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computational modeling  
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# NON-UNIFORM LB SIMULATIONS ON GPUS

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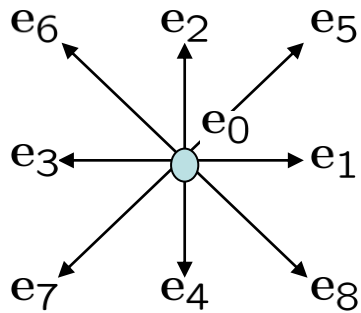
# Outline

- Lattice Boltzmann models
- General Purpose Graphics Processing Unit (GPGPU)
- Multiscale Method
- 2D non-uniform with high Re-Numbers
- 3D non-uniform
- LB on 96 GPGPUs
- Conclusions

# Lattice Boltzmann Equation (LBE)

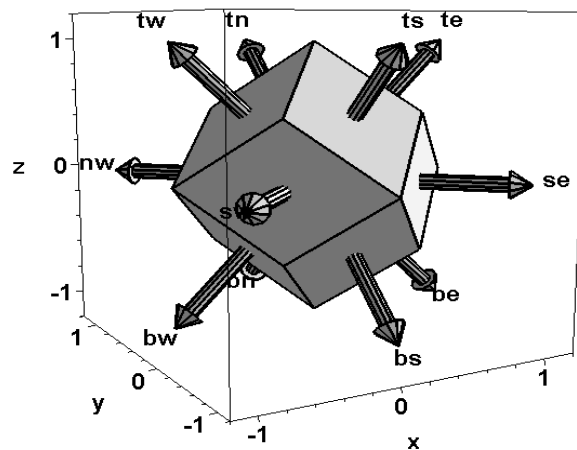
$$f_i(t + \Delta t, \mathbf{x} + \mathbf{e}_i \Delta t) = f_i(t, \mathbf{x}) + \Omega_i, \quad i = 0, \dots, b-1$$

- f      Mass fractions
- e      Microscopic velocity of the particles
- t      Time
- x      Space



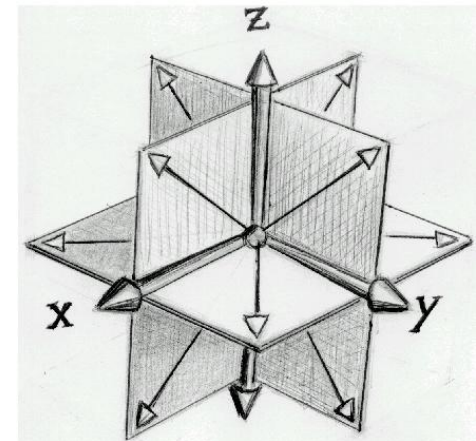
d2q9-Model

*Qian 92*



d3q13-Model

*d'Humieres 01*



d3q19-Model

*Qian 92*

# General Purpose Graphics Processing Unit (GPGPU)

- 30 multiprocessors with 8 processors each = 240 Processors
- Cores running at 1,3 GHz
- 4 GB device memory
- Memory bandwidth = 102 GB/sec
- 933 GFlops of theoretical single precision floating point performance (NVIDIA)
- CUDA –SDK



# Multiscale Lattice Boltzmann Method

## Motivation:

The lattice Boltzmann method: Cartesian grid

Standard approach: uniform resolution

regions with low dynamics as expensive as regions with strong dynamics

variable grid resolution required

## Solution:

Coupling of Cartesian domains with different resolution

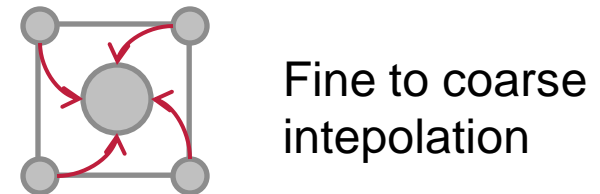
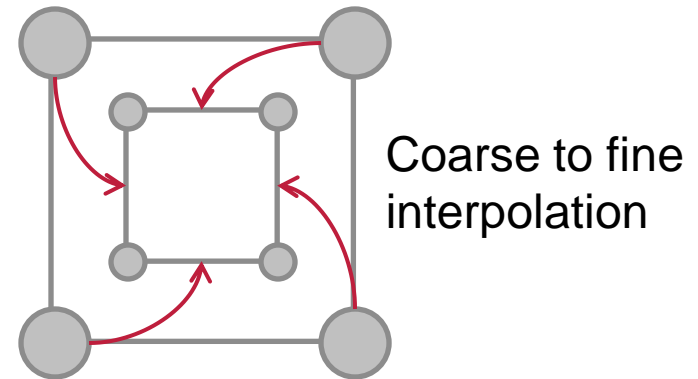
# Multiscale Lattice Boltzmann Method

Compact second order interpolation:

Shear rate known at nodes  
=> extra information on gradients of momentum

No time interpolation required

no special treatment of corners / edges






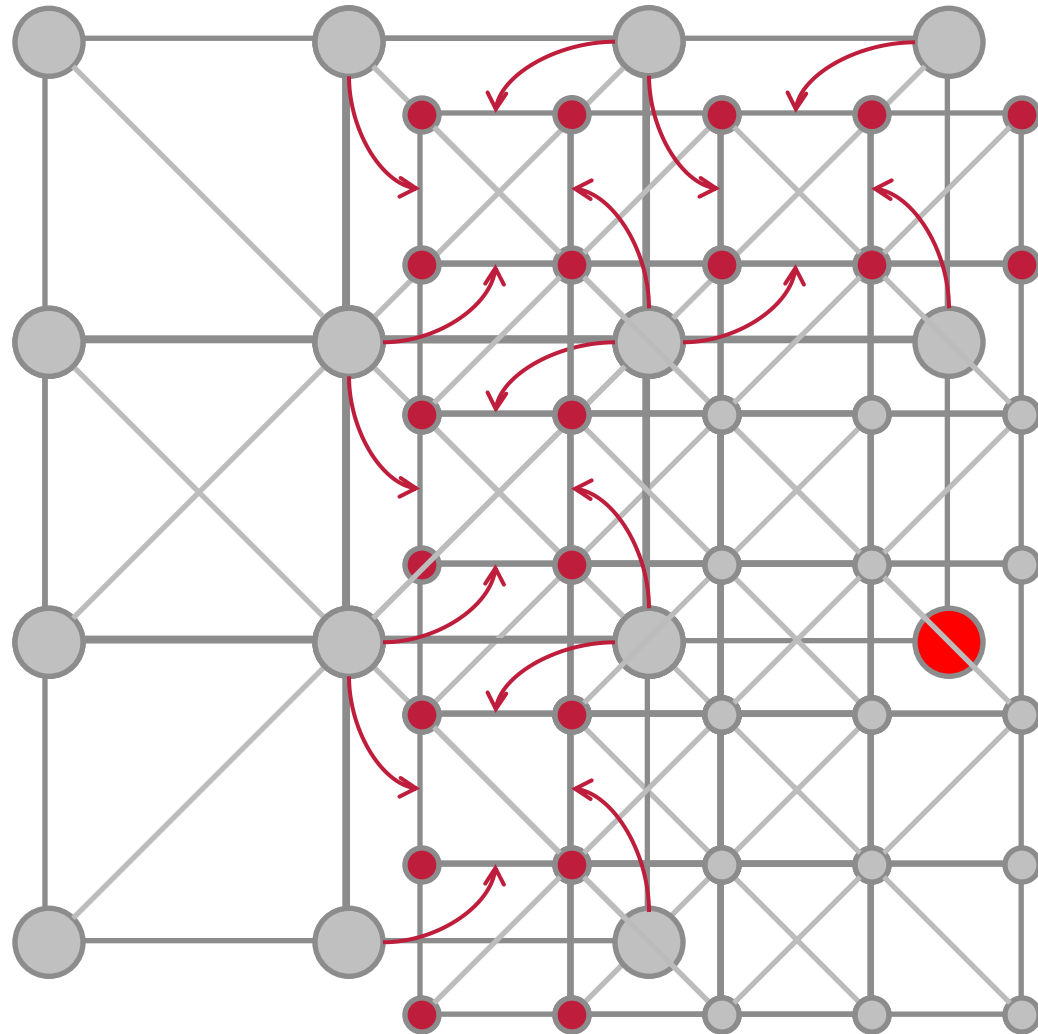
Geier, Greiner and Korvink 2009

# Multiscale Lattice Boltzmann Method

Interface condition:

