Università degli Studi di Padova
Centro di Ateneo di Studi e Attività Spaziali “Giuseppe Colombo”

PhD XXXIII cycle
Event: Request of admission to the third year of the PhD course

A novel numerical method for fluid-structure interaction problems

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Co-supervisor: Prof: Mirco Zaccariotto

MOTIVATIONS

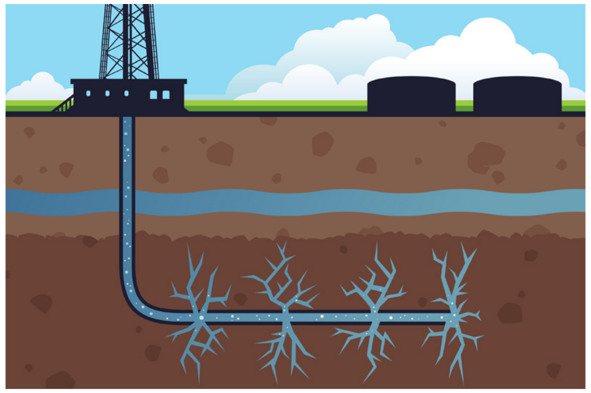
- **FLUID STRUCTURE INTERACTION (FSI) PROBLEMS**
  - **Interaction among a fluid flow and rigid or deformable solid structures:**
    - **Force exchange across sharp and complex interfaces**
    - **Time-evolving interfaces**
    - **Solid and fluid dynamics is governed by different constitutive laws**

  - **Complex dynamics, multi-physics, strong nonlinearity**

- **FSI is a key problem in aerospace engineering:**
  - **Liquid sloshing in fuel tanks**
  - **Acoustic induced vibration**
  - **Aeroelastic flutter of wings**

Additional complexity when solid fracture occurs within a fluid flow:

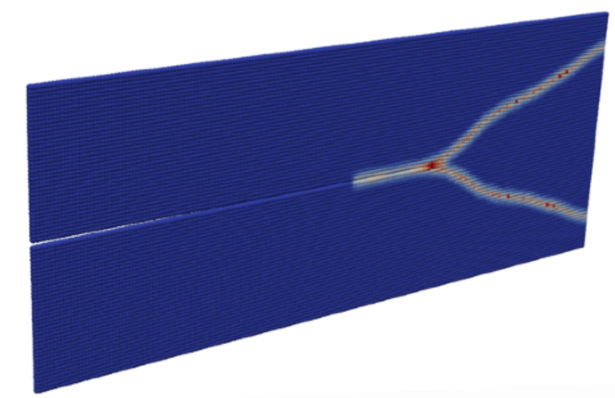
- **Hydraulic fracture**



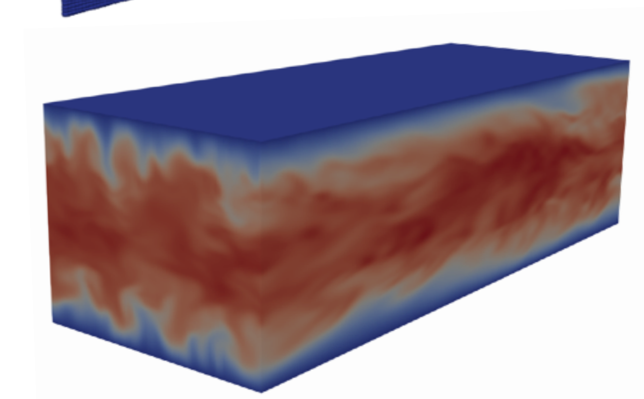
To date, a satisfactory numerical and theoretical description of FSI problems with hydraulic fracture remains a challenge and the capabilities of existing models for applications are still limited

OBJECTIVES AND METHODOLOGY

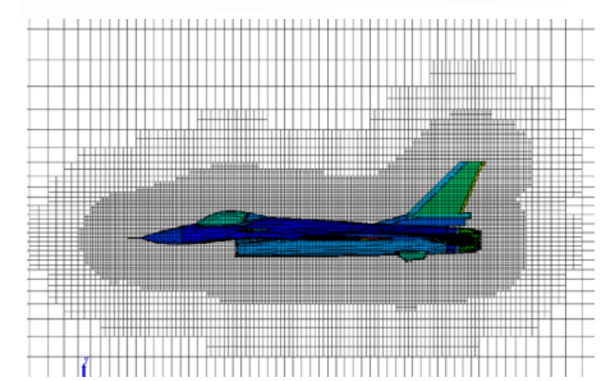
- **OBJECTIVES:**
  - **DEVELOPMENT OF A NUMERICAL TOOL CAPABLE TO REPRODUCE THE PHYSICS OF GENERIC FSI PROBLEMS ACCOUNTING FOR SOLID FRACTURE**
  - **INVESTIGATION OF FSI WITH SOLID FRACTURE**



- **METHODOLOGY:**
  - **PERIDYNAMICS (PD):** →
    - **Crack detection/branching and solid fracture prediction capabilities**



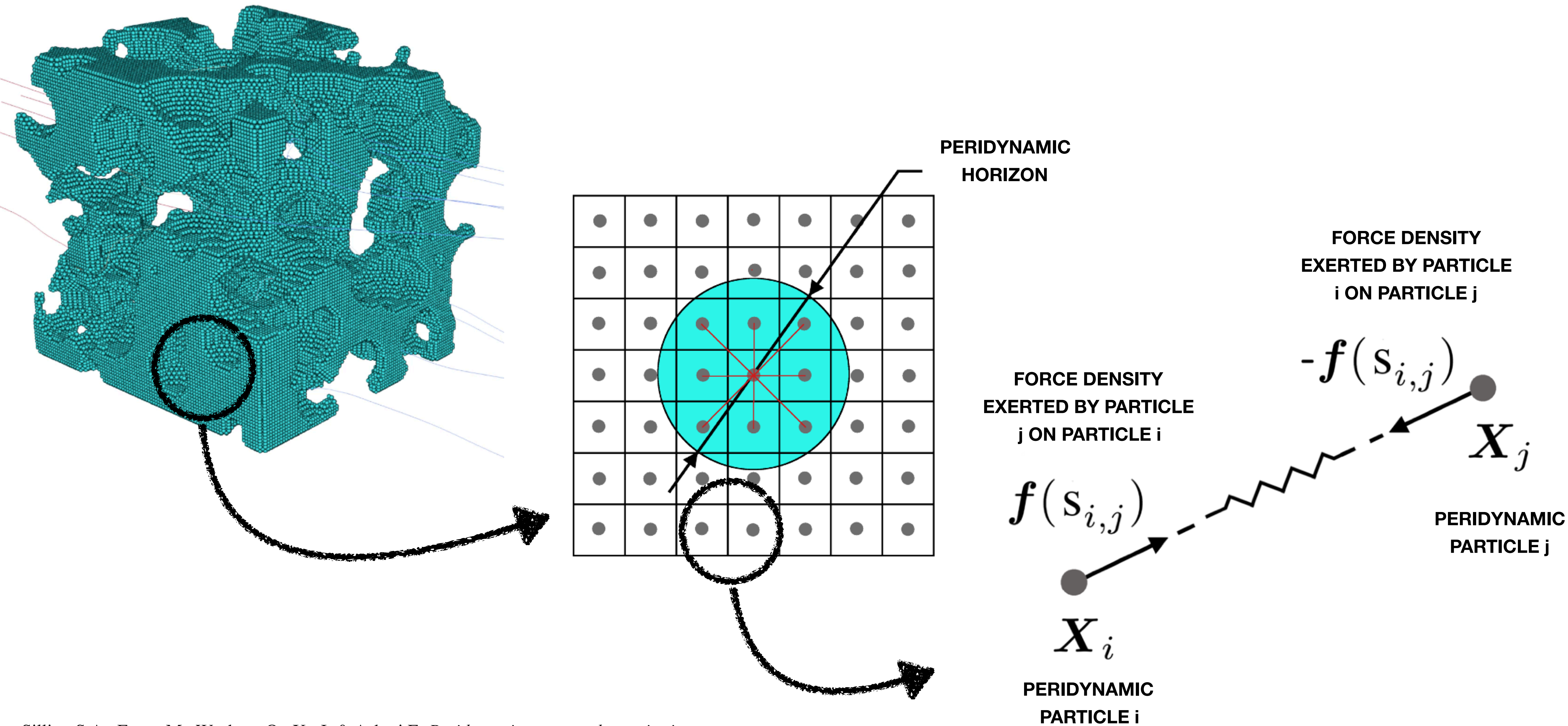
  - **NAVIER STOKES EQUATIONS (NS)** →
    - **Prediction of fluid flow dynamics**



  - **IMMERSED BOUNDARY METHOD (IBM)** →
    - **Coupling and force exchange across complex interfaces**

DISCRETE BOND-BASED PERIDYNAMICS: BASIC CONCEPTS

- **Peridynamics is a formulation of continuum mechanics based on non-local integral equations:**
  - **A discretized peridynamic solid is represented by 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, the *peridynamic horizon*, δ**

