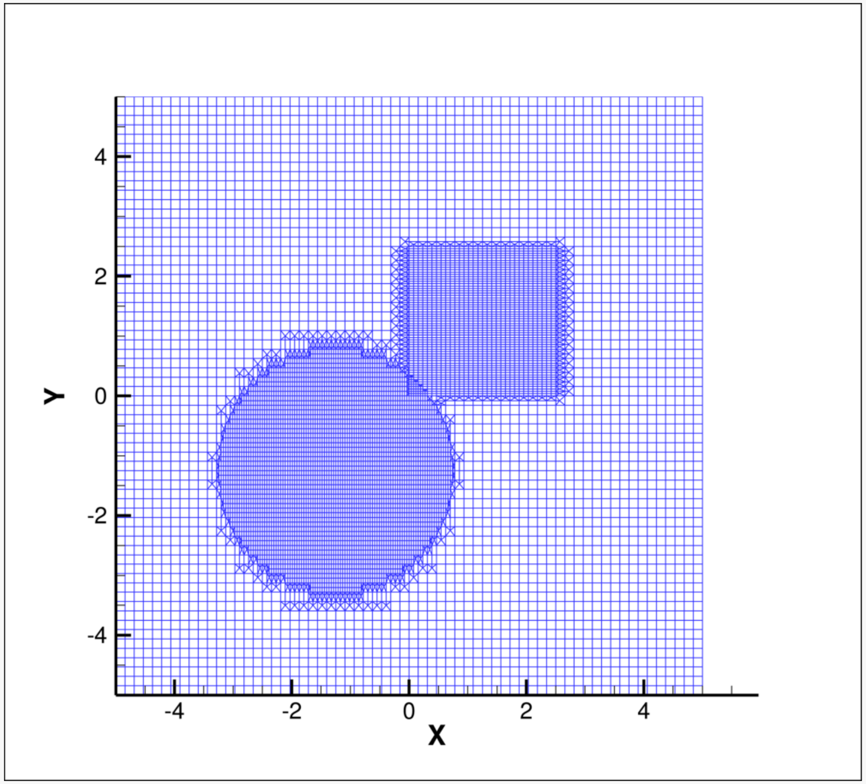
Example problem: Euler vortex

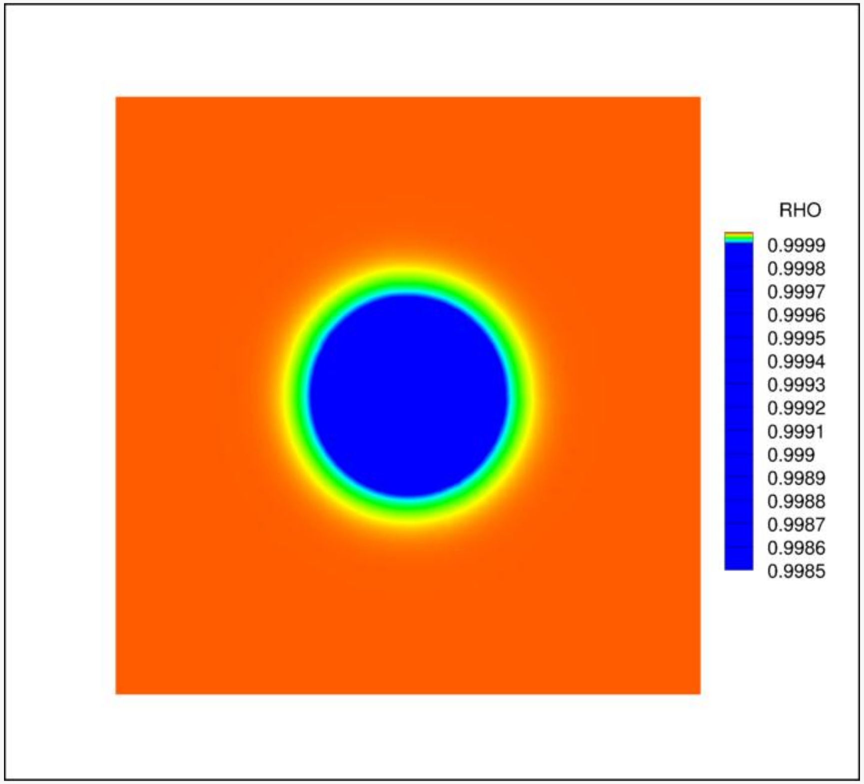
- Heuristic: Identify the non-SBP regions by computing and modify the operators just in those regions to ensure operator stability.
- This is not a solution-dependent fix like WENO. It is done as a pre-processing step



Naively trying to introduce more neighbors fails on "bad" grids

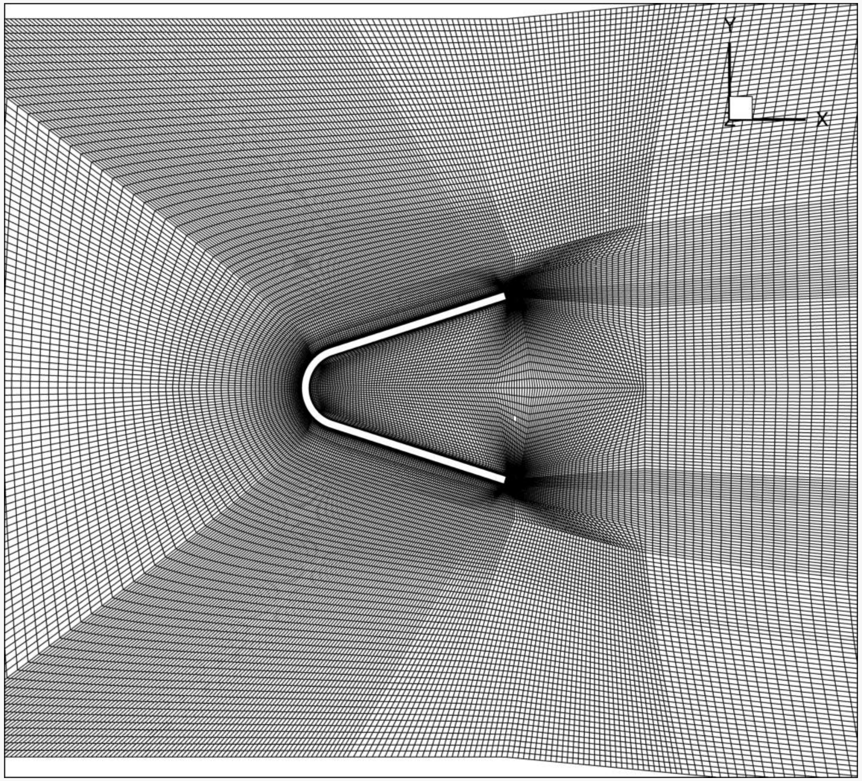
- E.g. Use polynomial reconstruction to consistently introduce more neighbors and increase the "accuracy"
- Euler vortex problem, grid with transitions and periodic boundaries:



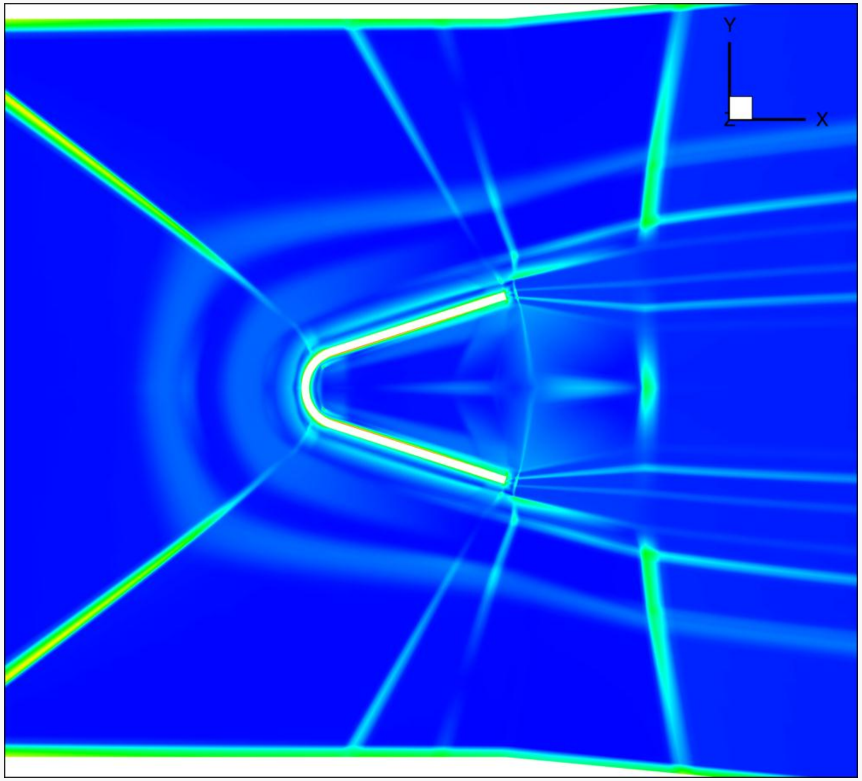


Application to complex mesh: Compressible subsonic flow in an augmenter

- Sub-sonic flow in an augmenter with complex flame-holder
- Block structured mesh with many grid transitions in size and skewness

