Adjoint-Based Mesh Adaptation and Shape Optimization for Simulations with Propulsion

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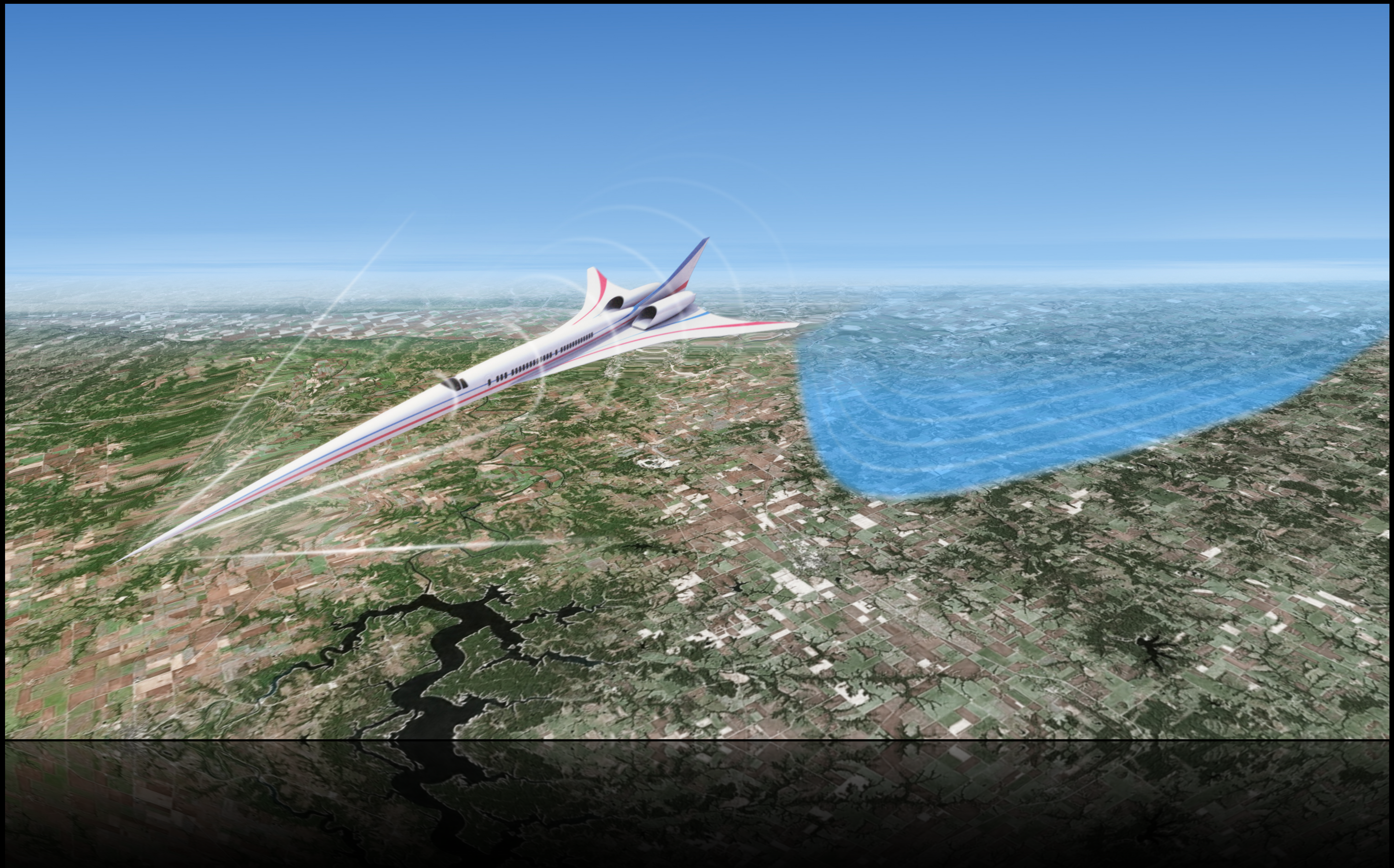
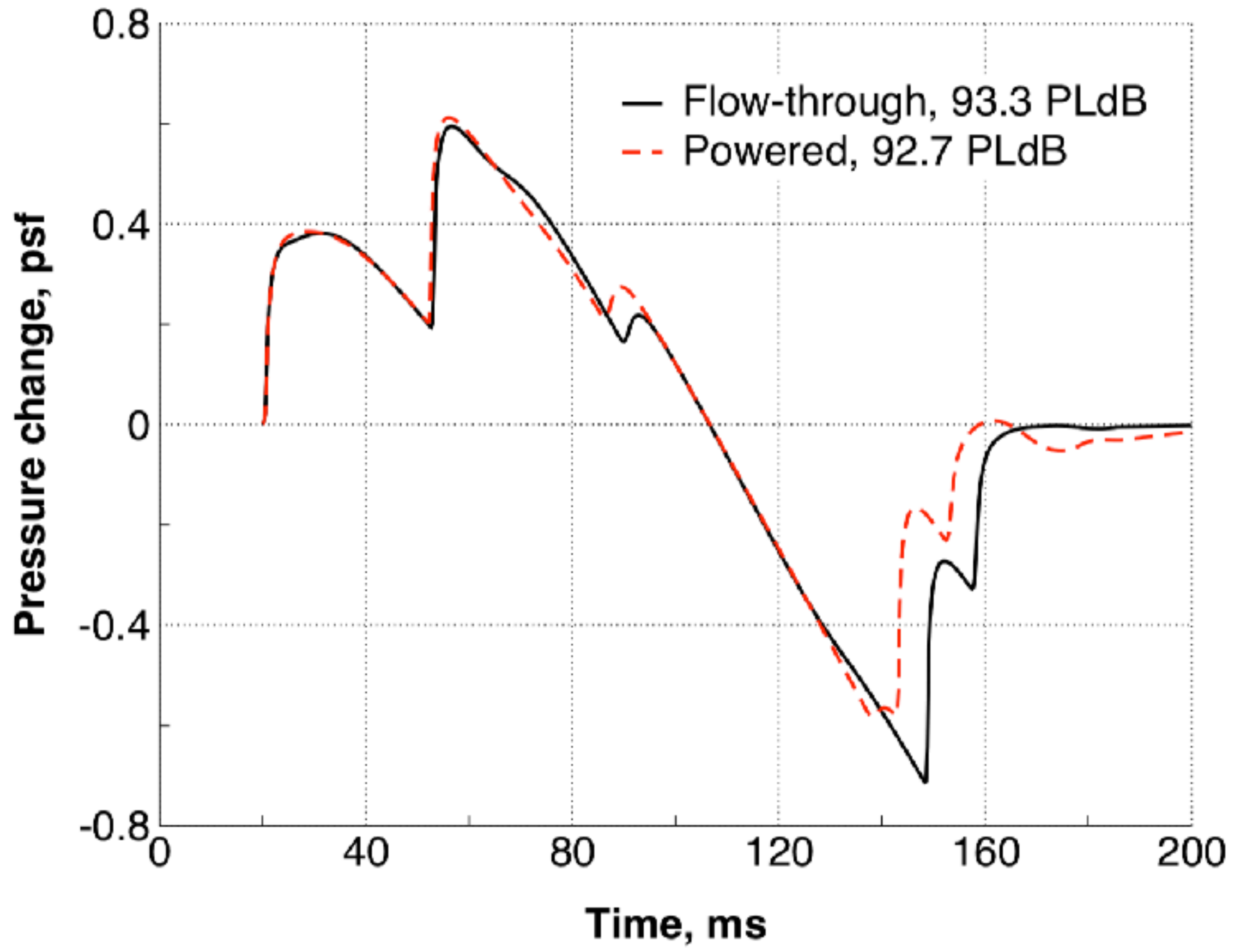
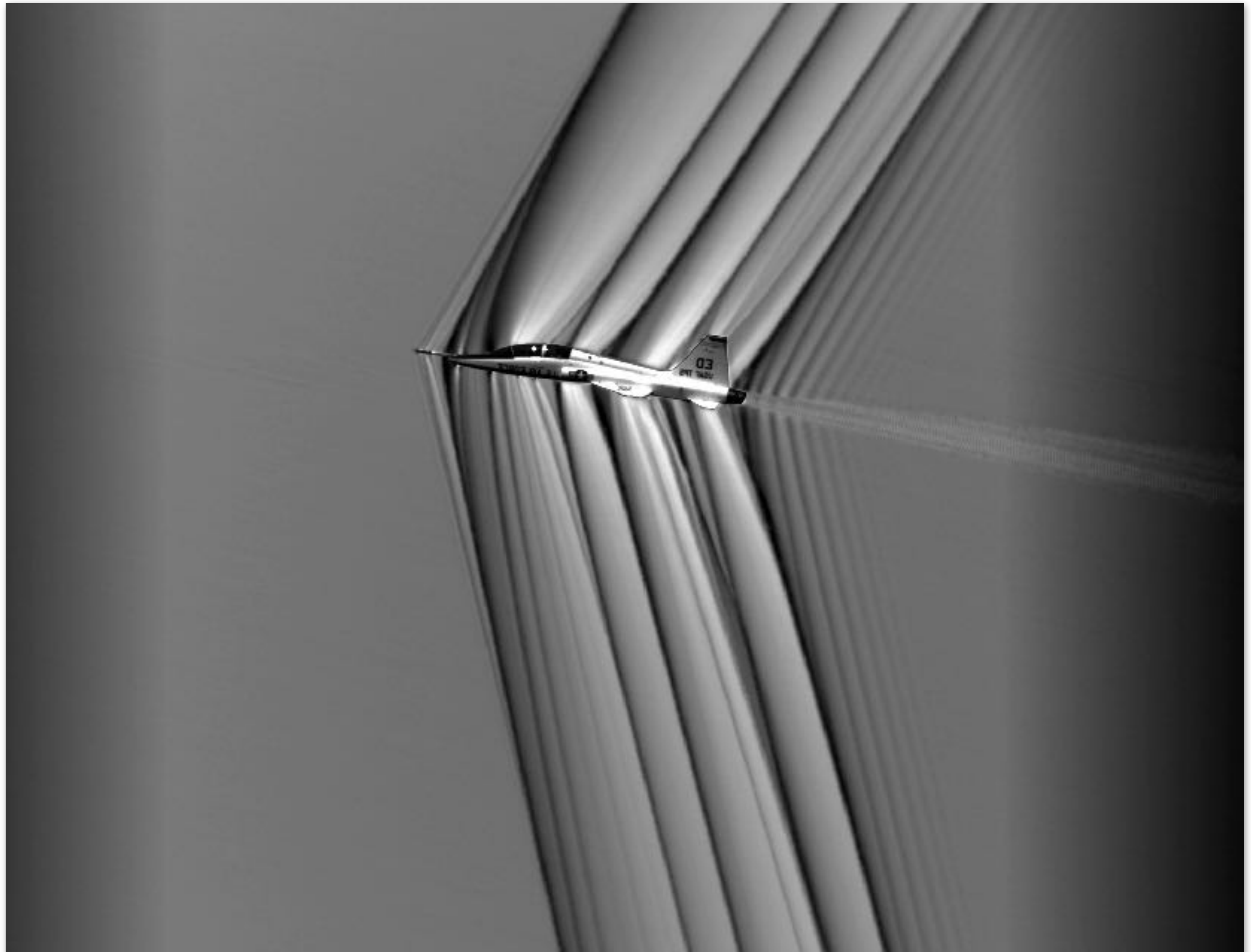


Commercial Supersonic Technologies III
2019 AIAA Aviation Forum
June 20, Dallas, TX

Motivation



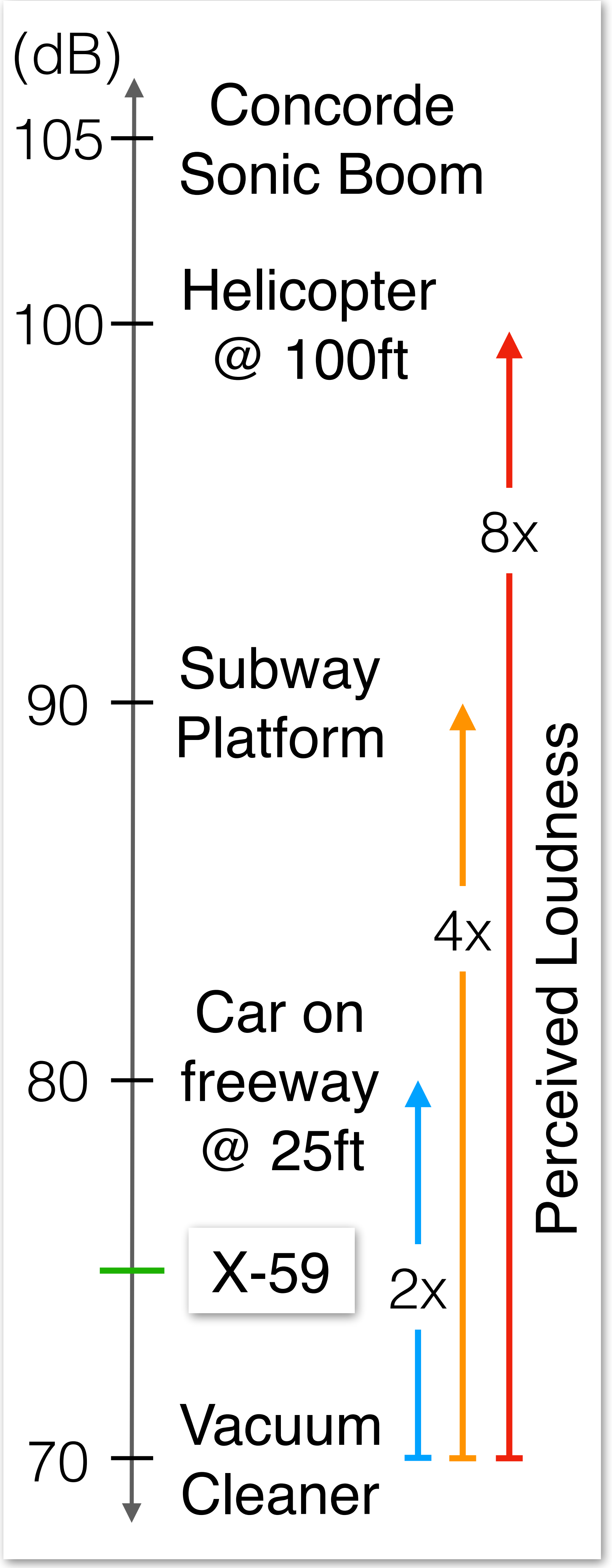
Ground pressure signature from a low drag business jet concept, M=1.5 (Wintzer et. al., NASA)

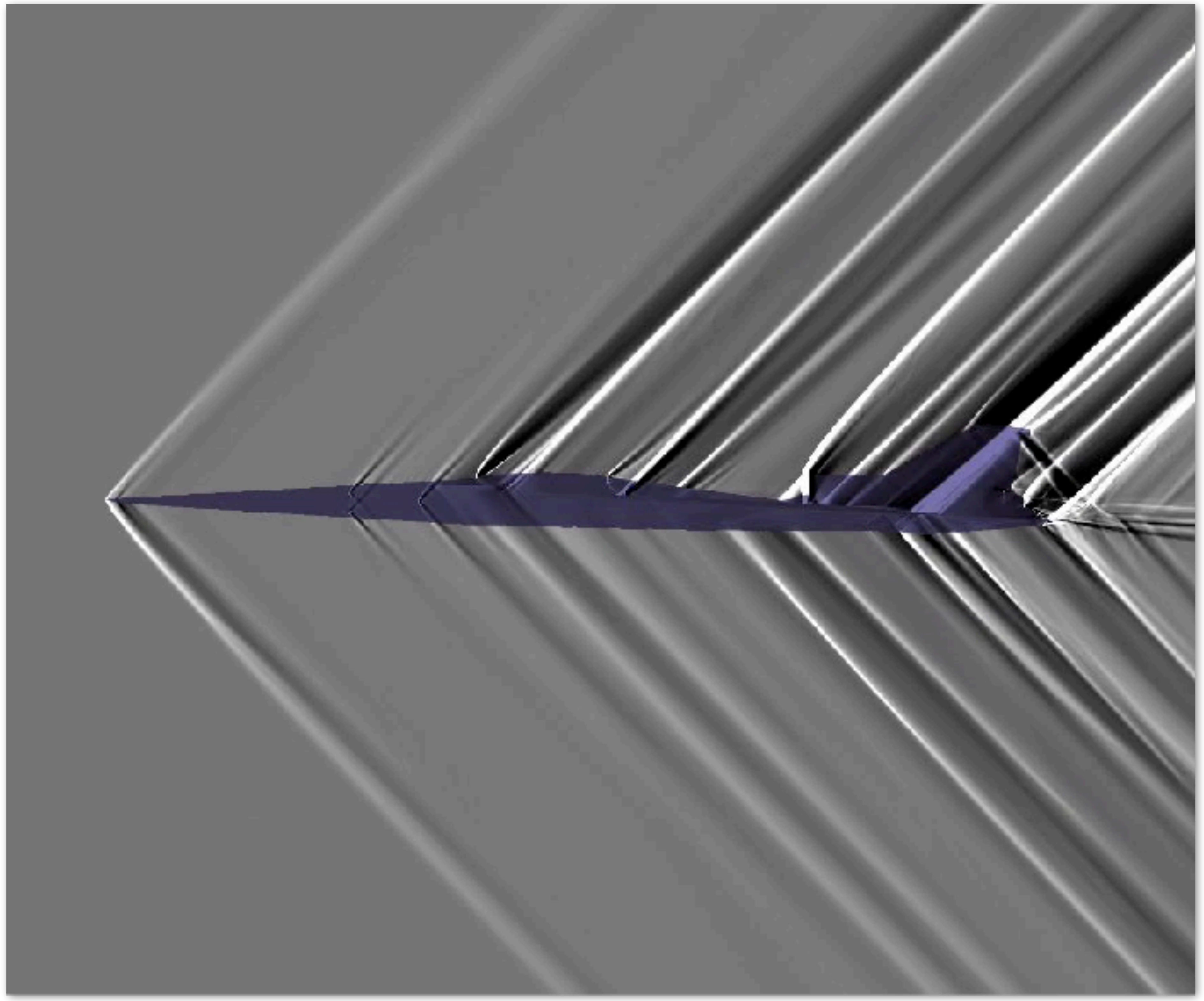


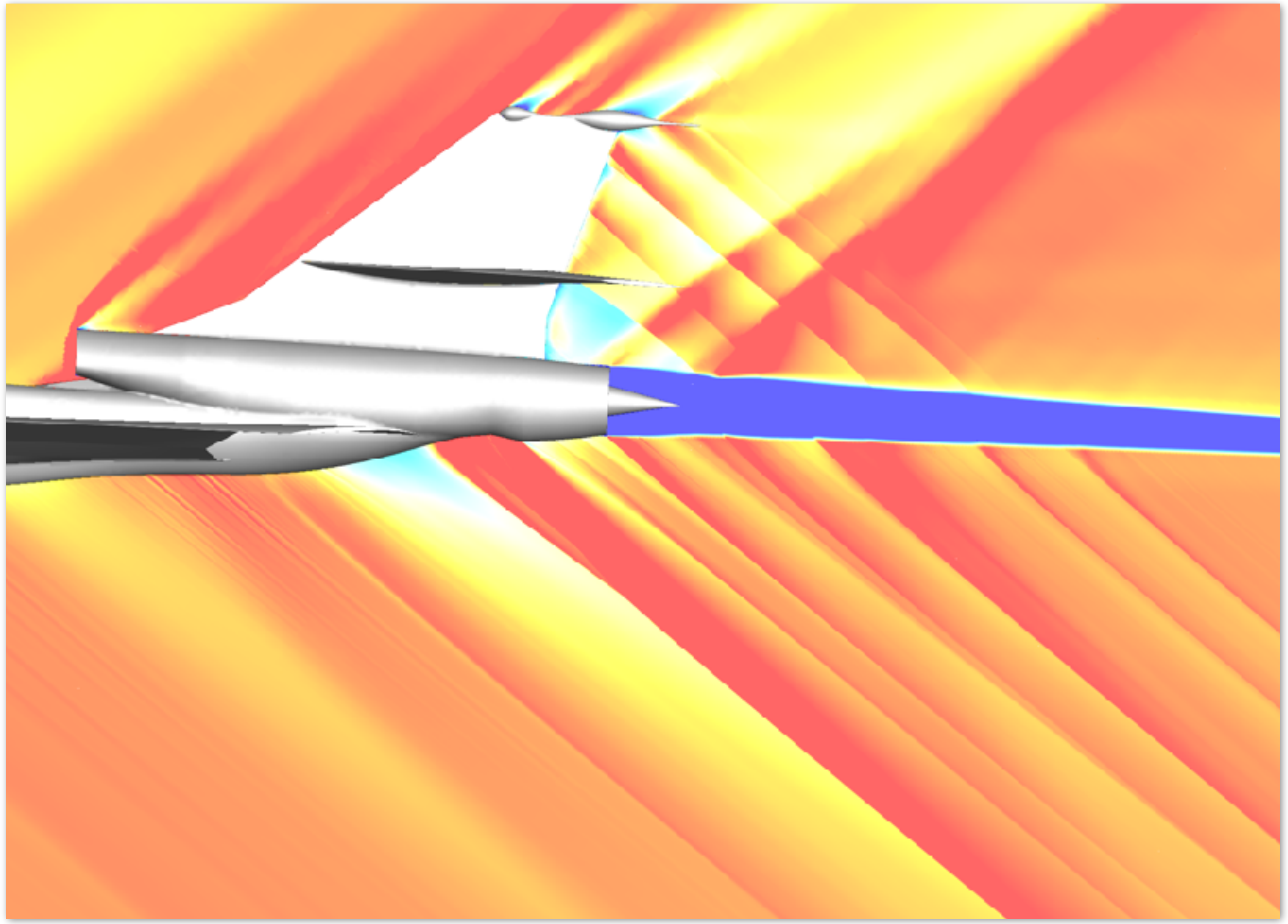
Schlieren of a supersonic T-38 (Heineck et. al., NASA)

Propulsion effects are secondary when loud sonic-booms are acceptable

Low Sonic-Boom Design







- Shaped pressure signature below aircraft: many shocks, but weaker and of similar strength
- Significant influence of inlet and nozzle exhaust: aft layout critical
- Mass flow rate, stagnation pressure recovery and flow distortion important parameters

Objectives

Reliable evaluation of mass flow rates through permeable boundaries

- Estimate and control discretization error
- Consider both computational domain outflow and inflow
- Applicable to simulating propulsion-system effects, as well as secondary flow paths
- Explore feasibility of handling more general outputs at domain boundaries

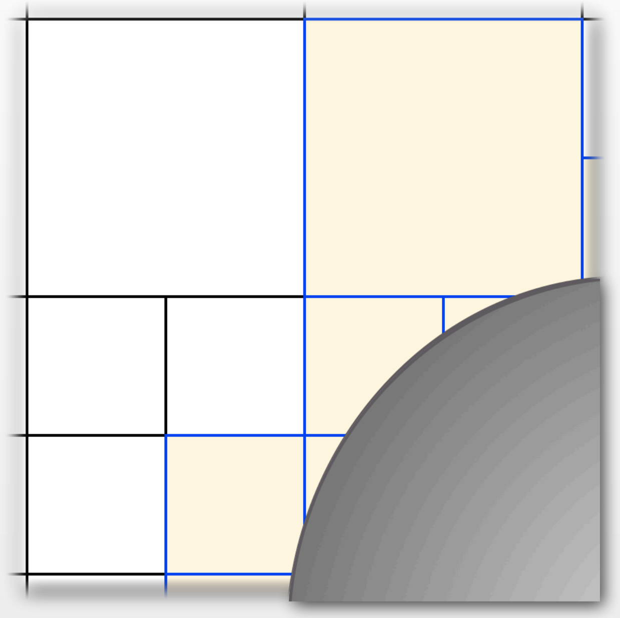
Design optimization subject to mass-flow-rate constraints

- Improve aerodynamic performance and reduce noise due to sonic boom
- Control discretization error in design space to improve confidence in final designs

Approach & Background

Flow Simulation

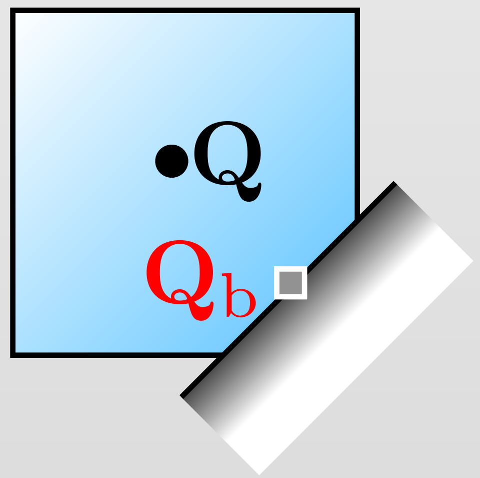
- Steady Euler equations, perfect gas
- Cartesian mesh with cut cells
- Second-order, finite-volume discretization
  - van Leer flux vector splitting
- RK4 with local time stepping, multigrid, and parallel computing



$$R_H(\mathbf{Q}_H) = 0$$

Wall Boundary Conditions

- Weakly enforced: form flux across boundary from boundary state
  - Slip wall: $U_\mathrm{n} = 0$
  - Permeable wall: $U_\mathrm{n} \neq 0$

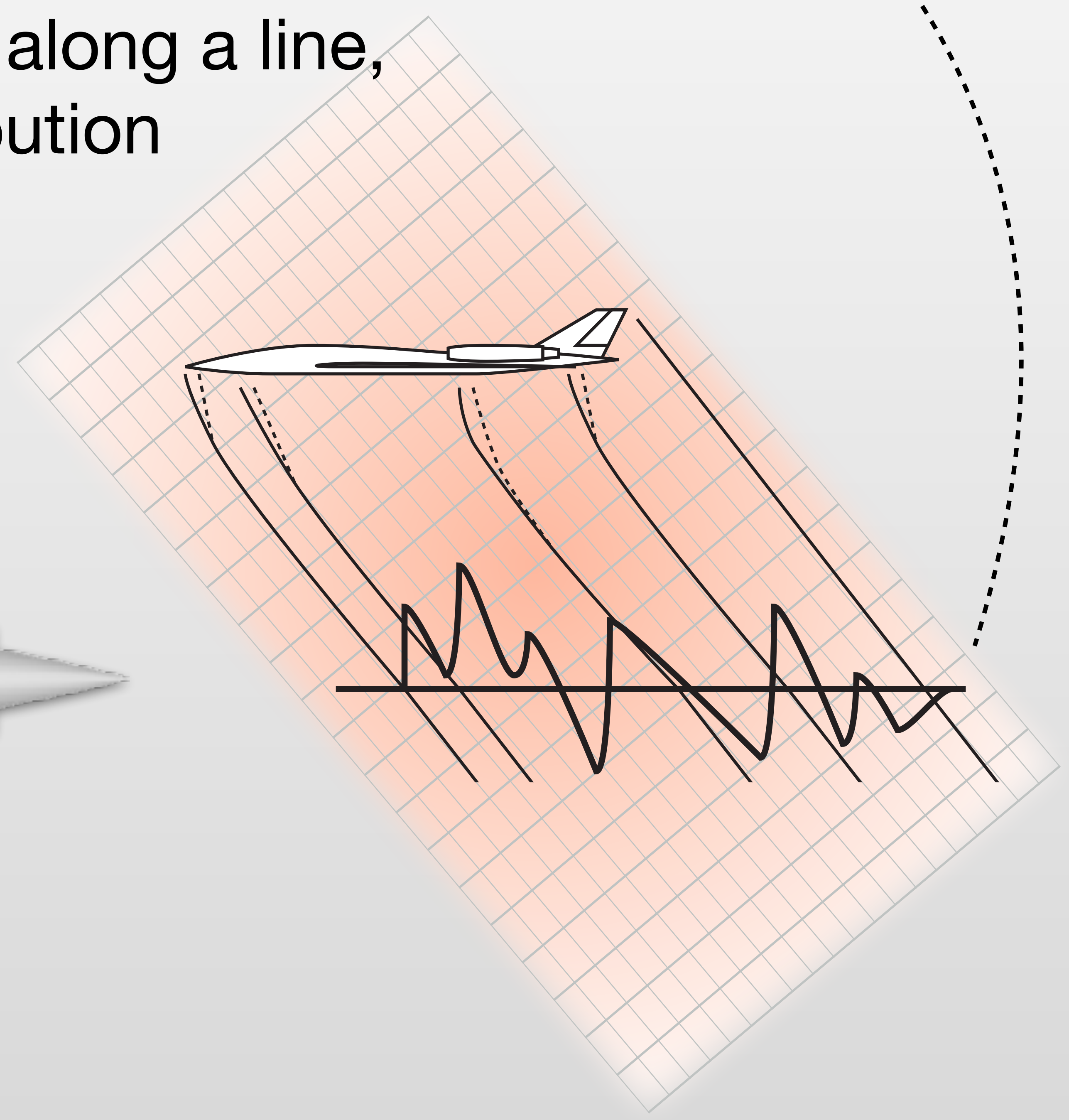


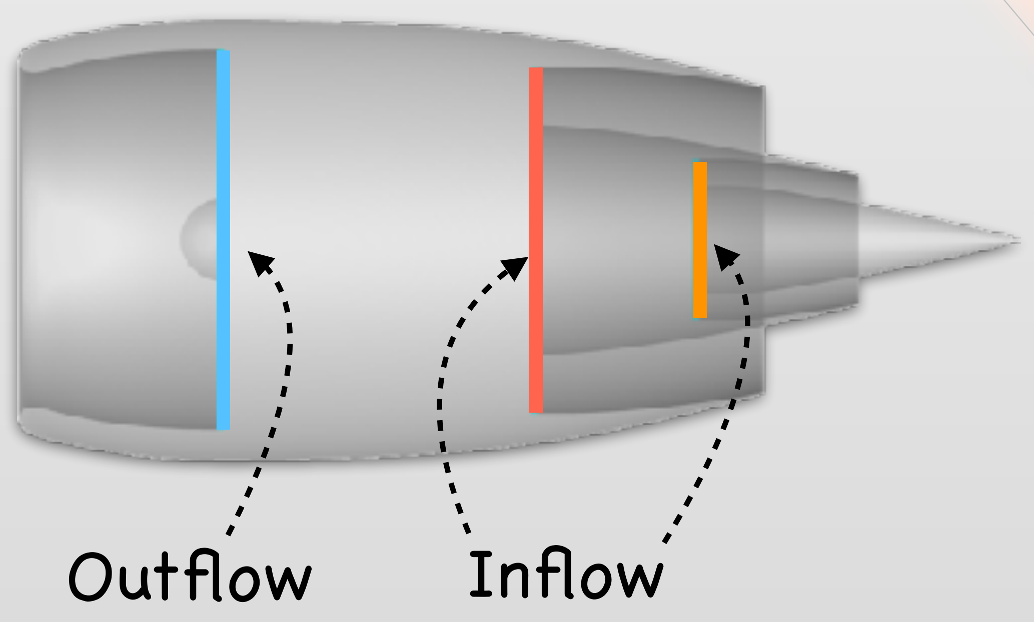
$$F \cdot \hat{n} = [0, p\,\hat{n}, 0]^\mathrm{T}$$

