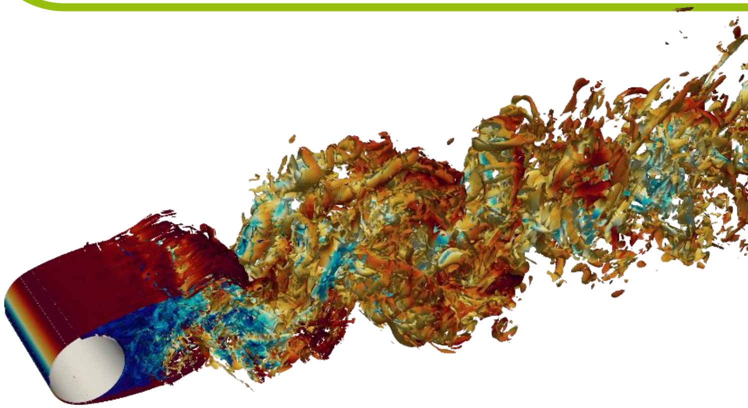
Development of a DGM Solver for Scale-Resolving Simulations (8170)

MS910 – 4th Intl. Workshop on High Order CFD Methods
ECCOMAS, Creta, June 9th 2016



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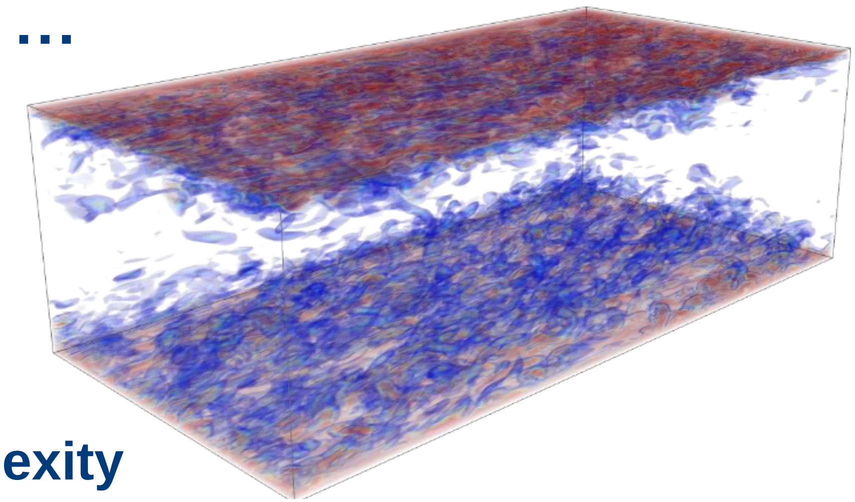
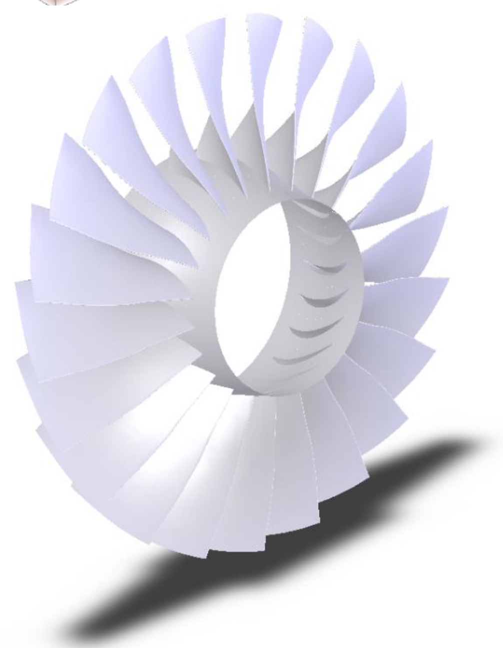
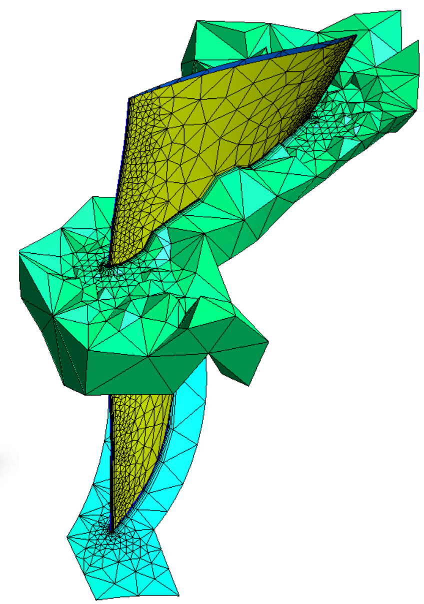
Doc. ref.: CMSD-NS-0XX-00

Enabling high resolution DNS/LES in industry

- **Academia: Spectral, FDM, …**
  - High accuracy
  - HPC
  - Low flexibility
- **Industry: FVM, FEM**
  - Low accuracy
  - Robustness ~ RANS, complexity
  - High flexibility
  - Moderate HPC performance
- **New CFD cores required**
  - Guaranteed accuracy, low error …
  - On unstructured meshes
  - Near BC, NMC, RSI, Chimera
  - High serial and parallel efficiency
  - Adaptivity ?







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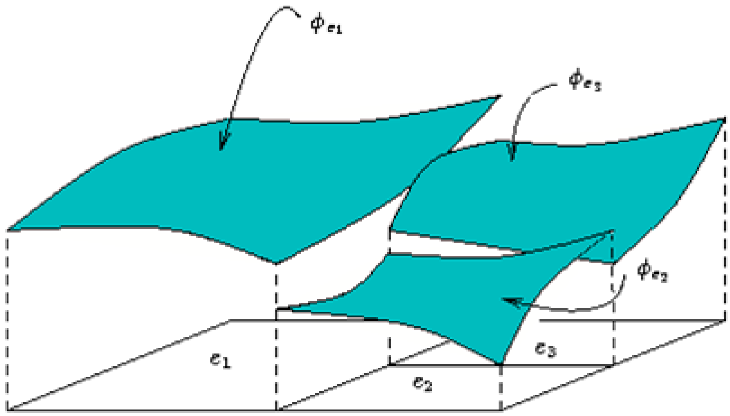
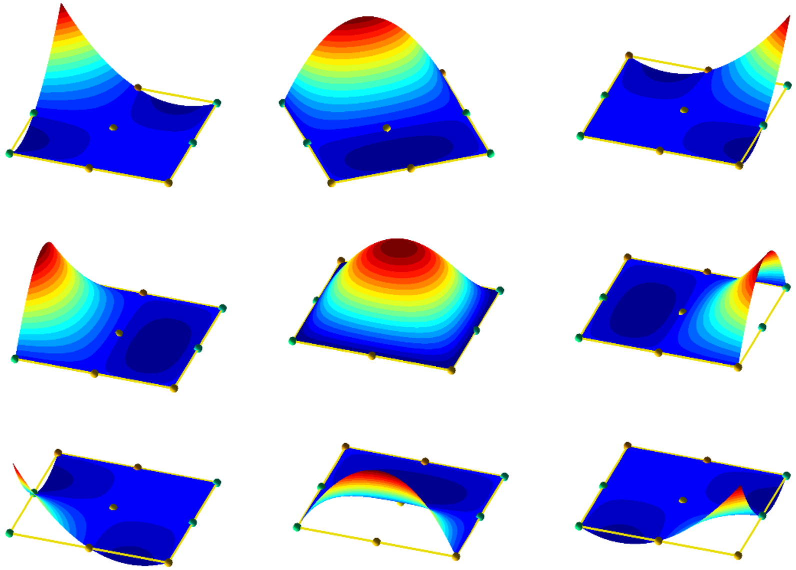
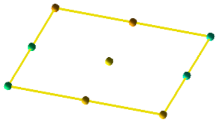
The Discontinuous Galerkin Method

- Reinterpretation
  - Coupled FEM formulation inside elements
  - coupled by internal boundary conditions
  - Structured stencil in the element



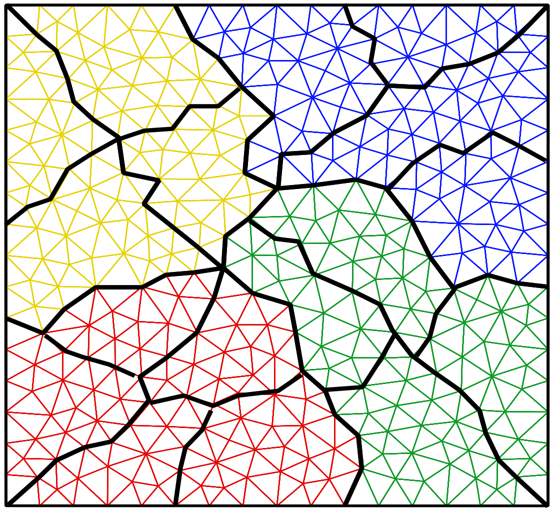
- Accuracy
  - Arbitrary order of accuracy (p+1) on unstructured meshes
  - Small dispersion/dissipation errors
  - Consistent treatment of boundaries and non-conforming connections

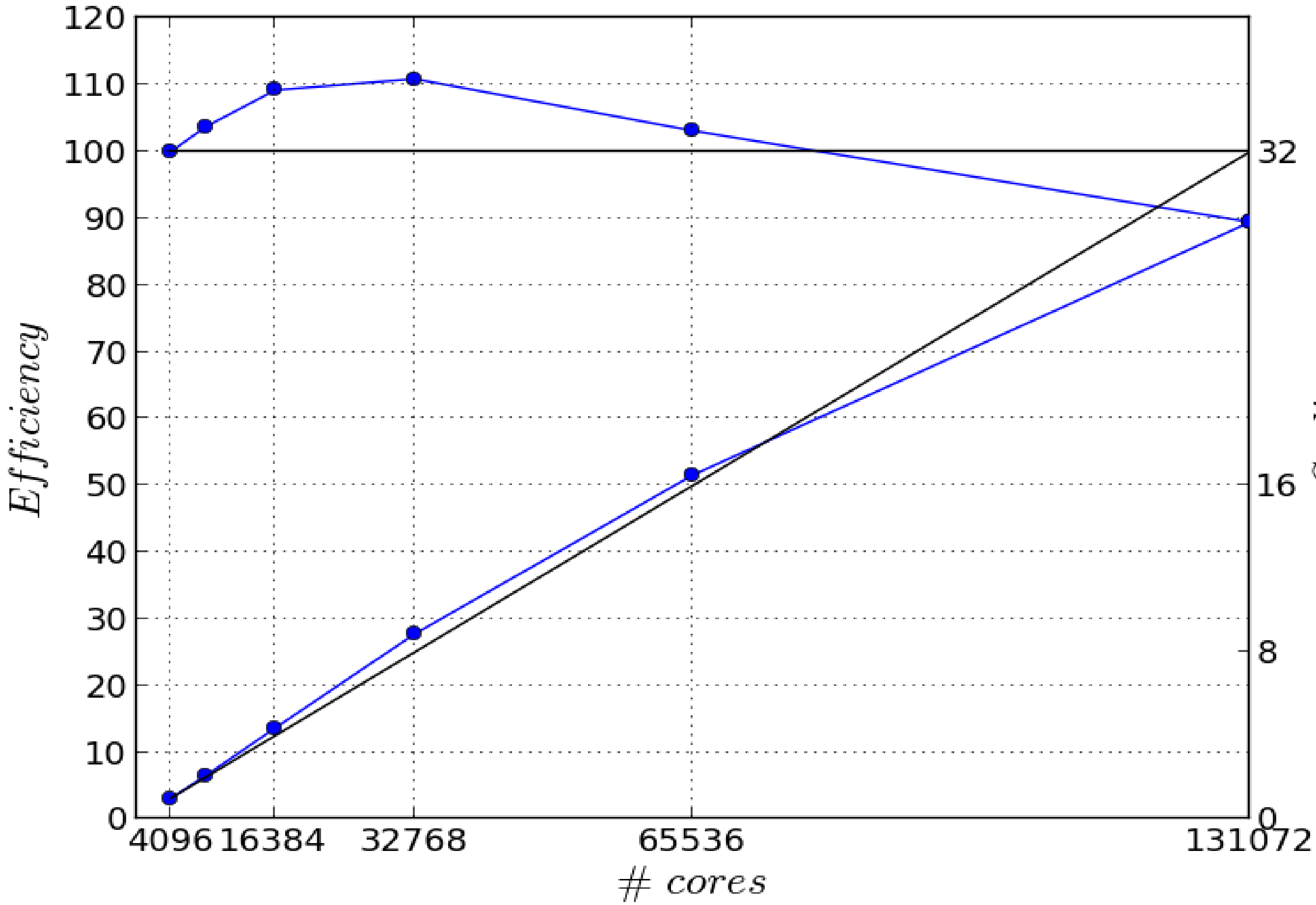




- Compact data / operations
  - Serial efficiency
  - High scalability

Strong scaling on BG/Q JUQUEEN (2 MPI / 32 OMP)

