Measuring the instantaneous 3-D vortex organization in a high Reynolds number supersonic boundary layer

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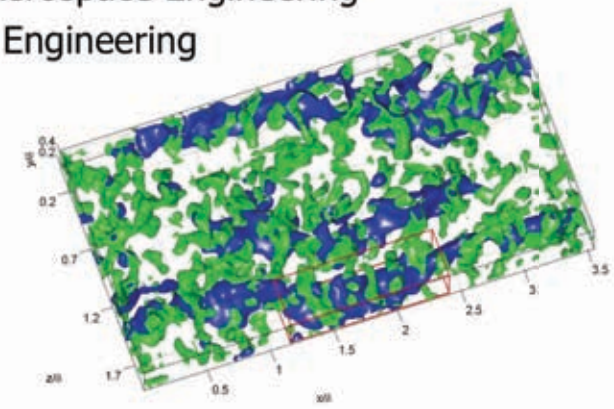


Nordita Seminar, KTH

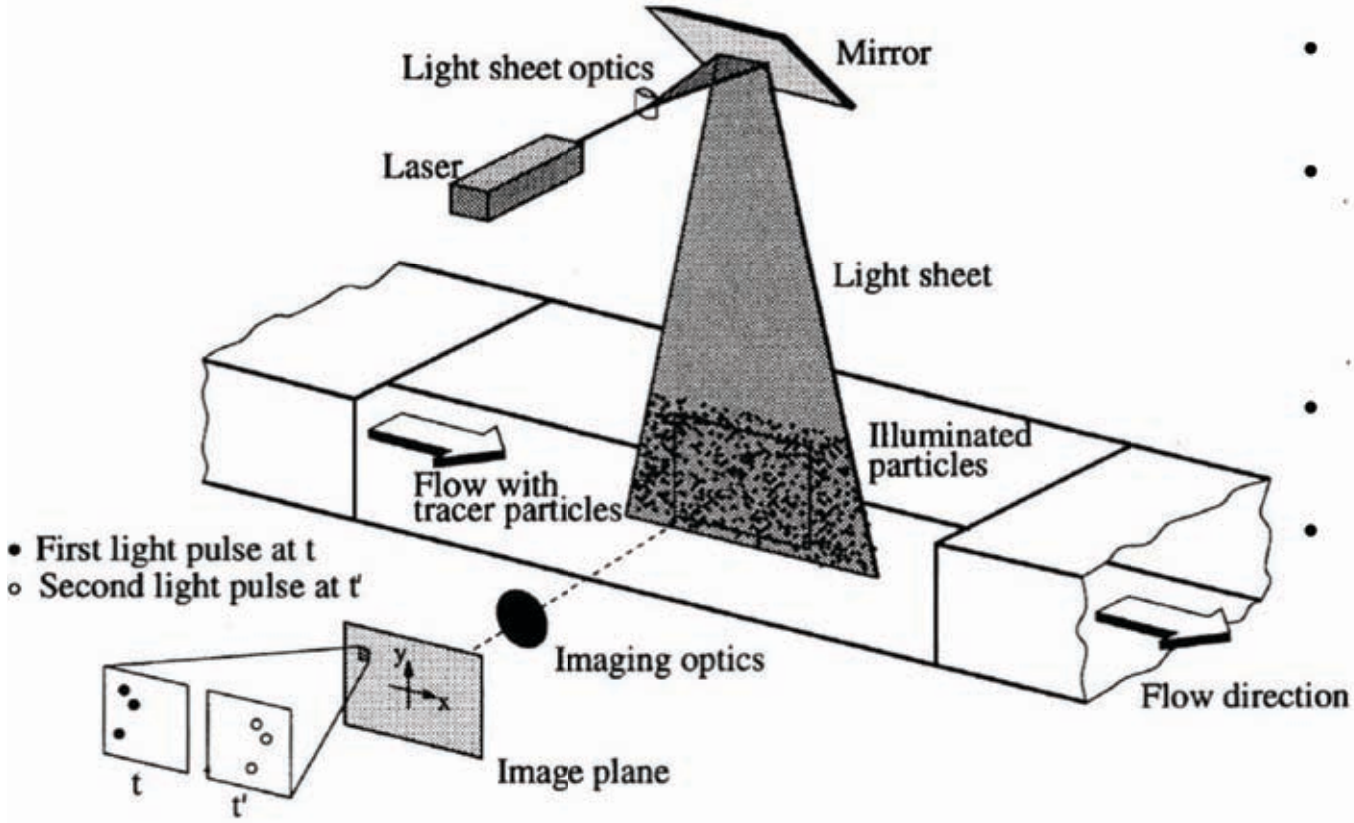
April 2010

Delft University of Technology

Outline

- **Working principle of 3D tomographic-PIV**
- **The application to turbulent boundary layers**
  - supersonic boundary layer $Re_\theta = 34{,}000$
- **Quantitative visualization of instantaneous vortical structures**
- **Streamwise+spanwise organization of bulges**

2D Particle Image Velocimetry (PIV)



[Raffel, Willlert, Kompenhans 1998]

- tracer particles
- illumination in light sheet ⇒ 2D (at t and $t+\Delta t$)
- recording (2 frames)
- measure in-plane particle displacement between frames (cross-correlation)

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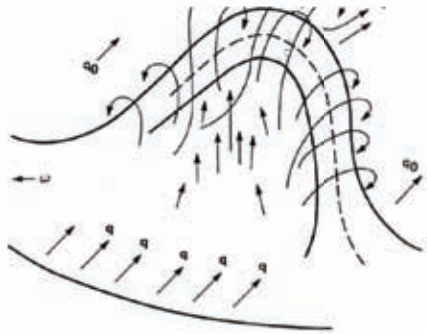
3D Tomographic-PIV

motivation and objectives

[Theodorsen 1952]



Turbulence is intrinsically 3D and the full description of the instantaneous structure requires 3D velocity information => 3D PIV

Combining the *simplicity of the photogrammetric approach* (3D-PTV) with *robust particle reconstruction procedure* not relying on particle identification, which in principle allows higher seeding hence information density

The photogrammetric approach *does not require* high speed cameras and lasers (as in scanning-PIV) so an extension to high speed flows is possible

time-resolved 3D measurements can be obtained using a high speed system

Tomographic Partice Image Velocimetry
Gerrit Elsinga, Fulvio Scarano, Bernhard Wieneke, Bas van Oudheusden,
***Exp Fluids* 2006, Vol. 41, pp. 933-947**

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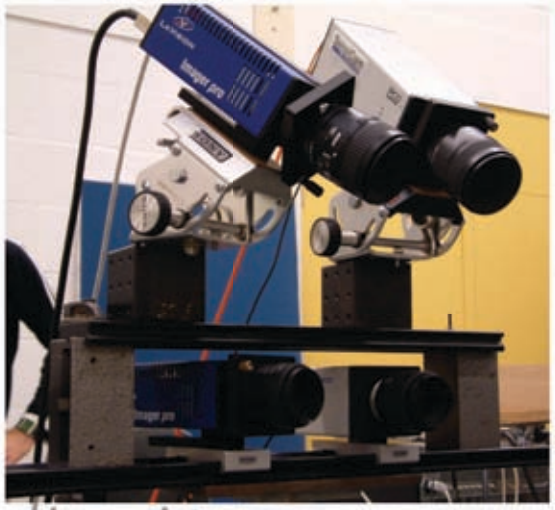
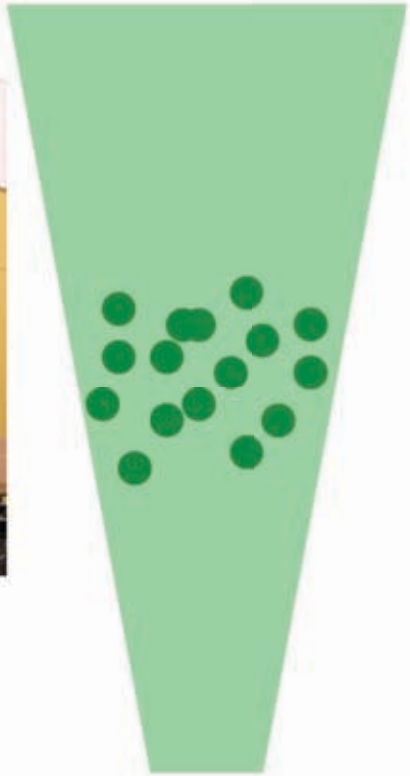
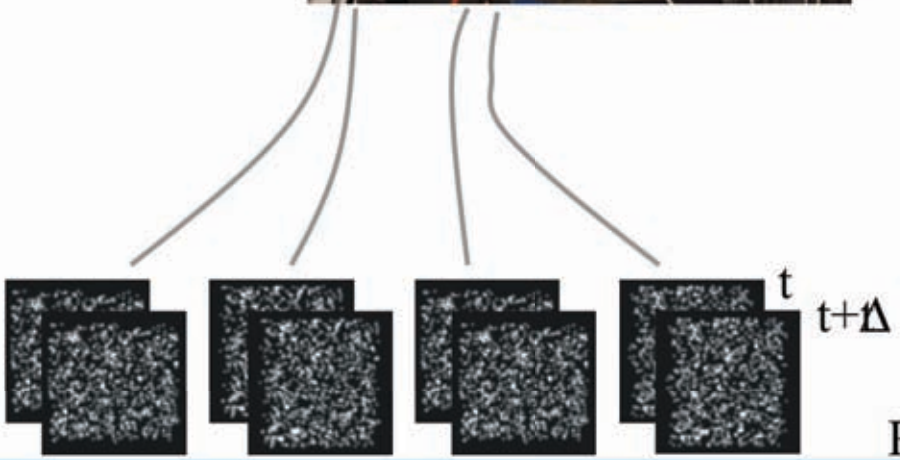
Working principle

imaging

- volume illumination
- 3 to 6 views/cameras typically 4
- each recording double frame images
- Scheimpflug adapters and large f/# to have entire volume in focus







