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FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT OF FLOW, HEAT AND COMBUSTION MECHANICS
RESEARCH GROUP FLUID MECHANICS

# LARGE EDDY SIMULATION OF ANNULAR FLOWS, TUBE BUNDLES AND SLOT JETS WITH OPENFOAM

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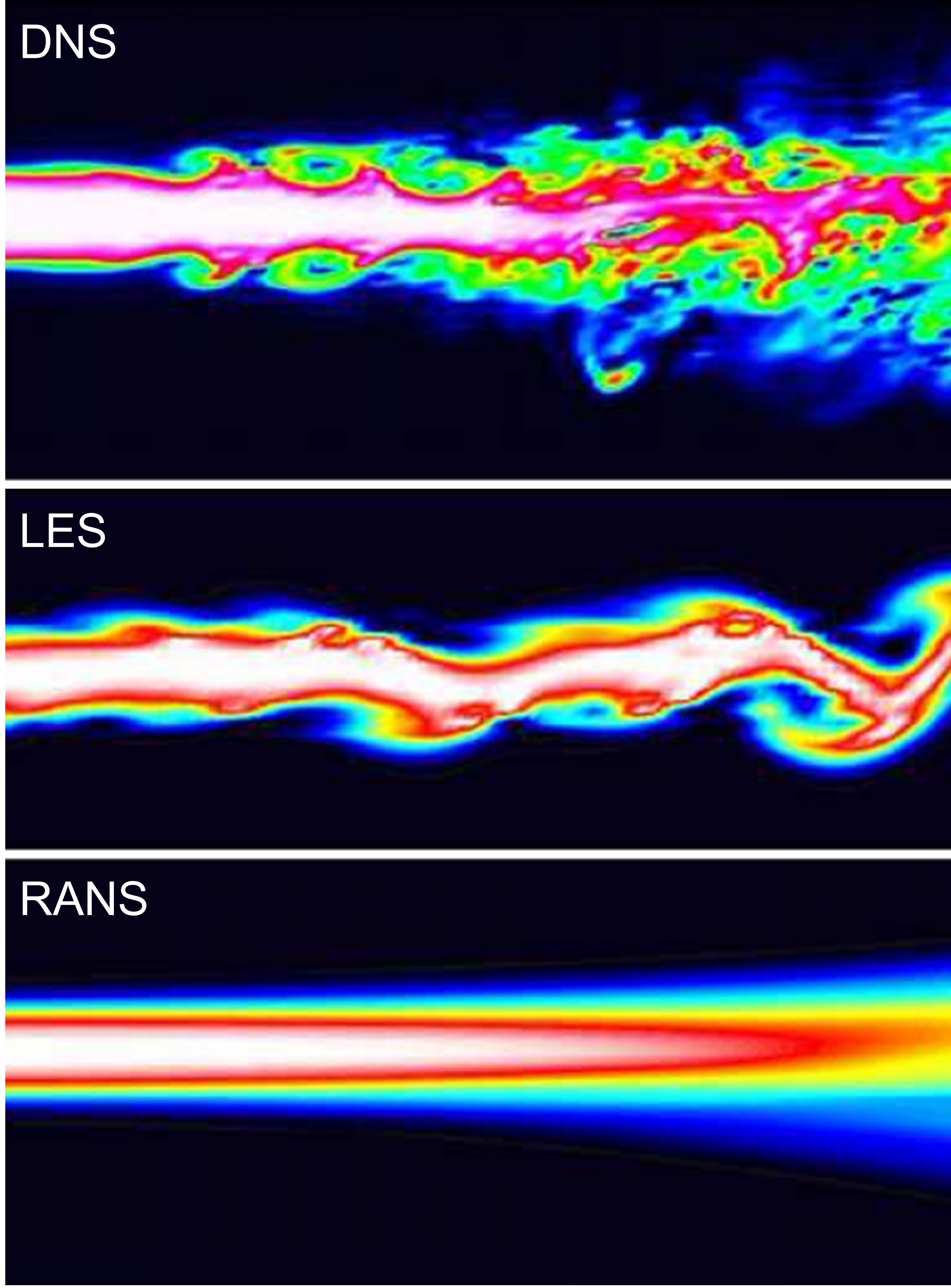
# OUTLINE

– Introduction
– Slot jet
– Tube bundle
– Annular flow
– Domain decomposition
– Comparison CFD packages
– Conclusion

# INTRODUCTION

Turbulence in flow

- Direct numerical simulation (DNS)
- Large eddy simulation (LES)
- Reynolds-averaged Navier-Stokes (RANS) simulation
- Hybrid methods such as (delayed) detached eddy simulation (D)DES




Source: https://www.evl.uic.edu/entry.php?id=2202

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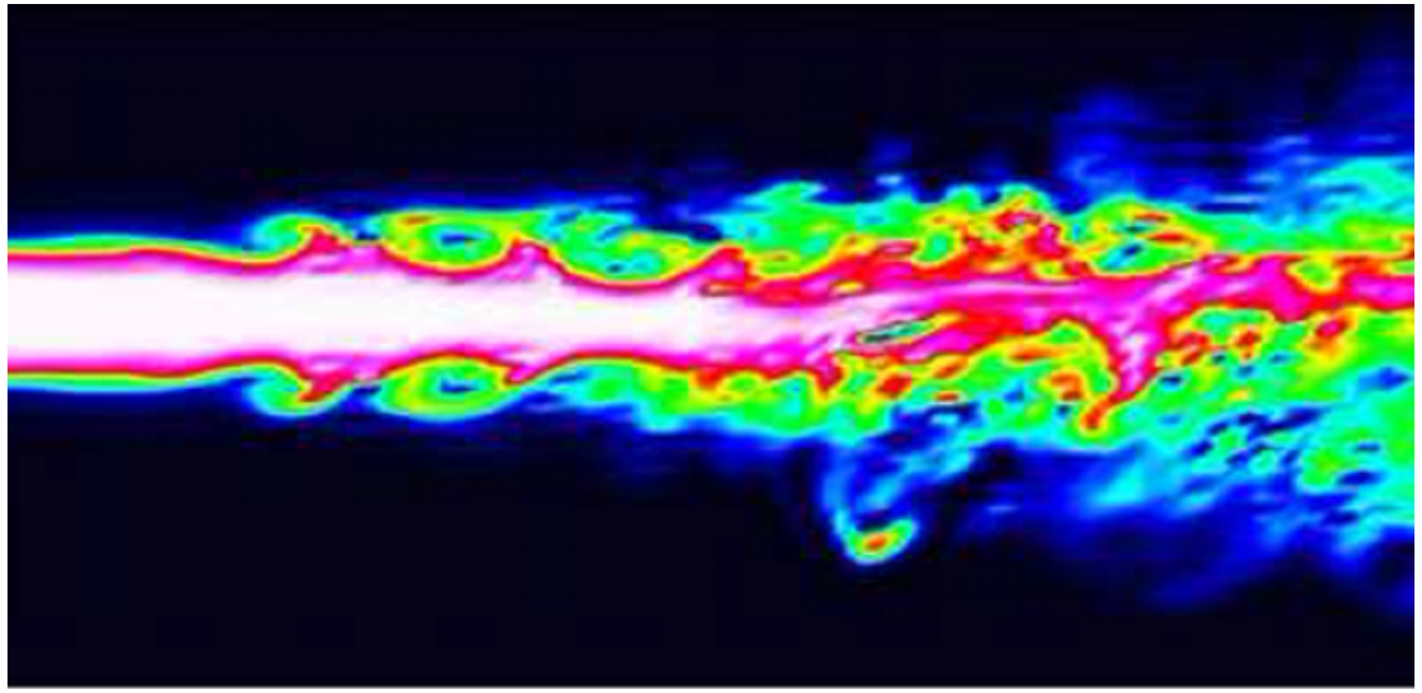
# INTRODUCTION

Direct numerical simulation (DNS)

- 3D unsteady calculation of all scales
- Number operations is proportional to $Re^3$
- Extreme computational cost, only $Re \sim \mathcal{O}(10^3)$



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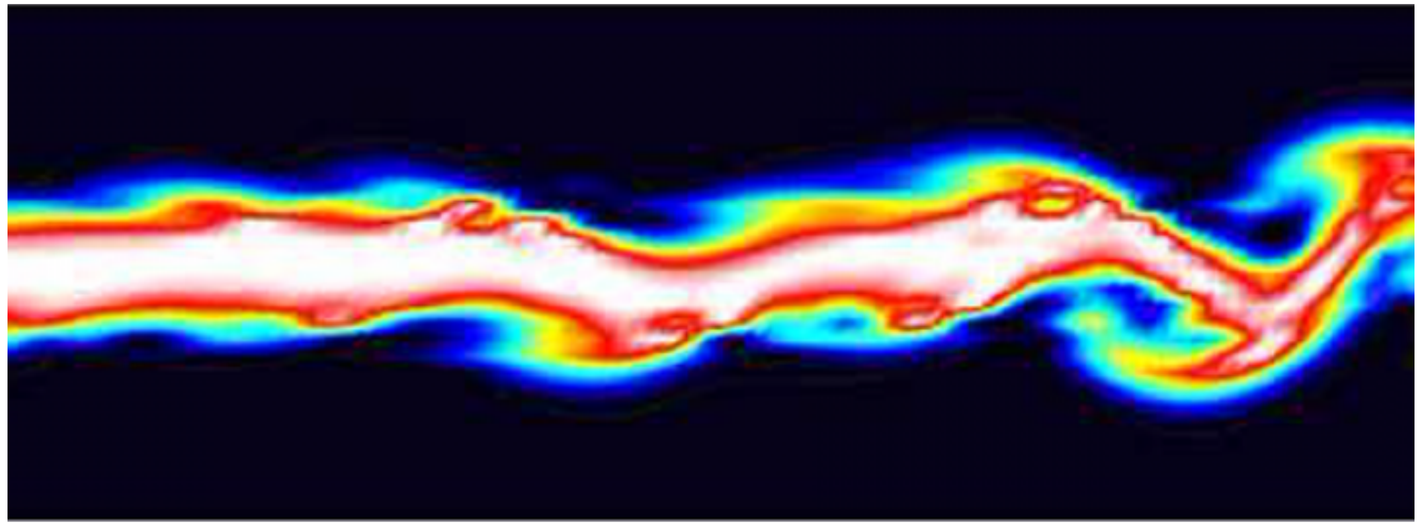
# INTRODUCTION

Large eddy simulation (LES)

- 3D unsteady calculation of scales above limit
- Model assuming isotropic turbulence below limit
- High computational cost, limited to $Re \sim \mathcal{O}(10^{4-5})$



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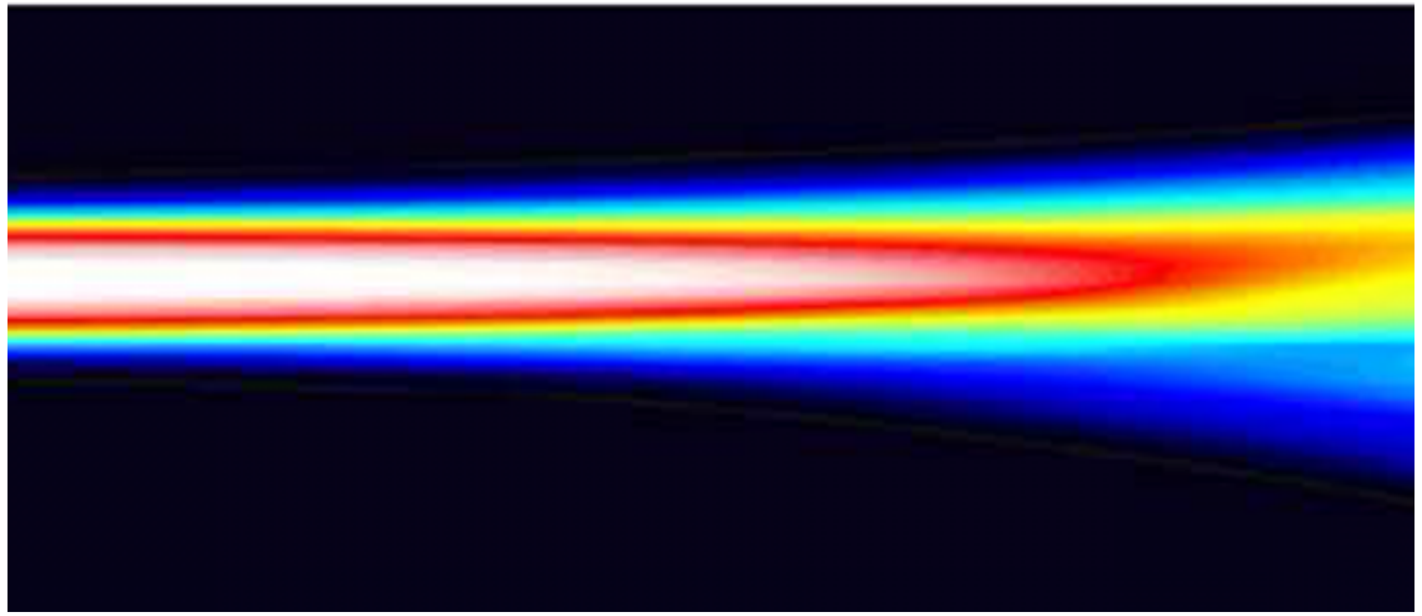
# INTRODUCTION

Reynolds-averaged Navier-Stokes (RANS) simulation

- 2D or 3D and steady or unsteady calculation
- Averaged flow equations
- Moderate computational cost, even for $Re > \mathcal{O}(10^6)$



