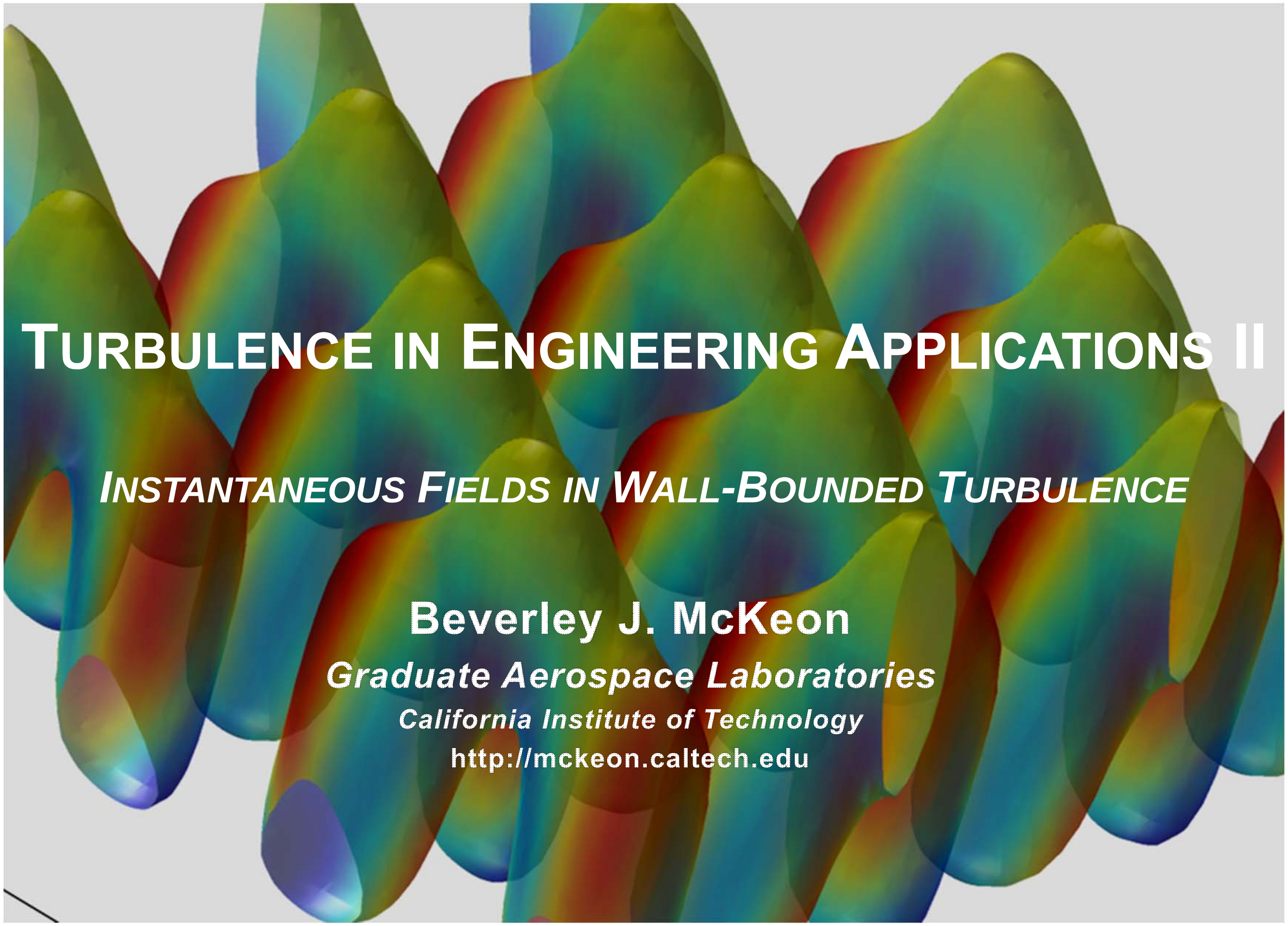

TURBULENCE IN ENGINEERING APPLICATIONS II

INSTANTANEOUS FIELDS IN WALL-BOUNDED TURBULENCE

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Graduate Aerospace Laboratories

California Institute of Technology

http://mckeon.caltech.edu

OUTLINE

- Introduction
- Review of the state of the art – data and scaling
- Modeling of observations: what do the models tell us about the underlying math?
- Challenges and opportunities

I will not address:

- Mean profile
- Higher order statistics
- Structure functions
- Scalar mixing, compressibility, wall roughness, non-Newtonian fluids, etc…
- Control

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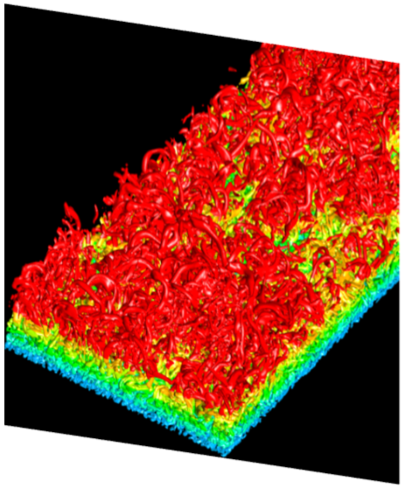
INTRODUCTION – BASIC CONCEPTS

- Definitions, terminology
- What is different about wall turbulence?
- Regions and scalings
- Data and experimental limitations



Reference papers

- *Marusic et al Phys. Fluids 22, 2010*
- *Smits, McKeon and Marusic, Annu. Rev. Fluid Mech. 43, 2011*

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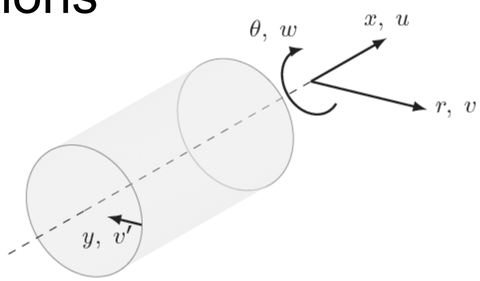
EQUATIONS OF MOTION

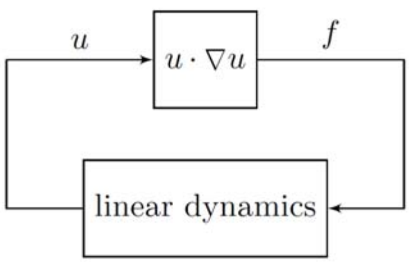
- Define an instantaneous velocity field and "fluctuations" relative to the mean



$$\tilde{\mathbf{u}}(t) = \mathbf{U} + \mathbf{u}(t)$$

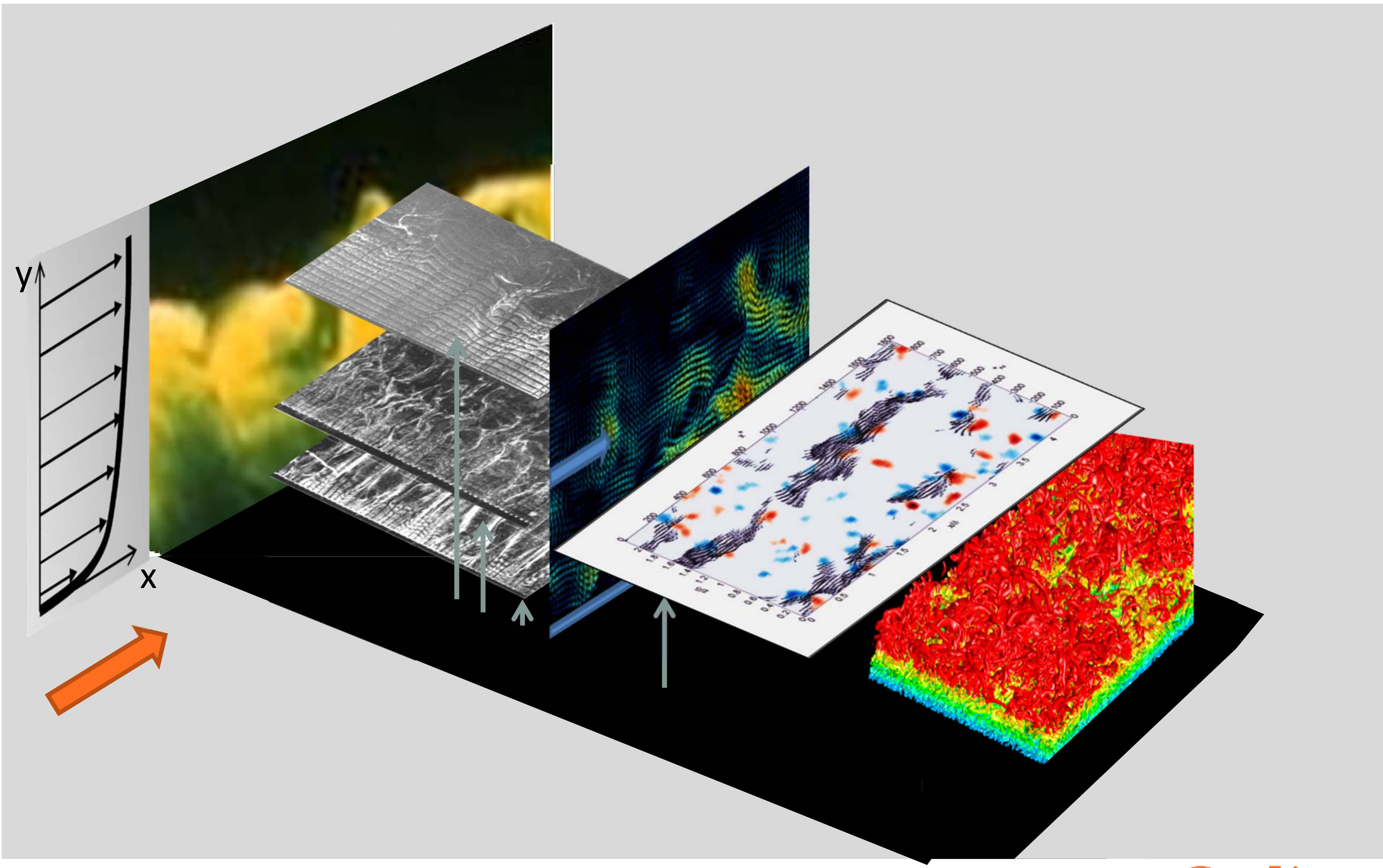
- Then the momentum equation reduces to:

$$\mathbf{u}_t + (\mathbf{u}\cdot\nabla)\mathbf{U} + (\mathbf{U}\cdot\nabla)\mathbf{u} + \nabla p - (1/Re_\tau)\nabla^2\mathbf{u} = \overbrace{-(\mathbf{u}\cdot\nabla)\mathbf{u}}^{\mathbf{f}}$$



- Plus continuity

WALL TURBULENCE HAS SPECIAL STRUCTURE



von Karman (1930)
Millikan (1938)
Coles (1952)

Gad-el-Hak
http://efluids.com

Kline, Reynolds, Schraub & Runstadler
J. Fluid Mechanics (1967)

LeHew, Guala & McKeon
Expts. in Fluids (2011)

Wu & Moin
http://ctr.stanford.edu

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Regions and scales

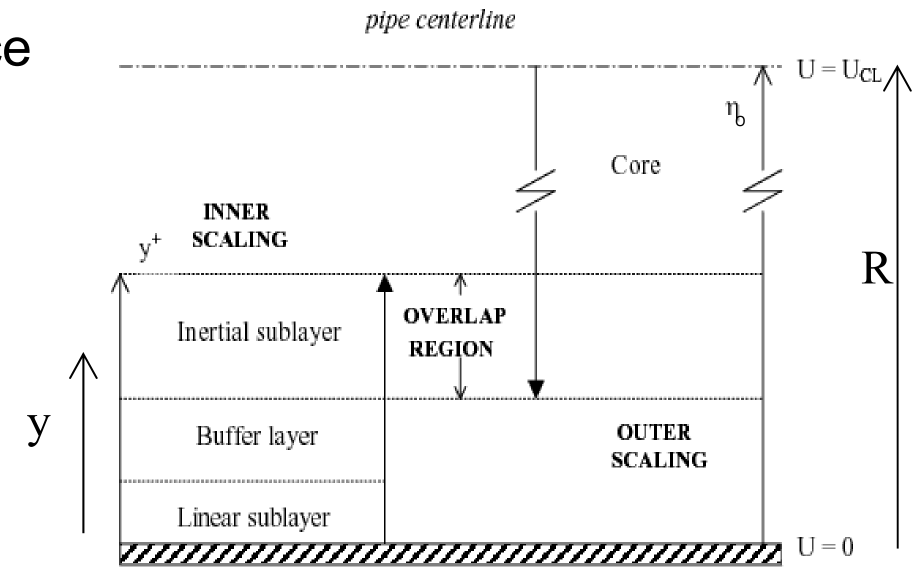
Physical space

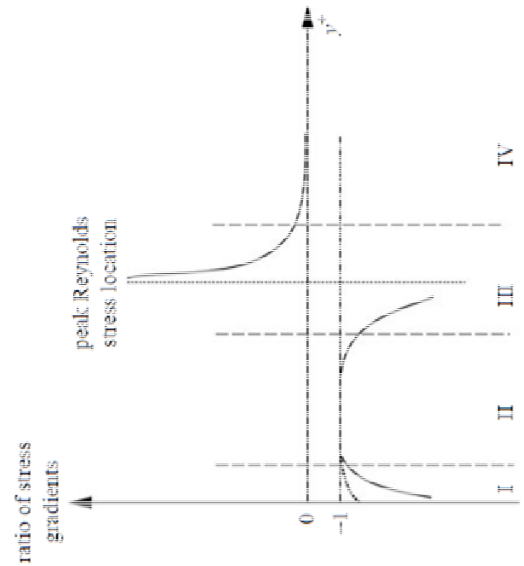
$$y^+ = \frac{y u_\tau}{\nu}$$

$$\eta_O = \frac{y}{R}$$

$$u_\tau = \sqrt{\frac{\tau}{\rho}}$$

$$R^+ = \frac{R u_\tau}{\nu}$$





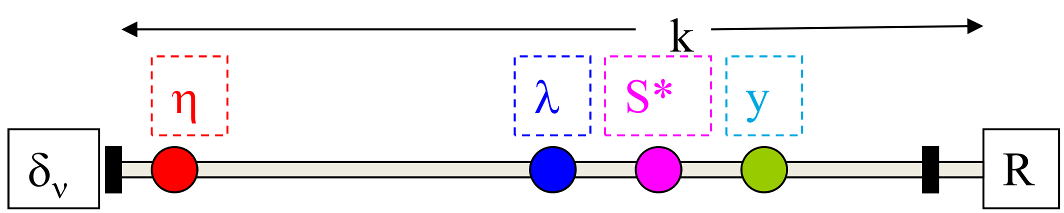
Klewicki, Wei, Fife & McMurtry, Phil. Trans. R. Soc. A 2007

Spectral space

$$\delta_\nu = \frac{\nu}{u_\tau}$$

$$\lambda = \sqrt{\overline{u^2} / \overline{(\partial u / \partial x)^2}}$$

$$S^* = \sqrt{\frac{\varepsilon}{S^3}} \qquad S = \frac{\partial U}{\partial y}$$



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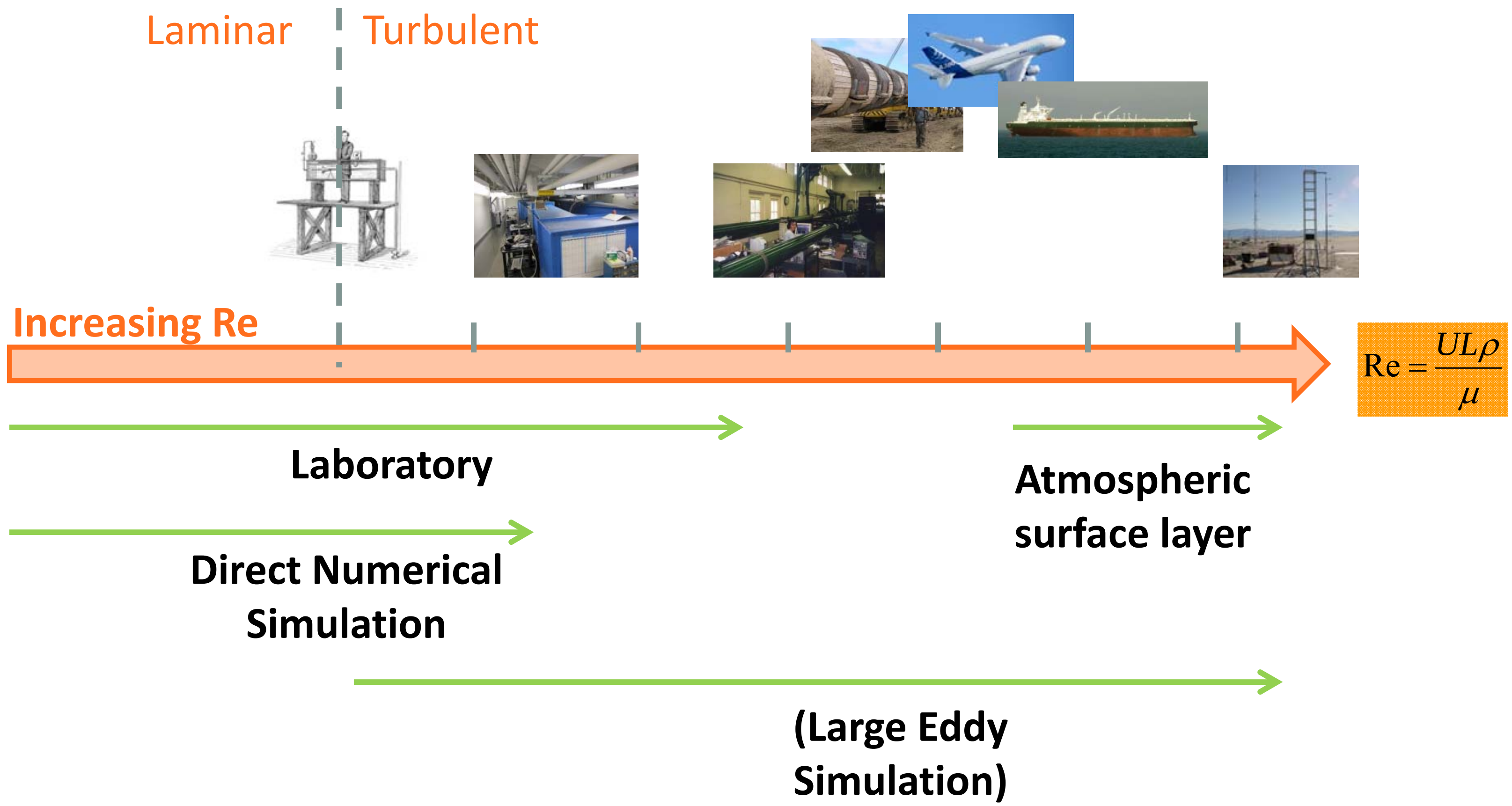
Introduction

WHAT DATASETS ARE AVAILABLE?