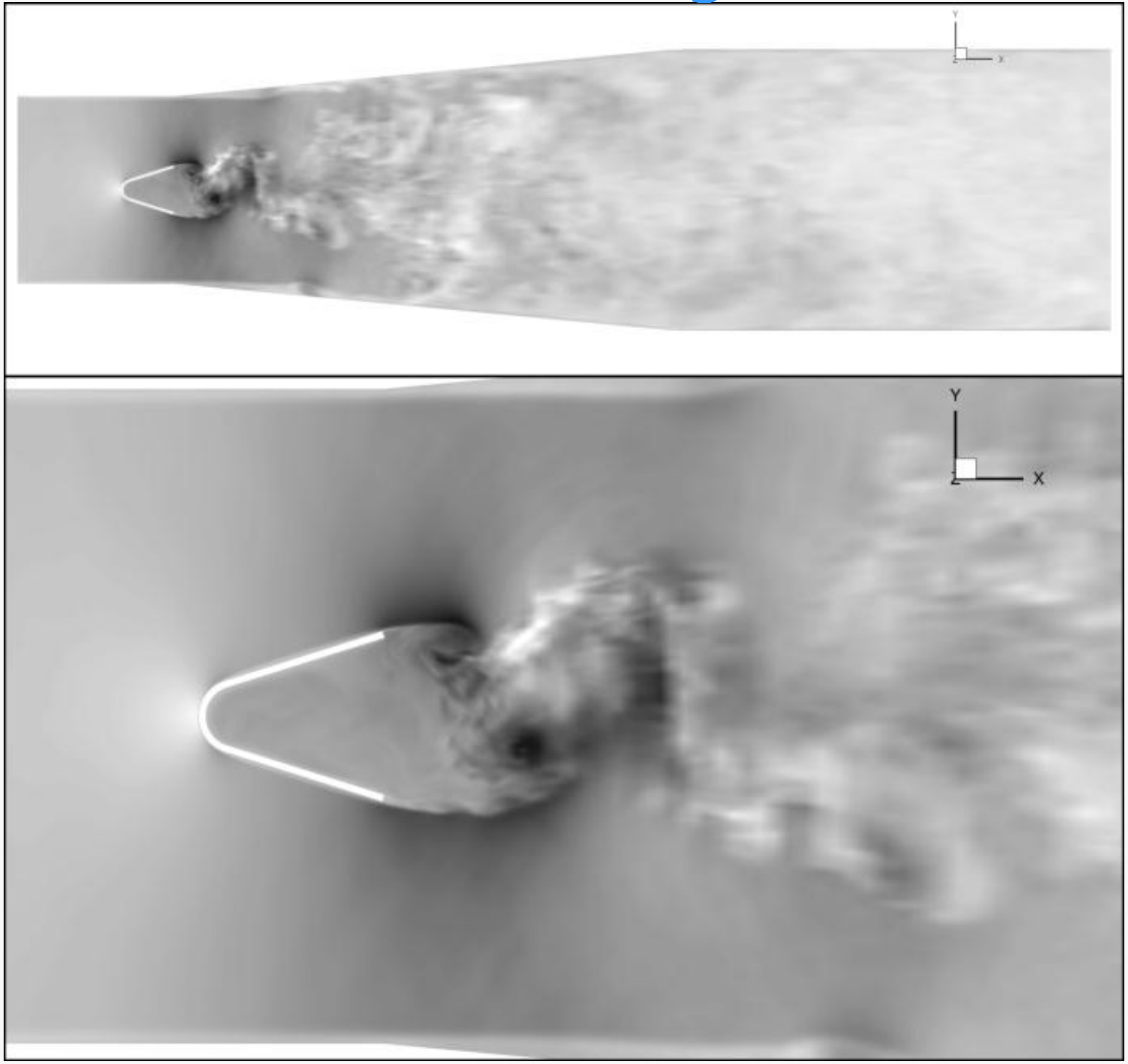


Mesh detail in plane through flameholder



Application to complex mesh: Compressible subsonic flow in an augmenter

Center plane through full domain (top) and detail (bottom) showing temperature

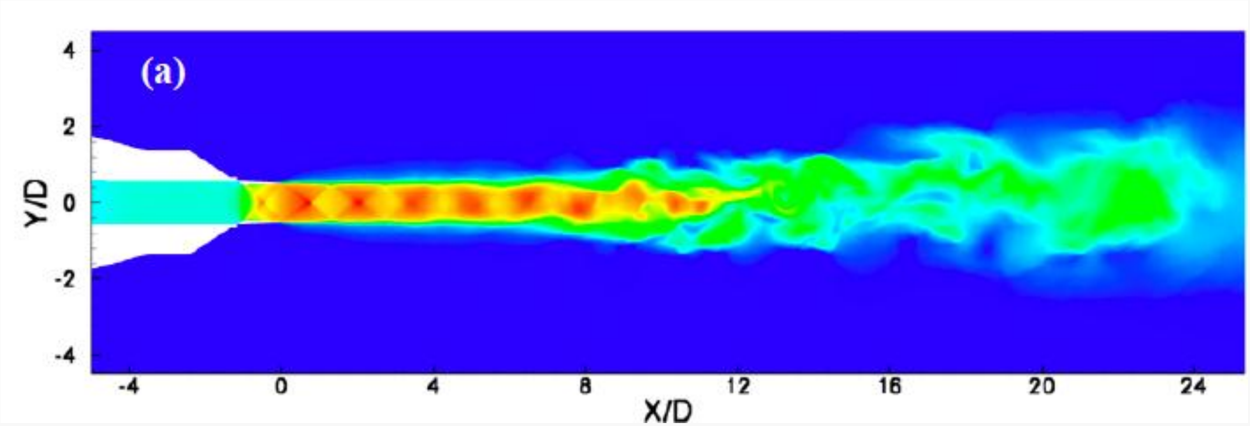


Discrete Conservation Principles

- Important for numerical algorithms to abide by higher Conservation Principles
- Low-Mach number flows: Conservation of kinetic energy in the inviscid limit
- Compressible flows: Conservation of 1st and 2nd moments of entropy (Honein and Moin, JCP, 2004)
- "Implicit LES" approaches such as "Miles" questionable

Comments on MILES/ILES

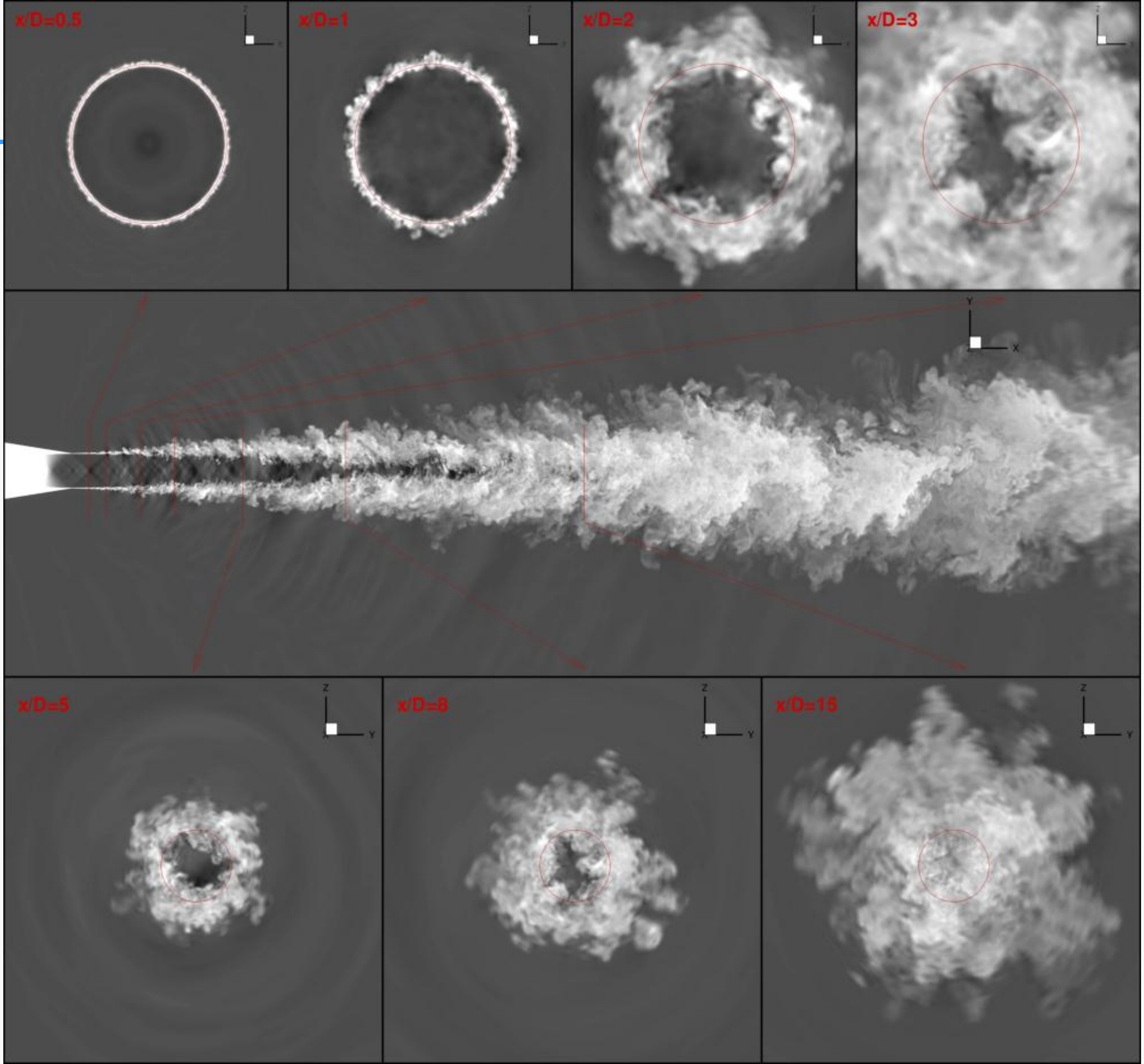
- Dissipation in MILES/ILES (where the truncation error is assumed to represent the sub-grid physics) can be very solution and grid-dependent, and often excessive
- Need to capture the turbulent fluctuations that led us to LES in the first place



