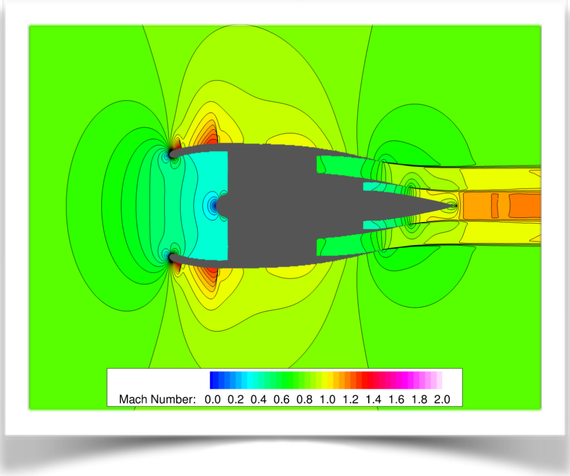
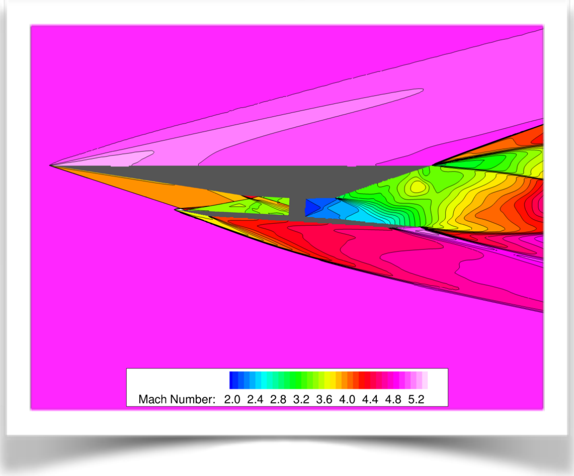
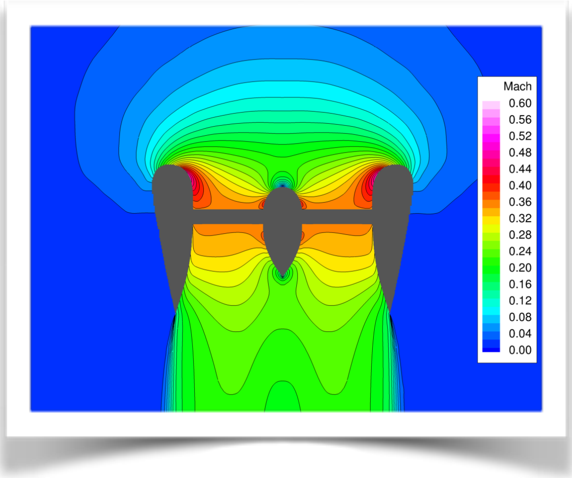




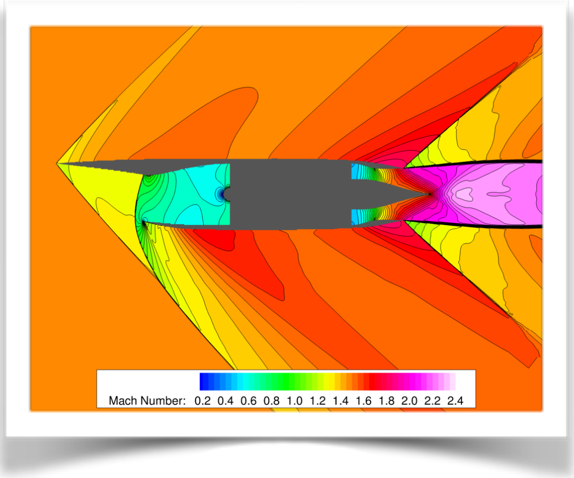
Formulation and Implementation of Inflow/Outflow Boundary Conditions to Simulate Propulsive Effects



David L Rodriguez
Michael Aftosmis
Marian Nemec

May 10, 2018
AMS Seminar Series

NASA Ames Research Center
Science & Technology Corporation

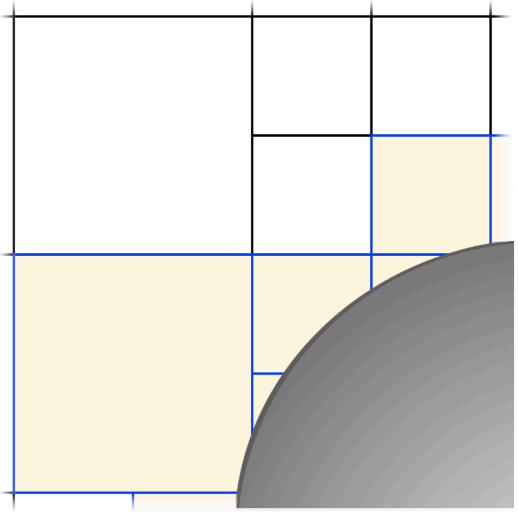


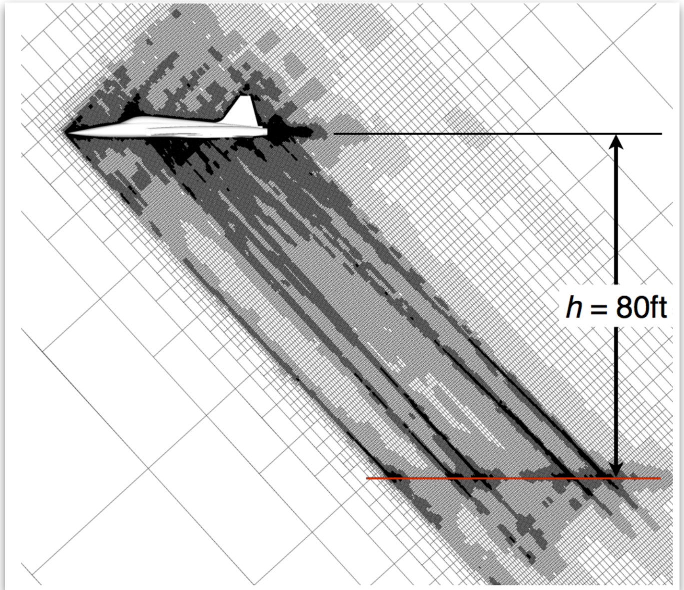
Computational Aerosciences Branch

Advanced Supercomputing Division

Cart3D Aerodynamic Analysis & Design Package

- Automated multilevel Cartesian mesh generation with adjoint-driven adaptive refinement
- Cut-cell approach in cells that include model surface
- Finite volume, 2nd-order accurate Euler solver with explicit Runge-Kutta time stepping and multigrid
- Steady or time-accurate
- Part of a design framework allowing for gradient-based aerodynamic shape optimization of user-specified functional
- Shown to be highly effective for analysis and design of low boom aircraft



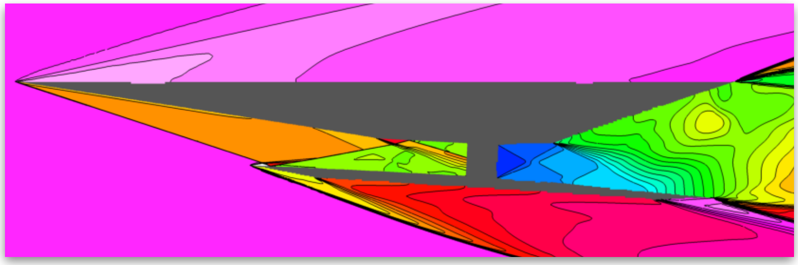


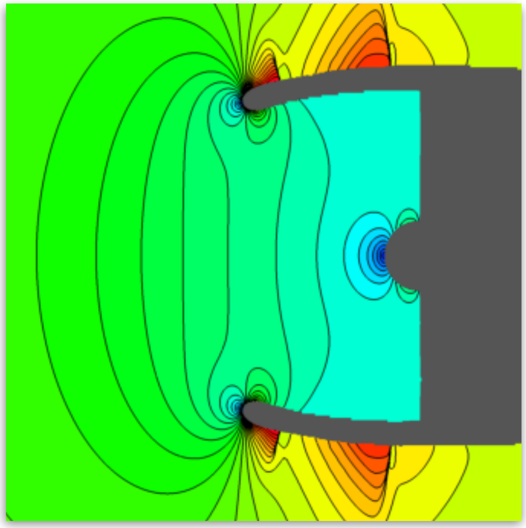
Motivation for New Boundary Conditions

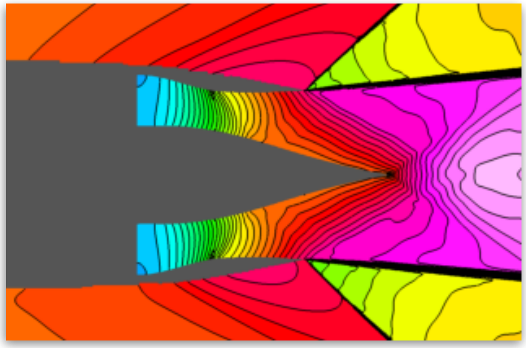
- Current **`SurfBC`** inflow/outflow boundary condition requires user to specify an entire state (ρ, u, v, w, p) at the boundary (Pandya, 2004)
  - Riemann solver is applied to compute flux at the boundary and thus boundary condition is always well-posed
  - Robust and flexible since it can be used for both inflow and outflow, subsonic and supersonic
- Inconvenient when user wants to specify inflow or outflow with minimal information
  - for subsonic flow through inlets, a common boundary condition is back pressure
  - for subsonic flow into nozzles, a common boundary condition is specifying total pressure and total temperature (and flow direction)
  - very difficult to specify mass flow rate, particularly in cases where nonlinear flow features are prevalent

Cart3D Surface Boundary Conditions

- Solid wall
- Specify full flow state and use Riemann solver (`SurfBC`)
  - Pandya, Murman, Aftosmis, 2004
  - for all inflows and outflows
- Subsonic Outflow
  - back pressure NEW
  - constant normal velocity NEW
- Subsonic Inflow
  - total pressure and total temperature NEW
  - mass flow rate and total temperature NEW

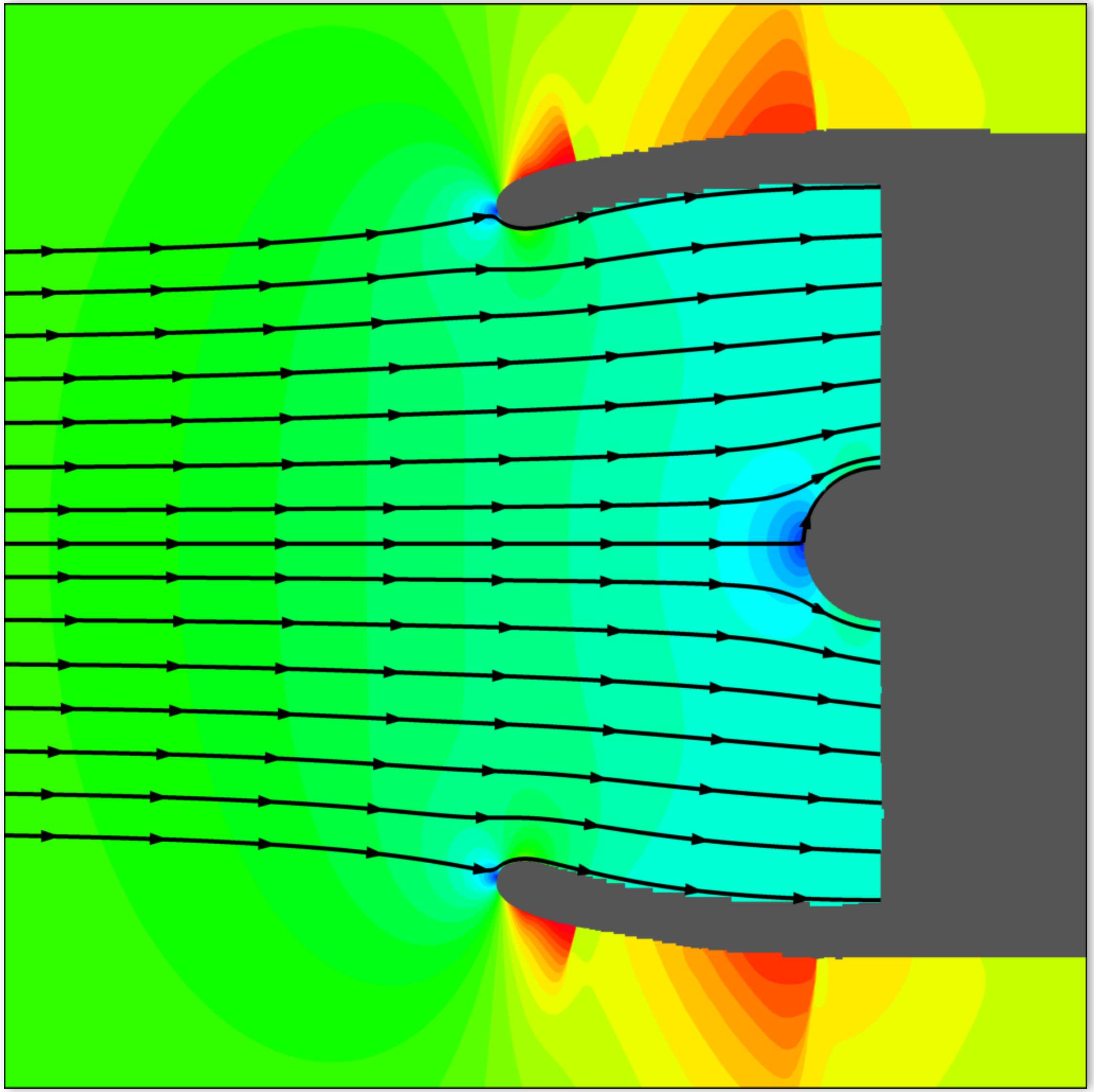






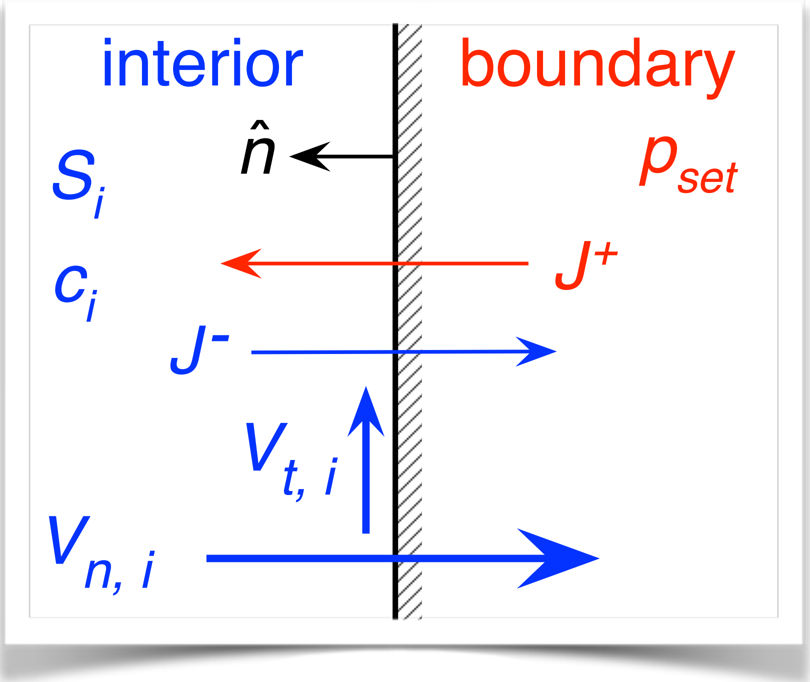
Subsonic Outflow Boundary Conditions

- One flow quantity specified at boundary
  - back pressure
  - normal velocity
- Four flow quantities extrapolated from interior



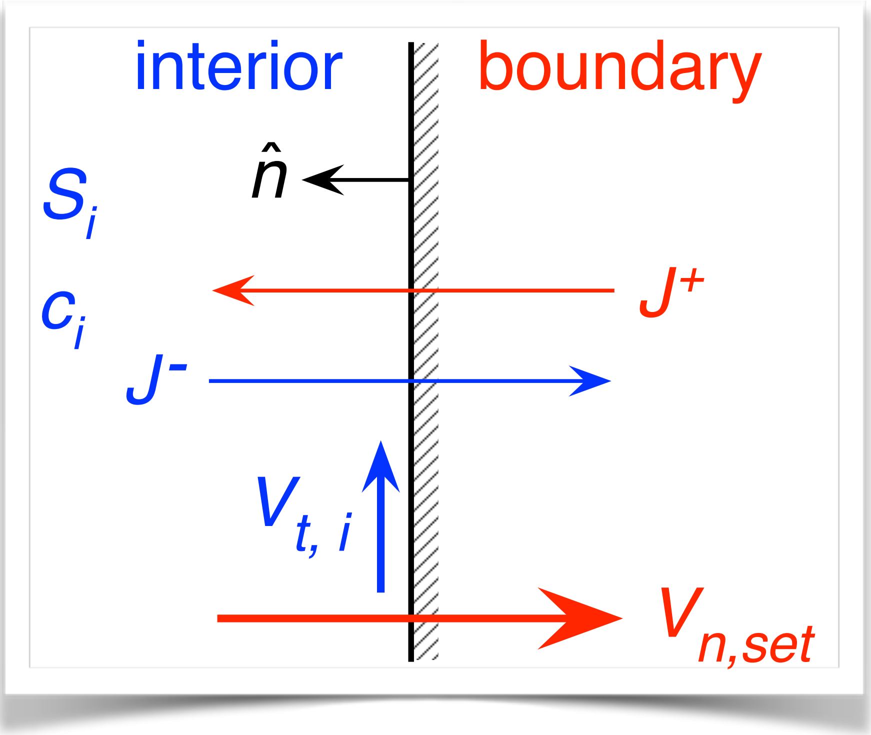
Back Pressure Outflow

- Most other CFD solvers have this common option
- Pressure set to specified value at boundary
- Entropy and tangential velocity extrapolated from interior
- Riemann invariants used to compute boundary state



- Safeguards
  - if flow reverses back into interior (back pressure too high), solid wall boundary enforced
  - if interior flow goes supersonic, compare back pressure to pressure after normal shock occurring at boundary
    - if set back pressure is higher, use after-shock state at boundary, forcing subsonic flow in the interior
    - if set back pressure is lower, extrapolate all flow attributes from interior (supersonic outflow)
- Can be difficult to obtain specific mass flow rate for nonlinear flows

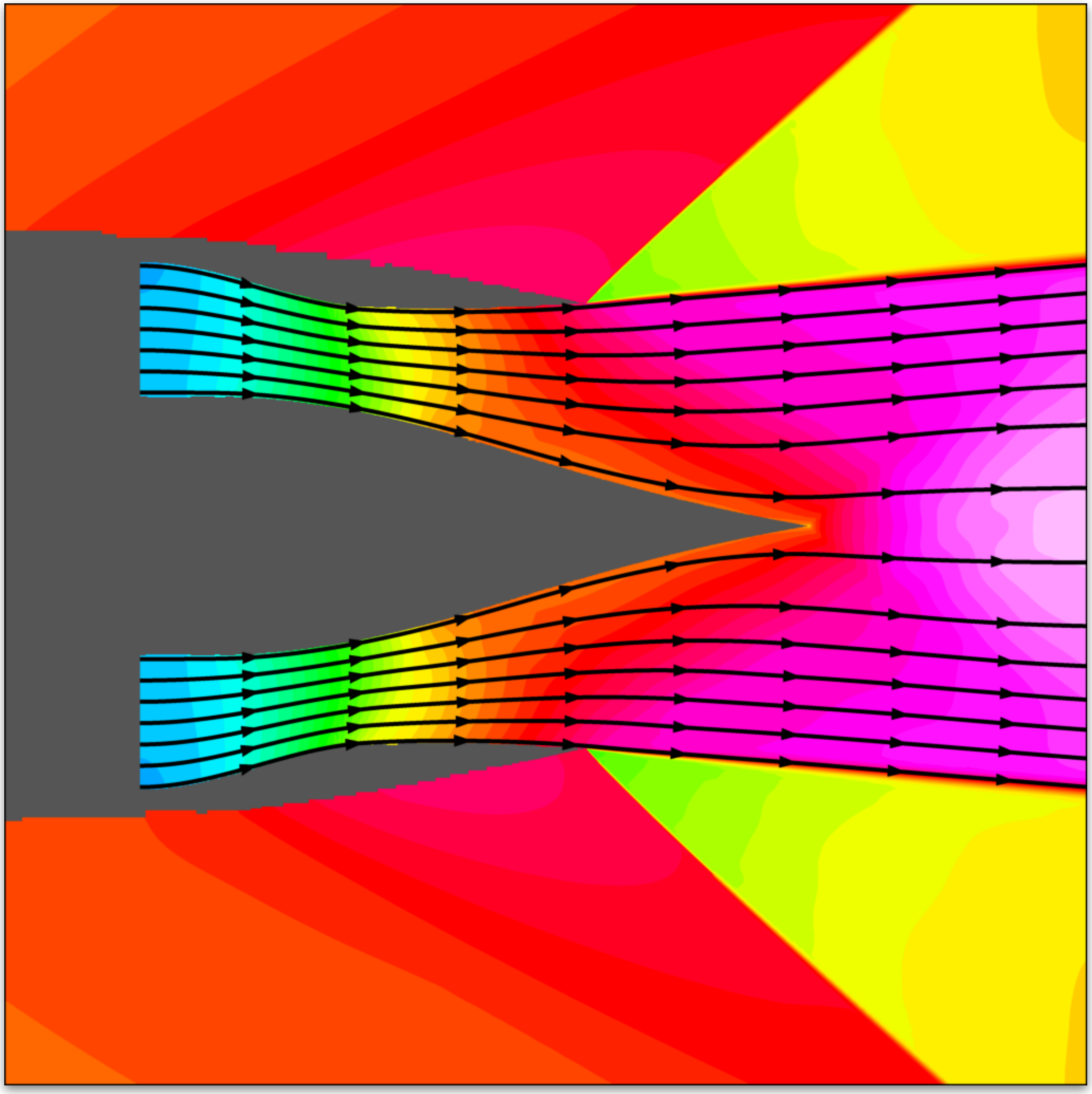
Constant Normal Velocity Outflow



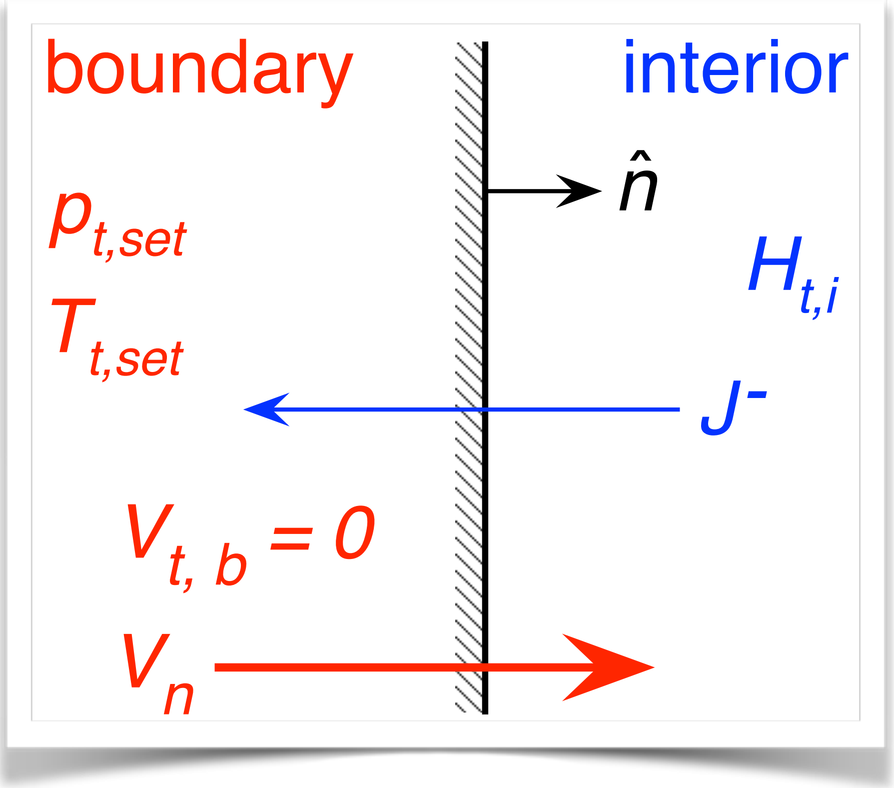
- Allows for robust mass flow rate steering
- Might better represent flow in front of an engine fan face (Pearson ’59, Reid ’69)
- Normal velocity set to specified value at boundary
- Entropy and tangential velocity extrapolated from interior
- Riemann invariants used to compute boundary state
- Safeguards
  - when interior flow is subsonic but boundary flow is supersonic (bad input velocity), flow is forced to be sonic (choked flow)
  - when interior and boundary flow are both supersonic, supersonic outflow is enforced (all interior quantities extrapolated)