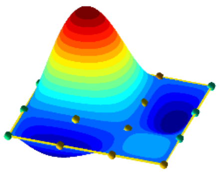




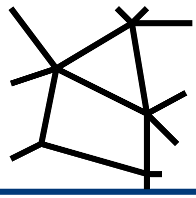
PRACE

32 fold reduction in restitution time

Argo platform



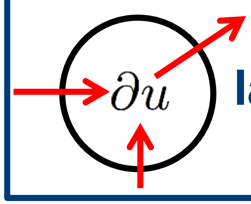
Function spaces and bases



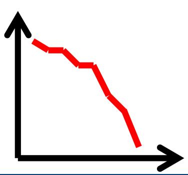
Adaptive curved mesh database

$$\int_e \frac{\partial \phi_i}{\partial x^k}$$

Discretisation and data structures

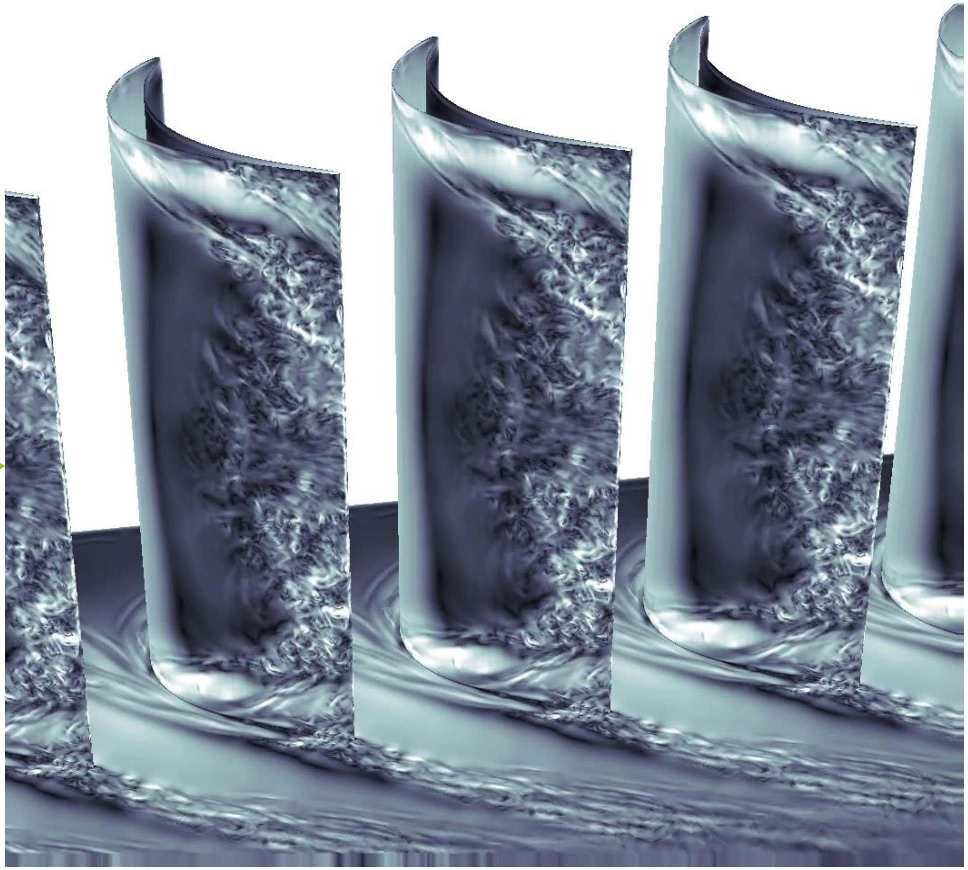


Constitutive laws / physical models

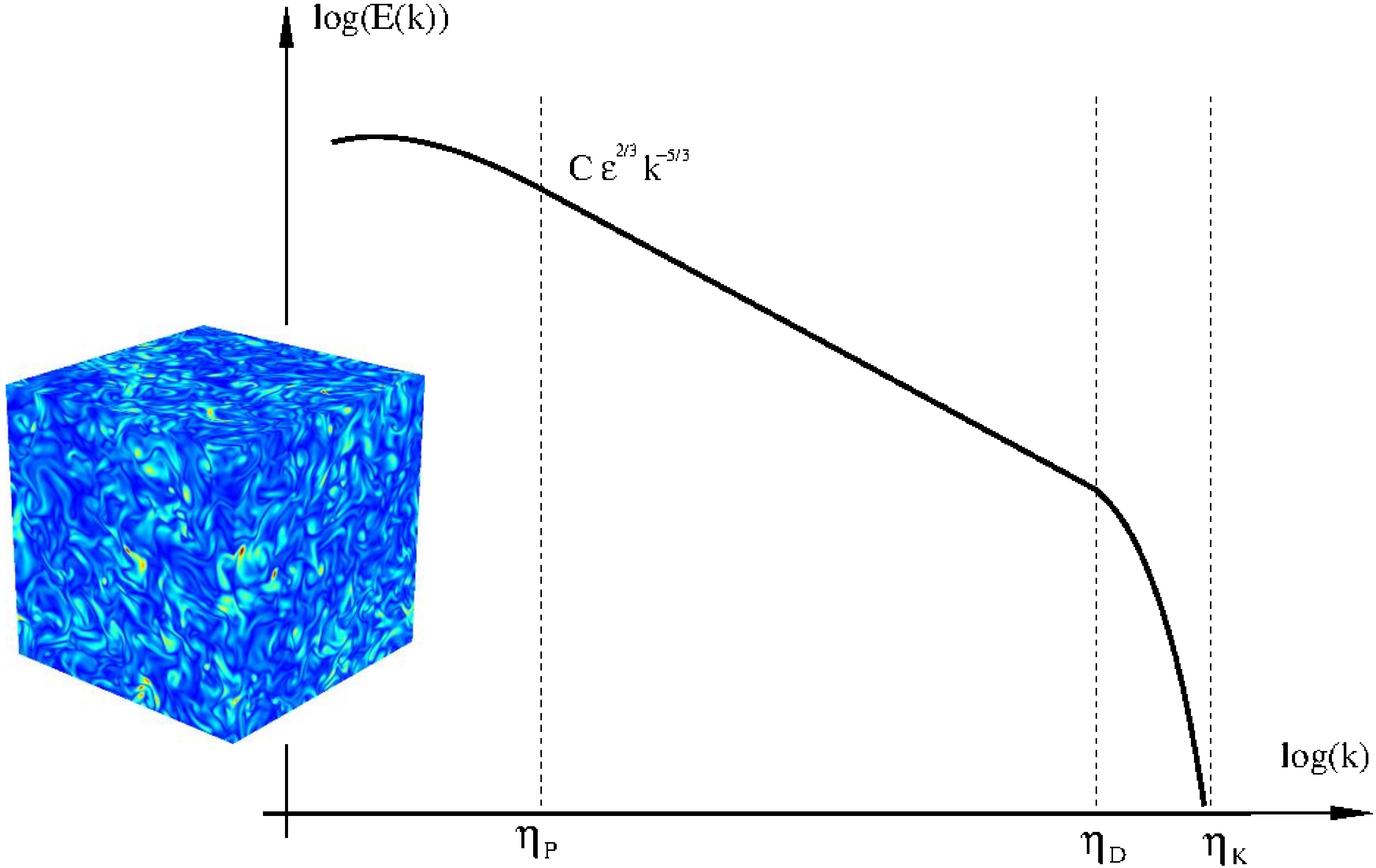


Solvers and time integrators

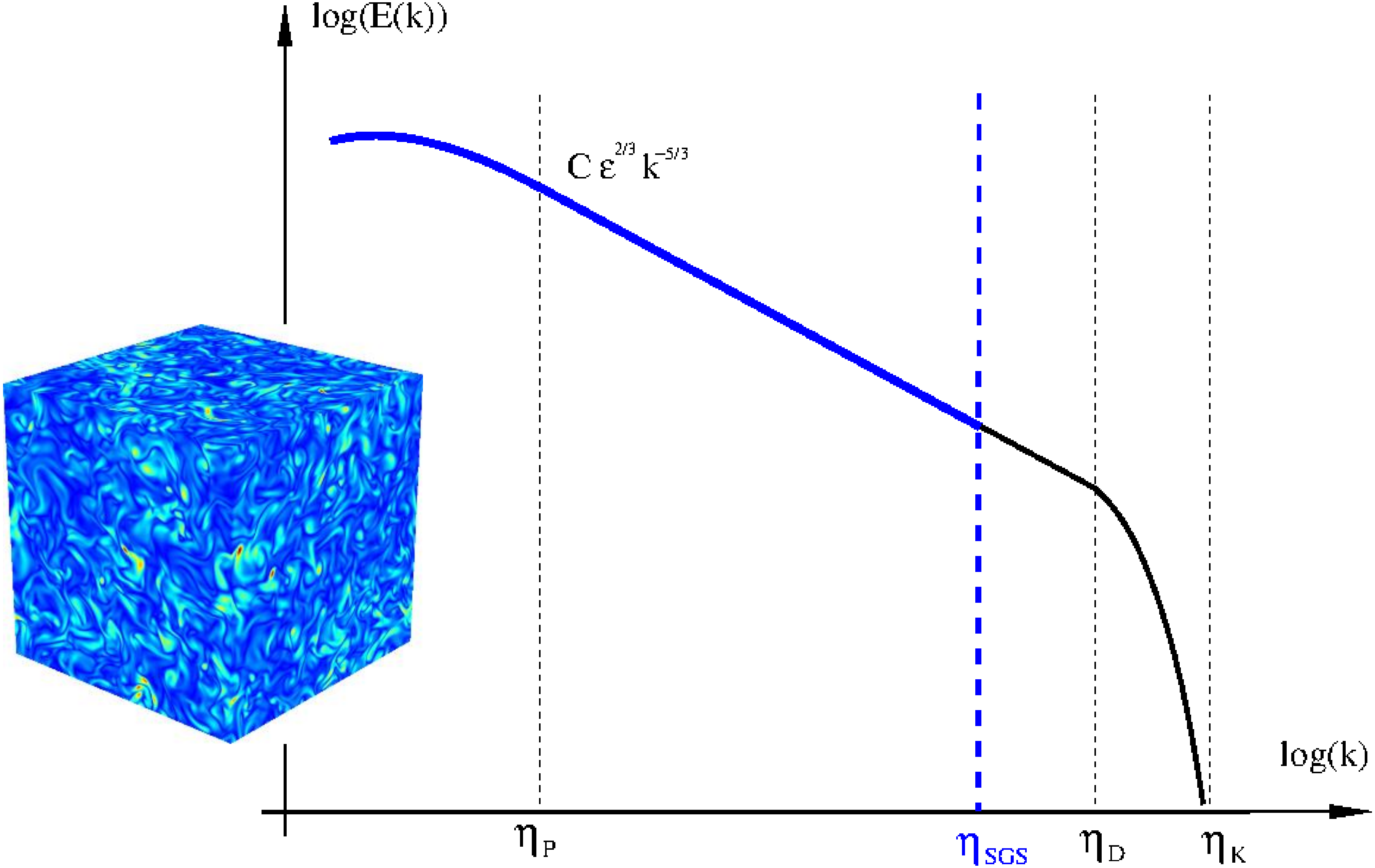
Argo



Need for accuracy in DNS / LES
Energy cascade for DNS



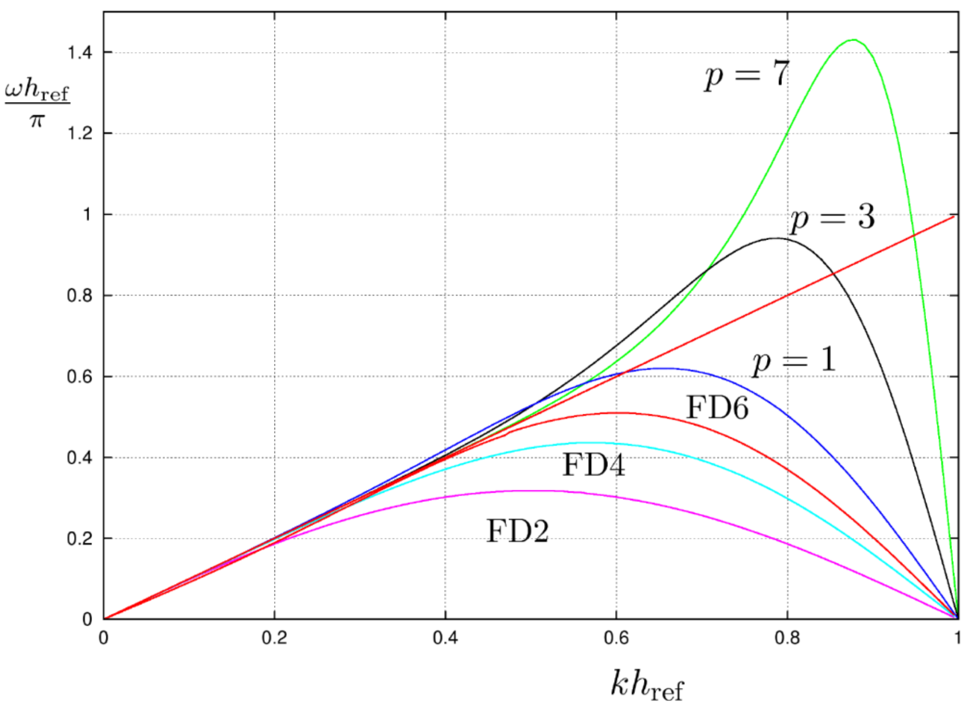
Need for accuracy in DNS / LES
Ideal LES

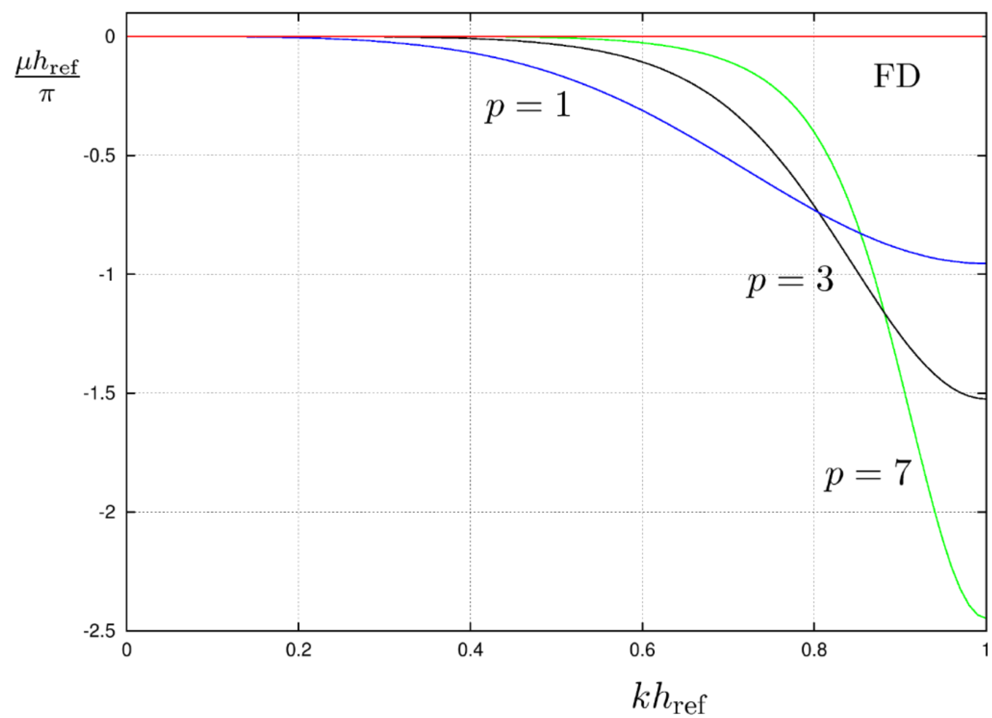


Need for accuracy in DNS / LES

Spectral properties of DGM in relation with other methods

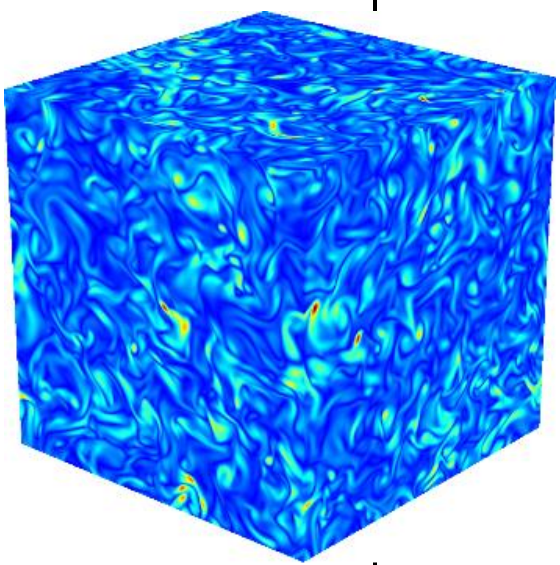
- Order of accuracy not really important as DNS and LES often not or marginally resolved (ie. operate near mesh cut-off)
- DGM is dissipative & energy stable <-> kinetic energy conservation
  - Non-linear convection: E-flux (Jiang & Shu 1994)
  - Diffusion : coercivity of SIPDG (Arnold 01)
- Dissipation/dissipation for effective resolution (Bernard 2005)