Liu et al. AIAA J. 2009, MILES

Need to do better

Temperature in a pressure-matched isothermal jet, Ma=1.5



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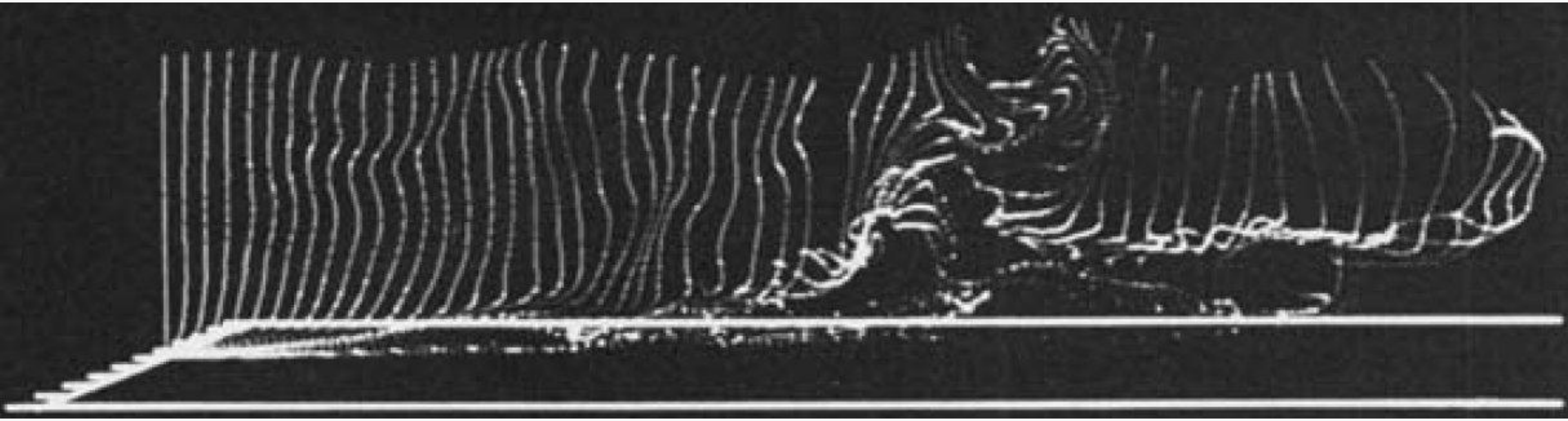
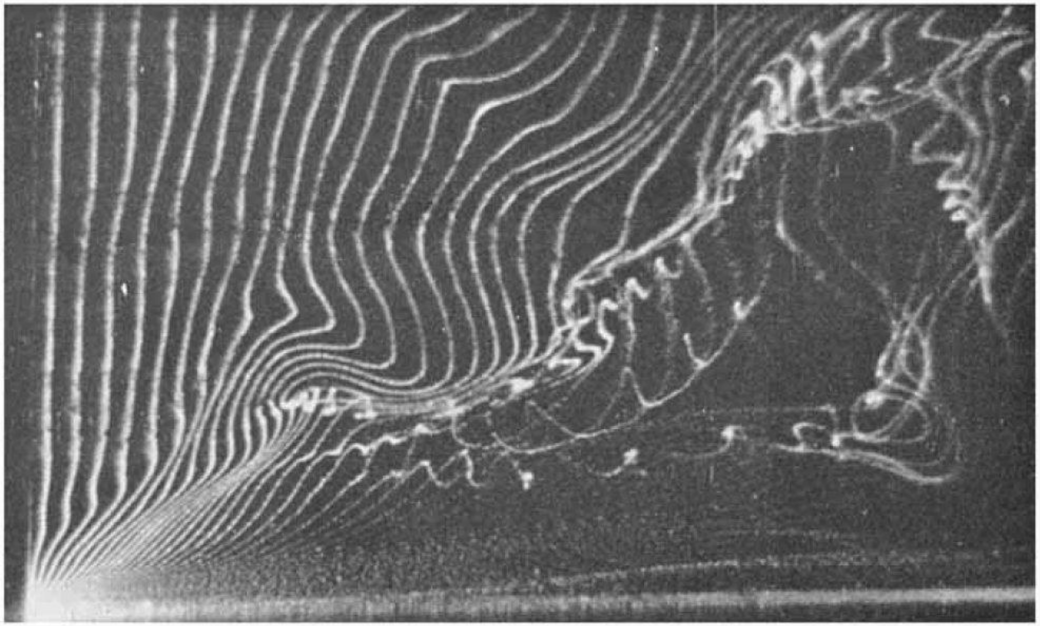
Part 4
Verification & Validation

A Simulation Milestone

Moin and Kim (1981,1985)



Simulation



Unsteady Visualizations Make an Impact!

Experiment

V & V QUIZ

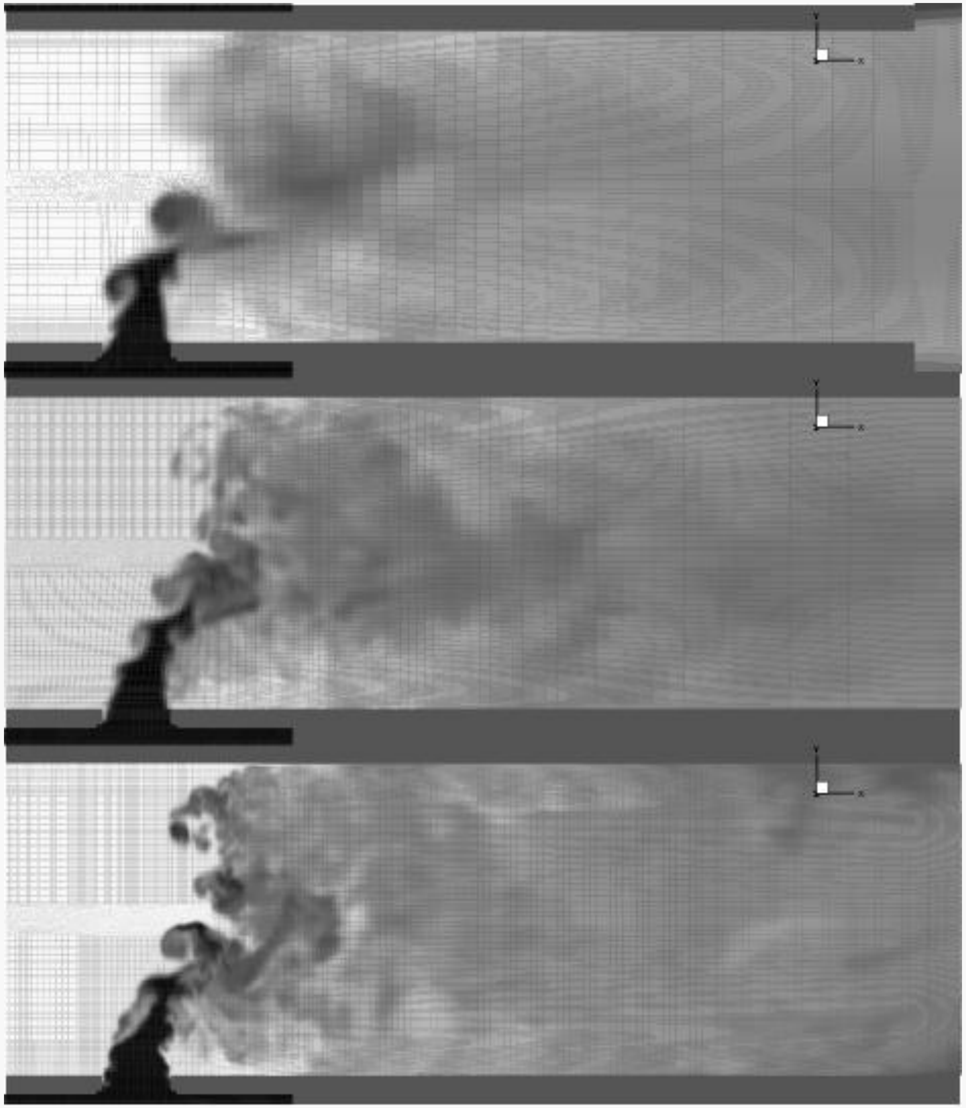
Explicit Filtered LES

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \overline{\bar{u}_i \bar{u}_j}}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}$$

- Recast convective term with additional filter
- Derived by including a part of the subgrid stress term in convective term
- Assumes filtering and differentiation commute
  - Lack of commuting filters has prevented widespread adoption of explicit filtering

Verification for traditional LES

- Grid converged LES is a DNS
  - Limit of DNS never achieved in practice
- Cannot verify LES this way



Kobayashi et al., 2008,
passive scalar, Sc =1

Mesh independent LES

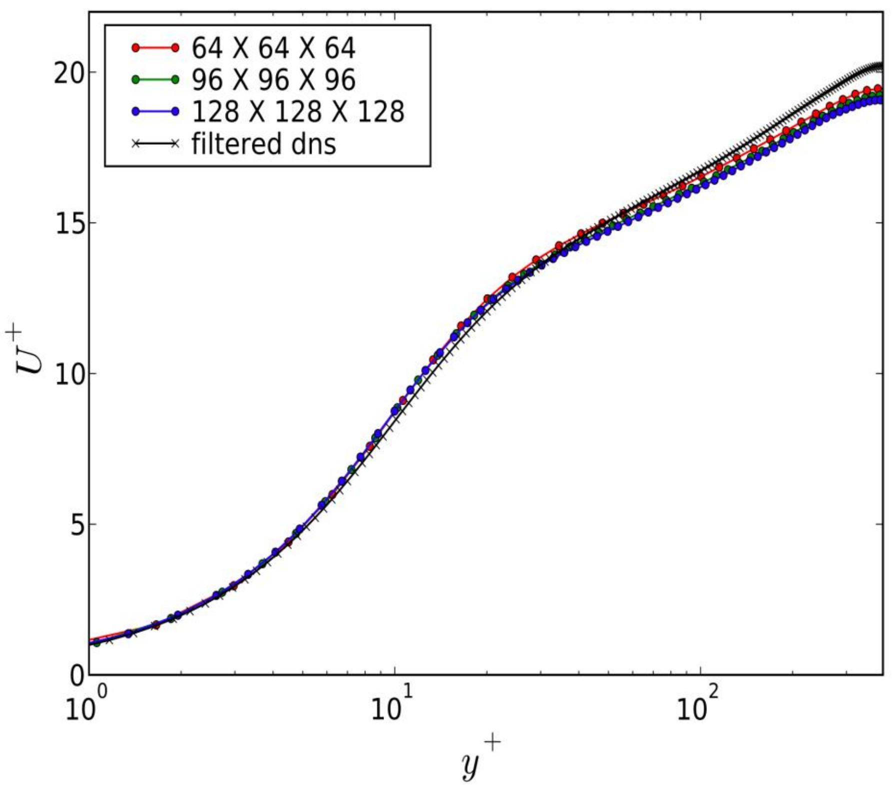
- Introduce a filter into the governing equations through the convective term