Step 1: synchronization  
coarse to fine



-  Standard node
-  Interface node invalid
-  Interface node valid

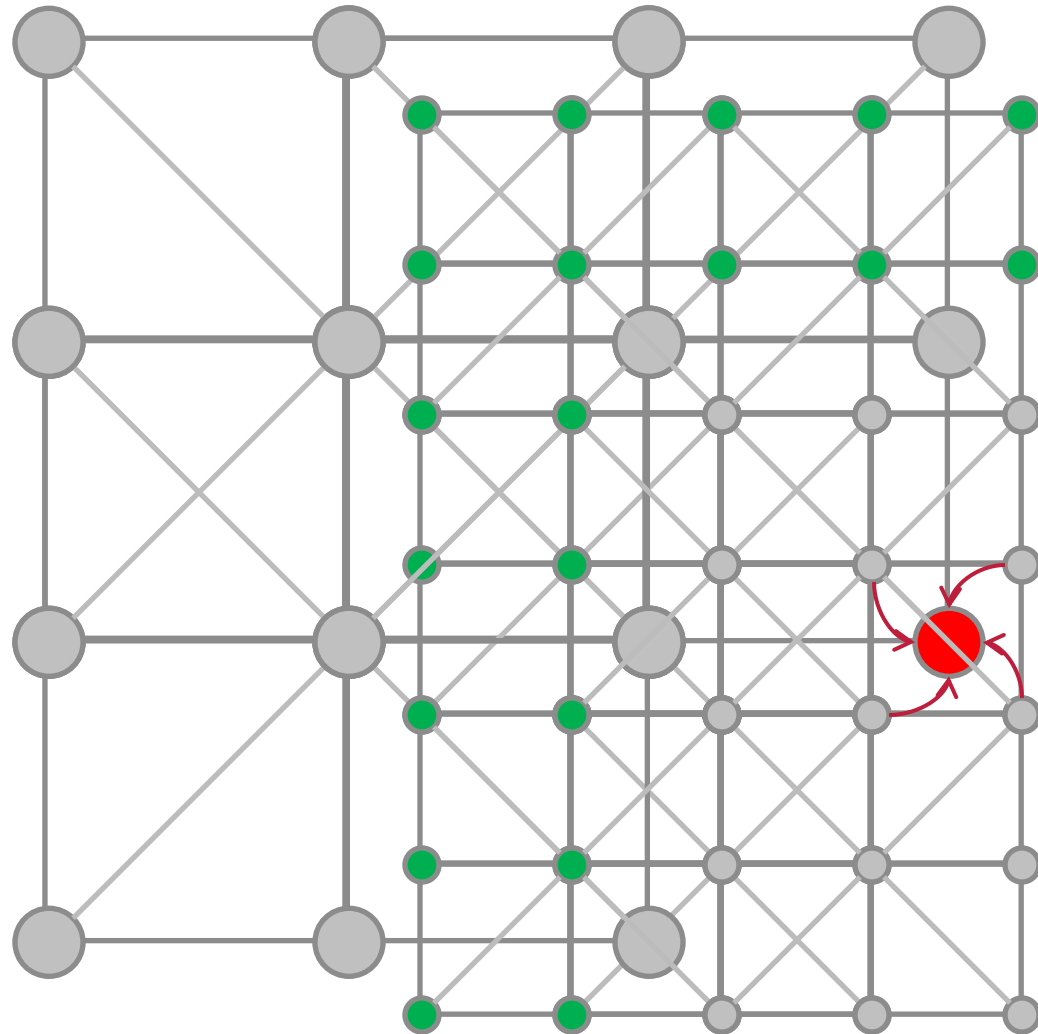


# Multiscale Lattice Boltzmann Method

Interface condition:

