Università degli Studi di Padova

High-Fidelity Modeling of Supersonic Decelerators for Planetary Descent

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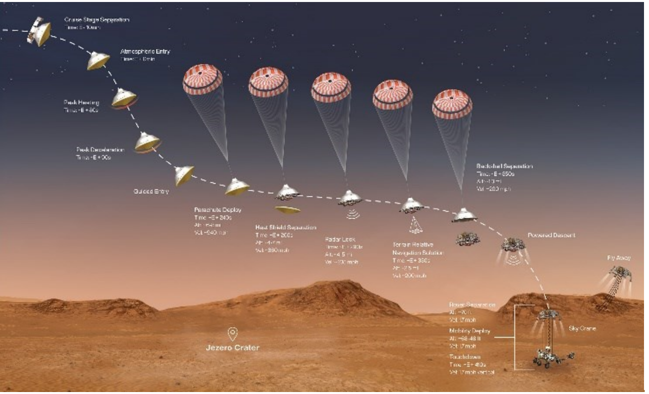
Supervisor: Prof. Federico Dalla Barba

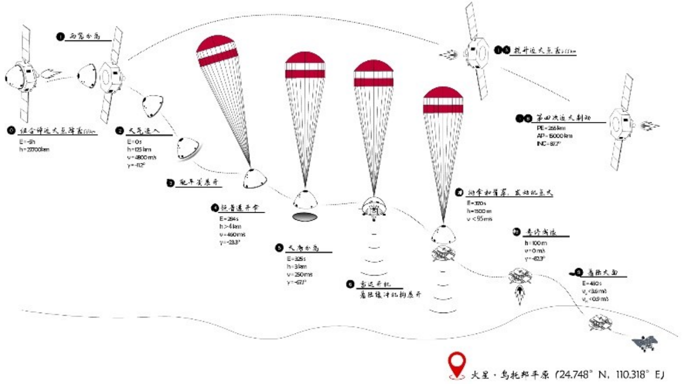
Co-supervisor: Prof. Francesco Picano

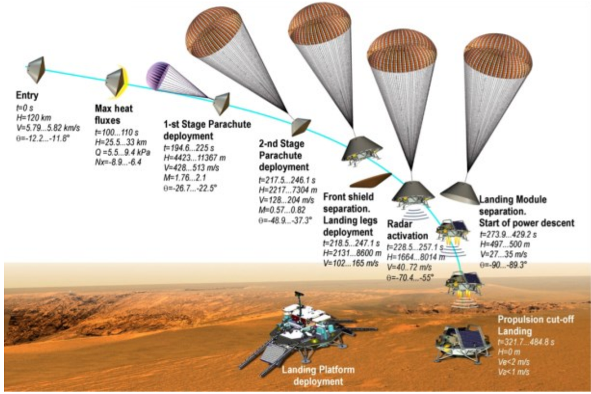
Admission to the second year – 13/09/2023

Introduction: context and motivations

Recent space exploration mission – Mars







Perseverance – Feb. 2021
(*NASA/JPL-Caltech*)

Tienwen-1 – May 2021
(*Info Shymkent*)

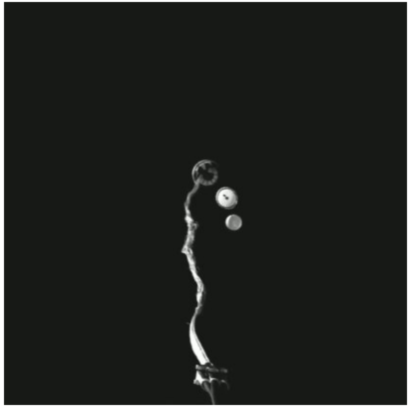
Rosalind Franklin – TBD
(*ESA/AOES Medialab*)

- Entry, descent and landing are considered the most critical phases for space exploration missions – decelerator **models** are still **insufficient** *(SAIR, 2016)*.

→ **Investigate aerodynamic phenomena concerning the descent phase of a capsule.**

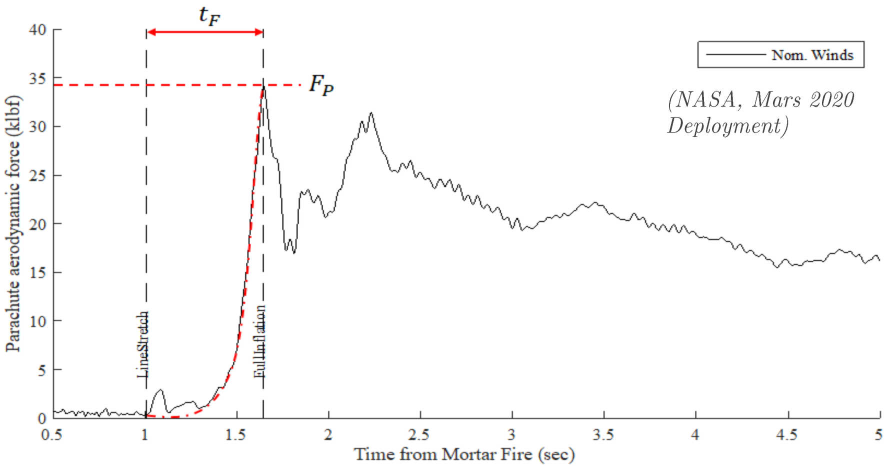
Introduction: objectives

- Development of a **fluid-structure interaction framework** to investigate transient **unsteady aerodynamic phenomena** concerning the **descent** phase of a capsule:



(ESA, Drop test 2021)

Inflation sequence and time



Peak loadings

(ESA, Drop test 2021)

Canopy instabilities

Progress and aim of the research

❖ Capsule and thick rigid-decelerator aerodynamics

- ✓ Simulation of a descent capsule at multiple angle-of-attack: study on the wake turbulence.
- ✓ Simulation of a rigid thick-interface (supersonic parachute) interacting with a capsule.
- ✓ Development of an analytical model for the parachute unsteady dynamics.