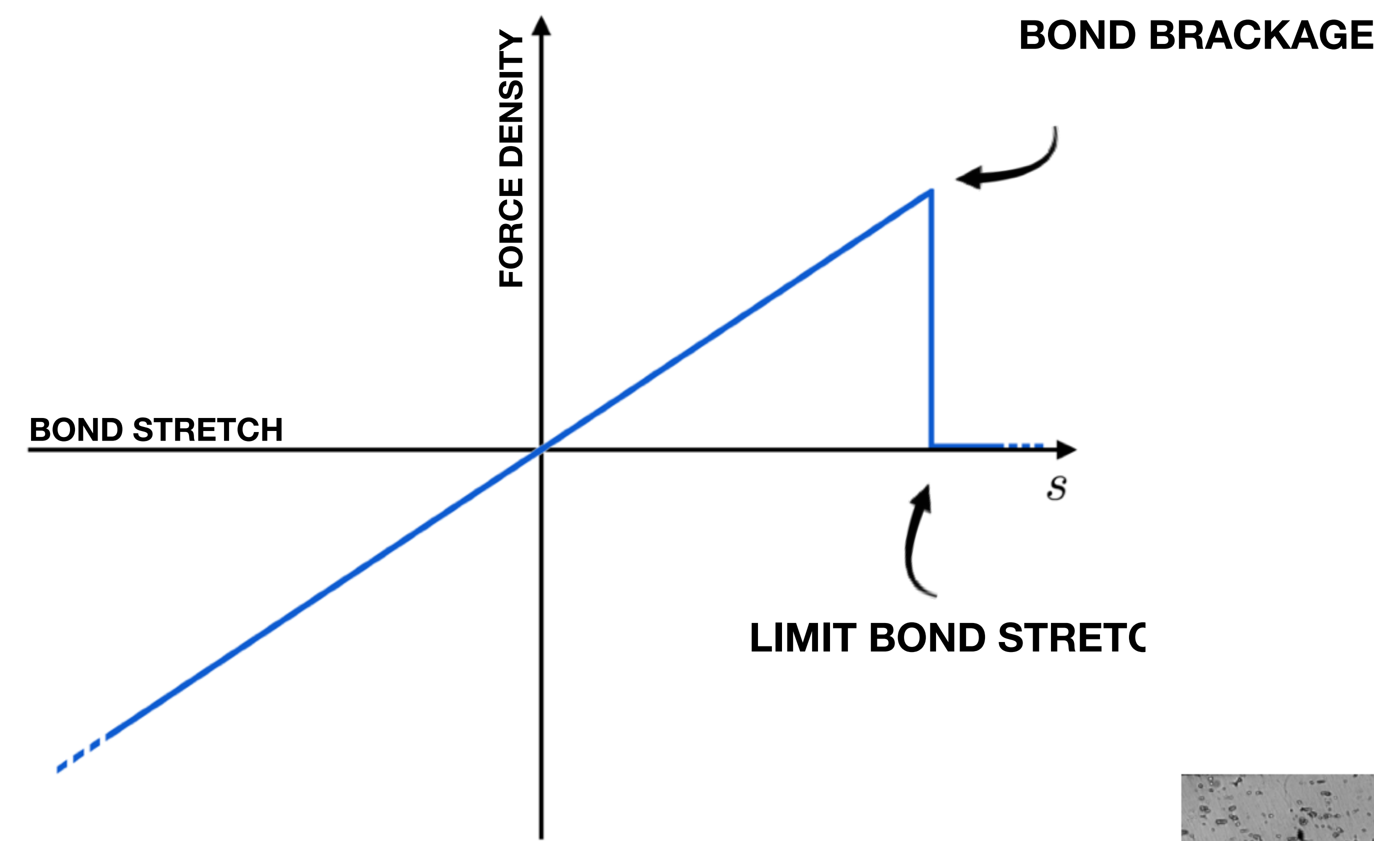


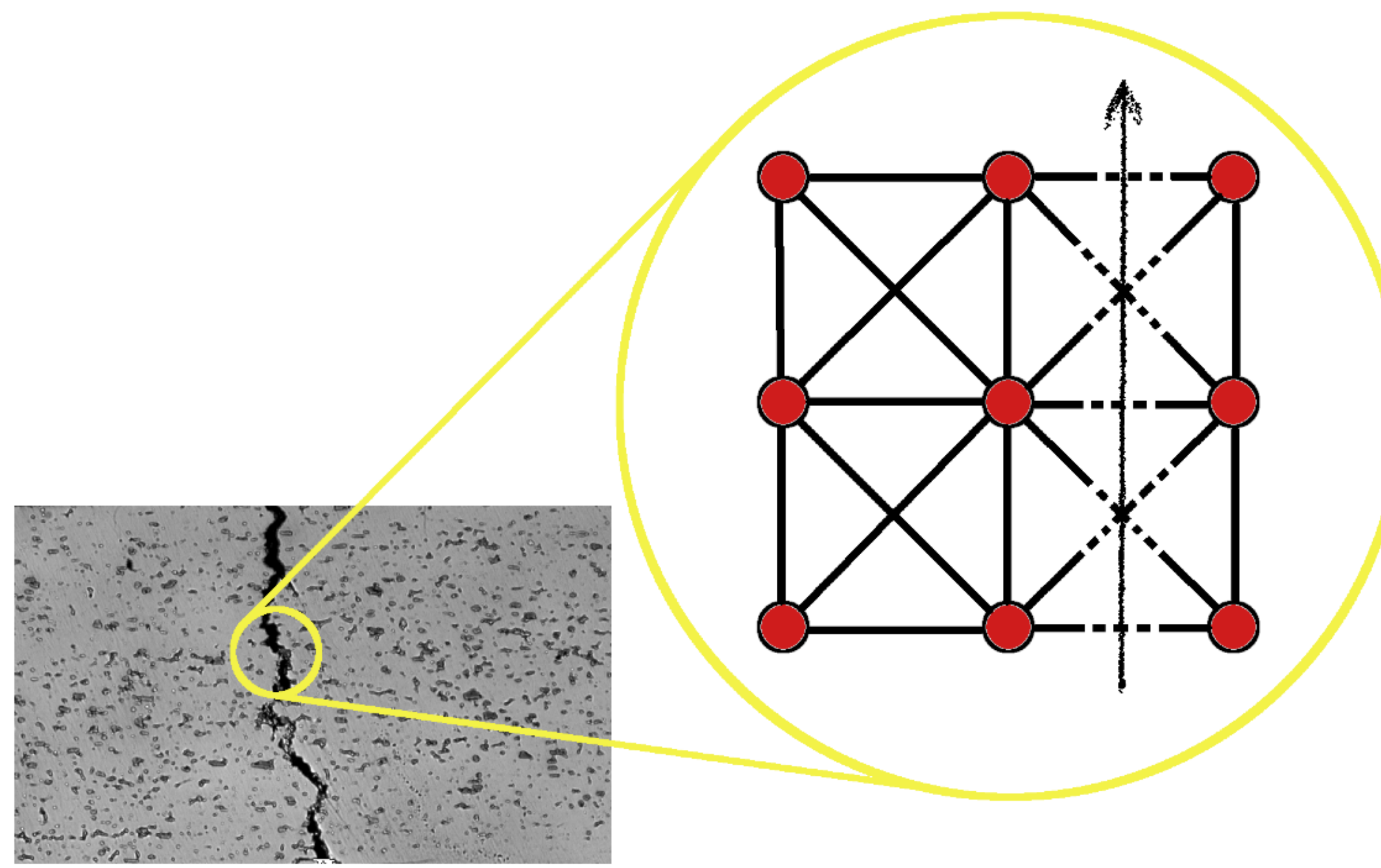
Silling S.A., Epton M., Weckner O., Xu J. & Askari E. *Peridynamic states and constitutive modeling*. Journal of Elasticity (2007).

Silling S.A. *Reformulation of elasticity theory for discontinuities and long-range forces*. Journal of Mechanics and Physics of Solids (2000).

