

Assessment of direct numerical simulation data of turbulent boundary layers



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Philipp Schlatter

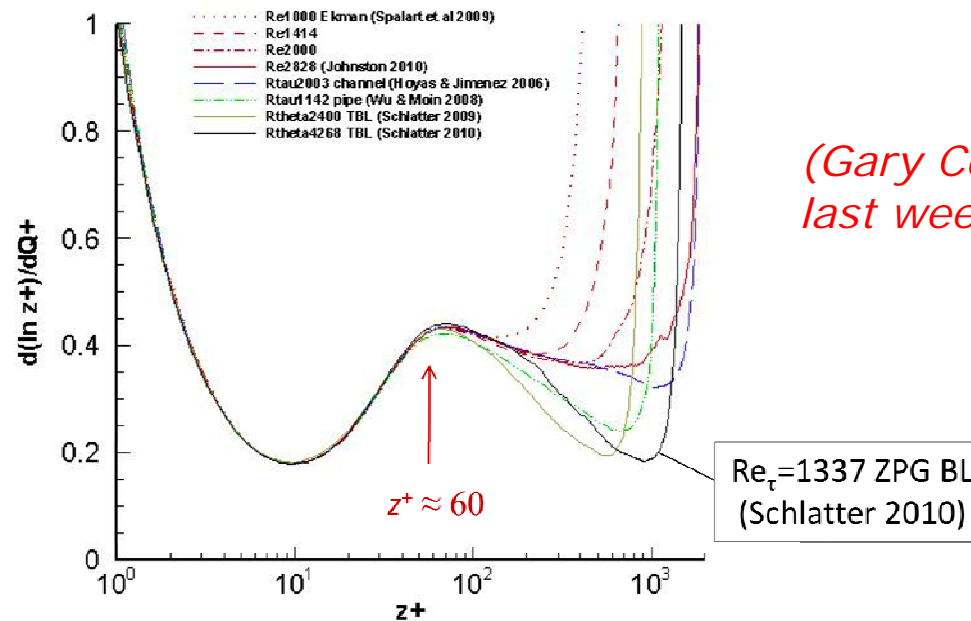
Ramis Örlü

Linné Flow Centre, KTH Mechanics,
Stockholm, Sweden

Nordita, April 29, 2010

Starting point

- And we are usually very confident about DNS data, at least when it comes to basic integral quantities and statistics, particularly in the near-wall region



*(Gary Coleman,
last week at NORDITA)*

All DNS flows (pipe, channel, Ekman, ZPG BL) agree below $z^+ \approx 60$

All “higher-Re” flows (DNS and exp, for pipe, channel, Ekman, ZPG BL) agree below $z^+ \approx 200$

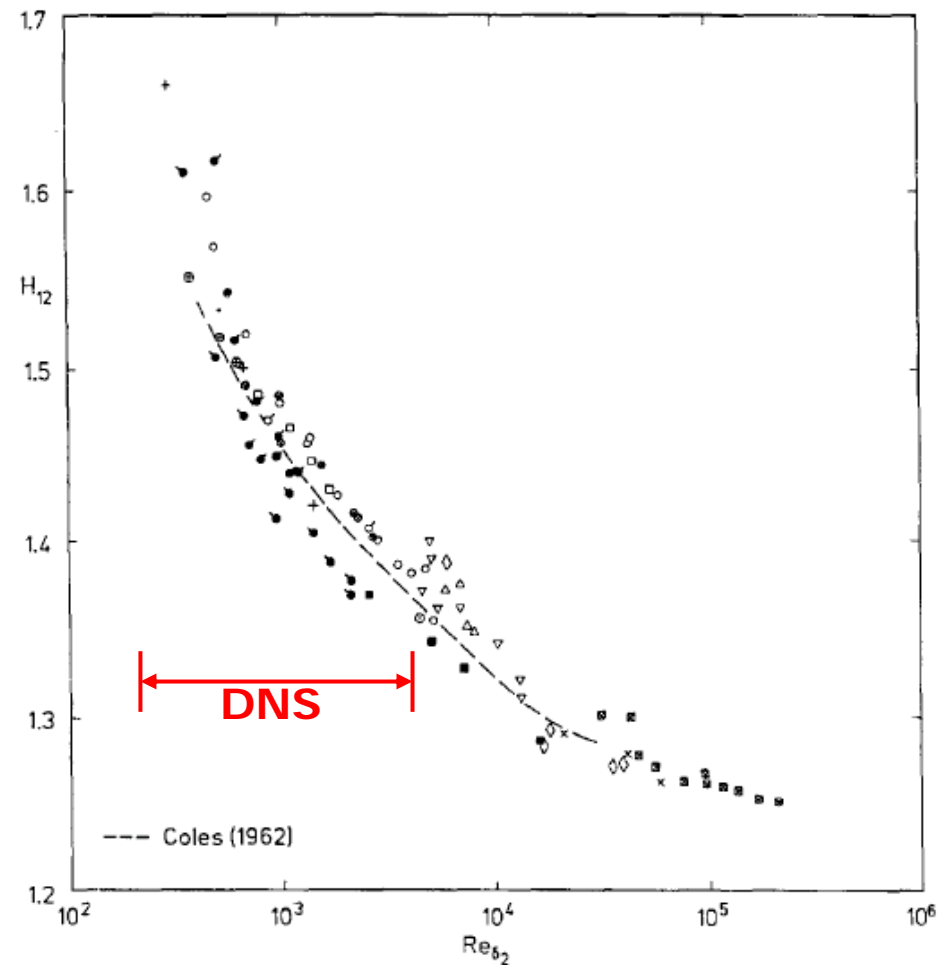
What we are used/expect to see ...



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- Assessment of available experimental data from ZPG TBL data (*Finley & Fernholz, 1996*) shows remarkable scatter in shape factor.
- More recent and consistent (re-) assessment of classical and recent data by *Chauhan et al (2009)*

Finley & Fernholz (1996)

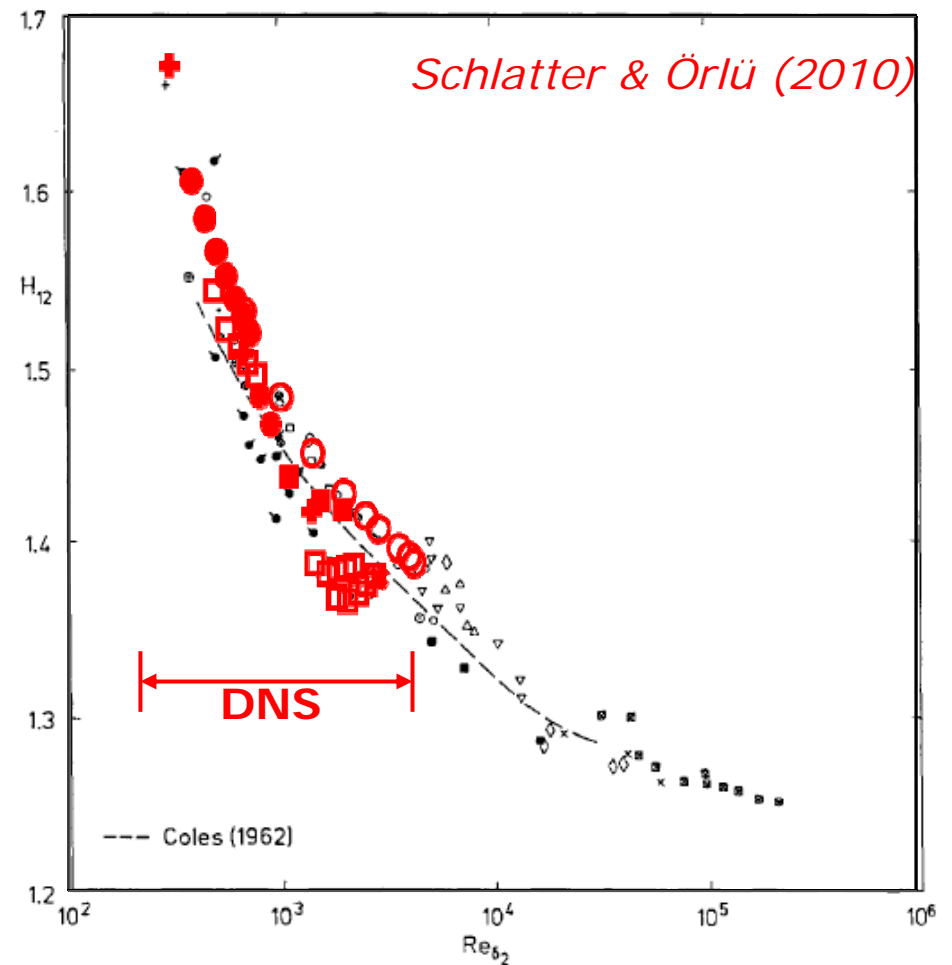


... and what “we” are not so used to see



- Physical experiments are commonly scrutinized before they are employed to calibrate, test, or validate experiments, scaling laws or theories
- DNS data are hardly scrutinized, when it comes to basic (integral) quantities, despite →
- Red symbols are data from 7 independent DNS from a ZPG TBL flow (*Schlatter & Örlü, 2010*)

Finley & Fernholz (1996)

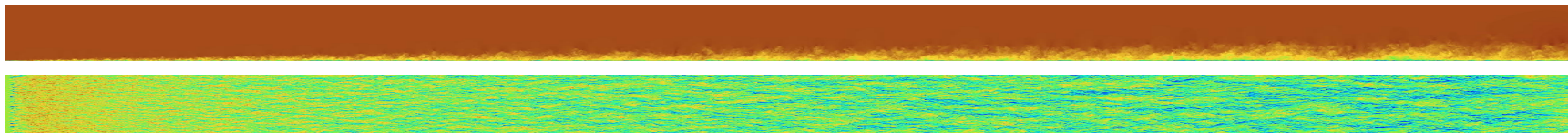


Employed ZPG TBL DNS data

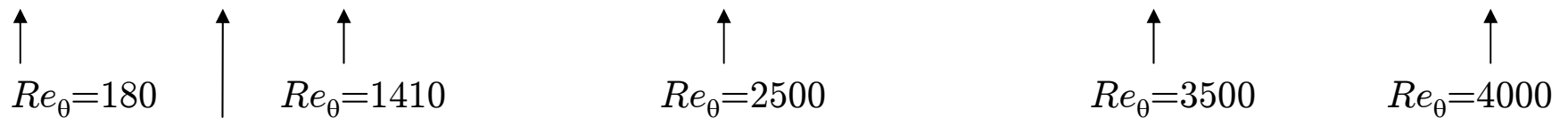
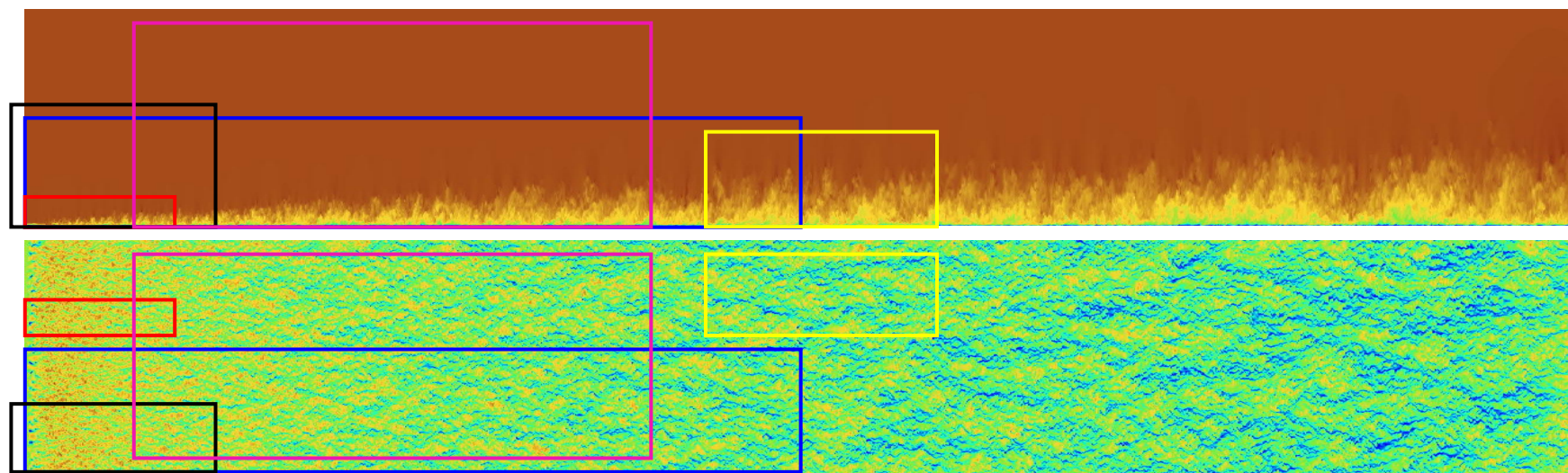
Reference	Re_θ	Method	Symbol
Spalart (1988)	300, 600, 1410	spectral spatio-temporal	+
Komminaho & Skote (2002)	383 – 716	spectral tripping at $Re_\theta \approx 200$ domain up to $Re_\theta \approx 750$	●
Khujadze & Oberlack (2004; 2007)	489 – 2807	spectral tripping close to resp. inflow domain length $\Delta Re_\theta \approx 500$	□
Ferrante & Elghobashi (2005)	2900	finite differences rescaling and recycling domain $Re_\theta = 2340 - 2900$	×
Simens <i>et al.</i> (2009)	1000, 1550, 1968	finite-difference/spectral rescaling and recycling domain $Re_\theta = 620 - 2140$	■
Schlatter <i>et al.</i> (2009a; 2009b)	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 $Re_\theta = 80$	*

TBL up to $Re_\theta = 4000$...

real aspect ratio:



aspect ratio 4:1 :



Schlatter *et al.* (2009)
 Simens/Jiménez (2009)

Skote (2001)
 Wu&Moin (2009)

Ferrante & Elghobashi (2004)

Employed channel DNS data

- In some cases the following channel flow DNS data has been utilised for comparison



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Abe et al 2004,
Kawamura et al 1999,
Tsukahara et al 2005



Iwamoto et al 2002



Del Álamo & Jimenez 2003,
del Álamo et al 2004,
Hoyas & Jimenez 2006

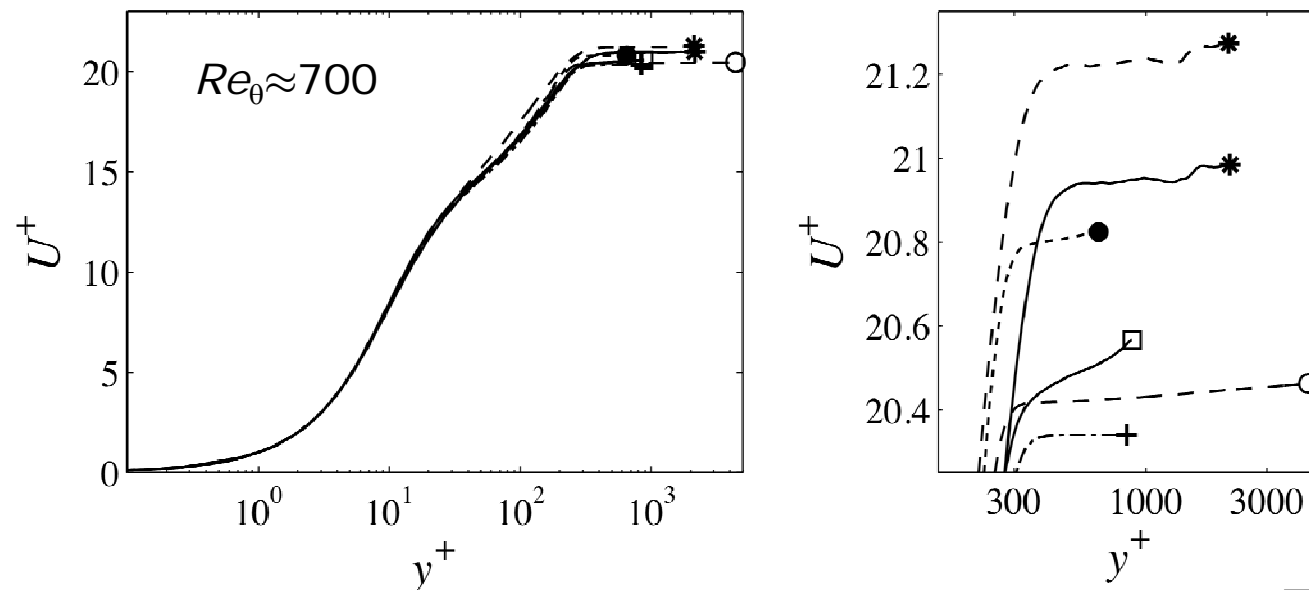


Justification for re-evaluation

- Integral quantities are often given as function of Re , however, **how** these were computed is often not given in detail
 → need for re-evaluation in a consistent manner
- Varying free-stream velocities for $y^+ > \delta^+$ implies (in conjunction with quite varying box length) unambiguous upper integral bound and free stream velocity
 → need for consistent re-evaluation, e.g. by means of a composite velocity profile (here: *Nickels, 2004*)