❖ Thin-interface IBM modeling and rigid thin-decelerator aerodynamics

- ✓ Development of a novel algorithm (Immersed-Boundary based) to deal with thin interfaces.
- ✓ One-dimensional testing and validation of the interface.
- ❑ Porting of the algorithm to three-dimension and implementation in STREAmS. (Y2)
- ❑ Wall-model implementation to deal with boundary-layer representation. (Y2)
- ❑ Simulation of a rigid thin-interface interacting with a descent capsule. (Y2)

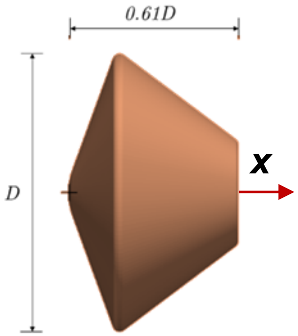
❖ Fluid-structure Interaction modeling

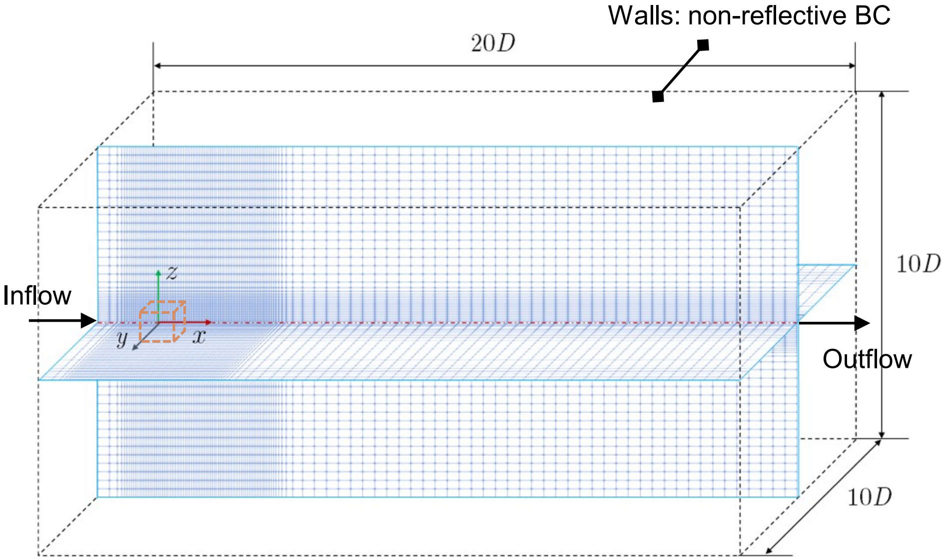
- ❑ Coupling of the IBM thin interface with the FEM structural model. (Y3)
- ❑ Simulation of the deployment sequence of a supersonic parachute during the descent. (Y3)

LES of a descent capsule: domain

- **Descent capsule** at different **angles-of-attack** (0° to 15°) – wake dynamics evaluation.
- Supersonic regime: $\boldsymbol{Ma} = \mathbf{2}$ and $\boldsymbol{Re} = \mathbf{10^6}$ - Martian atmosphere parameters.

- Altitude: ~ 9 km
- Temperature: ~ 220 K
- Density: ~ 0.0062215 Kg/m^3
- Pressure: ~ 265 Pa
- Viscosity: ~ 1.123E-05 Pa s
- Ideal gas: CO_2, ~ 95%
- D (ref. length) = 3.8 m