Subsonic Inflow Boundary Conditions

- Four flow quantities specified at boundary
  - velocity set to be normal to boundary (two flow quantities)
  - total pressure and total temperature
  - mass flow rate and total temperature
- One flow quantity extrapolated from interior



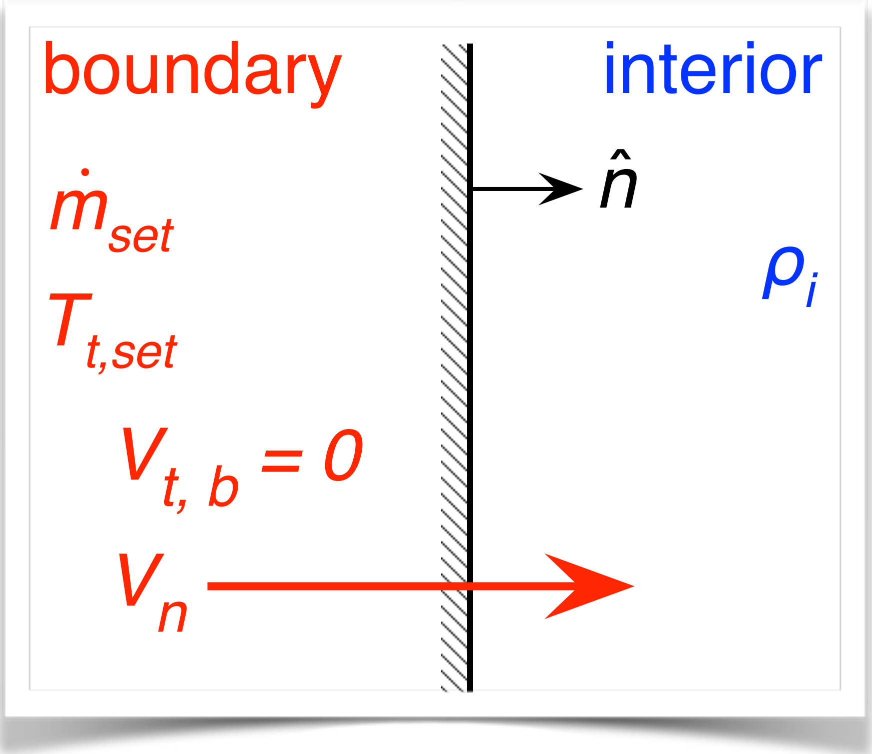
Stagnation Property Inflow



- Most other CFD solvers have this common option
- Total pressure and temperature set to specified value at boundary
- Tangential velocity set to zero, forcing inflow to be normal to surface
- Enthalpy is extrapolated from interior
- Riemann invariant used to computed boundary state
- Safeguards
  - when flow tries to reverse back into boundary, solid wall boundary enforced
  - inflow Mach number is limited to sonic, adjusting stagnation properties accordingly
- Cannot explicitly set a mass flow rate

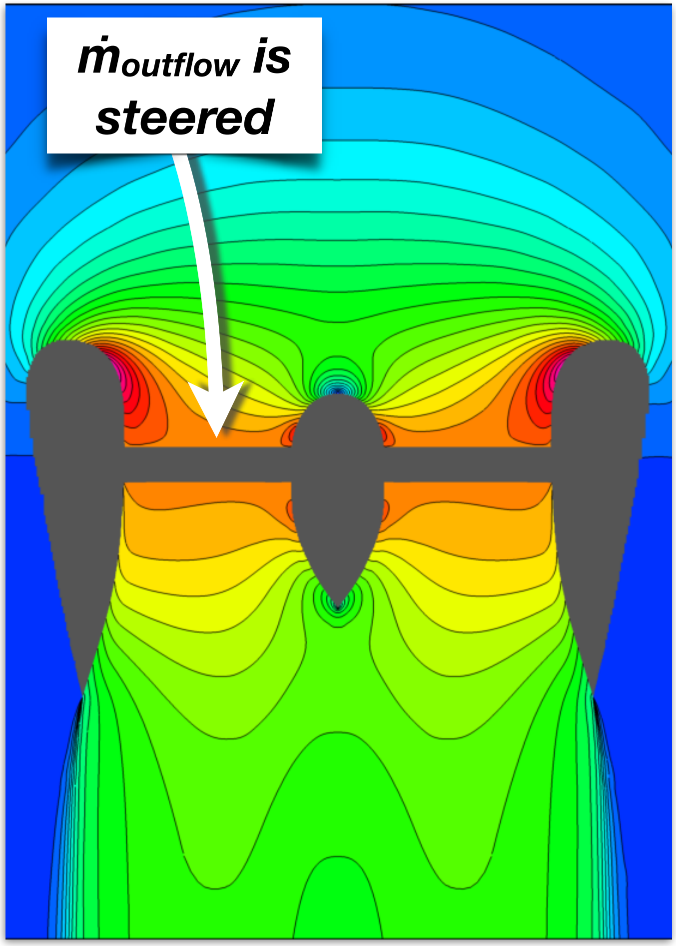
Mass Flow Rate and Total Temperature Inflow

- Allows for explicit mass flow rate control
- Mass flow rate and total temperature set to specified value at boundary
- Tangential velocity set to zero, forcing inflow to be normal to surface
- Density is extrapolated from interior
- Boundary flux computed from boundary state
- Safeguard
  - inflow Mach number is limited to sonic, adjusting boundary values accordingly



Mass Flow Rate Control

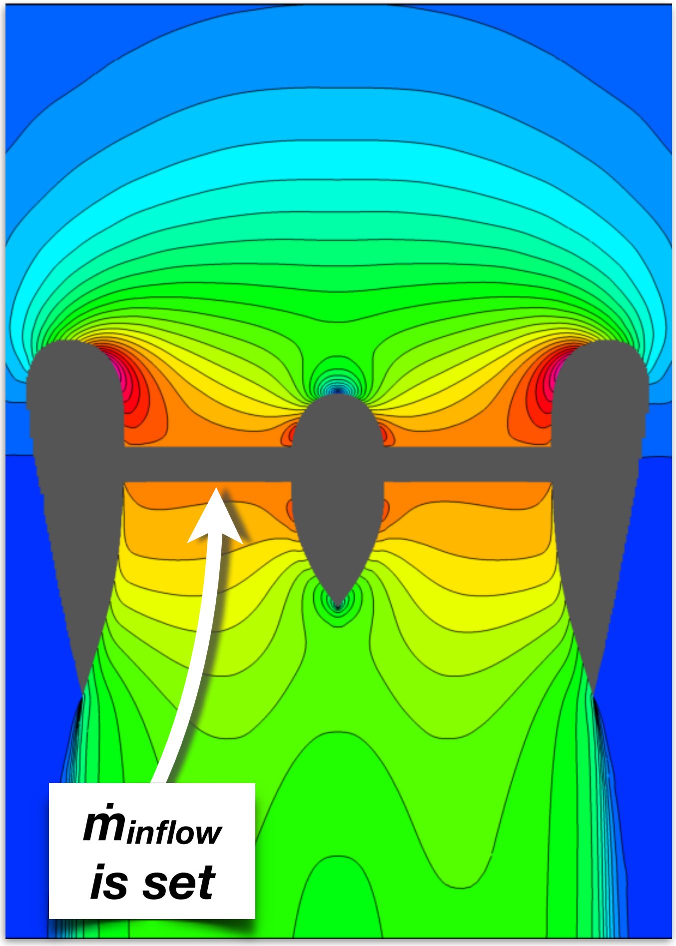
- Constant velocity outflow boundary condition can be steered to obtain specified mass flow rate out of the domain
  - average density over surface is computed
  - velocity out of domain is set based on desired mass flow rate
  - repeat every few iterations until solution converged and mass flow rate within tolerance



$\dot{m}_{outflow}$ is steered

Mass Flow Rate Control

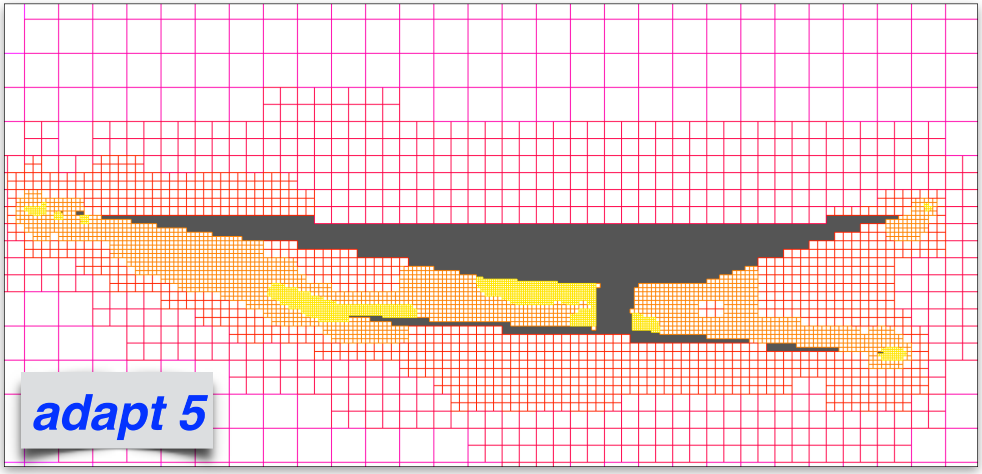
- Constant velocity outflow boundary condition can be steered to obtain specified mass flow rate out of the domain
  - average density over surface is computed
  - velocity out of domain is set based on desired mass flow rate
  - repeat every few iterations until solution converged and mass flow rate within tolerance
- Constant mass flow rate inflow boundary condition explicitly sets mass flow rate into the domain



$\dot{m}_{inflow}$ is set

Adjoint-Driven Adaptive Mesh Refinement

- All boundary conditions now implemented in adaptive mesh refinement process
- Updates to **`adjointCart`**, **`xSensit`**, **`adjointErrorEstQuad`**, etc.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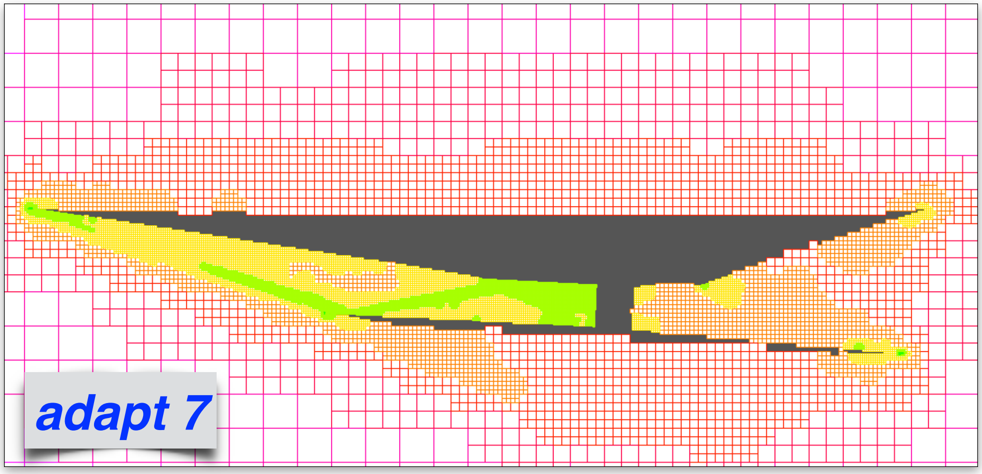
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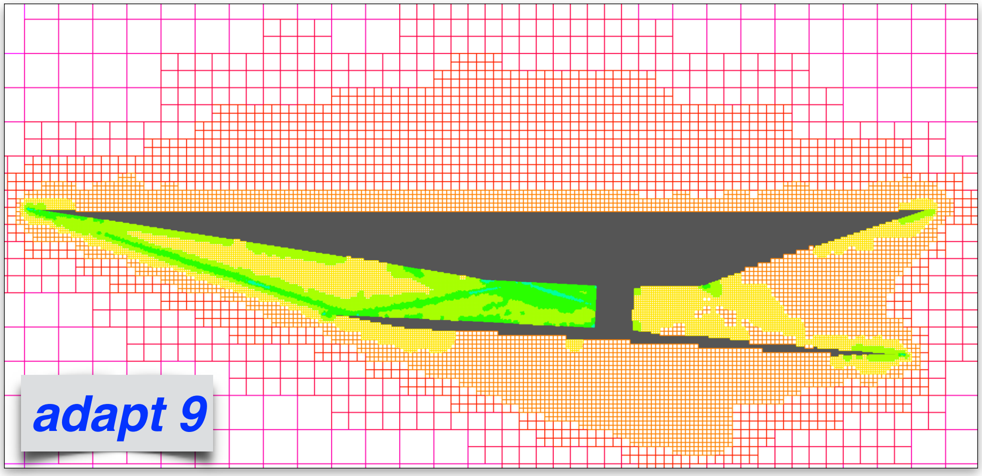
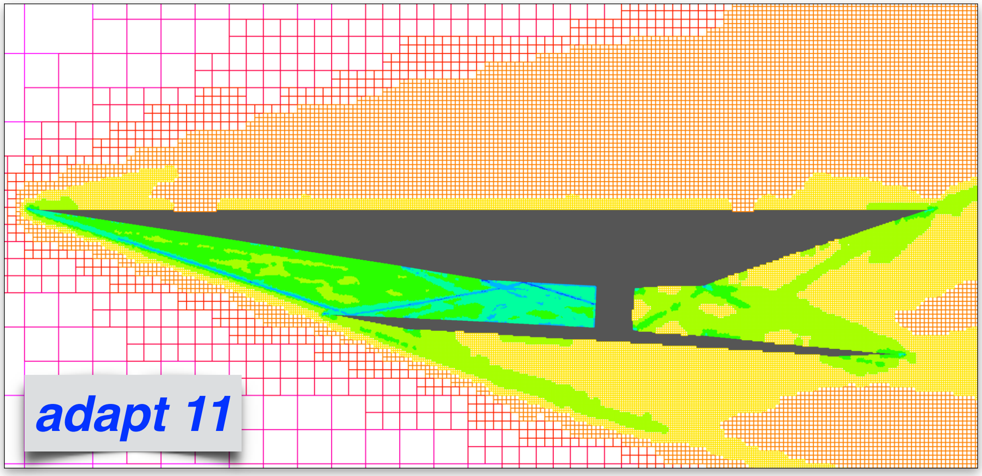
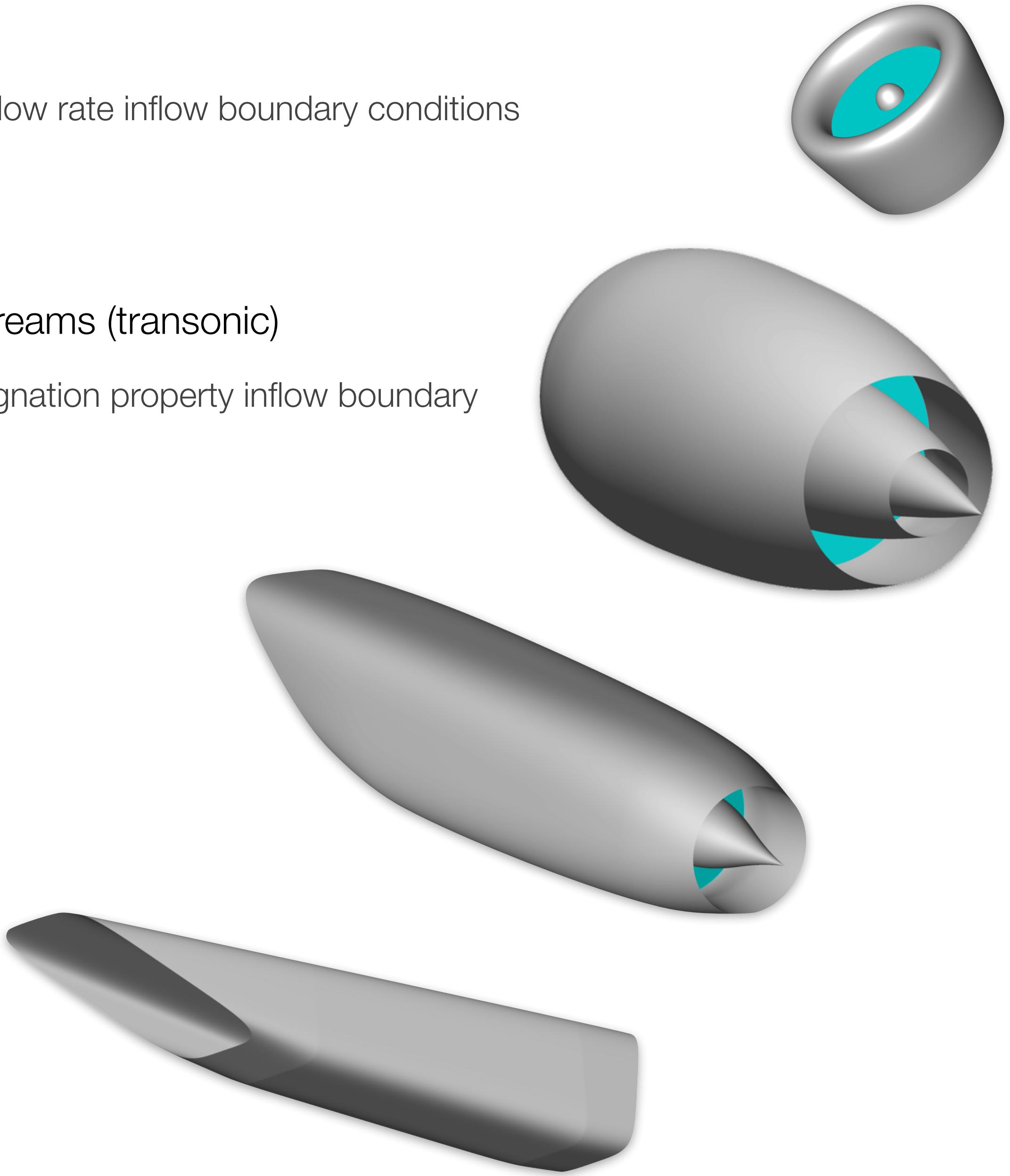

adapt 9


adapt 11

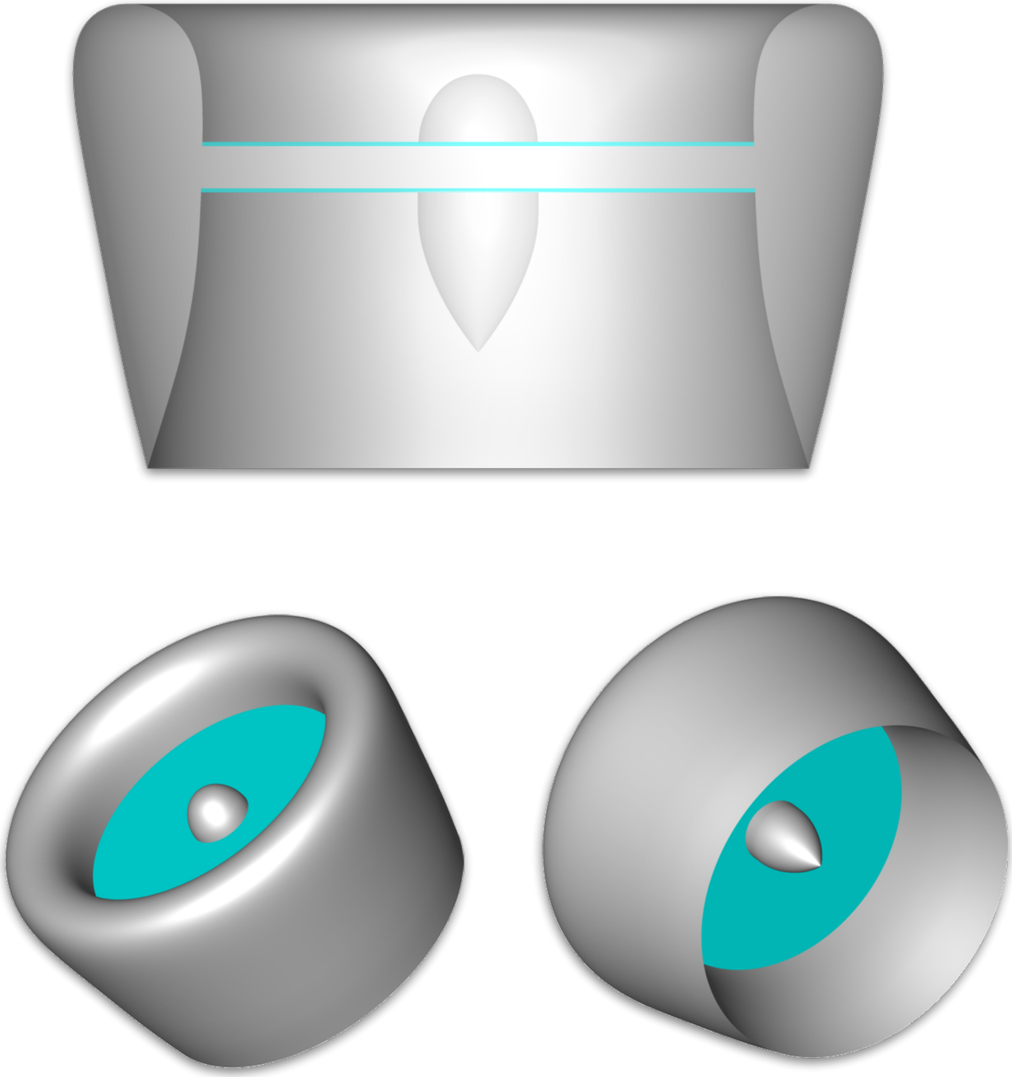
Application of New Boundary Conditions

- Ducted fan in near-hover (subsonic)
  - verification of back pressure outflow and mass flow rate inflow boundary conditions
  - mesh convergence through adaptive refinement
  - mass flow rate steering example
- Turbofan with both fan and turbine exhaust streams (transonic)
  - verification of constant velocity outflow and stagnation property inflow boundary conditions
  - mesh convergence through adaptive refinement
  - mass flow rate steering example
- Turbojet with 2-D ramp inlet (supersonic)
  - mesh convergence through adaptive refinement
  - mass flow rate steering example
- Scramjet (hypersonic)
- Low boom demonstrator
- Validation cases