Step 2: synchronization  
fine to coarse


-  Standard node
-  Interface node invalid
-  Interface node valid

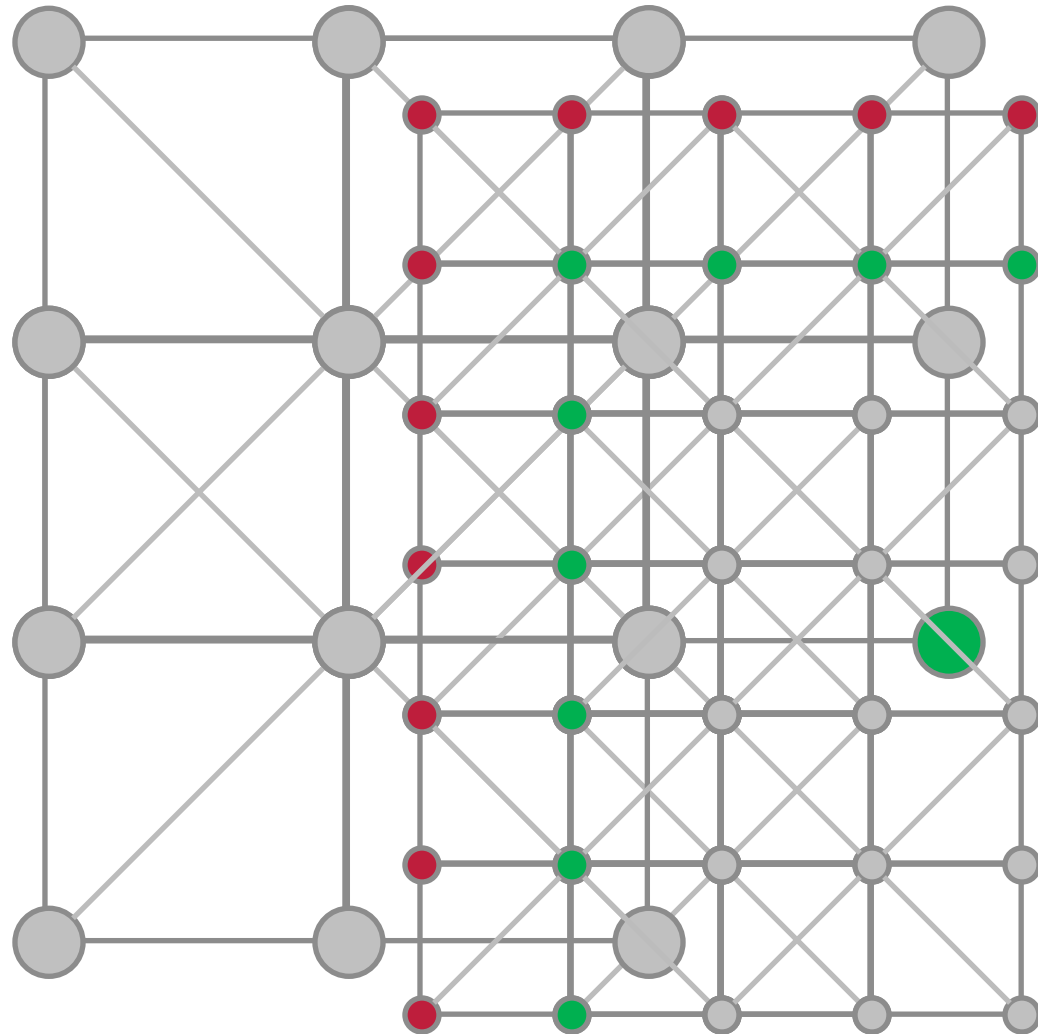


# Multiscale Lattice Boltzmann Method

## Interface condition:

Step 3: asynchronous time  
step on fine grid  
Boundary nodes become  
invalid




-  Standard node
-  Interface node invalid
-  Interface node valid

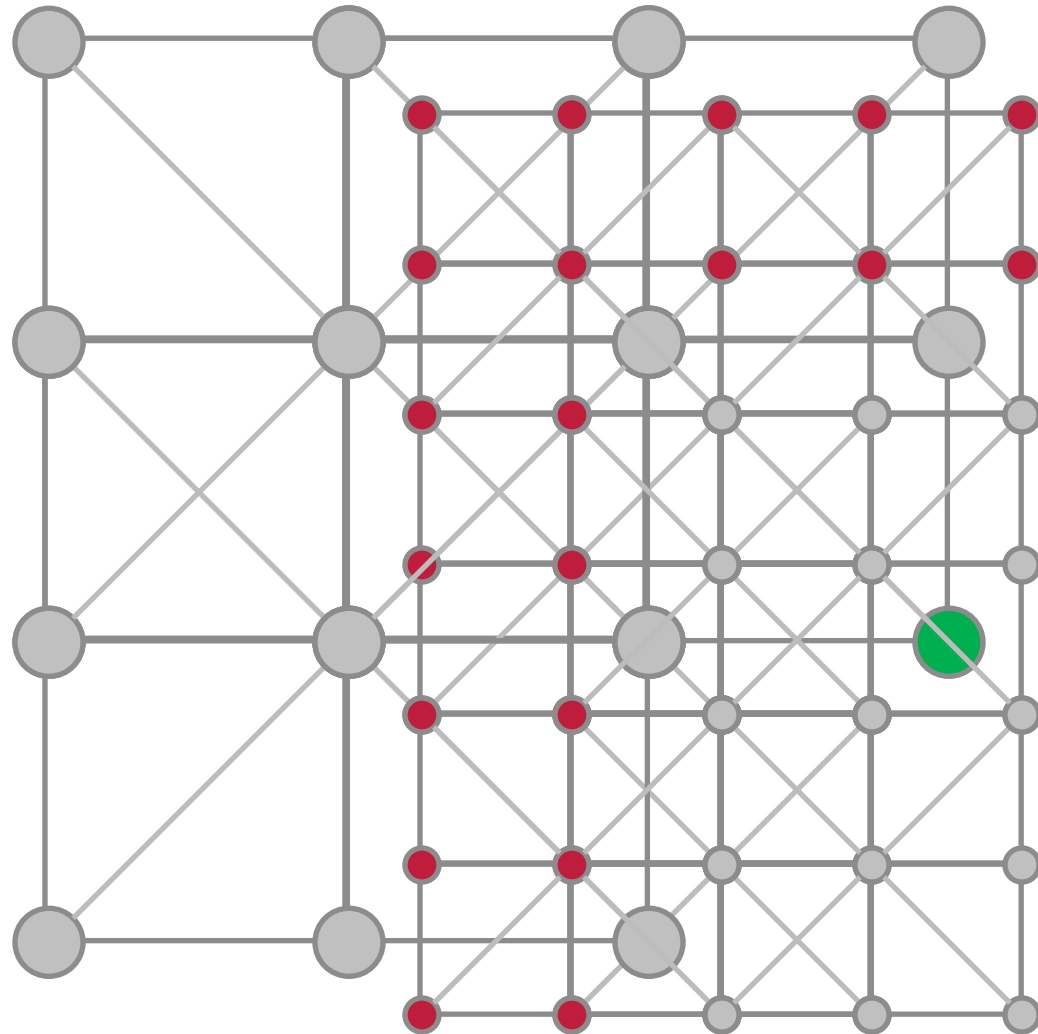


# Multiscale Lattice Boltzmann Method

## Interface condition:

Step 4: synchronous time step on fine grid  
Next layer of nodes become invalid




-  Standard node
-  Interface node invalid
-  Interface node valid

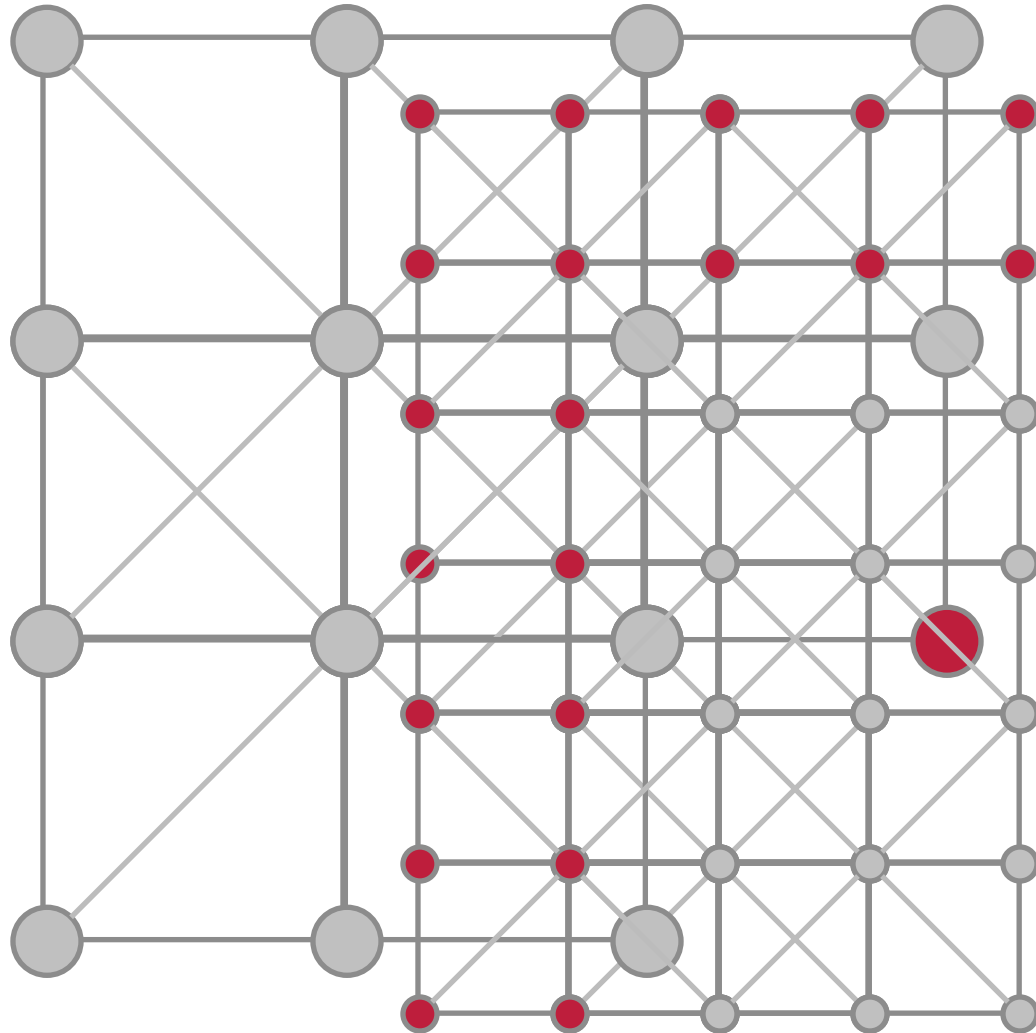


# Multiscale Lattice Boltzmann Method

## Interface condition:

Step 5: synchronous time step on coarse grid  
Coarse boundary nodes become invalid




