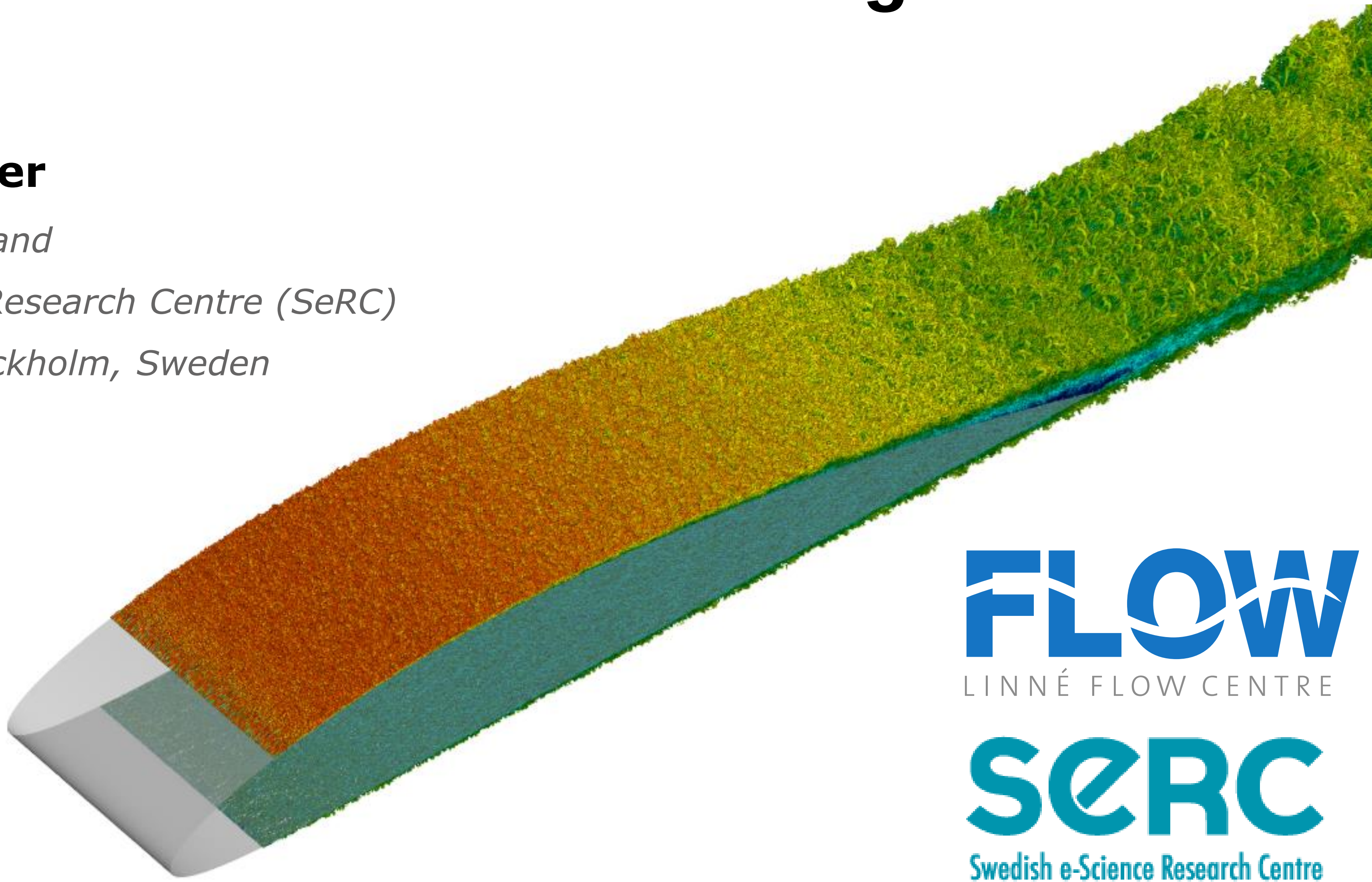
Progress on High-Order Simulations of Turbulence Around Wings



Philipp Schlatter

Linné FLOW Centre and

Swedish e-Science Research Centre (SeRC)

KTH Mechanics, Stockholm, Sweden

ETC – 16, August 2017

The Linné FLOW Centre and the Swedish e-Science Reserach Centre

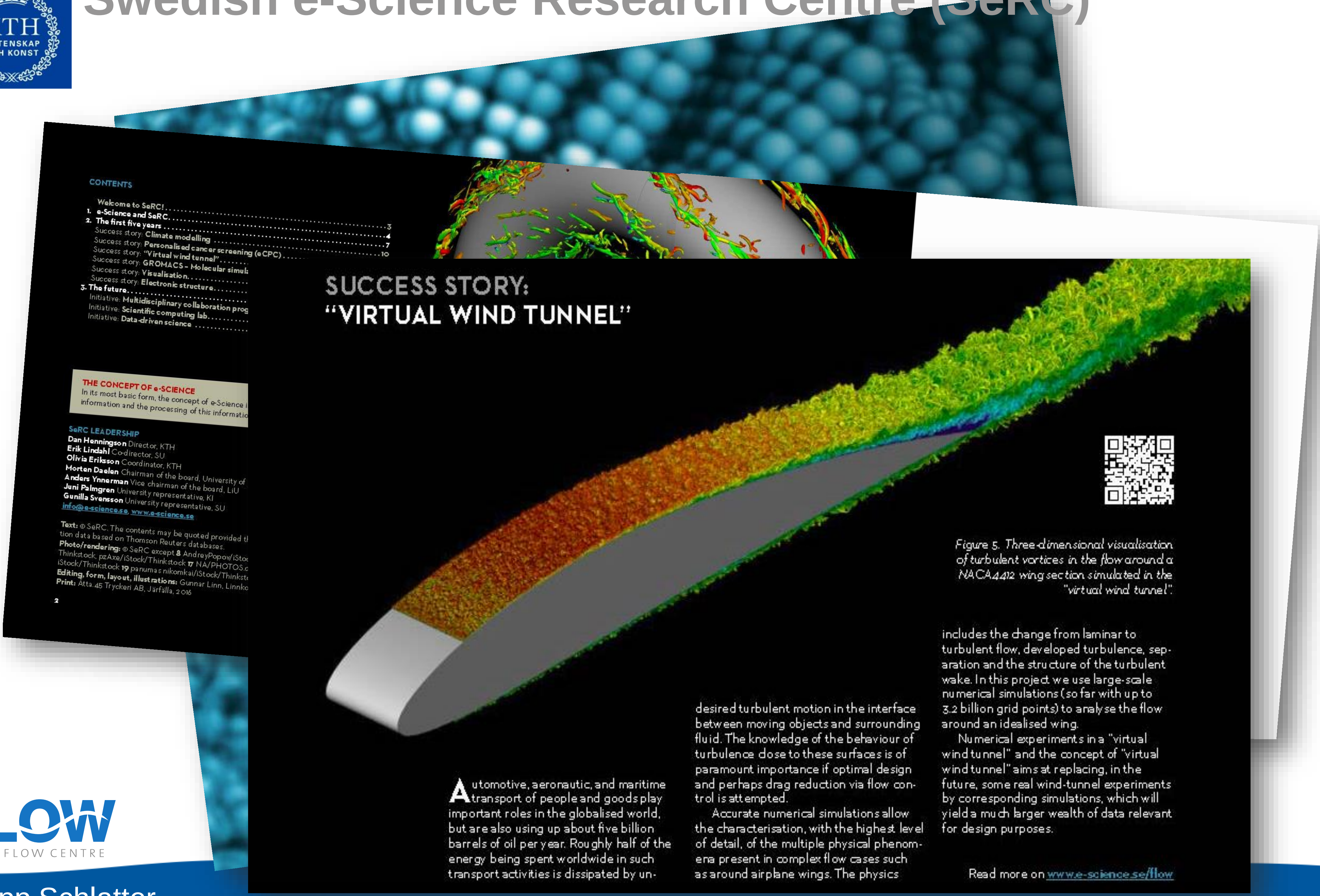
- Centre of excellence in **Fluid Mechanics** at KTH Stockholm (Sweden), 2007 – …
- Approx. 30 faculty and 50 PhD students

- Strategic research area in Sweden → ***e*-Science**
- Collaboration with visualisation, numerics, application experts…

The Linné FLOW Centre

https://www.youtube.com/watch?v=vnvmHxCv_y4

Swedish e-Science Research Centre (SeRC)



SUCCESS STORY:
"VIRTUAL WIND TUNNEL"

Figure 5. Three-dimensional visualisation of turbulent vortices in the flow around a NACA4412 wing section simulated in the "virtual wind tunnel".

Automotive, aeronautic, and maritime transport of people and goods play important roles in the globalised world, but are also using up about five billion barrels of oil per year. Roughly half of the energy being spent worldwide in such transport activities is dissipated by undesired turbulent motion in the interface between moving objects and surrounding fluid. The knowledge of the behaviour of turbulence close to these surfaces is of paramount importance if optimal design and perhaps drag reduction via flow control is attempted.

Accurate numerical simulations allow the characterisation, with the highest level of detail, of the multiple physical phenomena present in complex flow cases such as around airplane wings. The physics includes the change from laminar to turbulent flow, developed turbulence, separation and the structure of the turbulent wake. In this project we use large-scale numerical simulations (so far with up to 3.2 billion grid points) to analyse the flow around an idealised wing.

Numerical experiments in a "virtual wind tunnel" and the concept of "virtual wind tunnel" aims at replacing, in the future, some real wind-tunnel experiments by corresponding simulations, which will yield a much larger wealth of data relevant for design purposes.

Read more on www.e-science.se/flow

FLOW
LINNÉ FLOW CENTRE

Acknowledgements

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  A. Hanifi, D. Henningson
  KTH Mechanics

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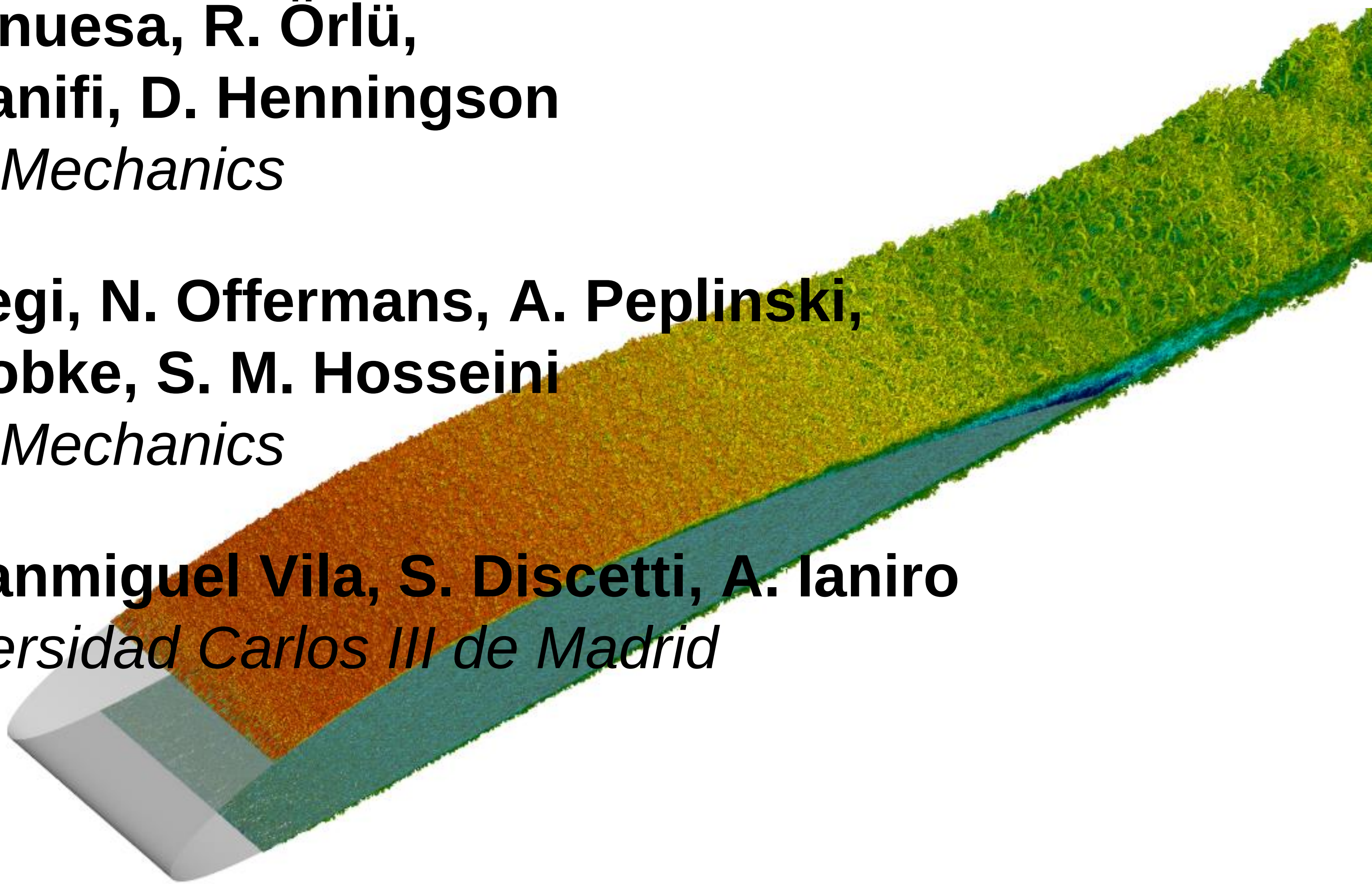
  A. Bobke, S. M. Hosseini
  KTH Mechanics

- **C. Sanmiguel Vila, S. Discetti, A. Ianiro**
  Universidad Carlos III de Madrid



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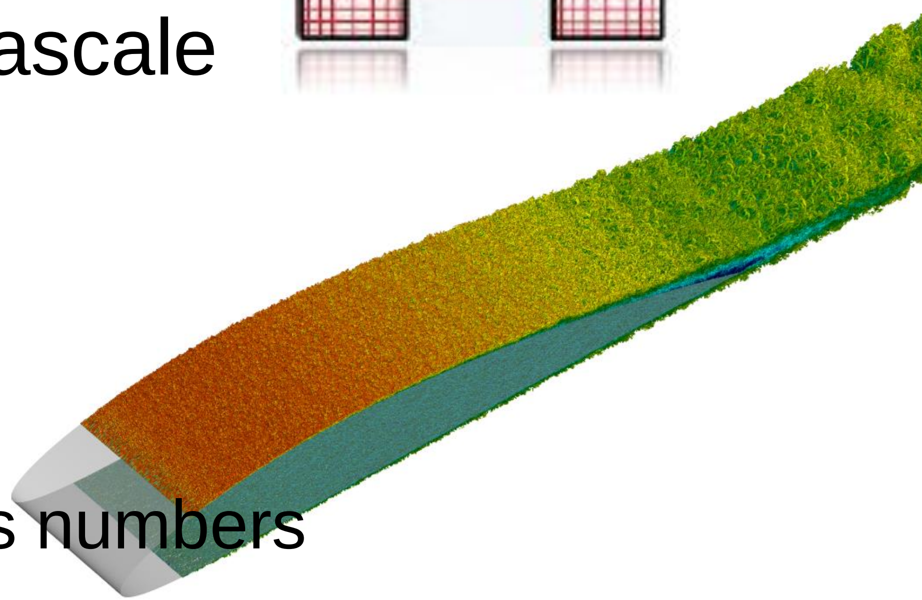
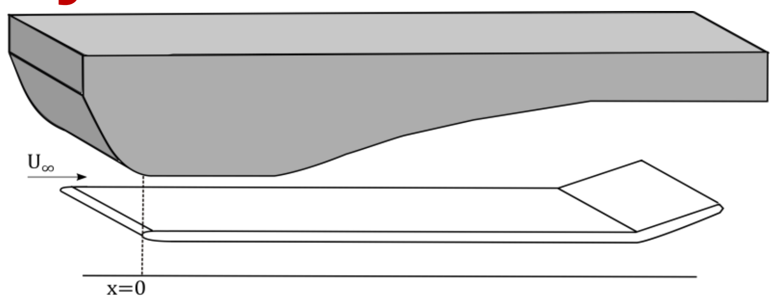
- Introduction
- **Spectral elements** and exascale
- **Wing simulations**
  - Setup and statistics
  - Backflow events
  - Higher and lower Reynolds numbers
- **Pressure gradient boundary layers**
  - History effects
- Conclusions and outlook
  - Compression and mesh refinement





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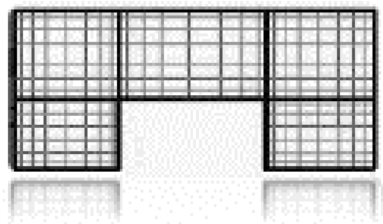
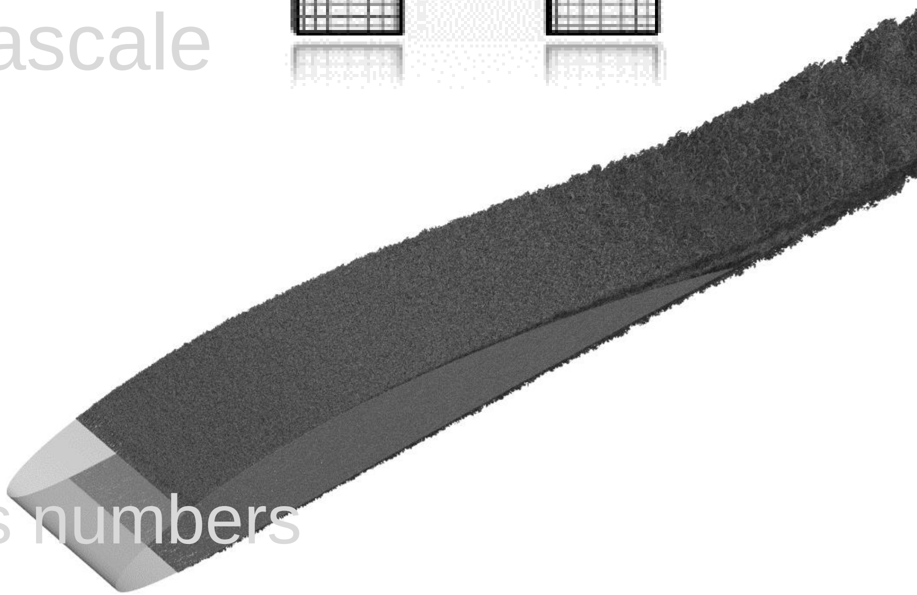
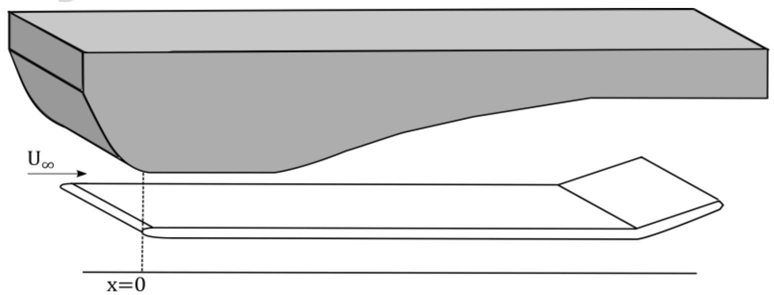
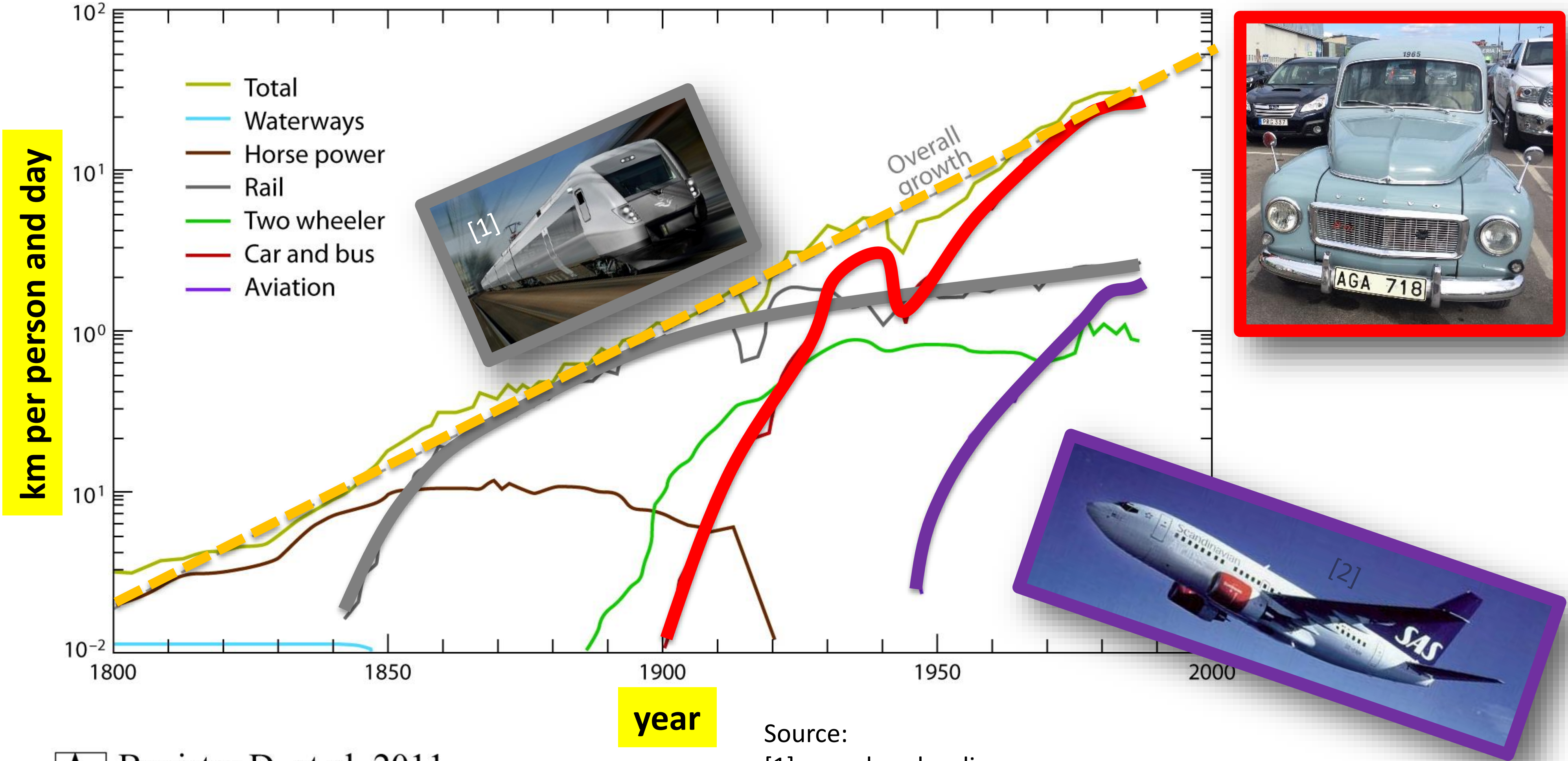






Why CFD?

Skin friction/drag reduction is the key for economically and ecologically more efficient transport



Banister D, et al. 2011.
Annu Rev. Environ. Resour. 36:247–70

Source:
[1] www.bombardier.com
[2] www.flysas.de

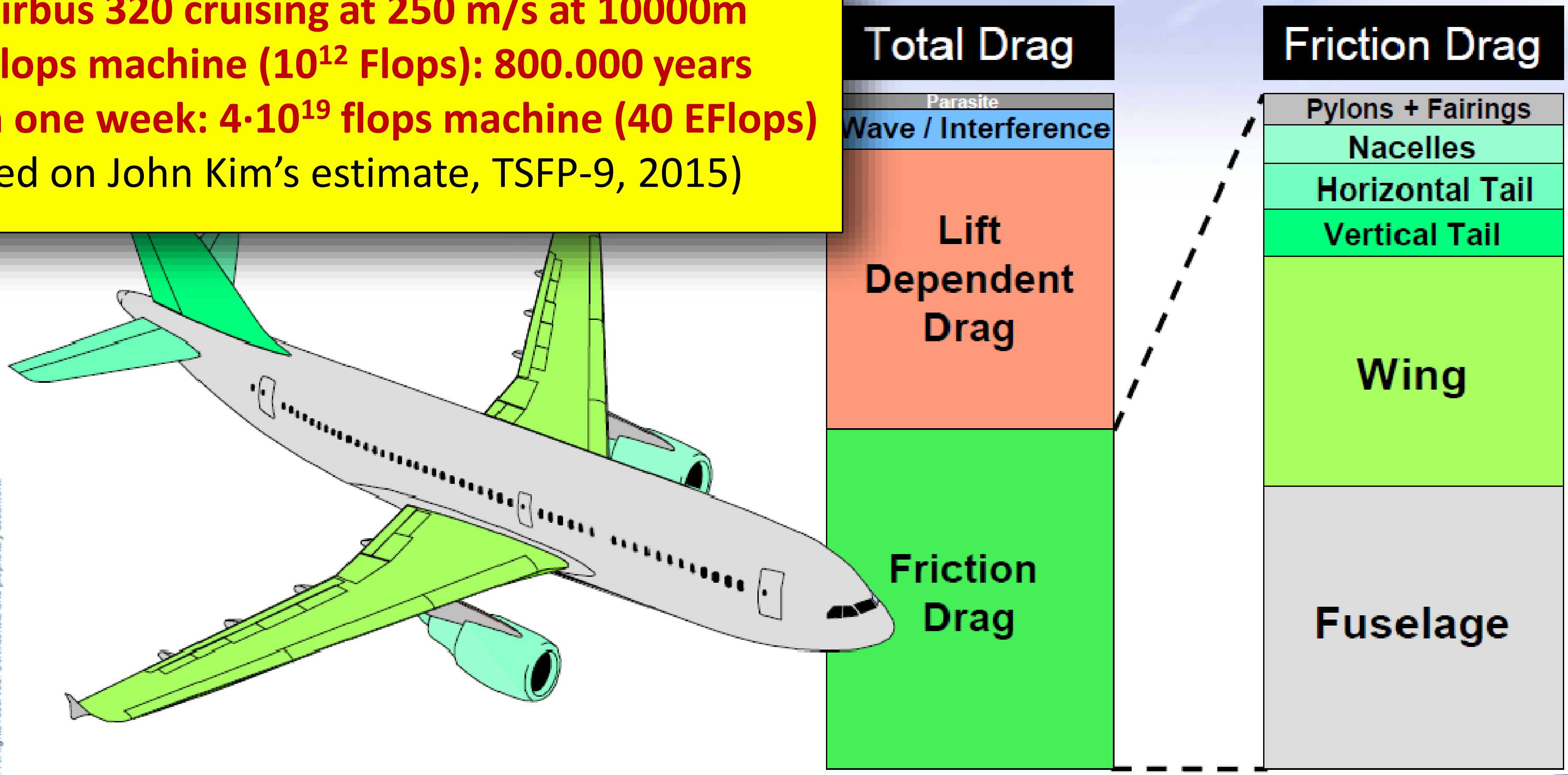
The Airbus Challenge, David Hills, 2008

A Brief Diversion Into Aircraft Drag

A world of challenge & opportunity

- Typical break down of overall aircraft† drag by form & component

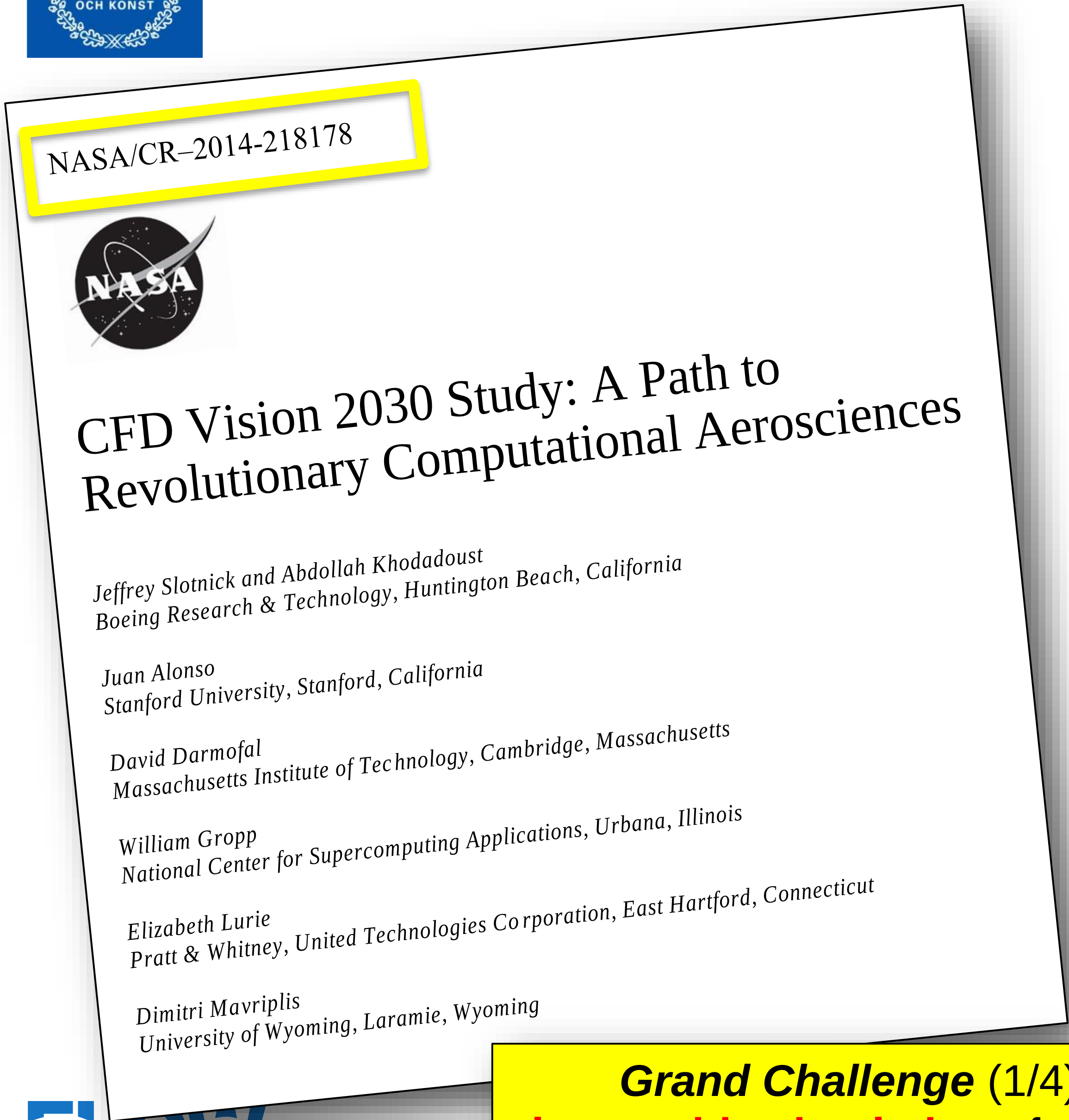
An Airbus 320 cruising at 250 m/s at 10000m
Teraflops machine (10^{12} Flops): 800.000 years
Result in one week: $4 \cdot 10^{19}$ flops machine (40 EFlops)
(based on John Kim's estimate, TSFP-9, 2015)



† = Based on a typical A320

AIRBUS

Motivation



NASA/CR–2014-218178

NASA

CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences

Jeffrey Slotnick and Abdollah Khodadoust
Boeing Research & Technology, Huntington Beach, California

Juan Alonso
Stanford University, Stanford, California

David Darmofal
Massachusetts Institute of Technology, Cambridge, Massachusetts

William Gropp
National Center for Supercomputing Applications, Urbana, Illinois

Elizabeth Lurie
Pratt & Whitney, United Technologies Corporation, East Hartford, Connecticut

Dimitri Mavriplis
University of Wyoming, Laramie, Wyoming

Key Findings

1. NASA investment in basic research and technology development for **simulation-based analysis** [..] must be reinvigorated if substantial advances in simulation capability are to be achieved.
2. **HPC hardware is progressing rapidly** [..].
3. The use of CFD in the aerospace design process is severely limited by the inability to accurately and reliably predict **turbulent flows with significant regions of separation.**
4. **Mesh generation and adaptivity** continue to be significant bottlenecks in the CFD workflow [..].
5. Revolutionary **algorithmic improvements** will be required [..].
6. **Managing the vast amounts of data** [..] will become increasingly complex [..].
7. [..] advances in individual component CFD solver **robustness and automation** will be required.