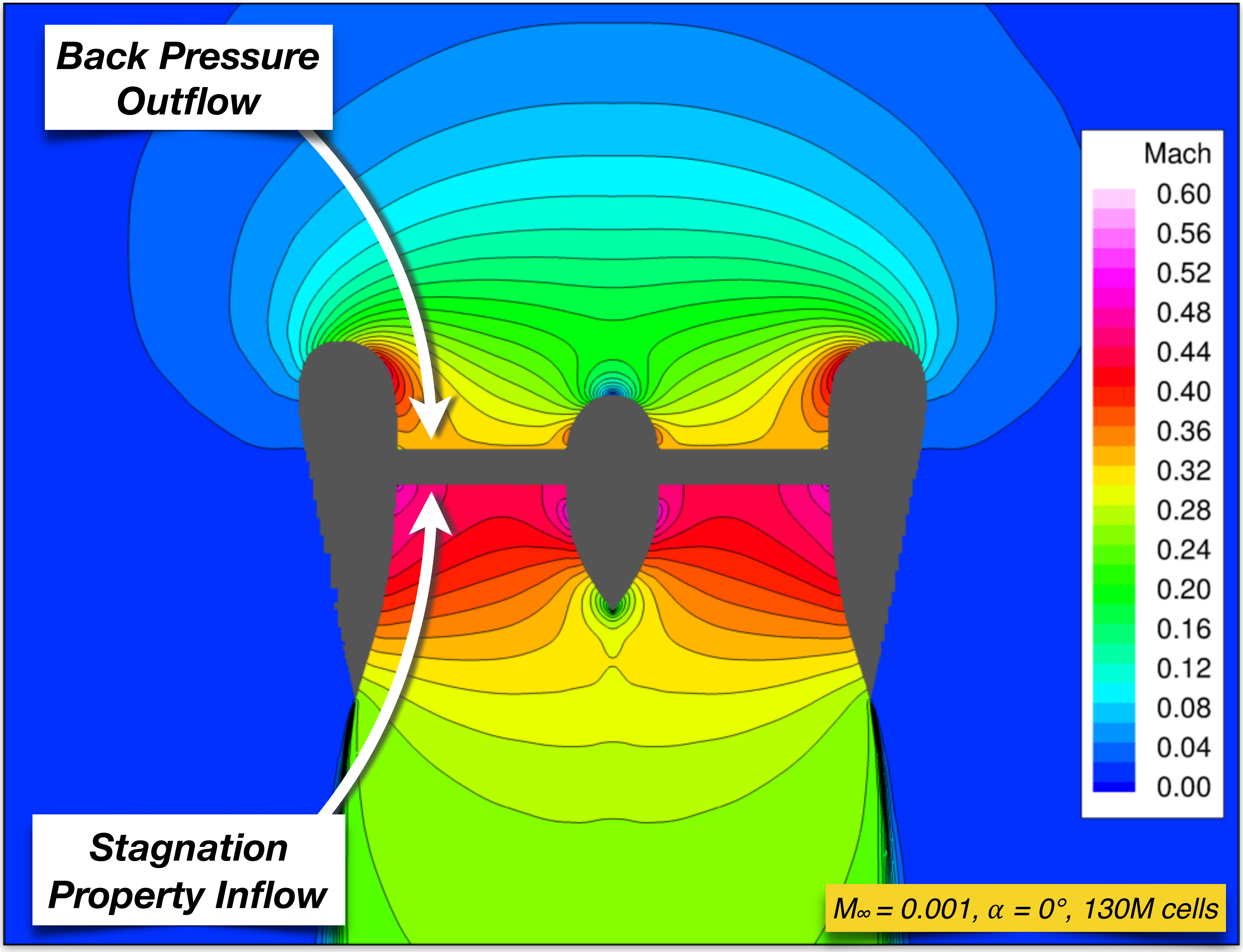


Ducted Fan in Hover

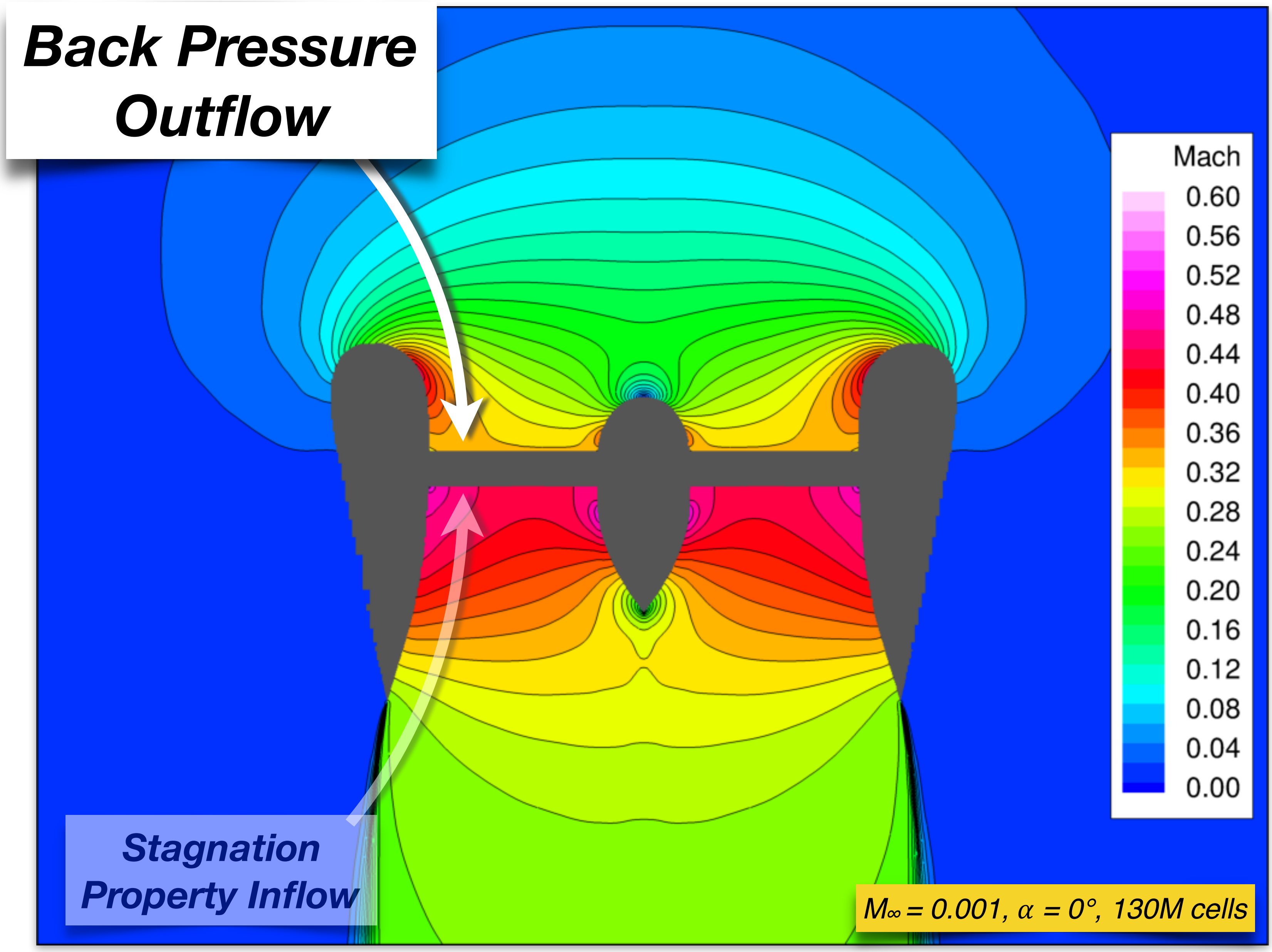
- Duct and center body housing motor to drive fan
- Very low freestream Mach number (0.001) to simulate near hover
- No angle of attack - axisymmetric flow
- Fan modeled as **annular disk**
- Inflow / Outflow boundary conditions enforced on disk to model fan effects



