VKI Lecture Series, "Accurate and Efficient Aero-acoustic Prediction Approaches for Airframe Noise", March 25th – 28th , Rhodes-St-Genèse, Belgium, 2013

Compressible LES for Airframe noise

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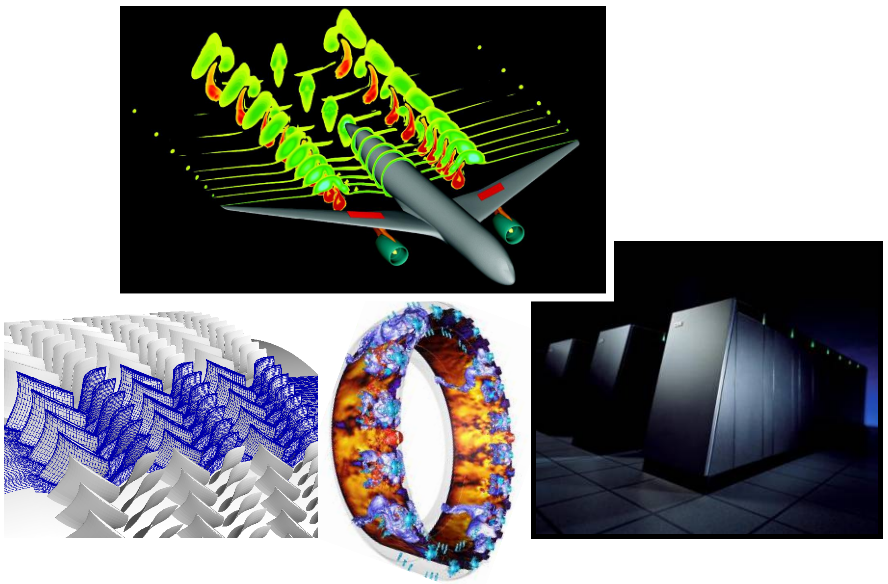
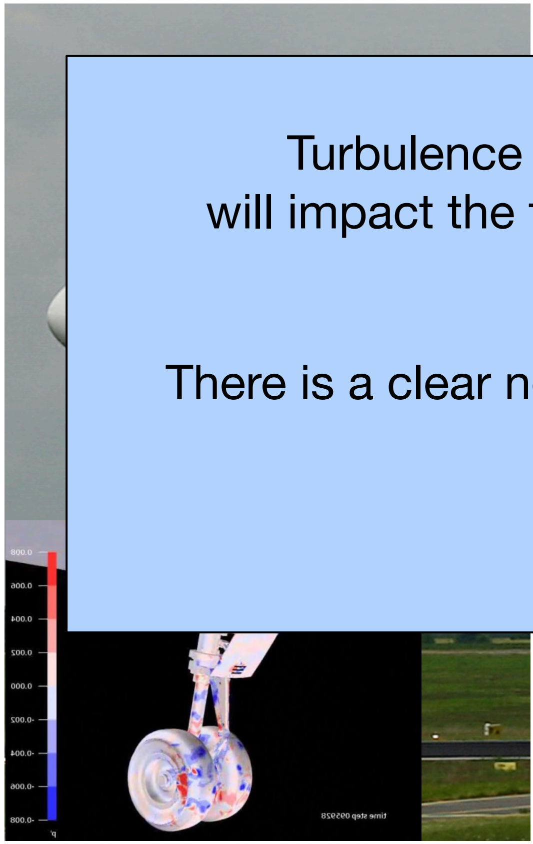
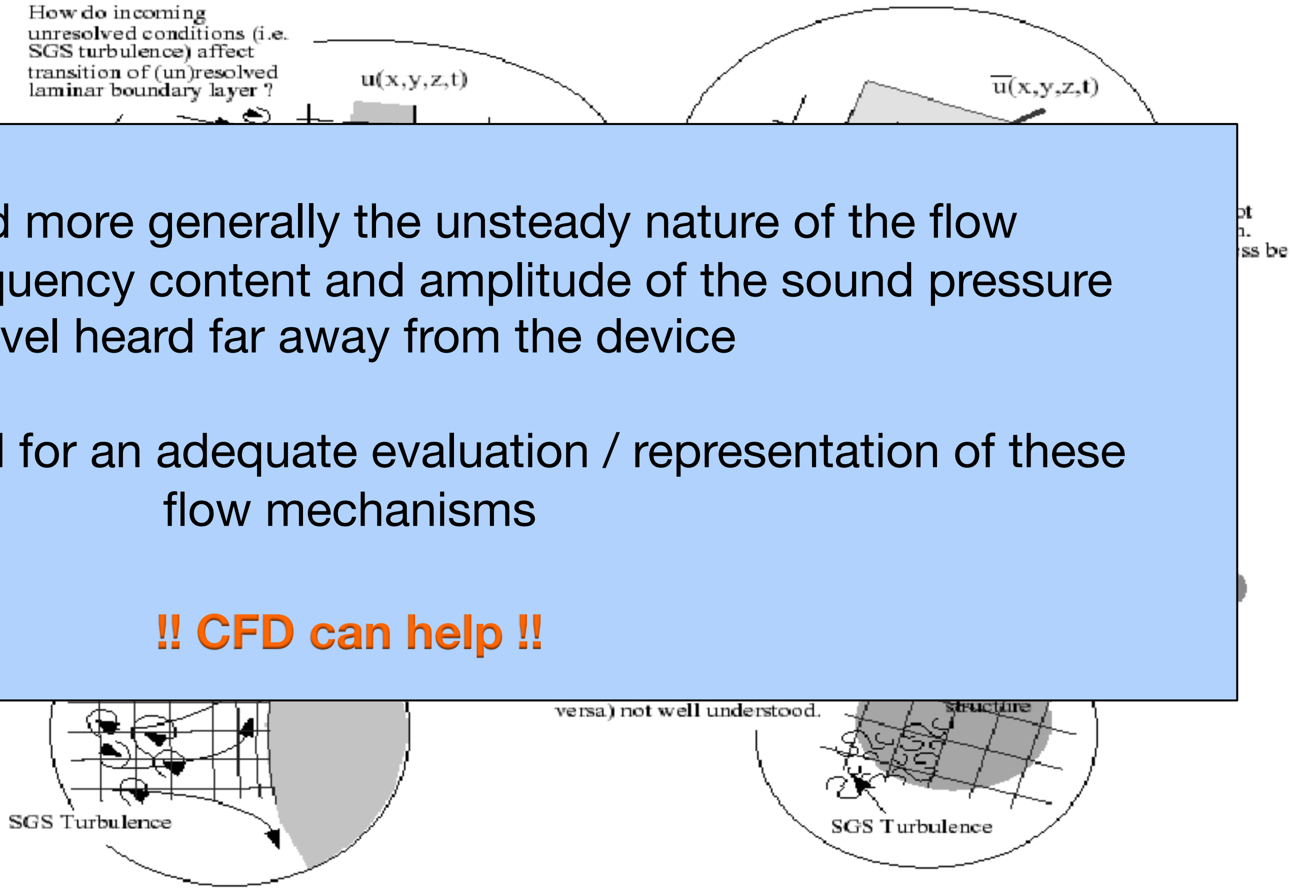


Accurate noise predictions require to anticipate many flow features:

Noise radiated far away from many aeronautical devices is the consequence of many different flow regimes around the device:

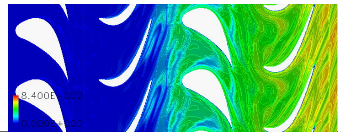


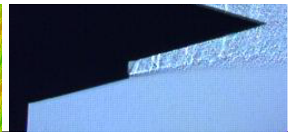


Turbulence and more generally the unsteady nature of the flow will impact the frequency content and amplitude of the sound pressure level heard far away from the device

There is a clear need for an adequate evaluation / representation of these flow mechanisms

!! CFD can help !!





The physical limit of CFD: Turbulence and the large range of flow scales

Aeronautical flows have a very high Reynolds number: $Re = \frac{\rho U L}{\mu} \Rightarrow N \propto (0{,}1\,Re)^{9/4}$

- Aircraft at cruise conditions:

  Boeing 747, Re ~ 2 10^9 => N ~ 4.75 10^{18}

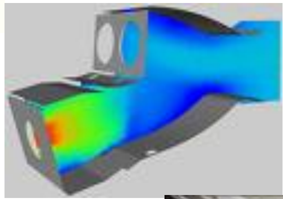
  Glider, Re ~ 1.6 10^6 => N ~ 2.8 $10^{11.25}$

- Compressor at operating conditions:

  Re ~ 5 10^6 => N ~ 37 $10^{11.25}$

- Combustor at operating conditions:

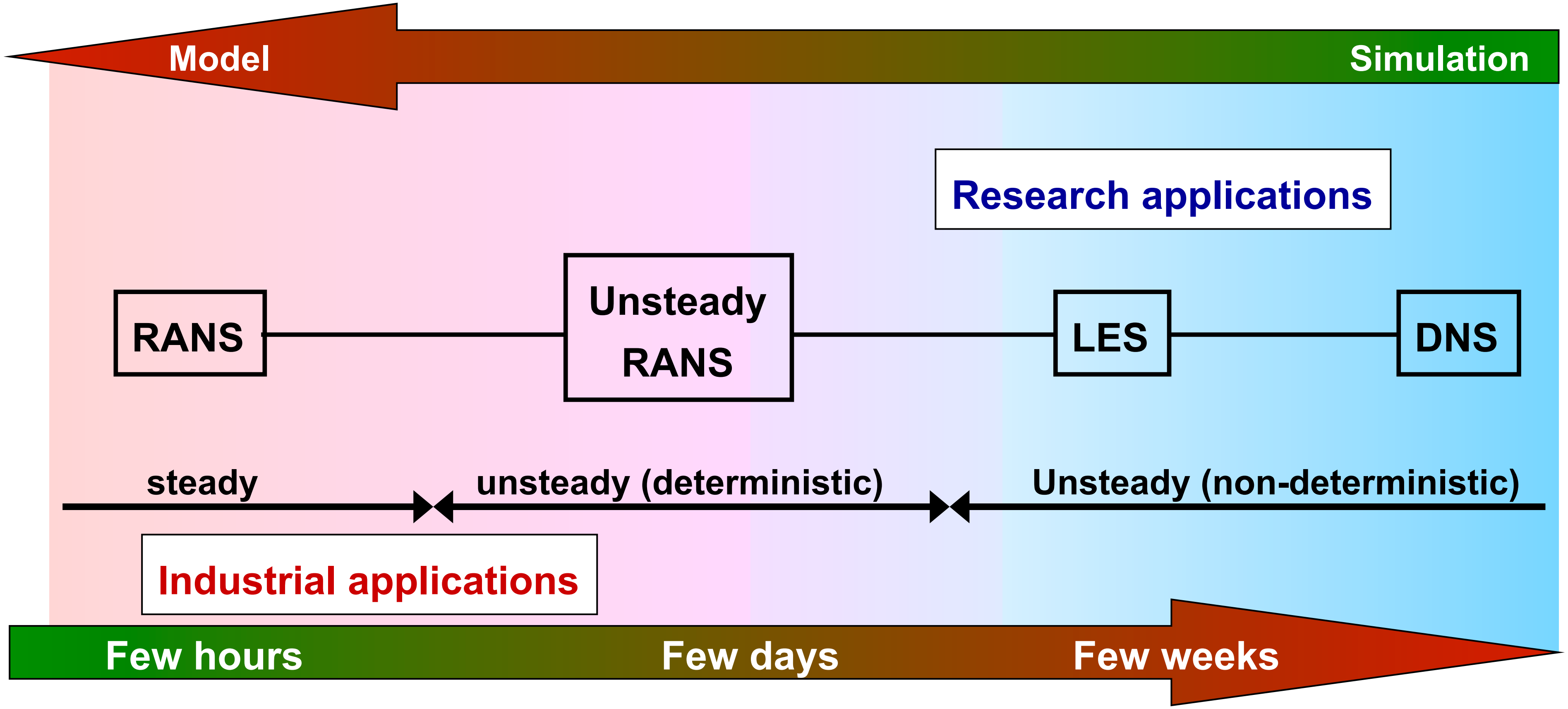
  Re ~ 5 10^5 => N ~ 37 10^9



- Turbine at operating conditions:

  Re ~ 1 10^6 => N ~ 1 $10^{11.25}$

Overview of the computational methods

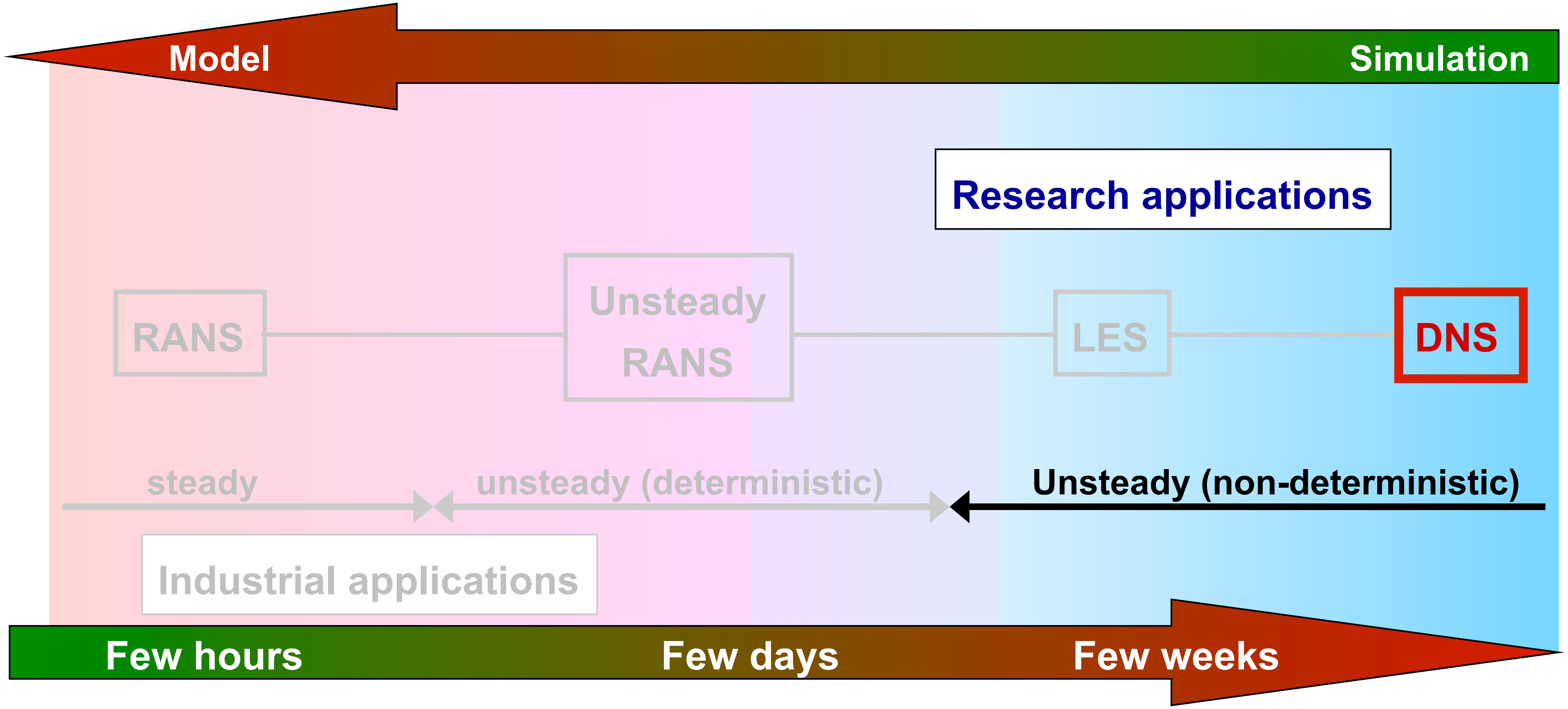


RANS: Reynolds-Averaged Navier Stokes

LES: Large Eddy Simulation

DNS: Direct Numerical Simulation

Overview of the computational methods



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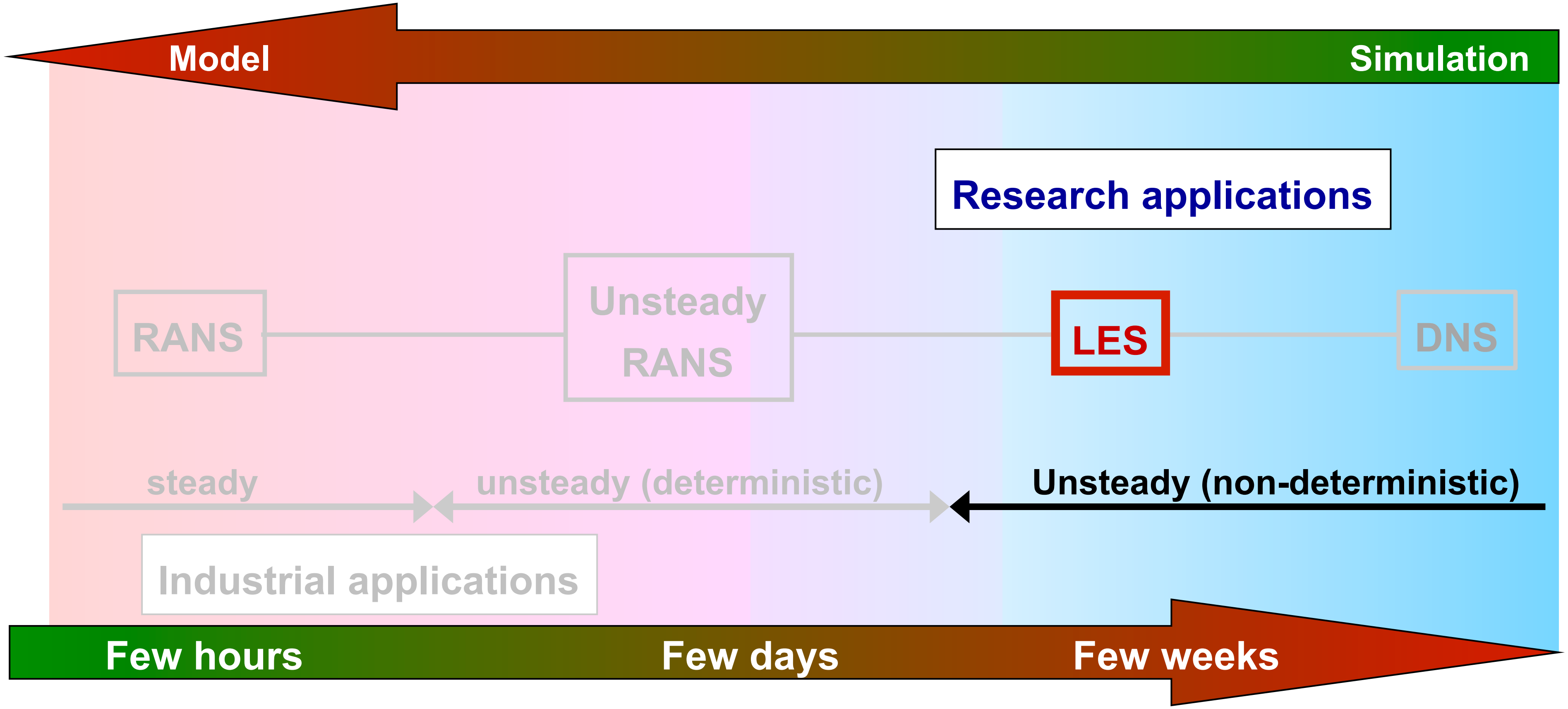