Grand Challenge (1/4): **Wall-resolved large-eddy simulation** of a full powered aircraft configuration in the full flight envelope

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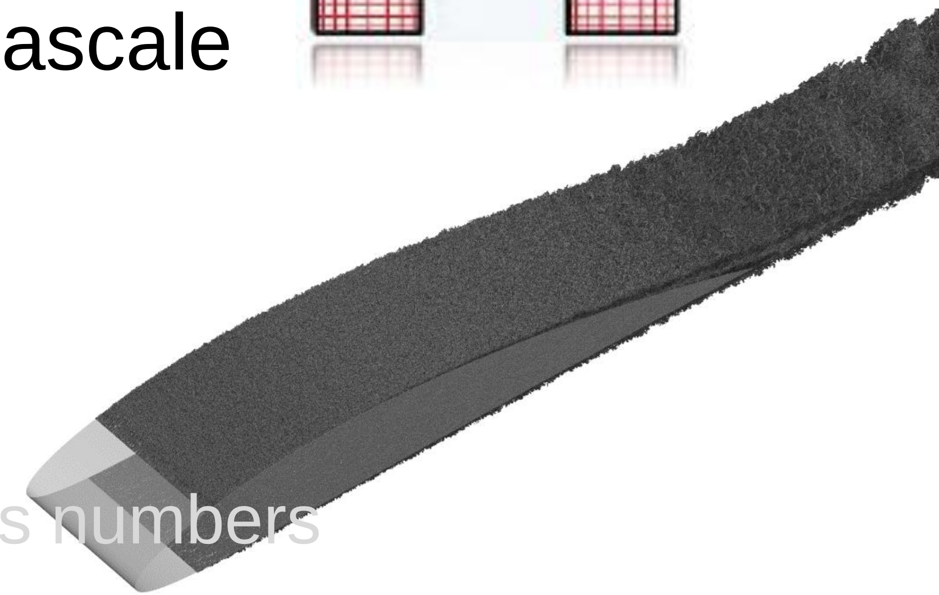
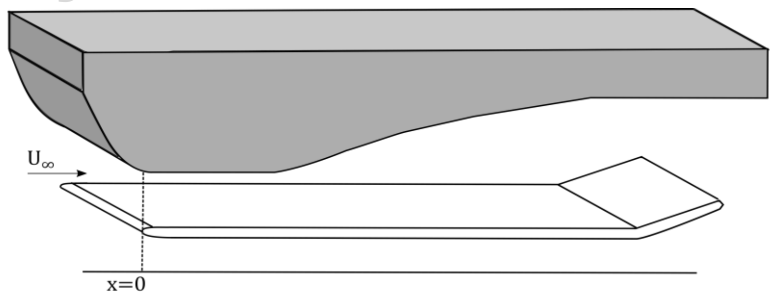
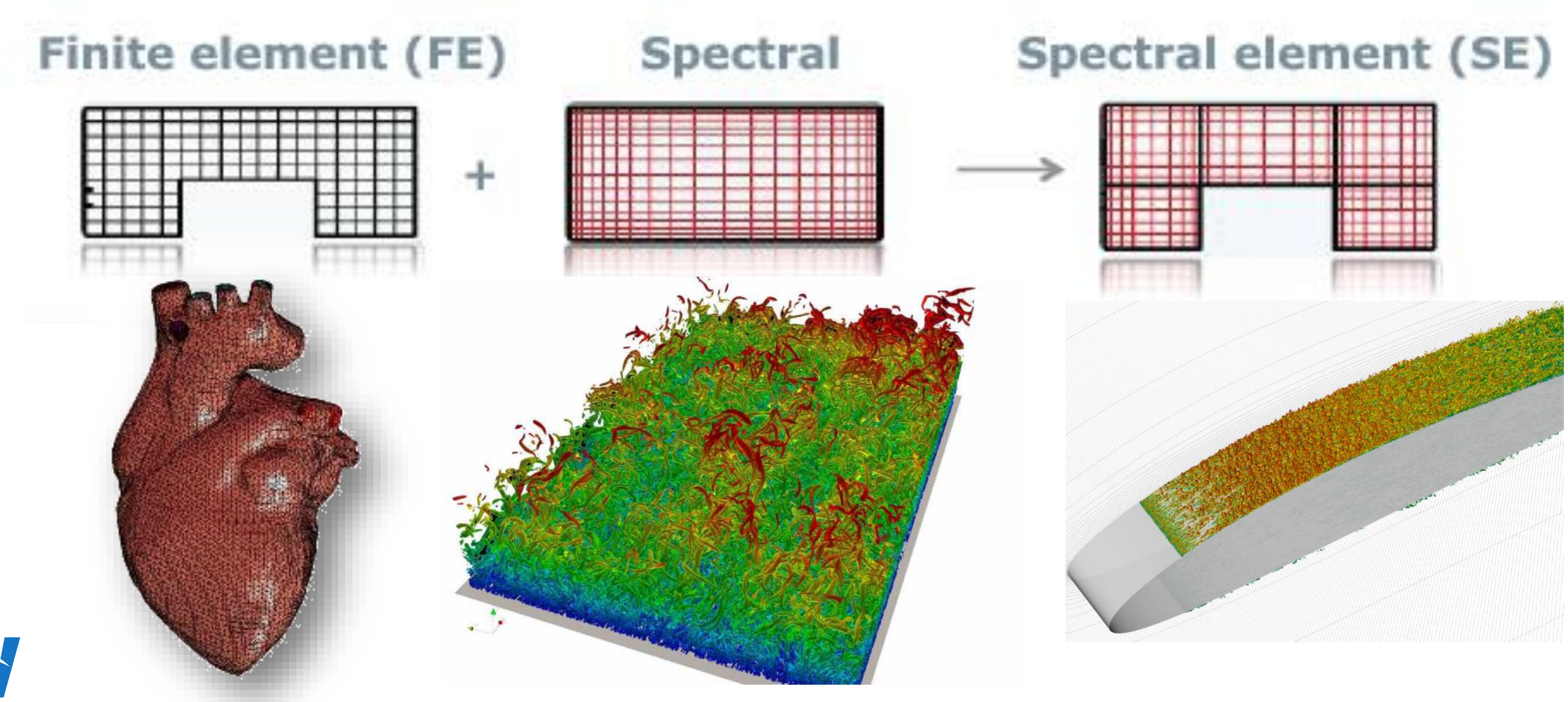




Why Spectral Elements?

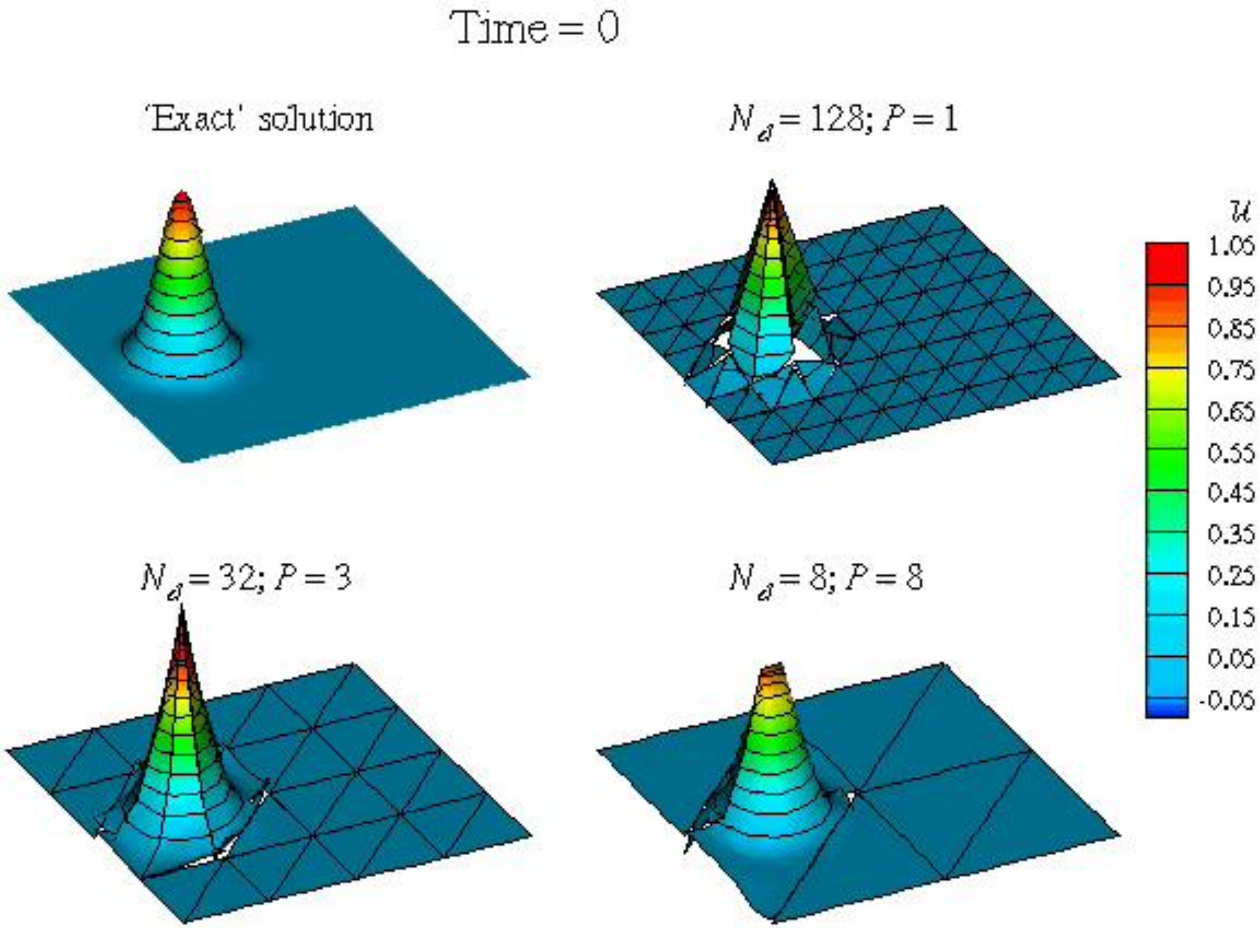
- **High-order numerical methods** are beneficial for accurate simulations of turbulent flows due to the significant scale disparity of the flow structures, both in time and space.

- Spectral elements allow to solve **flows in complex geometries**.



Why Spectral Elements?

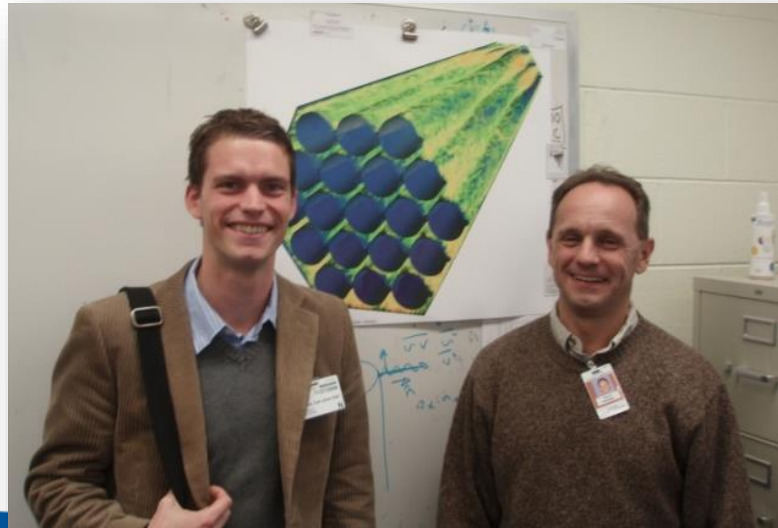
- **Higher order** p (vs. **smaller grid spacing** h) means more work per core/communication: **”convecting cone”**



From David Moxey, Univ. Exeter

Nek5000 – Spectral Elements

- SEM code by **Paul F. Fischer**, Argonne National Lab, USA
  Open source: `nek5000.mcs.anl.gov`
- 80 000 lines of **Fortran 77** (some C for I/O), MPI (no hybrid)
- **Gordon Bell Prize 1999** for algorithmic quality and performance
- **KISS** ("Keep it simple, stupid") – world's most powerful computers have very weak operating systems
- **EU Projects on algorithms** (CRESTA, ExaFLOW, …): adaptive meshing, GPUs, …
- Good scaling up to **1,000,000** ranks on Mira (10PFlops BG/Q)

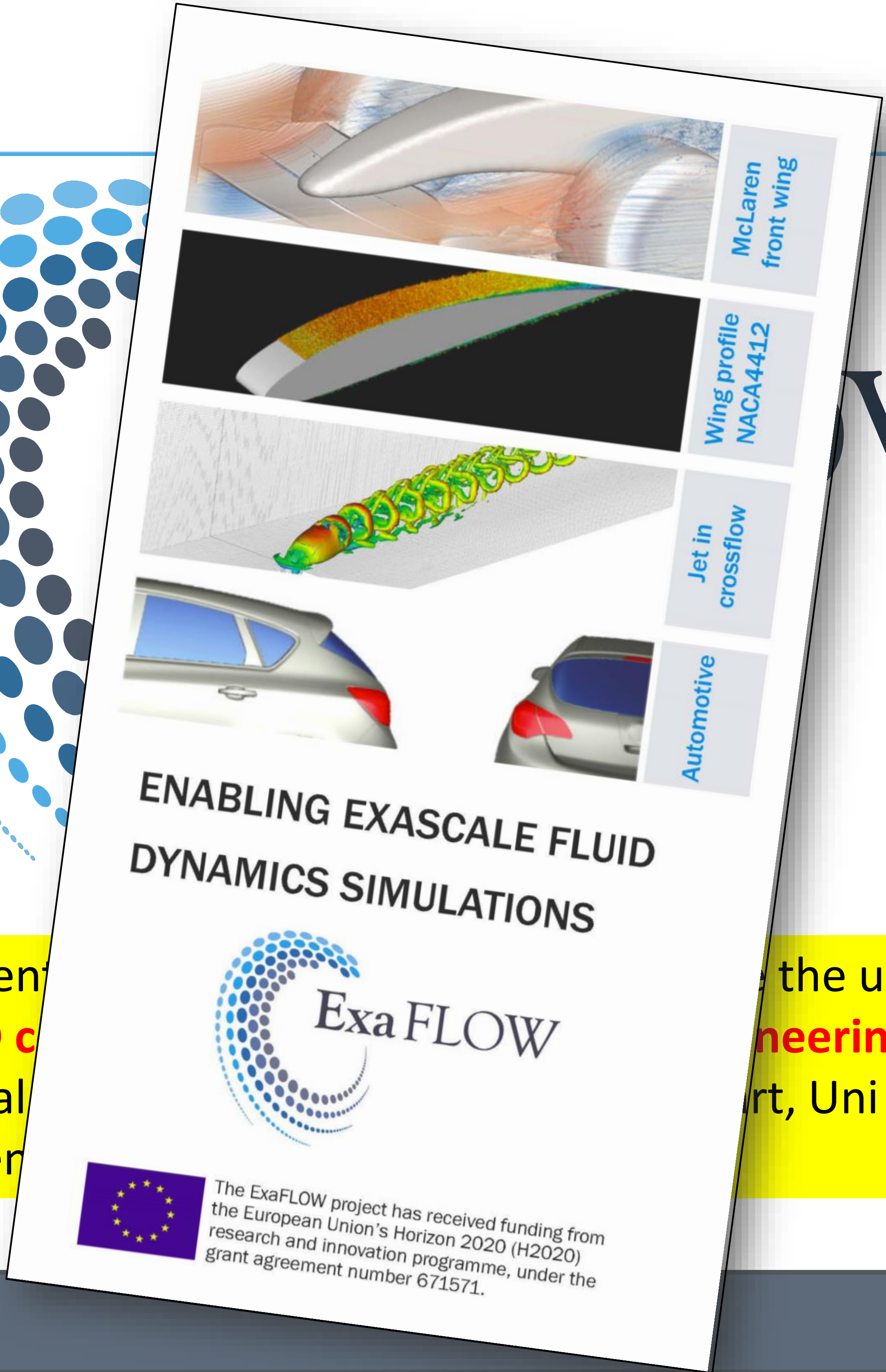


H2020 Project

→ Address current **algorithmic** bottlenecks to enable the use of **accurate CFD codes** for problems of practical **engineering interest.**

→ With: Imperial College, Southampton, Uni Stuttgart, Uni Edinburgh, EPFL, McLaren Racing, ASCS

H2020 Project



- → Address curren ... the use of **accurate CFD c ... neering interest.**
- → With: Imperial ... rt, Uni Edinburgh, EPFL, McLaren

ExaFLOW Team

Spectral Elements

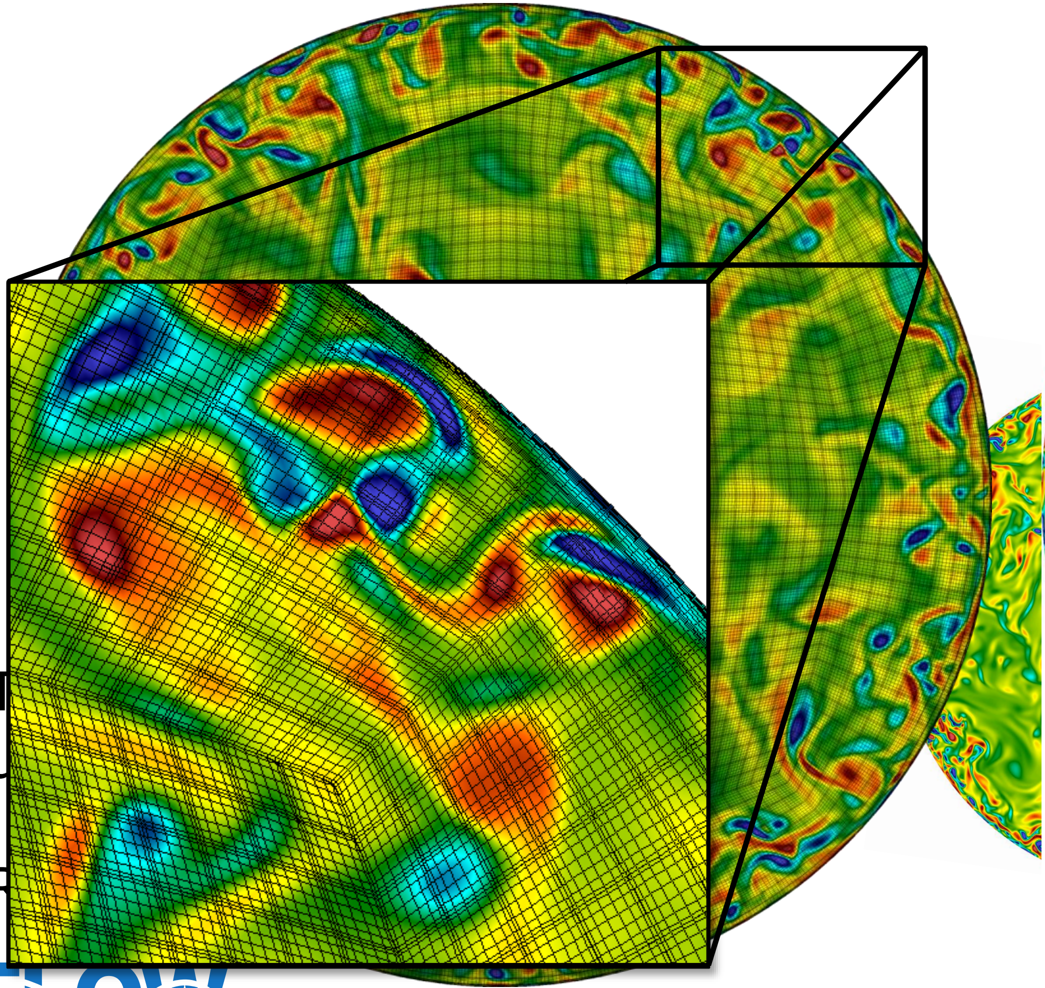
- Meeting Programme

Turbulent pipe flow at $Re_\tau=1000$
using Nek5000

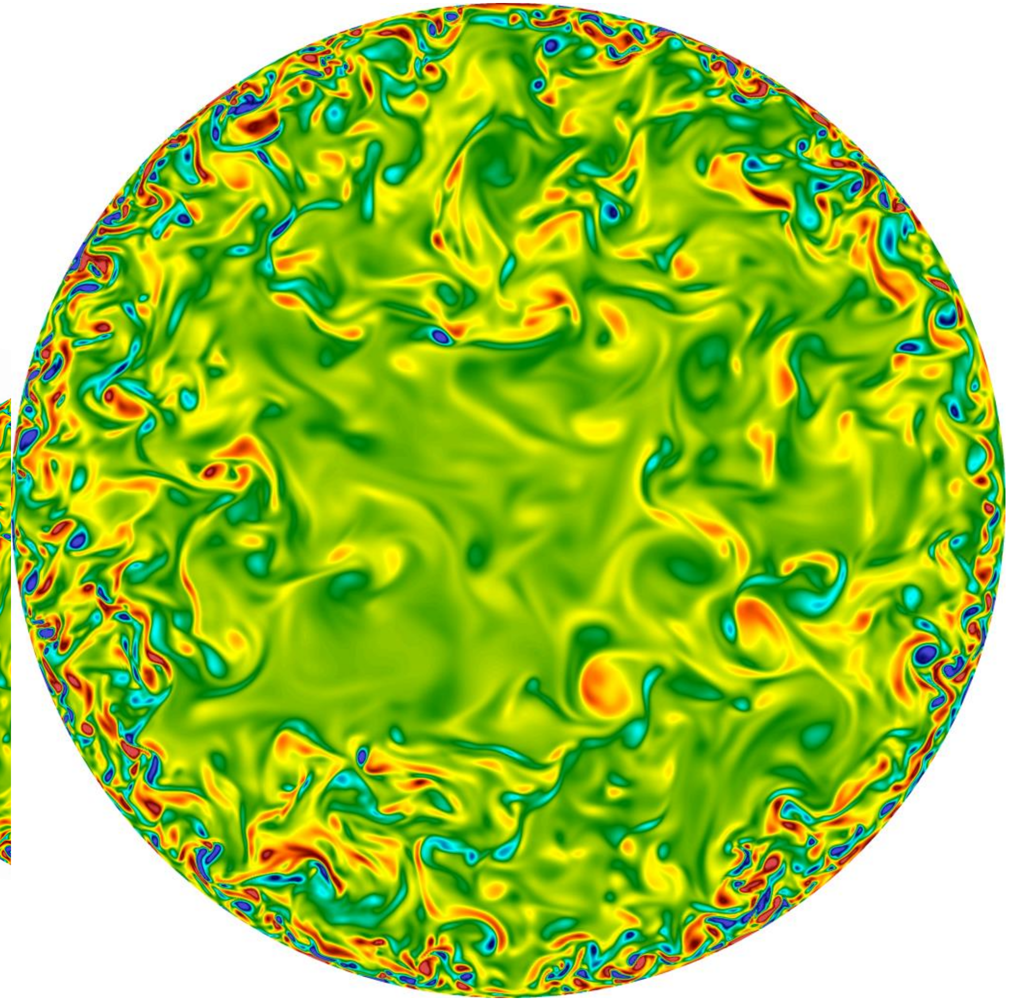
Ref.: El Khoury *et al.* 2013

Straight pipe (Axial vorticity)

$Re_\tau = 550$



$Re_\tau = 1000$



Ref. El Khoury *et al.* 2013

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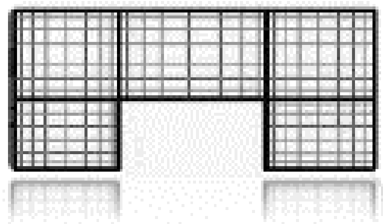

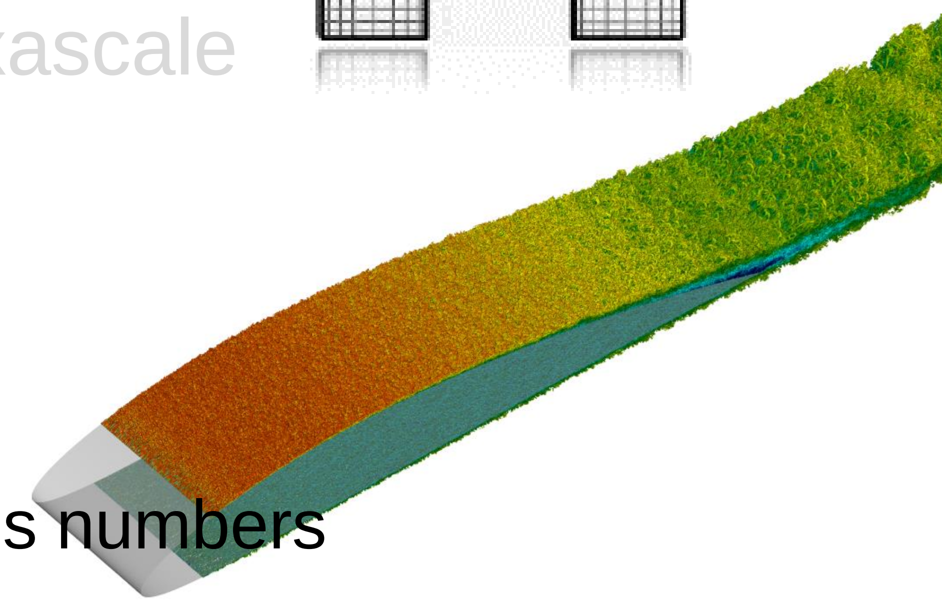

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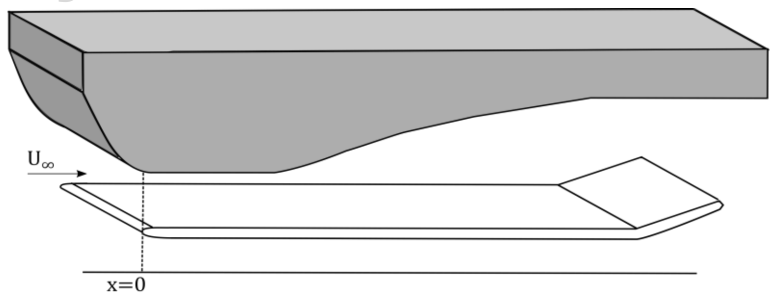

