UNIVERSITÀ
DEGLI STUDI
DI PADOVA

High fidelity simulations of high speed flows for aerospace problems

Michele Cogo - 37th Cycle

Supervisor: Prof. Francesco Picano

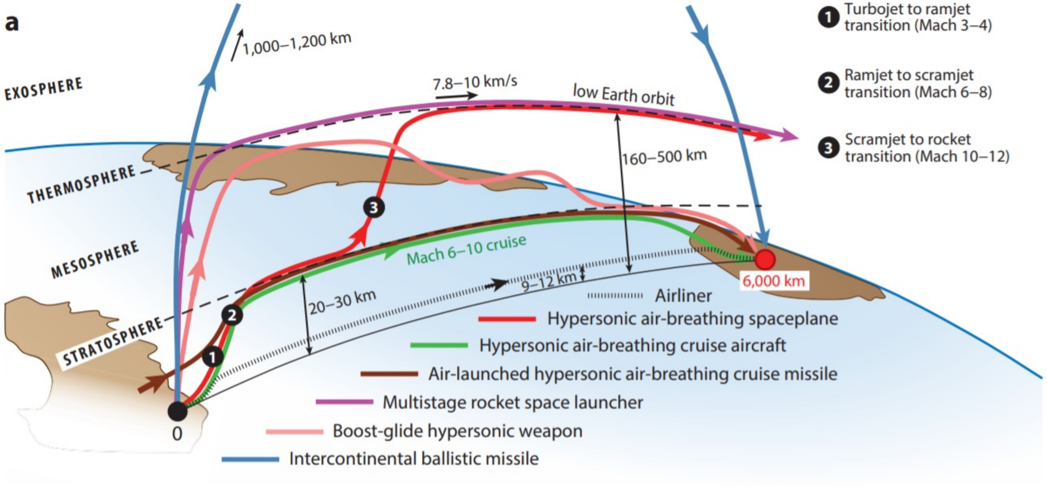
Admission to the third year - 13/09/2023

Project Motivations

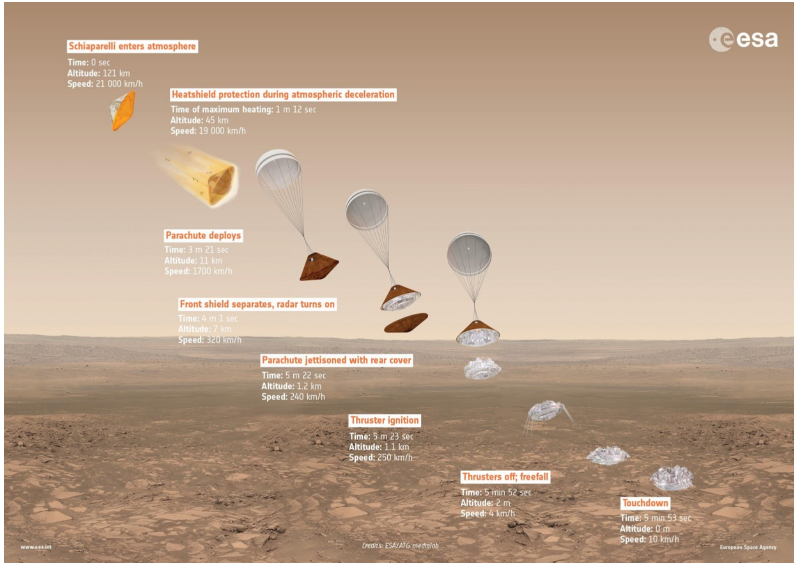
High-speed flows:

Flight trajectories on Earth…

…and reentry on Mars



Adapted from Urzay, Annual Review of Fluid Mechanics [2018]

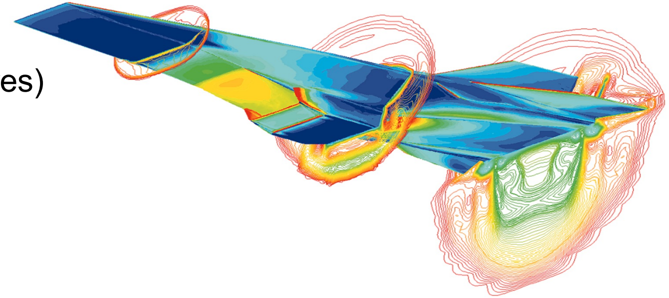


ESA website

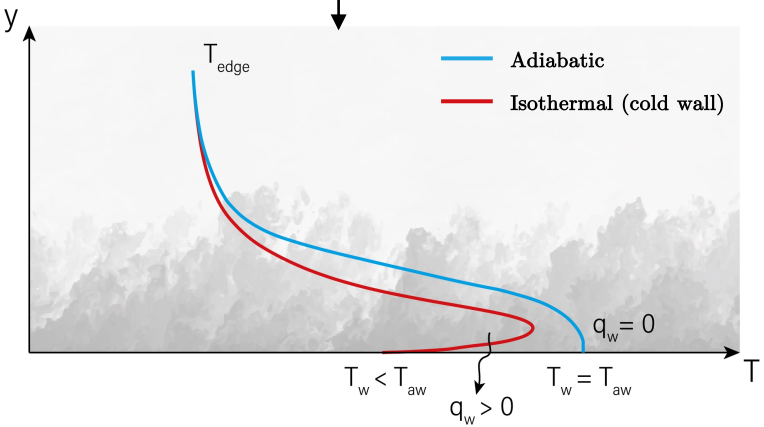
Project Motivations

Main features of high-speed flight at low altitudes:

- High Reynolds number (turbulent boundary layers)
- High freestream Mach numbers (intense shocks and large recovery temperatures)
- Possible chemical-reactions activated by high temperatures
- Aerodynamic heating (large thermal fluxes at the wall)



Source: NASA website



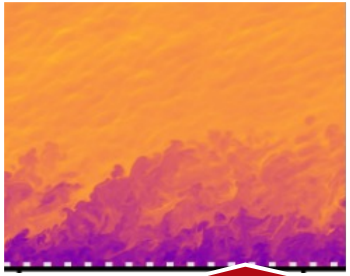
The presence of turbulent, hot and highly compressible boundary layers increase the mechanical and thermal loads on the vehicle!

