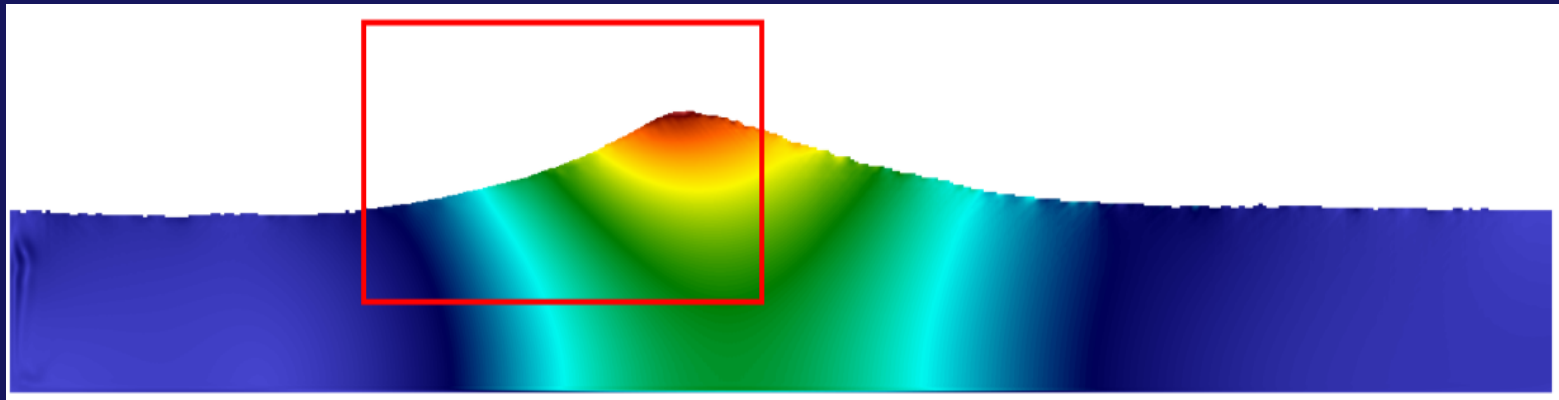


Marine 2017

*GPU-Accelerated LBM-VOF Two-Phase Flow Simulations with Grid Refinement*



M. Gehrke, D. Mierke, C.F. Janßen and T. Rung

Monday, May 15<sup>th</sup> 2017

*Fluid Dynamics  
and  
Ship Theory*

**TUHH**

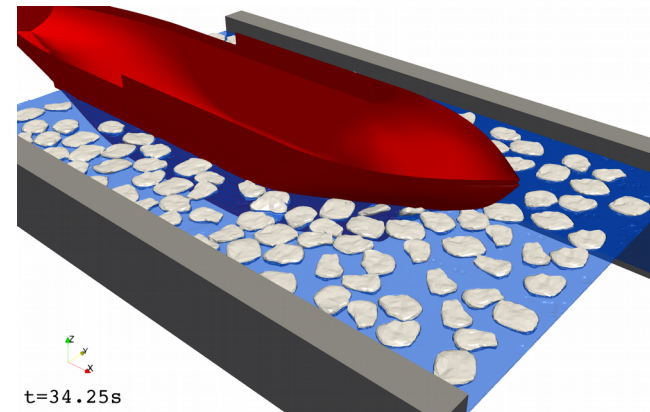
- **Introduction**
- **Theory**
  - Lattice Boltzmann Method
  - Volume of Fluid Interface Capturing Method
  - Grid Refinement Scheme for LBM
- **Validation / Application**
- **Summary and Outlook**

- **ProEis Research Project**

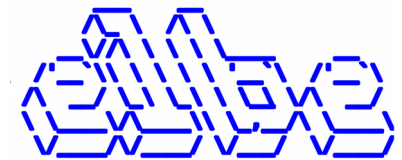
- Development of a numerical ice tank
- D. Mierke *et al.* (Tuesday, 16<sup>th</sup>)

*Validation of a GPU-accelerated  
fully viscous numerical ice tank*

- Implementation of a grid refinement technique is one of the main parts of the project



- **elbe “efficient lattice Boltzmann environment”**



- GPU accelerated Solver for singlephase and free surface flows
- Involving fluid structure interaction (rigid bodies, coupled to ODE)

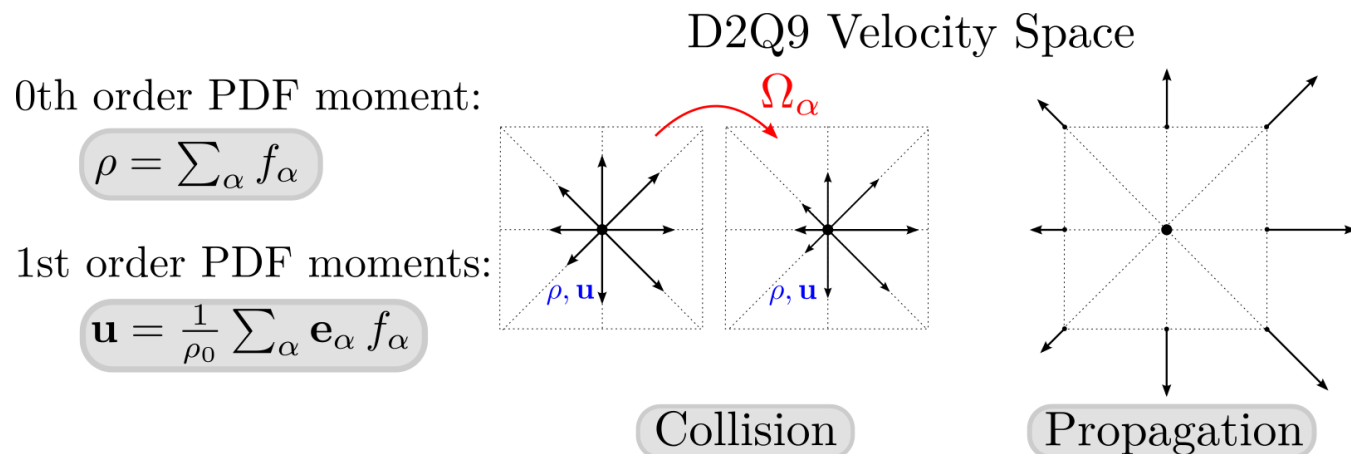
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# Lattice Boltzmann Method – Mesoscopic Methods

