About ``High'' Re Turbulent Boundary Layer Dynamics

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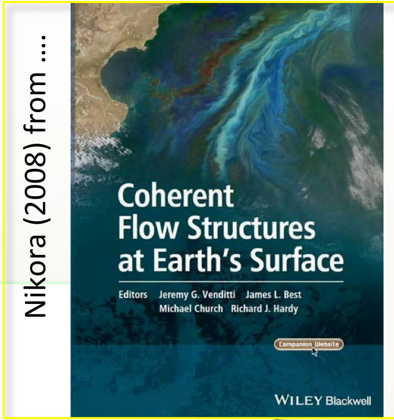
B. George, M. Tutkun, I. Marusic

Large range of temporal scales oceans



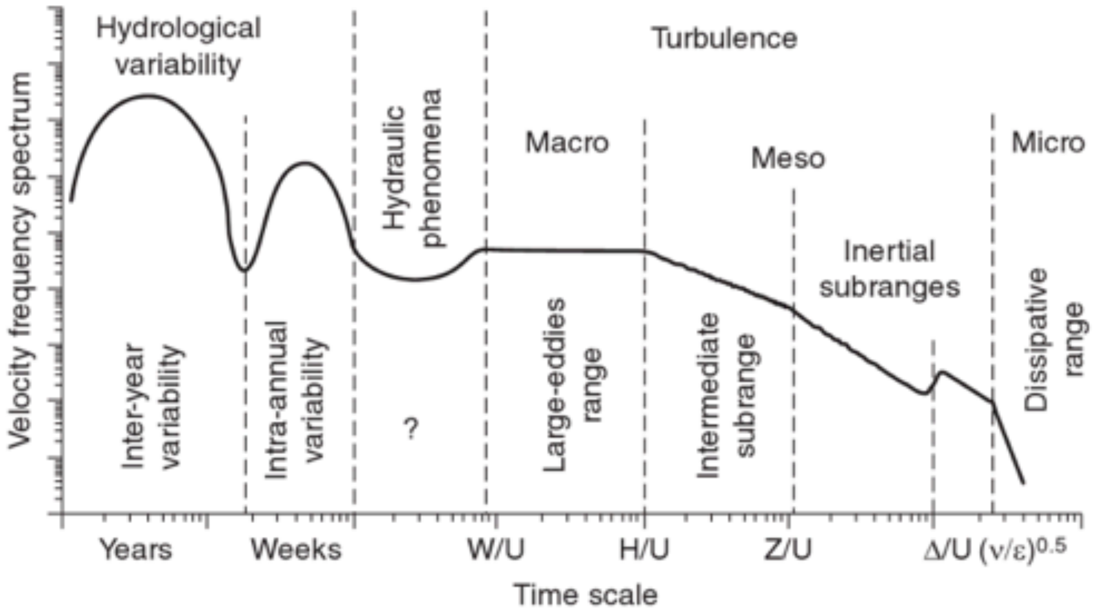


Figure 1.1 Velocity frequency spectrum of Nikora (2008). The spectrum is a conceptual model that shows the scale of variability in a river channel. It combines the scales of hydrological/climatic variability that drive flow variability in the channel and the turbulence spectum through a scale gap that corresponds to undefined hydraulic phenomena related to flow interactions with channel morphology, meanders and bars. The source of turbulent energy is the mean flow, which passes energy to turbulence via velocity shear and flow separation at the scale of the flow depth and roughness elements (bedforms, particle clasts, etc.). The macro scale corresponds to the largest eddies in the flow, which Nikora (2008) argues are clusters of bursts but could also be VLSM or long-wavelength pulsations of Marquis and Roy (this volume). The intermediate subrange corresponds to the scale of individual bursts, and the inertial subrange corresponds to regions where turbulent energy cascades from large eddies to small eddies without losing energy and exhibts the $-5/3$ slope typically exhibited by turbulence spectra. The dissipative micro-scale begins at the Kolmogorov microscale $(\nu/\varepsilon)^{0.5}$. W is the channel width, H is the flow depth, z is elevation above the boundary and Δ is the boundary roughness. Reprinted from Nikora, 2008, Copyright 2008, with permission from Elsevier.

Large range of temporal scales

160 JOURNAL OF METEOROLOGY VOLUME 14

POWER SPECTRUM OF HORIZONTAL WIND SPEED IN THE FREQUENCY RANGE FROM 0.0007 TO 900 CYCLES PER HOUR

By Isaac Van der Hoven
U. S. Weather Bureau[1]

(Manuscript received 11 October 1956)

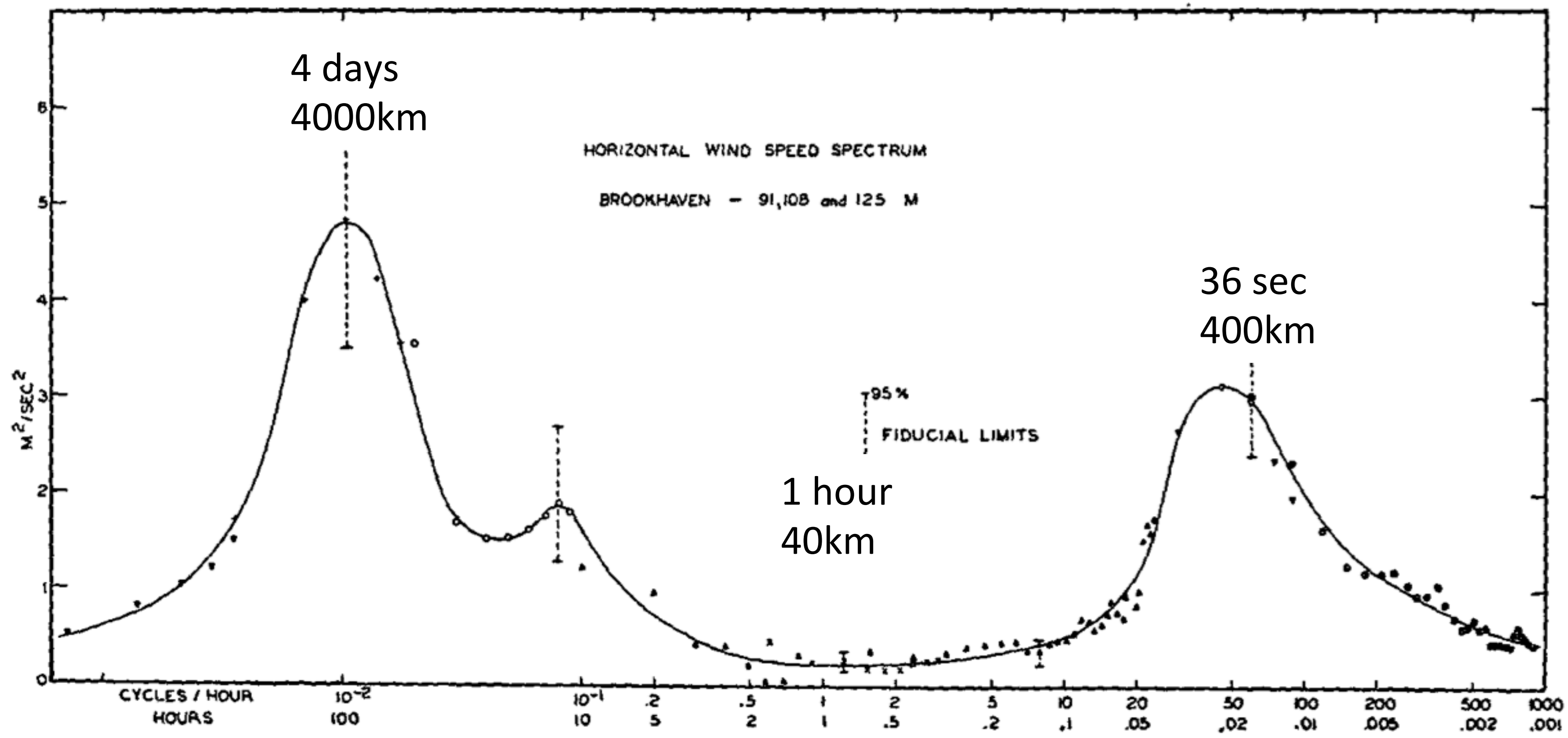
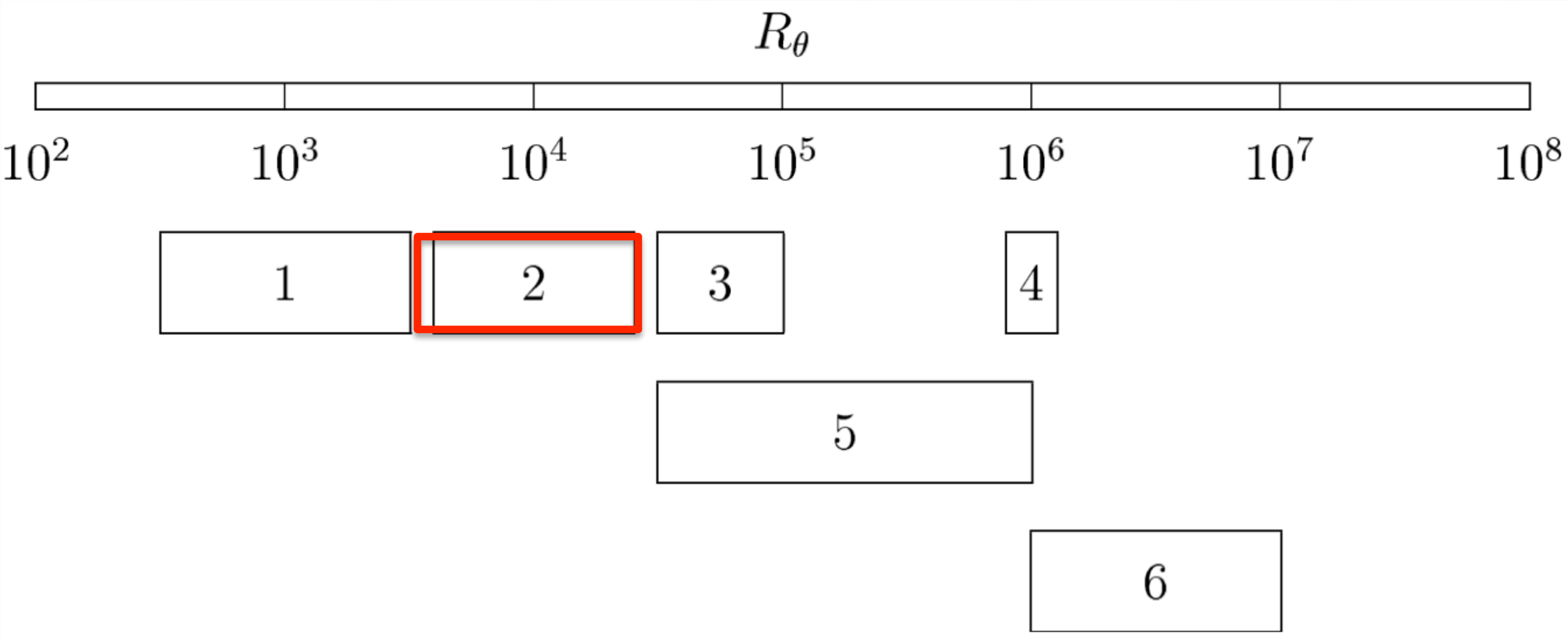


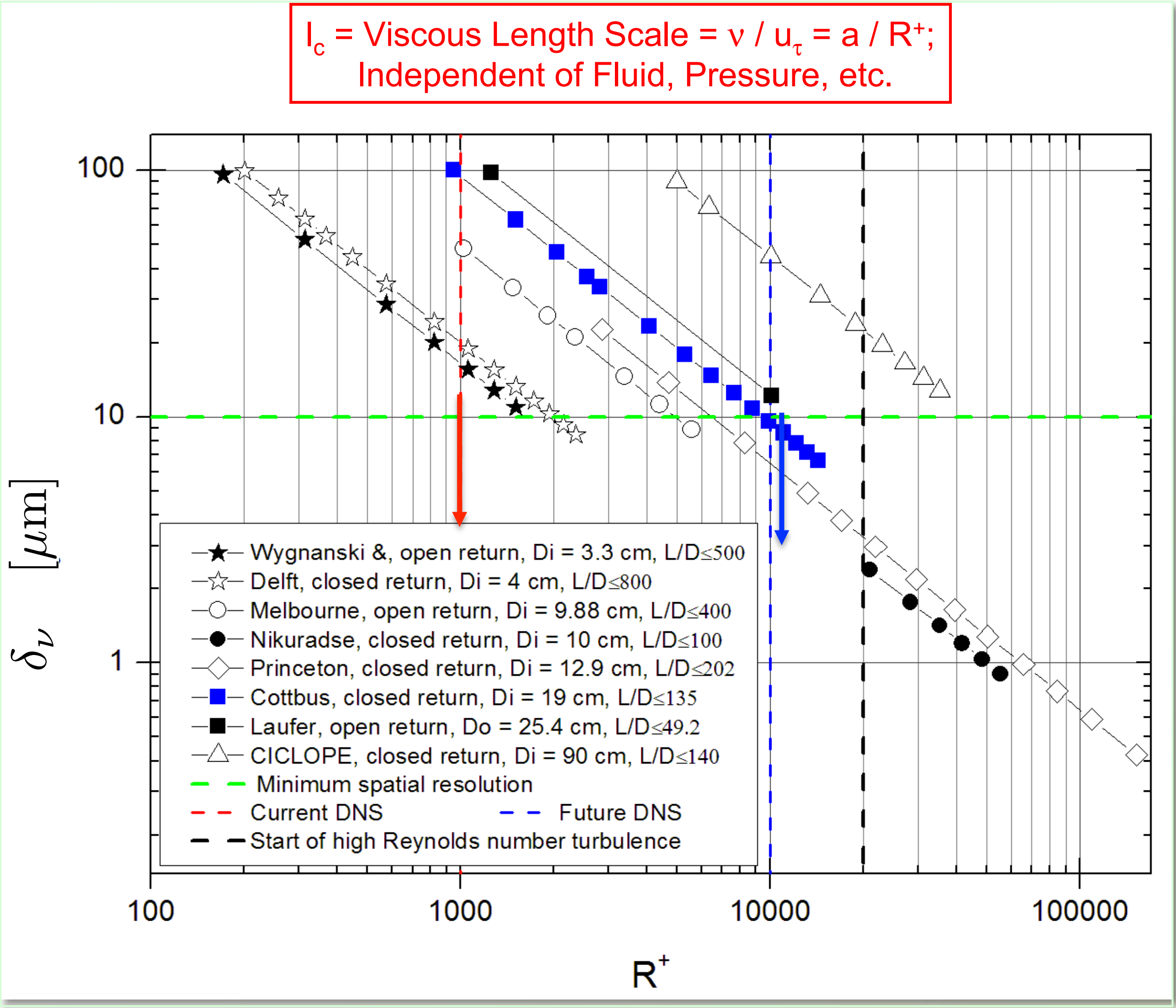
FIG. 1. Horizontal wind-speed spectrum at Brookhaven National Laboratory at about 100-m height. (See table 1 for date and time.)

Typical Reynolds number for wall flow

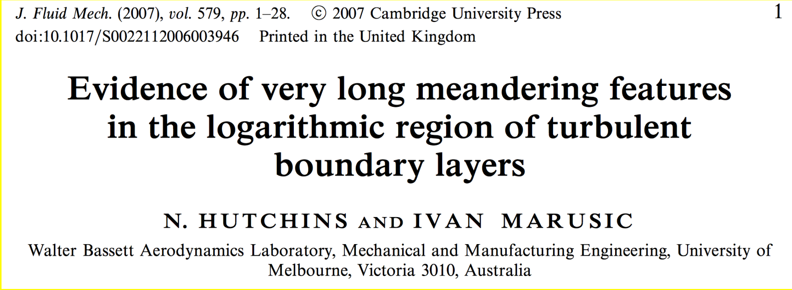


1 : Typical lab. or DNS
2 : LML
3 : National Transonic Facility
4 : Super pipe
5 : Flight/Ship
6 : Atmosphere

Facilities : how to go to High Re ?



