High-fidelity simulations of turbulent boundary layers on flat and curved surfaces

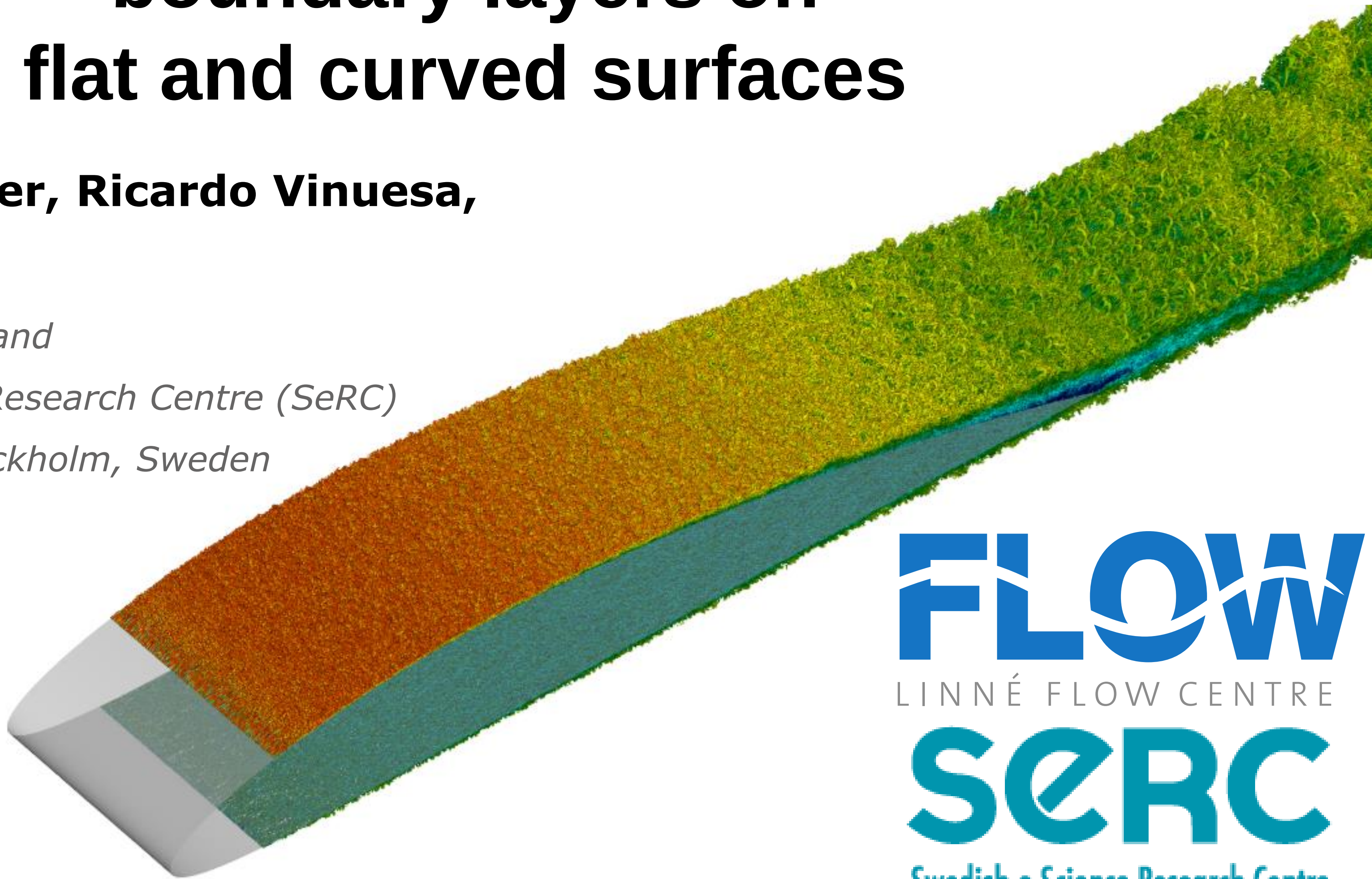
Philipp Schlatter, Ricardo Vinuesa,

Ramis Örlü

Linné FLOW Centre and

Swedish e-Science Research Centre (SeRC)

KTH Mechanics, Stockholm, Sweden



Marine 2019, Gothenburg, 14 May 2019

Outline

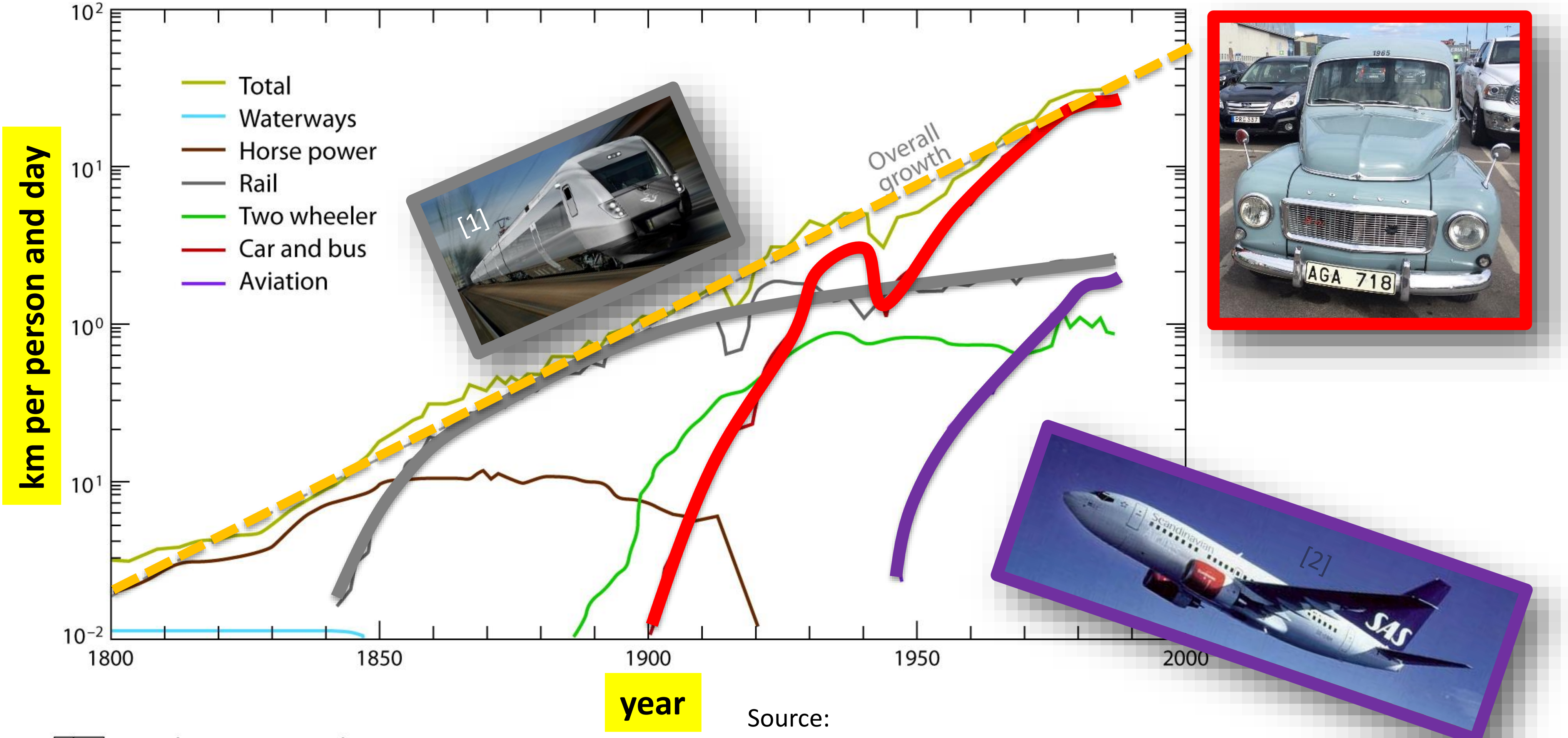
- Introduction – HPC
- Turbulent boundary layers – Simulation
- Wing simulations
- Flow control
- Codes and tools

Outline

- Introduction – HPC
- Turbulent boundary layers – Simulation
- Wing simulations
- Flow control
- Codes and tools

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

Navier-Stokes equations…

Data from Mira (ANL, 2013), million core hours

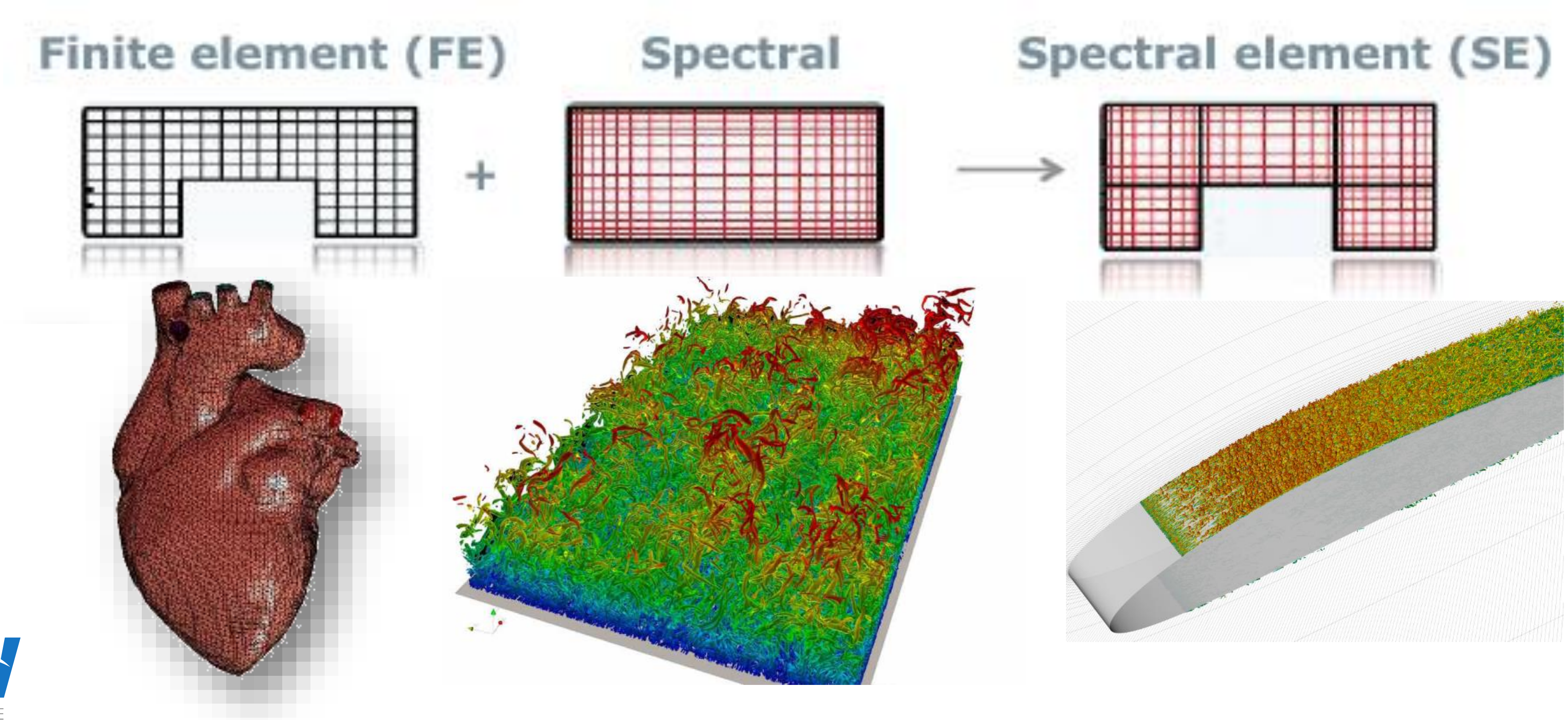
• Engineering/CFD	525	19%
• Subsurface flow & reactive transport	80	3%
• Combustion	100	4%
• Climate	280	10%
• Astrophysics	133	5%
	1118	**40%**

(fraction of Navier-Stokes based simulations on current supercomputers)

Why Spectral Elements?

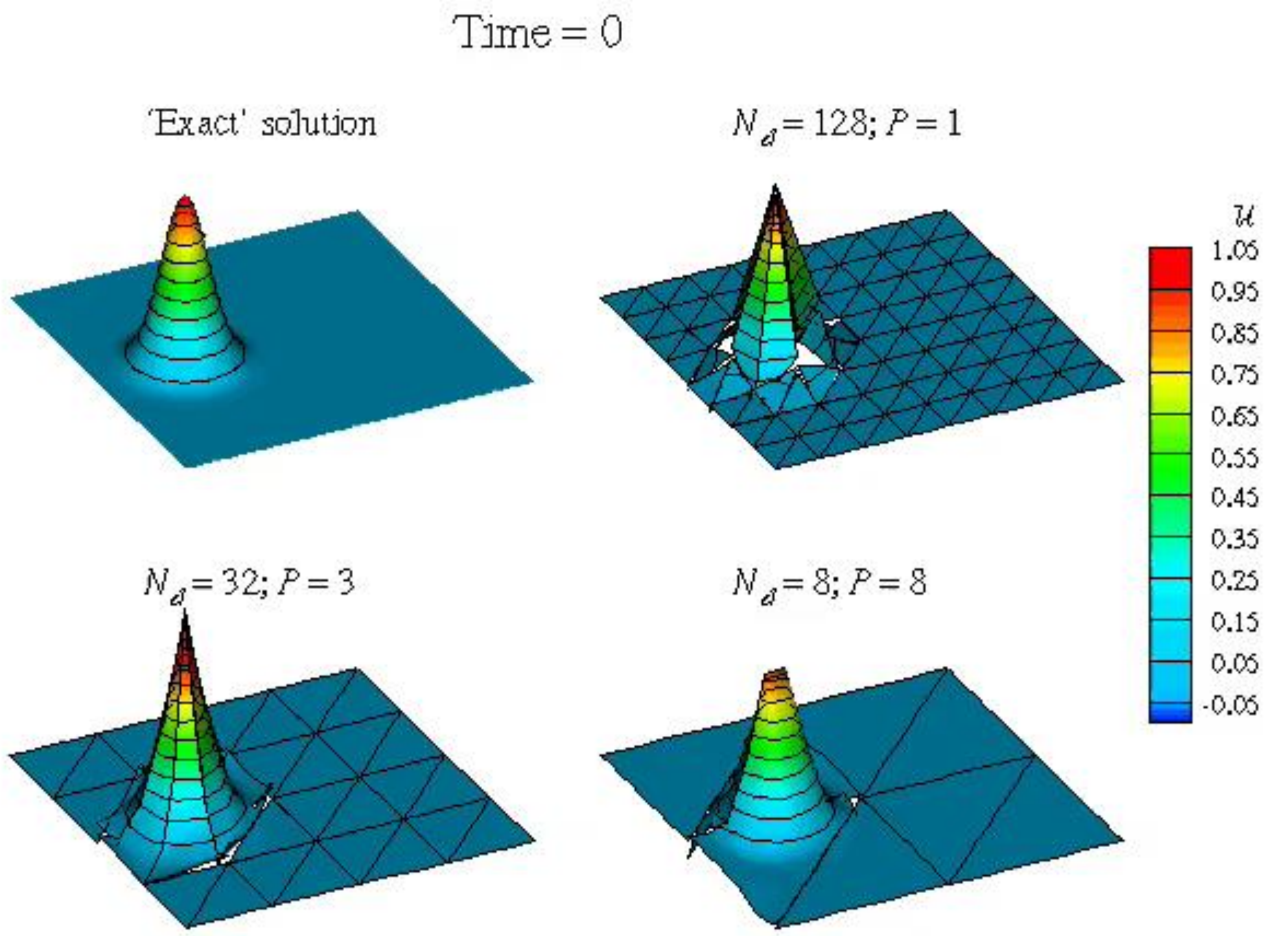
- **High-order numerical methods** are beneficial for accurate simulations of turbulent flows due to the significant scale disparity of the flow structures, both in time and space.

- 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”**



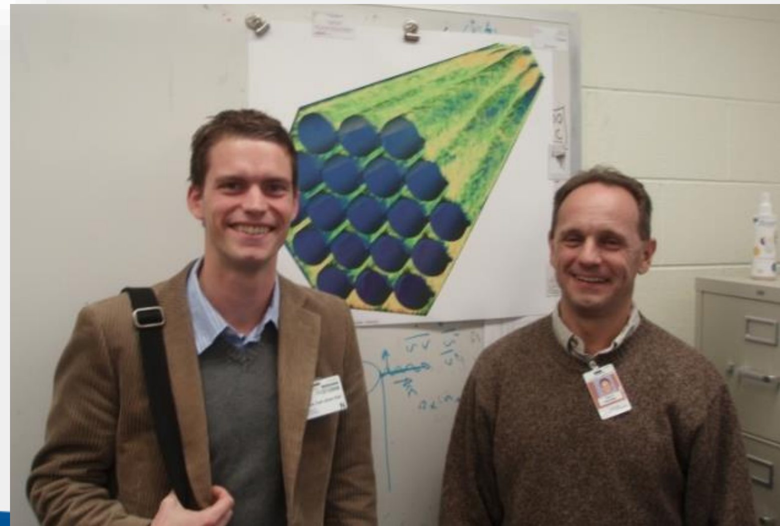
From David Moxey, Univ. Exeter

Nek5000 – Spectral Elements (CG)

- 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, Excellerat …): adaptive meshing, GPUs, …

ExaFLOW

- Good scaling up to **1,000,000** ranks on Mira (10PFlops BG/Q)



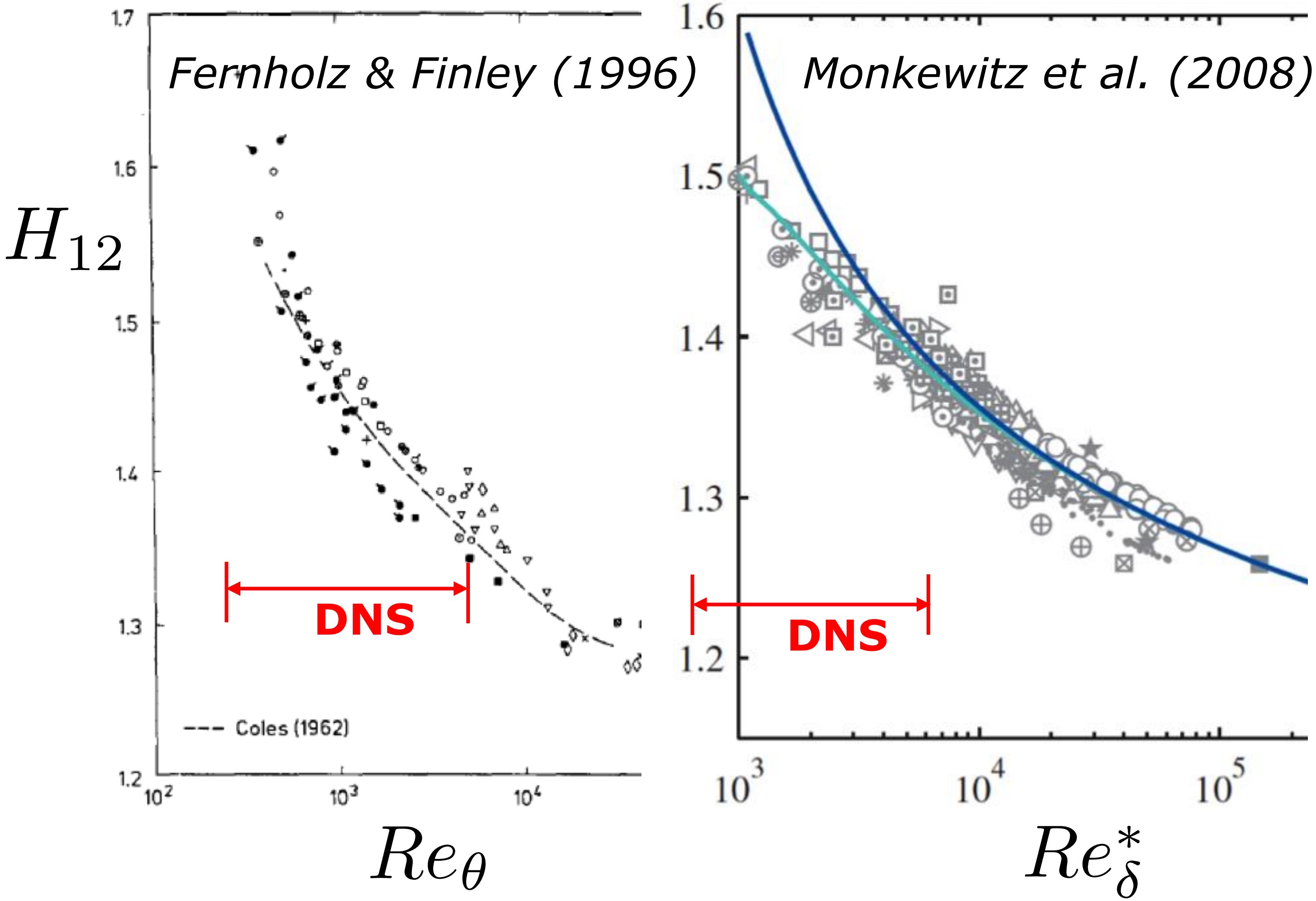
ExaFLOW Team

- → 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

Outline

- Introduction – HPC
- Turbulent boundary layers – Simulation
- Wing simulations
- Flow control
- Codes and tools

