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UNIVERSITÀ DEGLI STUDI DI PADOVA

A novel numerical method for fluid structure interaction problems

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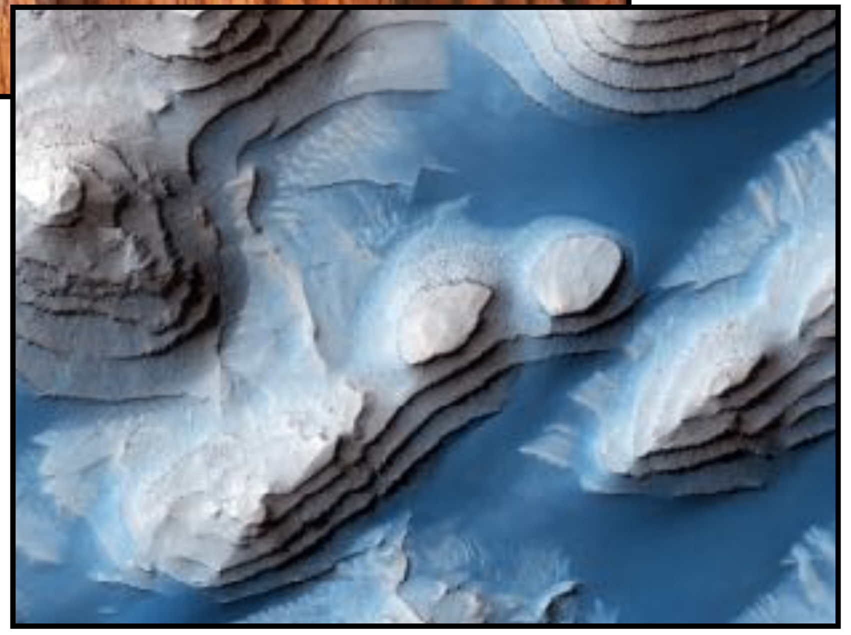
- **Fluid-Structure Interaction (FSI) problem:**
  - Interaction between a fluid flow and rigid or deformable solid structures:
    - Force exchange across **sharp, geometrically complex and time-evolving interfaces**
    - Solid mechanics and fluid dynamics governed by **different constitutive laws**
  - **Hydraulic Fracturing (HF)**
    - Fracture mechanics is involved
    - **Crack-formation, branching and break-up in solids** due to fluid-induced stresses or fluid-driven fatigue

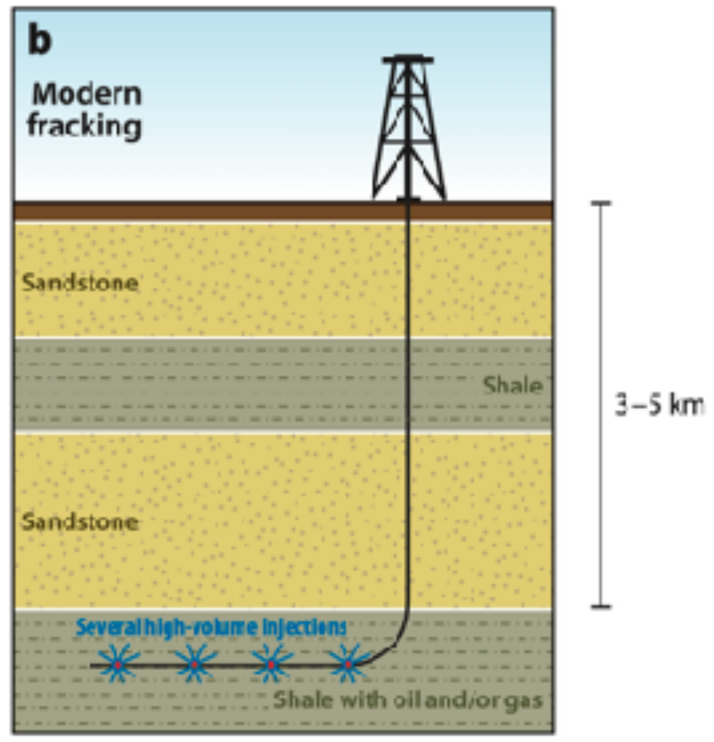
- **Multi-physics and strongly nonlinear problem**
- **Analytical solution are not possible**
- **Models for applications have limited reliability**

- **FSI and HF in aerospace engineering:**
  - Liquid sloshing in fuel tanks
  - Aeroelastic flutter of wings
  - **Formation of cracks in wings and turbo-machinery components**

- **FSI and HF in planetary sciences:**
  - **Erosion processes on planetary surfaces**

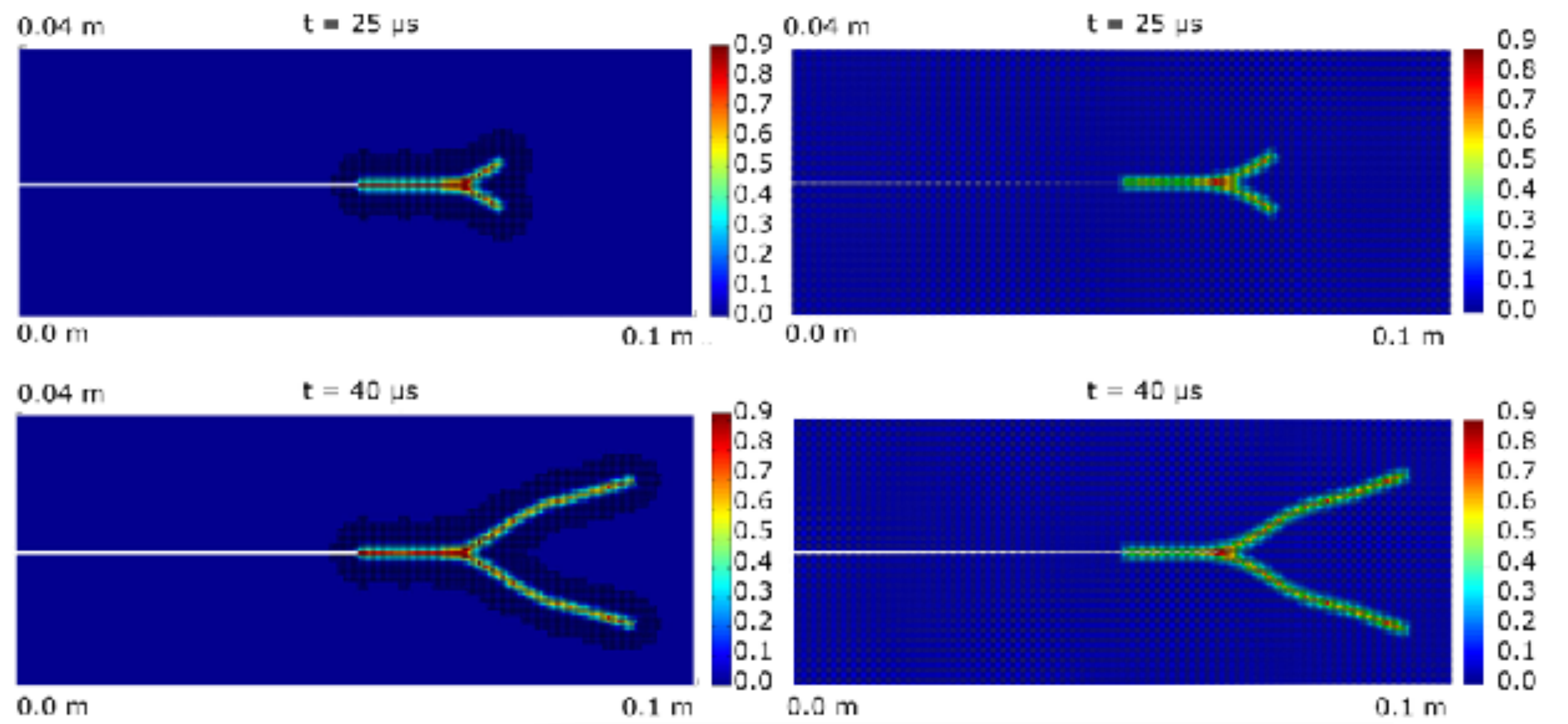


- **FSI and HF in geotechnic:**
  - Fracking



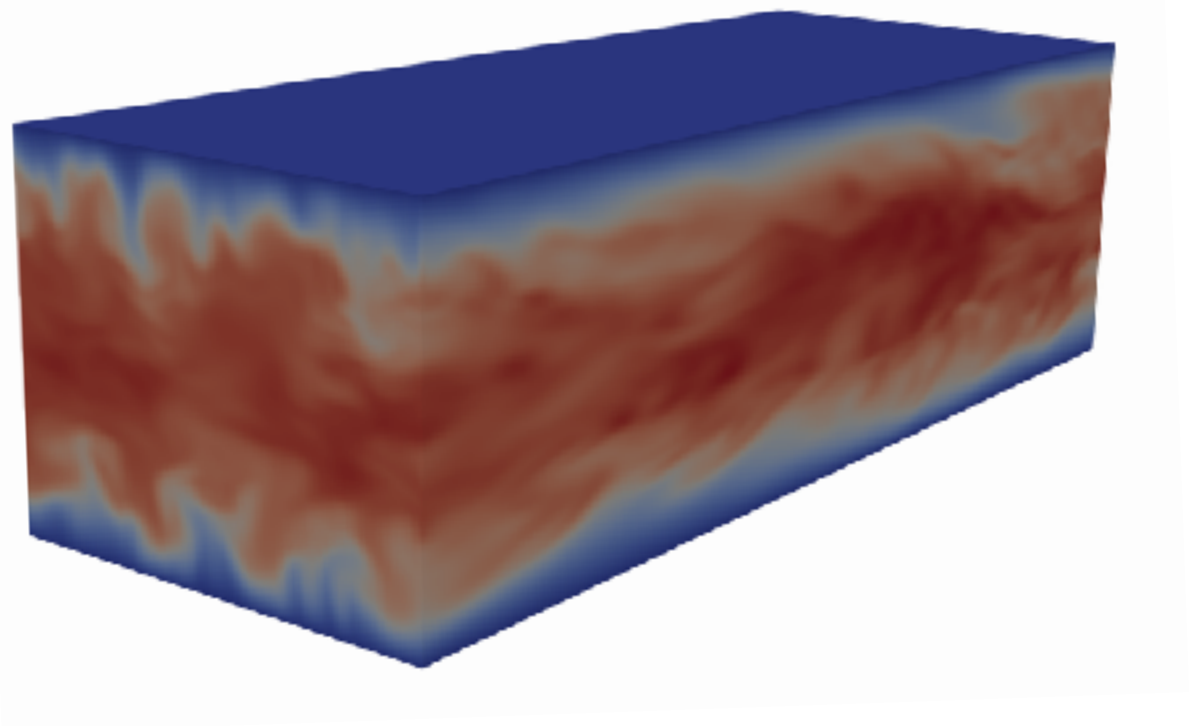
Norris et al. Annu. Rev. Earth Planet. Sci. 2016. 44:321–51

OBJECTIVES AND METHODOLOGY

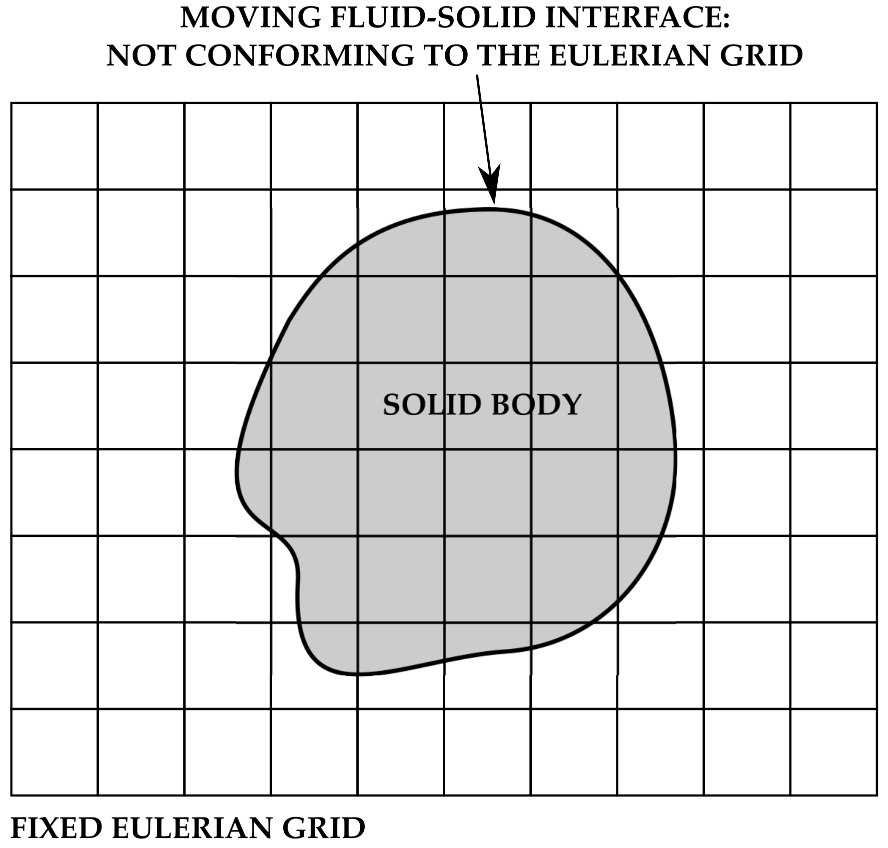


- **Objectives:**
  - **Development of a numerical tool capable to reproduce the physics of generic FSI problems involving solid fracture**
  - **Investigation of the physics of FSI with solid fracture**

- **Methodology:**
  - **Peridynamics (PD):**
    - Reformulation of solid mechanics in terms of integral equations
    - **Crack formation, crack branching and solid fracture are intrinsically accounted for in the theory**



  - **Incompressible Navier-Stokes equations (NS)**
    - Prediction of fluid flow dynamics
    - Direct Numerical Simulation (DNS): **all the scales of turbulent motions are directly solved on the computational grid without using turbulence model**
  - **Immersed Boundary Method (IBM)**
    - Imposition of no-slip and no-penetration BCs on geometrically complex interfaces
    - No need for grid update during simulation

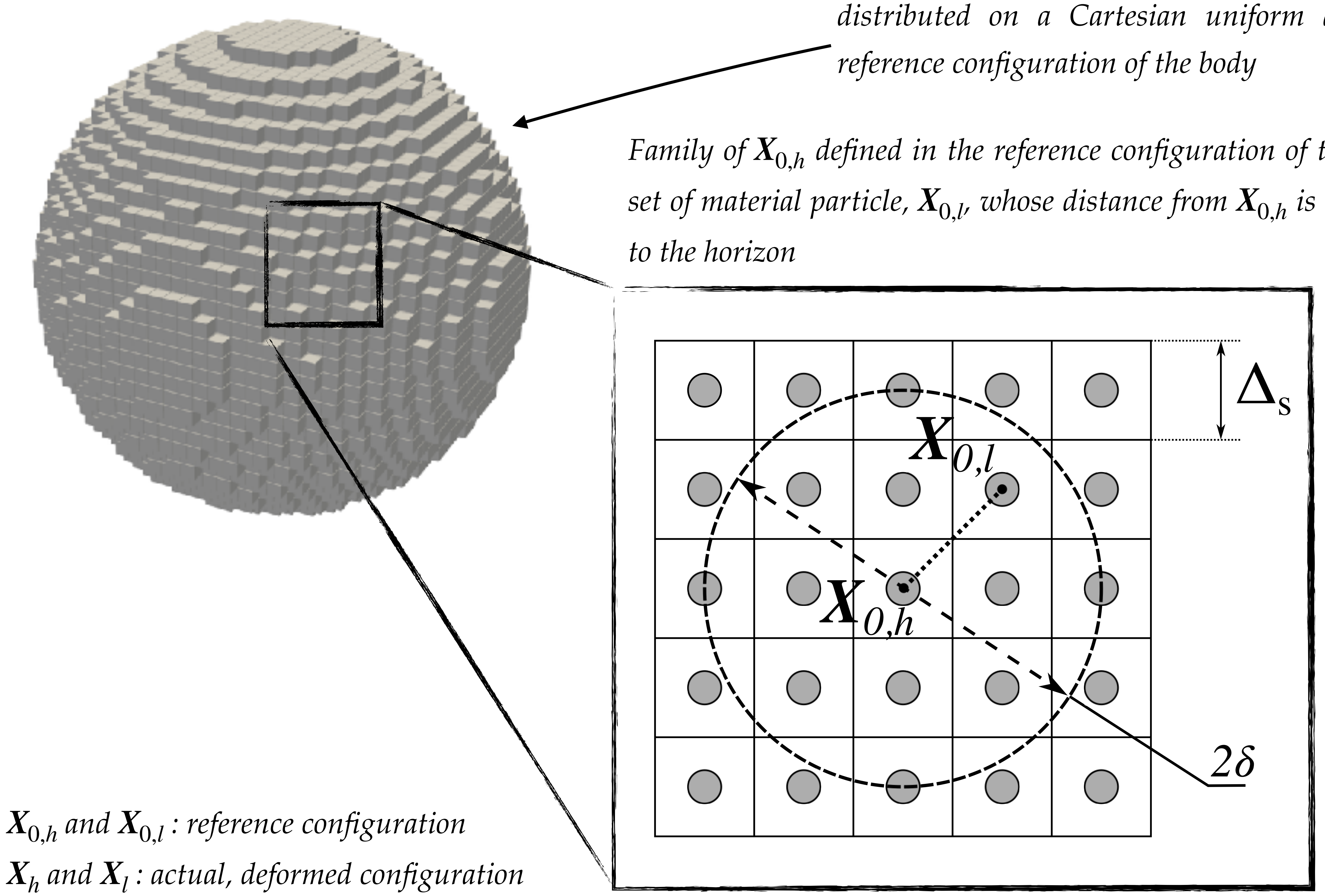


DISCRETE BOND-BASED PERIDYNAMICS: BASIC CONCEPTS

- **Peridynamics is a reformulation of continuum mechanics based on non-local integral equations:**
  - A discretized peridynamic solid is a **set of finite size material particles**
  - **Material particles mutually interact via micro-elastic potentials** that generate bond forces
  - **Interactions (*bonds*) vanish beyond a threshold distance, referred to as *horizon*, δ**

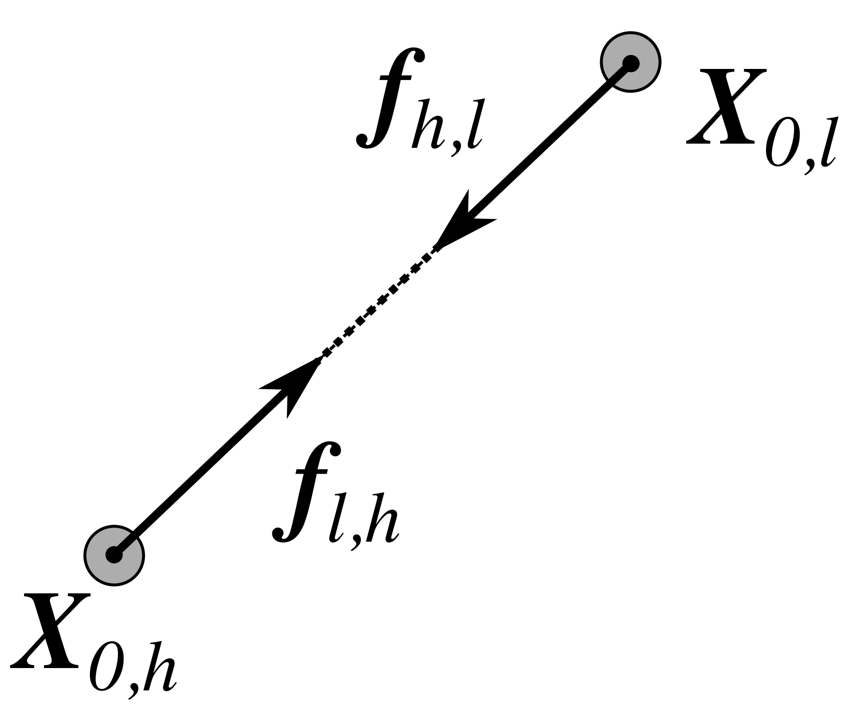
Body discretization: cubic and finite-size particles of edge-size Δs distributed on a Cartesian uniform and equispaced grid in the reference configuration of the body

Family of $\boldsymbol{X}_{0,h}$ defined in the reference configuration of the body: the set of material particle, $\boldsymbol{X}_{0,l}$, whose distance from $\boldsymbol{X}_{0,h}$ is less or equal to the horizon



$\boldsymbol{X}_{0,h}$ and $\boldsymbol{X}_{0,l}$: reference configuration

$\boldsymbol{X}_h$ and $\boldsymbol{X}_l$: actual, deformed configuration



- **Peridynamic equations:**

$$\frac{d\boldsymbol{X}_h}{dt} = \boldsymbol{U}_h$$

$$\frac{d^2\boldsymbol{X}_h}{dt^2} = \sum_{l=1}^{N_h} \boldsymbol{f}_{h,l}\, \Delta V_l + \boldsymbol{F}_{ext,h}$$

- $\boldsymbol{f}$ is a force density (force per unit volume square) and is referred to as ***pairwise density function***:
  - $\boldsymbol{f}_{h,l}$ is the force per unit volume square that material point $\boldsymbol{X}_l$ exerts on $\boldsymbol{X}_h$
  - $\boldsymbol{f}_{l,i} = -\boldsymbol{f}_{h,l}$ is the force per unit volume square that material point $\boldsymbol{X}_h$ exerts on $\boldsymbol{X}_l$
- **PROS:**
  - The usage of integral equations **avoids the onset of singularities in the evaluation of partial derivatives** that affect classical local theories when crack formation is taken into account
  - **Intrinsic crack management capabilities**
- **CONS:**
  - **High computational cost!**