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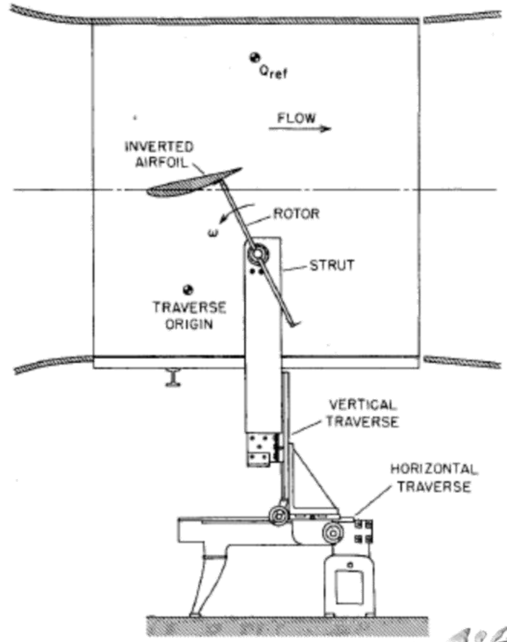
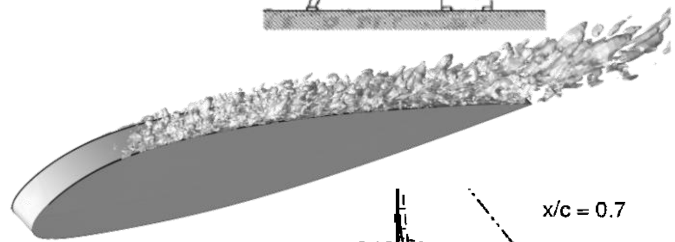
Short Literature Review: Airfoils



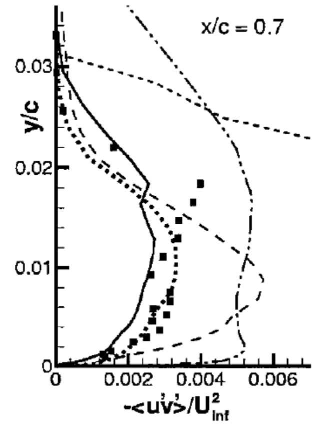
Experiments

- Coles & Wadcock (1979): NACA4412 **flying hotwires** at Re_c=1.5M and AoA=14º (max lift)
- **LDV** by Wadcock (1987) and Hastings & Williams (1987)

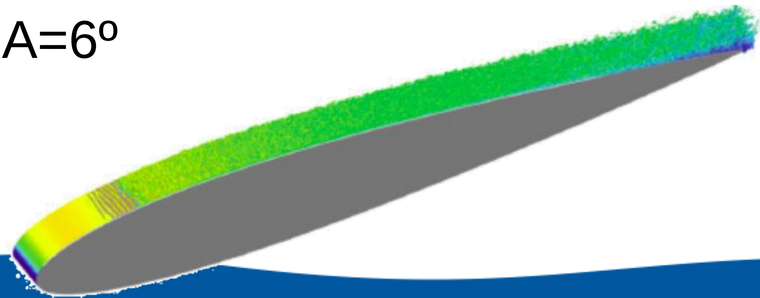


Simulations

- Jansen (1996): reproduce Wadcock (1987) with LES
- **LESFOIL project** (2000): LES at Re_c=2.1M, AoA=13.3º
  → Resolution and transition/separation modelling crucial!



- Rodríguez *et al.* (2013): DNS Re_c=50k at full stall
- Wolf et al. (2012): Tripped NACA0012 at Re_c=408k
- Sato *et al.* (2016): NACA0015 Re_c=1.6M AoA=6º



Short Literature Review: Airfoils

What do we want to know (among others)?

- **DNS (and LES) is not (yet) a design tool!** (Spalart & Venkatakrishnan 2016)
- **Reference data**, both experimentally and numerically, for all kinds of validations (wind tunnels, (hybrid-)models, …)
- Access to modelling terms, like vorticity transport
- **Fundamental turbulence questions** (turbulence+pressure gradient+separation+wake)
- Basic **control studies** with complex physics

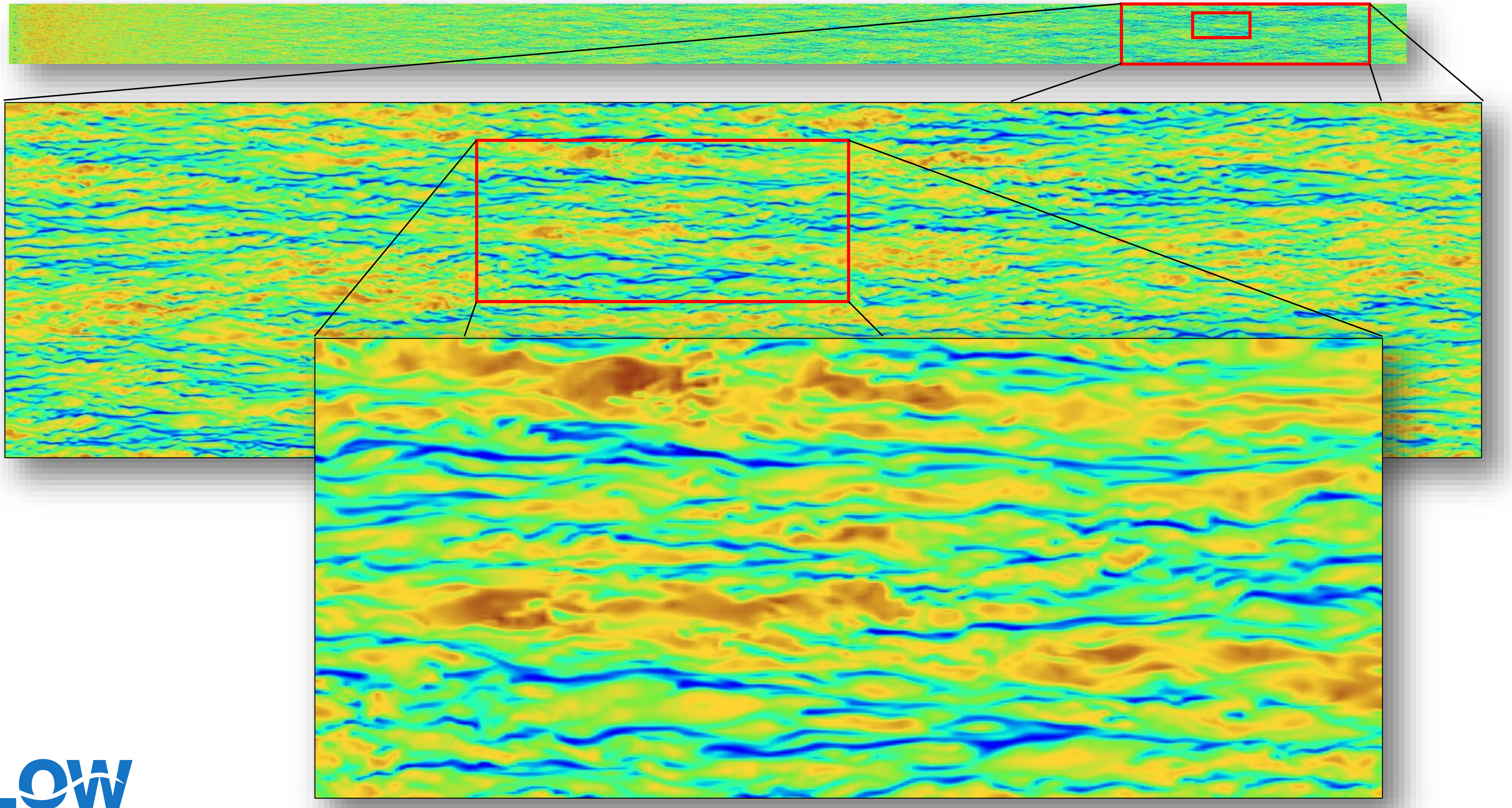
Turbulent flow close to solid walls...

TSFP-7 in 2011

Turbulent flow close to solid walls...

TSFP-7 in 2011

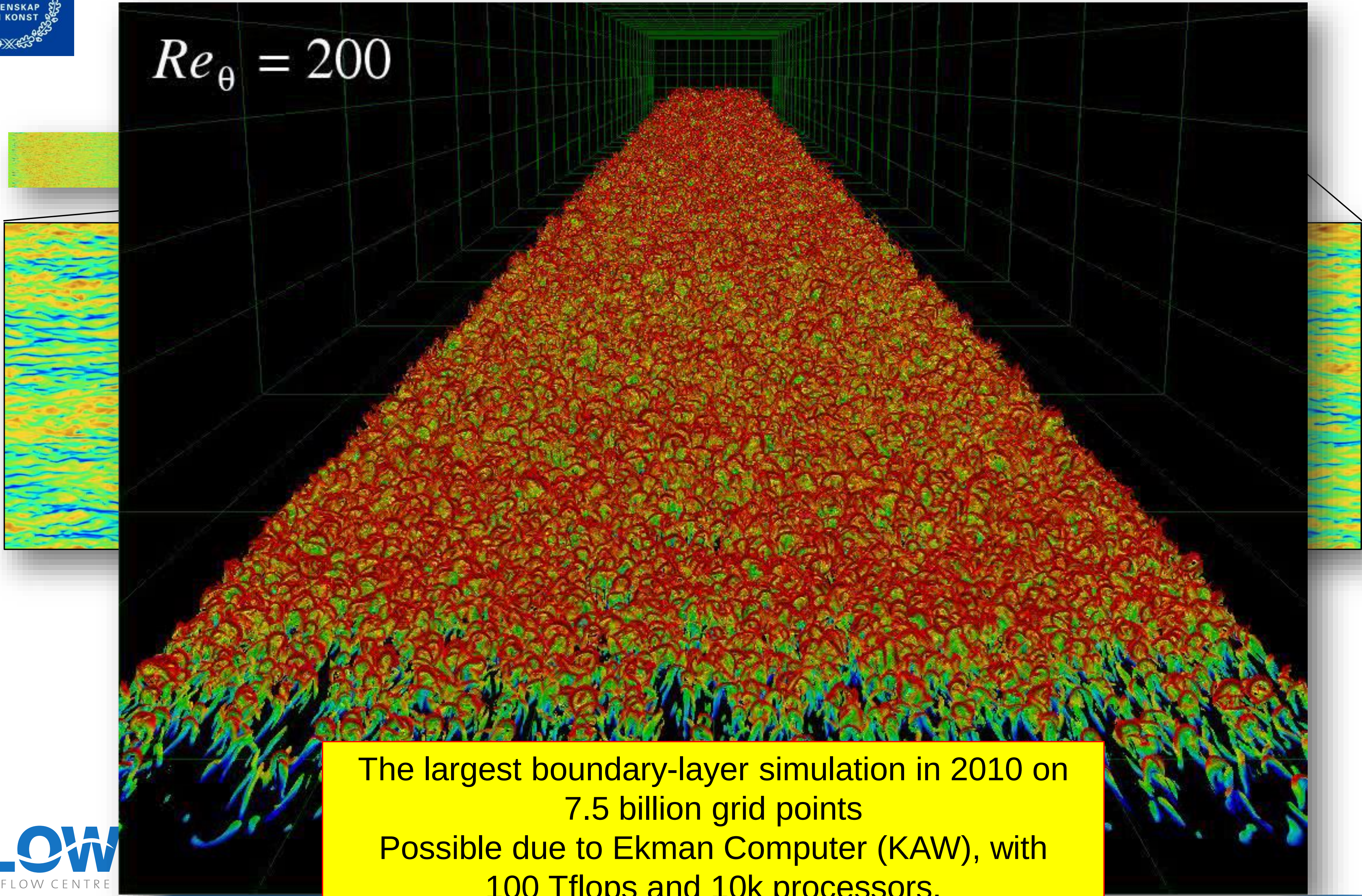
simulation result



LINNÉ FLOW CENTRE

Turbulent flow close to solid walls...

TSFP-7 in 2011



The largest boundary-layer simulation in 2010 on
7.5 billion grid points
Possible due to Ekman Computer (KAW), with
100 Tflops and 10k processors.

DNS of flow around a NACA4412 wing section; Re_c=400 000 and AoA=5°

now...

Entry #: V0078

APS Gallery of Fluid Motion 2015

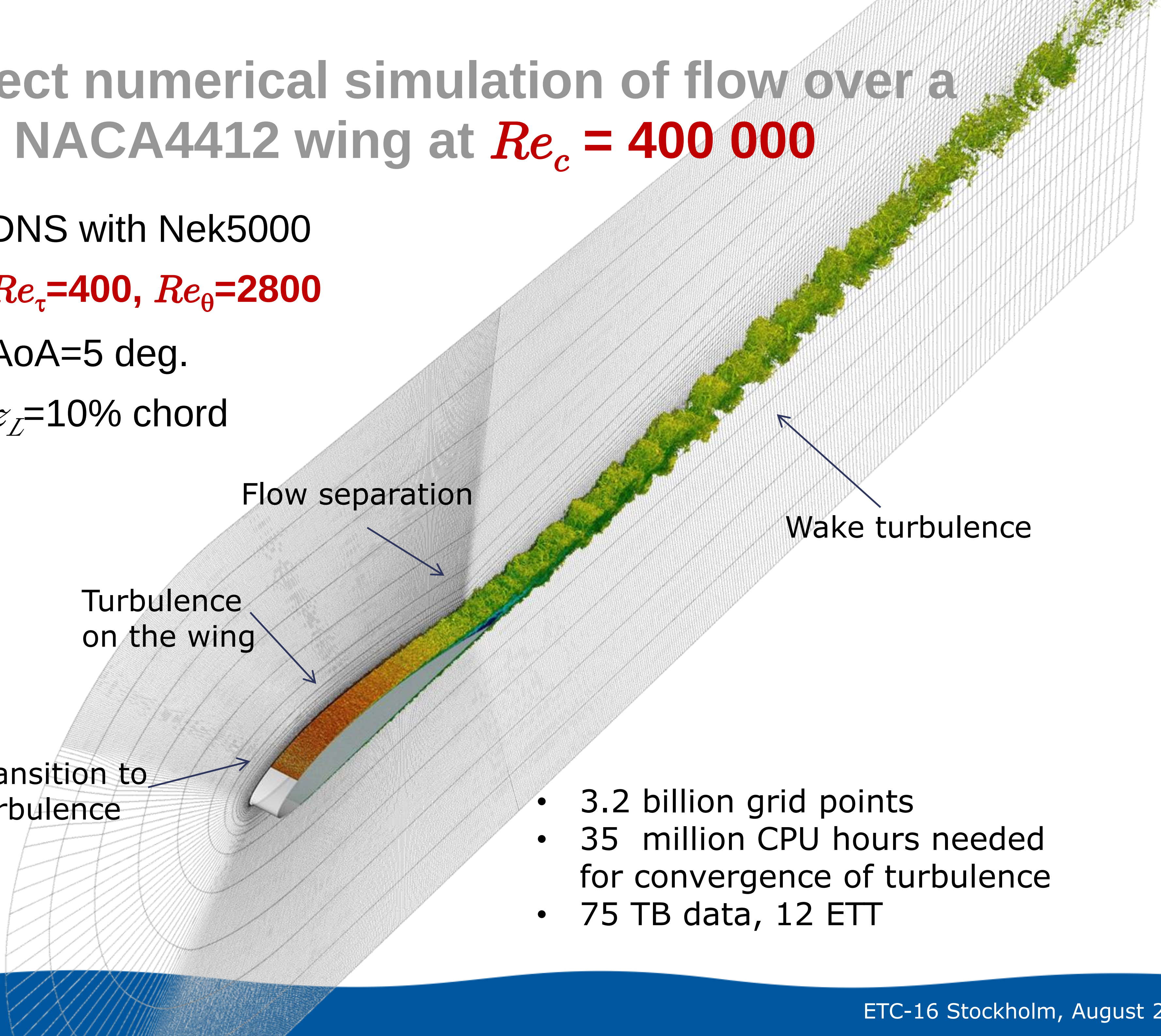
Turbulent flow around a wing profile, a direct numerical simulation

Mohammad Hosseini, Ricardo Vinuesa, Ardeshir Hanifi
Dan Henningson, and Philipp Schlatter

Linné FLOW Centre
and
Swedish e-Science Research Centre (SeRC)
KTH Mechanics, Stockholm, Sweden

Direct numerical simulation of flow over a full NACA4412 wing at Re_c = 400 000

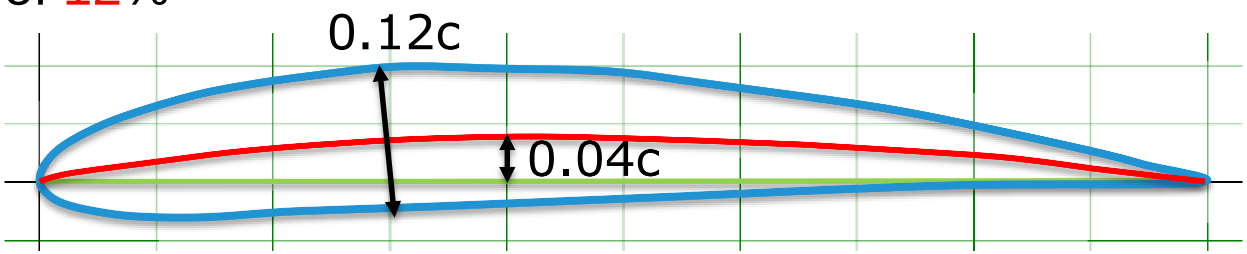
- DNS with Nek5000
- Re_τ=400, Re_θ=2800
- AoA=5 deg.
- z_L=10% chord



- 3.2 billion grid points
- 35 million CPU hours needed for convergence of turbulence
- 75 TB data, 12 ETT

NACA 4412 Airfoil

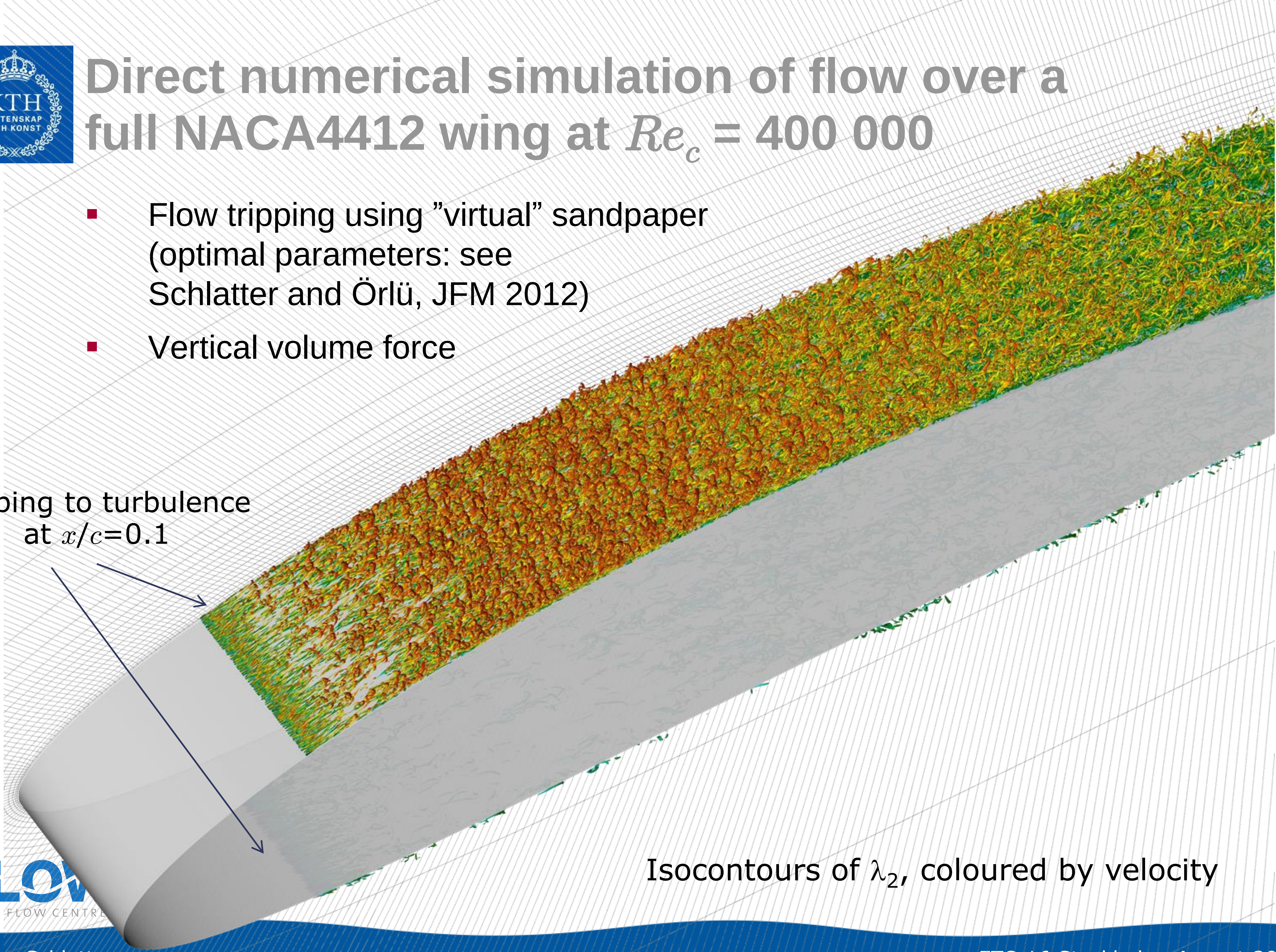
- **NACA 4412** → maximum camber of 4% at 40% chord with a maximum thickness of 12%



- Conventional airfoil for light aircraft, Re from 1M upwards
- Shape analytically given
- Studied since Pinkerton (1938)
- Good lift characteristics, benign stalling properties
- Pressure distribution independent of Reynolds number
- Example: **Luscombe 8** (designed in 1937)

Direct numerical simulation of flow over a full NACA4412 wing at Re_c = 400 000

- Flow tripping using ”virtual” sandpaper (optimal parameters: see Schlatter and Örlü, JFM 2012)
- Vertical volume force



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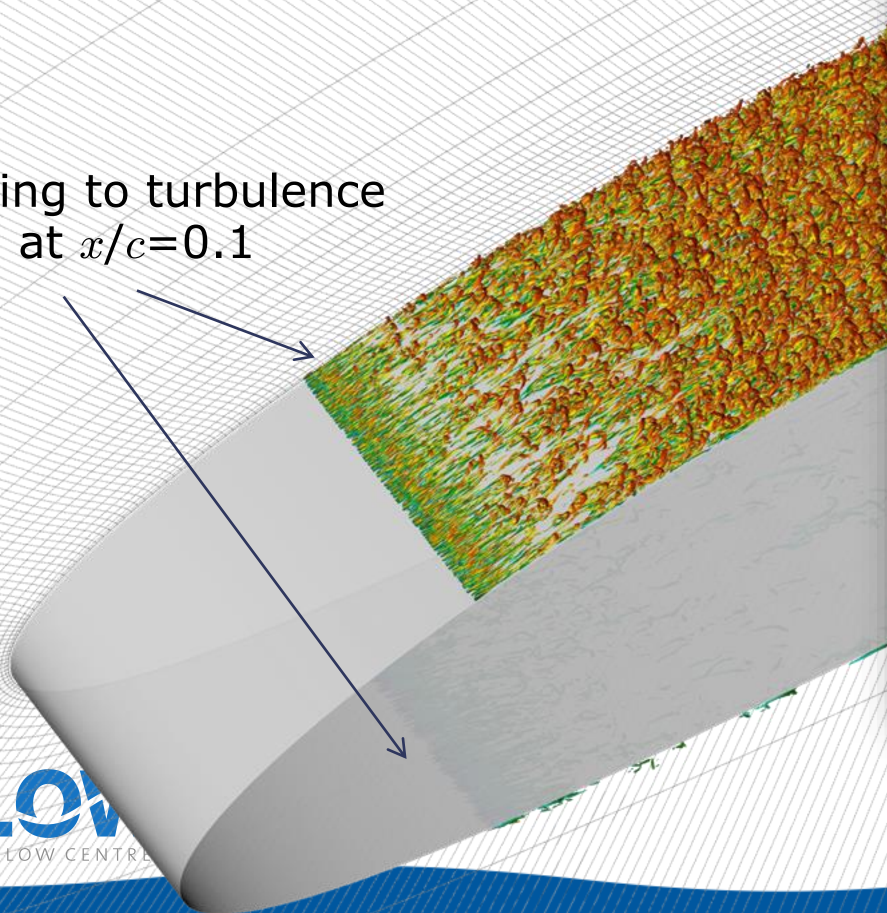
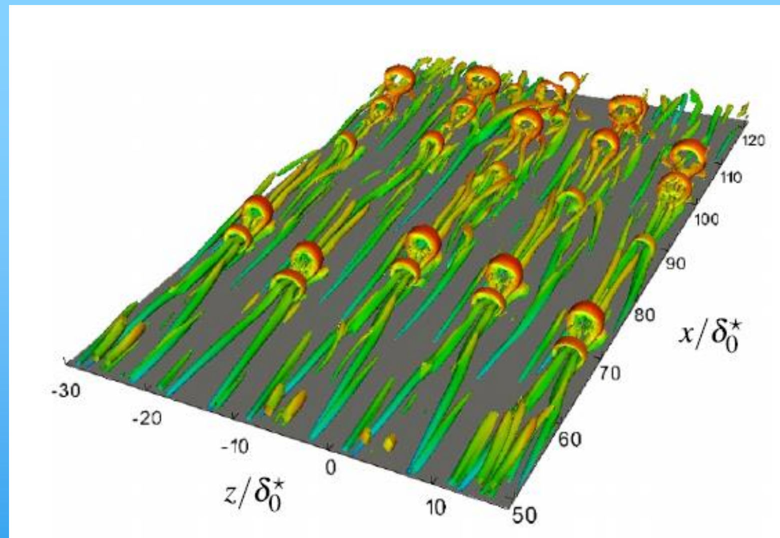


