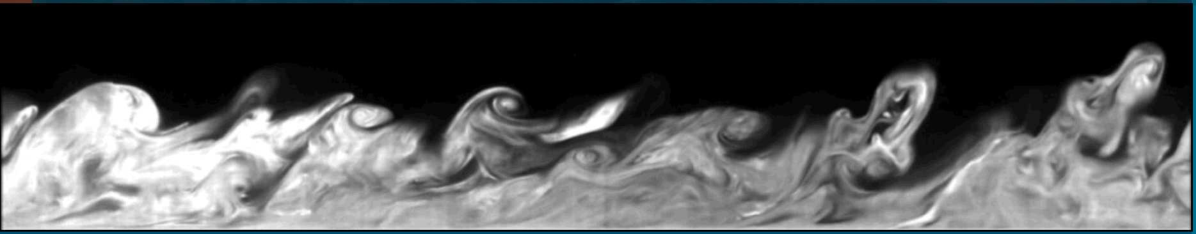
SAND2018-12232PE

Hairpin Vortex Packets in Oscillating Wall Turbulence



Lee, J. H., Kwon, Y. S., Hutchins, N., and Monty, J. P. (2012). Spatially developing turbulent boundary layer on a flat plate. *arXiv preprint arXiv:1210.3881*.

PRESENTED BY

Dr. Blake Lance, blance@sandia.gov

Penn State Fluid Dynamics Research Consortium

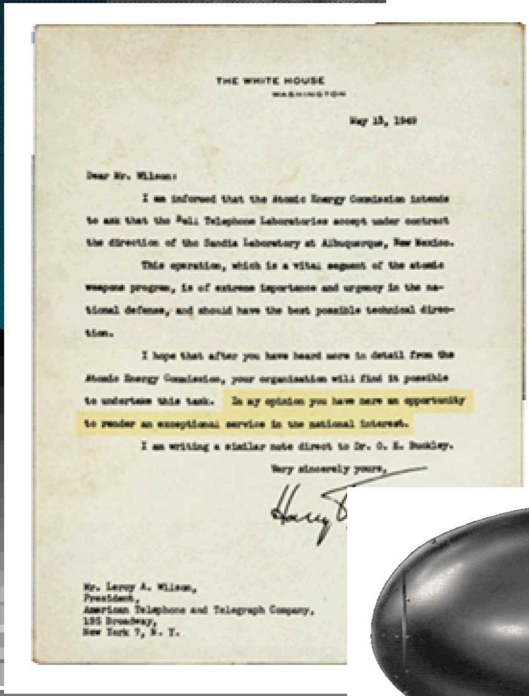
25 October 2018

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Lab's history is traced to the Manhattan Project

…In my opinion you have here an opportunity to render an exceptional service in the national interest.

- July 1945
  Los Alamos creates Z Division
- Nonnuclear component engineering
- November 1, 1949
  Sandia Laboratory established
- AT&T: 1949–1993
- Martin Marietta: 1993–1995
- Lockheed Martin: 1995–2017
- Honeywell: 2017–present



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

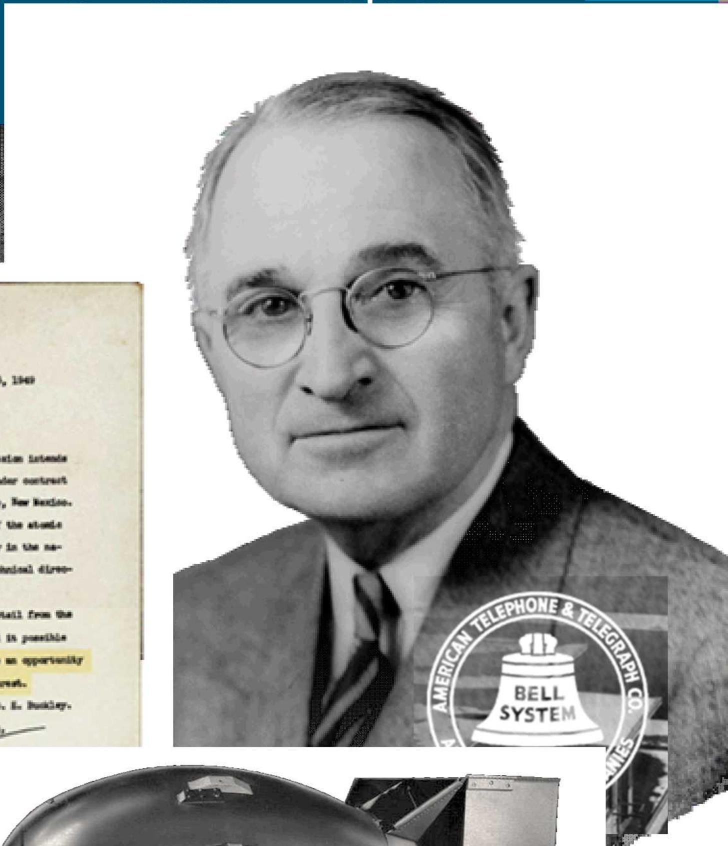
This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

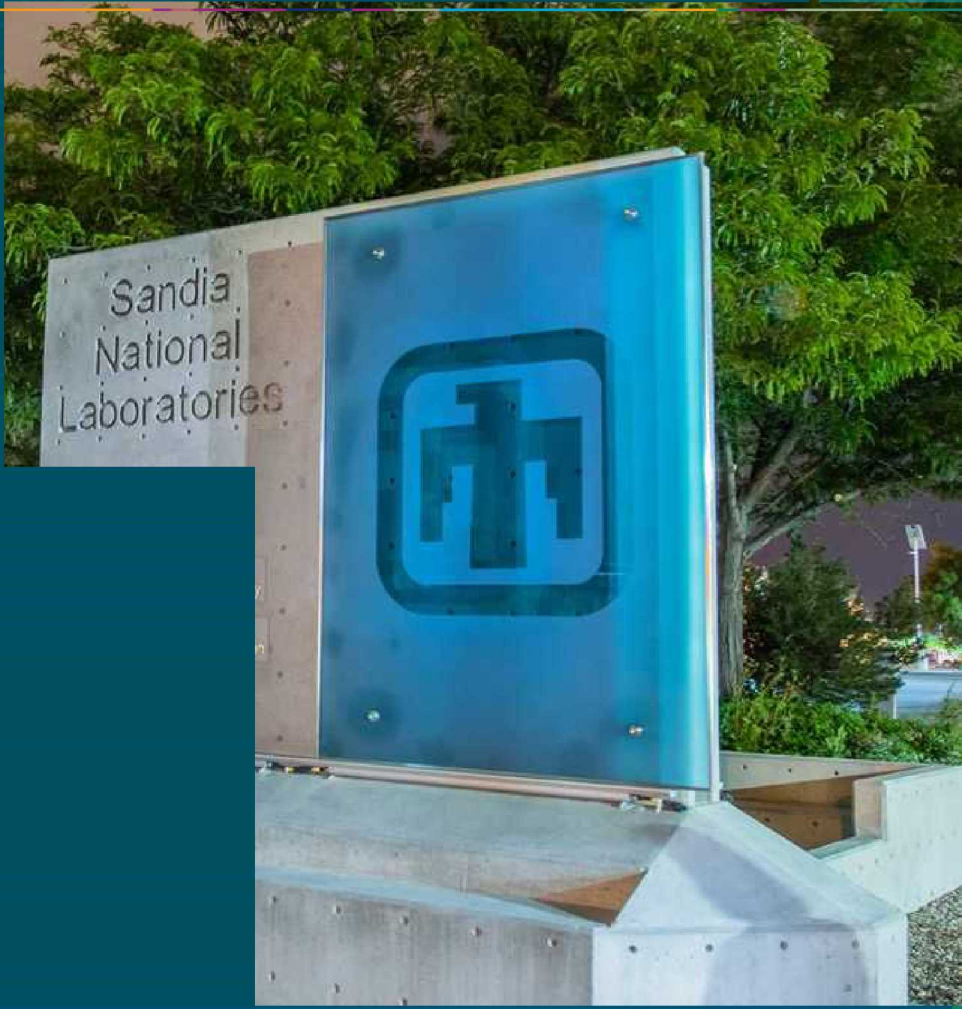
Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.



Sandia is a federally funded research and development center managed and operated by

National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc.: 2017 – present

Government owned, contractor operated



Sandia has facilities across the nation

Activity locations

- Kauai, Hawaii
- Waste Isolation Pilot Plant, Carlsbad, New Mexico
- Pantex Plant, Amarillo, Texas
- Tonopah, Nevada

Main sites

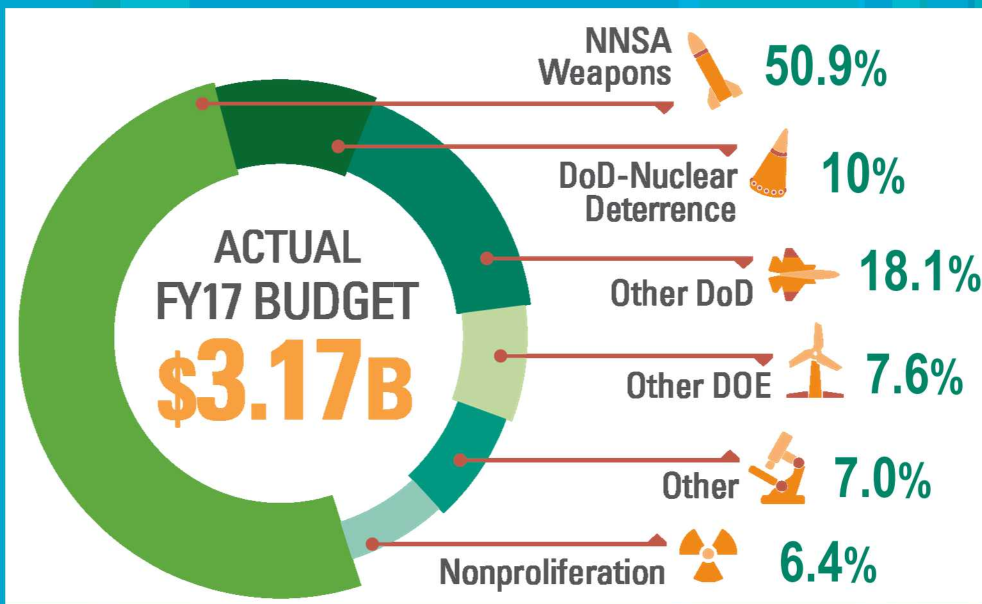
- Albuquerque, New Mexico
- Livermore, California

Our purpose statement defines what we do

Sandia develops advanced technologies to ensure global peace

Sandia's budget covers a broad range of work

[redacted]



OTHER

Department of Homeland Security

Other federal agencies | Nonfederal entities

CRADAs, licenses, royalties | Inter-entity work

DoD

Air Force | Army | Navy

Defense Threat Reduction Agency

Ballistic Missile Defense Organization

Office of the Secretary of Defense

Defense Advanced Research Projects Agency

Intelligence Community

OTHER DOE

Science

Energy Efficiency and Renewable Energy

Nuclear Energy

Environmental Management

Electricity Delivery and Energy Reliability

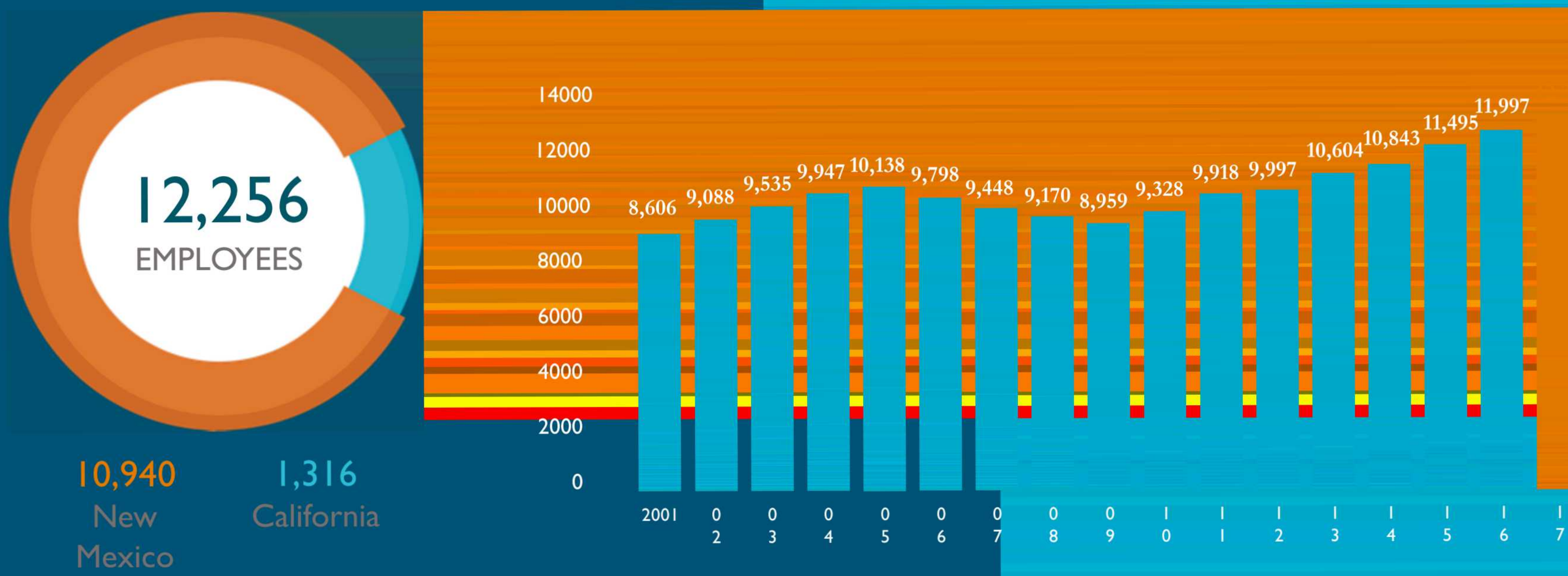
Other DOE

NONPROLIFERATION

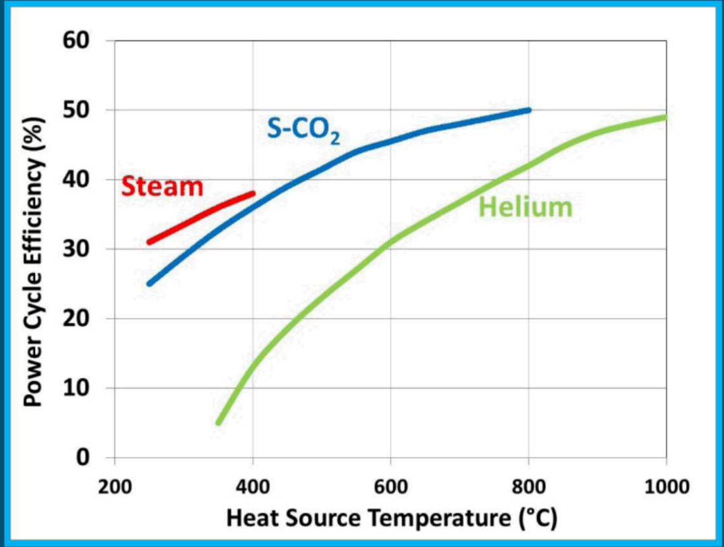
NNSA/NA20 | State Department

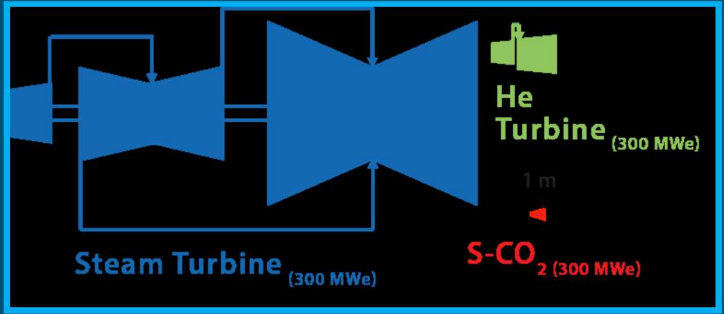
Sandia's workforce is growing

Staff has grown by over 3,000 since 2009 to meet all mission needs



Supercritical CO_2 Brayton cycles have the potential for high efficiency and low cost energy conversion (heat to electricity)



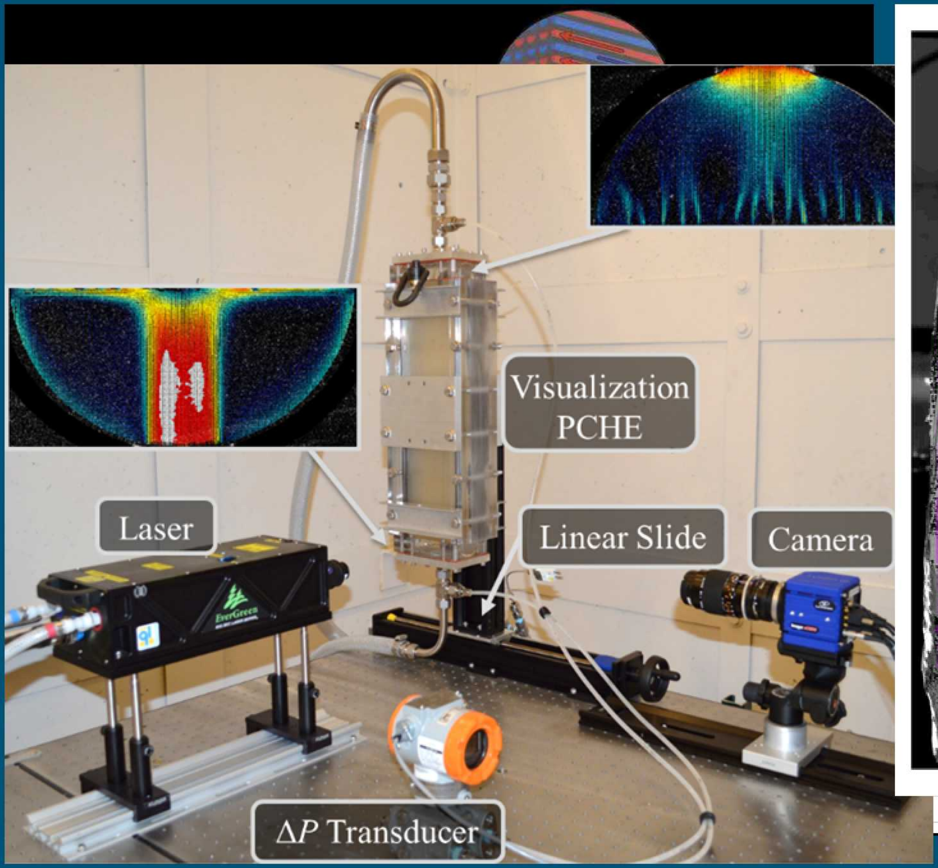


Microchannel heat exchangers are a critical technology

Brayton cycles use a large amount of heat recuperation or recycling

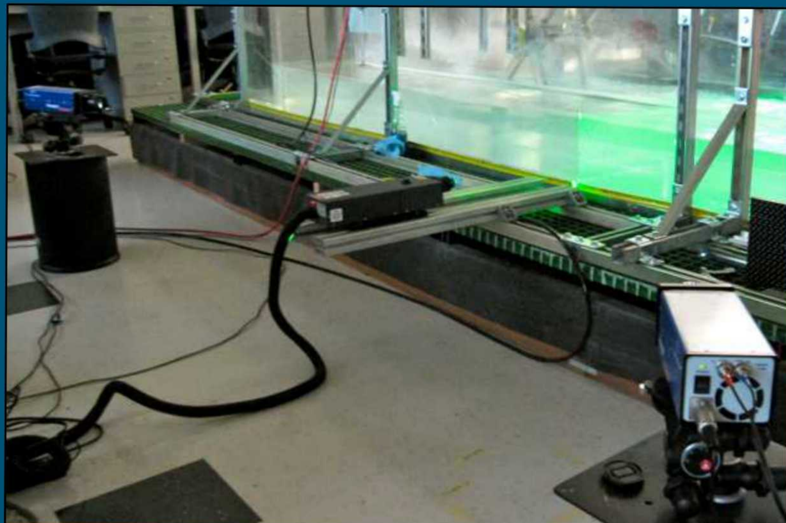
Microchannel heat exchangers are cheaper and smaller than typical shell and tube for high pressures