DISCRETE BOND-BASED PERIDYNAMICS: MATERIAL DAMAGE DETECTION

- **Automatic crack detection and crack branching:**
  - **A bond breaks when its stretch overcomes a threshold value, the limit bond stretch s_0**
  - **The limit bond stretch, s_0, is a function of a macroscopic property of the material, the energy release rate, G**
  - **Bond breakage is permanent**





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NAVIER STOKES EQUATIONS AND IBM

- **Liquid phase governed by incompressible formulation of NS equations.**
- **Fixed Eulerian grid and moving Lagrangian grid on liquid-solid interface.**
- **Force exchange accounted for via Immersed Boundary Method (IBM).**

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

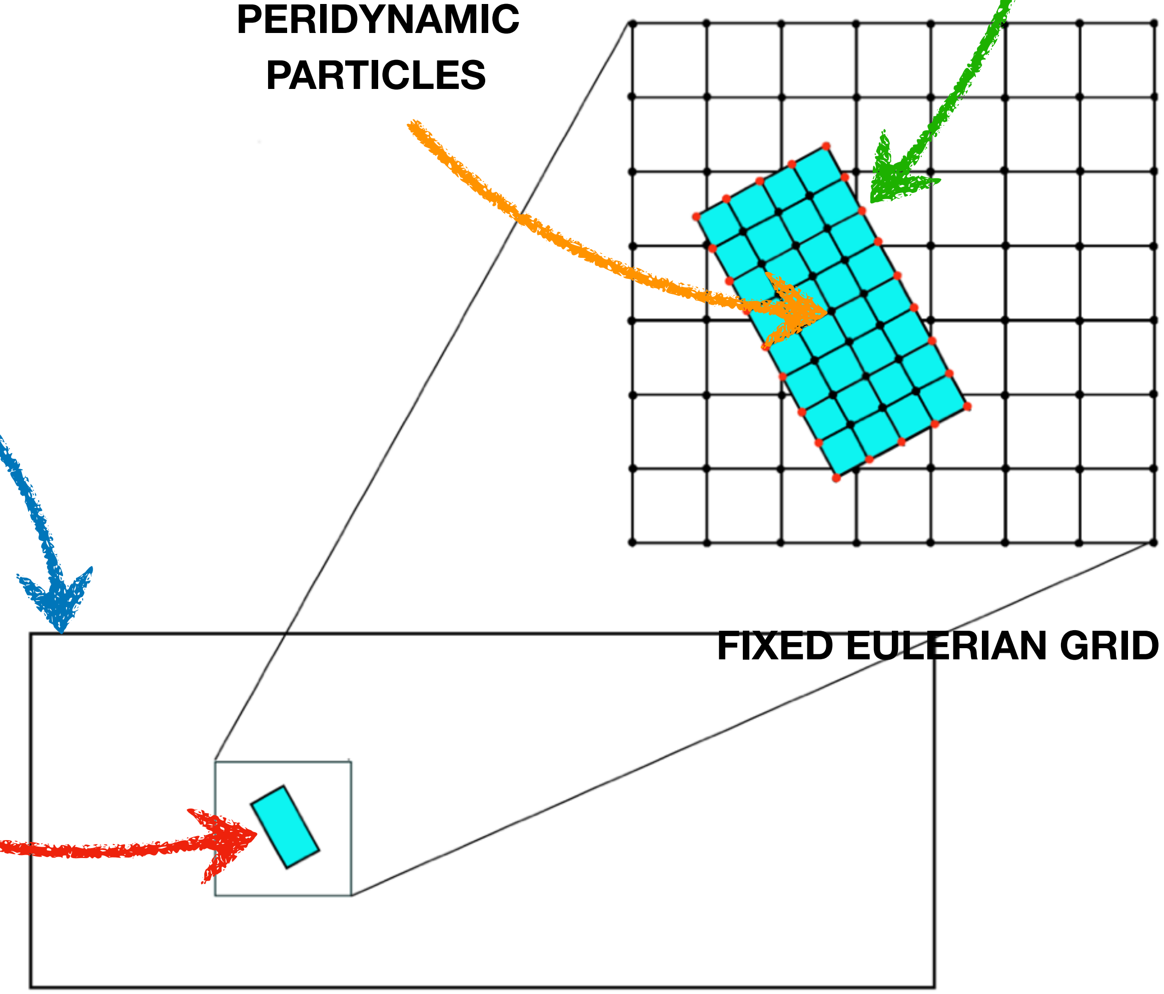
$$\rho_f \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} \right) = -\nabla p + \mu_f \nabla^2 \boldsymbol{u} + \rho_f \boldsymbol{f}$$

IBM FORCING ON THE LIQUID PHASE

MOVING LAGRANGIAN GRID

≡

SURFACE PERIDYNAMIC PARTICLES



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

- **PROBLEM: We have to impose no-slip and no-penetration boundary conditions for the fluid on the solid-liquid interface, but grid nodes do not coincide with the interface!**

- **IBM: a distributed force is used to impose BCs at the liquid-solid interfaces.**

- **IBM advantages:**
  - **Eulerian and Lagrangian grids are non conforming!**
  - **Force exchange across complex interfaces!**

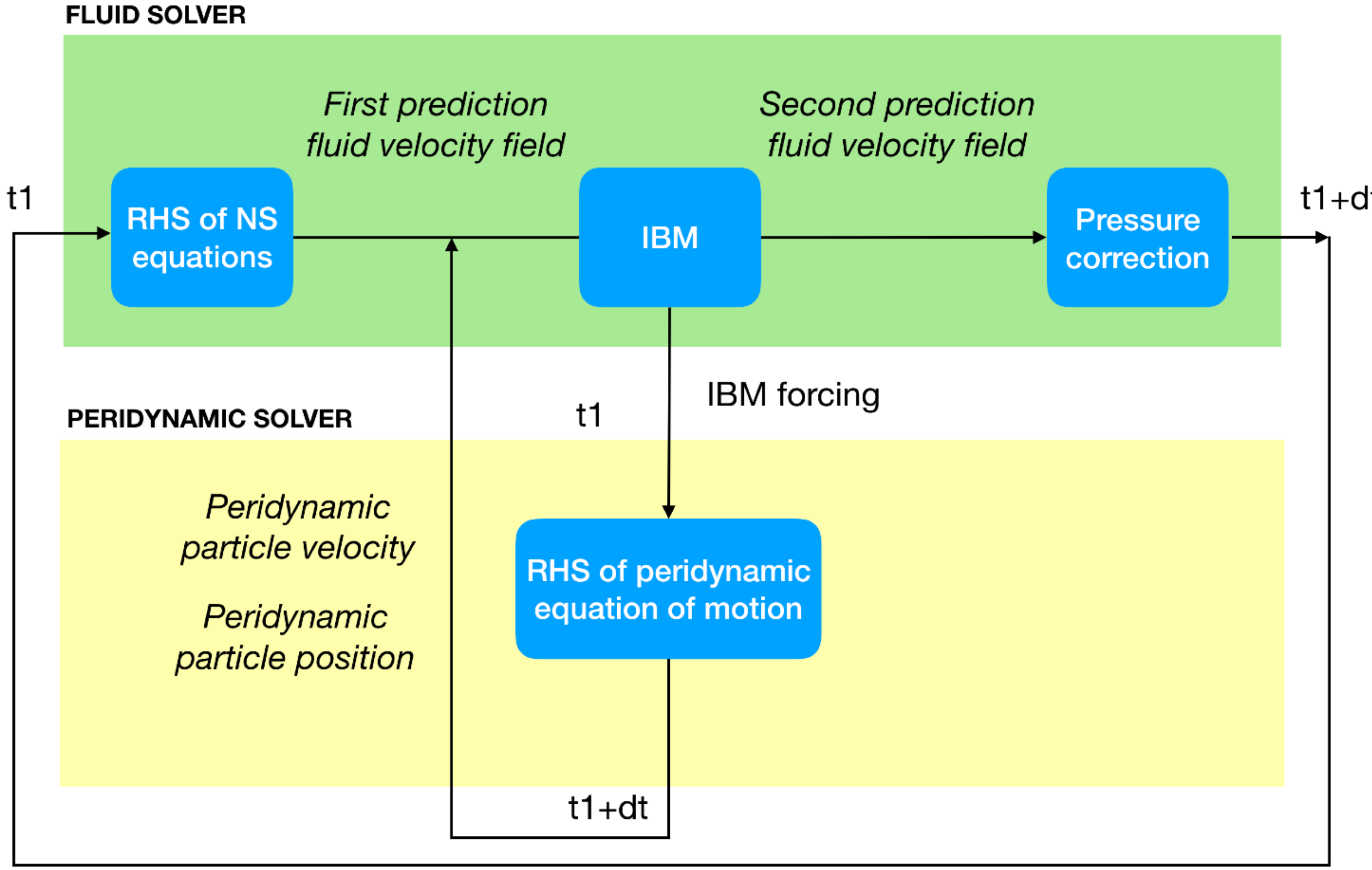
Mittal R. & Iaccarino G. *Immersed boundary Methods*. Annual Review of Fluid Mechanics (2005)

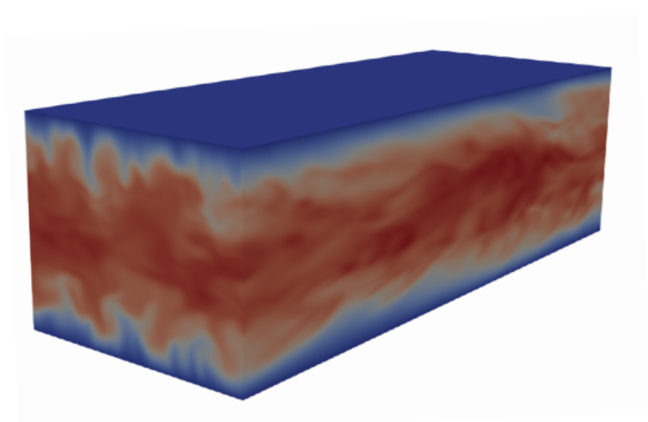
IMPLEMENTATION: AN OVERVIEW

- **FLUID SOLVER (CaNS by Pedro Costa):**
  - **Pressure correction algorithm**
  - **Second order finite difference schemes for space discretization**
  - **Third order, low storage Runge-Kutta time marching algorithm**

- **PERIDYNAMIC SOLVER:**
  - **Fully explicit algorithm**
  - **Fictitious damping of relative motions to filter high frequency vibrations**
  - **Third order, low storage Runge-Kutta time marching algorithm**

- **IBM:**
  - **Multidirect forcing scheme (3 steps)**





Costa P. *A FFT-based finite-difference solver for massively-parallel direct numerical simulations of turbulent flows*. arXiv preprint (2018).