DISCRETE BOND-BASED PERIDYNAMICS: PAIRWISE FORCE DENSITY AND BOND BREAK-UP

- **The pairwise density function, $f_{h,l}$, is a function of the bond stretch, $s_{h,l}$, and of the macroscopic mechanical properties of the material:**

$$f_{h,l} = c_0 \; s_{h,l} \; \Gamma_{h,l} \; \frac{\boldsymbol{X}_l - \boldsymbol{X}_h}{||\boldsymbol{X}_l - \boldsymbol{X}_h||}$$

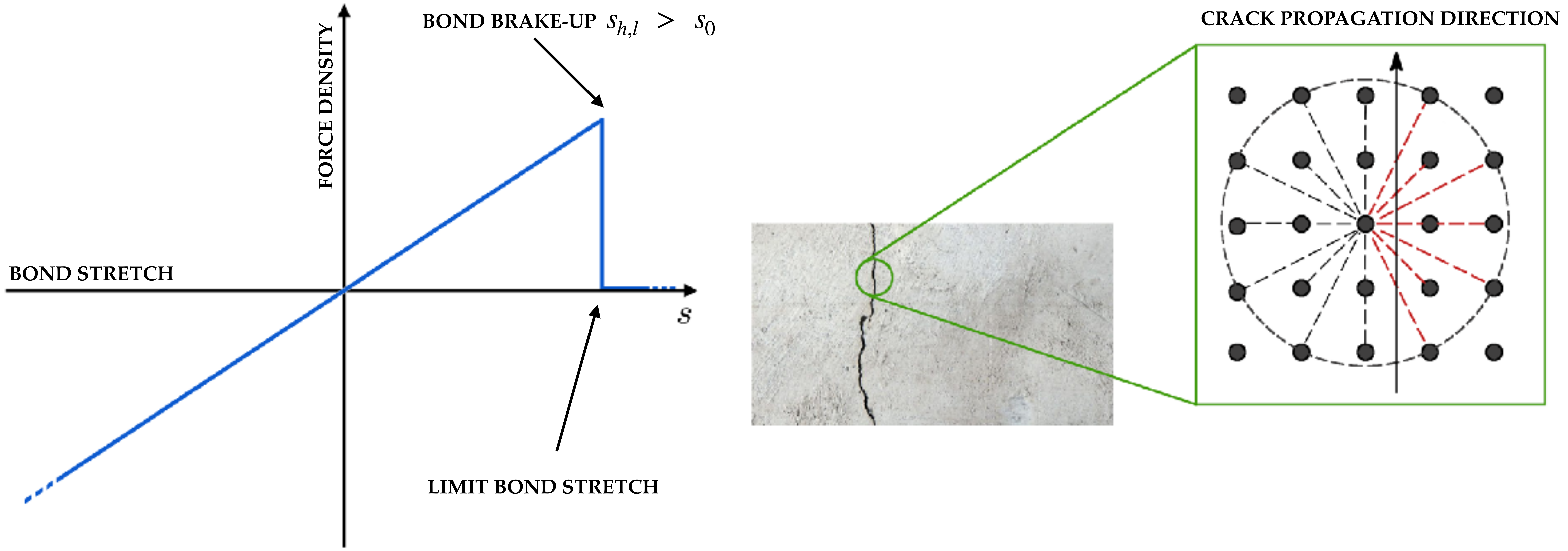
  - The ***bond stretch***, $s_{h,l}$, is the ratio between the actual relative distance in a particle pair, $|\boldsymbol{X}_l - \boldsymbol{X}_h|$, and the related distance in the reference configuration of the body, $|\boldsymbol{X}_{0,l} - \boldsymbol{X}_{0,h}|$:

$$s_{h,l} = \frac{|\boldsymbol{X}_l - \boldsymbol{X}_h|}{|\boldsymbol{X}_{0,l} - \boldsymbol{X}_{0,h}|}$$

  - c_0 is the ***bond micro-modulus*** and is a function of the Young's modulus, E ,and of the horizon, δ

  - The parameter $\Gamma_{h,l}$ accounts for bond break-up:

$$\Gamma_{h,l} = \begin{cases} 1, & s_{h,l} < s_0, \; \forall t \geq 0 \\ 0, & otherwise \end{cases}$$

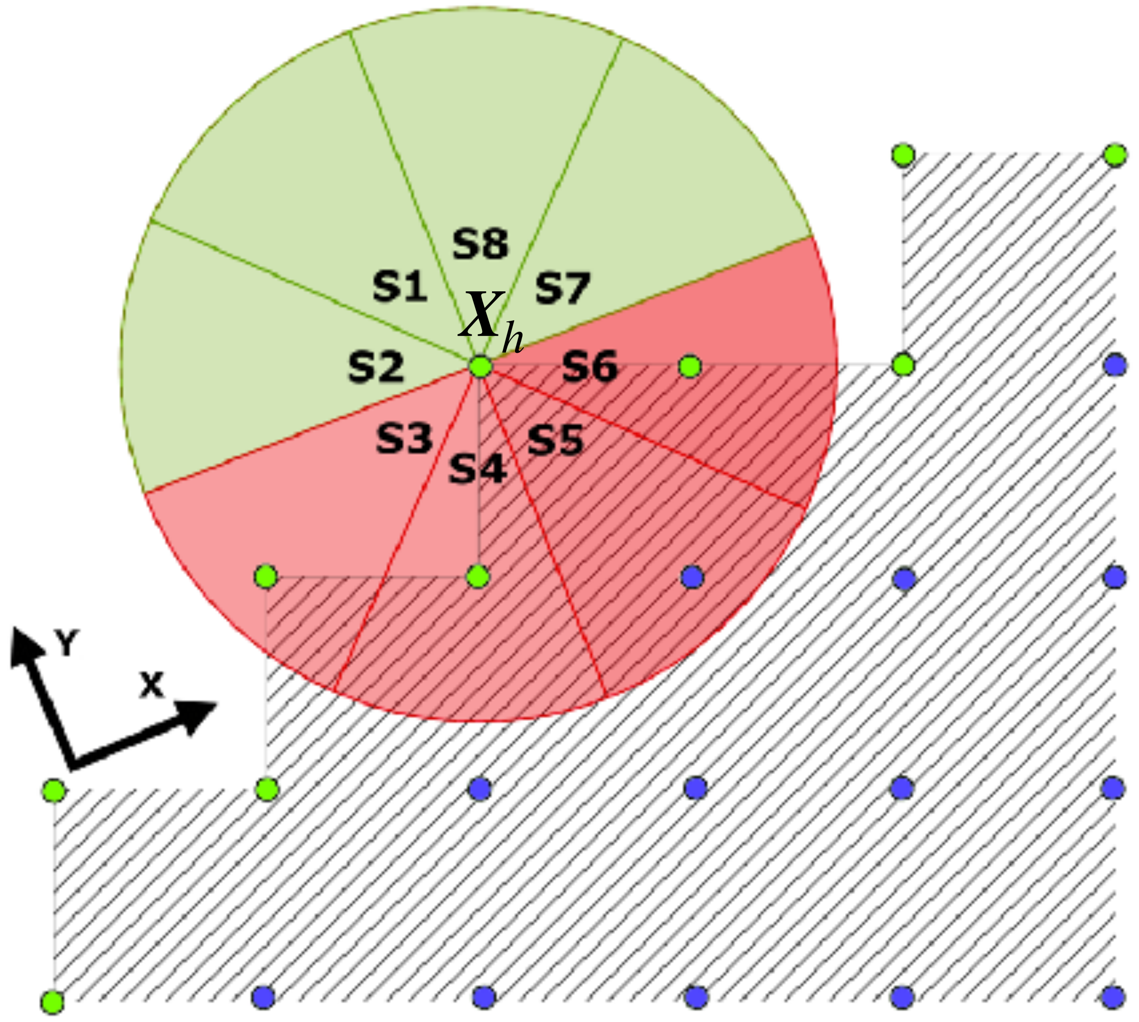


- Peridynamics - **Intrinsic crack detection and crack-branching prediction capabilities**:
  - **A bond breaks when its stretch, s, overcomes a threshold value, the limit bond stretch, s_0**
  - The limit bond stretch, s_0, is a function of the macroscopic mechanical properties of the material: the energy release rate, G, and the horizon, δ
  - **Bond breakage is permanent!**

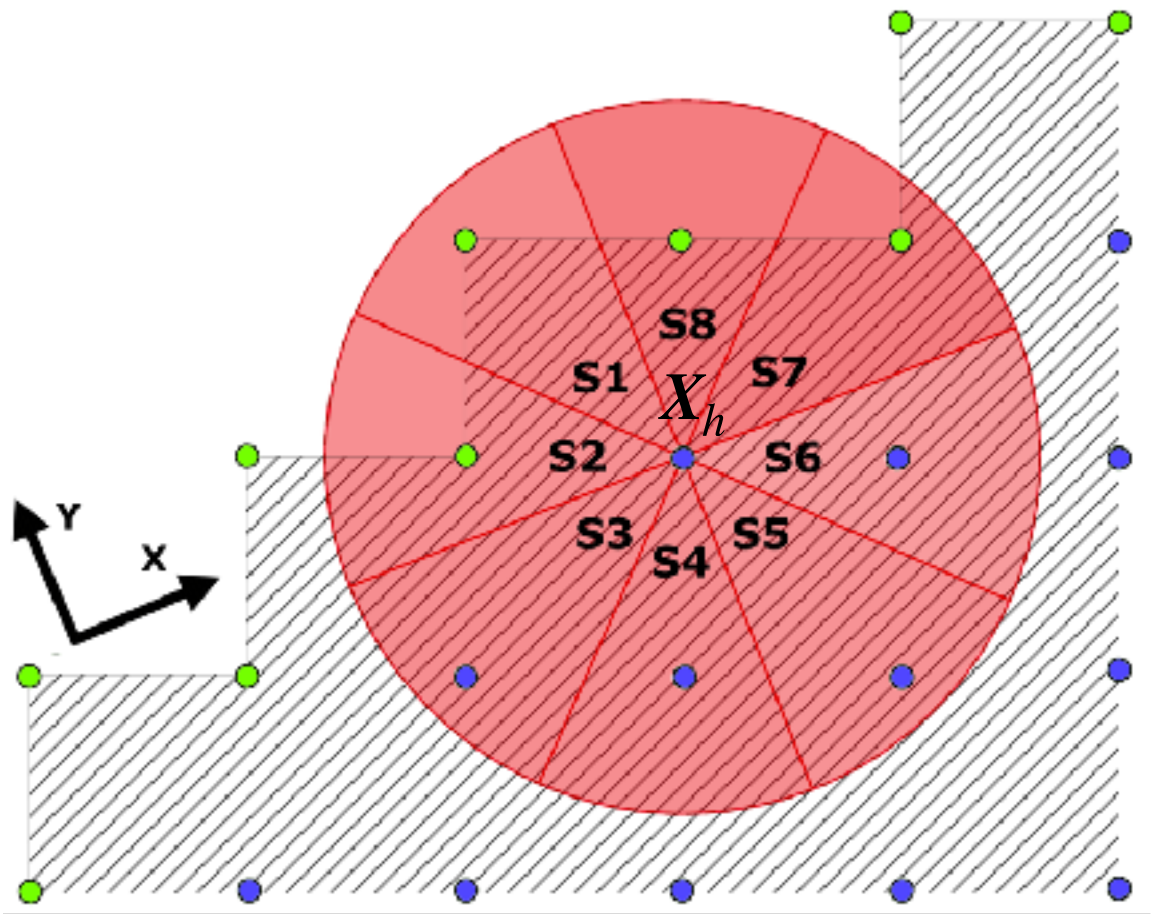
AUTOMATIC DETECTION OF SOLID SURFACES AND COMPUTATION OF NORMAL VECTORS

- **Solid surfaces are defined by means of a specific sub-set of material particles (*Lagrangian markers*)**
- A 3D surface detection algorithm is used to check if a material particle is located on the solid surface or interior
- Principle (2D case):
  - **The space surrounding each material particle, X_h , is divided into 8 circular sectors**
  - **Each particle, X_l , in the family of X_h is associated with only one of the sectors**
  - **CRITERION: a particle is located on the solid surface if 2 or more consecutive sectors are empty (90°)**

X_h **is on the surface**



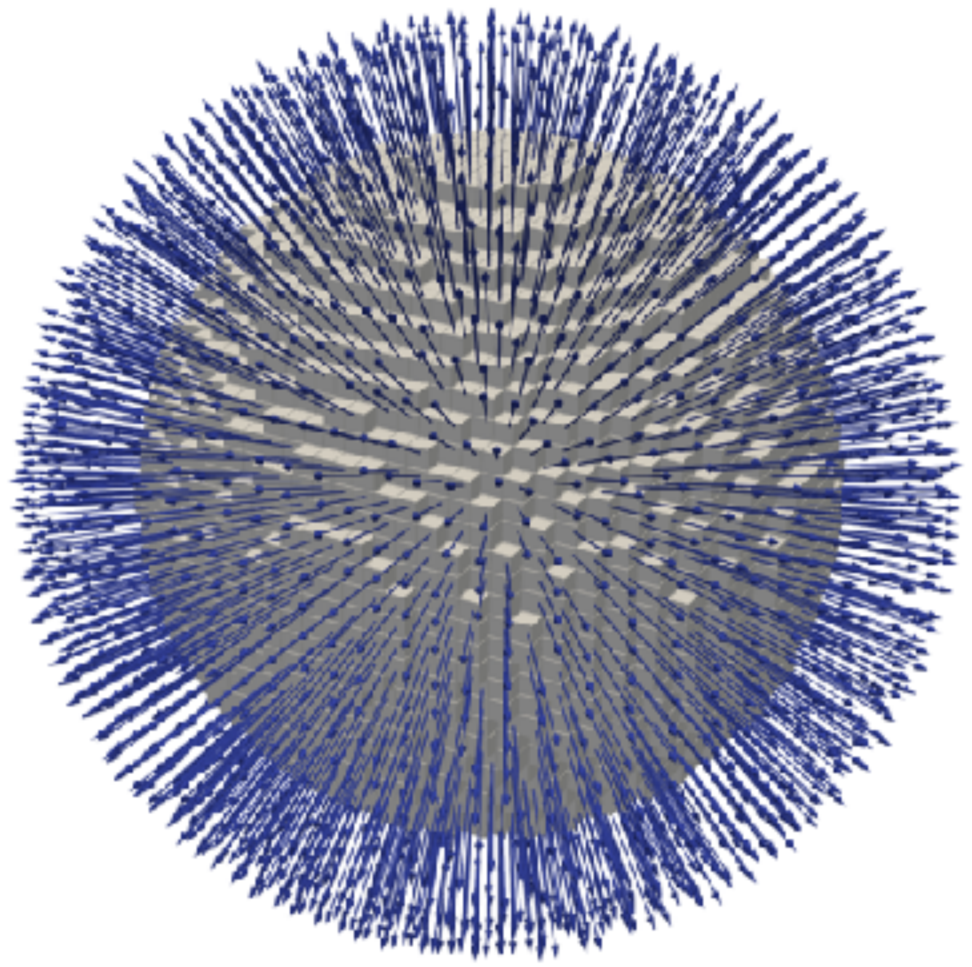
X_h **is the interior**



- The vectors normal to the surface can be computed at the position of each material particle located on the solid surface:

$$\boldsymbol{n}_h = -\frac{\sum_{l=1}^{N_h} (\boldsymbol{X}_l - \boldsymbol{X}_h)\Gamma_{h,l}\Delta V_l}{\sum_{l=1}^{N_h} \Gamma_{h,l}\Delta V_l}$$

- The basic idea is that of **volume-averaging the relative positions of the material particles X_l in the family of X_h**
- The normal unit vector is $\hat{\boldsymbol{n}}_h = \frac{\boldsymbol{n}_h}{|\boldsymbol{n}_h|}$, the tangent, $\hat{\boldsymbol{t}}_h$, and bi-normal vectors, $\hat{\boldsymbol{b}}_h$, follow immediately



Normals computed on the surface of a peridynamic-discretized sphere

THE NAVIER-STOKES EQUATIONS AND THE IMMERSED BOUNDARY METHOD

- The dynamics of fluid flows is described by employing the incompressible Navier-Stokes equations that are solved on a fixed, uniform and equispaced Eulerian grid:
- **All the length-scales of the turbulent motion are directly resolved on the grid without using turbulent model: Direct Numerical Simulation (DNS)**

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\rho_f \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} \right) = -\nabla p + \mu_f \nabla^2 \boldsymbol{u} + \rho_f \boldsymbol{F}_{IBM}$$

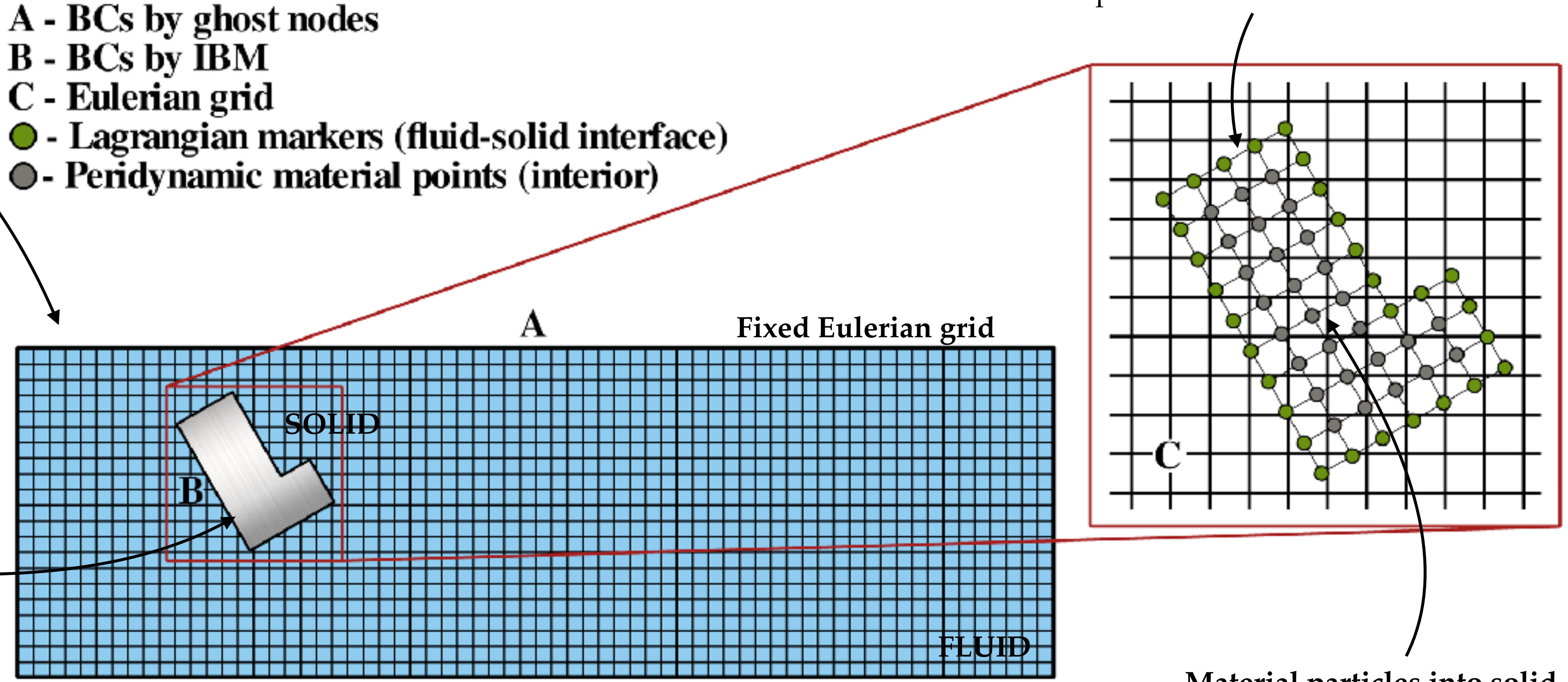
- **IBM PROS:**
  - **The eulerian grid can be non-conforming to the solid surface!**
  - Grid update is not necessary during the simulation to preserve the match of grid nodes with solid surfaces!
  - BCs can be easily and efficiently applied to geometrically complex interfaces!

BCs are directly imposed by means of ghost nodes at the limit boundaries of the computational domain

PROBLEM: BCs have to be imposed to the flow on the solid-liquid interface, but **the Eulerian grid nodes do not coincide with the moving solid surface.** BCs cannot be directly imposed on the grid nodes e.g. $u_{i,j,k} = 0$!

Immersed Boundary Method (IBM): a fictitious force field, $\boldsymbol{F}_{IBM}$, distributed on the grid nodes near the solid-fluid interface, is used to indirectly impose BCs!

Material particles defining the solid surface: wall BCs are applied to the flow at the position of these material points!