Outputs of Interest

- Aerodynamic force and moment coefficients
- Pressure at a point or along a line, equivalent area distribution
- Mass flow rates

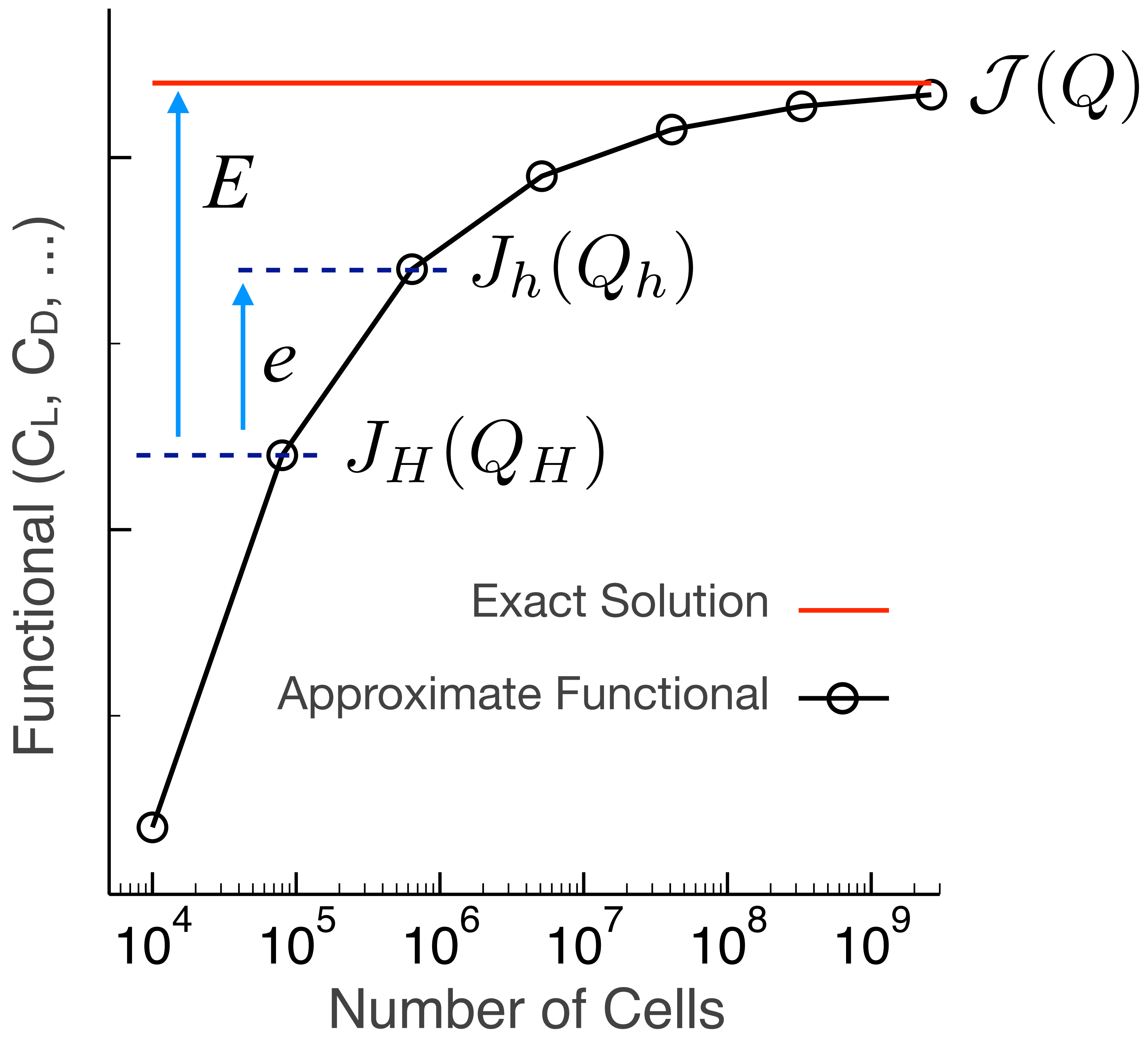
$$J_H(Q_H)$$

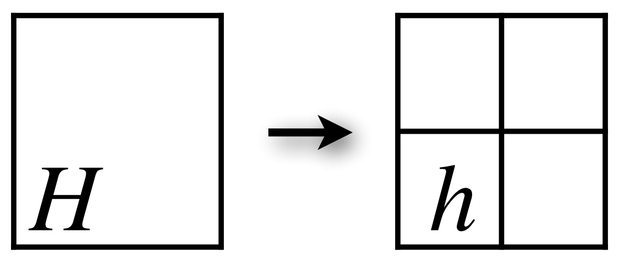




$$J_{\dot{m}} = \int_{\mathcal{B}} \rho U_\mathrm{n} dA$$

Method of Adjoint Weighted Residuals





- Goal is to compute relative error

$$e = |J_h - J_H|$$

- Then use asymptotic analysis to estimate total discretization error

$$E = \left(1 + \frac{1}{r^p - 1}\right) e$$

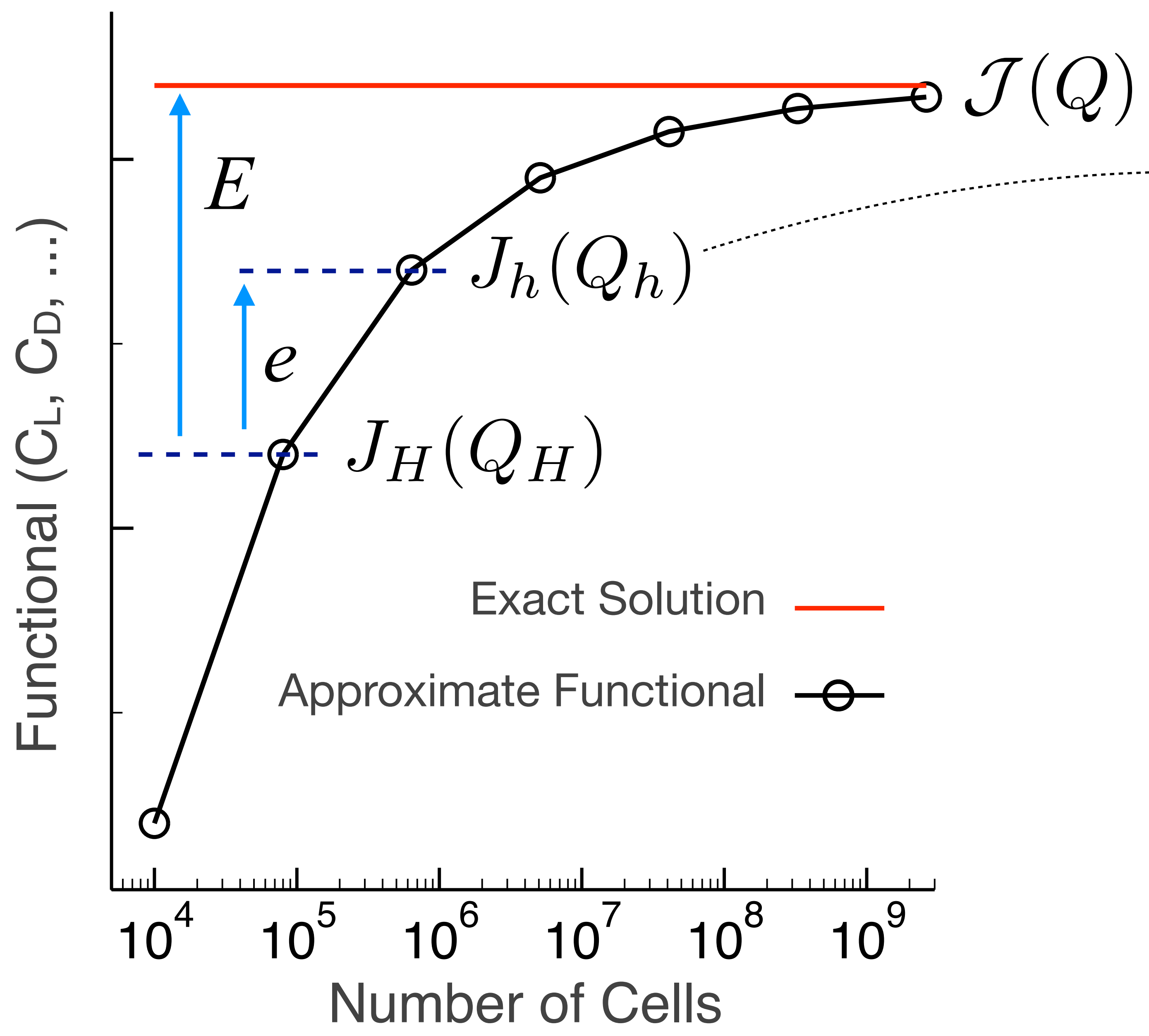
Refinement Ratio (r)   Order (p)

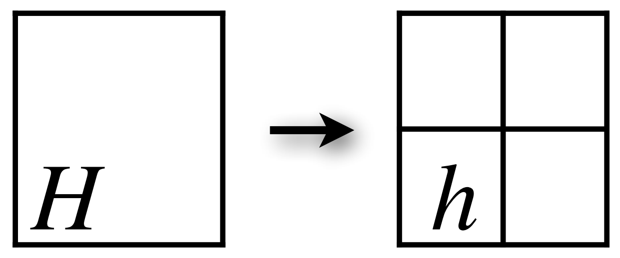
- Key step is to reliably estimate

$$J_h(\mathbf{Q}_h)$$

without solving on the fine mesh

Method of Adjoint Weighted Residuals





Linearize discrete flow residual and functional to obtain:

$$J_h(\mathbf{Q}_h) \approx J_h(\mathbf{Q}_h^H) - (\boldsymbol{\psi}_h^H)^{\mathrm{T}} \mathbf{R}_h(\mathbf{Q}_h^H) - (\boldsymbol{\psi}_h - \boldsymbol{\psi}_h^H)^{\mathrm{T}} \mathbf{R}_h(\mathbf{Q}_h^H)$$

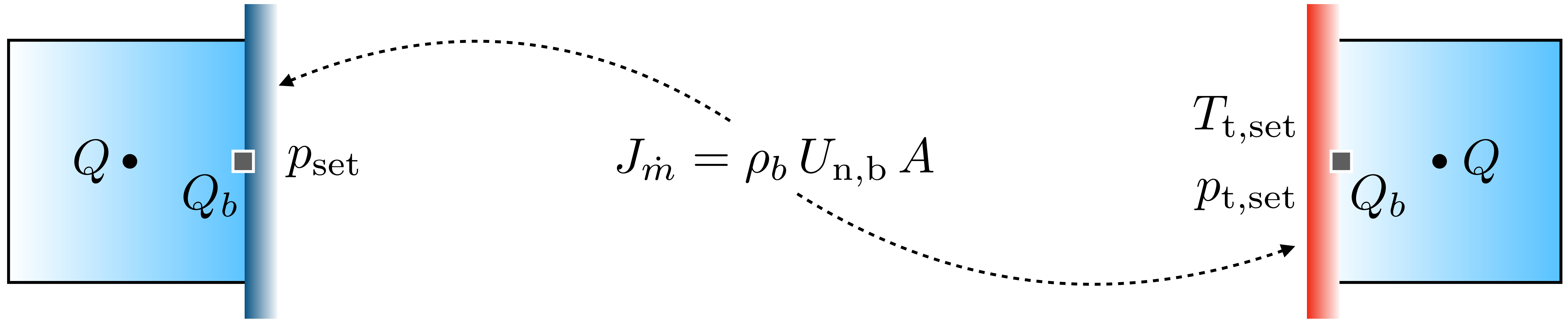
Adjoint equation:

$$\left[\frac{\partial \mathbf{R}_H(\mathbf{Q}_H)}{\partial \mathbf{Q}_H}\right]^{\mathrm{T}} \boldsymbol{\psi}_H = \frac{\partial J_H(\mathbf{Q}_H)}{\partial \mathbf{Q}_H}^{\mathrm{T}}$$

- Large linear system
- Defined by the discrete flow residual and functional
  - Includes all boundary conditions
- Converges to continuous adjoint equation in the fine mesh limit
  - Adjoint inconsistent formulations can generate spurious oscillations near the wall

Adjoints of Permeable Boundary Conditions

- Formulation assumes subsonic flow at boundary and uses one-dimensional Riemann invariants



Subsonic Outflow

- Suitable for engine inlets, ECS intakes, secondary flow paths
- Specify exit pressure, all other quantities come from interior

$$Q_b = \begin{bmatrix} \rho_b \\ U_{\text{n,b}} \\ U_{\text{t,b}} \\ p_{\text{set}} \end{bmatrix}$$

Subsonic Inflow

- Suitable for nozzle plenums, turbines, ECS vents
- Specify stagnation temperature and stagnation pressure

$$Q_b = \begin{bmatrix} \rho_b \\ U_{\text{n,b}} \\ 0 \\ p_b \end{bmatrix}$$

Adjoints of Permeable Boundary Conditions

Subsonic Outflow

$$Q_b = \begin{bmatrix} \rho_b \\ U_{\mathrm{n,b}} \\ U_{\mathrm{t,b}} \\ p_{\mathrm{set}} \end{bmatrix}$$

Subsonic Inflow

$$Q_b = \begin{bmatrix} \rho_b \\ U_{\mathrm{n,b}} \\ 0 \\ p_b \end{bmatrix}$$

$$\left(\frac{\partial \mathbf{F}_b}{\partial \mathbf{Q}_b} \frac{\partial \mathbf{Q}_b}{\partial \mathbf{Q}} \right)^{\mathrm{T}} \psi = \frac{\partial J_{\dot{m}}}{\partial \mathbf{Q}}^{\mathrm{T}}$$

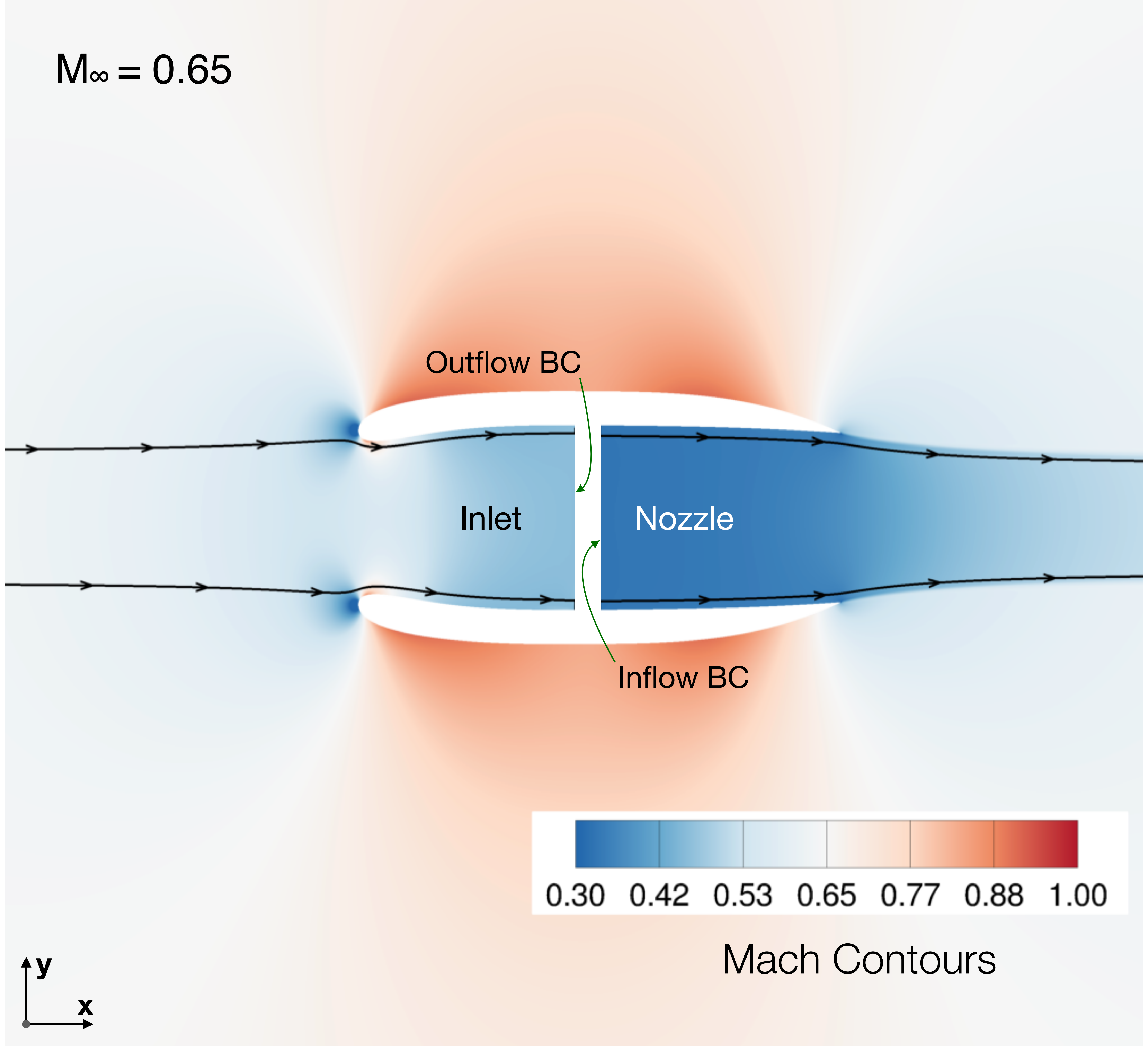
- Rank deficient matrix (rank three in 2D)
- Restricts choice of functionals on RHS to obtain a nonsingular system
  - Mass flow rate output involves 3 free parameters that match matrix rank, preliminary analysis indicates that the adjoint system is well-posed
  - Similar to slip-wall, where output must be a function of pressure because matrix is rank one
  - Perform numerical study to examine near wall adjoint solution

Numerical Study: Near-Wall Adjoint Solutions

- Subsonic, two-dimensional nacelle test case
- Specify exit pressure at the outflow of the inlet
- Specify stagnation temperature and pressure at the inflow of the nozzle
- Slip-wall boundary conditions everywhere else on the wetted surface
- Farfield is ~10 chords away

Test Cases

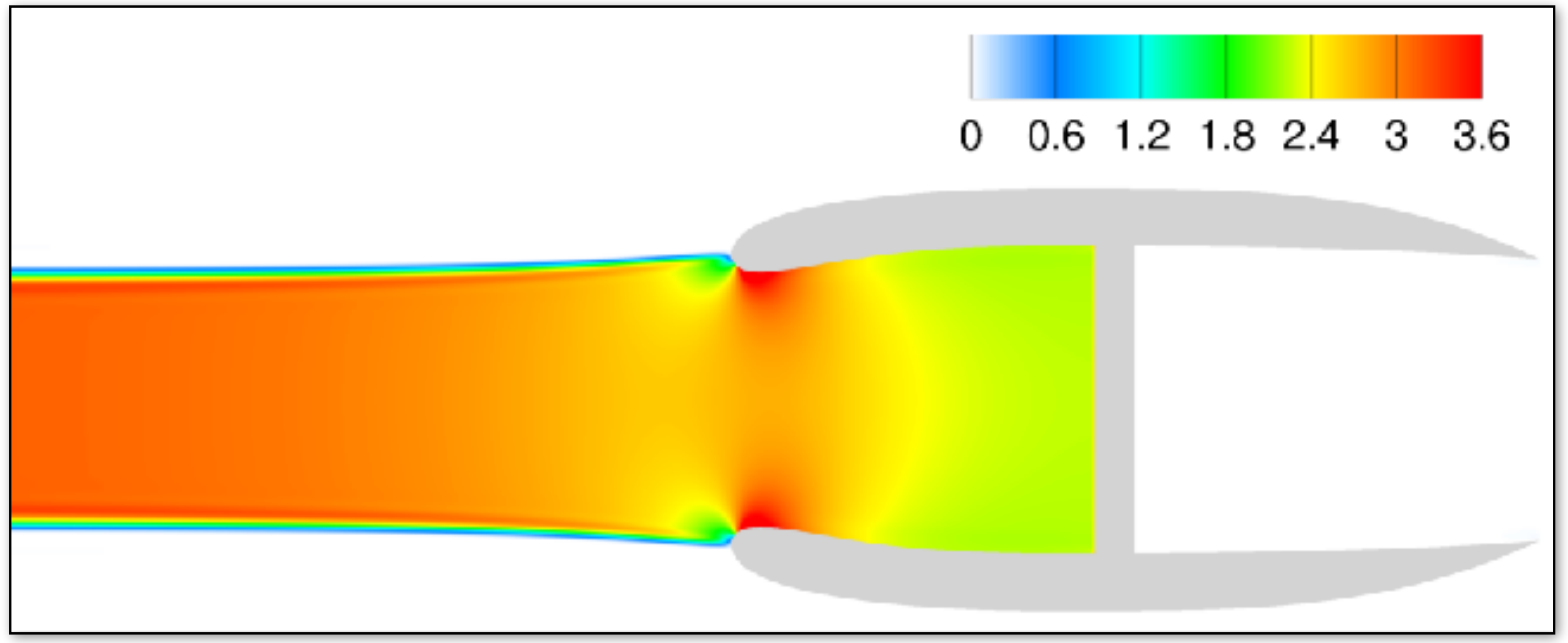
1. Measure mass flow rate at the outflow of the inlet
2. Measure mass flow rate at the inflow of the nozzle

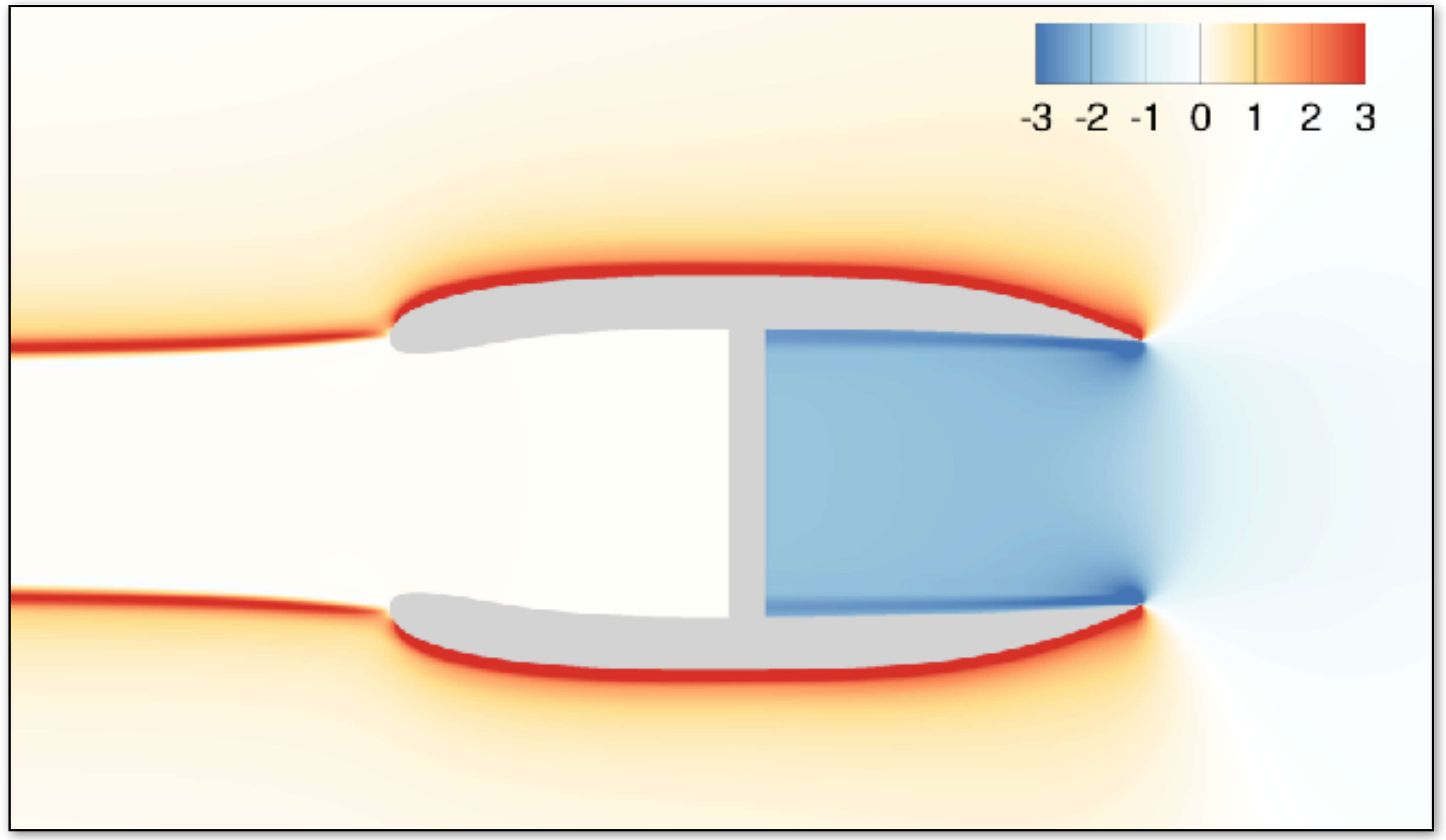


Numerical Study: Near-Wall Adjoint Solutions

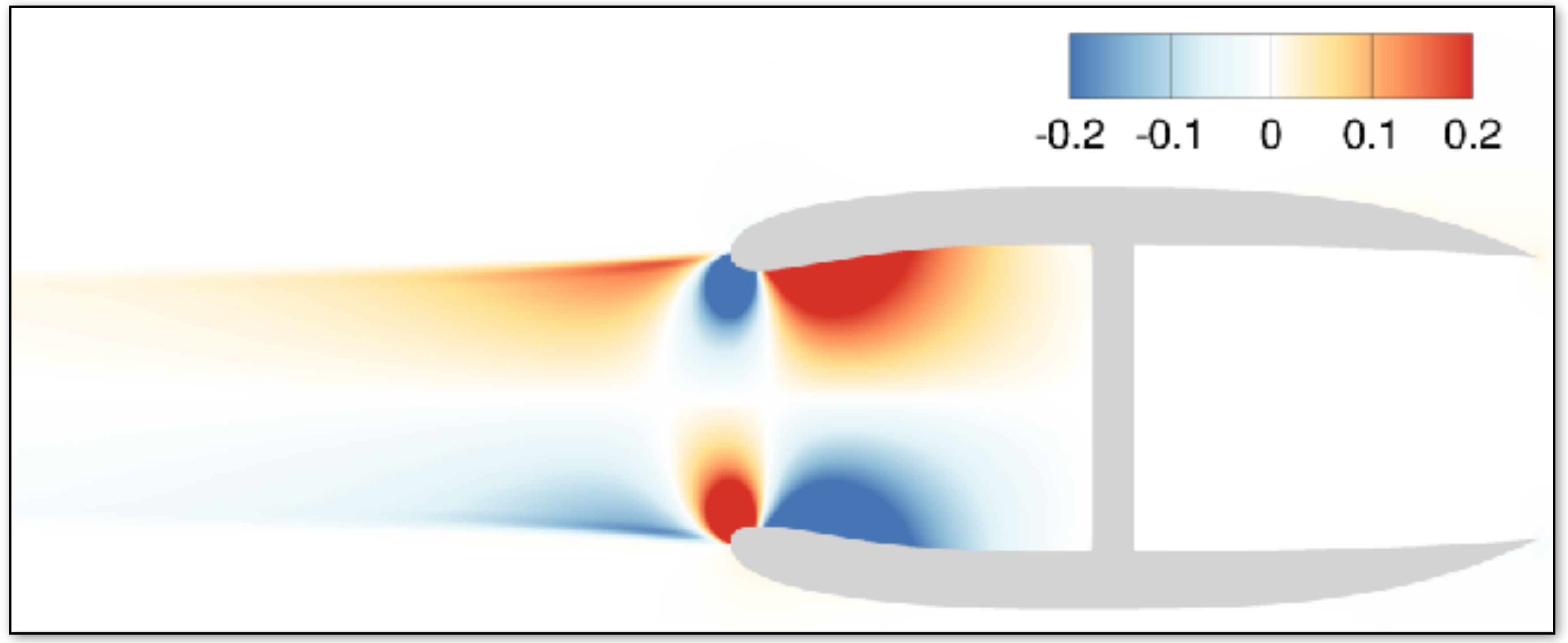
Test Case 1: Inlet Mass Flow Rate | **Test Case 2: Nozzle Mass Flow Rate**