- **Lattice Boltzmann equation (LBE) → PDF**

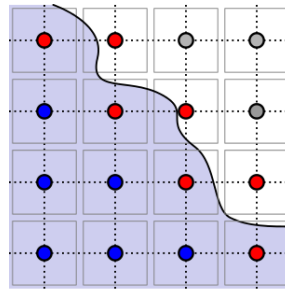
$$f_{\alpha}(t + \Delta t, \mathbf{x} + \Delta t \mathbf{e}_{\alpha}) - f_{\alpha}(t, \mathbf{x}) = \Omega_{\alpha}$$

- Left-hand side : transient change and particle advection
  - Right-hand side: models the particle interaction
- **Strictly local collision step → well suited for GPU acceleration**



# Volume of Fluid – Interface Capturing Method

- Immiscible Two-Phase flows dominated by denser phase
- Lighter phase imposed by free surface BC
- Additional phase field for mixture fraction (fill level) variable



- $\epsilon = 1$  : Fluid node
- $0 < \epsilon < 1$  : Interface node
- $\epsilon = 0$  : Gas node

$$\epsilon^{t+1} = \frac{m^{t+1}}{\rho^{t+1}} = \frac{\rho^t \epsilon^t + \sum_i \Delta m_i}{\rho^{t+1}}$$

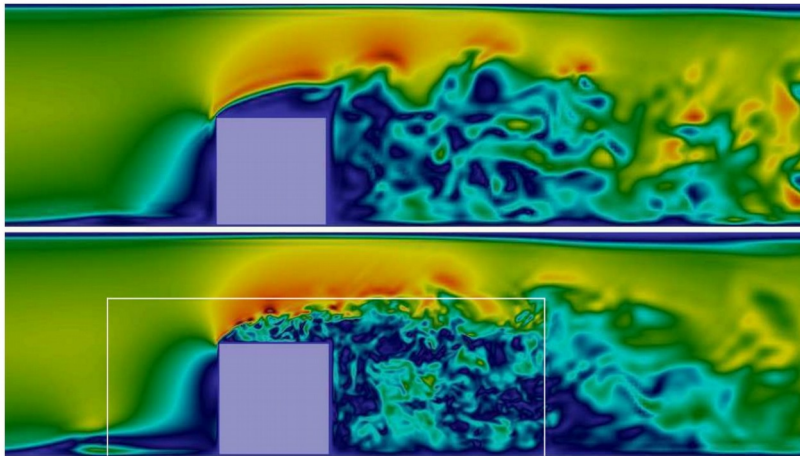
$$\Delta m_i = \Delta t A_i (f_I(t, \mathbf{x}) - f_i(t, \mathbf{x}))$$

$$A_i = \begin{cases} 1 & \text{Fluid Neighbor,} \\ \frac{\epsilon(t, \mathbf{x}) + \epsilon(t, \mathbf{x} + \Delta t \mathbf{e}_i)}{2} & \text{Interface Neighbor,} \\ 0 & \text{Gas or Obstacle Neighbor.} \end{cases}$$

- Free surface resp. Interface must be kept sharp / closed
- LBM VoF advection scheme  $\rightarrow$  mass flux based on PDFs

# Motivation – Grid Refinement

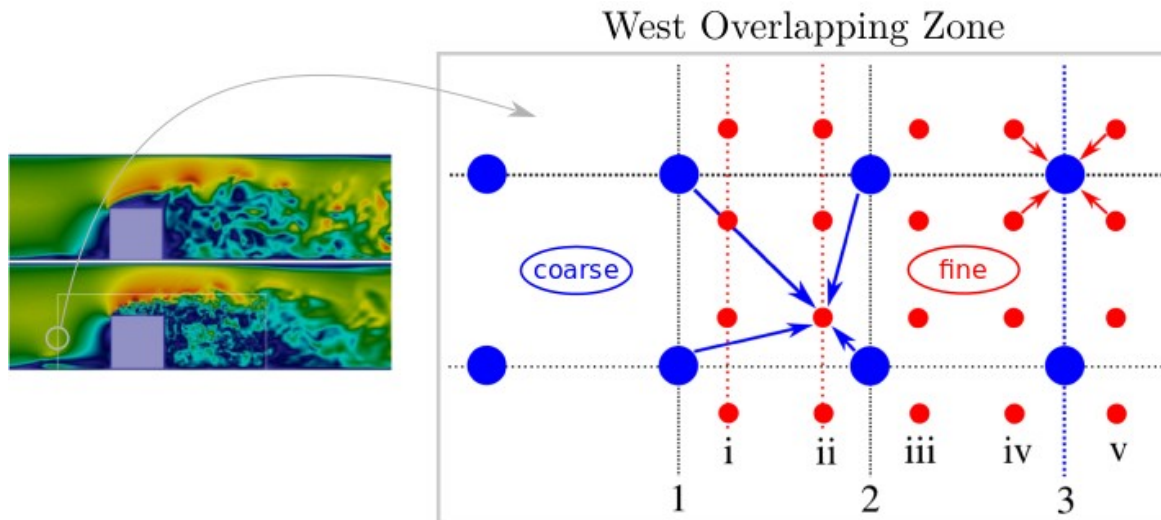
- **LBM implementations are mostly based on homogeneous isotropic Cartesian grids**
- **Local grid refinement is deployed to regions featuring small scale structures**
- **Within the LBM, the spatial and temporal discretizations are strongly coupled**



