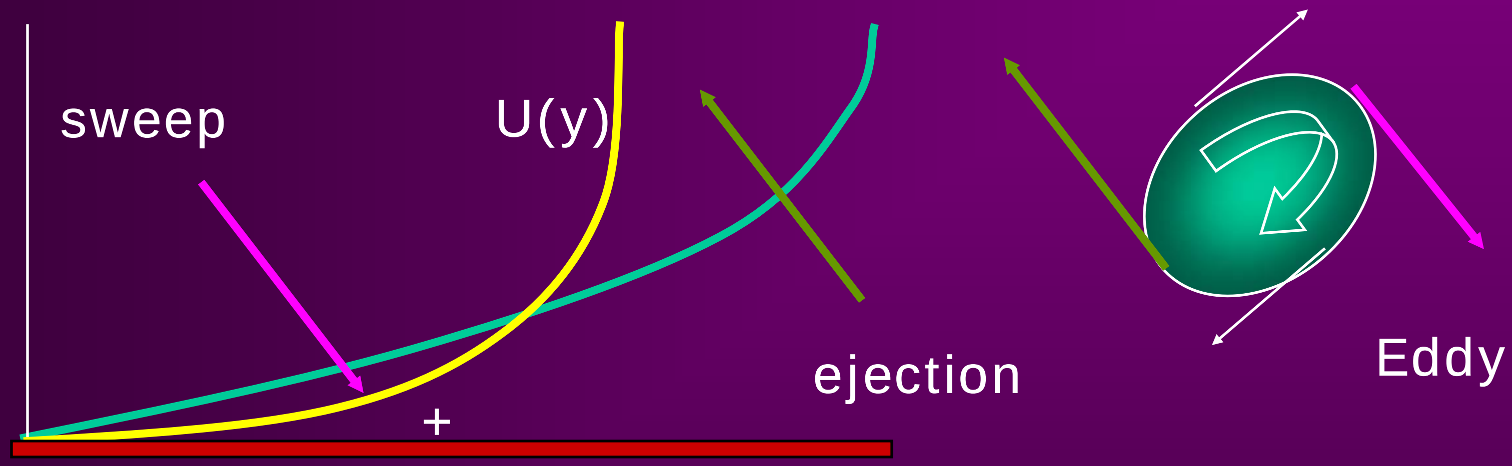
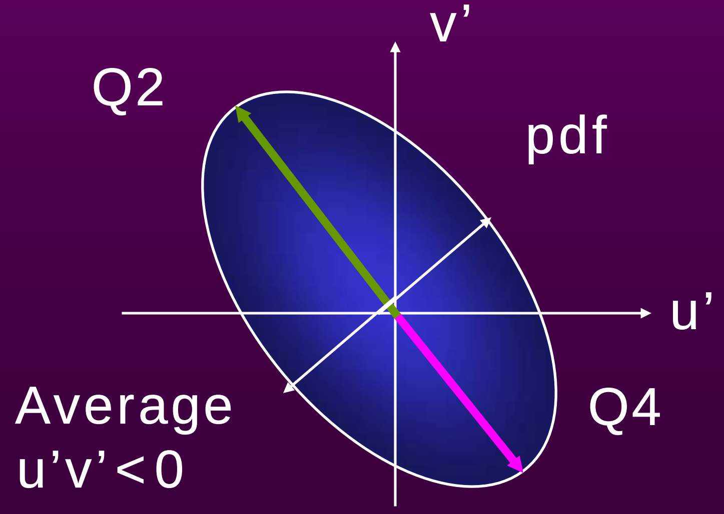
Organization in Wall Turbulence

R. J. Adrian

Laboratory for Energetic Flow and Turbulence
Department of Mechanical and Aerospace Engineering
Arizona State University-Tempe

How are Reynolds stresses and net forces created by vortices?

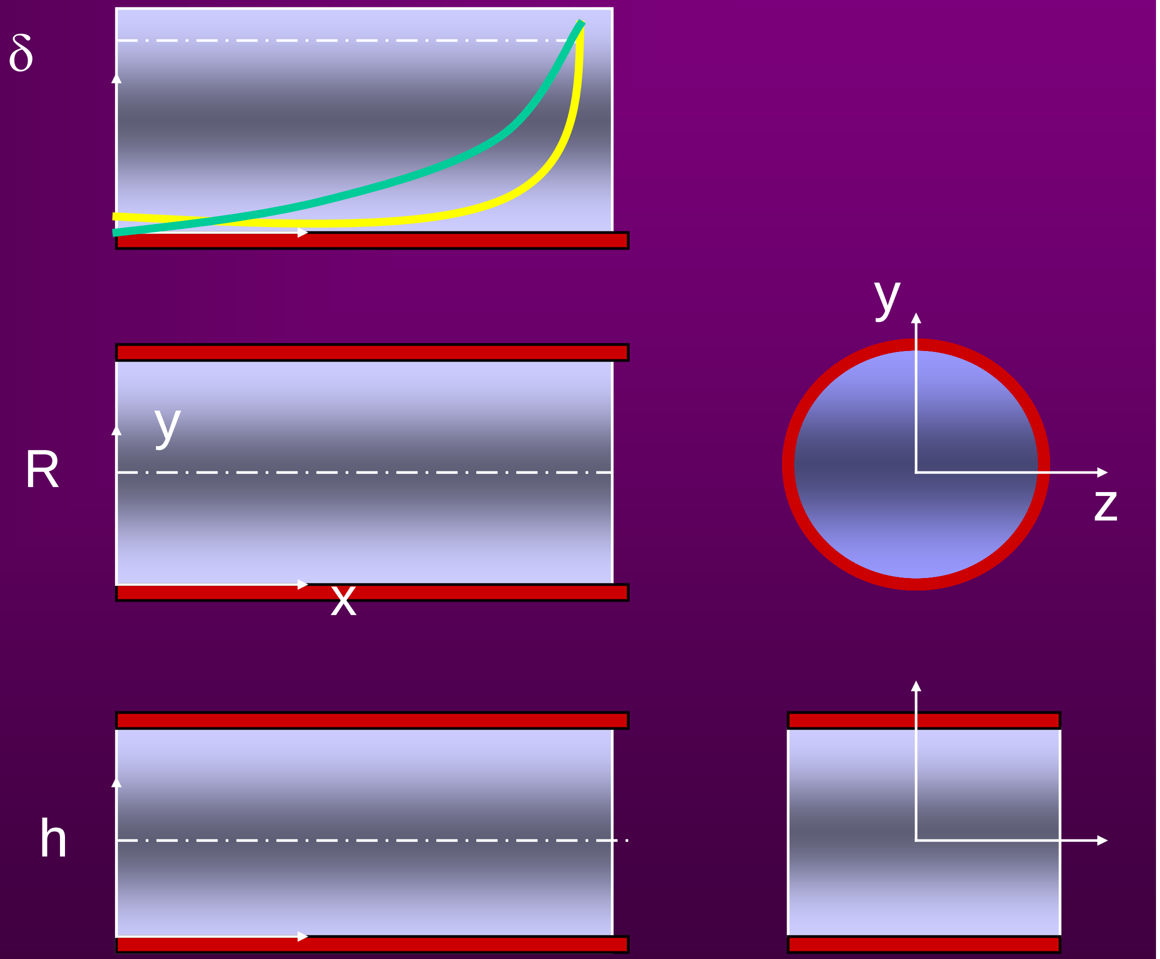




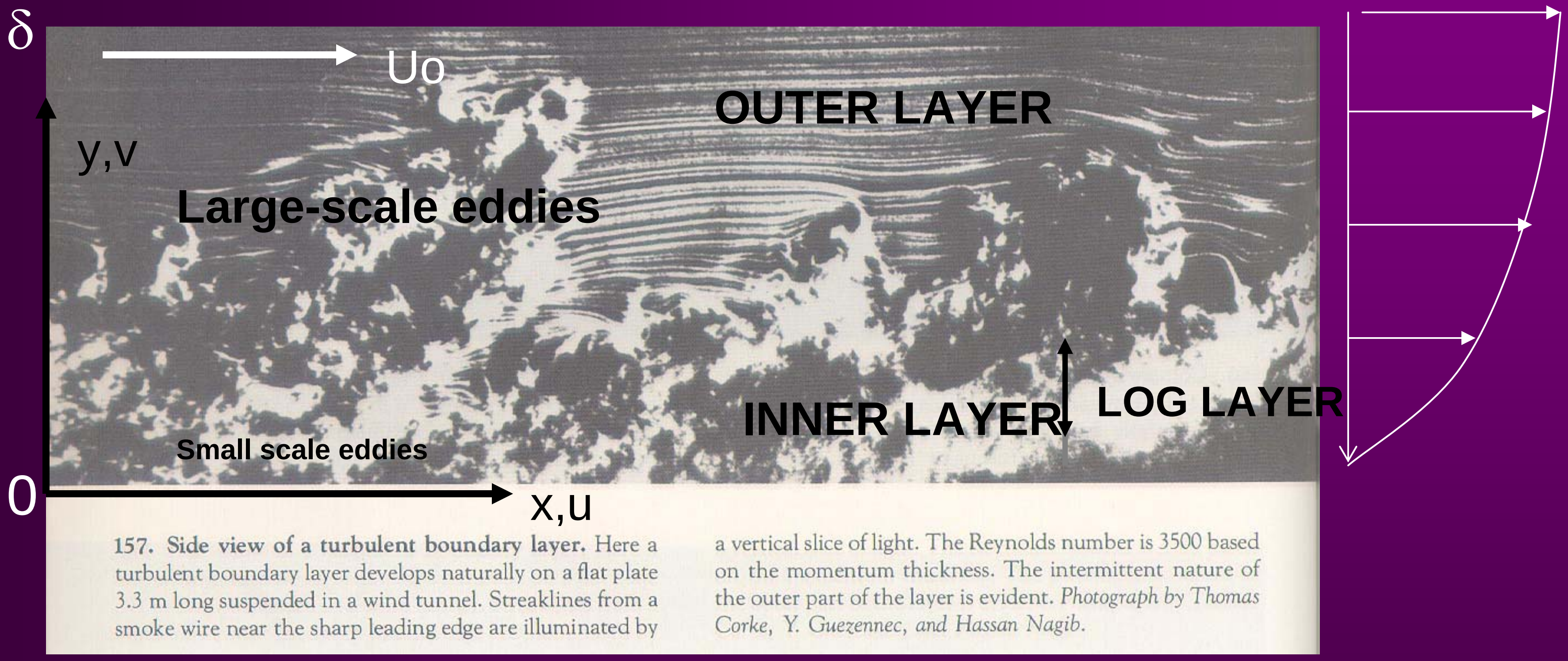
How do coherent eddies create sweeps and ejections?

Canonical Wall Flows

- Boundary layer
- Pipe
- Channel



Eddies in Wall Turbulence



157. Side view of a turbulent boundary layer. Here a turbulent boundary layer develops naturally on a flat plate 3.3 m long suspended in a wind tunnel. Streaklines from a smoke wire near the sharp leading edge are illuminated by a vertical slice of light. The Reynolds number is 3500 based on the momentum thickness. The intermittent nature of the outer part of the layer is evident. *Photograph by Thomas Corke, Y. Guezennec, and Hassan Nagib.*

VanDyke (1982)

Statistically inhomogeneous in the y-direction. Very small scales at wall and much larger scale,~δ, in outer region.

Theodorsen’s hairpin, low-speed streaks and quasi-streamwise vortices

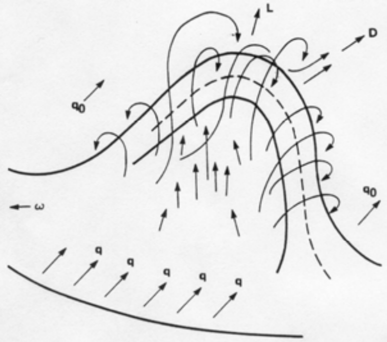
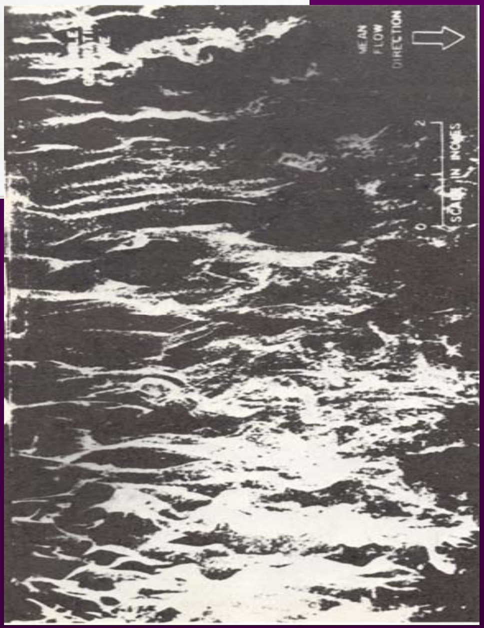
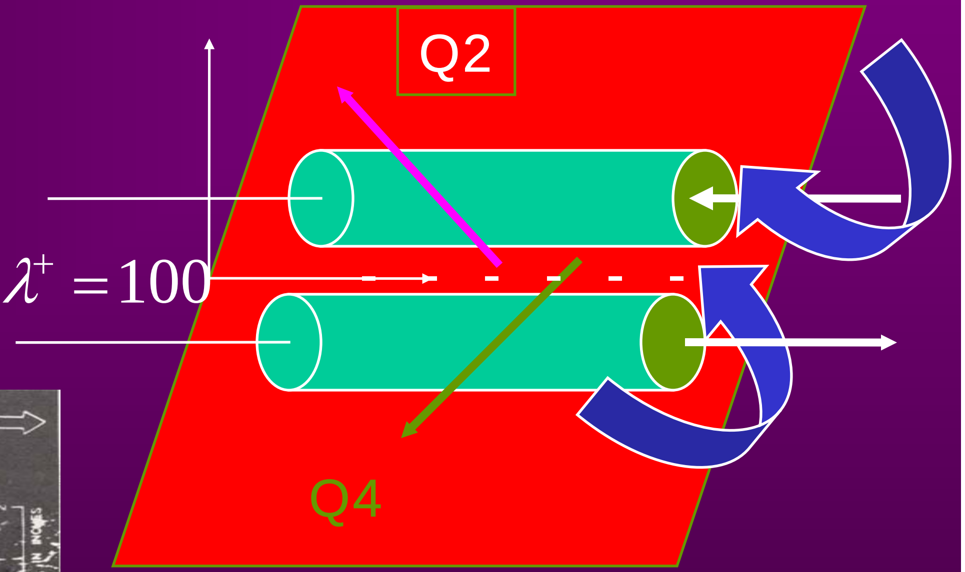


Figure 5 Primary structure of wall-bound turbulence (from Theodorsen 1952).

