Massively parallel Poisson solvers on unstructured meshes

Road towards Tera-Cell CFD…

V. Moureau, **G. Lartigue**

CORIA, UMR 6614, Rouen

http://www.coria-cfd.fr

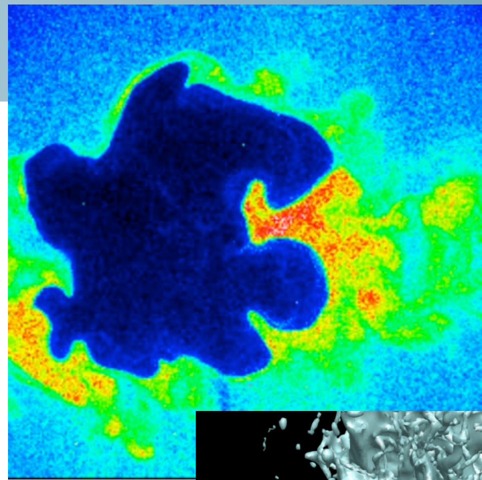
EQUIP@MESO

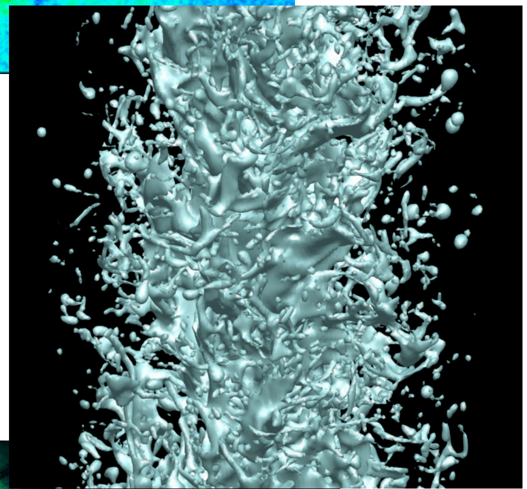
Outline

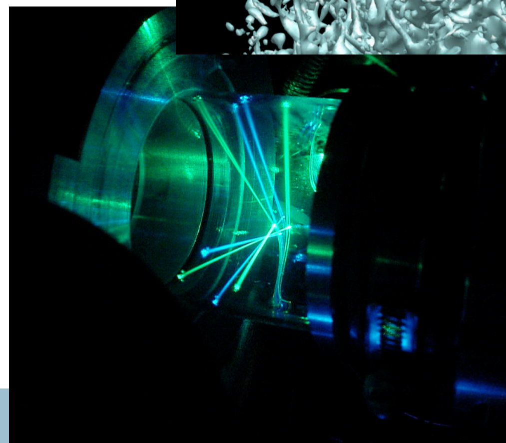
- Context and motivation
- The YALES2 code
- High performance linear solvers
- A few case studies
- Conclusions

Overview

- Joint lab from CNRS, INSA and University of Rouen
- 180 employees, 56 senior researchers
- 3 departments
  - Reactive flows
  - Turbulence, atomization and sprays
  - Optics and lasers
- Combustion modeling team
  - In the reactive flows department
  - 8 researchers + 12 PhD
    - Prof Luc Vervisch,
    - Prof Yves D'Angelo,
    - Dr Pascale Domingo,
    - Dr Vincent Moureau,
    - Dr Guillaume Ribert,
    - Dr Guido Lodato,
    - Dr Ghislain Lartigue,
    - Dr Emeline Noël







Why trying to model turbulent combustion ?

- 86% of the usable energy on earth is obtained through combustion
- Combustion occurs in many applications
  - Aeronautical engines, automotive industry, furnaces, …

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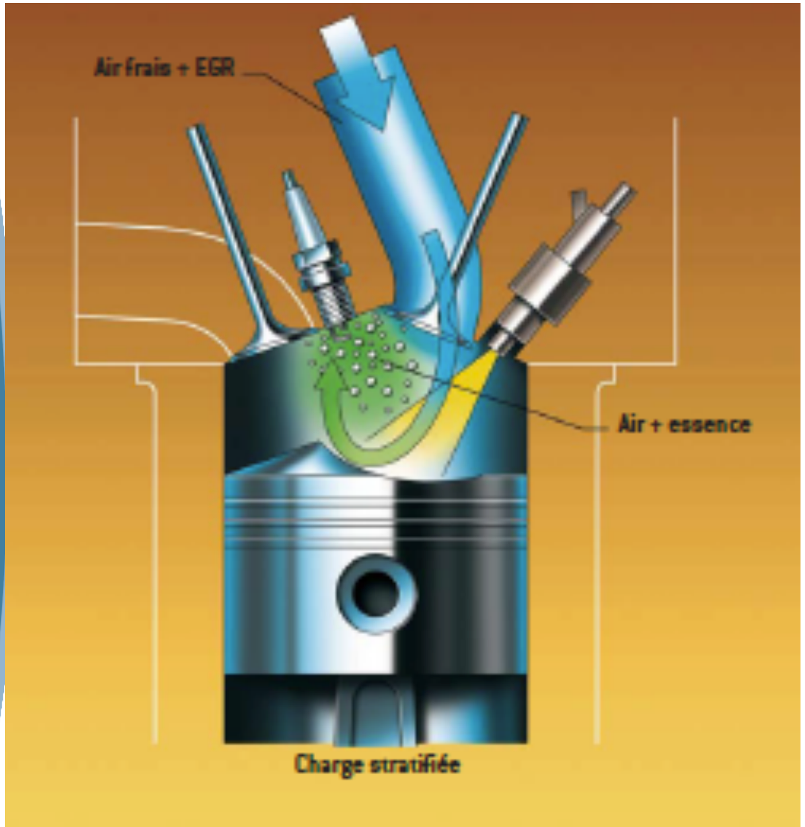

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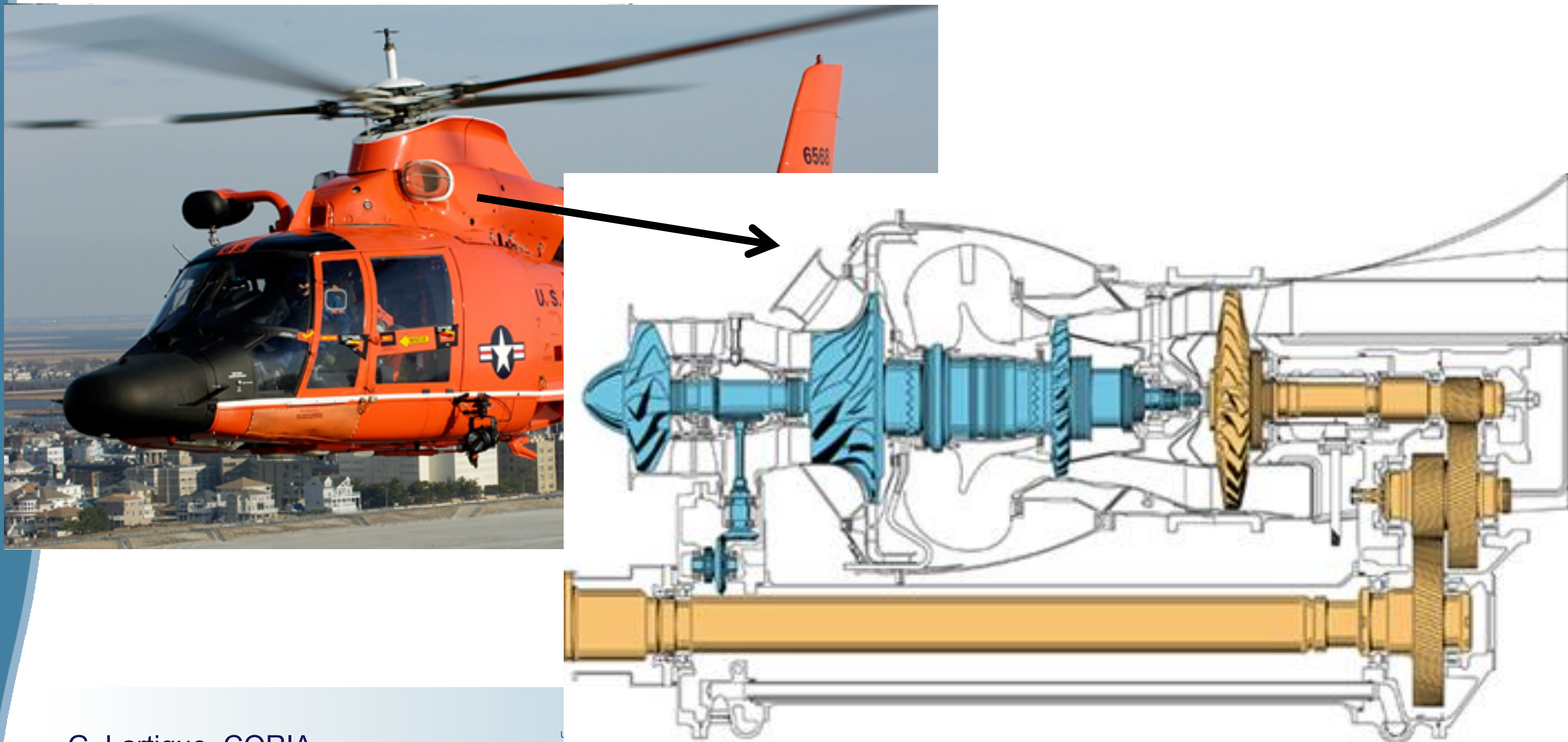
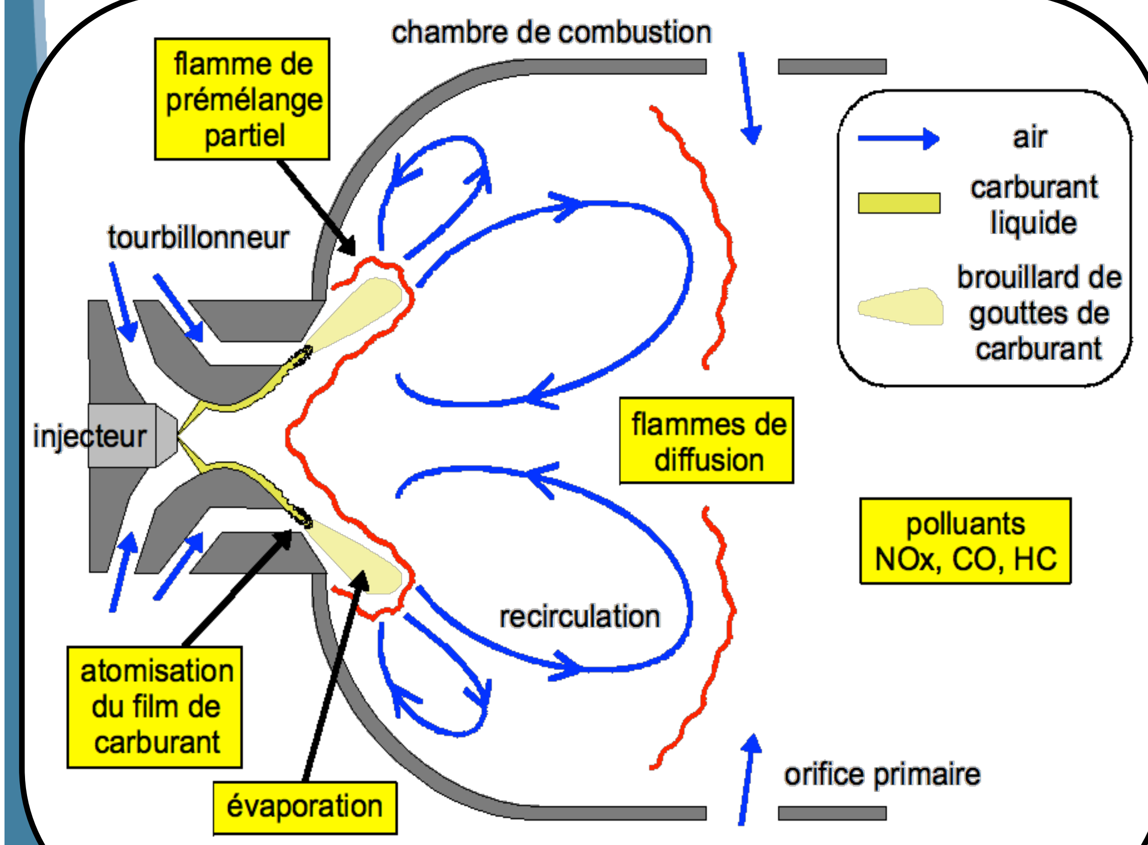


The challenge

- **Many phenomena at very different scales**



Aeronautical burner

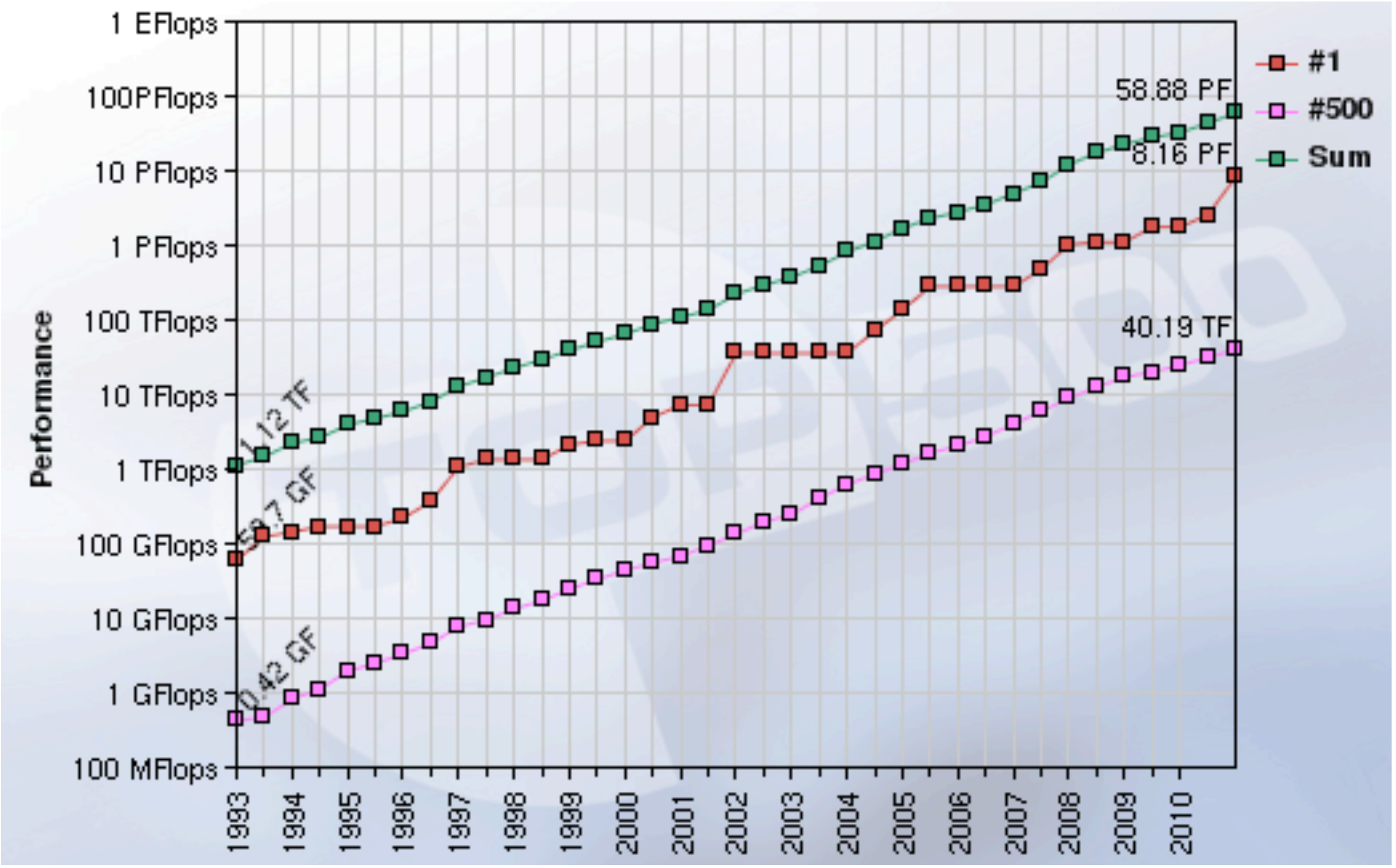
	Turbulence	10 mm 0.01mm
	Atomization	0.1 mm
	Spray transport	10 μm
	Evaporation	10 μm
	Combustion	0.1 mm

3 to 4 orders of magnitude

1-1000 billions cells

A great help: Moore's law

- **The power of desktop computers and super-computers doubles every 18 months**



http://www.top500.org/

Resources Hierarchy

- **4 classes of resources are available to researchers:**
  - **Workstations ~ 0.5Tflops**
  - **Tier-2 regional centers ~ 20Tflops**
  - **Tier-1 national centers ~ 200Tflops**
  - **Tier-0 european centers ~ 1'000Tflops**

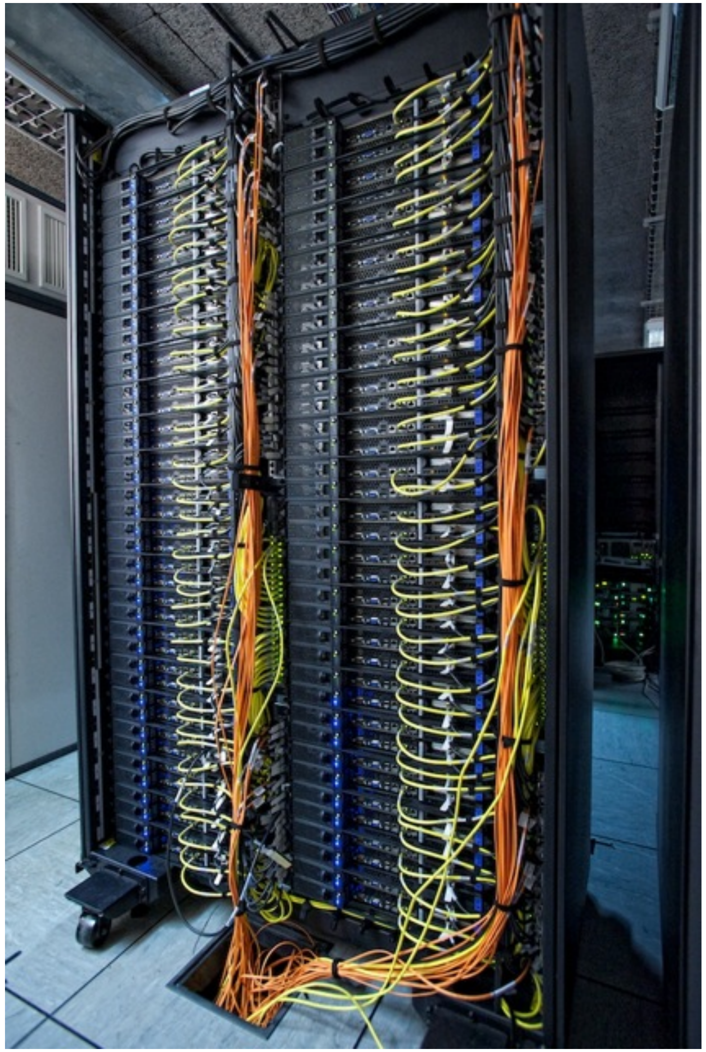
Resources Hierarchy

- **Step 1: 1-16 cores**
  - CAD,
  - Meshing,
  - Numerical parameters tuning,
  - Debugging
  - Visualization

- **Workstation (HP Z820)**
  - Intel Xeon E5-2687 @ 3.1GHz (x16) + 96Gb RAM + Nvidia Quadro 4000
  - 15Tb storage
  - 10k€ for 400Gflops peak
  - Good up to 1-5 Million cells

Resources Hierarchy

- **Step 2: 16-512 cores**
  - **Mesh refinement,**
  - **Statistically converged result on coarse LES,**
  - **Physical model validation,**
  - **Code optimisation**
- **Meso-Center (antares@CRIHAN)**
  - **Intel Nehalem/Westmere @ 2.8GHz (3kcores)**
  - **2Tb RAM / 280Tb fast access storage**
  - **~1M€ for 40Tflops peak**
  - **Good up to 100 Million cells**
  - **1-3 Millions CPU hours / year**



Resources Hierarchy

- Step 3: 512 – 4096 cores
  - Mesh refinement,
  - Statistically converged result on well resolved LES,
  - Small structure investigation, high-Reynolds numbers
  - Need severe code optimisation
- National Centers (IDRIS, CINES, TGCC, …)
  - Various architectures (IBM BG P/Q, Bull, SGI,)
  - 10kcores up to 80kcores
  - Good up to 5 Billion cells
  - 20 Millions CPU hours / year

Resources Hierarchy

- **Step 4: more than 4096 cores**
  - **Extreme mesh refinement,**
  - **Statistically converged DNS,**
  - **Full turbulence spectrum, combustion modeling, …**
  - **Algorithm optimisation (linear solvers)**
- **EC Tier-0 Centers (TGCC, Juelich, …)**
  - **Various architectures (IBM BG P/Q, Bull, SGI,)**
  - **100kcores minimum**
  - **Good up to 100 Billion cells**
  - **PRACE calls only**

