Università
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di Padova

High fidelity simulations of high-speed flows for aerospace problems

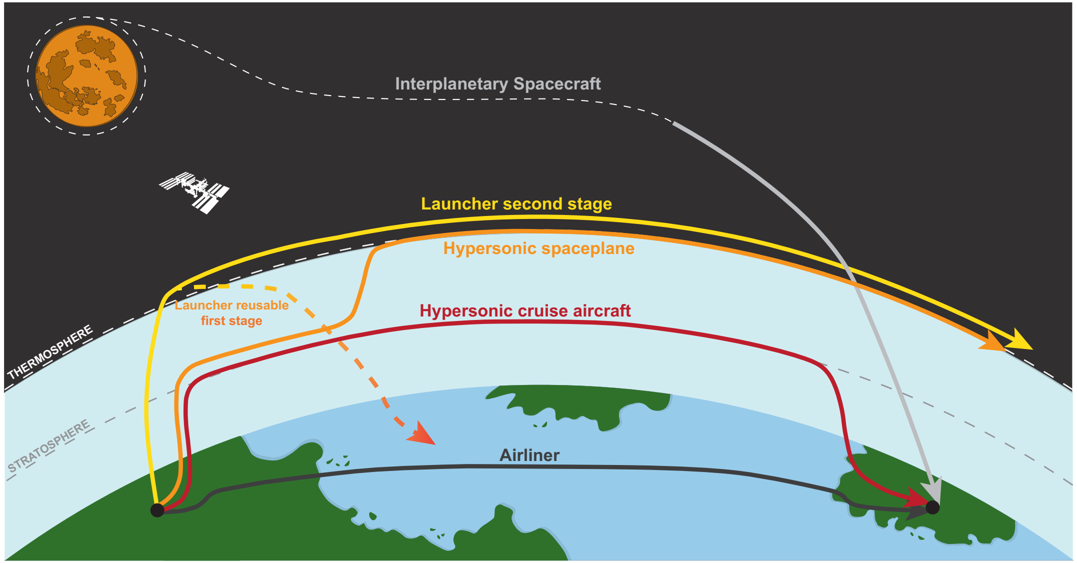
Michele Cogo - 37th Cycle

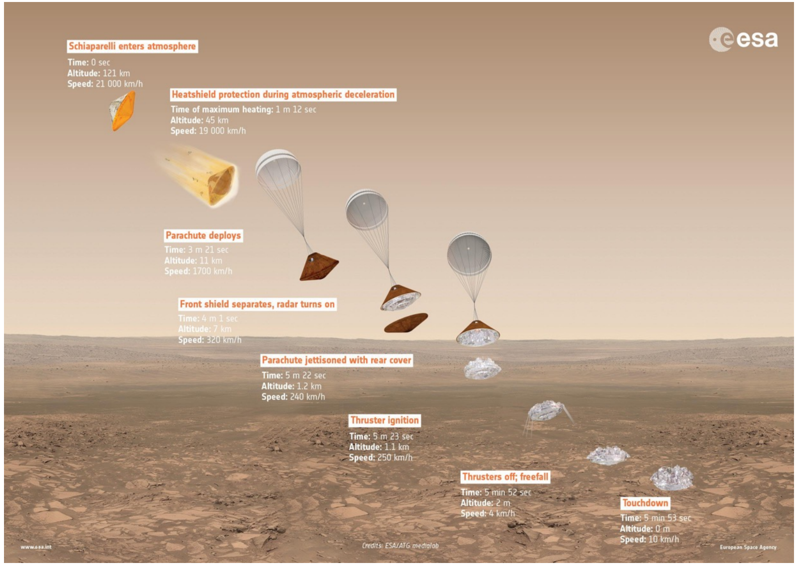
Supervisor: Prof. Francesco Picano

Admission to the final exam - 17/09/2024

High-speed flows:

Flight trajectories on Earth… …and reentry on Mars





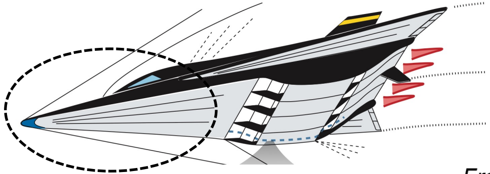
ESA website

Project Motivations

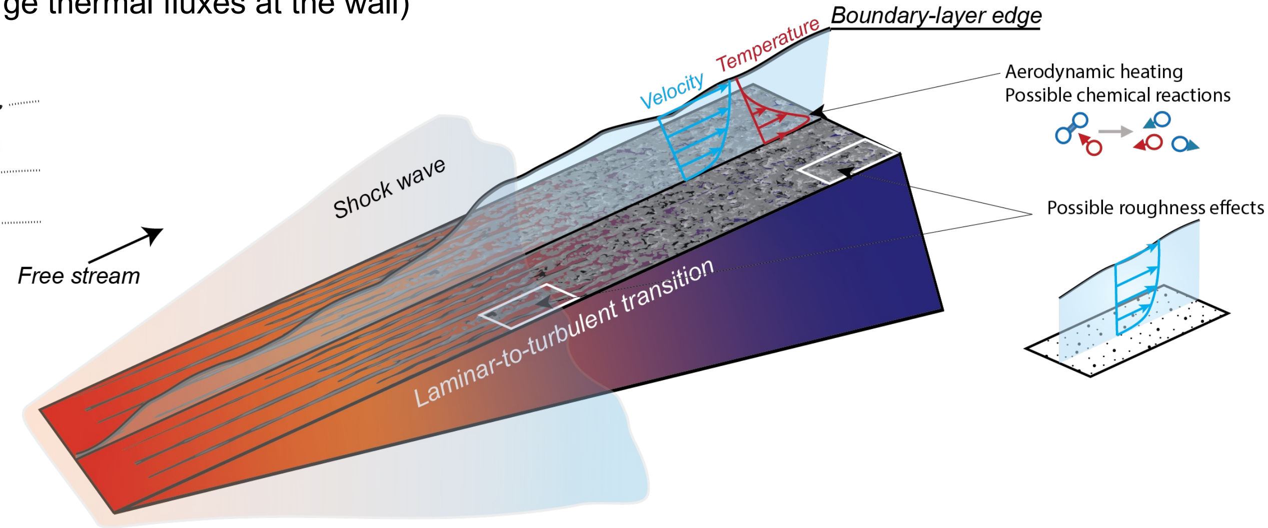
Main features of high-speed flight at low altitudes:

- 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)

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



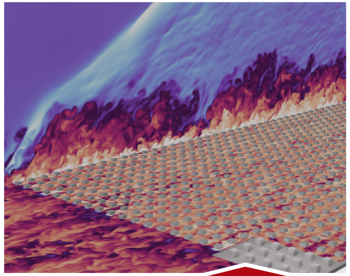
Adapted from Urzay et al., 2018, Annu. Rev. Fluid Mech.