Flow uniformity and failure modes are being studied

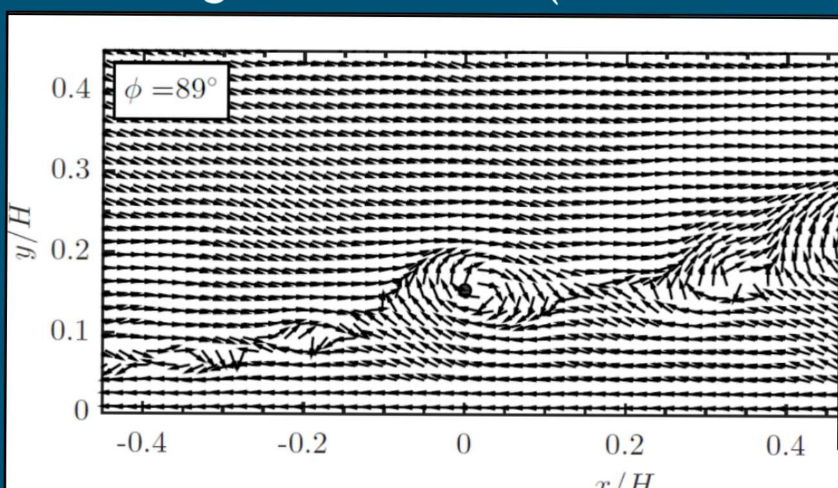


I've completed three previous fluid dynamics experiments

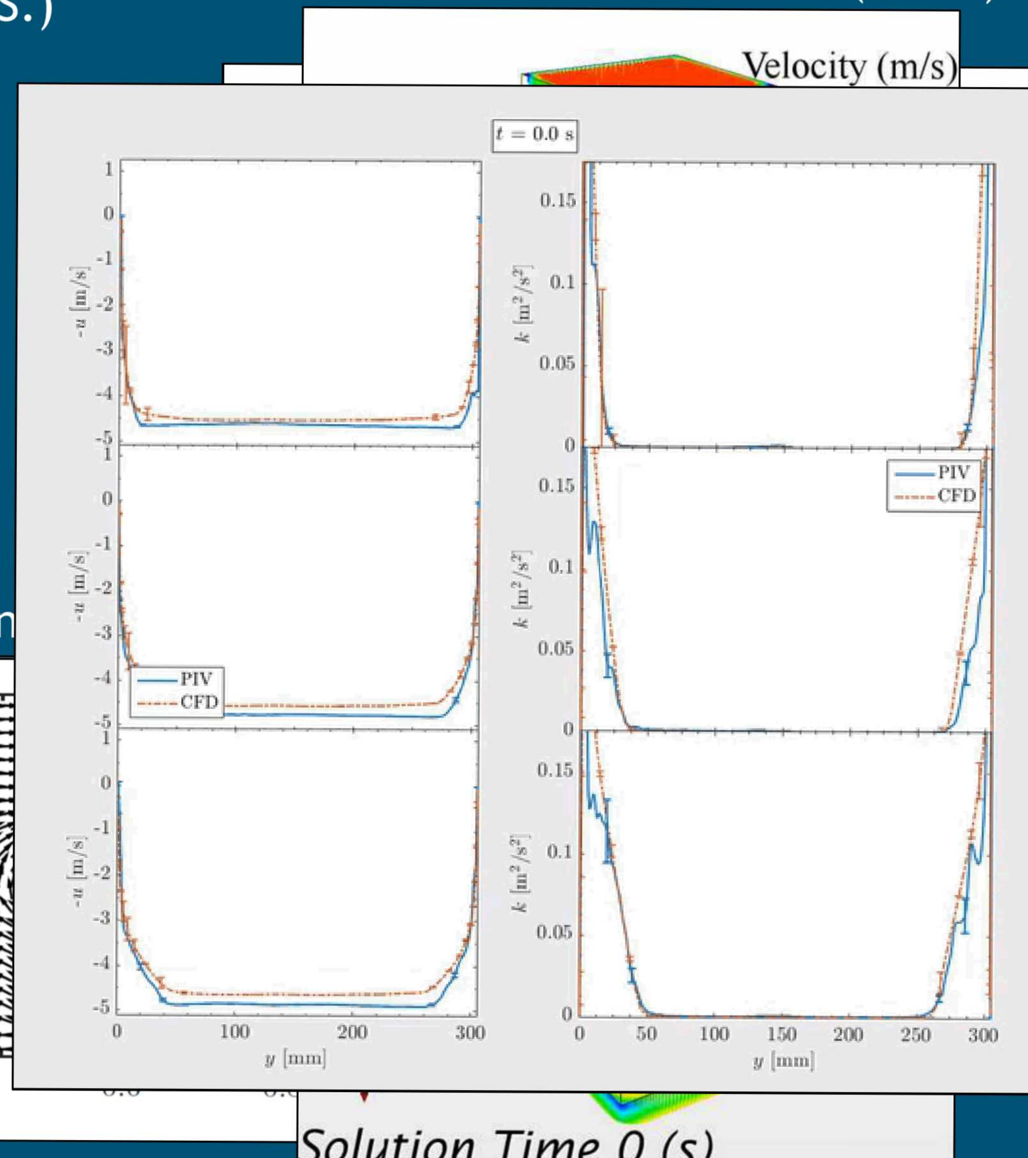
Algal Raceway Mixing Optimization (M.S.)



Oscillating Channel Flow (Sandia Intern

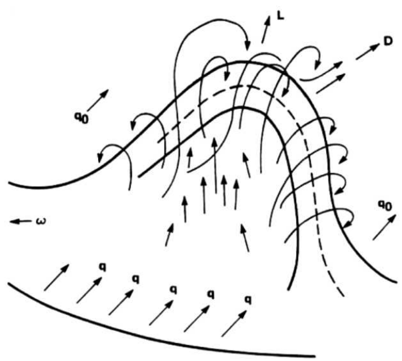


Transient Mixed Convection (Ph.D.)

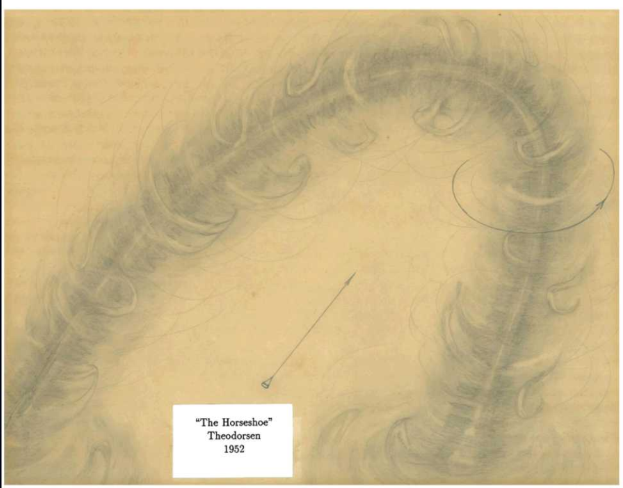


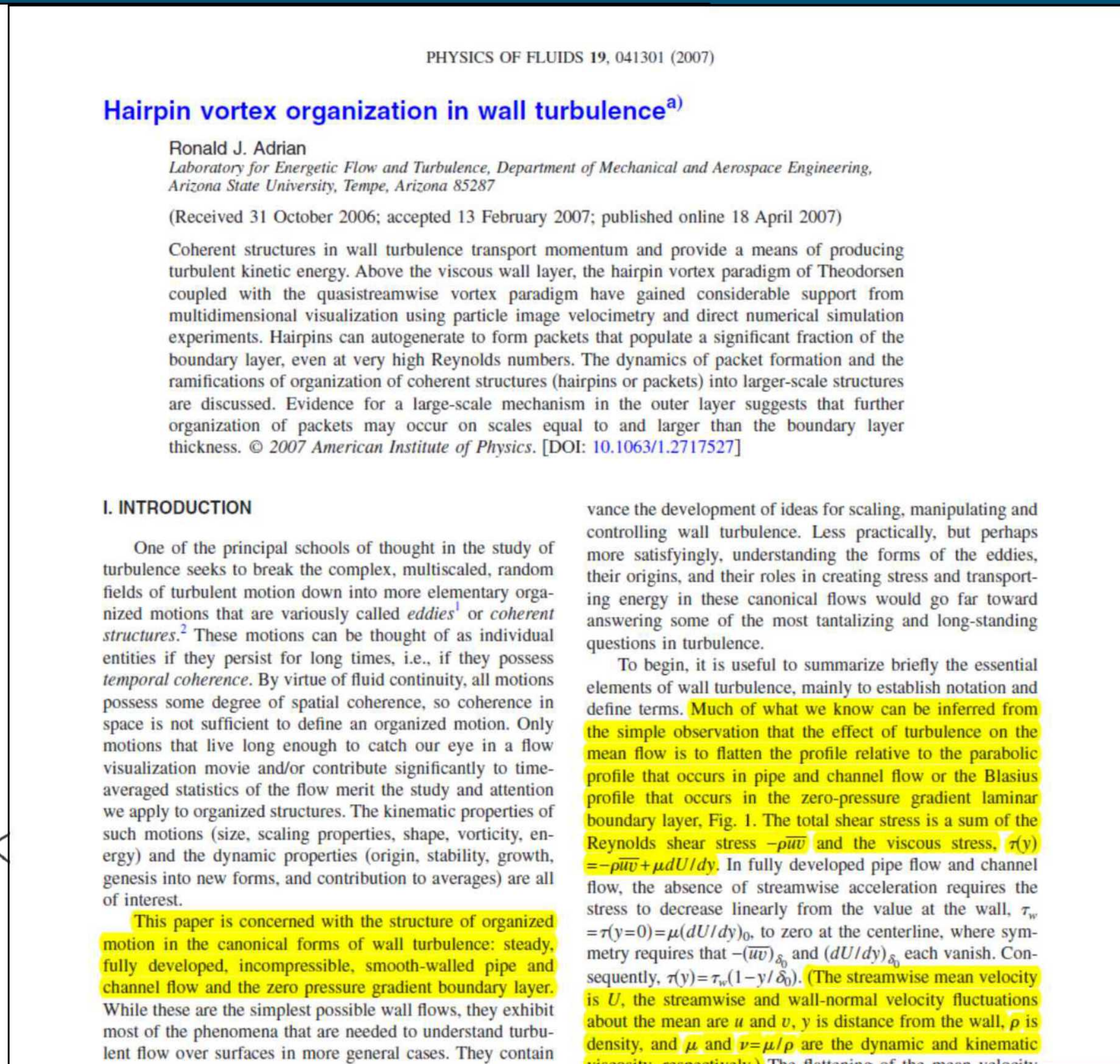
Coherent structures have been measured in steady turbulent boundary layers, but what about for oscillating flow?

(a)



(b)





PHYSICS OF FLUIDS 19, 041301 (2007)

Hairpin vortex organization in wall turbulence[a)]

Ronald J. Adrian
Laboratory for Energetic Flow and Turbulence, Department of Mechanical and Aerospace Engineering, Arizona State University, Tempe, Arizona 85287

(Received 31 October 2006; accepted 13 February 2007; published online 18 April 2007)

Coherent structures in wall turbulence transport momentum and provide a means of producing turbulent kinetic energy. Above the viscous wall layer, the hairpin vortex paradigm of Theodorsen coupled with the quasistreamwise vortex paradigm have gained considerable support from multidimensional visualization using particle image velocimetry and direct numerical simulation experiments. Hairpins can autogenerate to form packets that populate a significant fraction of the boundary layer, even at very high Reynolds numbers. The dynamics of packet formation and the ramifications of organization of coherent structures (hairpins or packets) into larger-scale structures are discussed. Evidence for a large-scale mechanism in the outer layer suggests that further organization of packets may occur on scales equal to and larger than the boundary layer thickness. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2717527]

I. INTRODUCTION

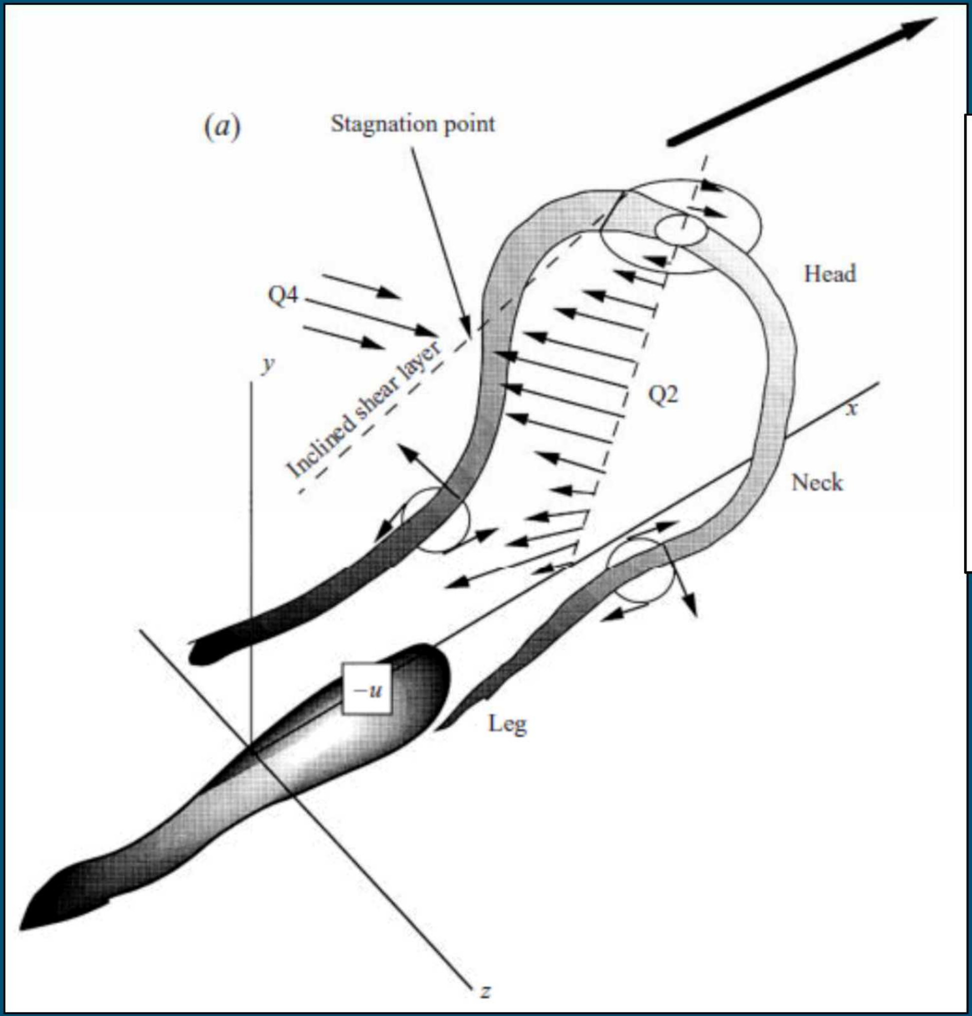
One of the principal schools of thought in the study of turbulence seeks to break the complex, multiscaled, random fields of turbulent motion down into more elementary organized motions that are variously called *eddies*[1] or *coherent structures*.[2] These motions can be thought of as individual entities if they persist for long times, i.e., if they possess *temporal coherence*. By virtue of fluid continuity, all motions possess some degree of spatial coherence, so coherence in space is not sufficient to define an organized motion. Only motions that live long enough to catch our eye in a flow visualization movie and/or contribute significantly to time-averaged statistics of the flow merit the study and attention we apply to organized structures. The kinematic properties of such motions (size, scaling properties, shape, vorticity, energy) and the dynamic properties (origin, stability, growth, genesis into new forms, and contribution to averages) are all of interest.

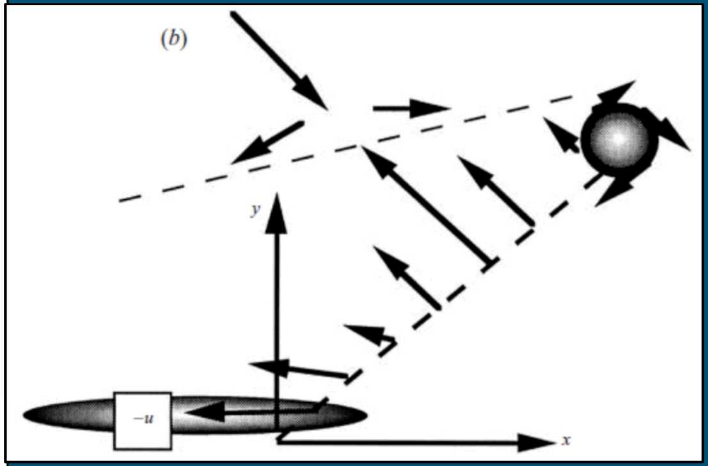
This paper is concerned with the structure of organized motion in the canonical forms of wall turbulence: steady, fully developed, incompressible, smooth-walled pipe and channel flow and the zero pressure gradient boundary layer. While these are the simplest possible wall flows, they exhibit most of the phenomena that are needed to understand turbulent flow over surfaces in more general cases. They contain

vance the development of ideas for scaling, manipulating and controlling wall turbulence. Less practically, but perhaps more satisfyingly, understanding the forms of the eddies, their origins, and their roles in creating stress and transporting energy in these canonical flows would go far toward answering some of the most tantalizing and long-standing questions in turbulence.

To begin, it is useful to summarize briefly the essential elements of wall turbulence, mainly to establish notation and define terms. Much of what we know can be inferred from the simple observation that the effect of turbulence on the mean flow is to flatten the profile relative to the parabolic profile that occurs in pipe and channel flow or the Blasius profile that occurs in the zero-pressure gradient laminar boundary layer, Fig. 1. The total shear stress is a sum of the Reynolds shear stress $-\rho\overline{uv}$ and the viscous stress, $\tau(y) = -\rho\overline{uv} + \mu dU/dy$. In fully developed pipe flow and channel flow, the absence of streamwise acceleration requires the stress to decrease linearly from the value at the wall, $\tau_w = \tau(y=0) = \mu(dU/dy)_0$, to zero at the centerline, where symmetry requires that $-(\overline{uv})_{\delta_0}$ and $(dU/dy)_{\delta_0}$ each vanish. Consequently, $\tau(y) = \tau_w(1-y/\delta_0)$. (The streamwise mean velocity is U, the streamwise and wall-normal velocity fluctuations about the mean are u and v, y is distance from the wall, ρ is density, and μ and $\nu=\mu/\rho$ are the dynamic and kinematic viscosity, respectively.) The flattening of the mean velocity

Hairpin Vortices have unique features

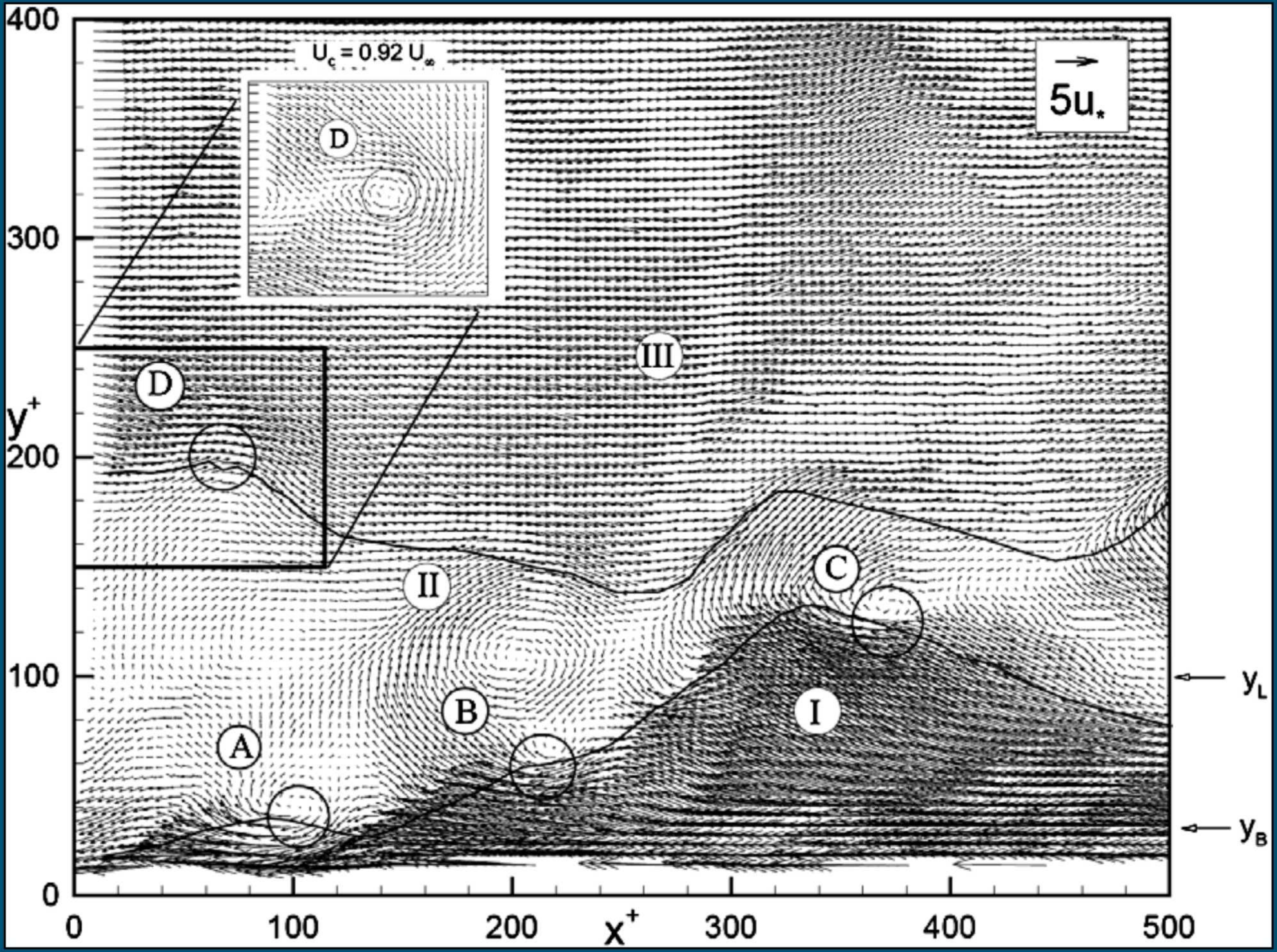




(*a*) Schematic of a hairpin vortex attached to the wall and the induced motion. (*b*) Signature of the hairpin vortex in the streamwise--wall-normal plane. The signature is insensitive to the spanwise location of the plane, until it intersects the concentrated core forming either side of
the hairpin.