Resources for future large-scale computations

- **Simulation time for a combustor with 10 billion tets (2020 target)**

IBM Power 7 Server
6 years with 256 cores

IBM Blue Gene/Q
1 day with 1.6 million cores

power

PC : 530 years with 6 cores

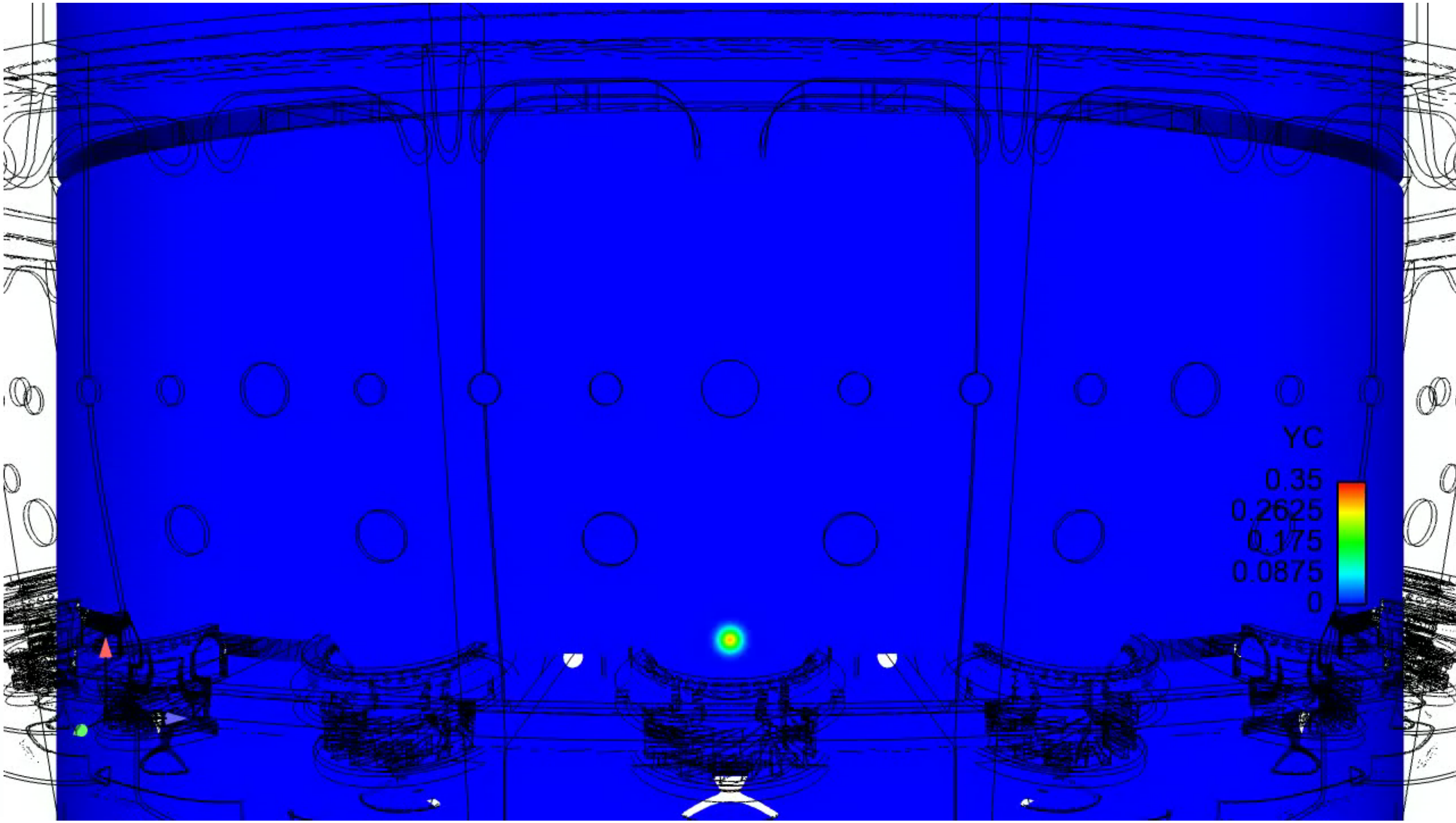
IBM Blue Gene/P
24 days with 300,000 cores

- **Many issues still have to be addressed**
  - Mesh generation, post-processing, **solving of large linear systems**, …

2012 industrial calculation: LES of an ignition sequence in a 360° SNECMA combustor

- 160M tets, 20h on 2048 cores of Airain@CCRT (200Tflops)

by J. Leparoux and G. Godel (Snecma Villaroche)



The YALES2 code

YALES2 www.coria.cfd.fr

YALES2

- YALES2 is an unstructured low-Mach number code for the DNS and LES of reacting two-phase flows in complex geometries. It solves the unsteady 3D Navier-Stokes equations

- It is used by more than 80 people in labs and in the industry
  - Labs: CORIA, I3M, LEGI, EM2C, IMFT, CERFACS, IFP-EN, ULB, …
  - Industry:

SAFRAN AEROSPACE · DEFENCE · SECURITY
AIRBUS AN EADS COMPANY
Rhodia
GDF SUEZ
AIR LIQUIDE
RENAULT
AREVA

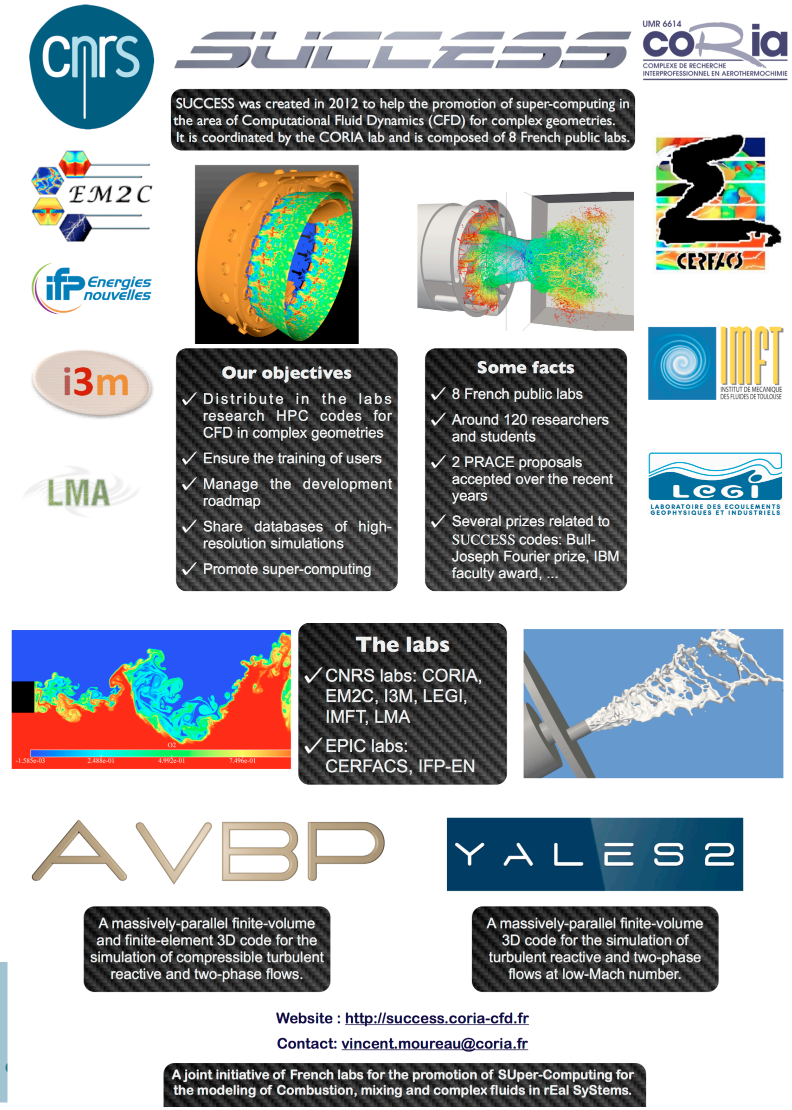
- Awards
  - 3rd of the Bull-Joseph Fourier prize in 2009
  - 2011 IBM faculty award

SUCCESS: http://success.coria-cfd.fr

- **SUCCESS is a joint initiative started in 2012 on LES of complex flows in realistic geometries and the promotion of super-computing**

- **Supported by CNRS**

- **Partners**
  - CORIA, Rouen (coordinator)
  - I3M, Montpellier
  - LEGI, Grenoble
  - EM2C, Châtenay-Malabry
  - IMFT, Toulouse
  - LMAP, Pau
  - CERFACS, Toulouse
  - IFP-EN, Rueil-Malmaison

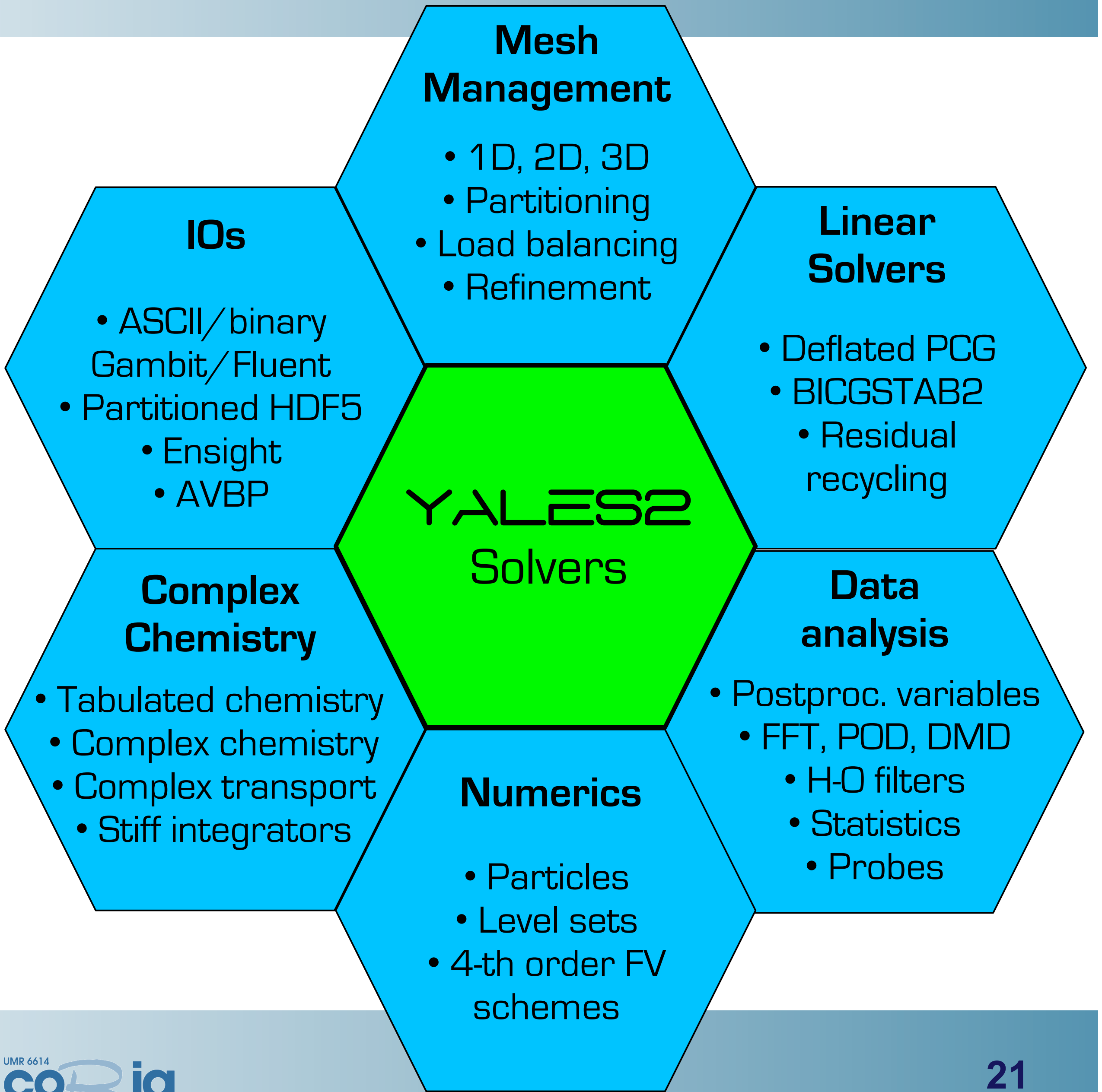


SUCCESS: Objectives

- **Distribution of HPC codes for LES of realistic geometries**
  - Codes: AVBP and YALES2
- **User training**
  - Several training sessions each year organized by CERFACS and CORIA
- **Collaborative development of the codes**
  - Shared development platforms: inle.cerfacs.fr (Redmine), www.coria-cfd.fr (Trac)
- **Sharing of the large simulation databases**
  - DOPACO project with CINES
- **Promoting super-computing at the national (GENCI) and European levels (PRACE)**
  - Joint PRACE proposals: example of X-Vampa with CORIA, CERFACS, LEGI

The YALES2 library (version 0.4.2)

- **2 main maintainers**
  - **V. Moureau**
  - **G. Lartigue**
- **243 000 lines of object-oriented f90**
- **Git version management**
- **Portable on all the major platforms (even ARM proc.)**



The YALES2 solvers

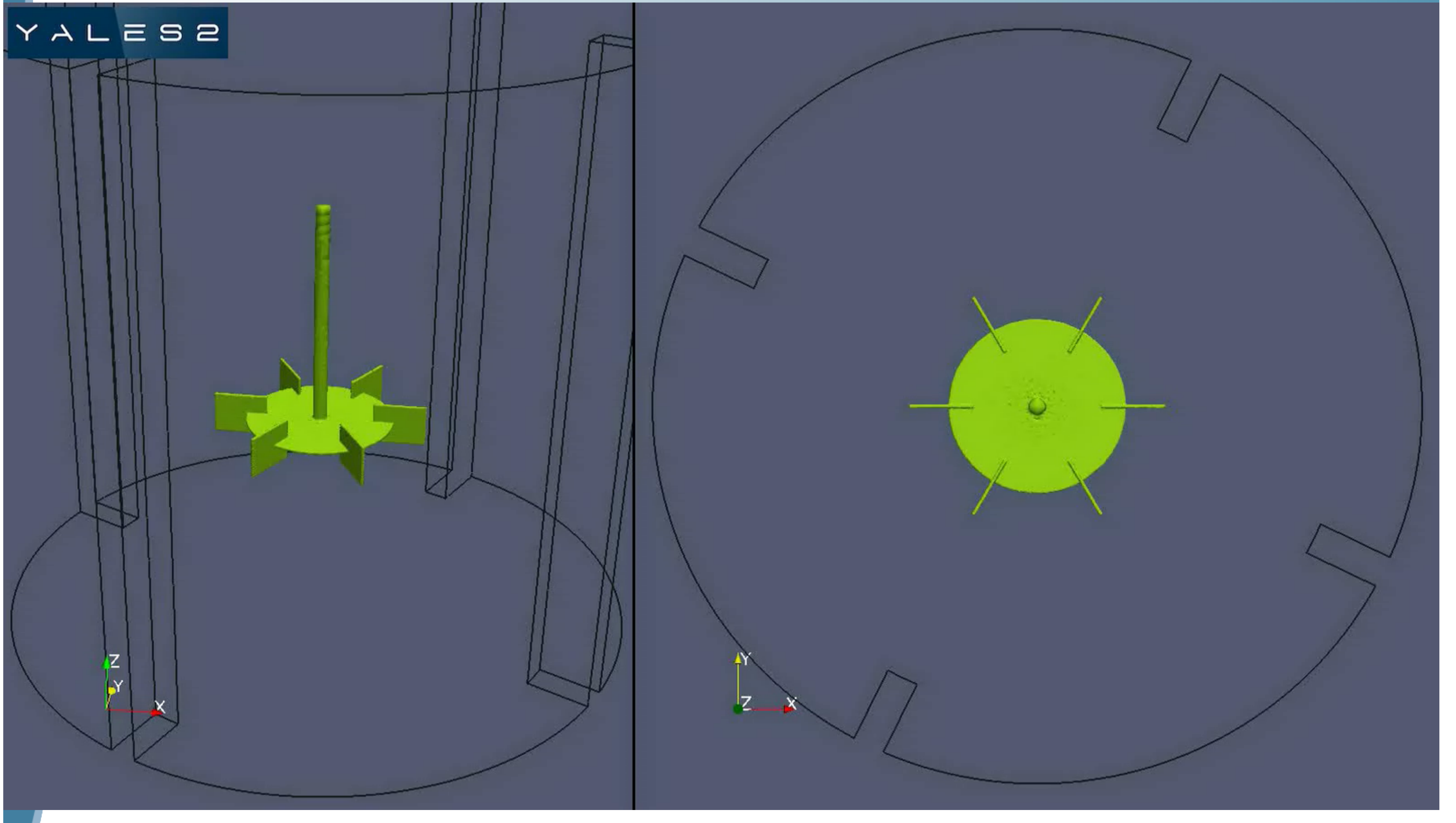
Mature solvers

- Scalar solver (SCS)
- Level set solver (LSS)
- Lagrangian solver (LGS)
- Incompressible solver (ICS)
- Variable density solver (VDS)
- Spray solver (SPS)
- Magneto-Hydrodynamic solver (MHD)
- Heat transfer solver (HTS)
- Linear acoustics solver (ACS)

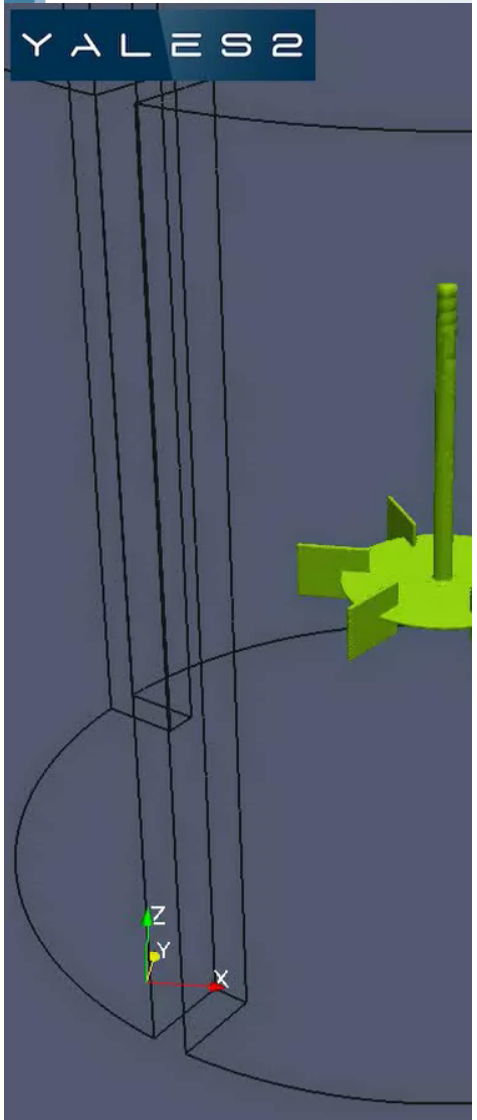
Work in progress

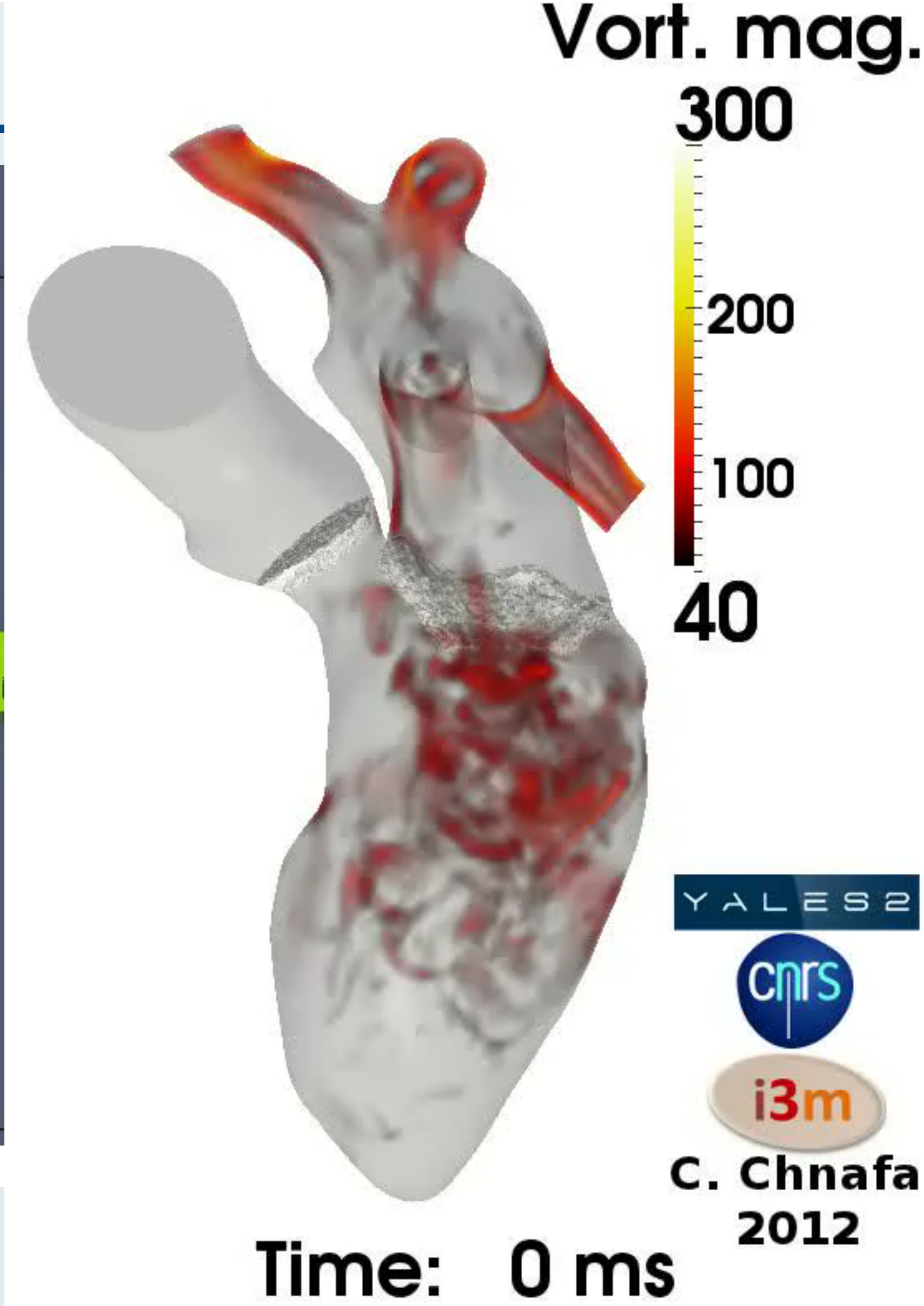
- Mesh movement solver (MMS)
- ALE solver (ALE)
- Radiative HT solver (RDS)
- Explicit compressible solver (ECS)
- Immersed boundary solver (IBS)
- Chemical reactor solver (CRS)