ISSUES
Resolution issues – space and time – in experiments
Computational expense (and scaling) in simulation

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REVIEW OF DATA AND SCALING

- Form and scaling of the fluctuation intensities
  - u, v, w
  - uv and implications for TKE production
- Spectral arguments
- Importance of the very long scales
- “Amplitude modulation”
  - or the phase relationship between large and small scales
- Structure
  - Hairpin vortices in the overlap region
  - Near-wall cycle

Spectral vs. physical picture, Tennekes and Lumley’s “typical eddy”

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SCALING OF THE SECOND ORDER STATISTICS: u,v,w

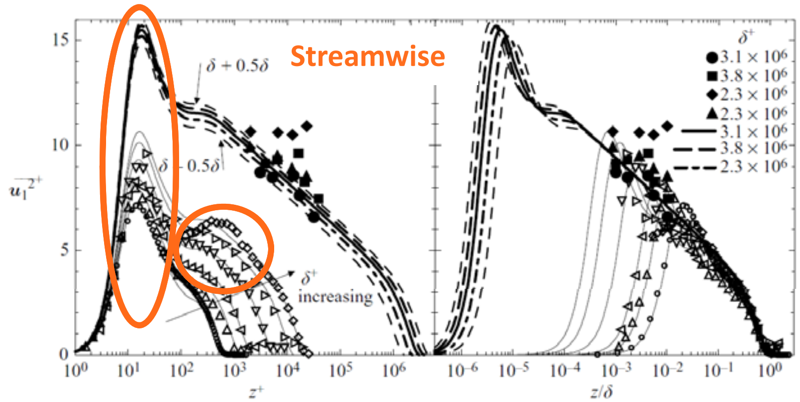
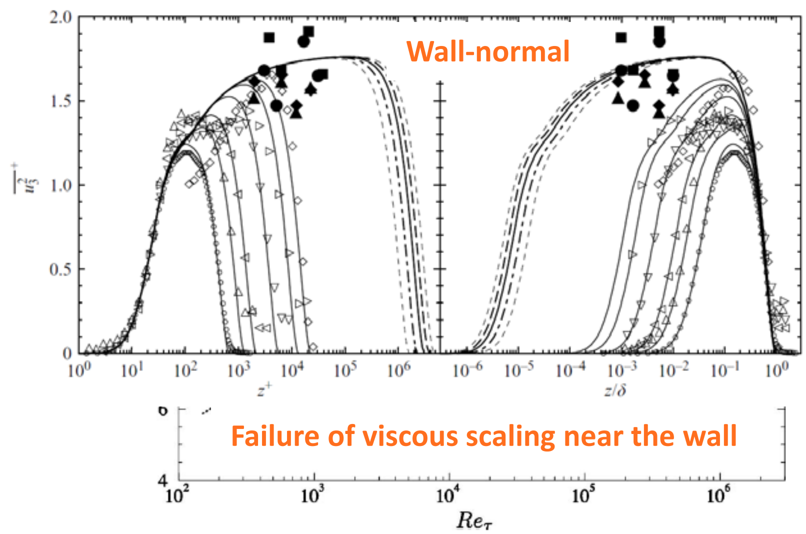
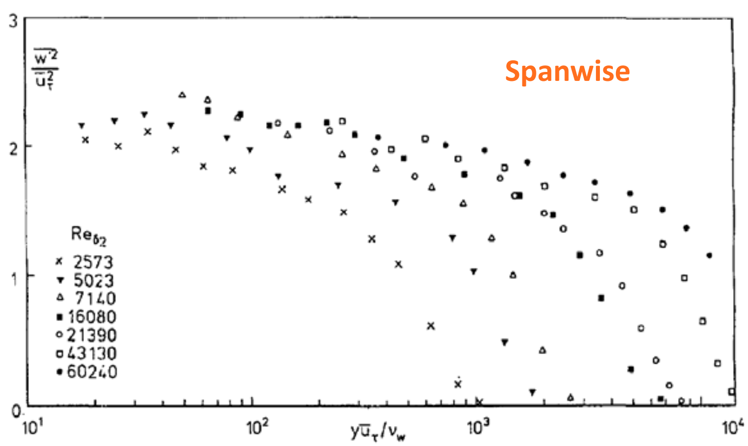
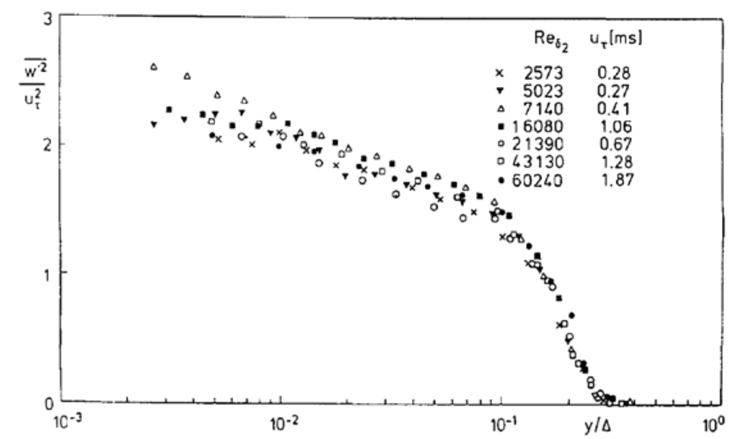


FIGURE 4. Streamwise turbulence intensities. Solid symbols are atmospheric data. Open symbols are laboratory data; $\delta^+ = 689$ (○)–Spalart (1988); 1335 (△), 2217 (◁), 5813 (▽), 13 490 (▷)–DeGraaff & Eaton (2000); 23 013 (◇)–Fernholz *et al.* (1995). Solid, dashed and dot-dashed lines are smooth-wall similarity formulations (equation (2.1)) that are also valid for rough walls in the outer region. Lighter dashed lines are similarity formulation for $\delta^+ = 3.1 \times 10^6$ if boundary-layer thickness is 50 % larger or smaller.







Kunkel & Marusic, J. Fluid Mech. 2006
Marusic et al, Phys. Fluids 2010
Fernholz & Finley, Prog. Aero. Sci. 1996

Non-simple scaling of the second order moments (made obvious with increasing Reynolds number)

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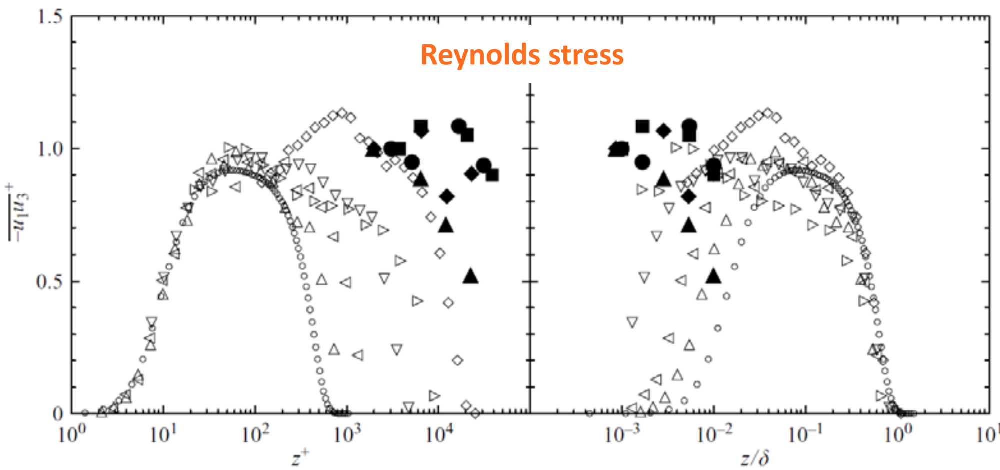
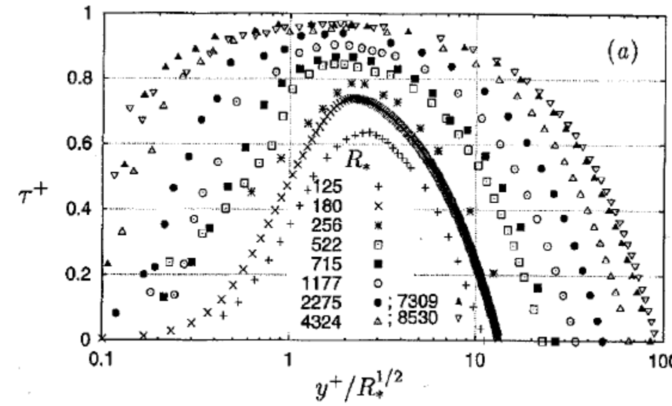
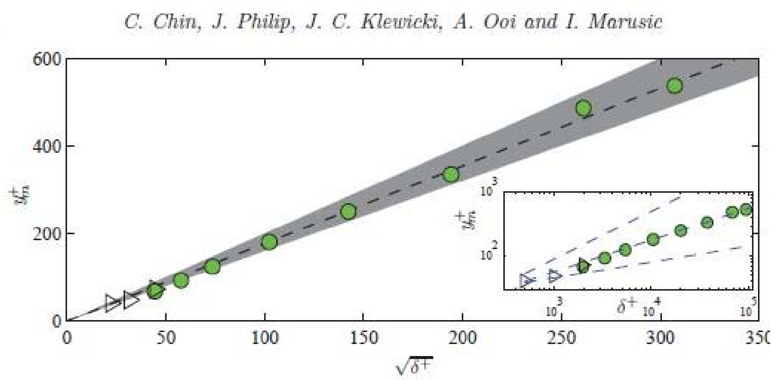
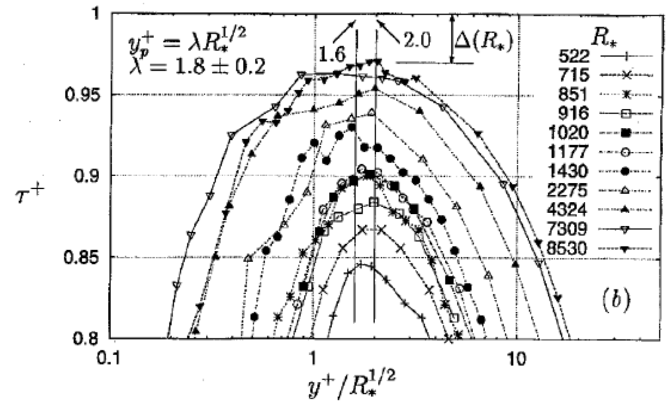
Data and scaling

SCALING OF THE SECOND ORDER STATISTICS: UV









Kunkel & Marusic, J. Fluid Mech. 2006
Sreenivasan & Sahay, 1997
Chin et al, J. Fluid Mech. to appear

Reynolds number variation of the peak Re stress location leads to inconsistencies in the classical scaling

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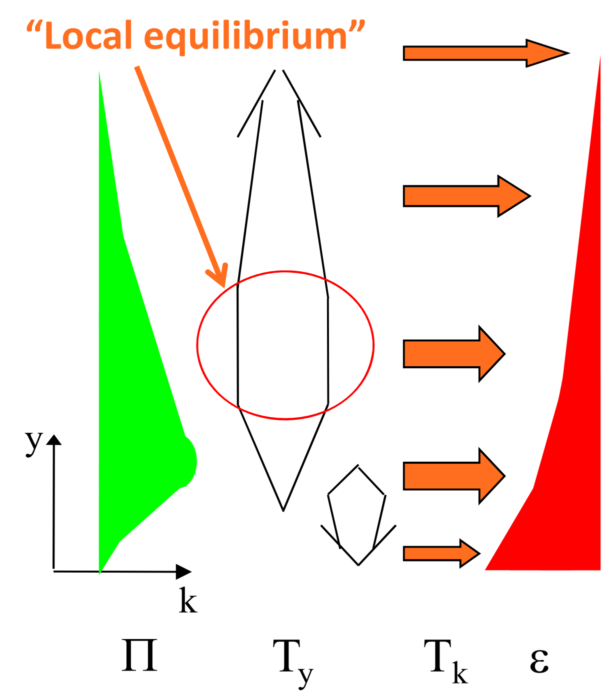
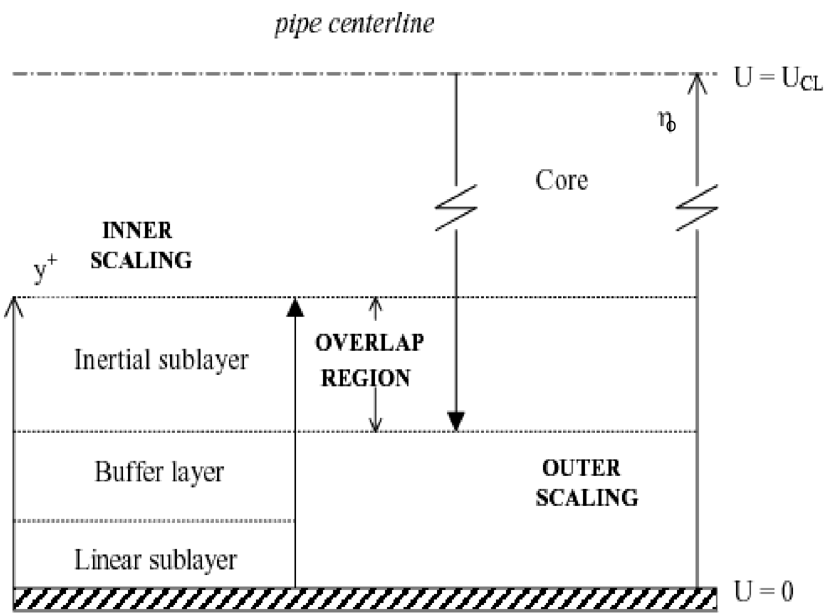
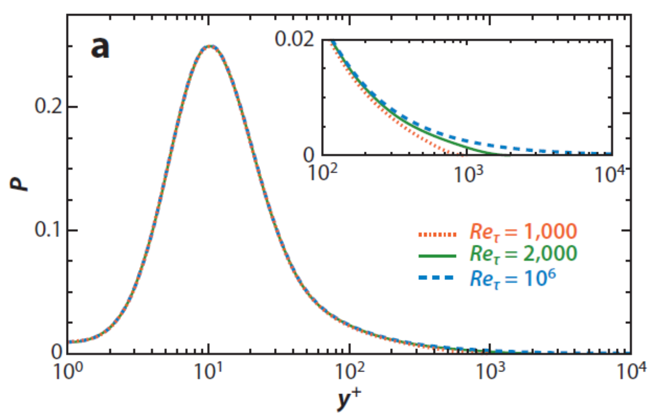
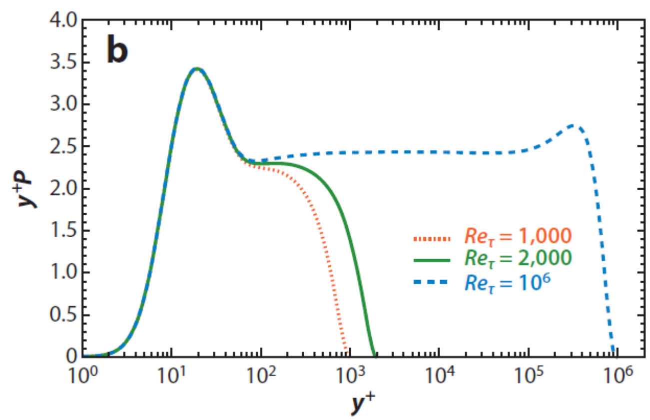
Data and scaling