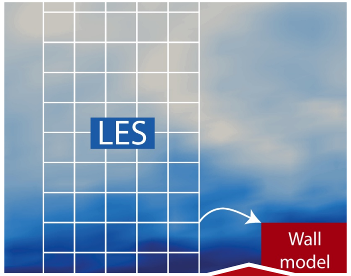
Main tasks

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 (Task #1)
2. Direct Numerical Simulations of high-speed turbulent boundary layers over rough walls (Task #2)
3. Wall-models for hypersonic turbulent boundary layers with chemical reactions (Task #3)

Computational methods for CFD

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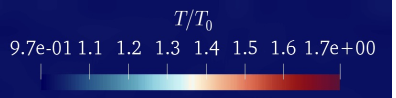
CISAS G. Colombo

How are turbulent flows modelled?

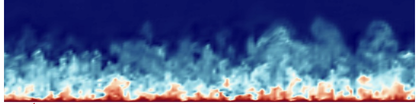
DNS	LES	RANS

← COMPUTATIONAL COST

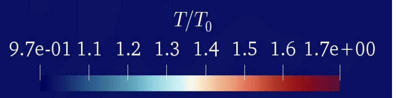
DNS



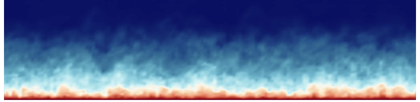
- Solves the full unsteady Navier-Stokes equations
- Resolves the whole spectrum of scales
- No modeling is required
- The cost is too prohibitive for industrial flows



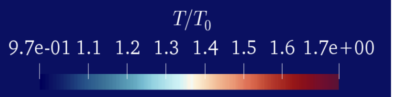
LES



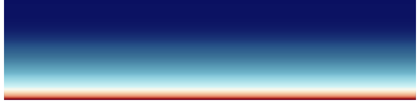
- Solves the spatially averaged N-S equations
- Large eddies are directly resolved, smaller-than-mesh eddies are modeled
- Less expensive than DNS, but still unpractical for industrial applications (especially for bounded flows)



RANS



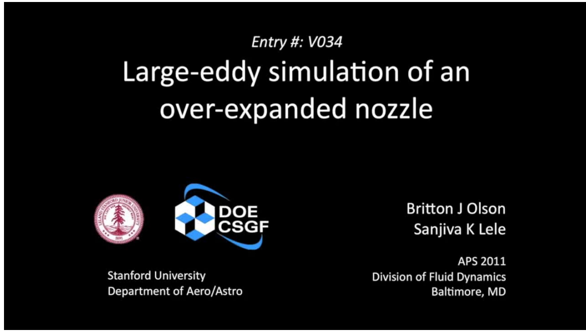
- Solves time-averaged N-S equations
- All turbulent length scales are modeled
- Most widely used approach for industrial flows



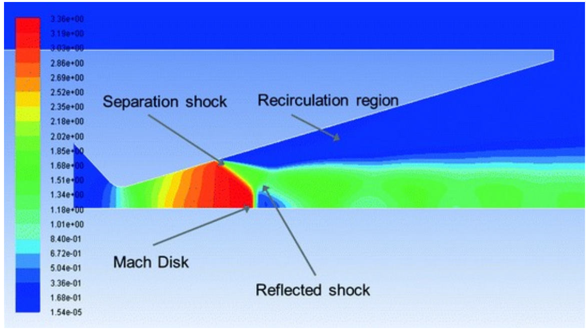
← PHYSICAL ACCURACY

No model!	Modelling small scales	Modelling all scales
$\Delta x \simeq \eta$	$\eta < \Delta x < L_0$	$\Delta x \simeq L_0$

Large-Eddy Simulation



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:

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

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

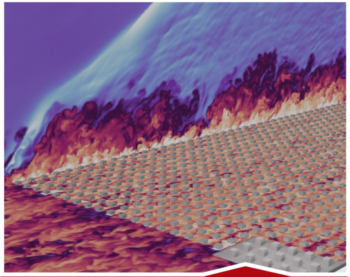
Calorically-perfect gas:

$$E = c_v T + u_i u_i / 2$$
$$H = E + p/\rho$$
$$p = \rho T$$

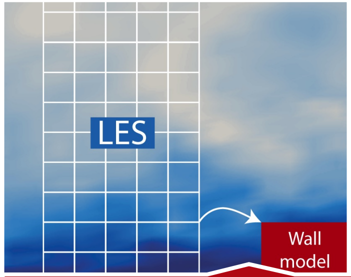
Main tasks

Three main tasks:

High-speed boundary layers over smooth walls



High-speed boundary layers over rough walls



Wall-models for hypersonic boundary layers

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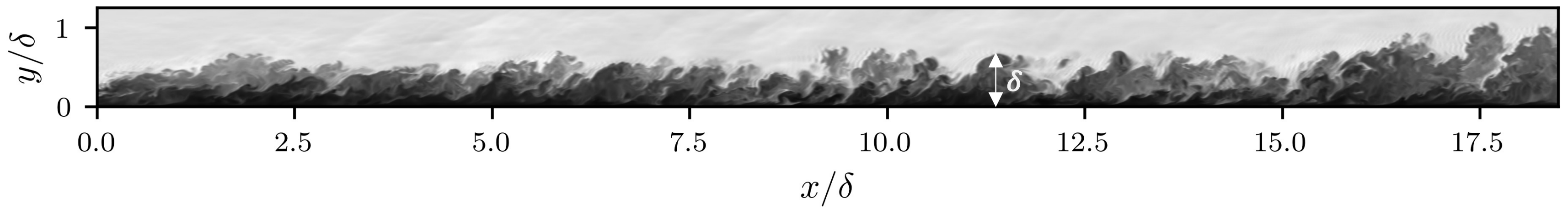
Objectives of this study:

