Progress in Simulations of Turbulent Boundary Layers

Philipp Schlatter

Ramis Örlü, Qiang Li, Geert Brethouwer,
Henrik Alfredsson, Arne Johansson, Dan Henningson

Linné FLOW Centre, KTH Mechanics,
Stockholm, Sweden

TSFP-7, Ottawa, July 31, 2011

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Outline: Turbulent Boundary Layers

- Comparison of DNS
  - Re-evaluation of data
- New KTH simulations and experiments
  - Something about codes
  - Establishment of fully-developed turbulence
  - Detailed comparison to experiments
- Some findings and detours
  - Wall shear stress, negative velocities and high flatness
  - Modulation of near-wall turbulence
  - Three-dimensional effects
  - Suction boundary layer
  - Coherent structures (Eduction, Visualisations)
  - Passive scalars and free-stream turbulence
  - Sublayer scaling, finding the wall and correcting hotwires
  - Ongoing new simulation
- Conclusions

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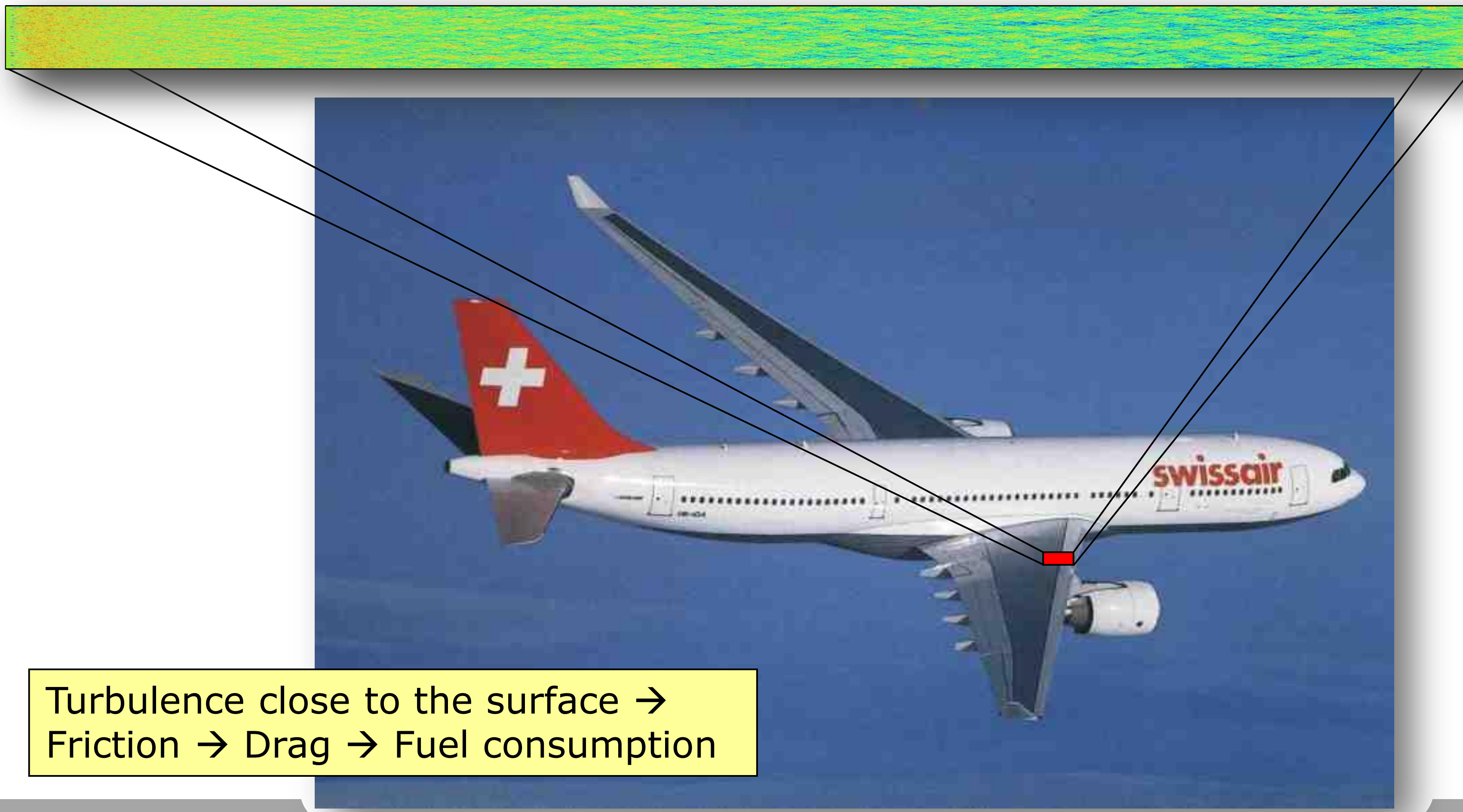
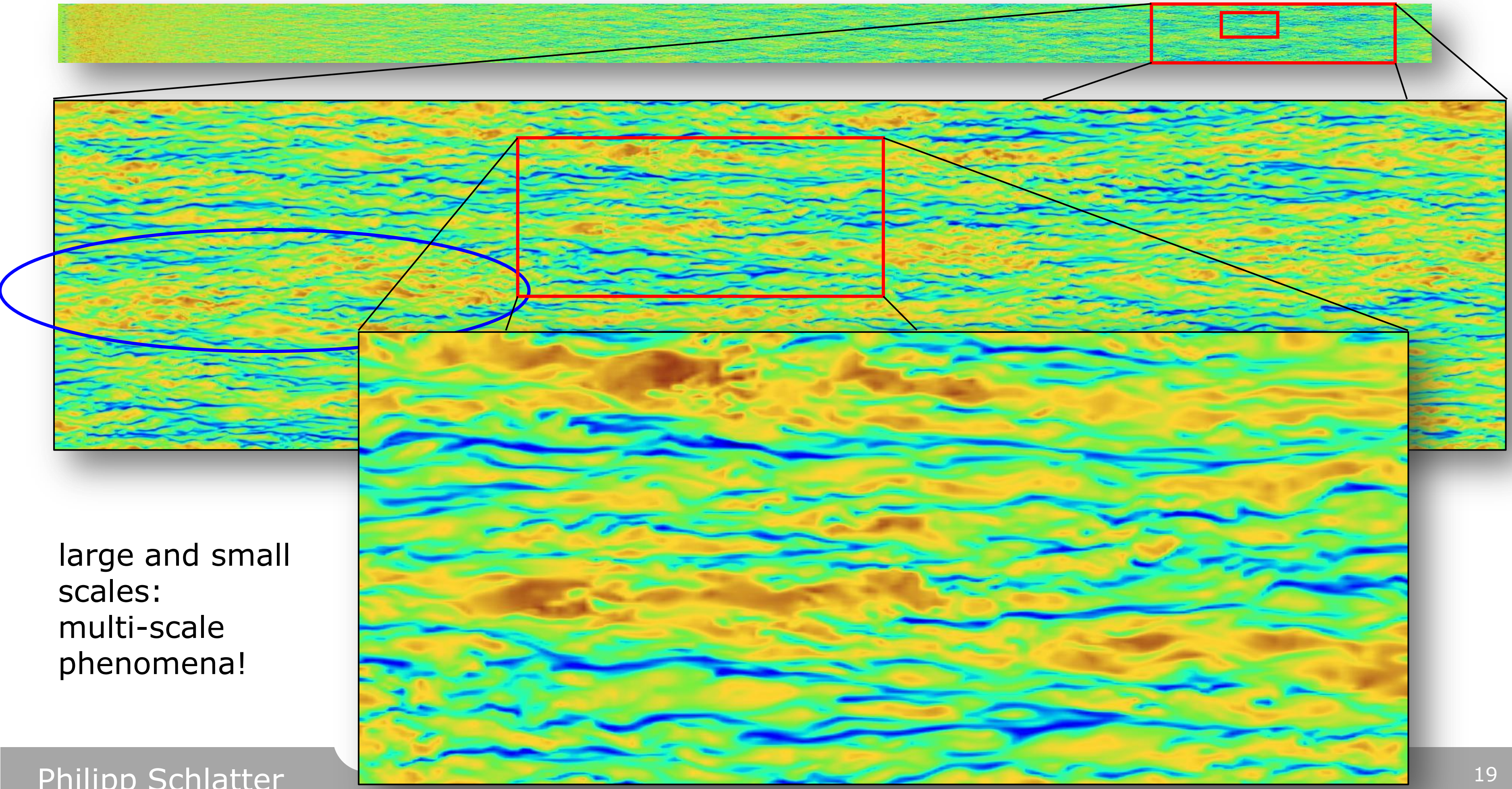
Turbulent flow close to solid walls...



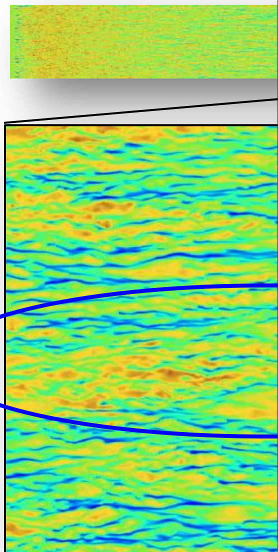
Turbulence close to the surface → Friction → Drag → Fuel consumption

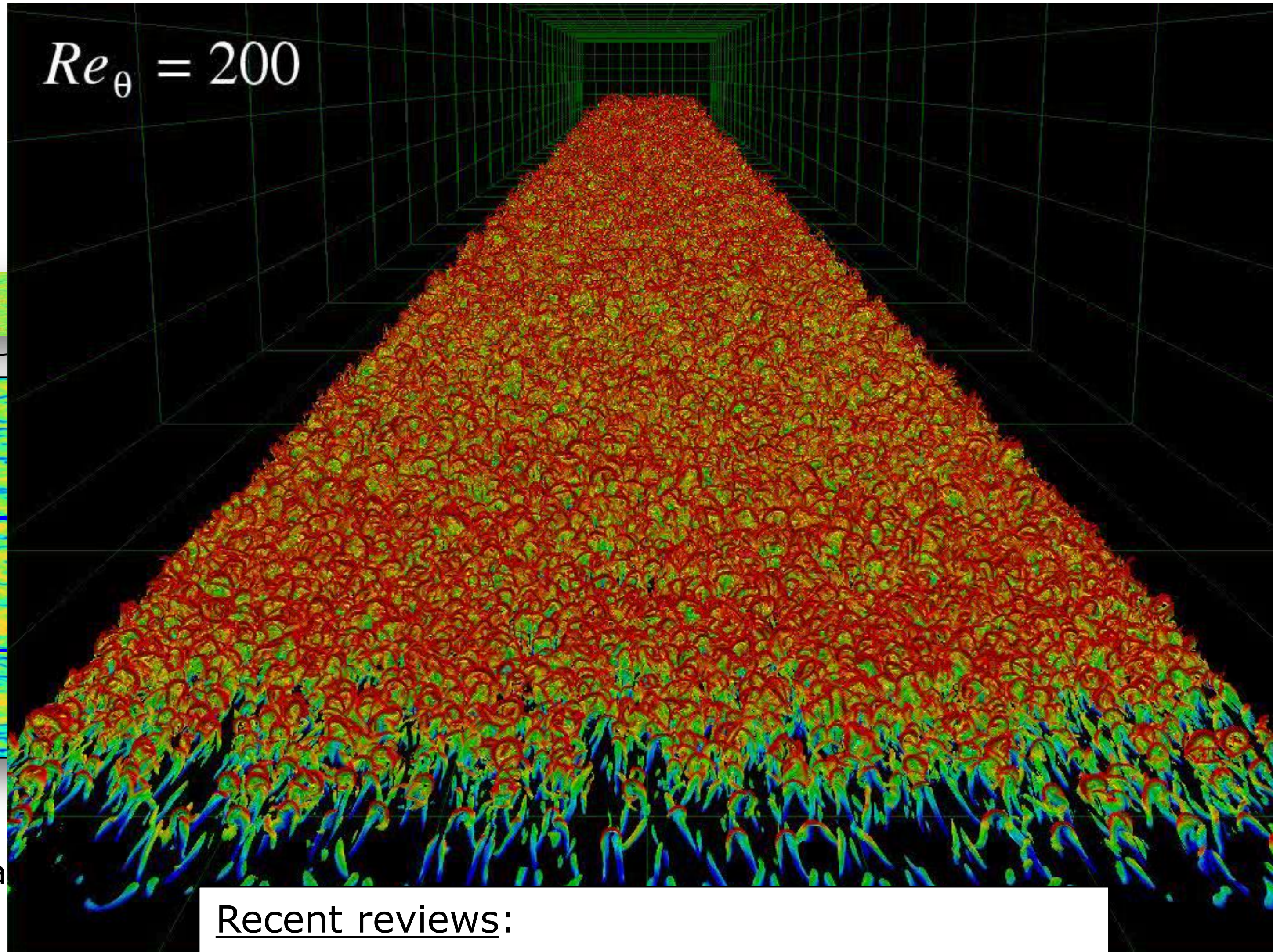
Turbulent flow close to solid walls...

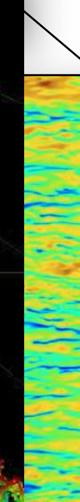
(simulation result)



large and small scales: multi-scale phenomena!







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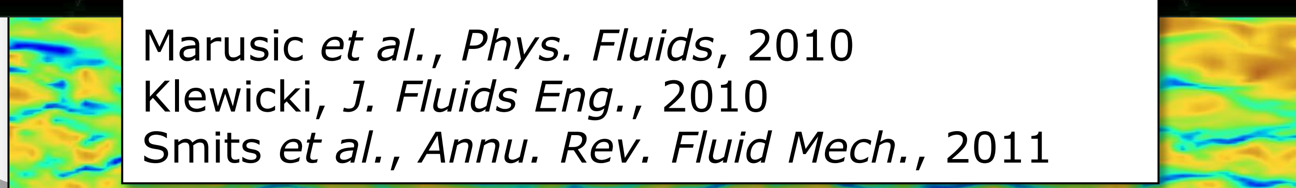

Recent reviews:

Marusic *et al.*, *Phys. Fluids*, 2010
Klewicki, *J. Fluids Eng.*, 2010
Smits *et al.*, *Annu. Rev. Fluid Mech.*, 2011

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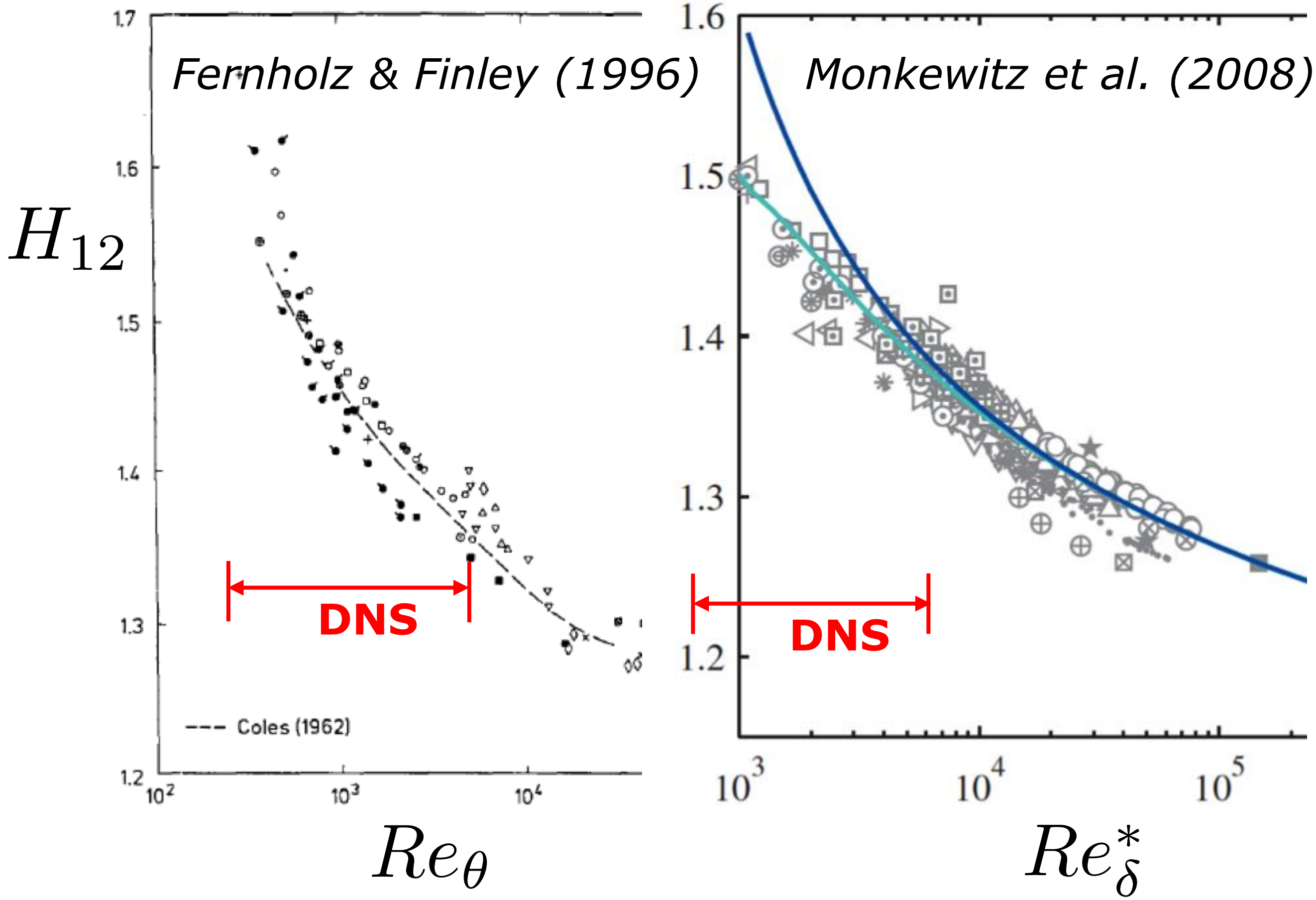
DNS of Turbulent Boundary Layers (TBL)

What we are used/expect to see …



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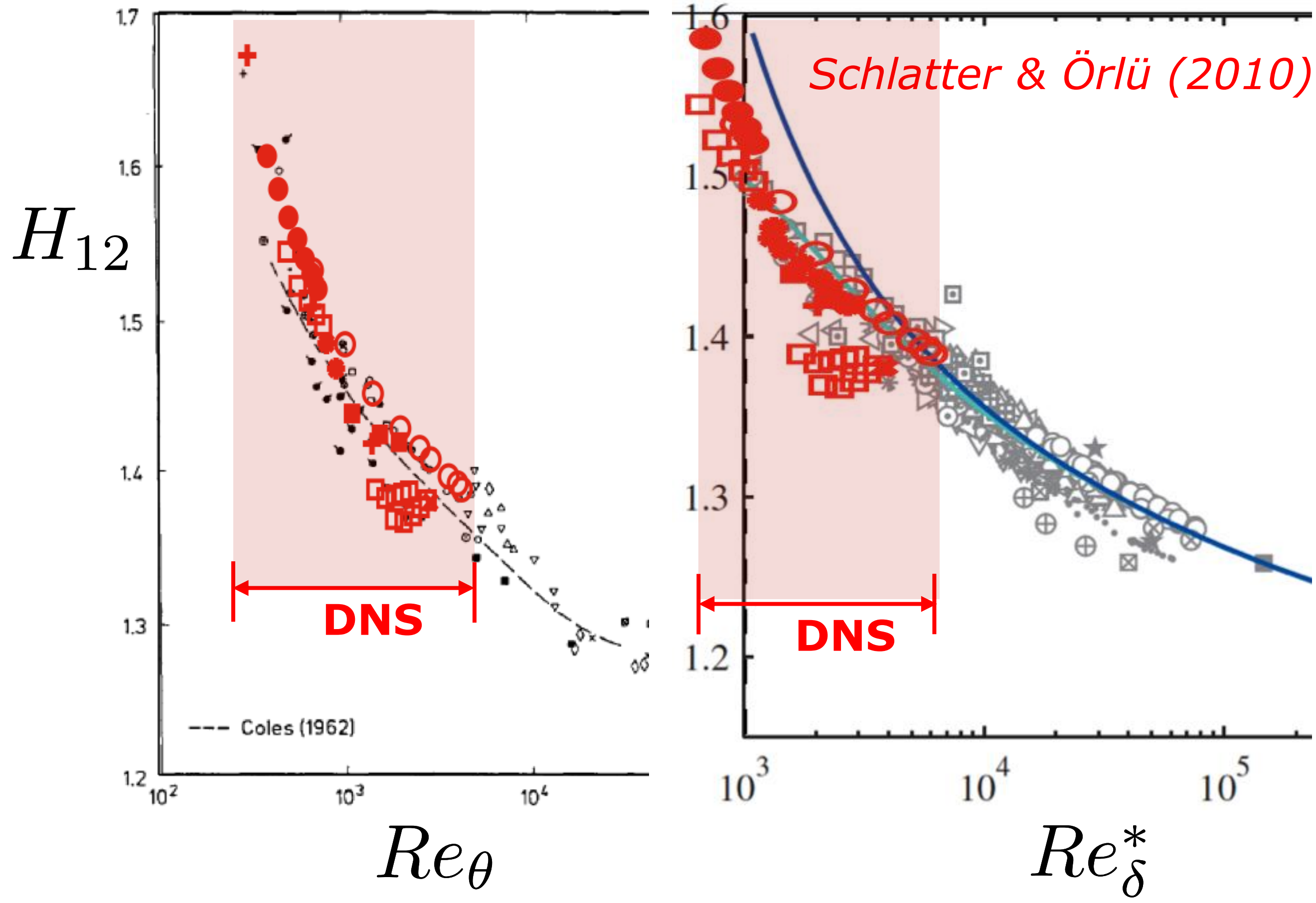
Compilation/ Assessment of experimental data from ZPG TBL flows

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



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

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

Employed ZPG TBL DNS data

Reference	Re_θ	Method	Symbol
Spalart (1988)	300, 600, 1410	spectral spatio-temporal	+
Komminaho & Skote (2002)	383 – 716	spectral tripping at $Re_\theta \approx 200$ domain up to $Re_\theta \approx 750$	●
Khujadze & Oberlack (2004; 2007)	489 – 2807	spectral tripping close to resp. inflow domain length $\Delta Re_\theta \approx 500$	□
Ferrante & Elghobashi (2005)	2900	finite differences rescaling and recycling domain $Re_\theta = 2340 - 2900$	× △
Simens *et al.* (2009)	1000, 1550, 1968	finite-difference/spectral rescaling and recycling domain $Re_\theta = 620 - 2140$	■
Schlatter *et al.* (2009*a*; 2009*b*)	677 – 4271	spectral tripping at $Re_\theta = 180$, single domain up to $Re_\theta \approx 4300$	○
Wu & Moin (2009)	800, 900	finite difference free-stream disturbances	∗
Wu & Moin (2010)	**900 – 1840**	laminar inflow at $Re_\theta = 80$	*
Lee & Sung (2011)	**2560**	**finite differences, recycling**	◇

Ref.: Schlatter & Örlü, *J. Fluid Mech.* 2010

Justification for re-evalution

- Integral quantities are often given as function of Re, however, ***how*** these were computed is often not given in detail
- Varying free-stream velocities for $y^+ > \delta^+$ implies (in conjunction with quite varying box height) unambiguous upper integral bound and free-stream velocity

→ Need for consistent re-evaluation!