From Sreenivasan 2007 Wallturb workshop, Viterbo

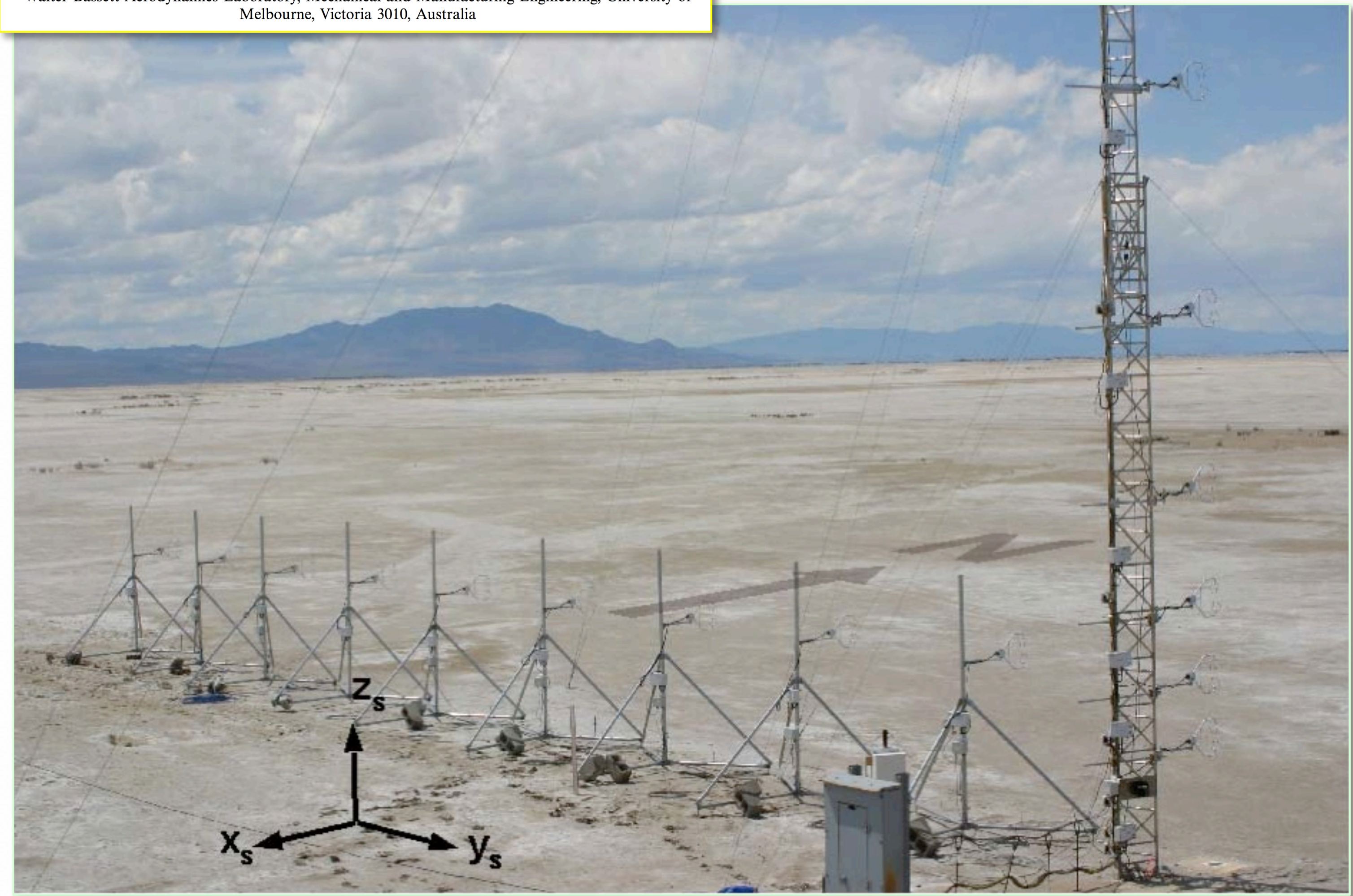

J. Fluid Mech. (2007), *vol.* 579, *pp.* 1–28. © 2007 Cambridge University Press 1
doi:10.1017/S0022112006003946 Printed in the United Kingdom

Evidence of very long meandering features in the logarithmic region of turbulent boundary layers

N. HUTCHINS AND IVAN MARUSIC

Walter Bassett Aerodynamics Laboratory, Mechanical and Manufacturing Engineering, University of Melbourne, Victoria 3010, Australia

Facilities : how to go to High Re ?



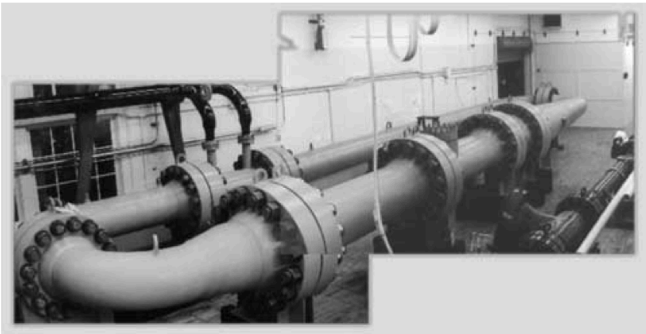
$$\delta \sim 60\mathrm{m}$$

$$Re_\tau \sim 0.66\ 10^6$$

SLTEST – Atmospheric surface layer – Utah salt flats

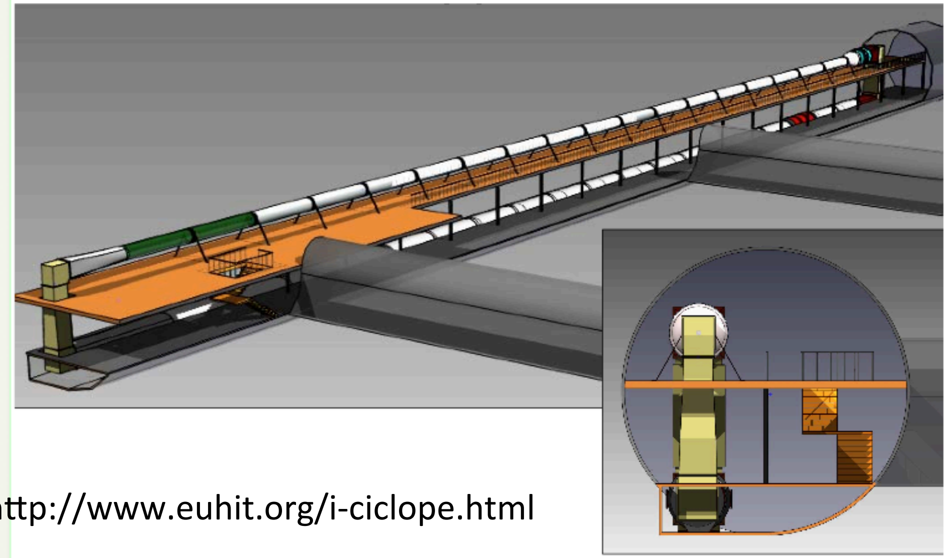
Superpipe in Princeton

- $R \approx 6.46$ cm
- $L/D = 200$
- High pressure (about 200 atm)
  $Re \approx 5000 - 38 \times 10^6$
- Small viscous length scales



CICLoPE Predappio, Forli (Italy)

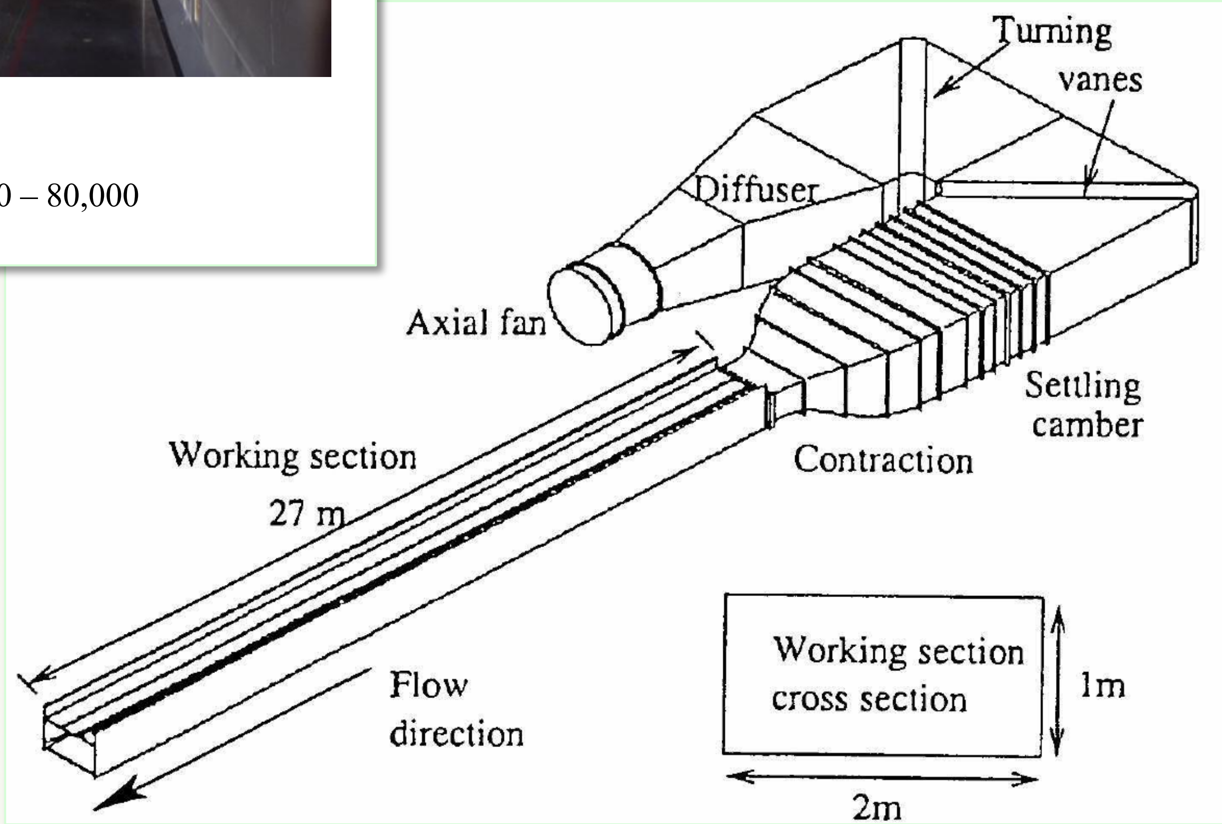
- Closed circuit
- Maximum velocity ≈ 50 m s^{-1}
- Atmospheric pressure
- Moveable test-section
- Diameter 75 cm
- Total length 130 m
- Possibility to create pressure gradients



http://www.euhit.org/i-ciclope.html

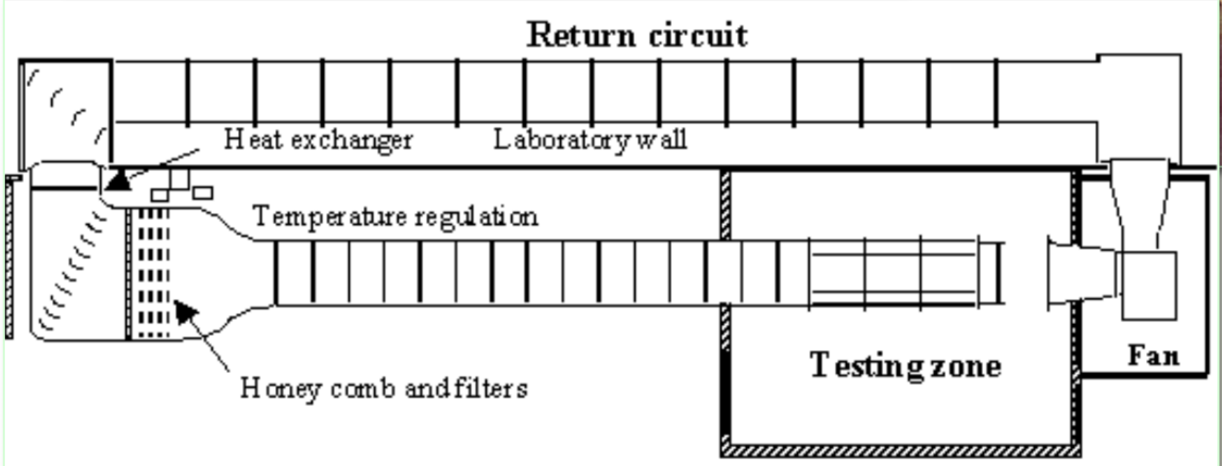
High Re wind tunnel University of Melbourne

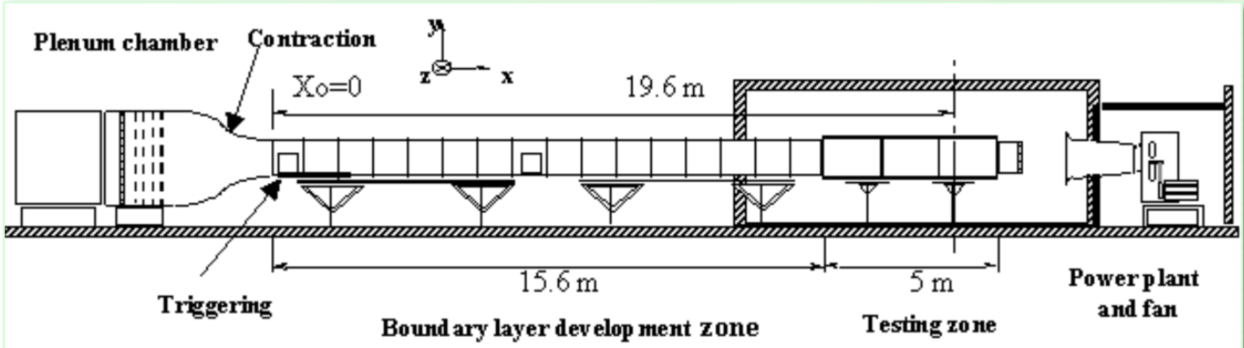
$Re_\theta = 60{,}000 - 80{,}000$

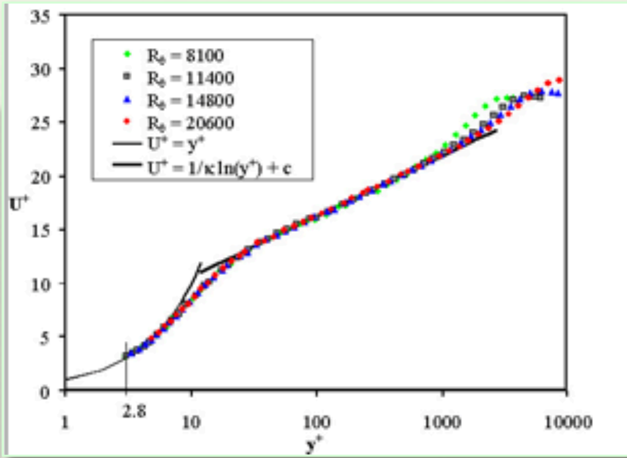


High Re Boundary Layer Wind Tunnel, Lille

U_e (m/s)	U_τ (m/s)	δ (m)	δ^+	R_θ	R_λ
3	0.110	0.345	2500	8100	300
5	0.185	0.323	4000	11500	400
7	0.254	0.304	5100	14800	460
10	0.350	0.302	7000	20600	570



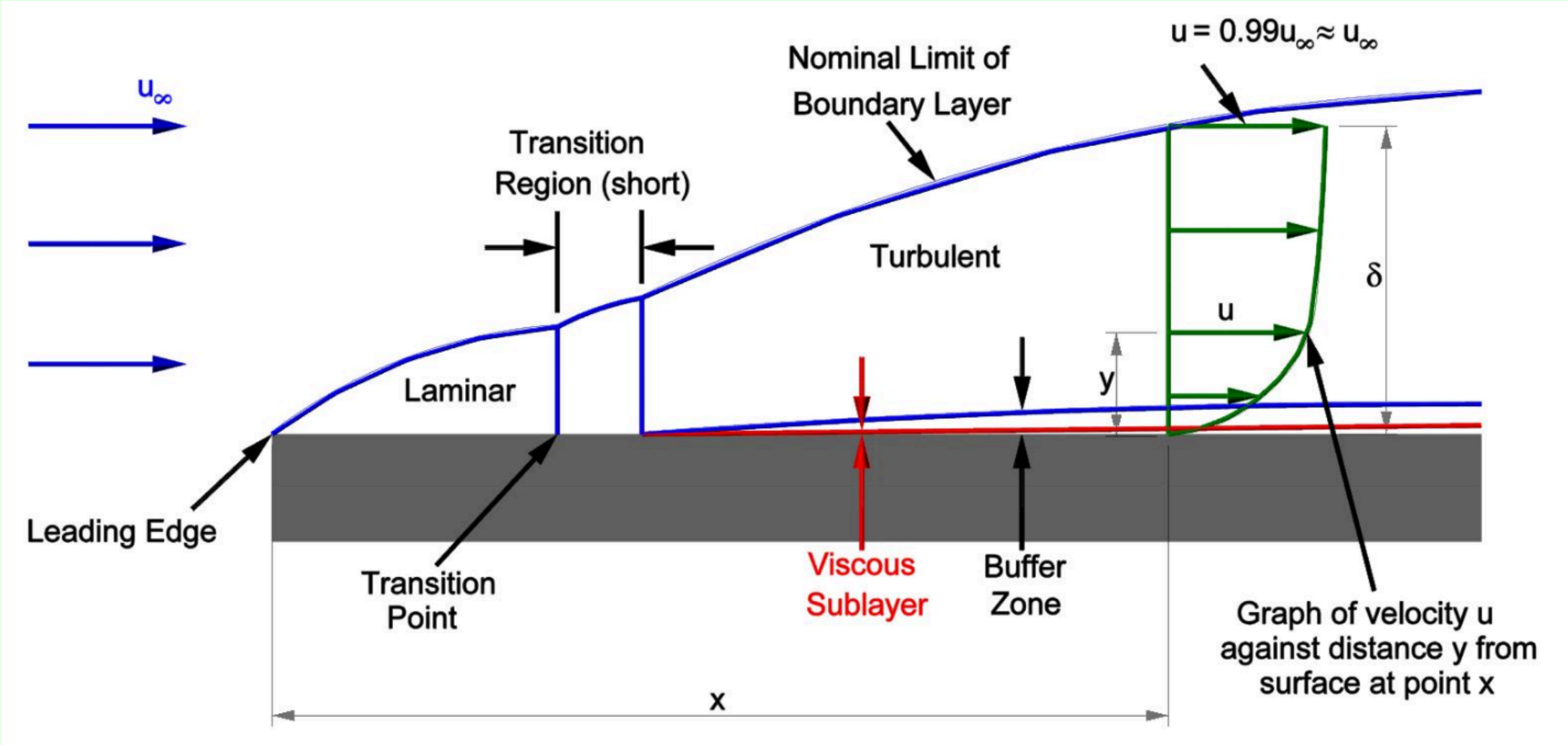


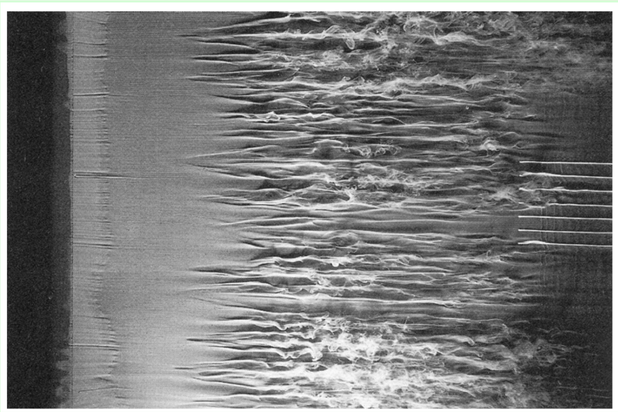


Reminders on Boundary Layers

- Zero pressure gradient
- Flat plate (no roughness)