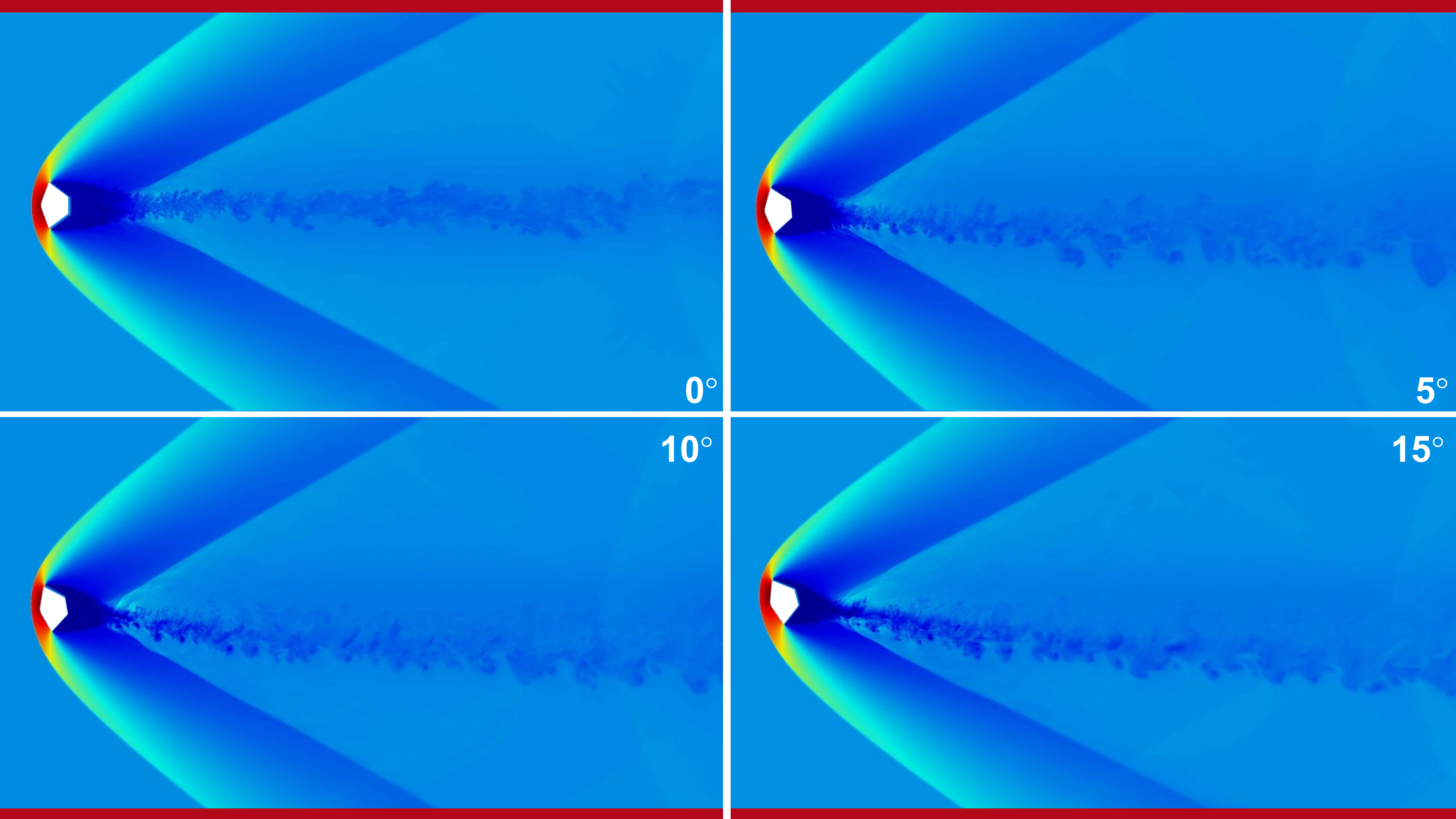




STREAmS 2.0

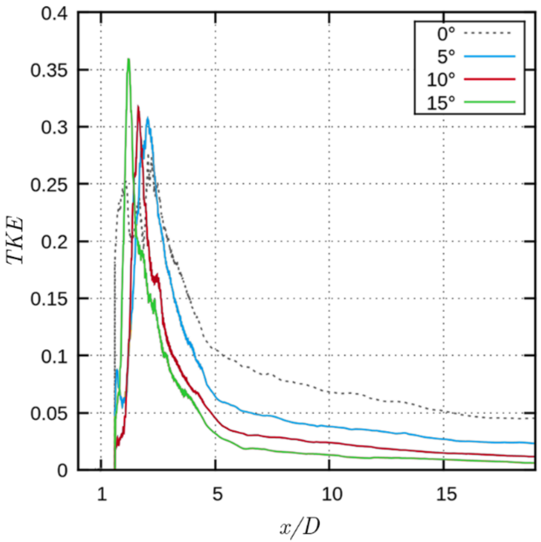
- Large-eddy simulation (LES) flows solver
- Massive parallelisation on GPU
- Built-in Immersed-Boundary Method (IBM) for complex geometries.

Performed on 32 GPU – MARCONI100 at CINECA

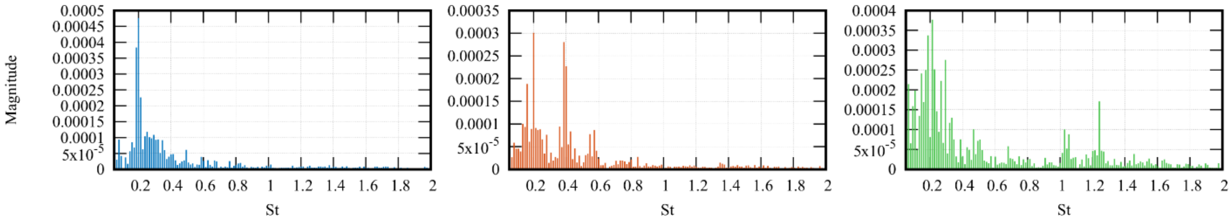


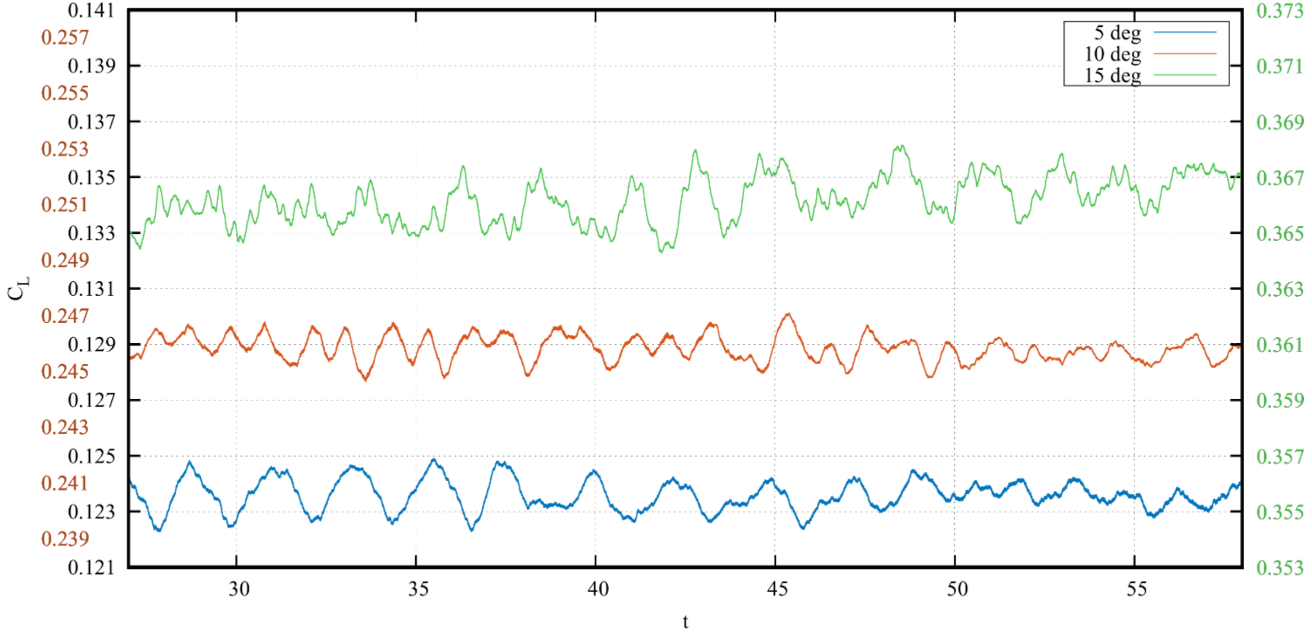
0°
5°
10°
15°

LES of a descent capsule: results



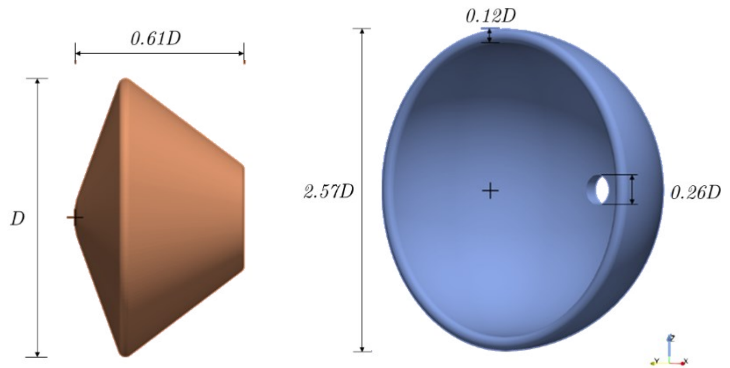
- TKE along the flow direction in the mid plane (axis) at different AoA.
- DFT Analysis of the lift coefficient at different AoA.