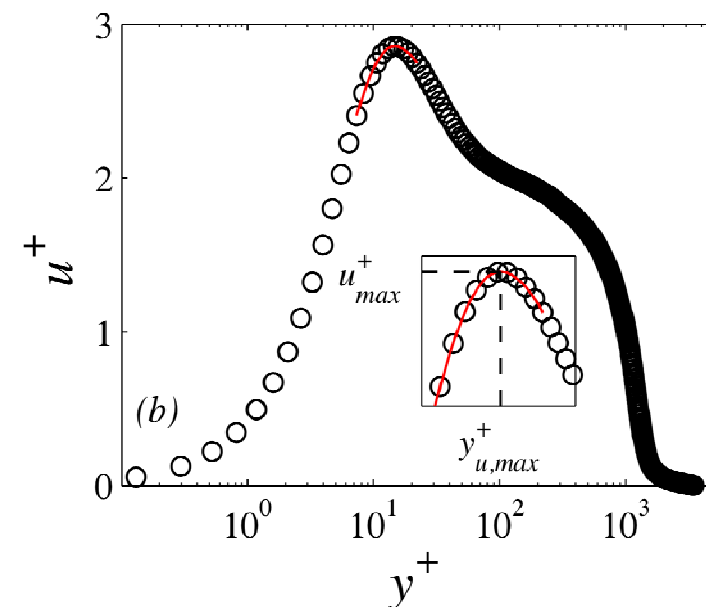
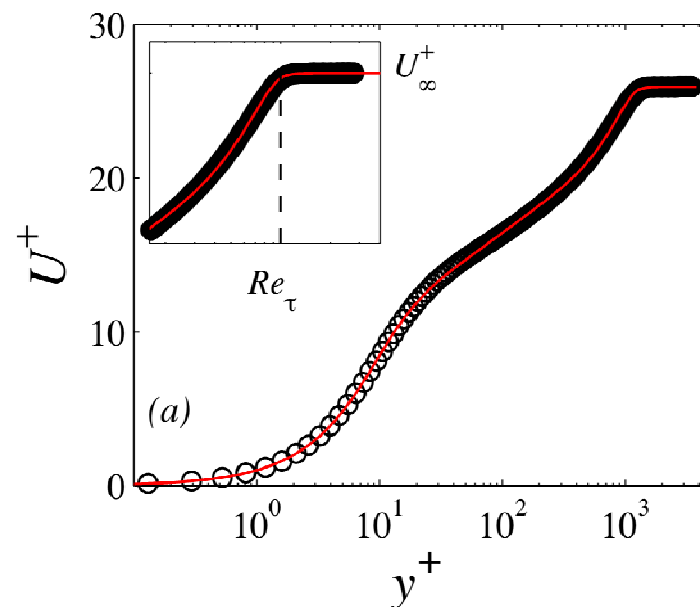


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Consistent way to re-evaluate

- 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



Comparative study, NOT an absolute!

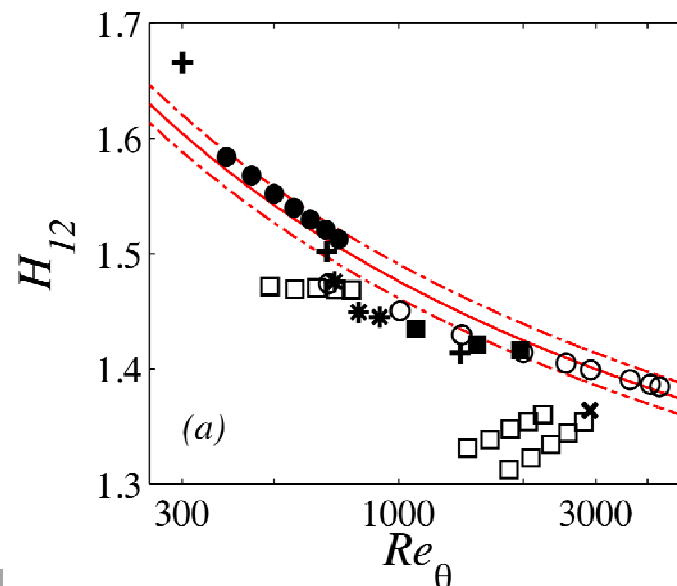
- We here merely aim to compare various DNS data sets, hence any consistent way is suitable,
- Note, that the absolute values are not the focus of our study, since the results are dependent on the method utilised



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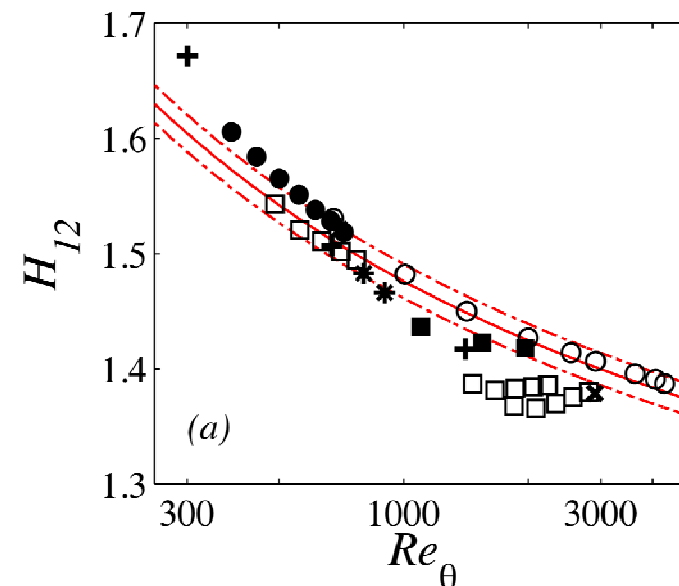
“end of box”

Simens et al, Schlatter et al, ... i.e. DNS studies



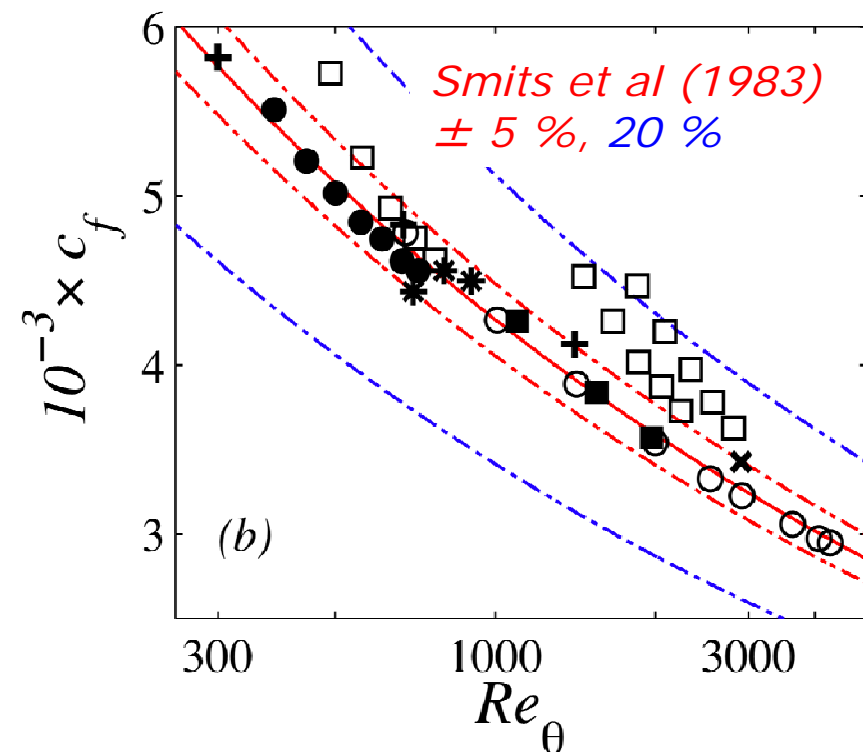
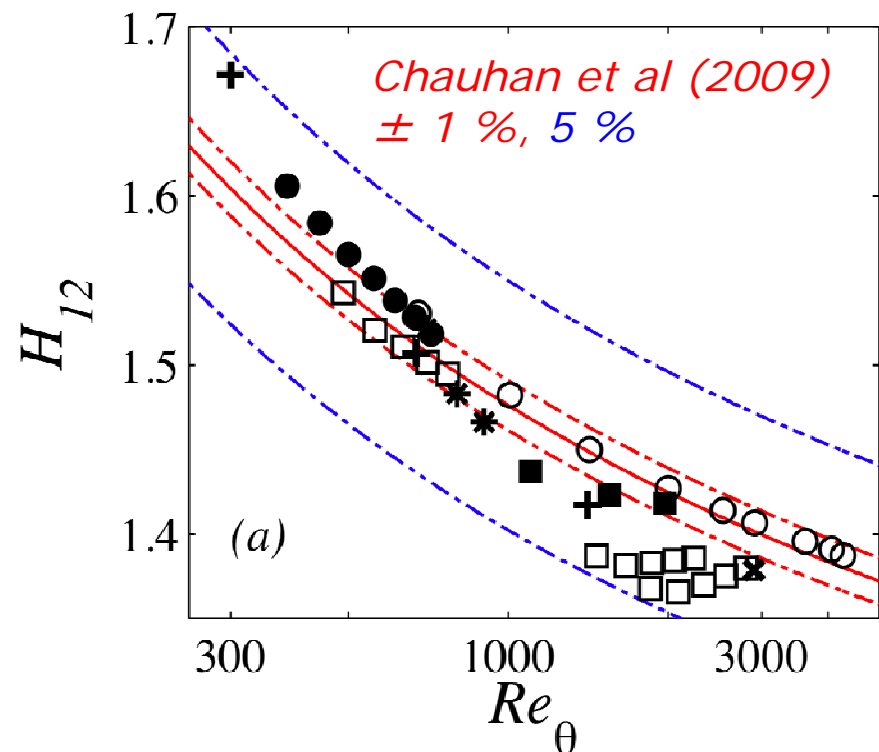
“composite fit”

Nickels, Chauhan et al ..., i.e. experimental studies



Shape factor & Skin friction

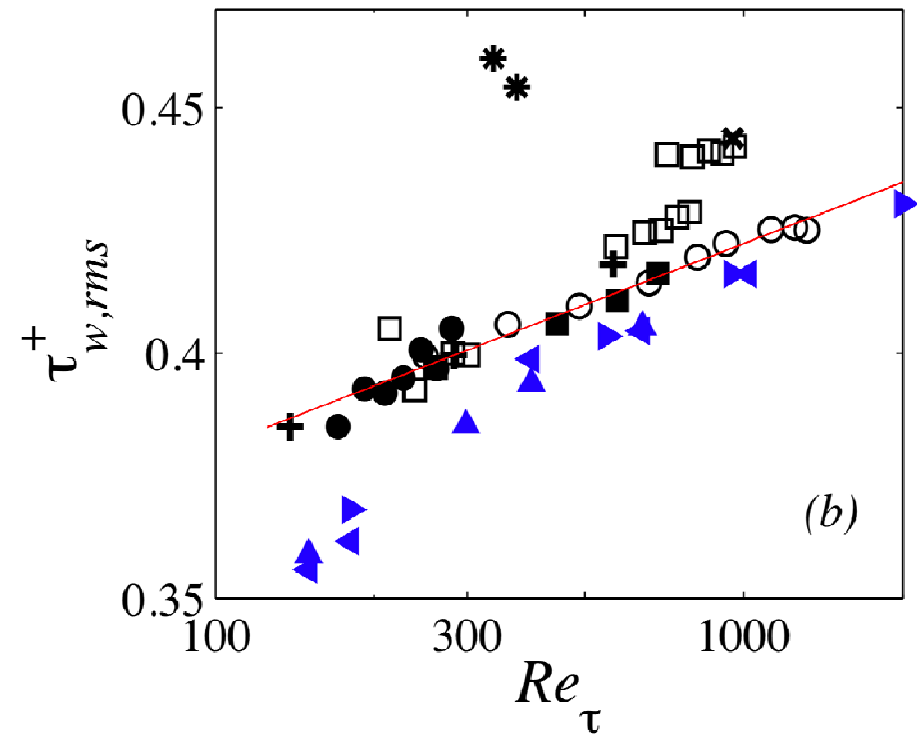
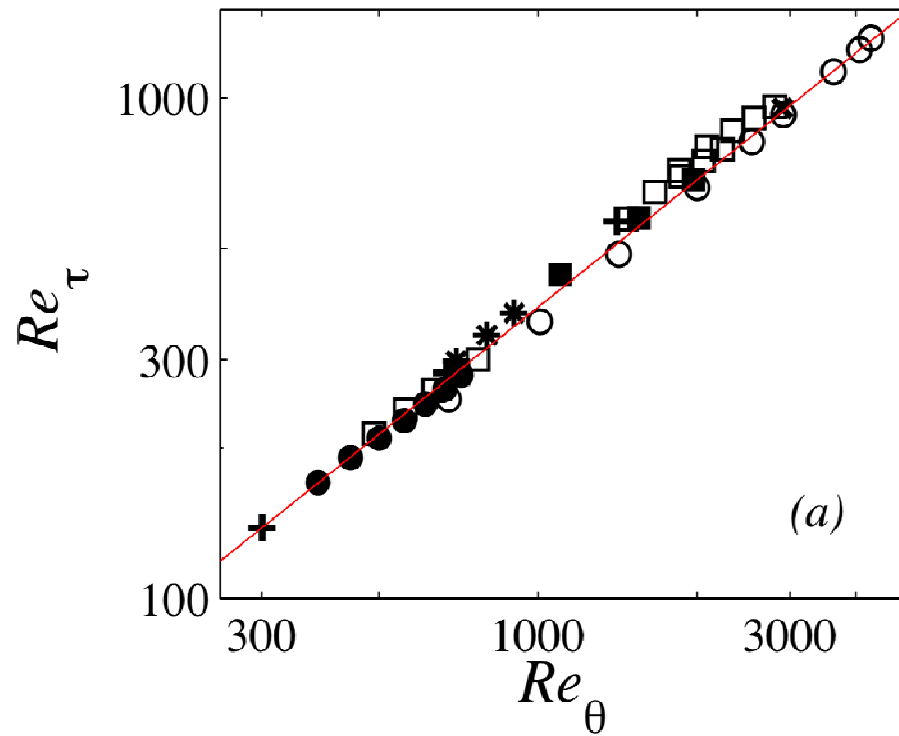
$$H_{12} = Re_{\delta^*} / Re_{\theta} = \int_0^{\delta_{99}^+} \left(1 - \frac{U^+}{U_{\infty}^+}\right) dy^+ / \int_0^{\delta_{99}^+} \frac{U^+}{U_{\infty}^+} \left(1 - \frac{U^+}{U_{\infty}^+}\right) dy^+$$



