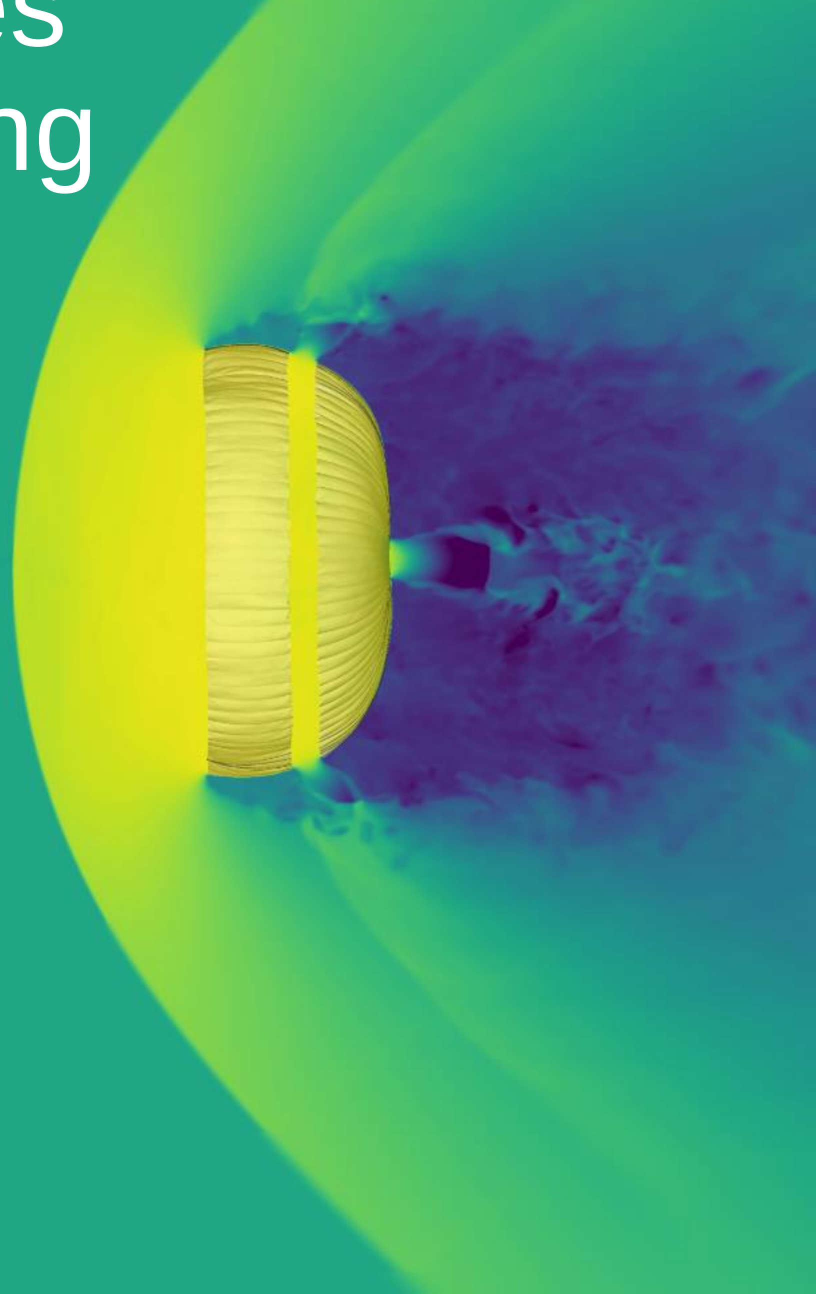
# Simulating Supersonic Parachutes For Mars Entry, Descent & Landing

NASA Langley/Ames EDL Seminar for Summer Interns
June 30, 2022




*Francois Cadieux*

*Jordan Angel*

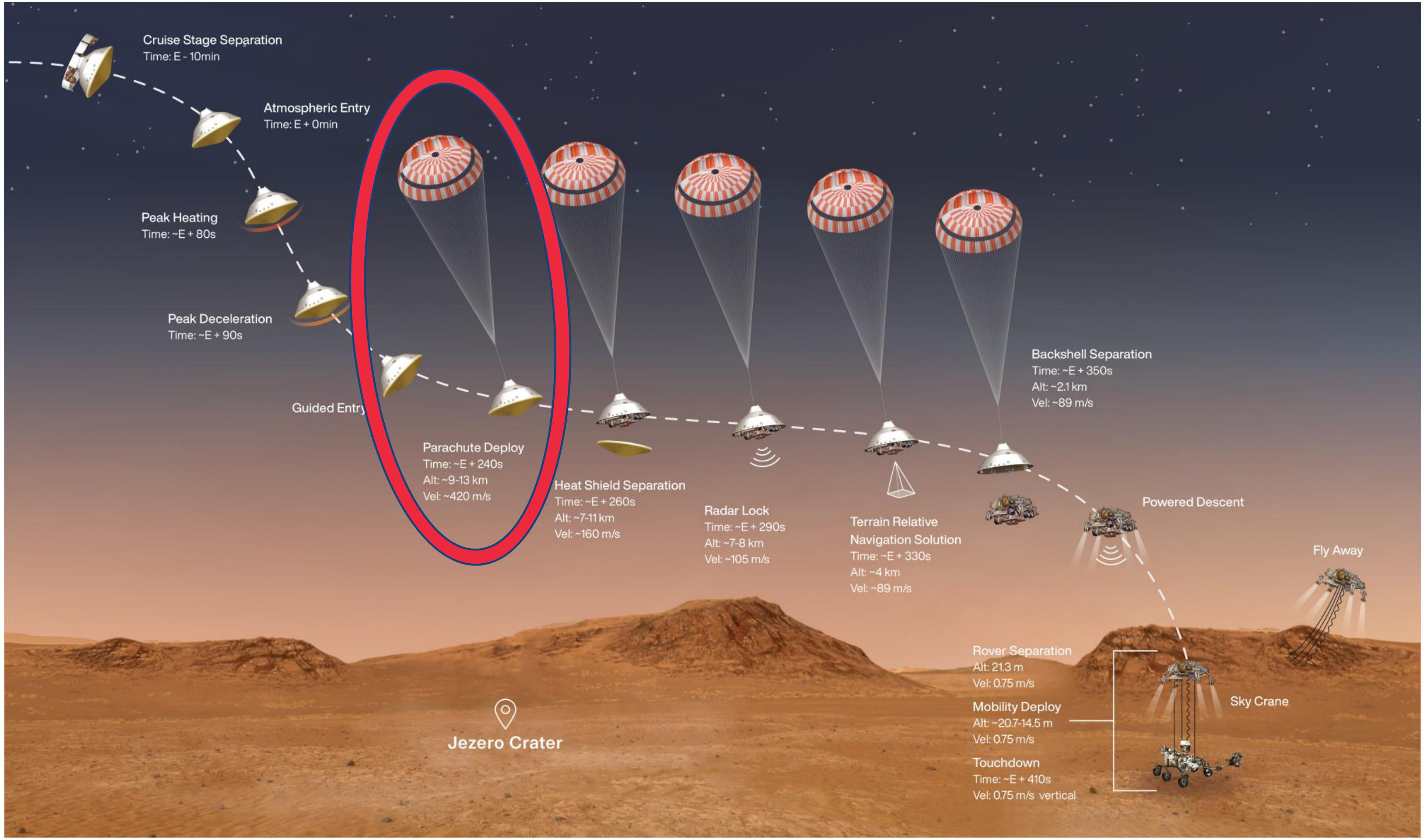
*Michael Barad*

*Cetin Kiris*

*with work done by Jonathan Boustani*

**POC: *cetin.c.kiris@nasa.gov***

# Context: Perseverance Rover's EDL Profile



# Motivation: Low Density Supersonic Decelerator

NASA JPL: https://youtu.be/9yRWhu0UGYw?t=74

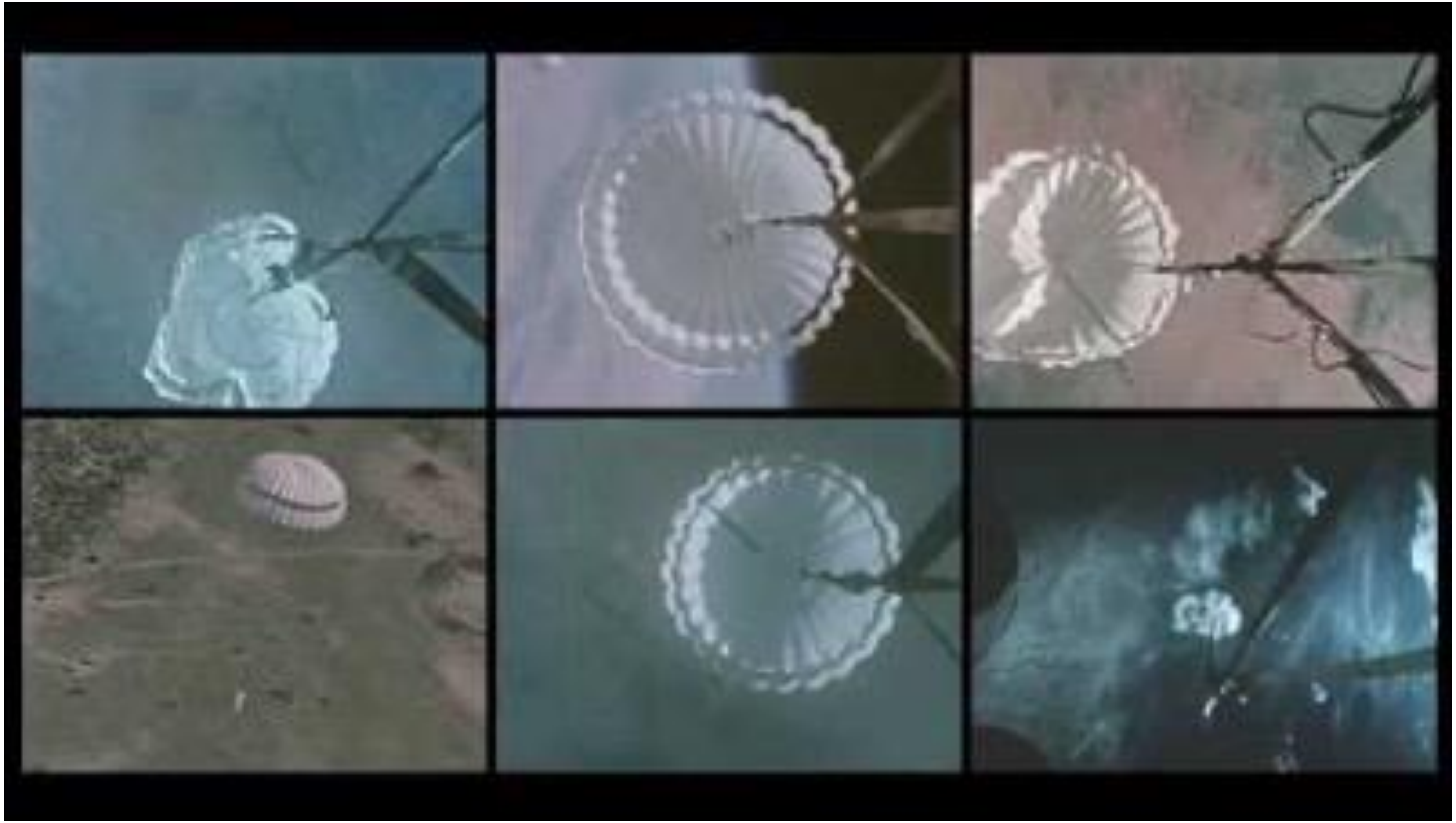
# Motivation: Low Density Supersonic Decelerator

- Low density supersonic decelerator (LDSD) project aimed to test two novel technologies:
  - an inflatable decelerator
  - *a new Disksail parachute design* [1]
- Disksail parachute showed signs of damage early on during its inflation and ultimately was ripped apart
- Cause of failure still poorly understood today
- Leading hypothesis is that the new Disksail design itself caused more severe stresses than seen in previous disk-gap-band (DGB) parachutes [2]:
  - its larger shoulder region may have pulled the disk portion of the canopy flat earlier in the inflation process, causing the fabric to tear under the increased load

*(NASA/JPL)*

[1] Gallon, J., Witkowski, A., Clark, I. G., Rivellini, T., and Adams, D. S., “Low density supersonic decelerator parachute decelerator system,” AIAA Aerodynamic Decelerator Systems (ADS) Conference, 2013, p. 1329
[2] Clark, I. G., Gallon, J. C., and Witkowski, A., “Parachute Decelerator System Performance During the Low Density Supersonic Decelerator Program’s First Supersonic Flight Dynamics Test,” 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, 2015, p. 2130

# ASPIRE: Testing a Parachute for Mars



NASA JPL: https://youtu.be/AcAgnQ9K7UY

# Problem Description

**LDSD Parachute Failure**

- LDSD project demonstrated that NASA & JPL could not predict the failure of a new parachute system design, or establish with confidence the cause of failure after the fact

**ASPIRE:**

**3 Successful Tests**

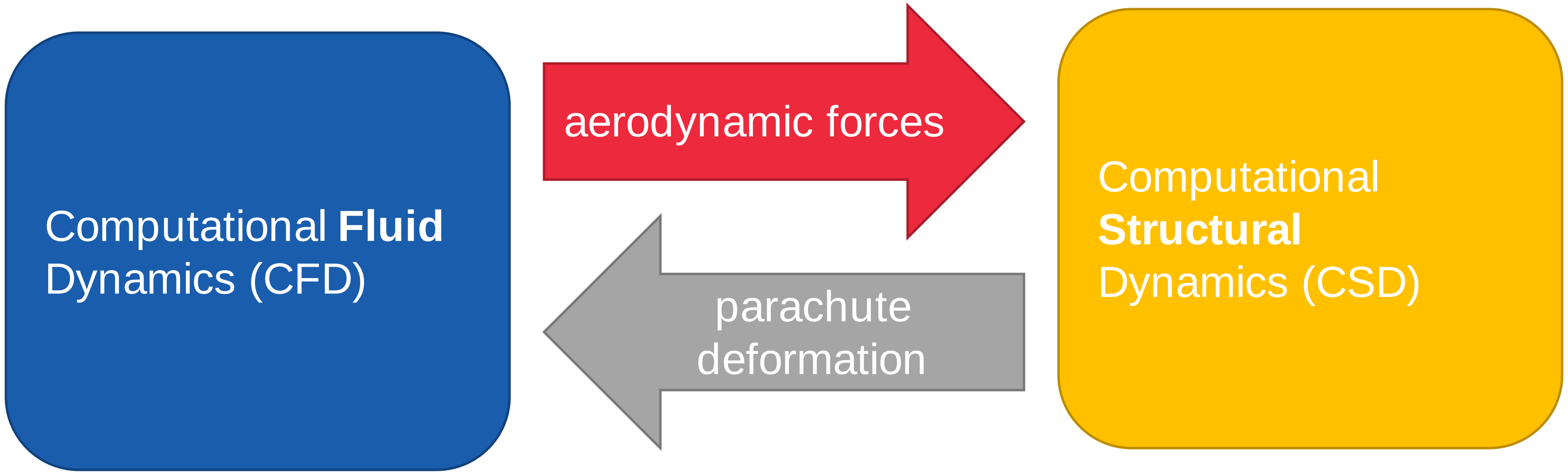
- The Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) tested parachutes intended for Mars landings (e.g. Perseverance) in supersonic conditions in the upper earth atmosphere

**Fluid-Structure Interaction (FSI) Simulations**

- FSI simulations could provide insight at much lower cost and eventually provide stress predictions across parachute system