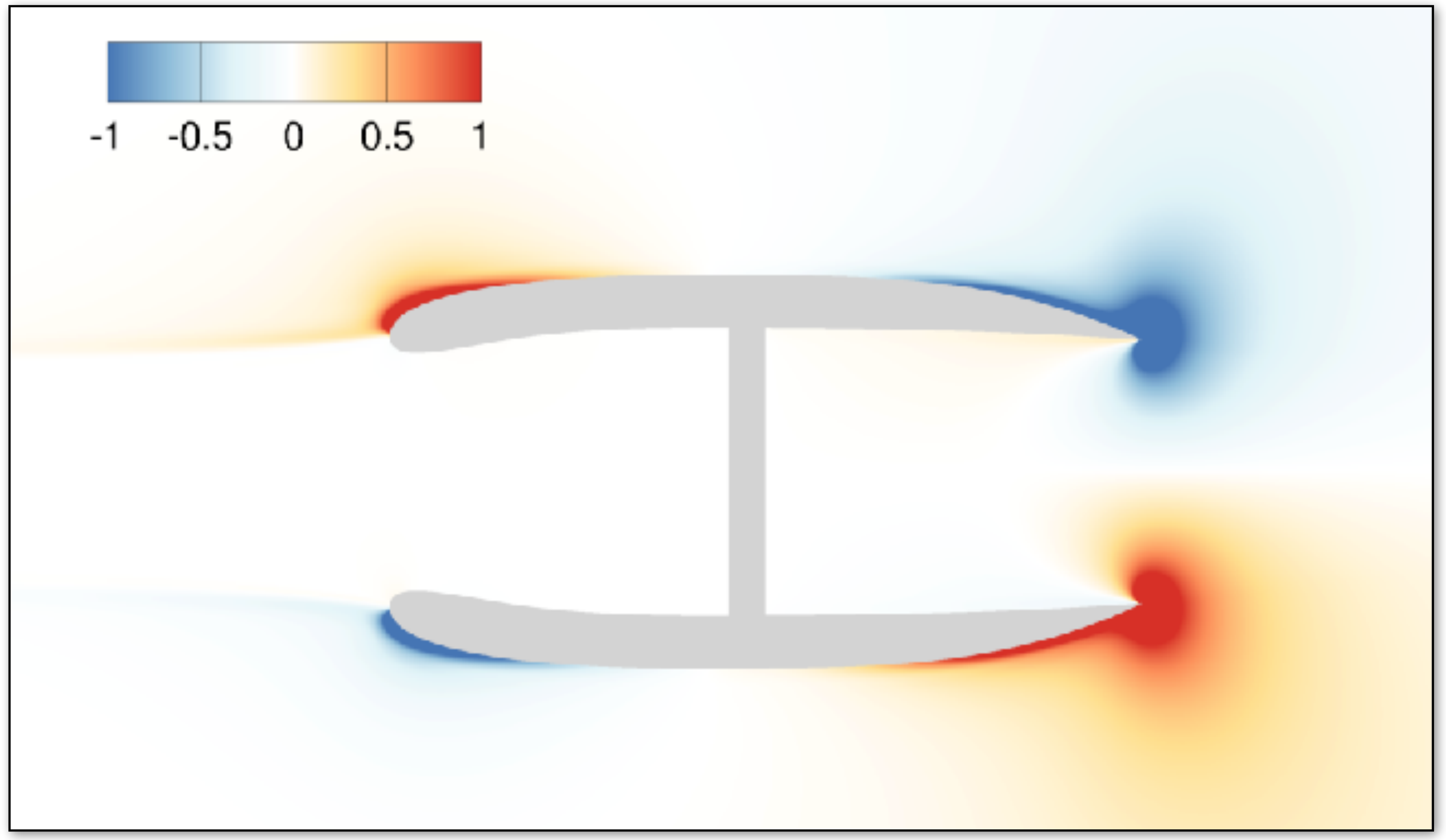
x-momentum Adjoint





y-momentum Adjoint





Aerodynamic Shape Optimization

$$\min_{X} \quad J\left(X, \mathbf{Q}\right)$$

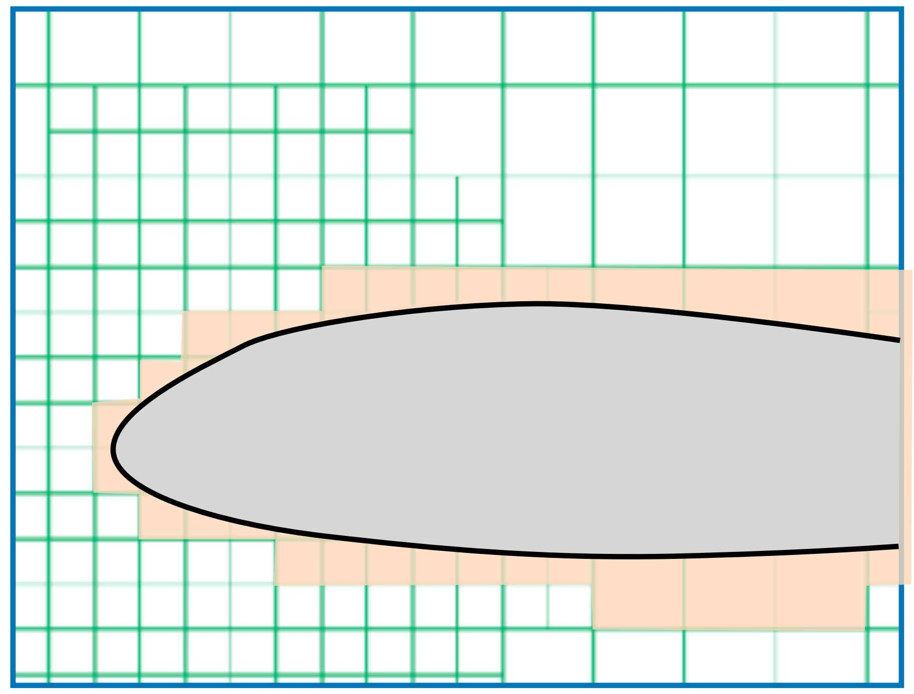
subject to

$$R\left(X, \mathbf{Q}\right) = 0 \qquad \forall X \in \Omega$$

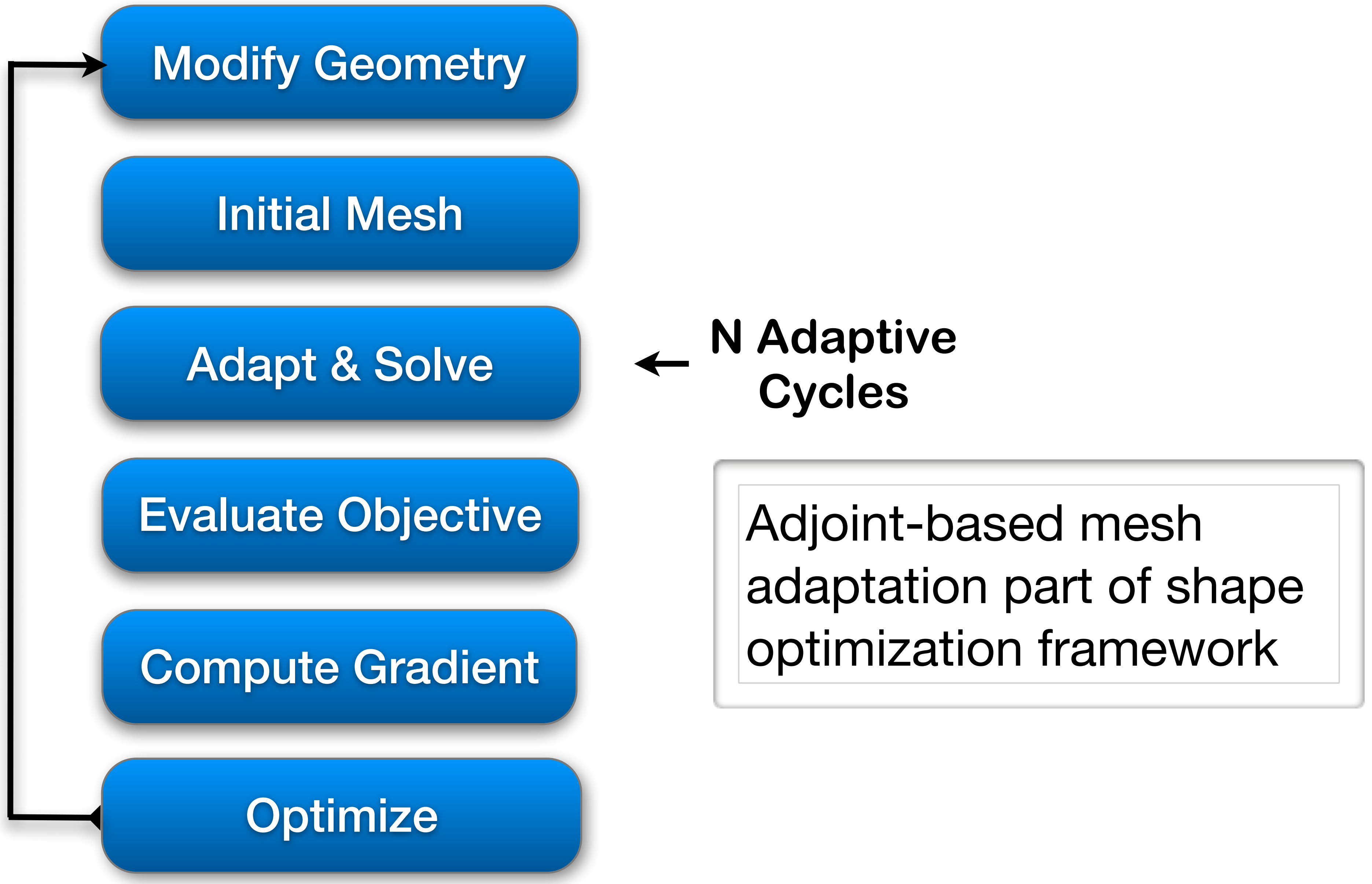
- Gradient-based approach

$$\frac{\mathrm{d}J}{\mathrm{d}X} = \frac{\partial J}{\partial X} - \psi^{\mathrm{T}} \frac{\partial \mathbf{R}}{\partial X}$$

- Mesh sensitivities confined to cutcells, triangulation connectivity and topology allowed to change



Adjoint Optimization Framework



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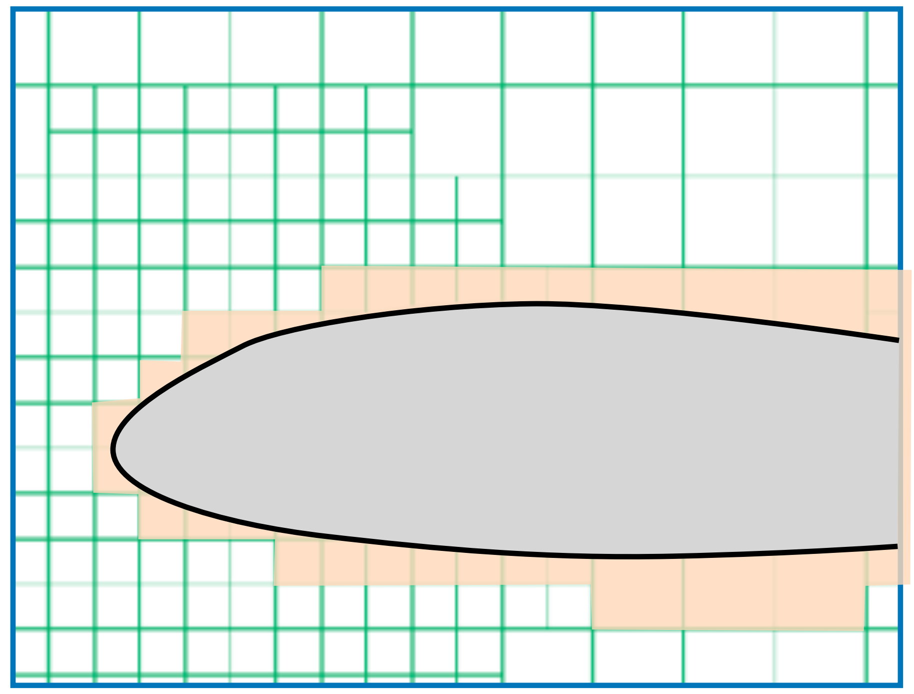
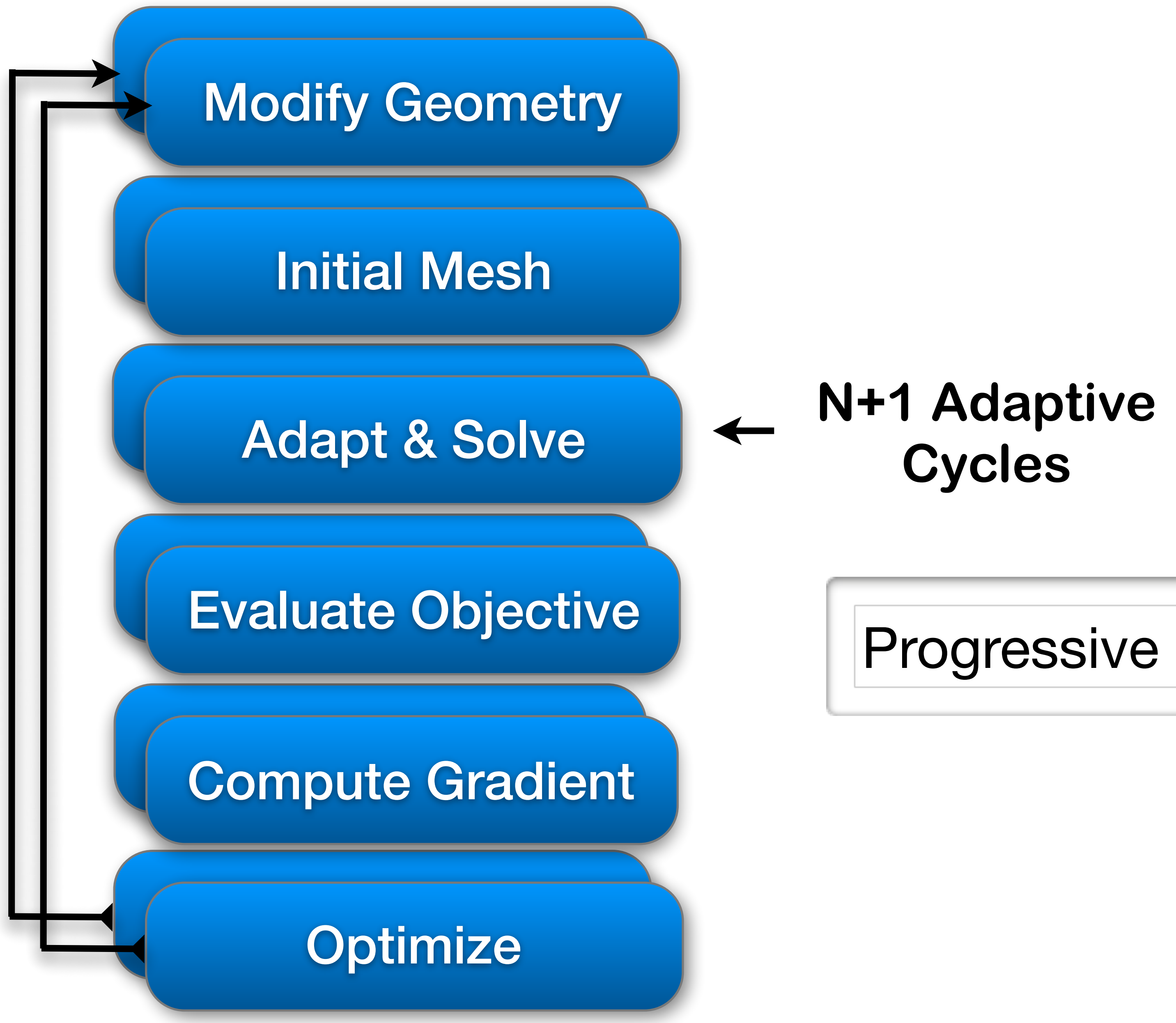


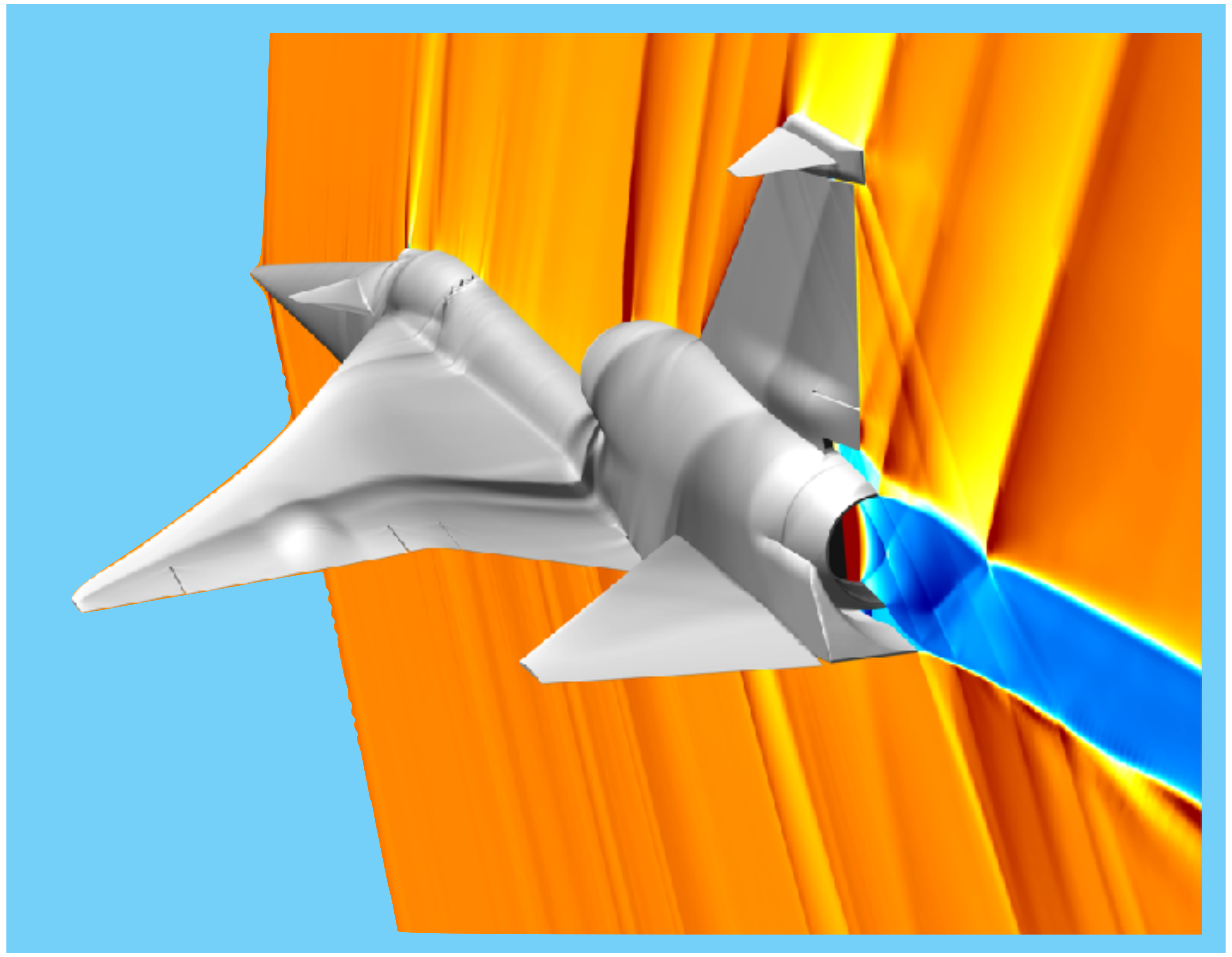
Adjoint Optimization Framework

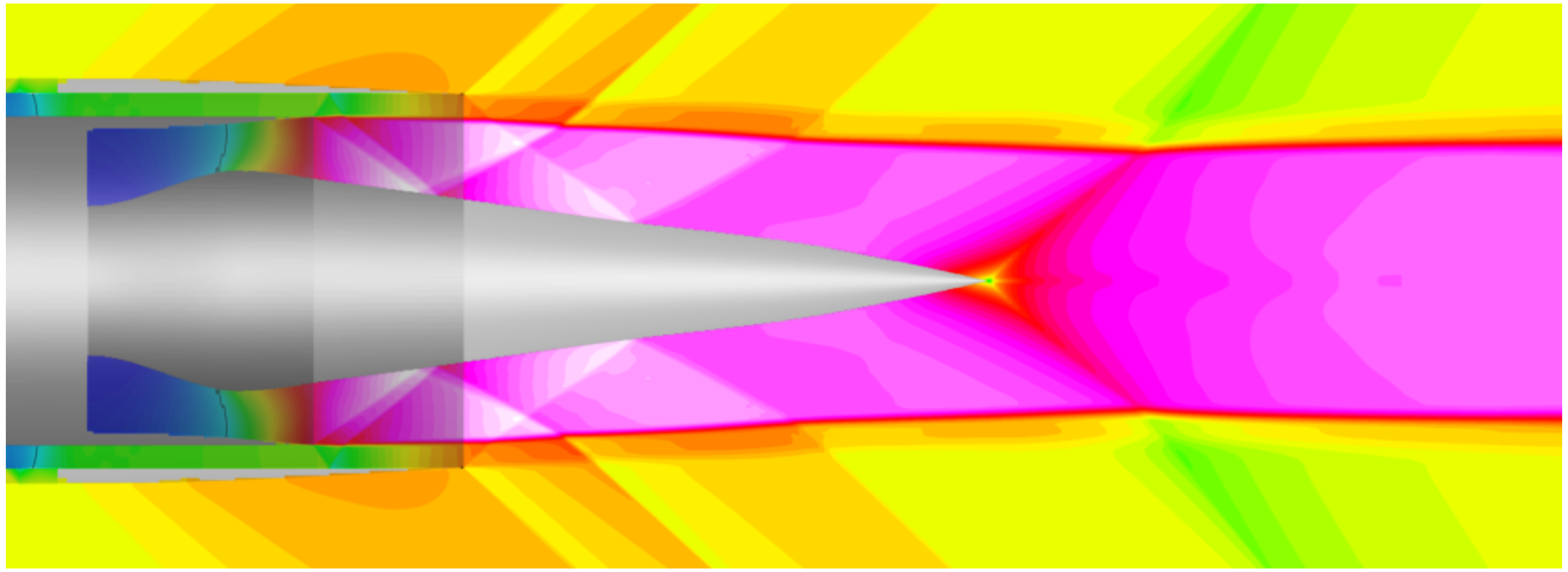


Progressive Optimization

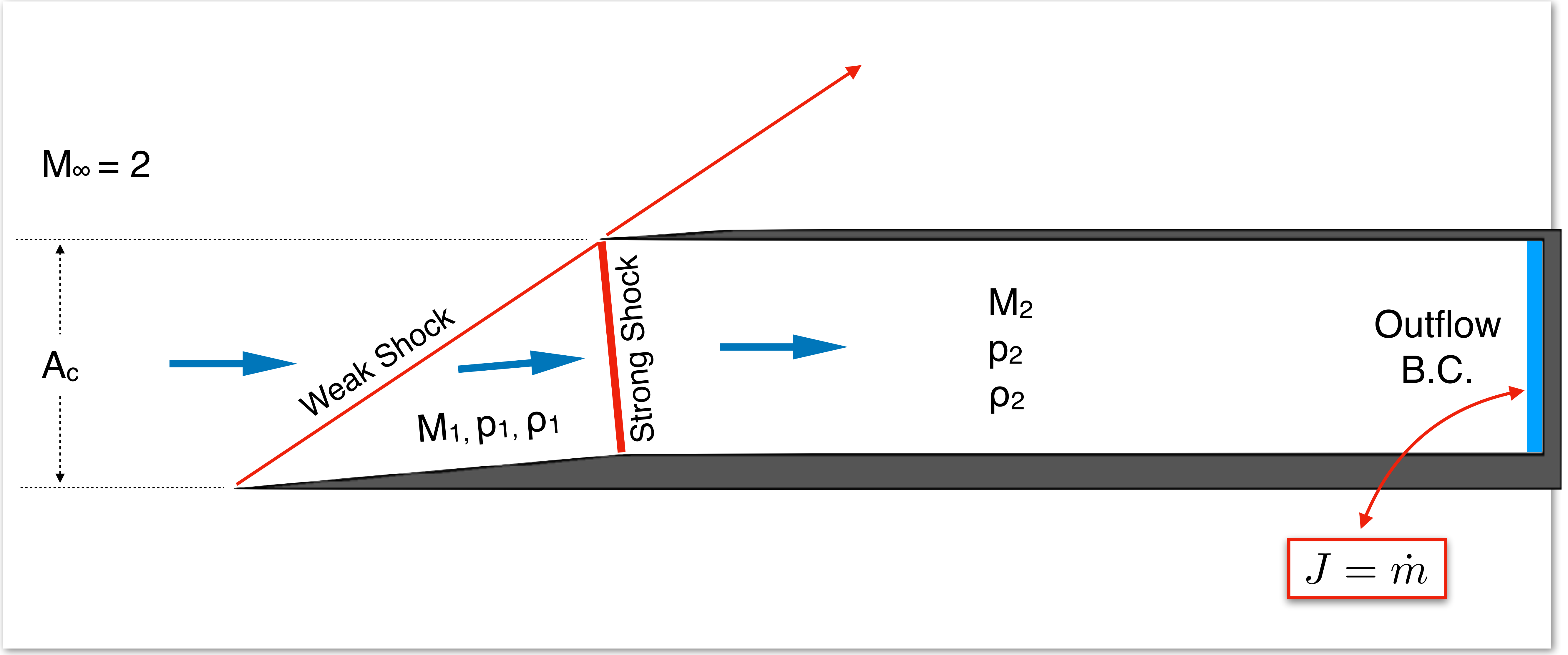
Results

1. Verification
    - Two-shock diffuser
2. Analysis
    - LBFD prototype example
3. Optimization
    - Supersonic Nozzle Shape Optimization