Material particles into solid interior

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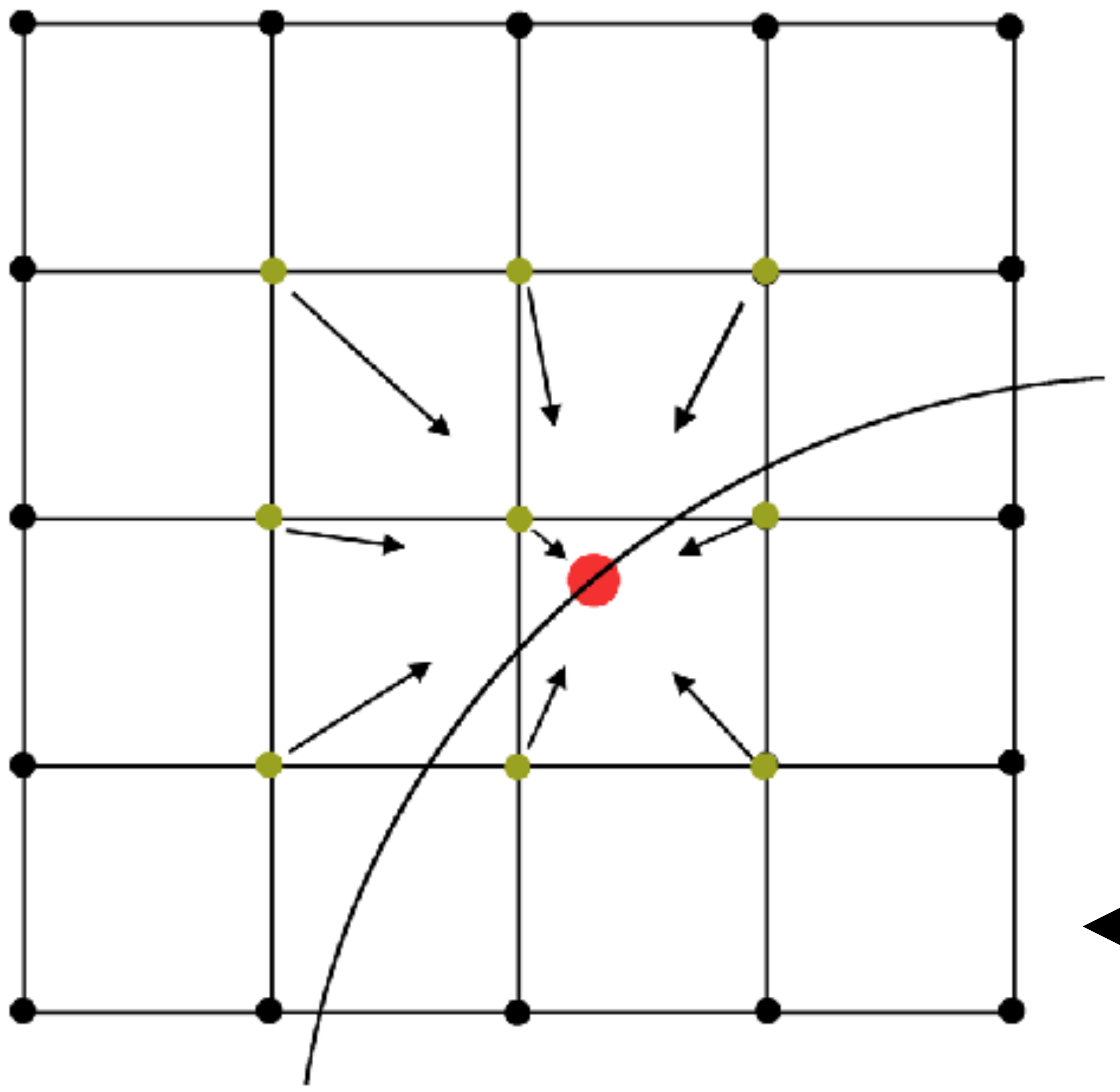
IMMERSED BOUNDARY METHOD: COMPUTATION OF THE FLUID FORCING

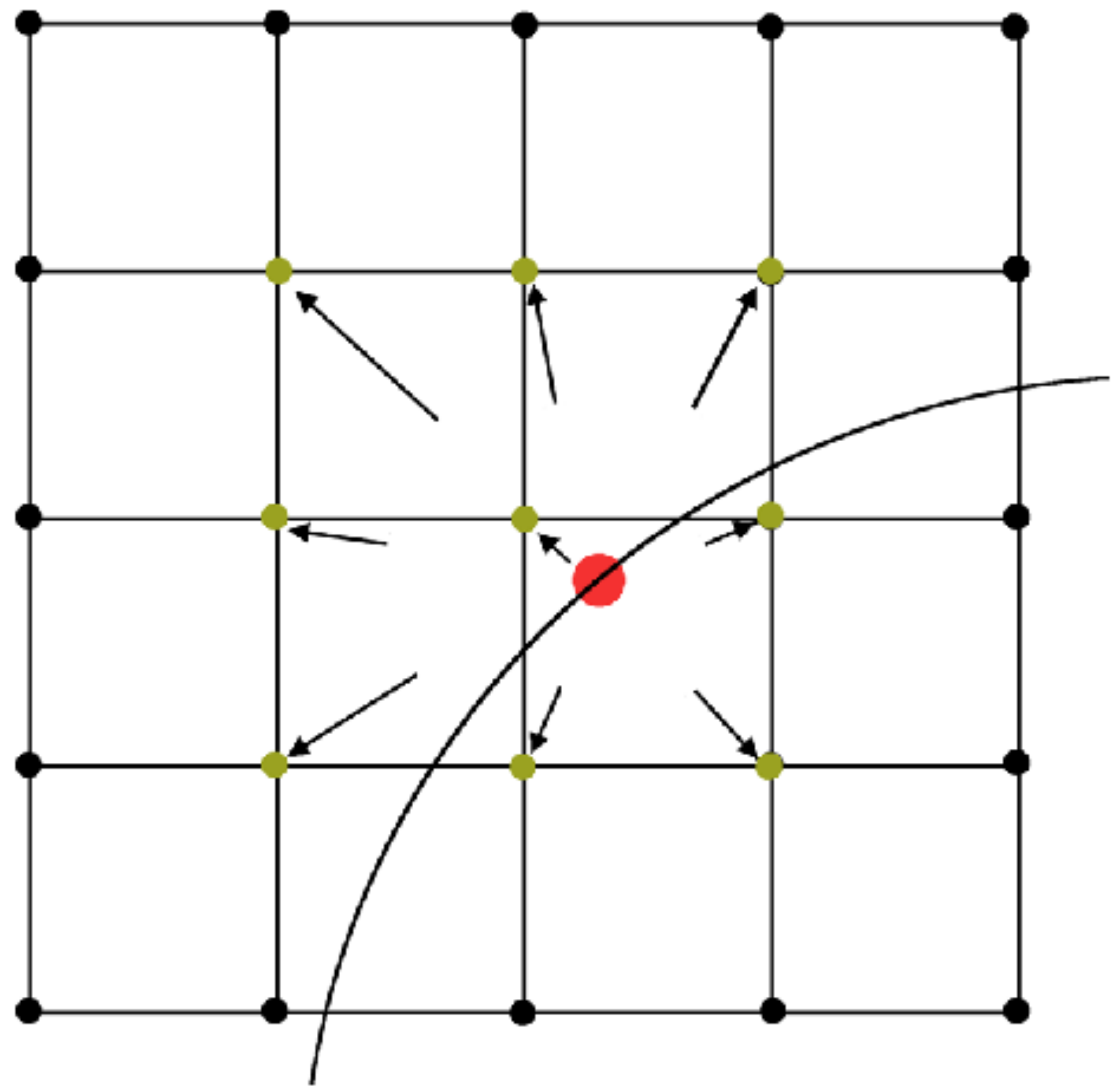
- **PROBLEM:** boundary conditions have to be imposed to the flow on the moving solid-liquid interface:
  - **no-slip boundary condition**
  - **no-penetration boundary condition**
- IBMs employ a fictitious force field applied to the fluid flow such that, **near the interface, the fluid is forced to move with the same local velocity of the solid body**
- The force field can be computed by using an iterative procedure (**multi-direct forcing scheme**) until convergence of the force field:

(1) Interpolation of fluid velocity field at the position of the solid particles located on the fluid-solid interface → **(2) Computation of the forcing** → **(3) Spreading of the forcing on the fluid grid**



$$\boldsymbol{F}_{IBM} = \frac{\boldsymbol{U}_h - \boldsymbol{U}_f(\boldsymbol{X}_h)}{\Delta t}$$

- $\boldsymbol{U}_h$ is the actual velocity of the material particle $\boldsymbol{X}_h$
- $\boldsymbol{U}_f(\boldsymbol{X}_h)$ is the fluid velocity field interpolated at the actual position of the centroid of the material particle $\boldsymbol{X}_h$
- Δt is the time step



COMPUTATION OF FLUID DYNAMIC FORCES

- The forces exerted by the liquid flow on the solid are computed by employing the ***normal probe method.*** For any material particles located on the solid surface:

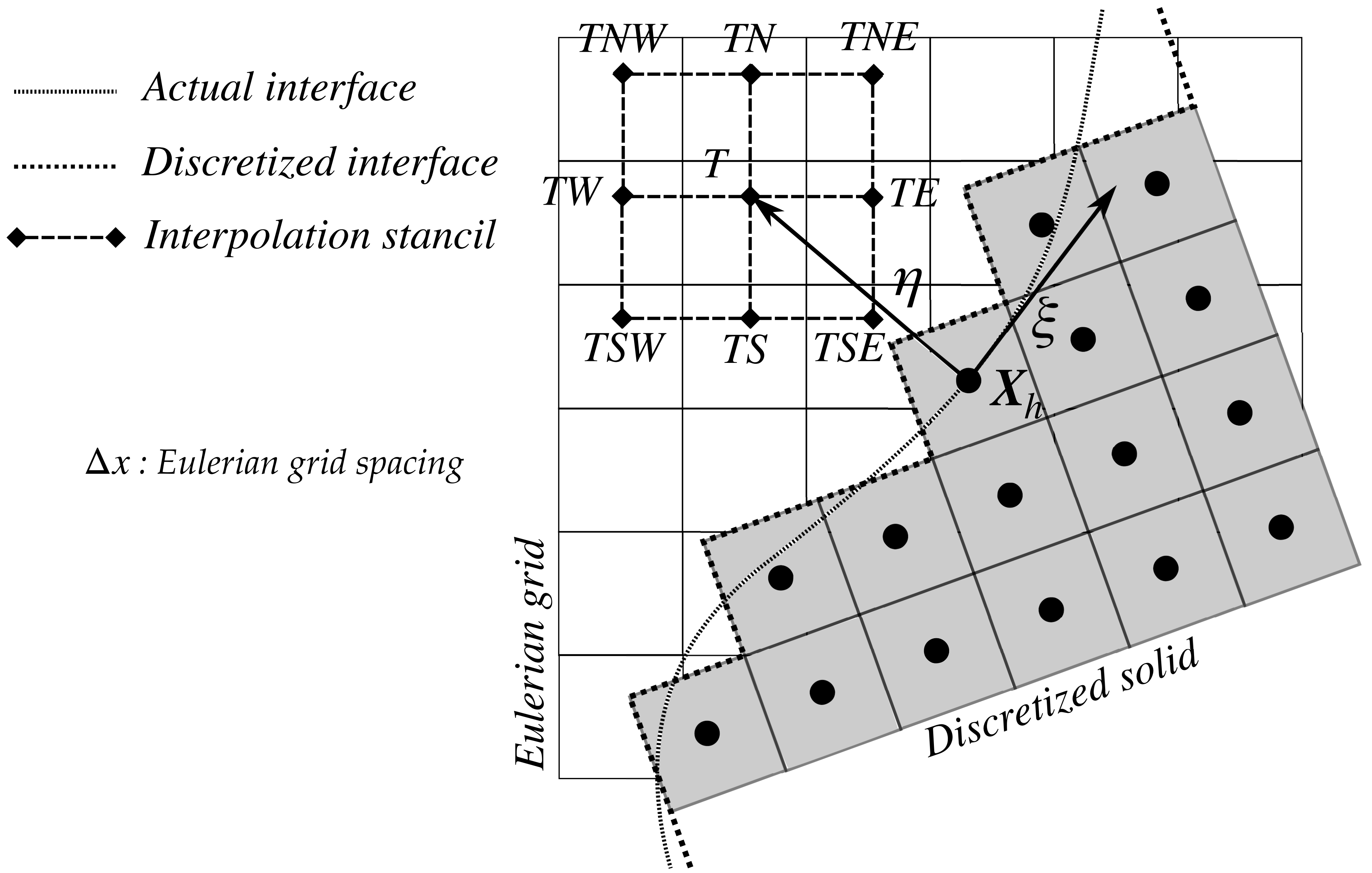
  1. **A probe of length $l_p = 2\Delta x$ starting from $\boldsymbol{X}_h$ is sent into the fluid along the direction defined by the local normal unity vector** to the surface, $\hat{\boldsymbol{n}}$
  2. **Interpolation of the flow velocity field** at the probe tip (point **T**, see the stencil on the right) by tri-linear interpolation
  3. **Interpolation of flow pressure and pressure gradient** at the probe tip (point **T**, see the stencil on the right) by tri-linear interpolation (to compute $p|_{\boldsymbol{X}_h}$)
  4. **Computation of the shear and normal stresses,** $\tau_\xi, \tau_\eta, \tau_\zeta$**,** at the probe root (position $\boldsymbol{X}_h$) in the local coordinate system, (ξ, η, ζ)
  5. **Change of reference frame.** Stresses transformation from local frame, (ξ, η, ζ), to global coordinate system, (x, y, z): $\tau_\xi, \tau_\eta, \tau_\zeta \rightarrow \tau_x, \tau_y, \tau_z$

$$\tau_\xi = \mu_f \frac{\partial u_\xi}{\partial \eta}\bigg|_{\boldsymbol{X}_h} \qquad \frac{\partial u_\xi}{\partial \eta}\bigg|_{\boldsymbol{X}_h} = \frac{(\boldsymbol{U}_f(\boldsymbol{X}_T) - \boldsymbol{U}_h)\cdot \hat{\boldsymbol{t}}}{l_p}$$

$$\tau_\eta = \mu_f \frac{\partial u_\eta}{\partial \eta}\bigg|_{\boldsymbol{X}_h} - p\big|_{\boldsymbol{X}_h} \qquad \frac{\partial u_\eta}{\partial \eta}\bigg|_{\boldsymbol{X}_h} = \frac{(\boldsymbol{U}_f(\boldsymbol{X}_T) - \boldsymbol{U}_h)\cdot \hat{\boldsymbol{n}}}{l_p}$$

$$\tau_\zeta = \mu_f \frac{\partial u_\zeta}{\partial \eta}\bigg|_{\boldsymbol{X}_h} \qquad \frac{\partial u_\zeta}{\partial \eta}\bigg|_{\boldsymbol{X}_h} = \frac{(\boldsymbol{U}_f(\boldsymbol{X}_T) - \boldsymbol{U}_h)\cdot \hat{\boldsymbol{b}}}{l_p}$$

*$\boldsymbol{U}_f(\boldsymbol{X}_T)$ fluid velocity filed interpolated at the probe tip, **T***

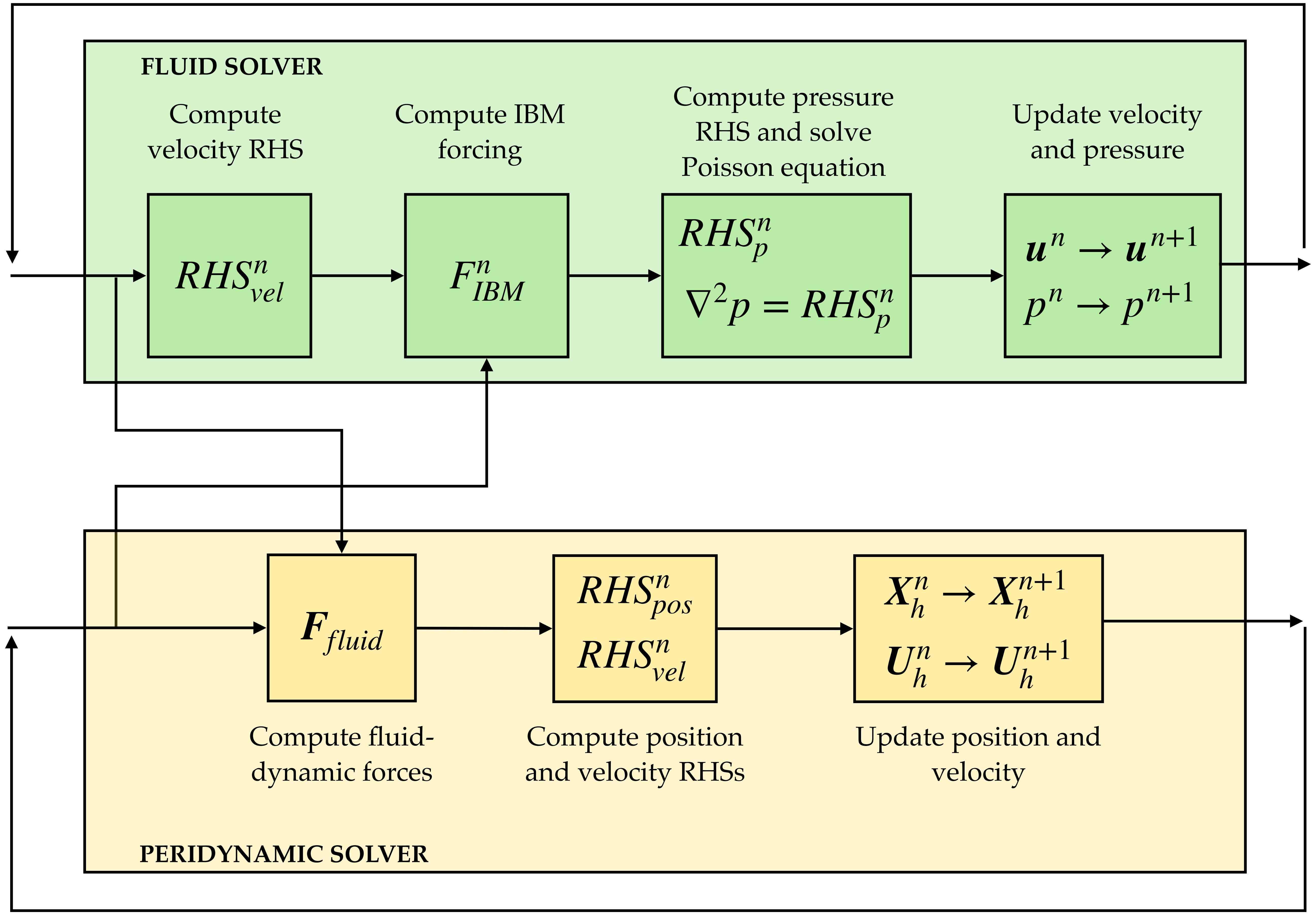


2D schematic of the interpolation stencil used to compute shear and normal stresses in the local frame of reference

- A local frame of references centered at $\boldsymbol{X}_h$ is defined:
  - ξ along local tangent vector, $\hat{\boldsymbol{t}}$
  - η along local normal vector, $\hat{\boldsymbol{n}}$
  - ζ along local bi-normal vector, $\hat{\boldsymbol{b}}$

NUMERICAL IMPLEMENTATION

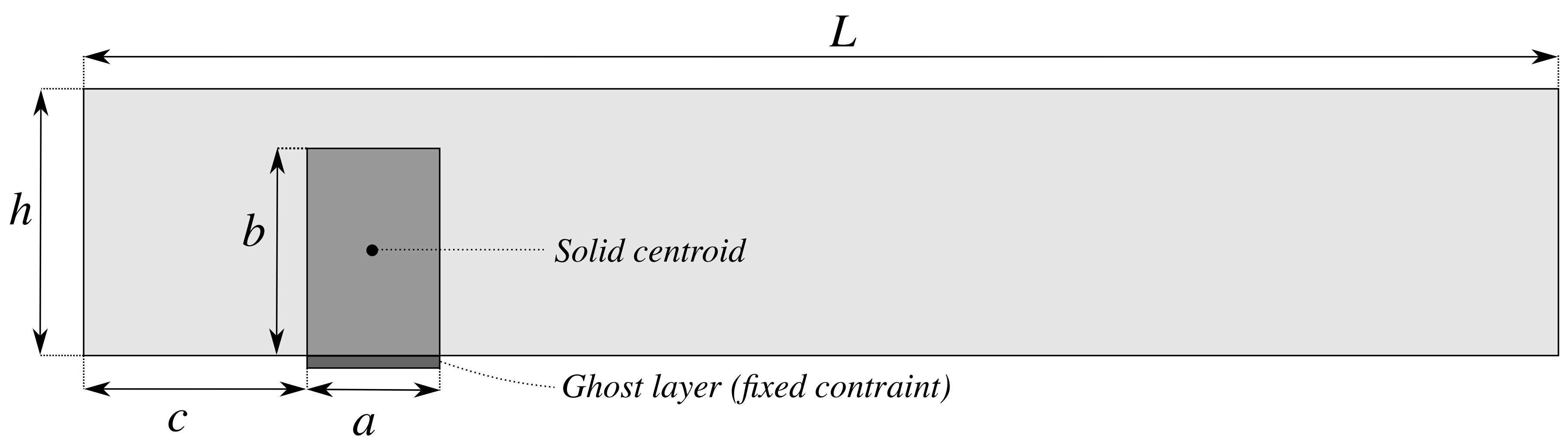
- **The procedure has been implemented to obtain a numerical code to address FSI problems considering crack formation, crack branching and fracture:**
  - **FLUID SOLVER (developed upon open-source CaNS by Pedro Costa):**
    - Second order **finite difference schemes** for space discretization
    - Third order, low storage **Runge-Kutta** time marching algorithm
    - **Pressure correction** algorithm
  - **PERIDYNAMIC SOLVER:**
    - **Fully explicit** algorithm
    - Third order, low storage **Runge-Kutta** time marching algorithm
  - **IBM:**
    - Multi-direct forcing scheme (3 steps)
  - **PARALLELIZATION:**
    - **MPI-based parallel structure.** The code can be run on both shared and distribute memory systems (tested up to 1024 cores)
    - Excellent scaling performances