A detailed description of the flow dynamics is essential to predict drag and thermal fluxes

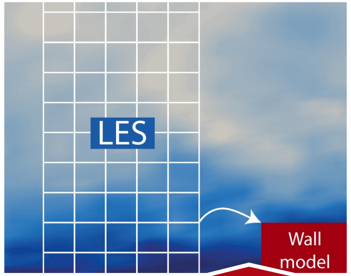
Main tasks

Three main tasks:

High-speed boundary layers over smooth walls



High-speed boundary layers over rough walls



Wall-models for hypersonic boundary layers

In collaboration with:

Sapienza Università di Roma

TU Delft
Sapienza Università di Roma

Stanford University

Objectives of this study:

1. Direct Numerical Simulations of high-speed turbulent boundary layers over smooth walls
2. Direct Numerical Simulations of high-speed turbulent boundary layers over rough walls
3. Wall-modelled Large Eddy Simulations of hypersonic turbulent boundary layers

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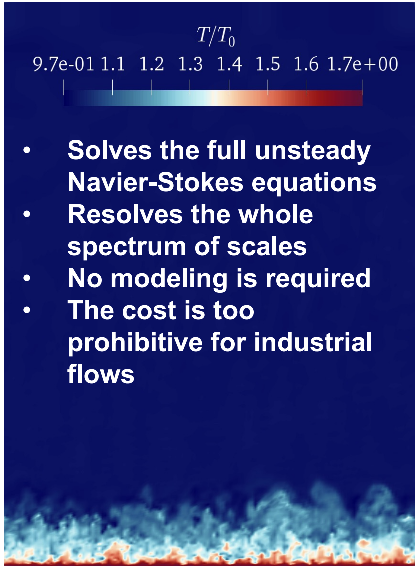
Computational methods for CFD

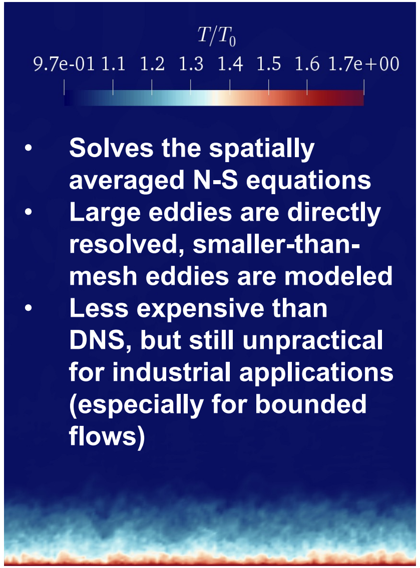
How are turbulent flows modelled?

DNS **LES** **RANS**

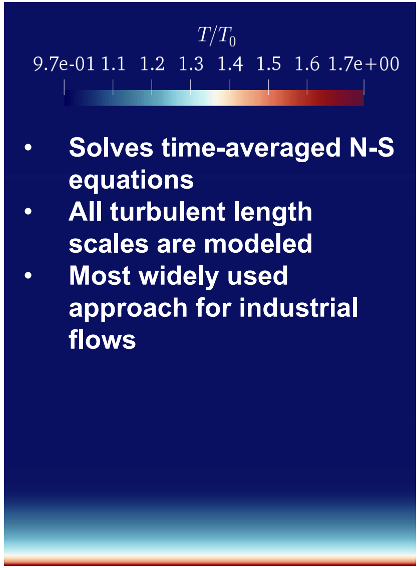
COMPUTATIONAL COST



- **Solves the full unsteady Navier-Stokes equations**
- **Resolves the whole spectrum of scales**
- **No modeling is required**
- **The cost is too prohibitive for industrial flows**



- **Solves the spatially averaged N-S equations**
- **Large eddies are directly resolved, smaller-than-mesh eddies are modeled**
- **Less expensive than DNS, but still unpractical for industrial applications (especially for bounded flows)**



- **Solves time-averaged N-S equations**
- **All turbulent length scales are modeled**
- **Most widely used approach for industrial flows**

PHYSICAL ACCURACY

No model!

$$\Delta x \simeq \eta$$

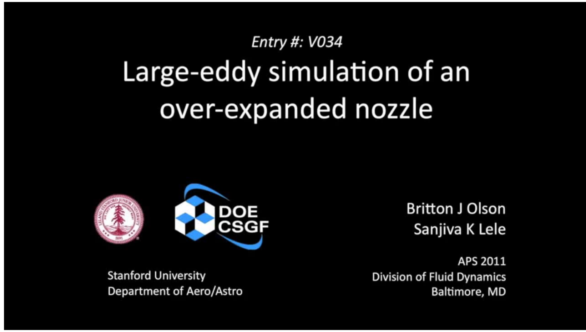
Modelling small scales

$$\eta < \Delta x < L_0$$

Modelling all scales

$$\Delta x \simeq L_0$$

Large-Eddy Simulation



Entry #: V034

Large-eddy simulation of an over-expanded nozzle

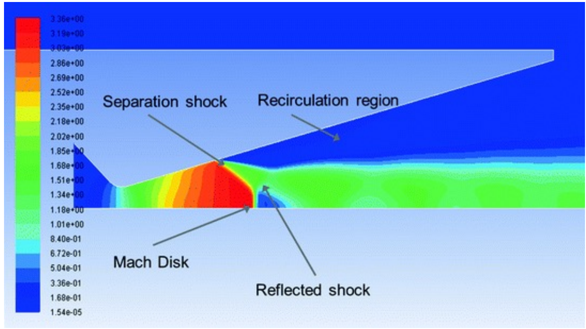
DOE CSGF

Britton J Olson
Sanjiva K Lele

Stanford University
Department of Aero/Astro

APS 2011
Division of Fluid Dynamics
Baltimore, MD

Reynolds-Averaged Navier-Stokes simulation



Tasks #1-2: Computational setup

Solver	Numerical method	Immersed boundary method
STREAmS (Bernardini et al. CPC 2021): • Open-source numerical solver for compressible flows • Supports MPI parallelization and multi-GPU architectures	Direct Numerical Simulation: • Navier-Stokes equations are solved with very high temporal and spatial resolution, down to the Kolmogorov scale • No model is employed	• Numerical method capable of representing the solid boundary on structured cartesian grids • Ghost-Point-Forcing Method -> the mesh nodes inside the solid boudary are used as ghost points to give the right boundary conditions (Piquet et al. [2016])

Navier-Stokes equations in the conservative formulation:

$$\frac{\partial \mathbf{U}}{\partial t} = -\frac{\partial \mathbf{F_j}(\mathbf{U})}{\partial x_j} + \frac{\partial \mathbf{F}_{\nu \mathbf{j}}(\mathbf{U})}{\partial x_j}$$

$$\mathbf{U} = \begin{bmatrix} \rho \\ \rho u_j \\ \rho E \end{bmatrix} \quad \mathbf{F}_{\nu \mathbf{j}}(\mathbf{U}) = \frac{\sqrt{\gamma} M_\infty}{Re} \begin{bmatrix} 0 \\ \sigma_{ij} \\ \sigma_{ij} u_j - \frac{1}{Pr} \frac{\gamma}{\gamma - 1} q_j \end{bmatrix} \quad \mathbf{F_j}(\mathbf{U}) = \begin{bmatrix} \rho u_j \\ \rho u_i u_j + p \delta_{ij} \\ \rho u_j H \end{bmatrix}$$