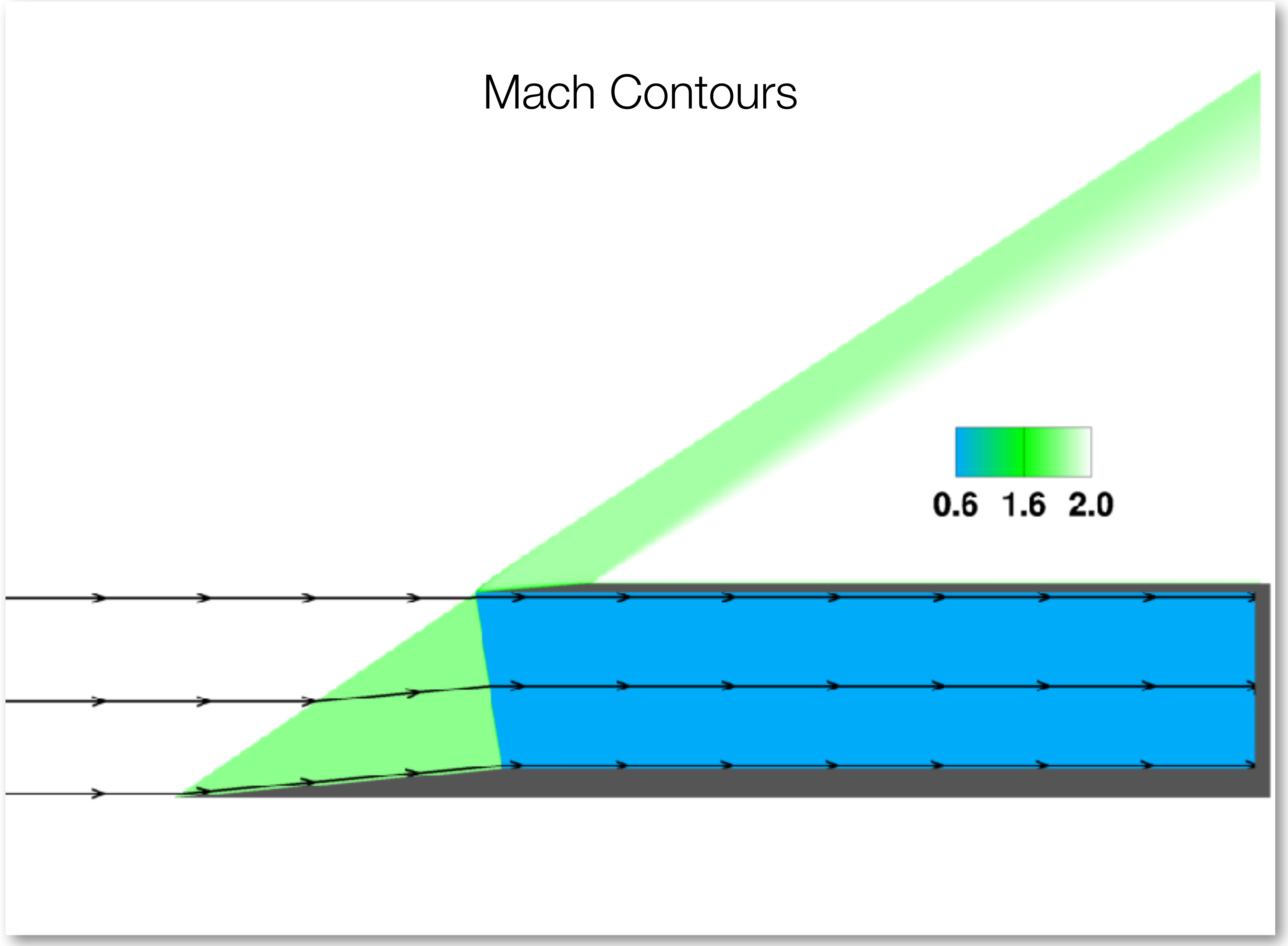




Mass Flow Verification Test



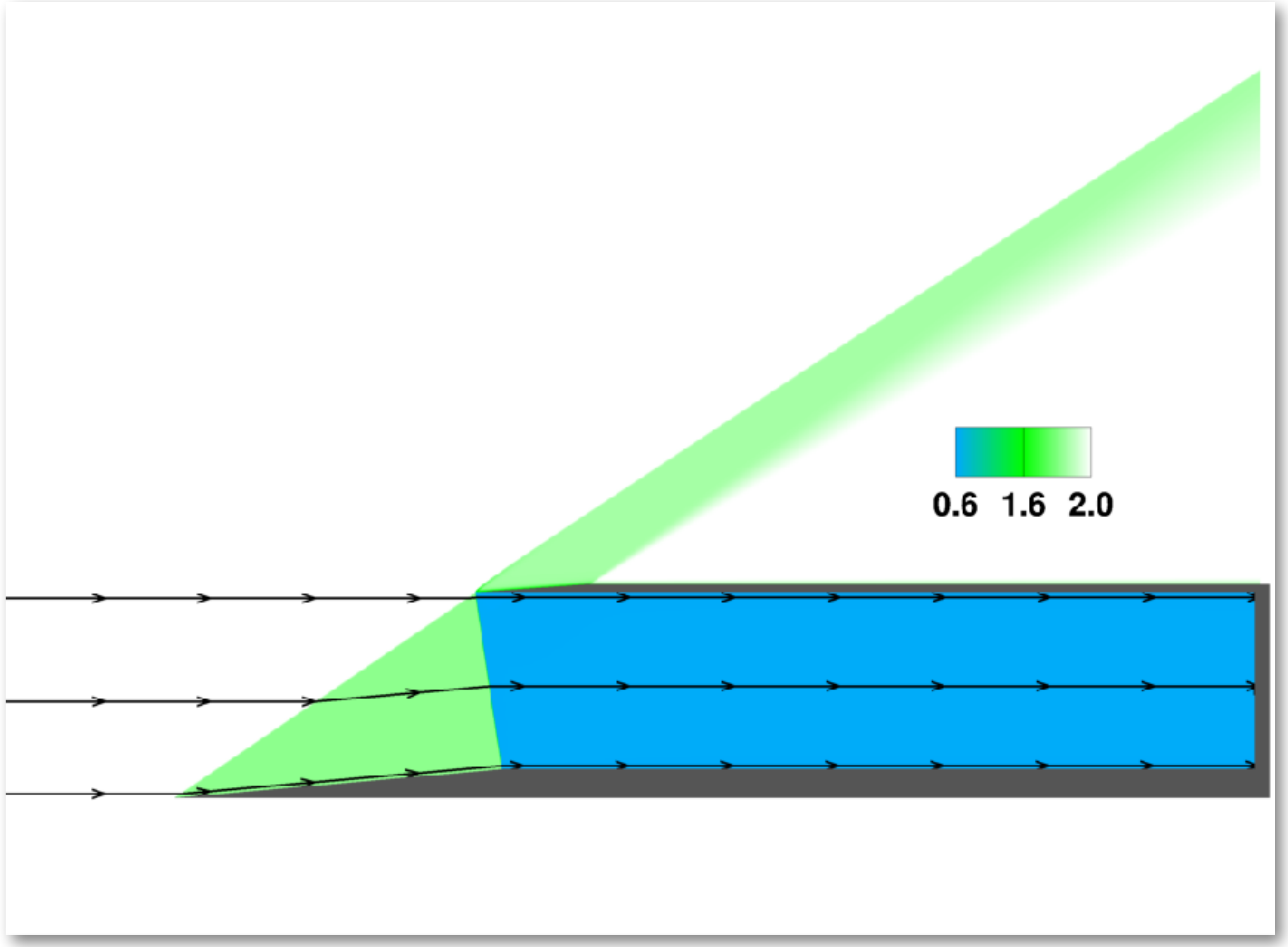
Two-Shock Wedge



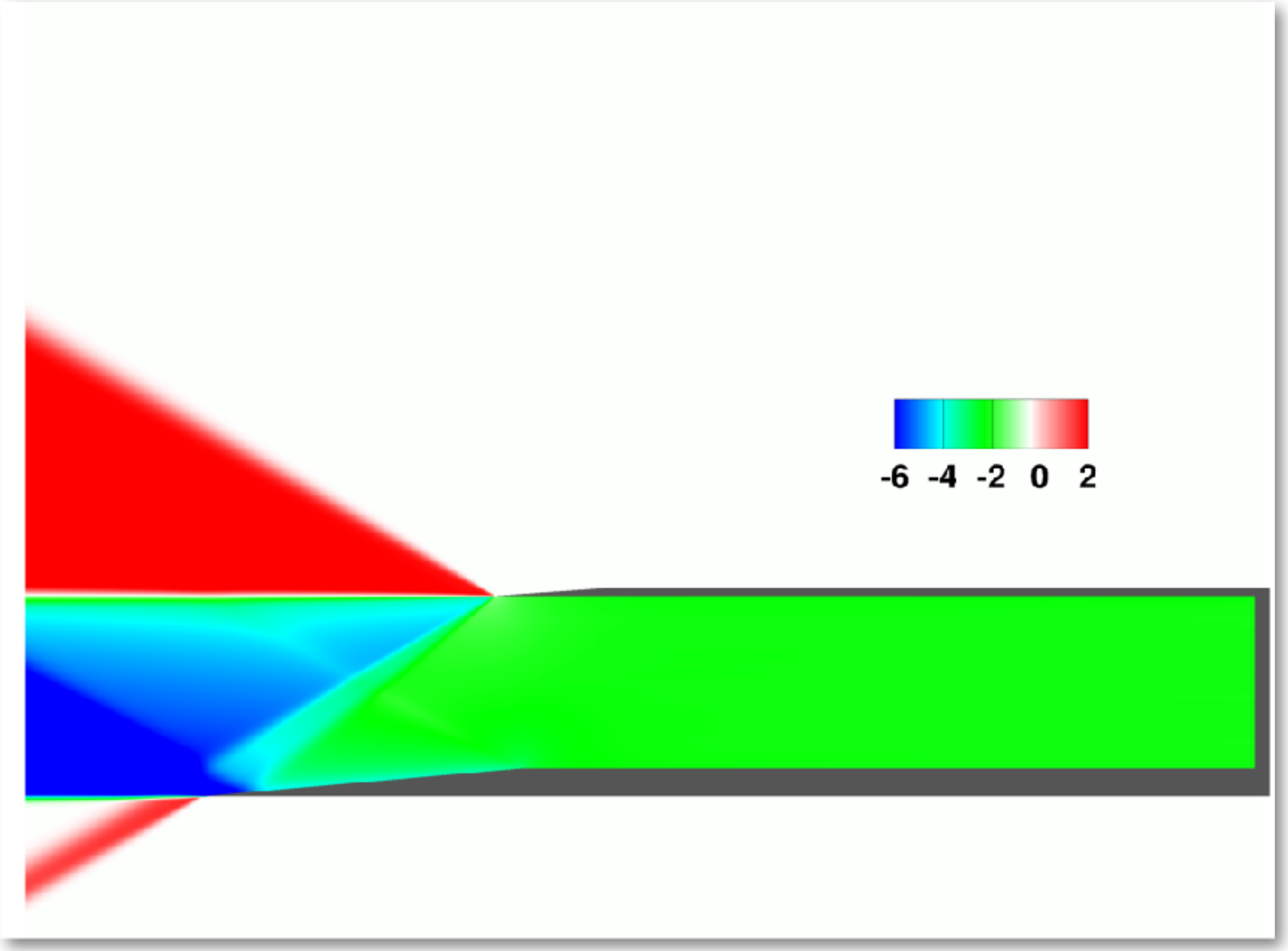
- 2D test case that mimics a supersonic inlet
- Two shock system with no spillage at upper lip
  - 5° wedge
  - Analytic outflow exit pressure specified
- Exact mass flow rate independent of flow state inside inlet
- Slip-wall on wetted surface except for inlet outflow

Flow and Adjoint Solutions

Mach Contours



Density Adjoint



Uniform Refinement

Exact Error

$$E = |\mathcal{J} - J_H|$$

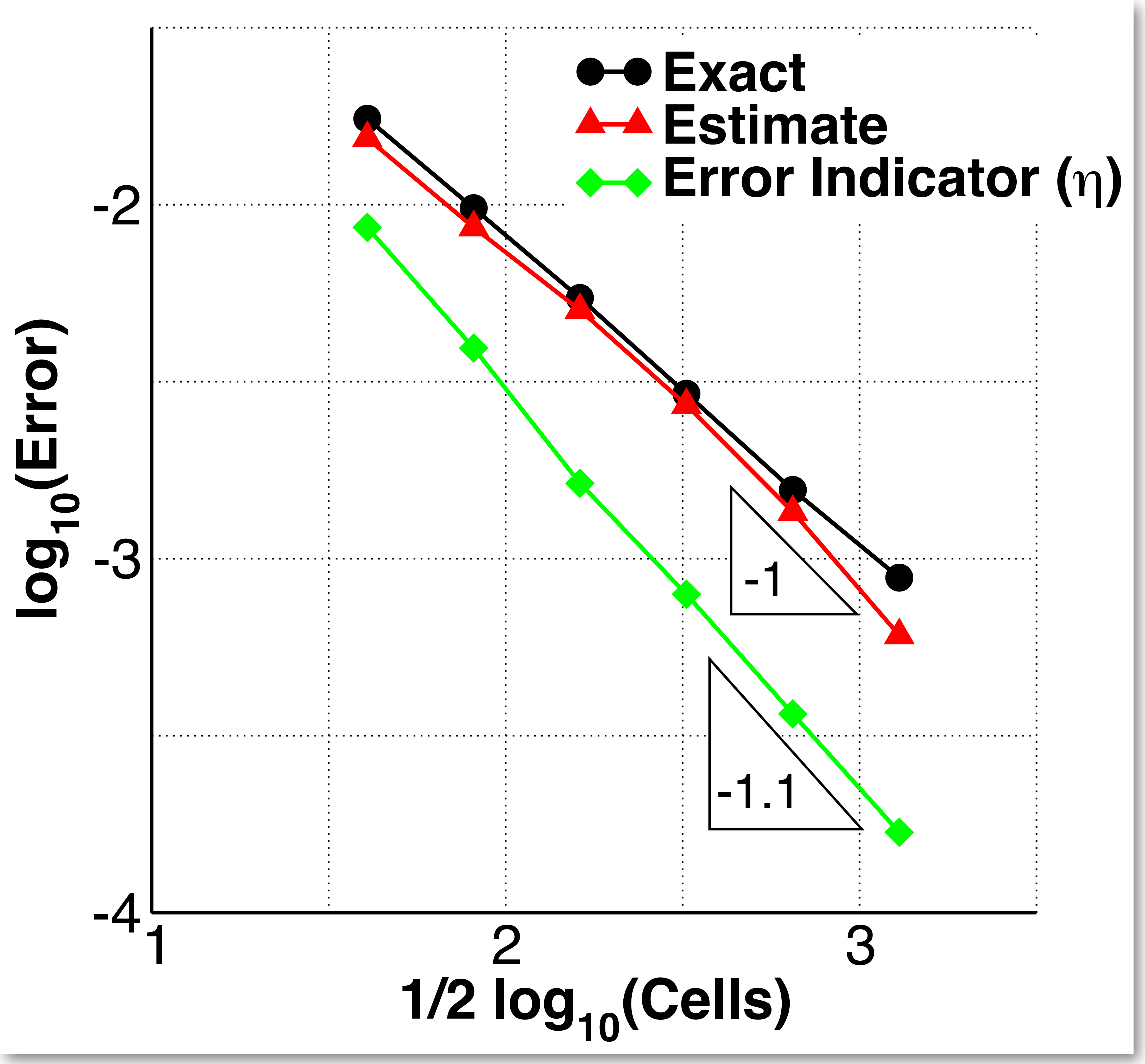
Error Estimate

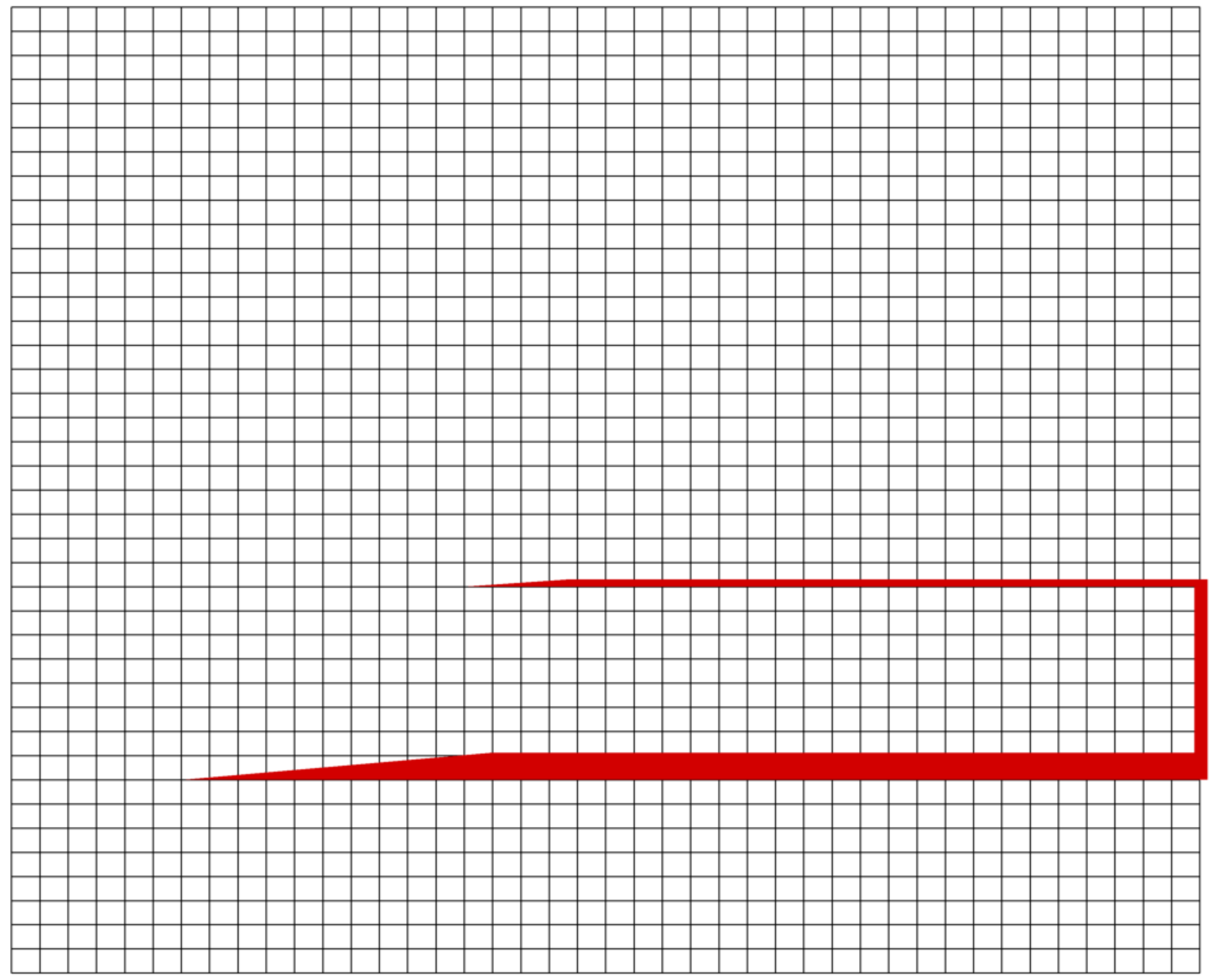
$$E \approx |J_c - J_H|$$

$$J_c = J_h(\mathbf{Q}_\mathrm{L}) - \psi_{\mathrm{TQ}}^{\mathrm{T}} \mathbf{R}_h(\mathbf{Q}_\mathrm{L})$$

Error Indicator

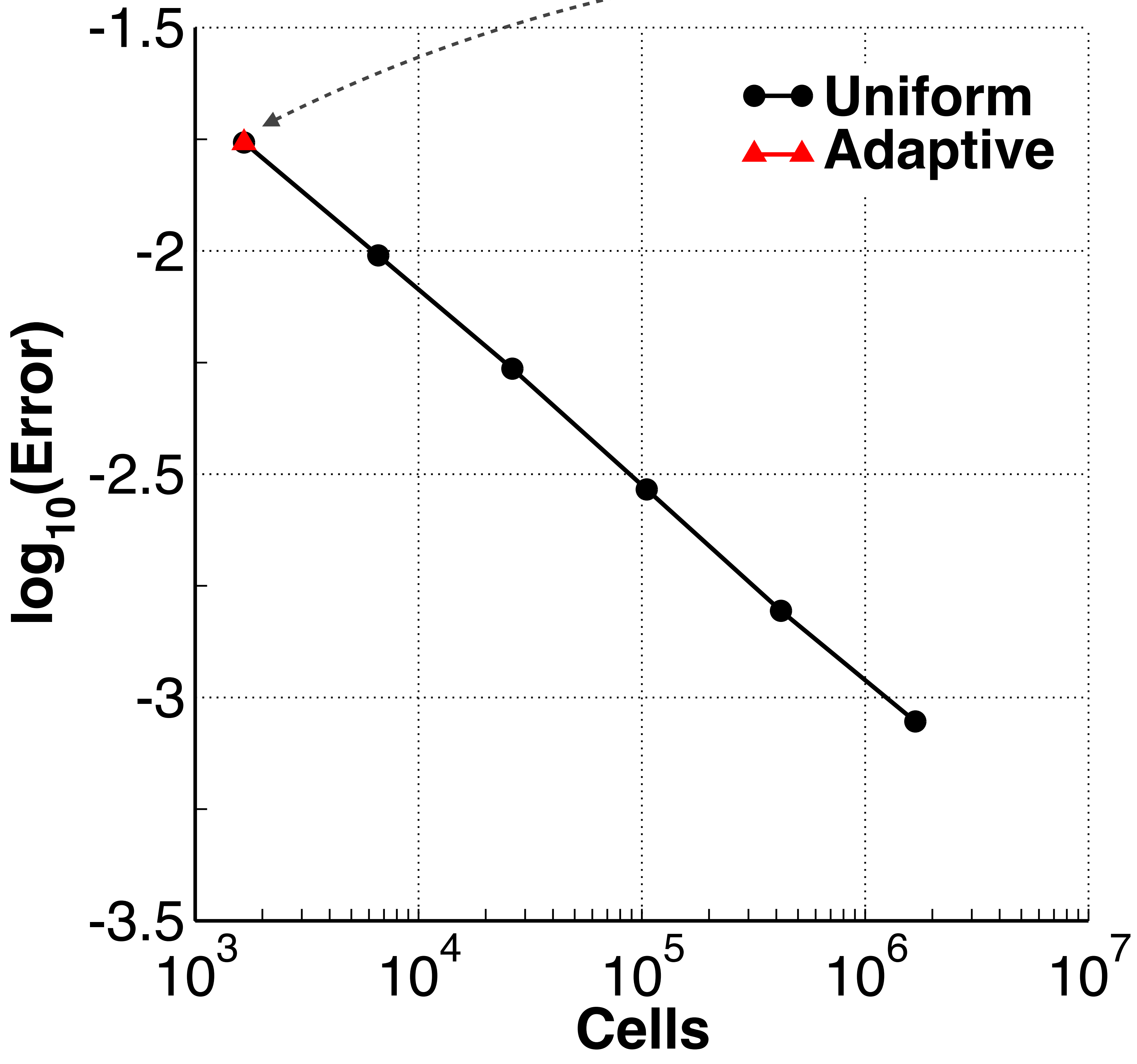
$$\boldsymbol{\eta}_H = \left| \left(\psi_{\mathrm{TQ}} - \psi_{\mathrm{TL}}\right)^{\mathrm{T}} \mathbf{R}_h(\mathbf{Q}_L) \right|$$