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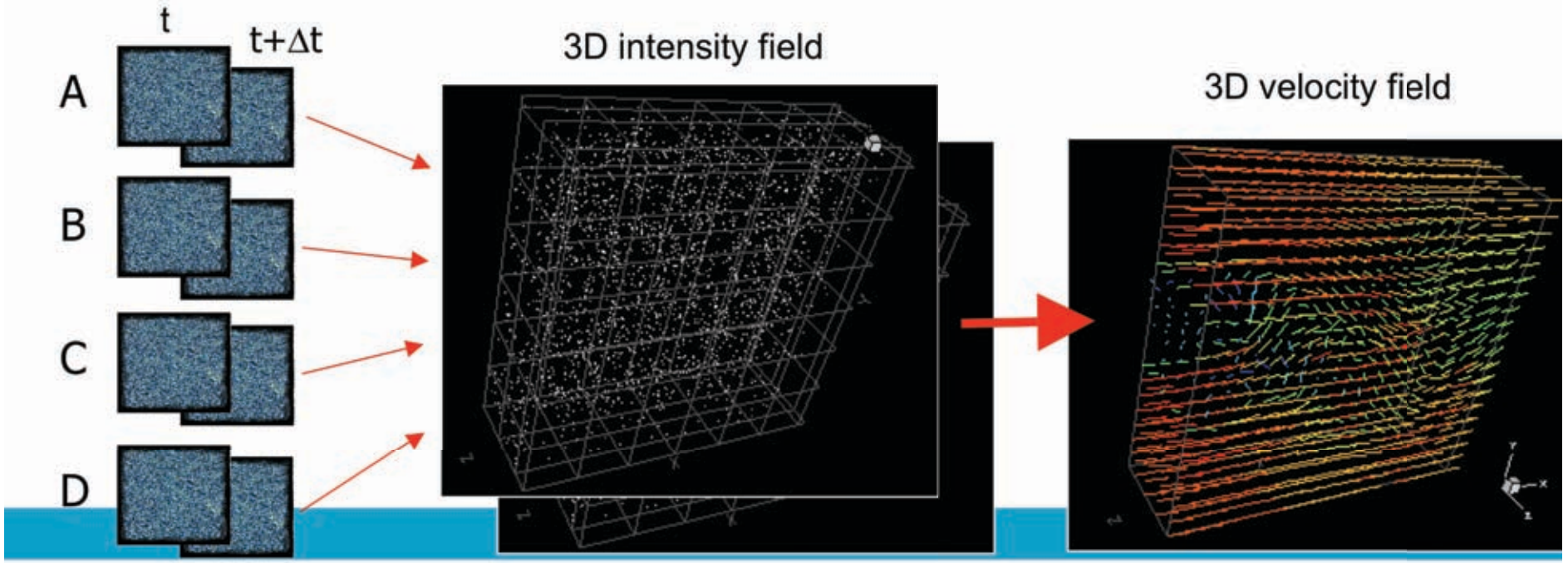
Working principle

particle reconstruction and cross-correlation

- calibration: mapping the physical space onto the image coordinates identical to Stereo-PIV
- 3D tomographic reconstruction: returnes 3D light intensity map (*in a voxel array*) and does not require particle detection
- 3D cross-correlation: with interogation deformation, iterative multi-grid



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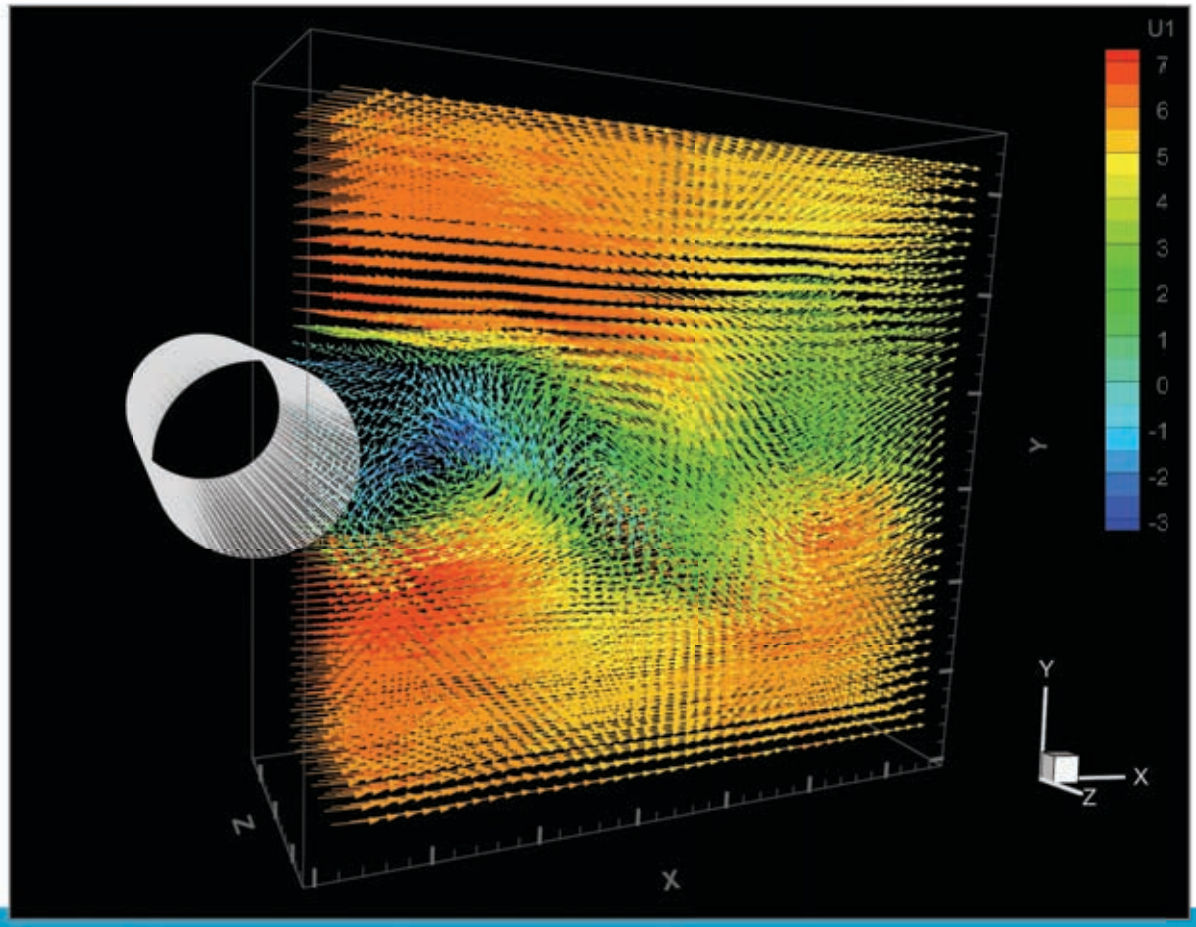
First experimental results: Cylinder wake $Re_D = 2700$

FOV: 40 x 40 x 8 mm
= 730 x 731 x 184 voxel

Interrogation volumes:
31 x 31 x 31 voxel
75% overlap

Number of vectors:
77 x 79 x 15
= 91.000



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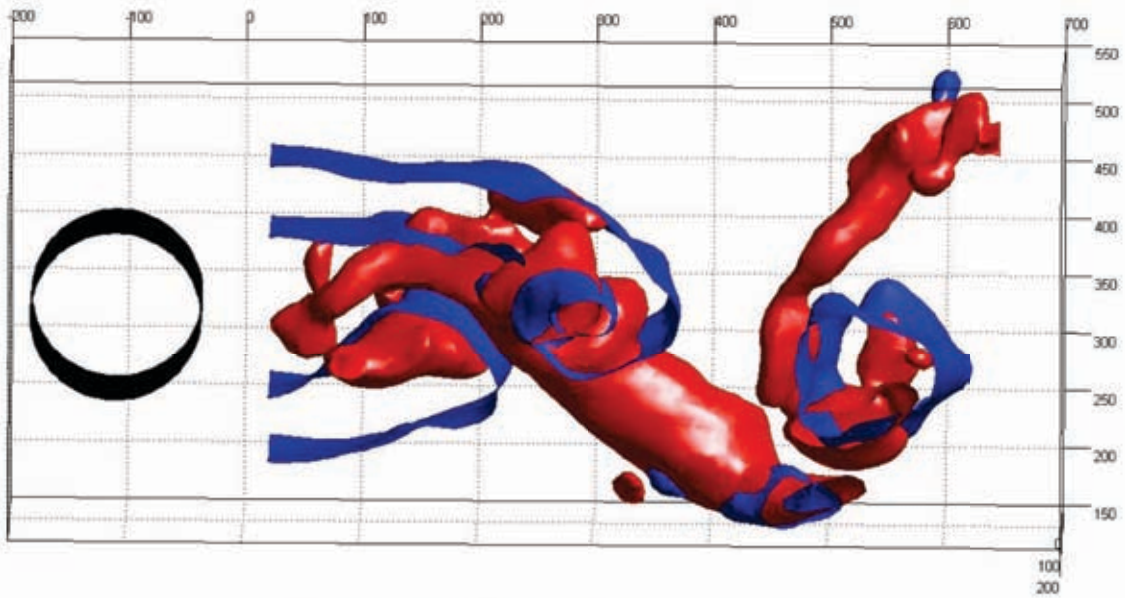

vorticity iso-surface

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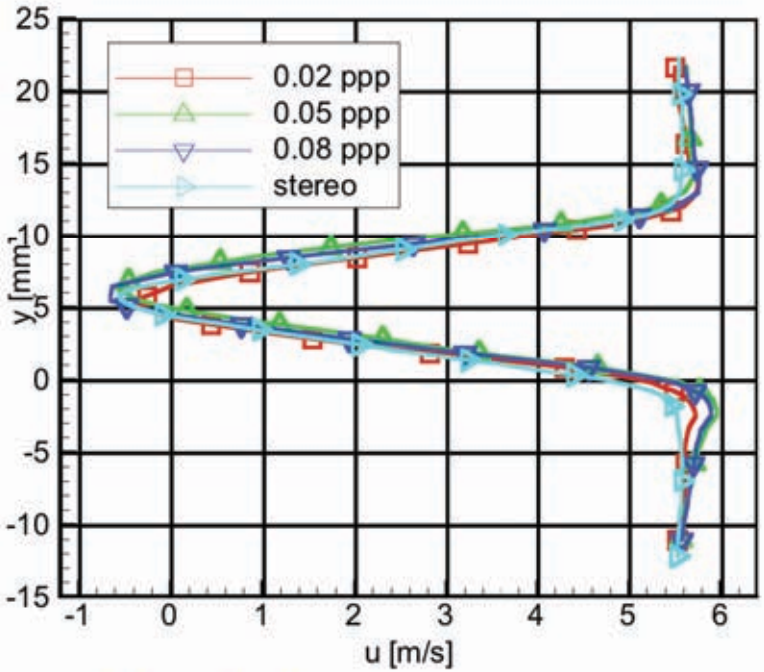
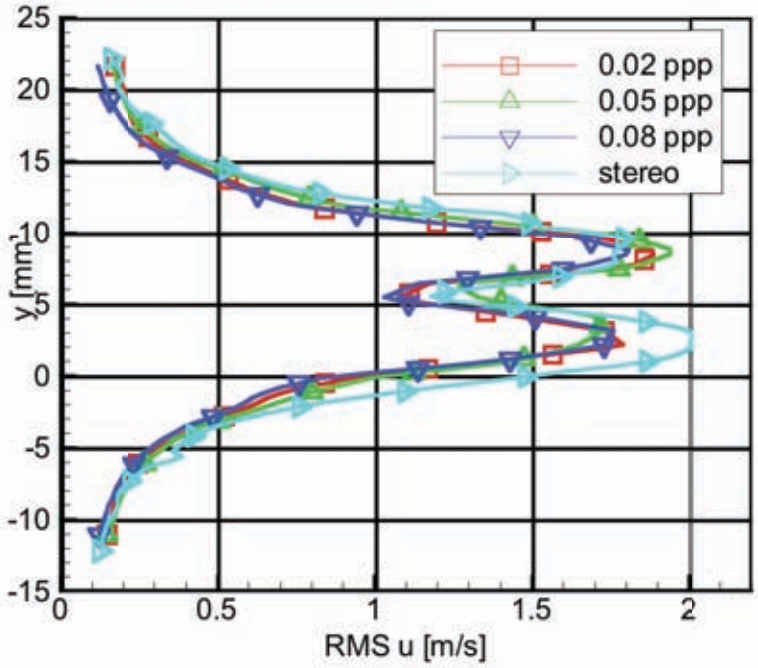
Validation: Comparison with Stereo-PIV