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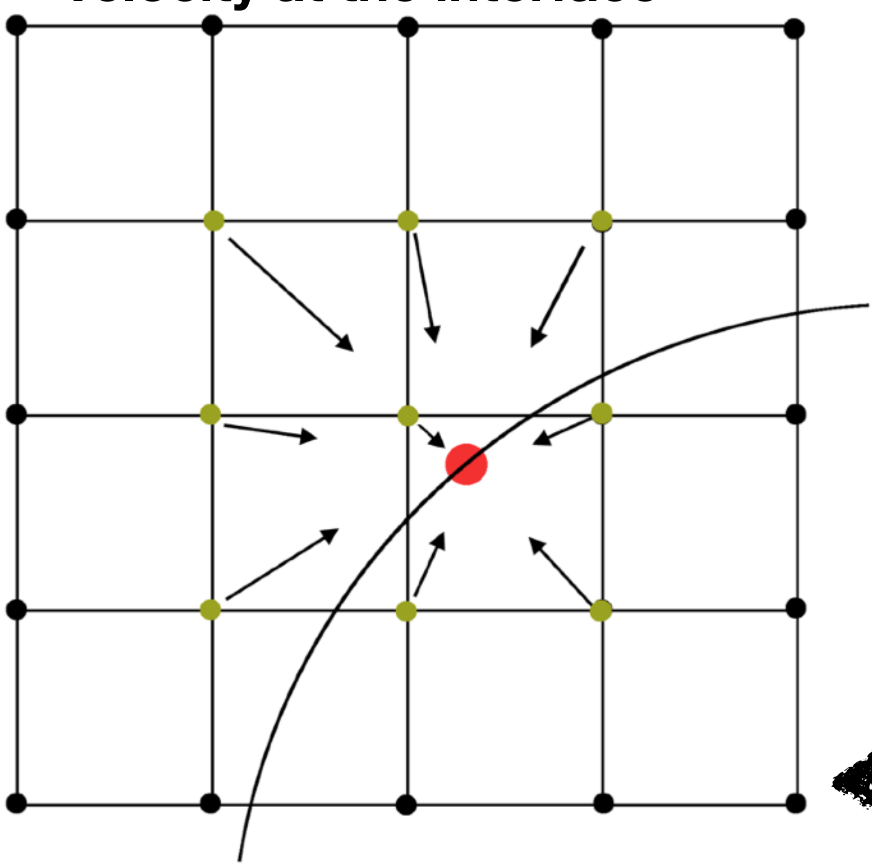
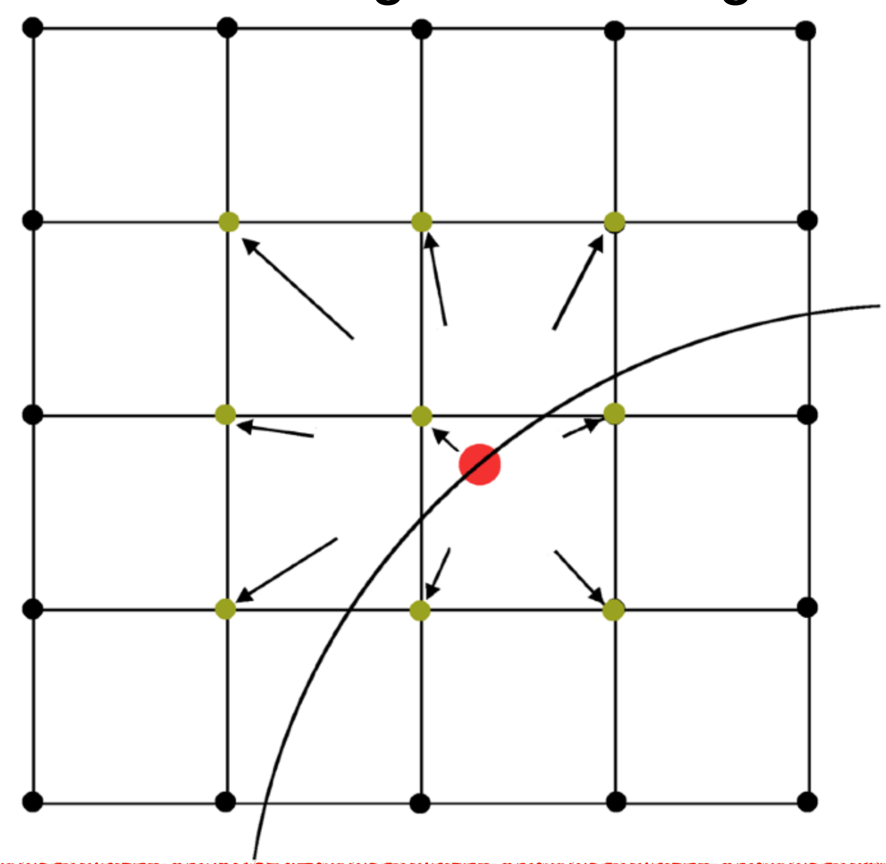
IMPLEMENTATION: IBM

- **PROBLEM: We have to impose boundary conditions on the solid-liquid interface:**
  - **No-slip**
  - **No-penetration**
- **We want to compute a fictitious force field to be 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**
- **Iterative procedure:**

1) Interpolation of fluid velocity at the interface → **2) Computation of the IBM forcing term** → **3) Spreading of the IBM forcing on the fluid grid**