IMPLICATIONS FOR TURBULENCE PRODUCTION









Peak production corresponds with near-wall cycle only for low Reynolds number

Marusic, Mathis & Hutchins, Int J. Heat Fluid Flow, 2010

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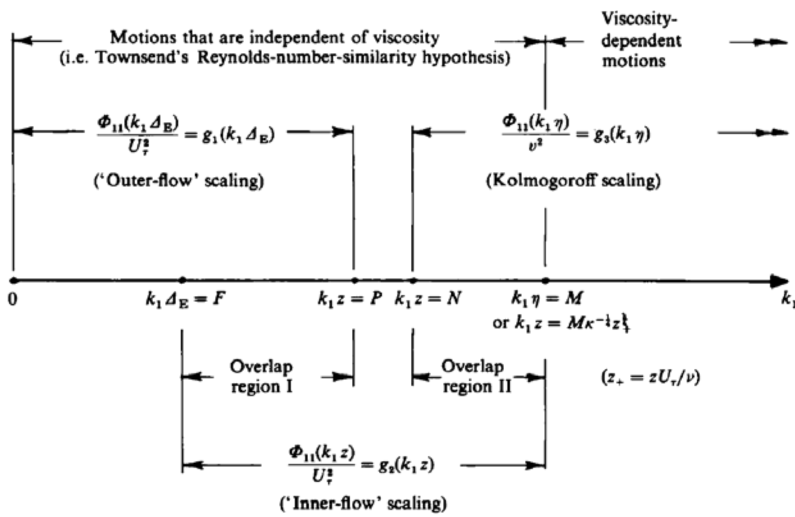
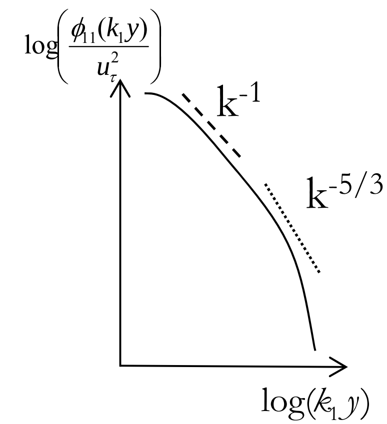
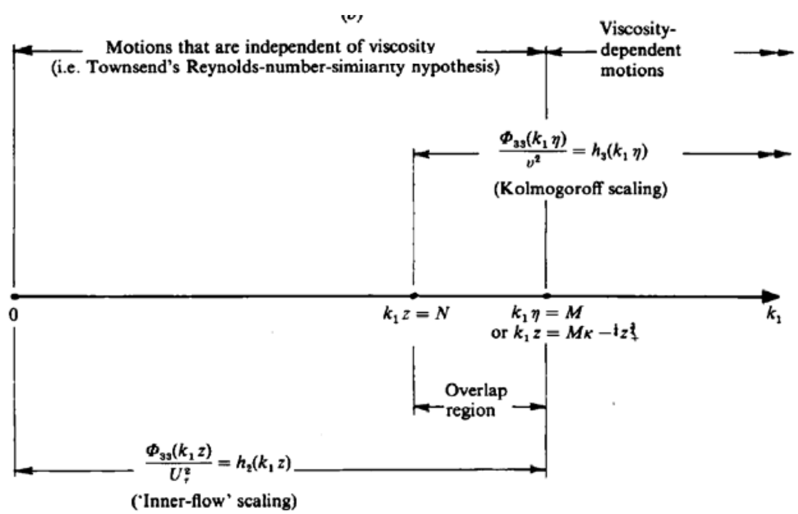
SPECTRAL ARGUMENTS

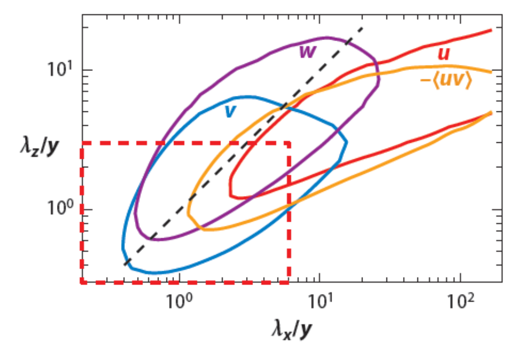
Wall-parallel





Wall-normal





Perry, Henbest & Chong, J. Fluid Mech. 1986
Jimenez, Annu. Rev. Fluid Mech. 2012

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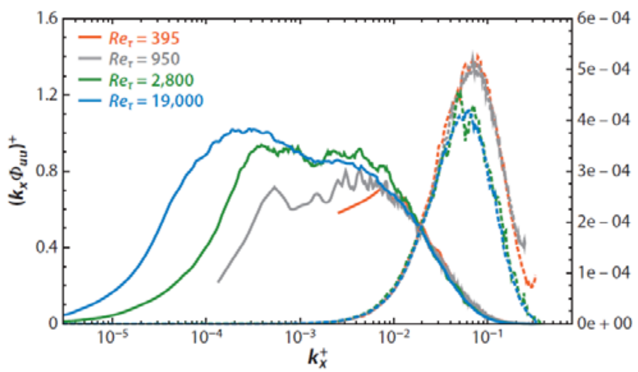
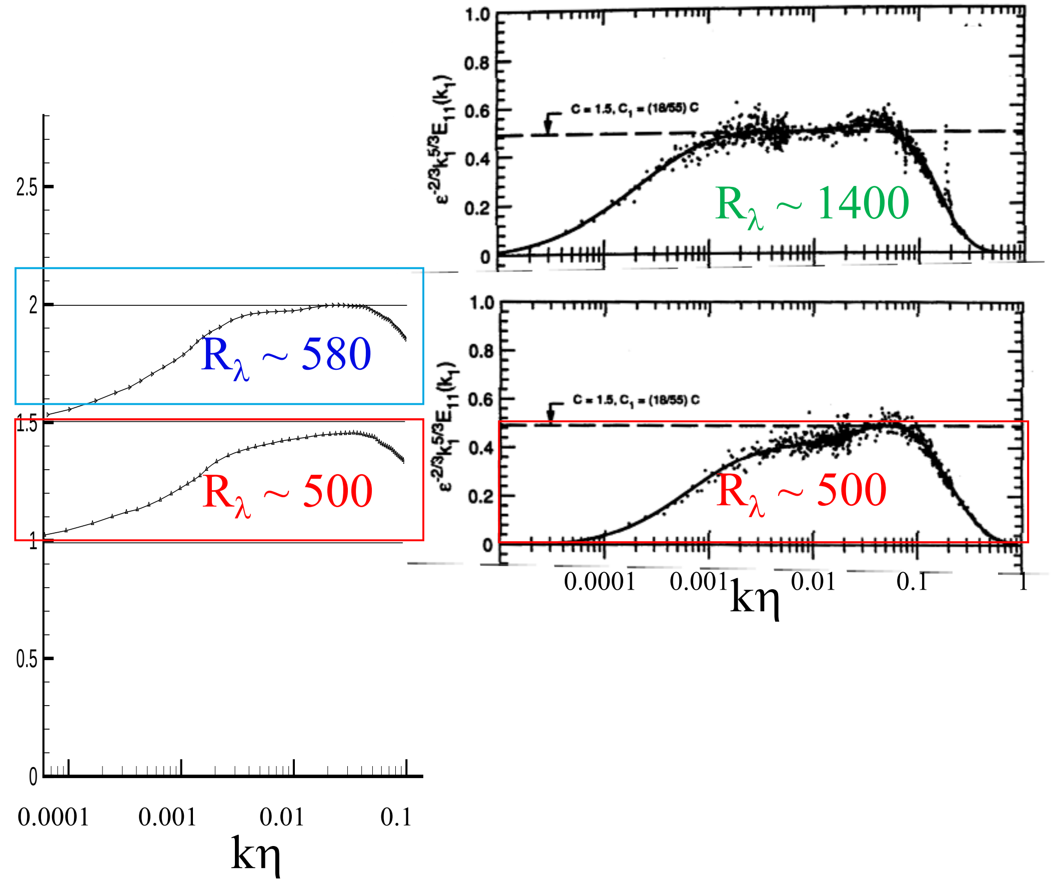
KOLMOGOROV-TYPE SCALING?



(Some sort of) scale separation is achieved

$S^*/\eta = 110$ $S^*/\eta = 160$ $S^*/\eta=140$ $S^*/\eta=440$

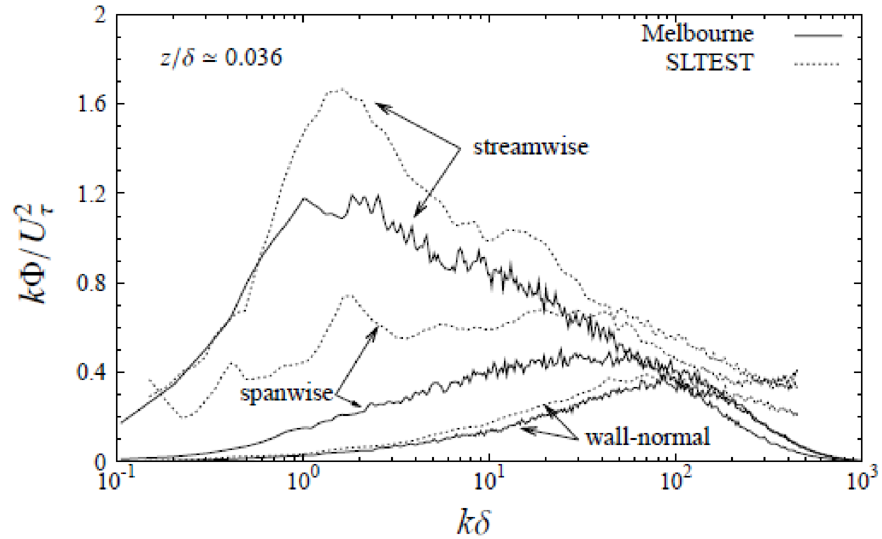


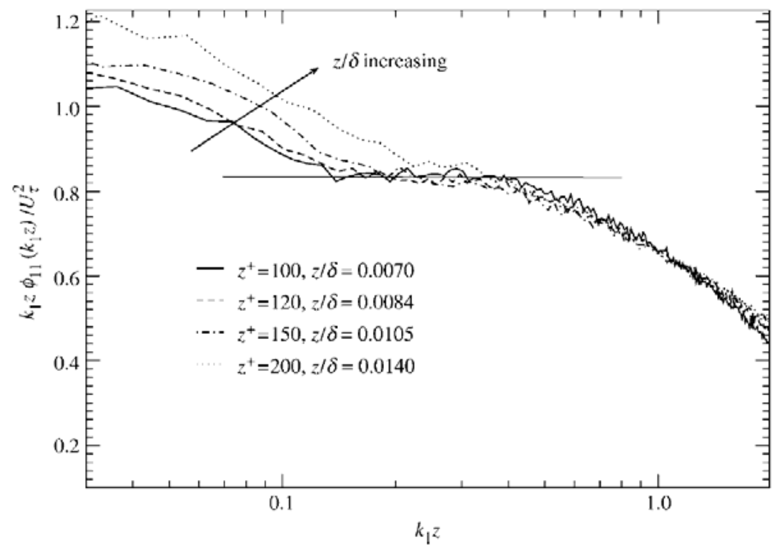
Superpipe, $Re_D = 1 \times 10^6$ (y/R < 0.1)

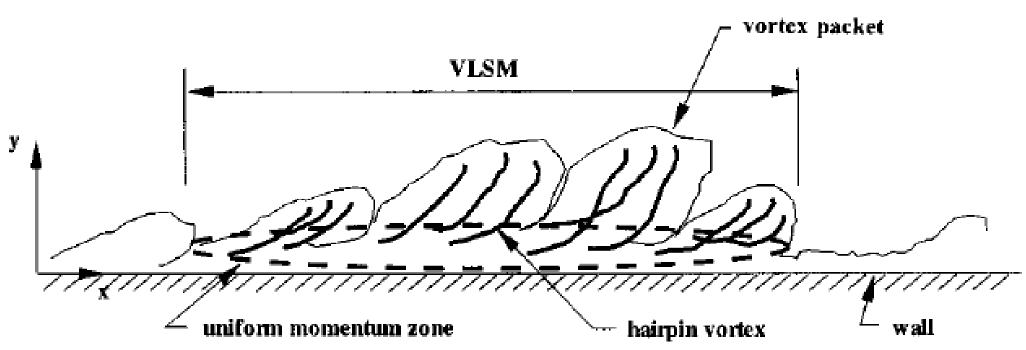
Turbulent boundary layer (y/R = 0.1)

Smits, McKeon & Marusic, Annu. Rev. Fluid Mech. 2011
McKeon & Morrison, Phil. Trans. R. Soc. A 2007
Saddoughi & Veeravalli, J. Fluid Mech. 1994

k^{-1} SCALING?







Marusic, Mathis & Hutchins, Int J. Heat Fluid Flow, 2010
Nickels, Marusic, Hafez, Hutchins & Chong, Phil. Trans. R. Soc A 2007
Kim & Adrian, Phys. Fluids, 2000

LOGARITHMIC SCALING OF u'^{2}

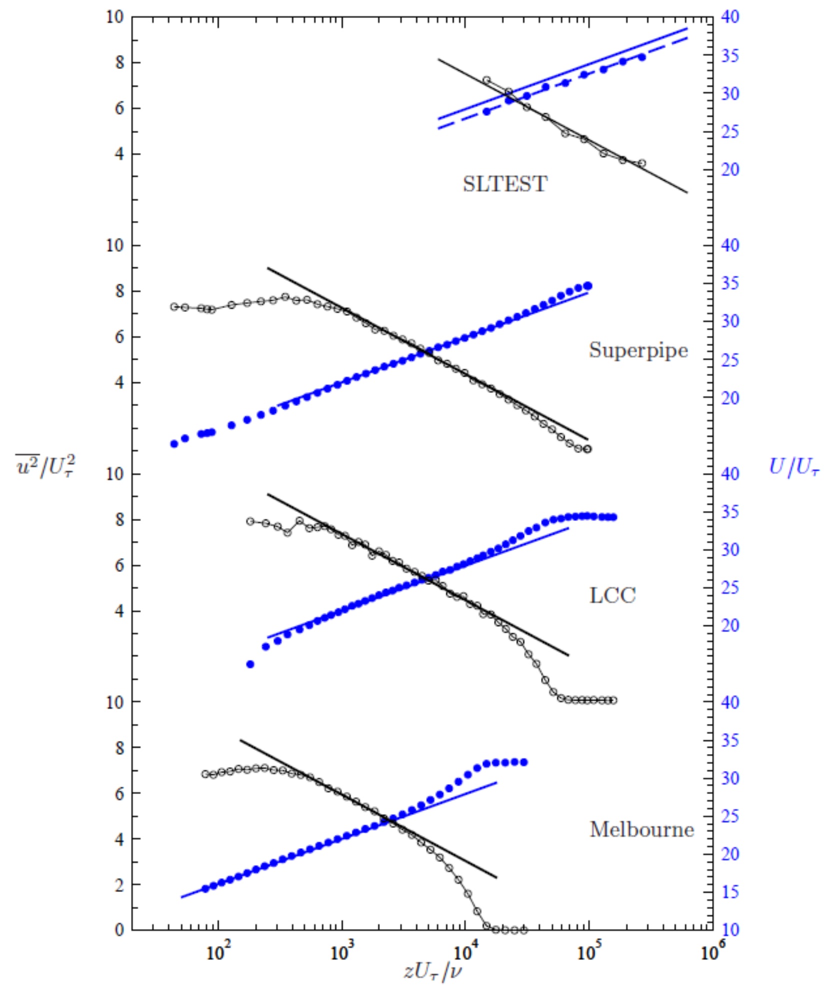
Marusic, Monty, Hultmark & Smits, J. Fluid Mech. 2013

Attached eddy hypothesis (more later) can be used to show that

$$\frac{\overline{u^2}}{U_\tau^2} = C_1 + D_1 \log\left(\frac{\delta}{z}\right)$$

$$\frac{\overline{v^2}}{U_\tau^2} = C_2 + D_2 \log\left(\frac{\delta}{z}\right)$$