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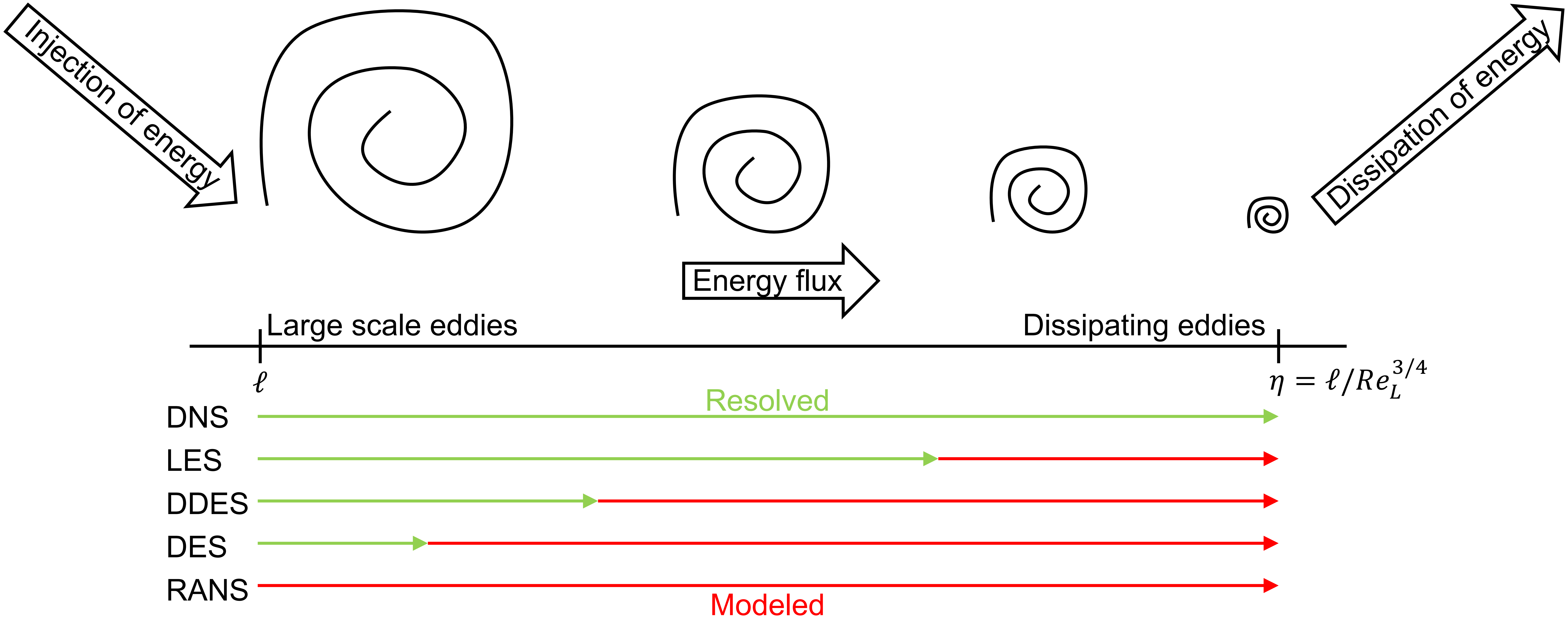
# INTRODUCTION

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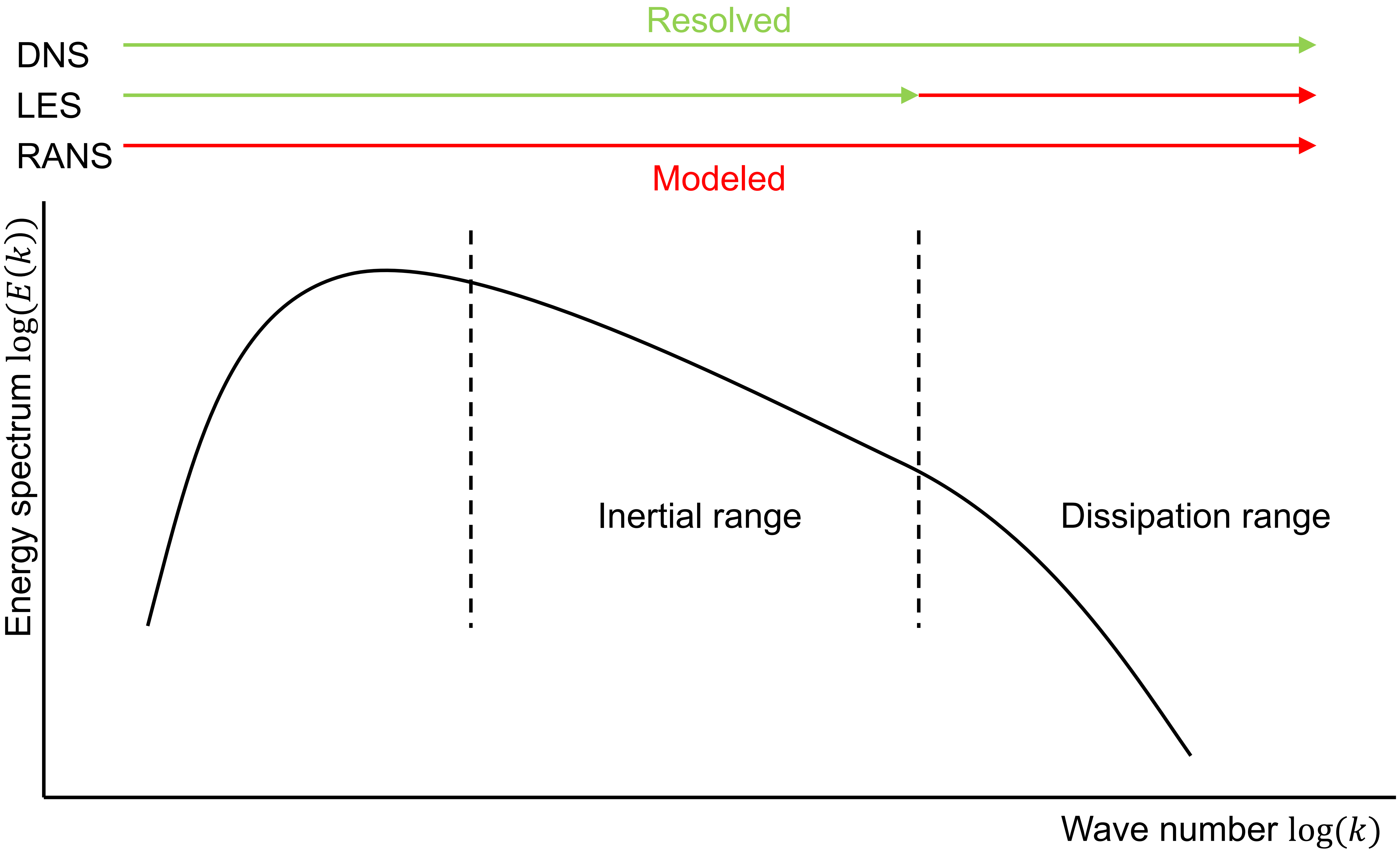
# INTRODUCTION

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# SLOT JET

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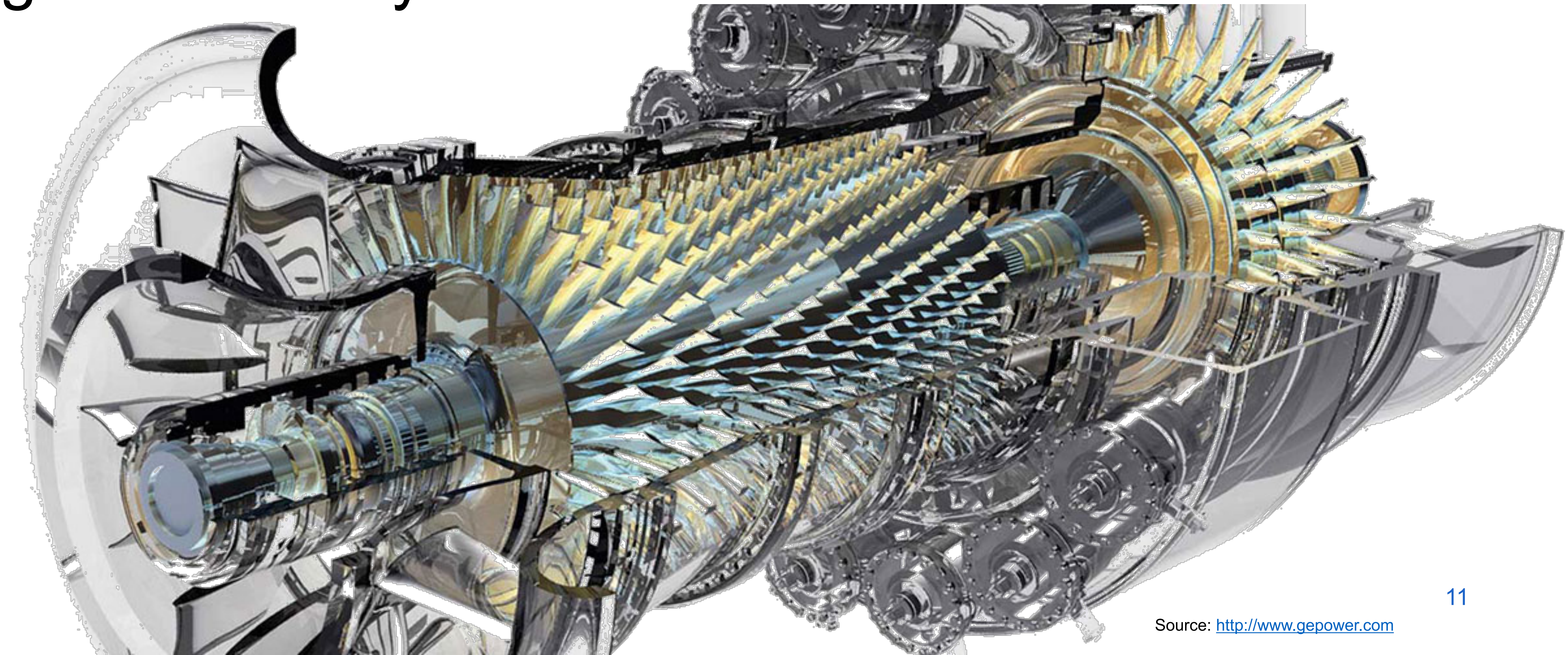
# SLOT JET

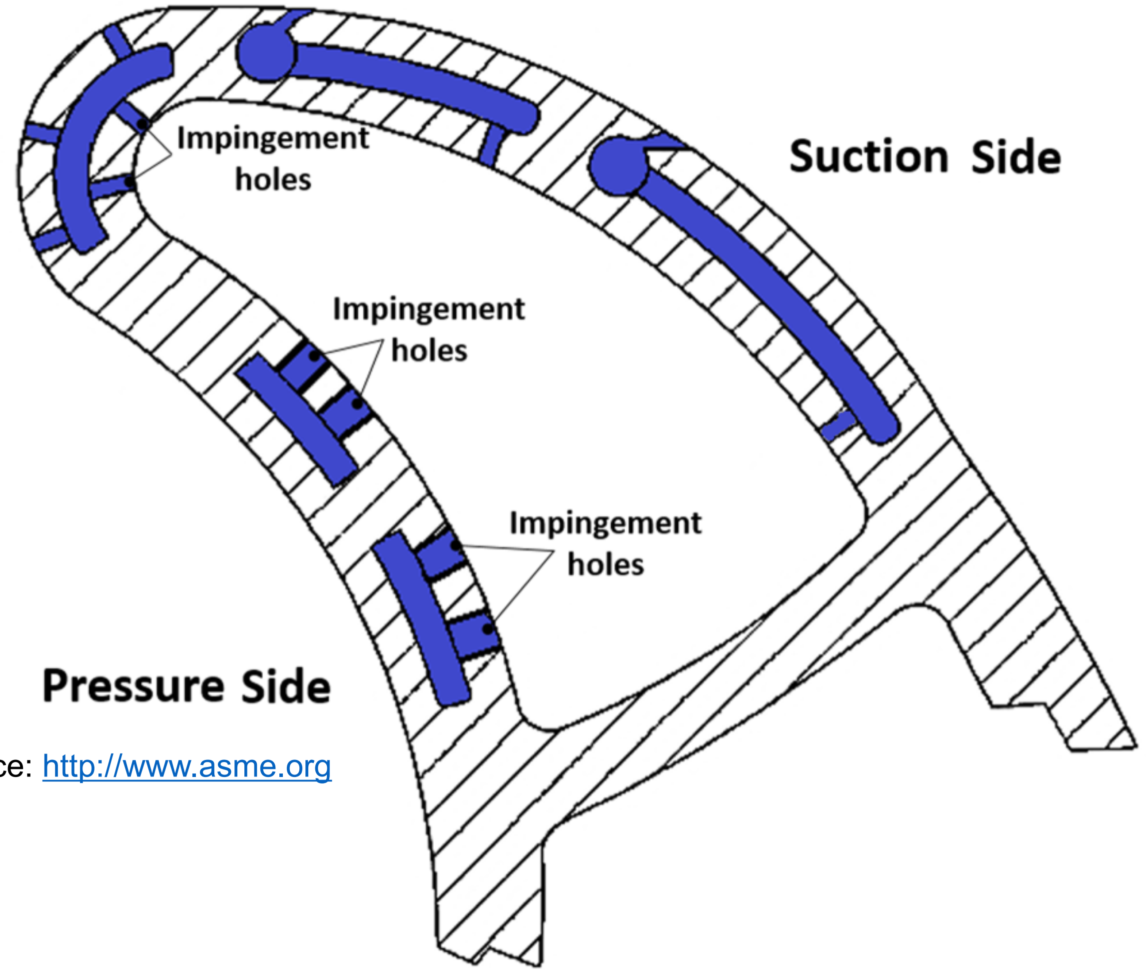
Cooling of gas turbine blades with impingement
→ Better cooling means higher gas temperatures and thus higher efficiency



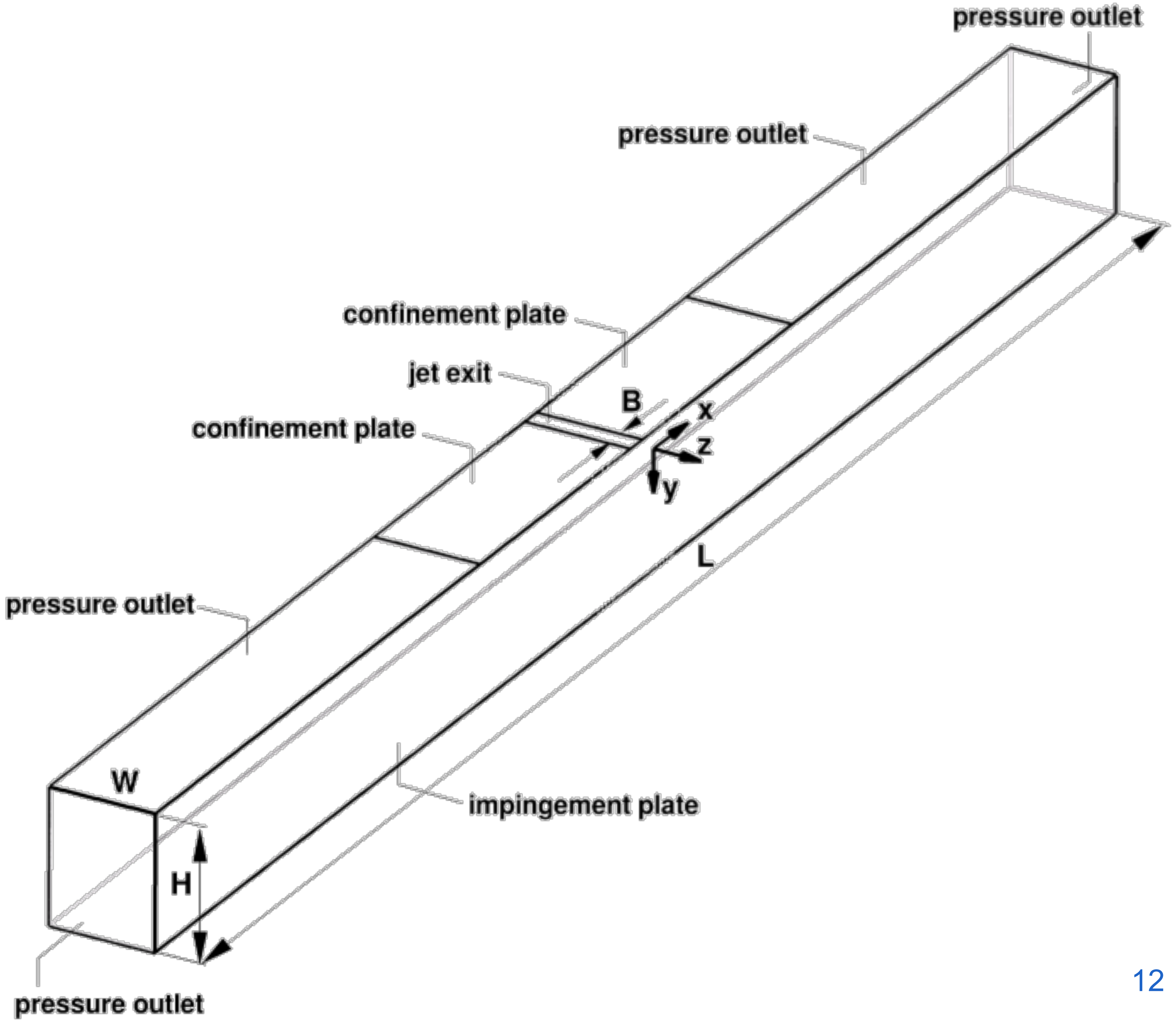
Source: http://www.gepower.com

# SLOT JET

Impingement cooling → Jet impinging on plate
in turbine blade




Source: http://www.asme.org

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# SLOT JET

LES with dynamic Smagorinsky model in OpenFOAM [3]

