Simulation Techniques & Scientific Computing

UNIVERSITÄT SIEGEN

Scalable simulations of hemodynamics in intracranial aneurysms

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LRZ Project ID: pr45du

LRZ Review Meeting, Garching

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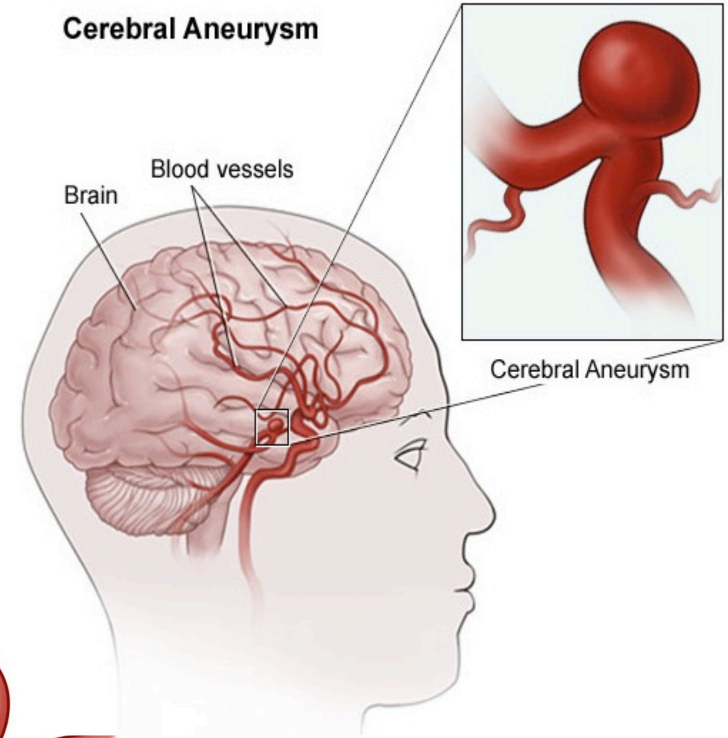
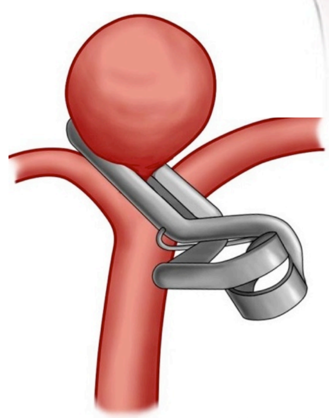
Intracranial Aneurysm

- Localized dilation of blood vessel
- Rupture (SAH) can be lethal
- Risk Factors:
    - Smoking, Narcotics like Cocaine
    - Family History, High Blood Pressure
- Symptoms:
    - Localized Headache
    - Dilated Pupils
    - Pain above and behind eye
- Statistics:
    - Suffering: 1 in 50 people
    - Ruptures: 8-10 per 100,000 who suffer
- Treatment Options:
    - Surgical Clipping
    - Endovascular Coiling





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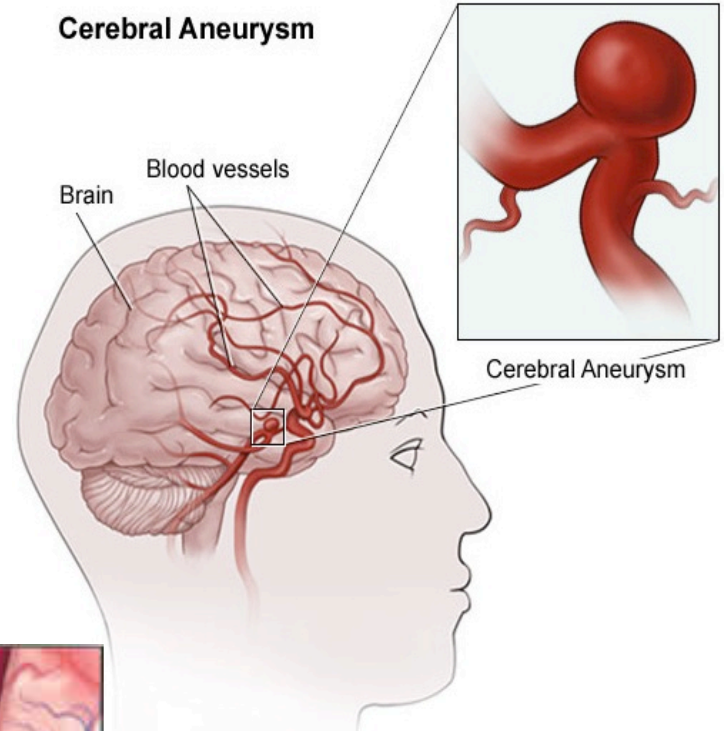