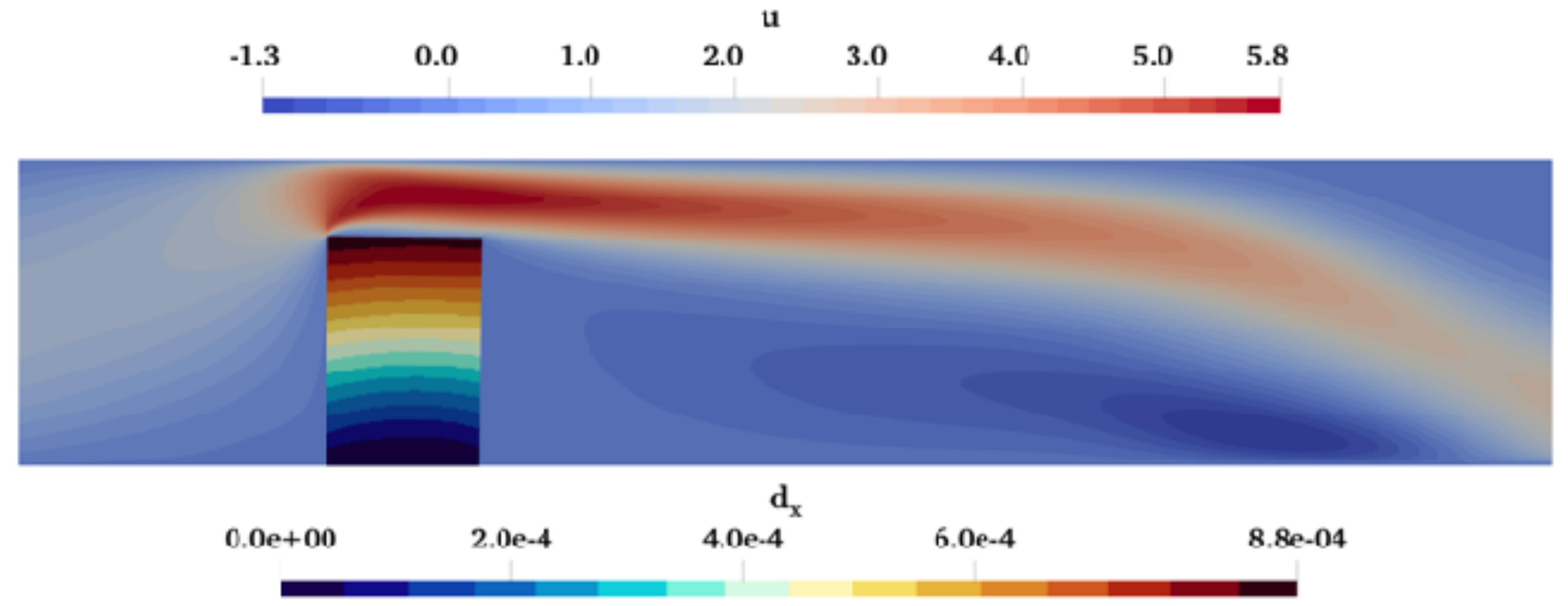


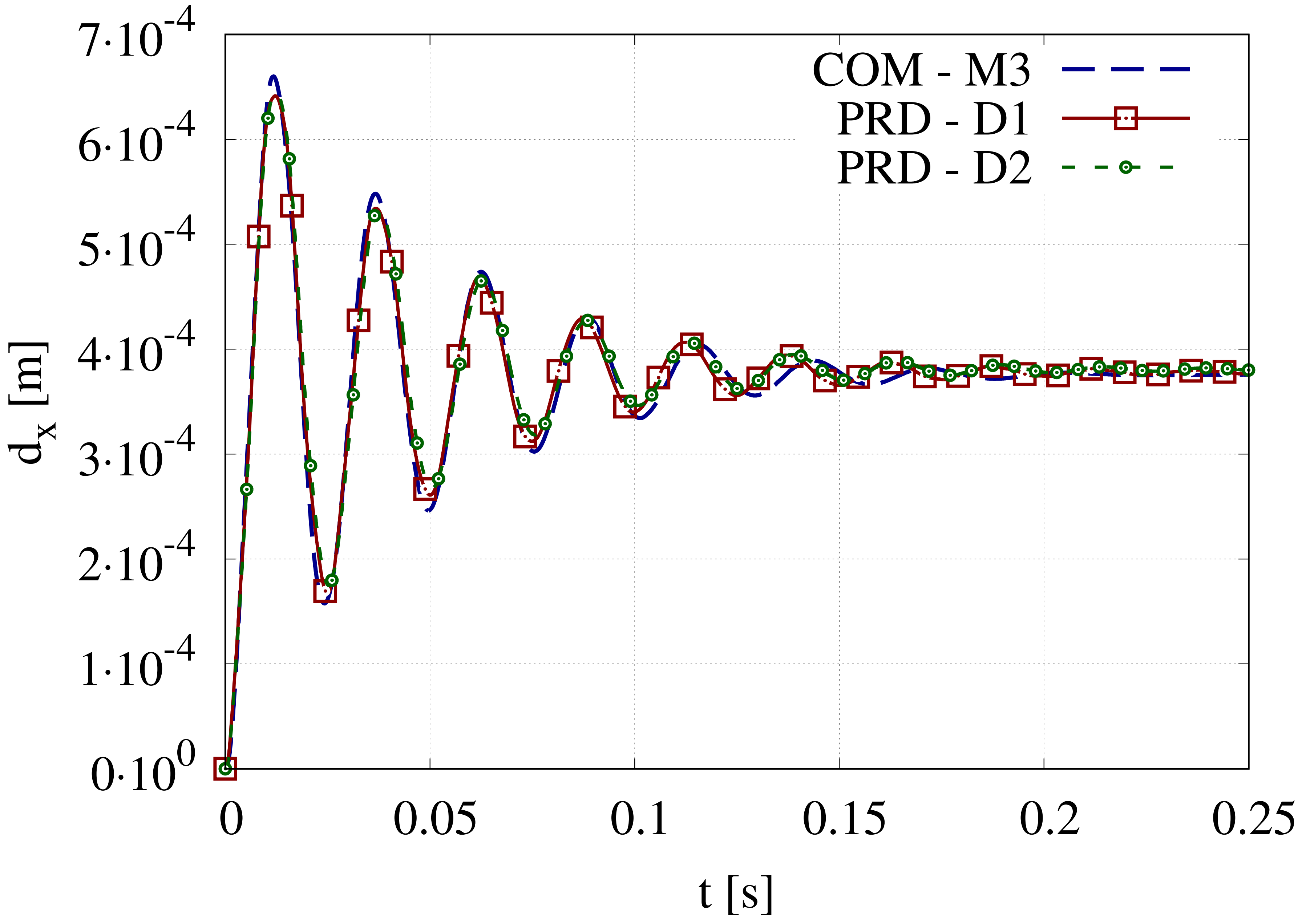
VALIDATION: FULLY COUPLED FSI BENCHMARK

- **2D rectangular and linear elastic solid in a laminar channel flow:**
  - Initial conditions: stationary laminar flow around the fixed and rigid rectangle
  - The structure is released and let deform
  - The structure bends until a stationary deformed configuration establishes

- **Validation by comparison:**
  - **The temporal evolution of the position of the solid centroid is chosen as target quantity**
  - Two different peridynamic discretization are considered to asses grid convergence (D1 and D2)
  - **The results predicted using the present numerical tool are compared with the results obtained using a commercial software COMSOL MULTIPHYSICS**



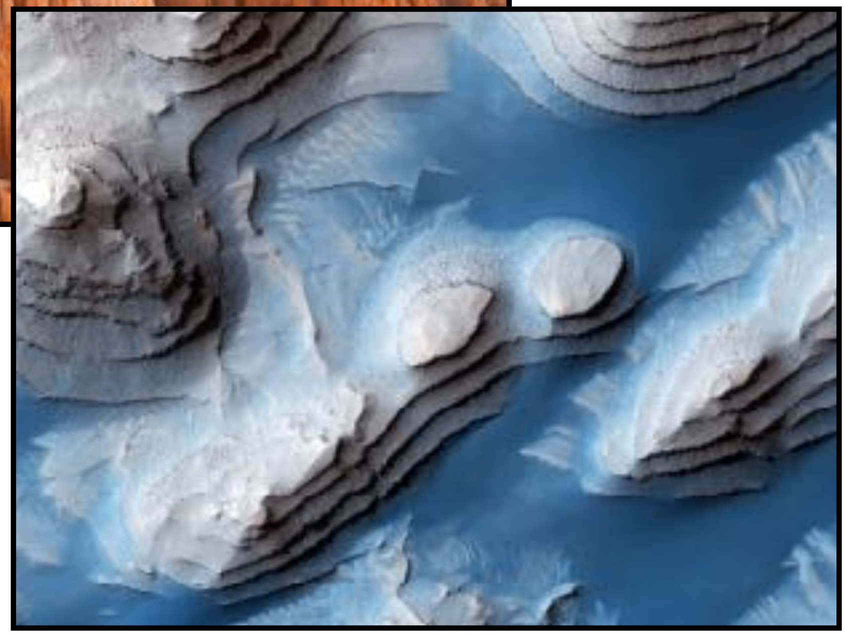




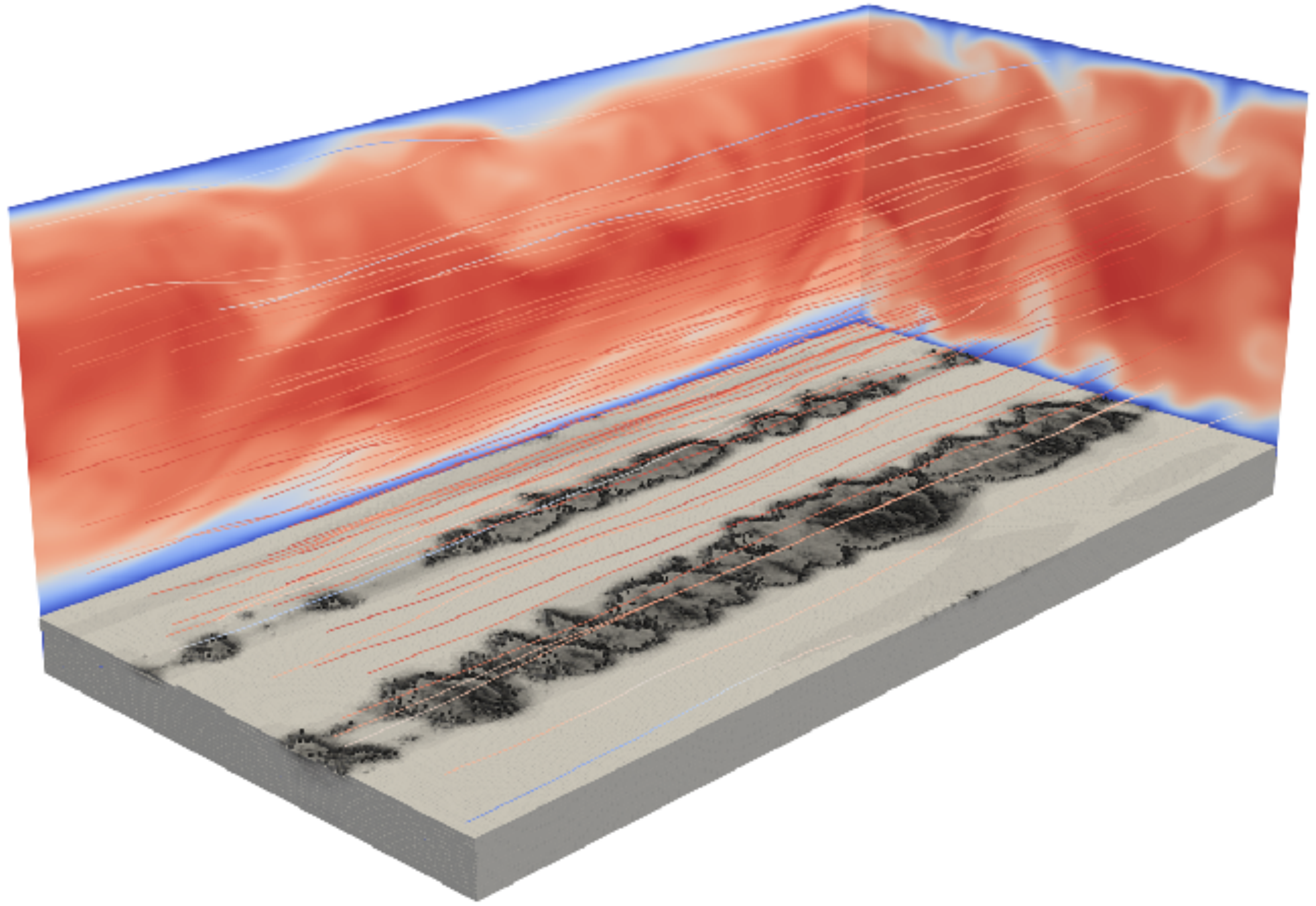
- **Testing and validation campaign:**
  - Many validation benchmarks to validate the methodology:
    - Crack detection and propagation
    - Computation of fluid forces
    - IBM
- Methodology and related validation in: ***Dalla Barba F., Picano F. (2020). A novel approach for direct numerical simulation of hydraulic fracture problems.*** *Flow, Turbulence and Combustion, Vol. 105, p. 335-357, ISSN: 1386-6184, doi: 10.1007/s10494-020-00145-x.*

APP. #1: NUMERICAL STUDY OF THE EROSION OF A BRITTLE SUBSTRATE IN A TURBULENT CHANNEL FLOW

- **Problem description:**
  - An incompressible, **fully-turbulent stream flows through a rectangular-cross-section channel**
  - The channel is **periodic along the flow and span-wise directions**
  - The upper and lower walls of the channel are rigid and impermeable
  - **A solid layer with linear-elastic and brittle mechanical properties is attached to the lower wall of the channel** (the lower wall acts as a rigid and impermeable substrate)
  - Relevance: the problem is of relevant interest in environmental and planetary sciences (e.g. erosion processes, geomorphology, etc.) as well as in aerospace field (e.g. erosion due to intensive turbulent flows in contact with ablative material, nozzle throat erosion in rocket engine, etc.)

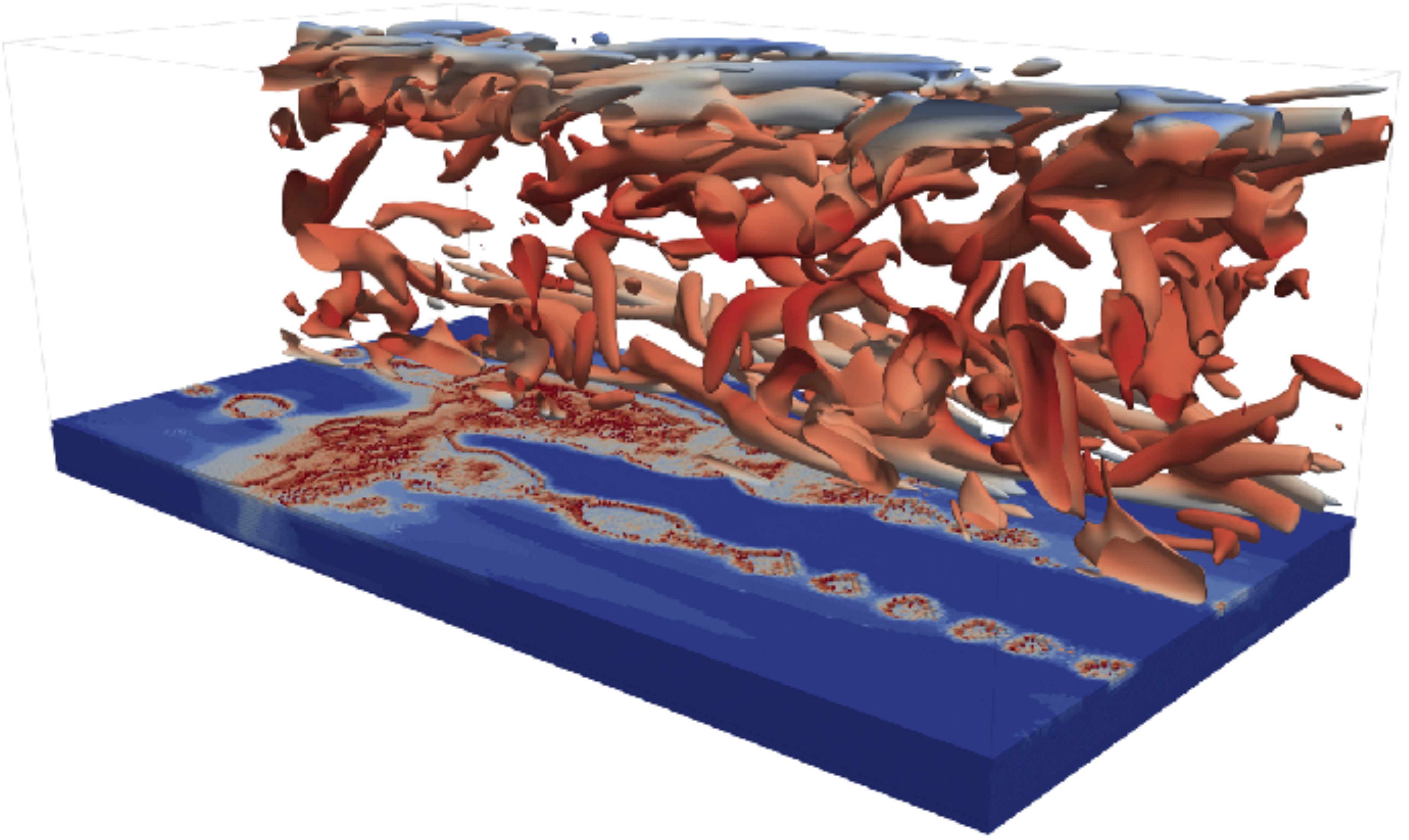


- **Mechanical properties (non-dimensional):**
  - Bulk Reynolds number: $Re_b = U_b h/\nu_f = 4500$
  - Friction Reynolds number: $Re_\tau = u_\tau h/\nu_f = 147.5$
  - Young's modulus: $E/(\rho_f U_b^2) = 2.0 \cdot 10^{-1}$
  - Poisson ratio: $\nu_s = 0.25$
  - Density ratio: $\rho_s/\rho_f = 5$
  - Fracture energy release rate: $G_0/(Eh) = 2.6 \cdot 10^{-5}$



APP. #1: SIMULATION SET-UP

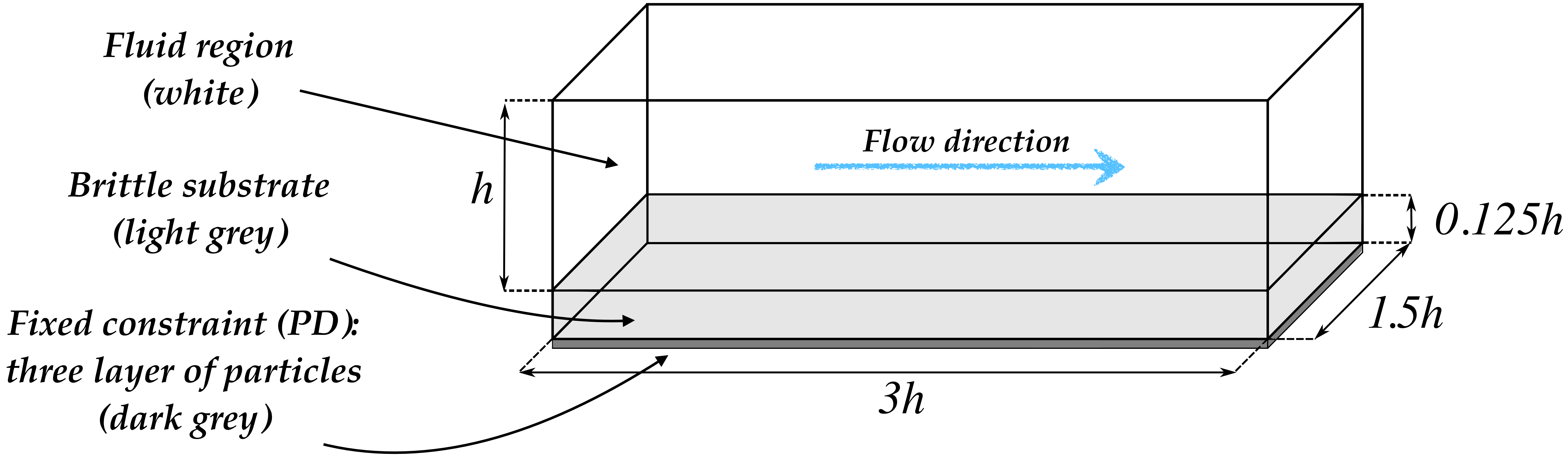
- **Rectangular computational domain for the Eulerian phase:**
  - Periodic BCs along the flow and span-wise directions
  - No-slip and no-penetration BCs on the upper and lower boundaries of the domain
  - Eulerian grid: $N_x \times N_y \times N_z = 288 \times 144 \times 108$ nodes



- **Peridynamic representation of the brittle, erodible substrate by cubic partitioning:**
  - Solid substrate attached to the impermeable and rigid lower wall of the channel
  - Cubic particles on a Cartesian grid in the reference configuration:

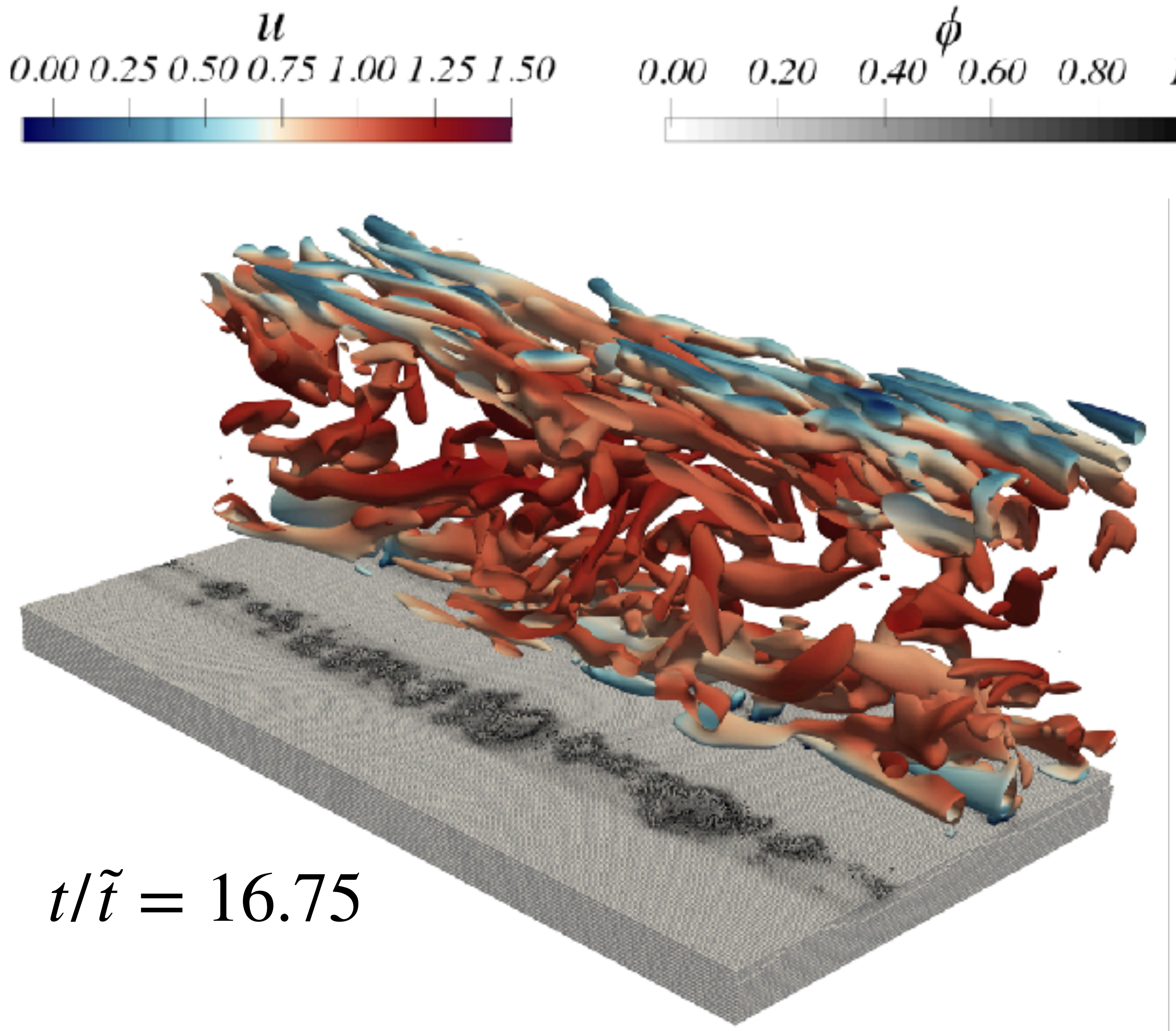
    $N_x \times N_y \times N_z = 288 \times 144 \times 14$

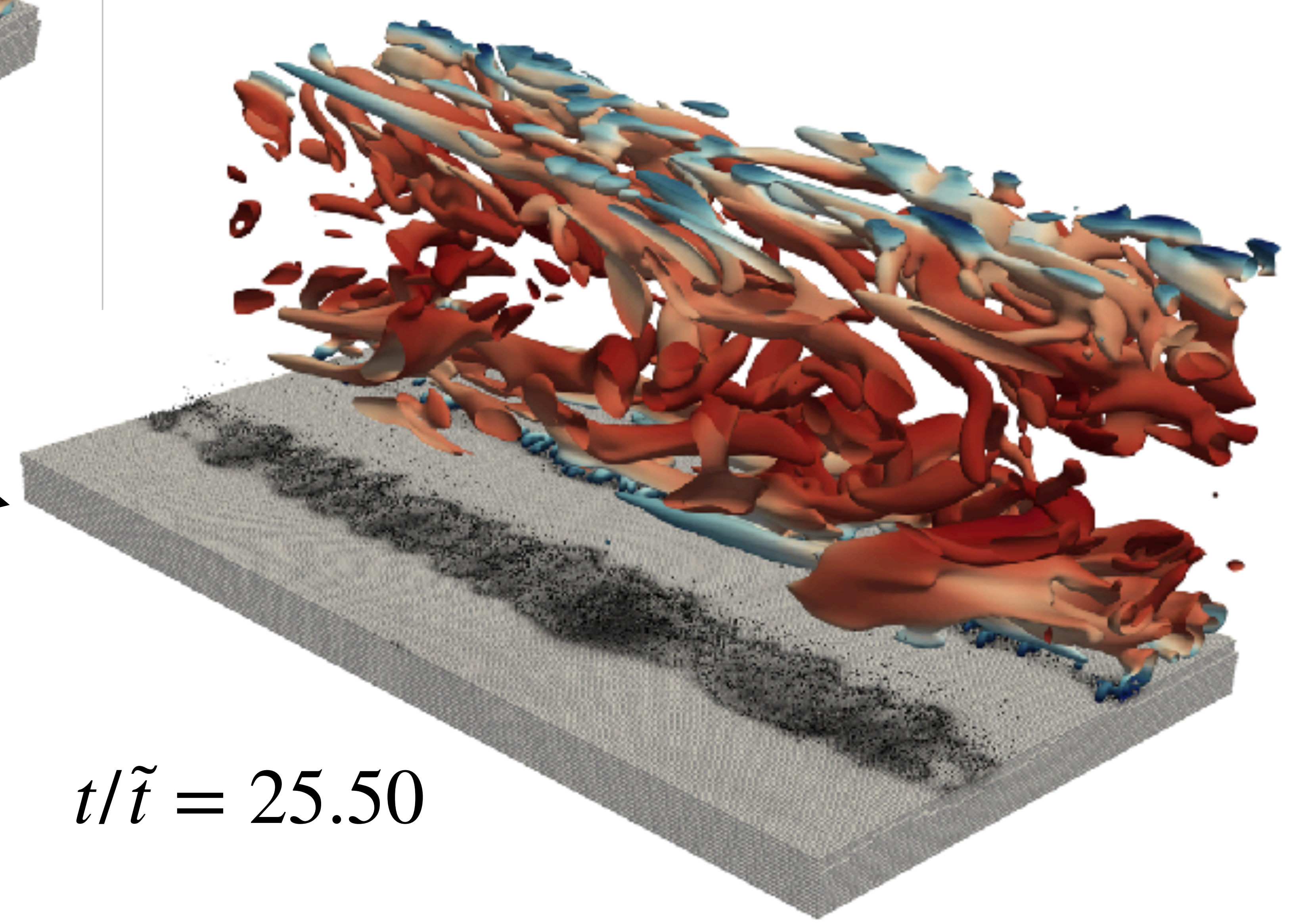
- **Initialization:**
  - Fully-developed turbulent flow
  - Statistically-stationary **equilibrium configuration for the deformation of the solid substrate**

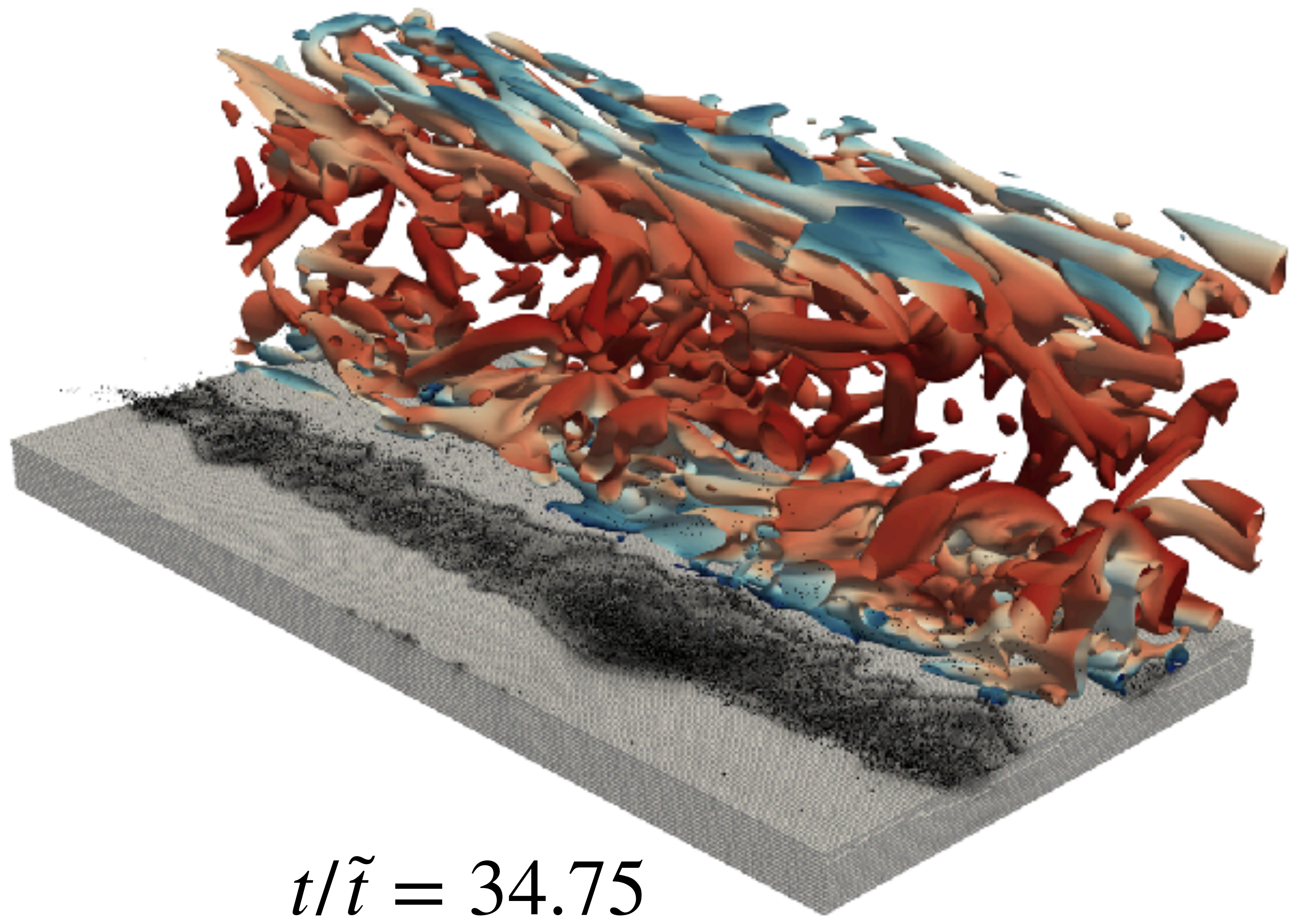


APP. #1: PHENOMENOLOGY OF TURBULENCE-DRIVEN EROSION

- **Erosion by fluid-drive fatigue mechanism:**
  - Turbulent fluctuations can locally (and randomly) increase the **intensity of wall stresses up to the ultimate strength of the brittle substrate**
  - **Local damages are produced and cracks form**
  - Cracks reduce the local strength of the substrate
  - Lower intensity hydrodynamic stresses can produce a damage
  - **Damage accumulates over time until break-up occurs**





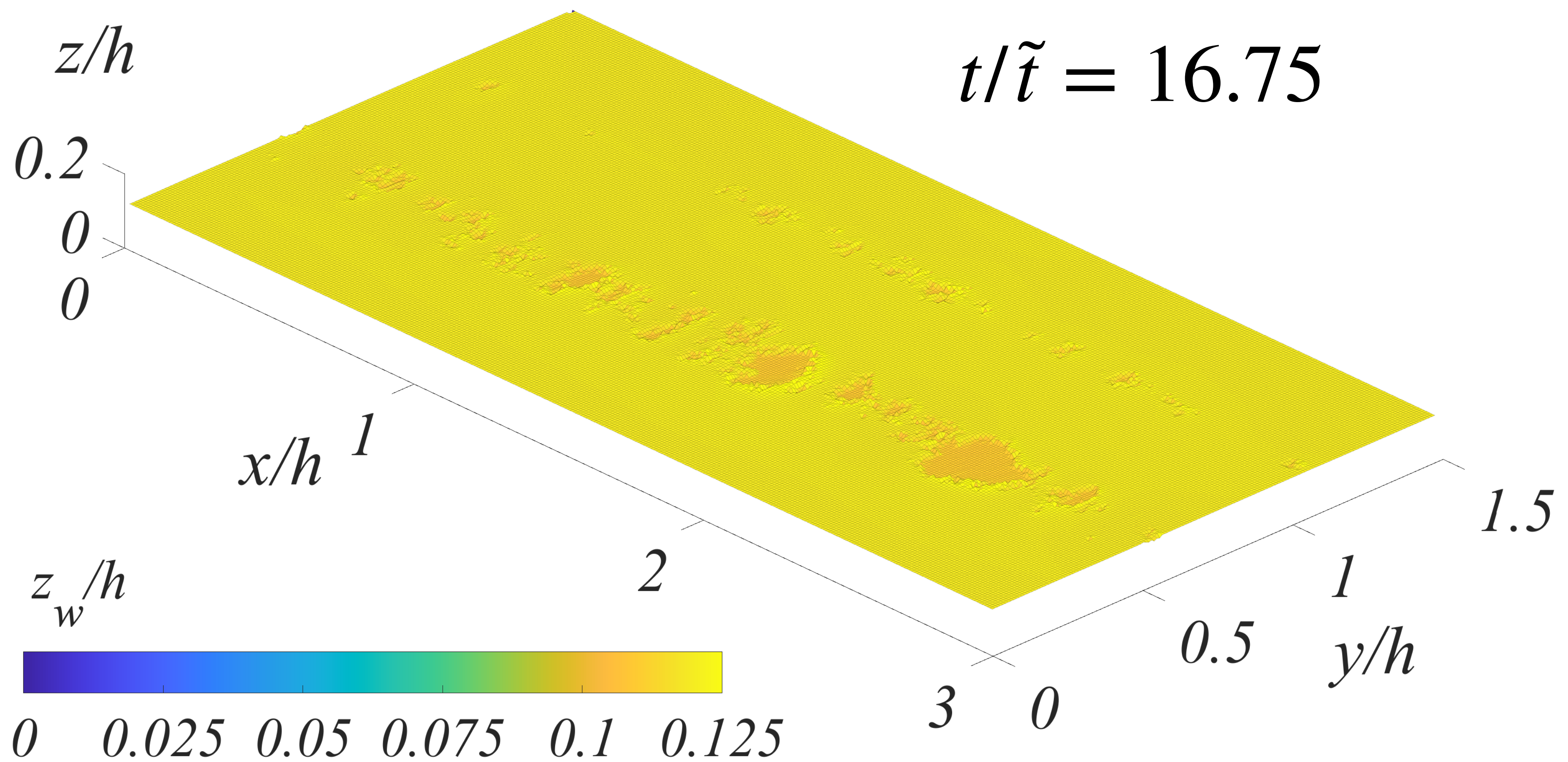


Coherent structures of the flow by Q-criterion ($Q = 1$)

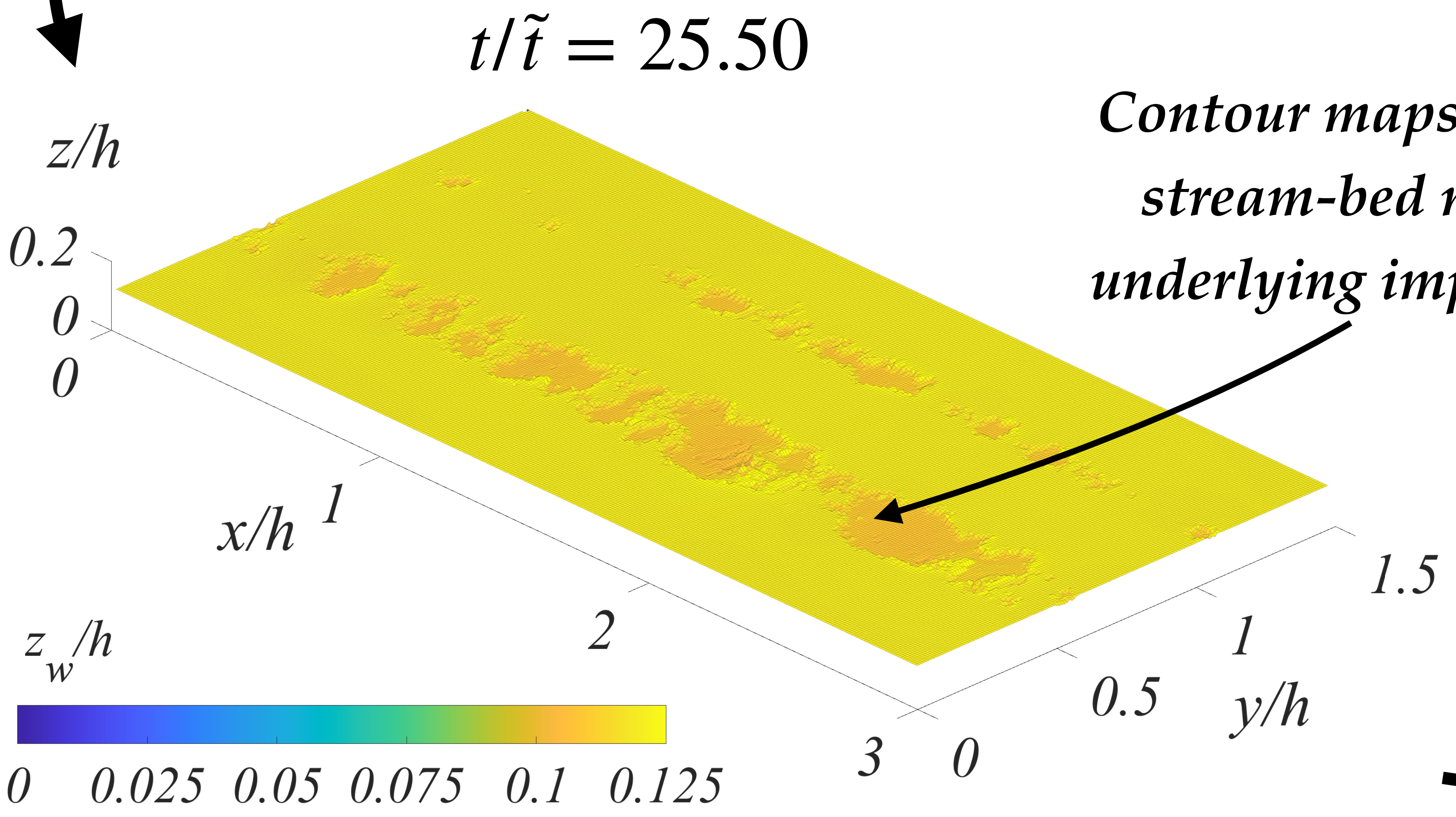
Damage level, Φ

Axial velocity of the flow, u

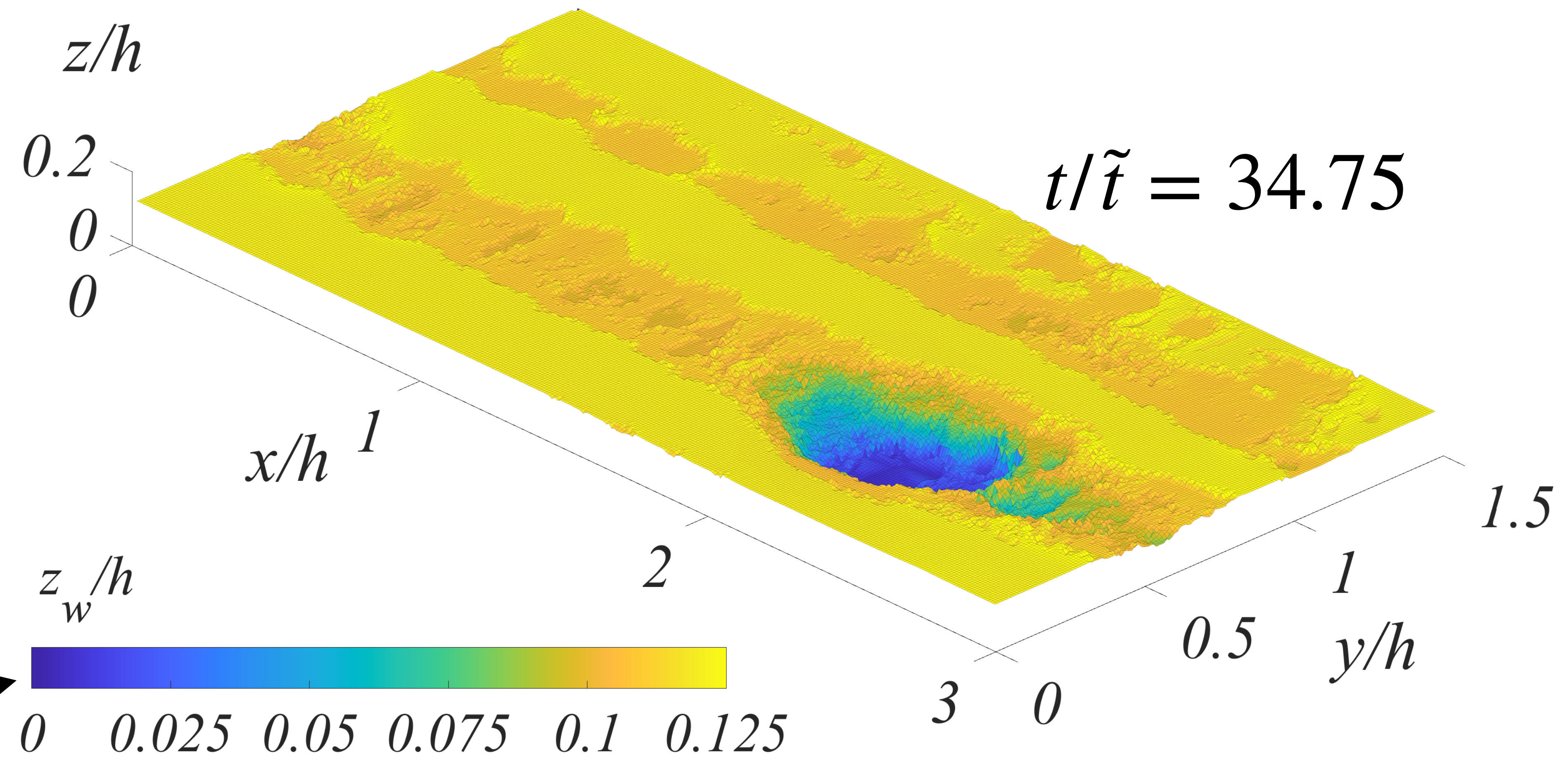
APP. #1: SCOUR-STRUCTURES ON THE ERODIBLE STREAMBED