Ducted Fan - Example Solution



Ducted Fan - Example Solution

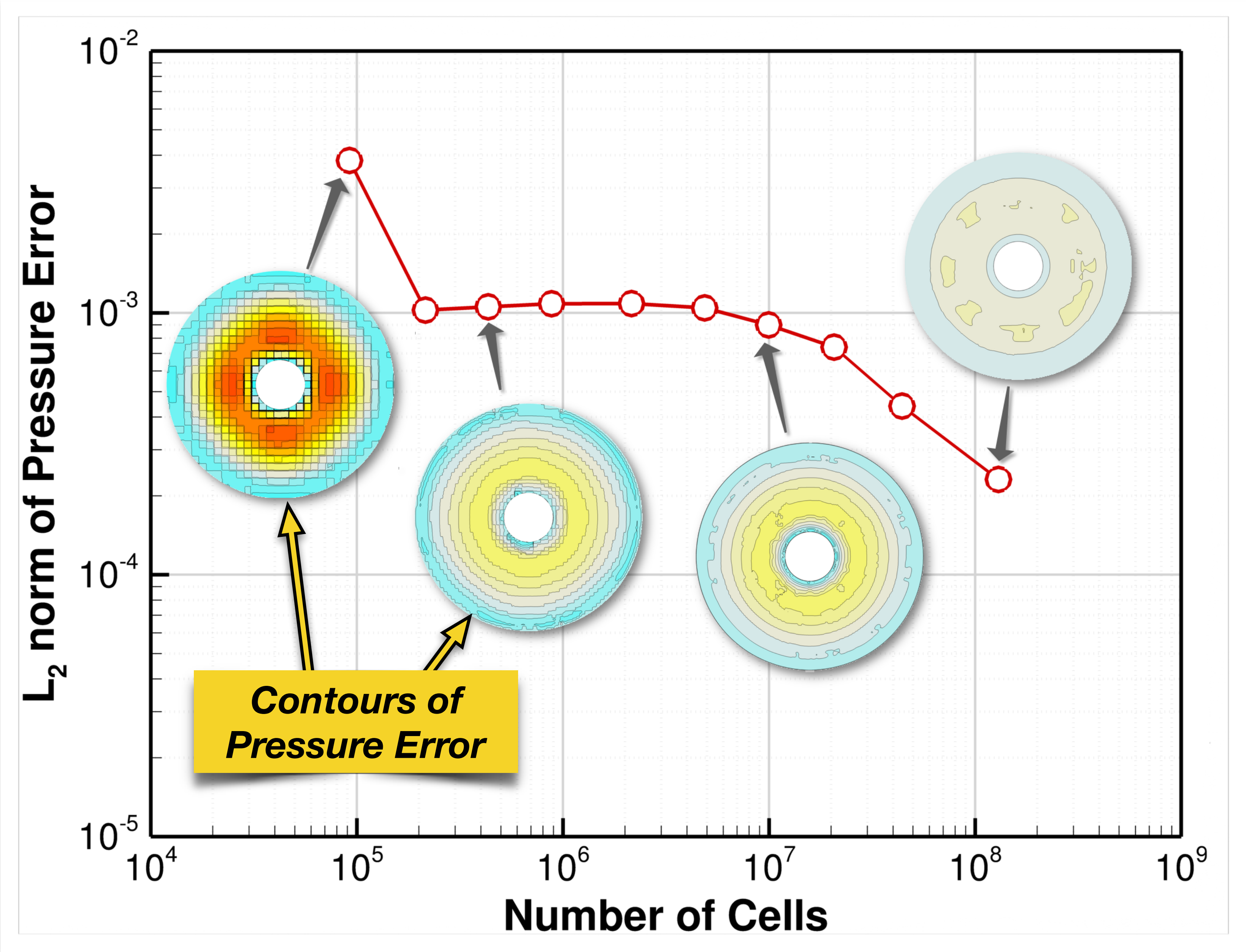


Back Pressure Outflow

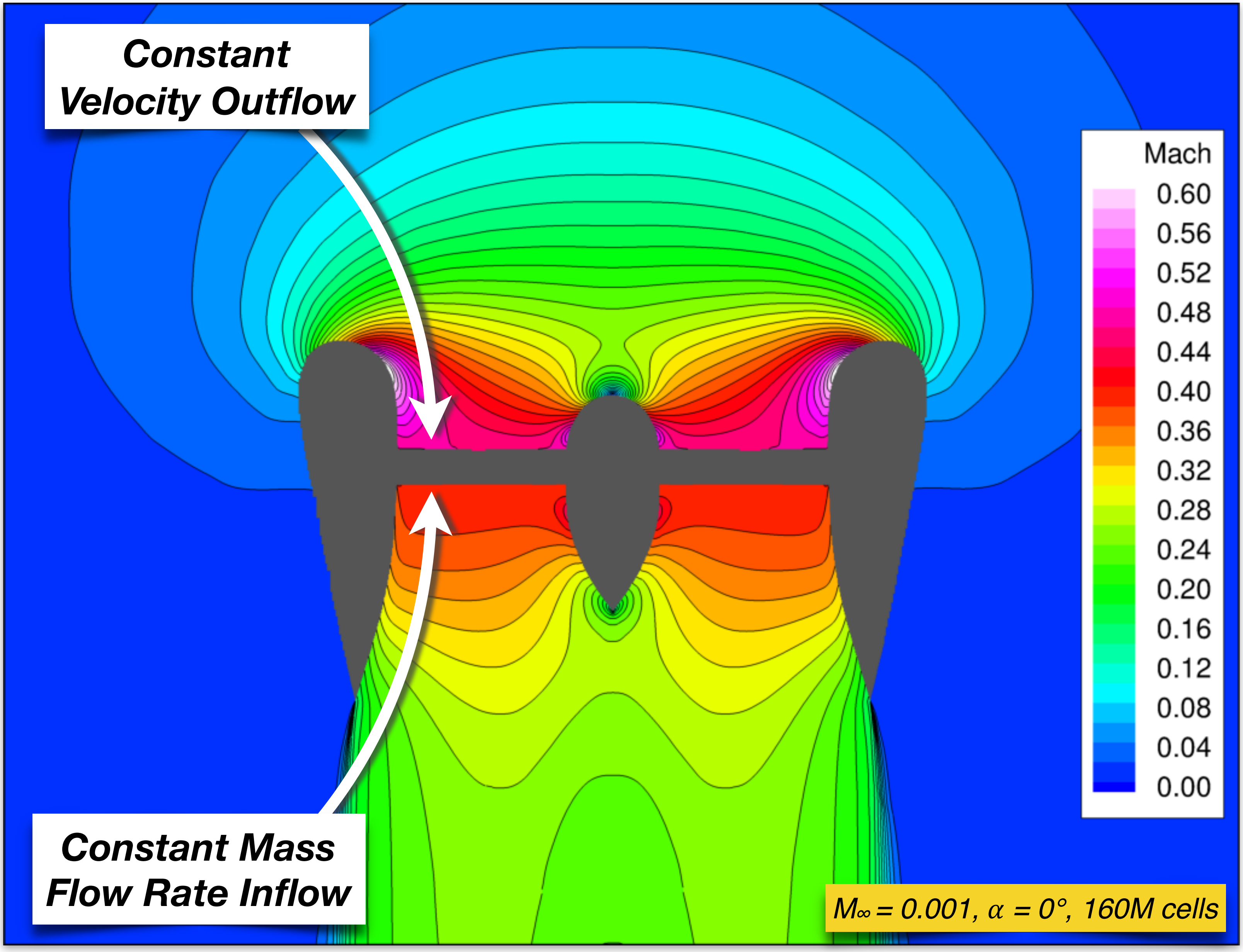
Stagnation Property Inflow

$M_\infty = 0.001$, $\alpha = 0°$, 130M cells

Back Pressure B.C. Mesh Convergence



Ducted Fan - Example Solution

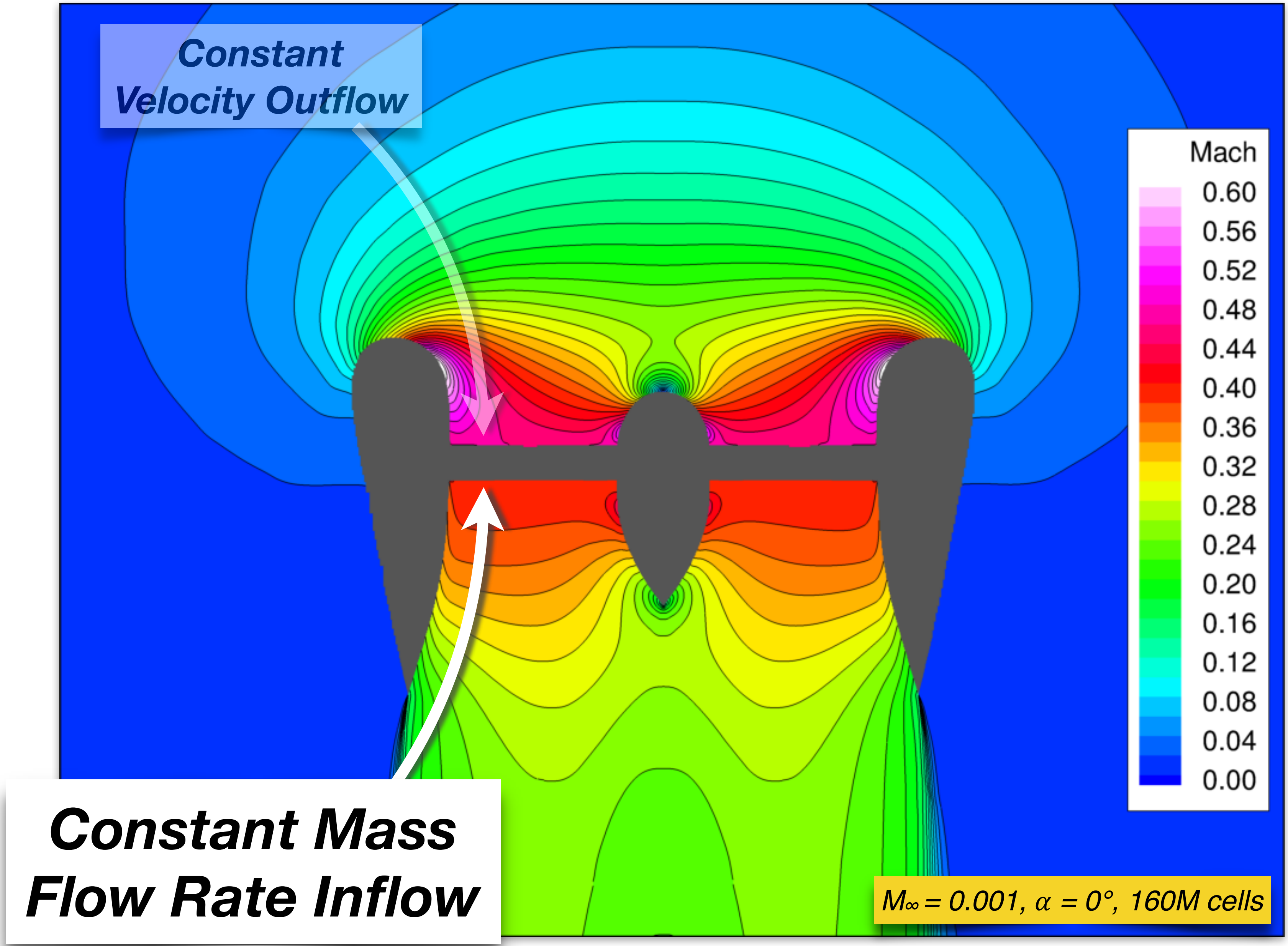


Constant Velocity Outflow

Constant Mass Flow Rate Inflow

M∞ = 0.001, α = 0°, 160M cells

Ducted Fan - Example Solution

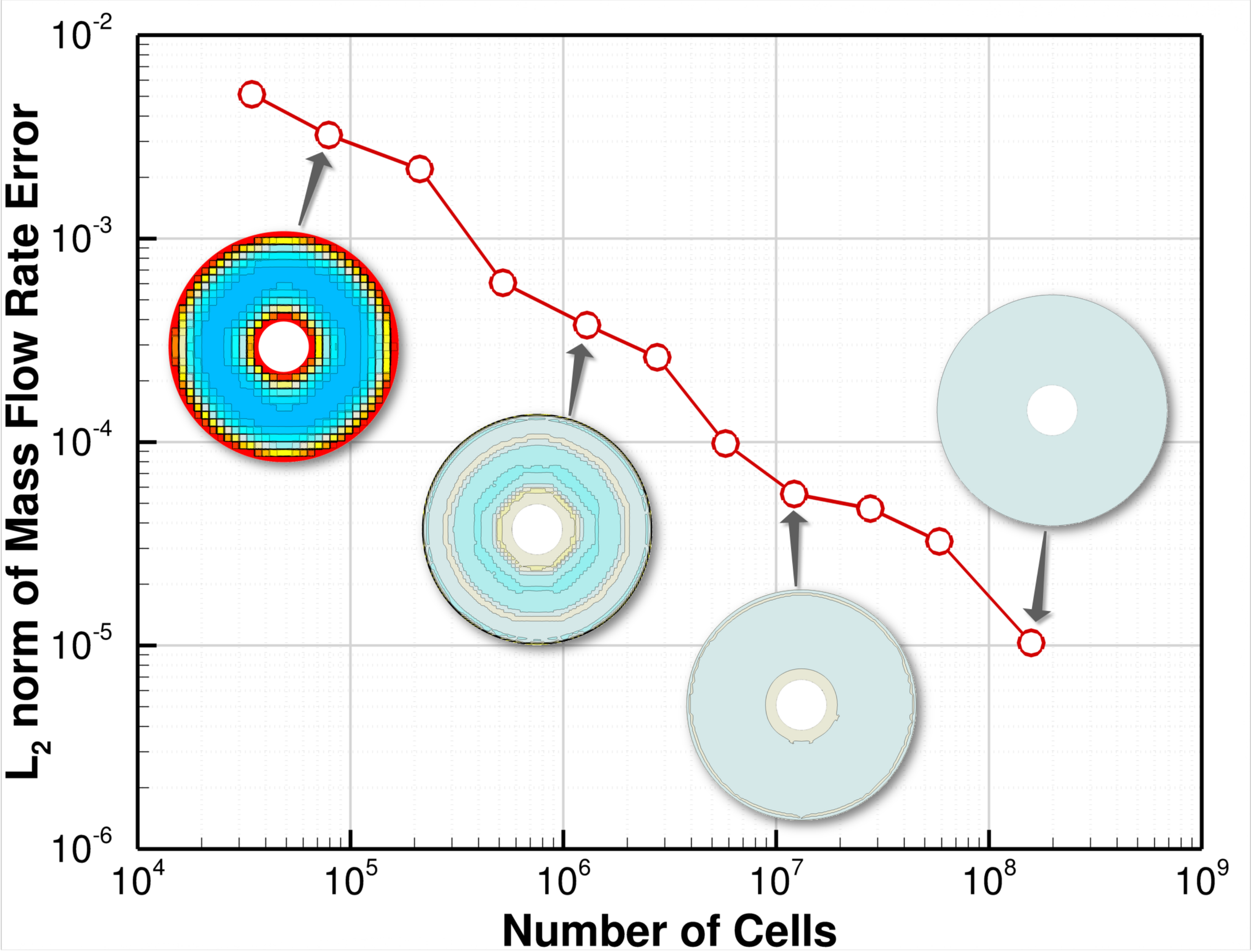


Constant Velocity Outflow

Constant Mass Flow Rate Inflow

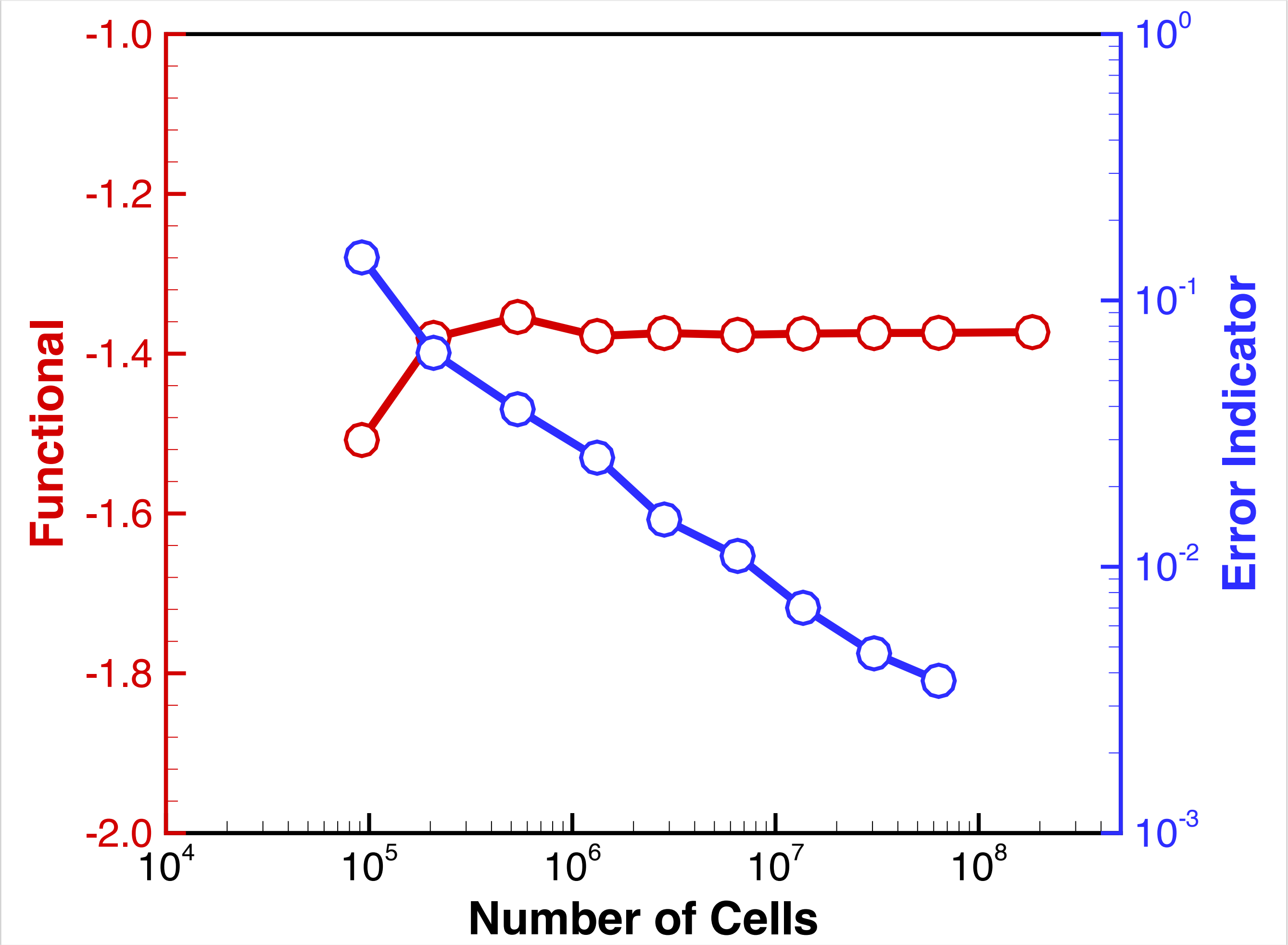
$M_\infty = 0.001$, $\alpha = 0°$, 160M cells

Constant Mass Flow Rate B.C. Mesh Convergence



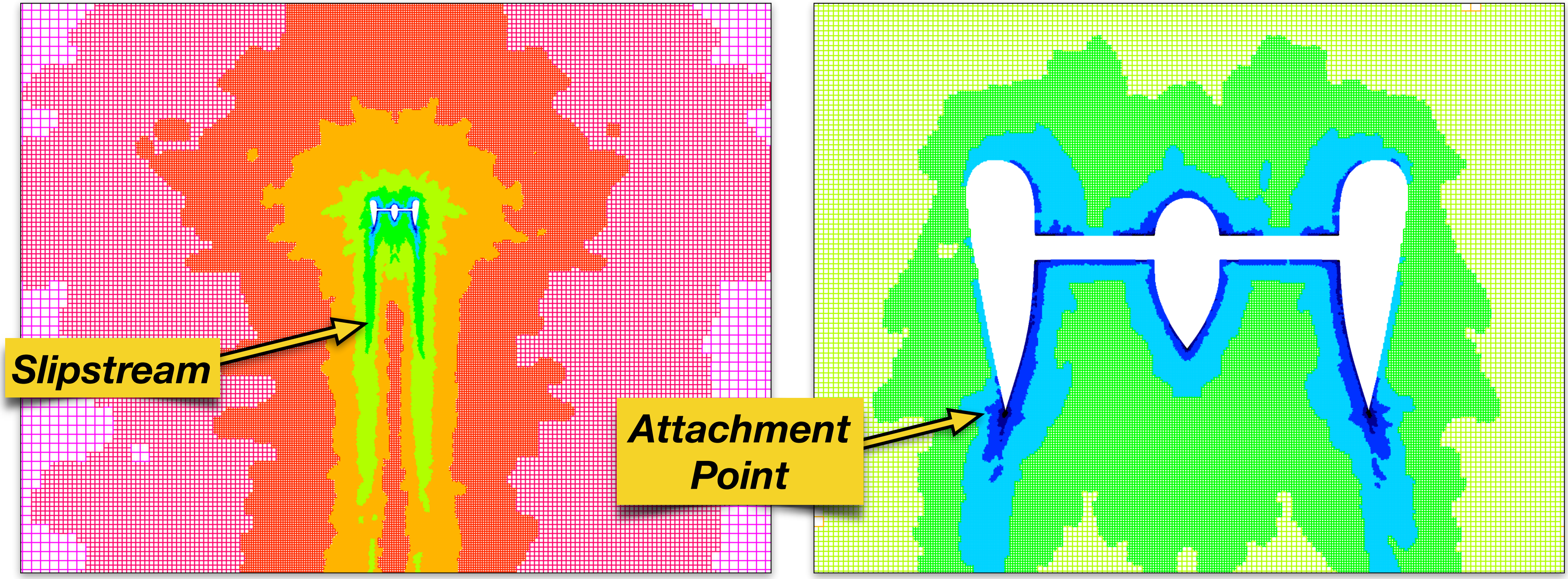
Ducted Fan - Mesh Convergence

- Good convergence of functional (drag)
- Steady reduction in error estimate



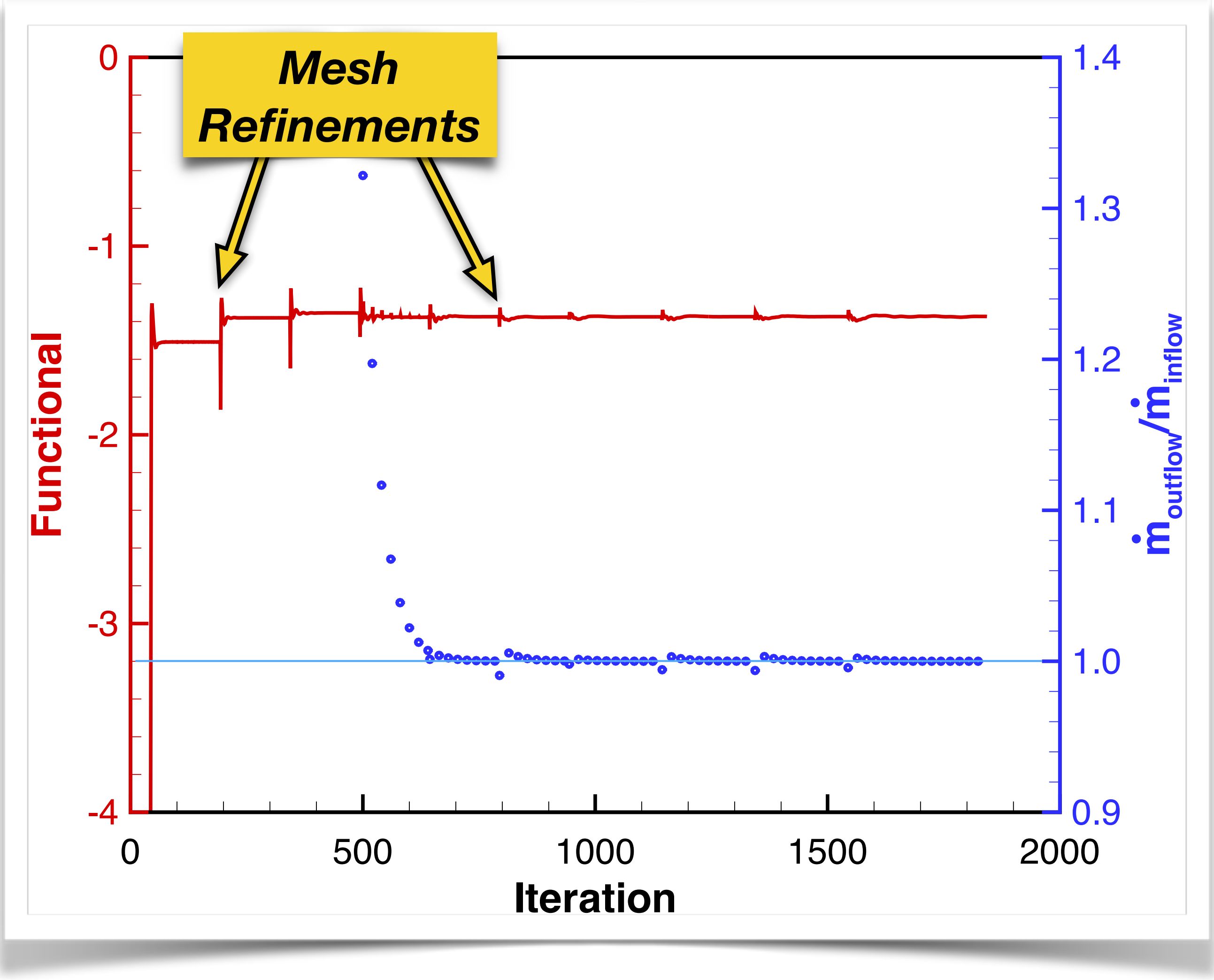
Ducted Fan - Adaptively Refined Mesh

- Colors represent cells of same level of refinement
- Mesh was refined at surface, at shear layer of exhaust flow, and near attachment point

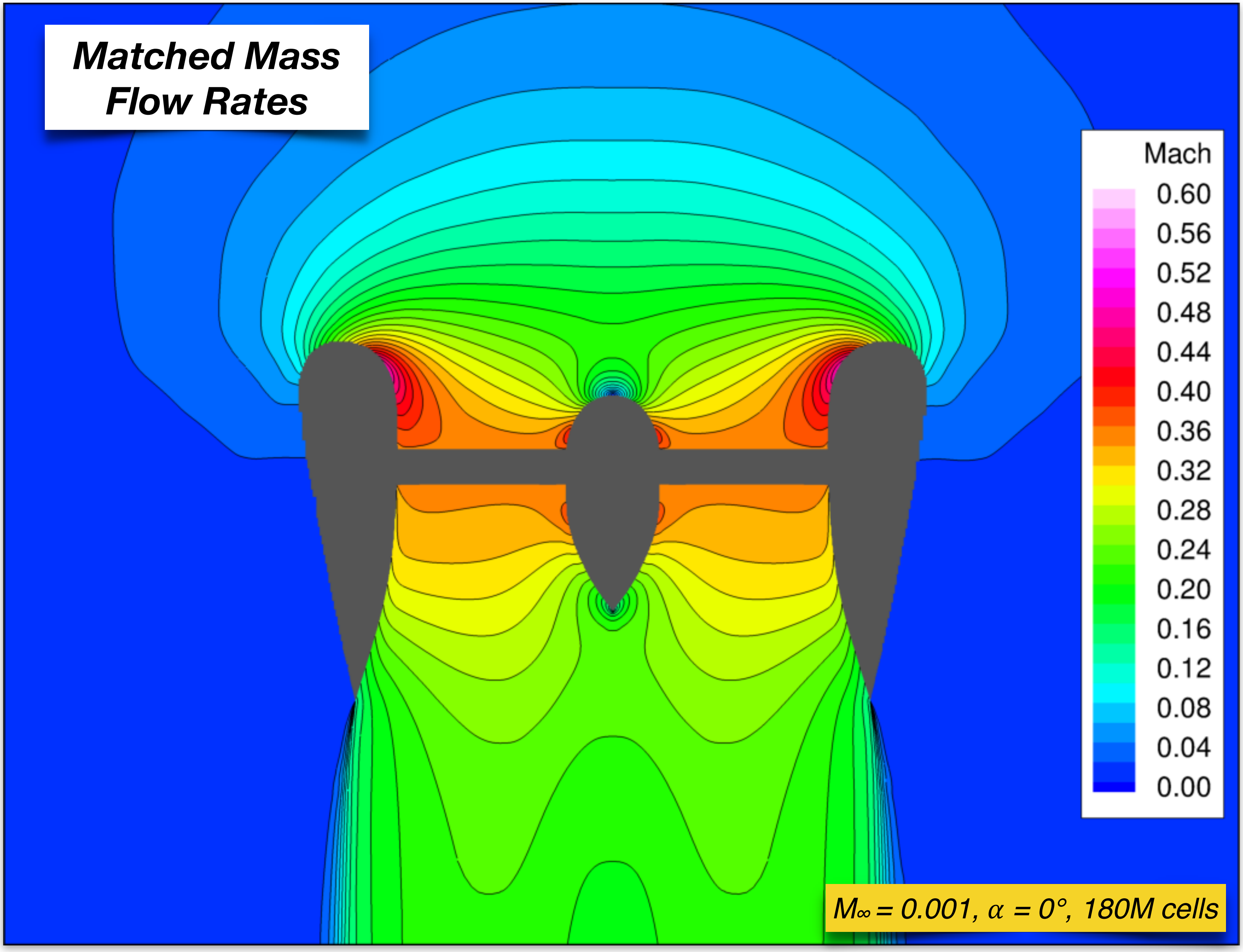


Ducted Fan - Mass Flow Rate Steering

- Inflow mass flow rate ($\dot{m}_{inflow}$) set through boundary condition
- Outflow mass flow rate ($\dot{m}_{outflow}$) steered to match
- Mass flow rate quickly converges and continues to converge through each refined mesh



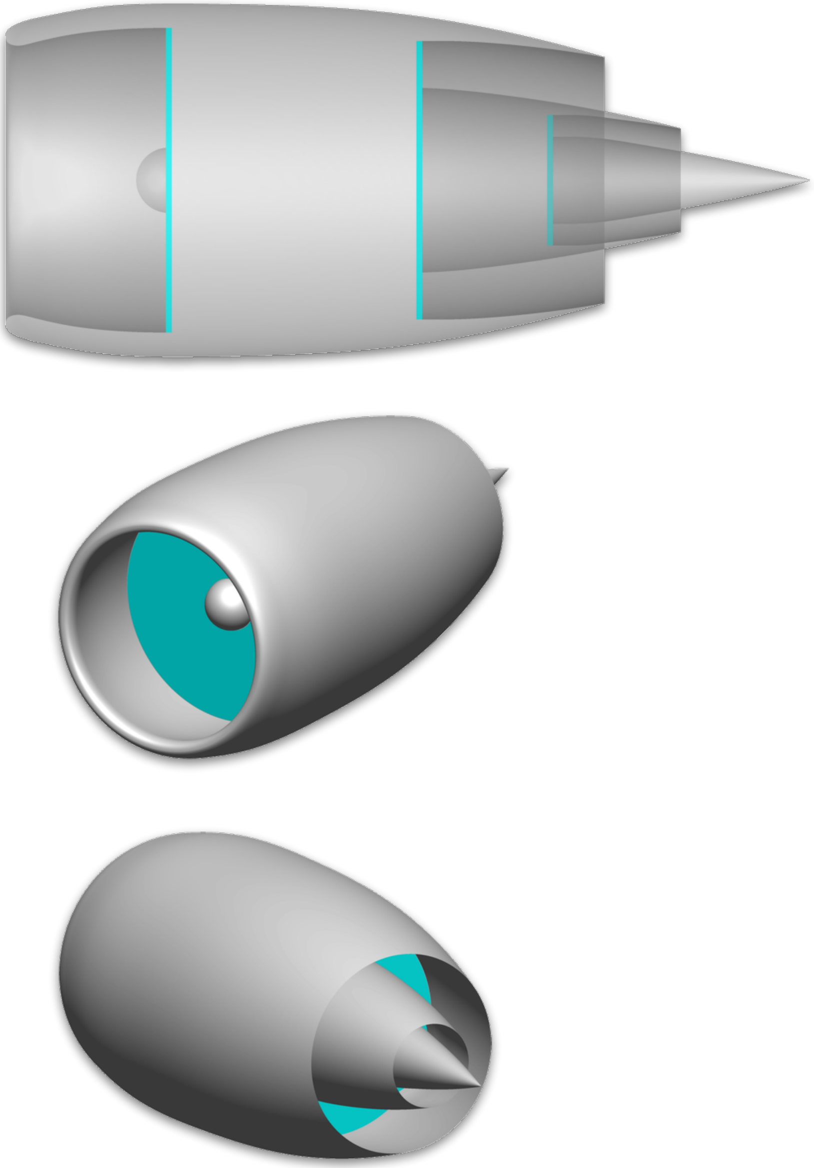
Ducted Fan - Example Solution



Matched Mass Flow Rates

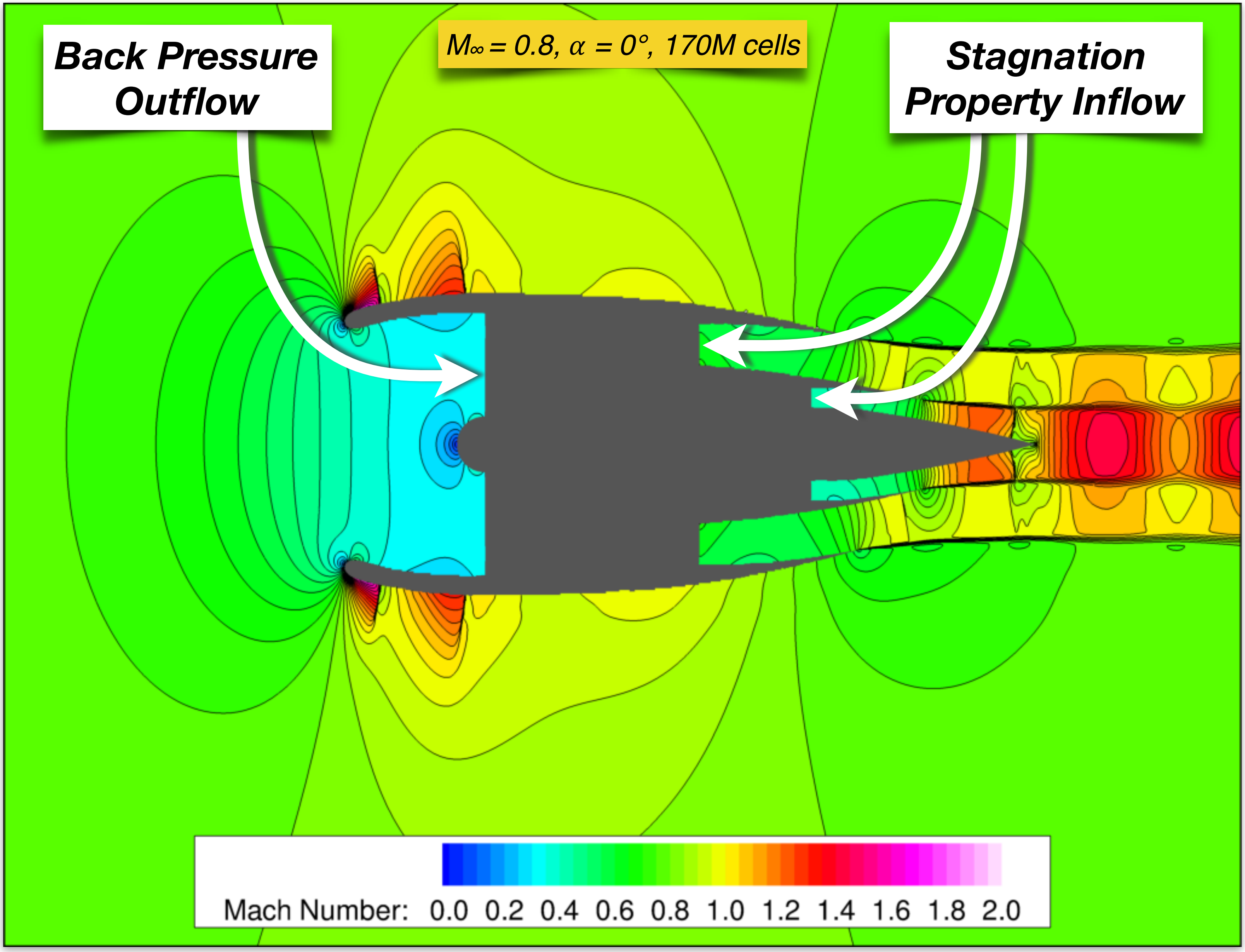
$M_\infty = 0.001$, $\alpha = 0°$, 180M cells