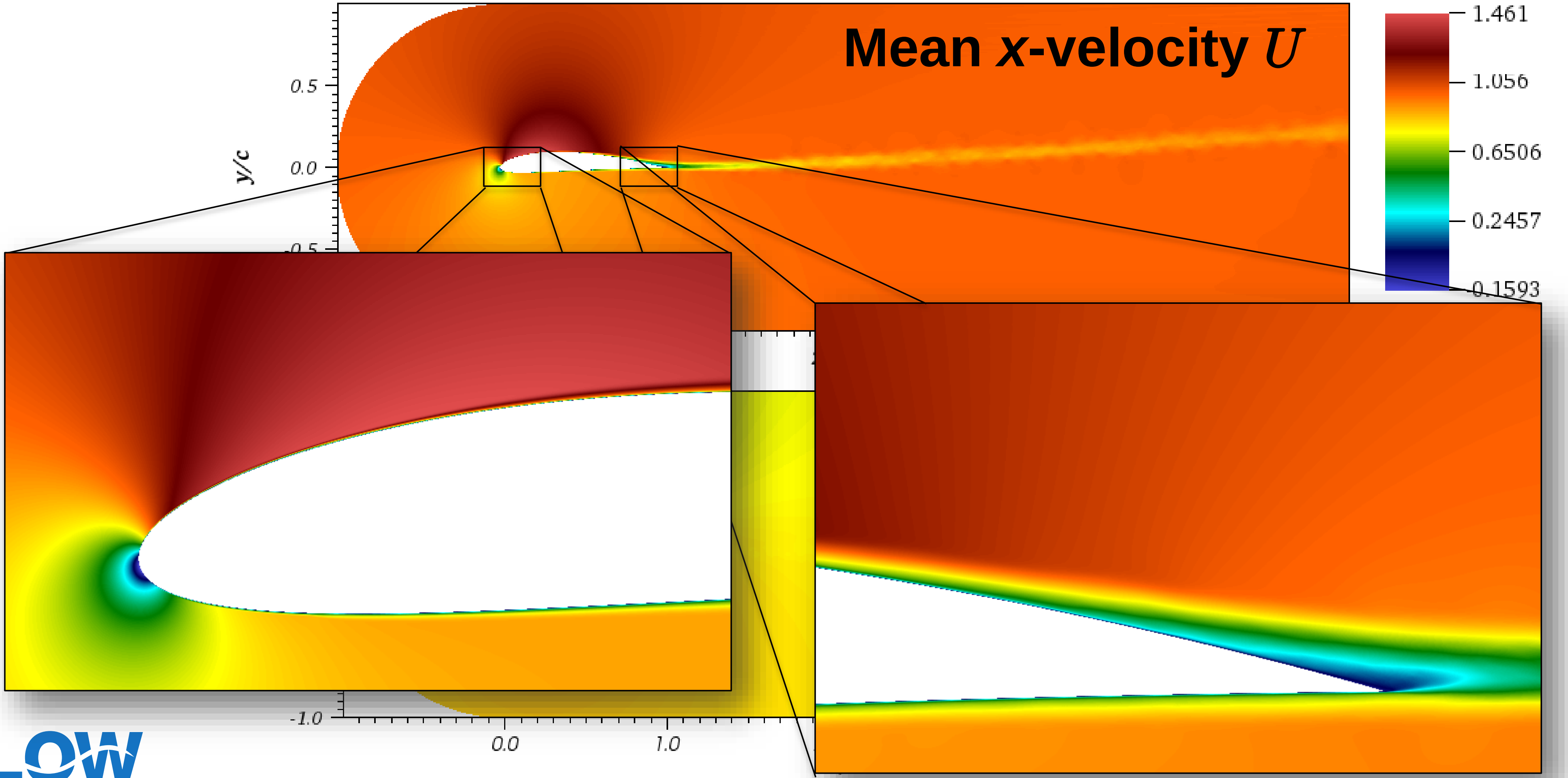


Initial generation of hairpins (varicose instability)
- see Eitel-Amor *et al.* (PoF 2015) and Schlatter *et al.* (EJM/BF 2014)

Isocontours of λ_2, coloured by velocity

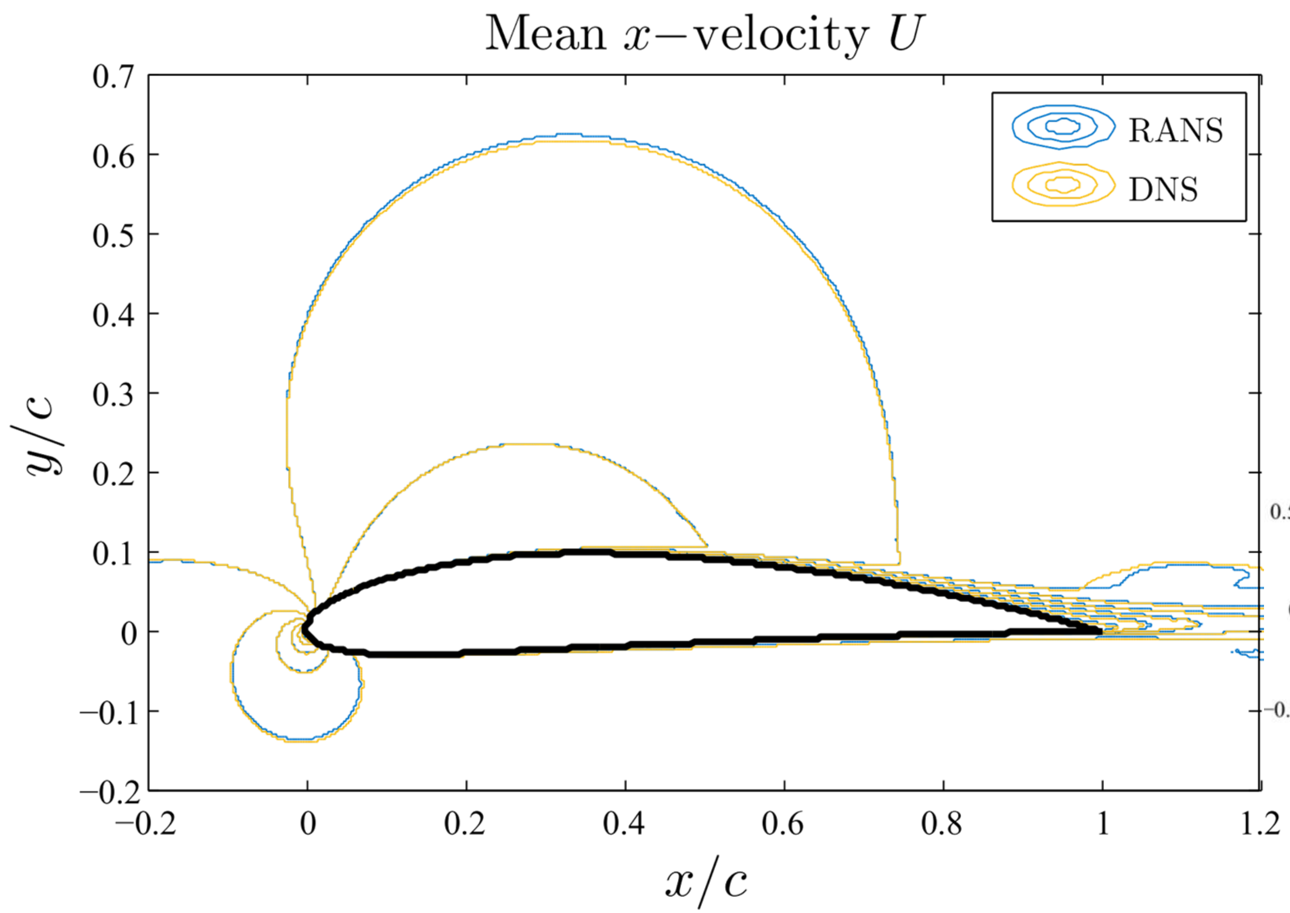
Direct numerical simulation of flow over a full NACA4412 wing at Re_c = 400 000

- Flow statistics: Averages of Turbulence

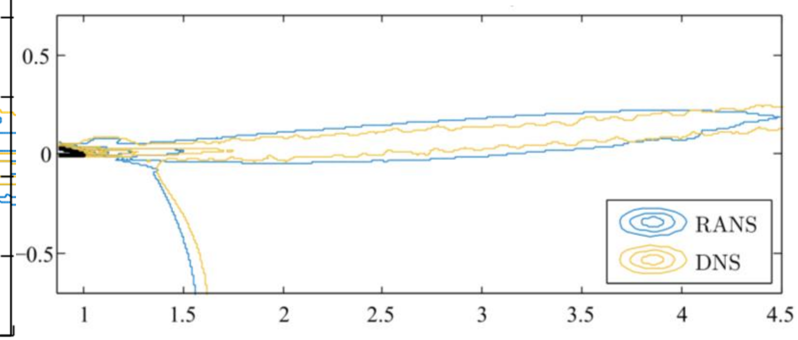


Direct numerical simulation of flow over a full NACA4412 wing at Re_c = 400 000

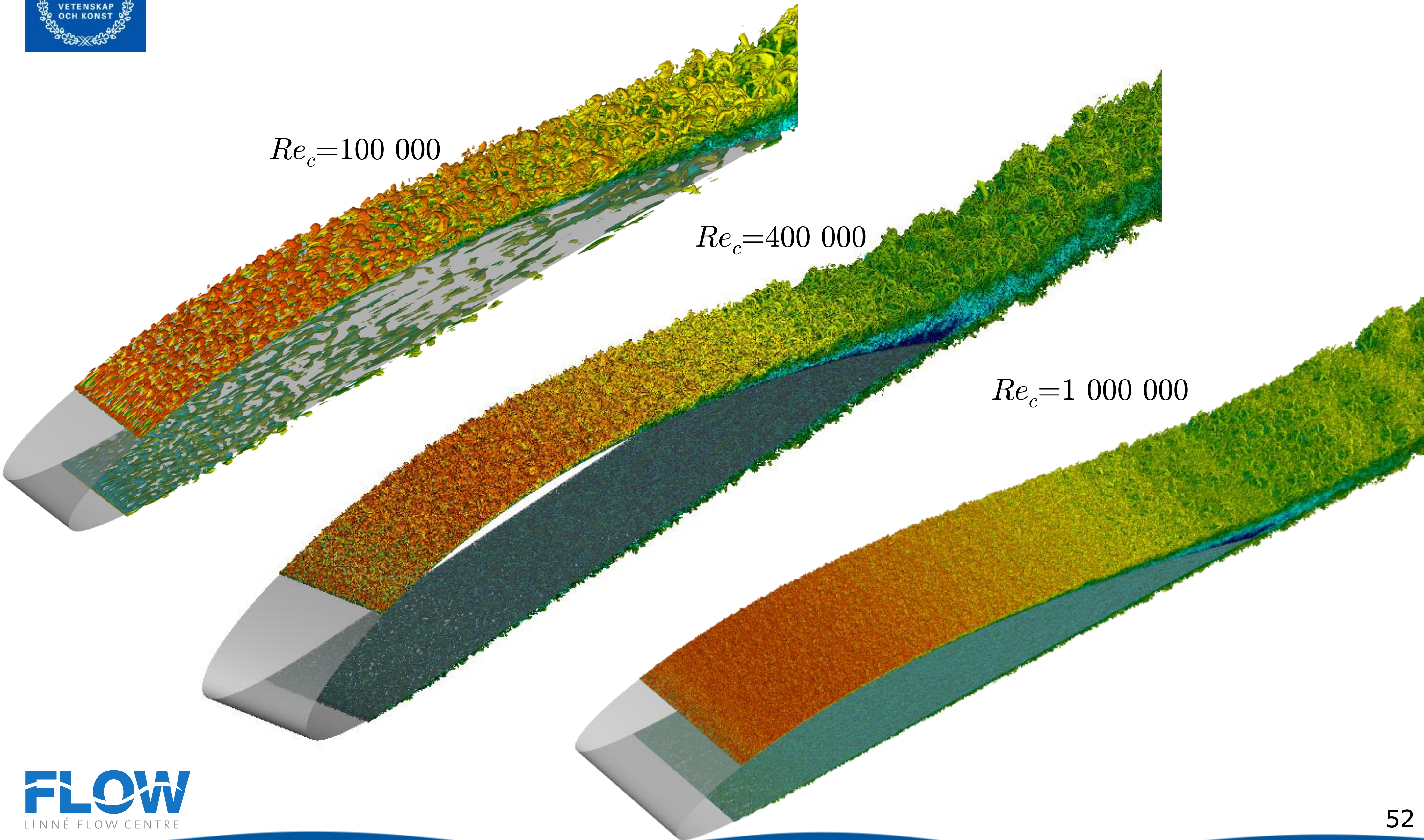
- Same geometry simulated with state-of-the-art RANS to design the mesh and boundary conditions
- Excellent agreement between RANS and DNS 🙂!



Wake region



Three different wings….



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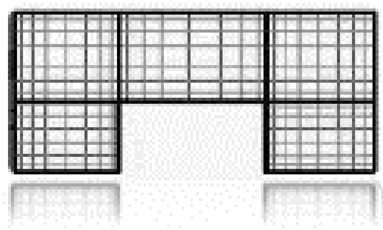
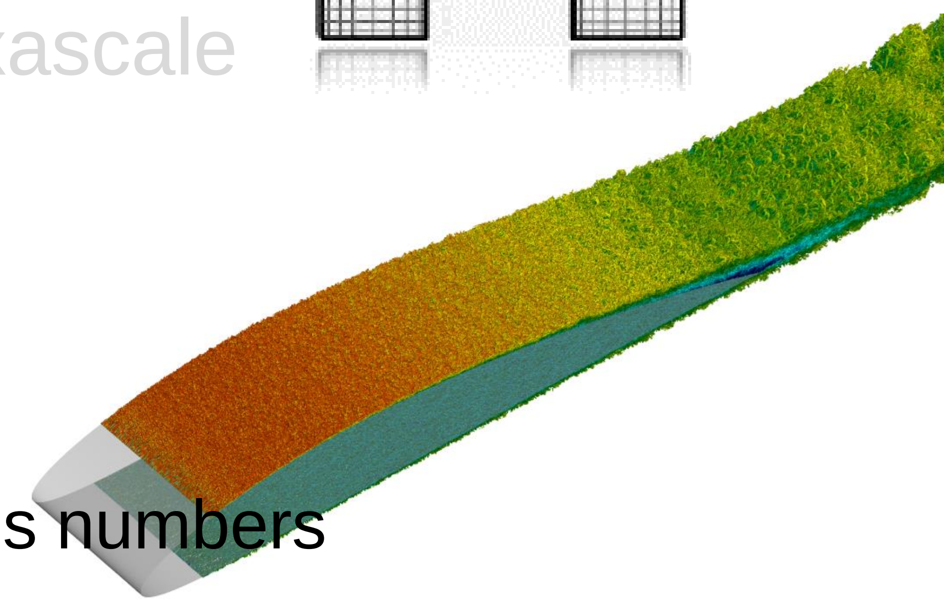
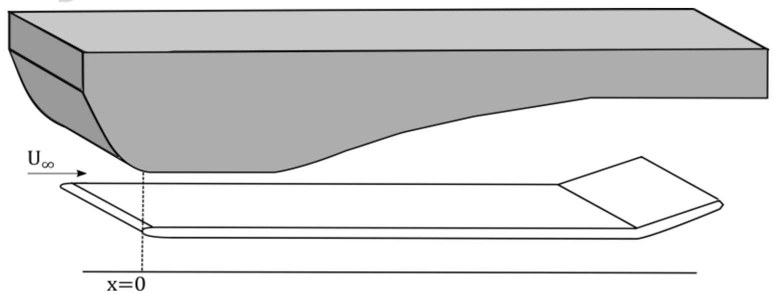


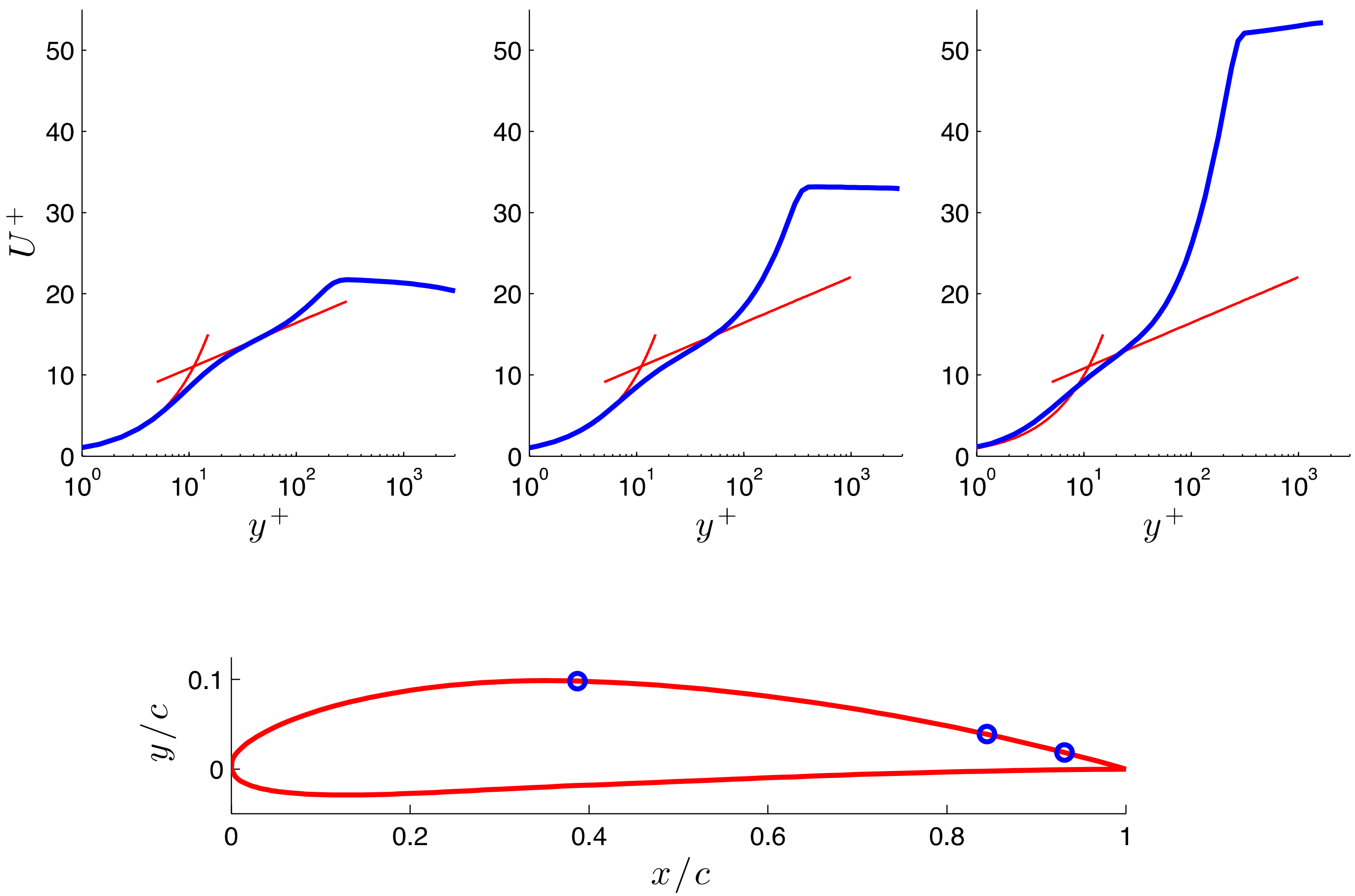


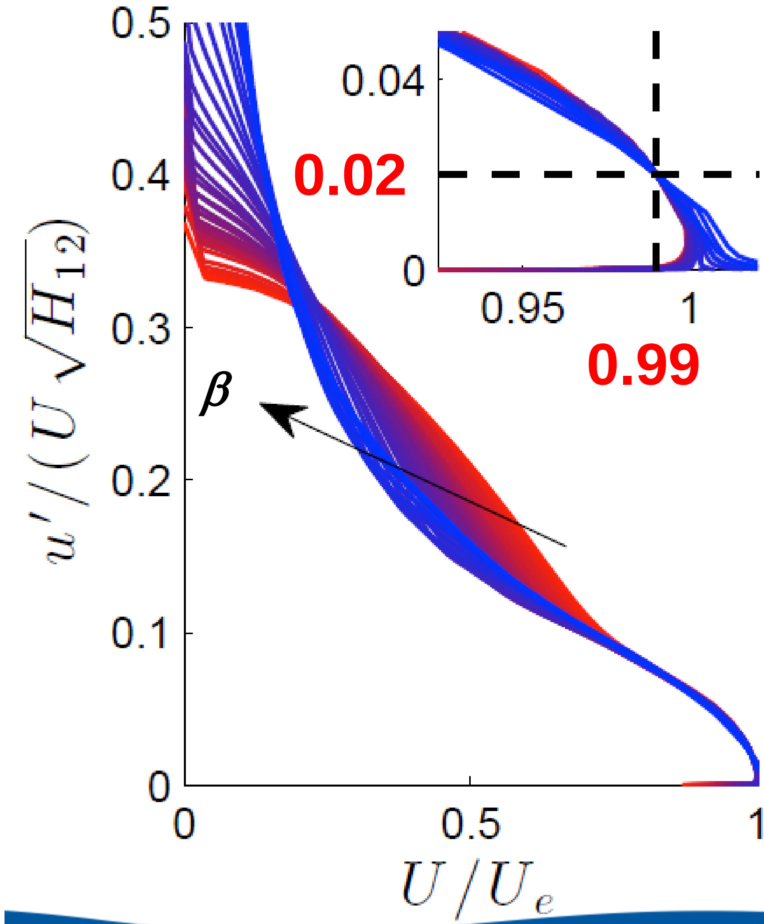


Determine the BL edge height and velocity in APG TBLs

Vinuesa *et al.* (*Phys. Fluids* 2016)

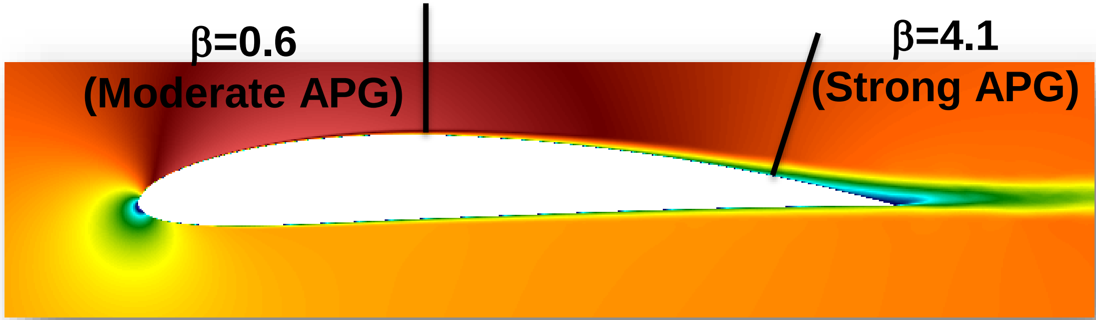
- TBLs with streamwise curvature/pressure gradients can pose problems (for wake formulations) when determining the boundary-layer edge
- Since PG TBLs scale in **diagnostic form** (Dróżdż *et al., 2015*), the turbulence intensity is a robust workaround.



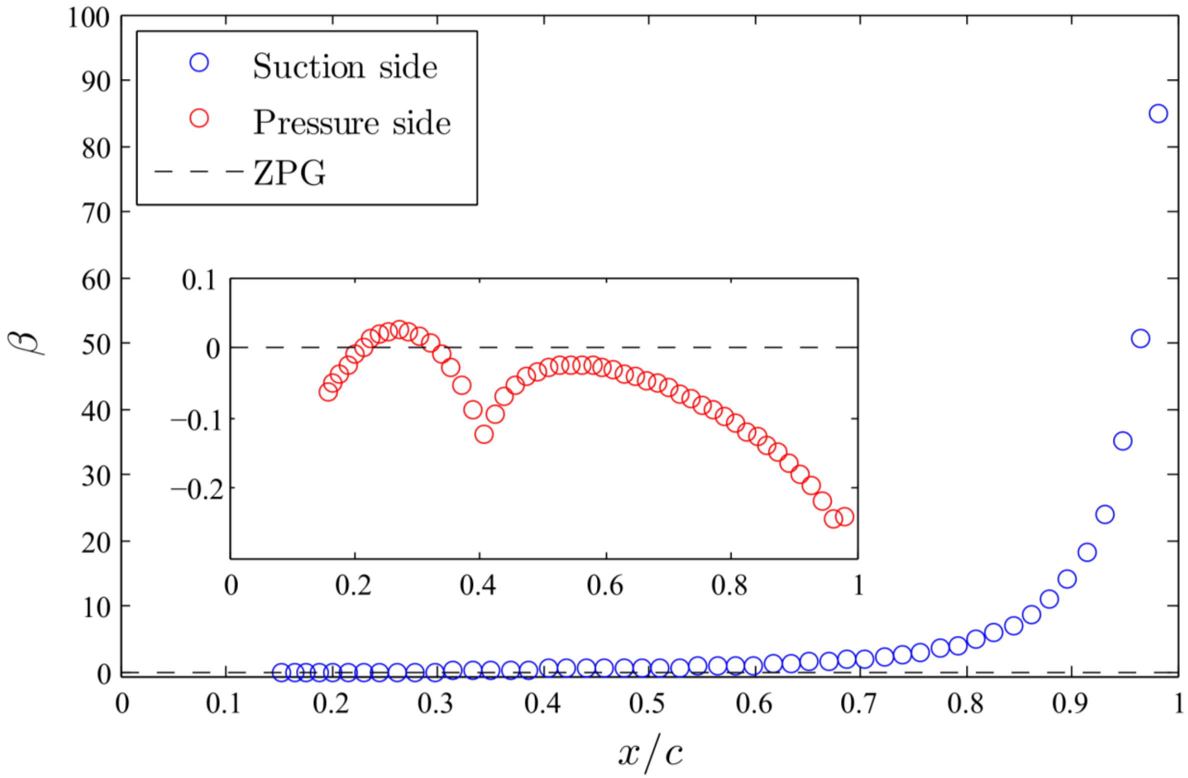


Pressure gradient effects on TBLs

- Local pressure gradient is characterised in terms of the **Clauser parameter β**

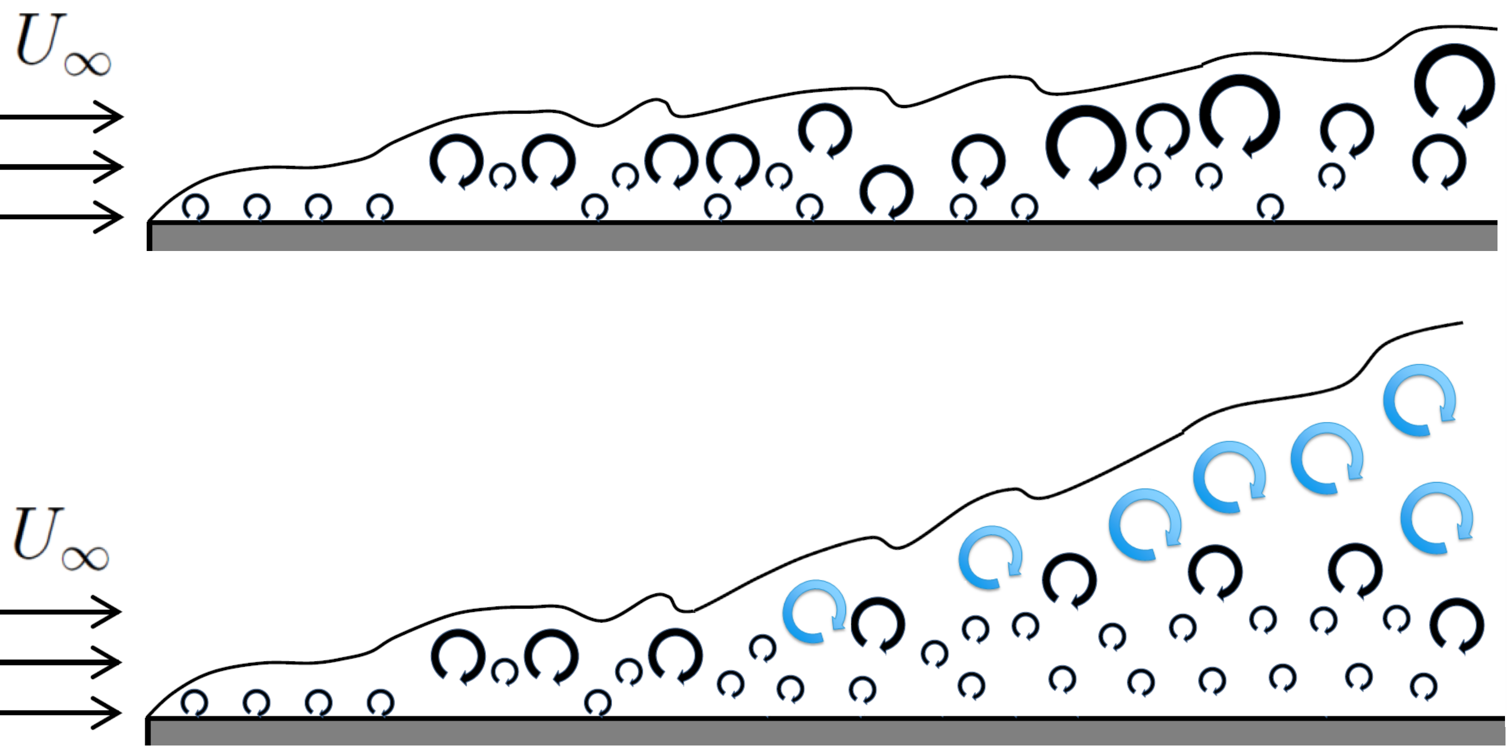


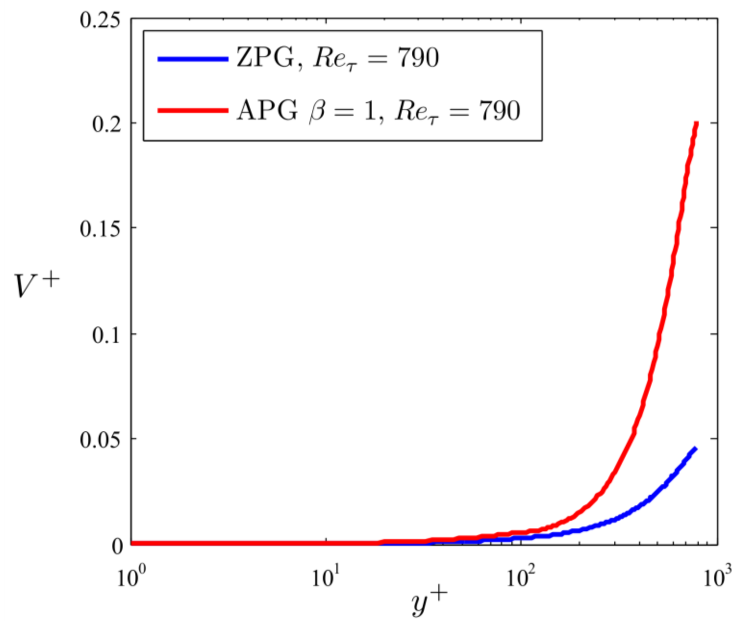
$$\beta = \frac{\delta^*}{\tau_w} \frac{\mathrm{d}P}{\mathrm{d}x}$$