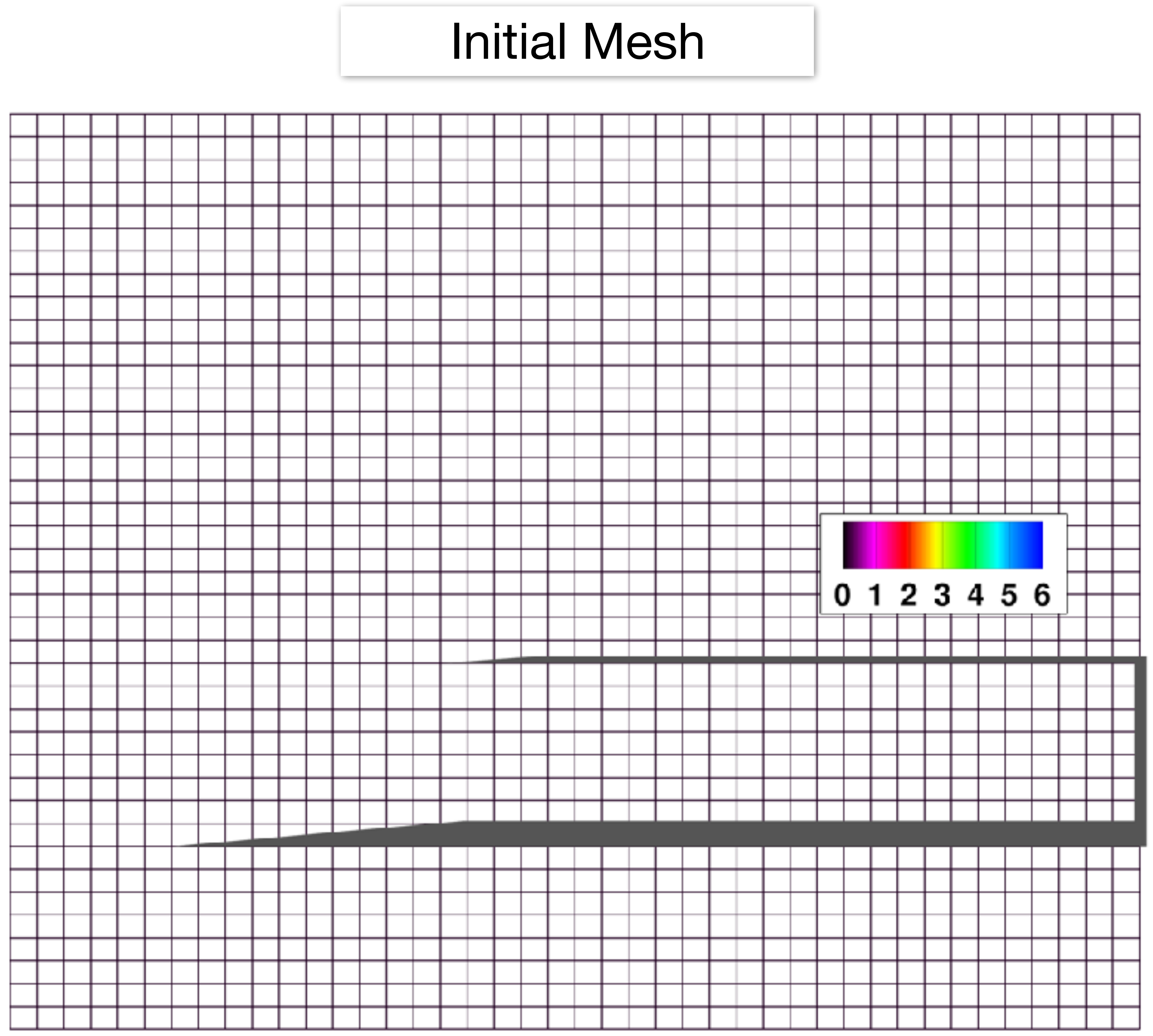




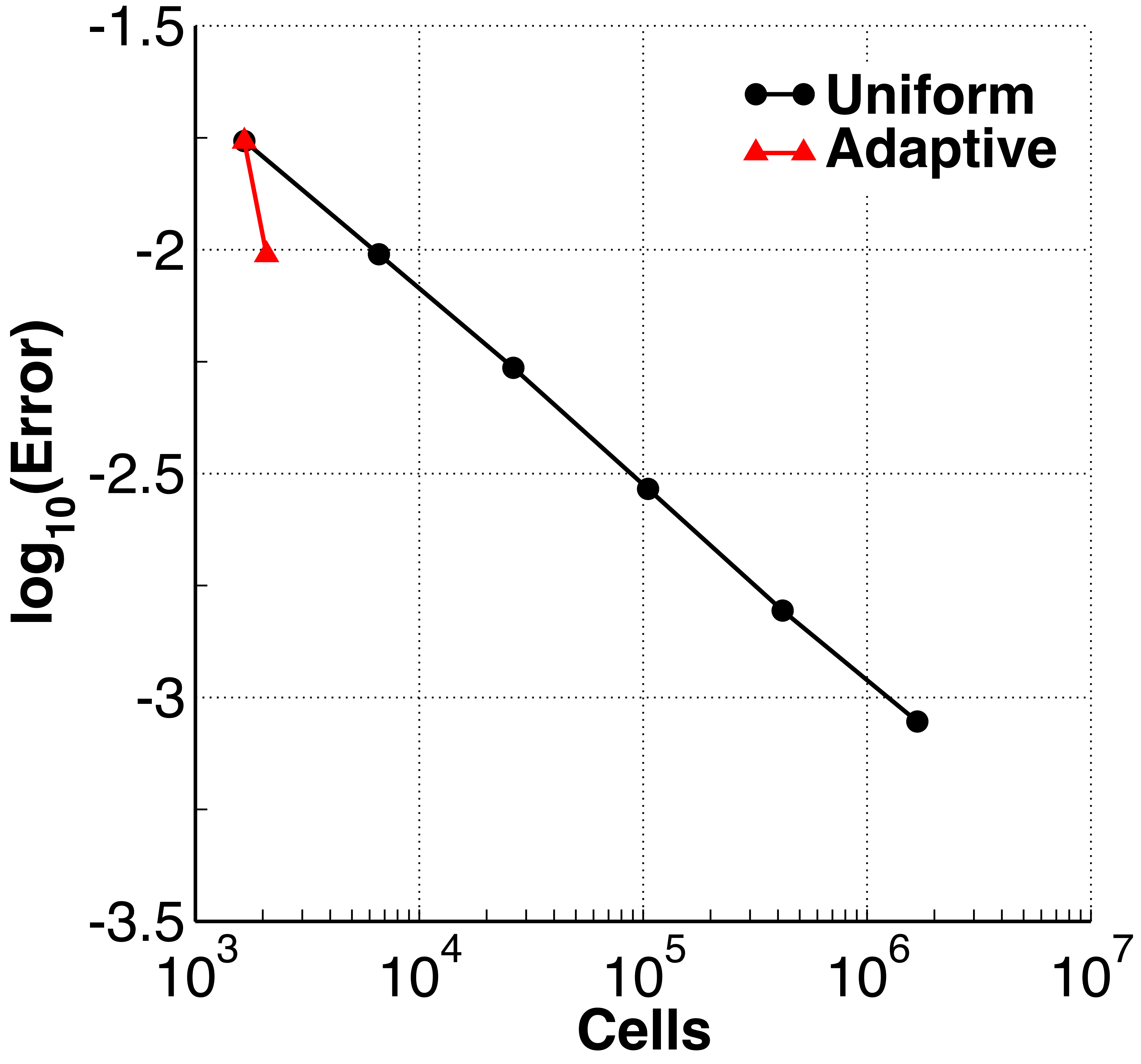
Initial Mesh

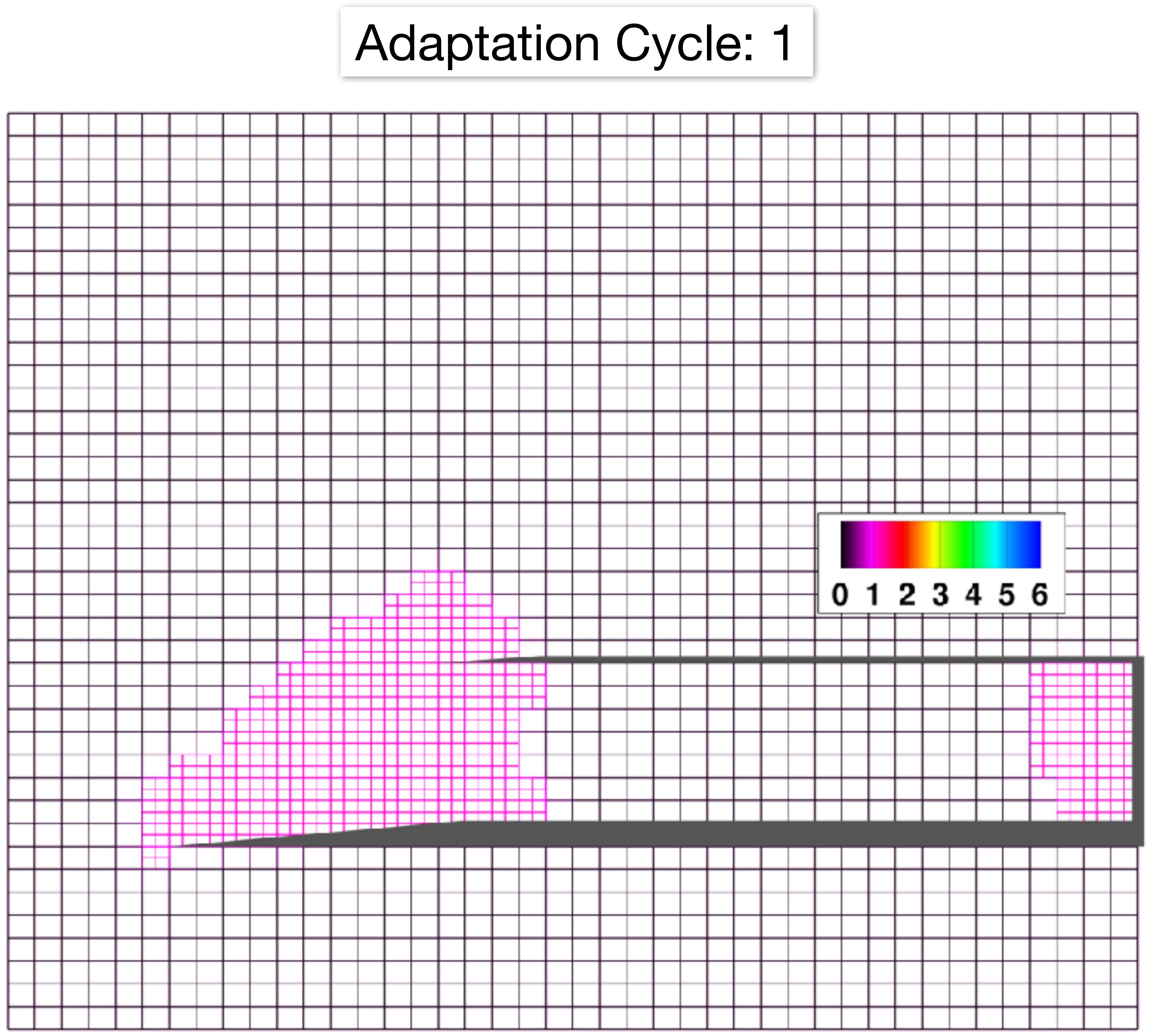
Adaptive Refinement



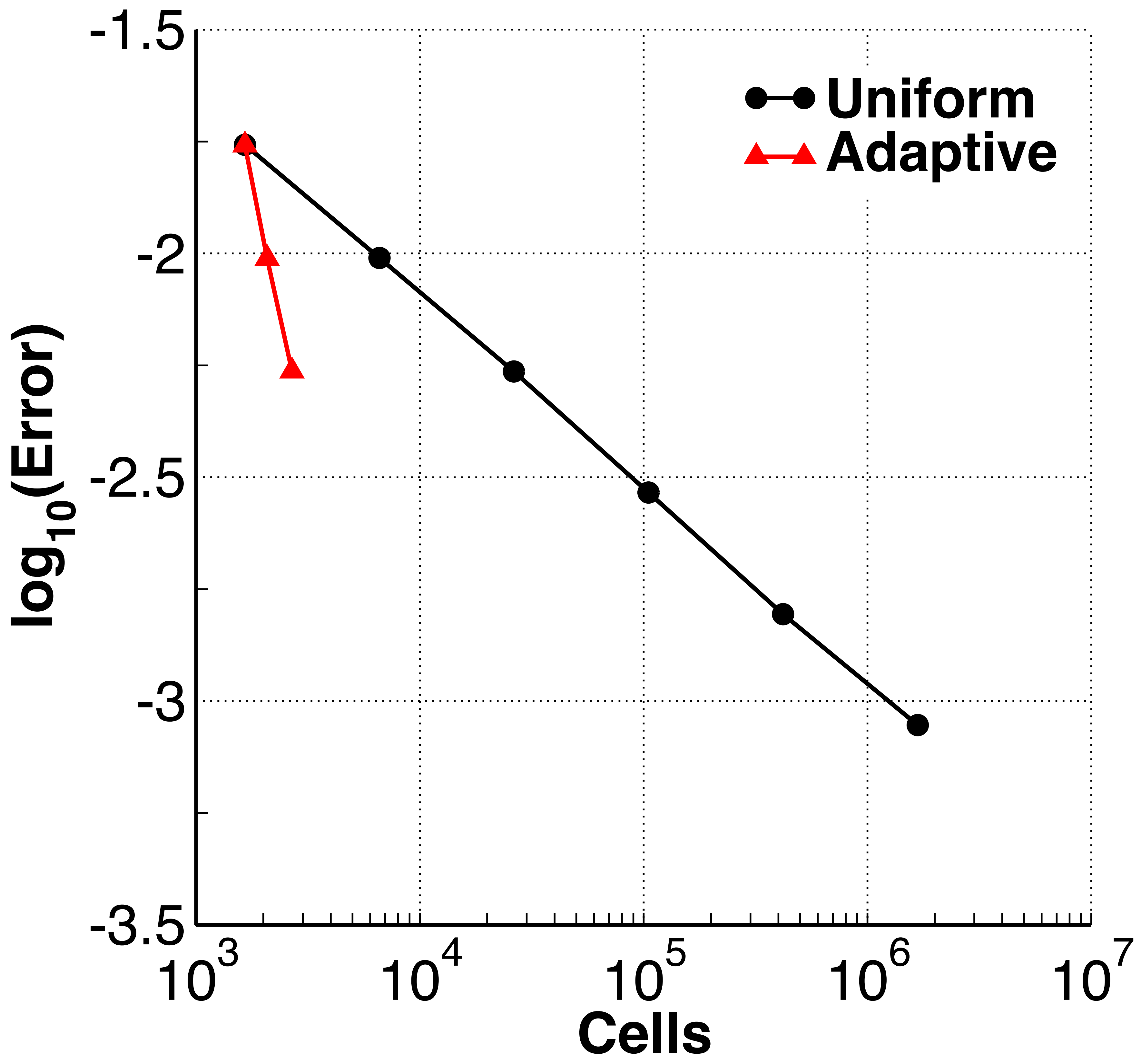


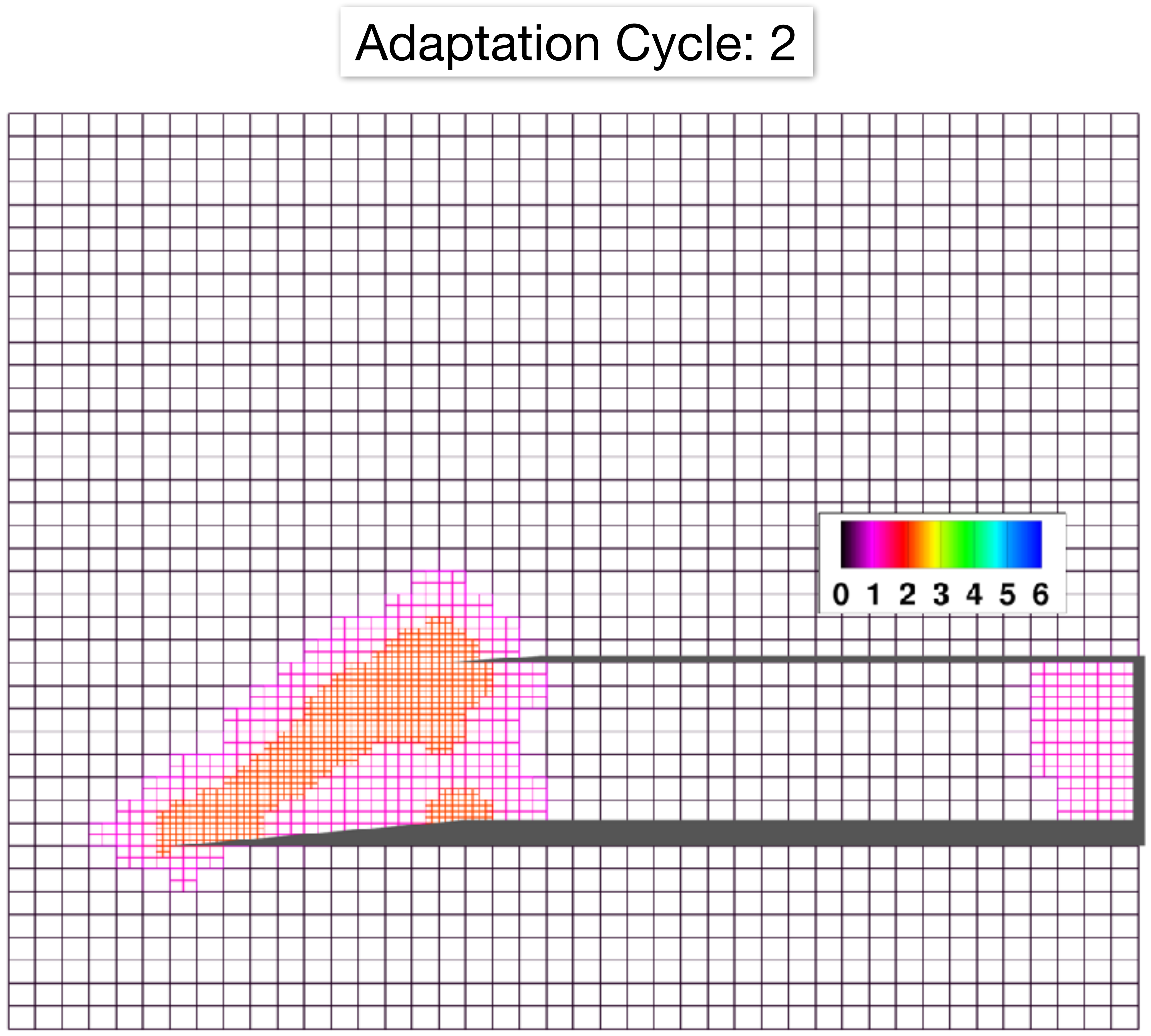
Adaptive Refinement



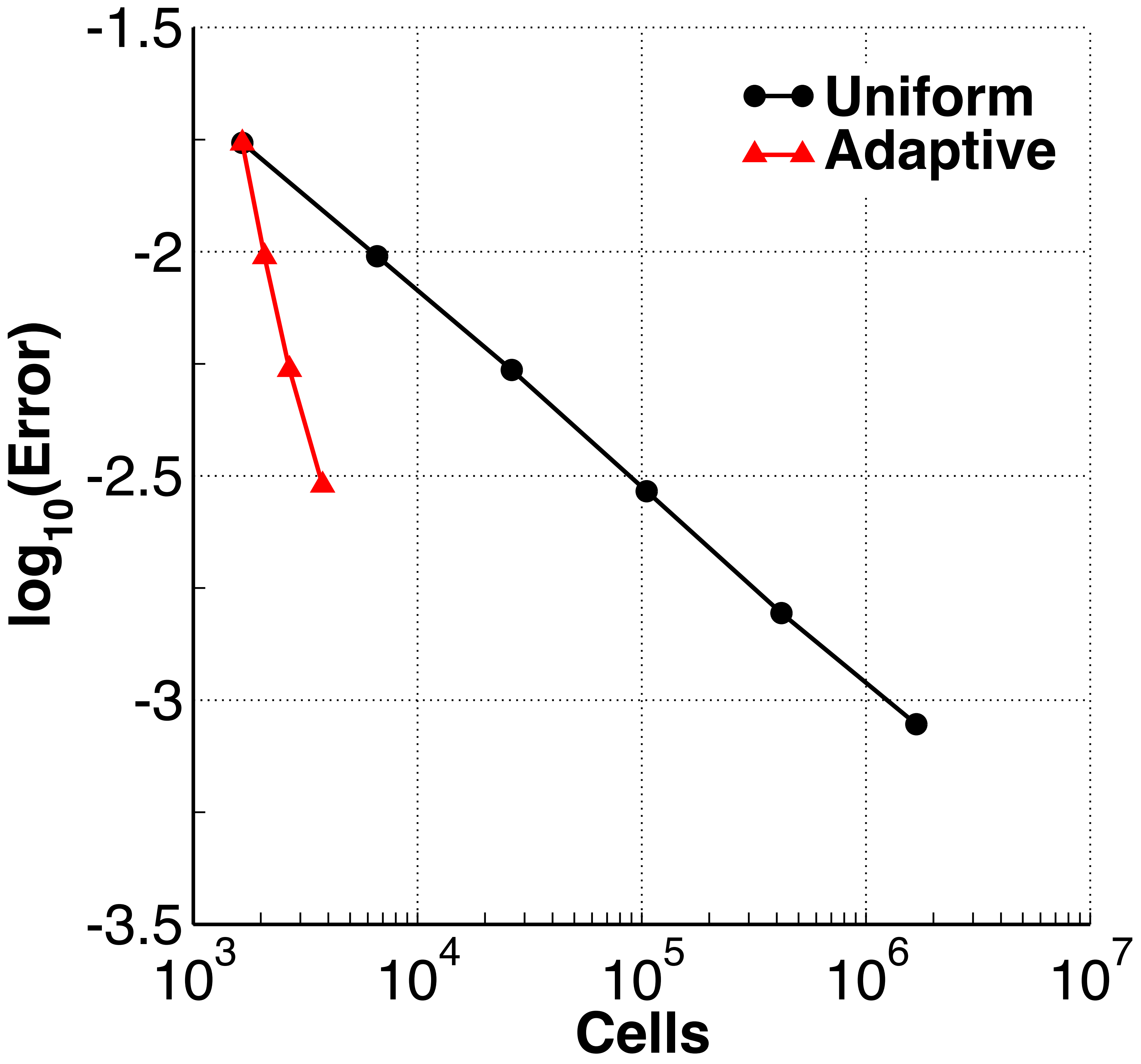


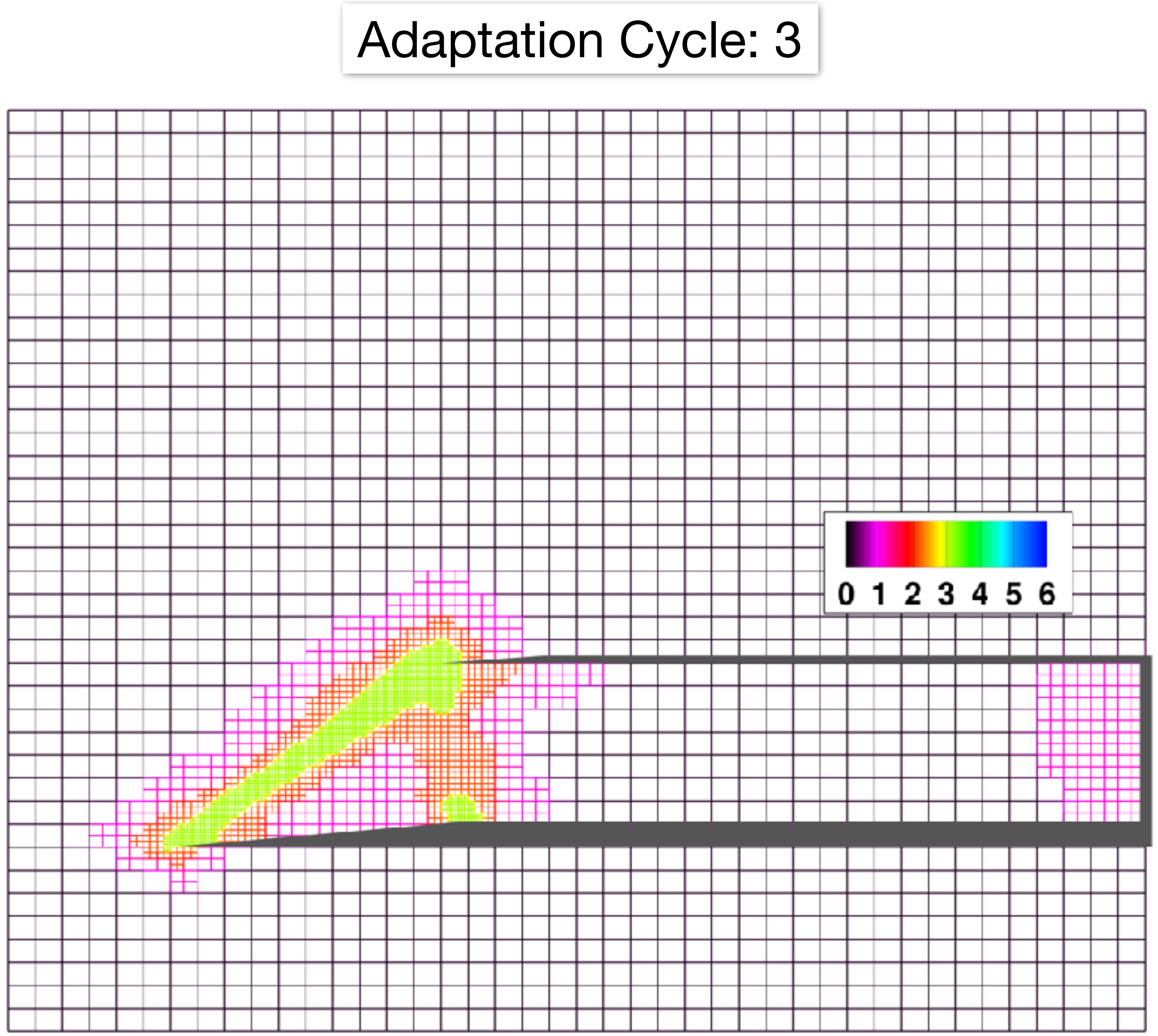
Adaptive Refinement





Adaptive Refinement





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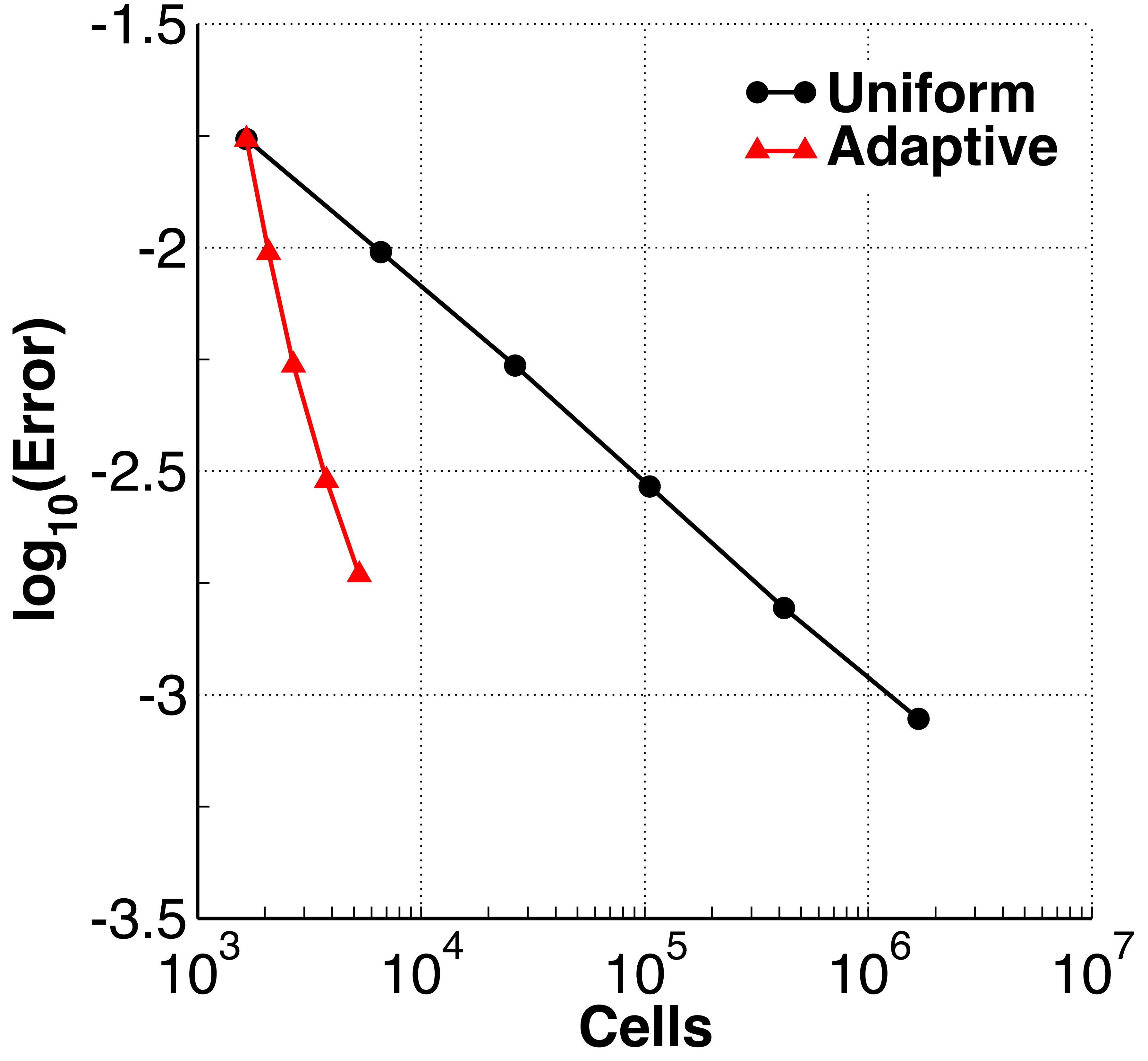
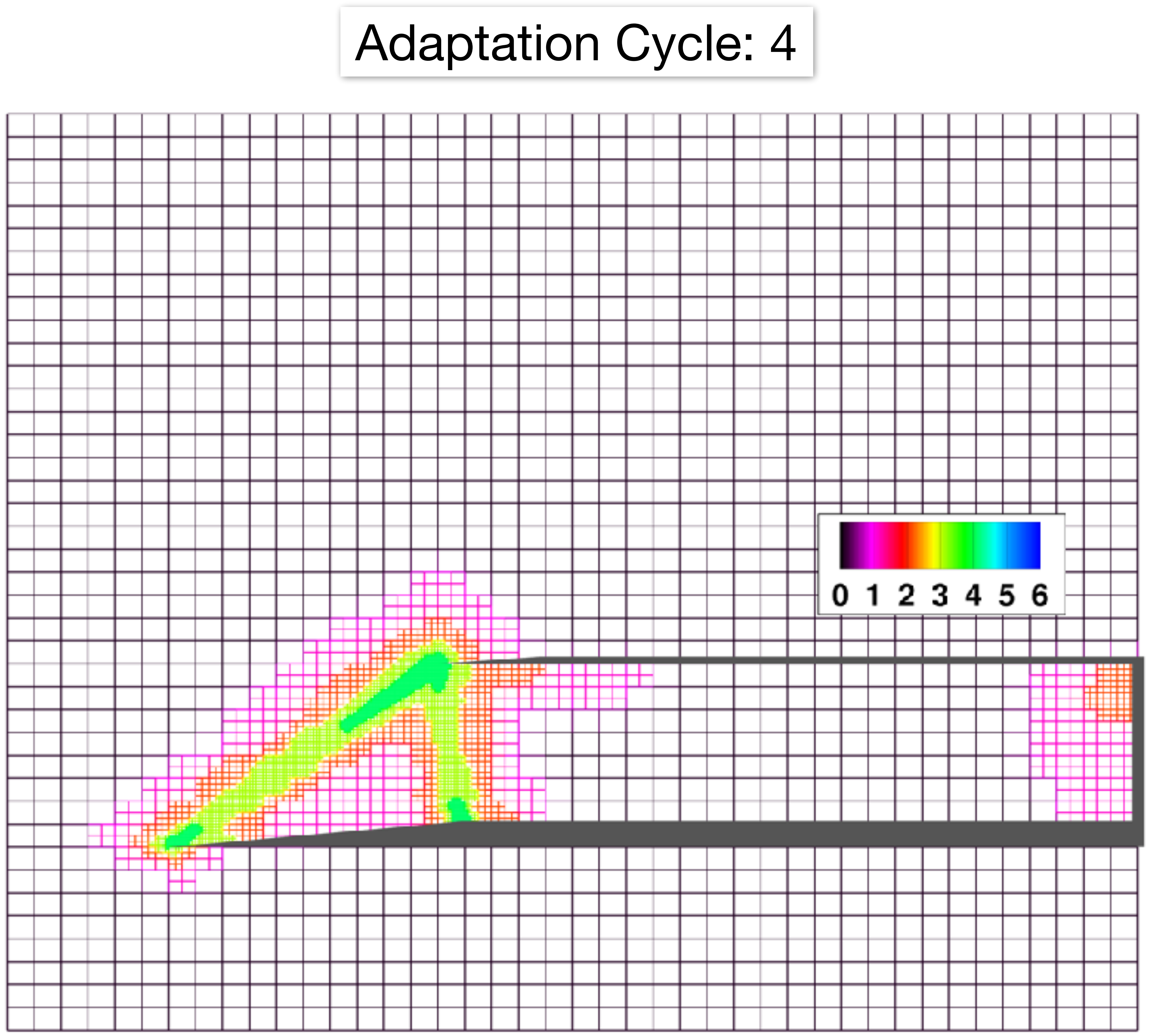
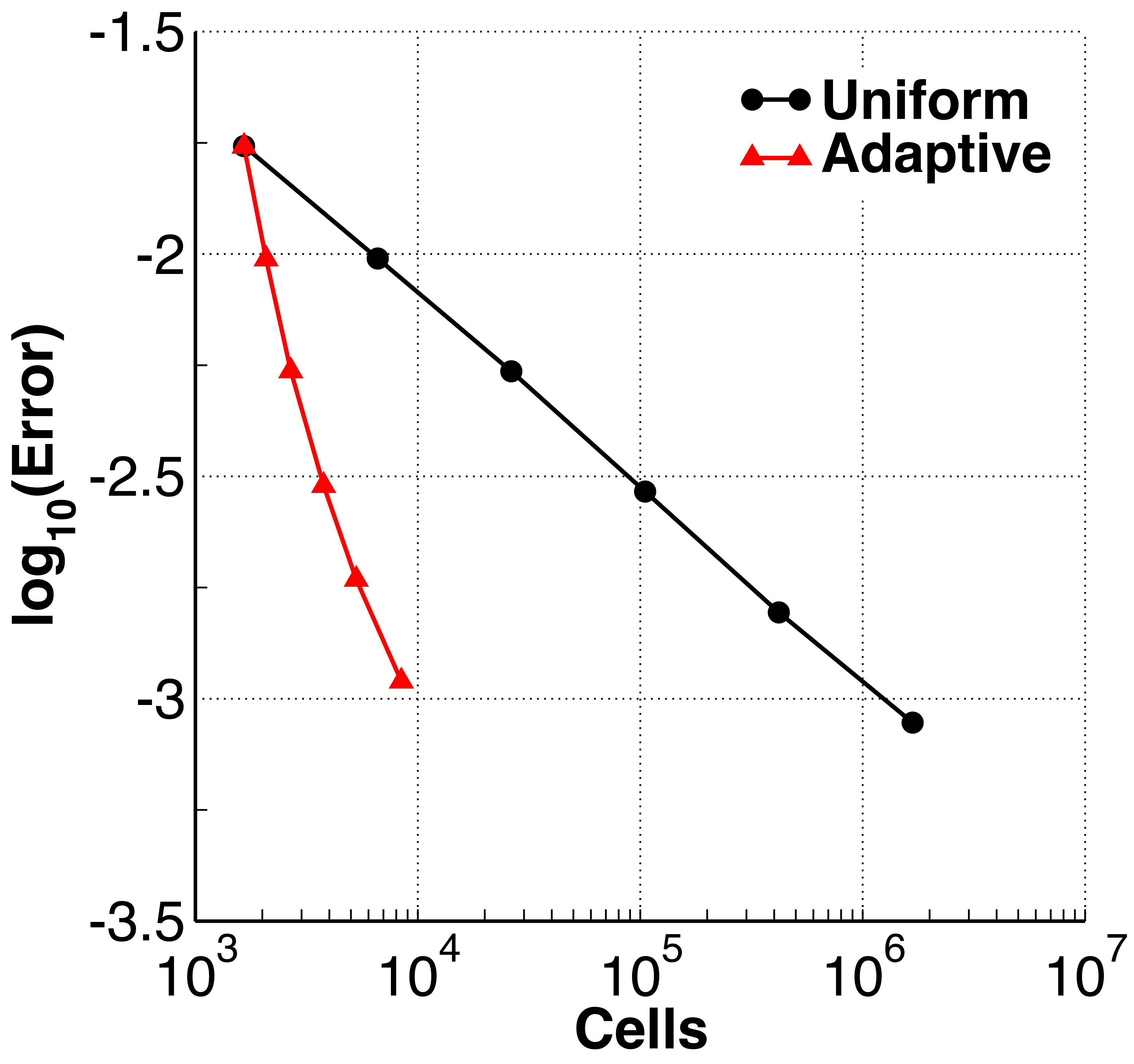
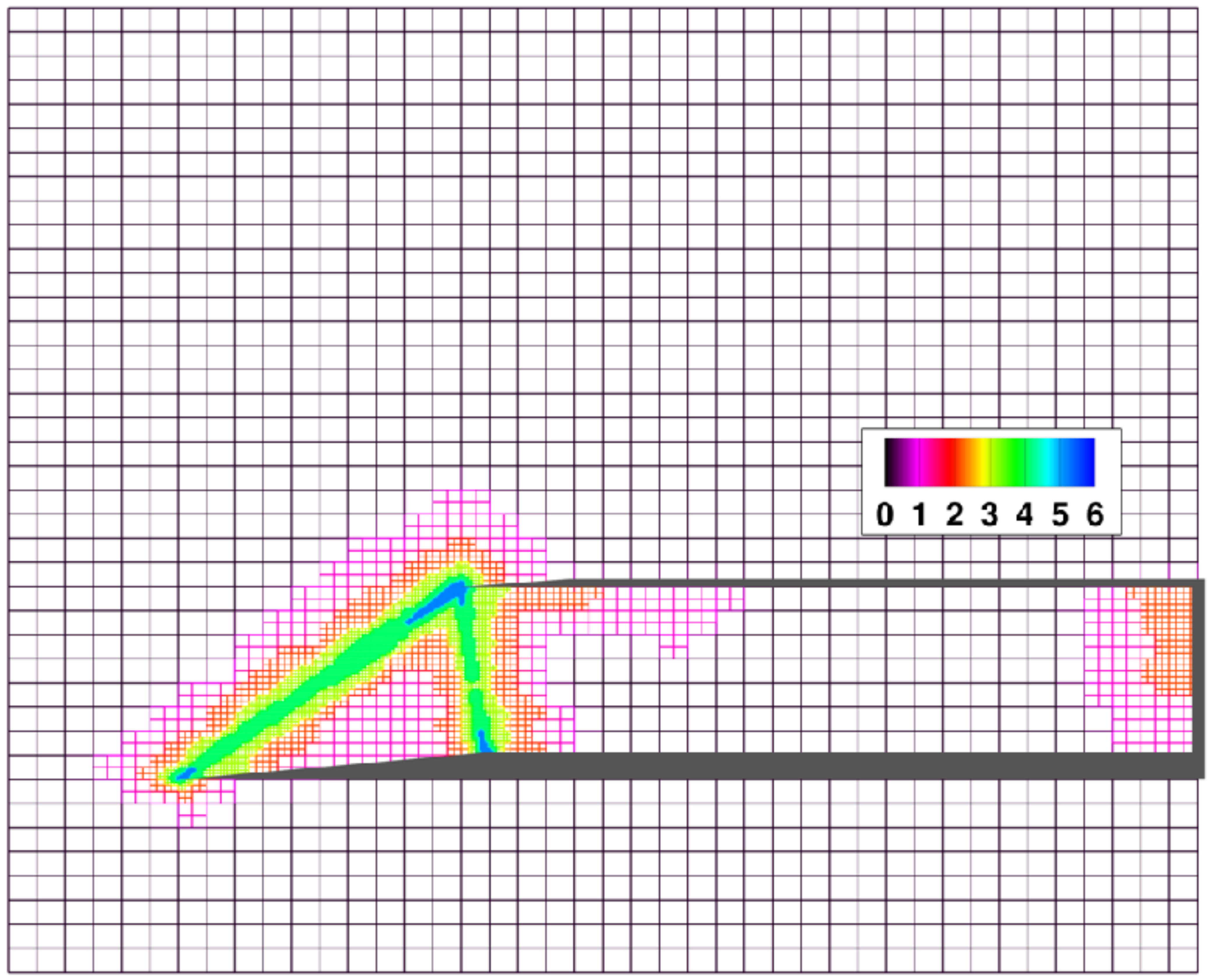