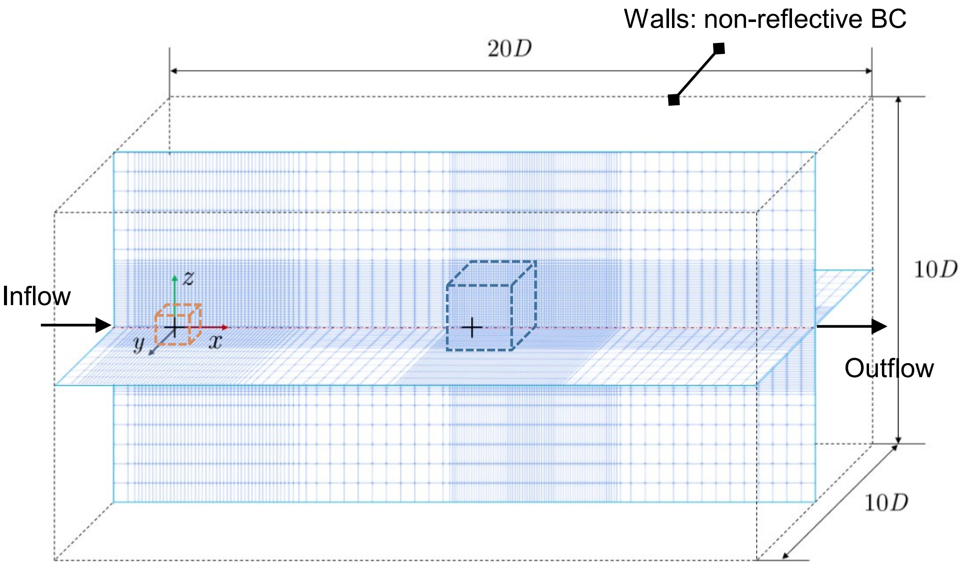




LES of a rigid thick-interface (parachute)

- **Rigid** (mock-up) parachute configuration: evaluate **fluid-dependant** instabilities only.
- Supersonic regime: $\boldsymbol{Ma} = \mathbf{2}$ and $\boldsymbol{Re} = \mathbf{10^6}$ - Martian atmosphere parameters.





- Large-eddy simulation (LES) flows solver
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Performed on 64 GPU – MARCONI100 at CINECA