1. **Direct Numerical Simulations of high-speed turbulent boundary layers over smooth walls (Task #1)**
2. Direct Numerical Simulations of high-speed turbulent boundary layers over rough walls (Task #2)
3. Wall-models for hypersonic turbulent boundary layers with chemical reactions (Task #3)



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

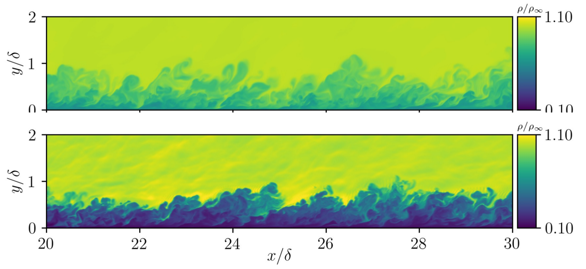
T_w

Wall temperature

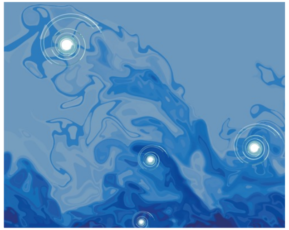
Large variations of thermodynamic properties (e.g. density)

$M_\infty = 2$

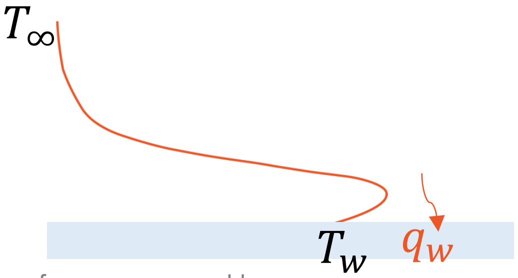
$M_\infty = 6$



Greater separation of turbulent scales

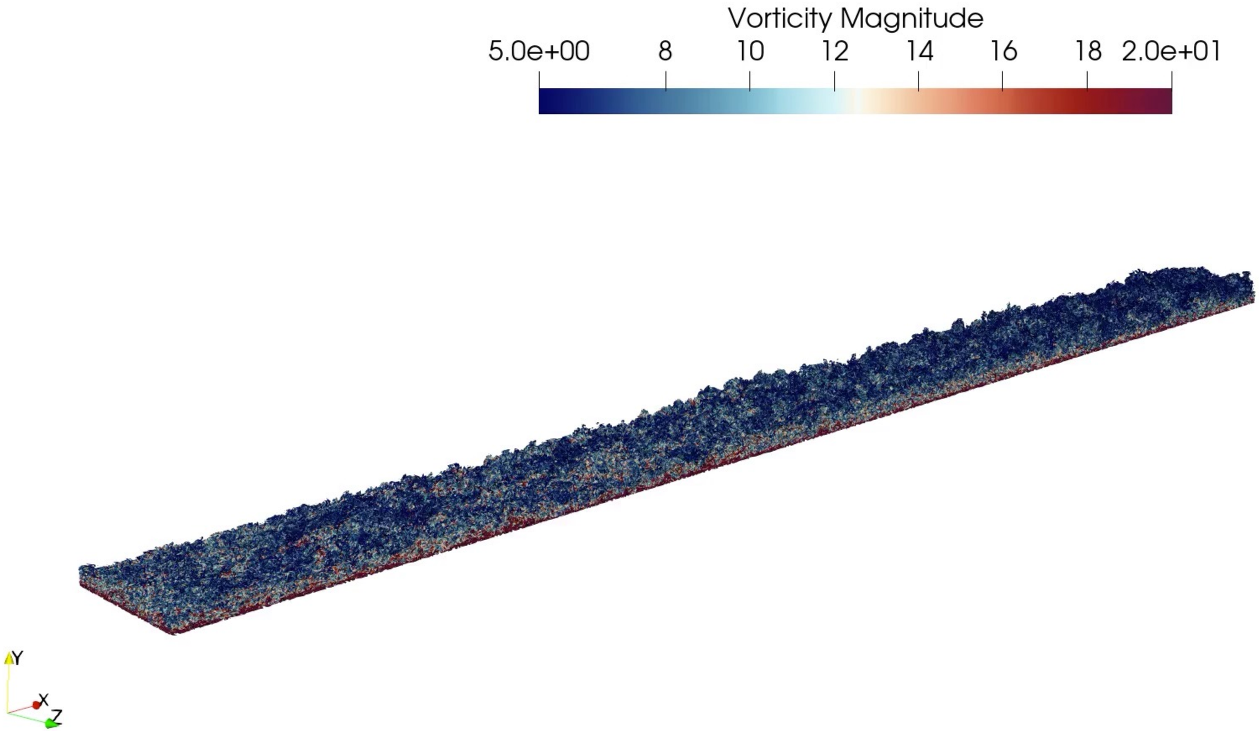


Large wall heat fluxes (aerodynamic heating)