What we are used/expect to see …

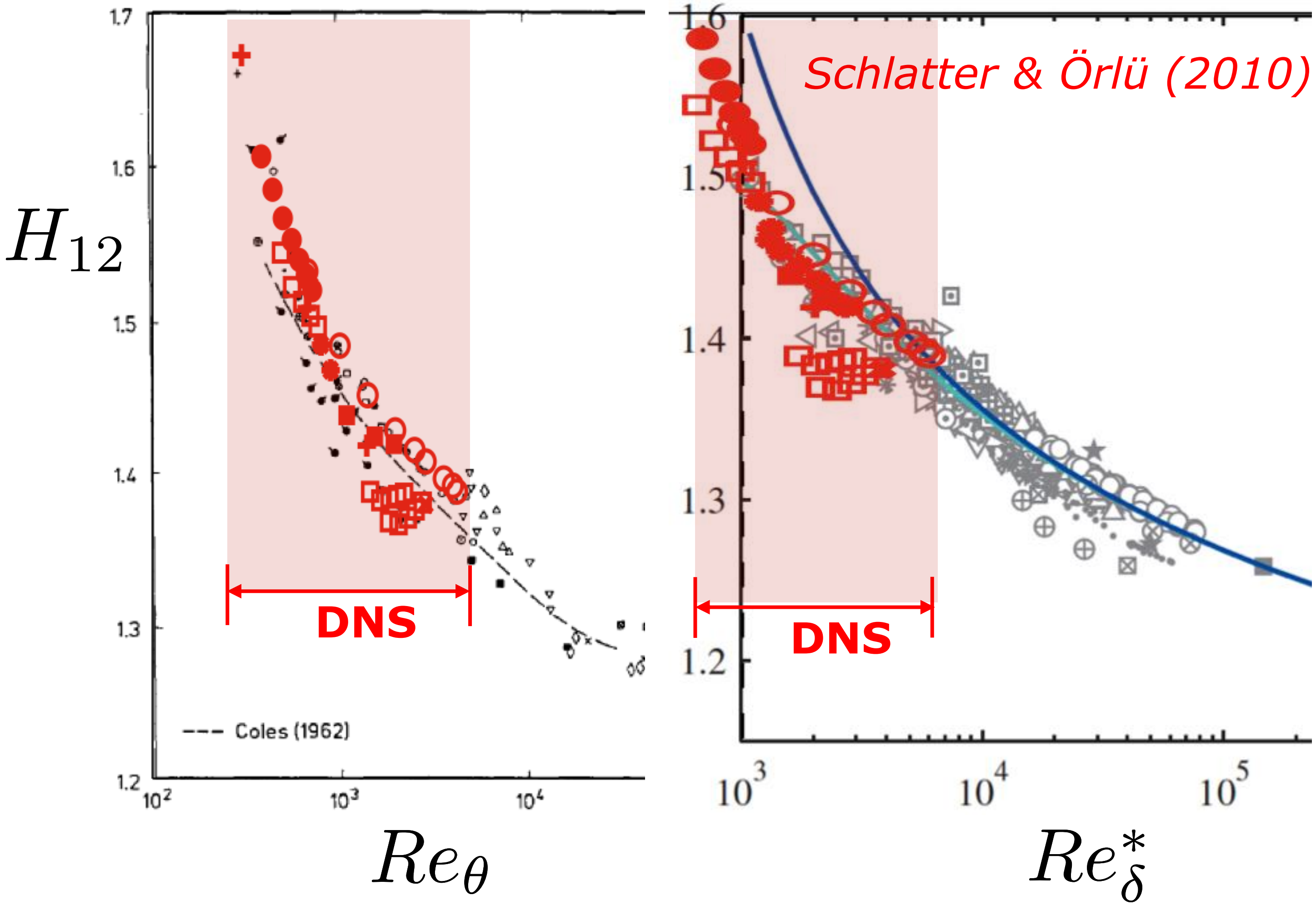


ROYAL INSTITUTE OF TECHNOLOGY

Compilation/ Assessment of experimental data from ZPG TBL flows

Physical experiments are commonly scrutinised before they are employed to calibrate, test, or validate other experiments, scaling laws or theories

… and what “we” are not so used to see



KTH VETENSKAP OCH KONST

ROYAL INSTITUTE OF TECHNOLOGY

Red symbols are data from 7 independent DNS from ZPG TBL flows

Simulation data are hardly scrutinised, when it comes to basic (integral) quantities

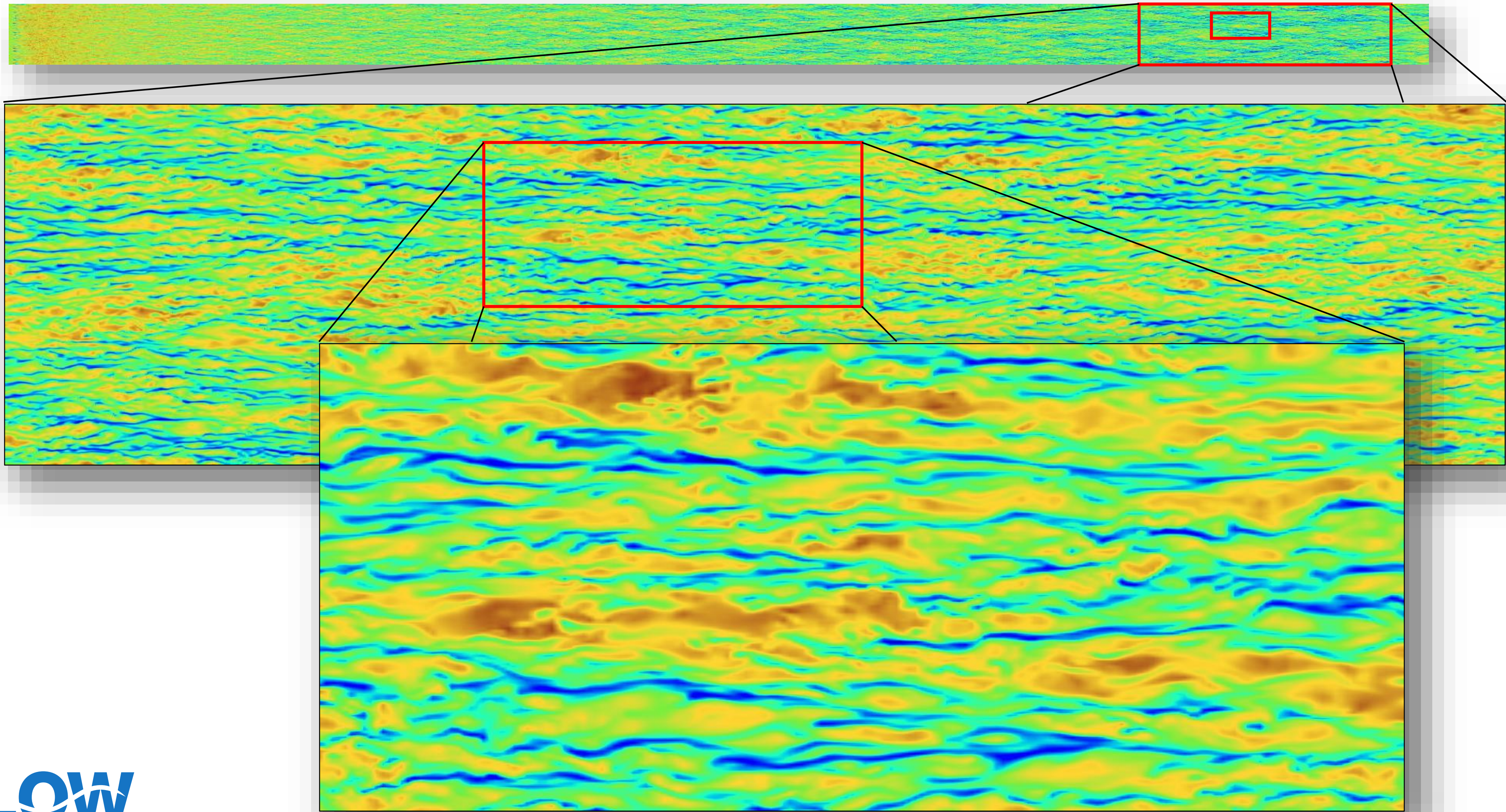
Turbulent flow close to solid walls...

TSFP-7 in 2011

Turbulent flow close to solid walls...

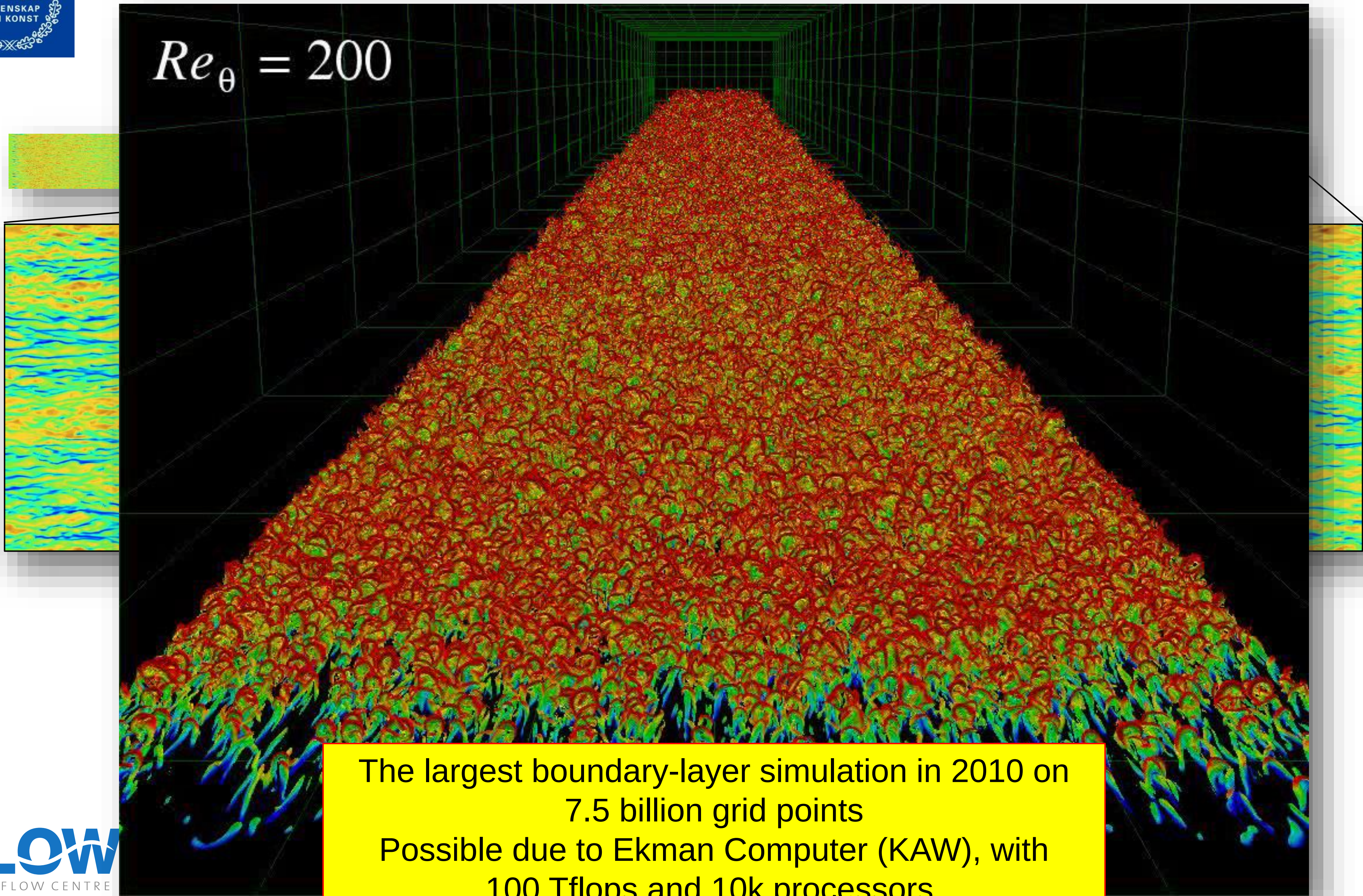
TSFP-7 in 2011

simulation result



FLOW
LINNÉ FLOW CENTRE

Turbulent flow close to solid walls...

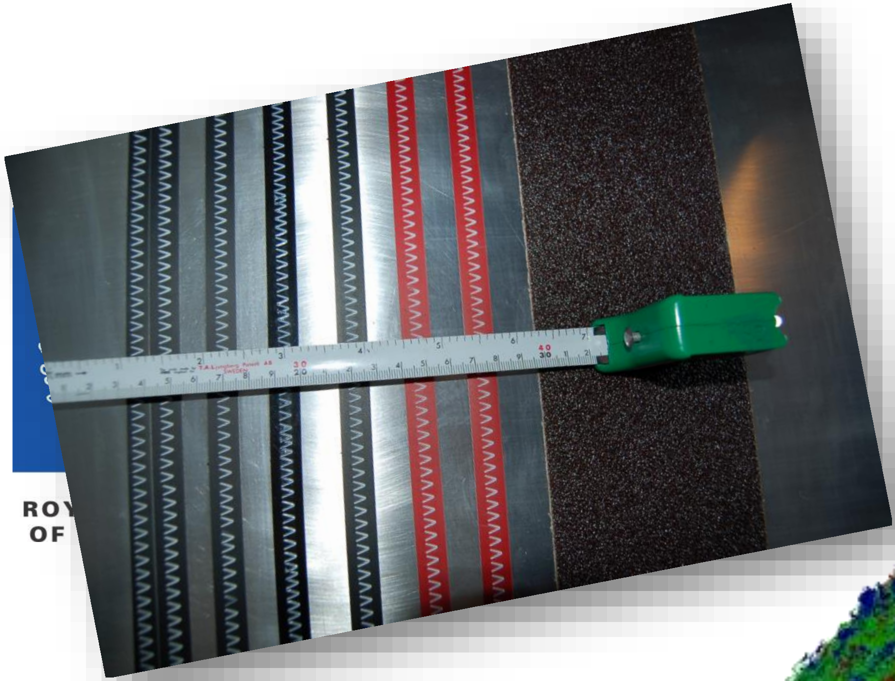


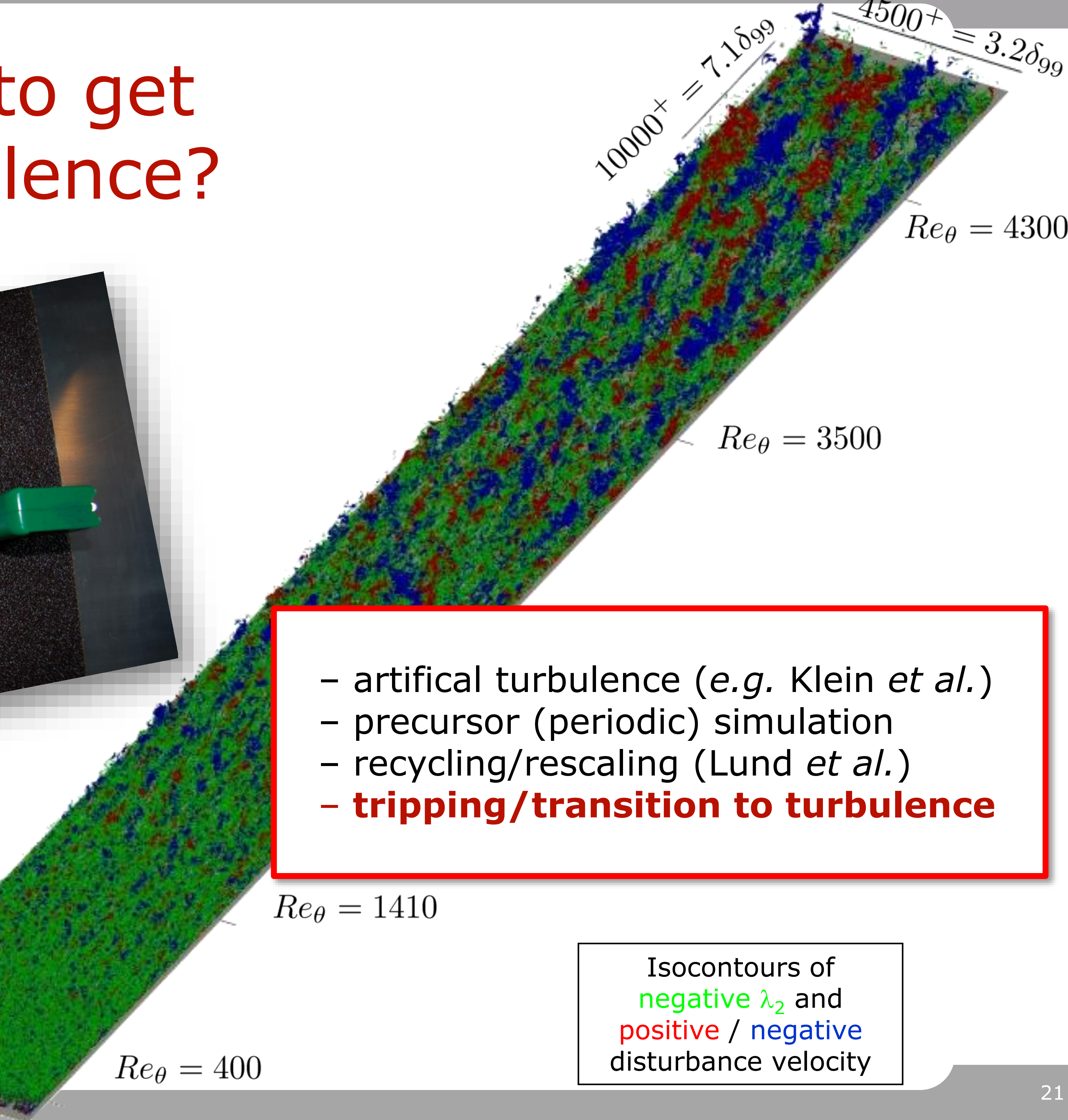
The largest boundary-layer simulation in 2010 on
7.5 billion grid points
Possible due to Ekman Computer (KAW), with
100 Tflops and 10k processors.

How to get turbulence?

ROYAL INSTITUTE
OF TECHNOLOGY

How to get turbulence?