R. J. Adrian, C. D. Meinhart, and C. D. Tomkins, "Vortex organization in the outer region of the turbulent boundary layer," J. Fluid Mech. **422**, 1 (2000).

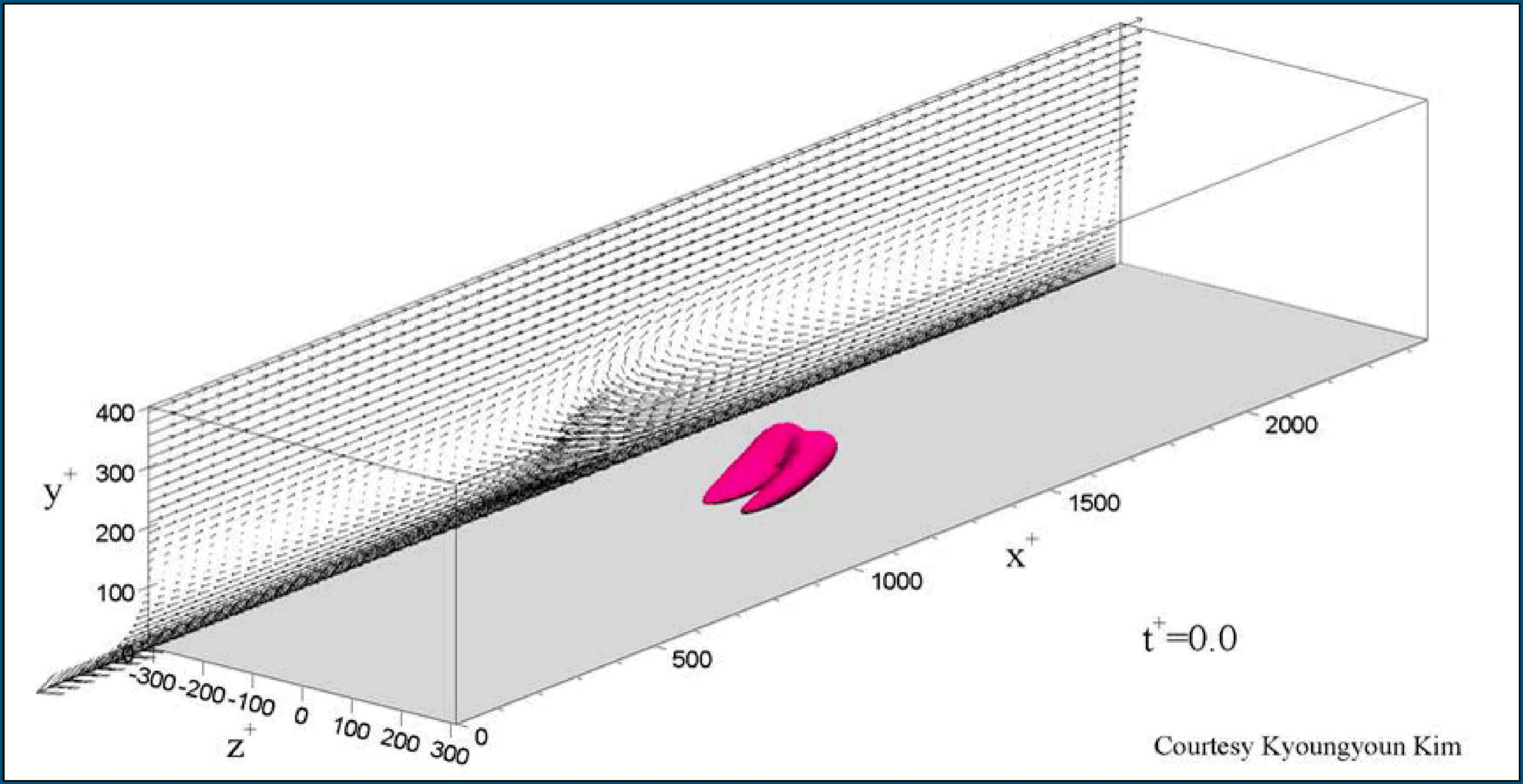
Instantaneous vector fields have regions of uniform momentum



Hairpin vortex signatures in a PIV measurement of flow in the streamwise-wall-normal plane of a turbulent boundary layer, Re_θ =930. The heads of the hairpins are labeled A, B, C, and D. Note the correspondence between the flow patterns below and behind each head with the hairpin signature. Zones of uniform momentum are labeled I, II, and III. The reference frame for the vectors is translating at 80% of the free-stream velocity.

R. J. Adrian, C. D. Meinhart, and C. D. Tomkins, “Vortex organization in the outer region of the turbulent boundary layer,” J. Fluid Mech. **422**, 1 (2000).

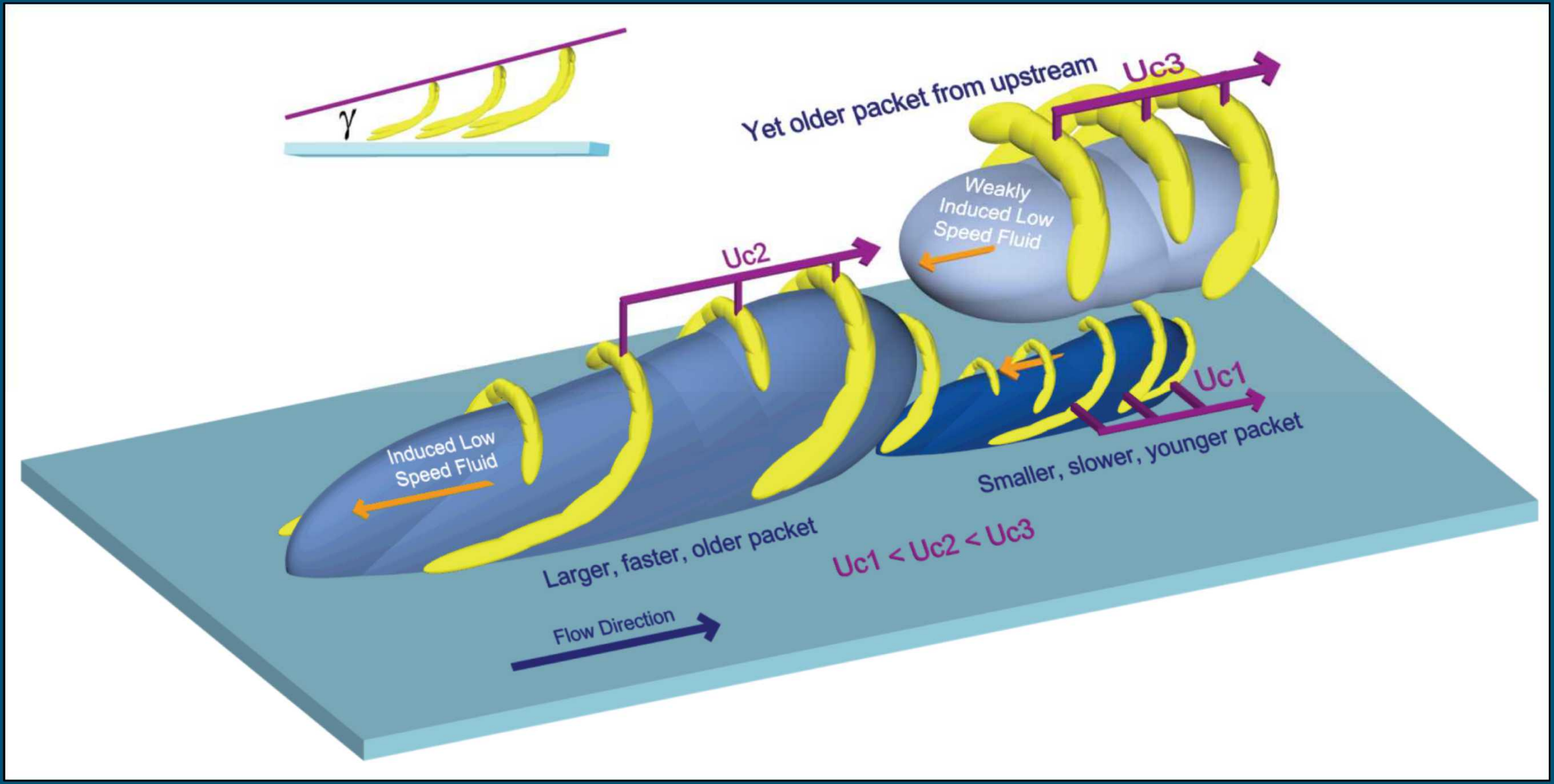
Hairpin Vortices have been predicted with DNS in boundary layers



Evolution of a packet of hairpins from a conditional Q2 event. Surface is an isosurface of swirling strength. The Reynolds number is Re_τ =395.

J. Zhou, R. J. Adrian, S. Balachandar, and T. M. Kendall, "Mechanisms for generating coherent packets of hairpin vortices in channel flow," J. Fluid Mech. **387**, 353 (1999).

Hairpin Vortices come in packets and have scales that depend on their age



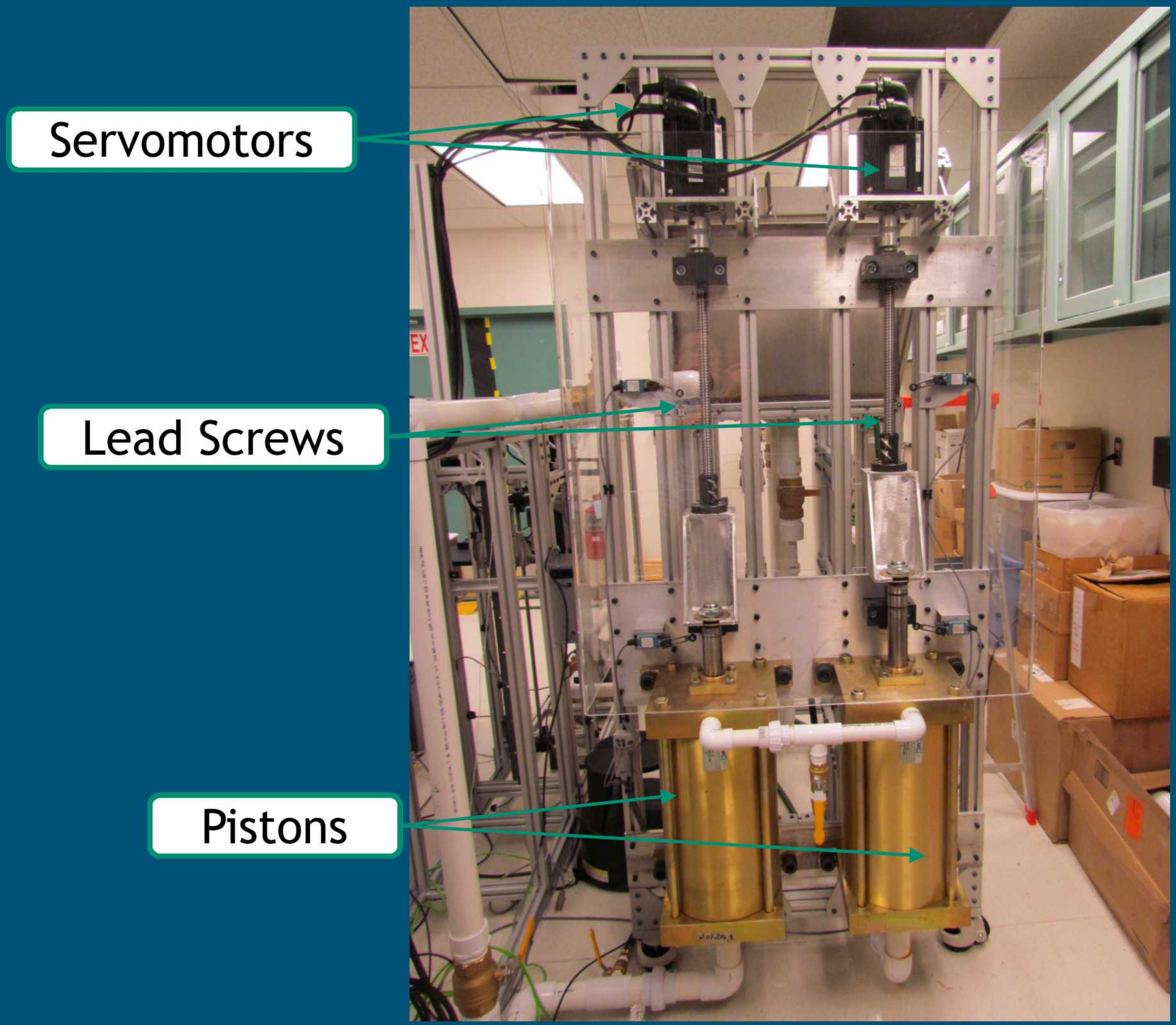
Conceptual scenario of hairpins attached to the wall and growing in an environment of overlying larger hairpin packets

R. J. Adrian, C. D. Meinhart, and C. D. Tomkins, "Vortex organization in the outer region of the turbulent boundary layer," J. Fluid Mech. **422**, 1 (2000).

Our coherent structures experimental facility is called the SEAWOLF

Sediment Erosion Actuated by Wave Oscillations and Linear Flow

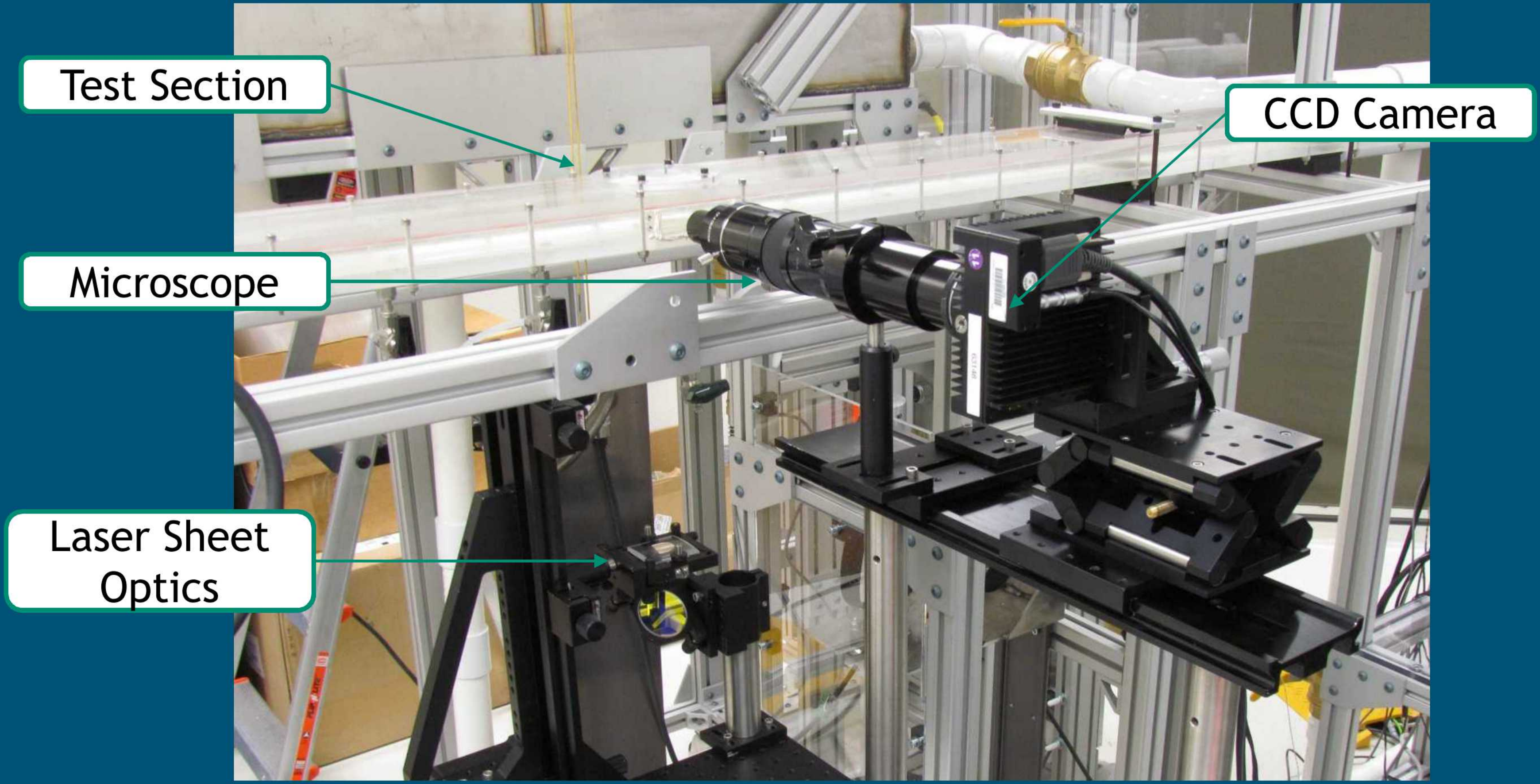
Oscillating flow was driven by a pair of piston-cylinders



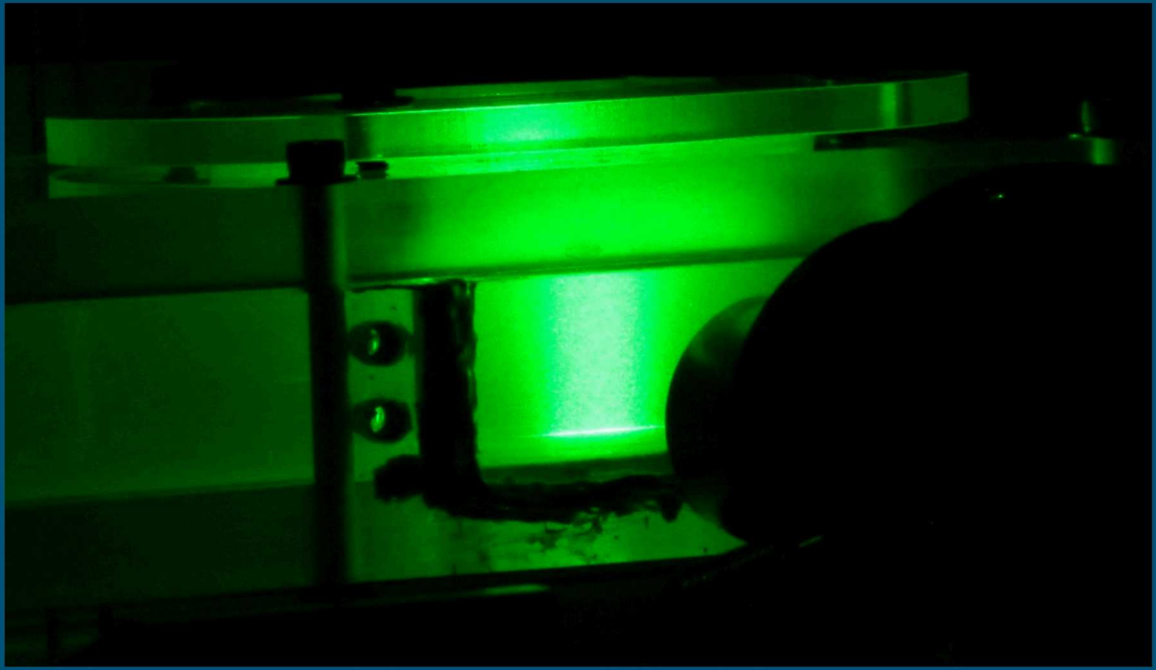
Dual 10” pistons driven by servomotors to produce oscillating flow

