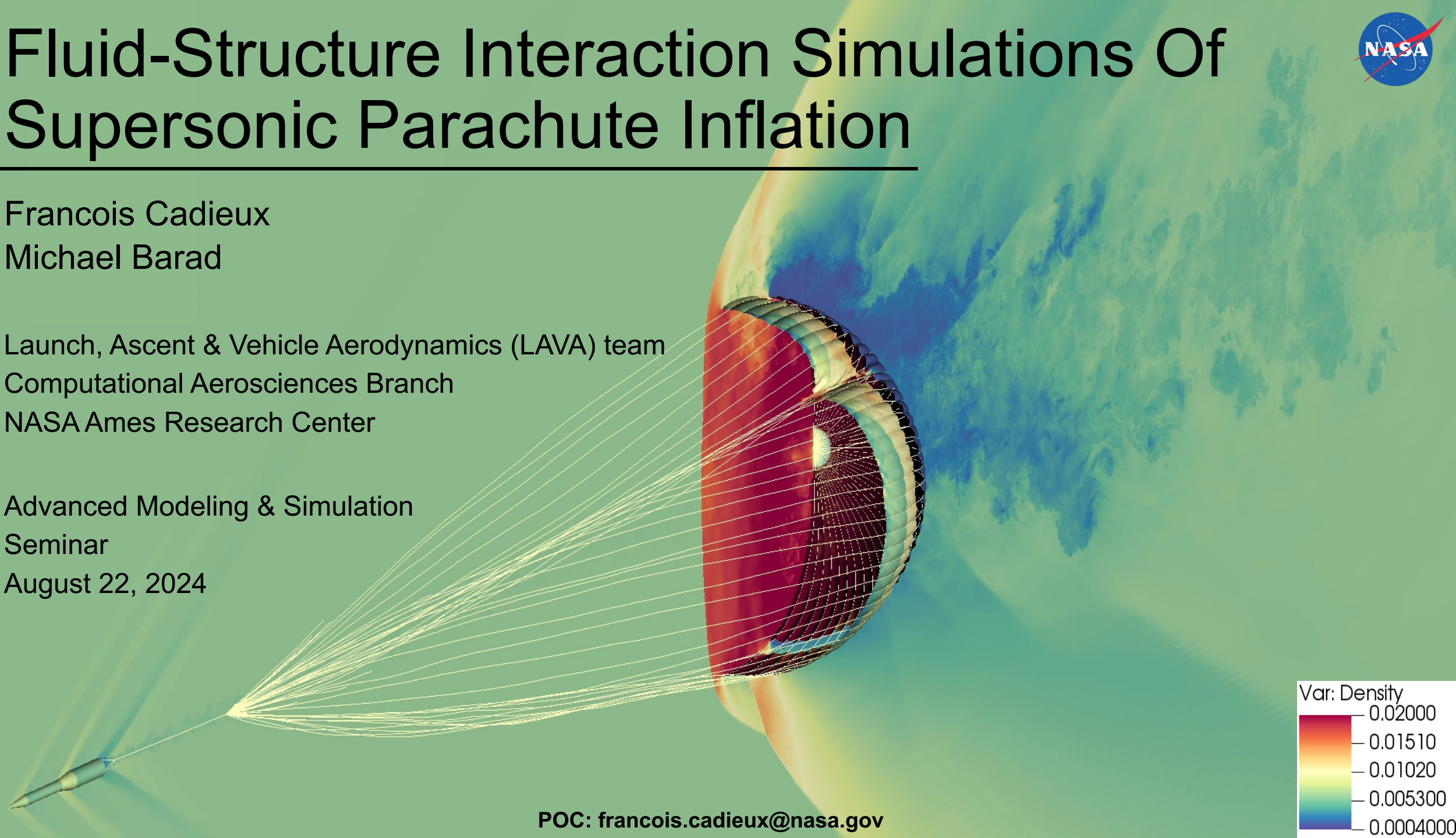
Fluid-Structure Interaction Simulations Of Supersonic Parachute Inflation

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NASA Ames Research Center

Advanced Modeling & Simulation
Seminar
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Context: Perseverance Rover's Descent Profile

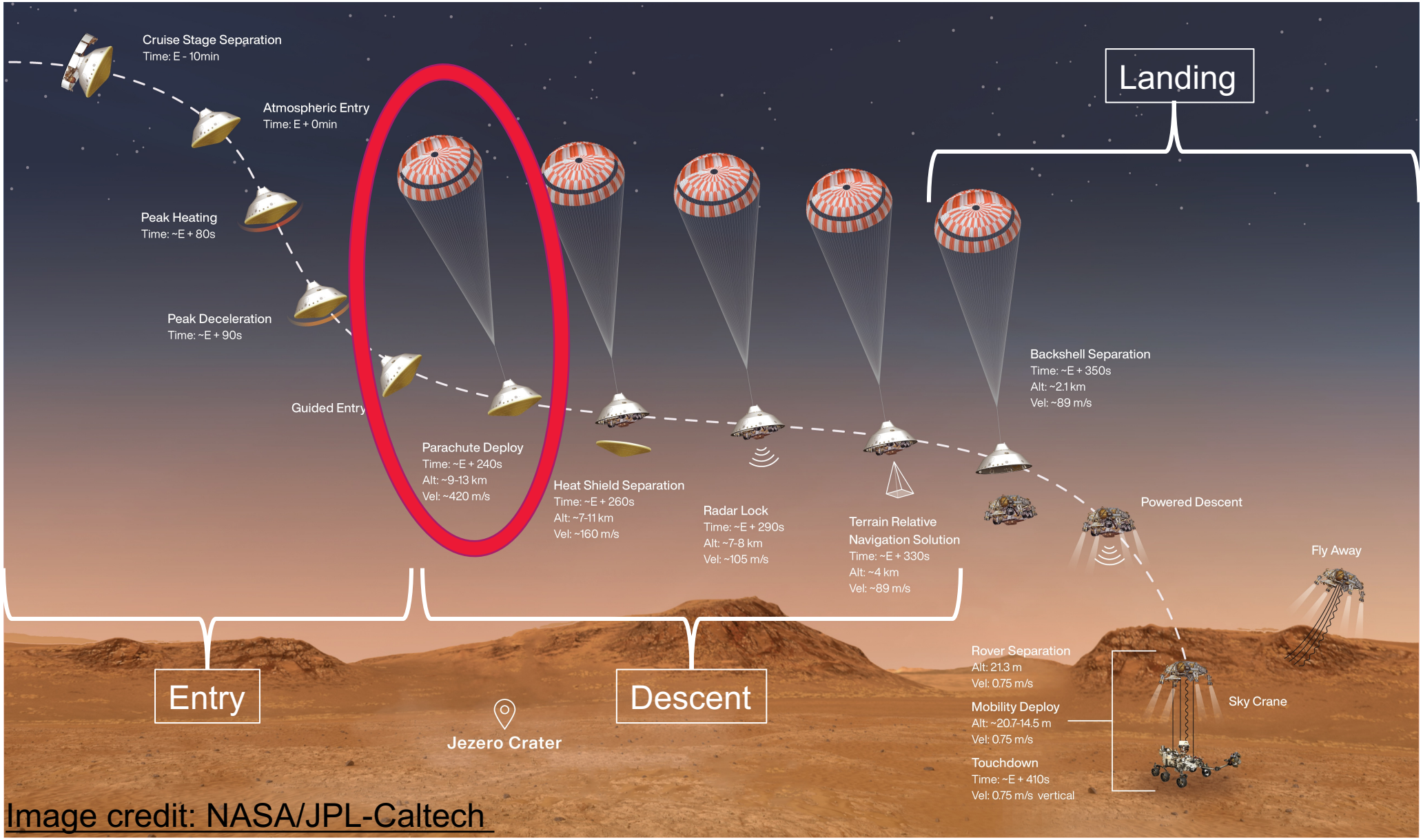


Image credit: NASA/JPL-Caltech

https://www.jpl.nasa.gov/images/pia24285-perseverance-rovers-entry-descent-and-landing-profile

Modeling Parachute Is Challenging

Parachutes…

- are typically deployed from packed state in a bag so each path to inflation is fairly unique, full of self-contact, and inherently unsteady
- go through large non-linear deformations during inflation
- are incredibly thin (e.g. ~76 microns)
- are made of porous woven (orthotropic) fabric
- are made of materials that are not fully characterized across range of strain in which they are used

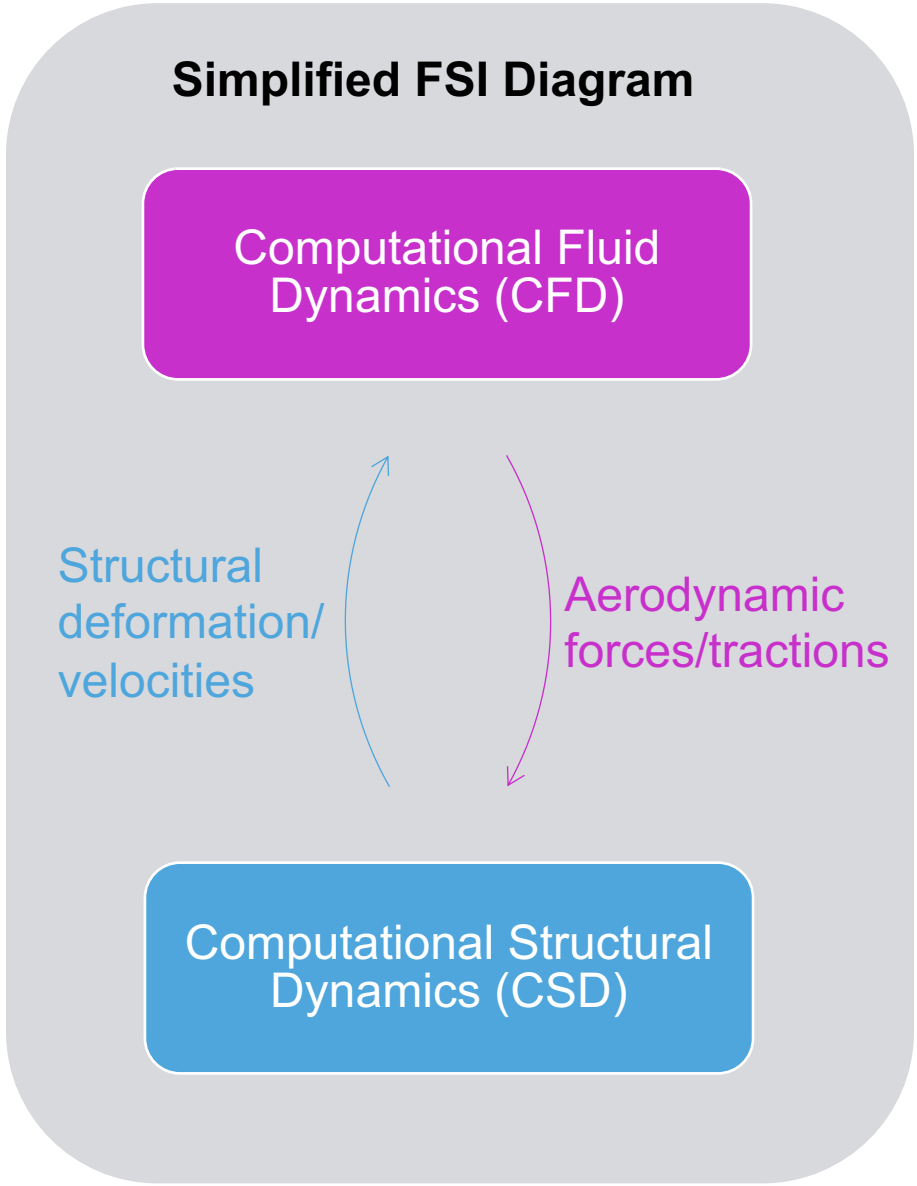


This high-definition video was taken on Sept. 7, 2018, during the third and final test flight of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) campaign to certify the Mars 2020 parachute. It was the fastest inflation of this size parachute in history and created a peak load of almost 70,000 pounds of force.
Credits: NASA/JPL-Caltech
https://www.nasa.gov/feature/jpl/third-aspire-test-confirms-mars-2020-parachute-a-go

Why Simulate Supersonic Parachute Inflation?

Fluid-structure interaction (FSI) simulations, once validated, have the potential to:

- Accelerate the design of new parachute systems and mitigate risks by simulating more scenarios than can be flight tested
- Account for difference in parachute performance with blunt aeroshell versus slender payload used in flight tests
- Provide insight into parameters or phenomena not easily measured or reproduced in wind tunnel or flight tests



Objectives

- Develop FSI tool capable of simulating parachute systems of interest to NASA

- Continue improving and validating FSI tool by simulating the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) flight tests



Iso-surfaces of q-criterion colored by total pressure showing detailed turbulent structures captured in previous FSI simulations of ASPIRE SR01 flight. Payload and parachute system are shown in gray.

Goals For FSI Validation

Metrics to validate in order of increasing difficulty:

a) Peak opening loads

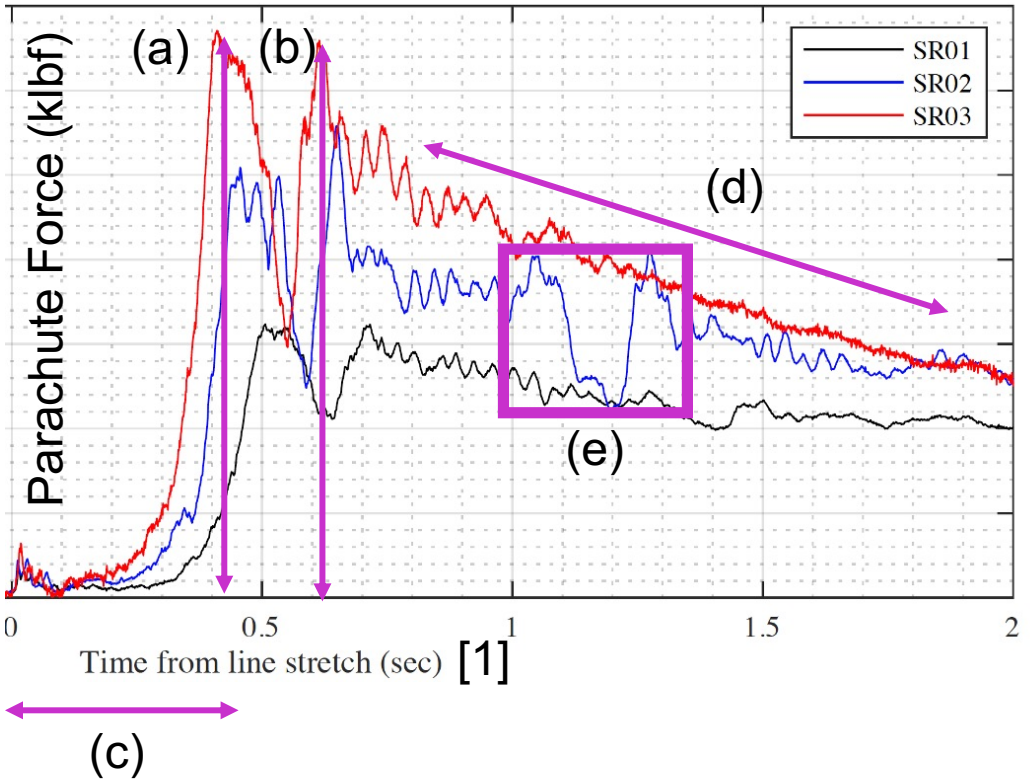
b) Post-inflation dynamics (e.g. trough and rebound peak)

c) Inflation rate and time

d) Aerodynamic coefficients as a function of Mach, dynamic pressure, and angle of attack for “steady” descent phase

e) Dynamic stability: response to angle of attack changes due to wake recontact or wind gusts/shear

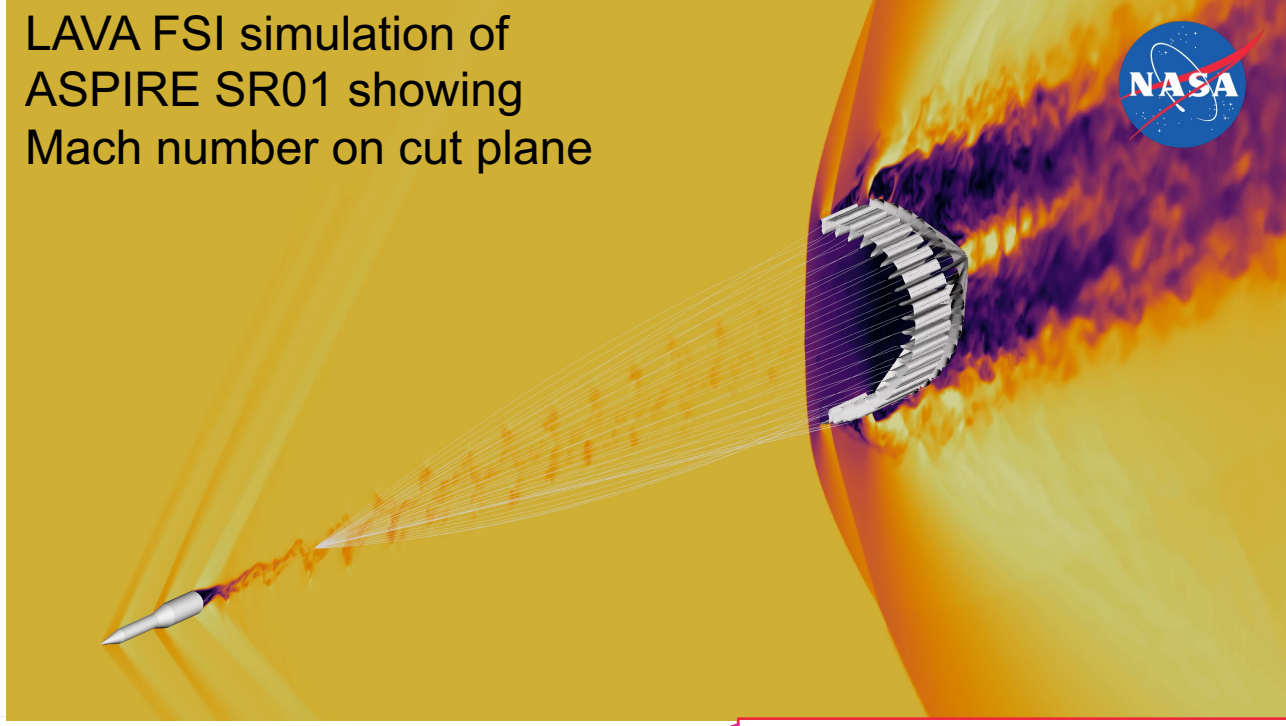
f) Detailed spatial distribution of stress magnitude in canopy fabric to predict failure (requires accurate model of woven orthotropic fabric, and gore seams)