Boundary layer over a flat plate: a global wiew

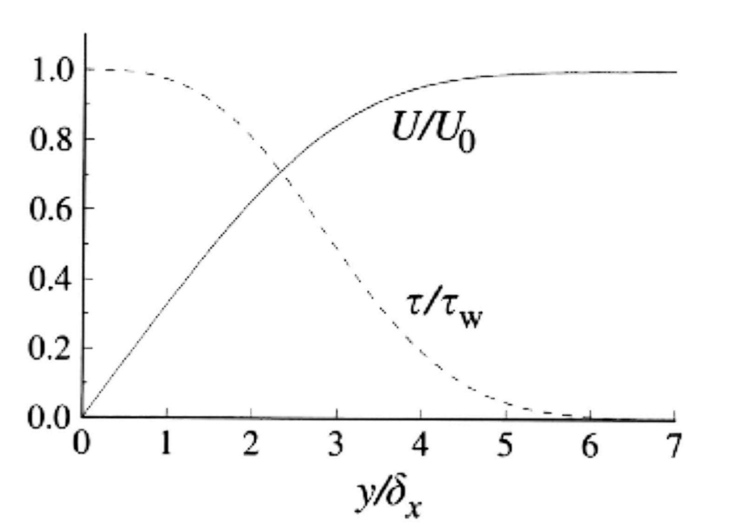




Dye sheet in water, Re 75,000
[Werlé, ONERA]

Boundary layer over a flat plate: a global wiew

Pope (2000)

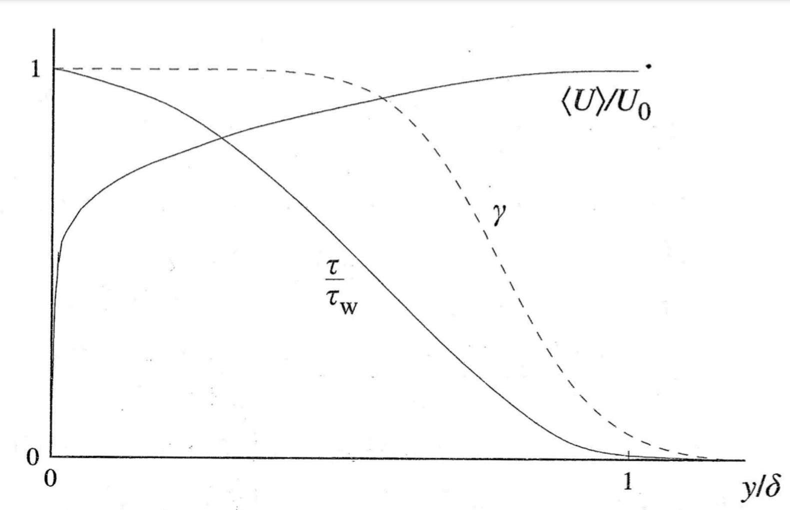


Normalized velocity and shear-stress profiles from the Blasius solution for the zero-pressure-gradient laminar boundary layer on a flat plate: y is normalized by $\delta_x \equiv x/\mathrm{Re}_x^{1/2} = (x\nu/U_0)^{1/2}$.

Laminar

- Only molecular viscosity

Pope (2000)



Profiles of the mean velocity, shear stress and intermittency factor in a zero-pressure-gradient turbulent boundary layer, $\mathrm{Re}_\theta = 8{,}000$. (From the experimental data of Klebanoff (1954).)

Turbulent

- Additional turbulent visosity
- Steeper gradients close to the wall
- Intermittent zone

Integral scale units

$$\delta^*(x) = \delta_1(x) = \int_0^\infty (1 - \frac{U(x,y)}{U_0(x)})\, dy$$

$$\theta(x) = \delta_2(x) = \int_0^\infty \frac{U(x,y)}{U_0(x)}(1 - \frac{U(x,y)}{U_0(x)})\, dy$$

$$H = \delta^*/\theta$$

Wall units $\delta_\nu = \nu/U_\tau$

$$U_\tau = \sqrt{\tau_w/\rho}\ ;\ U^+ = \frac{U}{U_\tau}\ ;\ y^+ = \frac{yU_\tau}{\nu}\ ;\ Re_\tau = \frac{U_\tau \delta}{\nu}$$

Laminar case

$$\tau_w = \rho\nu\left(\frac{\partial U}{\partial y}\right)_{y=0}$$

Turbulent case

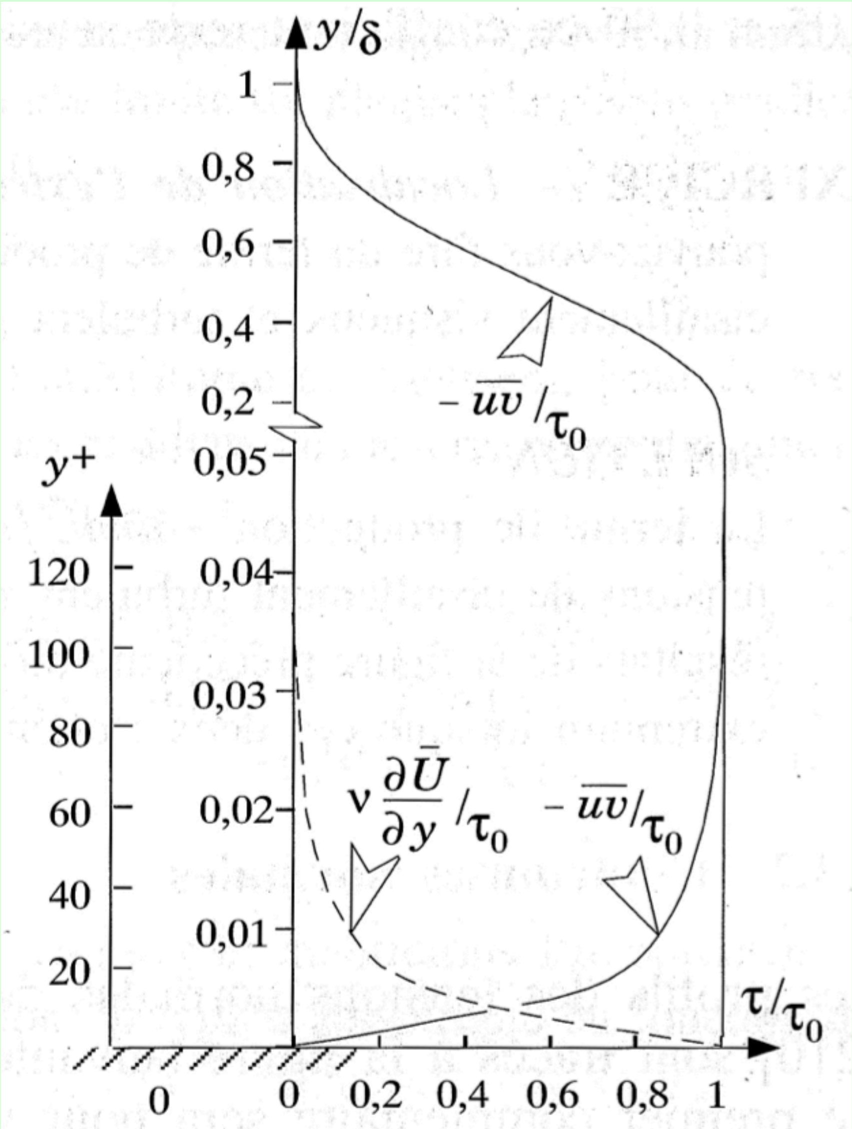
e.g.: Von Karman's Momentum Integral Equation

$$\frac{d\theta}{dx} = \frac{\tau_w}{\rho U_0^2} - \frac{\theta}{U_0}(H+2)\frac{dU_0}{dx}$$

$$\text{w.o. longitudinal gradient: } \tau_w = \rho U_0^2 \frac{d\theta}{dx}$$

Or other integral laws ... Coles etc

Very close to the wall the global shear stress is dominated by viscous effects

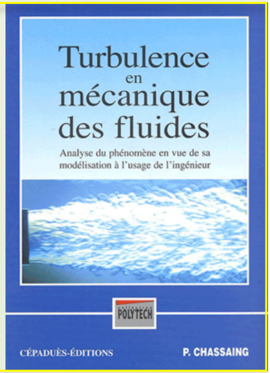


$$\tau_0 = \tau_{vis.} + \tau_{turb.} = \rho\nu\frac{\partial U}{\partial y} - \rho < u'v' >$$

Data from Klebanov (1954)

$$Re_\delta = 8.1\ 10^4\ ;\ \delta = 7.6\ \mathrm{cm}\ ;\ U_\infty = 15.2\ \mathrm{m/s}$$

[Chassaing 2000]



Annu. Rev. Fluid Mech. 2011. 43:353–75

High–Reynolds Number Wall Turbulence

Alexander J. Smits,[1] Beverley J. McKeon,[2] and Ivan Marusic[3]

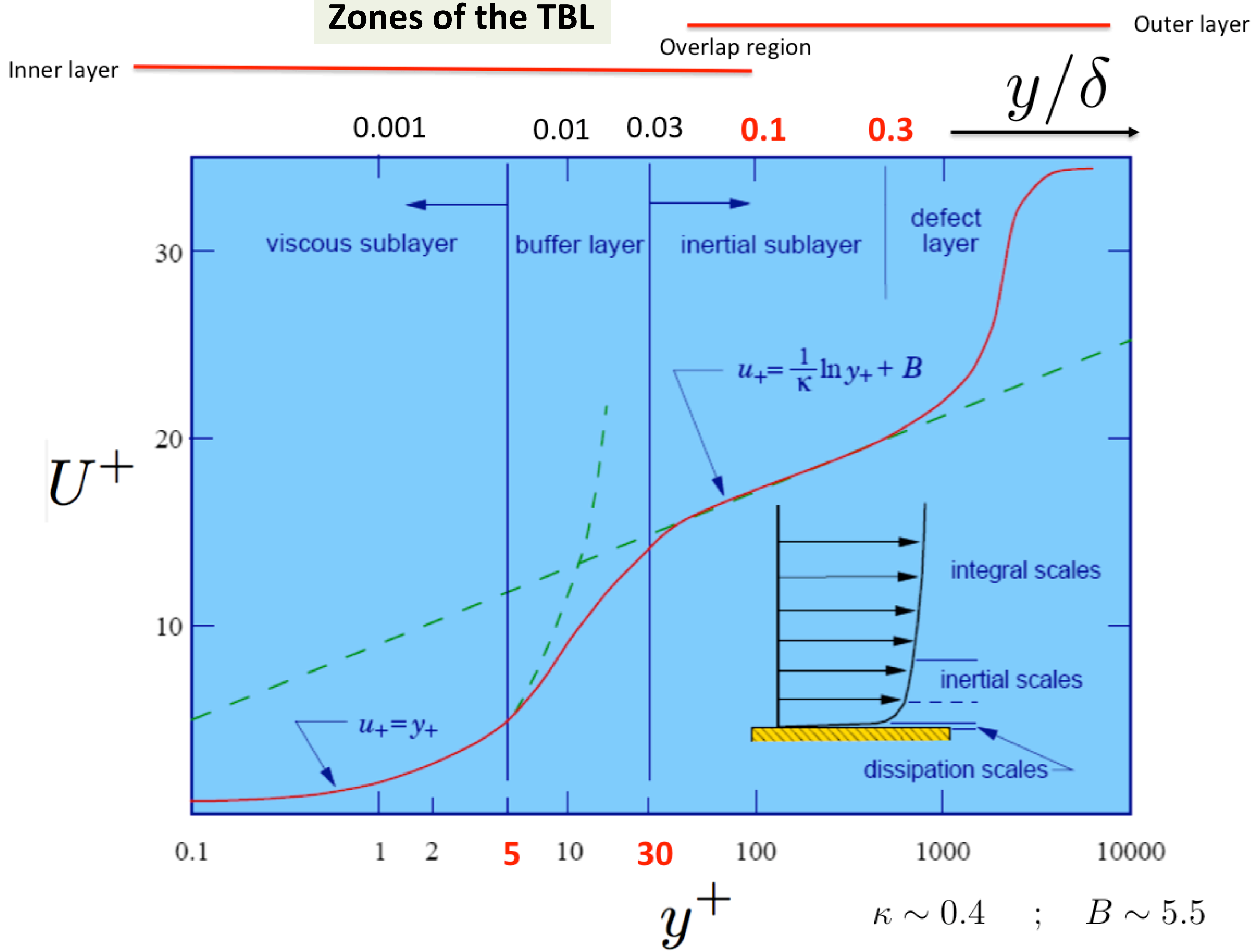
LAW OF THE WALL/LAW OF THE WAKE

In Coles's (1956) description, the velocity profile outside the viscous-dominated near-wall region is described as the sum of a logarithmic part and a wake component, so that the variation of the mean velocity U with distance from the wall y is described by

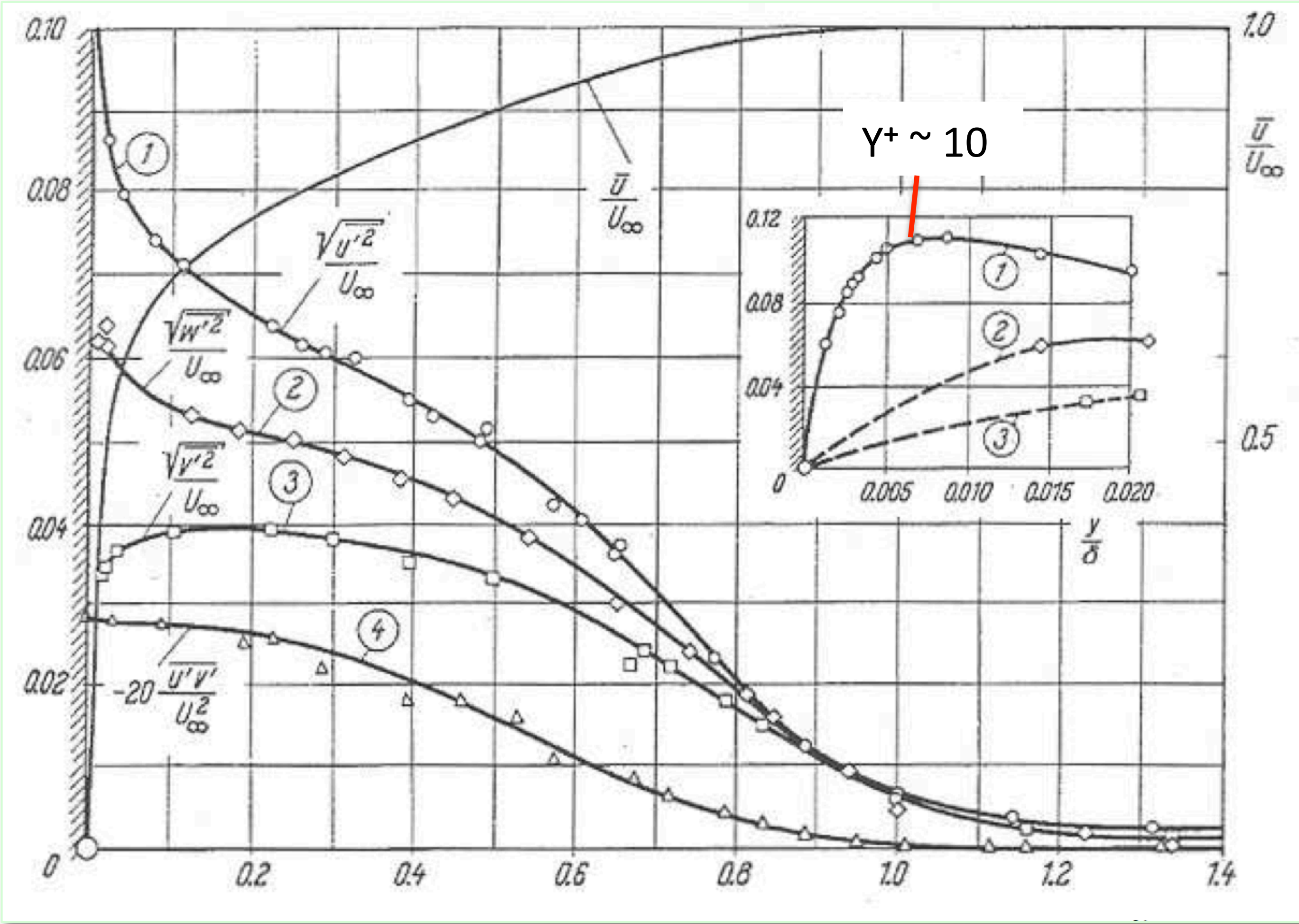
$$\frac{U}{u_\tau} = \frac{1}{\kappa} \ln \frac{y u_\tau}{\nu} + B + \frac{2\Pi}{\kappa} W\left(\frac{y}{\delta}\right),$$

where u_τ is the friction velocity, ν is the fluid kinematic viscosity, δ is the boundary-layer thickness, W is the wake function, and Π is the wake factor. Here, B and κ are constants, called the additive constant and von Kármán's constant, respectively.