The PIV system was assembled from borrowed parts with LabVIEW used for timing and image acquisition

Infinity Microscope and RedLake CCD digital camera



Particle Image Velocimetry (PIV)



- Flow seeded with 10 µm diameter hollow glass spheres
- Seed particles illuminated by laser sheet
- Commercial software (DaVis) computes the cross-correlation

So far you have seen the turbulent boundary layer time-mean velocity in wall coordinates

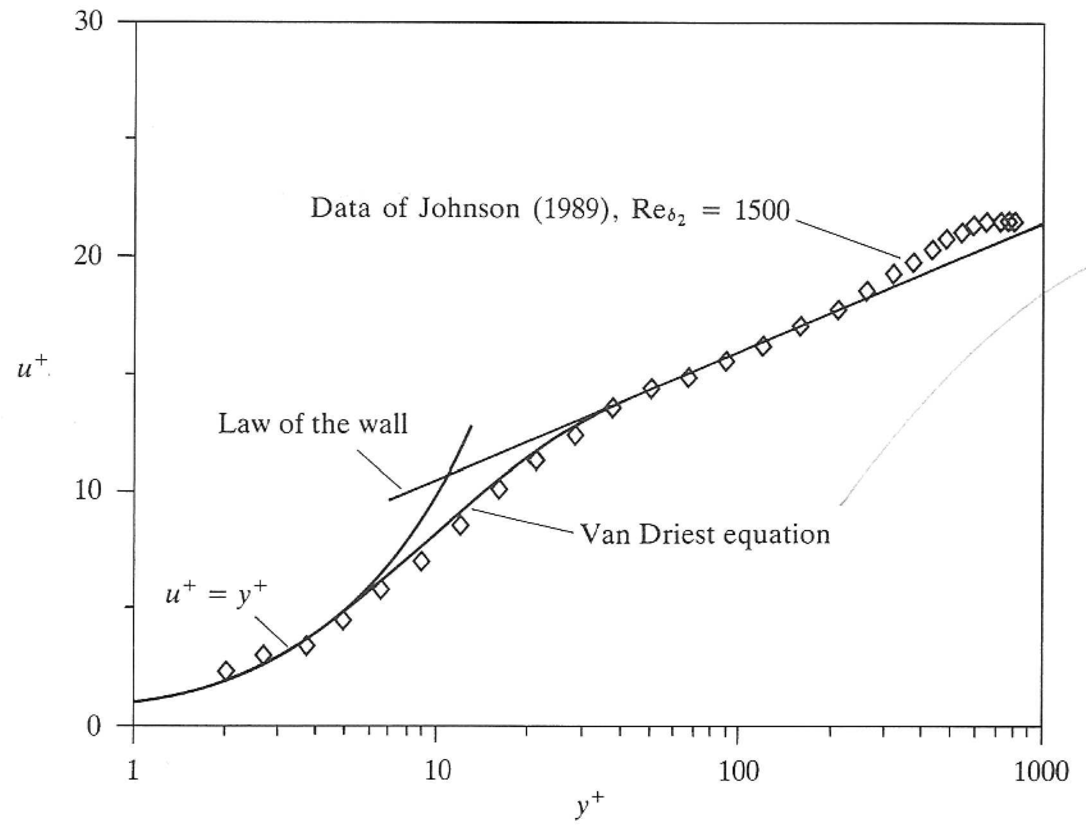


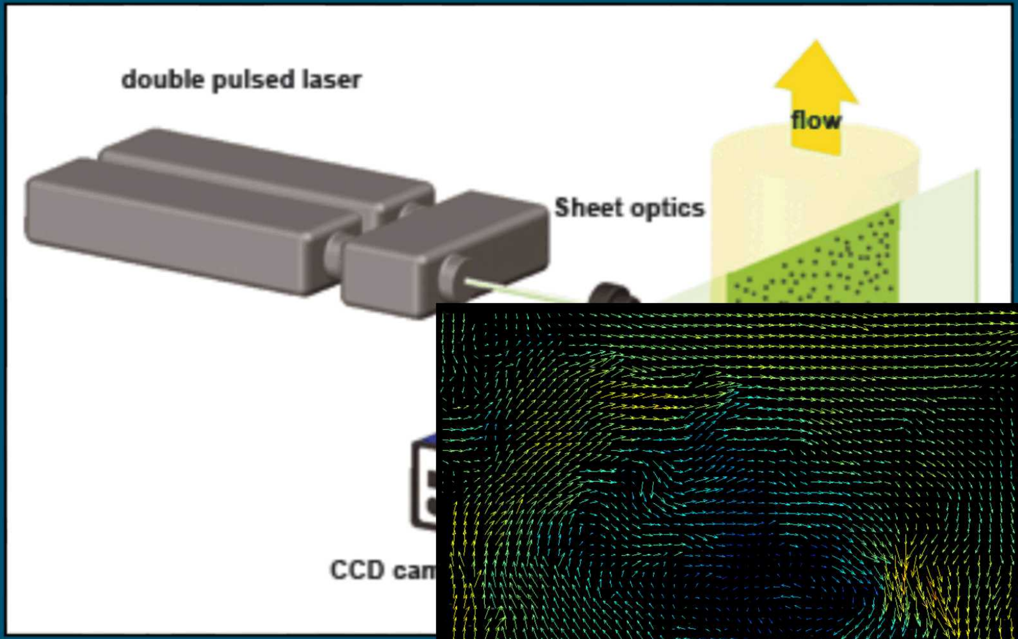
Figure 11-5 The Van Driest sublayer (constant free-stream velocity): the sublayer as calculated using the Van Driest equation with $A^+ = 25.0$.

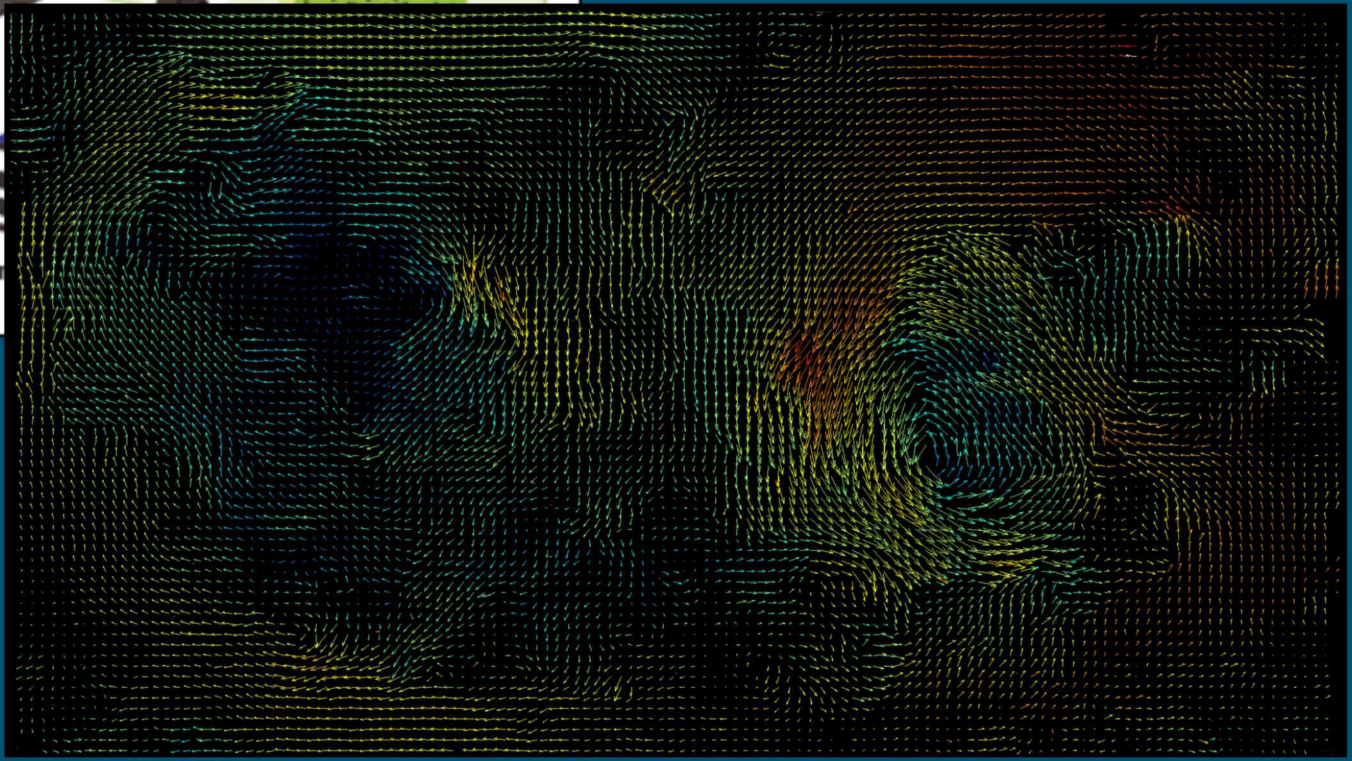
W. M. Kays, M. E. Crawford, and B. Weigand, Convective Heat and Mass Transfer, McGraw-Hill (2012).

Turbulent flow has Coherent Structures (spatial order that persists in time)

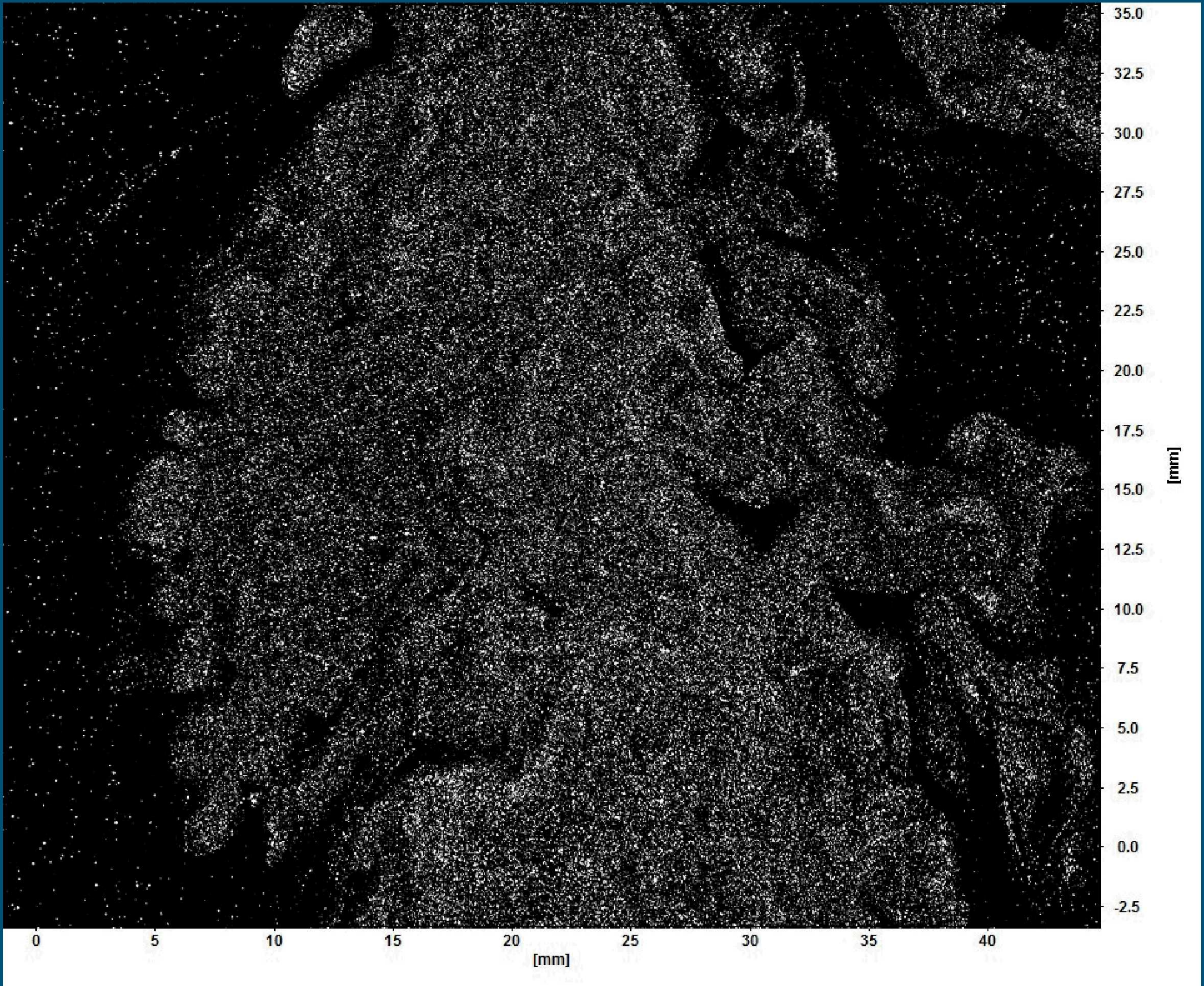
Lee, J. H., Kwon, Y. S., Hutchins, N., and Monty, J. P. (2012). Spatially developing turbulent boundary layer on a flat plate. *arXiv preprint arXiv:1210.3881*.

Particle Image Velocimetry (PIV) is an excellent tool for measuring Coherent Structures

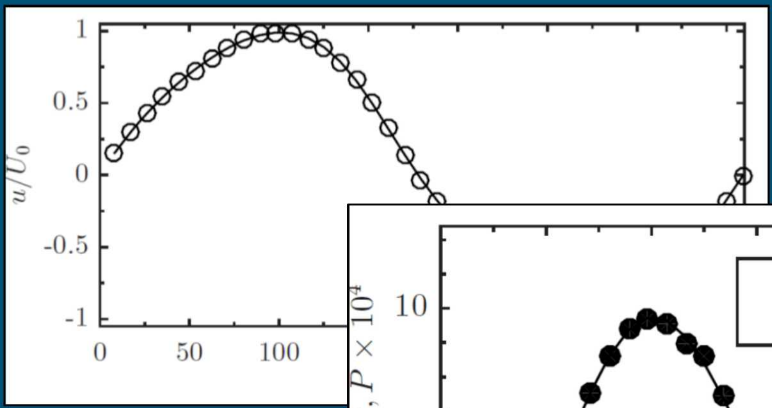


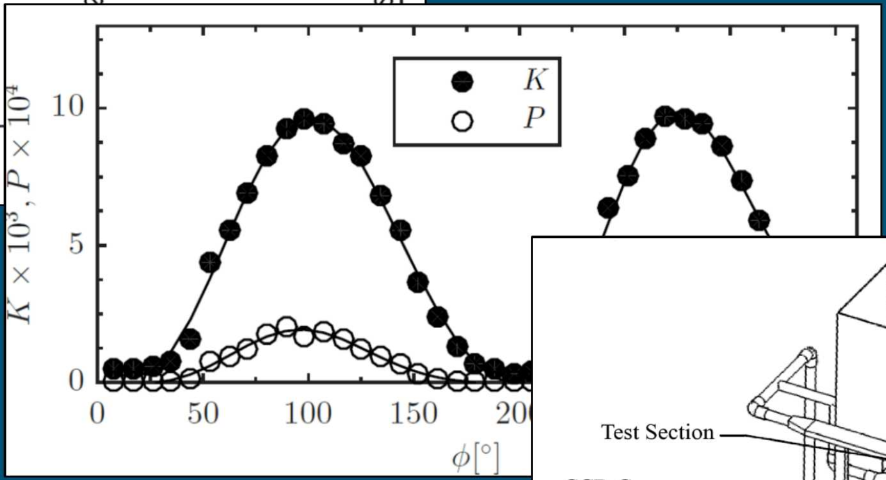


Your eye can track the fluid motion in most PIV images

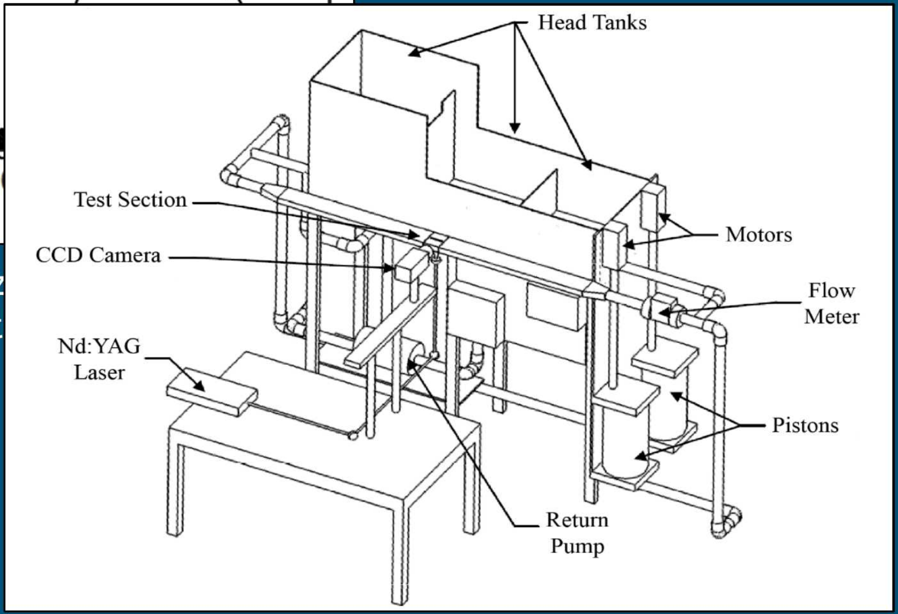


Hairpin Vortices exist in steady turbulence, but what about oscillating turbulence?