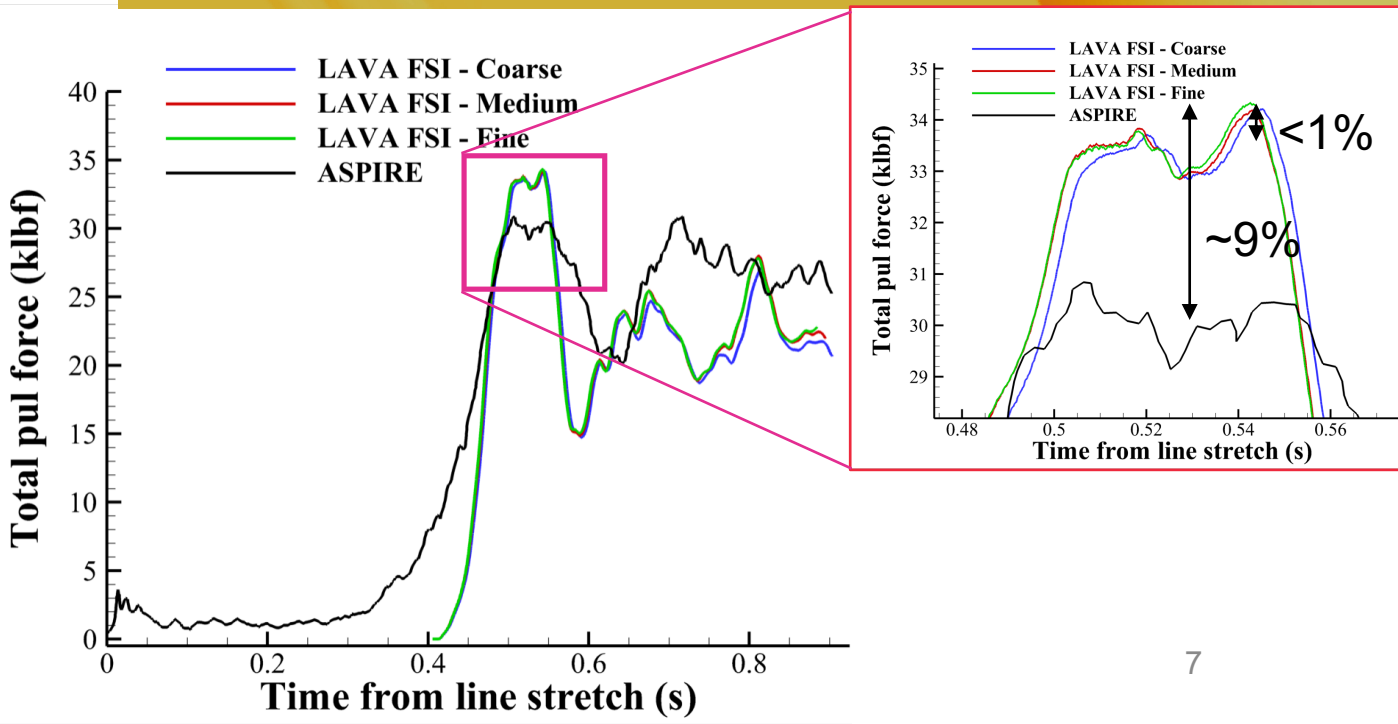


[1] Sonneveldt, Bryan S., Ian G. Clark, and Clara O'Farrell. "Summary of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) Sounding Rocket Tests with a Disk-Gap-Band Parachute." *AIAA Aviation 2019 Forum*. 2019.

Previous Work

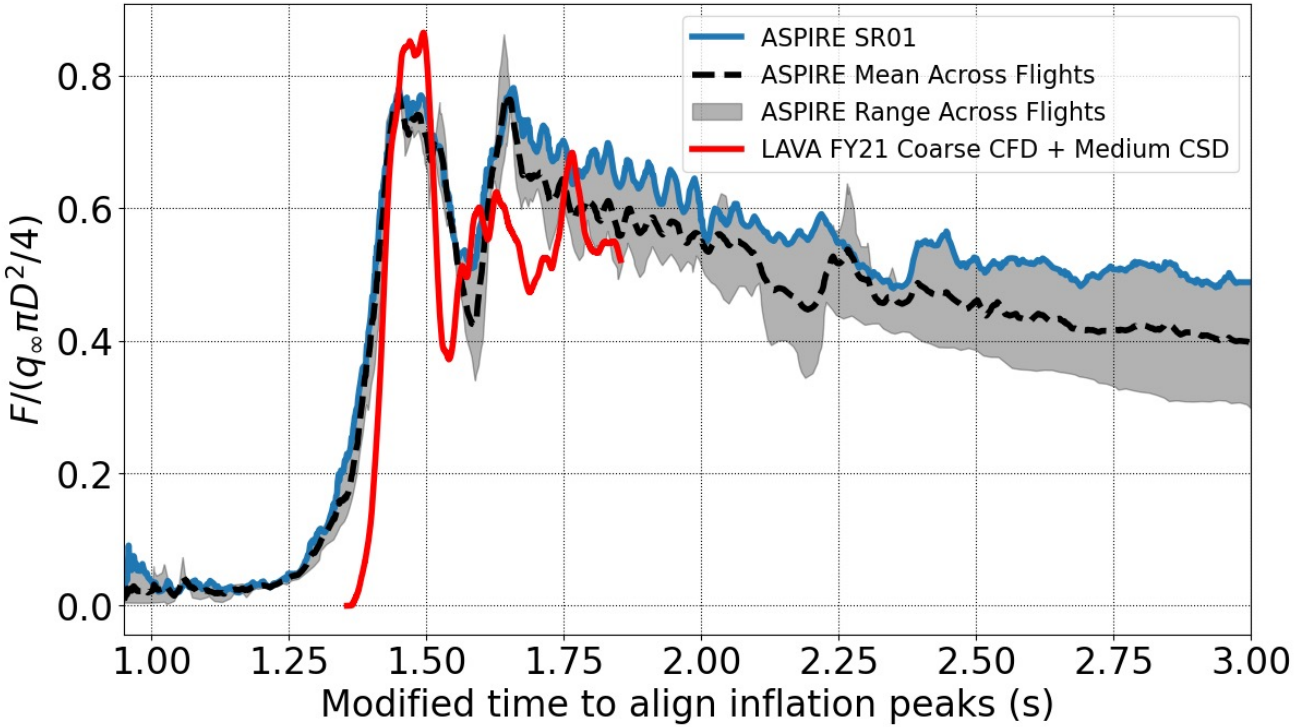
- AMS Seminar presented 12/02/2021 by Jonathan Boustani: https://www.nas.nasa.gov/pubs/ams/2021/12-02-21.html
- LAVA team performed simulations of the ASPIRE SR01 flight with material properties derived from scarce published data on F-111 Nylon (and a lot of guess work)
- Demonstrated CFD can predict peak pull-force within 10% of measured in flight
- Investigated structural grid sensitivity and showed again less than 1% change in predicted pull-force
- For more details, please refer to: Boustani, Jonathan, et al. "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test." Aerospace Science and Technology 126 (2022): 107596 https://doi.org/10.1016/j.ast.2022.107596





Investigating 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



Variation in recorded pull-force across ASPIRE flights:

inflation peak ~ 3%
post-inflation trough ~ 42%
rebound peak ~ 15%
deceleration phase ~ 20%

How To Further Improve FSI?

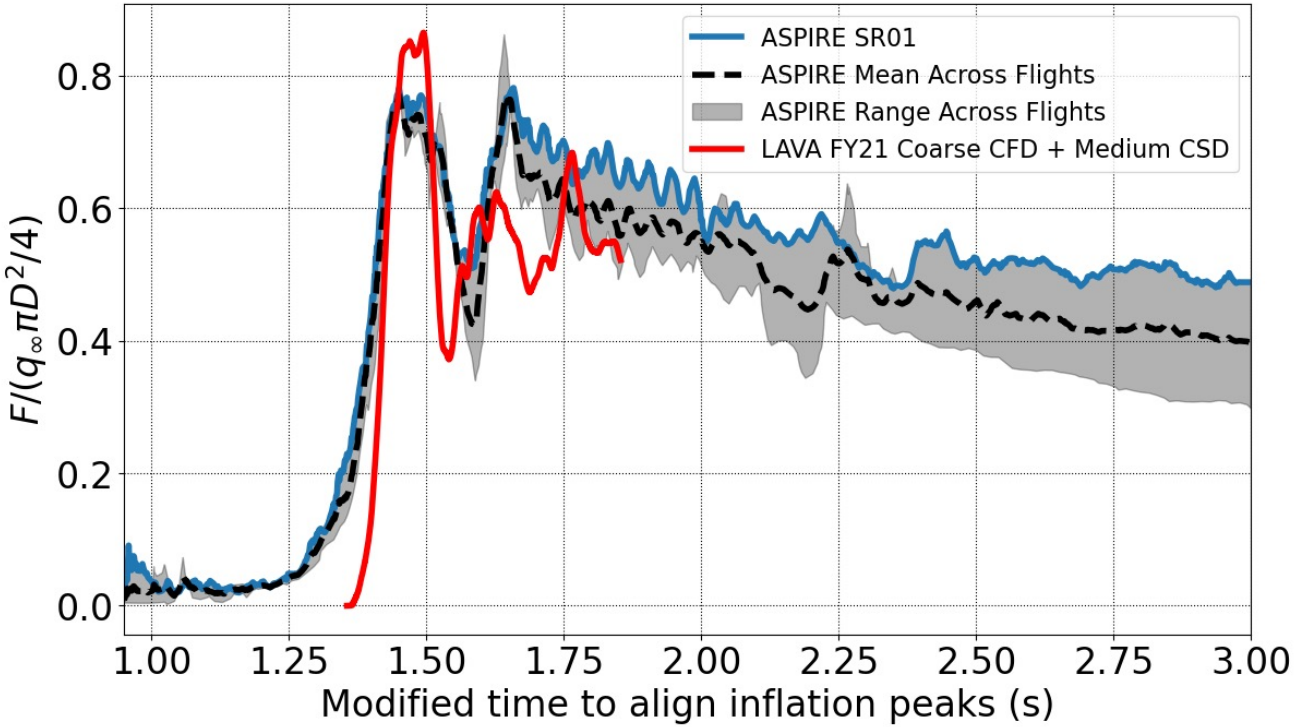
Relax the simplifying assumption of infinite mass inflation (payload is traveling at constant velocity)

- finite mass inflation -- payload decelerates as parachute generates drag -- should reduce peak loads by 5-10% for $\mathrm{M_R} \approx 60$ [1] and produce a downward slope in the stable deceleration phase

Refine structural model of parachute to be more representative of the as-constructed chute

- Use published data for SR02/SR03 parachute material properties from JPL/Airborne Systems
- Model gore seams more accurately

Change initial parachute shape to improve inflation time, inflation rate, and reduce stress



Mass ratio $\mathrm{M_R} = \frac{m_{total}}{\rho(S_0 C_D)^{\frac{3}{2}}}$ is the ratio of inertial to drag forces expressed in terms of the system mass over the mass of air ingested by the parachute at full inflation:

- $\mathrm{M_R} \to 0$: payload decelerates to terminal velocity within parachute inflation time
- $\mathrm{M_R} \to \infty$: payload does not decelerate during inflation

[1] Knacke Parachute Recovery Systems Design Manual

Methodology: Overview

Launch, Ascent and Vehicle Aerodynamics (LAVA) FSI framework

Cartesian CFD Module
- Adaptive Mesh Refinement (AMR)
- Immersed boundary ghost cell method
- Porosity boundary condition
- Explicit Runge-Kutta time integration

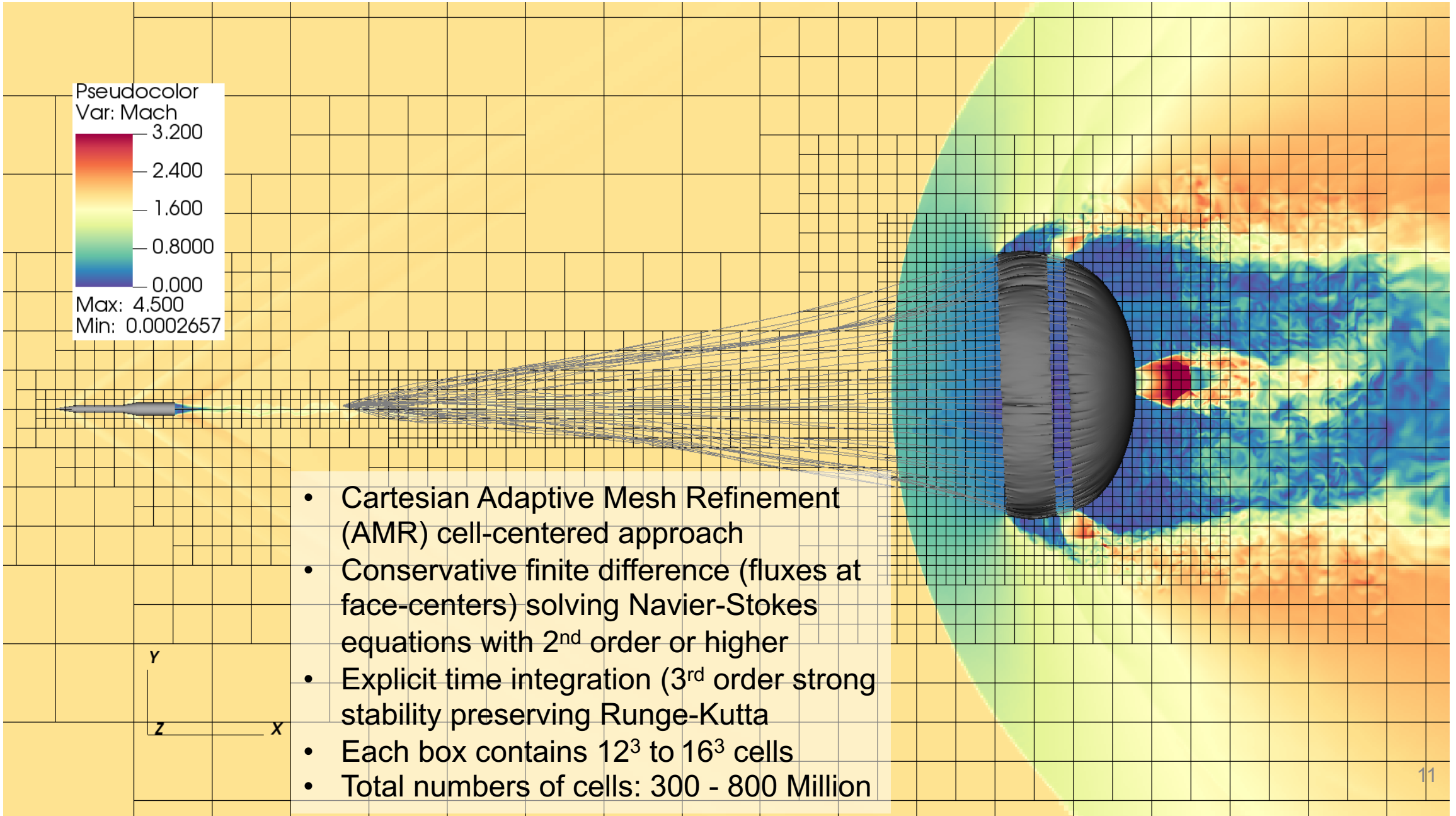
Finite Element CSD Module
- Saint Venant-Kirchhoff hyperelastic model
- MITC3 shell elements for canopy fabric
- Timoshenko beams for lines
- Explicit central difference with damping

Free Flight Module
- Solves rigid body motion equations
- Coupled with aerodynamic forces from CFD and nodal forces from CSD
- Explicit Runge-Kutta time integration

Contact Mechanics Module
- Physics-based model based on momentum of fabric elements
- Solves for canopy self-contact forces that are input to CSD

For more details on the method, please refer to: Boustani, Jonathan, et al. "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test." *Aerospace Science and Technology* 126 (2022): 107596 https://doi.org/10.1016/j.ast.2022.107596