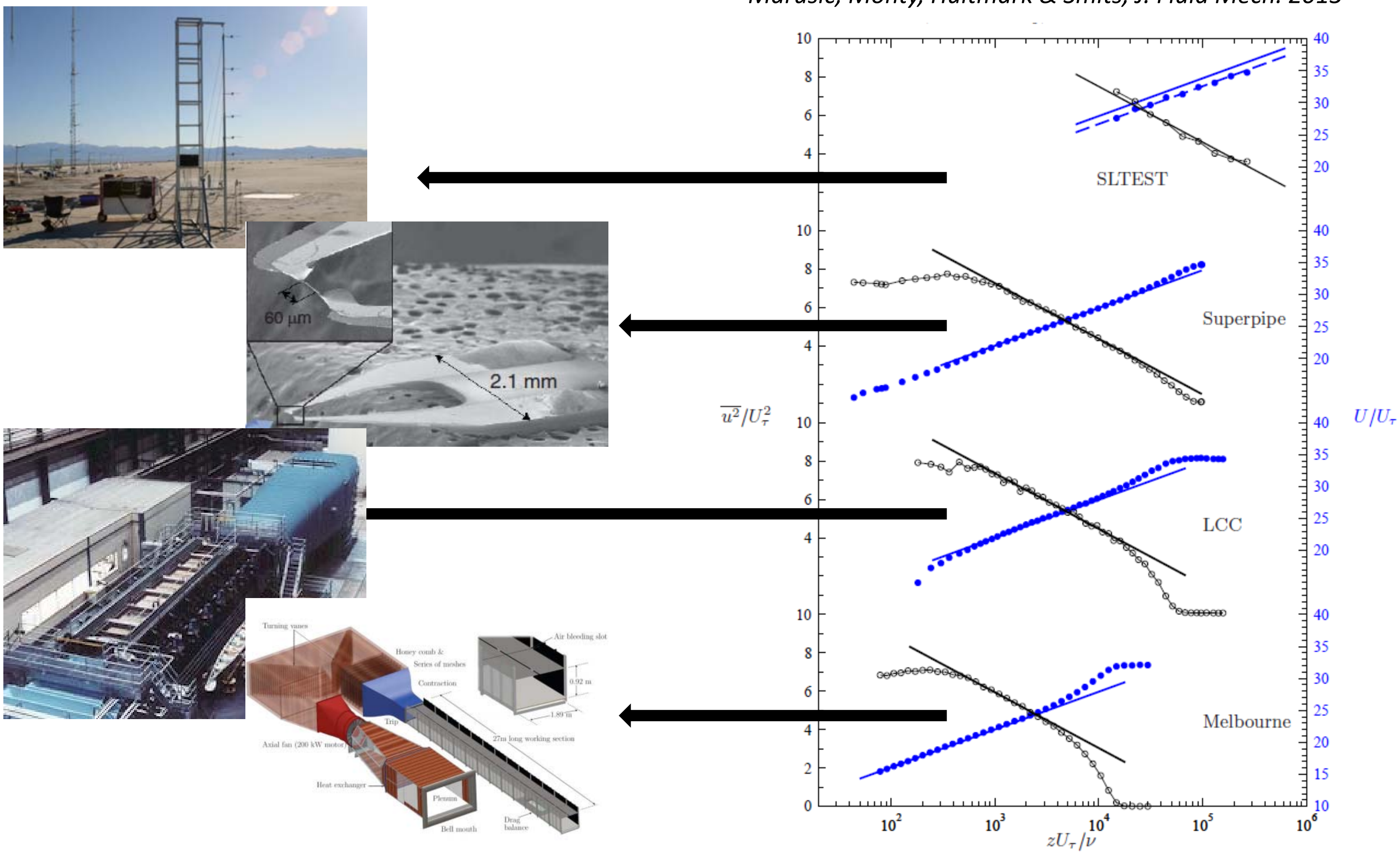
$$\frac{\overline{w^2}}{U_\tau^2} = C_3,$$



Perry, Henbest & Chong, J. Fluid Mech. 1986

LOGARITHMIC SCALING OF u'^{2}

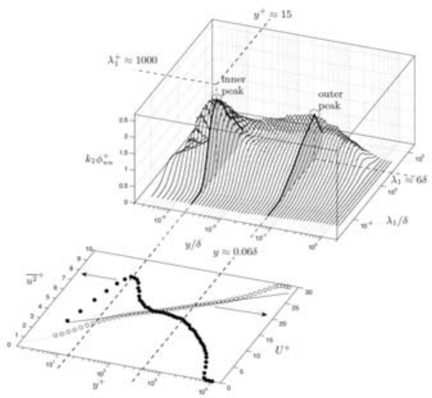
Marusic, Monty, Hultmark & Smits, J. Fluid Mech. 2013

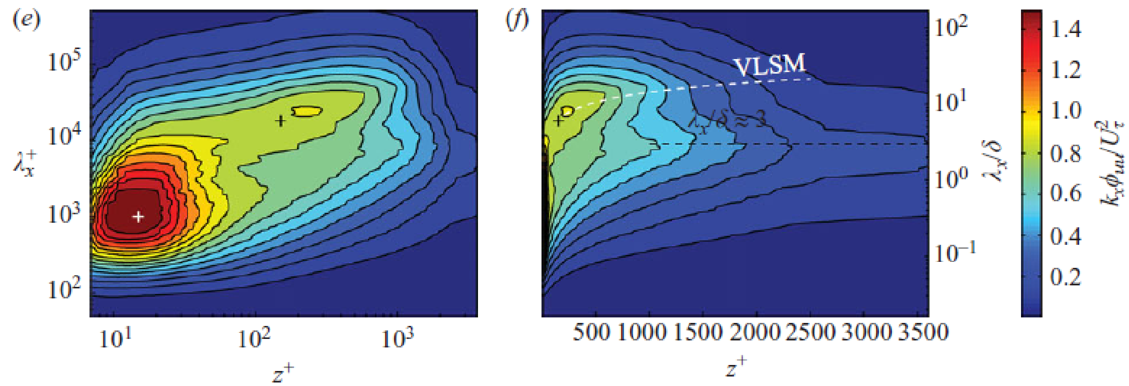


Hultmark et al, Phys. Rev. Letters 2012
http://www.mech.unimelb.edu.au/fluid-mechanics/walter-bassett.html
https://portal.navfac.navy.mil/portal/page/portal/navfac/navfac_ww_pp /navfac_hq_pp/navfac_bdd_pp/eul/projects/large_cavitation_channel/index.html

Data and scaling

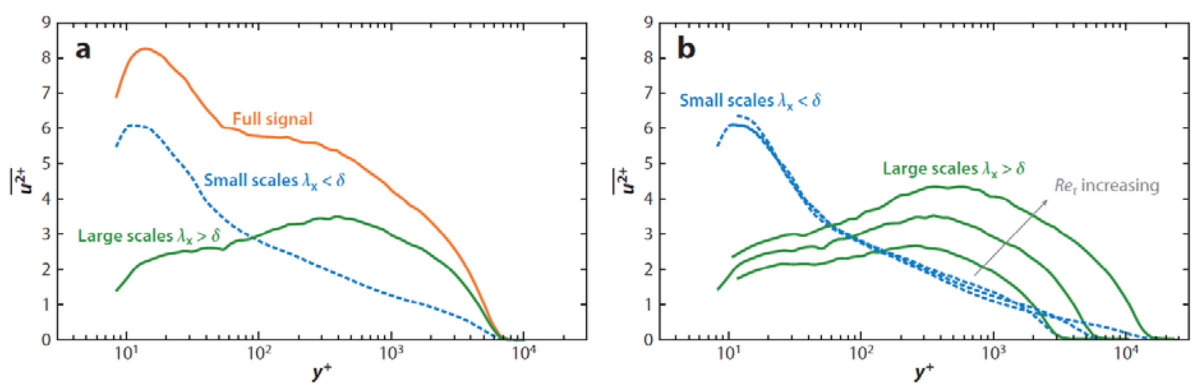
FOOTPRINT OF THE SUPERSTRUCTURES/VLSMS





Spectral footprint of the VLSMs is a secondary peak in the streamwise spectrum

- **becomes increasingly energetic as the Reynolds number increases**
- **cohabits with the near-wall peak at low Reynolds number**



Important implications for scaling & modeling

Things get easier at higher Re!

Marusic, Mathis & Hutchins, Int J. Heat Fluid Flow, 2010
Monty et al, J. Fluid Mech., 2009
Hutchins & Marusic, Phil. Trans. R. Soc. A, 2007

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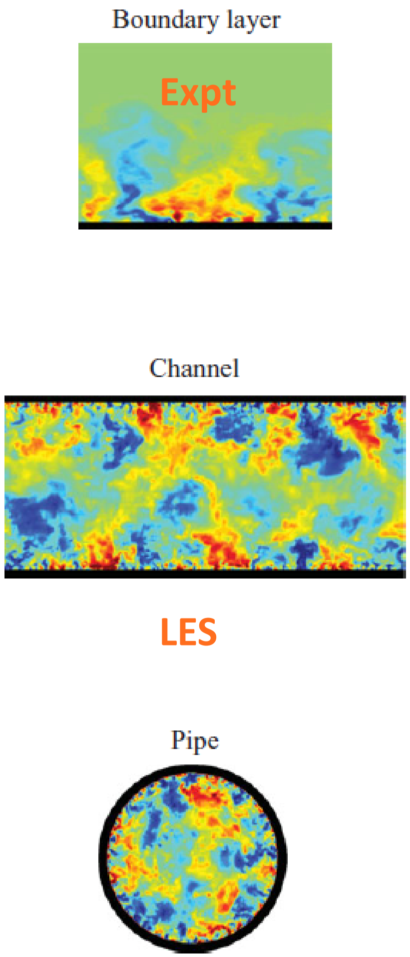
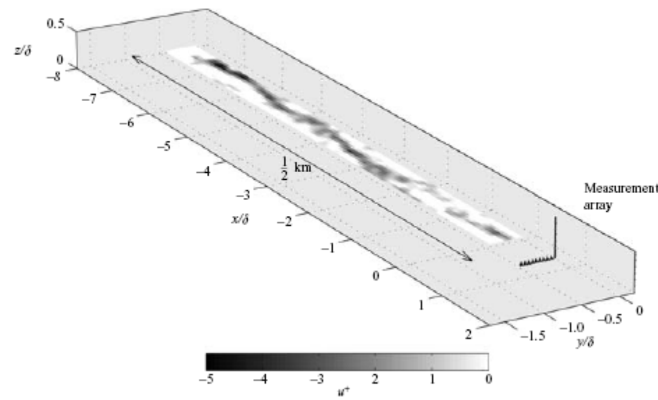
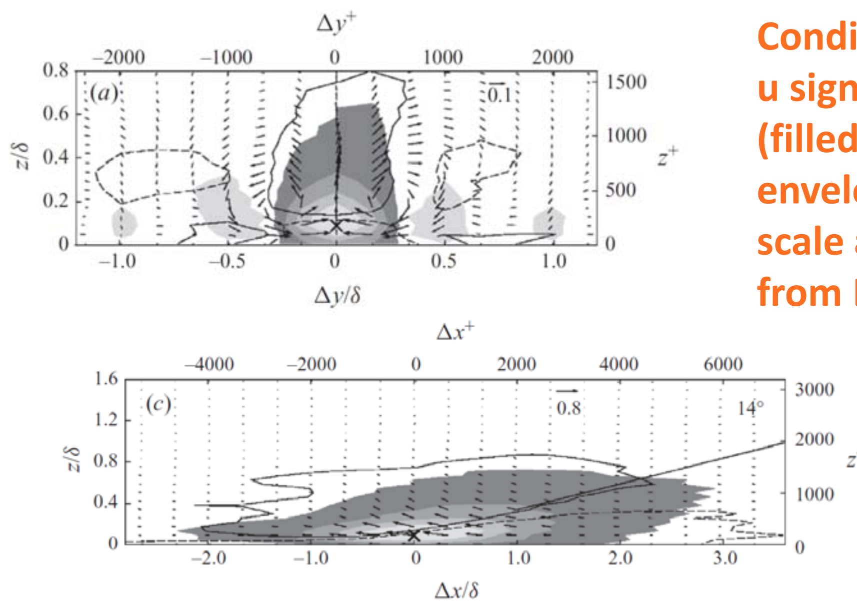
OBSERVATIONS OF SUPERSTRUCTURES/VLSM





Reconstructed u signal of the superstructures in the ASL



Conditionally averaged u signal of the VLSM (filled contours) and envelope of the small scale activity (lines) from LES

Monty et al, J. Fluid Mech., 2009
Hutchins & Marusic, J. Fluid Mech., 2007
Chung & McKeon, J. Fluid Mech., 2011

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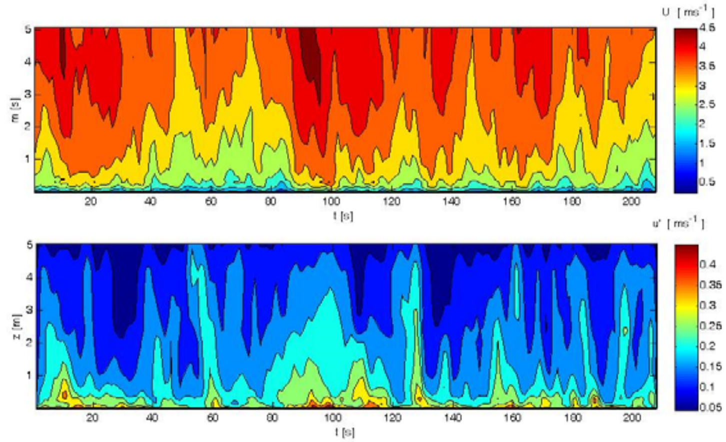
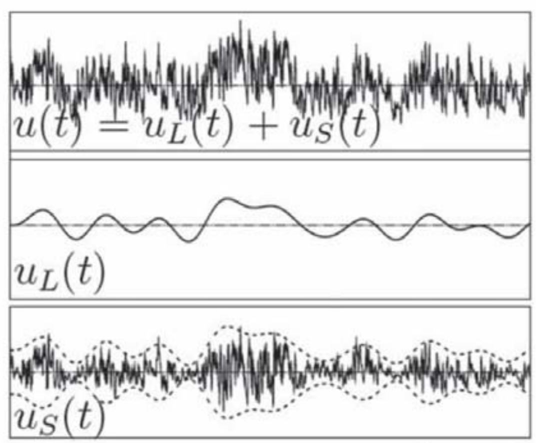
MODULATION OF ALL VELOCITY COMPONENTS





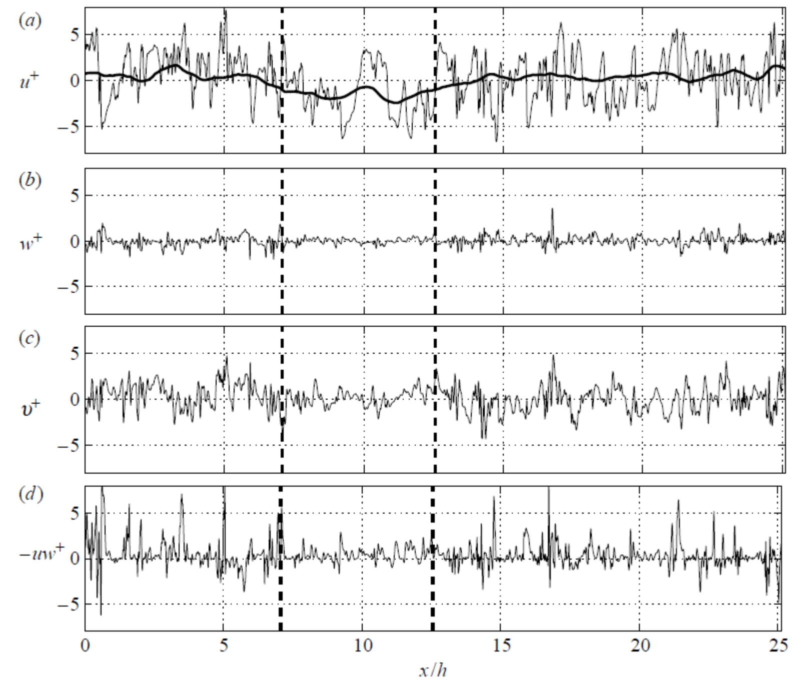


Figure 6. Example fluctuating velocity signals from the $Re_\tau \approx 950$ channel of del Álamo *et al.* (2004) at $z^+ = 15$. (*a*) Fluctuating u component, thicker line shows large-scale component, (*b*) wall-normal w fluctuation, (*c*) spanwise v fluctuation, (*d*) Reynolds shear-stress fluctuation. Dashed vertical lines show region of negative large-scale fluctuation.