Conclusion

- methods agree within 0.5 m/s or 0.3 voxel displacement
- velocity accuracy does not change with particle density (*ppp*) for present range

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Investigation of coherent motion in turbulent boundary layers

overview of experiments

- **Low speed boundary layer** [Elsinga et al. 2007, AIAA-2007-1305]
  W-tunnel (air) δ_{99} = 24 mm
  U_e = 10 m/s Re_θ = 1900

- **Supersonic boundary layer** [Elsinga et al. 2010, JFM 644]
  TST-tunnel δ_{99} = 20 mm
  U_e = 510 m/s Re_θ = 34000 M_e = 2.1

  (+ **shock wave BL interaction**) [Humble et al. 2009, JFM 622]

- **Time resolved air** [Schröder et al. 2007, Exp Fluids 44]
  1m-tunnel of DLR-Göttingen U_e = 7 and 10 m/s
  recording frequency 3000 to 5000 Hz

- **Time resolved water** [Schröder et al. 2008, Elsinga & Marusic 2010, Phys Fluids 22]
  water-tunnel of TU-Delft U_e = 0.5 m/s δ_{99} = 37 mm Re_θ = 2400
  recording frequency 1000 to 3000 Hz

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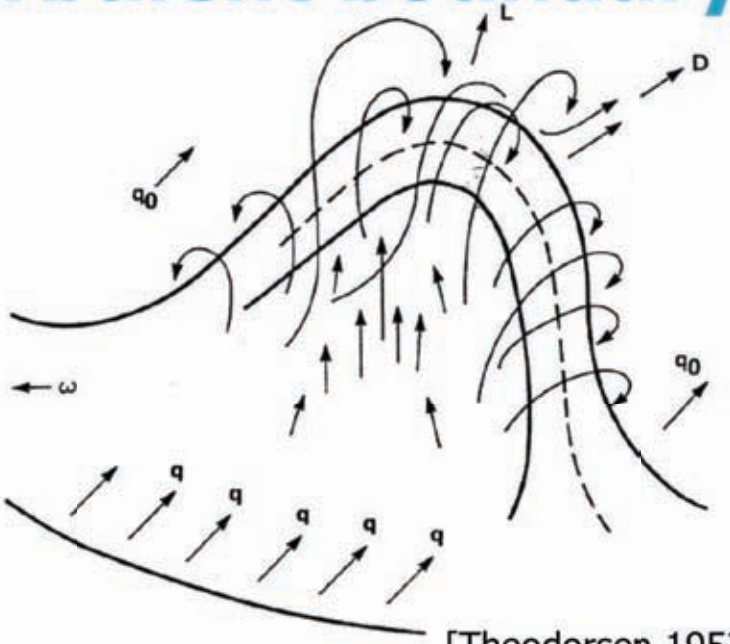
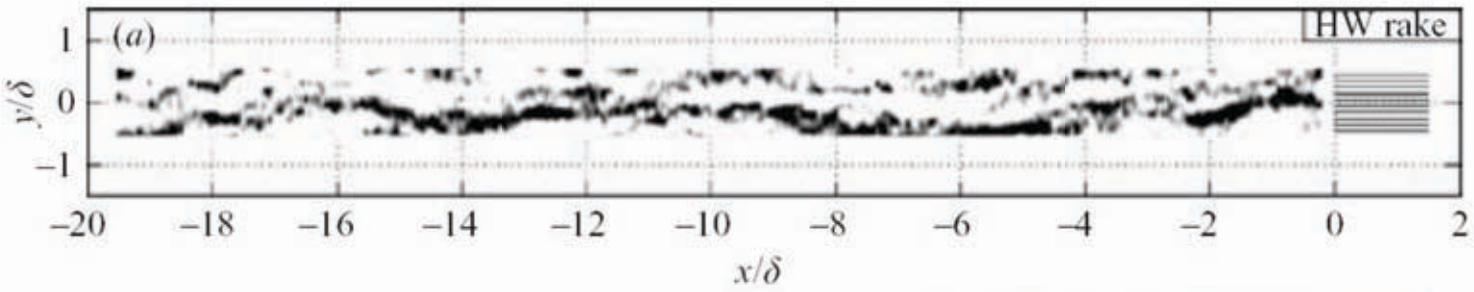
Flow structures in turbulent boundary layers

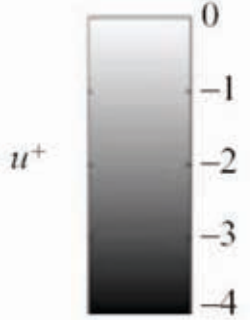
Types of structures

- hairpins / arches / canes
- streamwise vortices
- very long low speed zones



[Theodorsen 1952]





[Hutchins and Marusic 2007]

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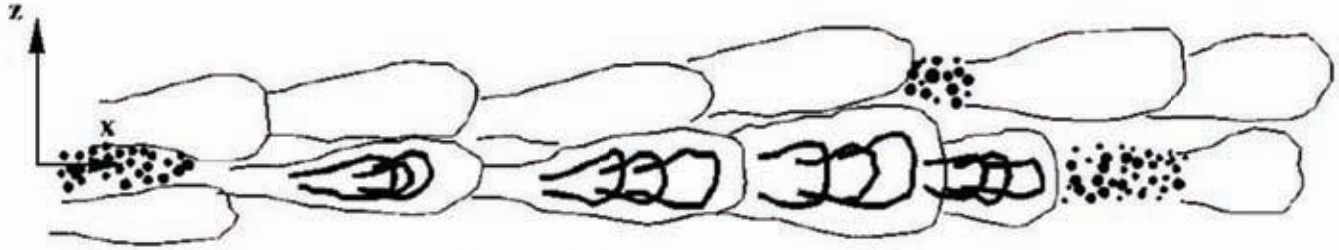
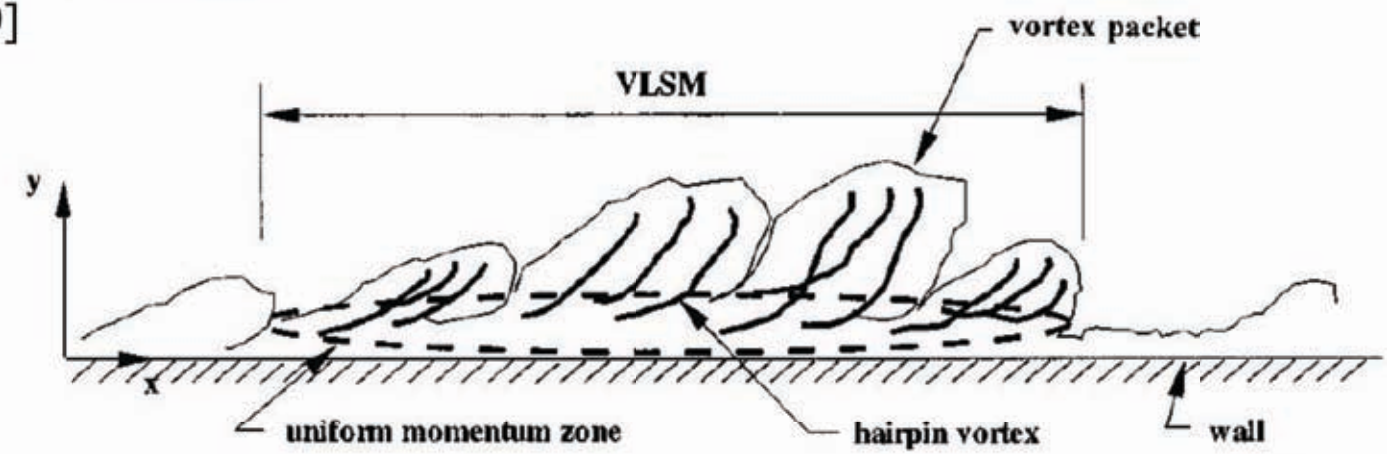
Relation between hairpins and low speed zones



Top view

Proposed model

based on signatures in hot wire data
[Kim and Adrian 1999]

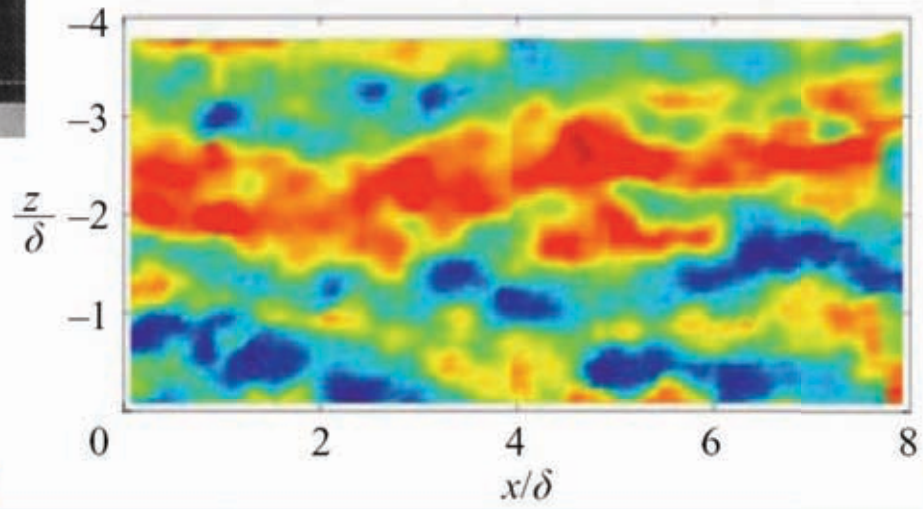


Side view

Some history of instantaneous structures observed in supersonic boundary layers (at high Re)

Rayleigh scatter

[Smits 1991]



Planar PIV

[Ganapathisubramani et al. 2006]