Zones of the TBL

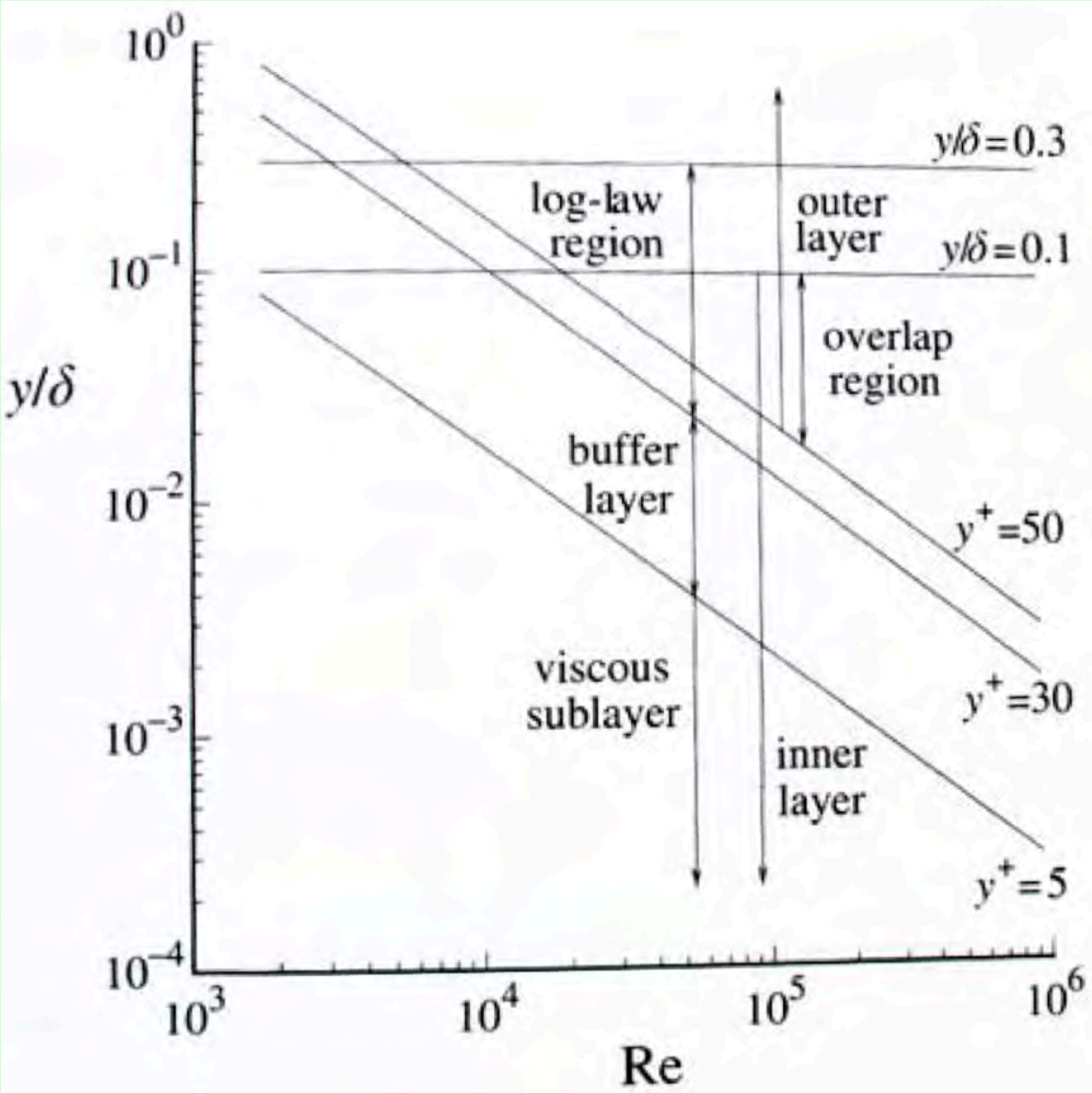


- Strong anisotropy
- longitudinal component dominant
- turbulence maximum in the buffer layer

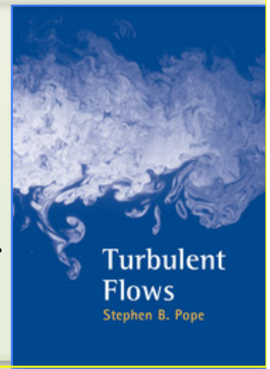


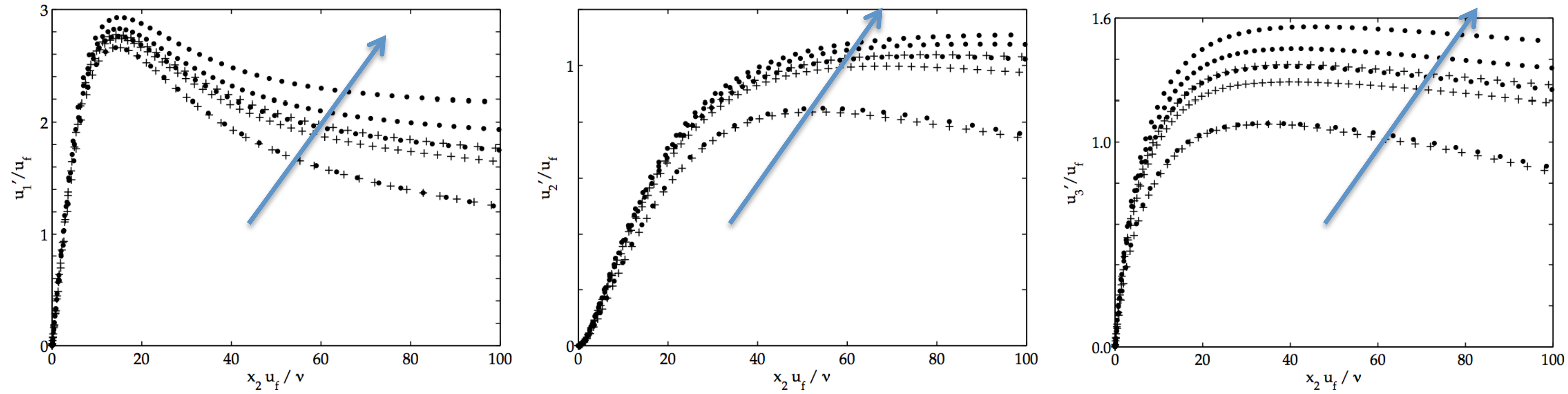
Klebanov (1955) *[H. Schlichting, Boundary-Layer Theory, sixth ed., MacGraw-Hill]*

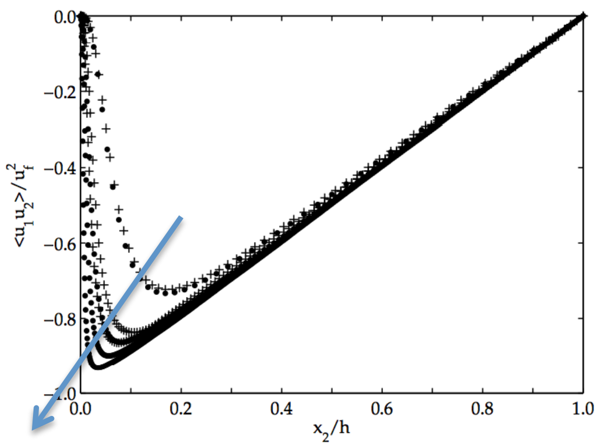
The relative size of zones is Re dependent



Pope 2000







Channel flow

Moser, Kim & Mansour (1999)

$+$ $Re^+ = 180$, $Re^+ = 395$, $Re^+ = 590$

Hoyas & Jiménez (2006)

$\bullet$ $Re^+ = 180$, $Re^+ = 550$, $Re^+ = 950$, $Re^+ = 2000$

TKE Production max @ $Y^+ \sim 12$

Peak of energy moves with Re

Let's go to the zoo

Recents review :

Annu. Rev. Fluid Mech. 2011. 43:353–75

High–Reynolds Number Wall Turbulence

Alexander J. Smits,[1] Beverley J. McKeon,[2] and Ivan Marusic[3]

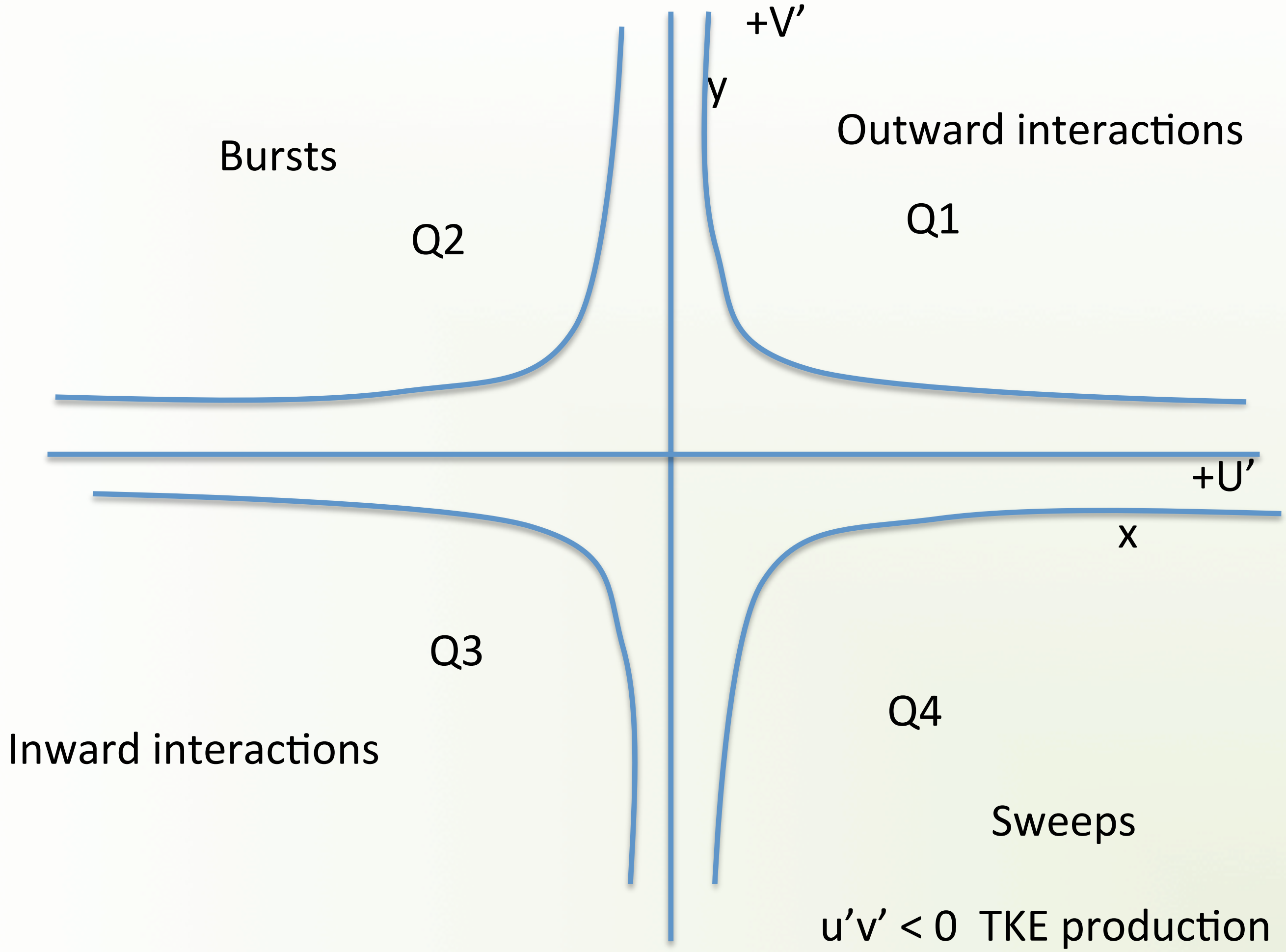
PHYSICS OF FLUIDS **22**, 065103 (2010)

Wall-bounded turbulent flows at high Reynolds numbers: Recent advances and key issues

I. Marusic,[1] B. J. McKeon,[2] P. A. Monkewitz,[3] H. M. Nagib,[4,a)] A. J. Smits,[5] and K. R. Sreenivasan[6]

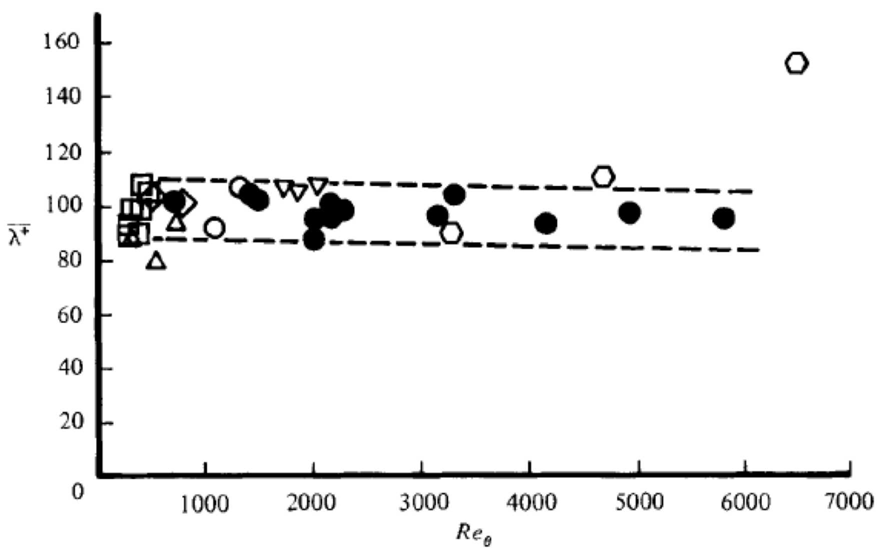
4 types of organisation

- Inner streaks associated with the near-wall cycle with a spanwise scale of O(100+)
- hearpin, horshoes from wall region into overlap region
- LSMs (Large Scale Motions) of scale O(δ) packets of hairpins
- VLSMs (Adrian and co- workers) or “superstructures” (Marusic and coworkers) with streamwise length scales of O(10 δ)


+V'
y
Outward interactions
Q1
Bursts
Q2
+U'
x
Q3
Inward interactions
Q4
Sweeps
u'v' < 0 TKE production

4 QUADRANTS

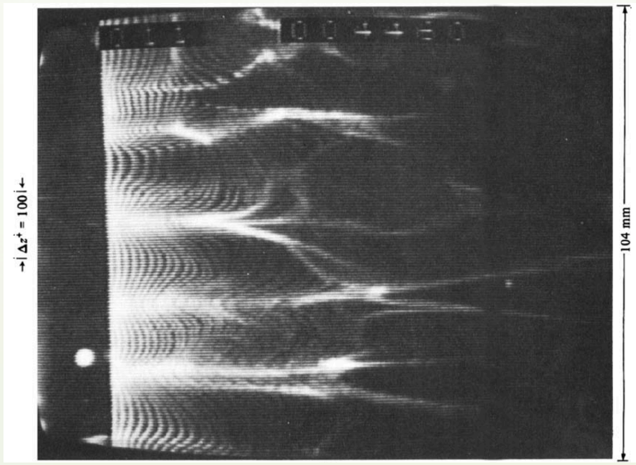
- Inner streaks associated with the near-wall cycle with a spanwise scale of O(100+)



J. Fluid Mech. (1983), *vol.* 129, *pp.* 27–54 27
Printed in Great Britain

The characteristics of low-speed streaks in the near-wall region of a turbulent boundary layer

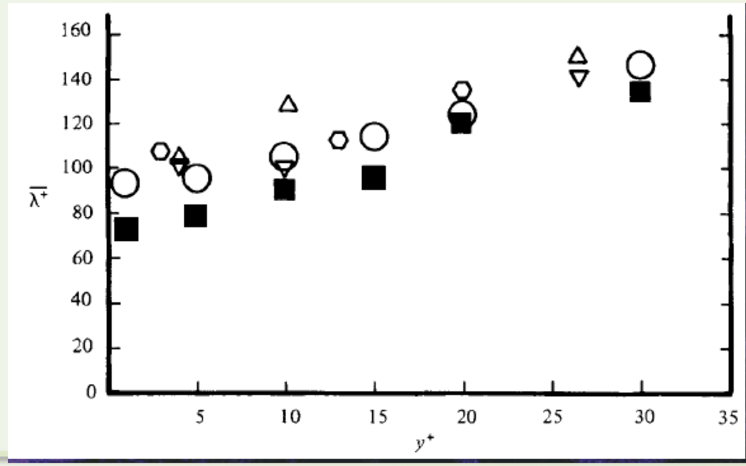
By C. R. SMITH AND S. P. METZLER



Typical sizes (in wall unit)