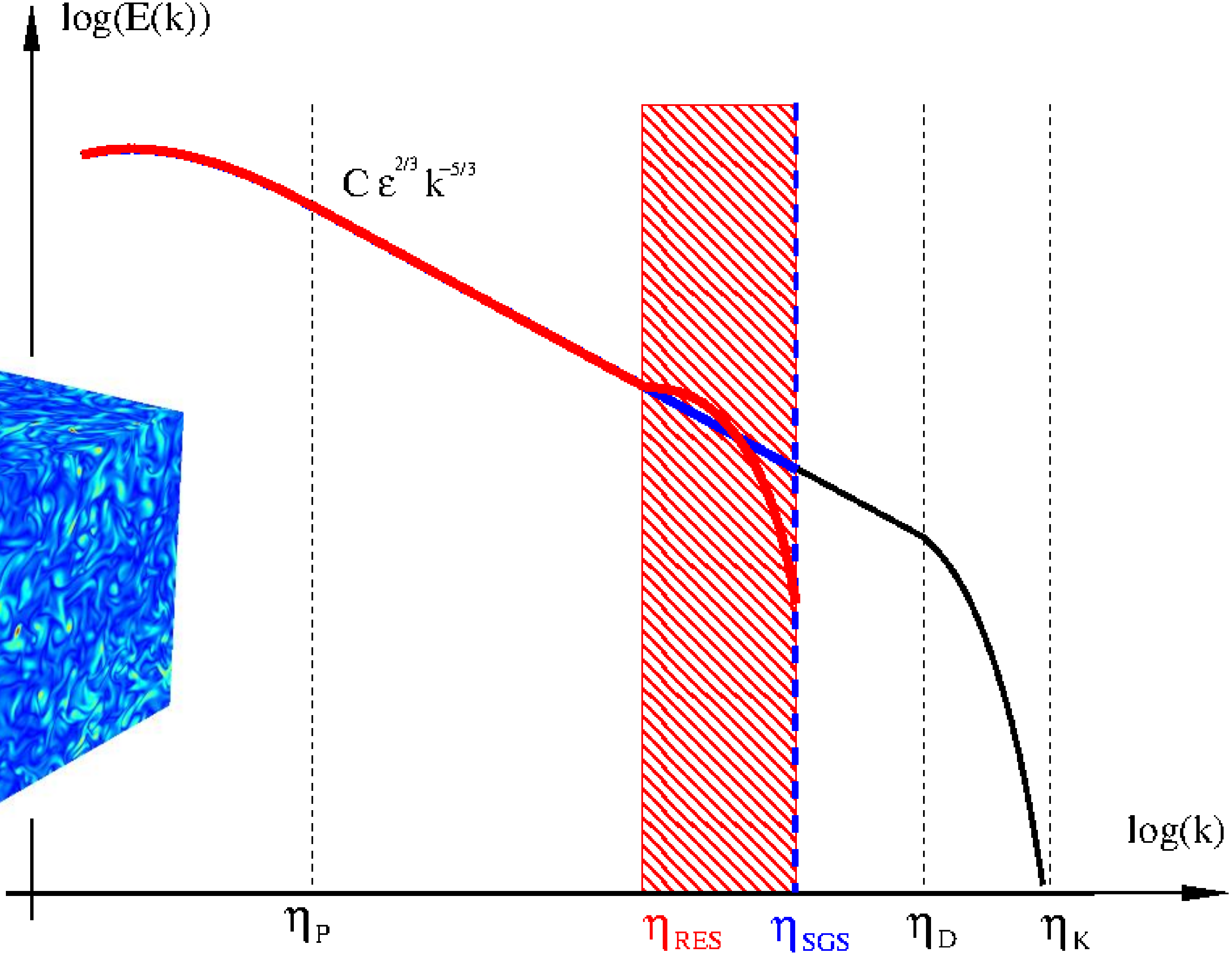




Need for accuracy in DNS / LES

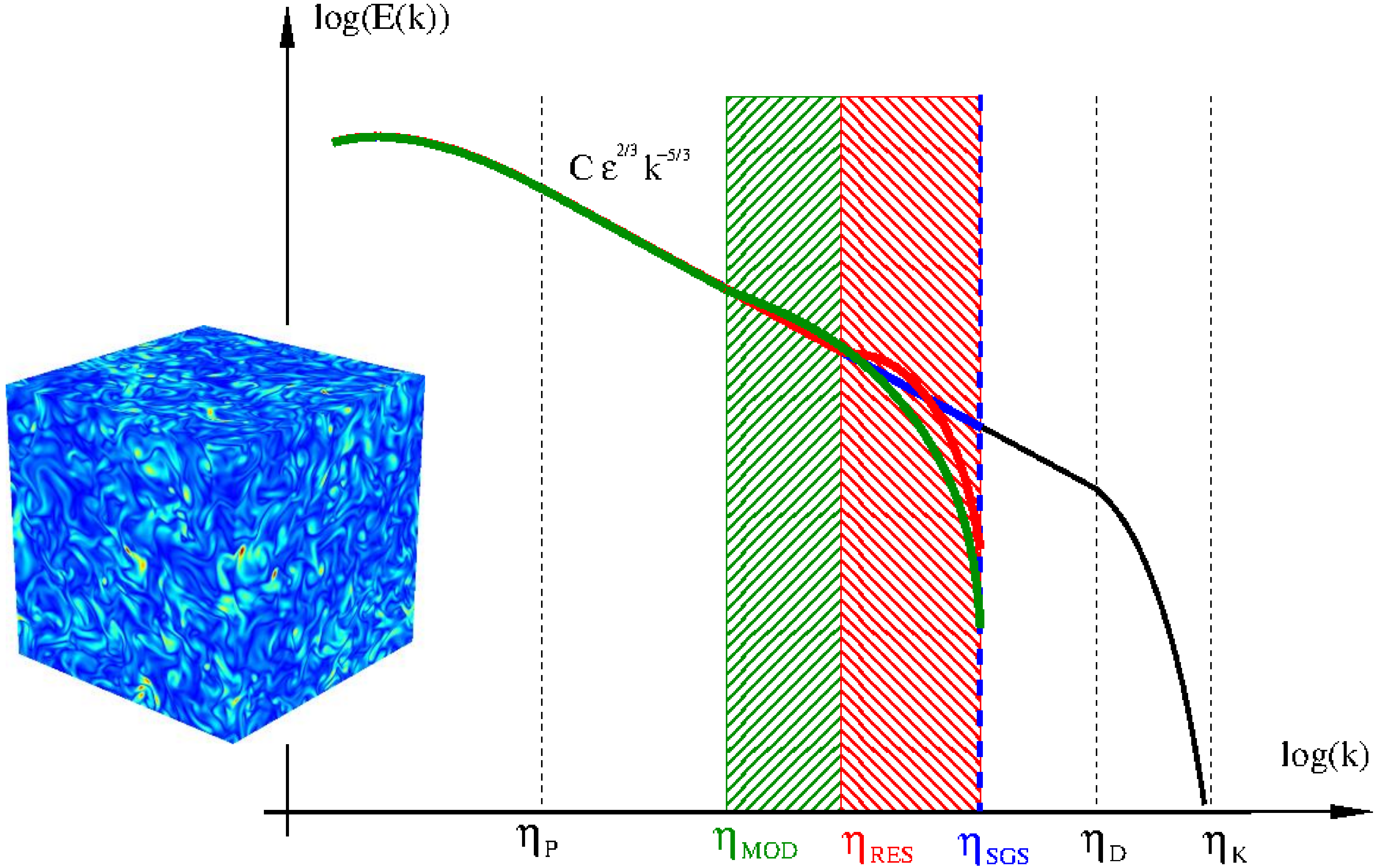
Realistic DNS and LES including numerical error





Need for accuracy in DNS and LES

Combination with VMS SGS



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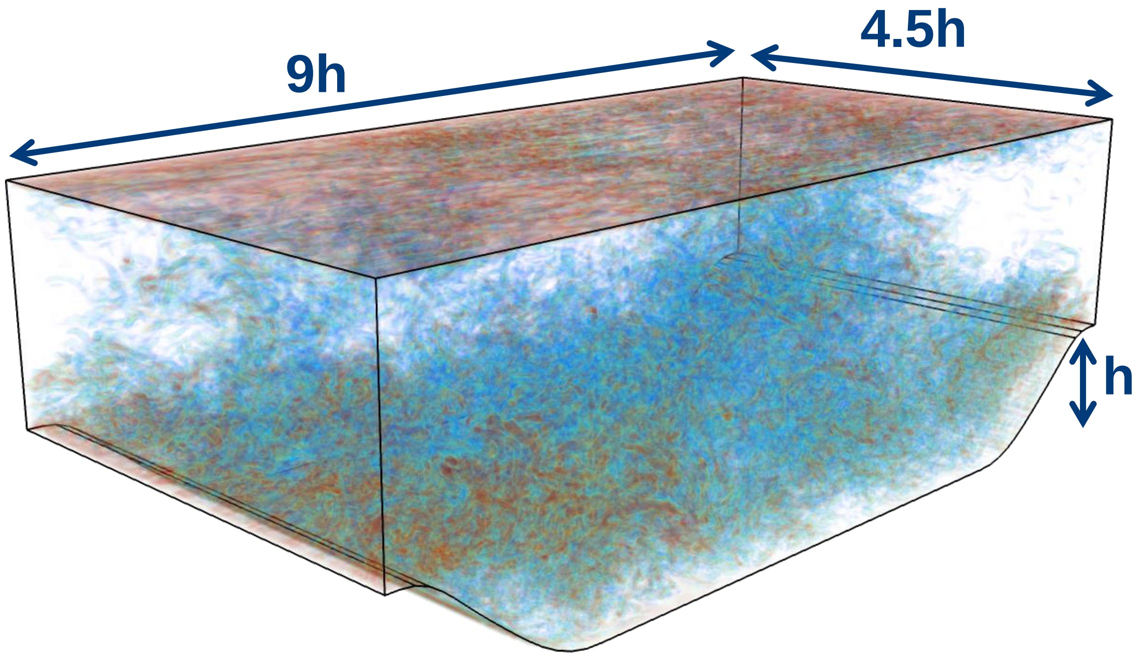
DNS and LES of the periodic flow over a 2D hill



- **Periodic domain in span and axial direction**
- **Mass flow forcing**

$$u_b = \frac{1}{2.035h} \int_h^{3.035h} u(y)dy \rightarrow Re_b = \frac{u_b h}{\nu}$$

$$\left(\frac{dp}{dx}\right)^{n+1} = \left(\frac{dp}{dx}\right)^{n+1} - \frac{1}{A_c \Delta t} \left(\dot{m}^* - 2\dot{m}^n + \dot{m}^{n-1}\right)$$

IDiHOM

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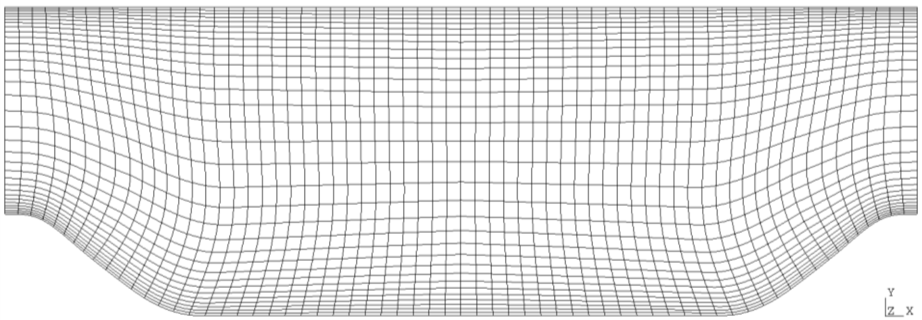
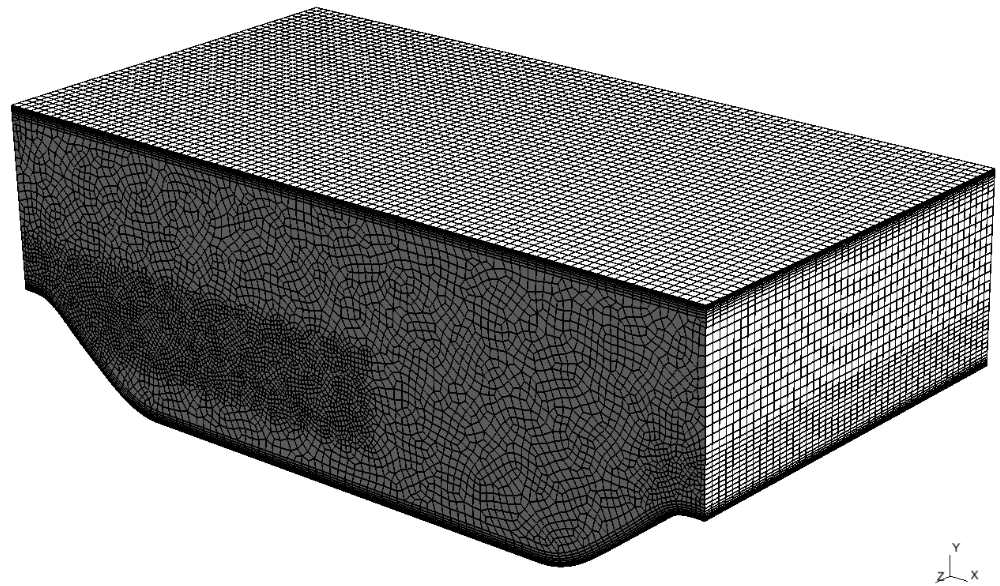
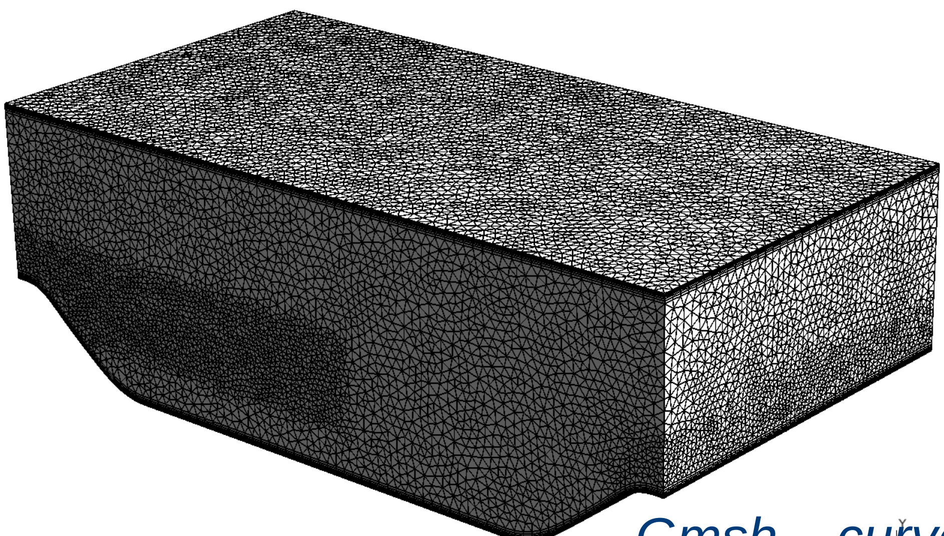
DNS and LES of the periodic flow over a 2D hill
structured mesh

IGG, coarsened from structured
524k hex, ~33M dof with p=3 (1/4)