Guala, Metzger & McKeon, JFM 2011
Marusic, Mathis & Hutchins, Science, 2010
Hutchins & Marusic, PTRSA, 2007

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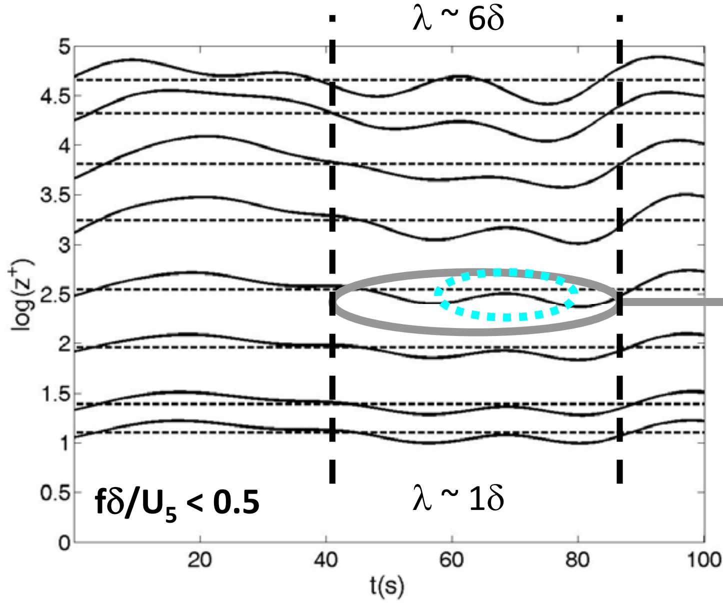
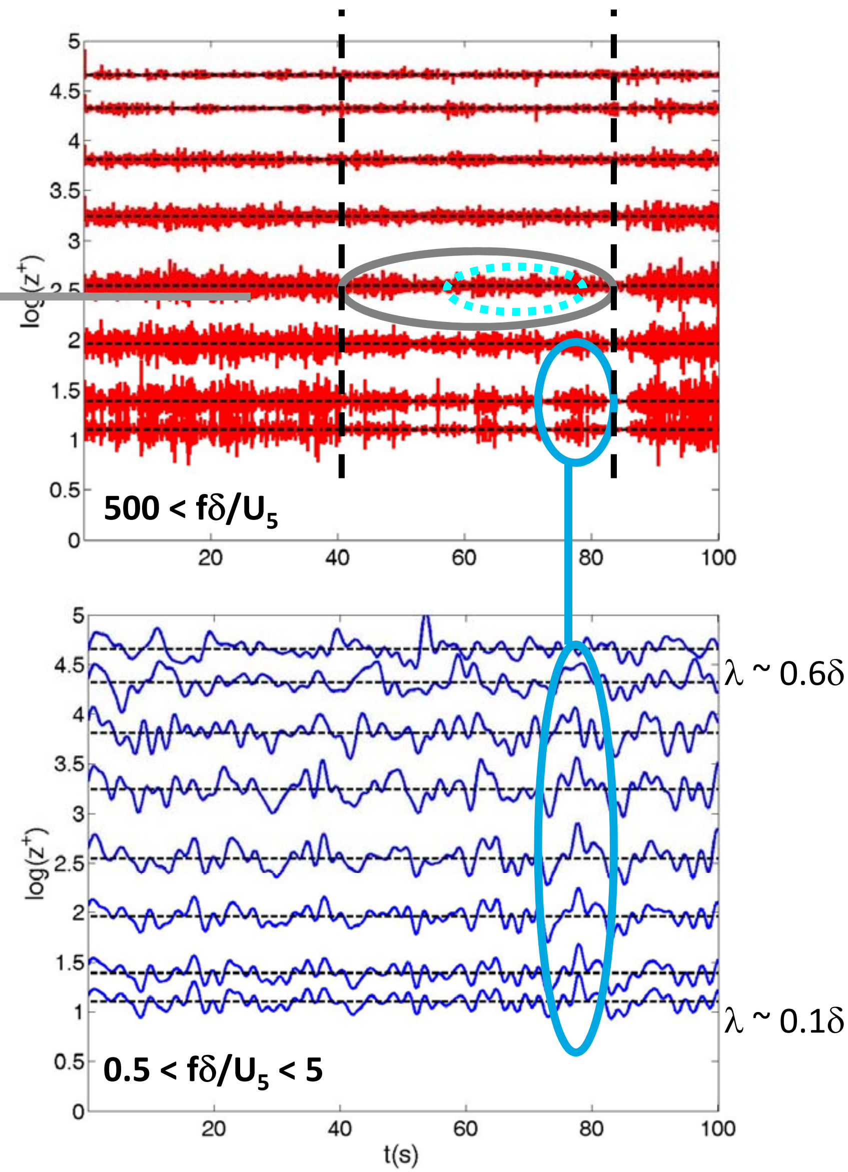
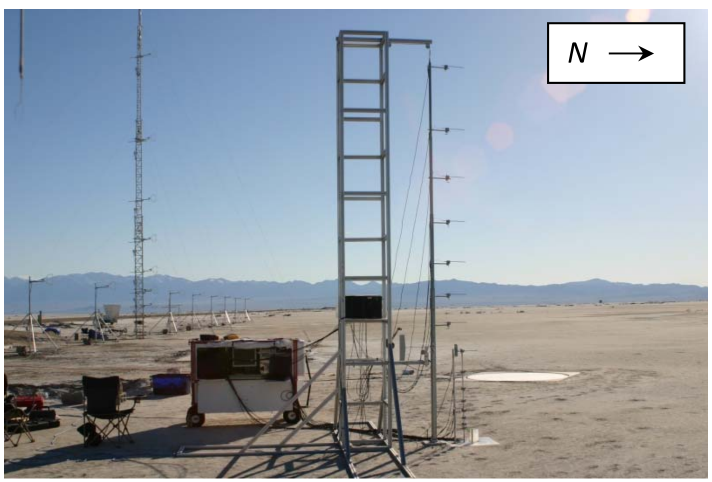
A HIERARCHY OF SCALE MODULATION







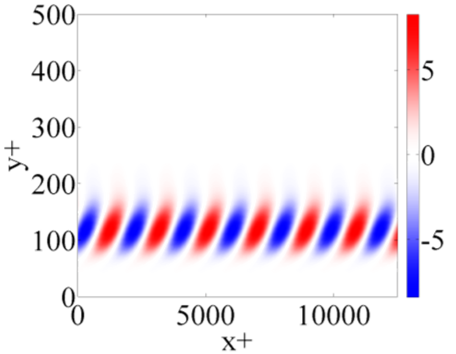
Metzger, Holmes & McKeon, Phil. Trans Royal Soc. 2007

AMPLITUDE MODULATION AS A LINEAR PHENOMENON

(k, n, c, A) *u*

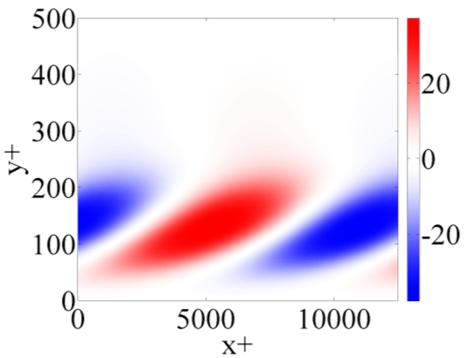
k_1

(+/- 6 , +/-6, 2/3, -1.00i)



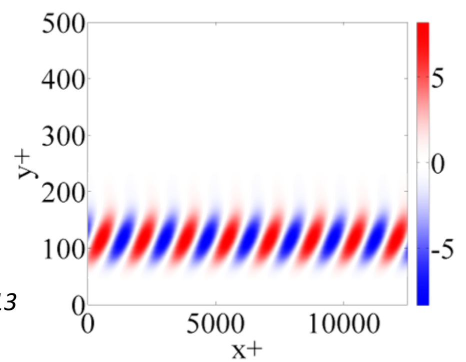
k_2

(+/- 1 , +/- 6, 2/3, 4.50)



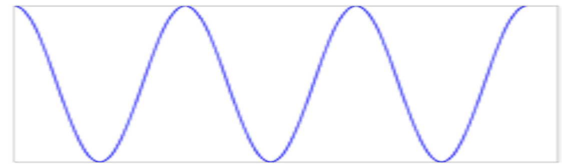
k_3

(+/- 7, +/-12, 2/3, 0.83i)

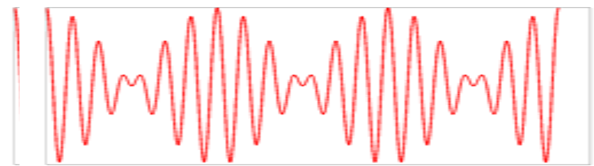


Sharma & McKeon, J. Fluid Mech., 2013

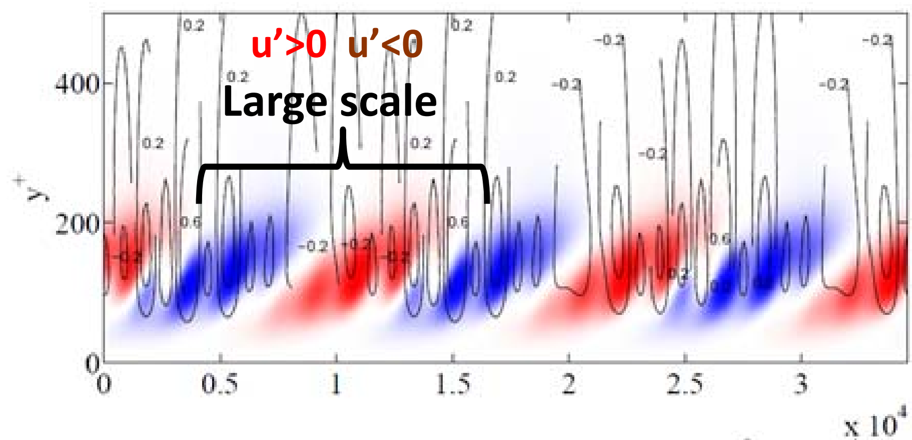
k_2



$k_1 + k_3$



$k_1 + k_2 + k_3$



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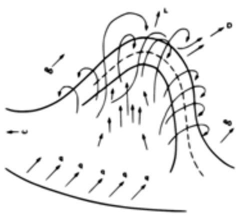
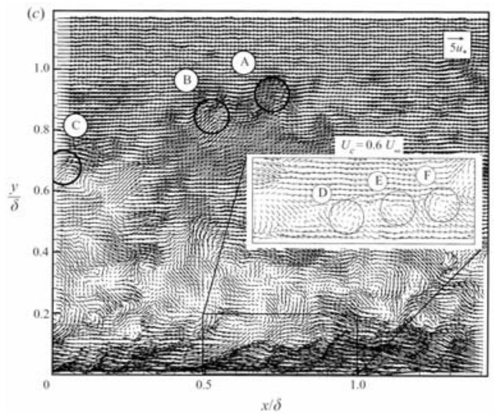
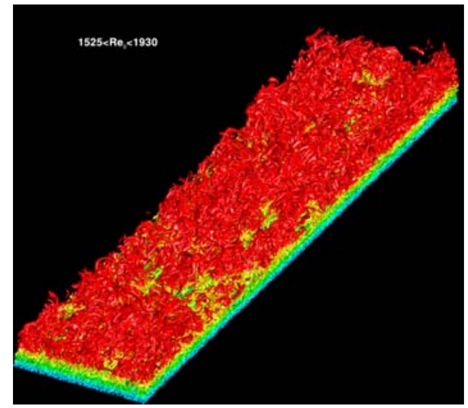
Data and scaling

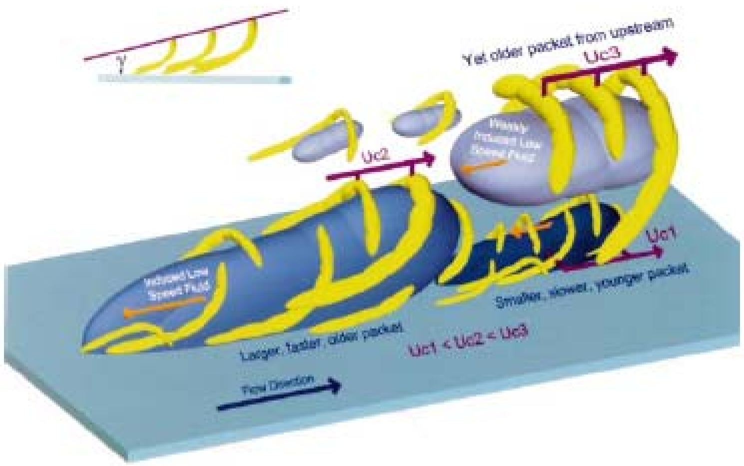
HAIRPIN VORTEX PARADIGM

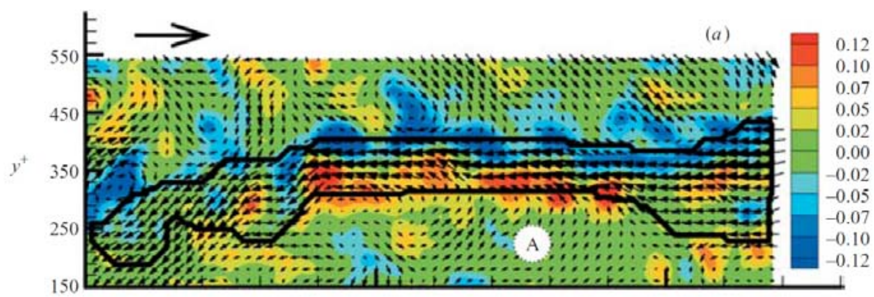


Theodorsen's hairpin vortices identified* in experiments and DNS









"Packets of packets"?
Clear Re stress organization around packets

BUT is this a low Re phenomenon?

Theodorsen, Proc. Midwest Mechanics Symp. 1952
Adrian, Meinhart & Tomkins, J. Fluid Mech. 2000
Wu & Moin, Phys. Fluids 2010
Kim & Adrian, Phys. Fluids 1999
Ganapathisubramani, Longmire & Marusic, J. Fluid Mech. 2003

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Data and scaling

NEAR-WALL ACTIVITY

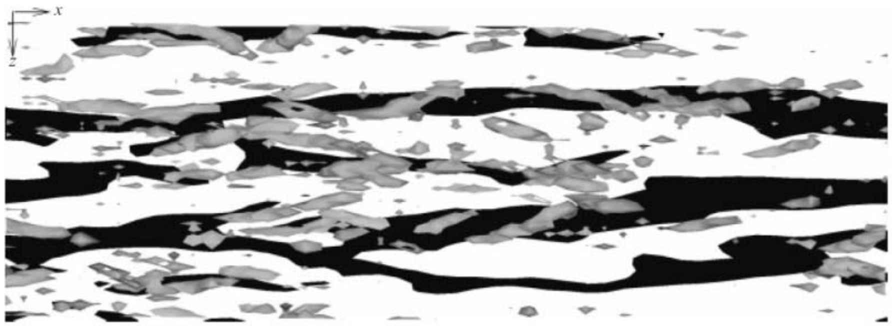
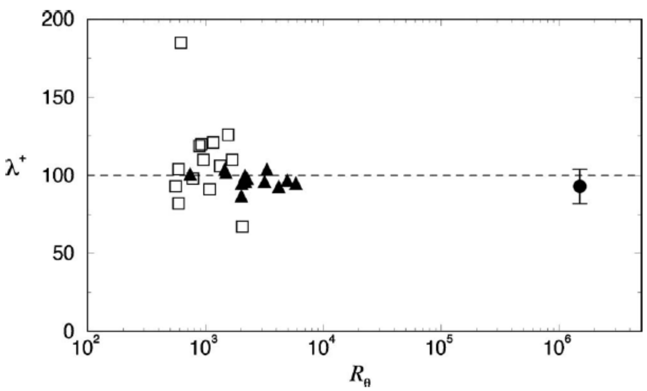
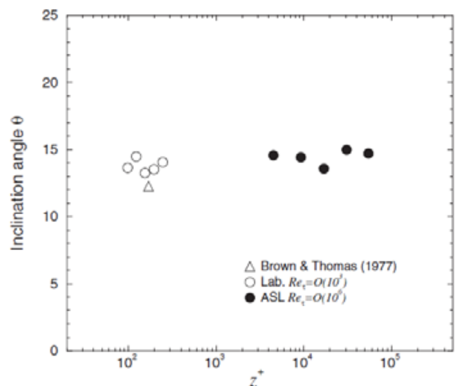
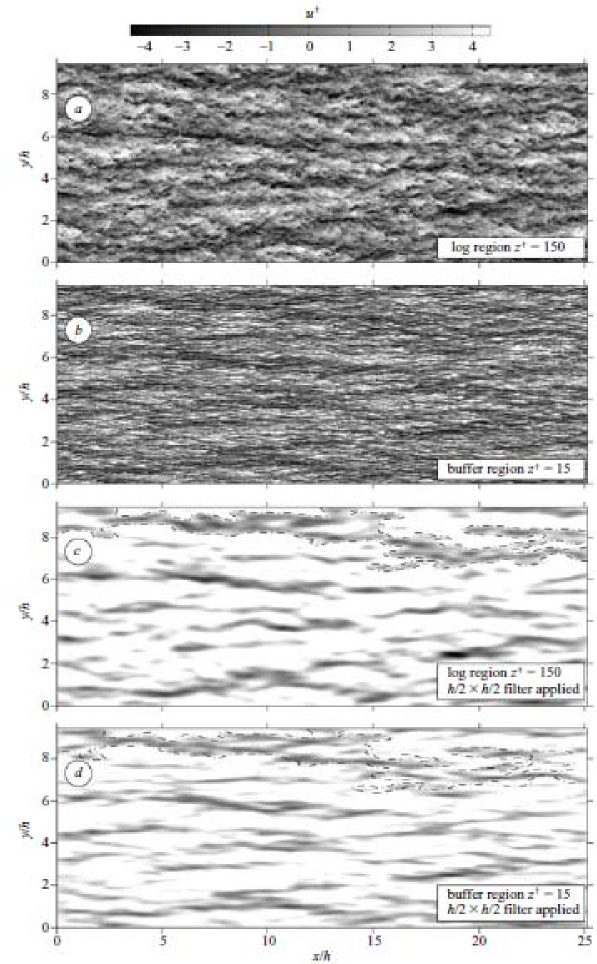


FIGURE 1. Top view of the near-wall region covering $(x^+, z^+) = (1400, 450)$ in the streamwise and spanwise directions. Lifted low-speed streaks (black) denote $u' < 0$ at $y^+ = 20$ and streamwise vortices (grey-shaded) are indicated by the λ_2 vortex definition (Jeong & Hussain 1995) in the region $0 < y^+ < 60$.