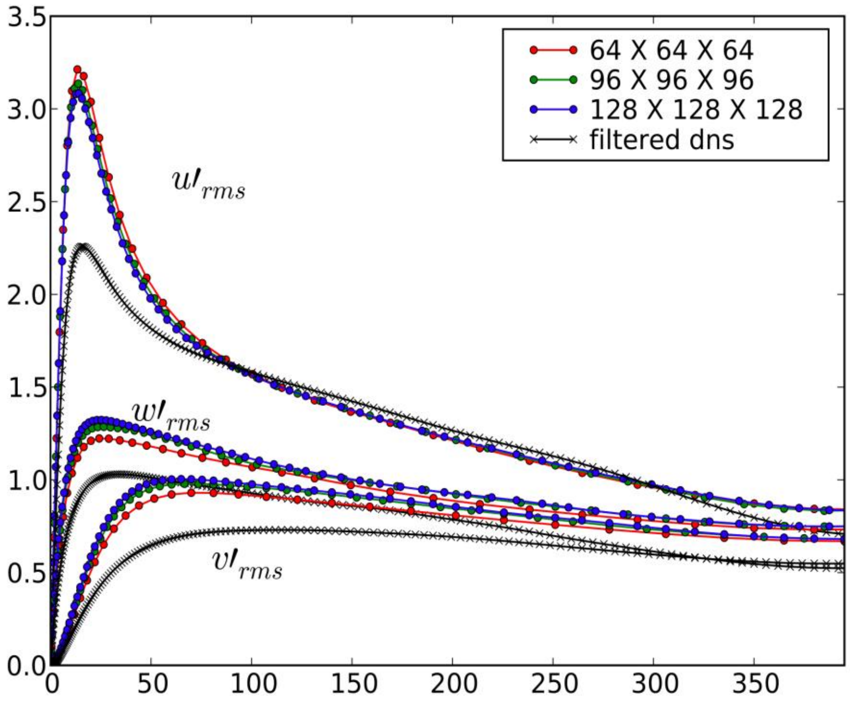
$$\frac{\partial \bar{u}_i}{\partial t} + \boxed{\frac{\partial \overline{\bar{u}_i \bar{u}_j}}{\partial x_j}} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \boxed{\frac{\partial \tau_{ij}}{\partial x_j}}$$

$$\tau_{ij} = \overline{u_i u_j} - \overline{\bar{u}_i \bar{u}_j}$$

- If the filter commutes with differentiation, it becomes possible to formally decouple the filter and grid scales and produce grid-independent LES (with refinement)
- Challenges for unstructured grids:
  - Unstructured commuting filters required – some progress here
  - Cost of this approach expected to be large for lower-order methods

Channel Flow (Re_τ = 395) Statistics





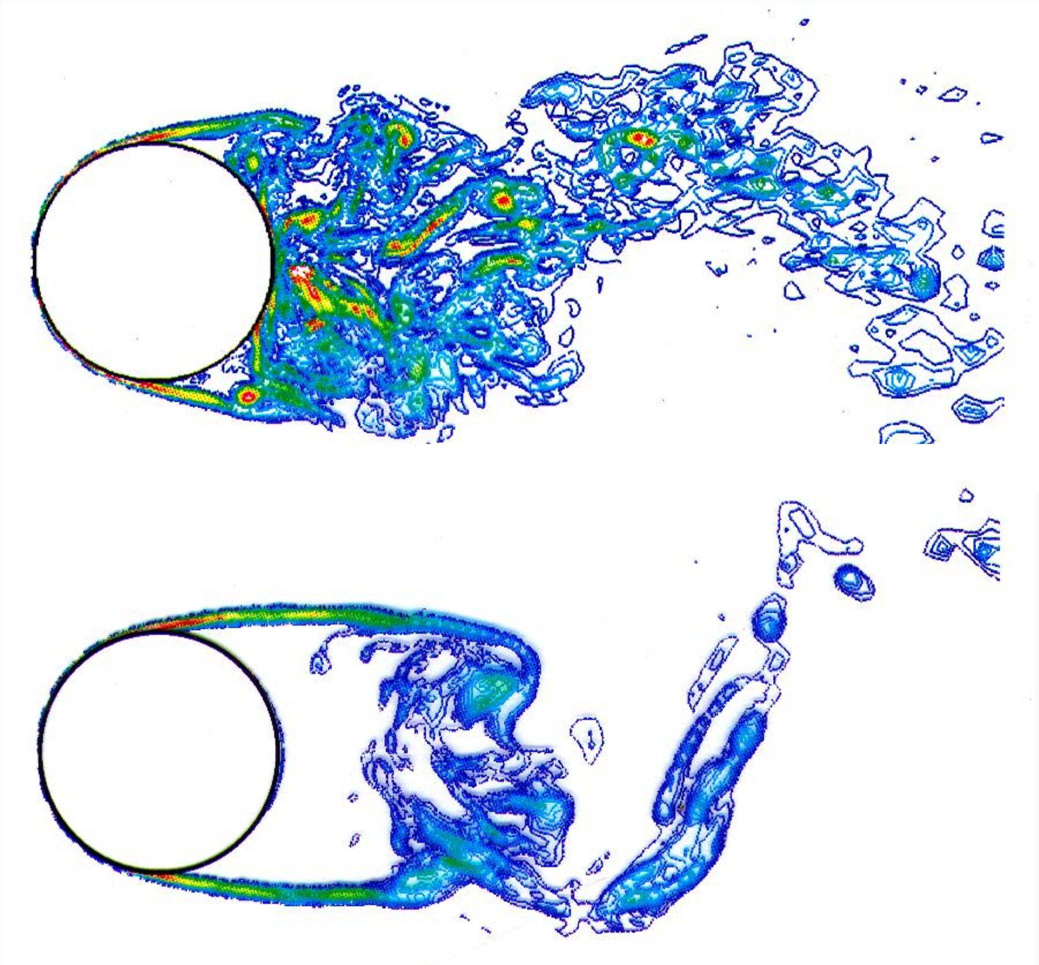
- Converged, grid-independent solutions obtained
- Failure to converge to filtered DNS due to modeling errors

Conclusions / Explicit Filtering

- Obtained grid independent statistics; true LES solutions
- Formally separated filtering operator from numerics
- Isolated errors due to SGS modeling

- Platform to characterize epistemic uncertainty in LES models

Which turbulence simulation is (more) correct?



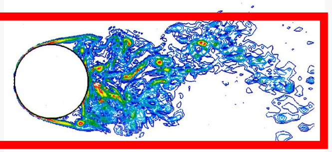
1.

2.

Cylinder, Re = 3900, Contours of instantaneous vorticity magnitude

Quiz: Continued…

1.



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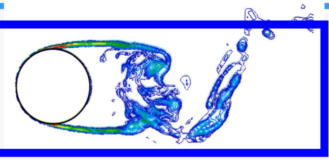
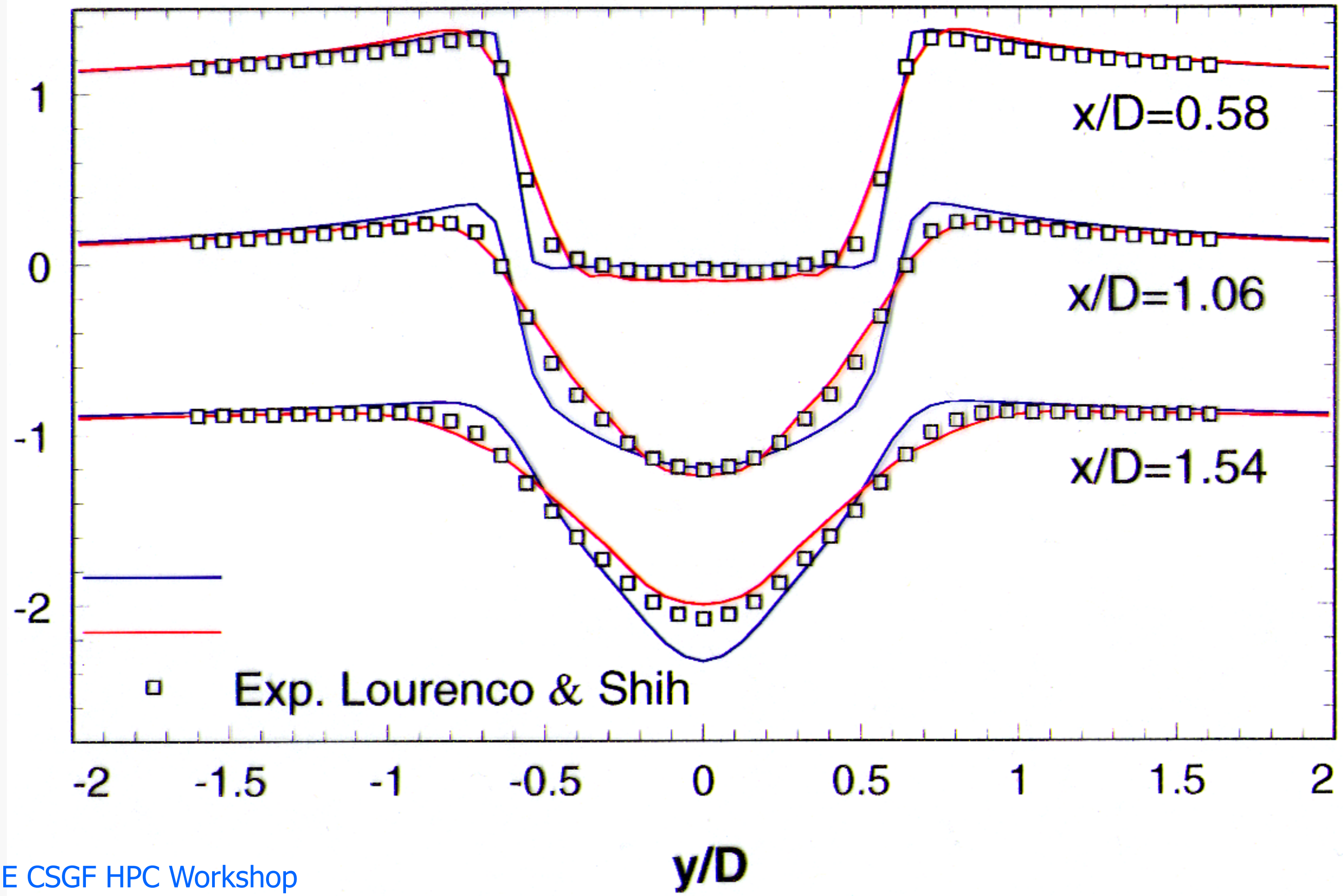
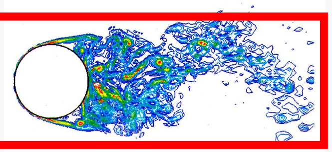
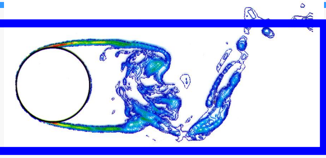