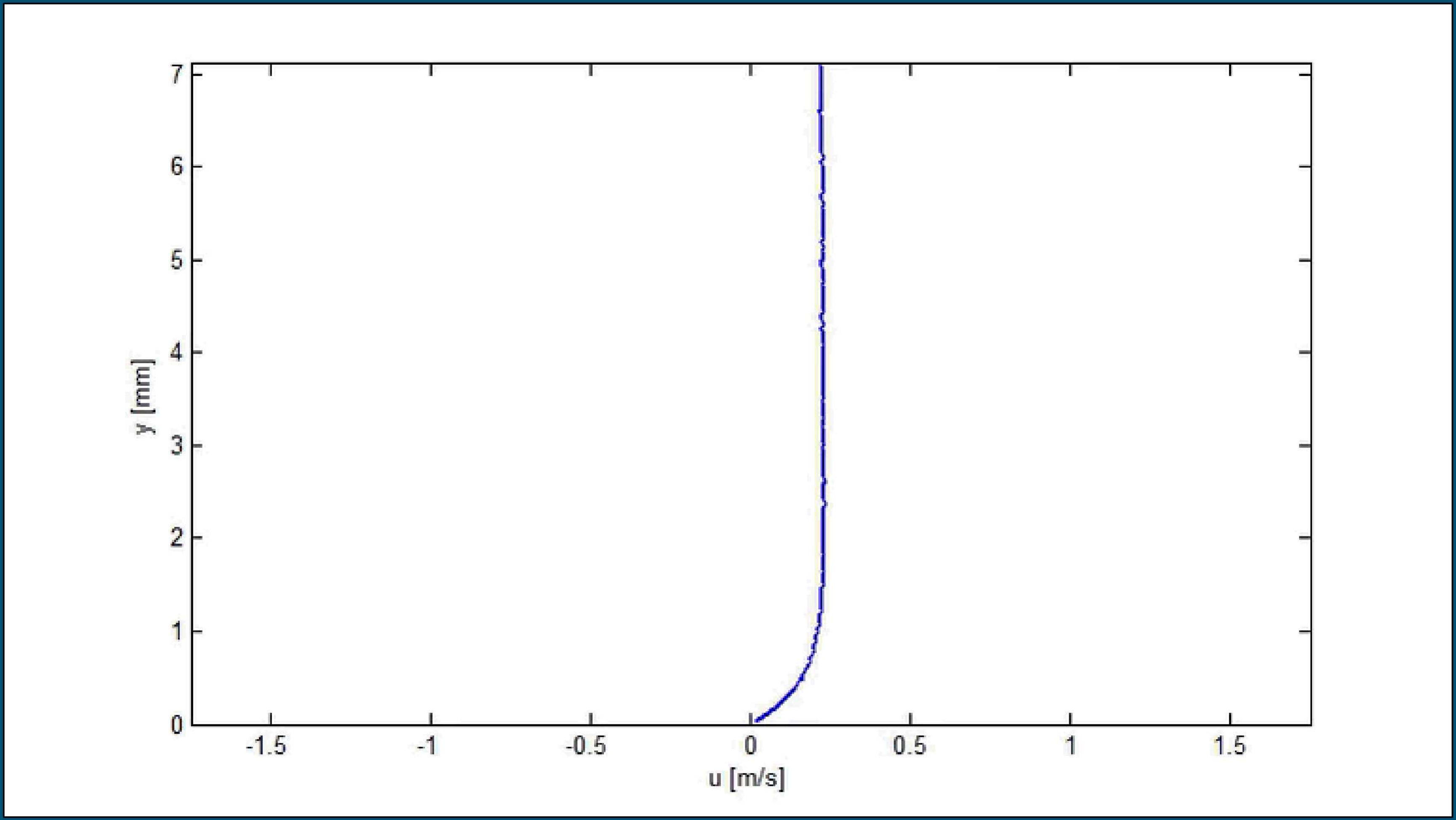
K and *P* are normaliz
of *k* and the product



SEAWOLF at Sandia National Labs

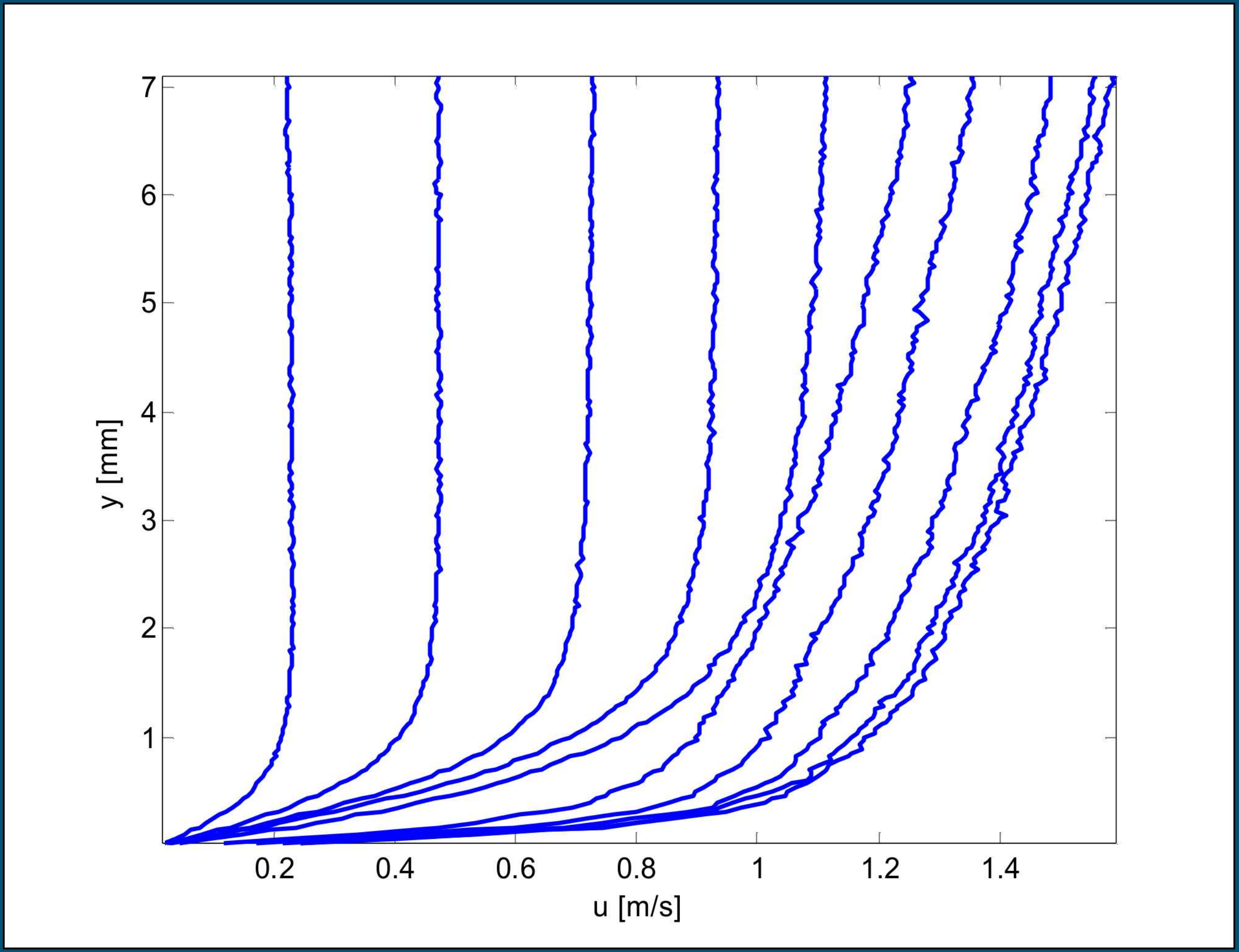
All Velocity Profiles

The flow begins laminar, but transition to turbulence is observed as the velocity increases.



¼ *T* - Velocity Profiles

The flow begins laminar, but transition to turbulence is observed as the velocity increases.



Typically the Reynolds number for oscillating flow is Re_δ

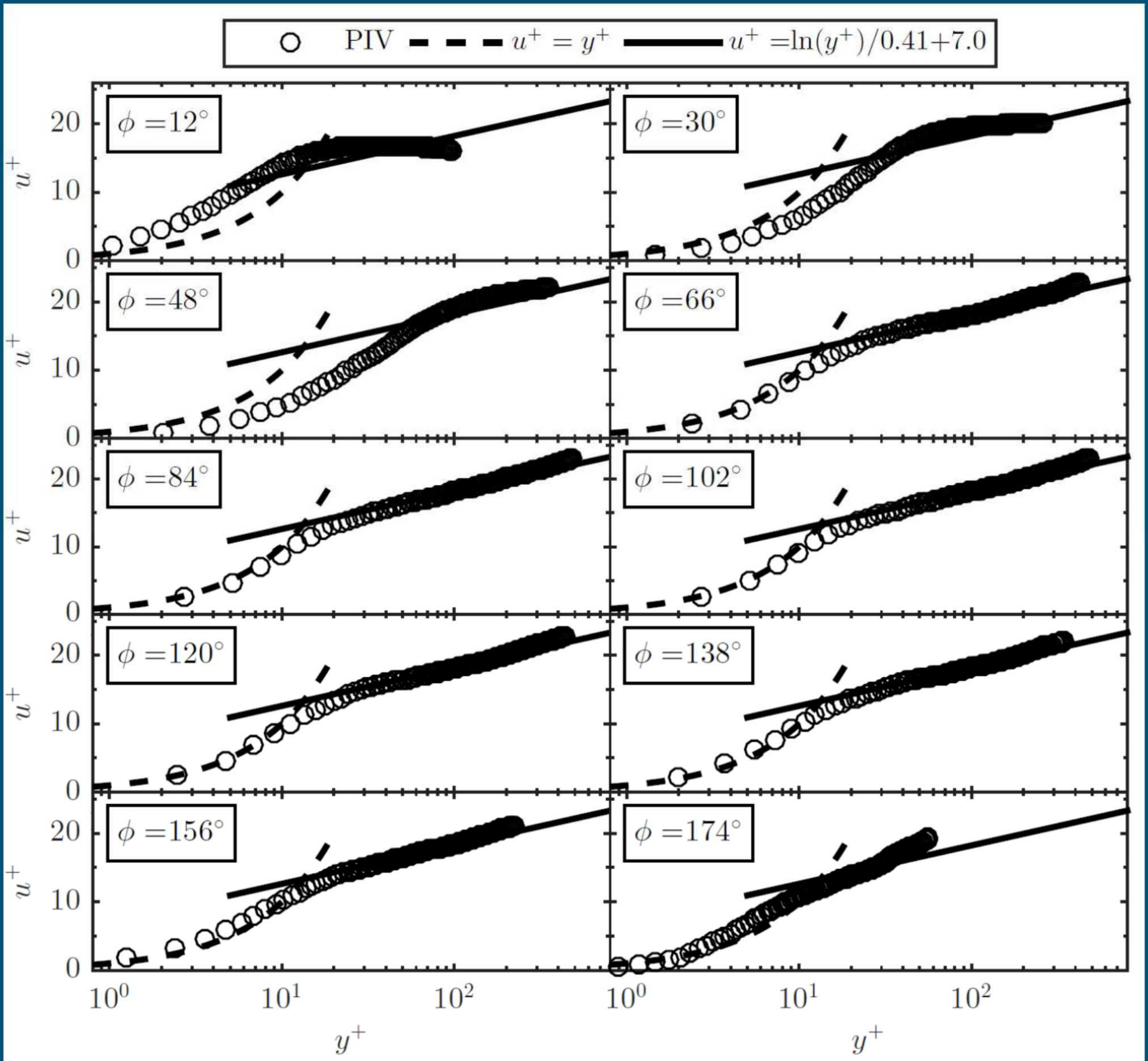
$$\mathrm{Re}_\delta = \frac{U_0 \delta}{\nu}$$

The Stokes-layer thickness is given by δ

$$\delta = \sqrt{\frac{2\nu}{\omega}}$$

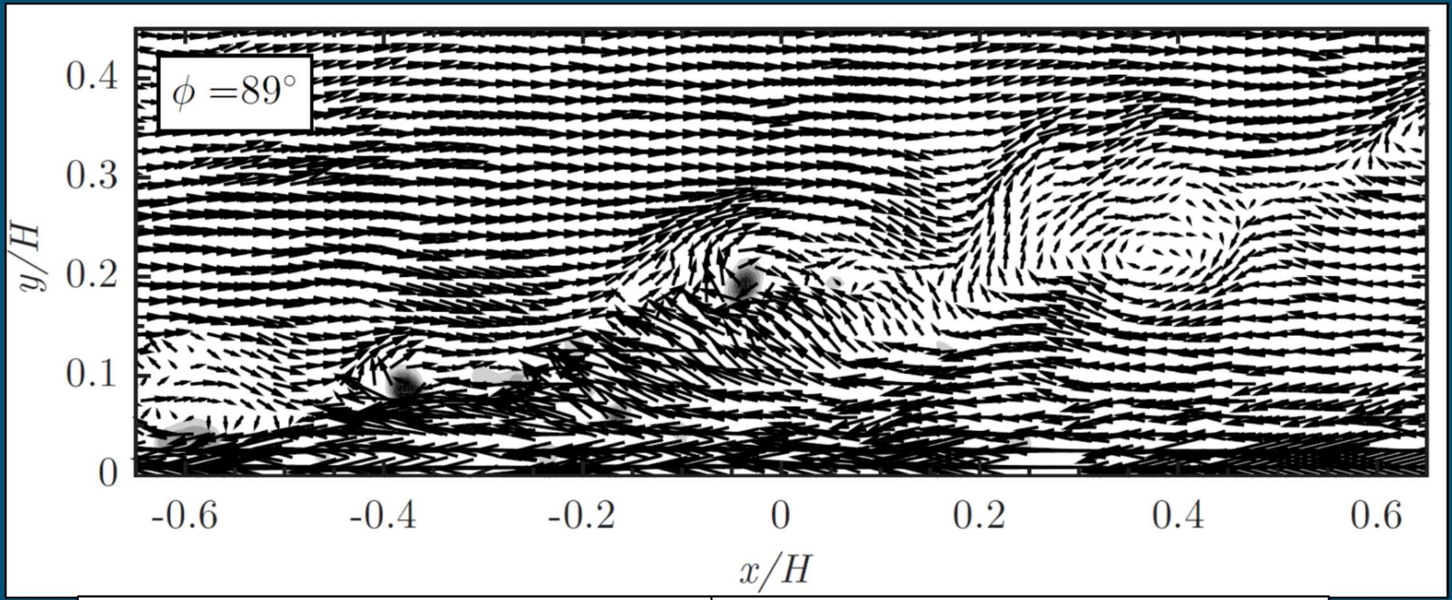
U_0 [m/s]	Re_δ
0.81	1440
1.35	2400
1.89	3360

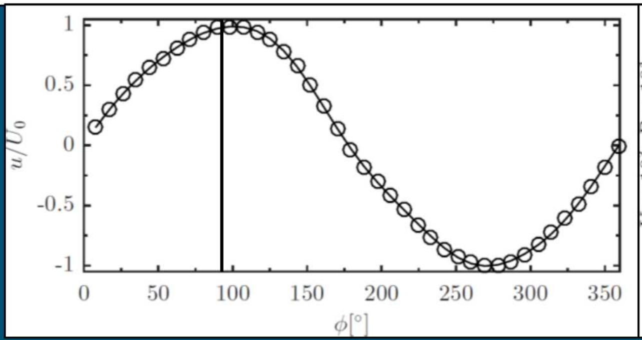
Nondimensional velocity profiles at turbulent phases are similar to those of steady flow

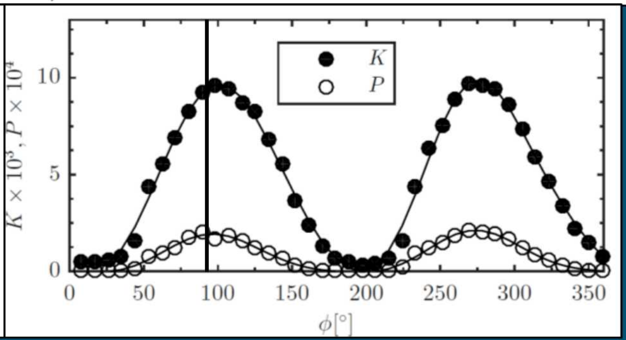


They do exist for oscillating flow

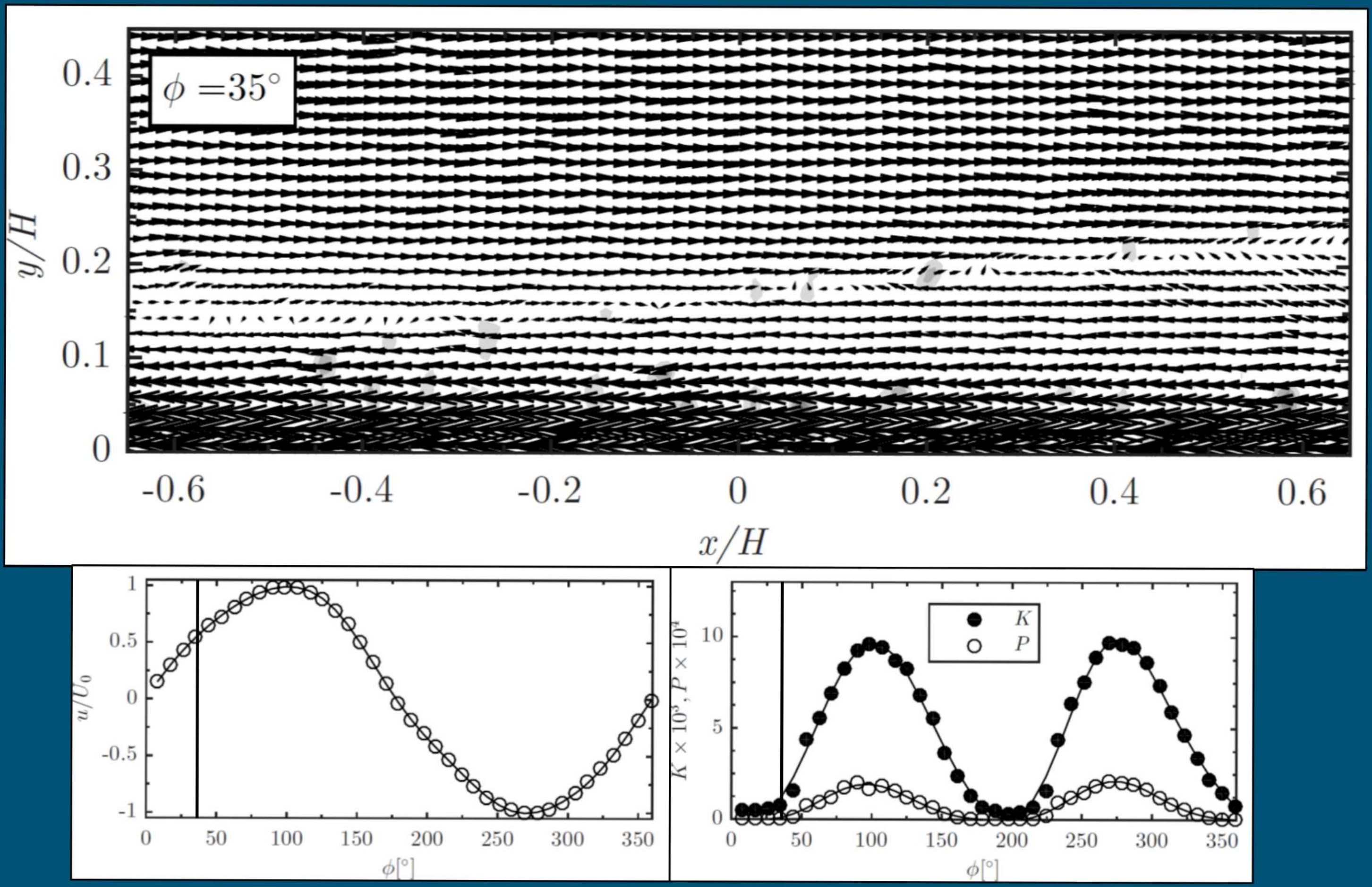
Instantaneous velocity fields with 90% of the mean streamwise subtracted and swirl strength in the background to highlight vortex cores



