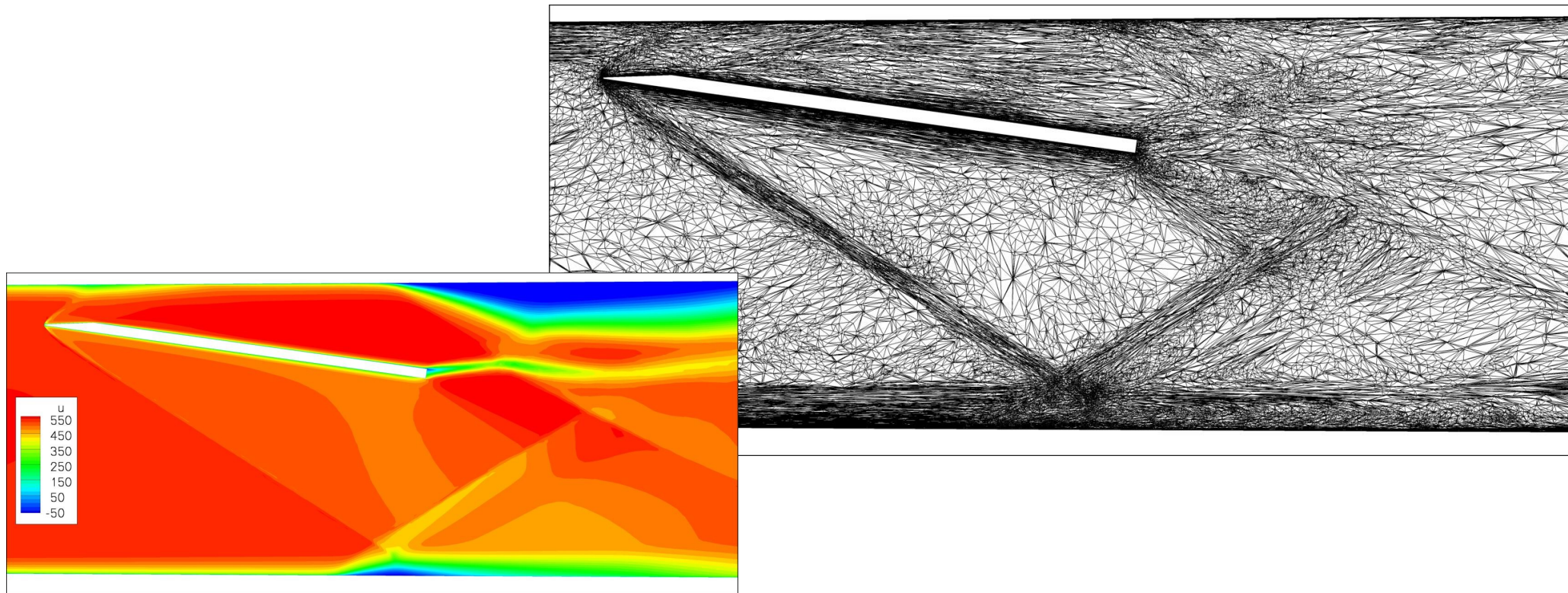


Anisotropic Adaptation Based on Output and Local Error Estimates



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Computational AeroSciences Branch
FUN3D Development Team
NASA Langley Research Center

Local Error and Output Adaptation

Local error based

- Feature based adaptation
- Flow solver/physics agnostic
- Not as robust
- Requires more manual interaction

Output error based

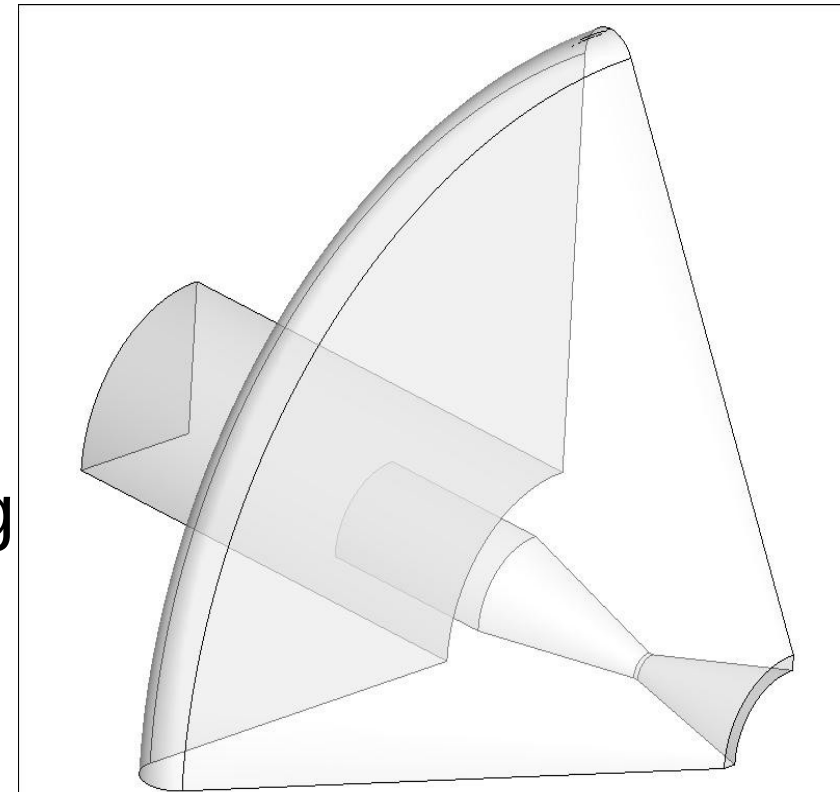
- Requires adjoint solution
- More robust
 - Transport of errors
- Fewer user controlled parameters

Local Error Adaptation Example

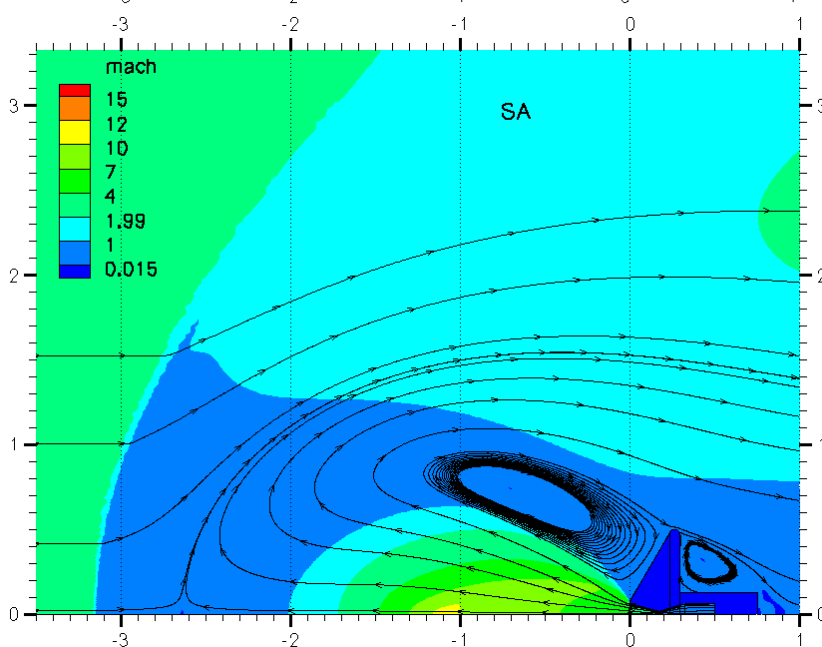
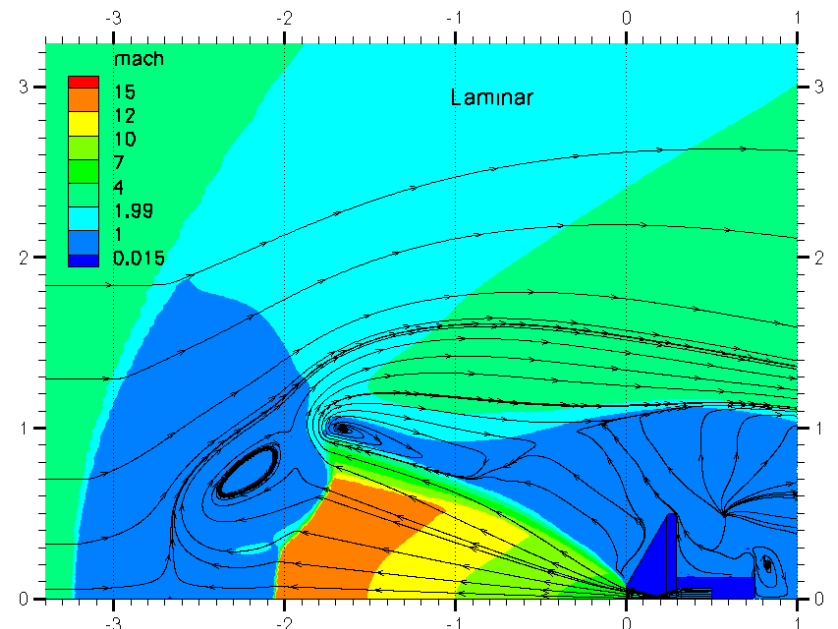
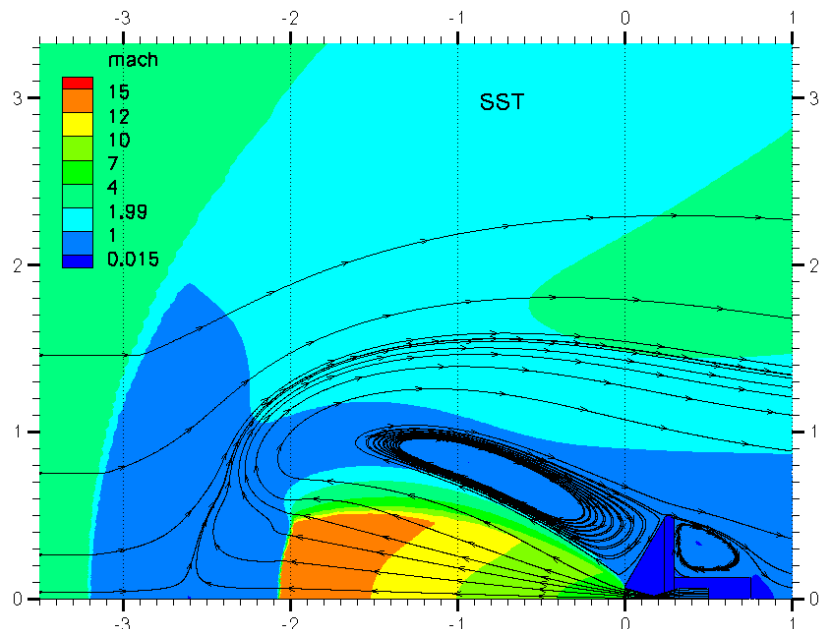
- Launch and entry vehicle applications
 - Supersonic retro-propulsion
- Required trial and error to gain practitioner expertise
 - Motivates the remainder of this talk

Supersonic Retro-Propulsion

- Future robotic and manned exploration architectures include SRP, which is at low Technology Readiness Level
- Assess existing CFD SRP capabilities and identify necessary technology investments
- Findings since October 2009
 - Jet turbulent shear layer mixing critical
 - Flow field very sensitive to grid resolution