Methodology: CFD

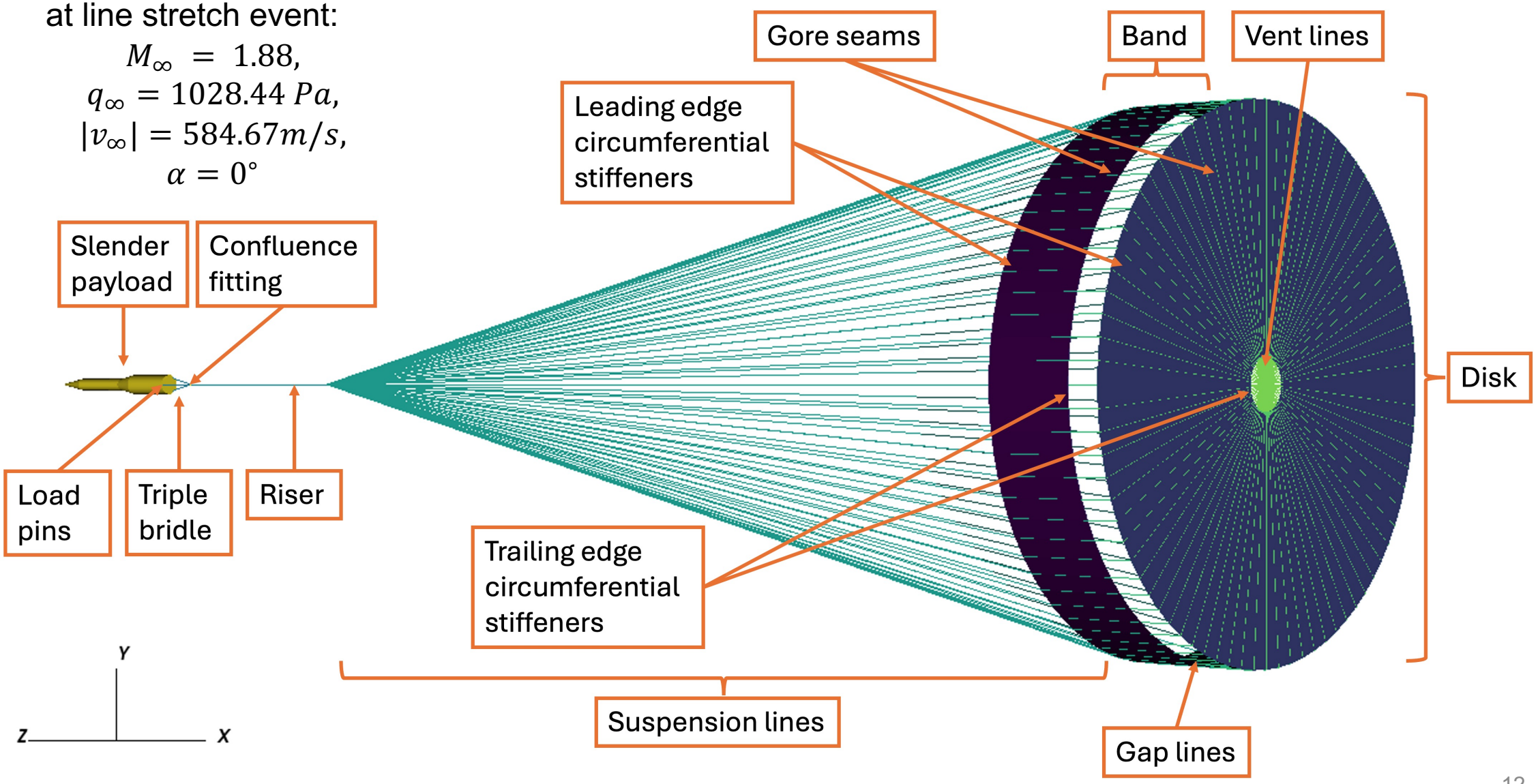


- Cartesian Adaptive Mesh Refinement (AMR) cell-centered approach
- Conservative finite difference (fluxes at face-centers) solving Navier-Stokes equations with 2nd order or higher
- Explicit time integration (3rd order strong stability preserving Runge-Kutta
- Each box contains 12^3 to 16^3 cells
- Total numbers of cells: 300 - 800 Million

ASPIRE SR03 Problem Statement

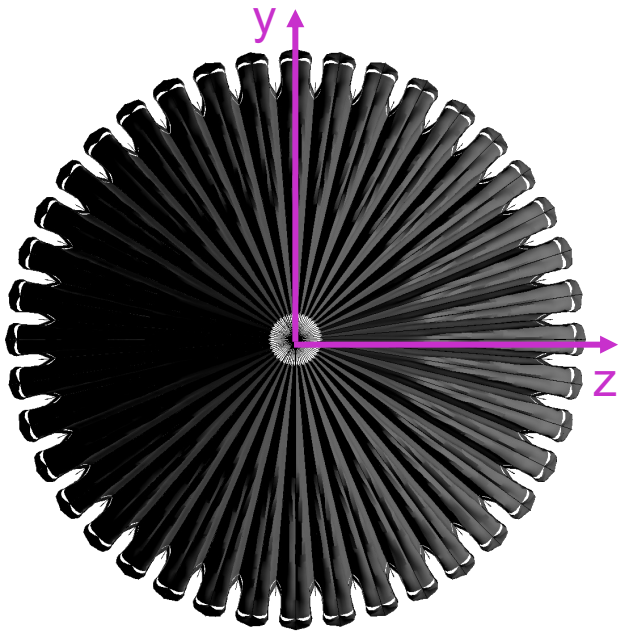
Freestream conditions at line stretch event:

$$M_\infty = 1.88,$$
$$q_\infty = 1028.44\ Pa,$$
$$|v_\infty| = 584.67 m/s,$$
$$\alpha = 0°$$

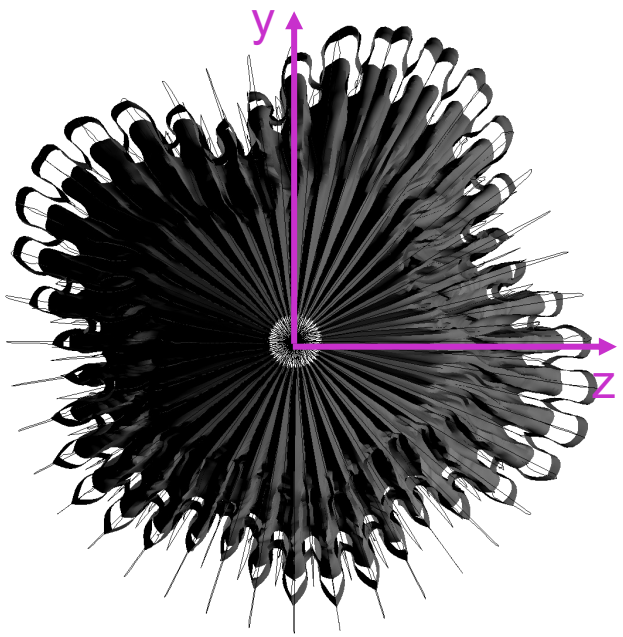


Parachute Initial Shape Improvement 1

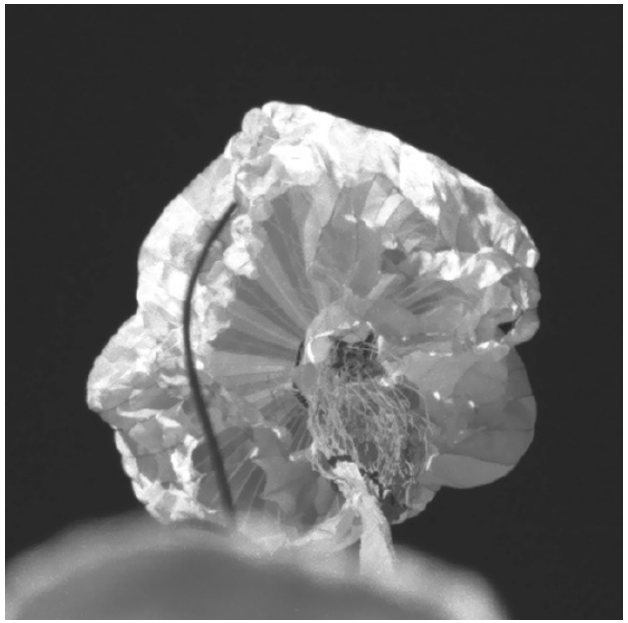
- Starting from SR01 efforts: fold chute into accordion-like shape from diameter D to 0.4D
- Sharp edges cause issues, so pre-inflate with CSD + contact mechanics with constant surface normal force for a short time
- Resulting shape is too symmetric, so we add a circumferentially varying force to pre-inflation step



Initial shape consistent with previous FSI of SR01



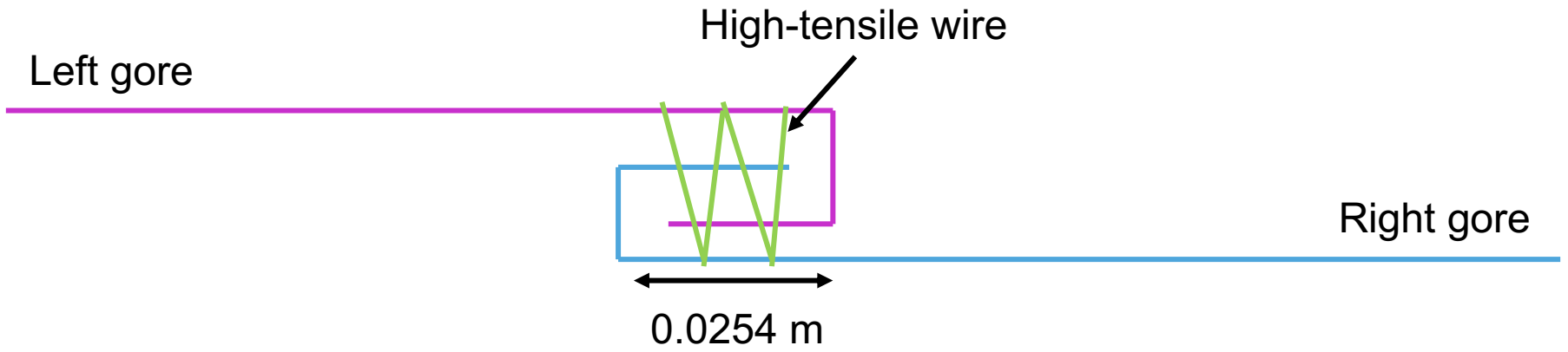
New asymmetric initial shape



ASPIRE SR03 at t=0.25 s after line stretch.
Credit: NASA/JPL-CalTech

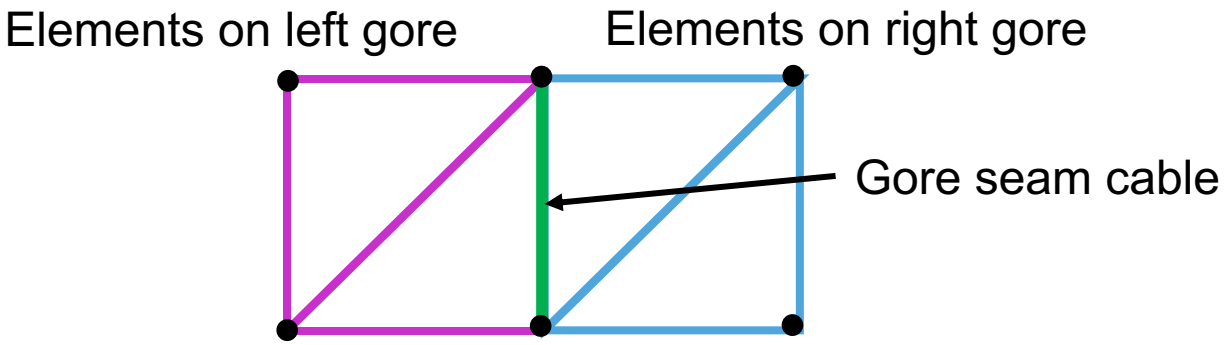
Modeling Gore Seams

- Stitching at the gore seams implies 4 layers of canopy fabric + high tensile strength wire

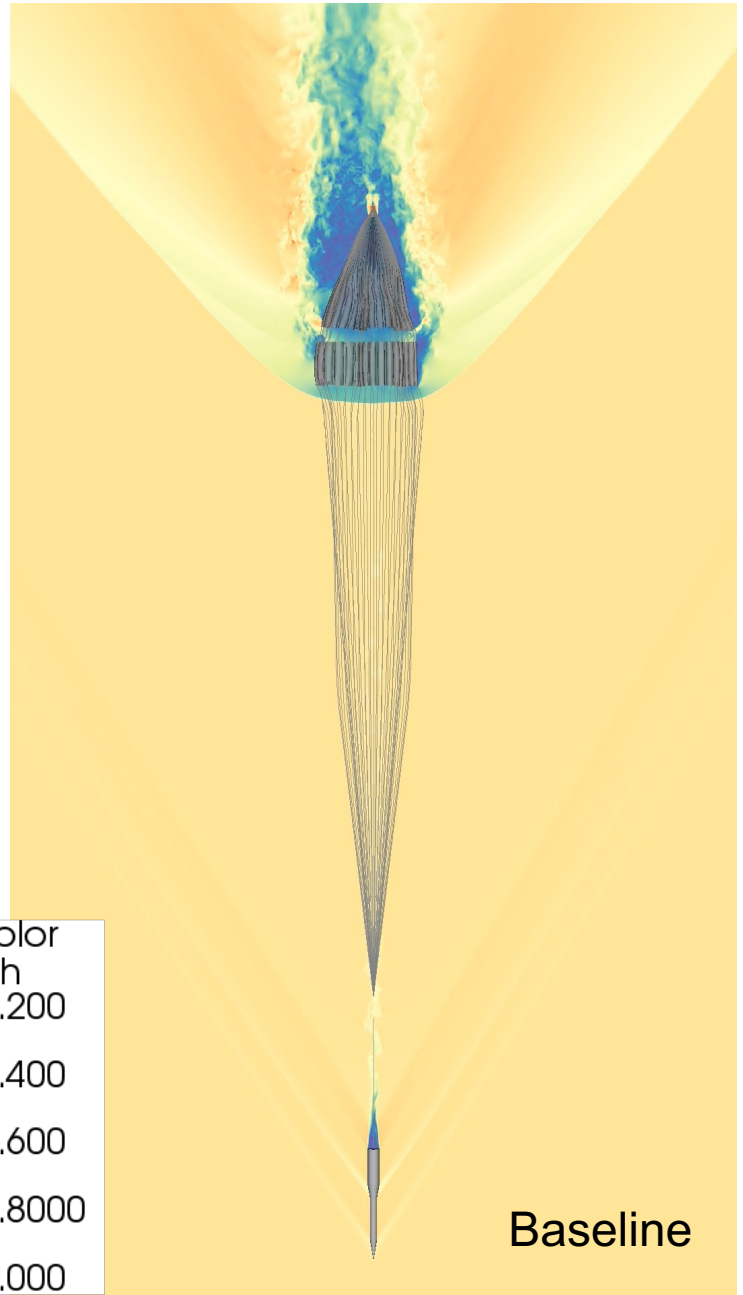


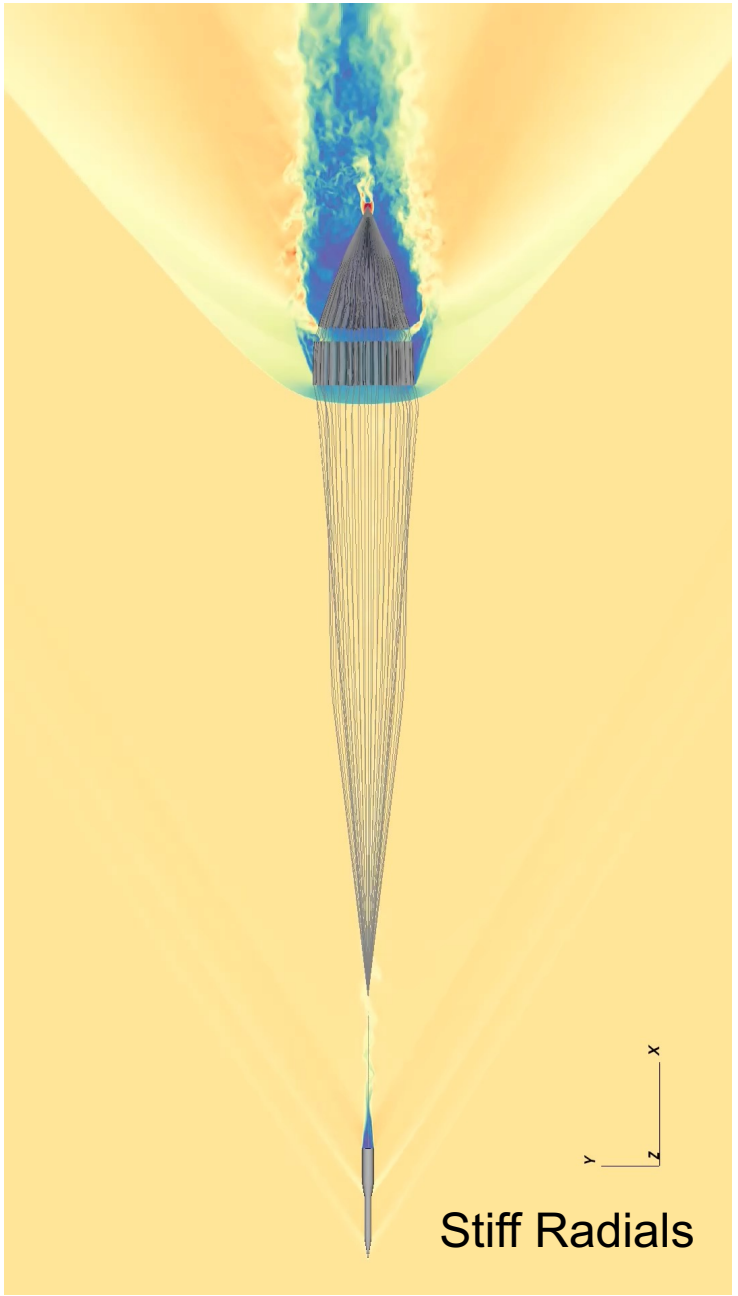
- Baseline: gore seams are not modeled

- Stiff Radials: model gore seams as Timoshenko beams with a Young's modulus of 3.87×10^{10} Pa



Results: Adding Radial Gore Seams





Changes the inflated parachute shape

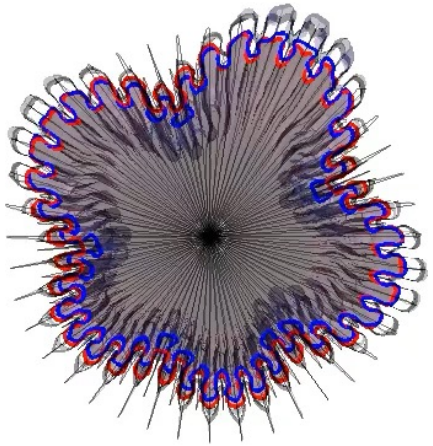
Adds local radius of curvature to each gore

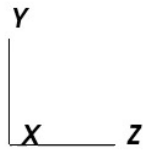
Restricts maximum projected area disk can stretch to