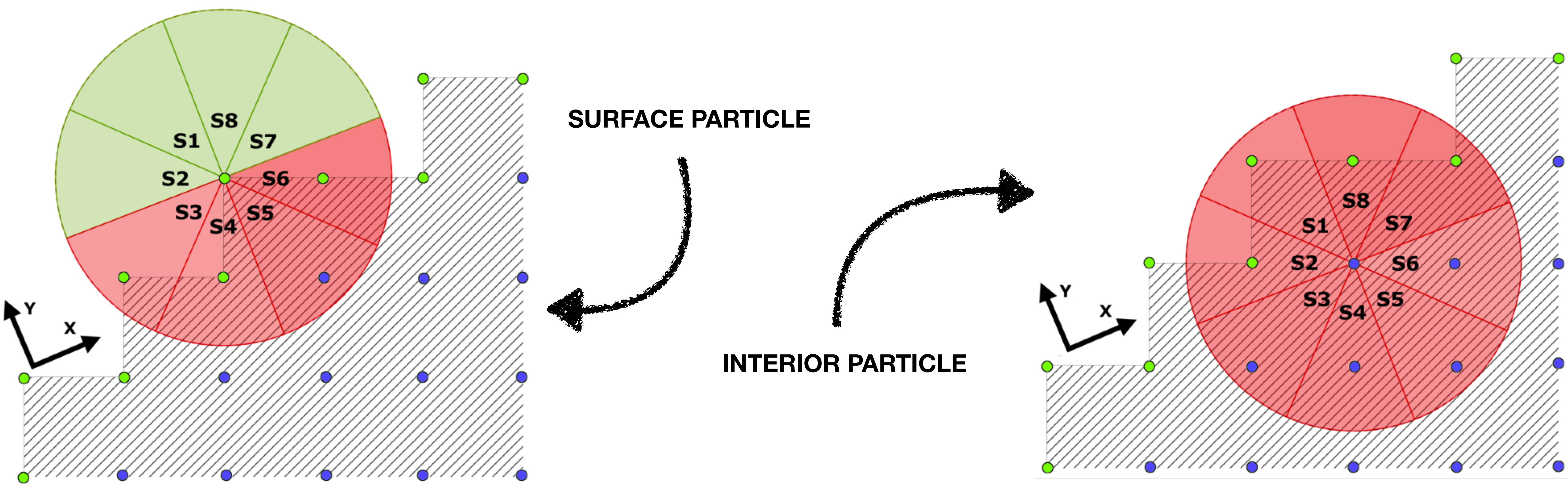


$$F = \frac{U_l - U_s}{\Delta t}$$



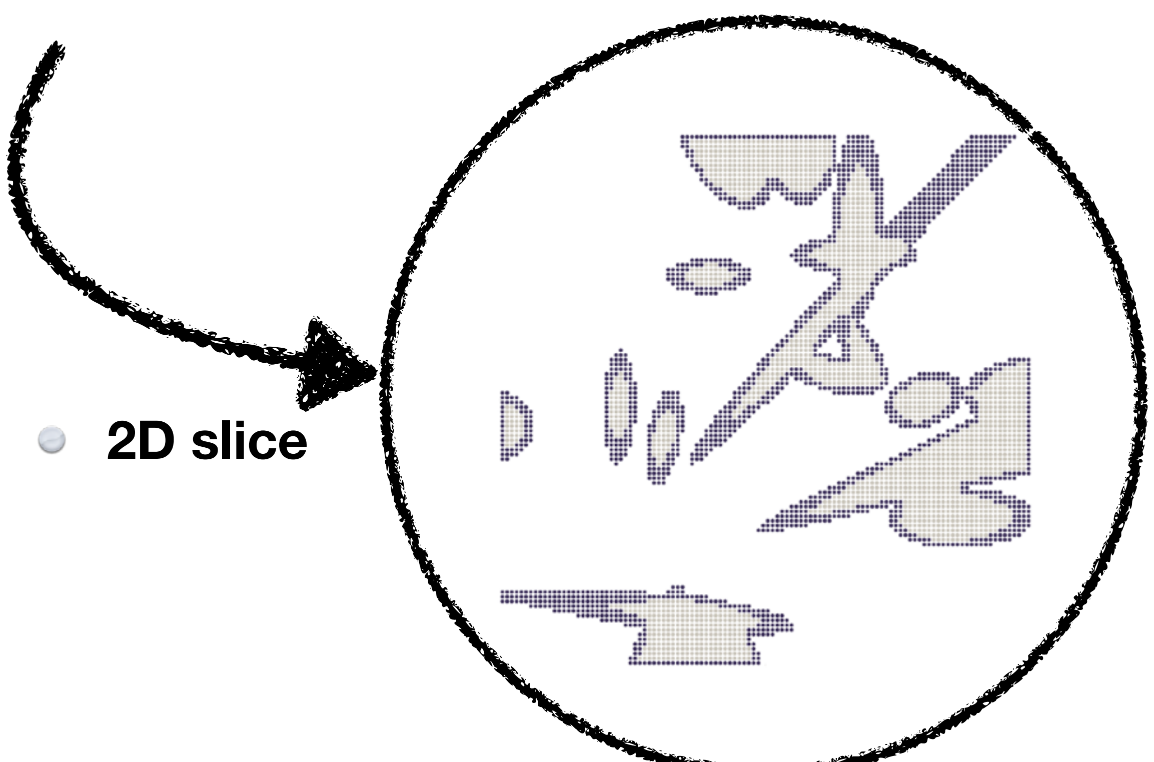
IMPLEMENTATION: SURFACE DETECTION ALGORITHM

- **A 3D surface detection algorithm is used to check if a peridynamic particle is located on the liquid-solid interface or in the solid interior. The detection of surfaces is used to:**
  - **Build the Lagrangian grid for the IBM algorithm**
  - **Compute normal and shear stresses exerted by the fluid on the surface of the solid body**
  - **Compute contact forces between solid bodies**
- **Principle (2D case):**
  - **For each peridynamic particle, the surrounding space is divided in 8 circular sectors**
  - **Each particle in the horizon of the selected particle is associated with one of the sectors**
  - **CRITERION: a particle is on the interface if 2 or more consecutive sectors are empty (90°)**

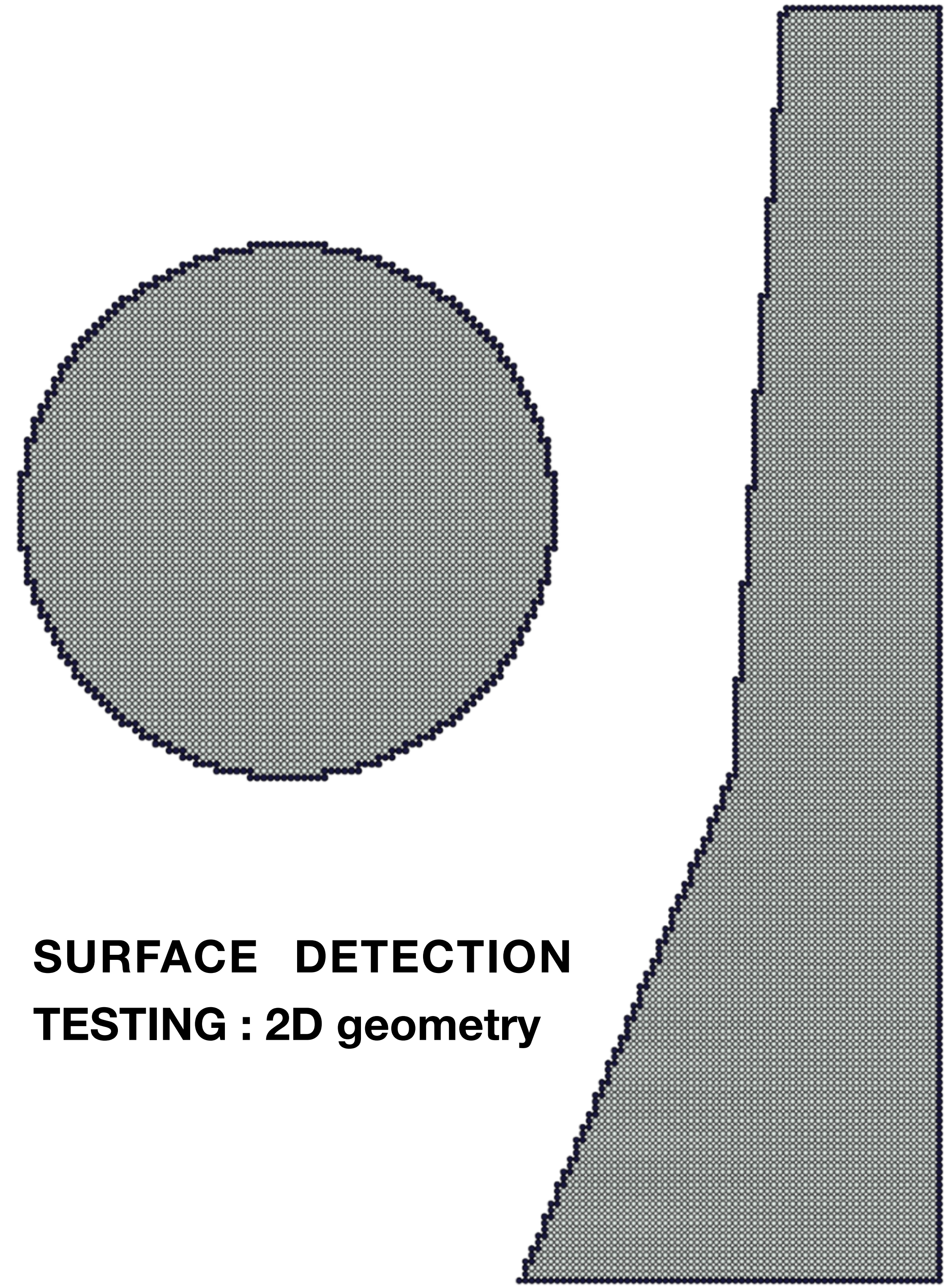


IMPLEMENTATION: SURFACE DETECTION ALGORITHM - EXAMPLES

- **SURFACE DETECTION TESTING: 3D set of cylindrical fibers with variable section**