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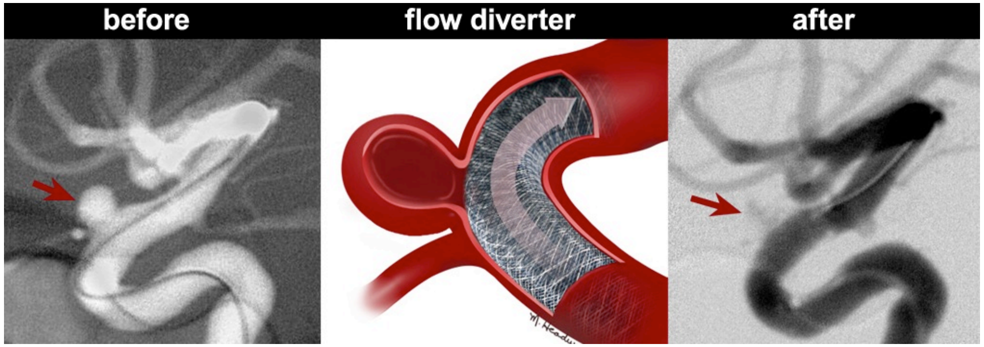
- Intracranial stenting:
  - Flow diversion to increase clotting
  - Optimal control of flow by stent configuration



Outline

- The APES Simulation Framework
- Scaling on SuperMUC
- Simulation Results
- Conclusions and on-going research

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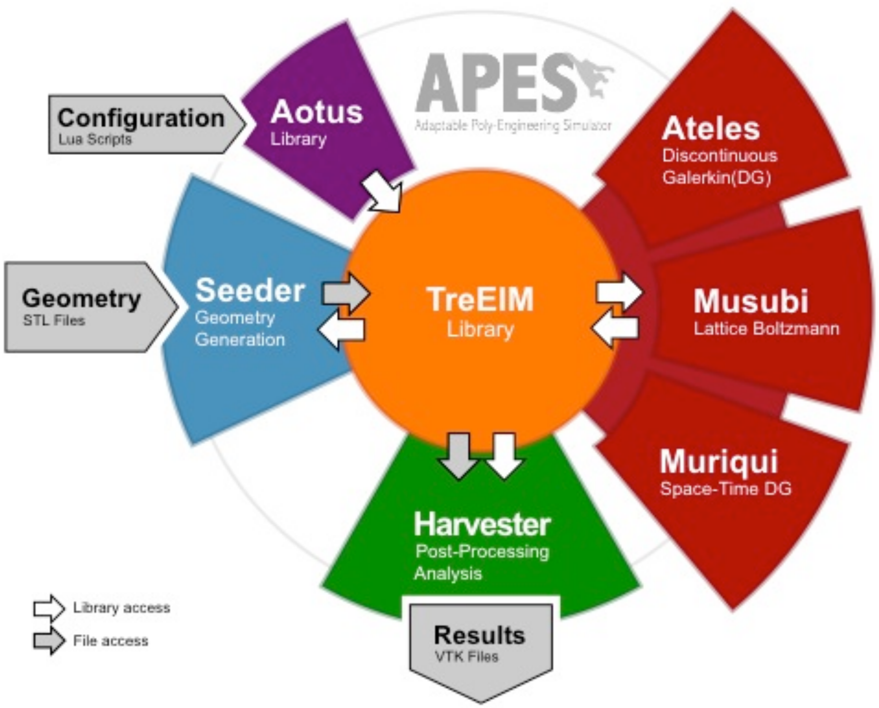
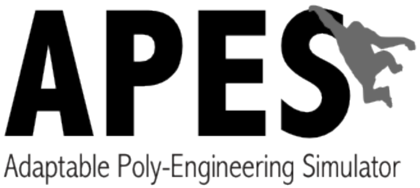


https://bitbucket.org/apesteam/musubi



- End-to-end parallel simulations
- Mesh generator, flow solvers, post processor
- Flexible, Scriptable, Portable
- Efficient Parallel I/O
- Flow solvers:
  - DG solver for Conservation equations: *Ateles*
  - LBM Solver: *Musubi*

The APES Simulation Framework

- Musubi:
  - Lattice Boltzmann Solver
  - Highly suitable for flow in aneurysms
  - Multispecies flow
  - Passive scalar transport
  - Complex boundaries
  - Local grid refinement
  - Open Source:

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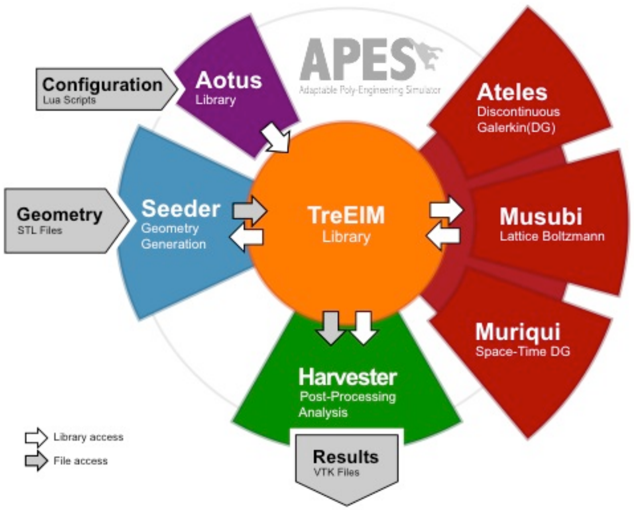
APES
Adaptable Poly-Engineering Simulator