-  Standard node
-  Interface node invalid
-  Interface node valid

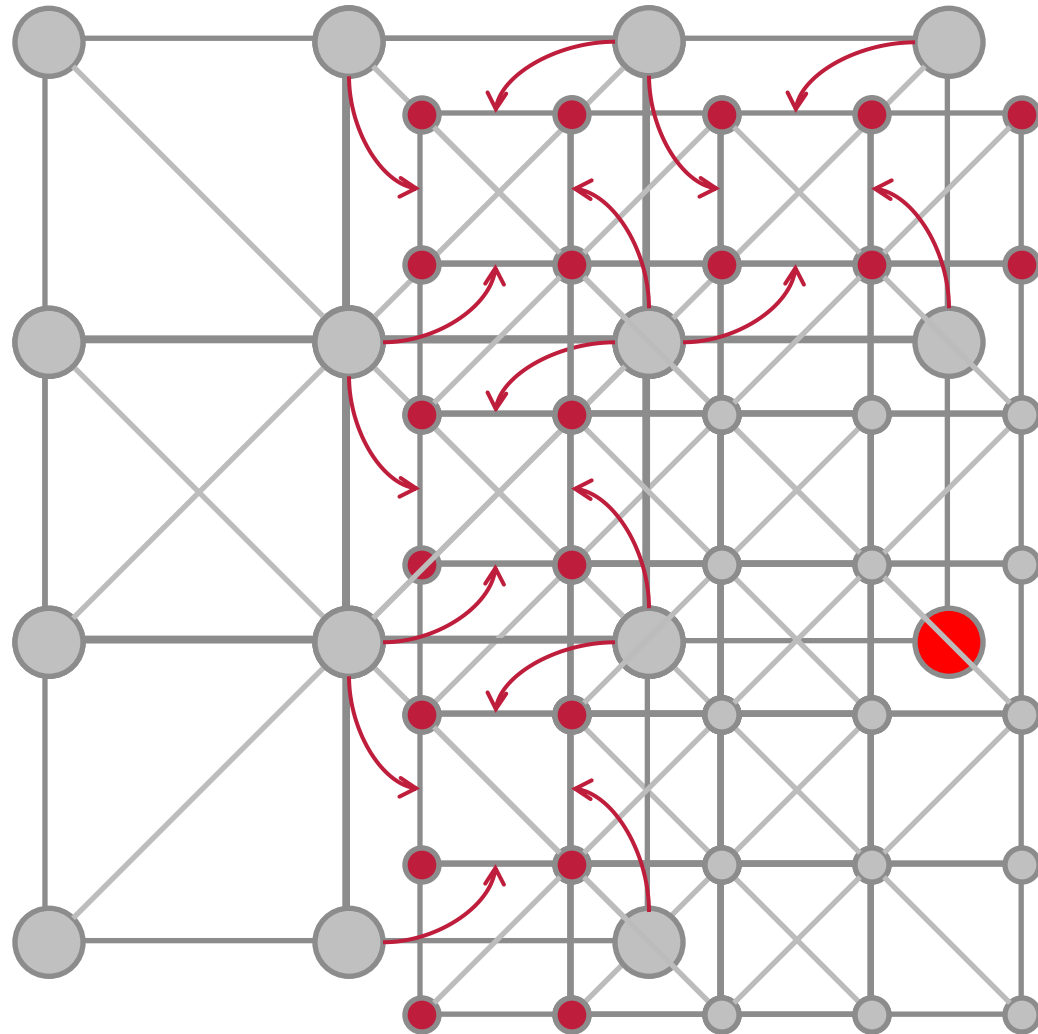


# Multiscale Lattice Boltzmann Method

Interface condition:

Step 6: back to state of step 1

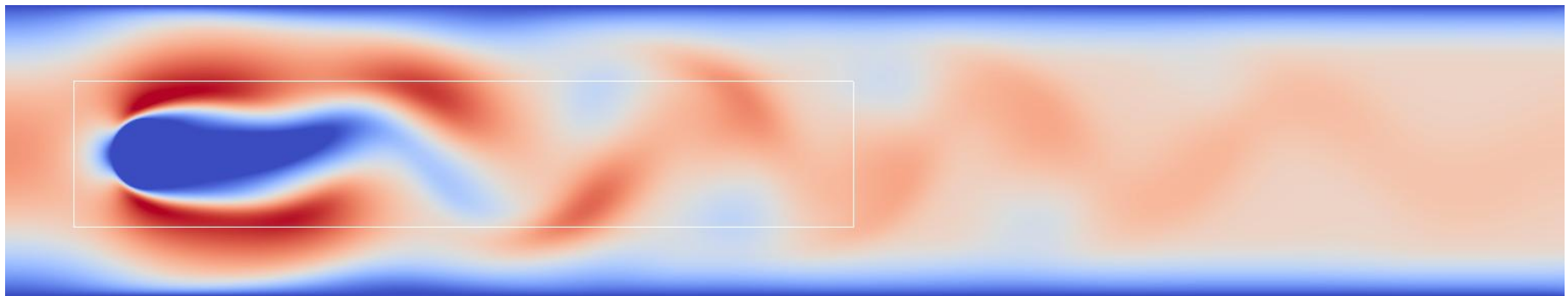
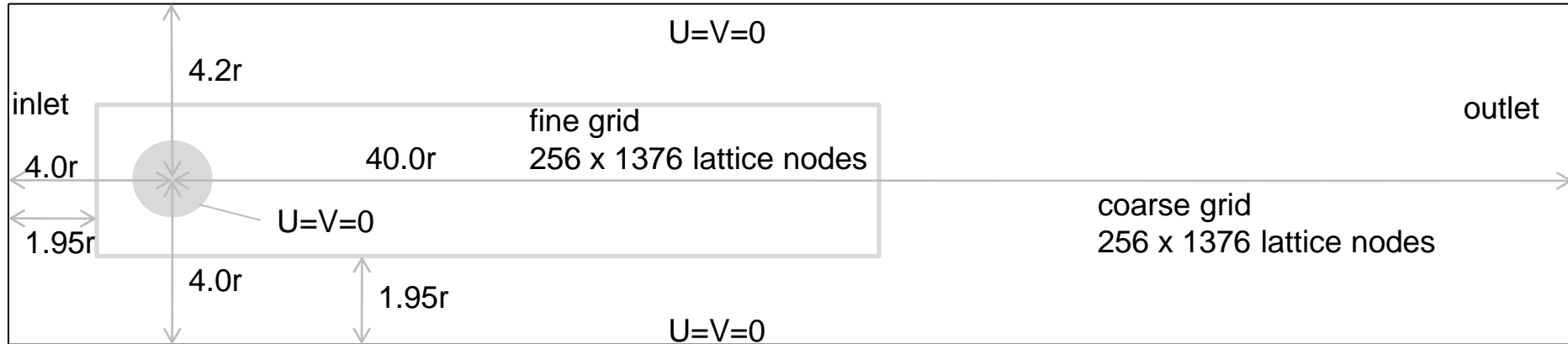
-  Standard node
-  Interface node invalid
-  Interface node valid



# Validation

## The flow past a cylinder

Schäfer and Turek 1996



# Validation

| Re  | Parameter | incompressible | compressible |
|-----|-----------|----------------|--------------|
| 20  | Cd        | 5.58904        | 5.41912      |
|     | Cl        | 0.0090671      | 0.0085598    |
| 100 | Cd        | 3.24188        | 3.22707      |
|     | Cl        | 0.977958       | 1.00898      |
|     | St        | 0.3            | 0.3          |

| Re  | Parameter | Crouse        | Schäfer and Turek |
|-----|-----------|---------------|-------------------|
| 20  | Cd        | 5.585-5.627   | 5.57-5.59         |
|     | Cl        | 0.017-0.0119  | 0.0104-0.011      |
| 100 | Cd        | 3.2645-3.2650 | 3.22-3.24         |
|     | Cl        | 0.9492-1.0709 | 0.99-1.01         |
|     | St        | 0.305-0.3076  | 0.295-0.305       |

# Performance Analysis

- NUPS – number of node updates per second
- comparison of uniform and non-uniform case
- equal # of degrees of freedom
- 100.000 time steps
- 3 diff. Resolutions

## Uniform

2048 x 15350

1024 x 7680

512 x 3840

## Non-Uniform

1024 x 15360 x 2

512 x 7680 x 2

256 x 3840 x 2

# Performance Analysis

Relation of Performance (uniform and non-uniform)

|              | Resolution<br>[nodes] | NUPS<br>[x10 <sup>6</sup> ] | NUPS<br>[%] | Time<br>[s/10 <sup>5</sup> Δt] |
|--------------|-----------------------|-----------------------------|-------------|--------------------------------|
| Uniform      | 2048x15360            | 911.62                      | 100.00      | 3450.73                        |
| Non-uniform* | 2x1024x15360          | 828.07                      | 90.84       | 5223.46                        |
| Uniform      | 1024x7680             | 920.59                      | 100.00      | 854.27                         |
| Non-uniform* | 2x512x7680            | 835.27                      | 90.73       | 1294.62                        |
| Uniform      | 512x3840              | 902.55                      | 100.00      | 217.83                         |
| Non-uniform* | 2x256x3840            | 767.71                      | 85.06       | 352.13                         |

\* effective number of NUPS - no coarse nodes under fine grid

# Performance Analysis

Relation of Performance (uniform and non-uniform)