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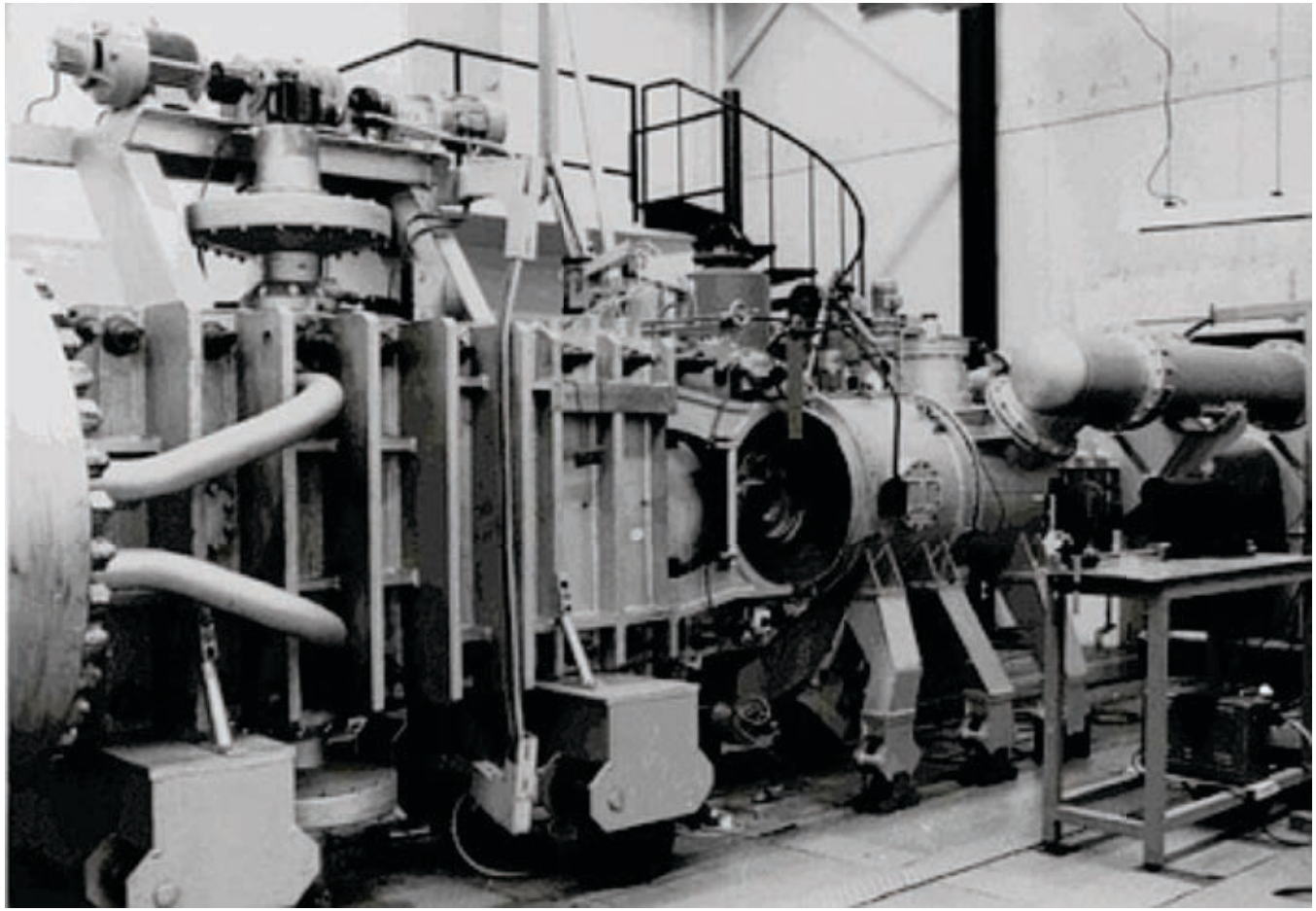
Experimental setup TST



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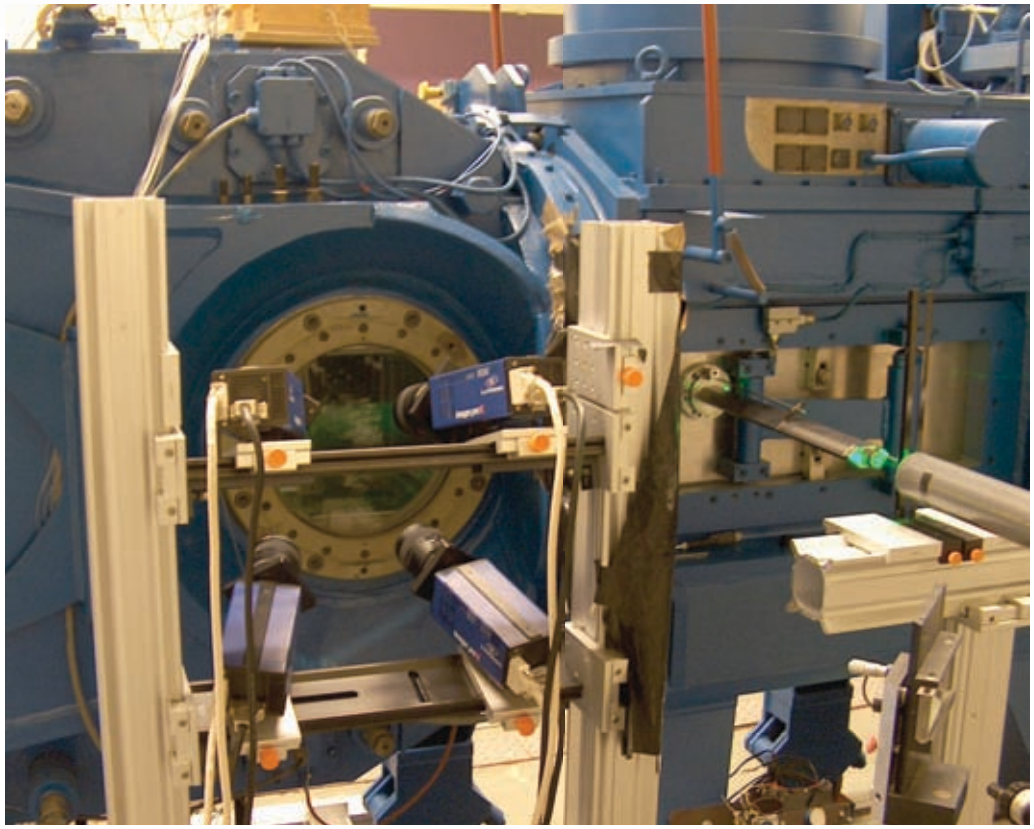
Experimental setup TST



TST-27 supersonic wind tunnel

Boundary layer over glass tunnel window

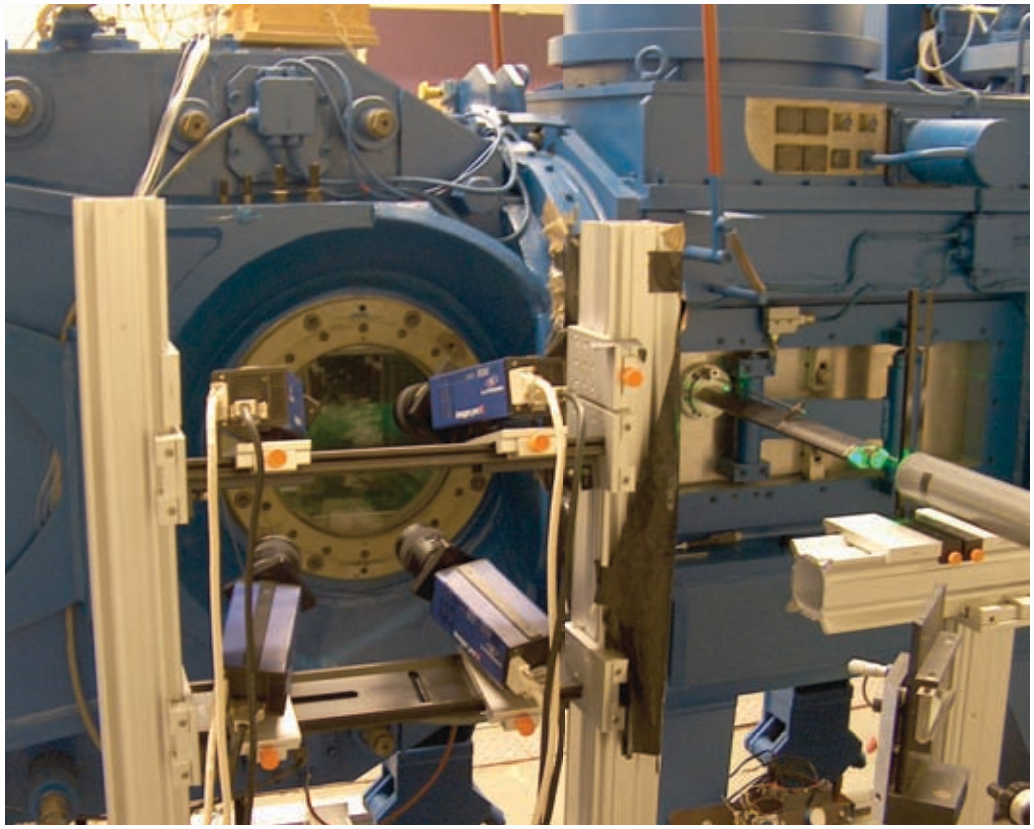
U_e = 510 m/s
M_e = 2.1
Re_θ = 34000
δ_{99} = 20 mm

4 CCD cameras
2048x2048 pixels

measurement volume
70x40x6.5 mm^3

volume self-calibration
max/ave error: 1.2 / 0.4 pixels

Experimental setup TST



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4 CCD cameras
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measurement volume
70x40x6.5 mm^3

volume self-calibration
max/ave error: 1.2 / 0.4 pixels

fluctuating Mach number <0.2 ⇒ compressibility effects small

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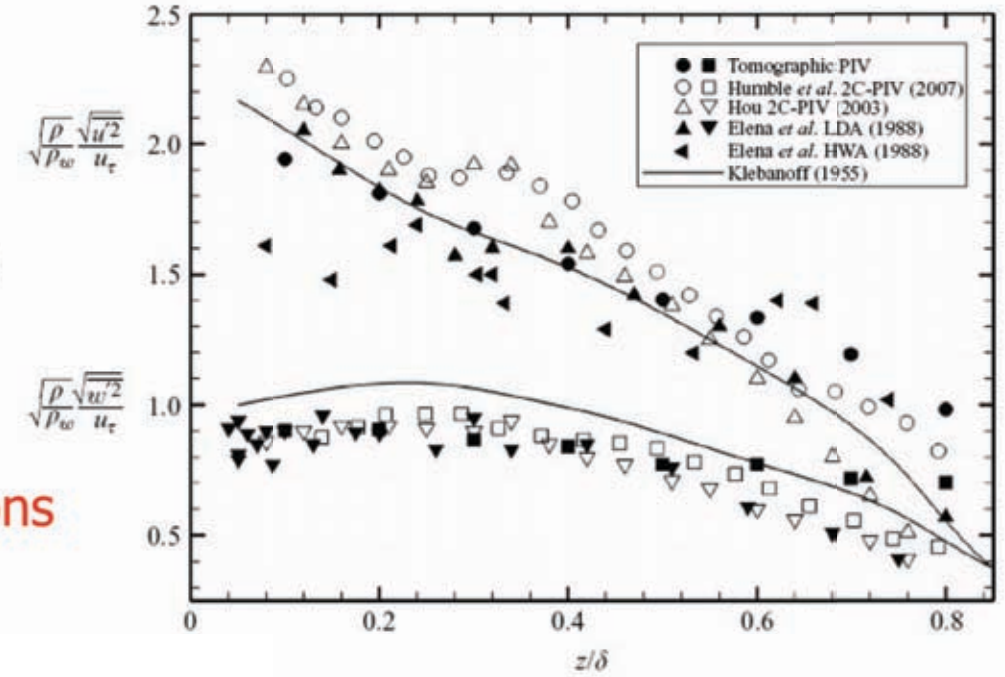
Spatial resolution

Spatial resolution: 700 wall units, 0.1δ, 2.0 mm

(note: Kolmogorov scale in outer layer order 70 wall units)