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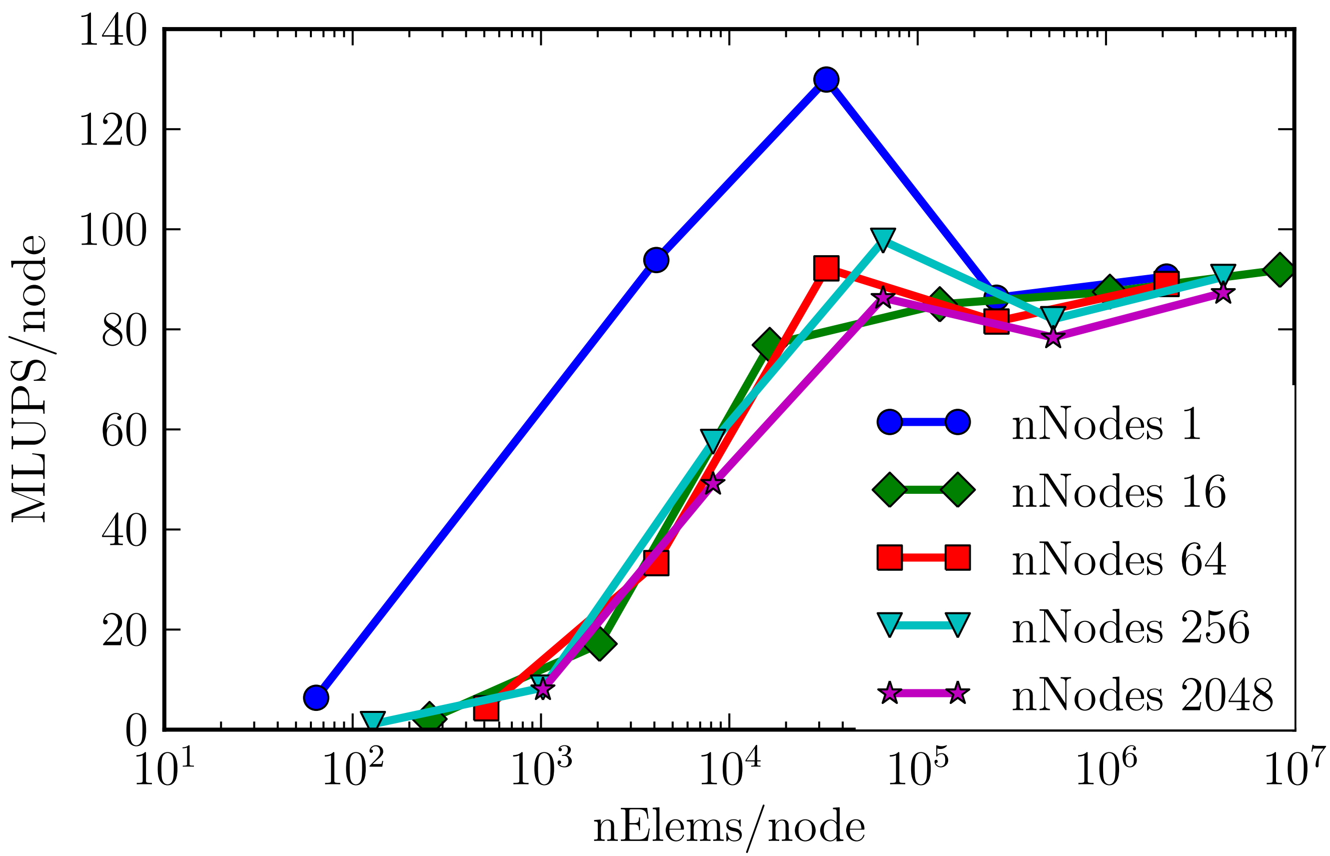