Task #1: Visualization

Visualization of Q-criterion at Mach 6



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Task #1: Selected Results

<u>First study:</u>

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

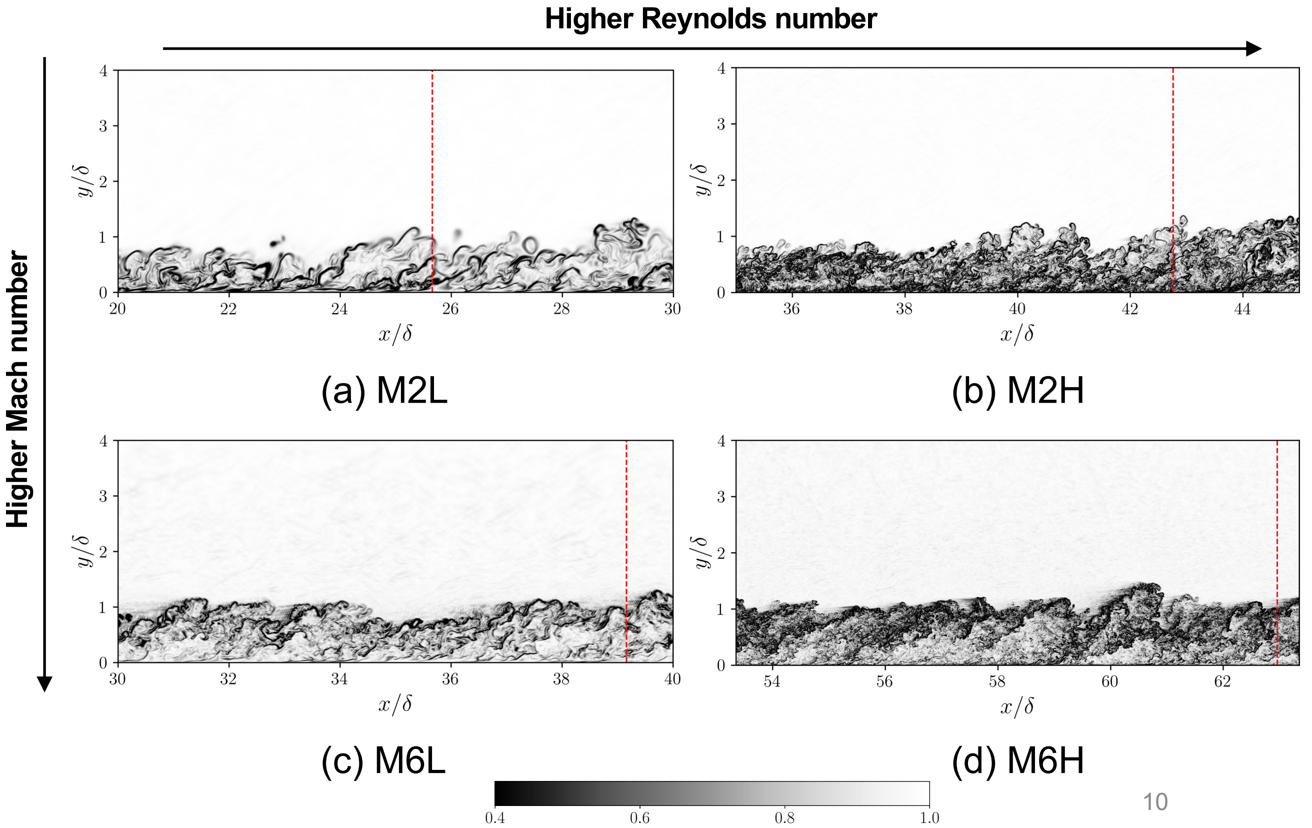
Key points discussed:

- 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



Task #1: Selected Results

Second study:

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

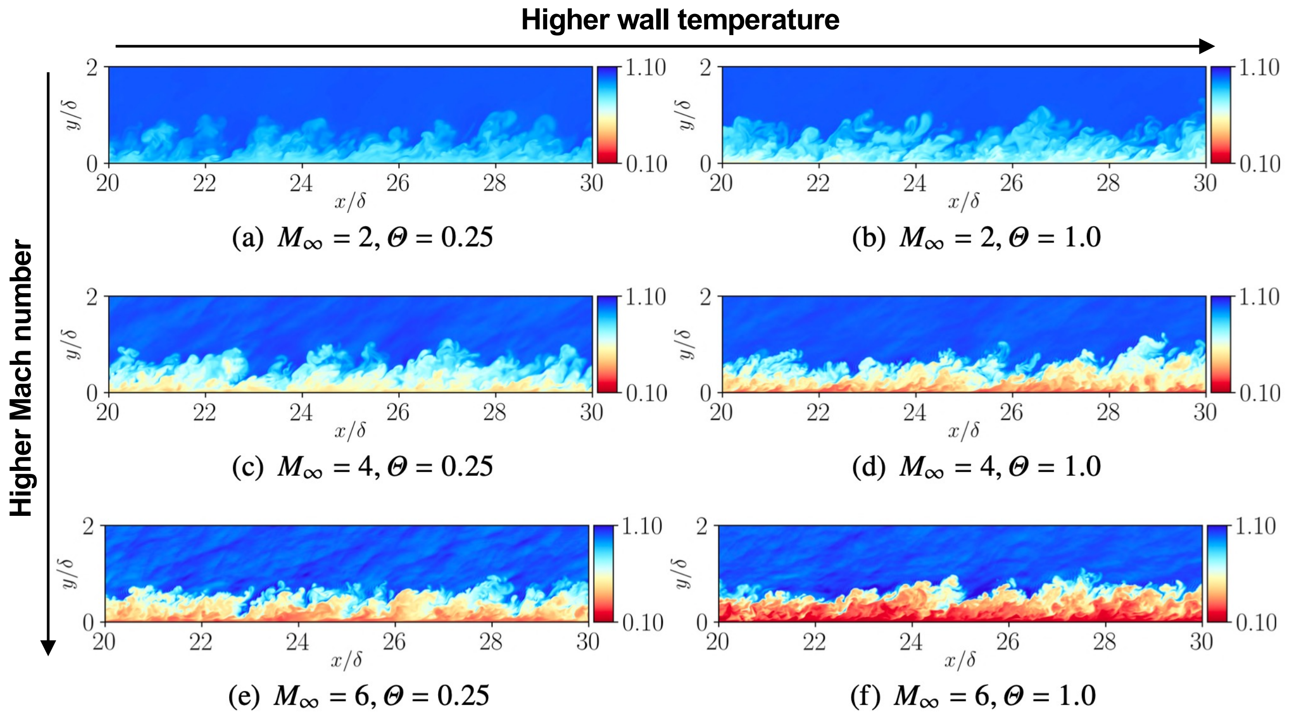
Key points discussed:

- 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



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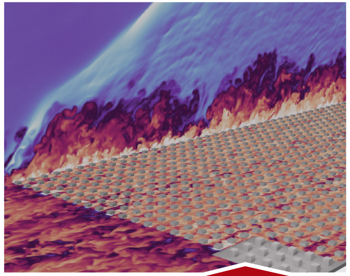
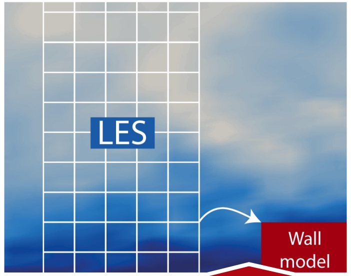