Reynolds number insensitivity of near-wall structure
BUT also footprint of log layer structures (VLSM)

Schoppa & Hussain, J. Fluid Mech. 2002
Marusic et al, Phys. Fluids 2010
Heuer & Marusic, Phys. Rev. Letters 2007
Hutchins & Marusic, J. Fluid Mech. 2007

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MODELING CONCEPTS

Review of (some) models for regions of the flow

What do the models tell us about the math?

Structure-based models vs. energy norms

- Attached eddy hypothesis (Townsend, Perry, Marusic, et al)
- Near-wall structure, minimal flow unit
- Structure implied by the mean momentum balance
- Properties of the linear(ized) N-S operator
  - Non-normality, transient growth and disturbance amplification
  - Resolvent analysis
- Importance (or not) of exact solutions

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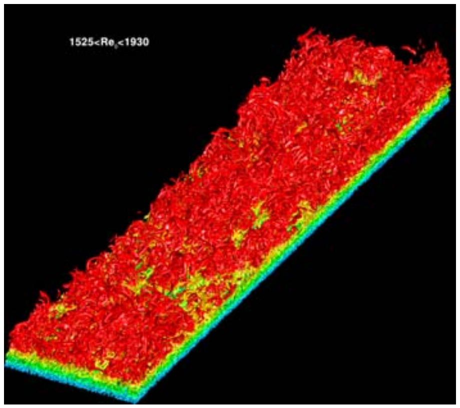
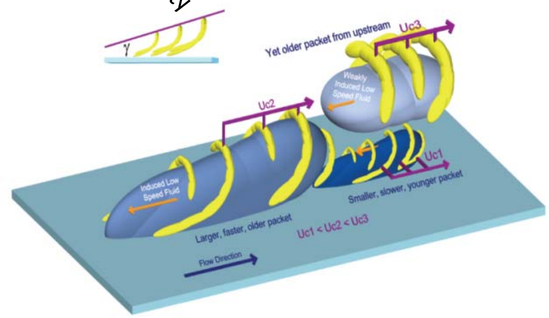
DECONSTRUCTING WALL TURBULENCE



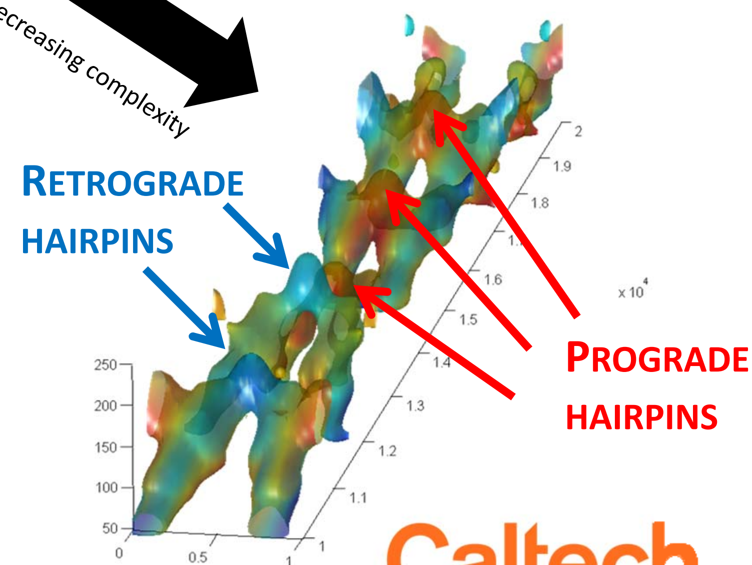
Wu & Moin, http://ctr.stanford.edu, J. Fluid Mech. 2008

Decreasing complexity



Adrian, Meinhart & Tomkins, J. Fluid Mech. 2000

Decreasing complexity



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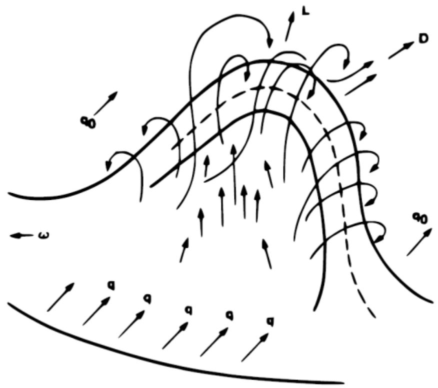
ATTACHED EDDY HYPOTHESIS



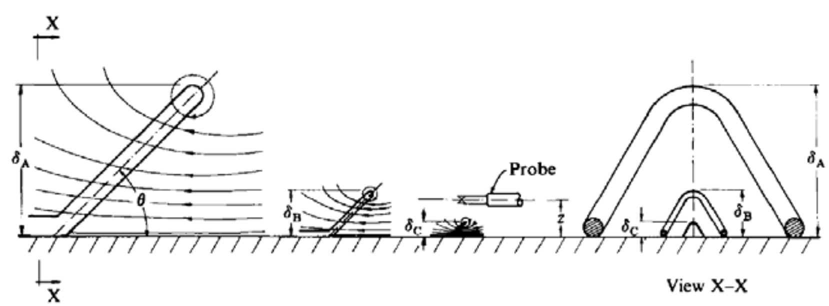
Theodorsen vortex (1952)

Sketch (Weske) of Theodorsen vortex (1952)

"…the main energy-containing motion of a turbulent wall-bounded flow may be described by a random superposition of such (attached) eddies of different sizes, but with similar velocity distributions." (AAT, 1956, 1976)

eddies of size y per unit wall area = A/y

i.e. pdf inversely proportional to distance from the wall, or more accurately, eddy size



Townsend, 1956, 1976
Perry, Henbest & Chong, J. Fluid Mech. 1986

THE NEAR-WALL CYCLE

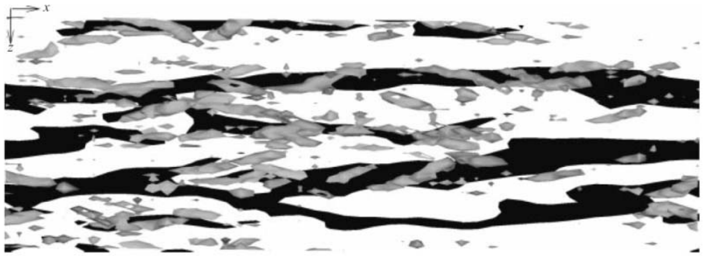
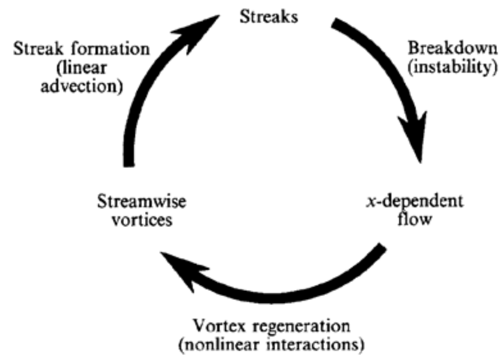


FIGURE 1. Top view of the near-wall region covering $(x^+, z^+) = (1400, 450)$ in the streamwise and spanwise directions. Lifted low-speed streaks (black) denote $u' < 0$ at $y^+ = 20$ and streamwise vortices (grey-shaded) are indicated by the λ_2 vortex definition (Jeong & Hussain 1995) in the region $0 < y^+ < 60$.



Well-developed exact solutions for near-wall activity, captured in minimal flow unit”

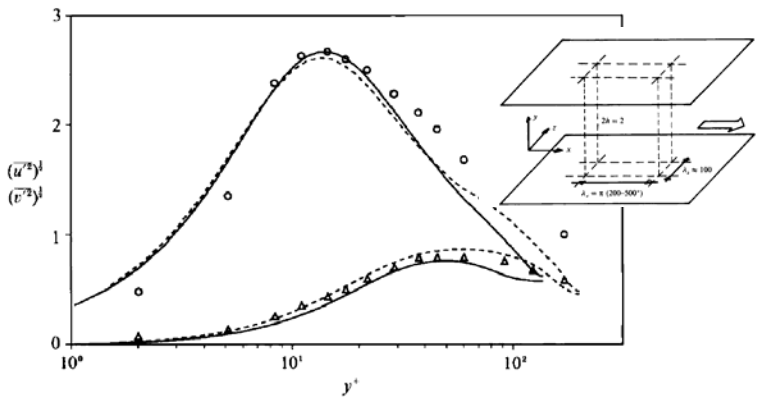


FIGURE 10. Near-wall turbulent intensities in wall coordinates. Solid lines: $Re = 3000$, $\lambda_x \times \lambda_z = \pi \times 0.3\pi$; dashed: $Re = 5000$, $0.6\pi \times 0.18\pi$. Symbols as in figure 9.

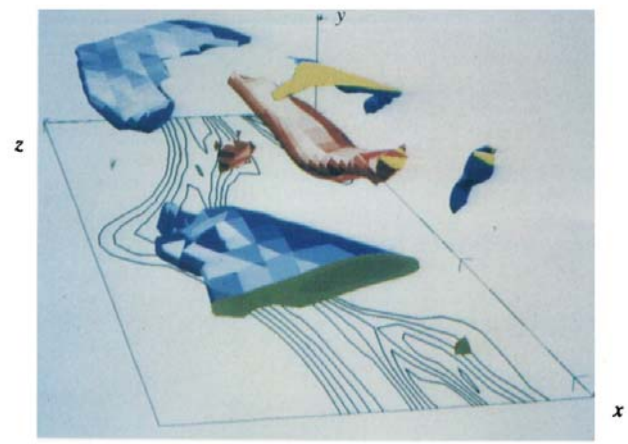
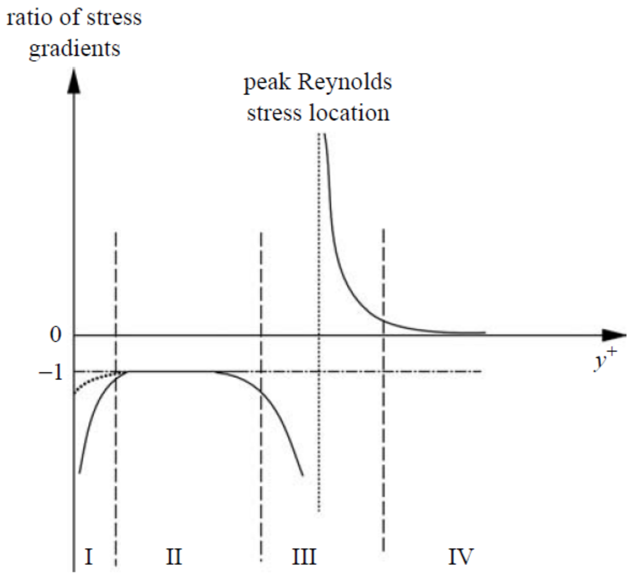


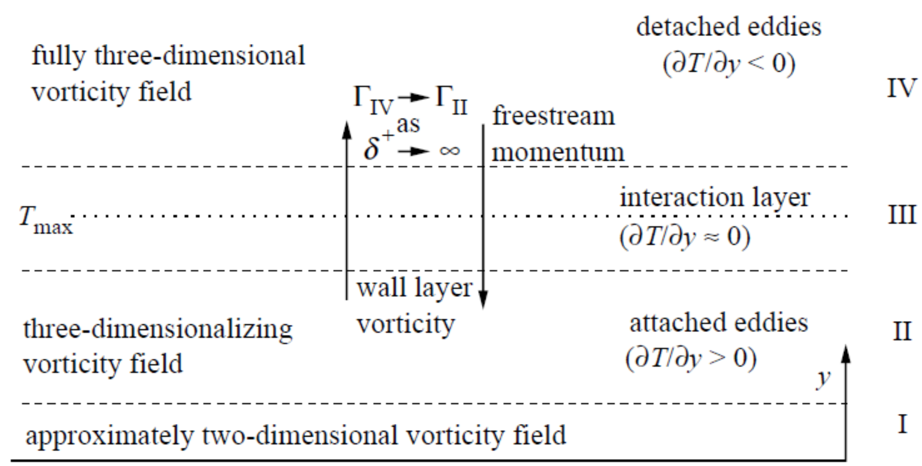
FIGURE 21. Three-dimensional view of the flow field in figure 20. Flow coming out of the page. Horizontal plane is $y^+ = 10$, with isolines for $\omega_z \geq -2.5$ (by 0.25). Surfaces are $\omega_x = -0.75$ (blue), and $\omega_x = 1.1$ (red), between $y^+ = 20$ and 50. Figure displays full horizontal extent of computational box.

Schoppa & Hussain, J. Fluid Mech., 2002
Hamilton, Kim & Waleffe, J. Fluid Mech., 1995
Jimenez & Moin, J. Fluid Mech., 1991

STRUCTURE ADMITTED BY MEAN MOMENTUM BALANCE

$$0 = \frac{1}{\delta^+} + \frac{d^2U^+}{dy^{+2}} - \frac{d\langle uv\rangle^+}{dy^+}$$





Klewicki et al, Phil. Trans. Royal Soc., 2007

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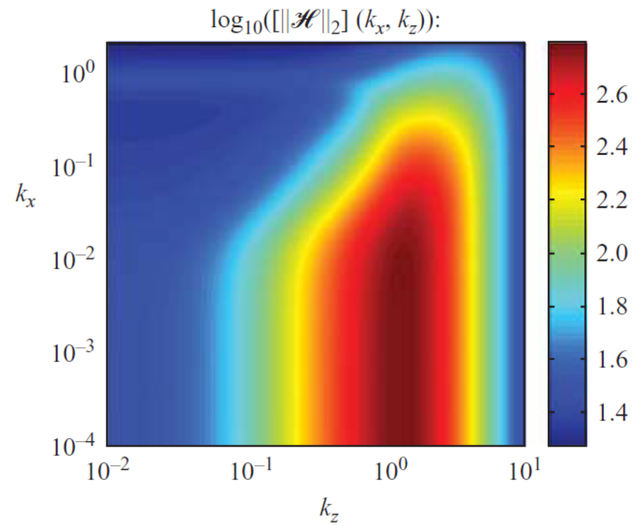
TRANSIENT GROWTH AND NON-NORMALITY



Input-output transfer function H

k_x=0 mode is always most amplified

Two spanwise wavelengths can be identified

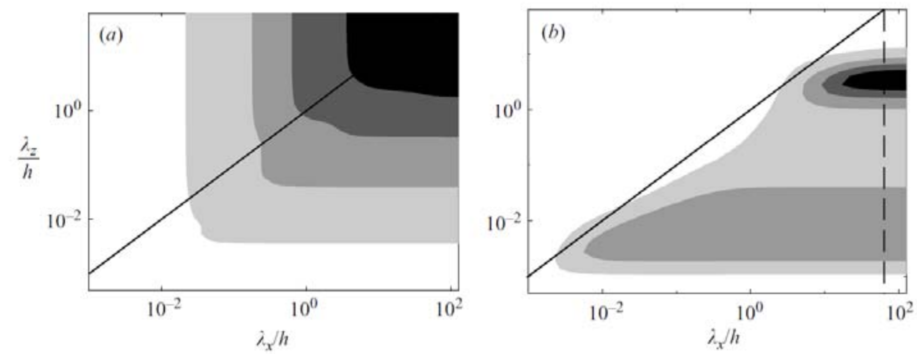


FIGURE 2. (*a*) Imaginary part $\sigma_{I,1}h/u_\tau$ of the least damped eigenvalue of (2.3)–(2.4), represented as a function of λ_x/h and λ_z/h. The levels represented are, from dark to light, $-1(\times 10)-1000$. (*b*) Maximum transient growth G as a function of λ_x/h and of λ_z/h. The levels represented are, from light to dark, $1.5(+1)4.5$. The solid straight line is $\lambda_x = \lambda_z$. The dashed vertical line is $\lambda_x = 60h$. In both figures $Re_\tau = 2\times 10^4$.