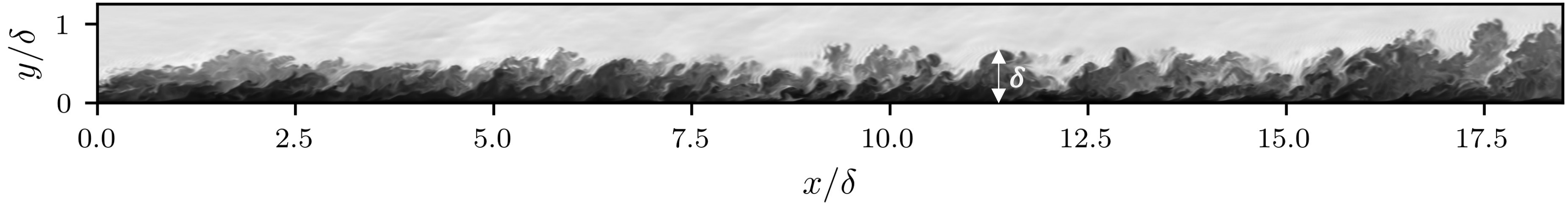
Calorically-perfect gas:

$$E = c_v T + u_i u_i / 2$$

$$H = E + p/\rho$$

$$p = \rho T$$

Task #1: Motivations



High-speed boundary layers are a representative of the thin region near the aircraft surface. Their study is of critical importance for estimating the drag and heat transfer experienced by the vehicle.

Key parameters of the study:

$$M_\infty = u_\infty / a_\infty$$

Mach number

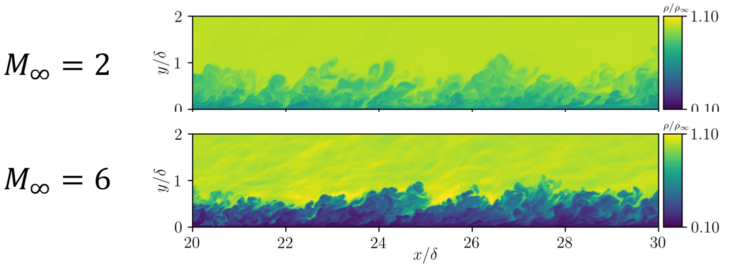
$$Re_\tau = \bar{\rho}_w u_\tau \delta / \bar{\mu}_w$$

Friction Reynolds number

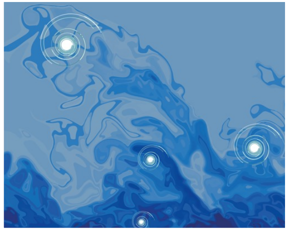
$$T_w$$

Wall temperature

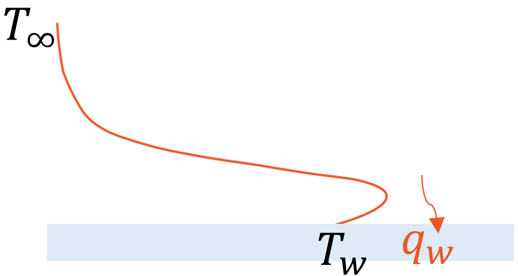
Large variations of thermodynamic properties (e.g. density)



Greater separation of turbulent scales

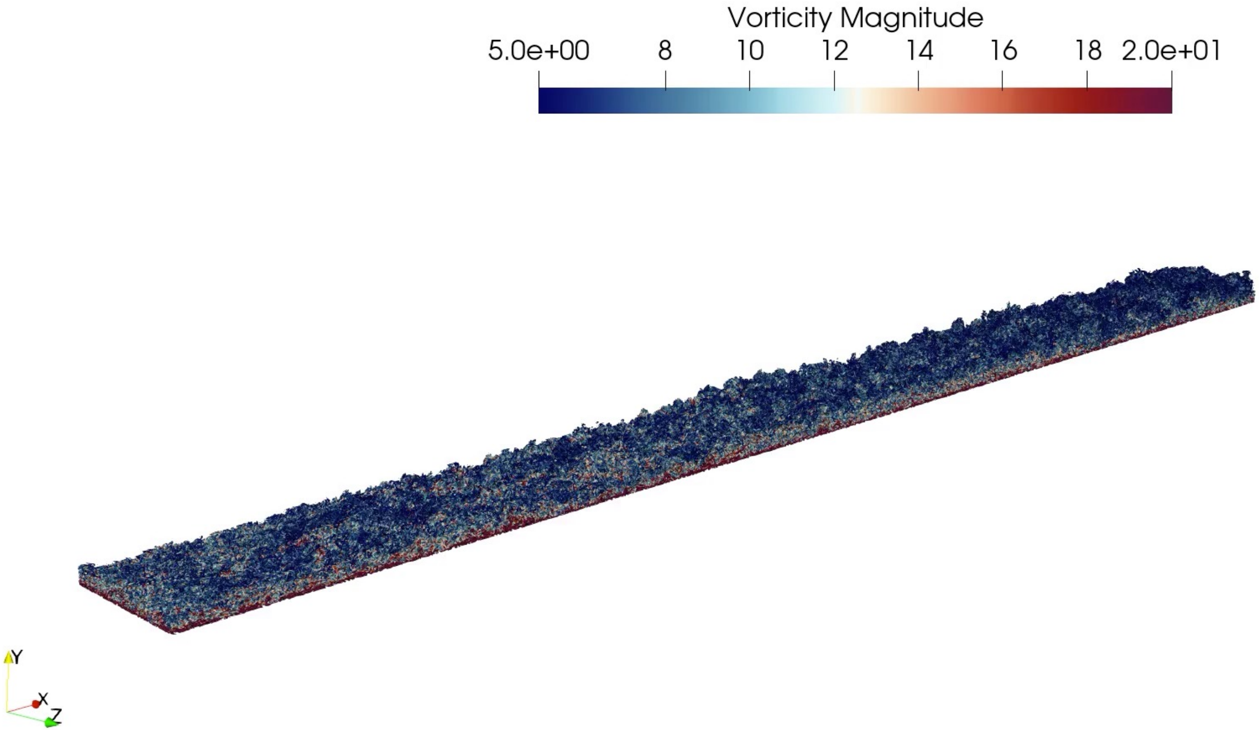


Large wall heat fluxes (aerodynamic heating)



Task #1: Visualization

Visualization of Q-criterion at Mach 6



Task #1: Selected Results

First study:

Effect of **Reynolds** and **Mach** numbers on high-speed zero-pressure-gradient turbulent boundary layers