Streamwise	>1000	O(15-20δ)
Spanwise	100	
Wall normal	10	

Spanwise scale increases with y



Streak bursting cycle

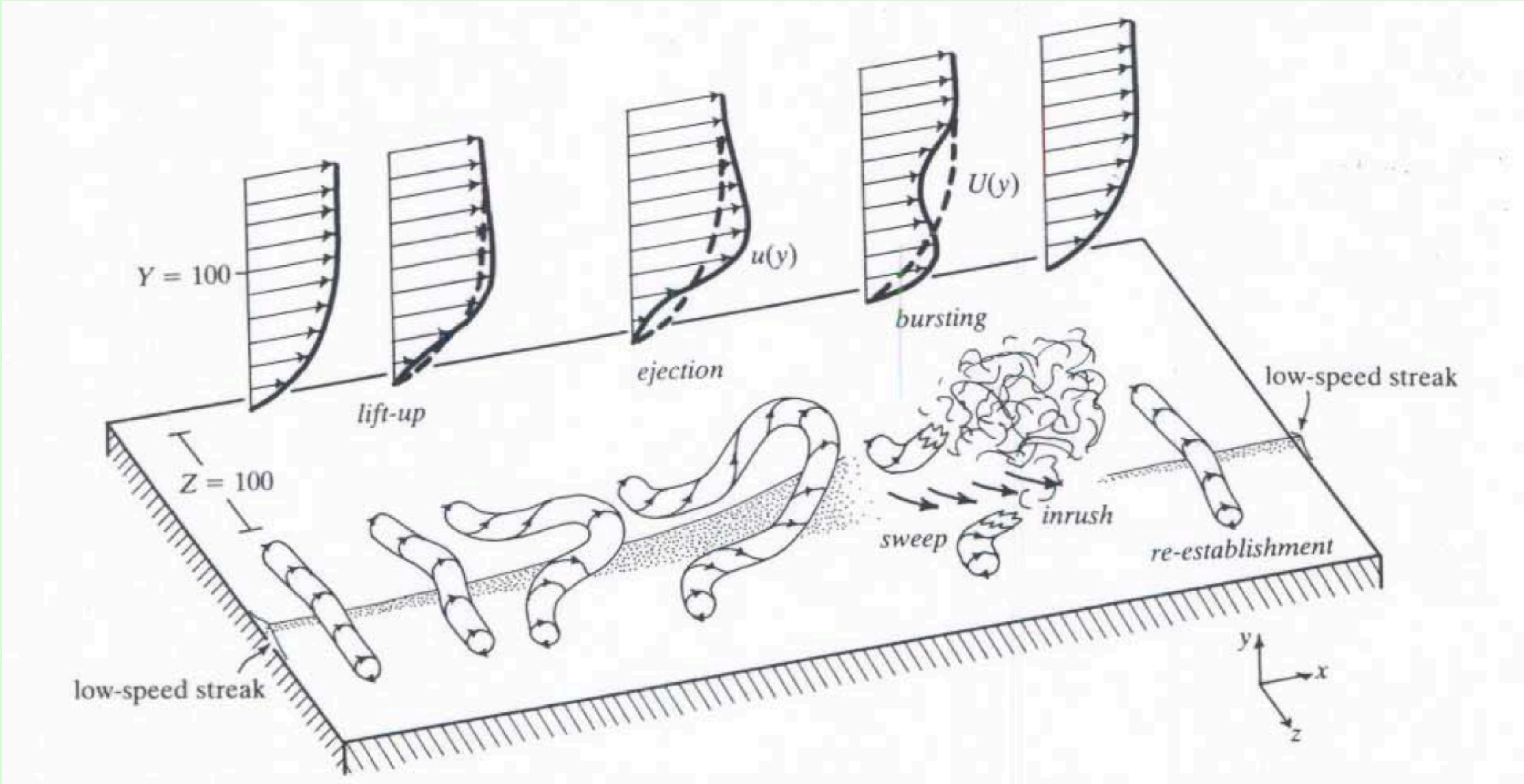
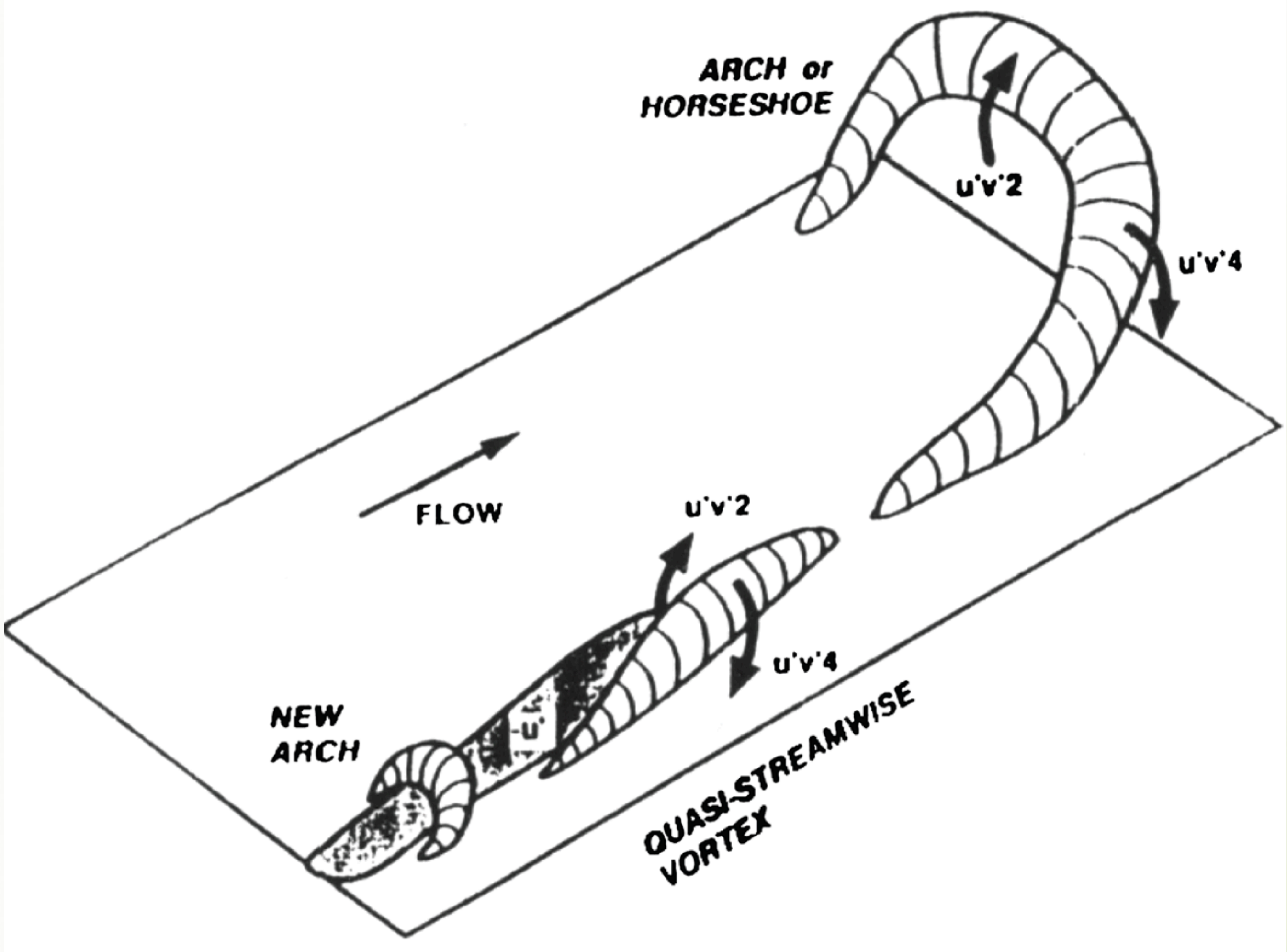


Figure 6.15 Model of the streak-bursting cycle. The developing hairpin vortex is shown as it might be seen by an observer travelling with it. The velocity profiles on the left are plotted with respect to the ground.

Allen 1985

Robinson 1991



- hearpin, horshoes from wall region into overlap region

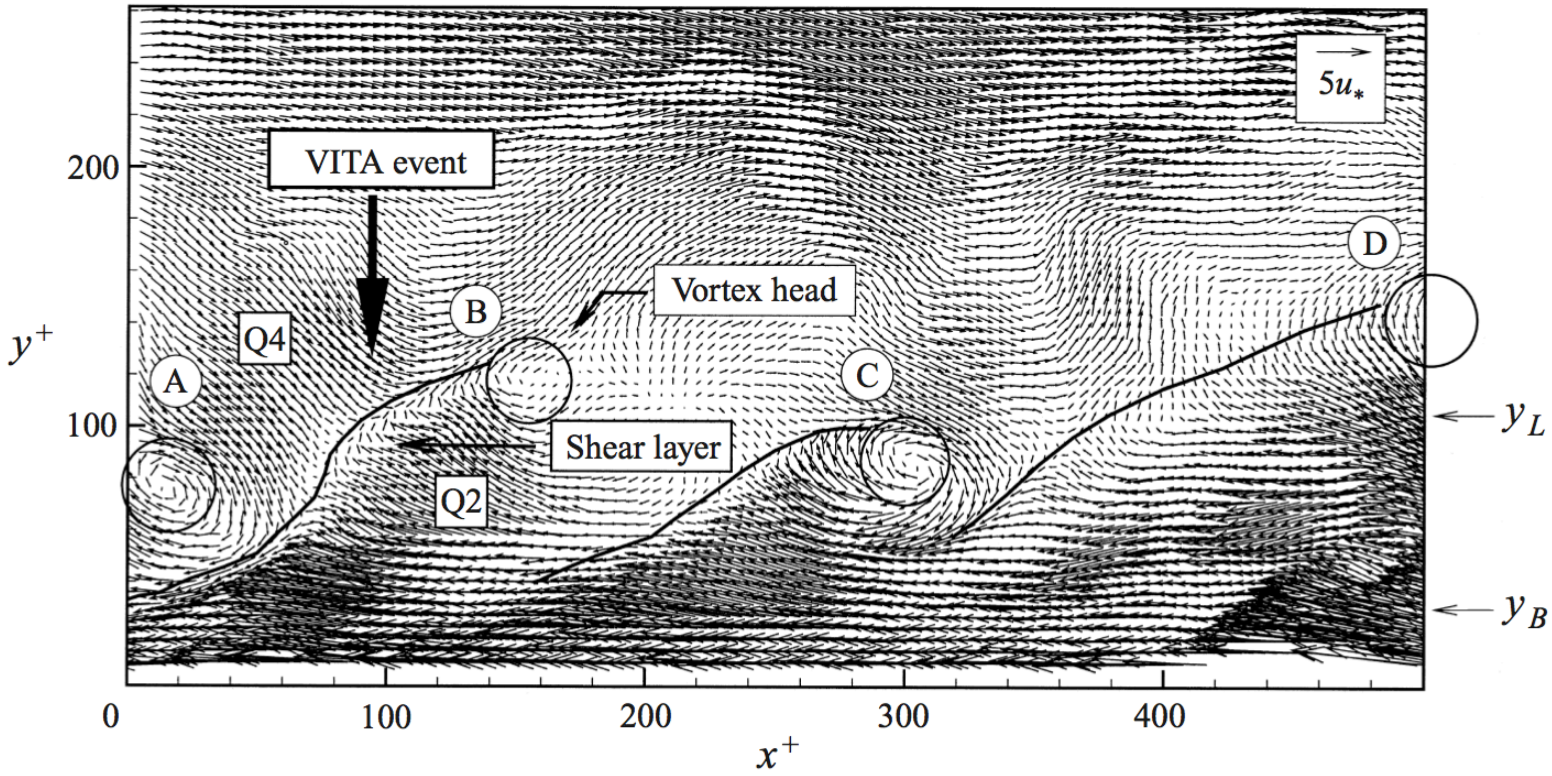
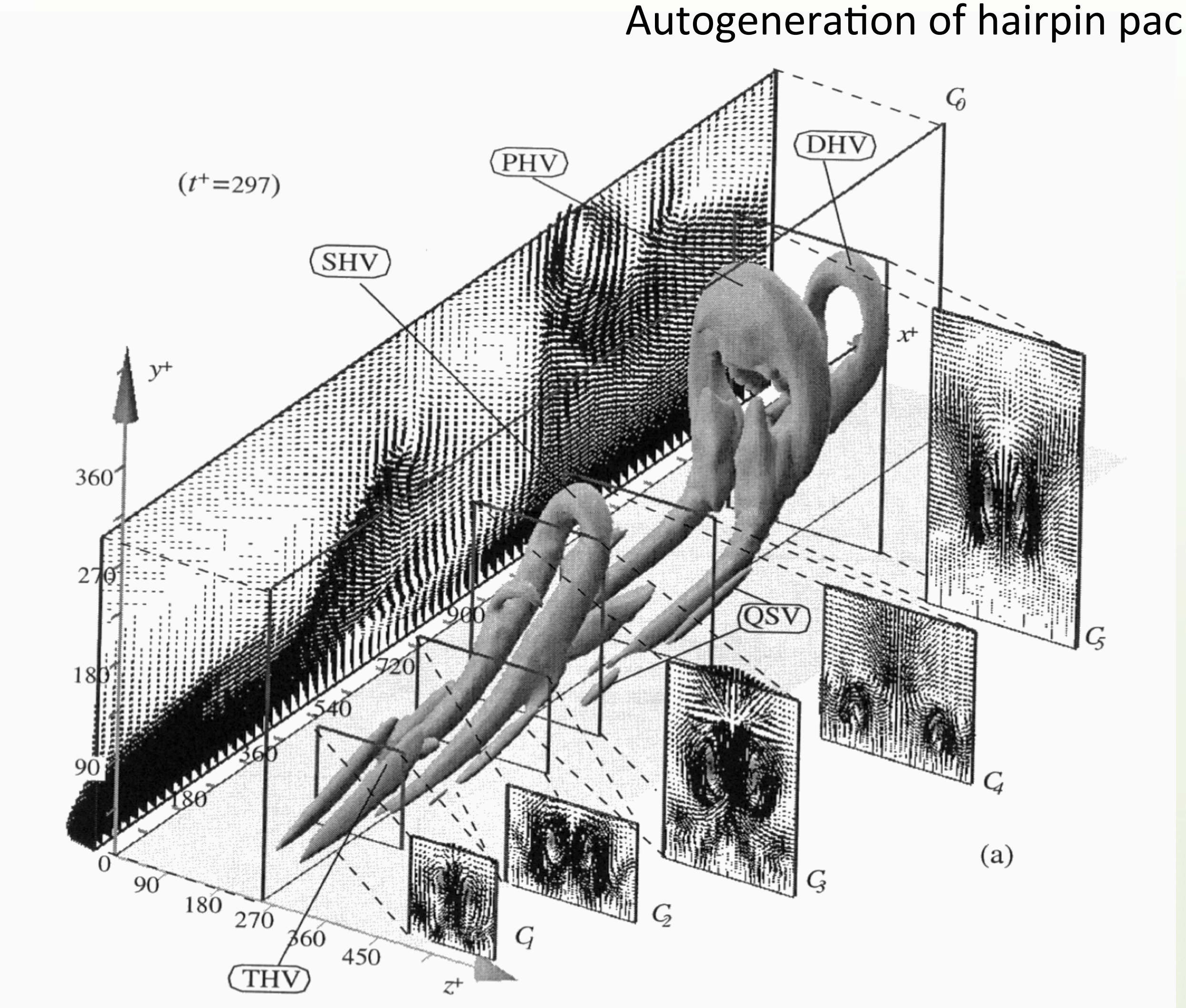


FIGURE 11. Near-wall realization at $Re_\theta = 930$ showing four hairpin vortex signatures aligned in the streamwise direction. Instantaneous velocity vectors are viewed in a frame-of-reference moving at $U_c = 0.8U_\infty$ and scaled with inner variables. Vortex heads and inclined shear layers are indicated schematically, along with the elements triggering a VITA event.

Adrian, Mehnardt, Tomkins 2000

CHANNEL FLOW

Autogeneration of hairpin packets

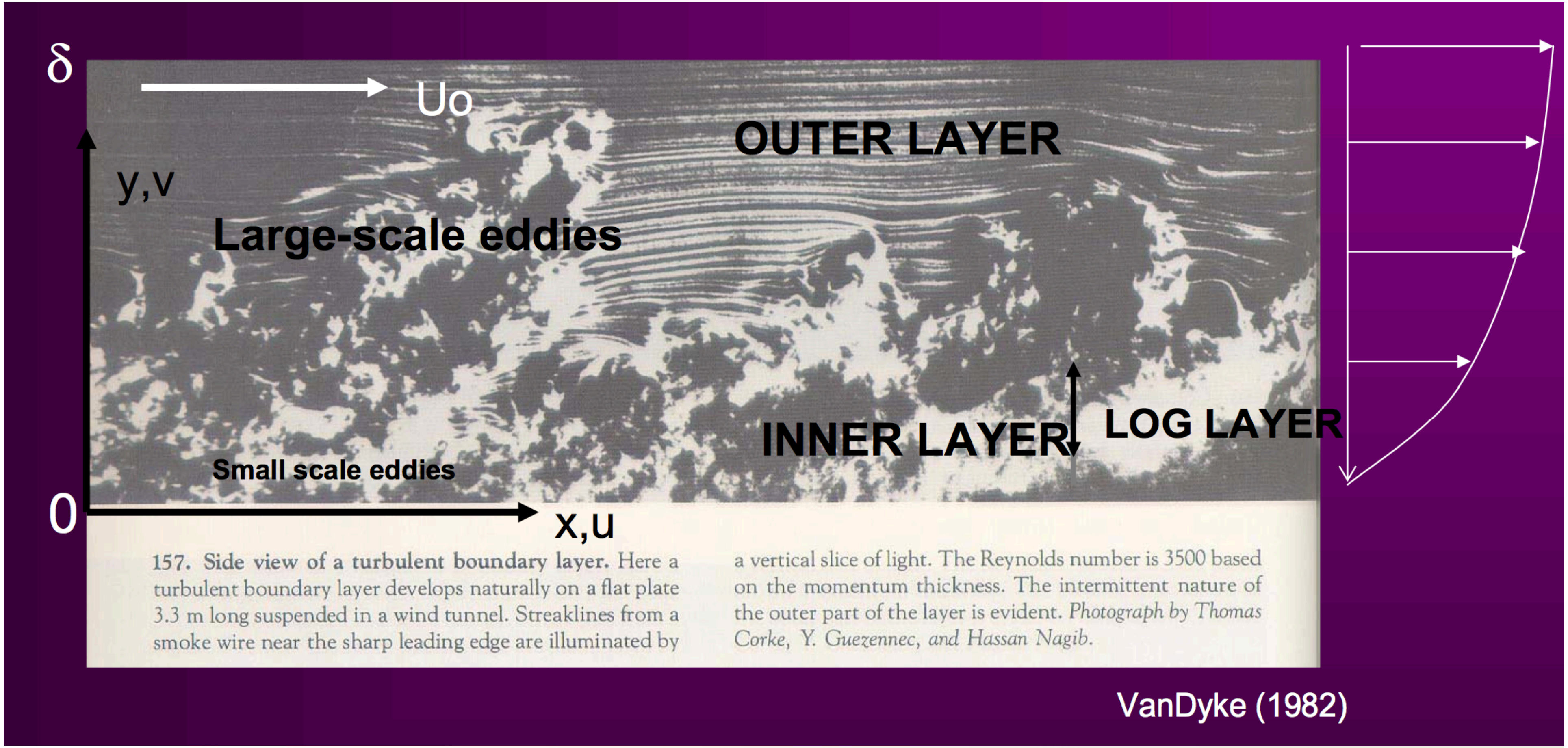


Low reynolds

Zou et al 1995

Reτ=300

δ-scale motions

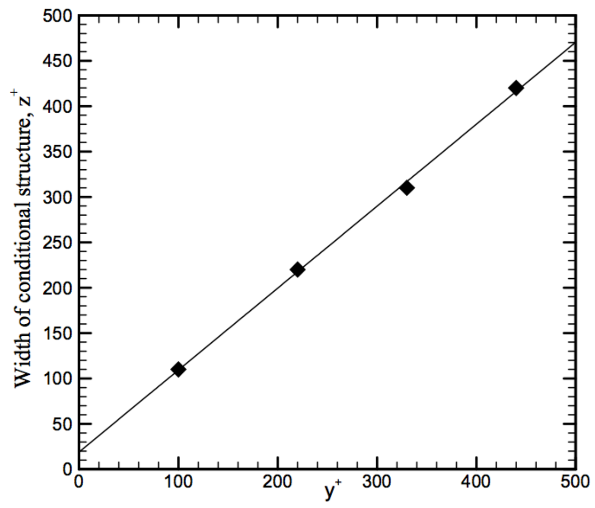


From Adrian AIAA meeting 2007

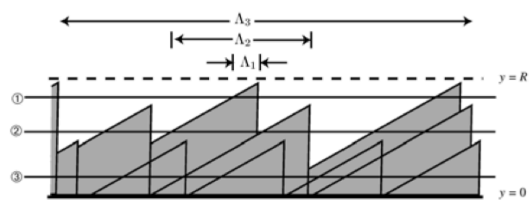
Adrian 2005

Scale Growth

- Spanwise size of conditional eddy grows linearly through the log layer- implies a hierarchy of increasingly larger scales similarity of packet angles Implies self-similar growth. L~y
- Mechanism 1: continuous growth of hairpins in an aging packet
- Mechanism 2: discontinuous growth by hairpin merger