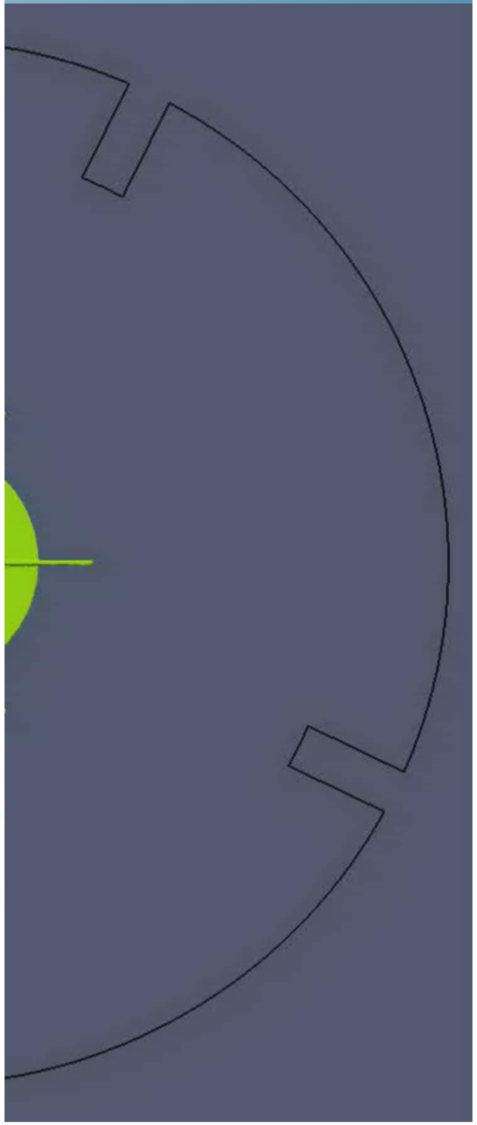
The YALES2 solvers



The YAL

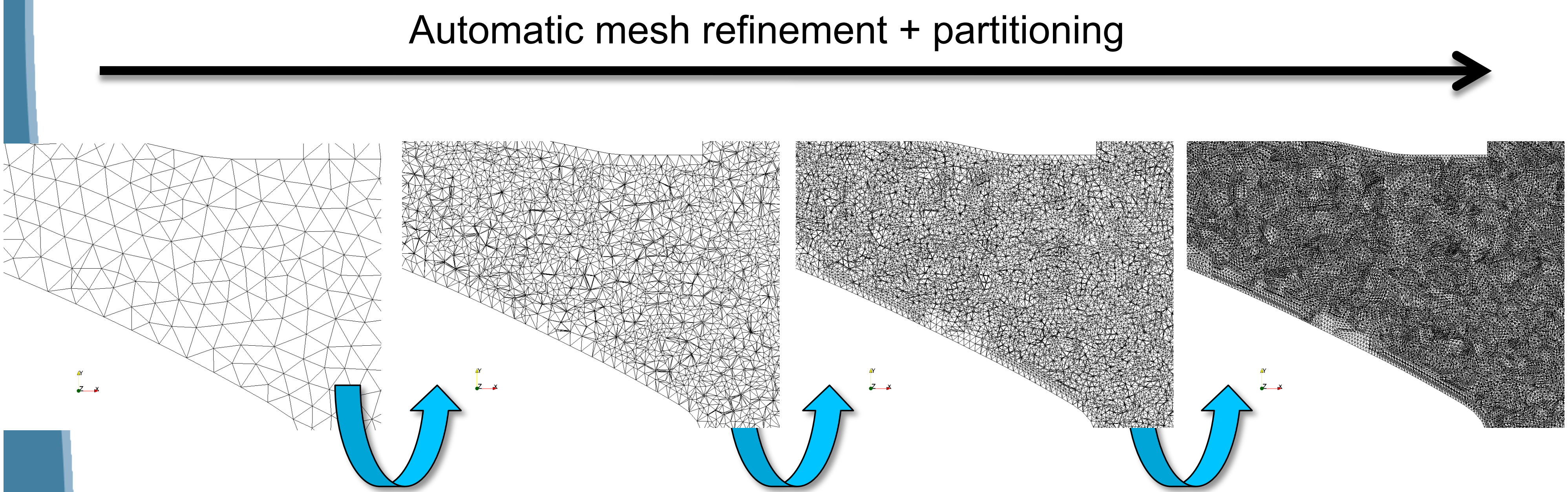

YALES2
Z
Y
X


Vort. mag.
300
200
100
40
YALES2
cnrs
i3m
C. Chnafa
2012
Time: 0 ms



Mesh management

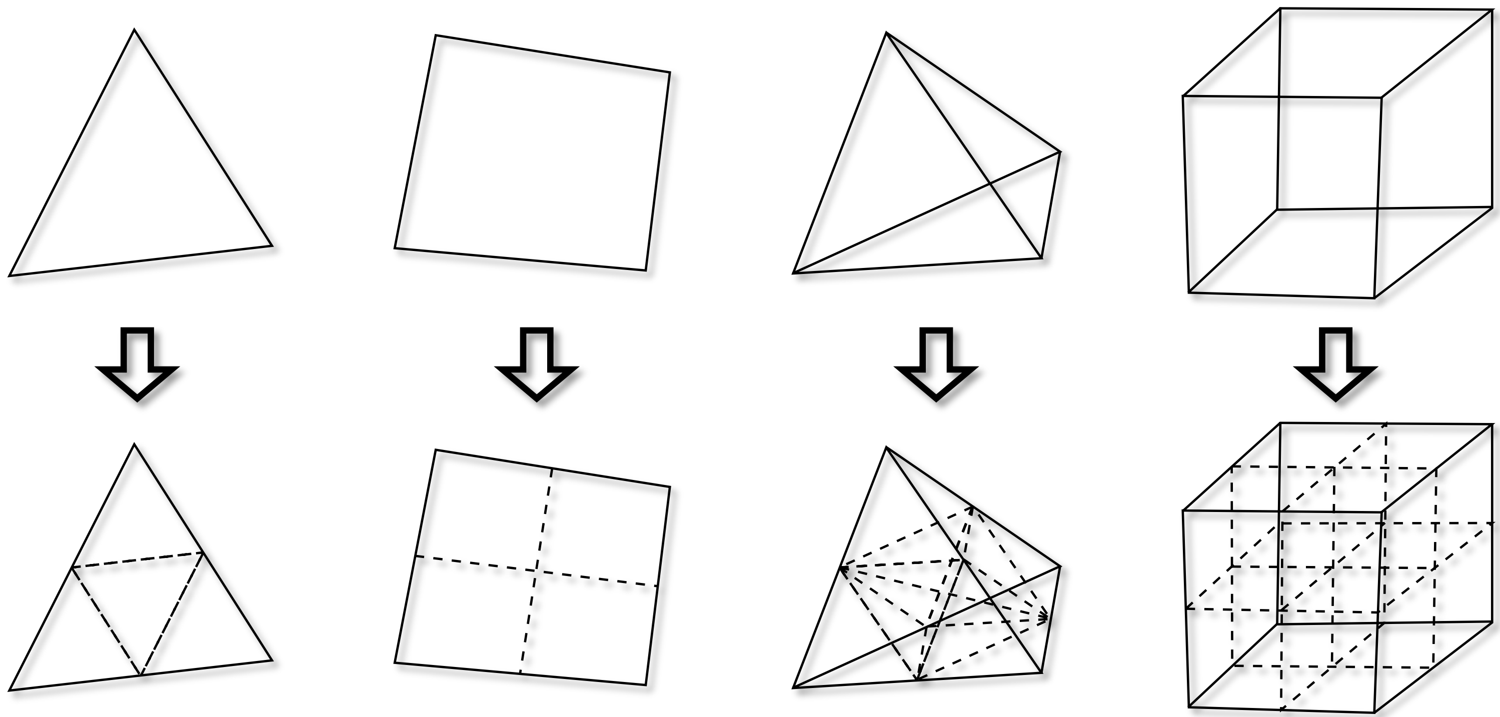
Strategy: refinement and partitioning



Size	2M	14M	110M	878M
Number of blocks	1	16	128	1024
Number of files	1	16	128	256

Mesh generation

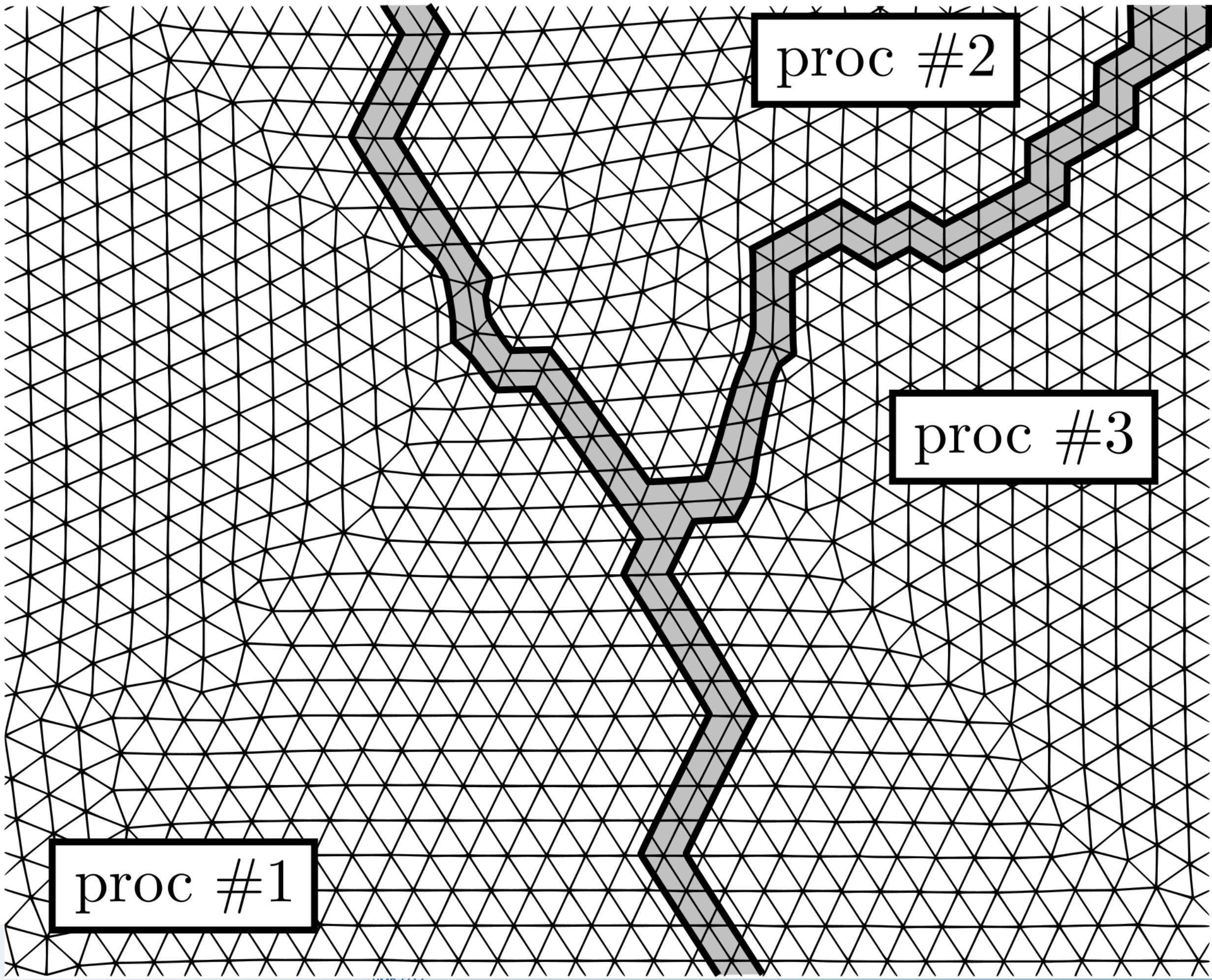
- Homogeneous mesh refinement allows to reach massive mesh sizes. The only constraint is that the geometry has to be well described by the first mesh.



- For tets, mesh refinement is not obvious (Rivara 1984)

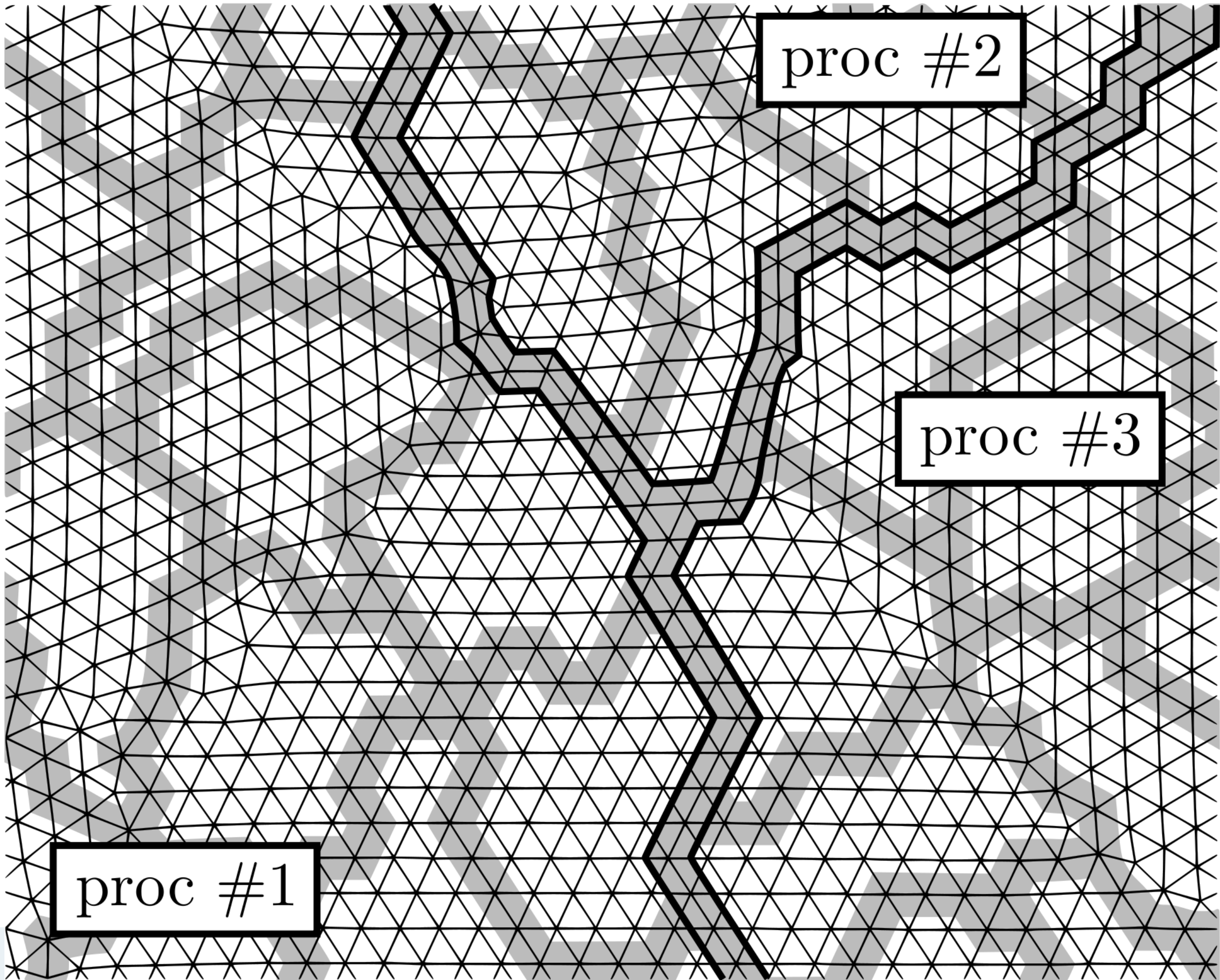
Mesh management on the processors

- 1st solution: single-level domain decomposition
- Several available libraries: Metis, Scotch, …

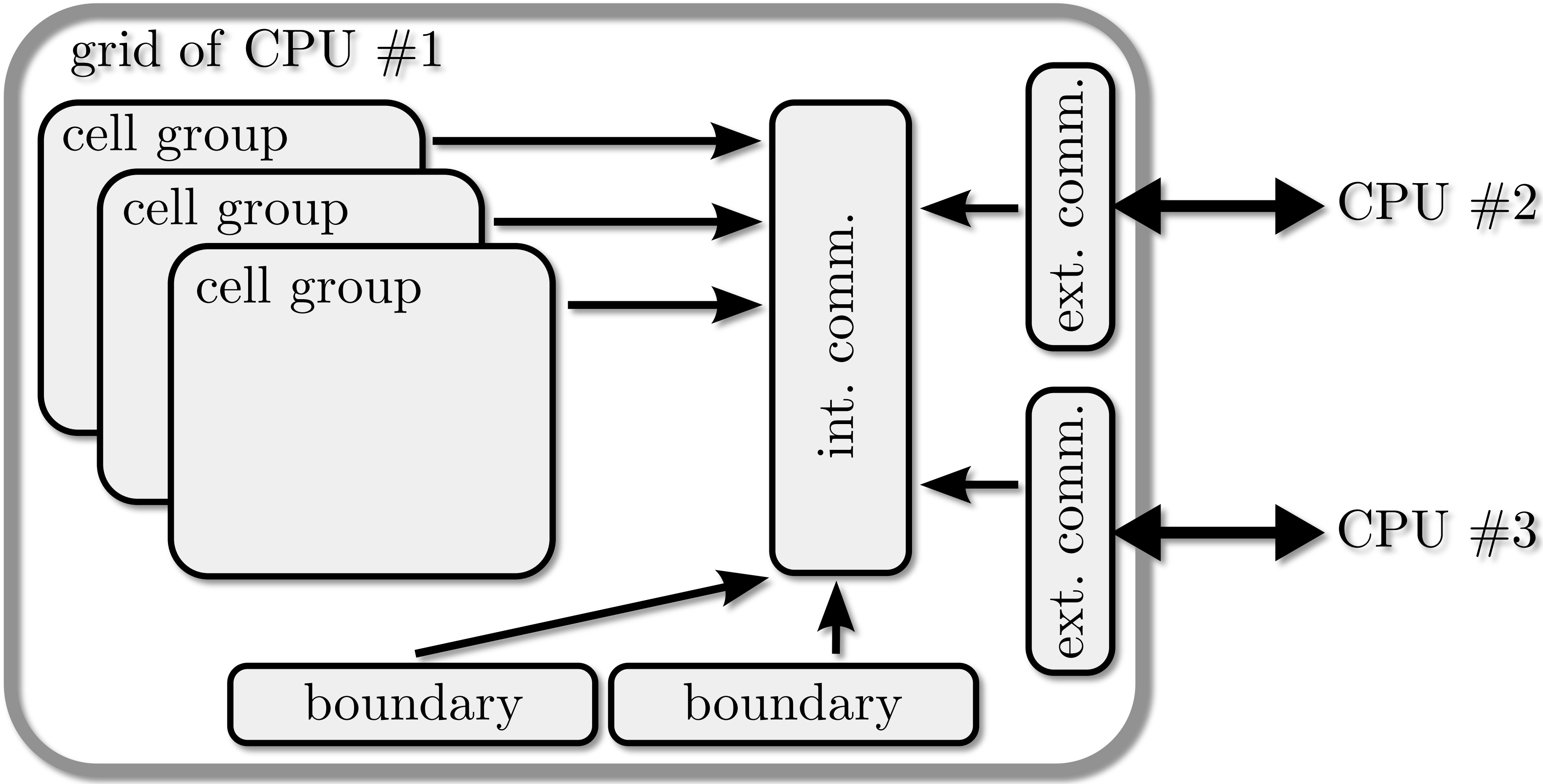


Mesh management on the processors

- 2nd solution: two-level domain decomposition (Moureau et al 2011)



Data structure



- Moureau, V., Domingo, P. & Vervisch, L., 2011, « Design of a massively parallel CFD code for complex geometries », invited paper in Comptes Rendus de l'Académie des Sciences.