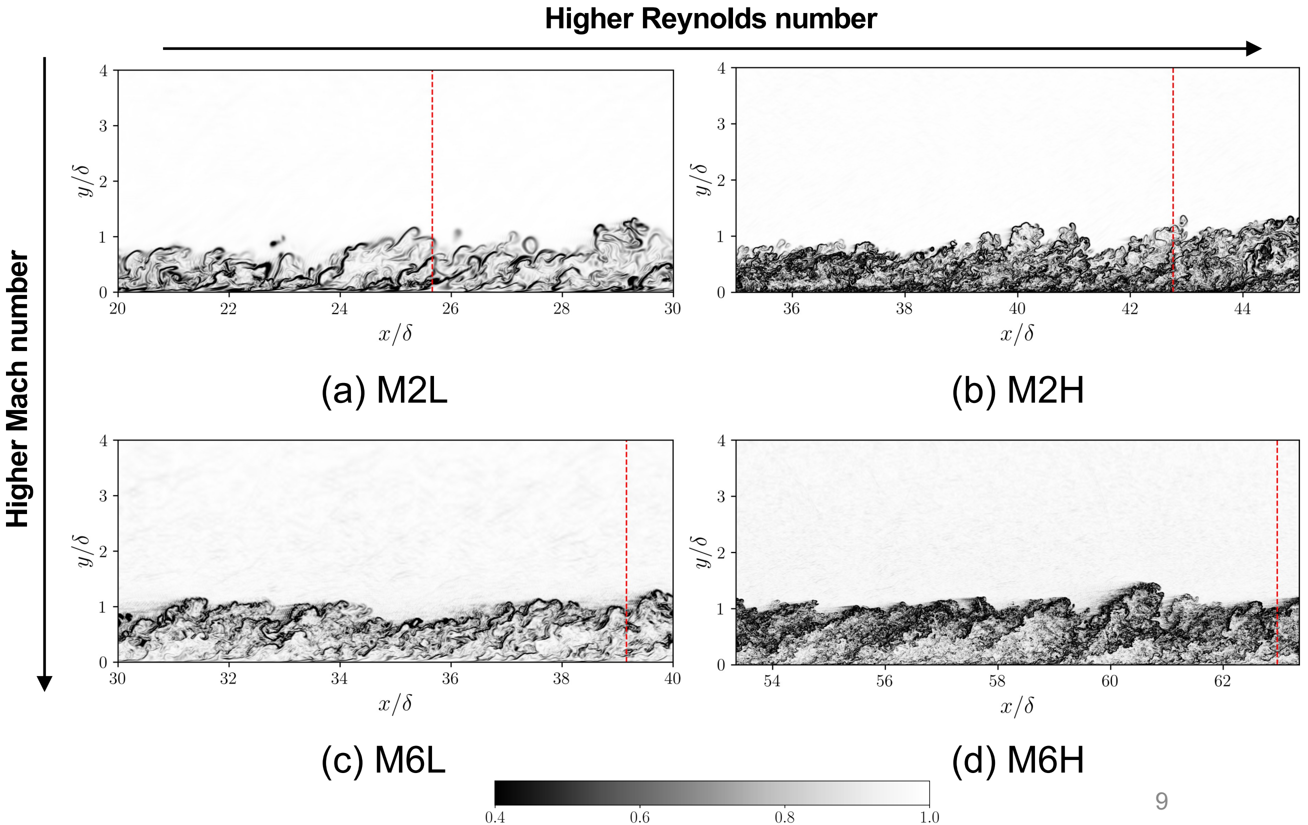
Key points discussed:

- Correlation between velocity and temperature fluctuations
- Uniform momentum and temperature zones
- Validity of compressibility transformations and temperature-velocity relations
- Spatial organization and length scales

Database:

- $M_\infty = 2, 6$
- $Re_\tau = 450, 1950$

Contours of the density gradient in a streamwise wall-normal plane



(a) M2L

(b) M2H

(c) M6L

(d) M6H

Task #1: Selected Results

Second study:

Effect of **Mach number** and **wall temperature** on high-speed zero-pressure-gradient turbulent boundary layers

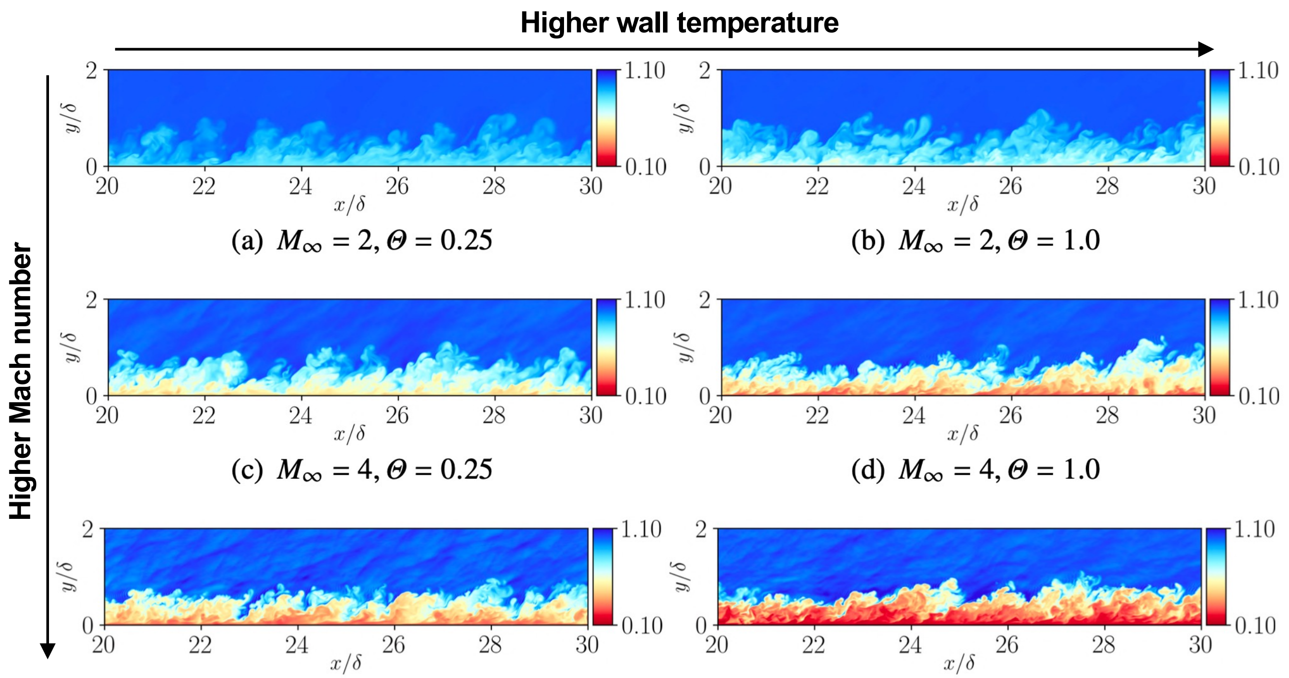
Key points discussed:

- Correlation between velocity and temperature fluctuations
- Validity of the Reynolds analogy
- Modulation of scales separation
- Similarities and differences of Mach number and wall-cooling effects

Database:

- $M_\infty = 2,\ 4, 6$
- $Re_\tau = 450$
- $\Theta = 0.25, 0.5, 0.75, 1$ (non-dimensional wall temperature)