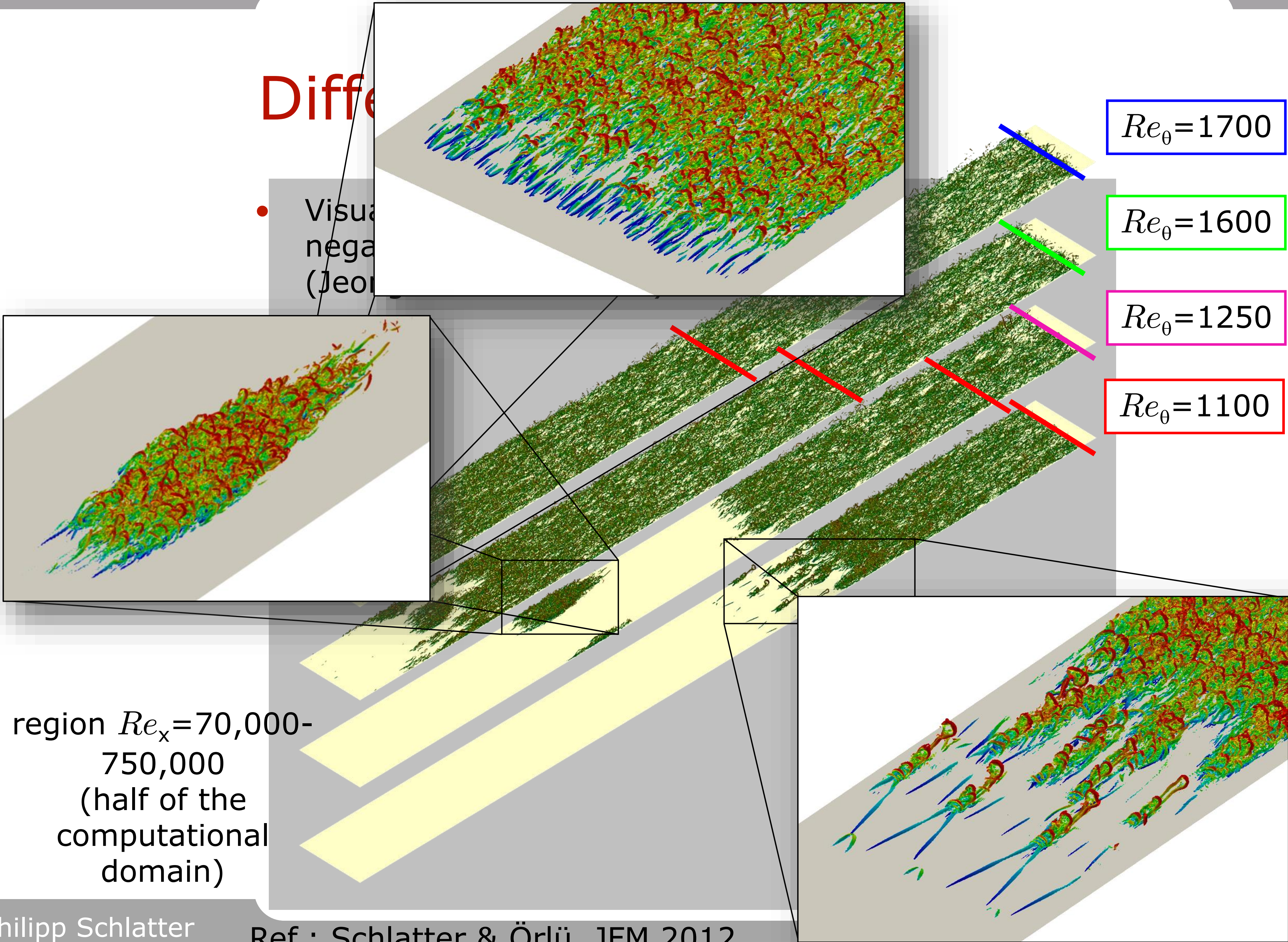


- artifical turbulence (*e.g.* Klein *et al.*)
- precursor (periodic) simulation
- recycling/rescaling (Lund *et al.*)
- **tripping/transition to turbulence**

Isocontours of negative λ_2 and positive / negative disturbance velocity

Diffe

- Visua nega (Jeon



region Re_x=70,000-750,000 (half of the computational domain)

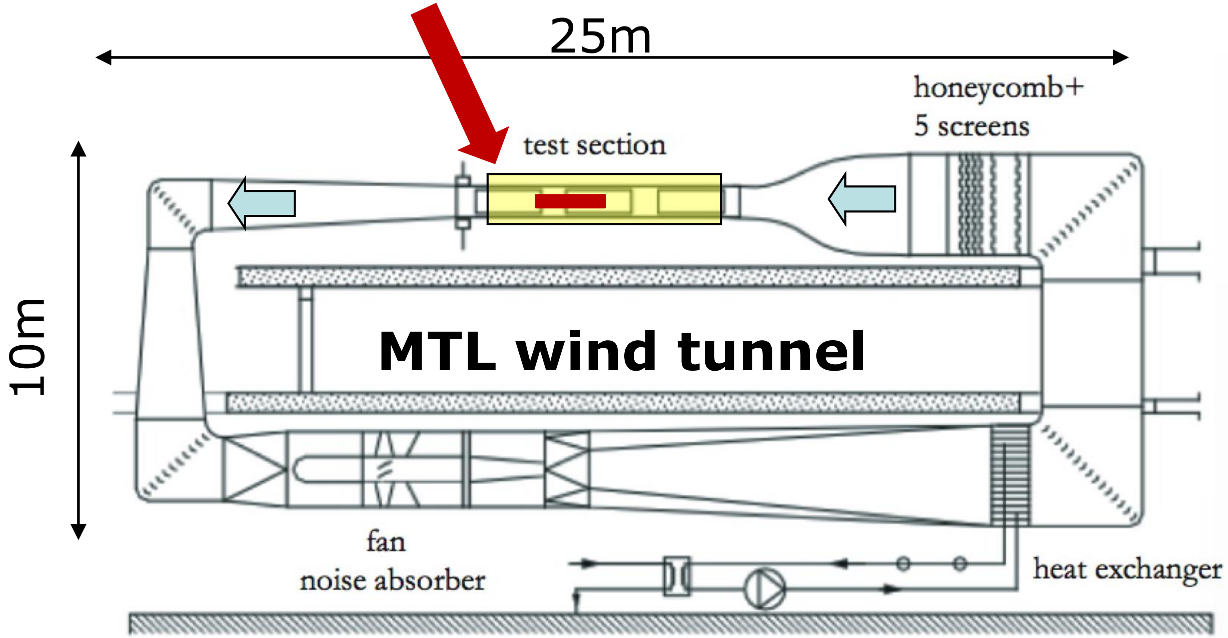
Ref.: Schlatter & Örlü, JFM 2012

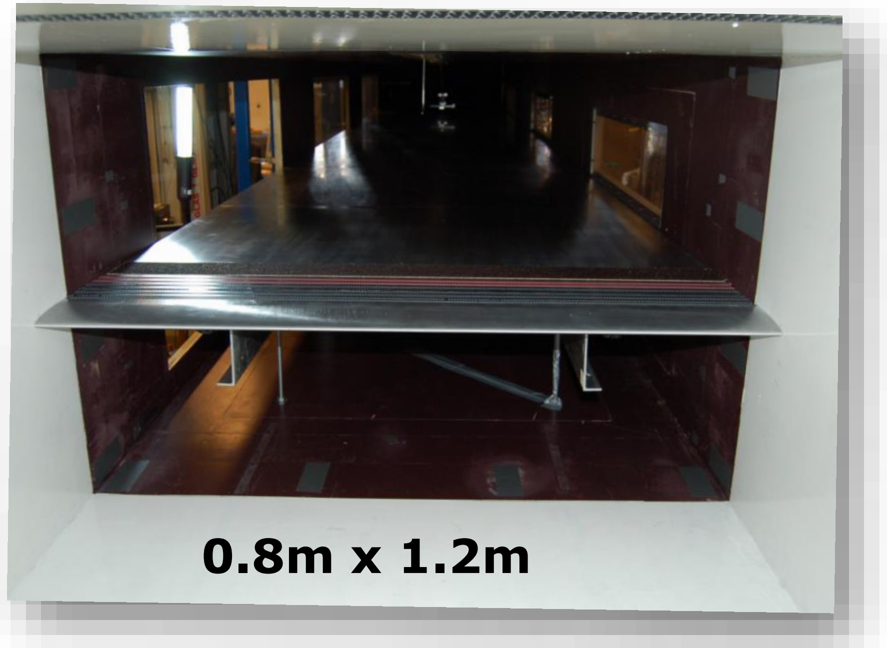
ROYAL INSTITUTE OF TECHNOLOGY

Let's compare DNS and experiments…

New experiments at KTH

- ZPG TBL flow in the range 2300< Re_θ <7500 (*Örlü, 2009*)
  - single hot-wire measurements at 1.65m from leading edge of a 7m long plate fulfilling "**equilibrium**" criteria *(à la Chauhan et al. 2009)*
  - independent skin friction measurements by means of **oil-film interferometry**
  - **DNS** corresponds to a 2m stretch…





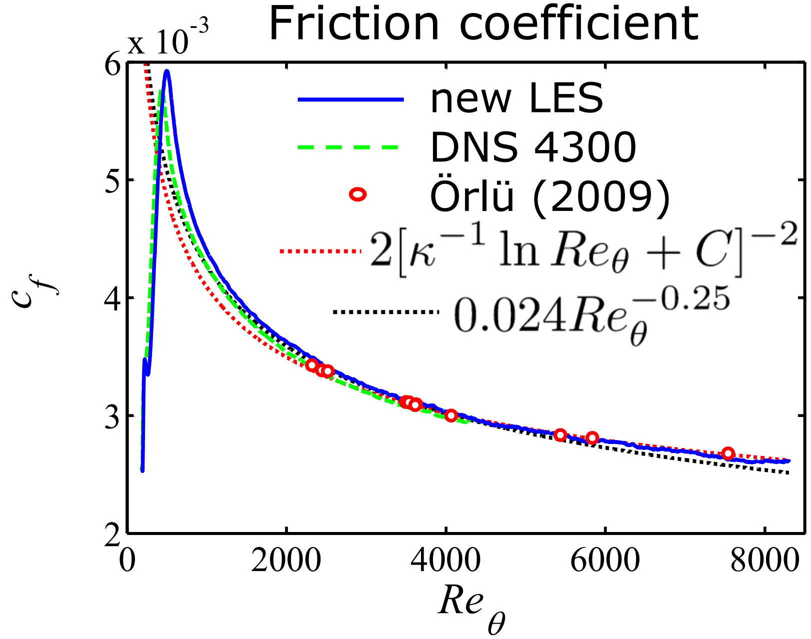
PhD thesis Örlü 2009

TBL LES up to Re_θ=8300

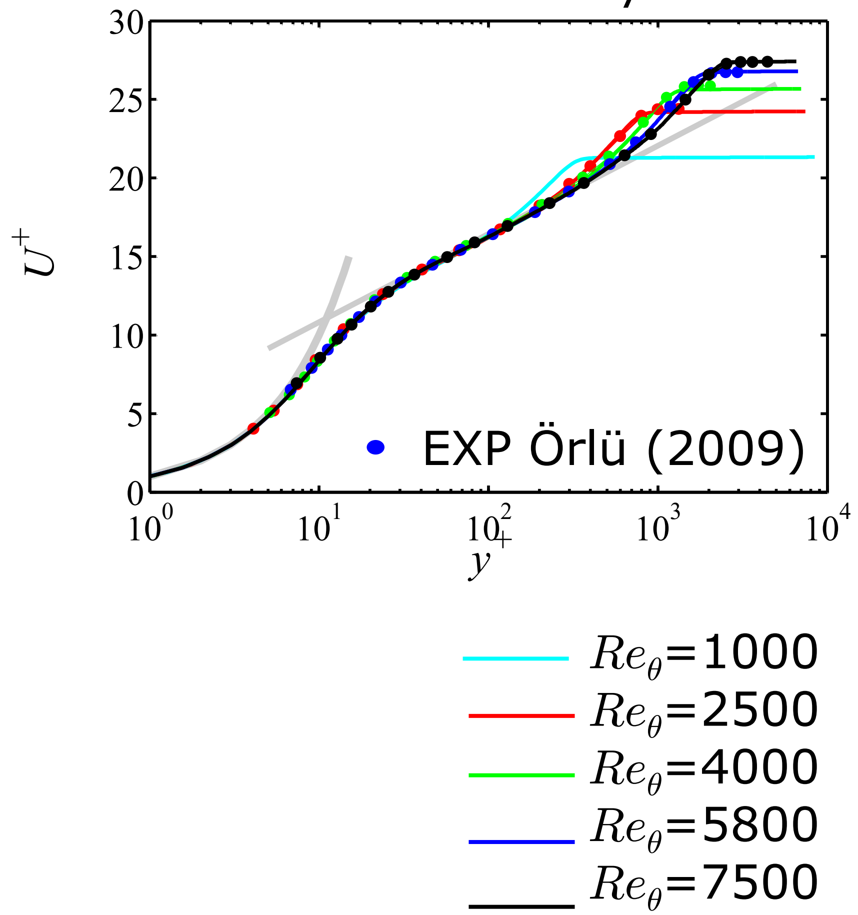
- **Ongoing** LES (using ADM-RT)

ROYAL INSTITUTE OF TECHNOLOGY

Friction coefficient



Mean velocity



Domain: 13500 x 400 x 540δ_0^*

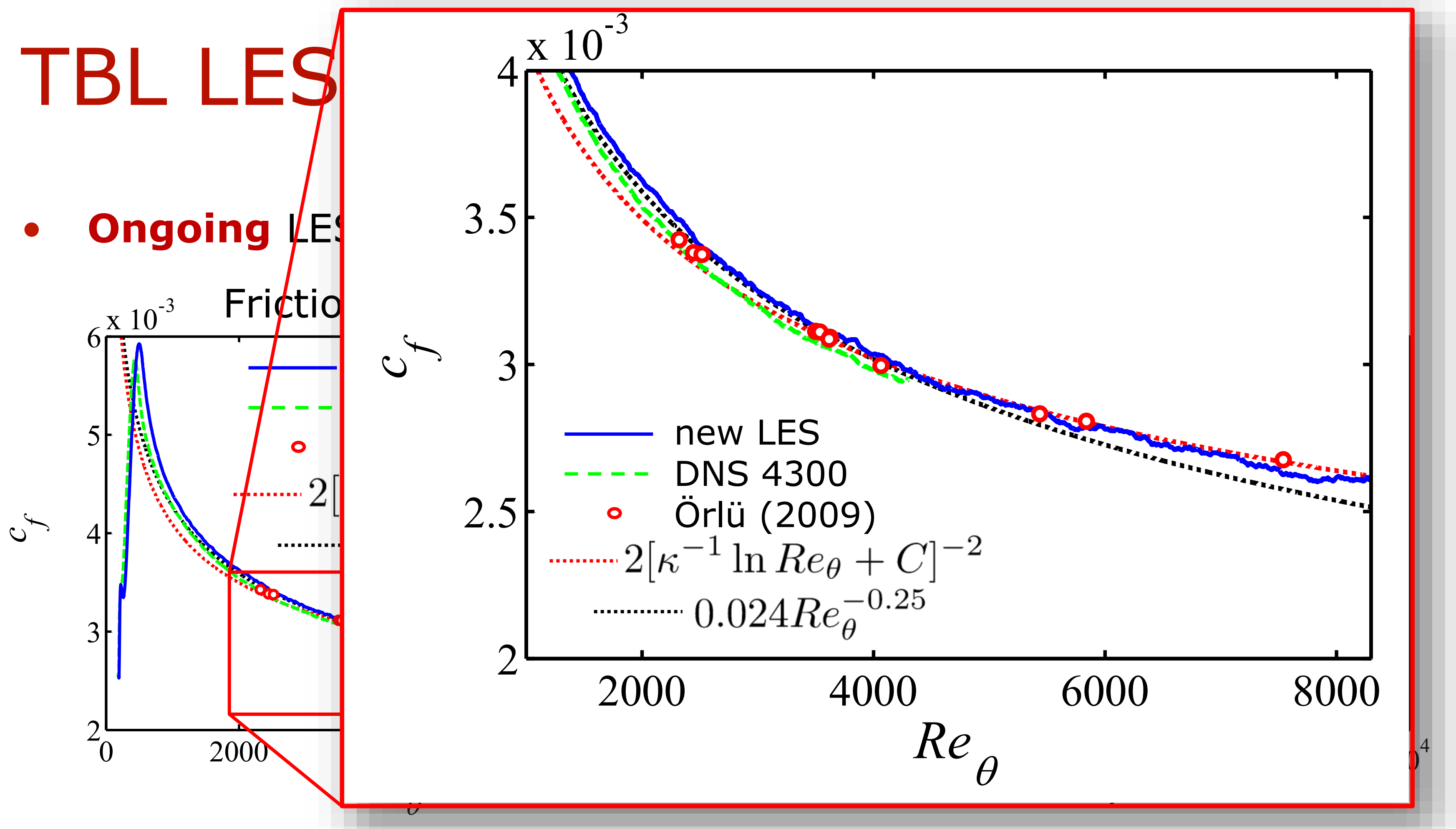
Re_θ = 500-8300 ; Re_τ = 2500

Resolution: 9216 x 513 x 768
(8.5 billion grid points)
Δx^+=18, Δy^+=0.06-16, Δz^+=8

Eitel-Amor *et al.* 2014

TBL LES

- **Ongoing** LES

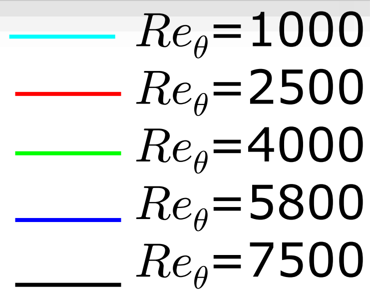


ROYAL INSTITUTE OF TECHNOLOGY

Domain: 13500 x 400 x 540δ_0^*

Re_θ = 500-8300 ; Re_τ = 2500

Resolution: 9216 x 513 x 768
(8.5 billion grid points)
Δx^+=18, Δy^+=0.06-16, Δz^+=8

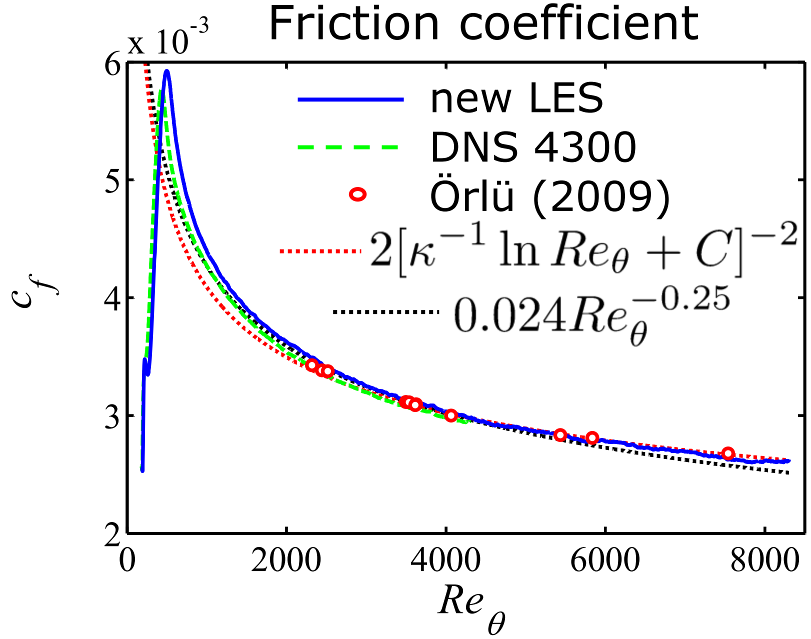


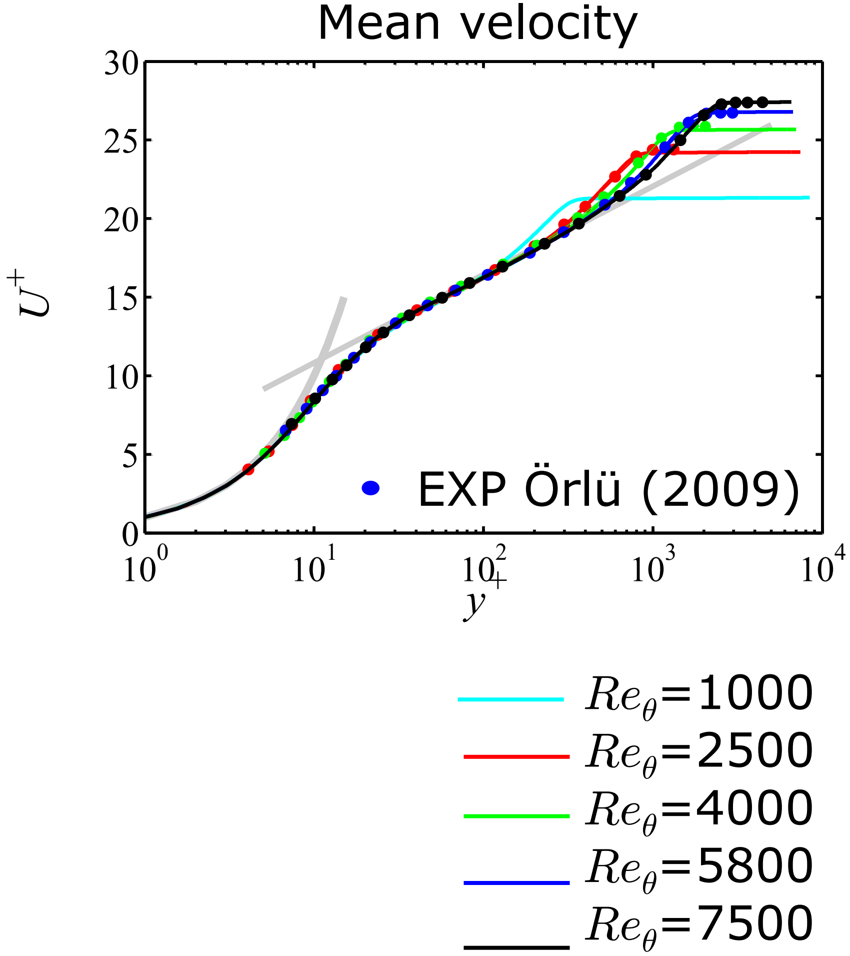
Eitel-Amor *et al.* 2014

TBL LES up to Re_θ=8300

- **Ongoing** LES (using ADM-RT)