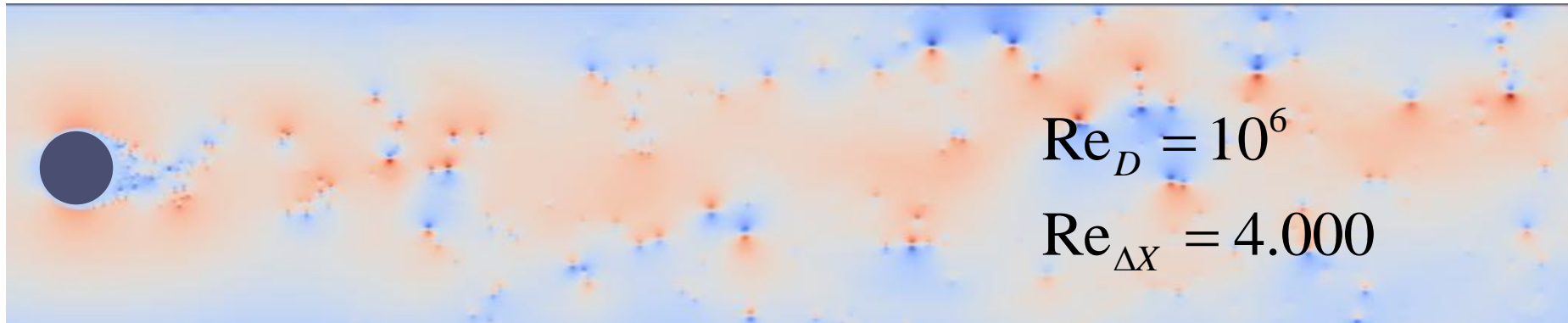
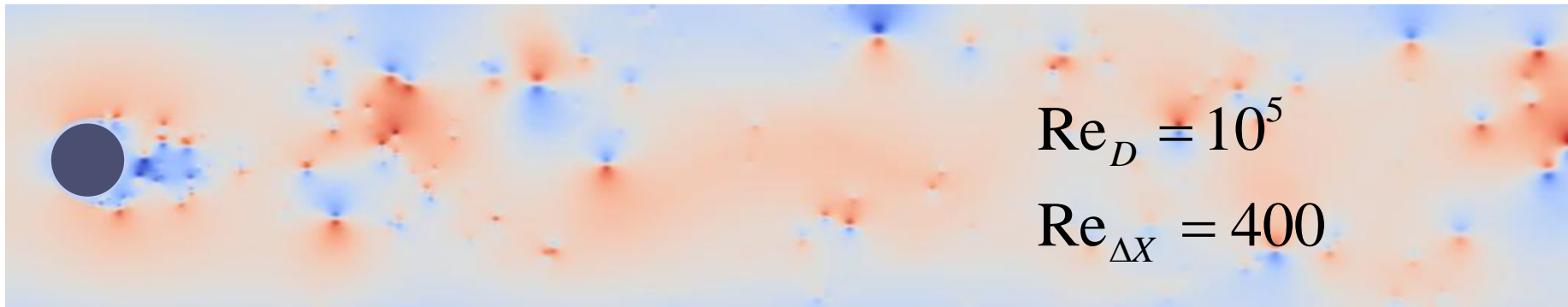
|              | Resolution<br>[nodes] | NUPS<br>[x10 <sup>6</sup> ] | NUPS<br>[%] | Time<br>[s/10 <sup>5</sup> Δt] |
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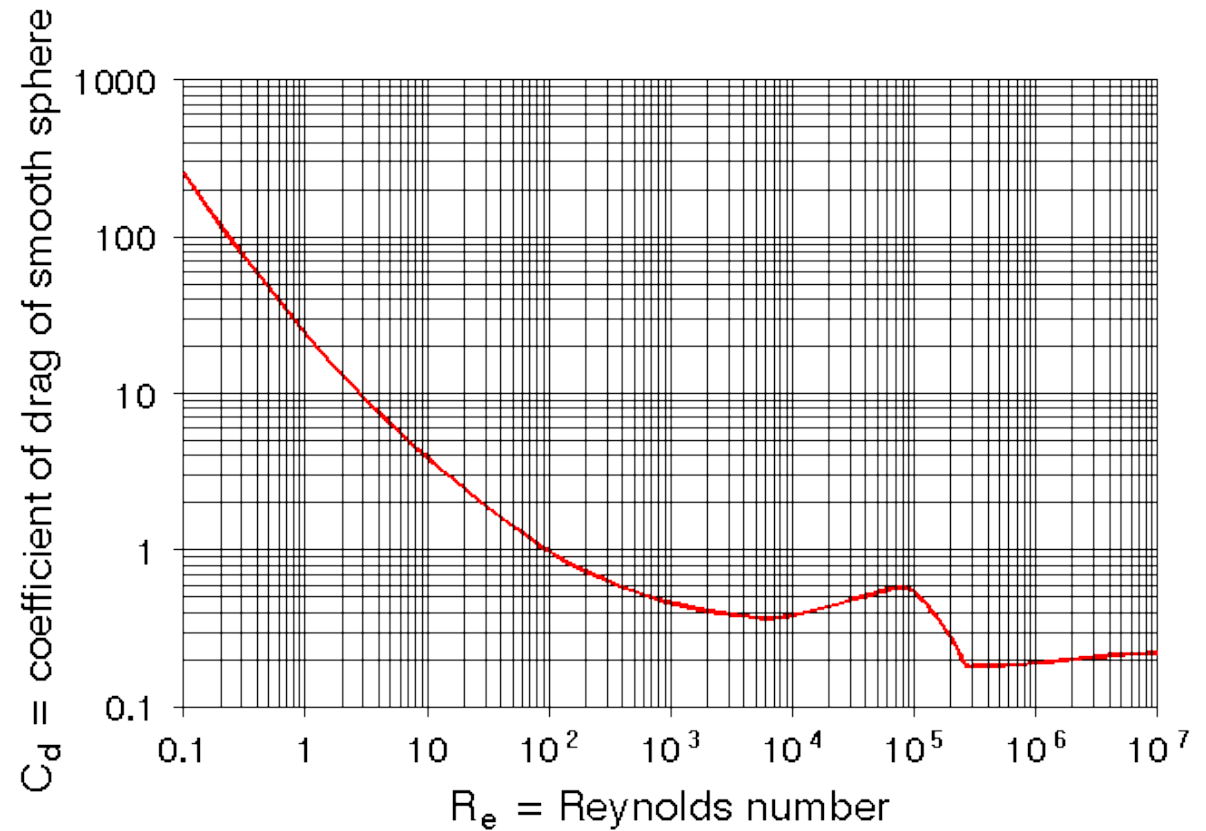
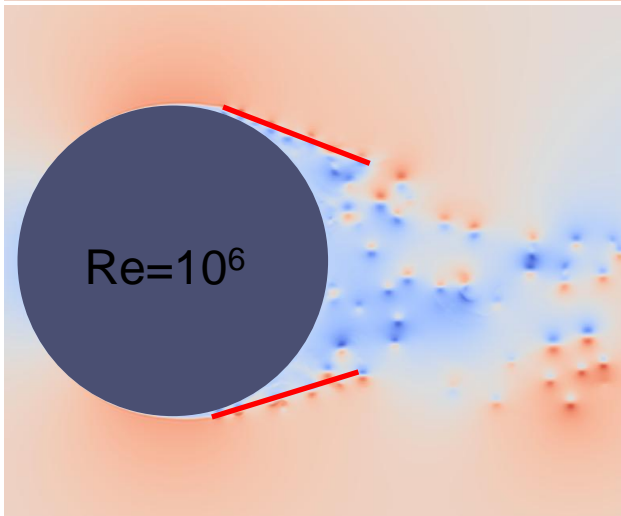
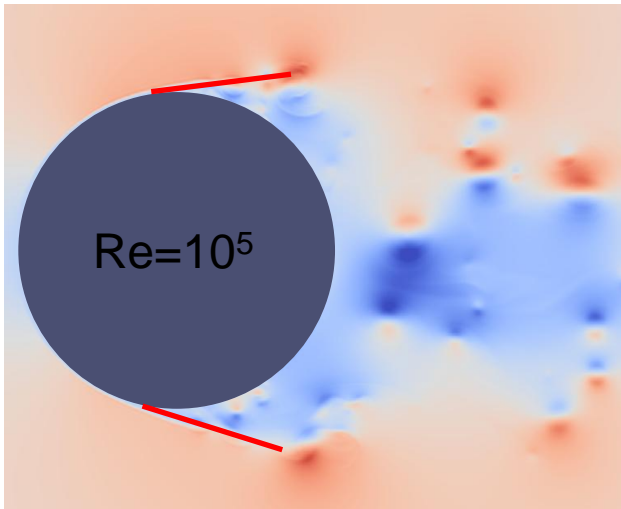
# Cascaded LB: testing stability limits ...