Contours of density in a streamwise wall-normal plane



(a) $M_\infty = 2, \Theta = 0.25$

(b) $M_\infty = 2, \Theta = 1.0$

(c) $M_\infty = 4, \Theta = 0.25$

(d) $M_\infty = 4, \Theta = 1.0$

(e) $M_\infty = 6, \Theta = 0.25$

(f) $M_\infty = 6, \Theta = 1.0$

Cogo M, Baù U, Chinappi M, Bernardini M, Picano F. Assessment of heat transfer and Mach number effects on high-speed turbulent boundary layers. Journal of Fluid Mechanics. 2023;974:A10. doi:10.1017/jfm.2023.791

Task #2: Motivations

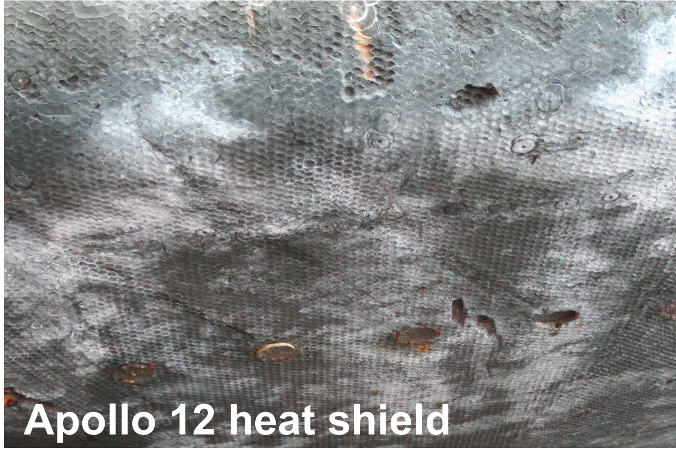
Boundary layer with sourface roughess:

Tipically high-speed vehicles exhibit regular or irregular patterns of roughness.
Turbulent boundary layers exhibit higher skin friction and mixing, causing increased vehicle drag and heating.

Key questions:

- How does surface roughness affects turbulence near the wall at high speeds?
- What is the effect of Mach number and roughness level in the alteration of drag and heat transfer?

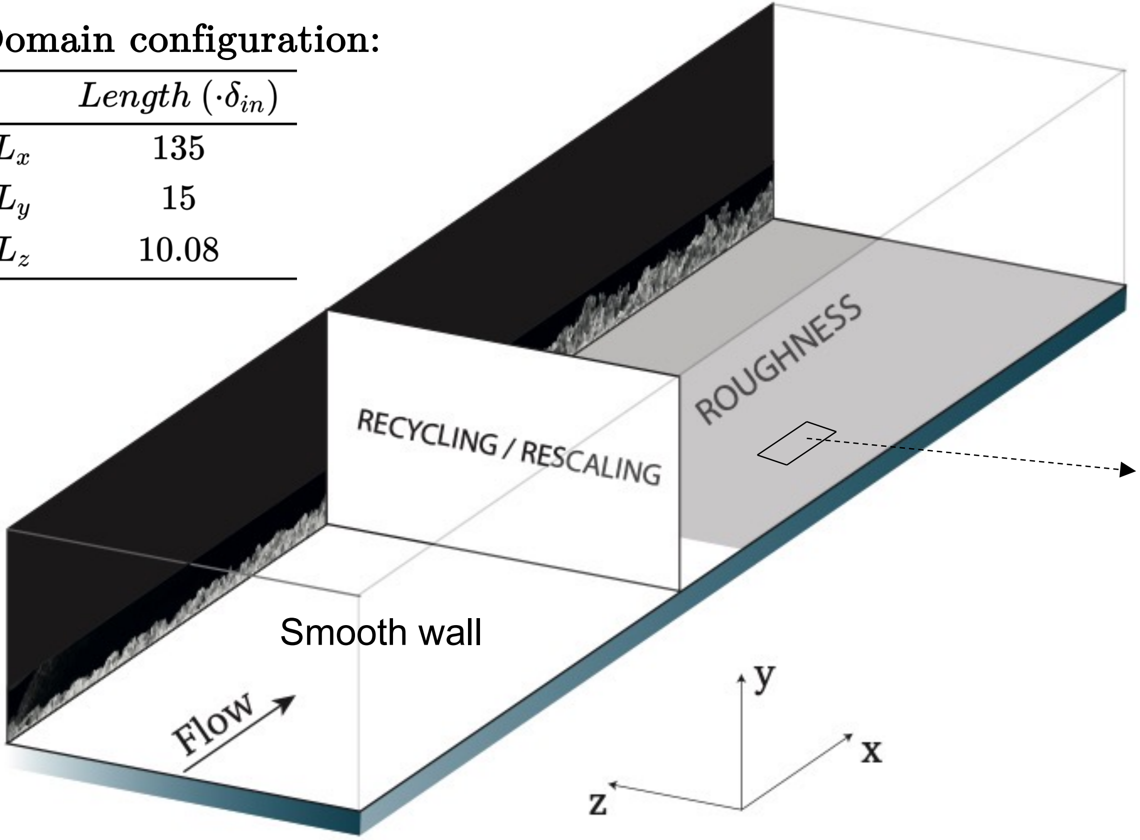

Space shuttle Discovery


Apollo 12 heat shield

Task #2: Computational domain

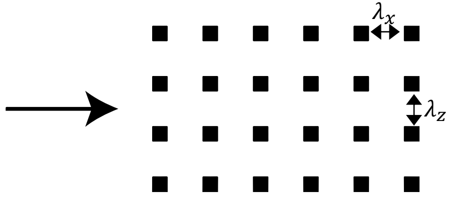
Domain configuration:

	Length $(\cdot\delta_{in})$
L_x	135
L_y	15
L_z	10.08

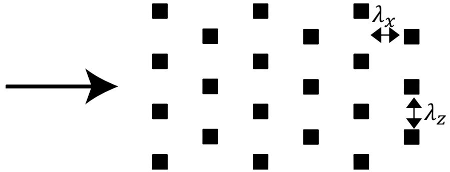


Two configurations are considered:

Aligned (CB-A)