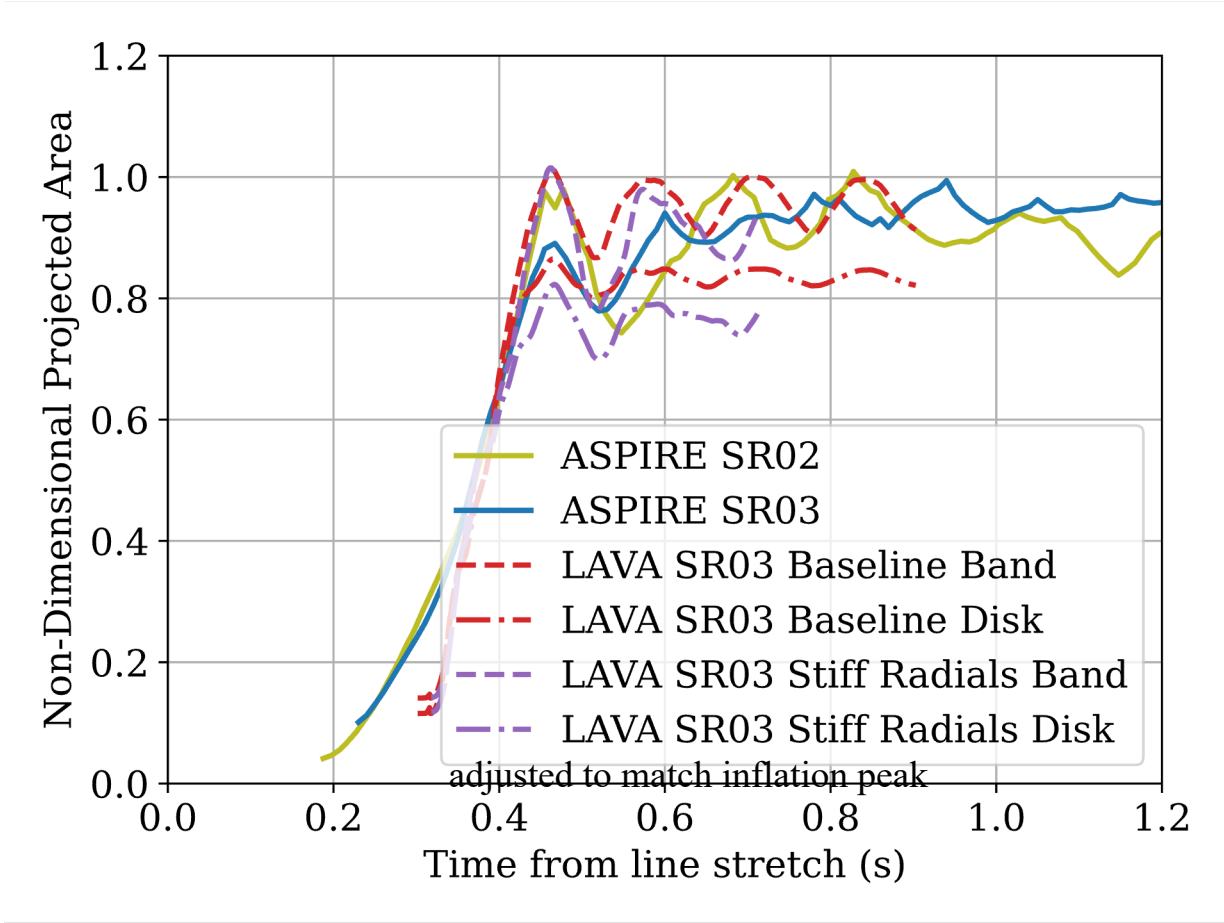
Note: movies are not synchronized due to slightly different output frequency

Results: Adding Radial Gore Seams

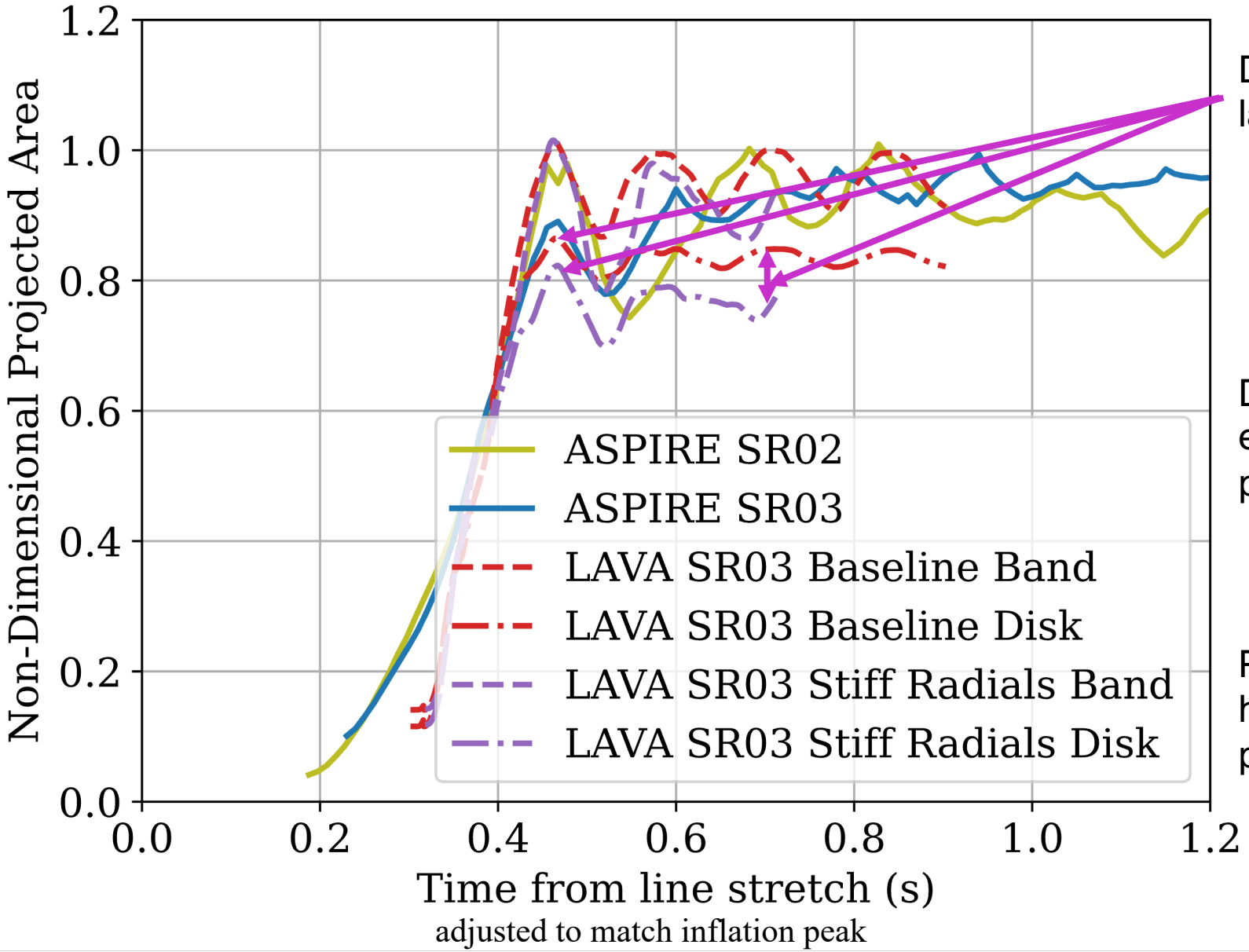
Time = 0.000239879 s
Disk Leading Edge
Blue: Baseline
Red: Stiff Radials







Results: Adding Radial Gore Seams

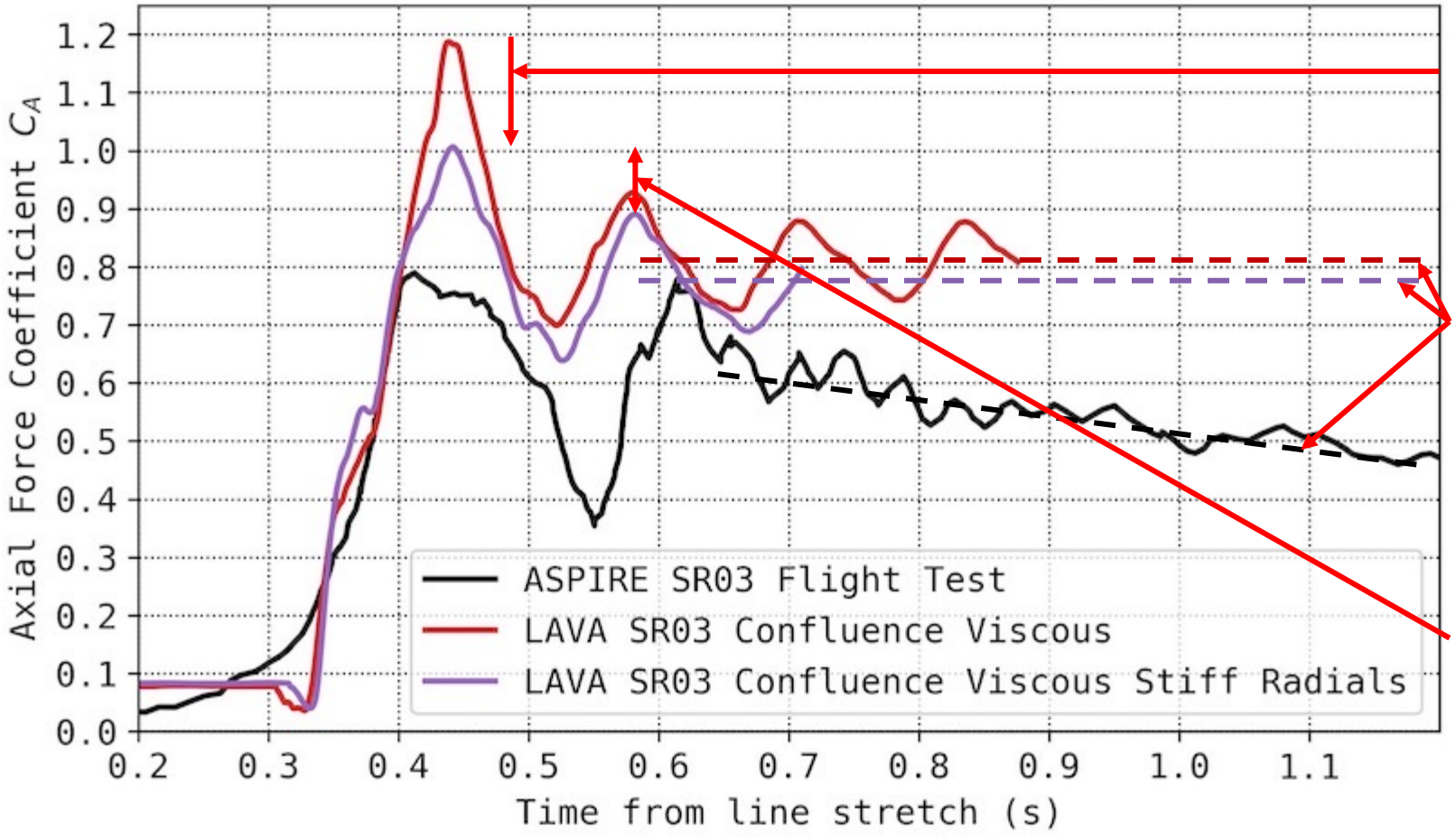


Disk without gore seams stretches to a larger area than disk with gore seams

Disk is the primary drag contributor, so we expect parachute with gore seams will produce less drag

Projected area is computed using convex hull algorithm in both ASPIRE (from pictures) and FSI (from surface)

Results: Adding Radial Gore Seams



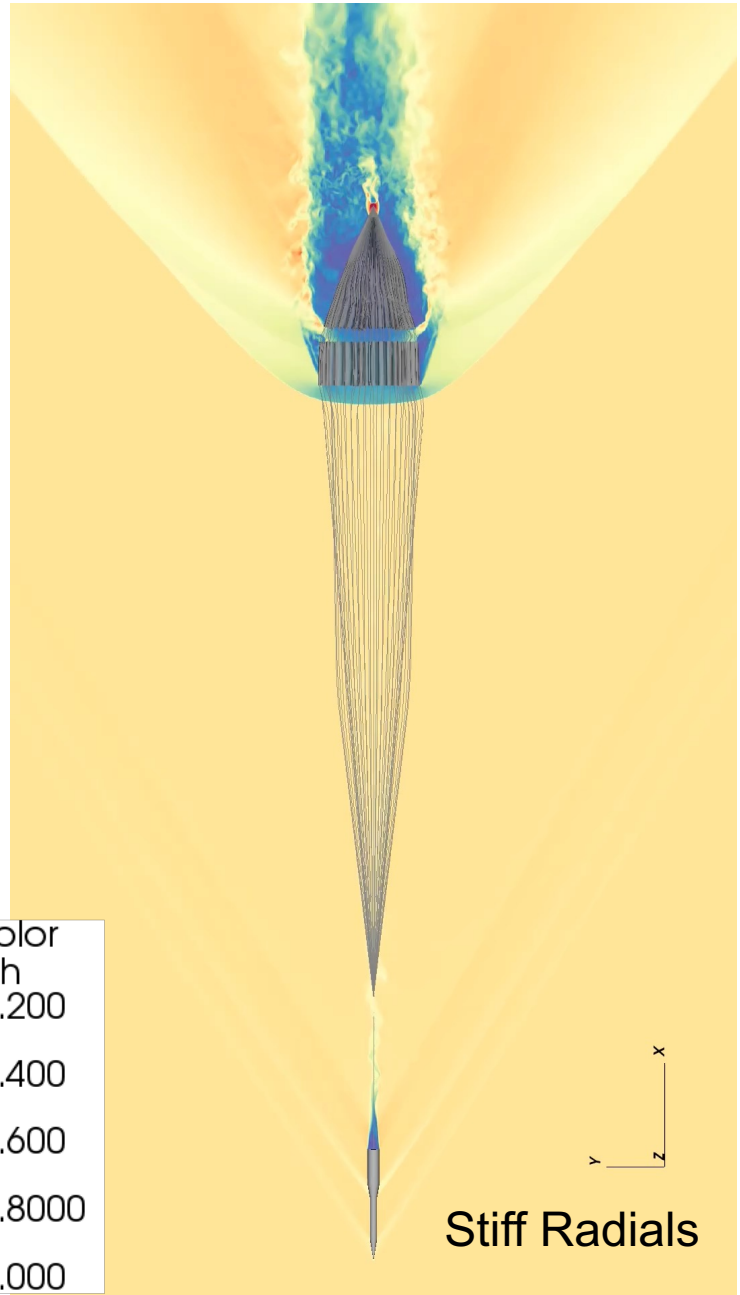
Causes 18% drop in predicted parachute aerodynamic drag driven by smaller projected area

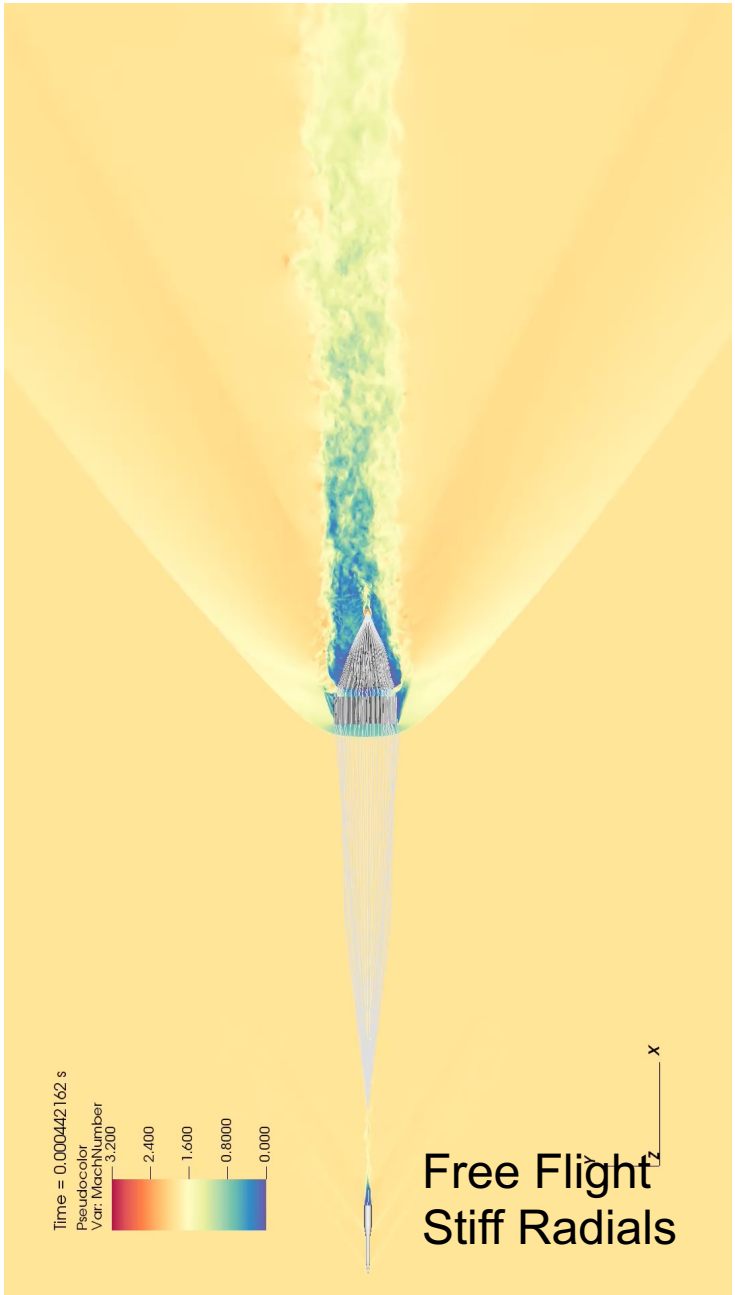
Trends toward lower statistically stationary drag for t>0.6s than without gore seams, whereas SR03 flight trends downward due to deceleration

Reduces difference between inflation peak and rebound peak

Note: FSI curves are shifted in time to take out phase difference due to different time to inflation