ROYAL INSTITUTE OF TECHNOLOGY



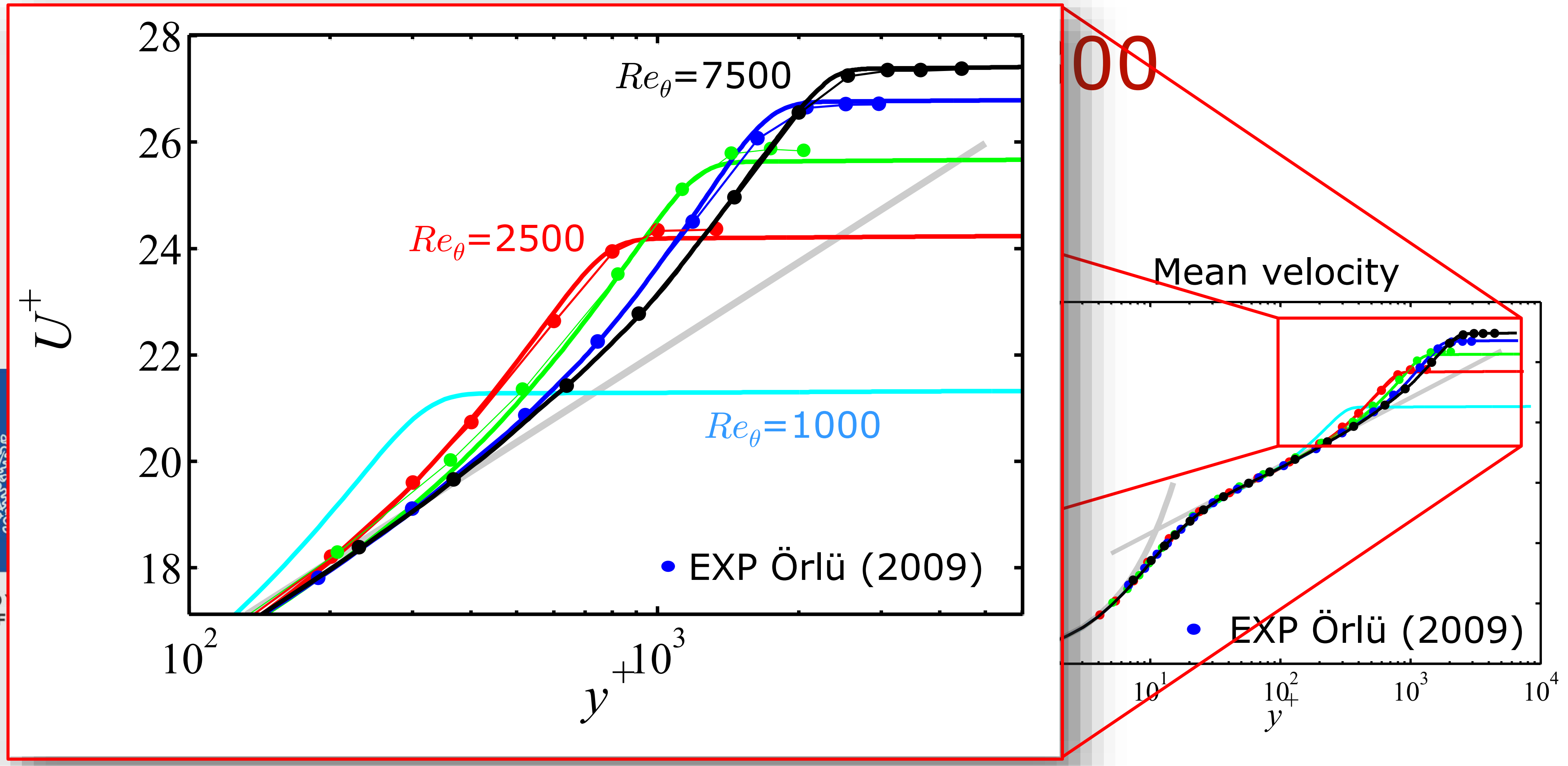


Domain: 13500 x 400 x 540δ_0^*

Re_θ = 500-8300 ; Re_τ = 2500

Resolution: 9216 x 513 x 768
(8.5 billion grid points)
Δx^+=18, Δy^+=0.06-16, Δz^+=8

Eitel-Amor *et al.* 2014



Domain: 13500 x 400 x 540δ_0^*

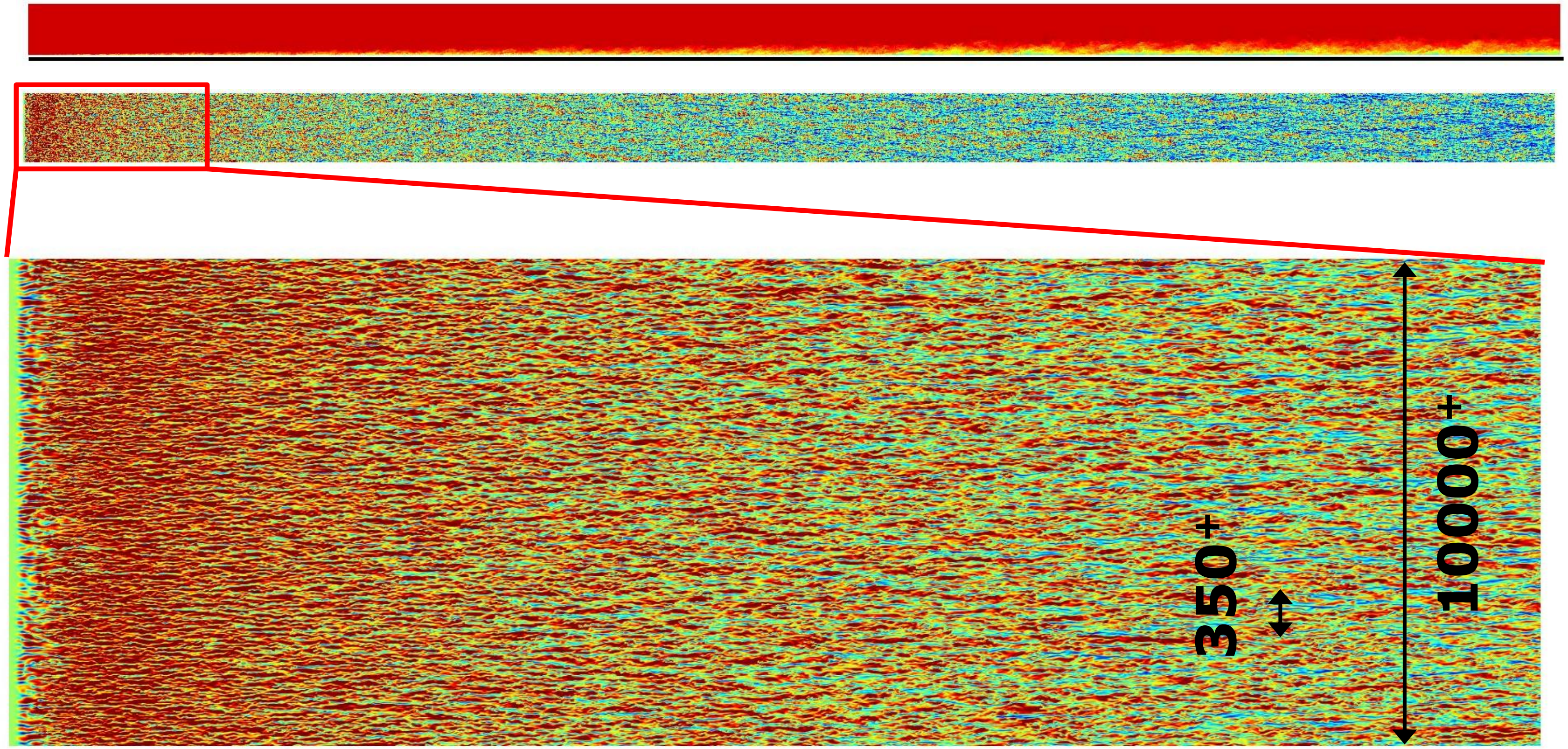
***Re_θ* = 500-8300 ; *Re_τ* = 2500**

Resolution: 9216 x 513 x 768
(8.5 billion grid points)
Δx^+=18, Δy^+=0.06-16, Δz^+=8

Eitel-Amor *et al.* 2014

Visualisation

- Streamwise velocity u in wall-parallel plane $y^+ \approx 15$

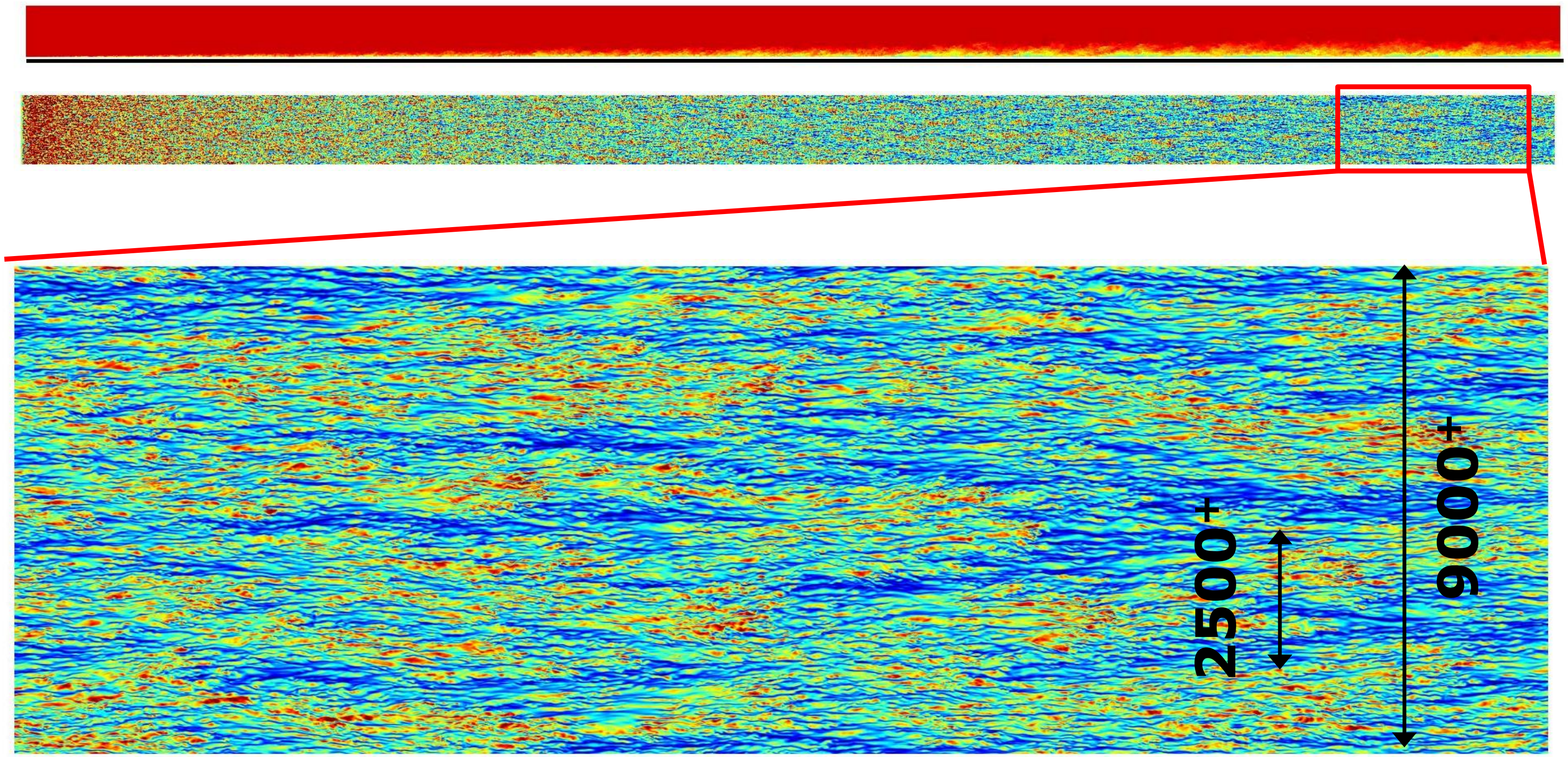


Re_θ=180-1400 Re_τ=350

Eitel-Amor *et al.* 2014

Visualisation

- Streamwise velocity u in wall-parallel plane $y^{+} \approx 15$



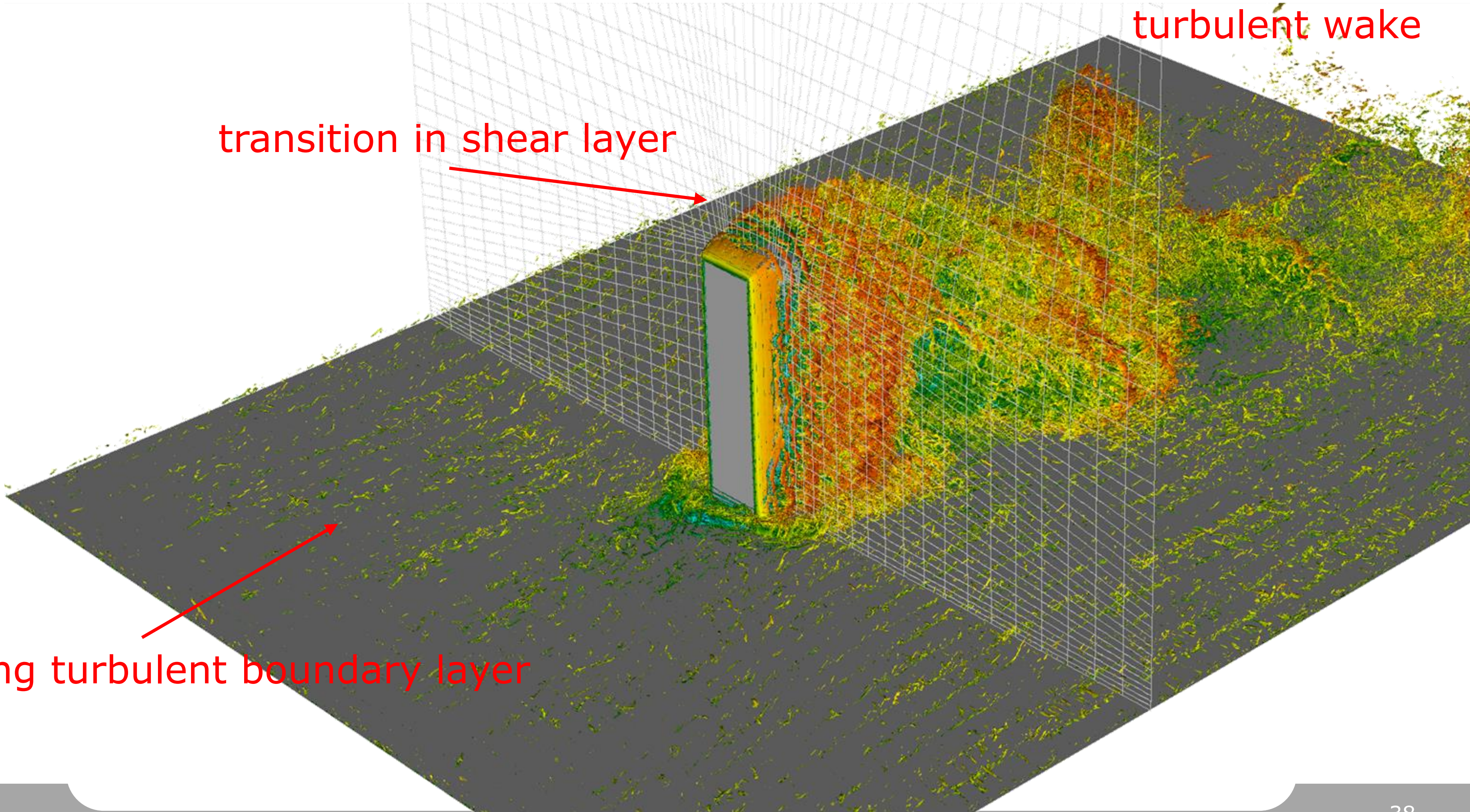
Re_θ=8300 Re_τ=2500

ROYAL INSTITUTE OF TECHNOLOGY

Eitel-Amor *et al.* 2014

TBL with ”obstacles”

- ”Skyscraper” reference case: Canadian CFD Challenge (2014)