Embedded post-processing

Embedded post-processing of iso-contours

- YALES2 has a feature named “POSTPROC_DUMP”, which allows to dump the cells of a plane or an iso-contour in the pre-partitioned HDF5 format

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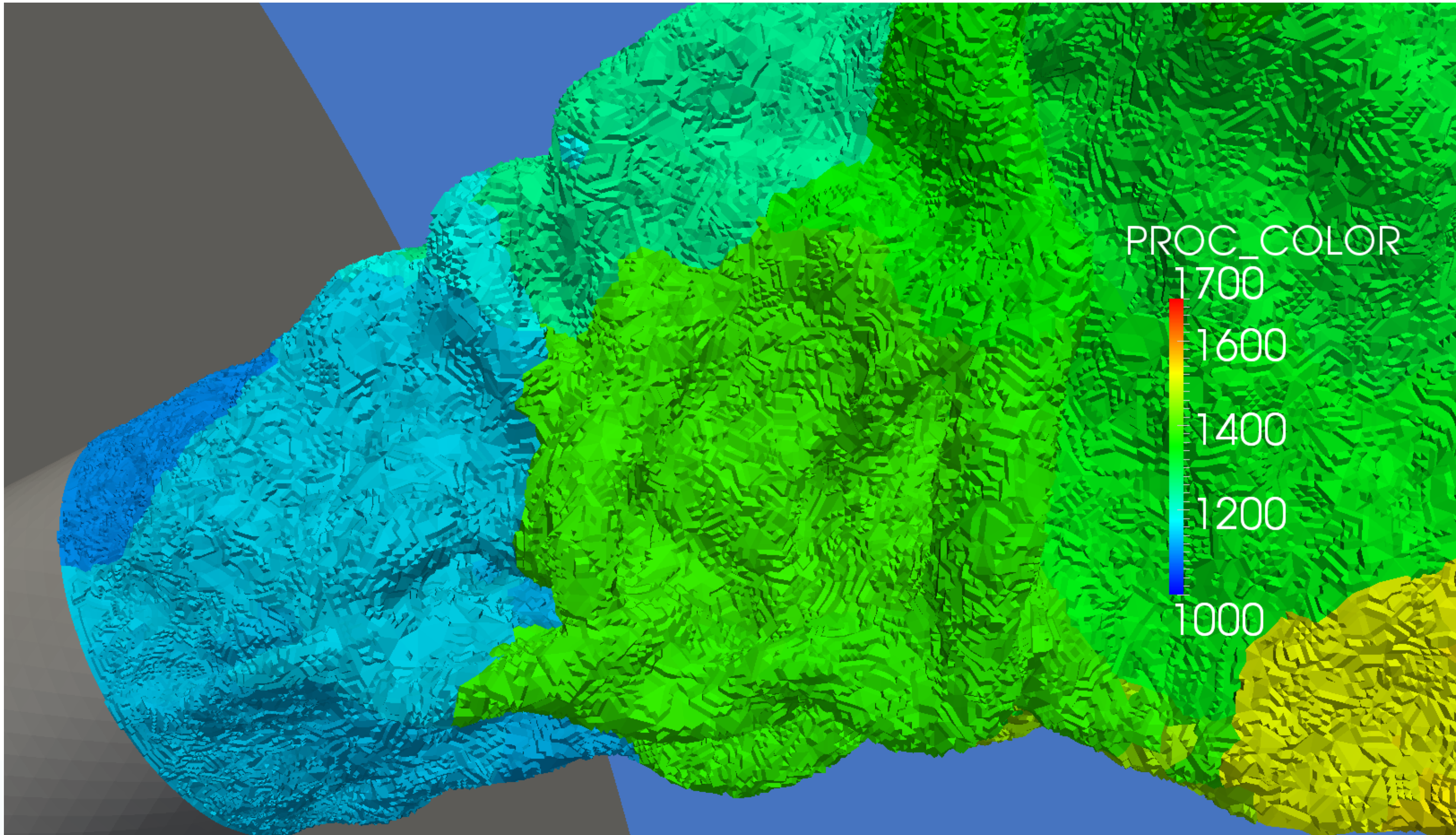

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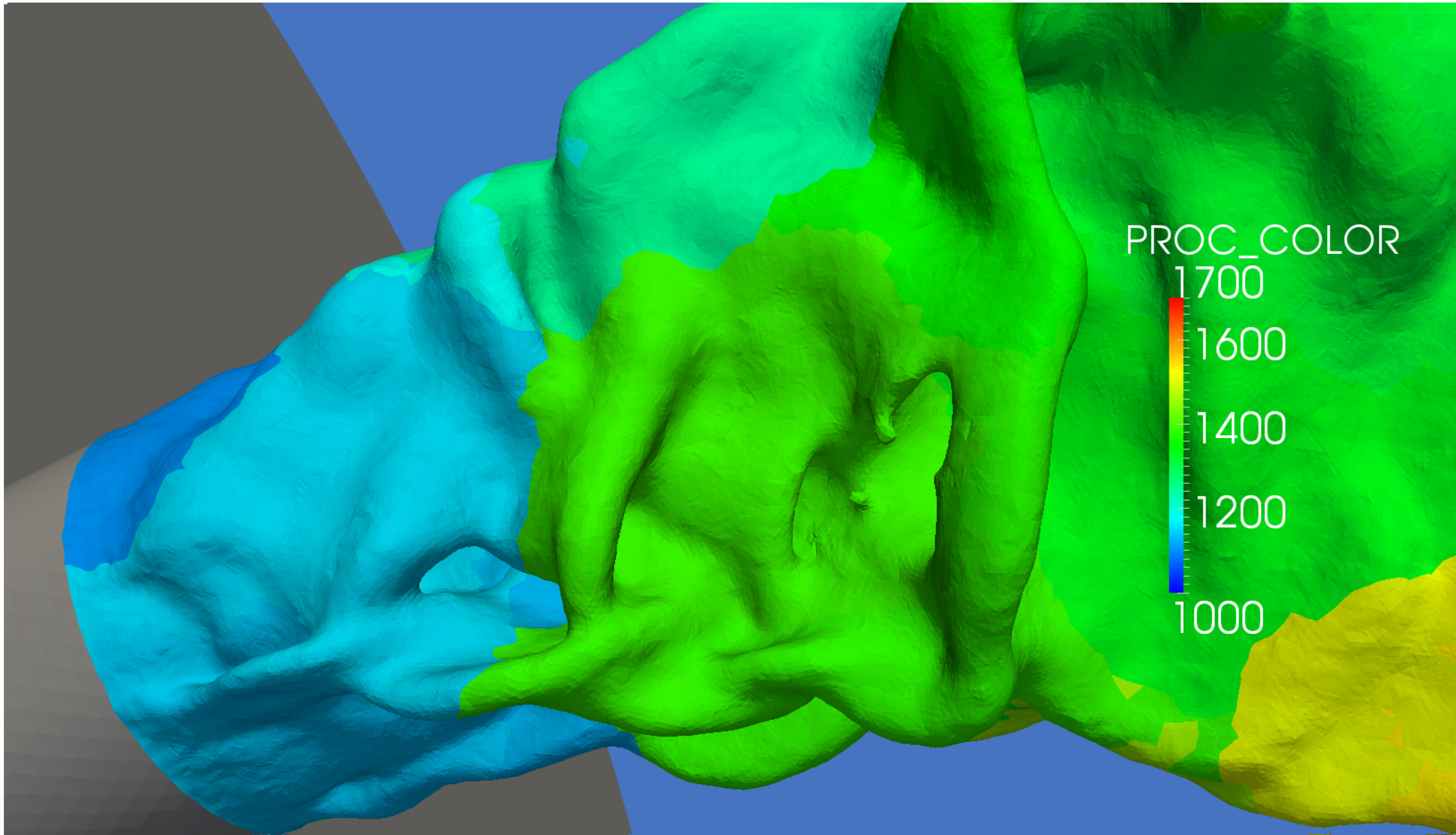
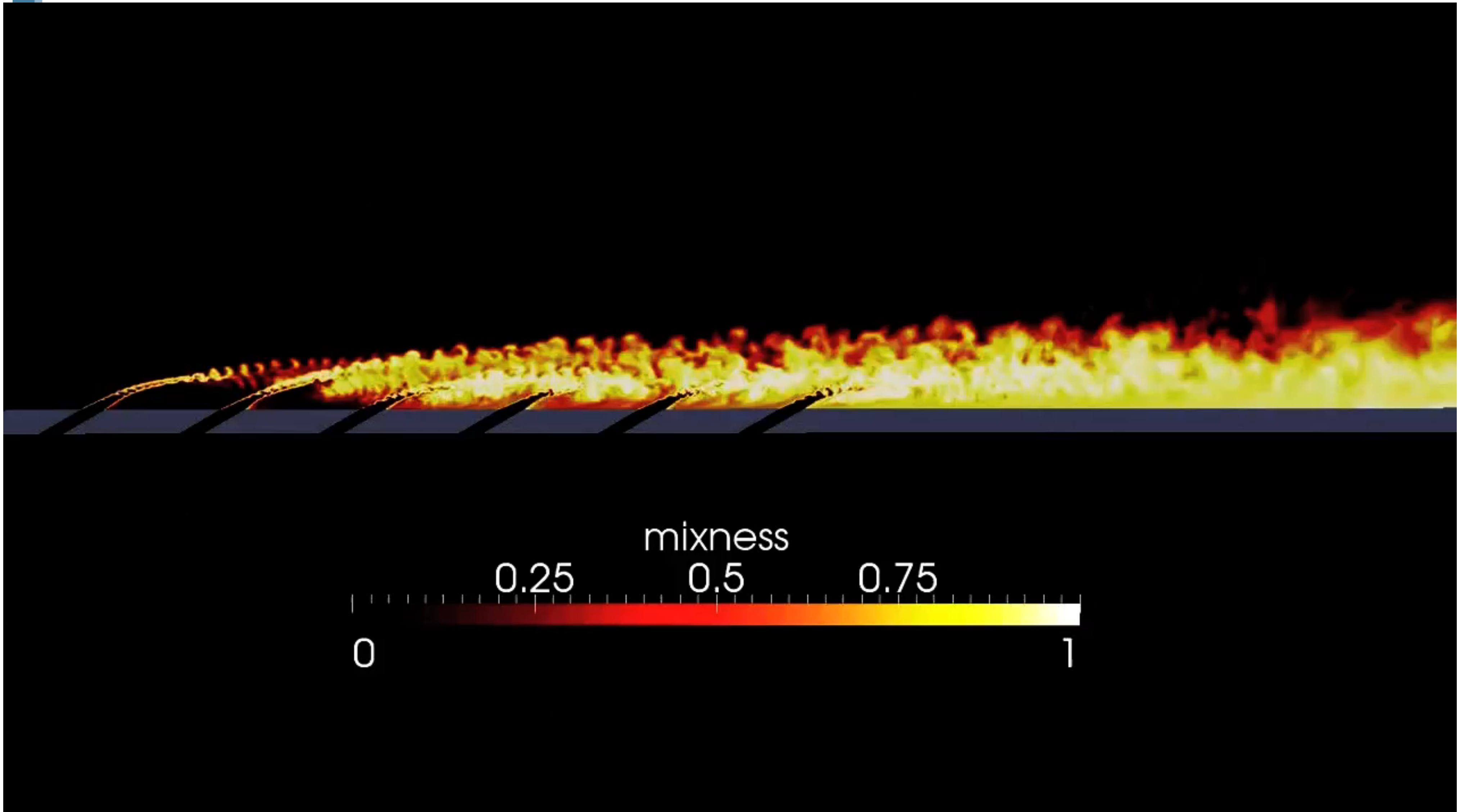


Embedded post-processing of planes

- A movie can be made for any run at no cost
- Example with a mesh of 110 million tets on 1024 cores of Curie, CEA



High-performance linear solvers

Governing equations

- **For DNS of iso-thermal flows at low-Mach number**
- **Velocity equation**

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\frac{1}{\rho}\nabla P + \frac{1}{\rho}\nabla \cdot \tau$$

- **Divergence-free constraint**

$$\nabla \cdot \mathbf{u} = 0$$

- **Often solved with projection methods (Chorin 1968)**

$$\nabla \cdot \left(\frac{1}{\rho}\nabla P\right) = \frac{\nabla \cdot \mathbf{u}^{\star}}{\Delta t} \quad \Longleftrightarrow \quad Ax = b$$

Solving the Poisson equation

- The Poisson equation is elliptic…
- Each points in the domain depends on EVERY other points
- Massive communications amongst cores
- 80% of CPU cost in the Poisson solver for most of the cases

$$\frac{1}{\rho}\begin{pmatrix} \ddots & \ddots & 0 & 0 & 0 \\ \ddots & \ddots & \ddots & 0 & 0 \\ 0 & 1/\Delta x^2 & -2/\Delta x^2 & 1/\Delta x^2 & 0 \\ 0 & 0 & \ddots & \ddots & \ddots \\ 0 & 0 & 0 & \ddots & \ddots \end{pmatrix}\begin{pmatrix} \\ \\ P_i \\ \\ \\ \end{pmatrix} = \begin{pmatrix} \\ \\ \left.\frac{\nabla\cdot\mathbf{u}^\star}{\Delta t}\right|_i \\ \\ \\ \end{pmatrix}$$

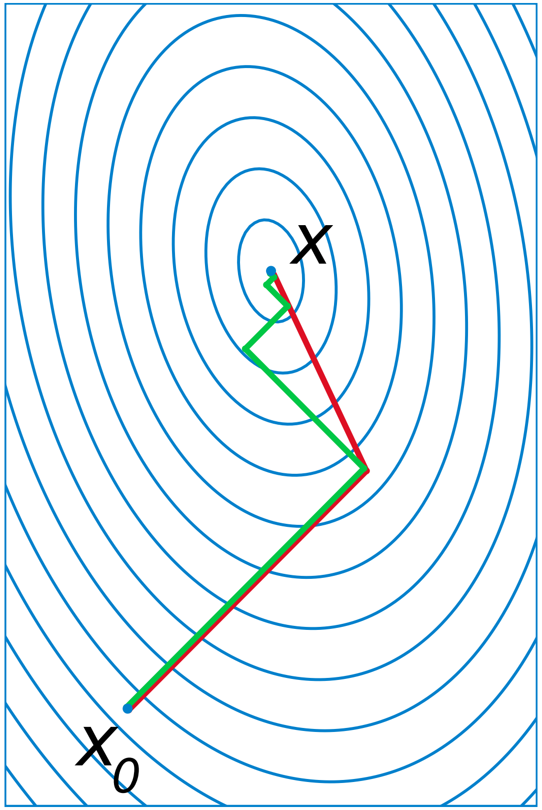
- The A matrix is symmetric with a non-dominant diagonal.
- Dedicated linear solvers (PCG, MG, DPCG, …) must be used

Gradient methods

- Minimize a functional whose gradient is the actual linear system

$$f(x) = \frac{1}{2}x^T Ax - x^T b \qquad \nabla f(x) = Ax - b$$

- Ex: steepest descent, conjugated gradient, …



- The conjugated gradient minimize the number of research direction by orthogonalizing them ➔ convergence guaranteed in finite time

- How to achieve convergence up to a given precison in a minimum number of iteration?

- Solution: PRECONDITIONNING!!!

Gradient methods

- If κ is the conditionning number of the matrix the error decrease as:

$$\frac{\|e_k\|_A}{\|e_0\|_A} \leq 2\left(\frac{\sqrt{\kappa}-1}{\sqrt{\kappa}+1}\right)^k$$

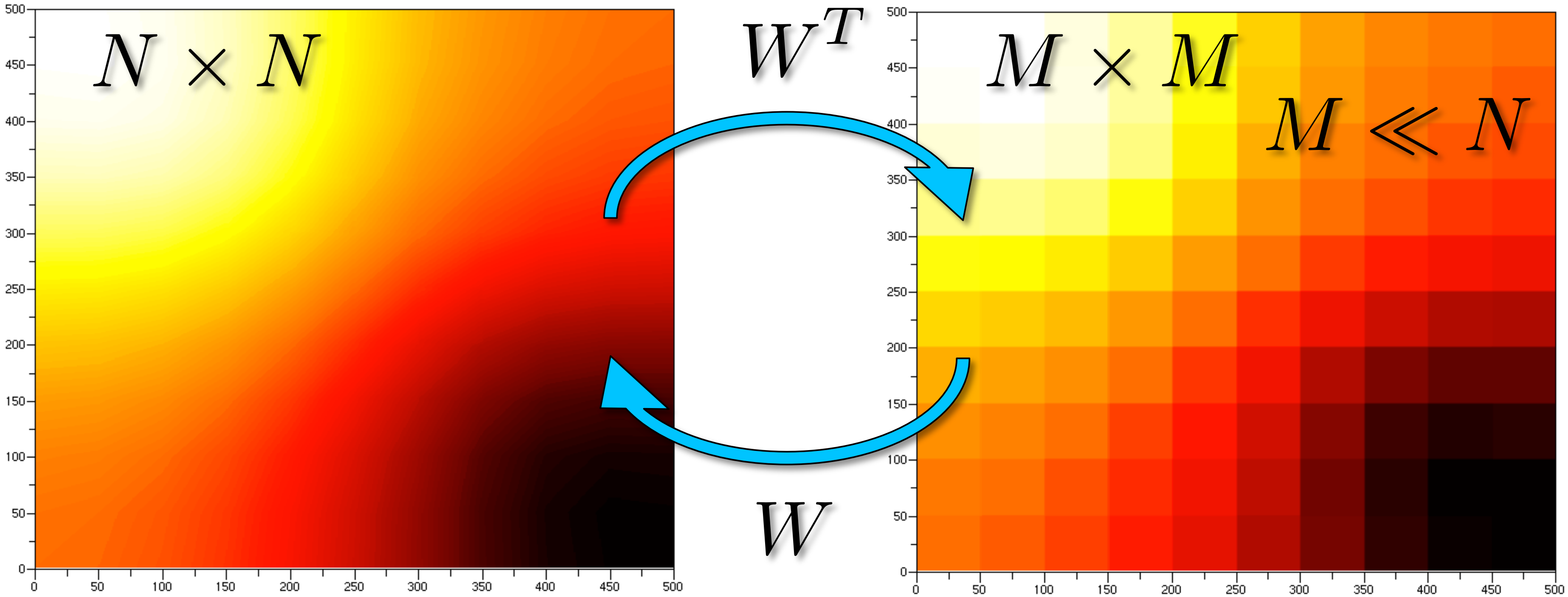
Instead of solving the initial problem: $Ax = b$

We try to solve the equivalent problem: $K^{-1}Ax = K^{-1}b$

- Various preconditionners can be used sequentially…
- A straightforward preconditionner is to use the inverse of the diagonal of A. In this case the new problem as a unitary diagonal…
- Deflation is a recent method to build performant preconditionners

The Deflated Preconditioned Conjugate Gradient (Nicolaides 1987)

- The principle is very close to the one of algebraic multi-grids

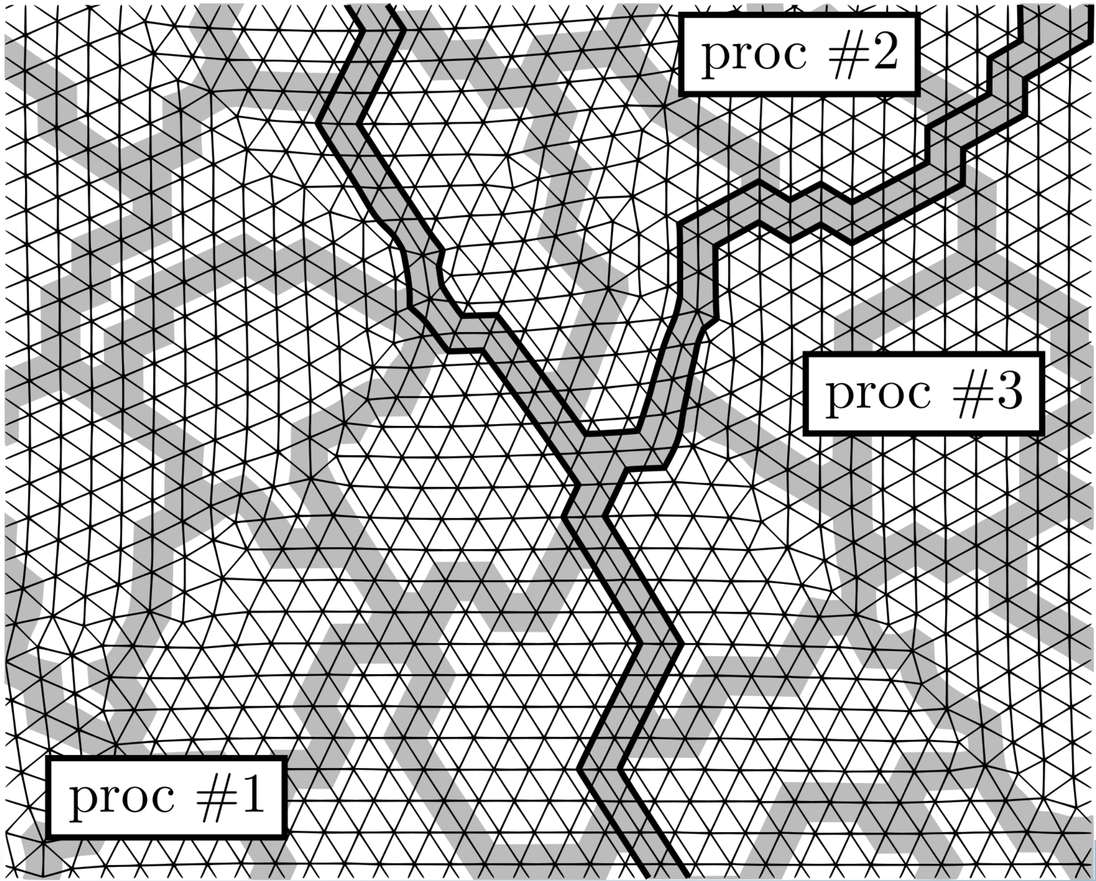


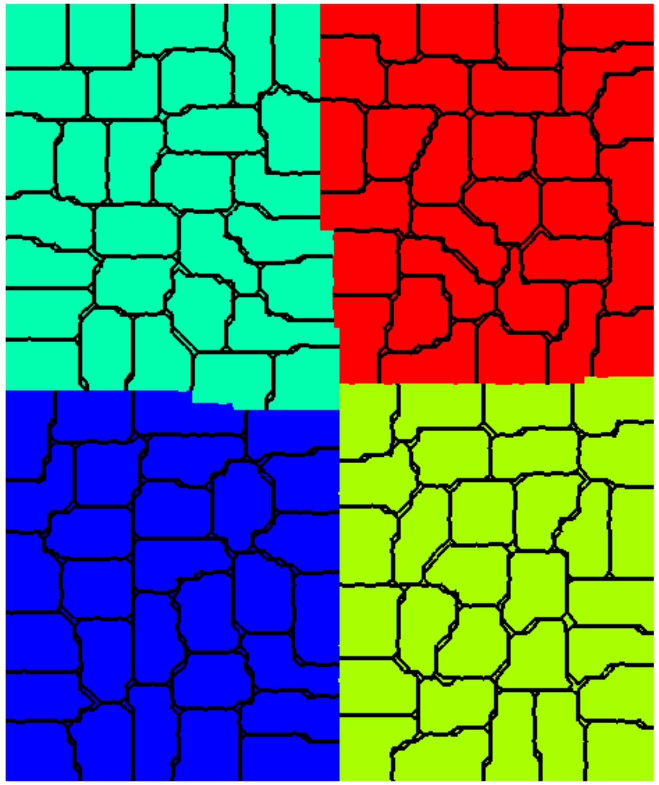
- The PCG preconditioning is based on a projection operator

$$P = I - W\hat{A}^{-1}W^T A \qquad \hat{A} = W^T A W$$

Implementation in YALES2

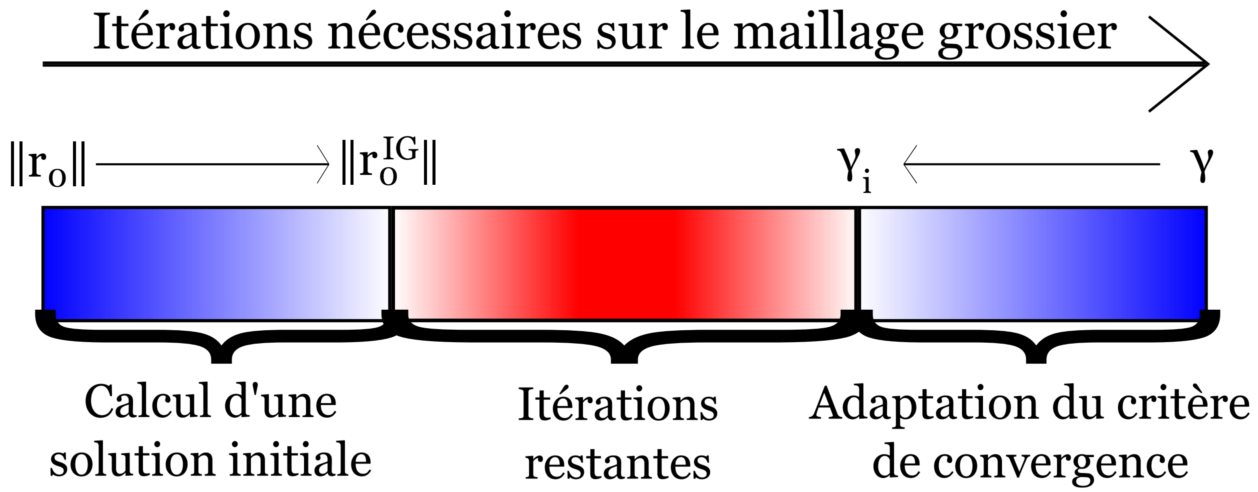
- Deflation is quite easy to implement if a coarse mesh is available. Restriction and prolongation operators are well defined.
- In YALES2, the DPCG uses the two-level domain decomposition.