Turbofan in Transonic Flow



- Transonic diffuser with fan hub
- Two stream exhaust with cone nozzle for turbine flow
- Mach 0.8 freestream, no angle of attack (axisymmetric flow)
- Fan / Compressor face modeled as **annulus**, outflow boundary condition applied
- Fan and turbine exhaust planes modeled as **annuli**, inflow boundary conditions applied

Turbofan - Example Solution

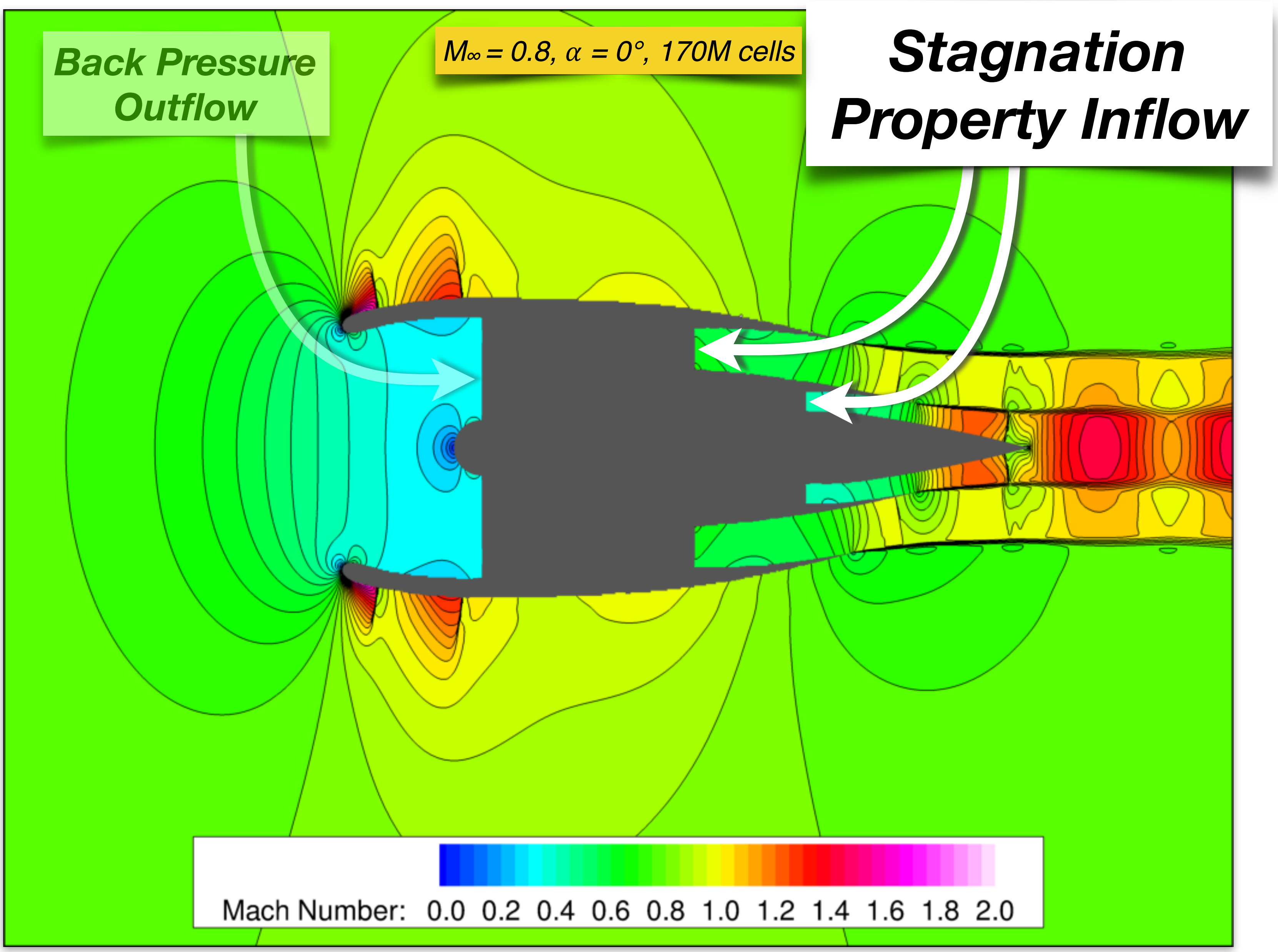


$M_\infty = 0.8$, $\alpha = 0°$, 170M cells

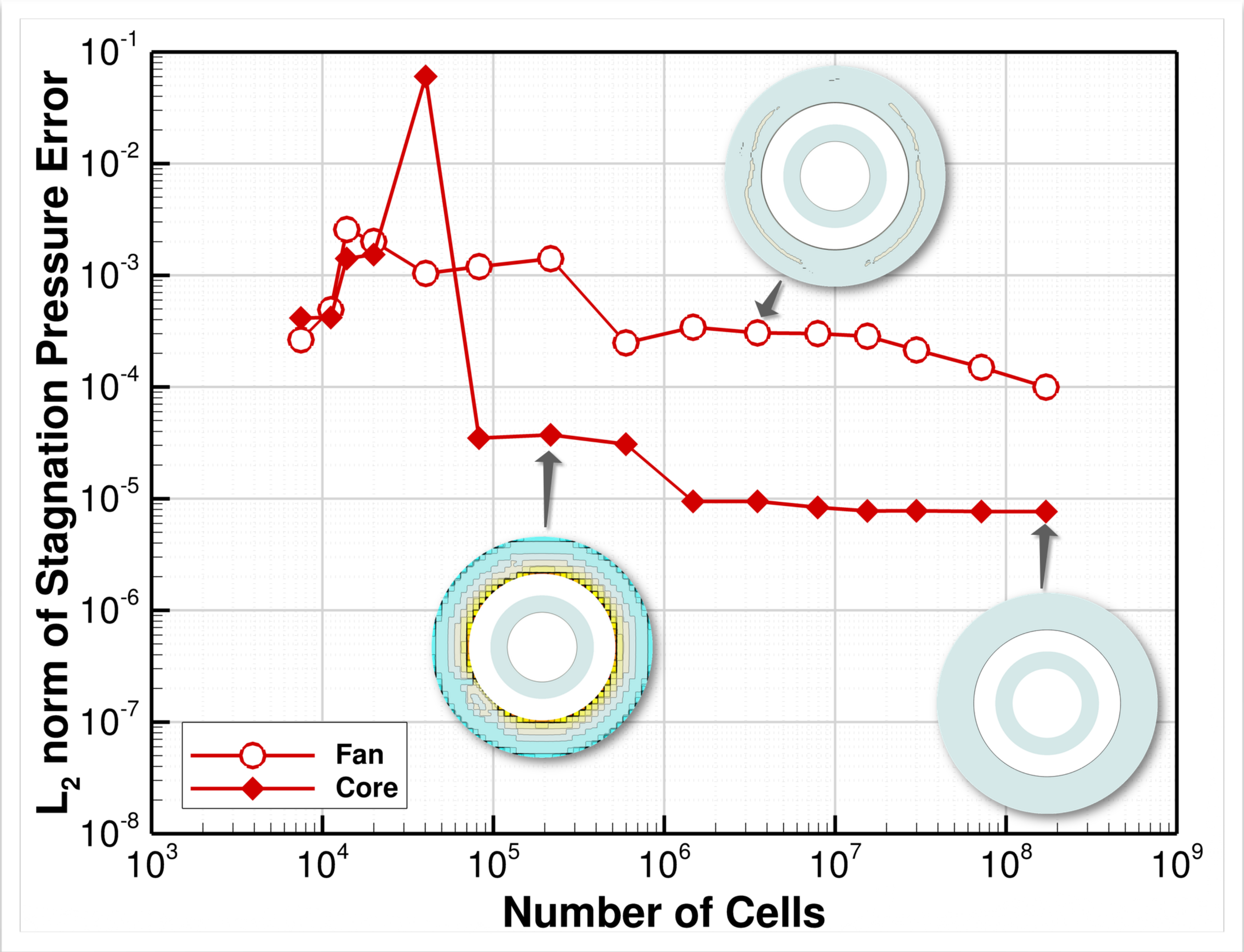
Back Pressure Outflow

Stagnation Property Inflow

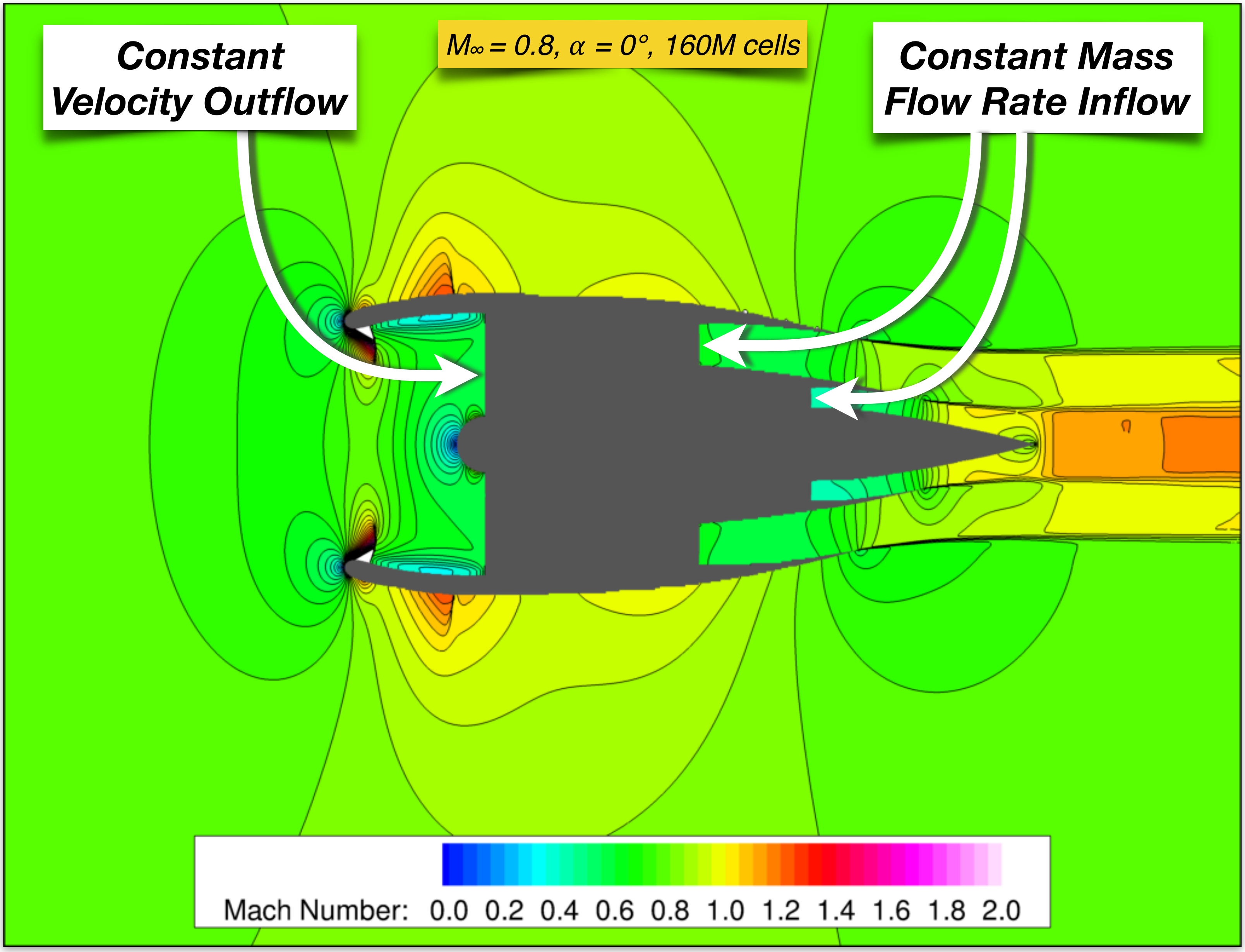
Turbofan - Example Solution



Stagnation Property B.C. Mesh Convergence



Turbofan - Example Solution

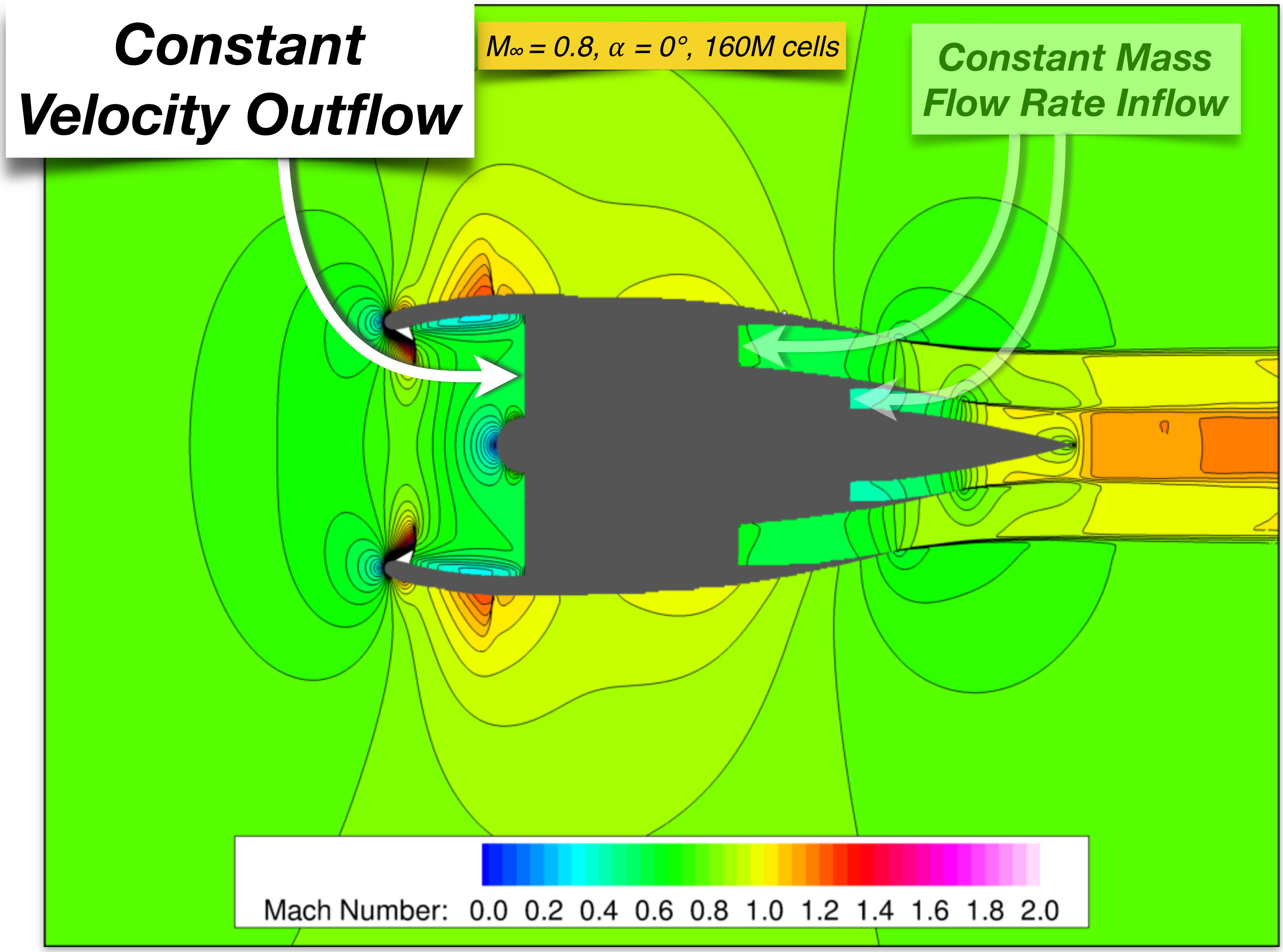


Constant Velocity Outflow

$M_\infty = 0.8$, $\alpha = 0°$, 160M cells

Constant Mass Flow Rate Inflow

Turbofan - Example Solution

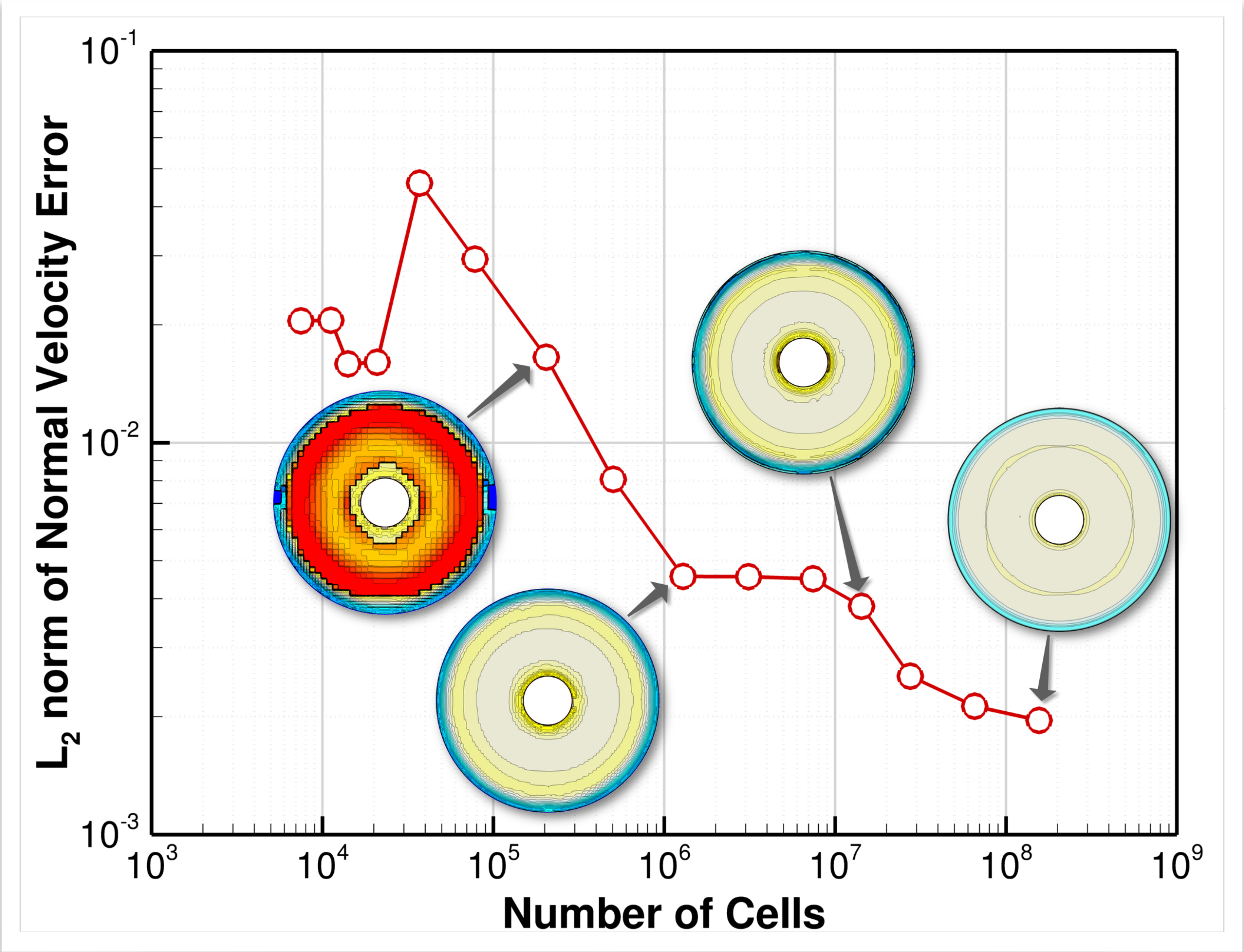


Constant Velocity Outflow

$M_\infty = 0.8$, $\alpha = 0°$, 160M cells

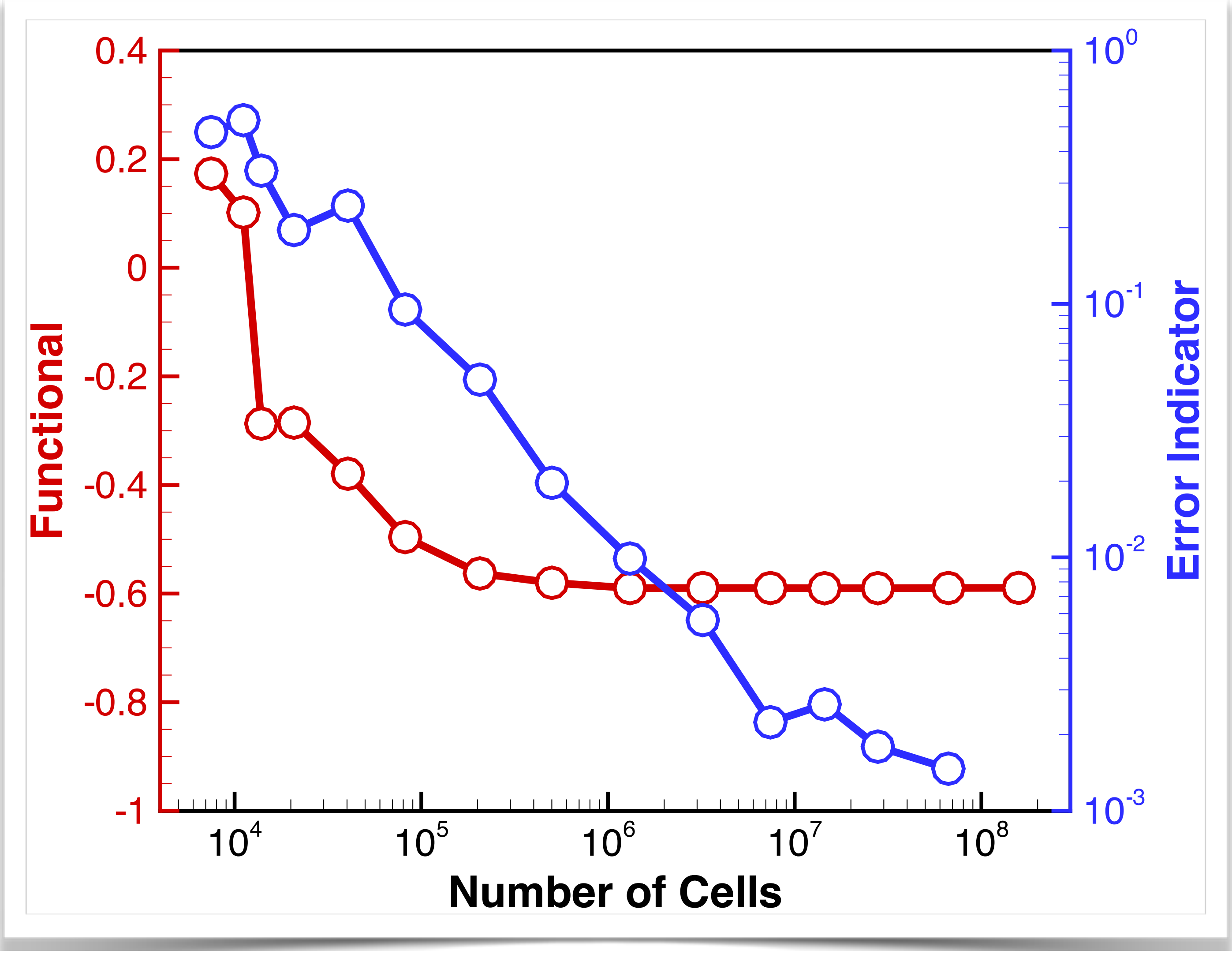
Constant Mass Flow Rate Inflow

Constant Velocity B.C. Mesh Convergence