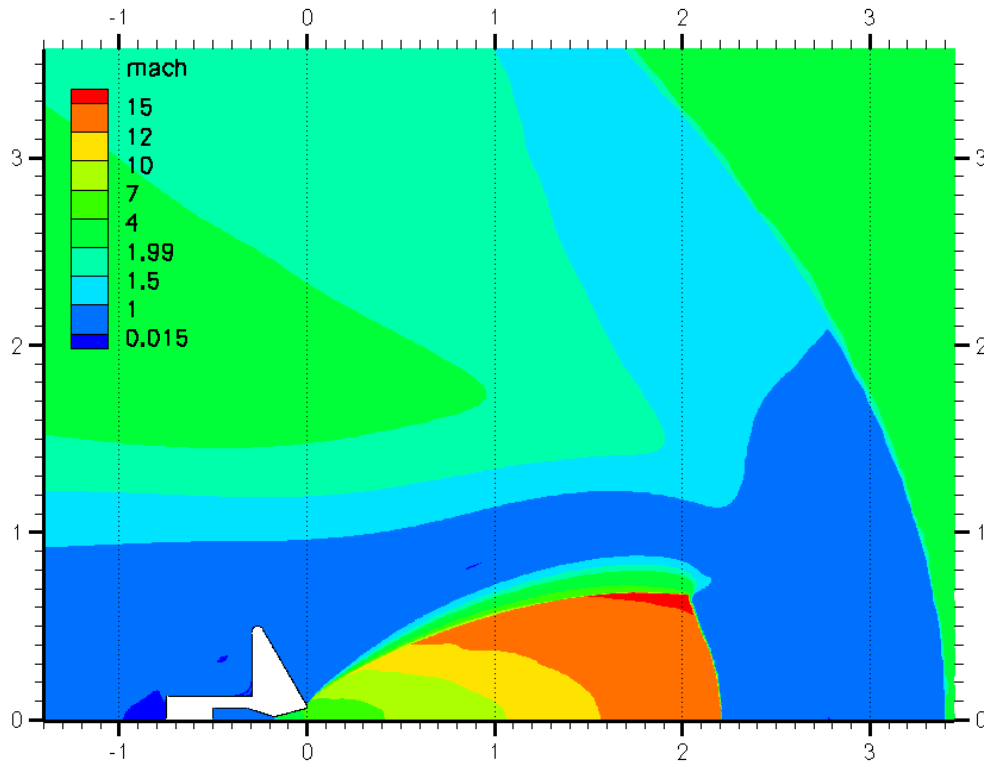


Modeling Effects*

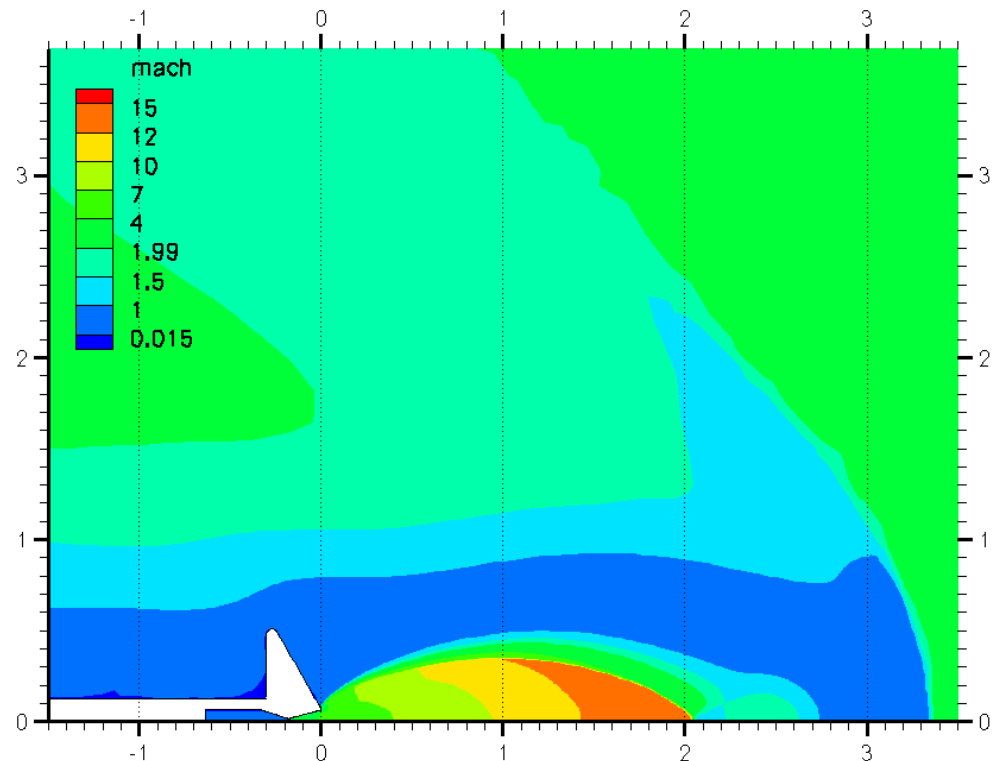


*Grid resolution has similar effect

Success and Failure of Local Error Estimate Adaptation



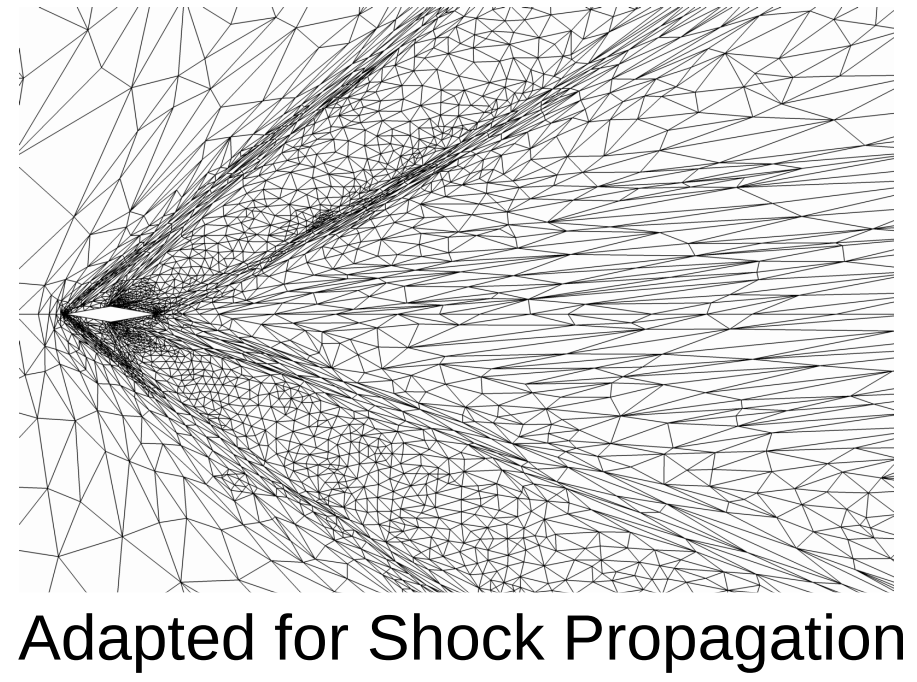
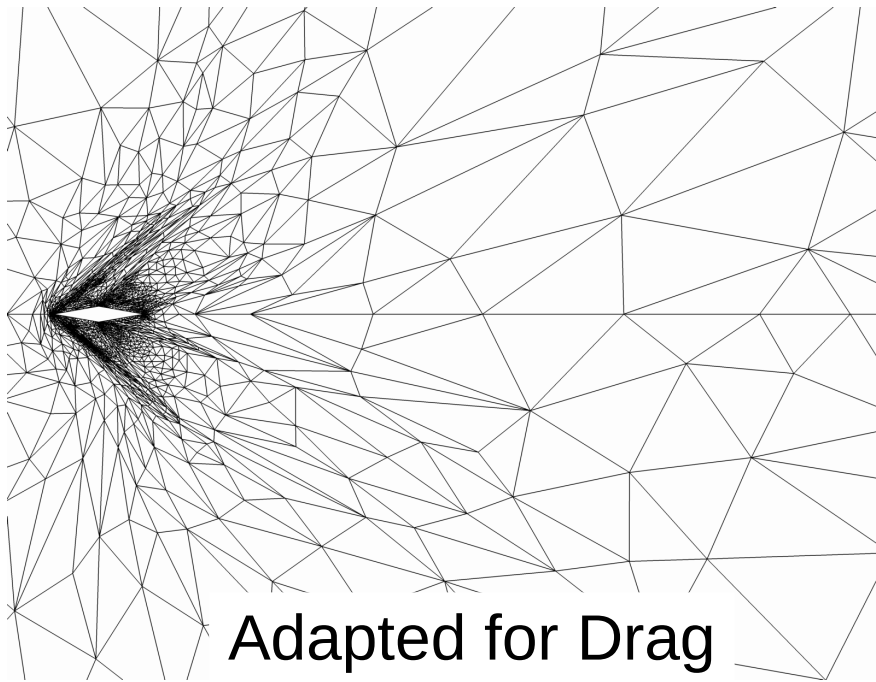
Expected flow field was produced when initial grid was fine enough and practitioner had experience



Different flow field was produced when initial grid was too coarse during initial simulations

Output-Based Adaptation

- Mathematically rigorous approach involving the adjoint solution that reduces estimated error in an engineering output
- Uniformly reducing discretization error is not ideal from an engineering standpoint - some errors are more important to outputs



Selected Related Works

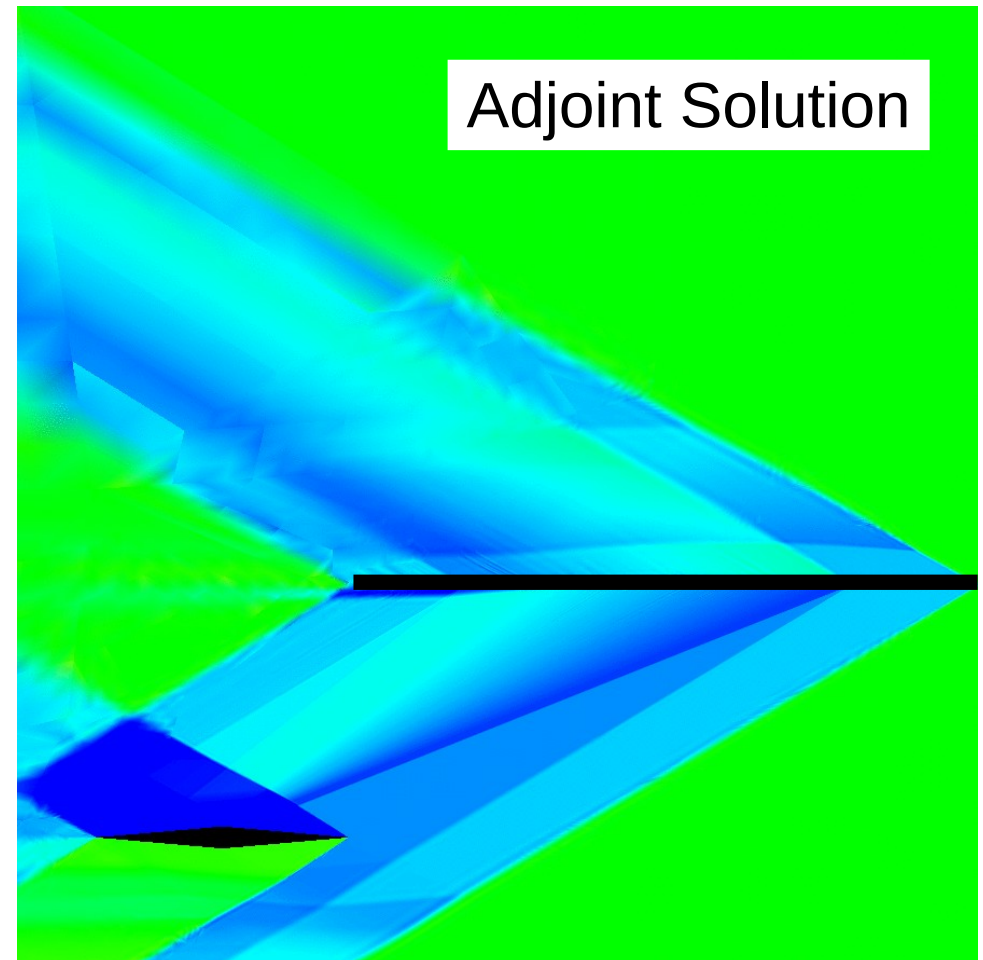
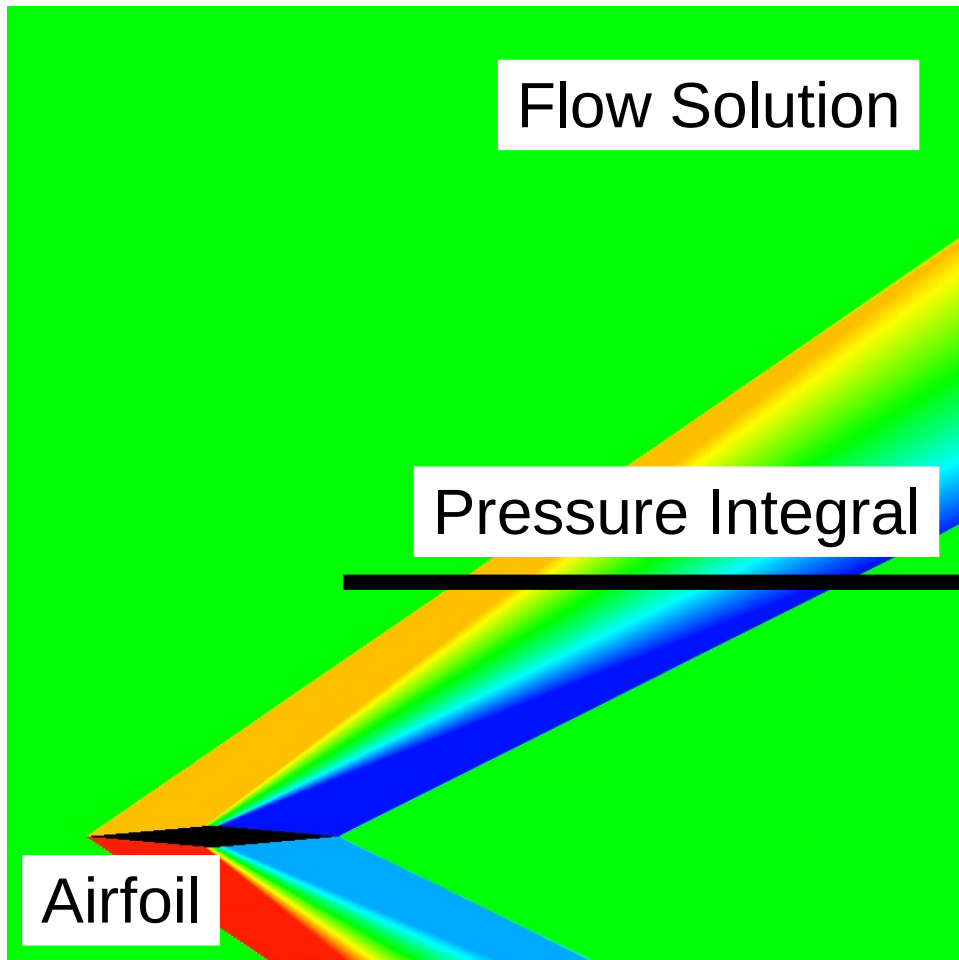
- Nemec and Aftosmis (NASA Ames)
 - Inviscid CART3D produces entire simulation databases
- Loseille (GMU)
 - Both output and local error estimate inviscid adaptation from continuous perspective
- Darmofal (MIT)
 - Higher-order discontinuous Galerkin
 - NRA cooperative agreement

NASA Langley Effort

- Pioneering 3D anisotropic output-based adaptation for turbulent simulation
- Utilizing the FUN3D framework to impact a large range of applications

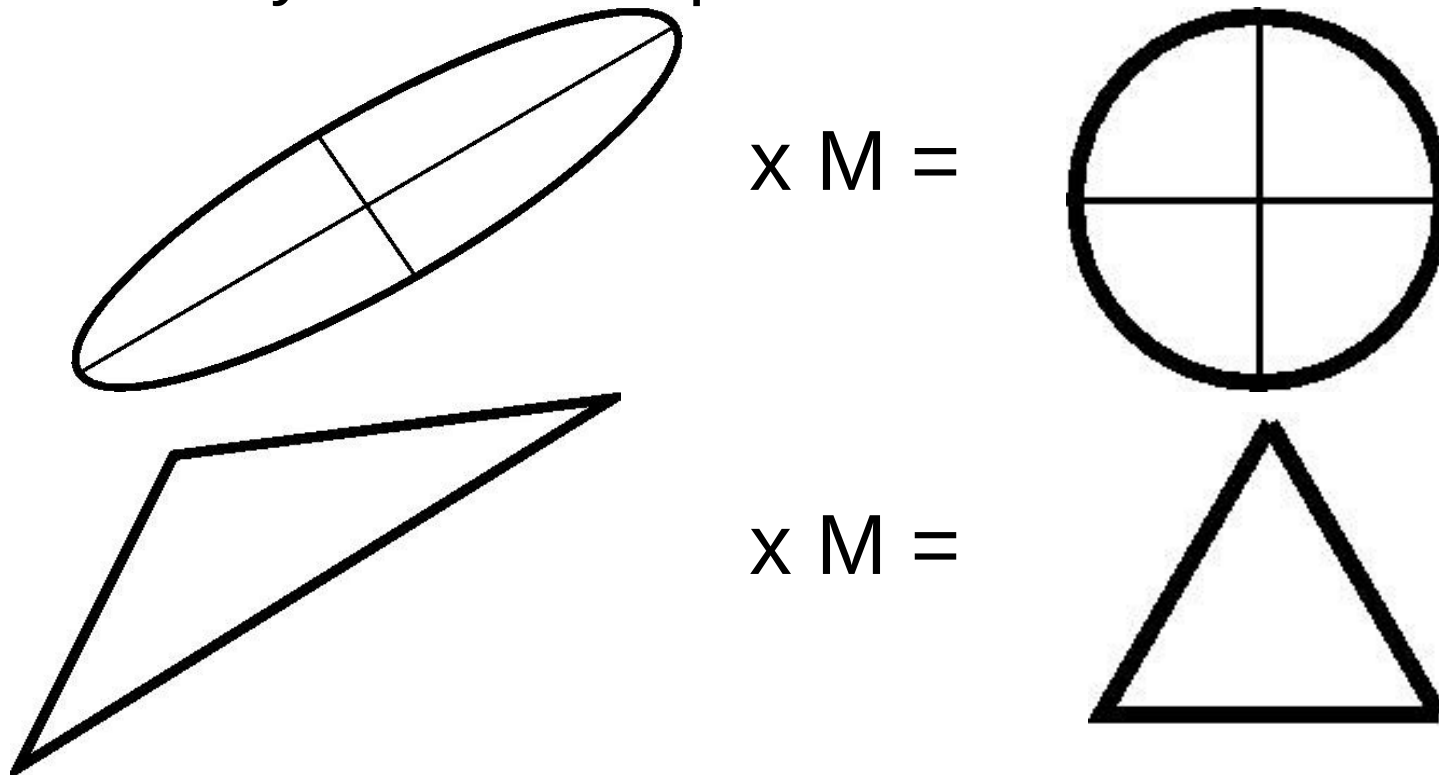
Shock Propagation Example

- Adaptation is targeted to improve off-body pressure integral output for diamond airfoil



Adaptation Mechanics

- Parallel node insertion, node movement, element collapse, and element swap
 - Very general approach to iteratively drive mesh to satisfy an anisotropic metric M