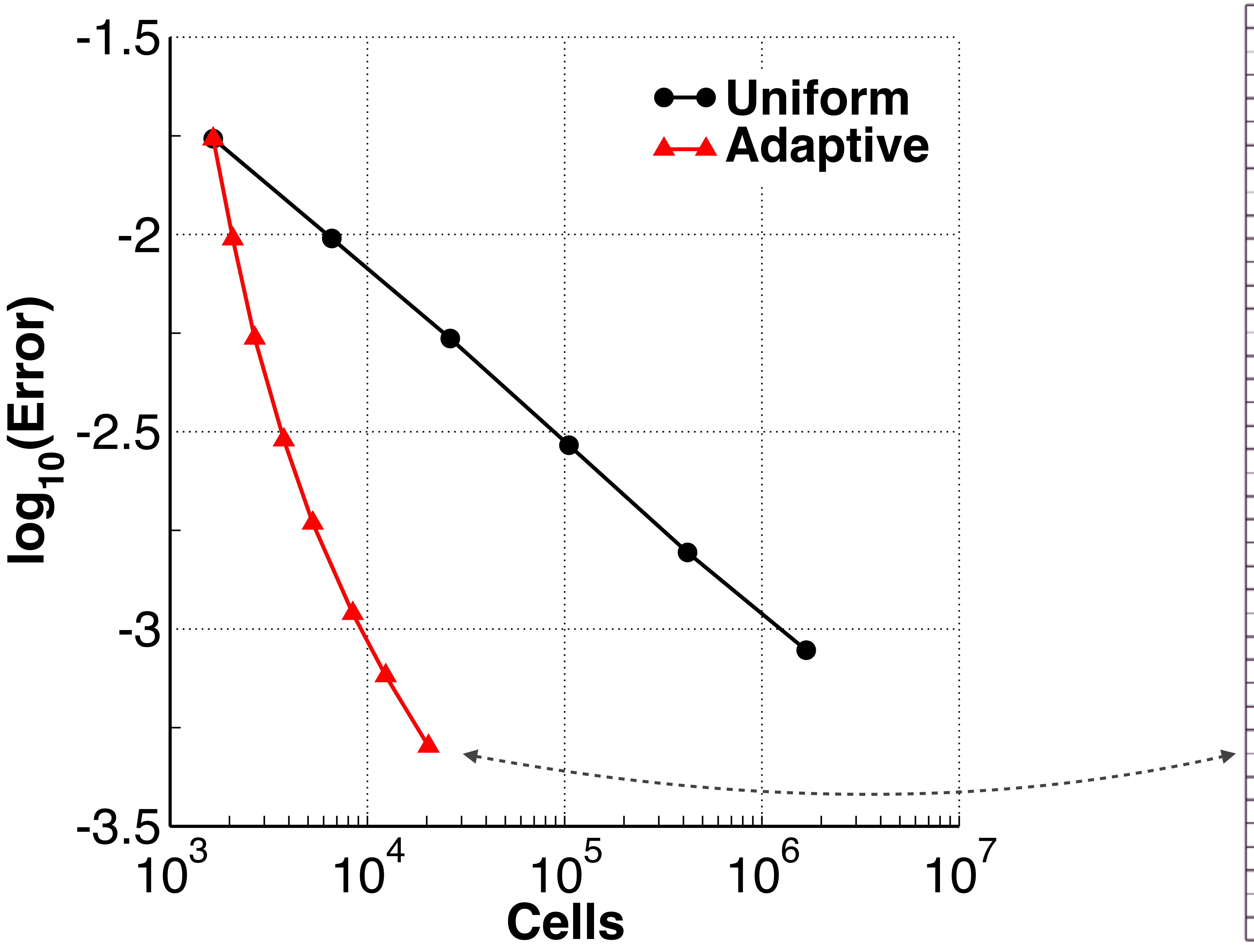
Adaptive Refinement

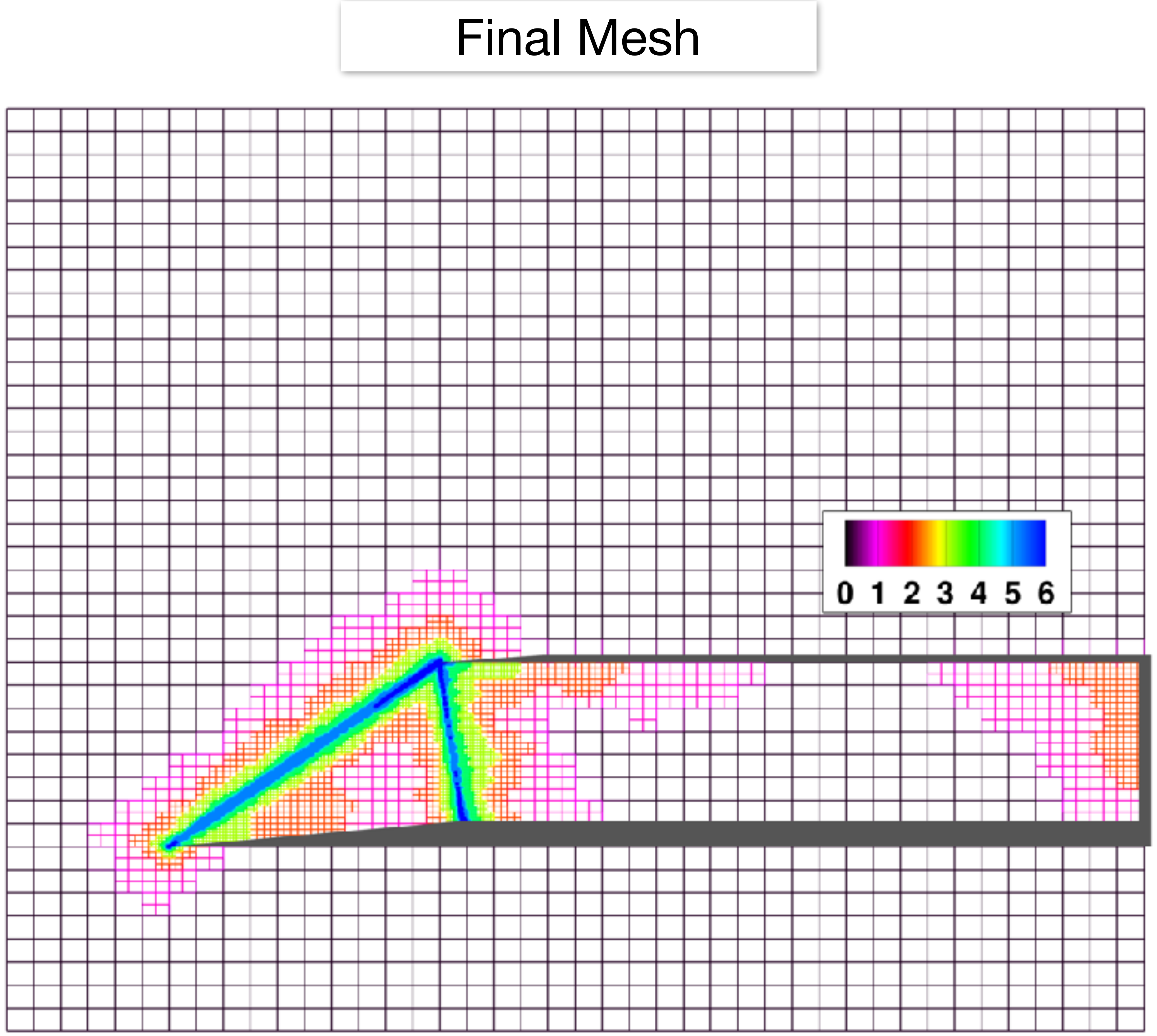


Adaptation Cycle: 5



Adaptive Refinement



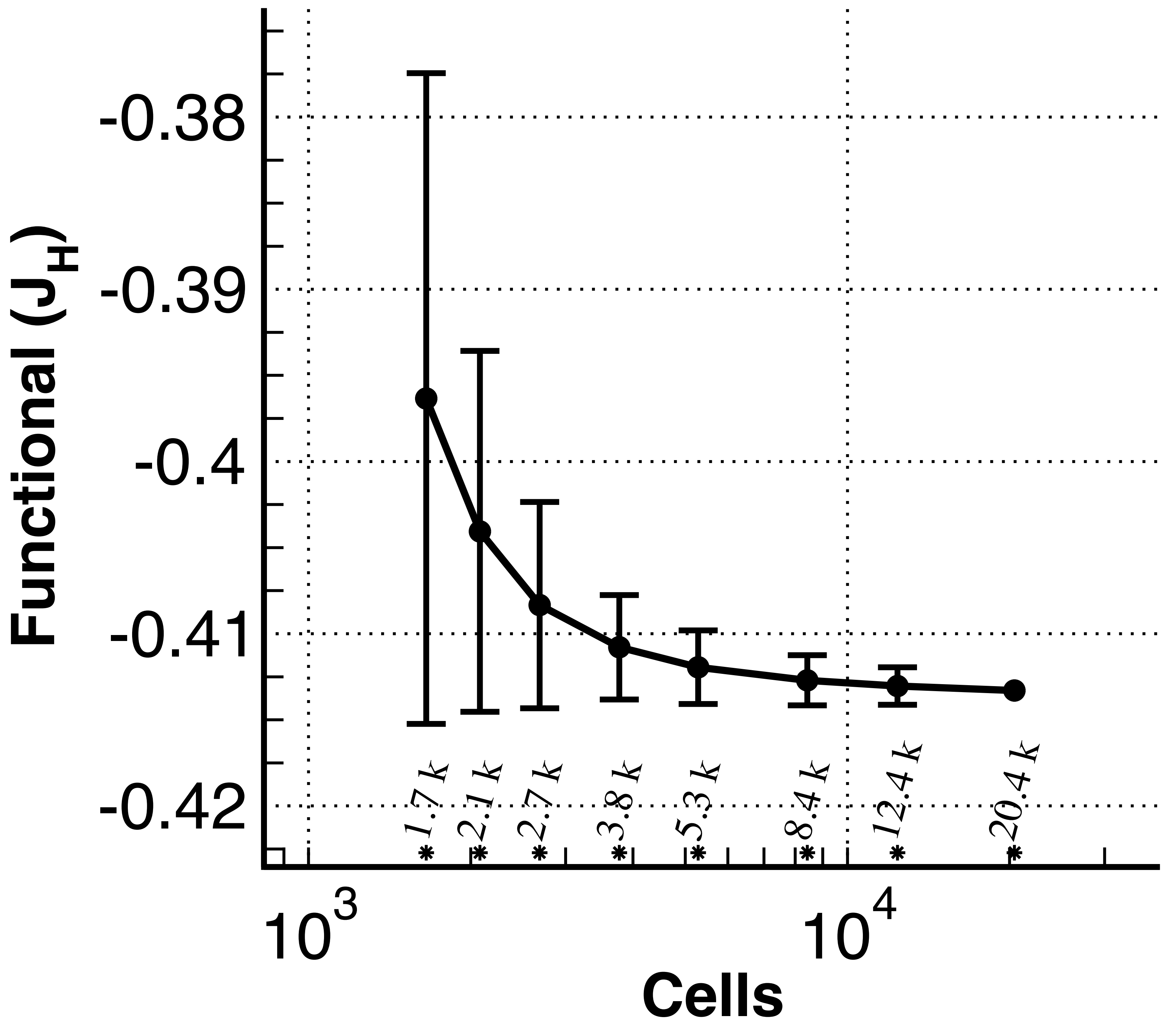


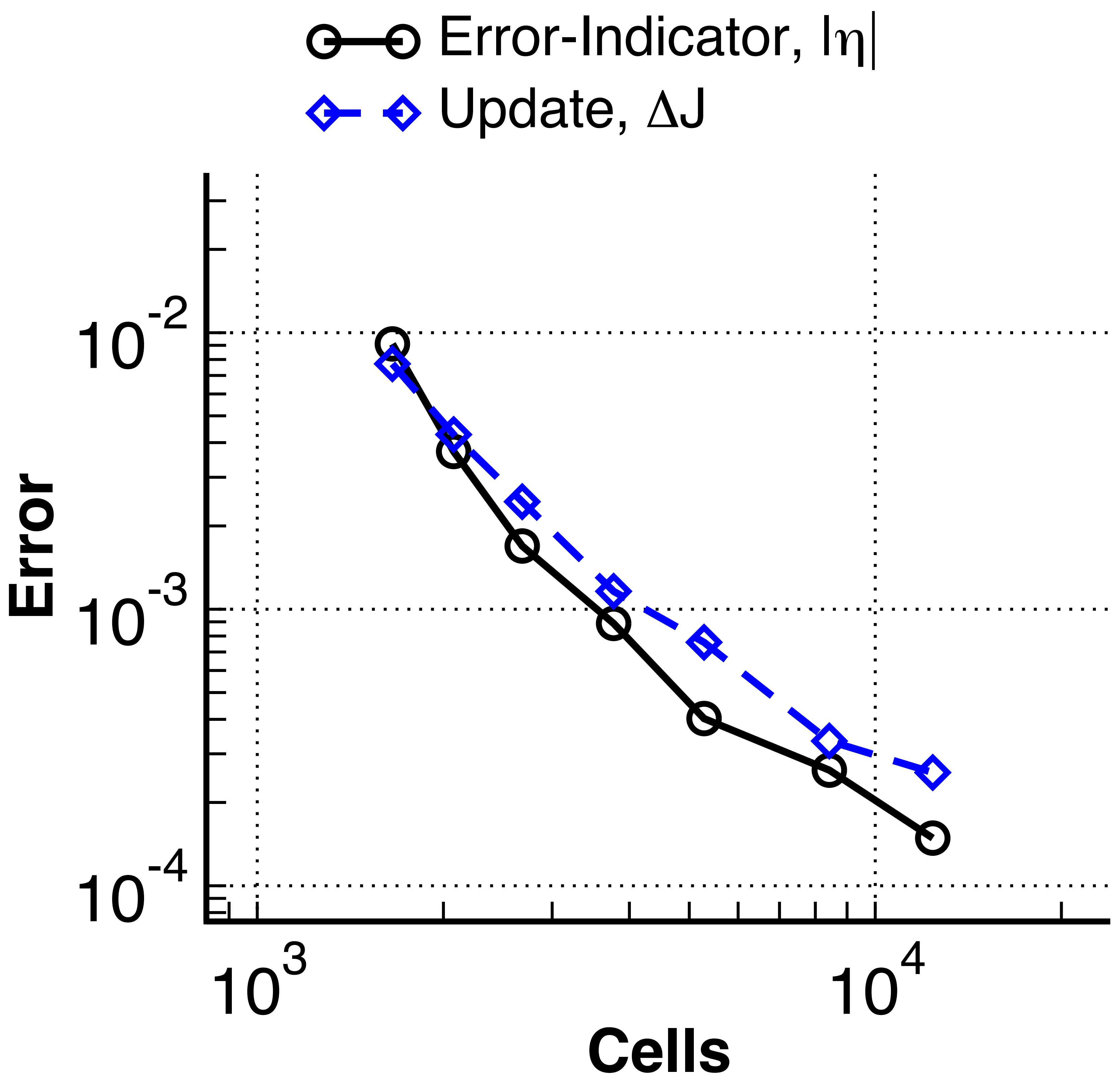
Adaptation Convergence History

Error Bars

$$E \approx |J_c - J_H|$$

$$J_c = J_h(\mathbf{Q}_\mathrm{L}) - \boldsymbol{\psi}_{\mathrm{TQ}}^{\mathrm{T}} \mathbf{R}_h(\mathbf{Q}_\mathrm{L})$$



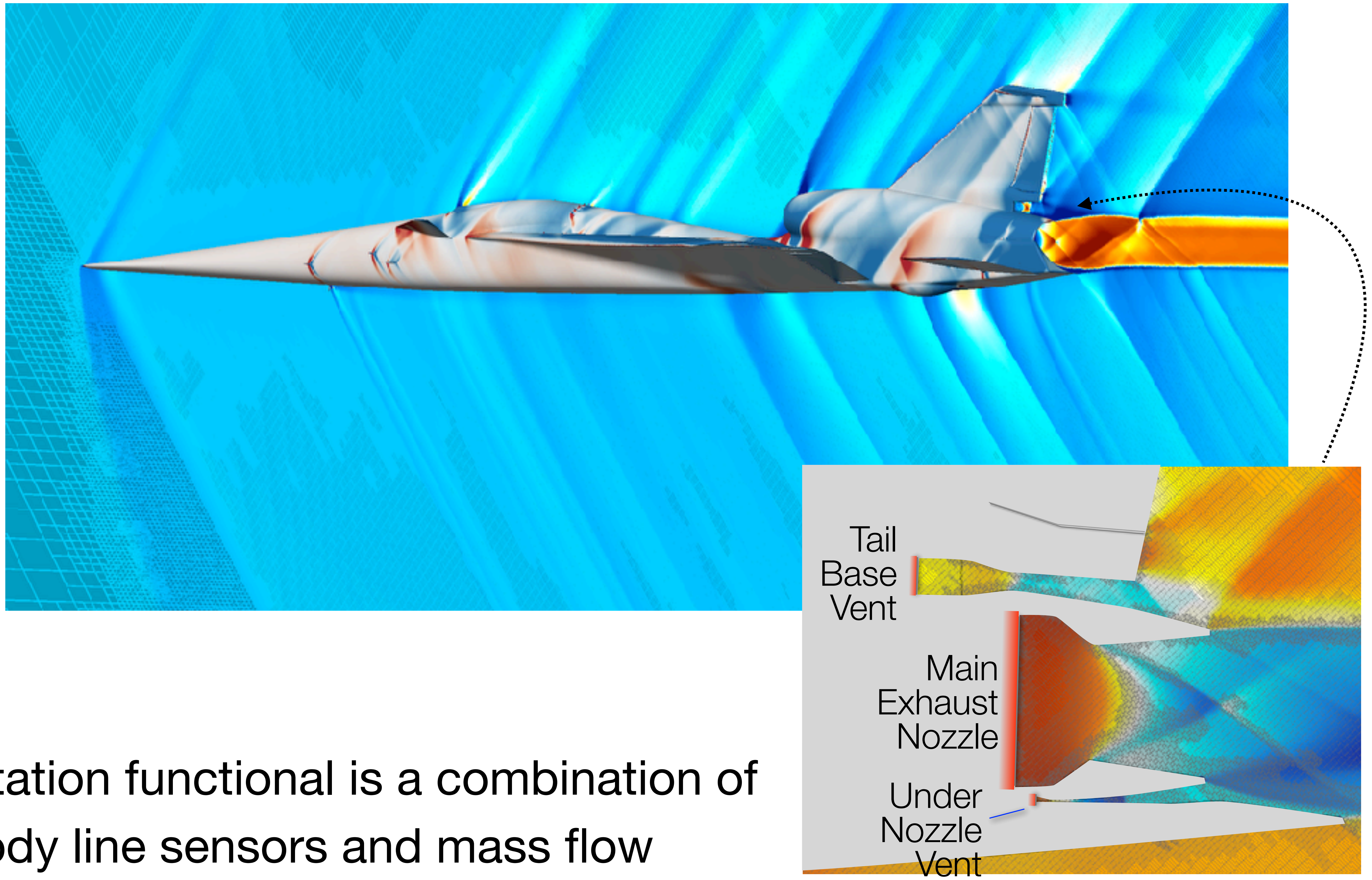


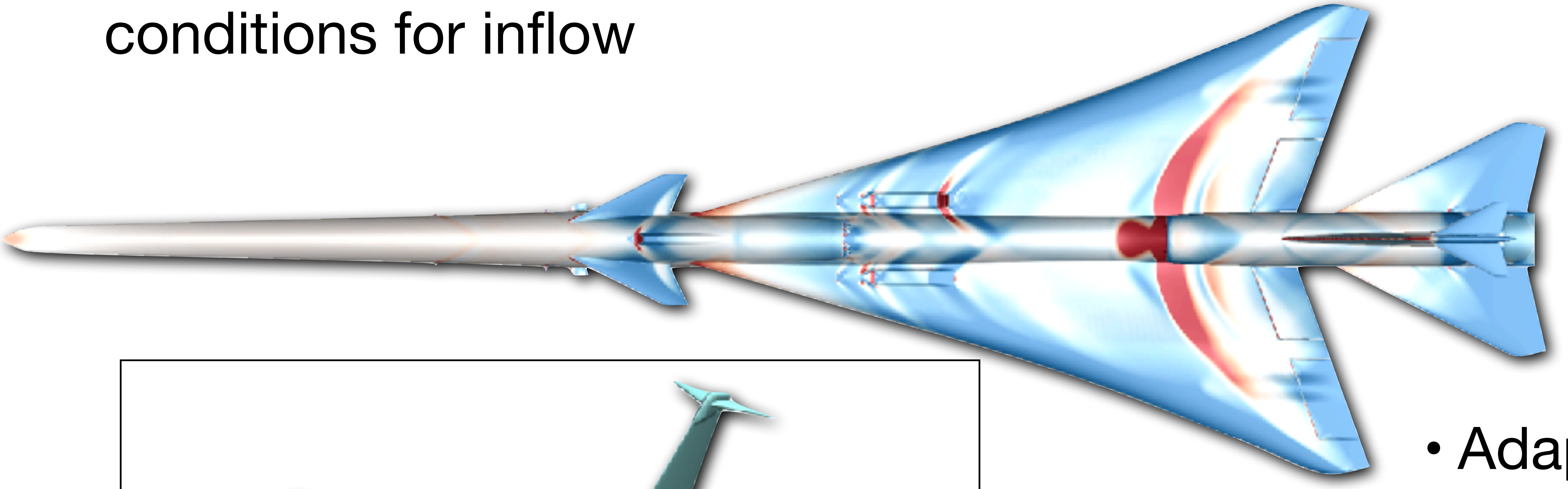
Error Indicator

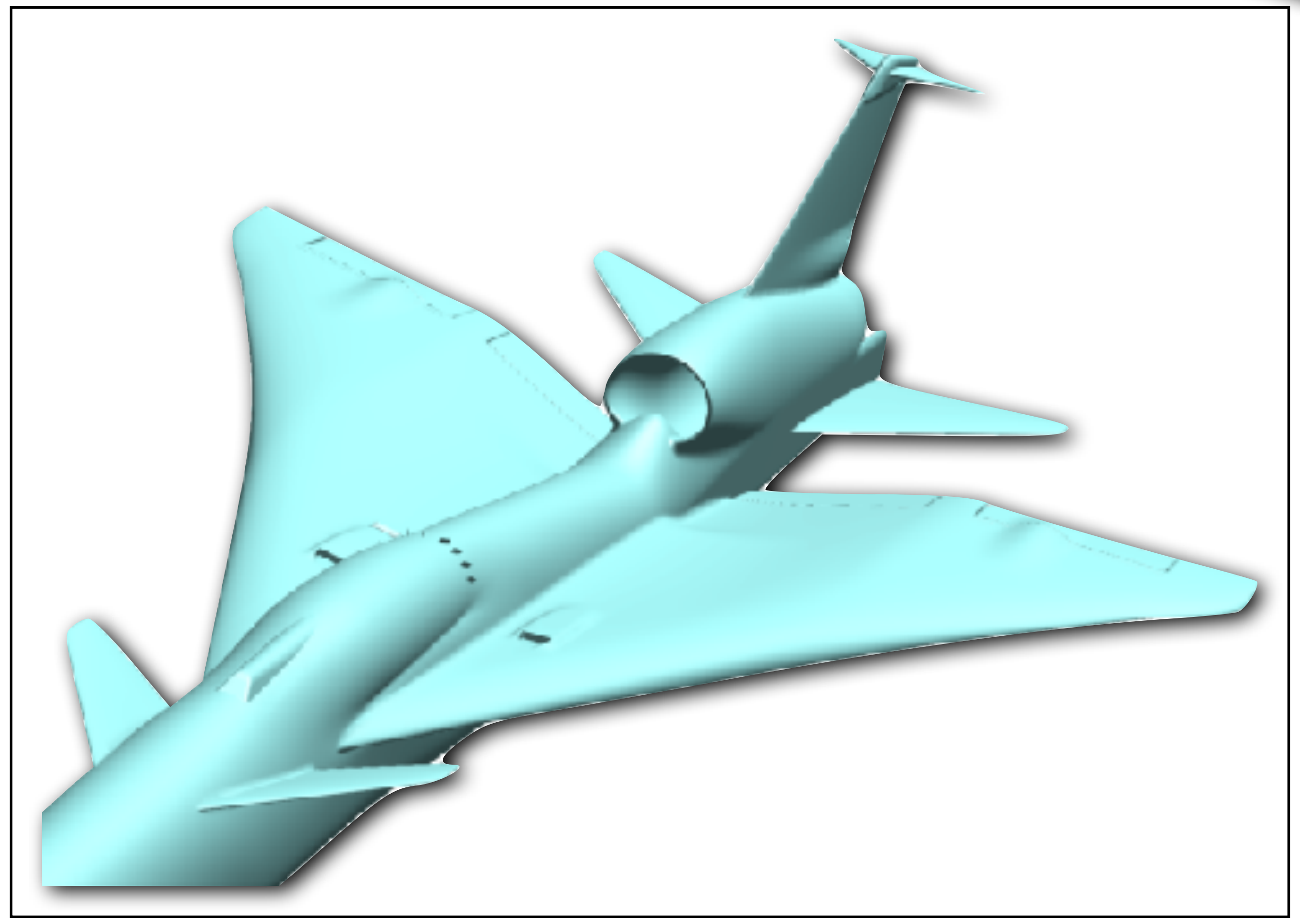
$$\boldsymbol{\eta}_H = \left| \left(\boldsymbol{\psi}_{\mathrm{TQ}} - \boldsymbol{\psi}_{\mathrm{TL}}\right)^{\mathrm{T}} \mathbf{R}_h(\mathbf{Q}_L) \right|$$