High-speed boundary layers over rough walls



Wall-models for hypersonic boundary layers

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Task #2: Motivations

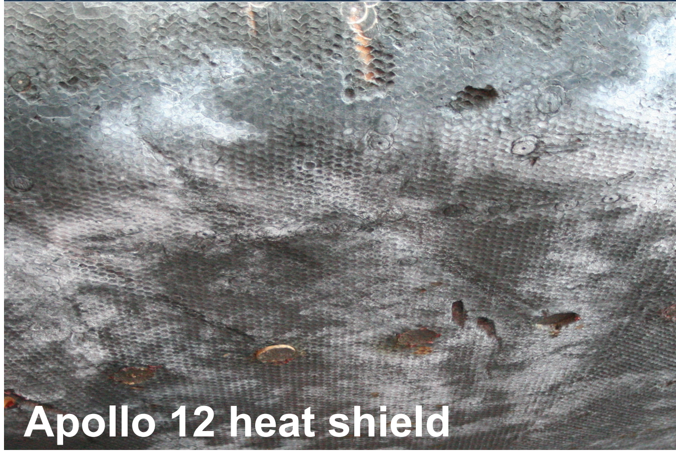
Boundary layer with sourface roughess:

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

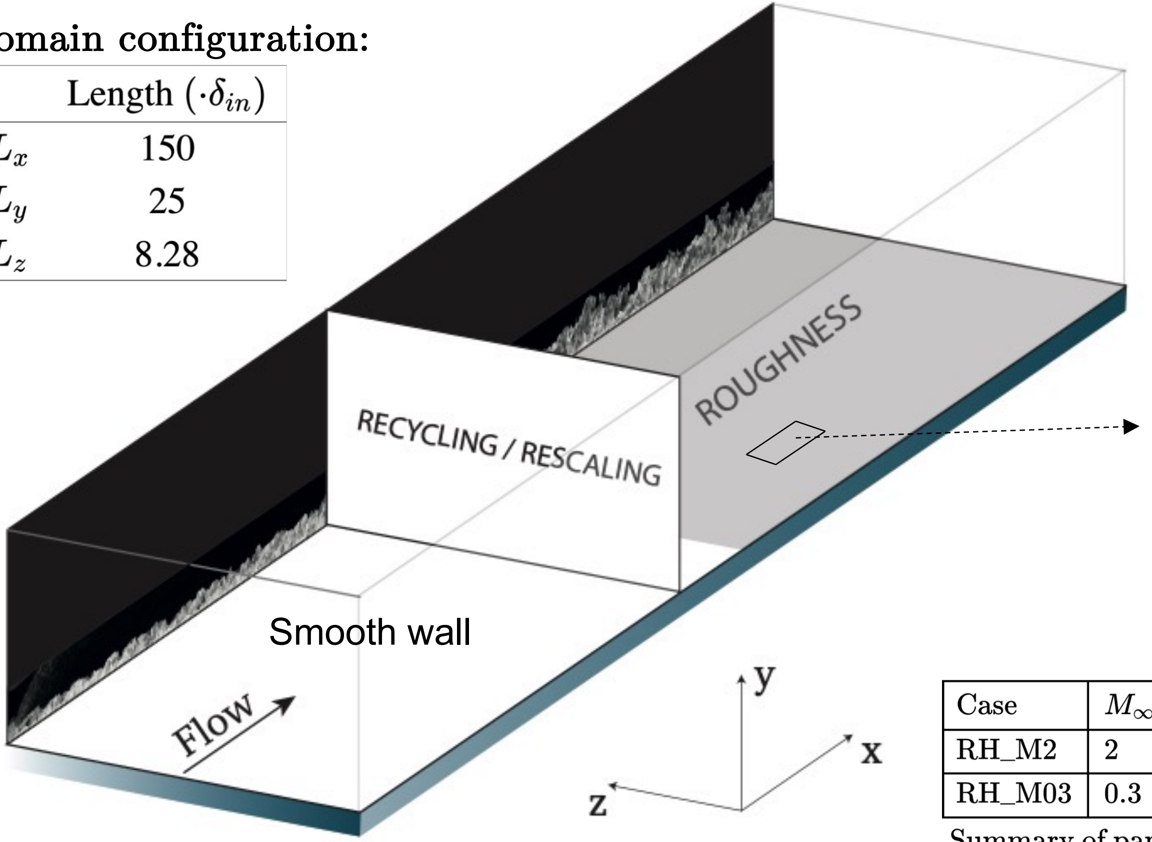


Apollo 12 heat shield

Task #2: Computational domain

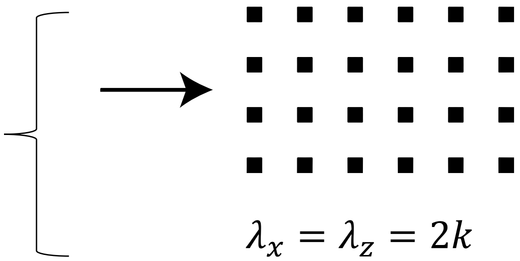
Domain configuration:

	Length ($\cdot\delta_{in}$)
L_x	150
L_y	25
L_z	8.28



Recycling station: $x = 40\ \delta_{in}$
Roughness starts: $x = 55\ \delta_{in}$

Pattern of aligned cubical elements:

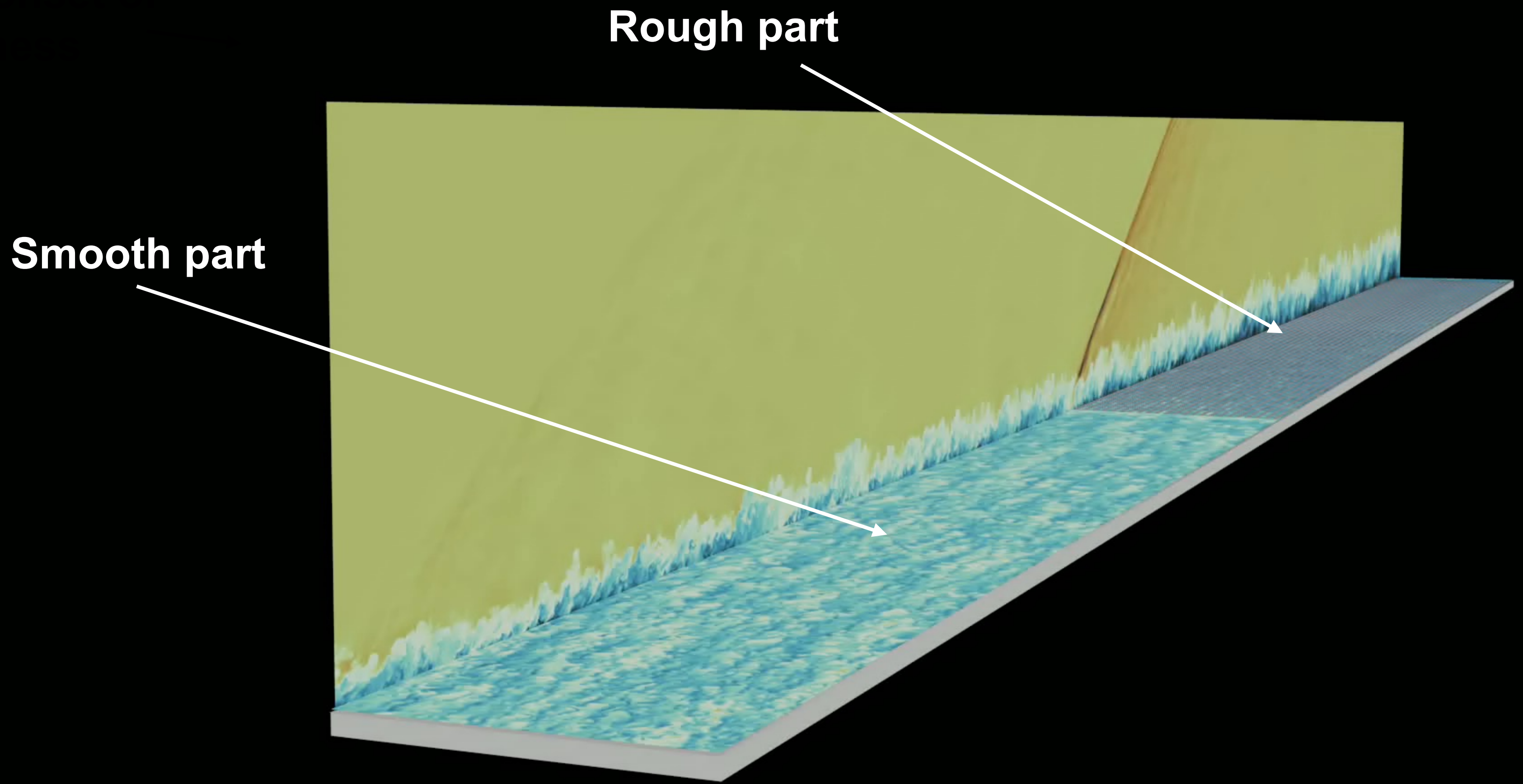


$\lambda_x = \lambda_z = 2k$

$k = 0.12\ \delta_{inflow}$

Case	M_∞	Re_τ	N_x	N_y	N_z	$N_{\text{nodes}} \cdot 10^9$
RH_M2	2	600 – 1600	20240	556	1408	15.8
RH_M03	0.3	650 – 1700	20240	556	1408	15.8