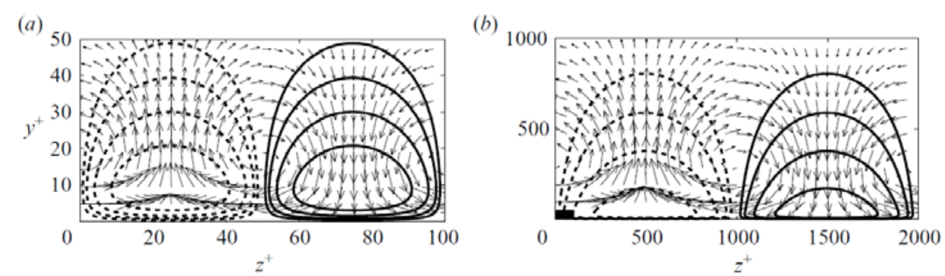


FIGURE 5. Transverse view of the optimal solution for $\lambda_x = 60h$, $Re_\tau = 2\times 10^4$. The arrows indicate the initial (v, w) field and the longest one is unity in the same arbitrary units used for u. The contours represent the most amplified streamwise velocity and the levels represented are $0.125(\times 2)2$. The solid contours are $u > 0$ and the dashed ones are $u < 0$. (*a*) $\lambda_z^+ = 100$. (*b*) $\lambda_z^+ = 2000$; the small solid black box in the bottom left corner is the size of the axes in (*a*).

Jovanovic & Bamieh, J. Fluid Mech. 2005
del Alamo & Jimenez, J. Fluid Mech. 2006

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IMPORTANCE OF LINEAR COUPLING

$$\frac{d}{dt}\begin{bmatrix}\hat{v}\\ \hat{\omega}_y\end{bmatrix} = [A]\begin{bmatrix}\hat{v}\\ \hat{\omega}_y\end{bmatrix} + \begin{bmatrix}\mathcal{N}_v\\ \mathcal{N}_{\omega_y}\end{bmatrix} \qquad [A] = \begin{bmatrix}L_{\text{os}} & 0\\ L_{\text{c}} & L_{\text{sq}}\end{bmatrix}$$

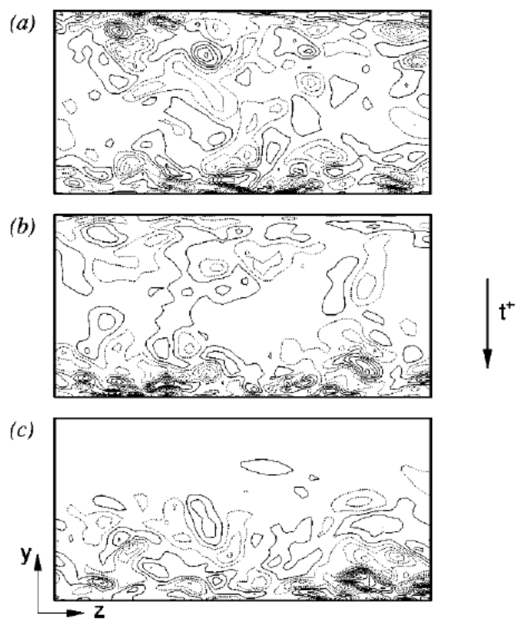


FIG. 2. Contours of streamwise vorticity in $y-z$ plane: (a) $t^+=0$; (b) $t^+=20$; (c) $t^+=200$. $-80<\omega_x<80$ with 18 contour levels. Note that $L_c=0$ only in the upper-half of the channel.

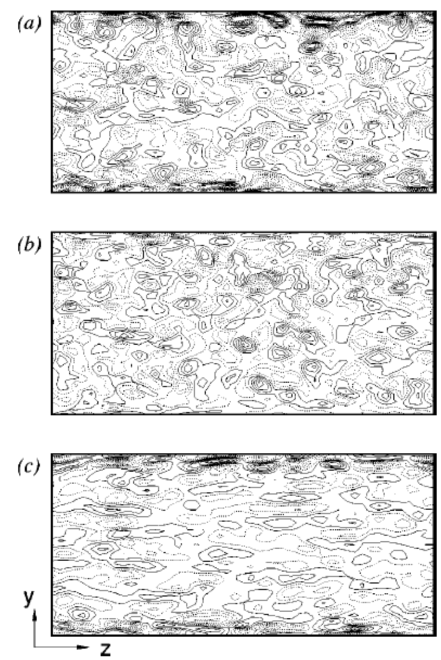
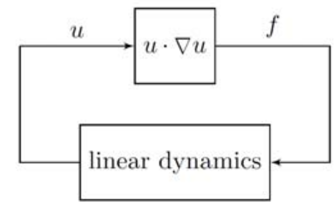


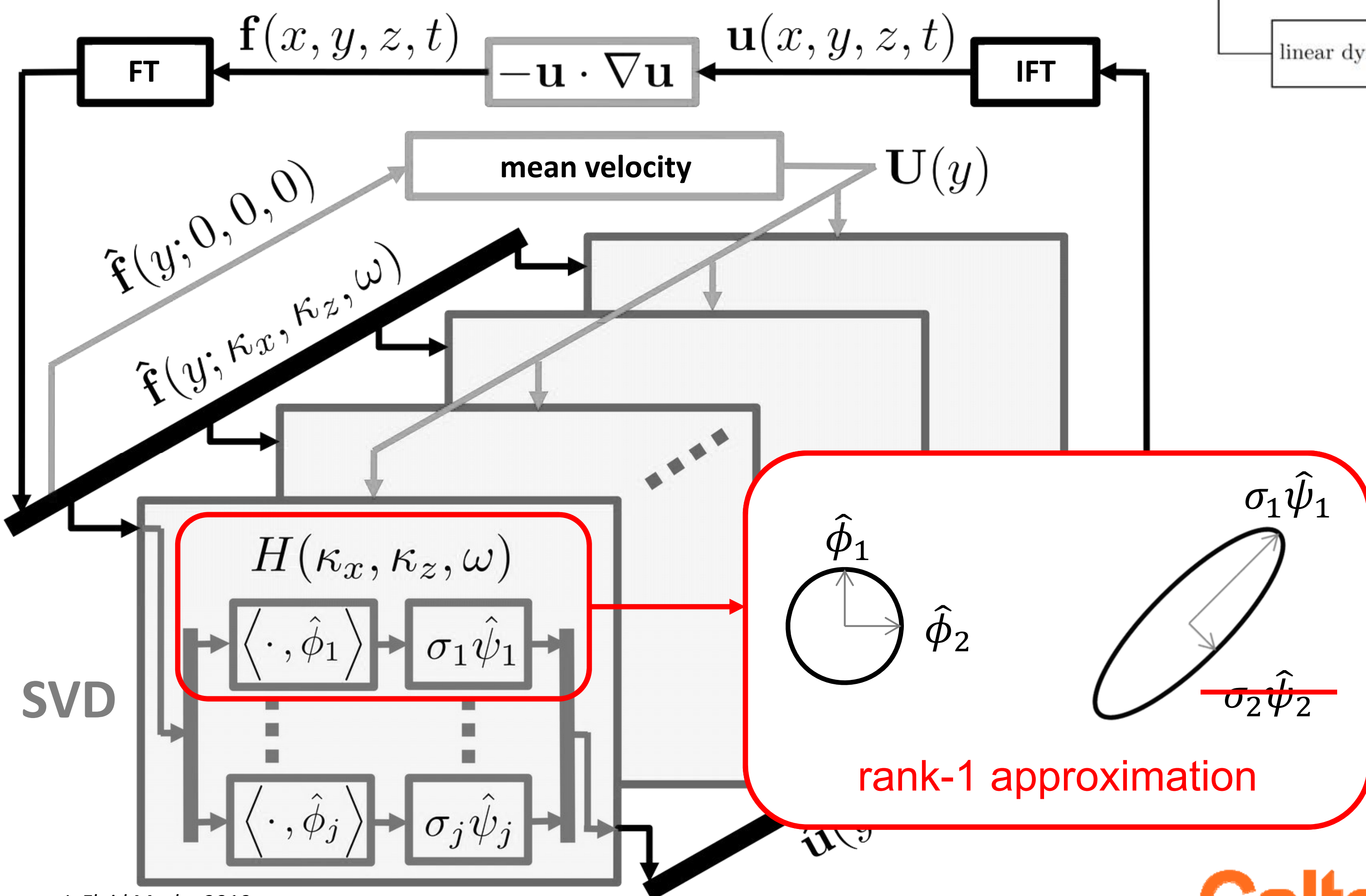
FIG. 4. Contours of streamwise vorticity in $y-z$ plane at $t^+=20$, started from an initial random field: (a) Case 1, regular turbulent flow; (b) Case 2, without the linear coupling term, L_c; (c) Case 3, without the nonlinear terms. Contour levels are the same as Fig. 2.

Linear coupling is responsible for streamwise streaks, nonlinearity for the correct spacing

Kim & Lim, Phys. Fluids, 2000

GAIN-BASED DECOMPOSITION





McKeon & Sharma, J. Fluid Mech., 2010
Moarref, Sharma, Tropp & McKeon, J. Fluid Mech., 2013

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EXACT TRAVELING WAVE SOLUTIONS

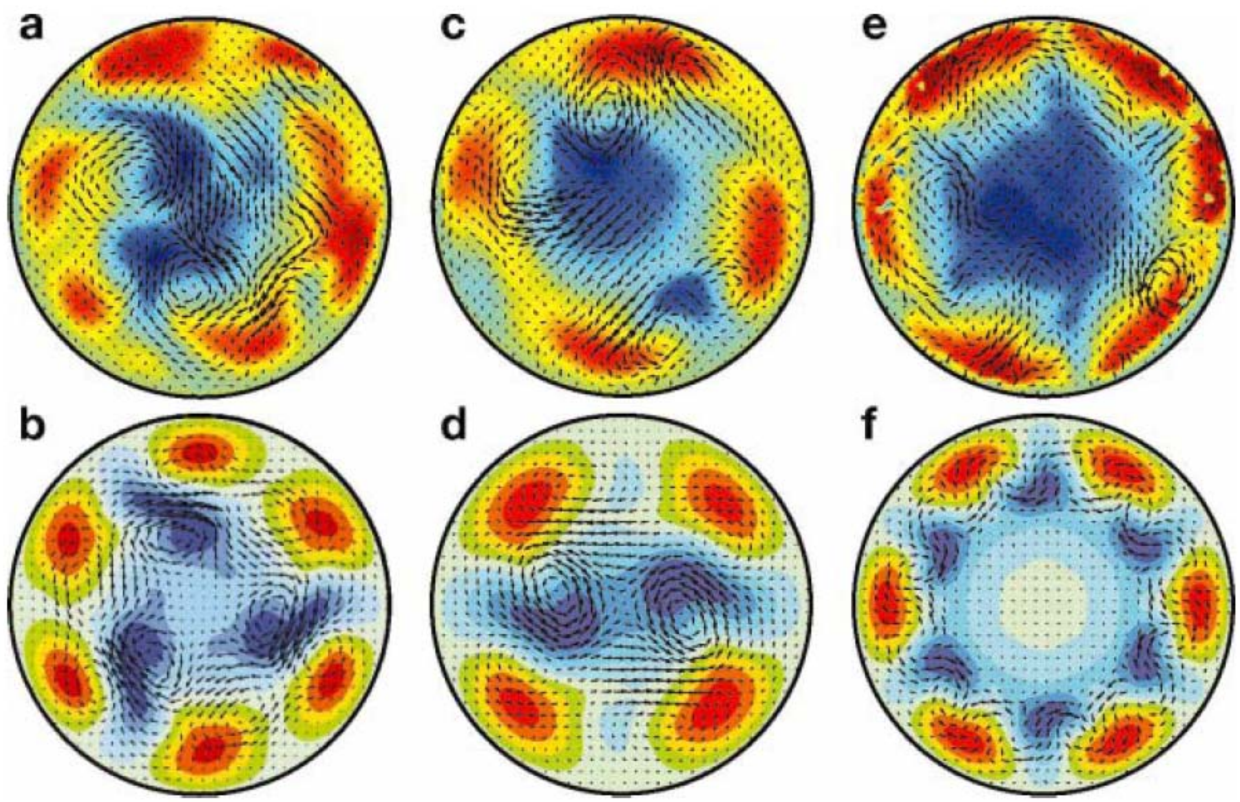

Figure 5

Pairing (*a* & *b*, *c* & *d*, *e* & *f*) between flow structures detected in experimental cross sections (*top row*) and numerically determined traveling waves (*bottom row*). The representation of the velocity fields is the same as in **Figure 4**. From Hof, van Doorne et al. (2004).

Eckhardt, Schneider, Hof & Westerweel, Annu. Rev. Fluid Mech., 2007

PROPER ORTHOGONAL (K-L) DECOMPOSITION

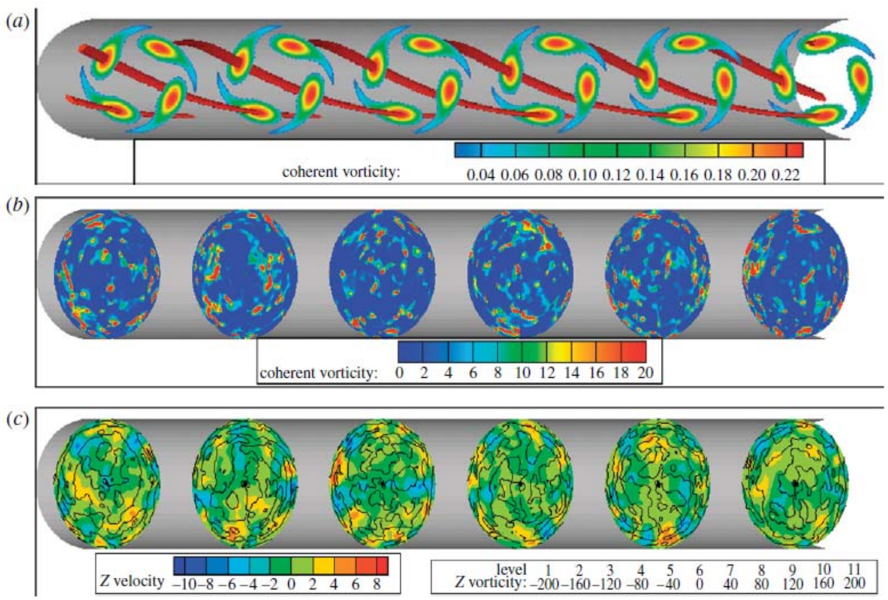

Figure 1. Three-dimensional view of an example (*a*) Fourier POD mode and (*b*,*c*) a method of snapshots POD mode. The Fourier POD mode is the (3, 2, 1) mode, and plotted are six cross sections of coherent vorticity (degree of swirl) and isosurfaces of 95% maximum coherent vorticity. With a streamwise wavenumber of 3, there are three twists of the structure in the streamwise direction. In a similar fashion, cross sections of (*b*) coherent vorticity and (*c*) streamwise velocity with contours of streamwise vorticity are shown for the most energetic snapshots mode, showing much more spatial variation in its structure in the streamwise and azimuthal directions compared with the Fourier mode.