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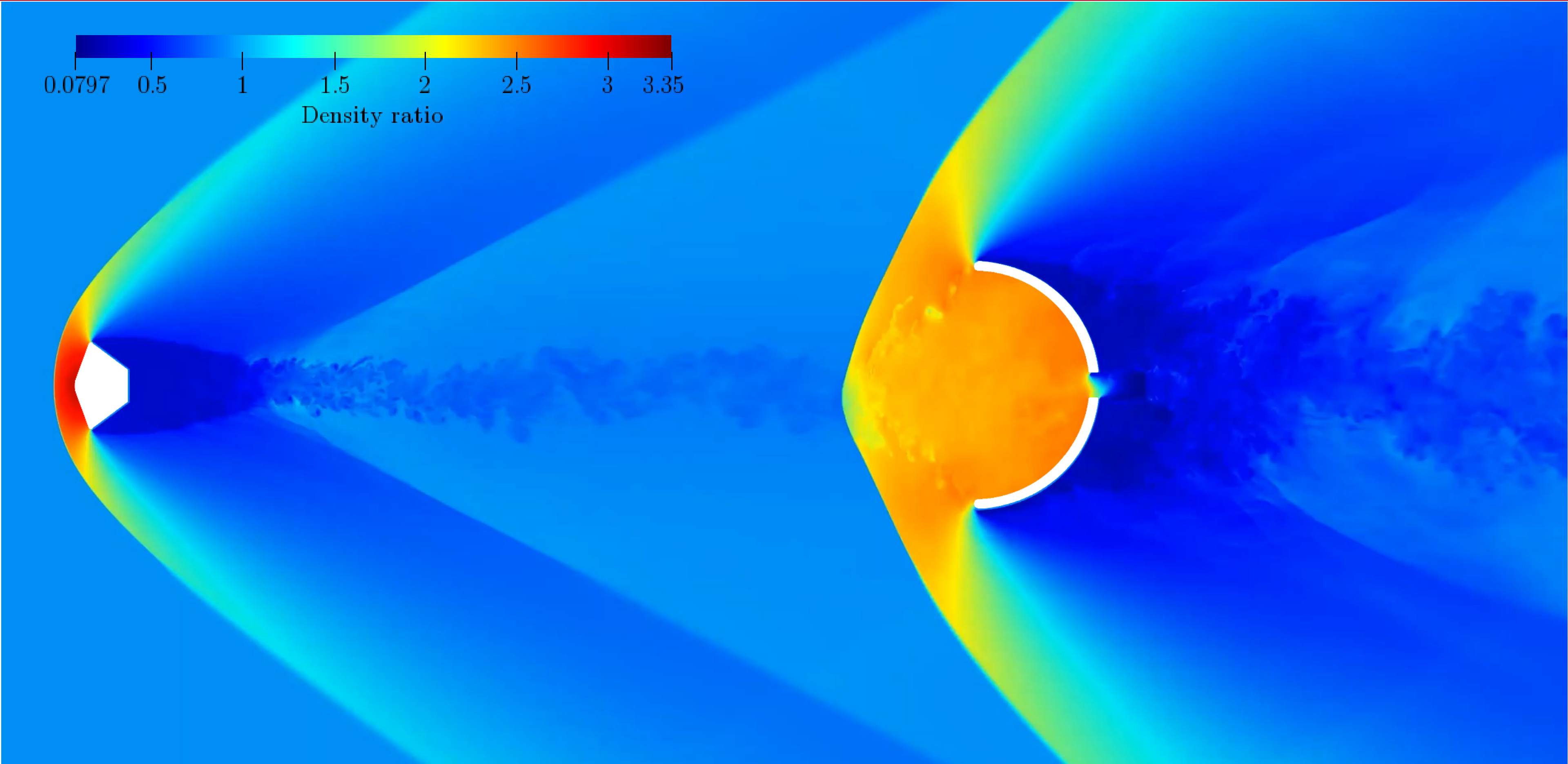
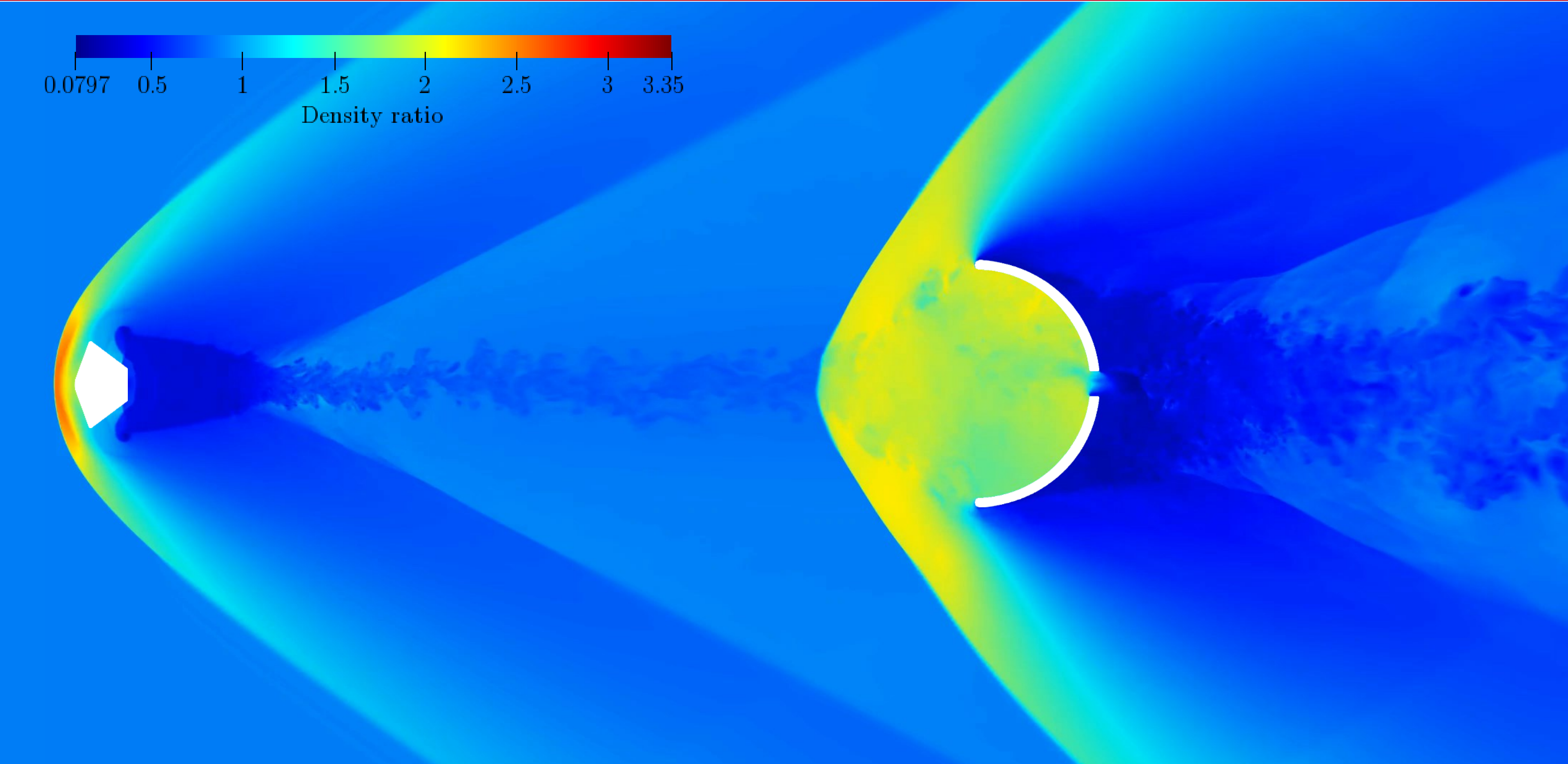
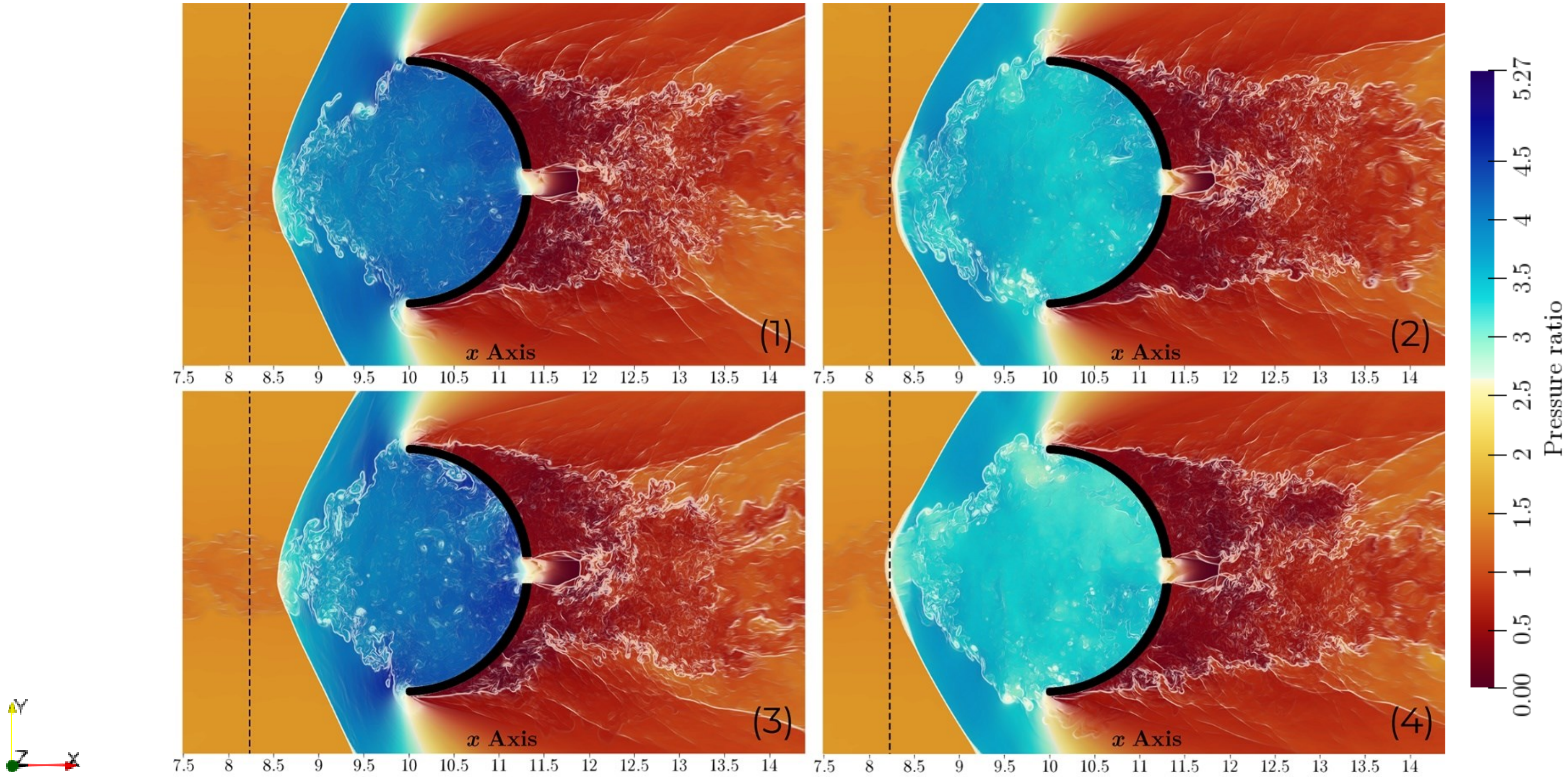
LES of a rigid thick-interface (parachute)