Adaptation Metric

- Output-based size specification scales the stretching and orientation of the Mach Hessian grid metric (Venditti and Darmofal)

$$M = \left| \frac{\partial^2 \text{Mach}}{\partial x^2} \right| = X \begin{bmatrix} \left(\frac{1}{h_1} \right)^2 & & \\ & \left(\frac{1}{h_2} \right)^2 & \\ & & \left(\frac{1}{h_3} \right)^2 \end{bmatrix} X^T$$

Adaptation Metric

- Output-based size specification scales the stretching and orientation of the Mach Hessian grid metric (Venditti and Darmofal)

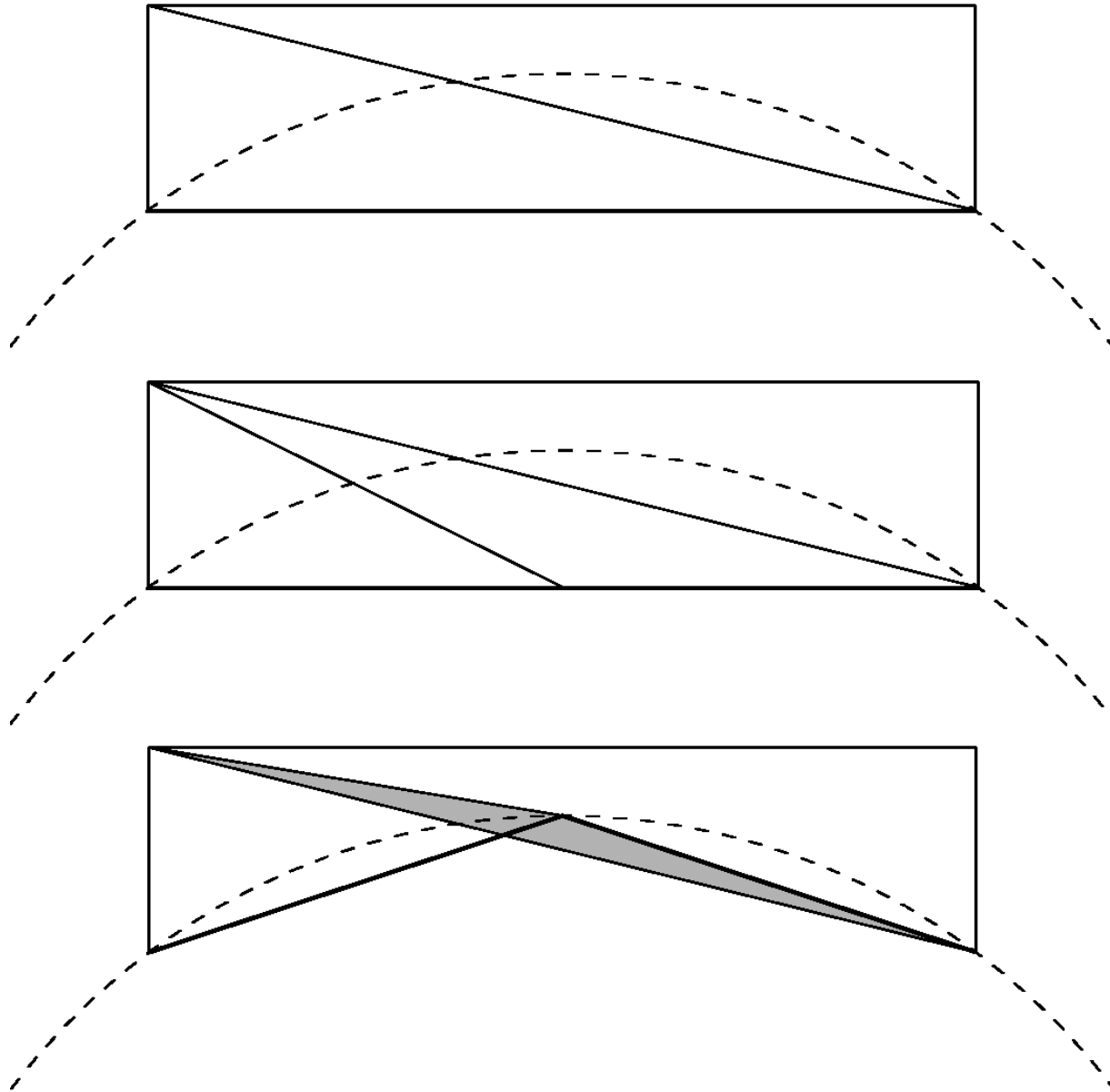
$$e_{\kappa} = \frac{|(\hat{\lambda} - \bar{\lambda})R(\hat{u})| + |(\hat{u} - \bar{u})R_{\lambda}(\hat{\lambda})|}{2}$$

$$\frac{h_{\text{request}}}{h_{\text{current}}} = \left(\frac{e_{\text{tol}}}{\sum e_{\kappa}} \frac{e_{\text{tol}}}{Ne_{\kappa}} \right)^{\omega}$$

Highly Anisotropic Adaptation

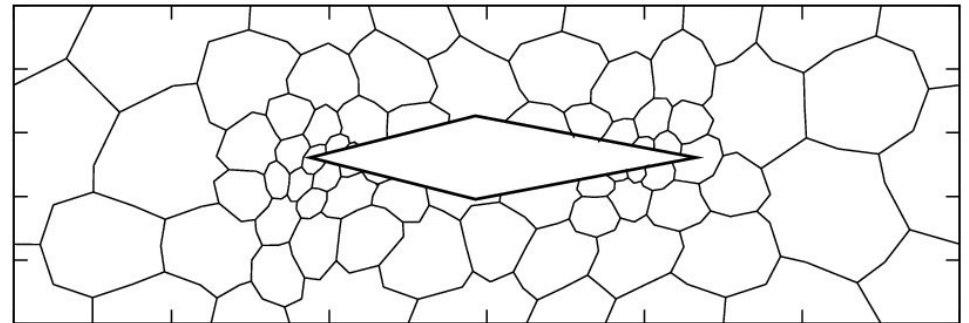
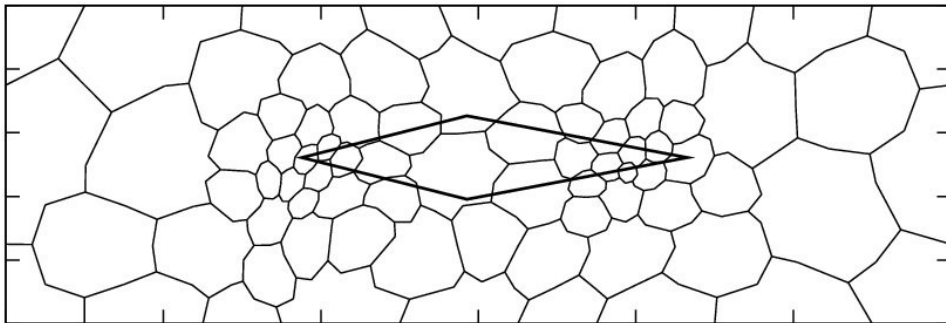
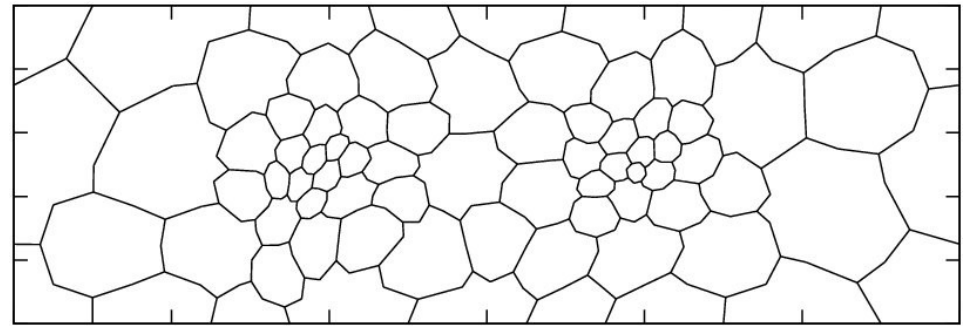
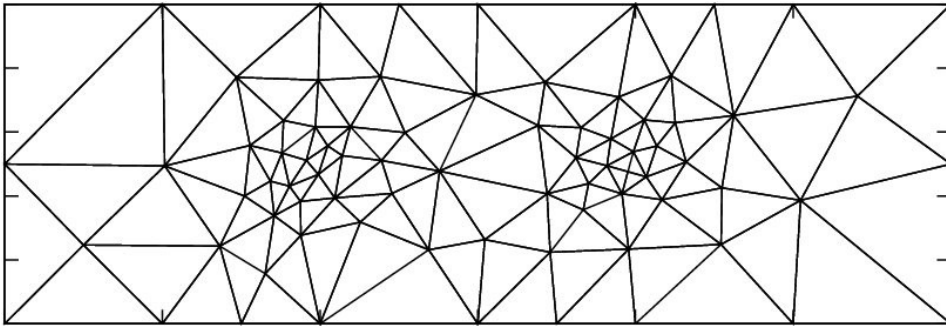
- Mapped isotropic methods produce large face angles
 - Discretization issues for gradient reconstruction
 - Mechanics unable to satisfy resolution request with face angle limits
 - *Circumvented with hybrid methods*
- Boundary recovery becomes increasingly difficult
 - *Circumvented with cut cells*

Curved Boundary Adaptation



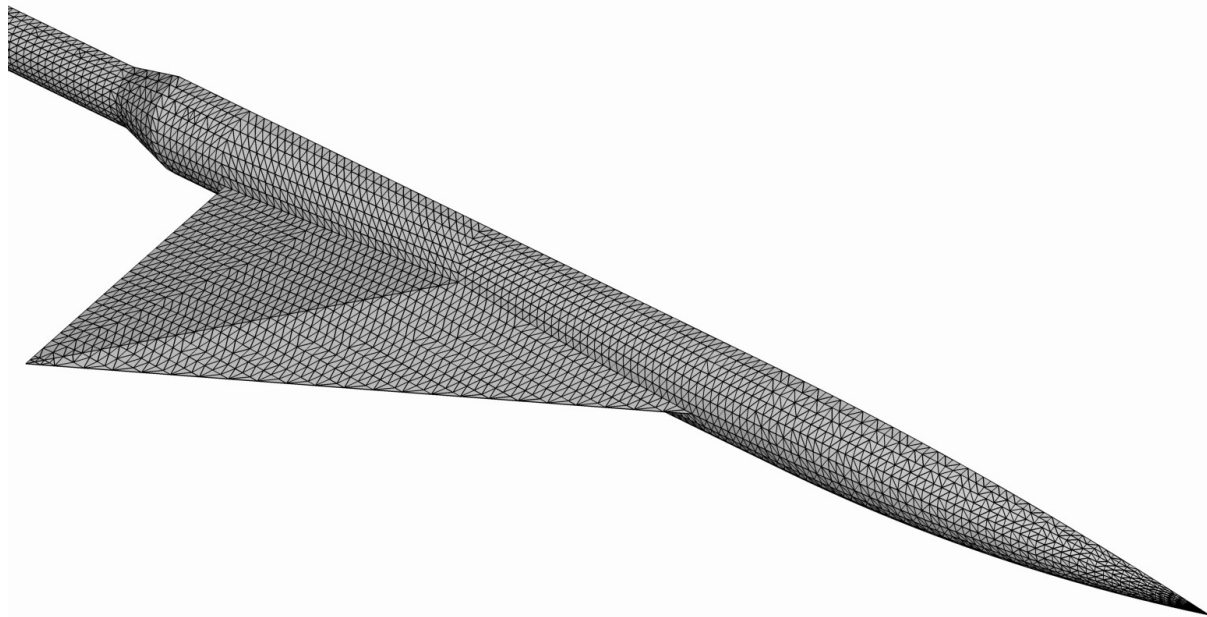
Cut-Cell Method

- Background volume grid
- Surface grid of geometry
 - Boolean subtracted from median dual background grid



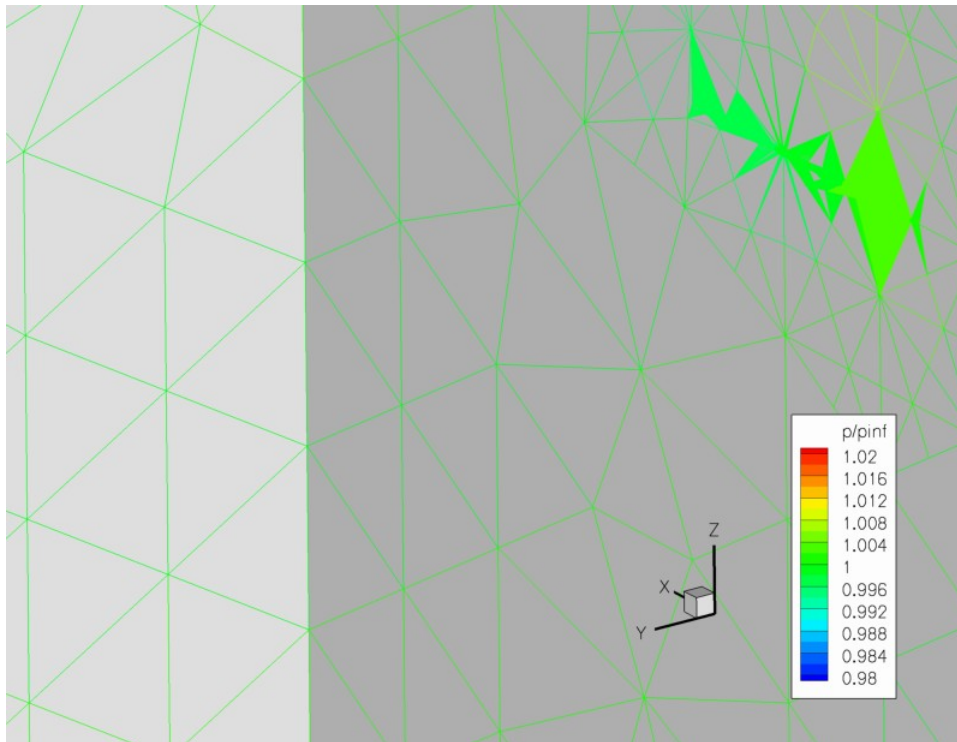
Sonic Boom Applications

- Output-based adaptation has increased the automation of shock propagation simulations
- Euler delta wing body example