T. Theodorsen, 1952, Proc.
Midwest MechancsSymposium,
Columbus, OH

$\lambda^+ = 100$

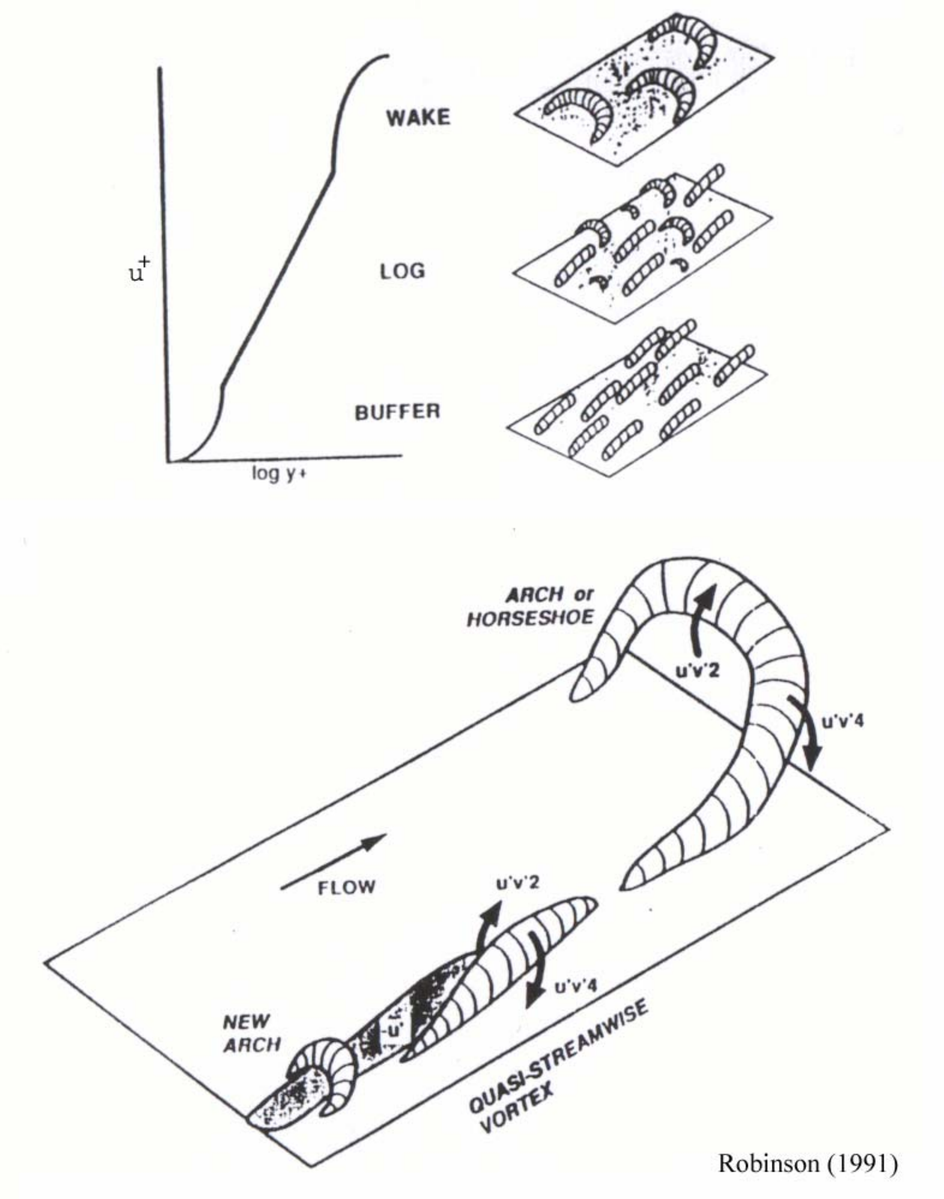




Quasi-streamwise vortices and low-speed wall-streaks also generate R-shear stress
Kim, Moser, Moin 1987

Rundstadtler, Kline, Schraub and Reynolds 1963

Robinson (1991) Low Re DNS of Spalart



Robinson (1991)

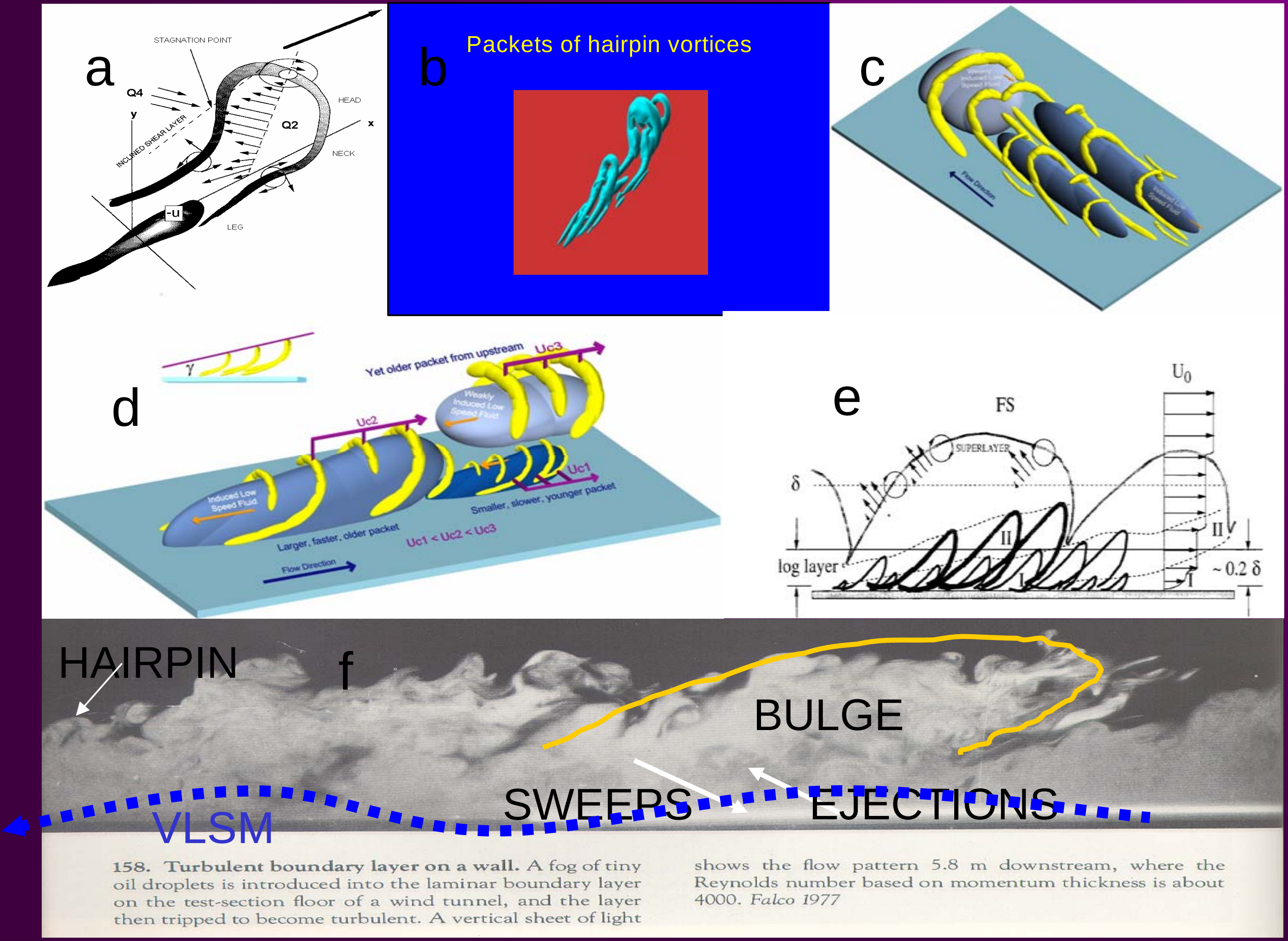
Important Contributions

- Theodorsen 1952 Hairpin model
- Townsend-attached eddies (1952) and LSM (1958)
- Rundstadtler, Kline, Schraub and Reynolds 1963
- Head and Bandyopadhyay 1980, 1981 hairpins in low to high Re BL
- C. R Smith 1984 successive hairpins in low Re BL
- Perry and Chong 1986 randomly scattered hairpin model
- Robinson and Kline 1991 DNS structure
- Smith et al 1991 successive hairpin generation model
- Many others: Antonia,Blackwelder, Bradshaw, Brodkey, Brown, Cantwell, Coles, Comte-Bellot, Dimotakis, Eckelman, Falco, Hanratty, Hussain, Jimenez, Kim, Klewicki, Kovasznay, Kibens,Marusik, Moser, Moin, Nagib, Smits, Sreenivasan, Wallace, Waleffe, Wark, Willmarth, Wei,…..
- In the early 1990's two important new tools became available to study structure:
  - DNS--3-D, full set of variables, but low Re and some effects of domain size and BC's
  - PIV--2-D, velocity vectors, but higher Re and real BC's and IC's
  - Both made it possible to observe vorticity and the interior of wall layers without the diffusive blurring of small scales
- Today's story begins with these developments

Contributors

- EXPERIMENTS: DETERMINING THE STRUCTURE OF WALL TURBULENCE
  - T. J. Hanratty
  - K. C. Kim, Pusan
  - C. Meinhart, PhD 1994
  - C. Tomkins, MS 1998, PhD 2000
  - K. Christensen, PhD 2000
  - S. Hommema, PhD 2001
  - M. Guala, PhD (Genoa) 2002
  - B. J. Balakumar, PhD 2005
- CHANNEL FLOW DNS: MECHANISMS FOR CREATING VORTEX PACKETS
  - S. Balachandar
  - T. Kendall. MS 1992
  - J. Zhou, PhD 1995
  - Z. C. Liu

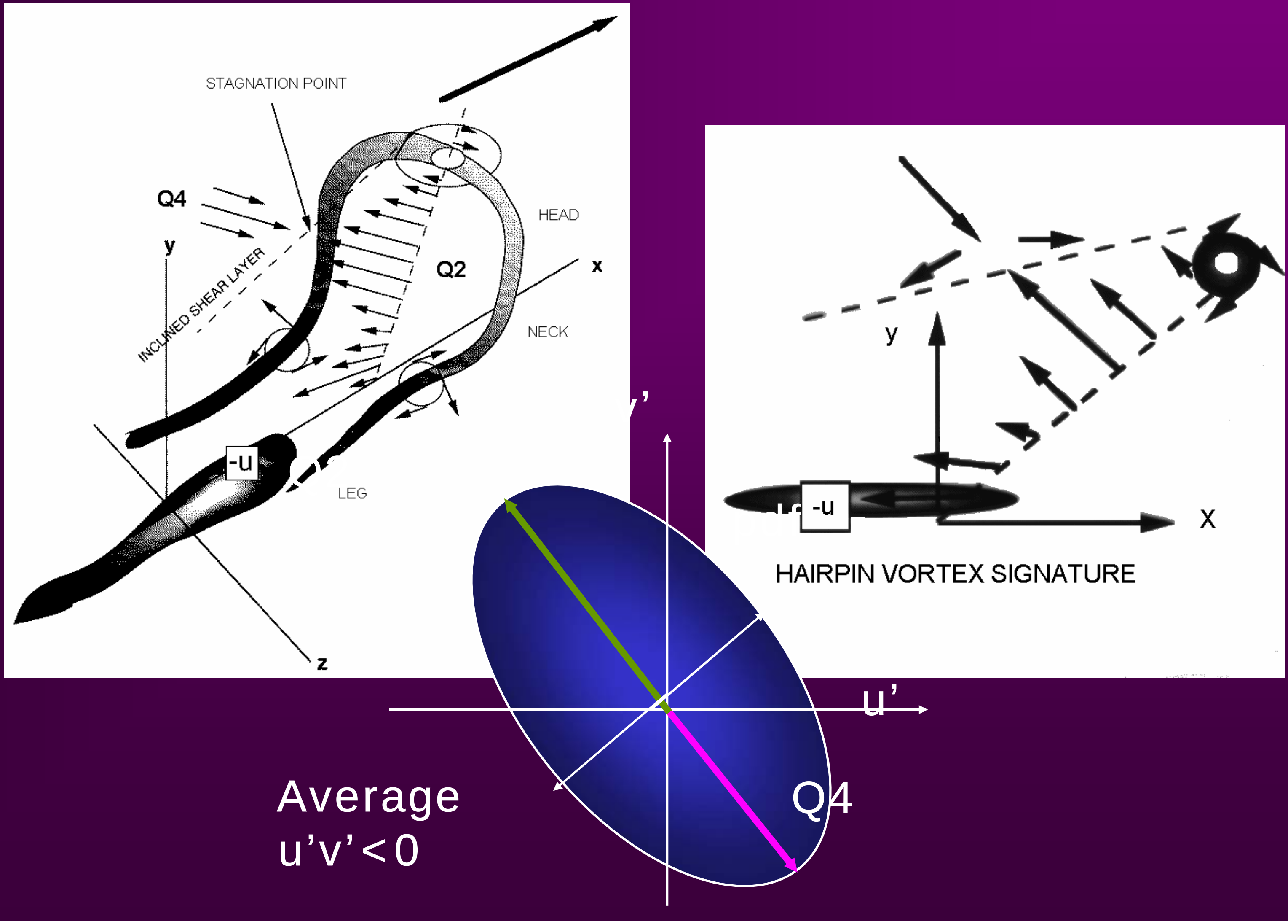
Outline



158. Turbulent boundary layer on a wall. A fog of tiny oil droplets is introduced into the laminar boundary layer on the test-section floor of a wind tunnel, and the layer then tripped to become turbulent. A vertical sheet of light shows the flow pattern 5.8 m downstream, where the Reynolds number based on momentum thickness is about 4000. *Falco 1977*