D2Q9 two grid levels, GPU (single precision)

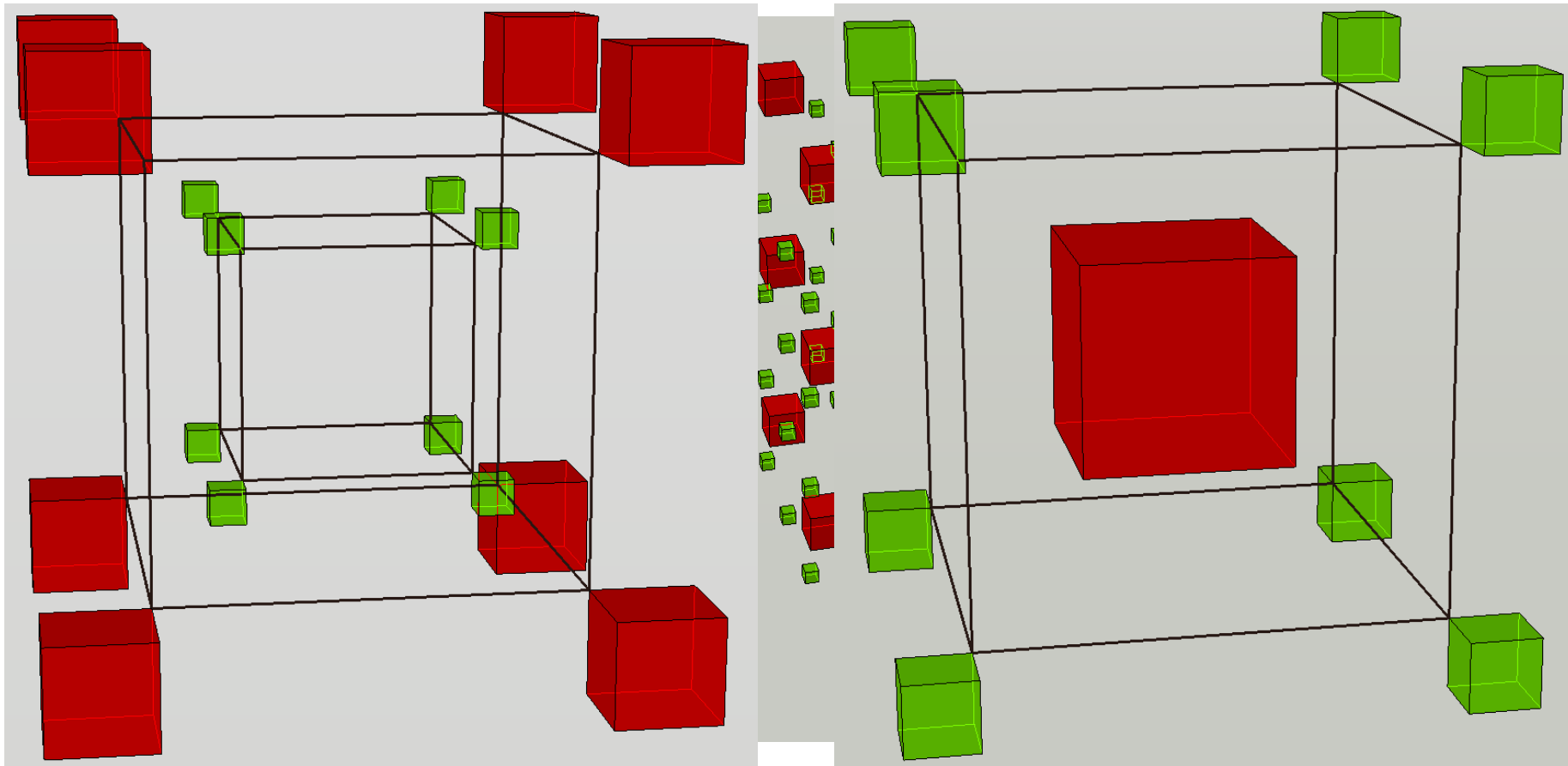
Each level holds  $2.048 \times 10.990$  grid nodes ( $2 \times 10^8$  *DOF*)  $\frac{\Delta x_{coarse}}{\Delta x_{fine}} = 2$