Gmsh, 2D curved and extruded
294k hexahedra, ~19M dof at p=3





Gmsh – curved mesh
521k tet, 99k prisms, ~14M dof at p=3

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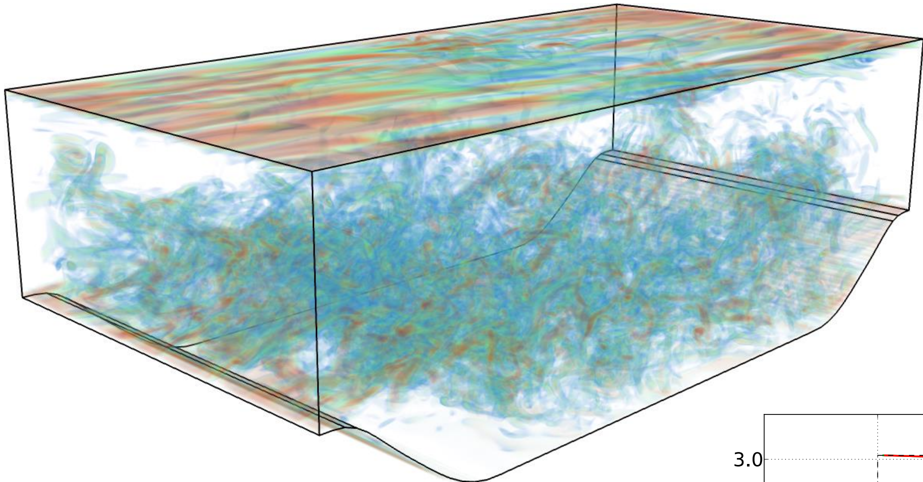
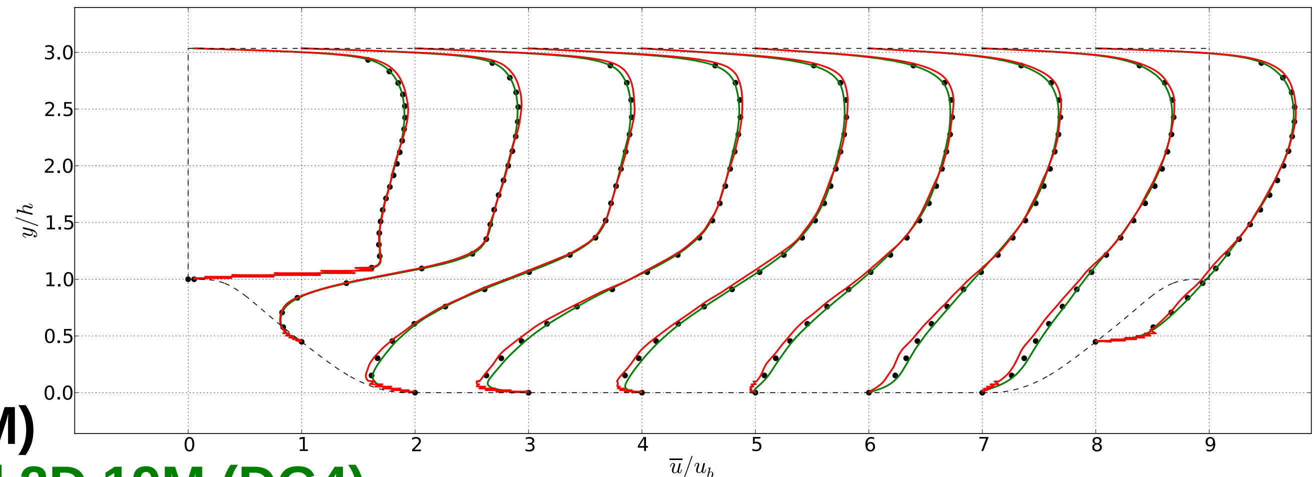
Periodic flow over a 2D hill
DNS at Re=2800

Re_b = 2800, M=0.1 Scheme: DGM(4), implicit time-stepping





- **DNS LESOCC 13M (FVM)**
- **DNS Argo Unstructured 2D 19M (DG4)**
- **DNS Argo Unstructured 3D 14M (DG4)**

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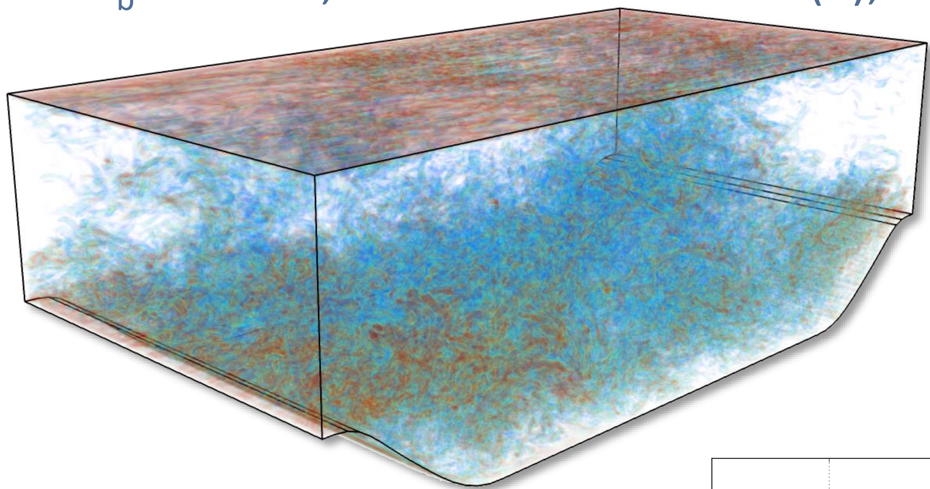
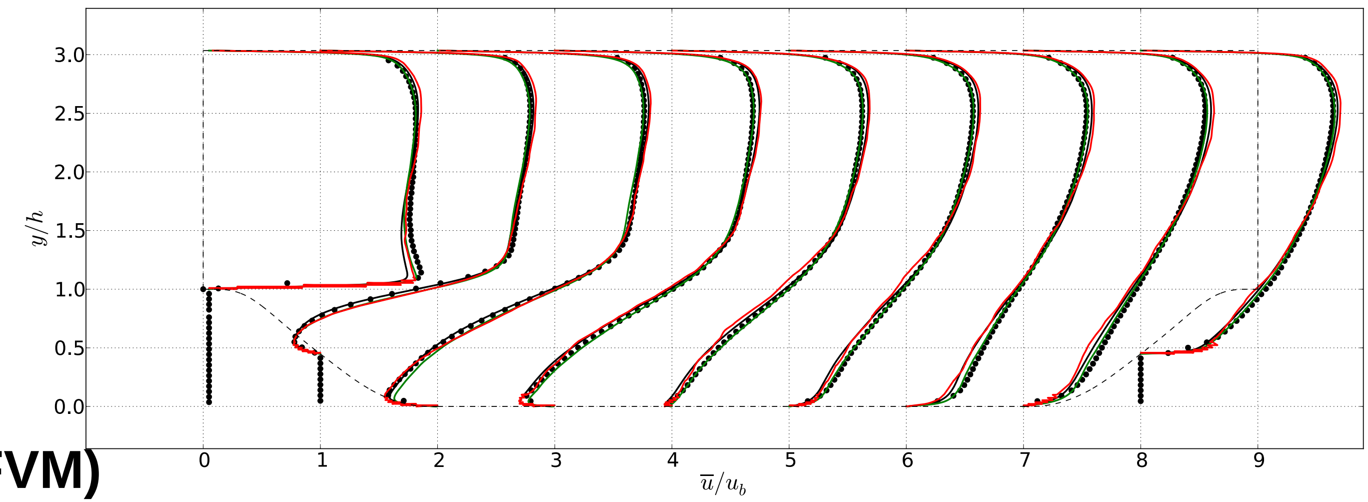
Periodic flow over a 2D hill

LES at Re=10595

Re_b = 10595, M=0.1 Scheme: DGM(4), implicit time-stepping

IDIHOM





- **Experiment**
- **LES LESOCC 13M (FVM)**
- **LES Argo Unstructured 2D 19M (DG4)**
- **LES Argo Unstructured 3D 14M (DG4)**

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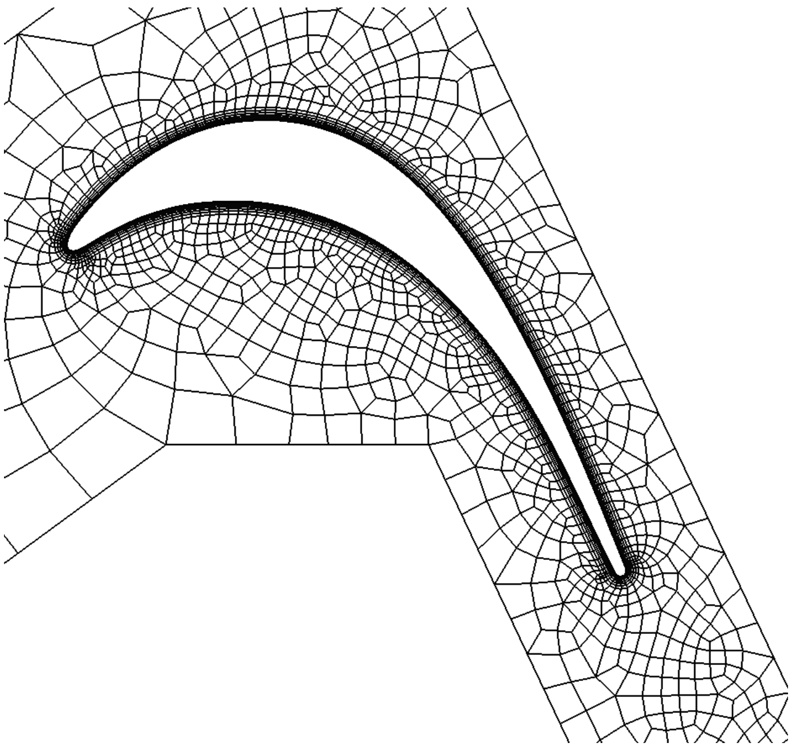
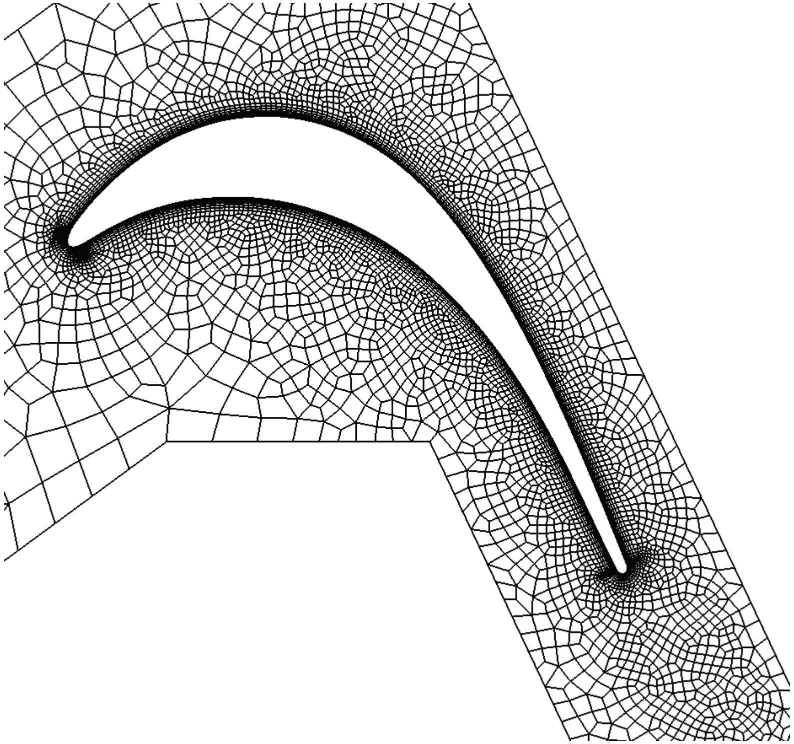
AS2 – DNS of LP Turbine T106A at Re=60k

Calibration experiments for transition models

- **Validation on a well documented case for DNS**
  - **Numerous publications (Sandberg 2012/2014, Michelassi 2003, …)**
  - **Inlet angle correction from 37.7° to 45.5° (Michelassi et al.)**
- **Similar mesh strategy on coarse and baseline meshes**





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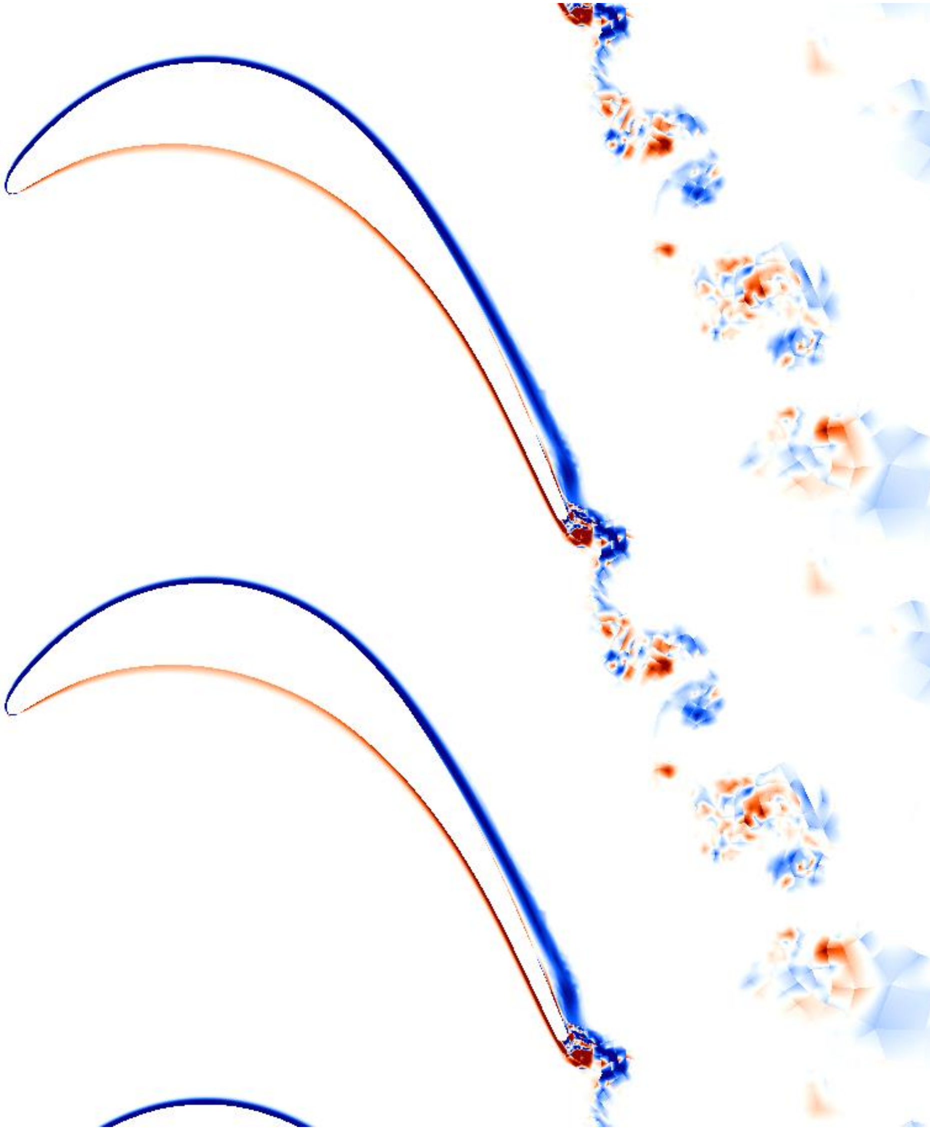
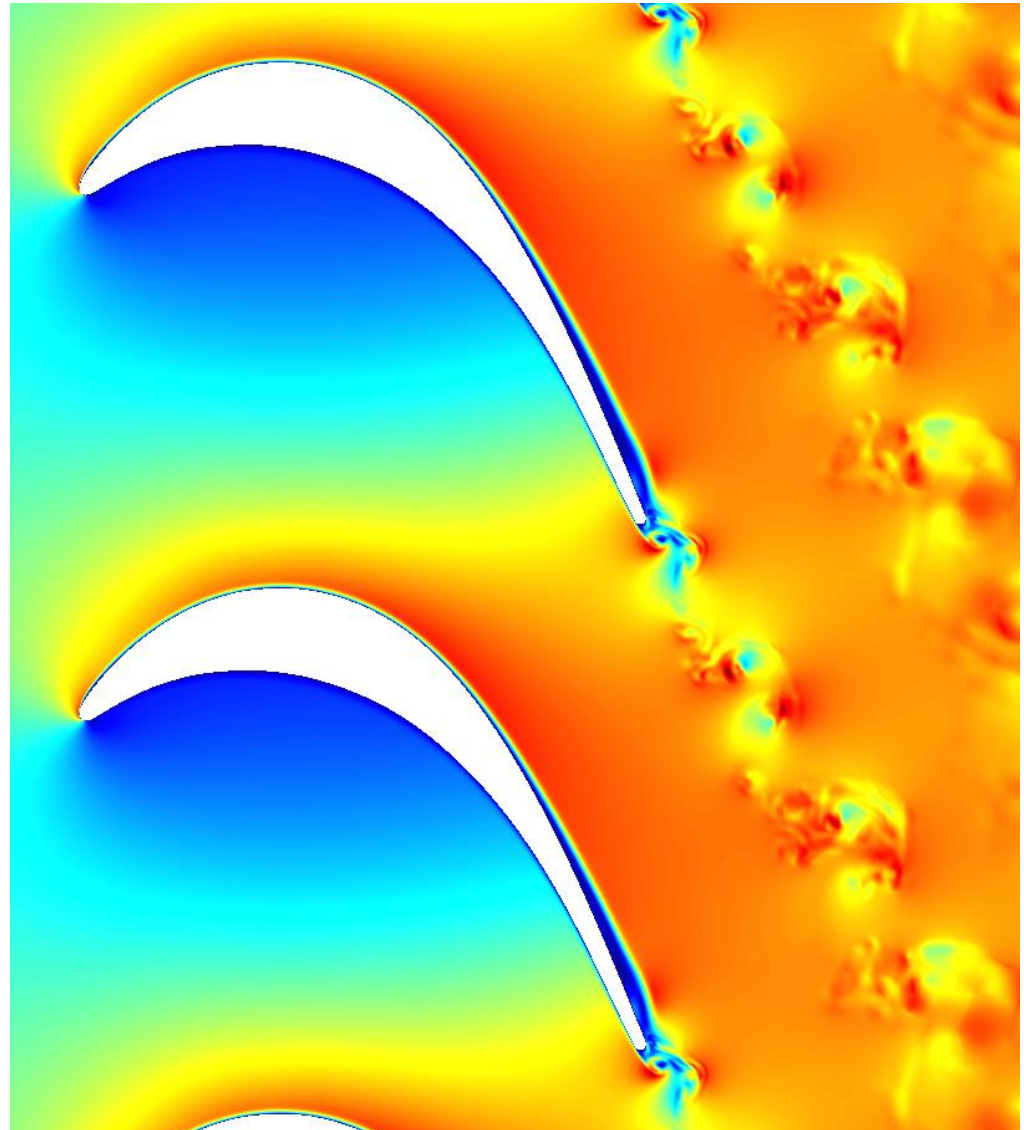
AS2 - DNS of the LPT T106A at Re=60k