RANS: Reynolds-Averaged Navier Stokes

LES: Large Eddy Simulation

DNS: Direct Numerical Simulation

I] Fundamentals of LES modeling:

=> Governing Eqs and models

- LES fundamentals and closure problem
- SGS for free stream turbulent flows
- Wall resolved versus Wall modeled LES

=> Numeric

III] Compressible LES – capabilities, validations and noise predictions:

=> LES of turbulent flows

=> LES of self-sustained unstable flows (impacting jet)

=> LES based CAA on industrial like applications

IV] Conclusions and perspectives:

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Starting point of all flow description is Navier-Stokes (incompressible version):

Mass conservation:
$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

Momentum conservation:
$$\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_l{}^2} \quad (2)$$

To which

$$\mathrm{Re} = \frac{\rho\, u\, L}{\mu},$$

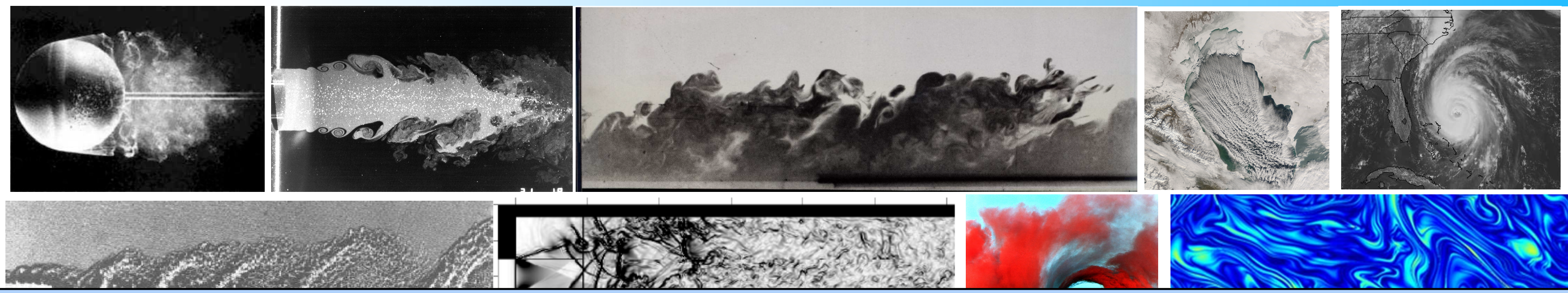
when $\mathrm{Re} >> 1$ Turbulence occurs

Non-line

=>

- in complex flows: prbl for the analysis – need to linearize around something which is difficult to anticipate

Viscosity is present (as well as pressure) and introduces damping which counteracts non-linearities



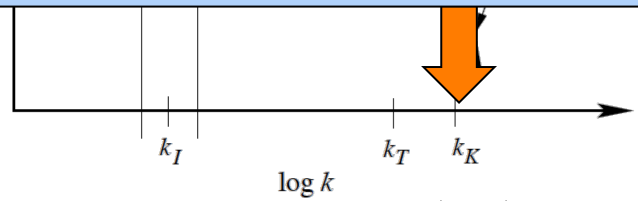
The turbulent flow field evolves due to the competition between

large energetic flow scales

and

dissipative scales
(i.e. mechanical energy transformed into heat)

Due to the prohibitive numerical cost of solving everything manipulations of the NS eqns need new governing eqns for which this competition needs to be modeled



Whatever the **mathematical operations applied to Navier-Stokes**
since the problem is non-linear, a closure problem arises

$$\langle f(x,t)\rangle_L = G * f(x,t) \qquad G*\frac{\partial f}{\partial t} = \frac{\partial}{\partial t}\left[G*f\right], G*\frac{\partial f}{\partial x_i} = \frac{\partial}{\partial x_i}\left[G*f\right], G*1=1 \quad (1)$$

=> new unknowns appear [1-4]:

<u>Momentum:</u>

$$\tau_L(u_i,u_j) = \langle u_i u_j\rangle_L - \langle u_i\rangle_L\langle u_j\rangle_L \quad (2)$$

<u>Total energy:</u>

$$\tau_L(u_i,\partial p/\partial x_j) \quad (3)$$

$$\begin{aligned}\tau_L(u_i,u_j,u_k) = \langle u_i u_j u_k\rangle_L - \langle u_i\rangle_L \tau_L(u_j,u_k) - \langle u_j\rangle_L \tau_L(u_i,u_k) \\ - \langle u_k\rangle_L \tau_L(u_i,u_j) - \langle u_i\rangle_L\langle u_j\rangle_L\langle u_k\rangle_L\end{aligned} \quad (4)$$

[1] T. Poinsot and D. Veynante, Theoretical and Numerical Combustion (2005).
[2] P. Sagaut, Large Eddy Simulation for incompressible flows (2002).
[3] P. Moin et al., Phys. of Fluids, A3(11), p. 1746-2757, 1991.
[4] M. Germano, J. Fluid Mech., 238, p. 325-336, 1992.

Two operators exist today:

$$\langle f(x,t)\rangle_L = G * f(x,t) \qquad G*\frac{\partial f}{\partial t} = \frac{\partial}{\partial t}\left[G*f\right], G*\frac{\partial f}{\partial x_i} = \frac{\partial}{\partial x_i}\left[G*f\right], G*1=1$$

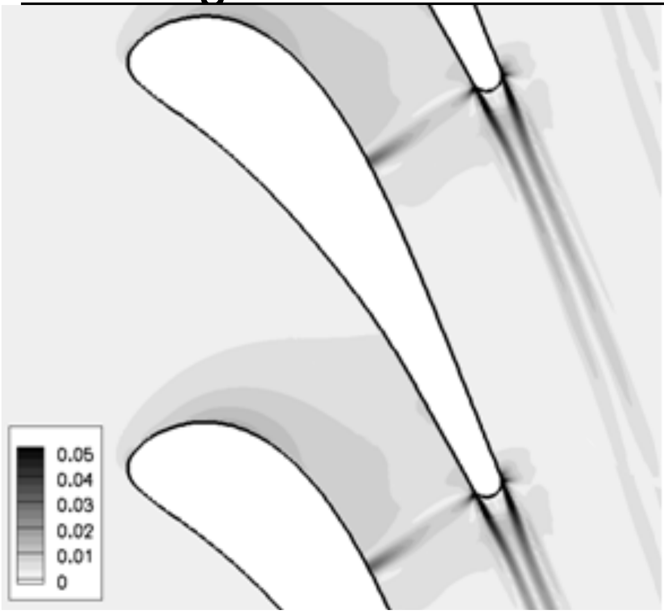
1/ Use an ensemble of flow realizations: RANS / URANS

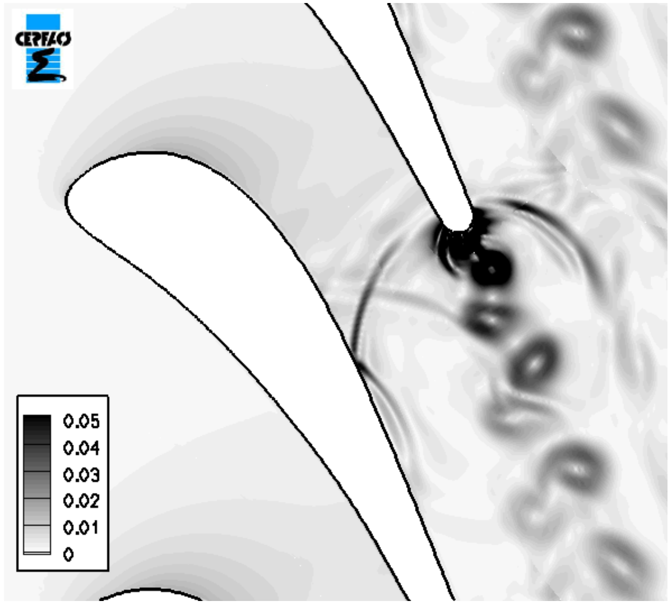
$$\left\{u_i^{(1)}(x,t), u_i^{(2)}(x,t), \ldots, u_i^{(n)}(x,t), \ldots, u_i^{(N)}(x,t)\right\}$$

$$G*f(x,t) = \frac{1}{N}\sum_1^N f^{(n)}(x,t) = \langle f(x,t)\rangle_L = \overline{f}(x,t)$$

$$f'(x,t) = f(x,t) - \overline{f}(x,t) \quad \Rightarrow \quad \overline{f'}(x,t) = 0, \quad \overline{\overline{f}}(x,t) = \overline{f}(x,t)$$

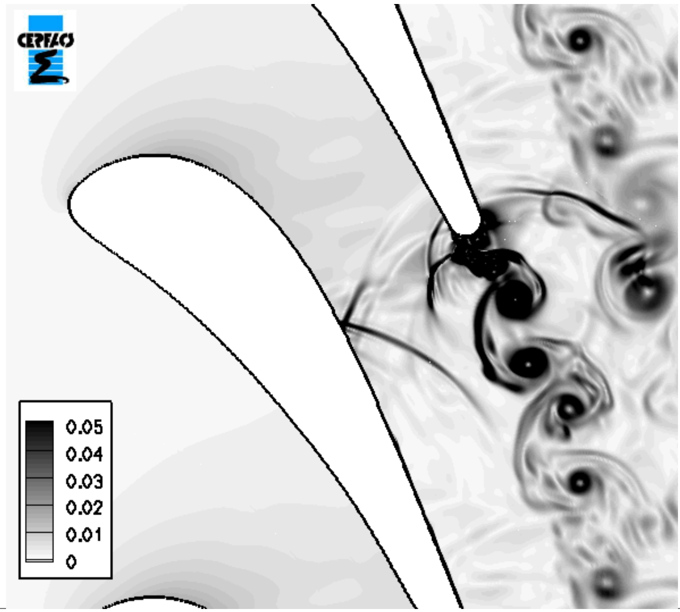
Modeling – Different formalisms => different sol. : RANS – URANS - LES





T. Léonard et al., in ASME Turbo-Expo, Glasgow, 2010.

N. Gourdain et al., in ASME Turbo-Expo, Vancouver, 2011.



Instantaneous gradp flow field (*elsA*)

- RANS predicts a non-physical shock-wave,
- URANS predicts the vortex shedding but flow features are damped by artificial viscosity,
- LES demonstrates its capacity to transport flow vortices and acoustic waves.

[1] Sieverding et al, ASME, 2003.
[2] Sieverding et al., J. Turbomach., 2004.

$$\tau_L(u_i, u_j) = \langle u_i u_j \rangle_L - \langle u_i \rangle_L \langle u_j \rangle_L$$

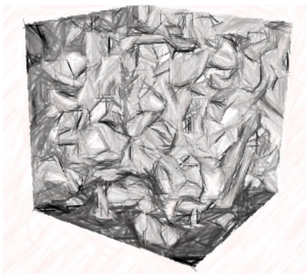
Turbulence modeling is the art of providing closure / models for the above tensor

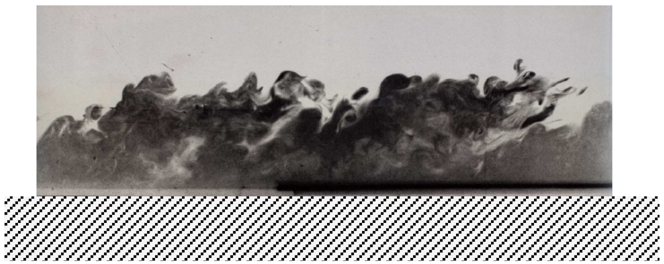
Clearly closures will be ***specific to the operator*** introduced (RANS, URANS, LES…)

Clearly closures will be ***specific to the flow turbulent characteristic properties***

=> need to identify typical turbulent flows and their properties

Free stream turbulence vs **Wall turbulence**





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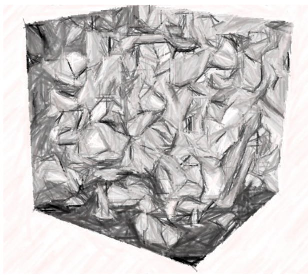
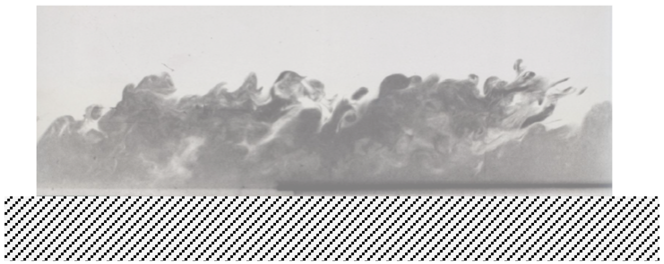
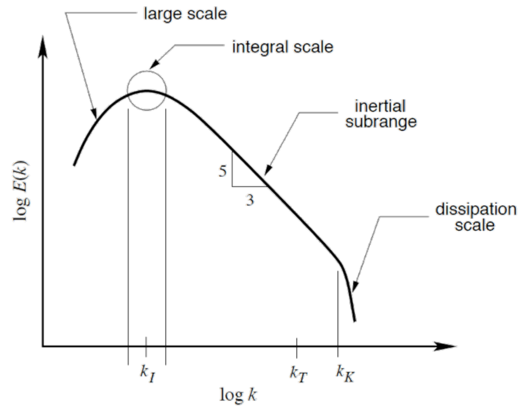




If an inertial range exists, whatever the flow (homogeneous, isotropic or not), **small scales (SGS quantities) can be assumed at equilibrium with the dissipation…**

Production of SGS energy $-\tau_{ij}\overline{S}_{ij}$
Balances viscous dissipation: ε_v

SGS velocity scale



$$\varepsilon_v \approx q_{sgs}^3/l = q_{sgs}^3/\Delta$$

$$-\tau_{ij}\overline{S}_{ij} \sim q_{sgs}^3/\Delta$$

=> Postulates a Gradient hypothesis and mixing length model for the turbulent viscosity

$$\tau_{ij} \propto \nu_t\, S_{ij} \quad \text{with} \quad \nu_t \propto \Delta\, q_{SGS}$$

$$q_{sgs} \sim \Delta|\overline{S}| \qquad |\overline{S}| = [2\overline{S}_{ij}\overline{S}_{ij}]^{1/2}$$

Smagorinsky model (1963):

- $\nu_T = (C_S \overline{\Delta})^2 |\overline{S}|$
- Since the constant C_S (the Smagorinsky constant) is real, the model is absolutely dissipative:

$$\tau_{ij} \overline{S}_{ij} = -(C_S \overline{\Delta})^2 |\overline{S}|^3 \leq 0$$

- To evaluate C_S , assume a spectrum with an inertial range:

$$E(k) = \text{Ko}\, \varepsilon^{2/3} k^{-5/3}$$

- Integrate the dissipation spectrum k^2 E(k) over all resolved wavenumbers:

$$|\overline{S}|^2 \simeq 2 \int_0^{\pi/\overline{\Delta}} k^2 E(k) dk = \frac{3}{2} \text{Ko}\, \varepsilon^{2/3} \left(\frac{\pi}{\overline{\Delta}} \right)^{4/3} .$$

- With Ko = 1.41 this gives $C_S \approx 0.18$

Pros & Cons:

- *Purely dissipative model (no feedback to resolved scales – numerically stable ☺)*
- *Loss of locality (integrated spectrum)*
- *One constant to have dissipation and SGS??? (alignment of τ_{ij} with S_{ij})*

Recursive filtering (Germano's identity, 1991):

Introduce two two filter scales:

$$< U_i >_L = \int U_i(x_j - x_j^{'}, t)\, G(x_j - x_j^{'})\, dx_j^{'}$$

$$< U_i >_{\mathcal{L}} = \int U_i(x_j - x_j^{'}, t)\, \mathcal{G}(x_j - x_j^{'})\, dx_j^{'}$$

Hence double filtering sequentially with G and then by $\mathbb{G}$, you get:

$<< U_i >_L >_{\mathcal{L}}, \quad << U_i >_L < U_j >_L >_{\mathcal{L}},$	Accessible quantities
$< \tau_L(U_i, U_j) >_{\mathcal{L}} = < (< U_i U_j >_L - < U_i >_L < U_j >_L) >_{\mathcal{L}}$	Unclosed terms (no miracle)

For this identity, on needs to re-express:

$$\begin{aligned} << U_i U_j >_L >_{\mathcal{L}} &= < \tau_L(U_i, U_j) + < U_i >_L < U_j >_L >_{\mathcal{L}} \\ &= < \tau_L(U_i, U_j) >_{\mathcal{L}} + \tau_{\mathcal{L}}(< U_i >_L, < U_j >_L) \\ &\quad + << U_i >_L >_{\mathcal{L}} << U_j >_L >_{\mathcal{L}} \end{aligned}$$

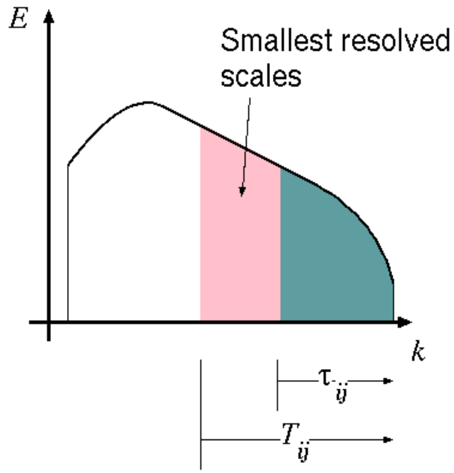
From this relation, one obtains:

$$\underbrace{<< U_i U_j >_L >_{\mathcal{L}} - << U_i >_L >_{\mathcal{L}} << U_j >_L >_{\mathcal{L}}}_{T_{ij}^r} = \underbrace{< \tau_L(U_i, U_j) >_{\mathcal{L}}}_{\hat{\tau}_{ij}^r} + \underbrace{\tau_{\mathcal{L}}(< U_i >_L, < U_j >_L)}_{L_{ij}}$$

[1] Germano et al., 1991.

Dynamic Smagorinsky model (1991):

$$T_{ij}^{r} = \hat{\tau}_{ij}^{r} + L_{ij}$$



Introducing the gradient diffusion model for the first two terms:

$$T_{ij}^{r} = -2\,(C_s\,\Delta_L)^2 < S^L \quad S^L{}_{ij} >_{\mathcal{L}}$$

$$\hat{\tau}_{ij}^{r} = -2\,(C_s\,\Delta_{\mathcal{L}})^2 < S^L >_{\mathcal{L}} \quad < S^L{}_{ij} >_{\mathcal{L}}$$

so that

$$L_{ij} = -2\,(C_s\,\Delta_L)^2 \underbrace{[< S^L\; S^L{}_{ij} >_{\mathcal{L}} - \alpha^2 < S^L >_{\mathcal{L}} < S^L{}_{ij} >_{\mathcal{L}}]}_{M_{ij}}$$

$$\alpha = \Delta_{\mathcal{L}} / \Delta_L$$

This is an over-determined system: 1 Cst and 6 eqns (sym. tensors)…

One way to evaluate C_s is to contract the tensor: i.e.

Pros & Cons:

- *Fully automated evaluation of the model Cst*
- *Potentially negative values of the coeff. (unphysical) => Need for regularization tech. (smoothing, volume average…)*
- *Added locality*

[1] Germano et al., 1991. [2] Lilly et al., 1992. [3] C. Meneveau et al., 1995.