- Central differencing with filtering of high-frequency ripples in space
- Second-order implicit in time

| Case | $L/B$ | $H/B$ | $W/B$ | $N_x$ | $N_y$ | $N_z$ | $N_{\mathrm{tot}}$ (M) |
|---|---|---|---|---|---|---|---|
| $H/B = 9.2$, $\mathrm{Re} = 20\,000$ | 80 | 9.2 | $\pi$ | 320 | 320 | 70 | 7.2 |
| $H/B = 4$, $\mathrm{Re} = 18\,000$ | 80 | 4 | $\pi$ | 320 | 180 | 70 | 4.0 |
| $H/B = 2$, $\mathrm{Re} = 10\,000$ (fine) | 80 | 2 | $\pi$ | 540 | 200 | 140 | 15.1 |

→ Impossible without HPC (up to 1024 cores of gulpin)

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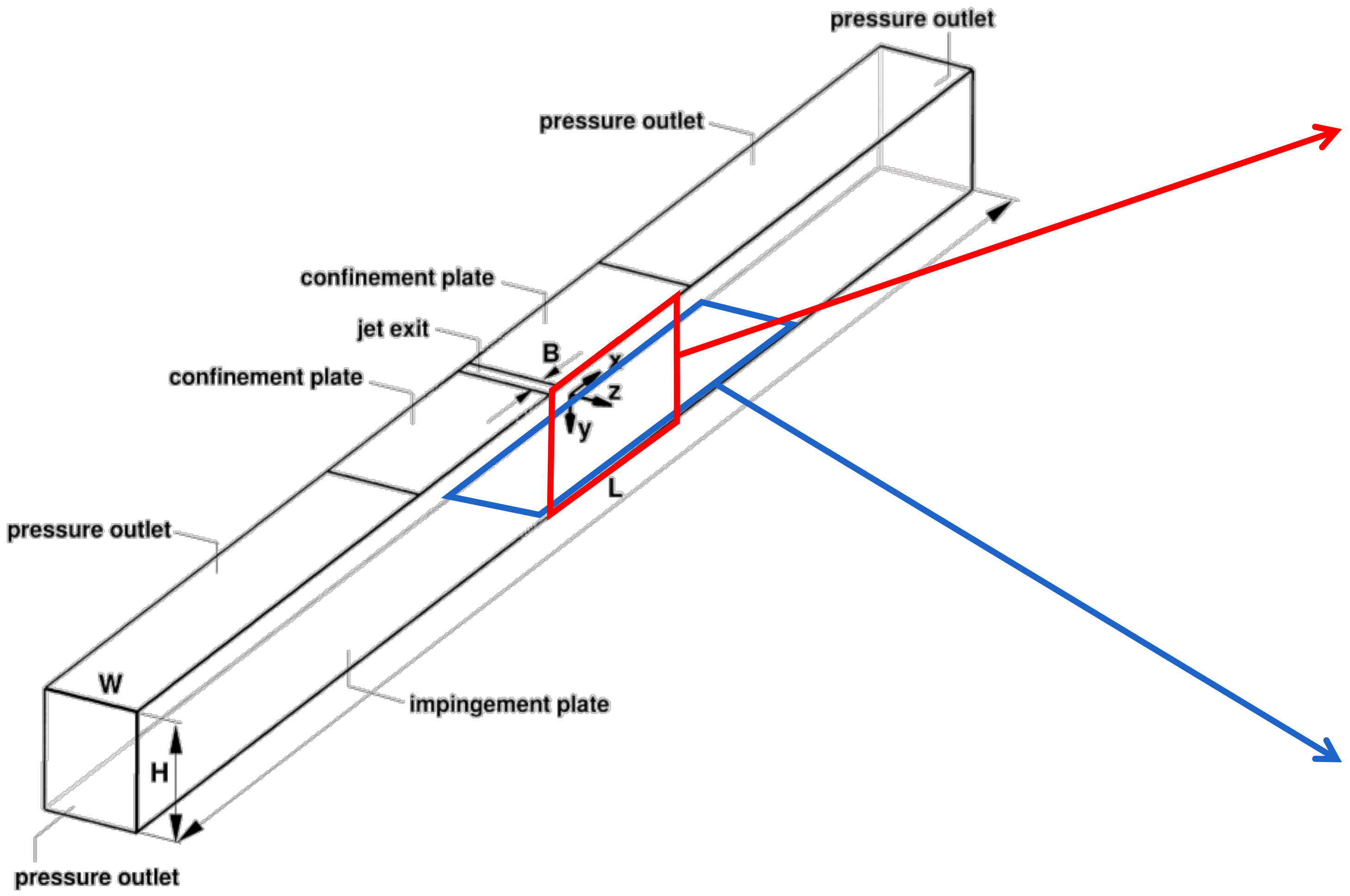
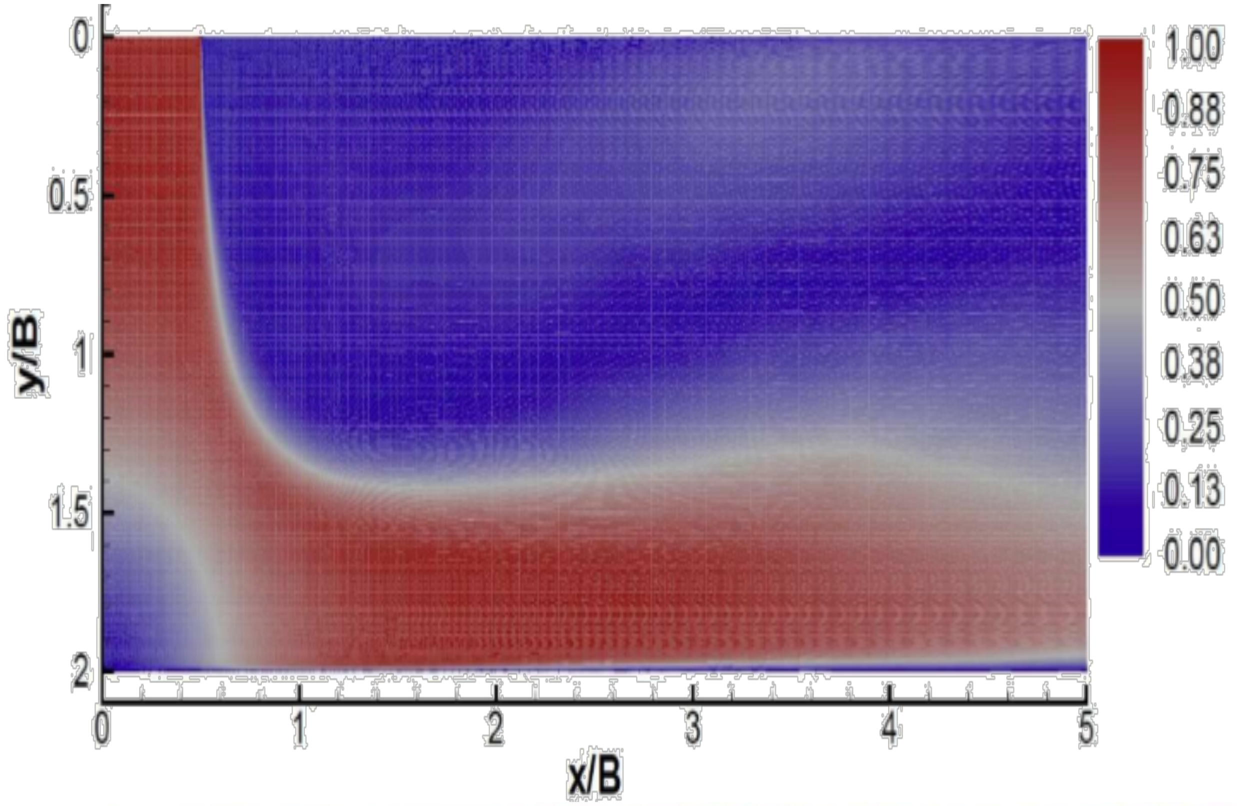
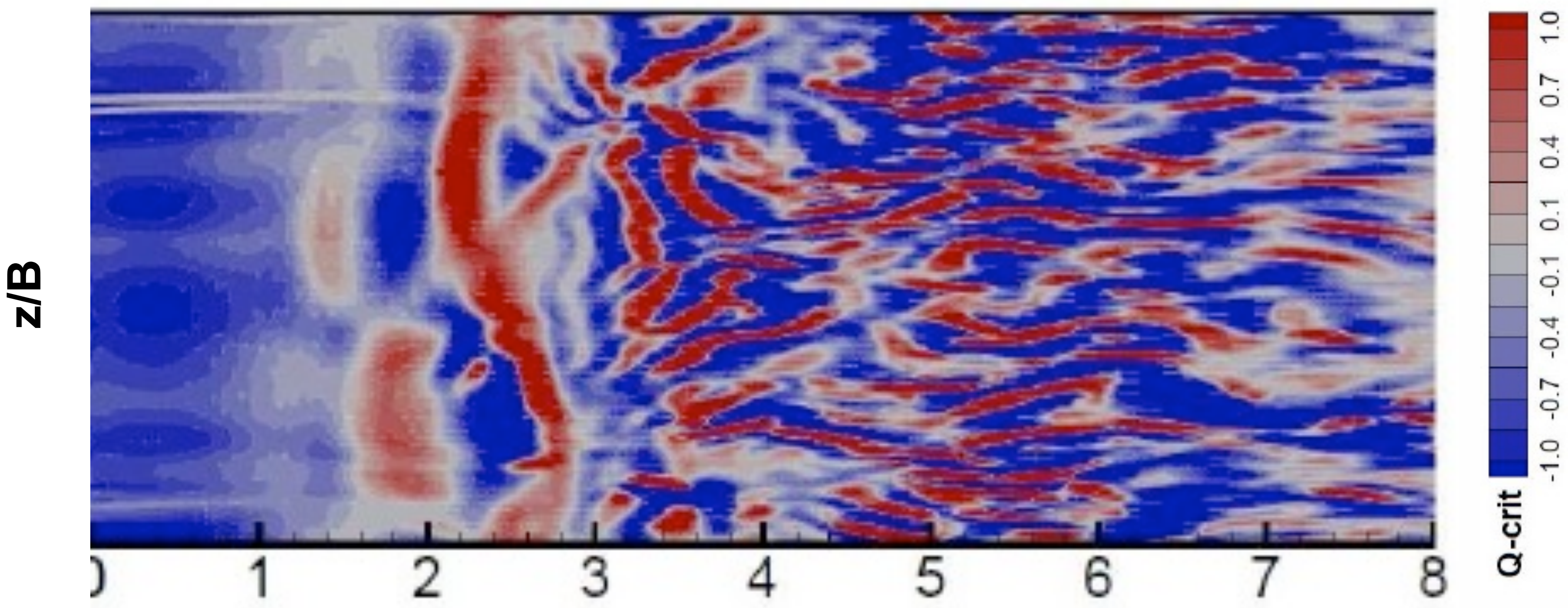
# SLOT JET

## Time-averaged velocity magnitude, Q-criterion

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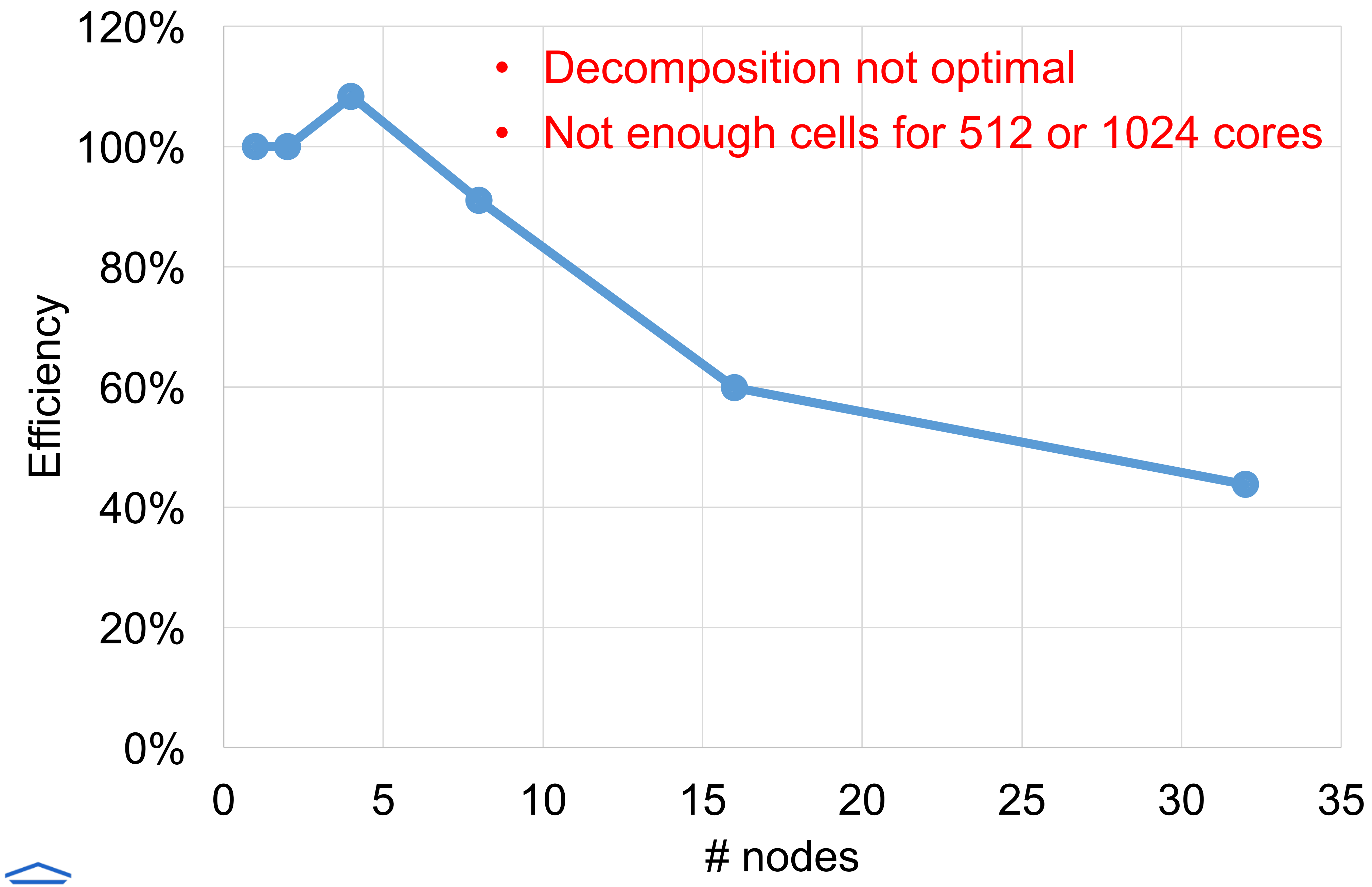
# SLOT JET