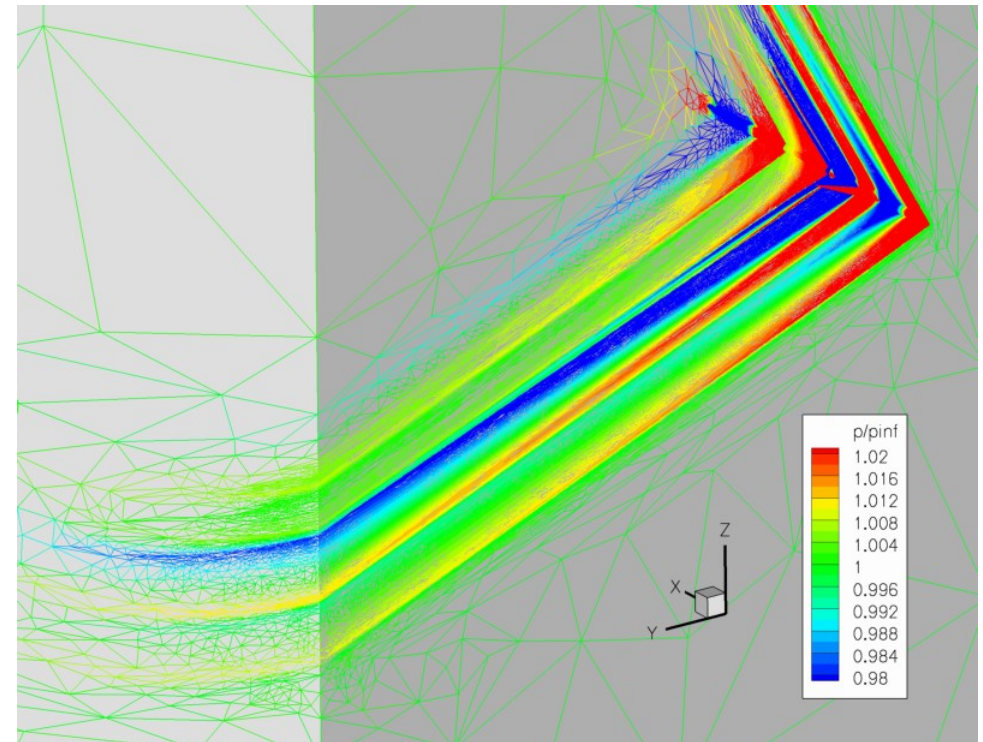


Delta Wing Body, 1.68 Mach

- Off-body pressure integral output

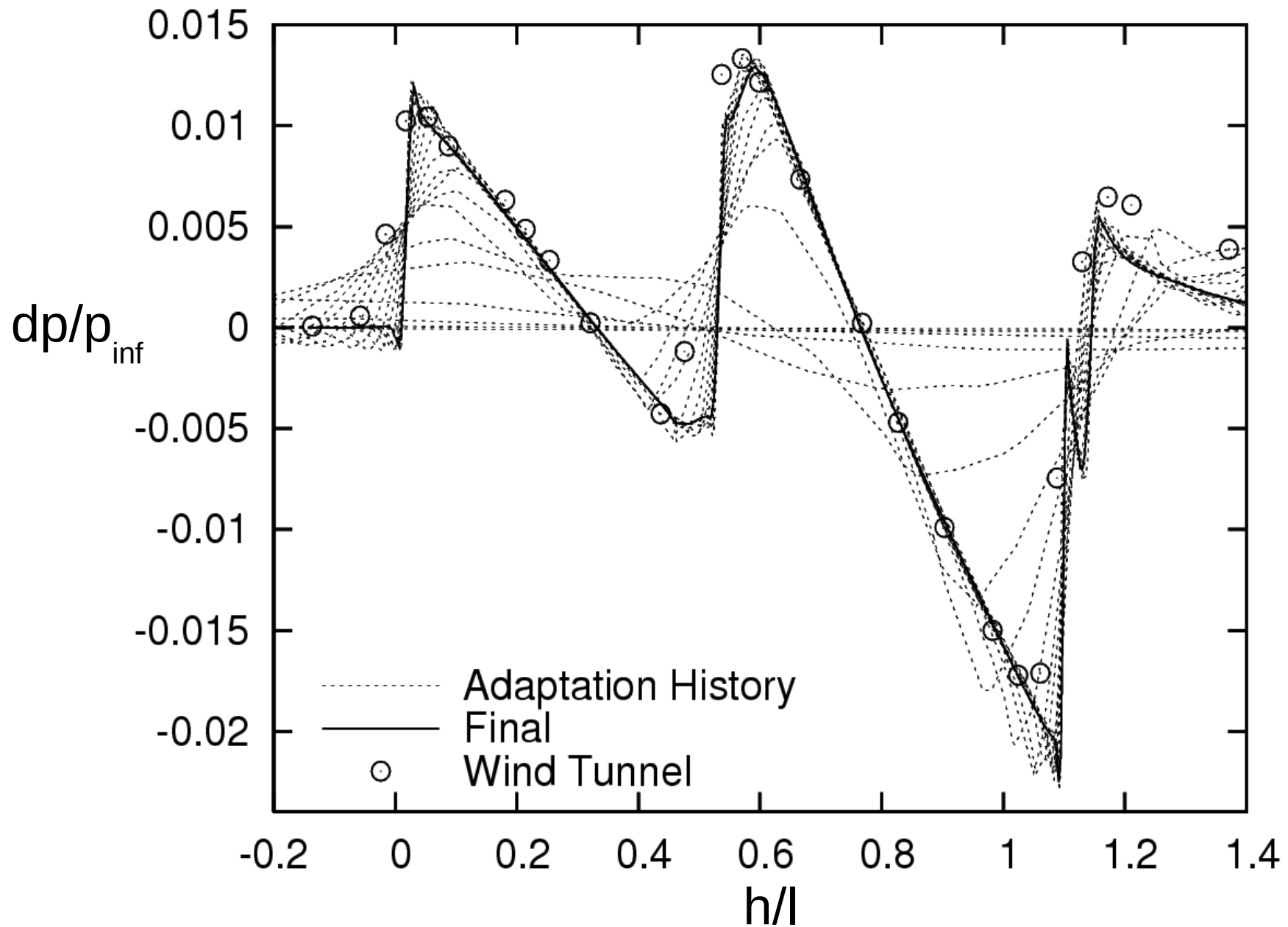


Initial Grid
2,800
Control volumes



Final Adapted Grid
4,900,000
Control volumes

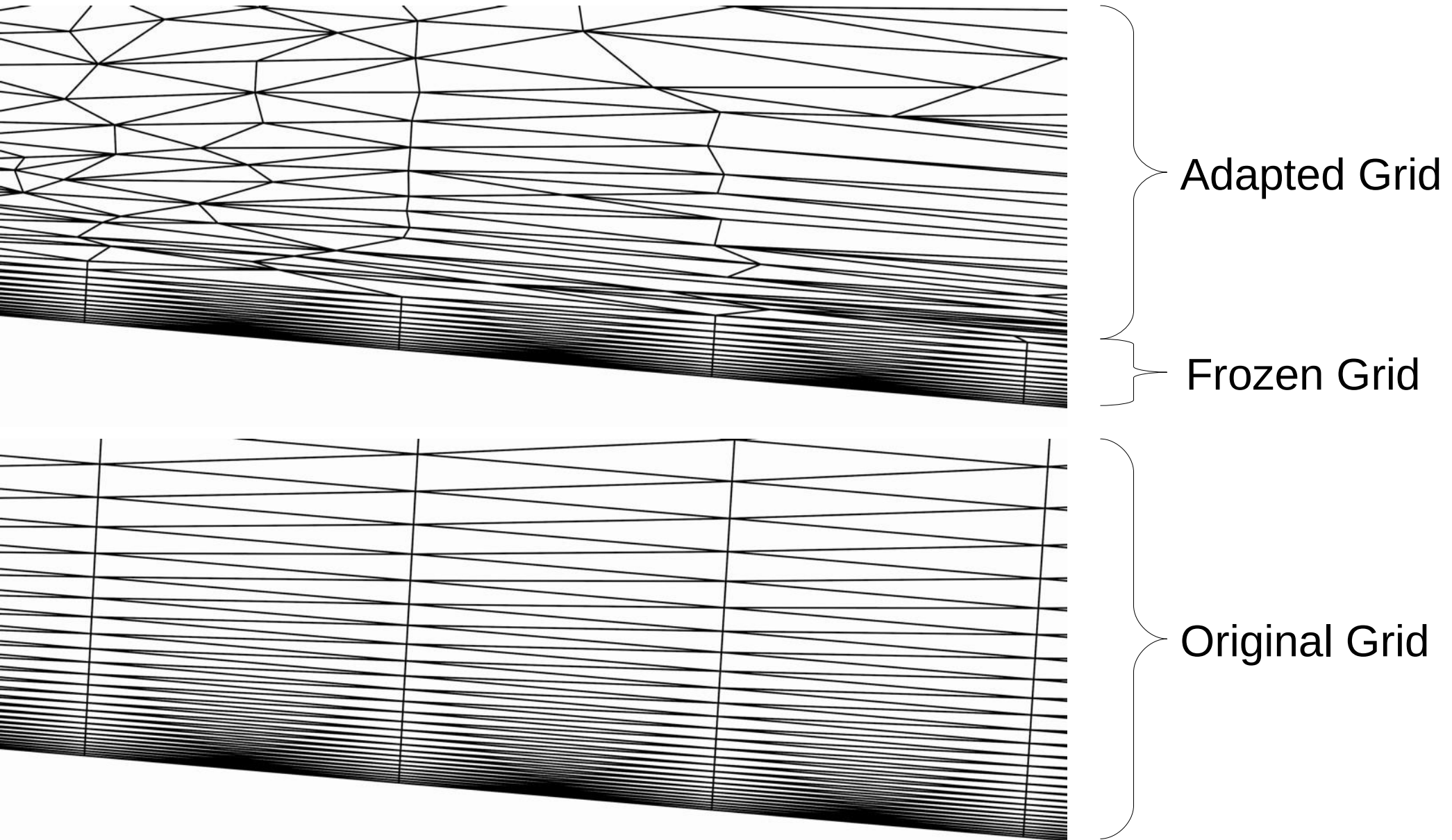
Delta Wing Body, 1.68 Mach



Adaptation For Viscous Flows

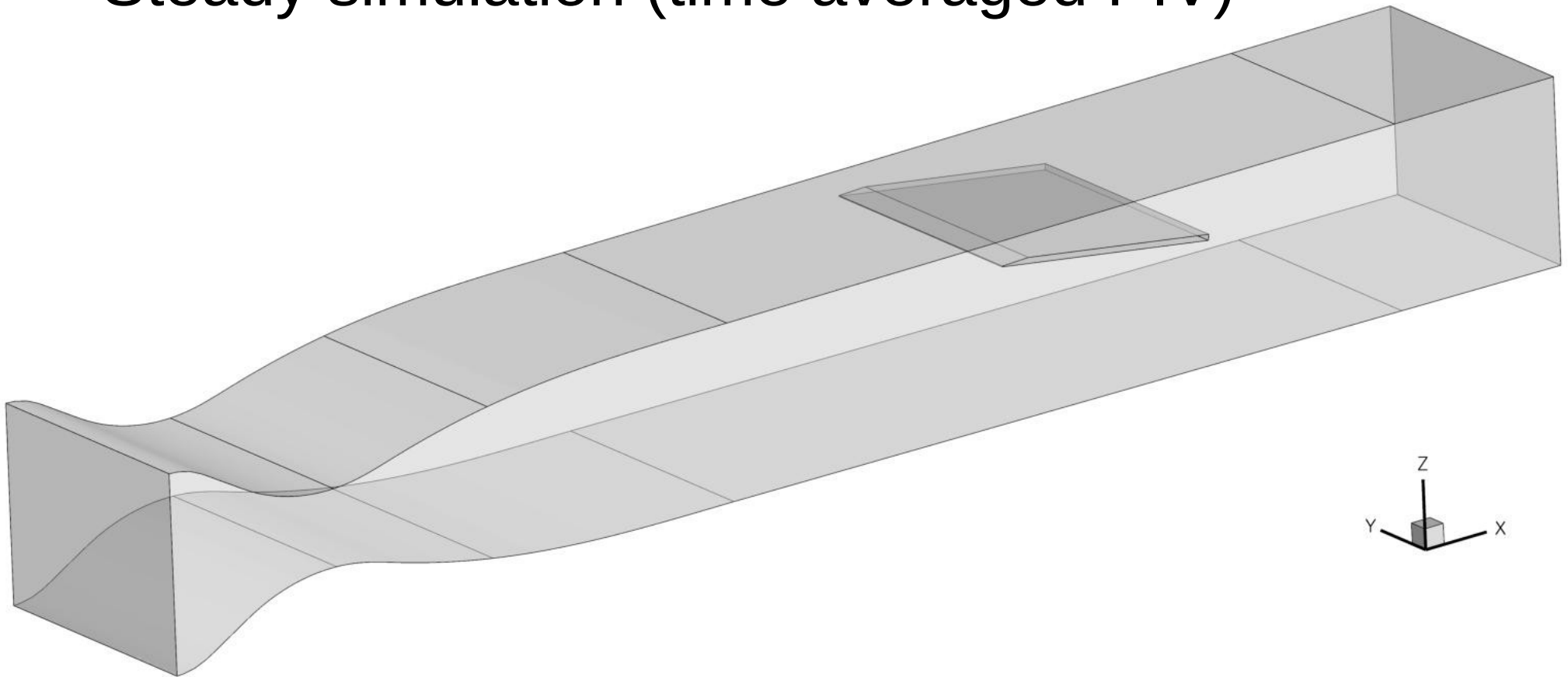
- Preliminary application of cut cell method to laminar flows
 - Leveraging on-going cell-centered research
- Interim hybrid approach: freeze near-body high aspect ratio and surface curvature regions of body-fitted grids
 - Applicable to off-body features but requires manual specification and generation of boundary layers

Hybrid Adaptation



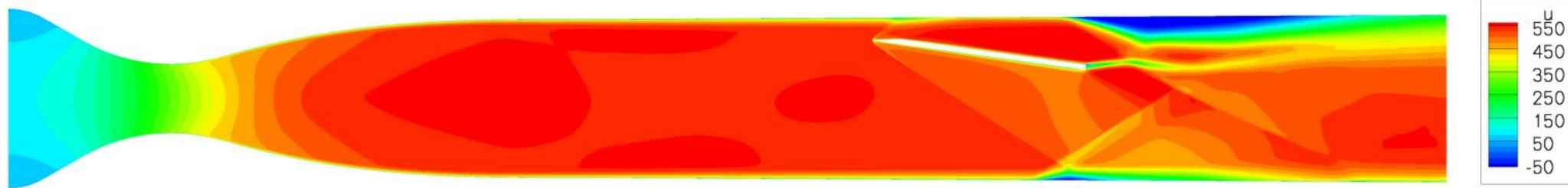
AIAA Supersonic Shock-Boundary Layer Interaction Workshop

- Test condition 1 (PIV measurements available)
- Mach 2.25, 8 deg wedge angle, drag target
- Steady simulation (time averaged PIV)