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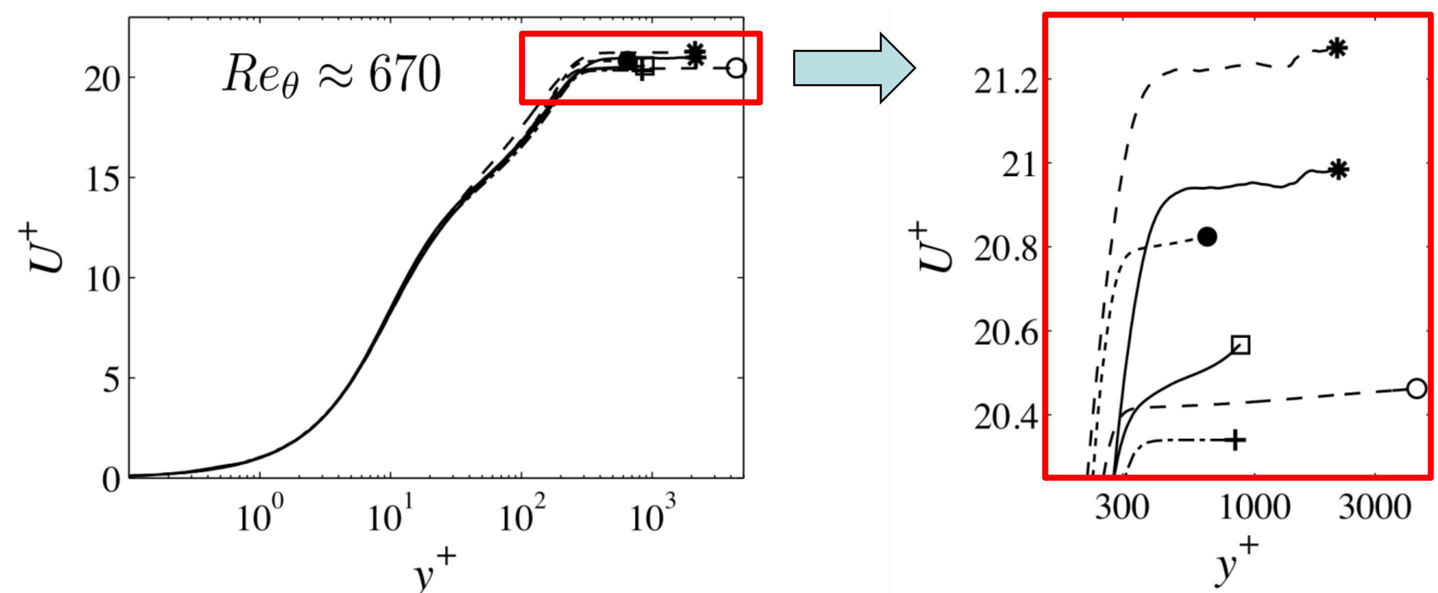

Consistent way to re-evaluate

- For the following re-evaluation we make use of the Nickels (2004) composite profile to determine free-stream velocity and the 99% boundary-layer thickness
- *Chauhan, Monkewitz & Nagib (2009)* composite profile for near-wall comparisons
- 4th order polynomial fit around maxima of Reynolds stresses to determine peak value and location

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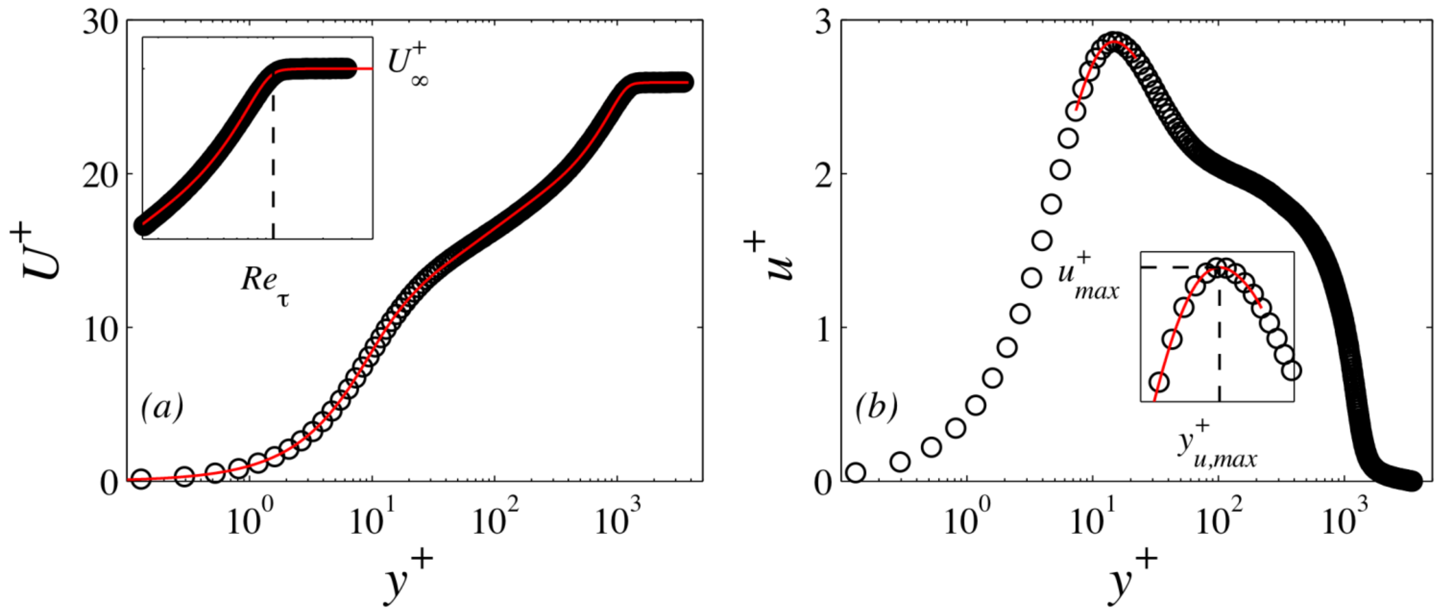
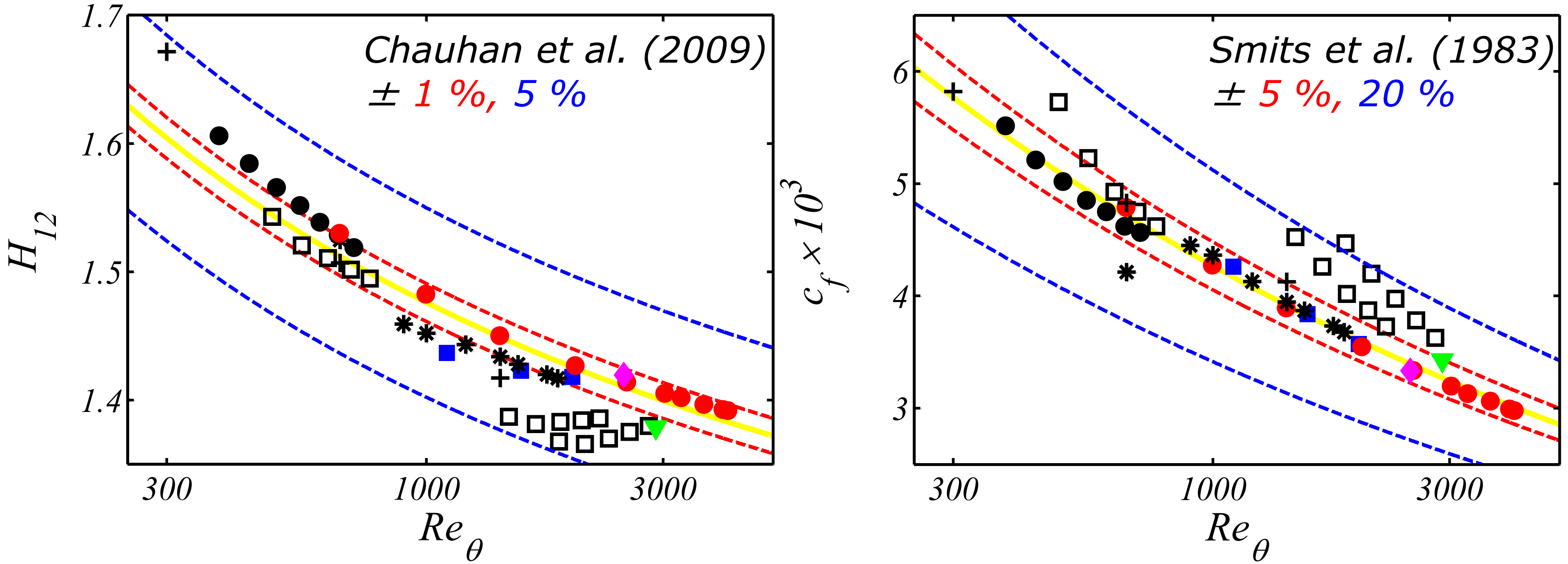


A closer look at DNS from ZPG TBL flows

Shape factor & Skin friction

- "we" are usually very confident about DNS data, at least when it comes to basic integral quantities, but …

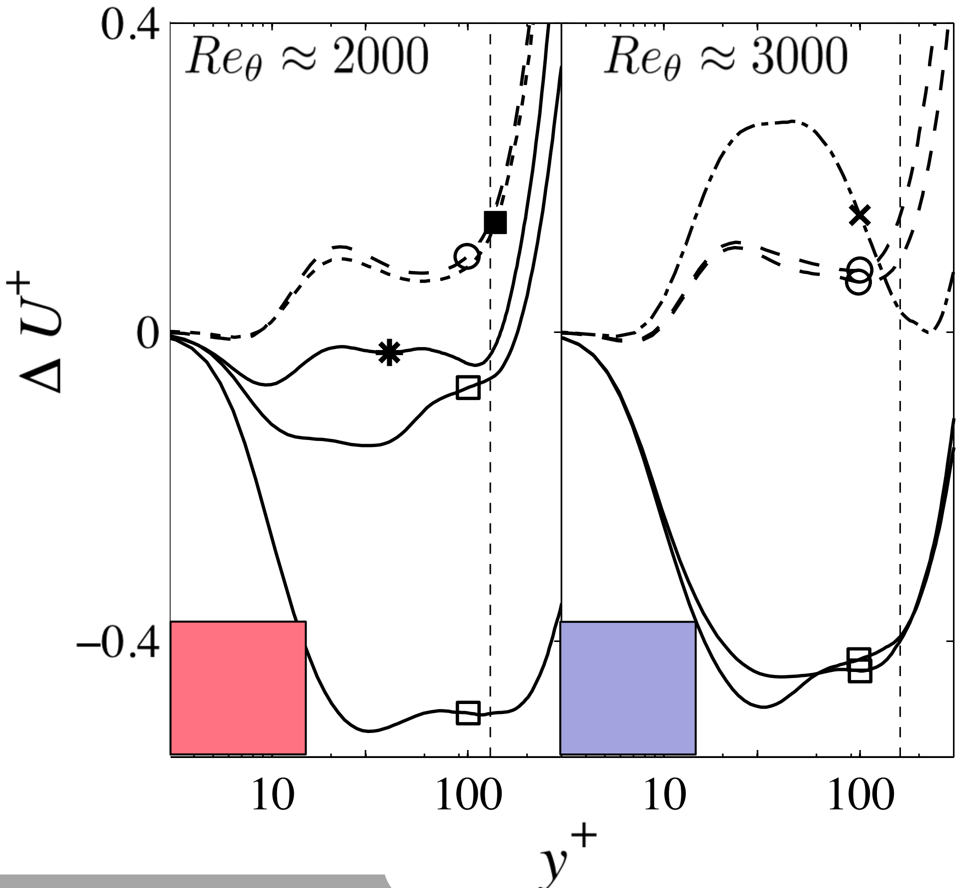


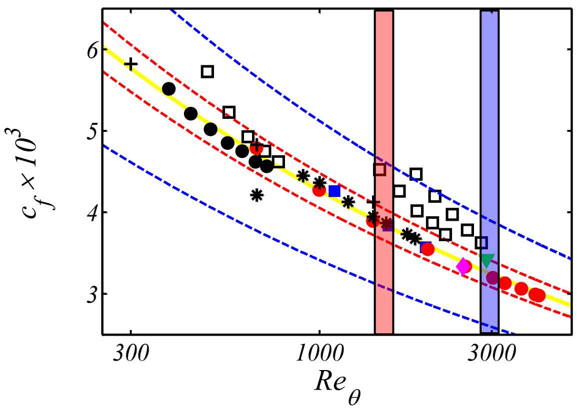
Data from 8 independent DNS (*Schlatter & Örlü, JFM, 2010*)

A closer look...

Inner layer

$$\Delta U^+ = U^+_{\text{DNS}} - U^+_{\text{Chauhan } et\ al.\ (2009)}$$





- “we” are usually very confident about DNS data, when it comes to mean velocity profiles, but …
- Note of caution: profiles have been utilised in the past to develop corrections for total-head probes, wall position, friction velocity, *etc*…

(see Örlü *et al.*, JPAS, 2010)

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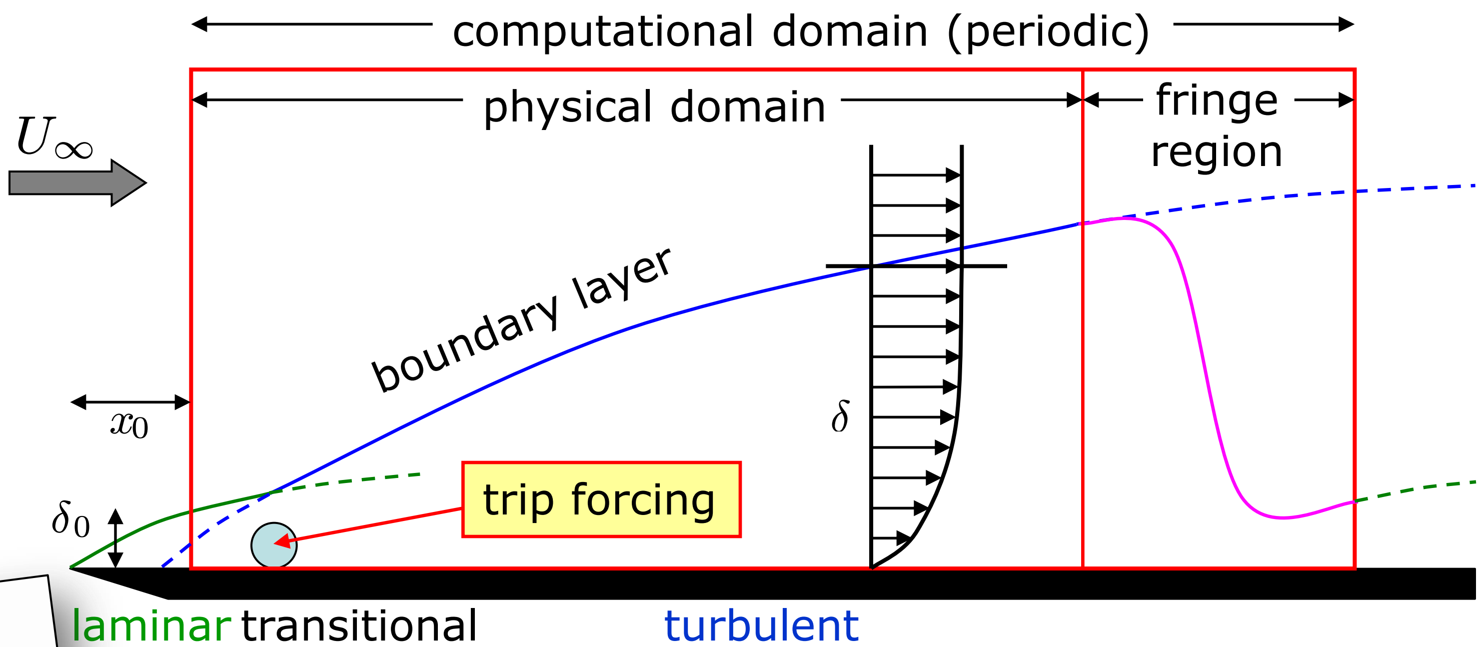
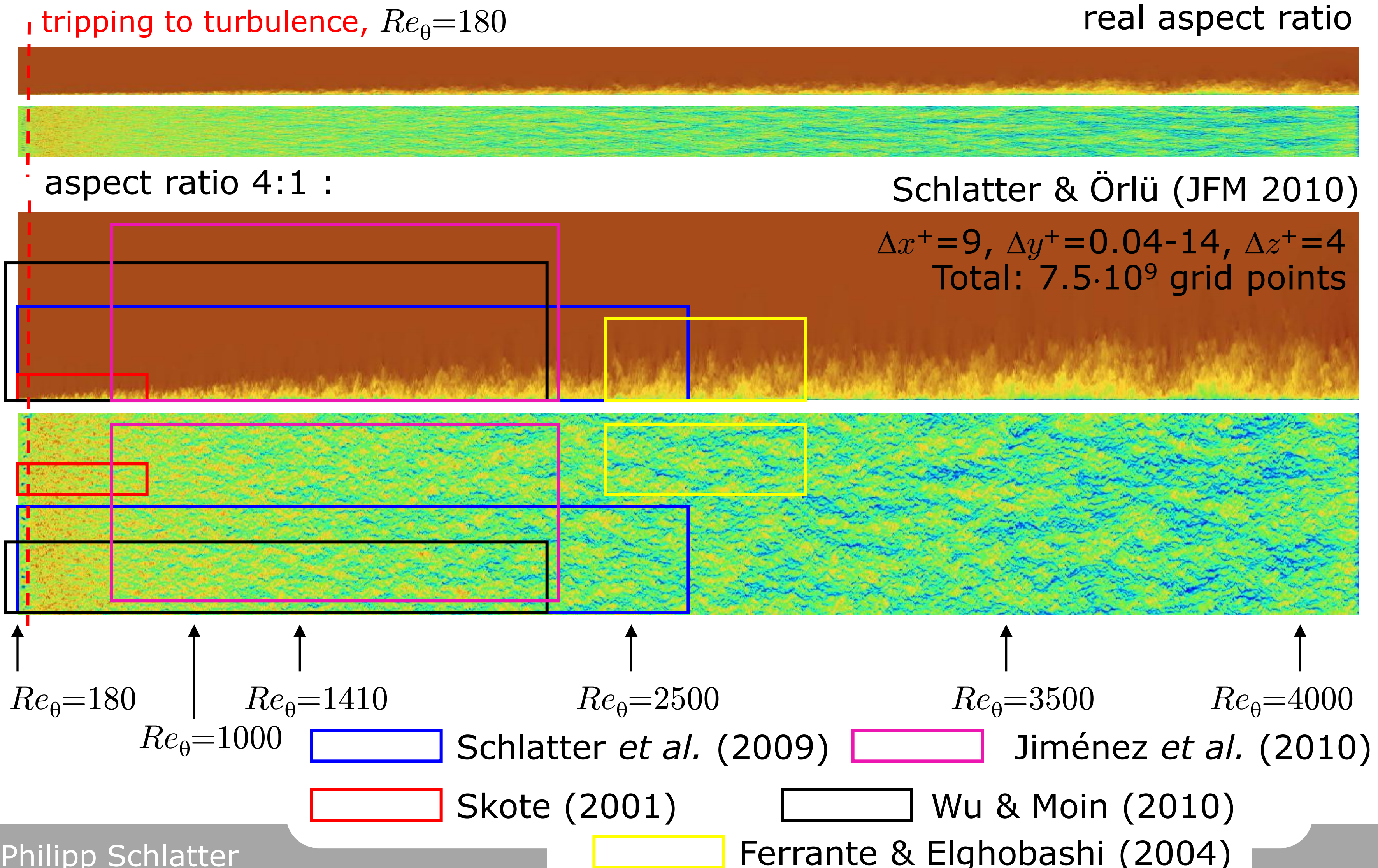
Need for new simulations close to experiments…

Spatial Boundary Layer

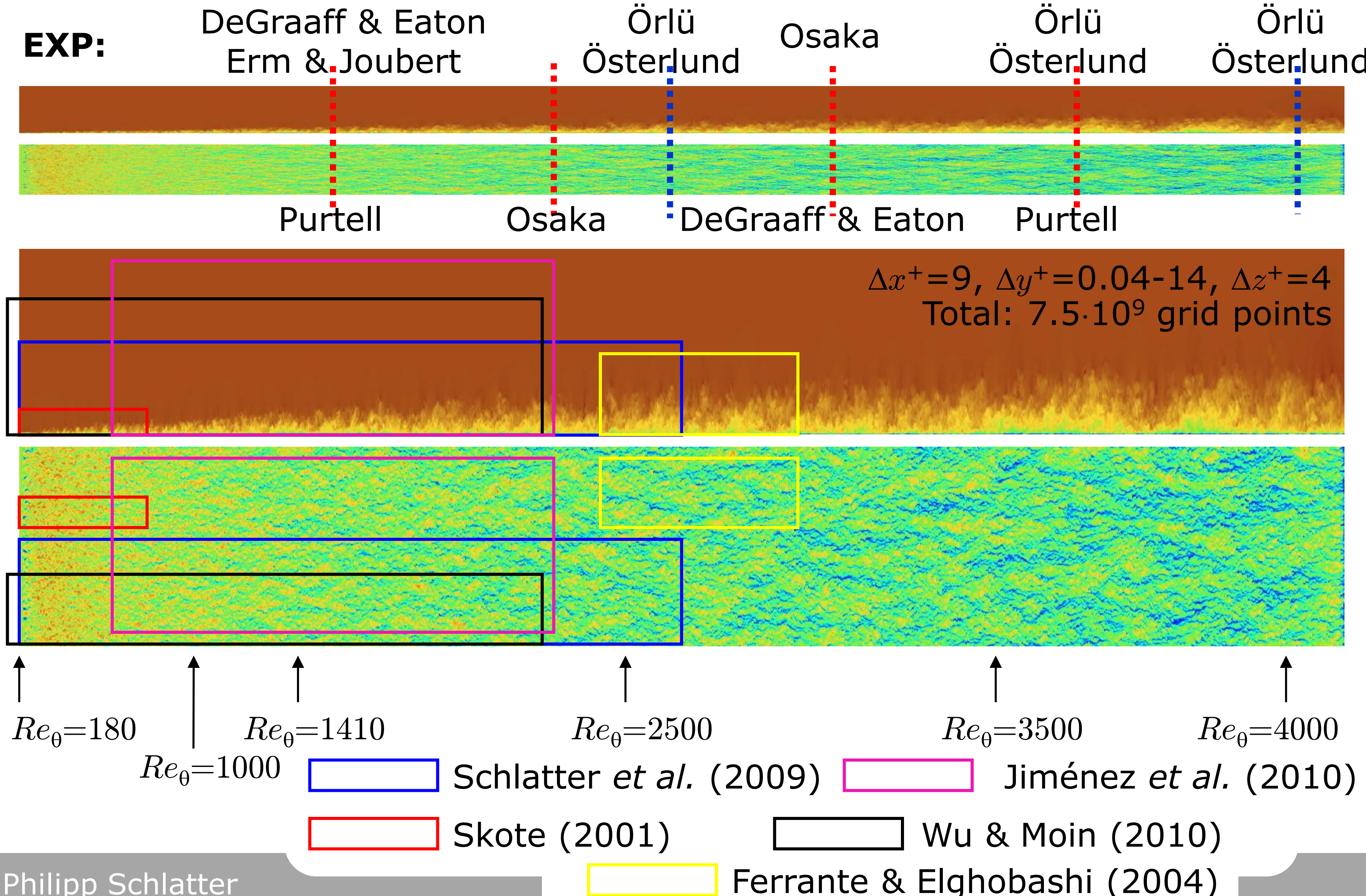


- Fully spectral method: Fourier/Chebyshev tau method
- Periodic boundary condition in the wall-parallel directions, no-slip at lower wall, Neumann conditions at upper boundary.
- Fringe region (volume force) to enforce laminar Blasius inflow
- Trip forcing to induce "natural" laminar-turbulent transition
- Code **SIMSON** (Chevalier *et al.* 2007) on up to 16384 cores BG/P

TBL up to $Re_\theta = 4300$...