Results: Effect of Deceleration





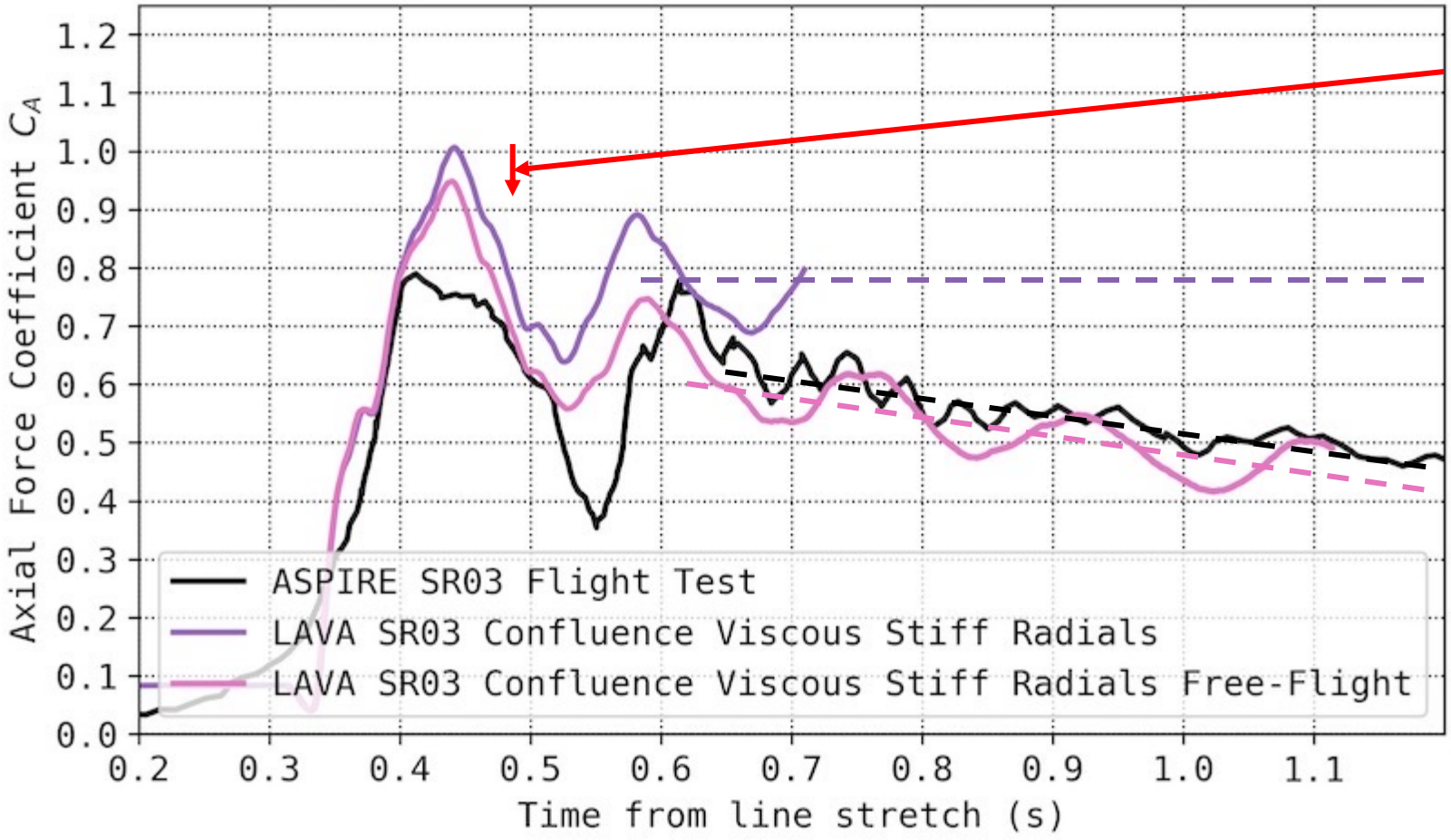
System decelerates as soon as parachute creates drag

Total (dynamic) pressure hitting canopy reduces with time due to deceleration

Bow shock strength reduces as the system decelerates

Note: movies are not synchronized due to slightly different output frequency

Results: Effect of Deceleration



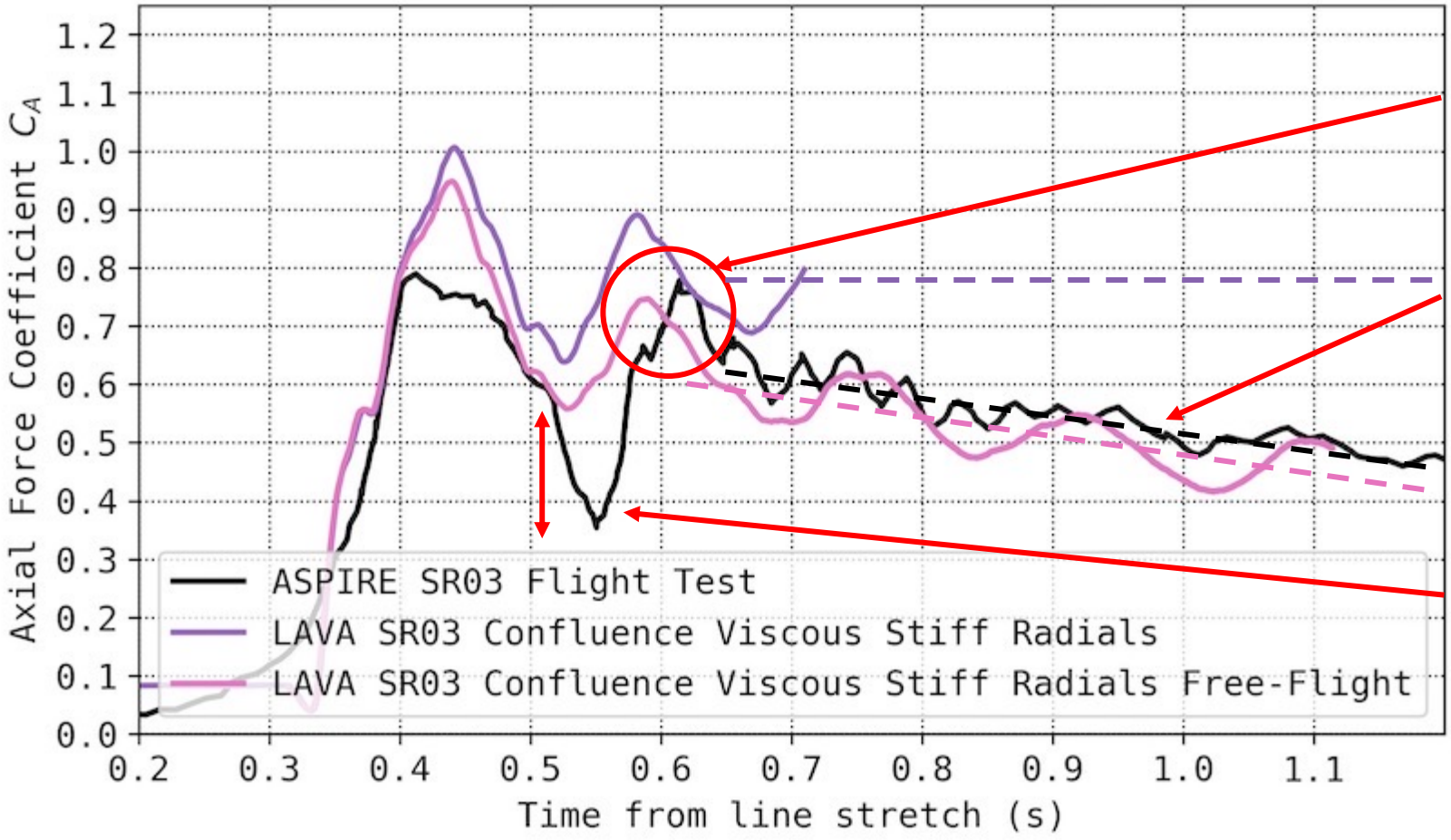
Causes 7% drop in predicted parachute aerodynamic drag

Driven by finite mass inflation instead of infinite mass inflation

Matches expected drop of ~10% from Knacke's Parachute Recovery Systems Design Manual for system's mass ratio

Note: FSI curves are shifted in time to take out phase difference due to different time to inflation

Results: Effect of Deceleration



Rebound peak now in excellent agreement with flight measurement

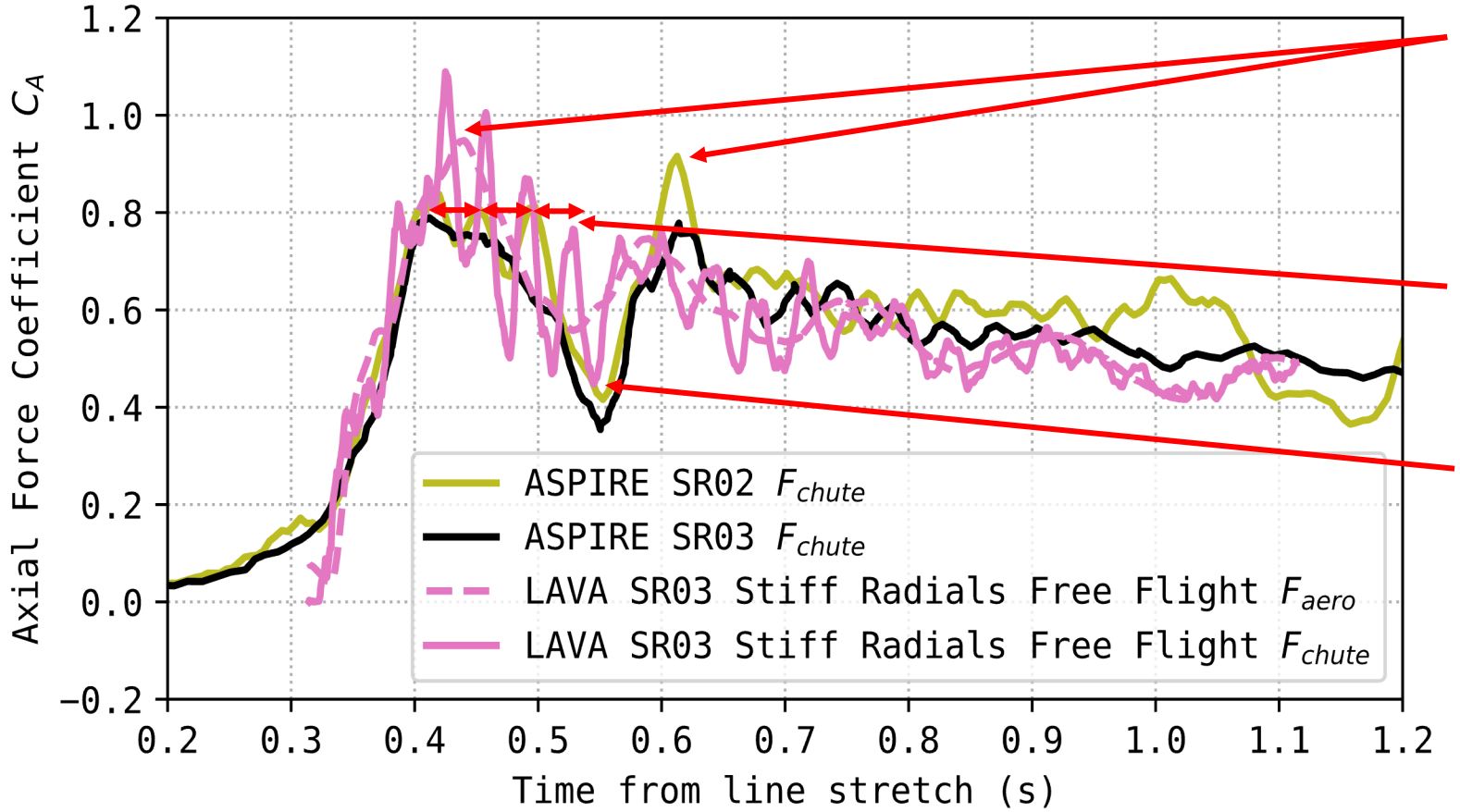
Stable deceleration phase shows matching downward slope due to reduction in dynamic pressure

Trough still appears to be over-predicted

Note: FSI curves are shifted in time to take out phase difference due to different time to inflation

Results: Effect of Deceleration

Compute total axial force parachute system imparts to payload (F_{chute}) to compare to parachute aero drag (F_{aero}) and SR02 and SR03 flight test F_{chute}



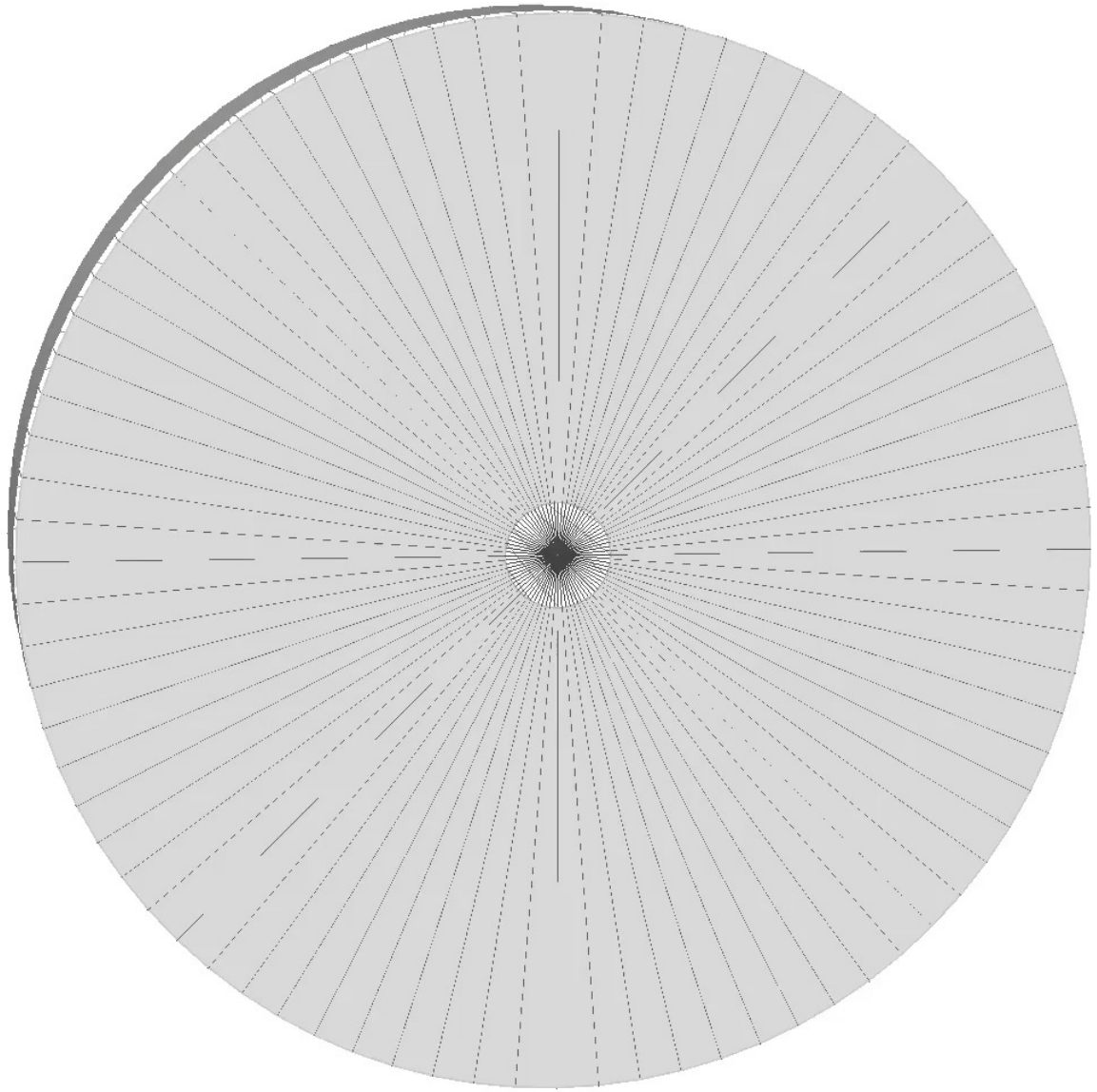
Inflation peak in family with SR02 rebound peak

F_{chute} captures suspension line mode seen in SR02 immediately following F_{aero} peak

Trough in F_{chute} in good agreement with SR02 meaning it's caused by slack in the lines, not just dip in projected area

Note: FSI curves are shifted in time to take out phase difference due to different time to inflation

Novel Method To Get Initial Parachute Shape



- Parachute shape could not be fully reconstructed from flight due to occlusion
- Perform structural dynamics with contact simulation of as-constructed parachute system with gravity in +x direction
- Bridle nodes attached to payload pinned in place

- Added simple line drag model with large drag constant to prevent suspension lines from bouncing back-and-forth
- Increased density of vent lines at t=7s to help fold canopy tighter