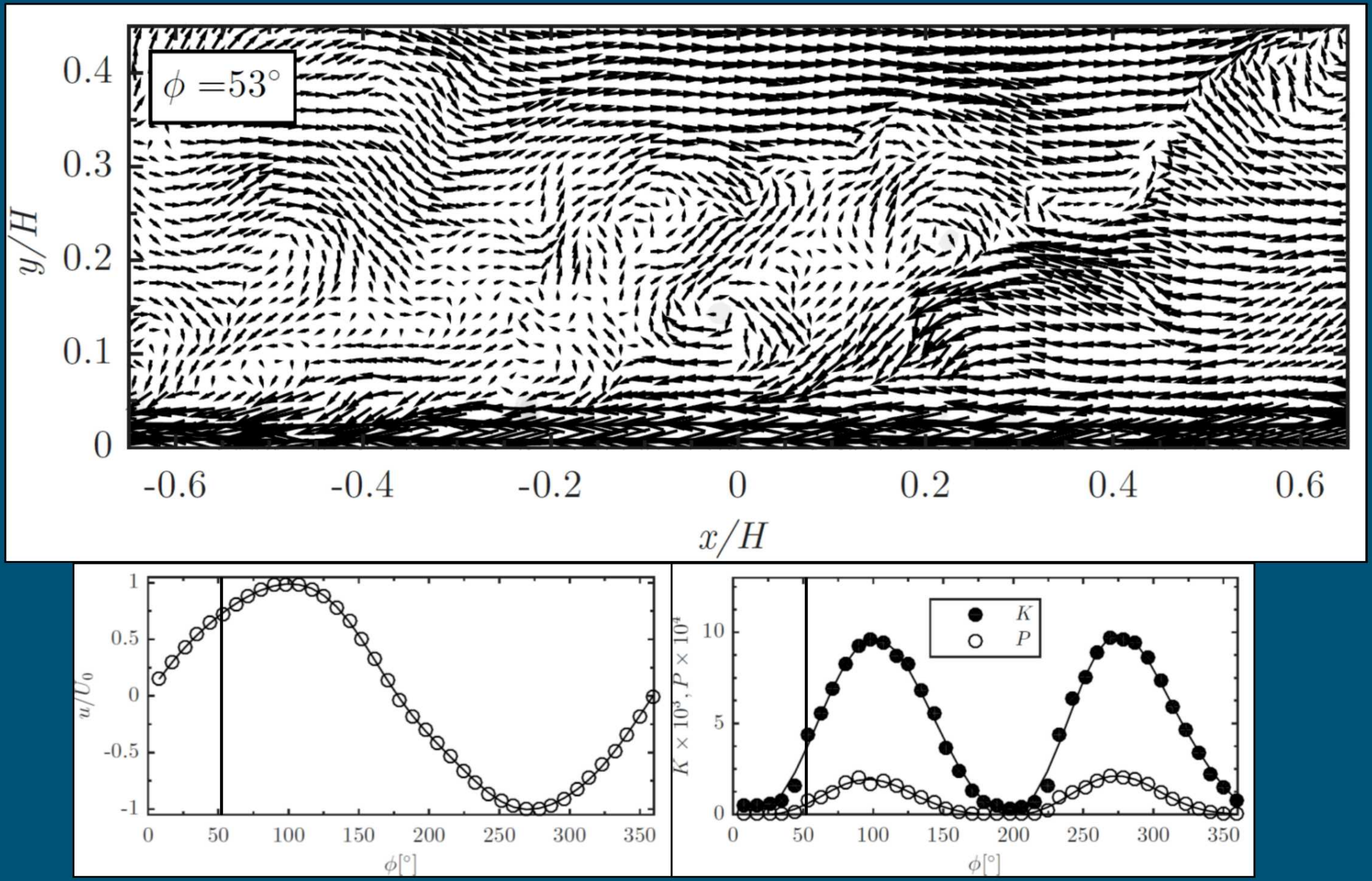




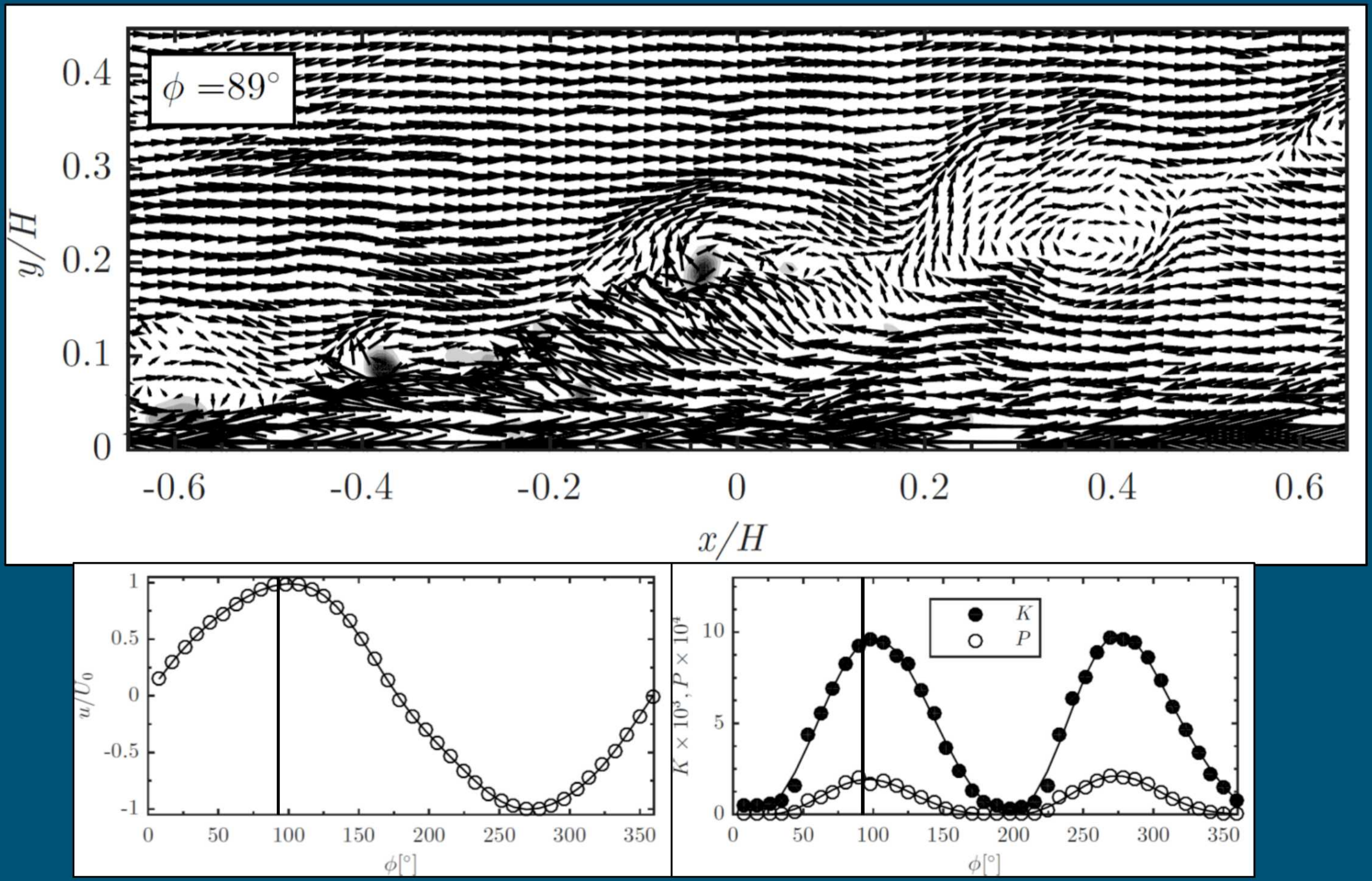
They do exist for oscillating flow



They do exist for oscillating flow



They do exist for oscillating flow



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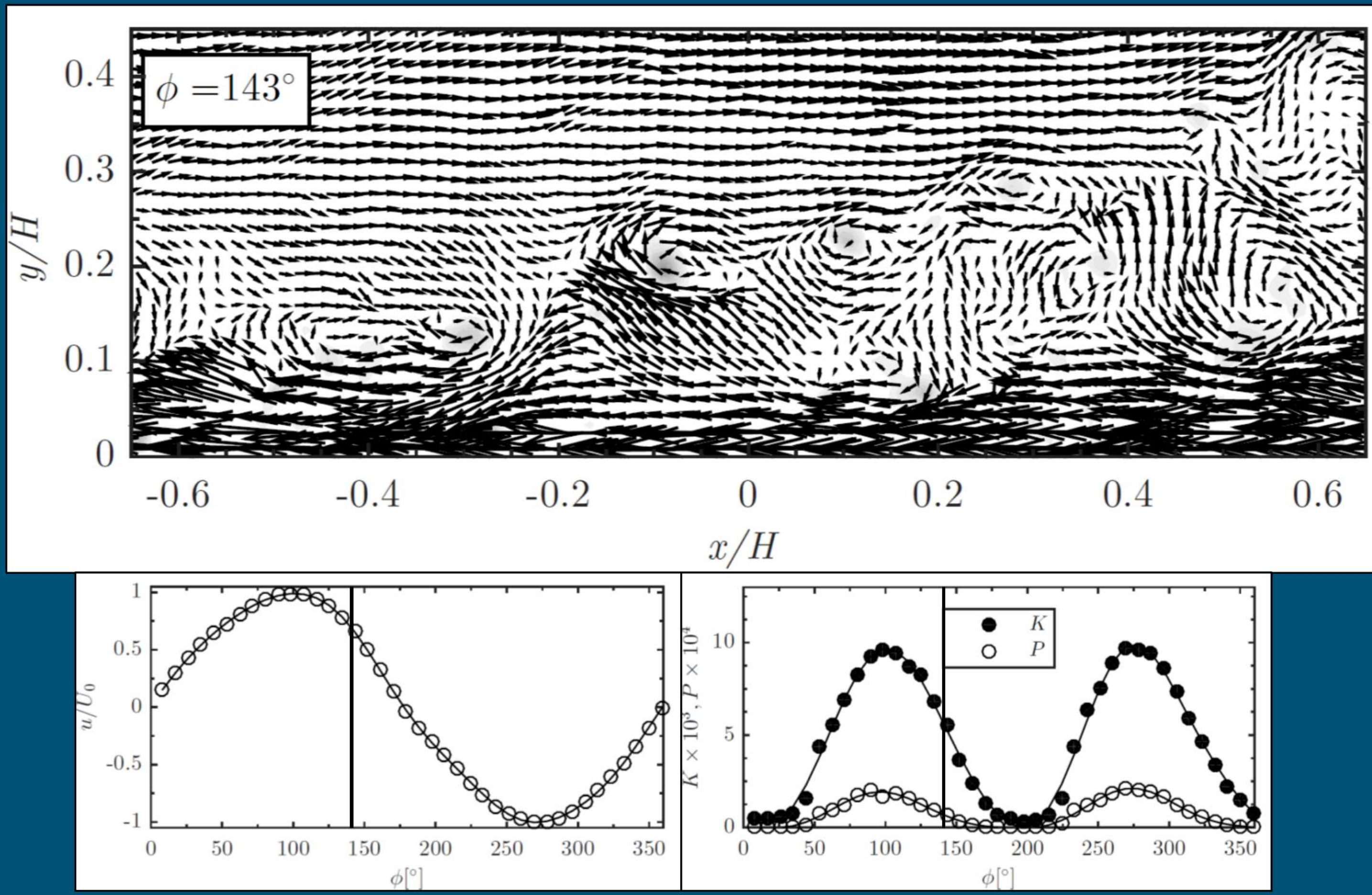
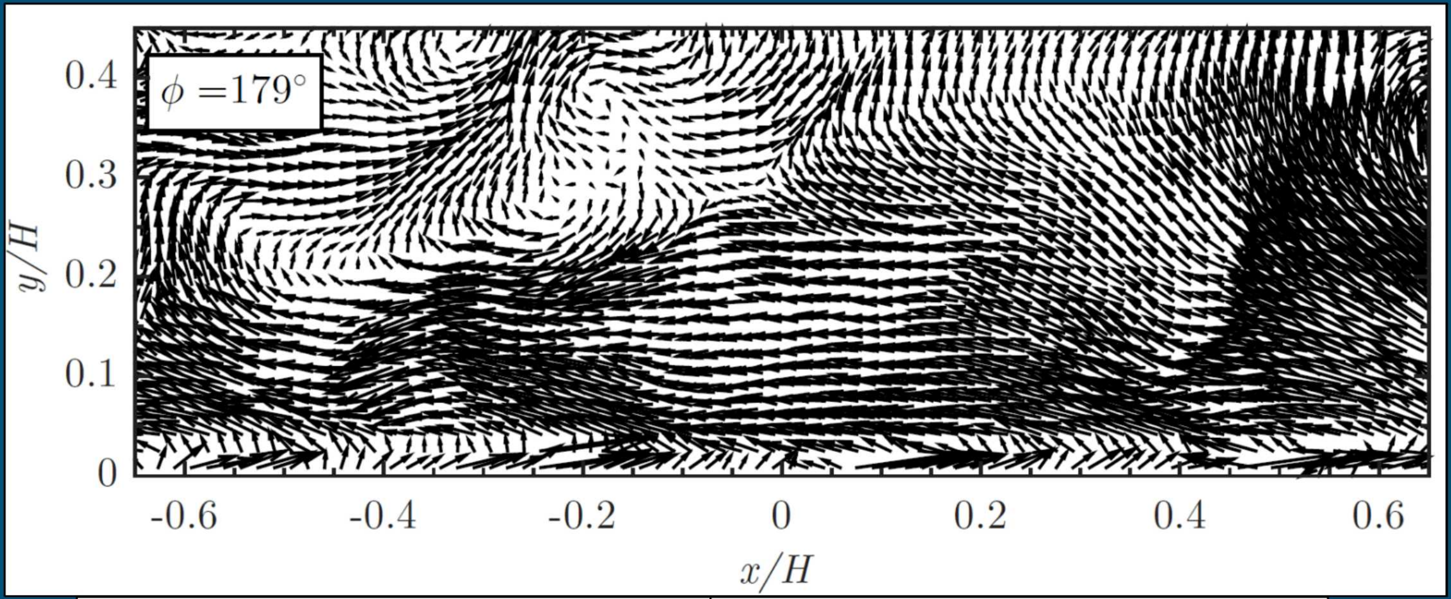
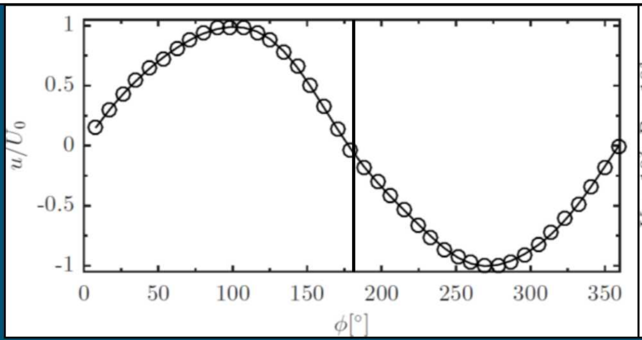
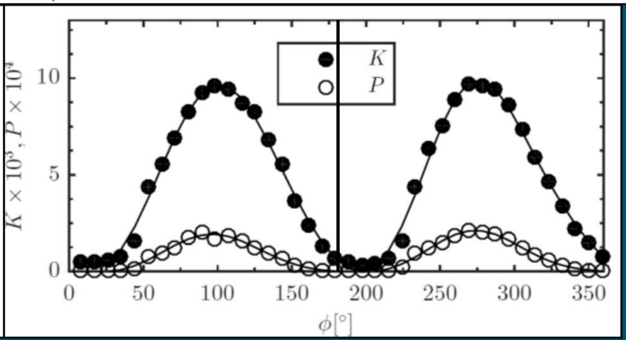


They do exist for oscillating flow







Christensen published a paper on conditional averaging to identify Hairpins

J. Fluid Mech. (2001), *vol.* 431, *pp.* 433–443. Printed in the United Kingdom

Statistical evidence of hairpin vortex packets in wall turbulence

By K. T. CHRISTENSEN AND R. J. ADRIAN

Laboratory for Turbulence and Complex Flow, Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, IL 61801, USA

(Received 14 October 2000 and in revised form 15 December 2000)

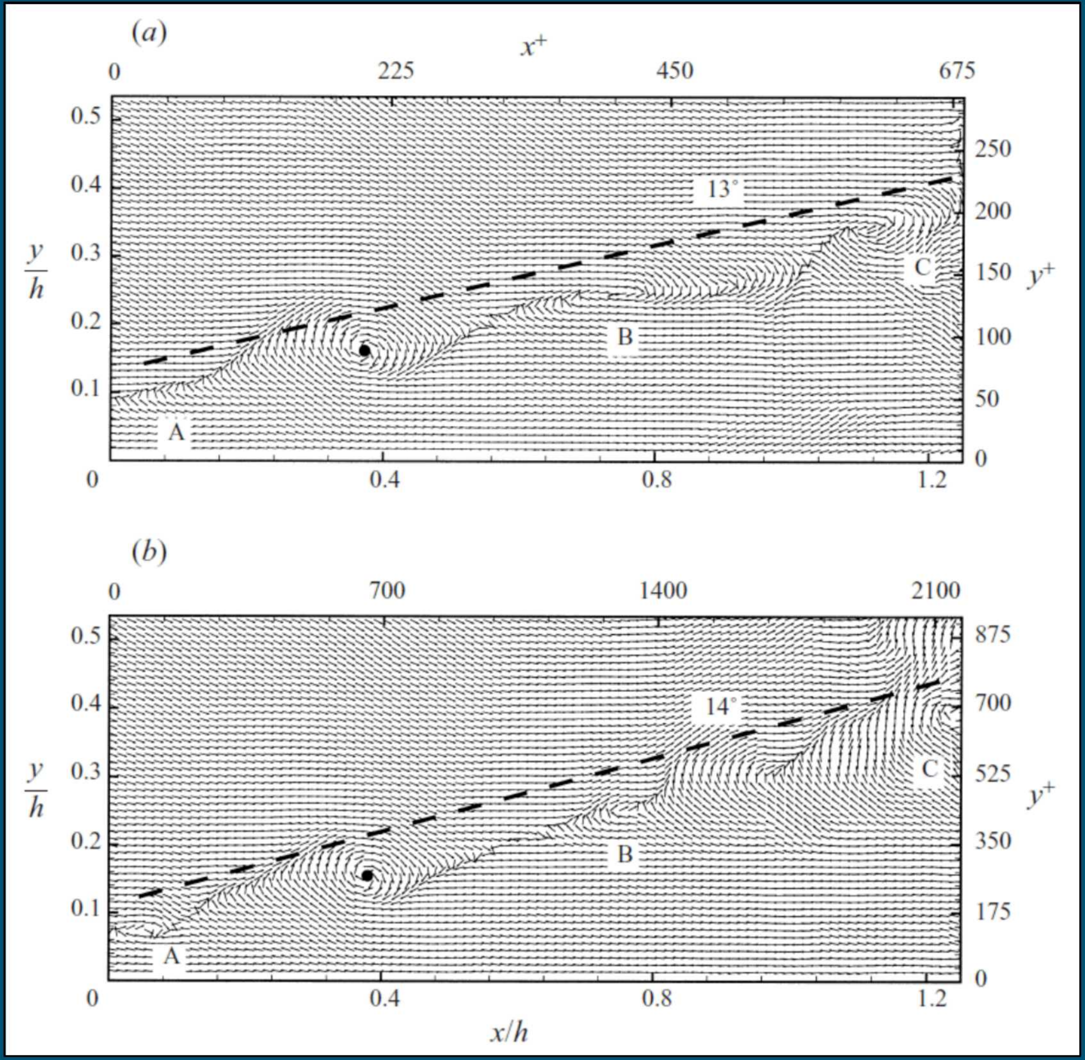
The structure of velocity in the outer region of turbulent channel flow ($y^+ \gtrsim 100$) is examined statistically to determine the average flow field associated with spanwise vortical motions. Particle image velocimetry measurements of the streamwise and wall-normal velocity components are correlated with a vortex marker (swirling strength) in the streamwise–wall-normal plane, and linear stochastic estimation is used to estimate the conditional average of the two-dimensional velocity field associated with a swirling motion. The mean structure consists of a series of swirling motions located along a line inclined at 12°–13° from the wall. The pattern is consistent with the observations of outer-layer wall turbulence in which groups of hairpin vortices occur aligned in the streamwise direction. While the observational evidence for the aforementioned model was based upon both experimental and computational visualization of instantaneous structures, the present results show that, on average, the instantaneous structures occur with sufficient frequency, strength, and order to leave an imprint on the statistics of the flow as well. Results at $Re_\tau = 547$ and 1734 are presented.

1. Introduction

The structure of turbulent flow near a boundary has been studied extensively over the past decades (for a comprehensive review of this history, the reader should consult Robinson 1991 and, more recently, the collection edited by Panton 1997). Moreover, there is broad evidence that a vortical structure qualitatively similar to the 'horseshoe

"Given the presence of a single spanwise vortex core (believed to be associated with the head of a hairpin vortex), what is the average fluctuating velocity field associated with this physical event? The best estimate of the average velocity field is the conditional
average of the velocity field given the presence of a vortex core."

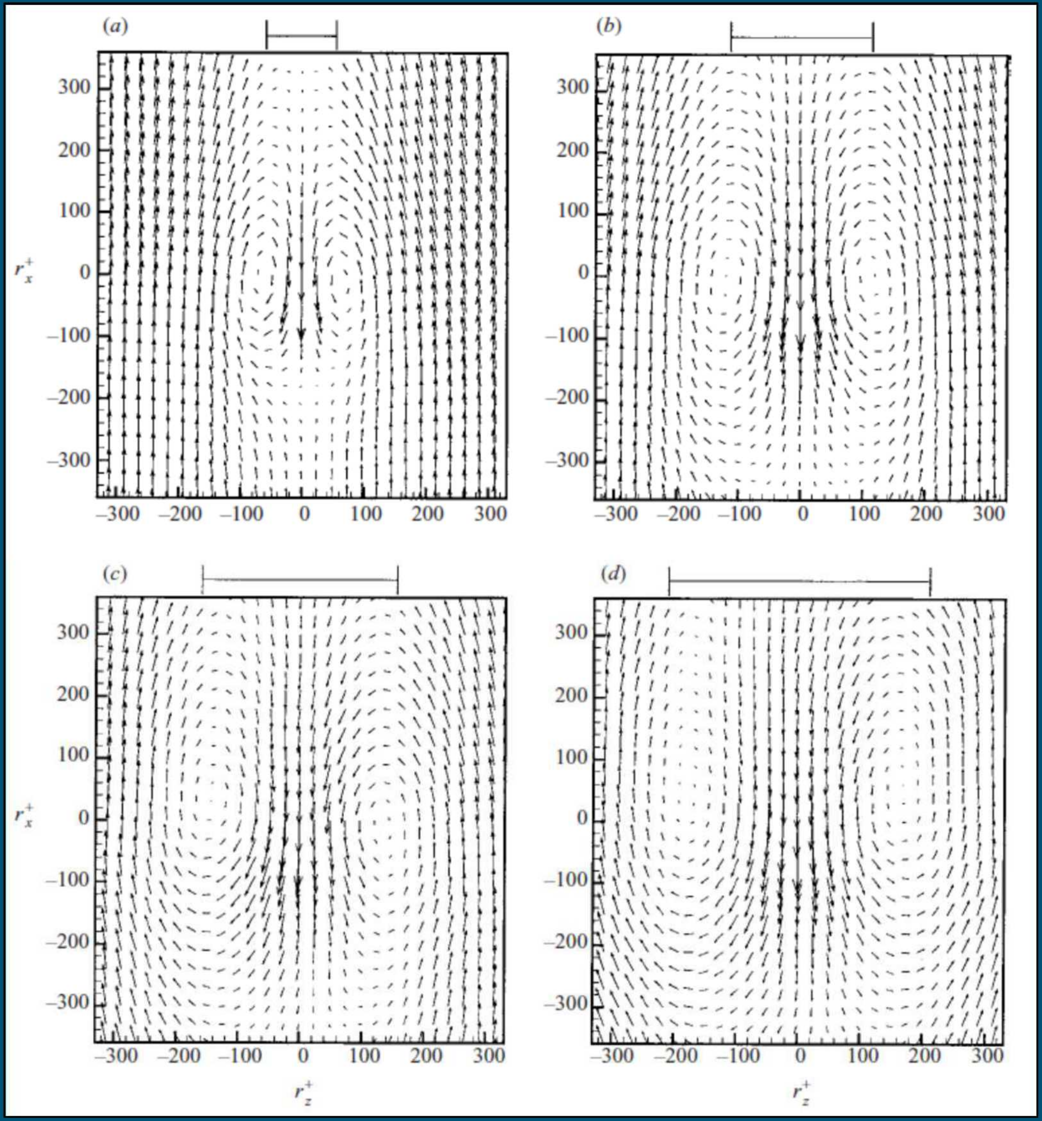
Christensen published a paper on conditional averaging to identify Hairpins



Linear stochastic estimation. The location of the swirling strength event is indicated by a solid circle. (*a*) $Re_\tau = 547$ ($y^+_{ref} = 83.6$); (*b*) $Re_\tau = 1734$ ($y^+_{ref} = 256.0$). Vectors have been normalized to unity by their respective magnitudes to highlight swirling motions away from the event location.