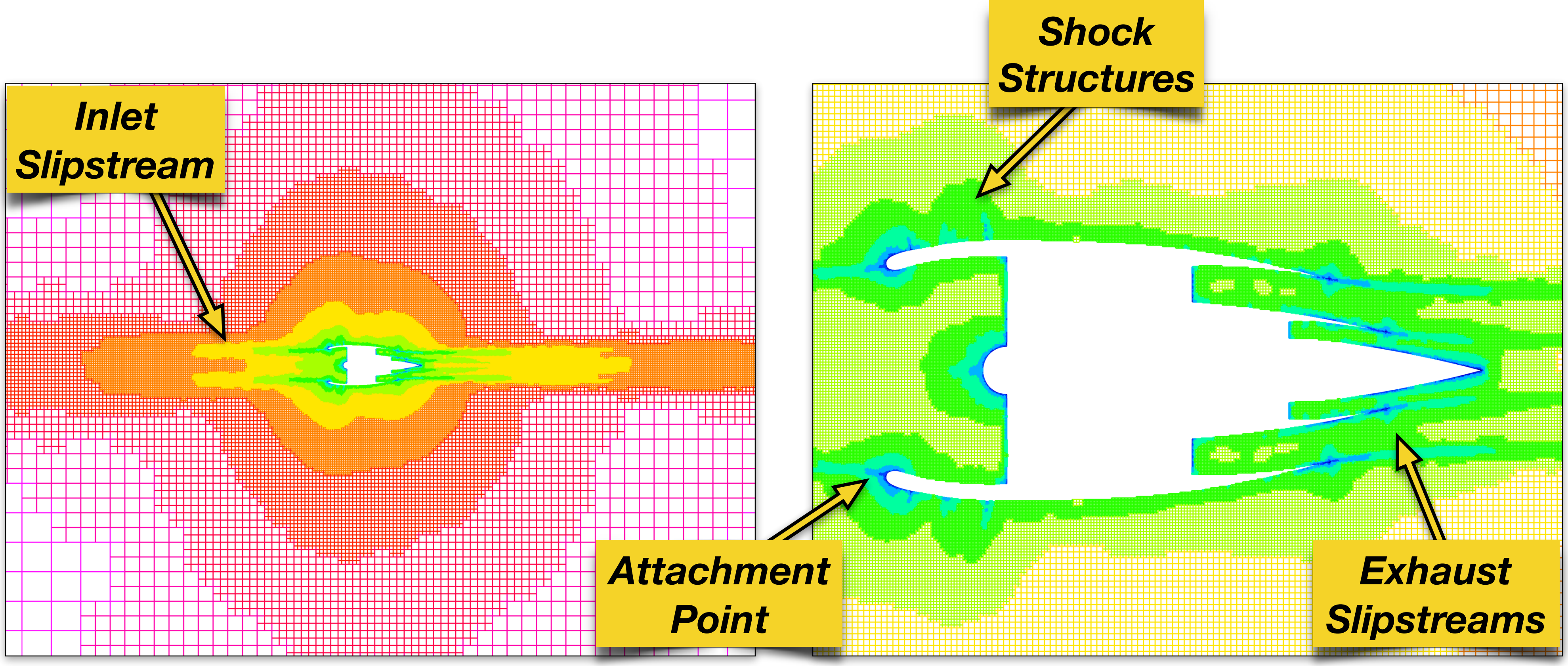
Turbofan - Mesh Convergence

- Good convergence of functional (drag)
- Steady reduction in error estimate



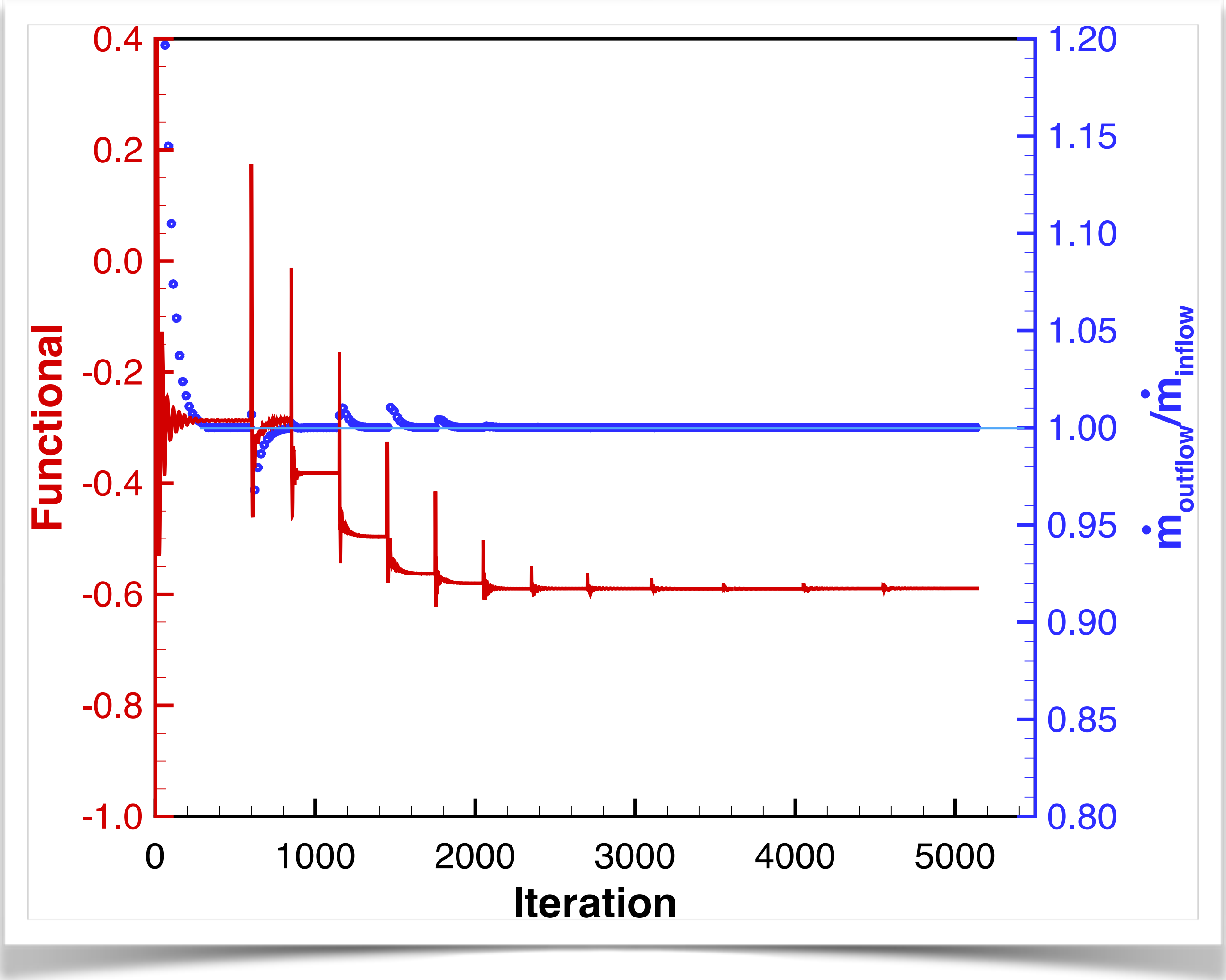
Turbofan - Adaptively Refined Mesh

- Colors represent cells of same level of refinement
- Mesh was refined at surface, at shear layer of inlet and exhaust flow, near attachment point, and at shock structures

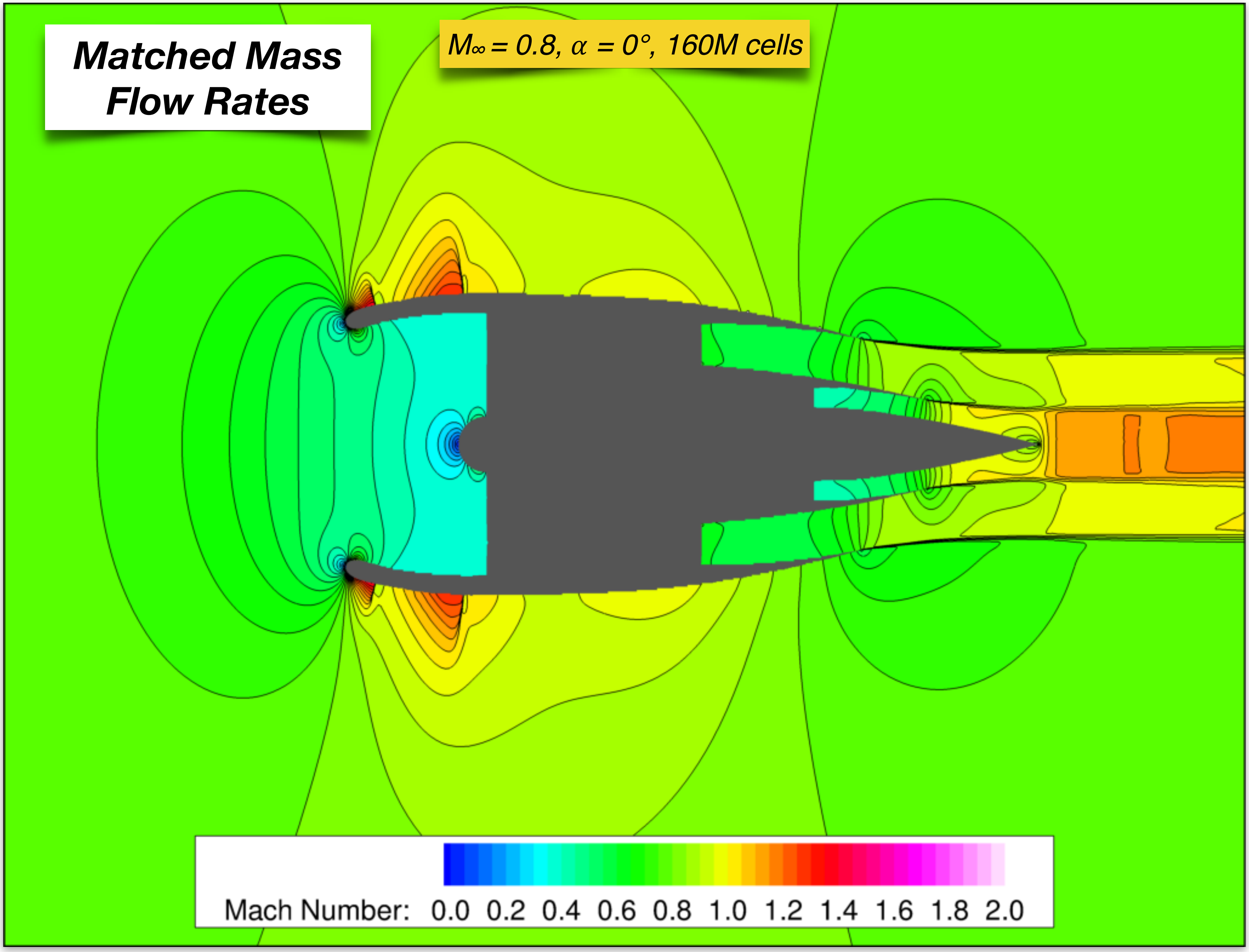


Turbofan - Mass Flow Rate Steering

- Inflow mass flow rate ($\dot{m}_{inflow}$) set through boundary condition
- Outflow mass flow rate ($\dot{m}_{outflow}$) steered to match
- Mass flow rate quickly converges and continues to converge through each refined mesh

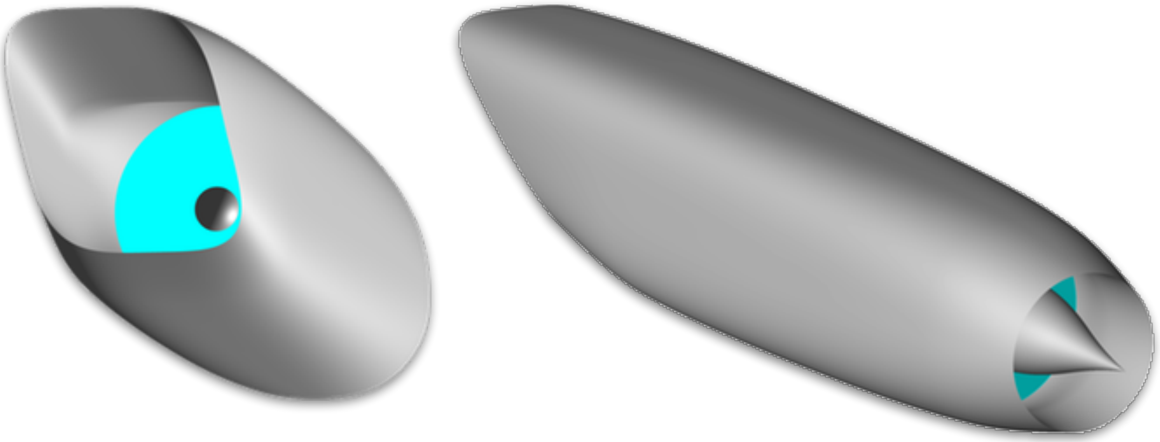


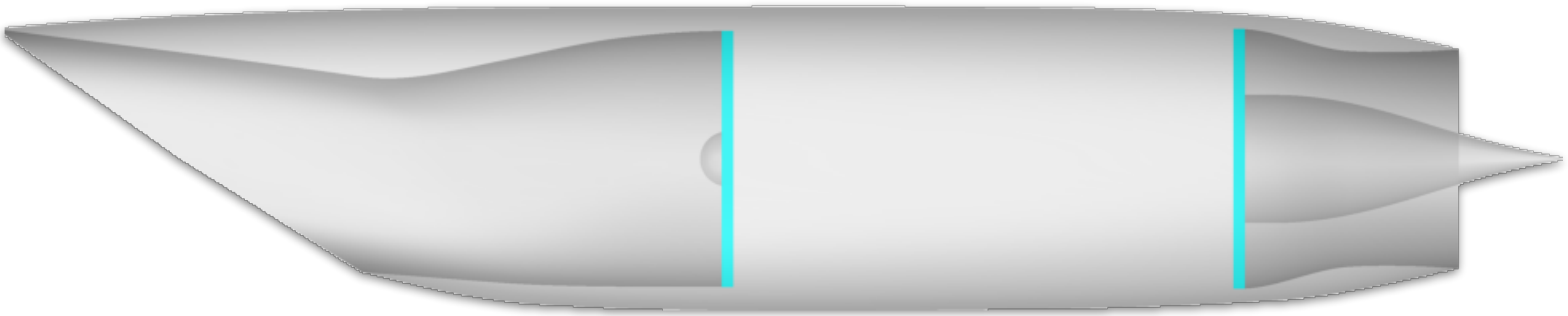
Turbofan - Example Solution



Turbojet in Supersonic Flow

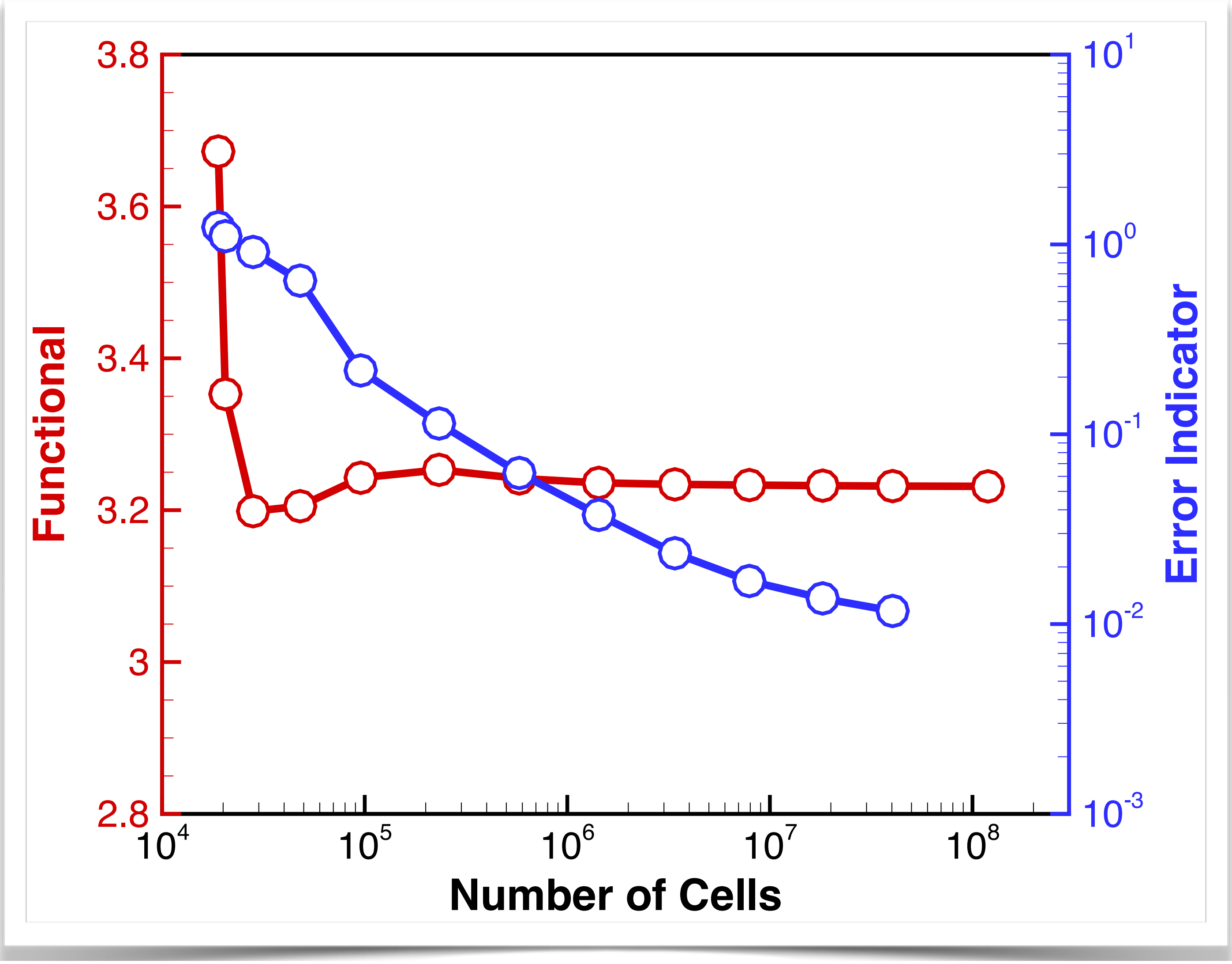
- 2-D ramp inlet design for normal terminal shock
- Converging-diverging duct with cone nozzle
- Mach 1.5 freestream, 1° angle of attack
- Outflow / Inflow boundary conditions applied to **annuli**