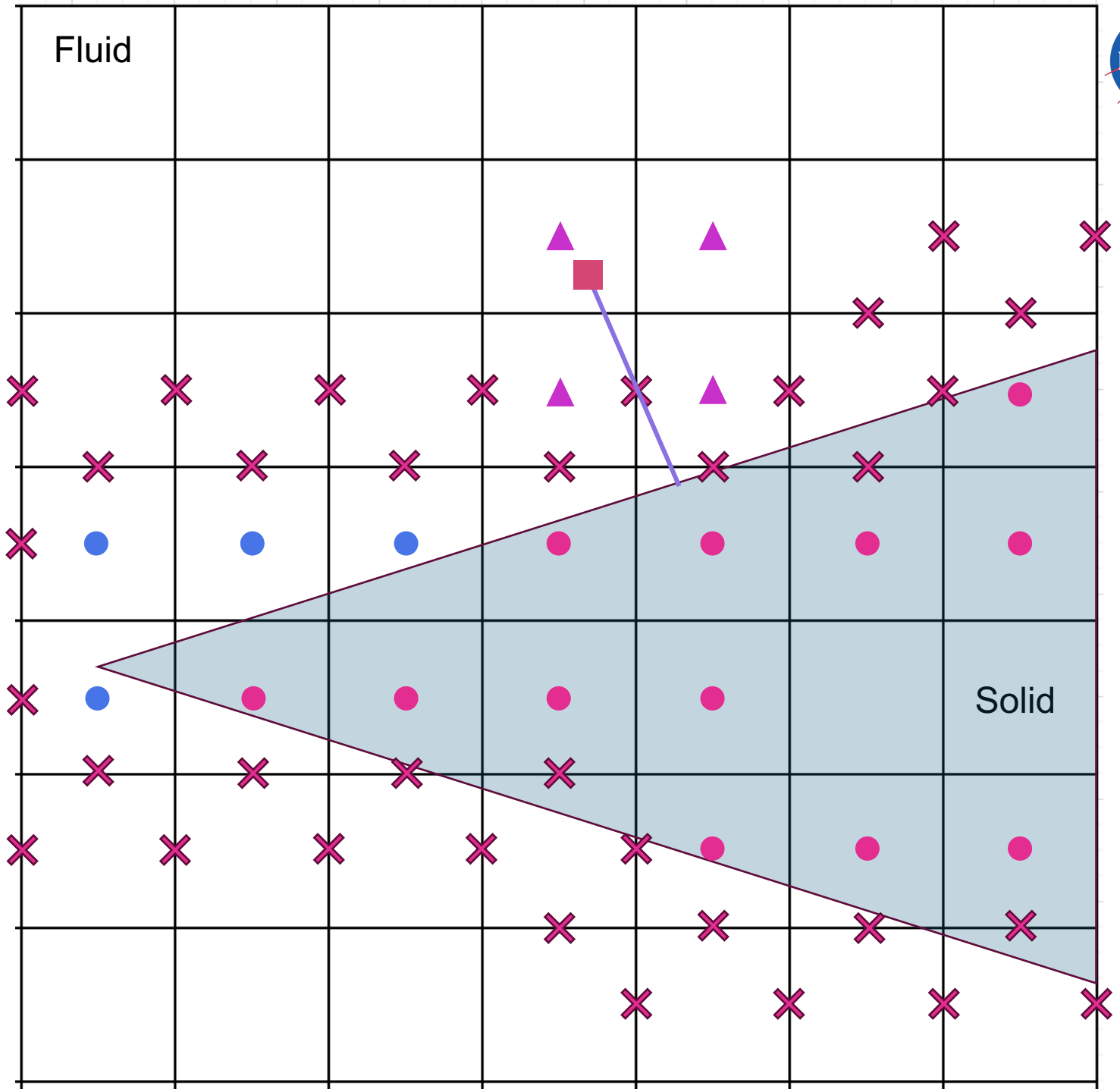
CPU Cost:
149k core-hours

Immersed Boundary Wall-Modeled LES

- Immersed boundary ghost cell
- Immersed boundary ghost-in-fluid cell
- Face where viscous flux is corrected using wall shear stress from wall model
- Example wall model matching point* for given face center
- Vector from closest point on surface to face center extended to matching point
- Interpolation stencil points for example wall model matching point

Leverage simple algebraic wall model that approximates Musker's turbulent boundary layer profile

*Only one matching point shown

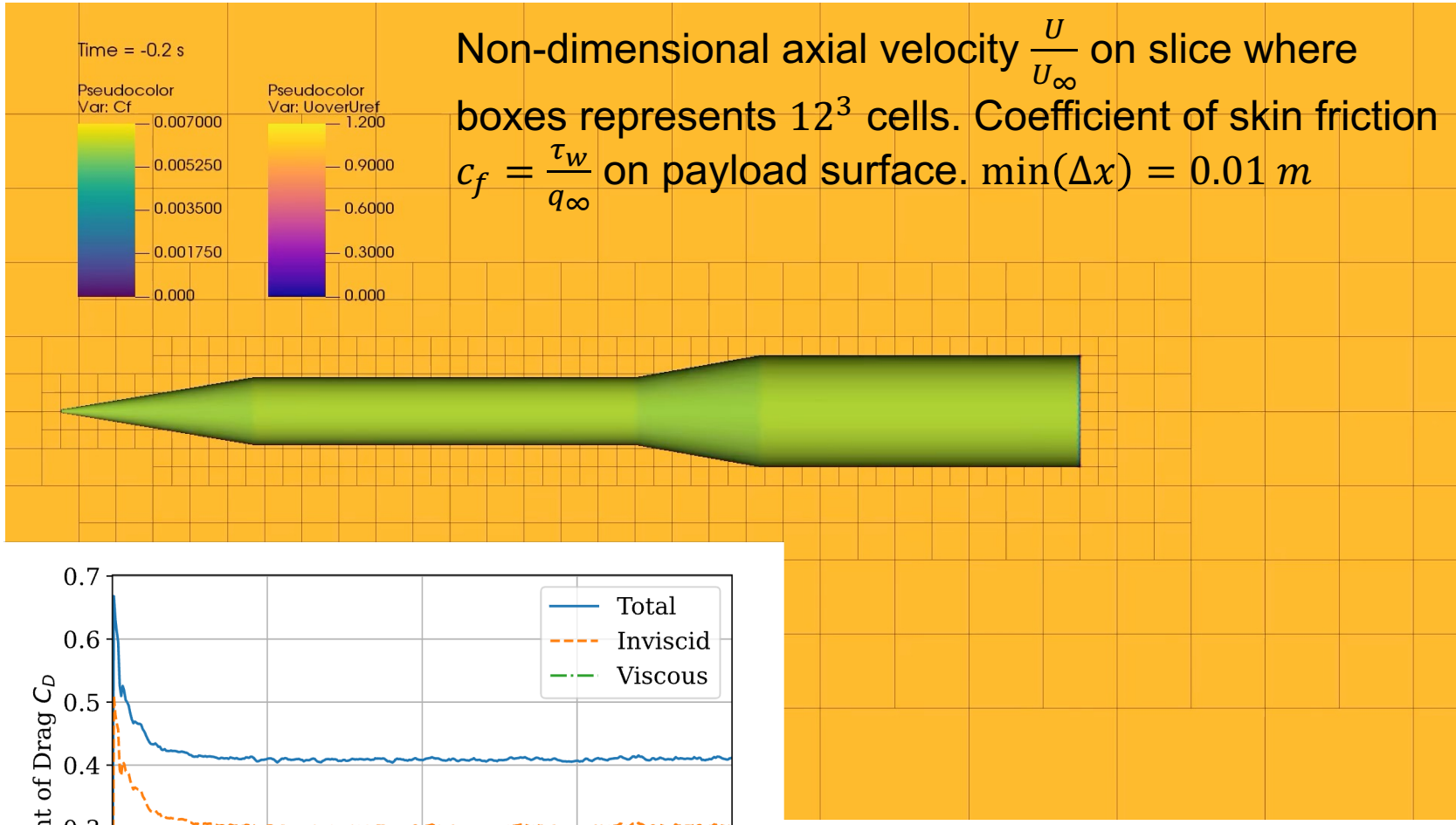


Pre-FSI WMLES Of Payload

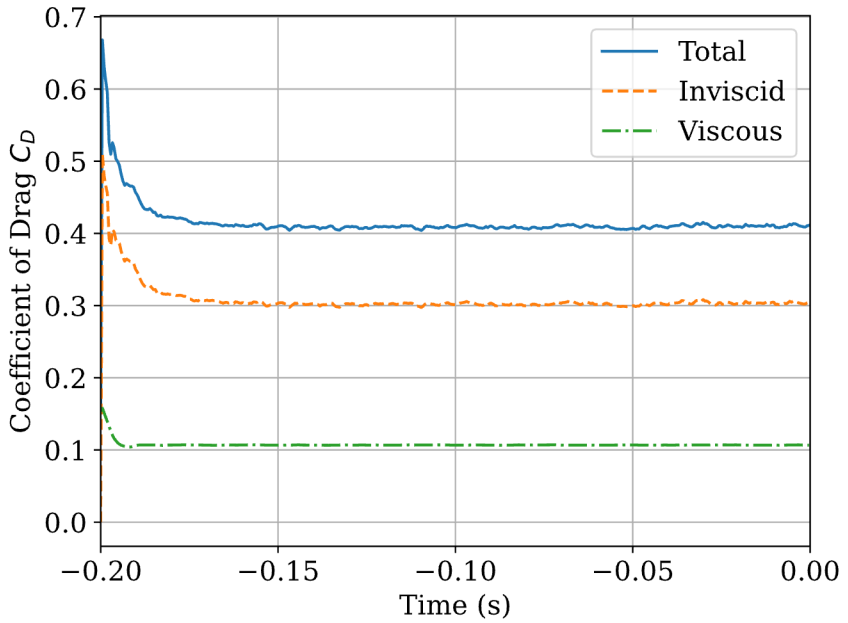
- Slender ASPIRE payload simulated for 0.2 seconds at line-stretch freestream conditions until aerodynamics load reach stationary state and wake reaches beyond parachute

- WMLES approach captures transition from laminar to turbulent boundary layer over payload, enhancing mixing in the wake

- Viscous forces represent nearly 20% of total drag on the payload, as expected from RANS simulations

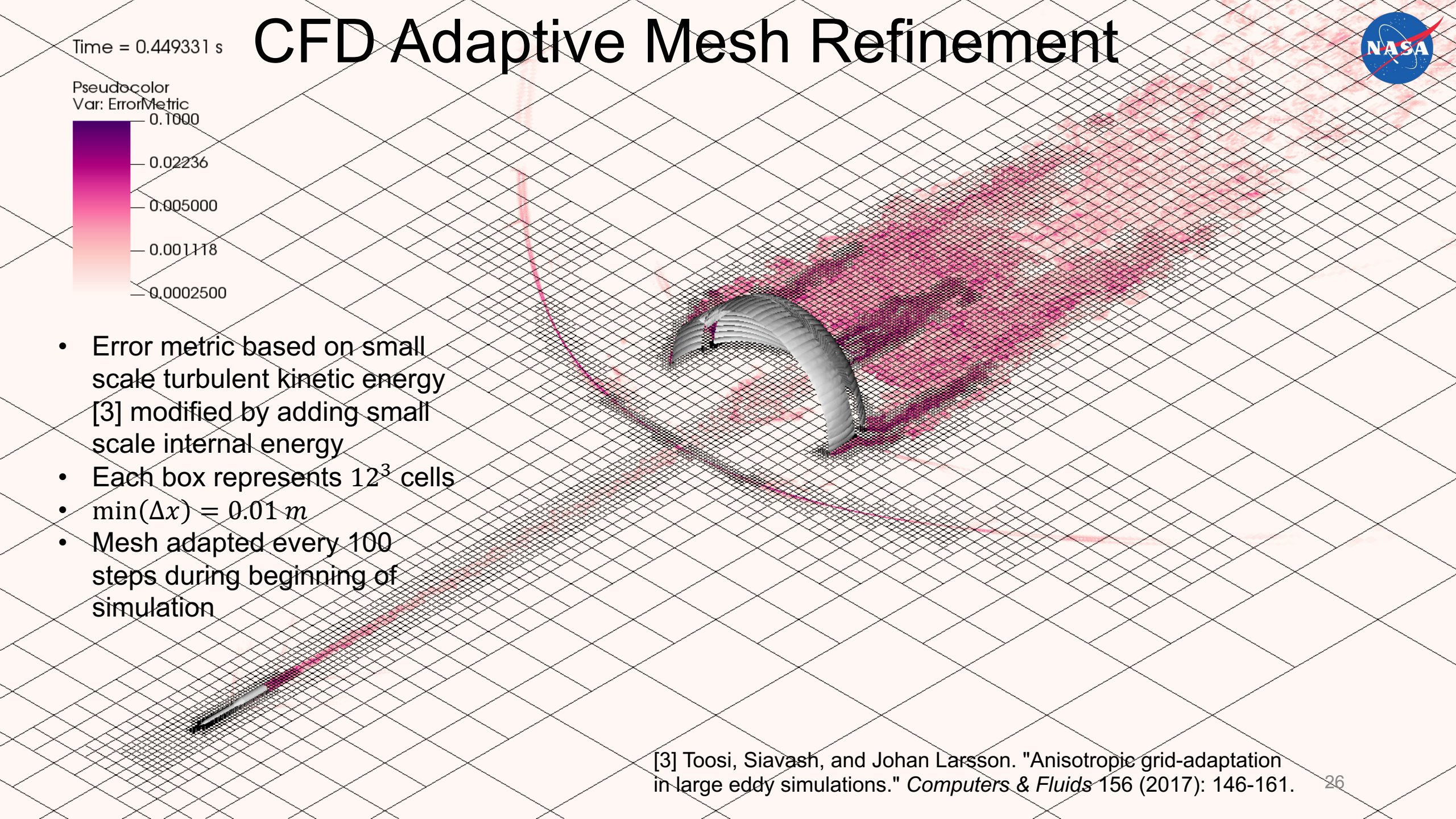


Non-dimensional axial velocity $\frac{U}{U_\infty}$ on slice where boxes represents 12^3 cells. Coefficient of skin friction $c_f = \frac{\tau_w}{q_\infty}$ on payload surface. $\min(\Delta x) = 0.01\,m$



CPU Cost:
7k core-hours

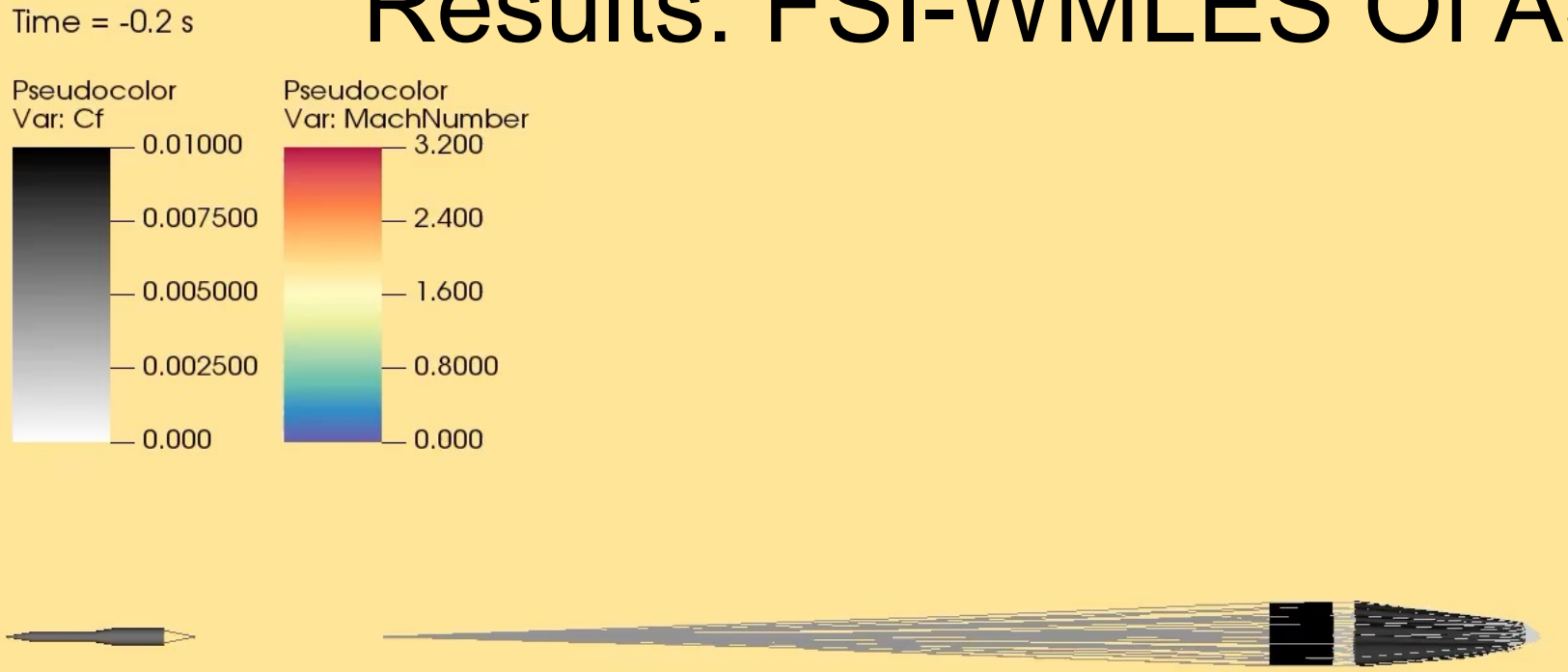
CFD Adaptive Mesh Refinement

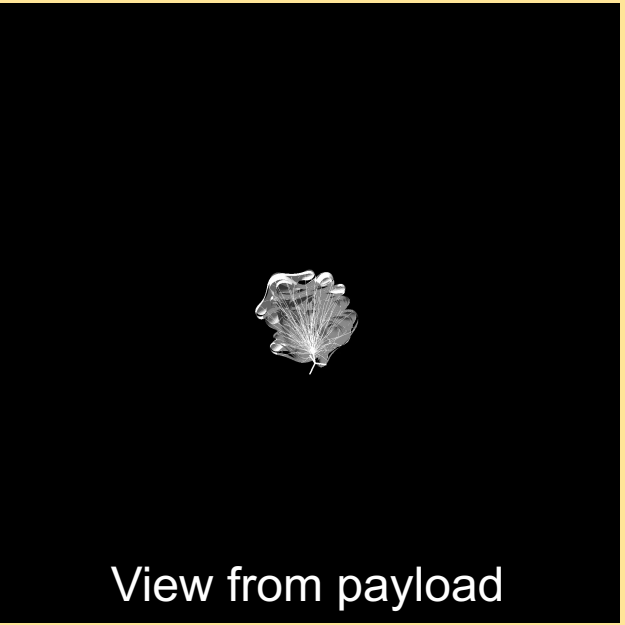


- Error metric based on small scale turbulent kinetic energy [3] modified by adding small scale internal energy
- Each box represents 12^3 cells
- $\min(\Delta x) = 0.01\,m$
- Mesh adapted every 100 steps during beginning of simulation

[3] Toosi, Siavash, and Johan Larsson. "Anisotropic grid-adaptation in large eddy simulations." *Computers & Fluids* 156 (2017): 146-161.