Vorticity and Mach number on baseline mesh





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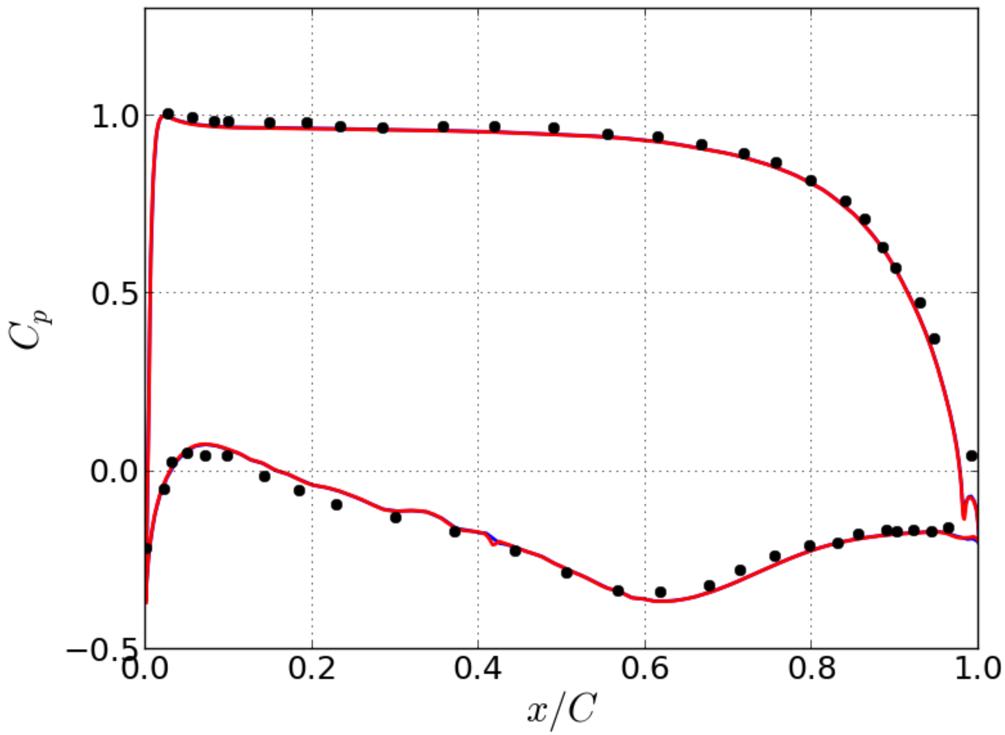
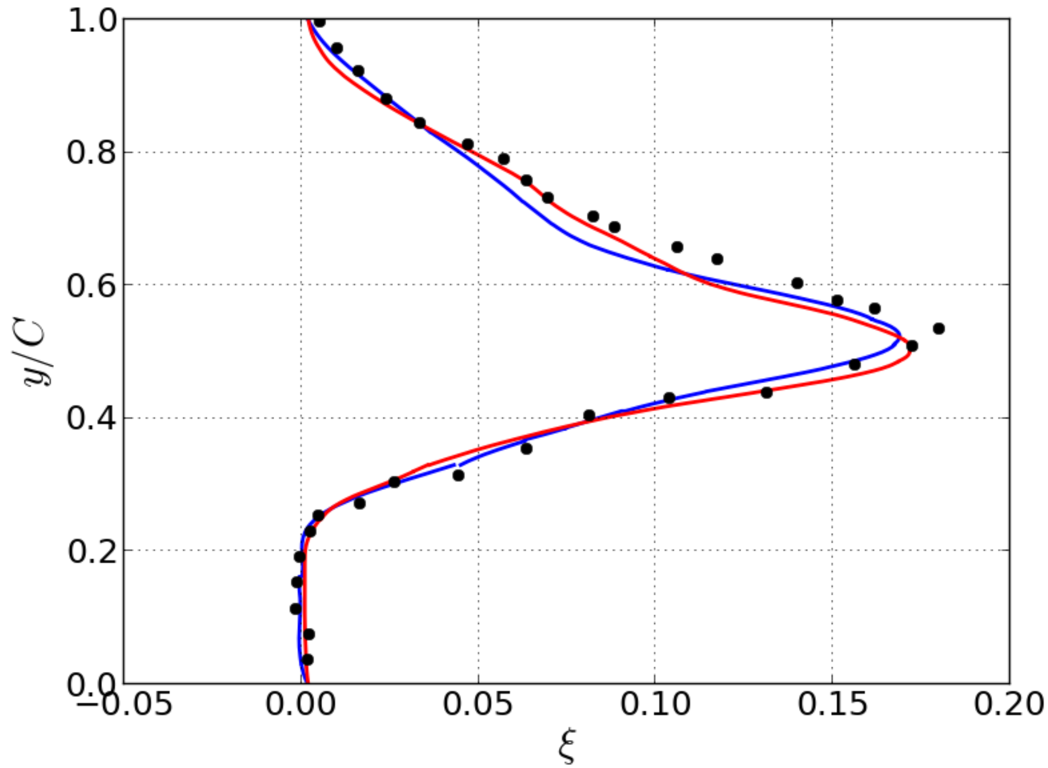
DNS of the LPT T106A at Re=60k

Comparison with Experimental Results





- **Experiment (Stadtmüller)**

– **Argo DGM (coarse)**

– **Argo DGM (baseline)**

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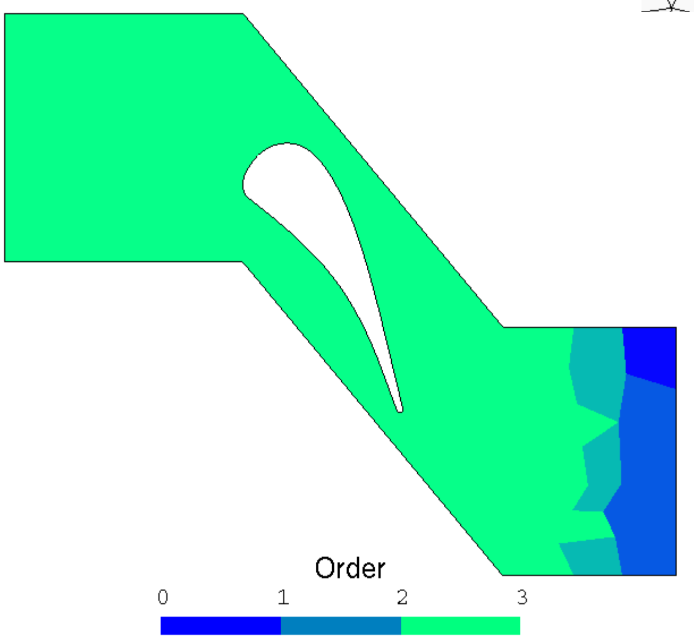
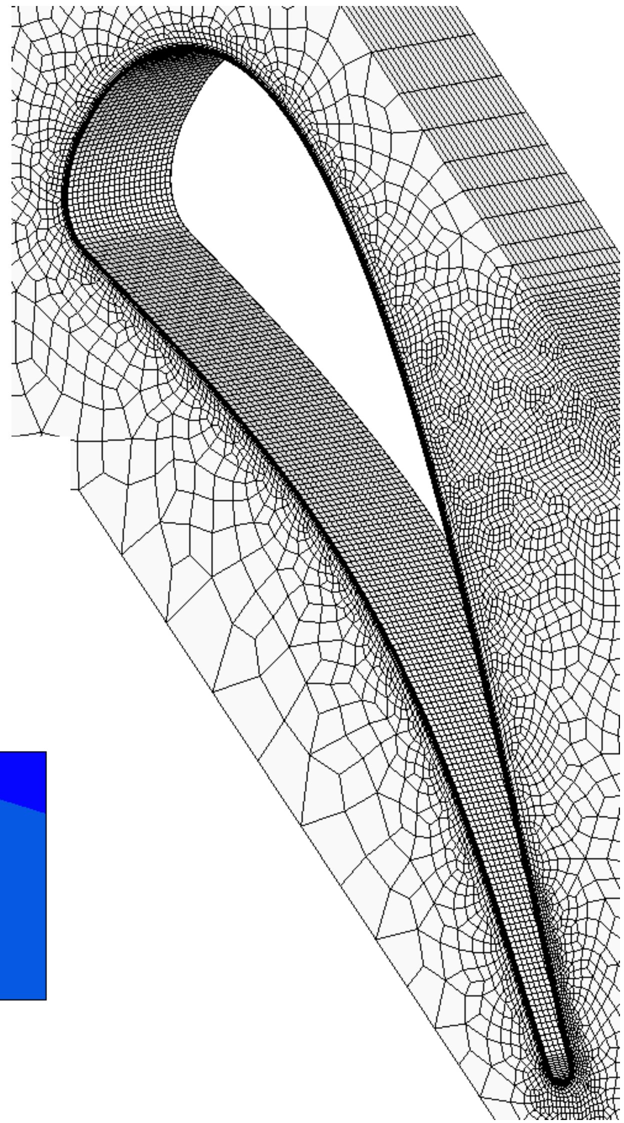
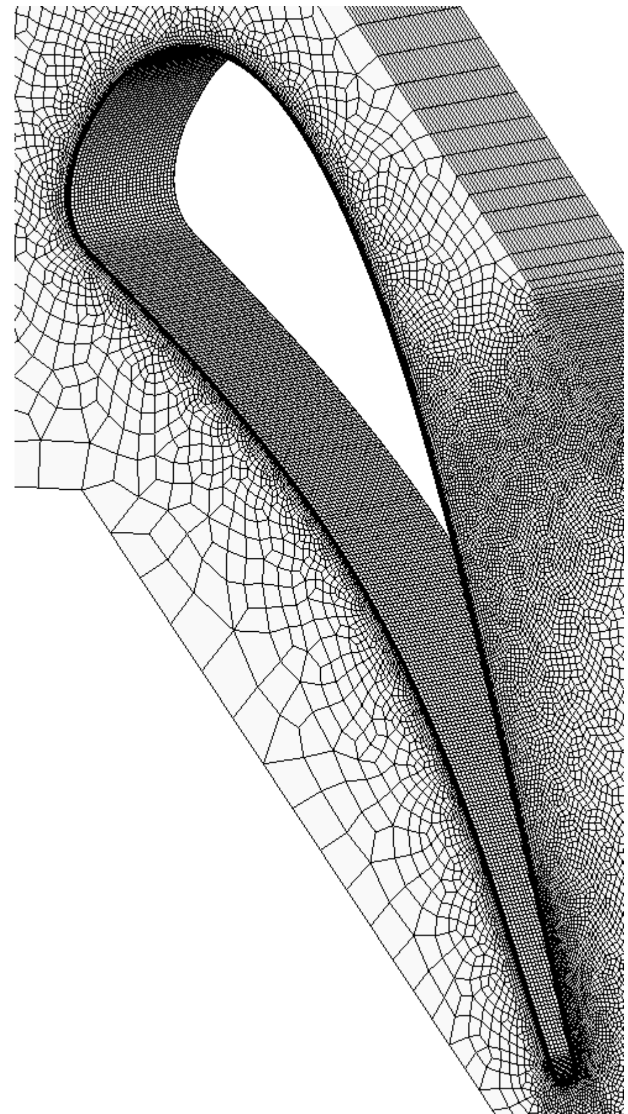
MUR235

- $M_{2,s}$ = 0.927
- $Re_{2,s}$=1.15x10^6
- TI = 2/4/6%







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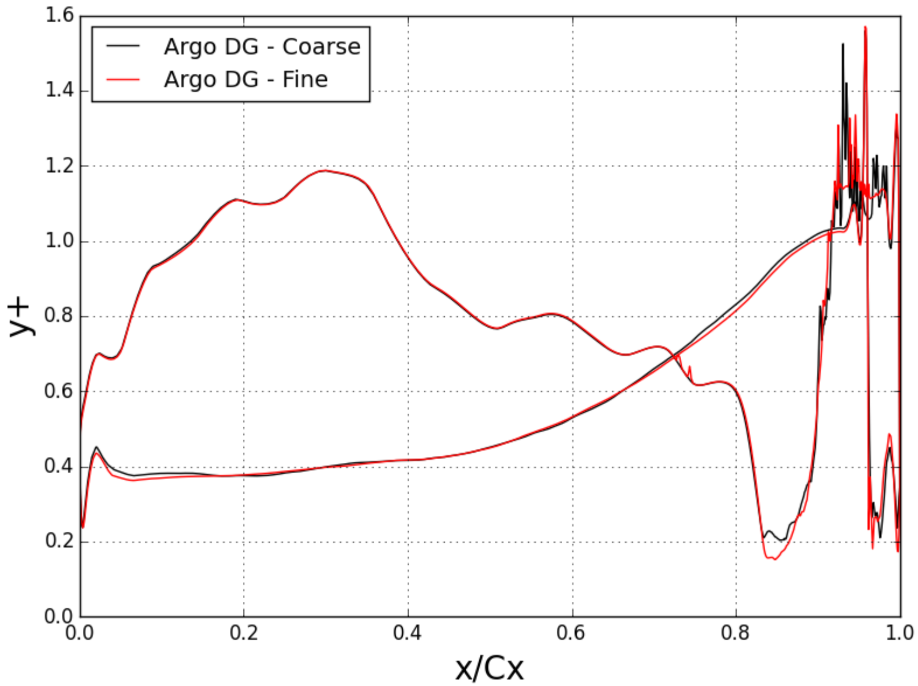
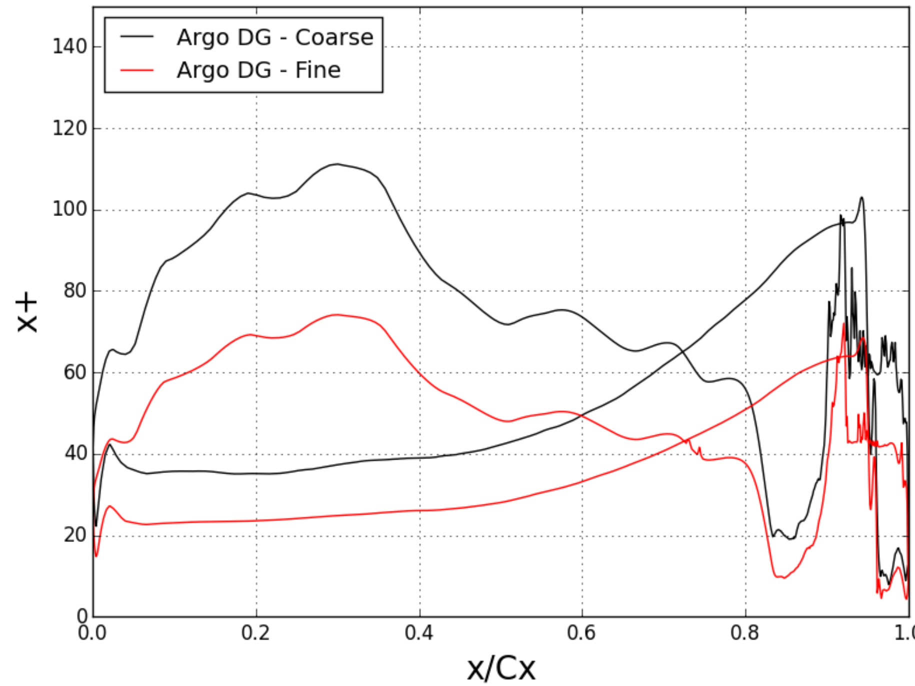
VKI LS89