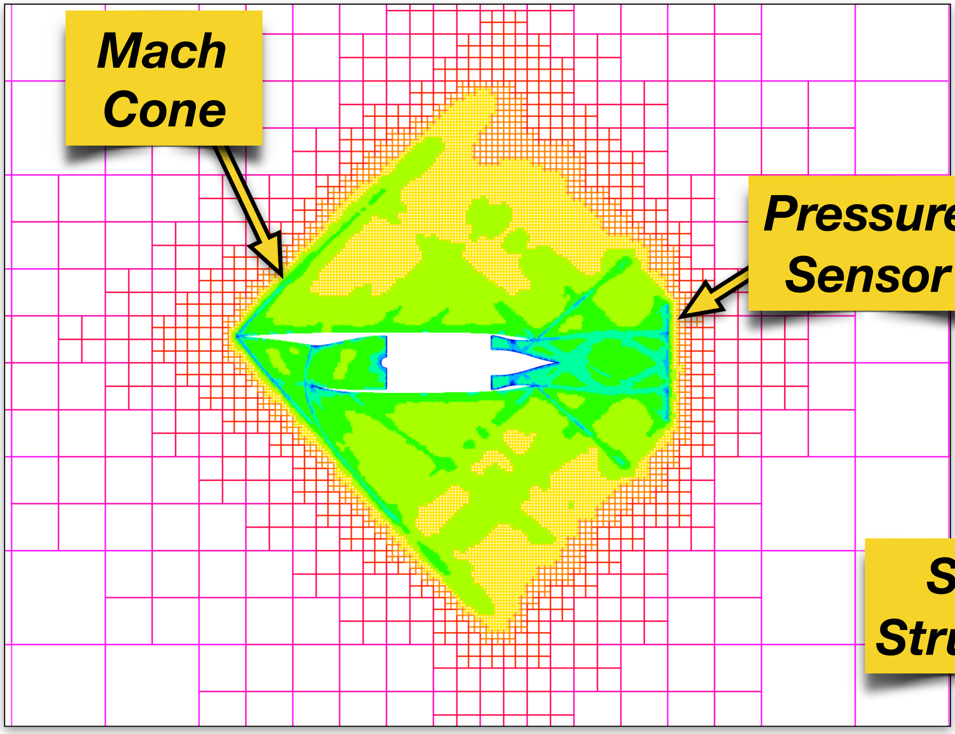
Turbojet - Mesh Convergence

- Good convergence of functional (thrust + lift + plume sensor)
- Steady reduction in error estimate



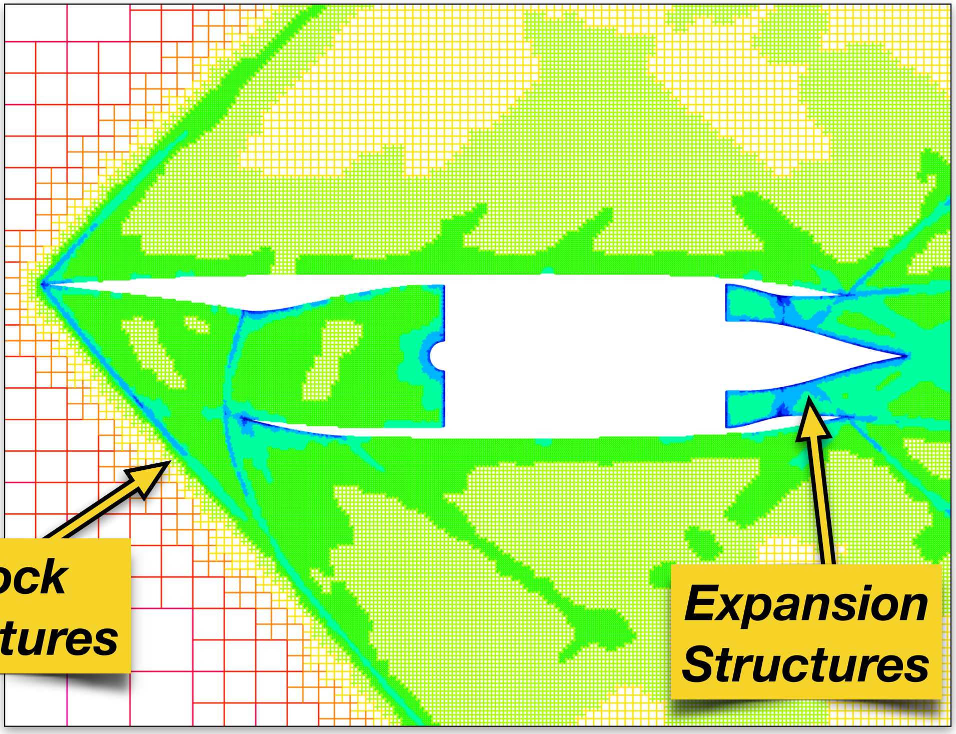
Turbojet - Adaptively Refined Mesh

- Colors represent cells of same level of refinement
- Mesh was refined at surface, within Mach cone of influence, at shock and expansion structures, and at plume shear layer influencing pressure sensor



Mach Cone

Pressure Sensor

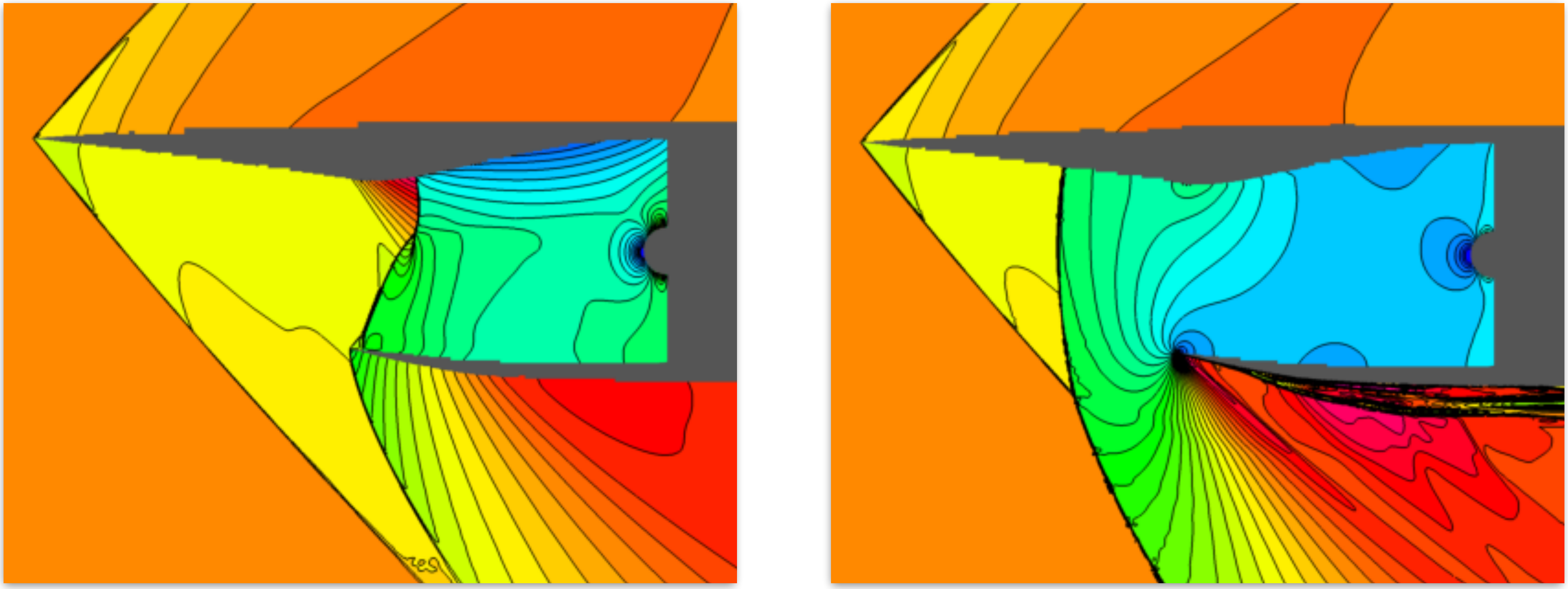


Shock Structures

Expansion Structures

Supersonic Inlet - Mass Flow Rate

- Usually need to specify mass flow rate through an inlet
- Often desirable to match nozzle mass flow rate if modeled
- Highly nonlinear flow features can make mass flow rate steering difficult in supersonic and even transonic inlets



Turbojet - Mass Flow Rate Steering

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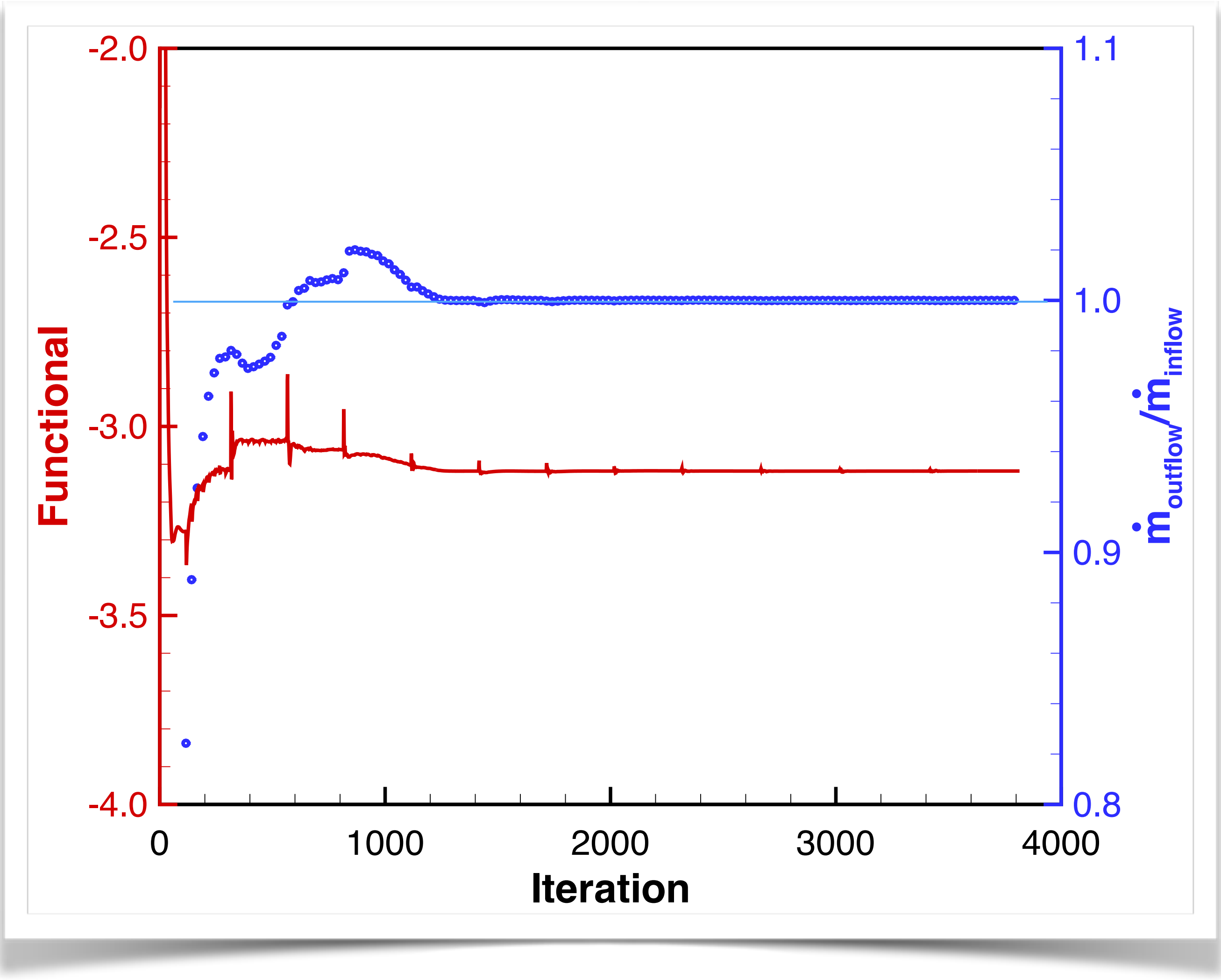
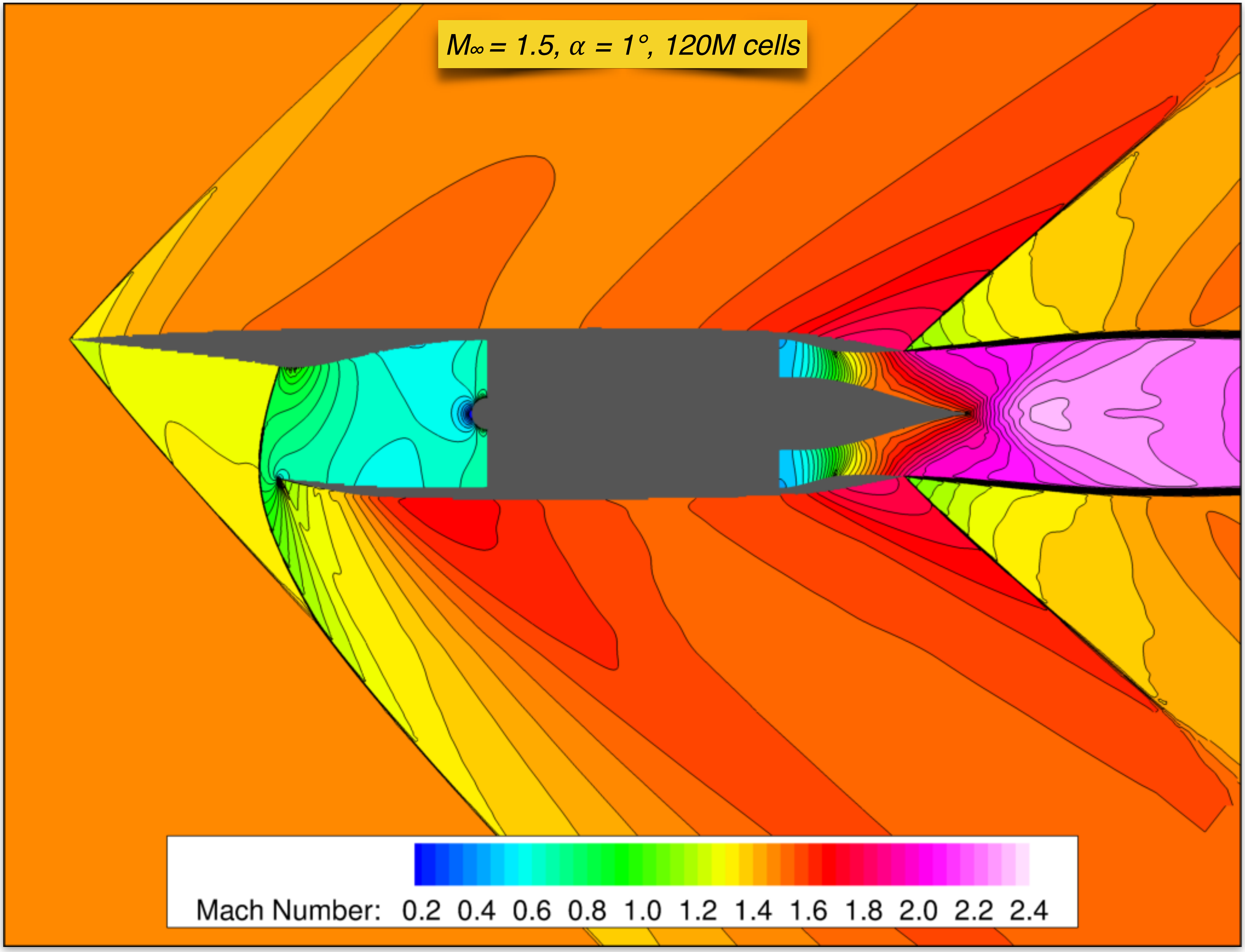
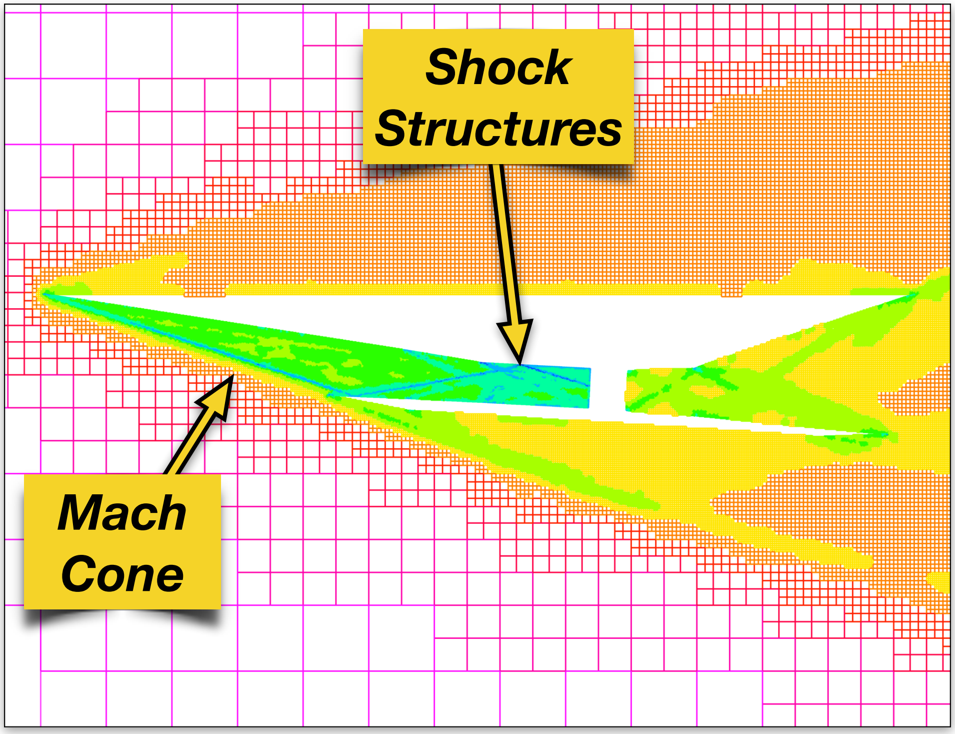


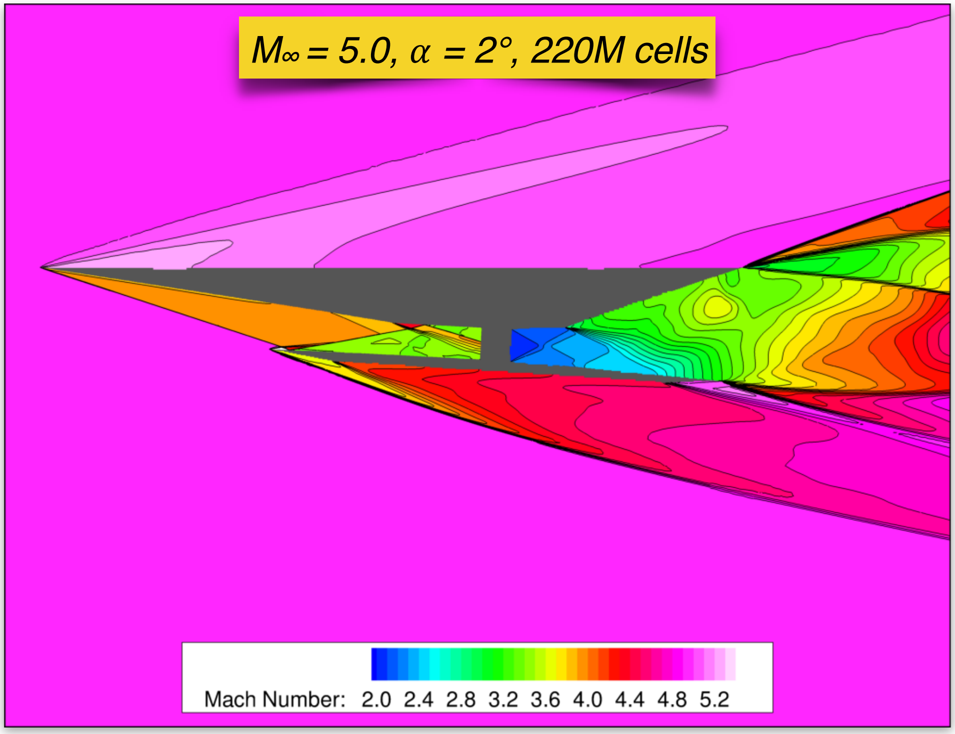
Turbojet - Matched Mass Flow Rates



Scramjet in Hypersonic Flow

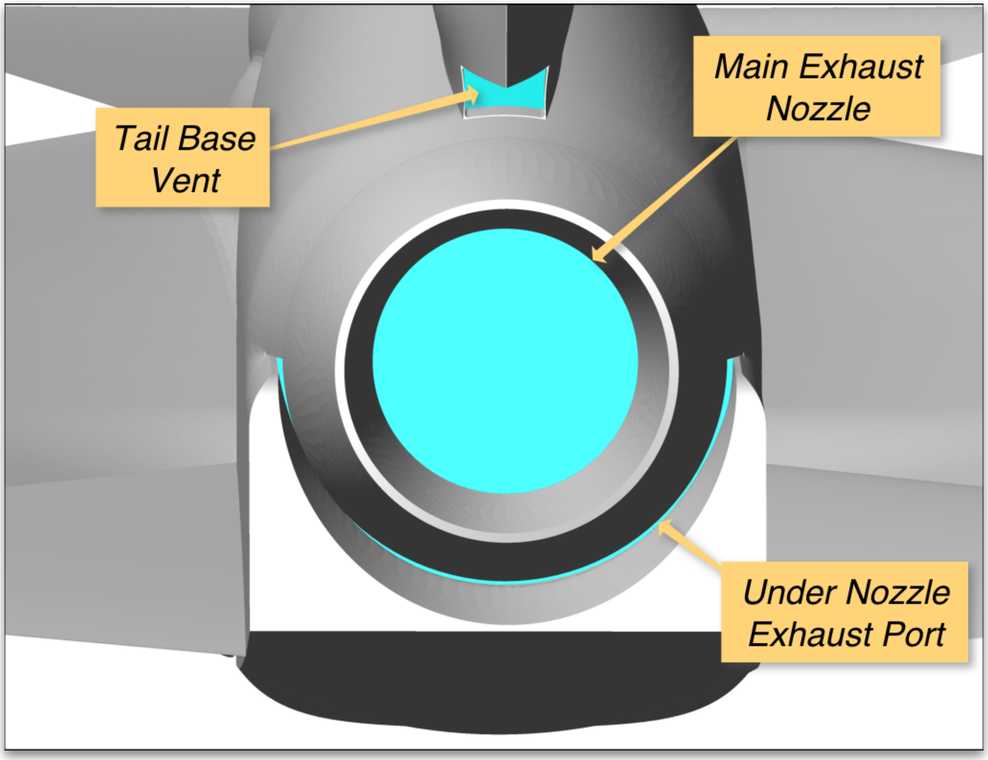
- Multiple ramp inlet and outlet, flow through burner remains supersonic
- Mach 5.0 freestream, 2° angle of attack
- Subsonic inflow / outflow boundary conditions not applicable
- Original full state with Riemann solver (`SurfBC`) boundary condition applied
- Mesh was refined at surface, within Mach cone of influence, shock and expansion structures, and plume shear layer influencing pressure sensor