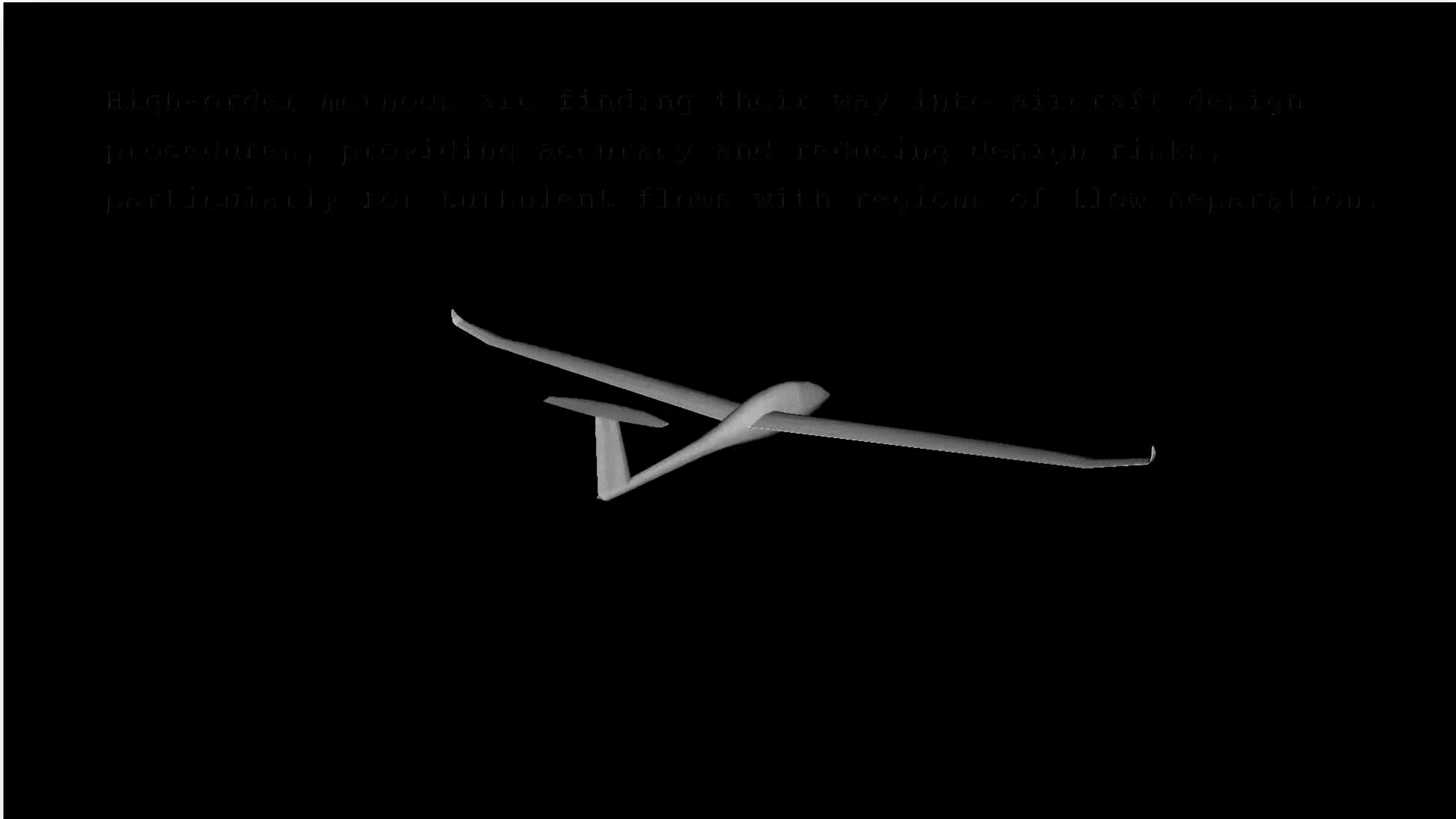
Vinuesa *et al.* 2015

ROYAL INSTITUTE
OF TECHNOLOGY

Outline

- Introduction – HPC
- Turbulent boundary layers – Simulation
- Wing simulations
- Flow control
- Codes and tools

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

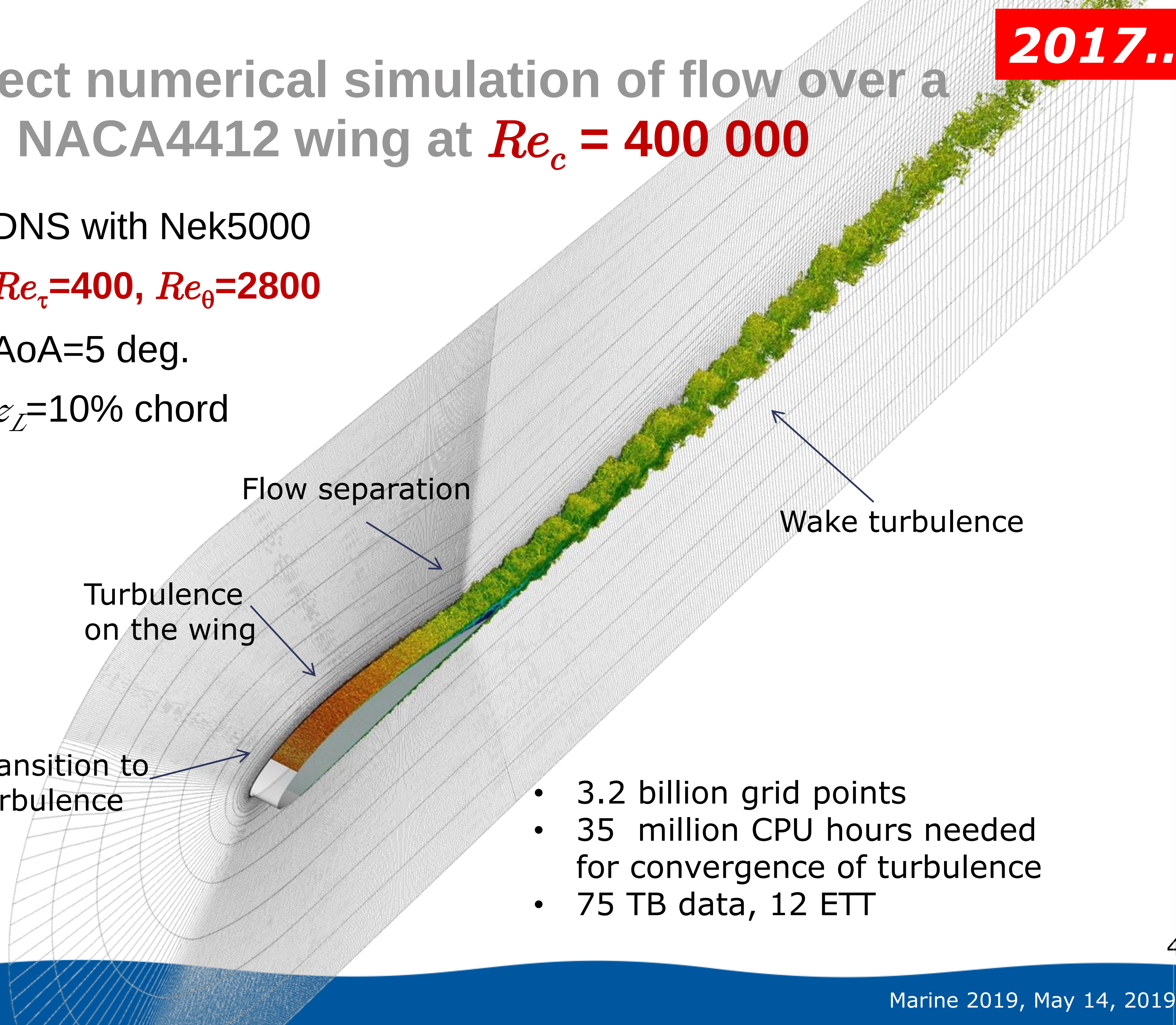


FLOW
LINNÉ FLOW CENTRE

2017...

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

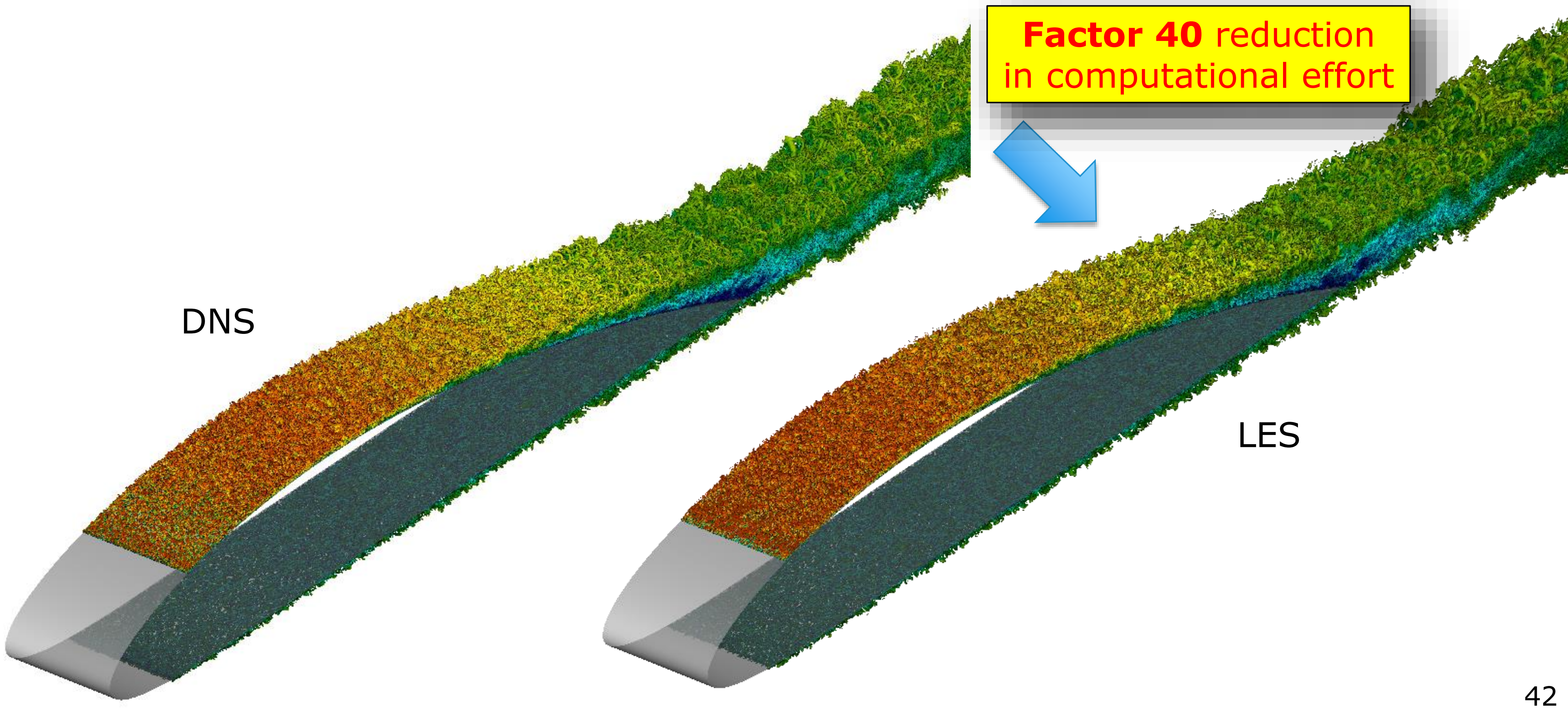
- DNS with Nek5000
- Re_τ=400, Re_θ=2800
- AoA=5 deg.
- z_L=10% chord



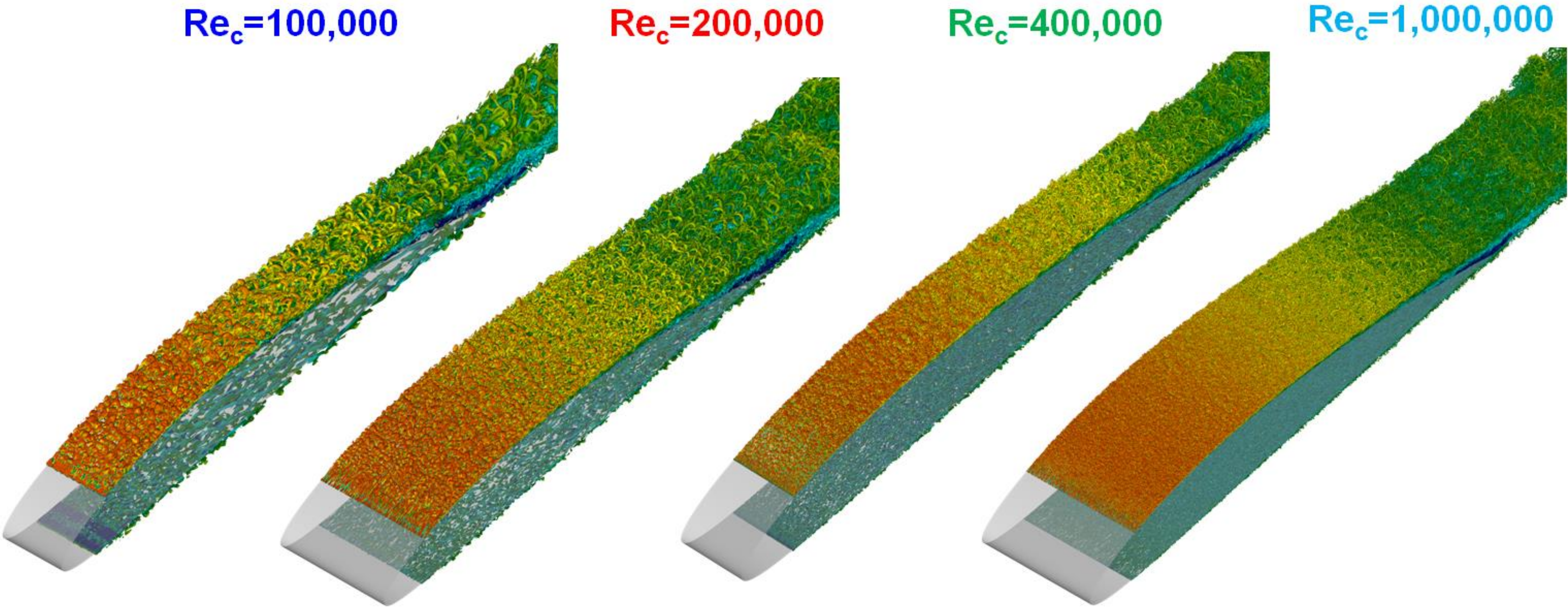
- 3.2 billion grid points
- 35 million CPU hours needed for convergence of turbulence
- 75 TB data, 12 ETT

LES towards $Re = 1\mathrm{M}$ and beyond…

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

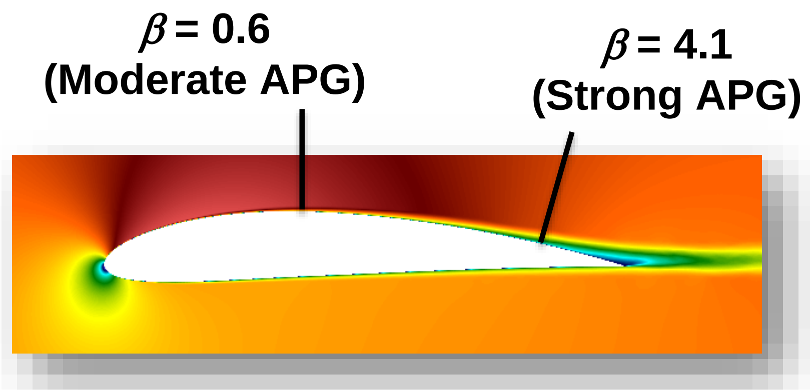


Four different wings…

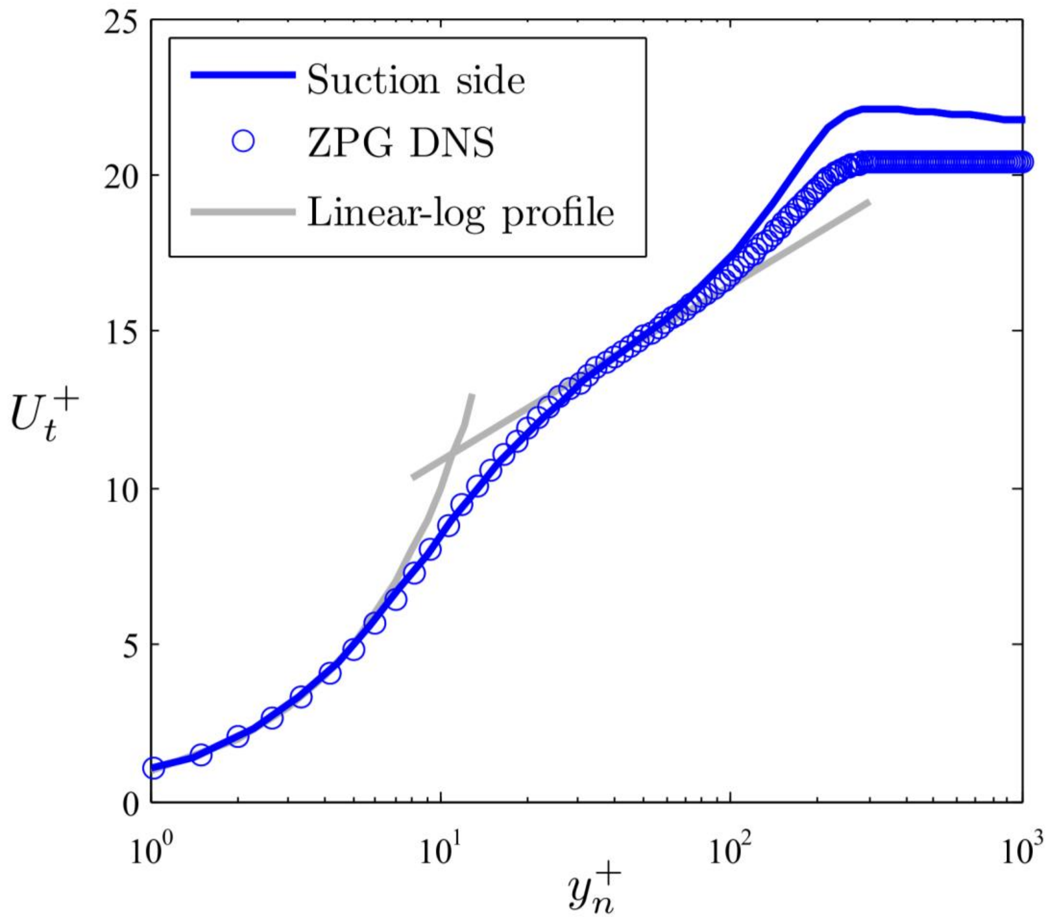


Vinuesa *et al.* Int. J. Heat Fluid Flow 2018

Mean velocity profiles



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

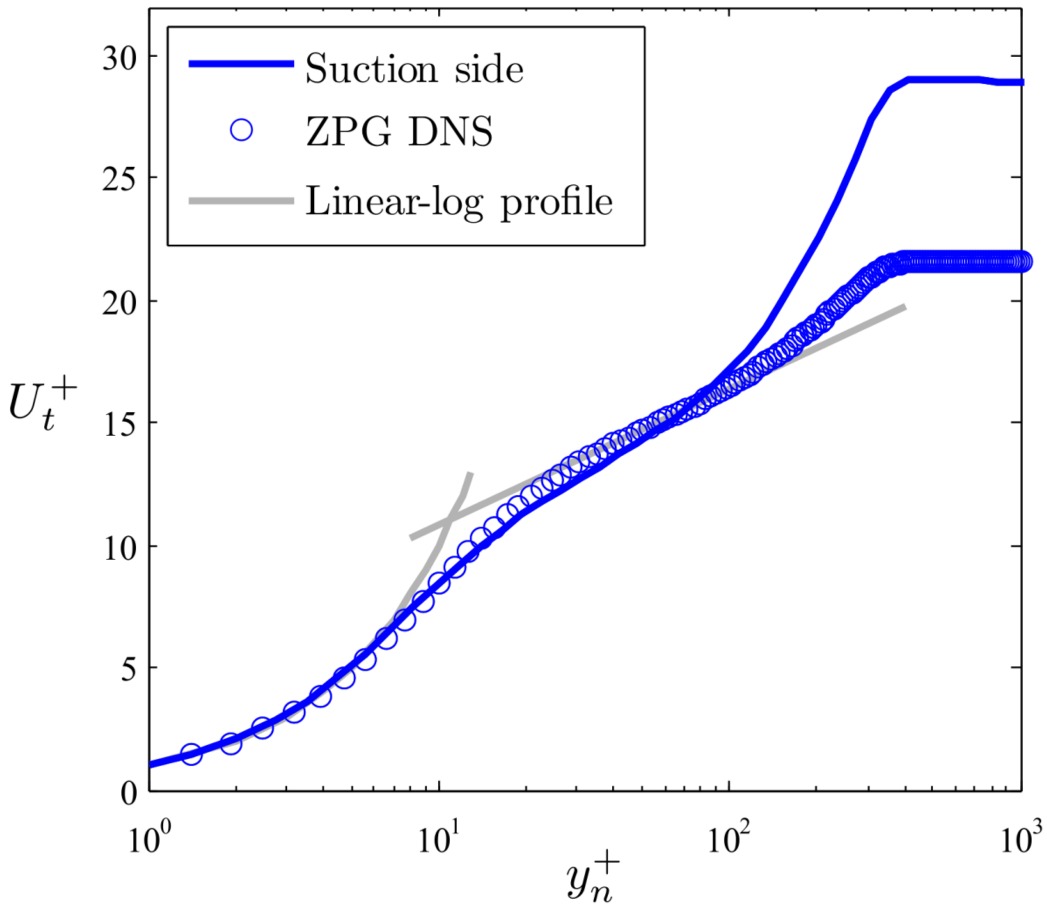


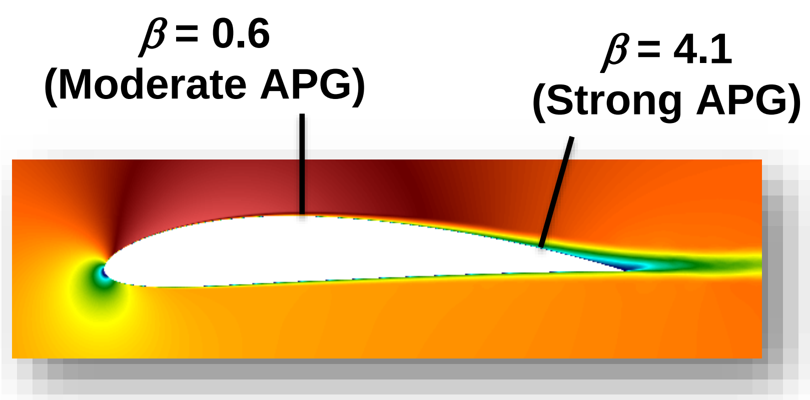
- Effect on the outer part, more prominent wake

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.