Comparison of mean streamwise velocity to experiments:

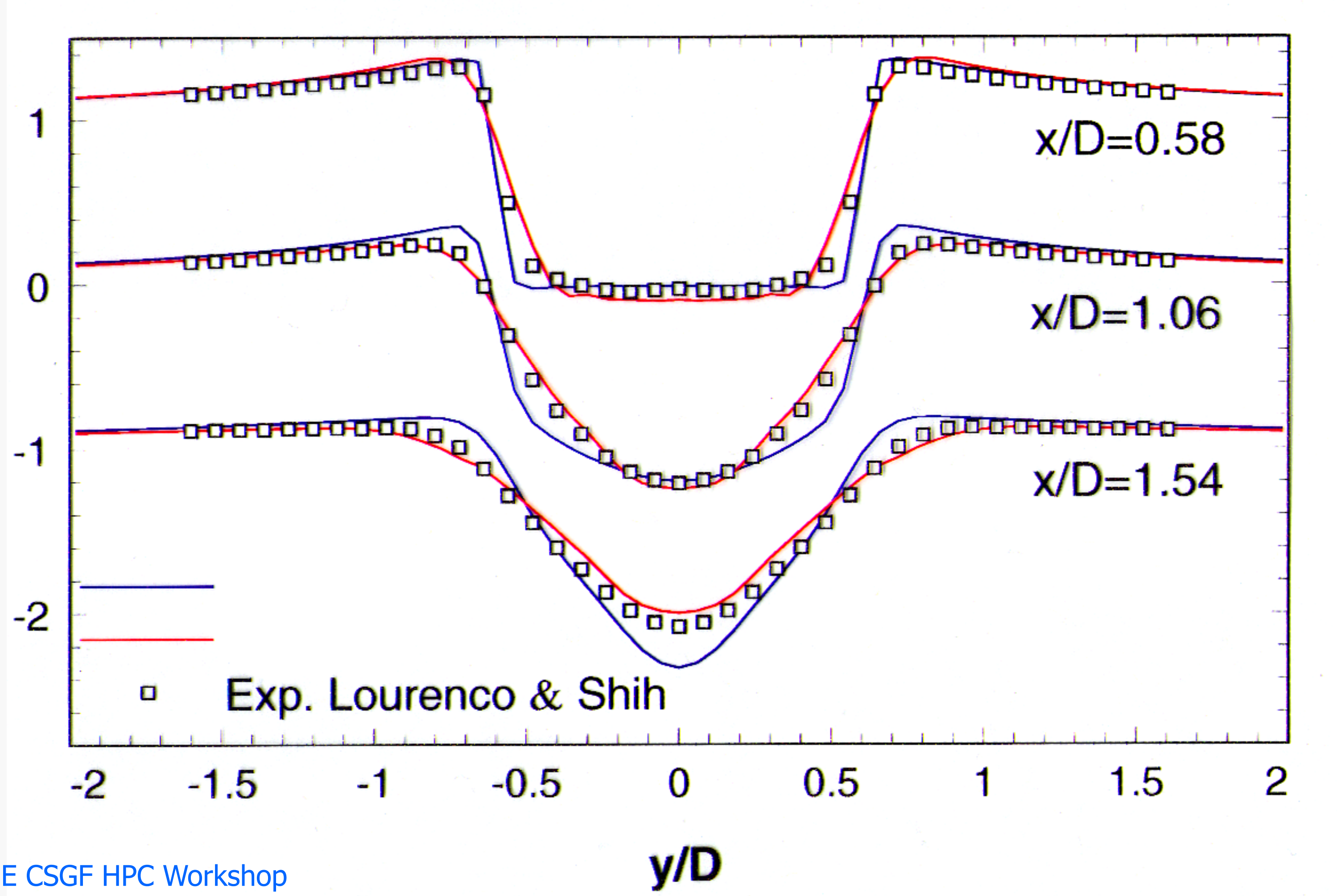


Quiz: Continued…

1.  $N_z=4$

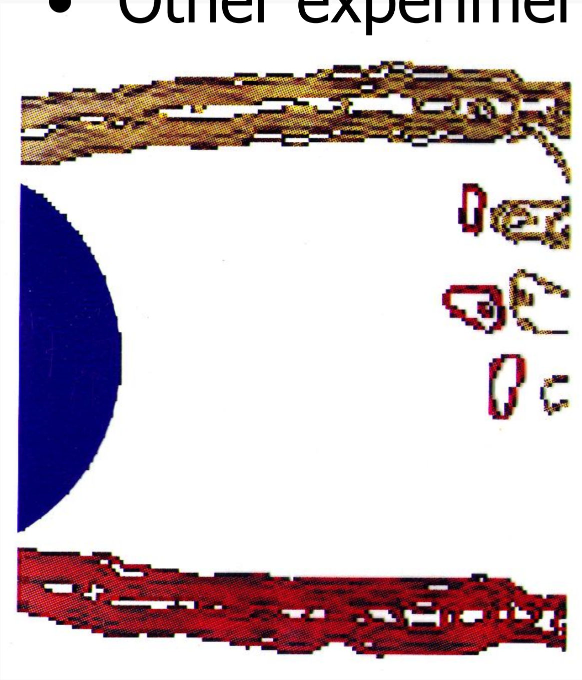
2.  $N_z=48$

Comparison of mean streamwise velocity to experiments:

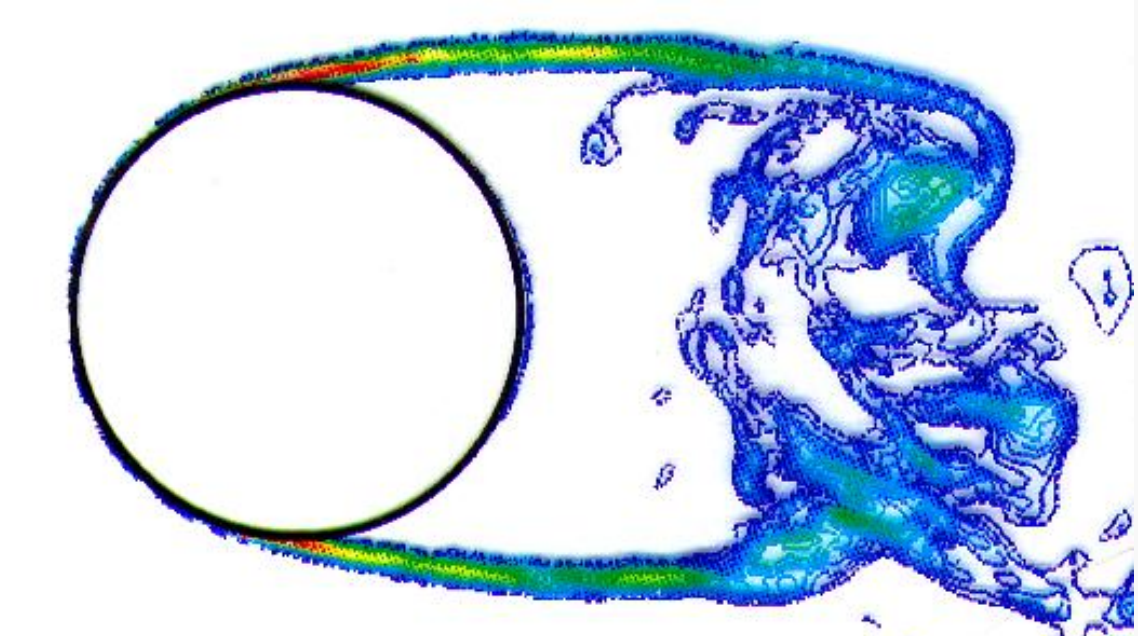


Answer: Number 2!

- Early transition was occurring in both experiment (due to vibration) and the very coarse simulation.
- Other experiments confirm the finer simulations.



PIV Experiment of Chyu and Rockwell (1996)



Numerical simulations with Nz = 48

Lesson:

Get the right results for the right reason.

DOE CSGF

Part 5
Uncertainty Quantification

Why do we have Uncertainty?

Differences between real system and CFD model

- Geometry definition
- Boundary condition specification
- Material properties

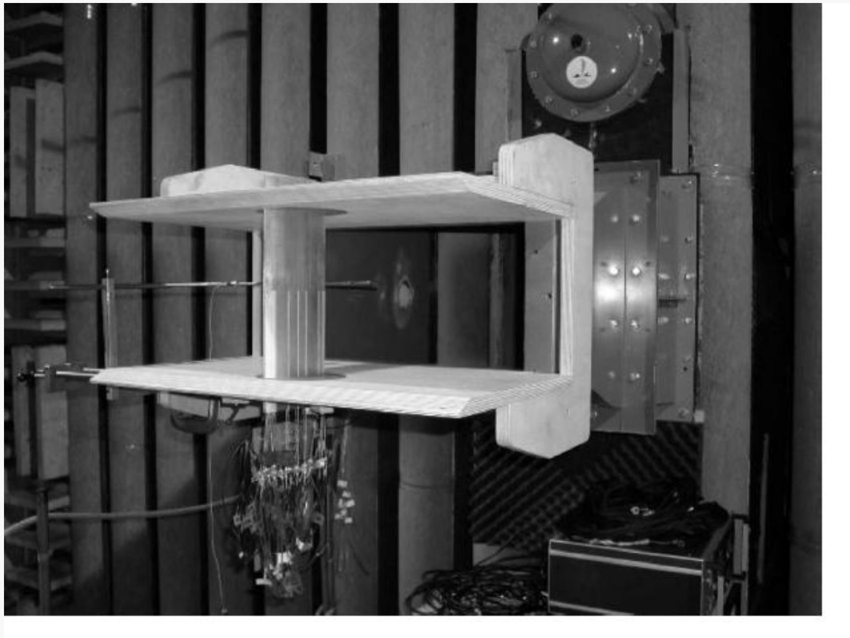
Modeling

- Effect of numerical errors (i.e. truncation errors)
- Physical modeling errors (i.e. turbulence models)
- Neglected physical processes (i.e. is buoyancy important?)

