Fundamental Aeronautics Program Annual Meeting

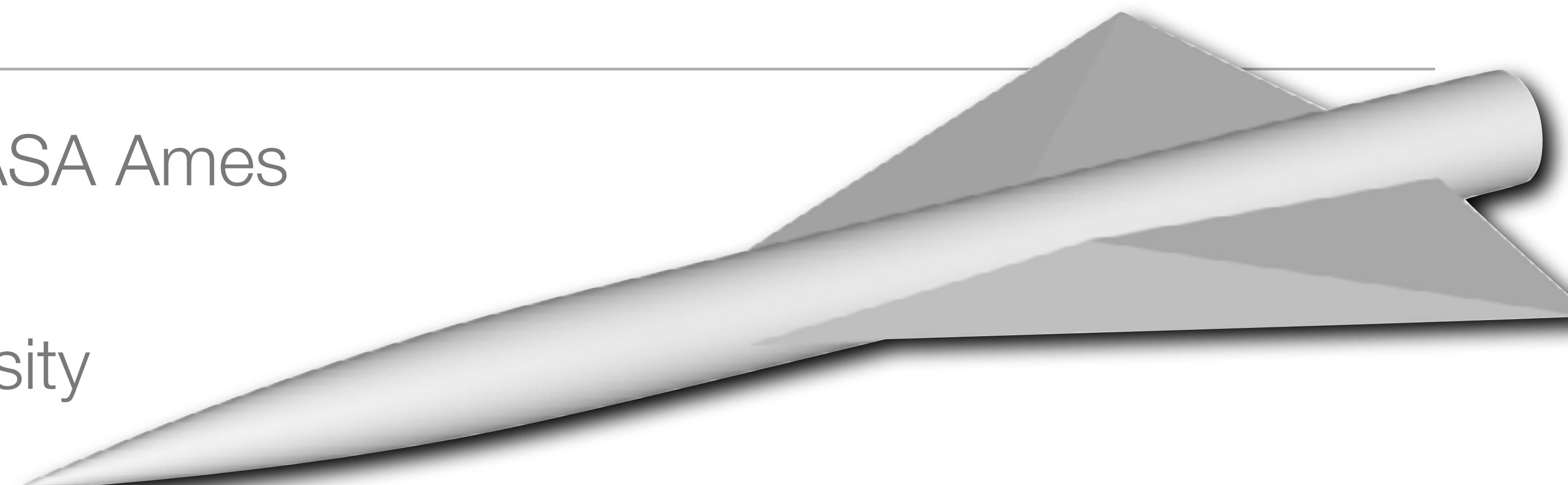
Sonic Boom Prediction Workshop

Sonic-Boom Prediction with Output-Based Adaptation and Cart3D

Michael Aftosmis, Code TNA, NASA Ames

Marian Nemec, ELORET Corp.

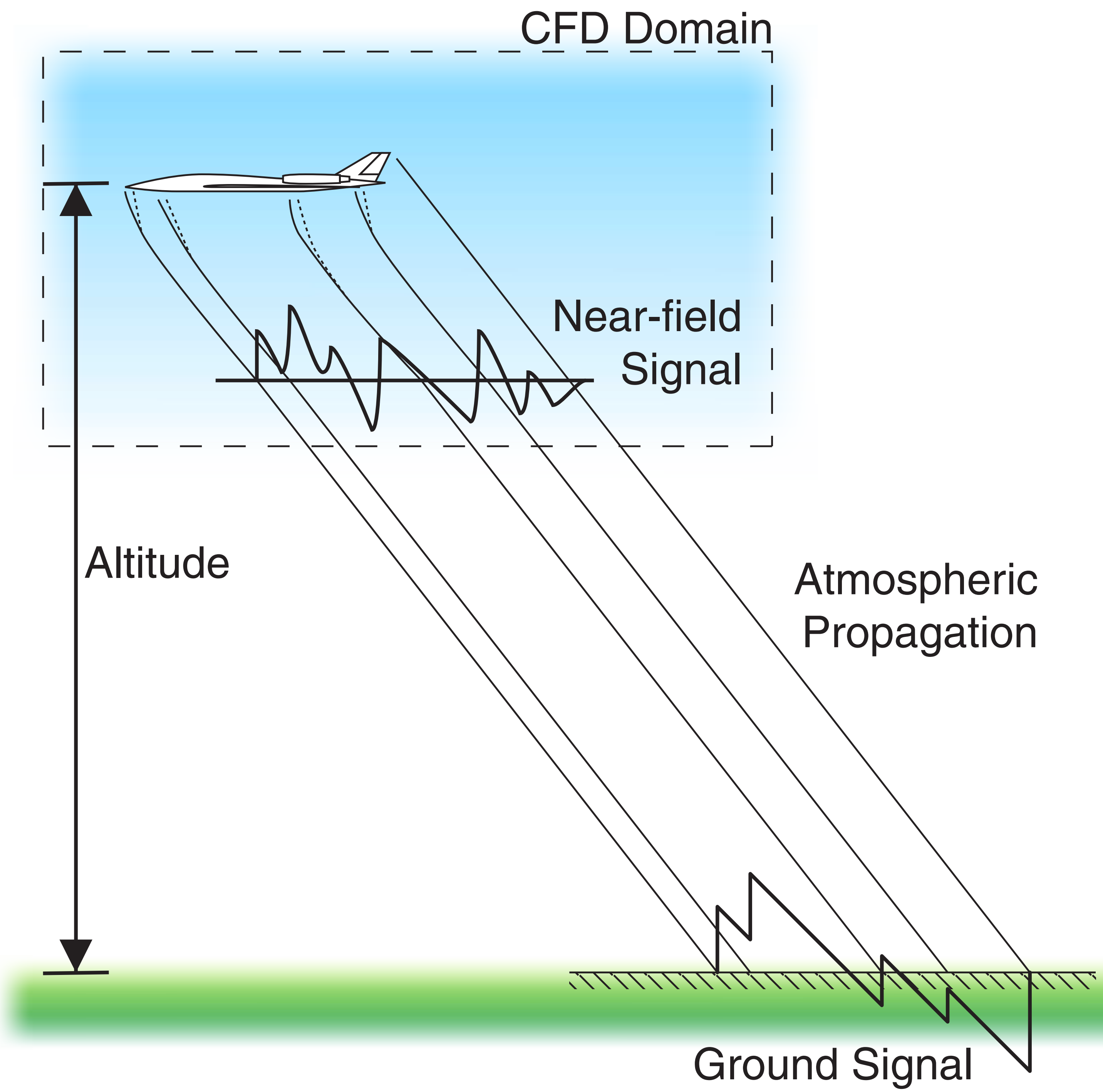
Mathias Wintzer, Stanford University



7-9 Oct. 2008

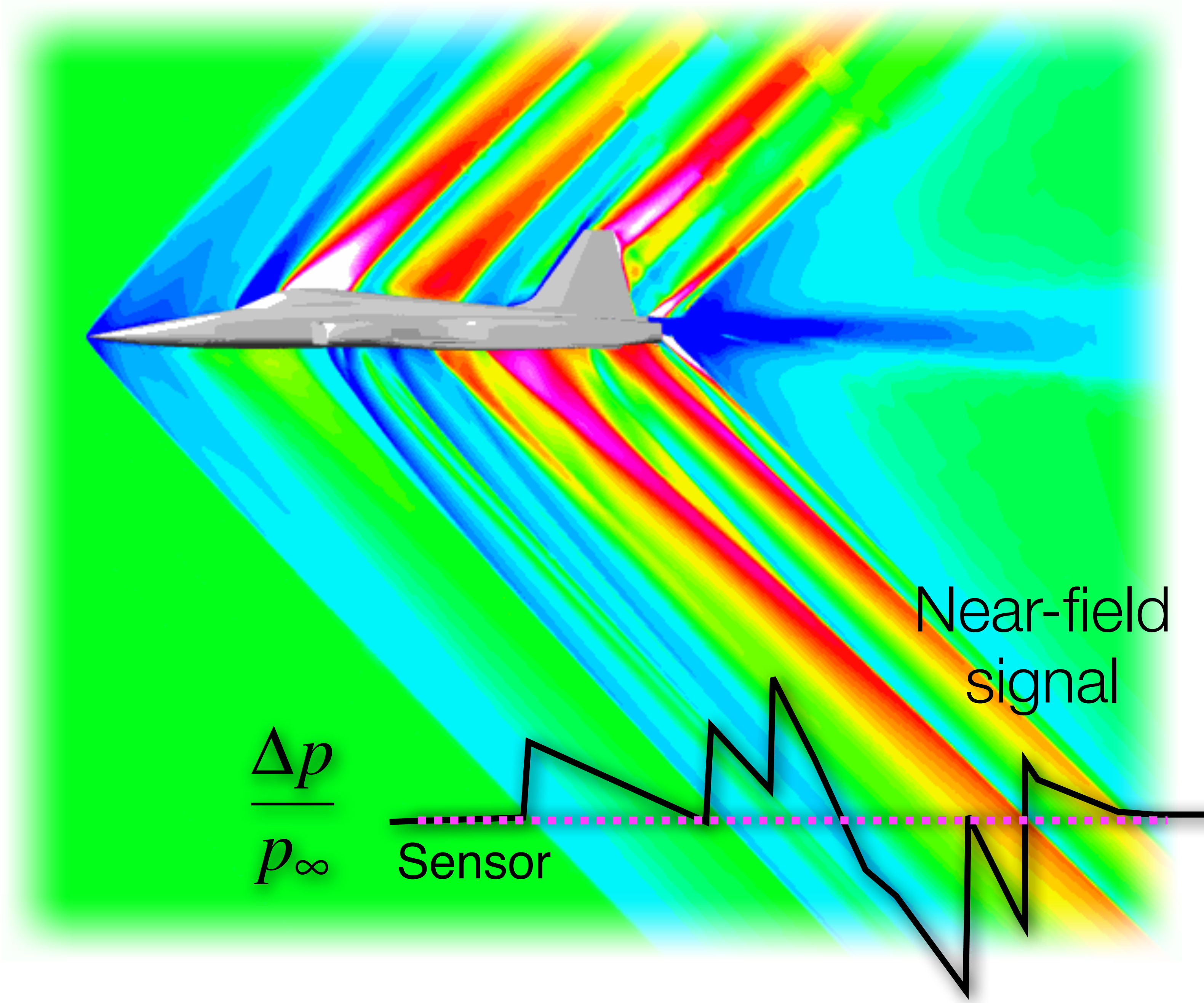
Problem Description

- Objective is ground signal
- Basic approach:
  - Compute accurate pressures in the "near-field"
  - Propagate to ground using atmospheric propagation code
- Fundamental difficulty
  - Can be expensive due to long propagation distances



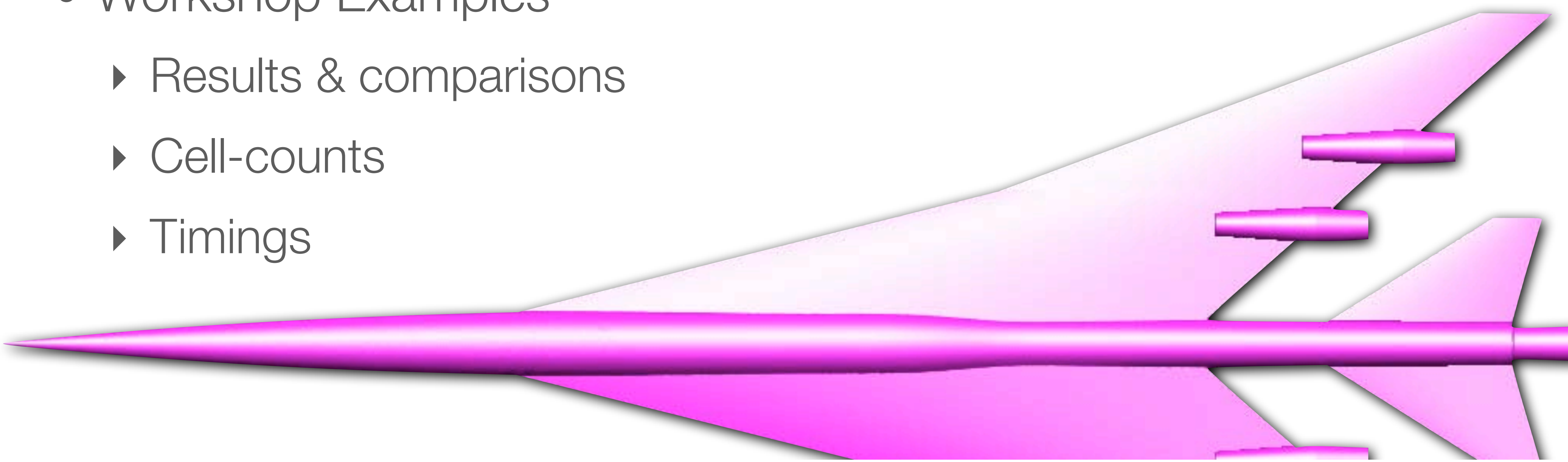
Approach

- Use adjoint-based mesh adaptation with Cart3D
- Drive adaptation with signal at off-body sensor in near/mid field
- Make every attempt to minimize expense of computation



Outline

- Method & Development history
- Basics of method
    - Generic example
    - Specialization for boom
- Workshop Examples
    - Results & comparisons
    - Cell-counts
    - Timings



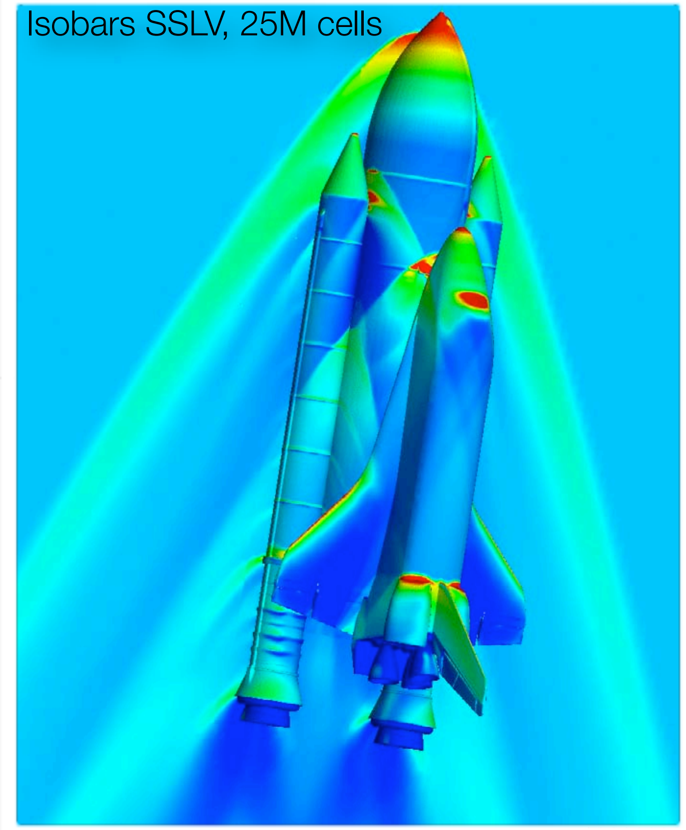
Cart3D: Overview

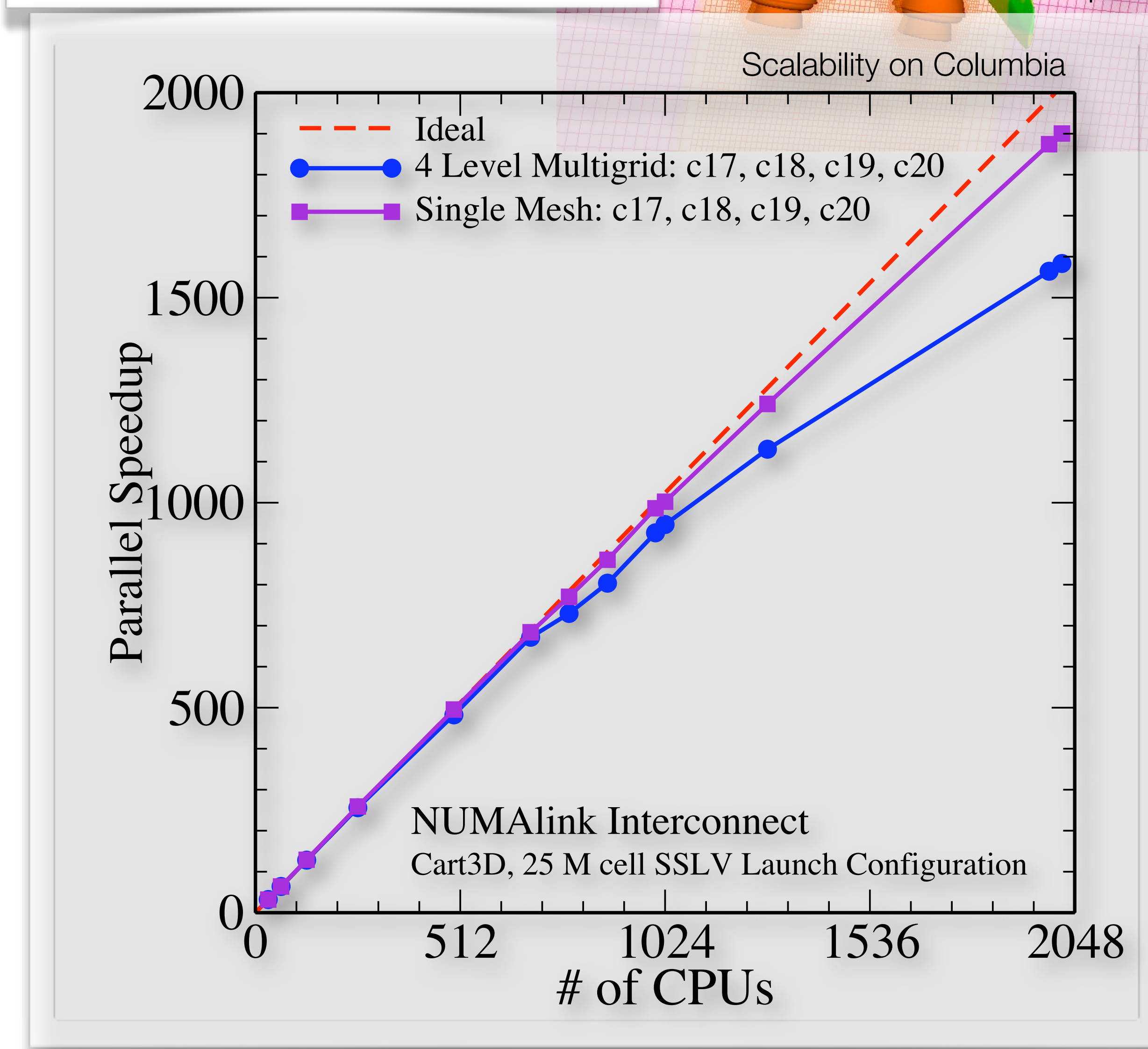
Cut-Cell Cartesian Method

- Fully-automated mesh generation from watertight geometry
- Unstructured Cartesian cells
- Insensitive to geometric complexity
- Multigrid accelerated upwind scheme

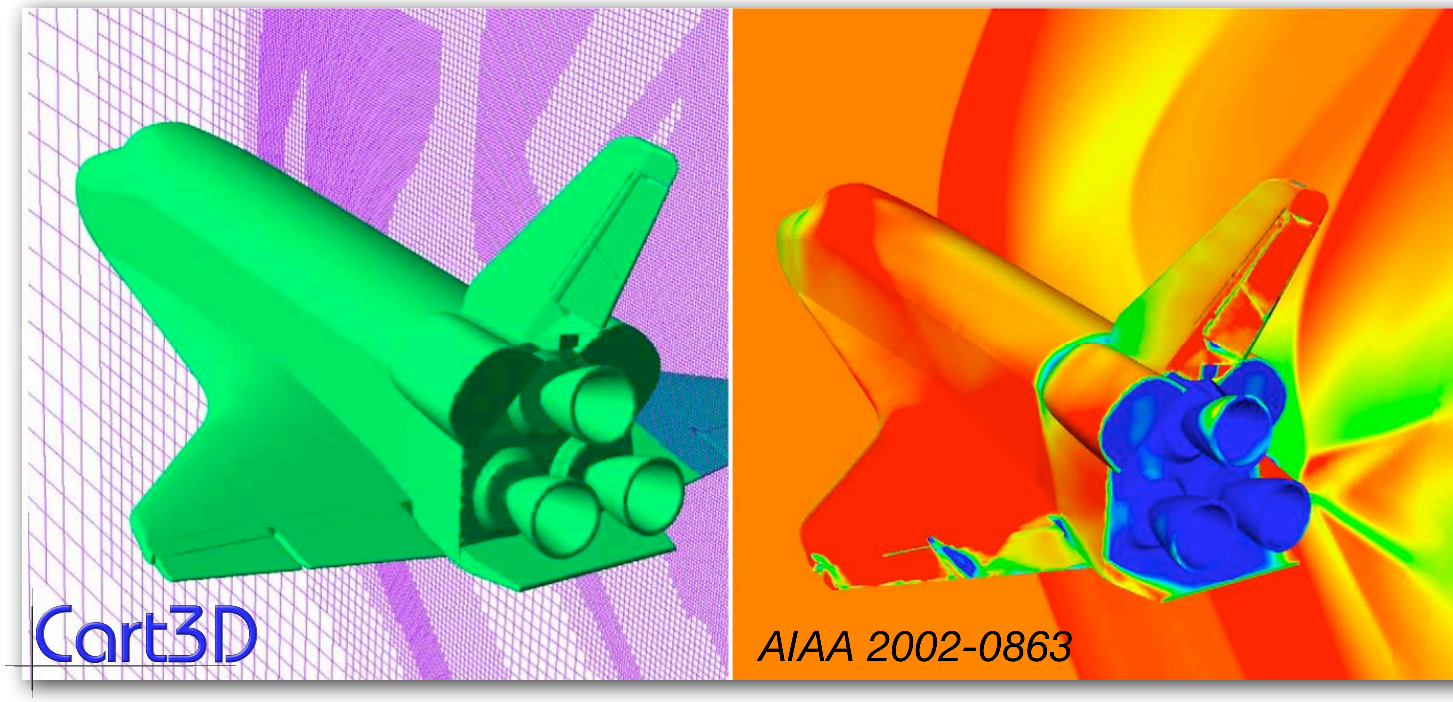
Highly Scaleable

- Domain decomposition
- “On-the-fly” mesh partitioning w/ SFC-based partitioner
- OpenMP and MPI builds
- Excellent scalability on Columbia, Pleiades and RTJones

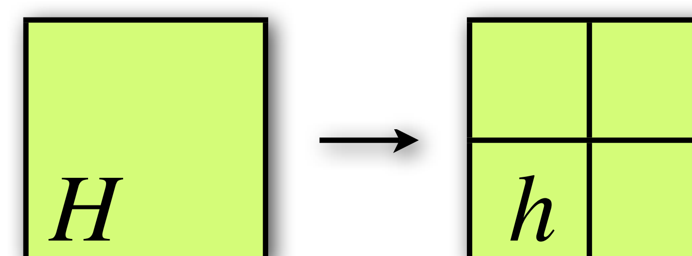




Cart3D: Mesh Adaptation



- Basic adaptation infrastructure for Cart3D developed in 2001-’02
- Adjoint approach involves solution of flow eqs. & corresponding adjoint eqs.
- Main Benefits:
  - **Efficiency:** Focus only on discretization error which impacts performance (functional)
  - **Credibility:** Every simulation includes:
    1. Mesh refinement study to demonstrate mesh convergence
    2. Adjoint correction term to functional
    3. Bound on remaining error in discrete solution



  - Goal is a **user independent** predictive tool!
    - Remove dependence on “expert knowledge” to generate good mesh
    - Even “expert” learns from final mesh
    - Remove user bias that even expert brings to meshing

Cart3D: Adjoint Development

Boom Prediction:

- *AIAA 2008-6593*, "Adjoint-Based Adaptive Mesh Refinement for Sonic-Boom Prediction," Wintzer, Nemec & Aftosmis

Adjoint-Based Adaptation:

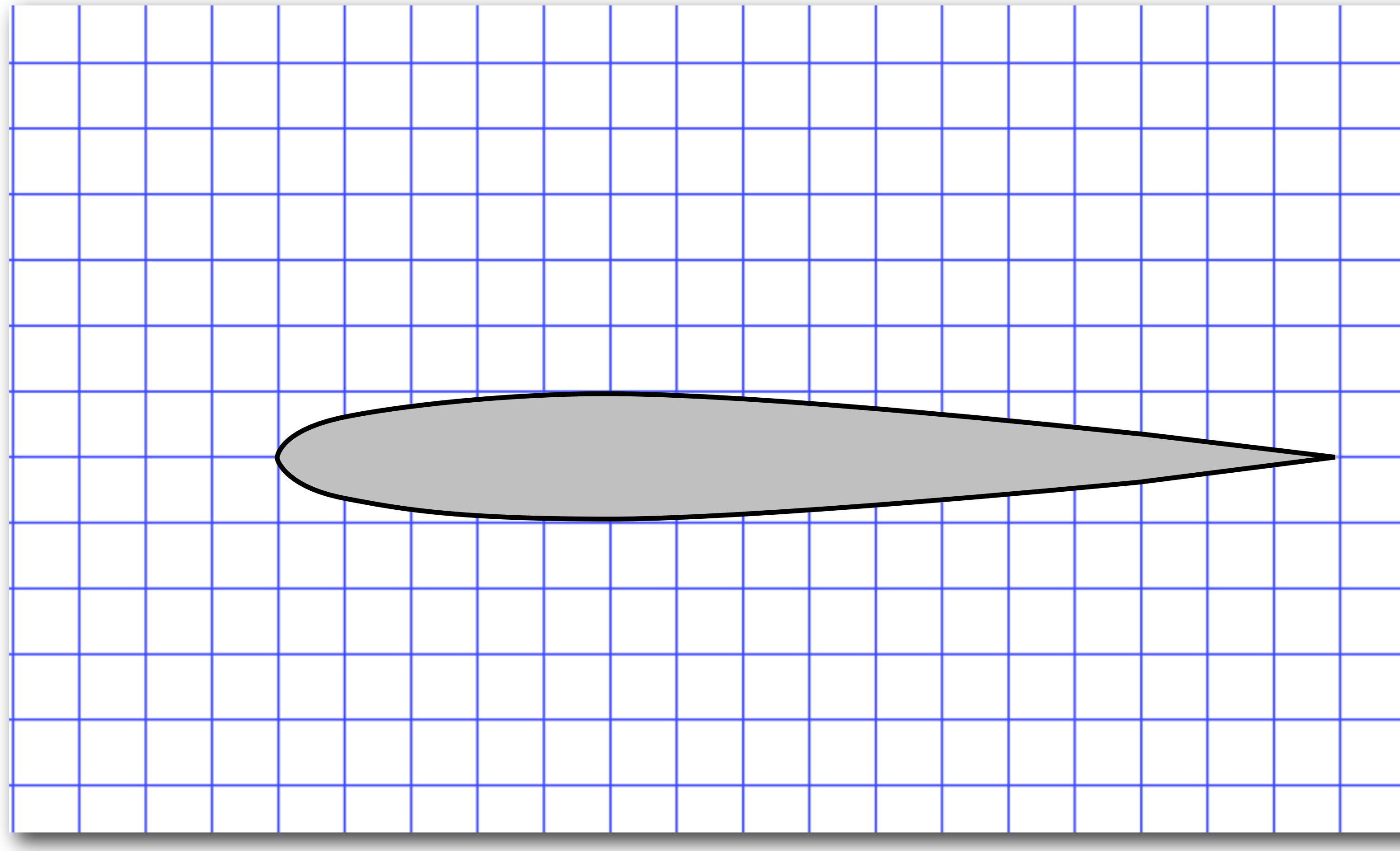
- *AIAA 2008-0725*, "Adjoint-based adaptive mesh refinement for complex geometries," Nemec & Aftosmis
- *AIAA 2007-4187*, "Adjoint error estimation and adaptive refinement for embedded-boundary Cartesian meshes", Nemec & Aftosmis

Adjoint Method for Cut-cell Cartesian Meshes

- *ICCFD 4*, "Adjoint sensitivity computations for an embedded-boundary Cartesian mesh method and CAD geometry," Nemec & Aftosmis. Ghent, 2006
- *AIAA 2005-4987*, "Adjoint algorithm for CAD-based optimization using a Cartesian method," Nemec & Aftosmis

Method Example

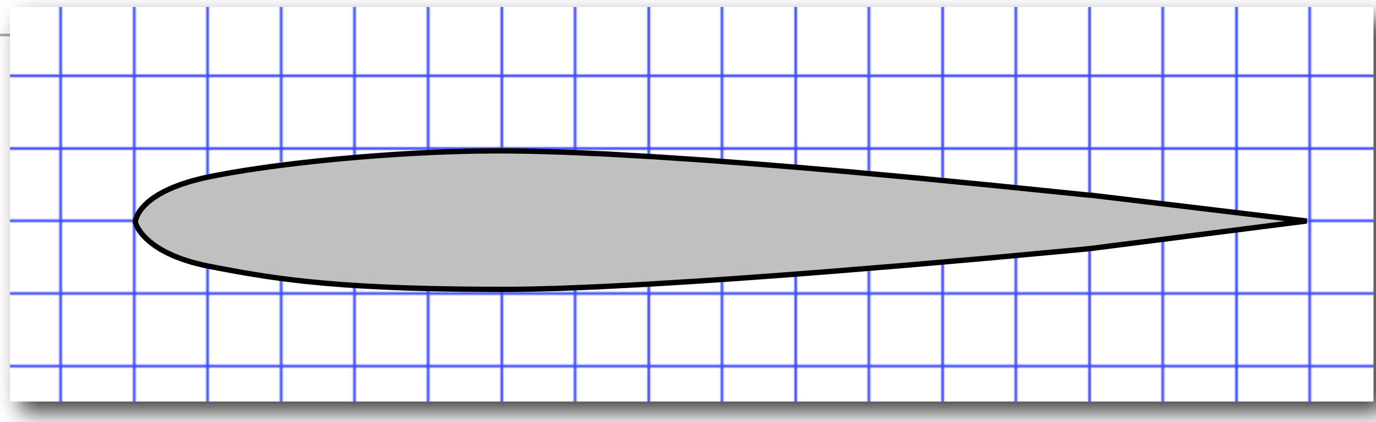
- NACA 0012 airfoil
  - $M_\infty = 0.8$,
  - $\alpha = 1.25°$
- Functional: C_D
- TOL: 4 counts

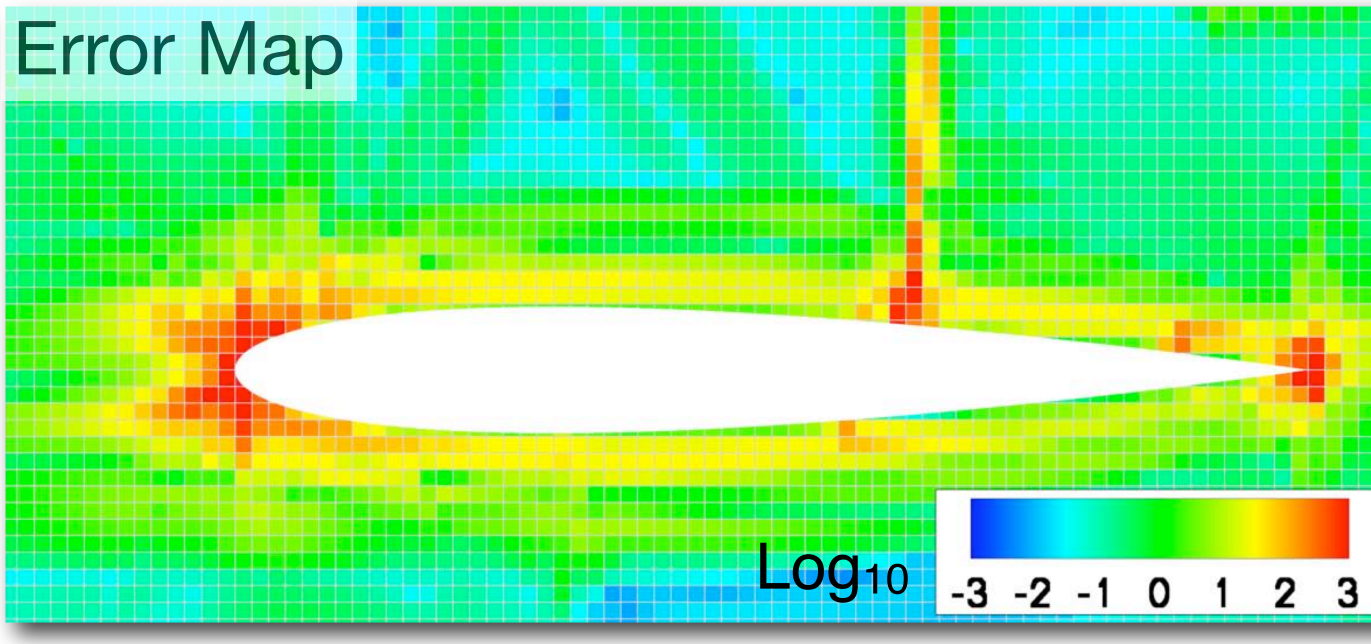


Method Example

1. Compute flow solution
2. Compute adjoint solution
3. Compute adjoint correction
4. Compute cell-wise error e_k

Net error: $$E = \sum_{k=0}^{N} e_k$$





Method Example

1. Compute flow solution

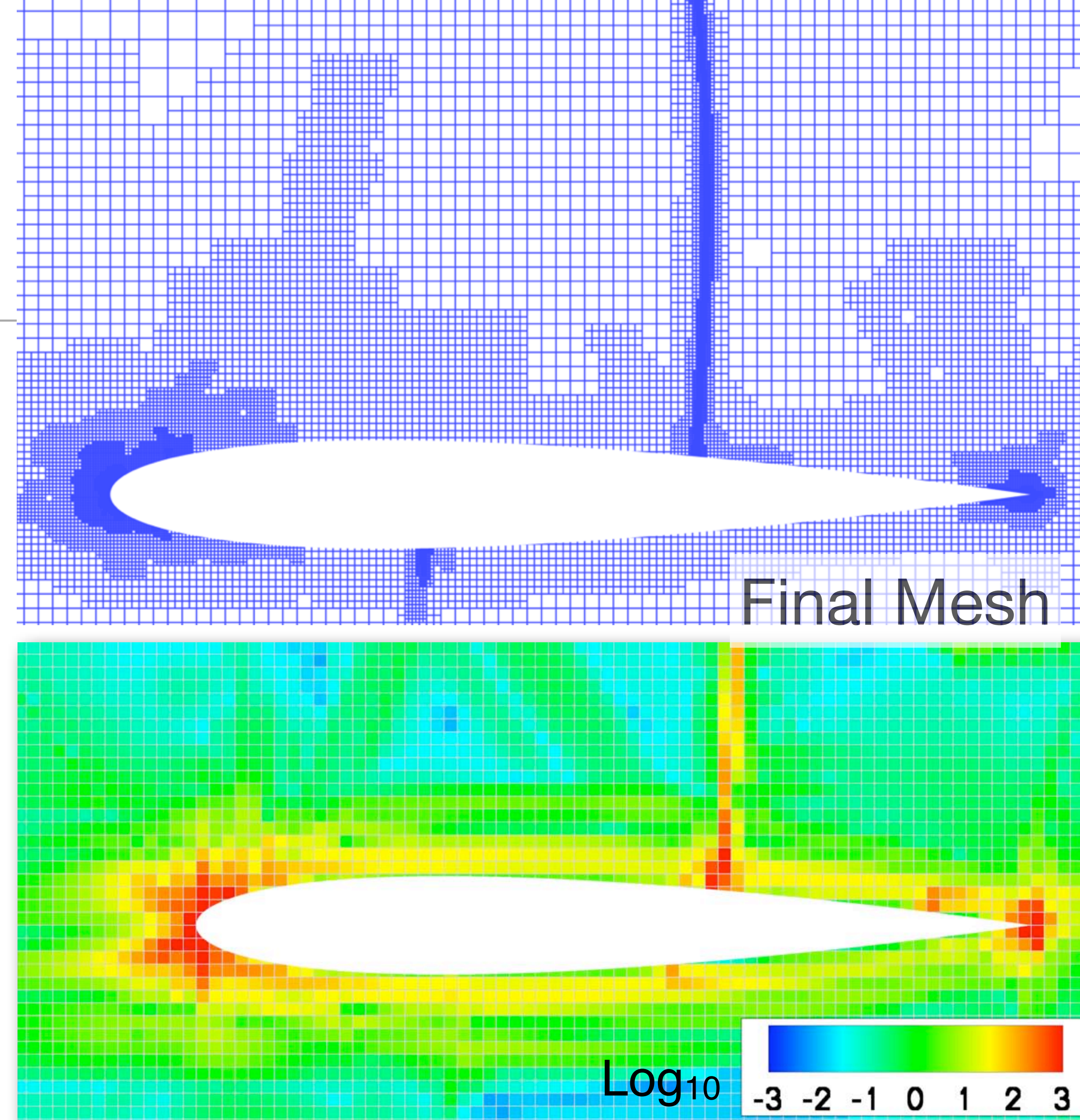
2. Compute adjoint solution

3. Compute adjoint correction

4. Compute cell-wise error e_k

   Net error: $$E = \sum_{k=0}^{N} e_k$$

5. Refine mesh where cell-wise error exceeds threshold

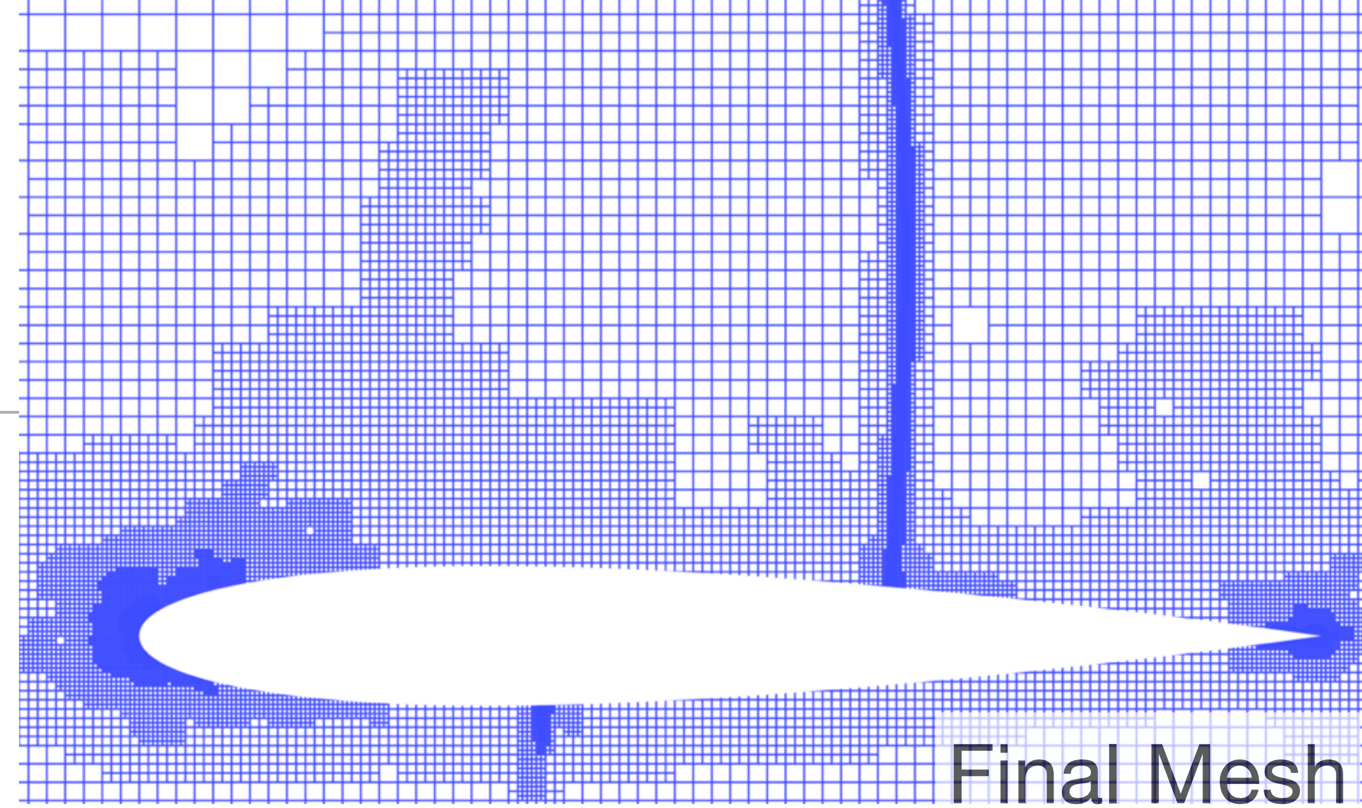


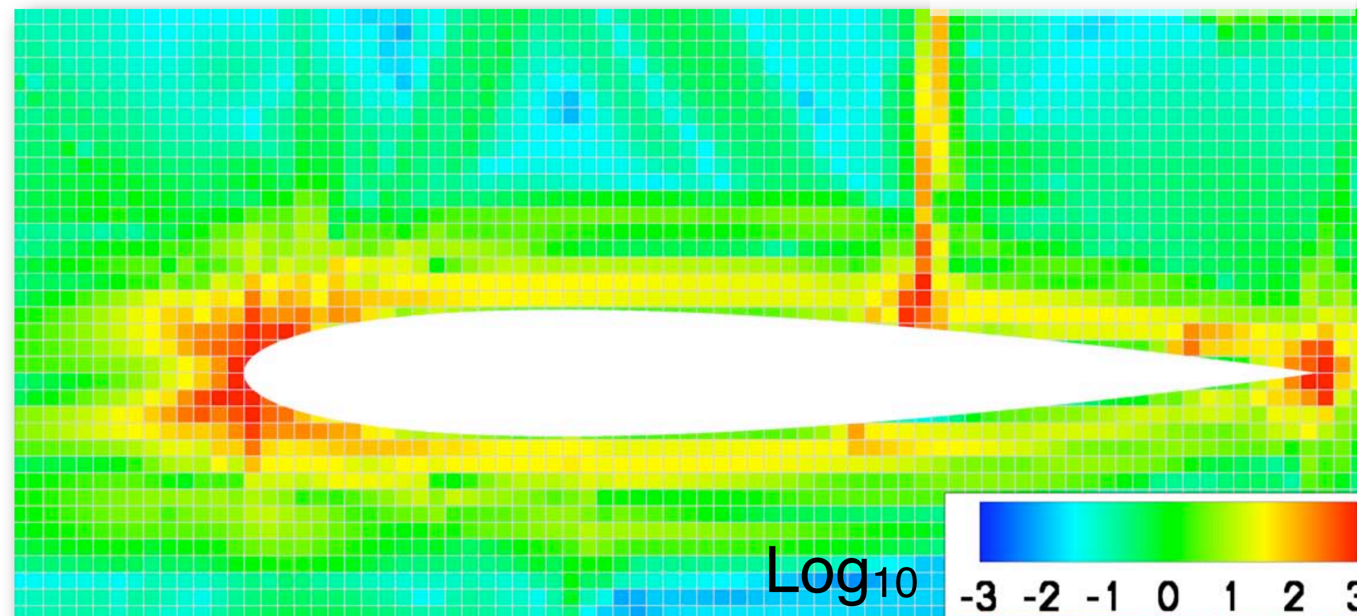
Method Example

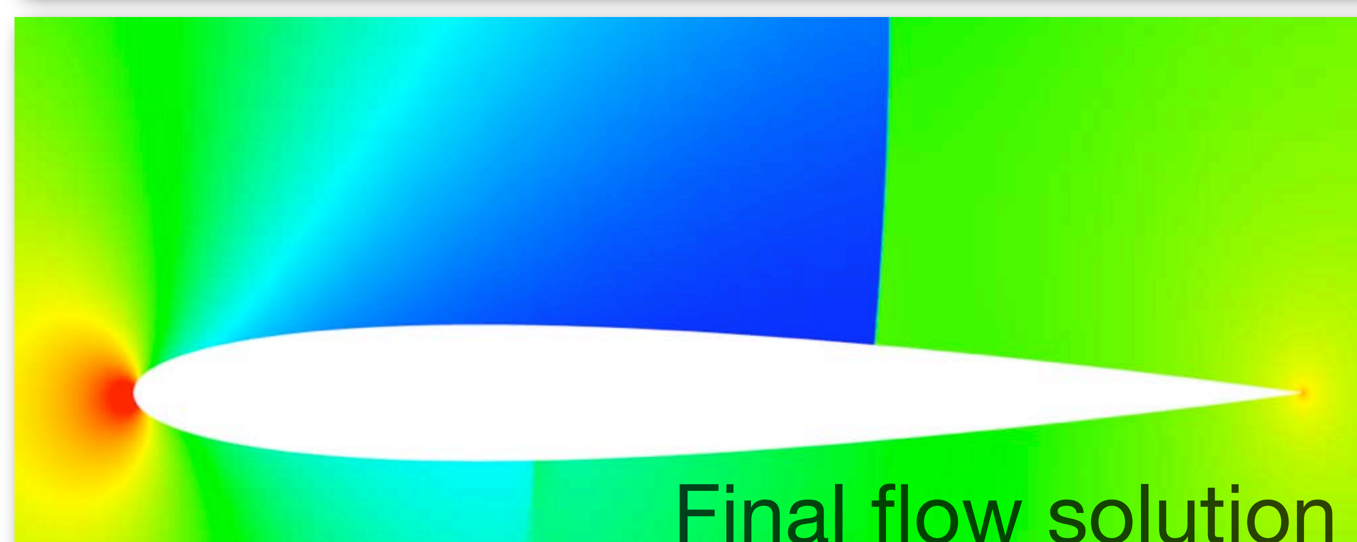
1. Compute flow solution
2. Compute adjoint solution
3. Compute adjoint correction
4. Compute cell-wise error e_k