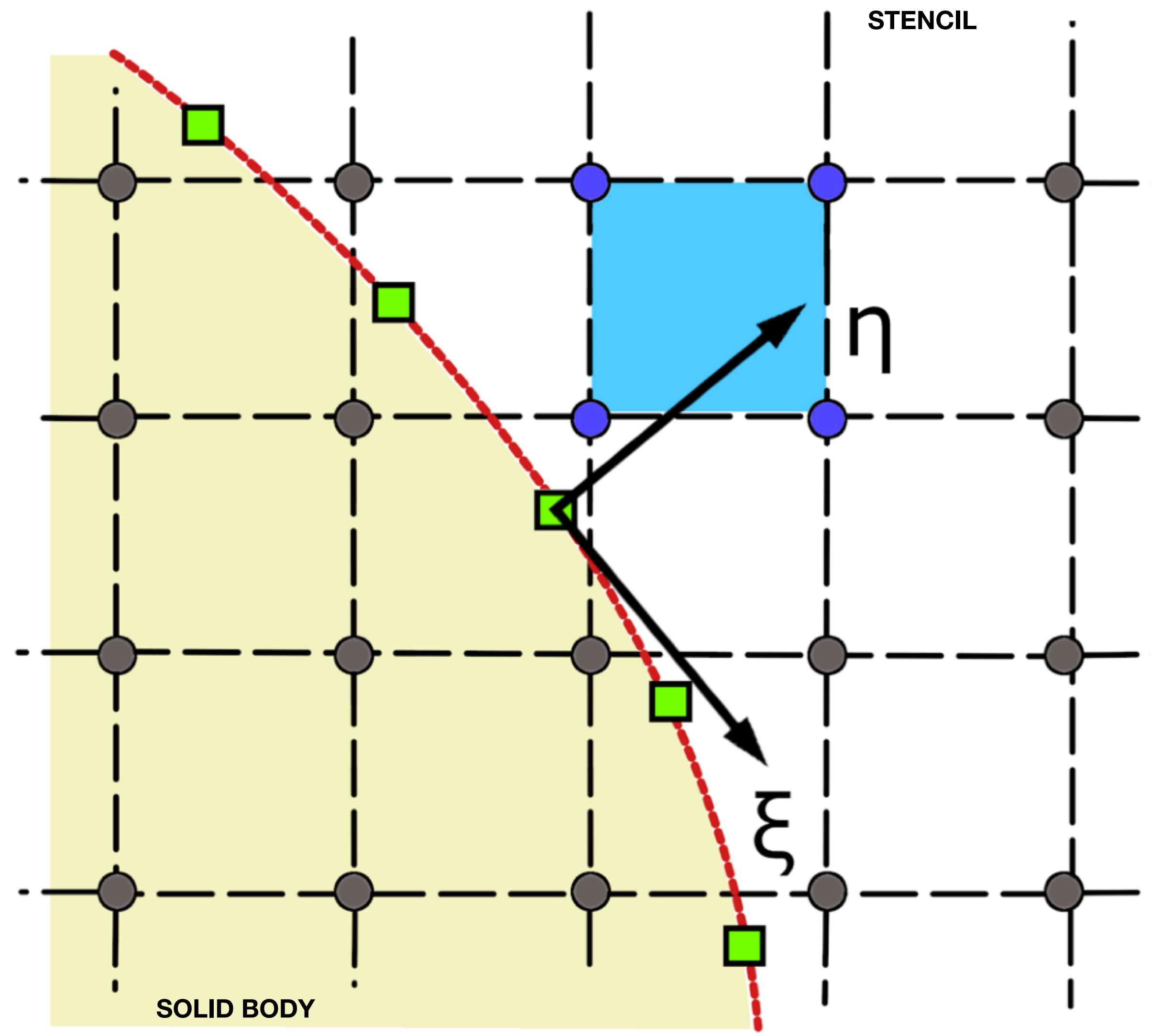
- **2D slice**

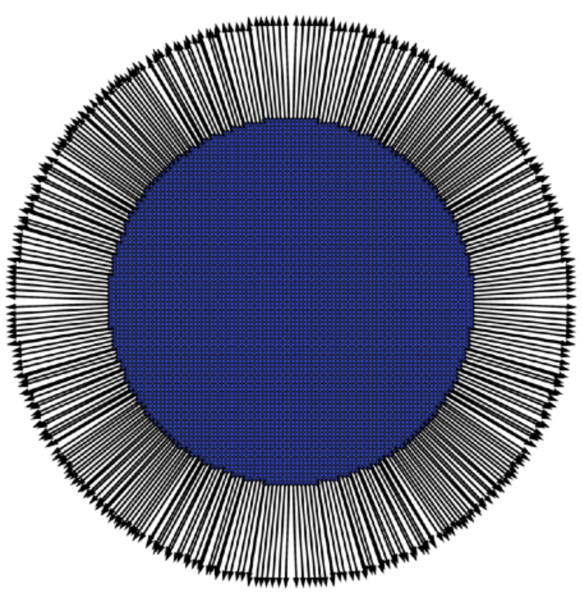


- **SURFACE DETECTION TESTING : 2D geometry**

IMPLEMENTATION: COMPUTATION OF HYDRODYNAMIC FORCES

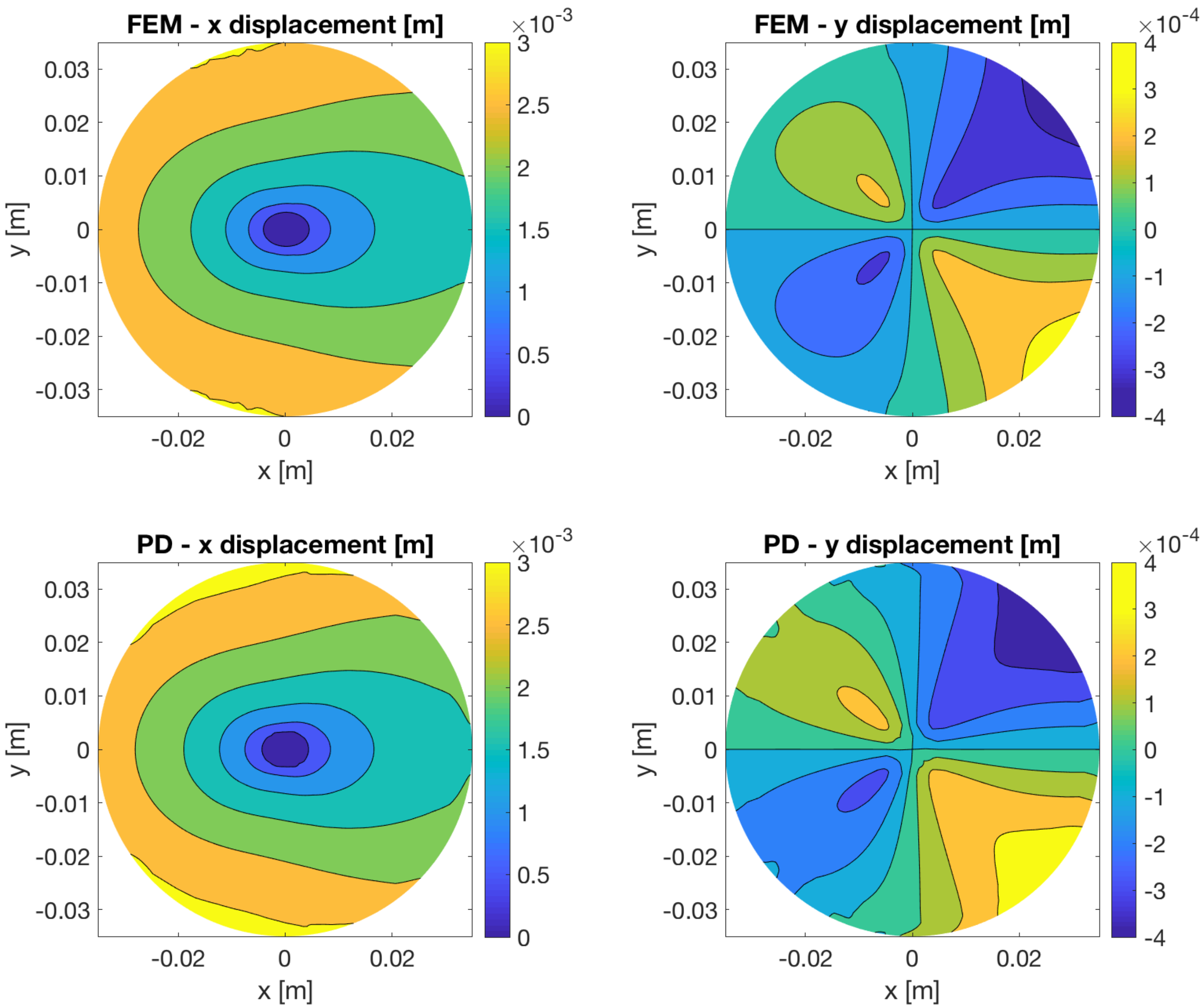
- **In order to compute the force exerted by the liquid phase on the solid the normal probe method is used:**
  - **Surface normal vector is computed for each peridynamic particle located on the interface**
  - **Stress tensor is computed on the Eulerian grid**
  - **Stress tensor components are interpolated at the tip of each normal vector**
  - **Shear and normal stress on the surface are computed via the stress tensor and passed to the peridynamic solver**
  - **Transformation between local (ξ,η) and global coordinate system (x,y) is needed.**





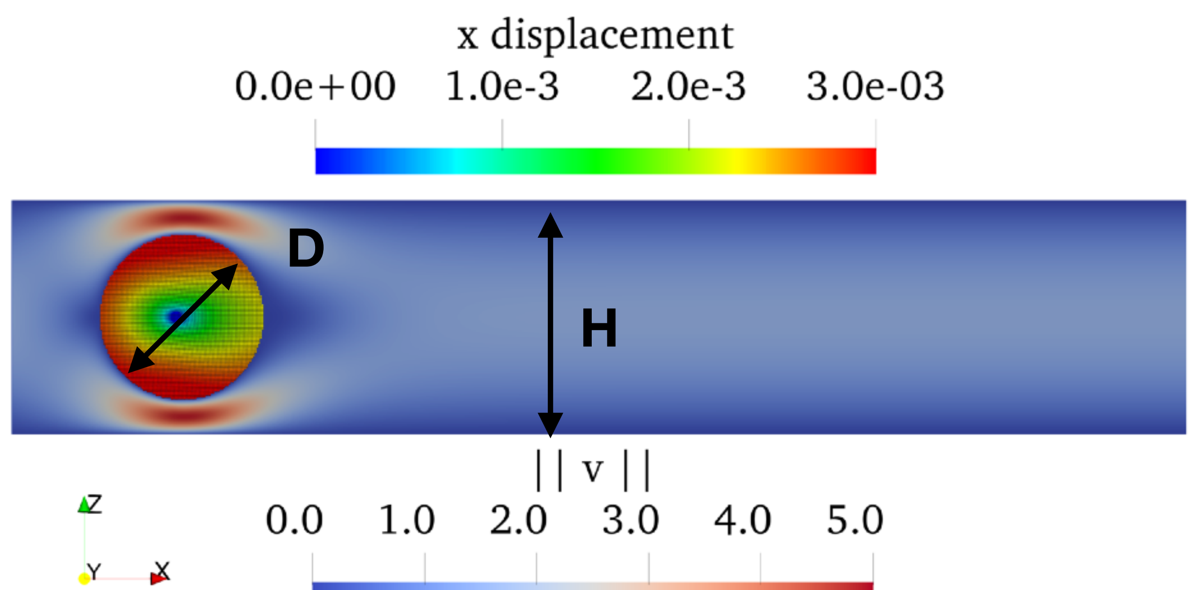
- **Surface normal vectors for a 2D cylinder**