# Research Objectives

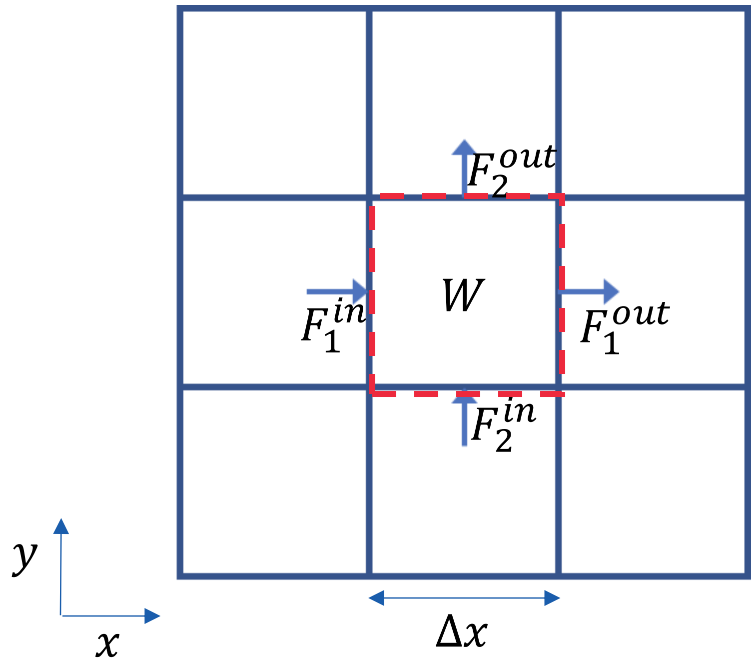
- Develop FSI capability to simulate supersonic parachute inflation




- Validate FSI predictions with ASPIRE test measurements
- Leverage FSI capability to help in design of next generation of parachutes using best practices established for ASPIRE

# Quick Overview of Unsteady CFD

- Advance conservation of mass, momentum, and energy equations for a gas using fluxes through faces of a control volume (dashed red square) in time from $t \rightarrow t + \Delta t$ given initial and boundary conditions:




$$\frac{\partial W}{\partial t} = -\frac{\partial F_j}{\partial x_j} \qquad W = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{bmatrix} \qquad F_j = \begin{bmatrix} \rho u_j \\ \rho u_1 u_j + p\delta_{1j} \\ \rho u_2 u_j + p\delta_{2j} \\ (\rho E + p) u_j \end{bmatrix}^*$$

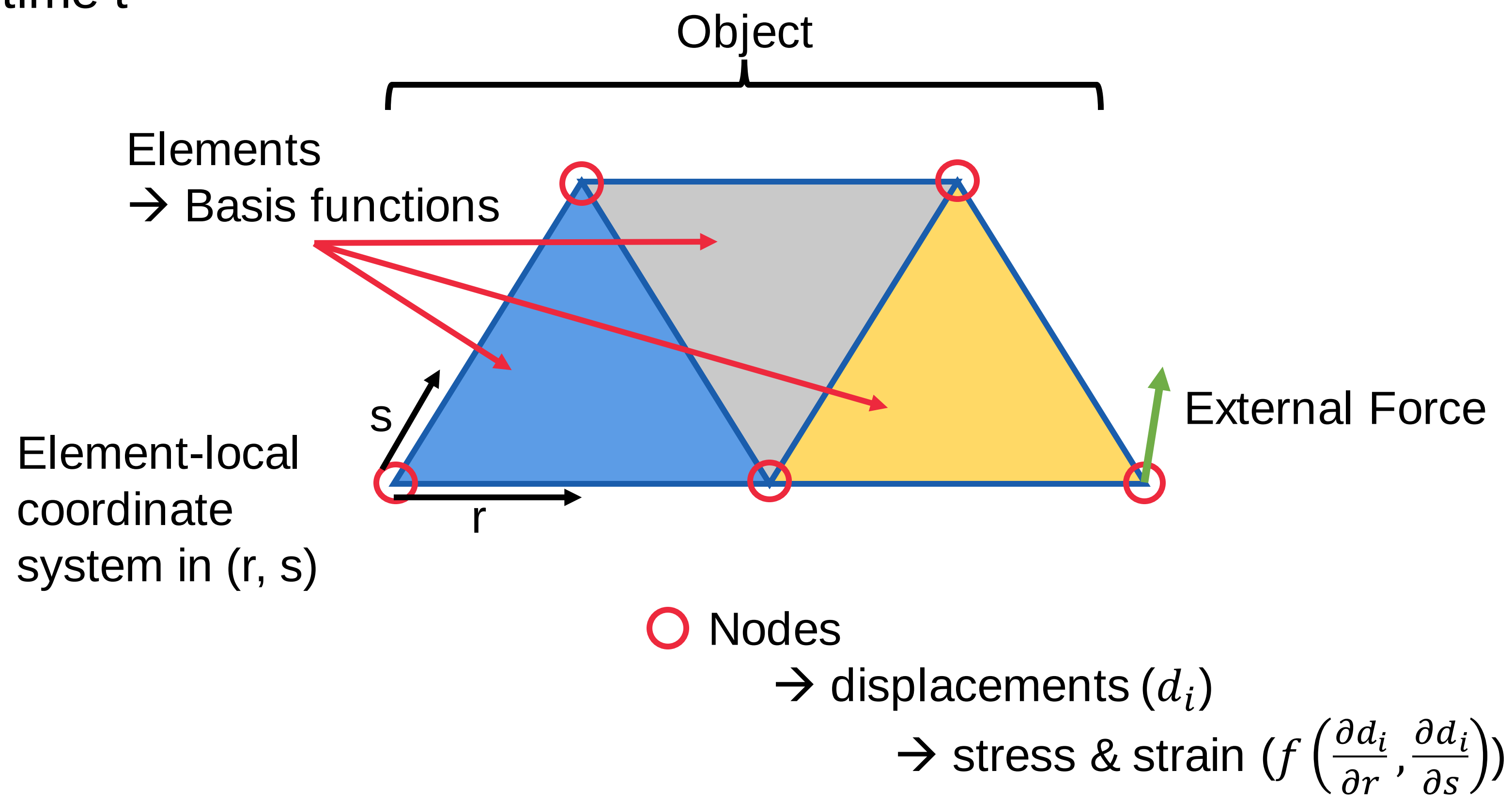
$W$: vector of conserved variables
$F_j$: flux in j direction
$\rho$ : density
$u$ : velocity in x direction
$v$ : velocity in y direction
$E$ : total energy
$p$ : pressure
$T$ : temperature
$R$ : gas constant
$c_v$ : specific heat at constant volume

$$p = \rho R T$$
$$E = c_v T + \frac{1}{2} u_i u_i$$

*Viscous fluxes are neglected for simplicity

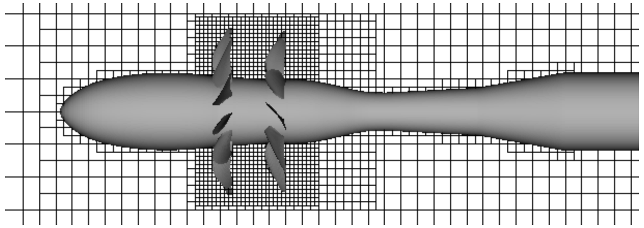
# Quick Overview of Unsteady CSD

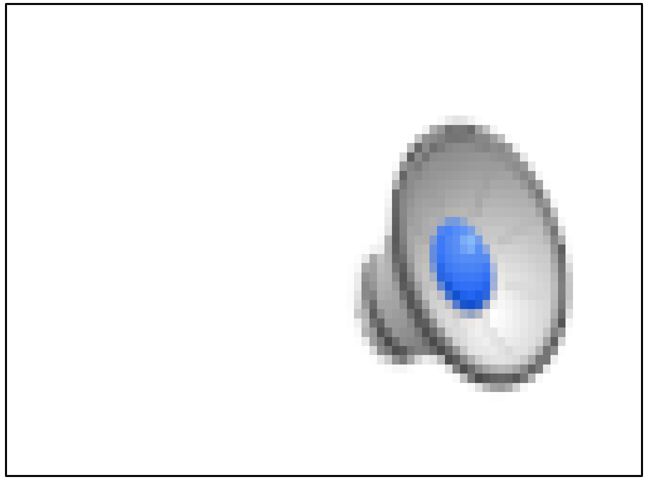
- Solve the equations of motion of nodes shared across finite elements (e.g. triangles) on an object for their displacements ($d_i$) to reach equilibrium between external forces and internal stresses (functions of gradients of d) at time t + Δt
- Given the object's material properties (e.g. thickness, density, Young's modulus, Poisson ratio) initial conditions, boundary conditions, and external forces acting on the nodes at time t



# Choosing a CFD Grid Paradigm

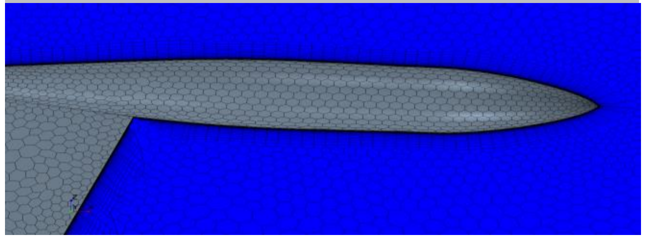
***Structured Cartesian AMR***

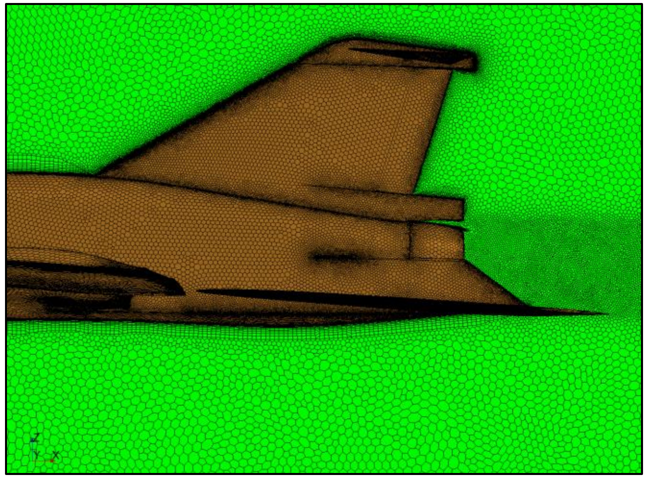




- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted → Resolution of boundary layers challenging

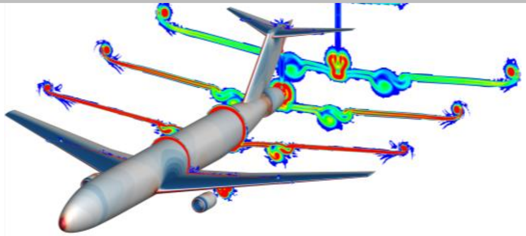
***Unstructured Arbitrary Polyhedral***

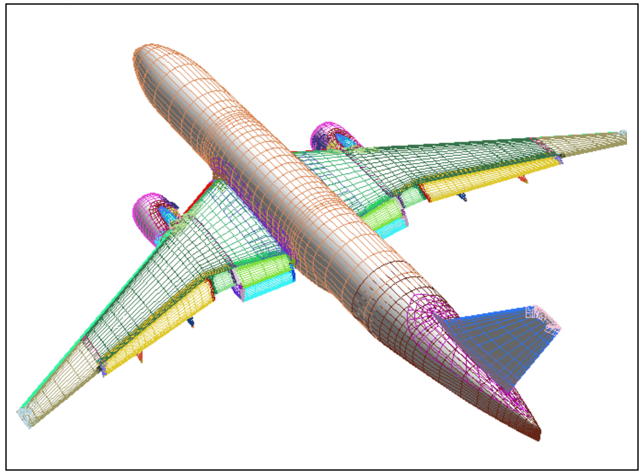




- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

***Structured Curvilinear***

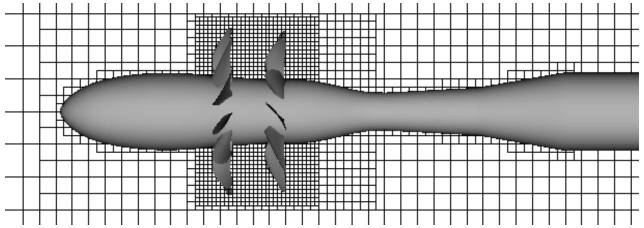


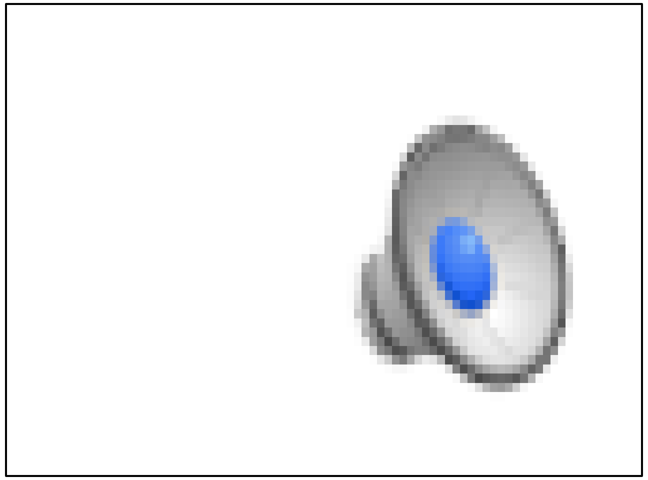


- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

# Choosing a CFD Grid Paradigm

***Structured Cartesian AMR***





- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted → Resolution of boundary layers challenging

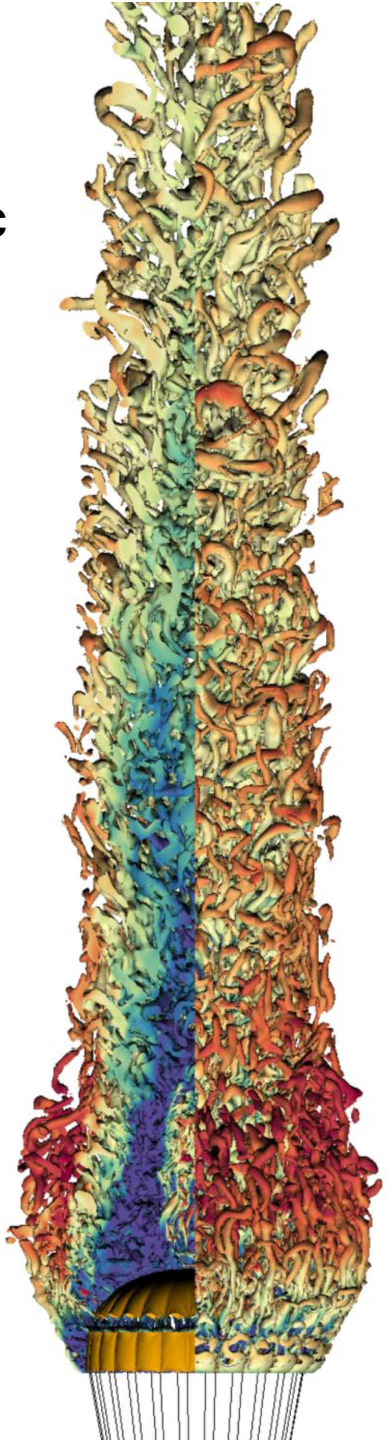
**Requirements for Simulating Supersonic Parachute Inflation Process:**

✓ Simulate inherently transient phenomenon in a time-accurate fashion efficiently