   Net error: $$E = \sum_{k=0}^{N} e_k$$

5. Refine mesh where cell-wise error exceeds threshold
6. If (E < TOL) Stop

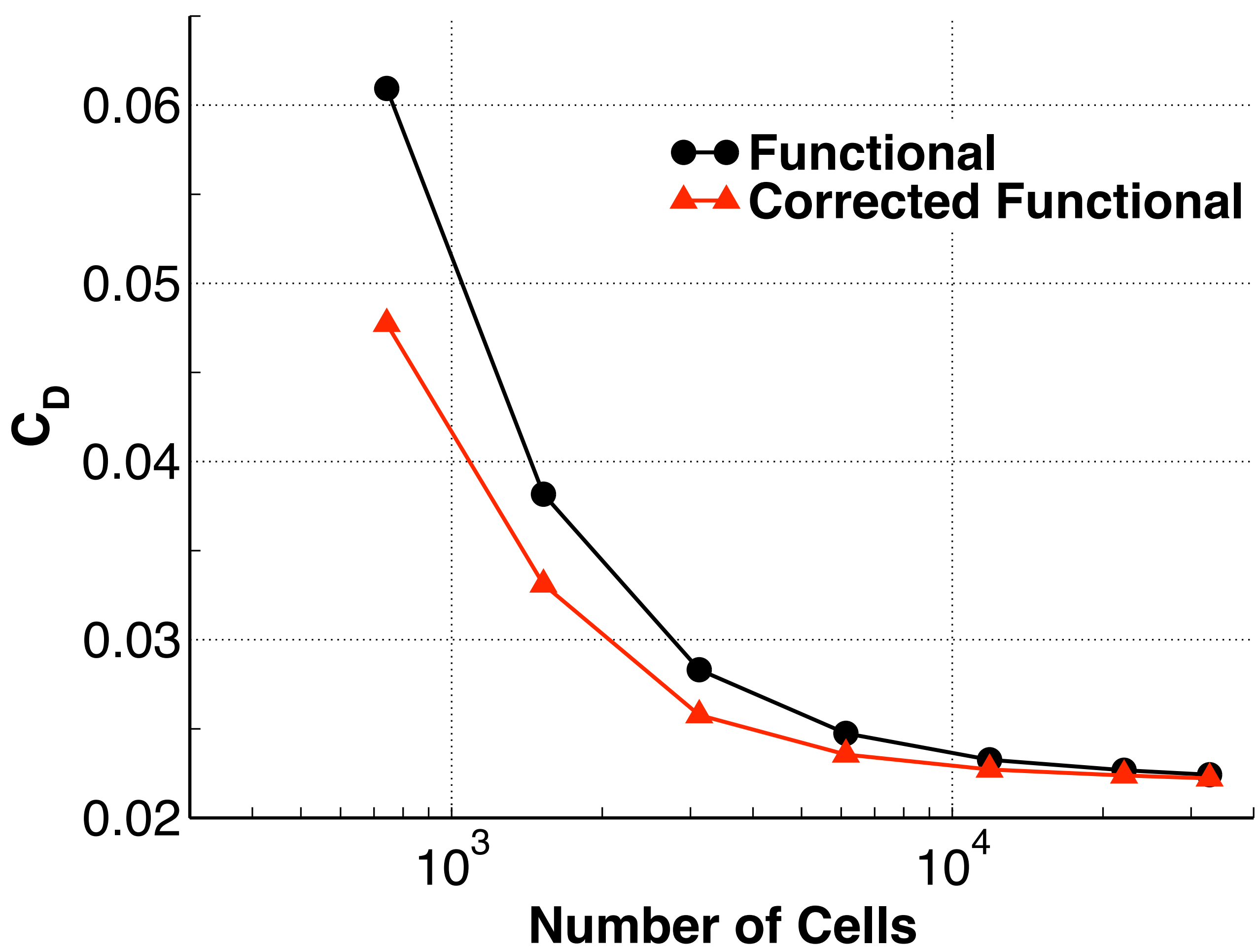




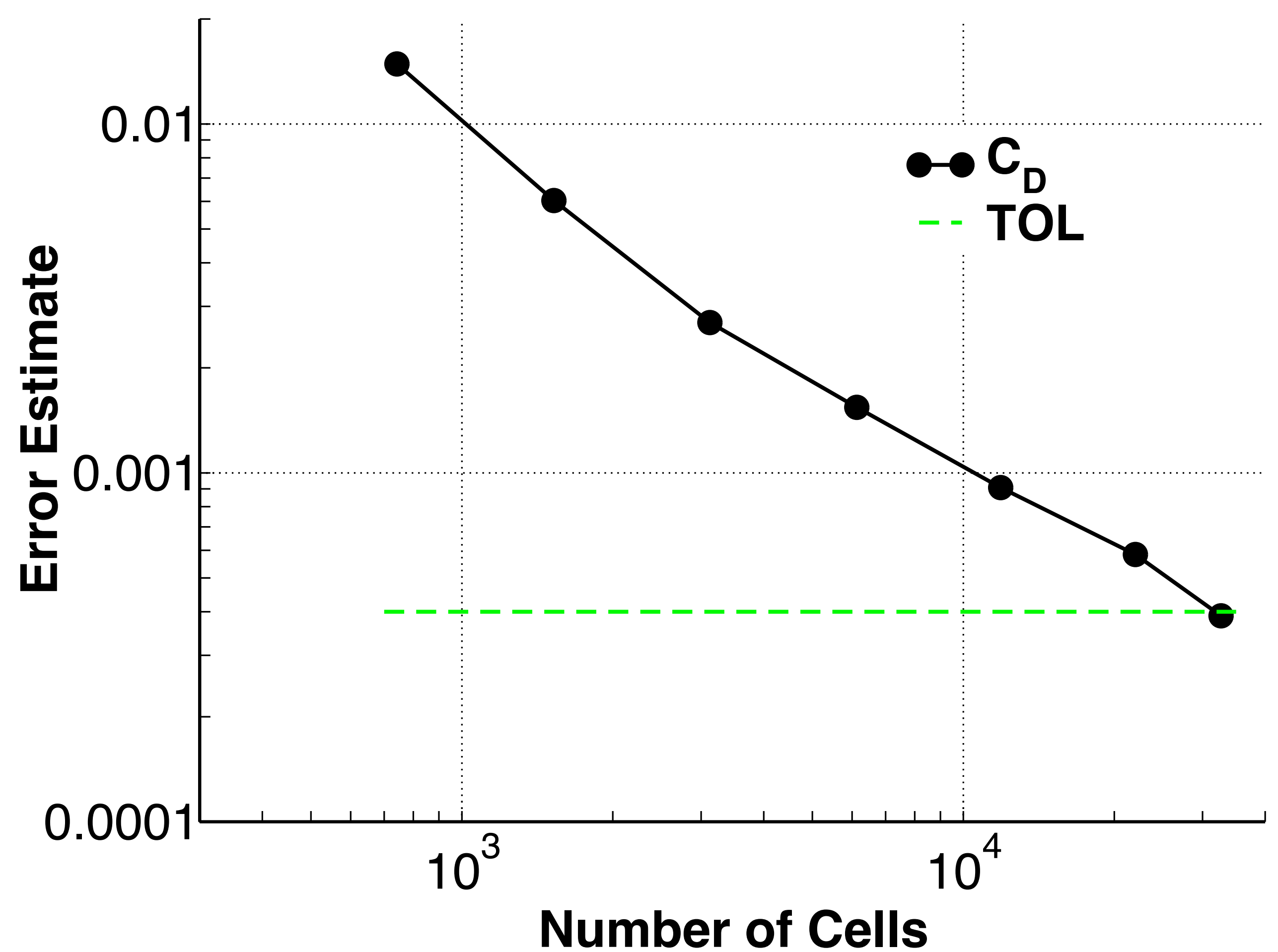


Method Example

Functional convergence

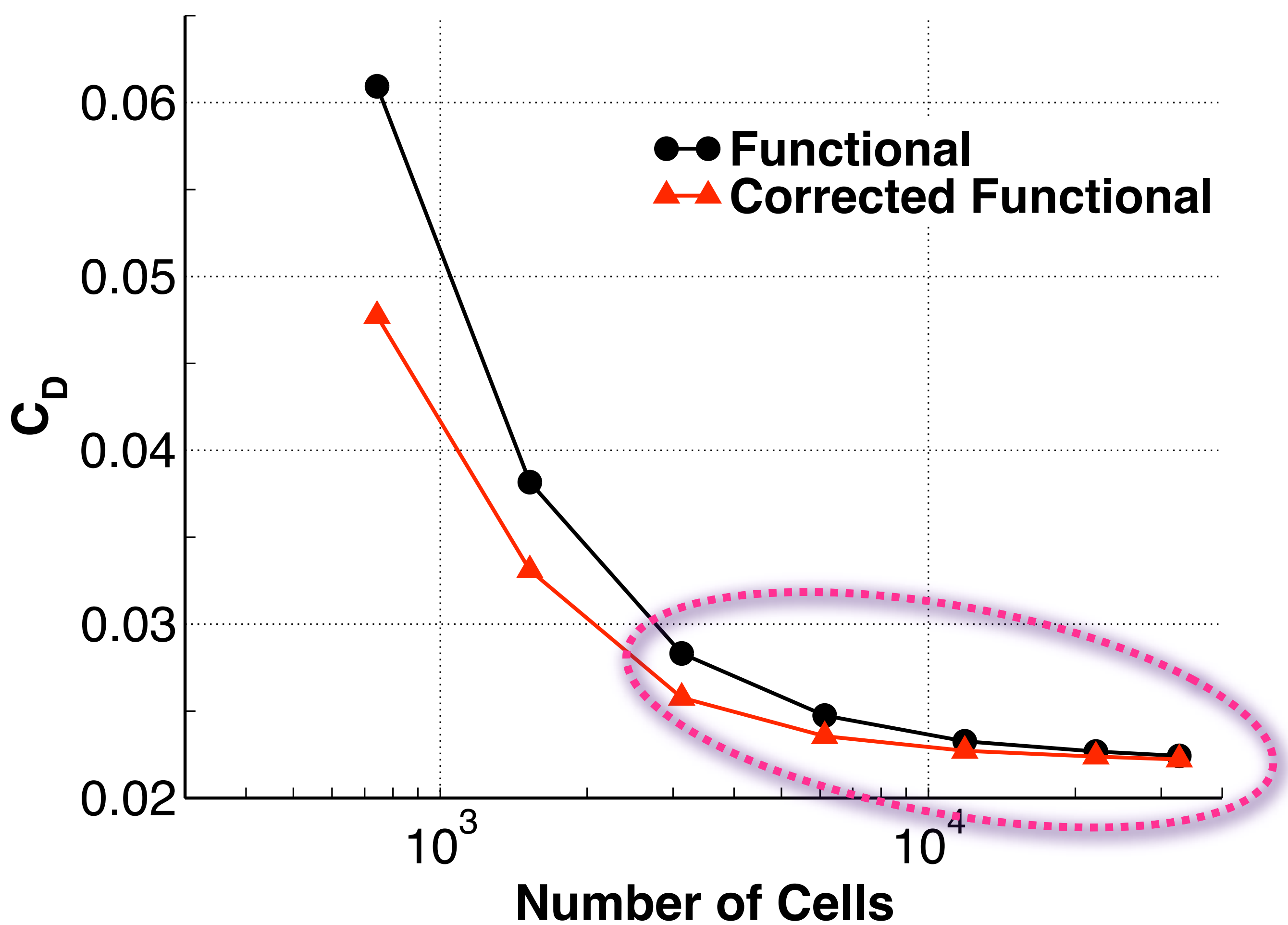


Estimate of Remaining Error

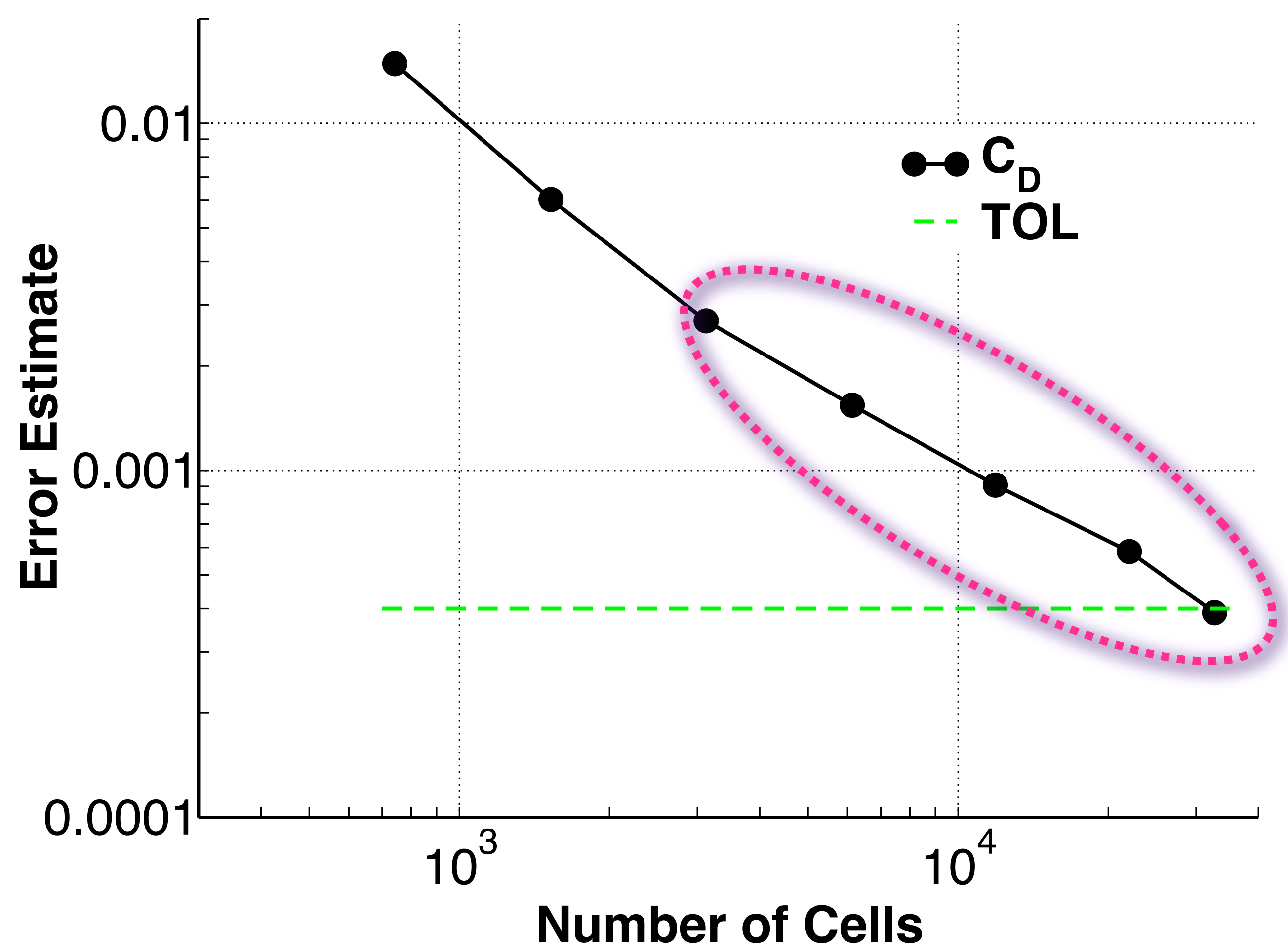


Method Example

Functional convergence



Estimate of Remaining Error

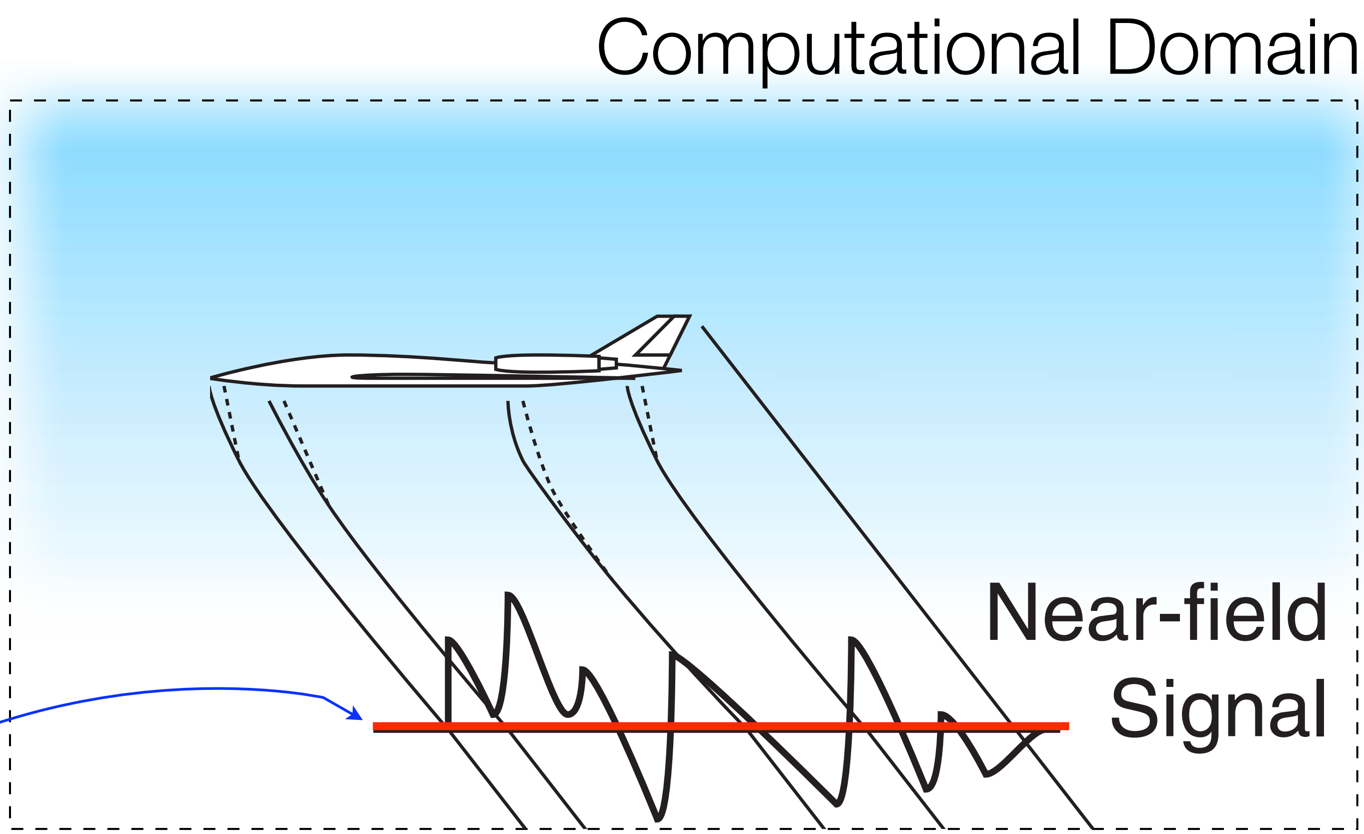


Corrected functional accurately predicts next answer.
Error steadily decreases.

Specialization for Sonic-Boom

- Re-examine simulation setup
- Signals propagating from body are measured along near-field sensor
- "Squared functional" used for sensor

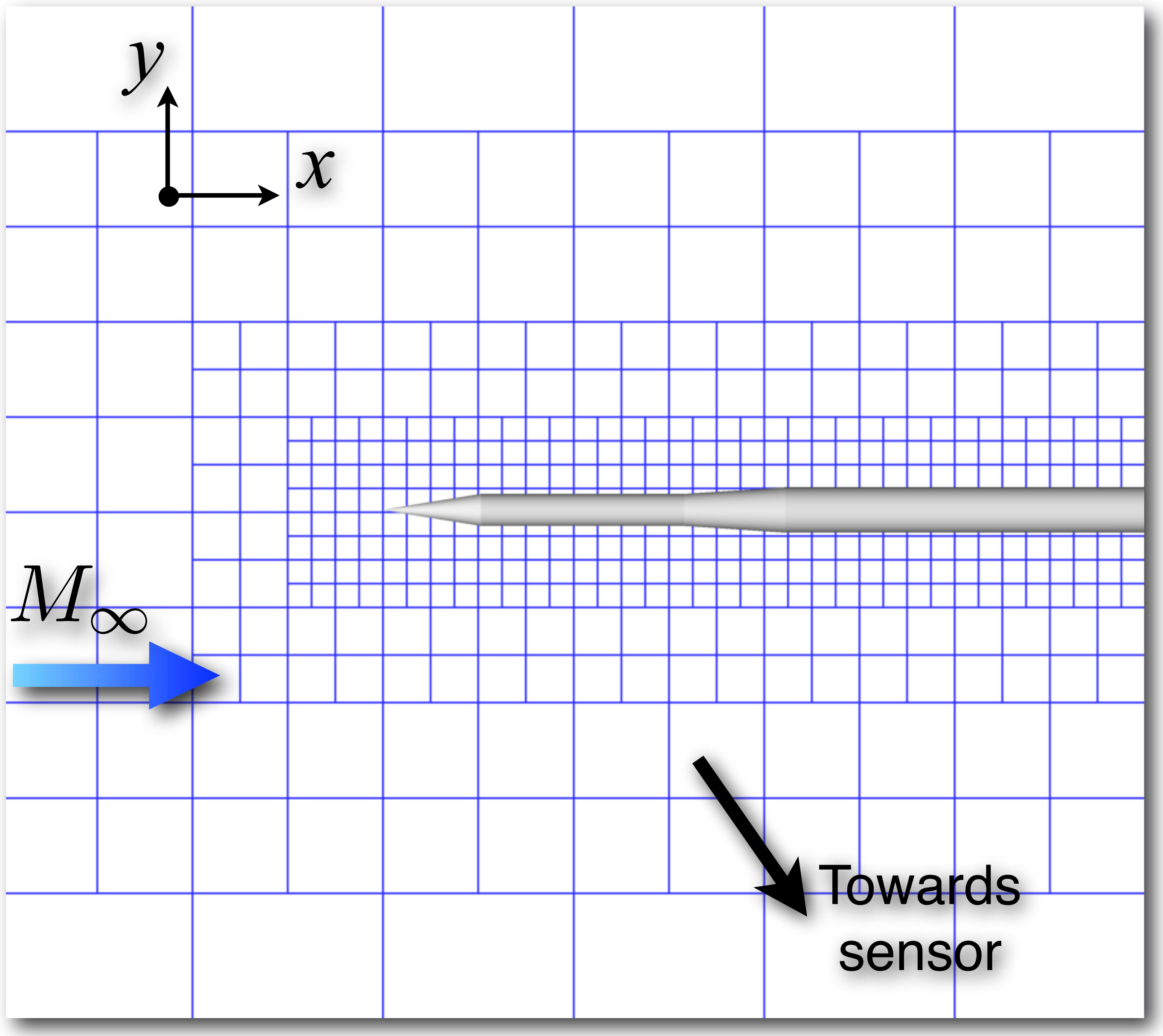
$$J_s = \int_0^L \left(\frac{\Delta p}{p_\infty}\right)^2 ds$$



- Introduced in AIAA-2008-0725
- Emphasizes peaks
- Vanishing derivative near $\Delta p = 0$

Specialization for Sonic-Boom

- Traditional problem layout
  - Cartesian-aligned edges
  - Cubic (isotropic) cells

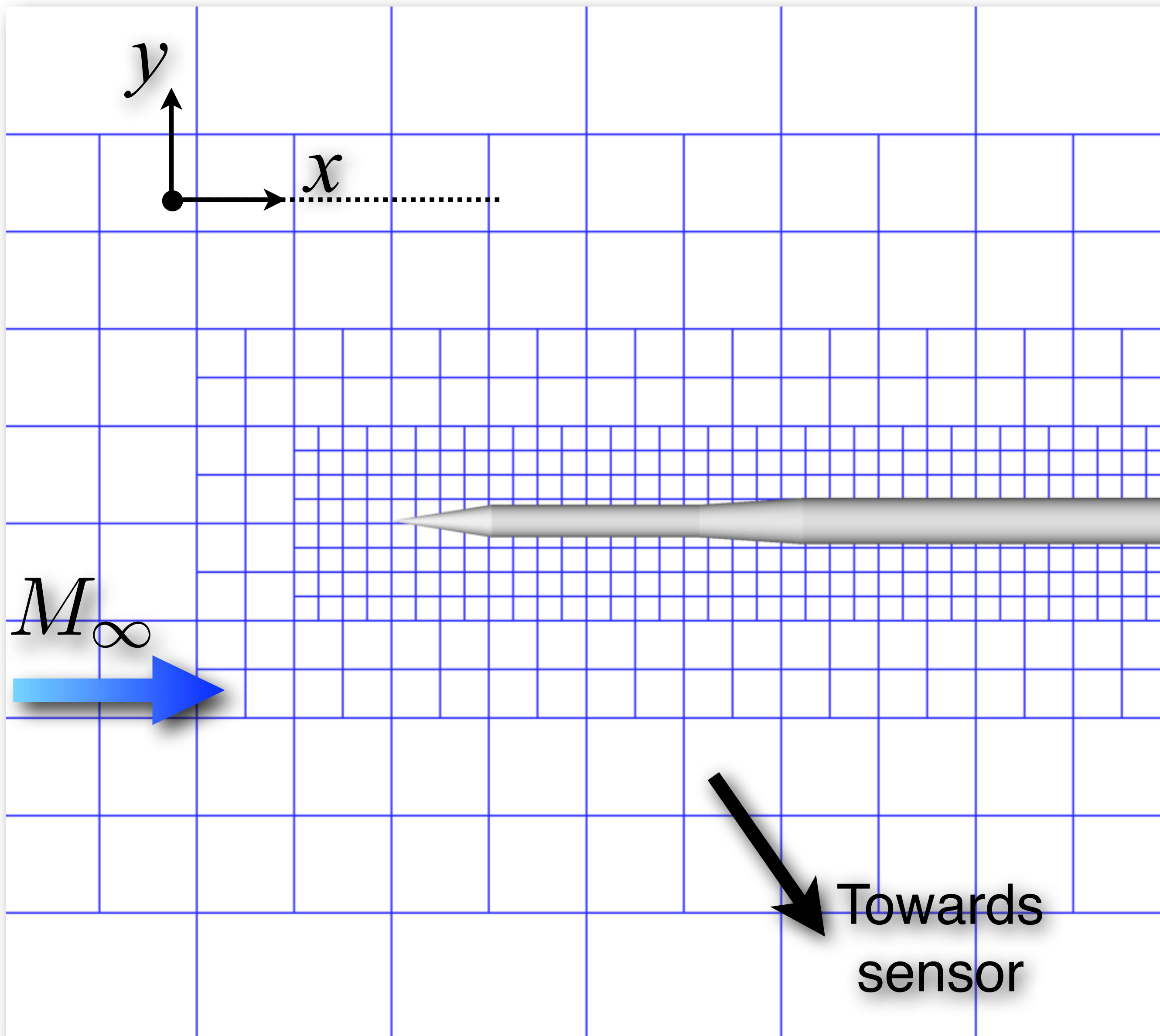


Specialization for Sonic-Boom

- To enhance signal propagation towards the sensor:

  Rotate mesh by Mach-angle, μ

$$\mu = \sin^{-1}\left(\frac{1}{M_\infty}\right)$$

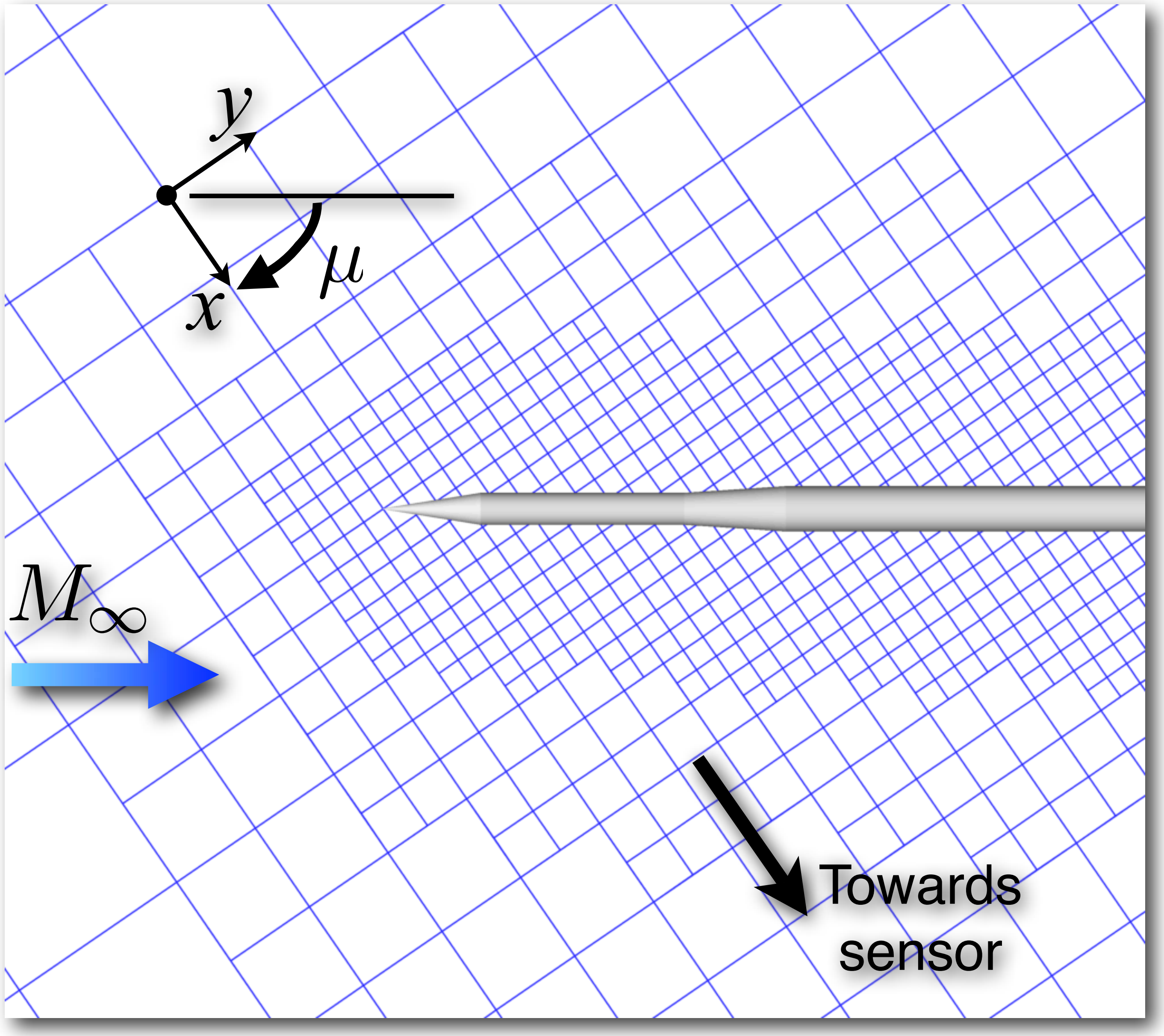


Specialization for Sonic-Boom

- To enhance signal propagation towards the sensor:

  Rotate mesh by Mach-angle, μ

$$\mu = \sin^{-1}\left(\frac{1}{M_\infty}\right)$$



AIAA 2008-0725

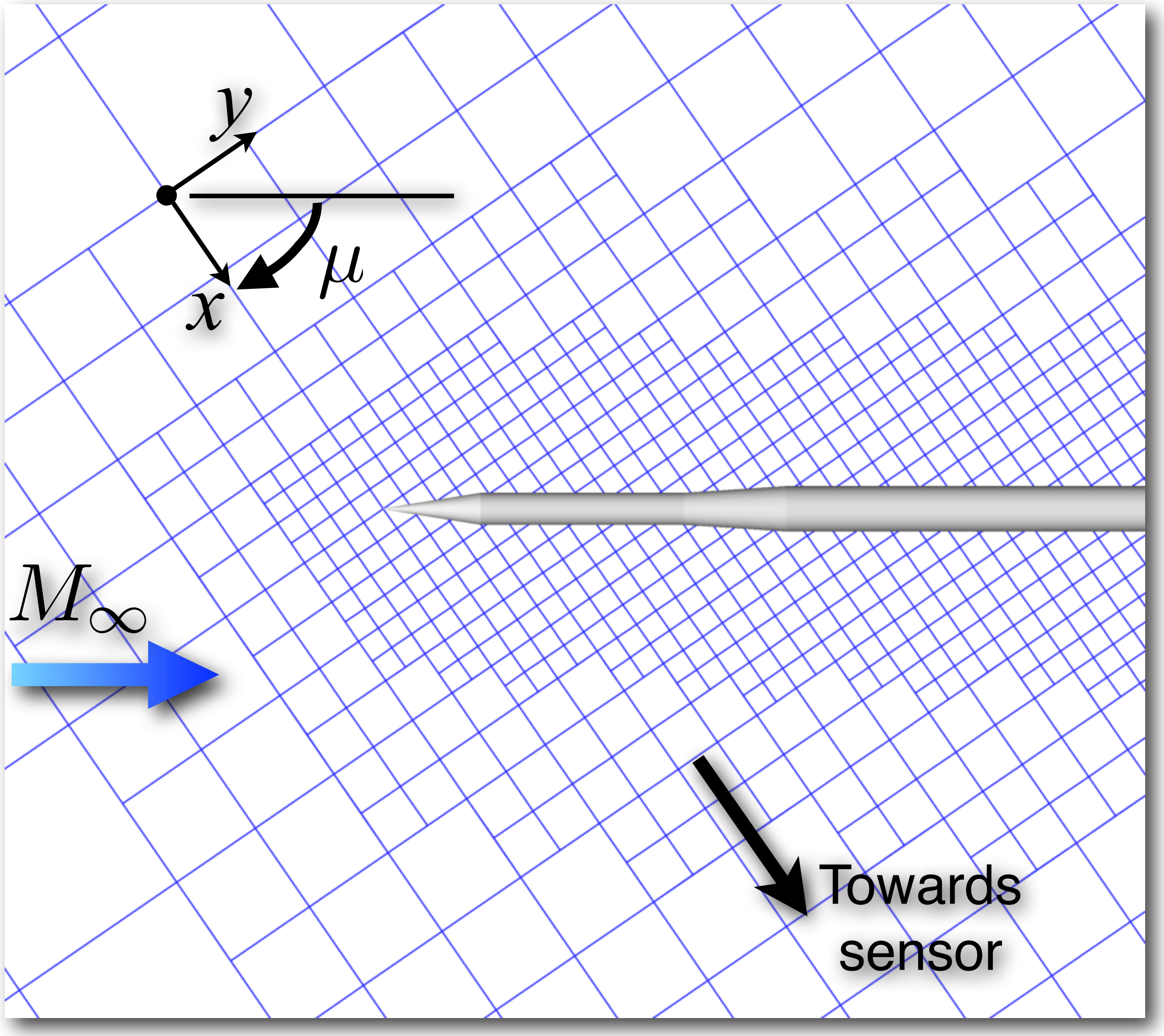
Specialization for Sonic-Boom

- To enhance signal propagation towards the sensor:

  Rotate mesh by Mach-angle, μ

$$\mu = \sin^{-1}\left(\frac{1}{M_\infty}\right)$$

- Stretch cells to increase per-cell propagation distance



AIAA 2008-0725

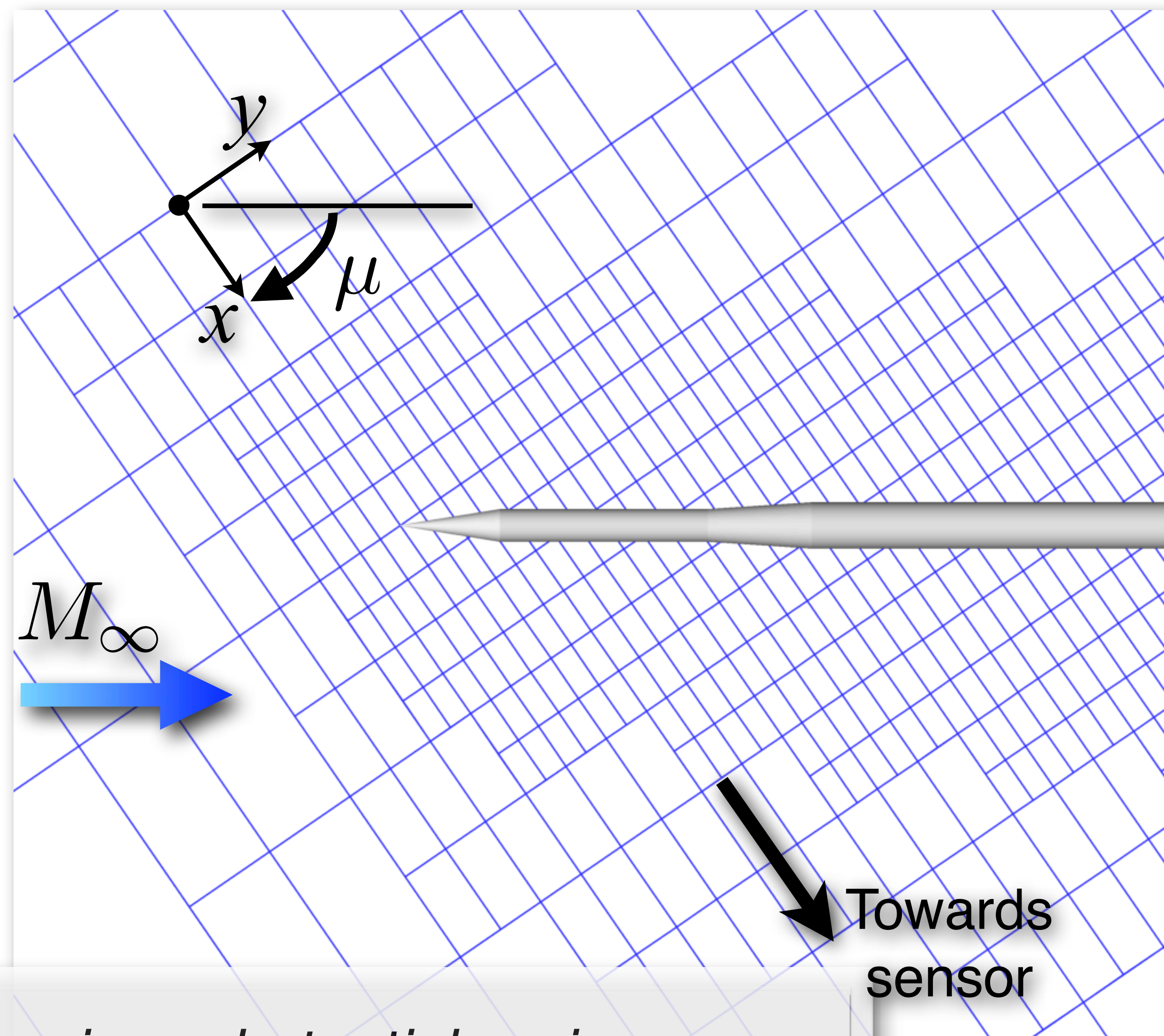
Specialization for Sonic-Boom

- To enhance signal propagation towards the sensor:

    Rotate mesh by Mach-angle, μ

$$\mu = \sin^{-1}\left(\frac{1}{M_\infty}\right)$$

- Stretch cells to increase per-cell propagation distance

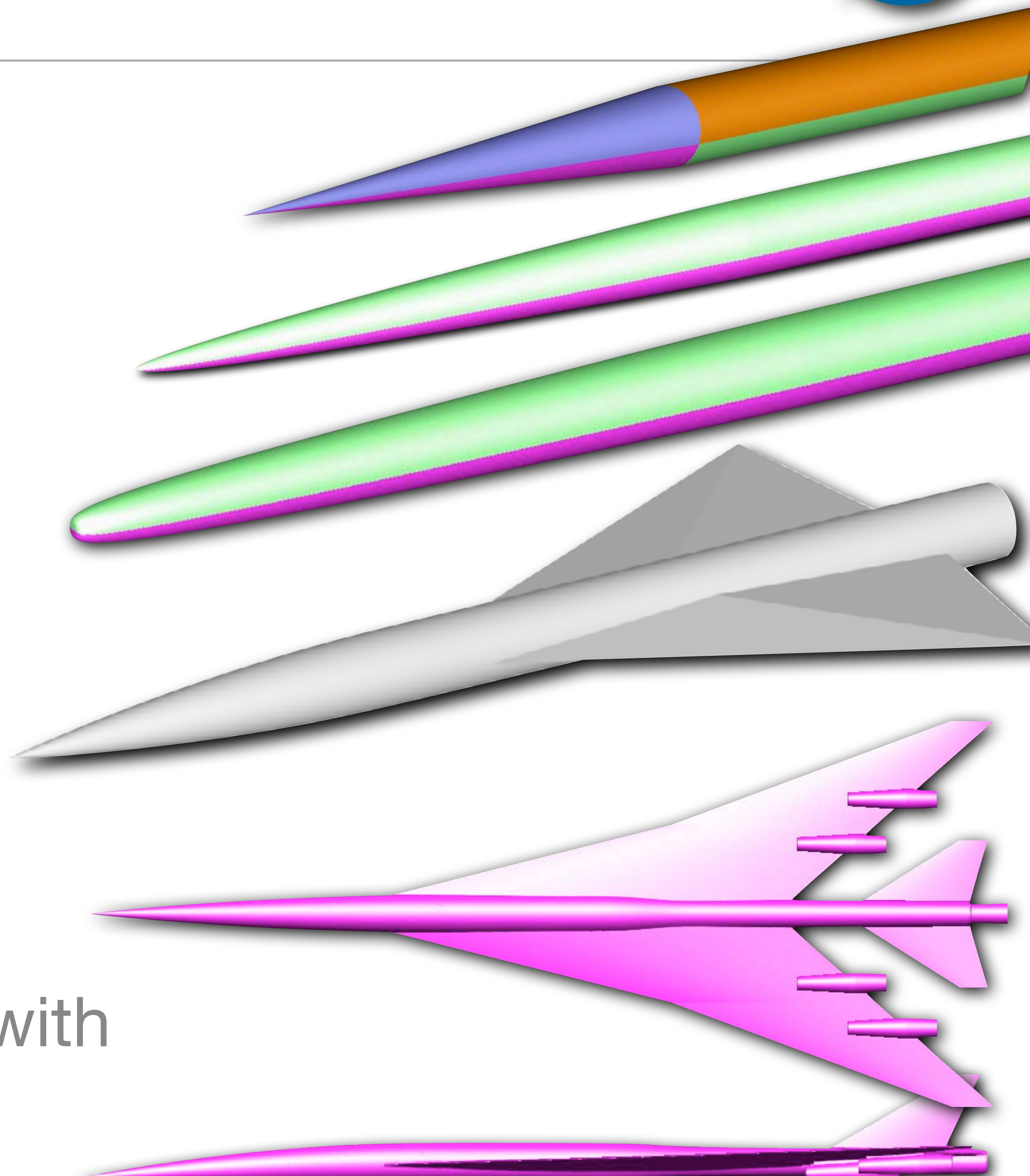


Rotation & stretching give substantial savings, see

Full investigations in AIAA 2008-0725 & 2008-6593

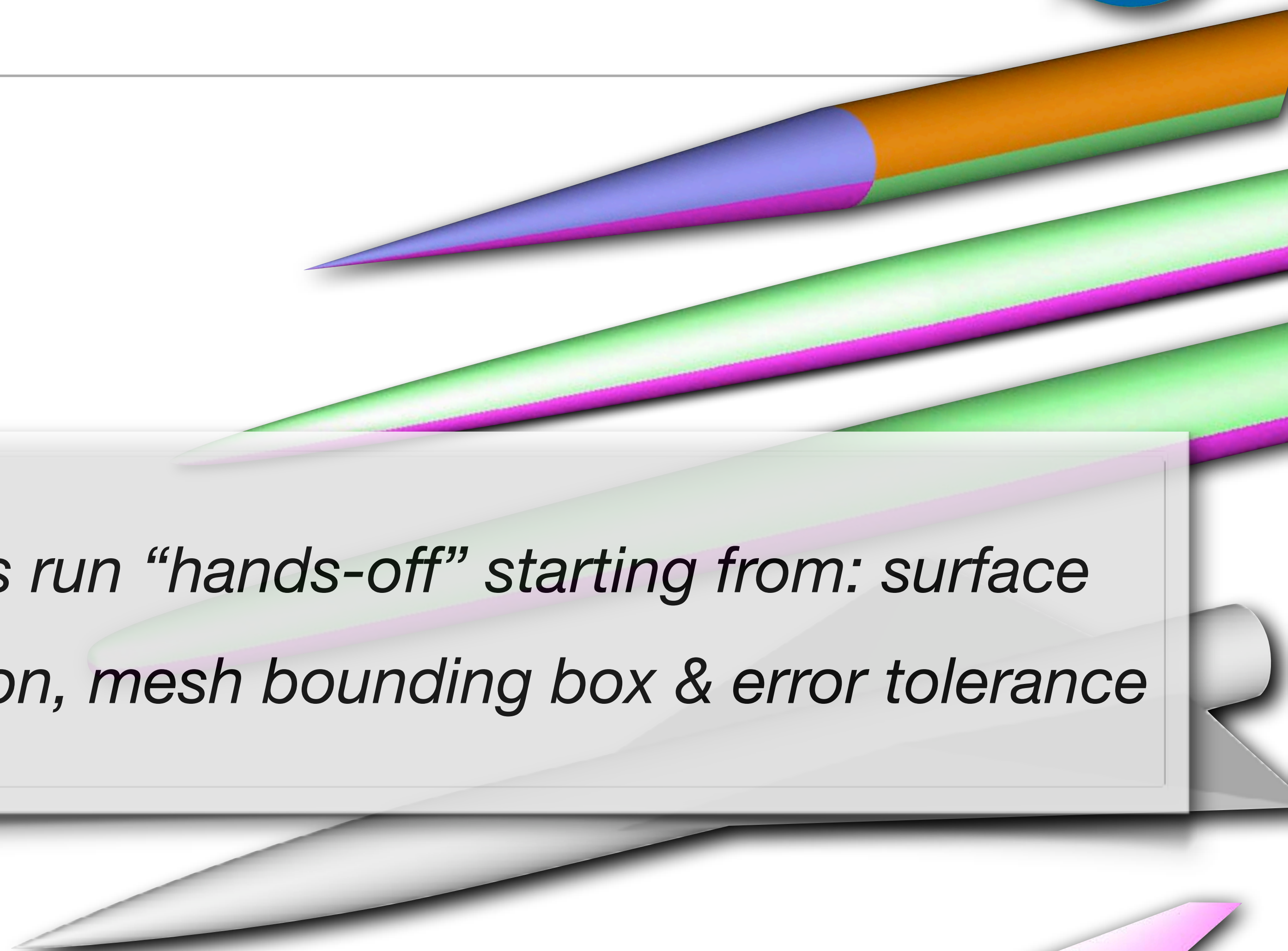
Results Overview

- Axisymmetric bodies
  - 6.48° Cone-cylinder
  - Parabolic
  - Quartic
- 69° Swept Delta-wing-body
- Ames Low Boom Wing Tail with Nacelles



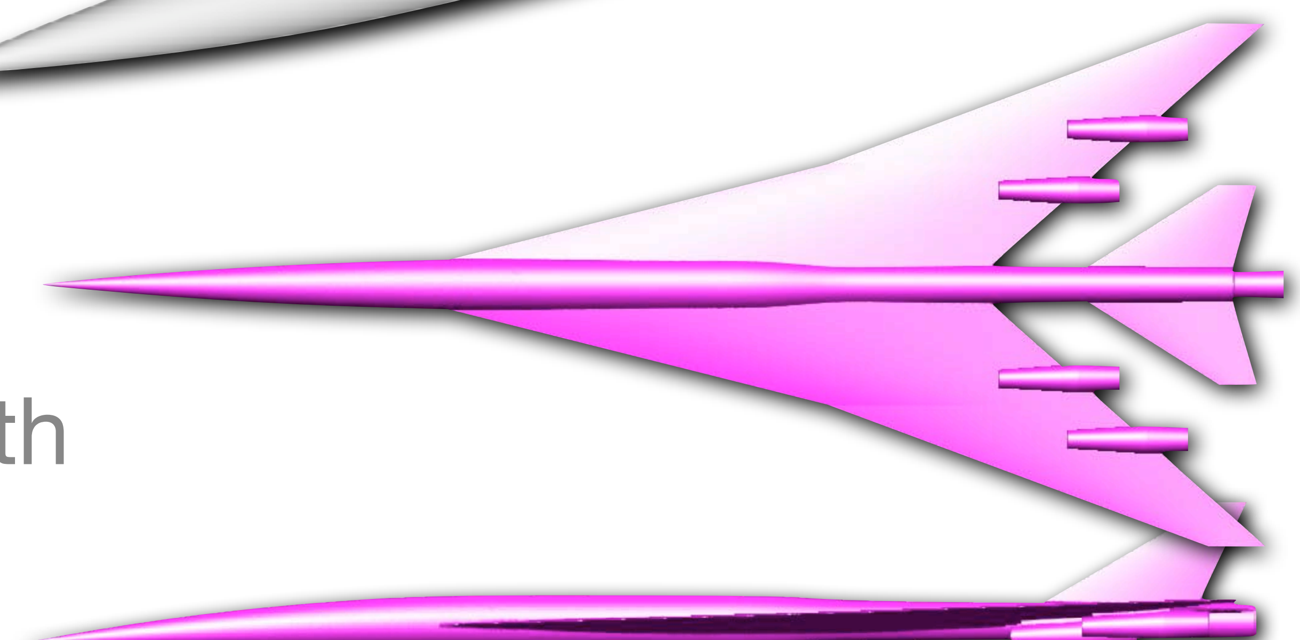
Results Overview

- Axisymmetric bodies
  - 6.48° Cone-cylinder
  - Parabolic
  - Quartic



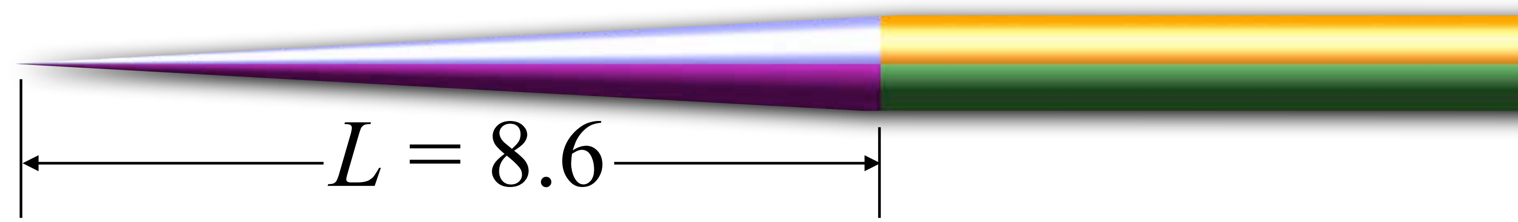
All cases run “hands-off” starting from: surface triangulation, mesh bounding box & error tolerance

- 69° Swept Delta-wing-body
- Ames Low Boom Wing Tail with Nacelles



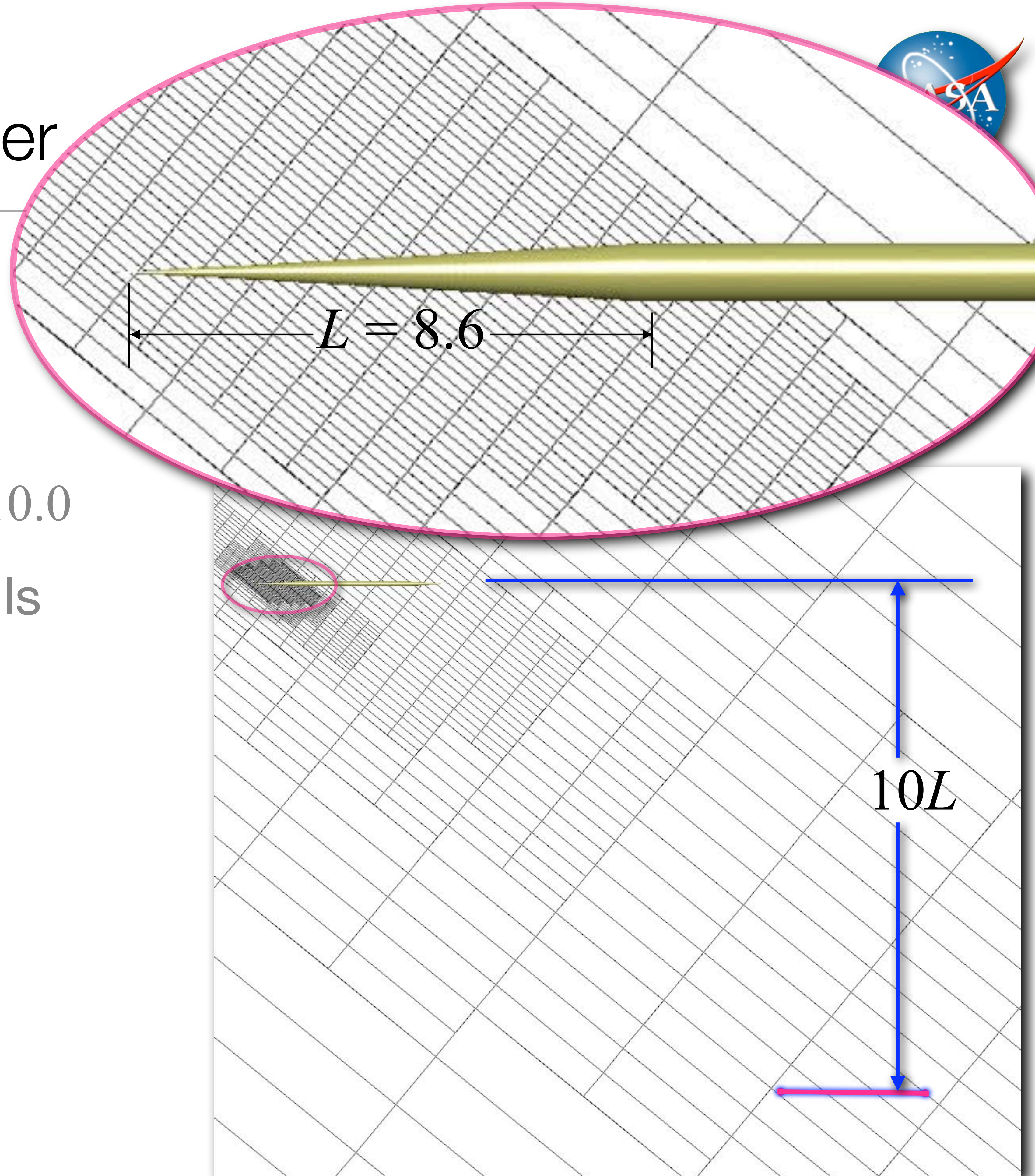
6.48° Cone-Cylinder

- NASA TM X-2219
  - $M_\infty = 1.68$
  - $\alpha = 0.0°$
  - Sensor offset, $h/L = 10.0$
- Initial mesh ~ 6300 cells



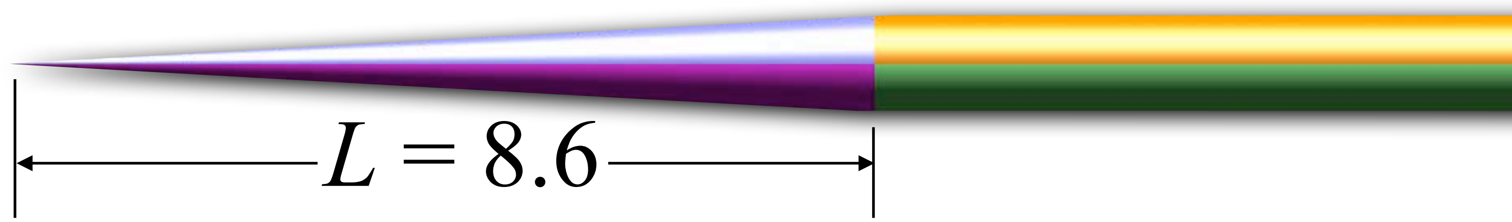
6.48° Cone-Cylinder

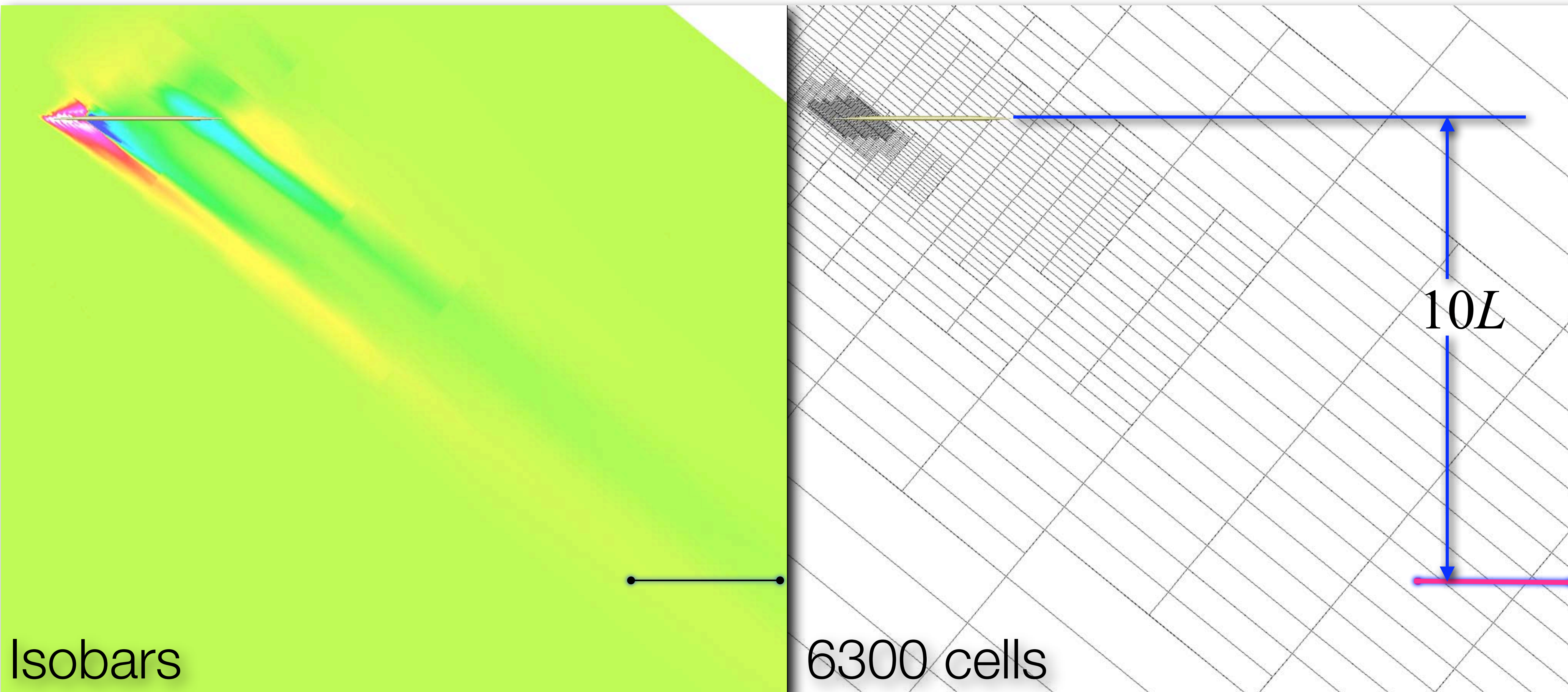
- NASA TM X-2219
  - $M_\infty = 1.68$
  - $\alpha = 0.0°$
  - Sensor offset, $h/L = 10.0$
- Initial mesh ~ 6300 cells



6.48° Cone-Cylinder

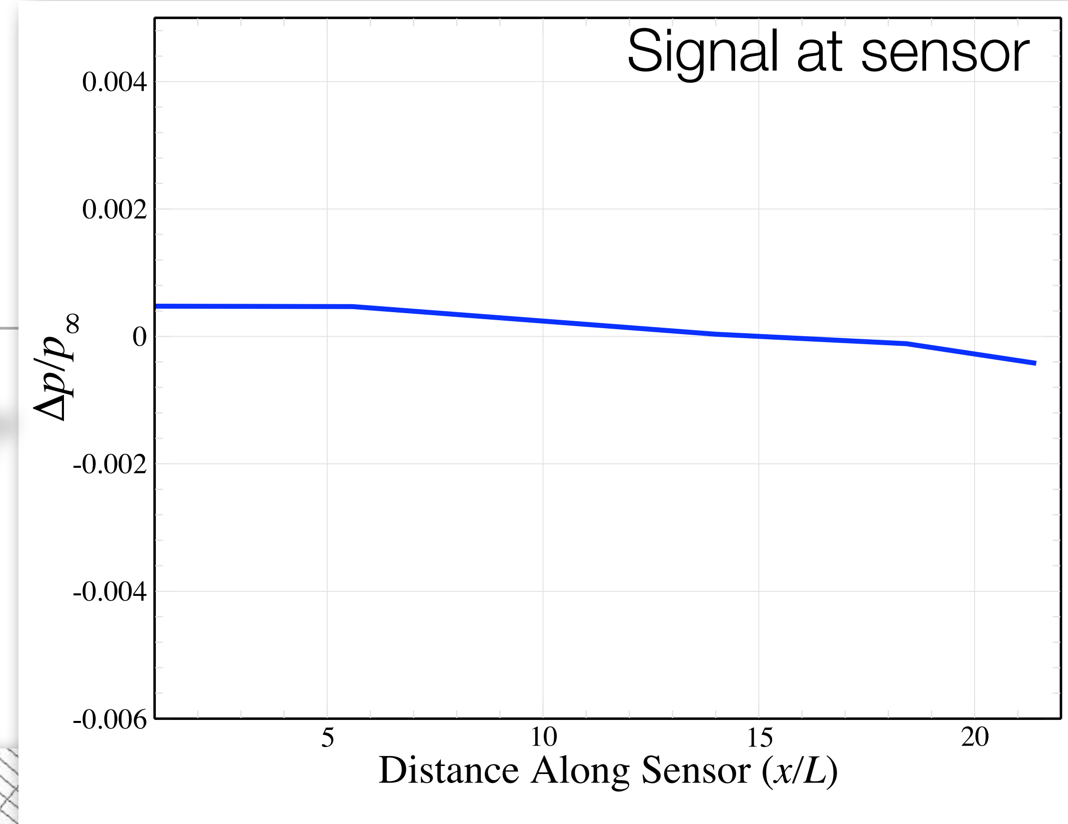
- NASA TM X-2219
  - $M_\infty = 1.68$
  - $\alpha = 0.0°$

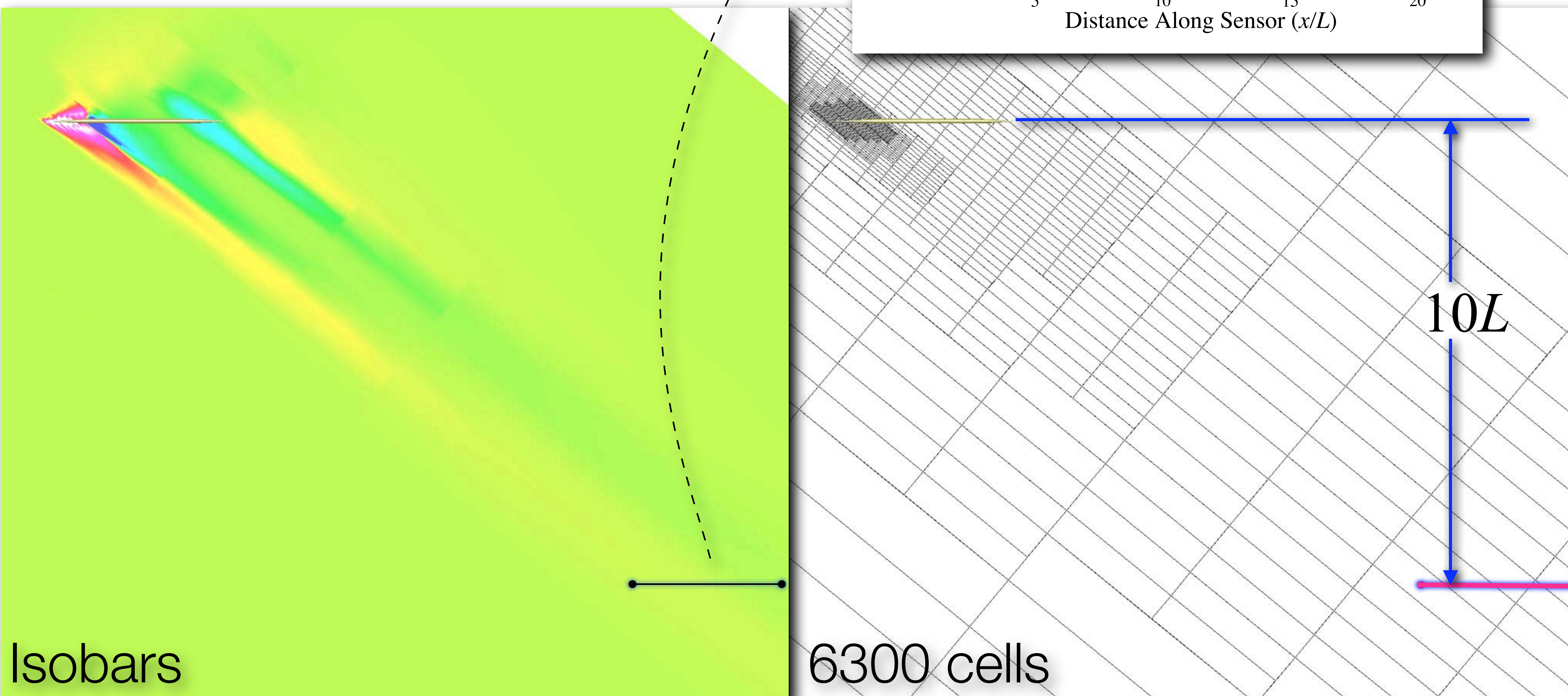




6.48° Cone-Cylinder

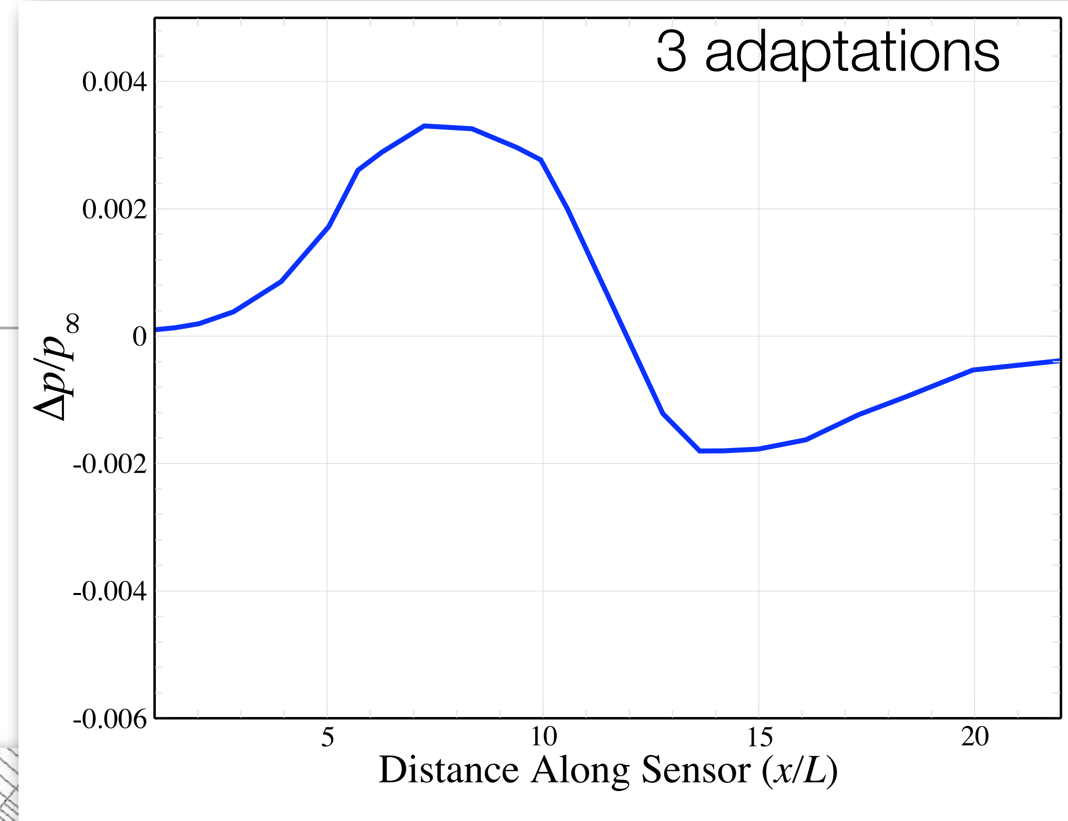
- NASA TM X-2219
  - $M_\infty = 1.68$
  - $\alpha = 0.0°$

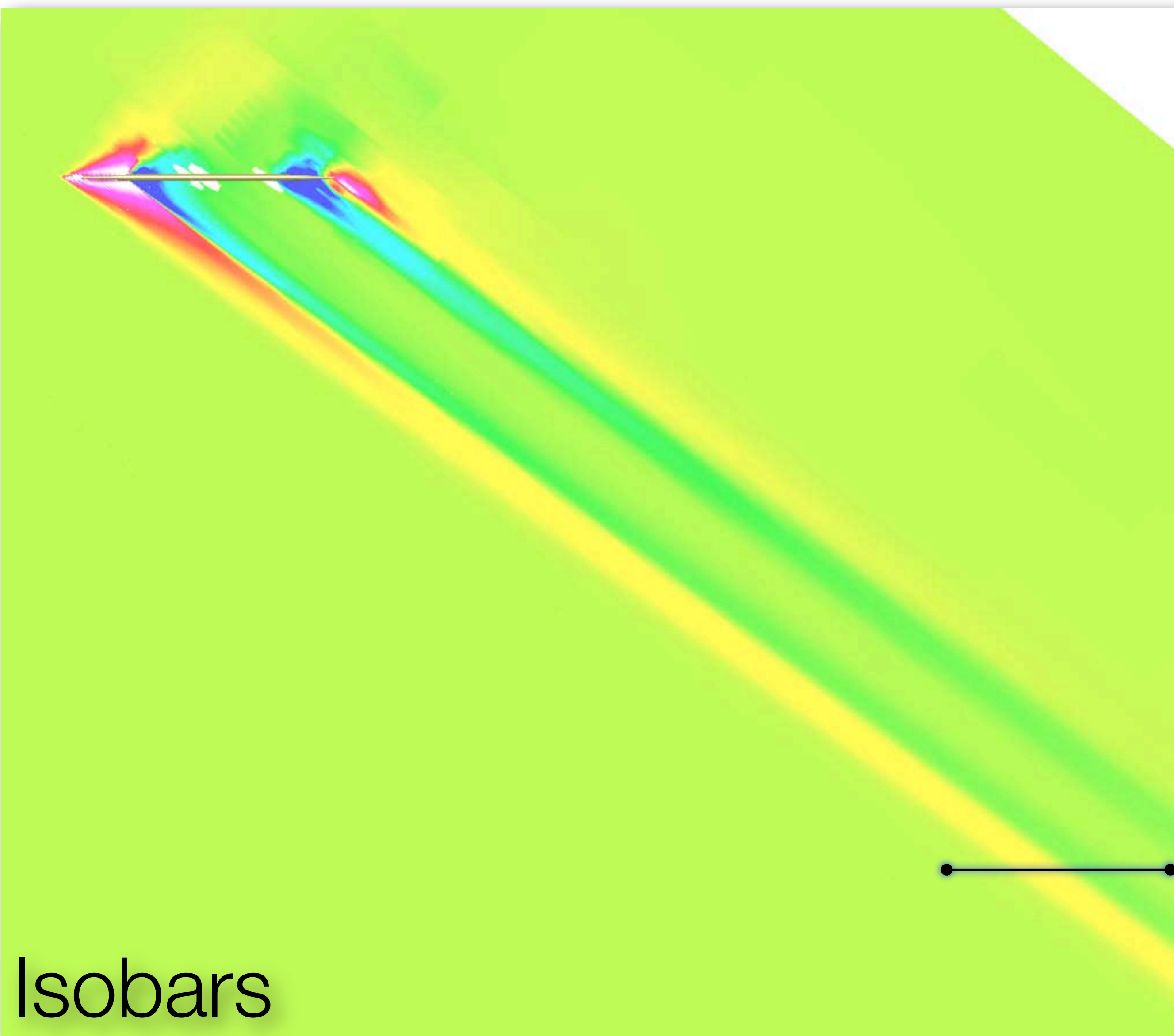


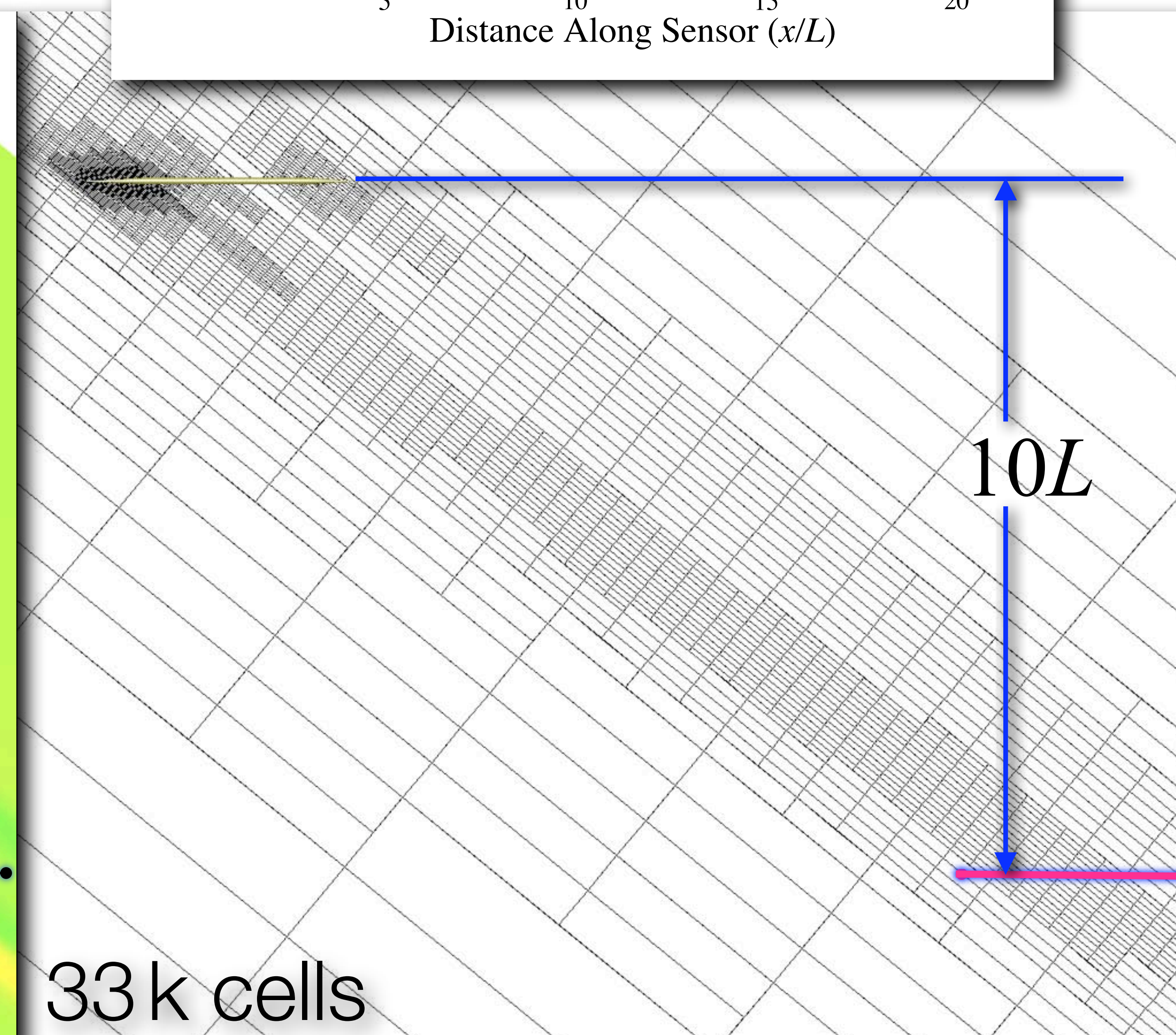


6.48° Cone-Cylinder

- NASA TM X-2219
    - $M_\infty = 1.68$
    - $\alpha = 0.0°$

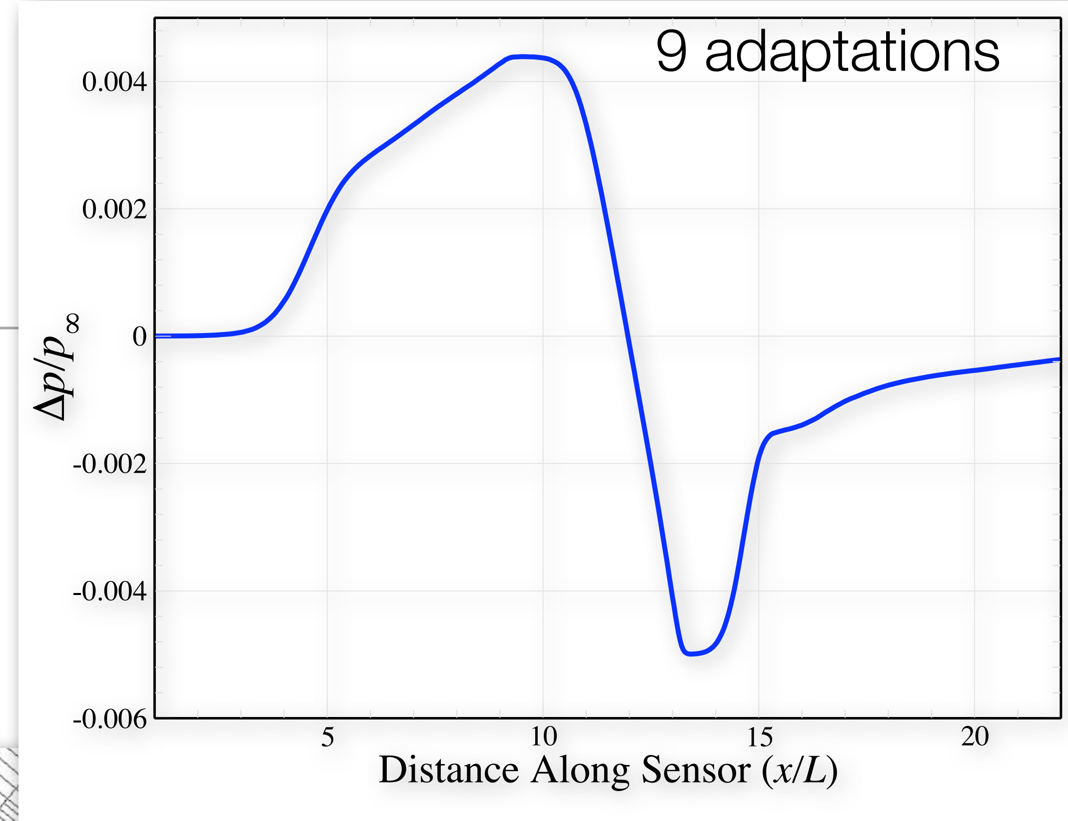


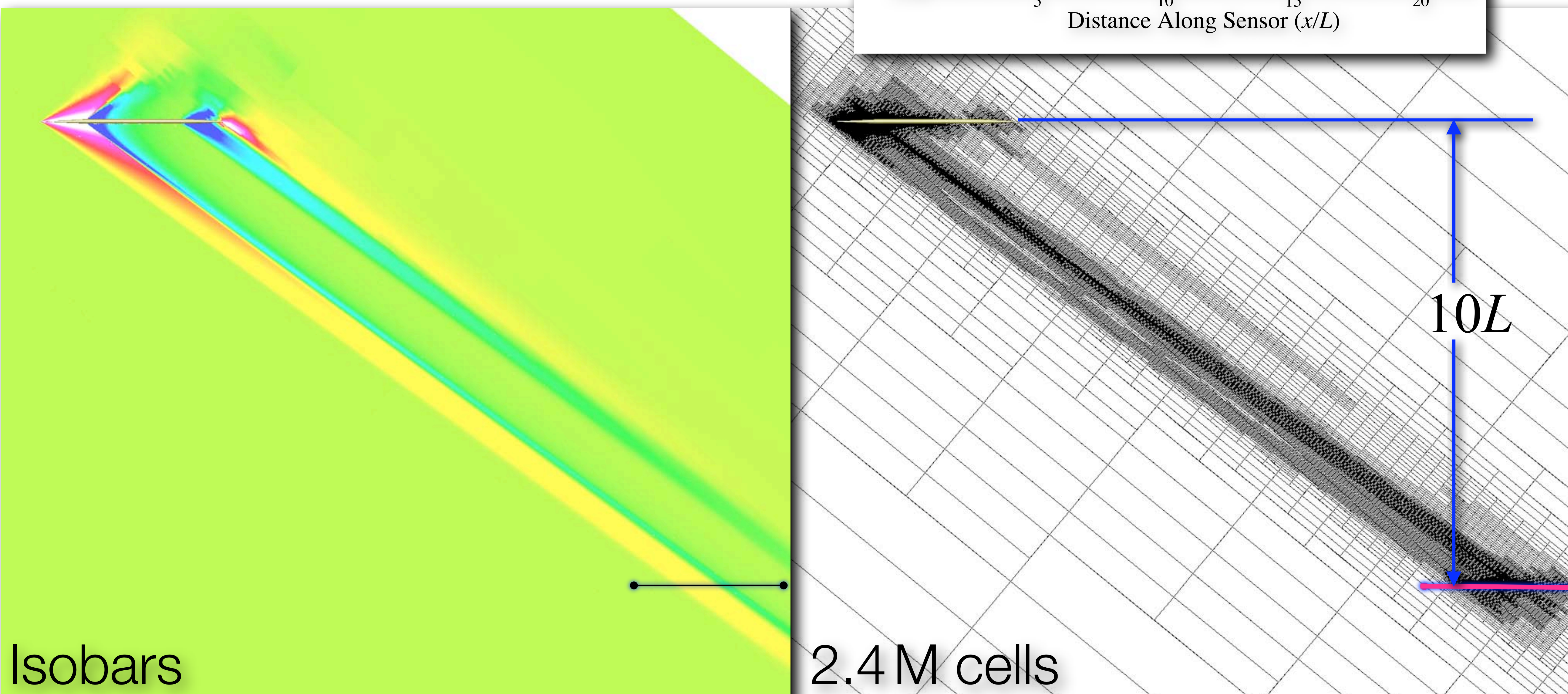




6.48° Cone-Cylinder

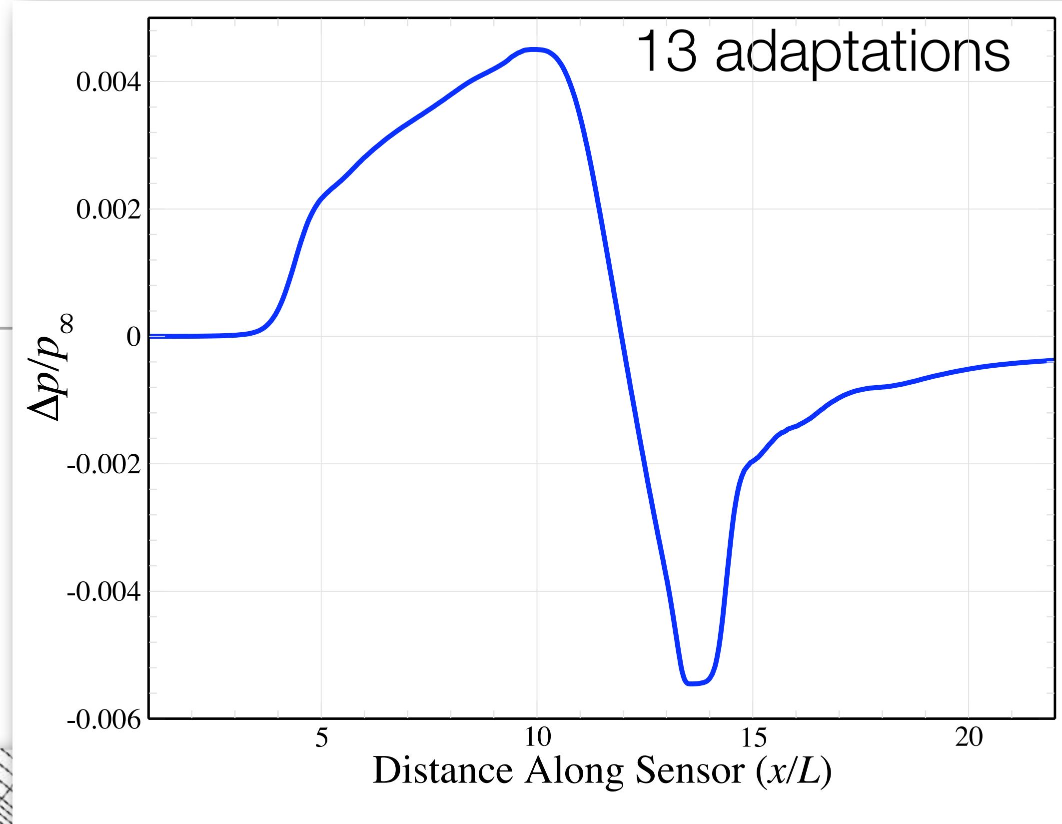
- NASA TM X-2219
  - $M_\infty = 1.68$
  - $\alpha = 0.0°$