Wall resolution

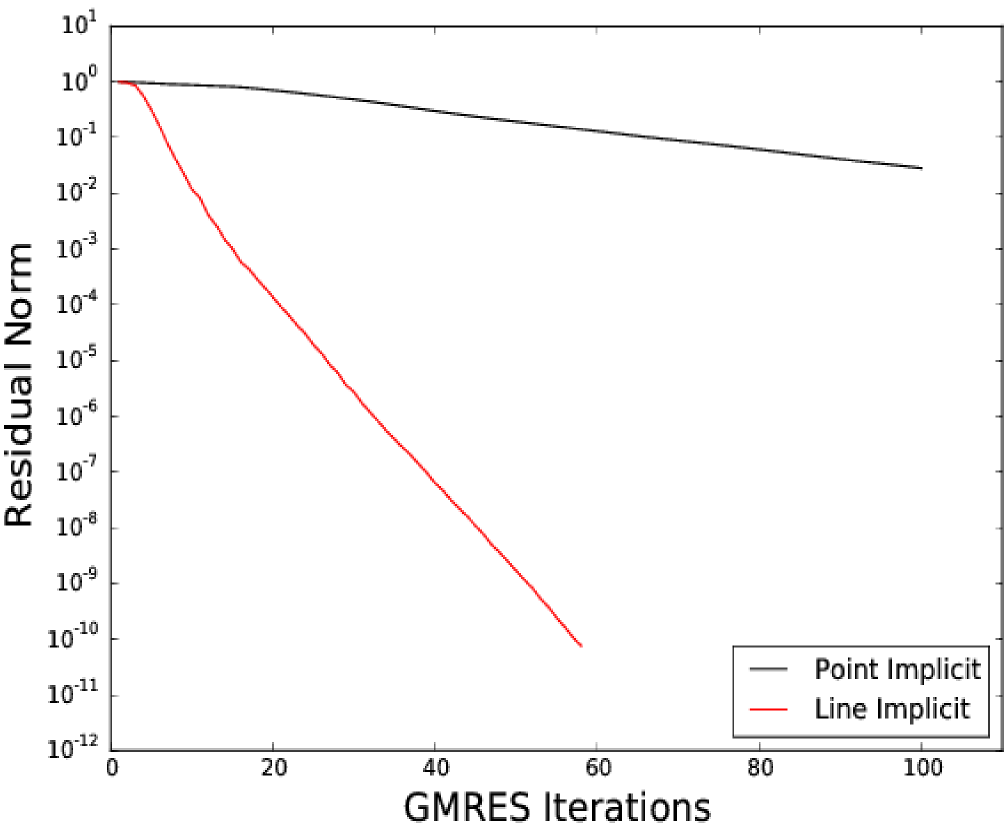


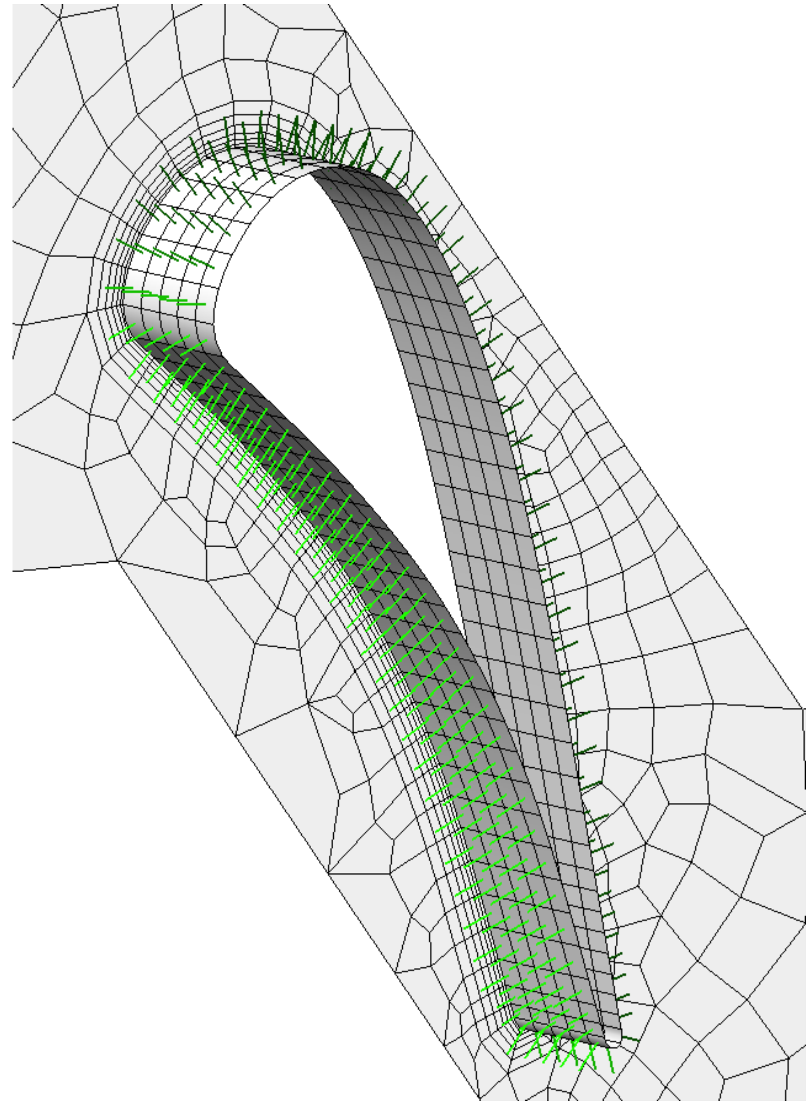


	y^+	x^+	Elmts	DOF	Procs	Wall Time / T_C
Coarse	1.3	110	0.23M	15M	416	28.5 h
Fine	1.3	70	0.69M	44M	1380	21.7 h

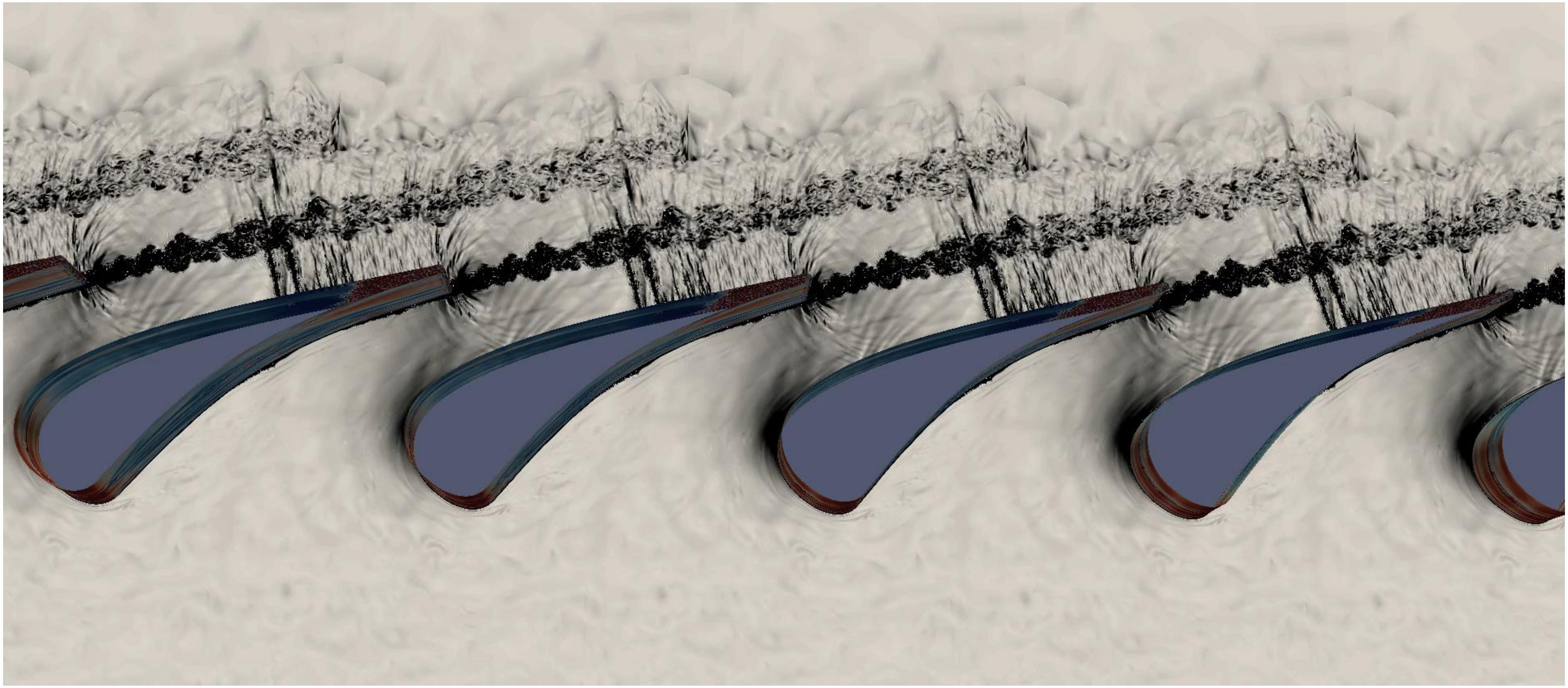
Line implicit preconditioner

BDF2/ESDIRK64
Newton-GMRES
Improve preconditioning on highly stretched meshes wrt bJacobi





VKI LS89



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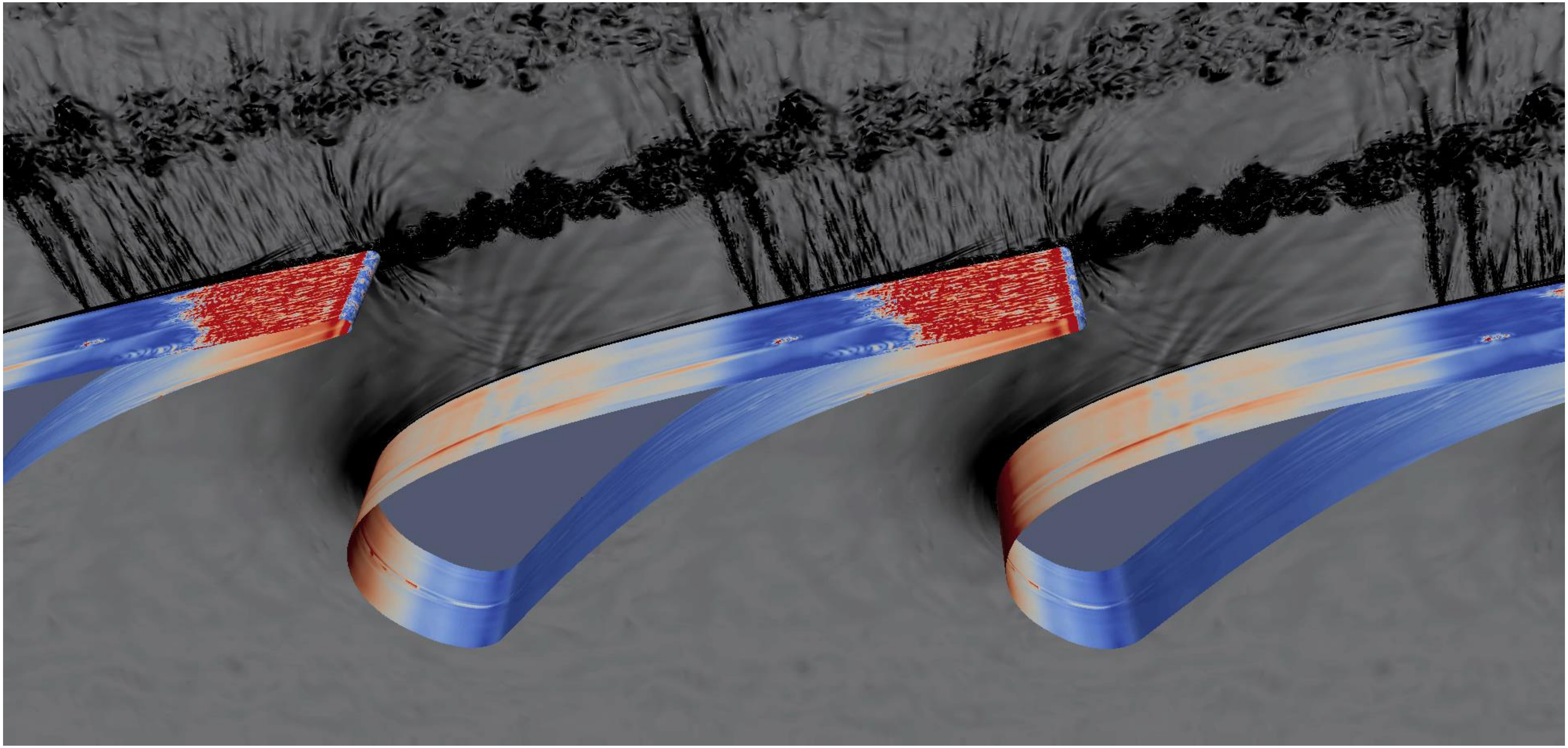
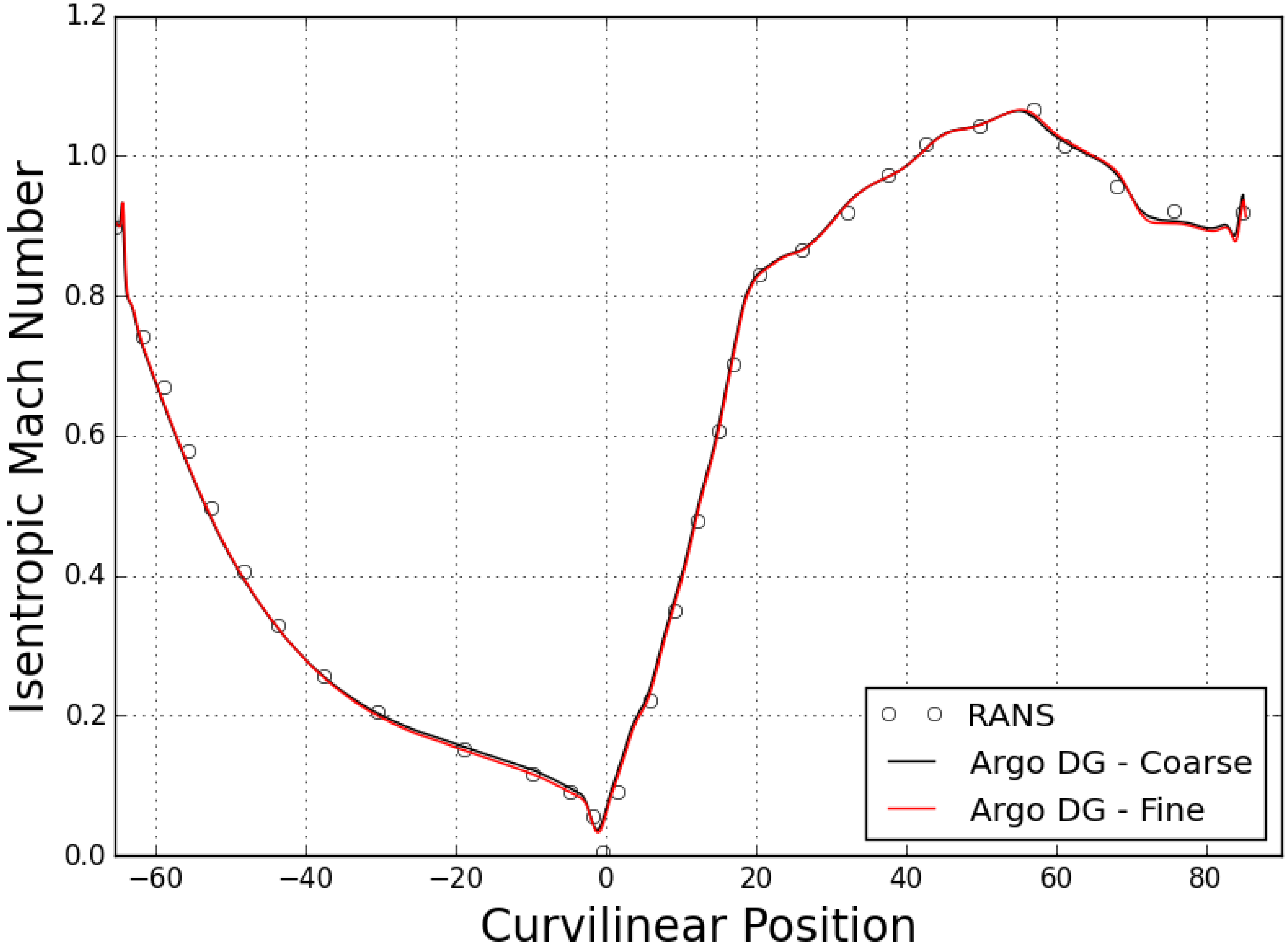