TBL up to $Re_\theta = 4300$...



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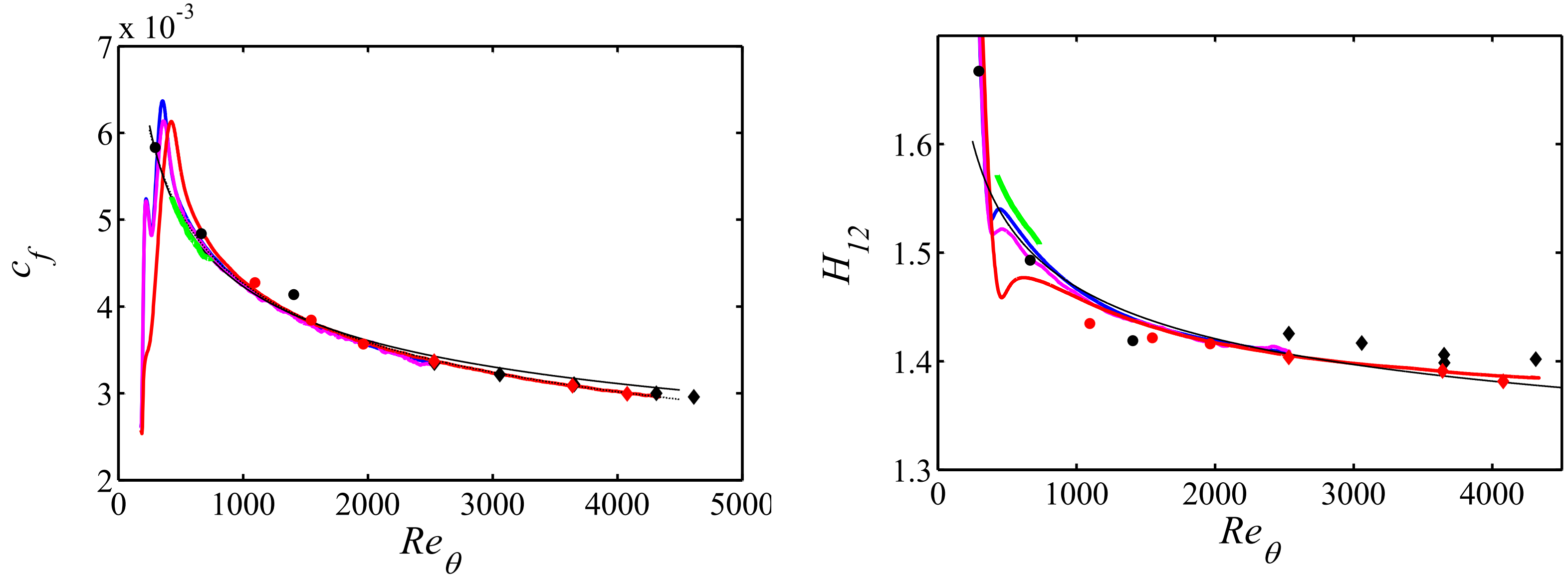
Some quick statistics…

Integral Quantities up to $Re_\theta=4300$

- Skin friction c_f and shape factor H_{12}



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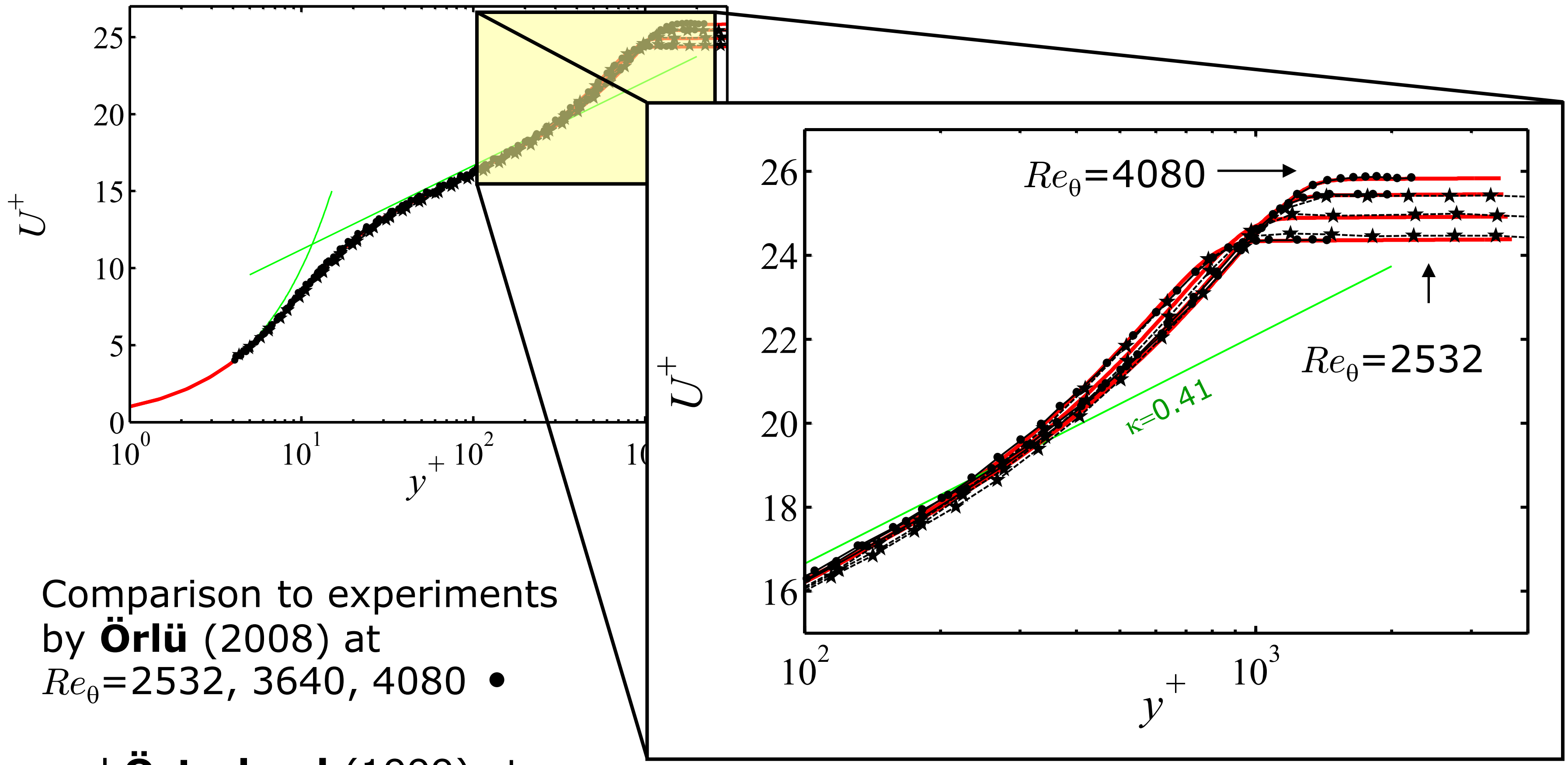
- ● DNS Spalart (1988) Re_θ=300, 670, 1410
- ● DNS Jiménez *et al.* (2009) Re_θ=1100, 1550, 2000
- ◆ EXP Österlund (1999) Re_θ=2500, 3000 ...
- ◆ EXP Örlü (2008) Re_θ=2500, 3000 ...
- — Correlations (Monkewitz *et al.* 2007, Österlund (1999))
- — DNS Skote (2001)

Medium DNS — Fine DNS — High DNS

DNS – Comparison to EXP



Comparison to experiments by **Örlü** (2008) at Re_θ=2532, 3640, 4080 •

and **Österlund** (1999) at Re_θ=2532, 3060, 3651 ···★···

—— present DNS at matching Re_θ

Von Kármán Integral Equation

- von Kármán equation $u_\tau^2 = U_\infty^2 \frac{\mathrm{d}\theta}{\mathrm{d}x} + \frac{\mathrm{d}}{\mathrm{d}x}\int_0^\infty \left(\langle u'^2\rangle - \langle v'^2\rangle\right)\mathrm{d}y$

$\approx -3 \cdot 10^{-5} U_\infty^2$

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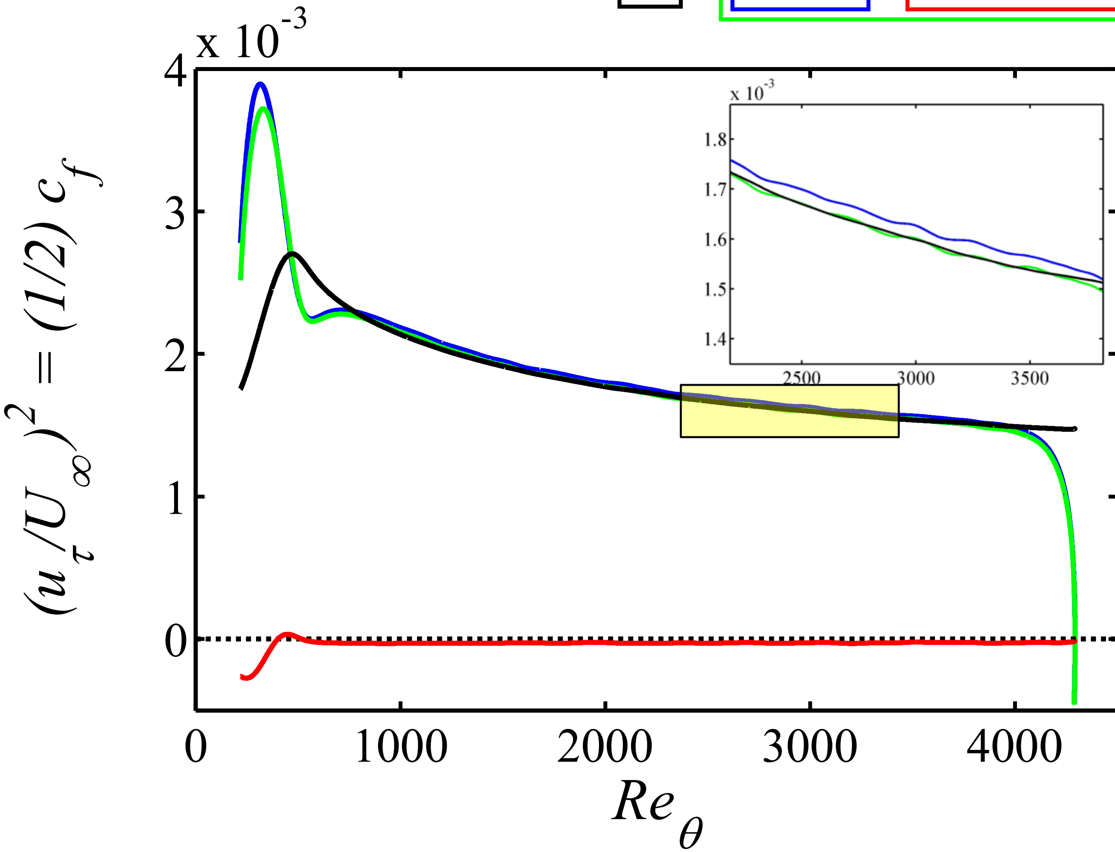
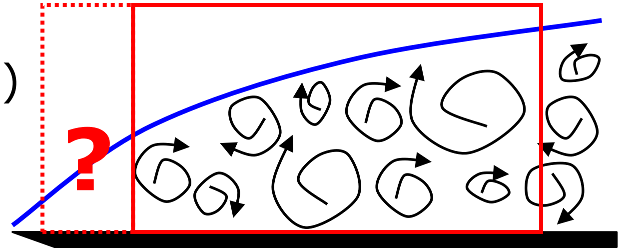


- Derived based on boundary-layer approximation
- Terms balance up to $\mathcal{O}(0.1\%)$

However, how about lower Reynolds numbers?

Evolution from initial conditions

- Spatial development → turbulence needs to be continuously generated close to / at the inflow:
  - artifical turbulence (*e.g.* Klein *et al.*)
  - precursor (periodic) simulation
  - recycling/rescaling (Lund *et al.*)
  - **tripping/transition to turbulence**



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- Immediate questions:
  - Depending on method, what inflow length is necessary?
  - Pressure gradient during adaptation/transition?
  - what is the lowest Re for ”fully developed” turbulence

Similar issues in experiments, see *e.g.* Erm & Joubert (1991), Castillo *et al.* (2004)

Ref.: Örlü & Schlatter, ETC-13, 2011

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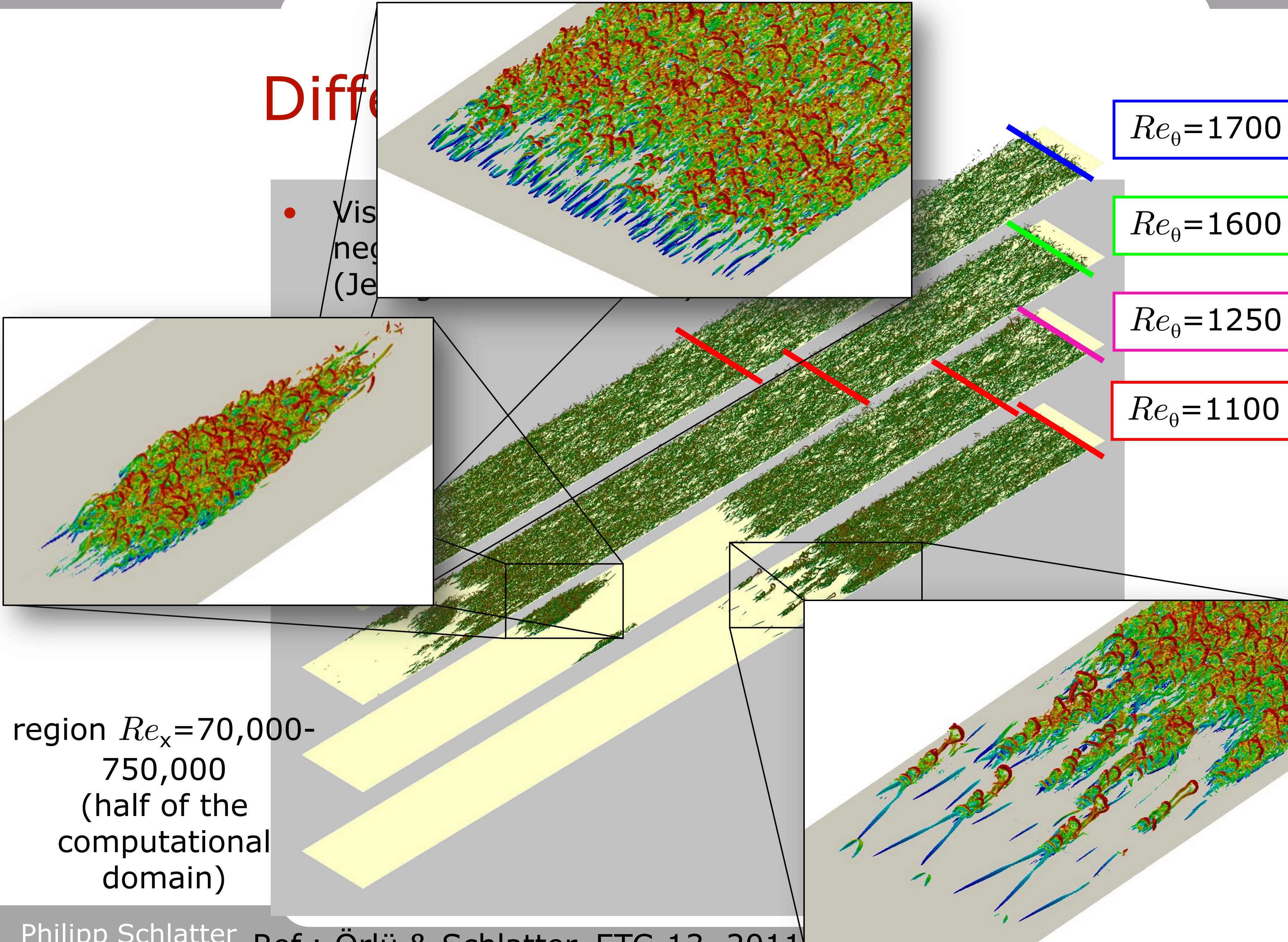

region Re_x=70,000-750,000 (half of the computational domain)

Ref.: Örlü & Schlatter, ETC-13, 2011

Inflow Length: Tripping

- We consider 4 different tripping mechanisms:
  a) baseline b) low amplitude
  c) low frequency d) Tollmien-Schlichting (TS) waves

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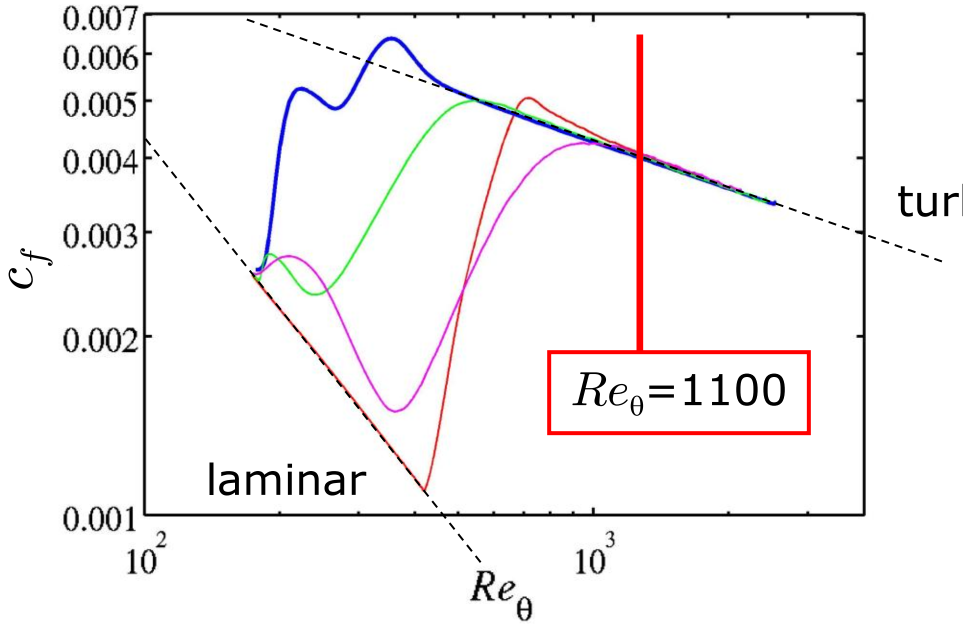
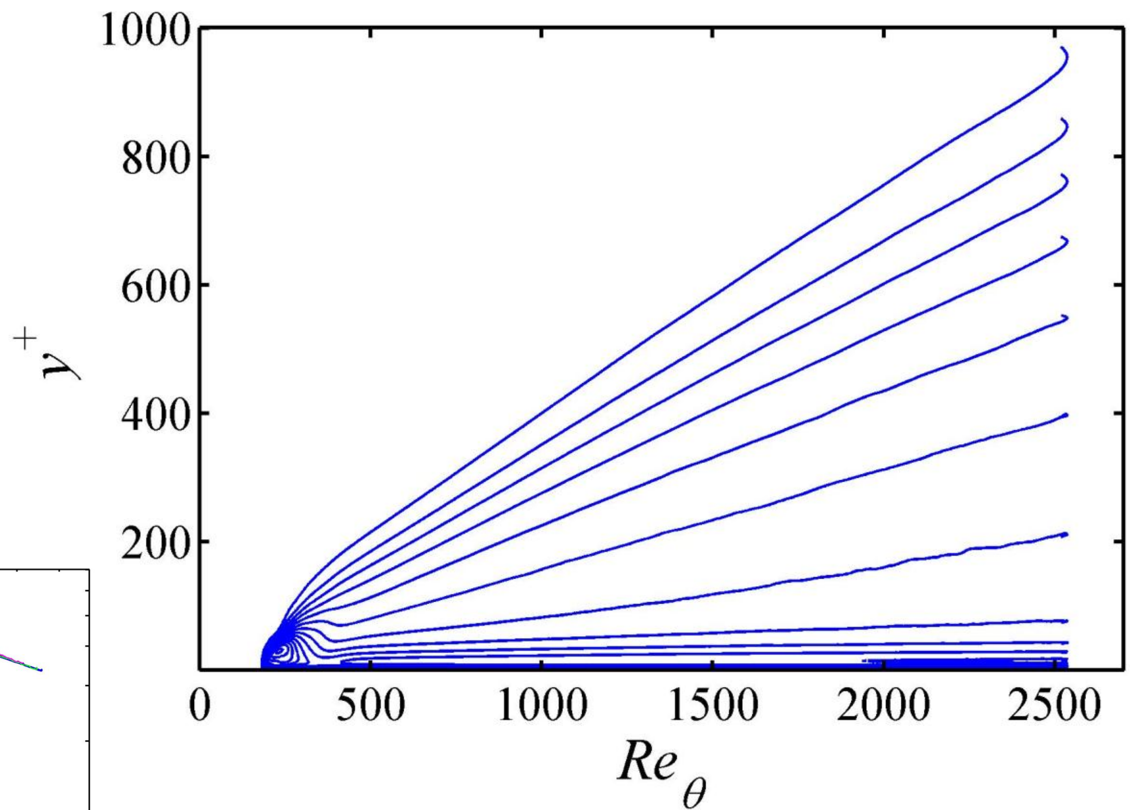
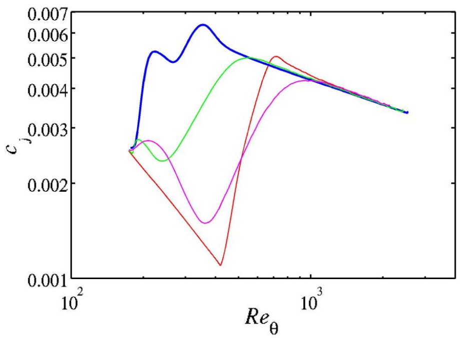


✓All simulations reach a common friction curve at some Re_θ.
✓Skin friction c_f is a measure for inner-layer convergence...?