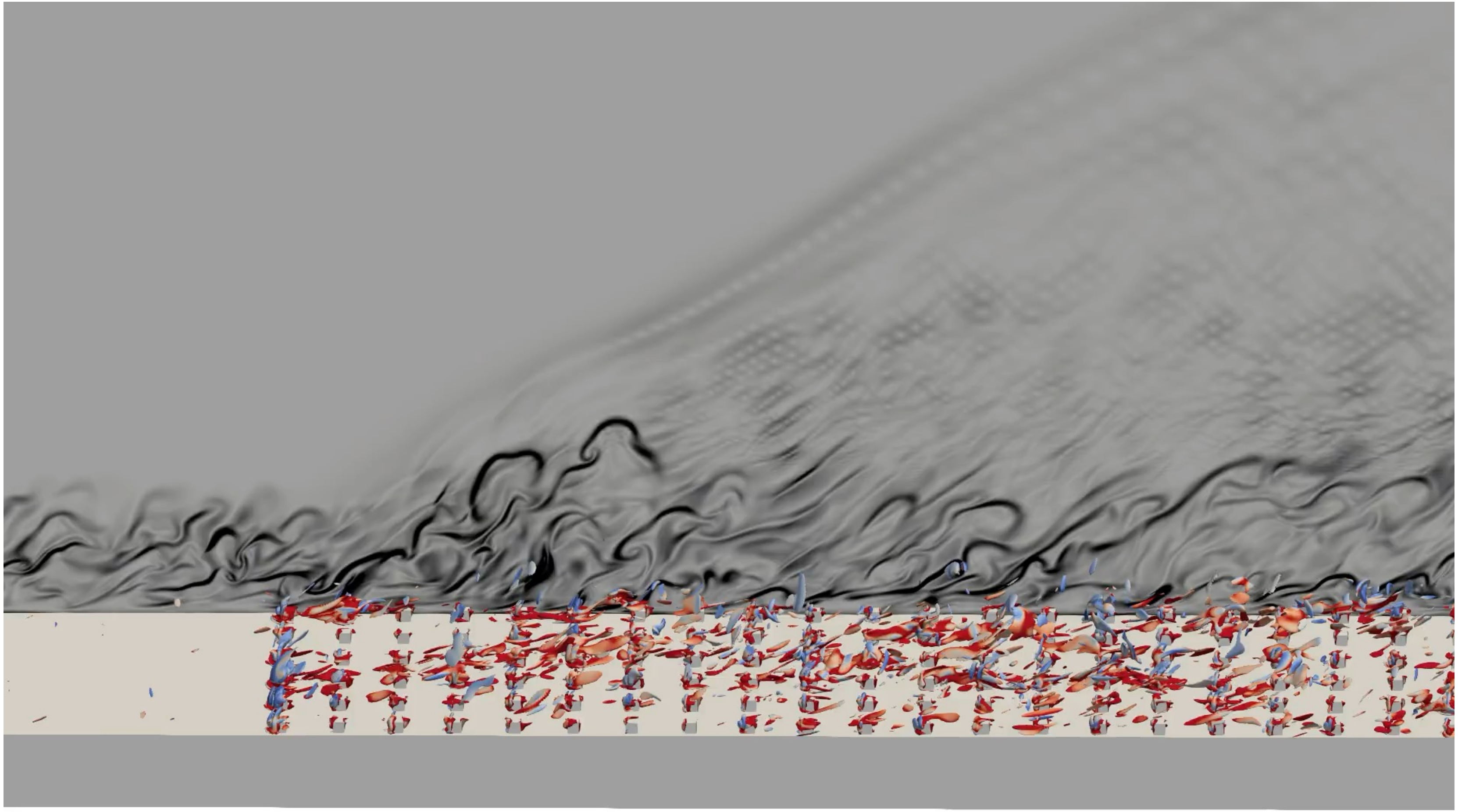
Staggered (CB-S)



$$\lambda_x = \lambda_z = 2k$$

$$k = 0.1\,\delta_{inflow}$$

Task #2: Visualization

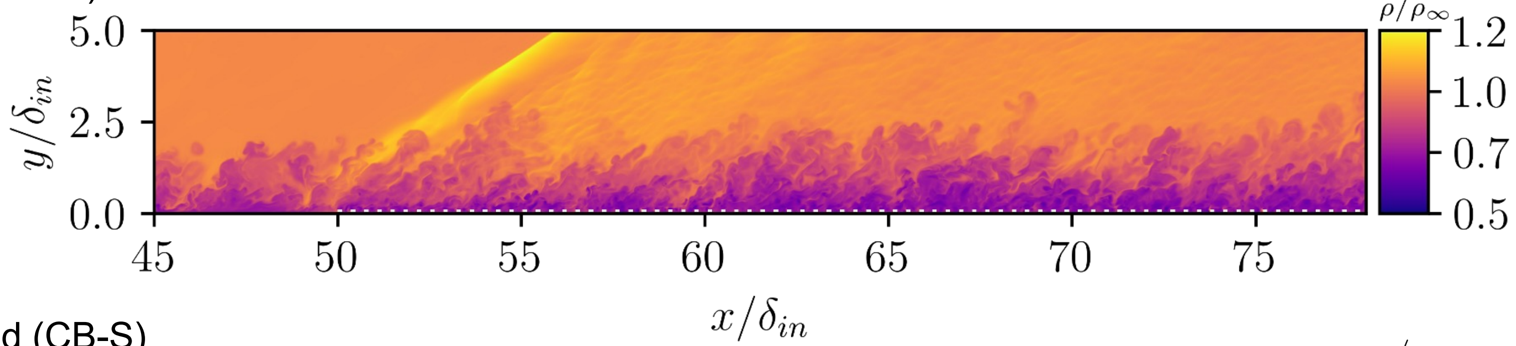


Task #2: Selected results

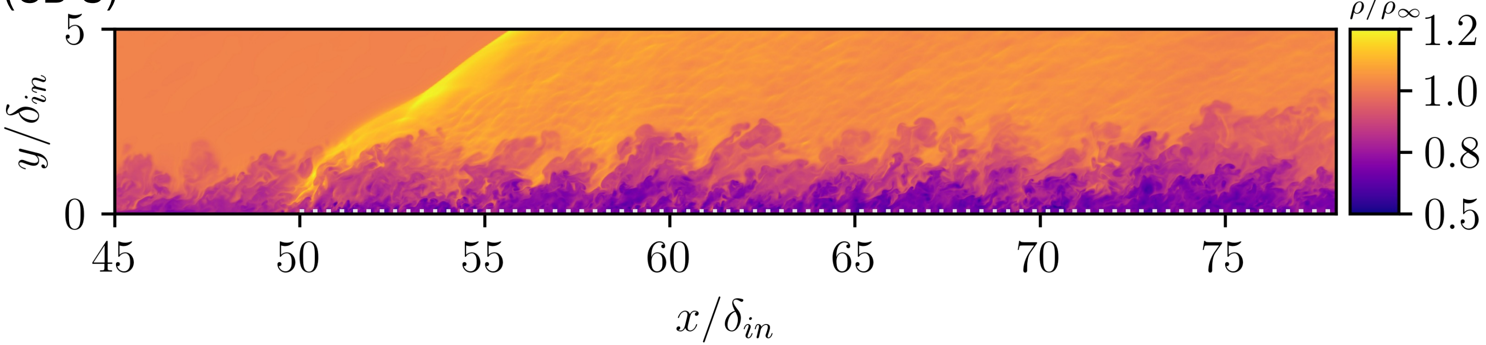
Wall-normal planes

$M_\infty = 2$

Aligned (CB-A)