✓ Resolve moving bow shocks, payload and canopy wake

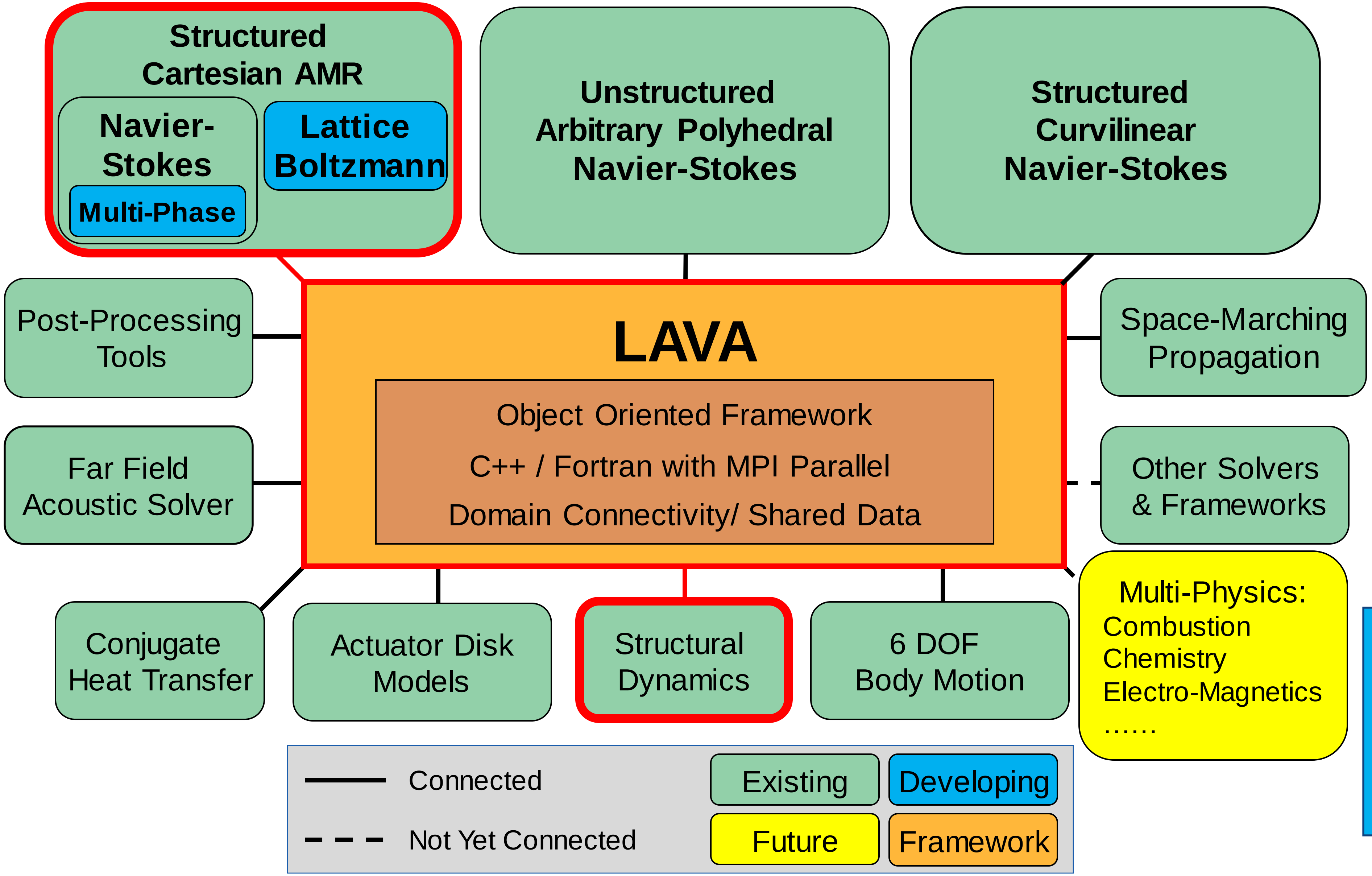
✓ Adapt grid to large deformations of parachute during inflation

✓ Thin attached boundary layers do not play a critical role in determining the inflation dynamics of the parachute: it is driven by ram drag, not viscous drag



*Isocontours of Q-criterion colored by Mach number where blue is lower and red is higher.*

# Launch, Ascent and Vehicle Aerodynamics

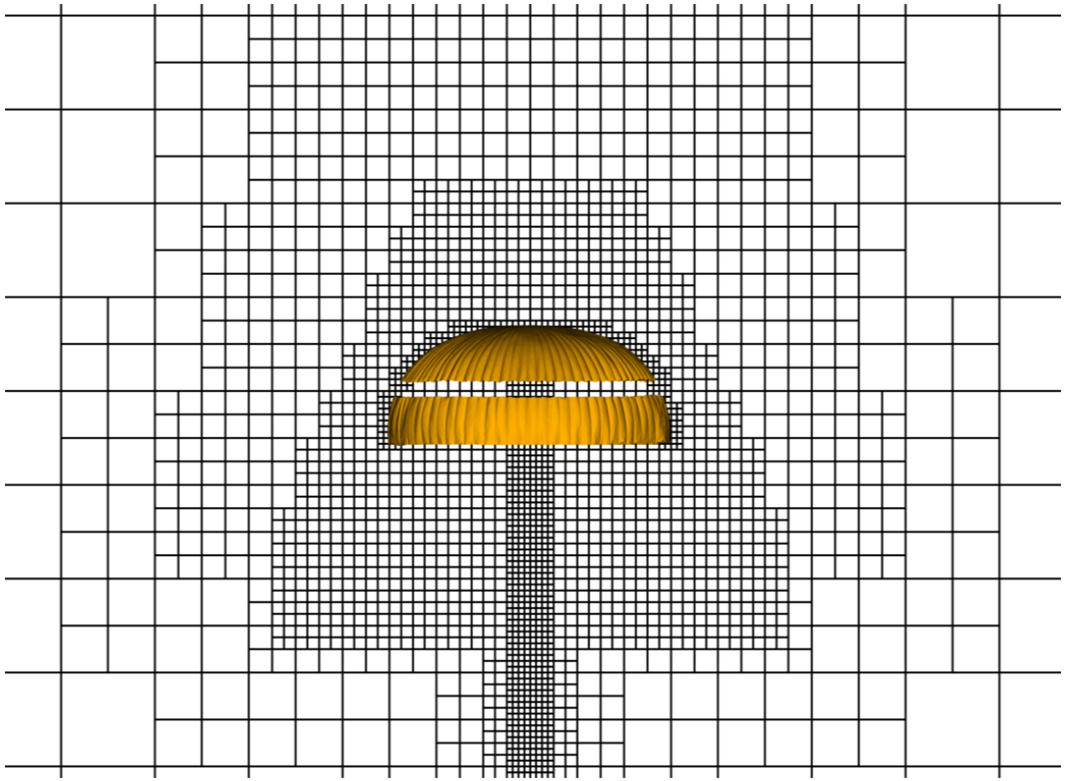



*Kiris at al. AIAA-2014-0070 & AST-2016*

***Other Development Efforts***
- Higher order and low dissipation
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)

# CFD Approach For Supersonic Parachute

- Automatically generate octree mesh based on limited user inputs
- Automatically adapt mesh to follow parachute surface as it deforms
- Enforce specific porosity of parachute fabric on oncoming flow with immersed boundary ghost-cell method
- Use explicit Runge-Kutta time integration
- Solve Euler equations with nominally fifth-order accurate shock capturing algorithm (weighted essentially non-oscillatory or WENO)



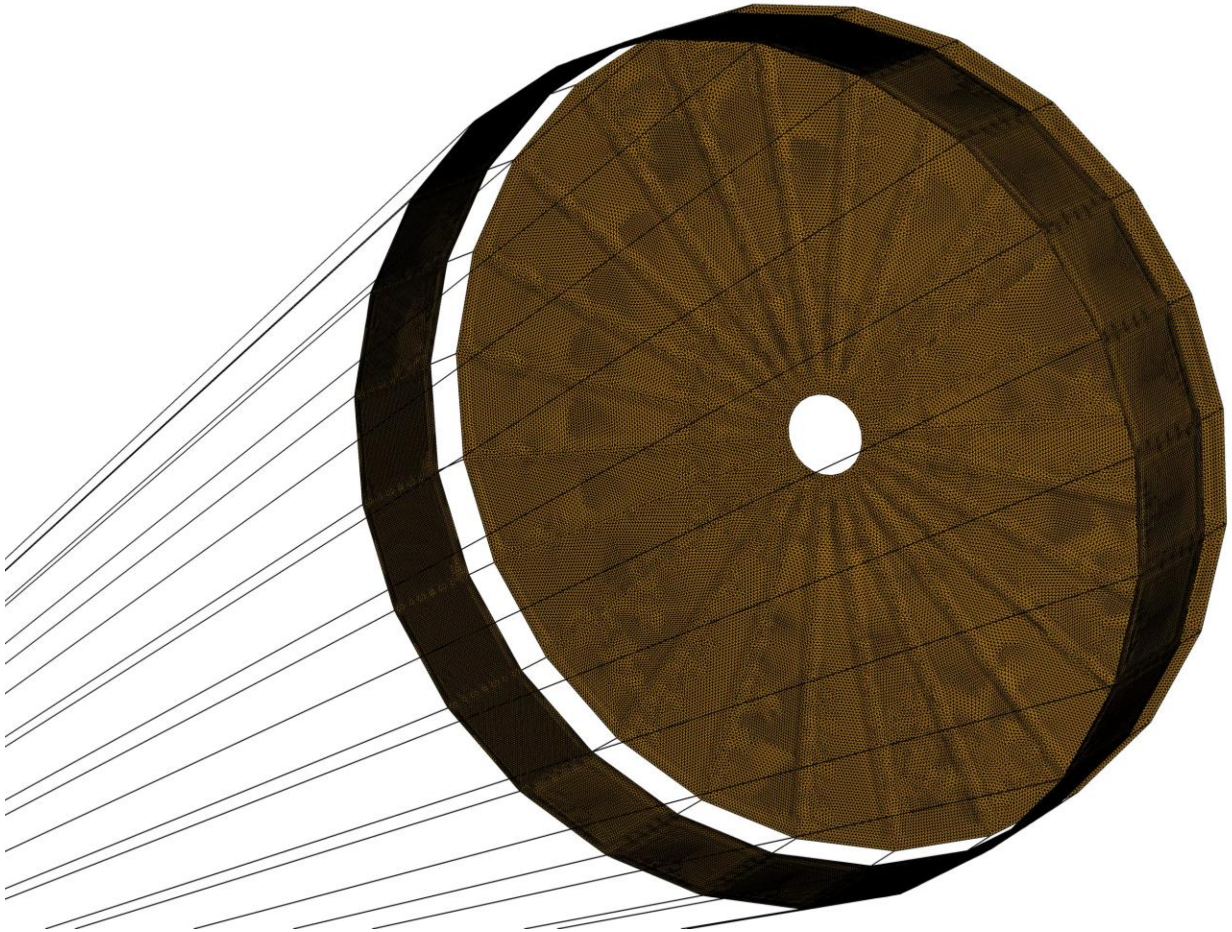
*Slice of a general Cartesian block structure around an inflated parachute geometry. Each block represents 16x16x16 grid points.*

For more details, please refer to [3]:

[3] Boustani, J., Cadieux, F., Kenway, G. K., Barad, M. F., Kiris, C. C., and Brehm, C., "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test," Aerospace Science and Technology, 2022, p. 107596

# CSD Approach For Supersonic Parachute

- Use geometrically non-linear finite elements with Saint Venant-Kirchhoff hyper-elastic material model to handle parachute’s large deformations
- Integrate equations in time using explicit second-order central scheme with high-frequency damping
- Leverage extended MITC3 triangular shell elements with 6 degrees of freedom (DOF) to alleviate shear-locking to model parachute fabric
- Model the suspension lines with Timoshenko beam elements with 6 DOF modified to allow for slack (“can’t push on a rope”)

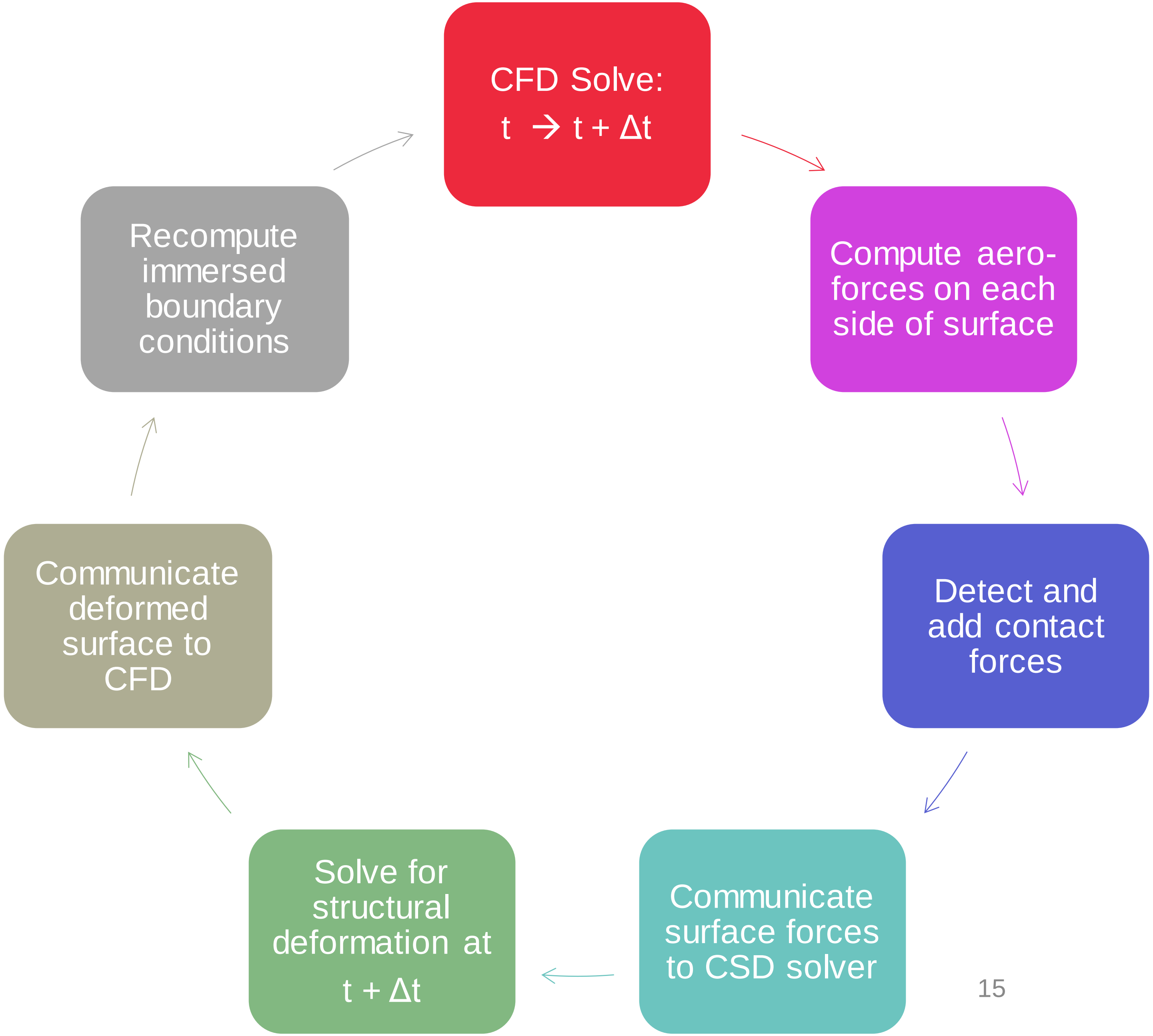


*Animation showing parachute structural mesh as it is deformed by a uniform outward pressure in a structural dynamics simulation (decoupled from CFD).*