Re-relation & fluc. wall shear stress

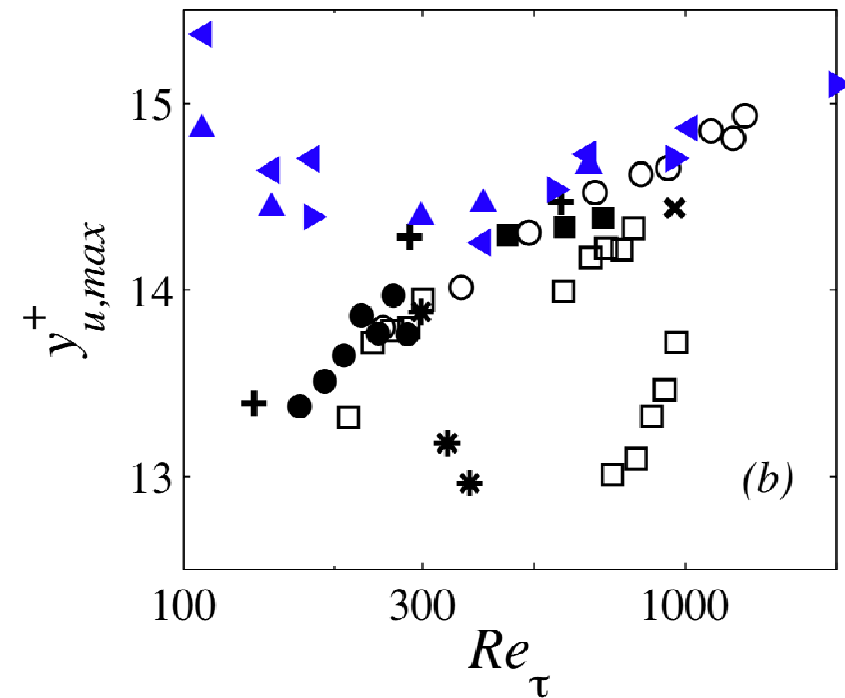
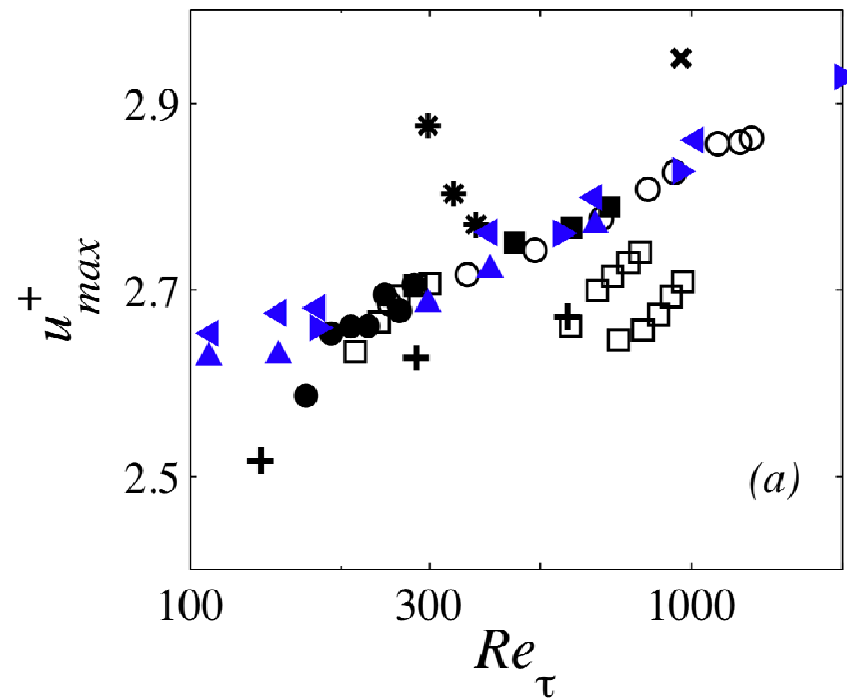
$$Re_\tau = \delta_{99}^+$$

$$\tau_{w,rms}^+ = \lim_{y^+ \rightarrow 0} \frac{u^+}{U^+}$$



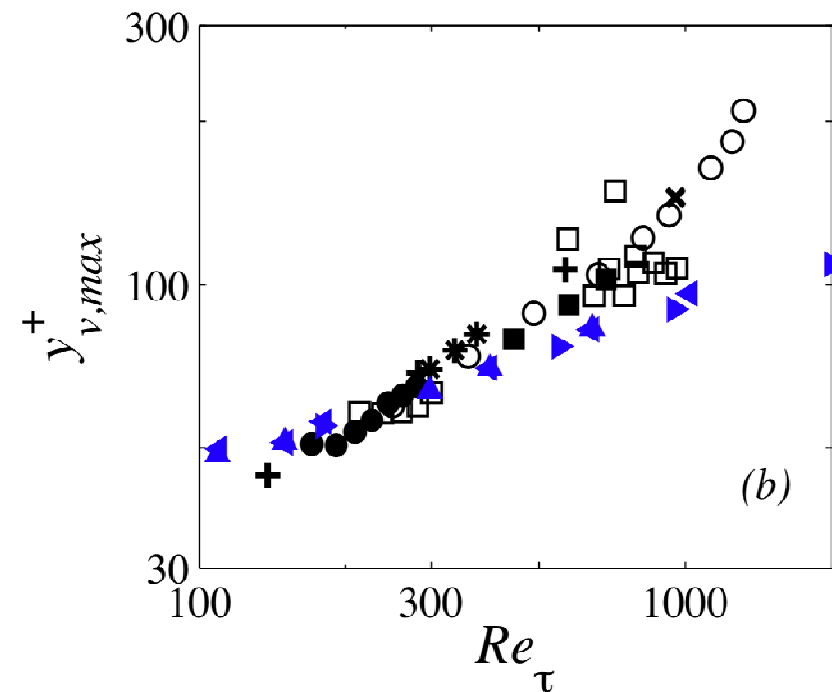
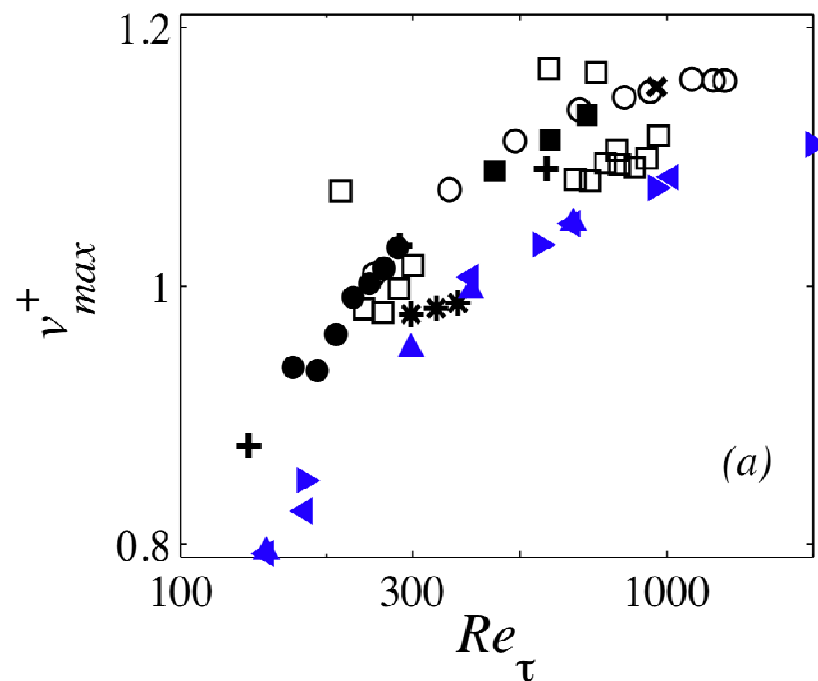
Near-wall behaviour (I)

- Streamwise velocity component



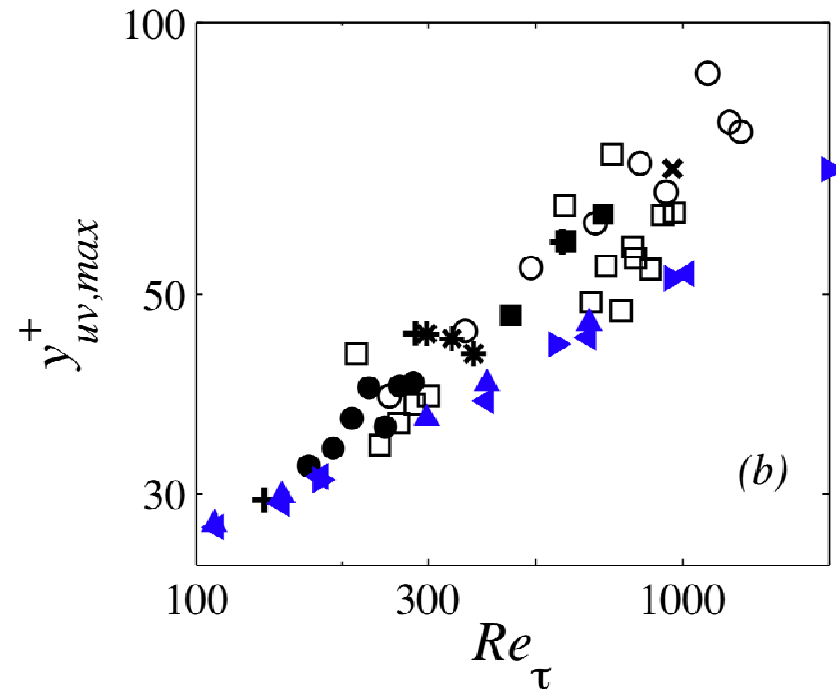
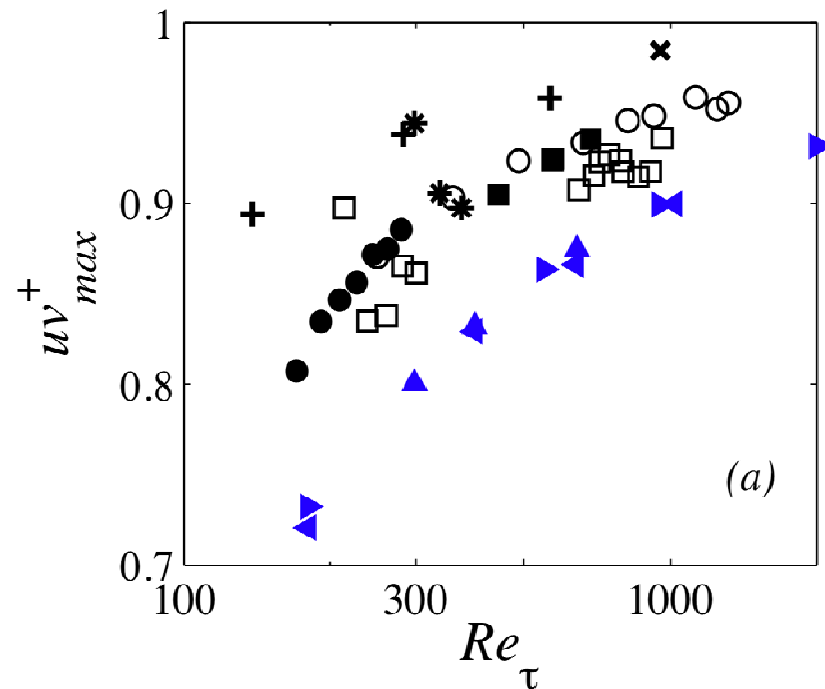
Near-wall behaviour (II)

- Wall-normal velocity component

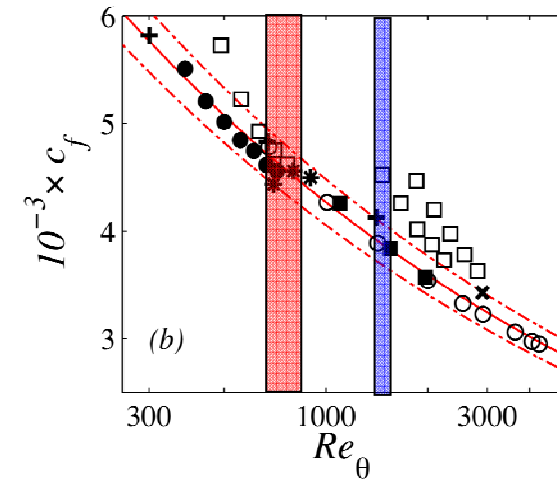
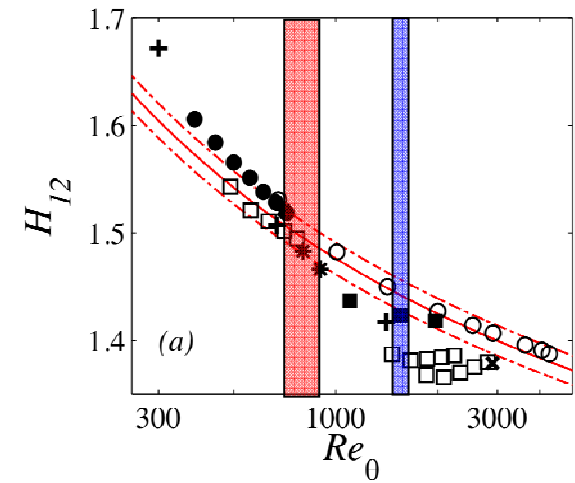
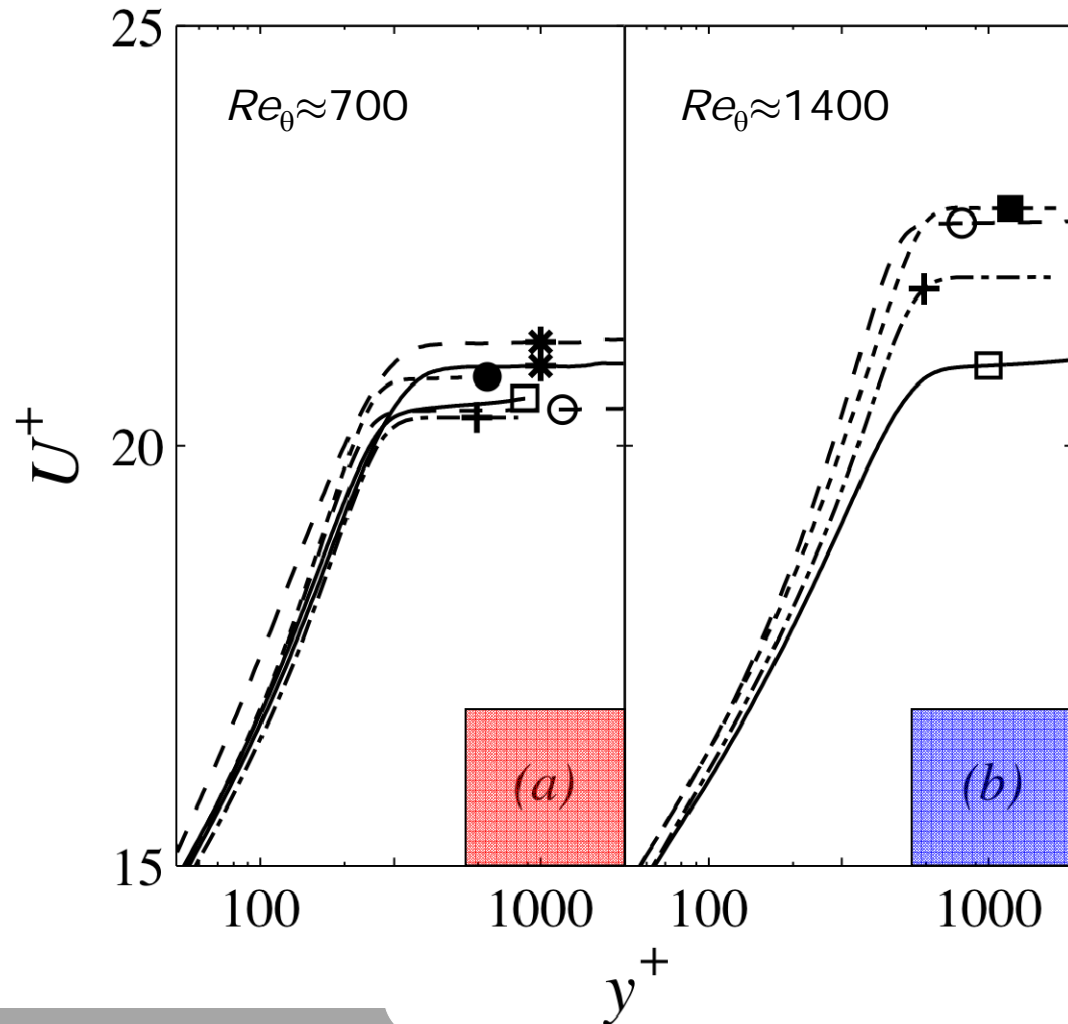


Near-wall behaviour (III)