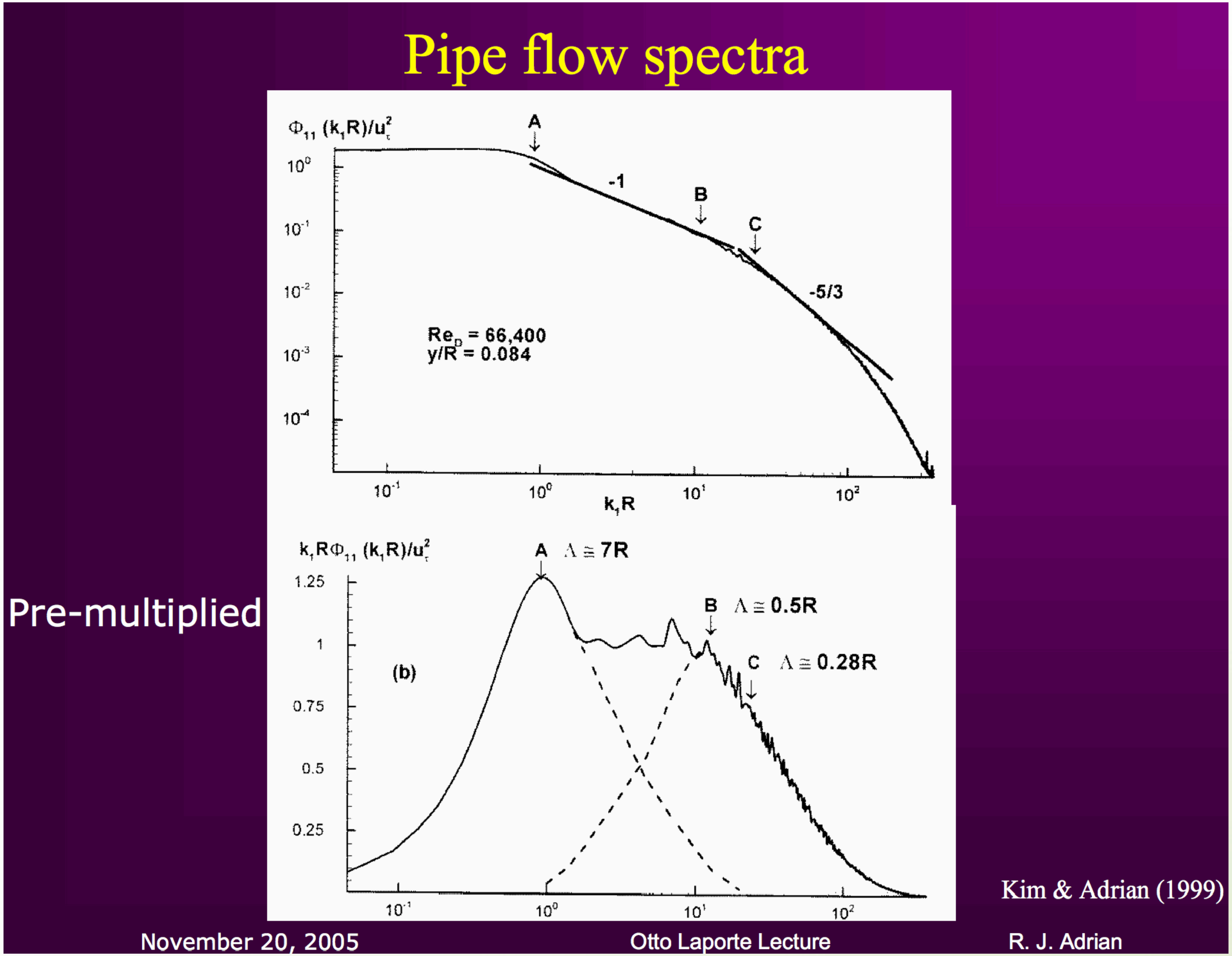


- δ-scale motions- 'large scale motions' L~ δ ('Bulges' in BL's)
- Super δ-scale motions- 'very large-scale motions', L>> δ



Simplified hairpin-vortex-packet model used to describe the distribution of streamwise kinetic energy among scales. Mean flow is from left-to-right. Hairpin vortex packets of differing scales are indicated as shaded regions.

Evidence of VLSM: pipe flow spectra



Hutchins Marusic jfm 2007

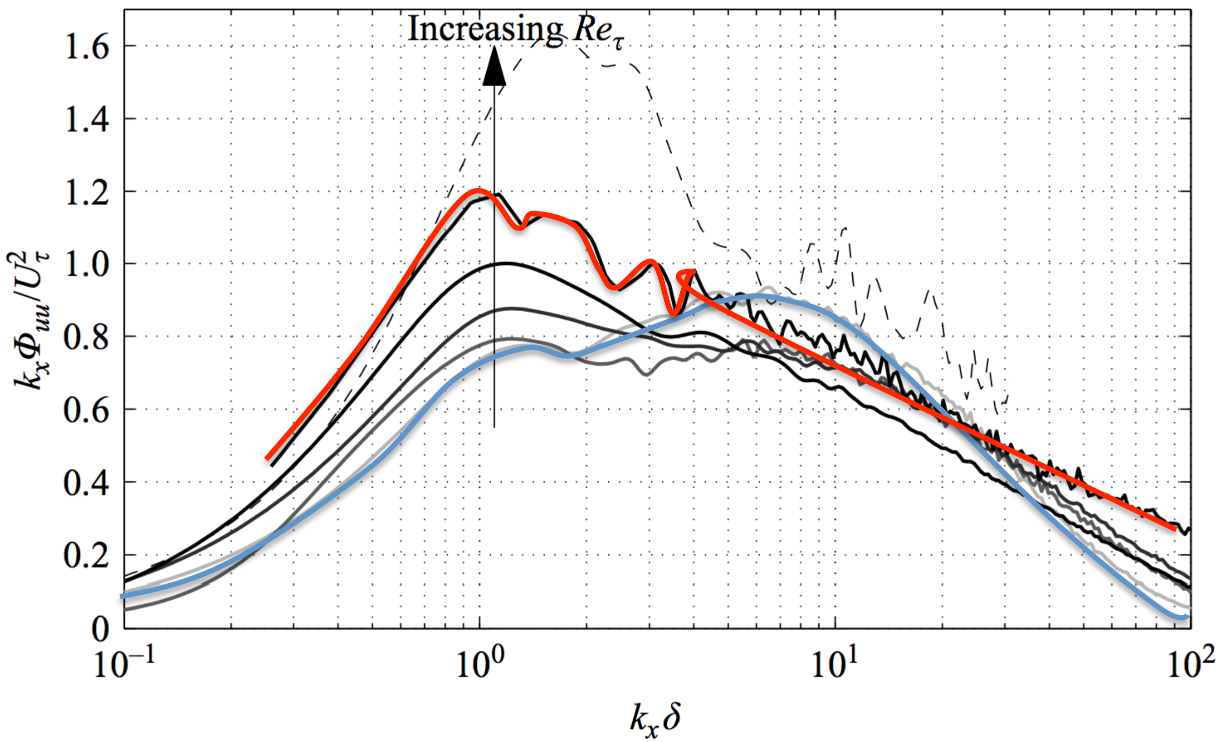


FIGURE 9. Pre-multiplied energy spectra $k_x\Phi_{uu}/U_\tau^2$ at $z/\delta = 0.06$ for laboratory hot-wire measurements. Line shading indicates Reynolds number. From lightest to darkest $Re_\tau = 1010$, 1910, 2630, 4110 and 7300. Dashed line shows sonic anemometer data from SLTEST (Utah 2005) at $Re_\tau \approx 6.6 \times 10^5$, $z/\delta = 0.06$.

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High–Reynolds Number Wall Turbulence

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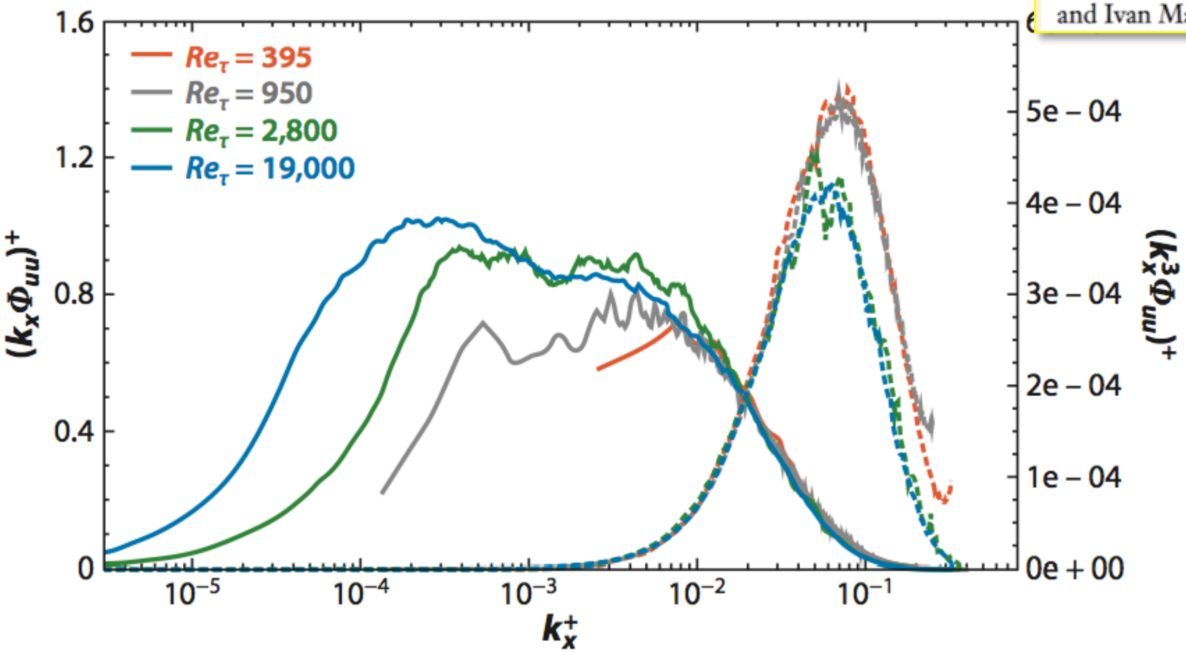

Figure 2

Streamwise u spectra at $y^+ \approx 100$ from direct numerical simulations (DNS) of channel flow at $Re_\tau = 395$ (Moser et al. 1999) and 950 (del Álamo et al. 2004) and turbulent boundary layer experiments at $Re_\tau = 2{,}800$ and 19,000 (Mathis et al. 2009a). For all cases $\eta^+ \approx 2.8$. Here, the area under $k_x\phi_{uu}$ is $\overline{u^2}$, and the area under $k_x^3\phi_{uu}$ is proportional to an estimate of ε, the turbulent dissipation rate. The differences between the DNS and experimental $k_x^3\phi_{uu}$ curves likely result from the limited spatial resolution of the experimental data, as the expectation is that this part of the spectrum is independent of Reynolds number.

TKE production vs Reynolds Number

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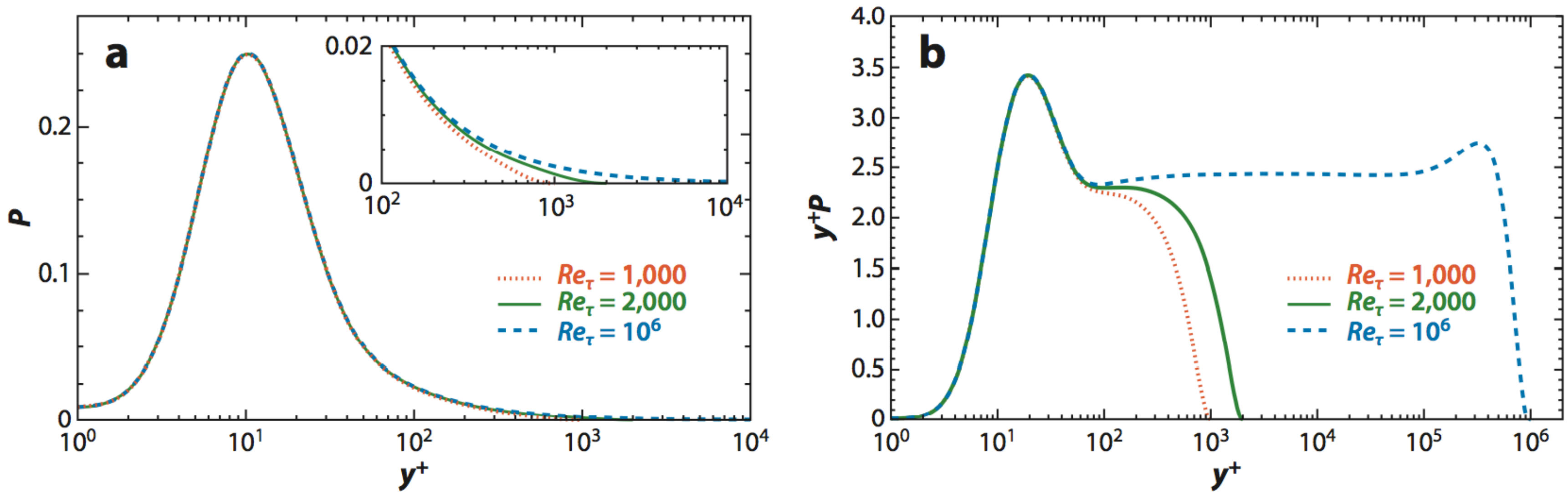
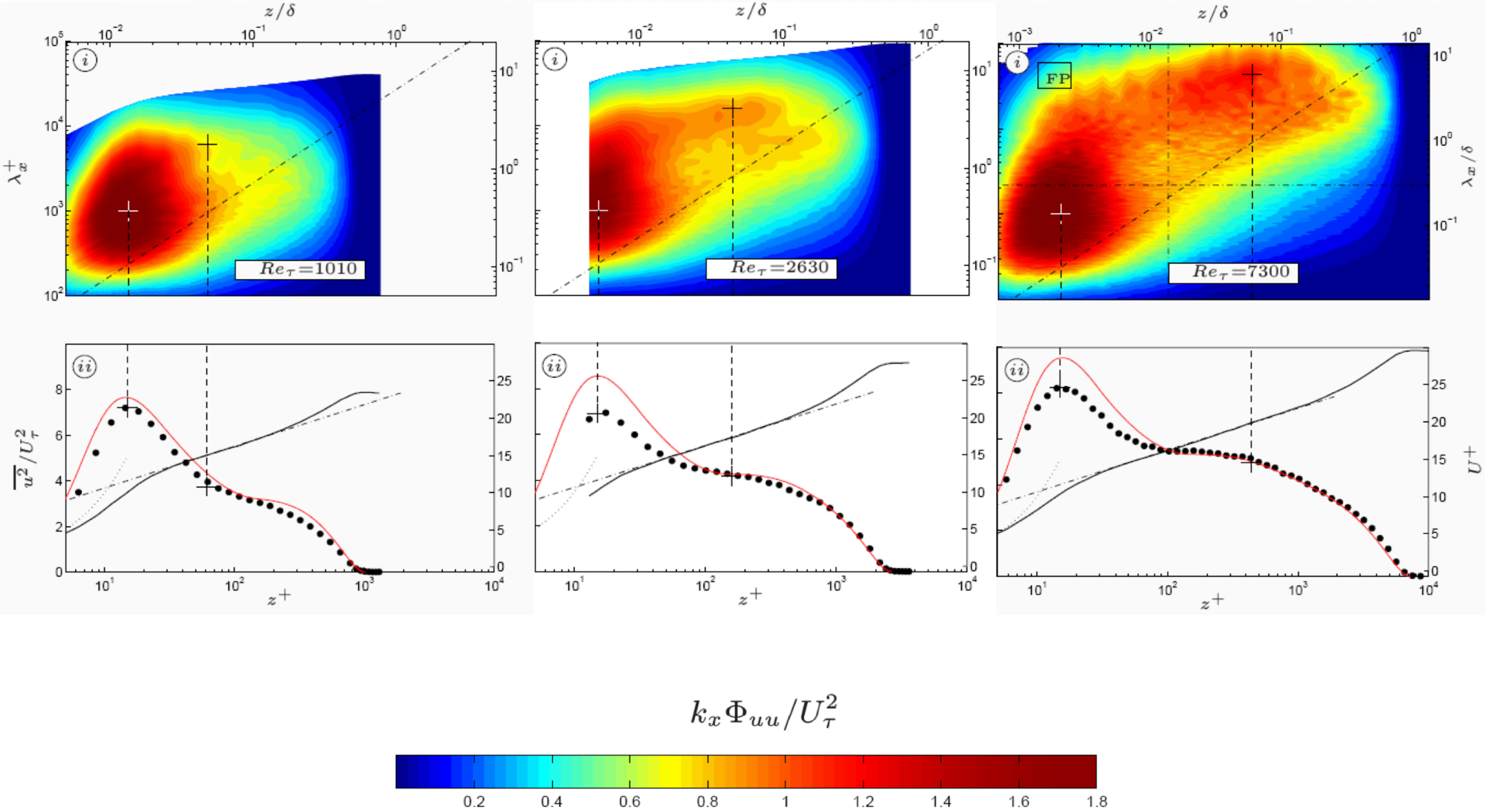