For more details, please refer to [3] and [4]:
[3] Boustani, J., Cadieux, F., Kenway, G. K., Barad, M. F., Kiris, C. C., and Brehm, C., “Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test,” Aerospace Science and Technology, 2022, p. 107596
[4] Boustani, Jonathan, et al. "Fluid-structure interactions with geometrically nonlinear deformations." *AIAA Scitech 2019 Forum*. 2019

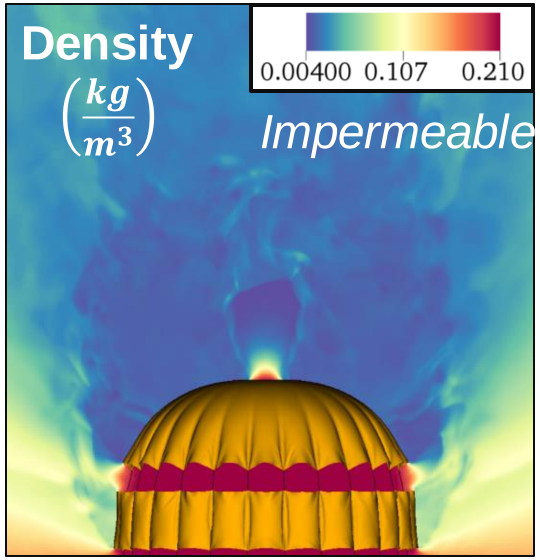
# CFD + CSD Coupling Approach

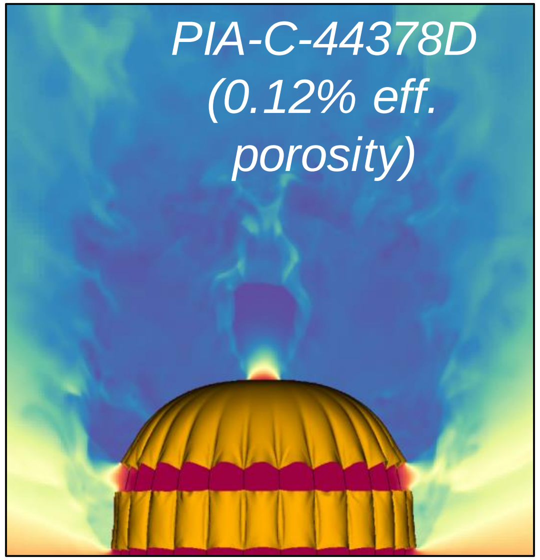
- Loose-coupling approach
- CFD time advancement limited by Courant–Friedrichs–Lewy (CFL<1) condition
- CSD time advancement is sub-cycled with a smaller Δt to satisfy critical time step if necessary

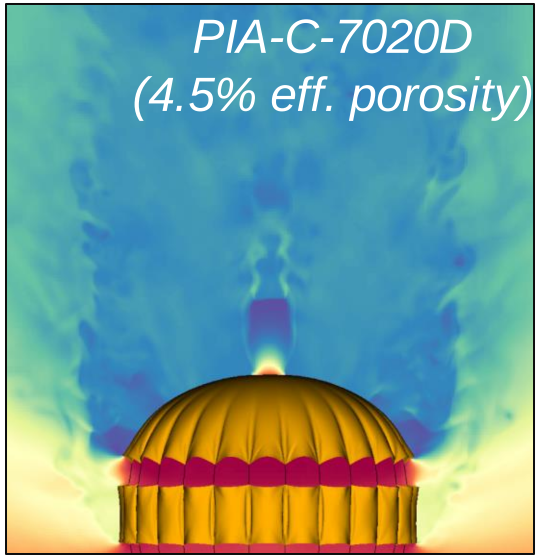


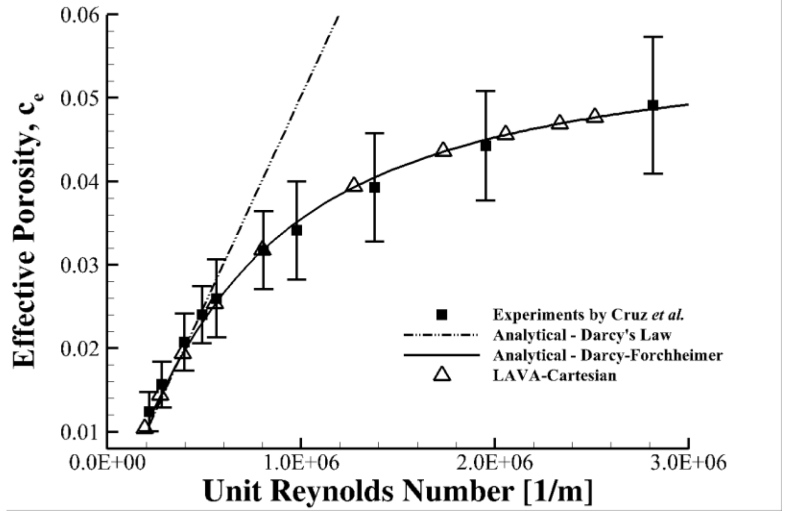
# Modeling Parachute Broadcloth Porosity

- Obtain closed-form solution to Darcy-Forchheimer momentum equation through porous material ($7.62 \times 10^{-6}$m thickness)
- Apply solution as a jump conditions in CFD to avoid requirement to resolve flow through the parachute's woven fibers (e.g. typical source term models)



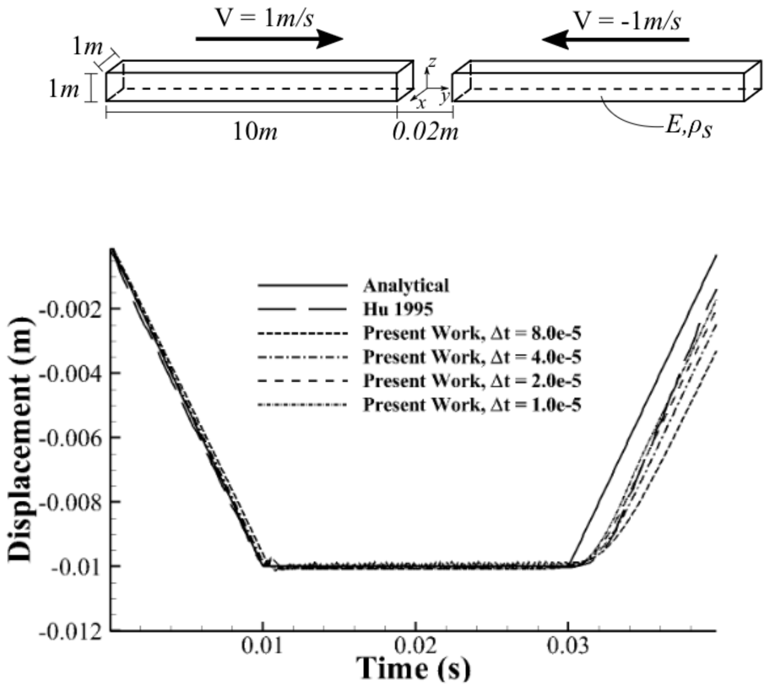

*Comparison of results from experiments by Cruz et al. and simulations by LAVA-Cartesian for PIA-C-7020D Type I broadcloth.*

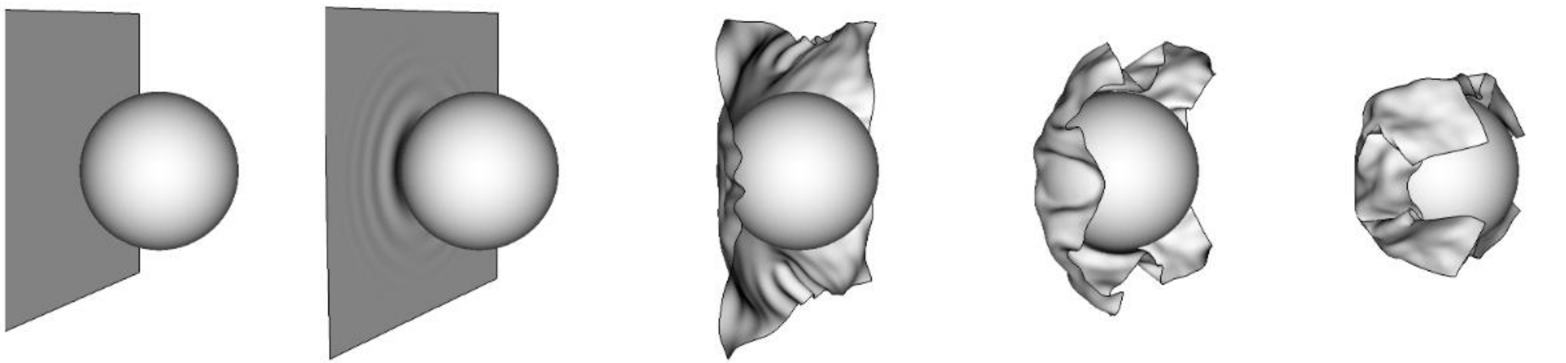
- Higher porosity → weaker recirculation → more stable dynamics

# Identifying and Enforcing Contact Mechanics

- Before communicating aerodynamic forces to structural dynamics, identify triangles on surface who could soon come into contact by checking if ray traced from one triangle face pierces another within a given distance
- If a pair of triangles have velocities that will close the gap between them and cause contact to occur, we add a momentum force that models an elastic collision: this allows contact without surface (self-) intersections

*Setup and results from a canonical 1D contact problem*



*Snapshots in time of a test case demonstrating the contact identification and enforcement method*

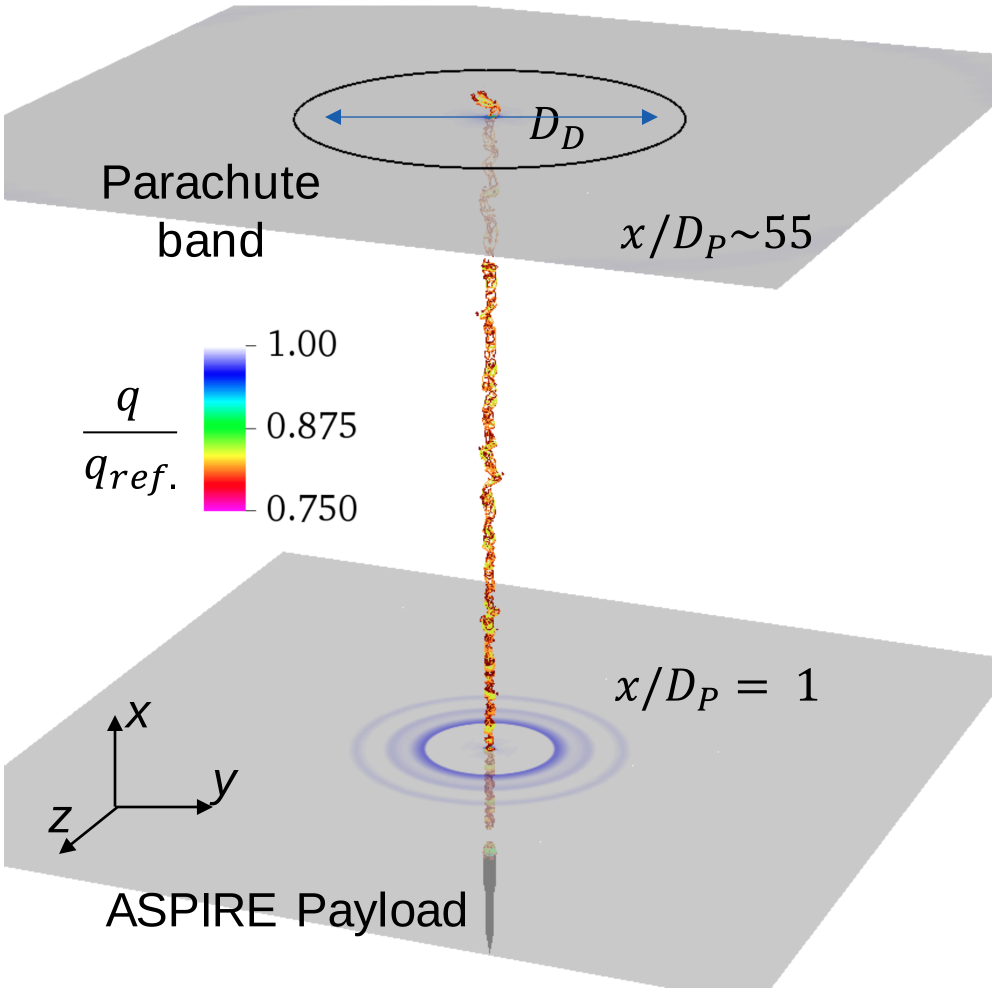
# Contact Demonstration For Parachute Inflation

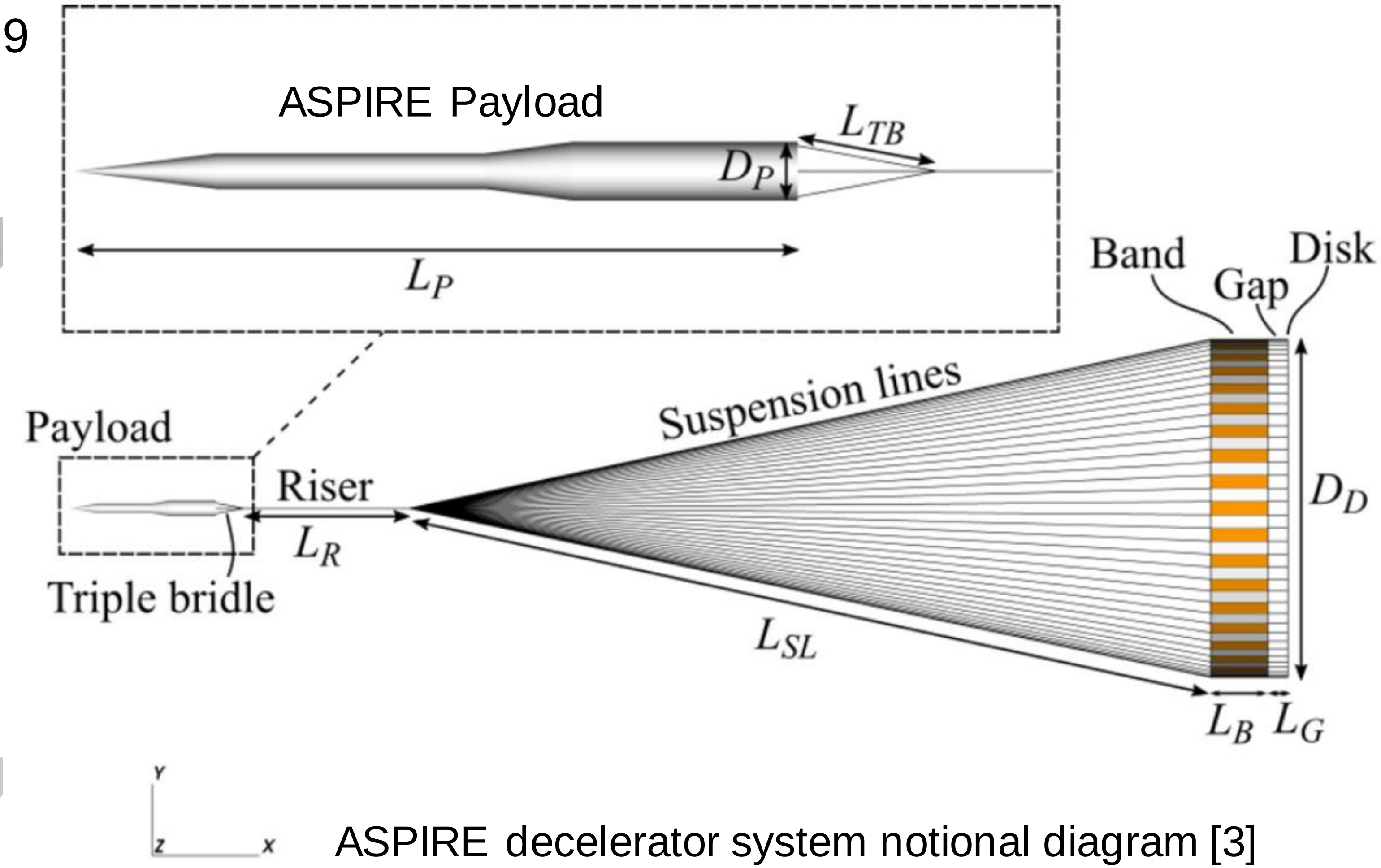
It’s not yet computational tractable to simulate the ASPIRE parachute as it rips out from its bag, so we start from a folded shape with 40% of its flat diameter, in which the 80 gores and 40 suspension lines are arranged like an accordion in 40 peaks and valleys