Effect of an APG on the outer region

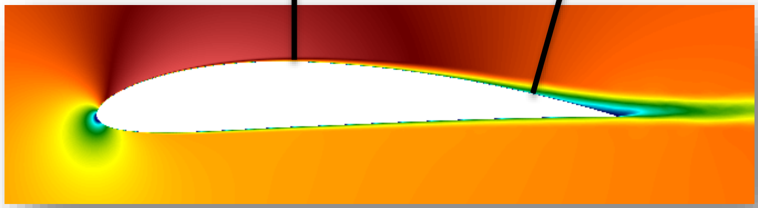
- APG increases the wall-normal momentum convection, leading to an increased boundary-layer thickness and a **more prominent outer region** (see *e.g.* Monty *et al.* 2011, Harun *et al.* 2013)



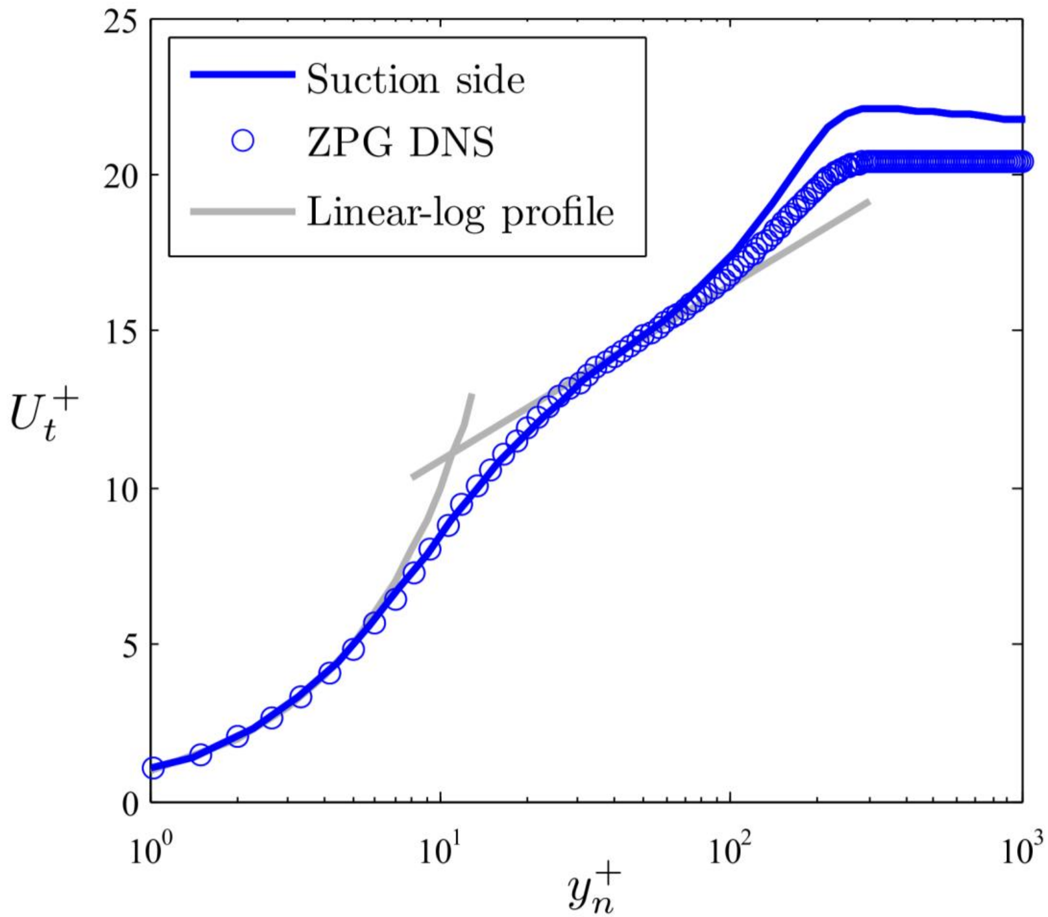


- **Increased wall-normal velocity** in APGs.
- More prominent outer region with **more energetic flow structures**.

Mean velocity profiles



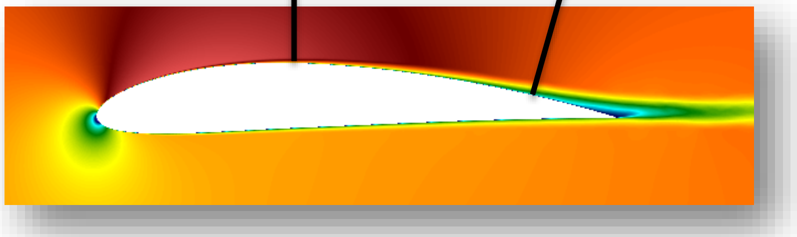
- Inner-scaled **mean flow** at x/c=0.4.



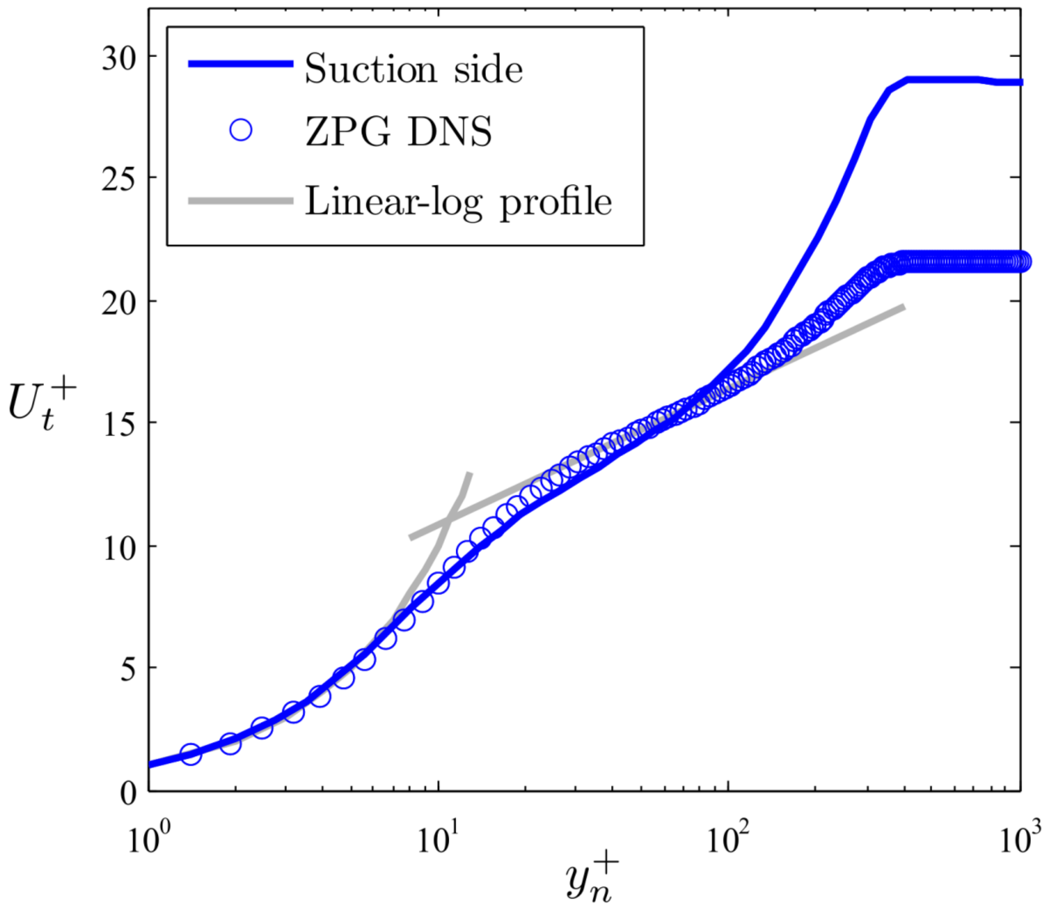
- Effect on the outer part, more prominent wake

Parameter	At x/c=0.4	ZPG (S&Ö)
Re_τ	242	252
Re_θ	712	678
H	**1.59**	**1.47**
C_f	4.1×10^{-3}	4.8×10^{-3}
κ	0.38	0.42
B	4.20	5.09
Π	0.56	0.31

Mean velocity profiles



- Inner-scaled **mean flow** at x/c=0.8.

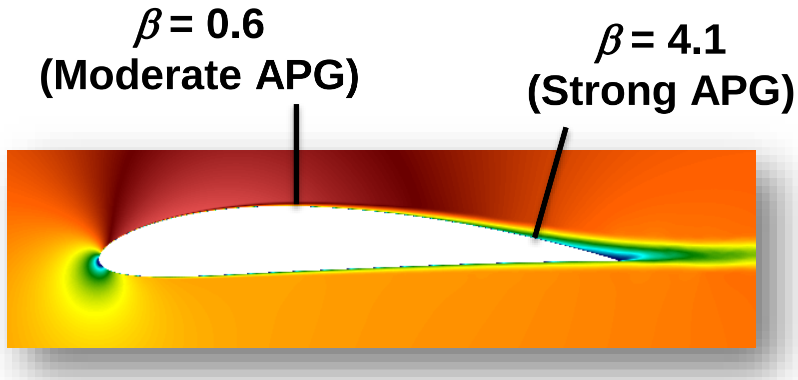


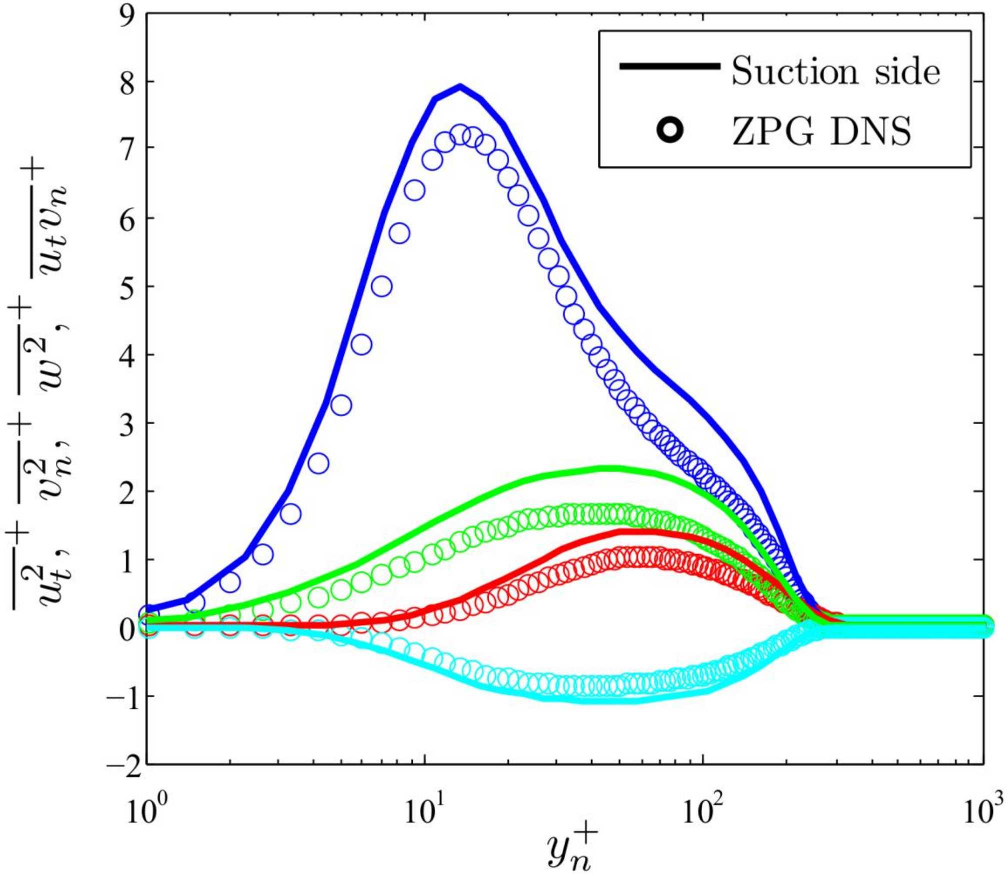
- Effect on the outer part (more prominent wake), but also in the incipient log region and even the buffer layer.

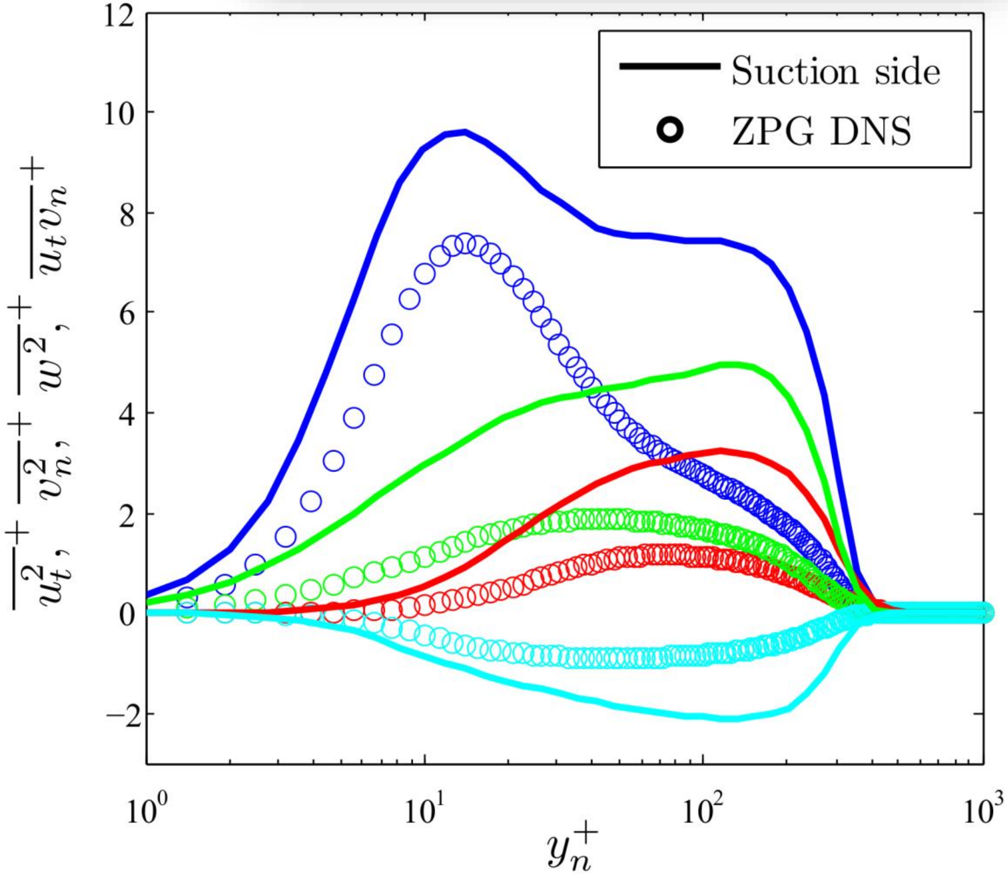
Parameter	At x/c=0.8	ZPG (S&Ö)
Re_τ	373	359
Re_θ	1,722	1,007
H	1.74	1.45
C_f	2.4×10^{-3}	4.3×10^{-3}
κ	0.33	0.41
B	2.08	4.87
Π	1.35	0.37

Reynolds stress tensor components

- **Reynolds stress tensor** at x/c=0.4 and 0.8.
- Comparison with **ZPG from Schlatter and Örlü,** 2010.

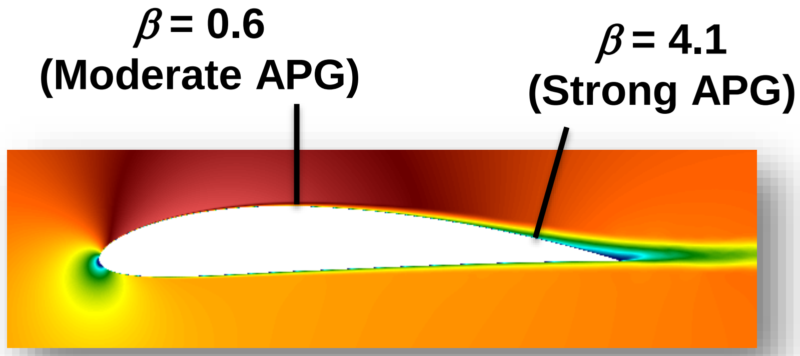


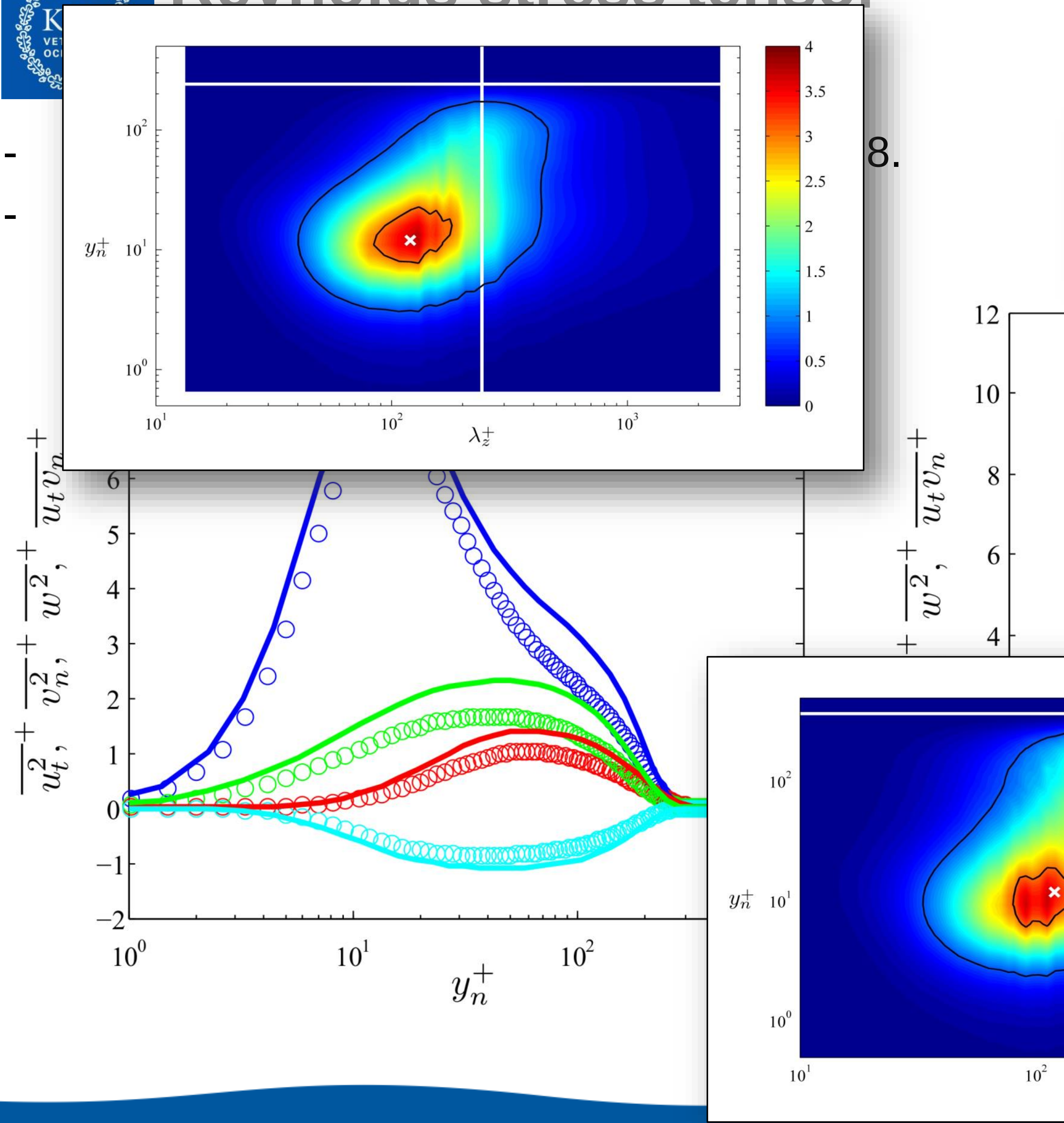
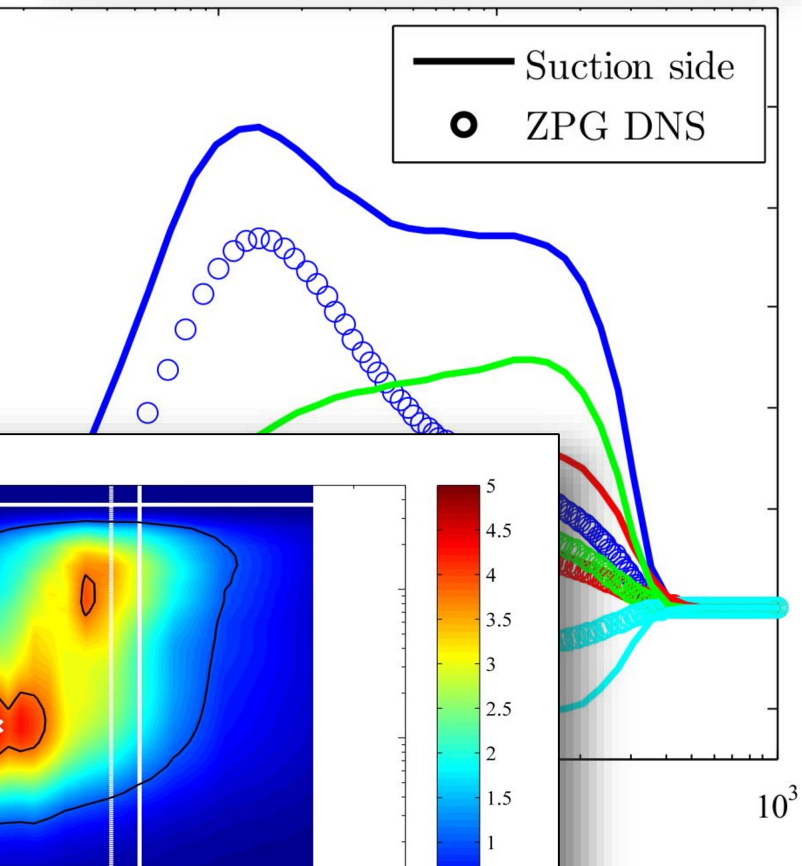




Reynolds stress tensor

-
- 8.



Outline

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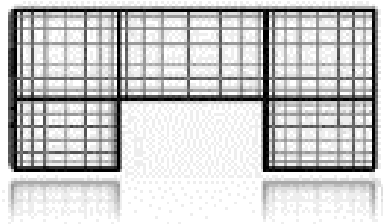
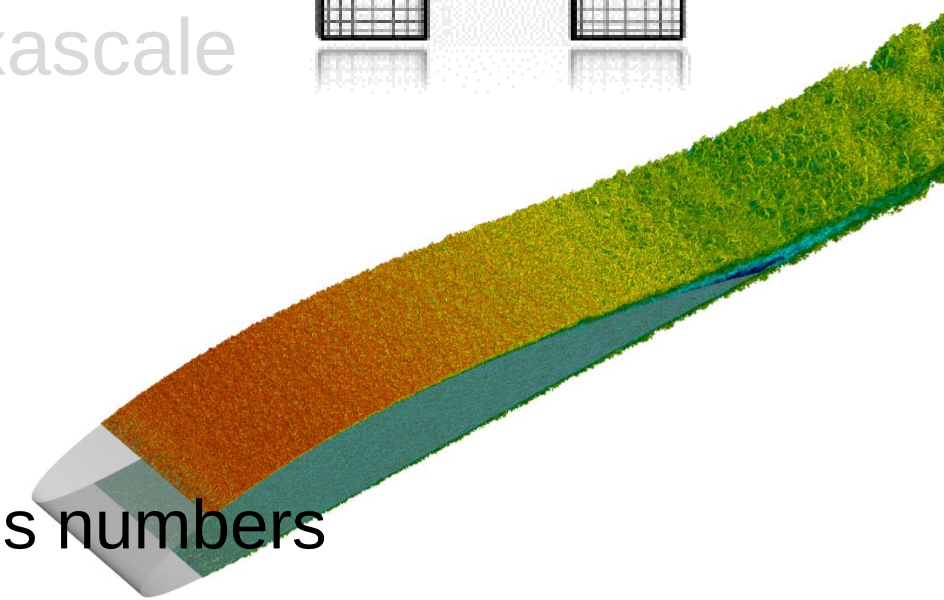
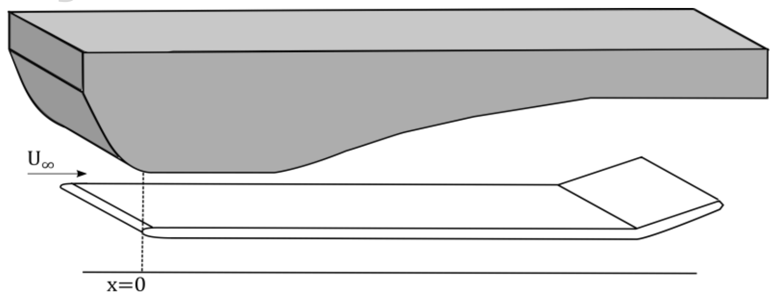
- **Spectral elements** and exascale



- **Wing simulations**
  - o Setup and statistics
  - o **Backflow events**
  - o Higher and lower Reynolds numbers



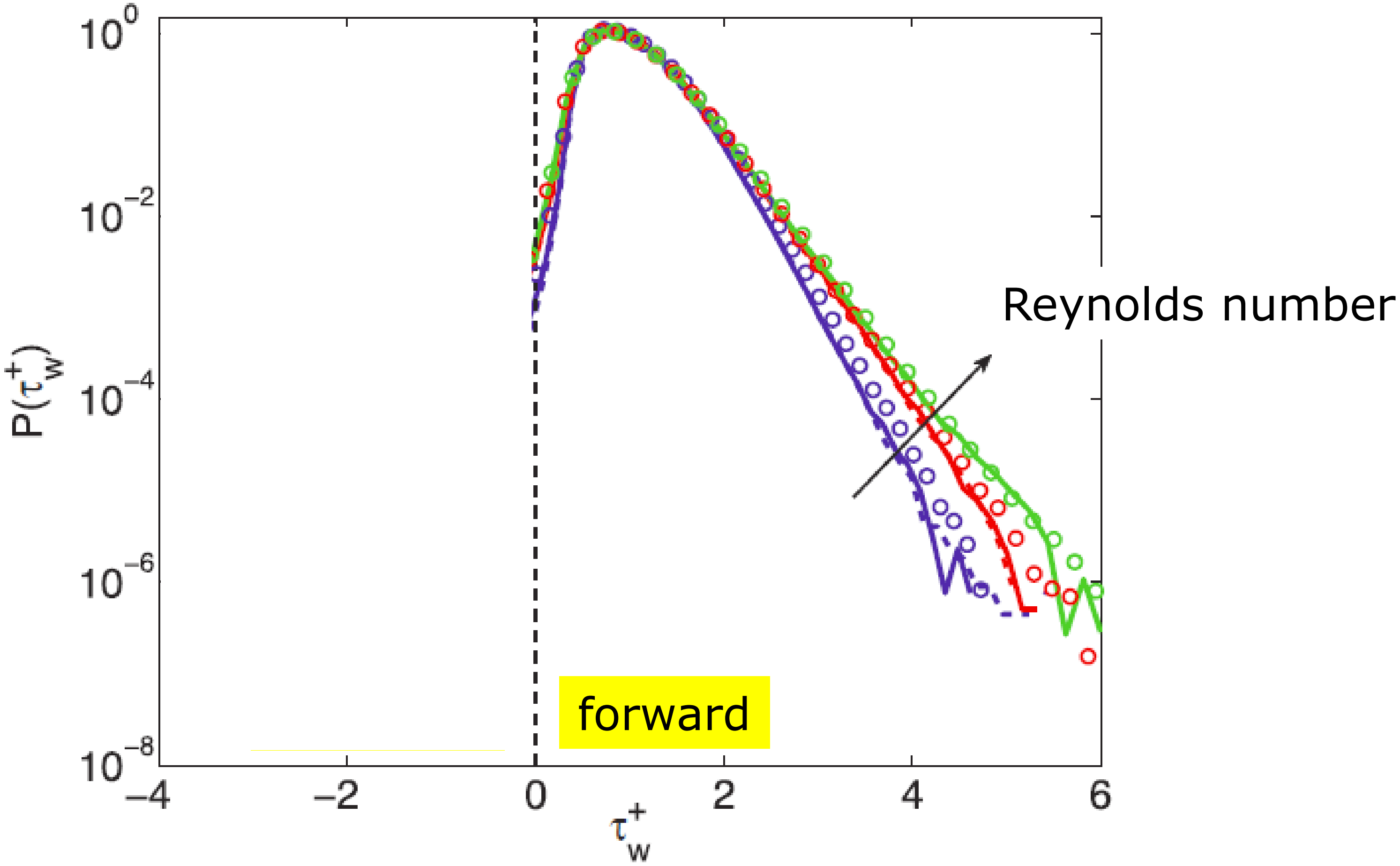
- **Pressure gradient boundary layers**
  - o History effects