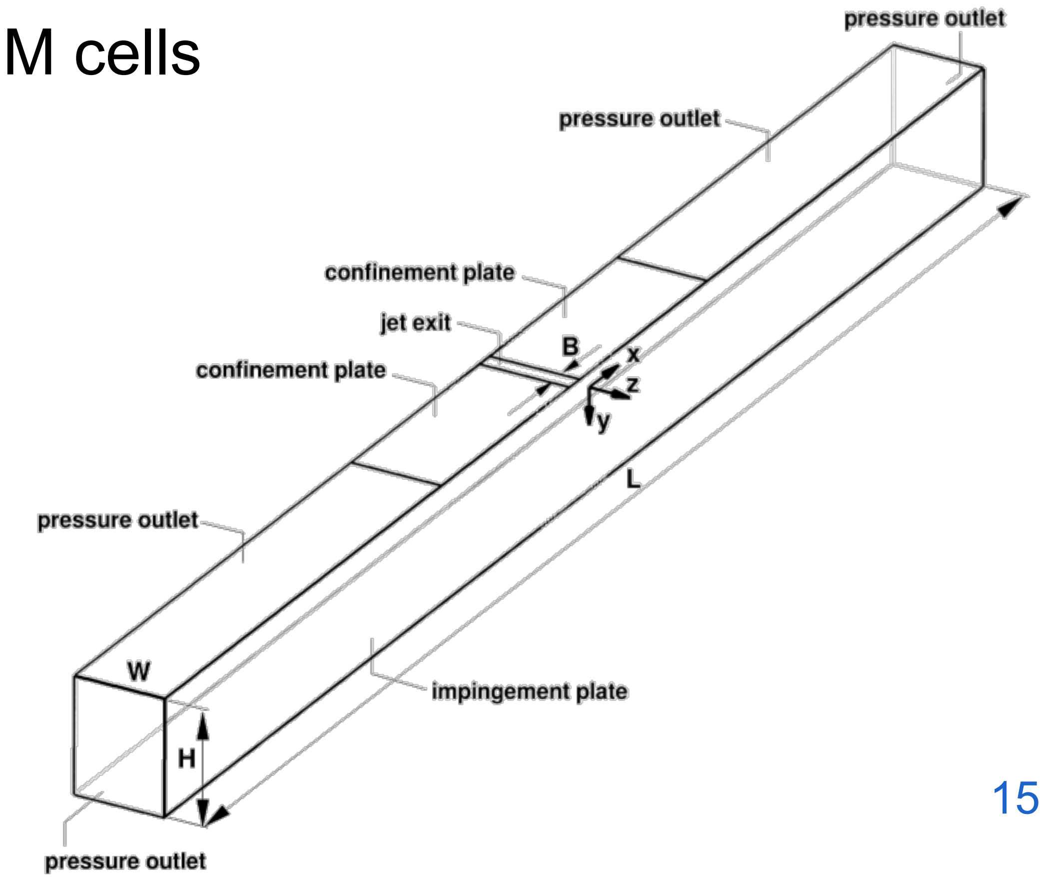
## Scaling on nodes with 4x8=32 cores of gulpin




| nodes | cores | decomposition |
|---|---|---|
| 1 | 32 | hierarchical zyx (8 4 1) |
| 2 | 64 | hierarchical zyx (8 4 2) |
| 4 | 128 | hierarchical zyx (16 4 2) |
| 8 | 256 | hierarchical zyx (16 8 2) |
| 16 | 512 | hierarchical zyx (16 8 4) |
| 32 | 1024 | hierarchical zyx (32 8 4) |

| Case | $N_x$ | $N_y$ | $N_z$ |
|---|---|---|---|
| $H/B = 2$, $\mathrm{Re} = 10\,000$ (fine) | 540 | 200 | 140 |

15.1M cells



# TUBE BUNDLE

# TUBE BUNDLE

Fatigue and fretting wear in tube bundles

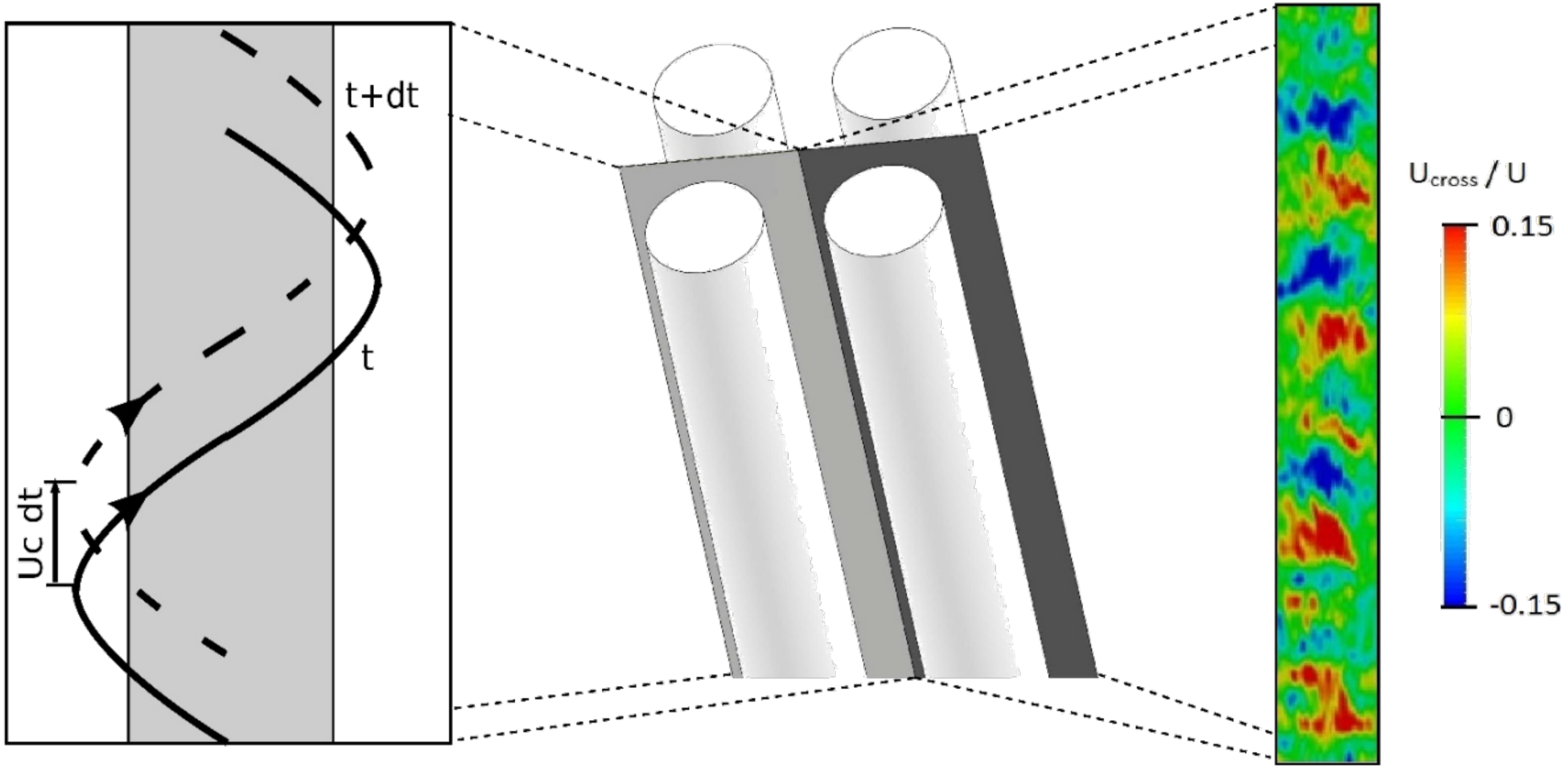
→ Tube rupture or leak

→ Cost and/or danger

Investigate contribution due to turbulence-induced vibration

# TUBE BUNDLE

Vortices in gaps between cylinders in tube bundles

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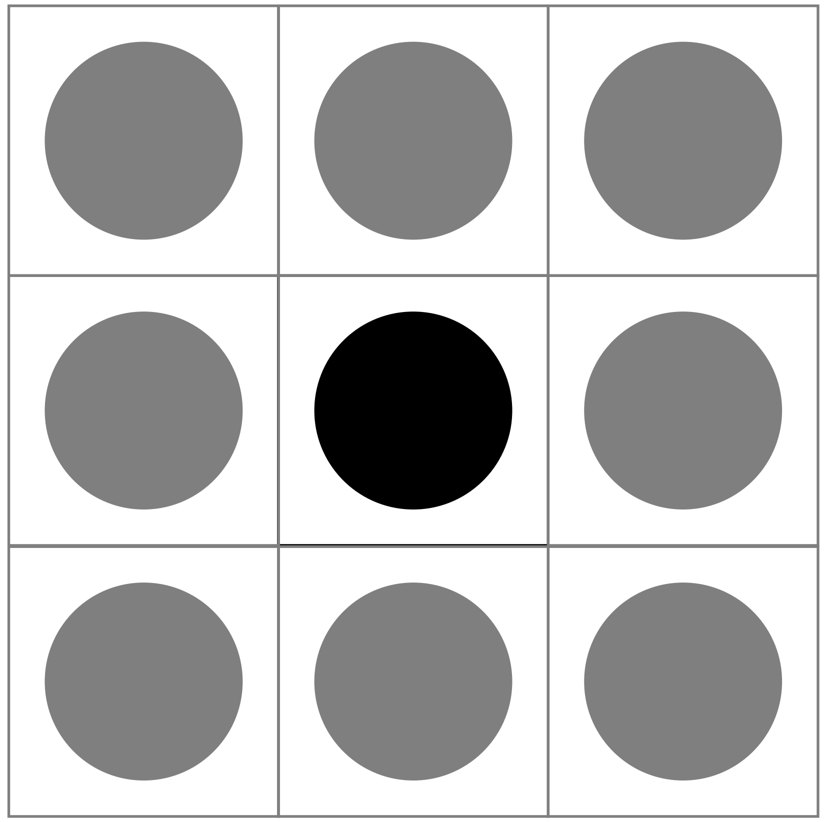
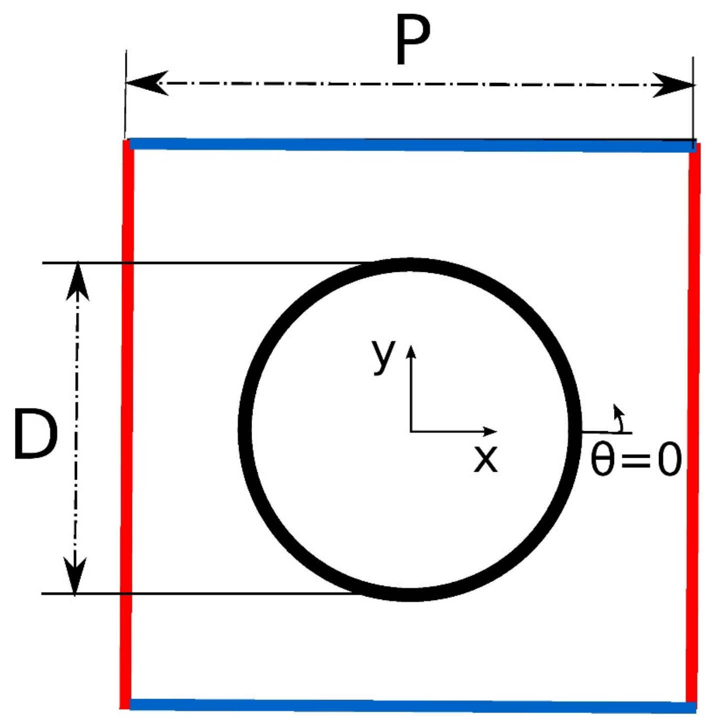
# TUBE BUNDLE

LES with dynamic Smagorinsky model in OpenFOAM [2]

Infinite array → periodic boundary conditions



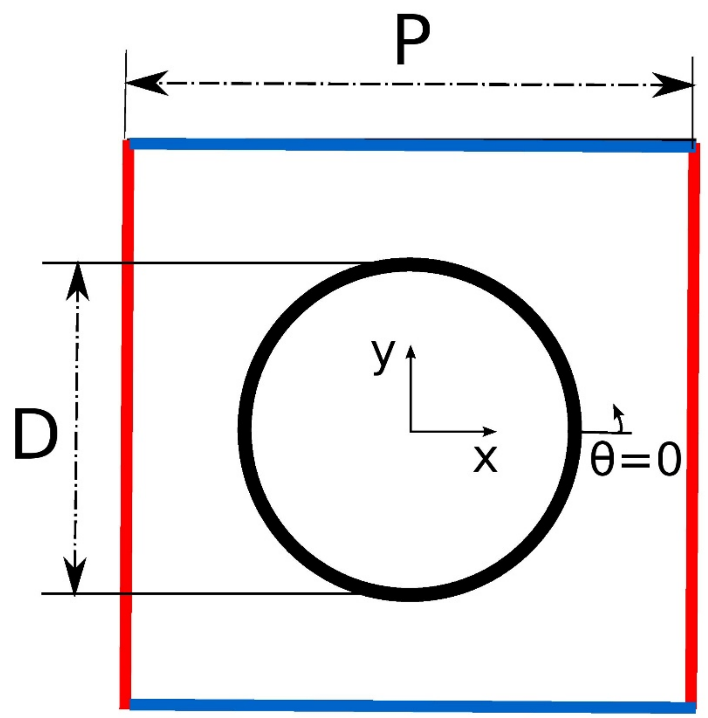


# TUBE BUNDLE

LES with dynamic Smagorinsky model in OpenFOAM [2]

Geometry → ~5M cells and 50k time steps

- $D = 0.2m$
- $P/D = 1.02 – 1.4$
- $D_h = 4\,(P^2 - \pi/4\,D^2) / (\pi\,D)$
- $Re_{Dh} = 10\,000$