*Animation showing parachute inflation from a structural-only simulation to evaluate the contact identification and enforcement algorithm. The CSD solver is exposed to a constant surface normal force.*

# ASPIRE Payload Wake

- ASPIRE tests used a slender payload instead of blunt aero-shell like that of Mars 2020
- Freestream Mach number ~ 1.79



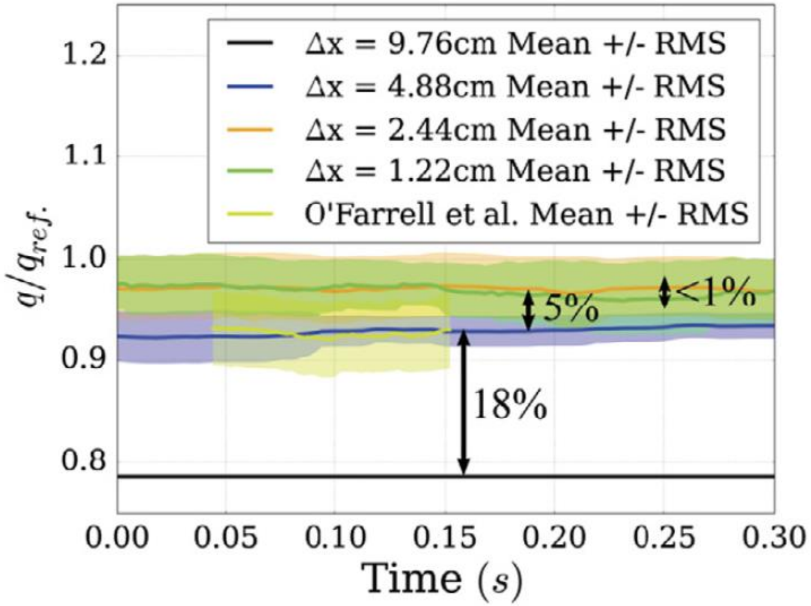




ASPIRE decelerator system notional diagram [3]

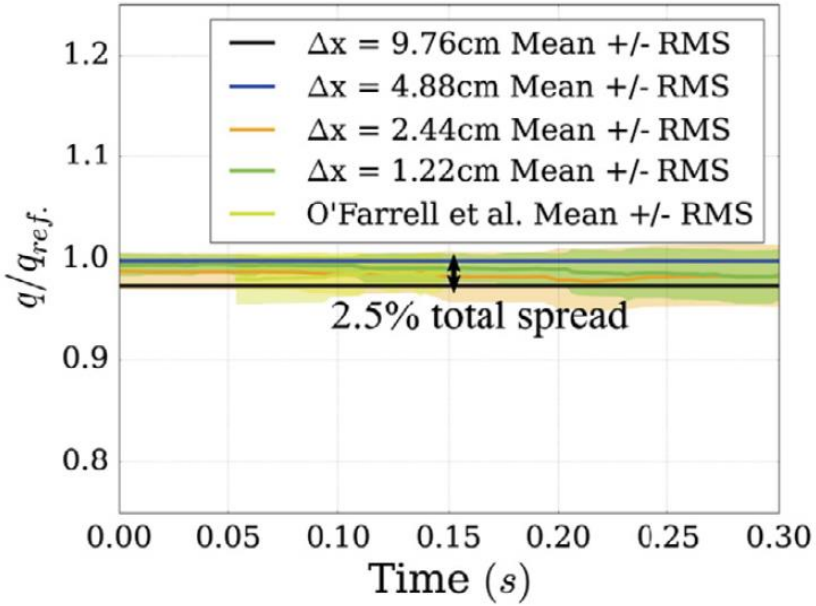

[3] Boustani, J., Cadieux, F., Kenway, G. K., Barad, M. F., Kiris, C. C., and Brehm, C., “Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test,” Aerospace Science and Technology, 2022, p. 107596

# ASPIRE Payload Wake Deficit

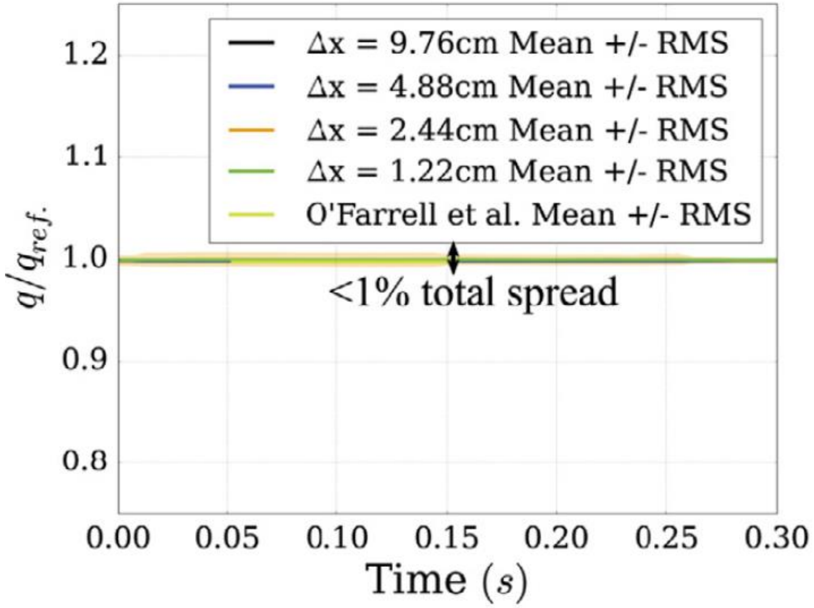
## CFD Grid Convergence Study Results




$x = 55\ D_P, y = 0.5\ D_P$




$x = 55\ D_P, y = \ D_P$




$x = 55\ D_P, y = \ 2D_P$

- Wake deficit is minor and very narrow
- < 1% change going from $\Delta x = 2.44\ cm$ to $\Delta x = 1.22\ cm$

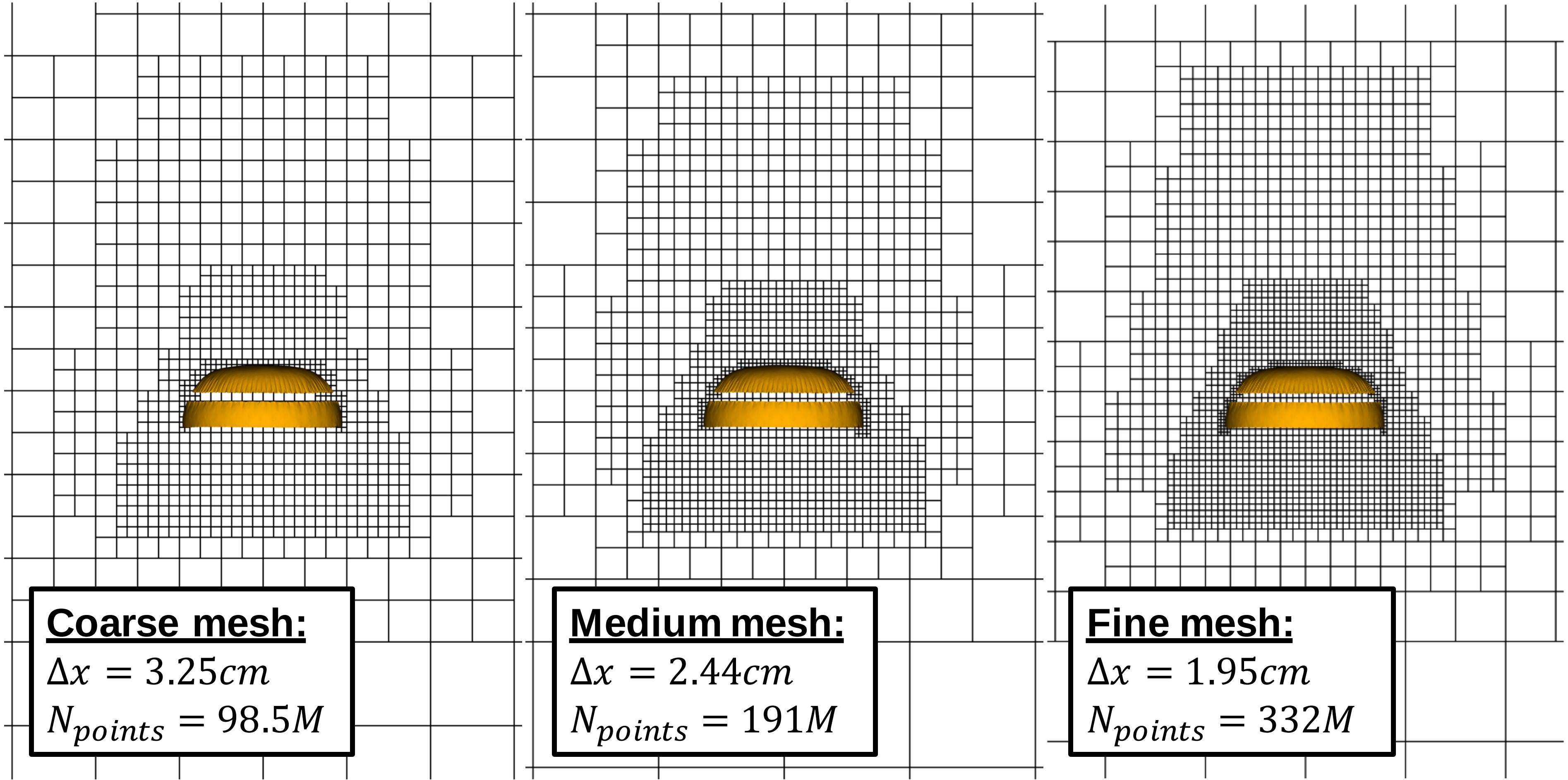
→ $\Delta x = 2.44\ cm$ is sufficient to capture wake deficit

# ASPIRE Inflated Static Canopy

**CFD Grid Convergence Study**

Grids are uniformly refined by factors of $2^{1/3}$ so the total number of cells doubles each time

Same freestream conditions as experience during test when suspension lines first record tension (aka line-stretch event): Mach number ~ 1.79

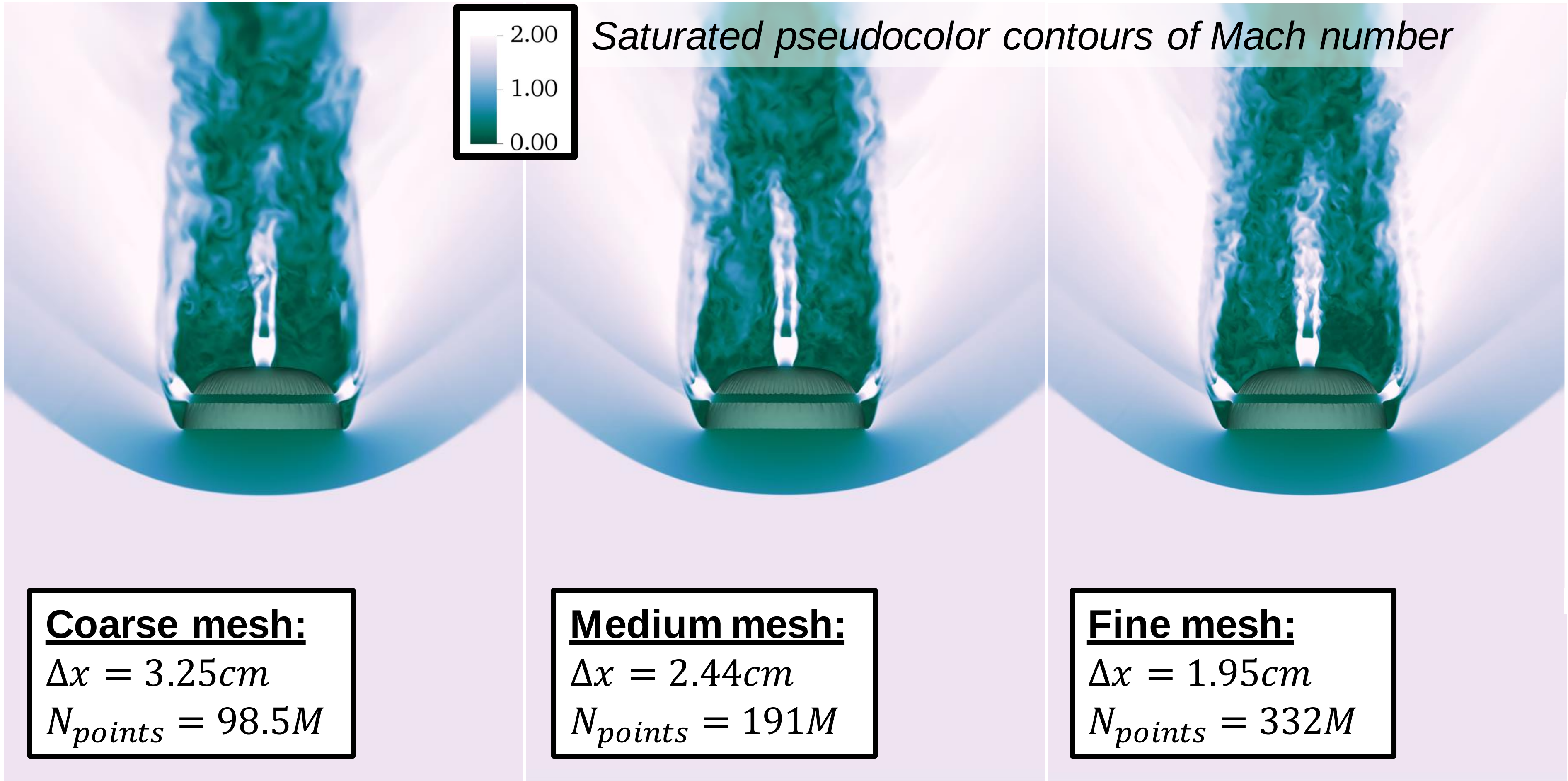


# ASPIRE Inflated Static Canopy

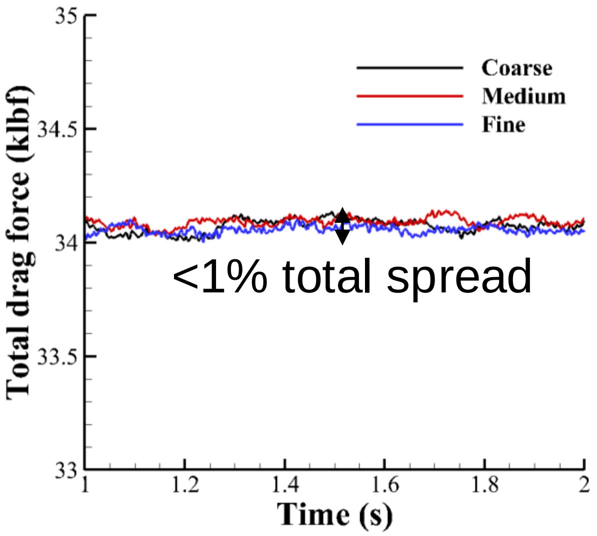
**CFD Grid Convergence Results**

Integrated drag is already converged with < 1% difference between all resolutions tested