- **Scour-structures:**
  - The surface of the stream-bed is initially flat
  - Random turbulent fluctuations give rise to small and **shallow scour-holes**
  - The **scour regions expand in the downstream direction** increasing their width and depth
  - The widening and deepening of scoured areas give rise by coalescence to **two elongated rims on the substrate**
  - As the process advances, **deep scour-holes can originate rapidly**



Contour maps of the height of the stream-bed measured from the underlying impermeable substrate



APP. #1: EROSION RATE: THE PROCESS ACCELERATES

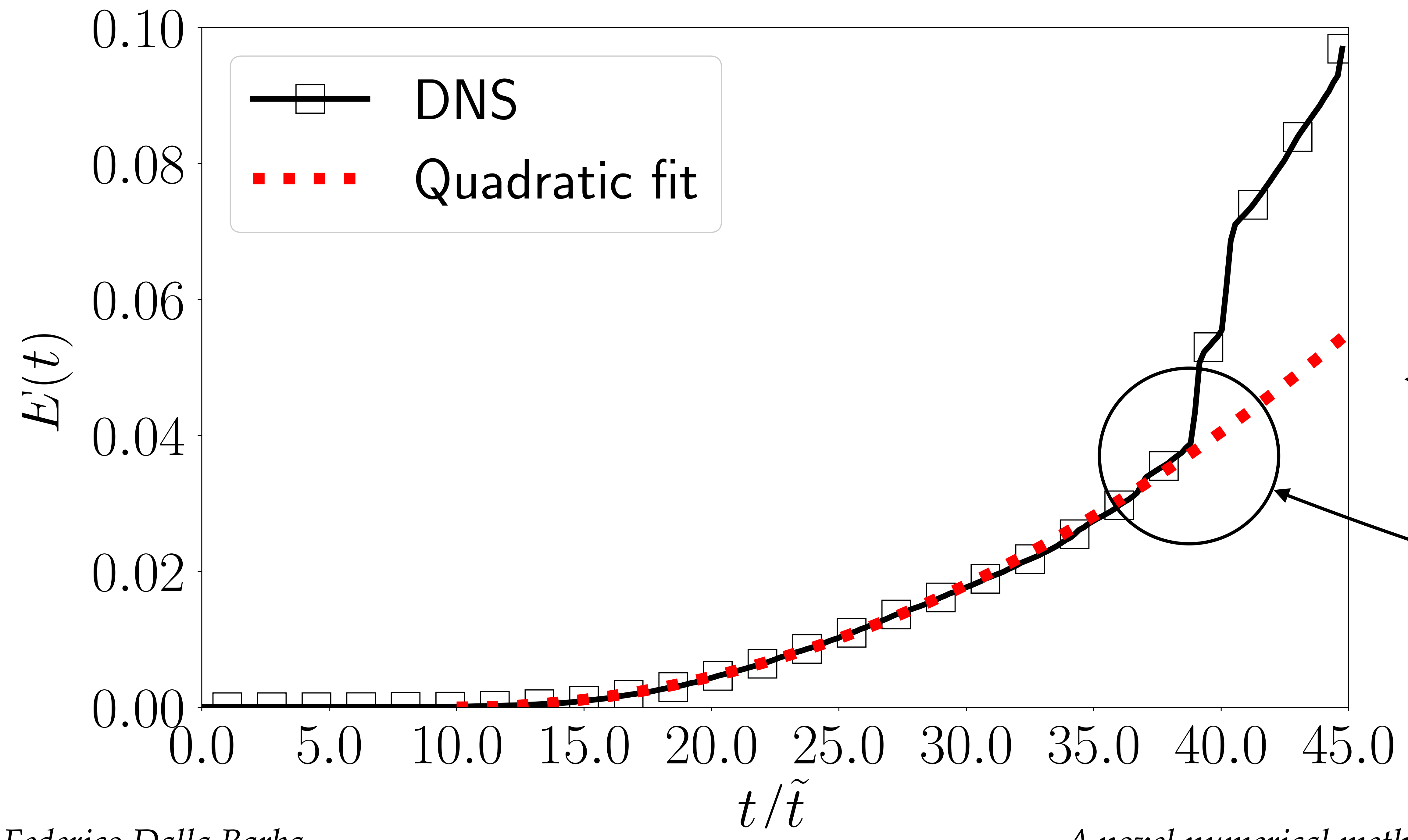
- **Volumetric erosion rate:**

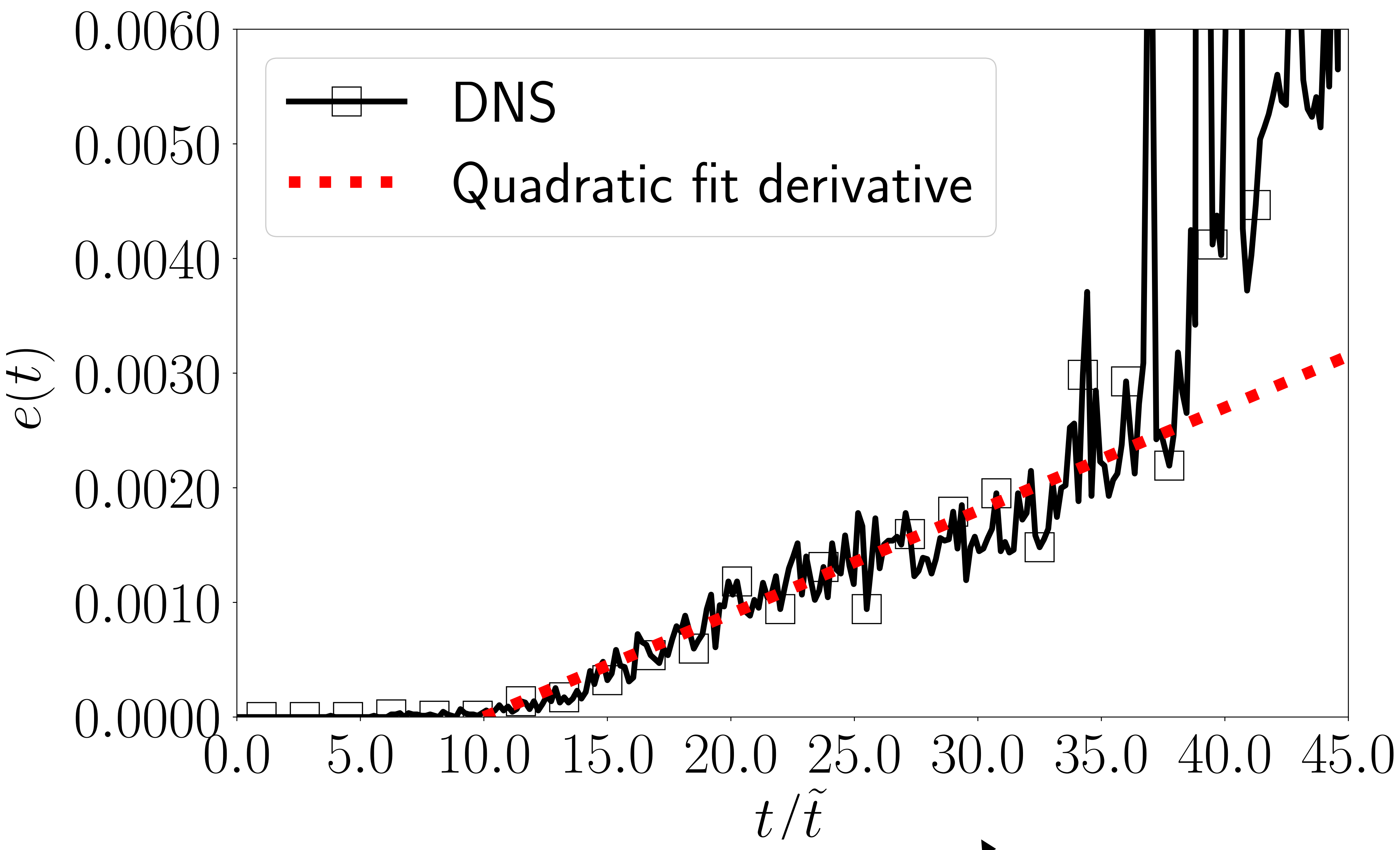
$$e(t) = \frac{d}{dt}\left(\frac{V(t) - V(0)}{V(0)}\right)$$

- **Volume of eroded material:**

$$E(t) = \int_0^t e(\hat{t})d\hat{t}$$

- **Rate of erosion:**
  - The volumetric erosion rate increases linearly in time
  - The total volume of eroded material grows quadratically
  - **The erosion process accelerates!**





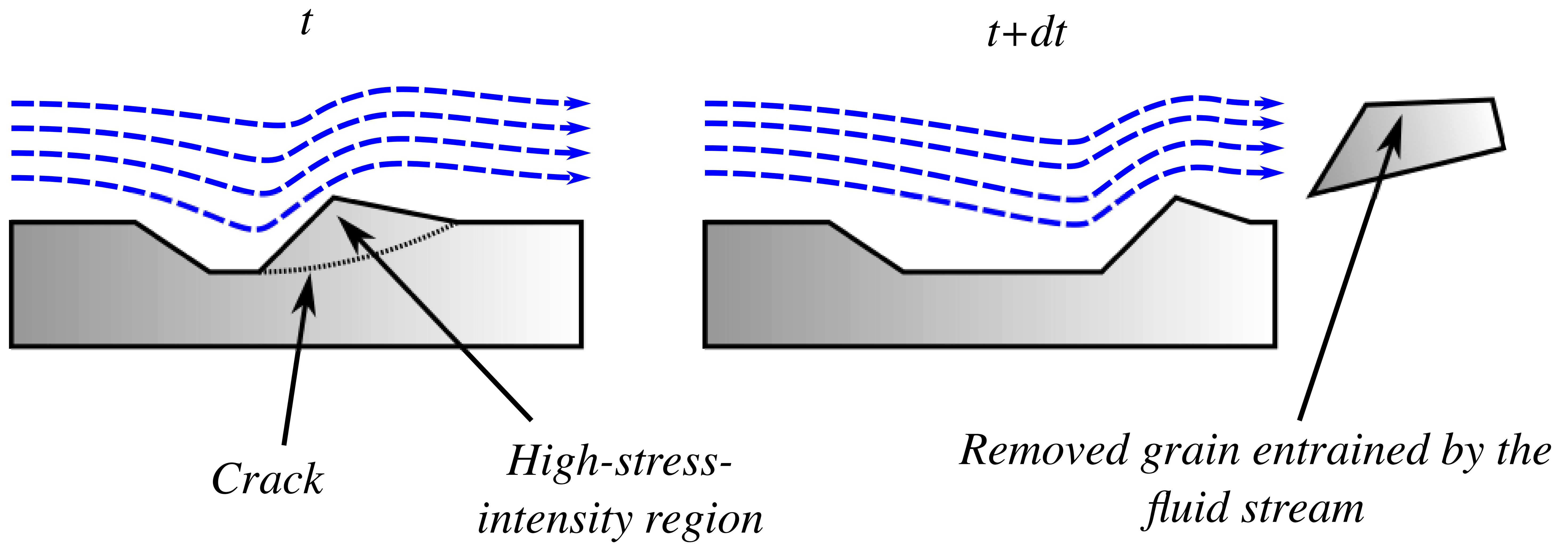
Volume of removed material versus time

Volumetric erosion rate versus time

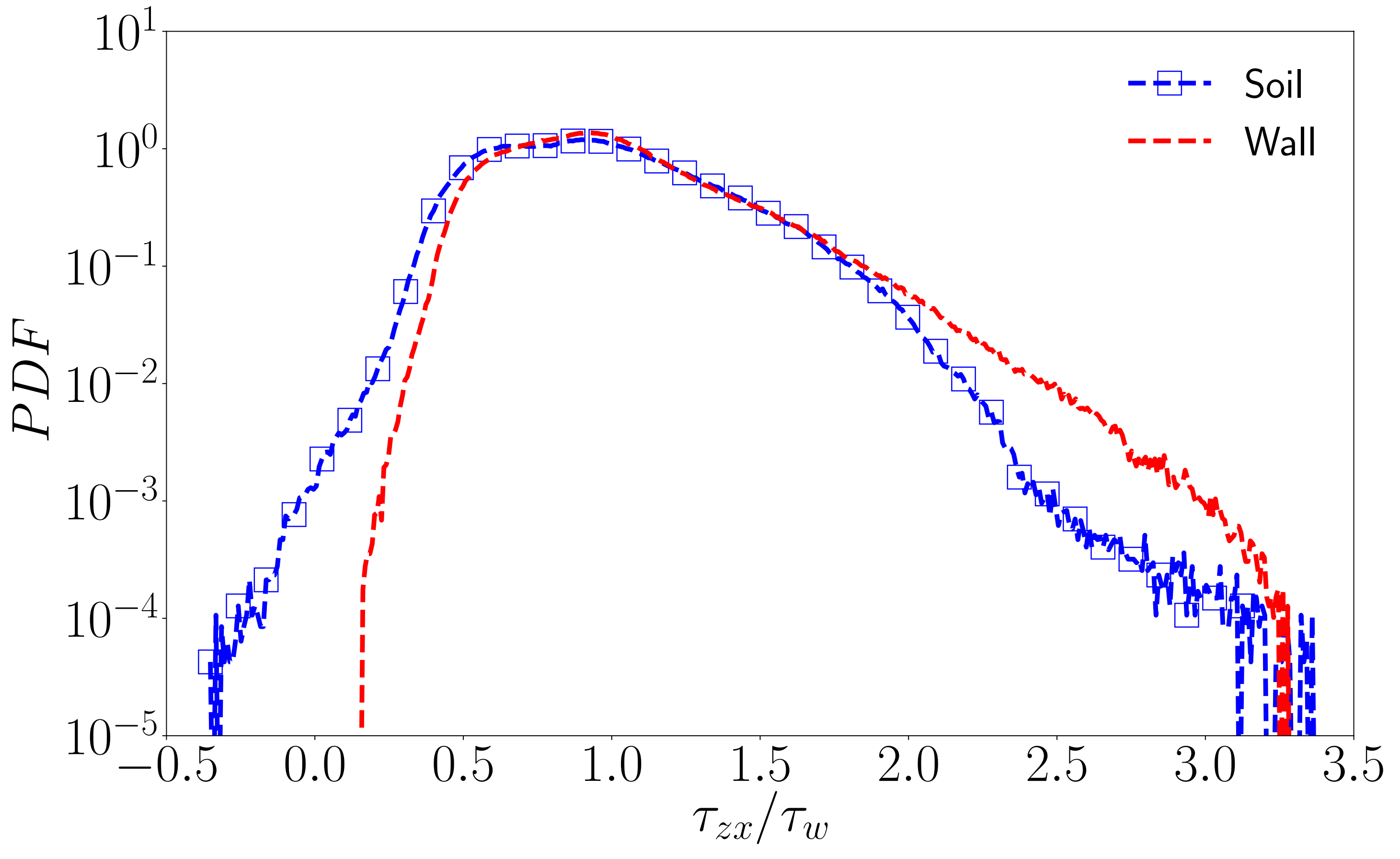
Random break-up event: formation of a deep scour-hole

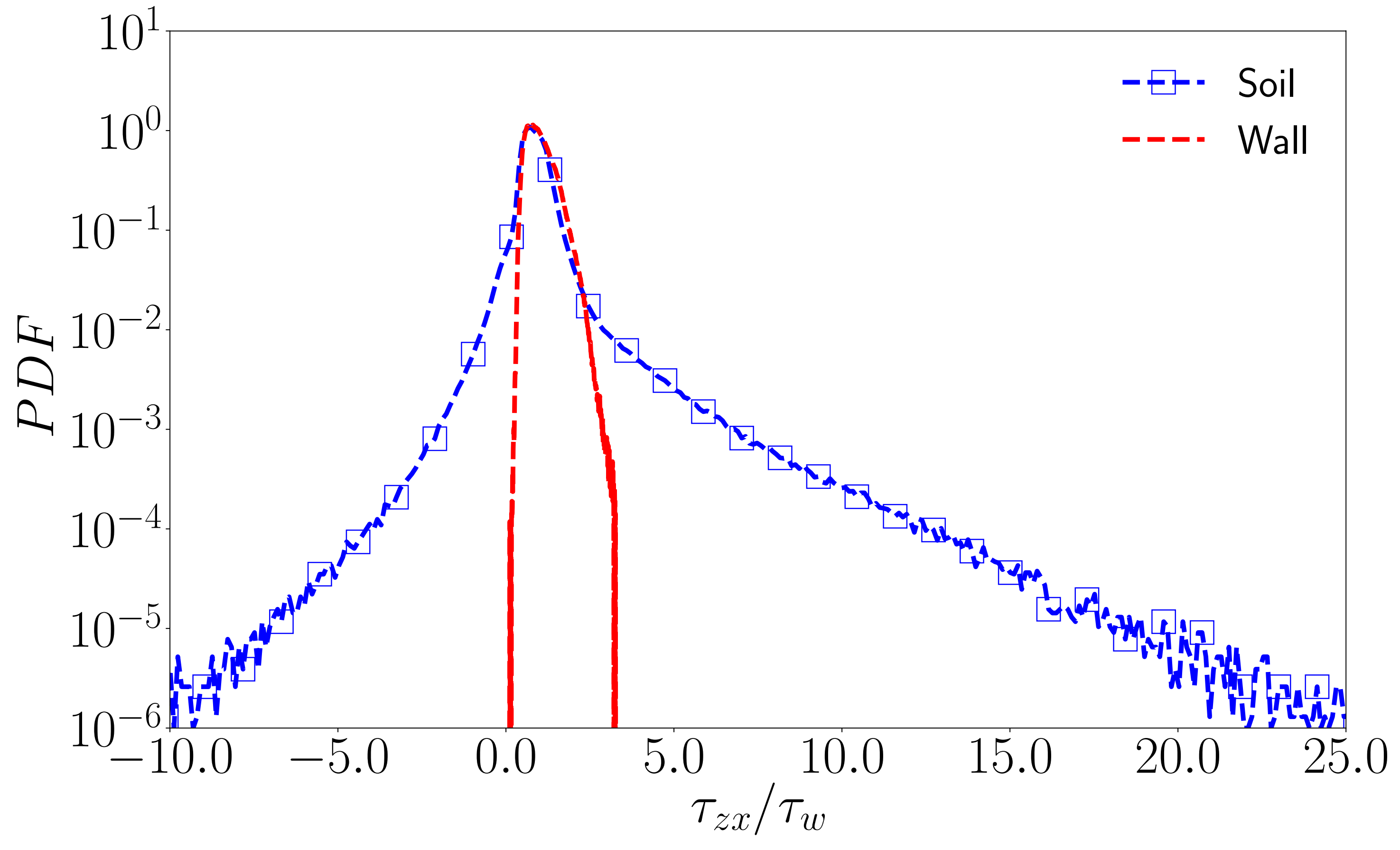
APP. #1: WHY EROSION ACCELERATES? STRESS ENHANCEMENT BY TURBULENCE-WALL INTERACTION

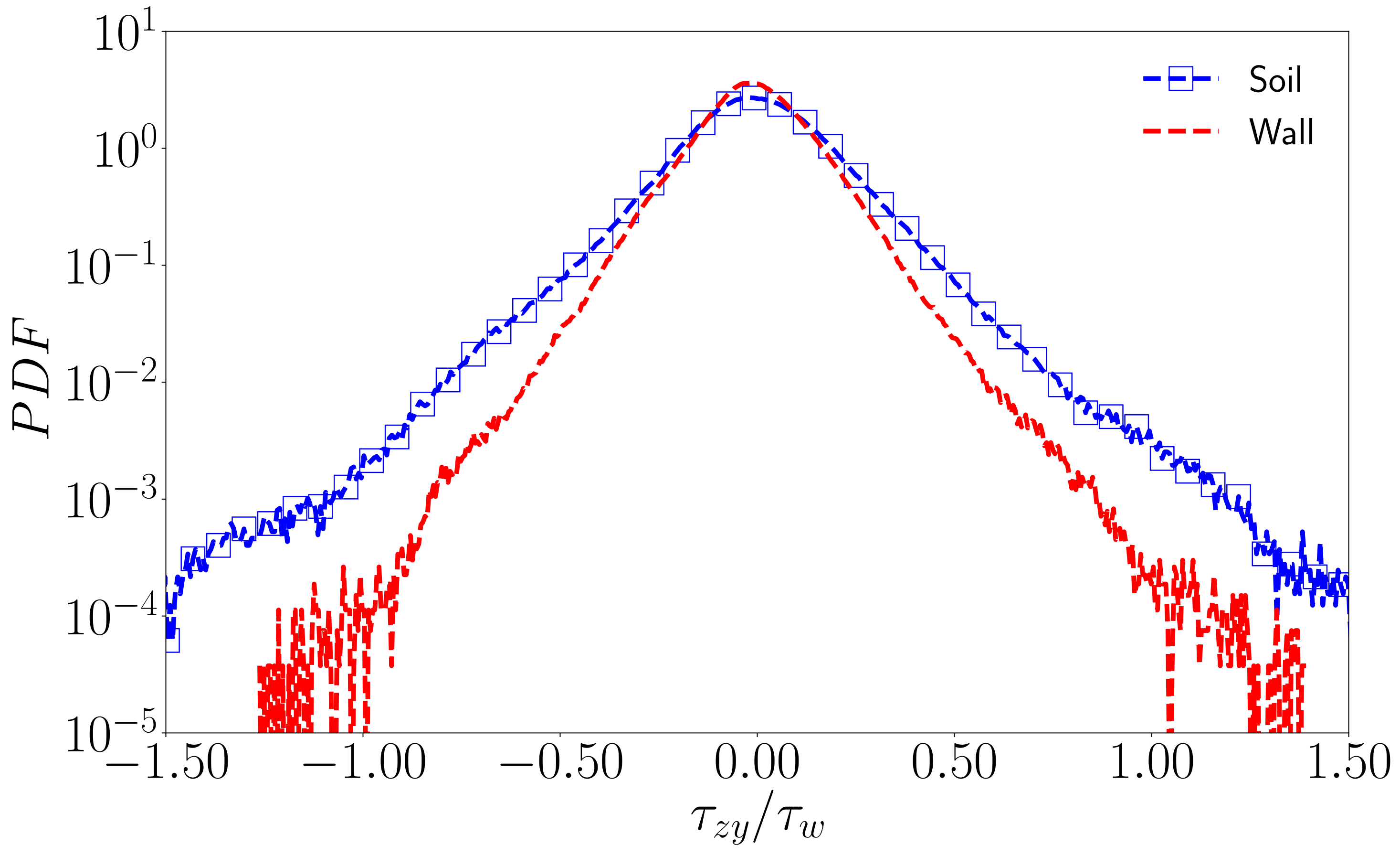
- Peaks on the stream-bed act locally as obstacles for the flow stream
- Small-scale and high-intensity vortexes originate over the peaks
- This **small-scale vortexes enhance the intensity of local wall-stresses up to 20 times the mean hydrodynamic stress**
- Peaks break-up and **the scoured regions expand in the downstream direction of the flow**
- The vortexes move downstream, stationing over the new peaks and sustaining the process
- **As the surface becomes more irregular, the number and intensity of small-scale coherent structures increases, enhancing the erosion rate and wall stresses**
- The erosion process globally accelerates!