Optimized deflated PCG

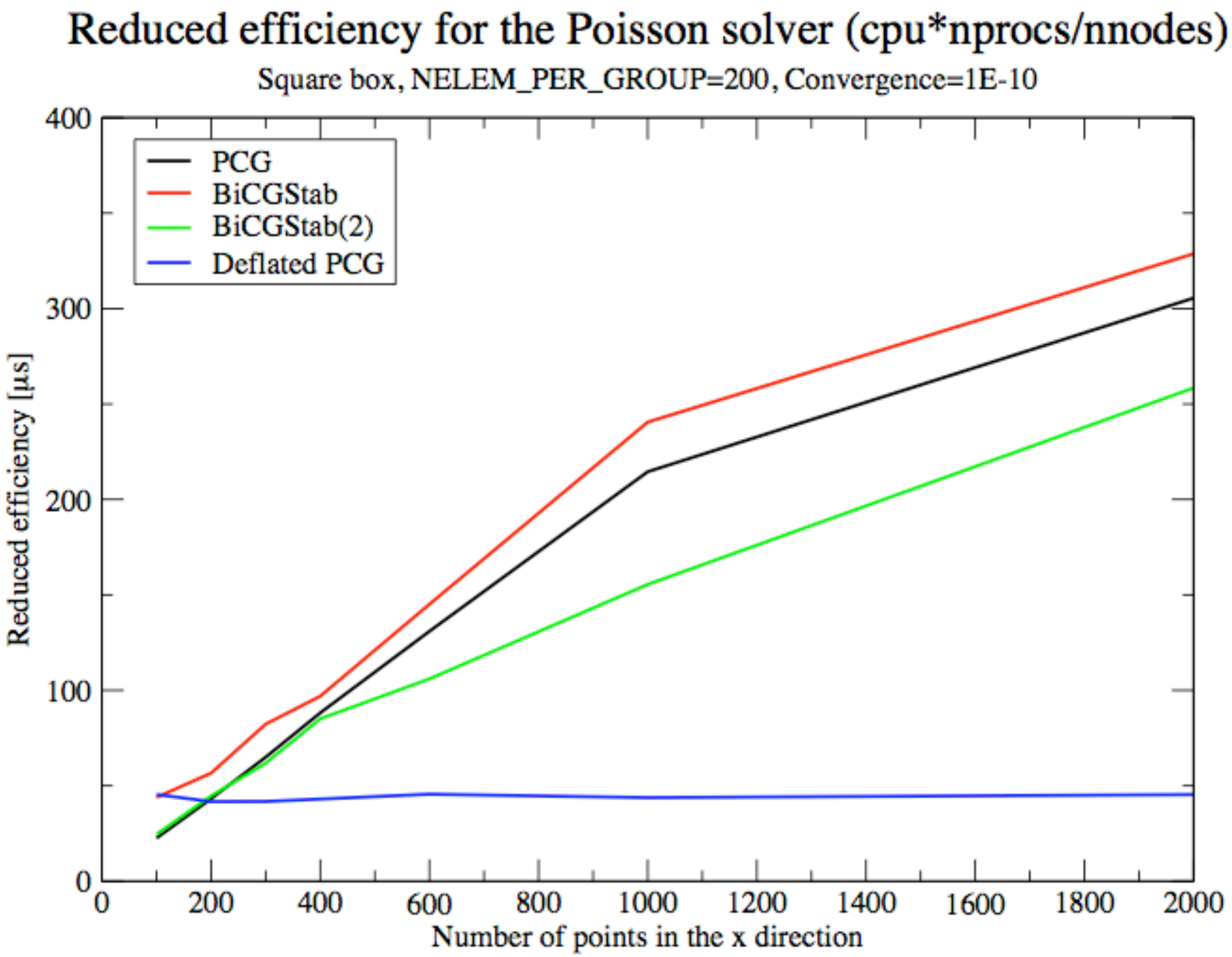
- **How to decrease the number of iteration of the solver?**



1. **Improve the initial guess ➔ residual recycling**
2. **Adaptation of the convergence criteria ➔ alignement criteria**

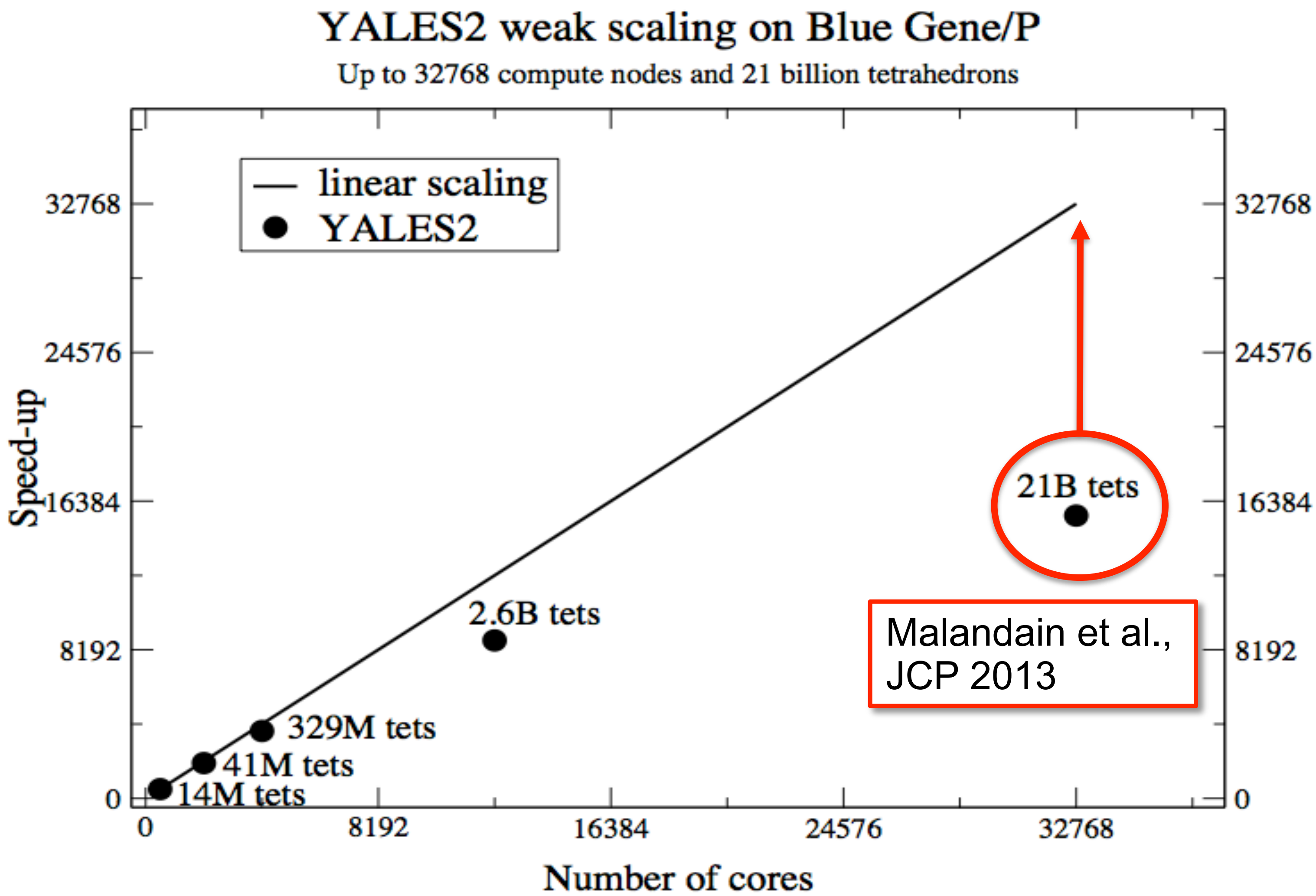
CPU cost of various CG methods

- **On 2D meshes**



CPU cost of various CG methods

- **On 3D meshes**



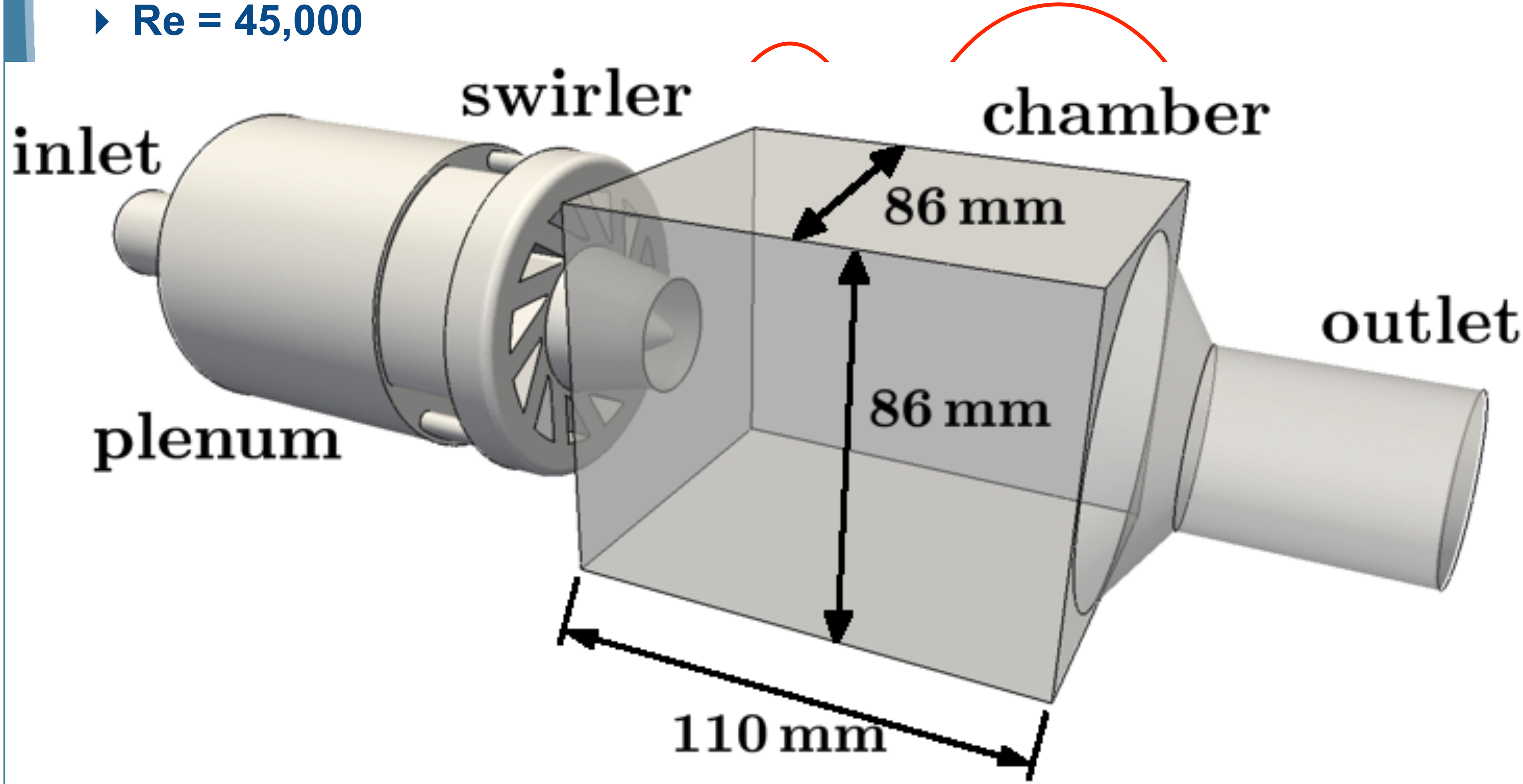
A few case studies

Preccinsta burner DNS

V. Moureau, L. Guédot, G. Lartigue, CORIA

PRECCINSTA burner

- Industrial lean air/methane burner designed by Turbomeca (SAFRAN)
- Re = 45,000



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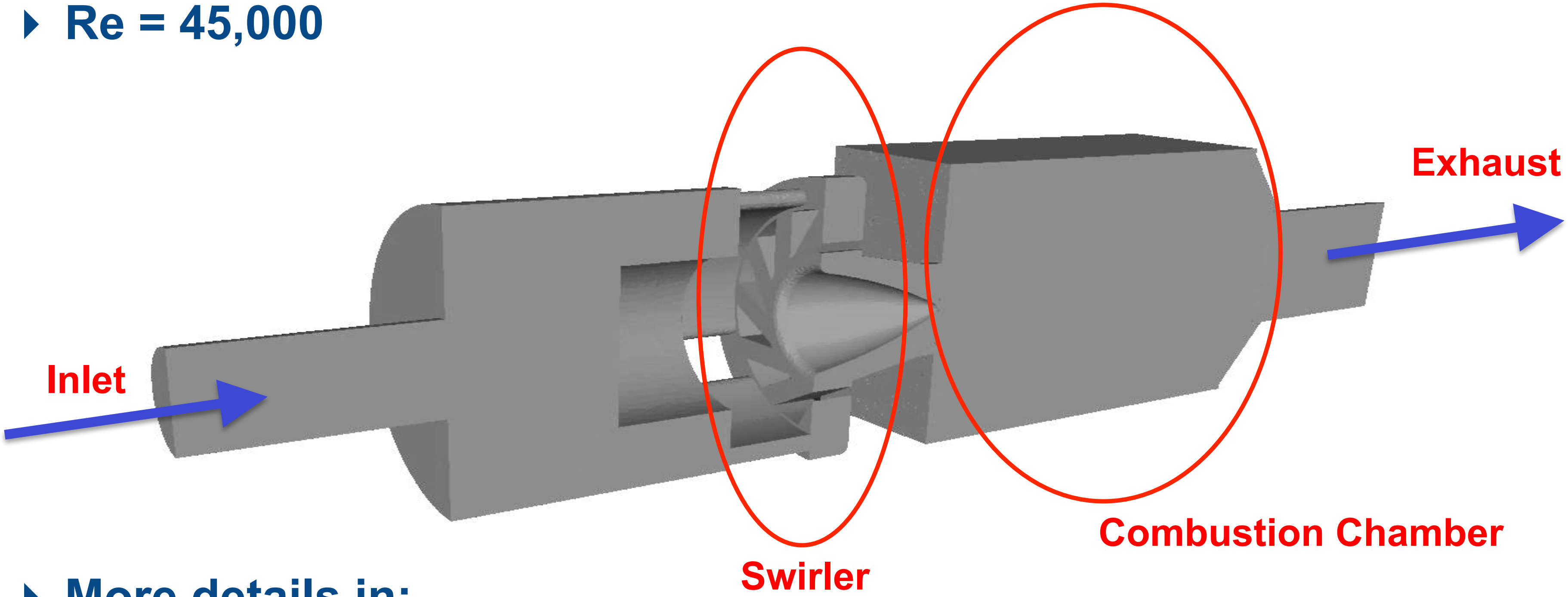
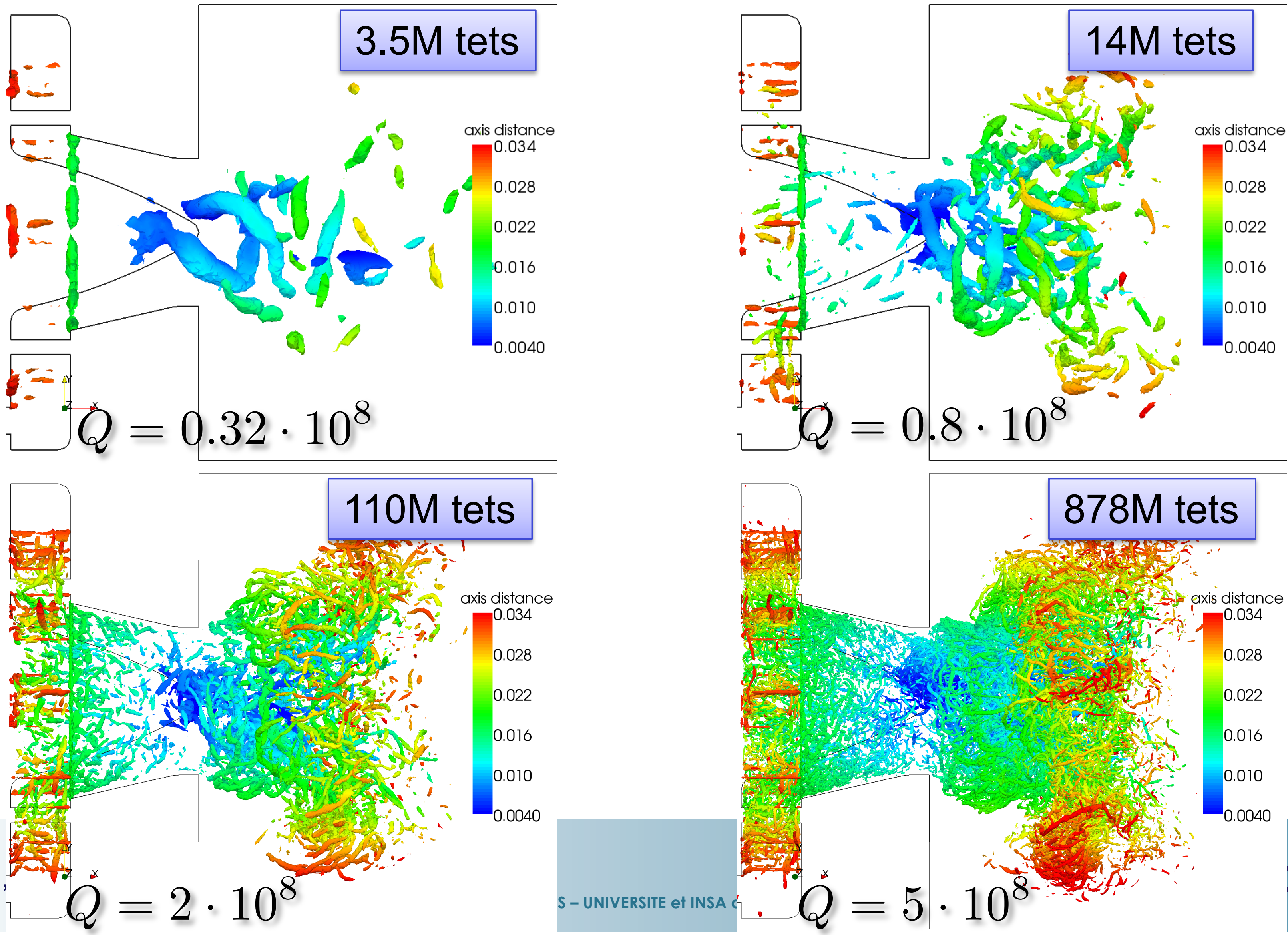


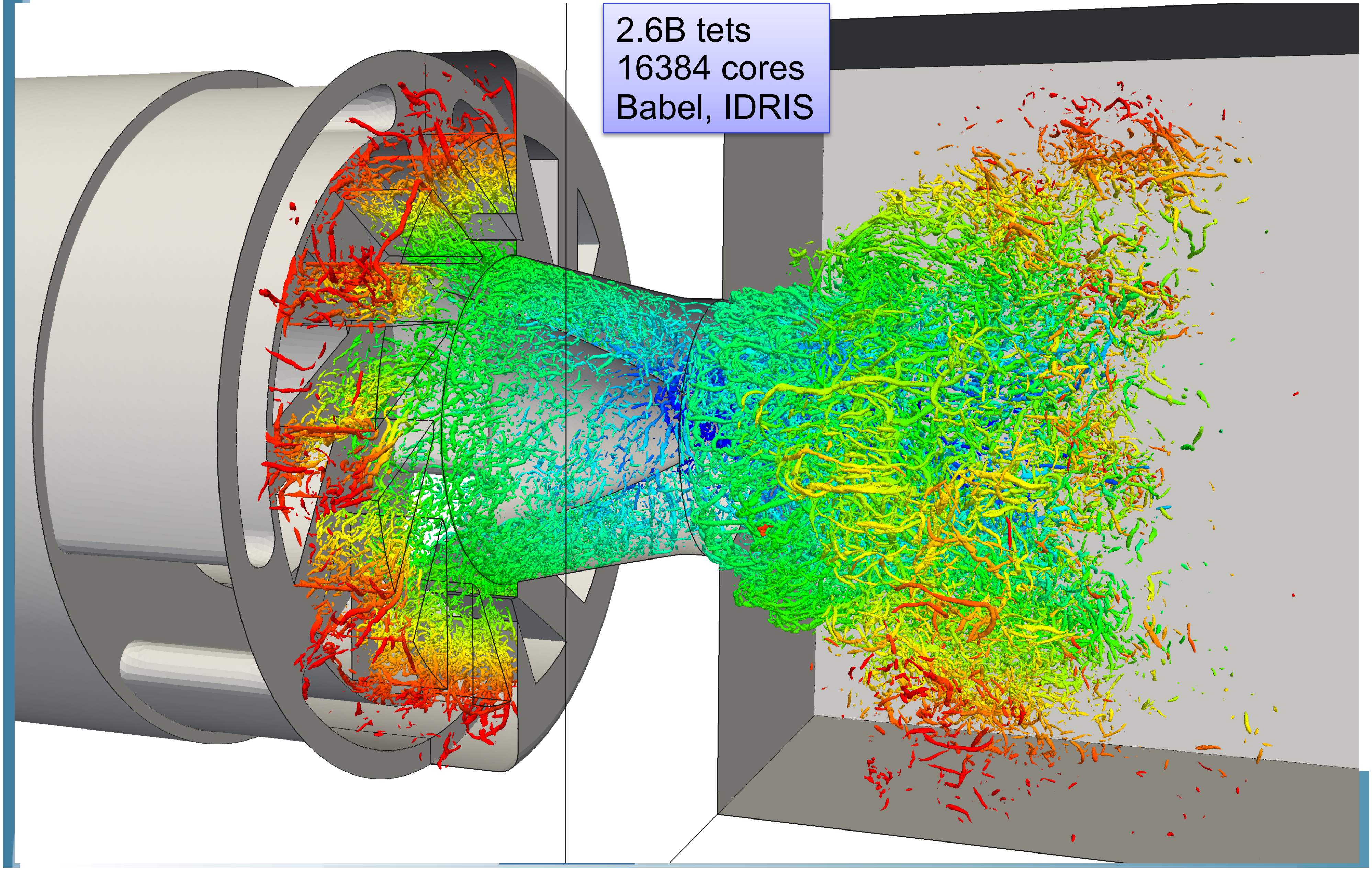
- More details in:
  - Roux et al, Combustion and Flame (2005)
  - Moureau et al, Journal of Computational Physics (2007) (2 papers)
  - Galpin et at, Combustion and Flame (2008)
  - Moureau et al, Combustion and Flame (2011)