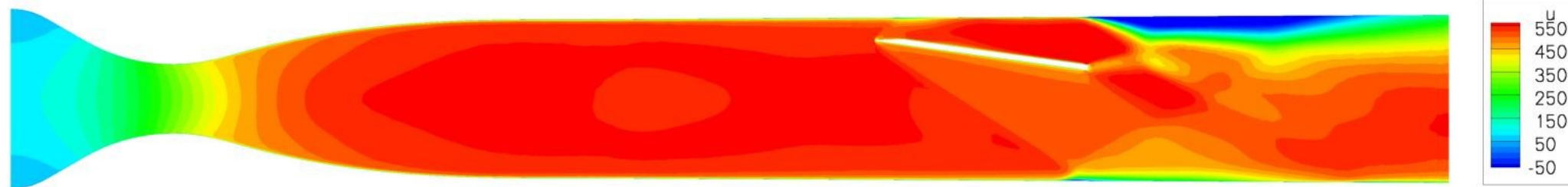


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U-Velocity on Adapted Grid

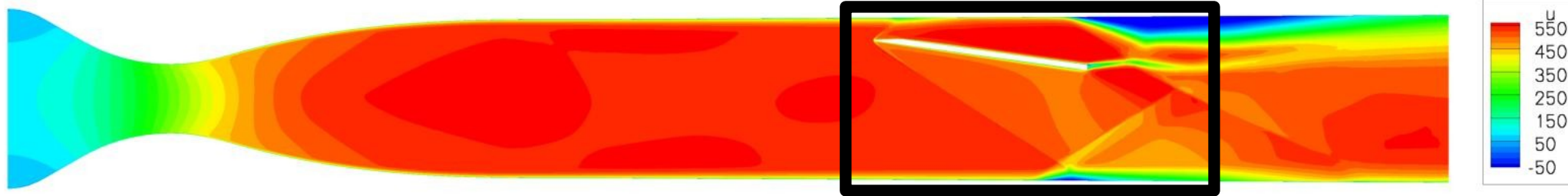


U-Velocity on Original Grid

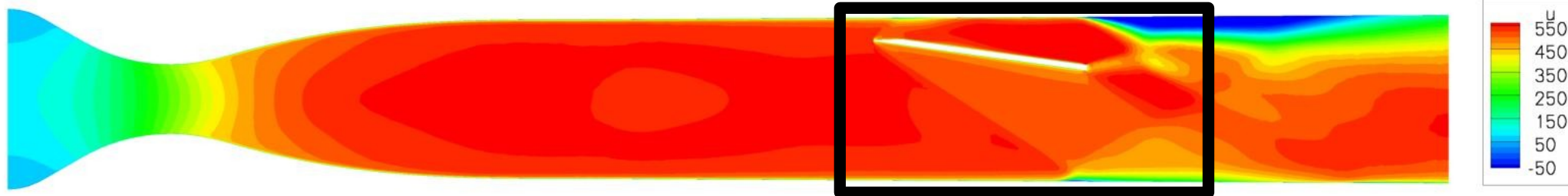


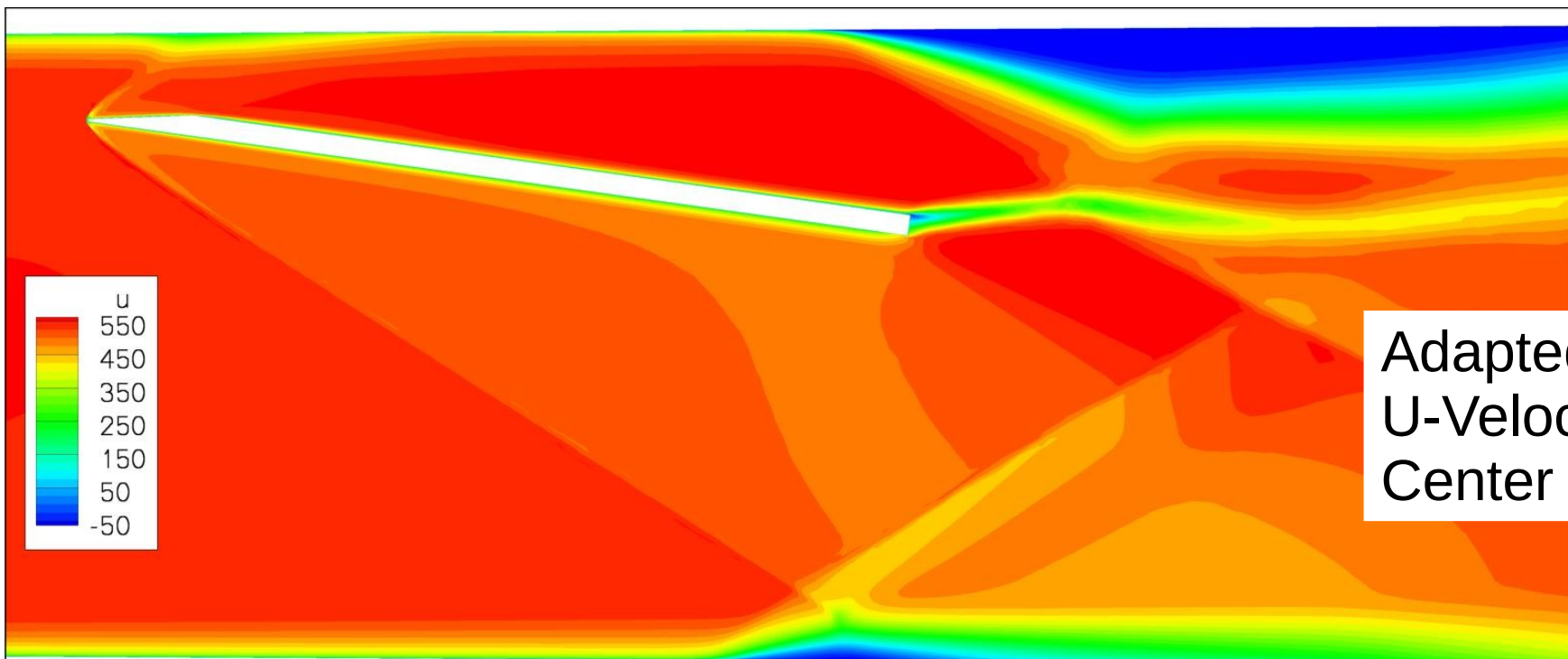
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U-Velocity on Adapted Grid