Inflow Length: Tripping

- Contours of u^+_{rms} (steps 0.25)





a) baseline b) low amplitude
c) low frequency d) Tollmien-Schlichting (TS) waves

Inflow Length: Tripping

- Contours of $u^{+}{}_{\text{rms}}$ (steps 0.25)

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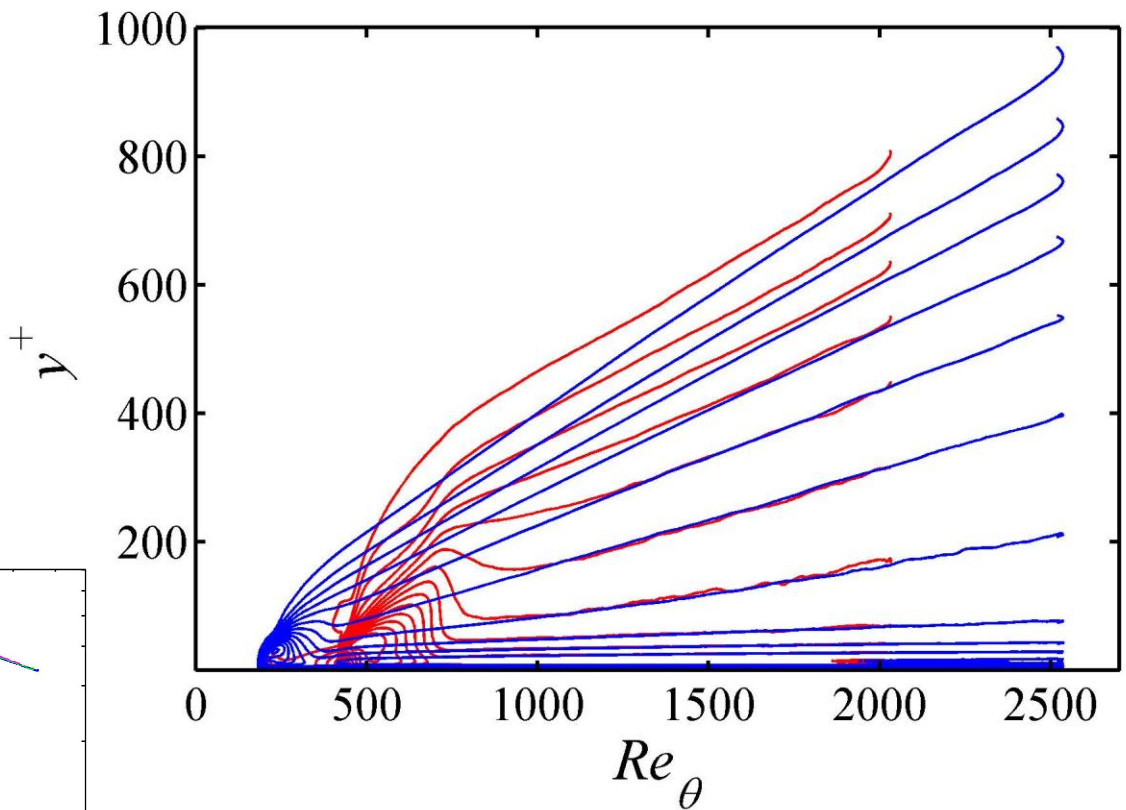
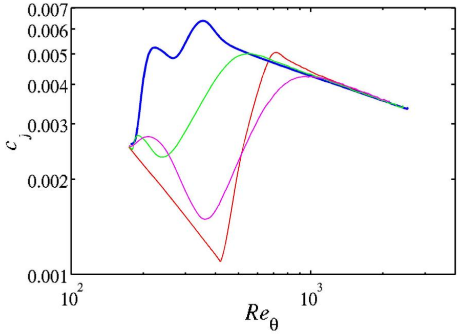
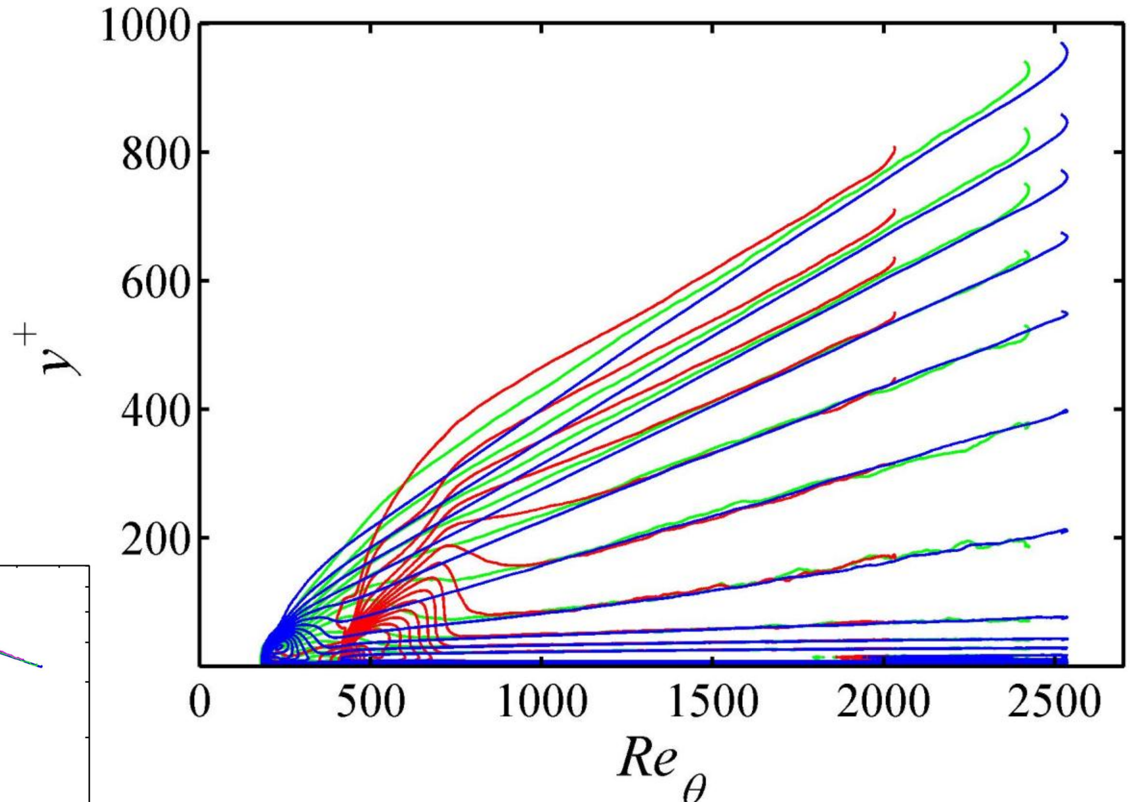




a) baseline
b) low amplitude
c) low frequency
d) Tollmien-Schlichting (TS) waves

Inflow Length: Tripping

- Contours of $u^+{}_{\mathrm{rms}}$ (steps 0.25)



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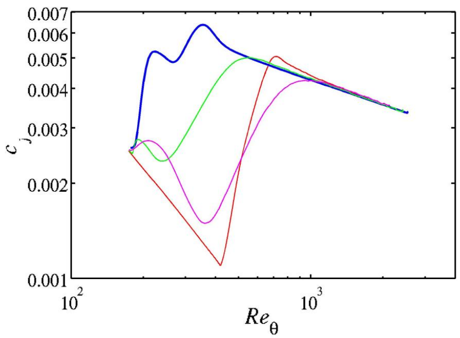

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Inflow Length: Tripping

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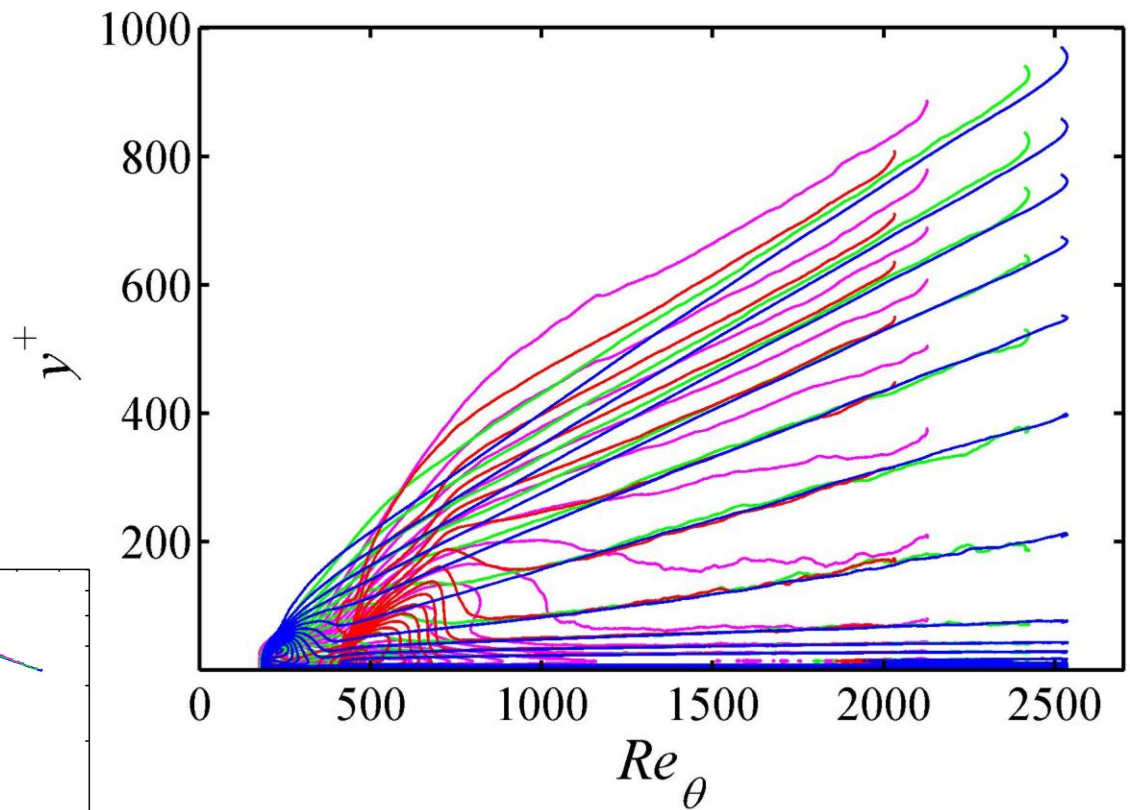

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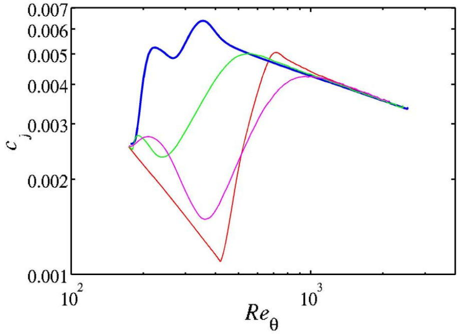
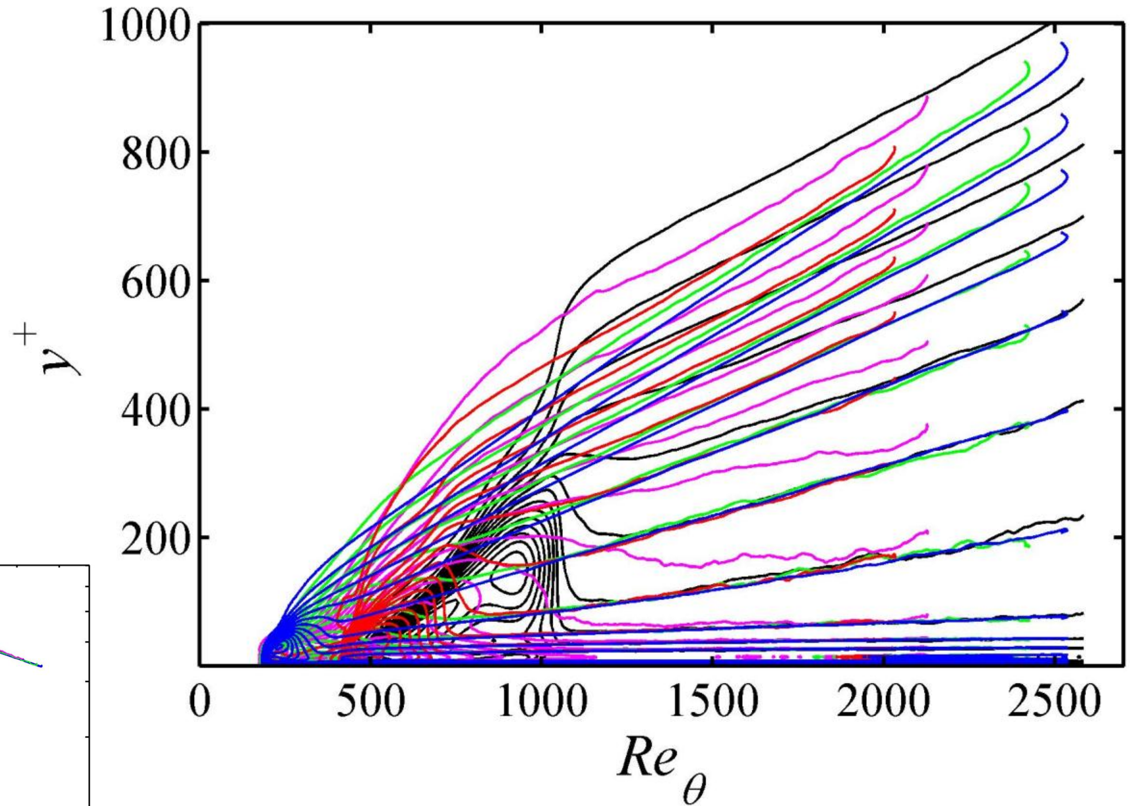


a) baseline — b) low amplitude —
c) low frequency — d) Tollmien-Schlichting (TS) waves —

Inflow Length: Tripping

- Contours of u^+_{rms} (steps 0.25)



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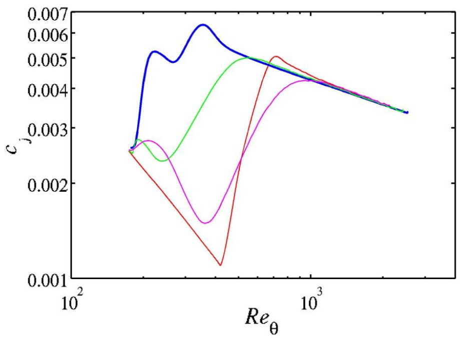
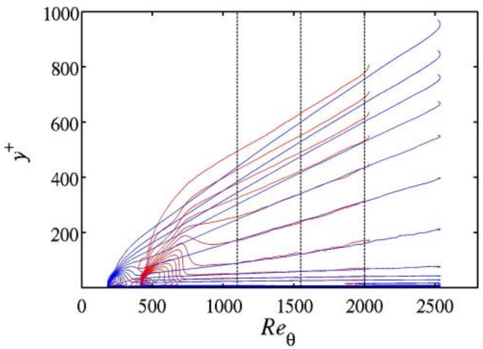


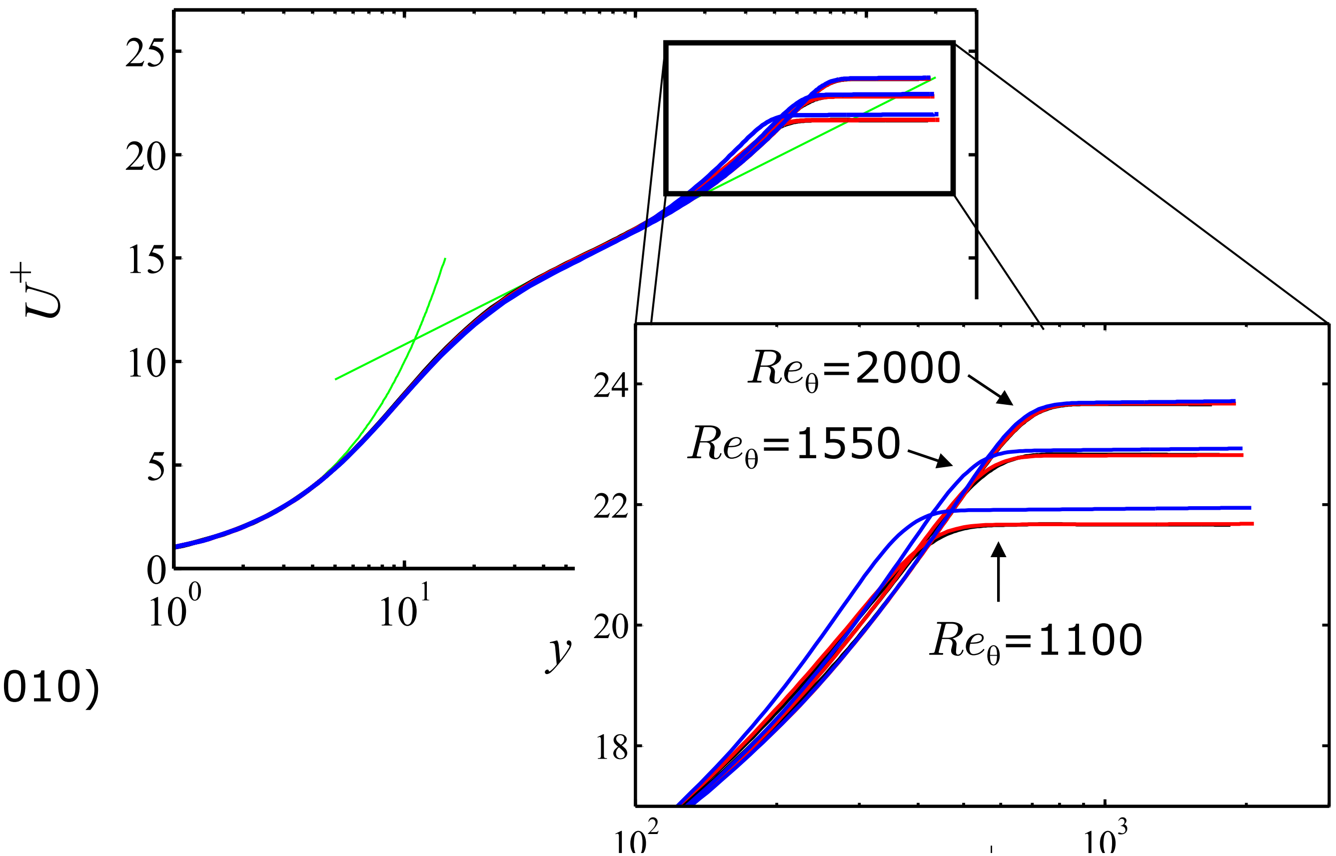
a) baseline — b) low amplitude —
c) low frequency — d) Tollmien-Schlichting (TS) waves —
— tripping at higher Re

Inflow Length: Tripping

- Consider three Re_θ=1100, 1550, 2000



baseline
TS-waves
Jiménez *et al.* (2010)