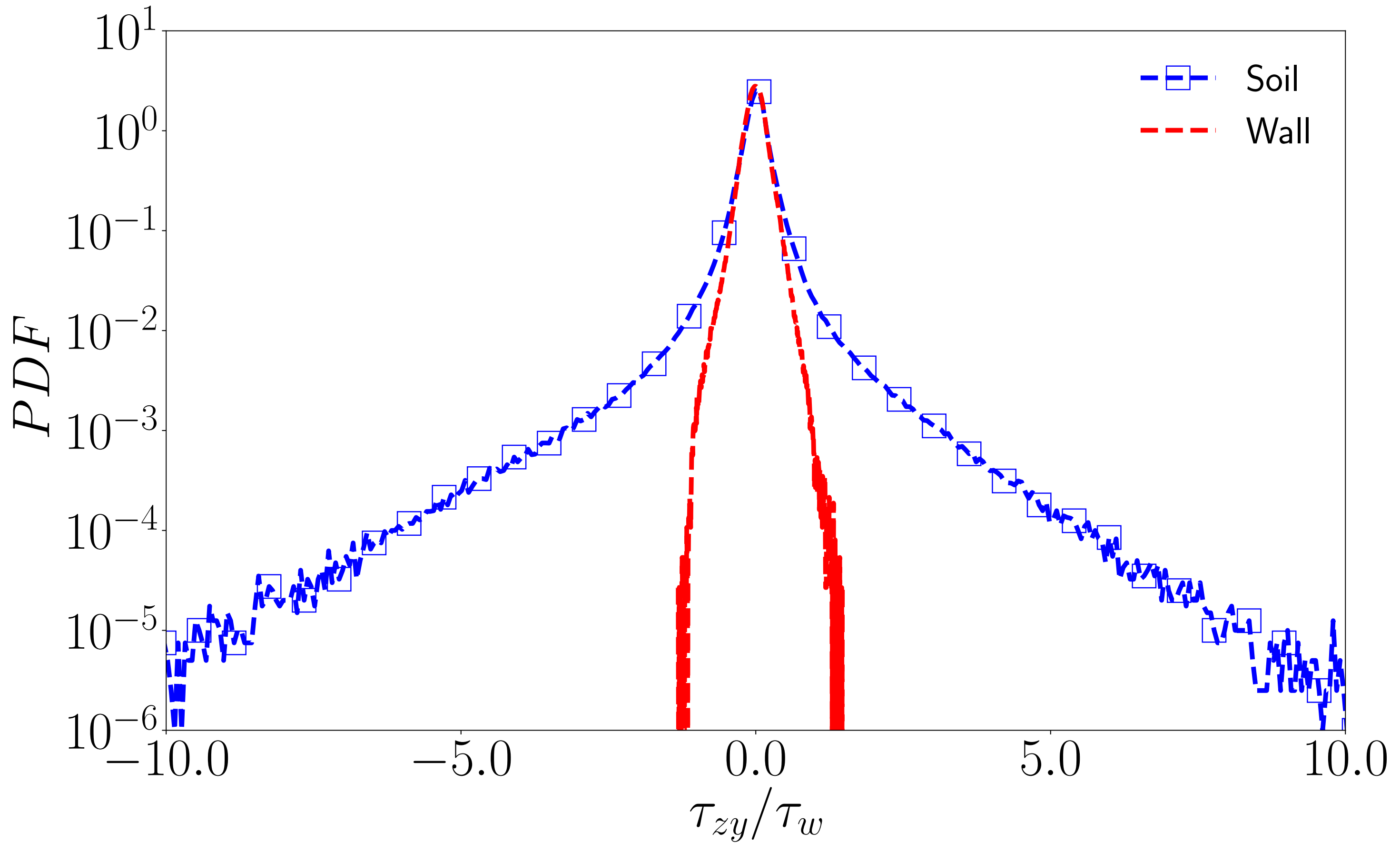


APP. #1: WHY EROSION ACCELERATES? PROBABILITY DENSITY FUNCTION OF WALL STRESSES





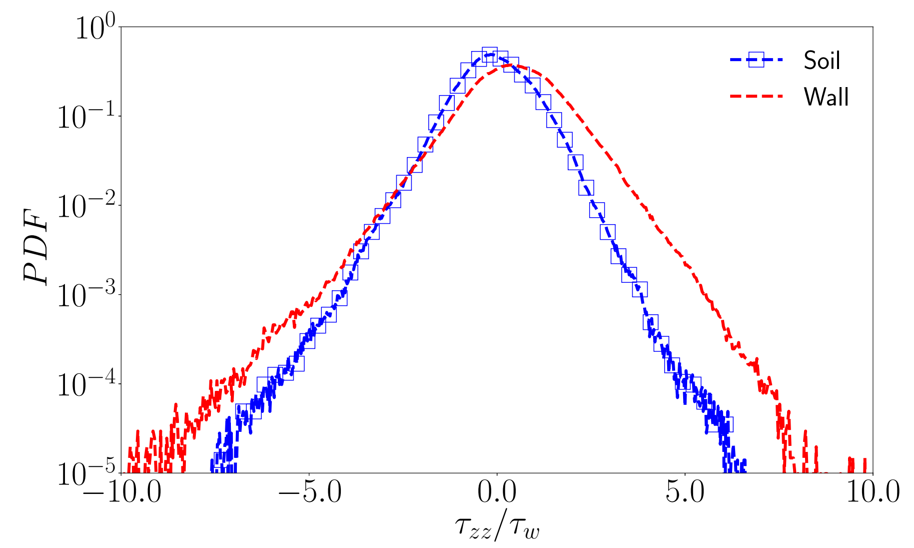


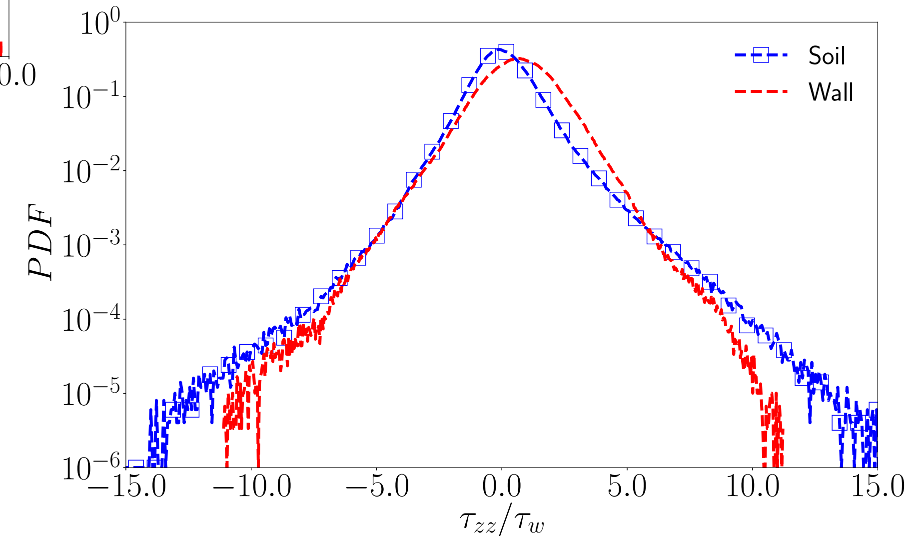


$t/\tilde{t} = 16.75$

$t/\tilde{t} = 25.5$

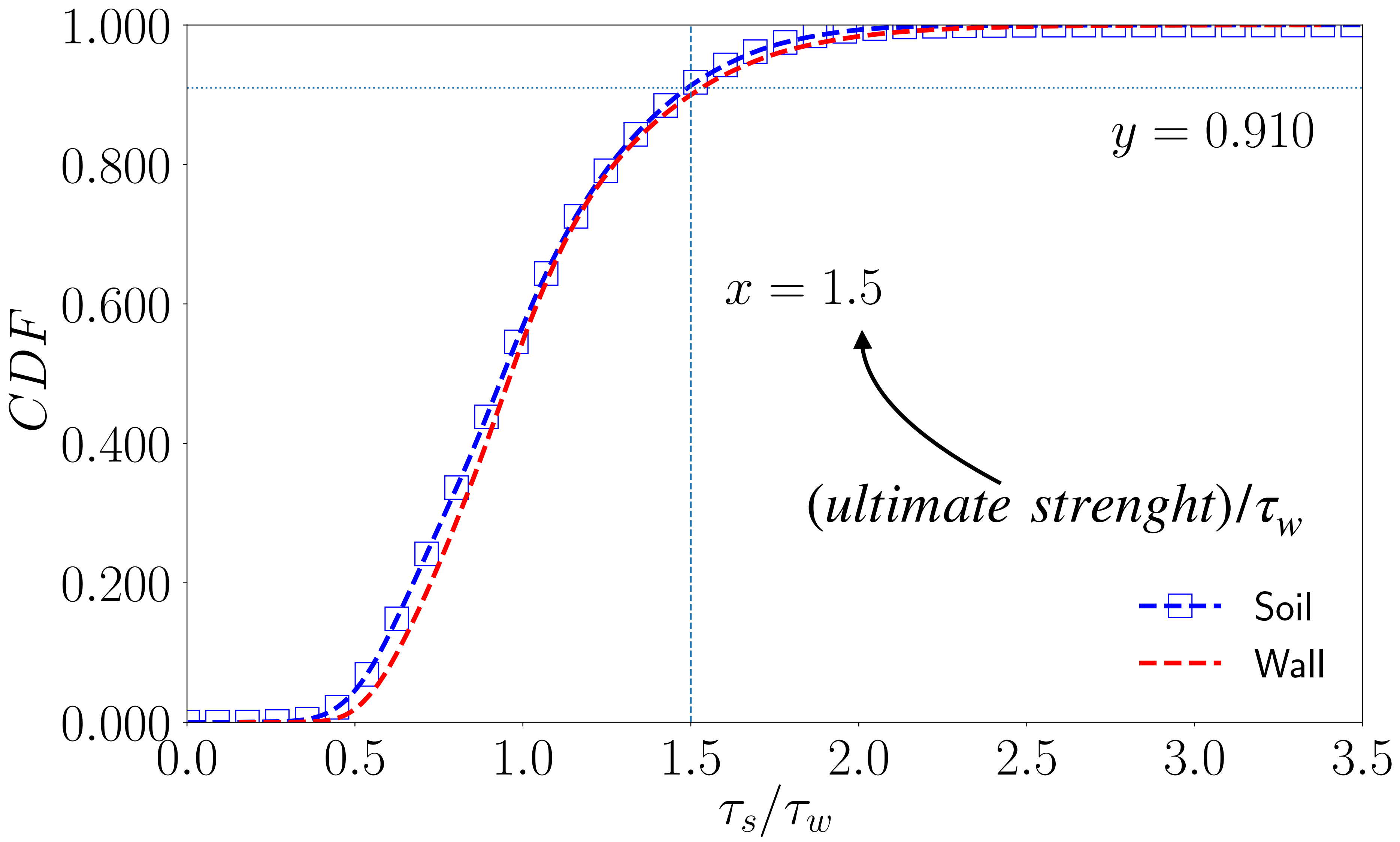
- The occurrence of high-intensity turbulent structures near the wall increases in time due to the scouring of the stream-bed.
- **High-intensity turbulent events enhance the local wall stresses.**
- **The PDFs of the wall stresses, τ_{zx}, τ_{zy}, τ_{zz}, wides-out.**



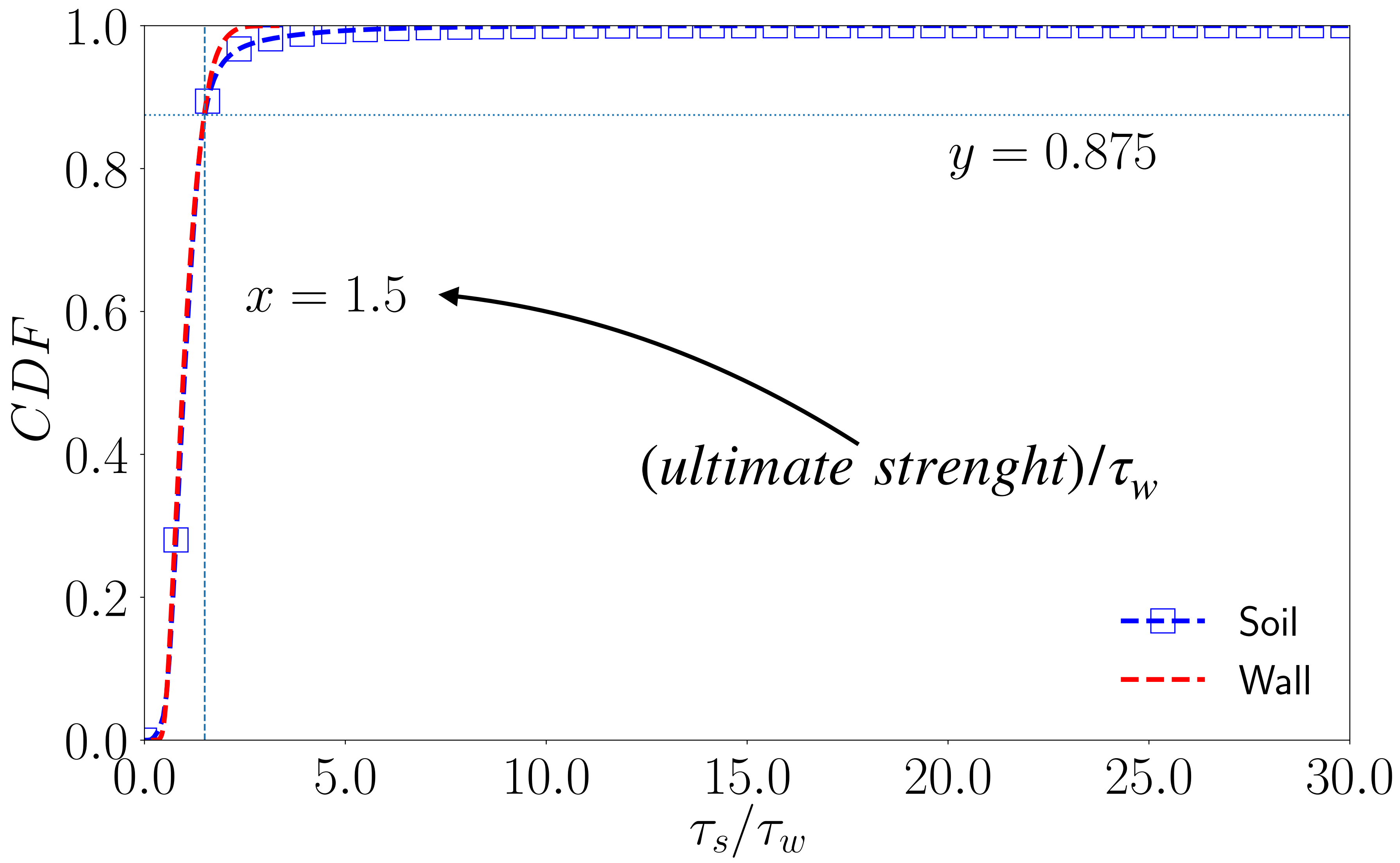


Spreading of the PDF of τ_{zz} (wall-normal stress) occurs but is less evident

APP. #1: WHY EROSION ACCELERATES? CUMULATIVE DENSITY FUNCTION OF WALL STRESSES



$t/\tilde{t} = 16.75$



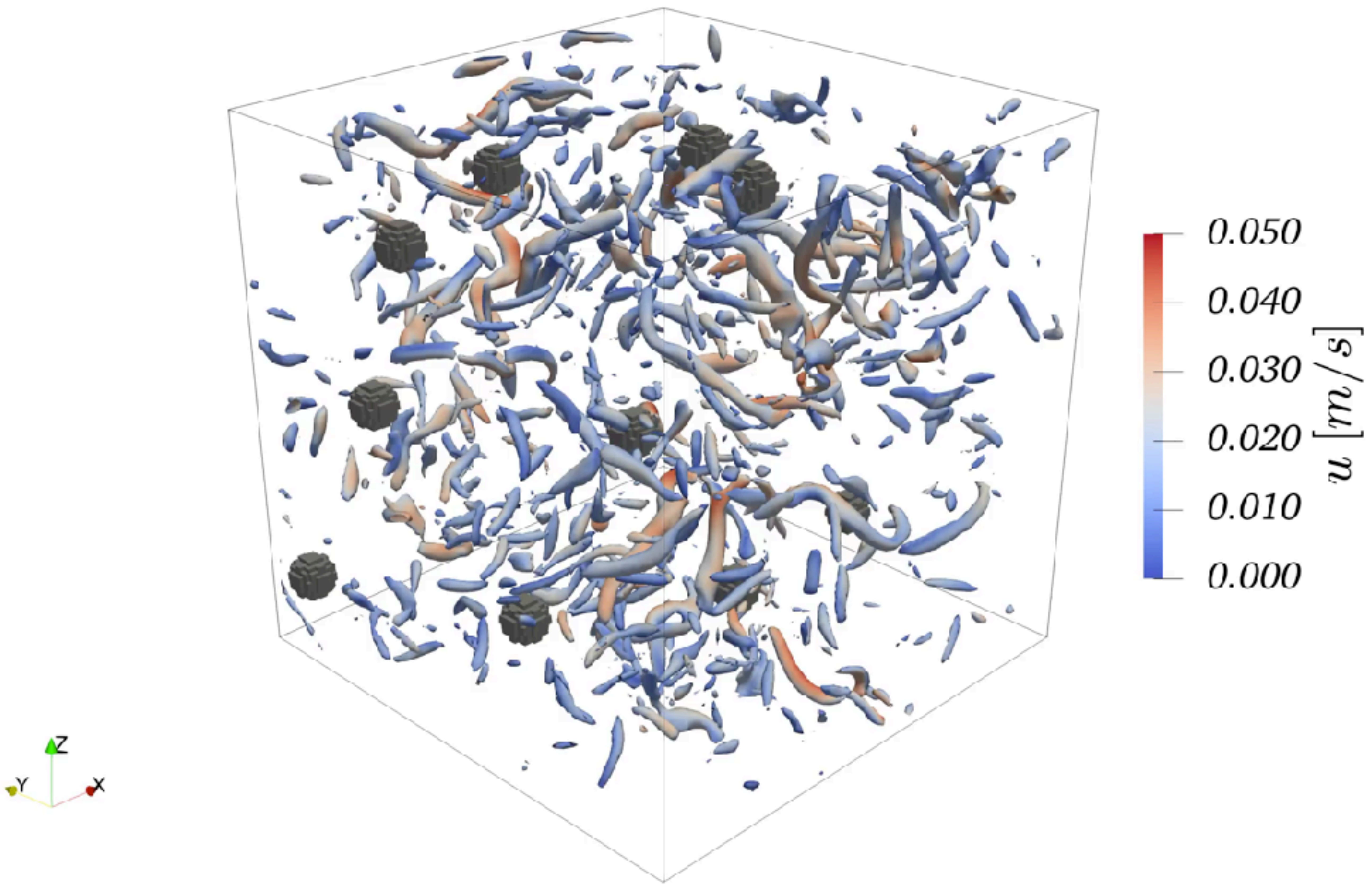
$t/\tilde{t} = 25.50$

- Results and discussion submitted to Journal of Fluid Mechanics (under consideration): **Dalla Barba F., Picano F. (2020).** *Direct numerical simulation of the scouring of a brittle stream-bed in a turbulent channel flow*

- By comparing the cumulative distribution function of the shear stress, $\tau_s = \sqrt{\tau_{zx}^2 + \tau_{zy}^2}$, with the ultimate strength of the material it results that:
  - At the beginning of the process the number of turbulent events leading to a break-up are only 9% of the overall turbulent events.
  - At the end of the process the number of turbulent events leading to a break-up increases up to 12.5% of the overall turbulent events!