LES of a rigid thick-interface (parachute)



Results: 'breathing instability'

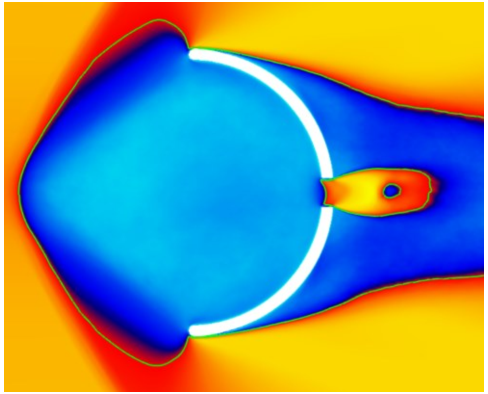


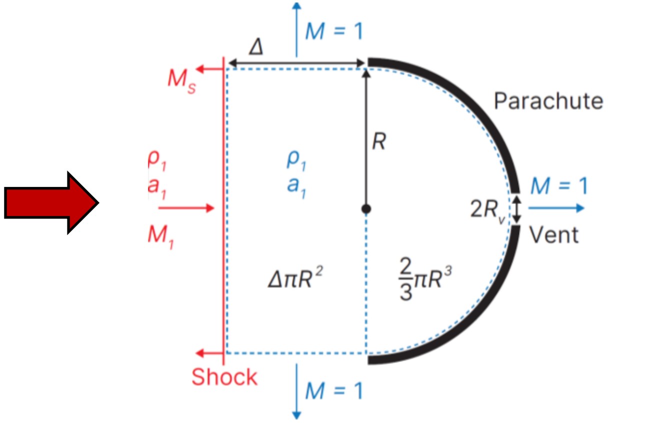
Zero-dimensional model: settings

- **Control volume:**

$$V(t) = \frac{2}{3}\pi R^3 + \pi R^2 \Delta(t)$$

$$\frac{\partial V}{\partial t} = \pi R^2 \frac{\partial \Delta}{\partial t}$$





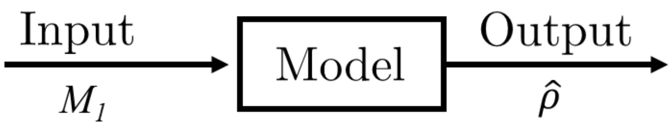
- **Mass conservation:**

$$\frac{\mathrm{d}}{\mathrm{dt}}\int_V \rho\,\mathrm{dV} = 0 \quad \Longrightarrow \quad \frac{\partial}{\partial t}(\rho_2 V) = \boxed{\pi R^2 \cdot M_1 a_1 \cdot \rho_1} - \boxed{\pi R_v^2 \cdot M_2 a_2 \cdot \rho_2 \; - \; 2\pi R\Delta \cdot M_2 a_2 \cdot \rho_2}$$

$$\hat{\rho} = \frac{\rho_2}{\rho_1} \quad \Longrightarrow \quad \frac{\partial \hat{\rho}}{\partial t} = \frac{\pi R^2}{V} M_1 a_1 - \frac{\hat{\rho}}{V}\left[\left(\pi R_v^2 + 2\pi R\Delta\right) a_2 + \pi R^2 \underbrace{\left(M_s - M_1\right) a_1}_{\partial\Delta/\partial t}\right] \qquad M_s = \sqrt{\frac{2\hat{\rho}}{(\gamma+1) - \hat{\rho}(\gamma-1)}}$$