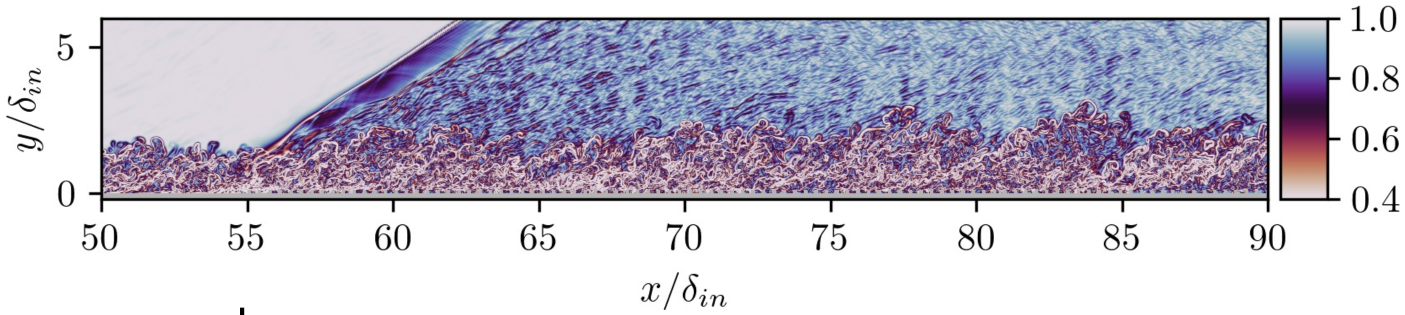
Summary of parameters of DNS study


Rough part
Smooth part

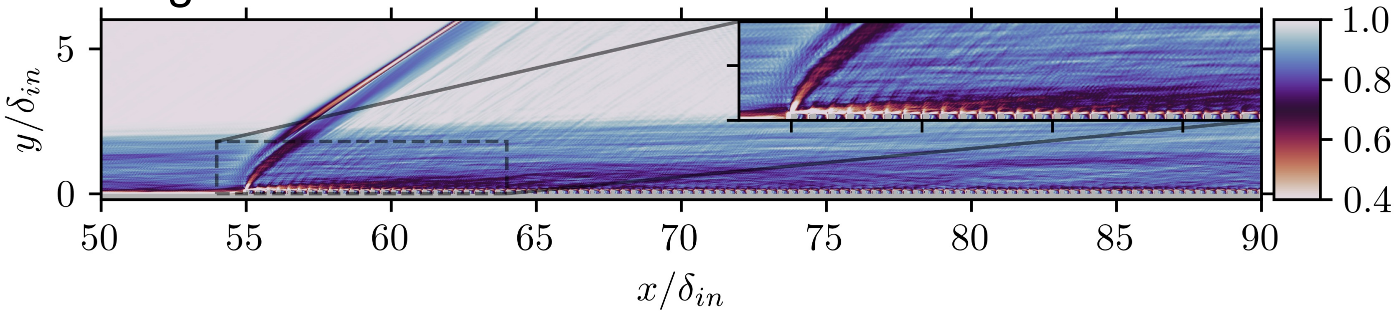
Task #2: Selected results

Wall-normal planes colored by the density gradient normalized between 0 and 1

RH_M2 instantaneous



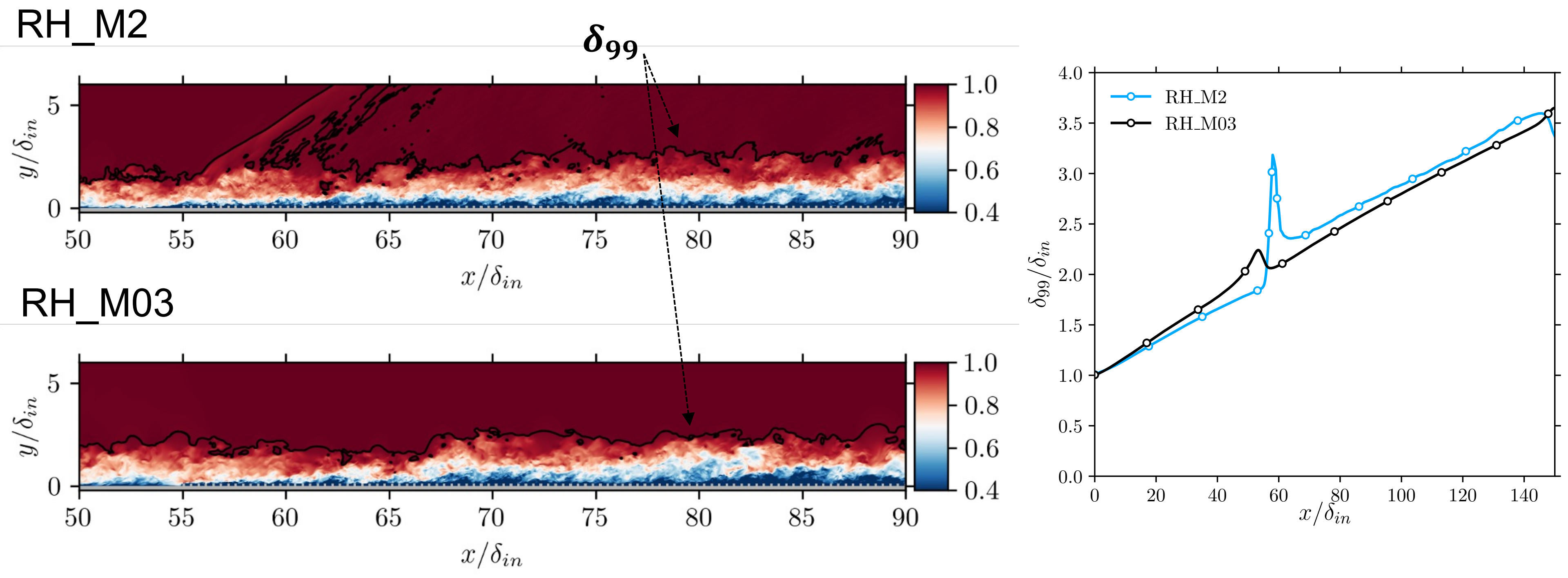
RH_M2 time averaged



The supersonic case shows an initial shock wave that is followed by a pattern of compression/expansion waves emanated from each element

Task #2: Selected results

Wall-normal planes colored by streamwise velocity normalized between 0 and 1



After the surface transition, the supersonic case has a more pronounced upward shift of the BL thickness. This fact contributes to the delay of equilibrium reached by the flow with the new surface.

Main tasks

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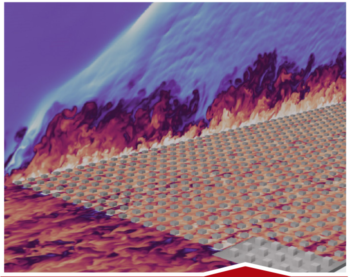
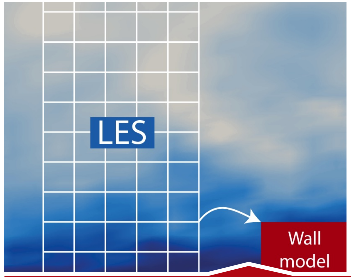


High-speed boundary layers over rough walls



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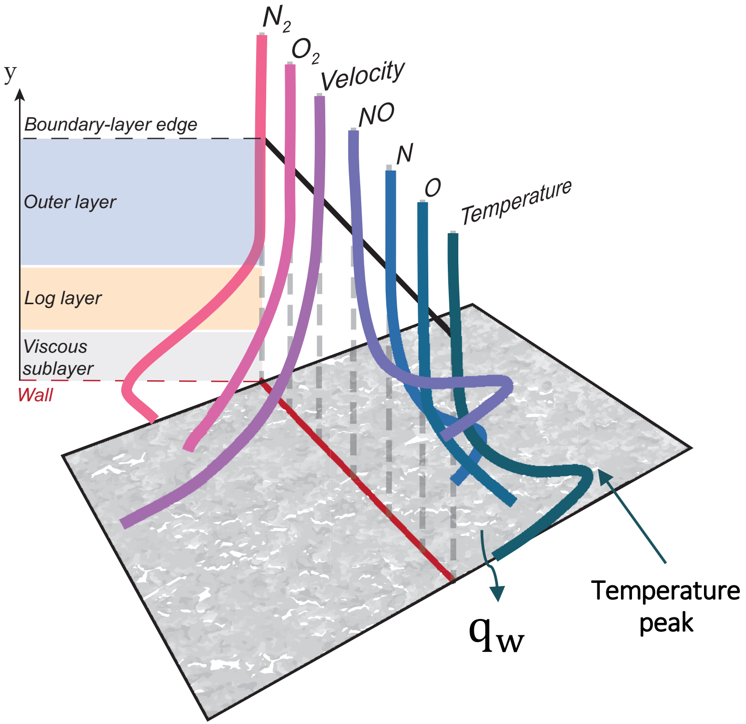
Task #3: Wall models for hypersonics

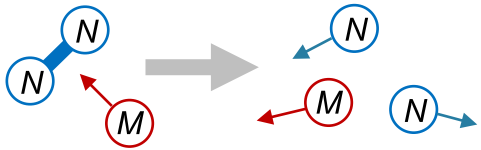
In high-speed boundary layers temperatures can get so high to activate chemical processes (dissociation and recombinatin of air).