Only noticeable difference is the level of detail captured in wake turbulence

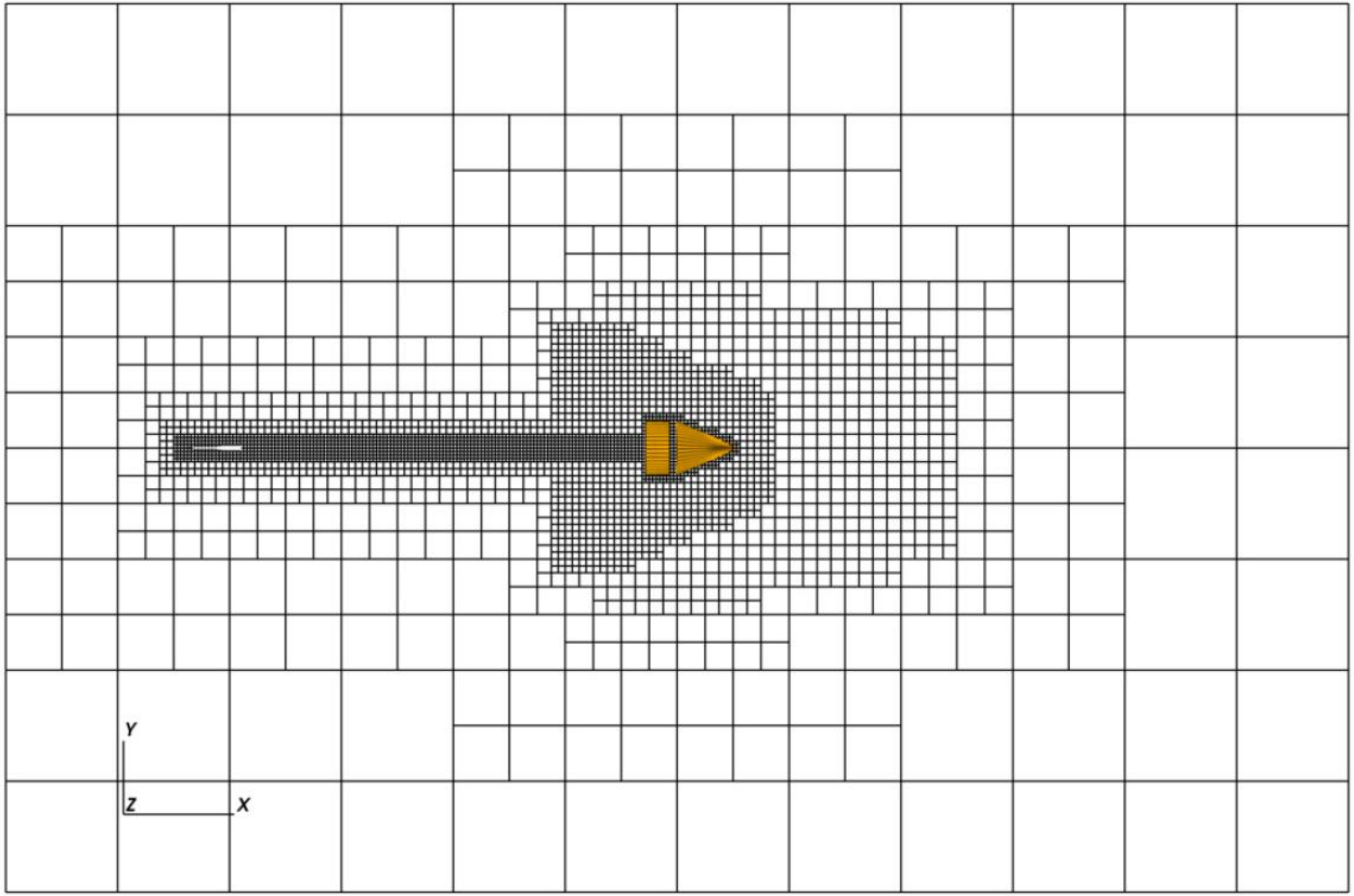



*Saturated pseudocolor contours of Mach number*



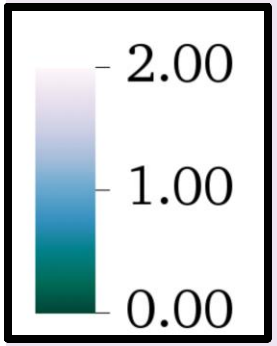
# Initial Cartesian AMR Grid For ASPIRE FSI

- Each box contain $16^3$ cells
- AMR is used to ensure parachute canopy is surrounded by fine grid cells during inflation
- Finest cells have $\Delta x = 2.4cm$ , and every subsequent level is twice larger in all directions



# ASPIRE Pre-FSI CFD Simulation

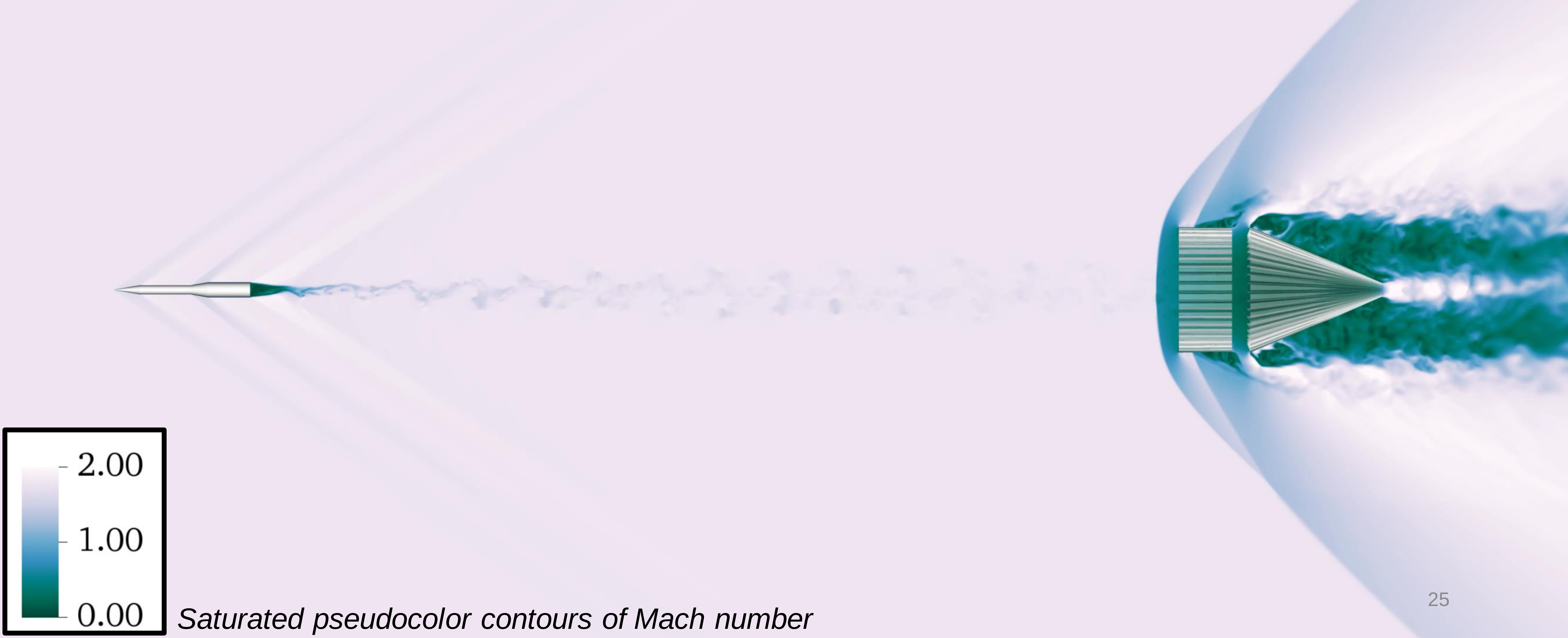
First: perform CFD simulation on static payload and static parachute canopy until aerodynamic loads reach stationary state (for repeatability)




*Saturated pseudocolor contours of Mach number*

# ASPIRE FSI Simulation

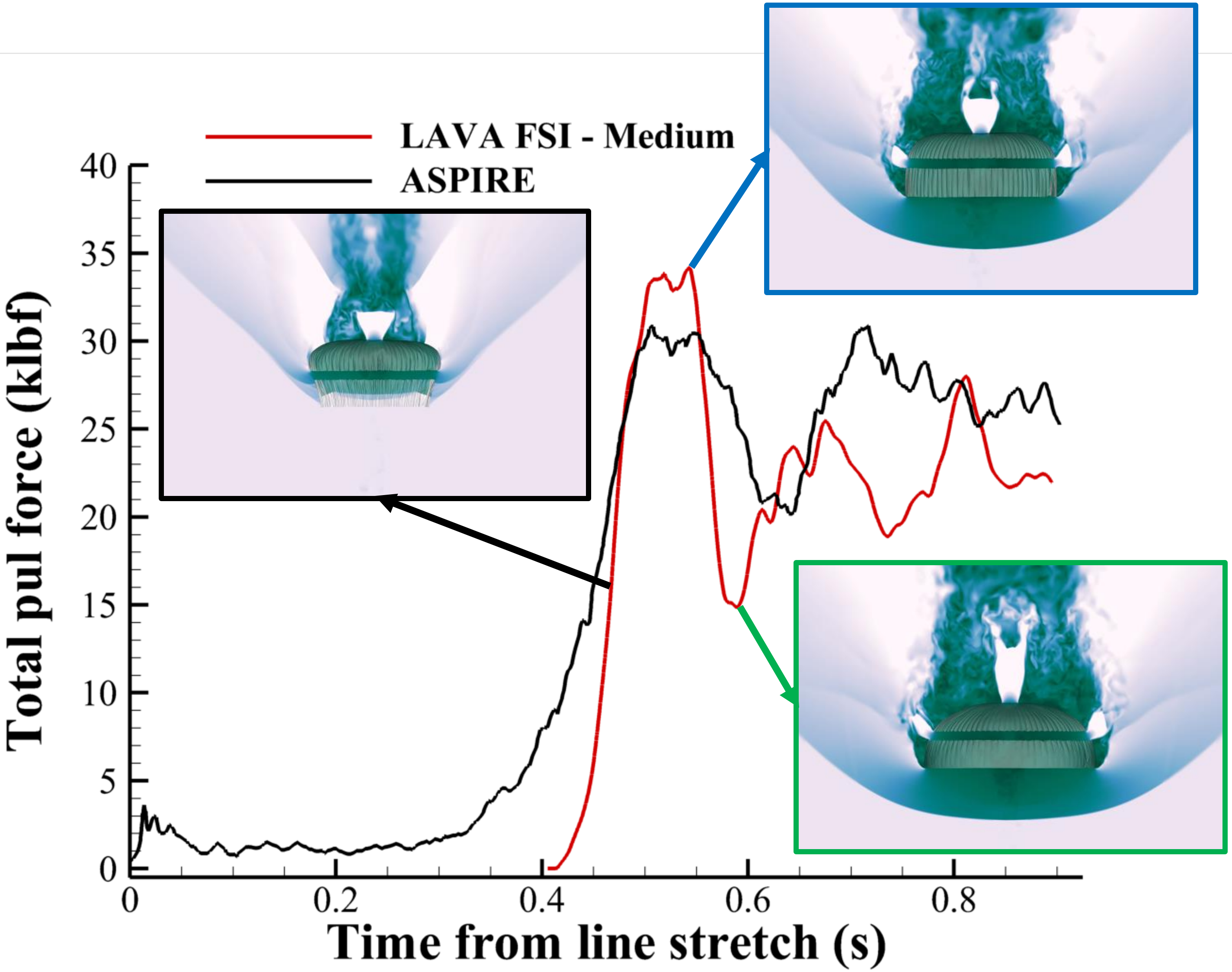
Second: restart from CFD-only simulation and allow parachute to deform through structural dynamics coupling while payload remains static. Notice the supersonic flow accelerating out of the gap between disk and band, and the interaction of the bow shock with the payload wake.




*Saturated pseudocolor contours of Mach number*

# Validation of ASPIRE SR01 FSI Simulation

- ASPIRE payload had 3 load pins to measure the tension in the triple bridle as a function of time with a measurement uncertainty of about 6% of peak load (±1.82 klbf)
- FSI simulation recorded the restoring force in the elements of each bridle to perform as close to apples-to-apples comparison of total pull force
- FSI shows qualitative behavior consistent with ASPIRE test
- FSI inflates faster and overpredicts inflation peak by ~10%
- FSI underpredicts trough and rebound peak by ~20%



# Possible Sources of Error

## 1. Numerical Error

- Occurs whenever the spatio-temporal scales of motion in the problem simulated are not sufficiently resolved
- Reducing this error is a matter of reducing $(\Delta t, \Delta x)$ while still integrating a large enough time interval to capture phenomenon of interest
- Grid convergence studies can provide an estimate of converged value of a quantity of interest (e.g. pull-force) and a measure of uncertainty related to numerical error

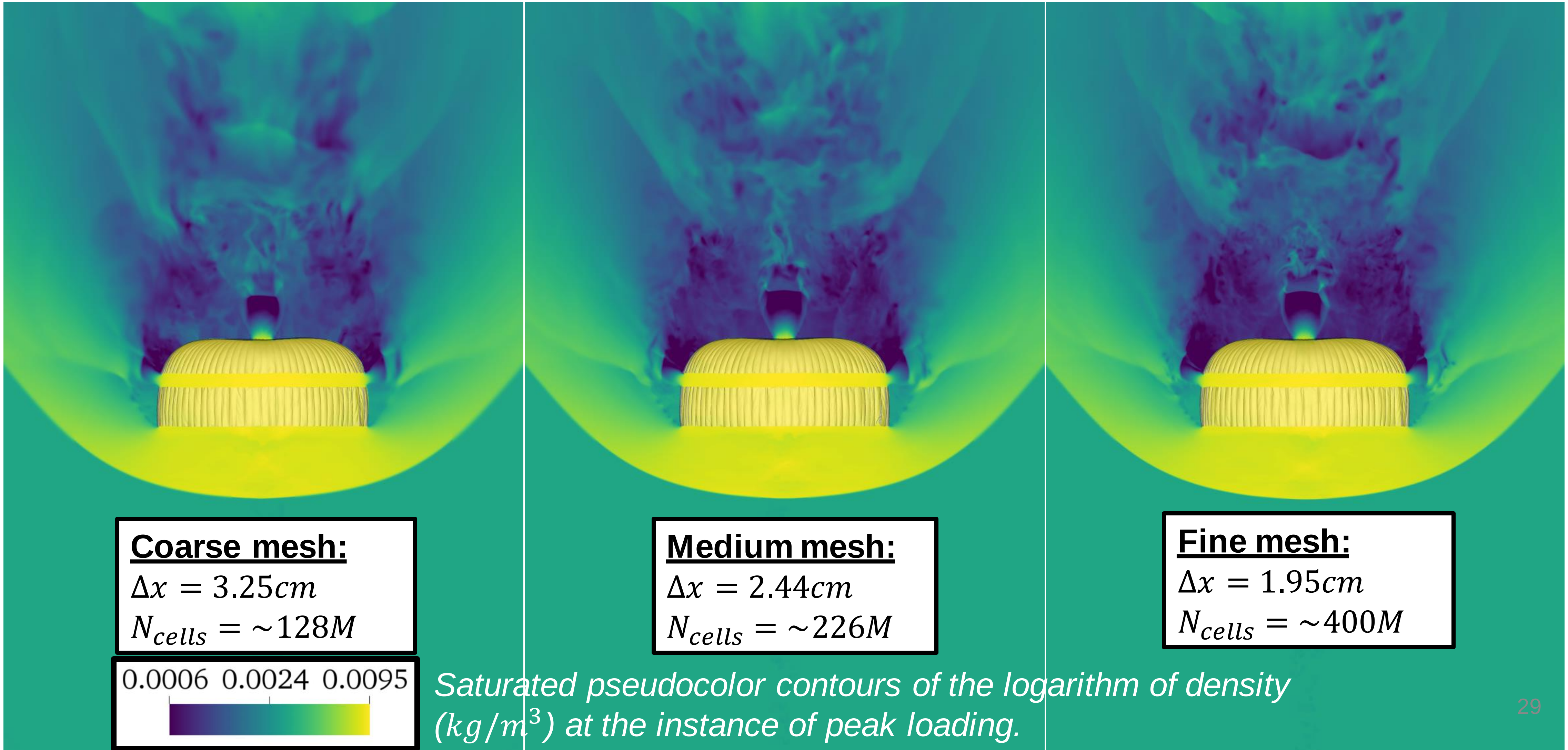
## 2. Modeling Error

- Modeling error occurs every time a simplifying assumption is made that does not fully represent the underlying physics
- Bounding this error requires obtaining the degree of sensitivity of quantities of interest to assumptions made by either removing or changing them one at a time
- Expert knowledge of the problem is often required to identify the assumptions that are most likely to cause significant changes in the quantity of interest

Assessing numerical and modeling errors are both computationally costly!