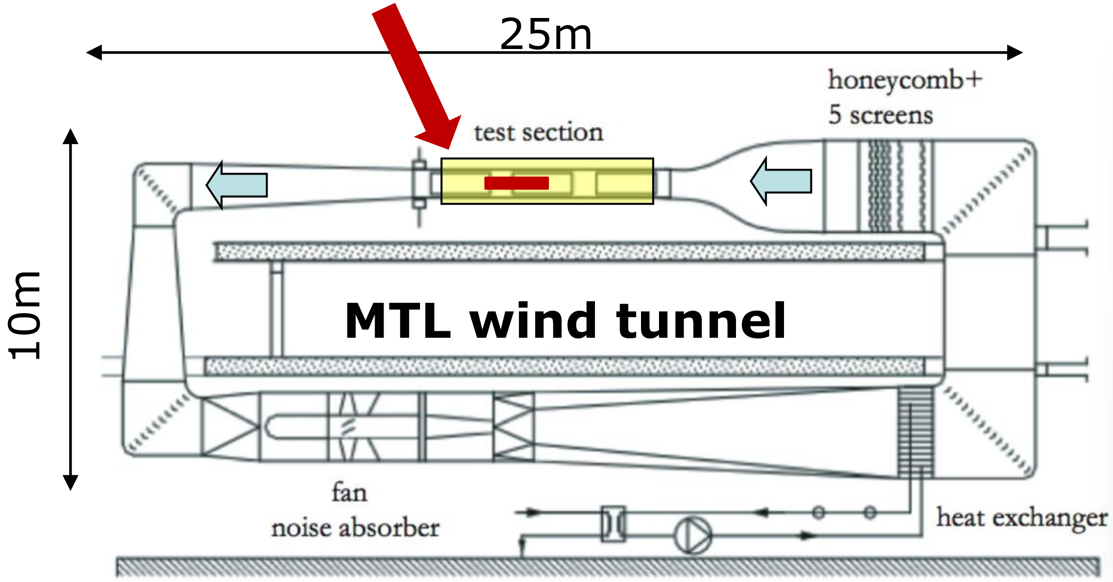


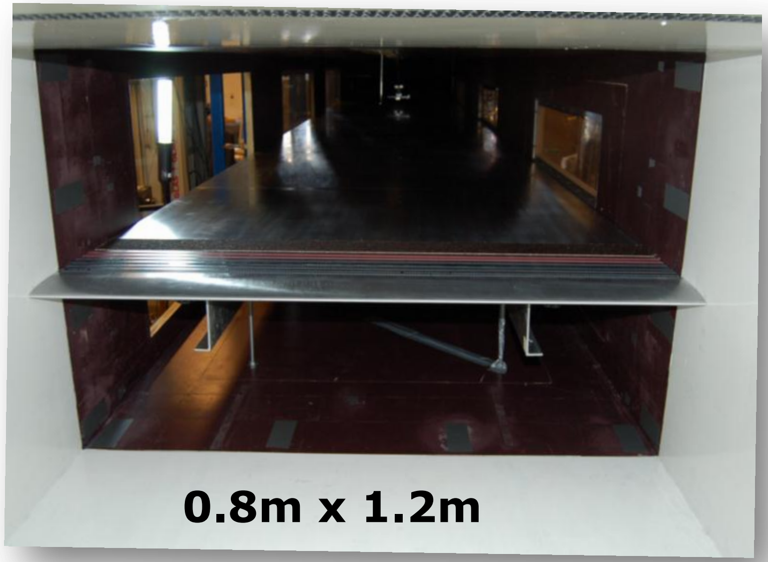
Ref.: Örlü & Schlatter, ETC-13, 2011

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…

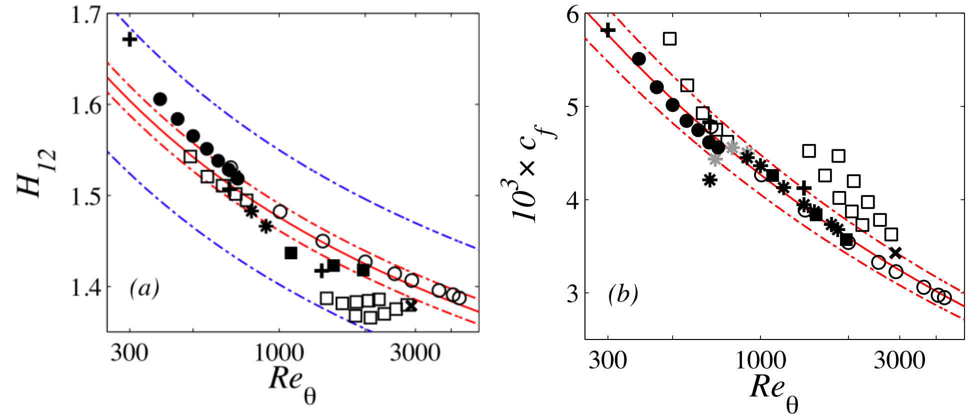




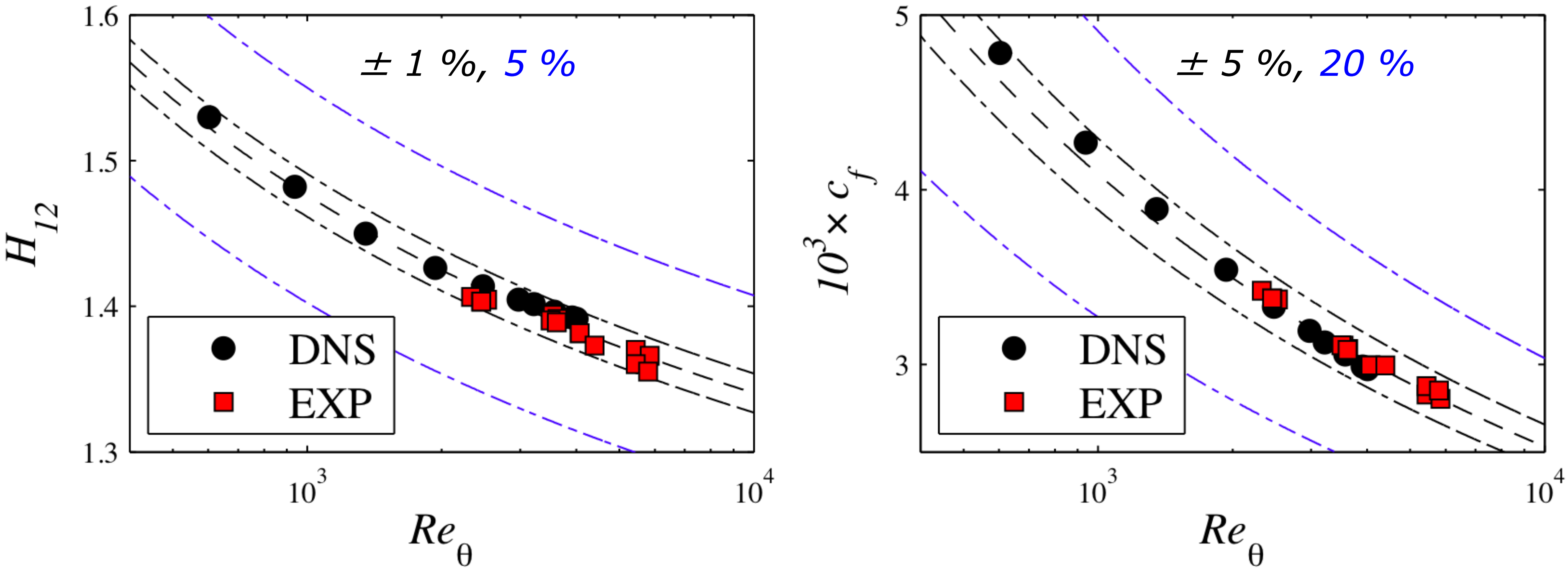
Thesis Örlü 2009

Shape factor & skin friction coefficient

Recall



- - - *Correlation by Chauhan et al. (2009)*



Örlü and Schlatter, iTi 2010

Shape factor & skin friction coefficient

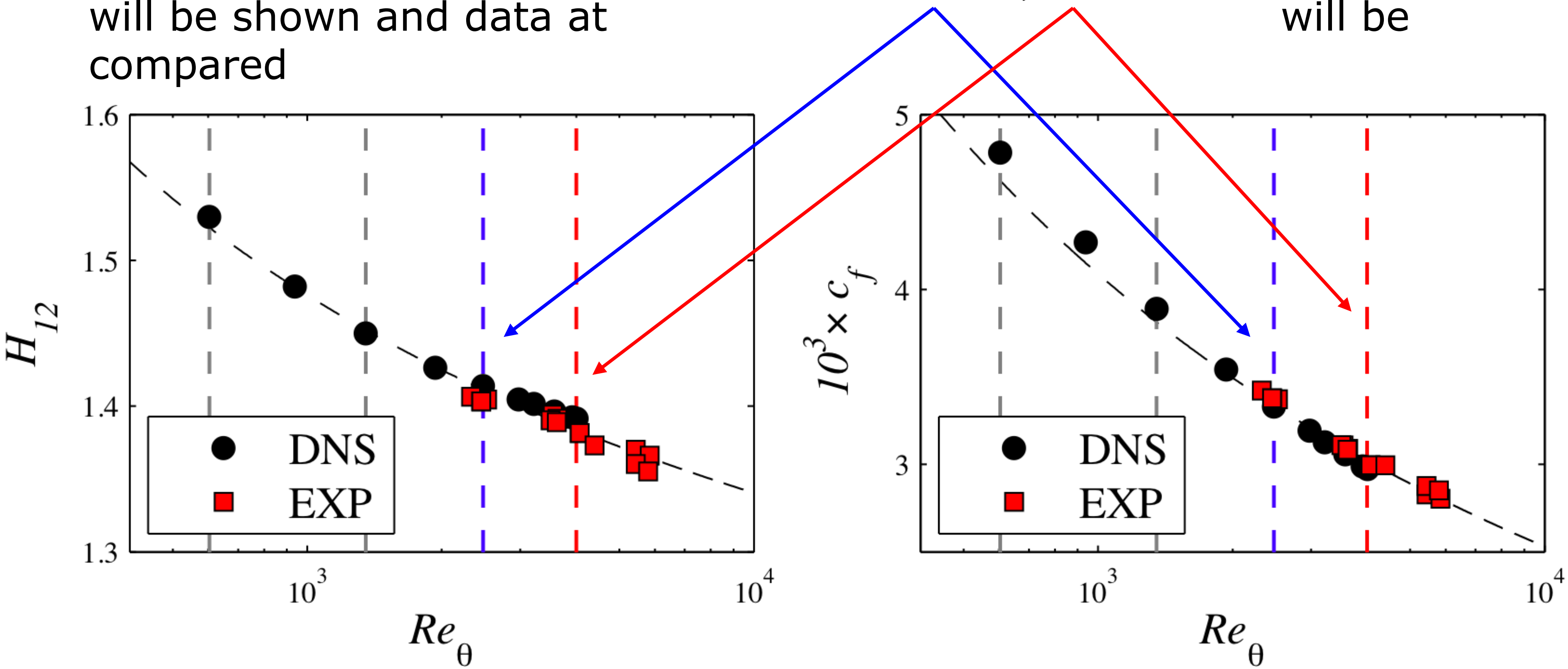
In the following slides data from DNS at

$$Re_\theta = 670, 1410, 2500, 4000$$

and experiments at

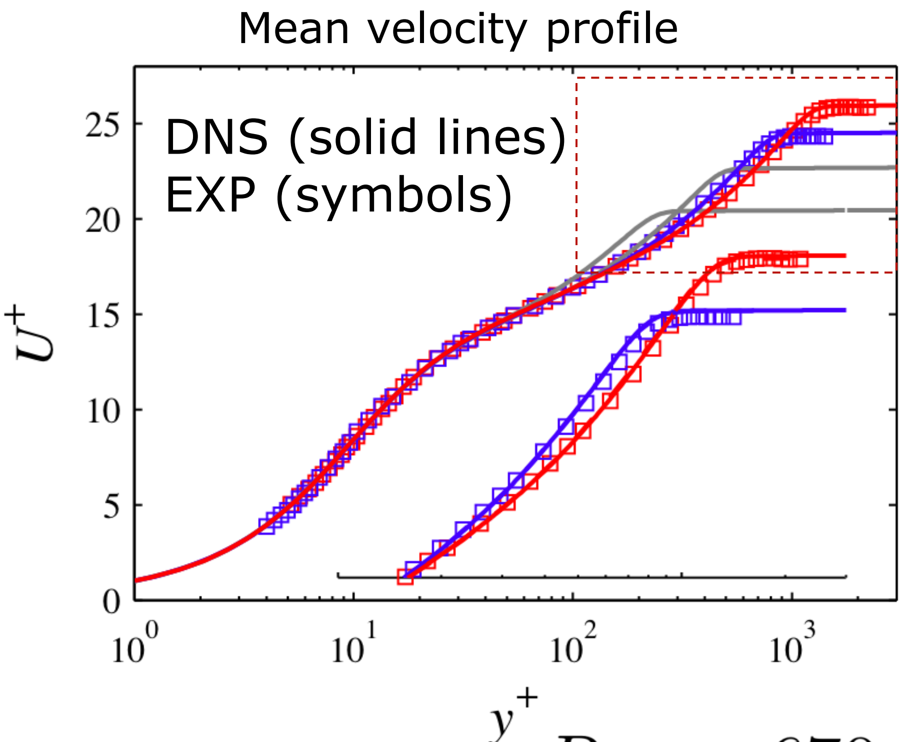
$$Re_\theta = 2500, 4000$$

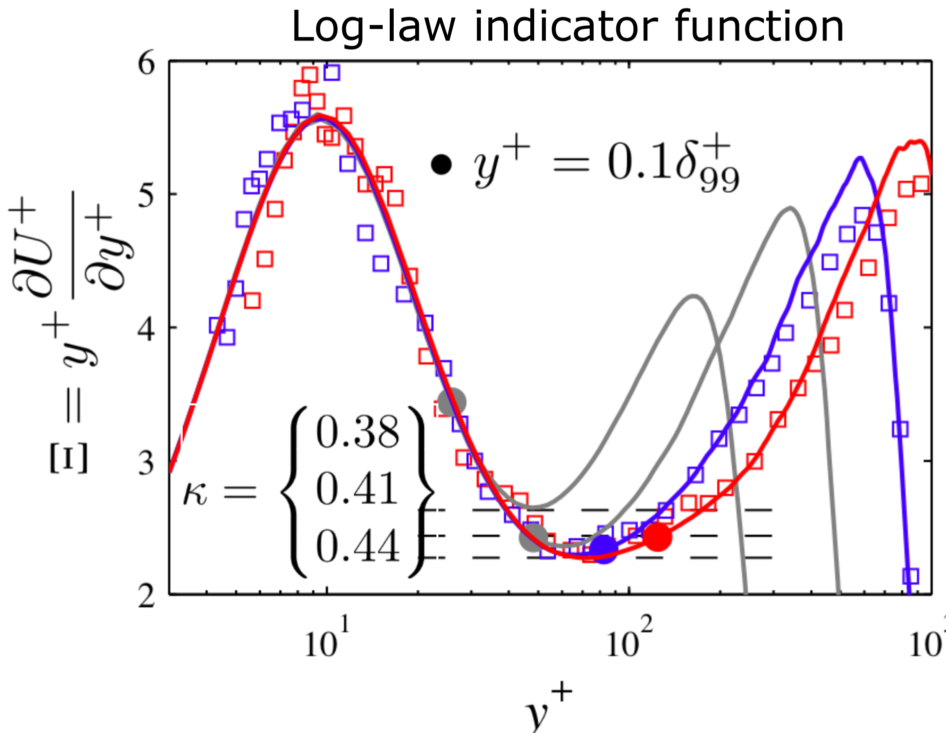
will be shown and data at will be compared



Örlü and Schlatter, iTi 2010

Mean streamwise velocity profiles





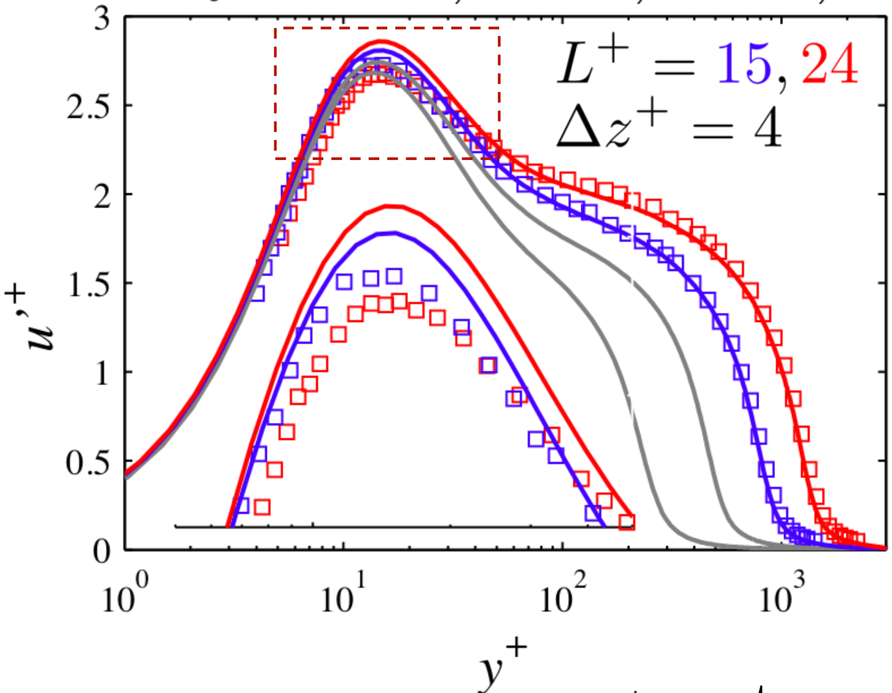
$Re_\theta = 670, 1410, 2500, 4000$

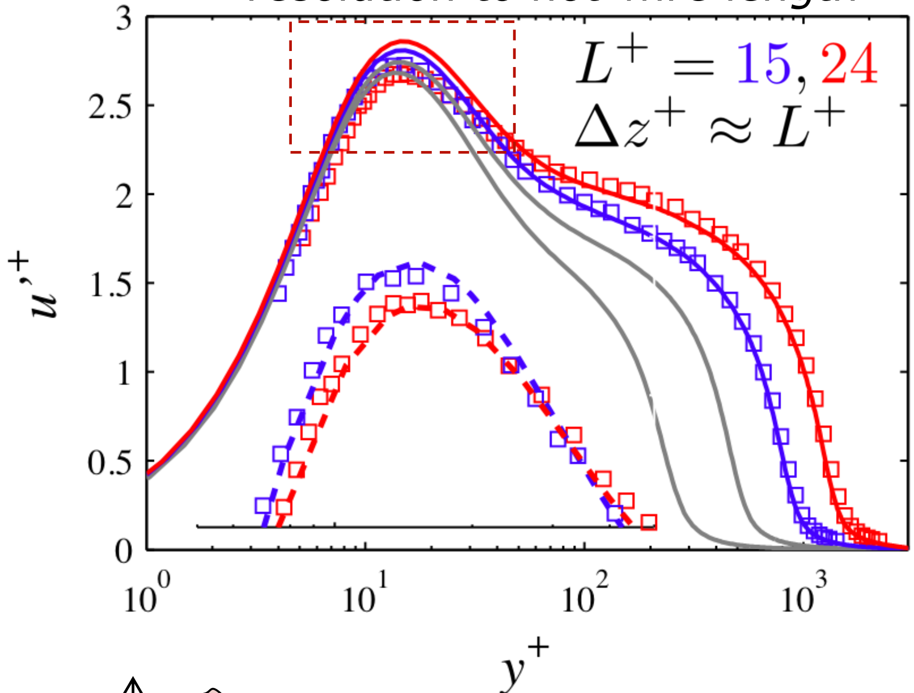
Örlü and Schlatter, iTi 2010

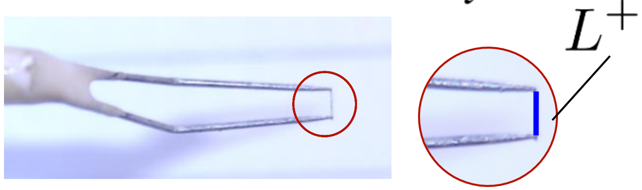
Turbulence intensity profiles

$Re_\theta = 670, 1410, 2500, 4000$

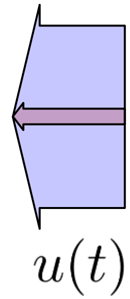
--- *DNS with matched spatial resolution to hot-wire length*

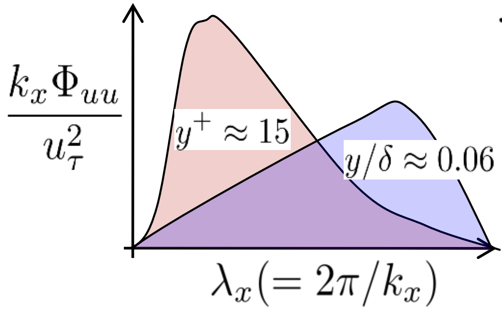






$u(t)_{\mathrm{meas}} = f(< e(t) >_L)$





(e.g. Örlü & Alfredsson, EF, 2010)

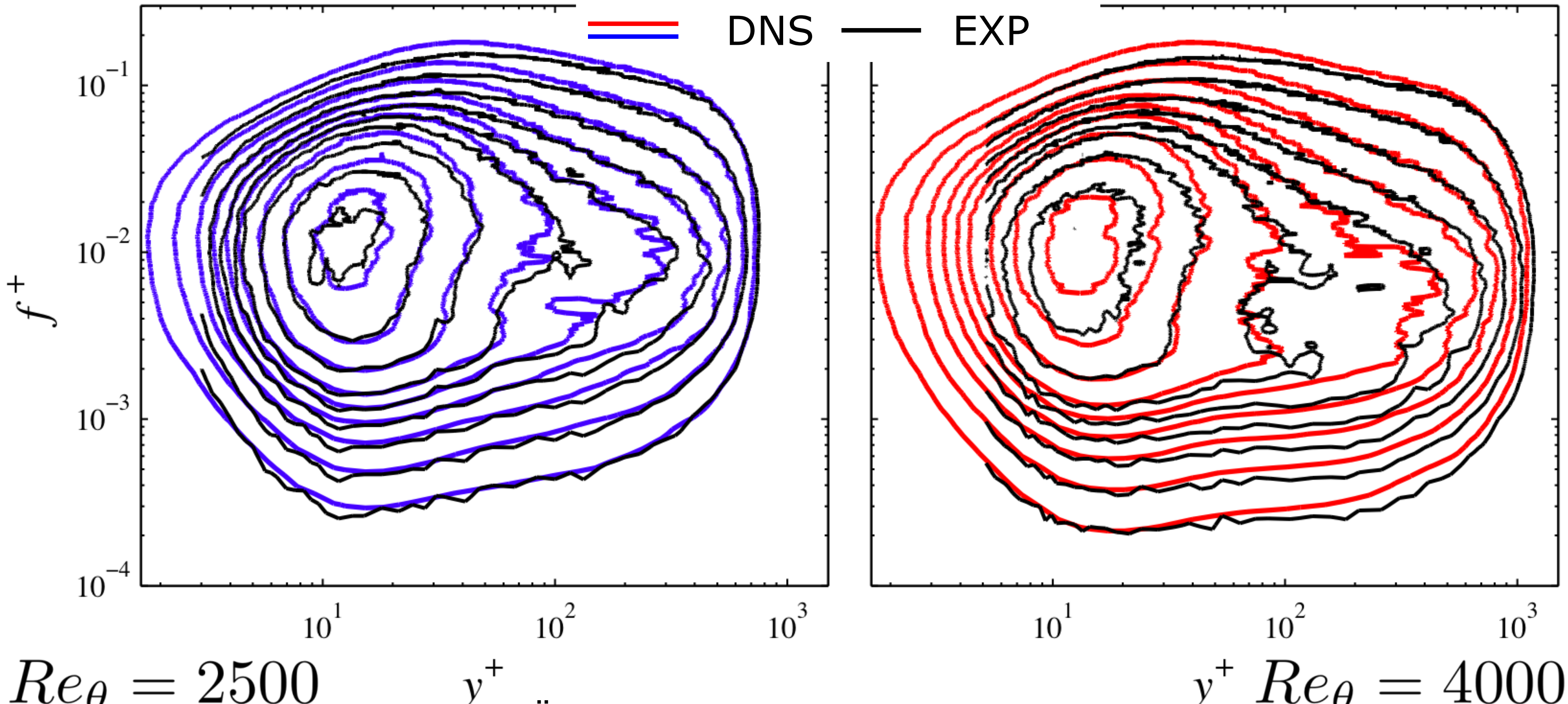
Pre-multiplied spectral map

$\Delta z^+ = 4,\ \Delta t^+ = 0.30$

$L^+ = 15,\ \Delta t^+ = 0.27$

$\Delta z^+ = 4,\ \Delta t^+ = 0.27$

$L^+ = 23,\ \Delta t^+ = 0.66$



$Re_\theta = 2500$ $Re_\theta = 4000$

Örlü and Schlatter, iTi 2010

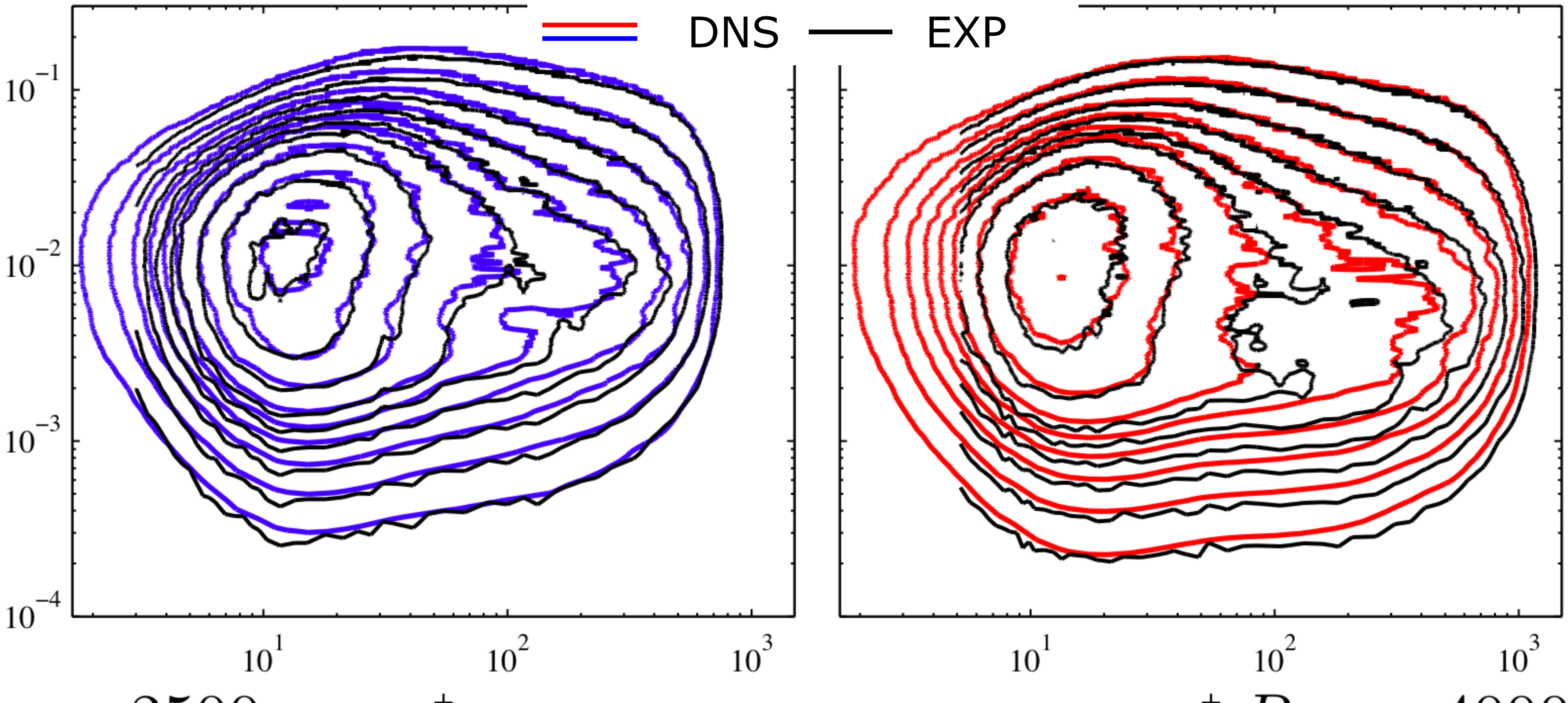
Pre-multiplied spectral map

$\Delta z^+ \approx L^+, \Delta t^+ = 0.30$

$L^+ = 15, \Delta t^+ = 0.27$

$\Delta z^+ \approx L^+, \Delta t^+ = 0.27$

$L^+ = 23, \Delta t^+ = 0.66$



$Re_\theta = 2500$

$Re_\theta = 4000$

Örlü and Schlatter, iTi 2010

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Wall-shear stress τ_w

Wall-shear stress fluctuation

Wall shear stress: $\tau_w = \mu \left. \frac{\partial u}{\partial y} \right|_w$ Fluctuation: $\tau_{w,rms}/\tau_w \equiv \tau^+_{w,rms} = \left. \frac{u}{U} \right|_{y \to 0}$

Main reference: Alfredsson *et al.* (1988): Explanation with spatial resolution...