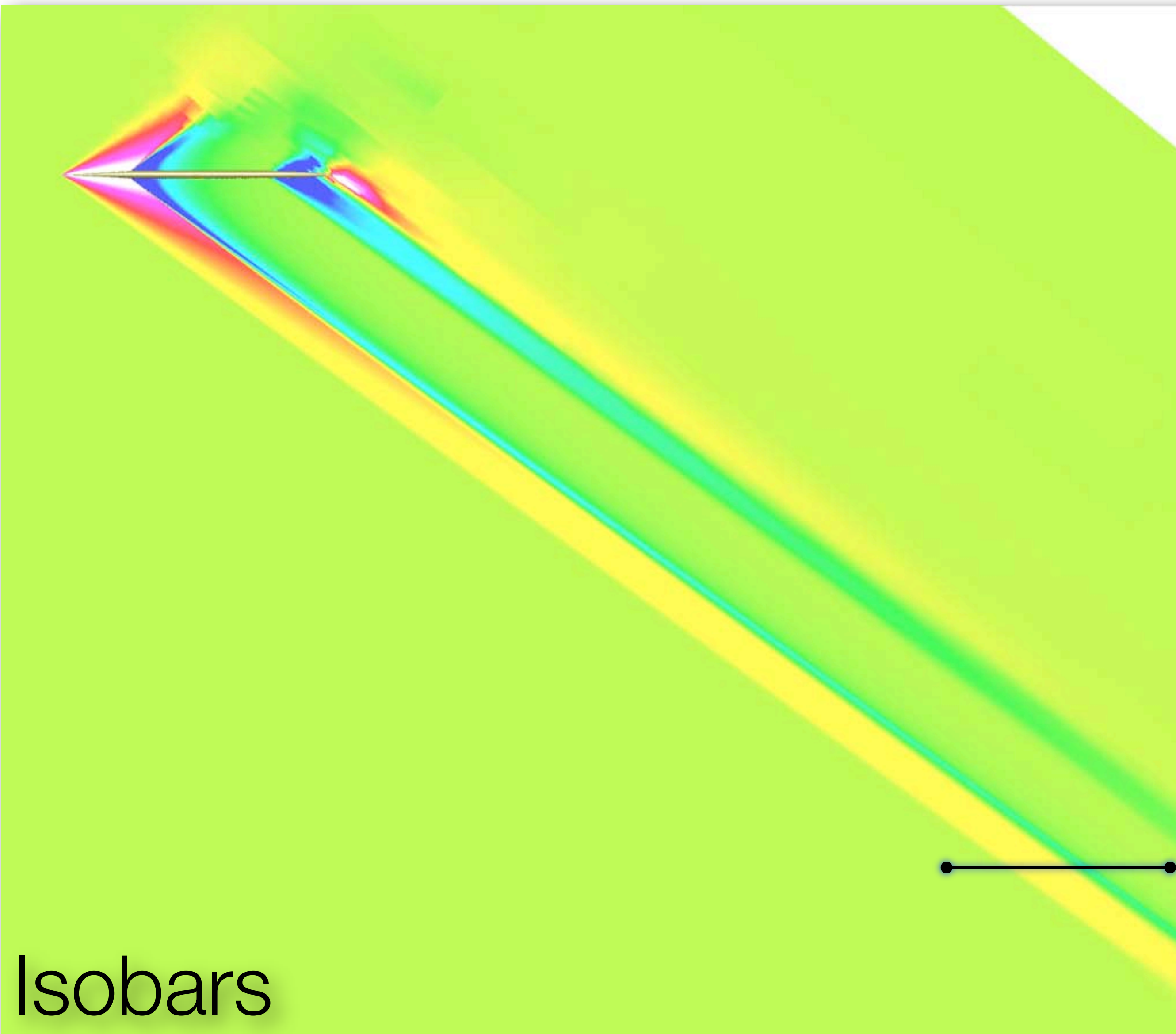


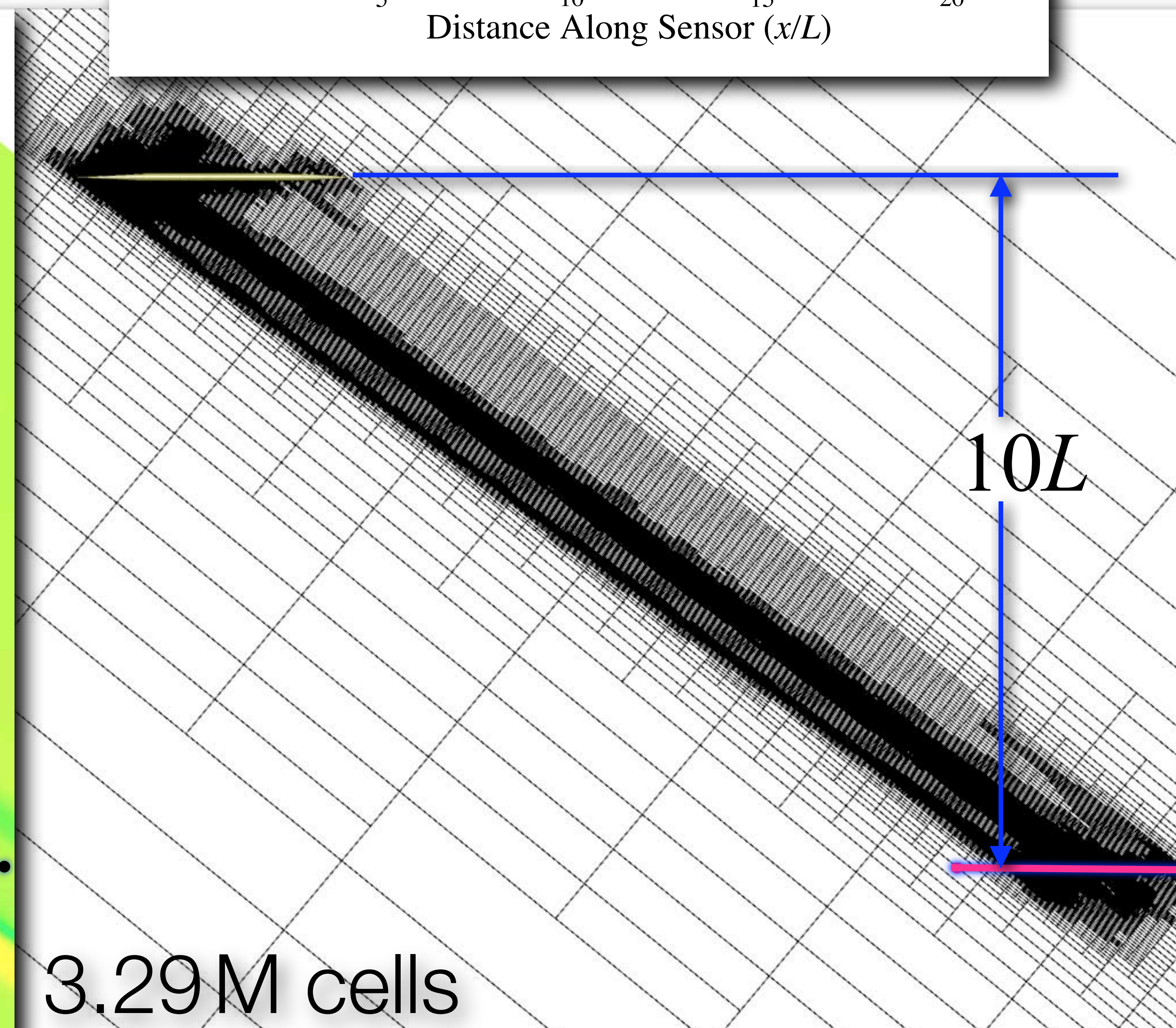


6.48° Cone-Cylinder

- NASA TM X-2219
  - $M_\infty = 1.68$
  - $\alpha = 0.0°$



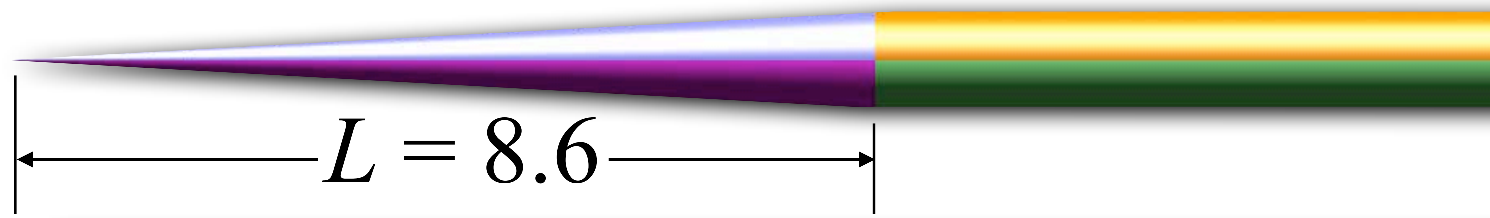


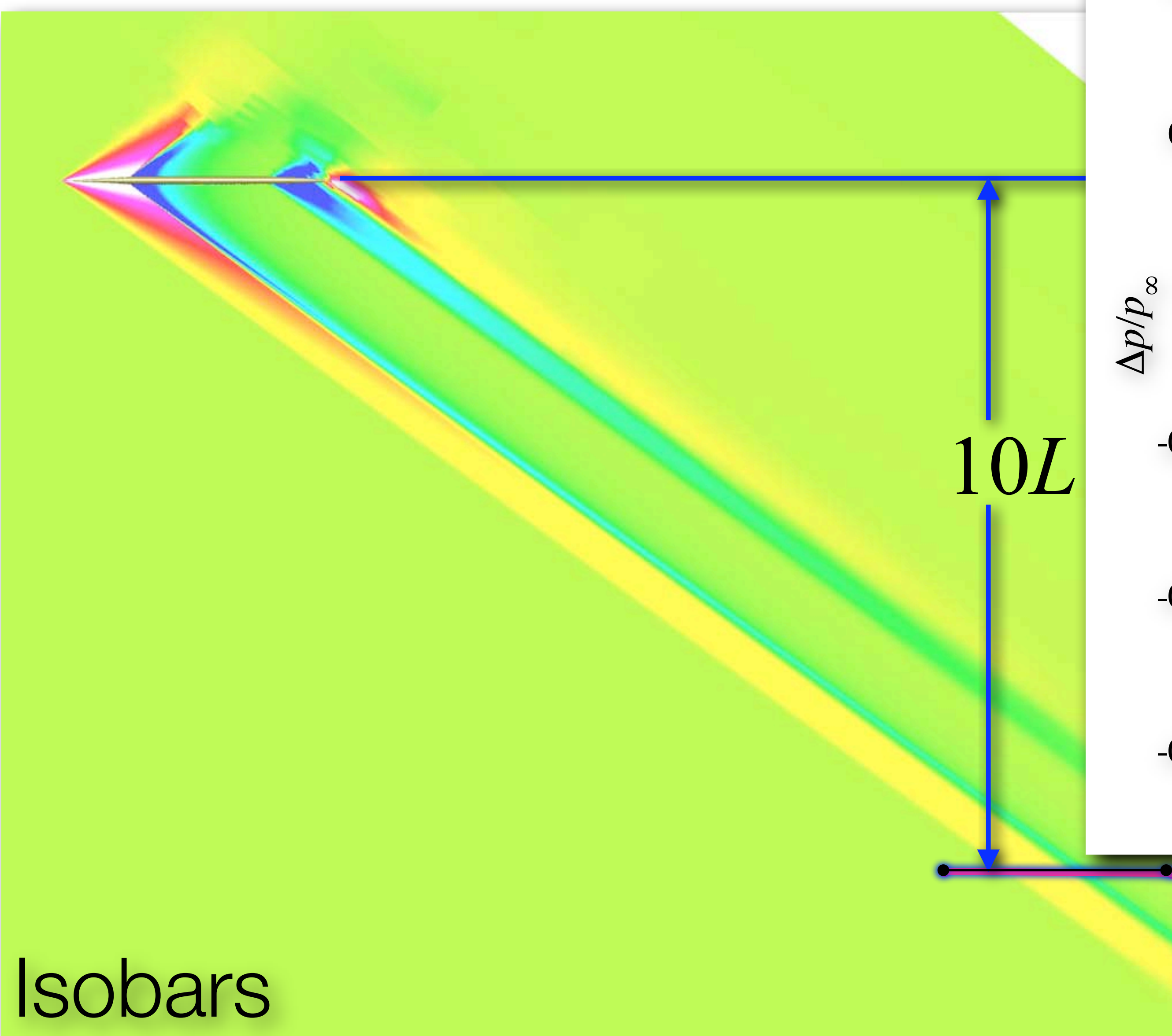


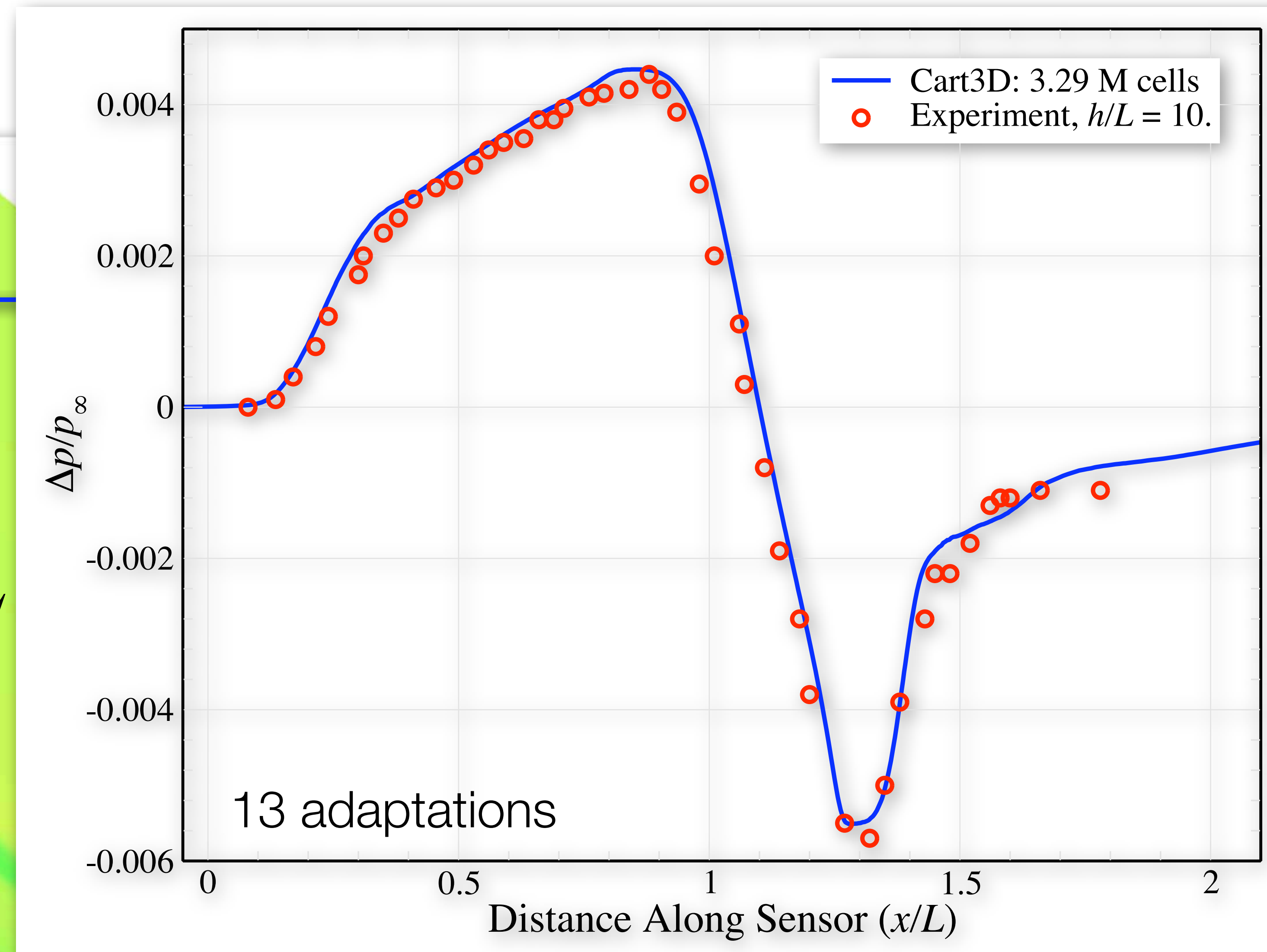
13 adaptations

6.48° Cone-Cylinder

- NASA TM X-2219
  - $M_\infty = 1.68$
  - $\alpha = 0.0°$

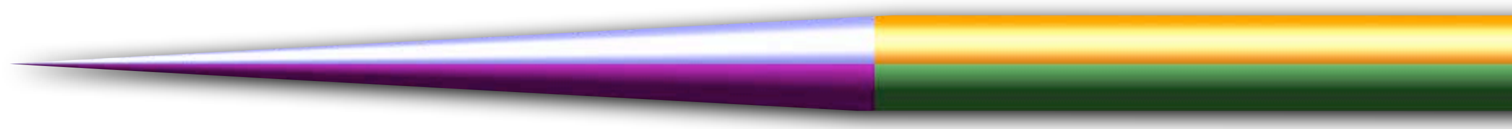


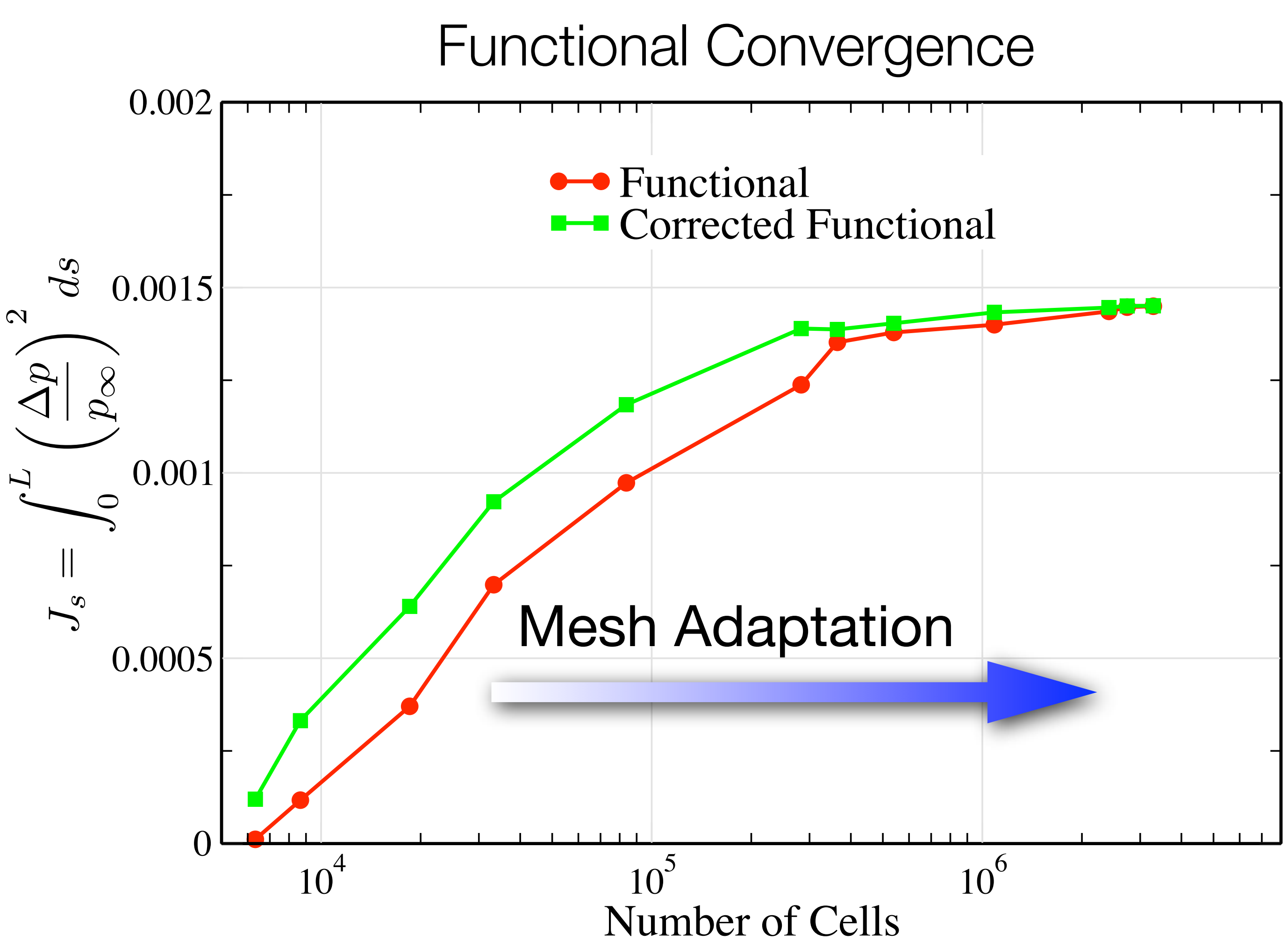


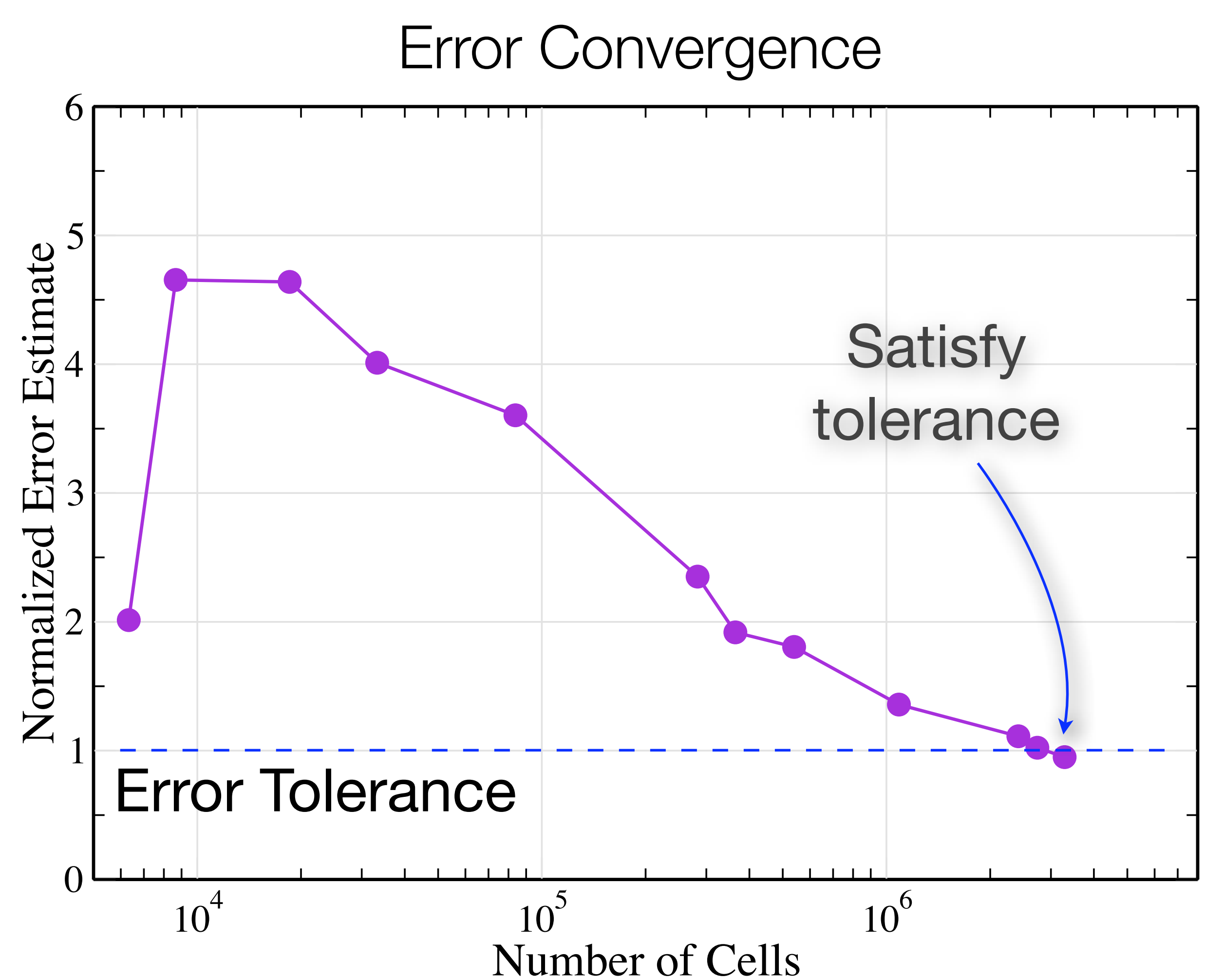


6.48° Cone-Cylinder

- NASA TM X-2219
  - $M_\infty = 1.68$, $\alpha = 0.0°$, $h/L = 10.0$

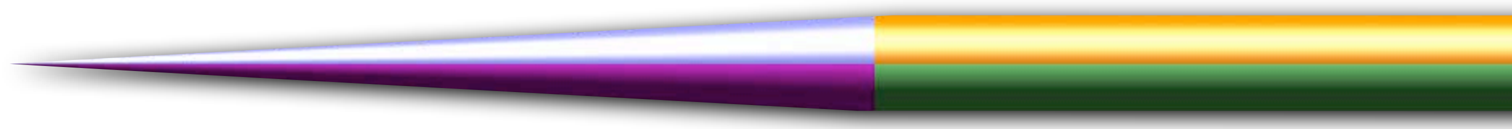


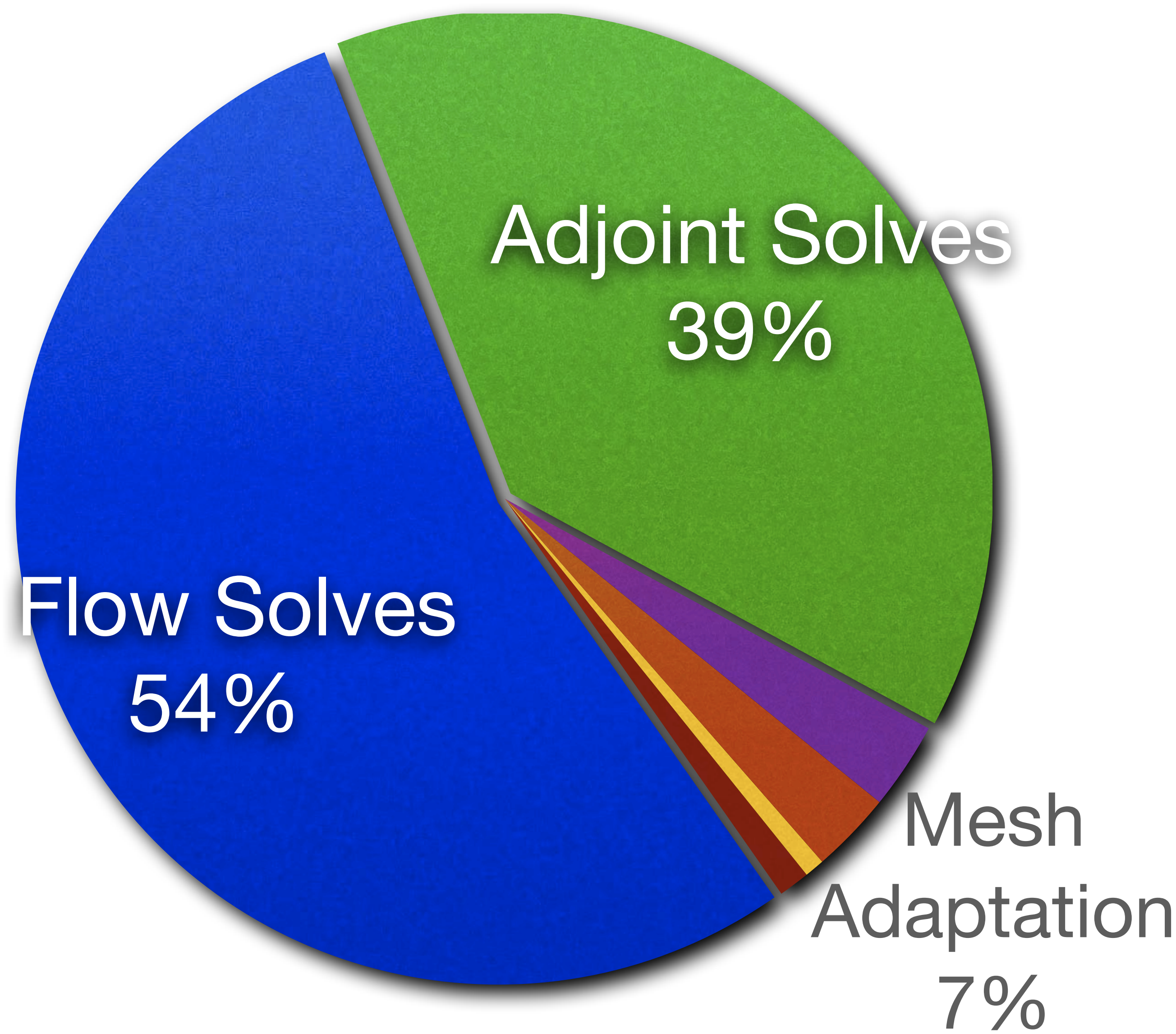




6.48° Cone-Cylinder

- NASA TM X-2219
  - $M_\infty = 1.68,\ \alpha = 0.0°,\ h/L = 10.0$
- Simulation performed on desktop workstation
  - Dual quad-core (8 cores)
  - Intel Xeon, 3.2Ghz
  - 16 Gb memory
- Total simulation time 41 mins. (all adaptations & mesh gen)

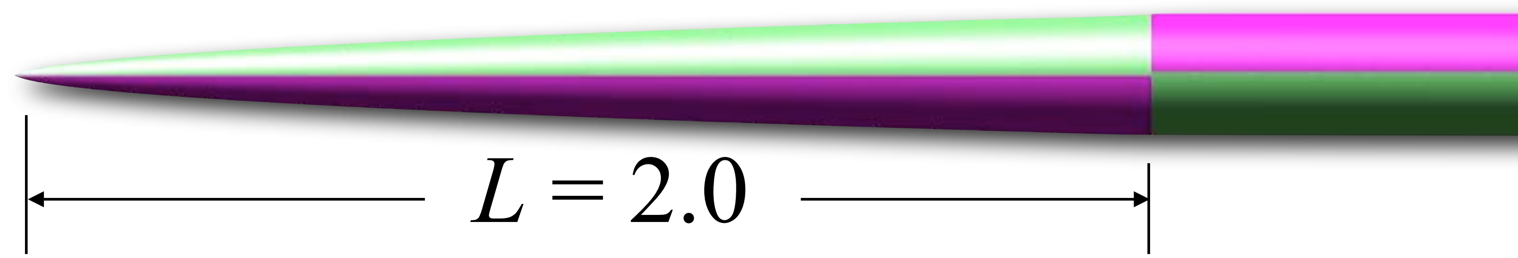




Total = 41 mins.

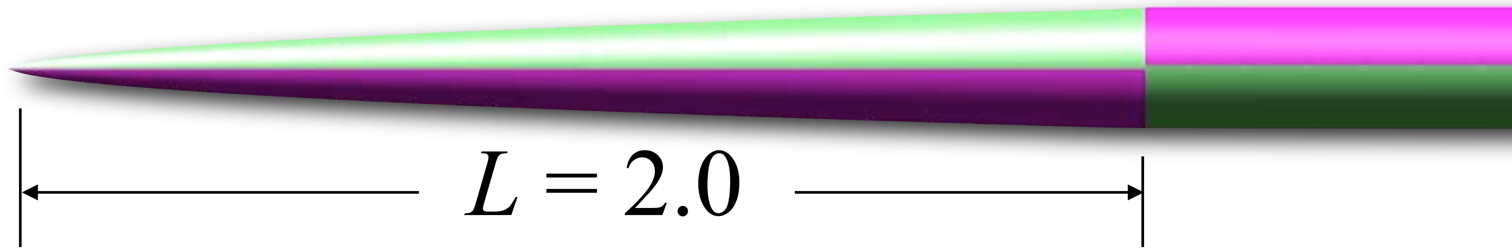
Parabolic: $r = f(x^{1/2})$

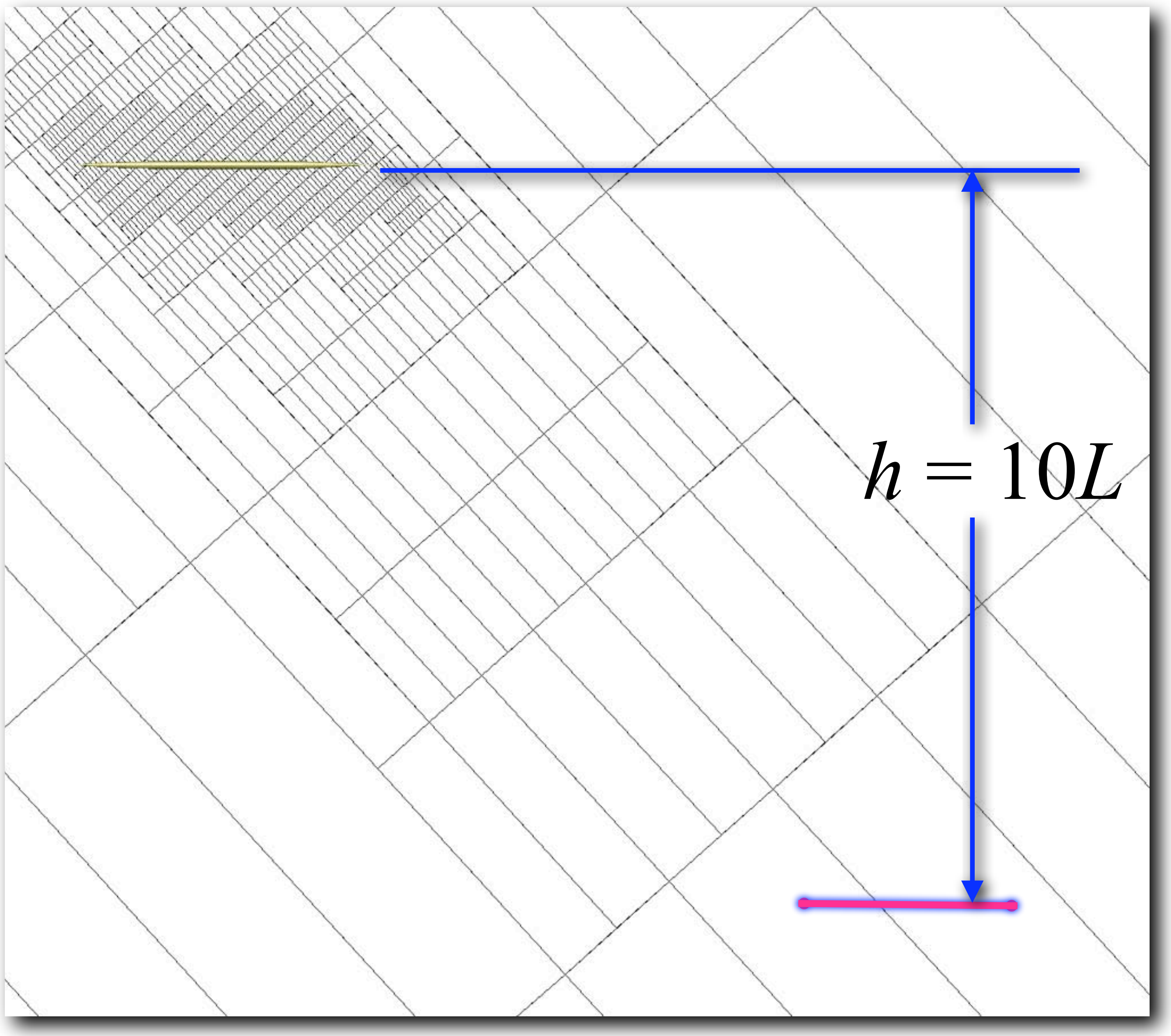
- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$
  - Sensor offset, $h/L = 10.0$
- Initial mesh ~3200 cells



Parabolic: $r = f(x^{1/2})$

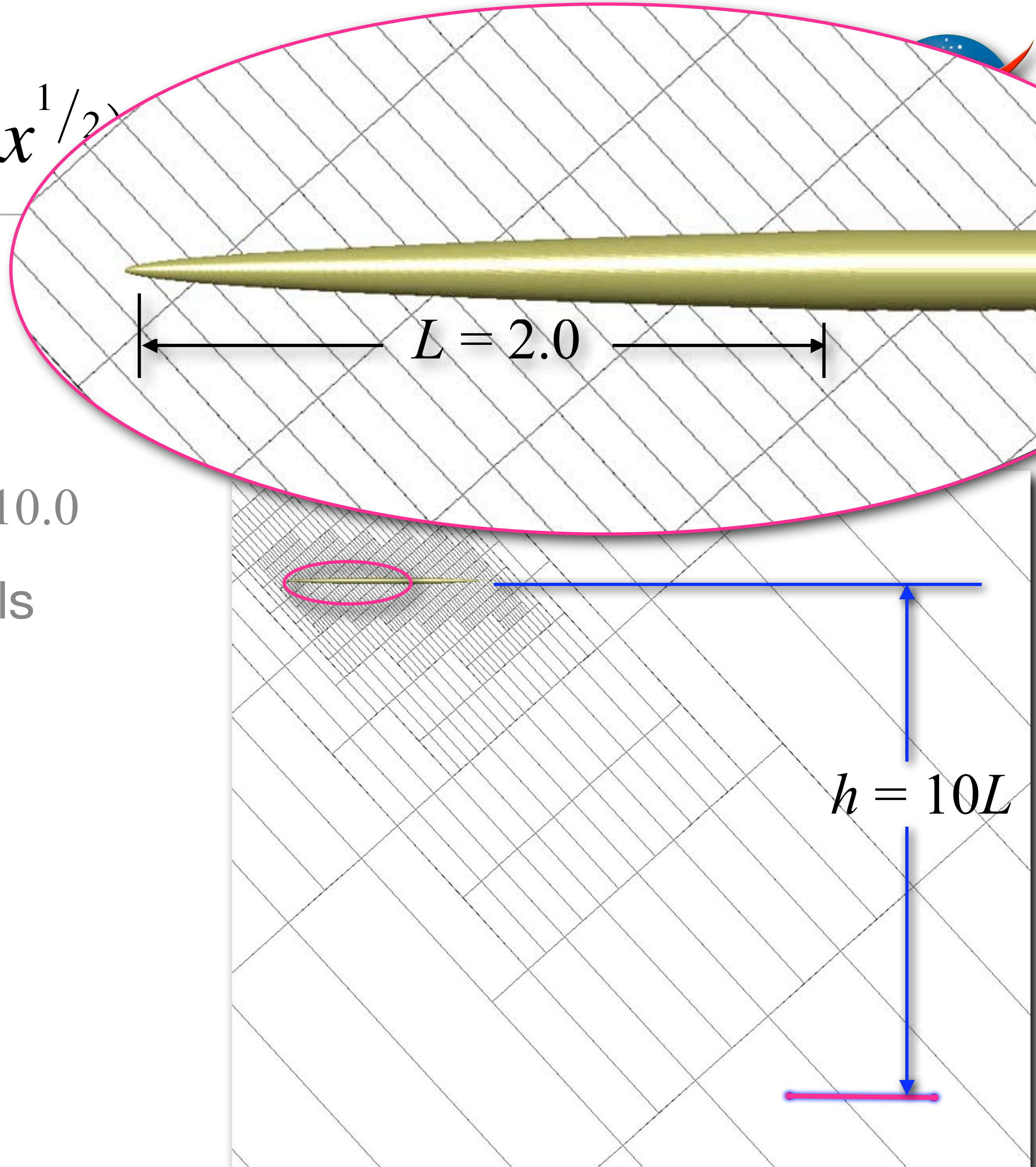
- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$
  - Sensor offset, $h/L = 10.0$
- Initial mesh ~3200 cells