- Conclusions and outlook
  - o Compression and mesh refinement

Basic result for turbulent boundary layers

- PDF of streamwise wall shear stress in channels and TBL

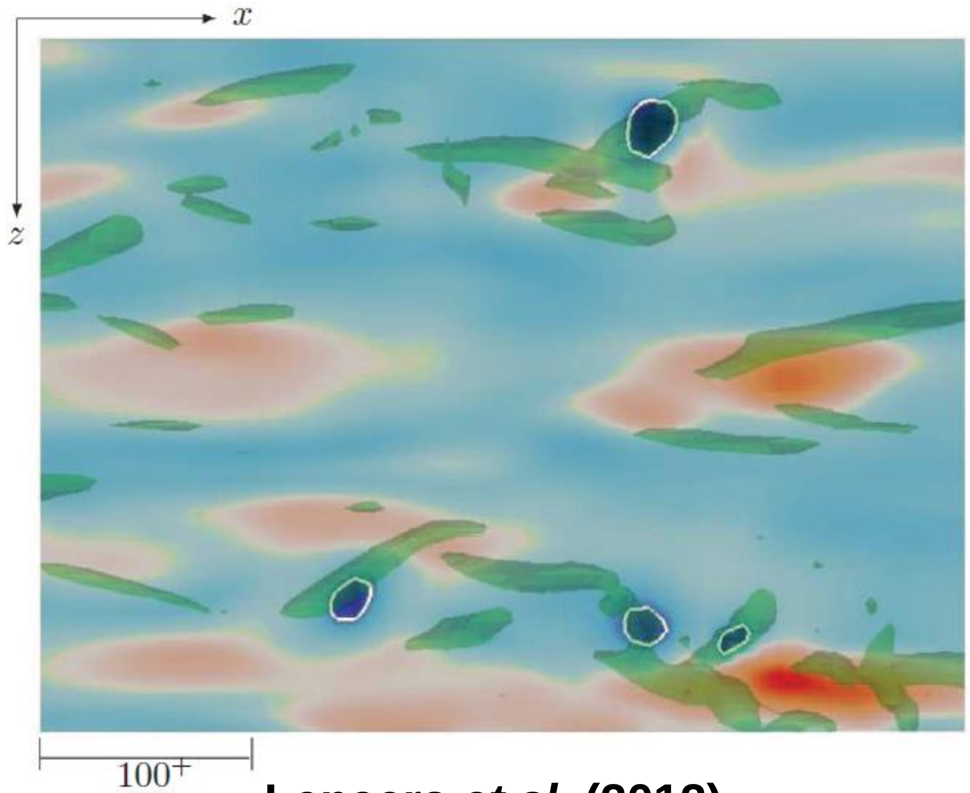


Ref.: Lenaers *et al.* (Phys. Fluids 2012)

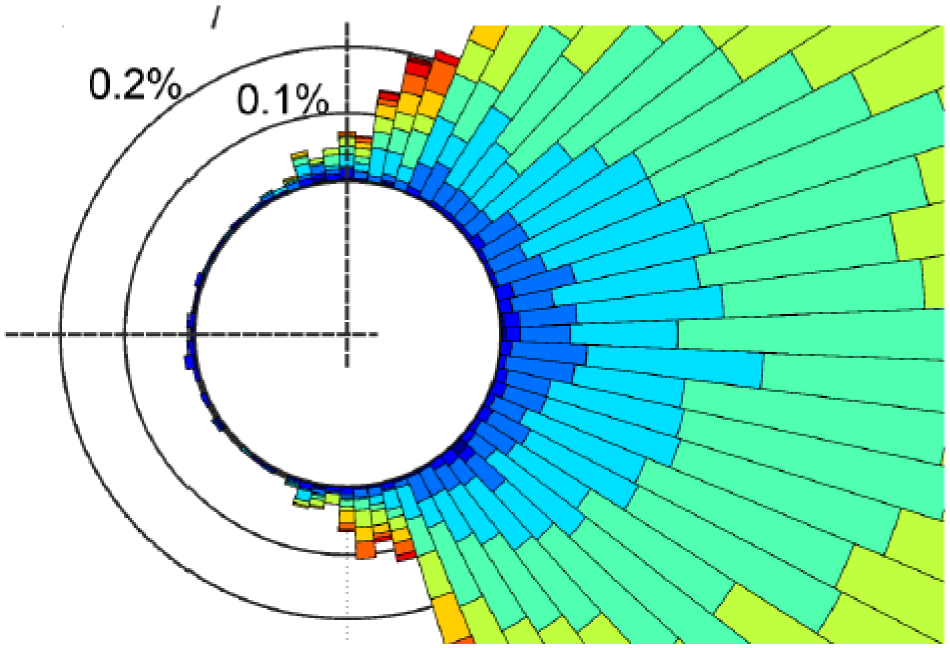
Basic result for turbulent boundary layers

- Lenaers *et al.* (2012) observed, in DNS of channel flow, 0.06% backflow at Re_τ=1,000 and 0.01% at Re_τ=180.

- This was confirmed **experimentally** by Brücker (2015) and Willert (2015), up to Re_τ=940 and 2,700, respectively.



Lenaers *et al.* (2012)

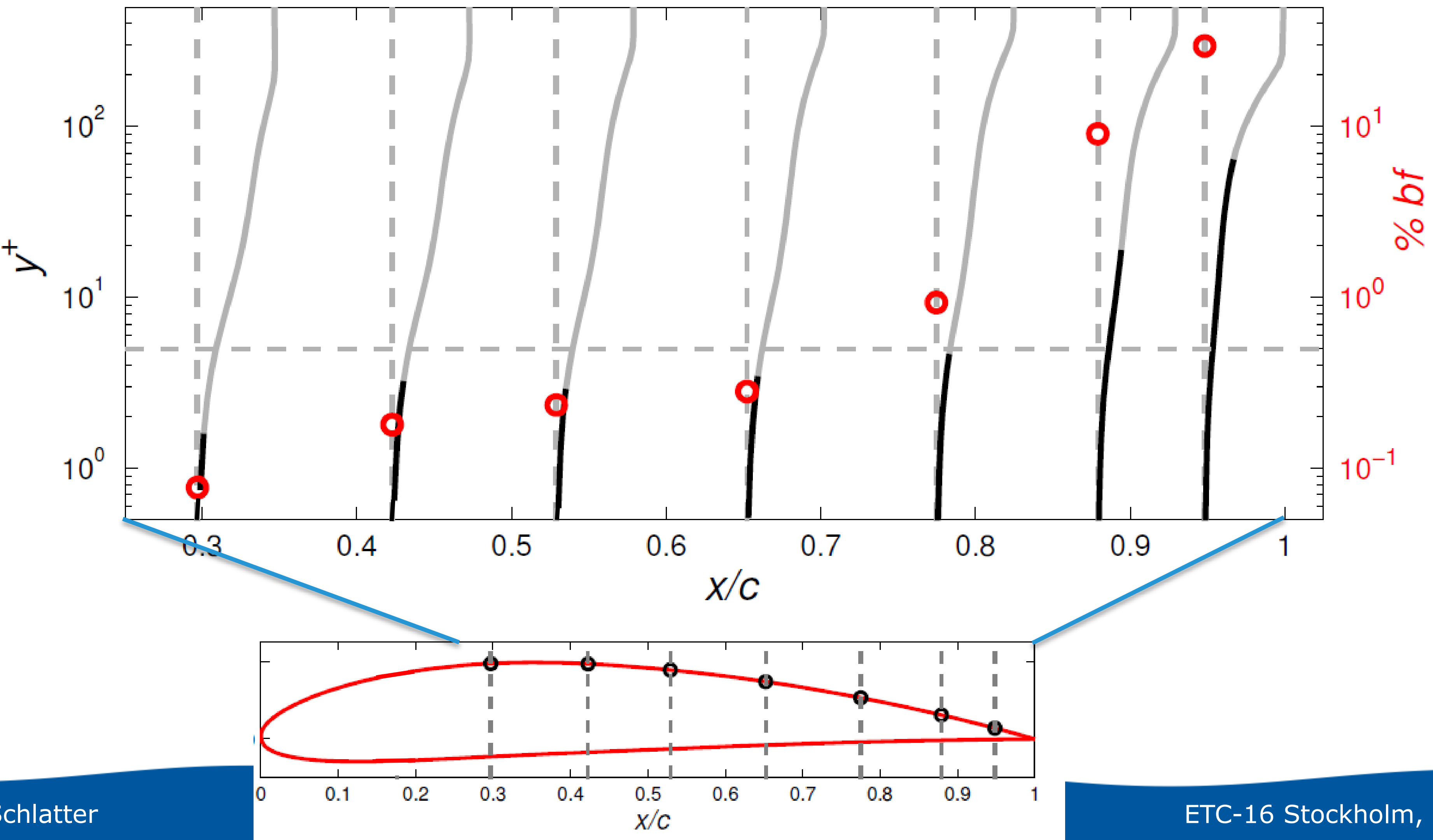


Brücker (2015)

Backflow in APG on a wing

Ref.: Vinuesa *et al.* J. Turb. (2017)

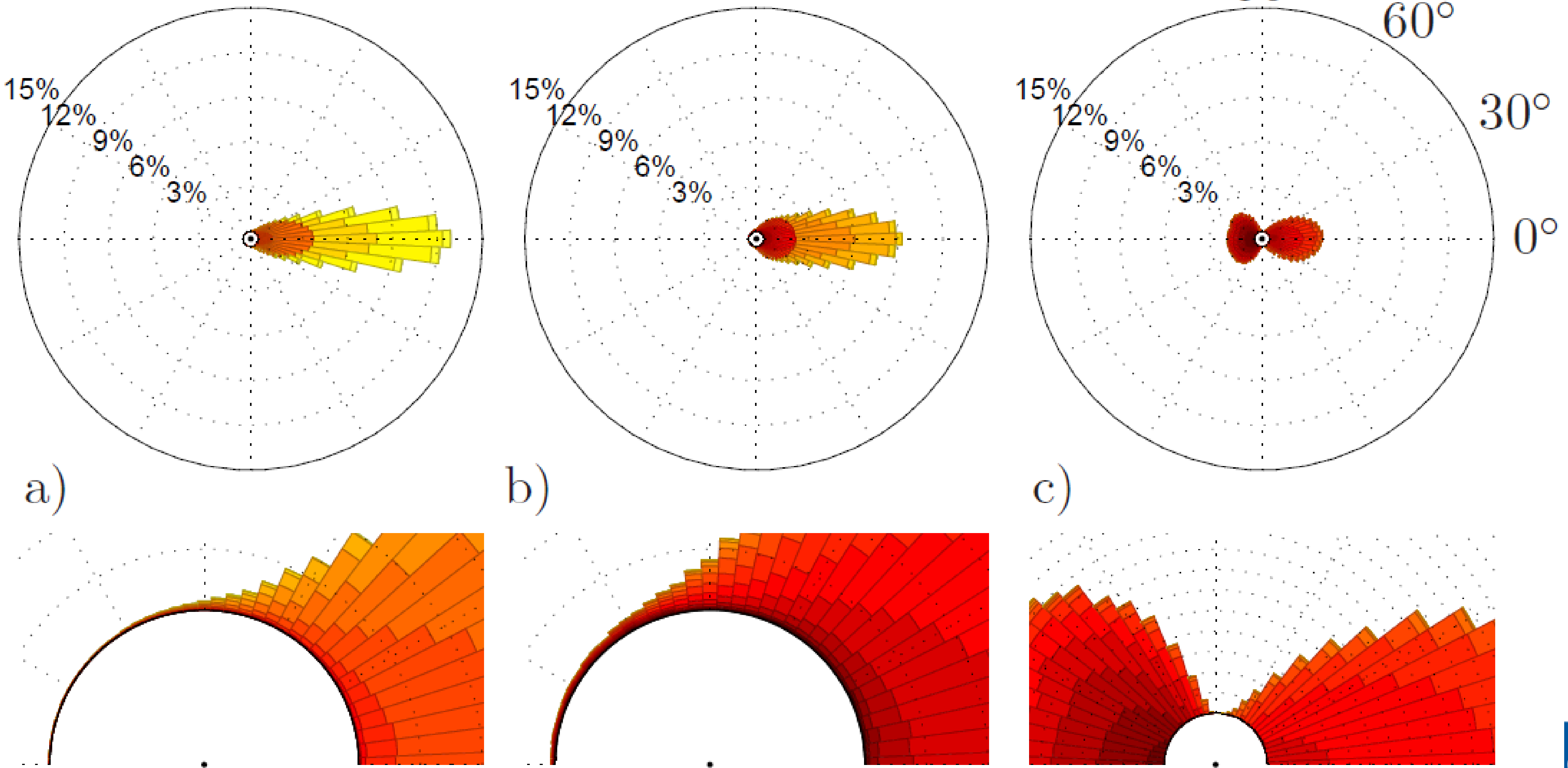
- Highlighted part of the profile shows >0.01% backflow.
- Maximum backflow of 30%.
- At x/c=0.3 already exceeded maximum backflow of 0.06% previously reported.



PDF of orientation of wall shear

Ref.: Vinuesa *et al.* J. Turb. (2017)

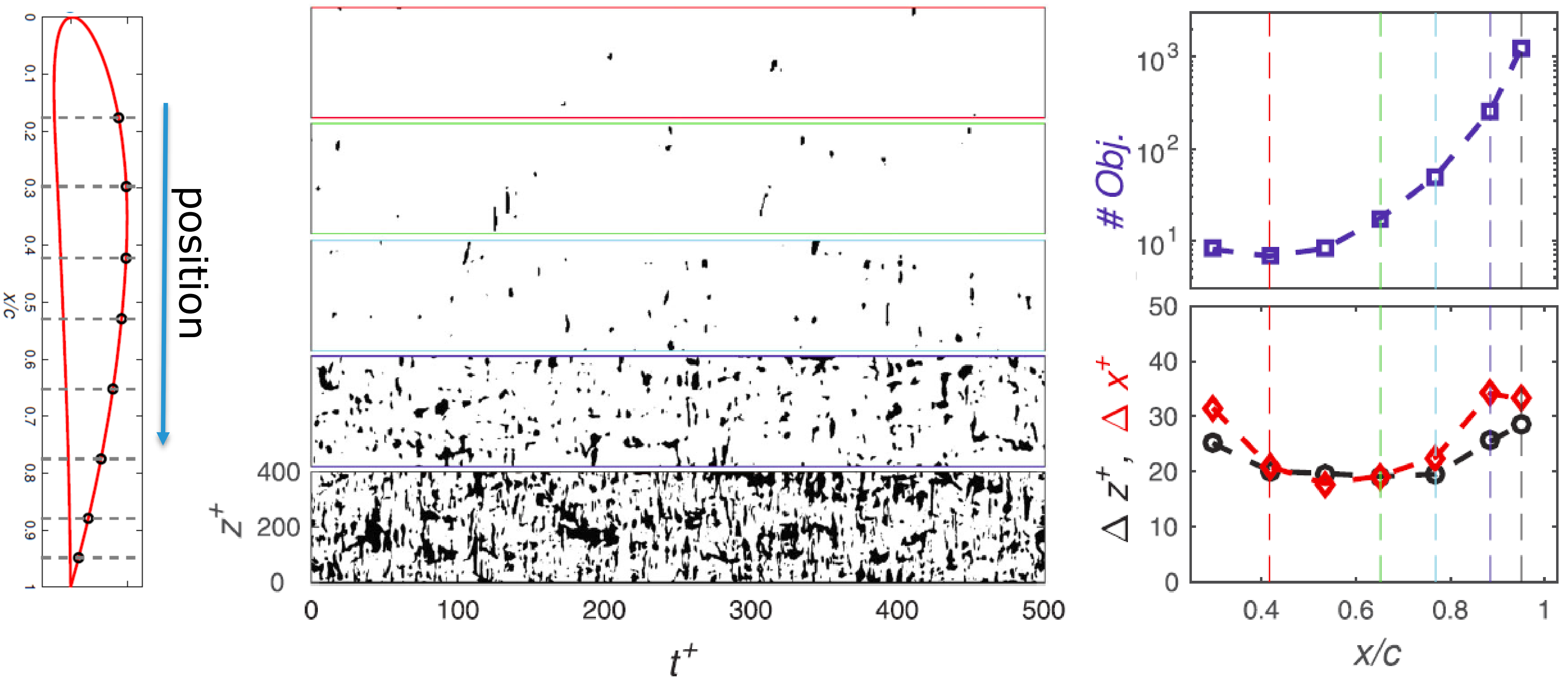
- Data at x/c=0.3, 0.65 and 0.95, with β=0.15, 1.6 and 35.
- Focus on extreme events: conditioned to $|\tau_w| > \tau_{wrms}$
- Stronger APGs lead to a **polarization** of the flow: either aligned or against the stream.



Influence of APG and chord position

Ref.: Vinuesa *et al.* J. Turb. (2017)

- Backflow events



Size of backflow events (in plus units) does not change, rather the **number increases!**

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- **Spectral elements** and exascale
- **Wing simulations**
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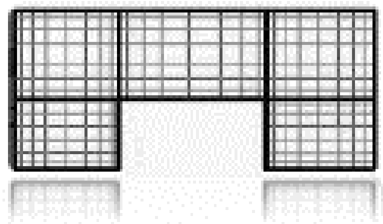
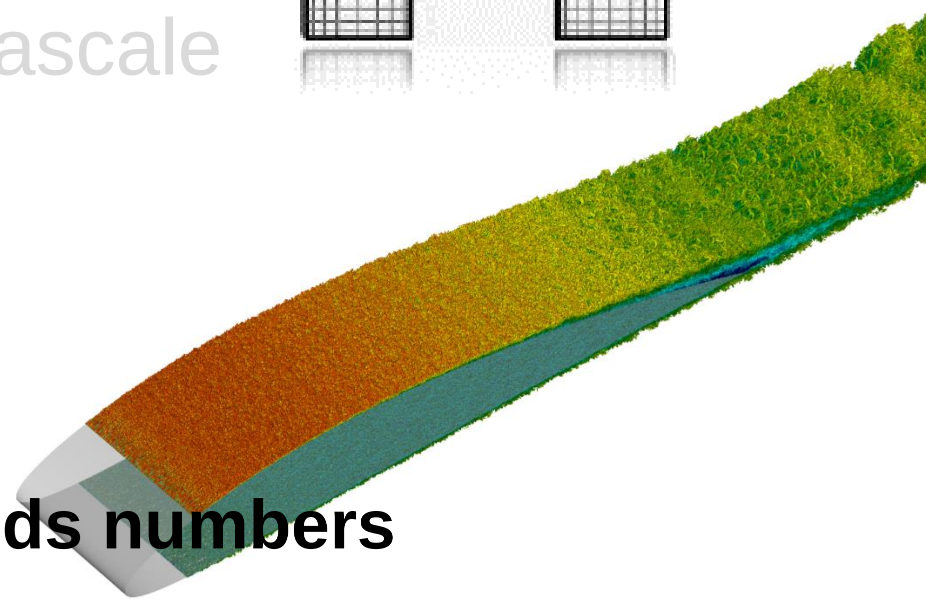
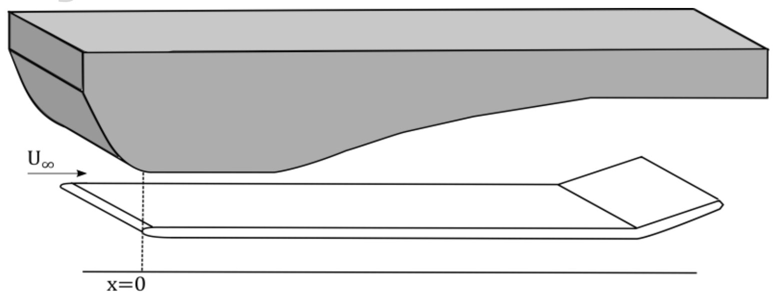
  - Backflow events
  - **Higher and lower Reynolds numbers**
- **Pressure gradient boundary layers**
  - History effects
- Conclusions and outlook
  - Compression and mesh refinement





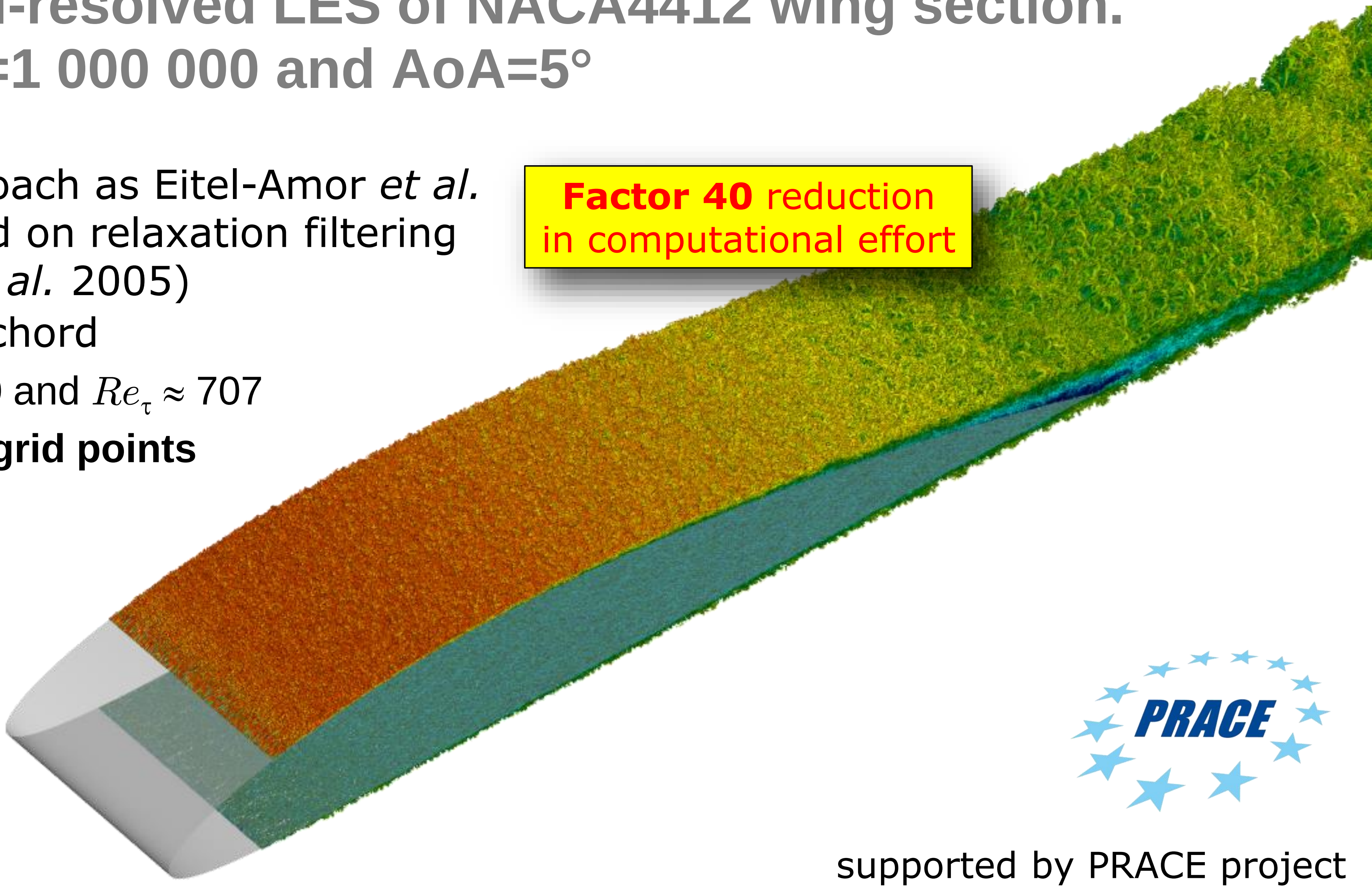


Well-resolved LES of NACA4412 wing section. Re_c=1 000 000 and AoA=5°

Similar approach as Eitel-Amor *et al.* (2014) based on relaxation filtering (Schlatter *et al.* 2005)

- z_L=**20%** chord
- $Re_\theta \approx$ 6,000 and $Re_\tau \approx$ 707
- **2.3 billion grid points**

Factor 40 reduction in computational effort



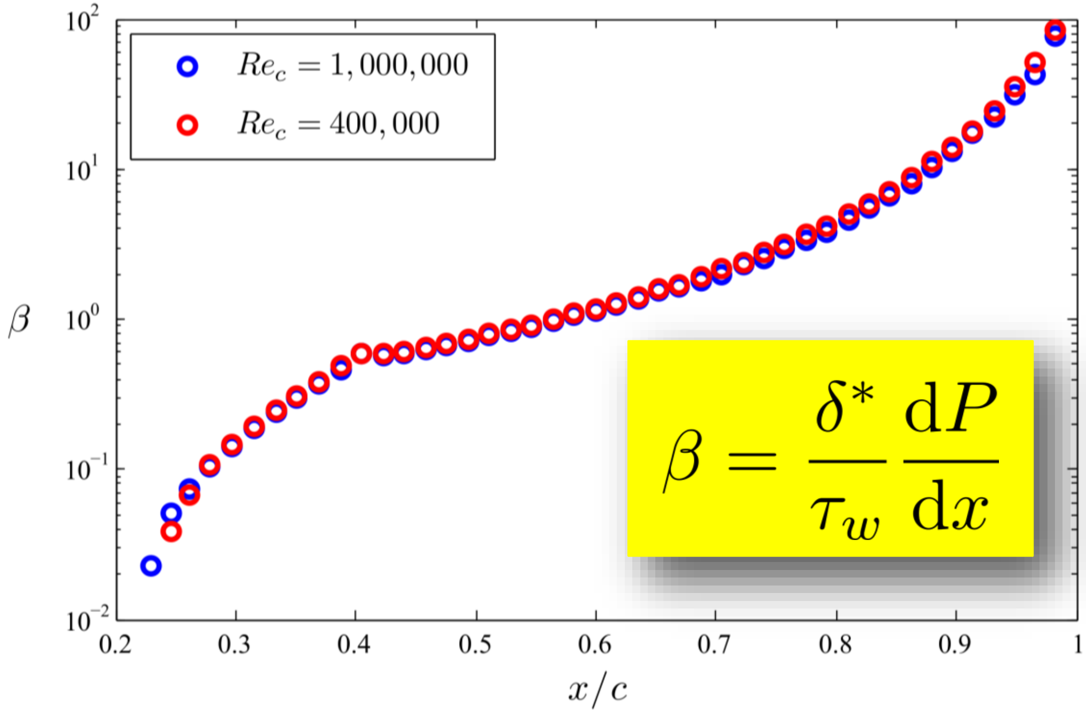
supported by PRACE project

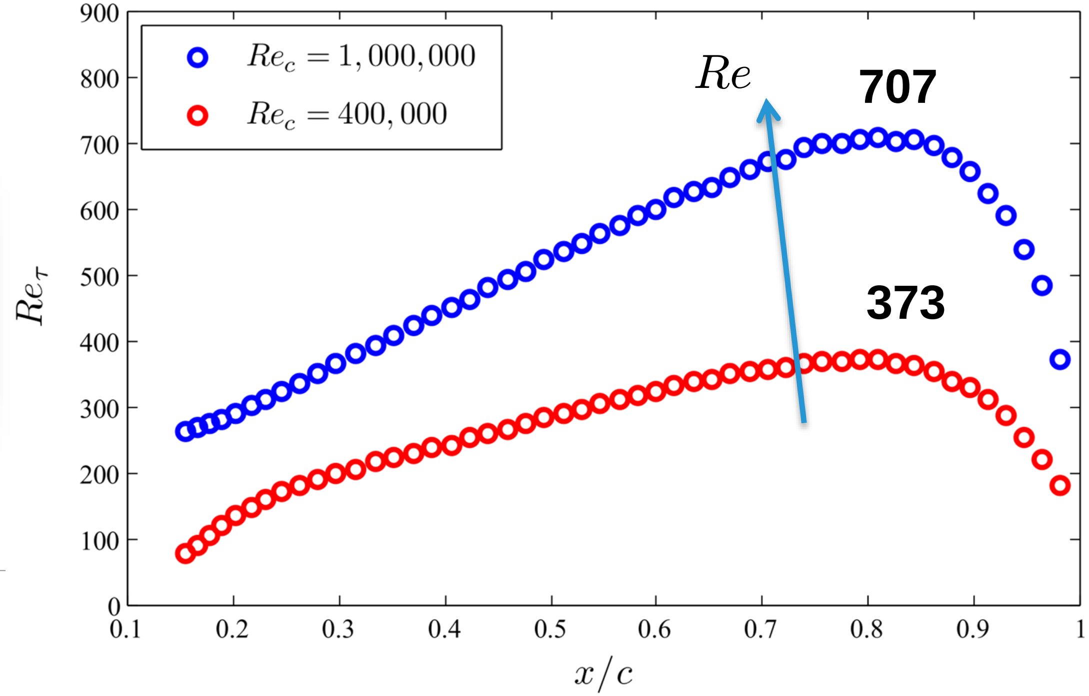
Resolution LES: $\Delta x^+<27$, $\Delta y^+{}_w<0.96$, $\Delta z^+<13$, $\Delta h<13\eta$
DNS: $\Delta x^+<10$, $\Delta y^+{}_w<0.5$, $\Delta z^+<5$, $\Delta h<5\eta$

Vinuesa *et al.* TSFP 10

Comparison of wings at Re_c=400k and 1 million
Boundary-layer development

- Comparison of β evolution with DNS at Re_c=400 000.