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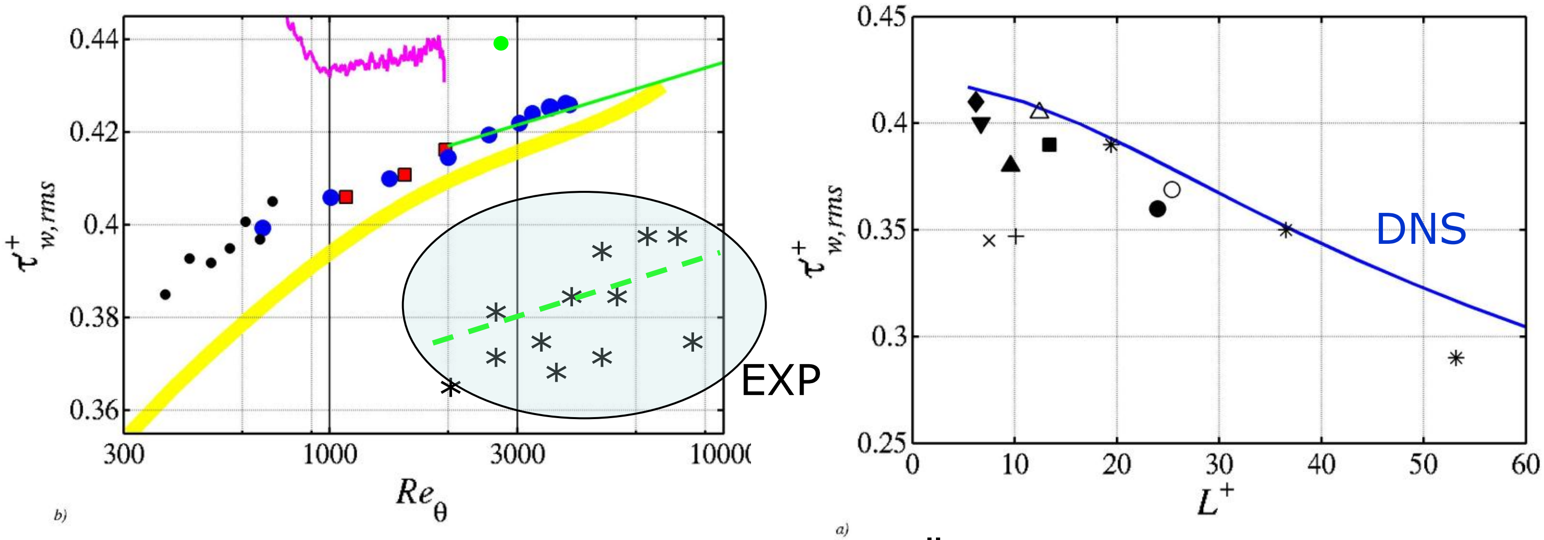


- Channel flows
- Skote (2001)
- Ferrante & Elghobashi (2005)
- Correlation Österlund ($*$)
- Schlatter & Örlu (2010)
- Jiménez *et al.* (2010)
- Wu & Moin, *Phys. Fluids* 2010

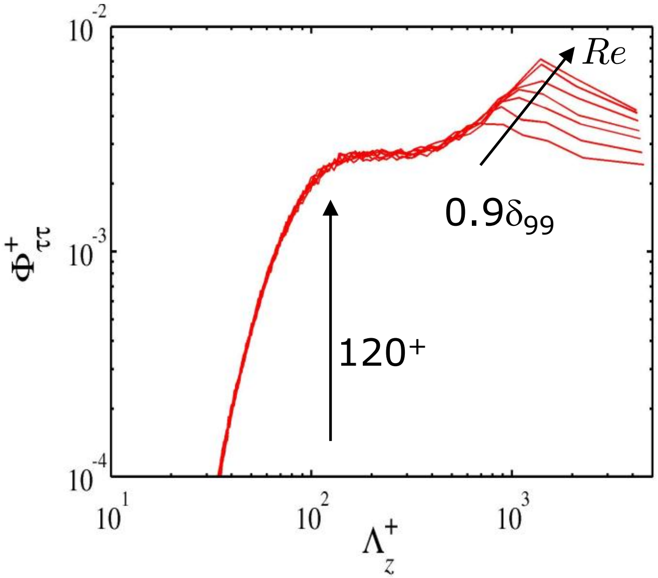
Ref.: Örlü & Schlatter, *Phys. Fluids*, 2011

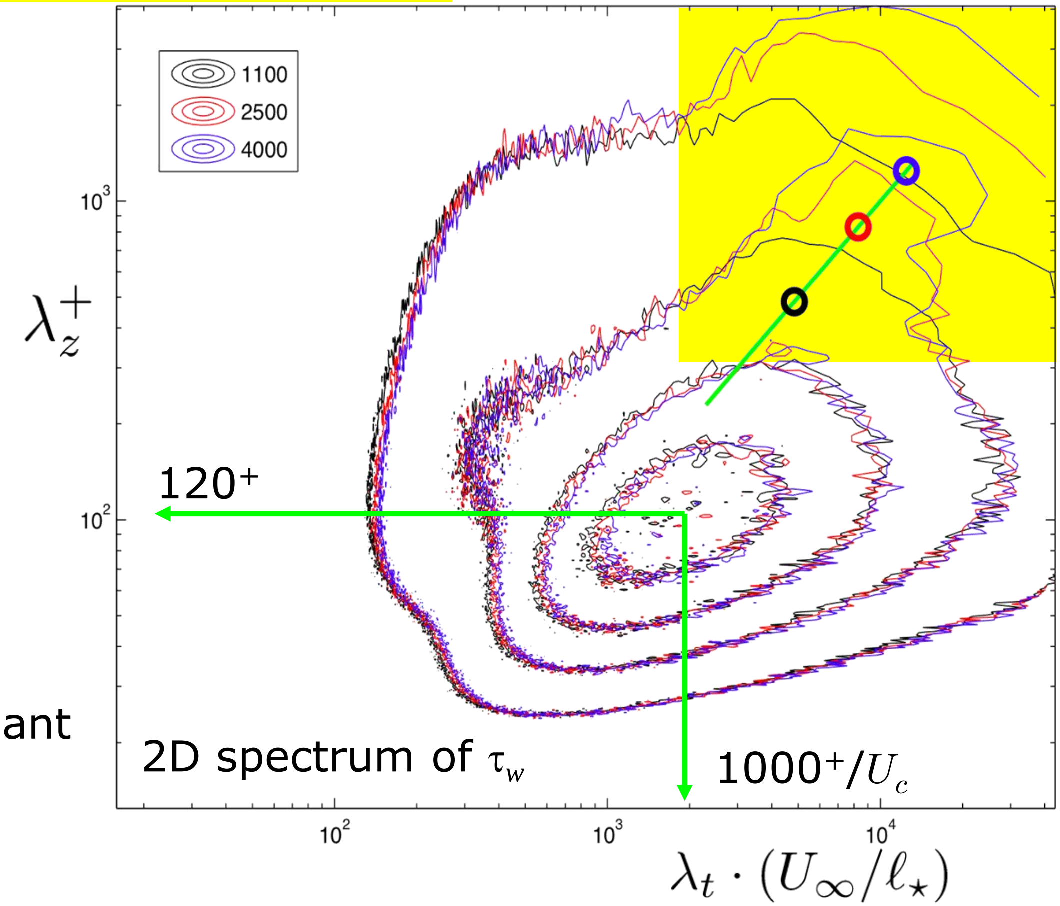
Wall-shear stress fluctuation

- Why increasing for all Re, even for low Re?

$$\tau_{w,\mathrm{rms}} = 0.298 + 0.018 \ln Re_\tau$$

Power spectrum of τ





→ Inner part essentially invariant (viscous scaling)

→ Outer peak scales in outer units and is increasing

Ref.: Örlü & Schlatter, *Phys. Fluids*, 2011

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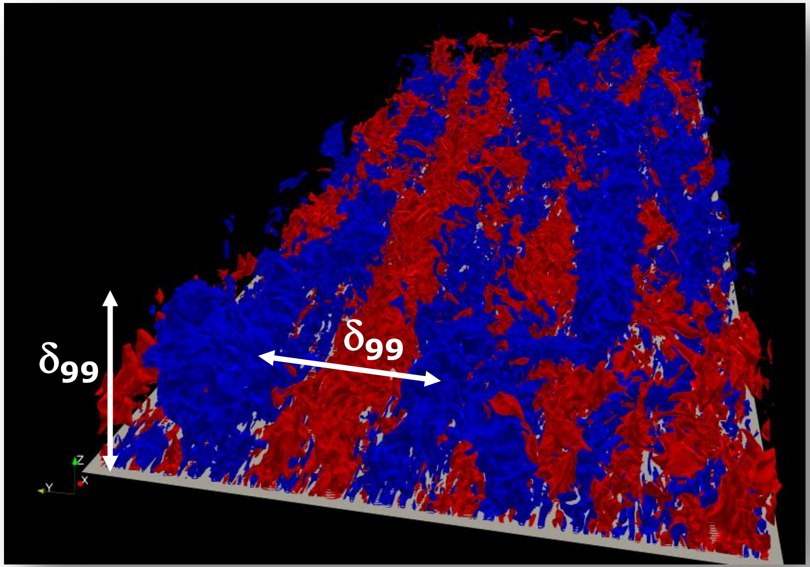
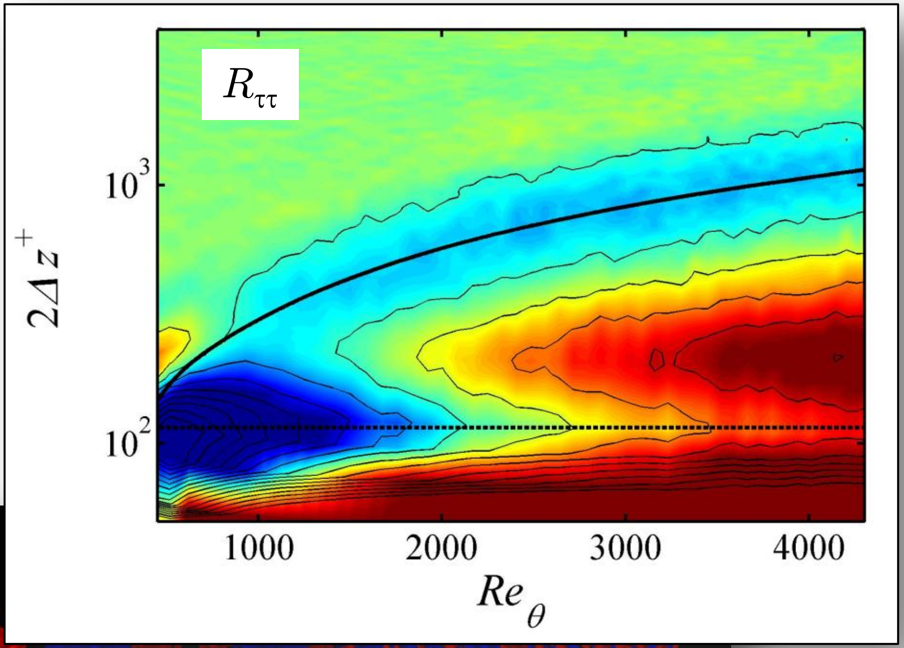
Spatial Structures…

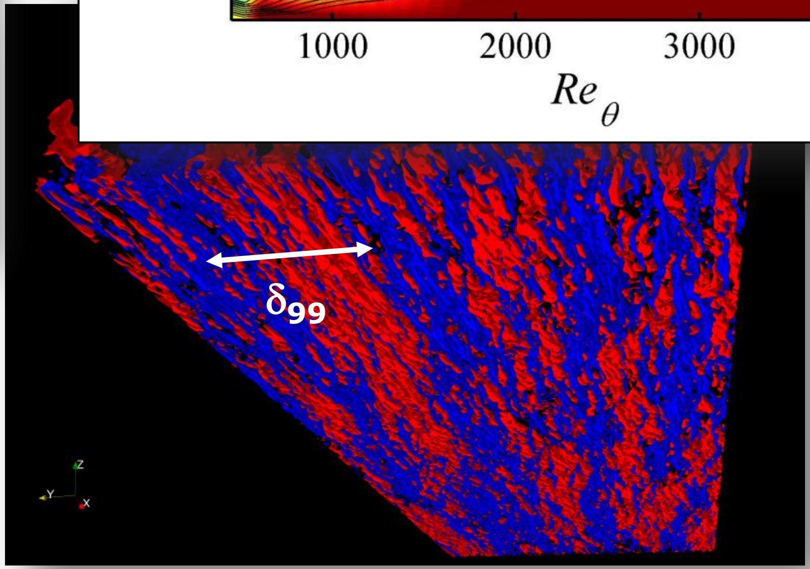
Disturbance Velocity

- positive and negative streamwise disturbance velocity ($\pm 0.1 U_\infty$)



view from top





view from bottom

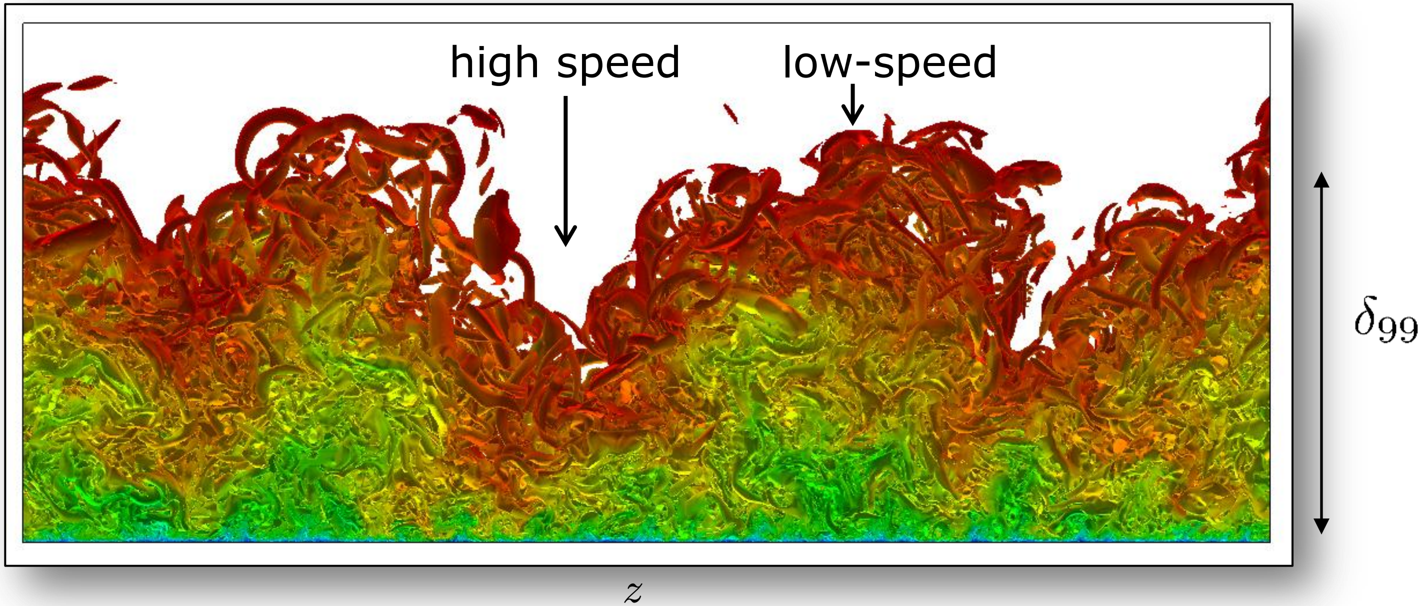
$\cdots\cdots$ $2\Delta z^+ = 115$

—— $2\Delta z/\delta_{99} = 0.85$

visualised domain:		at Re_θ=4000
length	7000^+	5.0 δ_{99}
width	4500^+	3.2 δ_{99}

Amplitude Modulation

- Cross-stream cut through the boundary layer



vortical structures, coloured by streamwise velocity

- currugated edge of the boundary layer
- clear modulation of the whole boundary layer (including near-wall region)

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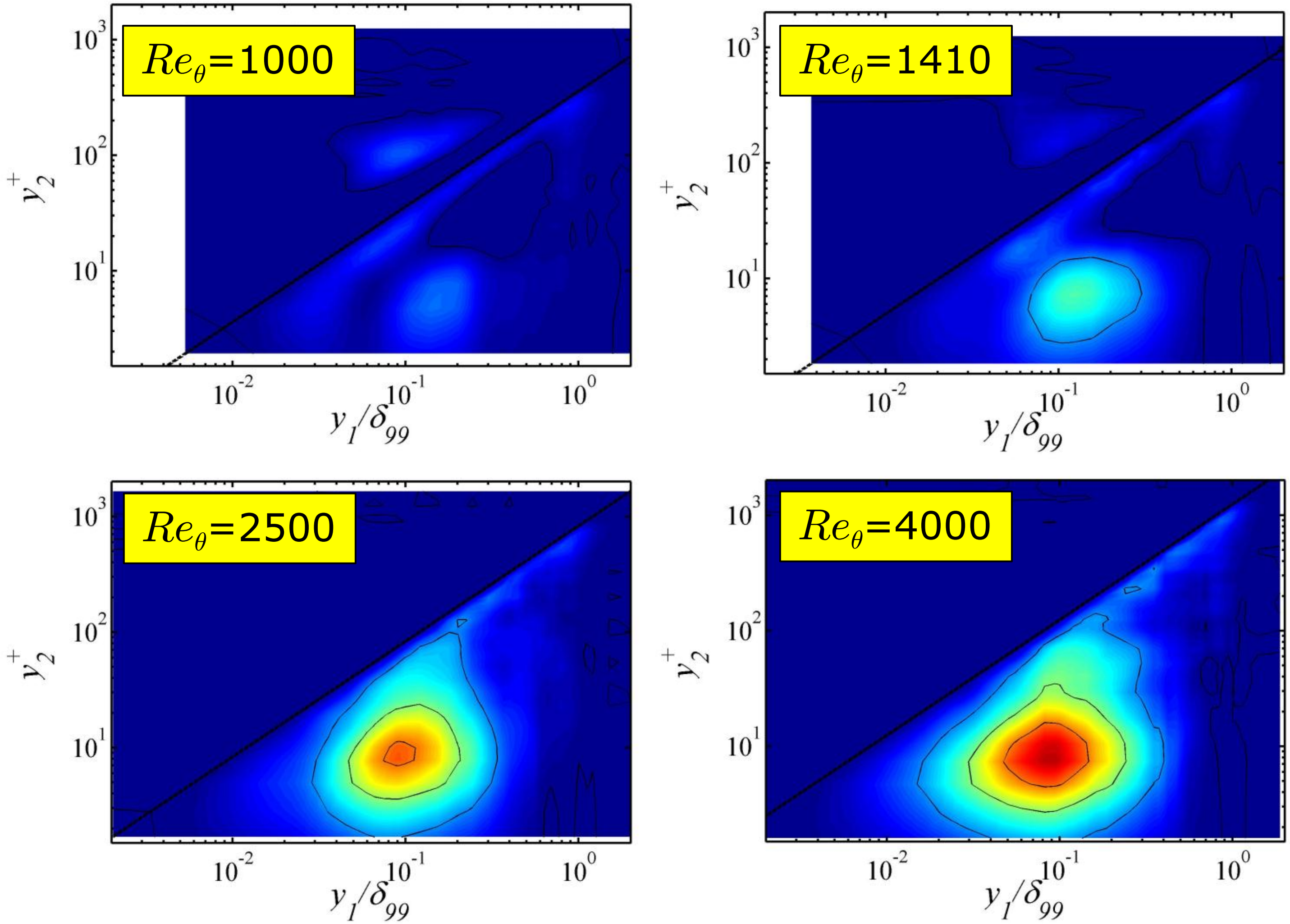
Amplitude Modulation

Remove symmetric part: $C_{mod}(y_1, y_2) = C^{2p}_{AM}(y_1, y_2) - C^{2p}_{AM}(y_2, y_1)$



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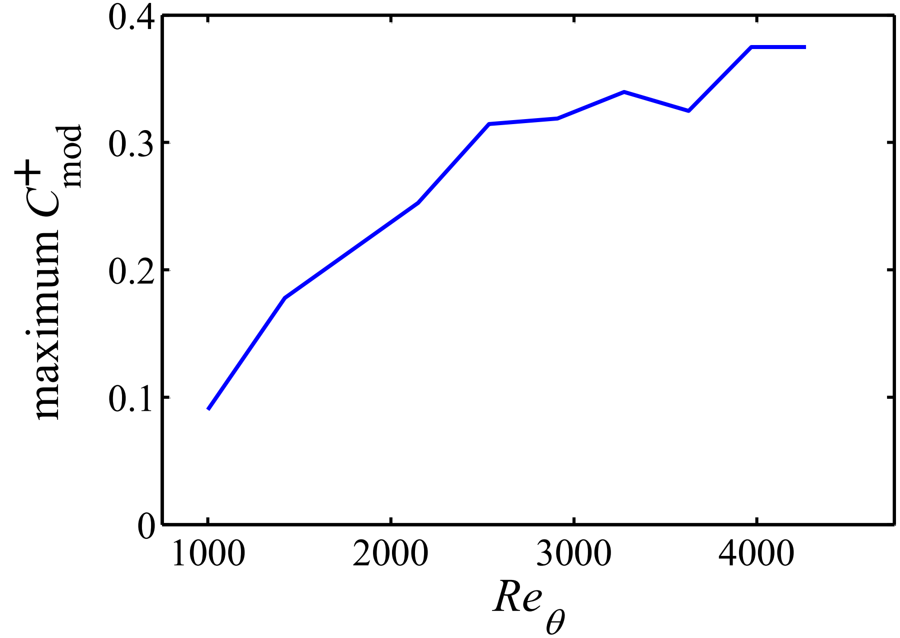
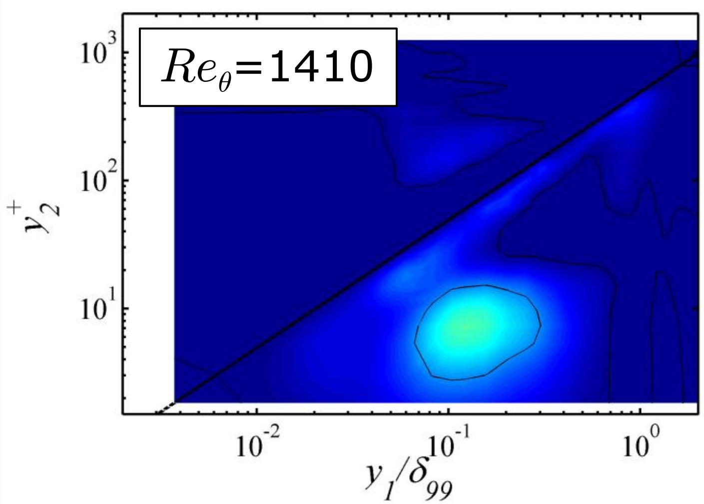
Refs.: Mathis *et al.* (2009); Bernardini & Pirozzoli, *Phys. Fluids* 2011

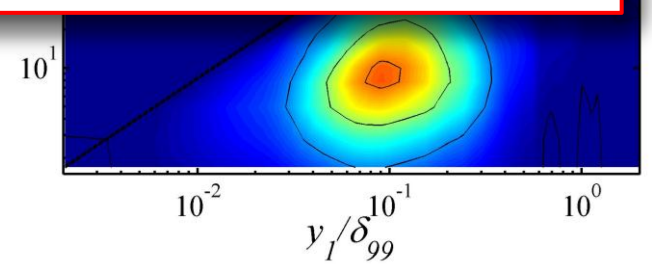
Amplitude Modulation

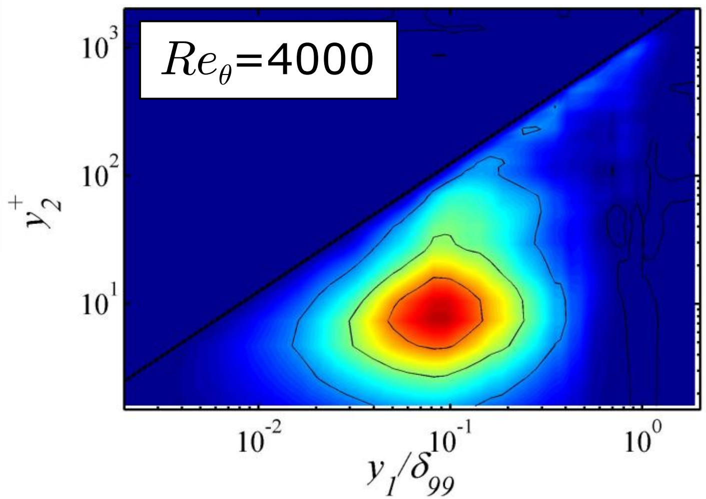


Increase of modulation coefficient in agreement with the findings by Bernardini & Pirozzoli 2011.

$$\ldots_2) = C^{2p}_{AM}(y_1, y_2) - C^{2p}_{AM}(y_2, y_1)$$







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Structures – Visualisation

”Focus on Fluids” (May 2009)...