Accounting for uncertainty in the simulations requires a new perspective on the computational paradigm

Example – Fan Noise Predictions

Validate predictions of flow-generated noise for a fan blade section



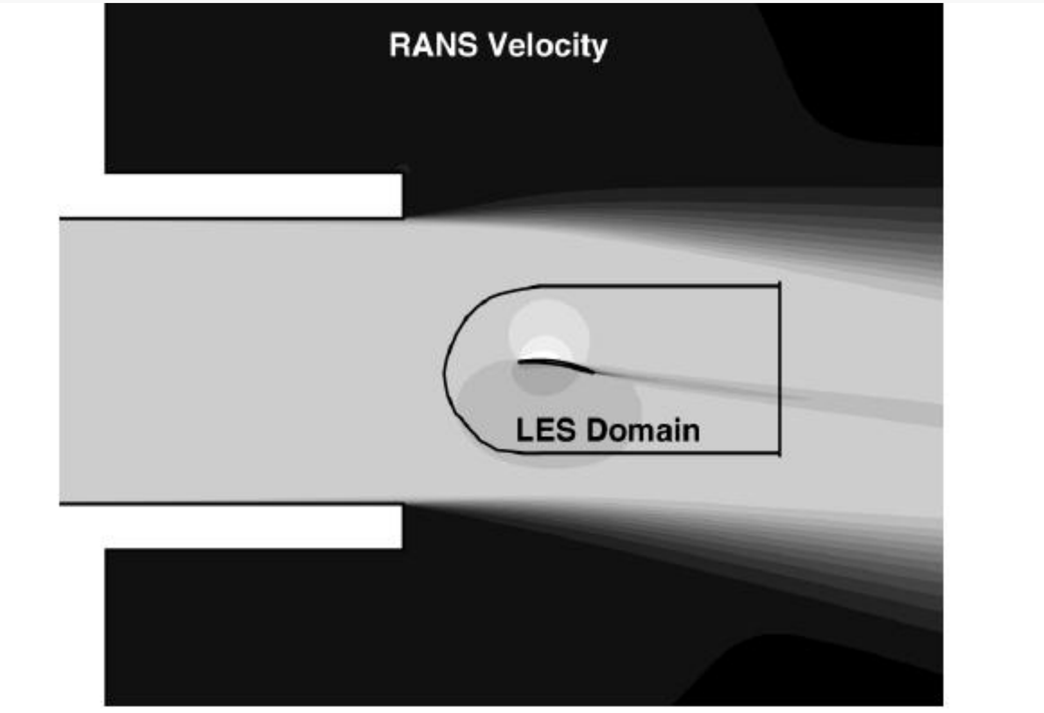
Experiments are carried out In large facility (anechoic chamber)

Need to represent the flow impinging on the airfoil accurately to perform meaningful comparisons

It is not feasible to perform high-fidelity simulations of the entire chamber

Example – Fan Noise Predictions

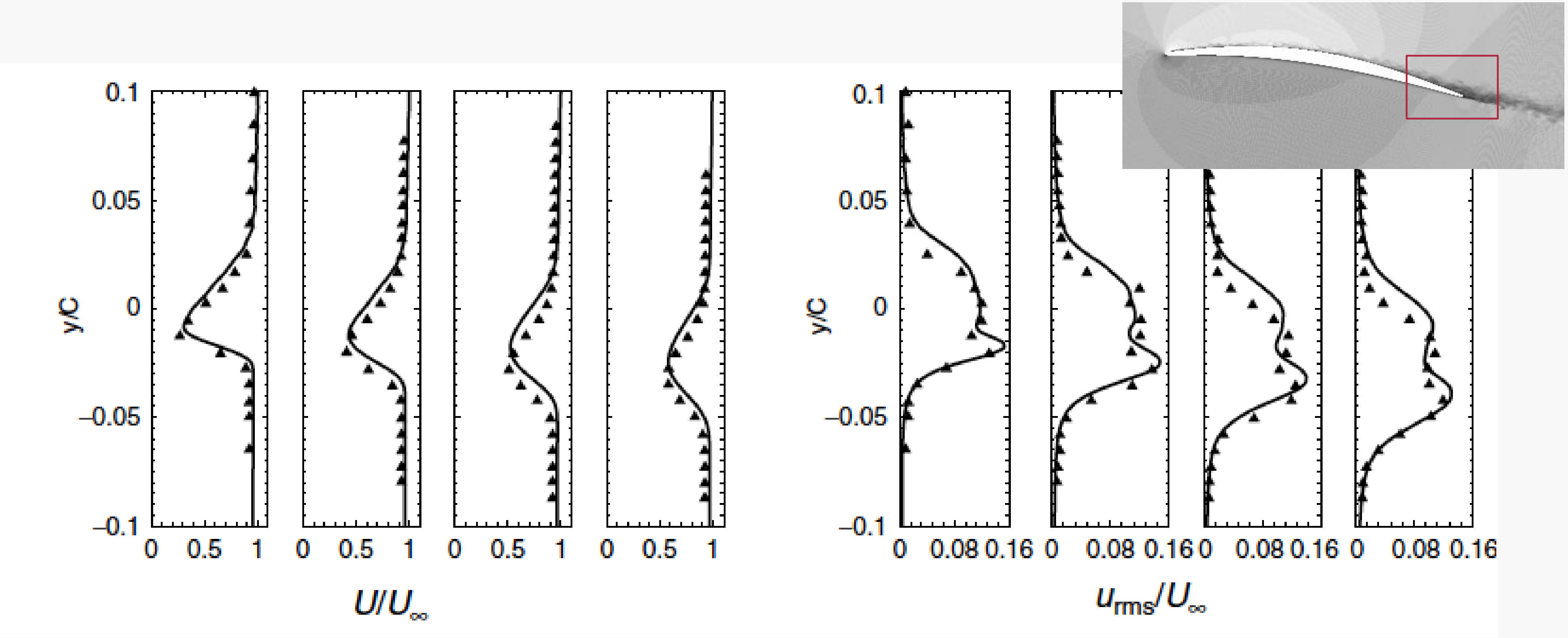
The strategy is to use low-fidelity simulations to provide boundary conditions to the high-fidelity ones



The computational effort (grid resolution) is concentrated on the smaller LES domain

Example – Fan Noise Predictions

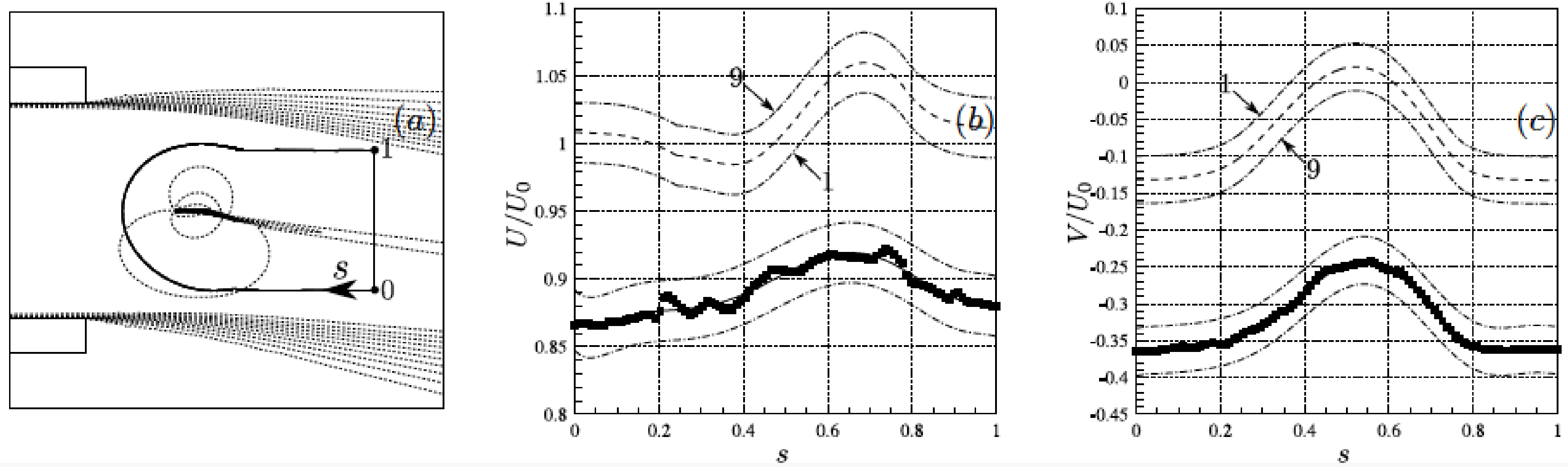
How accurate are the LES results? Are they affected by uncertainties in the specification of the boundary conditions (RANS simulations)?