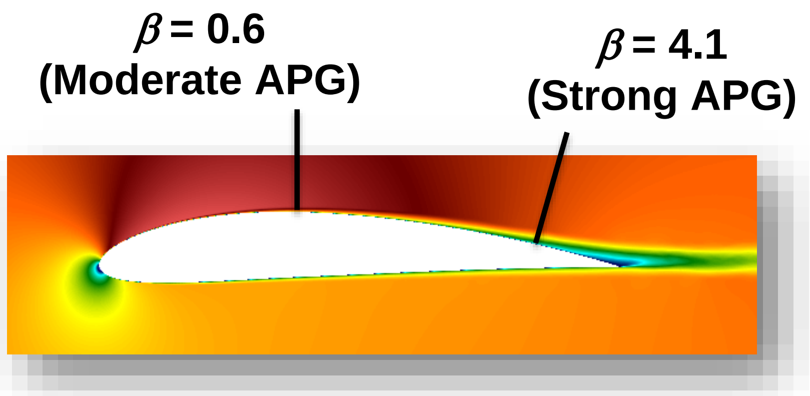


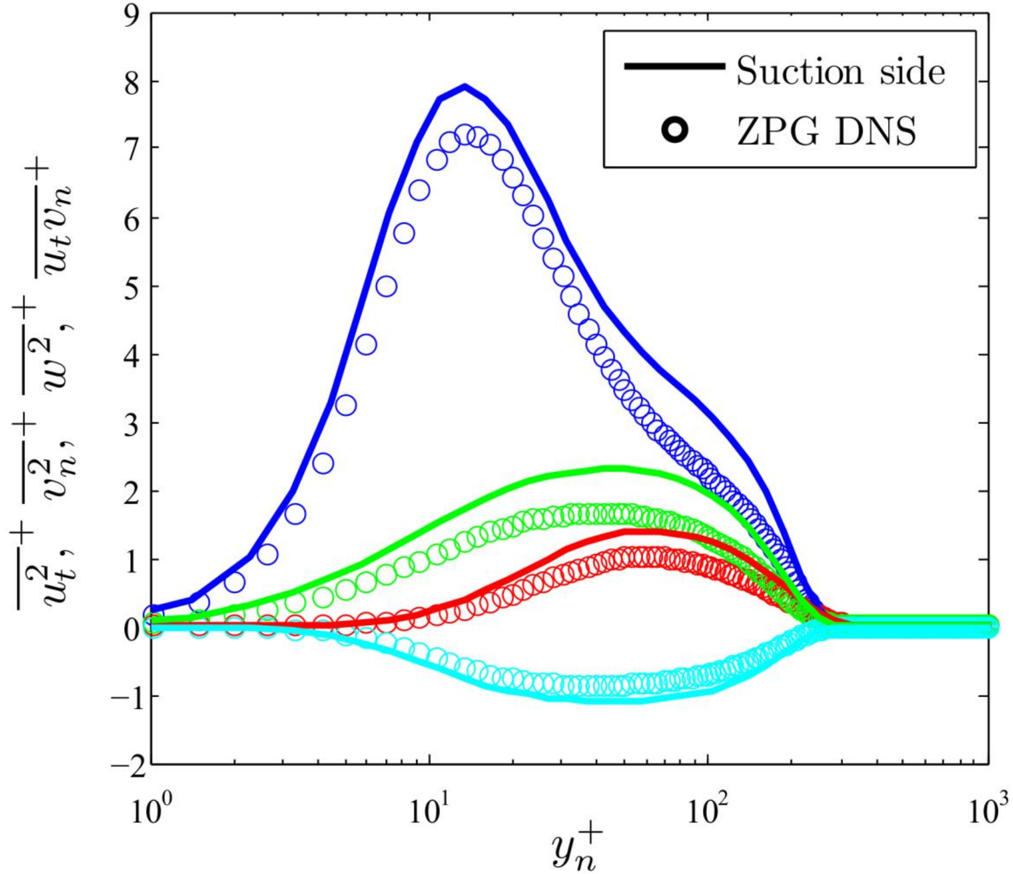
- Effect on the outer part (more prominent wake), but also in the incipient log region and even the buffer layer.

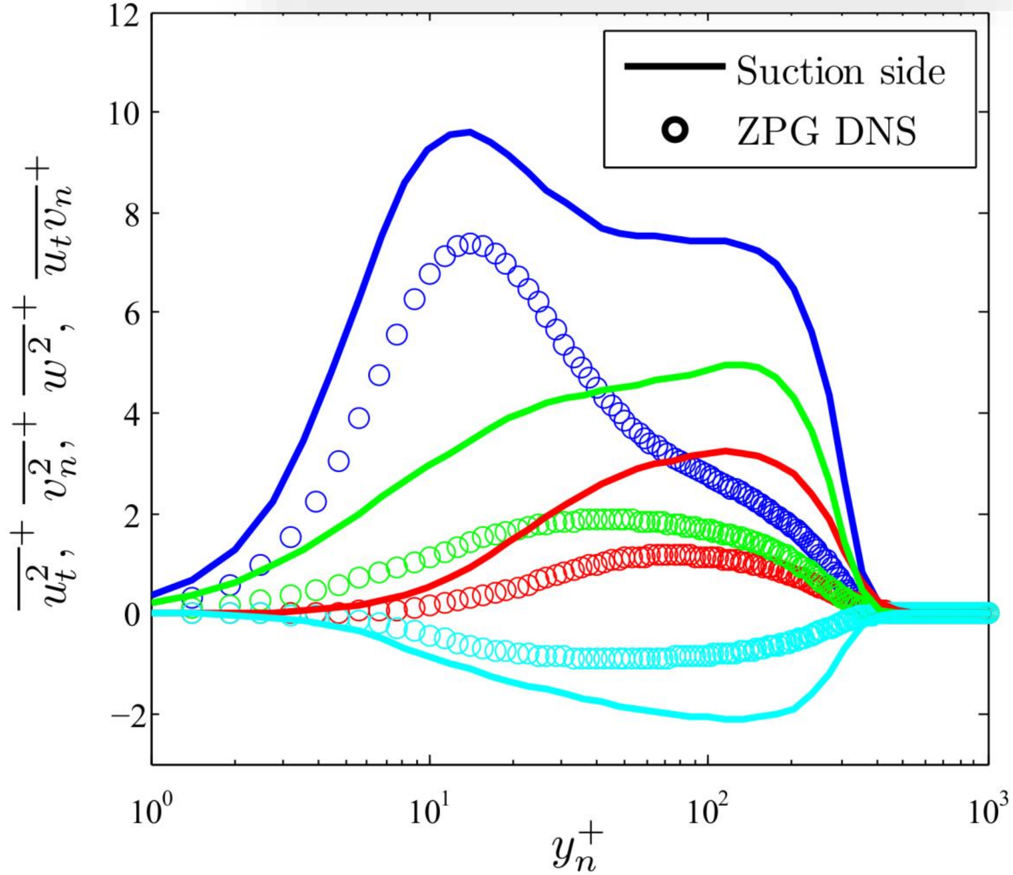
Parameter	At x/c=0.8	ZPG (S&Ö)
Re_τ	373	359
Re_θ	1,722	1,007
H	**1.74**	**1.45**
C_f	**2.4×10^{-3}**	**4.3×10^{-3}**
κ	0.33	0.41
B	2.08	4.87
Π	1.35	0.37

Reynolds stress tensor components

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



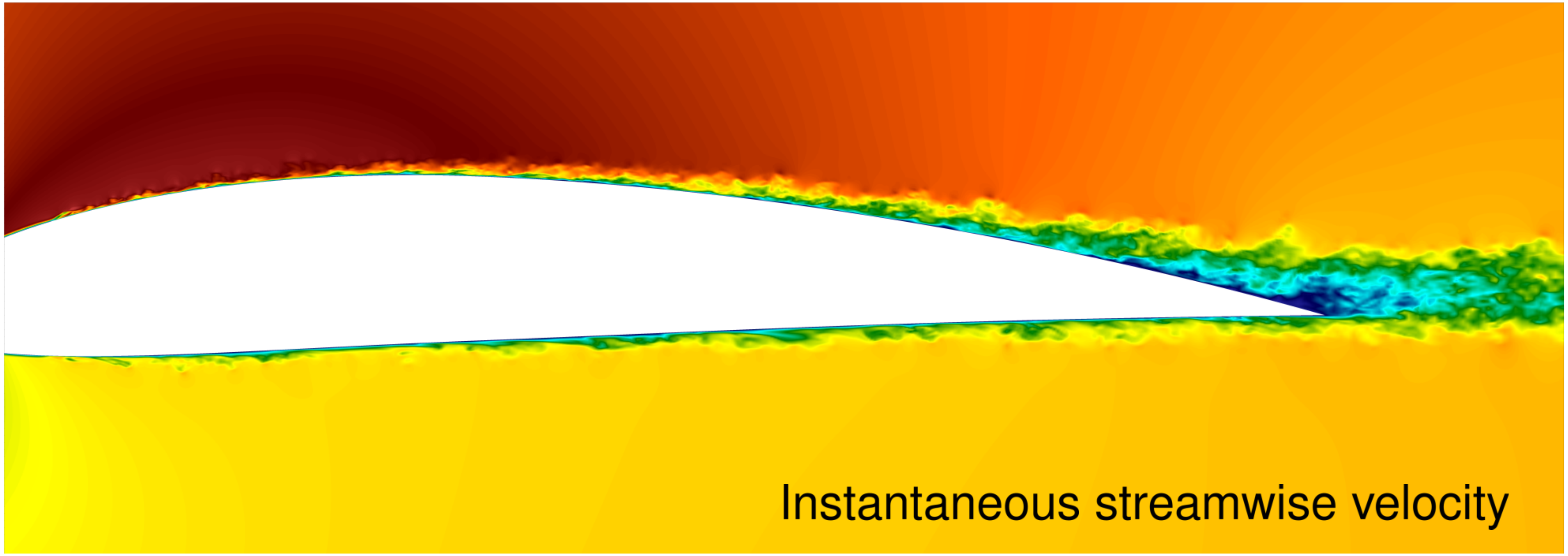




Outline

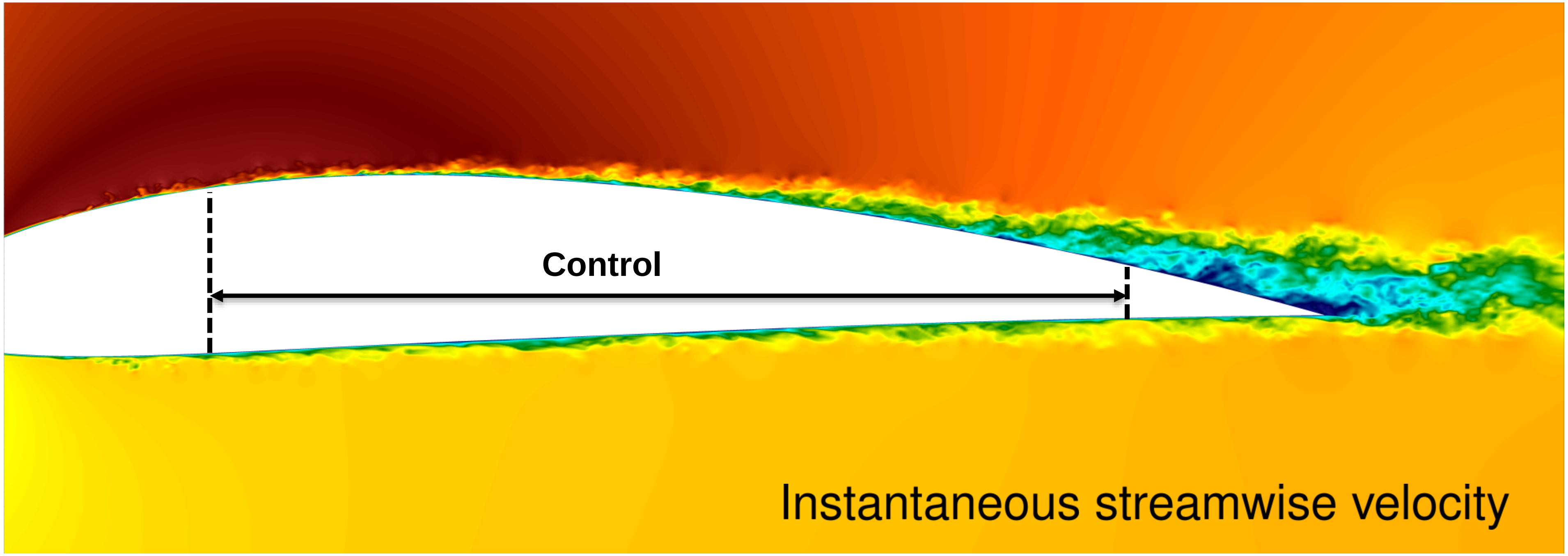
- Introduction – HPC
- Turbulent boundary layers – Simulation
- Wing simulations
- Flow control
- Codes and tools

Considered cases



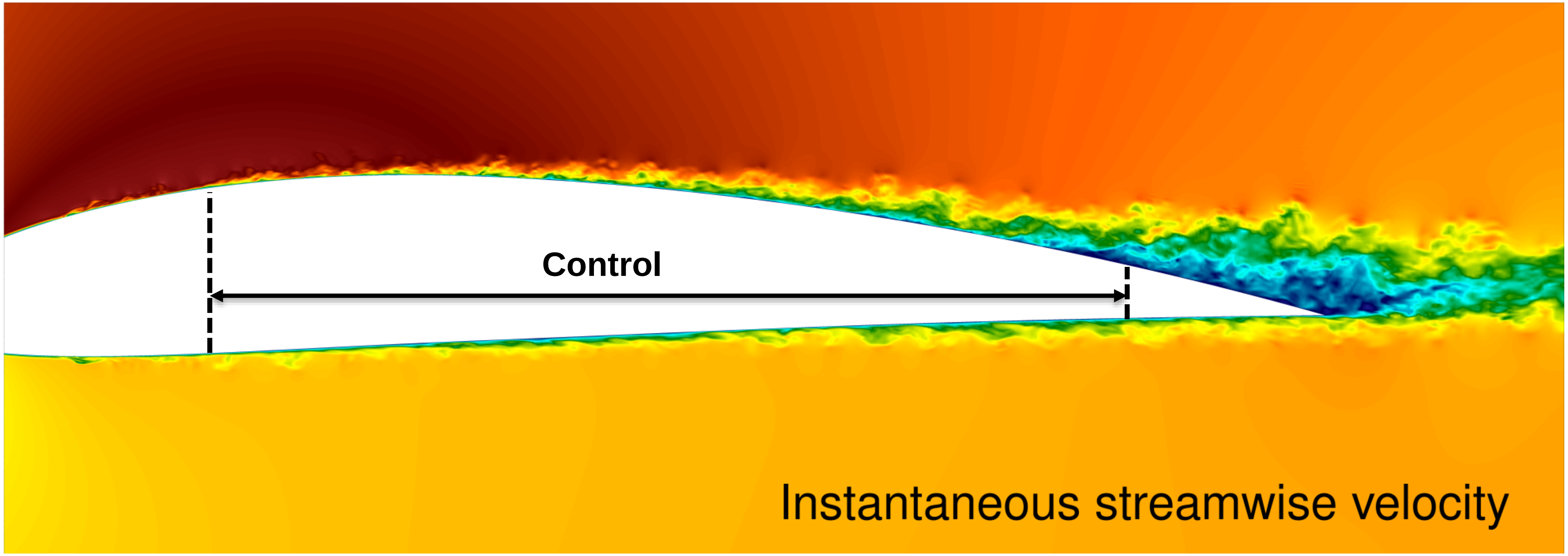
- **Reference case: NACA4412, $Re_c = 200,000$**
- Controlled case 1: Uniform blowing, $0.1\%U_\infty$, at $0.25 < x_c < 0.86$
- Controlled case 1: Uniform blowing, $0.2\%U_\infty$, at $0.25 < x_c < 0.86$
- Controlled case 1: Uniform suction, $0.1\%U_\infty$, at $0.25 < x_c < 0.86$

Considered cases



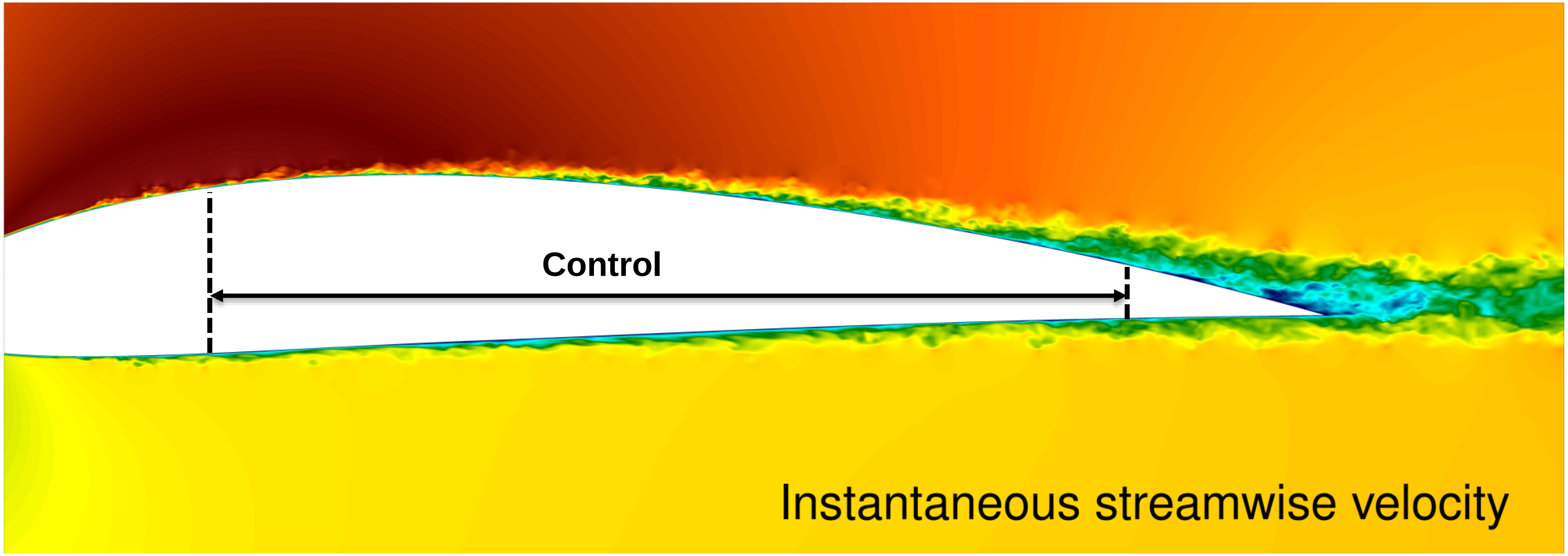
- Reference case: NACA4412, $Re_c = 200,000$
- **Controlled case 1: Uniform blowing, $\mathbf{0.1\% U_\infty}$, at $\mathbf{0.25 < x_c < 0.86}$**
- Controlled case 1: Uniform blowing, $0.2\% U_\infty$, at $0.25 < x_c < 0.86$
- Controlled case 1: Uniform suction, $0.1\% U_\infty$, at $0.25 < x_c < 0.86$