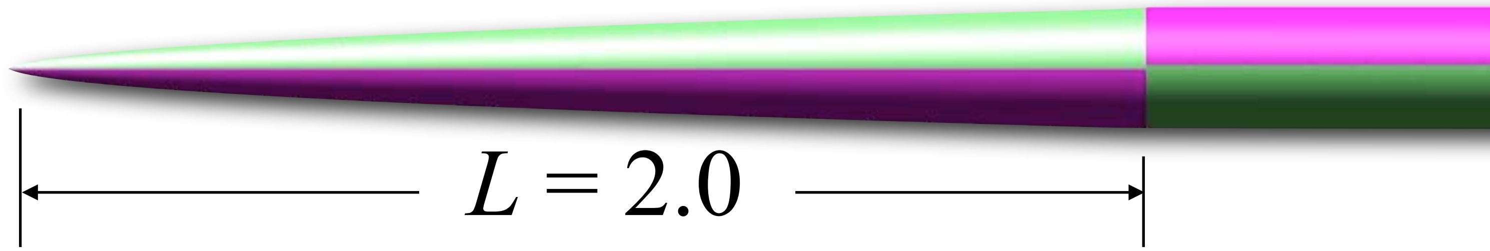
Parabolic: $r = f(x^{1/2})$

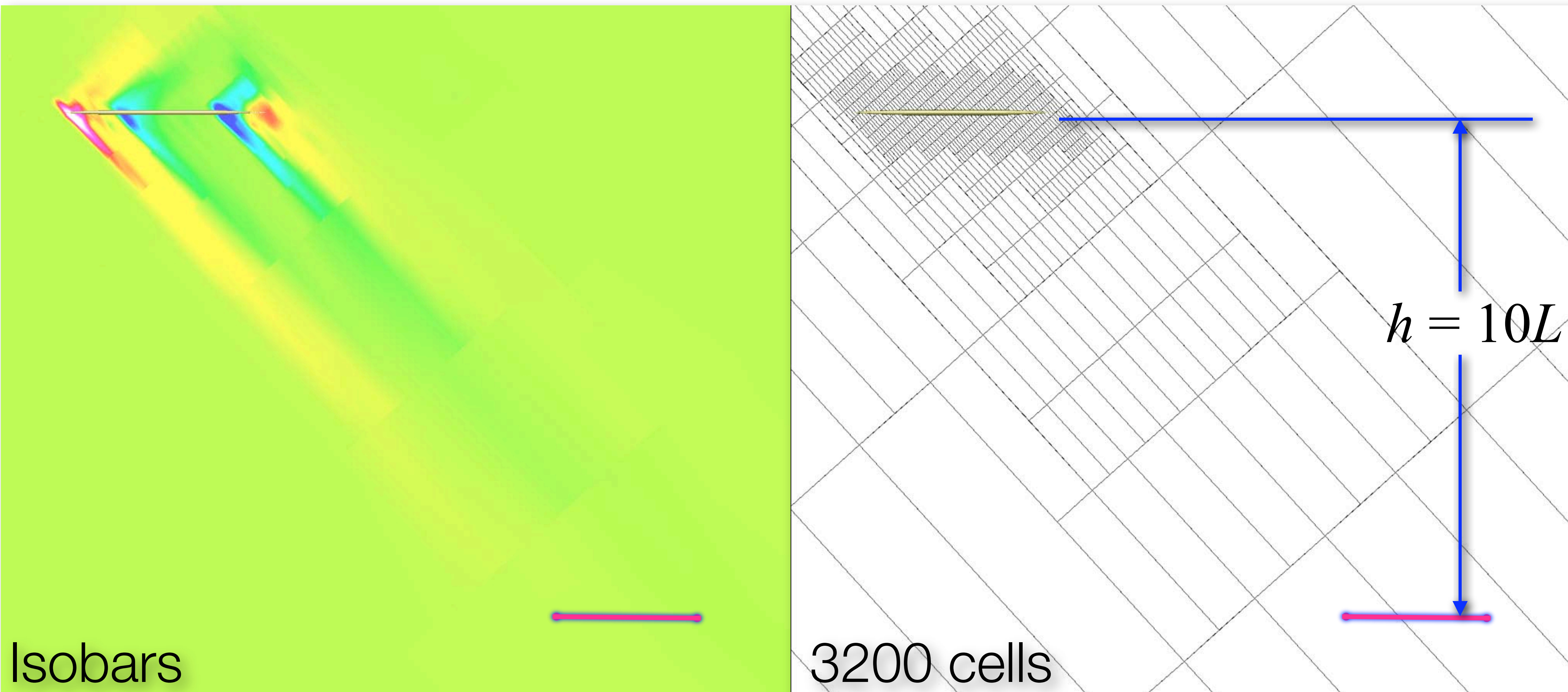
- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$
  - Sensor offset, $h/L = 10.0$
- Initial mesh ~3200 cells



Parabolic: $r = f(x^{1/2})$

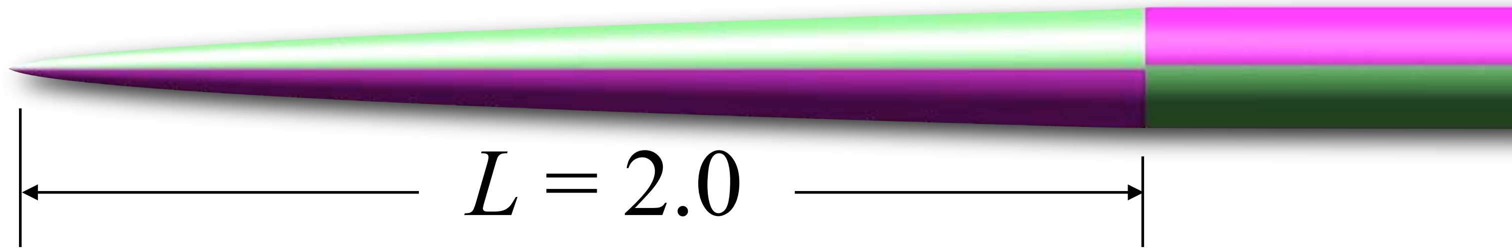
- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$

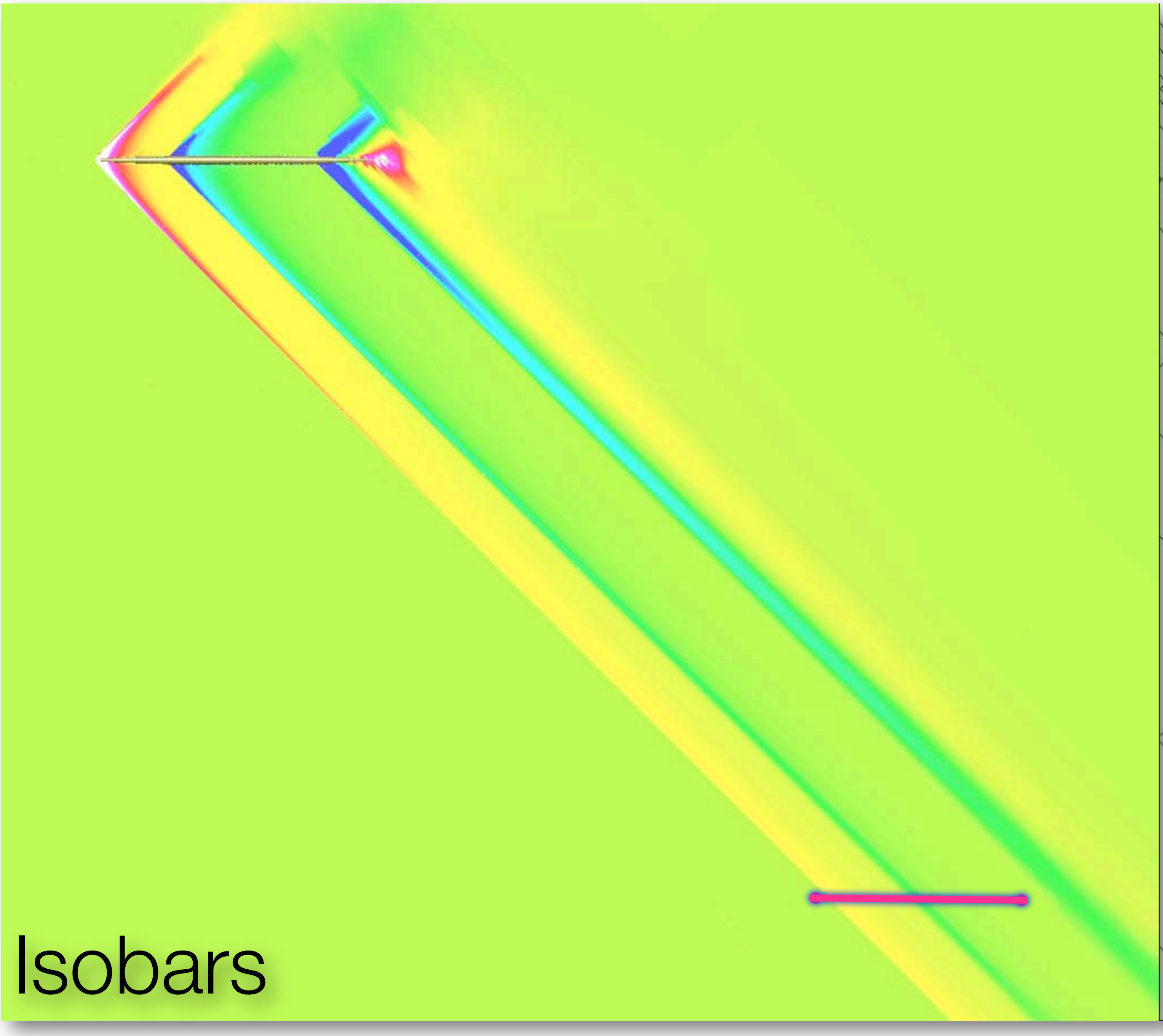


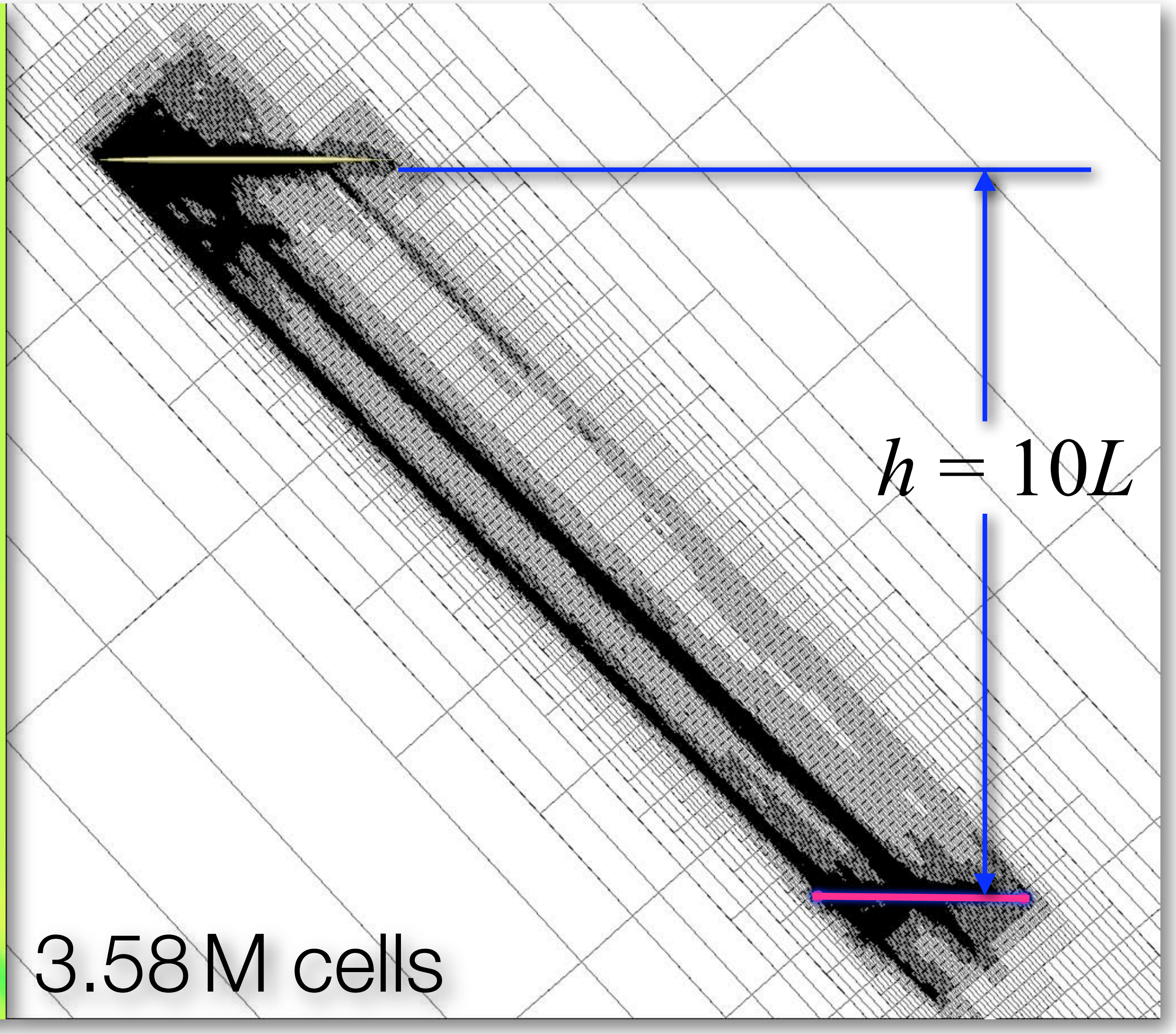


Parabolic: $r = f(x^{1/2})$

- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$

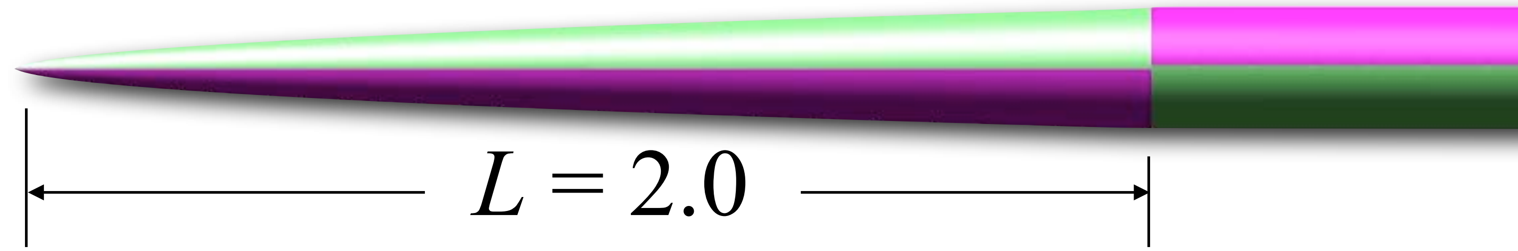


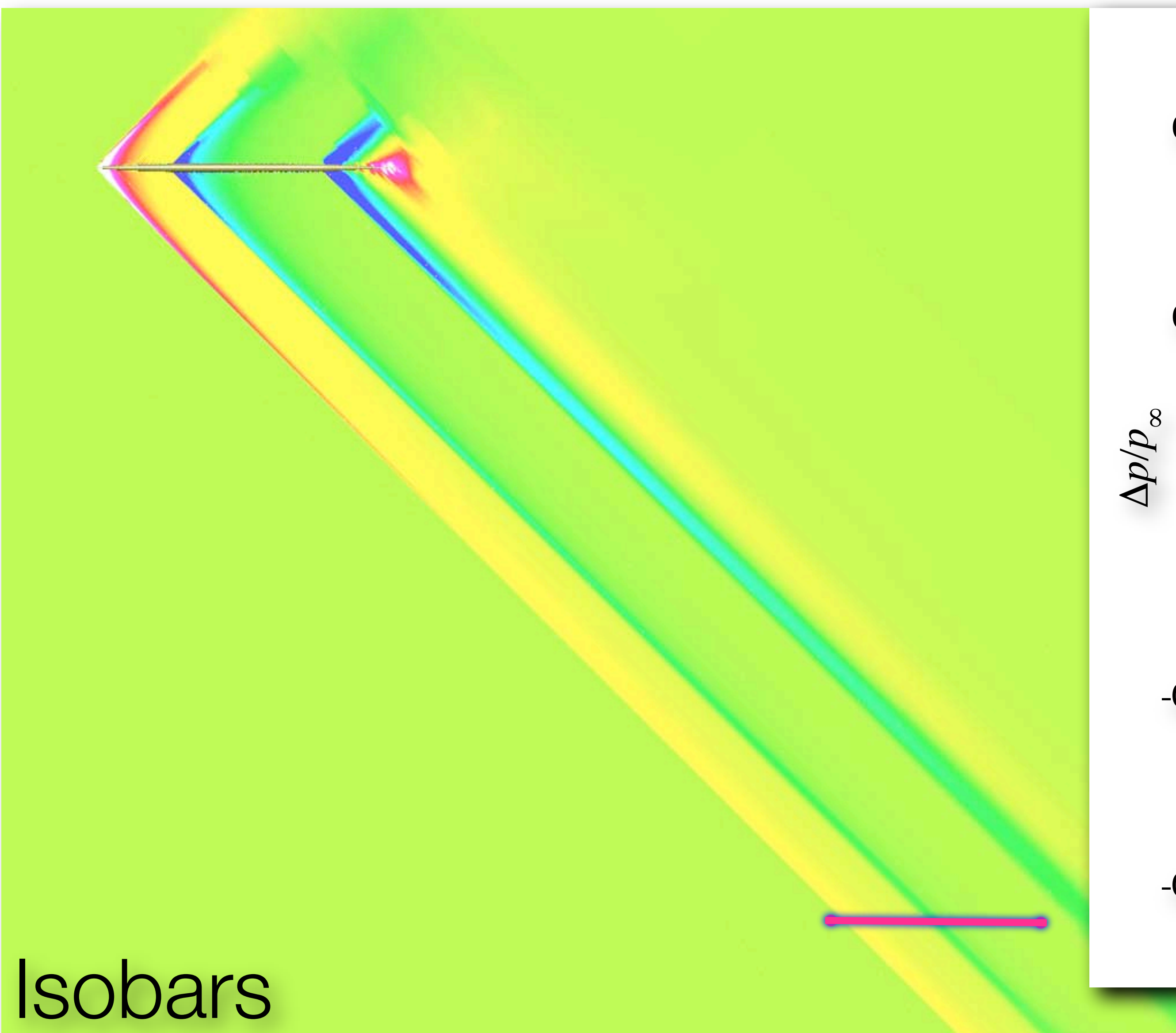


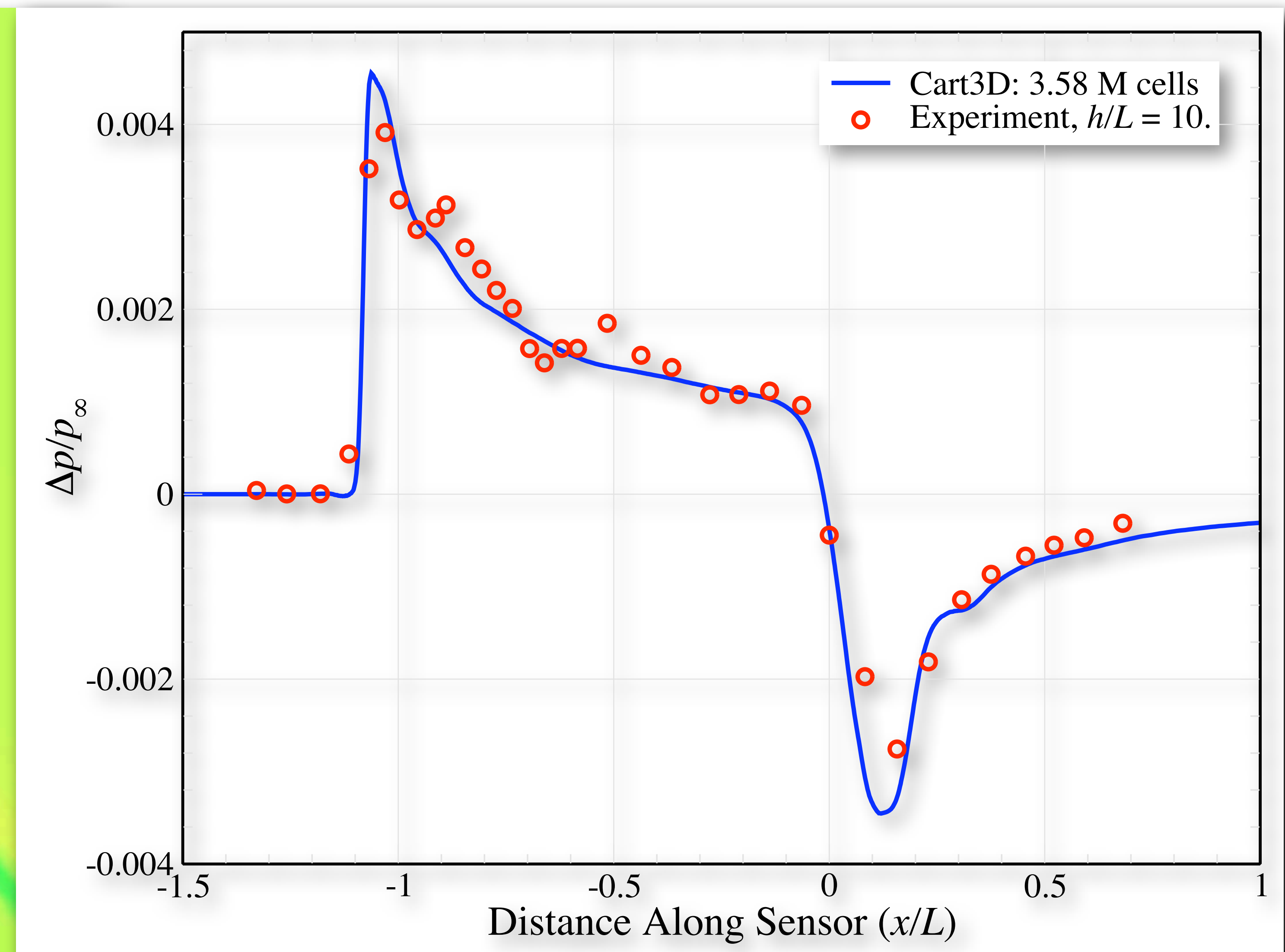


Parabolic: $r = f(x^{1/2})$

- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$

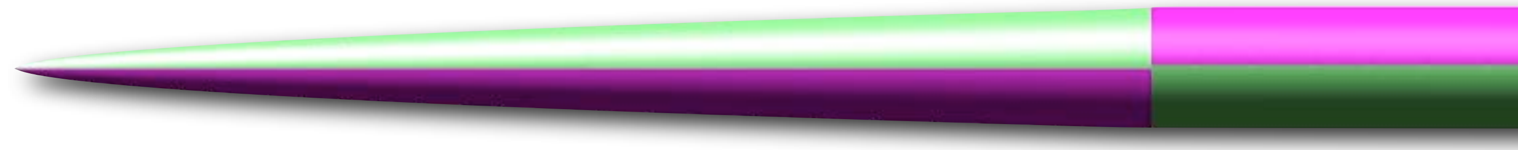


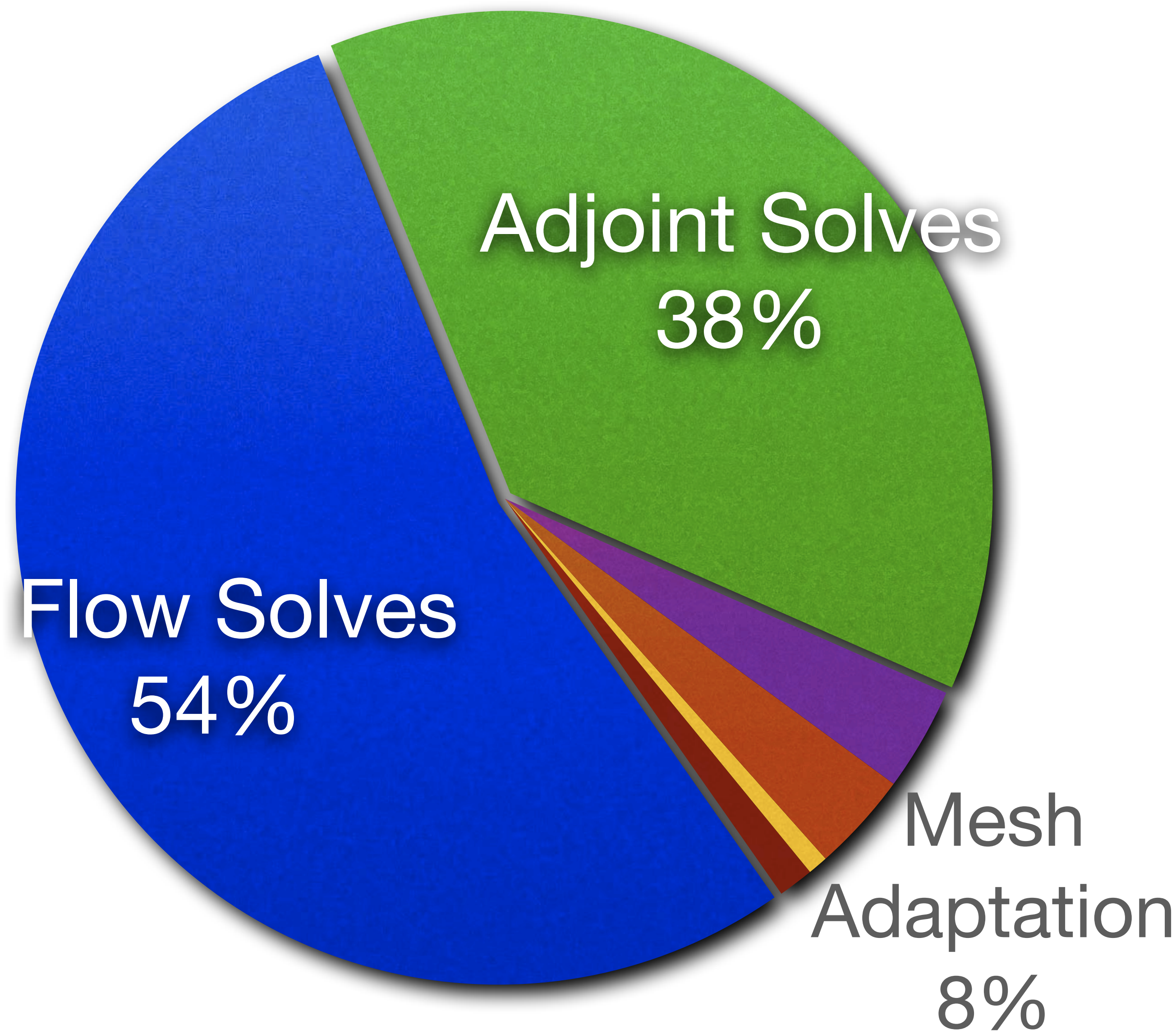




Parabolic: $r = f(x^{1/2})$

- NASA TN D-3106
  - $M_\infty = 1.41,\ \alpha = 0.0°$
  - $h/L = 10.0$
- Simulation performed on desktop workstation
  - Dual quad-core (8 cores)
  - Intel Xeon, 3.2Ghz
  - 16 Gb memory
- Total simulation time 75 mins. (all adaptations & mesh gen)

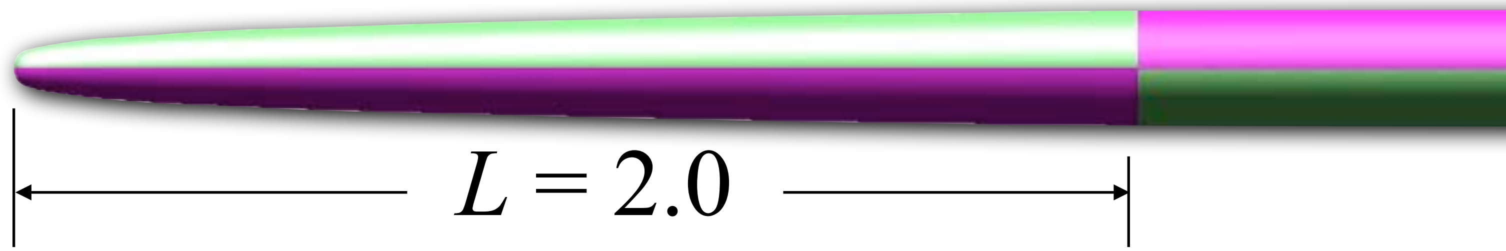




Total = 75 mins.

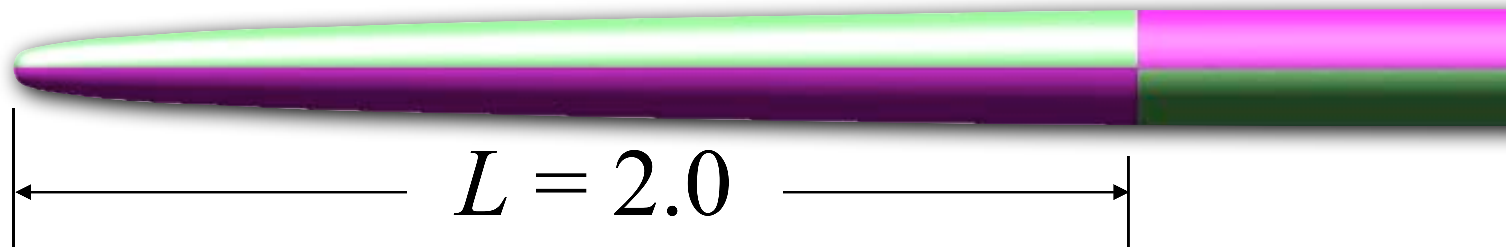
Quartic: $r = f(x^{1/4})$

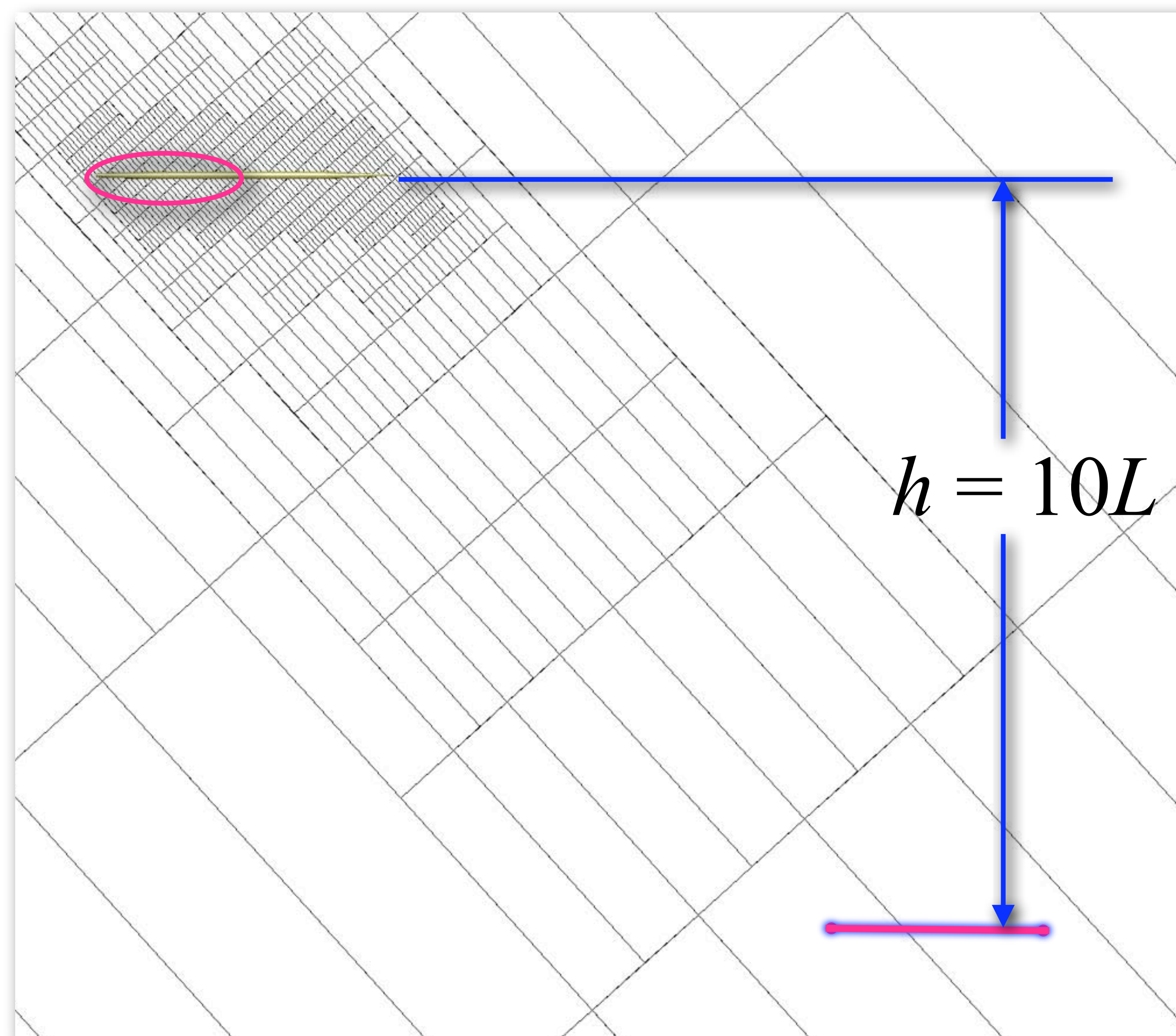
- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$
  - Sensor offset, $h/L = 10.0$
- Initial mesh ~ 3200 cells



Quartic: $r = f(x^{1/4})$

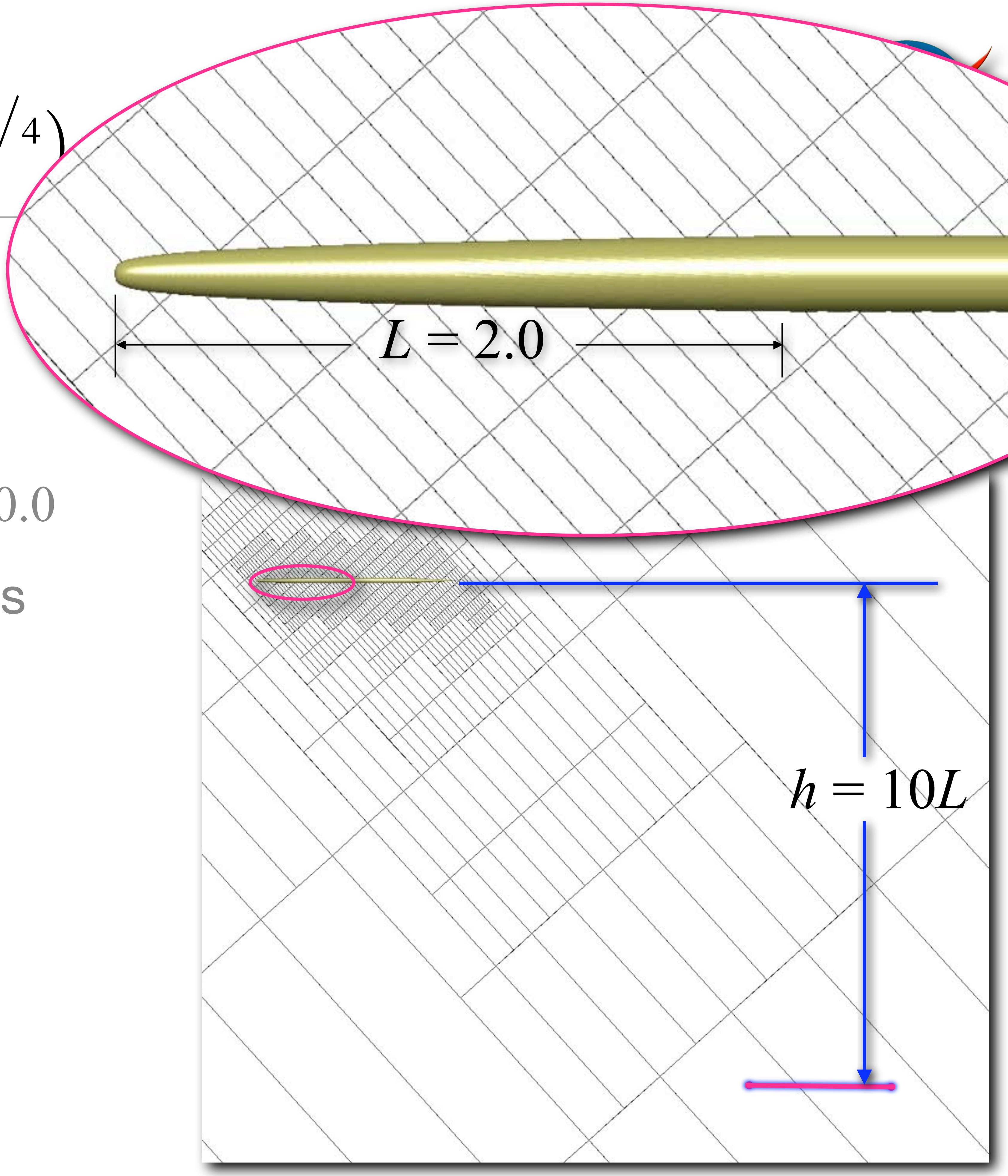
- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$
  - Sensor offset, $h/L = 10.0$
- Initial mesh ~ 3200 cells





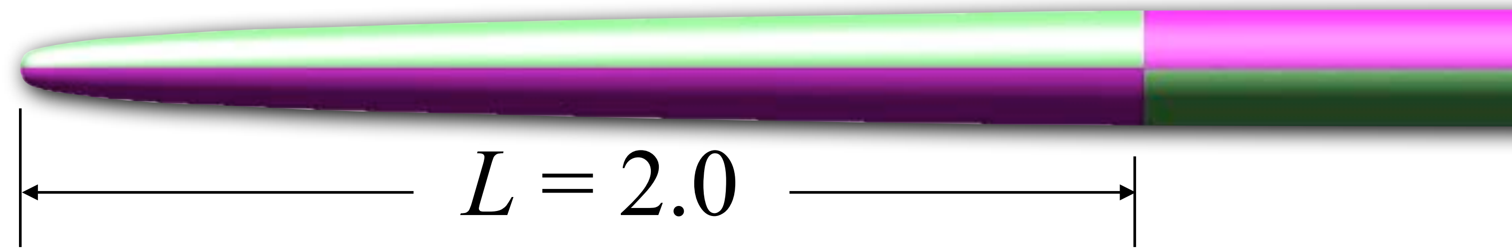
Quartic: $r = f(x^{1/4})$

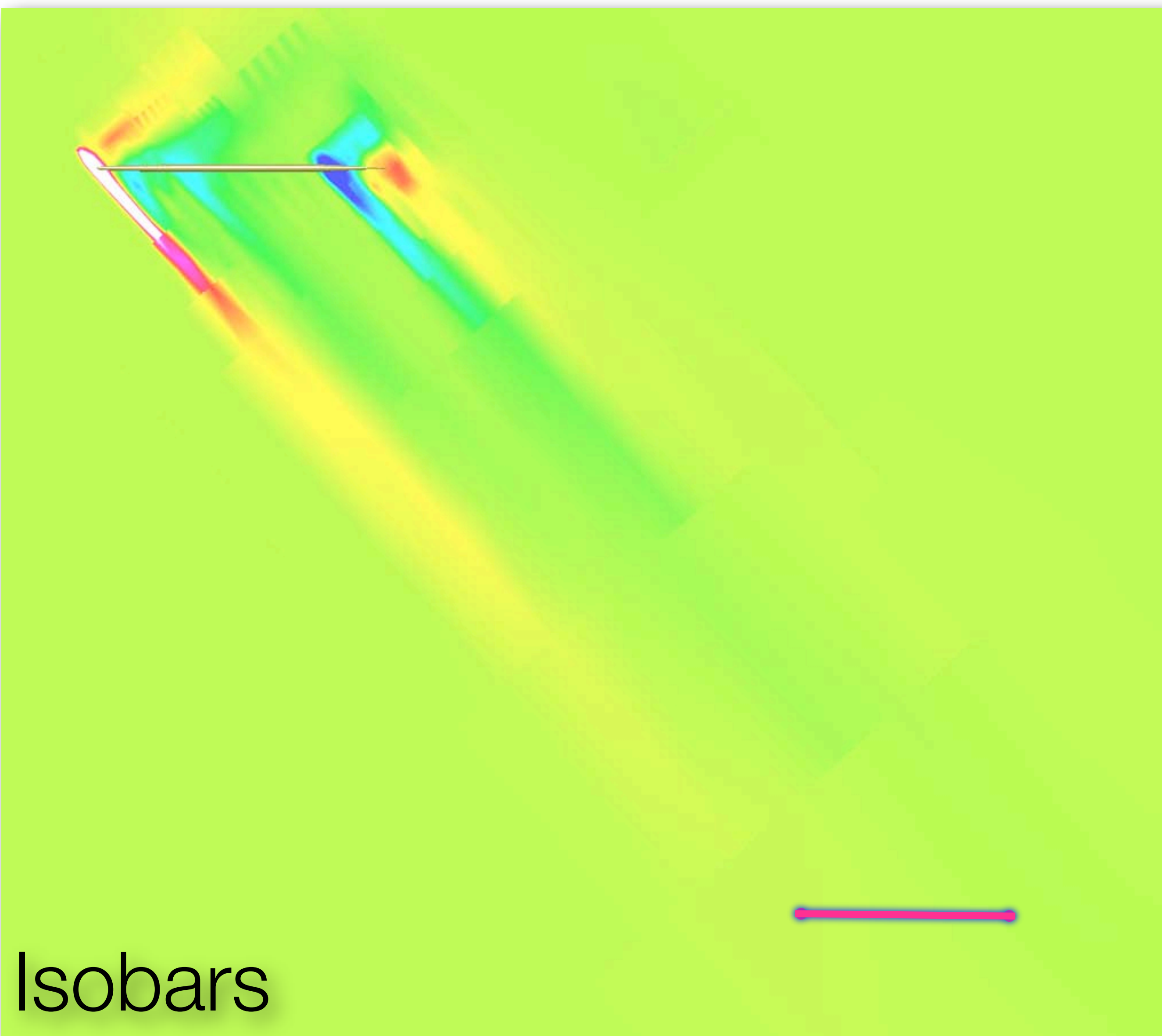
- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$
  - Sensor offset, $h/L = 10.0$
- Initial mesh ~ 3200 cells