Schematic of a modern hairpin vortex and its signature in velocity field

Modern view based on Theodorsen + quasi-streamwise



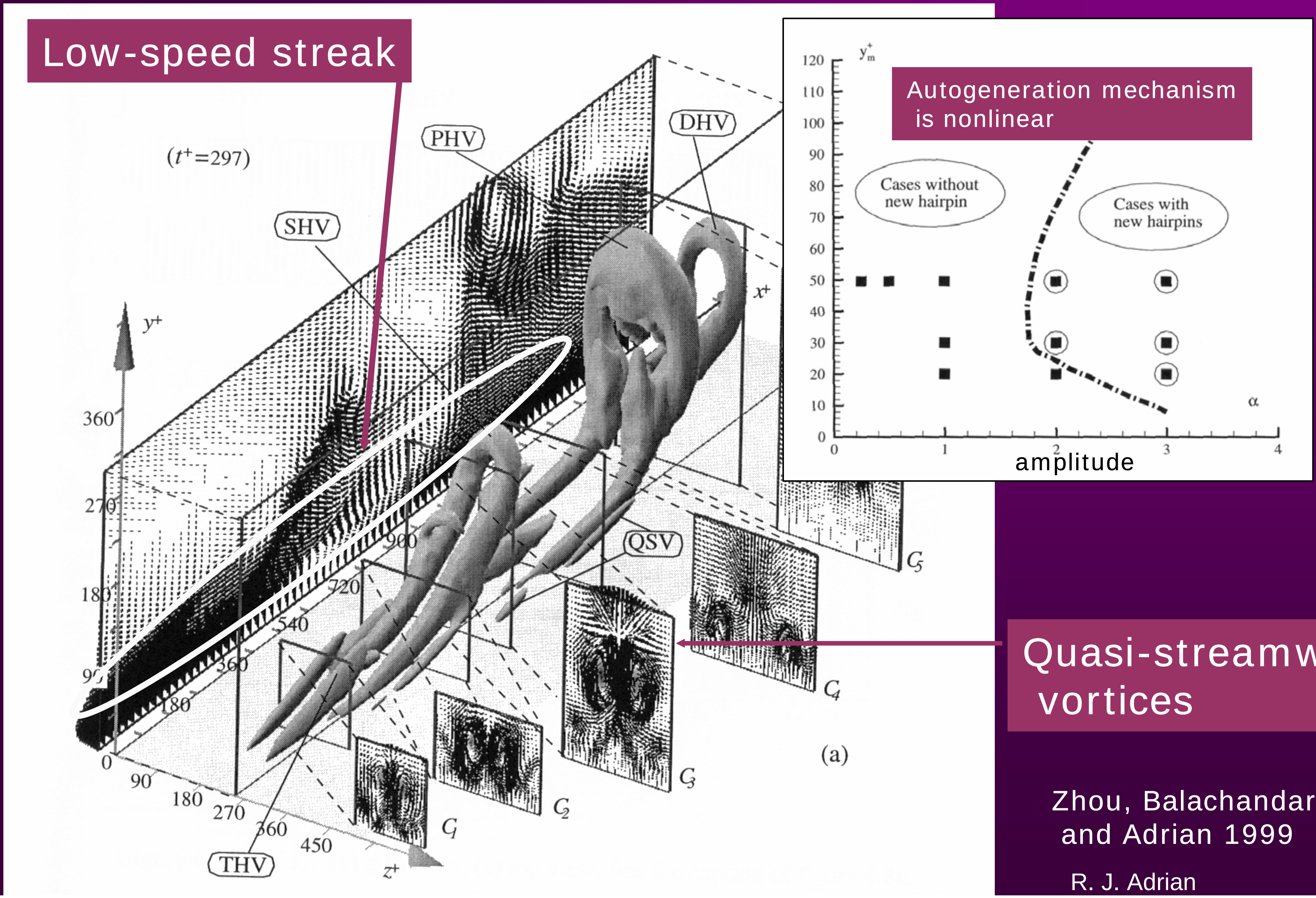
Average
u'v'<0

Implications of the Single Hairpin Paradigm

- Q2 events and Q4 events in hairpin eddies provide much of the mean Reynolds shear stress
- Quasi-streamwise vortices + shear at wall create low speed streaks in the buffer layer
- Synthesize much of the statistical behavior by randomly superposing hierarchies of hairpins (Perry, Chong, Li, Marusic and co-workers)
- Reynolds stress profiles, spectra, ….
- Perry, Li and Marusik: there is a missing large-scale component

Autogeneration of hairpin packet

(low Re channel flow)



Low-speed streak

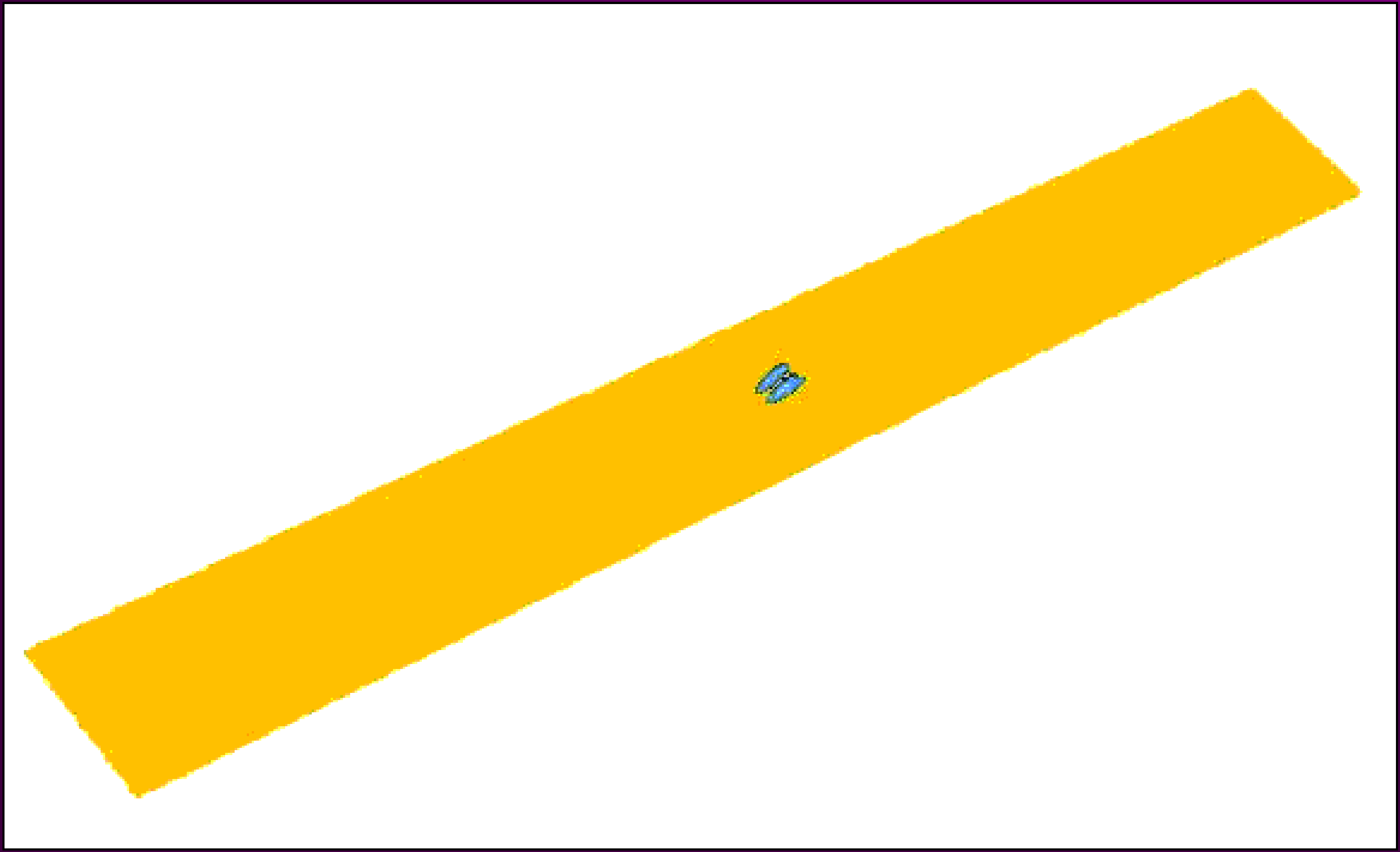
Autogeneration mechanism is nonlinear

Quasi-streamwise vortices

Zhou, Balachandar and Adrian 1999

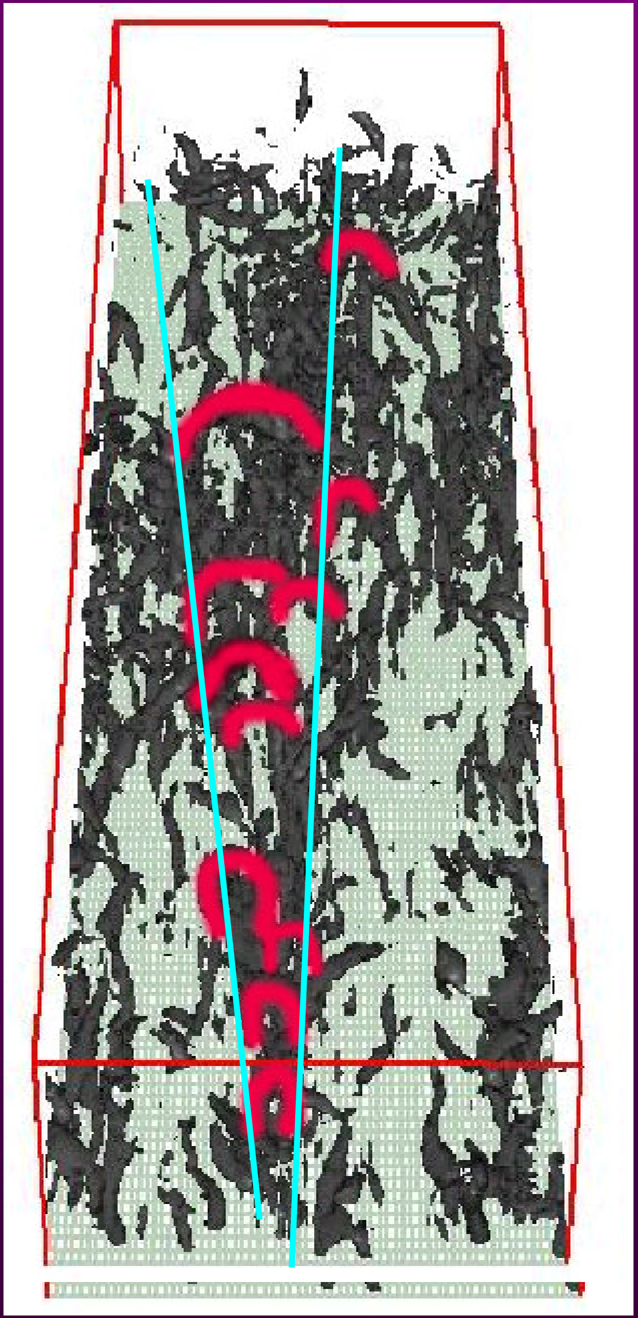
R. J. Adrian

Evolution of a slightly asymmetric disturbance into a chaotic packet



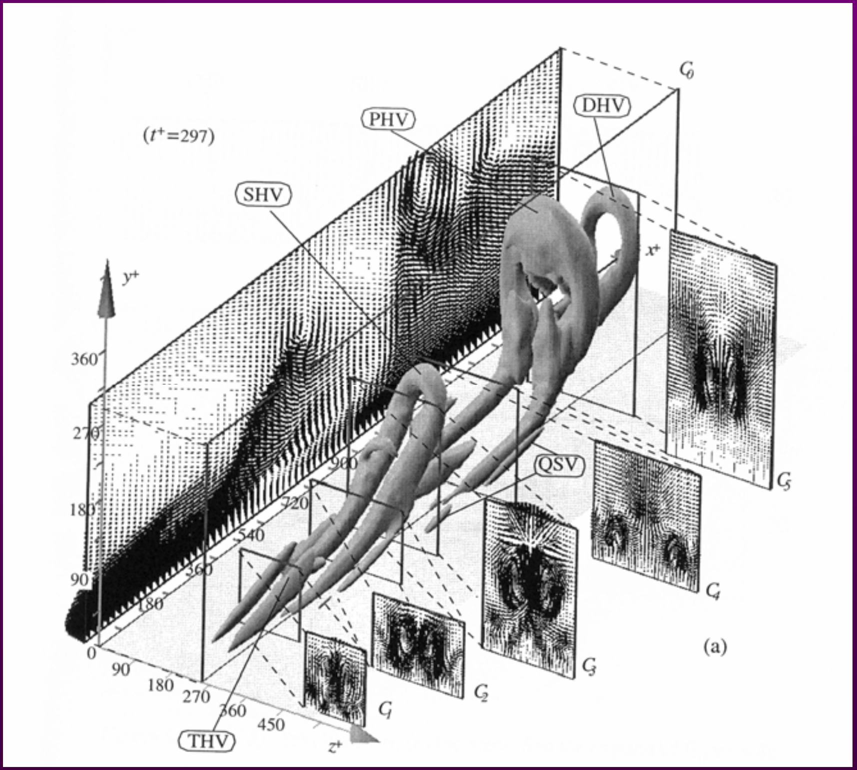
Hairpin packets in fully turbulent channel flow