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Clearly closures will be ***specific to the operator*** introduced (RANS, URANS, LES…)

=> to be discussed later on

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=> need to identify typical turbulent flows and their properties

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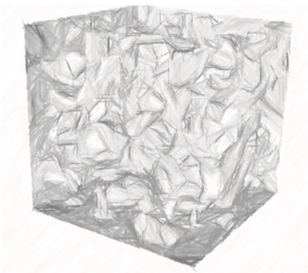
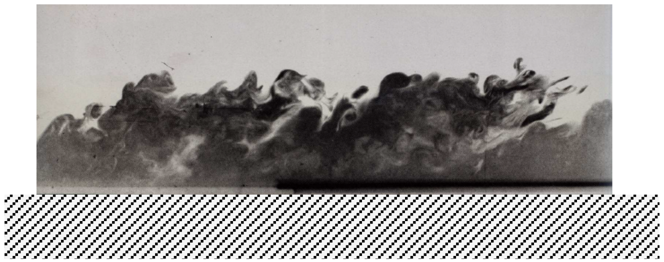
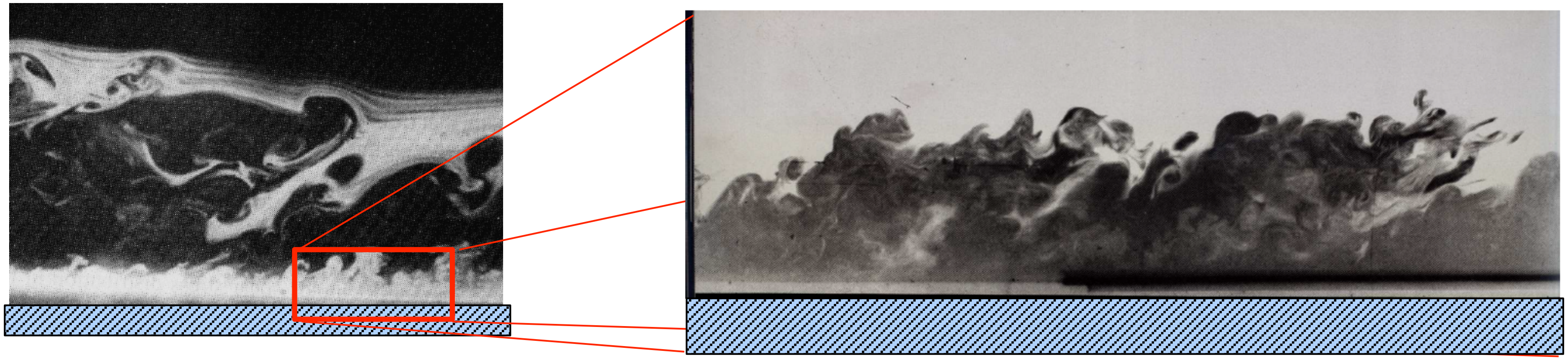


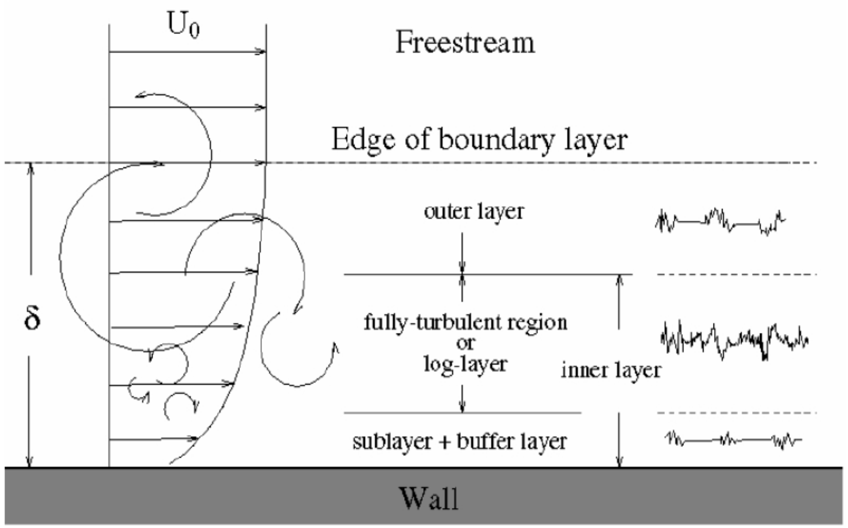




Wall turbulence (fully developed boundary layer) is highly anisotropic:

=> strong shear mean shear

=> different layers are present



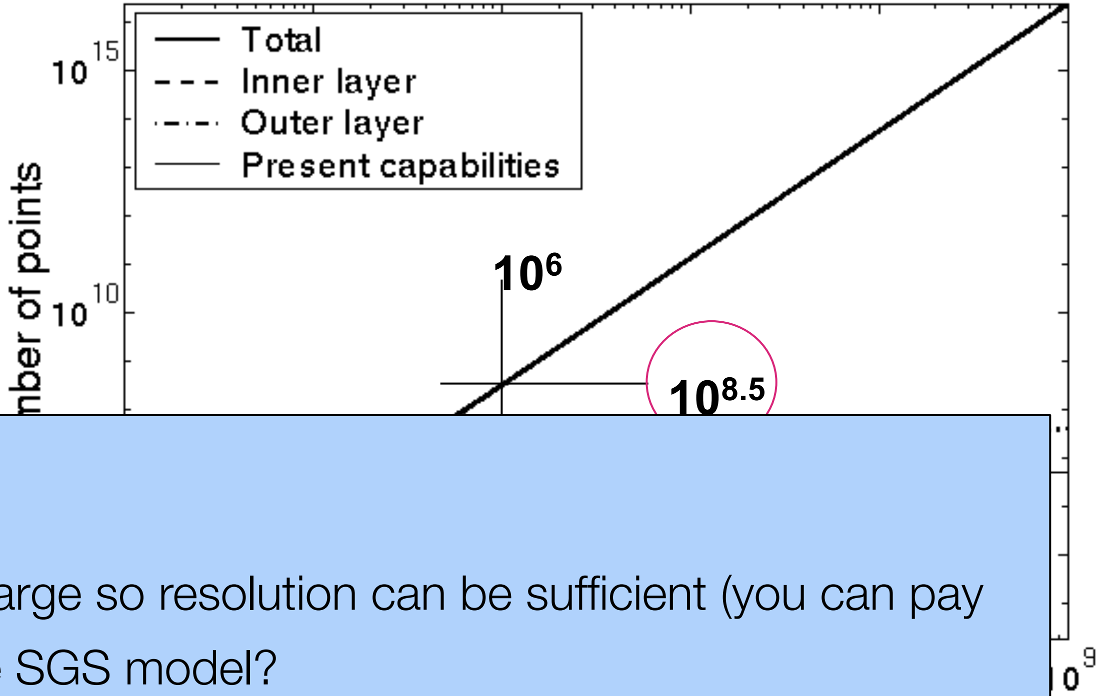
Region of interaction between outer BL flow and BL flow (intermittency)

Self-similar behavior of the flow

Self-similar laminar flow

From the previous findings dimensional analyses show (Piomelli 2002):

- inner layer $N_x N_y N_z \propto Re_L^{1.8}$
- outer layer $N_x N_y N_z \propto Re_L^{0.4}$

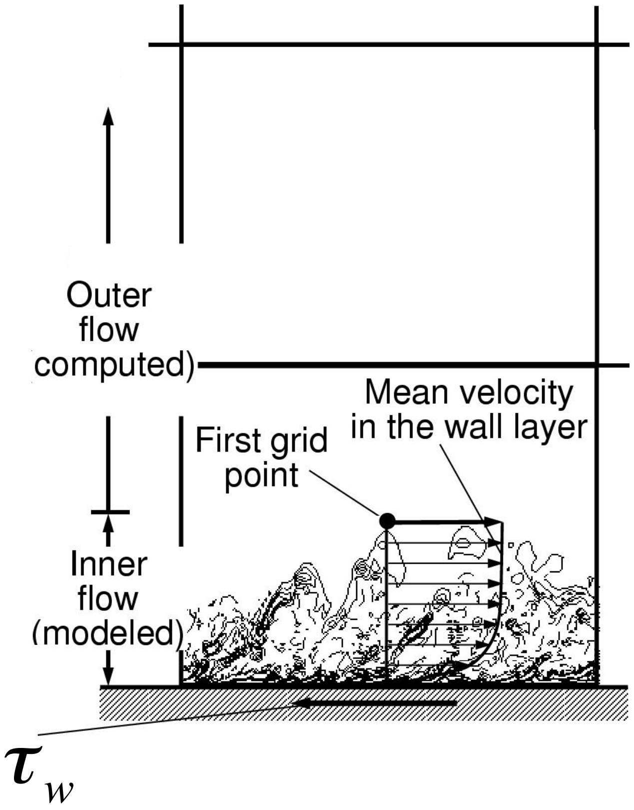


Two possibilities:

1/ Turbulent Re # is not too large so resolution can be sufficient (you can pay the price) but what about the SGS model?

2/ Turbulent Re # is too large; you need to model the entire wall problem…

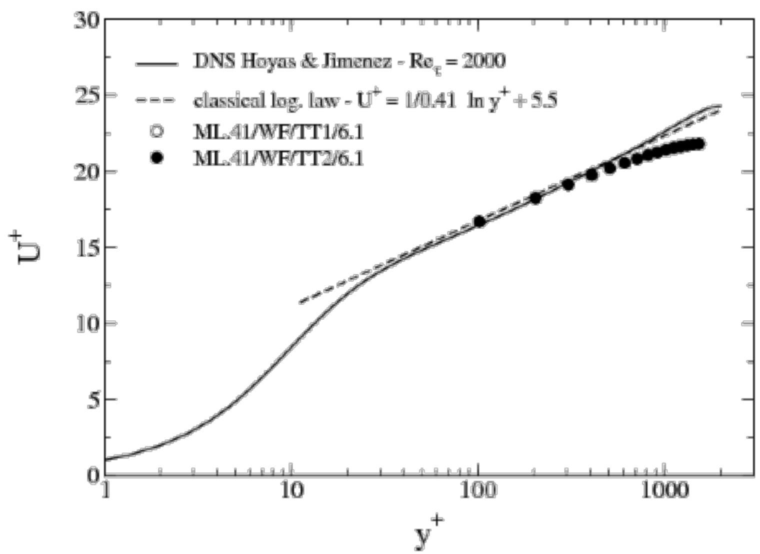
[1] Piomellii et al., 2002.



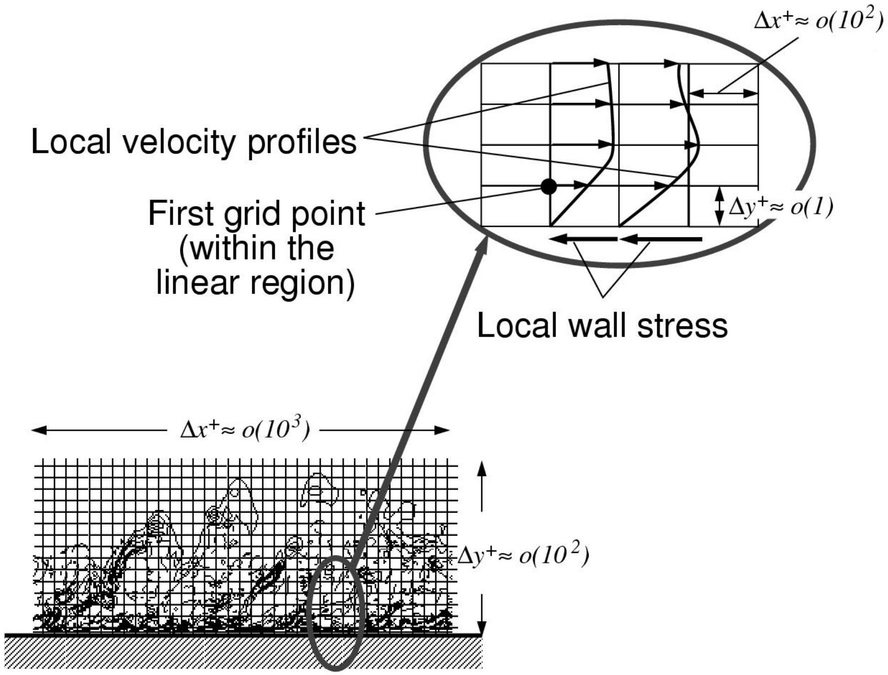
The entire dynamics of the BL is modeled:

- Statistically stationary BL hypothesis
- Non-transioning flow

⇒ Use of the Log-Law within the cell with inputs coming from the first off-the-wall-node



Wall law flow dynamics prevails (no pressure gradient) & the matching between turbulent SGS model and first cell wall law correction is OK…



The dynamics of the BL is simulated:

- Fully unsteady approach
- Non-transioning flow…

⇒ Constraints essentially reported on the SGS model

Works iff the SGS viscosity behaves as expected: $\nu_t \xrightarrow[y^+ \to 5]{} 0$

Velocity field near wall asymptotic limit yields: $\nu_t \propto O(y^{+3})$

Smagorinsky model: $\nu_t \propto \sqrt{S_{ij}\,S_{ij}} \propto O(u_1)$

!!! Impossible to use especially in the fully resolved context !!!

=> used in conjunction with a Law of the wall

WALE model[1]: $$\nu_t = (Cw\,\Delta)^2 \frac{\left(S_{ij}^d\,S_{ij}^d\right)^{3/2}}{\left(S_{ij}\,S_{ij}\right)^{5/2} + \left(S_{ij}^d\,S_{ij}^d\right)^{5/4}}$$

with $$S_{ij} = \frac{1}{2}\left(g_{ij} + g_{ji}\right), \quad g_{ji} = \frac{\partial \tilde{u}_i}{\partial x_j}, \quad S_{ij}^d = \frac{1}{2}\left(g_{ik}g_{kj} + g_{jk}g_{ki}\right) - \frac{1}{3} g_{ki}g_{ik}\,\delta_{ij}$$

Yielding: $S_{ij}^d\,S_{ij}^d \propto O(y^2)$ $\qquad \nu_t \propto O(y^3)$

Note: denominator is here for dimensionality purposes and its form is to avoid numerical singularities!

[1] F. Ducros et al., 1995.

Desired properties of a 'good' LES model:

For proper model behavior, the filter should be applied in the lower inertial range (around Taylor micro-scale)… But one can also enforce:

1/ as $\Delta \rightarrow 0$ if the concept is well posed then LES → DNS (fully resolved problem)

=> supposes that the model contribution vanishes adequately

2/ as $\Delta \rightarrow \infty$ similarly LES → RANS (fully modeled problem)

=> supposes that the model contribution reproduces a RANS closure

Few models today can fulfill these wishes… Smagorinsky will not !!!!

How about real flows:

- filtering and BC's?
- filter is rarely known,
- transitioning flows?

[1] P. Sagaut et al, 2001.
[2] Ferziger et al, 1998.
…

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=> LES based CAA on industrial like applications

IV] Conclusions and perspectives:

At some point you need to integrate numerically the modeled transport equations:

=> **LES:** *fully unsteady formalism where part of the turbulent spectrum activity (large scale interactions) is directly reproduced…*

=> **RANS:** *within the context of statistically stationary flows there is no explicit need for temporal accuracy (URANS – potentially needed)*

Equivalent Eqn

$$\frac{\partial u}{\partial t} + a\frac{\partial u}{\partial x} = \mathcal{G}\left(cfl, \Delta x, \frac{\partial^{2n} u}{\partial x^{2n}}, \frac{\partial^{2n+1} u}{\partial x^{2n+1}} ..\right)$$

2n : Dissipation
2n+1: Dispersion

Euler explicit and centered:

$$\mathcal{G} = -\frac{a\,\Delta x}{2}\nu \frac{\partial^2 u}{\partial x^2} - \frac{a\,(\Delta x)^2}{6}\frac{\partial^3 u}{\partial x^3}$$

Anti-diffusion = unstable!

Euler implicit and centered:

$$\mathcal{G} = \frac{a\,\Delta x}{2}\nu \frac{\partial^2 u}{\partial x^2} - \frac{a\,(\Delta x)^2}{6}\frac{\partial^3 u}{\partial x^3}$$

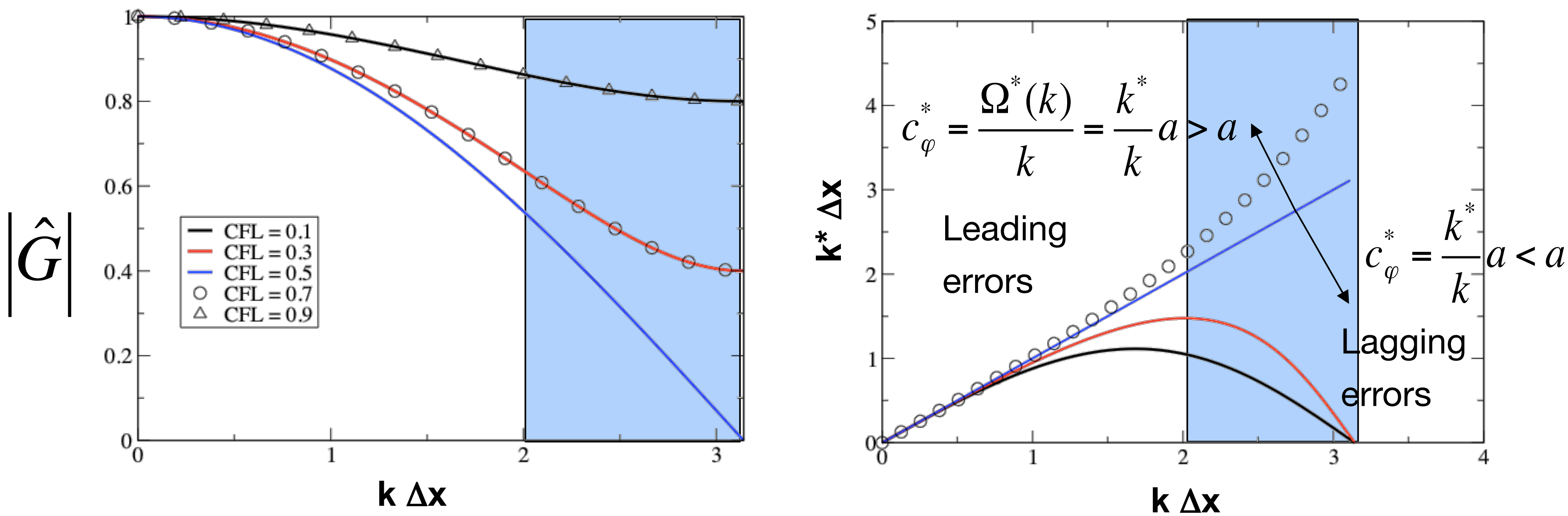
Euler explicit and upwind:

$$\mathcal{G} = \frac{a\,\Delta x}{2}(1-\nu) \frac{\partial^2 u}{\partial x^2} - \frac{a\,(\Delta x)^2}{6}\frac{\partial^3 u}{\partial x^3}$$

Numerical diffusion

The dissipation error (peak conservation):