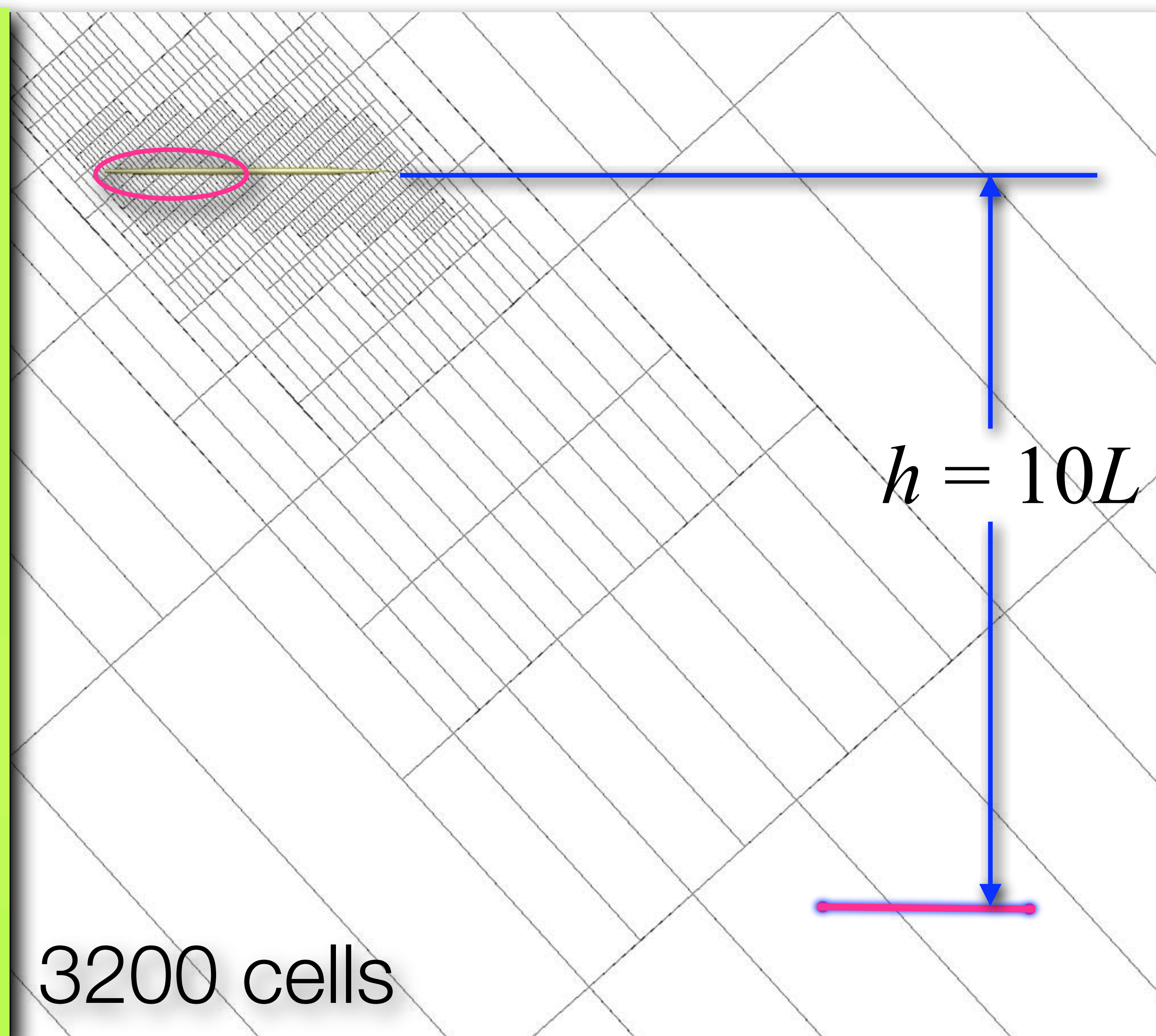


Quartic: $r = f(x^{1/4})$

- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$

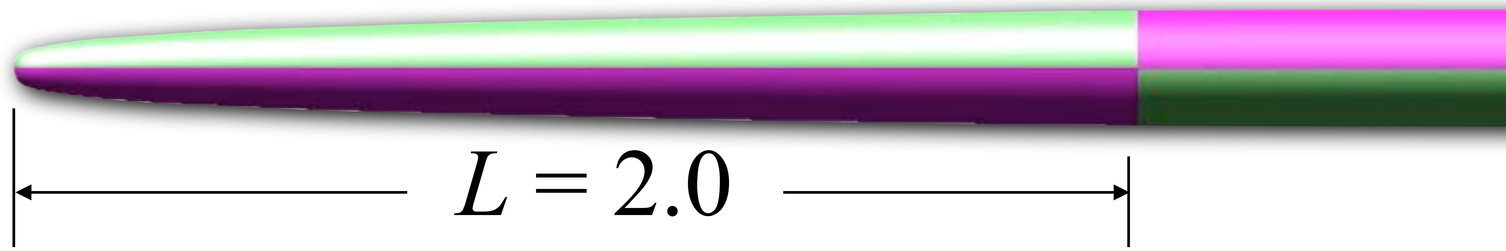


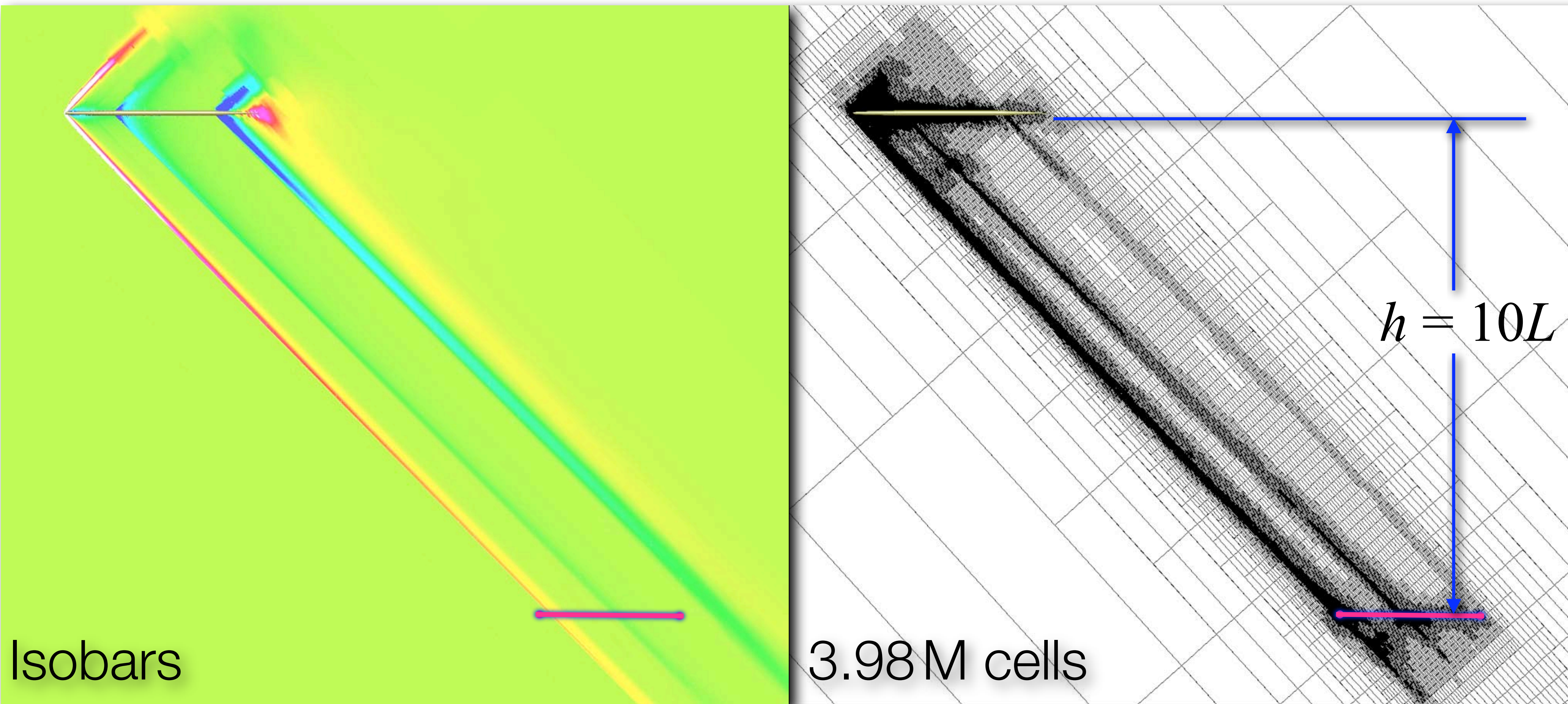




Quartic: $r = f(x^{1/4})$

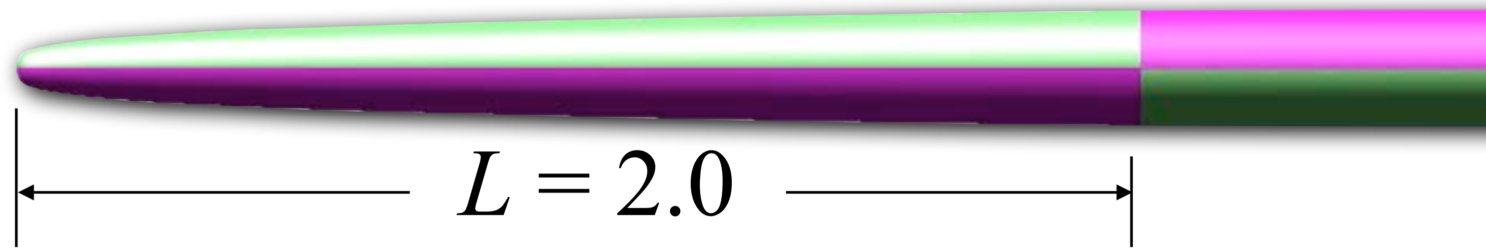
- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$

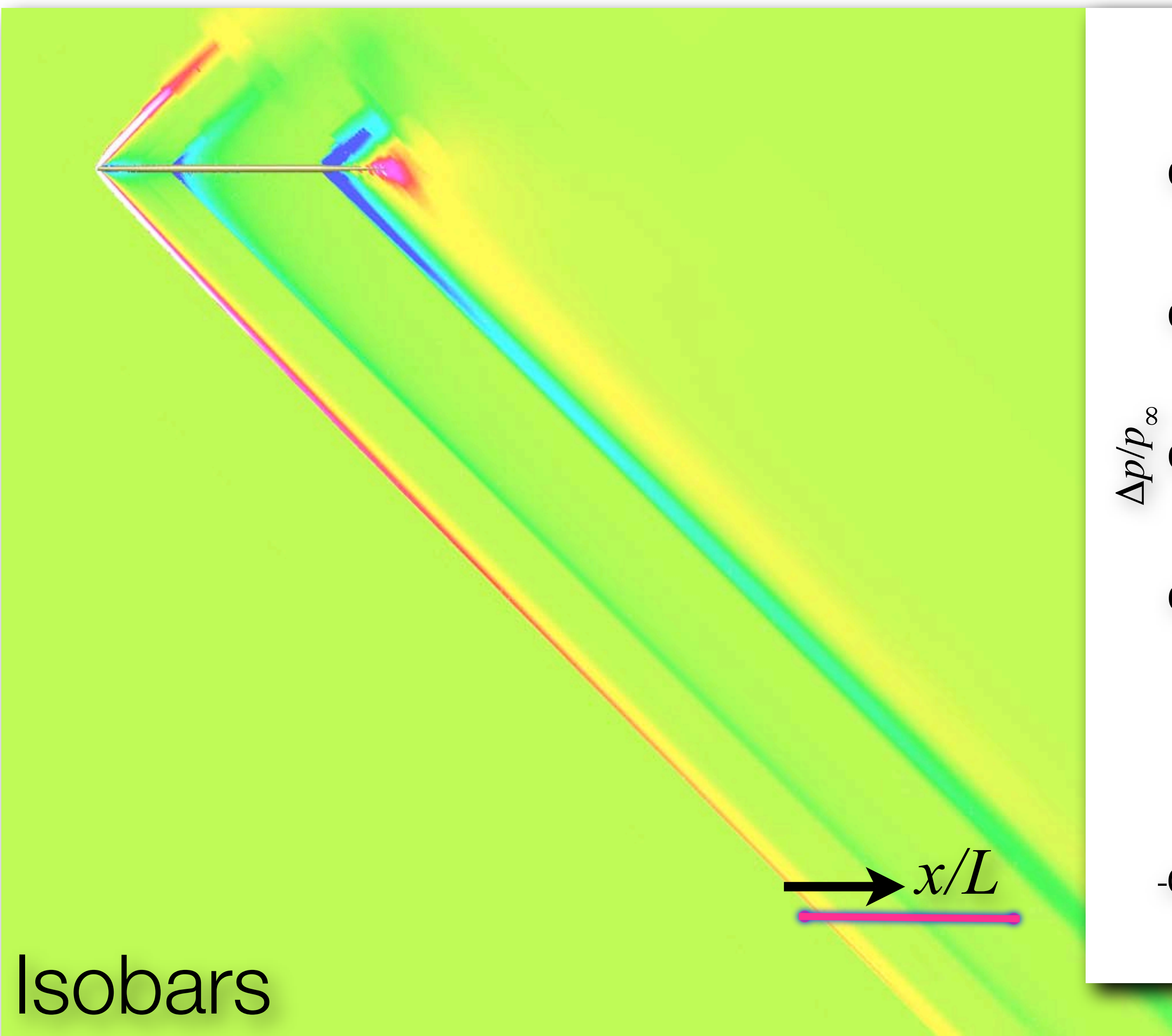


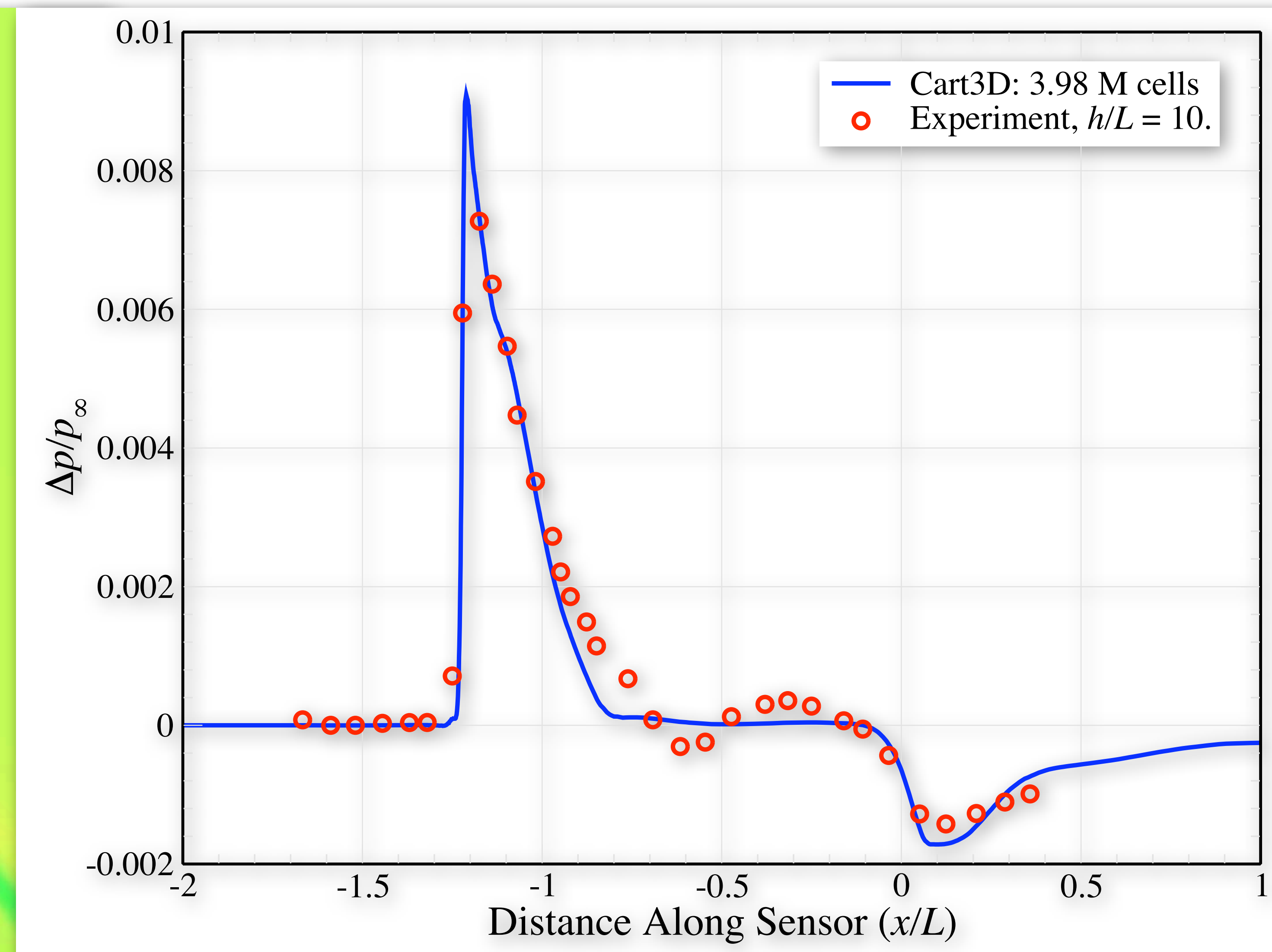


Quartic: $r = f(x^{1/4})$

- NASA TN D-3106
  - $M_\infty = 1.41$
  - $\alpha = 0.0°$

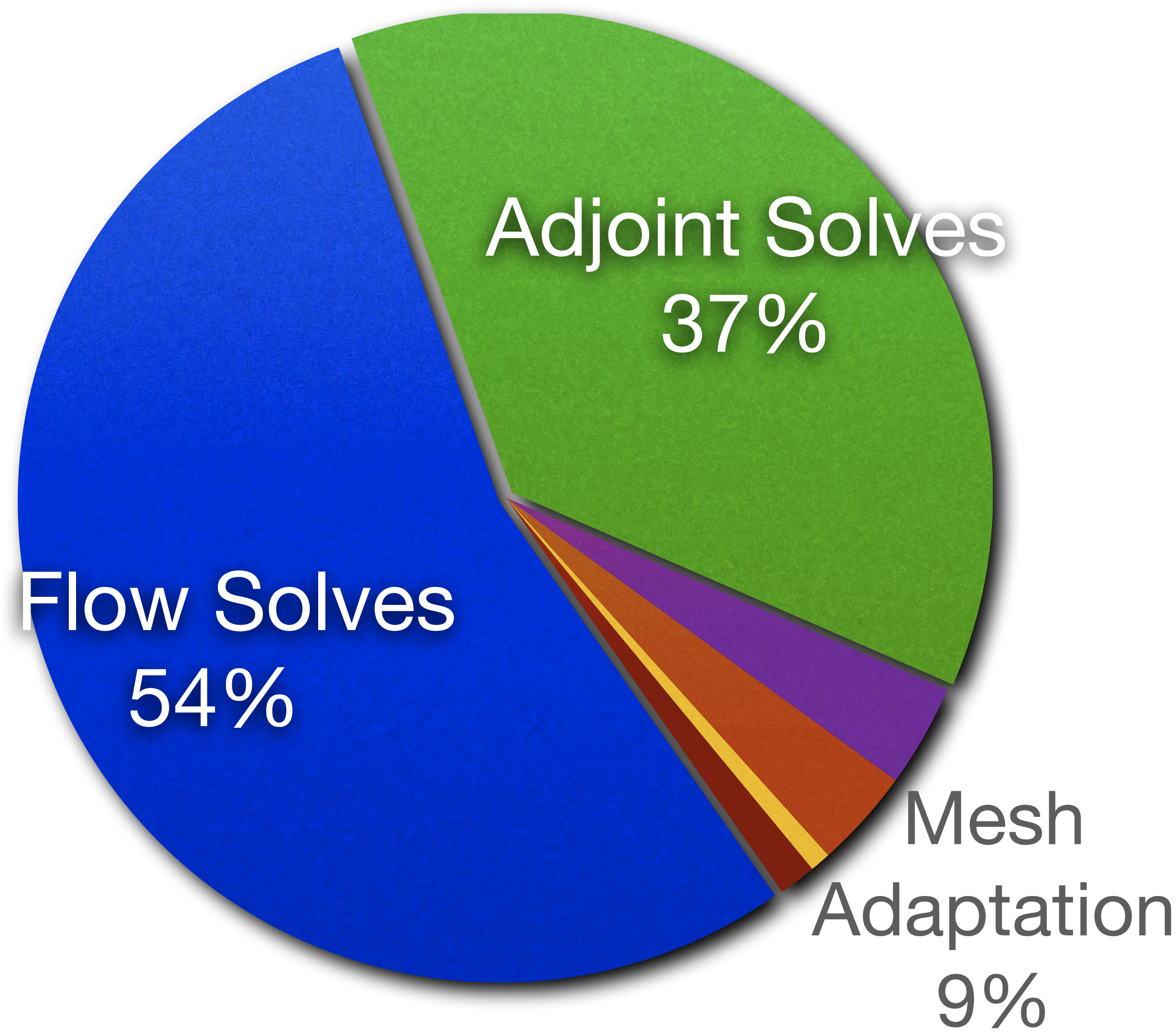






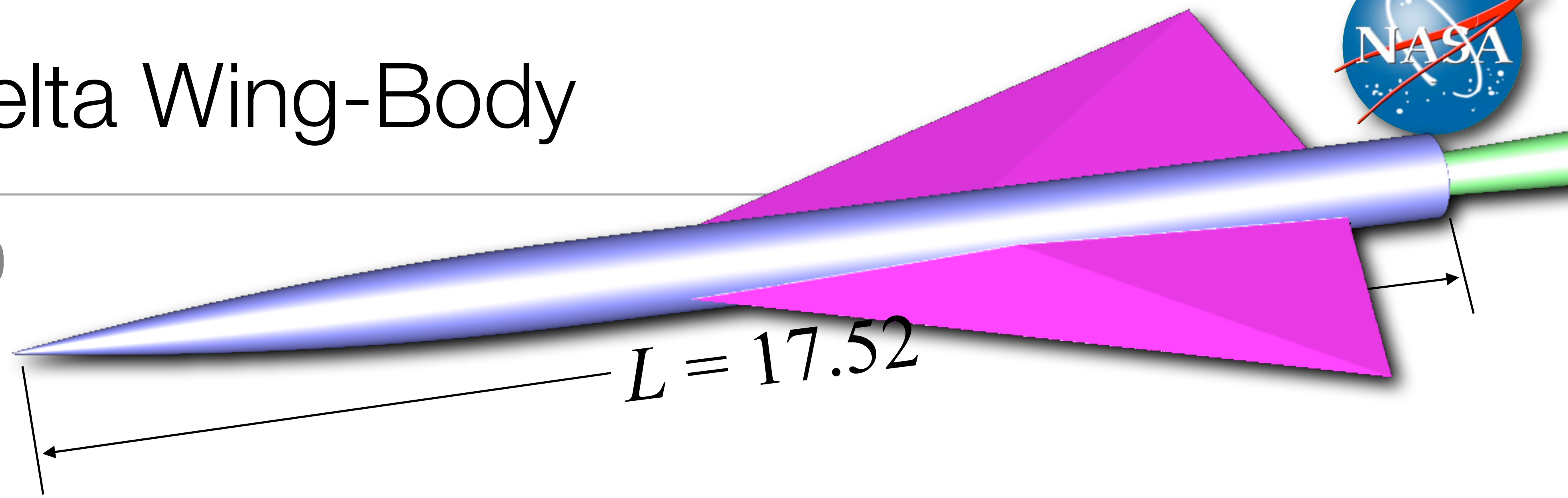
Quartic: $r = f(x^{1/4})$

- NASA TN D-3106
  - $M_\infty = 1.41,\ \alpha = 0.0°$
  - $h/L = 10.0$
- Simulation performed on desktop workstation
  - Dual quad-core (8 cores)
  - Intel Xeon, 3.2Ghz
  - 16 Gb memory
- Total simulation time 83 mins. (all adaptations & mesh gen)



Total = 83 mins.

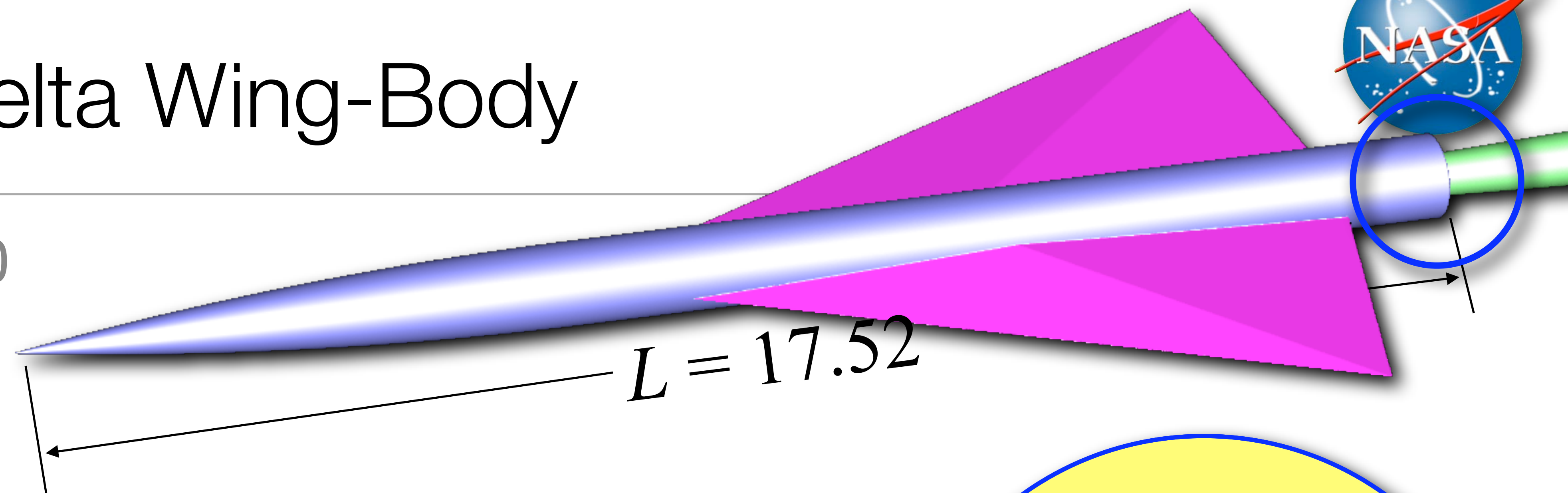
69° Swept Delta Wing-Body

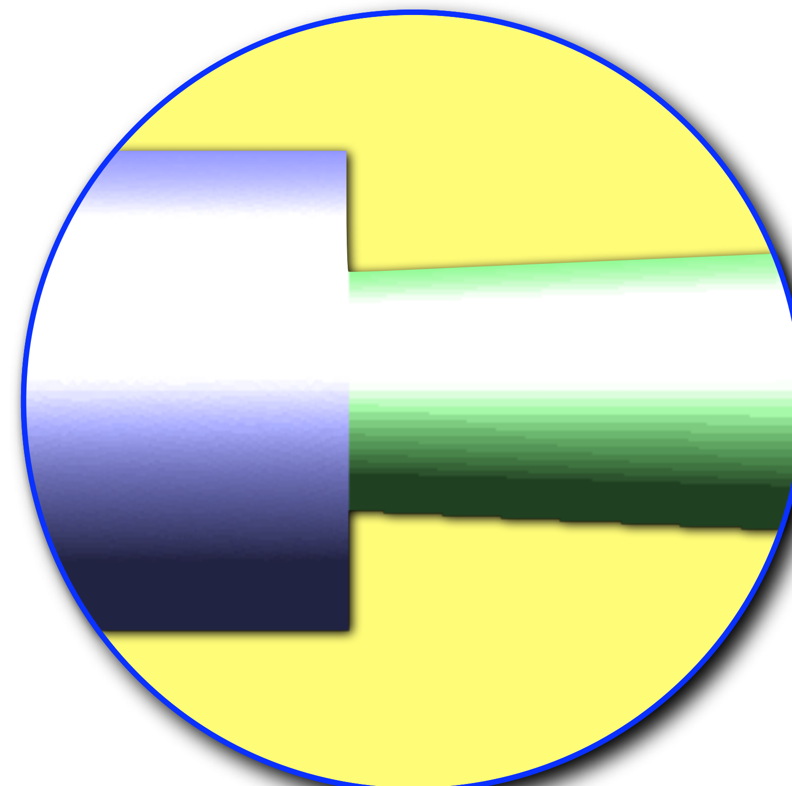


- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$
  - Sensor offset, $h/L = 3.6$ & $\{0.2, 0.4, 0.8, 1.2, 2.0, 2.8\}$
- Initial mesh ~ 22 k cells

69° Swept Delta Wing-Body

- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$
  - Sensor offset, $h/L = 3.6$ & $\{0.2, 0.4, 0.8, 1.2, 2.0, 2.8\}$
- Initial mesh ~ 22 k cells

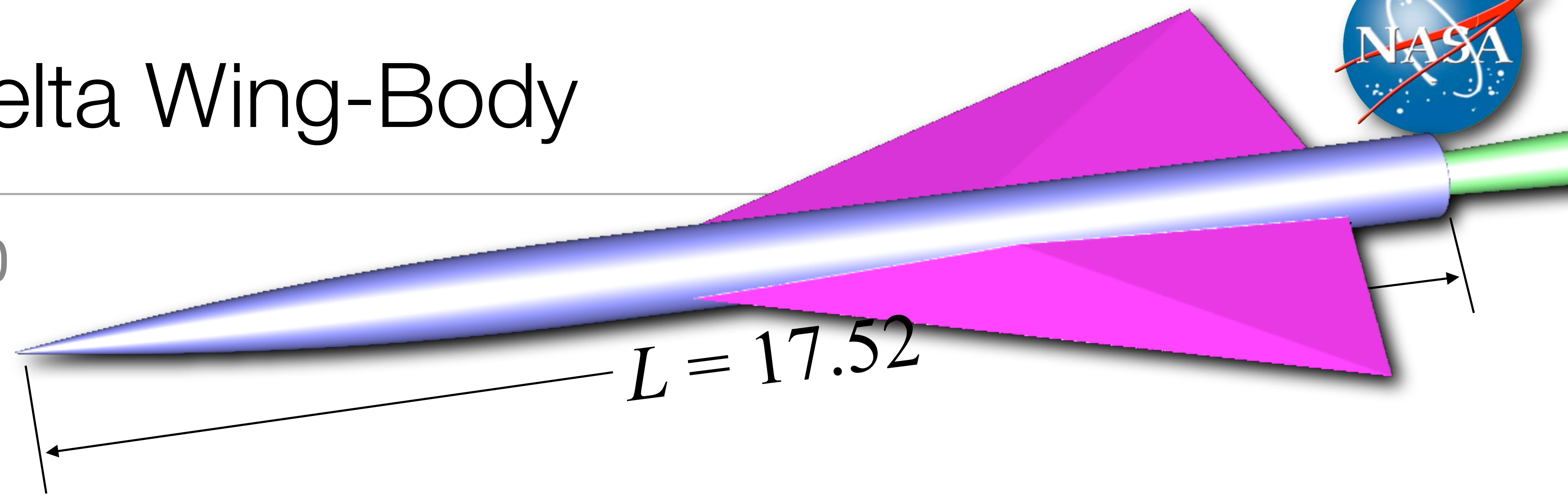




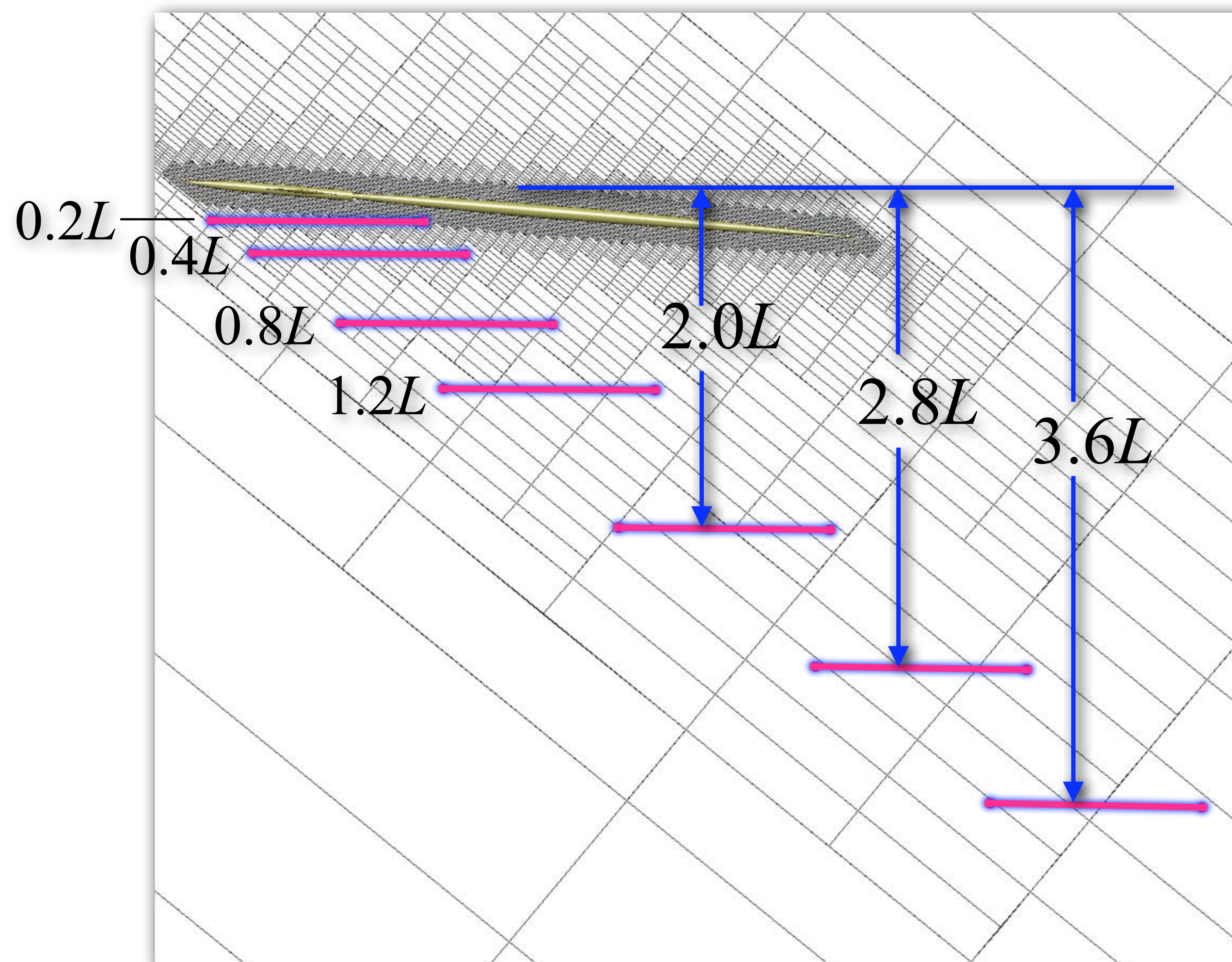
Stepped sting-body juncture

69° Swept Delta Wing-Body

- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$
  - Sensor offset, $h/L = 3.6$ & $\{0.2, 0.4, 0.8, 1.2, 2.0, 2.8\}$

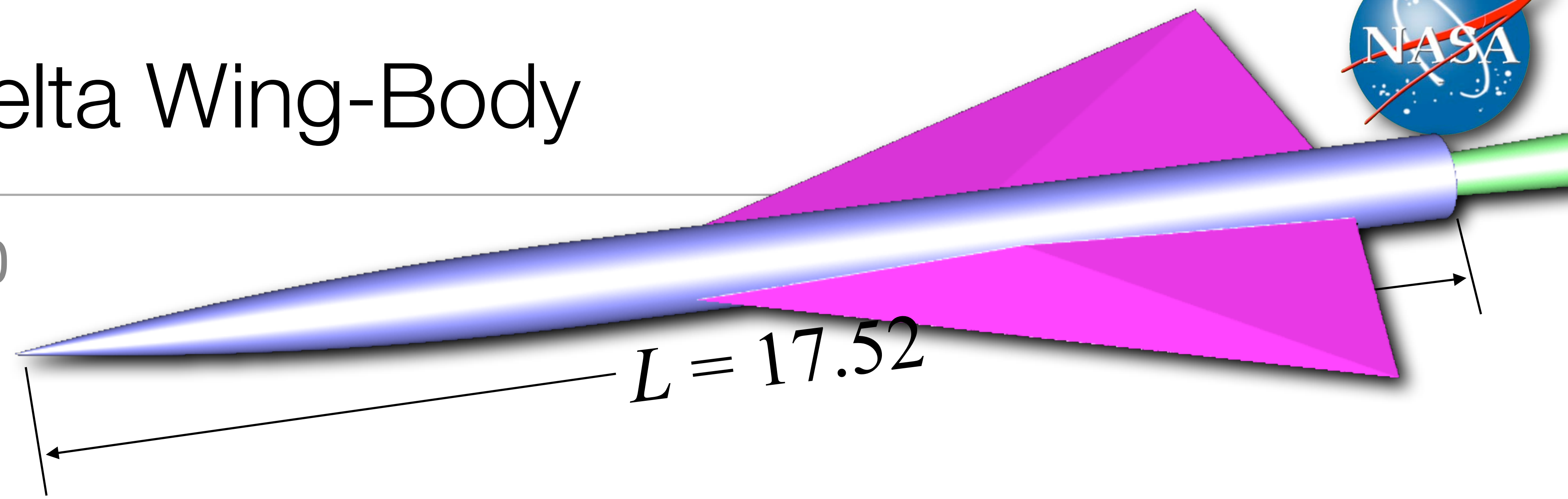


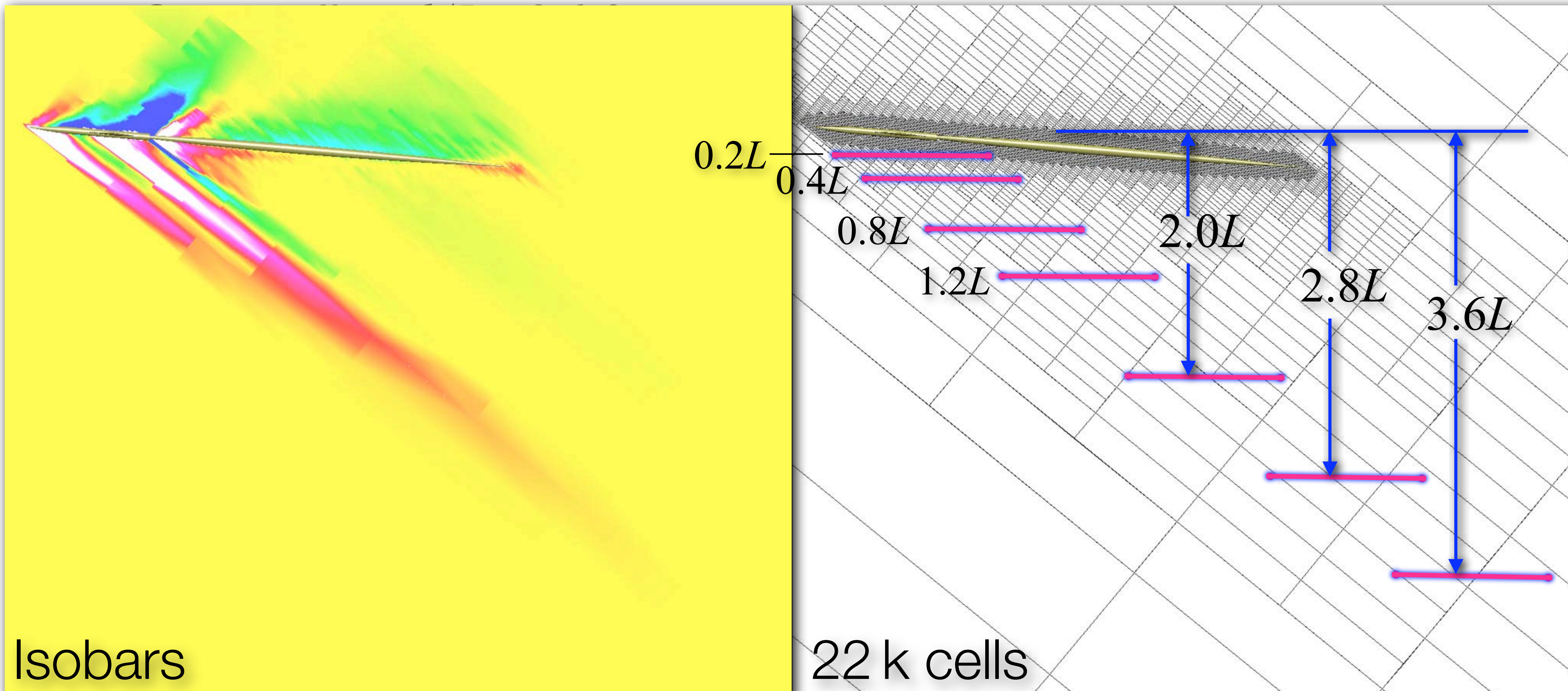
- Initial mesh ~ 22 k cells



69° Swept Delta Wing-Body

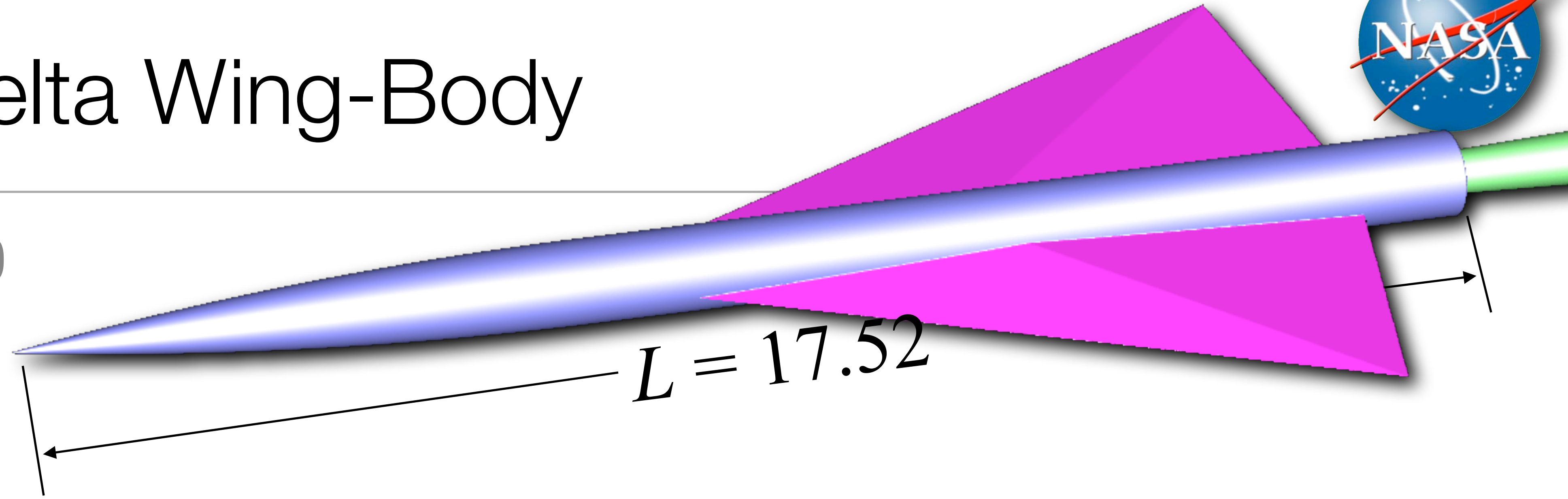
- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$