Velocity profiles at the trailing edge show discrepancies

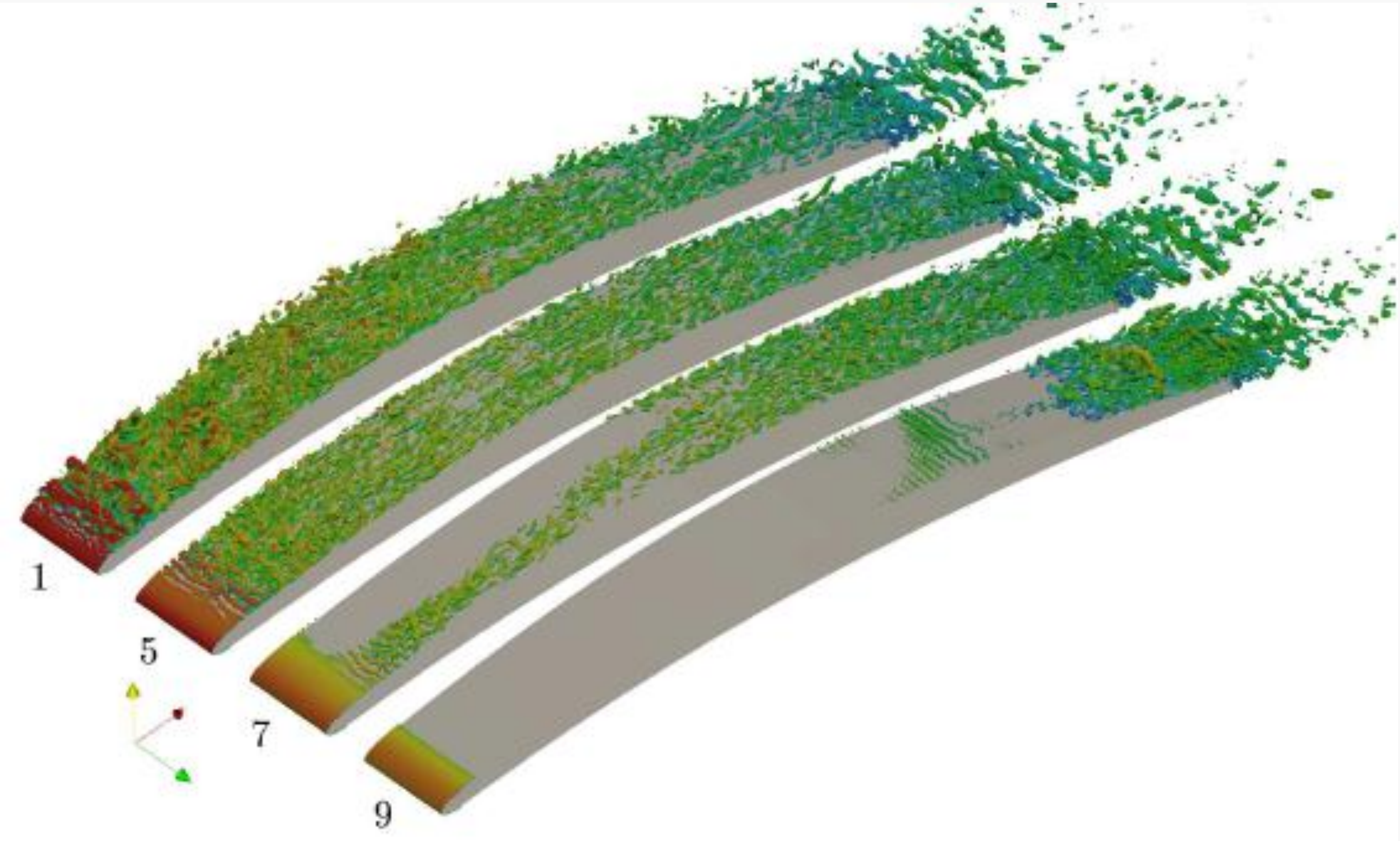
Example – Fan Noise Predictions

Differences between“real” velocity profiles and RANS estimate is assumed to be the uncertainty



UQ of Turbulence Simulations

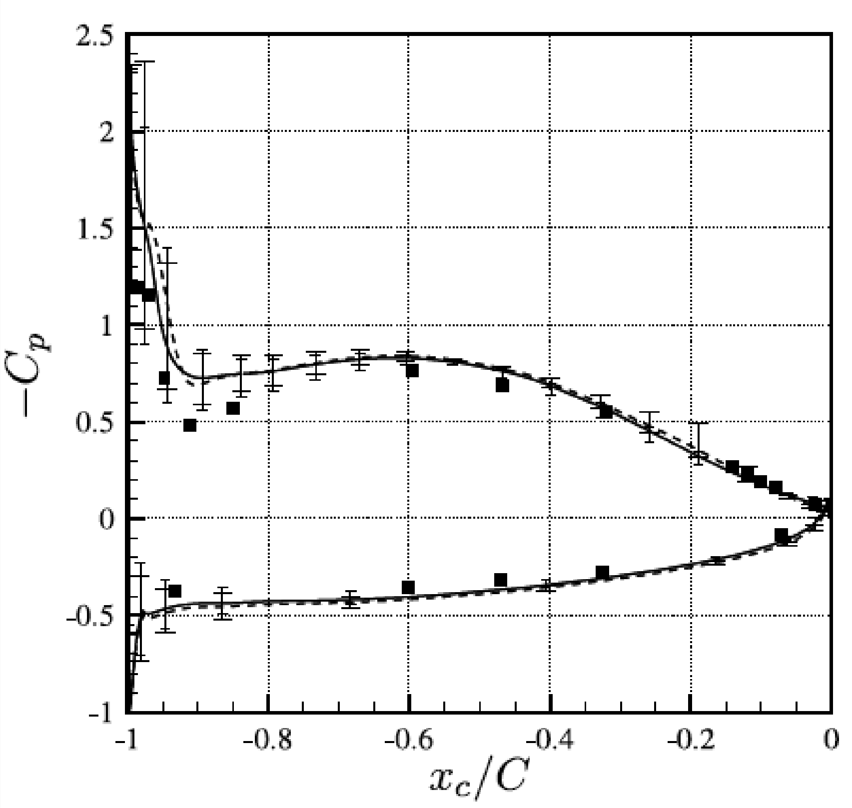
Multiple realizations corresponding to different boundary conditions lead to both laminar and turbulent boundary layers on the upper surface



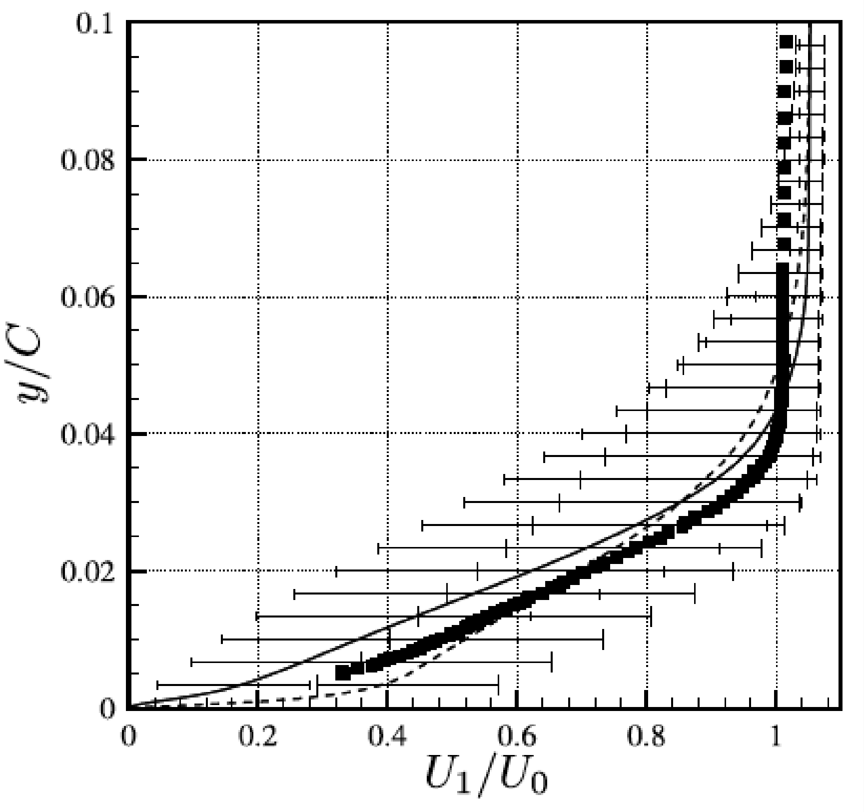
UQ of Turbulence Simulations

95% confidence intervals extracted from UQ/LES Simulations compared to experimental measurements (symbols)

Wall pressure distribution



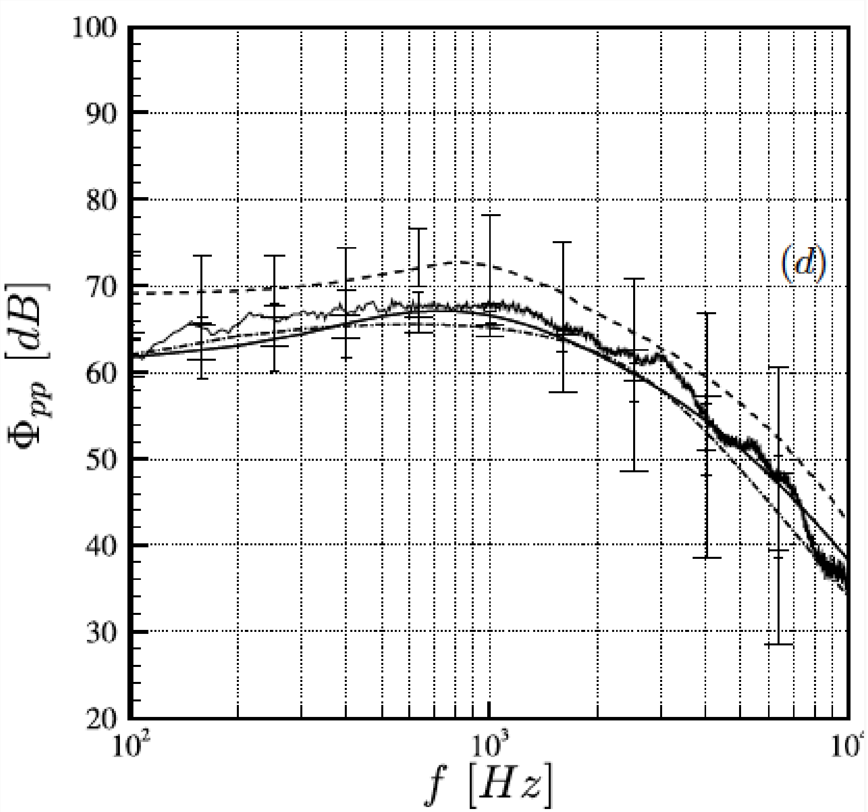
Streamwise velocity profile @ $x_c/C=0.95$