VALIDATION - COMPARATIVE TEST

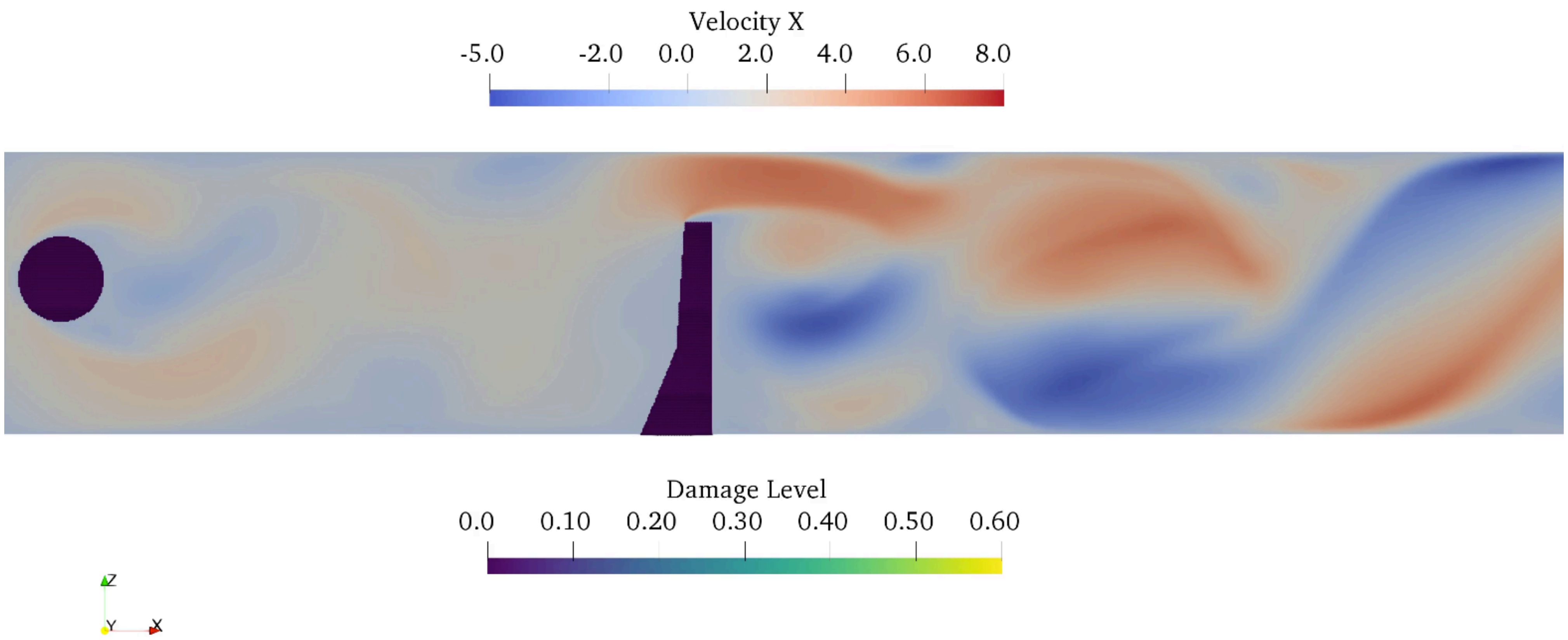


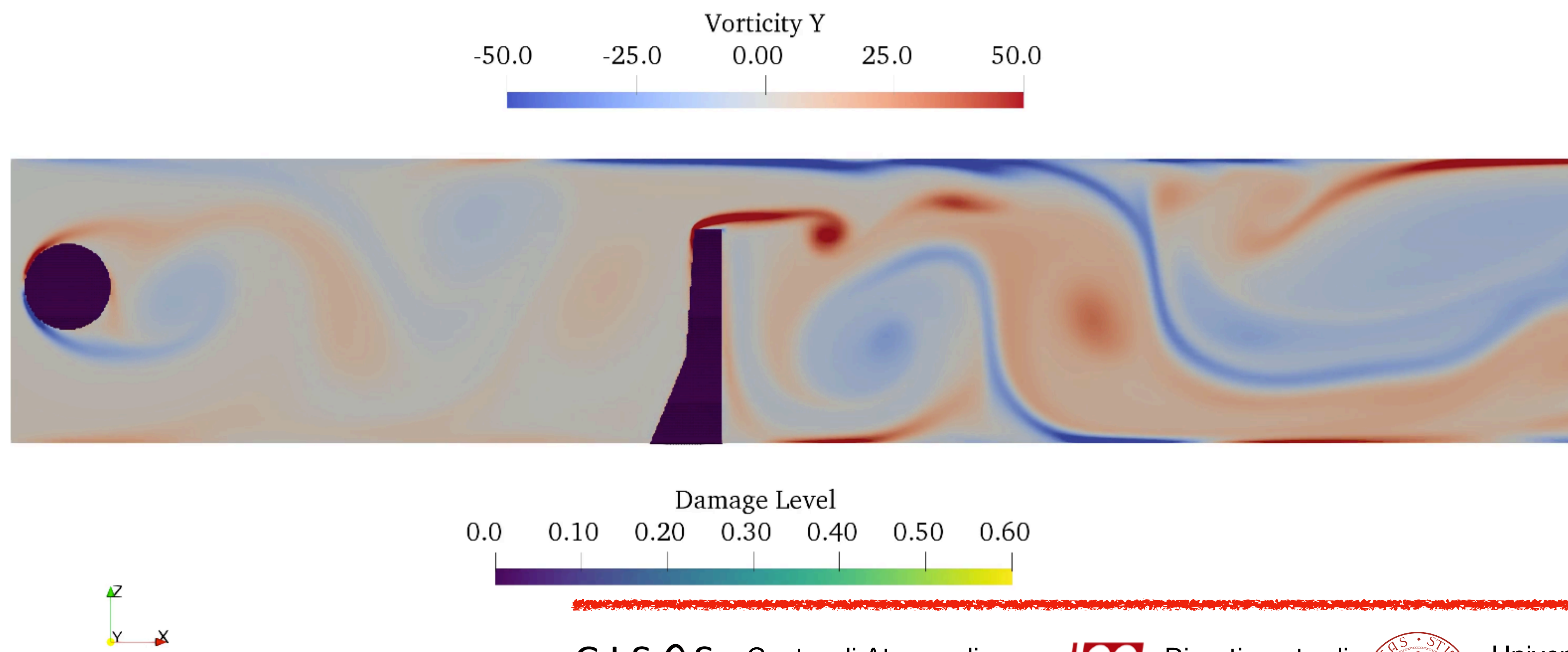
- **Comparison with Ansys Mechanical APDL (Finite Element Method) + Ansys Fluent (upper figures).**

- ## Elastic cylinder in laminar channel flow:
  - **2D laminar flow: $Re_B = 20$**
  - **Inflow-outflow-wall BCs (Poiseuille flow prescribed at inflow)**
  - **7K Lagrangian points**
  - **640 x 128 grid nodes in flow and wall normal directions**
  - **6h x h x 0.2h computational domain in flow, wall normal and span-wise directions**
  - **D/H = 0.7**
  - **E = 10^6 Pa**