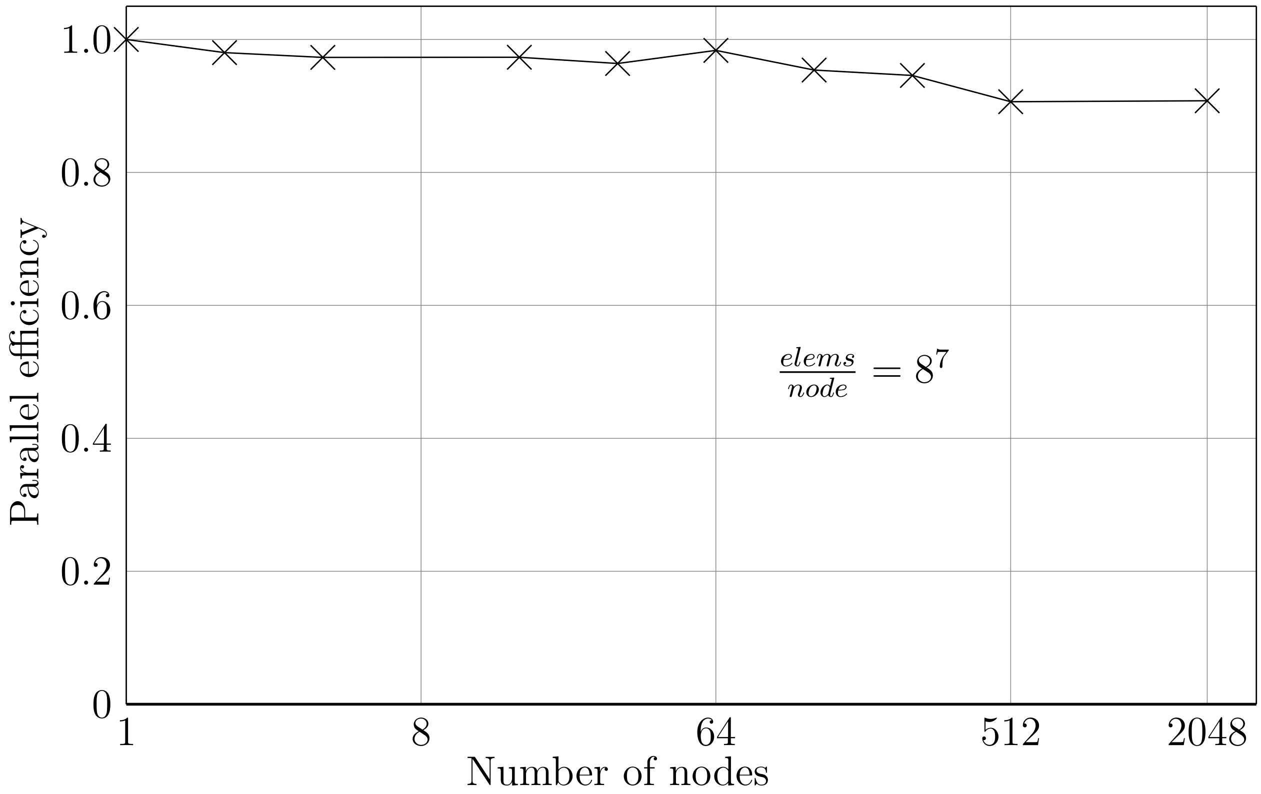
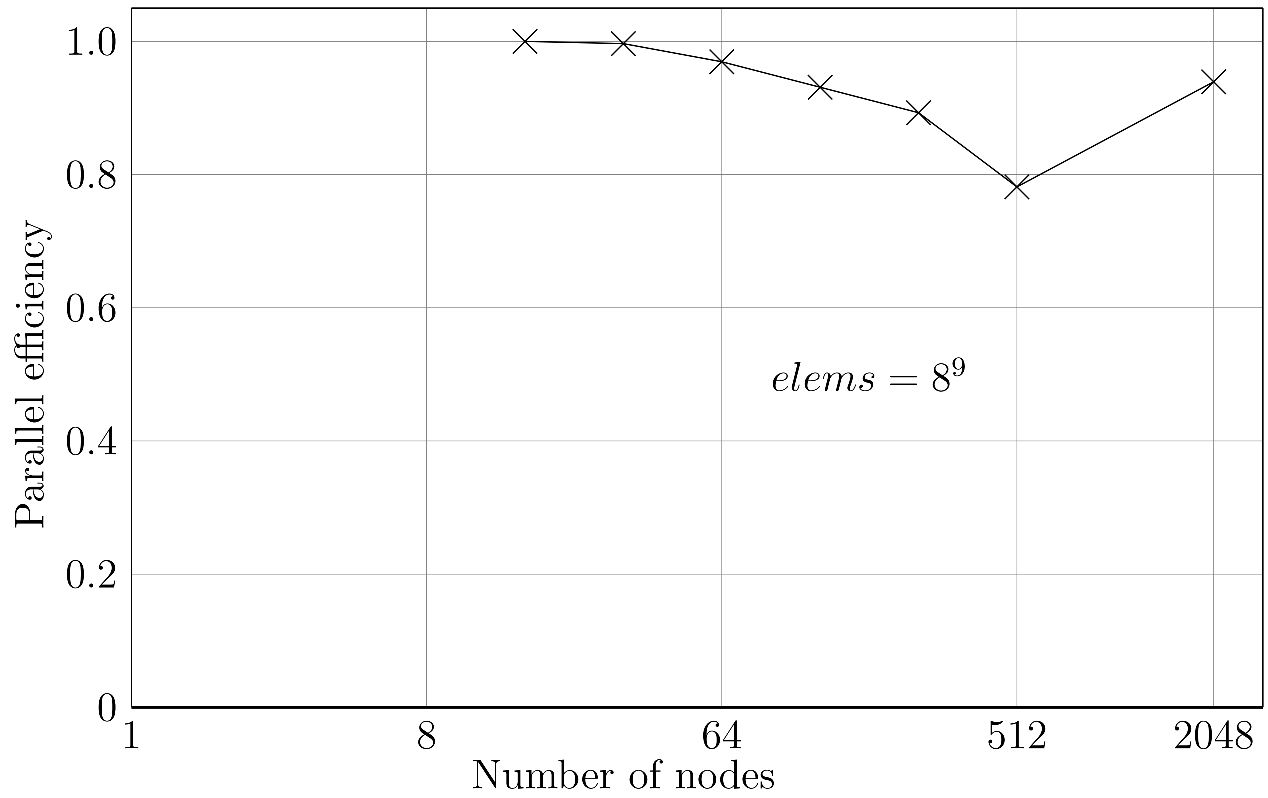
Musubi on SuperMUC: Performance Map