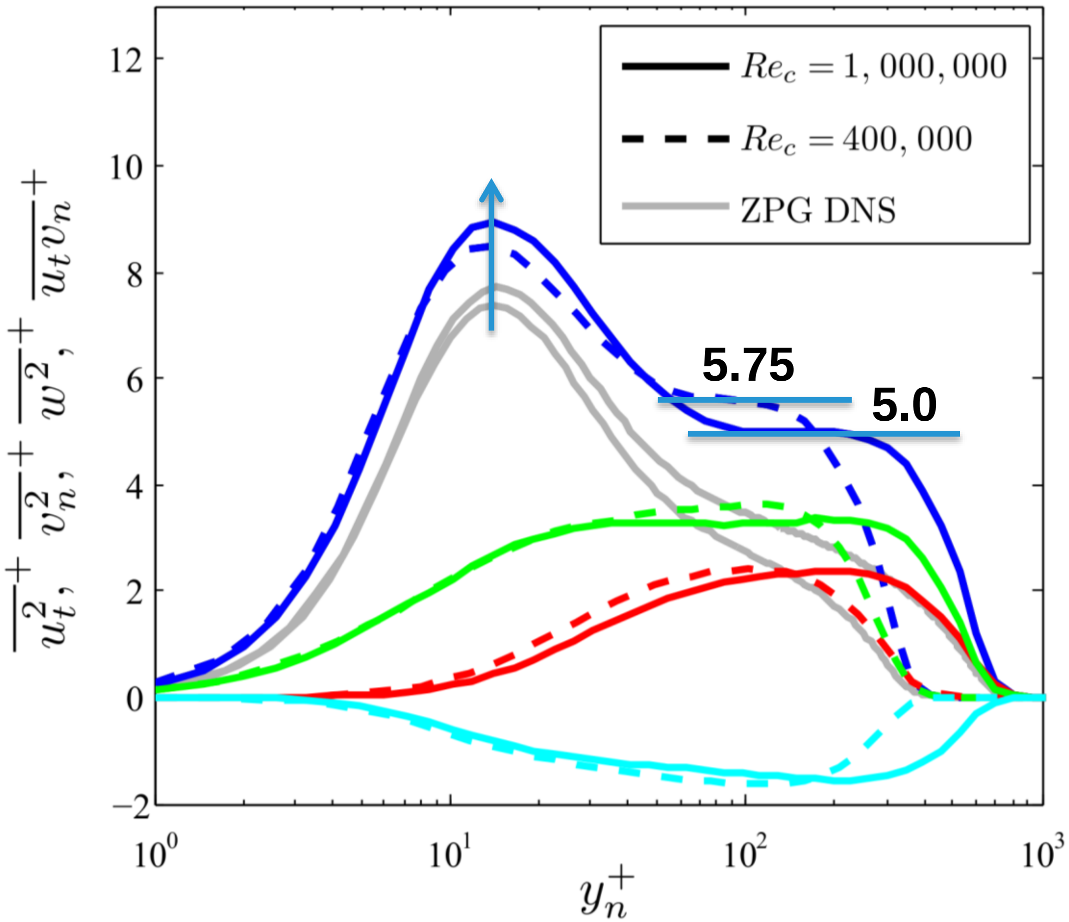


Pinkerton 1938: Limited influence of Re on pressure gradient

→ Re-effect on similar pressure gradient history!

Selected Reynolds stresses at x/c=0.7
APG magnitude: $\beta \approx 2$

- Comparison with matched ZPG at $Re_\tau \approx$ **356 and 671**



Ratio between inner peak and outer plateau	
Wing 400k	**Wing 1M**
1.48	**1.78**

Increase of uu^+ inner peak	
Wing	**ZPG**
≈5%	≈5%

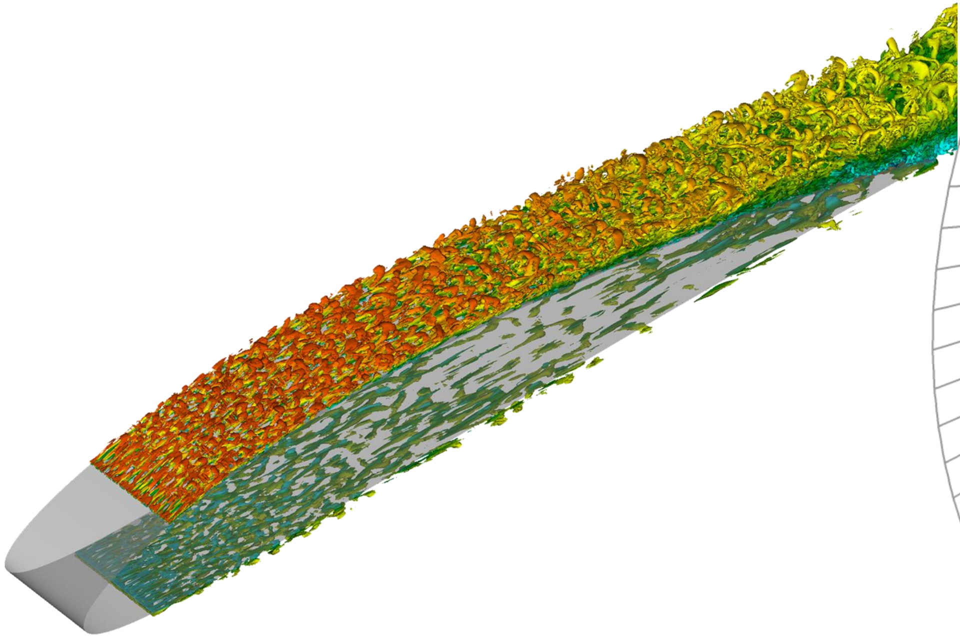
- Low-Re wing exhibits **higher energy accumulation in the outer region** of the boundary layer.
- *Low-Re wing is more sensitive to pressure-gradient effects.*

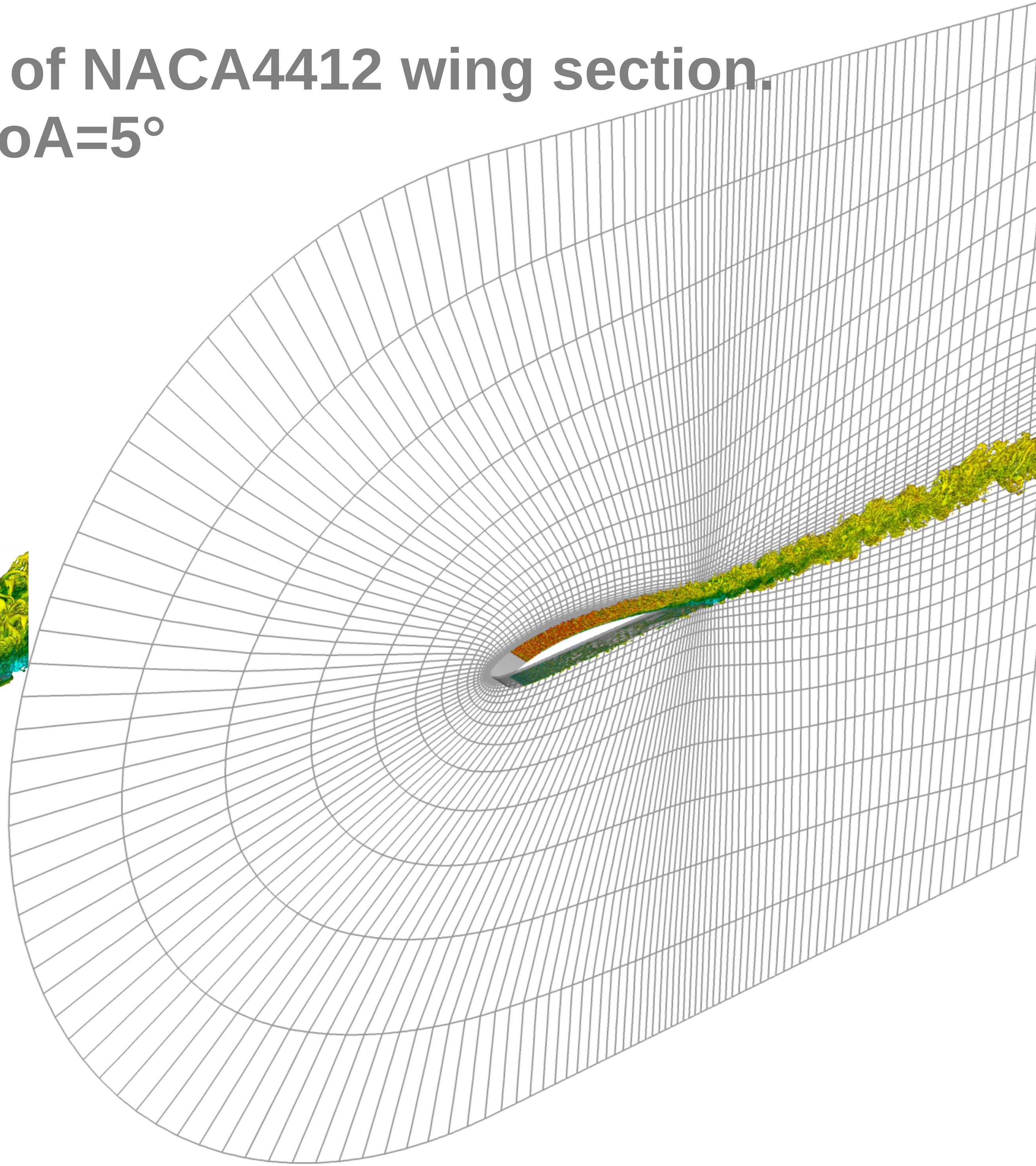
ZPG: Schlatter and Örlü, *J. Fluid Mech.* (2010)

LINNÉ FLOW CENTRE

Well-resolved LES of NACA4412 wing section. Re_c=100 000 and AoA=5°

- $Re_\theta \approx$ 1,050 and $Re_\tau \approx$ 140
- Flow tripped at x/c=0.1
- **48.4 million grid points.**
- Δx^+<18, Δy^+<0.64, Δz^+<9, Δh<9η



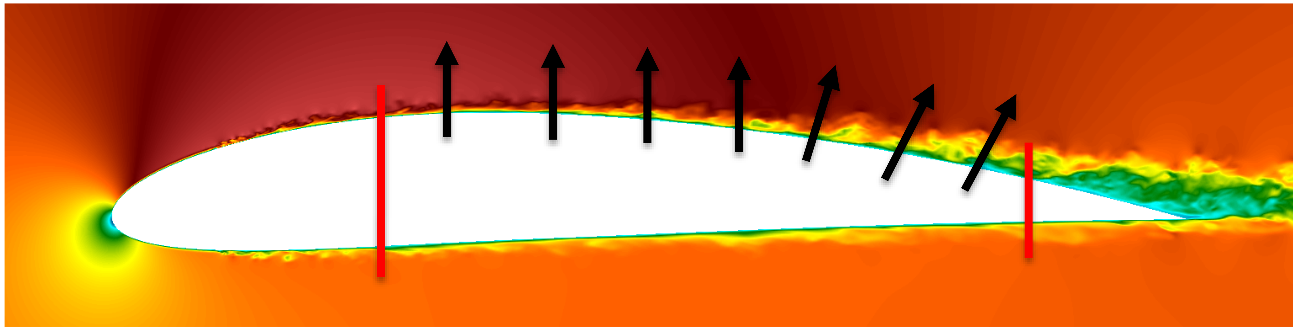


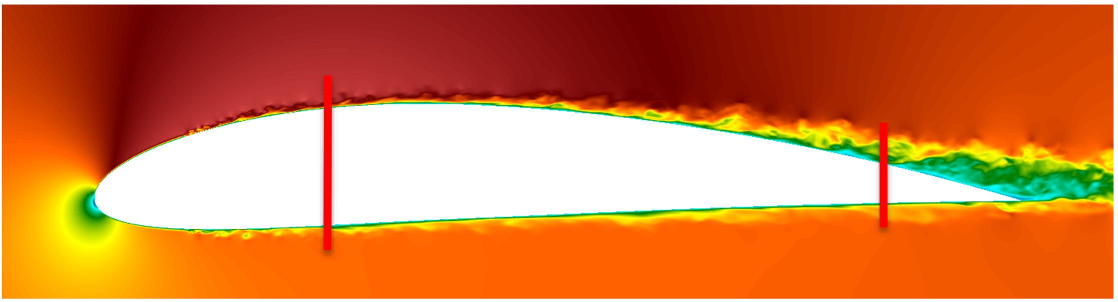
FLOW
LINNÉ FLOW CENTRE

Flow control through uniform blowing

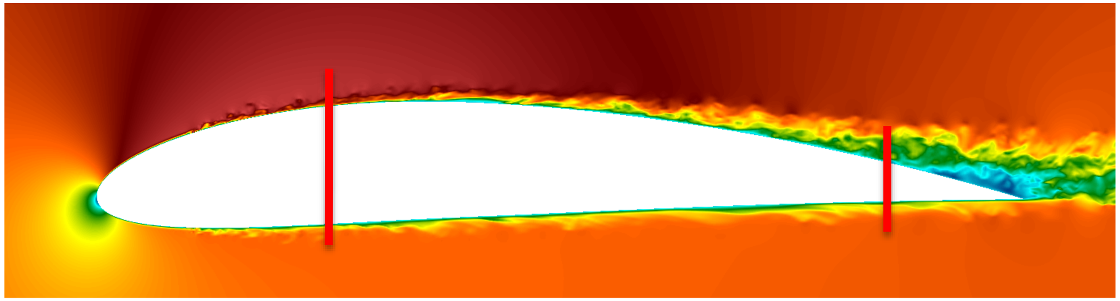
- Uniform blowing was applied on the suction side at $0.25 < x/c < 0.85$.
- Wall-normal velocity equal to 0.1% of the inflow.

$$V_{n,w} = 0.1\%\ U_\infty$$





uncontrolled

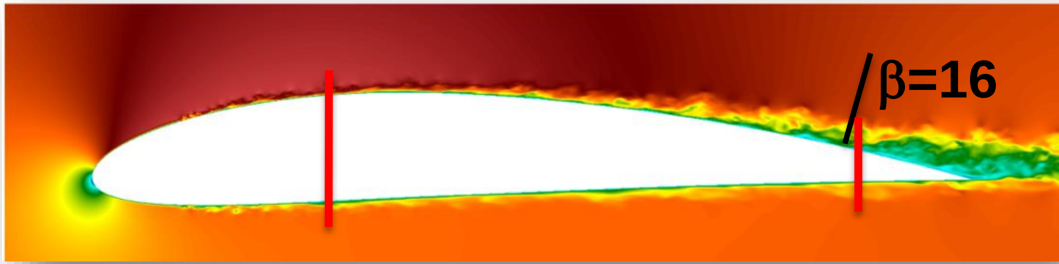


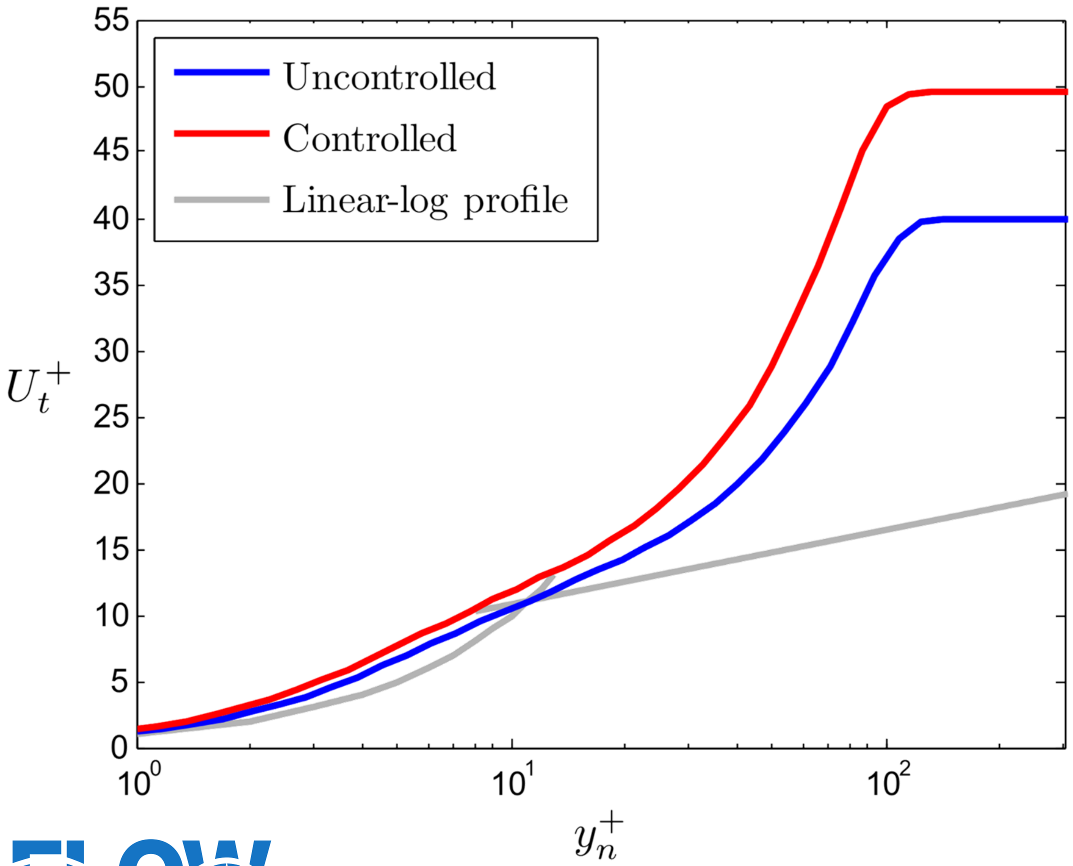
controlled

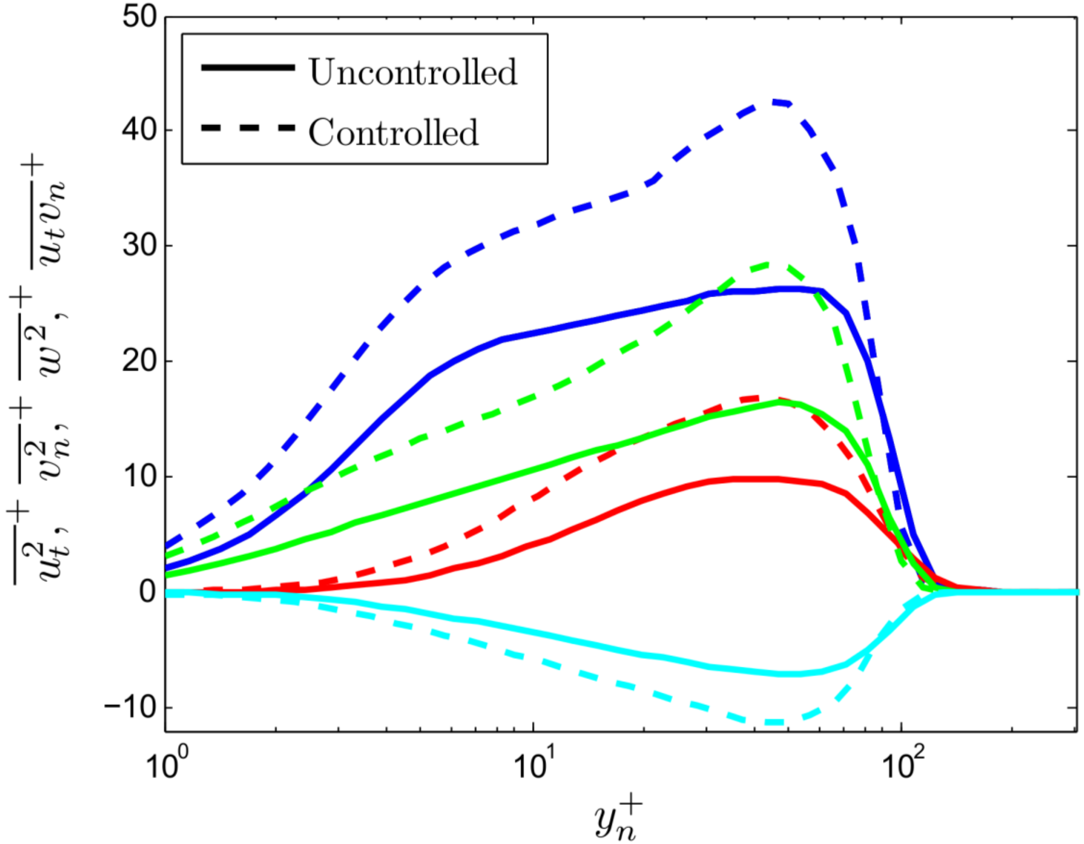
see *e.g.* Kametani *et al.* (2013, 2015)

Inner-scaled profiles

- **Reynolds-stress profiles** at x/c=0.85.
  Effect of blowing on mean and rms







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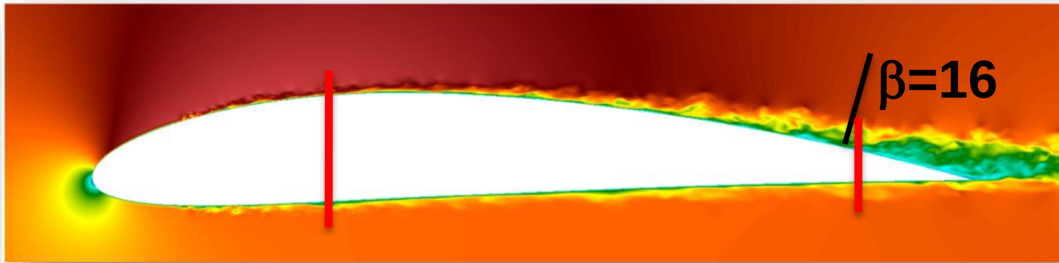

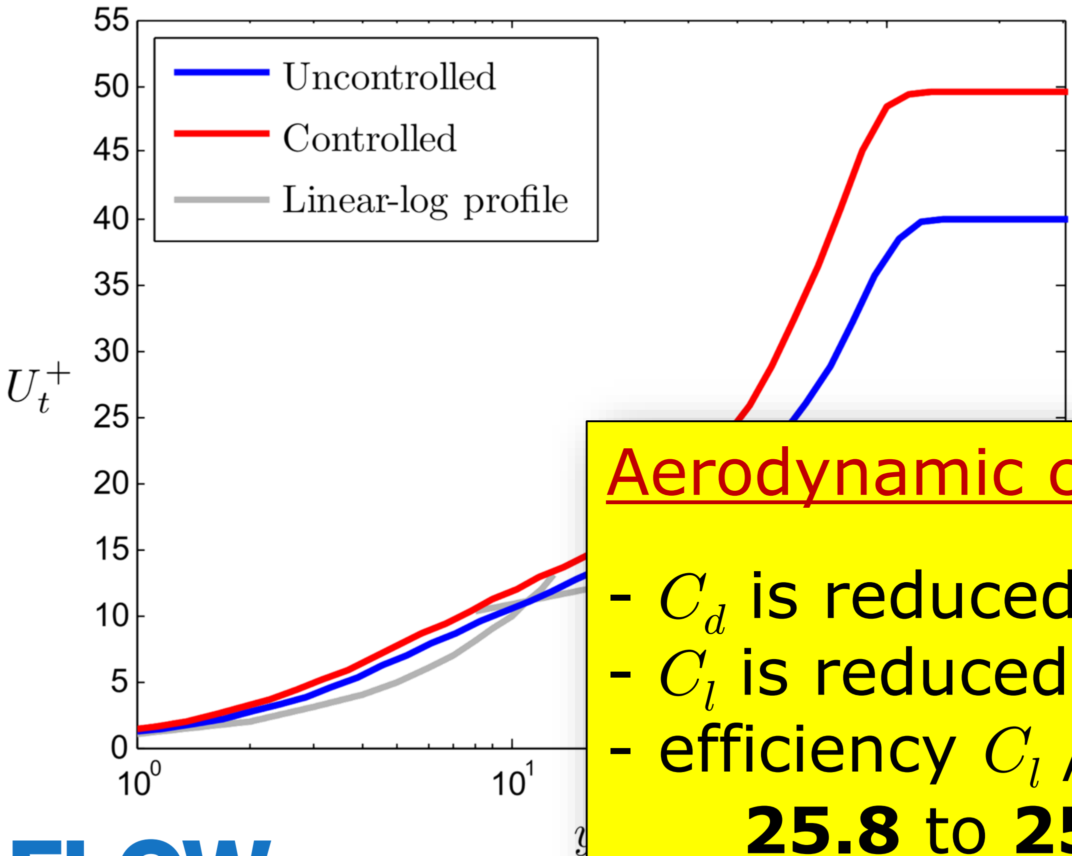

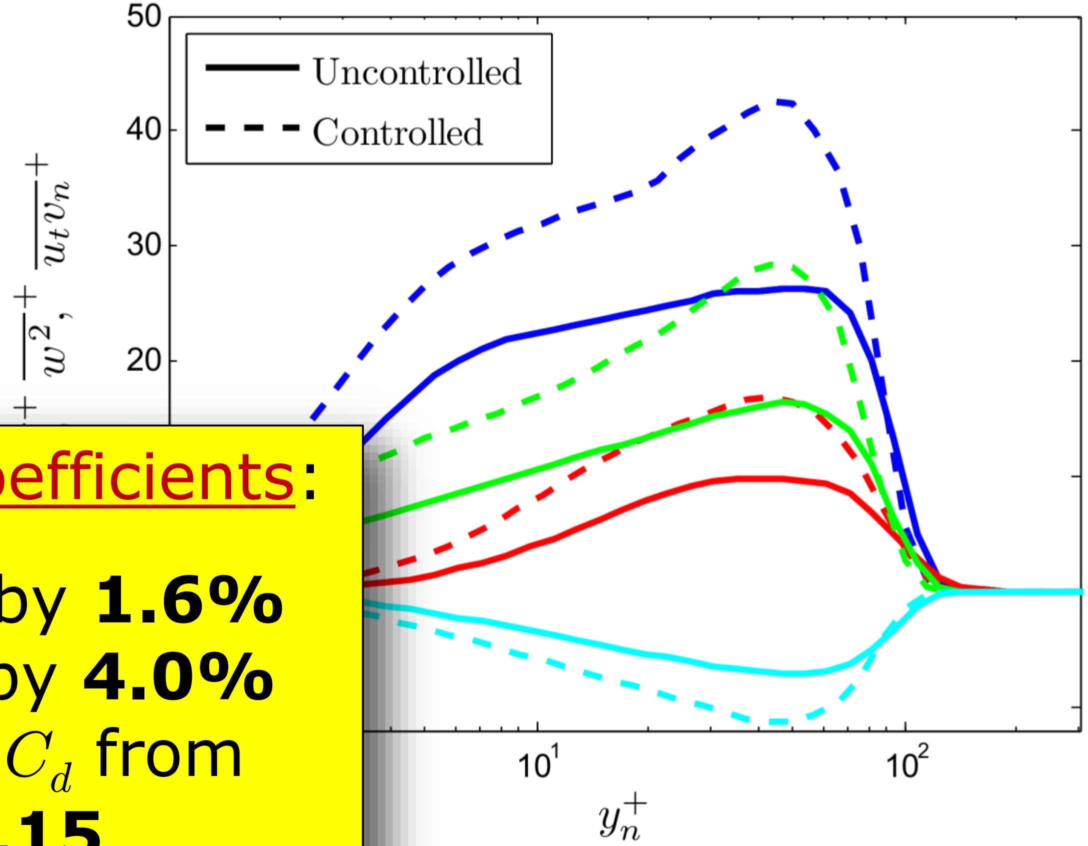

<u>Aerodynamic coefficients</u>:

- C_d is reduced by **1.6%**
- C_l is reduced by **4.0%**
- efficiency C_l / C_d from **25.8** to **25.15**.