# ASPIRE FSI Grid Convergence Study

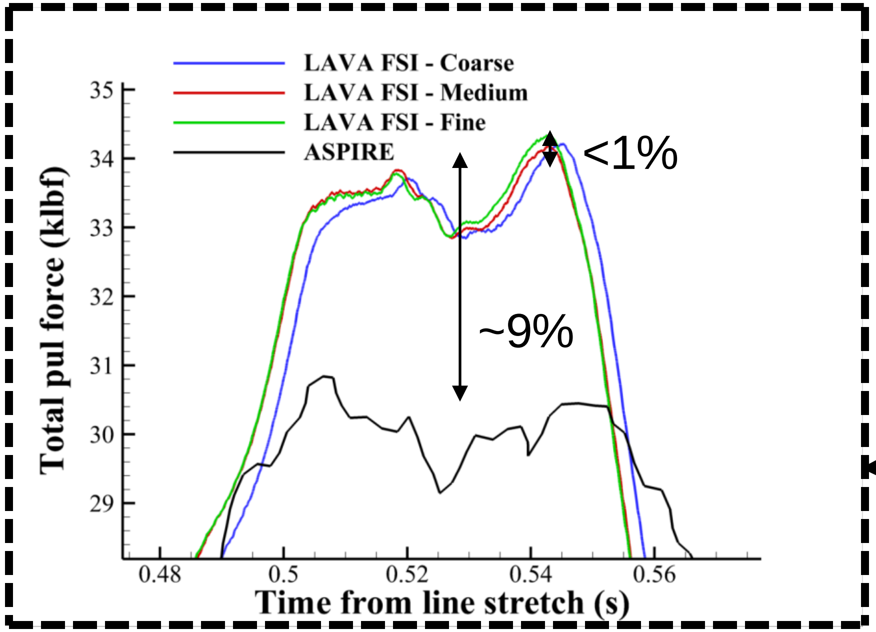
- In order to ensure differences between FSI and flight test are not due to CFD resolution, we coarsen by $2^{1/3}$ and refine by $1/2^{1/3}$ every cell in the domain and perform two more simulations

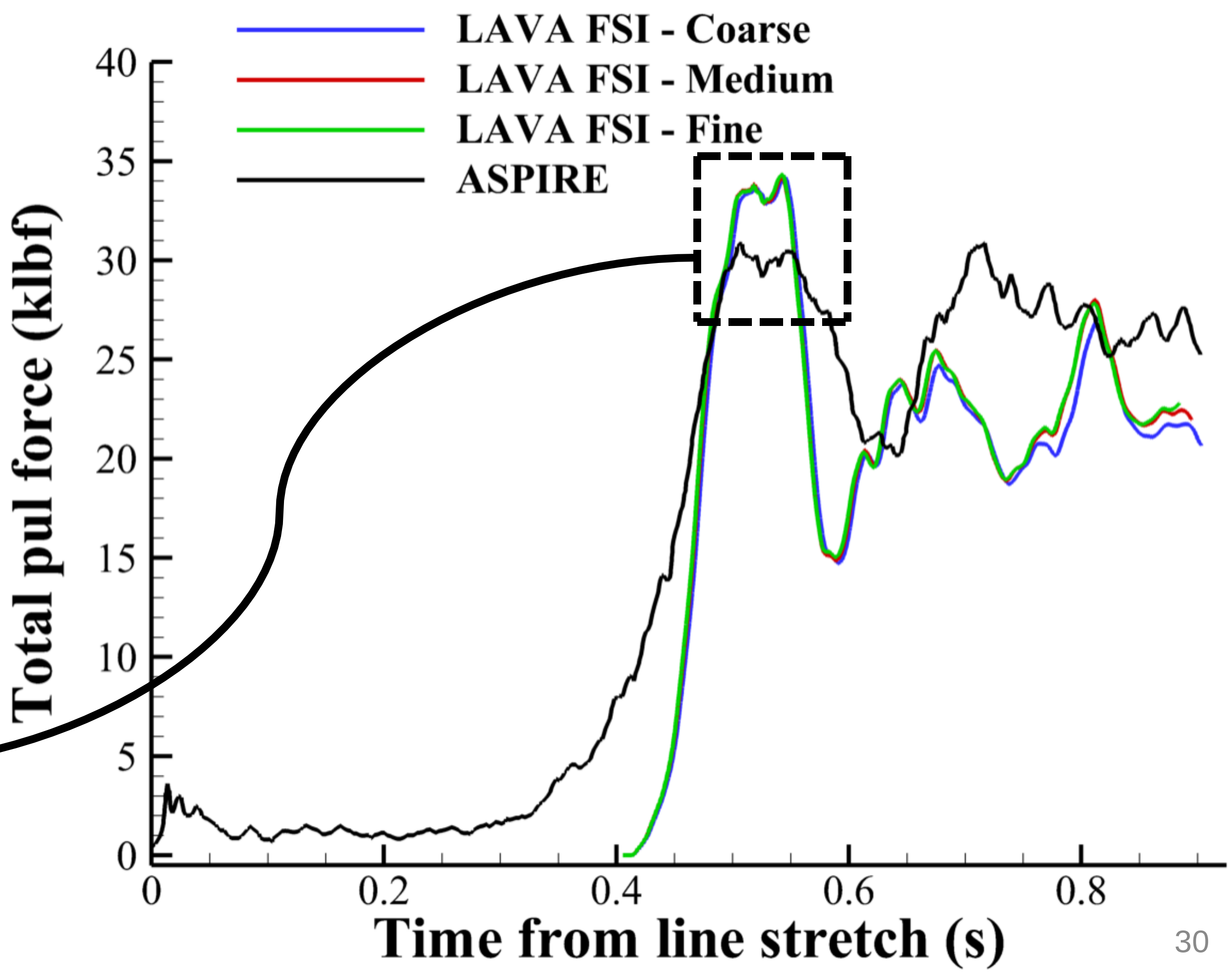



*Saturated pseudocolor contours of the logarithm of density ($kg/m^3$) at the instance of peak loading.*

# ASPIRE FSI Grid Convergence Results

- Observed clear convergence behavior: Medium and Fine grid are on top of each other
- All 3 CFD grid resolutions predict inflation peak load within 1% of each other



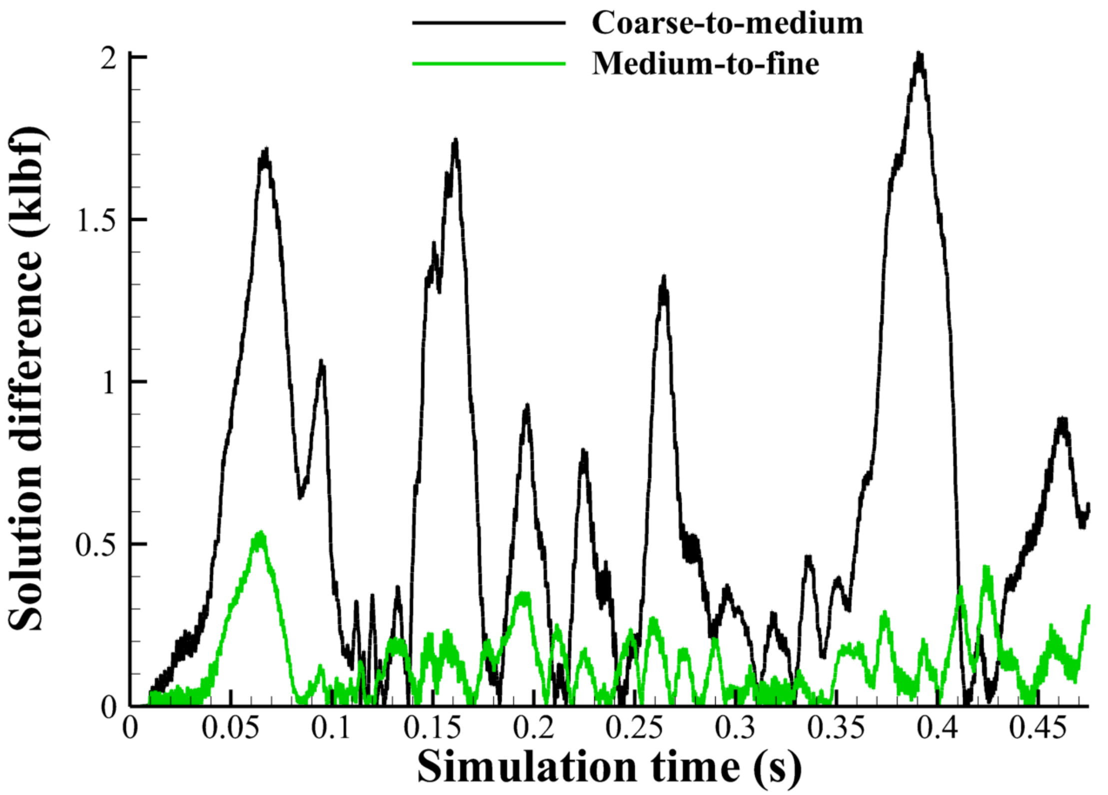



# ASPIRE FSI Grid Convergence Results

- Interpolate coarse and medium pull-force time curve onto fine and use mean difference from coarse-to-medium and medium-to-fine to compute a convergence rate
- CFD and CSD time integrator are 2nd order accurate, so obtaining 3rd order convergence indicates that spatial error from high-order shock capturing scheme dominates

**For the available time interval**

| Error Norm | Convergence Rate |
| --- | --- |
| L-1 | 2.99 |
| L-2 | 3.01 |
| L-∞ | 2.57 |

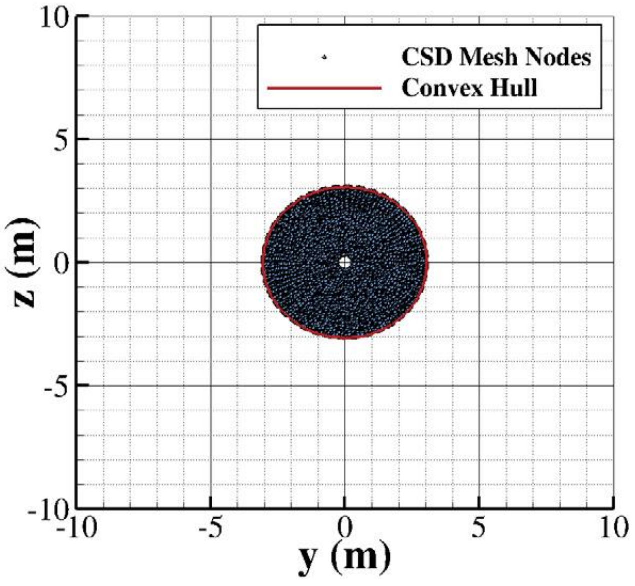



For more grid convergence metrics, please refer to [3]

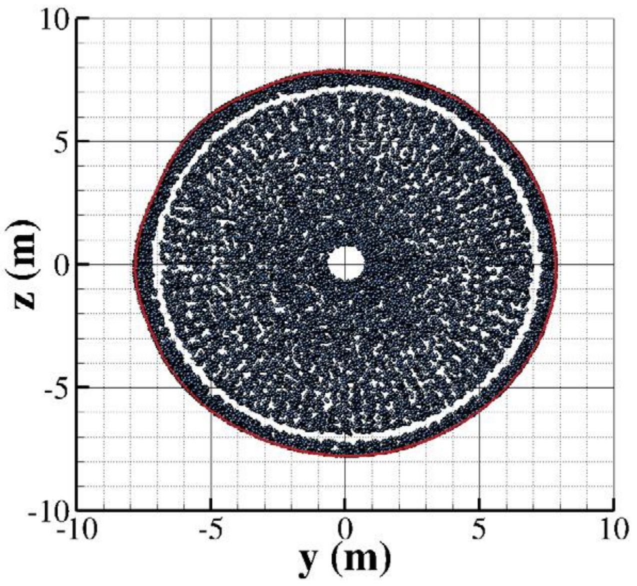

[3] Boustani, J., Cadieux, F., Kenway, G. K., Barad, M. F., Kiris, C. C., and Brehm, C., "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test," Aerospace Science and Technology, 2022, p. 107596