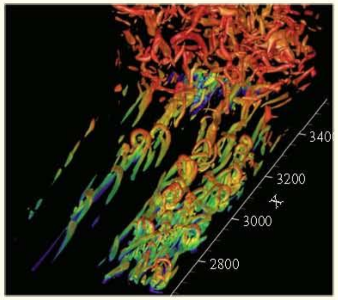
Journal of Fluid Mechanics

Focus on Fluids

Unravelling turbulence near walls

IVAN MARUSIC[1]

[1]Department of Mechanical Engineering, University of Melbourne, Victoria, 3010, Australia

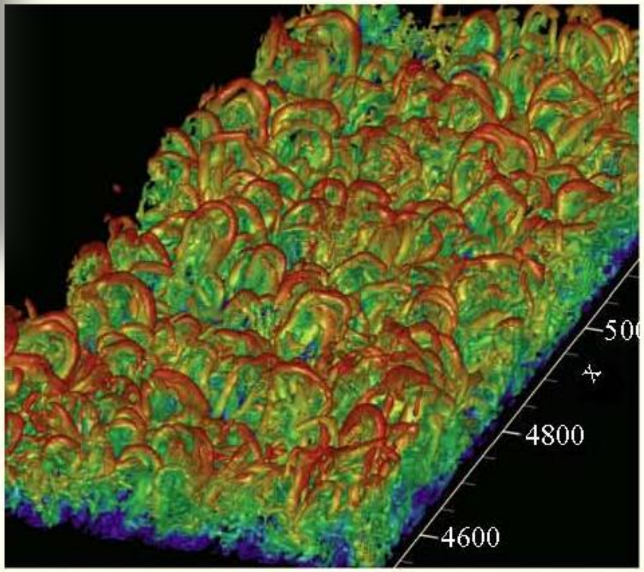


Turbulent flows near walls have been the focus of intense study since their first description by Ludwig Prandtl over 100 years ago. They are critical in determining the drag and lift of an aircraft wing for example. Key challenges are to understand the physical mechanisms causing the transition from smooth, laminar flow to turbulent flow and how the turbulence is then maintained. Recent direct numerical simulations have contributed significantly towards this understanding.

Keywords. Turbulent boundary layers, Transition

Figures:
Wu & Moin (JFM 2009)

FIGURE 1. Instantaneous view of the coherent structures observed in the simulation of Wu & Moin in the fully turbulent region. The vivid appearance of hairpin-shaped structures is noted.



Boundary Layer Visualisation

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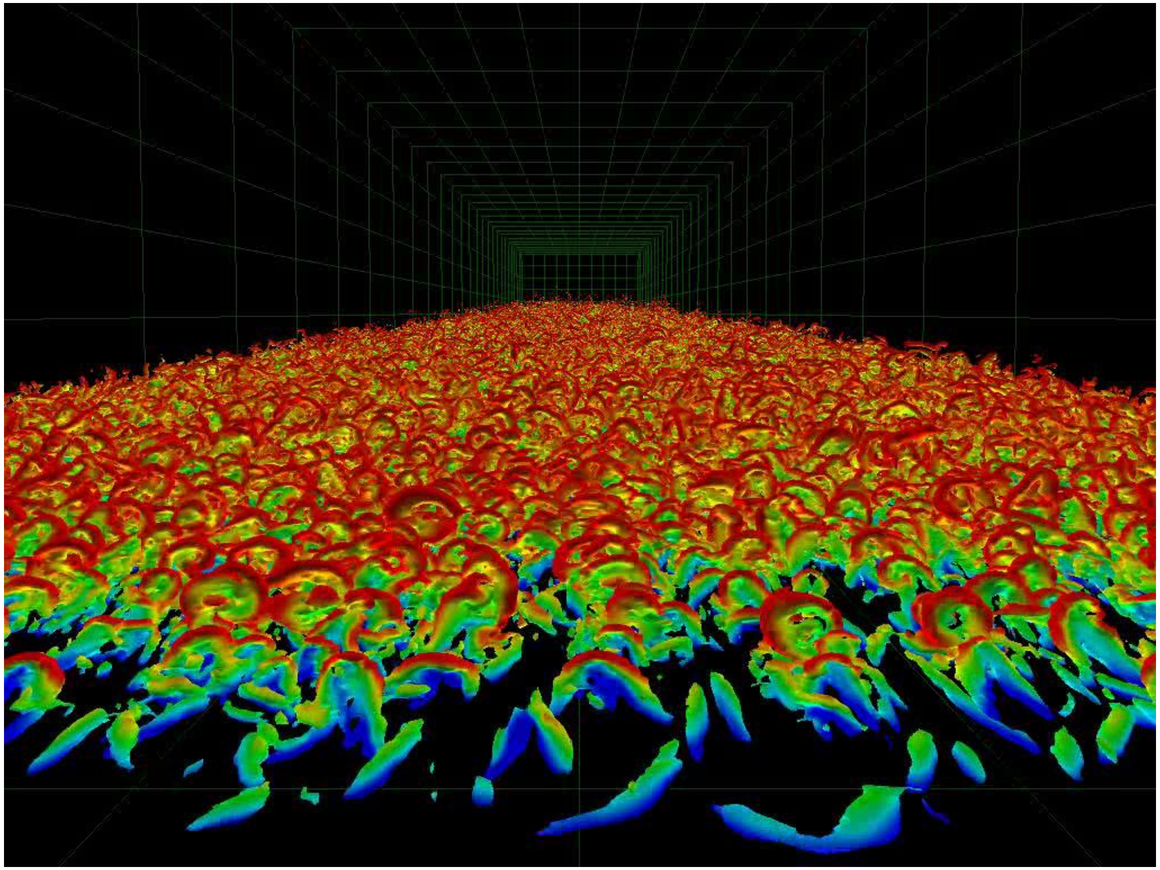
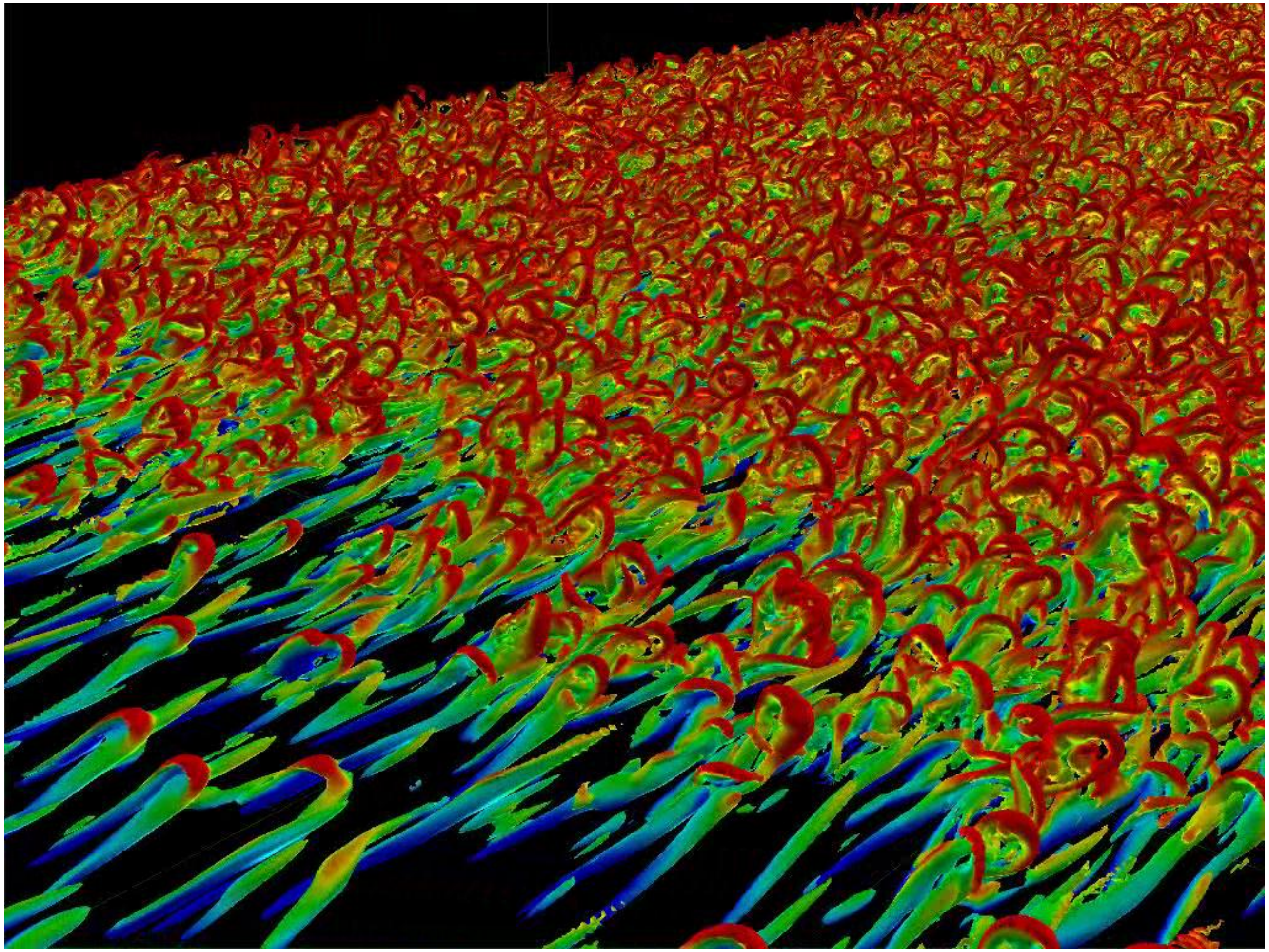


based on LES data

Boundary Layer Visualisation



based on DNS data

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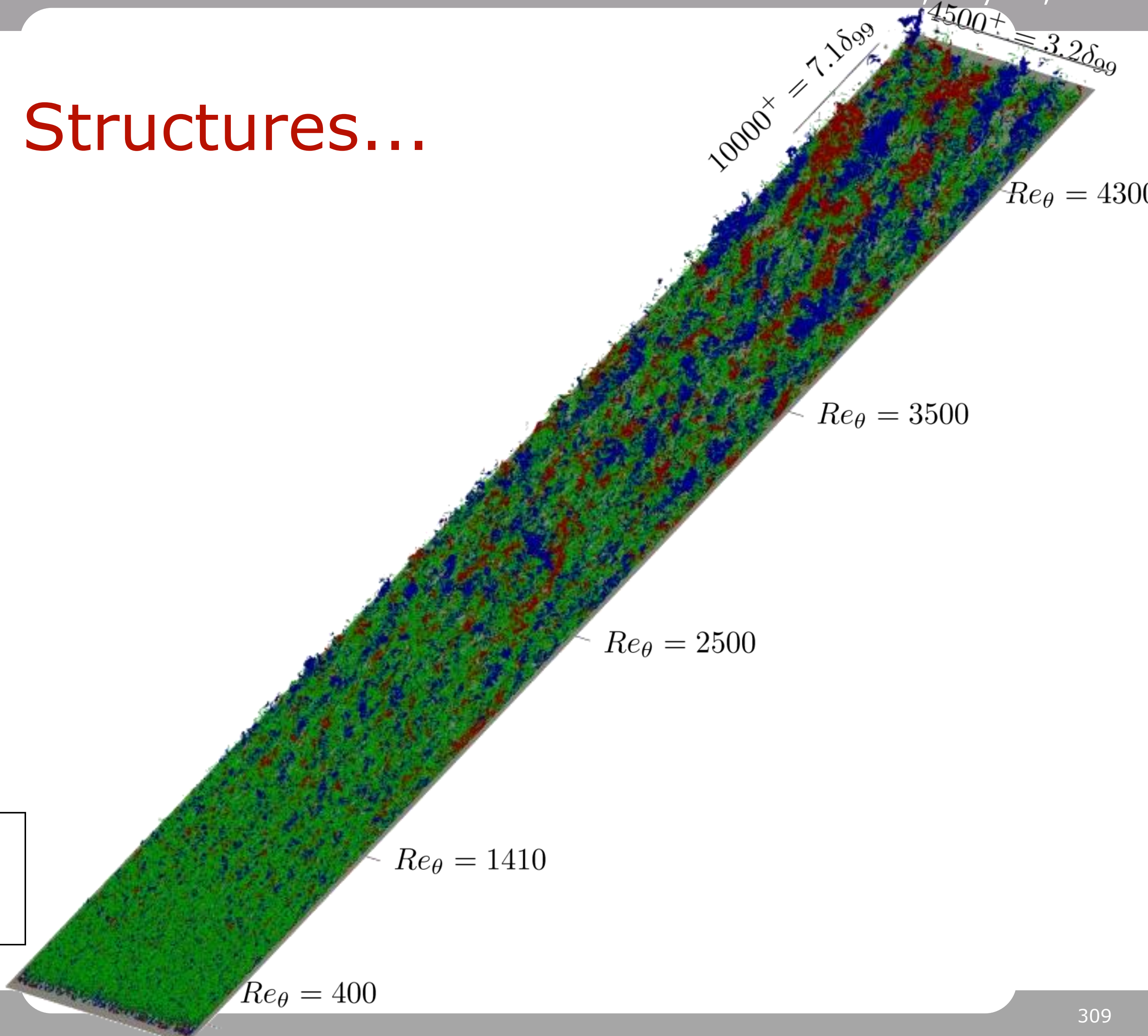
Structures...



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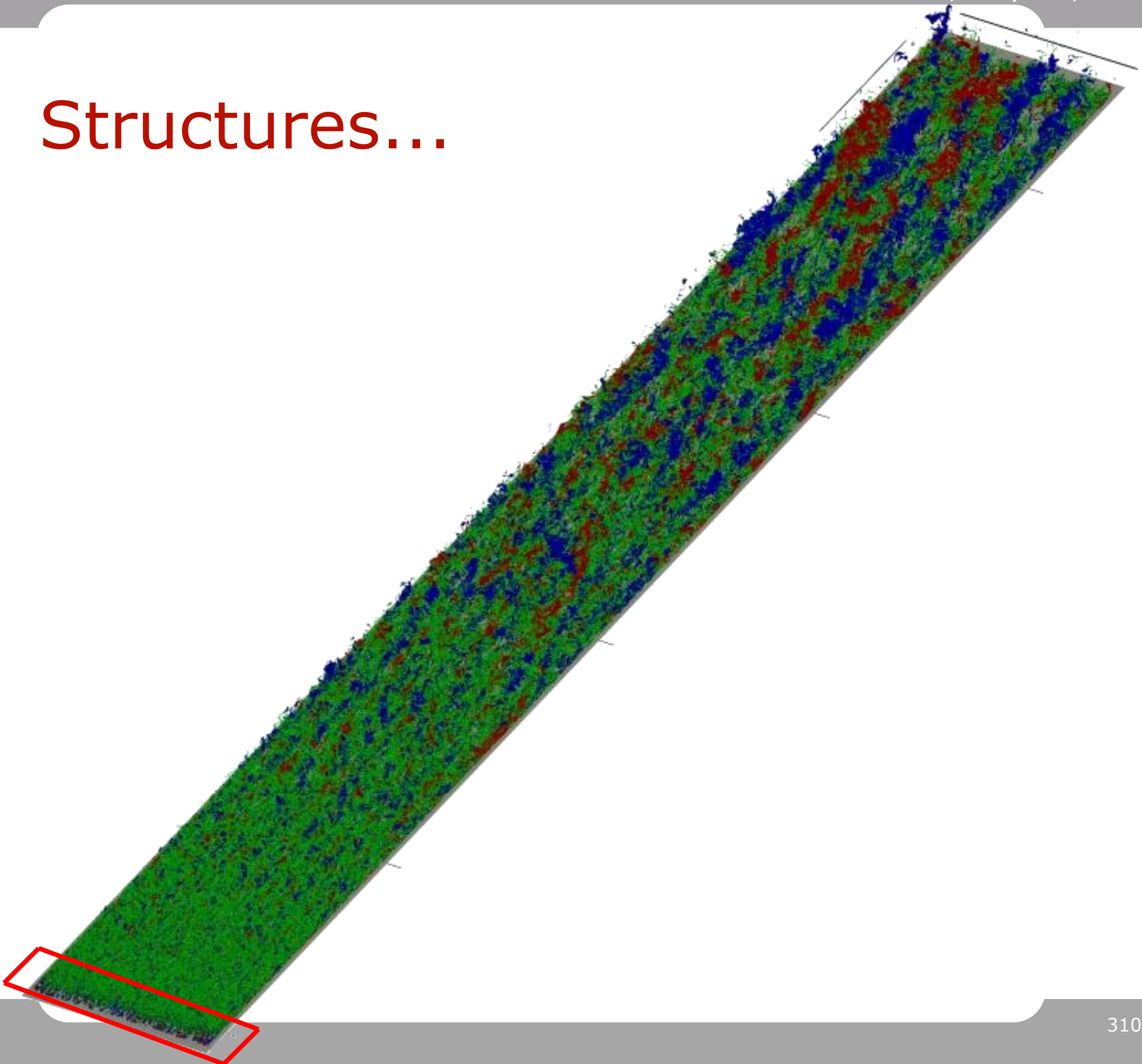
Isocontours of negative λ_2 and positive / negative disturbance velocity

Structures...



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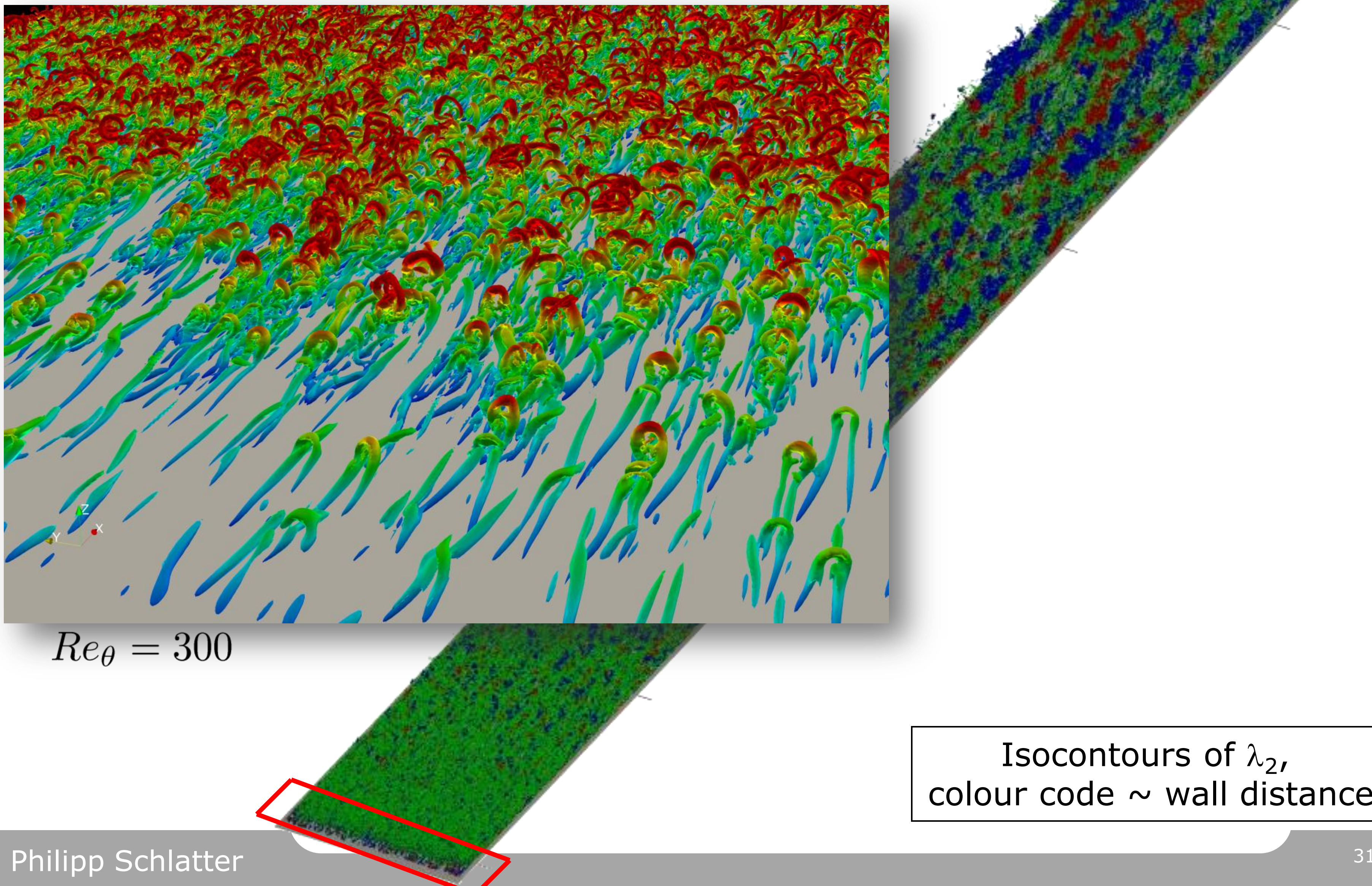
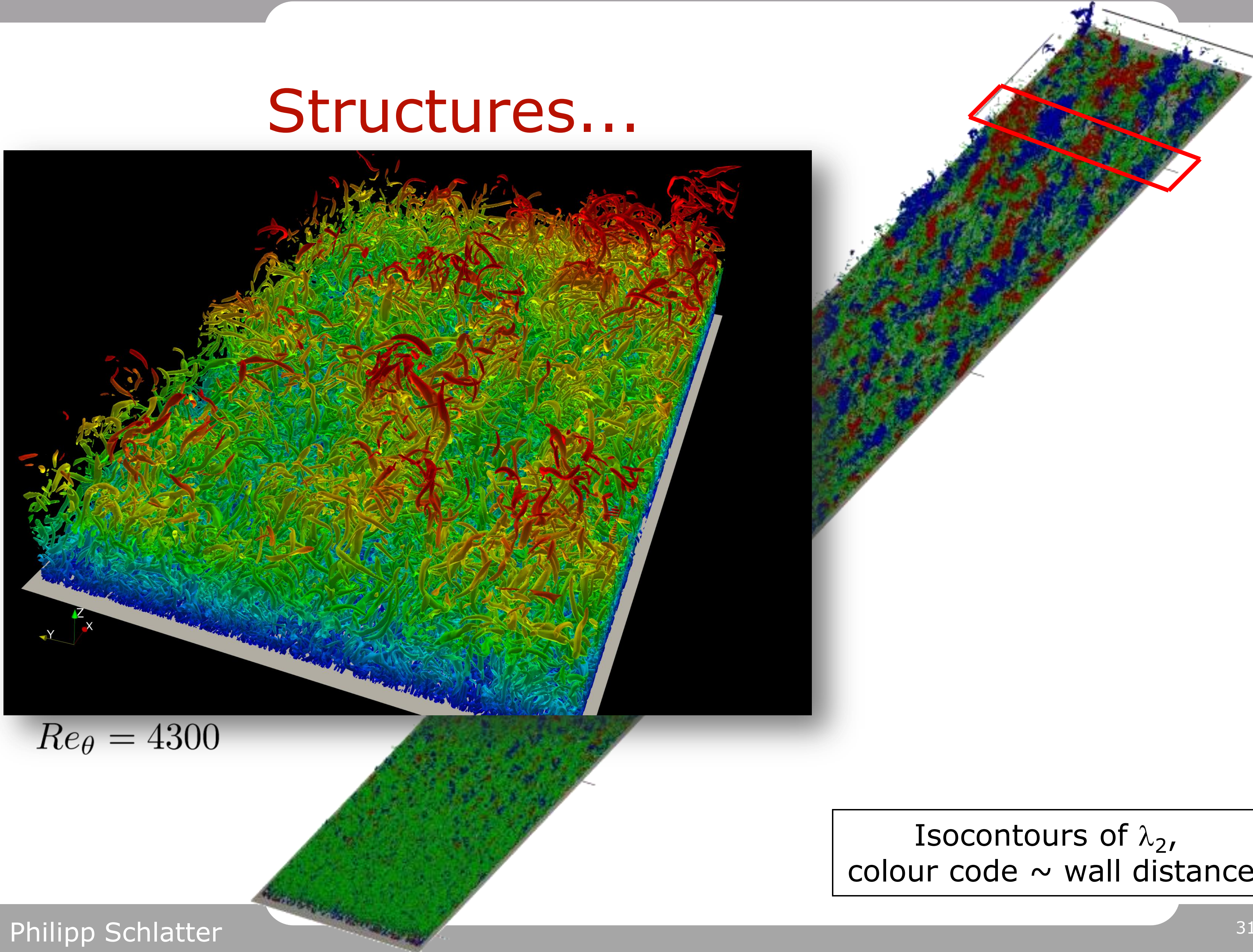
Structures...