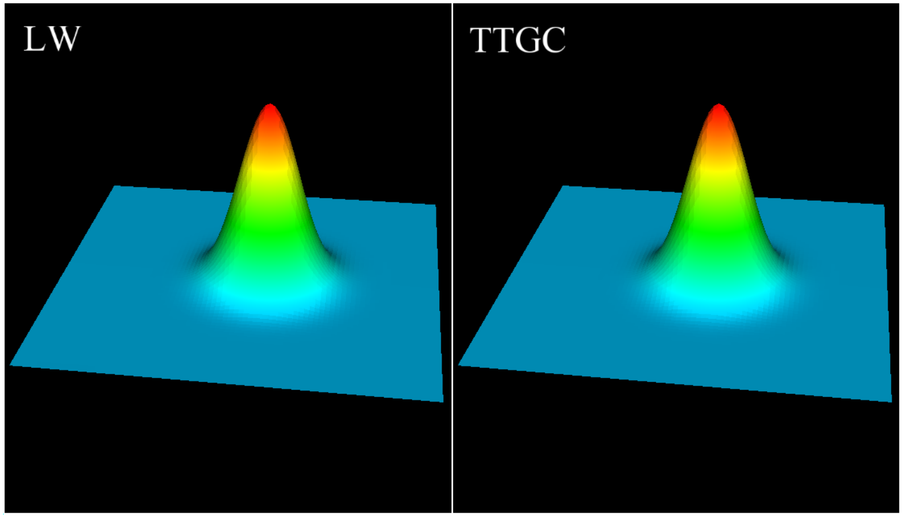
The dispersion error (propagation speed of info):



This is the region that is used for modeling and where the model is supposed to act the most to reproduced the SGS interactions needed for a proper temporal evolution of the predictions…

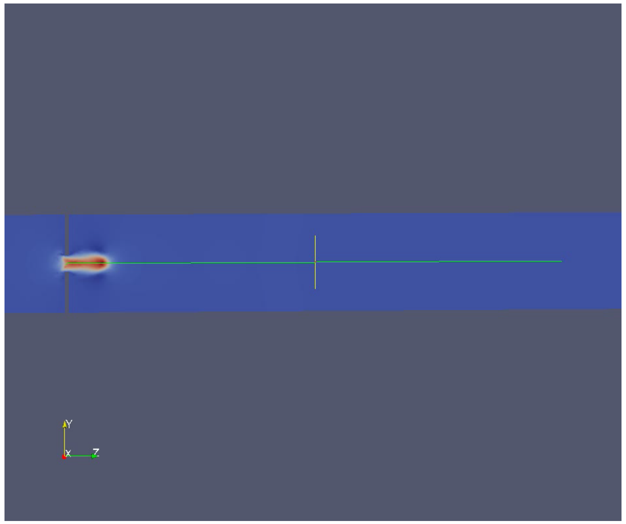
NOTE: Very large scales are not too affected if the scheme is centered

Gaussian convected on a 2D uniform mesh:

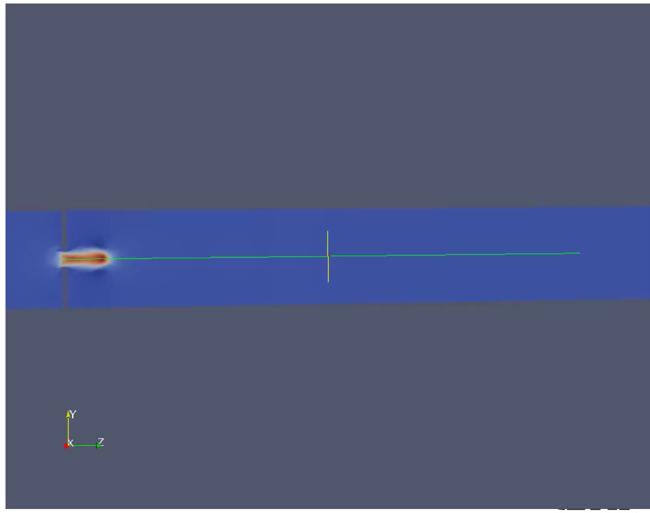


3D jet (H. Nguyen):

LW



TTGC



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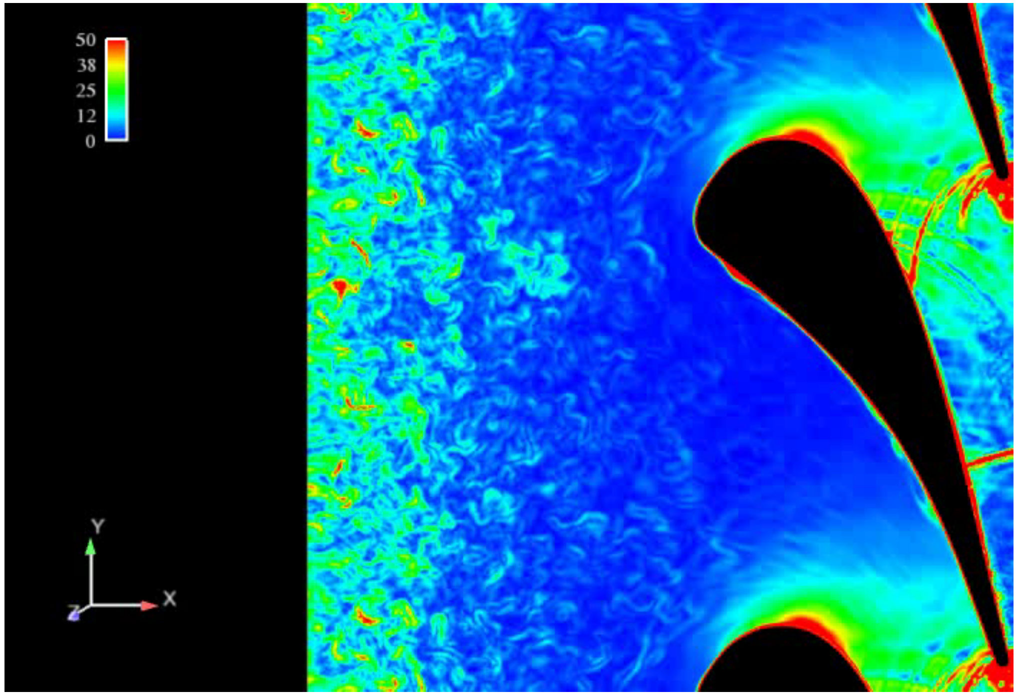
=> LES based CAA on industrial like applications

IV] Conclusions and perspectives:



- Highly sensitive to the wall flow state
  - Transitioning Boundary Layers
- Highly compressible (Shocks)
  - Shock / Boundary Layer interations
- Wake
  - Strong acoustic source
- Highly curved flow
  - Görtler instabilities

Test case	Re_2	$M_{is,2}$	$P_{i,0}$	$T_{s,wall}$	Tu_0
MUR129	$1.13\ 10^6$	0.840	$1.87\ 10^5\ Pa$	298 K	1.0%
MUR235	$1.15\ 10^6$	0.927	$1.85\ 10^5\ Pa$	301 K	6.0%

Heat Transfert Coeff.:

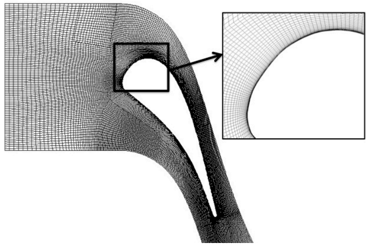
$$H = \frac{Q_{wall}}{T_\infty - T_{wall}}$$

[1] E. Collado et al., IJHMT, 2012.
[2] N. Gourdain et al., AIAA Propulsion and Power, 2012.
[3] T. Arts et al, VKI, 1990.

Wall resolved LES strategy:

- elsA

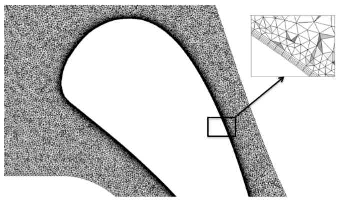
LES structured



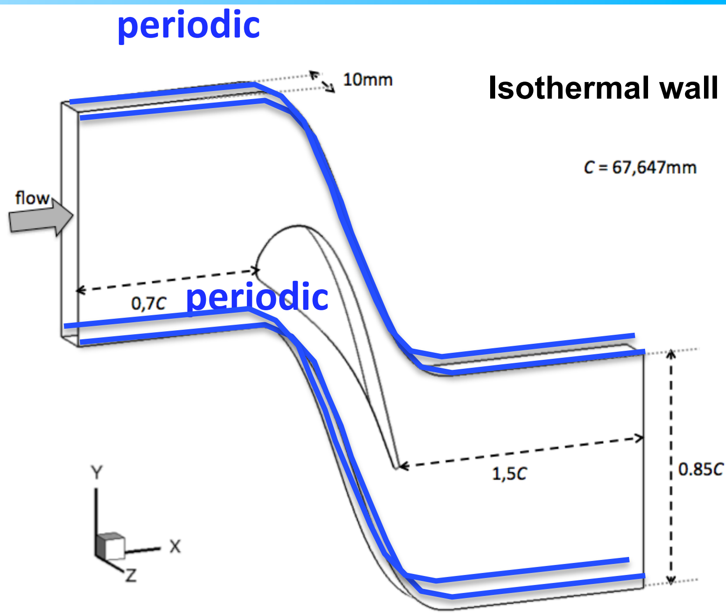
- 3D fully structured multi-blocks
- Implicit dual time integration $O(\Delta t^2)$
- y^+~1, 2µm, Δx^+~150, Δz^+~25
- 30 10^6 cells
- SGS model: WALE (Nicoud, 1999)
- Transition: cf. computation

- AVBP

LES unstructured



- 3D fully unstructured
- Explicitin time - Taylor Galerkin $O(\Delta t^3)$
- y^+~4, 8µm, Δx^+~$4\Delta y^+$, Δz^+~$4\Delta y^+$
- 30 10^6 cells
- SGS model: WALE (Nicoud, 1999)
- Transition: cf. computation



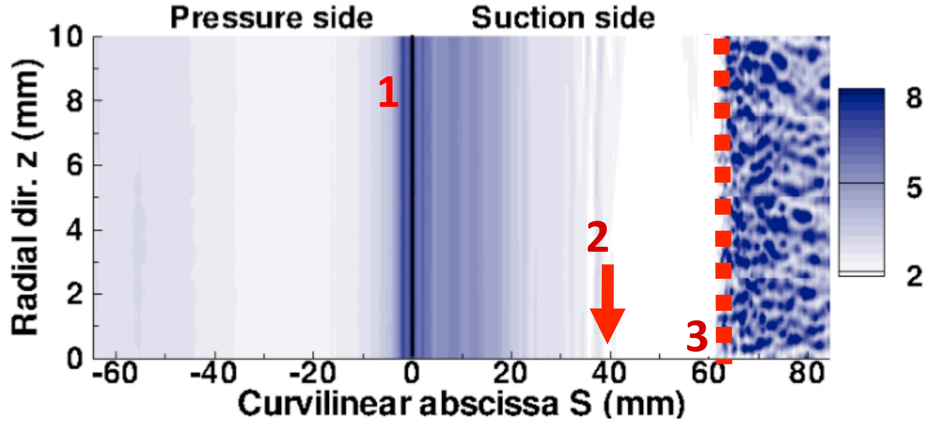
1/ Capabilities of the two LES numerical strategies to produce coherent flow predictions

2/ Numeric and code efficiencies

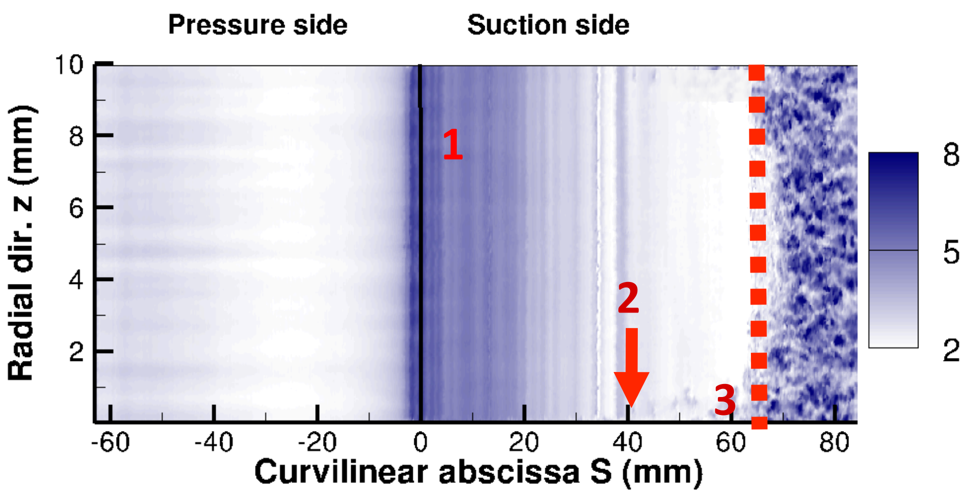
⇒ **Robustness of wall resolved LES to turbulent BL state sensitivity of the flow**

MUR 129: 0%

LES structured



LES unstructured



1: Laminar flow

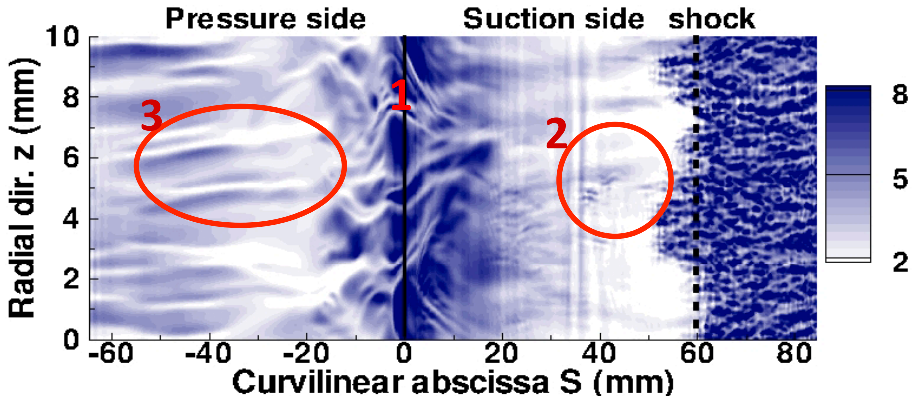
2: Impacting acoustic waves

3: Transition

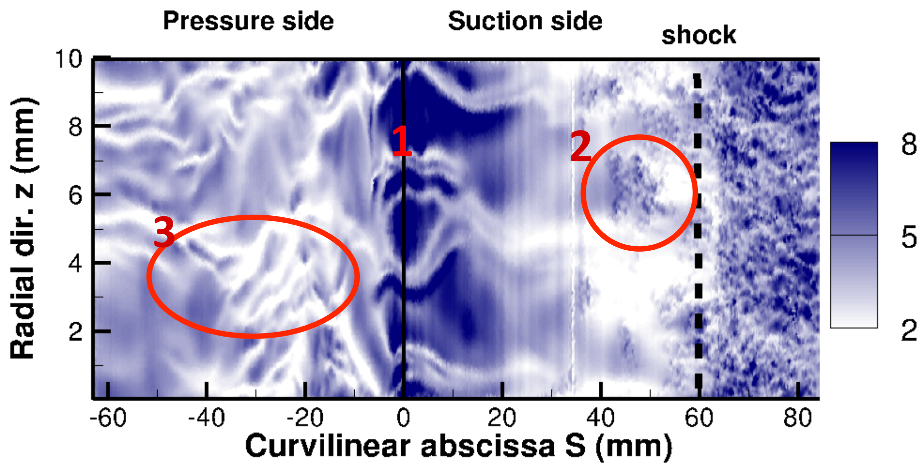
- Instantanenous field of the wall heat flux Q ($W.cm^{-2}$)
  - Transition occurs at S=60mm
  - Transition is initiated by a sonic point

MUR 235: 6%

LES structured



LES unstructured

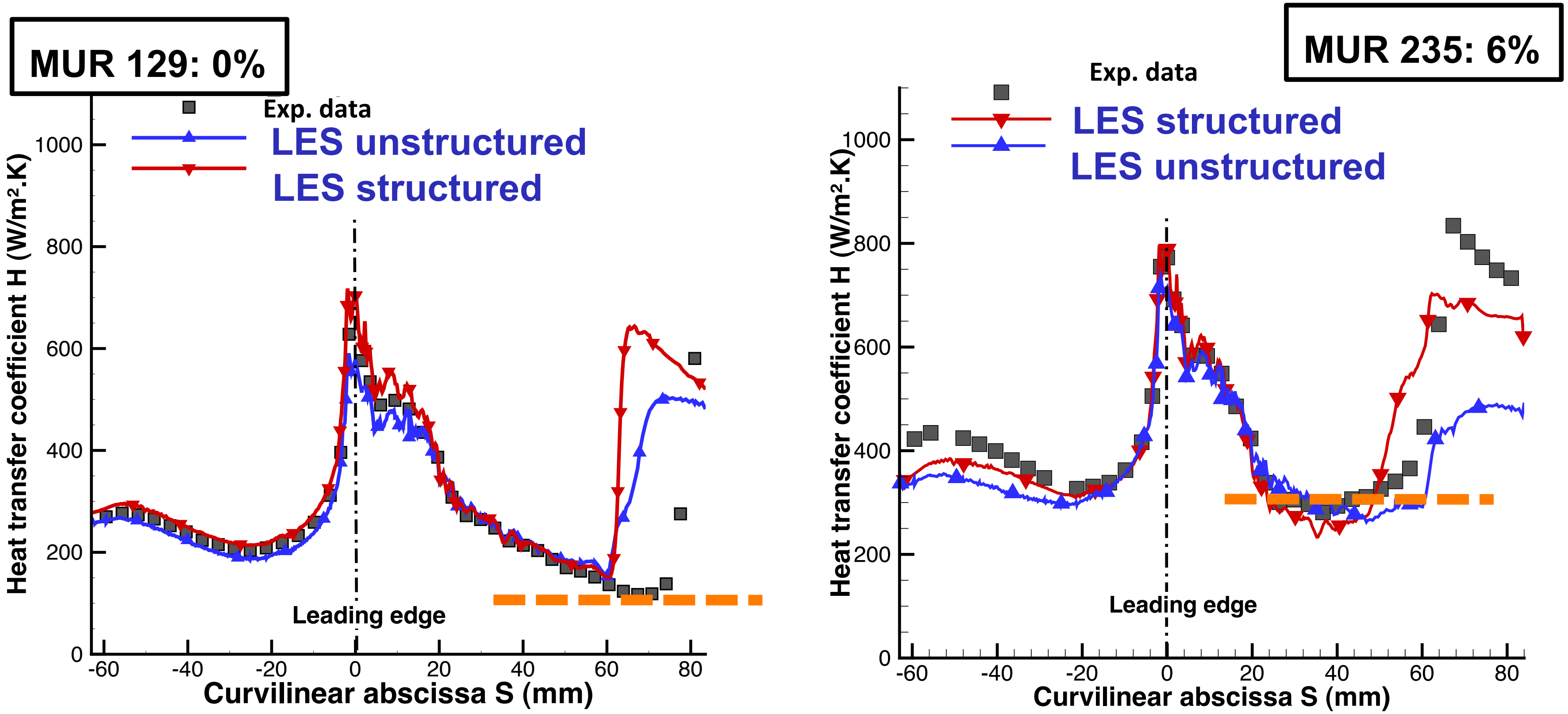


1: Incoming turbulence impacting the blade leading edge

2: Turbulent spots

3: Strecthed vortices (Görtler)

- Instantanenous field of the wall heat flux Q (W.cm^{-2})
  - Transition seems to be of «by-pass» type
  - Appears between S=40mm & S=60mm
  - Interaction between the shock and the transtionned turbulent boundary layer



- Pressure side: H under estimated by less 5%
- From S=-20 to S=50mm: Both LES provides prediction with a 5% error (cf. exp.)
- After transition: elsA under estimate by 25%, AVBP by 40%