$Re_\tau = 300$

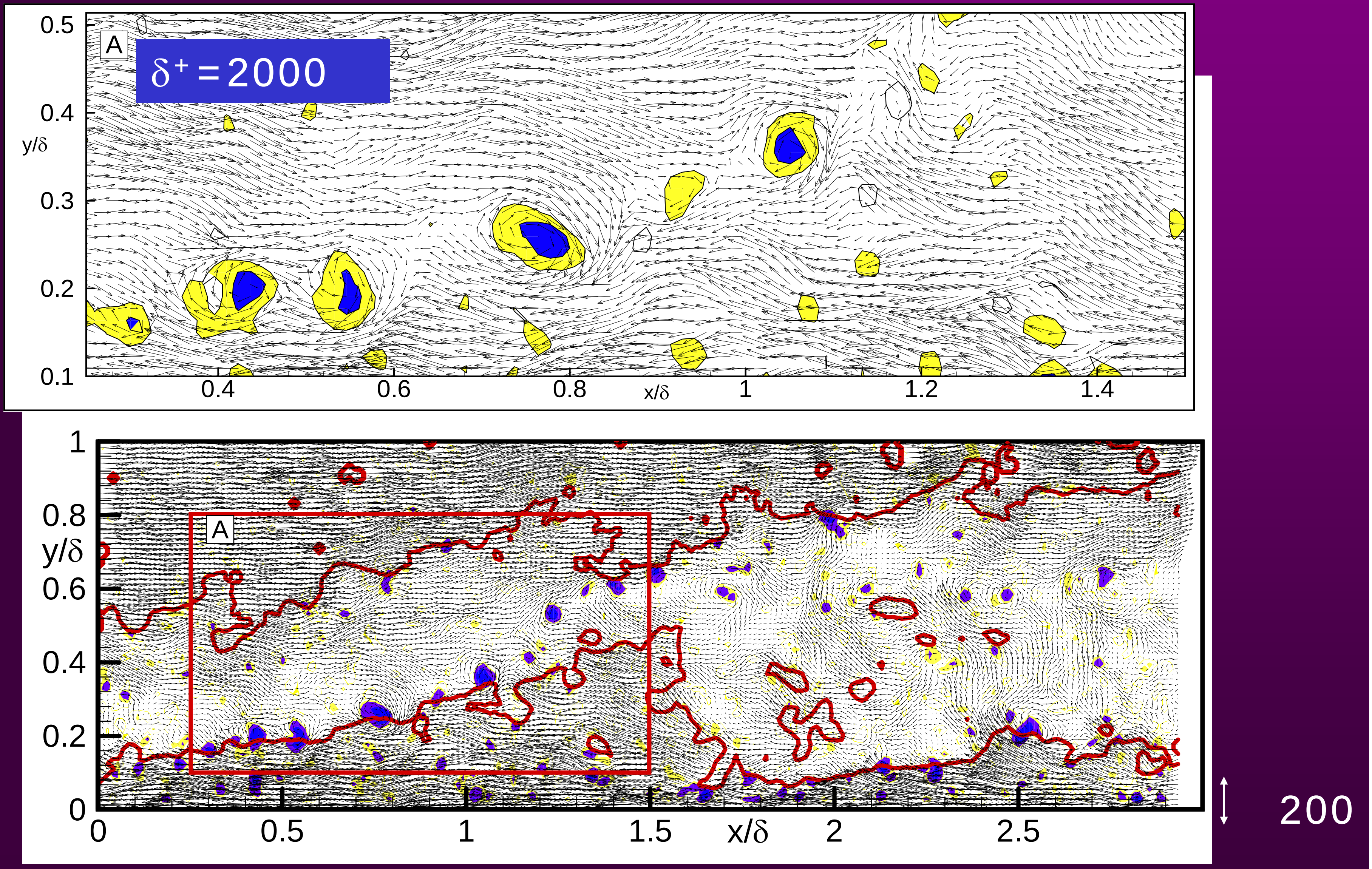


Packets at higher Reynolds numbers

- 1st hairpin is mature when its head is about 100 viscous wall units tall
- Near-wall packets grow up to about 200-300 viscous wall units, then they change
- Re_τ< 200-300 flows can barely contain mature packets
- Higher Re flows allow packets on many scales

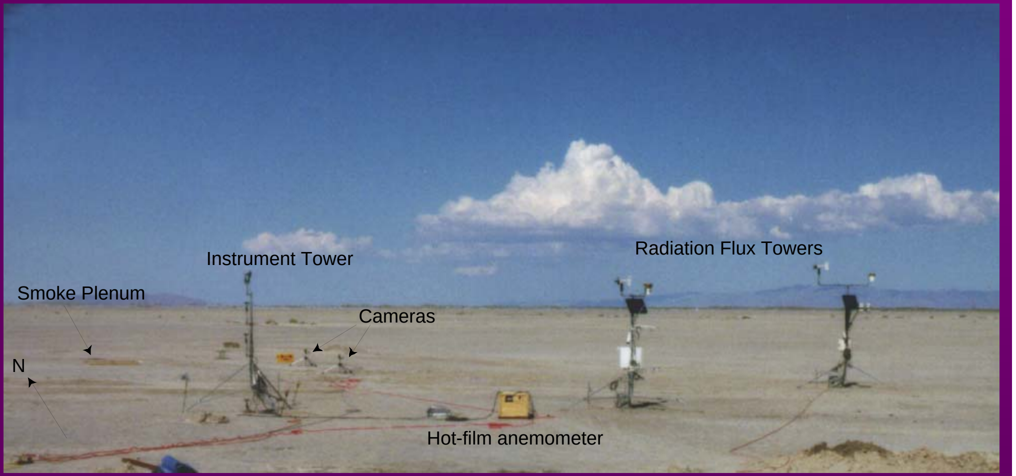


Packets at moderate Re



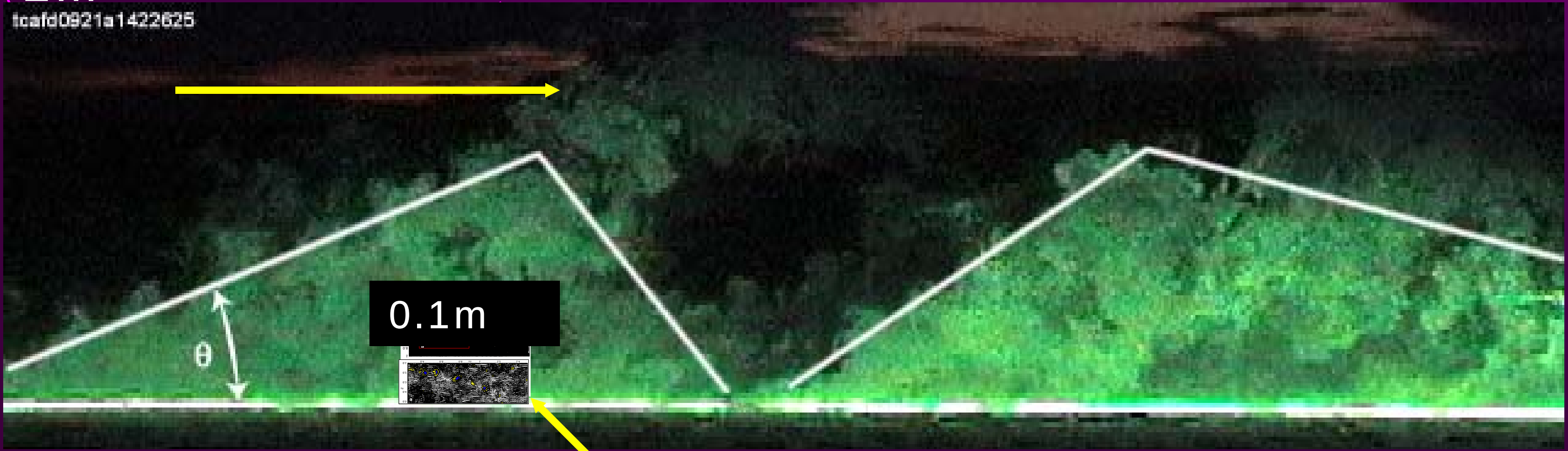
High Re: $Re_\theta \sim 10^6$

200m~top of BL



20m~ top of log layer

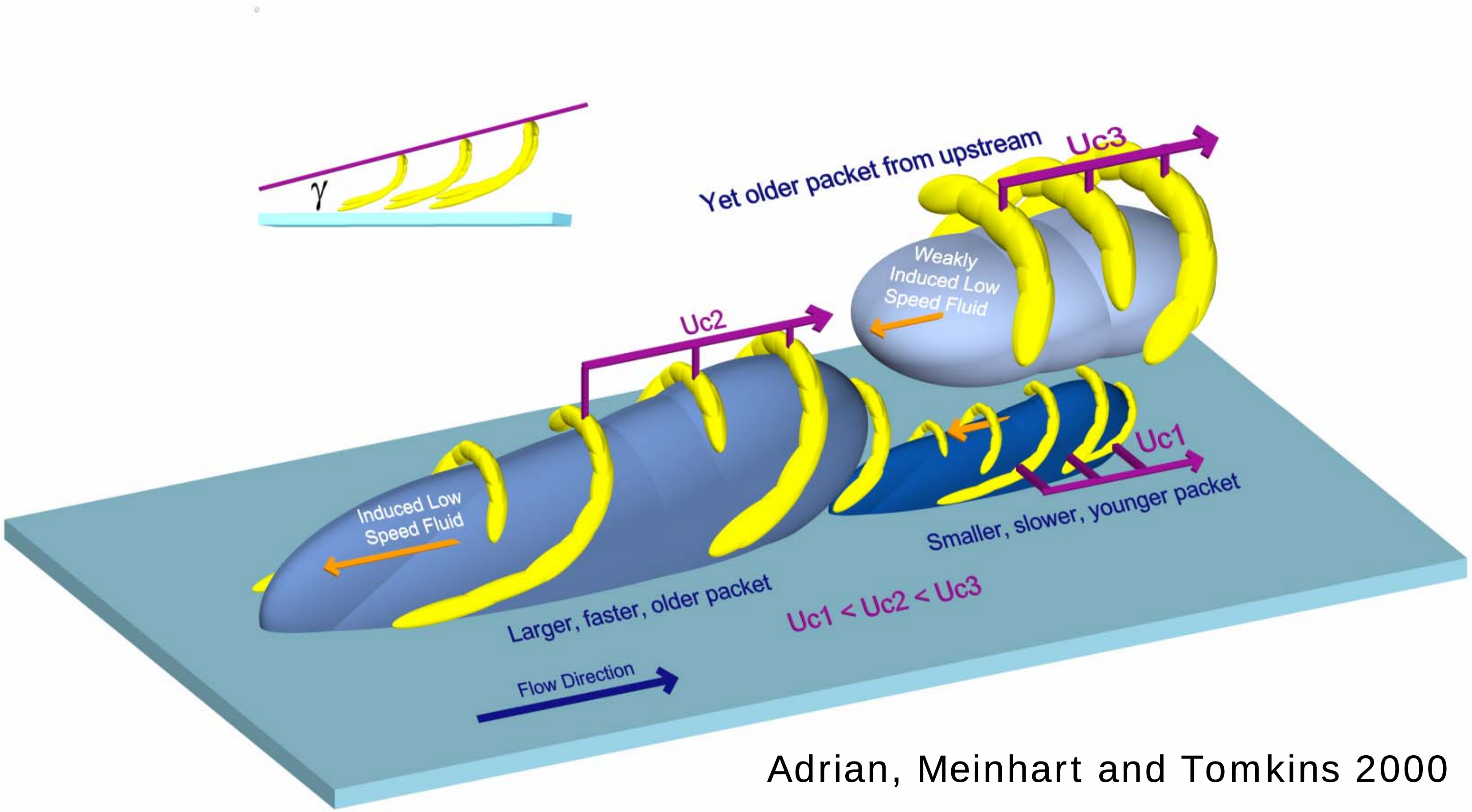
2m



0.1m

Lab BL

Hairpin Packet Hierarchy



Adrian, Meinhart and Tomkins 2000

At a given streamwise location, the BL consists of young packets close tom the wall and progressively older packets farther away from the wall- like geologic strata. Most prevalent in the log layer, but some grow all of the way to the top

Significance of hairpin organization into packets: 1. Coherent and incoherent stress

Let $\mathbf{u}_\alpha(\mathbf{x},t)$ be the velocity field of the αth hairpin, and let be the total field