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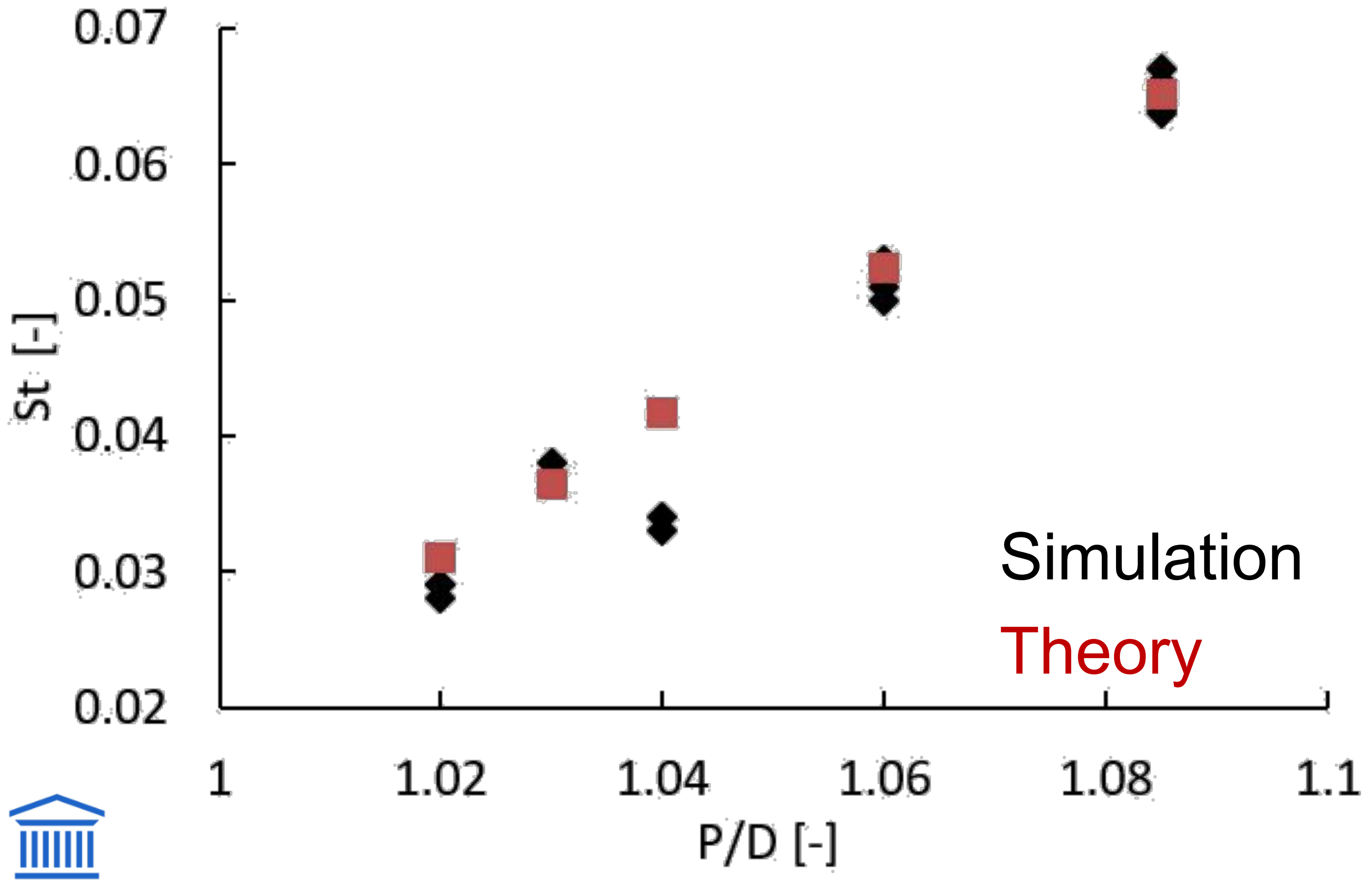
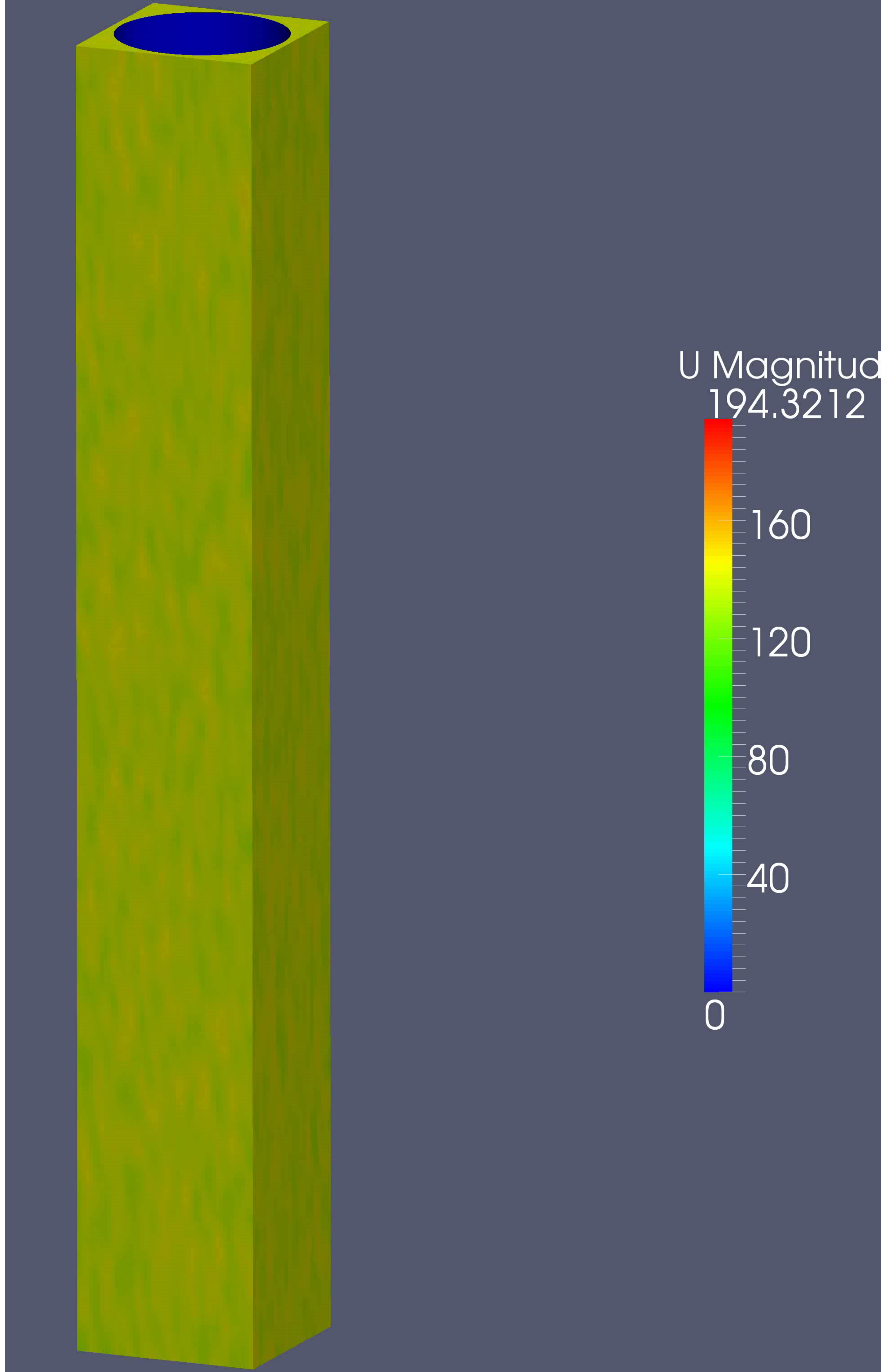
# TUBE BUNDLE

Velocity magnitude

Strouhal number for varying pitch/diameter

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# ANNULAR FLOW

# ANNULAR FLOW

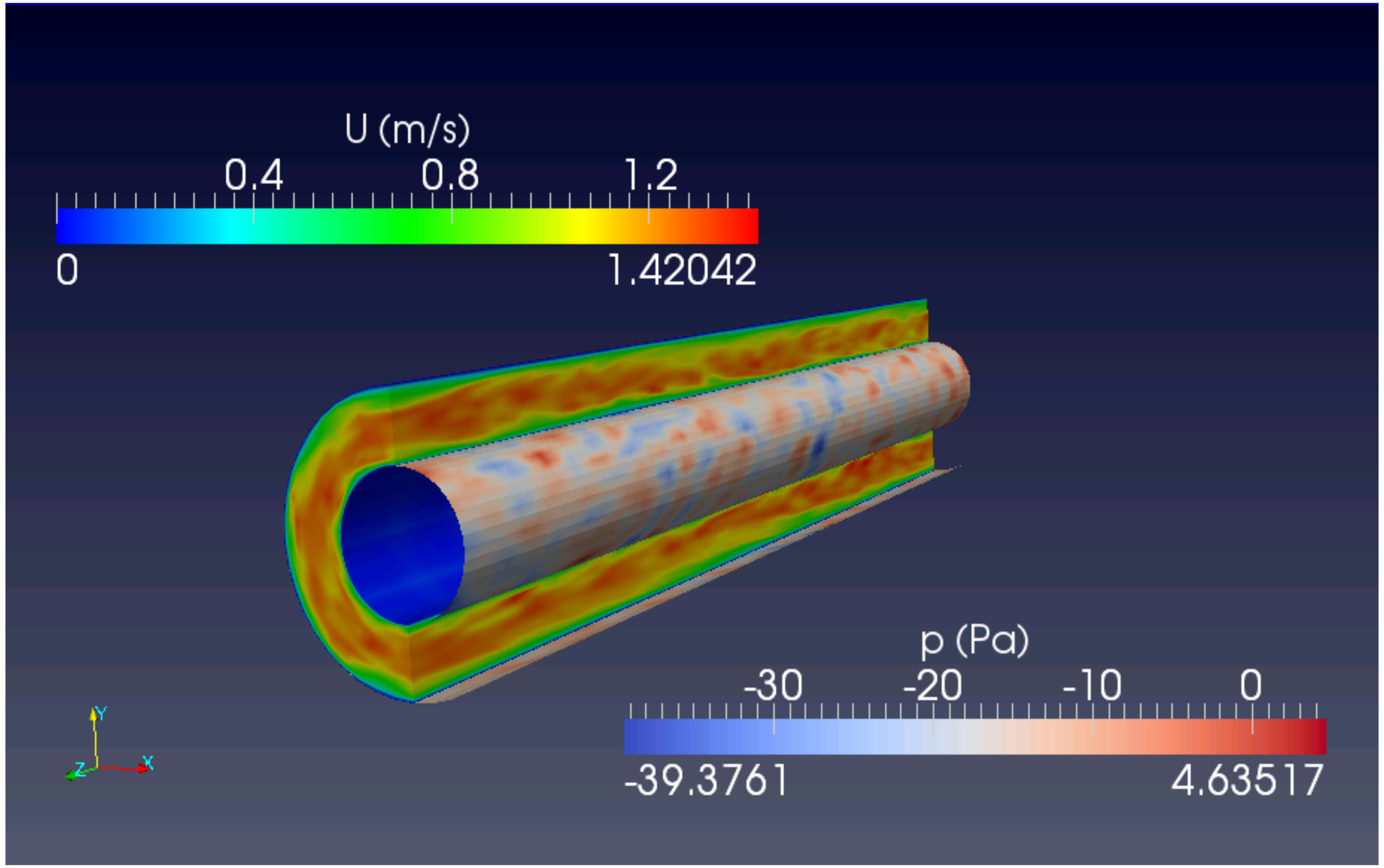
LES with dynamic Smagorinsky model in OpenFOAM [1]

Annular geometry

Flow field from LES

→ Pressure on wall

→ Vibration

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# ANNULAR FLOW

LES simulation corresponding to experiments by Chen

- Average velocity = 10 m/s
- Water density = 1000 $kg/m^3$
- Water viscosity = $10^{-3}$ kg/ms
- Hydraulic diameter = 0.0127 m
- Length = 10 hydraulic diameters
- Reynolds number = 127000

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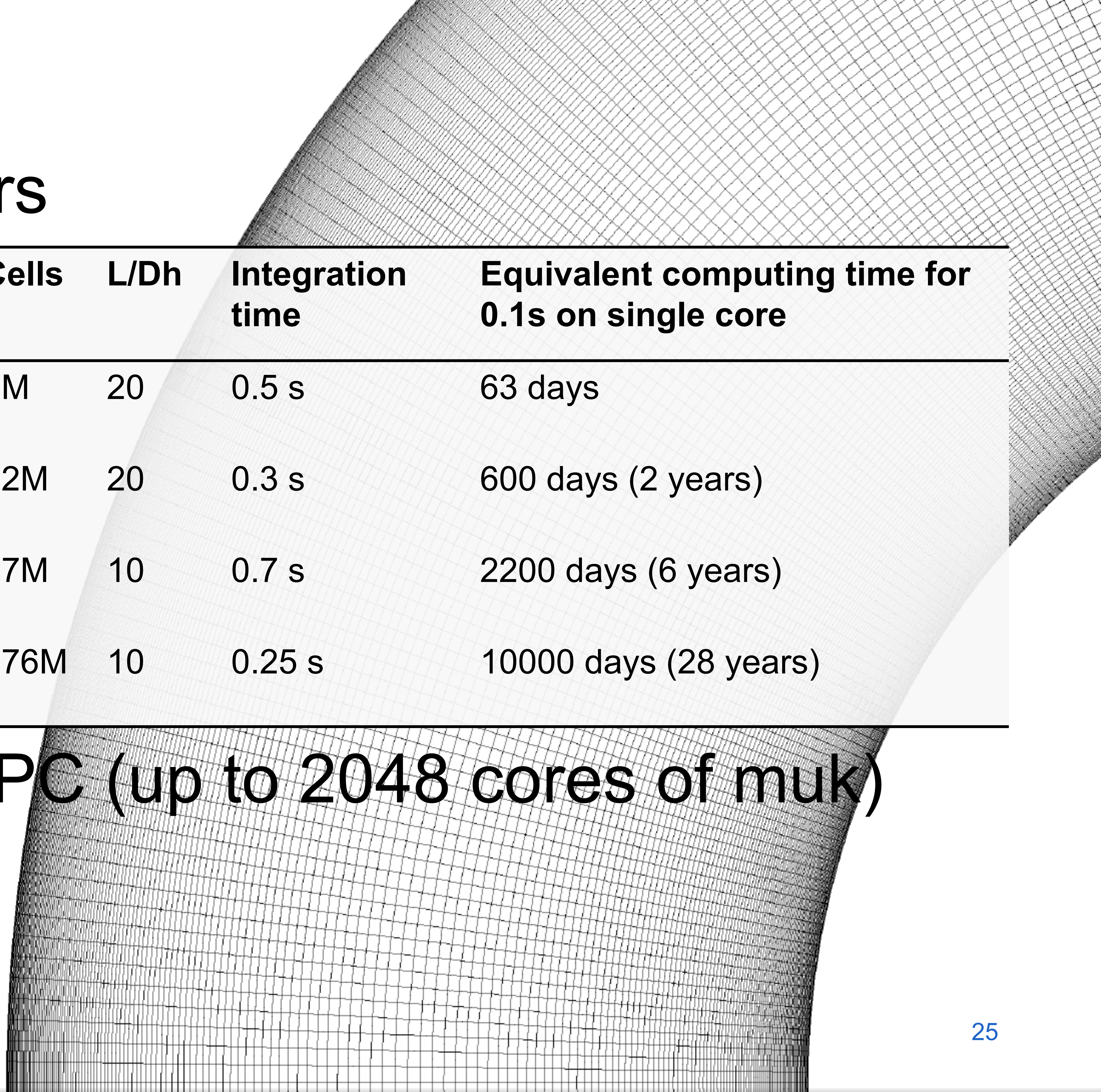
# ANNULAR FLOW