Decomposition using an energy norm leads to large d.o.f. representation

	channel $Re_\tau = 80$		FV $Re_\tau = 80$		channel $Re_\tau = 125$		pipe $Re_\tau = 150$	
	(m, n, q)	energy (%)	(m, n, q)	energy (%)	(m, n, q)	energy (%)	(m, n, q)	energy (%)
1	(0, 1, 1)	13.00	(0, 3, 1)	6.65	(0, 3, 1)	4.28	(1, 5, 1)	1.62
2	(0, 2, 1)	8.74	(0, 0, 1)	6.08	(0, 1, 1)	3.99	(1, 6, 1)	1.58
3	(0, 3, 1)	7.32	(0, 1, 1)	5.65	(0, 4, 1)	3.27	(1, 3, 1)	1.56
4	(0, 2, 2)	6.93	(0, 2, 1)	5.13	(0, 5, 1)	2.87	(1, 4, 1)	1.42
5	(0, 1, 2)	4.23	(0, 3, 2)	3.67	(0, 4, 2)	2.29	(0, 6, 1)	1.39
6	(0, 3, 2)	4.08	(0, 2, 2)	3.52	(0, 1, 2)	2.20	(1, 7, 1)	1.32
7	(1, 3, 1)	3.27	(0, 4, 1)	3.23	(0, 3, 2)	2.06	(0, 5, 1)	1.28
8	(0, 0, 1)	3.05	(0, 4, 2)	3.13	(0, 2, 1)	1.97	(0, 3, 1)	1.25
9	(1, 3, 2)	2.66	(0, 1, 2)	2.28	(0, 2, 2)	1.88	(1, 2, 1)	1.18
10	(0, 1, 3)	1.88	(1, 3, 1)	1.70	(0, 6, 1)	1.38	(0, 4, 1)	1.11
11	(1, 2, 1)	1.56	(1, 3, 2)	1.50	(0, 5, 2)	1.31	(0, 2, 1)	1.09
12	(0, 0, 2)	1.47	(0, 5, 1)	1.43	(1, 3, 1)	1.25	(2, 4, 1)	1.07
13	(1, 2, 2)	1.37	(1, 4, 1)	1.31	(1, 2, 1)	0.95	(2, 5, 1)	1.00
14	(0, 1, 4)	1.21	(1, 4, 2)	1.28	(1, 4, 1)	0.84	(1, 1, 1)	0.98
15	(0, 2, 3)	1.20	(1, 1, 1)	1.28	(1, 5, 1)	0.83	(2, 7, 1)	0.90

Duggleby, Ball & Schwaenen, Phil. Trans. R. Soc. A 2010

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DIRECT LYAPUNOV EXPONENT ANALYSIS

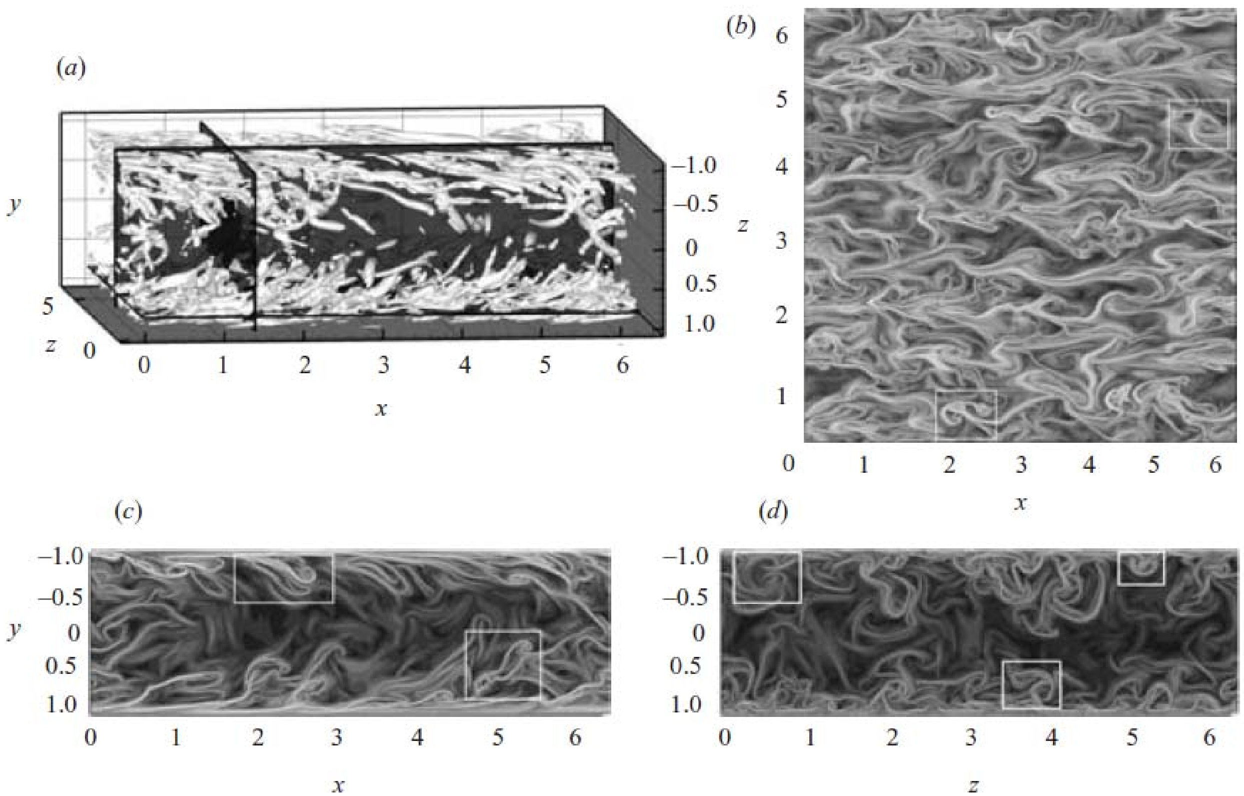

FIGURE 7. Two-dimensional DLE plots of the fully turbulent channel. (*a*) 1 % maximum Q superimposed with the location of the three planes, (*b*) constant wall-normal cut, (*c*) constant-spanwise cut ($y^+ = 33$), and (*d*) constant-streamwise cut.

Green, Rowley & Haller, J. Fluid Mech. 2007

CHALLENGES & OPPORTUNITIES

1. Self-sustaining processes. How can these be identified, characterized and compared? What are the connections between such processes at low (transitional) and high Reynolds numbers?

2. Connections between turbulent statistics, coherent structure and the Navier-Stokes equations. How can experimental and numerical observations be reconciled with, or derived from, the equations of motion?

3. Systems approaches to turbulence and control of engineering flows. What mathematical tools are brought into play by such approaches? What system structure is revealed? Can such approaches be used for modeling, prediction and/or control?

4. Low Reynolds number vs. asymptotically high Reynolds number. Which dynamics and phenomena retain their dynamical significance, and which are local phenomena? What can be learned from the opposite extreme in Reynolds number?

5. Modeling, prediction and control. How do we leverage fundamental understanding towards practical advances in engineering applications?

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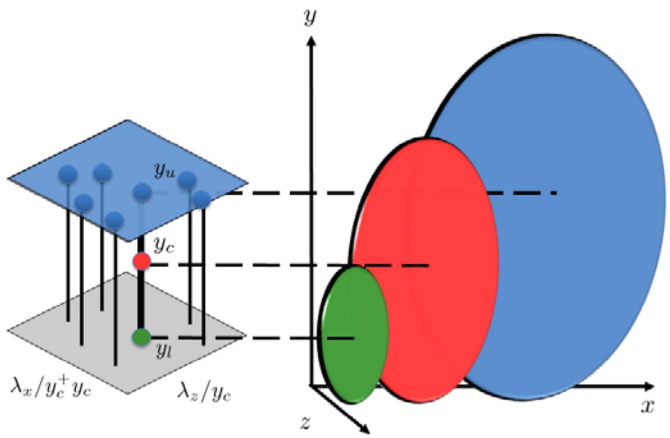
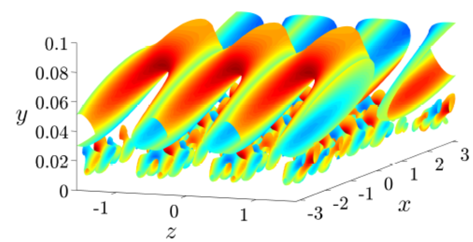
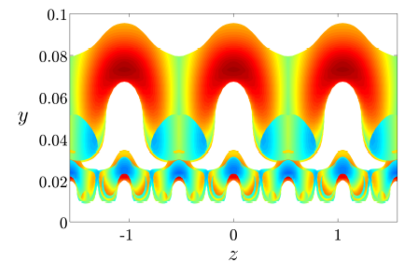
Challenges/opportunities

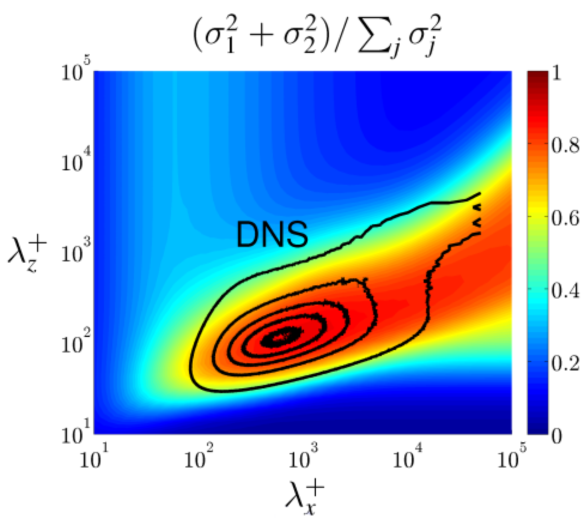
"Self-similar", "self-sustaining", "robust"…







Self-similar structural hierarchies lead to order reduction



Regions of high amplification (singular value in resolvent SVD) overlay energetic activity

This is a *robust* system

Moarref, Sharma, Tropp & McKeon, J. Fluid Mech., 2013

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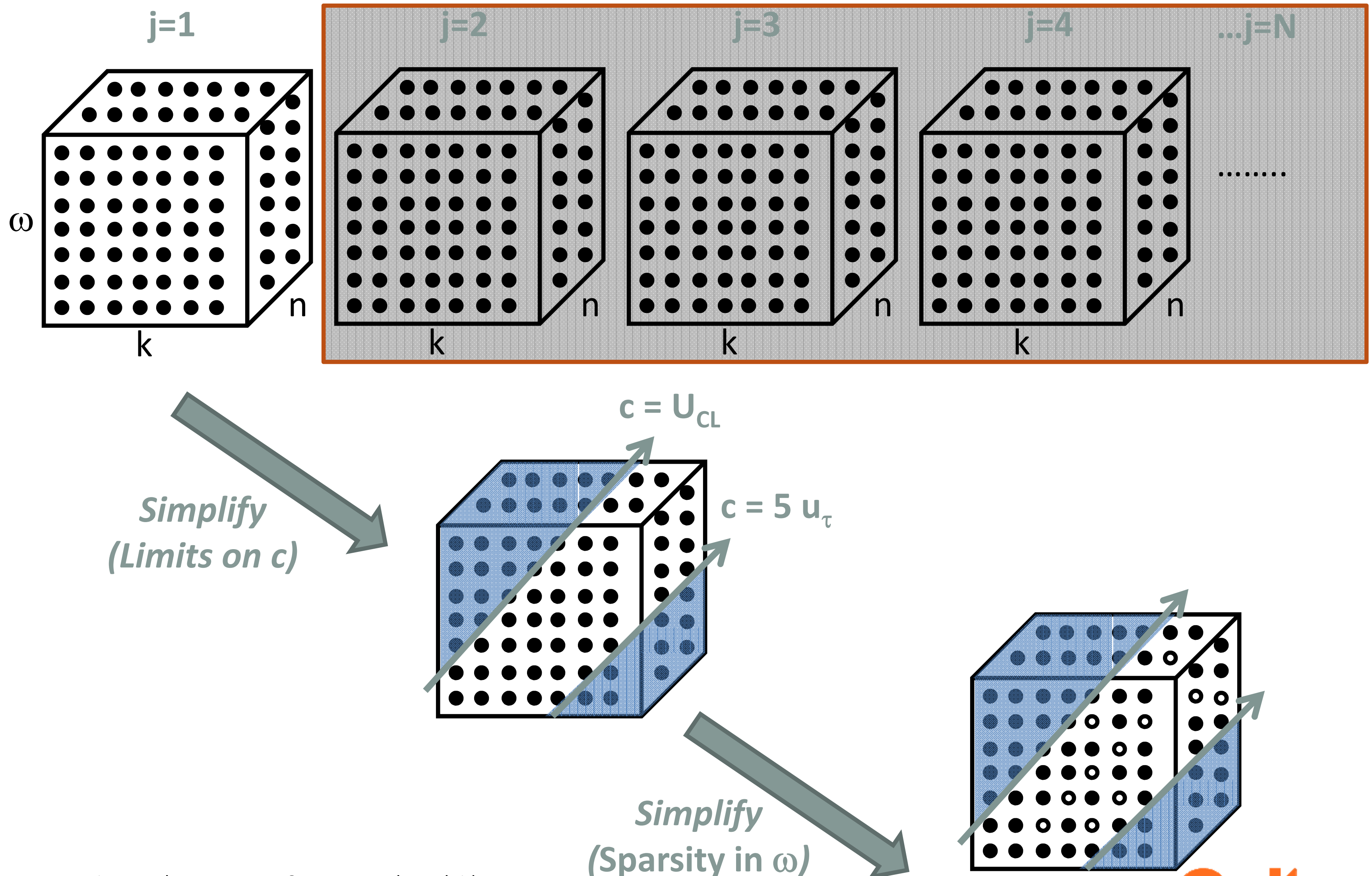
SPARSE



Bourguignon, Sharma, Tropp & McKeon, Phys. Fluids, 2014
Moarref, Sharma, Tropp & McKeon, J. Fluid Mech. 2013

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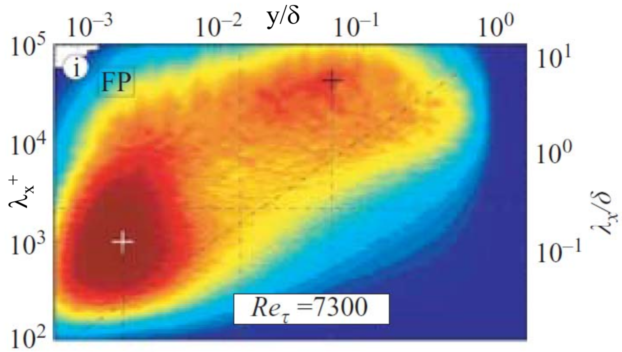
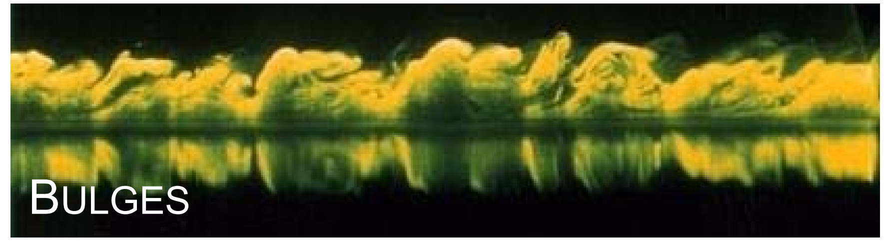
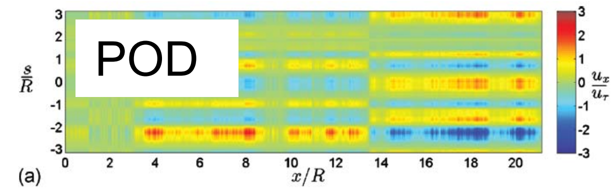
Challenges/opportunities

THE BUILDING BLOCKS OF TURBULENCE

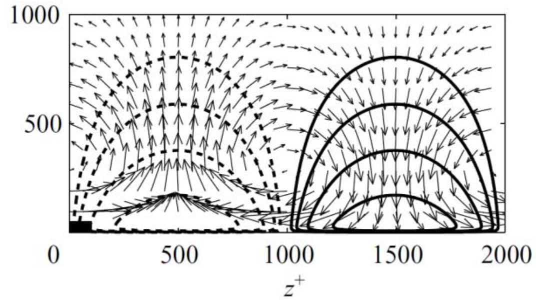
STATISTICS & SPECTRA



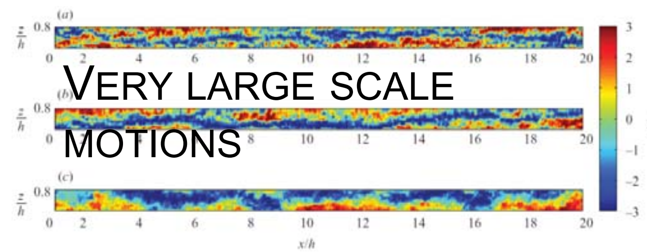




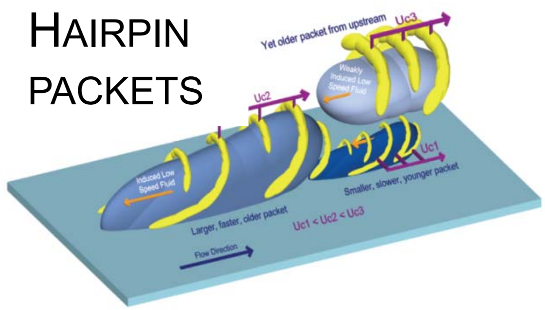
LINEAR RECEPTIVITY



“So, actually the elephant has all the features you mentioned…”



HAIRPIN PACKETS



Credits, CW from top left
Hutchins & Marusic
Gad-el-Hak
Hellstroem, Sinha & Smits
Monty, Stewart, Williams & Chong
Adrian, Meinhart & Tomkins
Del Alamo & Jimenez

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THEMES FOR THE WORKSHOP/PROGRAM

1. **Self-sustaining processes**. How can these be identified, characterized and compared? What are the connections between such processes at low (transitional) and high Reynolds numbers?

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