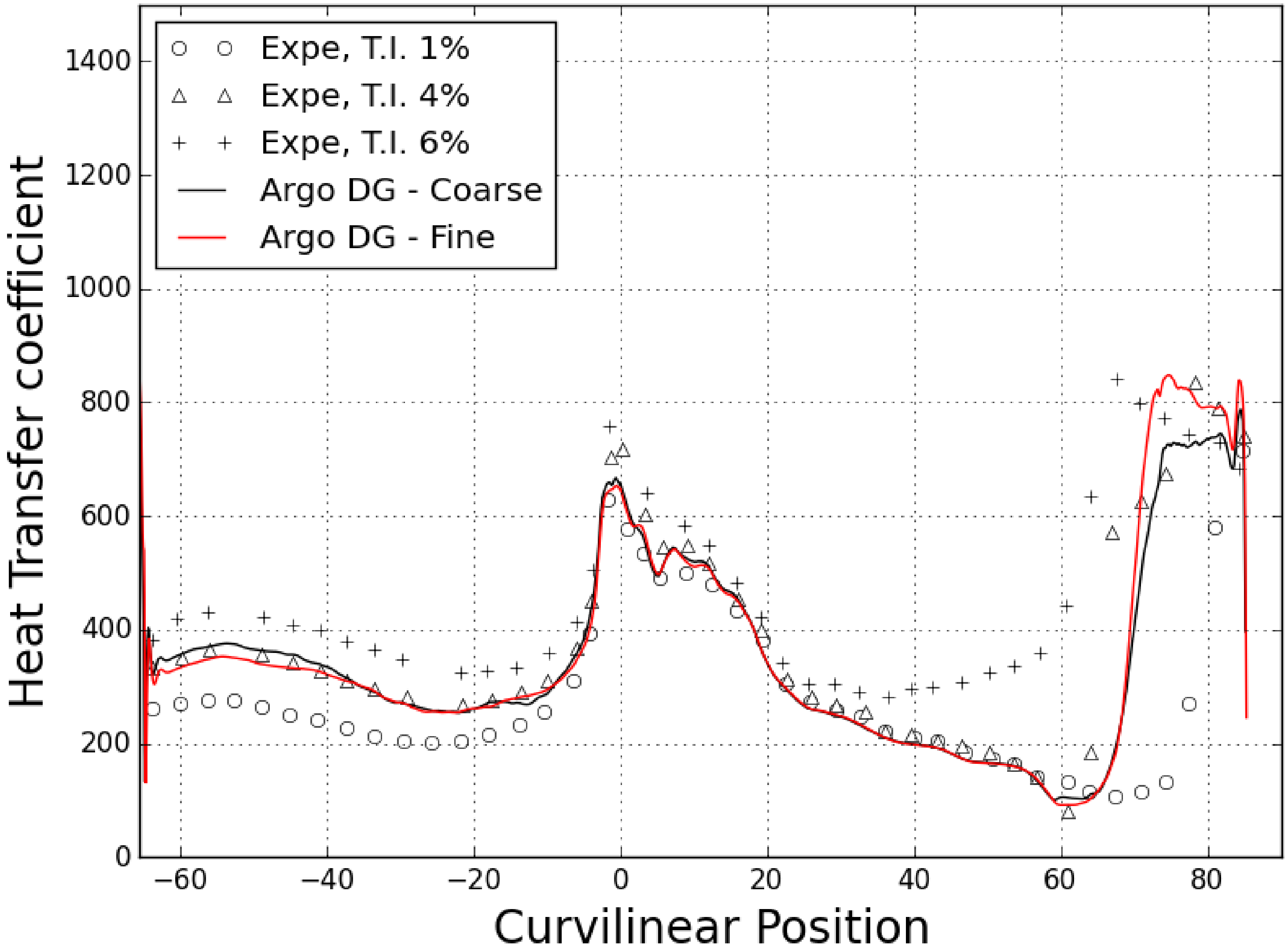
VKI LS89 MUR235

Pressure distribution



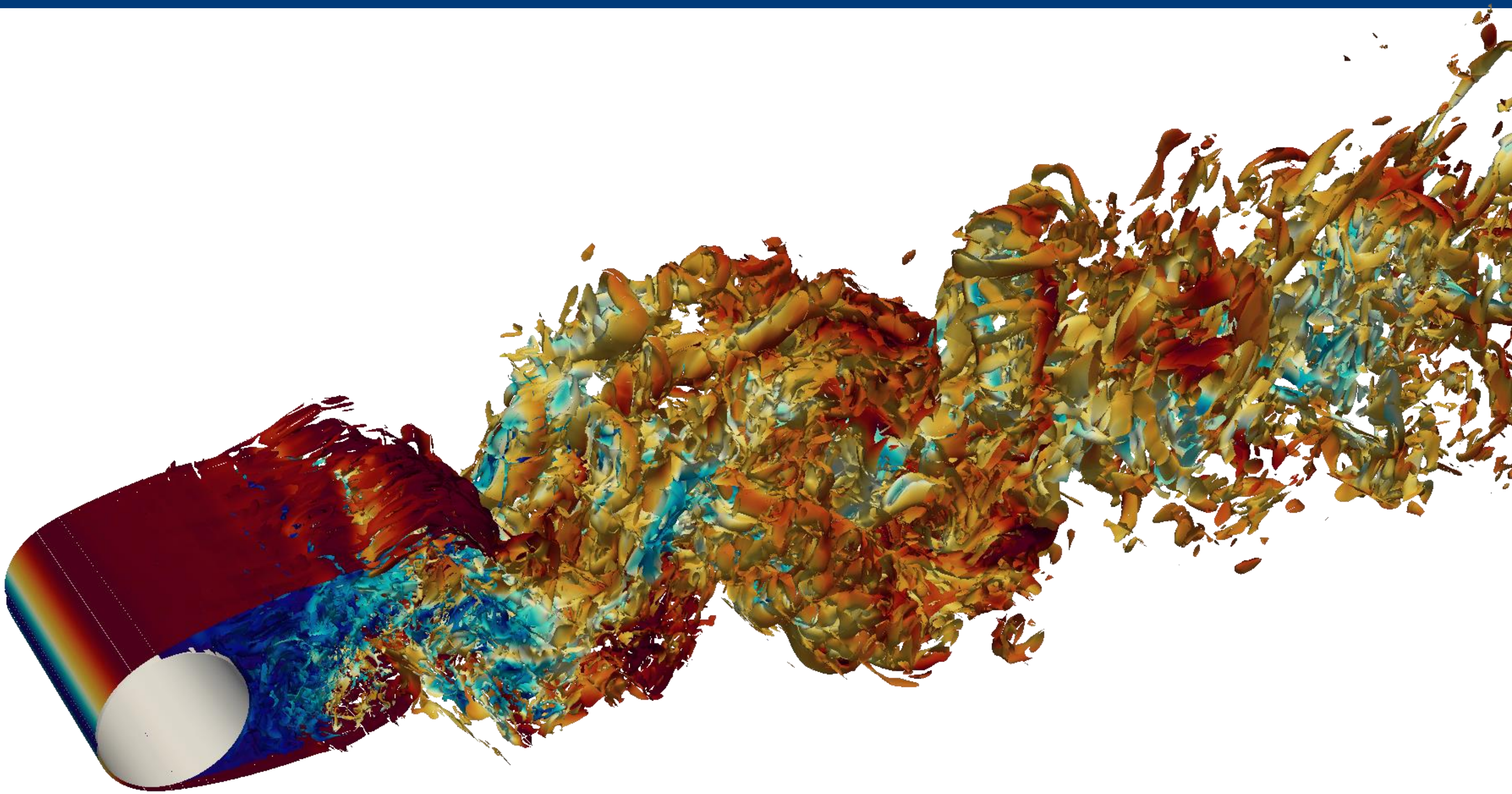
VKI LS 89

Capture transition (and impact on heat flux)