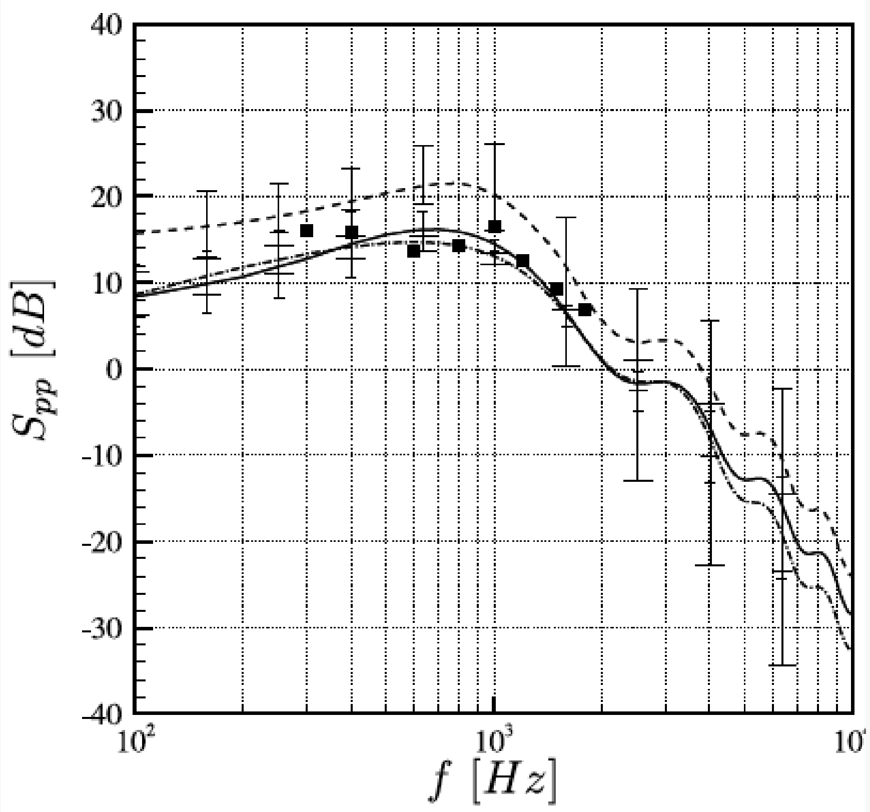
Noise Prediction

95% confidence intervals extracted from UQ/LES Simulations compared to experimental measurements (symbols)

Wall pressure fluctuations spectrum



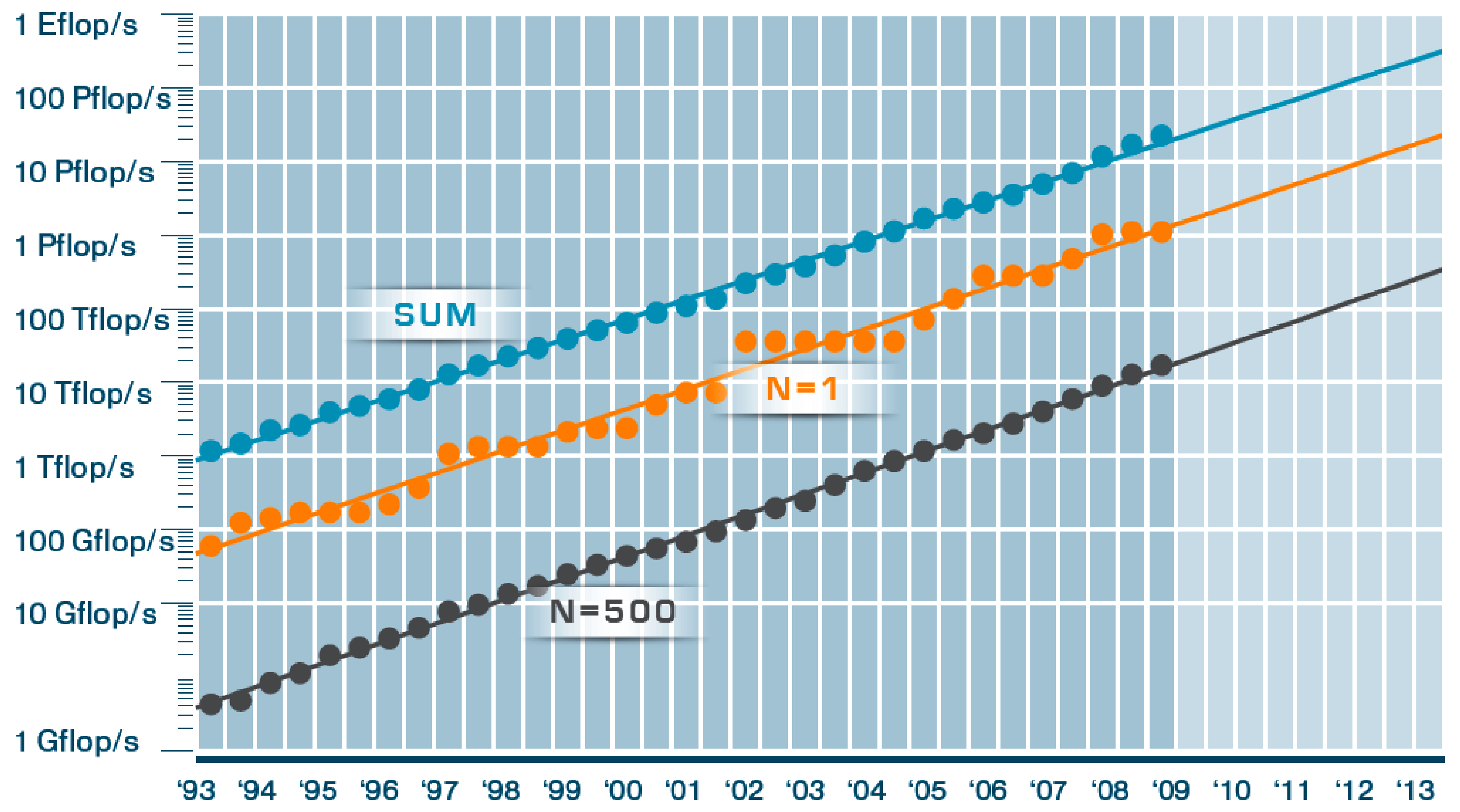
Sound pressure levels



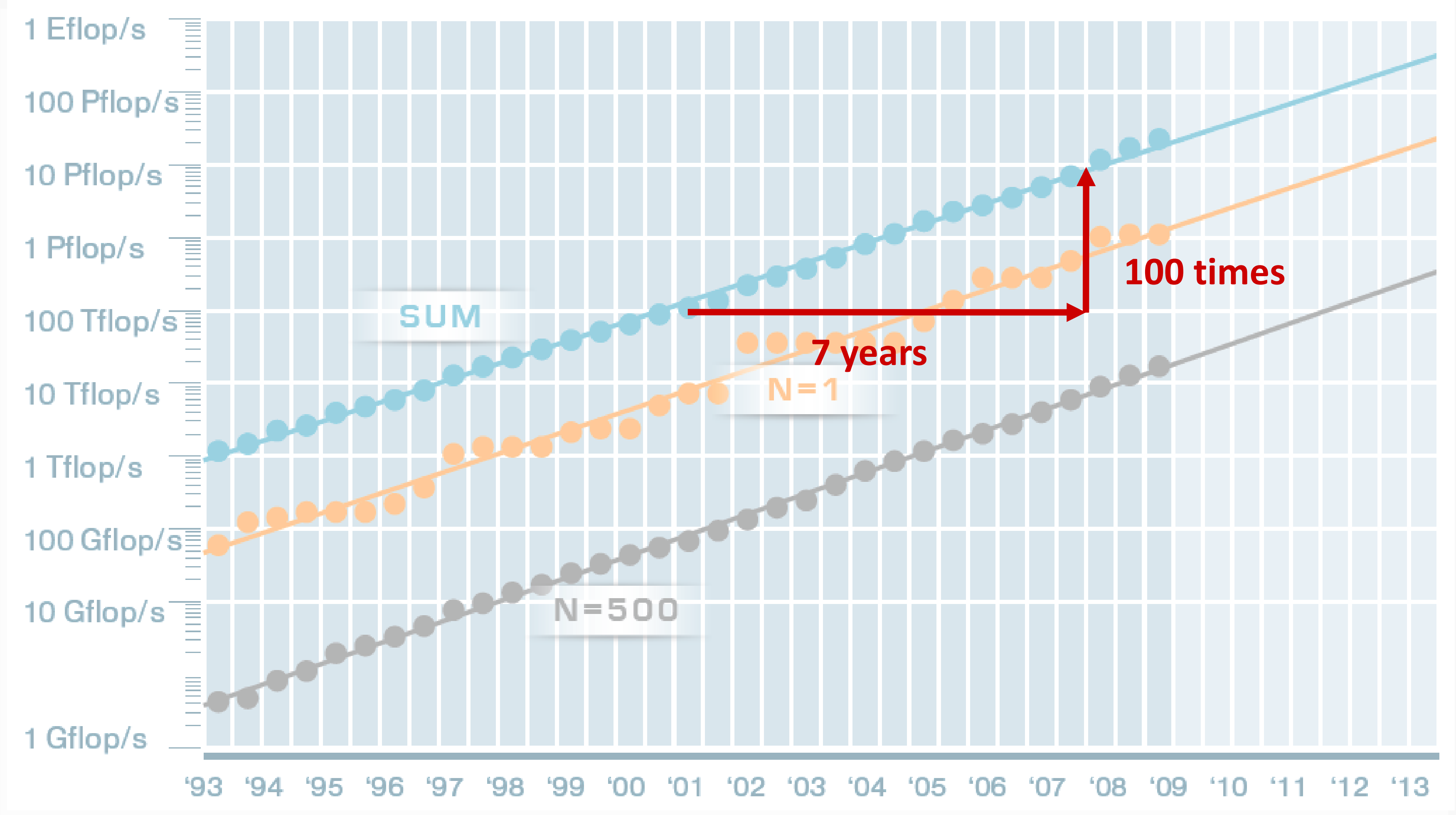
Part 6

Perspectives on Computer Science Aspects and Exascale

Growth in supercomputing power



Growth in supercomputing power



Summary

- Turbulence
- Success Stories
- Numerical Methods
- Validation and Verification
- Future Trends