Considered cases



- Reference case: NACA4412, $Re_c = 200,000$
- Controlled case 1: Uniform blowing, $0.1\% U_\infty$, at $0.25 < x_c < 0.86$
- **Controlled case 1: Uniform blowing, $\mathbf{0.2\% U_\infty}$, at $\mathbf{0.25 < x_c < 0.86}$**
- Controlled case 1: Uniform suction, $0.1\% U_\infty$, at $0.25 < x_c < 0.86$

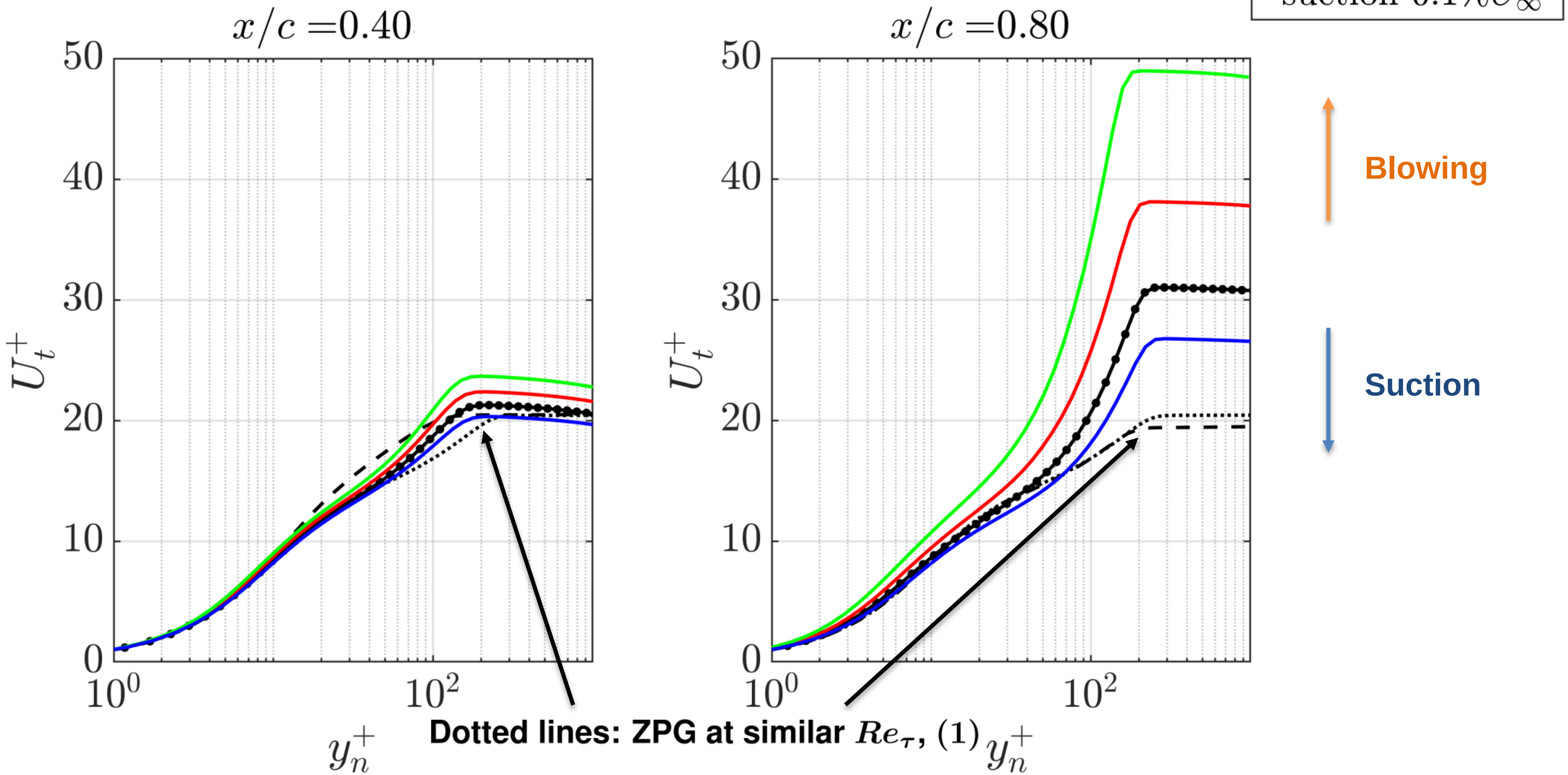
Considered cases



- Reference case: NACA4412, $Re_c = 200,000$
- Controlled case 1: Uniform blowing, $0.1\%U_\infty$, at $0.25 < x_c < 0.86$
- Controlled case 1: Uniform blowing, $0.2\%U_\infty$, at $0.25 < x_c < 0.86$
- **Controlled case 1: Uniform suction, $\mathbf{0.1\%U_\infty}$, at $\mathbf{0.25 < x_c < 0.86}$**

Comparison with pressure-gradient effects:

Inner-scaled mean tangential velocity



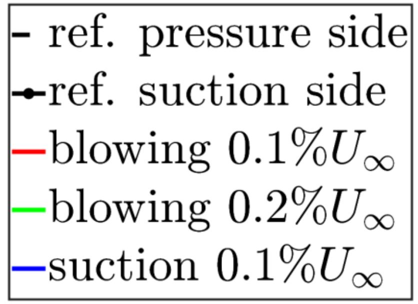
Blowing: $\uparrow U_t^+$ (as stronger APG)

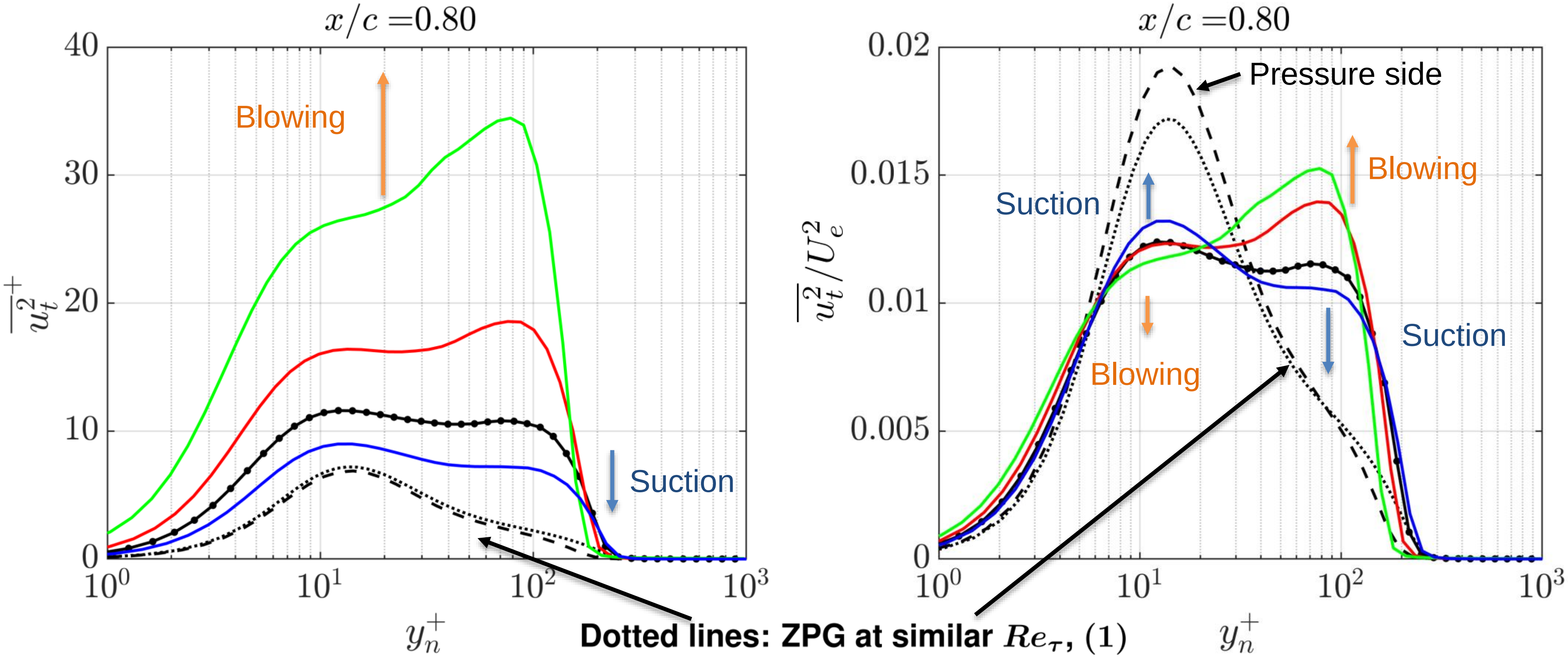
Suction: $\downarrow U_t^+$

(1): Schlatter & Örlü, J. Fluid Mech. (2018), 710:5-34

Comparison with pressure-gradient effects:

Fluctuations of the tangential velocity component (inner and outer scaling)





Blowing: $\uparrow \overline{u_t^2}^+$ (as APG)   Suction: $\downarrow \overline{u_t^2}^+$

Effects of the control on the aerodynamic efficiency:

	c_f		c_p		C_d	C_l	L/D
ref.	**0.0125**	+	**0.0071**	=	**0.0196**	**0.87**	**44**
blowing $(0.1\%U_\infty)$	**0.0119** $\downarrow$	+	**0.0082** $\uparrow$	=	**0.0201** $\uparrow$	**0.84** $\downarrow$	**42** $\downarrow$
blowing $(0.2\%U_\infty)$	**0.0115** $\downarrow$	+	**0.0091** $\uparrow$	=	**0.0206** $\uparrow$	**0.82** $\downarrow$	**40** $\downarrow$
suction $(0.1\%U_\infty)$	**0.0131** $\uparrow$	+	**0.0063** $\downarrow$	=	**0.194** $\downarrow$	**0.89** $\uparrow$	**46** $\uparrow$

- **Uniform blowing on the suction side decreases L/D!**
- **Uniform suction on the suction side improves L/D!**

(At this Reynolds number!)

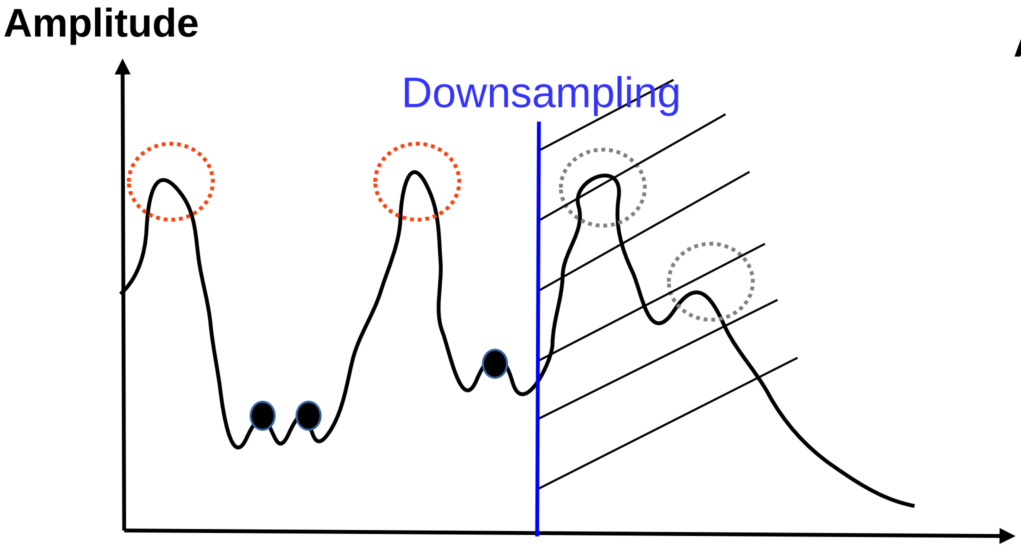
Outline

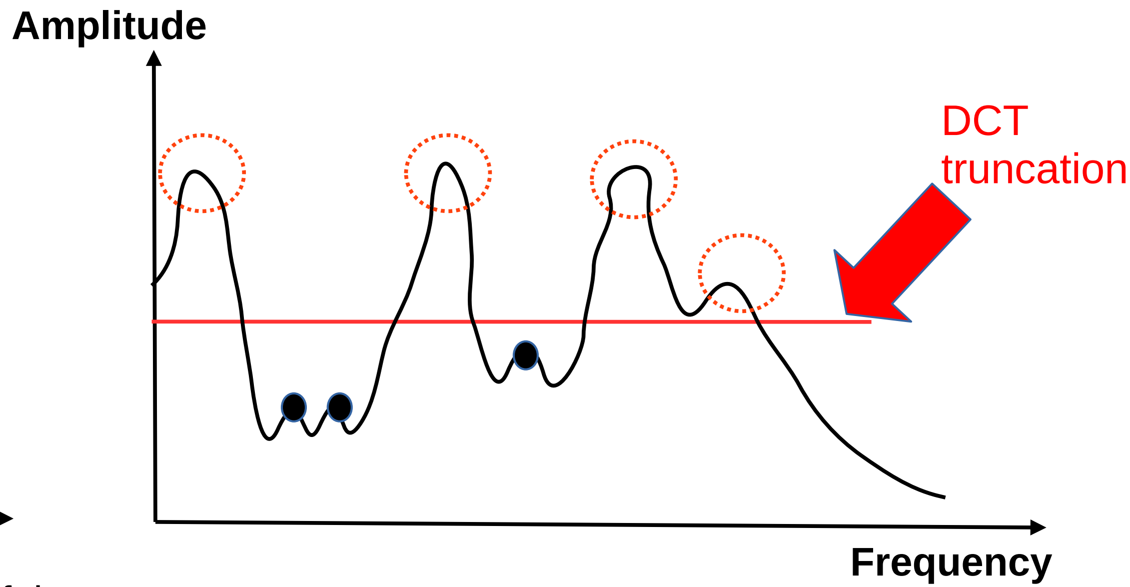
- Introduction – HPC
- Turbulent boundary layers – Simulation
- Wing simulations
- Flow control
- Codes and tools

ROYAL INSTITUTE OF TECHNOLOGY

DCT DATA COMPRESSION ALGORITHM

- Novelty: Truncation algorithm **based on the amplitude of the modes and not on the frequencies (downsampling)**.





Interesting case where the downsampling loses part of the relevant data and keep weak data.

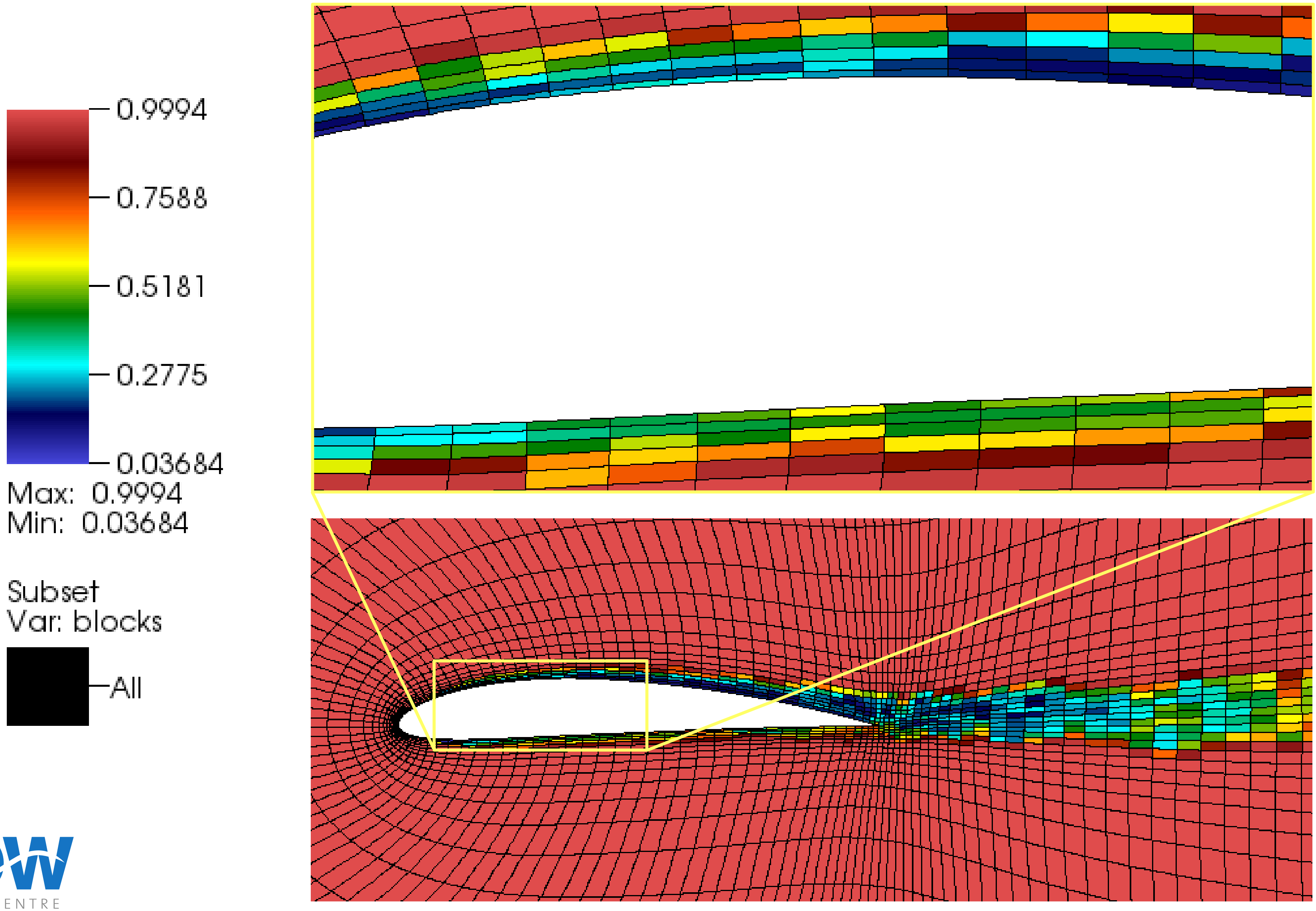
⇒ DCT truncation removes data in an adaptive way by removing the weak modes with less contribution to the whole flow representation.