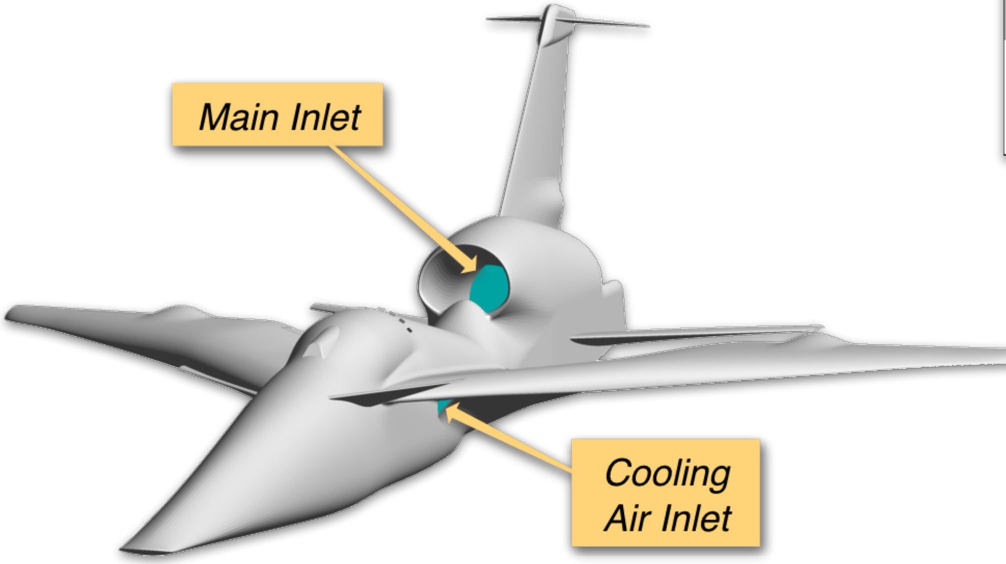


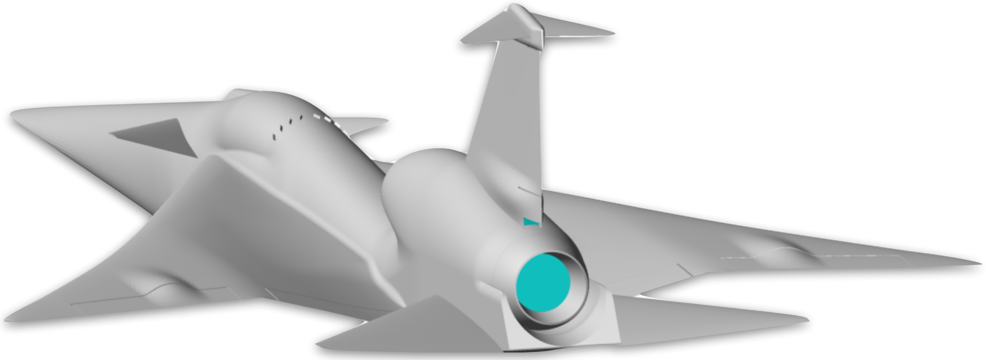


Low Boom Supersonic Demonstrator

- Realistically complex geometry
- Mach 1.4 freestream, 2.15° angle of attack
- 3 inlets and 3 exhausts

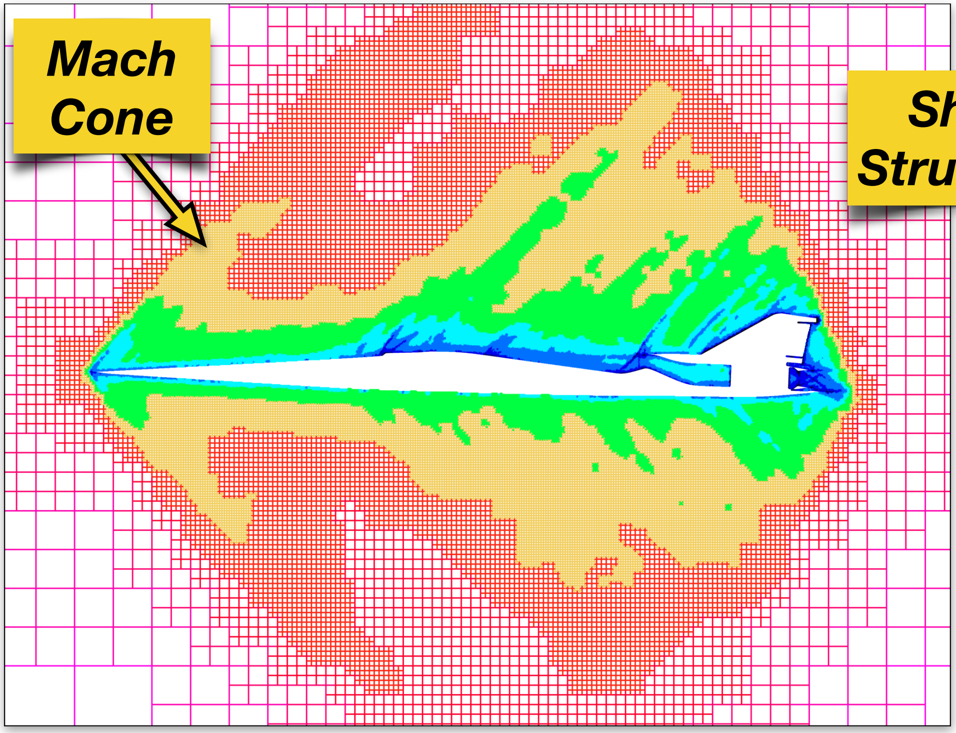


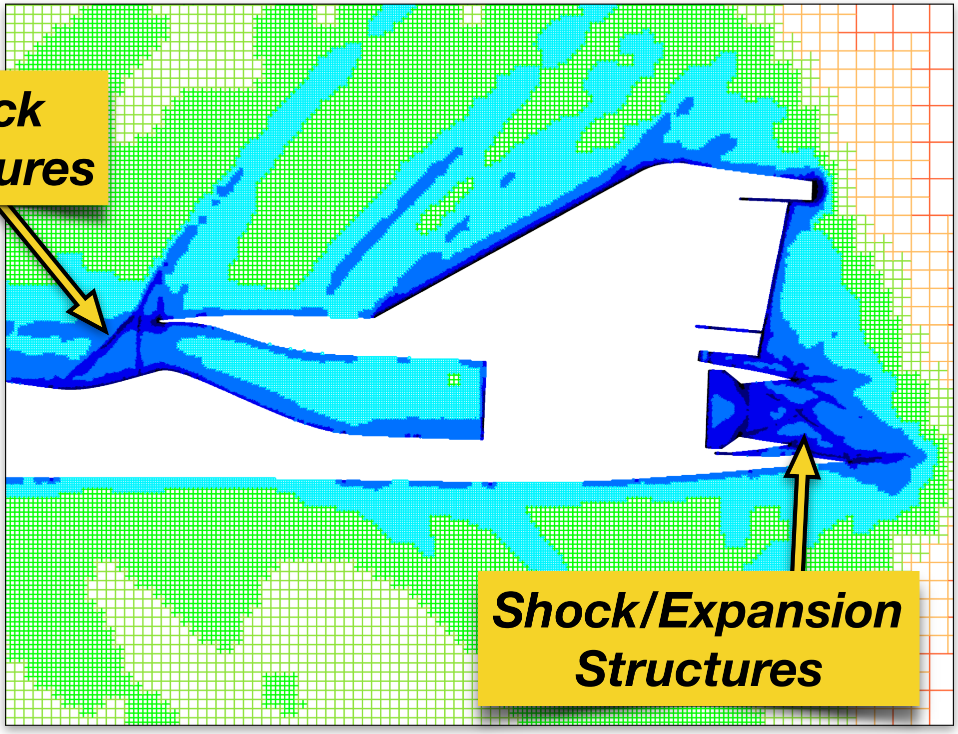




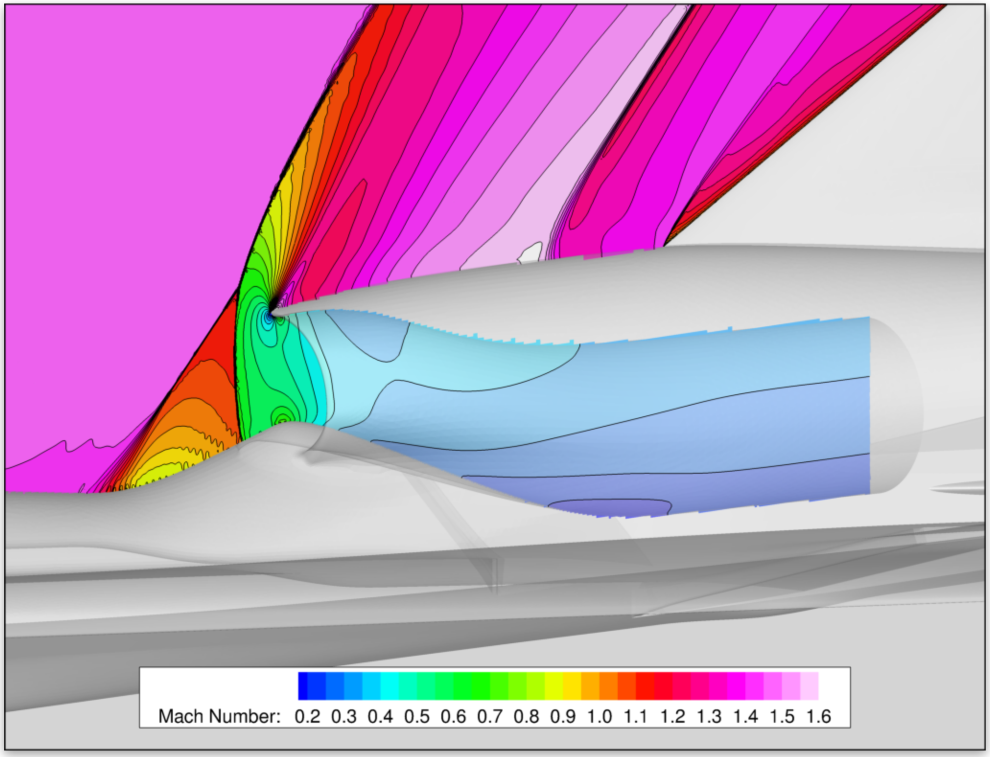
Low Boom Aircraft - Adaptively Refined Mesh

- Functional was aircraft drag
- Colors represent cells of same level of refinement
- Mesh was refined at surface, within Mach cone of influence, and at shock and expansion structures

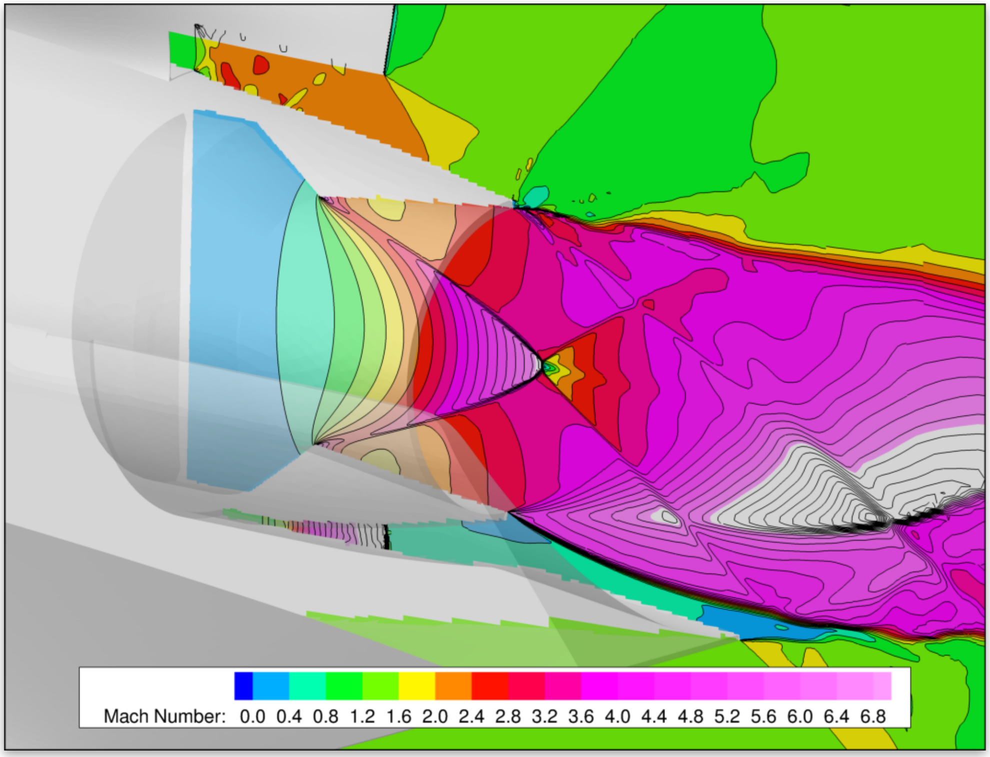




Low Boom Aircraft - Example Solution



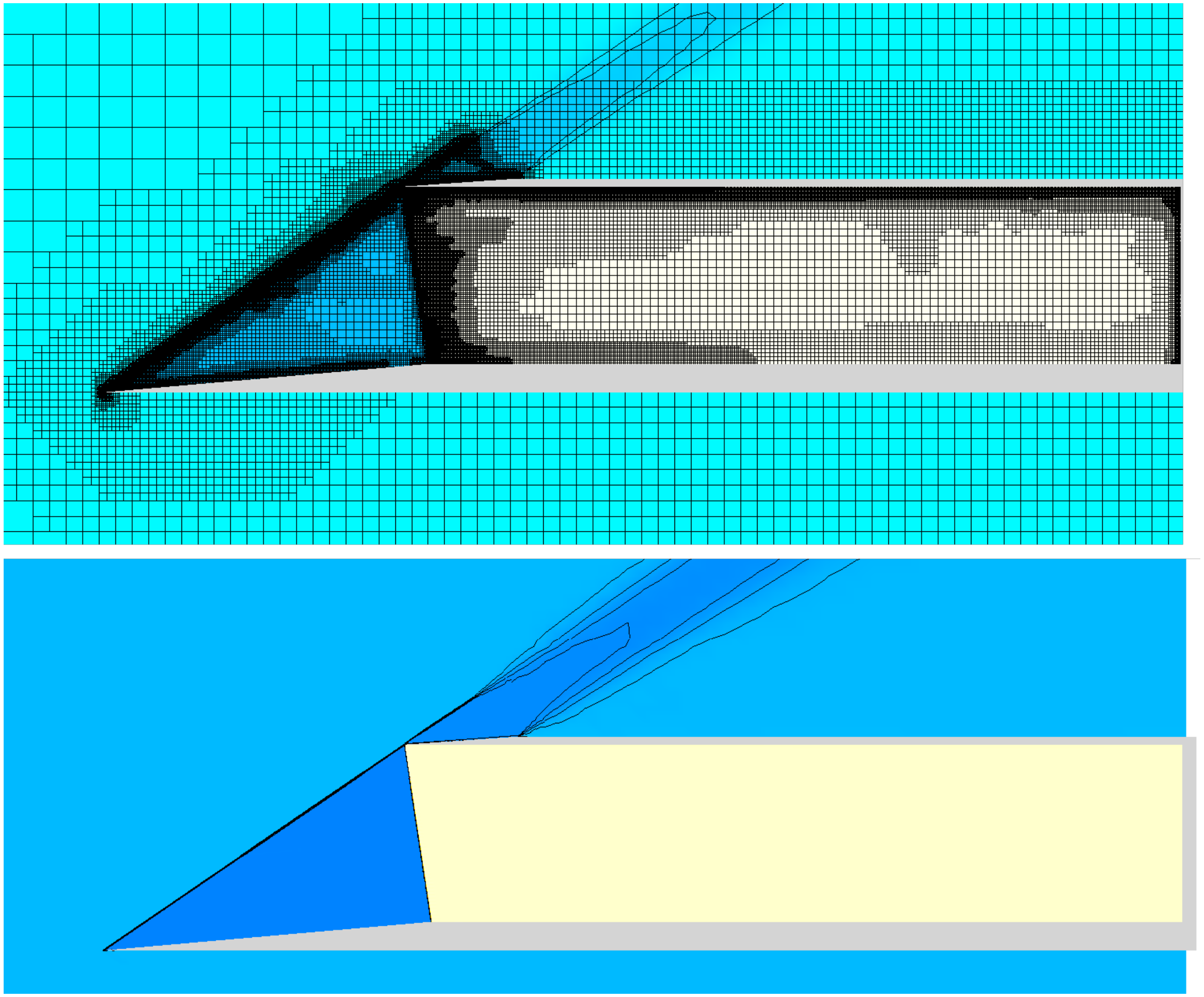
$M_\infty = 1.4$, $\alpha = 2.15°$,
70M cells (half-body mesh)



- Underwing inlet geometry is not fully realized
- Safeguards were active in these inlets (solid wall to not allow reverse flow)

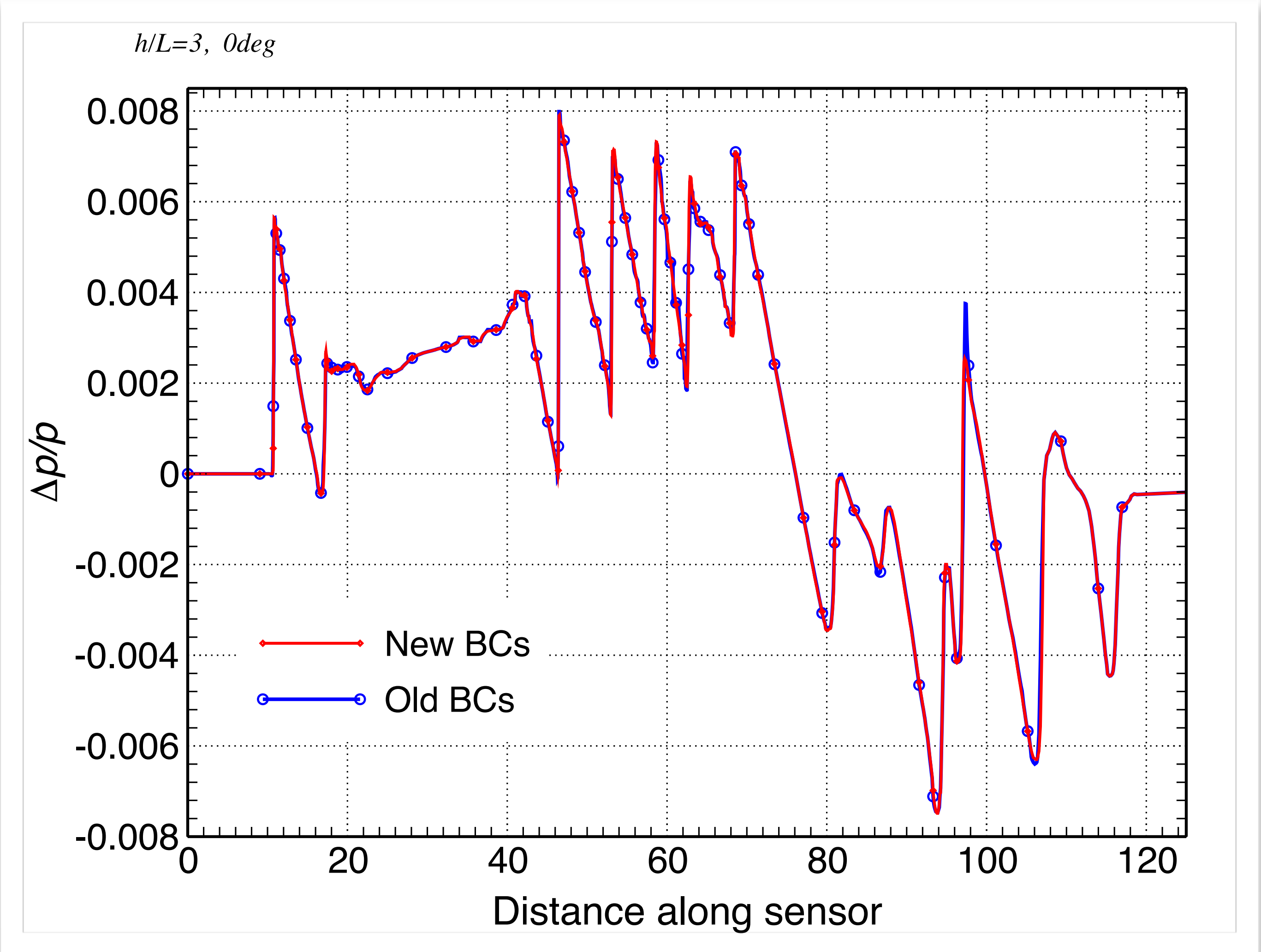
Validation Case - 2-Shock Inlet

- Same validation case was run with SurfBC (Pandya, 2004)



Verification Case - Low Boom Demonstrator Signature

- Low boom aircraft was analyzed original `SurfBC` and again new boundary conditions
- Near field signatures compared



Summary and Ongoing Work

- Four new subsonic inflow/outflow boundary conditions implemented to improve modeling of propulsion systems
- Robust mass flow rate control implemented for both inflow and outflow
- Demonstrated on notional propulsion systems in flight regimes ranging from subsonic to hypersonic
    - adjoint-driven mesh refinement demonstrated with all propulsion boundary conditions
    - new boundary conditions verified mesh convergence studies on notional examples
- Demonstrated on realistically complex low boom aircraft
- Some validation completed
- *Ongoing work*
    - *Implement additional functionals appropriate for propulsion systems*
    - *Extend design framework to include new propulsion boundary conditions and functionals*

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