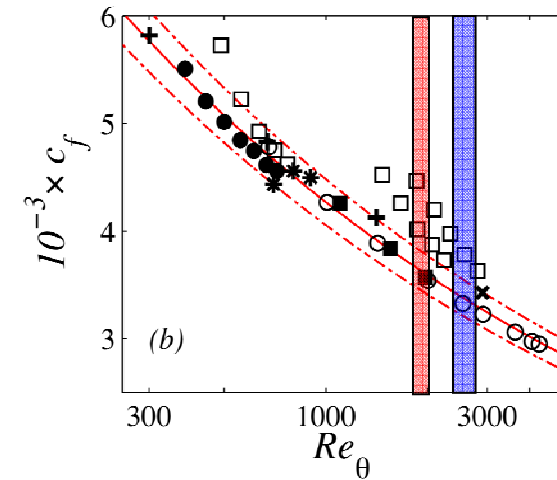
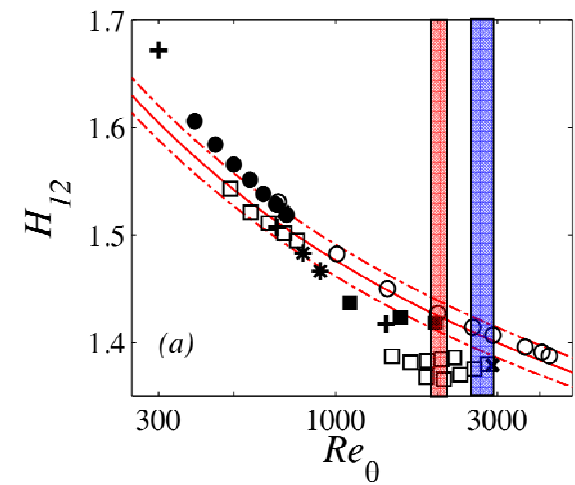
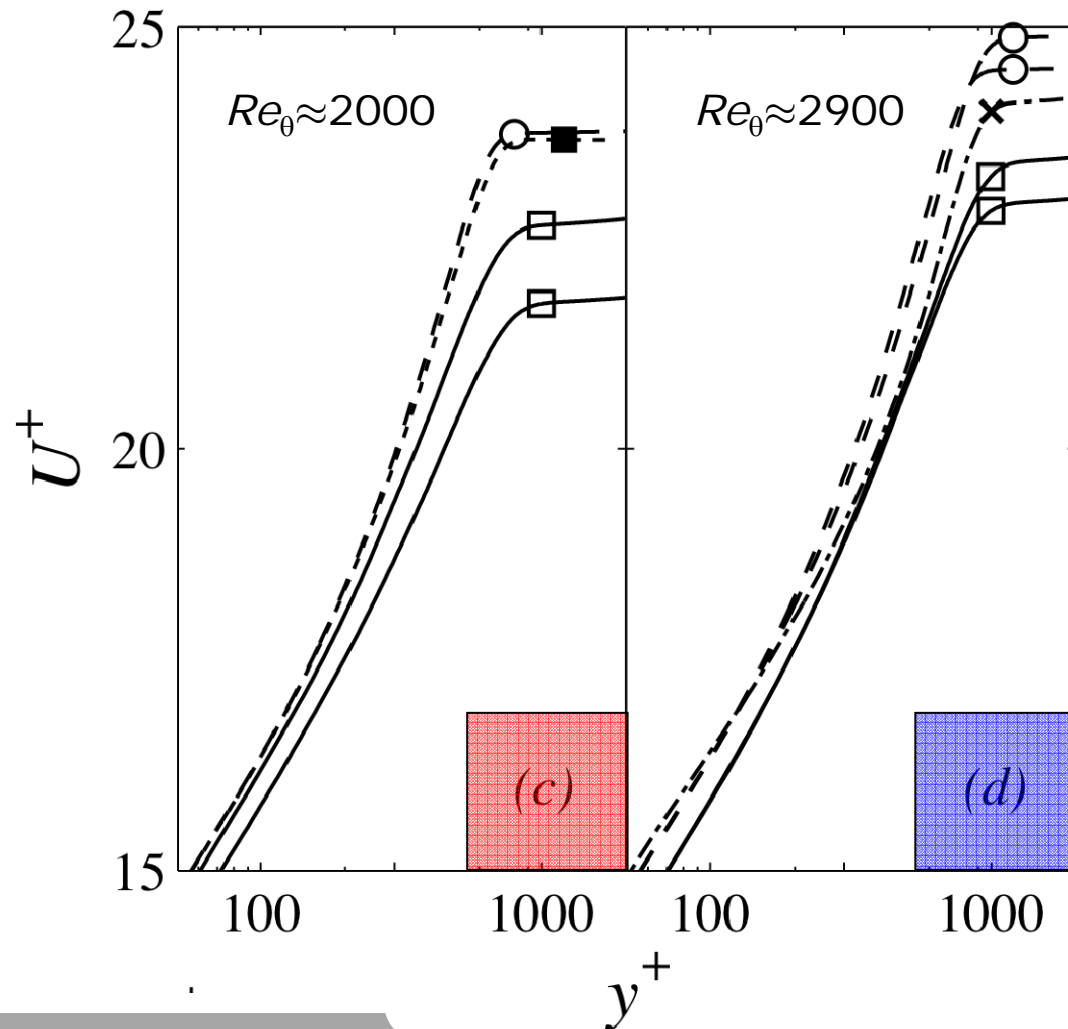
- Reynolds shear stress



Mean velocity profile: Wake region

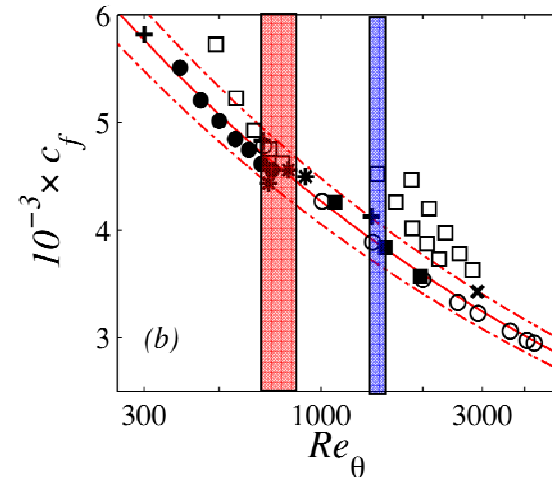
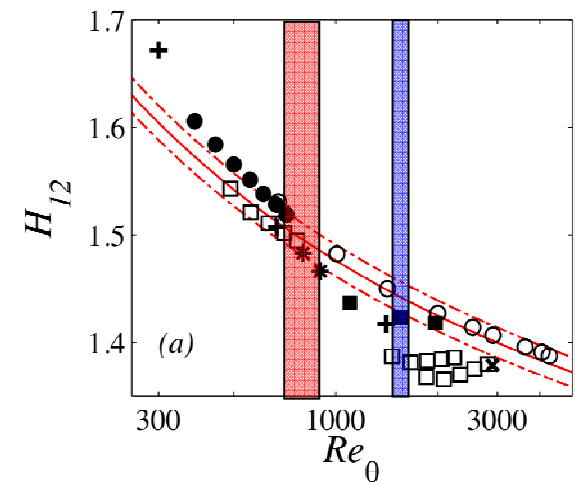
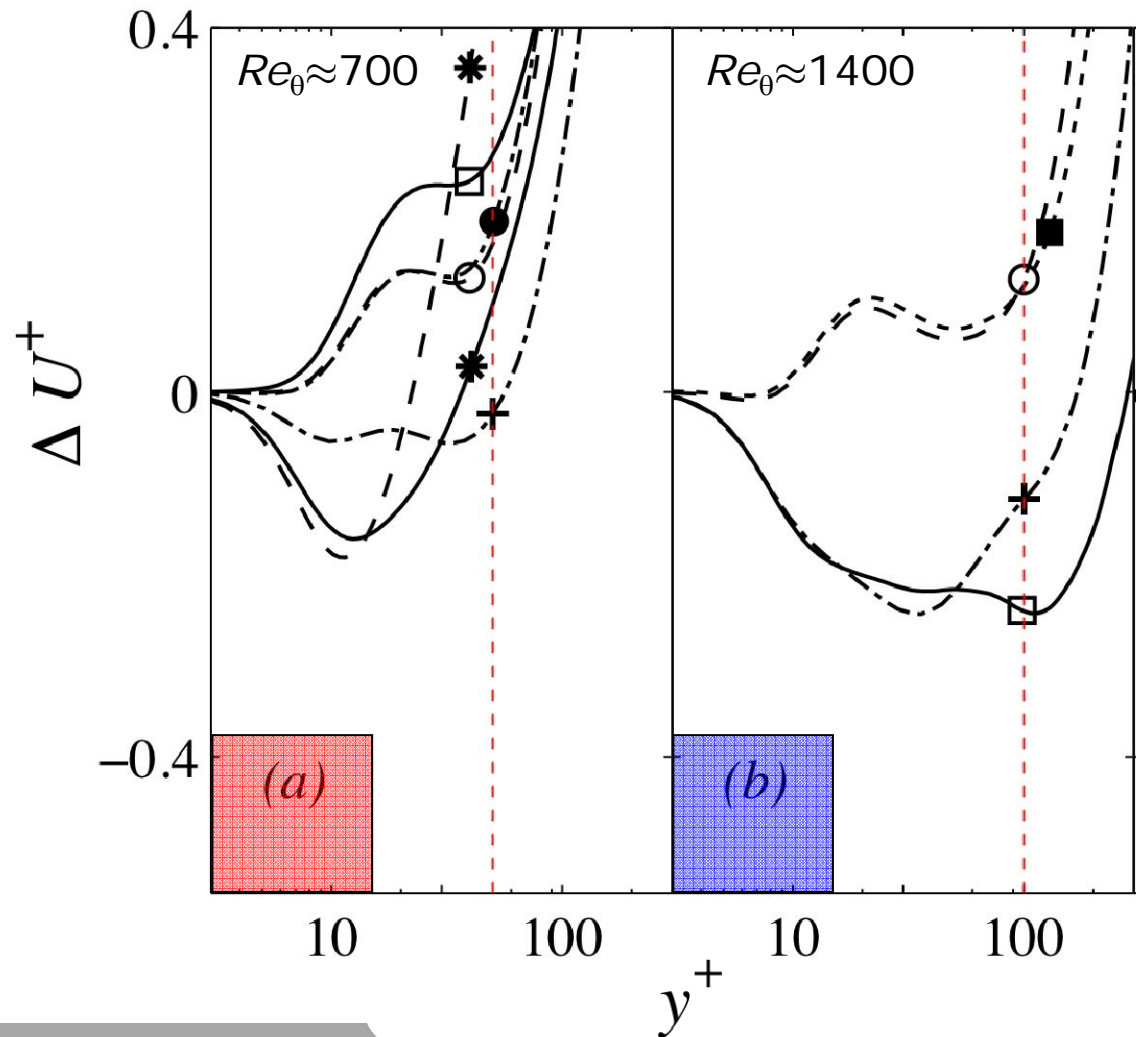


Mean velocity profile: Wake region



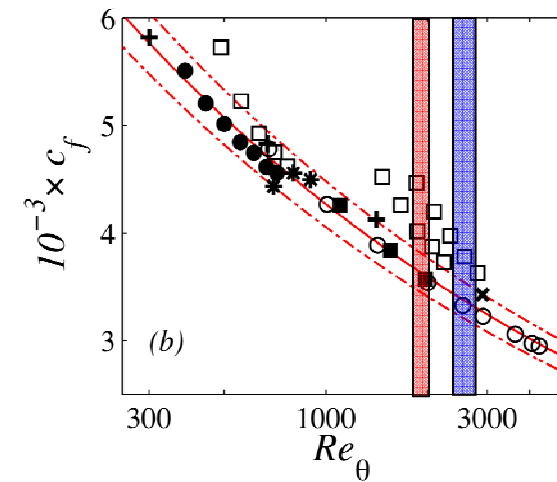
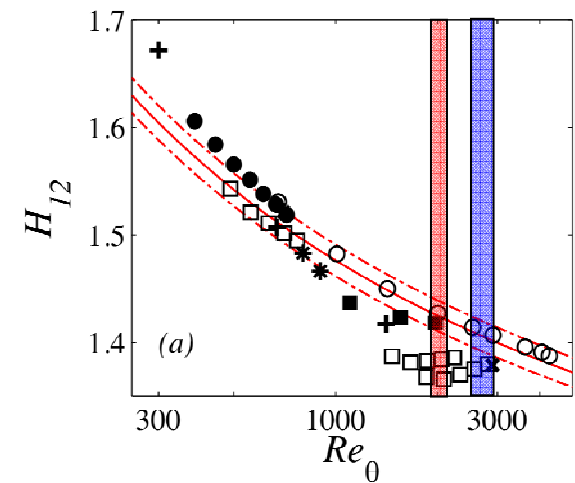
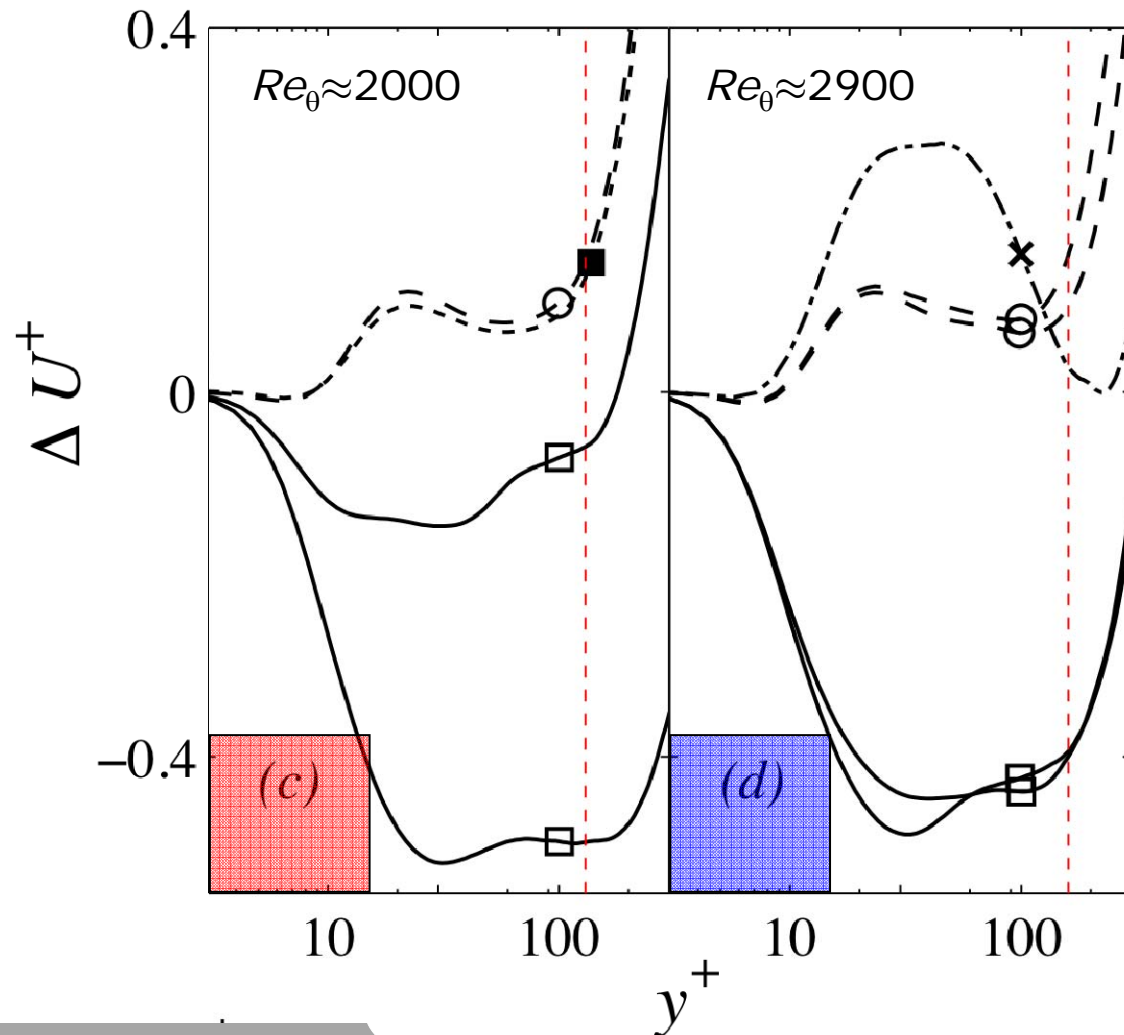
Mean velocity profile: inner region

(Deviation of mean profile from mod. Musker profile)



Mean velocity profile: inner region

(Deviation of mean profile from mod. Musker profile)



Conclusions I

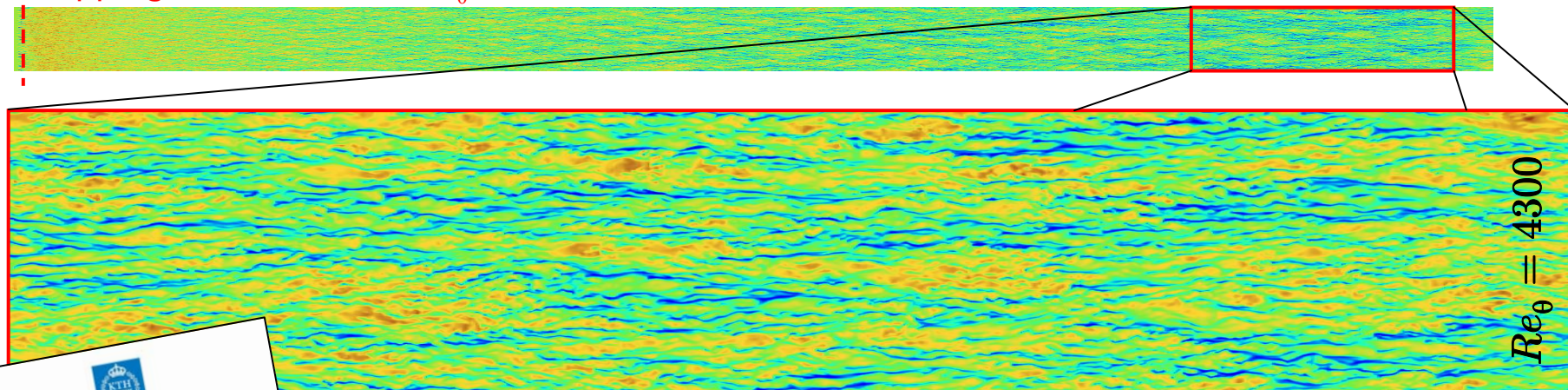


- **Comparison** of (nearly) all recent DNS of ZPG turbulent boundary layers (spatially evolving) with "high" Reynolds numbers ($Re_\theta > 1000$) and good resolution.
- **Consistent re-evaluation** of integral parameters to enable direct comparison → changes trends!
- Boundary layers give **significantly larger spread of data** compared to channels, even for "fundamental" quantities like profiles, H_{12} , rms peaks *etc.*
- DNS be treated as **"numerical" experiment**, and thus be subject to same scrutiny as **"real" experiments**.
- However, if sufficient care is spent on defining the setup (domain size, turbulence generation, boundary conditions, etc.), good results can be achieved by DNS (... as in a real experiment ...)