FLOW
LINNÉ FLOW CENTRE

RESULTS - wing case

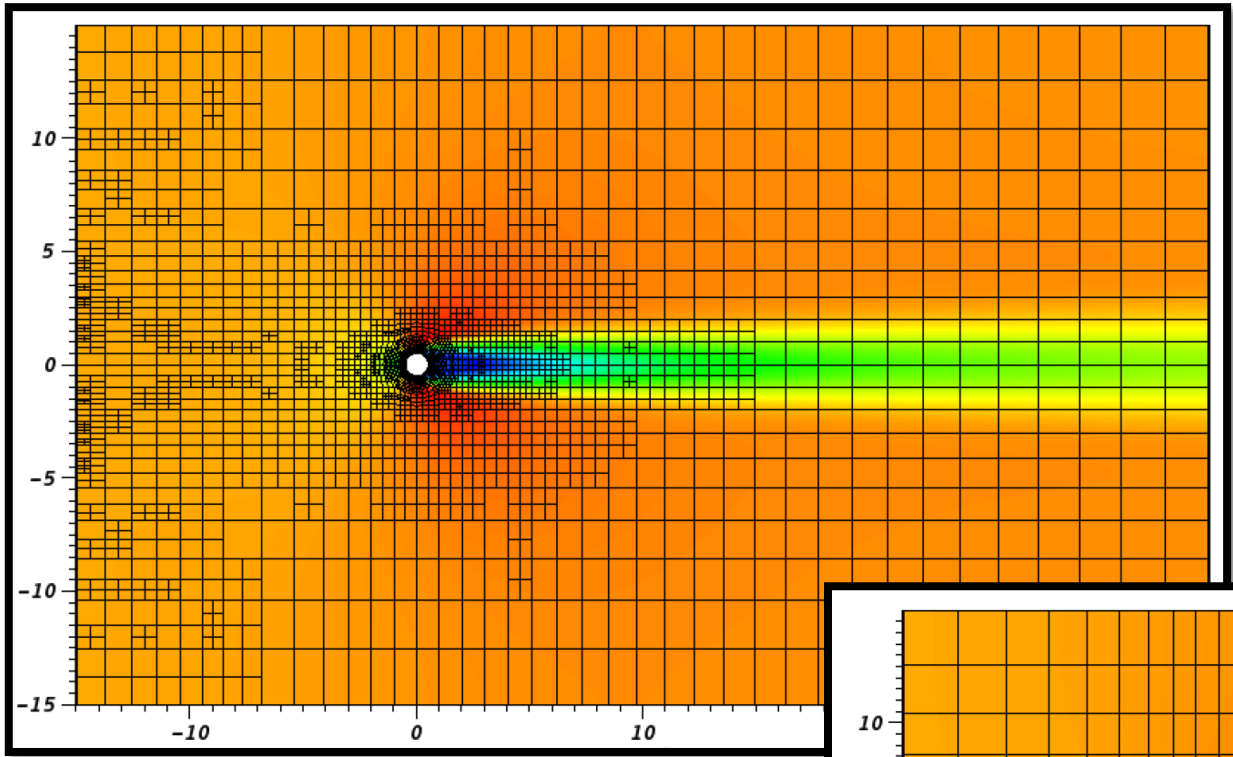
ROYAL INSTITUTE OF TECHNOLOGY

- Compression ratio (Error: 1e-4, Cr= 90%)

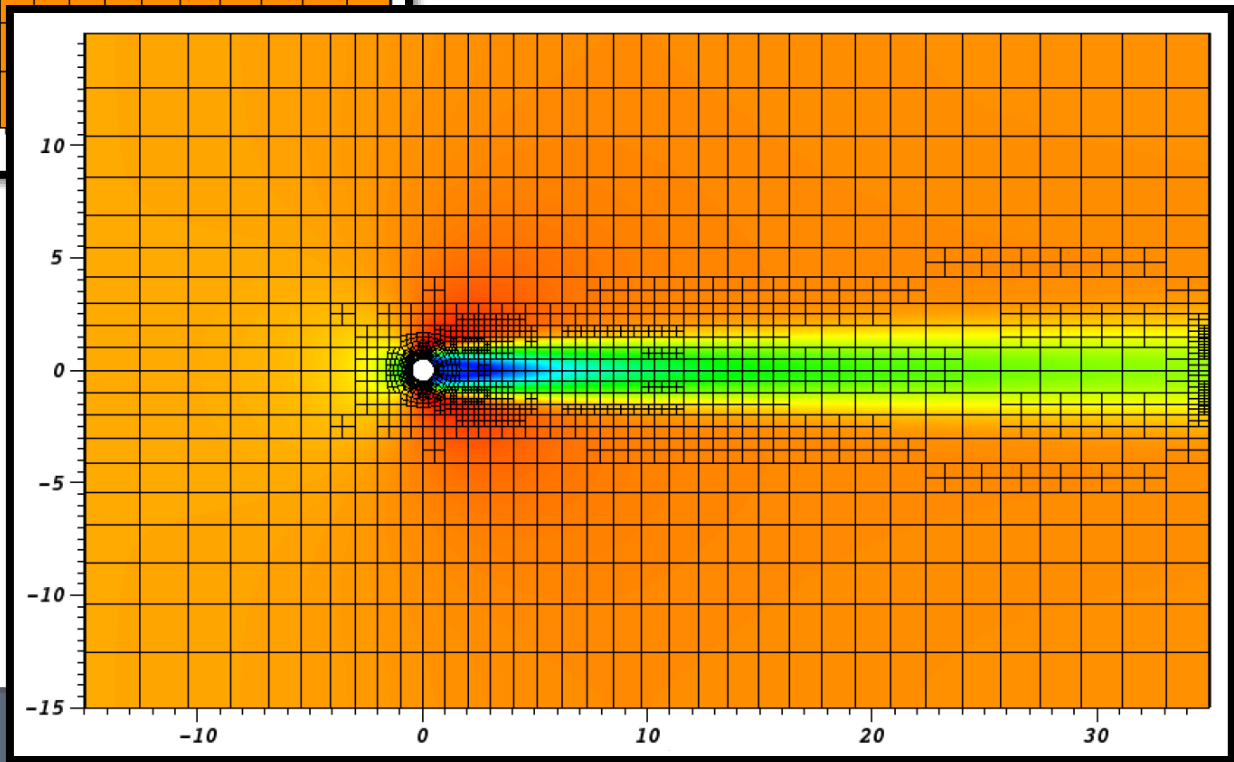


Ref. Otero et al. 2018

Adaptive *h*-refinement (AMR) – 2D cylinder flow



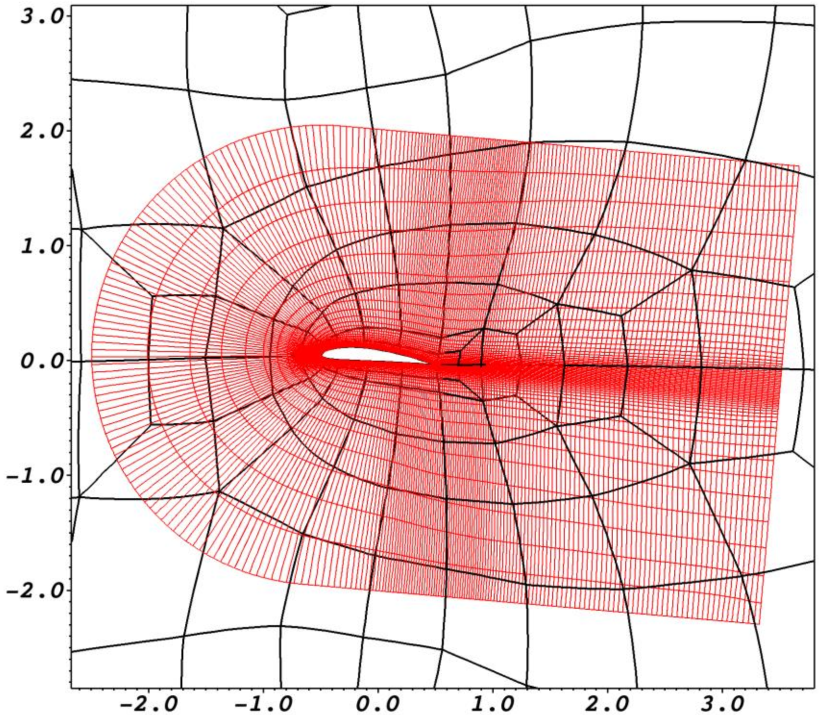
adjoint error estimators

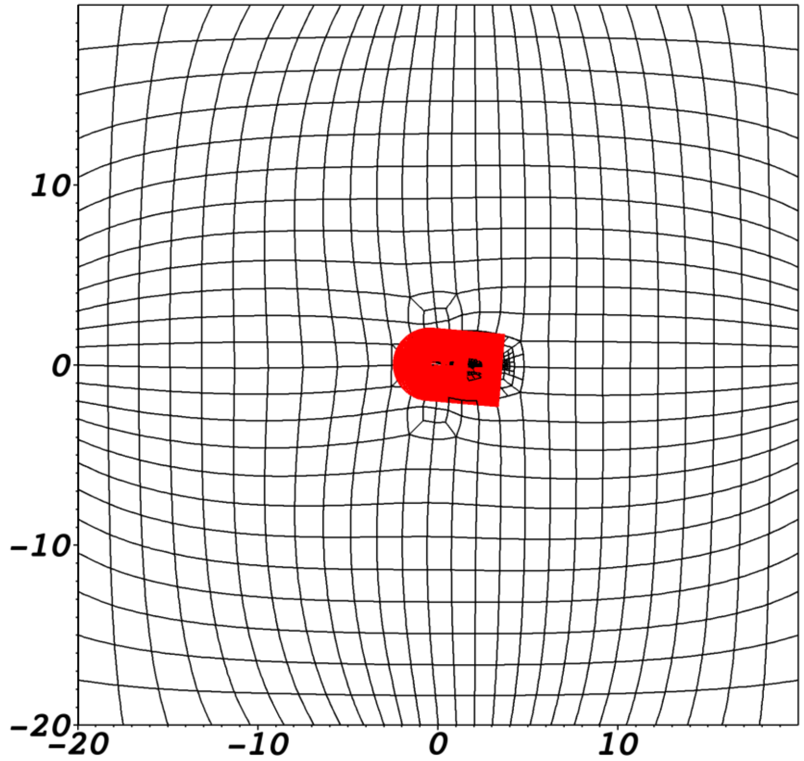


spectral error indicators

Ref. Offermans 2019

2D AMR NACA4412 Re_c = 200 000





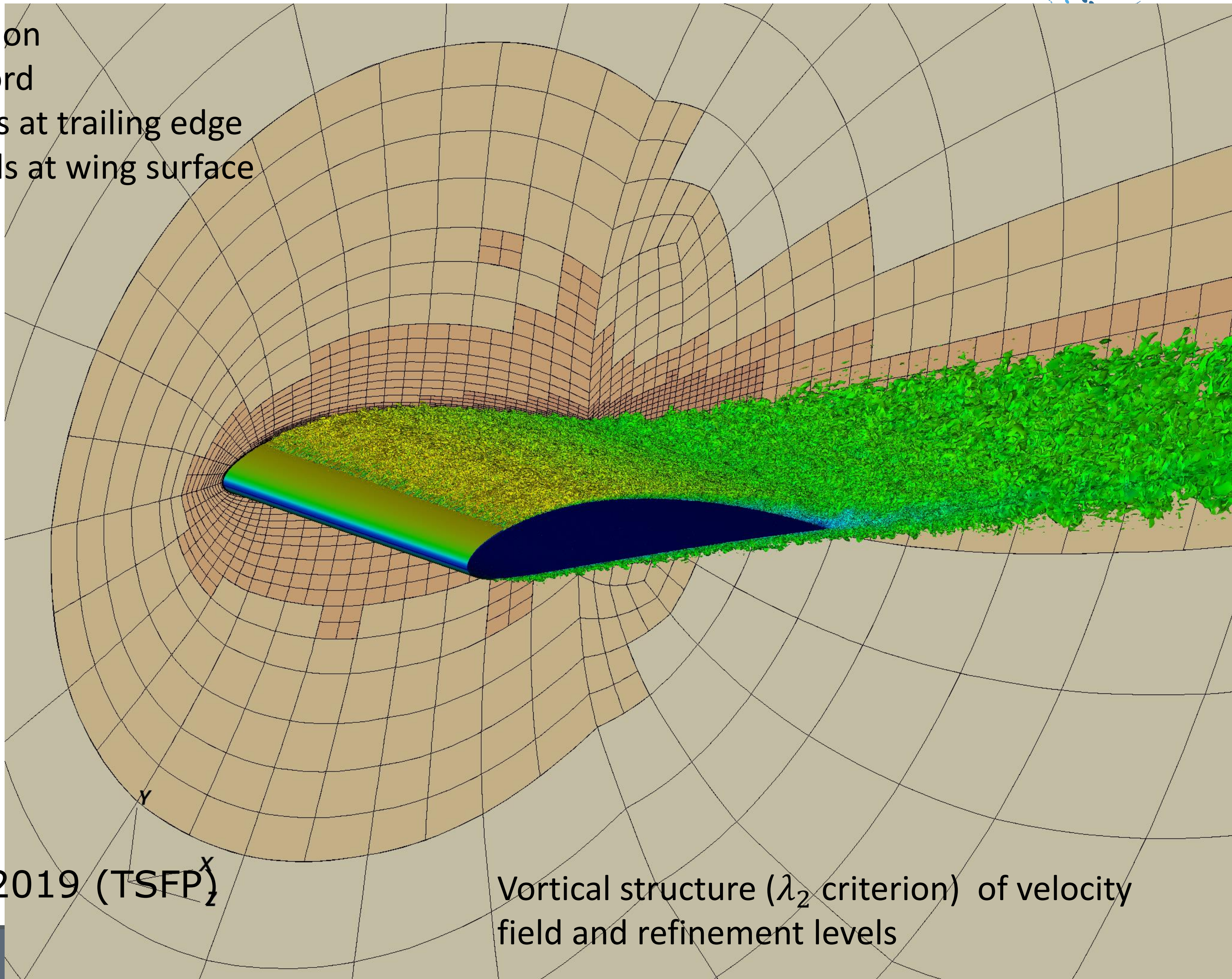
Comparison of mesh structure

Ref. Offermans 2019

3D AMR NACA4412 Re_c = 200 000

Tripped AMR simulation

- tripping at 10% cord
- 7 refinement leves at trailing edge
- 5 refinement levels at wing surface

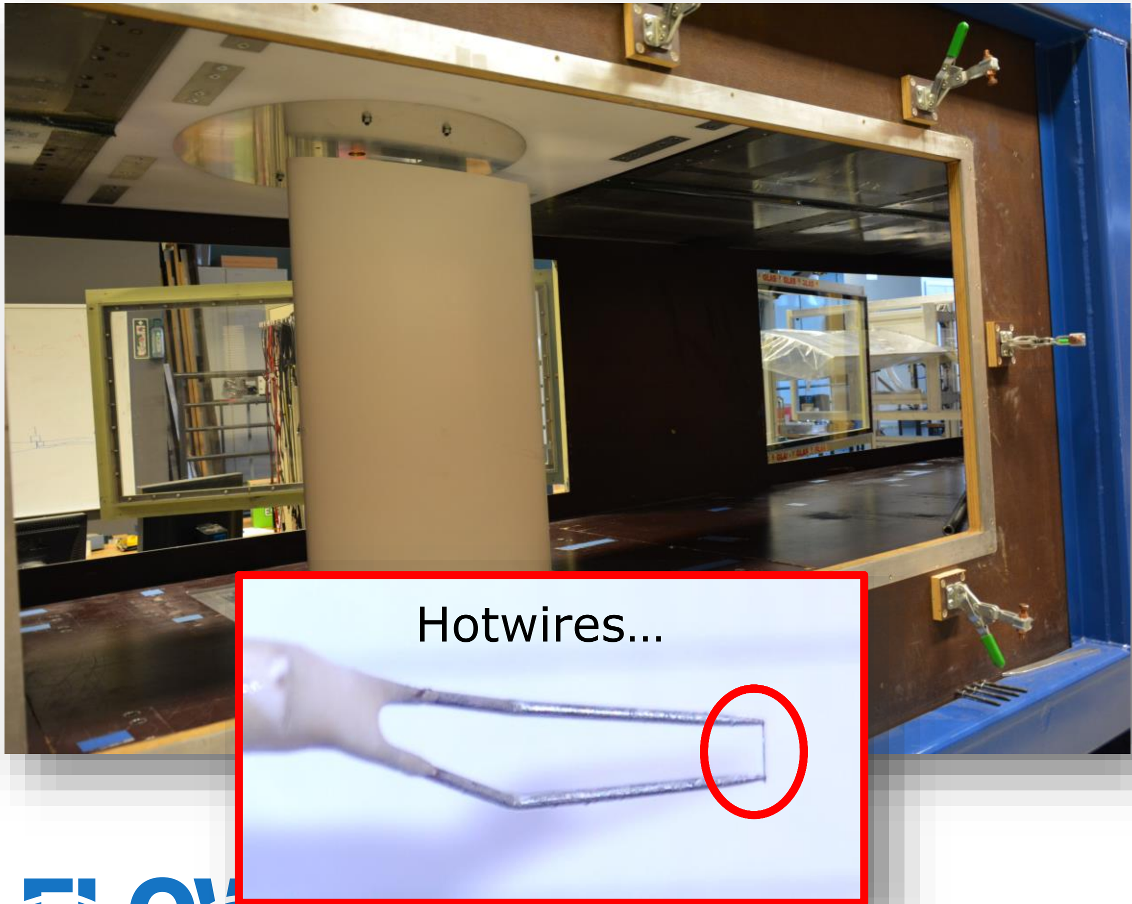


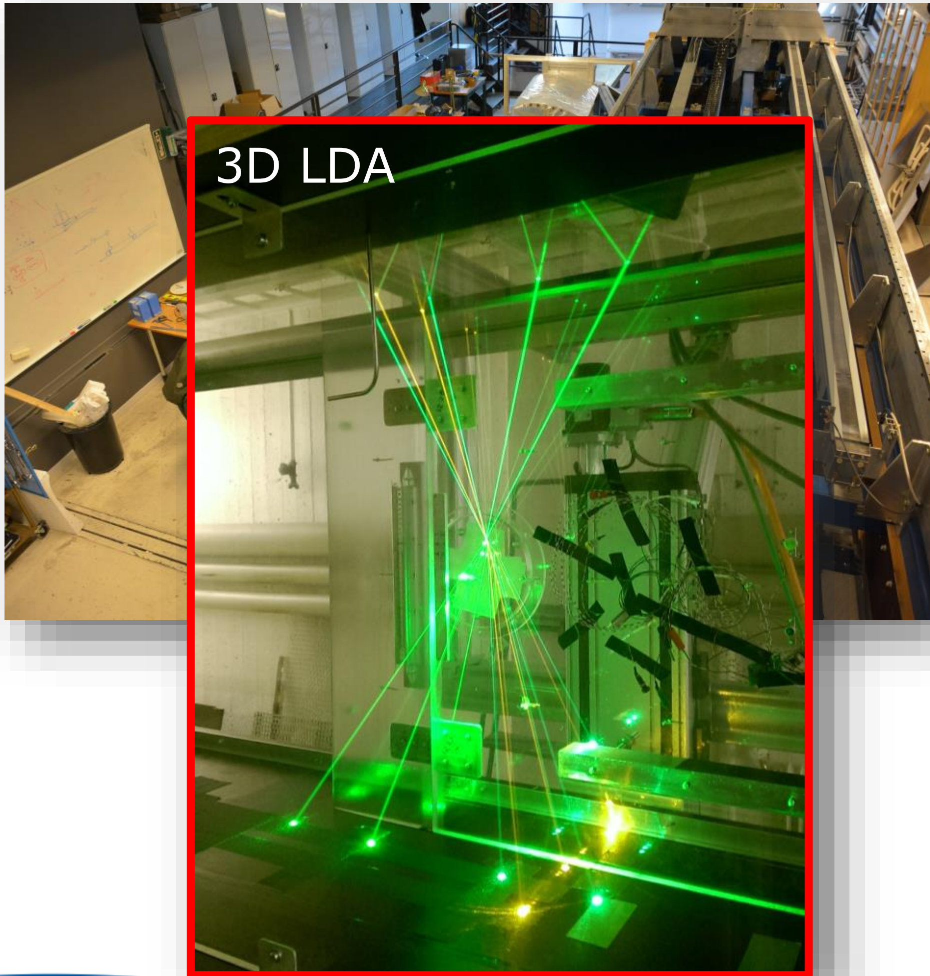
Vortical structure (λ_2 criterion) of velocity field and refinement levels

Ref. Tonarro *et al.* 2019 (TSFP)

"Real Experiments" in the MTL wind tunnel (KTH Mechanics)

- Validation experiments to identify shortcomings
- Reynolds number **"only"** up to 1.6 M !!!





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***
- Non-conformal meshes in **Nek5000** with adaptation.
- "**Virtual experiments**" enables characterisation of complicated flow cases with an unprecedented level of detail:
  - Influence of pressure gradients, comparison to flat plates, tracking of turbulence features, control, …
  - **Experiments in the MTL wind tunnel**
- **Code development**, new computer architectures, …
- **uncertainty analysis** for simulations

Thank You!