TEST CASE: IMPACT IN 2D POISEUILLE FLOW





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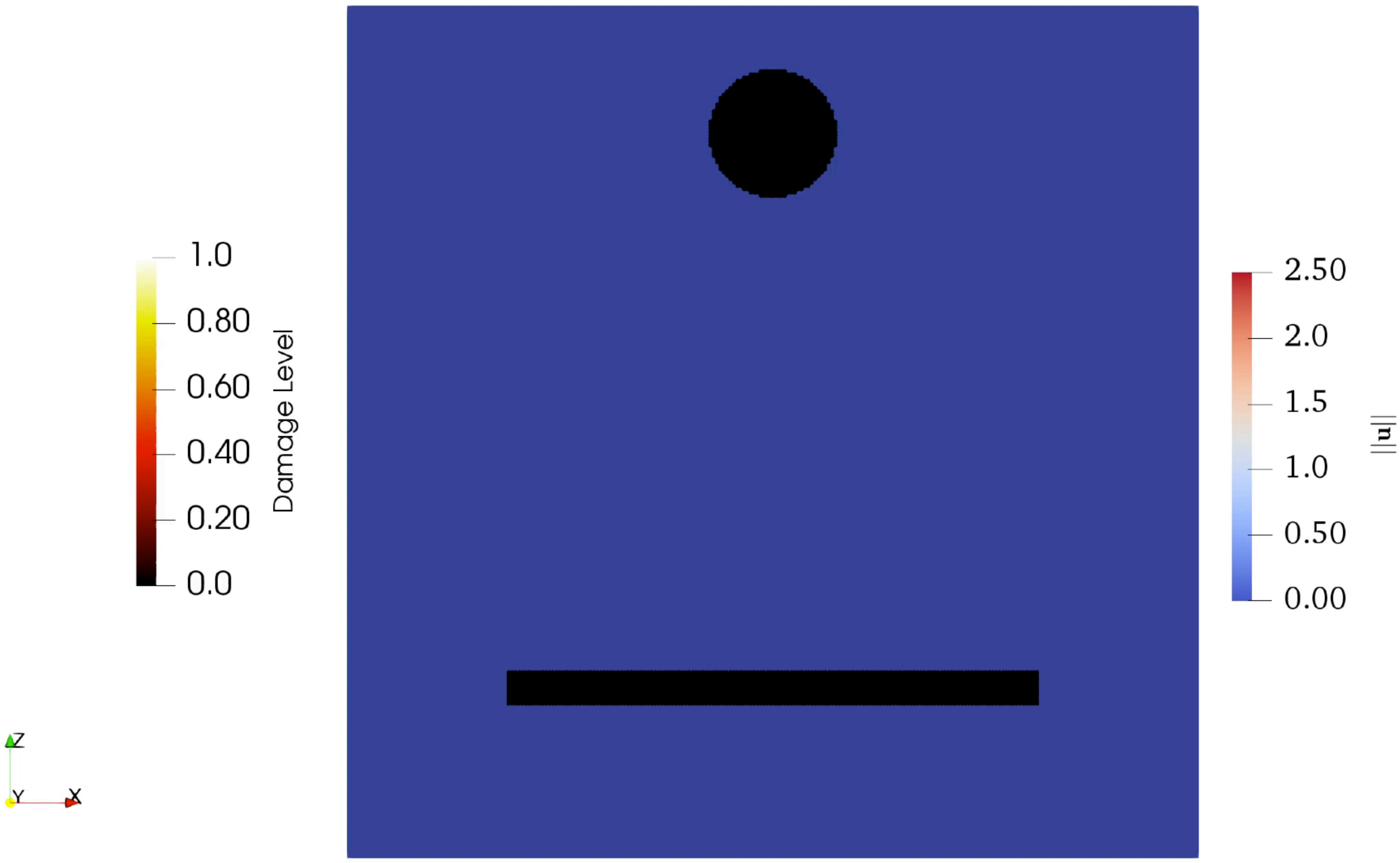
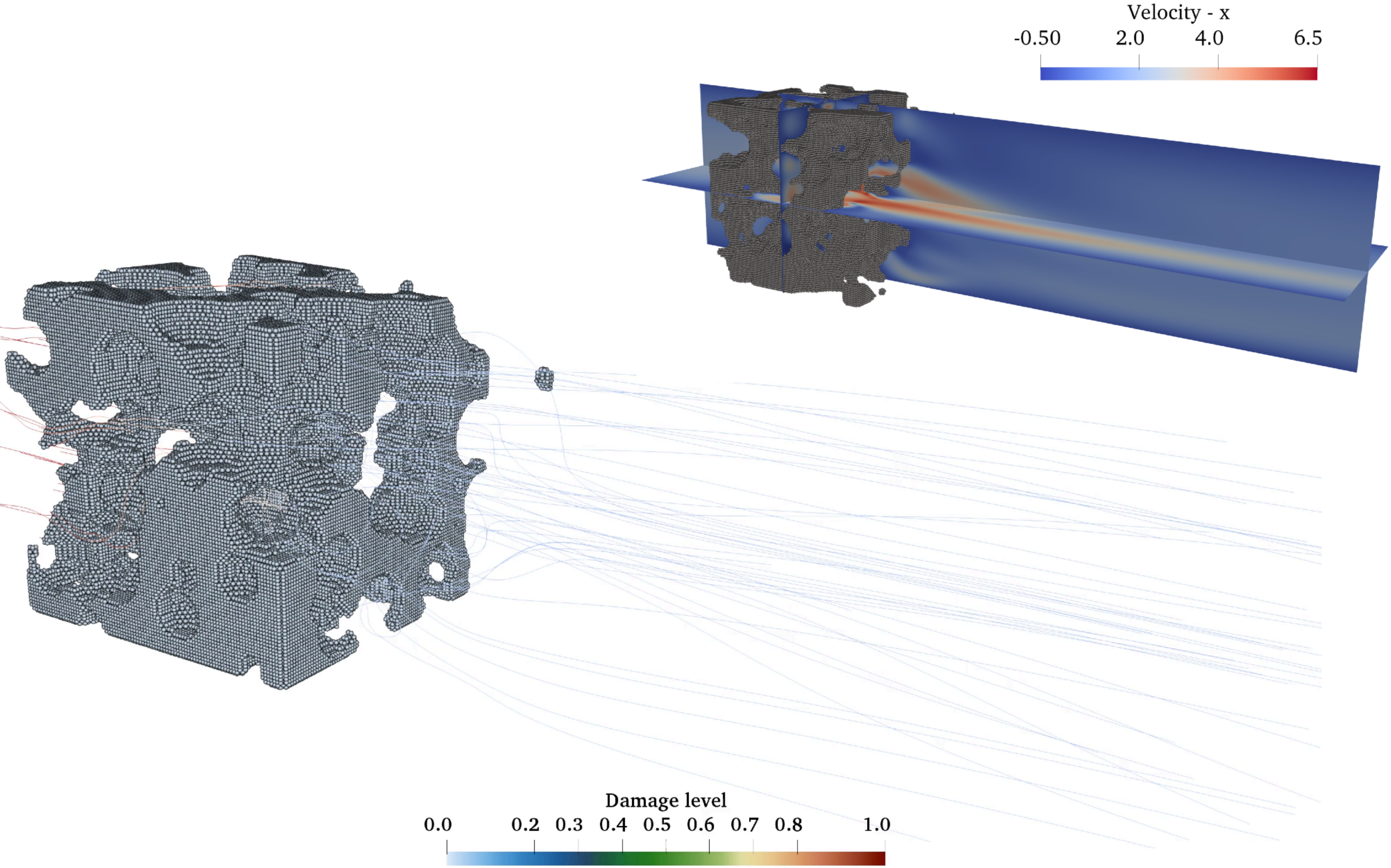
TEST CASE: FALLING SPHERE IN AIR AT REST



TEST CASE: FRACTURE OF POROUS MEDIA IN LAMINAR FLOW



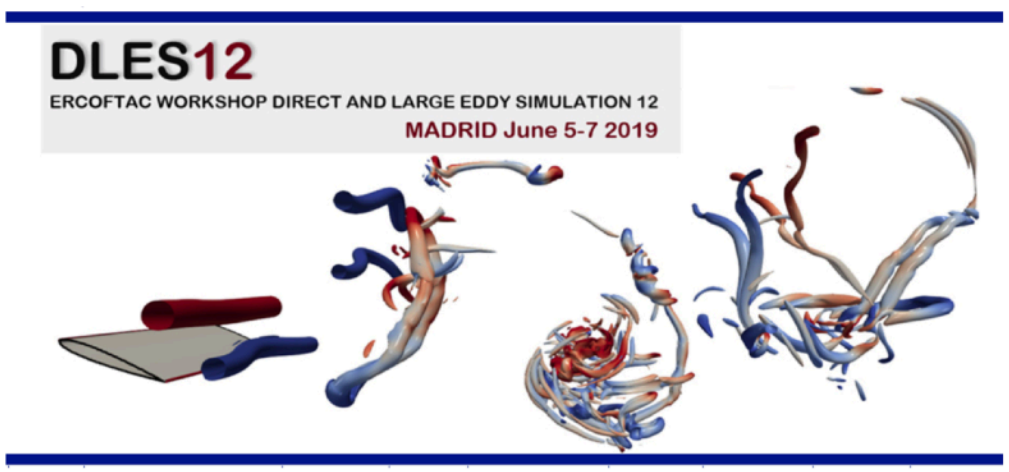
REPORT OF TASKS COMPLETED IN THE SECOND YEAR OF PhD COURSE

- **TASK 1: IMPROVEMENT OF THE COUPLING BETWEEN THE FLUID AND THE SOLID SOLVERS**
  - **Implementation of the normal probe method**
  - **Testing of different coupling strategies**

- **TASK 2: IMPROVEMENT OF THE FLUID SOLVER AND MPI PARALLELIZATION:**
  - **Major modifications required to improve the coupling between the solid and the fluid solver**
  - **Major modifications to improve the performances of the code on distributed memory systems**

- **TASK 3: TESTING CAMPAIGN FOR THE NEW SOLVER**
  - **Porous media fracture: simulation of the break up of a porous media using more than 1024 cores on Marconi cluster at Cineca**
  - **Impact of solid objects in incompressible flows**

- **TASK 4: Presentation at Direct and Large Eddy Simulation (DLES12) Madrid. The abstract has been selected for the Special Issue of FTaC, to comprise around 15 papers, selected from a total of the 108 papers that were presented orally at DLES12.**



- **TASK 5: Writing of a journal paper (work in progress)**

THANK YOU FOR YOUR ATTENTION!