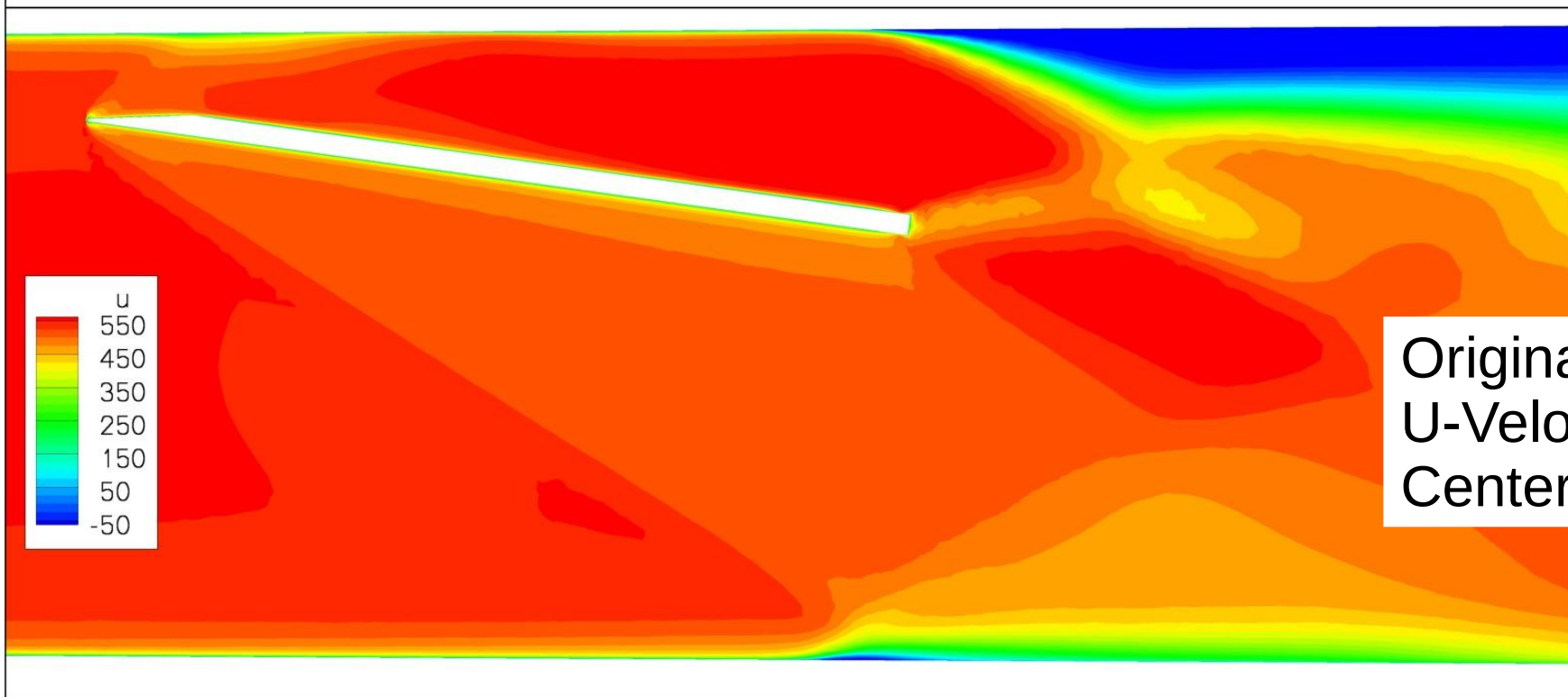


U-Velocity on Original Grid

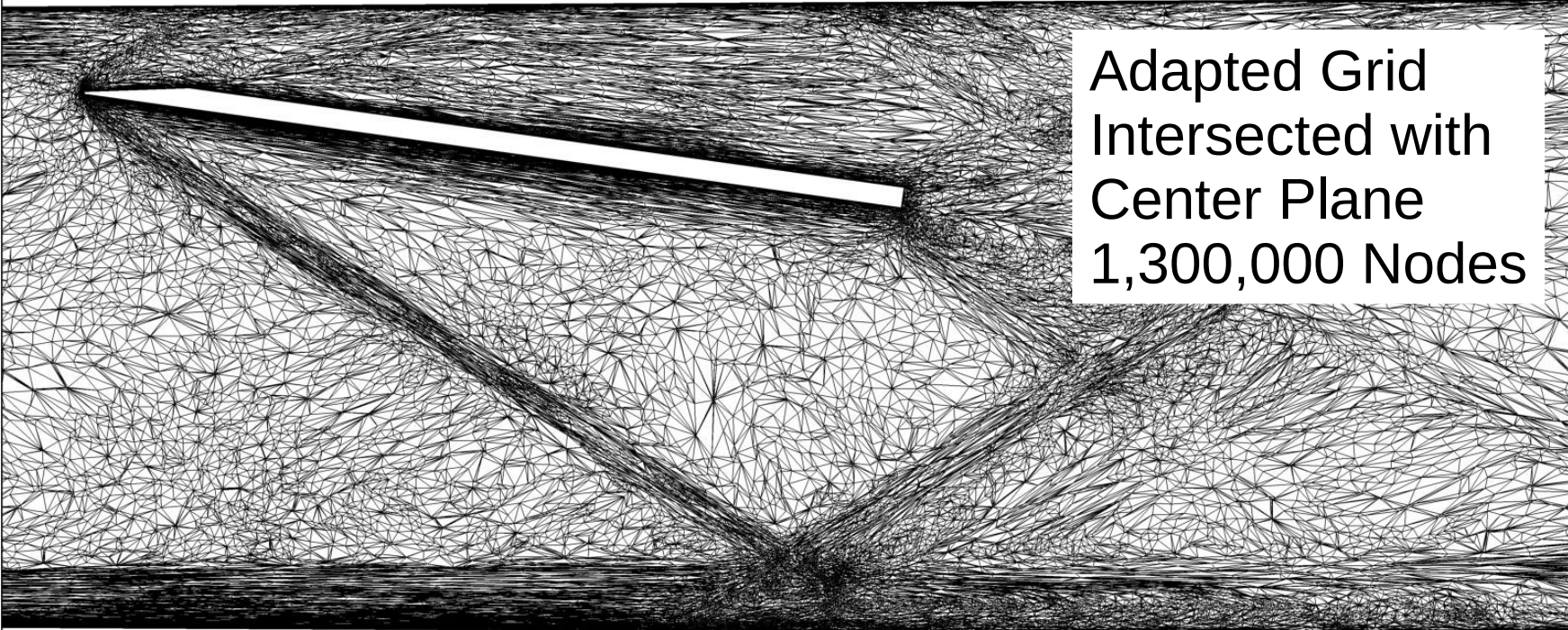




Adapted Grid
U-Velocity on
Center Plane

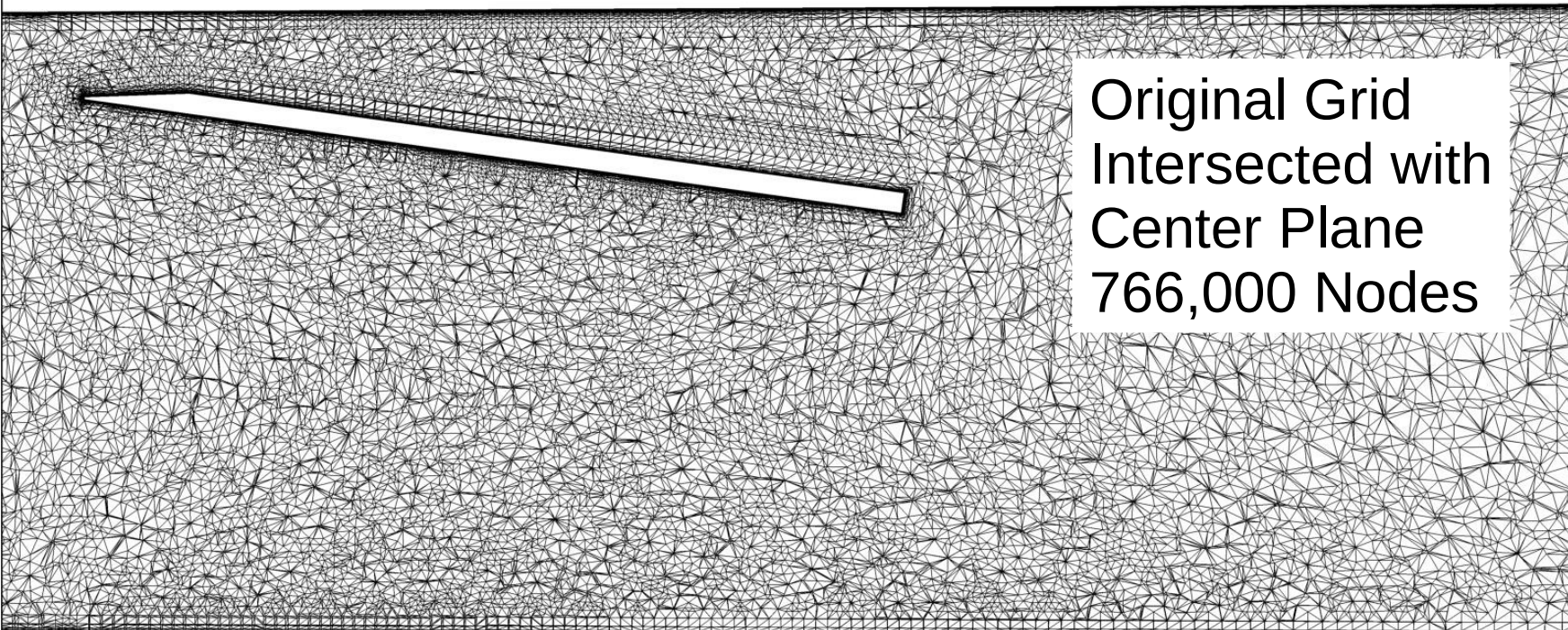


Original Grid
U-Velocity on
Center Plane



Adapted Grid
Intersected with
Center Plane
1,300,000 Nodes

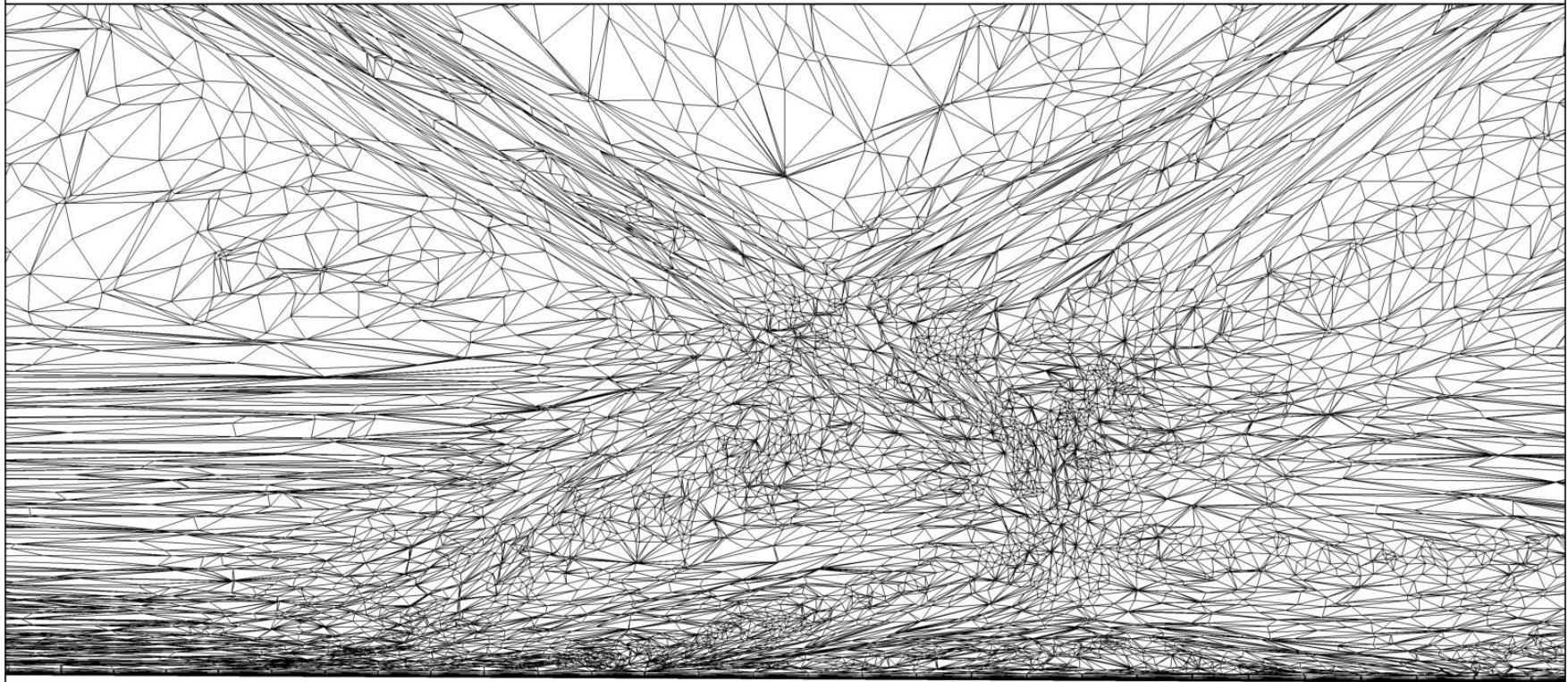
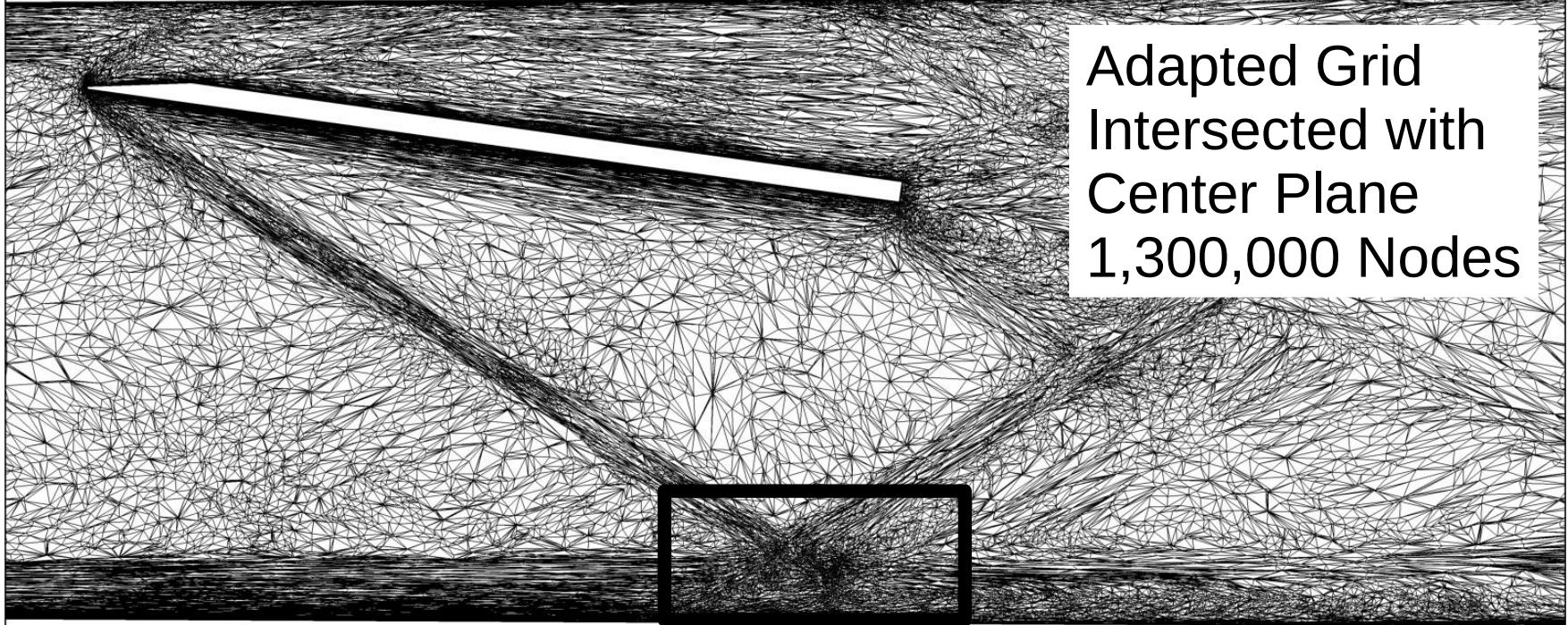
This visualization shows a highly refined, adaptive triangular mesh. The mesh is extremely dense in the regions immediately surrounding the airfoil, particularly in the leading edge and wake areas, where the flow gradients are highest. The density of the nodes decreases as the distance from the airfoil increases, following a structured, logarithmic-like decay. The airfoil itself is represented by a thick white line, and the background is filled with a complex pattern of small triangles.

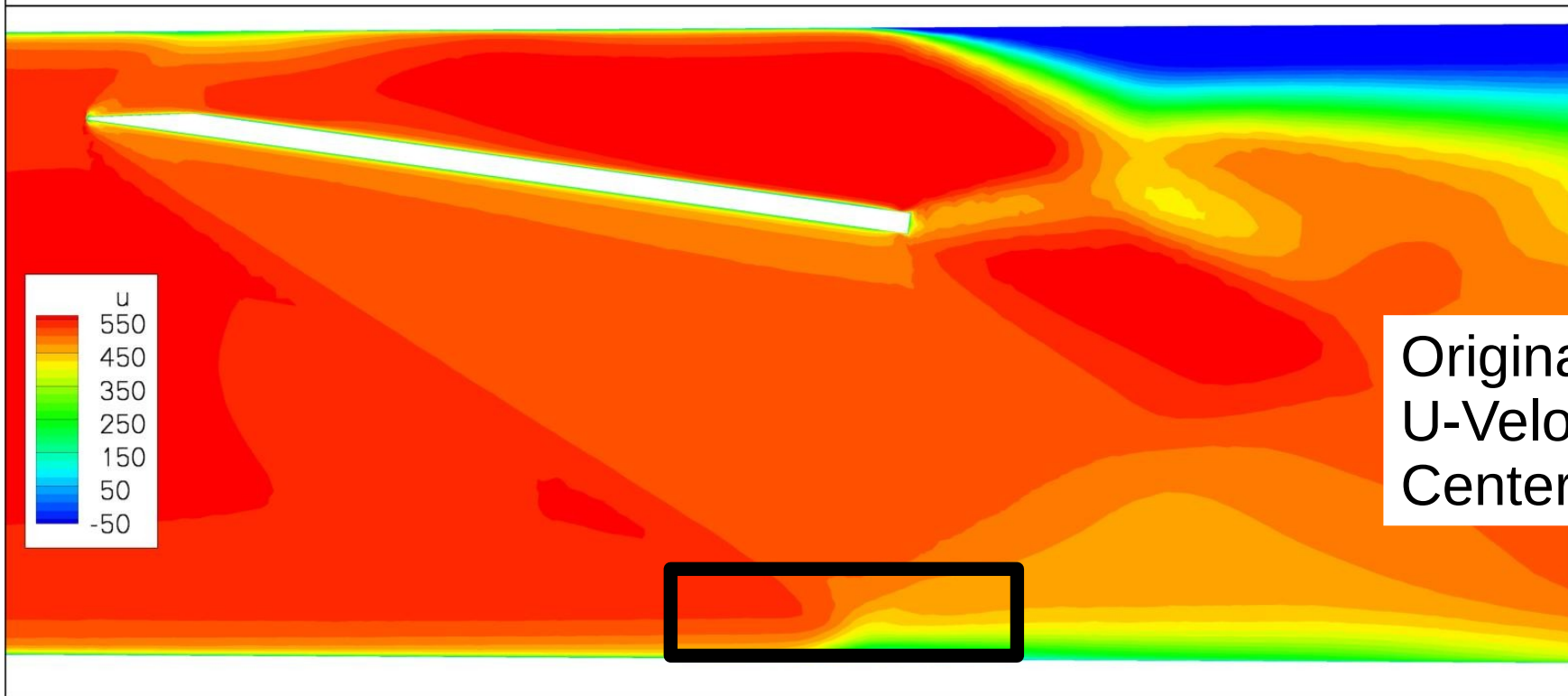
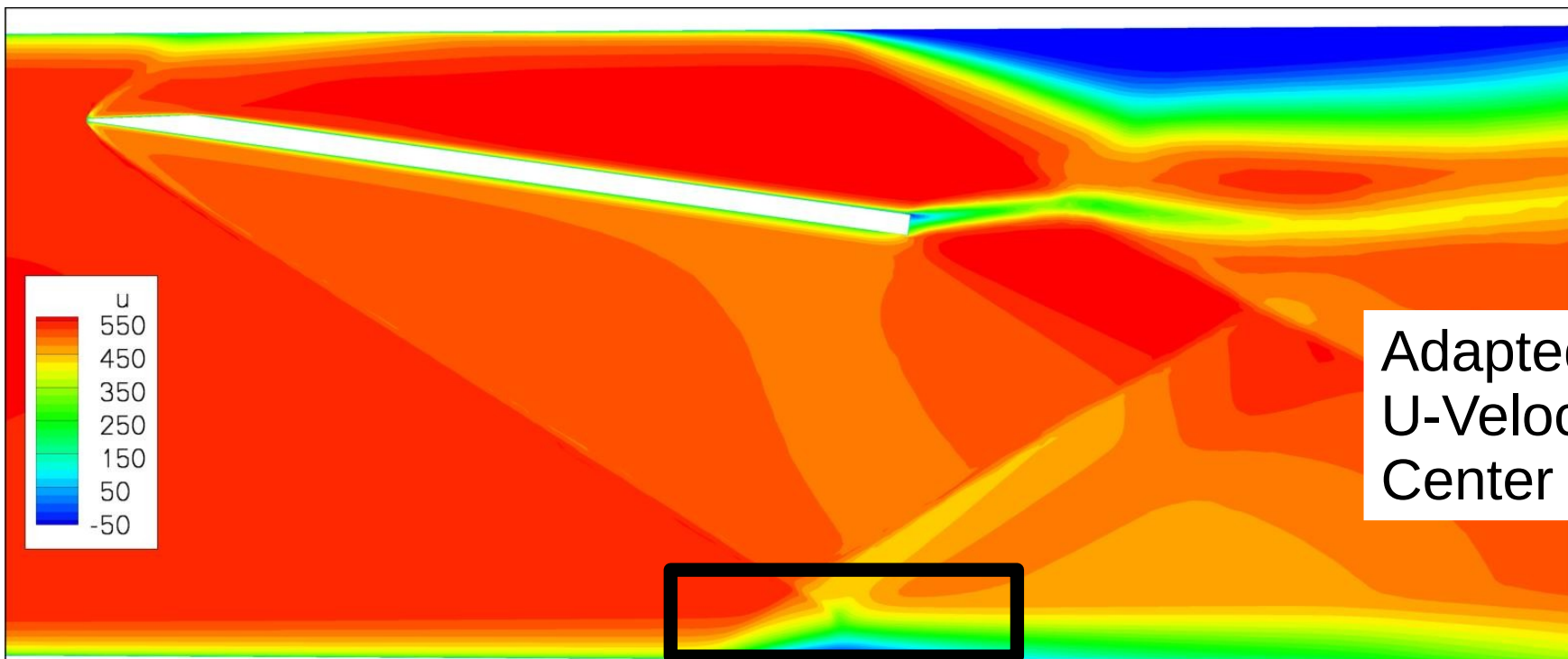


Original Grid
Intersected with
Center Plane
766,000 Nodes

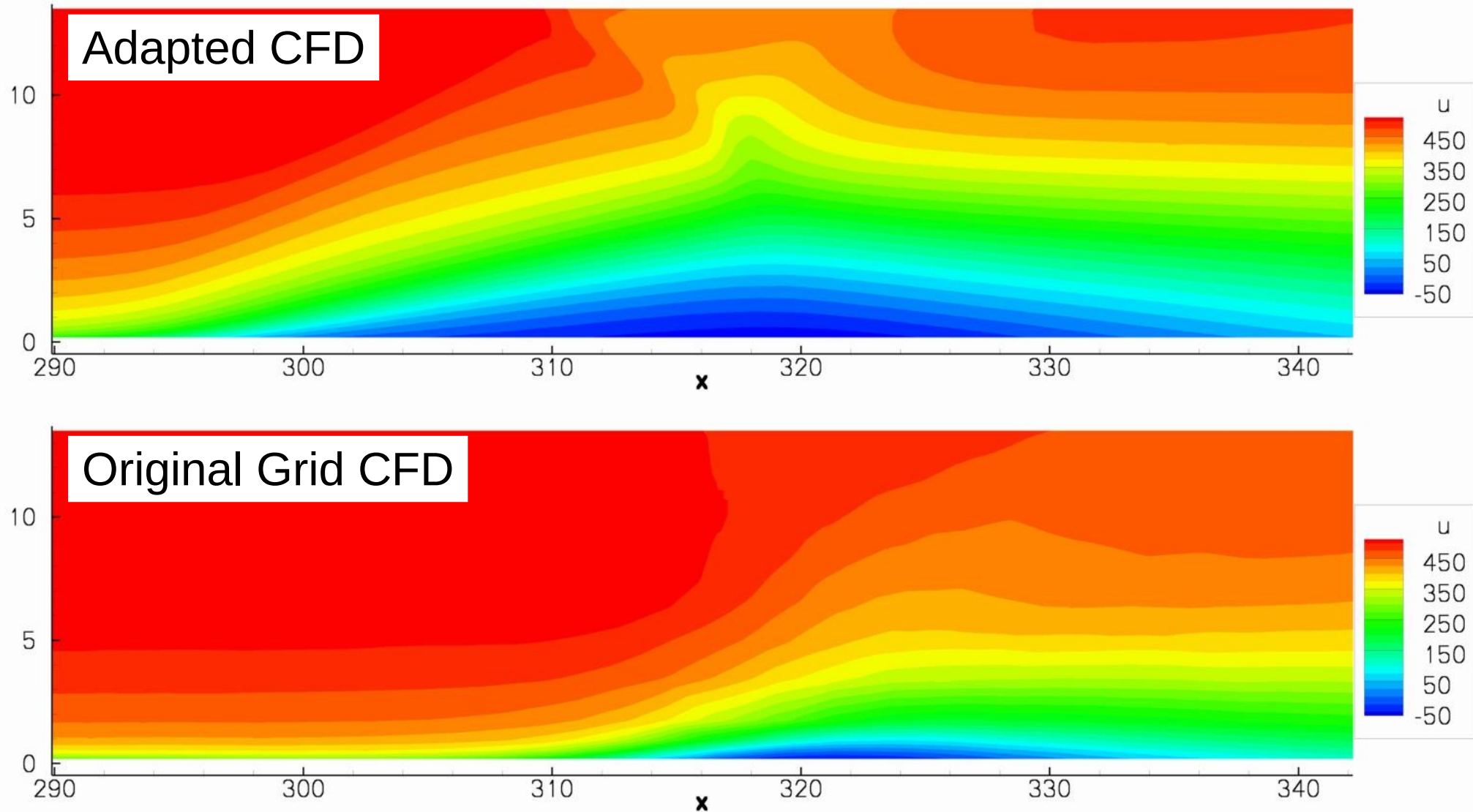
This visualization shows a coarser, more uniform triangular mesh compared to the adapted grid. The node density is lower overall, with fewer nodes concentrated in the high-gradient regions near the airfoil. The airfoil is again shown as a thick white line. The mesh is composed of larger triangles than the adapted grid, and the overall distribution is less refined, especially in the wake and near the leading edge.