## Discretization parameters

| Case | Nr | Δr+ | Nθ | Nz | Cells | L/Dh | Integration time | Equivalent computing time for 0.1s on single core |
|---|---|---|---|---|---|---|---|---|
| Case A | 80 | 3 | 200 | 500 | 8M | 20 | 0.5 s | 63 days |
| Case B | 140 | 1 | 300 | 1000 | 42M | 20 | 0.3 s | 600 days (2 years) |
| Case C | 200 | 2 | 480 | 800 | 77M | 10 | 0.7 s | 2200 days (6 years) |
| Case D | 200 | 2 | 800 | 1100 | 176M | 10 | 0.25 s | 10000 days (28 years) |

→ Impossible without HPC (up to 2048 cores of muk)



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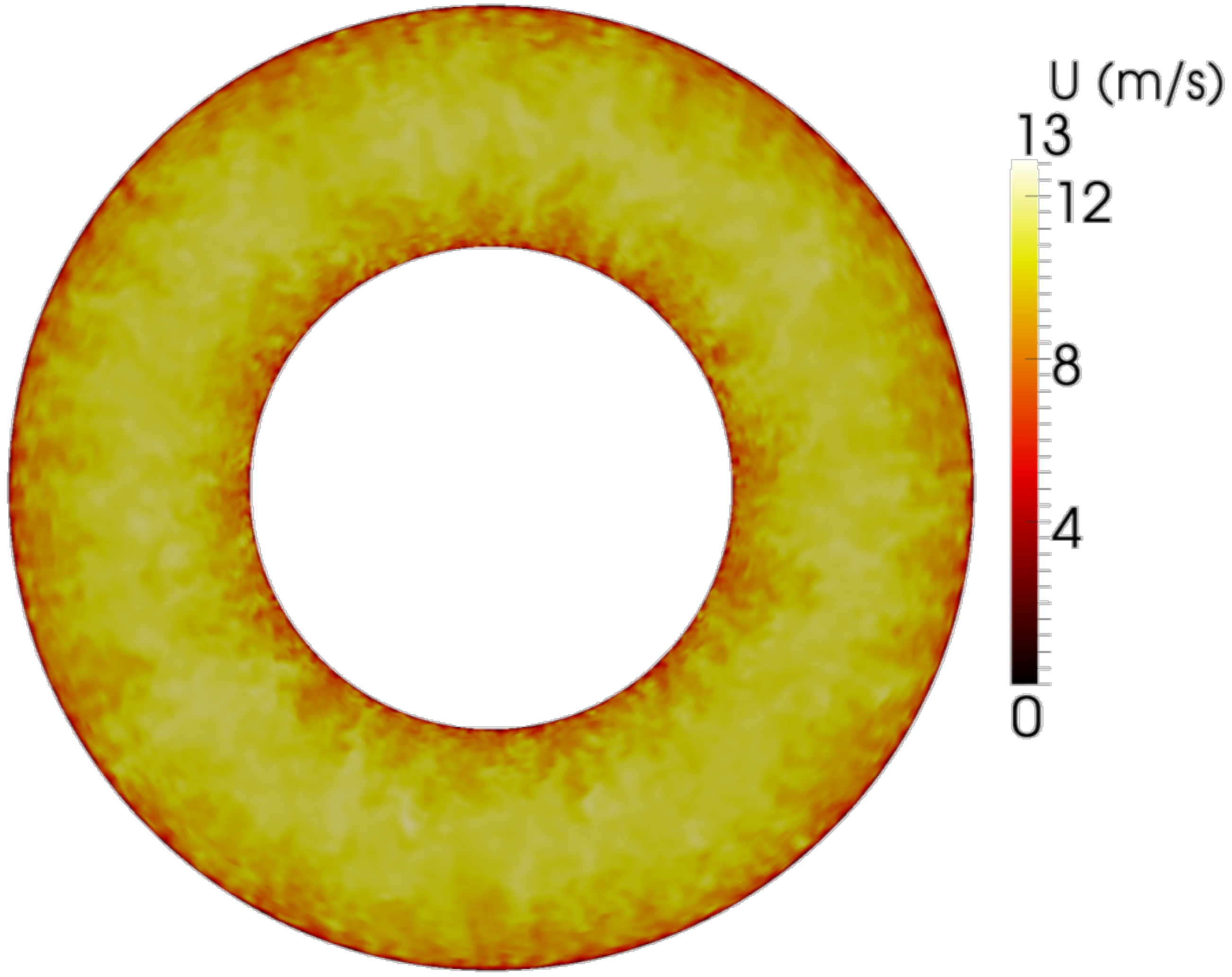
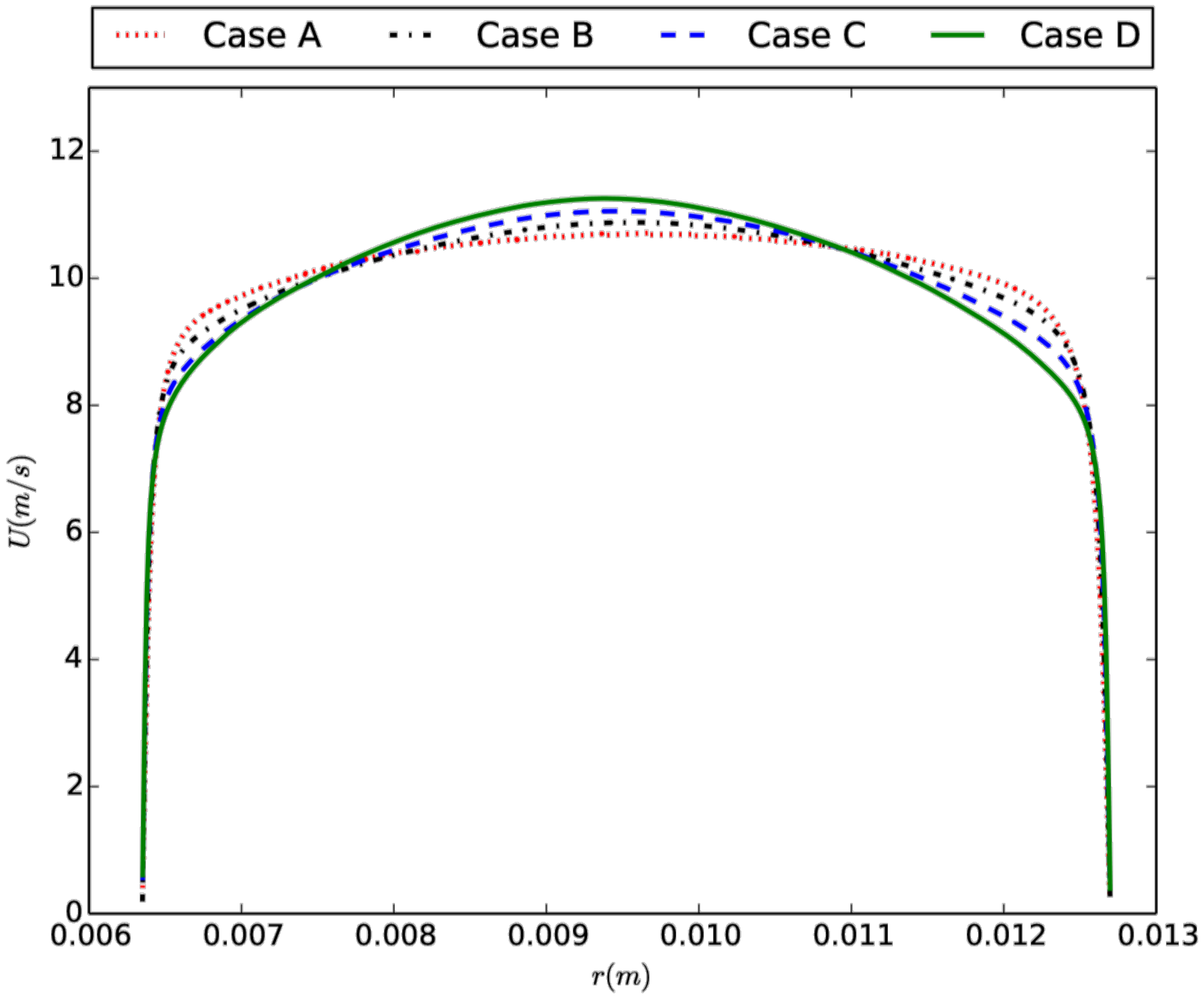
# ANNULAR FLOW

## Instantaneous velocity




## Averaged velocity profiles

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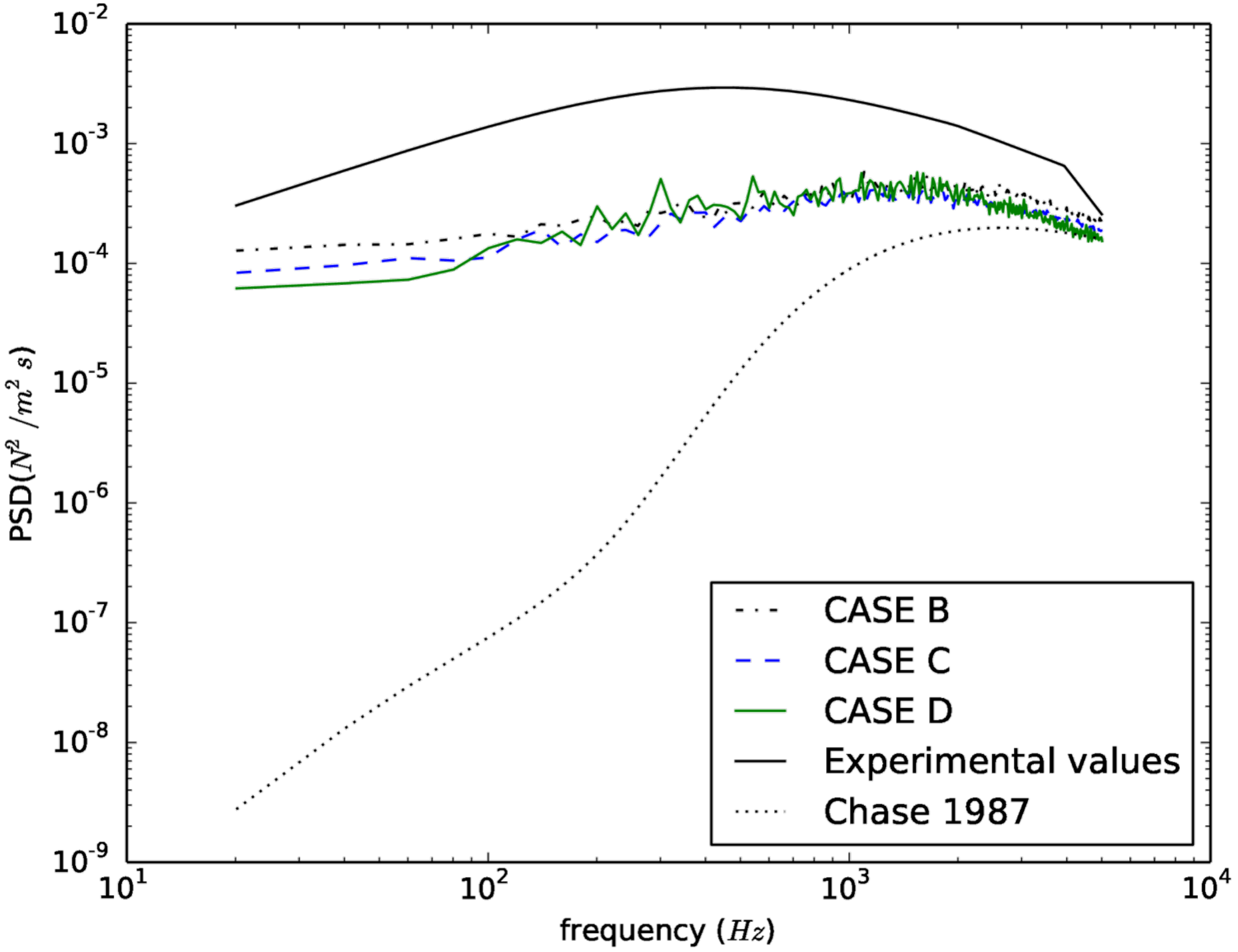
# ANNULAR FLOW