# ASPIRE FSI Grid Convergence Results

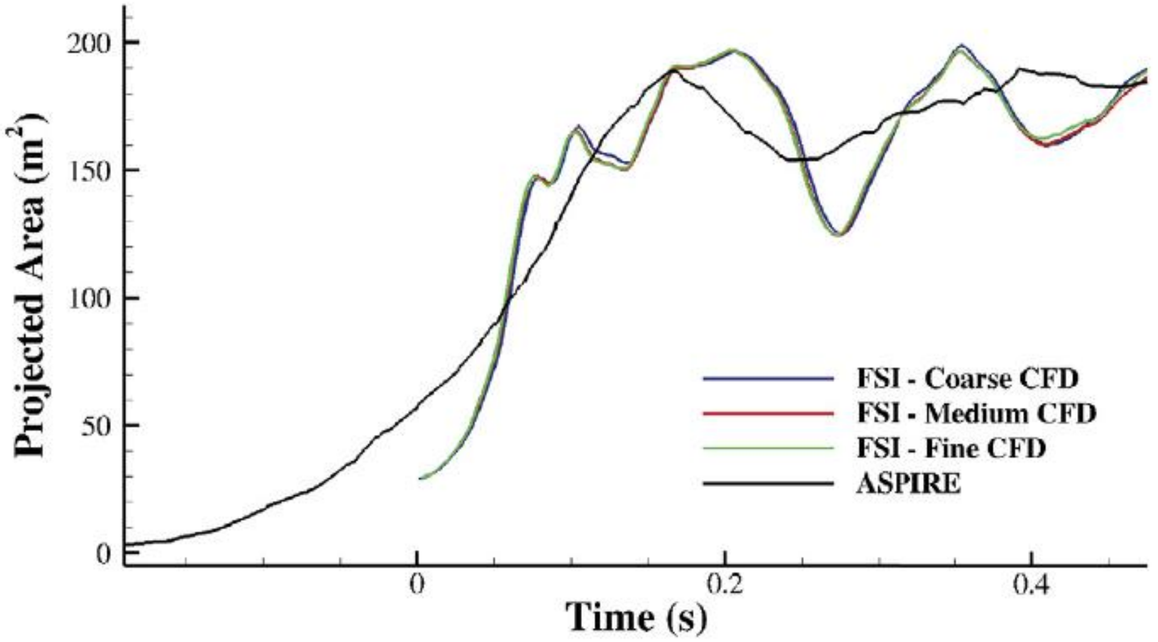
- We can compute projected area in a similar fashion to ASPIRE test
- All 3 CFD grid resolutions predict inflation peak projected area within 1% of each other
- FSI shows faster inflation and deeper rebound than measured during ASPIRE SR01




t = 0.0 s

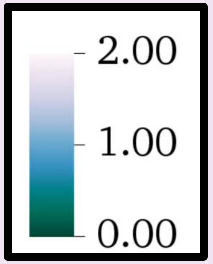



t = 0.18 s



# ASPIRE FSI Structural Grid Refinement

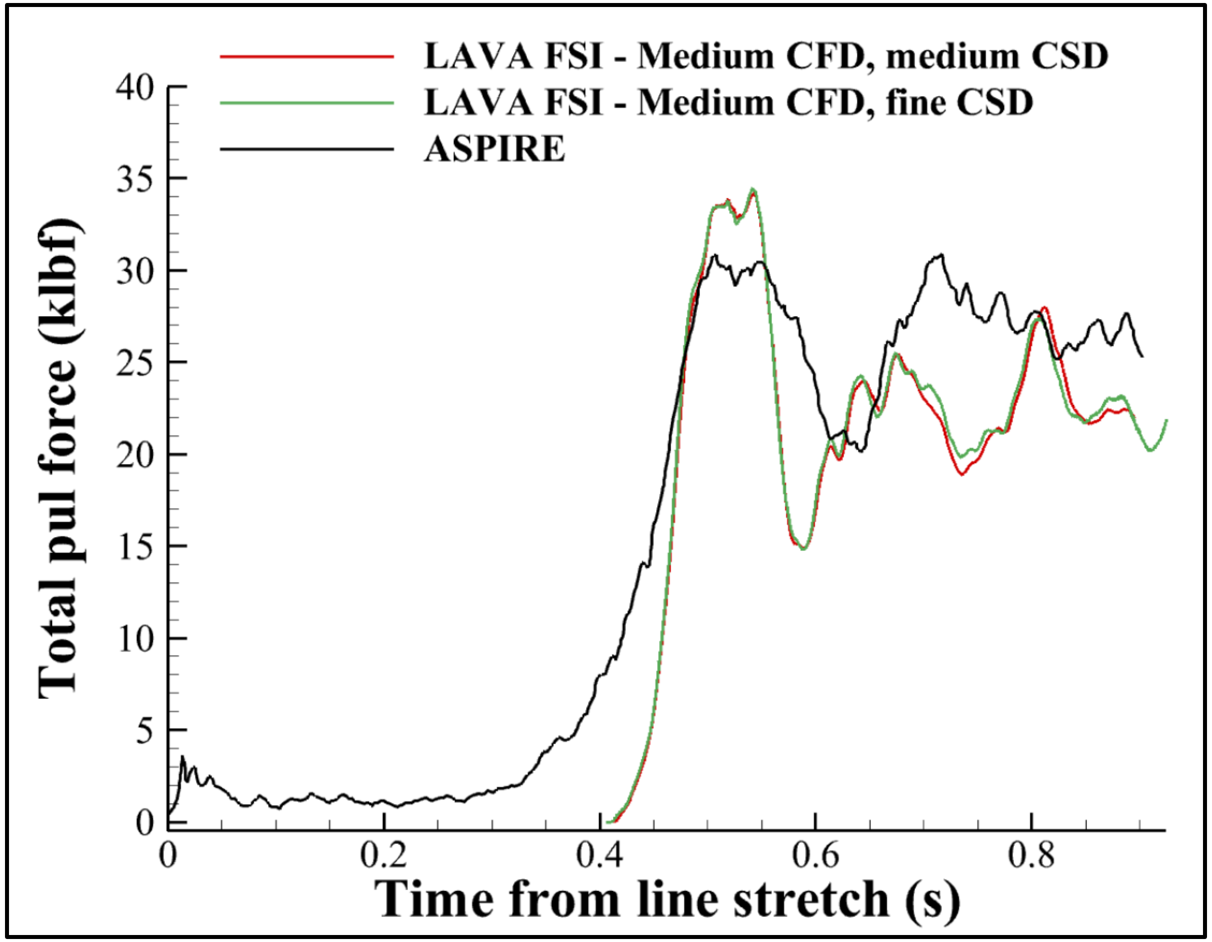
- In order to ensure differences between FSI and flight test are not due to insufficient structural grid resolution, we refine by $1/2^{1/3}$ every end on the parachute surface and perform another simulation (1.26M → 2.22M DOF)




*Saturated pseudocolor contours of Mach number shown on a cut-plane through the center of the domain for a medium CFD - fine CSD simulation of ASPIRE SR01.*

# ASPIRE FSI Structural Grid Refinement

- Results indicate <1% sensitivity for inflation peak, and only minor deviations in the post-rebound phase
- From CFD grid convergence study and structural refinement results we can eliminate both spatial discretizations as the source of the discrepancy between FSI and ASPIRE test data



# Computational Cost of FSI Simulations

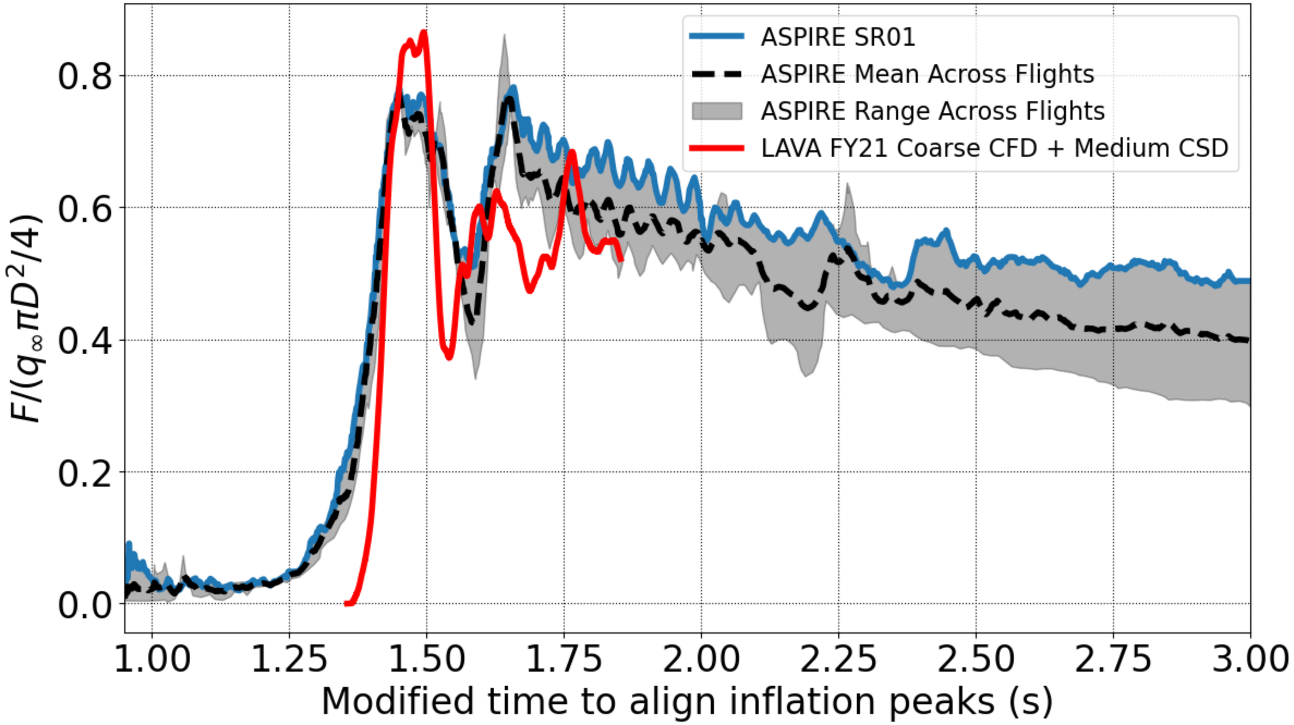
**Computational Cost**

| CFD Grid Cells | CSD Degrees of Freedom | Number of Cascade Lake CPU Cores | Wall time (hours) | Core-hours x$10^3$ |
|---|---|---|---|---|
| Coarse (~128M) | Medium (1.26M) | 1600 | 32 | 51.2 |
| Medium (~226M) | Medium (1.26M) | 960 | 67 | 64.3 |
| Fine (~400M) | Medium (1.26M) | 2400 | 70 | 168.0 |
| Medium (~226M) | Fine (2.22M) | 2400 | 58 | 139.2 |

- Turnaround time on coarse mesh is just over 24 hours: could enable system level studies
- Computational cost doesn't scale linearly: current bottleneck is not CFD or CSD solver, but reconstructing bounding volume hierarchy (BVH) of deformed parachute surface and querying it via ray-tracing to impose immersed boundary condition and compute surface aero forces, which is a function of the number of triangles on the surface, and the number of CFD cells in its vicinity that need boundary conditions

# A Note on Flight Test Uncertainty

- Measurement uncertainty is not the same as uncertainty stemming from repeated tests
- ASPIRE project conducted 3 tests: SR01, SR02, and SR03:
  - Each test saw differences in parachute diameter, materials, construction, and release mechanism, along with significant increases in dynamic pressure when released
- We can gain information about flight test repeatability if we non-dimensionalize the pull-force by parachute area and dynamic pressure




| Non-Dimensional Drag Force | ASPIRE Average Across Flights | LAVA FSI Predictions FY21 Coarse CFD + Medium CSD Mesh | ASPIRE Percent Variation Across Flights (+/-) | Percent Difference Btwn LAVA and ASPIRE Average |
|---|---|---|---|---|
| Inflation Peak | 0.773 | 0.865 | 3.42 | +11.9 |
| Rebound Peak | 0.798 | 0.624 | 14.93 | -21.8 |
| Trough | 0.409 | 0.372 | 42.10 | -9.1 |

# Sources of Uncertainty in FSI

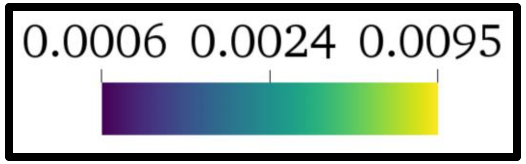
As demonstrated by CFD and CSD grid refinement studies, FSI simulations are repeatable and show little discretization related uncertainty. Flight tests non-dimensional inflation peaks are also highly repeatable and show little flight-to-flight variation.

We conclude that the discrepancy in predicted pull-force stems from **modeling errors**:

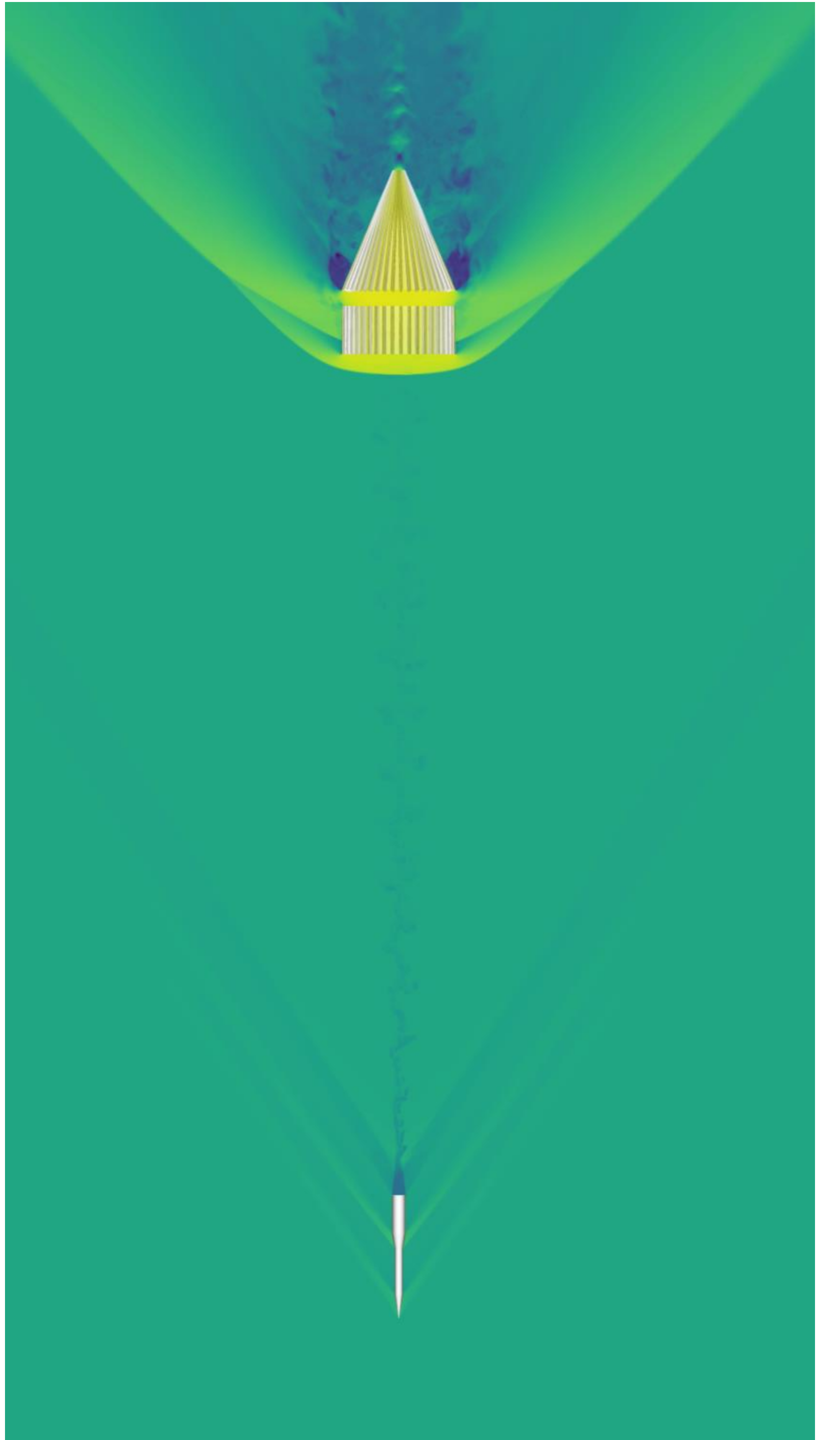
- initial parachute shape: folded accordion shape is never seen in flight test video
- parachute initial stress and velocity: assumed to be zero, causing impulse to the system
- flow initial conditions: parachute loads never reach statistically stationary state in flight test
- material modeling:
  - assumed all gore seams, disk and band leading and trailing edge had very strong Kevlar reinforcements but identical thickness due to lack of information
  - similarly assumed all suspension lines, riser and bridles were made from same material with identical strength and thickness but recently learned they are not
- effects of deceleration: the parachute drag causes the whole system to decelerate abruptly during inflation

# Forward Outlook

- Perform FSI simulations of the ASPIRE SR03 flight test with more detailed material properties recently published by JPL
- Explore the effects of flow and parachute initial conditions and try to reproduce JPL's recently published initialization procedure for code-to-code comparisons
- Investigate the effects of the full system's abrupt deceleration during inflation using a free-flight capability we are developing within LAVA Cartesian module




*Saturated pseudocolor contours of the logarithm of density* $(kg/m^3)$



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- Gaetan Kenway for helping to improve the parallel efficiency of the structural solver
- Timothy Sandstrom from NASA Ames Research Center for developing and maintaining an interface to the high-performance geometry kernels used in this work
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