Adapted Grid
Intersected with
Center Plane
1,300,000 Nodes

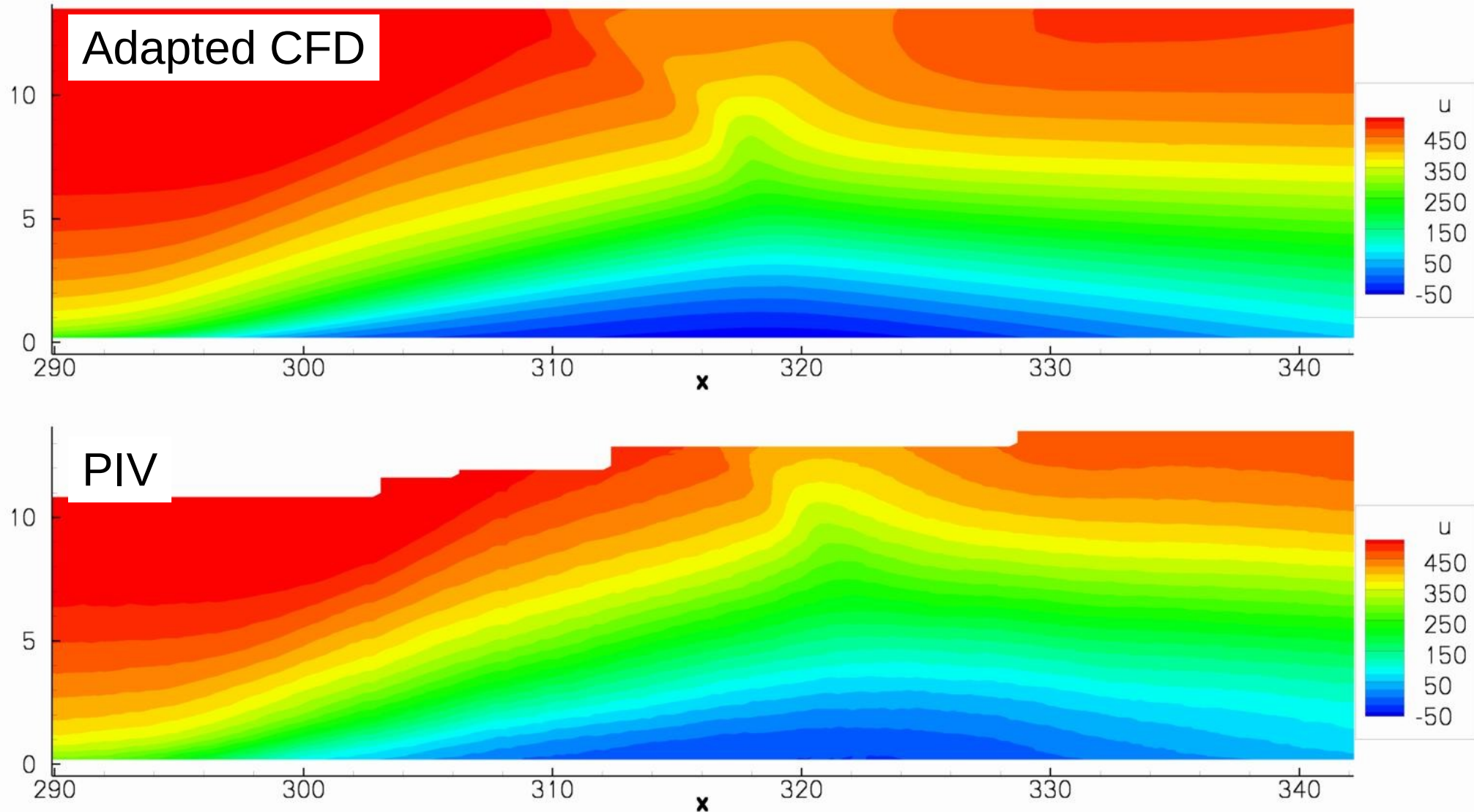




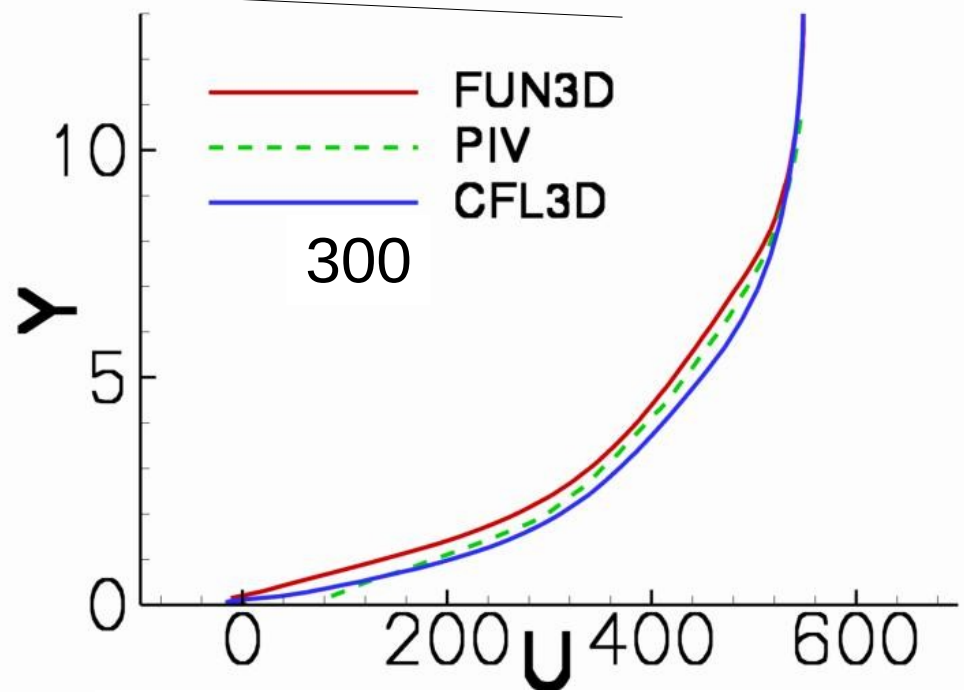
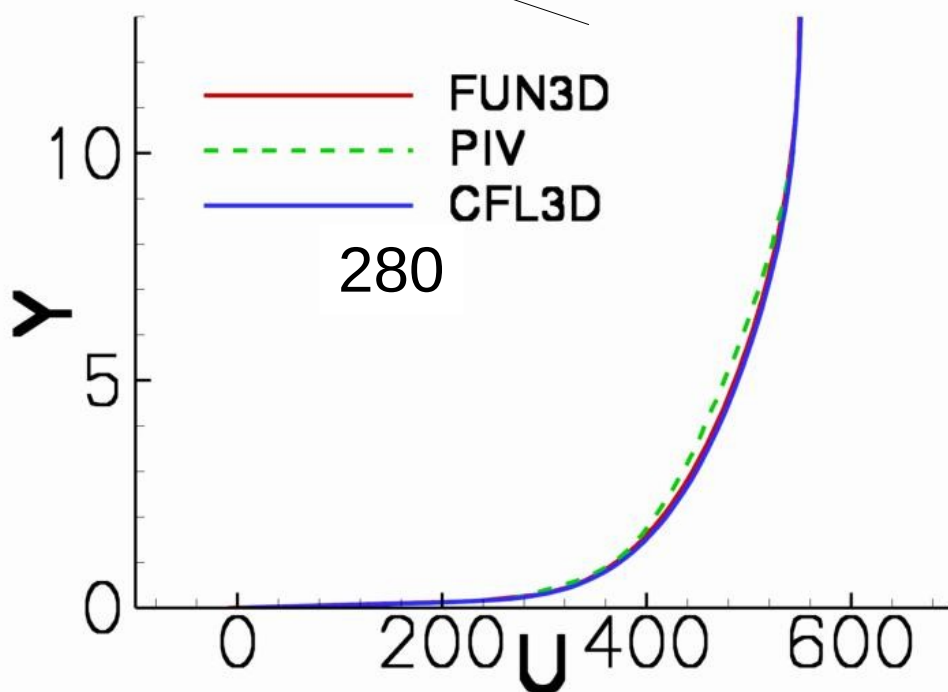
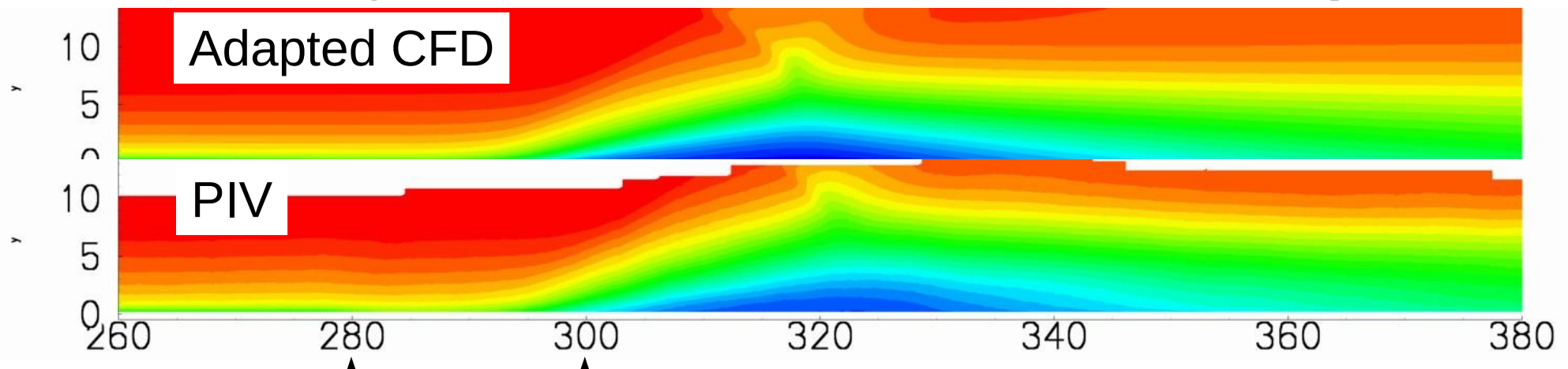
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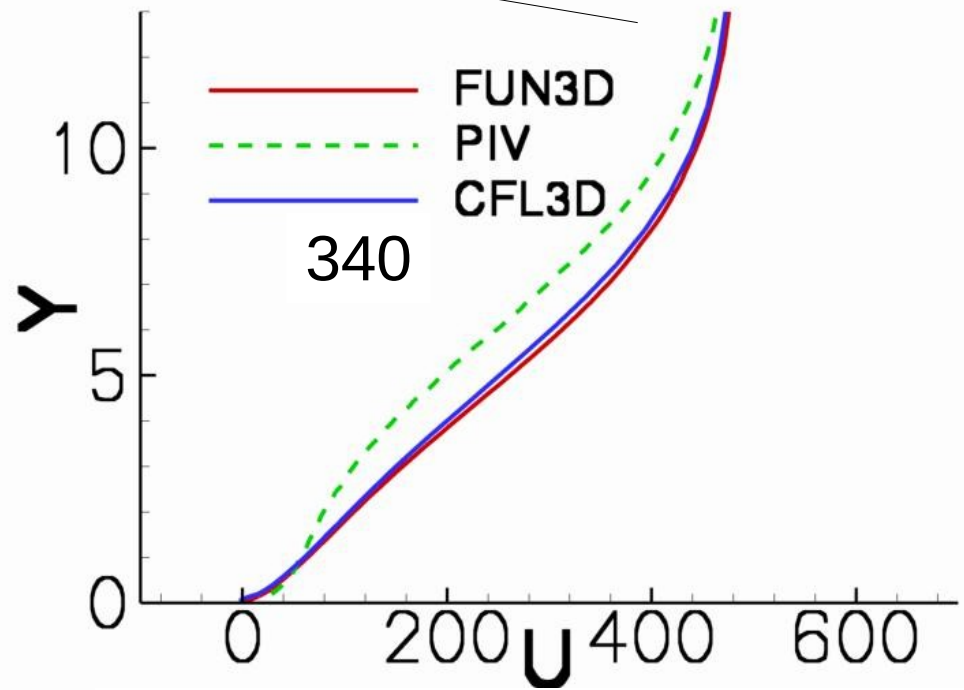
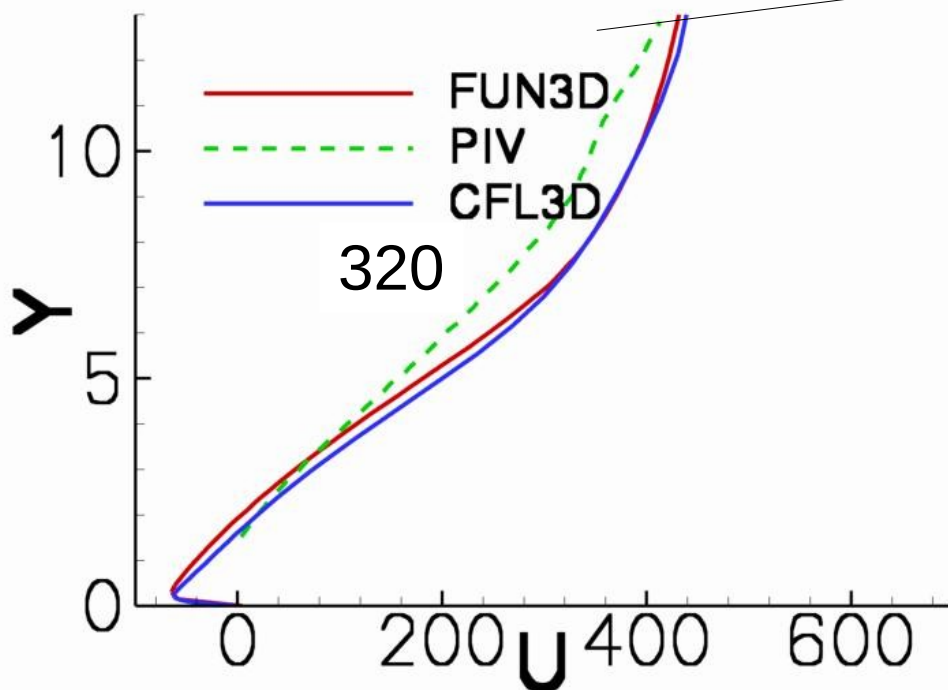
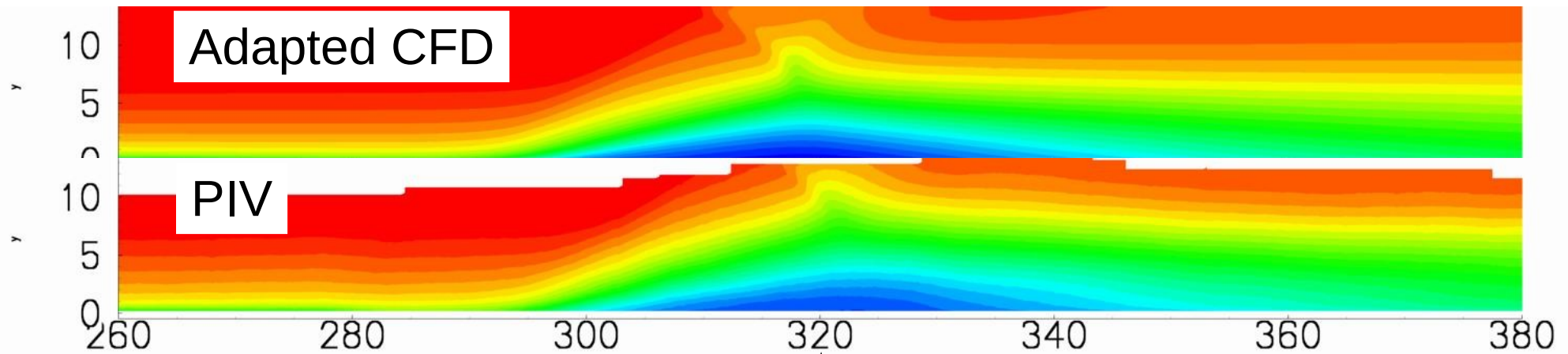
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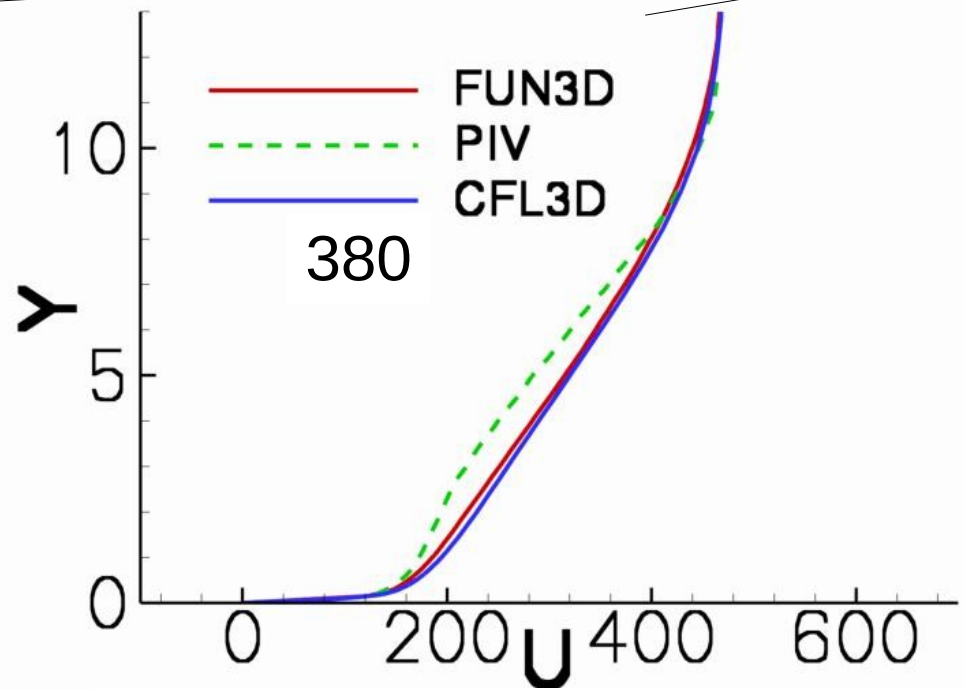
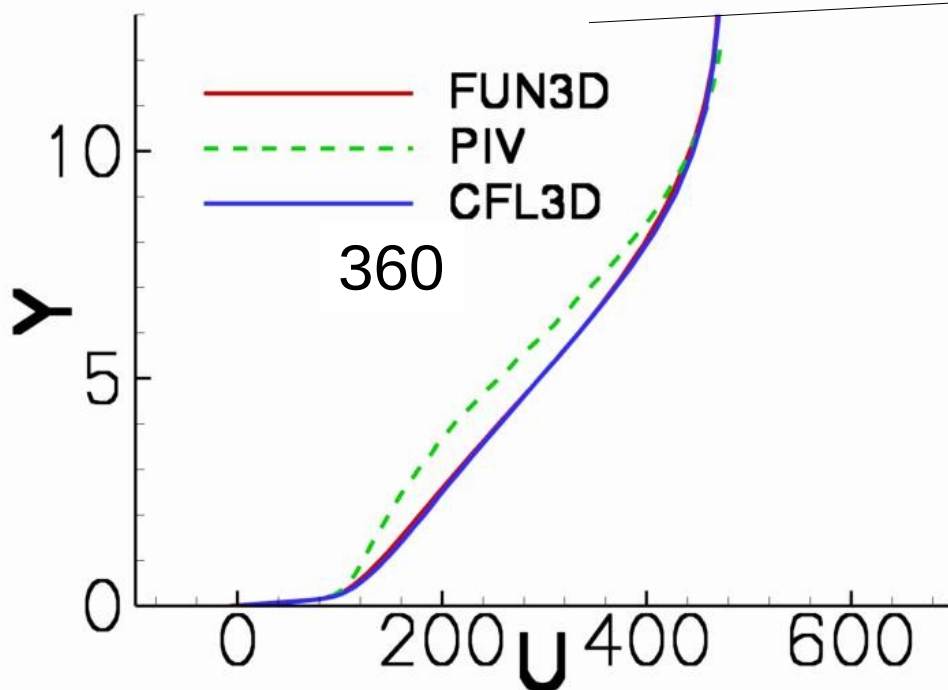
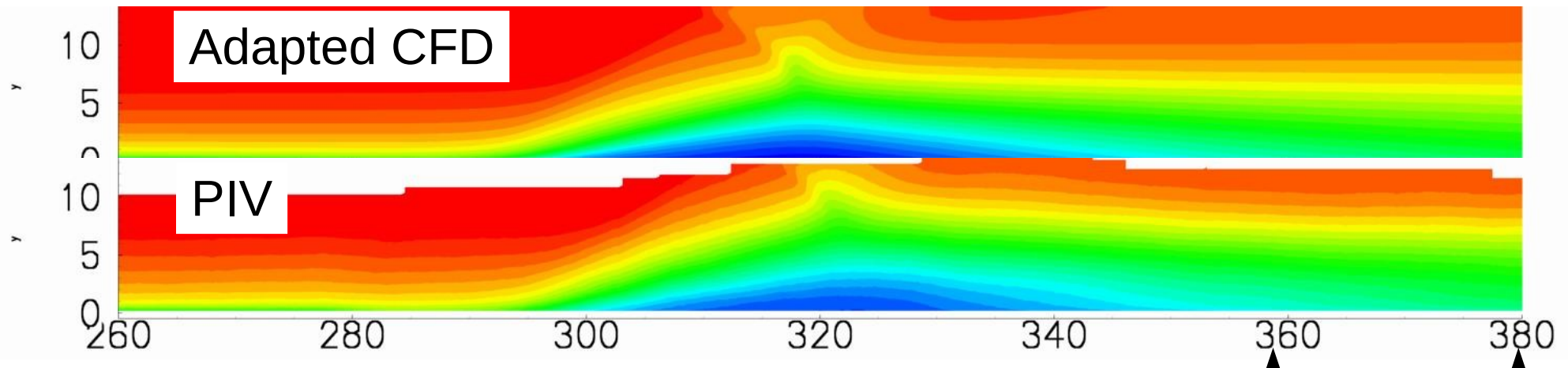
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AIAA Supersonic Shock-Boundary Layer Interaction Workshop