## Power spectral density of force/meter

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# DOMAIN DECOMPOSITION

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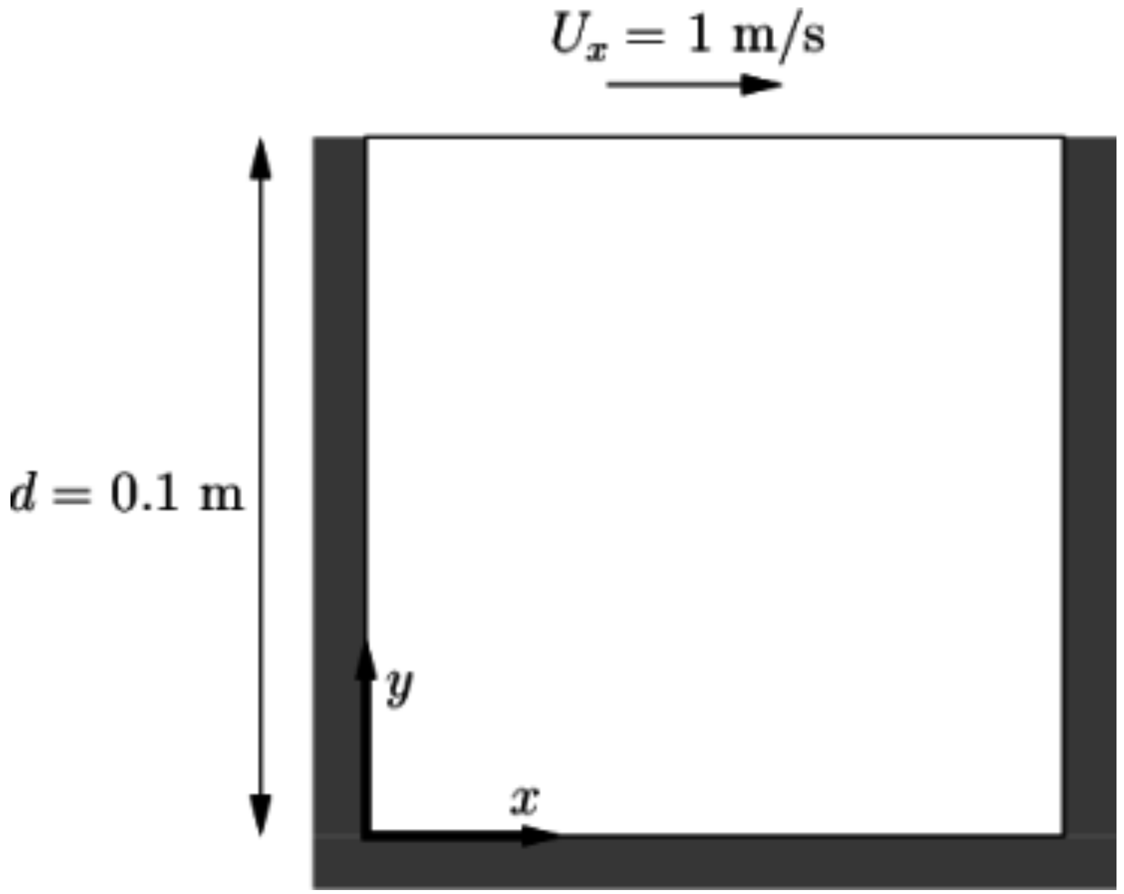
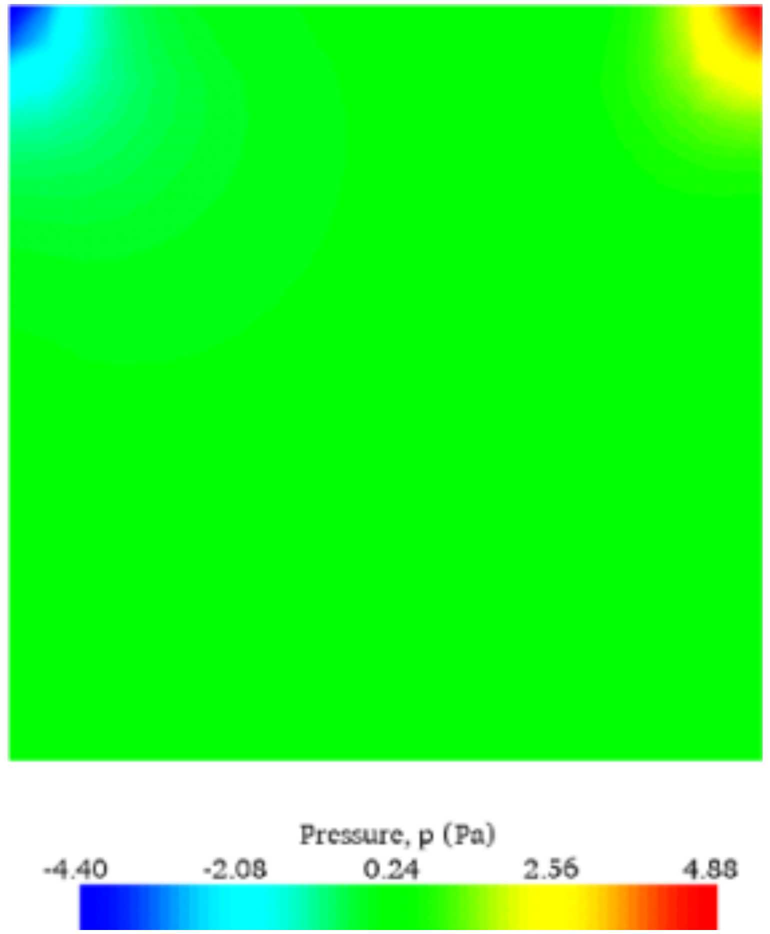
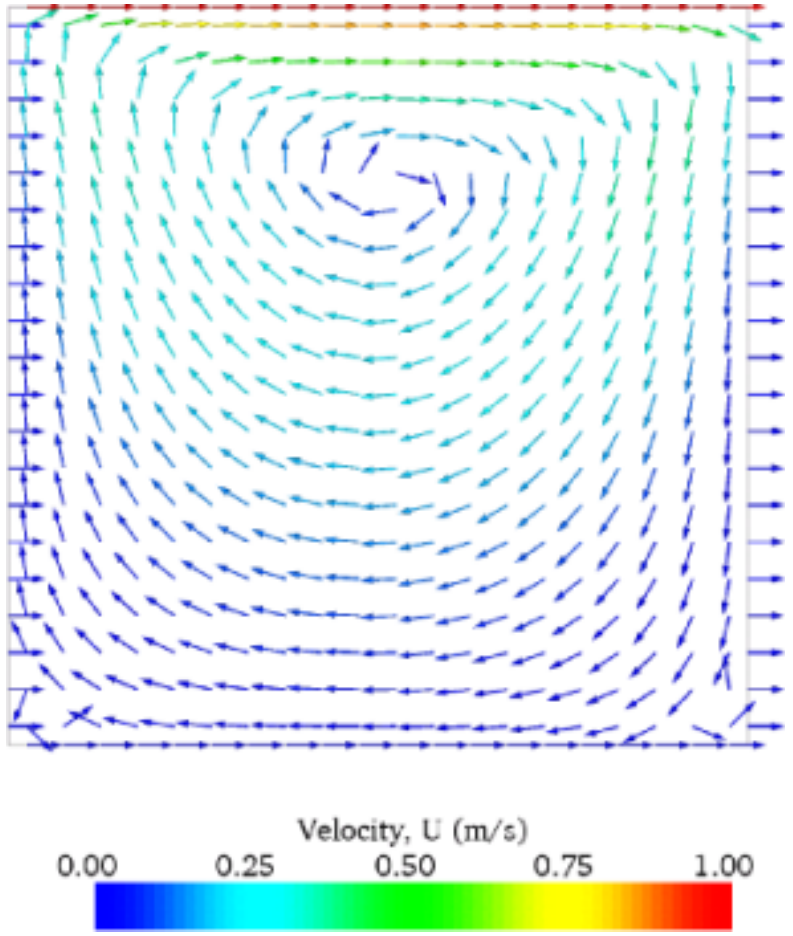
# DOMAIN DECOMPOSITION

Cavity case with icoFoam in OpenFOAM/4.1-intel-2016a on BrENIAC

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# DOMAIN DECOMPOSITION

Scaling tests

- Strong scaling: problem size stays fixed
- Weak scaling: problem size assigned to each processing element stays fixed

→ Here strong scaling on 51M and 206M cells because goal is to solve given problem as fast as possible

# DOMAIN DECOMPOSITION

Procedure

- Generate coarse mesh (blockMesh)
- Domain decomposition (decomposePar)
- Repeat
  - Select all cells (topoSet)
  - Refine selected cells (refineMesh)
- Solve on refined mesh (icoFoam)

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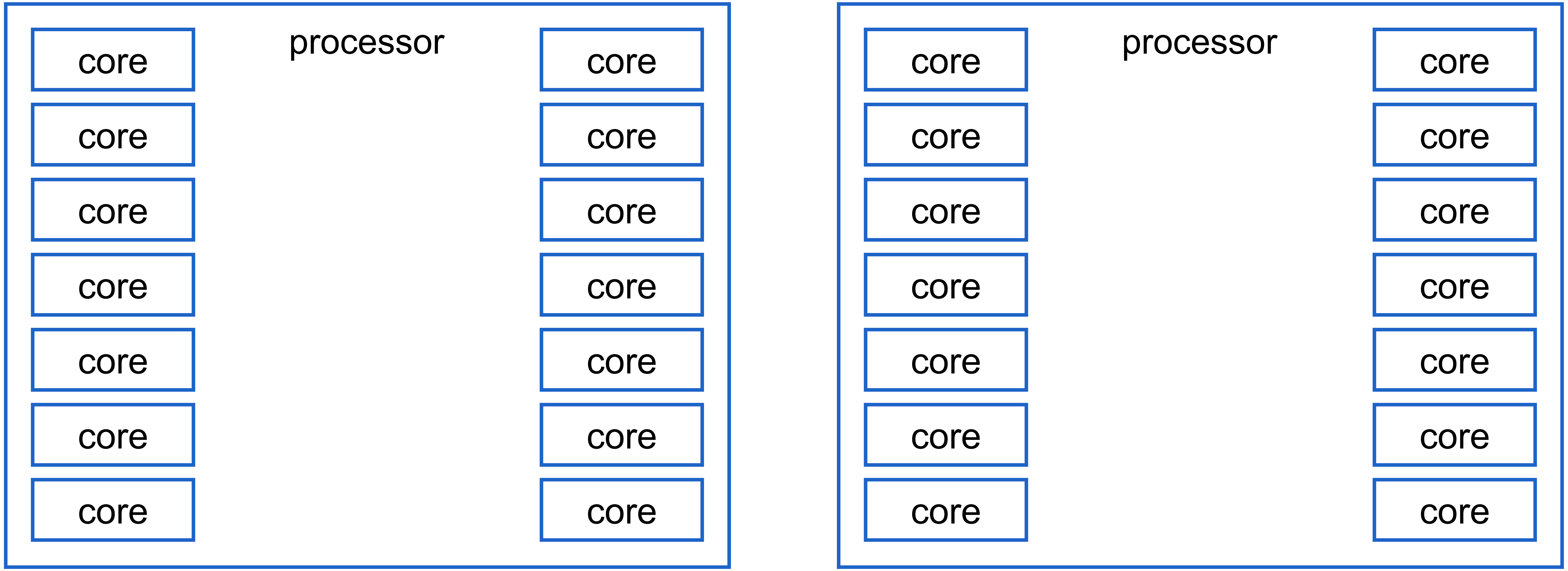
# DOMAIN DECOMPOSITION

Two Xeon E5-2680v4 processors per node of BrENIAC




→ 28 cores split in 4 groups of 7 cores per node

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# DOMAIN DECOMPOSITION

```
numberOfSubdomains  3584;
method          multiLevel;
multiLevelCoeffs
{
    level0
    {
        numberOfSubdomains  128;
        method simple;
        simpleCoeffs
        {
            n           (16 8 1);
            delta       0.000001;
        }
    }
    level1
    {
        numberOfSubdomains  28;
        method simple;
        simpleCoeffs
        {
            n           (4 7 1);
            delta       0.000001;
        }
    }
}
```

```
numberOfSubdomains  7168;
method          multiLevel;
multiLevelCoeffs
{
    level0
    {
        numberOfSubdomains  256;
        method simple;
        simpleCoeffs
        {
            n           (16 16 1);
            delta       0.000001;
        }
    }
    level1
    {
        numberOfSubdomains  28;
        method simple;
        simpleCoeffs
        {
            n           (4 7 1);
            delta       0.000001;
        }
    }
}
```

# DOMAIN DECOMPOSITION

Strong scaling on 206M cells (448x448 refined 5 times), with 448=28x16 (reference 2 nodes, too large for 1 node)

| # nodes | # cores | # x-dom | # y-dom | # x-cells | # y-cells | Actual Speedup | Efficiency % | # cells/core |
|---|---|---|---|---|---|---|---|---|
| 2 | 56 | 8 | 7 | 56 | 64 | 1.00 | 100.00 | 3670016 |
| 4 | 112 | 8 | 14 | 56 | 32 | 2.04 | 102.08 | 1835008 |
| 8 | 224 | 16 | 14 | 28 | 32 | 4.04 | 100.89 | 917504 |
| 16 | 448 | 16 | 28 | 28 | 16 | 8.26 | 103.31 | 458752 |
| 32 | 896 | 32 | 28 | 14 | 16 | 17.43 | 108.91 | 229376 |
| 64 | 1792 | 32 | 56 | 14 | 8 | 32.64 | 101.99 | 114688 |
| 128 | 3584 | 64 | 56 | 7 | 8 | 69.69 | 108.89 | 57344 |