- Pressure side: H under estimated by 15%
- From S=-20 to S=50mm: Both LES provides prediction with a 5% error (cf. exp.)
- After transition: elsA under estimate by 25%, AVBP by 40%

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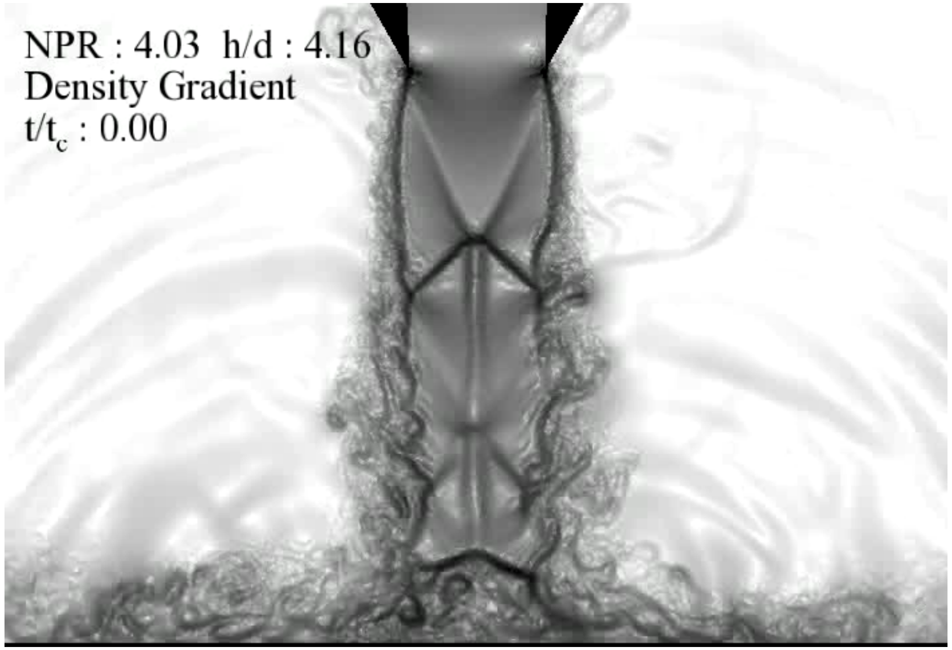
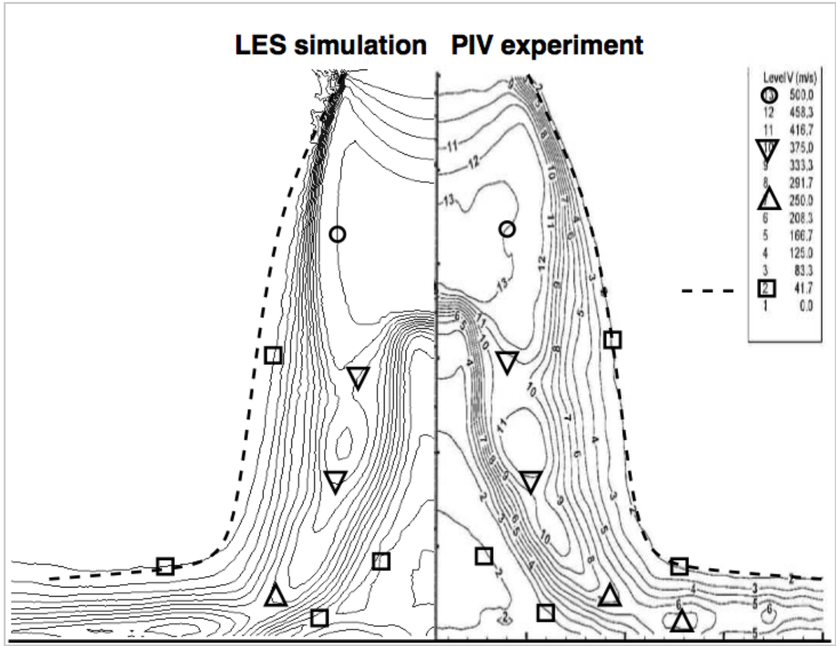
LES of turbulent wall impacting jets

Under-expanded impacting jet (Mach bottle): depending on h/d and Nozzle Pressure Ratio (NPR), stable or unstable flow can appear…[1]

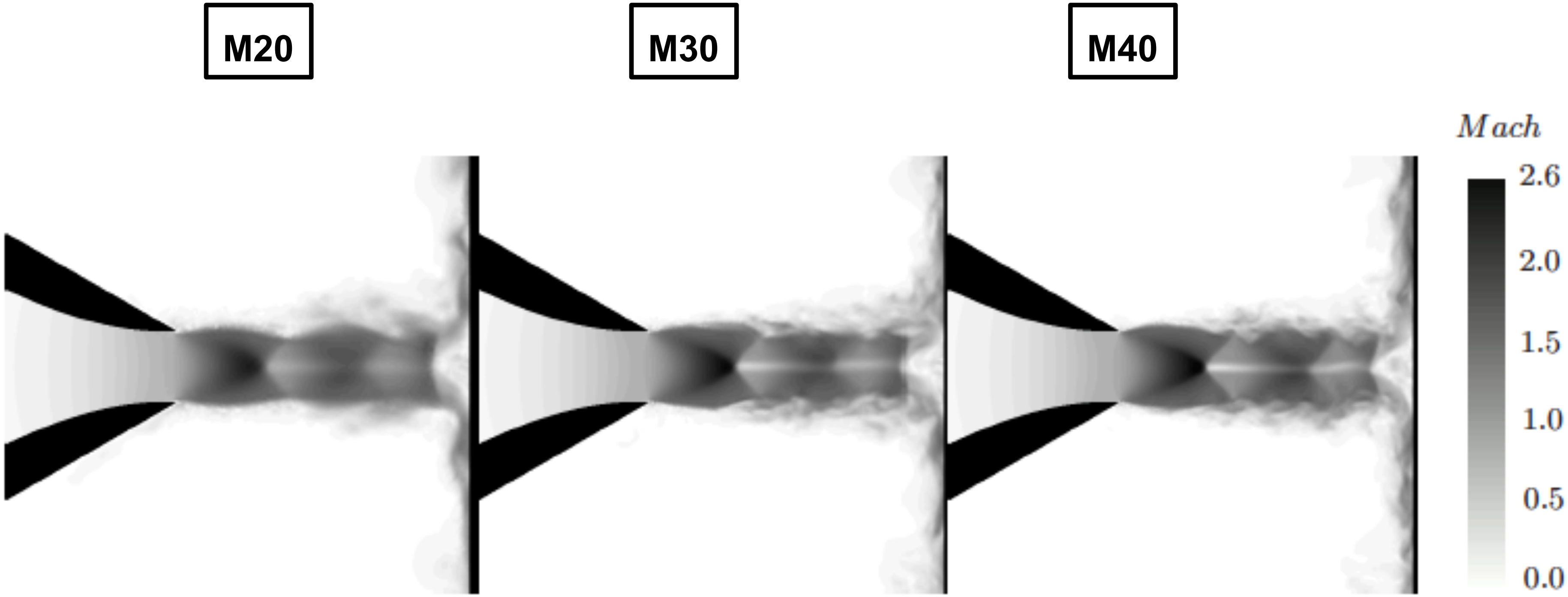
- Stable case to validate modeling (**wall modeled LES**), grid resolution… [2]
- Unstable case to see if LES captures the acoustic loop [3]





[1] B. Henderson et al., JFM, 542, 115, 2005.
[2] A. Dauptain et al., AIAAJ, 2010.
[3] A. Dauptain et al., AIAAJ, 2011.

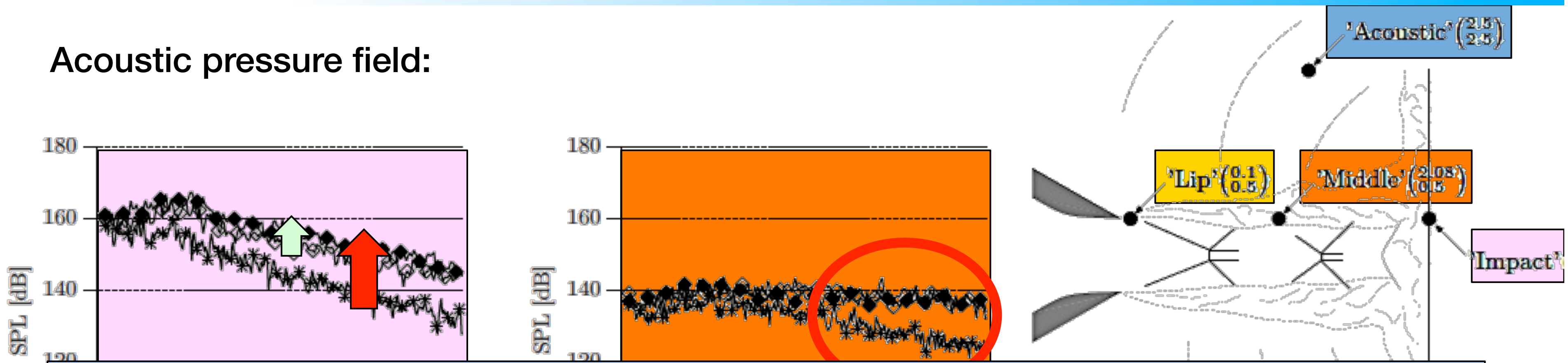
Sensitivity of the predictions: A. Dauptain et al., AIAAJ, 2010.



	$\Delta x/d$	Nodes	Tetrahedra	Memory size	Time step
M20	1/20	1 299 149	7 497 557	147MB	$0,524\mu s$
M30	1/30	2 763 143	16 026 453	312MB	$0,27\mu s$
M40	1/40	3 833 370	22 280 845	433MB	$0,214\mu s$

	one convective time		Total time used	
	$t_{cpu}^{conv.}$	$t_{hum.}^{conv.}$	$t_{cpu}^{tot.}$	$t_{hum.}^{tot.}$
M20	82.9 hr.	9.7 min.	17 955 hr.	35 hr.
M30	353.8 hr.	41.5 min.	17 412 hr.	34 hr.
M40	662.0 hr.	72.9 min.	19 938 hr.	39 hr.

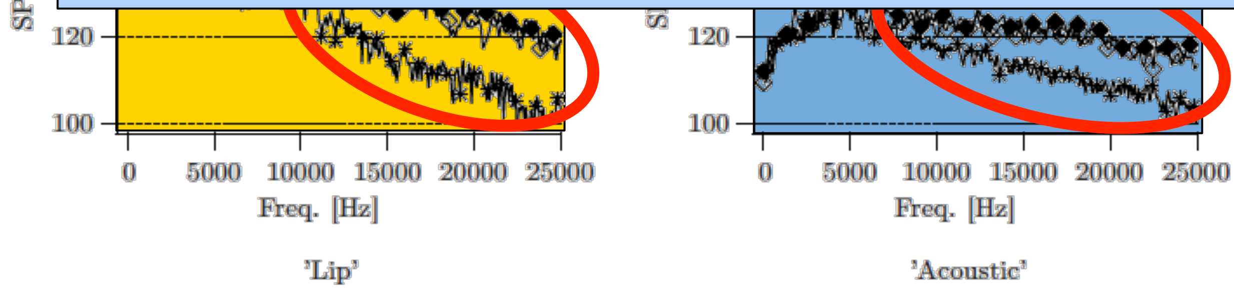
Acoustic pressure field:



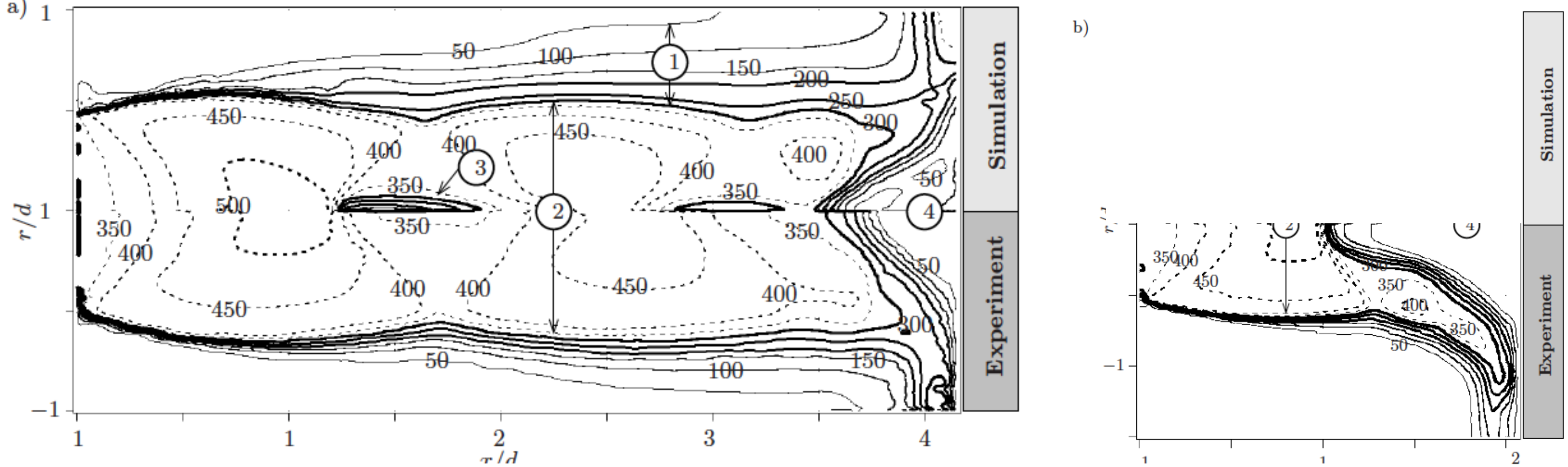
<u>Resolution (i.e. Energy containing structures) does impact SPL predictions:</u>

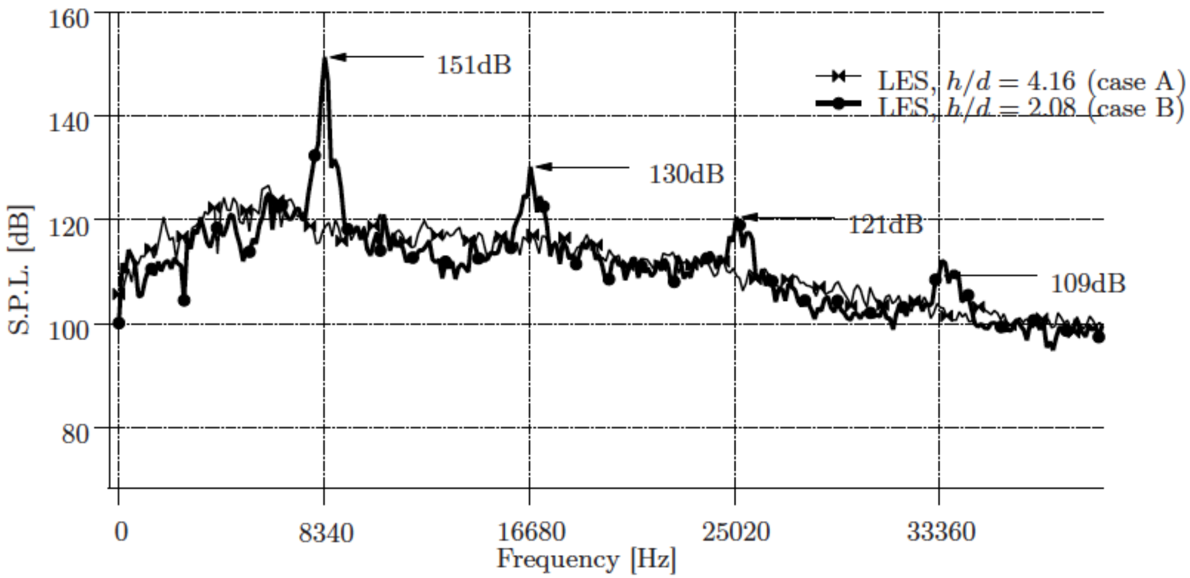
1/ Overall flow topology (mean field) does not seem so sensitive

2/ Unsteady features are however critical for good SPL results… Only a good resolution allows a somewhat grid independent result (increasing further does not change the freq. content of the SPL)

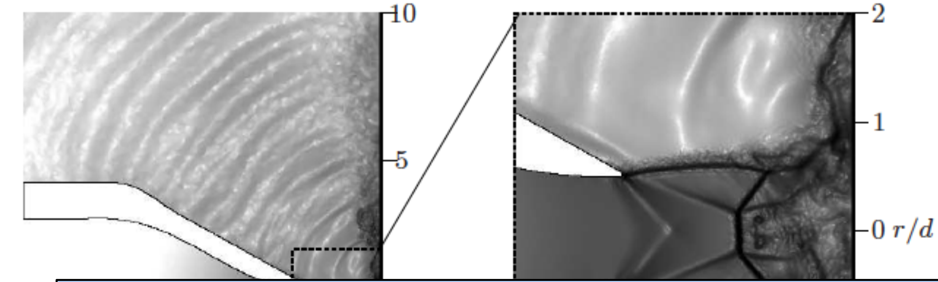


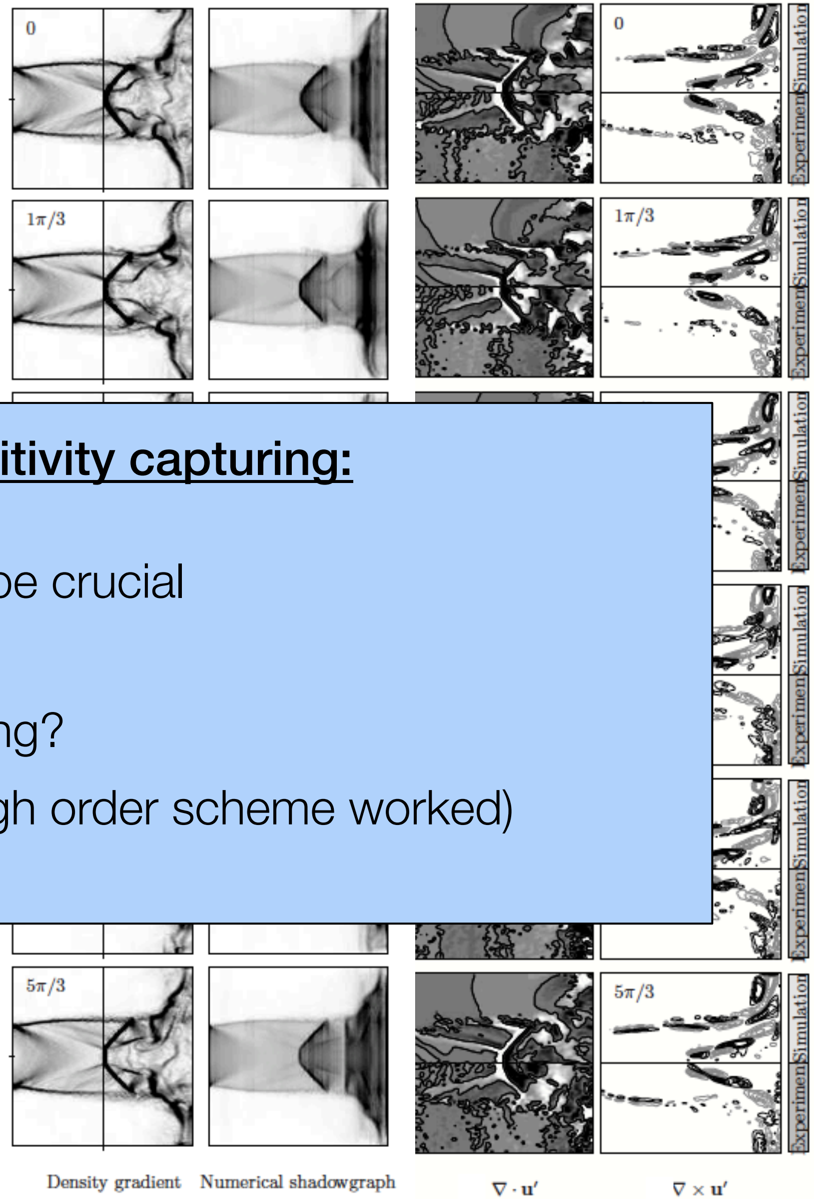
Change of operating condition: NPR = 4, h/d = 4.16 => 2.08 (A. Dauptain et al., AIAAJ, 2011)





Acoustic field – validation of the limit-cycle:





Careful use of LES allows proper flow sensitivity capturing:

1/ Here wall modeling does not seem to be crucial

2/ Grid resolution is of prime order

=> quid of the SGS modeling?