Comparison RMS velocities within 5%

⇒ Energy containing motions have been captured



[Humble et al. 2009, JFM 62

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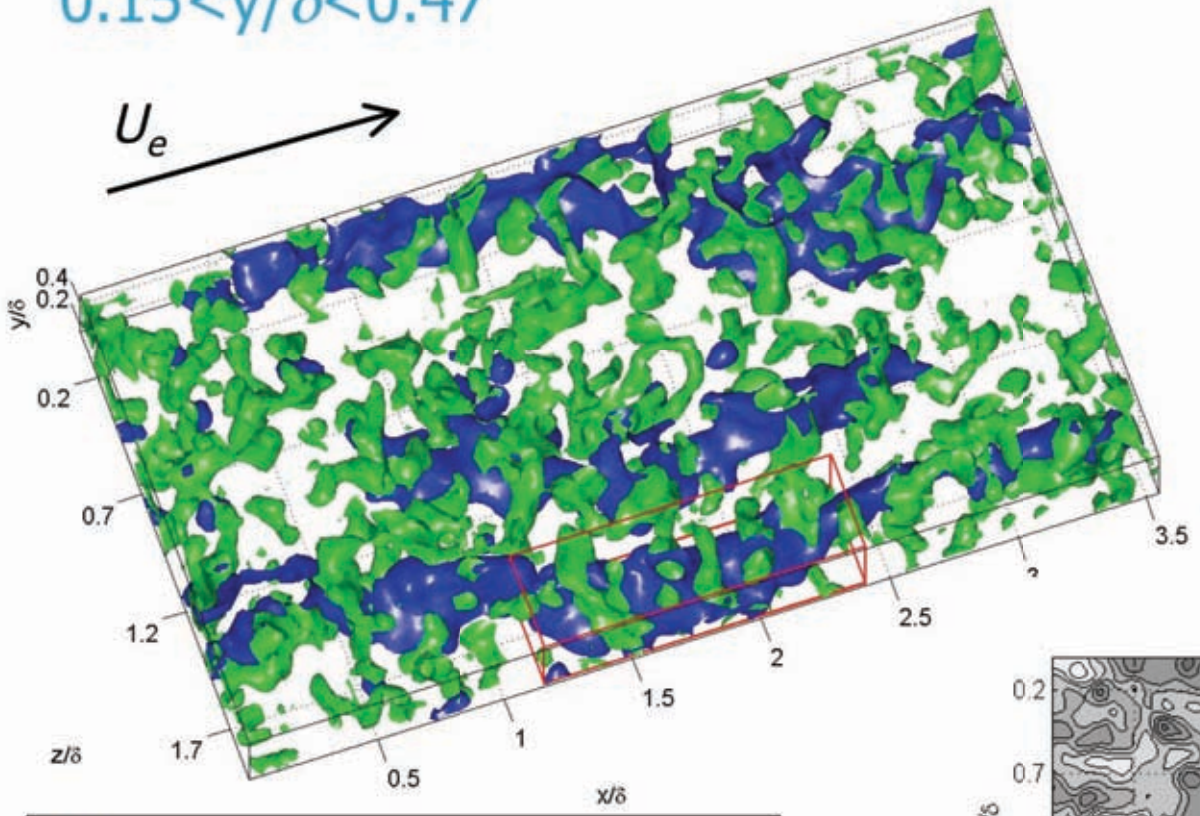
Instantaneous flow results

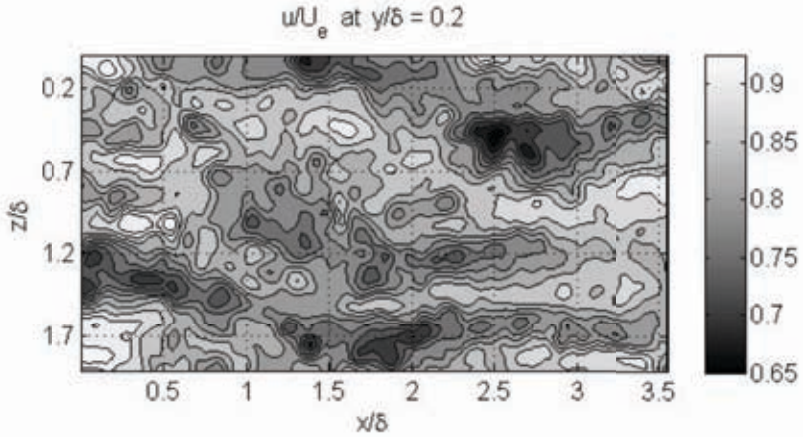
$0.15<y/\delta<0.47$



cross-correlation
window size
2x2x2 mm^3
(700 viscous units)

window overlap
75%

vectors per volume
142x77x14



blue:
low speed zones ($u < 0.8\ U_e$)
green:
vortical flow (Q-criterion)

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Instantaneous flow results

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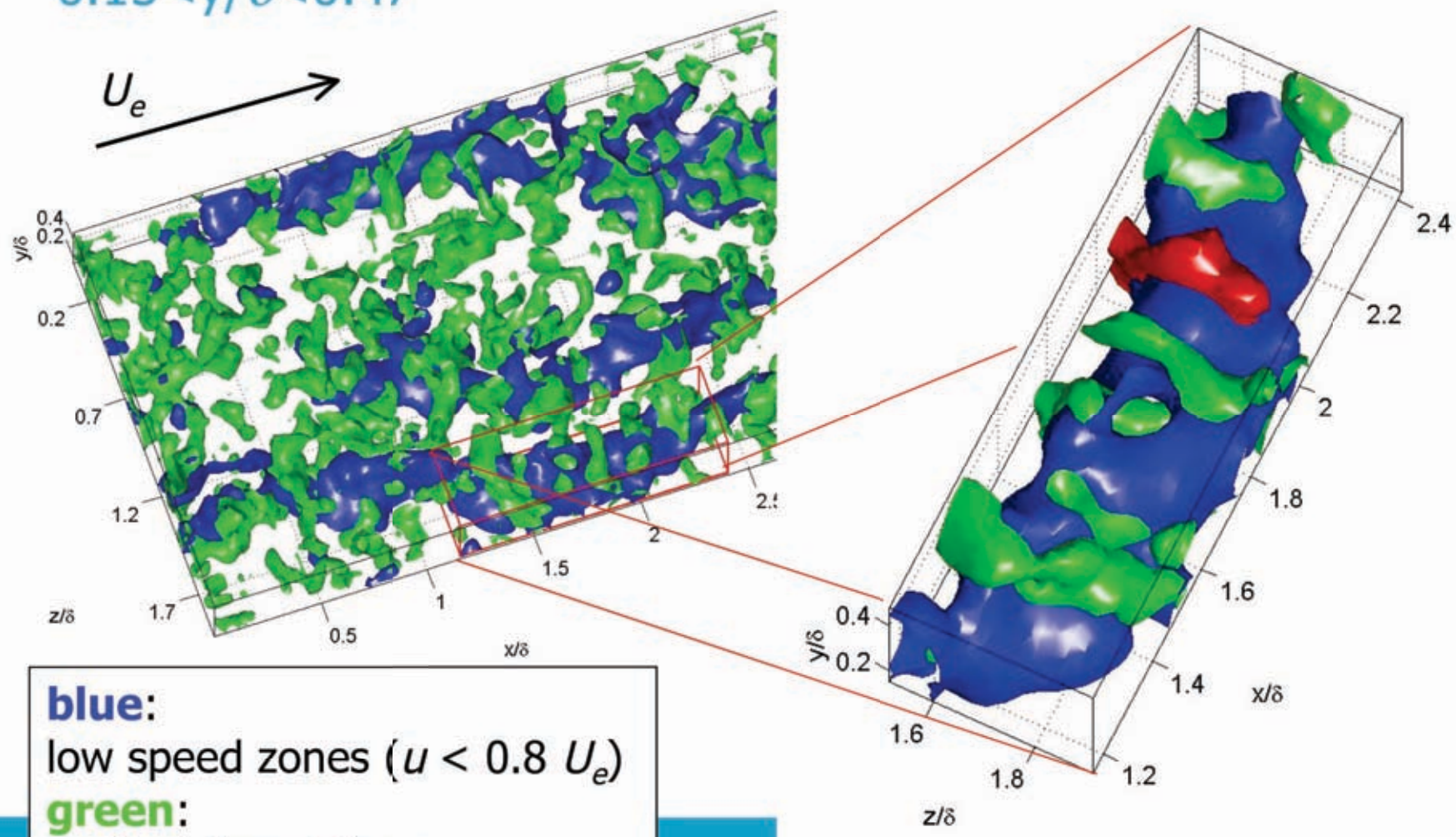

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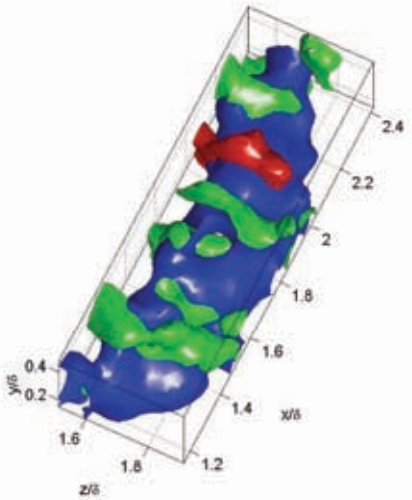
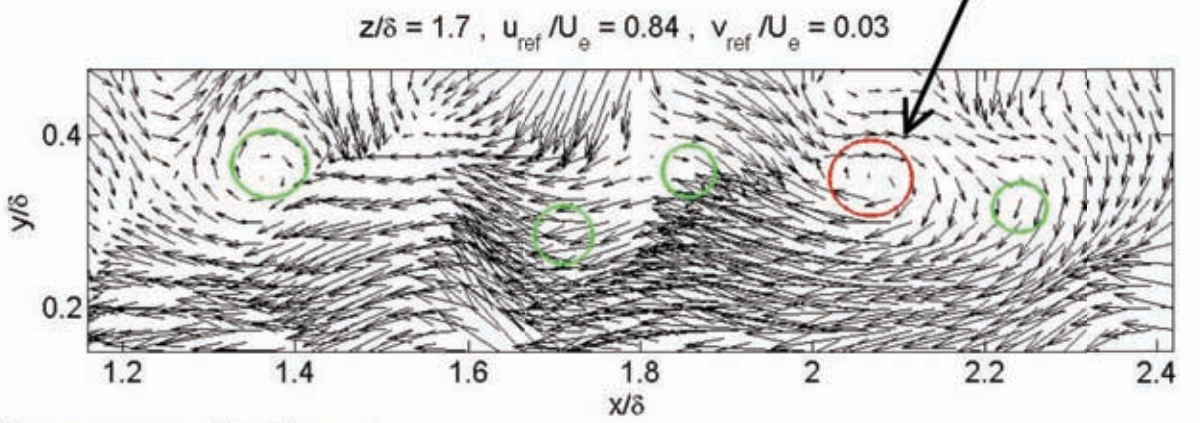
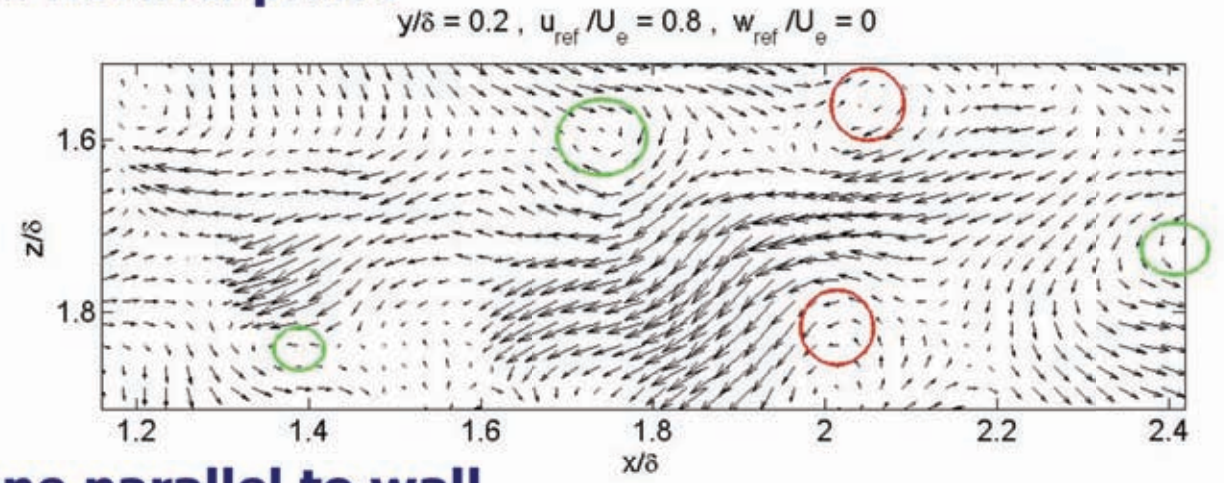
Hairpin packet