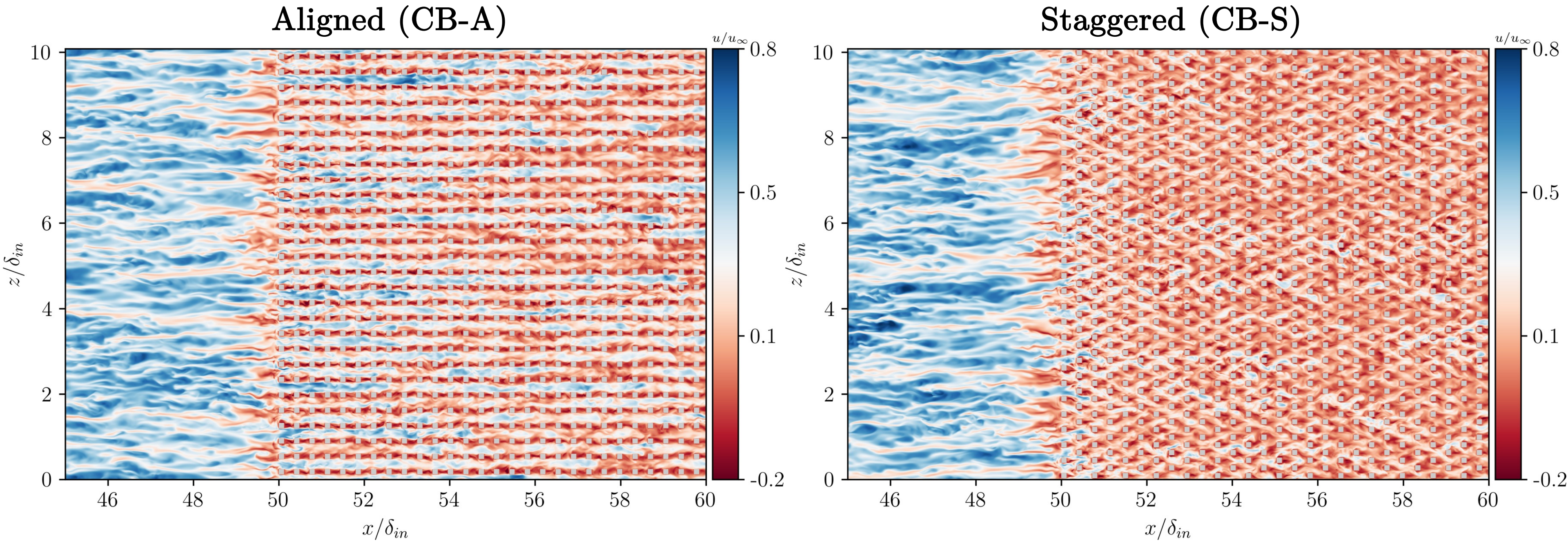
Staggered (CB-S)



The shock wave is more intense for the staggered case, as frontal area of roughness is larger

Task #2: Selected results

Wall-parallel planes below the roughness crest



In progress: analysis of the resulting friction and heat transfer at the wall. Comparison of results with the classical theory of roughness developed for low-speed flows.

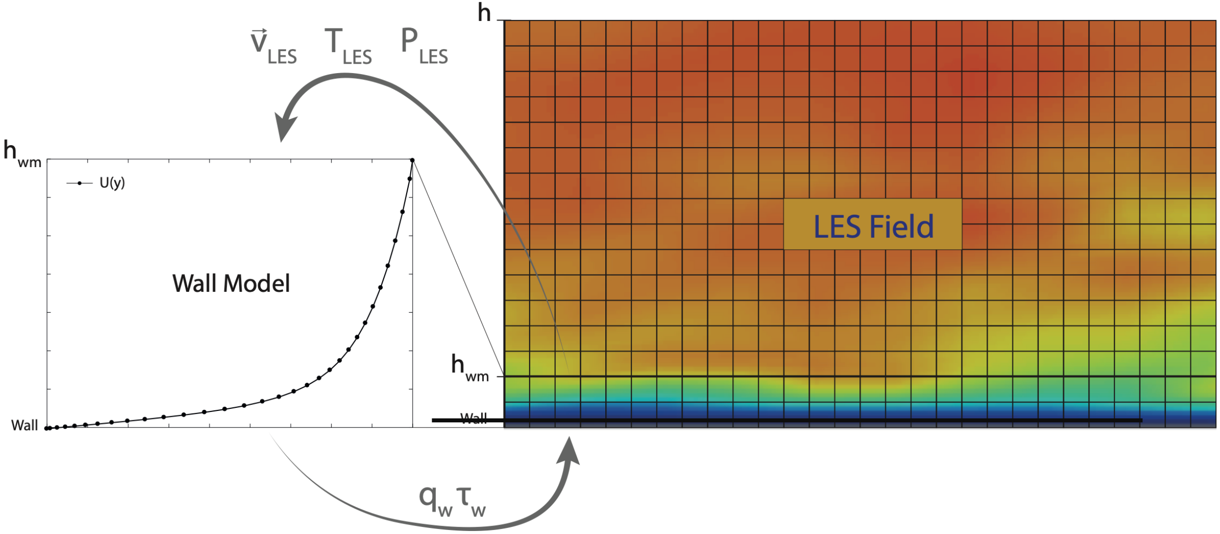
Task #3: Motivations

DNS simulations are very accurate but require extremely high computational cost, especially near the solid boundaries. This problem is also shared with LES, which has similar mesh requirements near the wall.

Features of Wall-Modelled LES:

Avoid resolving the near-wall scales by introducing a wall model that provides the computation of the wall shear stress τ_w and the wall heat flux q_w and feedback their values to the main solver.

- ✓ Massive reduction in computational cost
- ✓ Still able to predict non-stationary phenomena of the flow (in contrast to RANS)