Zero-dimensional model: results

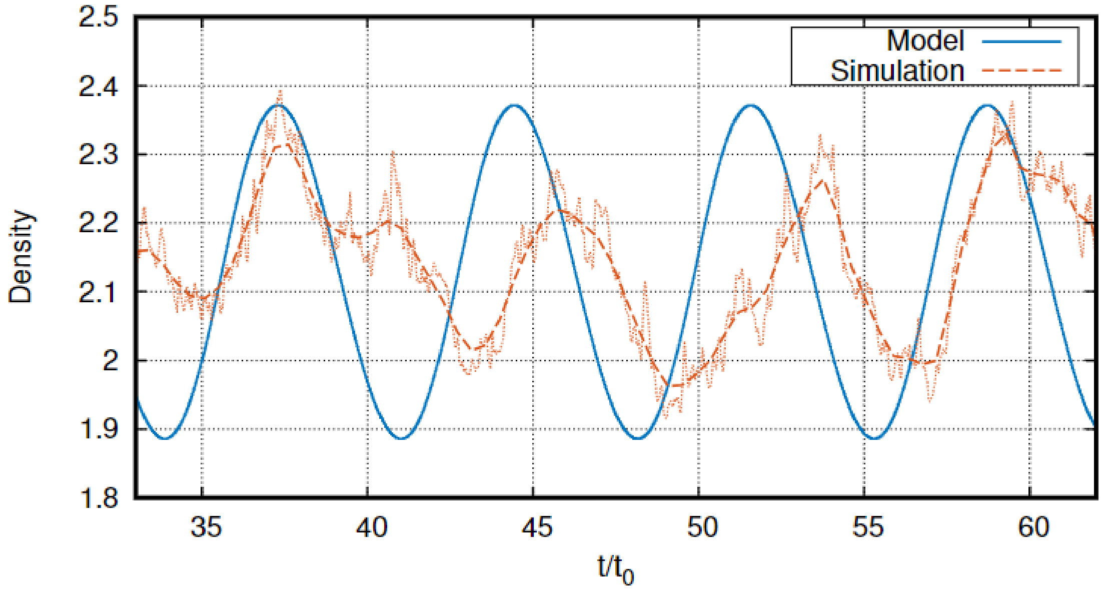
1. Modeled inflow Mach number



$$M_1(t) = M_e + A\sin(2\pi Sr \cdot t)$$

- Mean value, M_e= 1.60
- Amplitude, A = 0.10
- Strouhal number, $Sr = f\,D_0\,/\,u_\infty = 0.16$

From frequency analysis of the simulated value – we obtain density variation inside the canopy.



Work in progress and future steps

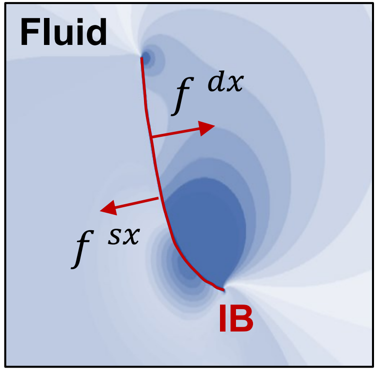
- **Increase the fidelity of the simulation**

  → High fidelity simulation and modeling of the parachute-capsule dynamics.

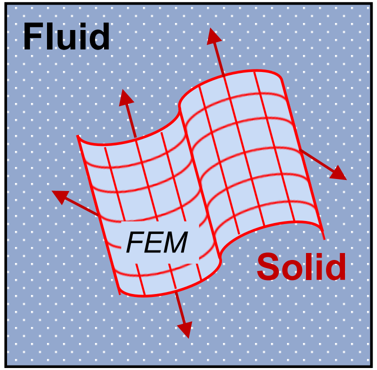
→ Introduce interface representation for the structure – **thin**. Allow displacements and **deformations**.

Methodology:

1. Large-Eddy Simulations (**LES**) to obtain a precise time-evolving solution of the flow field. **GPU** parallel **computing** enables its use, coupled to:



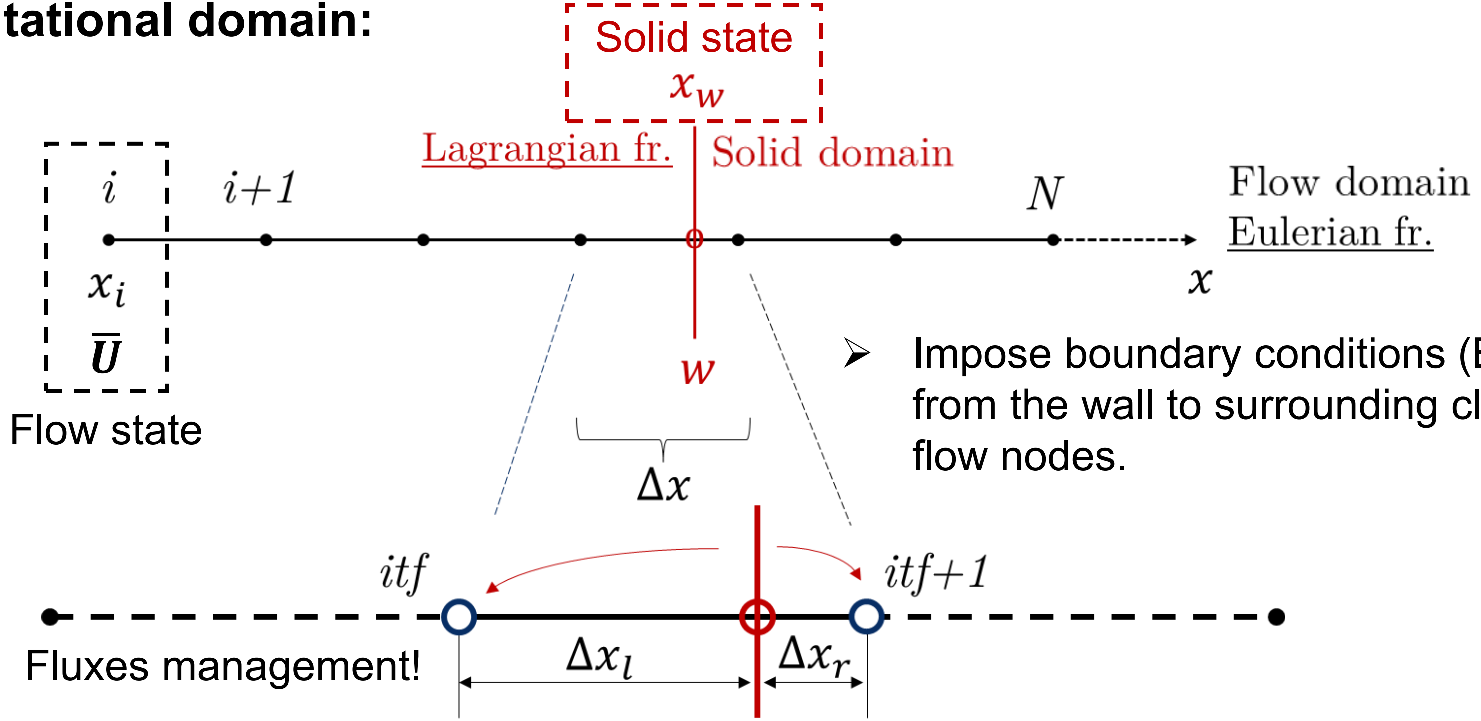
2. Novel Immersed-Boundary Method (**IBM**) to represent a infinitesimal thickness interface in the flow field and evaluate the fluid-structure force exchange.



3. Finite-Element Method (**FEM**) to deal with structure deformations – thin shells elements to model surface wrinkling and displacements.