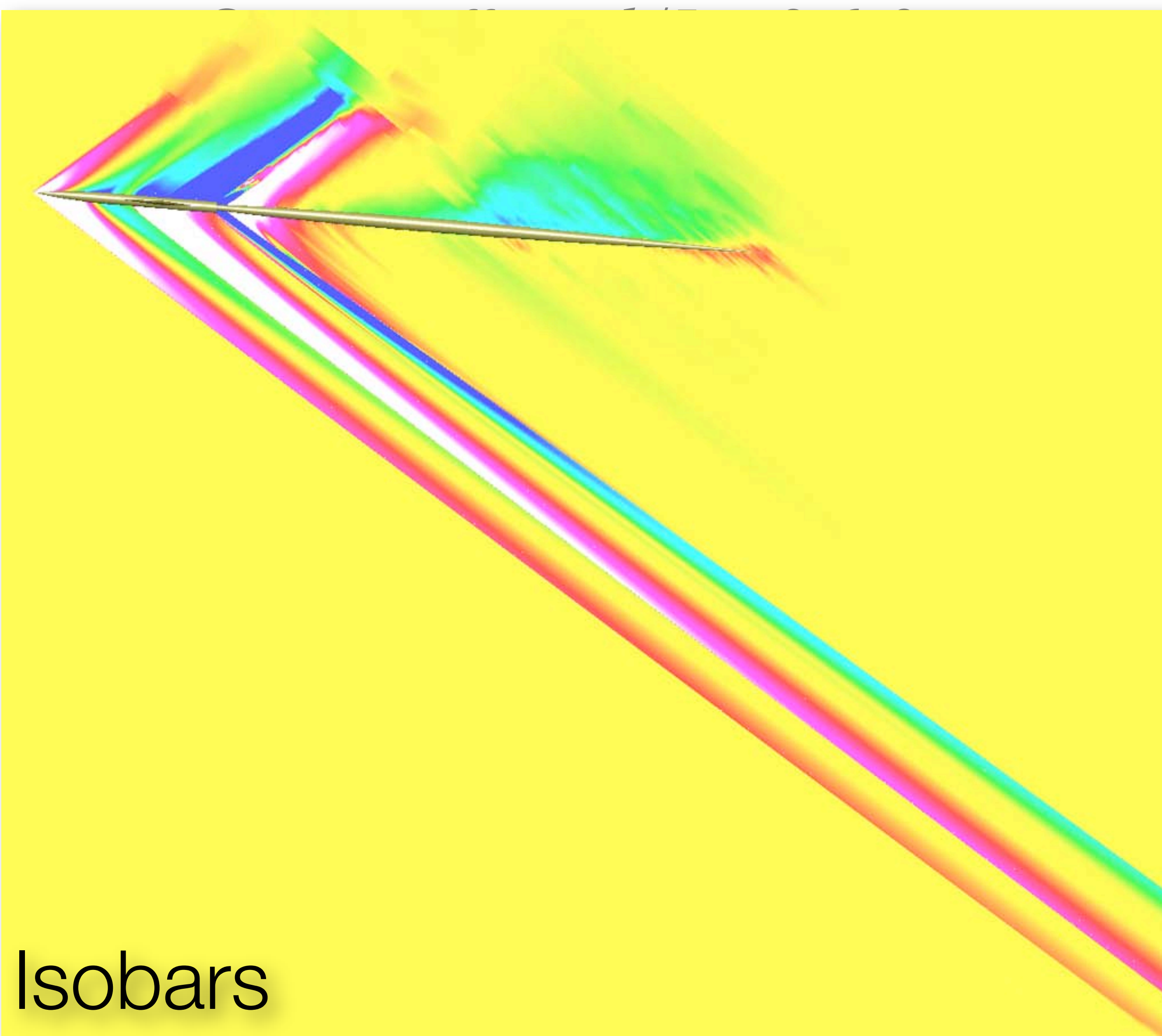


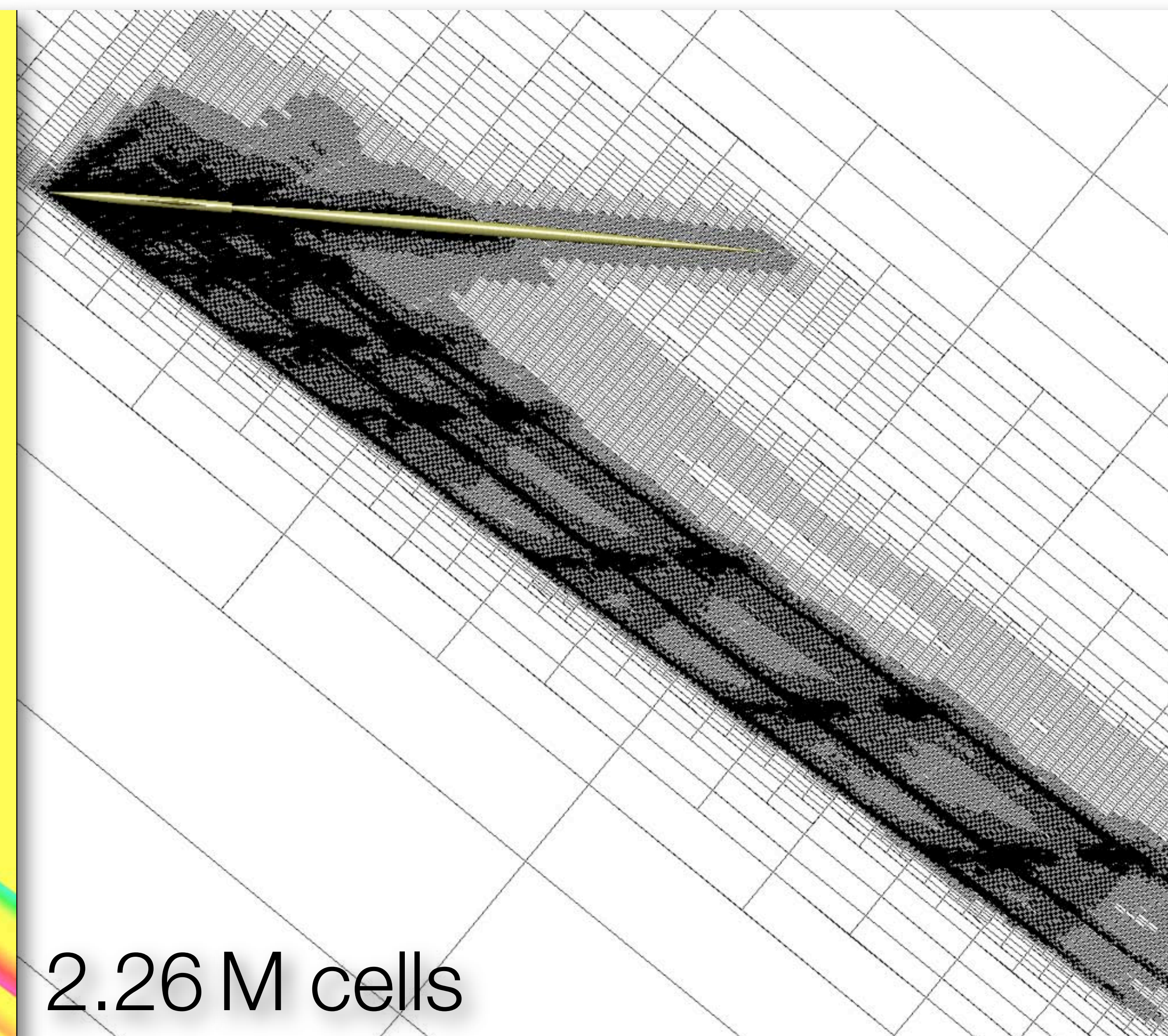


69° Swept Delta Wing-Body

- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$

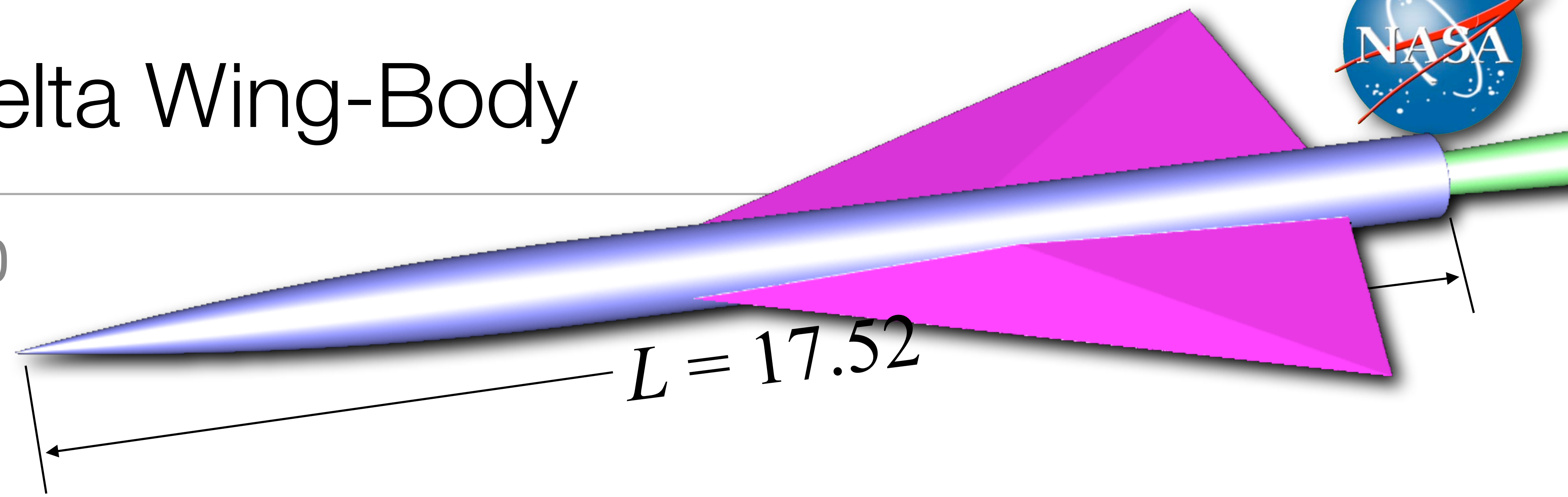


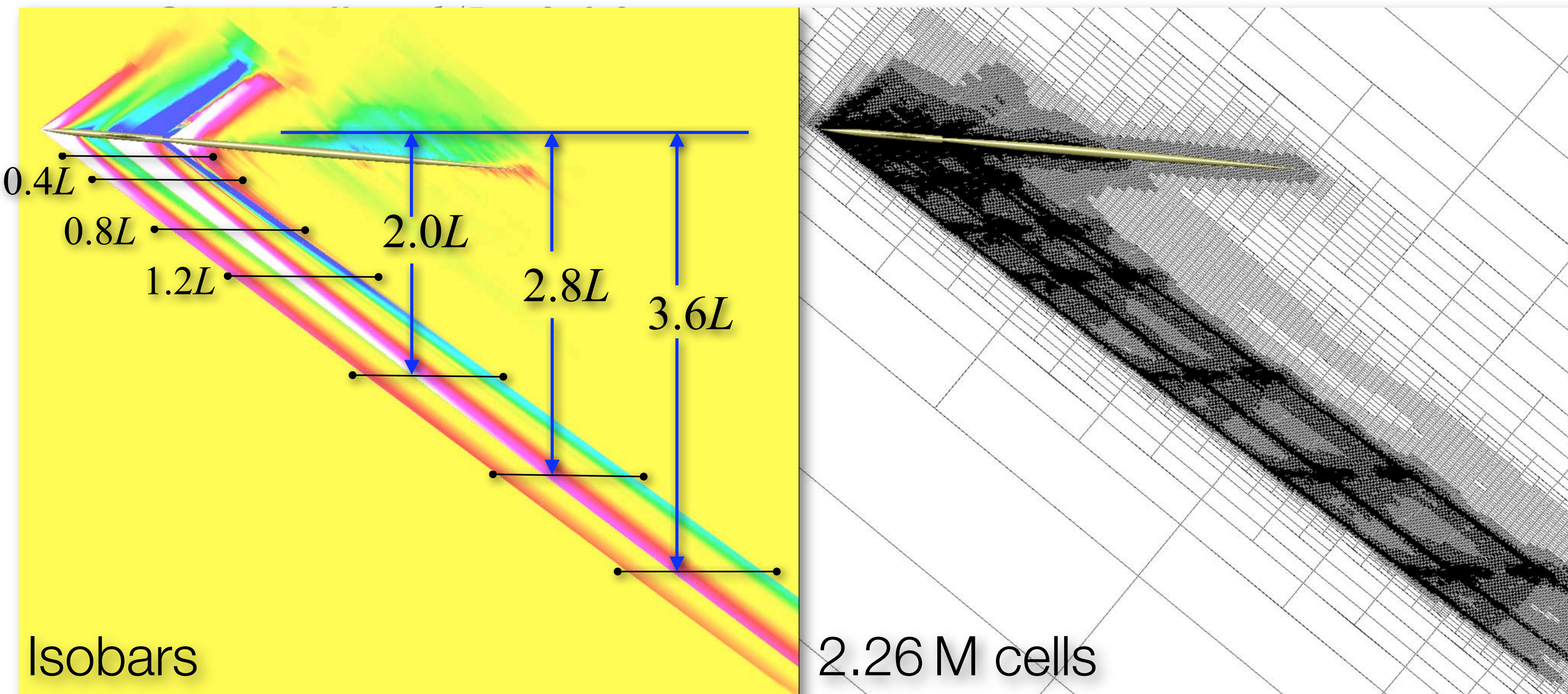




69° Swept Delta Wing-Body

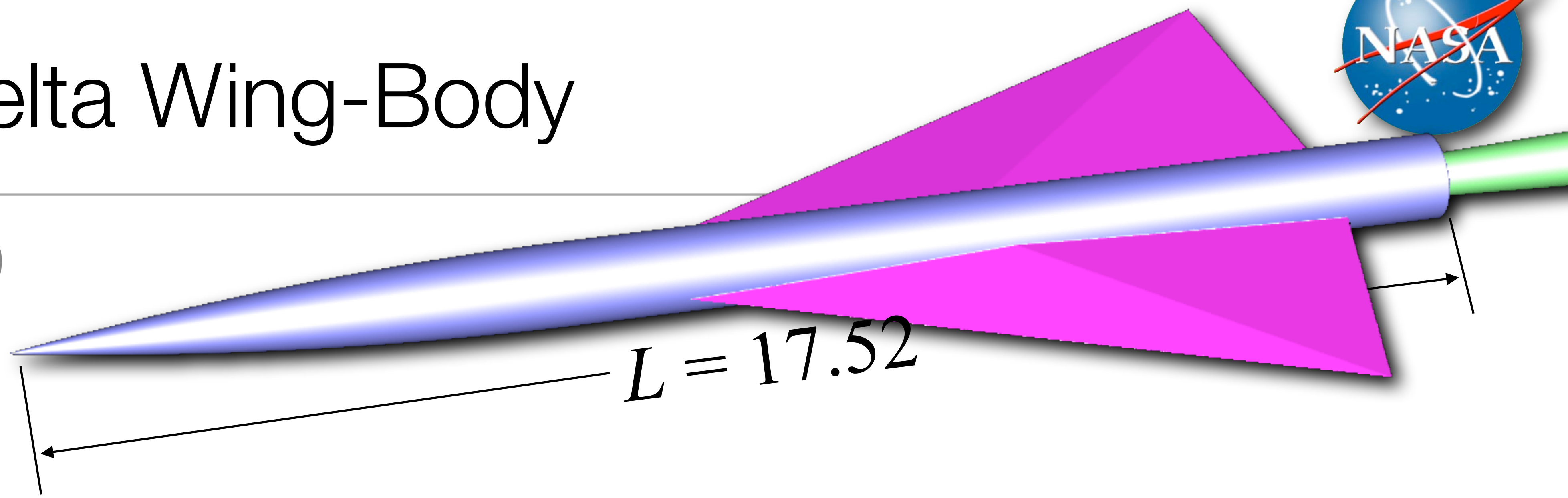
- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$

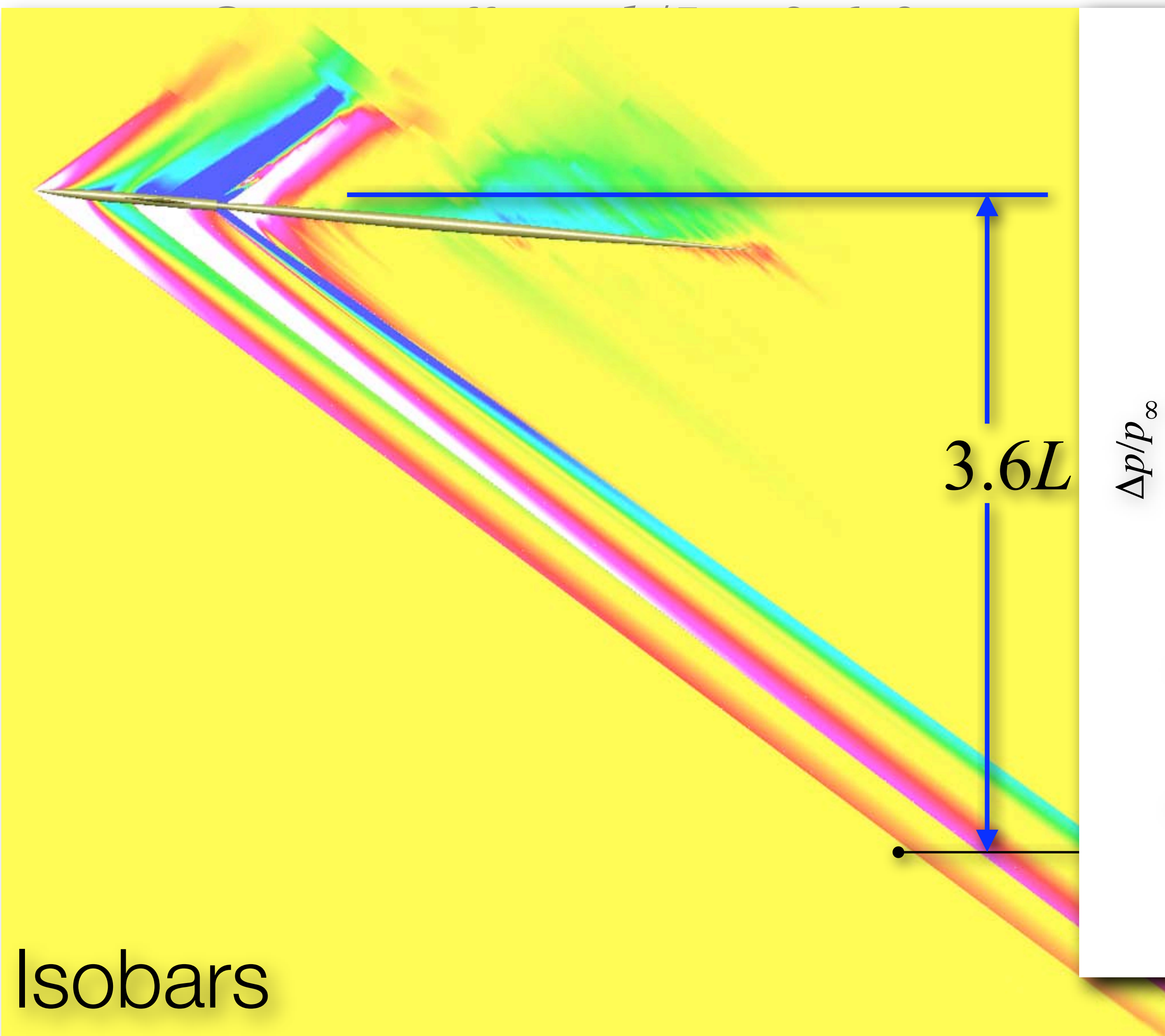


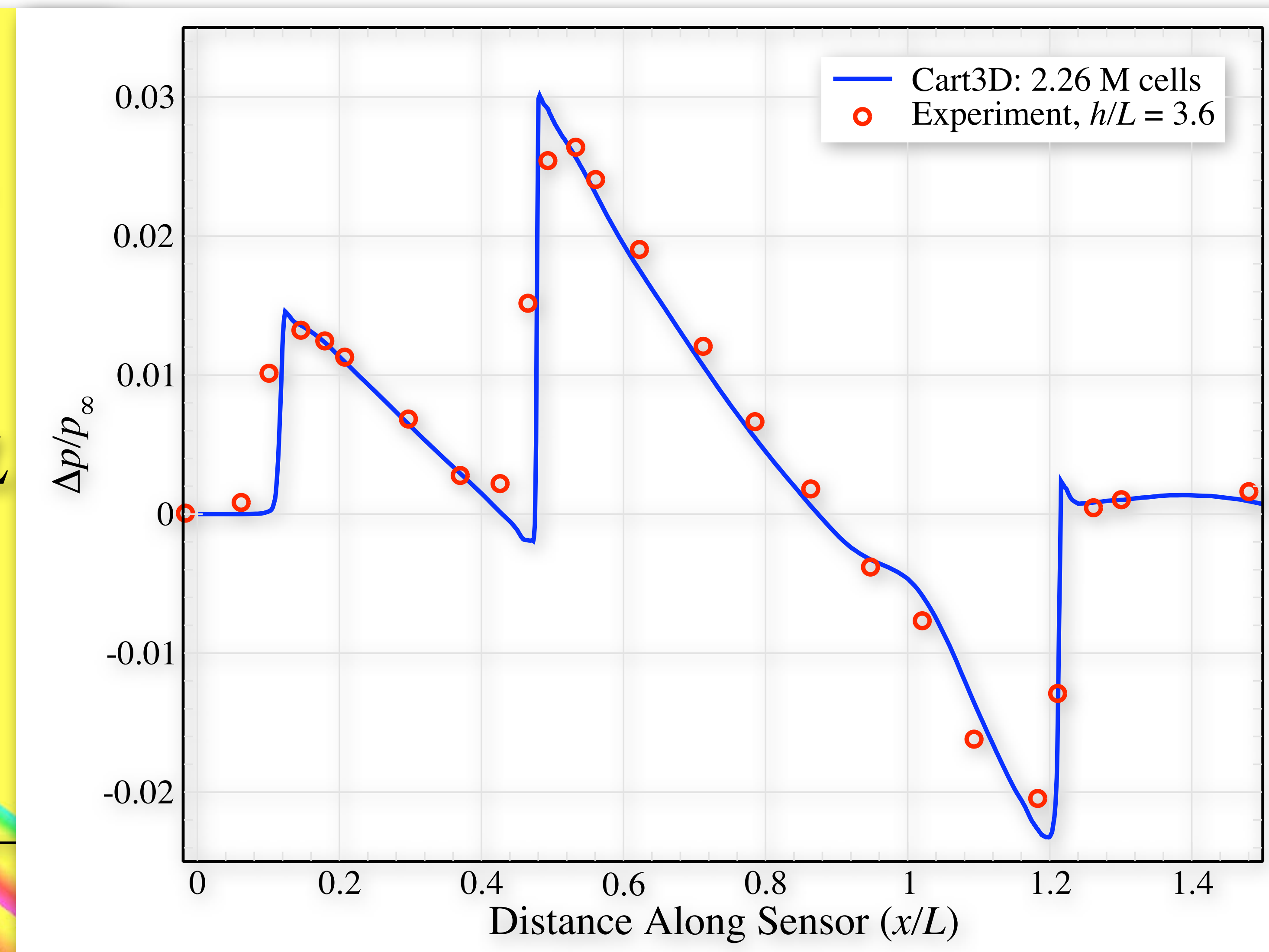


69° Swept Delta Wing-Body

- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$

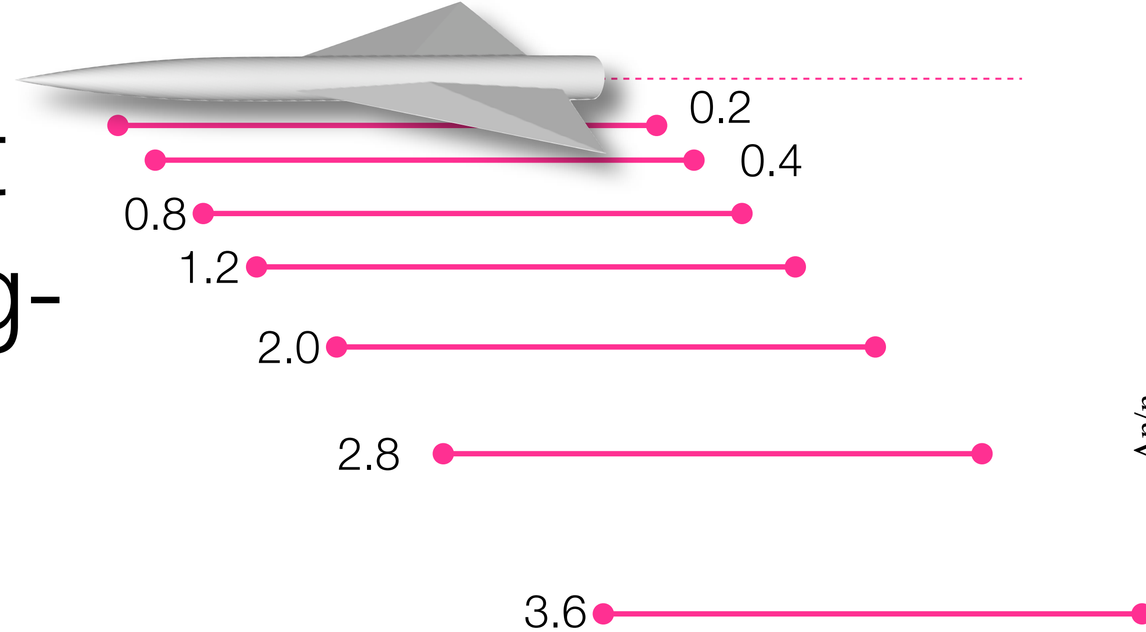


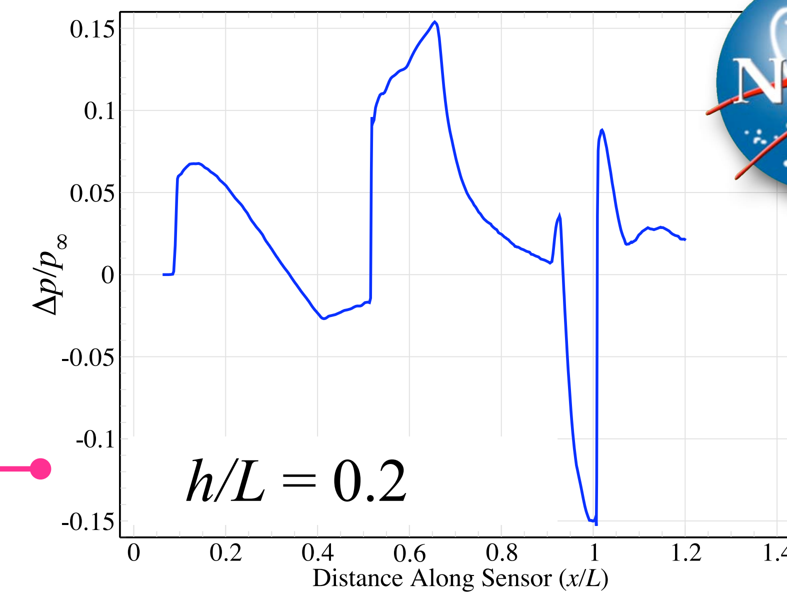


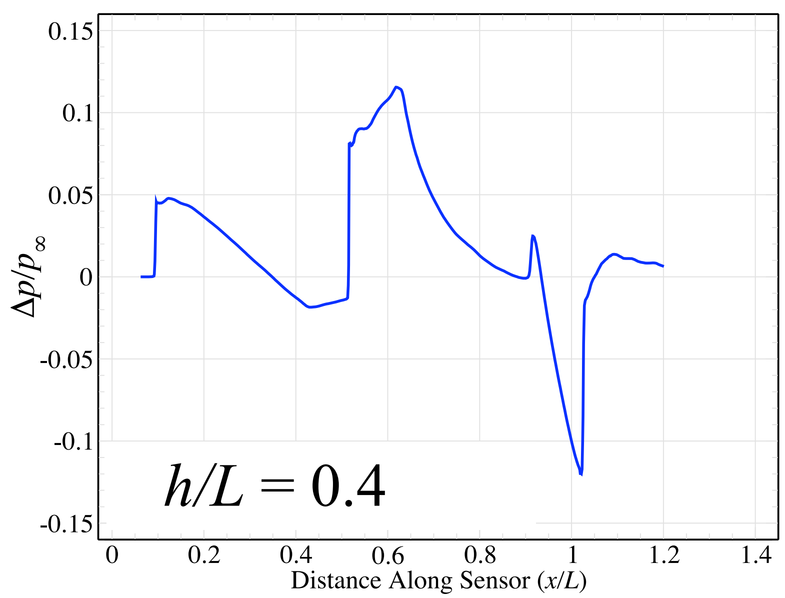


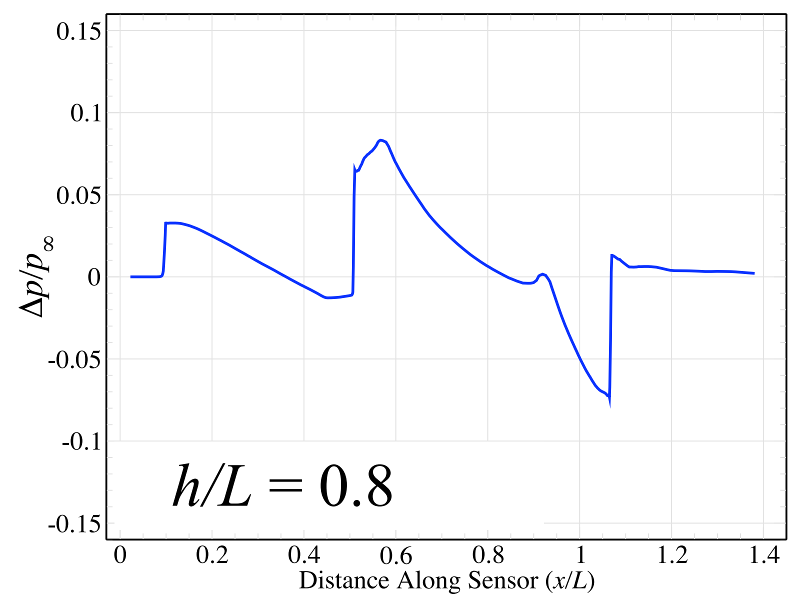
69° Swept Delta Wing-Body

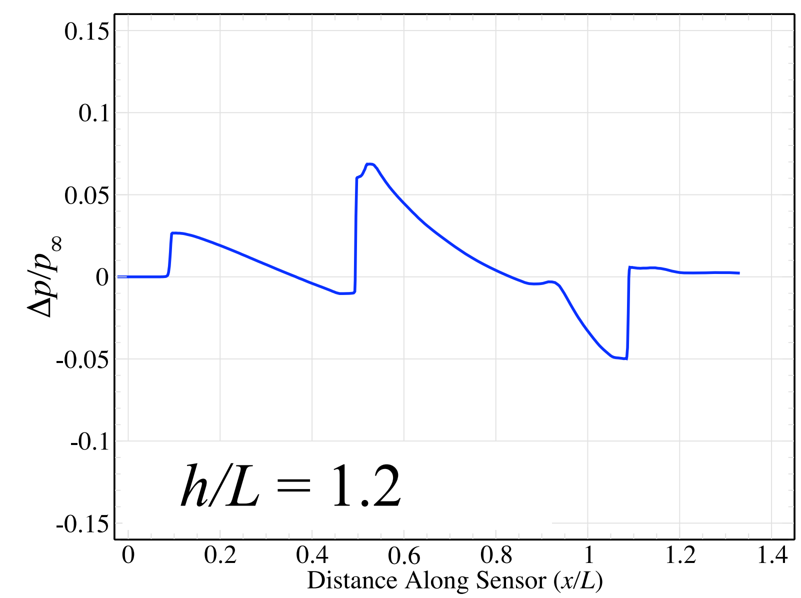
2.26M cells

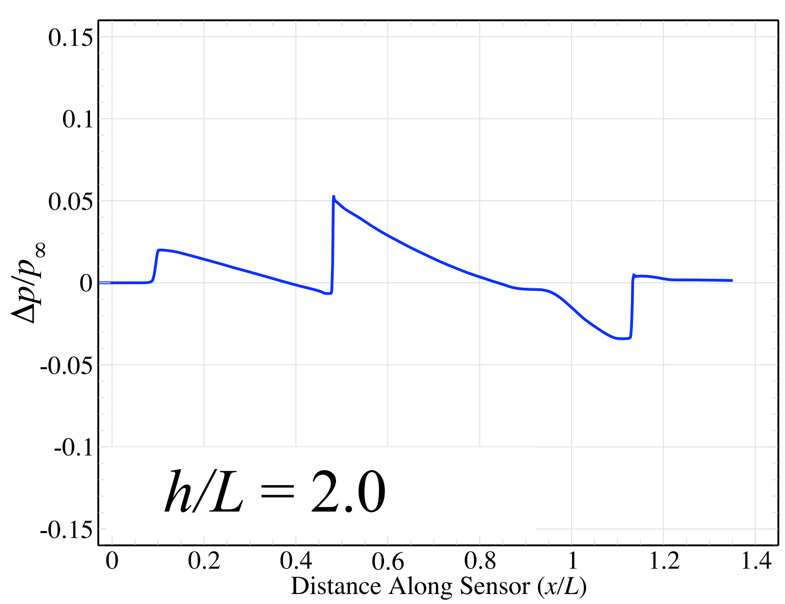


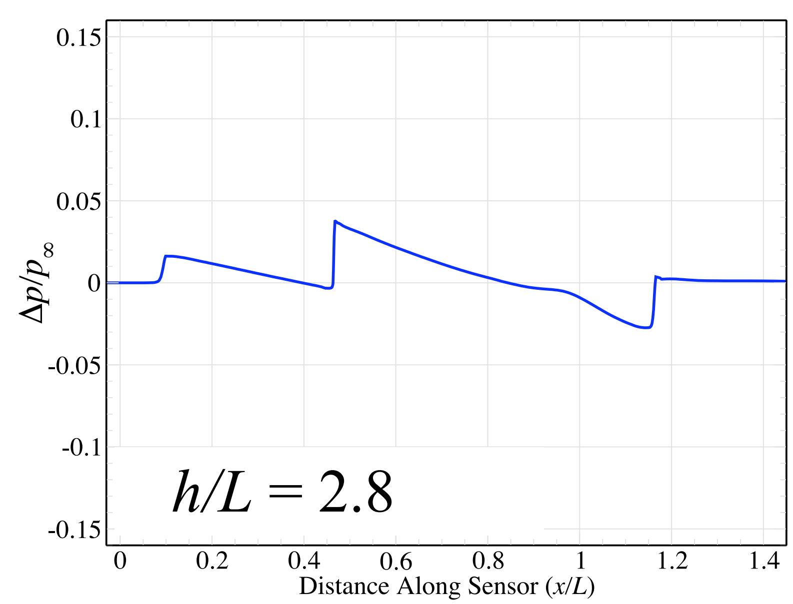


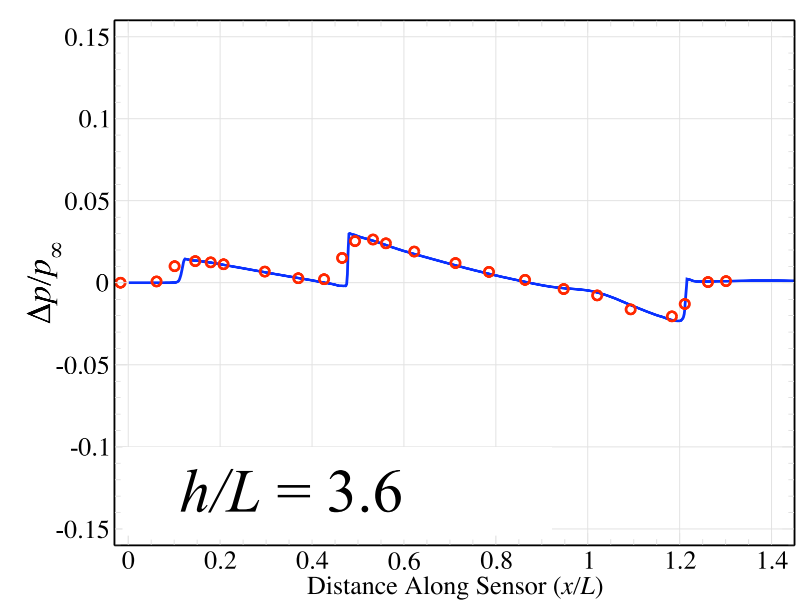




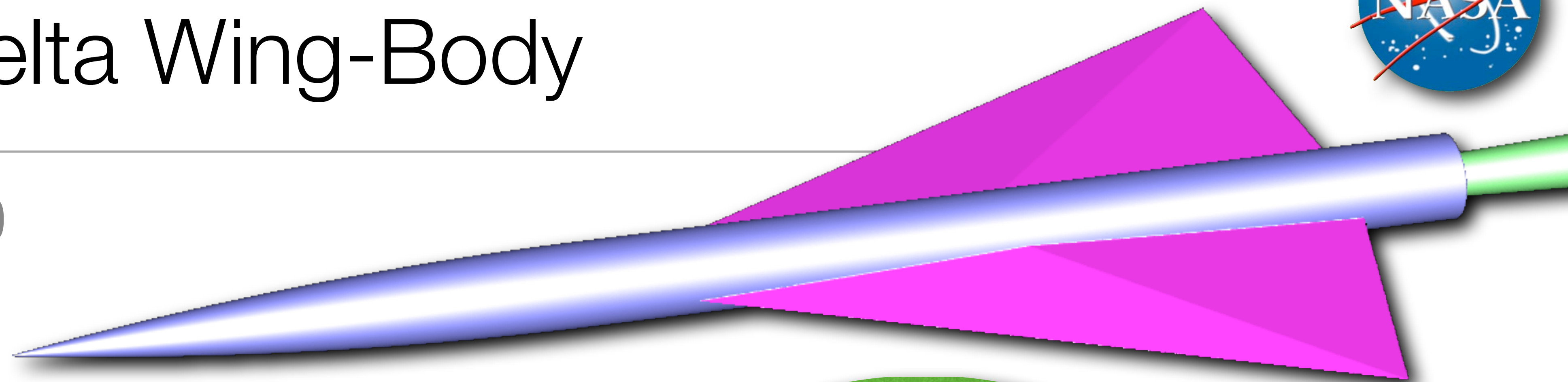




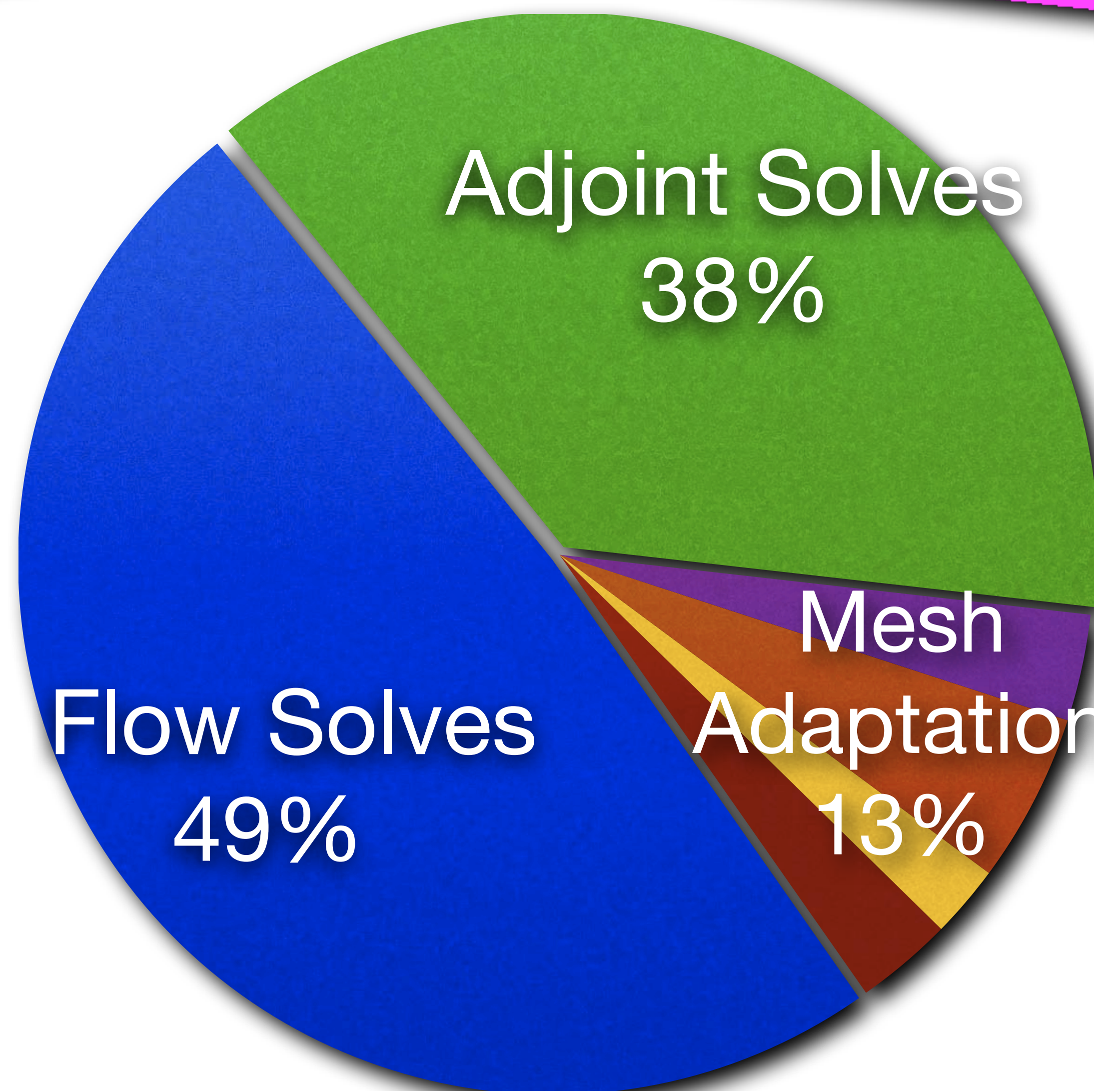




69° Swept Delta Wing-Body

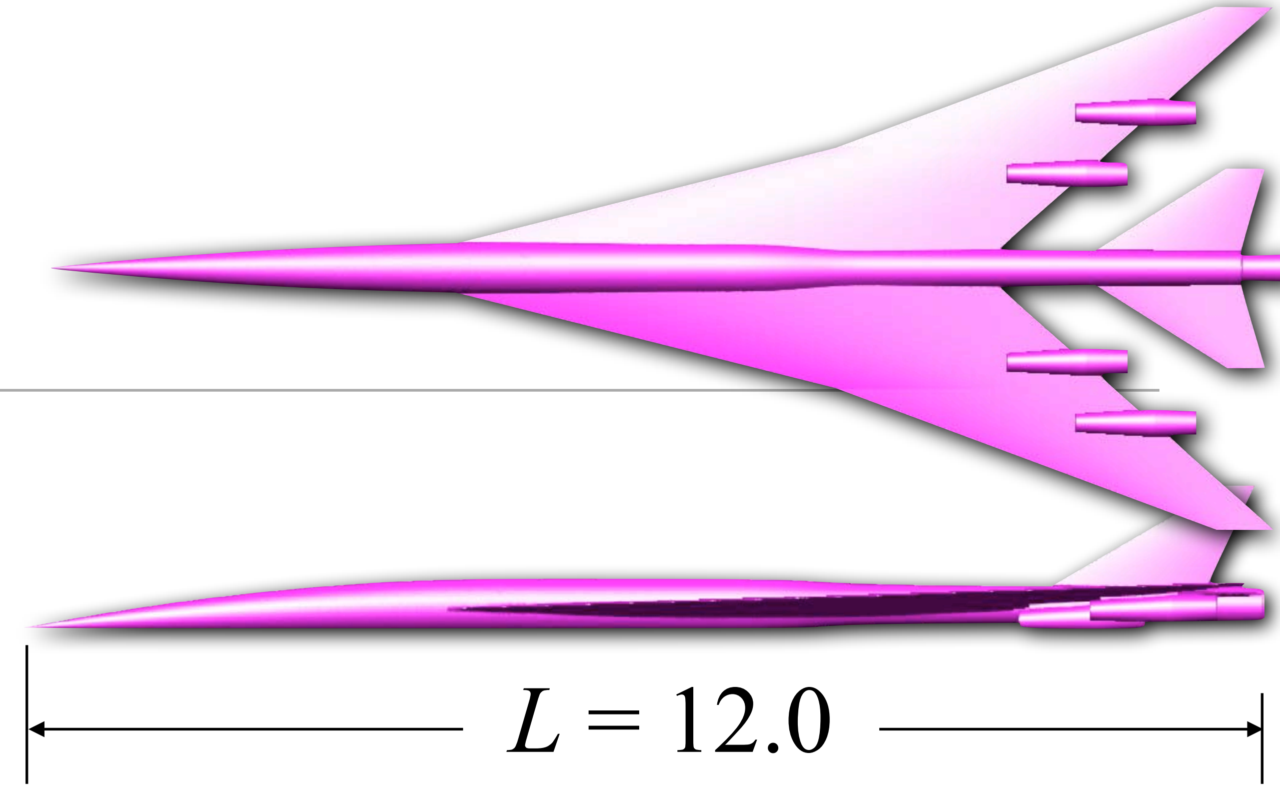


- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$
  - $h/L = \{.2, .4, .8, 1.2, 2.0, 2.8, 3.6\}$
- Simulation performed on desktop workstation
  - Dual quad-core (8 cores)
  - Intel Xeon, 3.2Ghz
  - 16 Gb memory
- Total simulation time 53 mins. (all adaptations & mesh gen)



Total = 53 mins.