Christensen, K. T. & Adrian, R. J. 2001 "Statistical evidence of hairpin vortex packets in wall turbulence." J. Fluid Mech. **431**, 433-443.

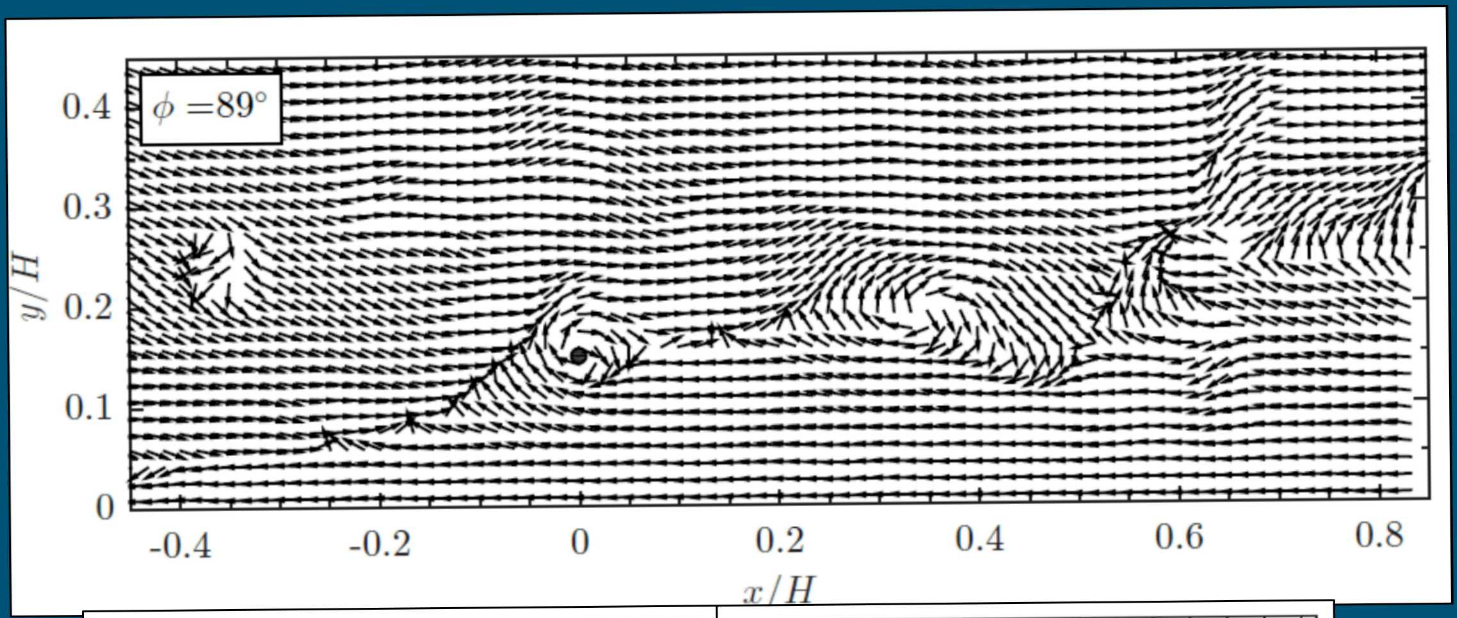
Conditional velocity fields in the *x-z* plane show counter-rotating vortices with low momentum between them

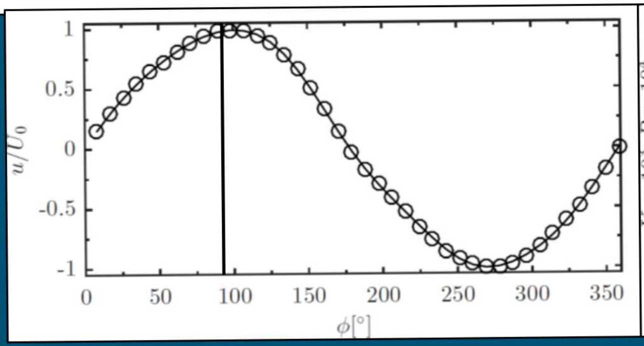


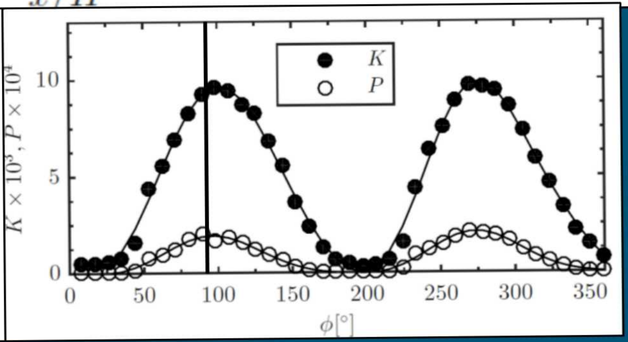
Conditionally averaged structure in the (*x*–*z*)-plane at Re_θ =7705. The specified event is a local *u*-minimum with $u<0.75U_\infty$. (*a*) *y*+ =100; (*b*) *y*+ =220; (*c*) *y*+ =330; (*d*) *y*+ =440.

C. D. Tomkins and R. J. Adrian, "Spanwise structure and scale growth in turbulent boundary layers," J. Fluid Mech. **490**, 37 (2003).

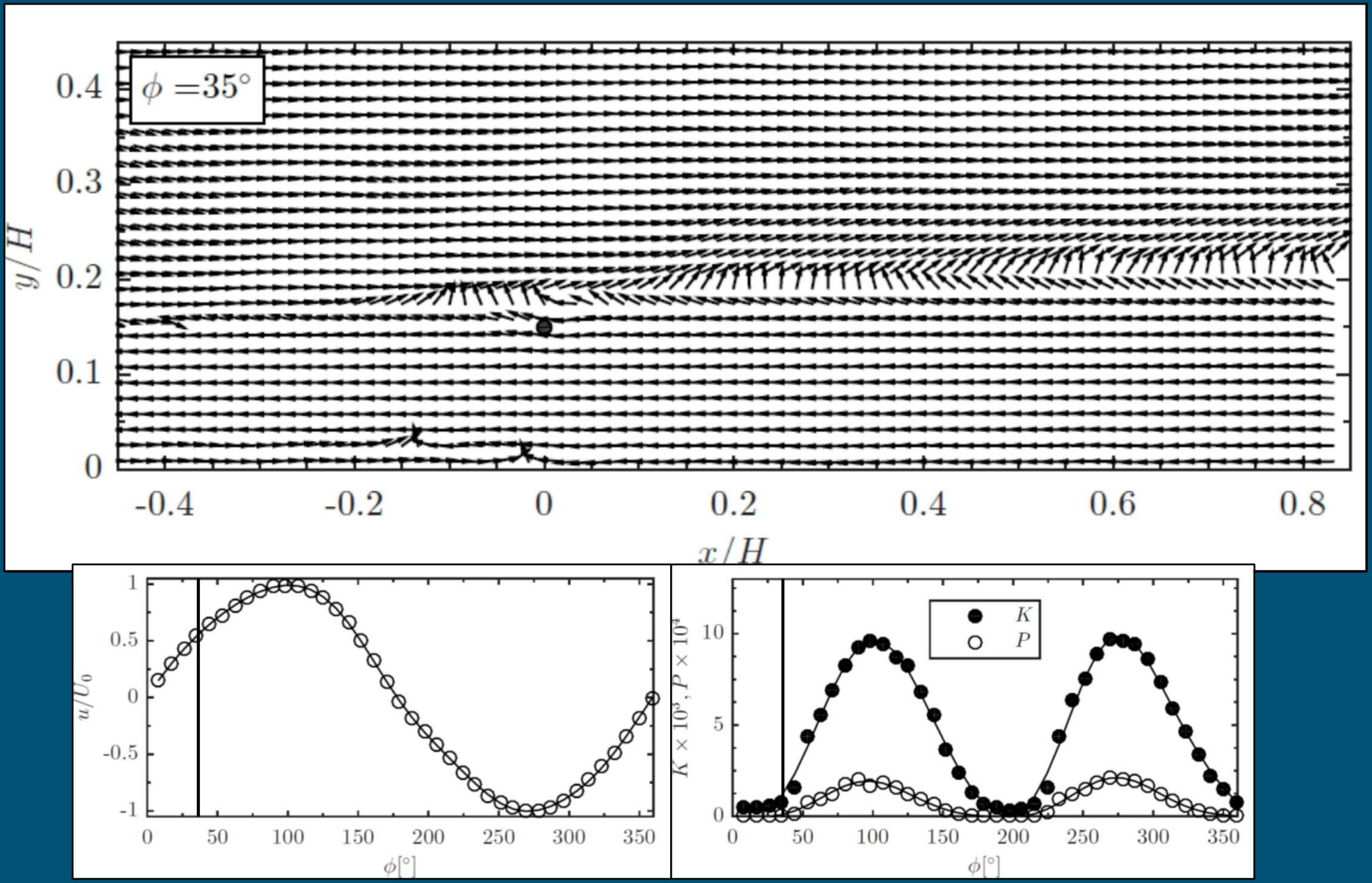
We used Christensen and Adrian's method to find them in oscillating flow