Immersed-boundary method: algorithm

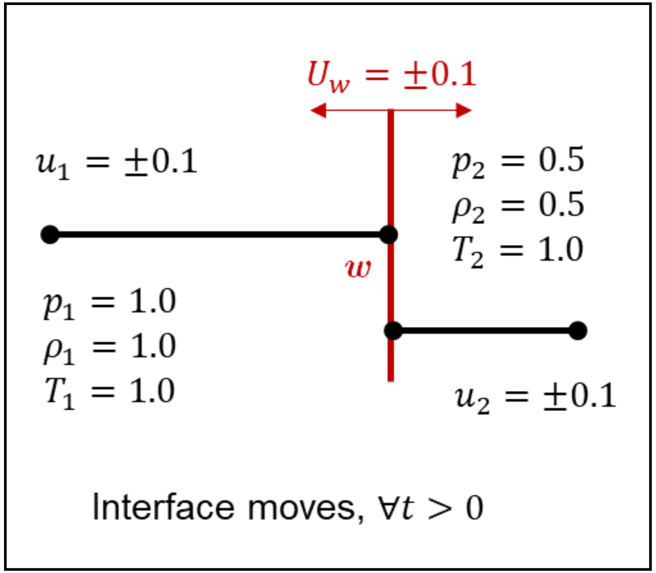
- **Computational domain:**

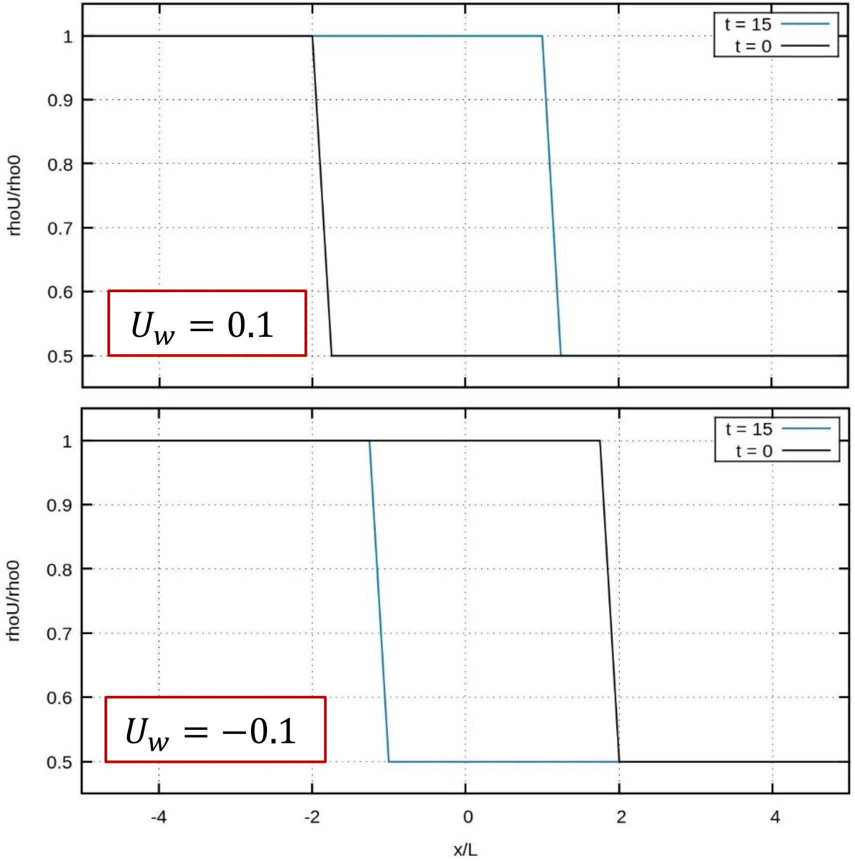


➢ Impose boundary conditions (BCs) from the wall to surrounding closest flow nodes.

- **Local fluxes** are corrected using wall **BCs**, extended to the flow state around the interface.

Immersed-boundary method: testing



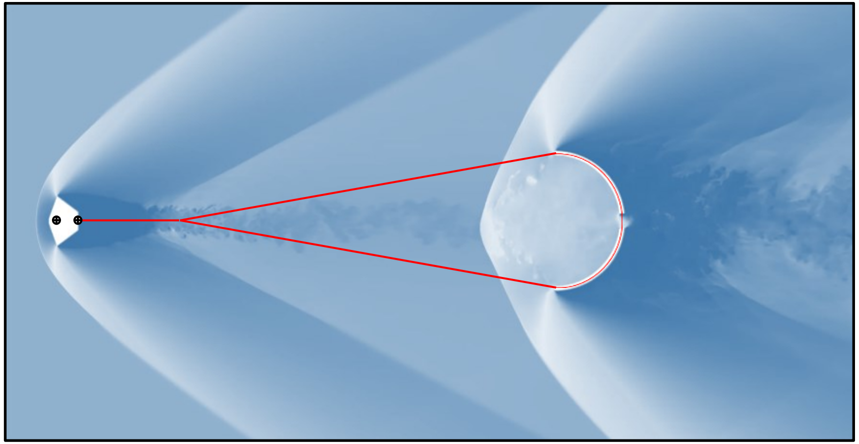


$N_x = 500$; $\Delta t = 0.001$;
Characteristic flux splitting and shock capturing

Final remarks

- Preliminary high-fidelity flow solutions on wake parachute and capsule dynamics have been obtained – gain insight on the involved unsteady phenomena.
- A **novel** Immersed-Boundary Method thin-interface strategy has been developed and tested in a compressible flow; the algorithm will be **implemented in STREAmS** to obtain 2D and 3D results of a decelerator trailing behind a forebody.

  - Tests case have shown that the algorithm can successfully represent a free interface being subjected to a compressible flow.
  - Preliminary results on the interaction between the forebody wake and the rigid moving thin interface are expected – these will be compared with previous high-fidelity rigid-thick tests.



Research outreach and production

AIDAA PhD Days

16th – 19th April	26th Aug. – 1th Sept.	4th – 6th September	7th – 8th September

- First article published on *Aerospace Science and Technologies.*

  L. Placco, M. Cogo, M. Bernardini, A. Aboudan, F. Ferri and F. Picano, Large-Eddy Simulation of the unsteady supersonic flow around a Mars entry capsule at different angles of attack, *Aerospace Science and Technology*, Volume 143, 2023, 108709, ISSN 1270-9638.

- CINECA's *LEONARDO-BOOSTER* (Exascale HPC center):
  IscraC and *IscraB* application – more than 250k computational hours requested.

Thank you for the attention