# ...reveals 2d „drag crisis“



# The grid refinement 3D

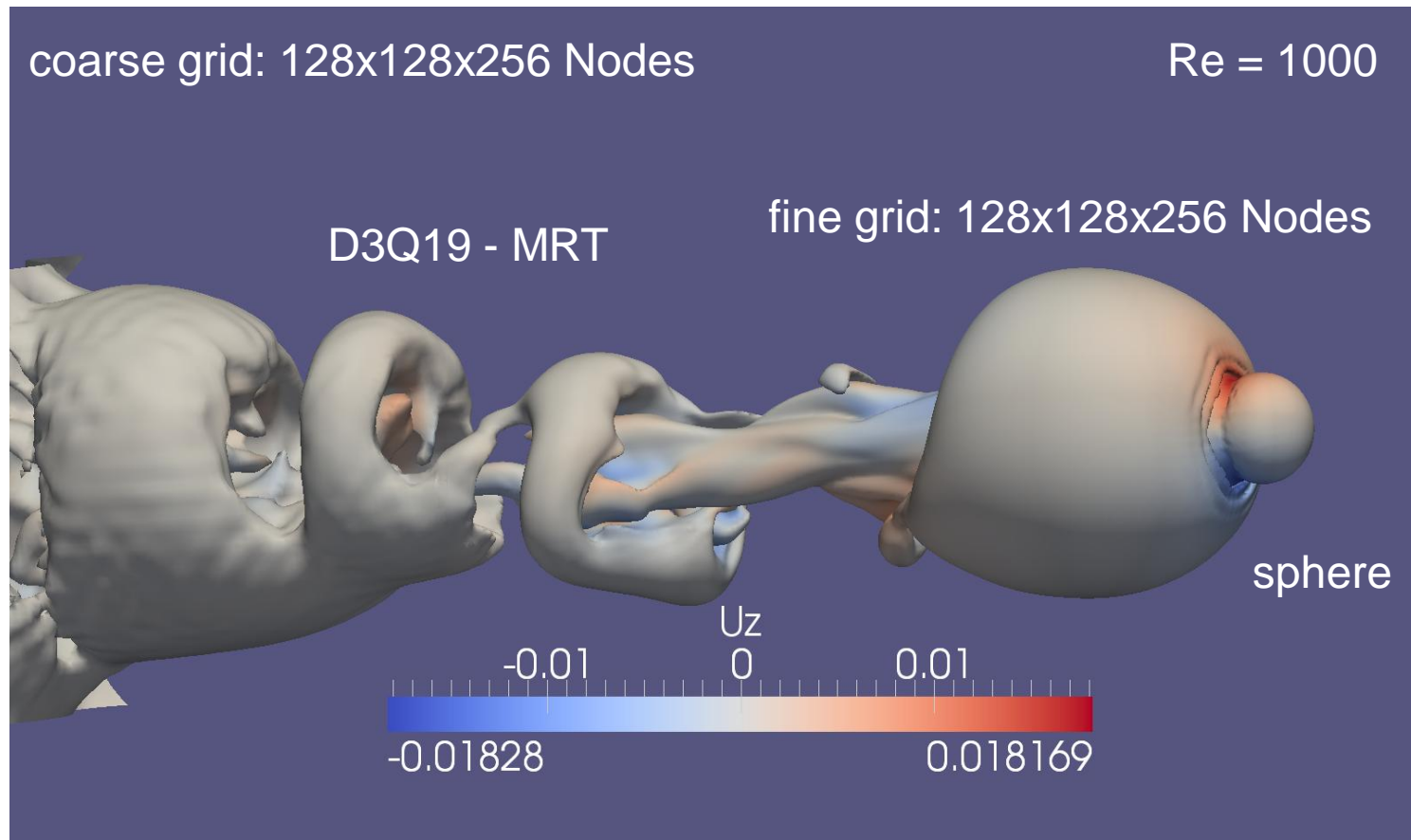


coarse to fine cell

fine to coarse cell

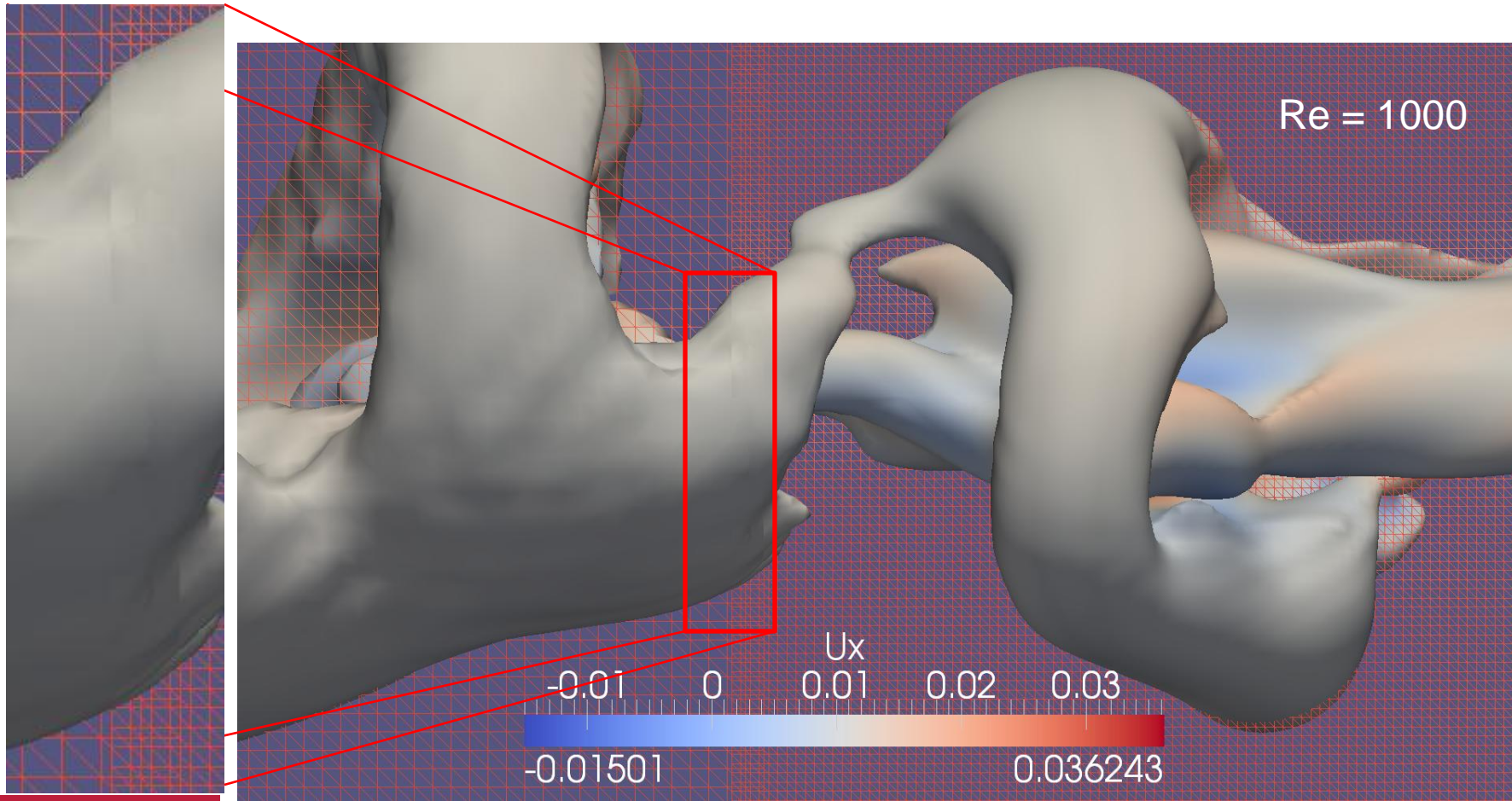
# Quality of results

Difference of quality between coarse and fine grid



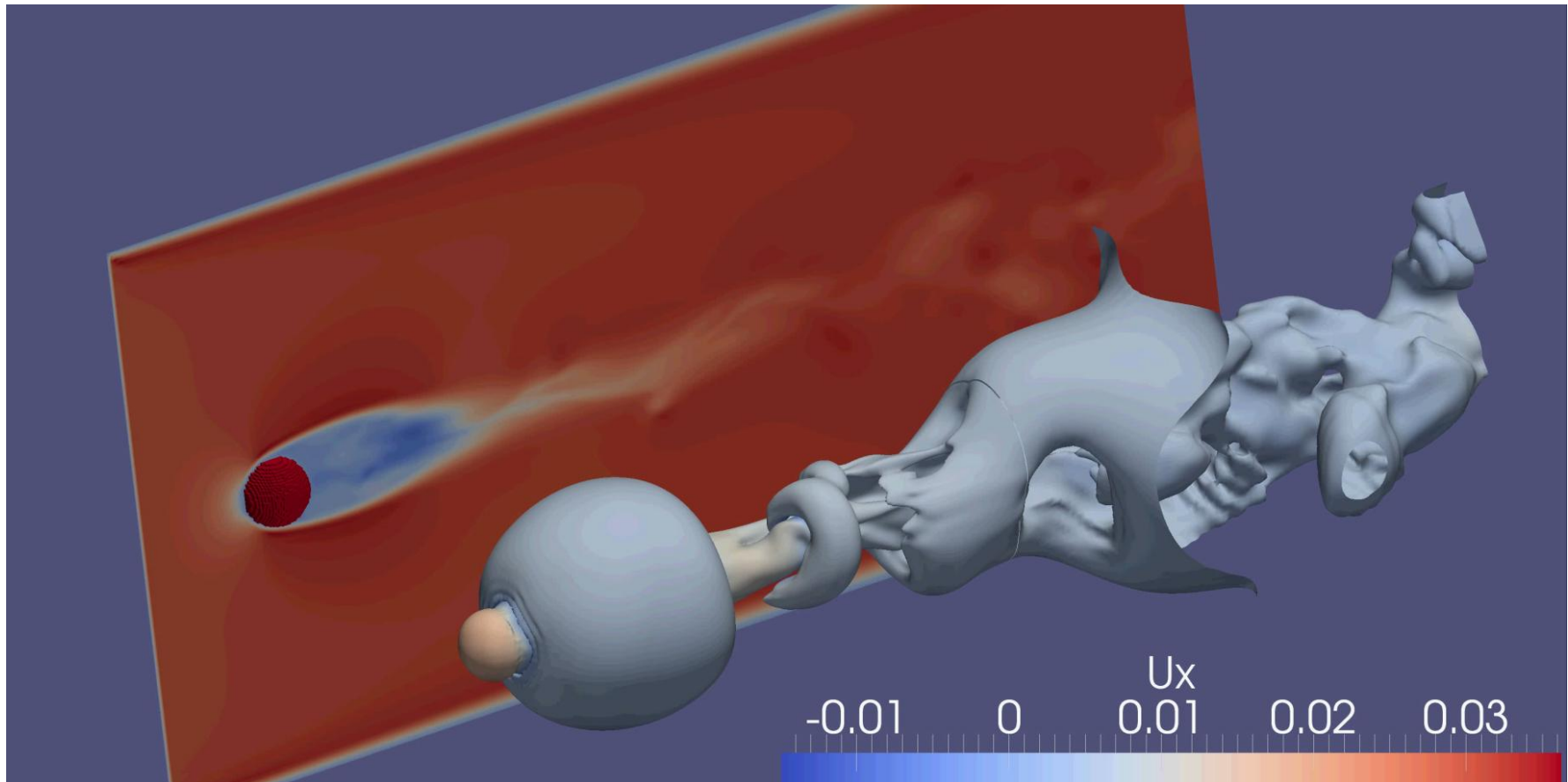
# Quality of results

Testcase: channel flow around a sphere (velocity in x direction)



# Quality of results

Simulation: Smoothly data transfer at the grid interface



# Performance Analysis

- NUPS – number of node updates per second
- comparison of uniform and non-uniform case
- equal # of degrees of freedom
- 1.000.000 time steps
- 3 diff. resolutions:

## Uniform

256 x 256 x 144

256 x 128 x 144

128 x 128 x 144

## Non-Uniform

256 x 192 x 96 x 2

256 x 192 x 96 x 2

128 x 96 x 96 x 2

# Performance Analysis

Relation of Performance (uniform and non-uniform)

|              | Resolution [nodes] | NUPS [ $\times 10^6$ ] | NUPS [%] |
|--------------|--------------------|------------------------|----------|
| Uniform      | 256x256x144        | 280.81                 | 100.00   |
| Non-uniform* | 2x256x192x96       | 212,25                 | 75.58    |
| Uniform      | 256x128x144        | 281.53                 | 100.00   |
| Non-uniform* | 2x256x96x96        | 204.39                 | 72.60    |
| Uniform      | 128x128x144        | 255.42                 | 100.00   |
| Non-uniform* | 2x128x96x96        | 176.61                 | 69.14    |

\* effective number of NUPS - no coarse nodes in fine grid

# Performance Analysis

Relation of Performance (uniform and non-uniform)

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\* effective number of NUPS - no coarse nodes in fine grid