X-59 / LBFD Prototype Test Case

- Typical analysis case: M=1.4 and $\alpha = 2.05°$
- Assess accuracy of simulations with and without mass-flow-rate outputs
- 3 inlets and 4 exhausts
- Specified exit pressure outflow and stagnation conditions for inflow





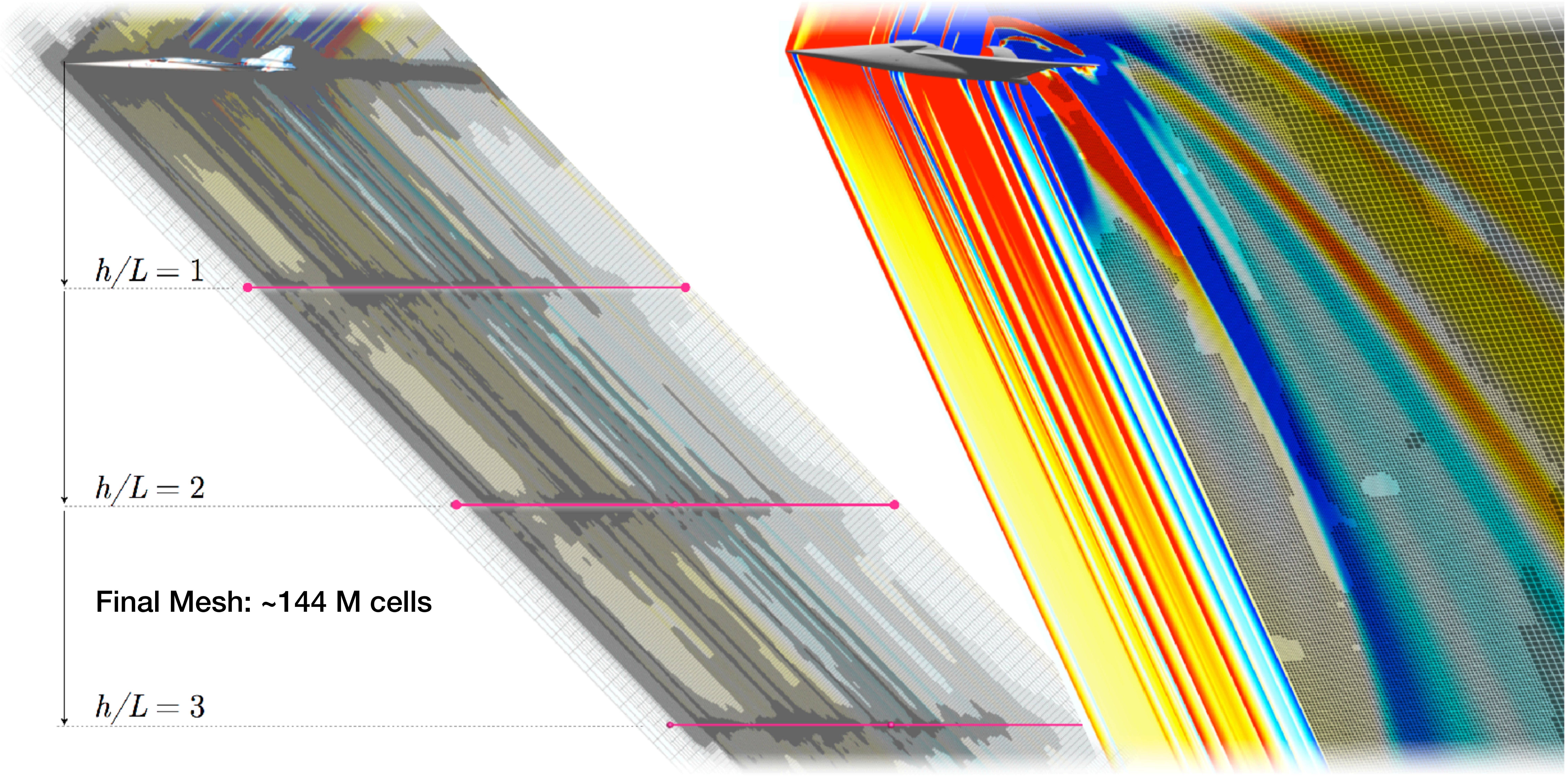


- Adaptation functional is a combination of off-body line sensors and mass flow rates

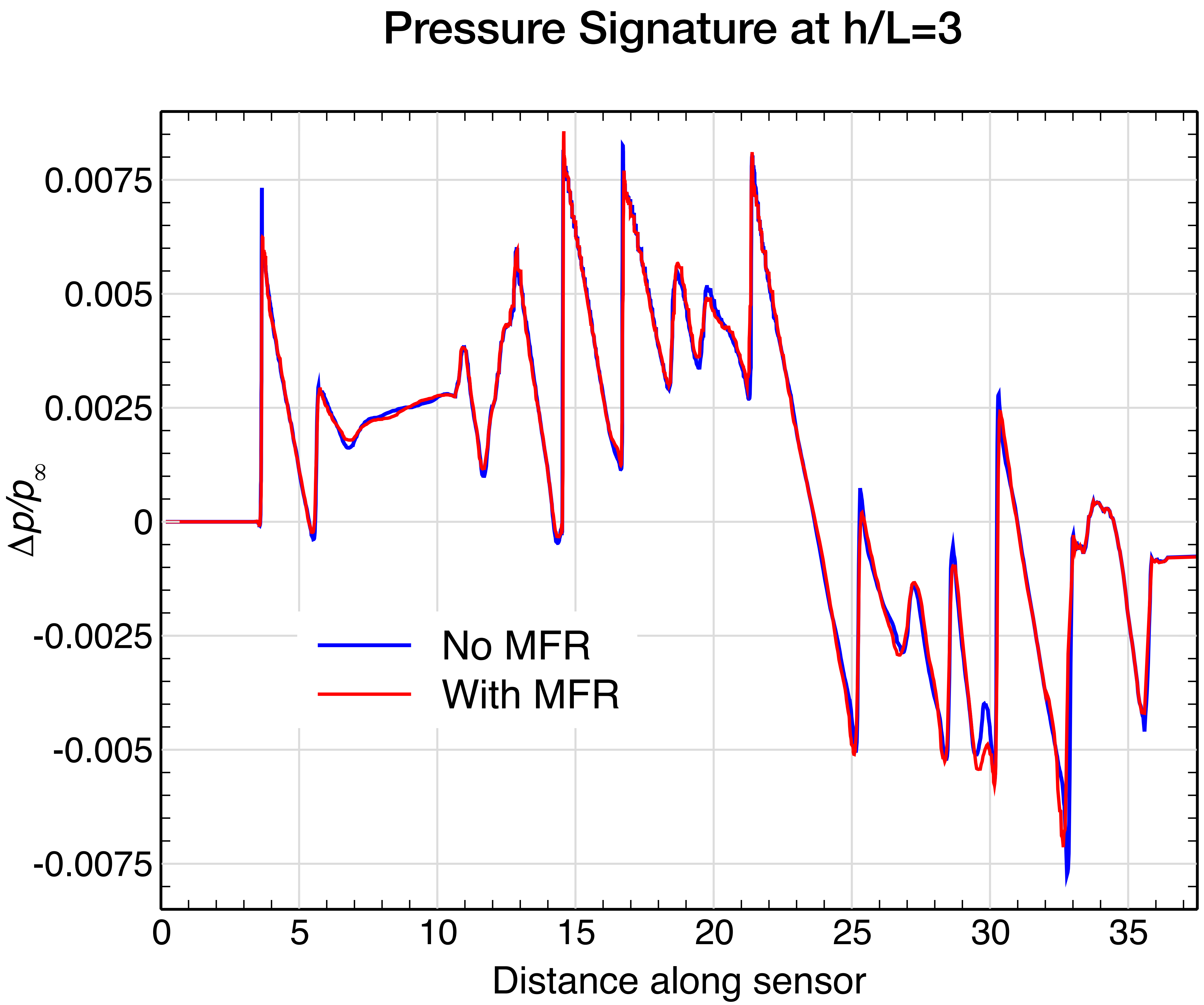
$$J = w_l J_l + w_{\dot{m}} J_{\dot{m}}$$

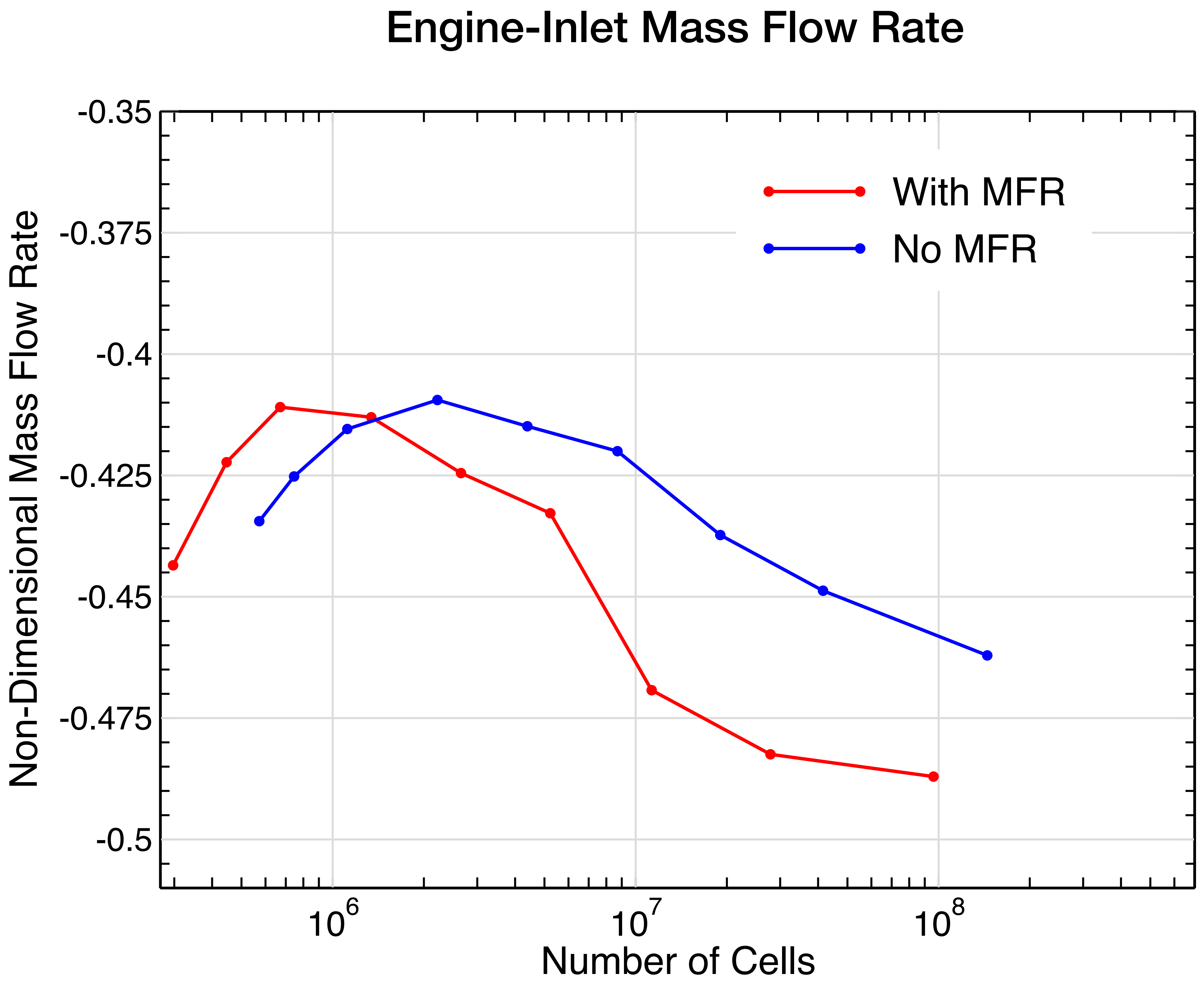
$$J_l = \int_0^L \left(\frac{\Delta p}{p_\infty}\right)^2 ds \qquad J_{\dot{m}} = \int \rho U_{\mathrm{n}} dA$$

Adapted Mesh for Multiple Sensor Locations

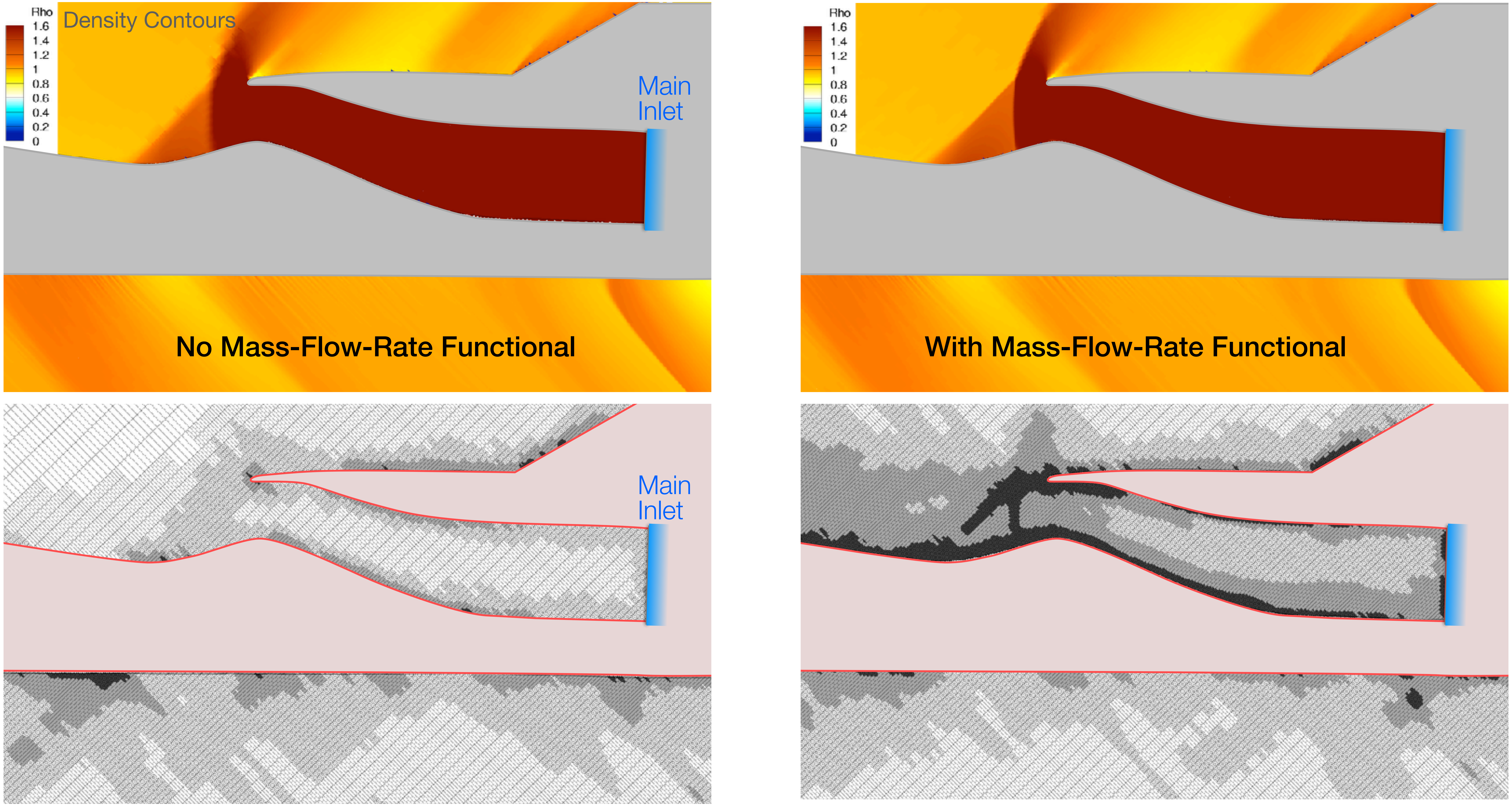


Output Convergence



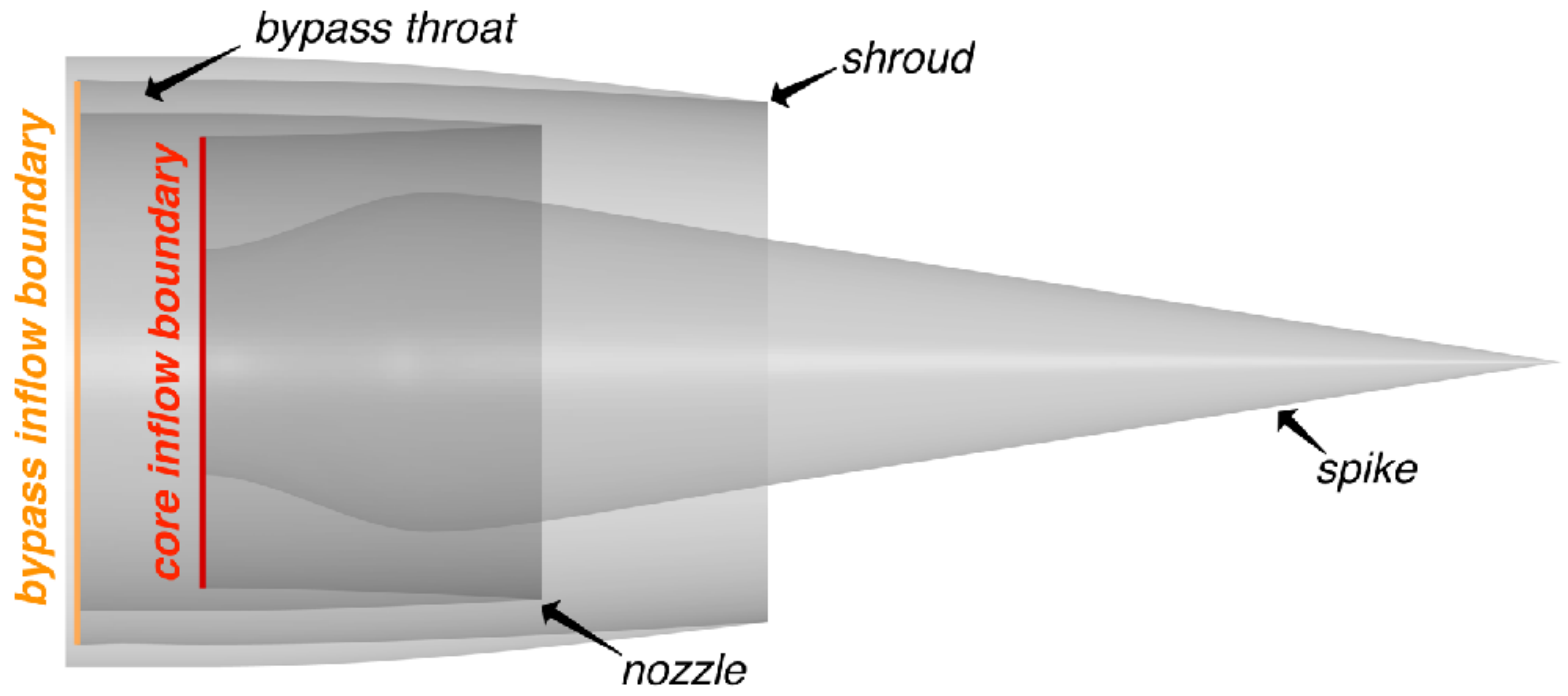


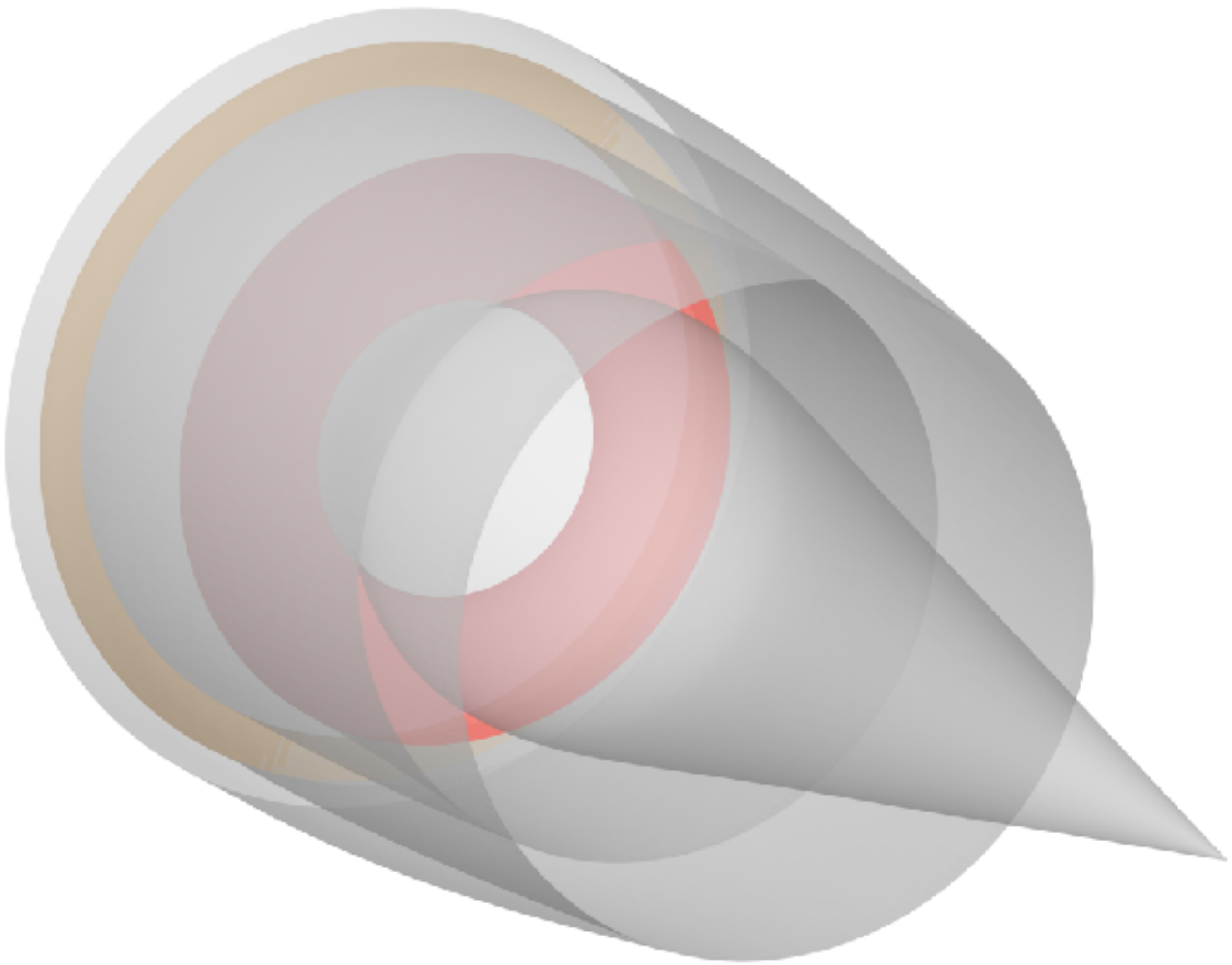
Comparison of Flow Solution and Mesh



Supersonic Nozzle Shape Optimization

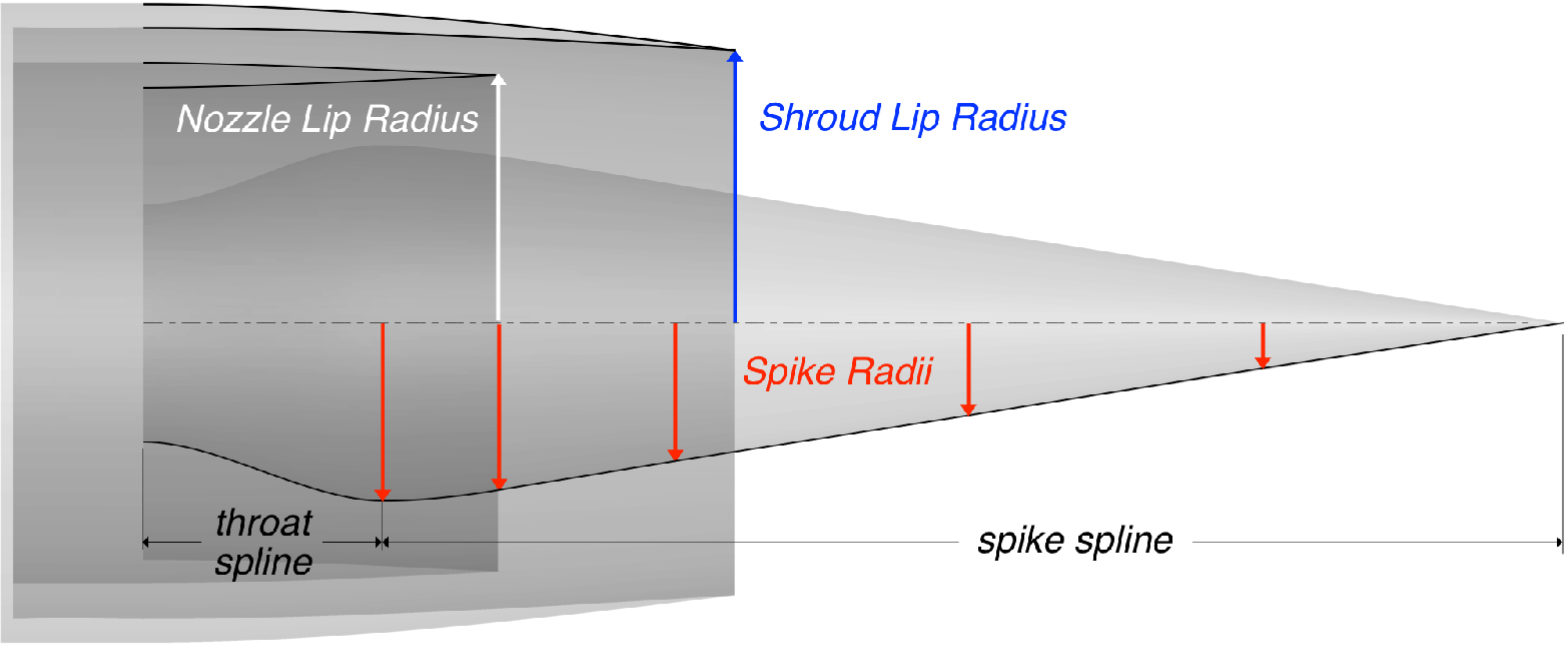
Dual-Stream Supersonic Spike Nozzle





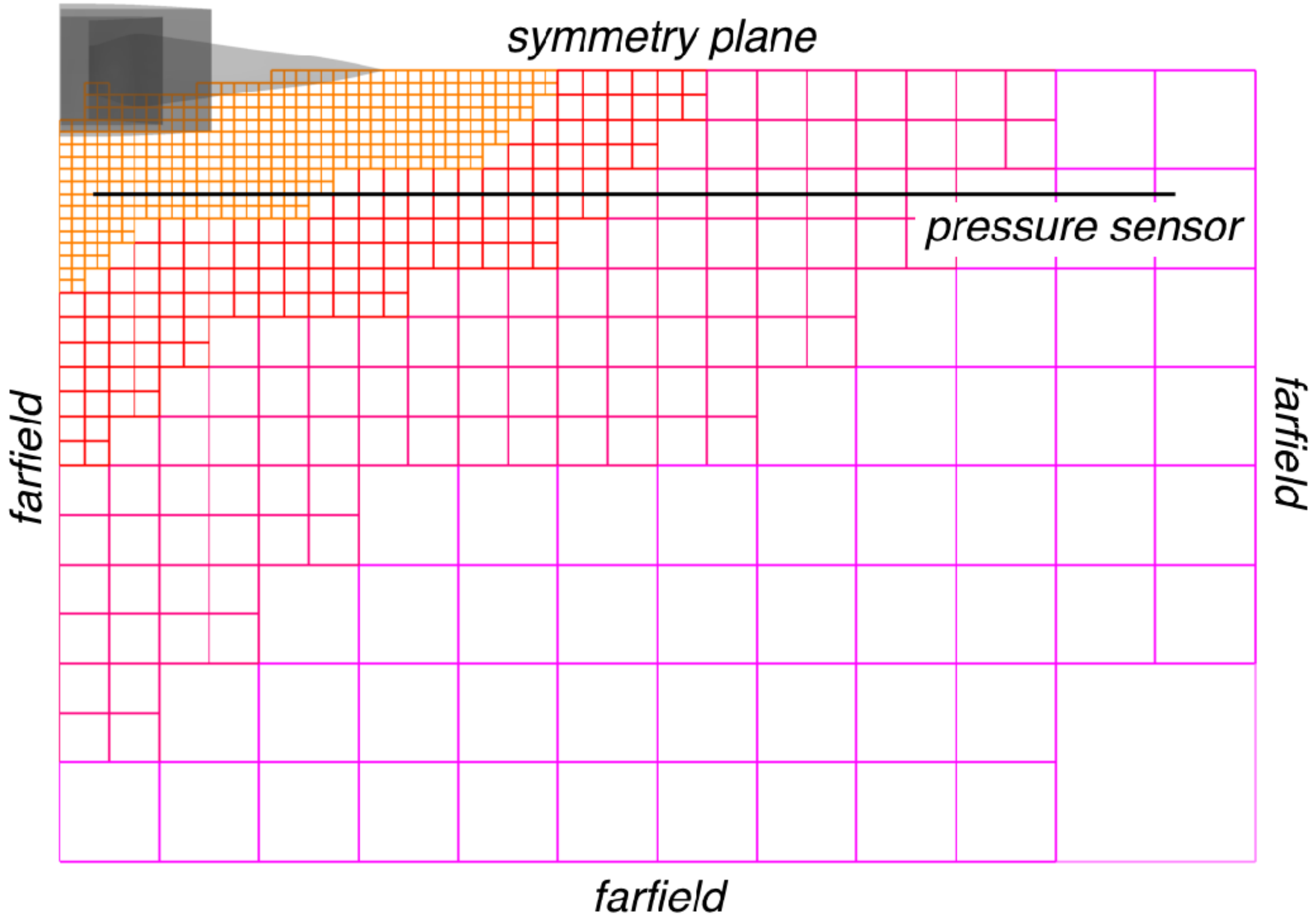
- M=1.4
- 2 inflow boundaries: hot core stream and cooler bypass stream
- Goal is to maximize thrust and minimize nearfield shock disturbances subject to fixed mass flow rates