PRECCINSTA: coherent structures (1/2)

- **Impact of the mesh resolution on the smallest resolved scales**



PRECCINSTA: coherent structures (2/2)



2.6B tets
16384 cores
Babel, IDRIS

PRECCINSTA: coherent structures (2/2)

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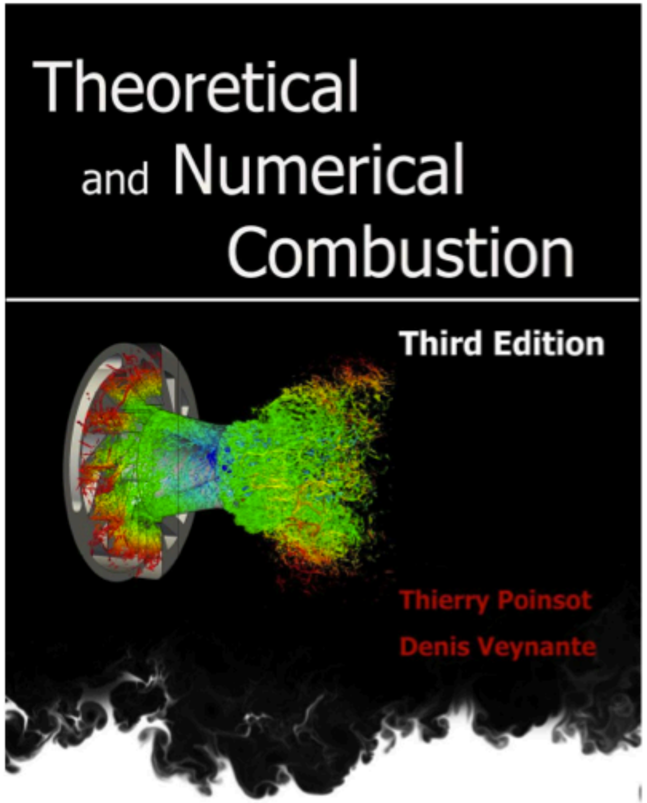
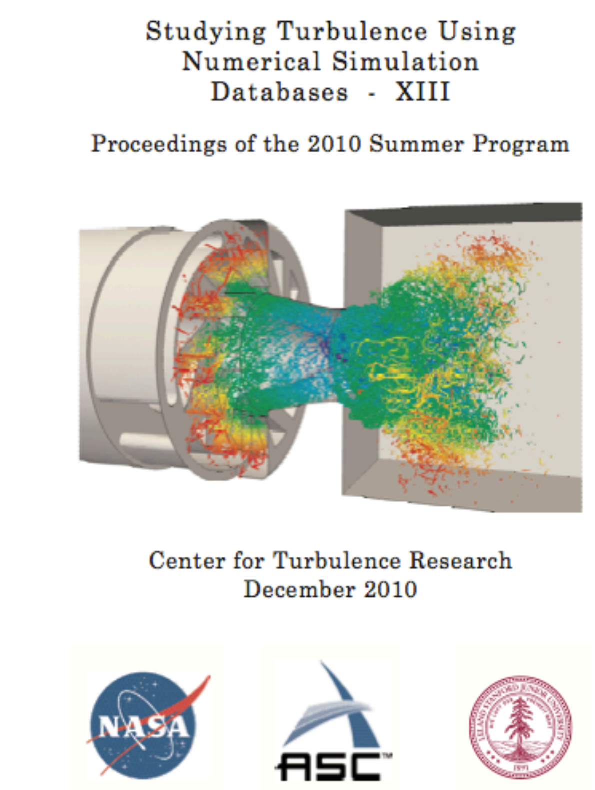




PRECCINSTA: coherent structures (2/2)

La Recherche, Novembre 2012

Limiter les polluants de réacteurs en simulant la combustion

Si l'on veut réduire de façon drastique les polluants émis par les avions, il est indispensable de comprendre les phénomènes physiques liés à la combustion au sein même des réacteurs. La modélisation numérique est devenue incontournable pour rendre les moteurs plus propres.

par VINCENT MOUREAU
chercheur au Complexe de recherche interprofessionnel en aérothermochimie (Coria) de Rouen.

La réduction des émissions de polluants est devenue une priorité dans l'aéronautique. En Europe, les constructeurs de moteurs d'avion et d'hélicoptère se sont ainsi engagés à respecter d'ici à 2020 les normes fixées par le Conseil consultatif pour la recherche aéronautique en Europe (Acare). Dans ce cadre, un avion construit en 2020 devra par exemple émettre 80 % d'oxydes d'azote de moins qu'un appareil de 2000. Et ses émissions de CO_2 devront être réduites de 50 %.

La clé pour atteindre ces objectifs ambitieux ? Améliorer la chambre de combustion, située au cœur même des moteurs. Dans ces machines tournantes de la famille des turbines à gaz, l'air extérieur est compressé dans un premier étage, puis mélangé avec du carburant pour être brûlé dans la chambre de combustion, avant la phase de détente à travers les turbines. La chambre de combustion joue un rôle capital car elle doit brûler de manière la plus complète et la plus propre possible la totalité du mélange air-carburant. C'est donc de ses performances que dépend la quantité de polluants émise dans l'atmosphère.

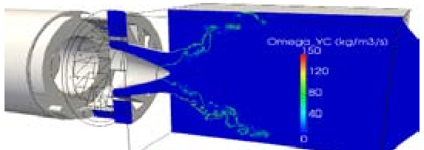
Multiplier le maillage

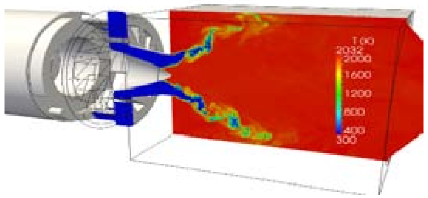
Or, concevoir une chambre de combustion performante est un réel défi technologique et scientifique tant les phénomènes qui s'y produisent sont complexes et multiples : injection et atomisation du carburant liquide sous forme de fines gouttelettes, évaporation du carburant liquide en carburant gazeux, mélange turbulent du carburant évaporé et de l'air, combustion du mélange en régime partiellement prémélangé ou non prémélangé*, échanges thermiques avec les parois, formation de multiples polluants tels que les suies, les oxydes d'azote et les hydrocarbures imbrûlés… Sans oublier que la combustion se produit dans des conditions extrêmes, à forte température et à forte pression pour avoir le meilleur rendement thermodynamique possible.

Pour mieux comprendre tous ces phénomènes physiques et ainsi dimensionner de la meilleure façon les chambres de combustion, la modélisation numérique est devenue un passage obligé. Il s'agit là de résoudre par ordinateur les équations de Navier-Stokes, qui gouvernent l'écoulement des fluides turbulents et réactifs. On a alors accès aux champs de température, de vitesse et, avec des modèles appropriés, aux émissions de polluants. Pour réaliser ces simulations, il est nécessaire de diviser la chambre de combustion en un grand nombre d'éléments géométriques élémentaires, des tétraèdres par exemple. L'ensemble de ces éléments est appelé le maillage. Comme en photographie, où plus le nombre de pixels est élevé et meilleure est la résolution de l'image, plus le nombre d'éléments du maillage est important et meilleure est la précision du modèle. En contrepartie, plus le maillage est dense et plus la puissance de calcul nécessaire va en augmentant.

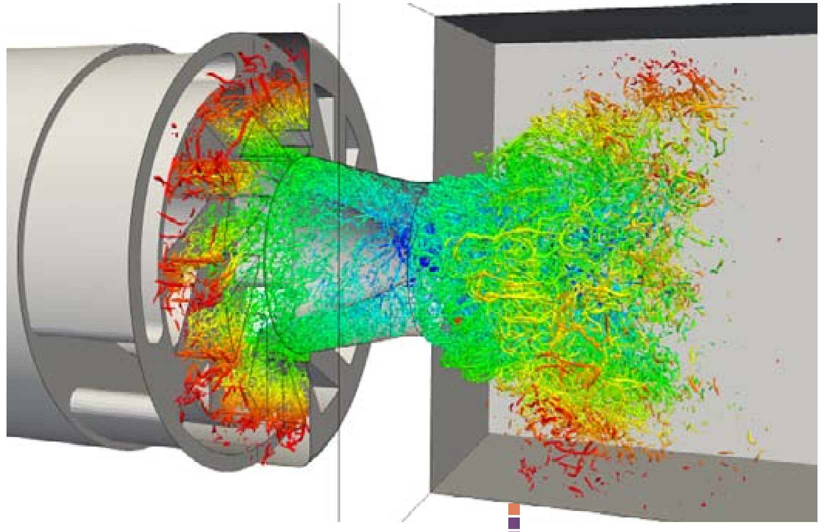
Au Coria, pour décrire le plus finement possible la combustion, des simulations dites massivement parallèles du phénomène ont été menées sur les superordinateurs nationaux exploités par Genci, dont le supercalculateur Curie, installé au Très grand centre de calcul du CEA, à Bruyères-le-Châtel (91), et européens dans le cadre du programme Prace. Chaque simulation a nécessité de l'ordre de 10 000 à 30 000 cœurs de calcul, soit l'équivalent de plusieurs milliers d'ordinateurs de bureau, et a duré une vingtaine d'heures. Ces simulations ont ensuite été ajoutées les unes aux autres pour atteindre des temps physiques simulés suffisamment longs.

* Le régime partiellement prémélangé correspond à un régime où l'air et le carburant se mélangent bien avant de brûler. En régime non-prémélangé, l'air et le carburant arrivent dans la zone de combustion de manière séparée.





Légende à composer



Légende à composer

Modéliser les chambres de combustion

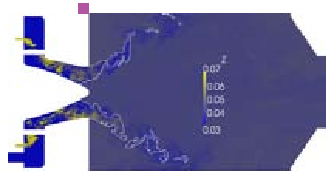
Pour exploiter au mieux une telle puissance de calcul, le Coria a développé un outil de simulation de haute performance : le logiciel Yales 2. Cet outil, utilisé actuellement par une soixantaine de chercheurs dans huit laboratoires français, leur a permis de modéliser des chambres de combustion de géométrie complexe sur un grand nombre de processeurs.

Concrètement, le Coria a cherché à simuler avec une très grande précision la combustion turbulente partiellement prémélangée au sein d'une chambre de combustion modèle, conçue par la société Turbomeca du groupe Safran, le leader mondial des turbines pour hélicoptères. Ce dispositif semi industriel a été l'objet de nombreuses études expérimentales et numériques dans différents projets européens. Les données recueillies par les chercheurs au cours des tests sont primordiales pour la validation des simulations numériques.

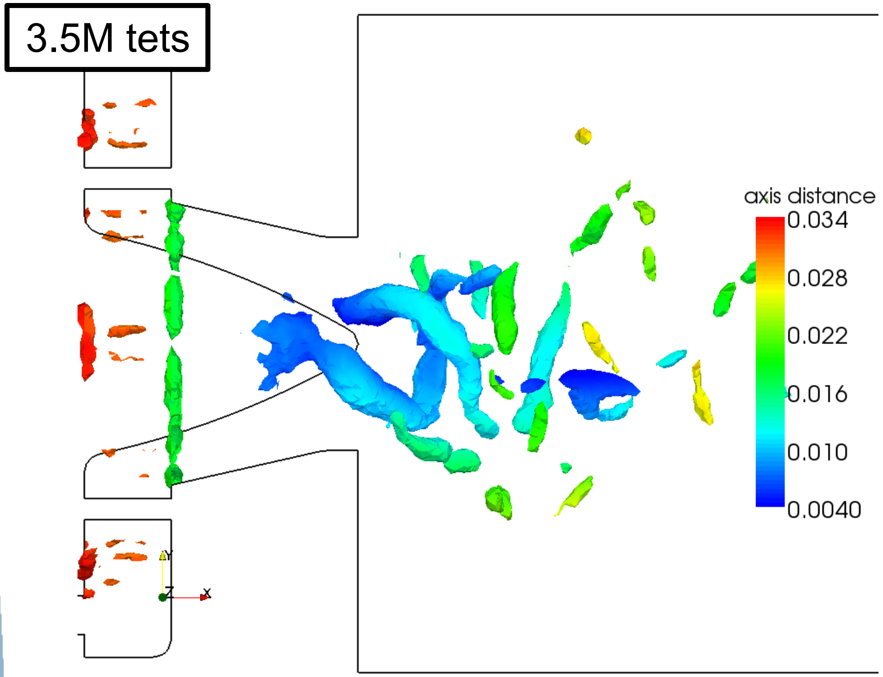
Grâce au logiciel Yales 2, le Coria est parvenu à reproduire la chambre de combustion avec une résolution spatiale encore jamais atteinte dans le domaine : 60 microns pour une chambre de combustion qui mesure 11 cm de hauteur. Au total, cette simulation aura nécessité un impressionnant maillage composé de 12,4 milliards d'éléments géométriques. Ce degré de précision a permis de visualiser les plus petits tourbillons qui apparaissent dans l'écoulement turbulent et la façon dont ils interagissent avec la flamme.

Cette base de données incroyablement riche, qui décrit en détail les effets de mélange de l'air et du carburant sur la flamme, est toujours en cours d'exploitation et devrait bientôt conduire à la conception de nouveaux modèles de combustion. Ces modèles, ajoutés aux méthodes de calcul et aux outils de simulation développés par les chercheurs, intéressent évidemment de près les motoristes de l'aéronautique. Ces derniers comptent rapidement les utiliser non seulement pour atteindre leurs objectifs de réduction des émissions de polluants. Mais également pour accélérer les cycles de développement de nouveaux moteurs.

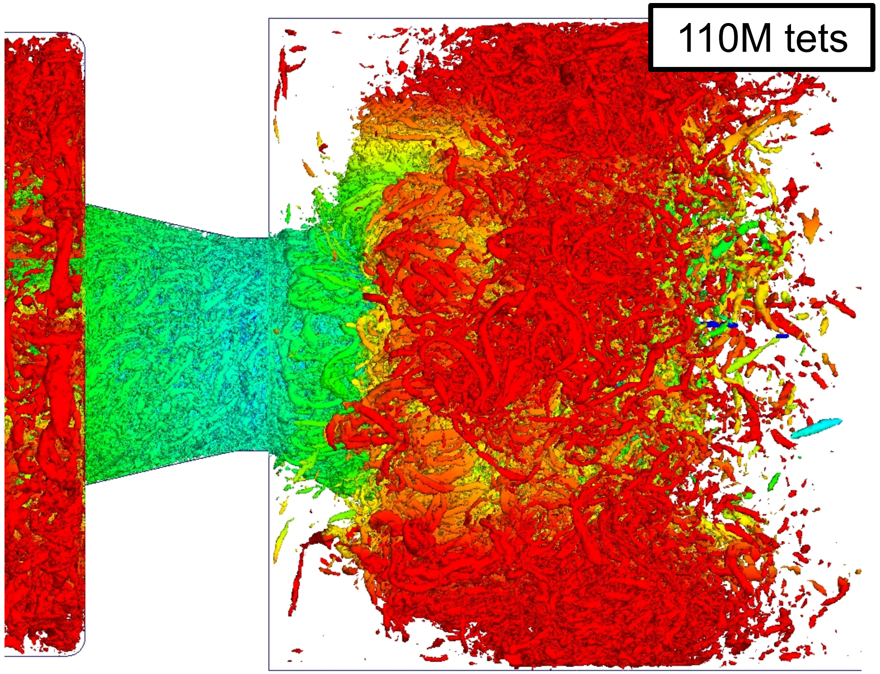
Légende à composer



A challenge: large-scale feature extraction



$$Q = 0.32 \cdot 10^8$$



$$Q = 0.32 \cdot 10^8$$

- **Issue with the Q-criterion (based on L2 norm of velocity gradients)**
  - **High values => smaller strutures resolved on the mesh**
  - **Low values => large structures + smaller ones**
- **Solution filtering of the solution**

A challenge: large-scale feature extraction

- **High-order implicit filter (L. Guédot et al.)**
  - **1D description of the filter (Raymond et al.)**

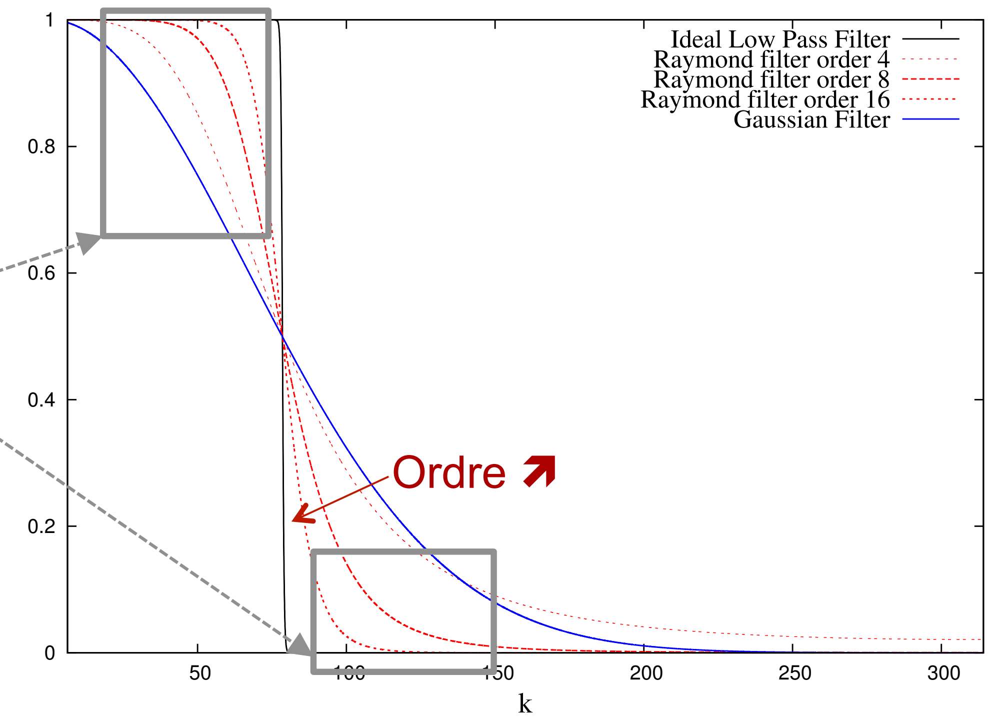
$$\bar{\phi} + \beta^p D^p \bar{\phi} = \phi \text{ with } \beta = \frac{\Delta x^2}{-4\sin^2(k_c \Delta x/2)}$$

D = second order derivative operator
Δx = homogeneous grid spacing
$2p$ = filter order
$k_c = \frac{2\pi}{\Delta}$ (cut-off wave number)
Δ = filter width

  - **Damping function**

$$\frac{\bar{A}}{A} = \left(1 + \frac{\sin^{2p}(k\Delta x/2)}{\sin^{2p}(k_c \Delta x/2)}\right)^{-1}$$

- Large structures less dissipated
- Small structures more dissipated

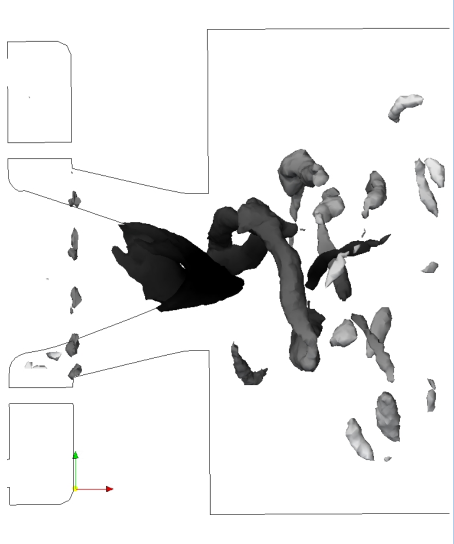
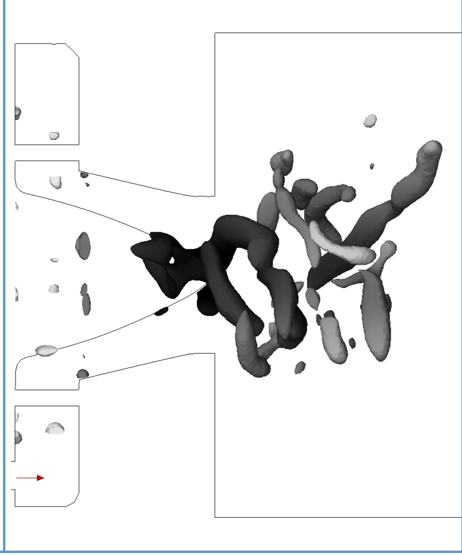
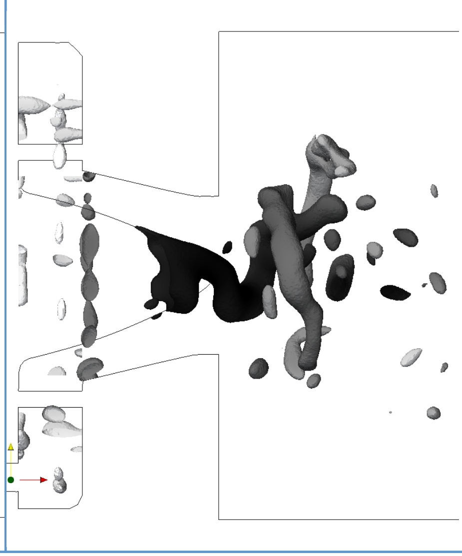
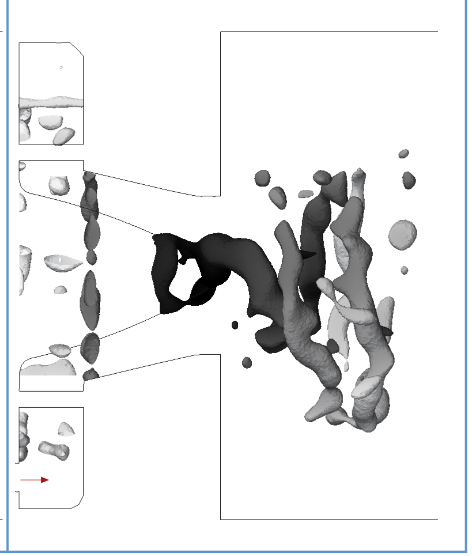