Simulation of Turbulent Boundary Layer

- DNS with $8192 \times 513 \times 768 = 8$ billion grid points
 $\Delta x^+ = 9$, $\Delta y^+ = 0.04-14$, $\Delta z^+ = 4$

tripping to turbulence, $Re_\theta = 180$

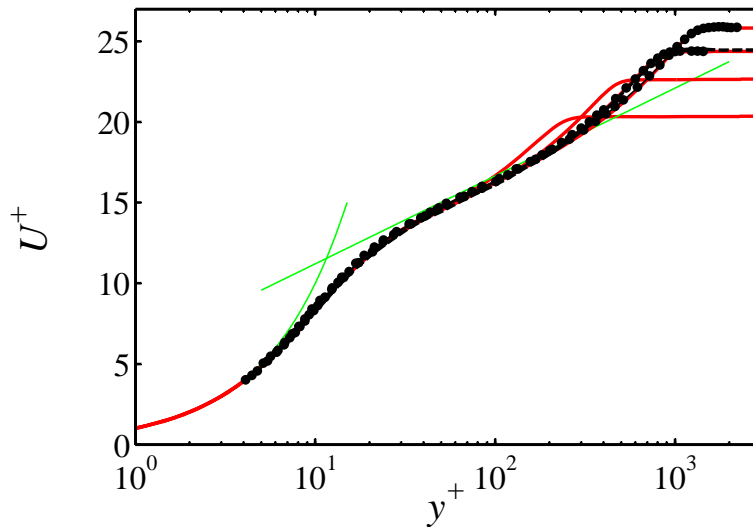


- Fully spectral method: Fourier/Chebyshev tau method
- Periodic boundary condition in the wall-parallel directions, no-slip at lower wall, Neumann conditions at upper boundary.
- Fringe region (volume force) to enforce laminar Blasius inflow
- Trip forcing to induce “natural” laminar-turbulent transition
- Code **SIMSON** (Chevalier *et al.* 2007) on $\mathcal{O}(1000)$ processors

Statistical Data up to $Re_\theta=4300$

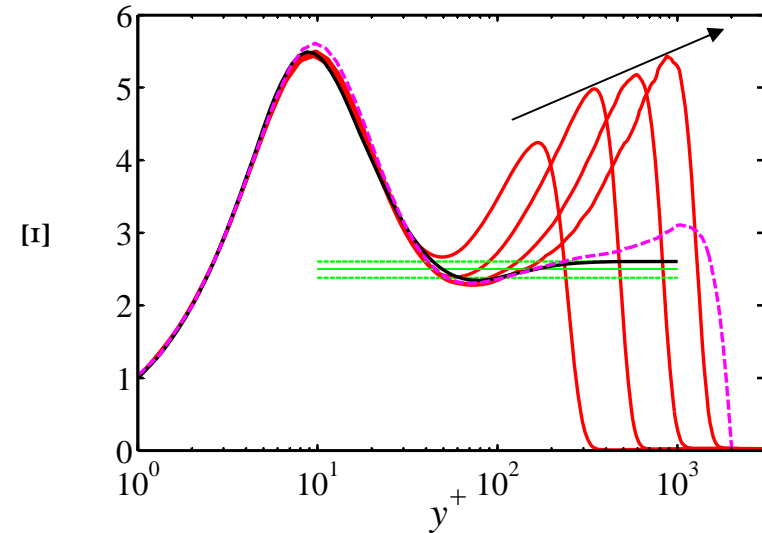
- Mean velocity profile

$$\langle U \rangle_{z,t}^+(y^+)$$



- Indicator function Ξ

$$\Xi = y^+ (d\langle U \rangle^+ / dy^+)$$



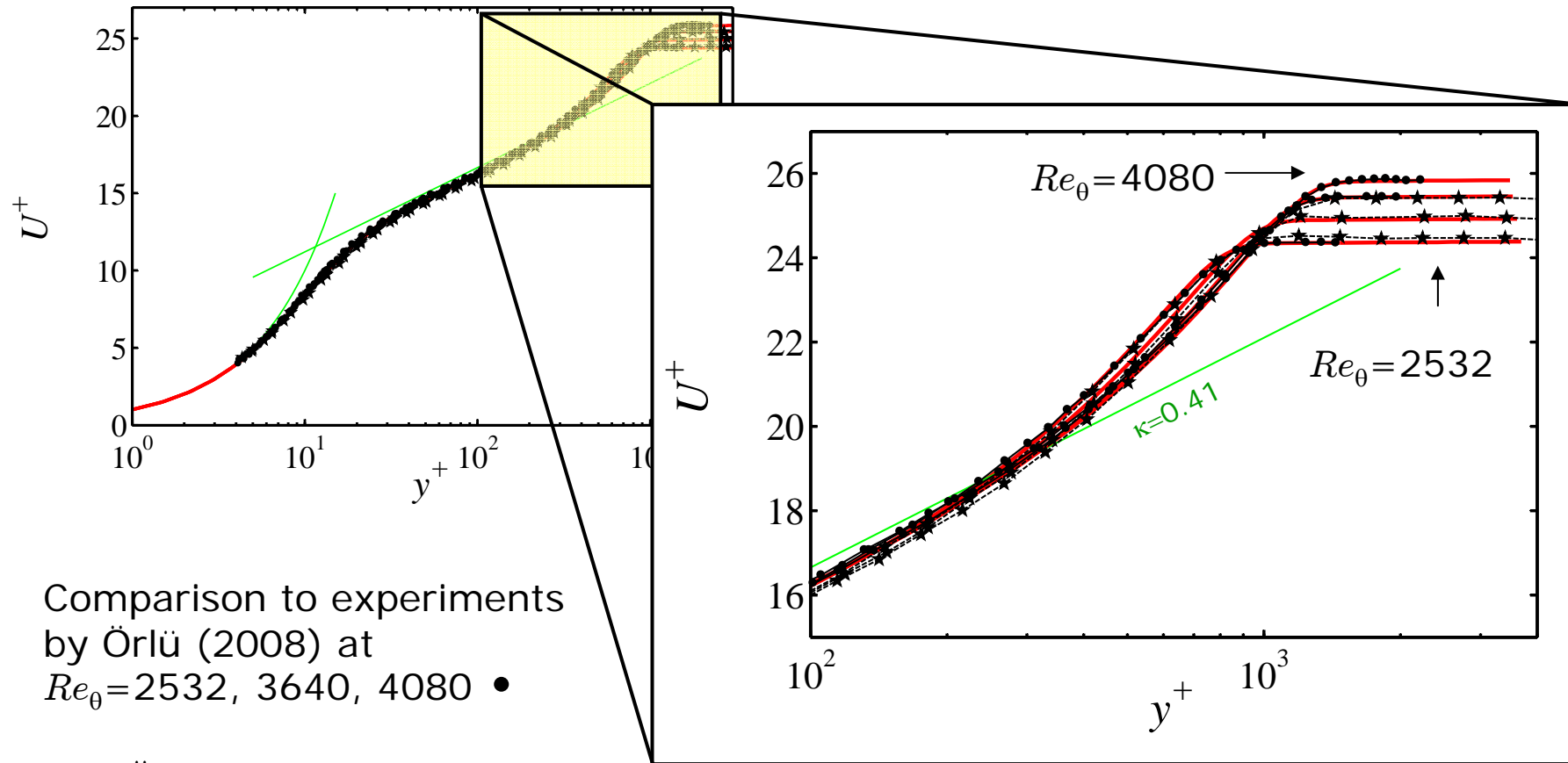
- EXP Österlund (1999) $Re_\theta=2500$
- EXP Örlü (2008) $Re_\theta=2500, 4300$

- DNS Hoyas & Jiménez (2006)
- Correlation Monkewitz *et al.* (2007)
- $1/\kappa=1/0.38, 1/0.4, 1/0.42$

— $U^+ = 1/0.41 \cdot \log(y^+) + 5.2$

$Re_\theta=670, 1410, 2500, 4300$: — DNS

DNS – Comparison to EXP



Comparison to experiments
by Örlü (2008) at
 $Re_\theta = 2532, 3640, 4080$ •

and Österlund (1999) at
 $Re_\theta = 2532, 3060, 3651$ ★

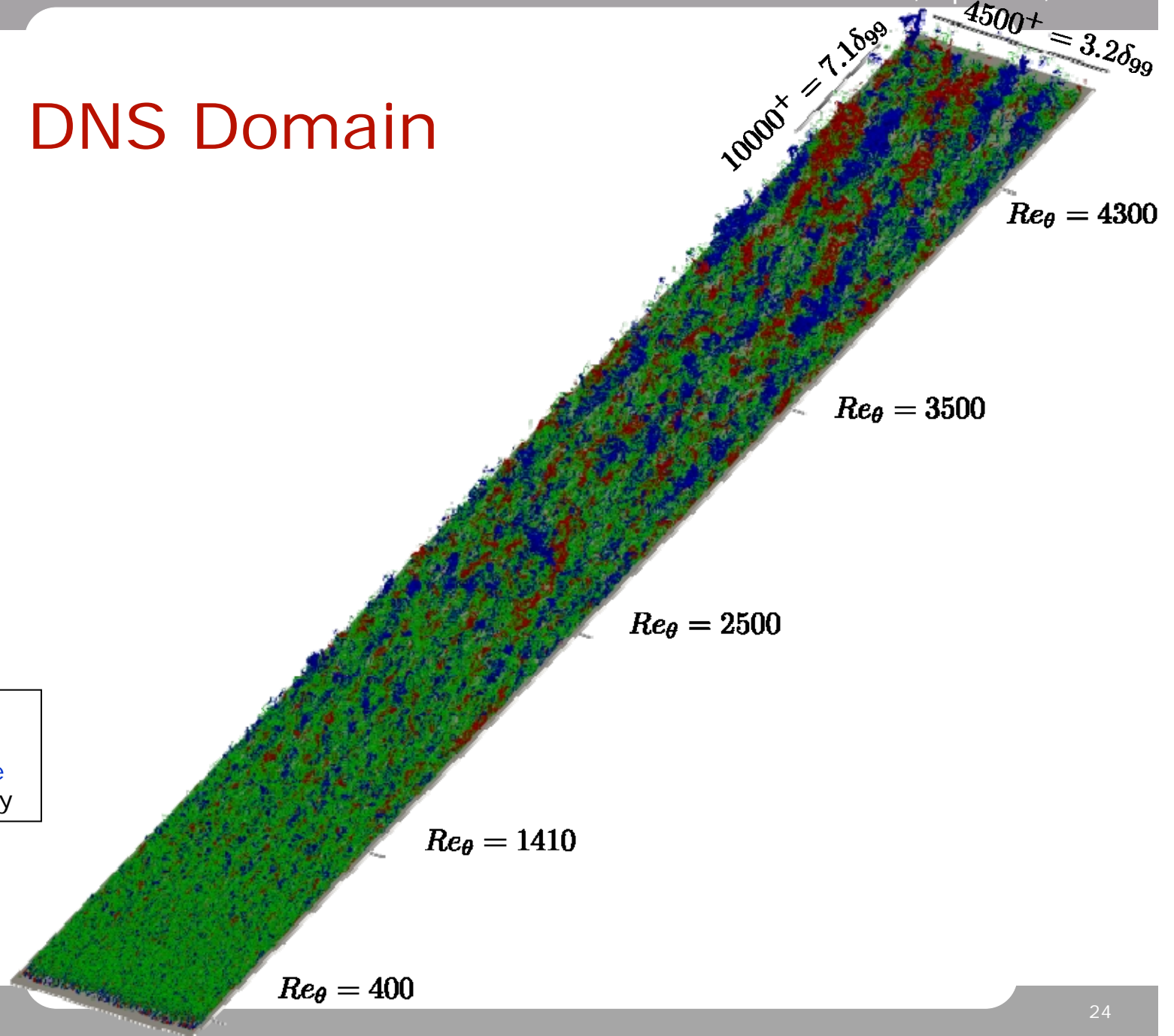
— present DNS at matching Re_θ

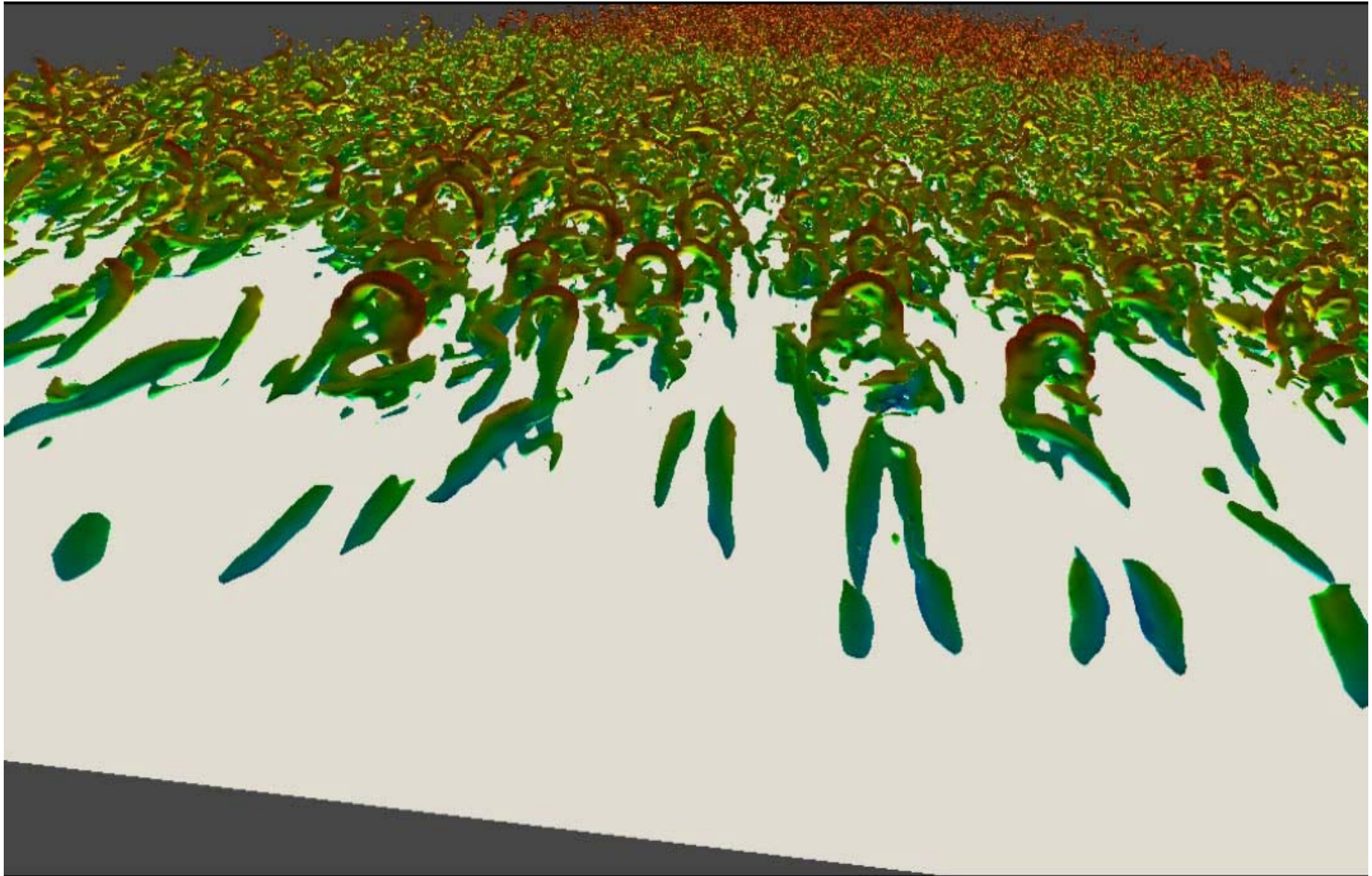
DNS Domain



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Isocontours of
negative λ_2 and
positive / negative
disturbance velocity

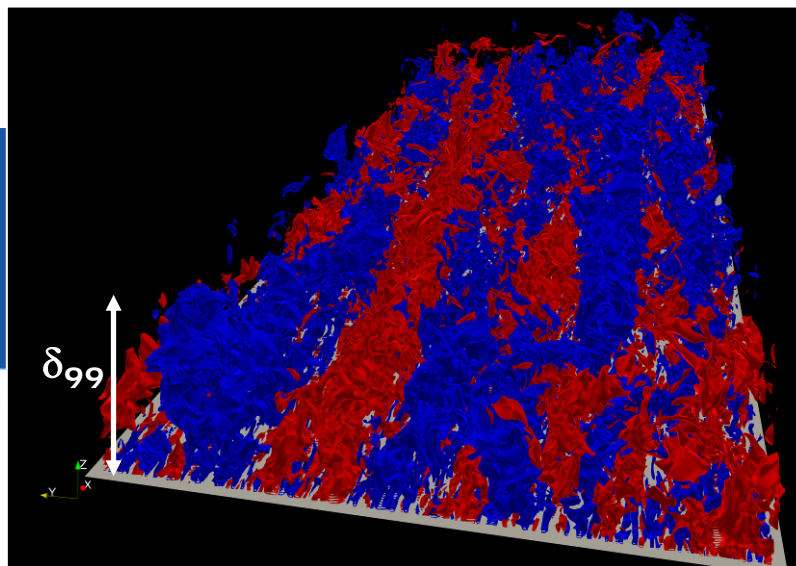




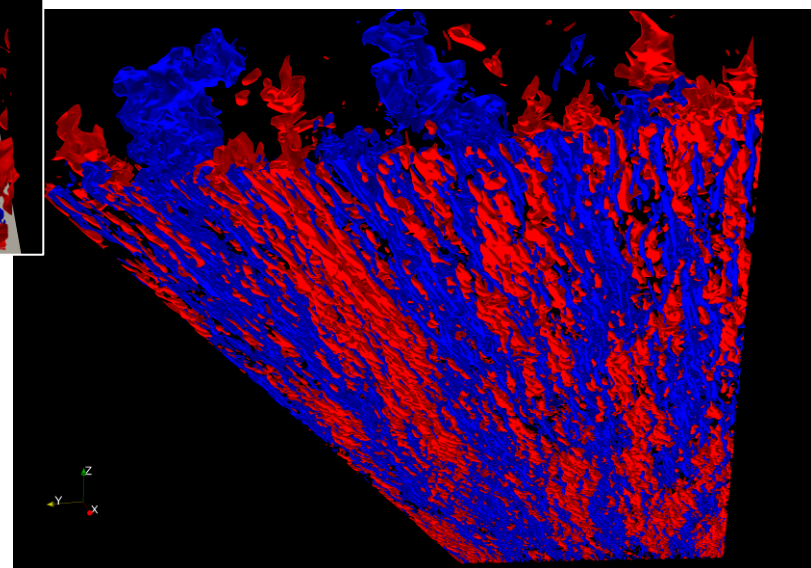
N. Jansson & R. Vilela De Abreu (NADA, KTH): $-\lambda_2$ surfaces, coloured by height.