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

The objective of this 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)





Hypersonic boundary layers

For this study, the DNS dataset of *Williams et al. (2023) is considered:**

$Re_\tau = \frac{\delta}{l_\nu} \approx 1200,$ *Friction Reynolds number*

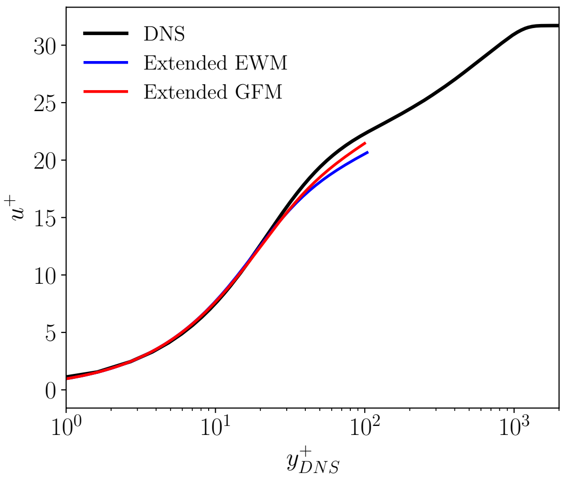
$M_\infty = 20,$ *Edge Mach number*

$Y_{O_2}^{wall} \approx 0.02,$ *Mass fraction of O_2 at the wall*

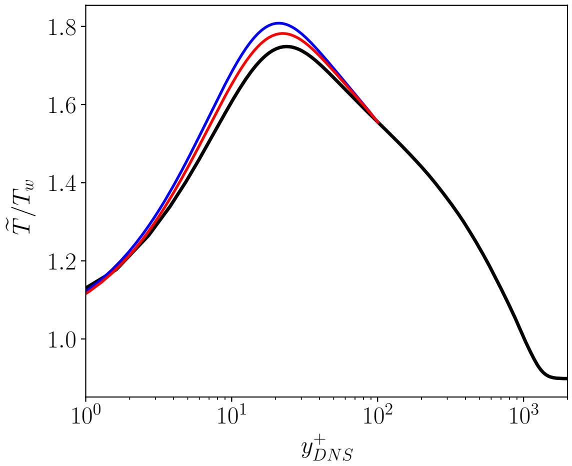
$T_w \approx 3000K$ *Wall temperature*

Benchmark DNS
Previous model
Proposed model

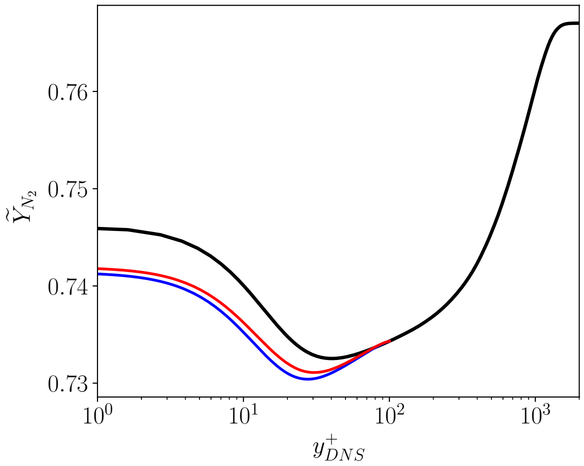
Velocity



Temperature



Molecular Nitrogen



The proposed model shows improved results for velocity and temperature, further improvements are needed for the prediction of chemical composition

*Williams et al., CTR Annual Research Brief, 2023

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.

Several other applications are directly related to the research activity!

Università degli Studi di Padova

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.
- Placco, L., **Cogo, M.,** Bernardini, M., Aboudan, A., Ferri, F., & Picano, F. (2023). Large-Eddy Simulation of the unsteady supersonic flow around a Mars entry capsule at different angles of attack. Aerospace Science and Technology, 143, 108709.
- **Cogo, M.,** Baù, U., Chinappi, M., Bernardini, M., & Picano, F. (2023). Assessment of heat transfer and Mach number effects on high-speed turbulent boundary layers. Journal of Fluid Mechanics, 974, A10.
- **Cogo, M.,** Williams, C. T., Griffin, K. P., Picano, F., & Moin, P. (2023). Inverse-velocity transformation wall model for reacting turbulent hypersonic boundary layers. Center for Turbulence Research Annual Research Briefs.
- **Cogo, M.,** Modesti, D., Bernardini, M. & Picano, F. (2024). Surface roughness effects on supersonic turbulent boundary layers. Journal of Fluid Mechanics, Under Review.

Conferences:

- 33rd Parallel CFD International Conference in Alba, Italy (25-27 May 2022).
- 14th European Fluid Mechanics Conference in Athens, Greece (13-16 September 2022).
- 76th Annual Meeting of the APS Division of Fluid Dynamics, Washington D.C. (19-21 November 2023)
- Invited talk at SISSA, Analysis Junior Seminar, SISSA Trieste, 16 February 2024
- Direct and Large-Eddy Simulation 14, Erlangen Germany, 10-12 April 2024
- PhD Days 2024, Scopello Italy, 6-9 May 2024

Visiting periods:

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

GANNT chart

Activity plan

			FIRST YEAR												SECOND YEAR												THIRD YEAR											
WBS NUMBER	TASK TITLE	% OF TASK COMPLETE	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 numb	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	100%																																				
2.4	Hypersonic turbulent boundary layer over a rough plate with DNS - Mach number effe	100%																																				
3	LES - Attached flows over smooth plates																																					
3.1	Analysis of the state of the art	100%																																				
3.2	A posteriori WMLES of hypersonic turbulent boundary layers - calorically perfect gase	100%																																				
3.3	A priori WMLES of hypersonic turbulent boundary layers - Thermally perfect gases	100%																																				
3.4	A priori WMLES of hypersonic turbulent boundary layers - chemically-reactng gases	100%																																				
4	Writing thesis and reports																																					
4.1	Reports for admission to the next year or conferences	90%																																				
4.2	Writing scientific papers	90%																																				
4.3	Writing thesis	90%																																				

Thanks for the attention

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