L. Guédot, G. Lartigue, V. Moureau, Design of high-order implicit filters on unstructured grids for the identification of large scale features in large-eddy simulations, DLES9, 2013

W.H. Raymond, A review of recursive and implicit filters. Monthly Weather Review, 1991

A challenge: large-scale feature extraction

- **Visualization of the Precessing Vortex Core on various mesh resolutions**

1.7 M	14M	41M	110M
			

- **The high-order implicit filters successfully extract large-scale features on massive unstructured grids**

Modeling of Heat Transfer on a low-Mach number turbine blade

N. Maheu, V. Moureau, P. Domingo, CORIA

G. Balarac, LEGI

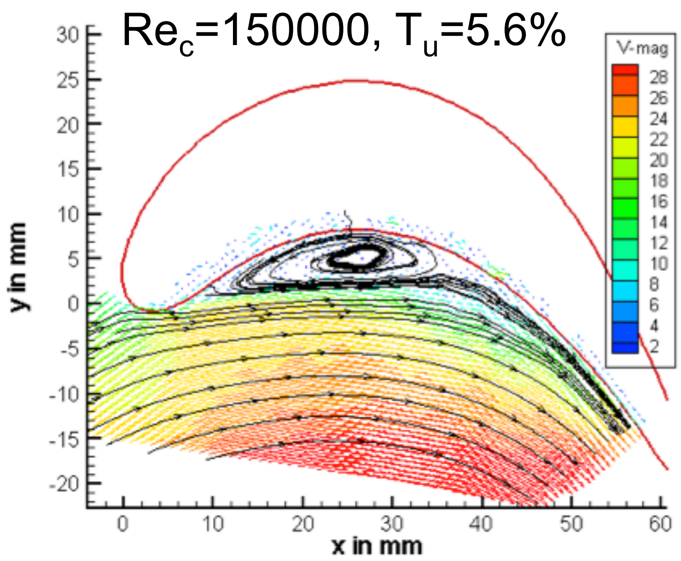
F. Duchaine, CERFACS

• MAHEU, N., MOUREAU, V., DOMINGO, P., DUCHAINE, F. & BALARAC, G. (2012) Large-eddy simulations of flow and heat transfer around a low-mach turbine blade. *CTR Summer Program.* Center for Turbulence Research, NASA Ames/Stanford Univ.

• MAHEU, N., MOUREAU, V. & DOMINGO, P. (2012) High fidelity simulation of heat transfer between a turbulent flow and a wall. *ERCOFTAC ETMM9.* Thessaloniki, Greece.

Study of heat exchanges on a turbine blade

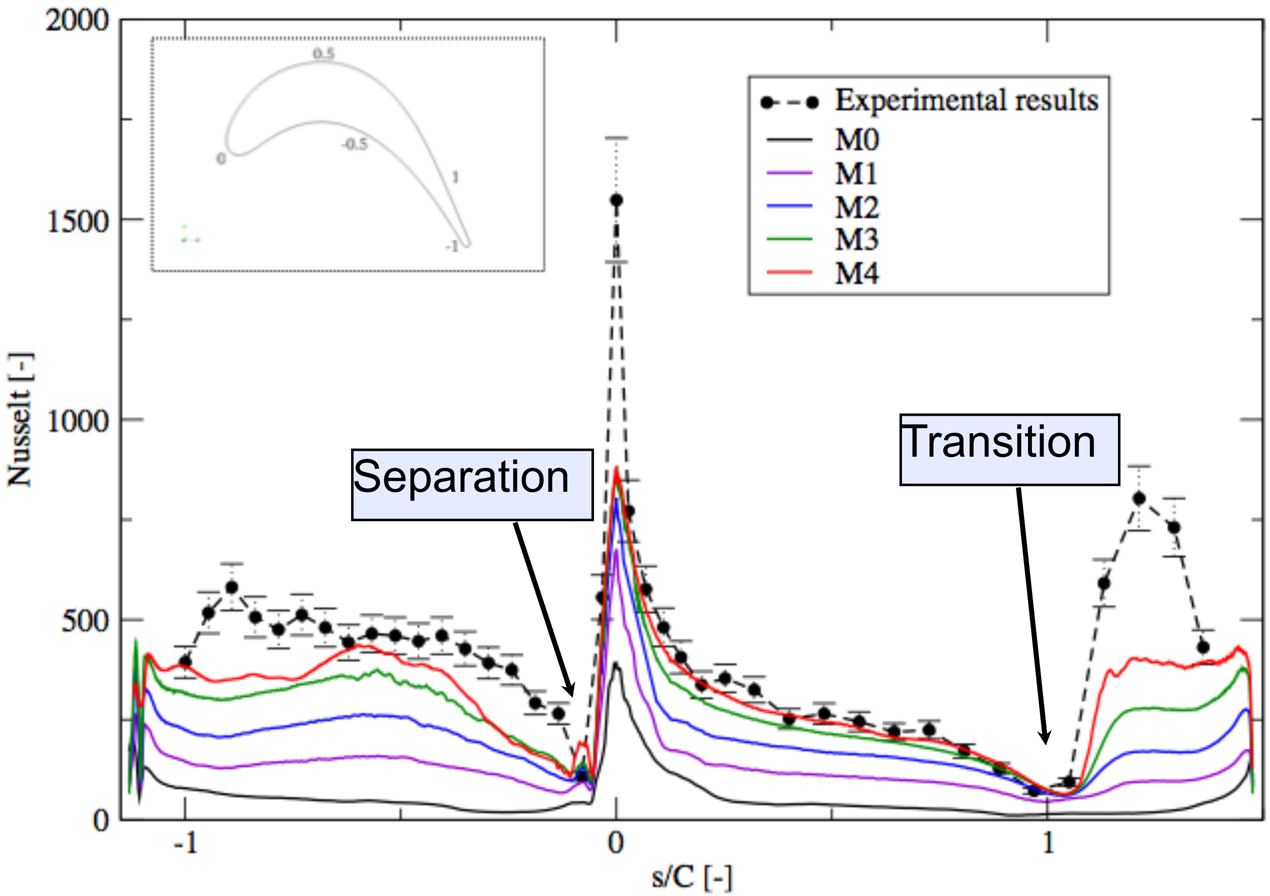
- **T7.2 blade from AITEB2 project**
- **Low-Mach number blade**
- **Experiments from Karlsruhe University**
- **LES mesh refinement study of heat transfer**



Mesh	Cell count	Node count	Min. cell size	Max Δy+, Δx+, Δz+	Blade Flow-Through time
M0	1.2M	220K	90 μm	93.3	32.0
M1	35M	5.8M	30 μm	30.4	33.9
M2	280M	47M	15 μm	15.2	11.1
M3	2.2B	367M	7.5 μm	7.6	4.5
M4	17.9B	3.0B	3.75 μm	3.8	0.9
M5	143B	23.8B	1.9 μm	(2.0)	(40 Δt)

Heat transfer on the blade

- **Resolved Nusselt number at the blade surface on each mesh, used as a heat transfer resolution indicator**



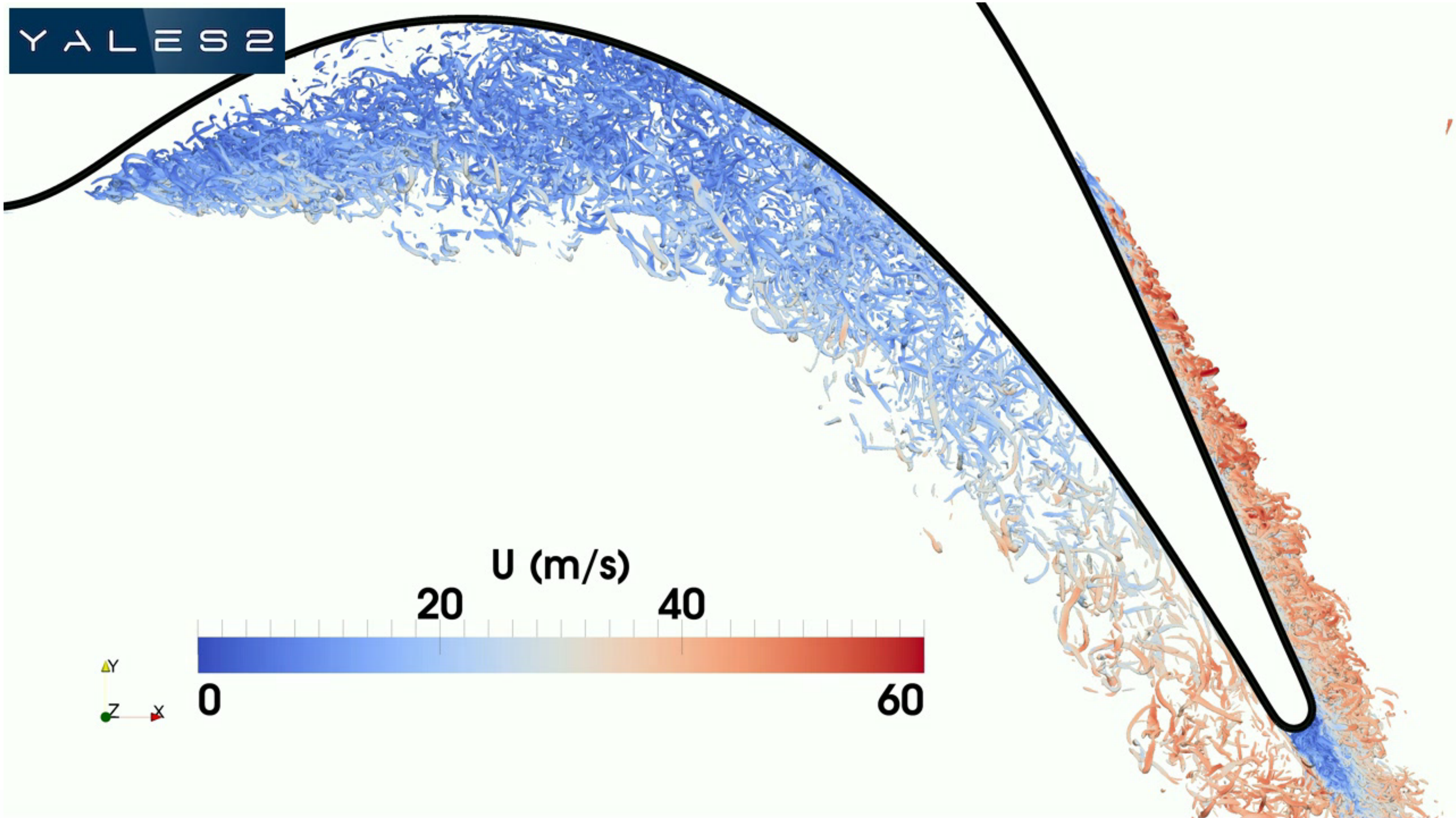
Nusselt number:

$$Nu = \frac{\tilde{q}C}{(T_\infty - T_w)\,\alpha}$$

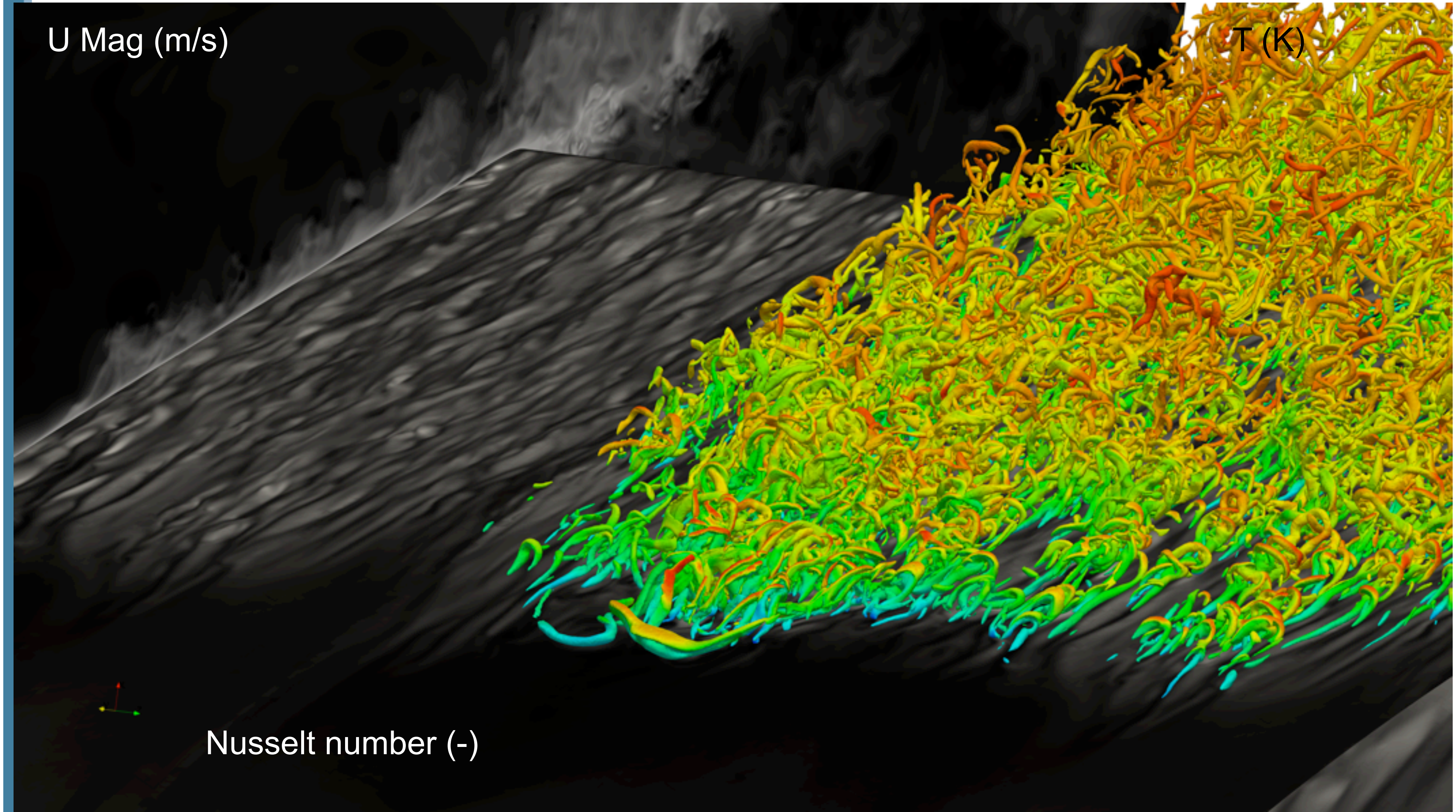
with $\tilde{q} = \alpha \nabla \tilde{T}$