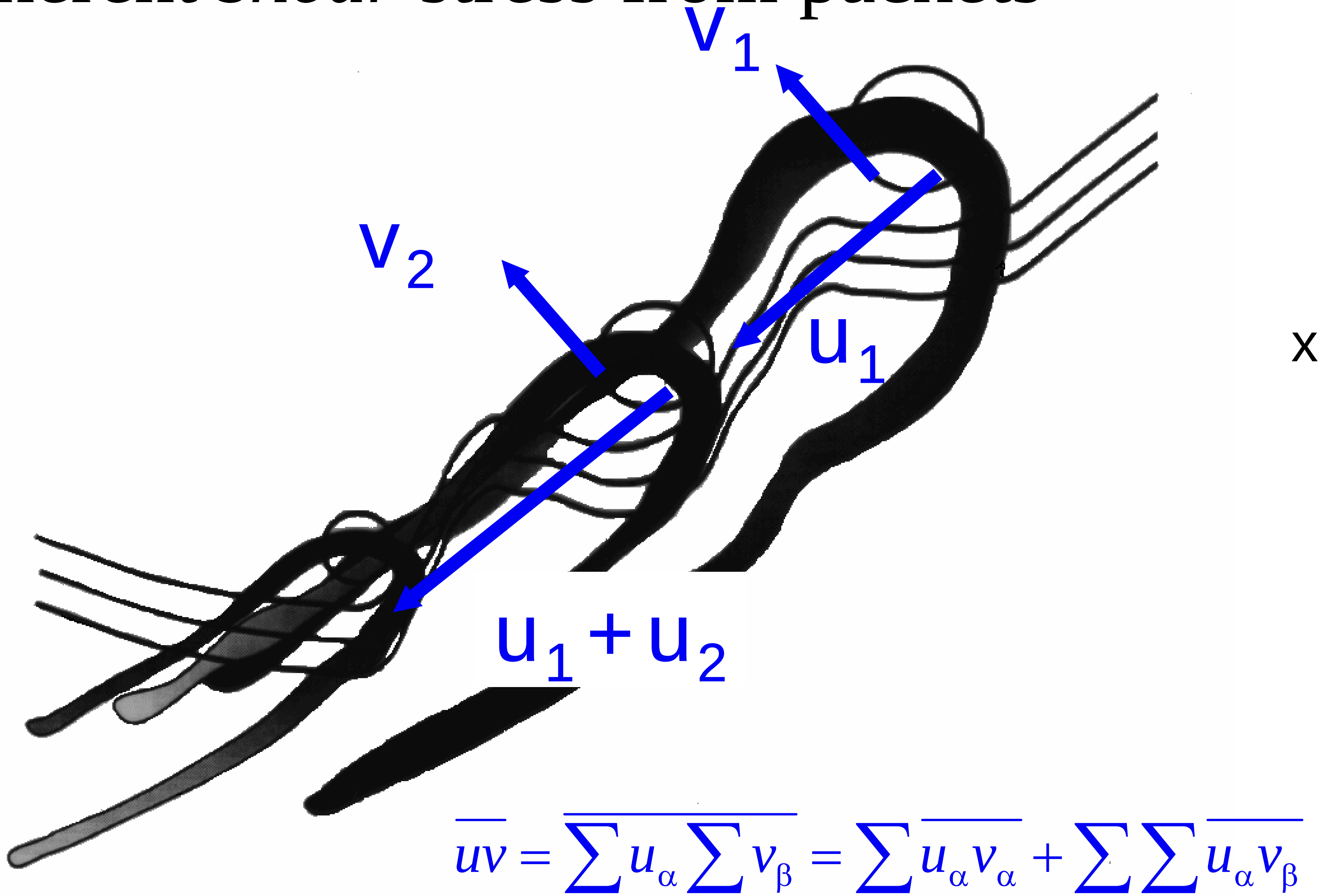
$$\mathbf{u}(\mathbf{x},t) = \sum_\alpha \mathbf{u}_\alpha(\mathbf{x},t).$$

Then the mean Reynolds shear stress is given by

$$\overline{uv} = \overline{\sum_\alpha u_\alpha \sum_\beta v_\beta} = \sum_\alpha \overline{u_\alpha v_\alpha} + \sum_\alpha \sum_{\beta\neq\alpha} \overline{u_\alpha v_\beta}$$

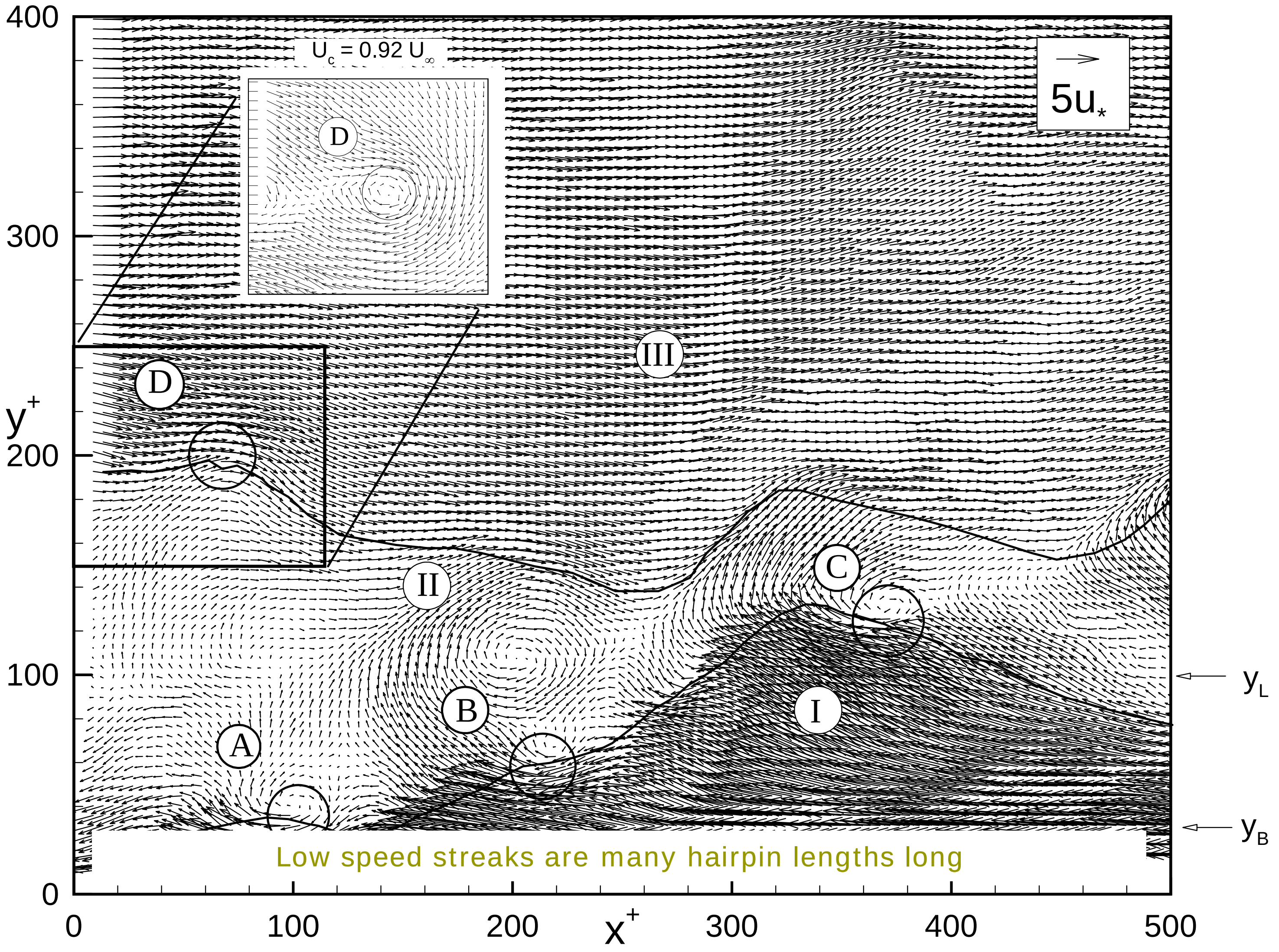
where the first term represents the addition of Reynolds stress contribution from individual hairpins in the packet, while the second term represents the contribution to the Reynolds shear stress from the **coherence of the spatial location of the hairpins within a packet**.

Coherent *shear* stress from packets



$$\overline{uv} = \overline{\sum_{\alpha} u_{\alpha} \sum_{\beta} v_{\beta}} = \sum_{\alpha} \overline{u_{\alpha} v_{\alpha}} + \sum_{\alpha} \sum_{\beta \neq \alpha} \overline{u_{\alpha} v_{\beta}}$$

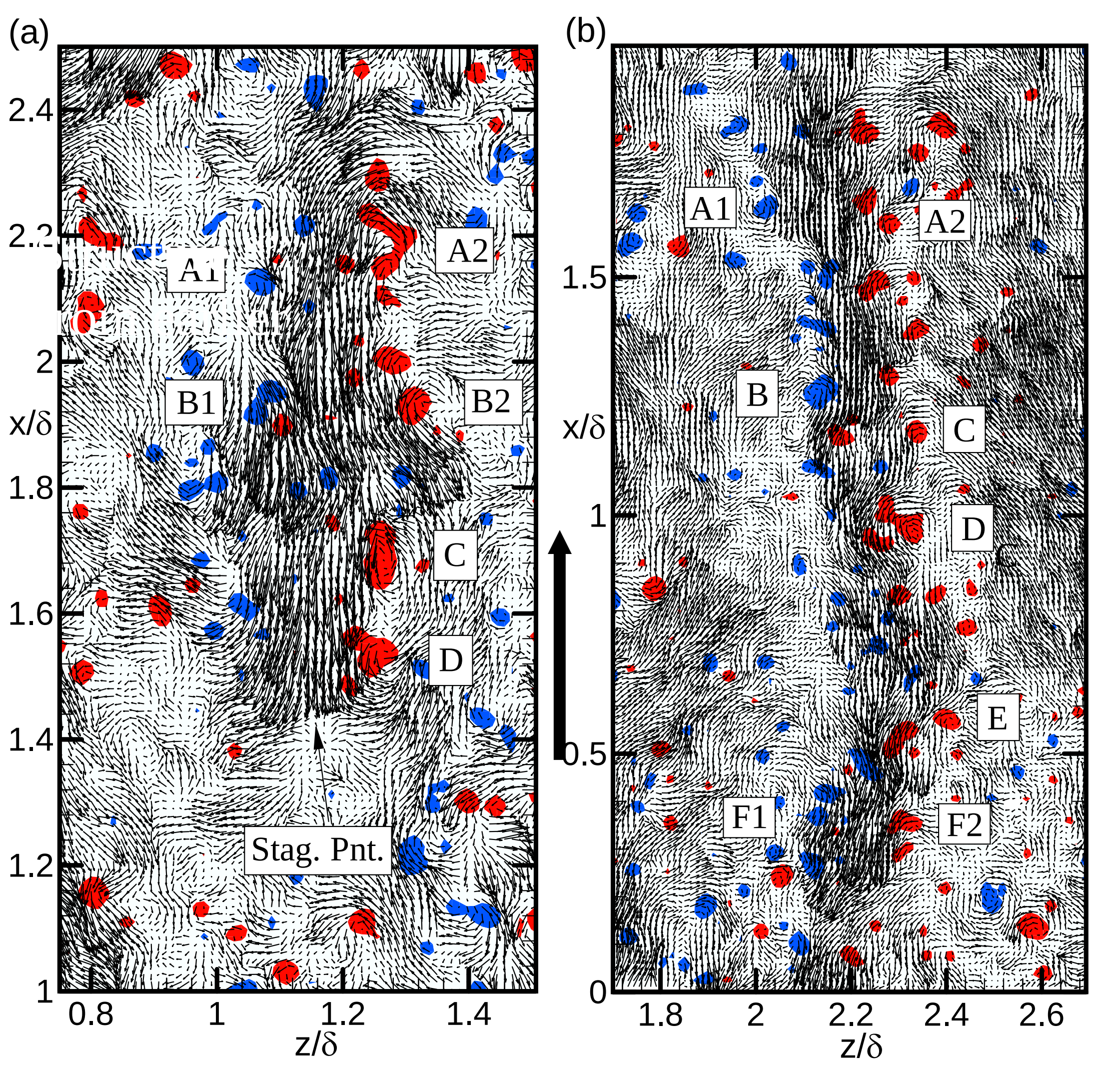
Significance of vortex organization into packets: 2. Low speed streaks are created by coherent back-induction of the concatenated hairpins

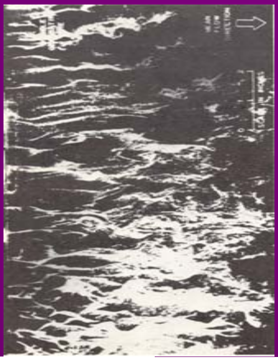


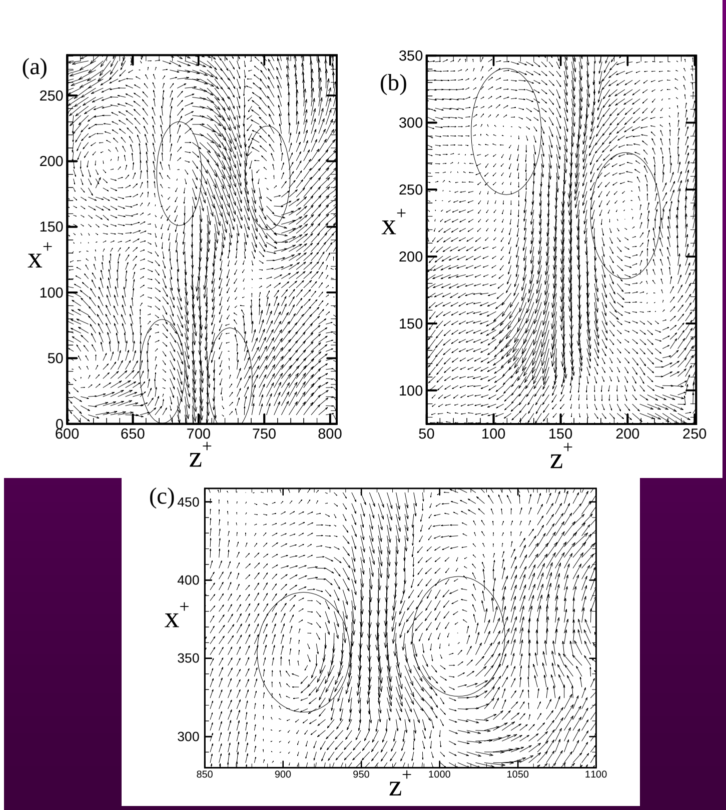
Low speed streaks are many hairpin lengths long