Musubi on SuperMUC: Weak Scaling (~2M cells/ node)



Musubi on SuperMUC: Strong Scaling (~134 M cells)



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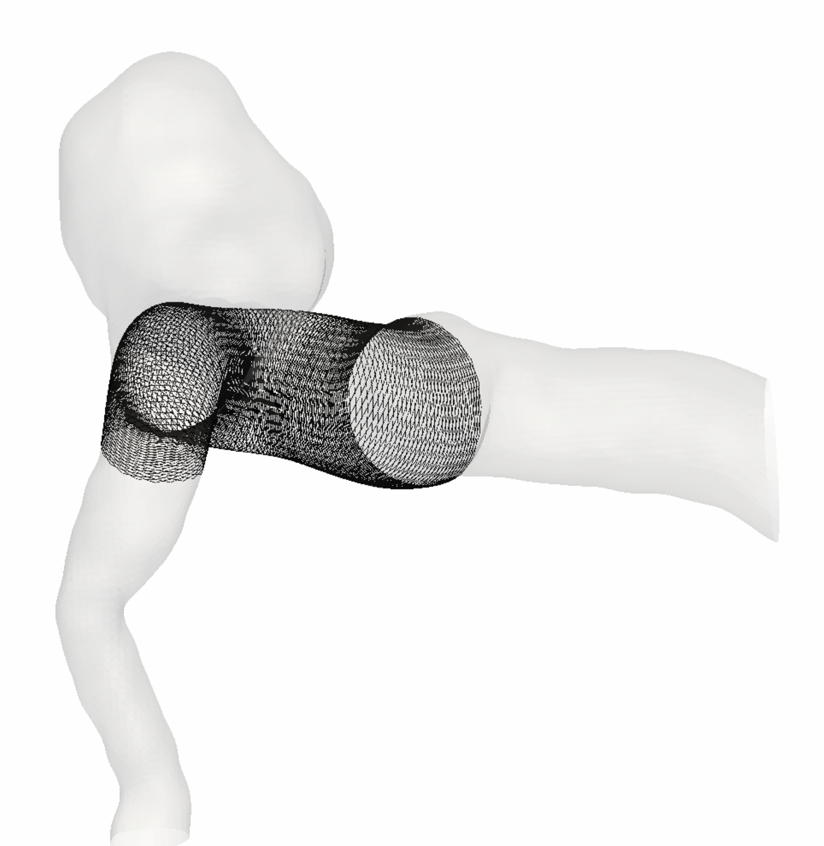
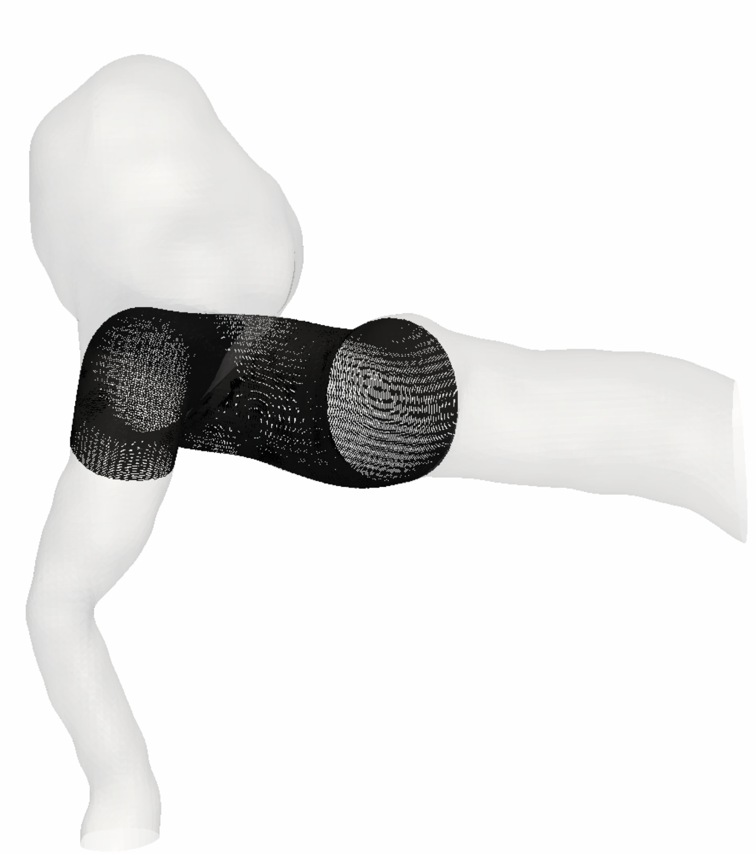
Aneurysm simulations



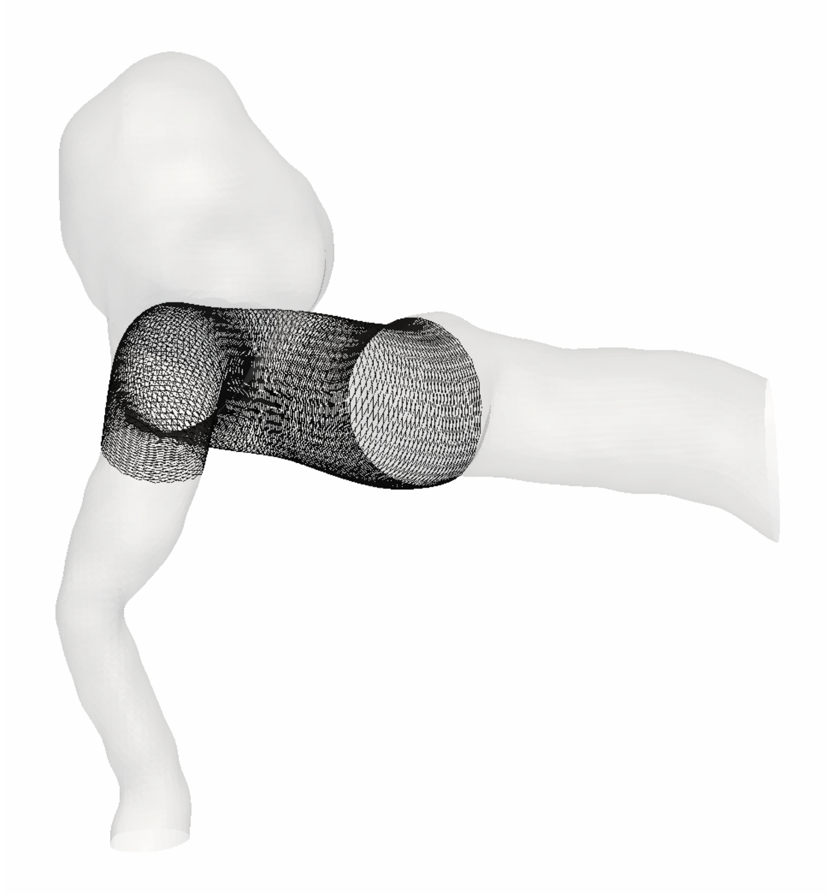
A patient specific aneurysm deployed with highly porous stent