=> quid of numeric (only high order scheme worked)

Phas

=> identical treatments to remove any uncertainty in the treatment

Overall recommendations on the modeling and validation strategies:

Validations of LES codes is not an obvious because you end up handling a fully dynamic system expressing interactions between:

- numeric
- SGS model
- grid resolution (structured vs unstructured)

…

Basic test cases are necessary and assessment of your modeling strategy needs to be faced to well mastered configurations where flow data (unsteady and mean) are available…

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Prediction of the sources is one thing, propagating them is another thing…

Most LES numerical scheme introduces too much dissipation & dispersion to preserve and propagate accurately the small amplitude pressure fluctuations over a long distance… LES needs to be coupled to another acoustic solver

=> CAA (Computational Aero-Acoustic)

Questions to be answered:

- What other code? Linearized Euler, Acoustic Analogy…
- What quantity to transfer?
- Where to extract the info?

1/ Broadband noise: free jets

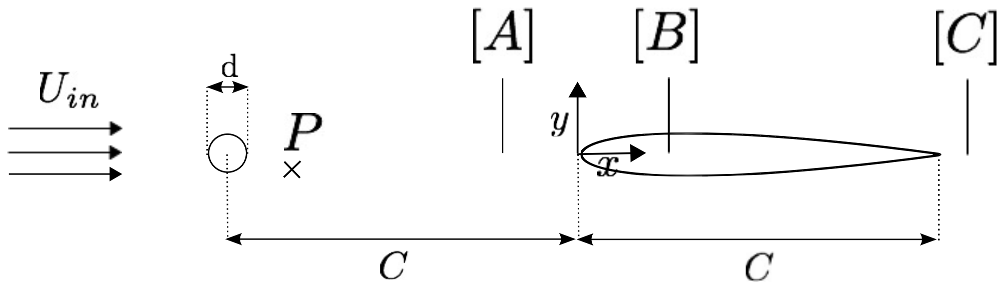
2/ Tone dominated noise: rod-airfoil interaction

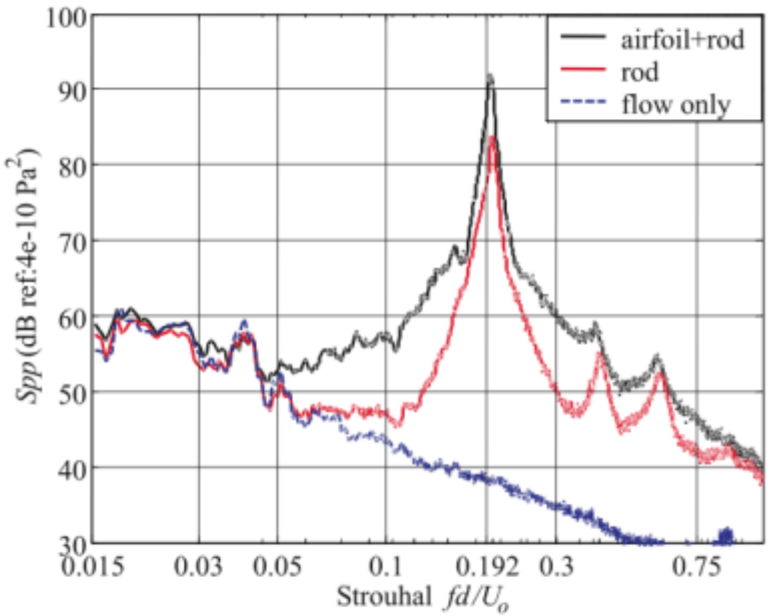
Classical benchmark [1]: J.-C. Giret et al. (CIFRE CERFACS / AIRBUS)

- Rod vortex shedding at St ~ 0.19
- Turbulence in the cylinder wake

  => Impingement of the shedded vortices on the airfoil generates the tone

  => turbulent containing wake generates the broadband noise





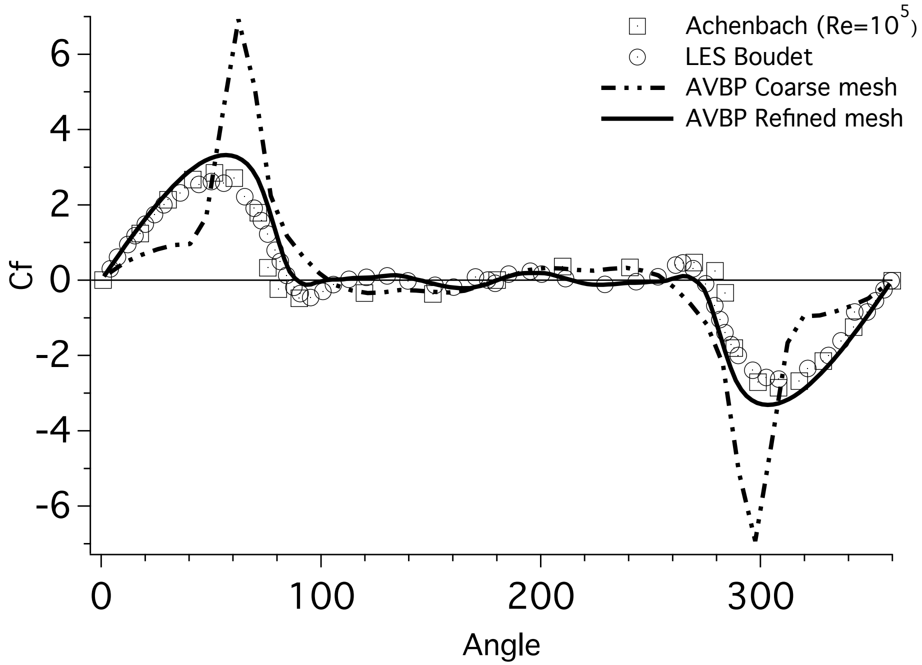
[1] Jacob et al, TCFD, 2005.

Mean flow prediction validations:

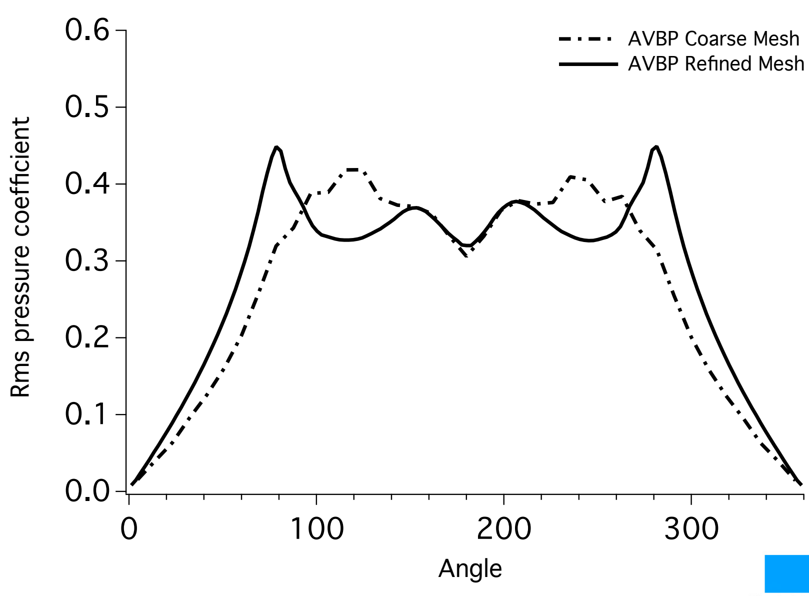
Wall resolved LES: i.e. WALE and initial guess for the first layer y^+

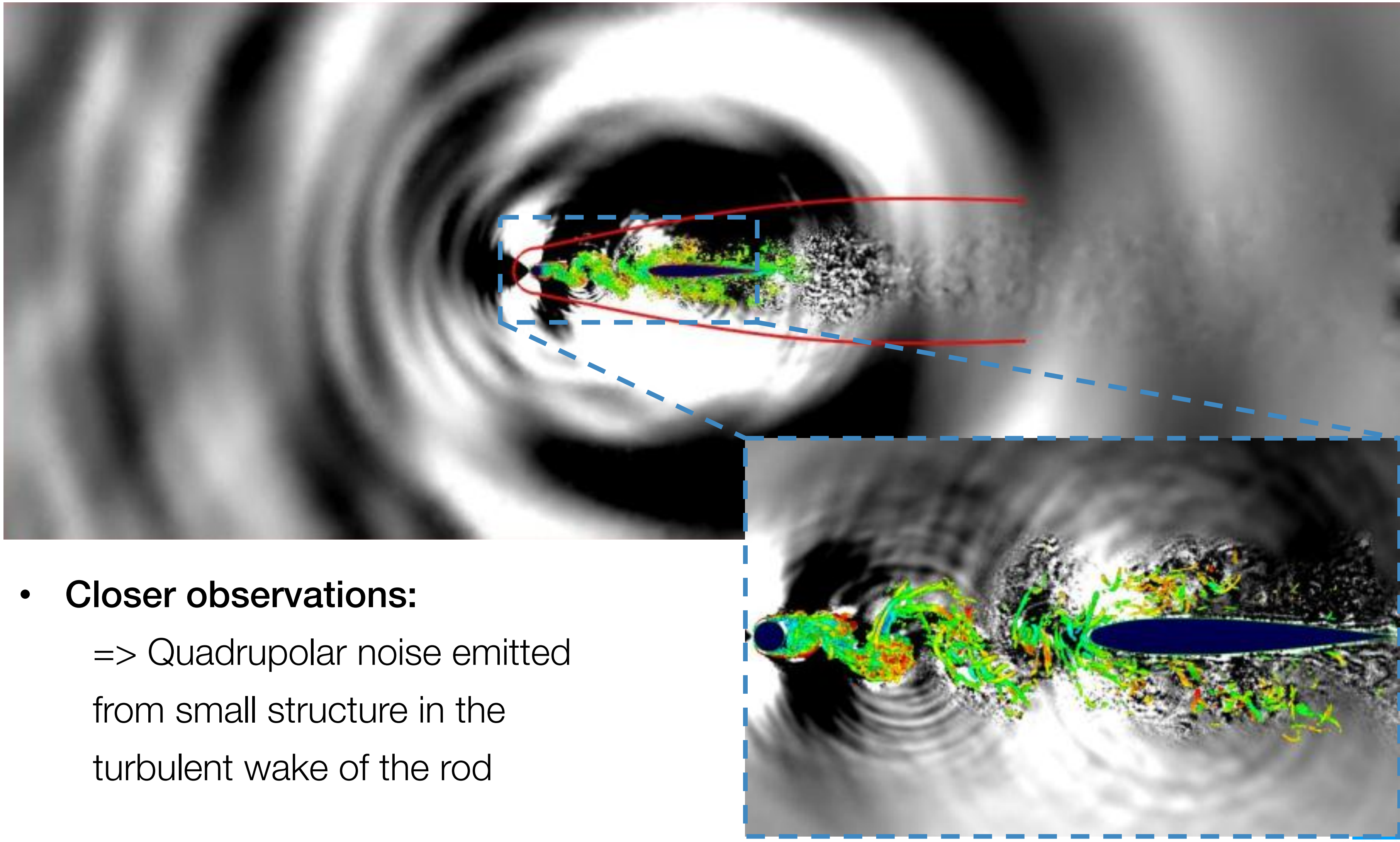
=> Cylinder BL is fully transitioning with a massive separation around +/-90°

Cylinder BL state



Pressure activity

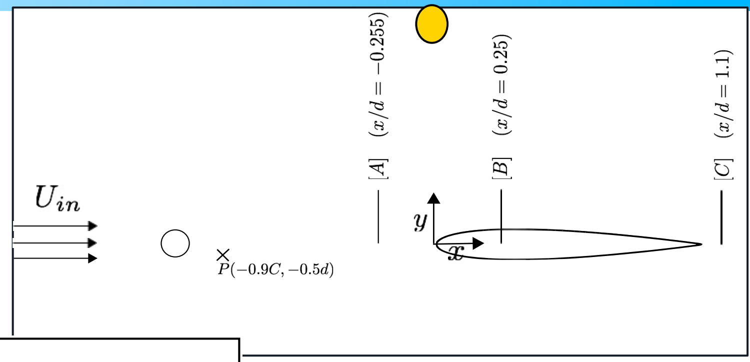


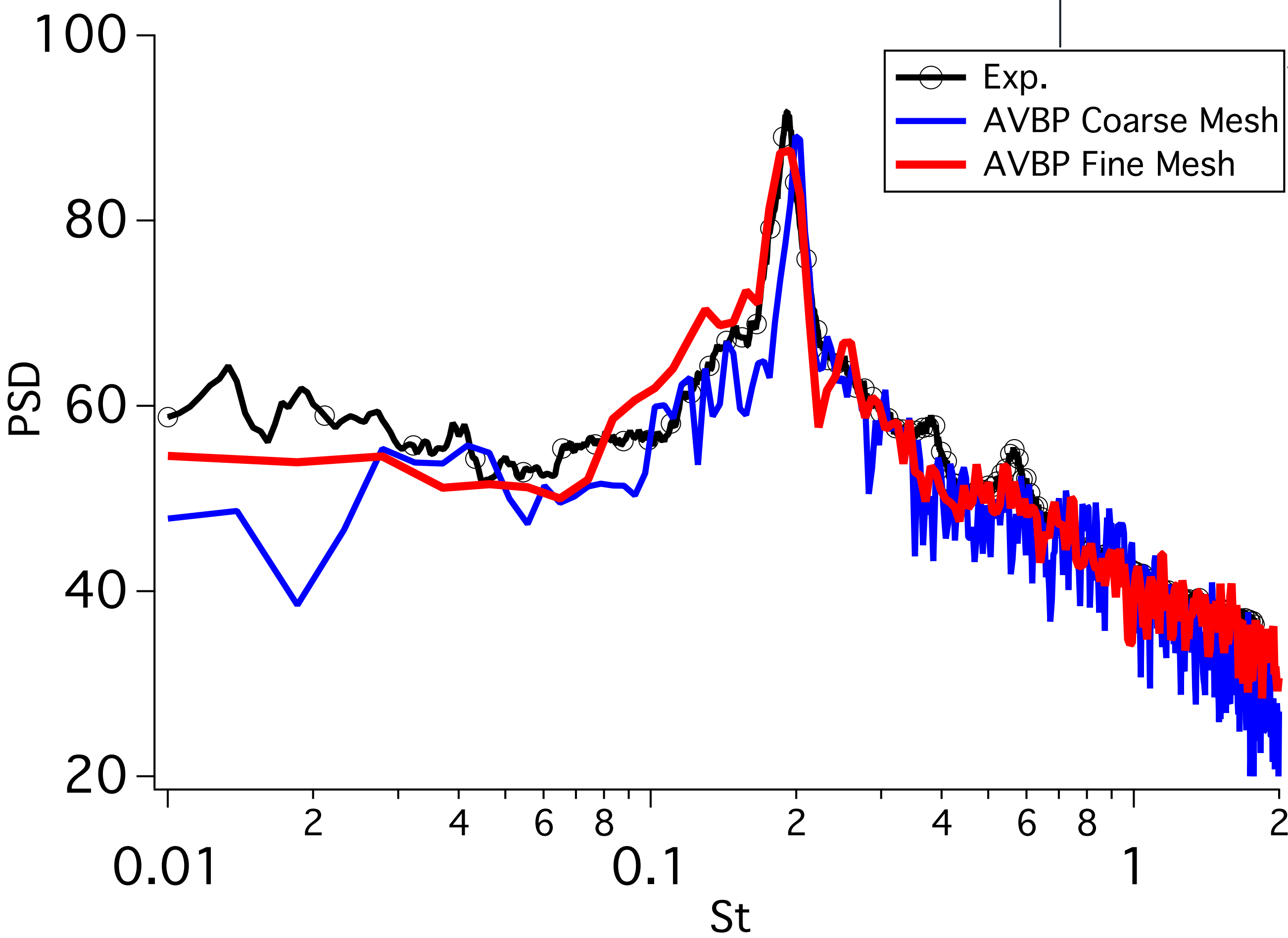


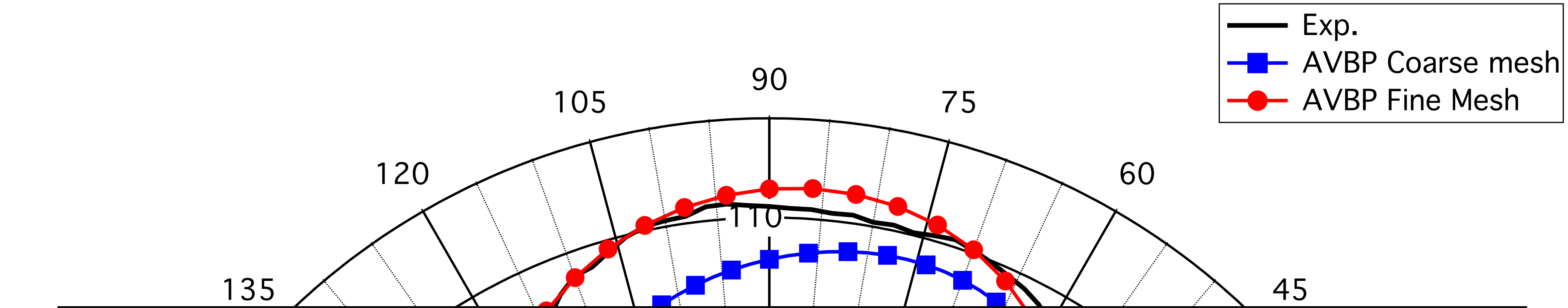
- **Closer observations:**

  => Quadrupolar noise emitted from small structure in the turbulent wake of the rod

PSD @ 90°


[A] (x/d = −0.255)
[B] (x/d = 0.25)
[C] (x/d = 1.1)
U_in
y
x
P(−0.9C, −0.5d)


Exp.
AVBP Coarse Mesh
AVBP Fine Mesh
PSD
100
80
60
40
20
0.01
0.1
1
2
4
6
8
St



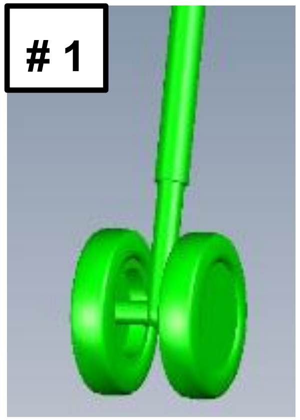
Preliminary conclusions for LES based CAA:

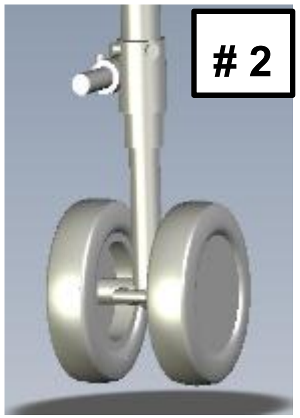
Wall modeling is crucial: not only does it impact the flow topology but by doing so, it will also impact the acoustic source locations and sound propagation.