Design Variables

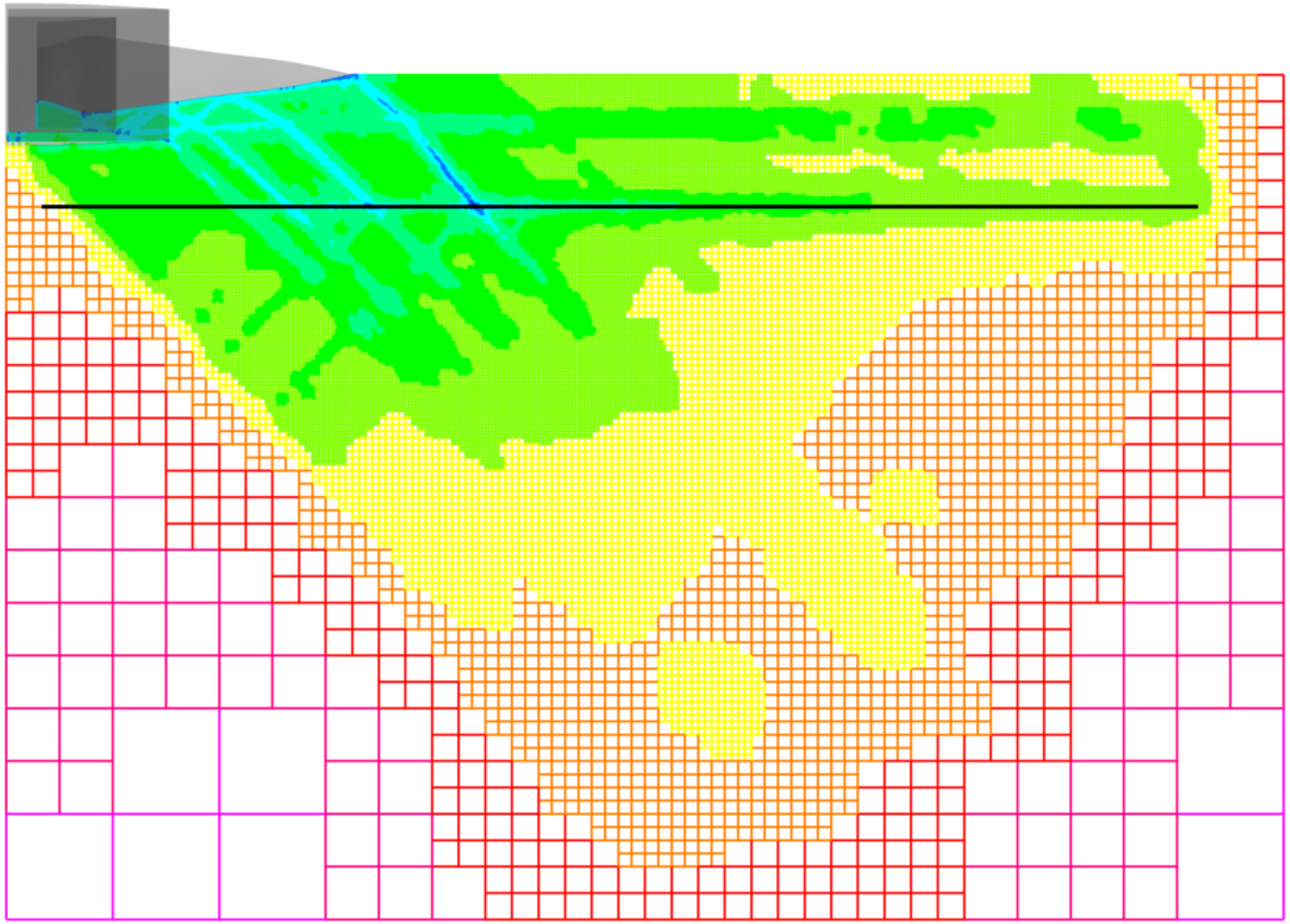


- Design Variables: 7
- Fixed length and minimum radii bounds

Initial Mesh and Computational Domain

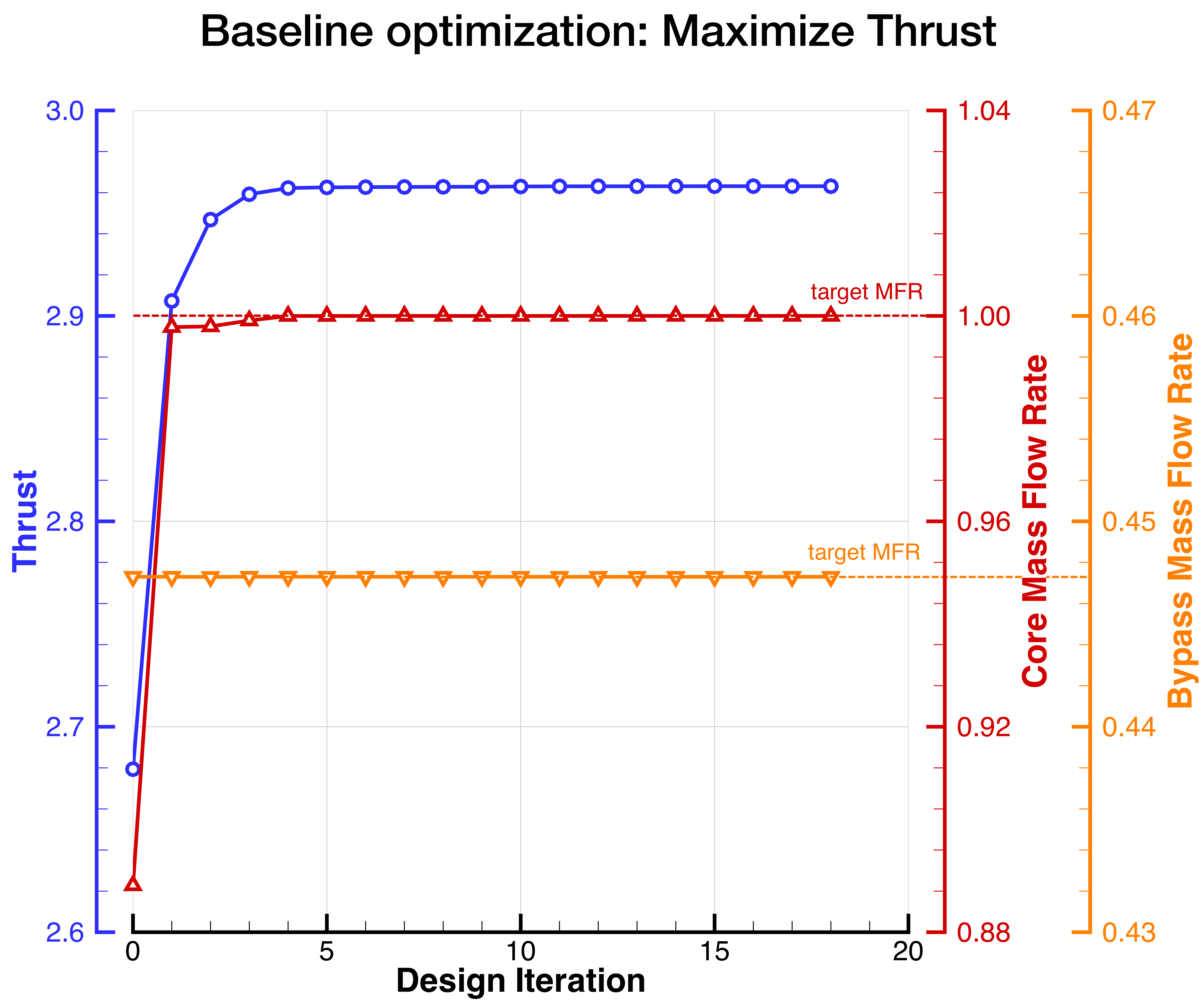


Final Mesh for Baseline Design

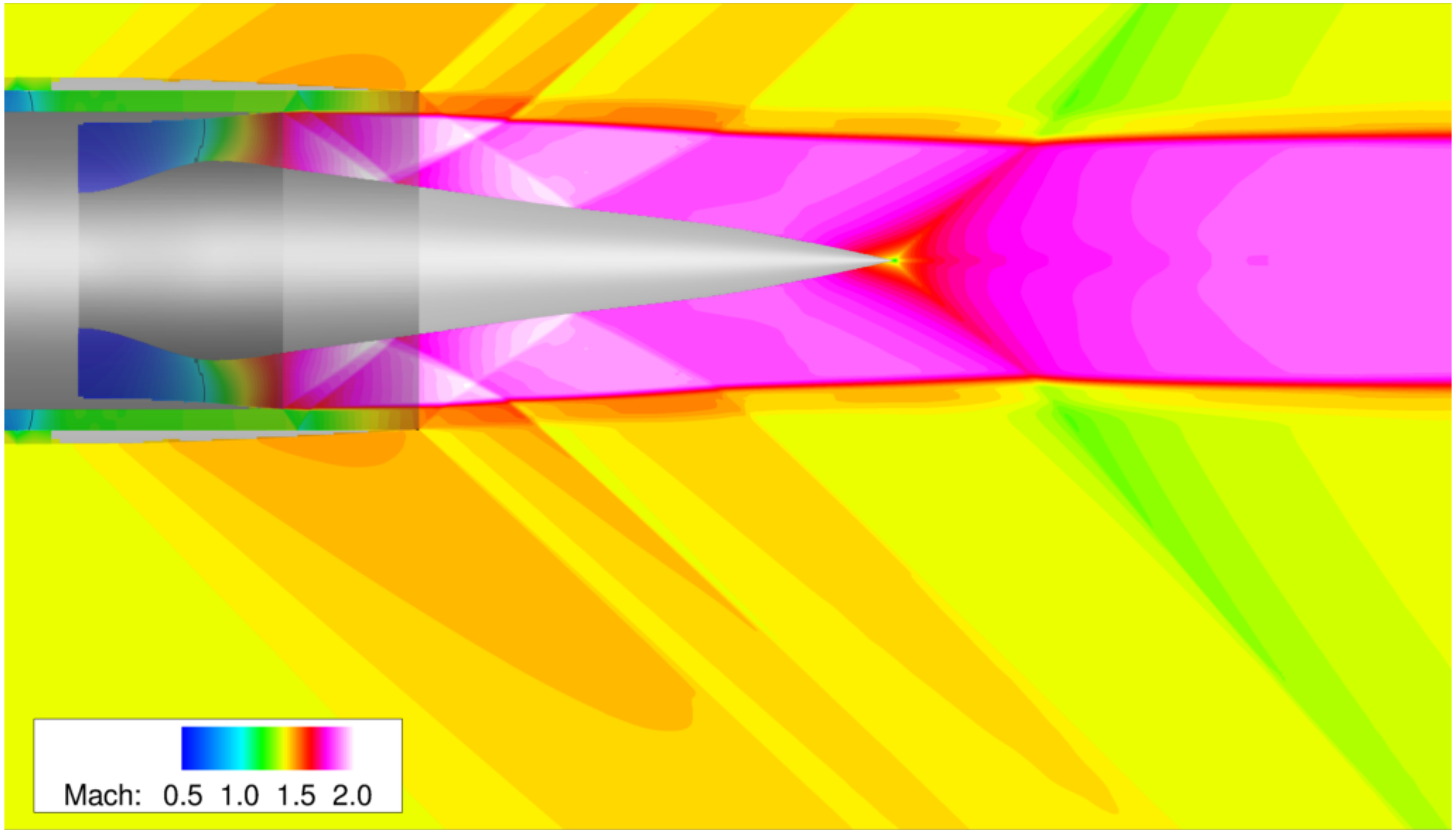


- Each design iteration uses 8 mesh adaptations
- Final mesh ~ 20M cells
- Adaptation functional is sum of thrust, mass flow rates, and line sensor

Optimization Convergence History

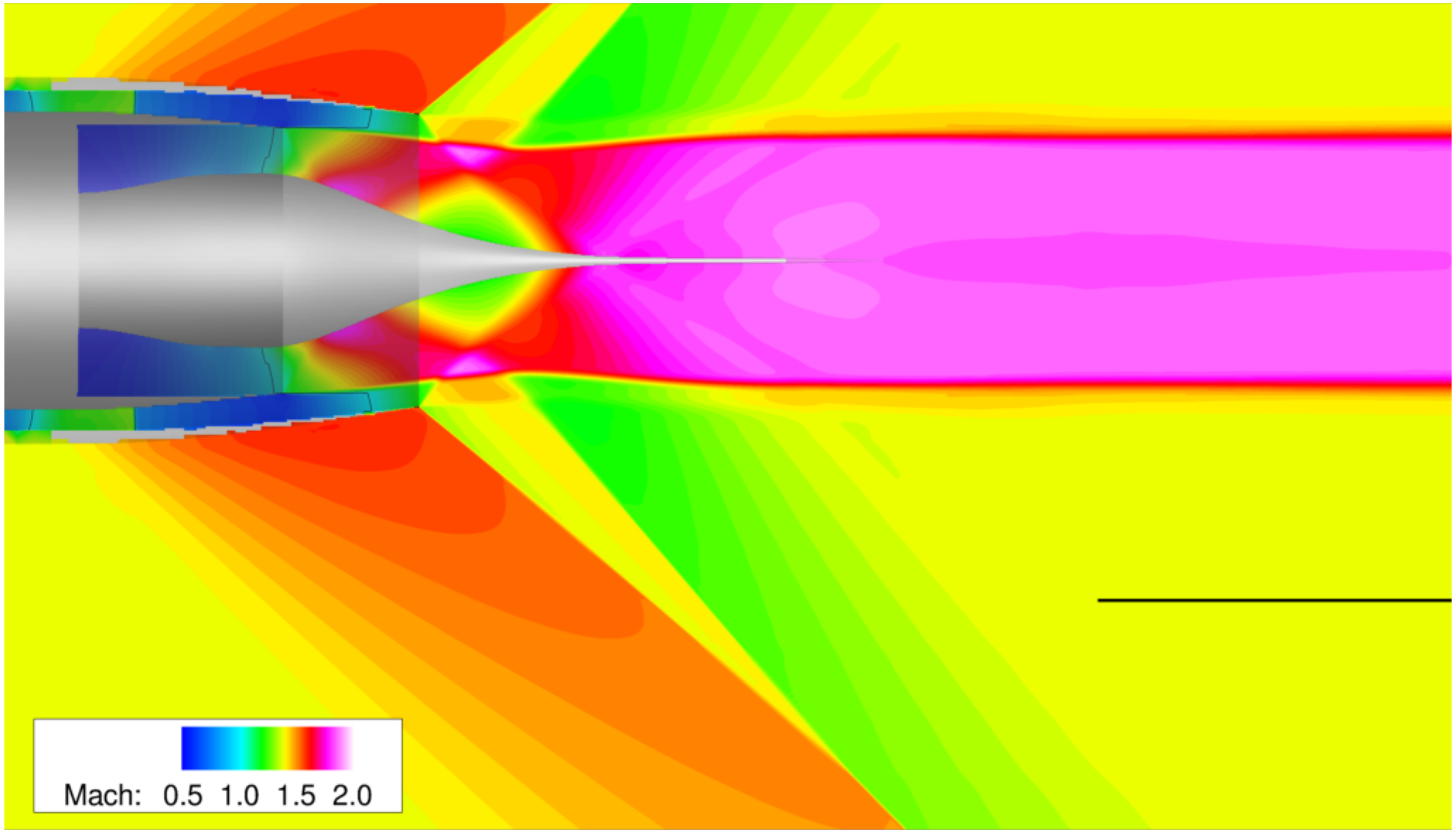


Maximize Thrust



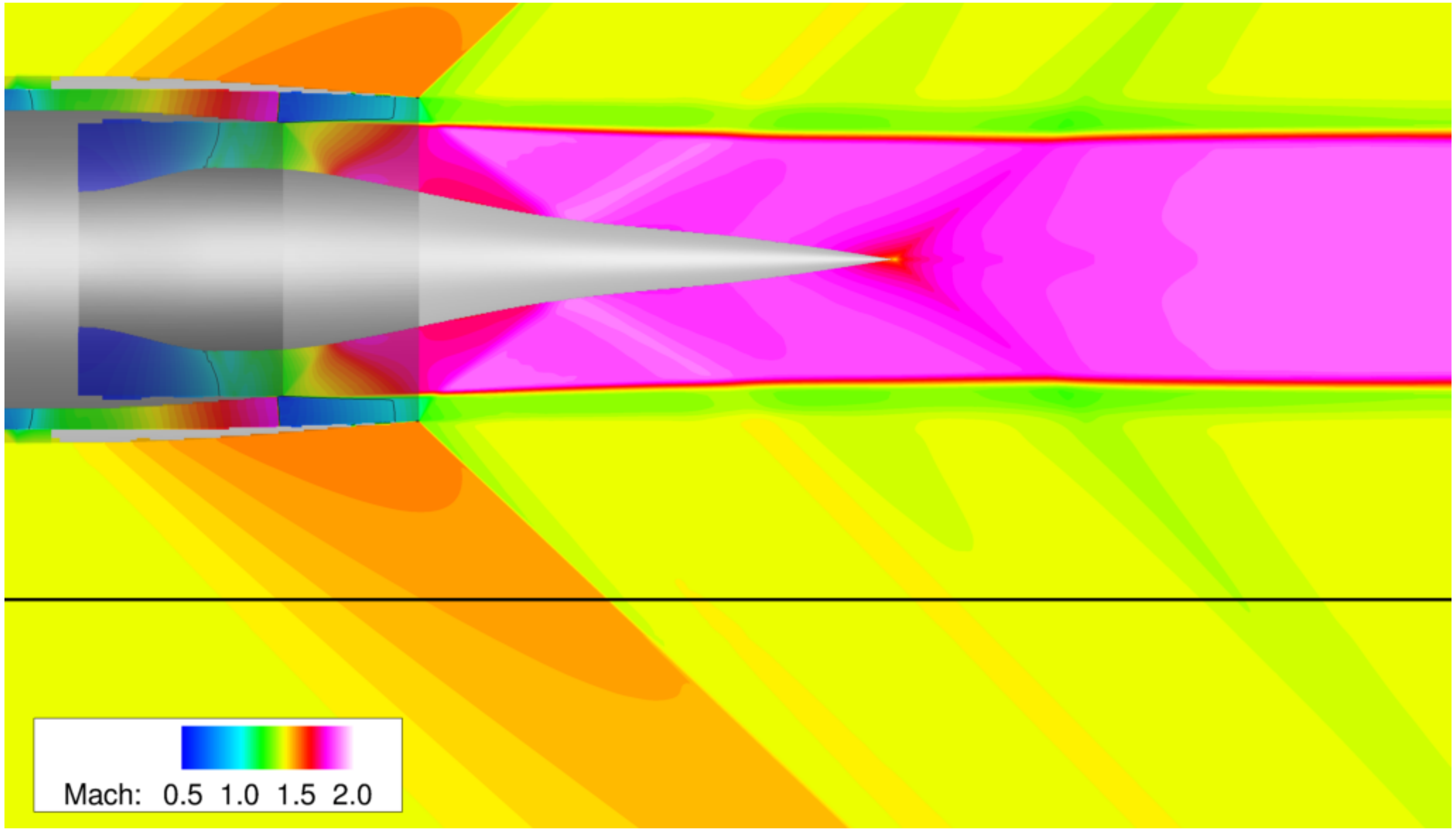
Several strong shocks in nearfield from cowl, shroud and spike tip

Maximize Thrust and Eliminate Aft Shock



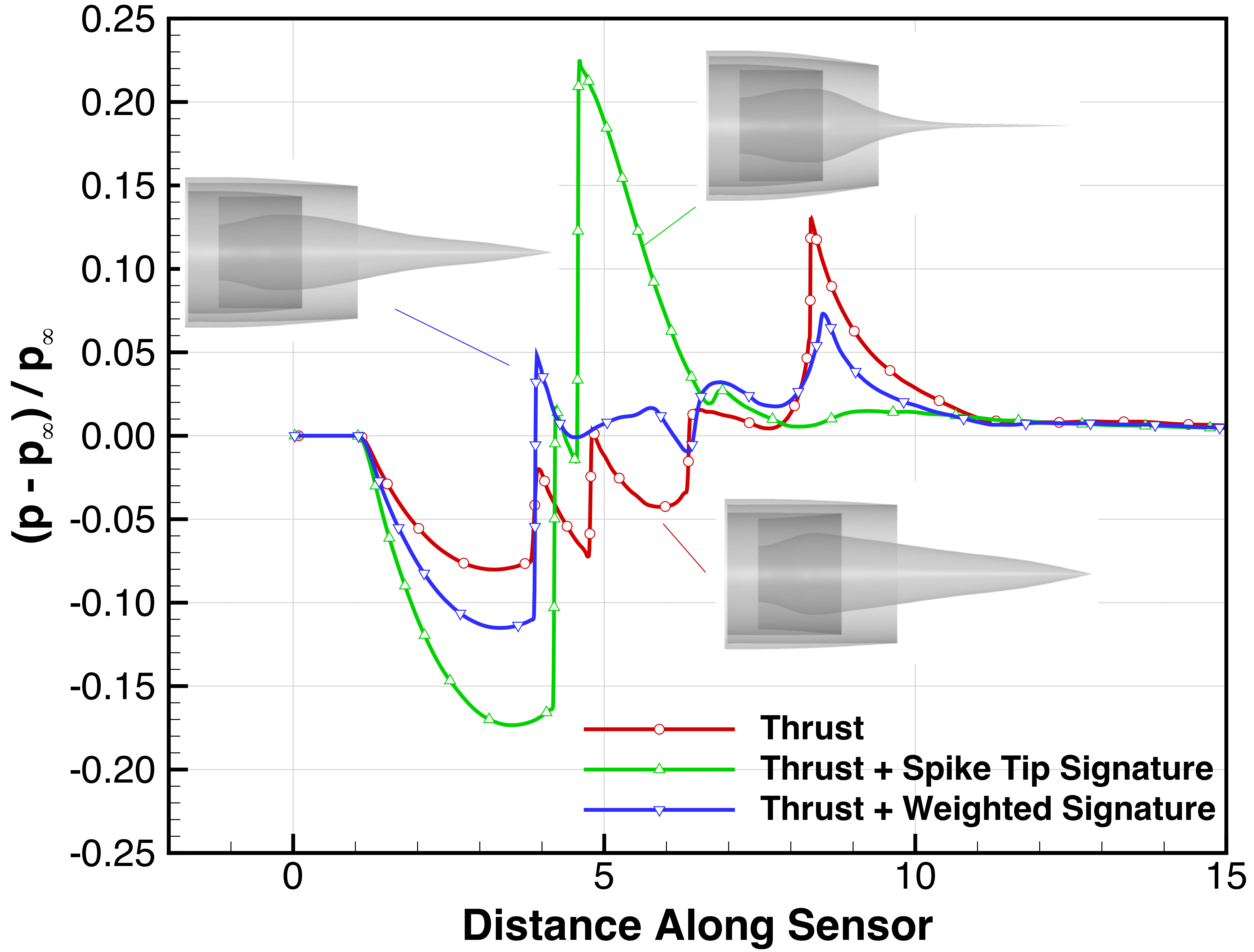
Shock-free at spike tip, but thrust reduced by 2.7%

Maximize Thrust and Attenuate All Shocks



Weak boat-tail and spike-tip shocks, and thrust within 1.7% of baseline

Comparison of Pressure Signatures



Conclusions

Reliable evaluation of mass flow rates at permeable boundaries

- Adjoint consistent implementation of permeable boundary conditions
- Numerical studies show no spurious oscillations in the near-wall adjoint
- Verification test problem demonstrates convergence to the exact solution at the expected rate
- *Specifying mass-flow-rate outputs in practical, low-boom simulations significantly improves prediction of these outputs without compromising pressure-signature accuracy*

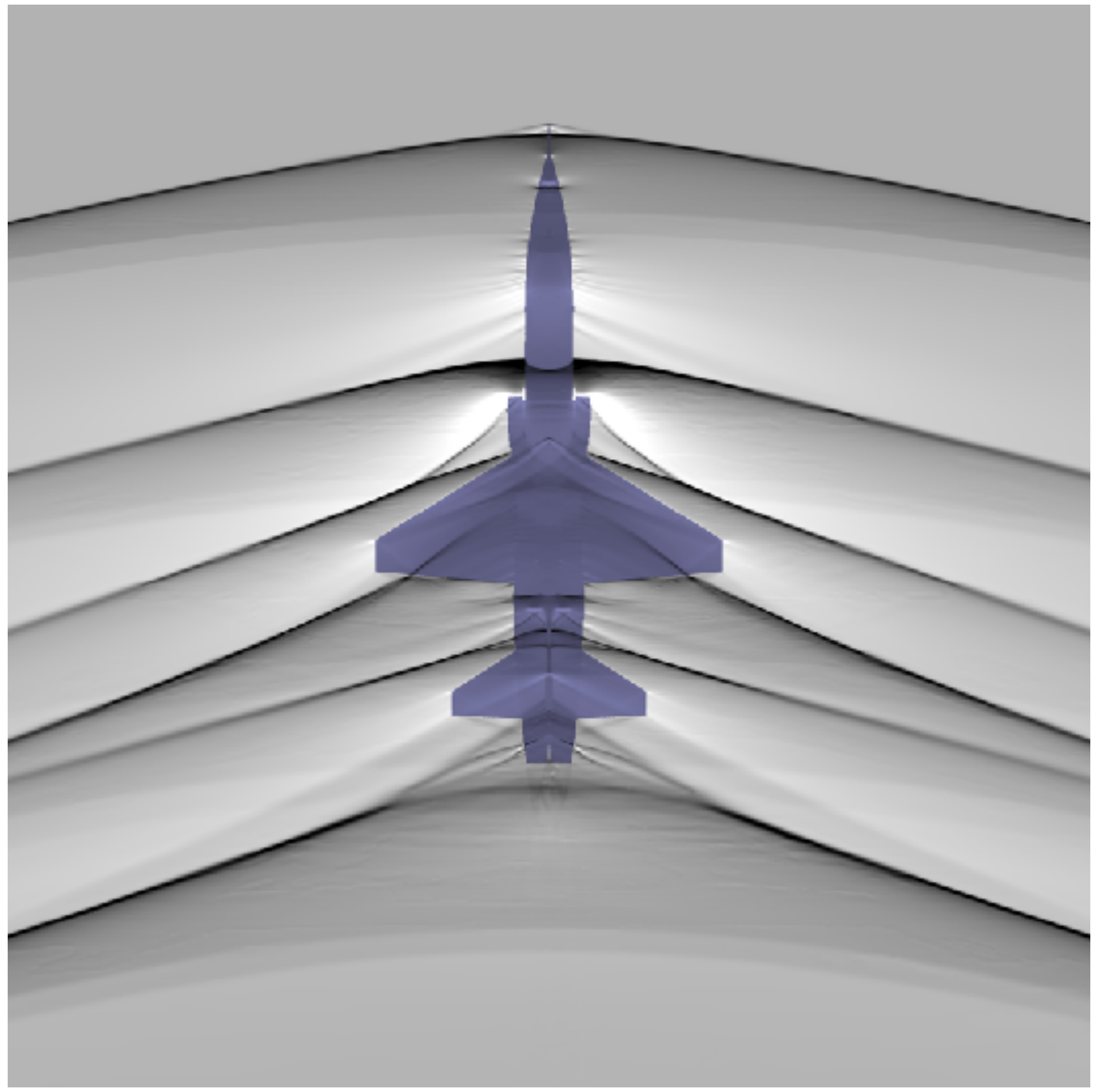
New capability to handle design optimization problems subject to mass-flow-rate constraints

- Efficient reuse of adjoint solutions and error control in low-boom shape optimization

Next step: Investigate adjoint consistency of more general outputs, e.g. total pressure recovery and flow distortion

Acknowledgements

- NASA's ARMD Commercial Supersonic Technology and LBFD/X-59 Projects
- NASA Ames Research Center contract NNA16BD60C
- NASA High-End Computing Program for computing resources



Questions?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