Figure 1

Turbulence kinetic energy production for a range of Reynolds numbers: (*a*) semi-logarithmic representation and (*b*) premultiplied representation (where equal areas represent equal contributions to the total production). The insert shows an expanded view of outer region. Here $P = -\overline{uv}^+ dU^+/dy^+$ is estimated using the law of wall-wake formulation for mean velocity for zero–pressure gradient boundary layers and the corresponding Reynolds shear stress profile as given by Perry et al. (2002). Figure taken from Marusic et al. (2010a). Reprinted with permission from Elsevier.



z/δ
λ_x^+
λ_x/δ
Re_τ=1010
Re_τ=2630
Re_τ=7300
FP
$\overline{u^2}/U_\tau^2$
U^+
z^+
$k_x\Phi_{uu}/U_\tau^2$

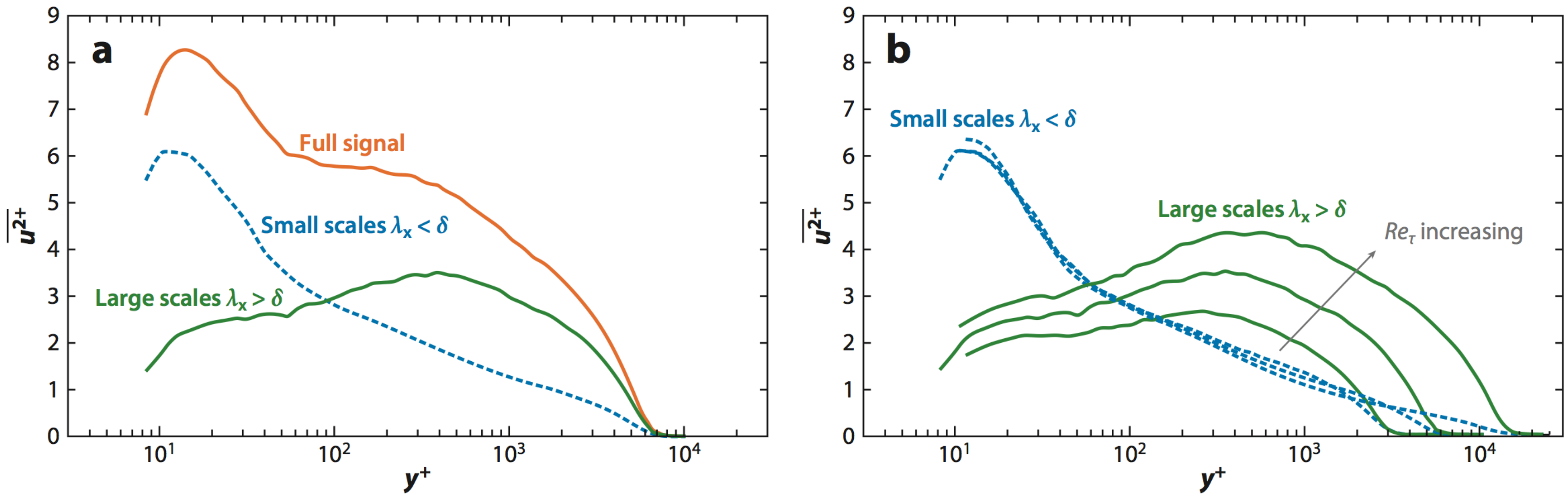


Figure 7

Scale decomposition of the streamwise turbulence intensity profile $\overline{u^2}/u_\tau^2$: (*a*) for $Re_\tau = 7{,}300$, together with the total (summed) contribution, and (*b*) for $Re_\tau = 3{,}900$, 7,300, and 19,000. Figure taken from Marusic et al. (2010a). Reprinted with permission from Elsevier.

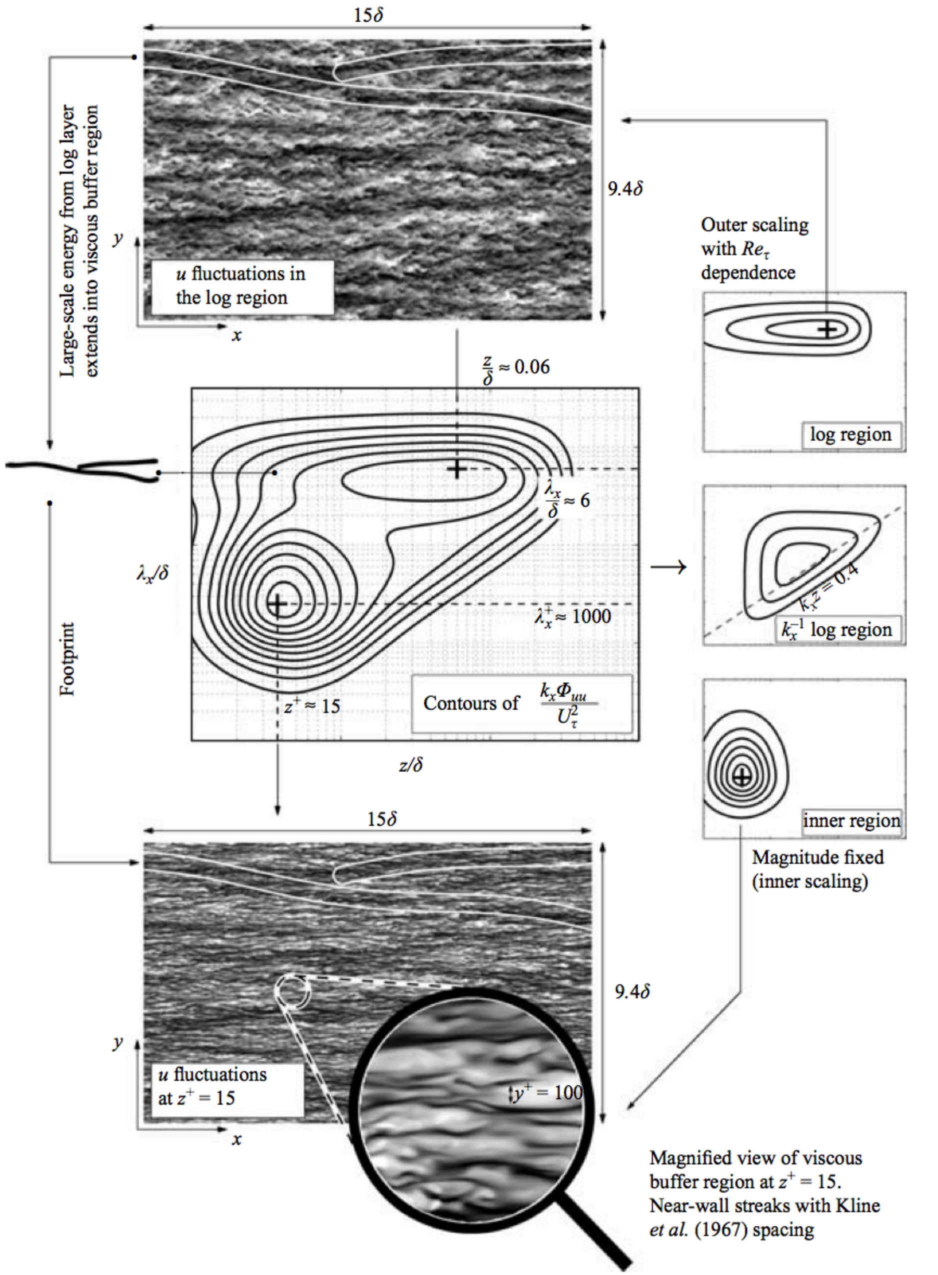


FIGURE 11. Schematic explaining the relative contributions to the energy spectra shown in figure 10. The main iso-contour plot has three salient components, as shown on the right-hand side.

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Evidence of very long meandering features in the logarithmic region of turbulent boundary layers

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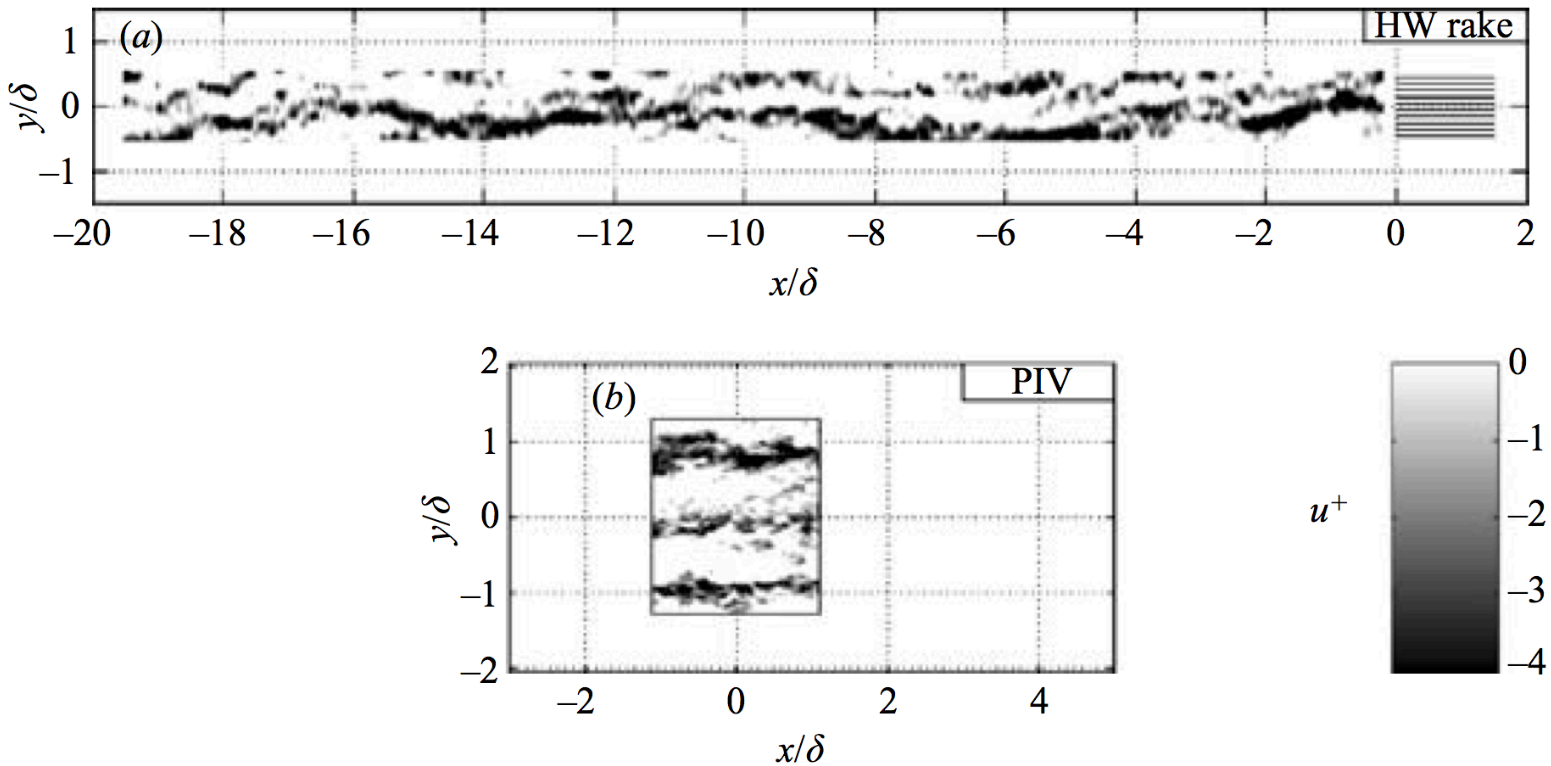


FIGURE 4. (a) Example of rake signal at $z/\delta = 0.15$ for $Re_\tau = 14\,380$. The x-axis is reconstructed using Taylor's hypothesis and a convection velocity based on the local mean, $\overline{U} = 15.9\,\mathrm{m\,s^{-1}}$. (b) Typical PIV frame for comparison at $Re_\tau = 1100$, $z/\delta = 0.087$. Shading shows only negative u fluctuations (see grey-scale).

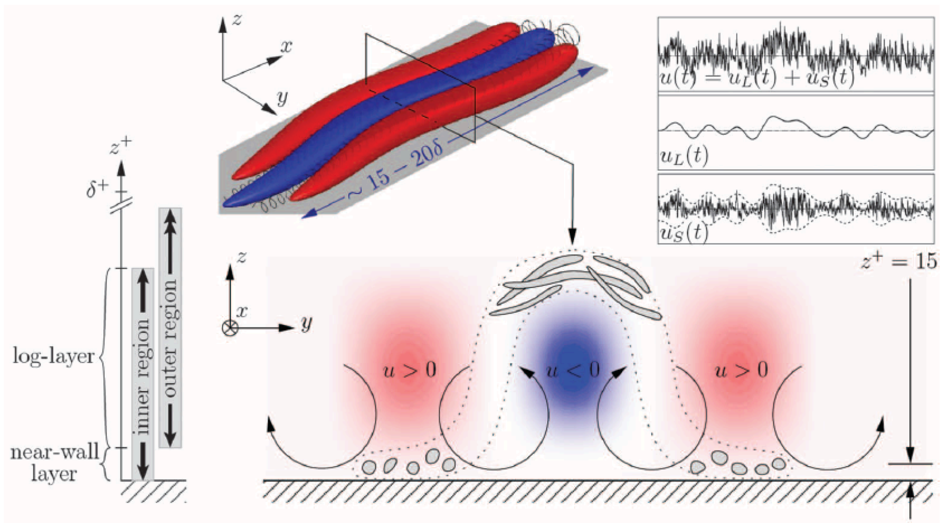
If one accepts the amplitude modulation effect as the mechanism linking the large-scale superstructures to the behavior of the near-wall region, then this leads to the possibility that a simple mathematical model may be devised that captures this interaction. This is very desirable, as it would allow prediction of the fluctuating velocity statistics in the near-wall region given only information about the large-scale signal in the log region. Such a model can be expressed as

$$u_P^+ = u^*(1 + \beta u_{OL}^+) + \alpha u_{OL}^+ \qquad (1)$$

where u_P^+ is the predicted u signal at z^+, u_{OL} is the fluctuating large-scale signal from the log region, u^* is the statistically "universal" signal at z^+ (normalized in wall units), and α and β are, respectively, the superimposition and modulation coefficients. Note that the model consists of two parts; the first part, $u^*(1 + \beta u_{OL}^+)$, models the amplitude modulation at z^+ by the large-scale motions, and the second part, αu_{OL}^+, models the superimposition of the large-scale motions felt at z^+.

Predictive Model for Wall-Bounded Turbulent Flow

I. Marusic,* R. Mathis, N. Hutchins



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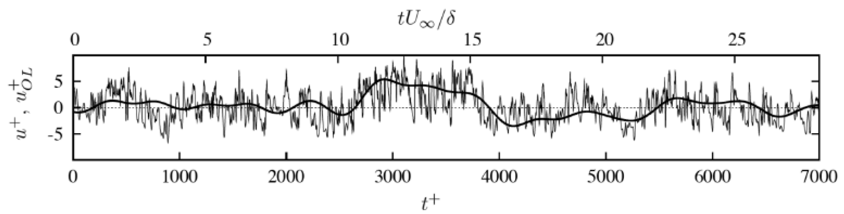


Fig. 2. Example of fluctuating signal u^+ at $z^+ = 15$ and large-scale fluctuating component u^+_{OL} in the outer layer (thick blank line) at $z^+ = 330$ measured in a turbulent boundary layer at $Re_\tau = 7300$.

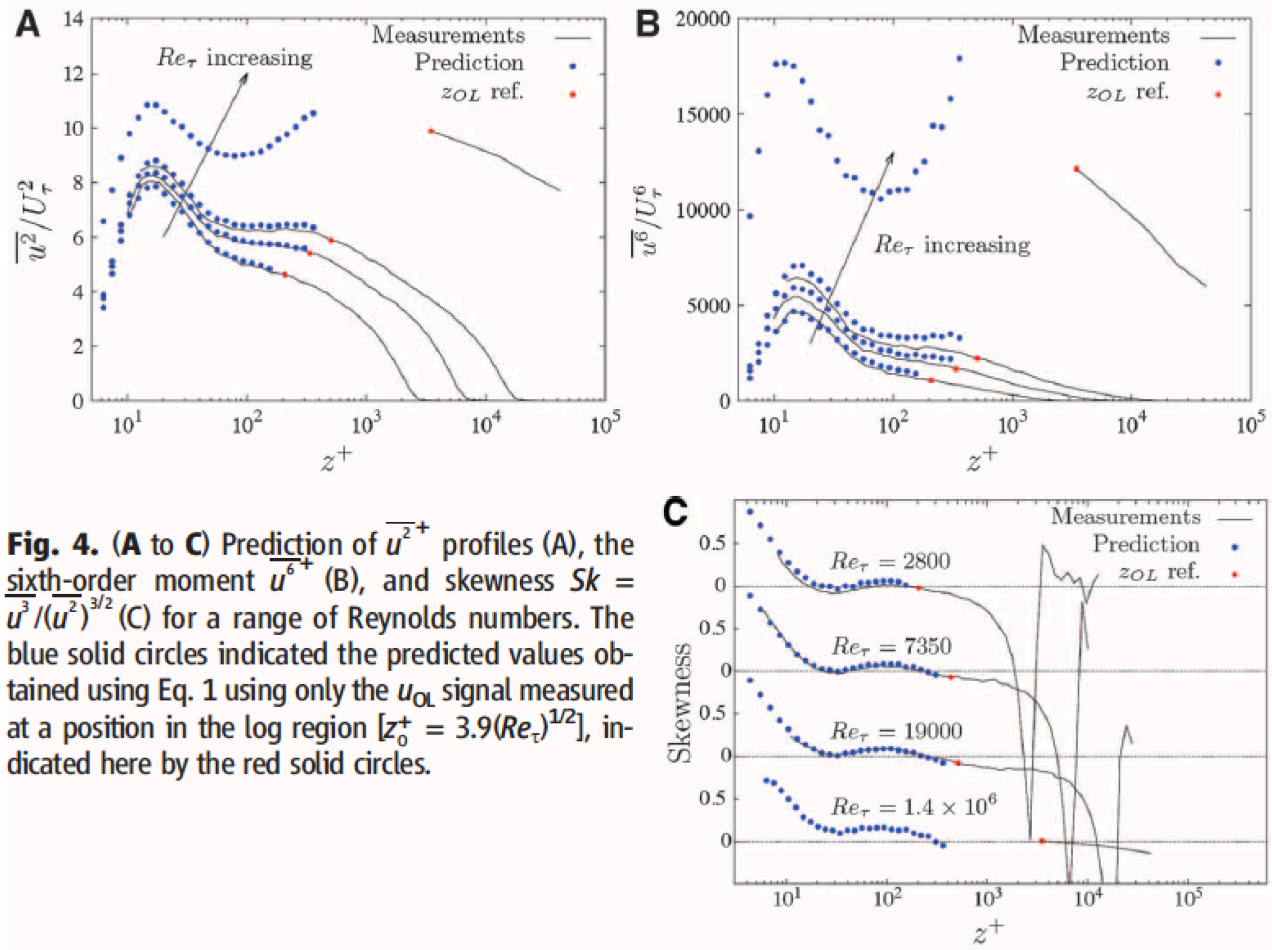


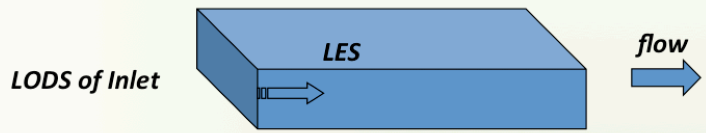
Fig. 4. (**A** to **C**) Prediction of $\overline{u^2}^+$ profiles (A), the sixth-order moment $\overline{u^6}^+$ (B), and skewness $Sk = \overline{u^3}/(\overline{u^2})^{3/2}$ (C) for a range of Reynolds numbers. The blue solid circles indicated the predicted values obtained using Eq. 1 using only the u_{OL} signal measured at a position in the log region [$z_0^+ = 3.9(Re_\tau)^{1/2}$], indicated here by the red solid circles.