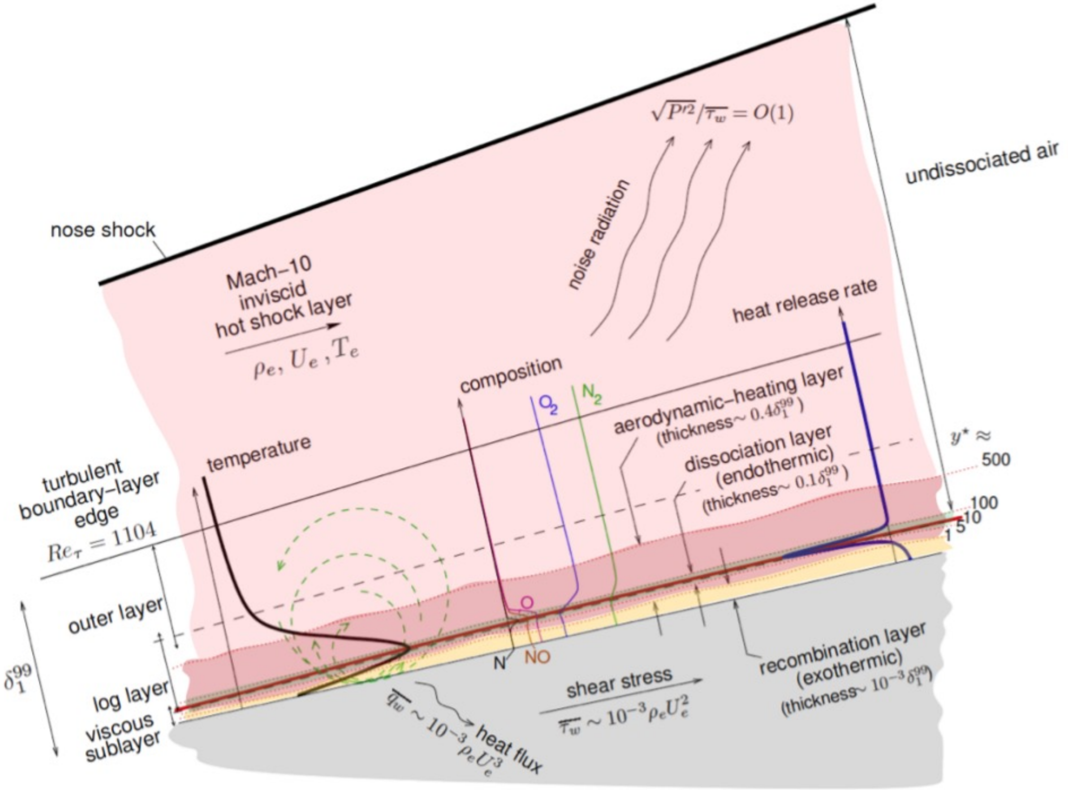
Task #3: Extension to hypersonics

In high-speed boundary layers temperatures can get so high to activate chemical processes (dissociation and recombinatin of air).

At the present time, there are no wall-models able to predict the variation of composition in the boundary layer.

The objective of my work is to develop and test new wall-models in the form of ordinary differential equations that can instantaneously predict:

- Velocity u
- Temperature T
- Mass fractions (O_2,N_2,NO,O,N)



Final remarks

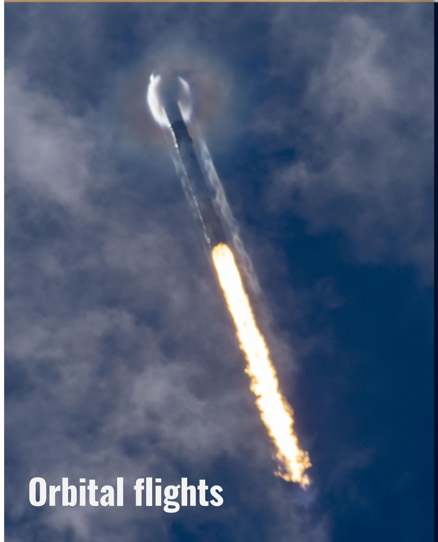
Summary of the past and future activities

- Investigation of the physics phenomena related to high-speed turbulent flows using high fidelity methodologies (DNS) on simple geometries.
- Application of high fidelity methodologies (DNS + IBM) on rough surfaces. Investigation of different geometries and Mach number effect.
- Development and testing of wall-models for high-speed boundary layers with chemical reactions.

<u>Several other applications are directly related to the research activity!</u>


Planetary Re-entry

Atmospheric flights


Orbital flights

Sub-orbital flights

Conferences, Publications, Grants

Publications:

- **Cogo, M.,** Salvadore, F., Picano, F., & Bernardini, M. (2022). *Direct numerical simulation of supersonic and hypersonic turbulent boundary layers at moderate-high Reynolds numbers and isothermal wall condition. Journal of Fluid Mechanics*
- De Vanna, F., Avanzi, F., **Cogo, M.**, Sandrin, S., Bettencourt, M., Picano, F., & Benini, E. (2023). *URANOS: A GPU accelerated Navier-Stokes solver for compressible wall-bounded flows.* Computer Physics Communications, 287, 108717.

Visiting researcher:

- Research period at TU Delft hosted by prof. Davide Modesti (4 months)
- Research period at Stanford University hosted by prof. Parviz Moin (6 months). Supported by Fulbright scholarship and Zegna founder's scholarship.

Conferences:

- **33rd Parallel CFD International Conference in Alba, Italy (25-27 May 2022).** Presentation of "DNS of supersonic and hypersonic turbulent boundary layers at moderate-high Reynolds numbers with heat transfer" and participation to the seminars.
- **14th European Fluid Mechanics Conference in Athens, Greece (13-16 September 2022).** Presentation of "Compressibility effects in supersonic and hypersonic turbulent boundary layers at high Reynolds numbers" and participation to the seminars.

GANNT chart

Activity plan

WBS NUMBER	TASK TITLE	% OF TASK COMPLETE	FIRST YEAR												SECOND YEAR												THIRD YEAR											
			T1			T2			T3			T4			T1			T2			T3			T4			T1			T2			T3			T4		
			O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
1	DNS - Attached flows over smooth plates																																					
1.1	Analysis of the state of the art	100%	■	■	■	■	■																															
1.2	Hypersonic turbulent boundary layer over a flat plate with DNS at high Reynolds numbers	100%		■	■	■	■	■	■	■	■																											
1.3	Investigation of Mach number and wall-cooling effects in a hypersonic boundary layer	100%										■	■	■	■	■	■																					
2	DNS - Attached flows over rough plates																																					
2.1	Analysis of the state of the art	100%										■	■	■	■	■	■																					
2.2	Hypersonic turbulent boundary layer over a rough plate with DNS - simulation setup	100%												■	■	■	■	■	■	■																		
2.3	Hypersonic turbulent boundary layer over a rough plate with DNS - geometry effect	50%													■	■	■	■	■	■	■	■							■	■	■	■						
2.4	Hypersonic turbulent boundary layer over a rough plate with DNS - Mach number effect	0%																												■	■	■	■					
3	LES - Attached flows over smooth plates																																					
3.1	Analysis of the state of the art	70%																				■	■	■	■	■												
3.2	Wall modelled LES of hypersonic turbulent boundary layers - calorically perfect gases	50%																						■	■	■	■	■	■	■								
3.3	Wall modelled LES of hypersonic turbulent boundary layers - Thermally perfect gases	50%																							■	■	■	■	■	■	■							
3.4	Wall modelled LES of hypersonic turbulent boundary layers - chemically-reactng gases	40%																								■	■	■	■	■	■	■						
4	Writing thesis and reports																																					
4.1	Reports for admission to the next year or conferences	60%							■	■			■	■											■	■											■	■
4.2	Writing scientific papers	60%			■	■	■	■	■	■					■	■	■	■			■	■	■	■					■	■	■	■						
4.3	Writing thesis	0%																									■	■	■	■	■	■	■	■	■	■	■	■

Thanks for the attention

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