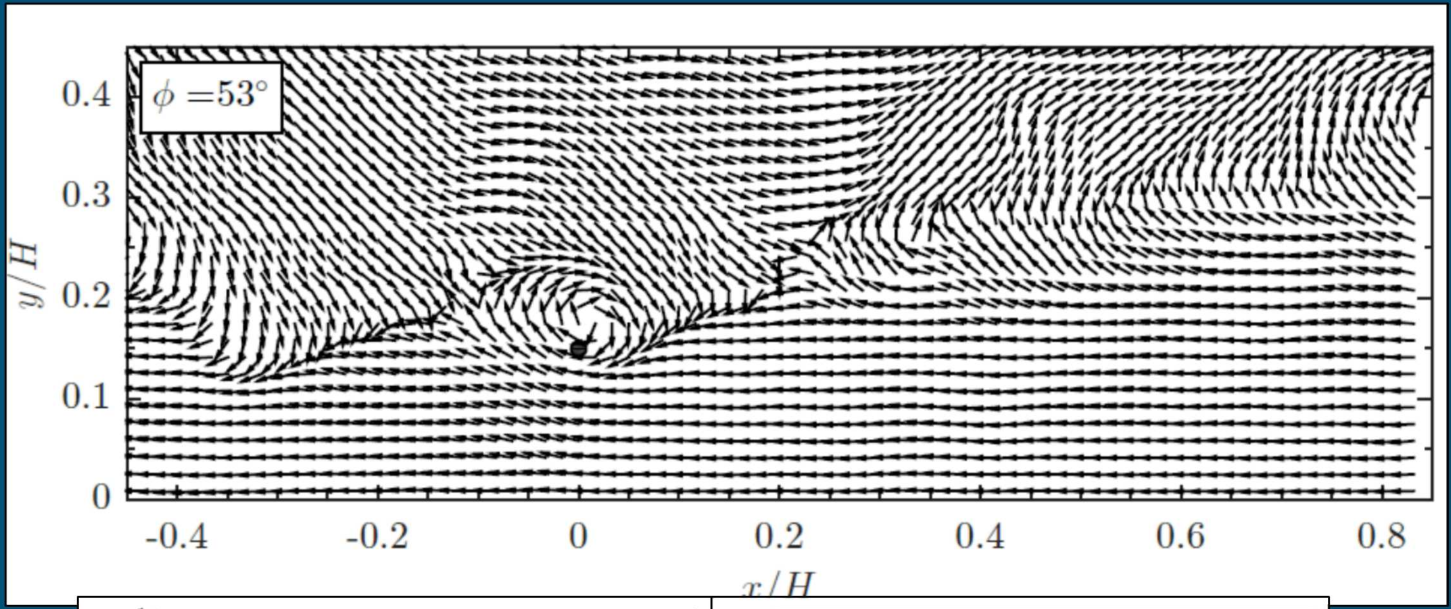


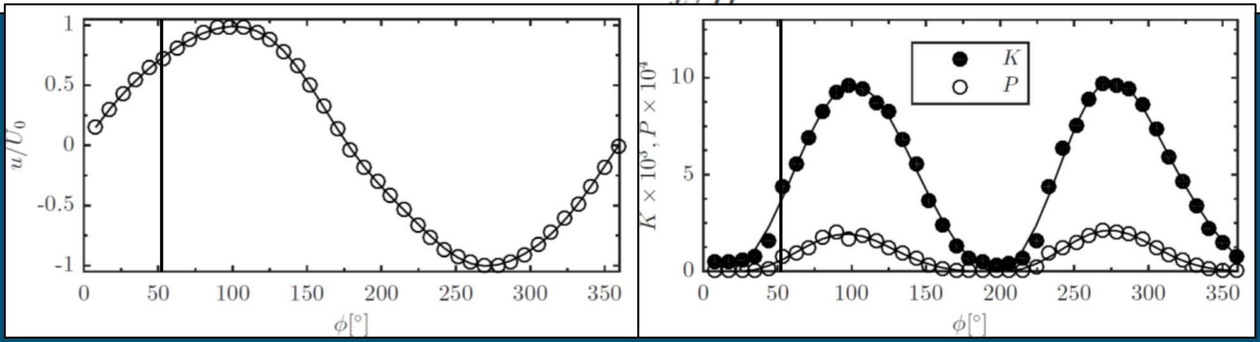


We used Christensen and Adrian's method to find them in oscillating flow



We used Christensen and Adrian's method to find them in oscillating flow





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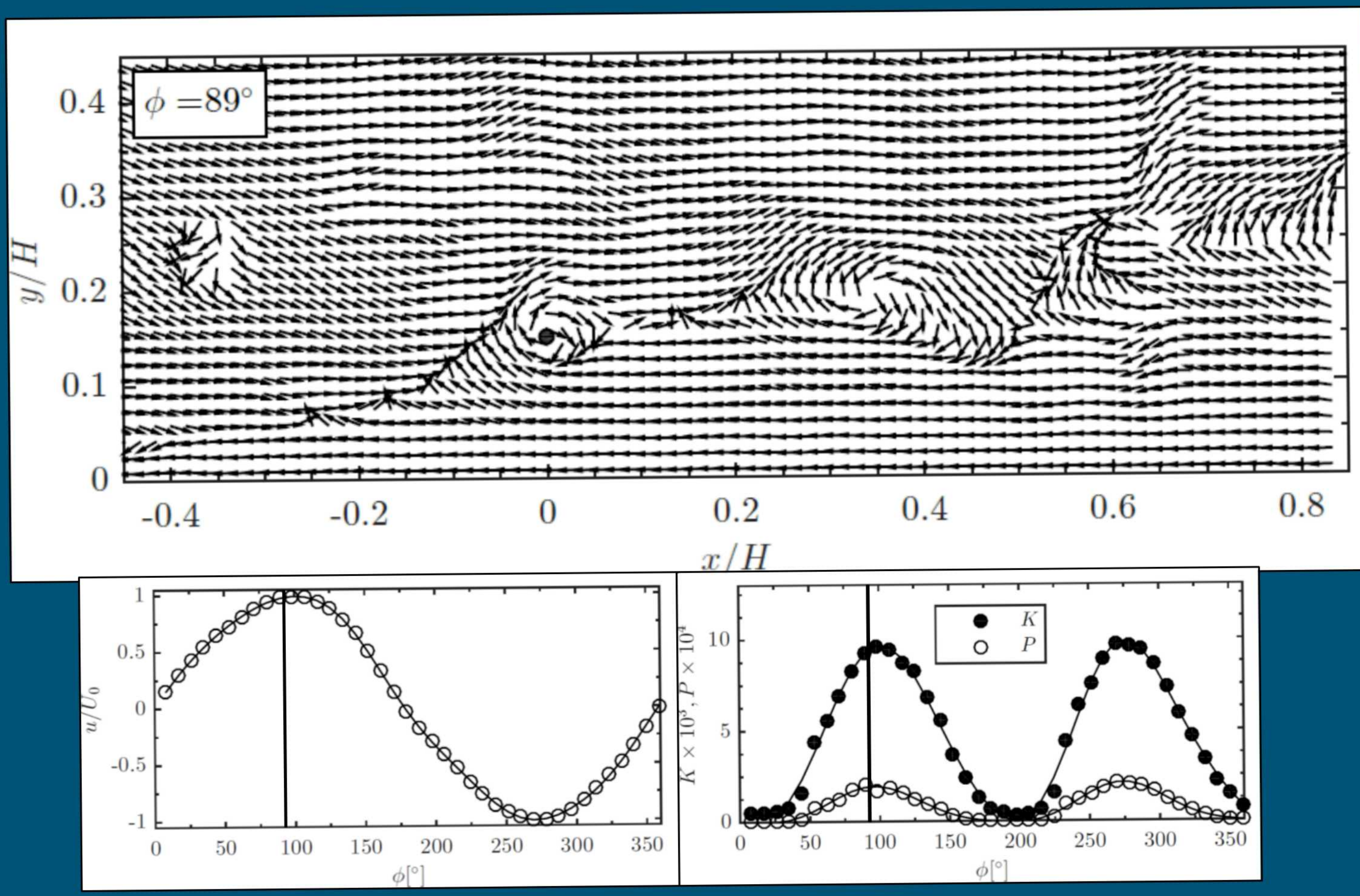
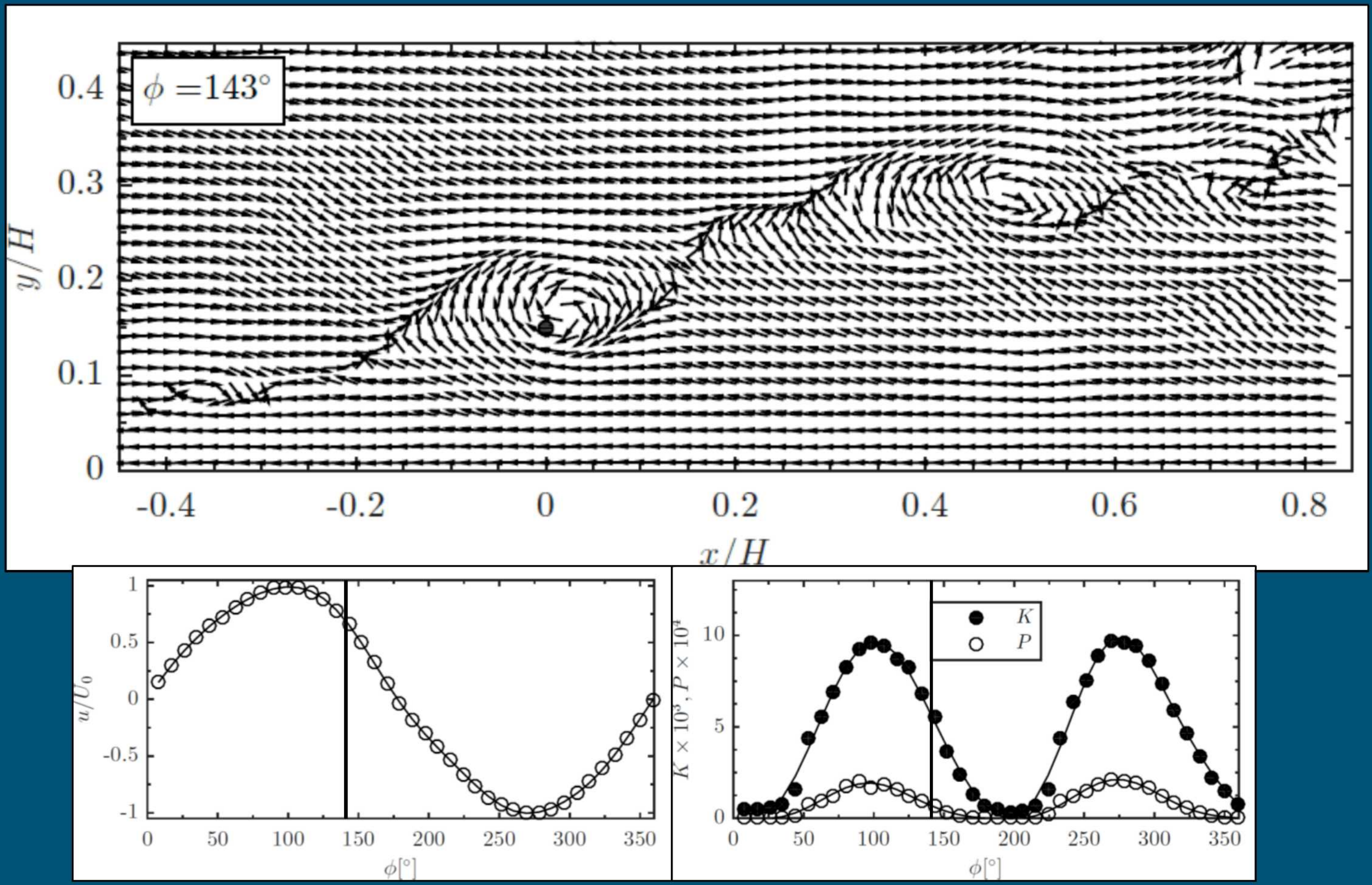
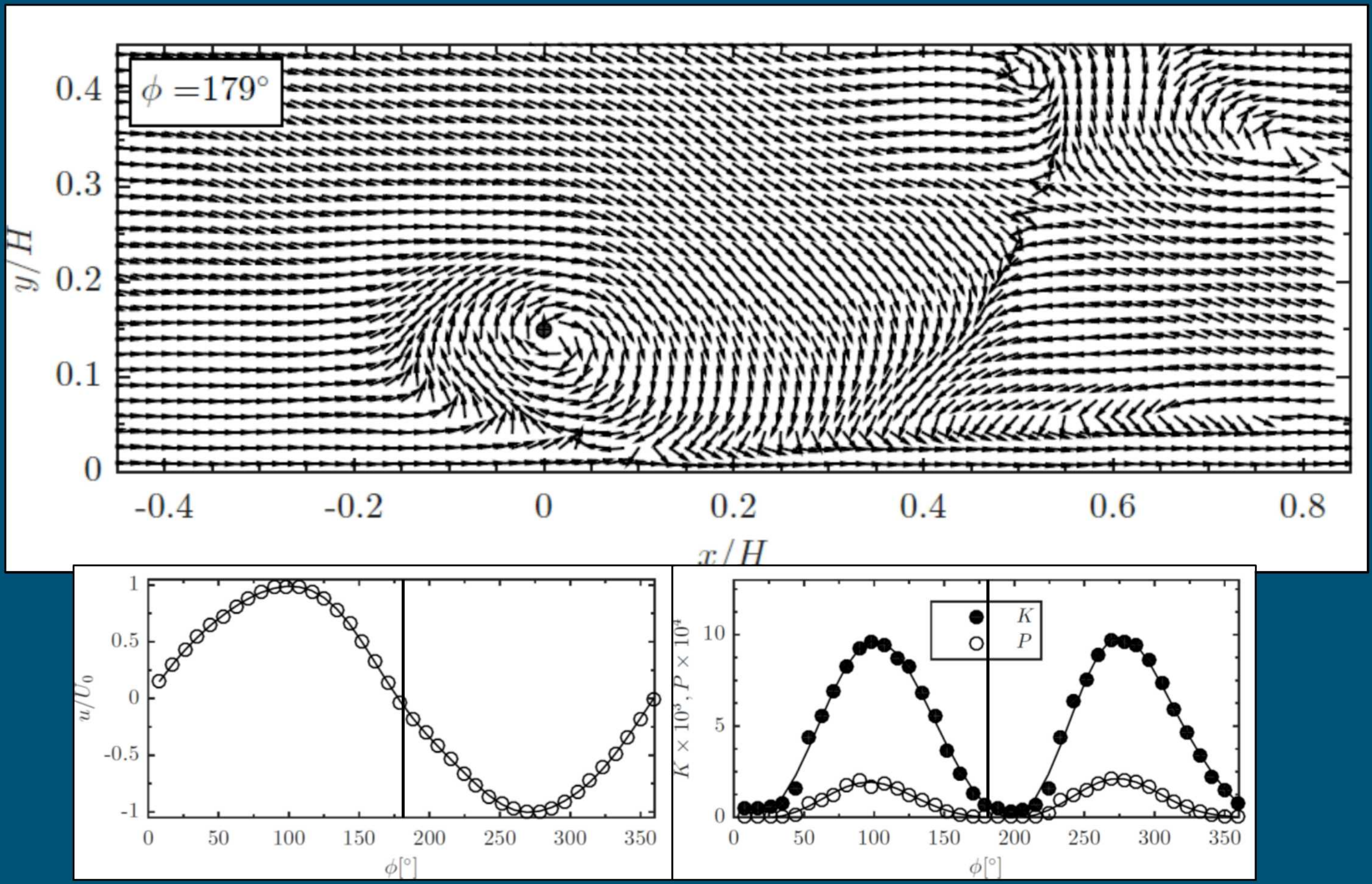


We used Christensen and Adrian’s method to find them in oscillating flow

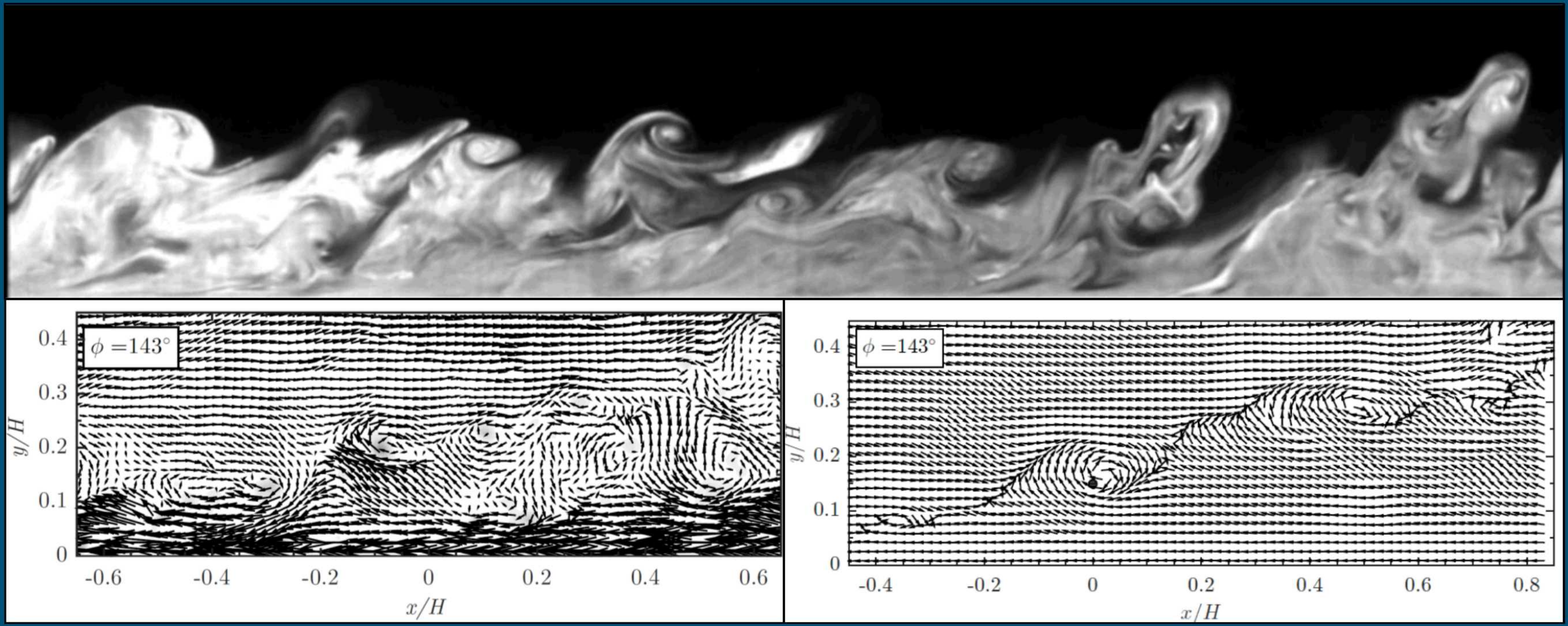


We used Christensen and Adrian's method to find them in oscillating flow



Hairpin Vortices are a fascinating feature of turbulent flow that can be identified with modern analysis

- They have been observed in steady boundary layer flow for several decades
- They have been identified with experiments as well as LES and DNS simulations
- We have identified them in oscillating flow and are writing a paper

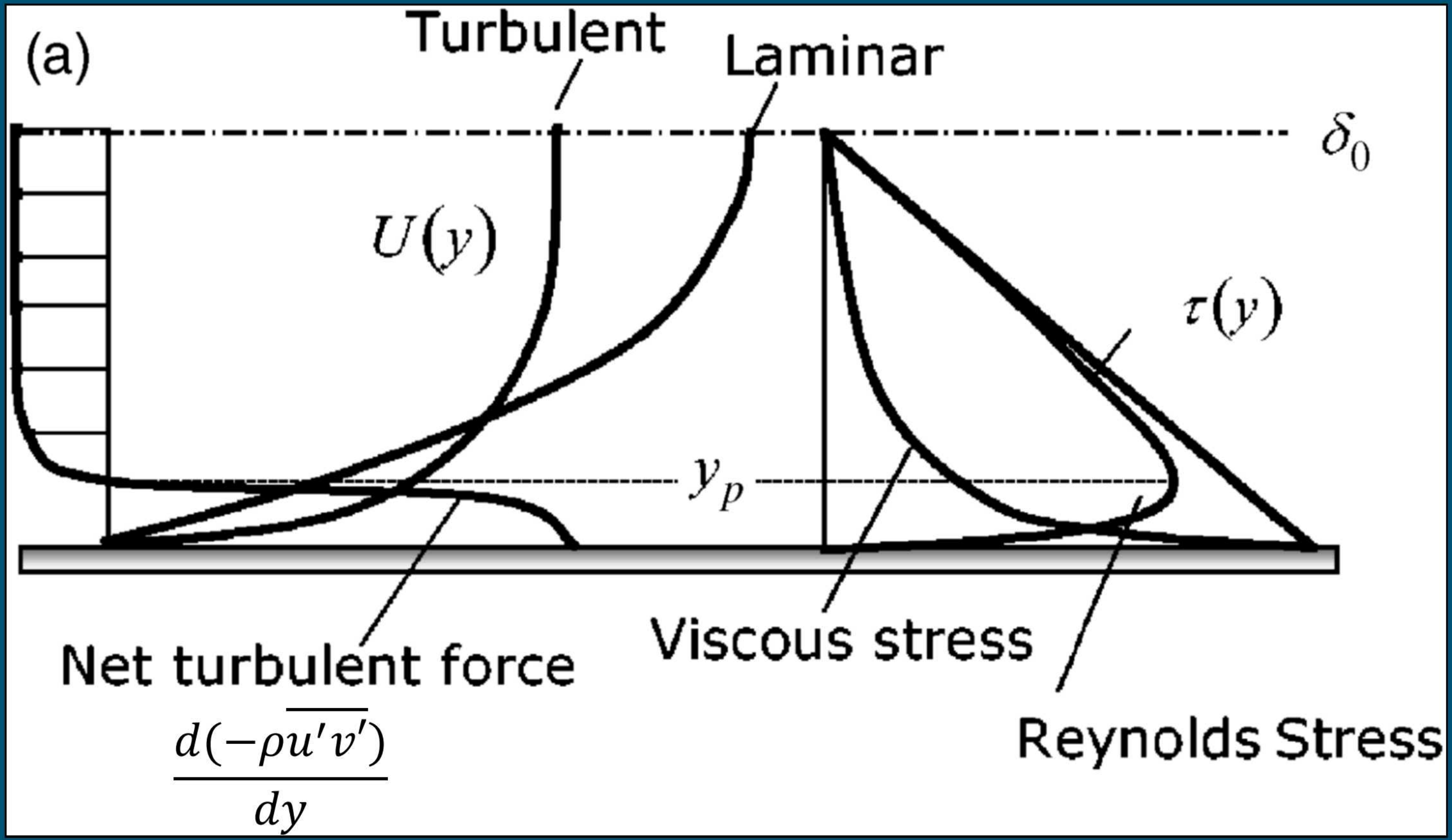


Acknowledgements

- Jesse Roberts was the project PI
- Barton Smith setup the PIV equipment and configured the system
- Sean Kearney was the master behind the analysis
- Guilde Copeland built the flow system

Backup

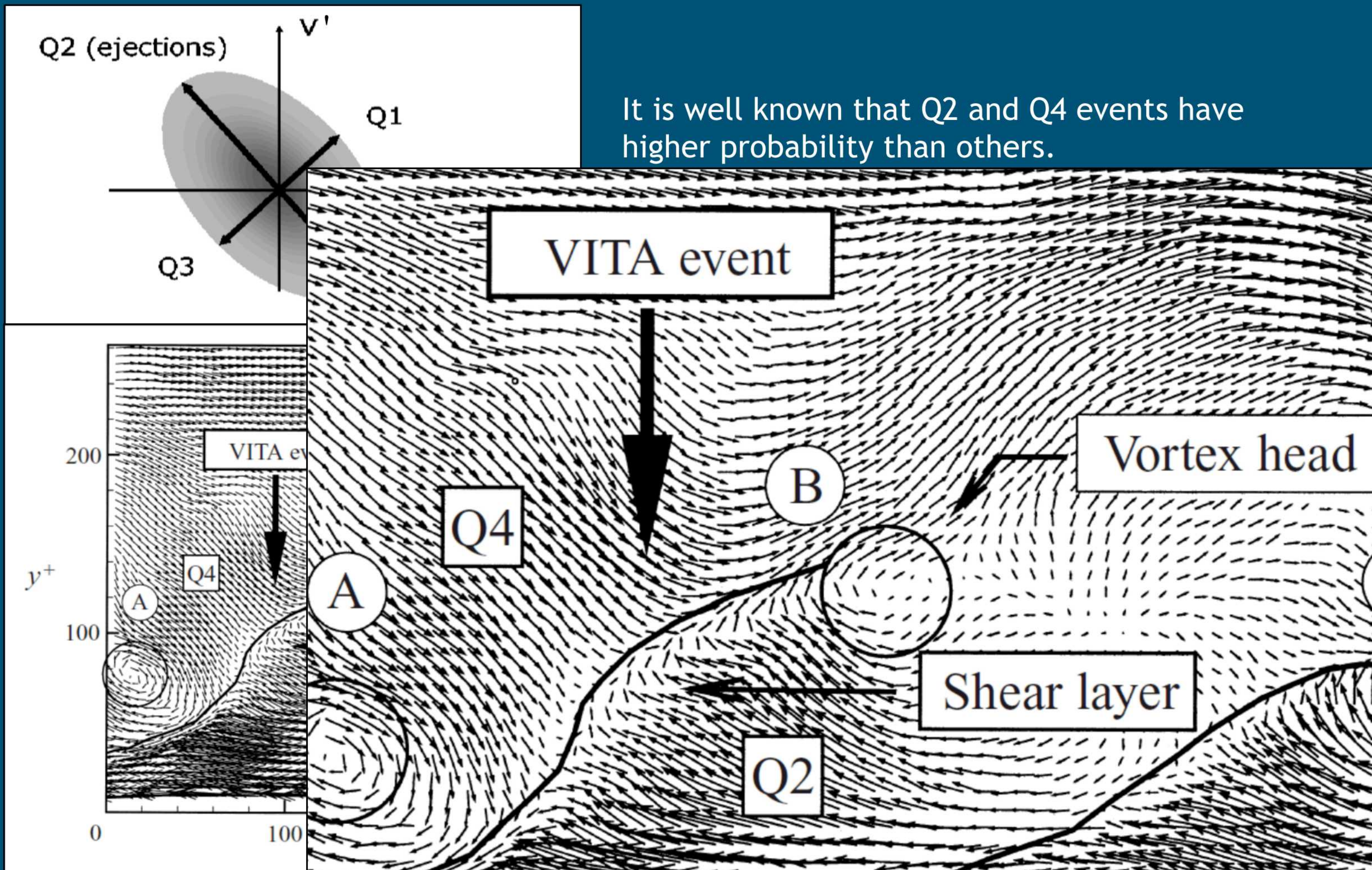
Steady, incompressible, smooth-wall, external, turbulent flow with zero pressure gradient is simple but rich



Adrian, R. J., 2007. "Hairpin vortex organization in wall turbulence". Physics of Fluids, 19, p. 041301.

Before reviewing the work of others, we need to define turbulent events

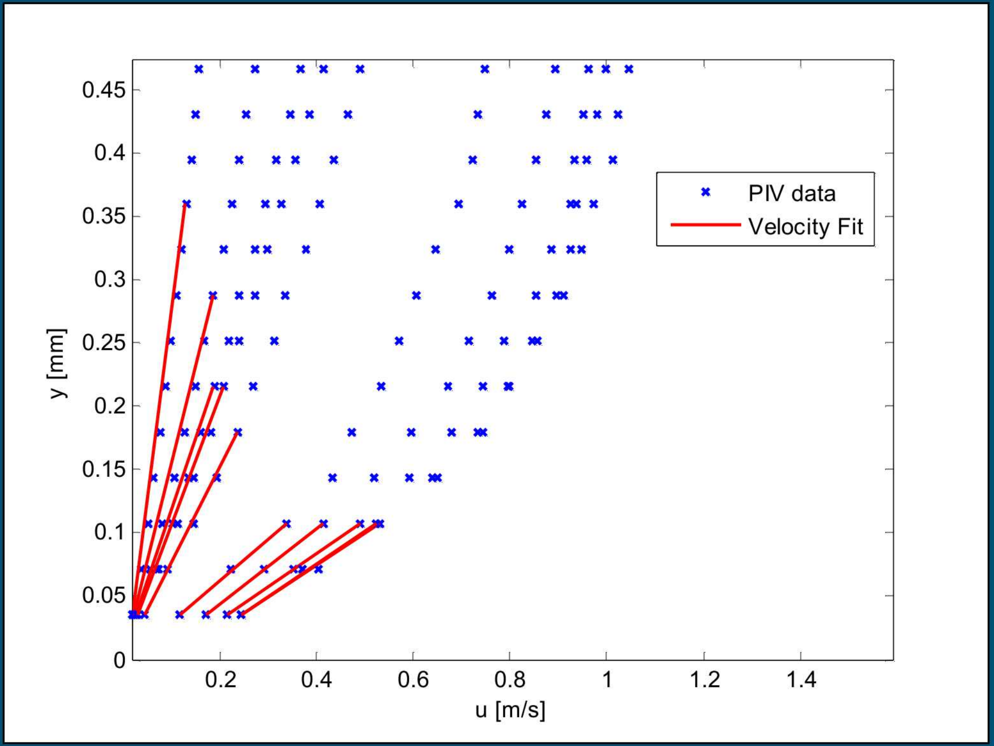
It is well known that Q2 and Q4 events have higher probability than others.



R. J. Adrian, C. D. Meinhart, and C. D. Tomkins, “Vortex organization in the outer region of the turbulent boundary layer,” J. Fluid Mech. **422**, 1 (2000).

Shear Stress from PIV Data

- Streamwise velocity gradient within VSL is fit for each phase
- Only points within 7 viscous wall units ($y^+ \leq 7$) are included
- A numeric solver converges on the number of points in the VSL.



$$\tau_s = \mu \partial u / \partial y \Big|_s \qquad u_\tau = \sqrt{\frac{\tau_s}{\rho}} \qquad y^+ = \frac{y u_\tau}{\nu}$$