wall normal plane



plane parallel to wall

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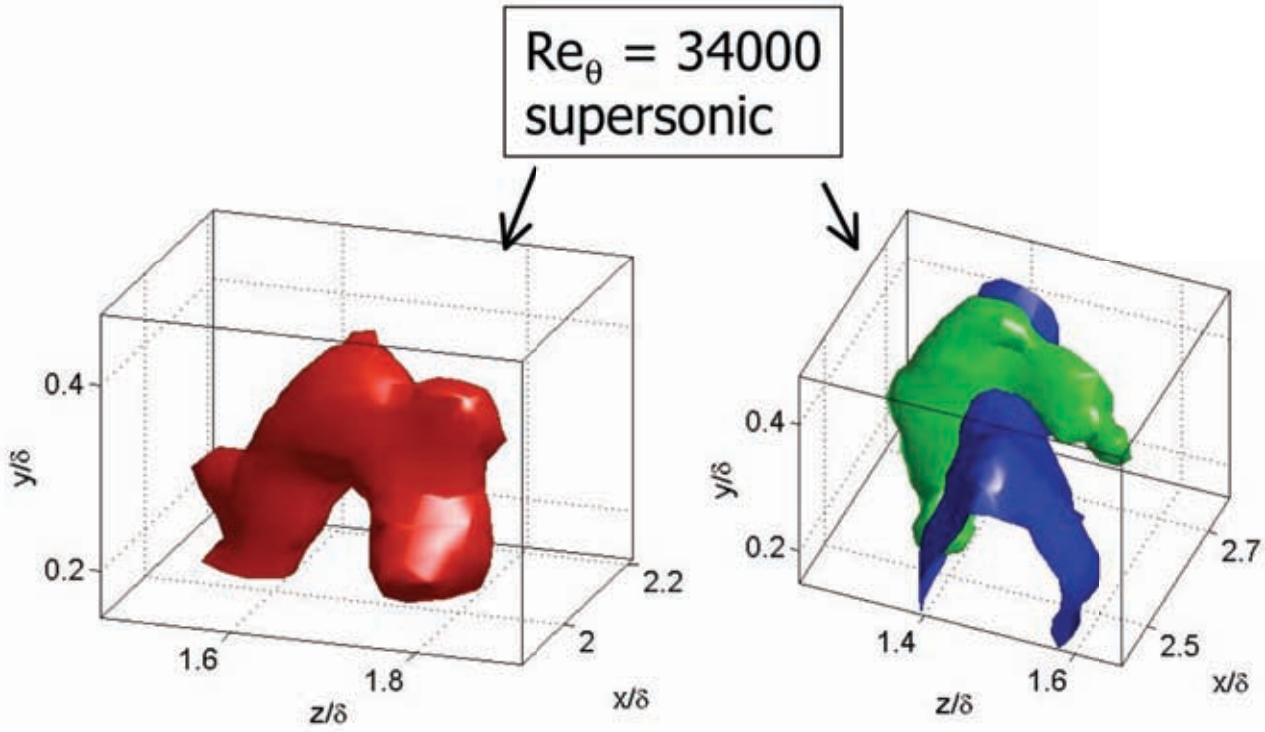
Individual hairpins



width: 0.20δ
height: 0.35δ

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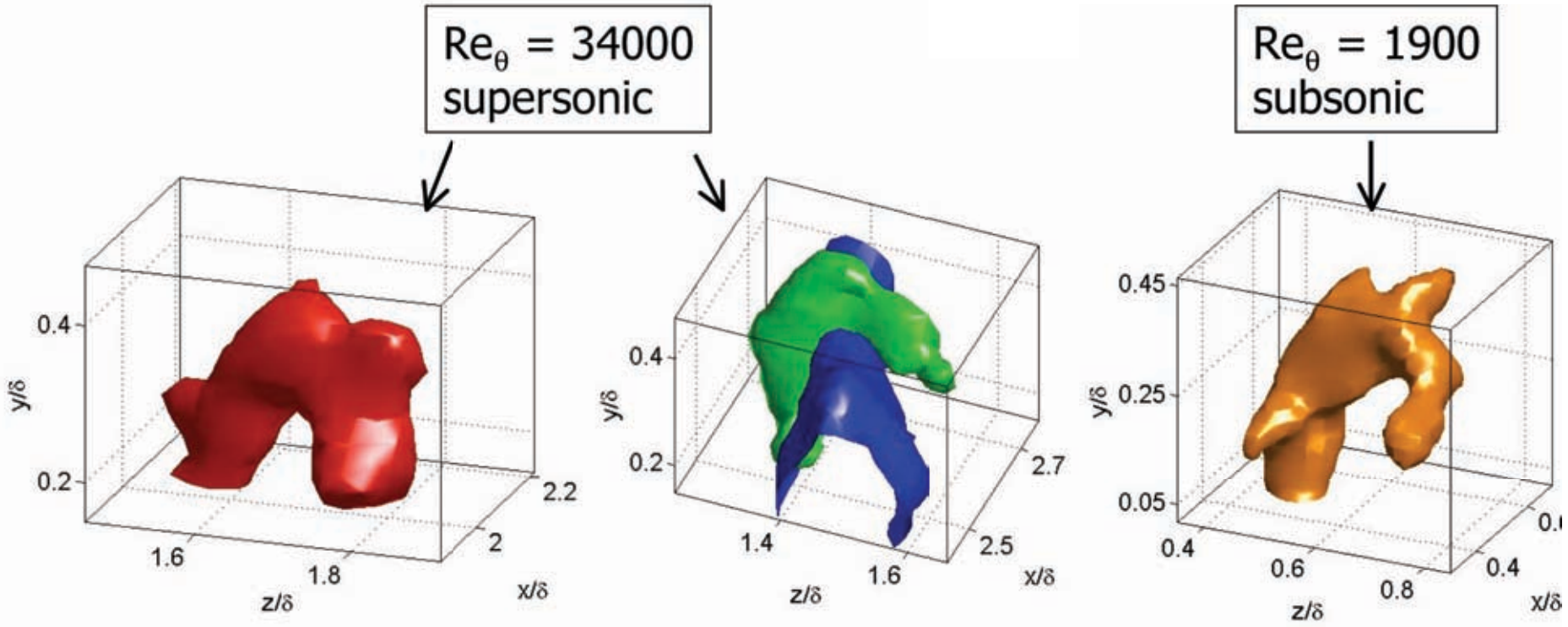
Individual hairpins



width: 0.20δ
height: 0.35δ

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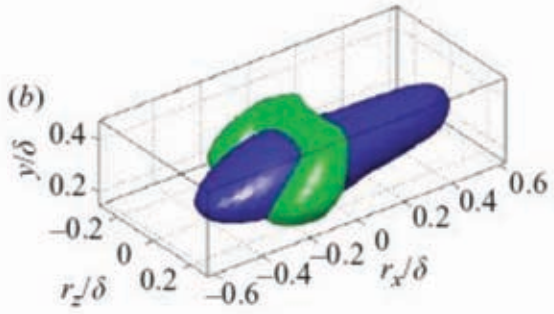
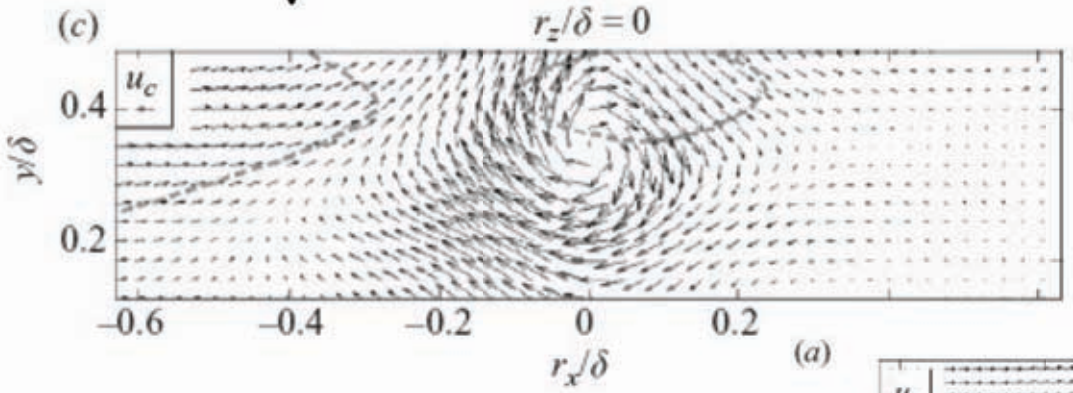
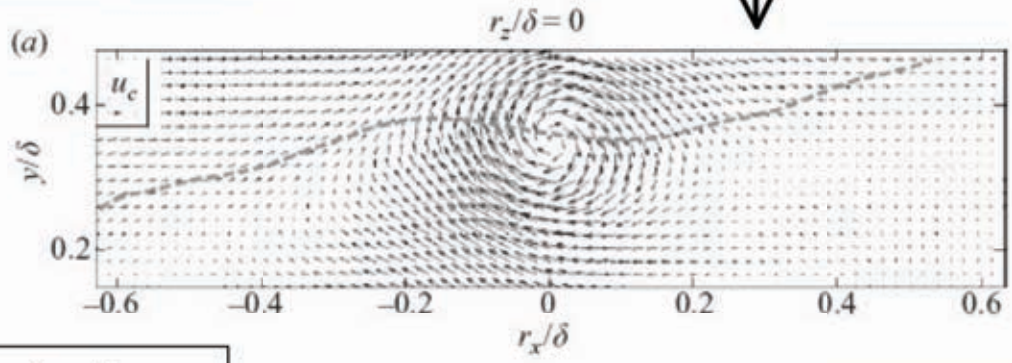
Conditional eddies