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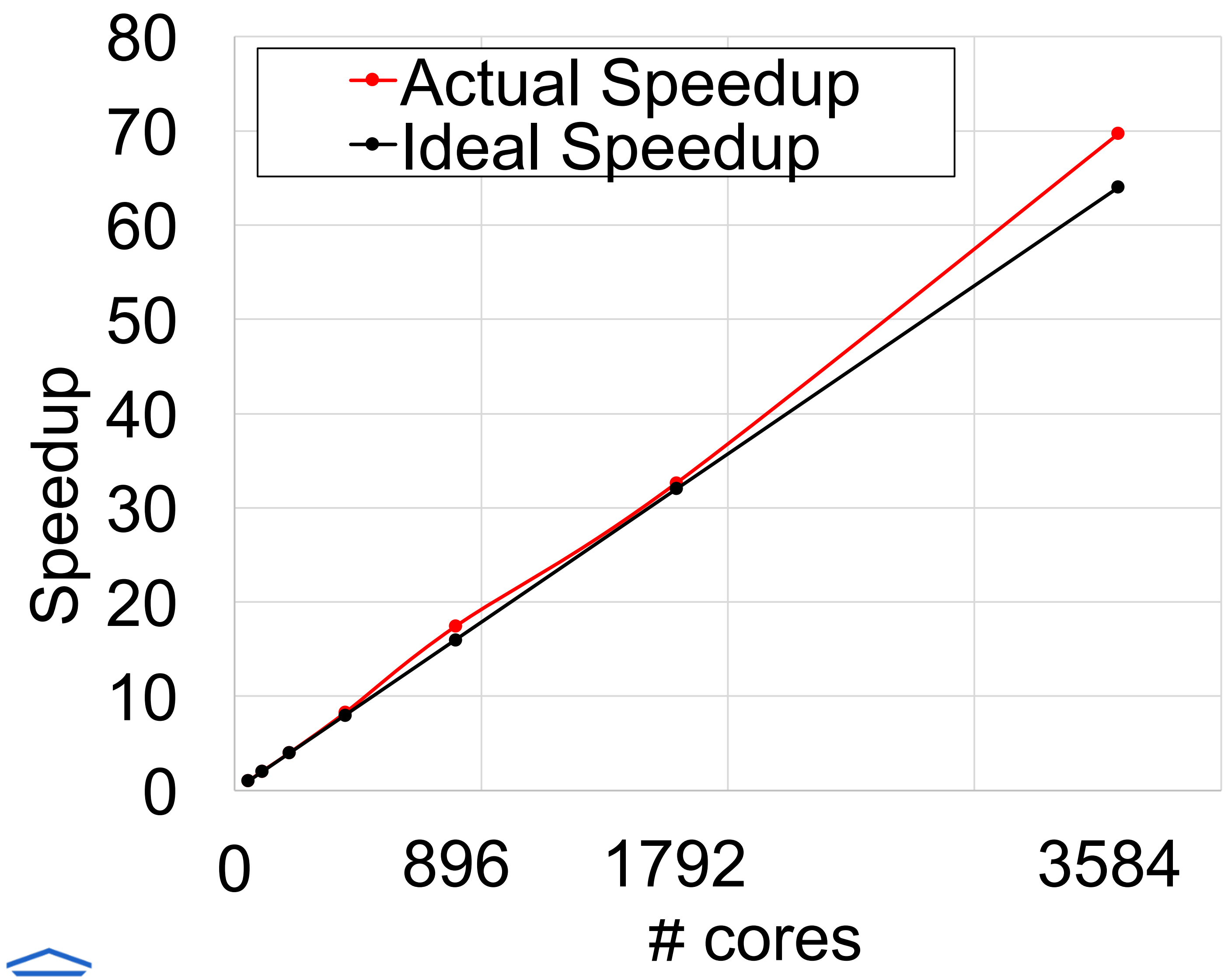
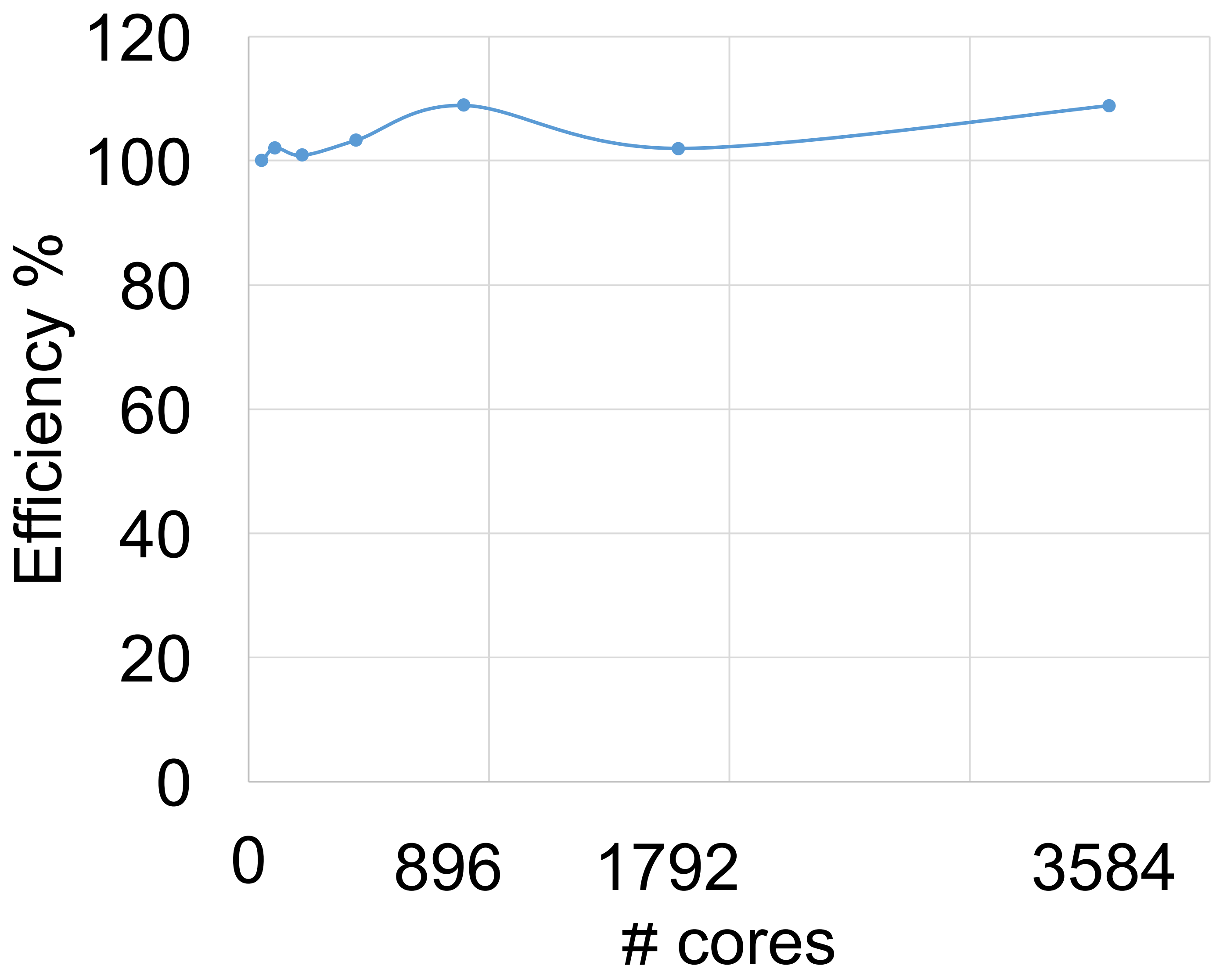
# DOMAIN DECOMPOSITION

Strong scaling on 206M cells (448x448 refined 5 times), with 448=28x16

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# DOMAIN DECOMPOSITION

Strong scaling on 51M cells (448x448 refined 4 times), with 448=28x16 and insufficient #cells/core

| # nodes | # cores | # x-dom | # y-dom | # x-cells | # y-cells | Actual Speedup | Efficiency % | # cells/core |
|---|---|---|---|---|---|---|---|---|
| 1 | 28 | 4 | 7 | 112 | 64 | 1.00 | 100.00 | 1835008 |
| 2 | 56 | 8 | 7 | 56 | 64 | 1.96 | 97.90 | 917504 |
| 4 | 112 | 8 | 14 | 56 | 32 | 4.09 | 102.20 | 458752 |
| 8 | 224 | 16 | 14 | 28 | 32 | 9.07 | 113.38 | 229376 |
| 16 | 448 | 16 | 28 | 28 | 16 | 23.66 | 147.86 | 114688 |
| 32 | 896 | 32 | 28 | 14 | 16 | 55.83 | 174.46 | 57344 |
| 64 | 1792 | 32 | 56 | 14 | 8 | 110.04 | 171.94 | 28672 |
| 128 | 3584 | 64 | 56 | 7 | 8 | 137.20 | 107.19 | 14336 |
| 256 | 7168 | 64 | 112 | 7 | 4 | 177.90 | 69.49 | 7168 |

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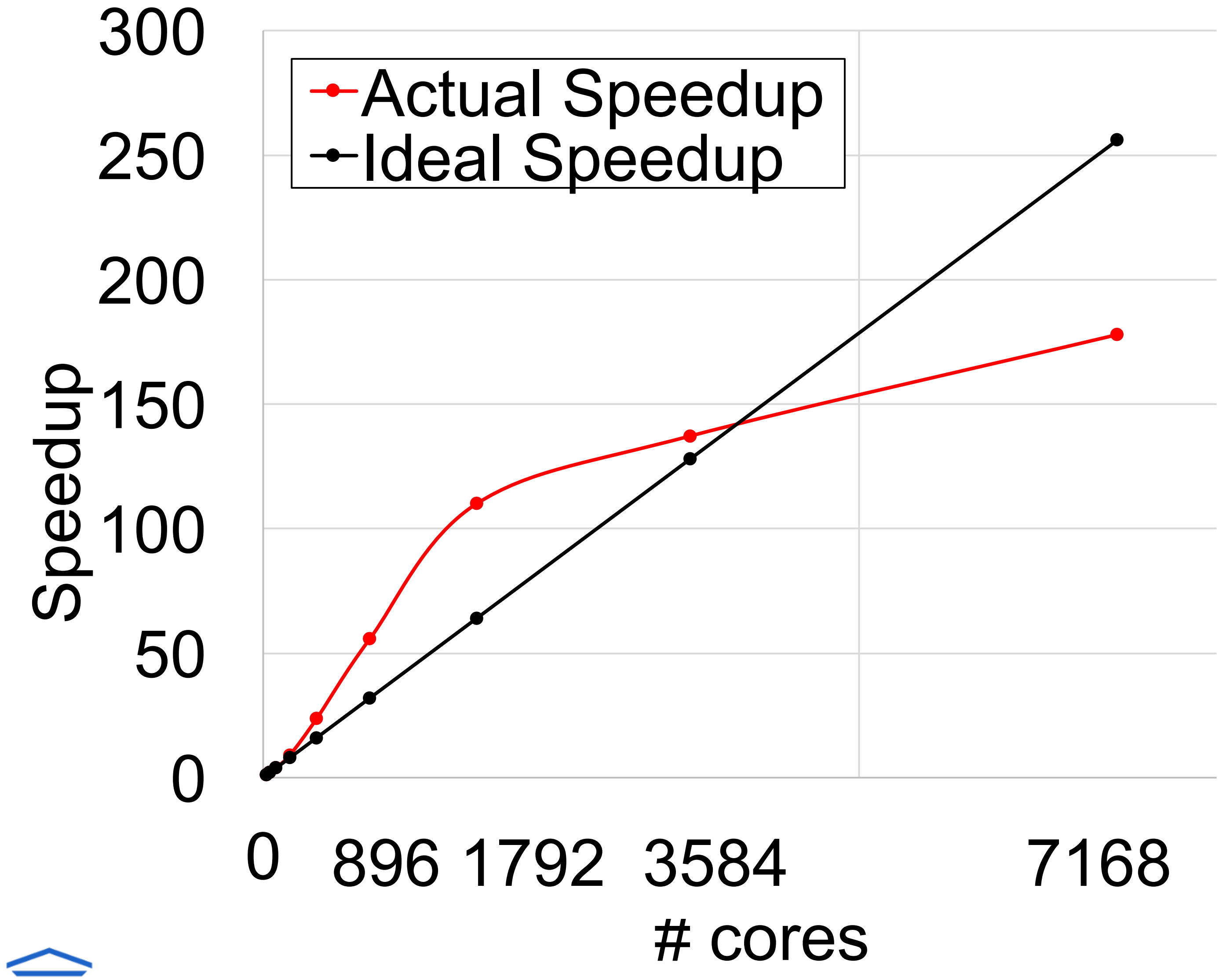
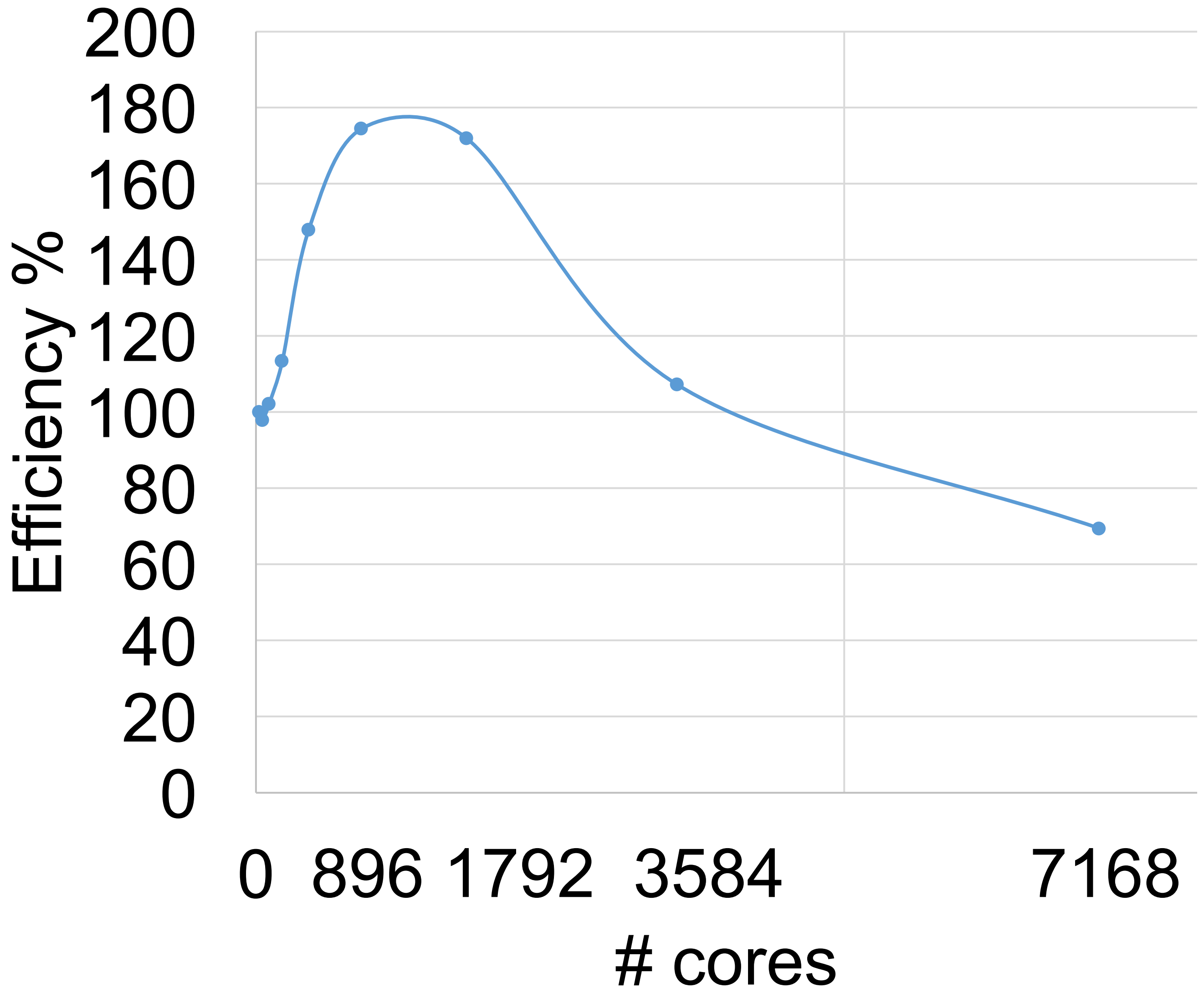
# DOMAIN DECOMPOSITION

Strong scaling on 51M cells (448x448 refined 4 times), with 448=28x16 and insufficient #cells/core

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# COMPARISON CFD PACKAGES

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# COMPARISON CFD PACKAGES

OpenFOAM compared with Fluent (personal **opinion/feeling**, not facts!)

+ Access to source code (but not always needed…)
+ No licenses, so good for HPC (but cost small compared to salary…)
+ Facilitates local and international collaboration
+ Accepted in scientific community
+ Fun!

- Less systematic validation (but always good to test it yourself…)
- Less documentation (but you can look in code…)
- Fewer features (but catching up and possibility to add your own…)
- Different branches (.com/.org/-extend) and incompatible versions
- Longer learning curve (developing requires C++ skills, no GUI…)

# CONCLUSIONS

LES simulation in OpenFOAM

- Results in agreement with other data
- Think about domain decomposition

CFD course

- Exercises in OpenFOAM next year
- Project can already be done in OpenFOAM this year

# REFERENCES

[1] J. De Ridder, J. Degroote, K. Van Tichelen, P. Schuurmans, and J. Vierendeels. Predicting turbulence-induced vibration in axial annular flow by means of large-eddy simulations. *Journal of Fluids and Structures*, 61:115–131, 2016. DOI: 10.1016/j.jfluidstructs.2015.10.011.

[2] L. De Moerloose, P. Aerts, J. De Ridder, J. Degroote, and J. Vierendeels. Numerical investigation of large-scale vortices in an array of cylinders in axial flow. Submitted to *Journal of Fluids and Structures.*

[3] S. Kubacki, J. Rokicki, E. Dick, J. Degroote, and J. Vierendeels. Hybrid RANS/LES of plane jets impinging on a flat plate at small nozzle-plate distances. *Archives of Mechanics*, 65(2):143–166, 2013.

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