Smallest resolved vortices

- LES with 18 billion tets on 16384 cores of Curie, CEA

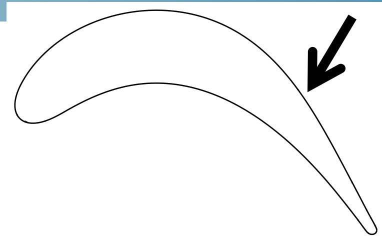


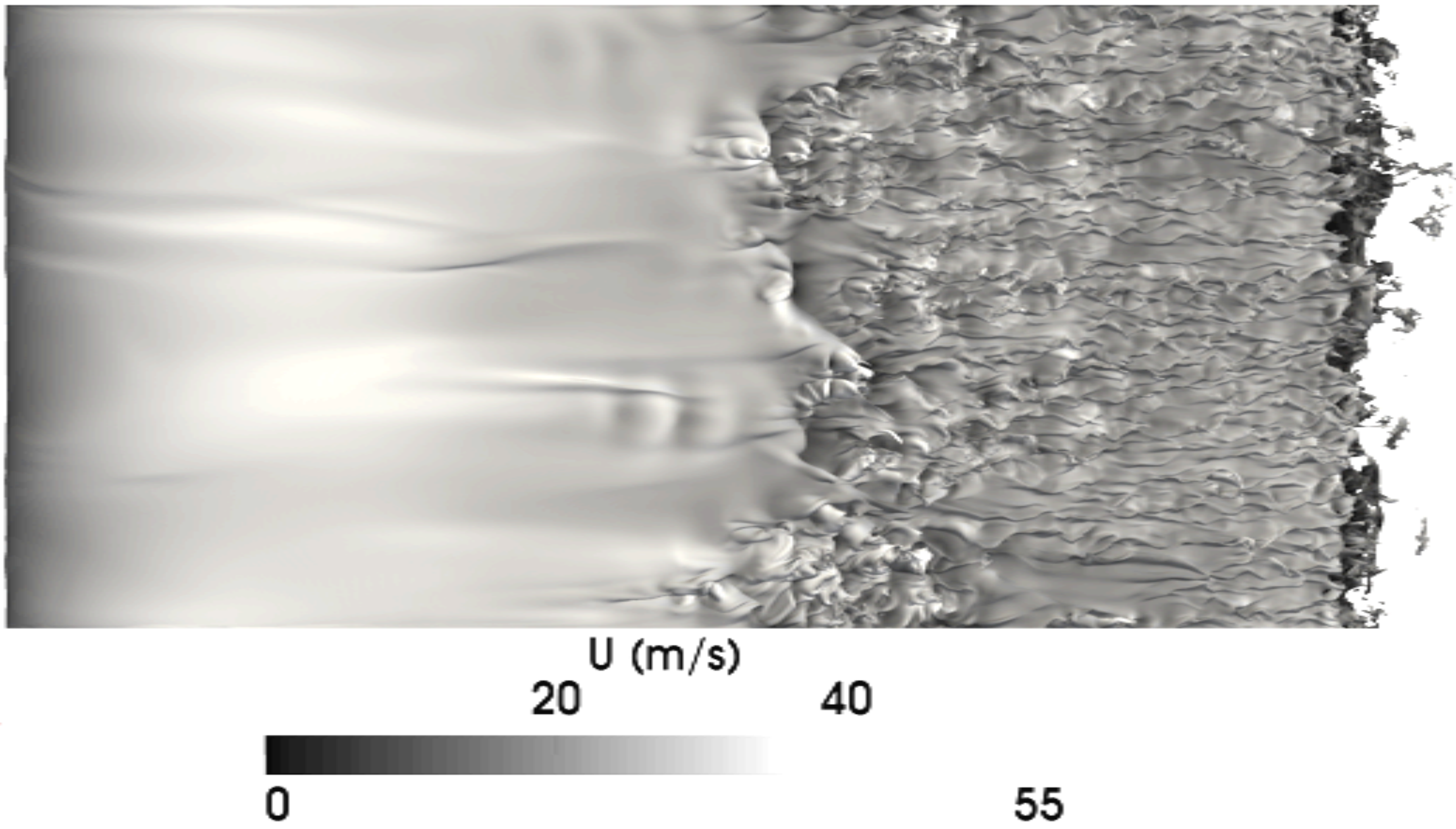
Transition on the suction side



Effect of turbulent eddies on heat transfer

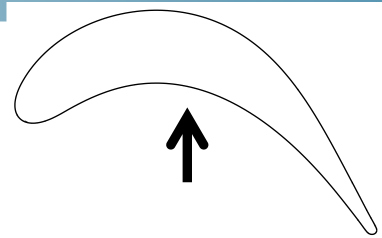
- Study of local heat transfer

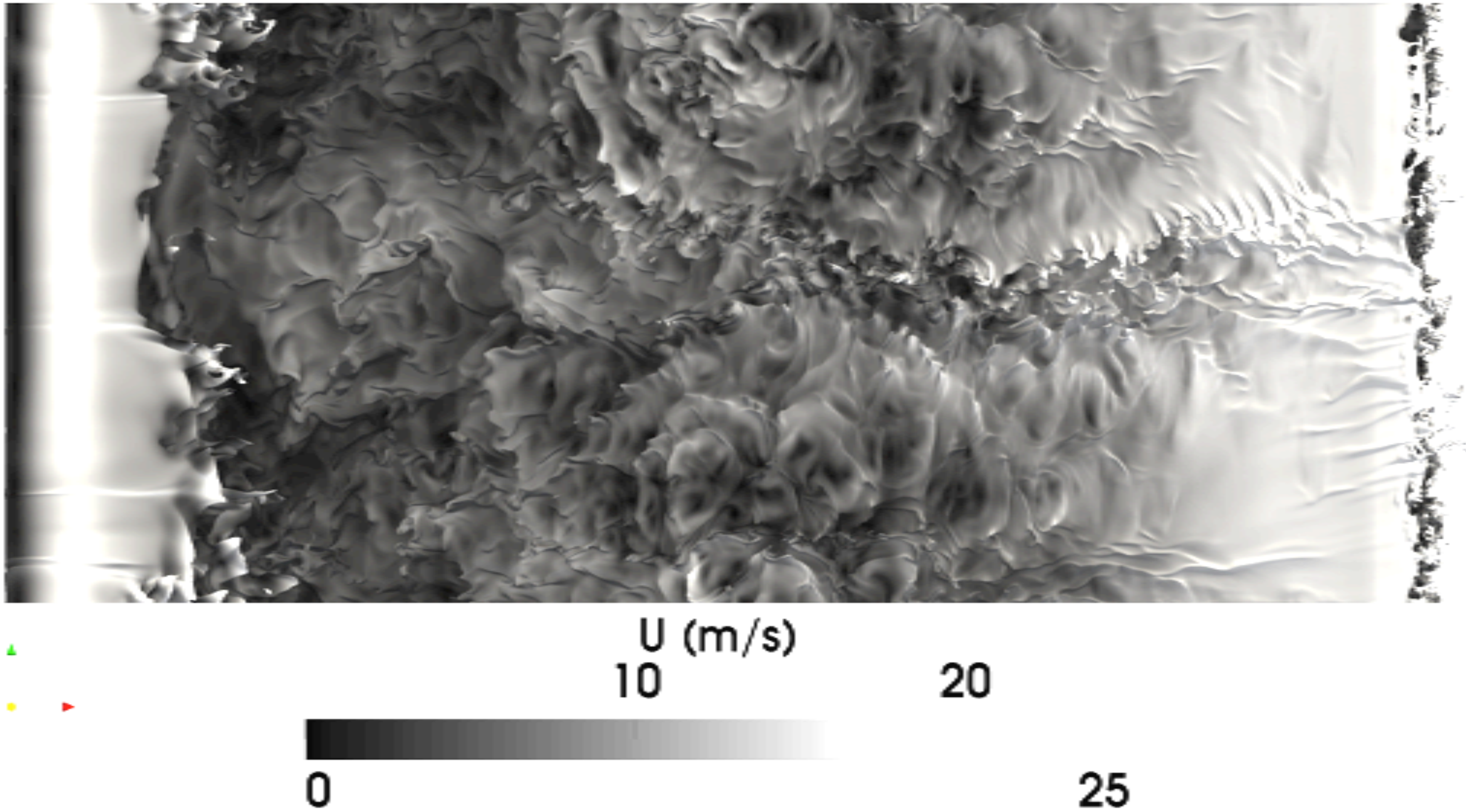




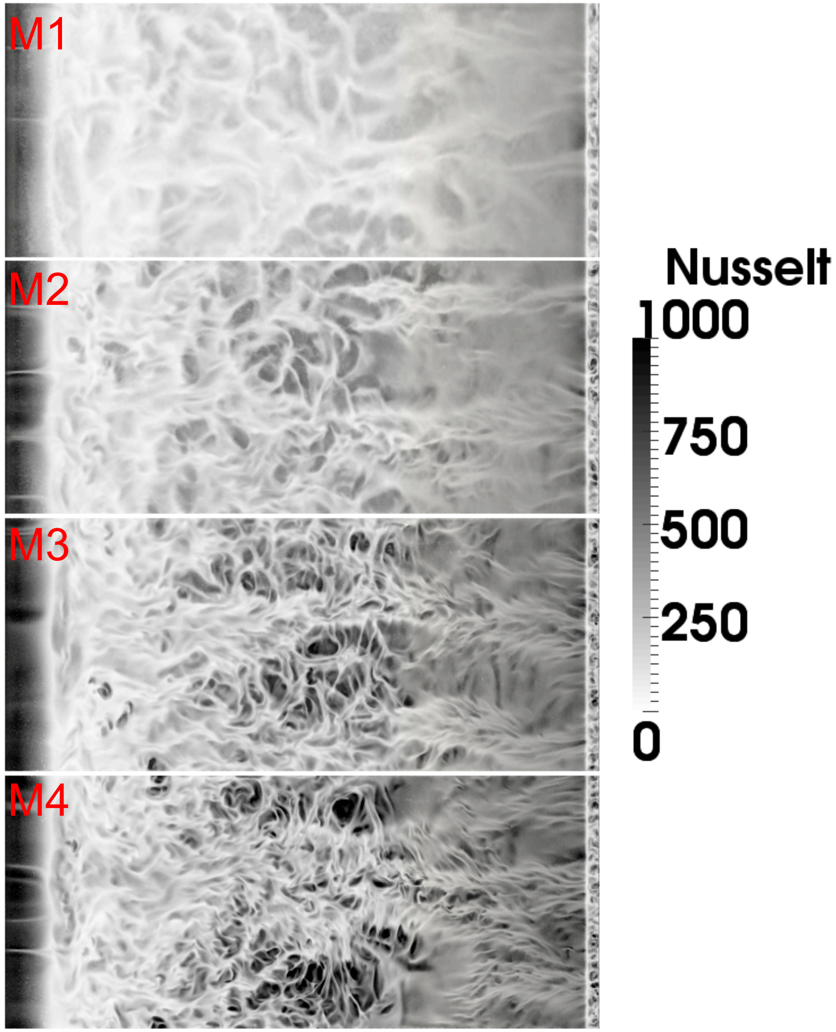
Effect of turbulent eddies on heat transfer

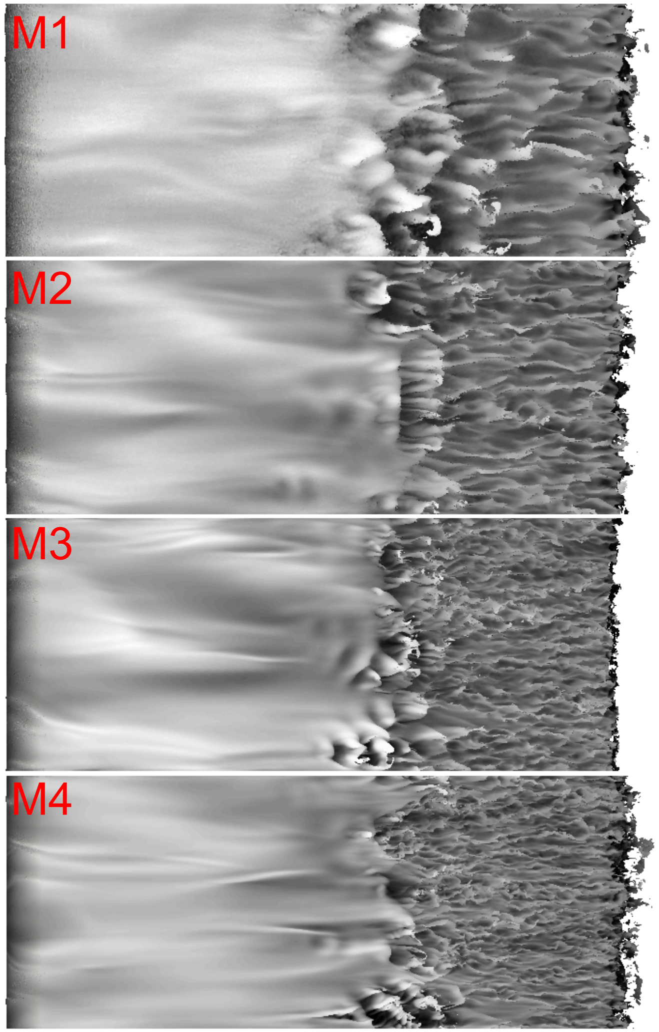
- Study of local heat transfer





Effect of turbulent eddies on heat transfer





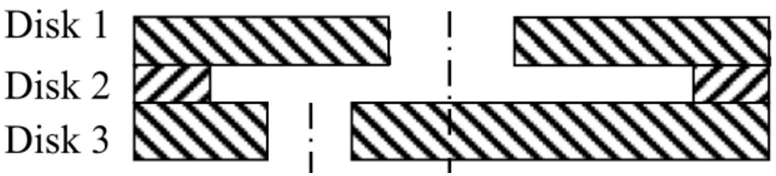
- Pressure side (wall values)
- Suction side (isoZ = 0.5 colored by velocity)

Primary atomization modeling

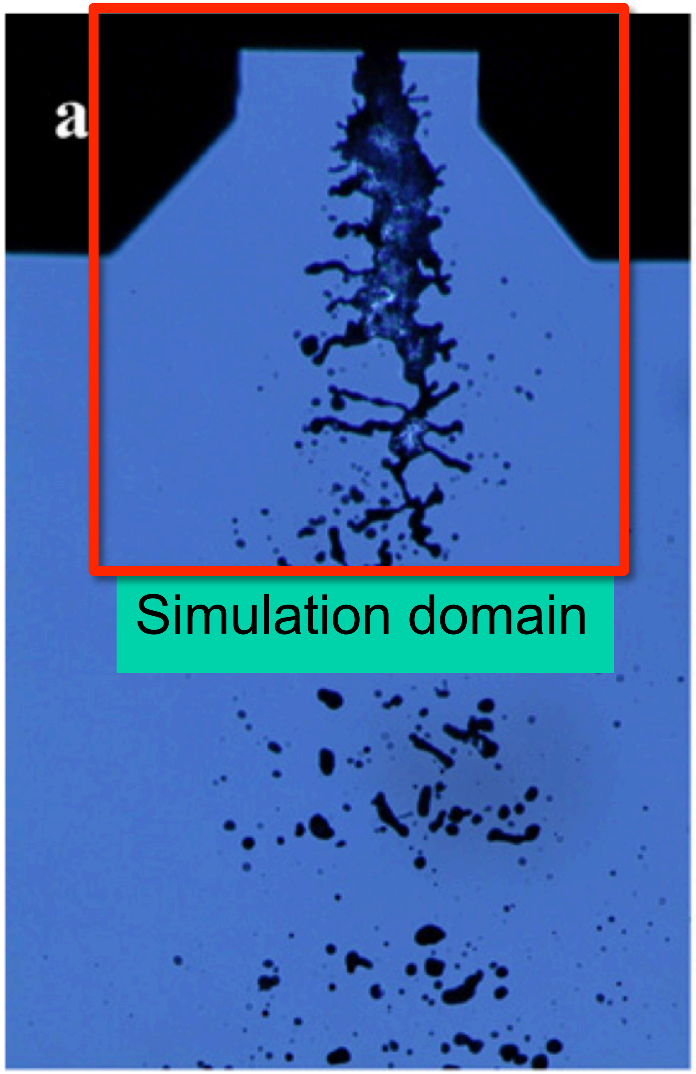
V. Moureau, A. Berlemont, T. Ménard, J. Cousin, CORIA
O. Desjardins, CORNELL, USA

Validation of a new method for primary atomization with large density ratios

- **A first validation is performed with the triple disk injector from Grout et al. 2007**
  - **Water and air experiment**
  - **Three disks are super-imposed**



  - **Re = 3653**
  - **We_L = 1061**
  - **Injector outlet = 180 μm**

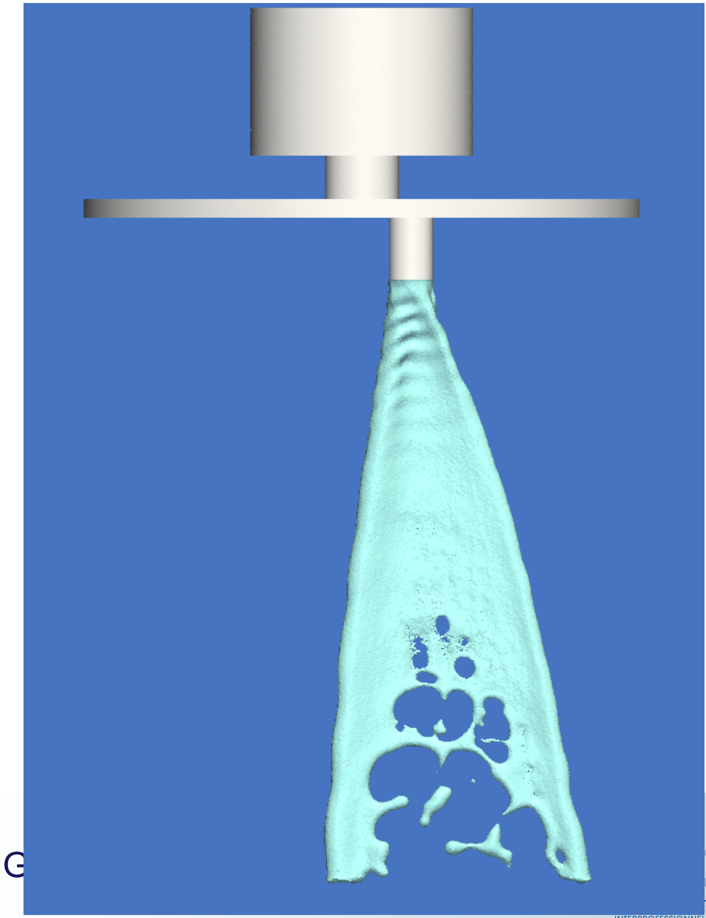


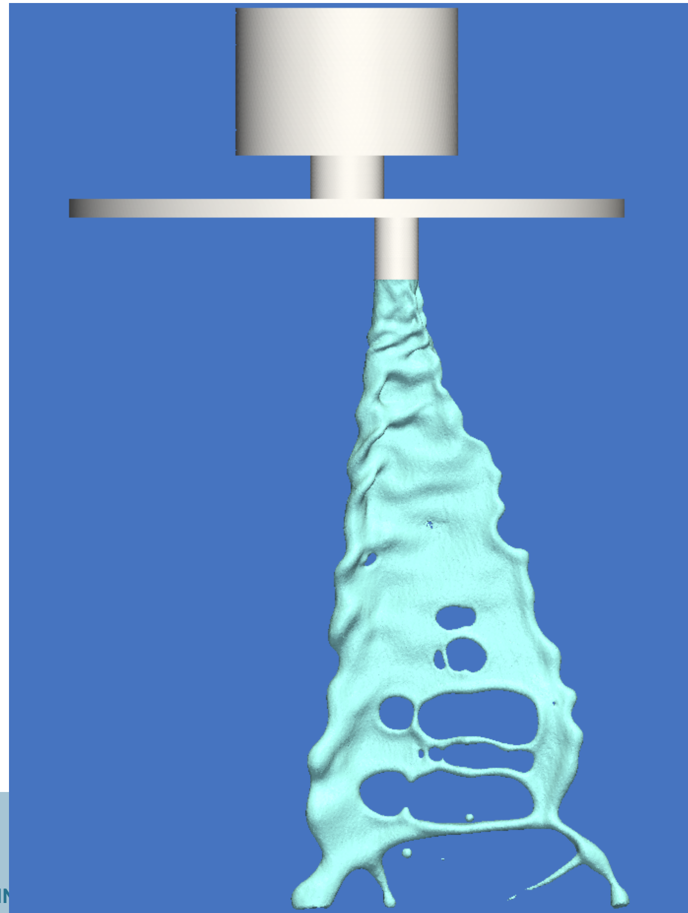
Triple disk injector: coarse calculations

- **Numerical results obtained with YALES2 on a Blue Gene/P**

25M tets, 512 processors
Mesh size around 10 μm

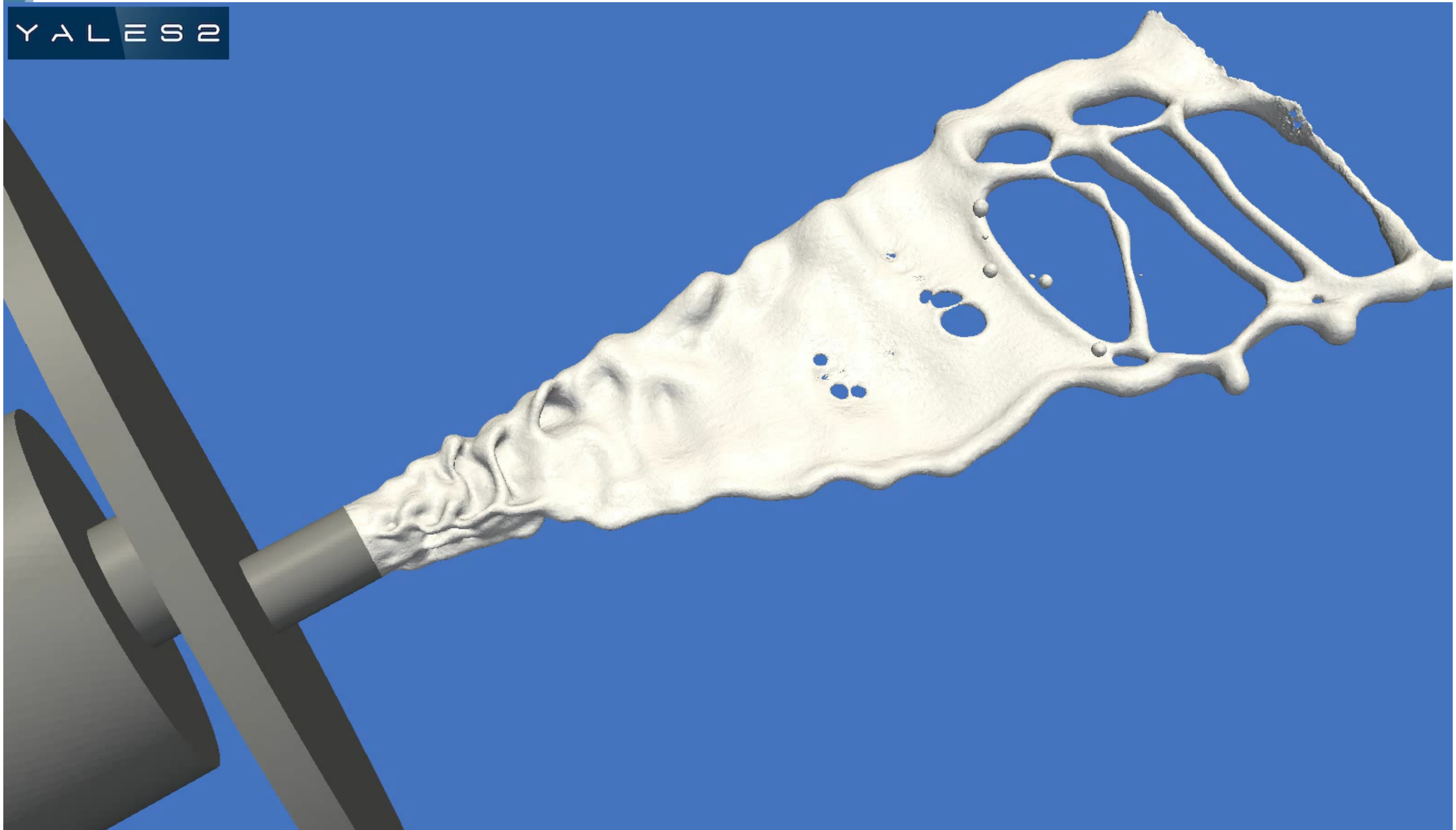
203M tets, 4096 processors
Mesh size around 5 μm





Triple disk injector: fine calculations

- If the mesh is further refined to 1.6B cells with a cell size of 2.5 μm
- 39 runs of 20h were performed on 8192 cores of the Curie machine

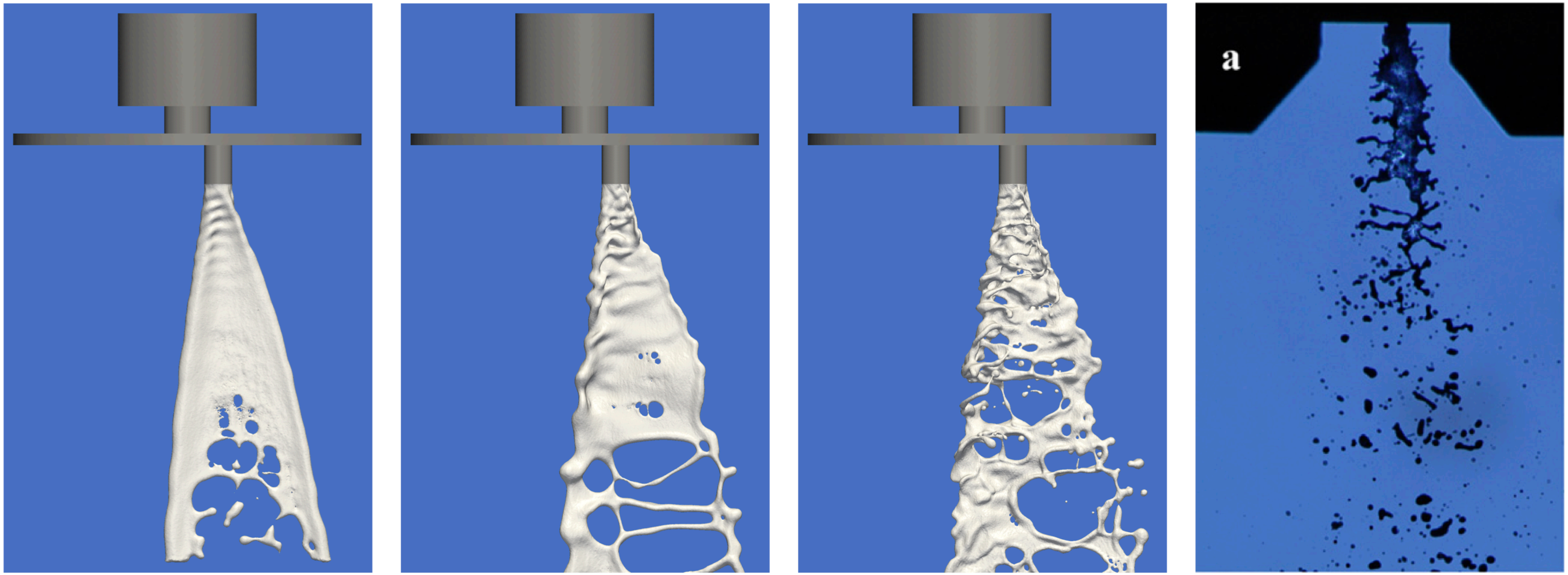


Complete mesh refinement study

FIRST – Fuel Injector Research for Sustainable Transport

- **Primary atomization is highly non-linear and requires very fine mesh resolution in order to capture the instabilities at the basis of the jet that are responsible for the break-up**

25M tets, Δx = 10 μm | 200M tets, Δx = 5 μm | 1.6B tets, Δx = 2.5 μm | experiment



Conclusions & perspectives

Conclusions & Perspectives

- **Billion-cell calculations are feasible on the current machines**
- **Their pre- and post-processing are still difficult**
- **Some remaining challenges and some potential solutions**
  - **Large-scale feature extraction: high-order implicit filters**
  - **Mesh generation: local mesh refinement, mesh skewness smoothing**
  - **Efficiency of multi-physics simulations: dynamic load balancing**
  - **Efficiency of low-Mach number algorithms on 1 million cores**
    - 3 level deflation algorithm
    - linear / quadratic deflation vectors

References & Acknowledgements

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