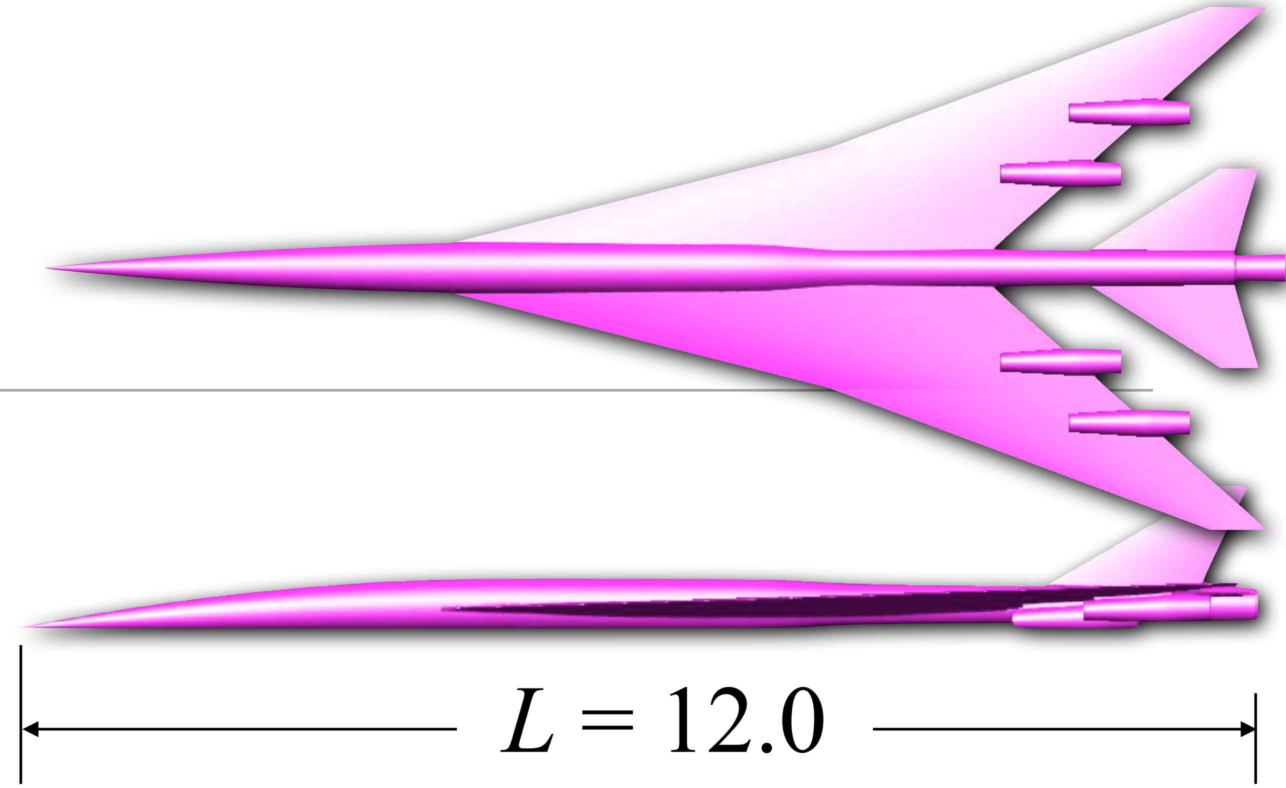
Ames Low-Boom Wing Tail

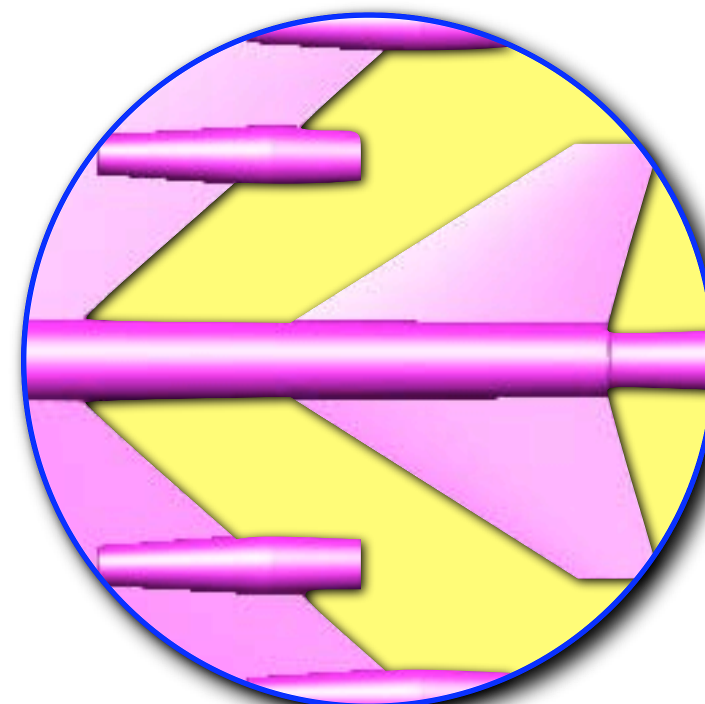


- NASA CP-1999-209699
  - $M_\infty = 2.0$
  - $\alpha = 2.0°$
  - Sensor offset, $h/L = 1.167$
- Initial mesh ~ 111 k cells

Ames Low-Boom Wing Tail

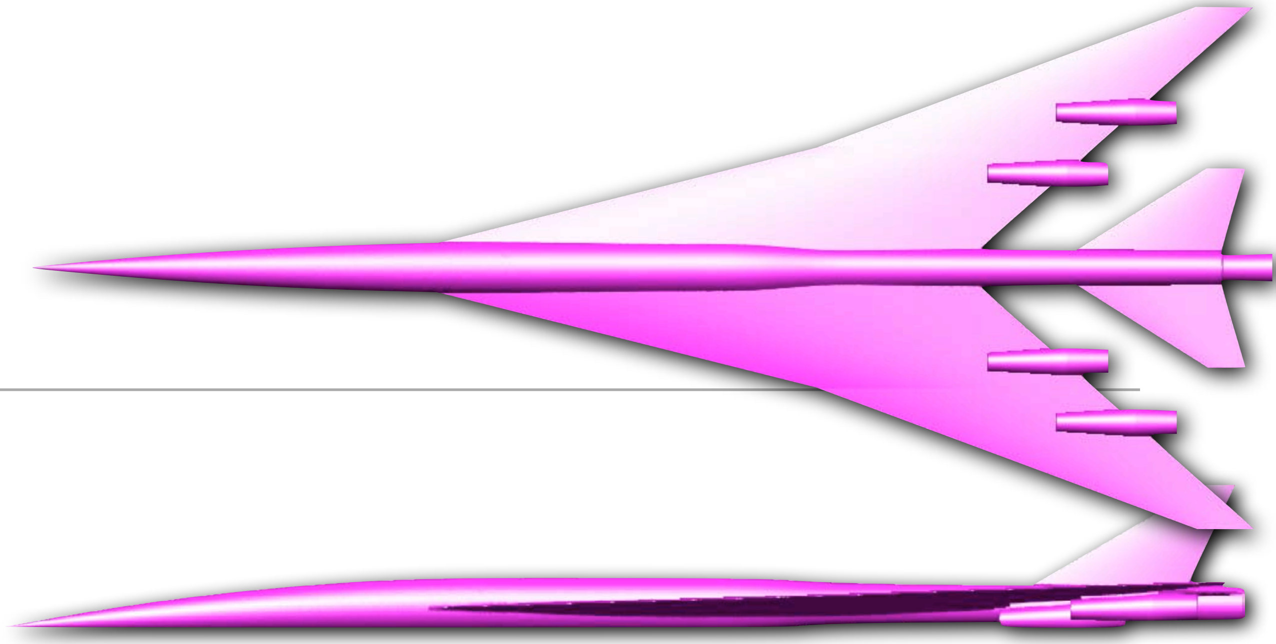
- NASA CP-1999-209699
  - $M_\infty = 2.0$
  - $\alpha = 2.0°$
  - Sensor offset, $h/L = 1.167$
- Initial mesh ~ 111 k cells



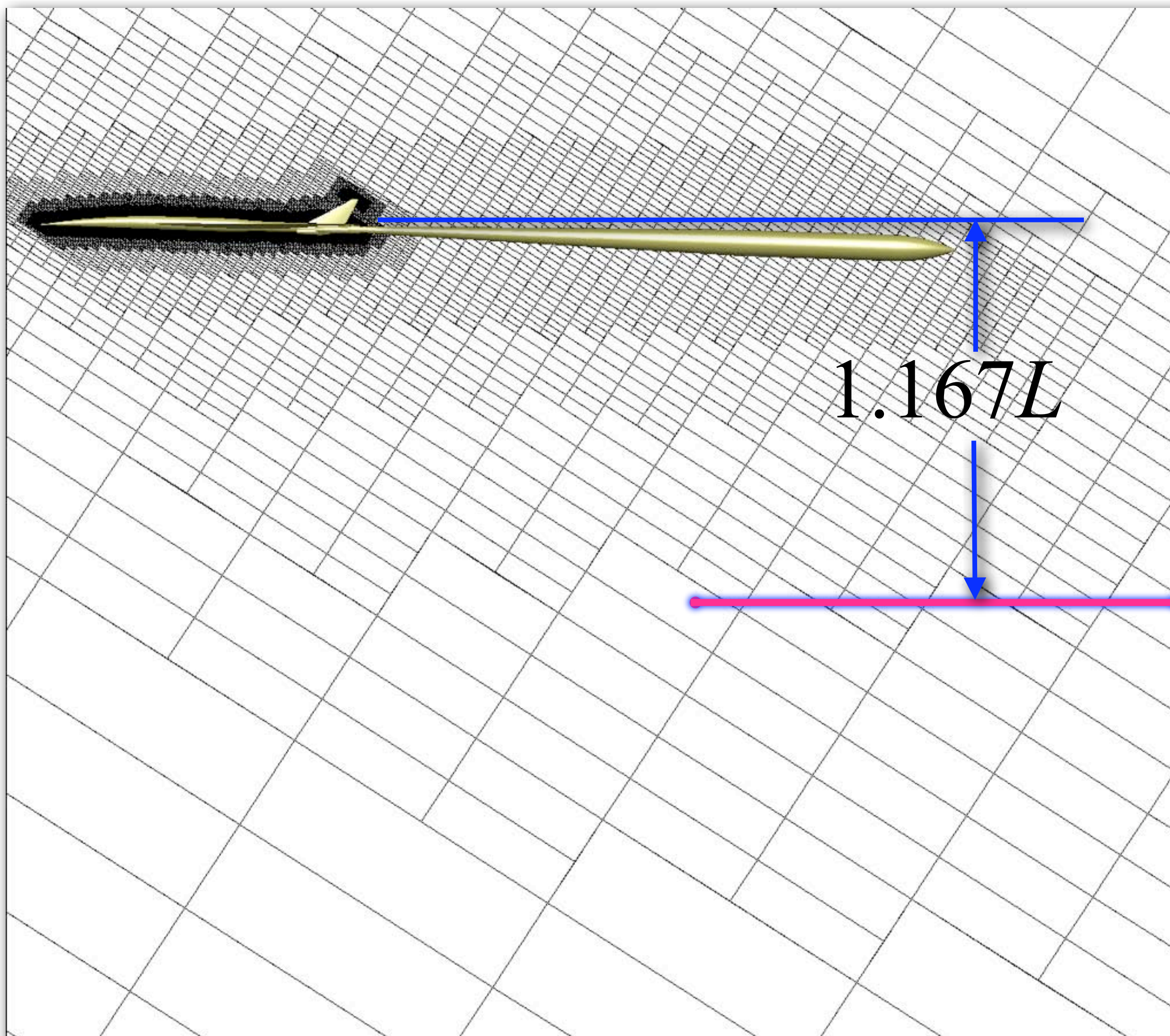


Stepped sting-body juncture

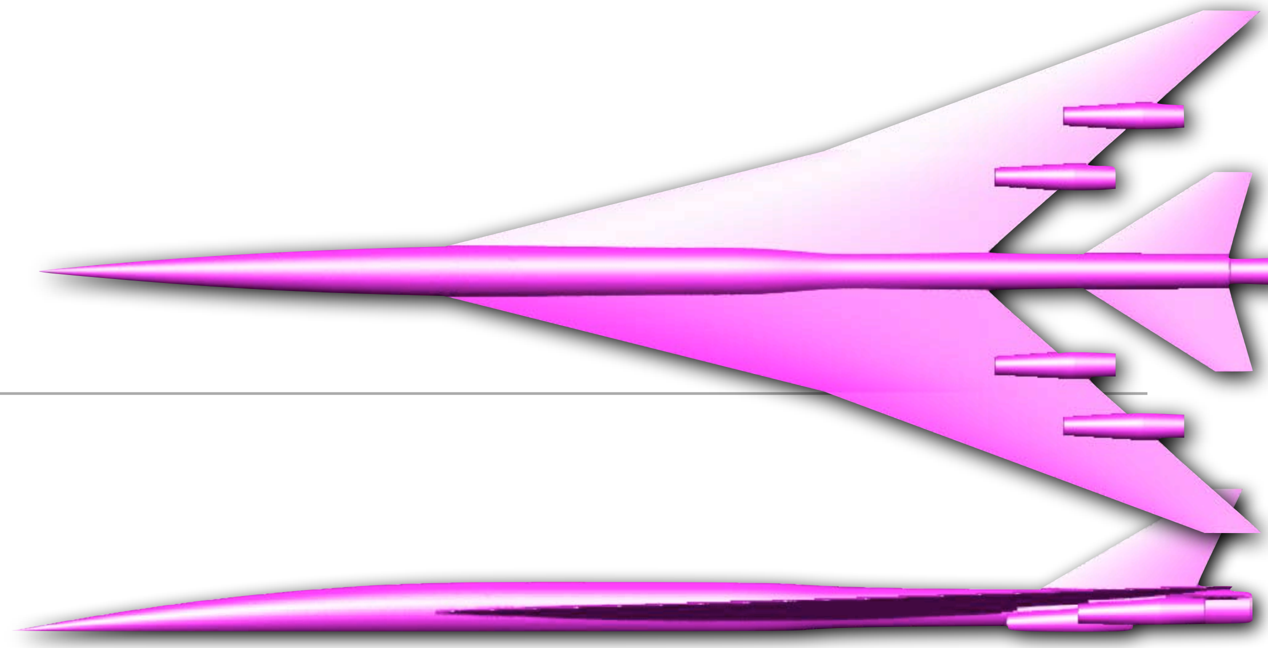
Ames Low-Boom Wing Tail



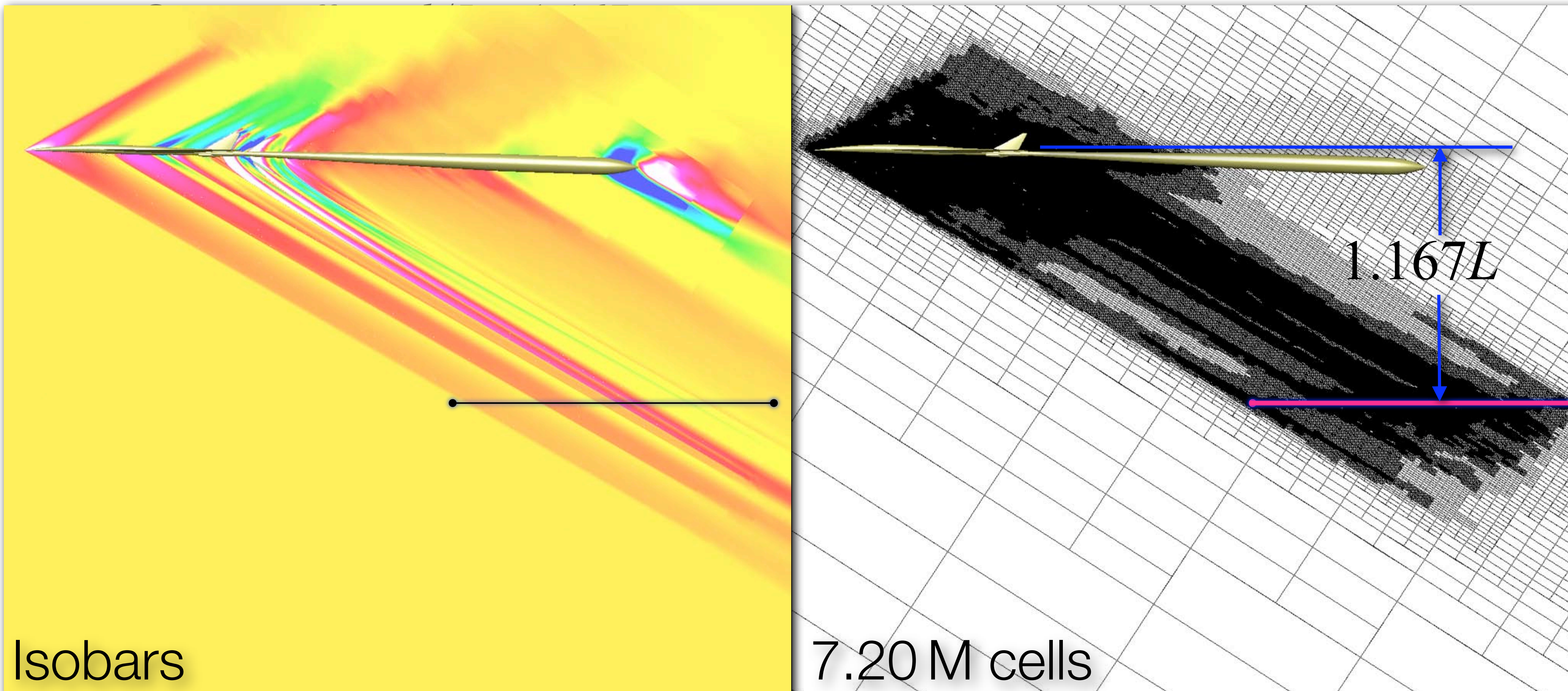
- NASA CP-1999-209699
  - $M_\infty = 2.0$
  - $\alpha = 2.0°$
  - Sensor offset, $h/L = 1.167$
- Initial mesh ~ 111 k cells



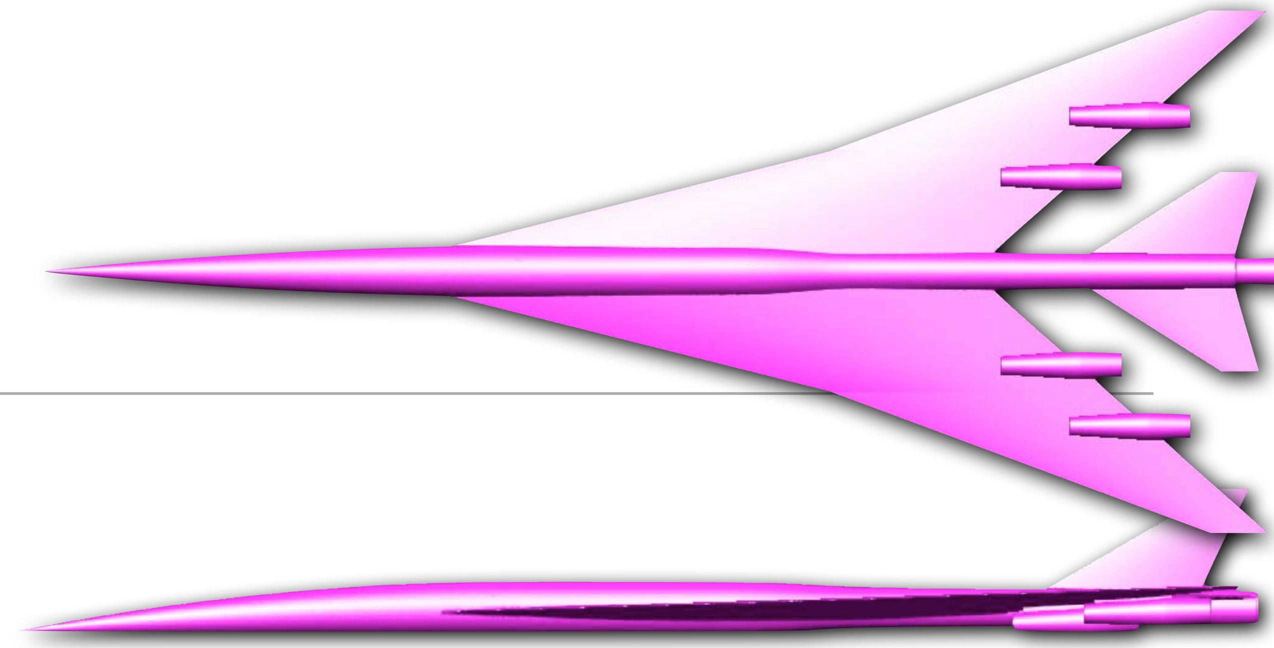
Ames Low-Boom Wing Tail



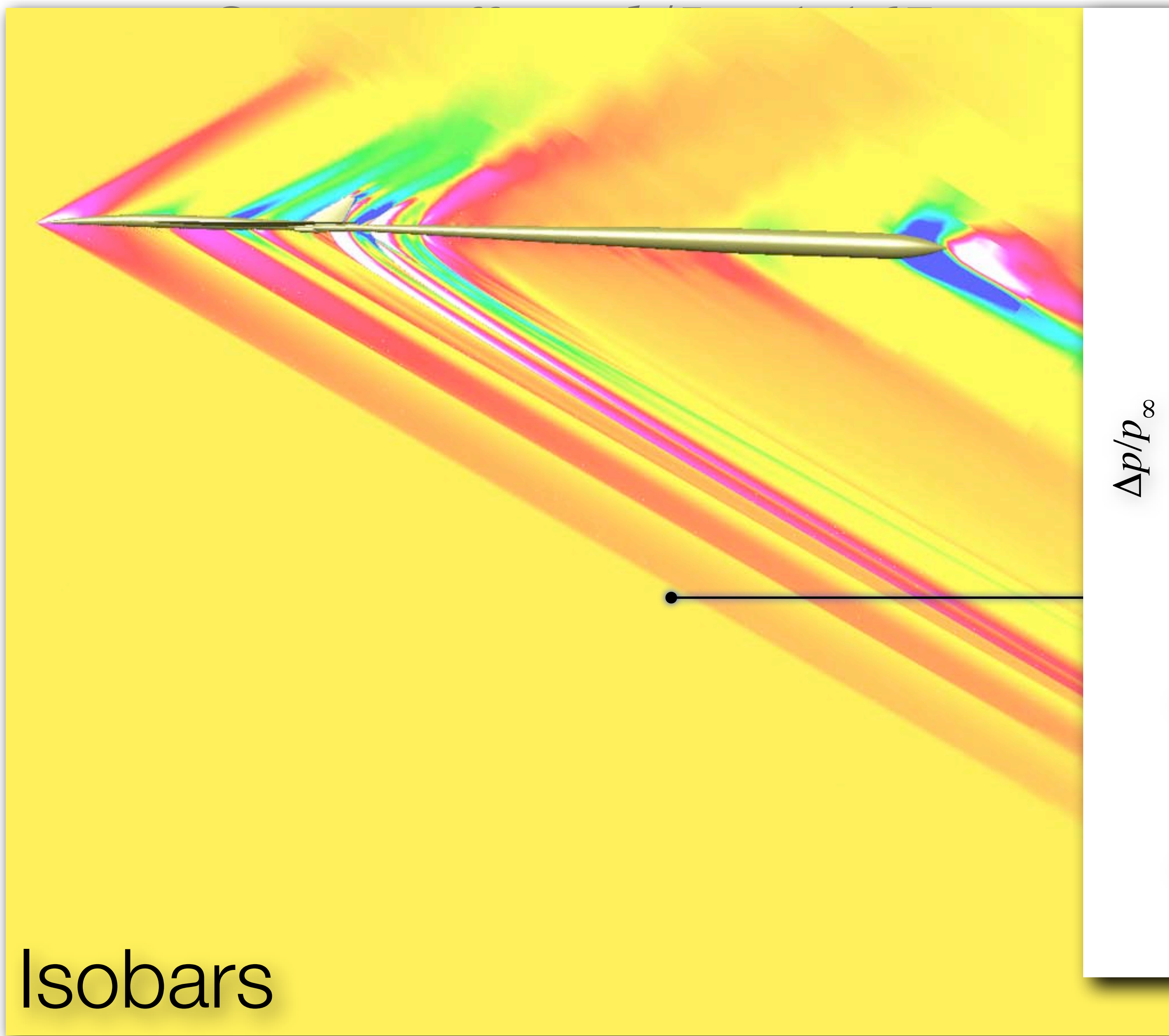
- NASA CP-1999-209699
  - $M_\infty = 2.0$
  - $\alpha = 2.0°$

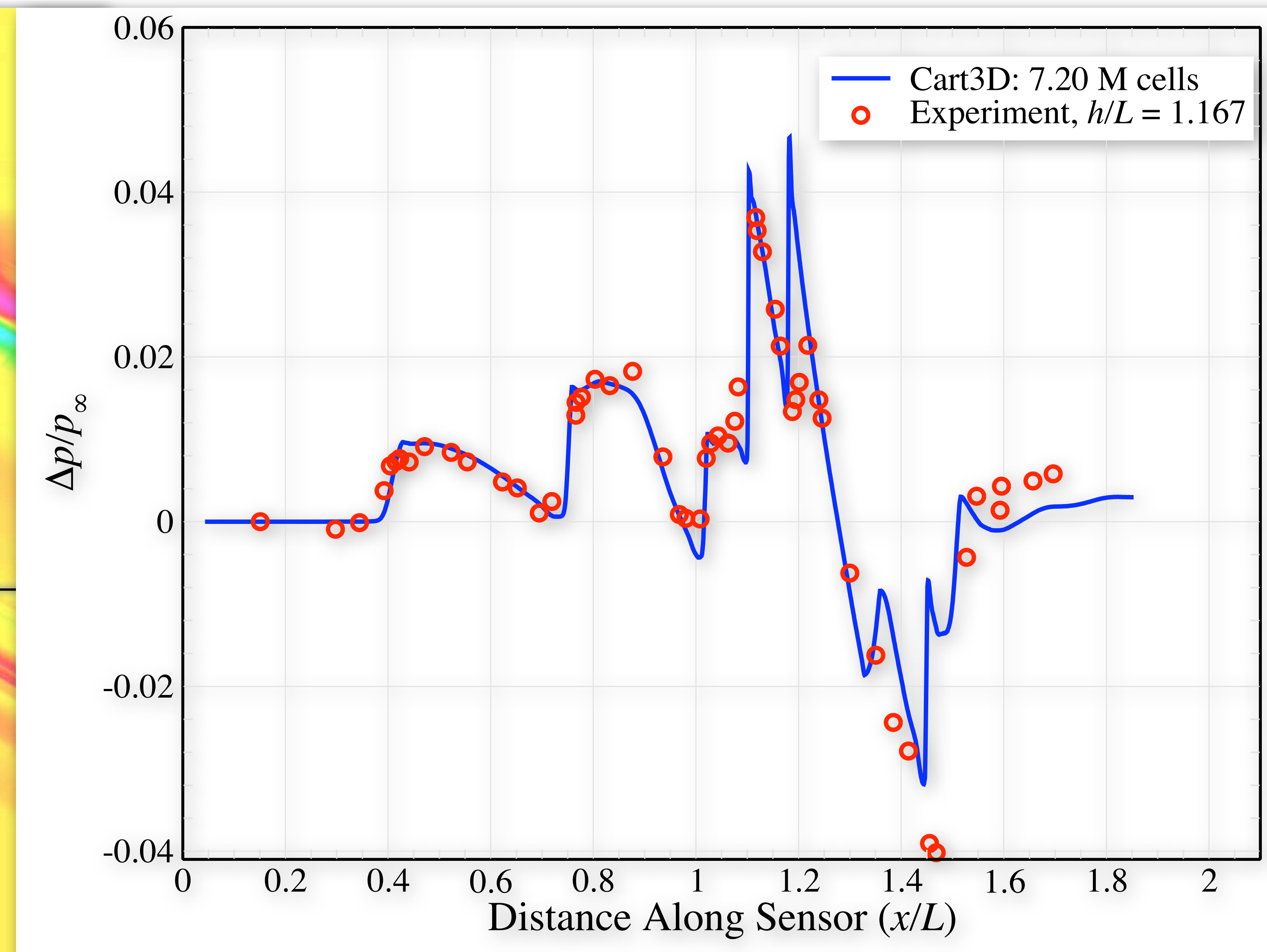


Ames Low-Boom Wing Tail

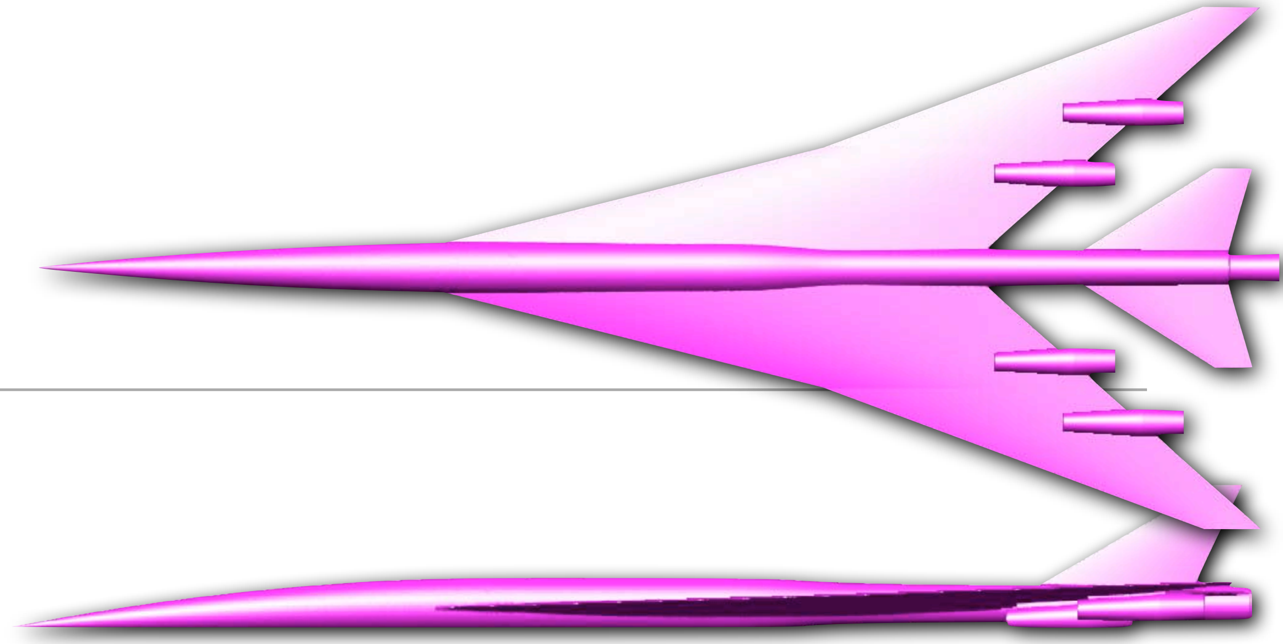


- NASA CP-1999-209699
  - $M_\infty = 2.0$
  - $\alpha = 2.0°$

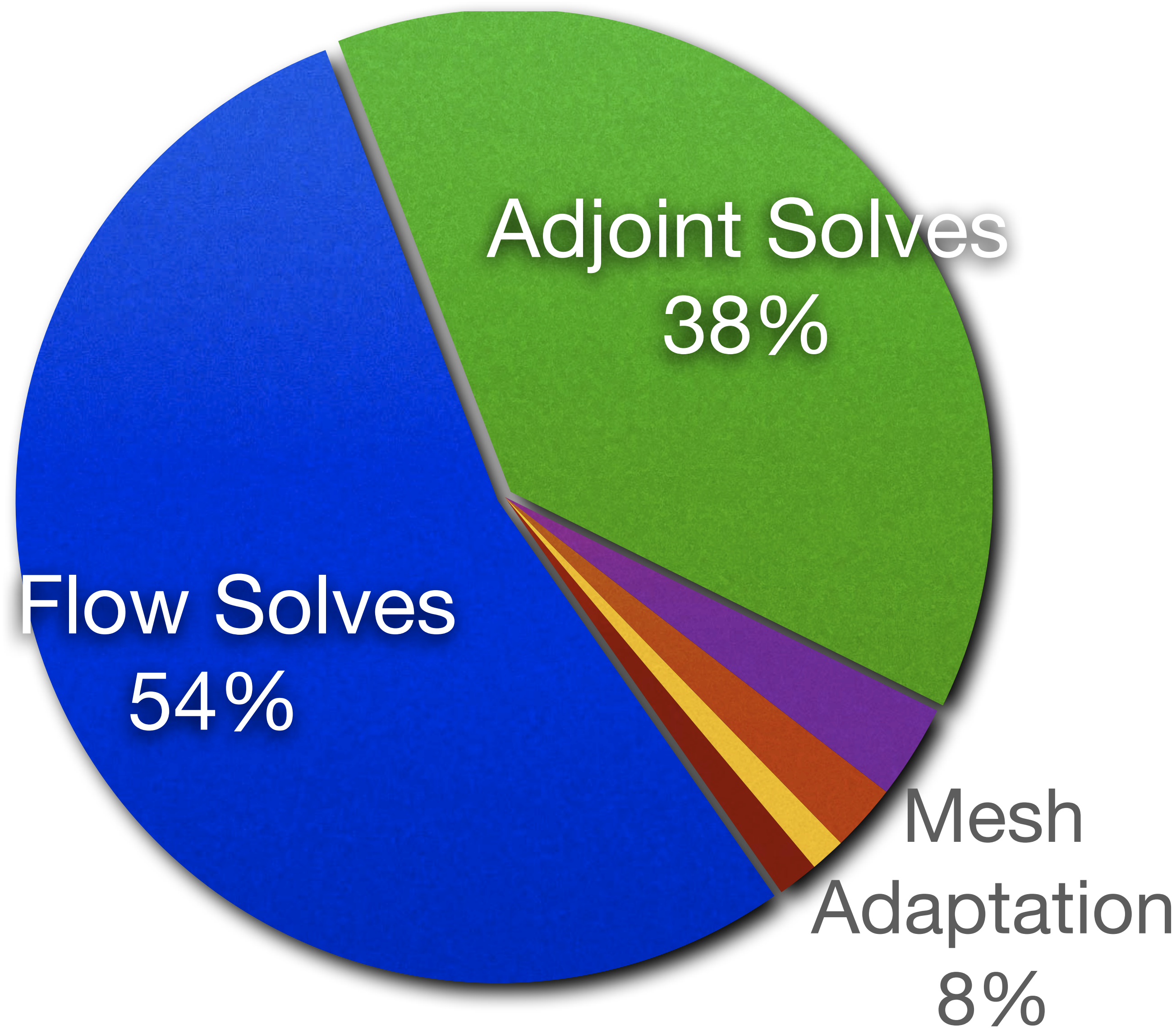




Ames Low-Boom Wing Tail



- NASA CP-1999-209699
  - $M_\infty = 2.0$
  - $\alpha = 2.0°$
  - Sensor offset, $h/L = 1.167$
- Simulation performed on desktop workstation
  - Dual quad-core (8 cores)
  - Intel Xeon, 3.2Ghz
  - 16 Gb memory
- Total simulation time 90 mins. (all adaptations & mesh gen)



Total = 90 mins.

Mesh Sizes and Computing Resources

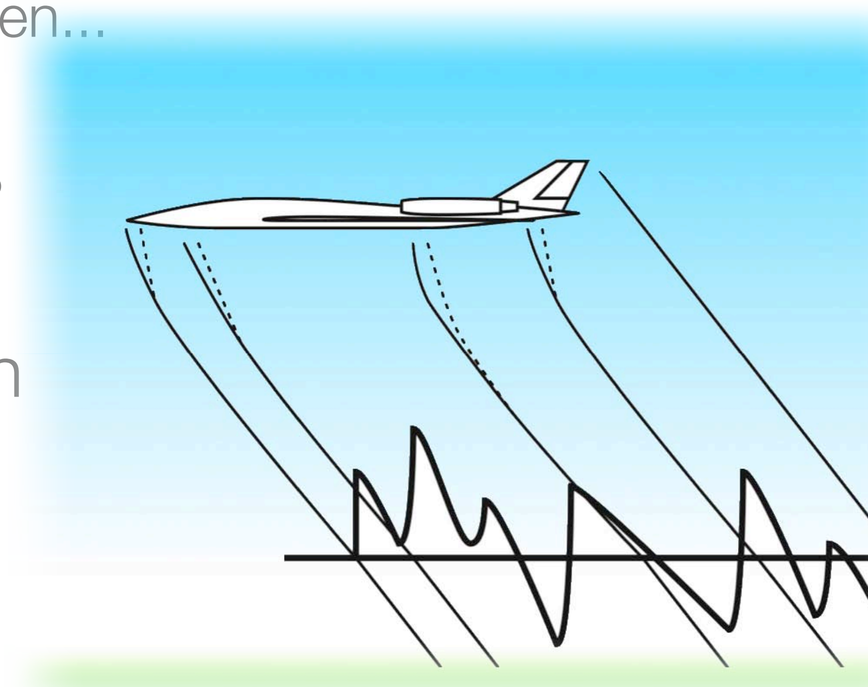
Configuration	Mach	AoA	*h*/*L*	Num. Control Volumes (on final mesh)	Net wallclock time (mins)[2]	Net CPU time (mins)
6.48° Cone-Cylinder NASA TM X-2219	1.68	0°	10	3.29×10^6	41 mins	328 mins
Parabolic Body of Revolution NASA TN D-3106	1.41	0°	10	3.58×10^6	75 mins	600 mins
Quartic Body of Revolution NASA TN D-3106	1.41	0°	10	3.98×10^6	83 mins	664 mins
69° Swept Delta Wing-Body NASA TN D-7160	1.68	4.74°	3.6 [1]	2.26×10^6	53 mins	424 mins
Ames Low Boom Wing Tail with Nacelles NASA CP-1999-209699	2.0	2.0°	1.167	7.20×10^6	90 mins	720 mins

[1] Delta wing body results at h/L = {0.2, 0.4, 0.8, 1.2, 2.0, 2.8, 3.6}, experimental data at h/L = 3.6 only

[2] All simulations on desktop workstation with dual quad-core (8 cores) Xeon processors, 16Gb memory

Summary and Future work

- Basic approach seems sound
  - Very good agreement with experiment for variety of geometry and conditions.
  - Robust and automatic, all cases same CFL, same limiter.
  - Reasonable turnaround time on commodity hardware.
  - 1-2 hrs on 8 cores for all workshop problems
  - Very economical! Workshop examples required from 2.3-7.2 M cells
  - Longer propagation distances and complex geometry easily within reach
- Best objective function?
  - Won't know until we start propagating signals to ground. Even then...
  - What are most important properties of near field signal?
  - What are acceptable boom profiles? dBA? Hardest on buildings?
- No issues outstanding before refocusing on propagation and shape design



Questions?