Slice (velocity magnitude) through the 3D fully turbulent flow around a surface mounted cube

# Grid Refinement – LBM-specific variables

- **Overlapping grids**
  - Bidirectional information exchange between the grids via bi-linear interpolations of the PDFs
  - Synchronization Step after each completed coarse grid time step  $\rightarrow$  2 x Collision + Propagation on the fine grid



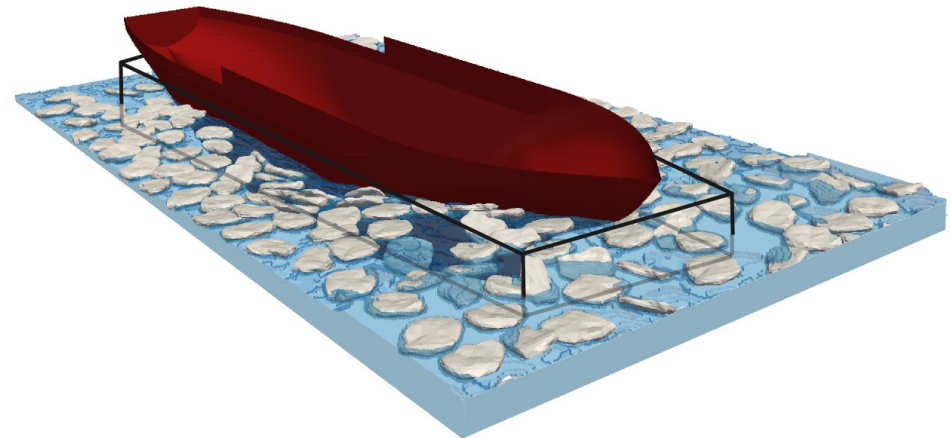
# Motivation – Grid Refinement for Free Surface Flows



- **Goal (Research Project):**

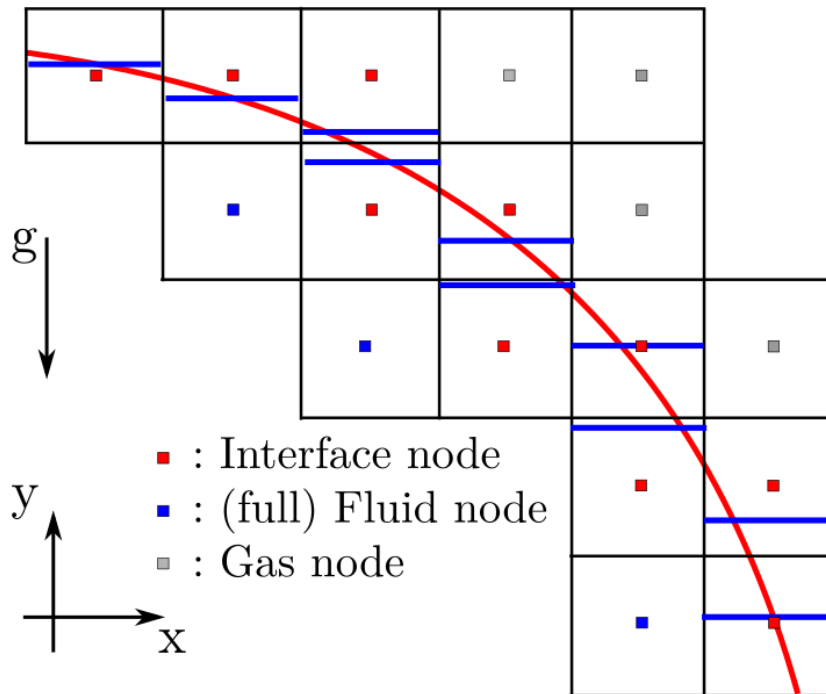
- Locally refined volume surrounding the ship's hull and / or ice floes
- Increase accuracy under the condition of a reasonable computational effort (comp. time and memory consumption)

- **For FS flows the inter-grid coupling of the mixture fraction poses a special algorithmic problem**



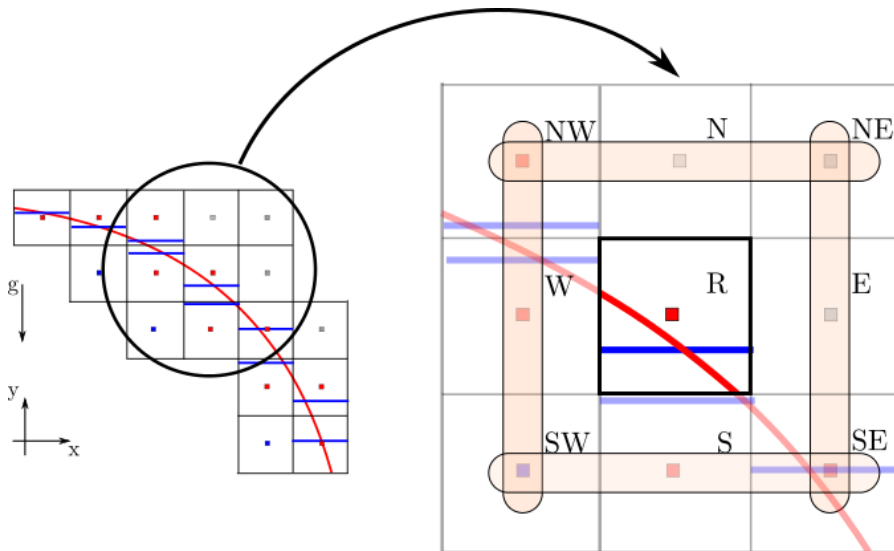
# VoF – Surface Orientation

- **Standard VoF holds no information of the free surface orientation**



- **Simple “gravity based” VoF Information**
  - Cells filled from the bottom
  - Surface normal coincides with y-axis (constant)
  - Discontinuous surface