Re_θ = 34000
supersonic



Re_θ = 1900
subsonic



- Convection velocity < average velocity
- Eddy contains large-scale motion

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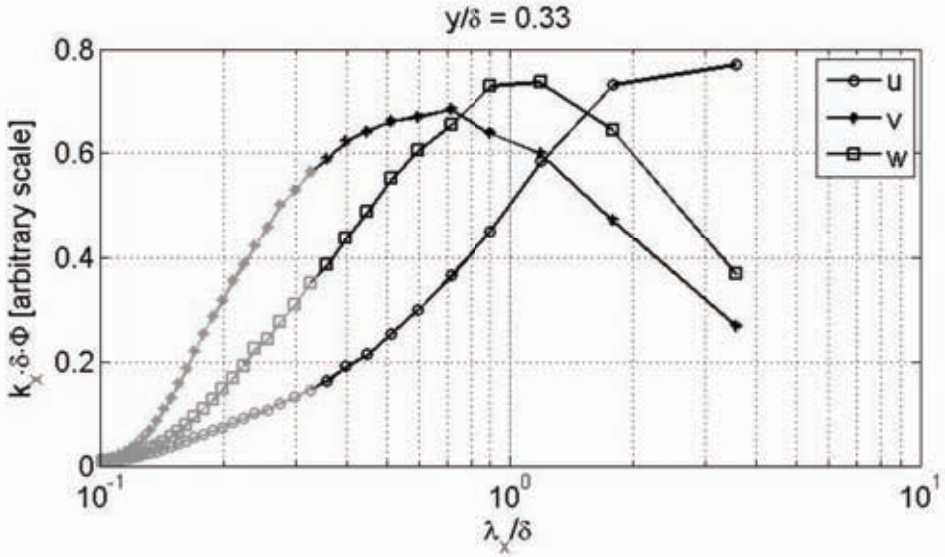
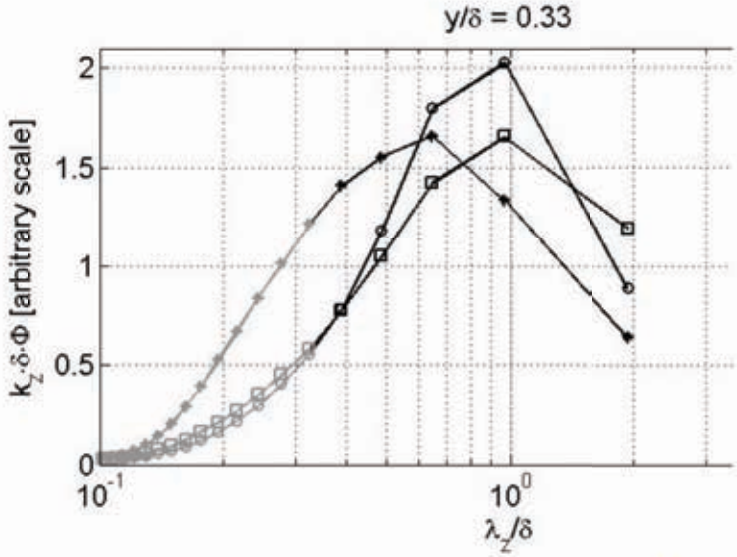
Large-scales *Pre-multiplied power spectra*



streamwise wavelength



spanwise wavelength

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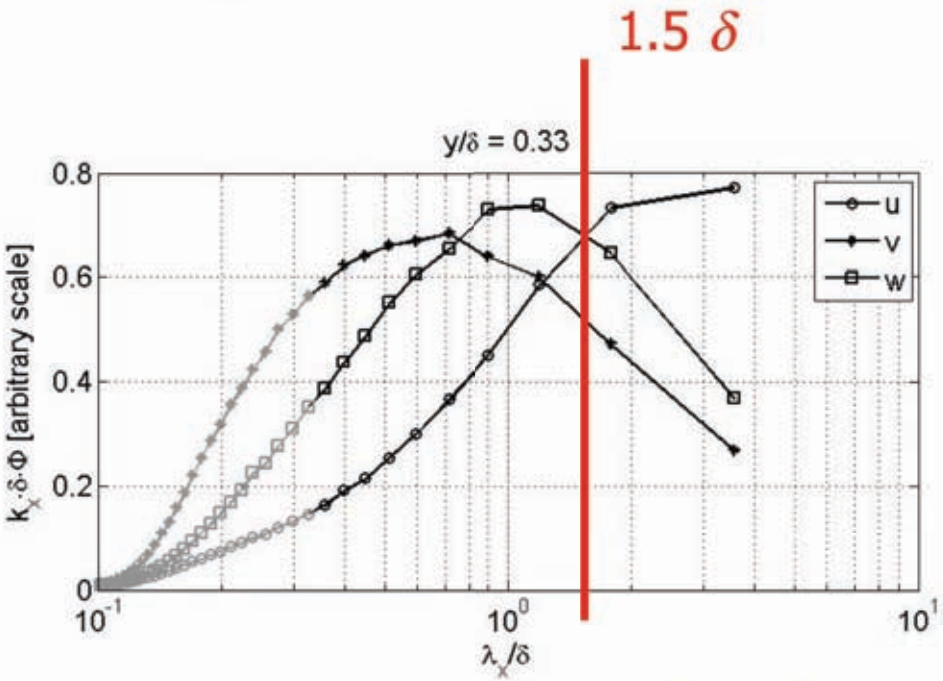
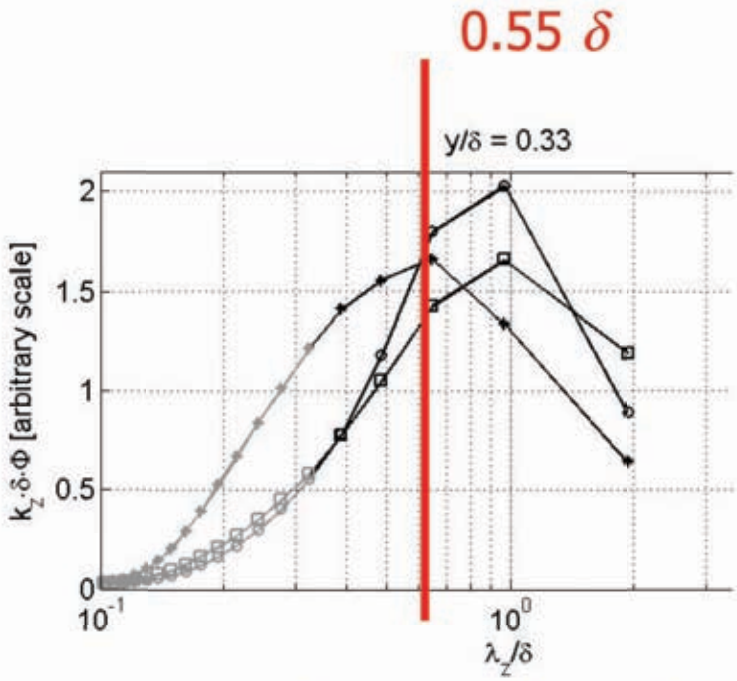


streamwise wavelength



spanwise wavelength

to bring up the large-scales: low-pass filter each velocity component using second order regression (kernel: 0.78δx0.18δx0.28δ in x,y,z)

$$f_{reg}(r_x,r_y,r_z) = a_0 + a_1 r_x + a_2 r_y + a_3 r_z + a_4 r_x r_y + a_5 r_x r_z + a_6 r_y r_z + a_7 r_x^2 + a_8 r_y^2 + a_9 r_z^2$$

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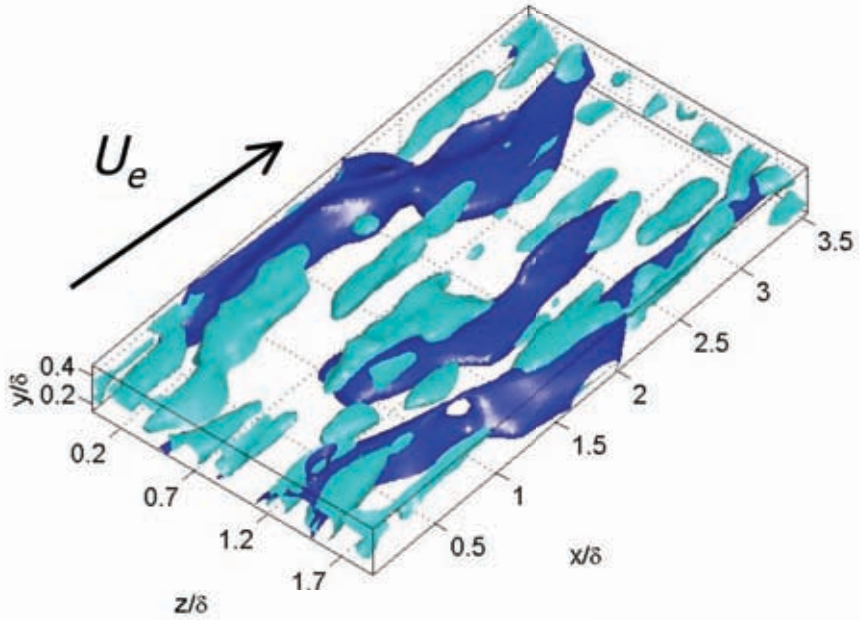
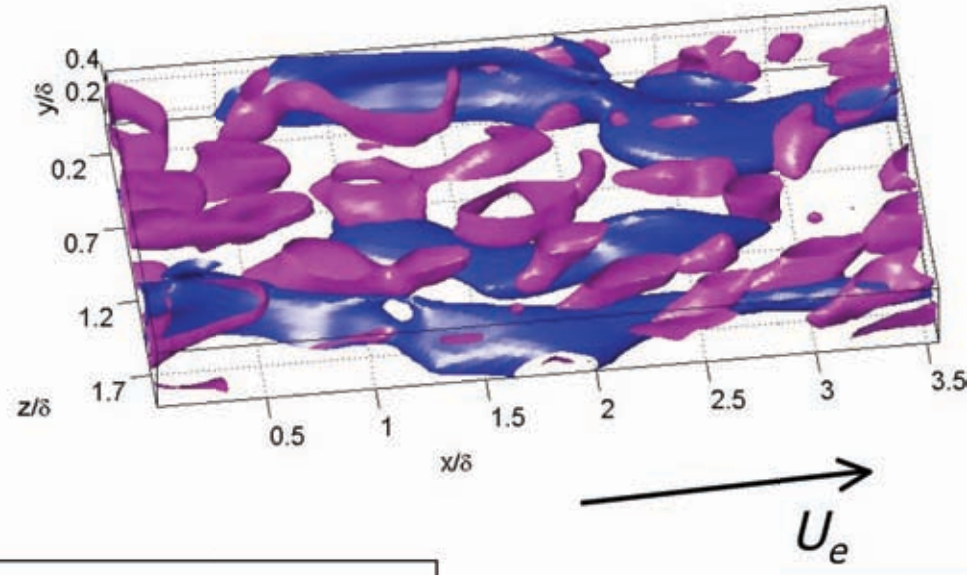
Large-scale vortical structures

cyan:
streamwise vortices
(2d swirling strength (v,w))

magenta:
wall-normal vortical flow
signature of large-scale hairpins
(2d swirling strength (u,w))





blue:
low speed zones ($u < 0.8\ U_e$)