Disturbance Velocity

- **positive** and **negative** streamwise disturbance velocity ($\leq 0.1U_\infty$)
at $Re_\theta=4000$



view from top



view from bottom

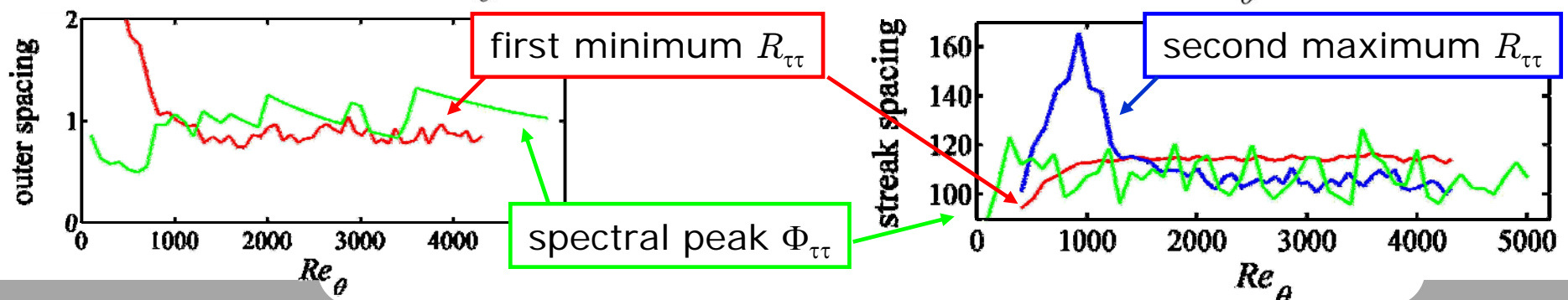
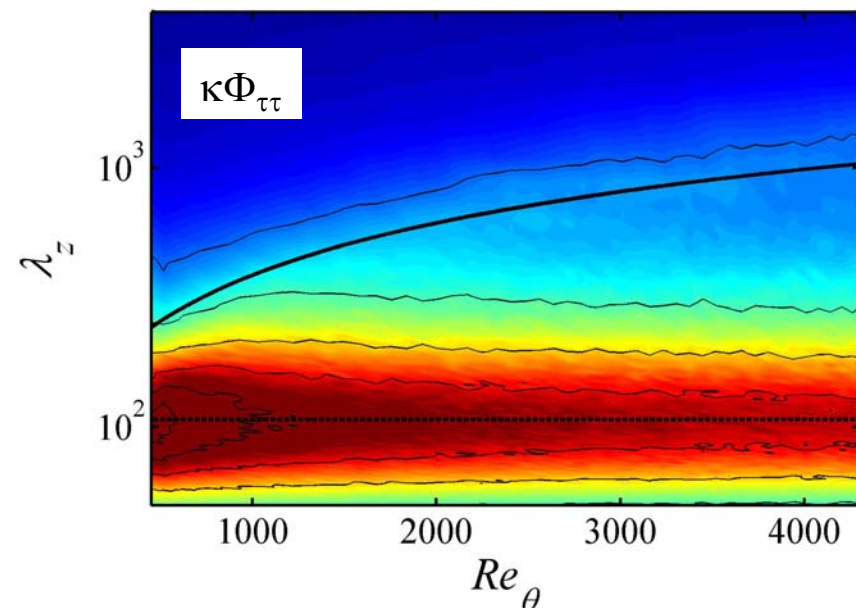
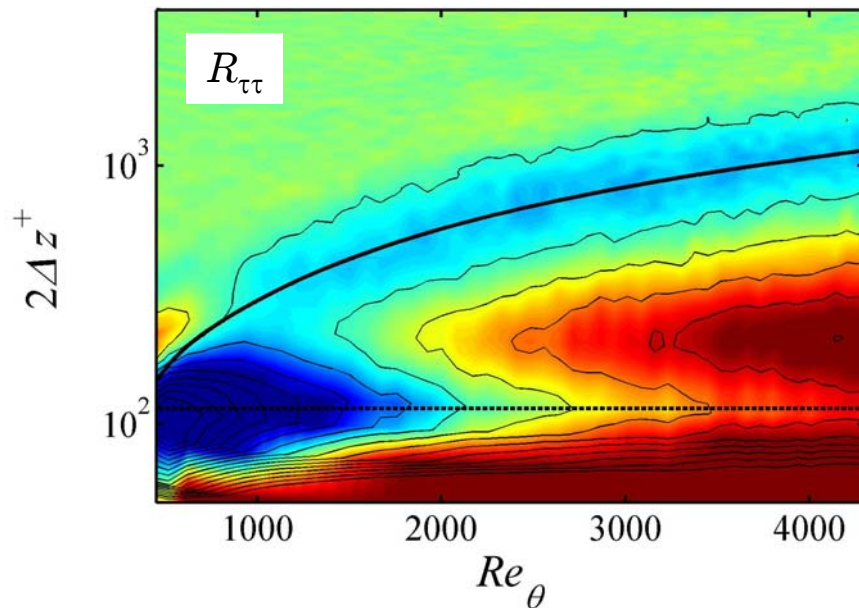
visualised domain:

length	7000+	5.0 δ_{99}
width	4500+	3.2 δ_{99}

Spanwise Scales

..... $2\Delta z^+ = 115$
 — $2\Delta z/\delta_{99} = 0.85$

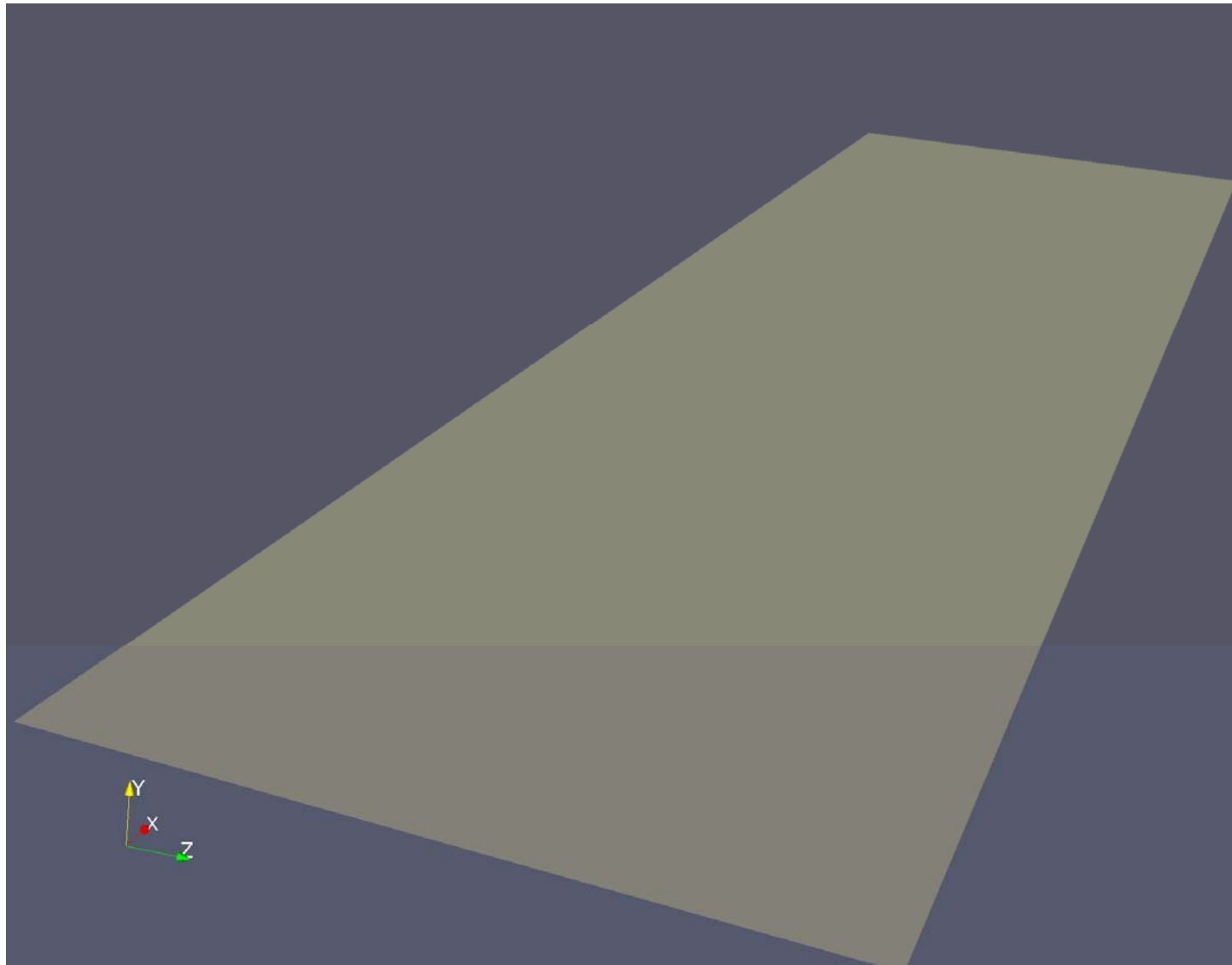
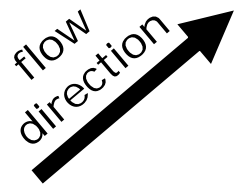
- Spanwise two-point correlation and premultiplied spectrum of wall shear stress τ_w



$Re_\theta = 4000$



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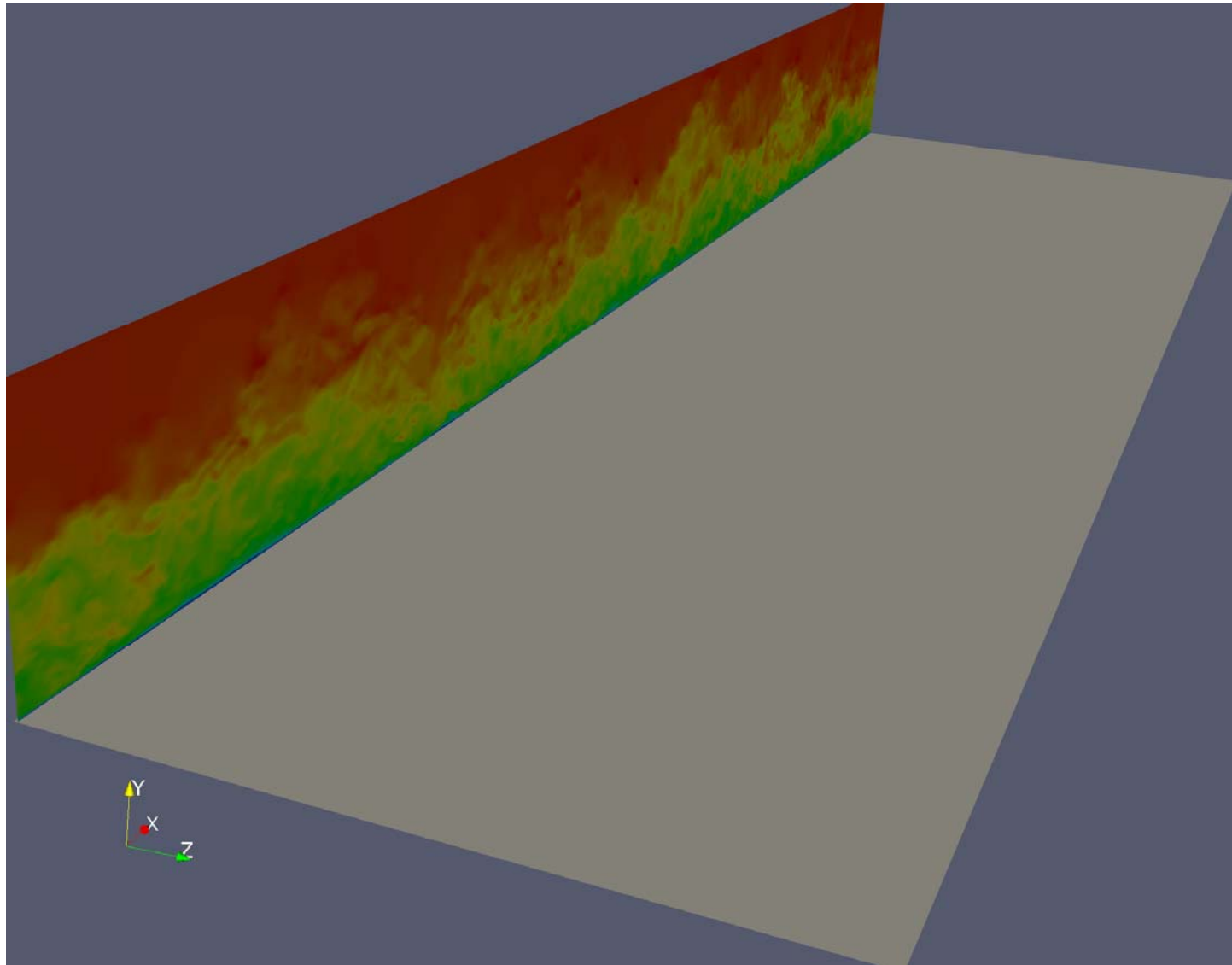
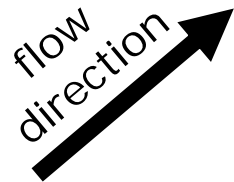


flat plate, $Re_\theta = 4000$

$$Re_\theta = 4000$$



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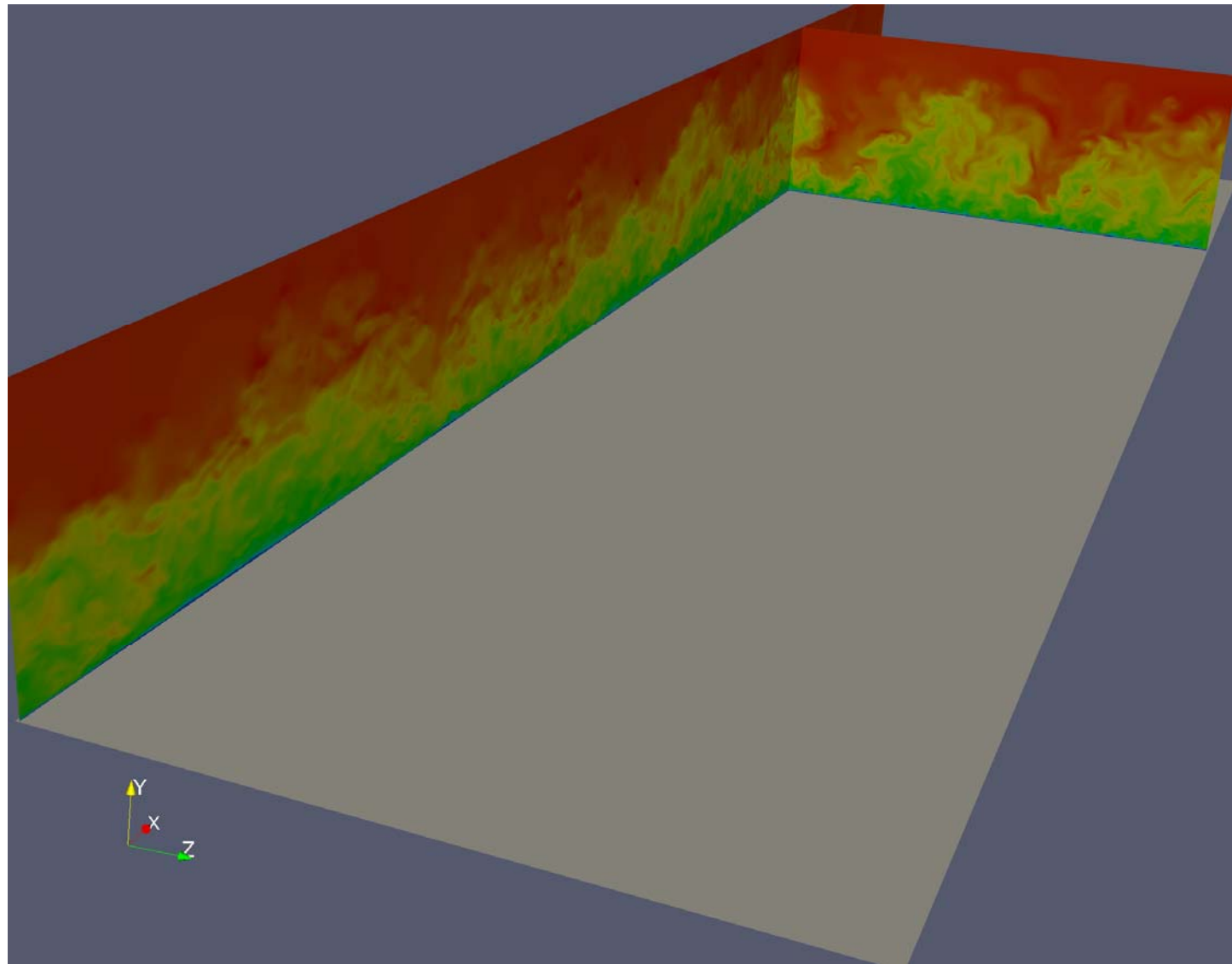
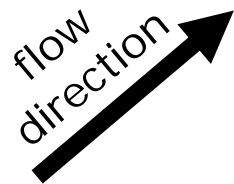
streamwise velocity u