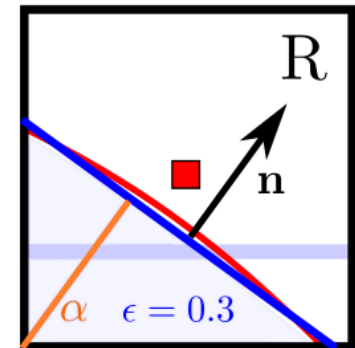
- **PLIC – Piecewise Linear Interface (Re-) Construction**
  - Node based approach



- : Interface node
- : (full) Fluid node
- : Gas node

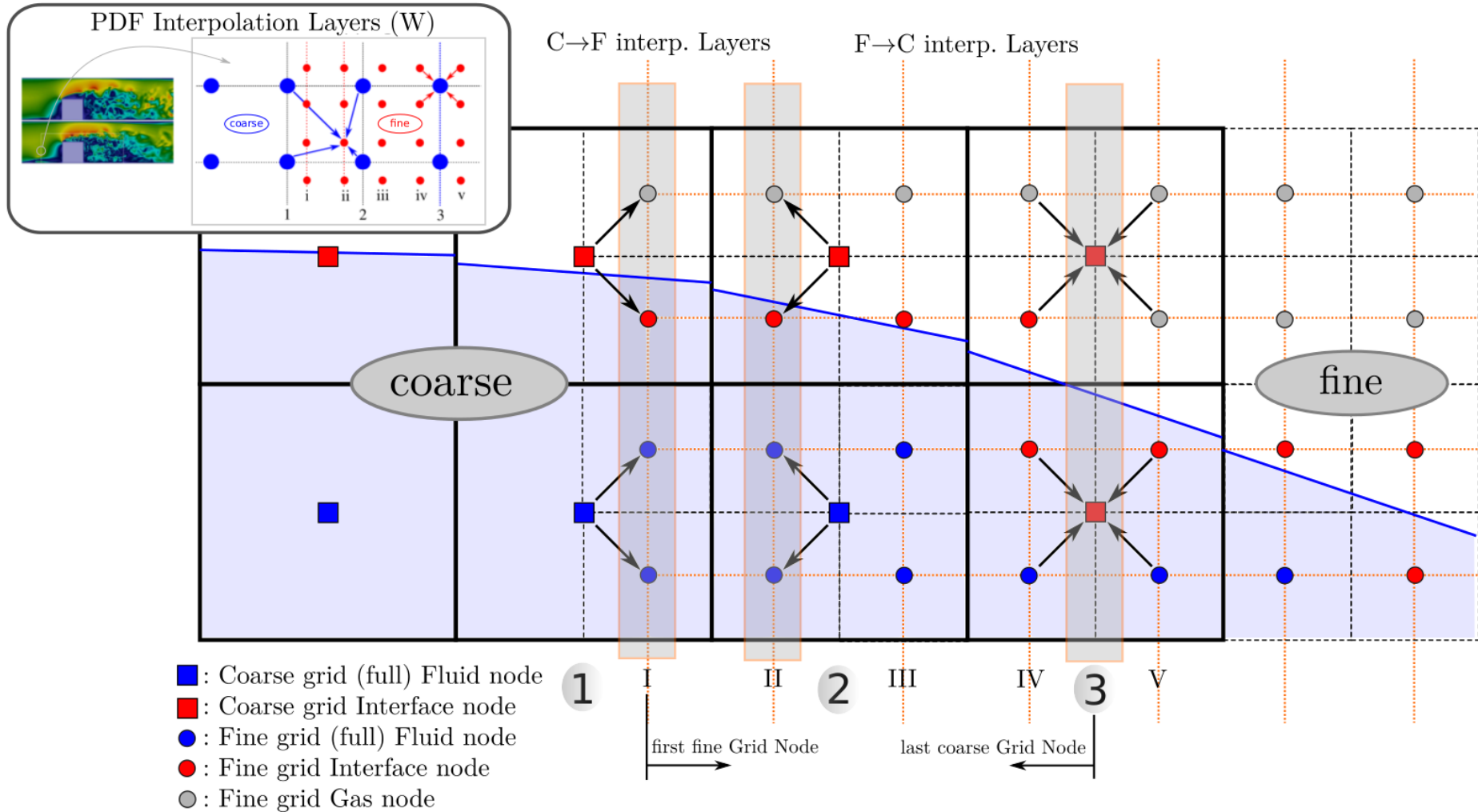
$$\begin{aligned}\epsilon_0 &= \epsilon(SE) + 2\epsilon(E) + \epsilon(NE) \\ \epsilon_1 &= \epsilon(SW) + 2\epsilon(W) + \epsilon(NW) \\ \epsilon_2 &= \epsilon(NW) + 2\epsilon(N) + \epsilon(NE) \\ \epsilon_3 &= \epsilon(SW) + 2\epsilon(S) + \epsilon(SE)\end{aligned}$$

$$\begin{aligned}\nabla\epsilon &= \frac{1}{2} \begin{pmatrix} \epsilon_0 - \epsilon_1 \\ \epsilon_2 - \epsilon_3 \end{pmatrix} \\ \mathbf{n} &= -\frac{\nabla\epsilon}{|\nabla\epsilon|}\end{aligned}$$