# GPU – Nodes (Ludwig)

## 1 GPU - Node



4 GPUs = 960 Cores  
(2 CPUs, 12 GB RAM)

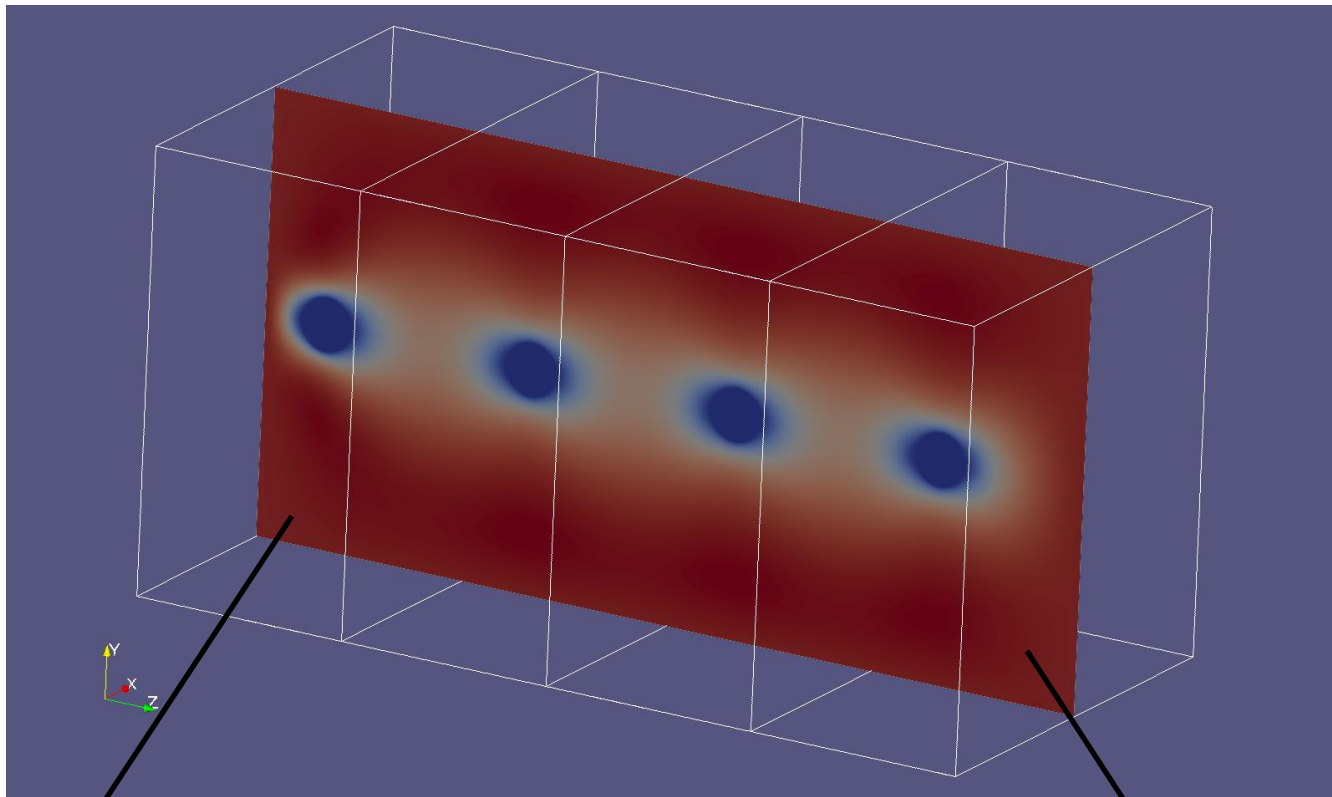
## 24 GPU - Nodes



96 GPUs = 23040 Cores  
(48 CPUs, 288 GB RAM)

# Results

Resolution 256x512x256 lattice-nodes = 3,66 GB/GPU



No. 1

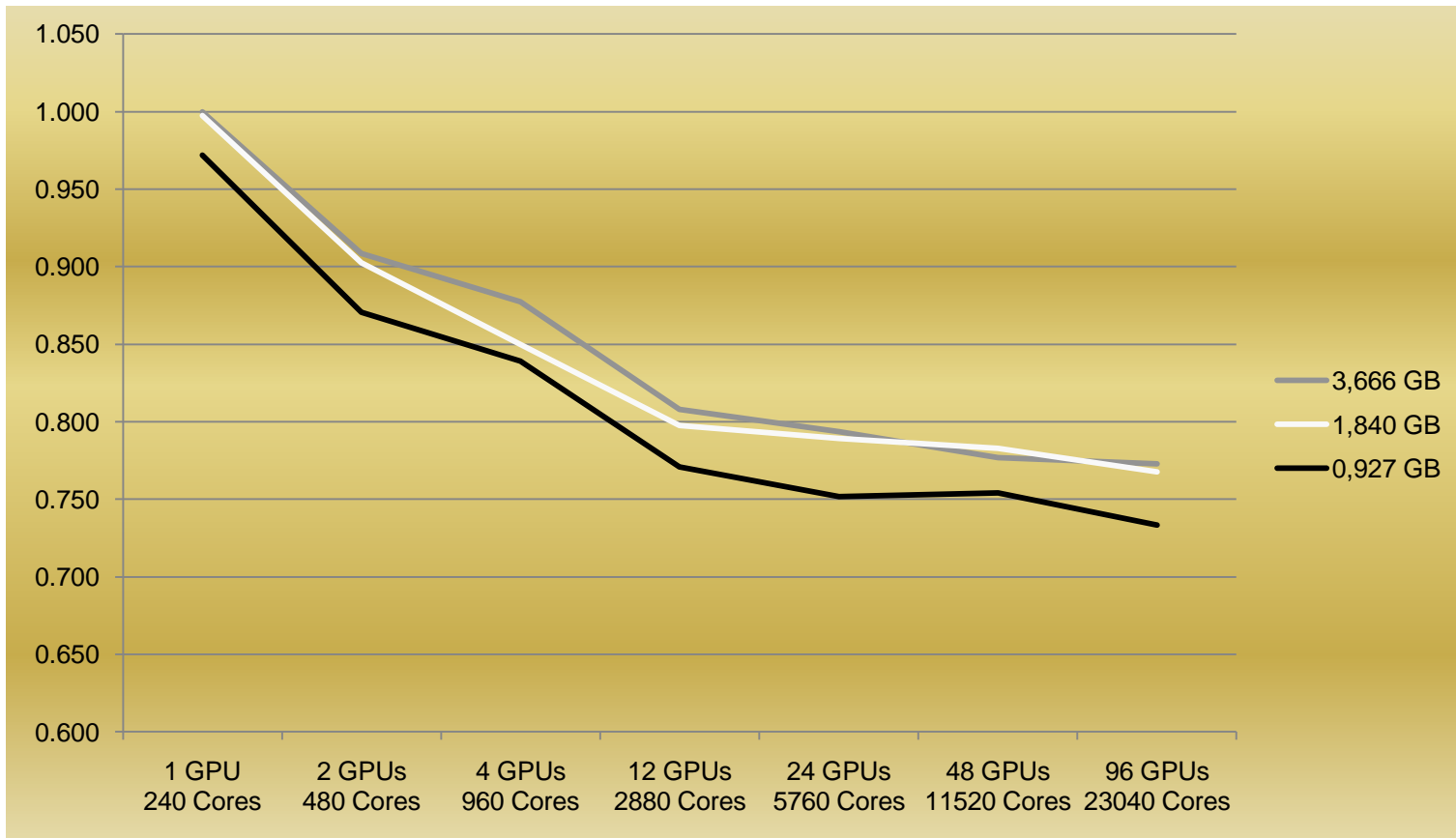
...

No. 96



# Results

## Results for 3 Resolutions



# Conclusion

## Conclusion:

- combination of uniform LBM with grid refinement on GPGPU is a mandatory step towards utilizing the full capability of LBM on GPUs
- compact second order interpolation allows high Re Numbers
- time interpolation is unnecessary
- no special treatment of corners / edges
- good scalability of parallel GPU Code

# Acknowledgments

- German BMBF funding the SKALB (Lattice-Boltzmann-Methoden für skalierbare Multi-Physik-Anwendungen) project (reference ID 01IH08003E).
- Funding by the DFG under grant GE 1990/2-1 (Konsistente Multiskalenströmungsmechanik mit der kaskadierten Lattice Boltzmann Methode).

***Thank you for your attention!***