Cylinder Re=3900

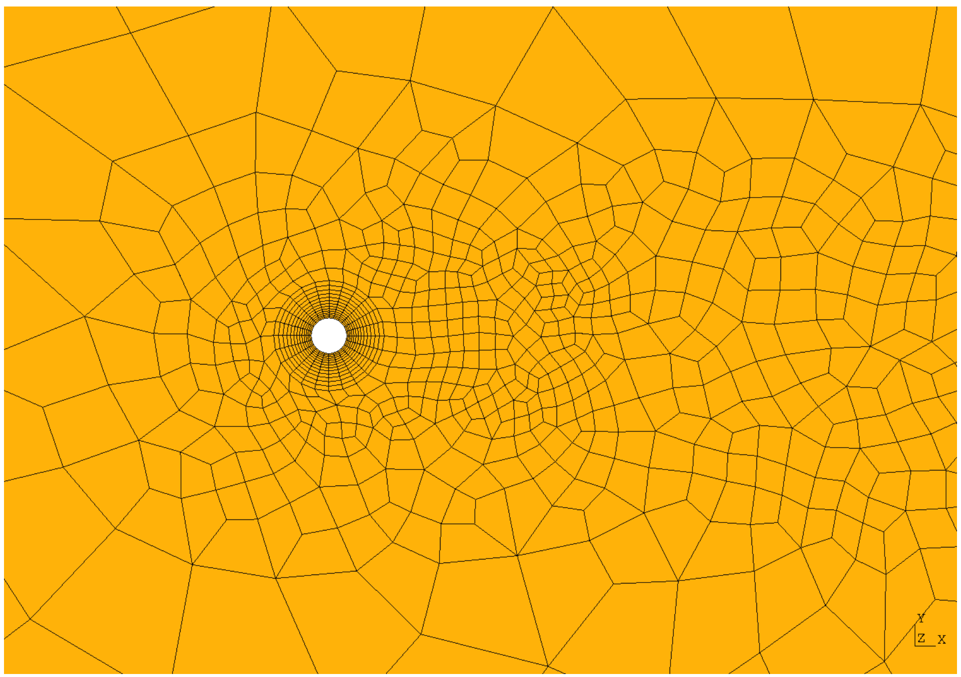
Test case AS1 of the HiOCFD4

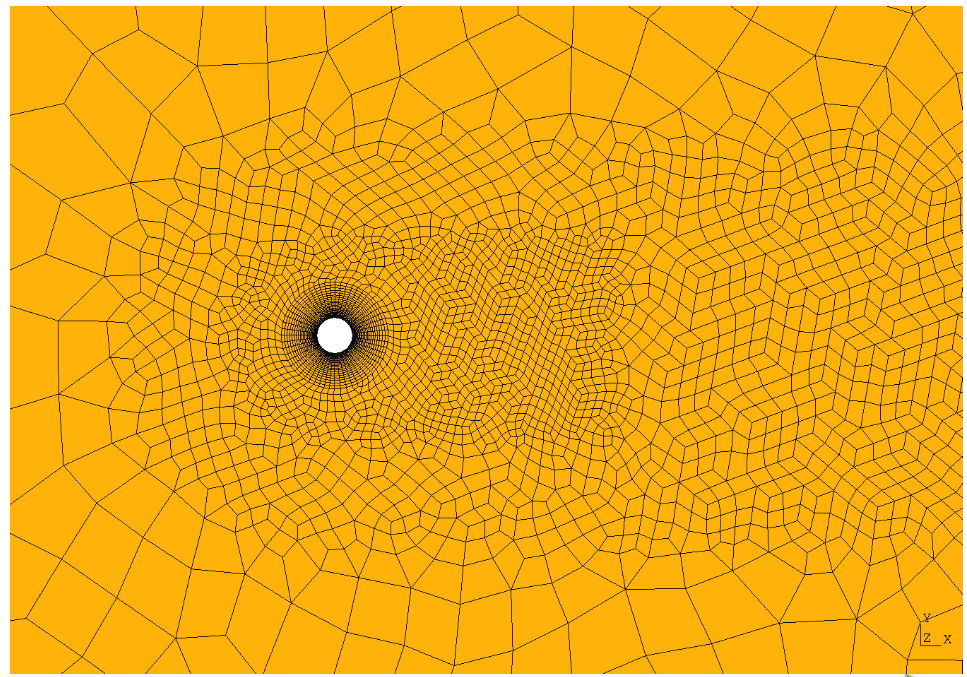


Cylinder Re=3900

Grid / temporal convergence studies on unstructured meshes

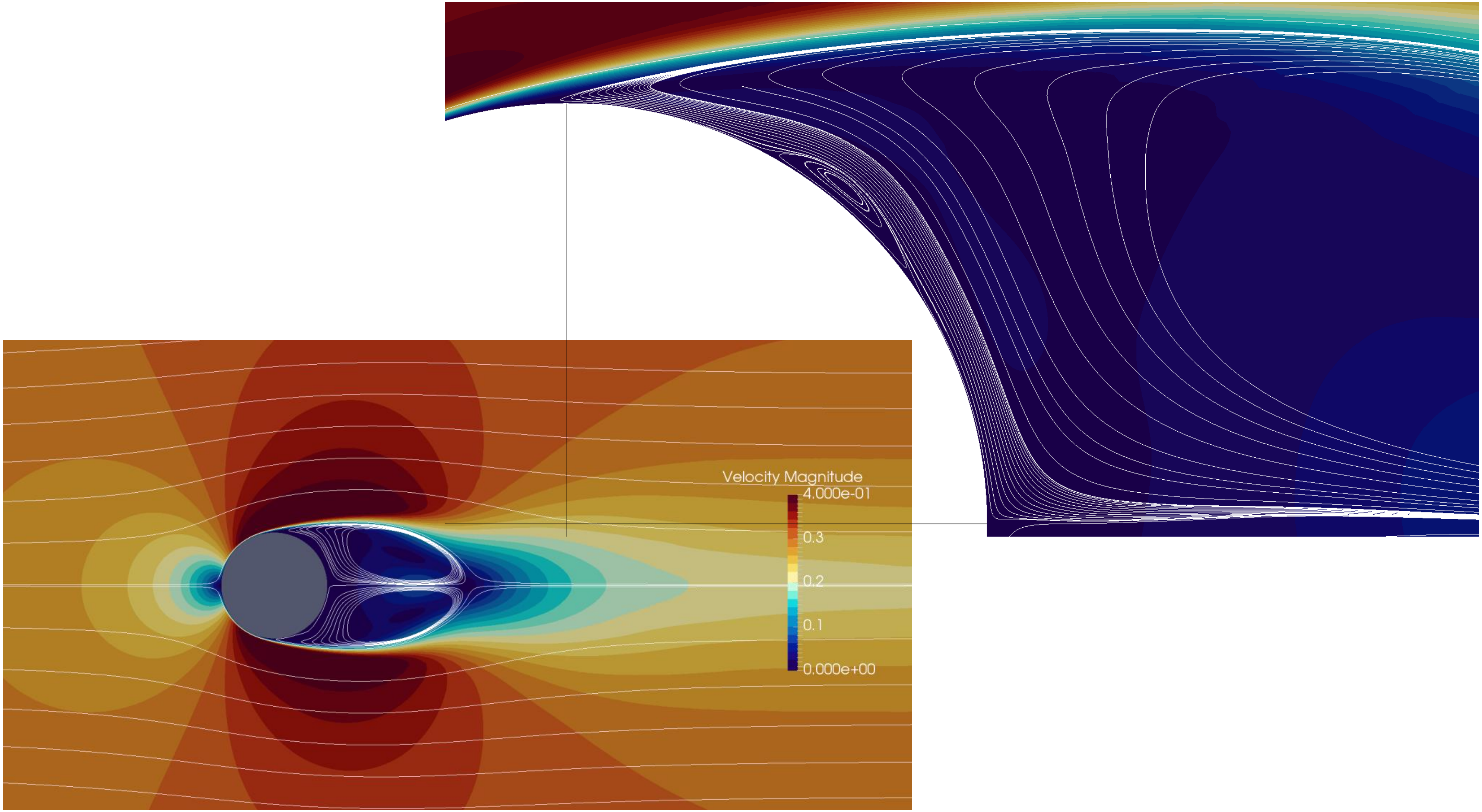
	Elements	Dof	
		P=3	P=4
Coarse	8344	534016	1043000
Medium	70800	4531200	8850000
Fine	500430	32027520	6255375



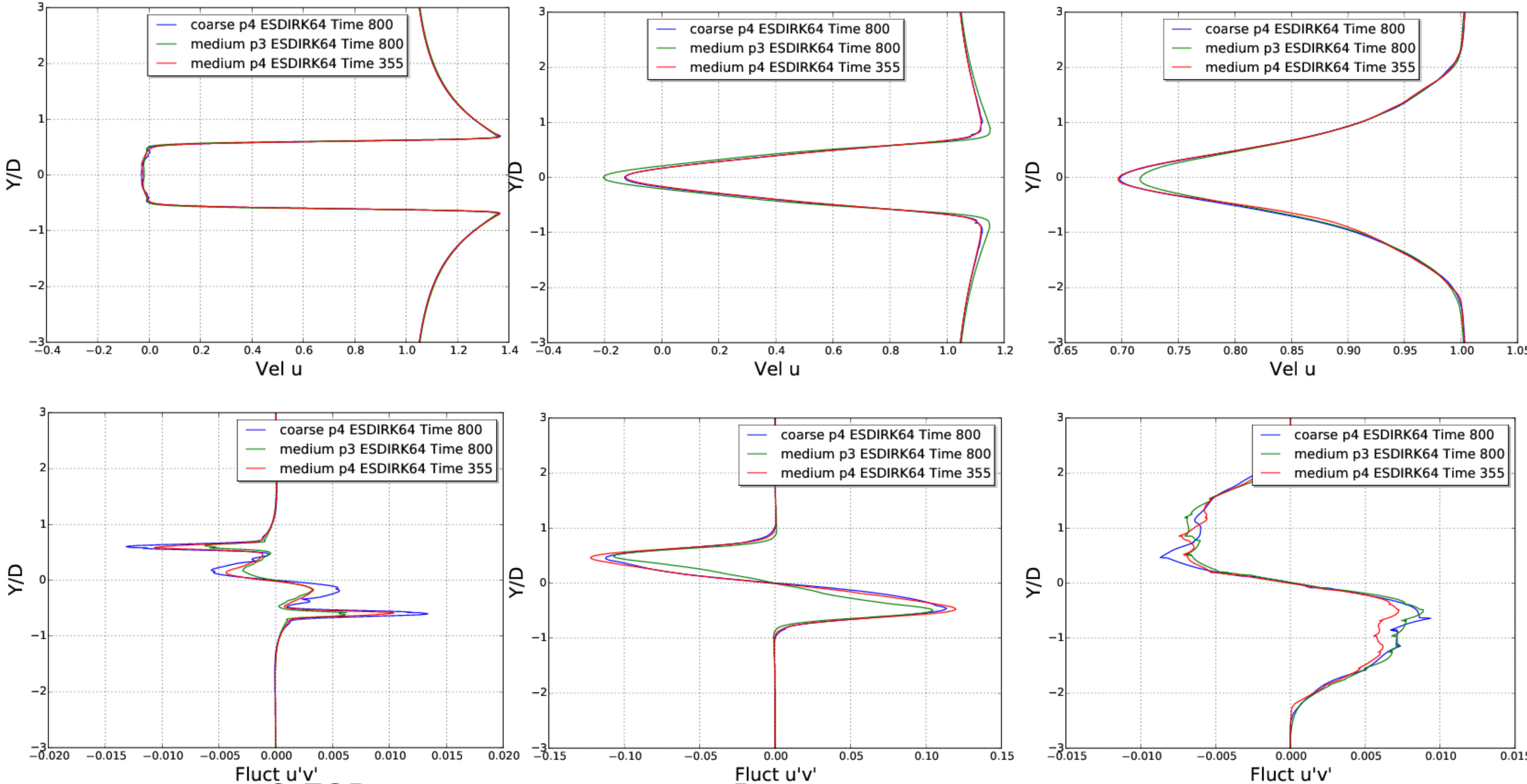


Cylinder Re=3900

Time-averaged flow field (medium p=3)



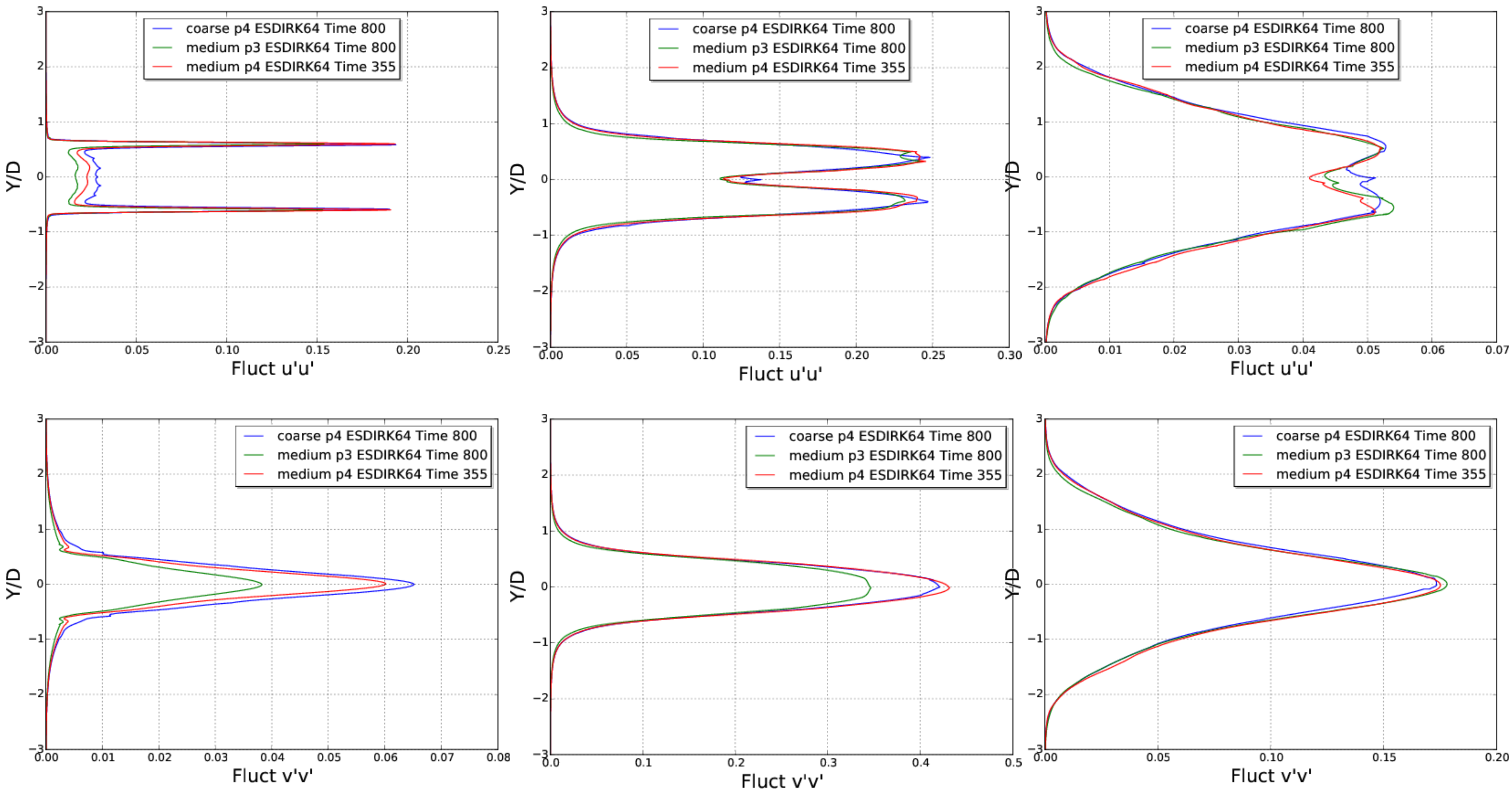
Cylinder Re=3900
Wake traverses



x=0.58D x=D x=5D

Cylinder Re=3900

Wake traverses



x=0.58D *x=D* *x=5D*

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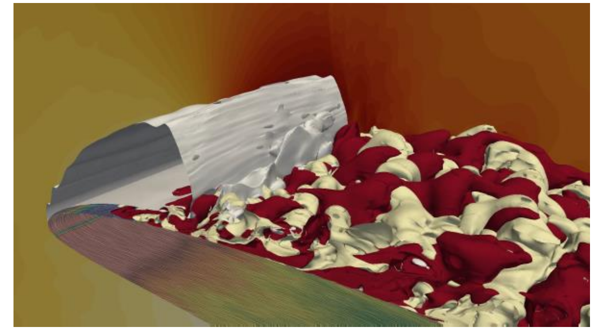
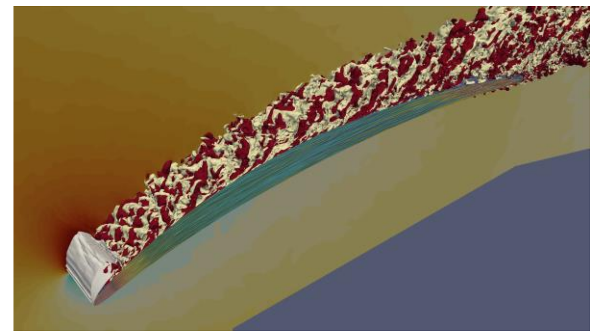
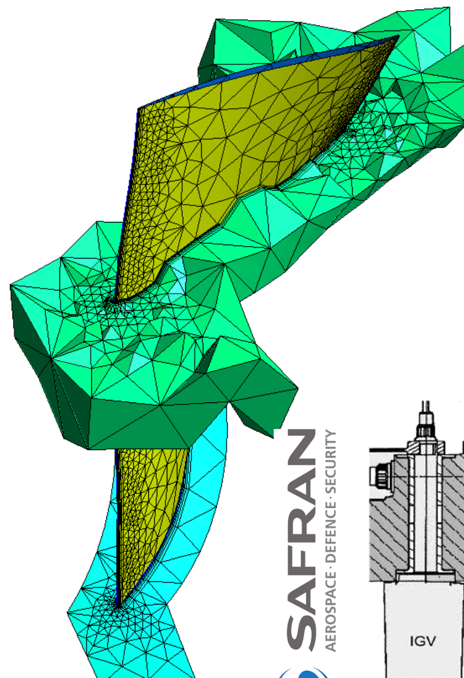
A new computational core

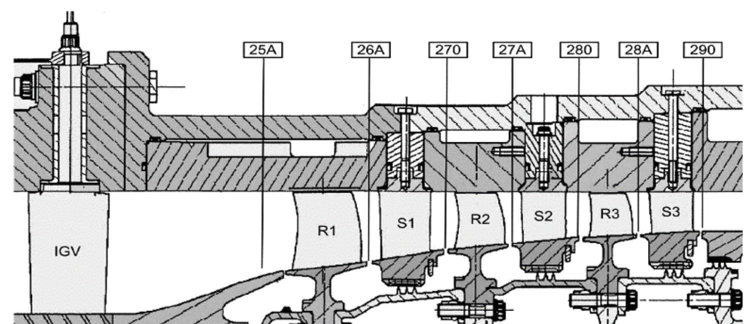
Accurate, efficient DNS and LES in complex geometry

- **Conclusions**
  - **High precision = low dispersion / dissipation**
    - « Low » cost for DNS, LES acoustics
    - Low interaction discretisation and SGS & ILES
    - unstructured, low quality mesh in complex geometry
  - **High performance computing**
    - unstructured implicit & petascale
    - Serial efficiency
    - Efficient implicit iterative methods
    - Physics agnostic !
- **Work in progress**
  - **WMLES multistage compressor**
    - Curved grid generation
    - Frames/NMC – Cagnone (7607)
  - **Developments**
    - ILES transonic turbulence (CTR)
    - Synthetic inlet turbulence
    - Wall modeled LES – Frère (7179)
    - *Unsteady hp-adaptation*









Acknowledgments

- Collaborations
  - Prof. Winckelmans and Prof. Chatelain – UCLouvain
  - Prof. Remacle – UCLouvain
  - Prof. Bricteux – Umons
  - Dr. Carton de Wiart – NASA
- Projects
  - IDIHOM (FP7)
  - Tilda (H2020)
  - Sinus & HPC4WE (ERDF/RW)
  - ELCI (PIA/Fr)
  - PRACE Tier1 FWB
- PRACE projects