- $\epsilon$  : mixture volume fraction
- $\mathbf{n}$  : PLIC surface normal
- $\alpha$  : plane coefficient
- $\rightarrow \alpha = \alpha(\epsilon, \mathbf{n})$

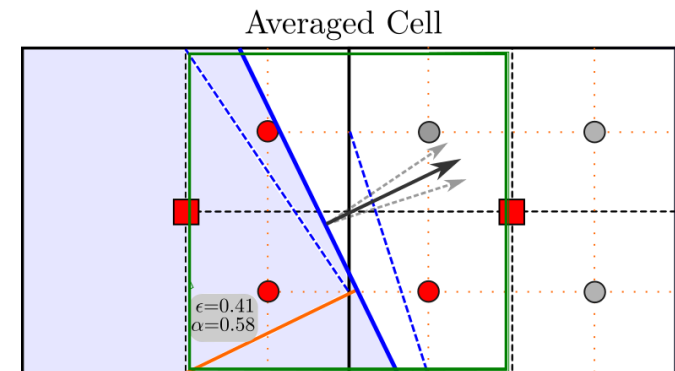
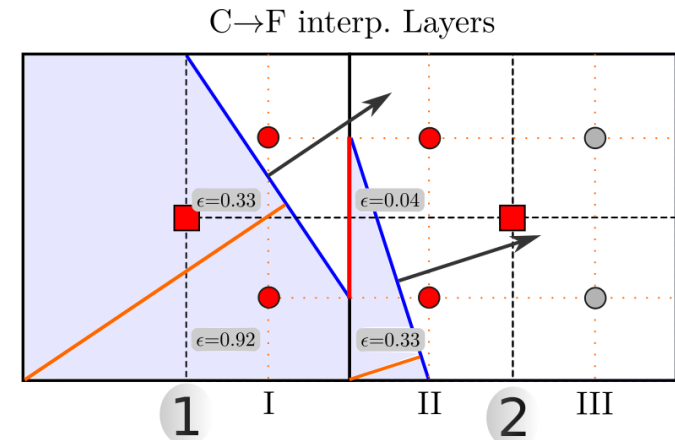
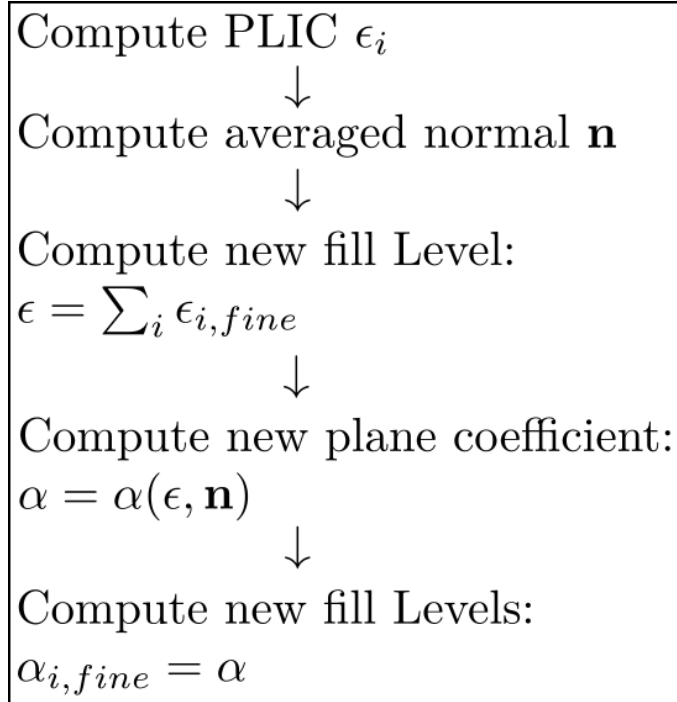
# Free Surface inter-grid coupling