near-wall streaks and larger structures further away

$$Re_\theta = 4000$$



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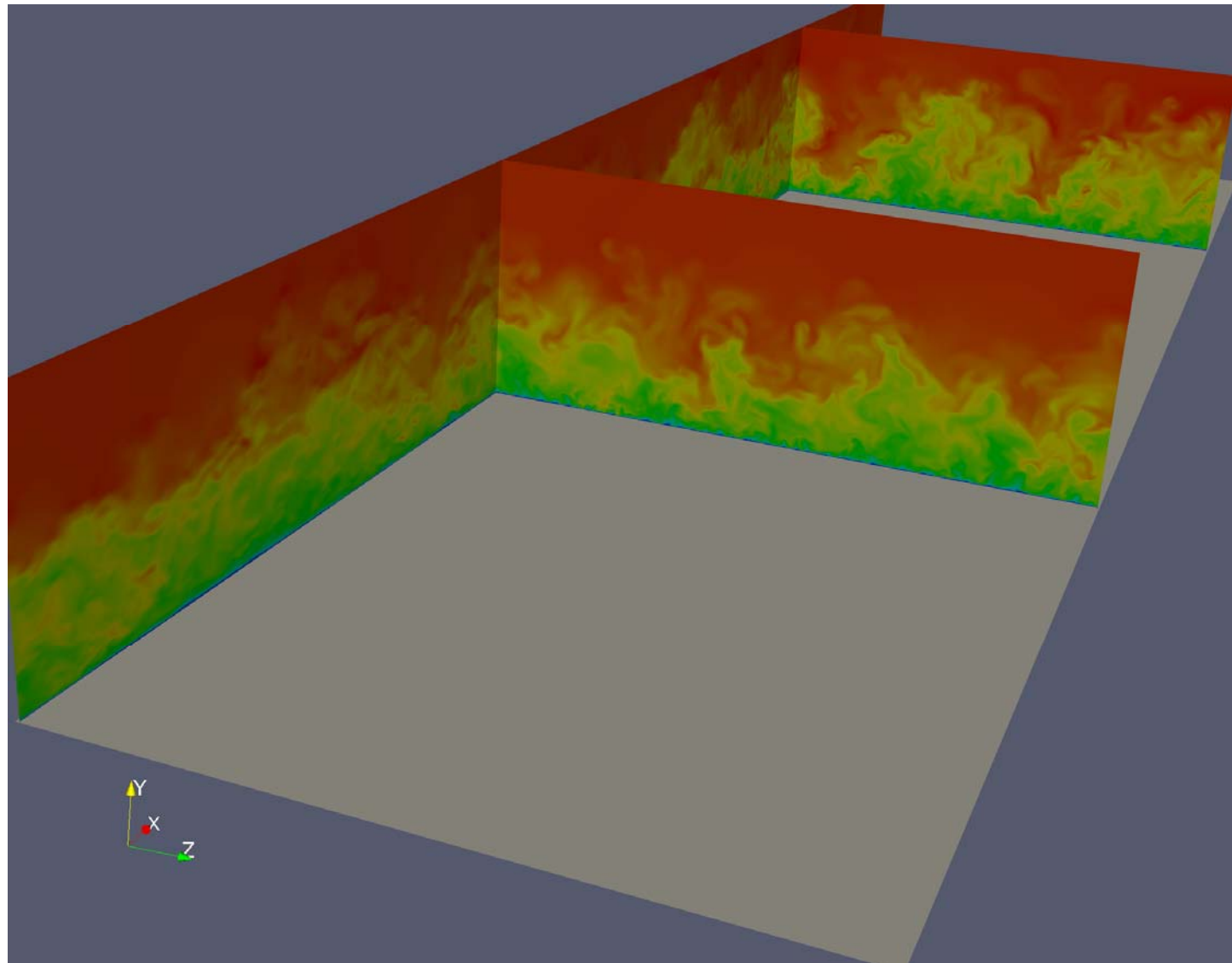
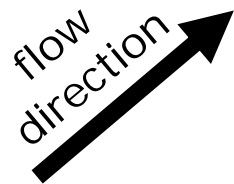
streamwise velocity u

near-wall streaks and larger structures further away

$$Re_\theta = 4000$$



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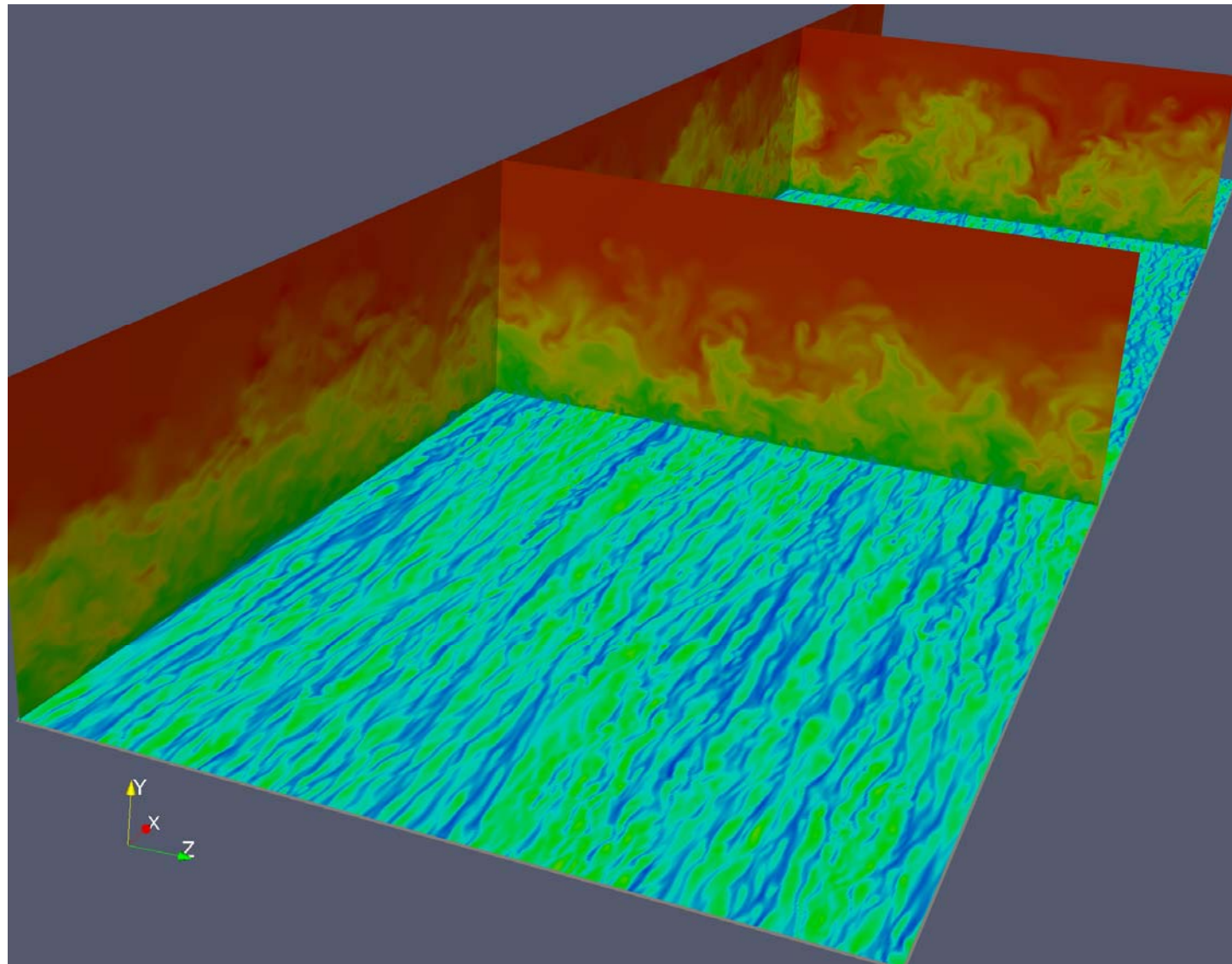
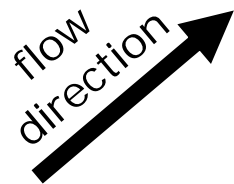
streamwise velocity u

near-wall streaks and larger structures further away

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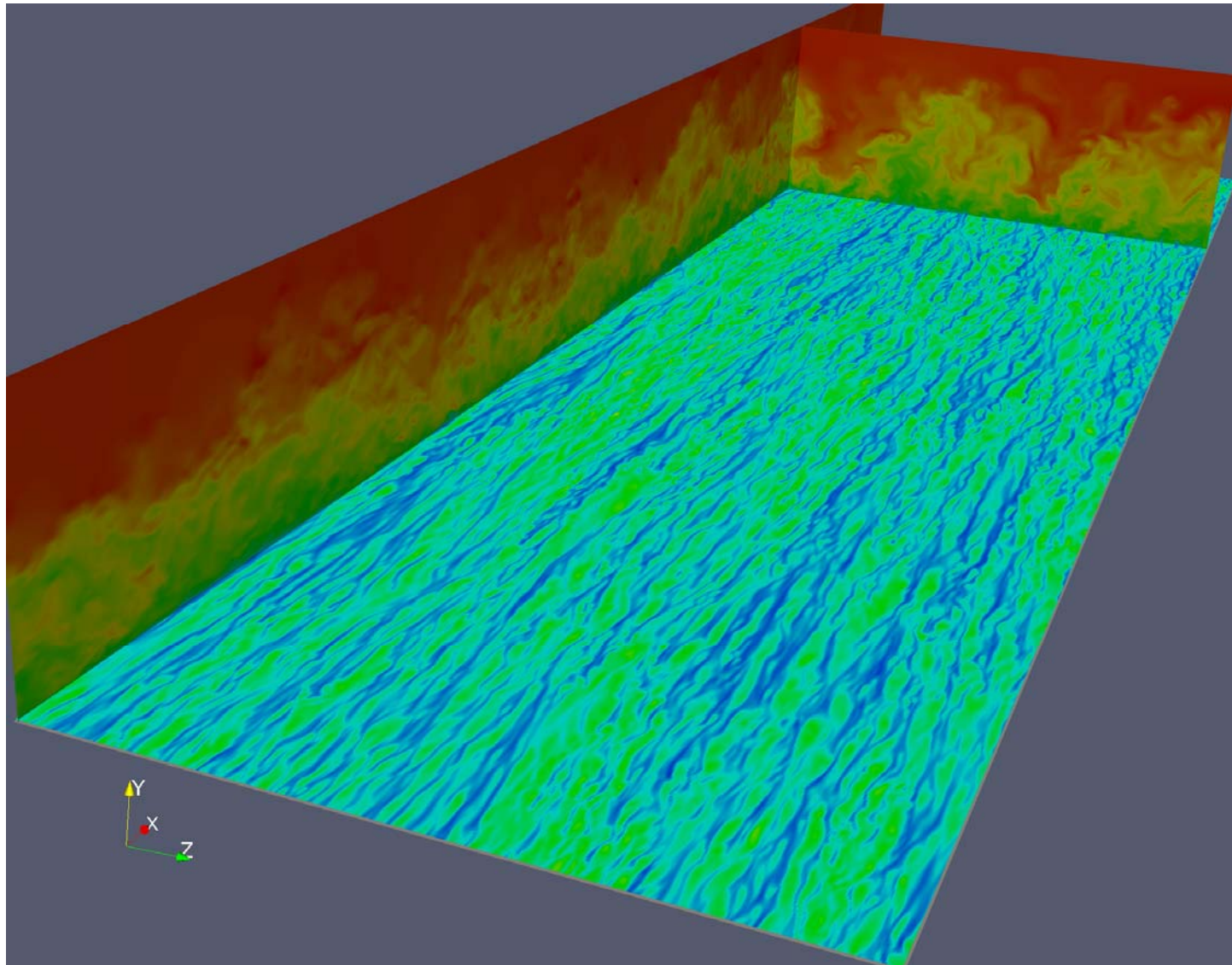
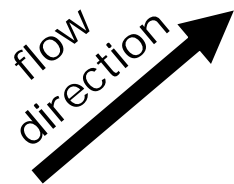
streamwise velocity u

"modulation" of near-wall structures by outer layer

$$Re_\theta = 4000$$



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streamwise velocity u

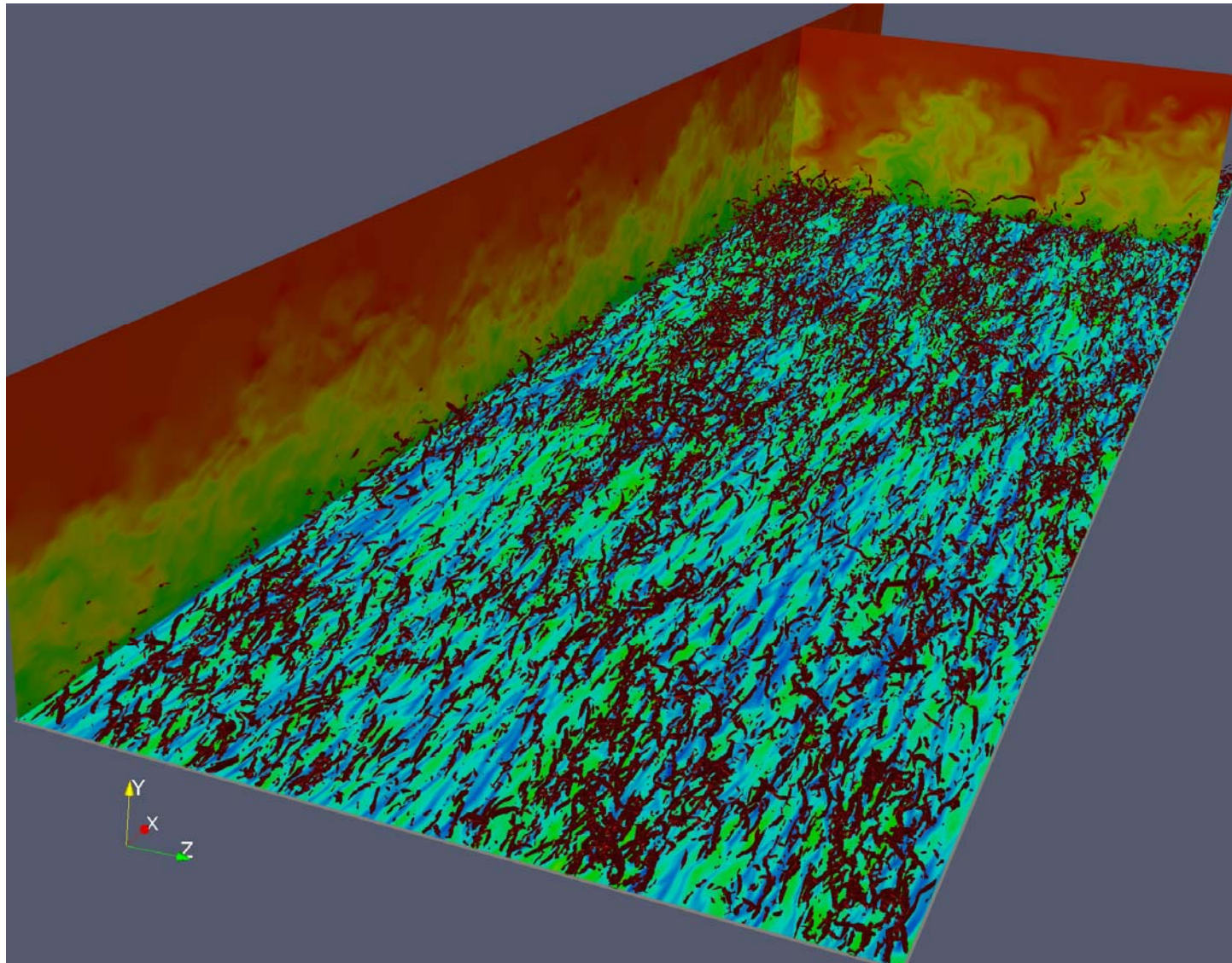
"modulation" of near-wall structures by outer layer