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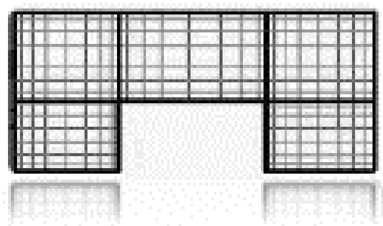

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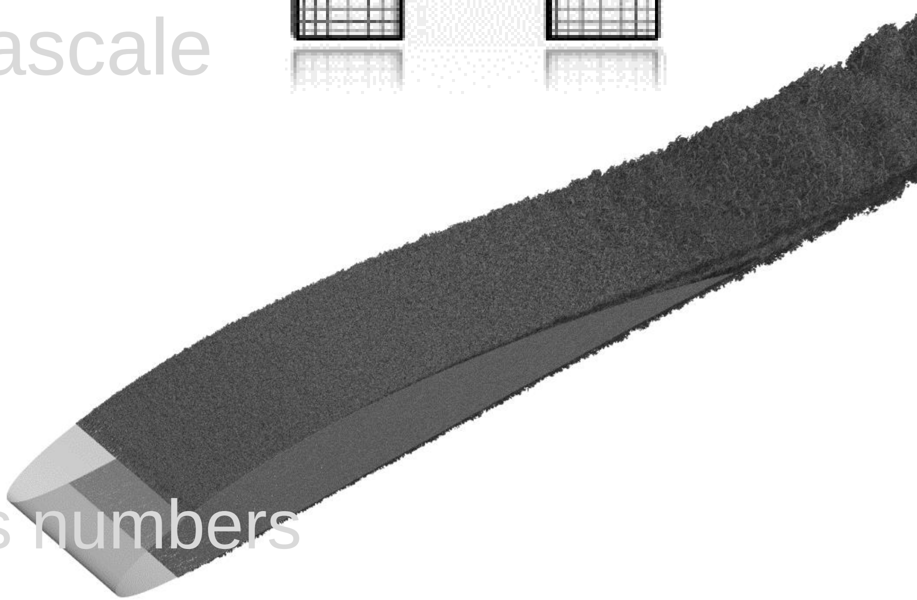

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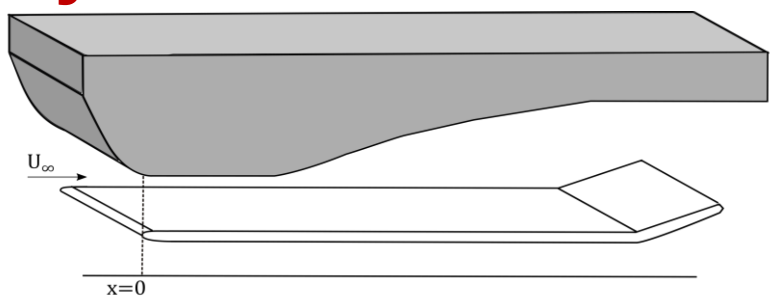
  - History effects



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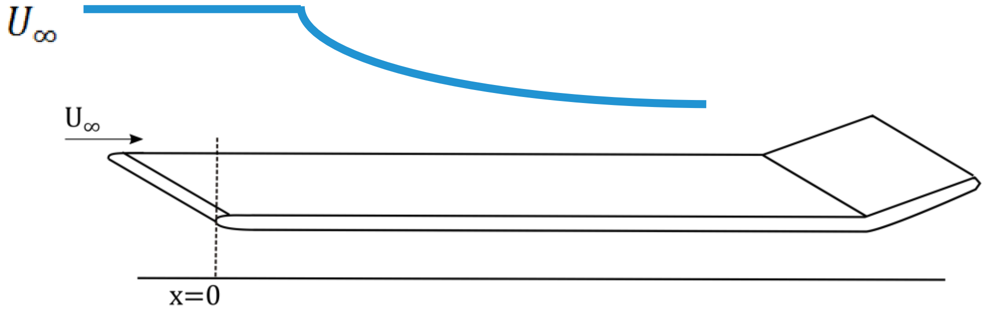
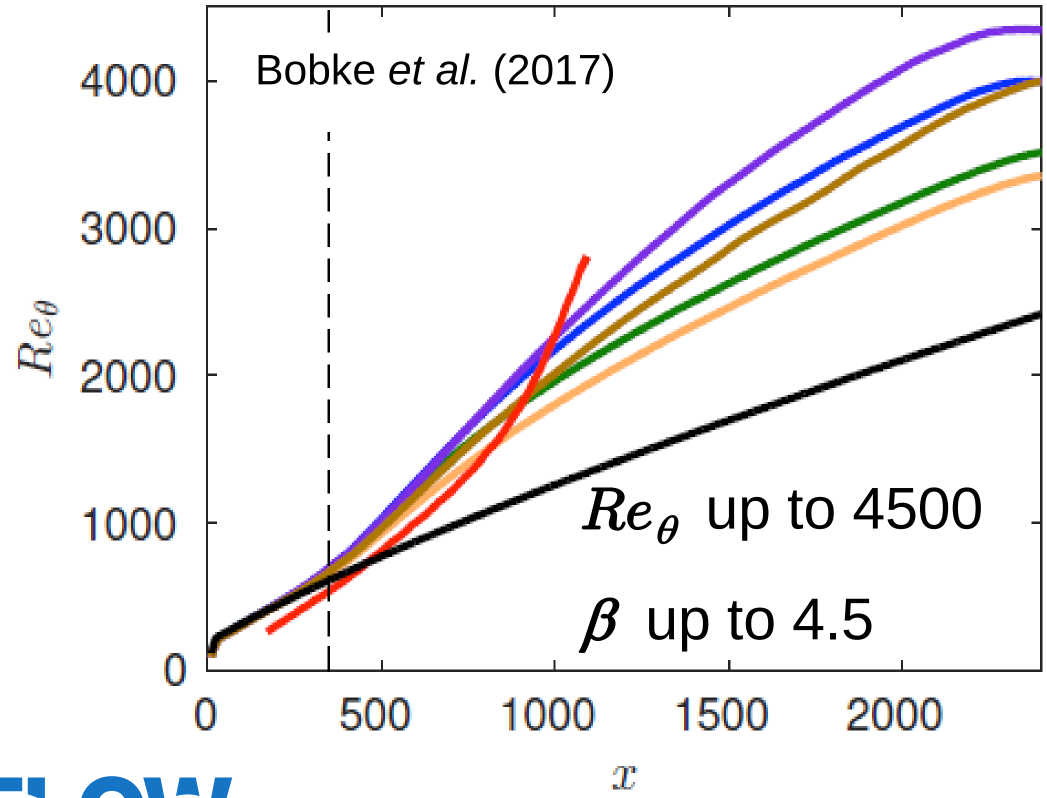
Simulations of ***flat-plate*** APG TBLs





- "Near-equilibrium" *(Townsend 1956, Mellor & Gibson 1966)* flows (constant m cases) with **non-constant β**

$$U_\infty = \left(1 - \frac{x}{x_0}\right)^m$$

- **constant β cases** (obtained through iteration of x_0 and m)

Case	Type	Color code
$m13$ (Bobke *et al.* 2016*b*)	LES	green
$m16$ (Bobke *et al.* 2016*b*)	LES	blue
$m18$ (Bobke *et al.* 2016*b*)	LES	purple
$b1$	LES	orange
$b2$	LES	brown
Wing (Hosseini *et al.* 2016)	DNS	red
ZPG (Schlatter *et al.* 2009)	DNS	black

Skin-friction prediction for (in-house) PG TBLs

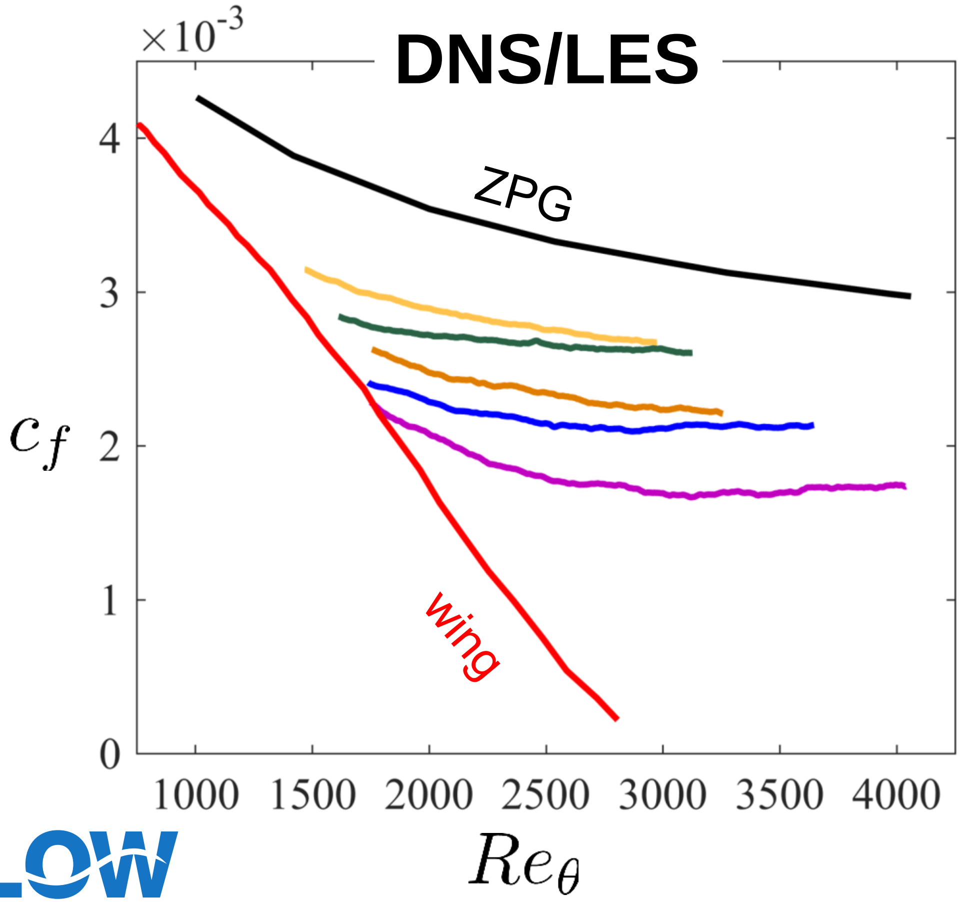
Case	Type	Color code
$m13$ (Bobke *et al.* 2016*b*)	LES	green
$m16$ (Bobke *et al.* 2016*b*)	LES	blue
$m18$ (Bobke *et al.* 2016*b*)	LES	purple
$b1$	LES	orange
$b2$	LES	brown
Wing (Hosseini *et al.* 2016)	DNS	red
ZPG (Schlatter *et al.* 2009)	DNS	black

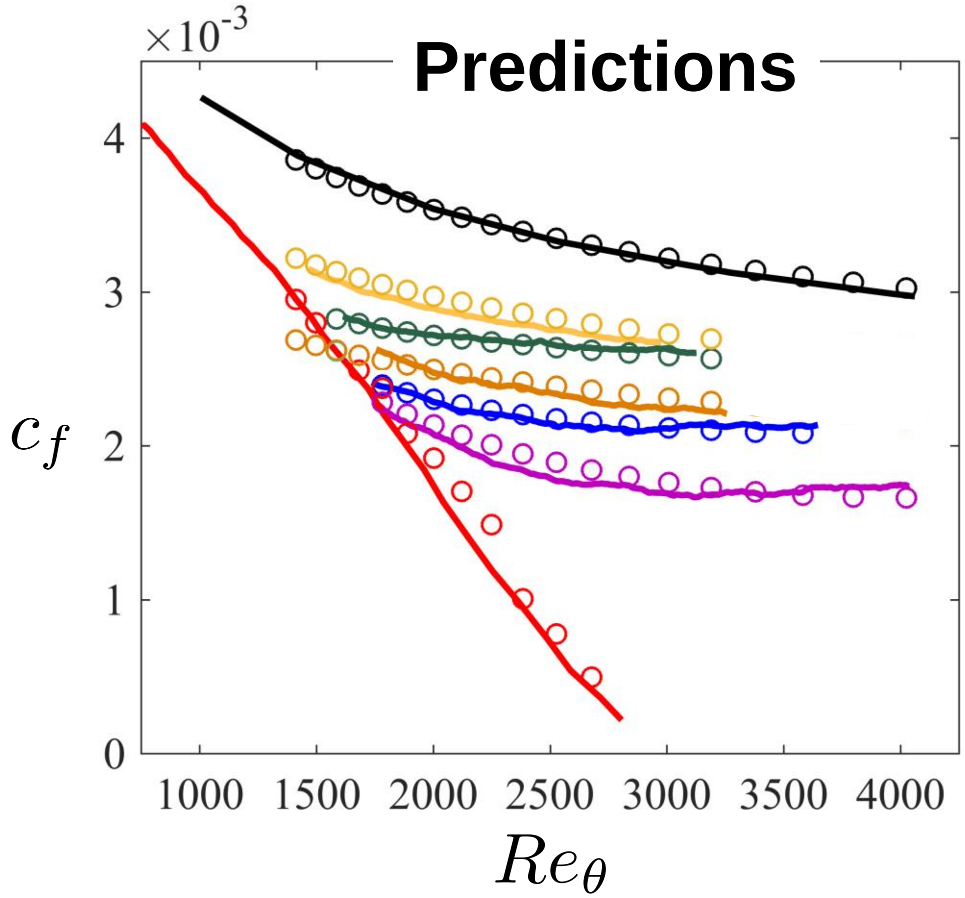
$$c_{f,PG} = \frac{c_{f,ZPG}}{H_{ZPG}^{\overline{\beta}/2}}$$

e.g. from ZPG correlations

Use known β - distribution

$$\overline{\beta}(Re_\theta) = \frac{1}{Re_\theta - Re_{\theta,0}} \int_{Re_{\theta,0}}^{Re_\theta} \beta(Re_\theta)\,\mathrm{d}Re_\theta$$

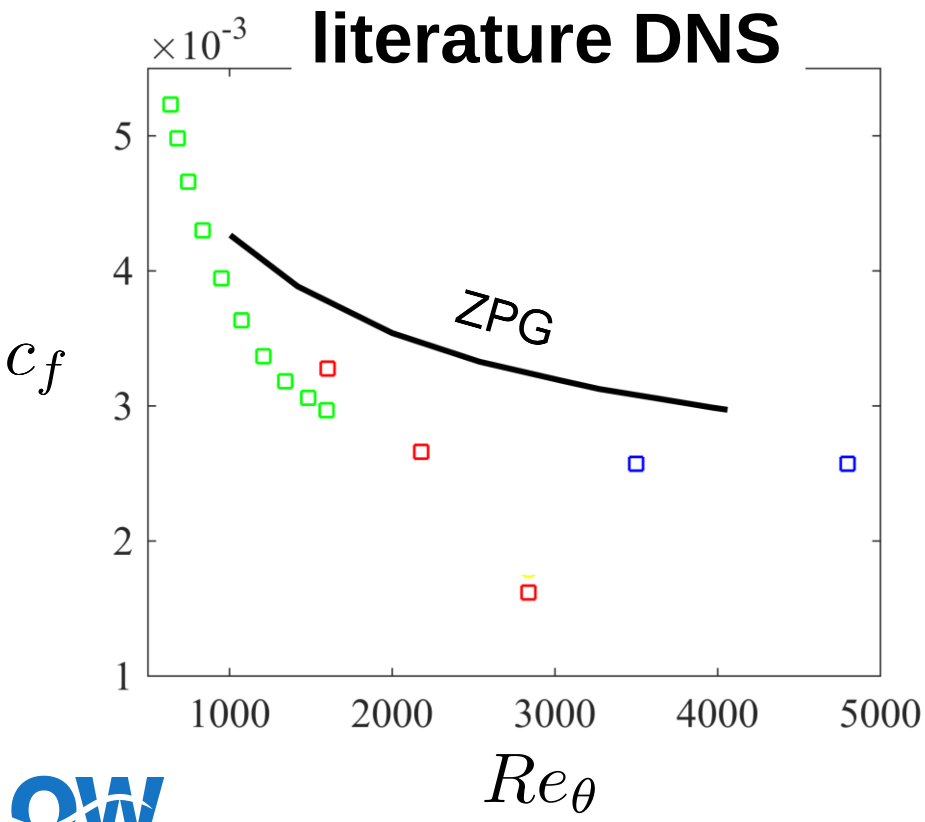


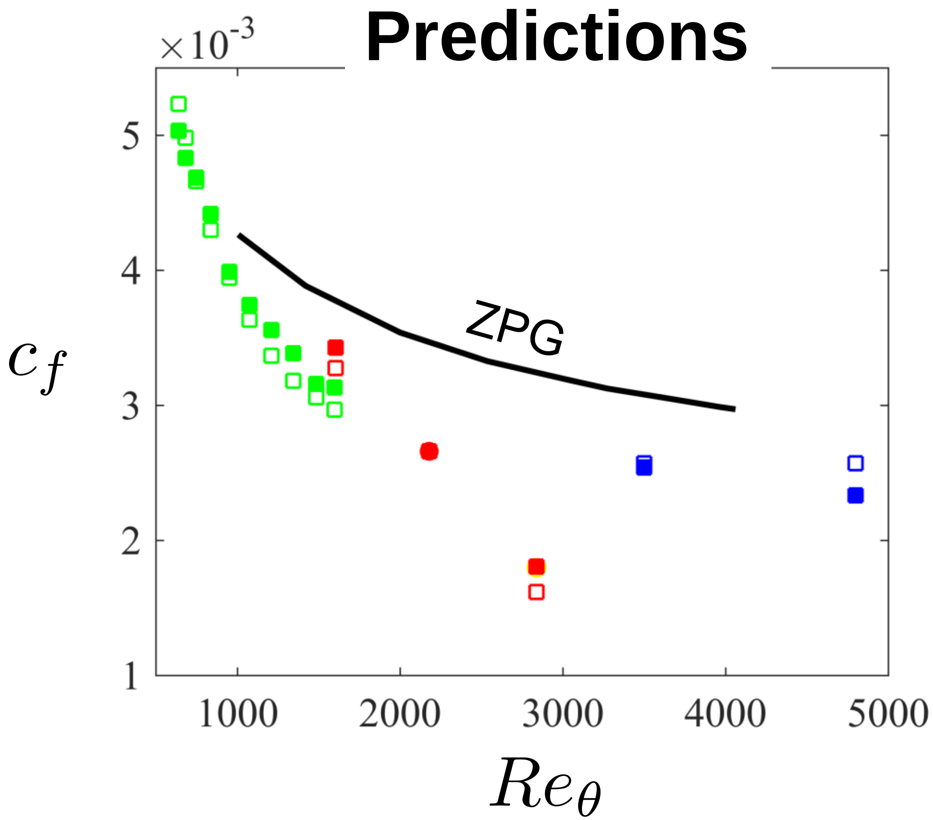


Skin-friction prediction for (literature) PG TBLs

$$c_{f,PG} = \frac{c_{f,ZPG}}{H_{ZPG}^{\overline{\beta}/2}}$$

Reference	Type of data	Range of Re_θ under study	Range of β	Symbol
Kitsios et al. (2016)	DNS	$3,500 < Re_\theta < 4,800$	$\simeq 1$	blue square
Lee (2017)	DNS	$1,605 < Re_\theta < 2,840$	$\simeq 0.73$, $\simeq 2.2$ and $\simeq 9$	red square
Spalart and Watmuff (1993)	DNS	$640 < Re_\theta < 1,600$	$-0.3 < \beta < 2$	green square





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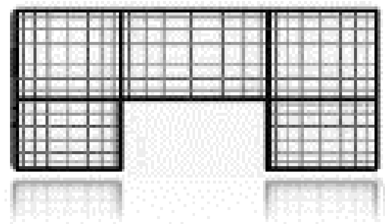

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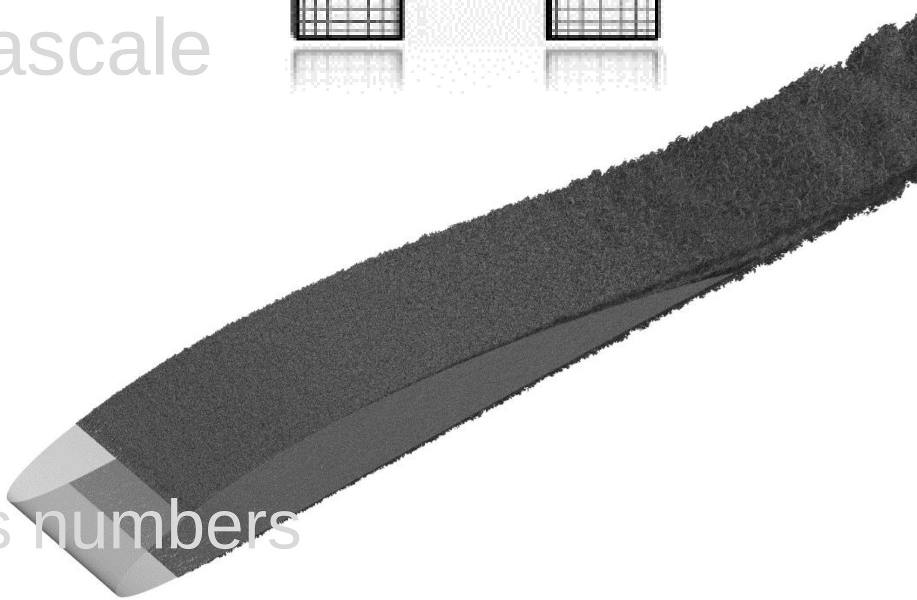

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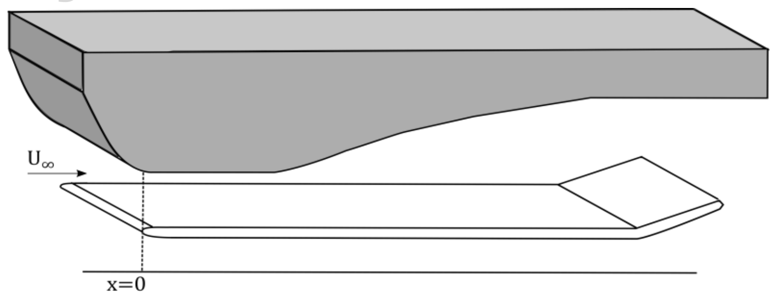
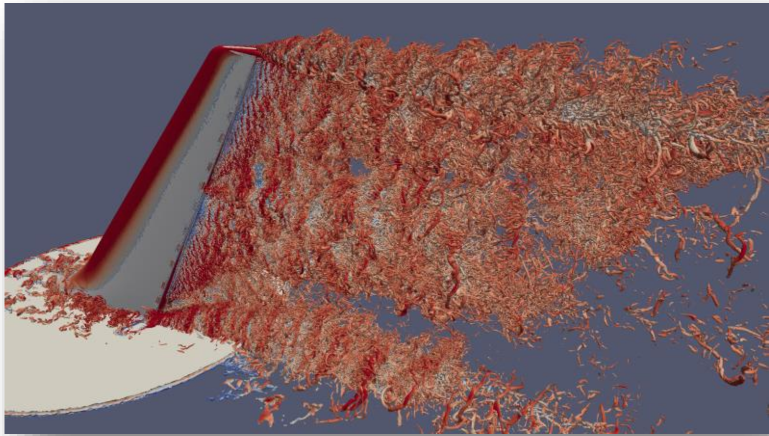


- Conclusions and outlook
  - Compression and mesh refinement

Outlook

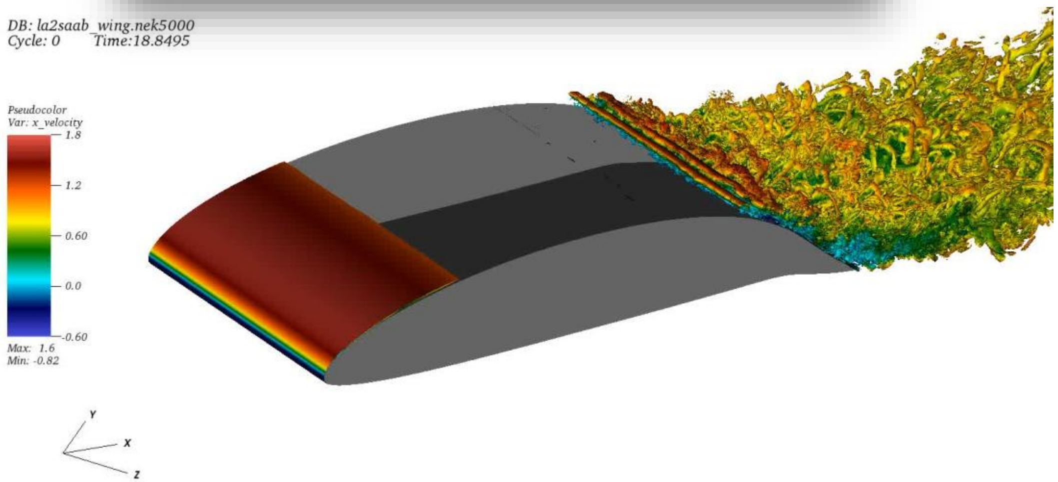
- More **complex (3D) geometries**

  Jansen, ALCF Early Science Projects



- **Pitching wings**

  Negi, KTH Mechanics

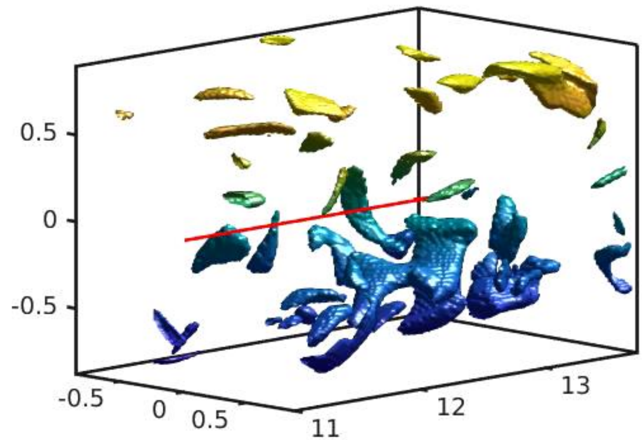


- **Experiments of NACA4412**

  Dogan, KTH Mechanics

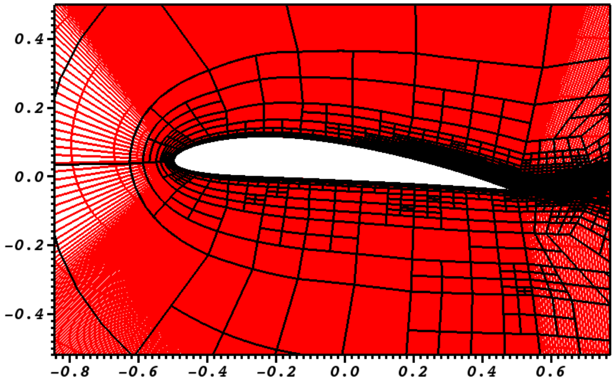
- **Analysis of structures** in APG TBL

  Atzori, KTH Mechanics



- **Adaptive mesh refinement, compression** *etc*.

Offermans/Peplinski, KTH Mechanics



Conclusions

- Large-scale simulations using **high-order (spectral) methods**

- Numerical databases with **highest Re in the literature**:
  DNS Re_c = *400 000* and **LES at Re_c = *1 000 000***
- Scaling effects at different Re_c relevant to important applications such as **flow control** and **pitching airfoils**.
- Analysis of interesting physics on airfoils, like backflow events, and **history effect**.

- The "**virtual wind tunnel**" enables characterisation of complicated flow cases with an unprecedented level of detail:
  - Influence of pressure gradients, comparison to flat plates, …
  - Tracking of turbulence features (vortices, clusters etc.)
  - Experiments in the MTL wind tunnel

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Acknowledgments:

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Thank You!