# Interface Sharpening

- **Irregular Interface configurations**

- Introduce “*Averaged cell*” composed of 2 coarse grid cells



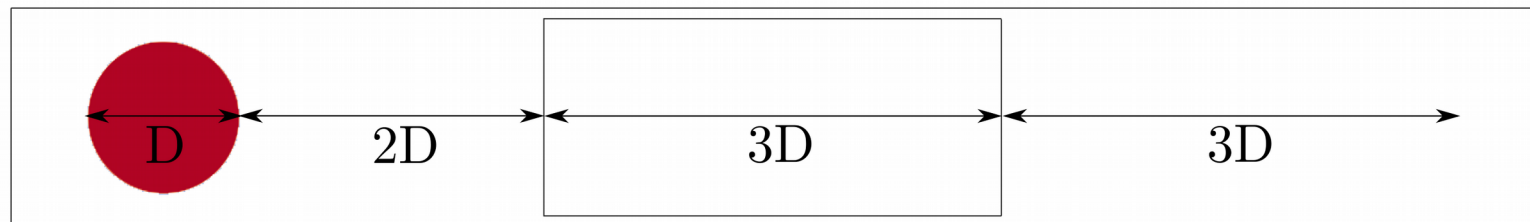
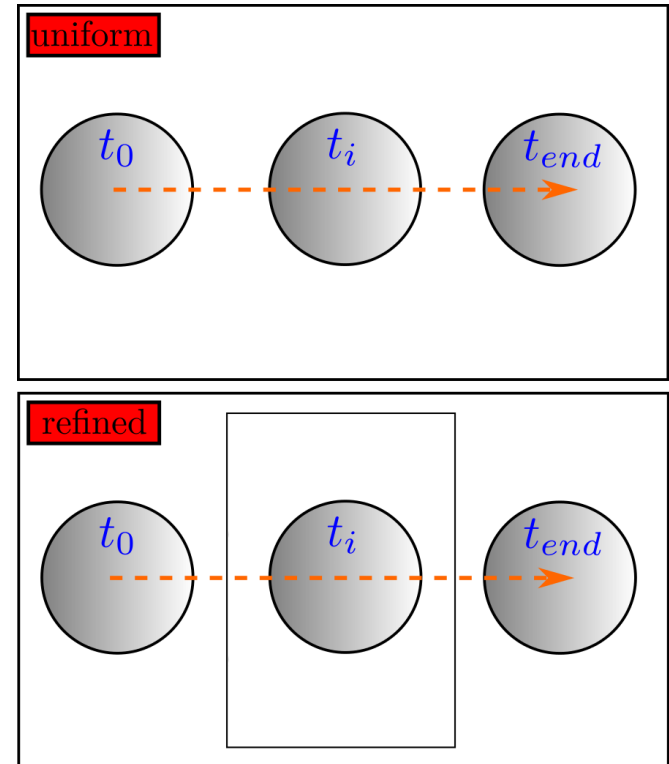
- : Coarse grid Interface node
- : Fine grid (full) Fluid node
- : Fine grid Interface node
- : Fine grid Gas node

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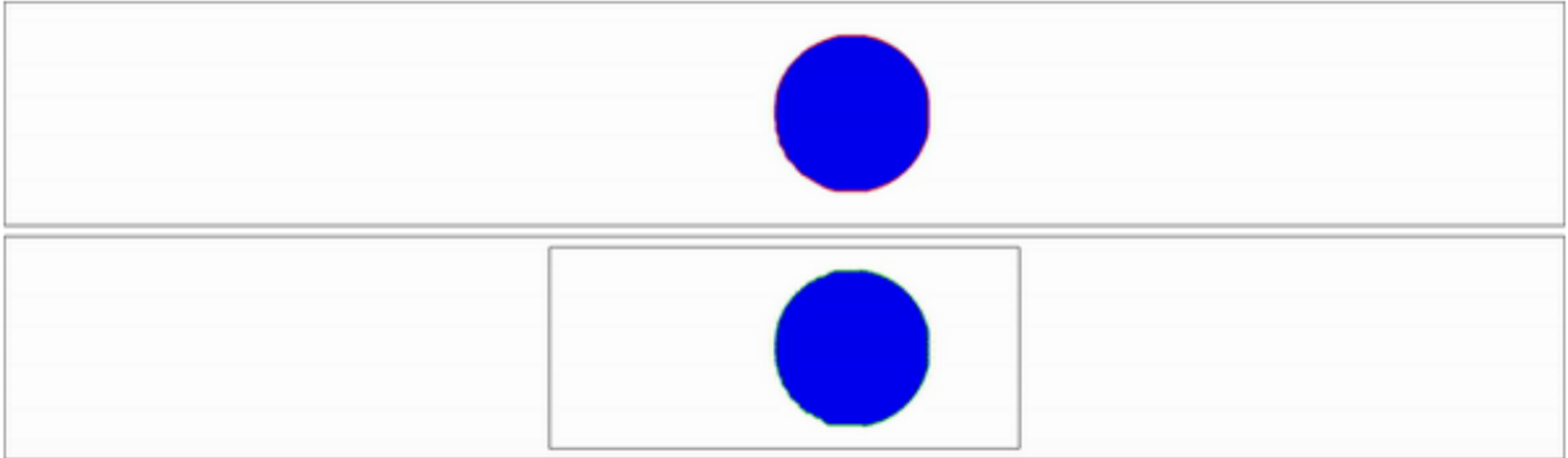
# Basic Validation: Drop Test Case

- **Test Case Description**

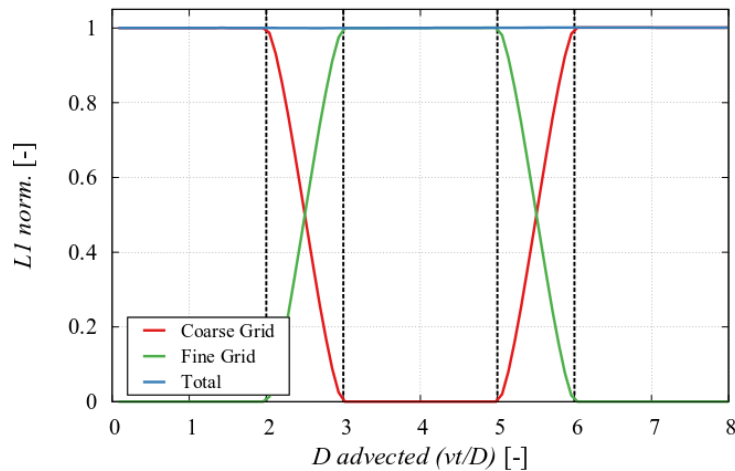
- Pure advection test case without solving the flow field
  - Prescribe velocity field
  - Initialize with PLIC information
- Advect circle (D) through domain