$Re_\theta = 4000$



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flow direction



$$\lambda_2 = -0.008$$

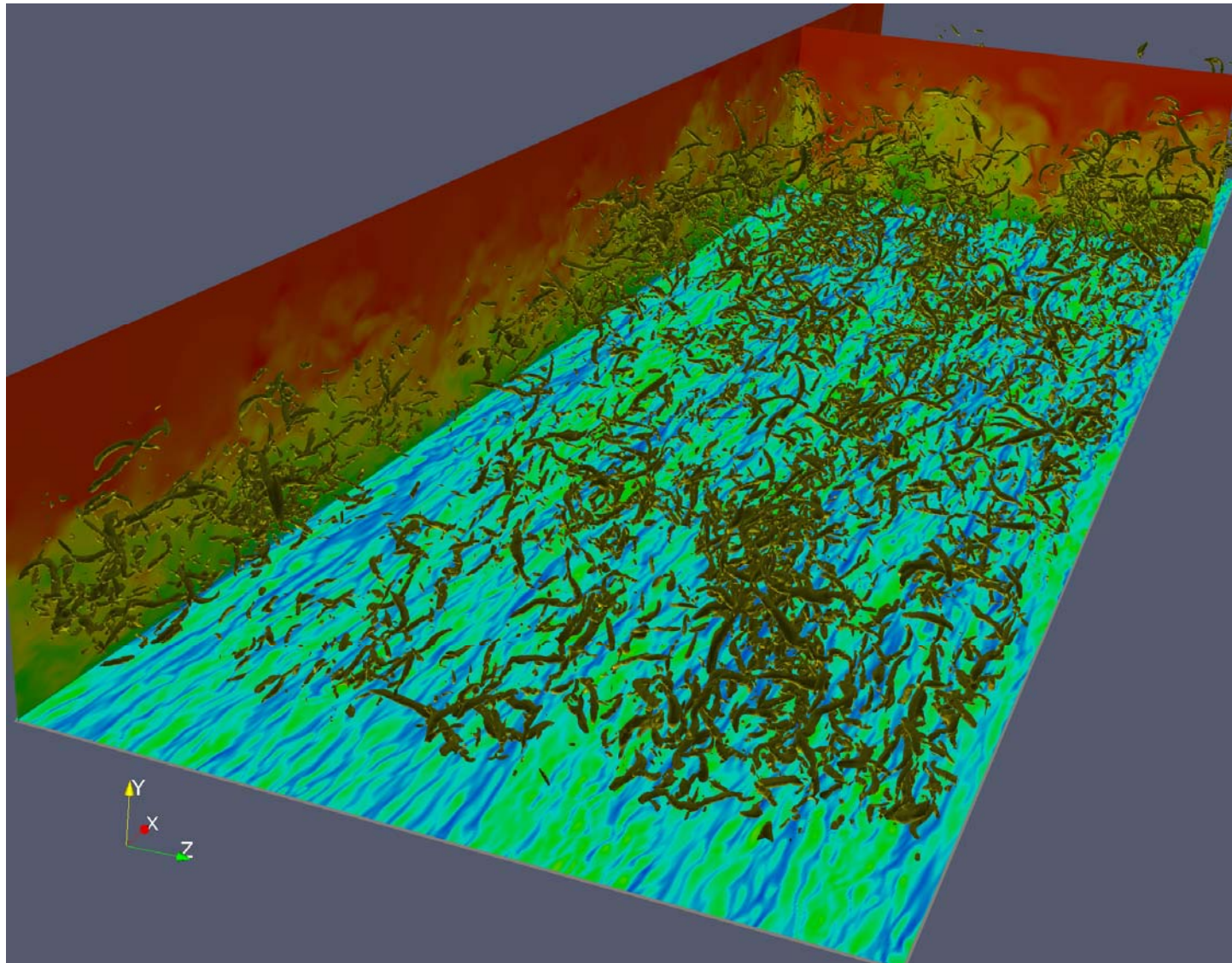
near the wall: high-speed region correlated with high vorticity region

$$Re_\theta = 4000$$



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flow direction



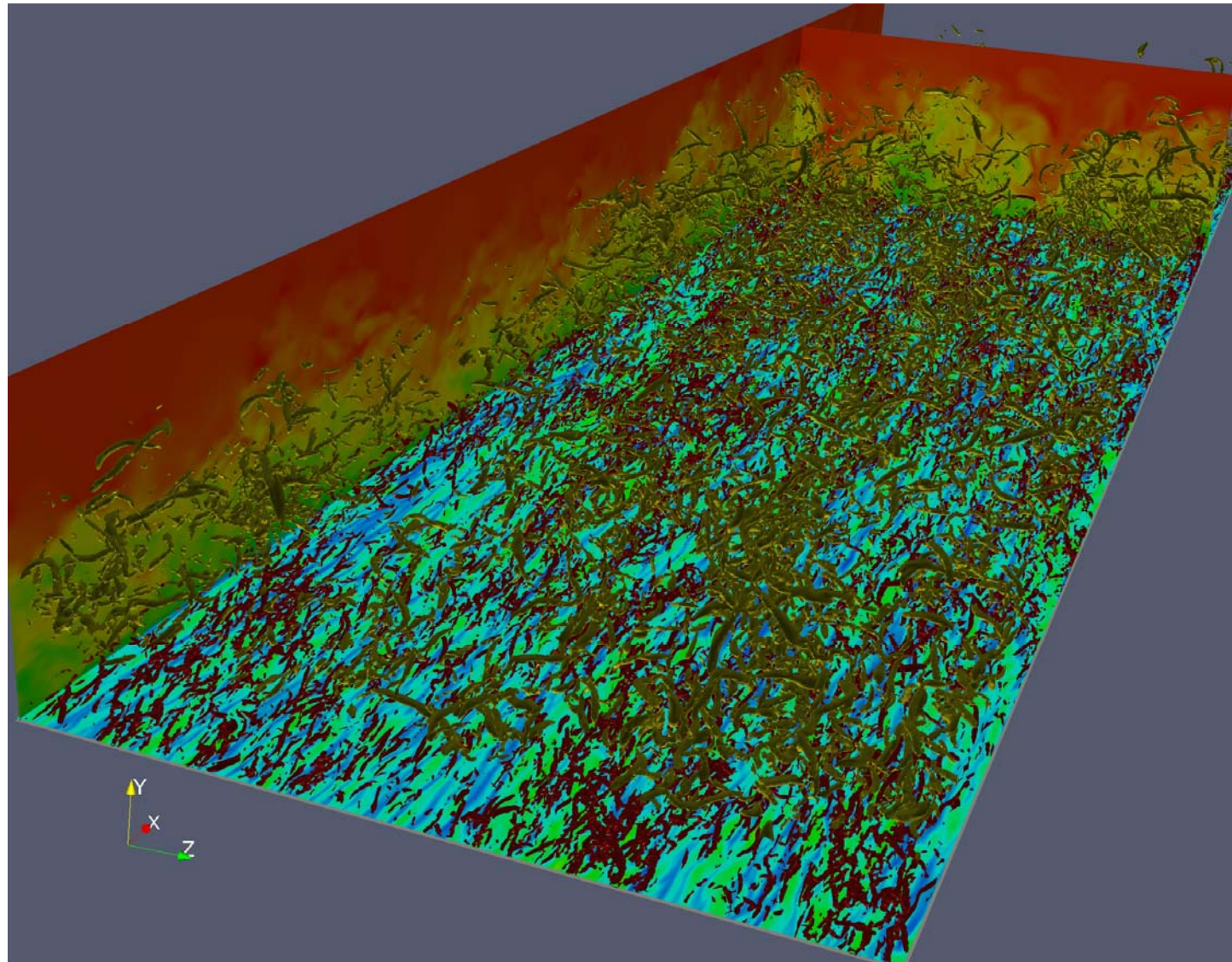
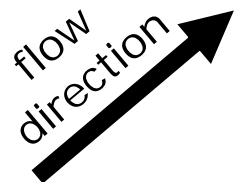
$$\lambda_2 = -0.002$$

away from the wall: low-speed region correlated with high vorticity region

$$Re_\theta = 4000$$



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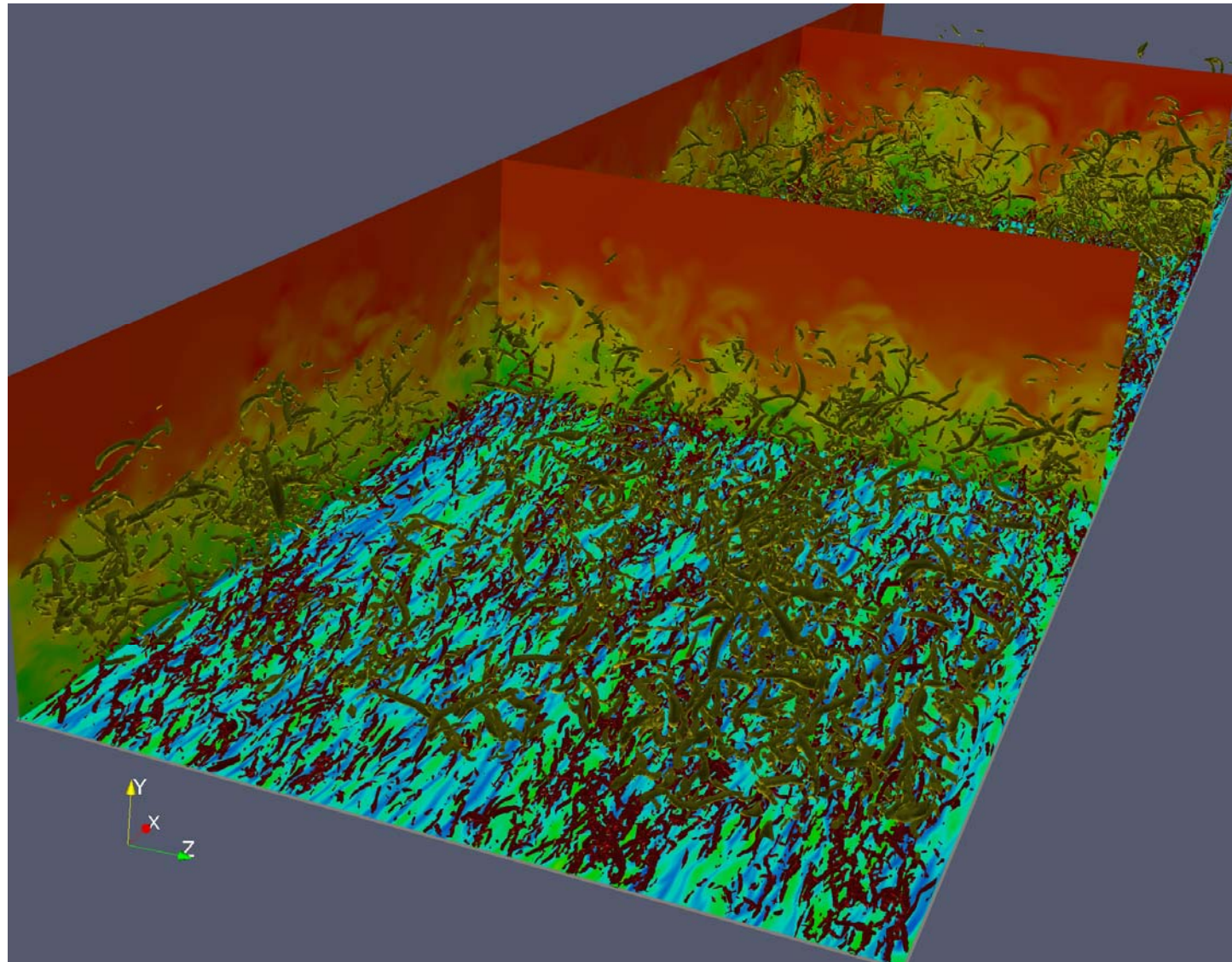
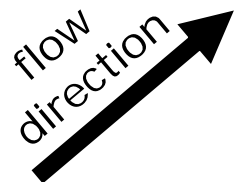


away from the wall: low-speed region
correlated with high vorticity region

$$Re_\theta = 4000$$



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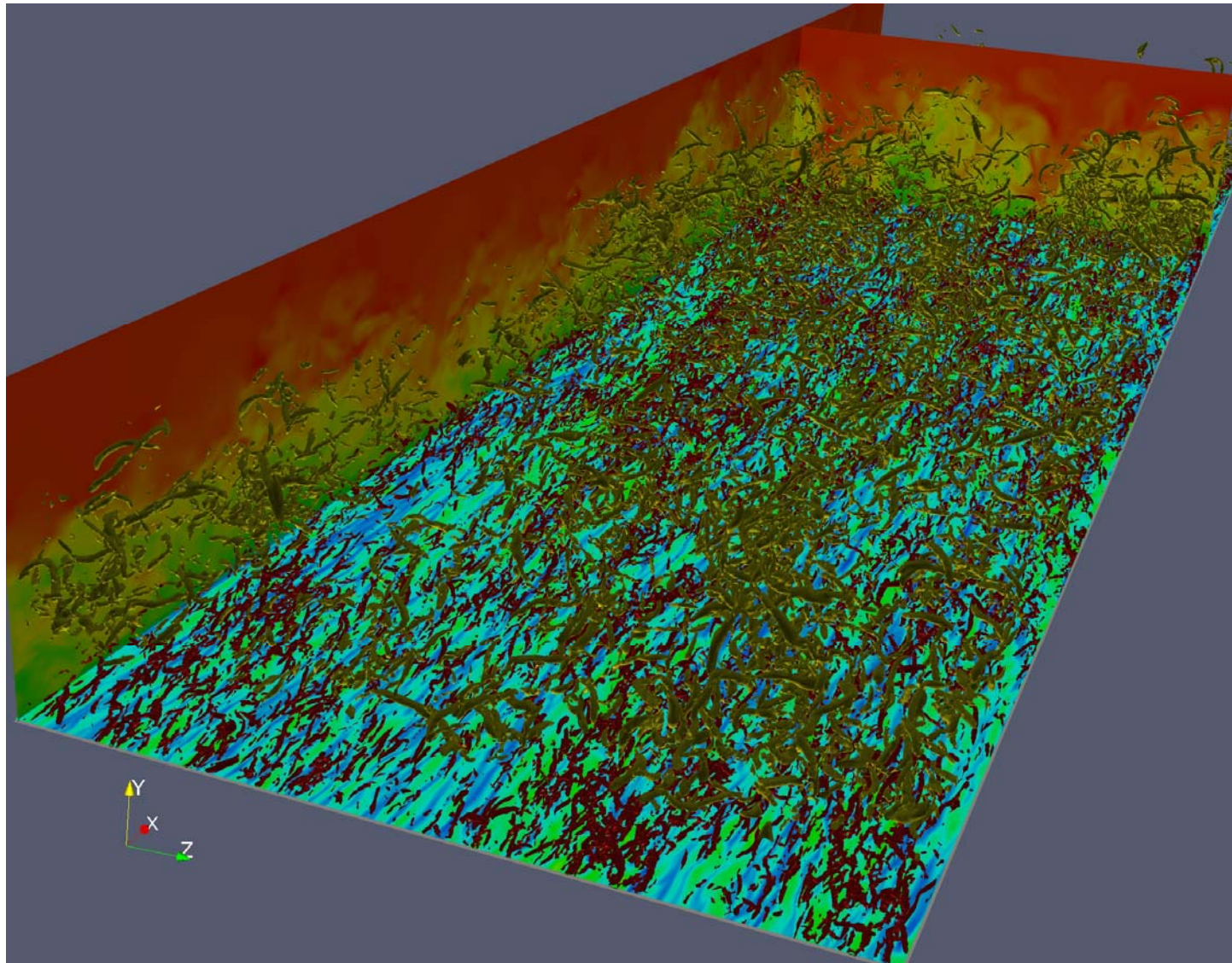
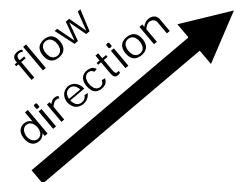


away from the wall: low-speed region correlated with high vorticity region

$$Re_\theta = 4000$$



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away from the wall: low-speed region
correlated with high vorticity region