Instantaneous fields at $Re_\theta = 7705, y^+ = 440$

(vectors and signed swirling strength)







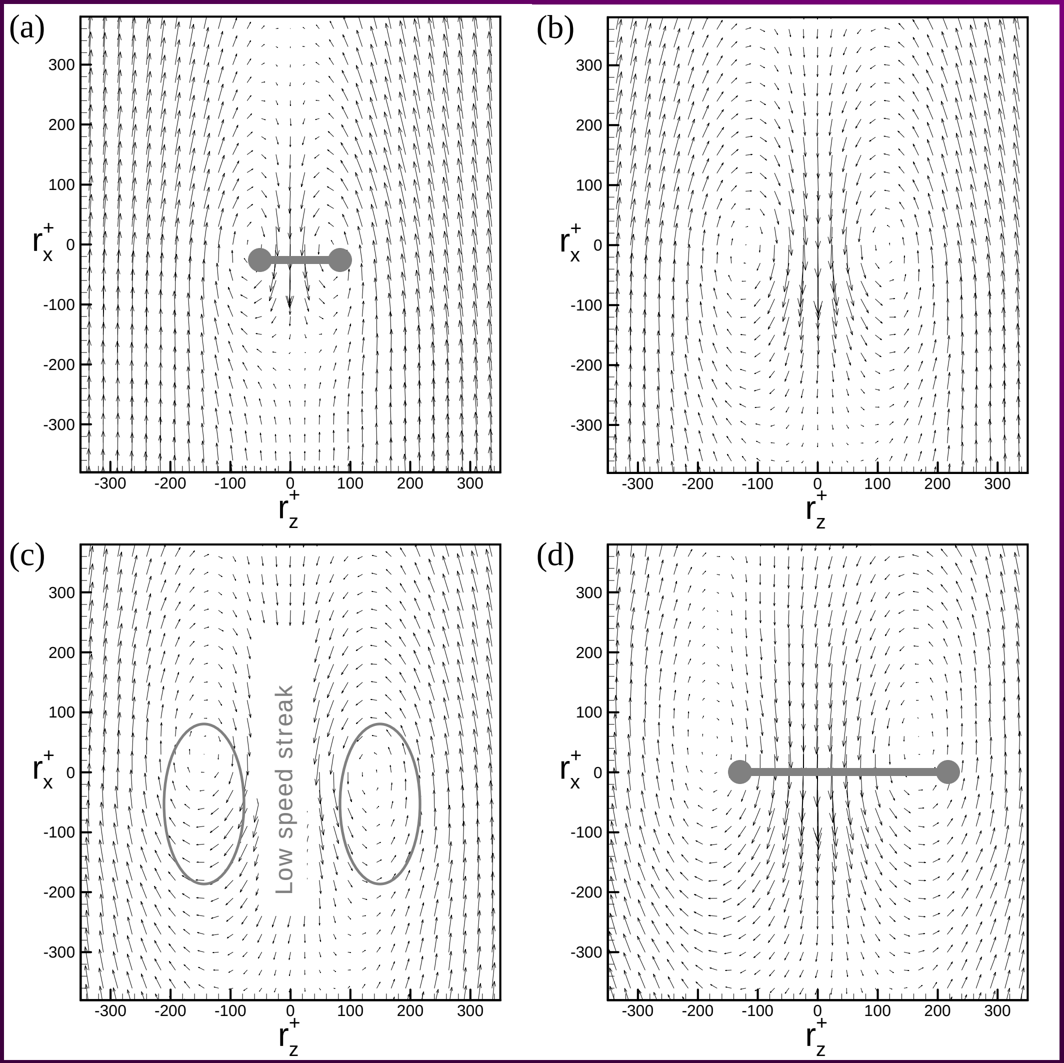
Extract dominant structure via conditional averaging: event is local u-minimum below threshold (75% of local mean)

$y^+ = 100$

$y^+ = 220$

$y^+ = 330$

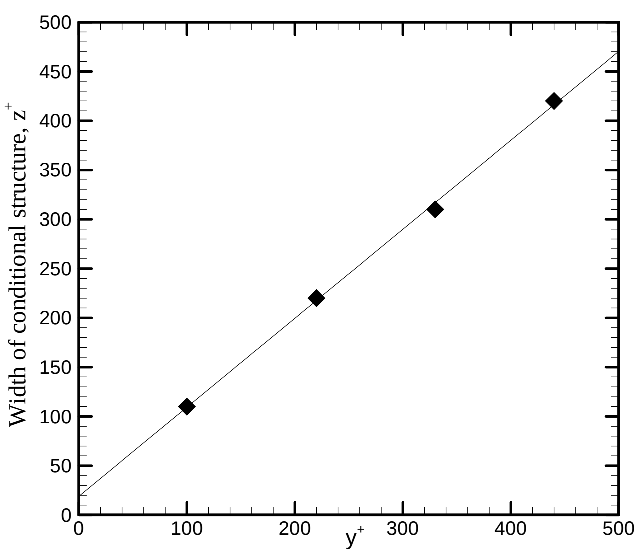
$y^+ = 440$



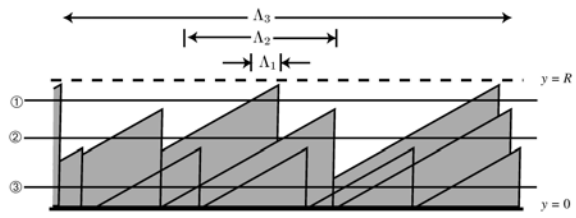
Courtesy C. Tomkins

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

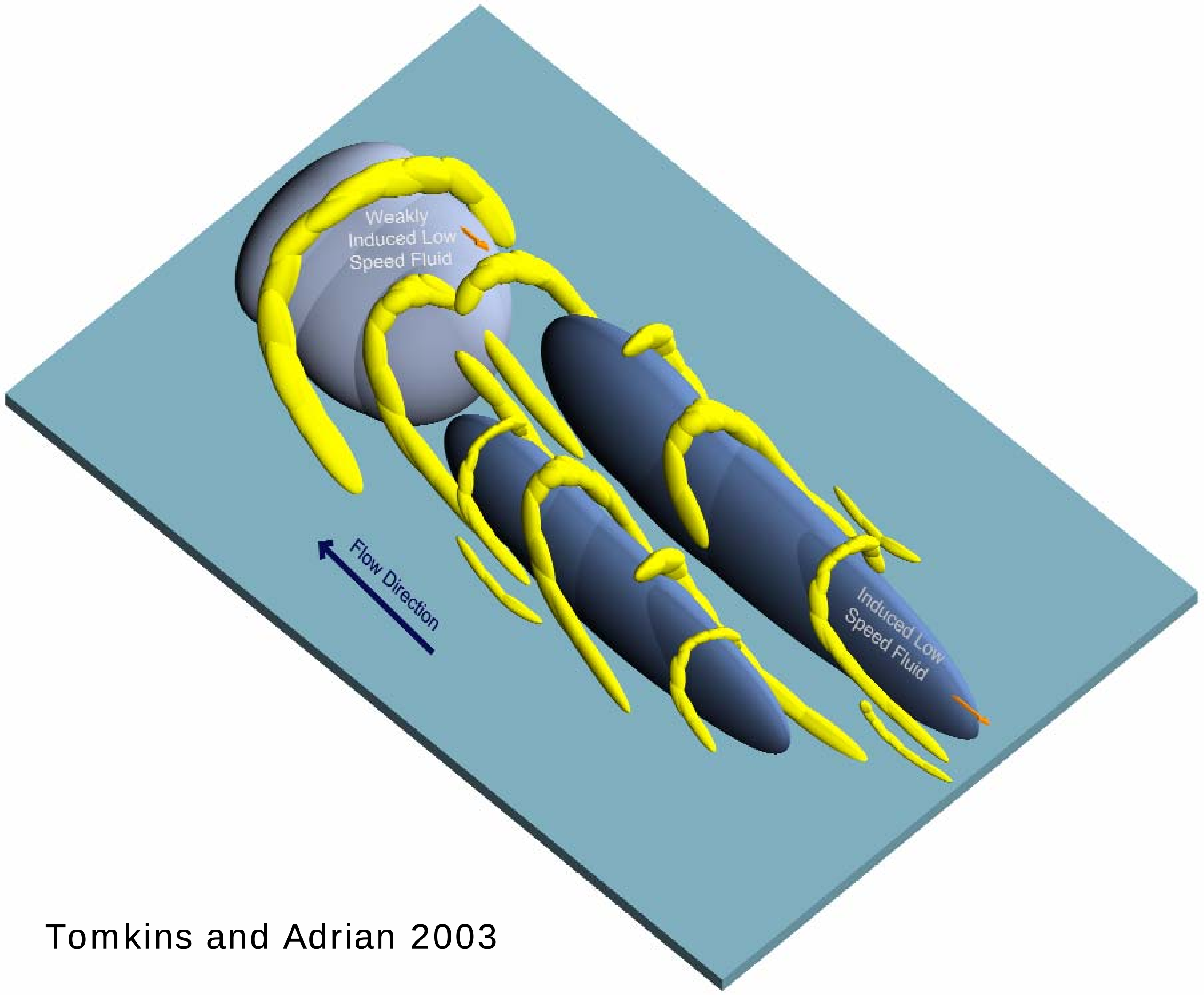


- δ-scale motions- ‘large scale motions’ L~ δ (‘Bulges’ in BL’s)
- Super δ-scale motions- ‘very large-scale motions’, L>> δ



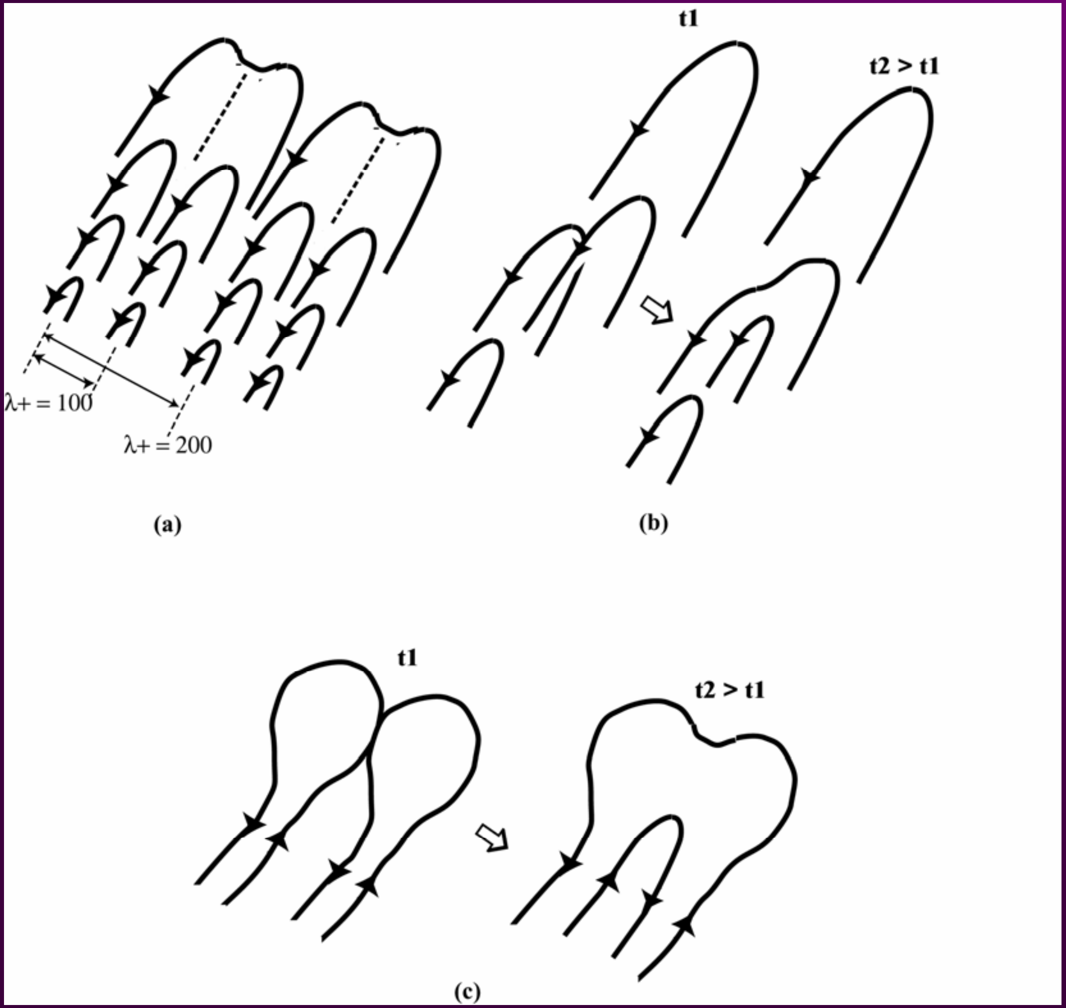
Simplified hairpin-vortex-packet model used to describe the distribution of streamwise kinetic energy among scales. Mean flow is from left-to-right. Hairpin vortex packets of differing scales are indicated as shaded regions.