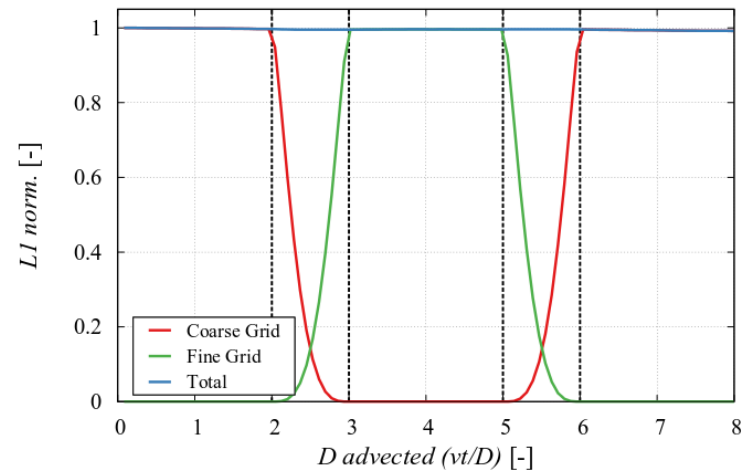
# Basic Validation: Drop Test Case – Time Series



Mass distribution on coarse and fine Grid



$I_x = \sum_i \epsilon (x_i - \text{cog}_{actual,i})^2$  Inertia x-component combined



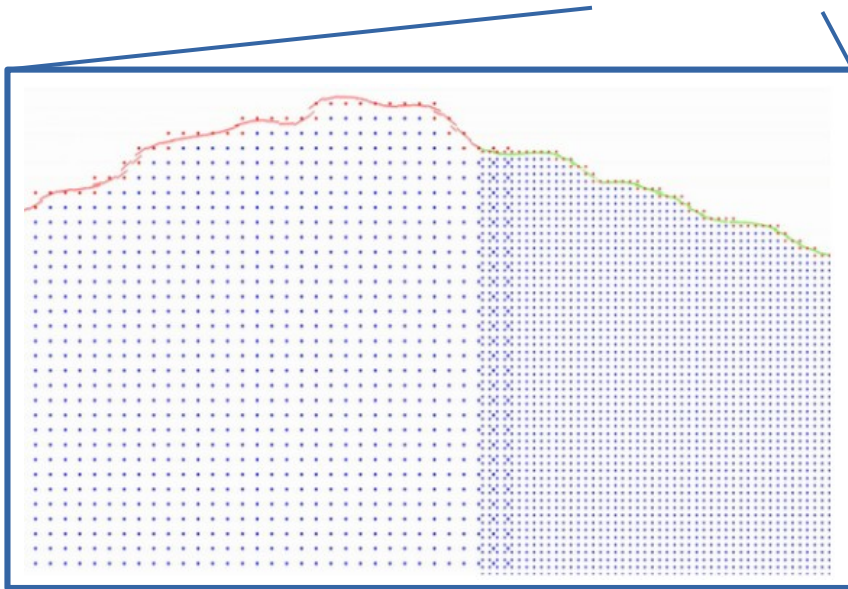
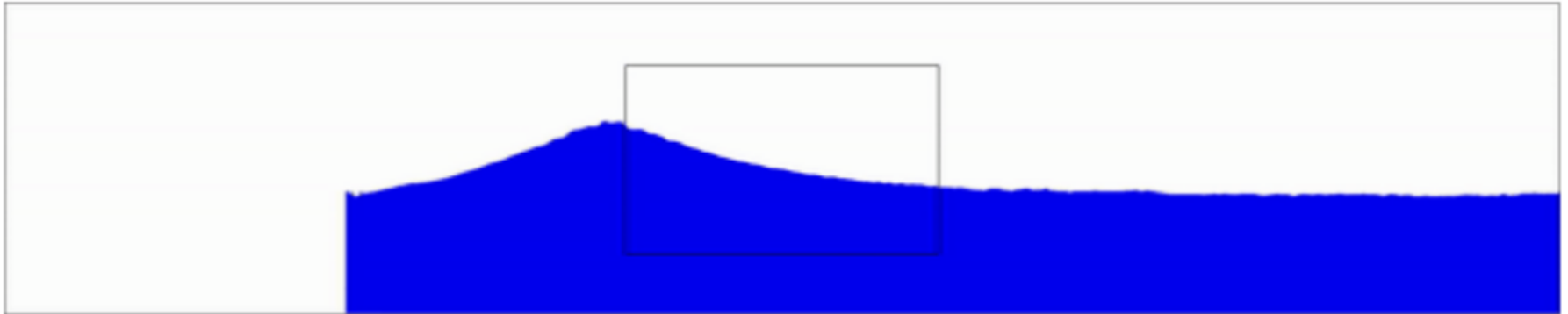
# Application: Wave Tank Test Case

- **Simulation of a solitary wave**
  - Moving obstacle as wave generator presets the waves specifications / characteristics
  - Outlet: Pressure boundary condition based on hydrostatic pressure
  - LBM collision included: full flow field solution