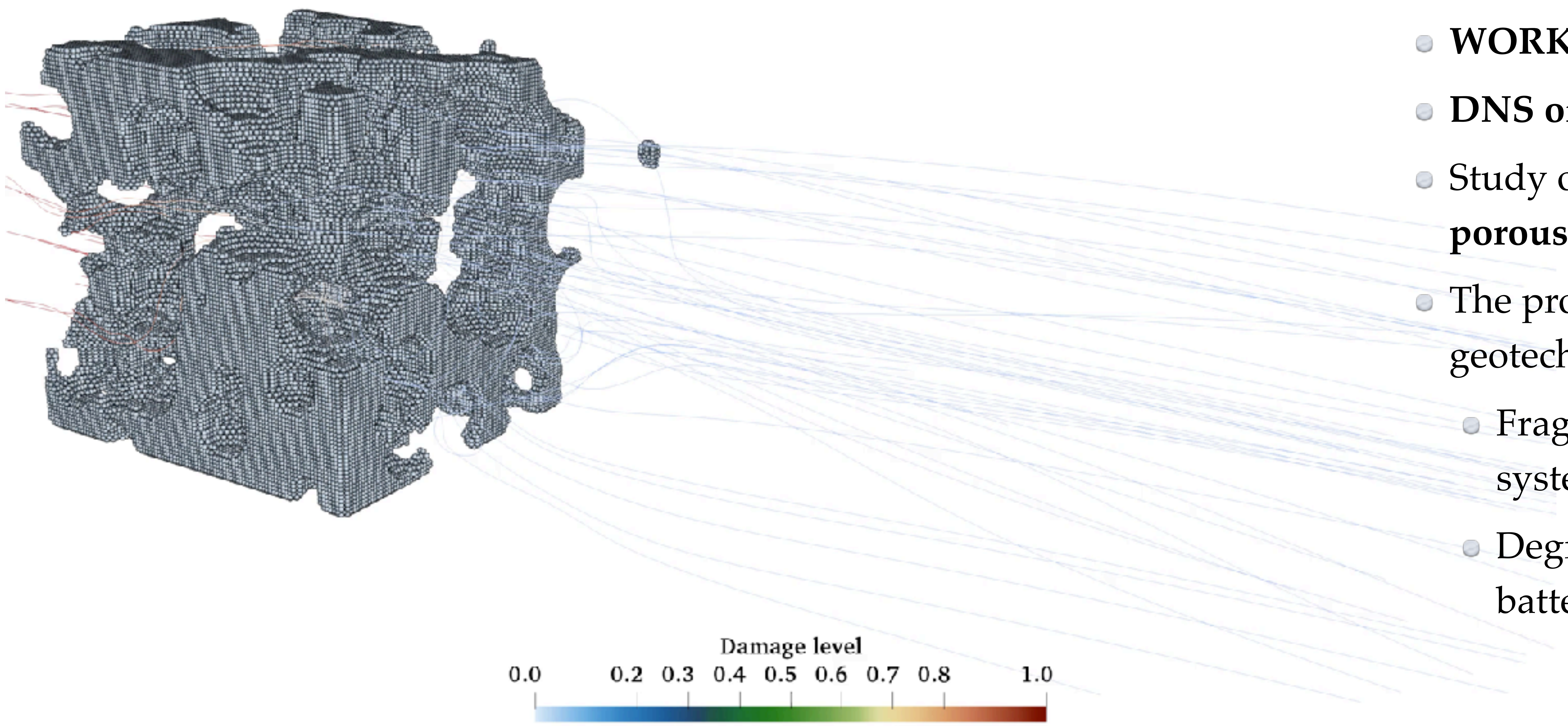
The irregular shape of the stream-bed promotes the formation of coherent, high-intensity turbulent structures. The latter, enhance at their turn the wall-stresses, promoting the break-up and the formation of more irregularities on the stream-bed.

FUTURE PERSPECTIVES: APP.#2 - BREAK-UP OF SOLID GRAINS IN HOMOGENOUS ISOTROPIC TURBULENCE



- **WORK IN PROGRESS**
- **DNS of homogeneous isotropic turbulence: solid grains of linear elastic and brittle materials are dispersed in the flow**
- Study of the mechanism leading to **fluid-driven-fatigue break-up of the grains**
- The problem is of relevant interest for environmental, geotechnical and industrial applications:
  - Fragmentation of micro plastics in oceans and sees
  - Flock disruption in multiphase flow

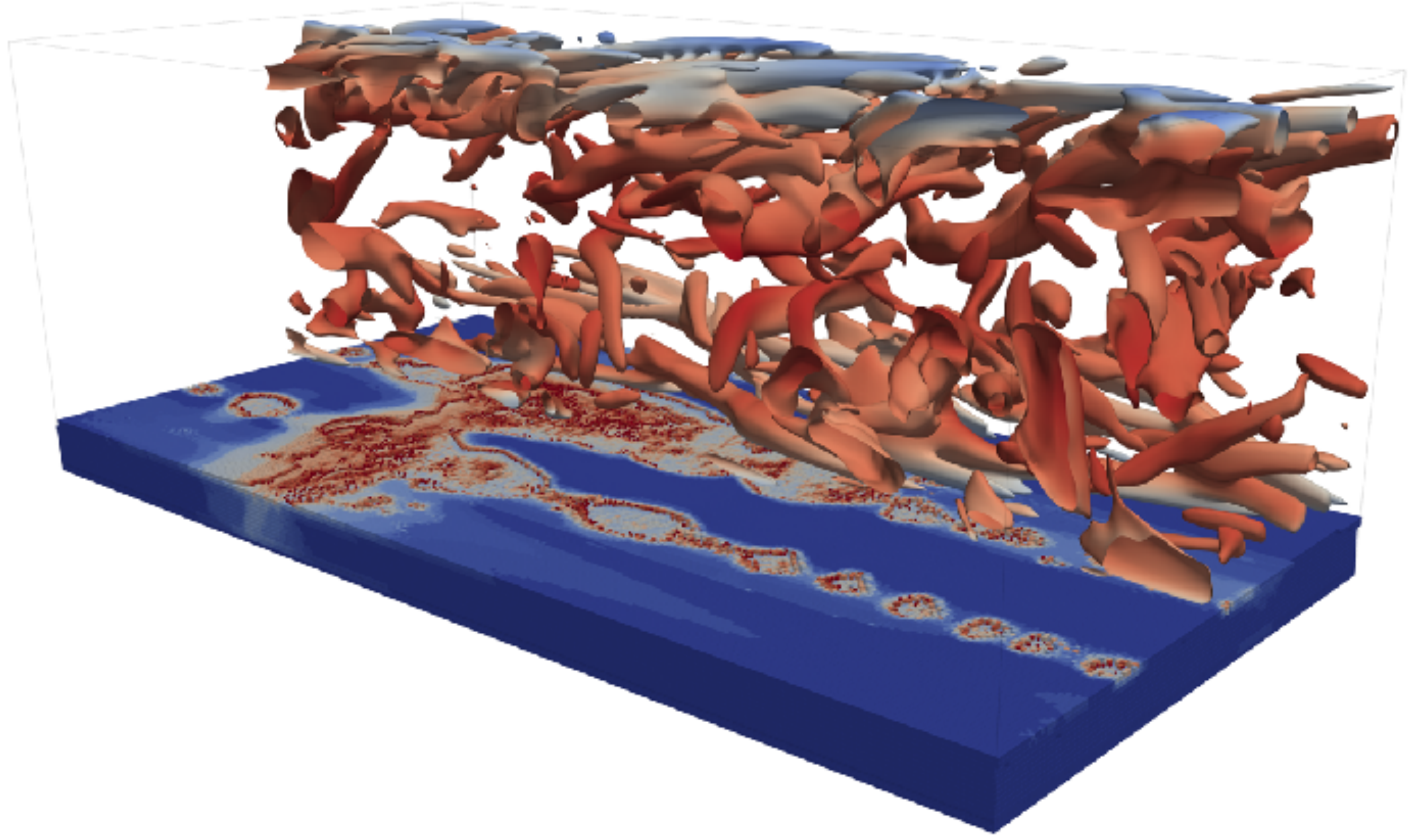
FUTURE PERSPECTIVES: APP.#3 - BREAK-UP OF POROUS MEDIA IN LAMINAR FLOWS

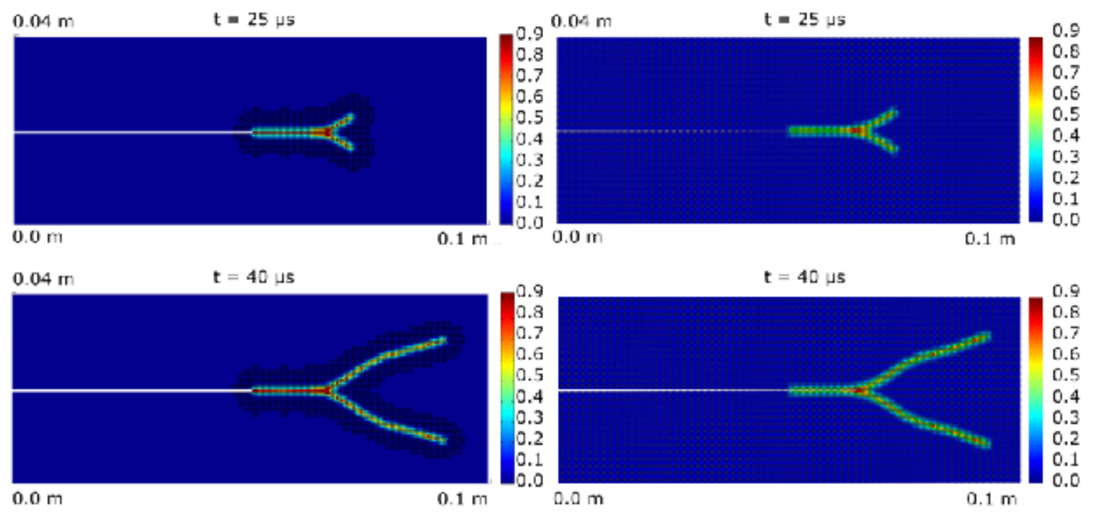


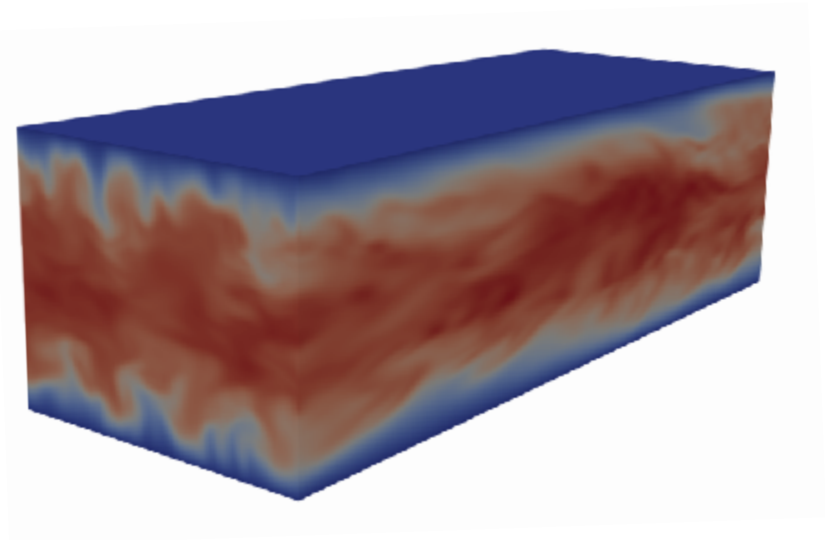
- **WORK IN PROGRESS**
- **DNS of laminar flow through a porous media**
- Study of the mechanism leading to the **break-up of a porous solid in laminar flow**
- The problem is of relevant interest for environmental, geotechnical and industrial applications:
  - Fragmentation of rocks and rock aggregates in fault systems
  - Degradation of porous electrodes in fuel cells and flow batteries

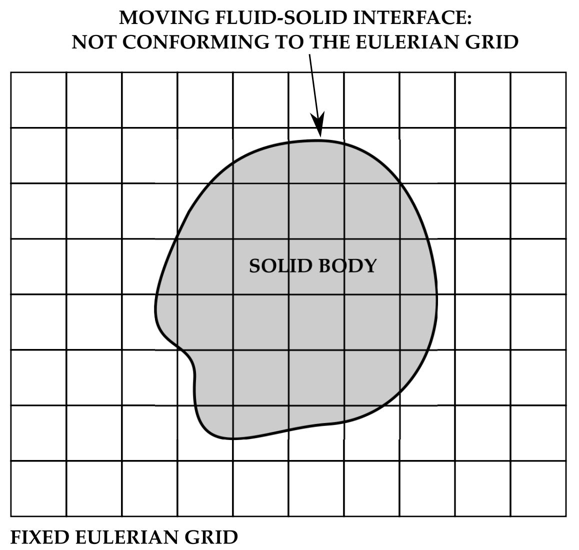
FINAL REMARKS AND OUTCOMES OF THE RESEARCH

- **FSI problems with crack formation and solid media fracture can be treated numerically in a Navier Stokes - peridynamics - IBM framework**
- **A massive parallel numerical tool capable to address general FSI problems accounting for crack formation and fracture in solids has been developed**
- Validation and testing have been performed obtaining promising results:
  - Capability of the solver to reproduce solid media fracture and crack branching due to fluid-induced forces
  - Capability of IBM to impose **no-slip and no-penetration boundary conditions on complex and time evolving interfaces**
  - **Accurate computation of fluid forces on solid via normal probe method**
  - **Automatic detection of cracks and new interfaces**









- The method and the new numerical equipment have been employed to address the simulation of the **erosion and break up of brittle substrate in turbulent flows:**
  - The **basic mechanisms governing the process have been identified and characterized**
  - The outcomes of the research and future development may be relevant in:
    - Environmental and planetary science applications, e.g. erosion processes on planetary surfaces
    - Aerospace applications, e.g. accurate control of the erosion of nozzle throat in rocket engines

PUBLICATIONS AND TRAINING ACTIVITIES

- **PUBBLICATIONS**
- **Ph.D. related publications:**
  - ***Dalla Barba F., Picano F. (2020). A novel approach for direct numerical simulation of hydraulic fracture problems.*** *Flow, Turbulence and Combustion, Vol. 105, p. 335-357, ISSN: 1386-6184, doi: 10.1007/s10494-020-00145-x.*
  - ***Dalla Barba F., Picano F. (2020). A new method for fully resolved simulations of fracturing in fluid-structure interaction problems.*** *In: ERCOFTAC Series. ERCOFTAC SERIES, Vol. 27, p. 469-475, Springer, ISBN: 978-3-030-42821-1, ISSN: 1382-4309, doi: 10.1007/978-3-030-42822-8_62.*
  - ***Dalla Barba F., Campagnari P., Zaccariotto M., Galvanetto U., Picano F. (2020). A fluid-structure interaction model based on peridynamics and Navier-Stokes equations for hydraulic fracture problems.*** *In: Proceedings of the 6th European Conference on Computational Mechanics: Solids, Structures and Coupled Problems, ECCM 2018 and 7th European Conference on Computational Fluid Dynamics, ECFD 2018. p. 89-100, International Centre for Numerical Methods in Engineering, CIMNE, Scottish Events Campus, gbr, 2018.*
- **Other publications produced during the Ph.D. course:**
  - *Ciottoli P.P., Battista F., Malpica Galassi R., Dalla Barba F., Picano F. (2020). Direct numerical simulations of the evaporation of dilute sprays in turbulent swirling jets. Flow, Turbulence and Combustion, 1-23, ISSN: 1386-6184, doi: 10.1007/s10494-020-00200-7.*
  - *Dalla Barba, F., Picano, F. (2019). Evaporation dynamics in dilute turbulent jet sprays. In: ERCOFTAC Series. ERCOFTAC SERIES, Vol. 25, p. 221-227, Springer, ISBN: 978-3-030-04914-0, ISSN: 1382-4309, doi: 10.1007/978-3-030-04915-7_30.*
  - *Dalla Barba F., Picano F. (2018). Clustering and entrainment effects on the evaporation of dilute droplets in a turbulent jet. Physical Review Fluids, Vol. 3, 034304, ISSN: 2469-990X, doi: 10.1103/PhysRevFluids.3.034304*

UNIVERSITÀ DEGLI STUDI DI PADOVA
Corso di Dottorato in Scienze, Tecnologie e Misure Spaziali

PERSONAL TRAINING PLAN OF DOCTORAL STUDENT FEDERICO DALLA BARBA

EDUCATIONAL ACTIVITIES ACTIVATED BY THE STMS PHD COURSE

Interdisciplinary Module/Activity	Lecturer	Expected credits	Frequency (YES/NO)	Exam (YES/NO)*	Date of exam	Attained credits
Exploring the solar system and its environment	Prof. Marzari / Pajola/ Lucchetti	4	YES	YES	17/05/2018	4
Fundamentals of measurements and PC-based applications	Prof. Pertile / Rossi	4	YES	YES	11/07/2018	4
Mechanical and thermal properties of material for aerospace constructions	Prof. Galvanetto / Zaccariotto	4	YES	YES*	14/03/2019	4
Preparation of a research proposal	Prof. Naletto	2	YES	YES	19/06/2020	2

Curriculum oriented seminars	Lecturer	Expected credits	Frequency (YES/NO)	Exam (YES/NO)*	Date of exam	Attained credits
Mechanics of vehicle	Prof. Franceschini	0.4	YES	YES	20/02/2018	0.4
The radiation environment in space: evaluating dose, material activation and radioprotection issues	Prof. Rando	0.4	YES	YES	28/02/2018	0.4
Analysis of complex dynamics using chaos indicators	Prof. Guzzo	0.4	YES	YES	29/03/2018	0.4
Optical coatings and their application in space environment	Prof. Corso	0.4	YES	YES	18/06/2018	0.4
Advanced Computational Modeling of Solid/Fluid Interactions	Prof. Picano	0.4	YES	YES	19/06/2018	0.4
Satellite Navigation and attitude control using GNSS	Prof. Caporali	0.4	YES	YES	23/01/2019	0.4
Space instrument testing with stratospheric balloons and drones	Prof. Bettanini	0.4	YES	YES	06/02/2019	0.4
High efficiency EUV optics for solar physics application	Prof. Corso	0.4	YES	YES	08/02/2019	0.4
Space application of panoramic lenses	Prof. Pernechele	0.4	YES	YES	16/04/2019	0.4
Finite Element Analysis of multi-phase porous media, with particular attention to strain localization and desiccation cracks	Prof. Sanavia	0.4	YES	YES	20/02/2010	0.4
Fly low cost experiments in Earth atmosphere and stratosphere: mission preparation and operations	Prof. Bettanini	0.08	YES	NO	-	0.08

OTHER EDUCATIONAL ACTIVITIES

Title of the activity (Date/Period/University)	Lecturer	Duration of activity	Expected credits	Frequency (YES/NO)	Exam (YES/NO)	Date of exam	Attained credits
Course: *Finite Elements Method*	Prof. Gambolati	32 h	6.4	YES	YES	10/07/2019	6.4
Course: *Reactive Fluid Mechanics*	Prof. Canu	12 h	0.48	YES	NO	-	0.48
Congress: *ECCM-ECFD, 11-12/06/18, Glasgow*		15 h (36x20 min talks + 2x90min plenary lectures)	0.6	YES	-	-	0.6
Congress: *Euromech 596, 09-10/05/18, Venice*	-	12 h (40x15min talks + 2x60 min plenary lectures)	0.48	YES	-	-	0.48
Didattica integrativa: Aerodinamica II, Laurea Magistrale Ingegneria Aerospaziale, primo semestre 2017/2018	-	30 h	2.4	-	-	-	2.4
Didattica integrativa: *Meccanica dei fluidi, Laurea in Ingegneria dell'Energia*, secondo semestre 2017/2018	-	10 h	0.8	-	-	-	0.8
Didattica integrativa: Aerodinamica, Laurea in Ingegneria Aerospaziale, primo semestre 2018/2019	-	10 h	0.8	-	-	-	0.8
Didattica integrativa: *Aerodinamica II, Laurea Magistrale in Ingegneria Aerospaziale, secondo semestre 2018/2019*		20 h	1.6	-	-	-	1.6
Didattica integrativa*: Aerodinamica, Laurea in Ingegneria Aerospaziale, primo semestre 2019/2020*	-	20h	1.6	-	-	-	1.6
Didattica integrativa*: Aerodinamica 2, Laurea Magistrale in Ingegneria Aerospaziale, secondo semestre 2019/2020*		10h	0.8				0.8
Didattica integrativa*: Laboratorio di fluidodinamica computazionale, Laurea Magistrale in Ingegneria Aerospaziale, secondo semestre 2019/2020*		10h	0.8				0.8
Total of expected ECTS credits attainable in educational activities (>30):			**34.84**	**Total of credits attained in educational activities (at date 29/10/2020):**			**34.84**

* Specify which exam will be done as an academic lecture.

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Thank you for your attention