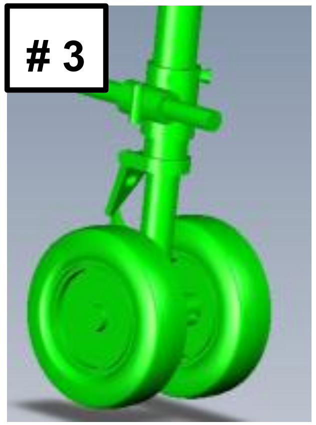
Note: For tone dominated flows, the intensity of the sources may not be so much affected…

LAGOON databasis: J.-C. Giret et al. (CIFRE CERFACS / AIRBUS)

- **Benchmark CFD/CAA codes**
  - Aerodynamic measurements (F2 wind tunnel)
  - Far-field acoustic measurements (Cepra 19 wind tunnel)
- Several operating points (Mach number 0.18 and 0.23)
- **3 geometries** with increasing geometrical complexity

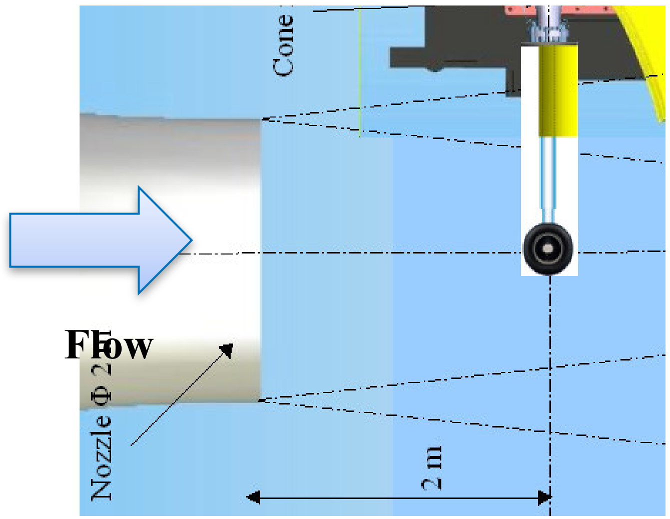






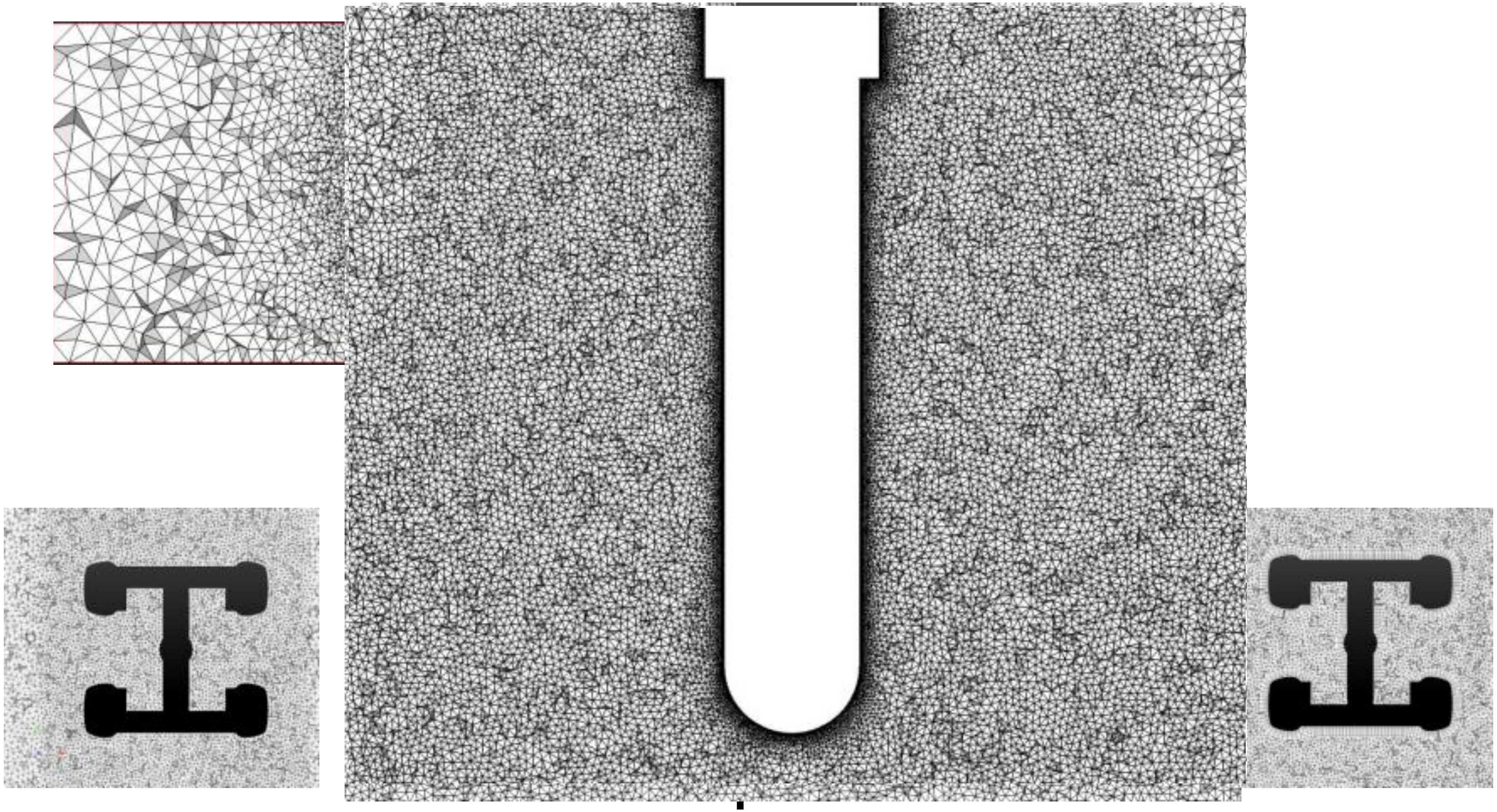
Codes: ElsA, SotonCAA, Openfoam, TAU, Powerflow

- **Geometry #1 selected at first a Mach number 0.23**
  - T_{in}=293K
  - V_{in}=78.8 m/s
  - P_{in}=99400 Pa



- **Full geometry with support considered**
  - CEPRA 19 design
  - No acoustic reflection from the ceiling

- **3 levels of refinement investigated**
  - Coarse: 10 million cells
  - Fine: 50 million cells (global refinement of the mesh)
  - Very fine: 75 million cells (additional refinement at the LG walls)

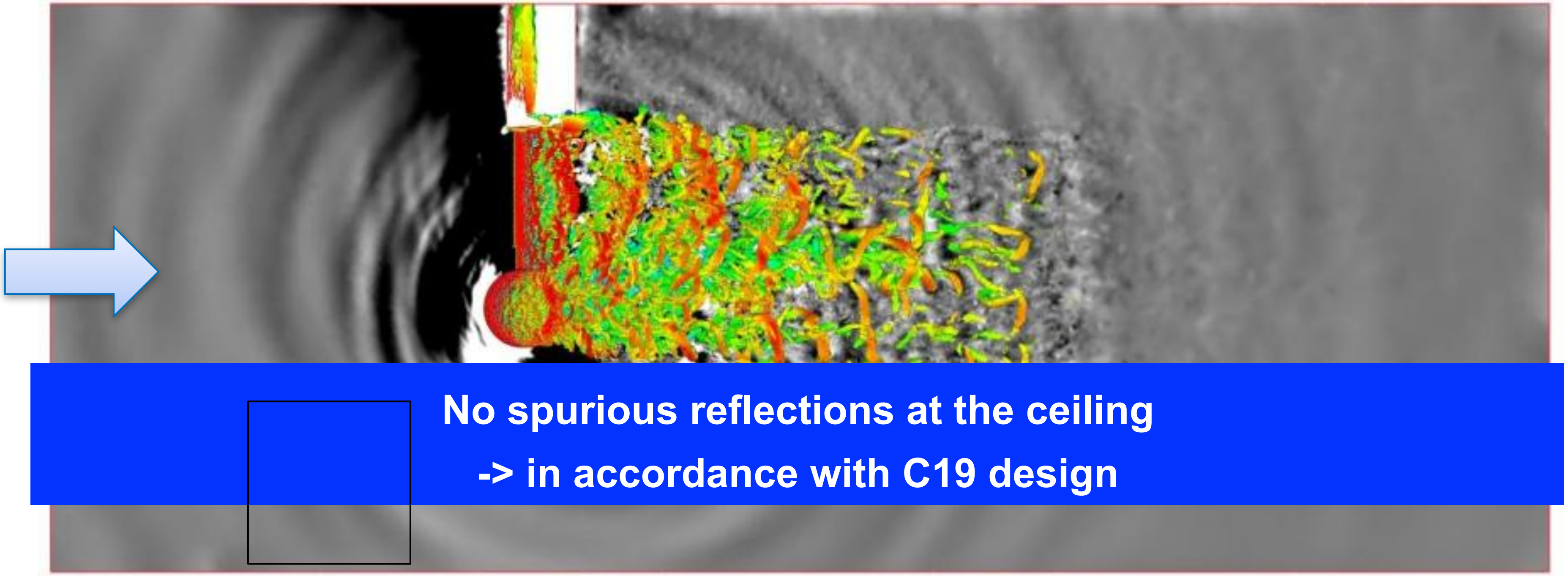


Coarse full tetra mesh

Coarse mesh with prism layers

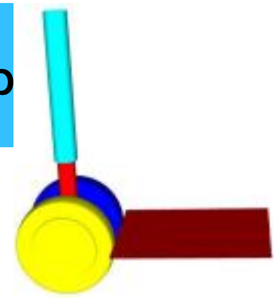
- **Fixed numerical scheme:**
  - TTG4A Scheme (Third order in space and Fourth order in time)
  - Explicit time marching, CFL=0.7

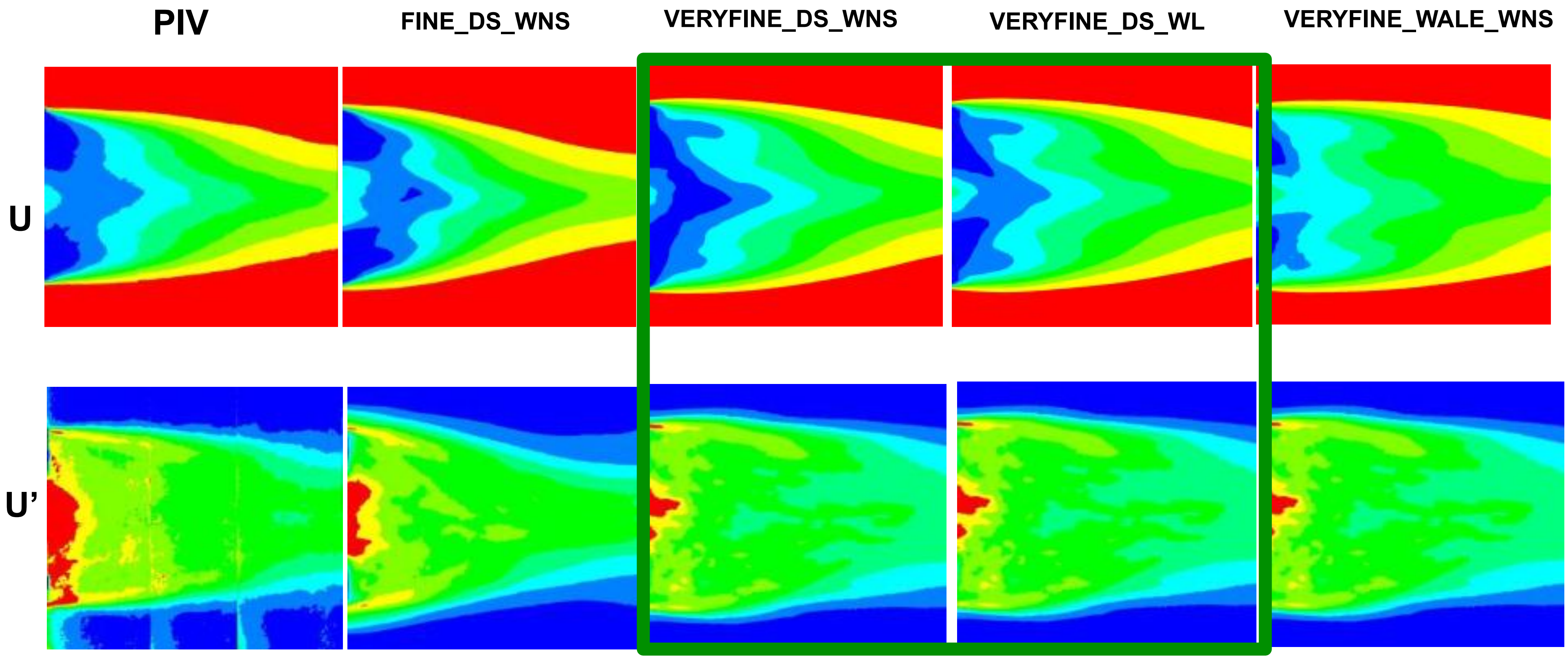
Casename	DoF	dt	CPU time (for 0.24 s)	Wall-law	SGS Model
FINE_DS_WNS	10 M nodes (50 M cells)	4.10^{-7} s	100 000 h	NO	DSMAGO
VERYFINE_DS_WNS	15 M nodes (75 M cells)	3.10^{-7} s	200 000 h	NO	DSMAGO
VERYFINE_WALE_WNS	15 M nodes (75 M cells)	3.10^{-7} s	200 000 h	NO	WALE
VERYFINE_DS_WL	15 M nodes (75 M cells)	3.10^{-7} s	200 000 h	YES	DSMAGO



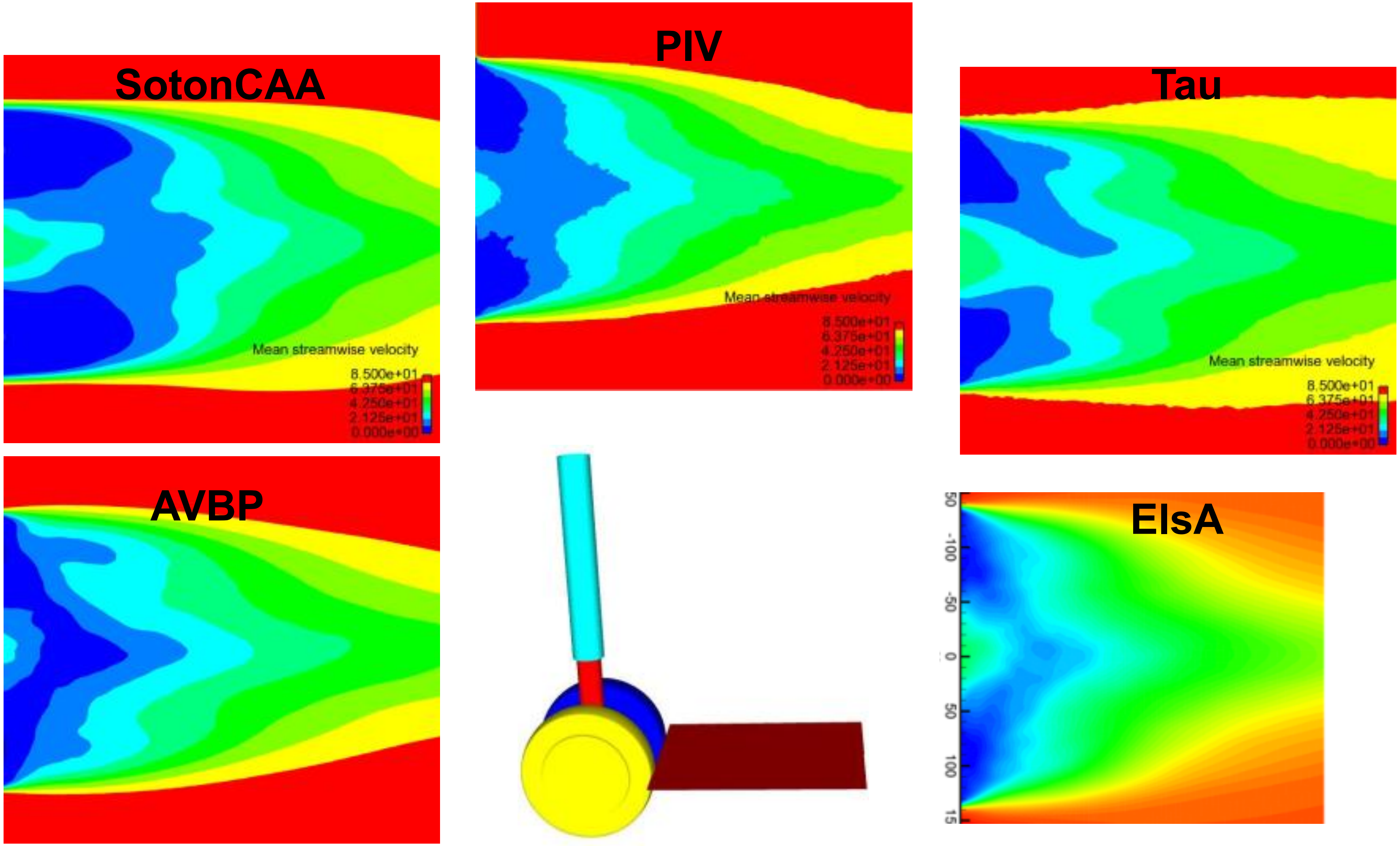
No spurious reflections at the ceiling

-> in accordance with C19 design

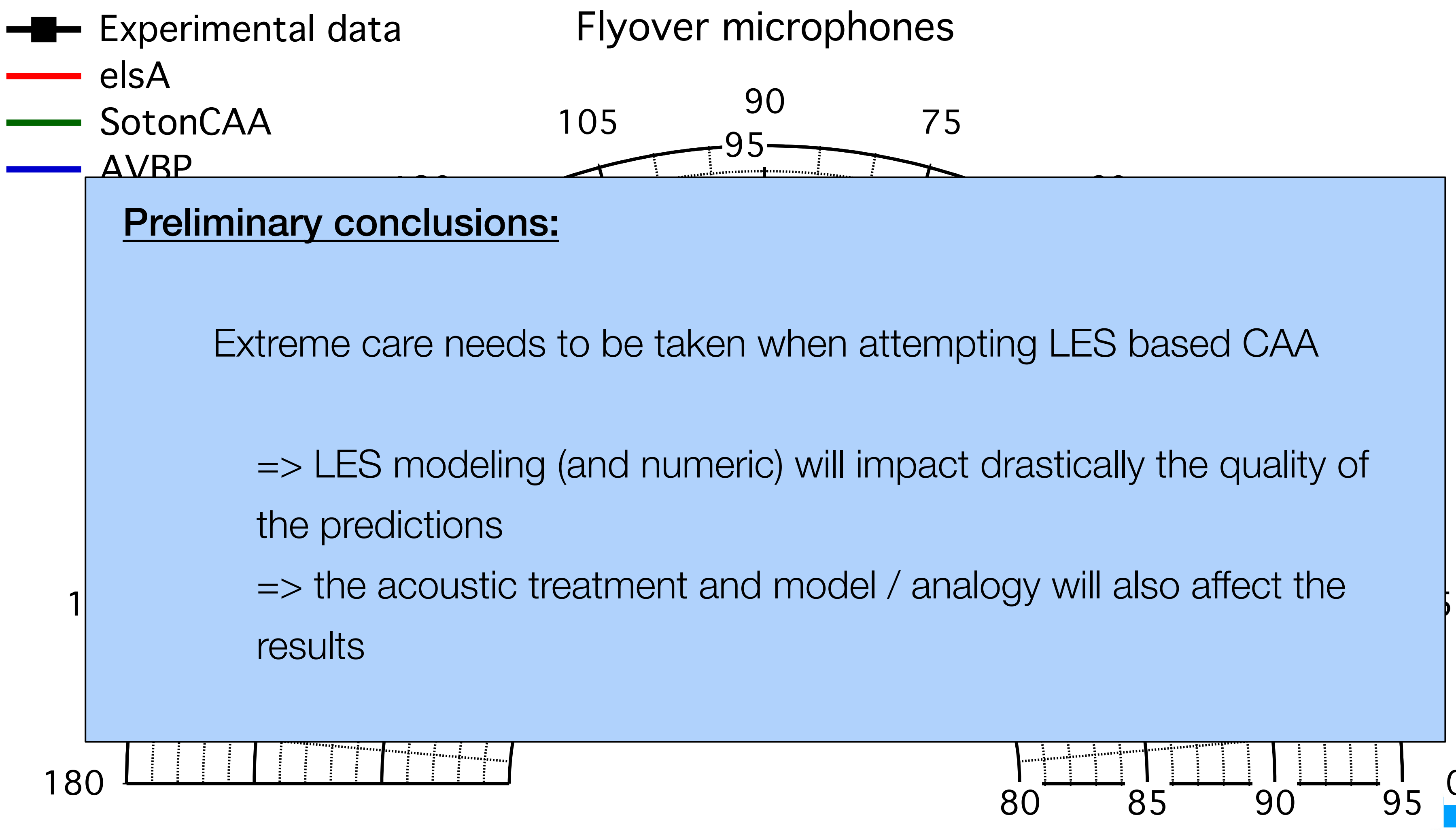




Best agreement obtained on VERYFINE Mesh with DSMAGO model with and without wall laws