AIAA Supersonic Shock-Boundary Layer Interaction Workshop



Acknowledgments

- Susan Cliff: delta wing body surface grid
- Chris Rumsey: CFL3D on SBLIW example
- Jan-Renee Carlson: propulsion implementation
- Bil Kleb: supersonic retro-propulsion example
- FUN3D development team

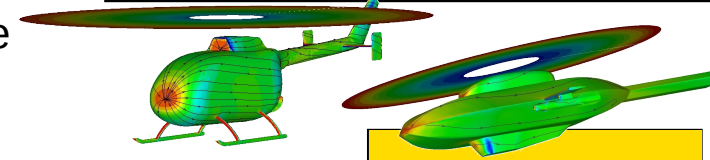
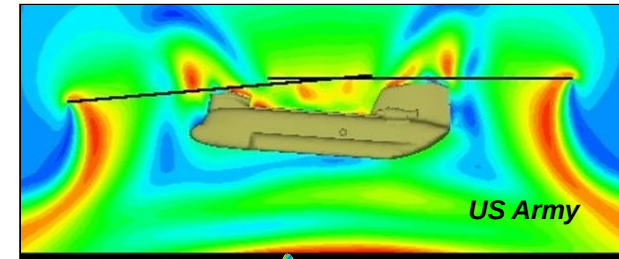
Future Work

- Element subdivision
 - Previous applications have been hindered without a robust error indicator
 - Preserve element shape for anisotropic prismatic and hexahedral boundary layer grids
 - Hierarchical
 - Time-accurate simulation
 - NRA with Steve Karman (University of Tennessee at Chattanooga)
- Viscous cut cell simulations

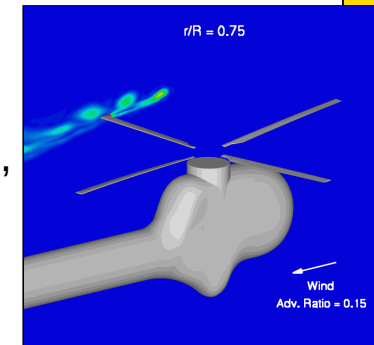
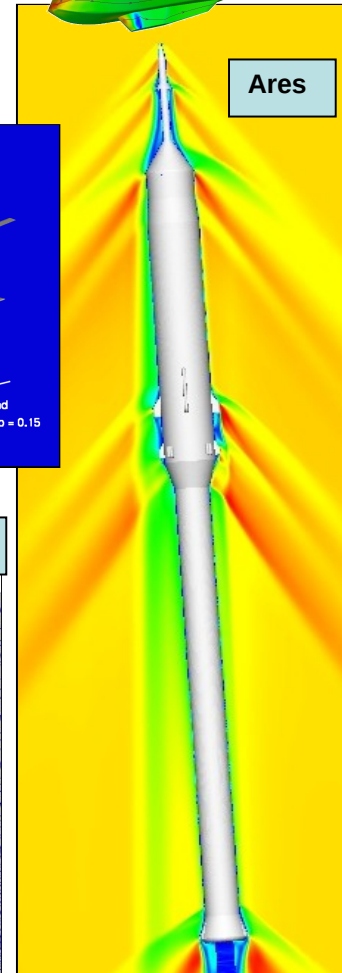
FUN3D Core Capabilities

<http://fun3d.larc.nasa.gov>

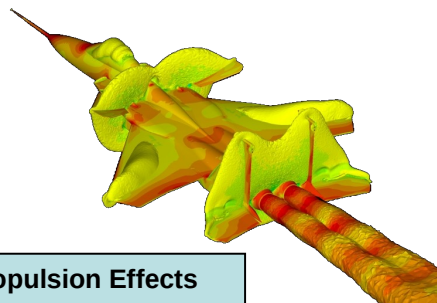
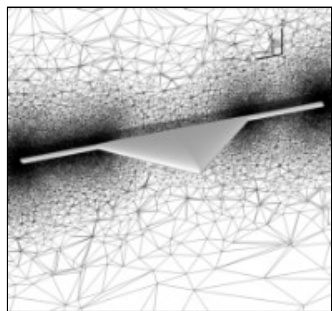
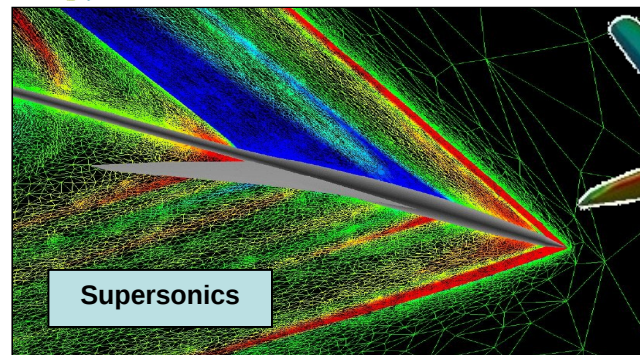
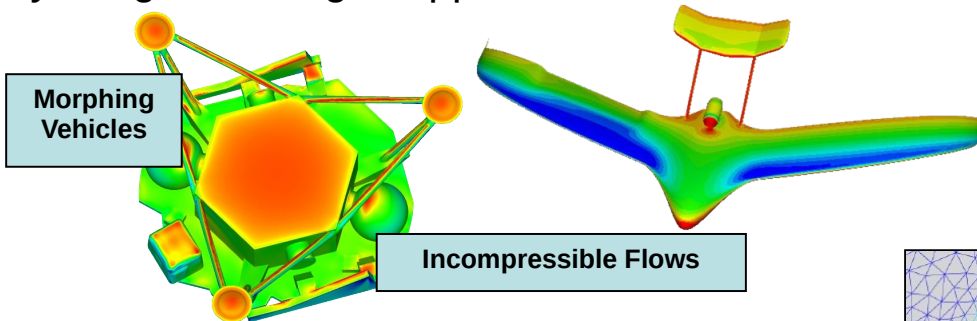
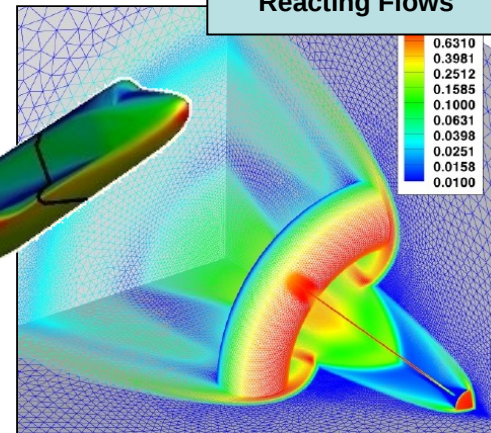
- **3D steady tetrahedral node-based RANS with SA turbulence model and adjoint for mesh adaptation**
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows; cell-centered schemes being investigated
- Used for numerous projects internal and external to NASA across the speed range
- General dynamic mesh capability: any combination of rigid/overset/morphing grids, including 6-DOF effects
- Aeroelastic modeling w/ mode shapes, full FEM, CC, etc
- Constrained/multipoint adjoint-based design and mesh adaptation
- Modern software practices including 24/7 testing
- Linear scaling through thousands of cores
- Capabilities fully integrated, large support team, online documentation, tutorials, etc



Rotorcraft



Reacting Flows



Propulsion Effects