Coupling experiments and unsteady computations & Stochastic approach for Low-Order Dynamical Systems

Global Objective

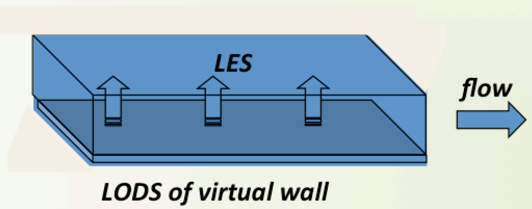
Make use low order descriptions (LODS/ROM) of the flow near boundaries to help in reducing the size/cost and efficiency in case of control of DNS/LES e.g.

- In a cross-section : inlet conditions.



- For wall bounded flows, In a section parallel to the wall, *away from the wall* : wall conditions.

  Y+ ~10-100



Why ?

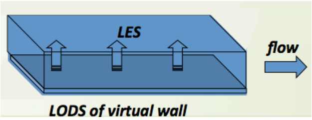
- ❑ Reduction of computational cost …

  Domain size –
  Evacuation of initial conditions

- ❑ Take into account rare events:

  Use the CFD to focus on selected events …

- ❑ Simulation of Controled Flows



Difficulties

- Impose high levels of turbulence to boundaries of a CFD
- Generate the ‘realistic dynamics’ (temporal evolution) of the incoming flow or boundary conditions…
- Take into account the organized character of the flow: coherent structures in their space and time relevant scales
- Provide reliable CFD at the first stages of the computational domain (for flow control,…)

Implications for experiments:

Spatial resolution ➔ mapping to surfaces and volumes!

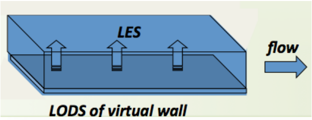
- rakes, brushes of sensors, PIV, …

Time resolution ➔ provide conditions at each time step of the *connected* computation!

- hot wires, TR-PIV (may be the solution … but still limited to low velocity flows)

Relevant information

- Multi-components of velocity (multi-wire probes, stereo PIV)
- Pressure (wall?), density, temperature



Whatever the solution is:

We need for Mathematical

&

Theoretical (based on physics) tools

- For spatial interpolation
- For spatial extrapolation
- For time prediction
- For data compression
- For combination of different flow data

We need tools for Qualification, Identification, Modelling of LS behaviour

Estimation :

- LSE
- LSE + time dependency

Decomposition

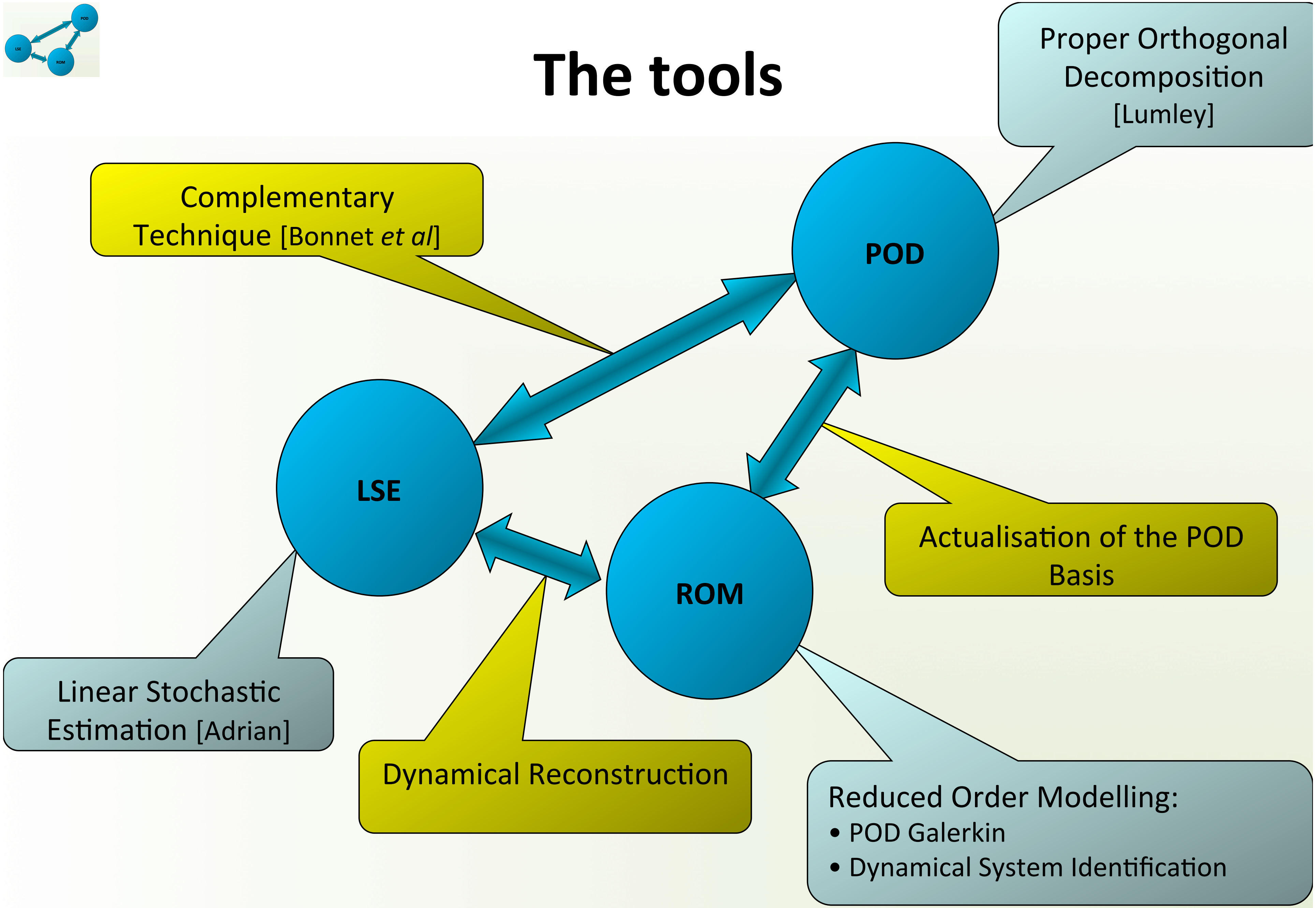
- POD (Proper Orthogonal Decomposition)
- SVD (Singular Value Decomposition)
- DMD (dynamical mode decomposition)
- Stability modes Linearised, Parabolised, non linear, ...
- Complementary techniques

Projection (Galerkin) may require closure

Identification techniques

- Least mean square
- Penalisation
- Optical flows
- ARMAX
- 4D var
- …

The tools


Proper Orthogonal Decomposition [Lumley]
Complementary Technique [Bonnet *et al*]
POD
LSE
ROM
Actualisation of the POD Basis
Linear Stochastic Estimation [Adrian]
Dynamical Reconstruction
Reduced Order Modelling:
• POD Galerkin
• Dynamical System Identification

L.S.E. Linear Stochastic Estimation

estimated

measured

$$\widetilde{u}_i(x,y,z,t) = \sum_{n=1}^{N_p} b_n(x,y,z) P_n(t)$$

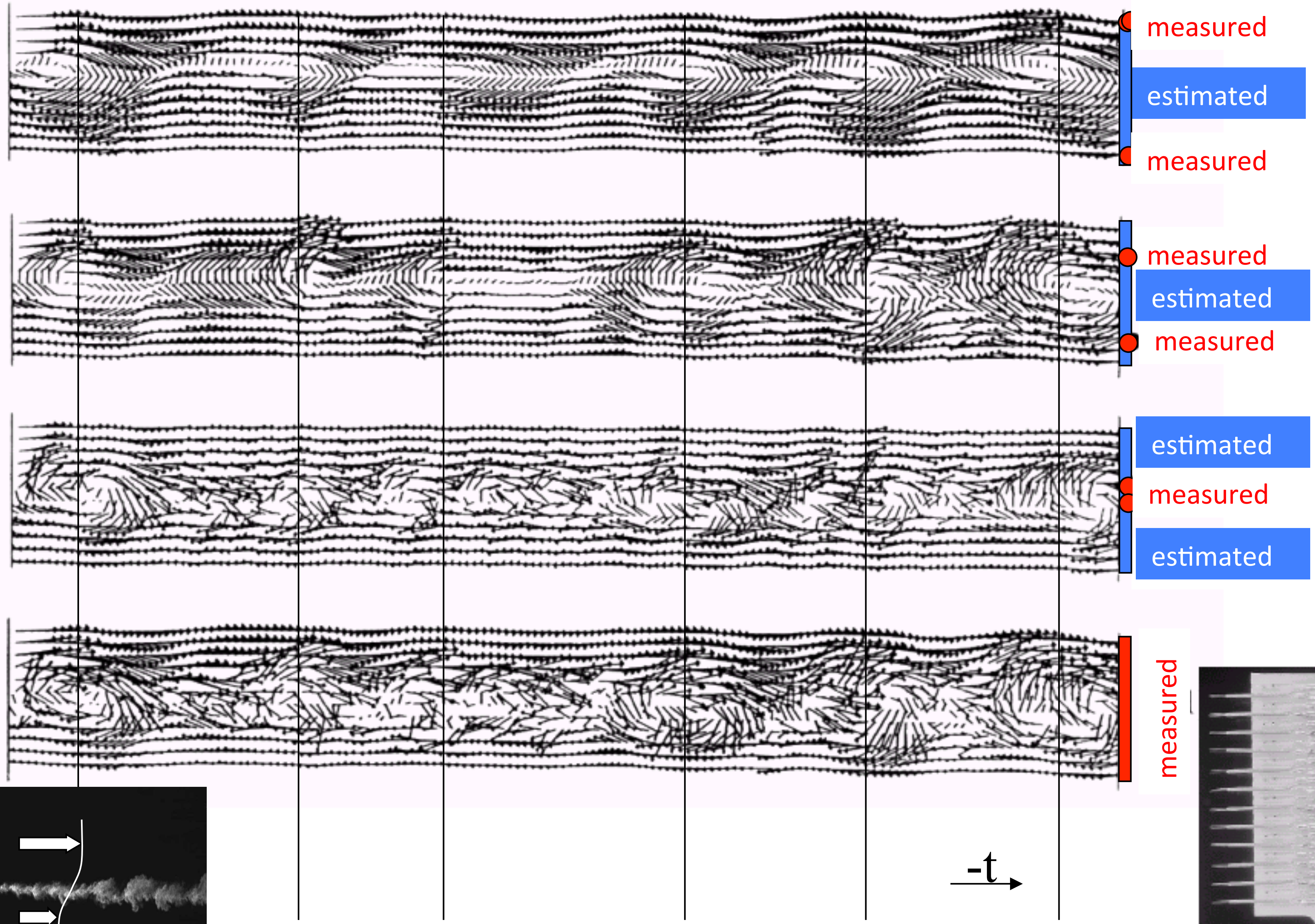
LSE depends on the choice of parameters

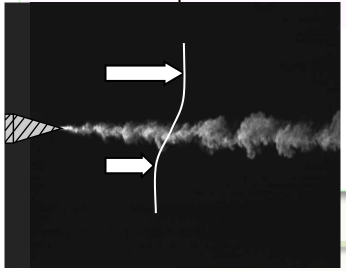
$$b_n(x,y,z) < P_n(t) P_m(t) > = < u_i(x,y,z,t) P_m(t) >$$

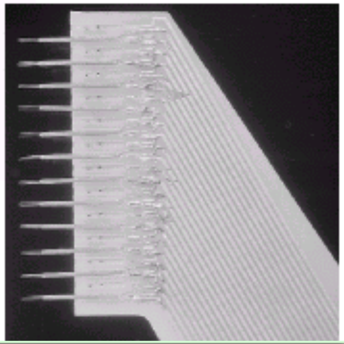
Remarks:

- LSE possible only if a correlation exists
- The nature of parameters and estimates can be different
- Parameters can include time delays

Linear Stochastic Estimation : in a turbulent plane mixing layer







velocity → velocity

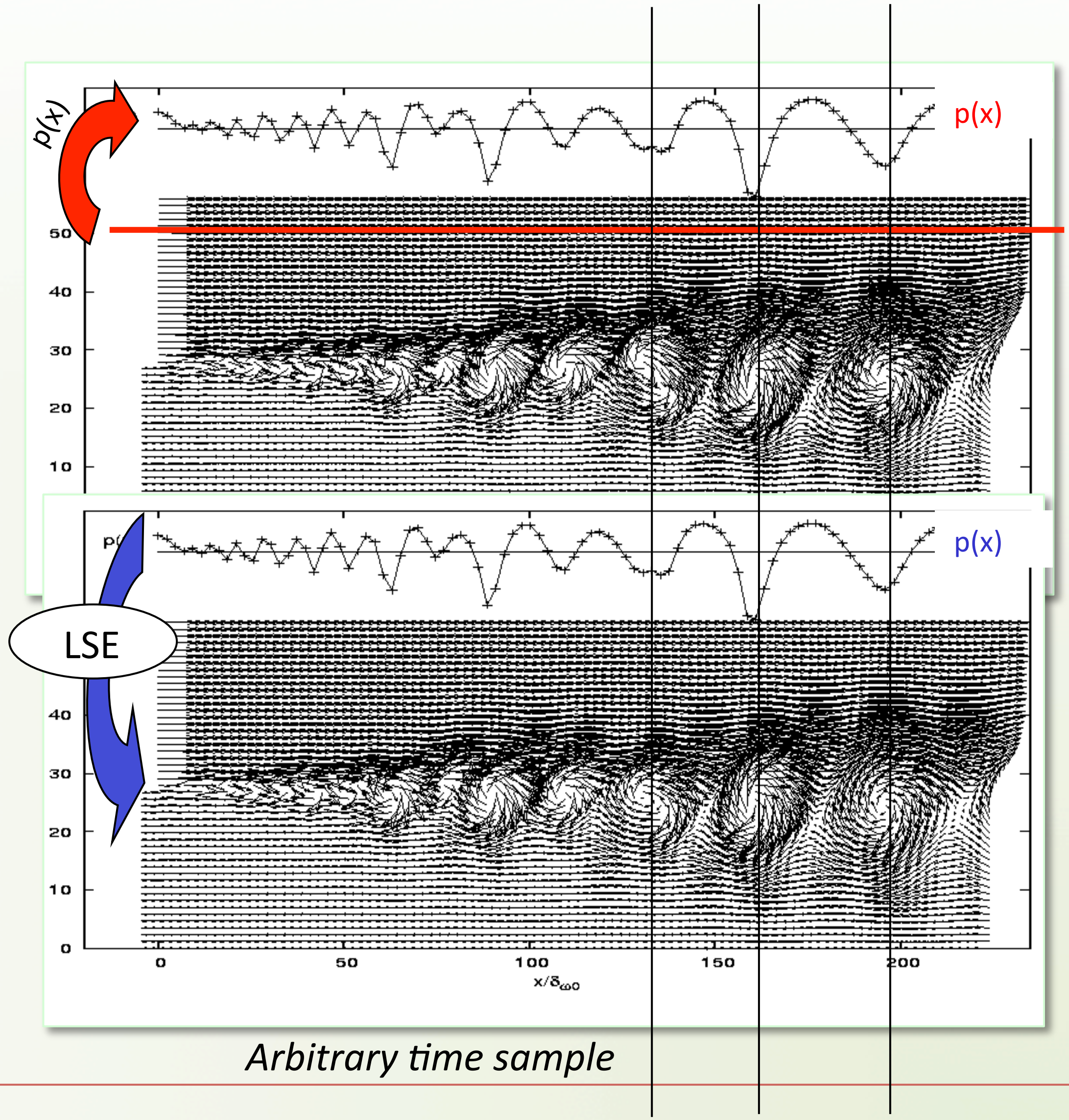
LSE of velocity from pressure in a plane mixing layer (DNS)

DNS 2D - plane ML

- ❑ computation

L.S.E based on p(x)

- ❑ estimated velocity



Arbitrary time sample

pressure → velocity