Results: FSI-WMLES Of ASPIRE SR03

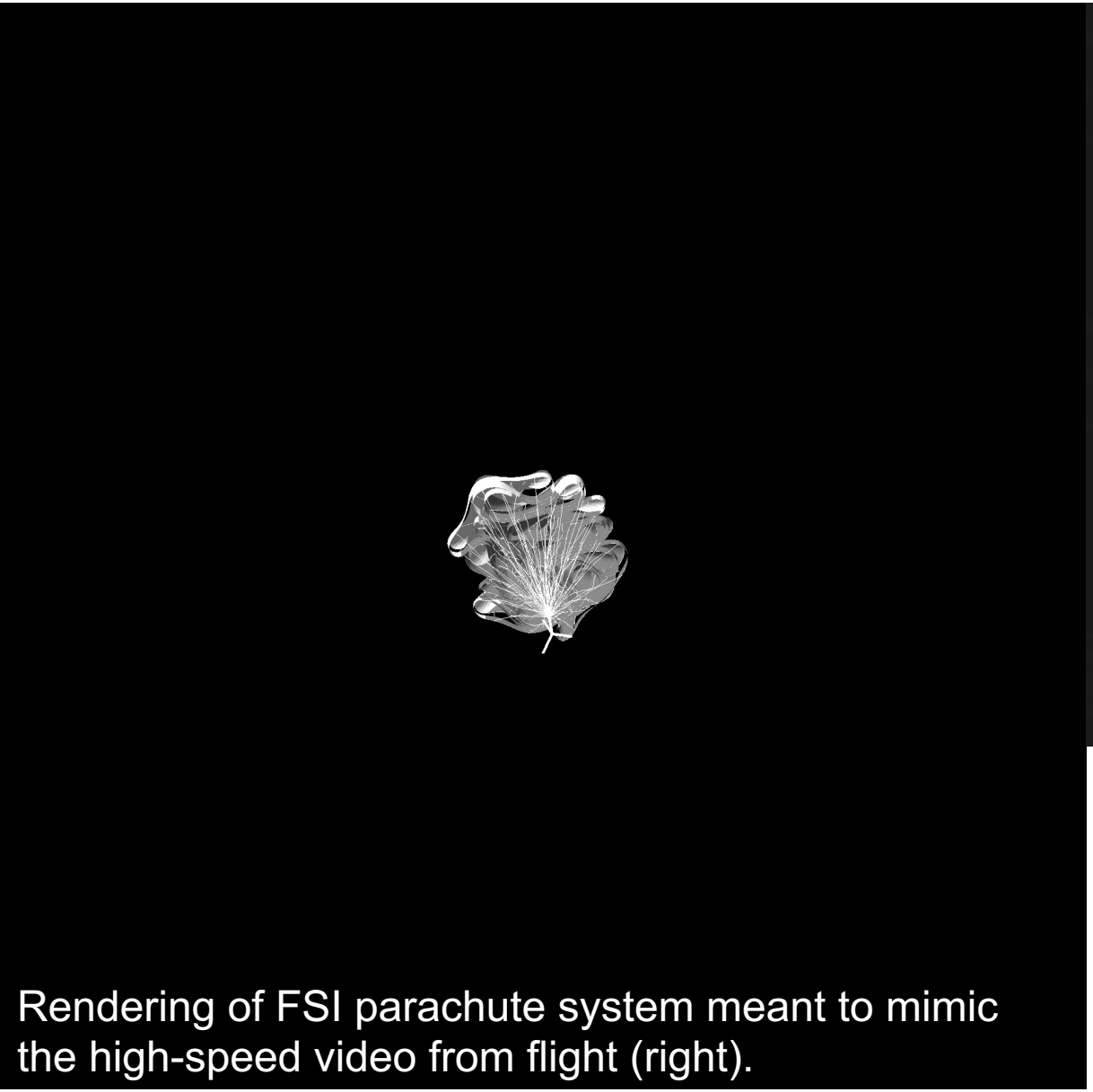




Mach number on the slice and skin friction coefficient on the payload and canopy surface. Vent, gap, suspension, riser, and bridle lines shown in gray.

CPU Cost:
747k core-hours

Qualitative Comparison to ASPIRE SR03



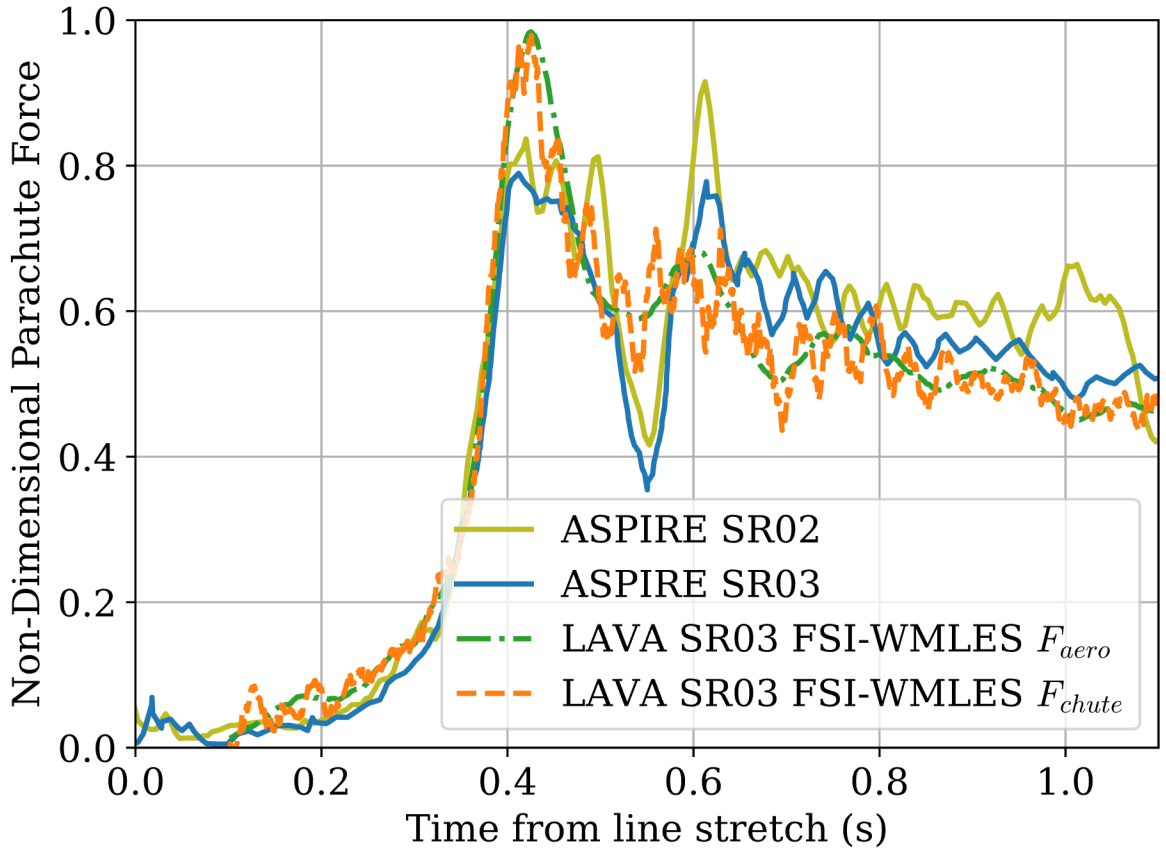
Rendering of FSI parachute system meant to mimic the high-speed video from flight (right).



This high-definition video was taken on Sept. 7, 2018, during the third and final test flight of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) campaign to certify the Mars 2020 parachute. It was the fastest inflation of this size parachute in history and created a peak load of almost 70,000 pounds of force. ***Credits: NASA/JPL-Caltech***
https://www.nasa.gov/feature/jpl/third-aspire-test-confirms-mars-2020-parachute-a-go

Results: Parachute Force

Parachute force (F_{chute}) is the total axial force the parachute system imparts to the payload.
Parachute aerodynamic drag (F_{aero}) is the integrated axial force over the parachute canopy in FSI.



*FSI is offset by +0.1 s and SR02 offset by -0.0375 s to remove phase shift due to different inflation times.

For ASPIRE:

$$F_{chute} = F_{LP} - m_{chute} a_{payload}$$

where

F_{LP} = sum of forces measured at load pins
m_{chute} = parachute mass
$a_{payload}$ = measured payload acceleration

For FSI:

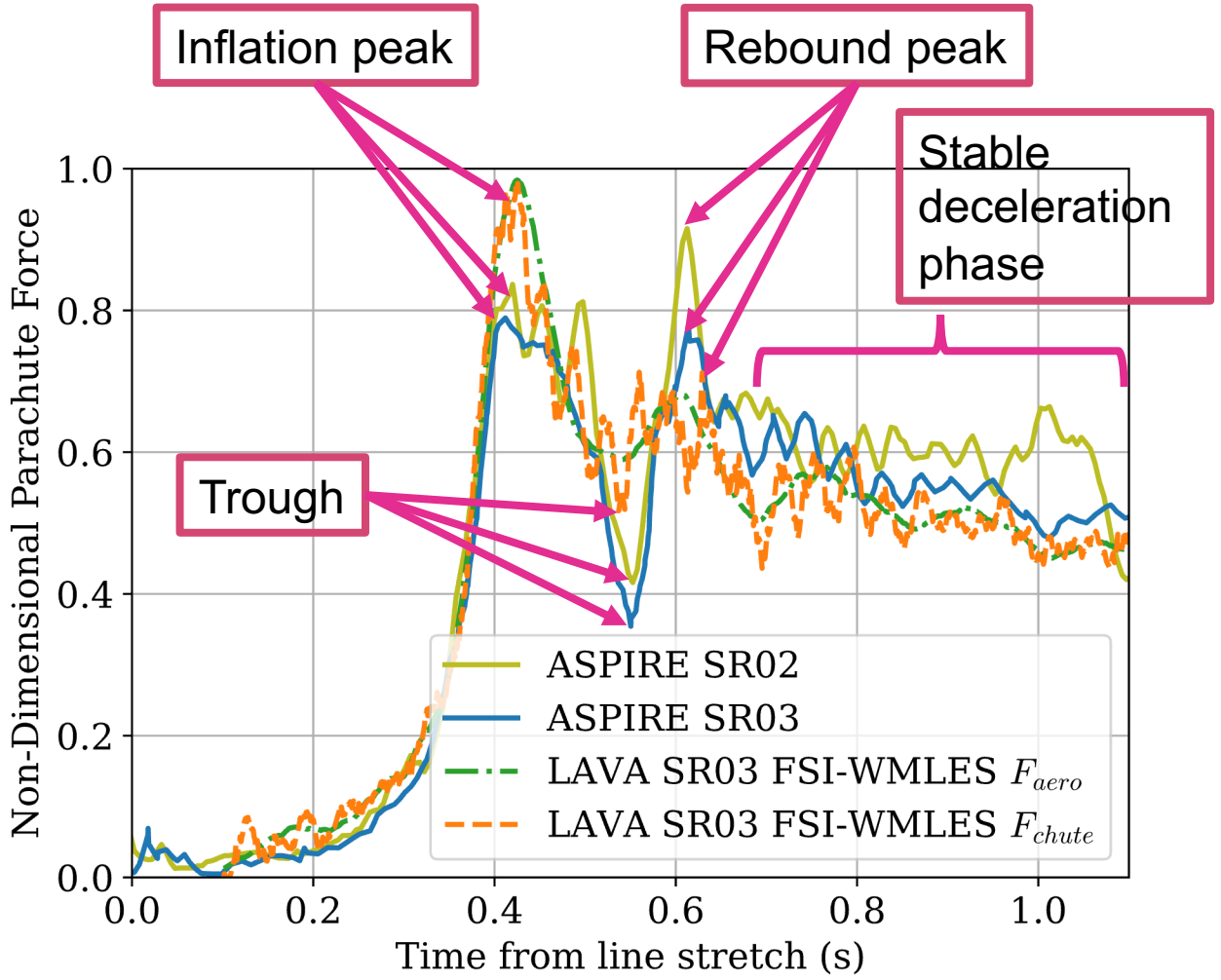
$$F_{chute} = -m_{total} a_{payload} - F_{payload,aero}$$

where

m_{total} = total mass of system
$a_{payload}$ = payload acceleration
$F_{payload,aero}$ = payload aerodynamic drag

Note that the payload is decelerating so $a_{payload} < 0$ so terms $-ma_{payload} > 0$

Results: Parachute Force

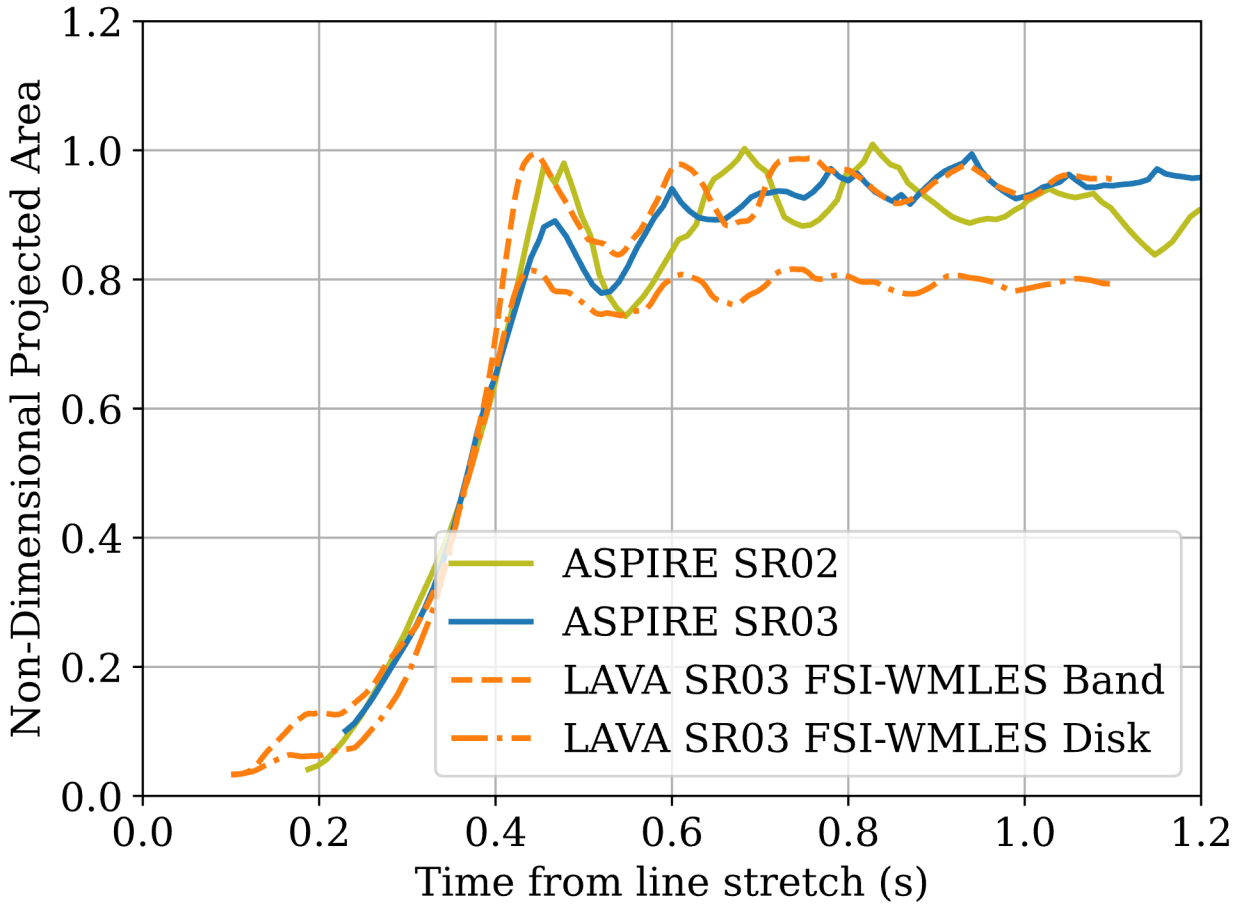


*Time offset to go from CFD time to "time from line stretch" is +0.1 s.