Detailed comparison with LAGOON to be produced



Preliminary conclusions:

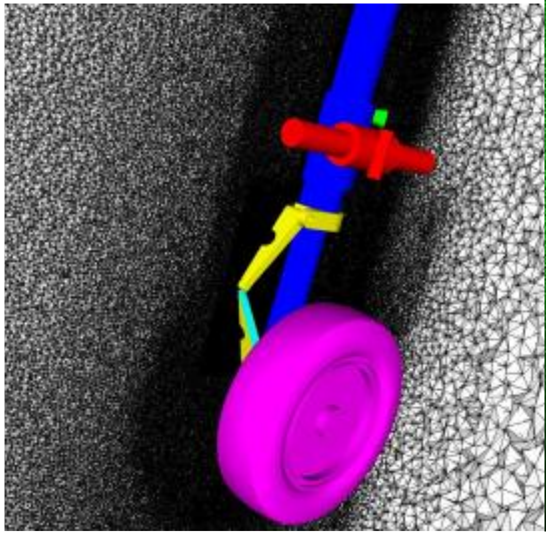
Extreme care needs to be taken when attempting LES based CAA

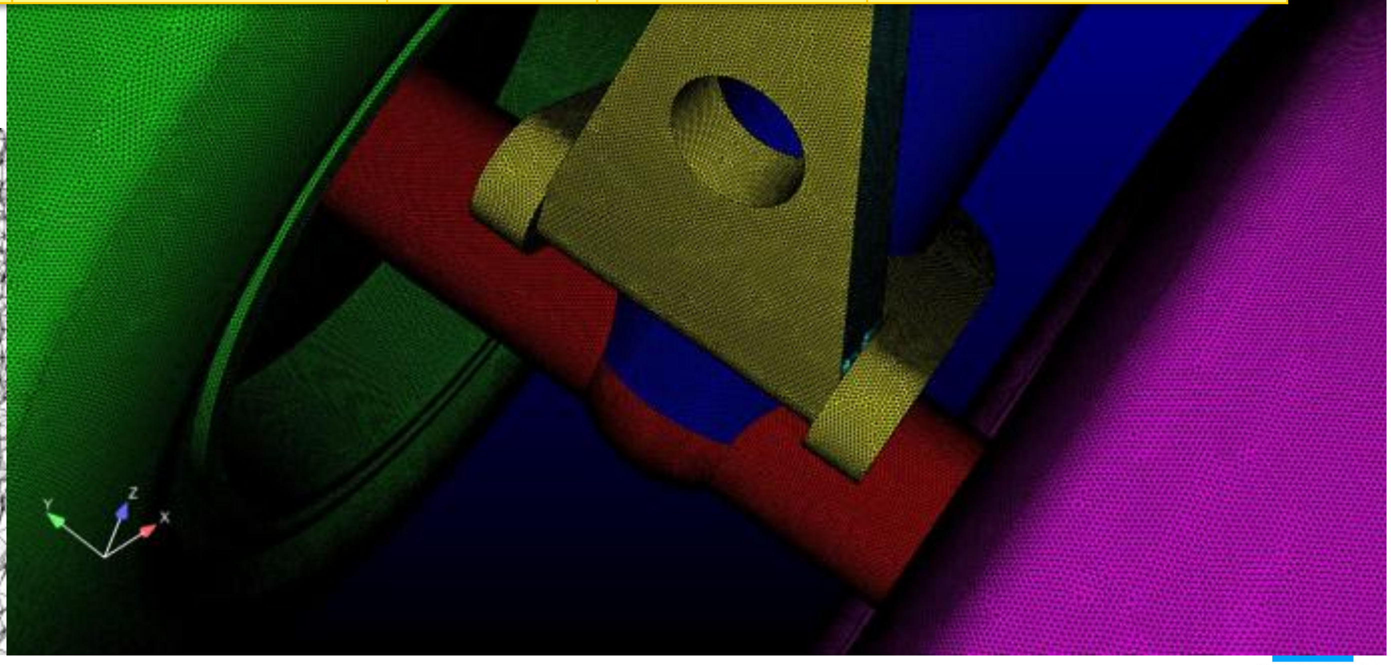
=> LES modeling (and numeric) will impact drastically the quality of the predictions

=> the acoustic treatment and model / analogy will also affect the results

- **Geometry #2:** added complexity (torque link)

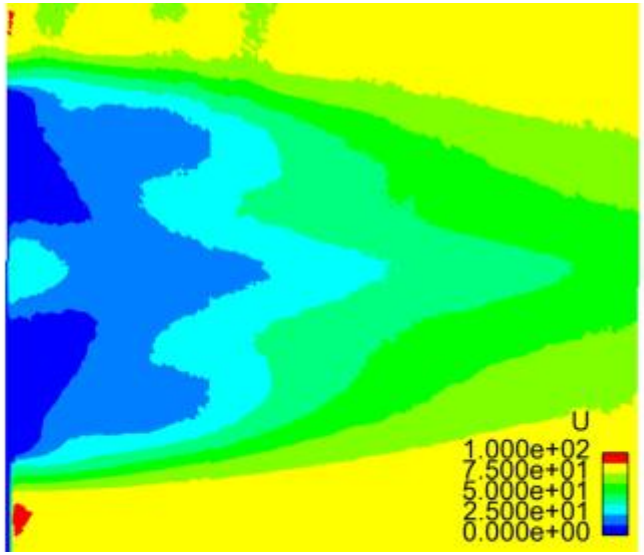
Casename	DoF	dt	T	CPU time
VERYFINE#2_DS_WNS	22M nodes (110M Elements)	2.10^{-7} s	0.12s	~200 000 H Cpu
VERYFINE#3_DS_WNS	24M nodes (120M Elements)	2.10^{-7} s	0.12s	~200 000 H Cpu



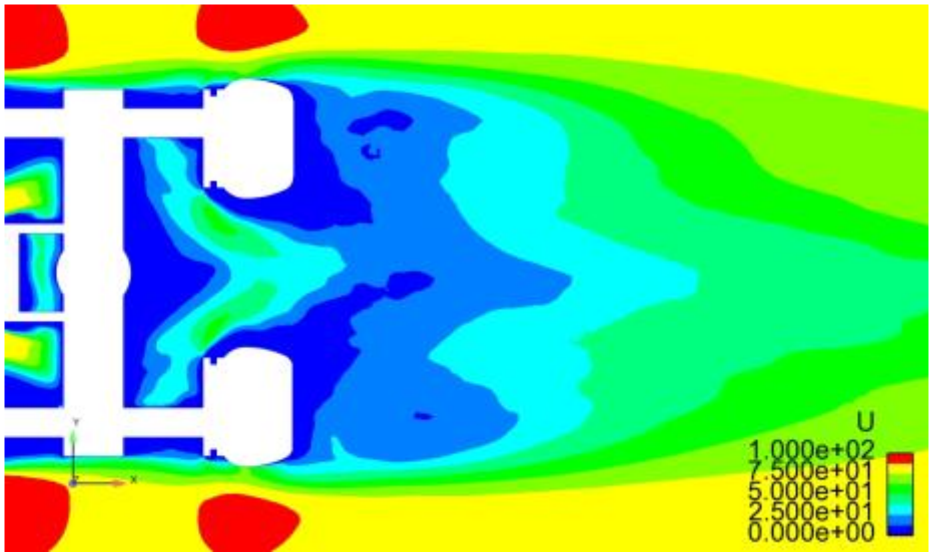


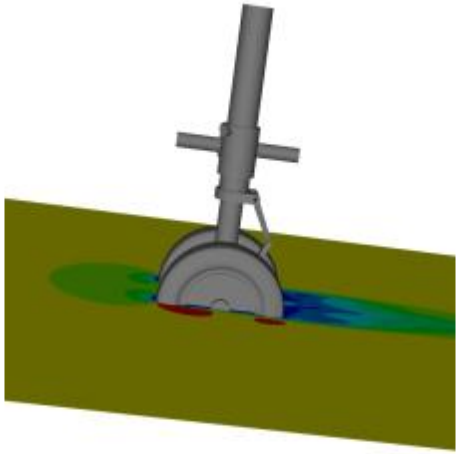
Axial component of the velocity vector

PIV



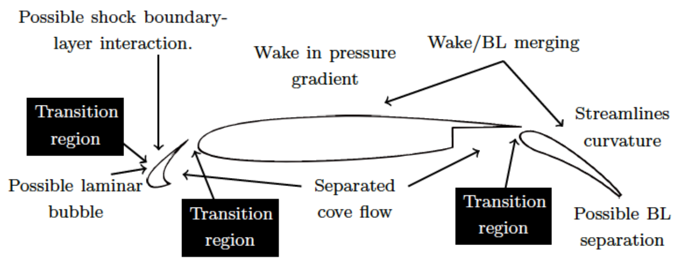
VERYFINE#3_DS_WNS



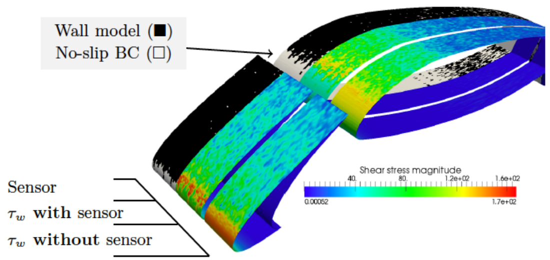


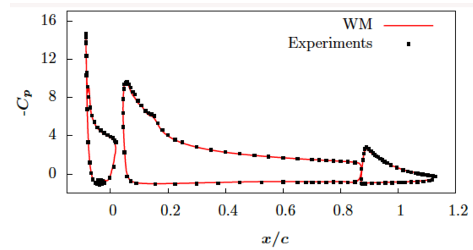
Other on going industry like applications

1/ production of VALIANT EU Project & partners:

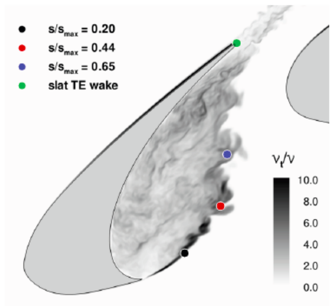


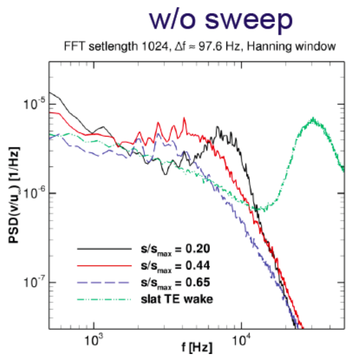
2/ Bodart et al. (Stanford):

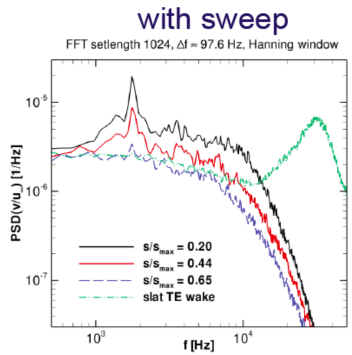




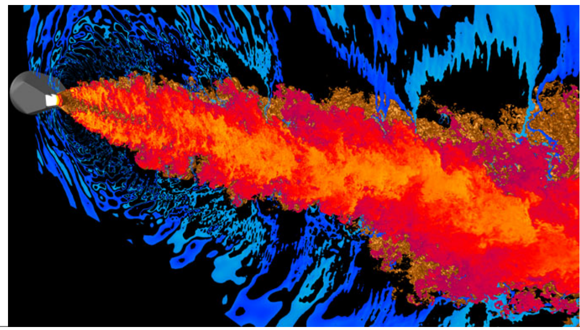
3/ Thiele et al. (DLR):







4/ Jet noise by ECL and Stanford:



I] Fundamentals of LES modeling:

=> Governing Eqs and models

- LES fundamentals and closure problem
- SGS for free stream turbulent flows
- Wall resolved versus Wall modeled LES

=> Numeric

III] Compressible LES – capabilities, validations and noise predictions:

=> LES of turbulent flows

=> LES of self-sustained unstable flows (impacting jet)

=> LES based CAA on industrial like applications

IV] Conclusions and perspectives:

LES based CAA offers:

- Good potential for flow unsteadiness predictions (better representation of the acoustic sources)

- Tone generated noise is a priori the easiest to reproduce

GOOD NEWS

=> Modeling will dominate and will do the difference

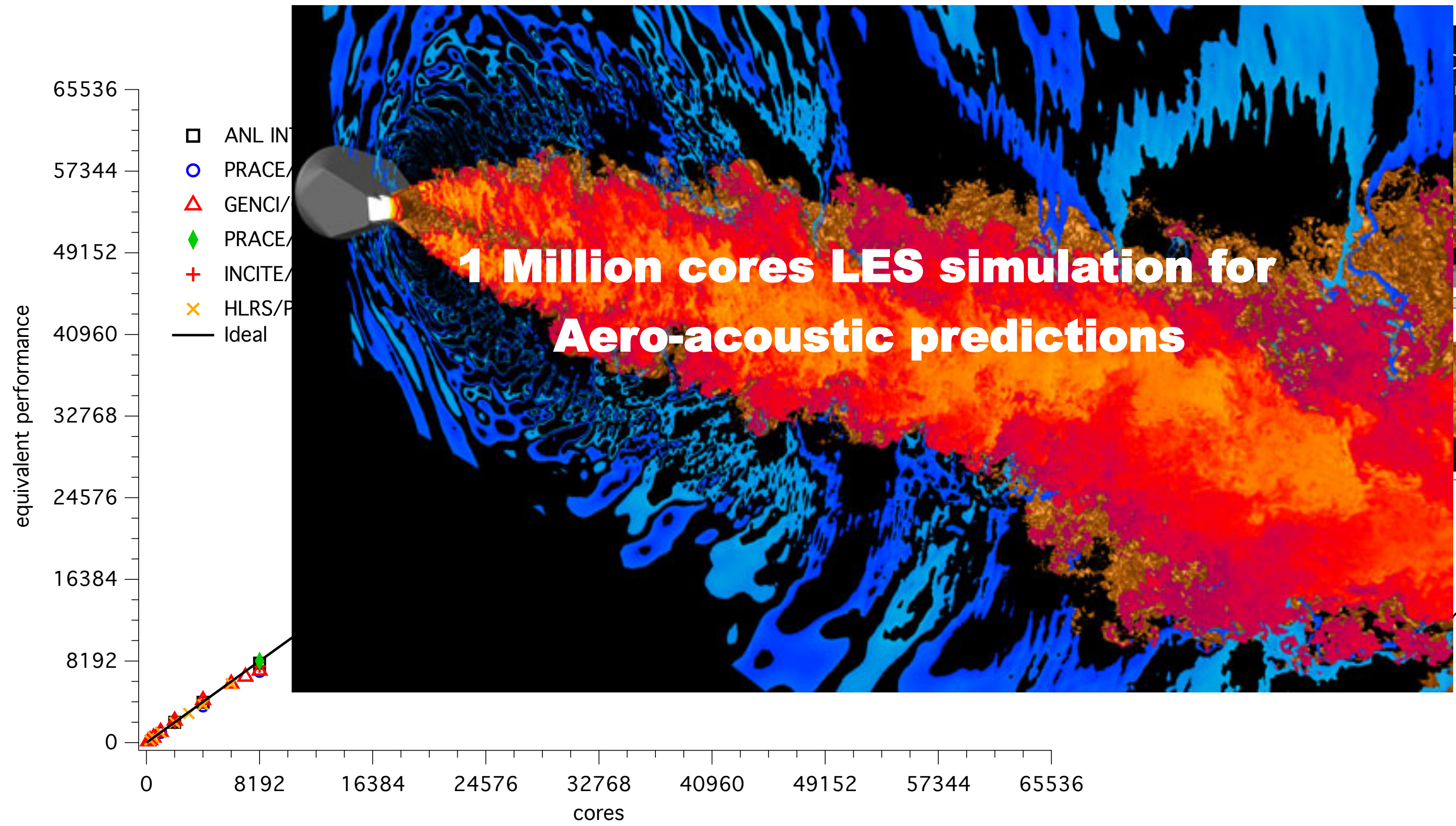
Not only on the LES side (SGS, wall…) but also on the acoustic side.

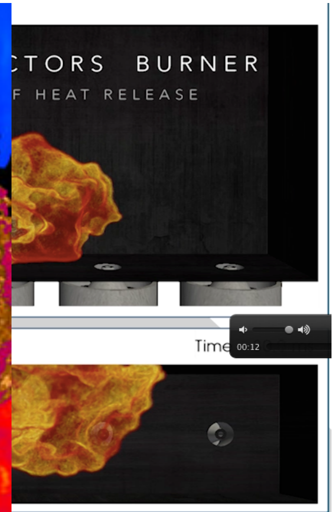
=> Numeric and massively parallel codes will be required

Note: Acoustic BC's need to treated with care for proper representation

Where do we stand on the LES side:

Today codes are able to produce computations using O(10^3-10^5) cores **efficiently**:





fully transient

few ms