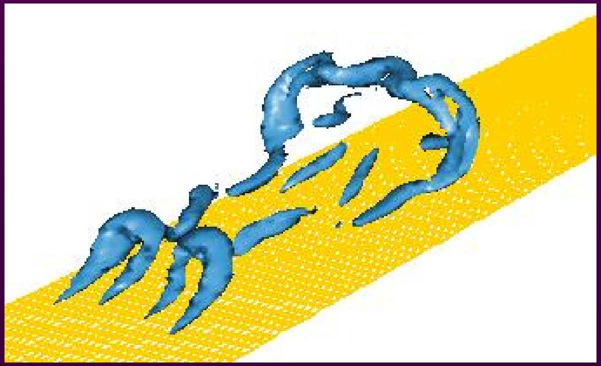
Discontinuous growth mechanism (Wark-Nagib): Merging of vortex packets reduces the number of packets per unit width, thereby allowing growth of scale in z to continue



Tomkins and Adrian 2003

Spanwise Merger Scenarios





δ–scales

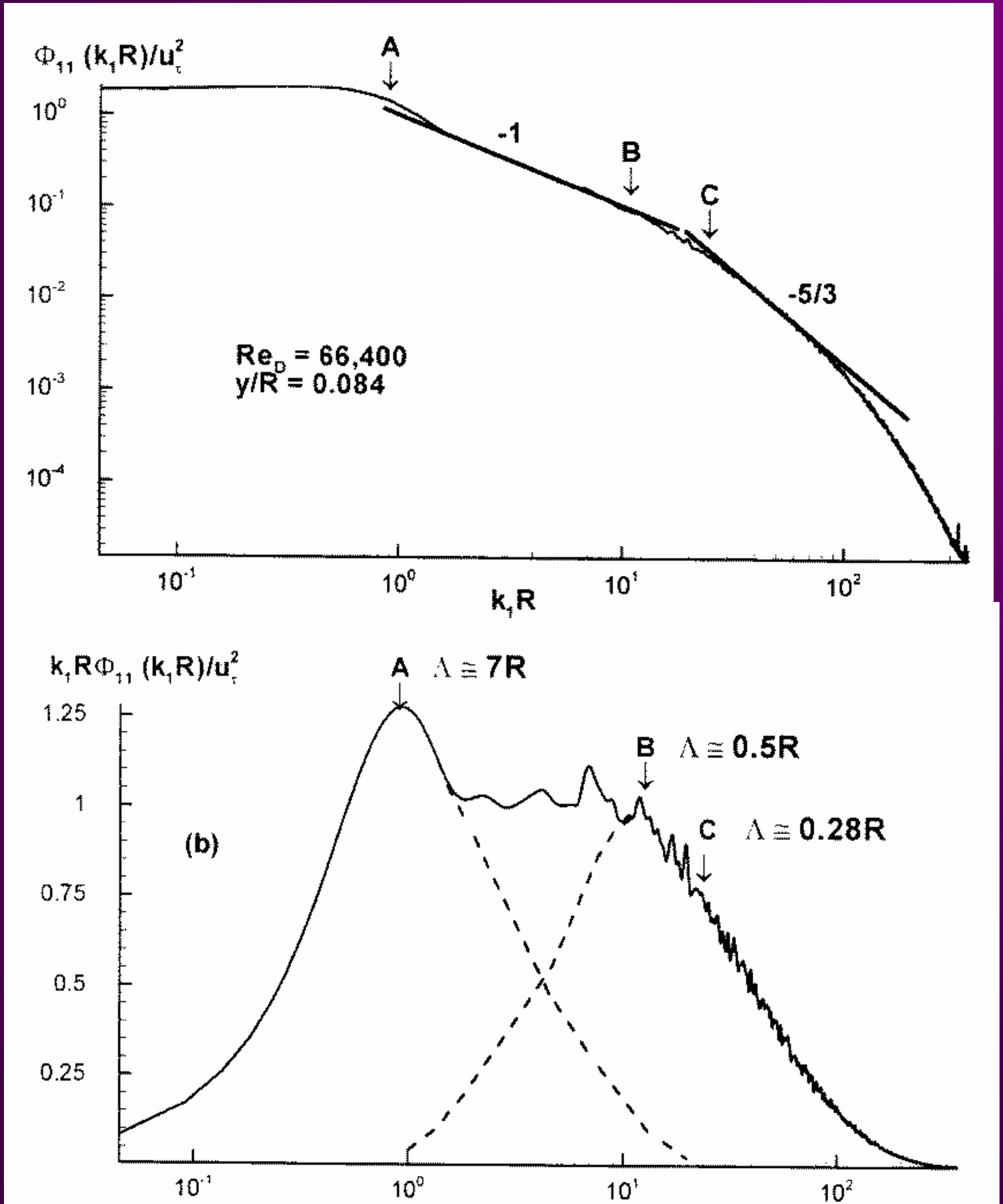
- Motions whose length scales are of the order of the boundary layer thickness
- Townsend (1958), Grant (1958)-”active” and “inactive” structures
- Bradshaw, Murlis and Tai (1971),Kovasznay, Kibens and Blackwelder (1970)-bulges ~2δ x δ
- Townsend (1976)-Main, stress carrying turbulence and large, energetic, but inactive turbulence
- Lekakis (1987) -Long tails on R_{ij} suggest that large scales also contribute to shear stress
- Perry and Marusic (1995)- a δ-scale wake component is needed to make their BL model work well
- Perry and coworkers (1980’s) data suggests a bimodal distribution in velocity spectra and structures with $\Lambda >> R$ in pipe flow

Super δ–scales
or
Very large-scale motions

- Scales whose streamwise extent significantly exceeds the thickness of the wall layer, nominally > 3δ (or 3R or 3h)
- How much kinetic energy do they carry?
- Do they contribute substantial Reynolds *shear* stress?

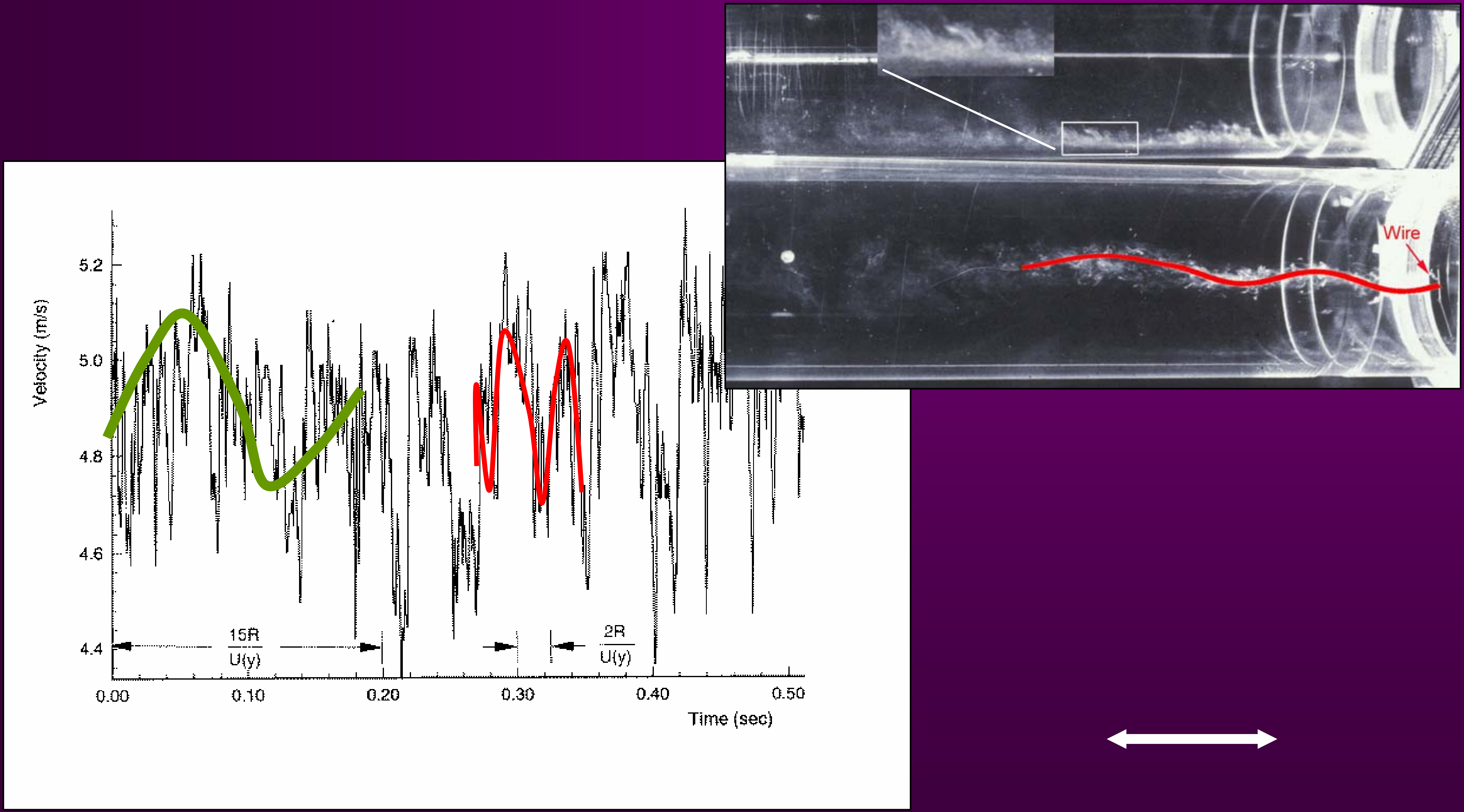
Pipe flow spectra

Pre-multiplied

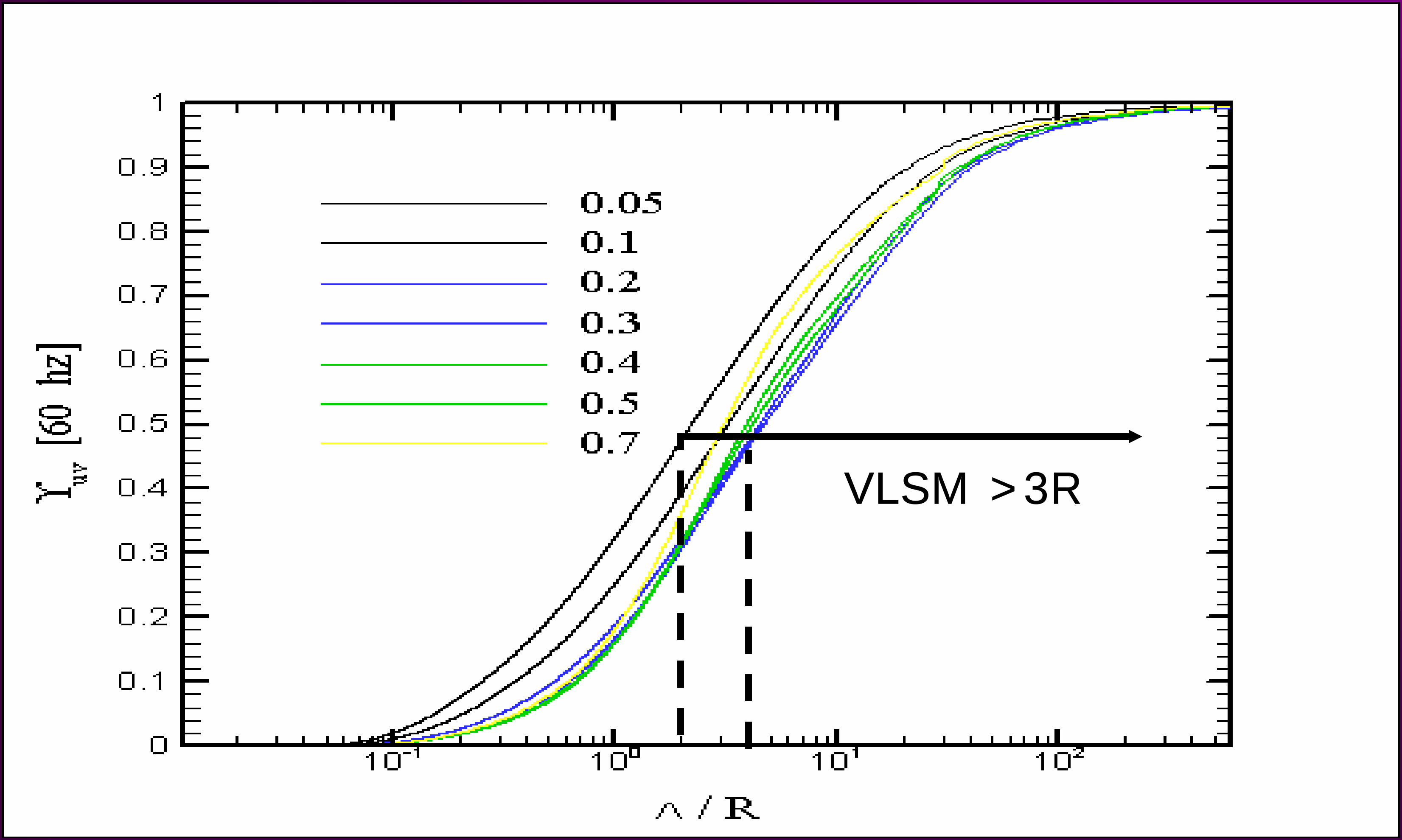


Kim & Adrian (1999)

VLSM's


Velocity (m/s)
5.2
5.0
4.8
4.6
4.4
15R
U(y)
2R
U(y)
0.00
0.10
0.20
0.30
0.40
0.50
Time (sec)
Wire

Cumulative uv in scales < Λ



VLSM contribution to net force

$$\frac{d\langle uv\rangle}{dy}$$

How much do the super-δ turbulent structures contribute to the net Reynolds stress force, -d<uv>/dy ?