A patient specific aneurysm deployed with less porous stent

Geometries provided by THROMBUS project partners

Aneurysm simulations

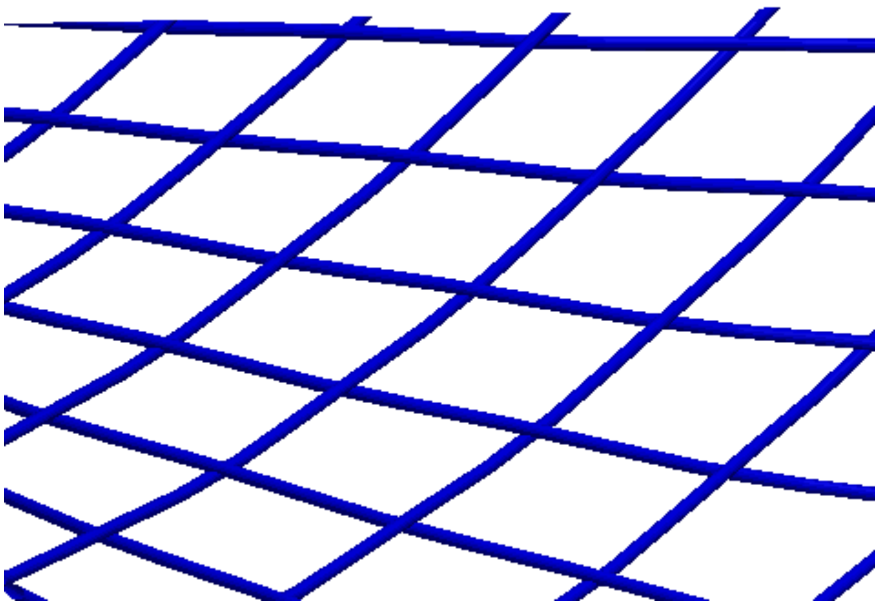


Details:

- Non-uniform mesh of 15 and 7.5 µm with local refinement around stent
- ~ 500 million elements
- 4 cardiac cycles (4 seconds) are usually simulated on 16000 *SuperMUC* cores for flow quantification

The need for HPC

Resolving the thin wires of the stent:



Cross section of the stent which opens towards the aneurysmal sac

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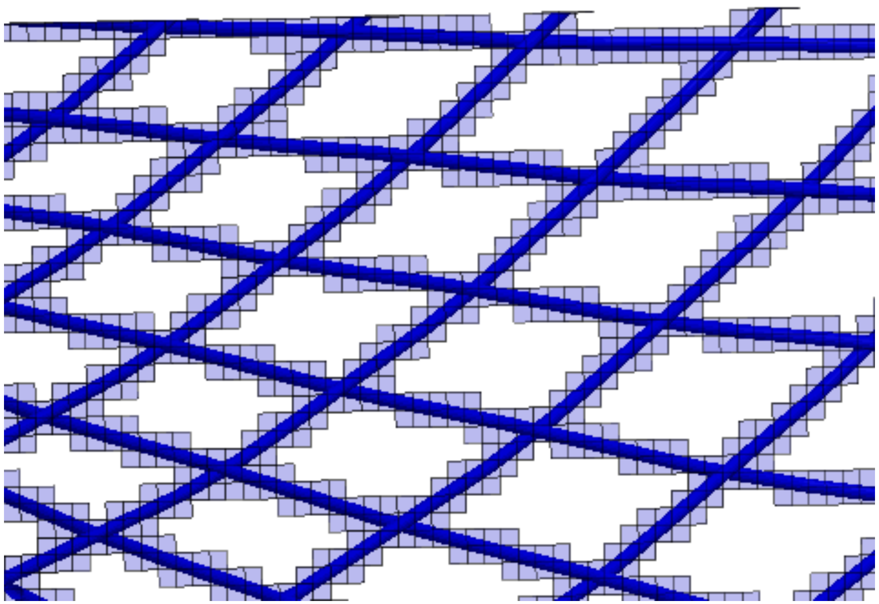

The coarse computational mesh on the top of stent

Details:

- Uniform mesh of 30 µm
- ~ 60 million elements
- 4 cardiac cycles (4 seconds) are usually simulated on 16000 *SuperMUC* cores for flow quantification

CFD: Computational Fluid Dynamics
Or
Confounding Factor Dissemination

American Journal of Neuroradiology
David F. Kallmes, MD

The need for HPC

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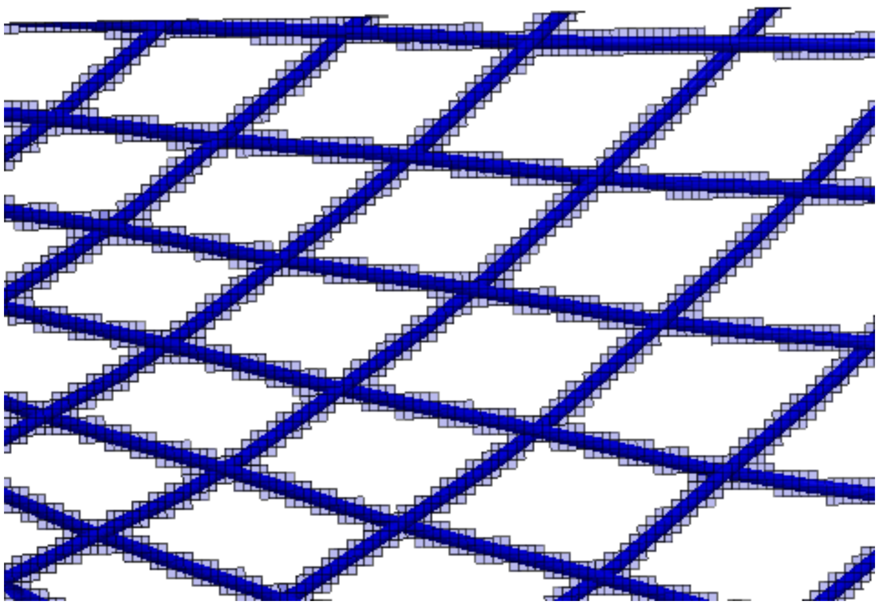


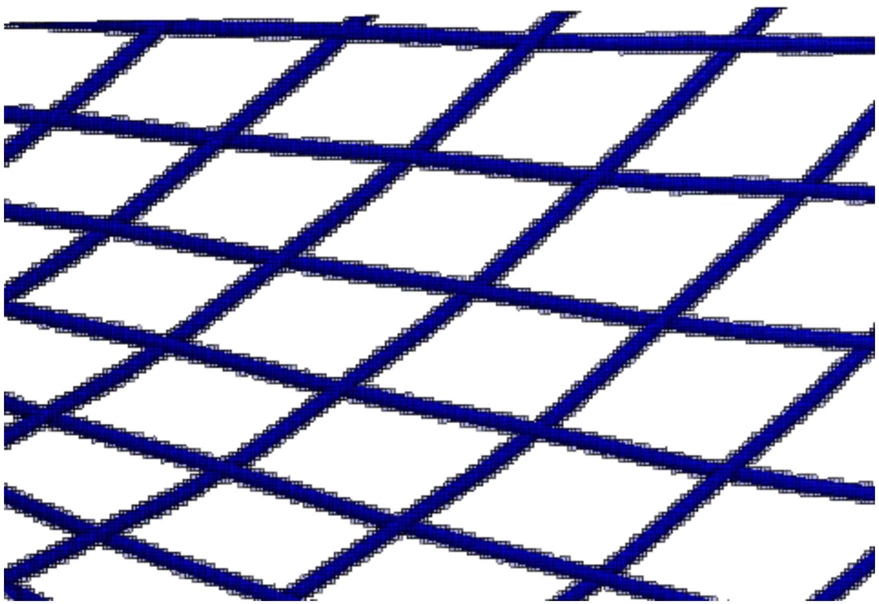
The fine computational mesh on the top of stent

Details:

- Uniform mesh of 15 µm
- ~ 470 million elements
- 4 cardiac cycles (4 seconds) are usually simulated on 16000 *SuperMUC* cores for flow quantification

The need for HPC

Resolving the thin wires of the stent:

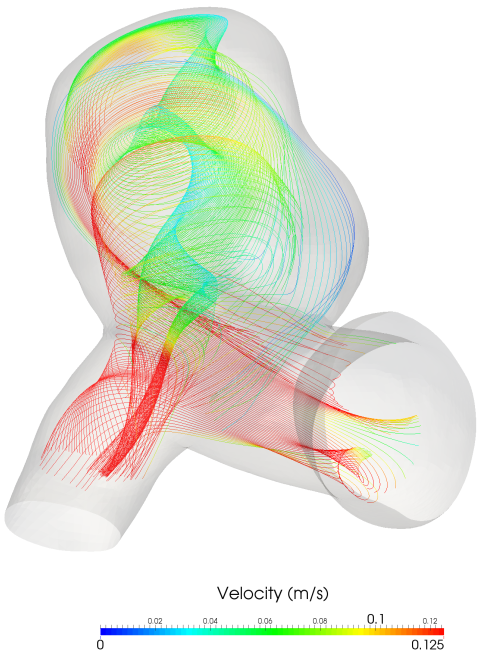


The FINAL computational mesh on the top of stent

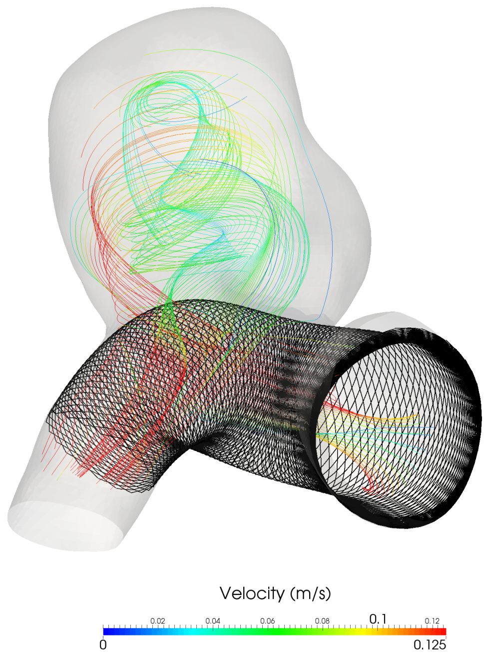
Details:

- Non-uniform mesh of 15 and 7.5 µm with local refinement around stent
- ~ 500 million elements
- 4 cardiac cycles (4 seconds) are usually simulated on 16000 *SuperMUC* cores for flow quantification

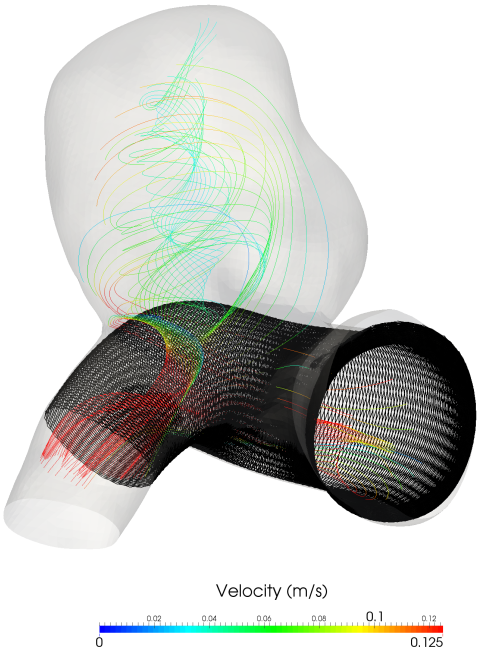
Flow profile inside aneurysm



Velocity streamlines in non-stented aneurysm at peak systole

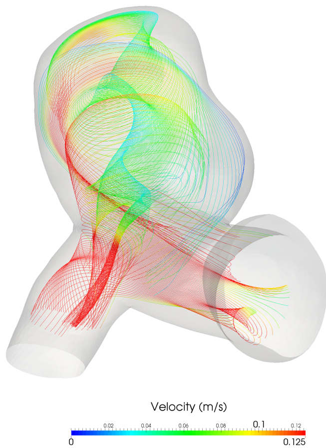


Velocity streamlines in aneurysm with highly porous stent at peak systole



Velocity streamlines in aneurysm with less porous stent at peak systole

Flow profile inside aneurysm



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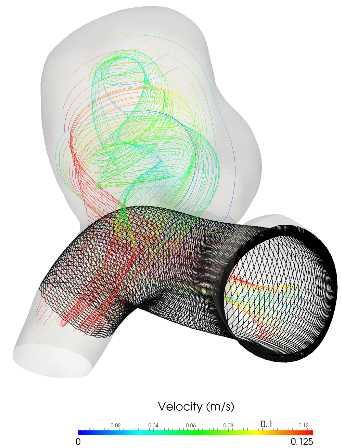

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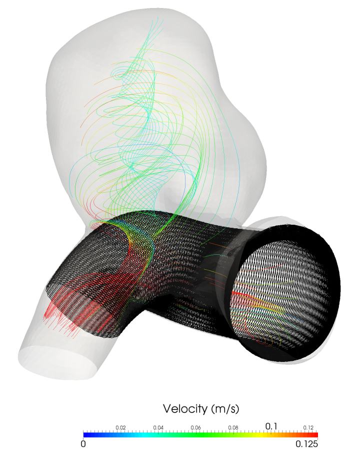

Velocity streamlines in aneurysm with less porous stent at peak systole

- Aneurysmal flow reduction by stents:
  - 35% by highly porous stent
  - 50% by less porous stent
- Both stent causes some reflection in the parent artery
- Stent increases *residence time* of blood, which increases clotting

Zimny, S., Chopard, B., Malaspinas, O., Lorenz, E., Jain, K., Roller,., & Bernsdorf, J. (2013).
A multiscale approach for the coupled simulation of blood flow and thrombus formation in intracranial aneurysms. *Procedia Computer Science, 18*, 1006-1015.

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- Present results elucidate grid requirements for simulations in stented aneurysms and quantify flow reduction to predict stent induced thrombosis
- Improvements in the sustained simulation performance of APES
- Dynamic Load Balancing for complex cases like local grid refinement
- Quantification of high frequency flow fluctuations in bifurcation aneurysms:
  - *A space-time refinement study at extreme scale with up to 1 billion cells and 9 million time steps per second is under review*
- Modeling of cyclic Cerebrospinal Fluid (CSF) and Chiari I malformation

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Thank You Very Much for your Attention!

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