- Over-predicts inflation peak drag by 17%, but within family when compared to SR02 rebound peak
- Match downward slope of flight test during stable deceleration phase
- Predicts suspension line mode of ~27 Hz (~0.038 s) in close agreement with flight tests for F_{chute}

Results: Projected Area

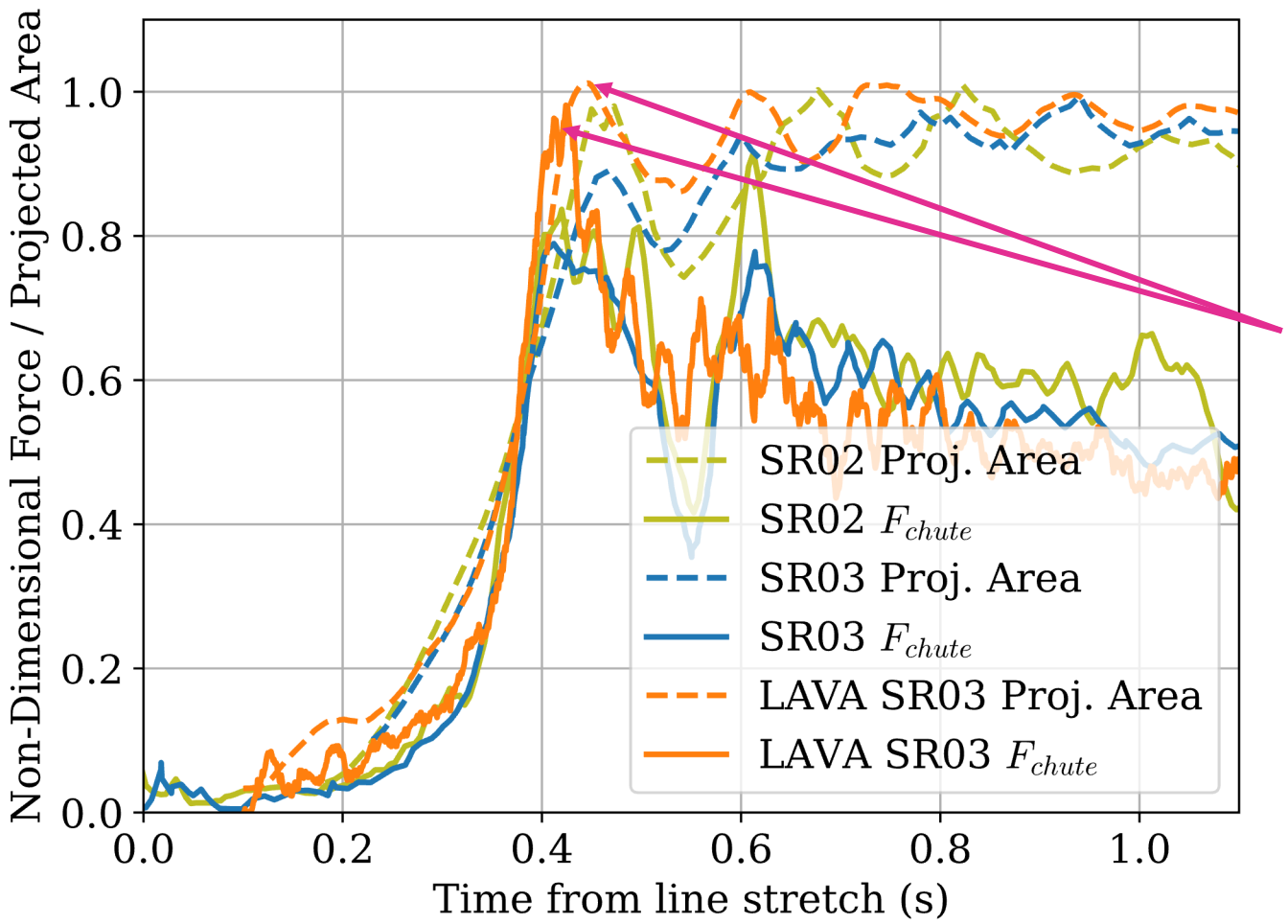
Projected area is computed using convex hull algorithm in both ASPIRE (from pictures) and FSI (from surface)



*FSI is offset by +0.1 s and SR02 offset by -0.0375 s to remove phase shift due to different inflation times.

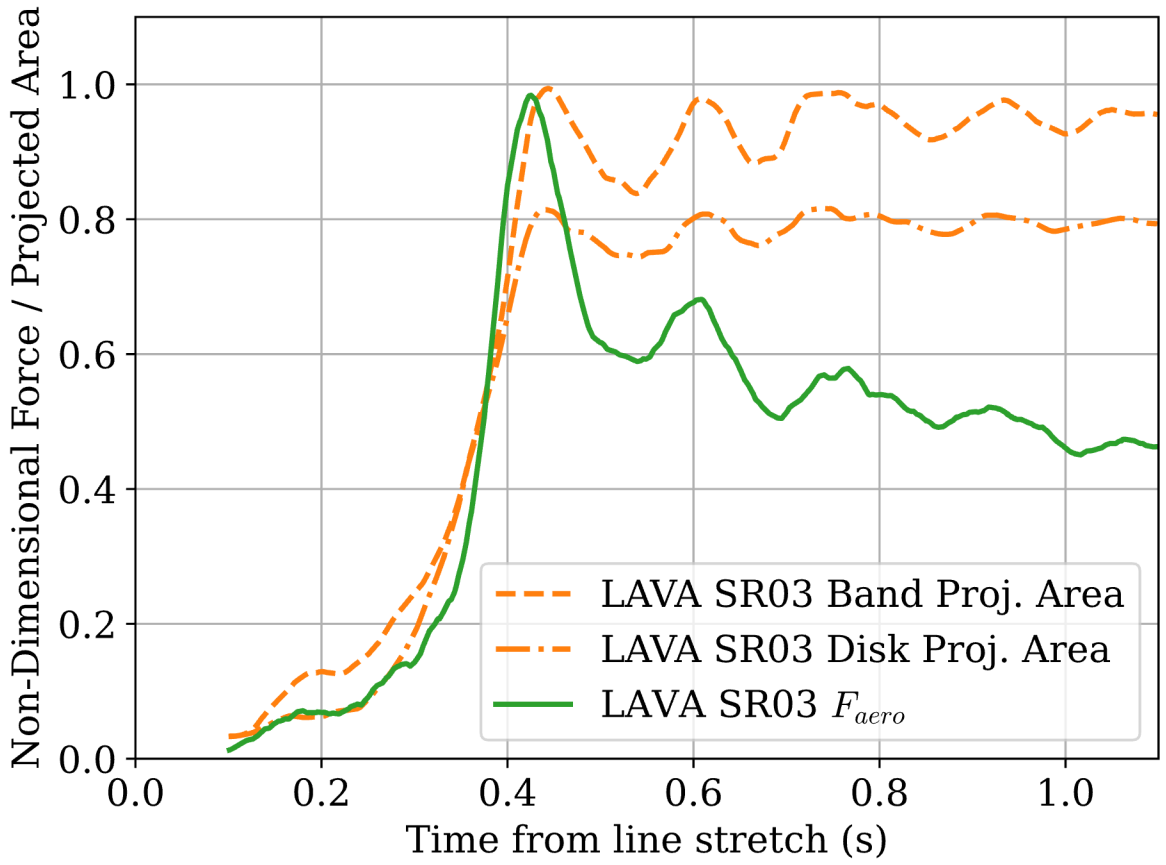
- Inflation rate matches well until 0.4s after which FSI parachute model predicts faster inflation
- Over-predicts first area peak by 12% compared to SR03, but within 5% of SR02
- Displays area “breathing” mode in good agreement with SR03

Results: Chute Force vs Projected Area



- FSI correctly captures flight test trend where peak F_{chute} precedes first area peak

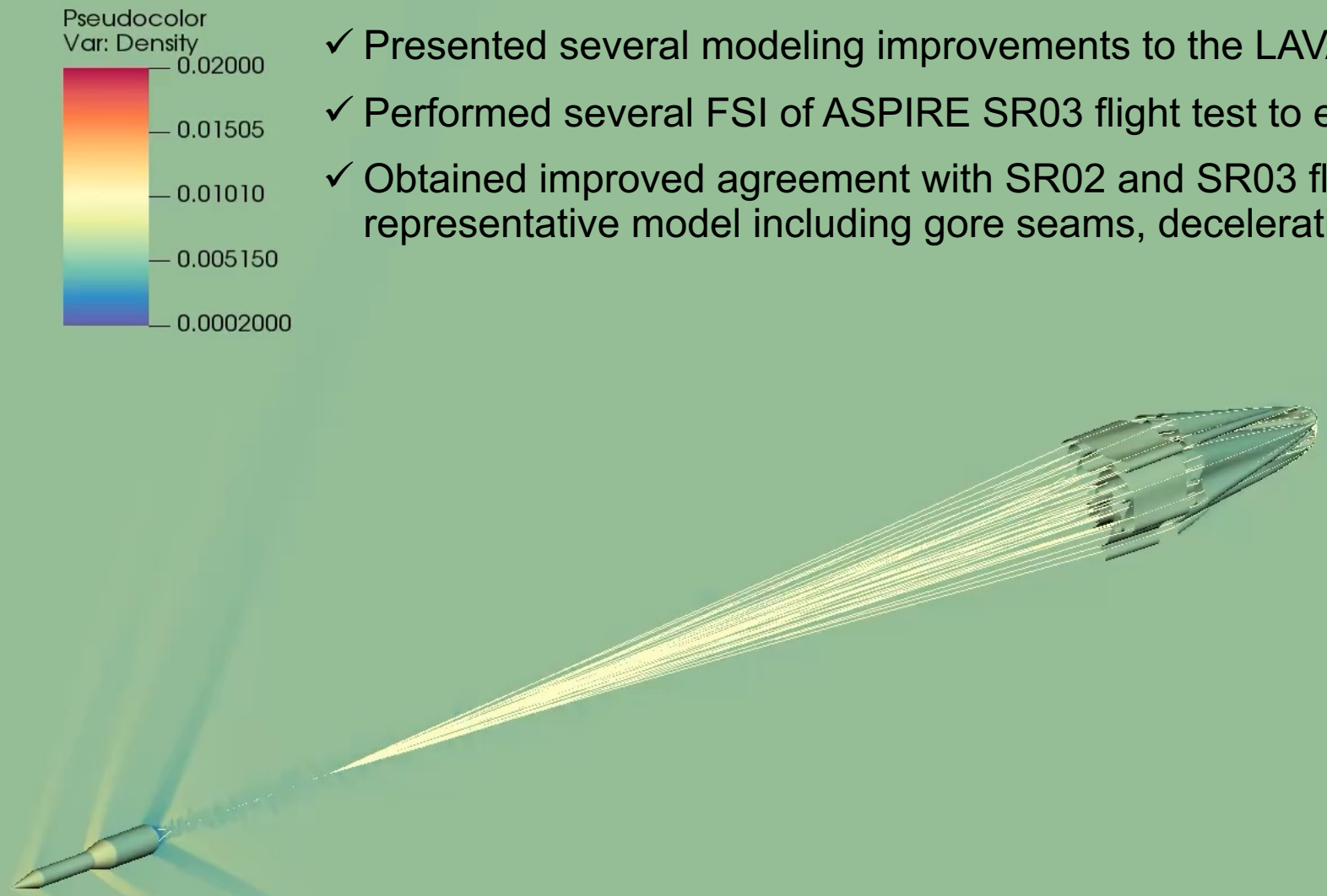
Results: Drag Vs Disk Area



- As expected, aerodynamic drag is directly correlated with the projected area after initial peak

Conclusions

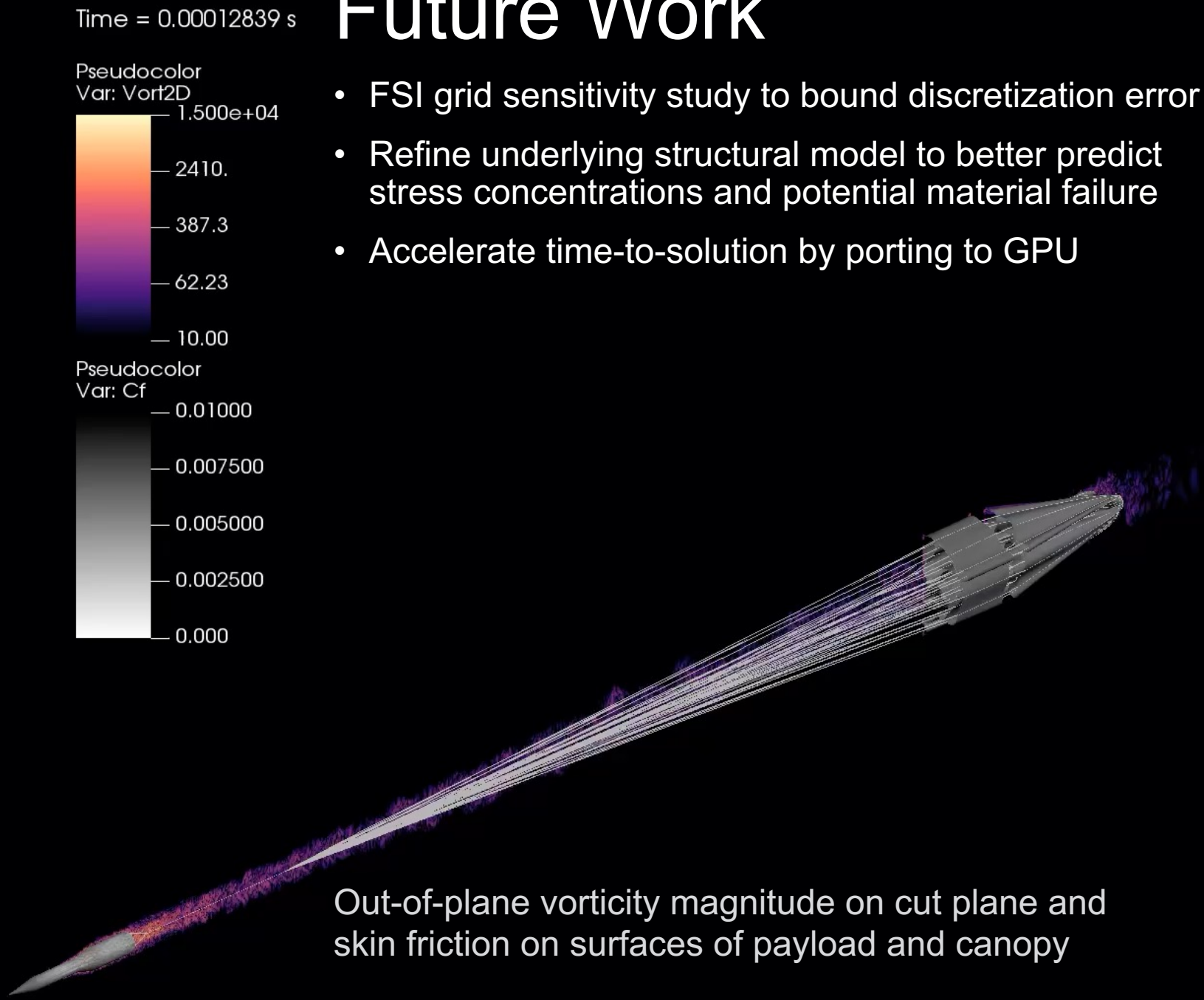
- ✓ Presented several modeling improvements to the LAVA FSI capability
- ✓ Performed several FSI of ASPIRE SR03 flight test to elucidate their individual effect
- ✓ Obtained improved agreement with SR02 and SR03 flight test measurements with most representative model including gore seams, deceleration, and tighter initial parachute shape



Density on surfaces and cut plane

Future Work

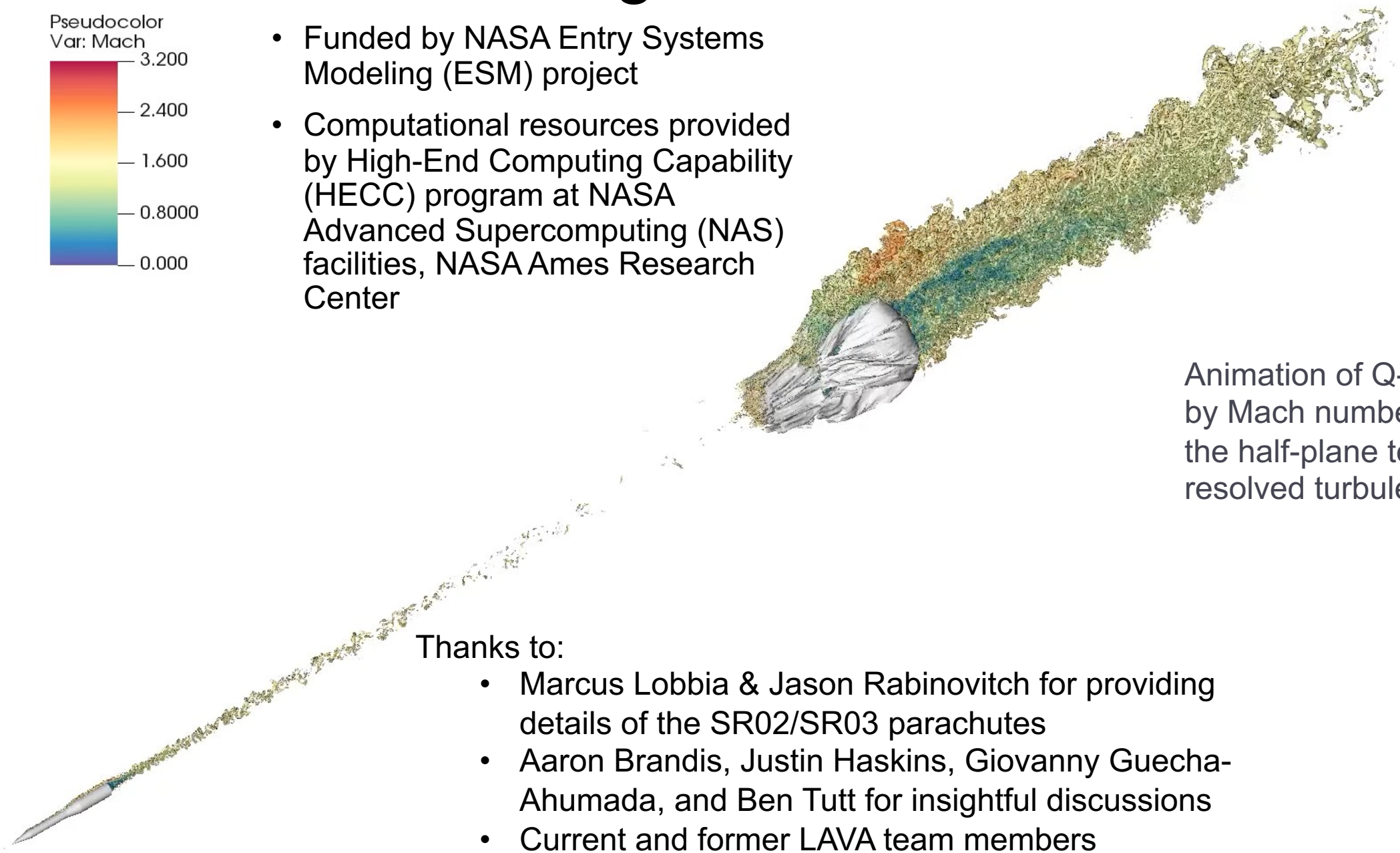
- FSI grid sensitivity study to bound discretization error
- Refine underlying structural model to better predict stress concentrations and potential material failure
- Accelerate time-to-solution by porting to GPU



Out-of-plane vorticity magnitude on cut plane and skin friction on surfaces of payload and canopy

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Animation of Q-criterion colored by Mach number and clipped at the half-plane to highlight resolved turbulent structures

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