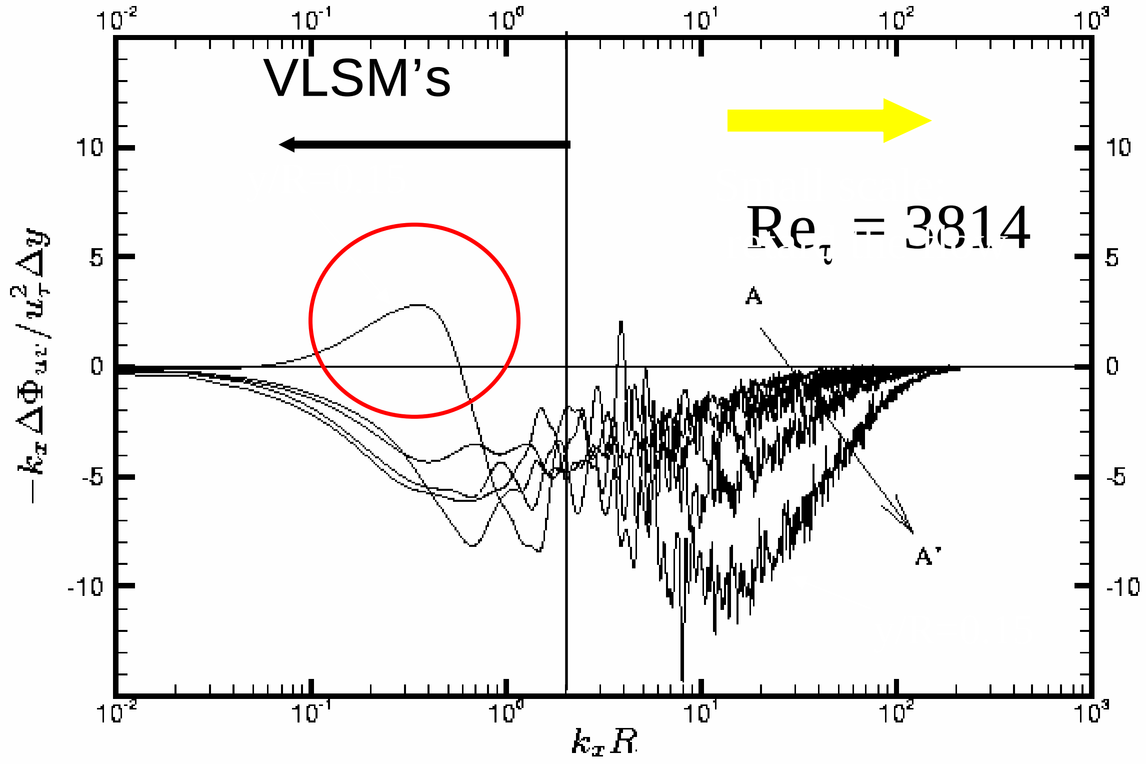
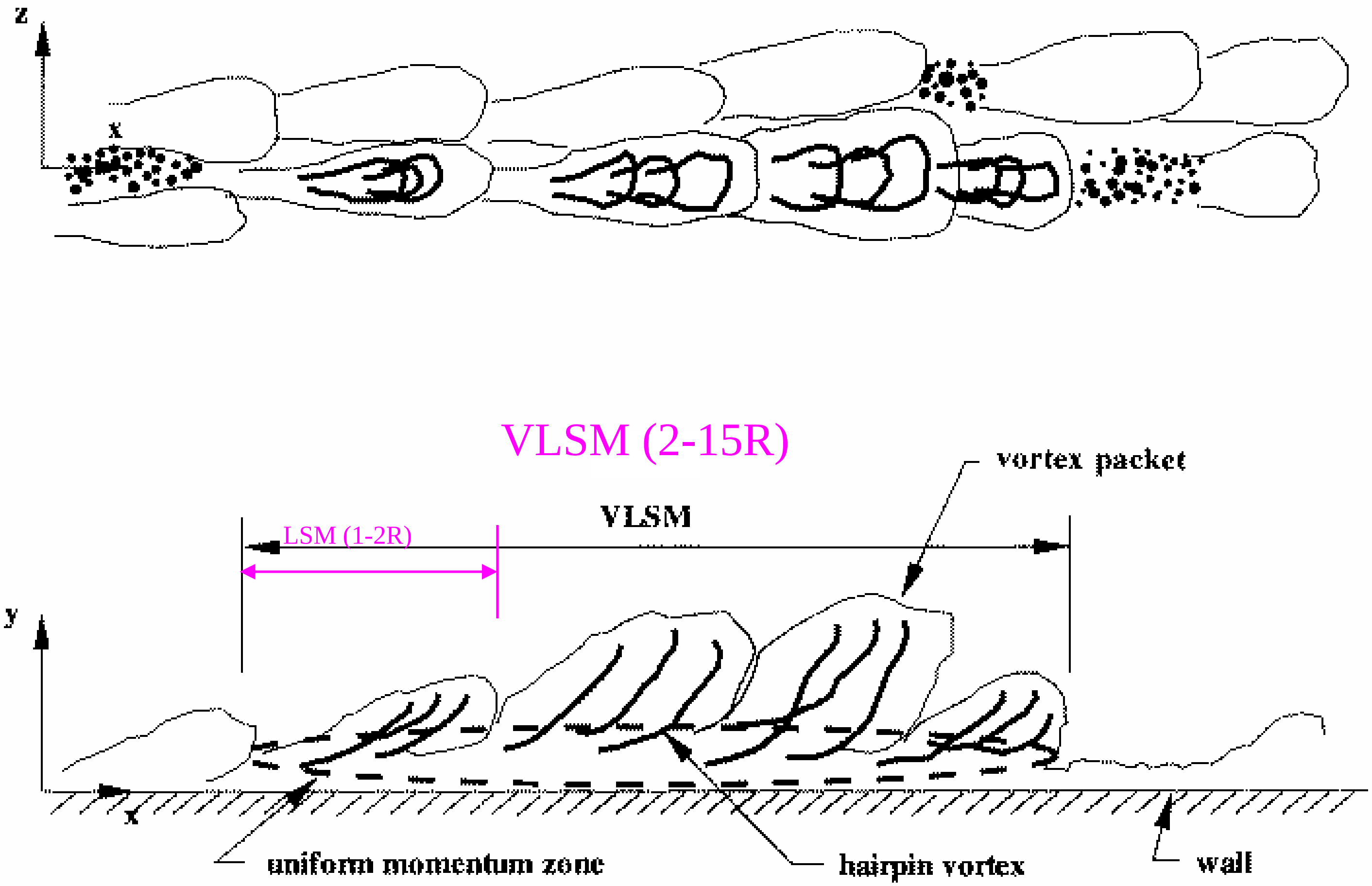


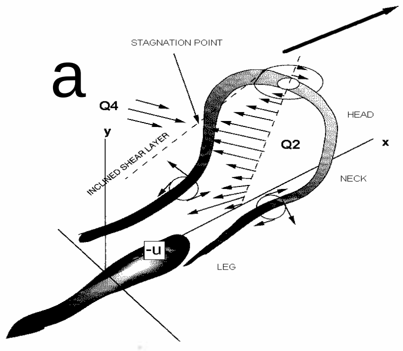
FIGURE 27. Vertical derivative of pre-multiplied co-spectra, Φ_{uv}, for $Re_\tau = 3,814$. The curves represent $y/R = 0.6$, 0.45, 0.35, 0.25 and 0.15, respectively, as transit is made along the line A–A'. Note that the peak on the low wave numbers region is on the y/R=0.15 curve.


z
x
VLSM (2-15R)
vortex packet
VLSM
LSM (1-2R)
y
x
uniform momentum zone
hairpin vortex
wall

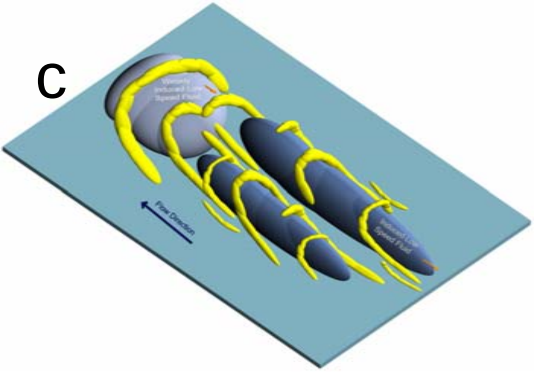
Other Stress Mechanisms

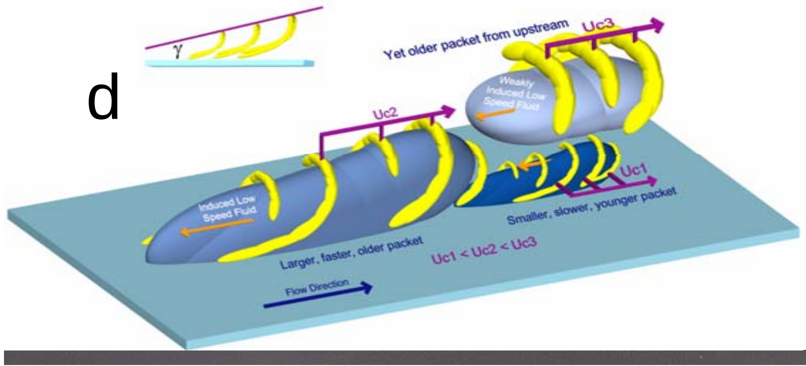
- Quasi streamwise vortices
  - Waleffe outer
  - Schoppa and Hussain -inner
- ‘Cats paw’ down bursts at atmospheric Reynolds numbers
  - (Hunt, Carlotti and Hogstrom).
  - Increasing turbulence in outer layer as Re increases may make large outer scales more important

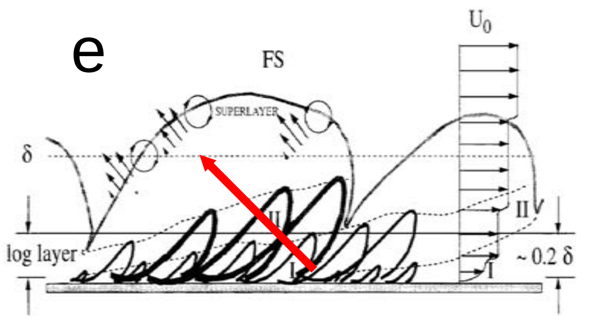
Summary

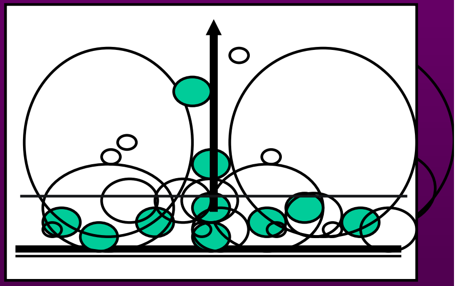


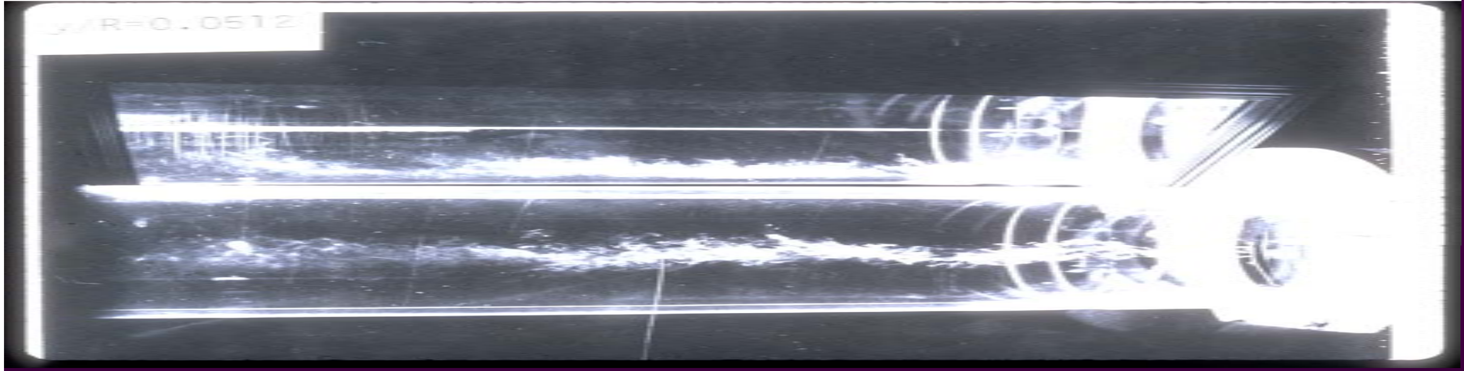
Packets of hairpin vortices











Summary

- **Incoherent stress:** The Reynolds stress due to individual eddies
    - Quasi streamwise vortices near the wall
    - Hairpin near the wall and in the log layer
- **Coherent stress: The Reynolds stress due to coherent organization of groups of eddies**
    - Enhances the total stress
- **Coherent vortex induction:**
    - leads to zones of approximately uniform momentum in the interiors of the packets. Packets act like solenoids to intensify the back induction
- **Very Large Scale Motions (super δ-scale)**
    - Carry substantial fraction of R-stress in the outer region
- **RANS Modeling**
    - Correct transport coefficients for >LSM contribution and compute >LSM motions in a 3-D ,time-dependent RANS

Thank you, DFD!