$Re_\theta = 300$

Isocontours of λ_2,
colour code ~ wall distance

Structures...



$Re_\theta = 4300$

Isocontours of λ_2,
colour code ~ wall distance

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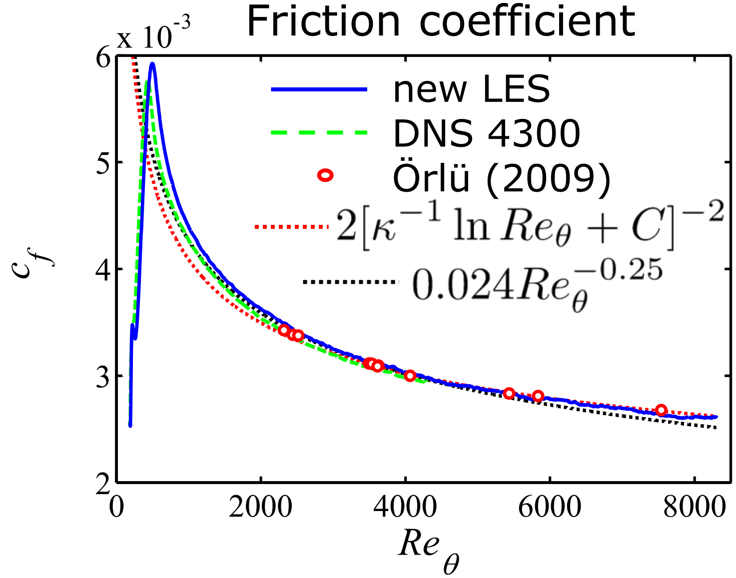
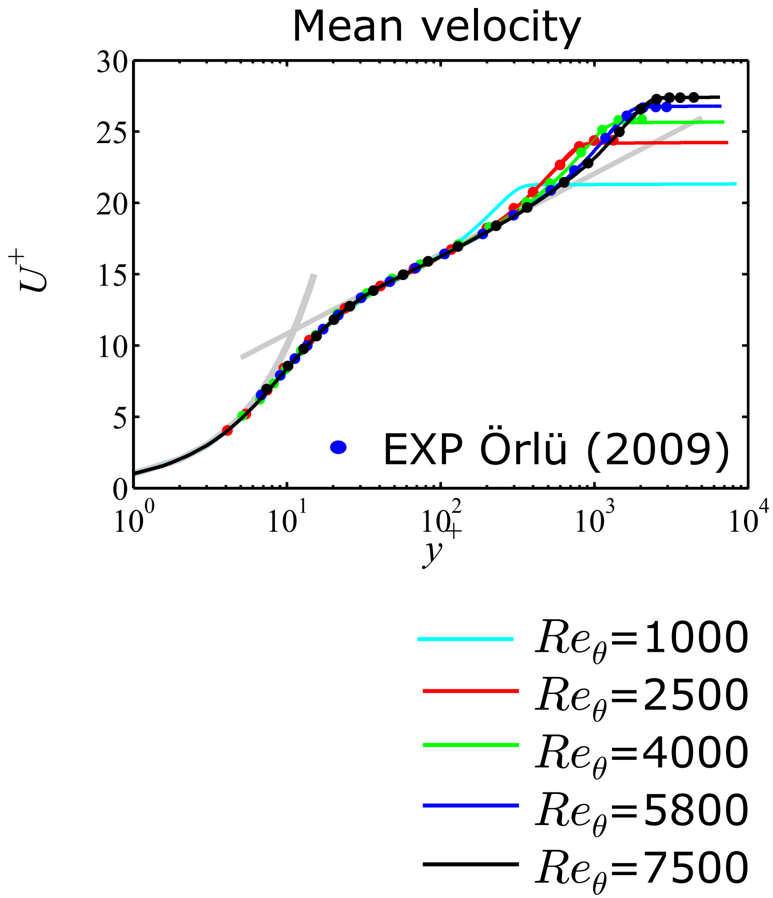
Preliminary Results: Ongoing simulation up to $Re_\theta = 8300$

LES up to Re_θ=8300

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





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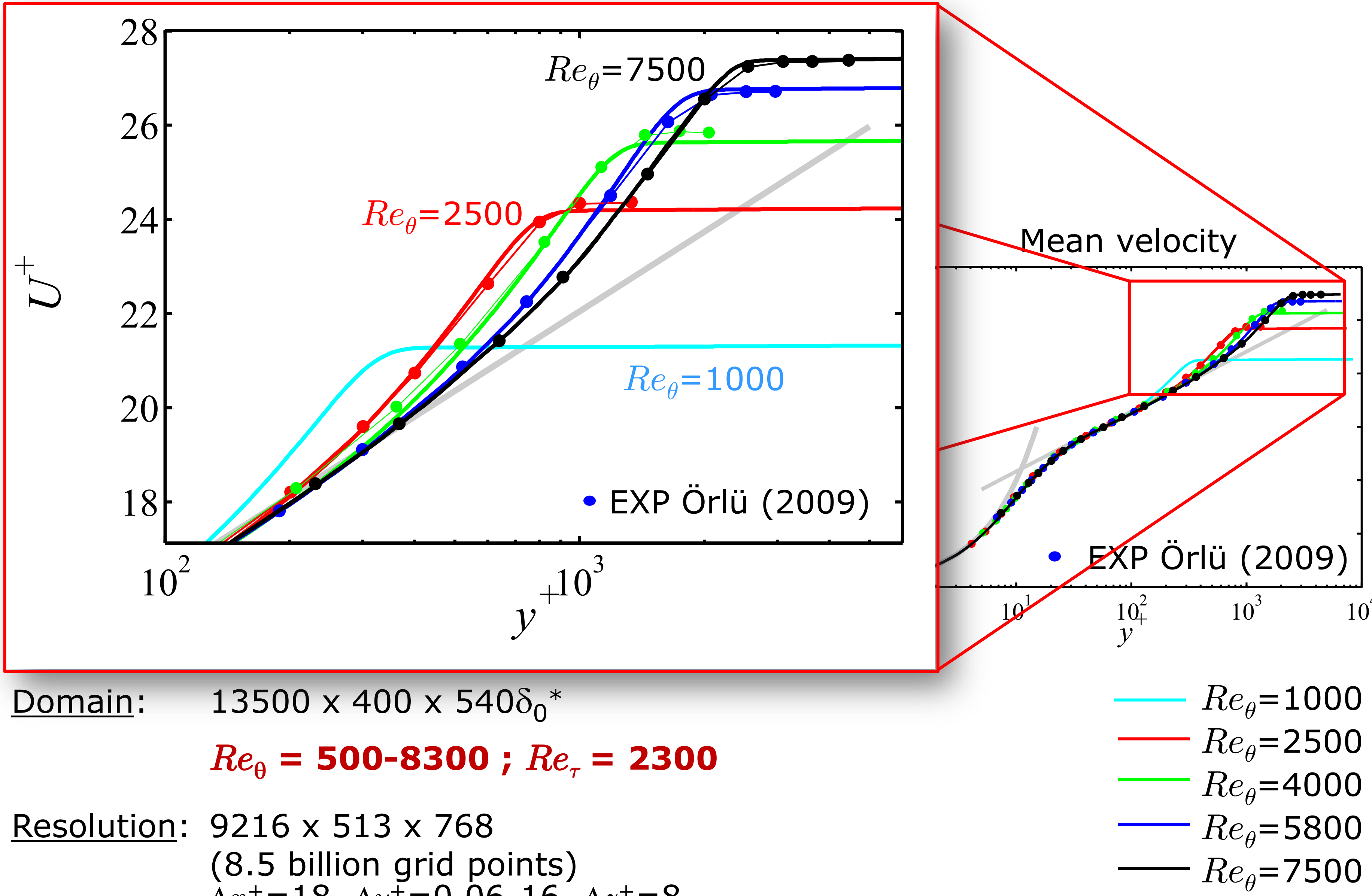
Domain: 13500 x 400 x 540δ_0^*

Re_θ = 500-8300 ; Re_τ = 2300

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



Domain: 13500 x 400 x 540δ_0^*

***Re_θ* = 500-8300 ; *Re_τ* = 2300**

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

LES up to Re_θ=8300

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

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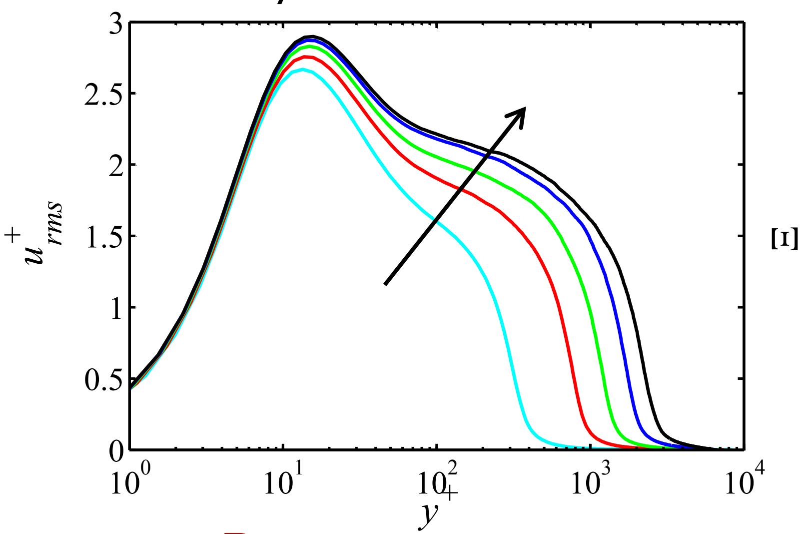

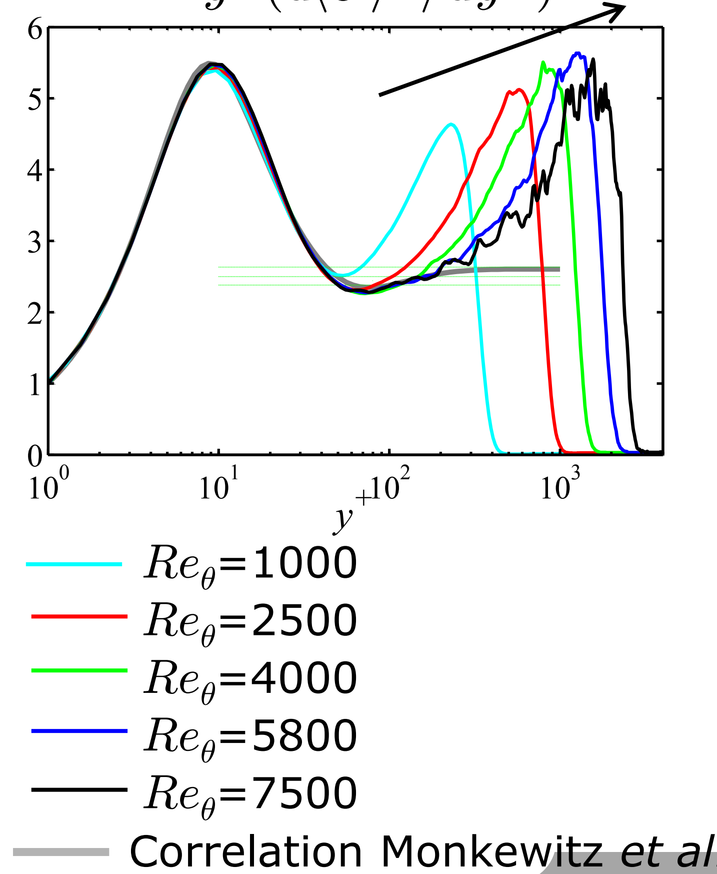

Re_θ = 500-8300 ; Re_τ = 2300

- Good agreement at lower Reynolds number with other DNS/LES
- Good agreement with experiments at higher Re
- Proper scaling behaviour at higher Re

Conclusions

DNS data for a spatial turbulent zero pressure gradient turbulent boundary layer from Re_θ=180 up to Re_θ=4300, using ~$7.5 \cdot 10^9$ grid points.

NUMERICAL EXPERIMENT

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1. **Statistics/budgets/spectra/PDF** *etc.* in excellent agreement with experiments
2. **Outer-layer convergence** and fully developed state for boundary layers. When do we have a ”good” simulation?
3. Large-scale structures $\mathcal{O}(\delta_{99})$ with **footprint/modulation** visible at the wall
4. Visualisation of **coherent structures** in high-Re turbulent boundary layers: No clear hairpin vortices detected except for low-Re (transition) region.

Data and visualisations at: **`www.mech.kth.se/~pschlatt/DATA`**

Contact me: **`pschlatt@mech.kth.se`**

Acknowledgments:

SeRC
Swedish e-Science Research Centre

FLOW
LINNÉ FLOW CENTRE

KTH
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PDC
HPC

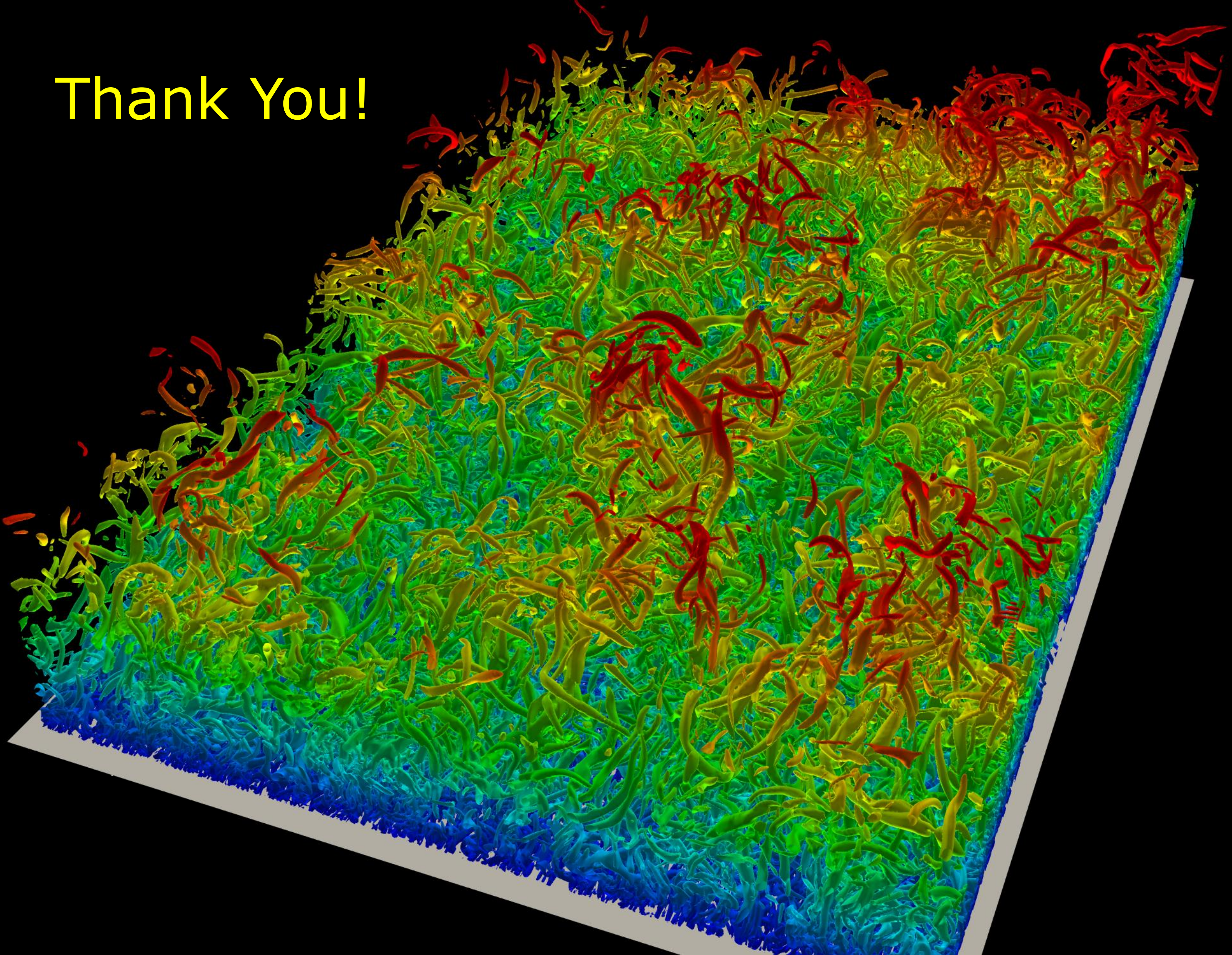
NSC
National Supercomputer Centre at Linköpings universitet

Knut och Alice Wallenbergs Stiftelse

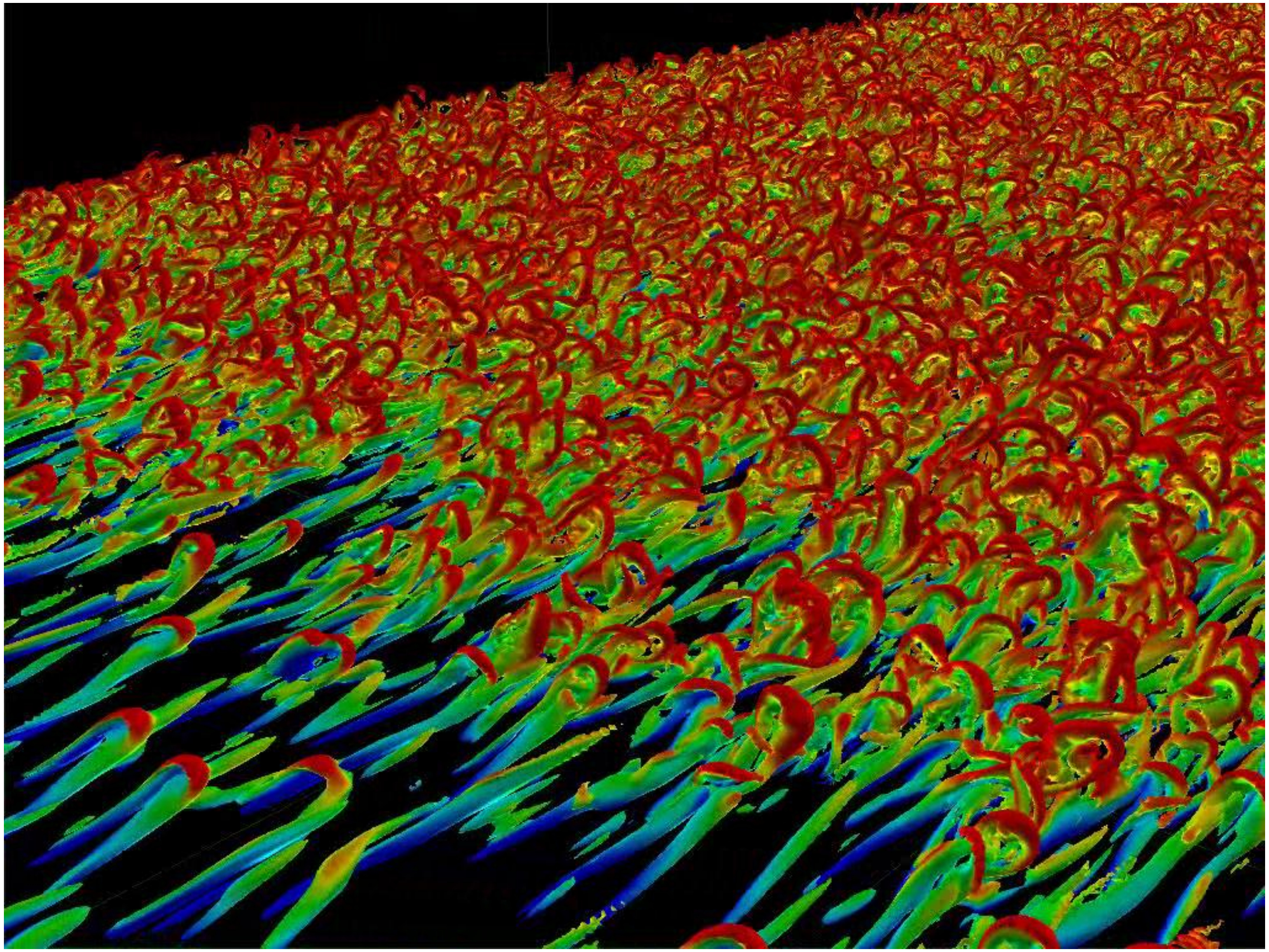
Vetenskapsrådet

SNIC
Swedish National Infrastructure for Computing

Thank You!



Boundary Layer Visualisation



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based on DNS data