# Application: Wave Tank – Overlapping Detail

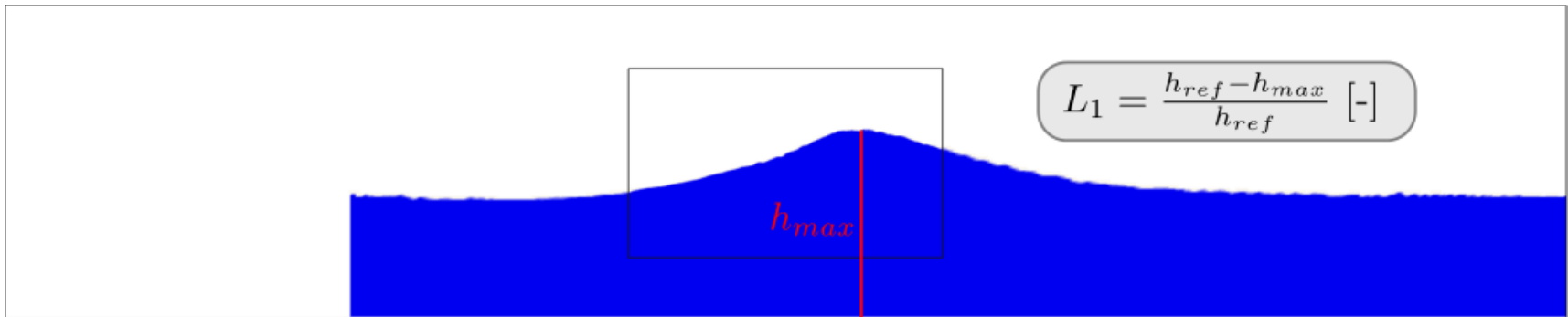
- Fine grid outlined



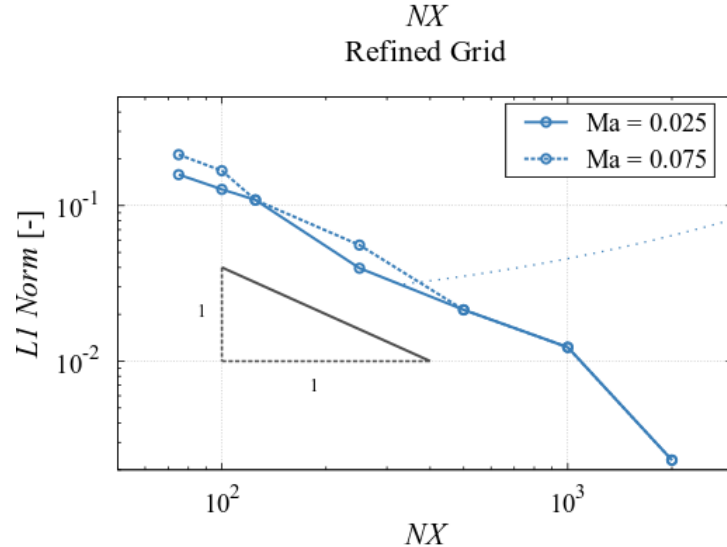
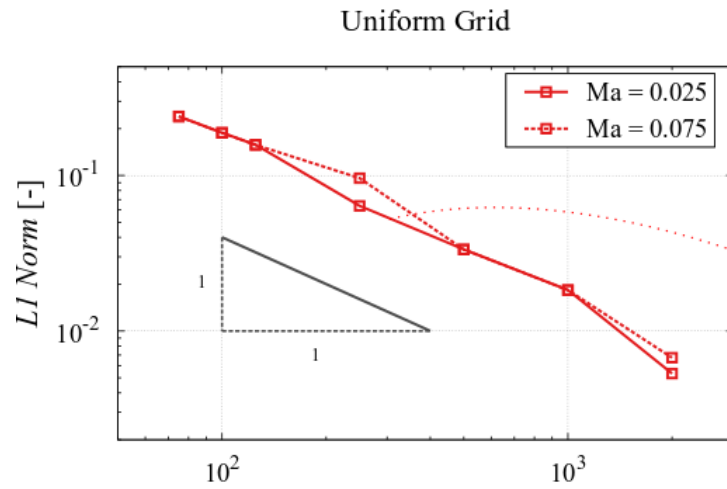
- **West Overlapping Detail**
  - Red dots: Interface nodes
  - Red Line: PLIC **coarse**
  - green Line: PLIC **fine**
- **Smooth grid transition**

# Wave Tank Test Case – Evaluation

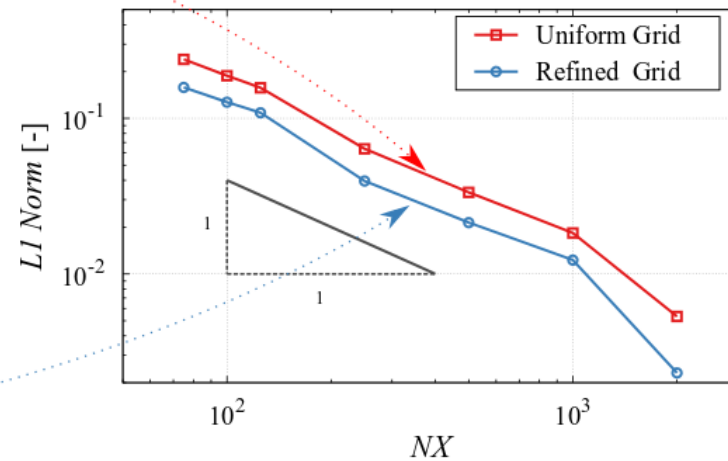
- **Quantify deviation of coarse and fine grid simulation**
  - Compute L1 Norm of maximum wave elevation at fixed time step (60% of the overall simulation time)
  - Quantify amplitude error, phase error not considered so far



# Wavetank Testcase – L1 Error Norm



L1 Norm Uniform vs. Refined for  $Ma = 0.025$



- **Fine grid simulation leads to overall lower L1 error**

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- **Summary**
  - Introduced a novel LBM grid refinement scheme for free surface flows based on PLIC
  - Validated based on two underlying test cases
- **Ongoing and future work**
  - Extension to the FS 3D module + validation
  - Objects (e.g. ice floes) can be located in grids with different refinement levels (has to be considered in the integration of fluid loads and the floe advection)
  - Enable moving refined grids for free surface flows