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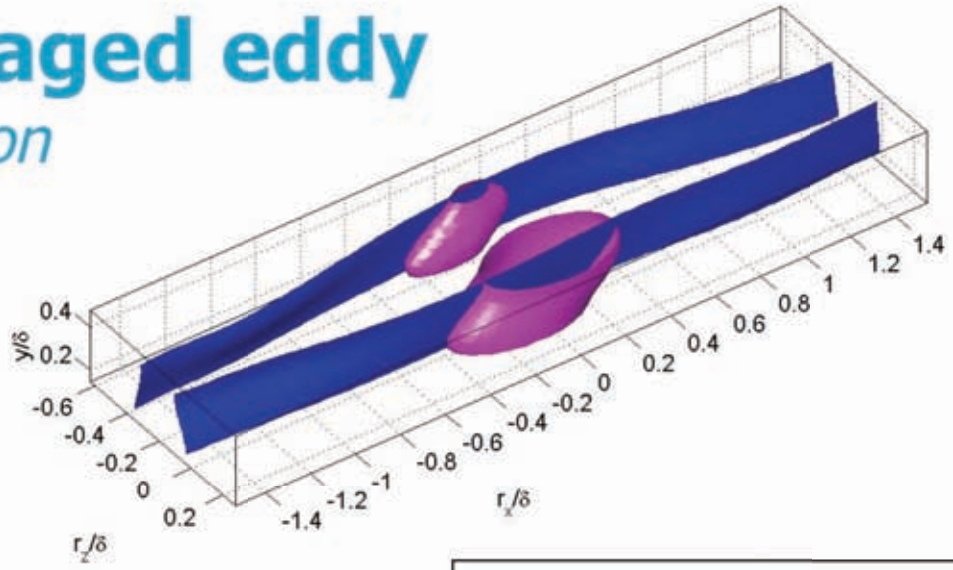
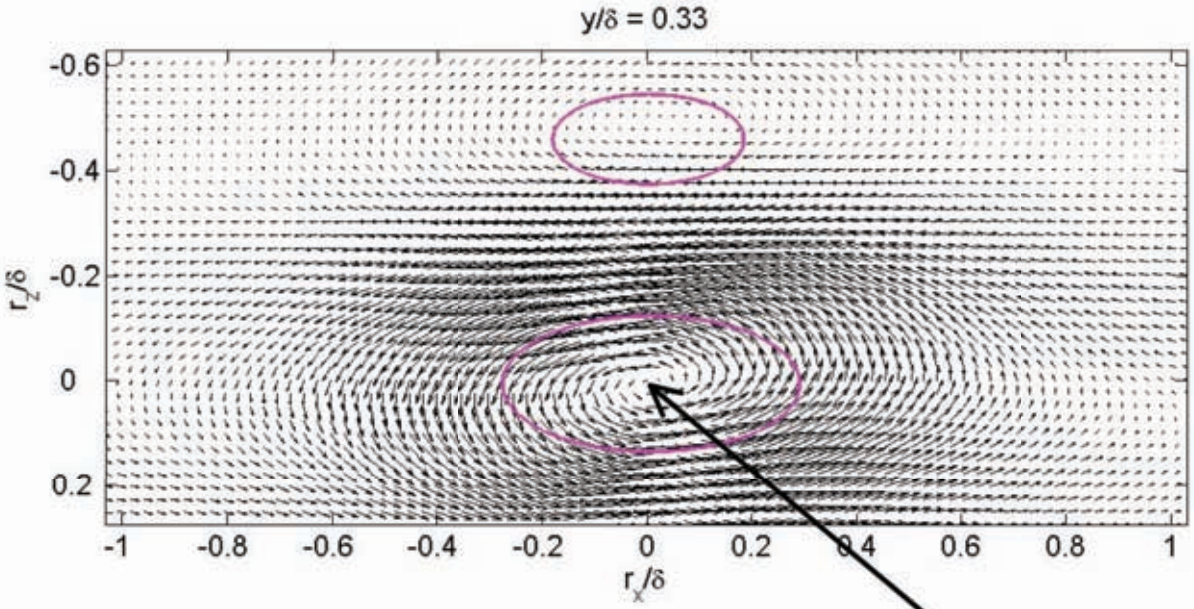
Conditional averaged eddy

linear stochastic estimation

average flow associated to a wall-normal swirl event





blue:
low speed zones
magenta:
large-scale hairpin signature
(*Q*-criterion)

event location

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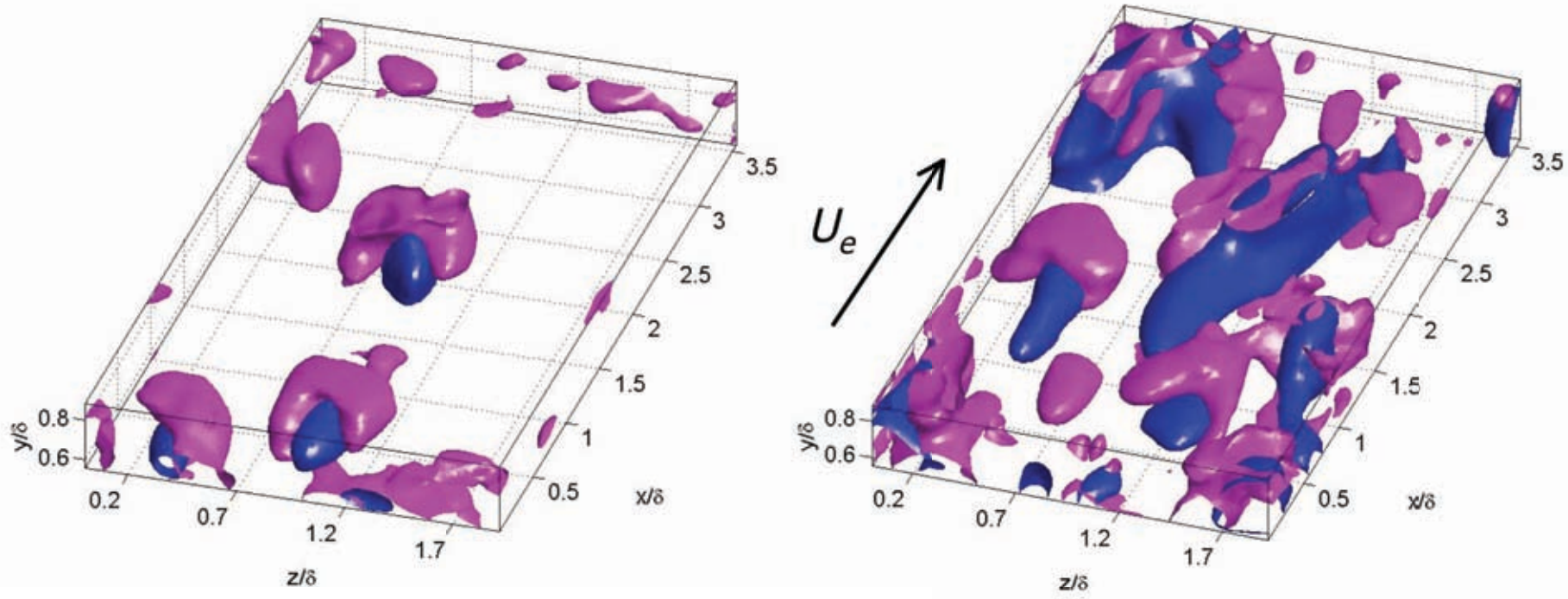
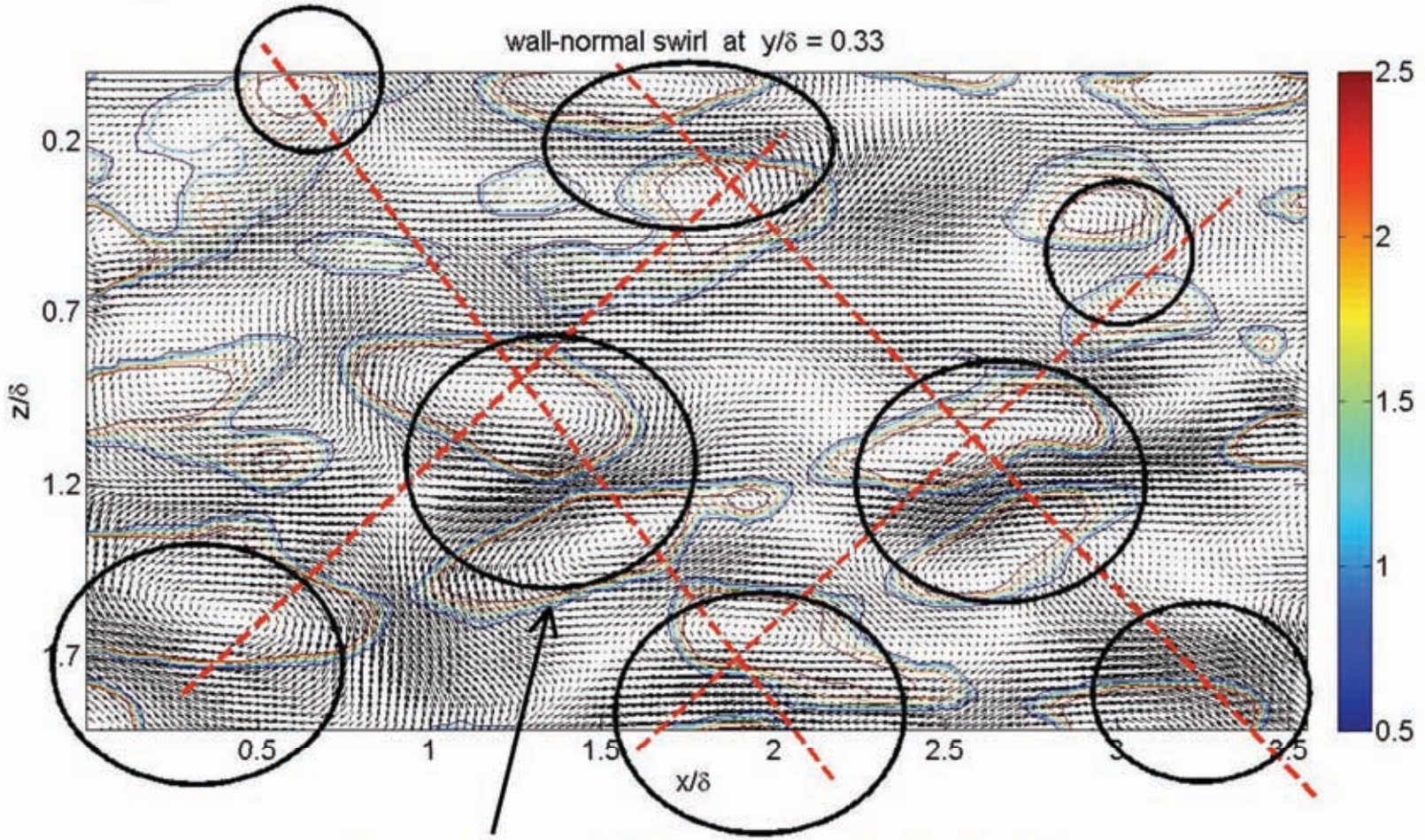
Heads large-scale hairpins

in filtered data above $y/\delta = 0.6$

blue:
low speed zones
magenta:
vortical flow
(*Q*-criterion)



Diagonal arrangement of large-scale hairpins



signature of large-scale hairpin in low-passed velocity field

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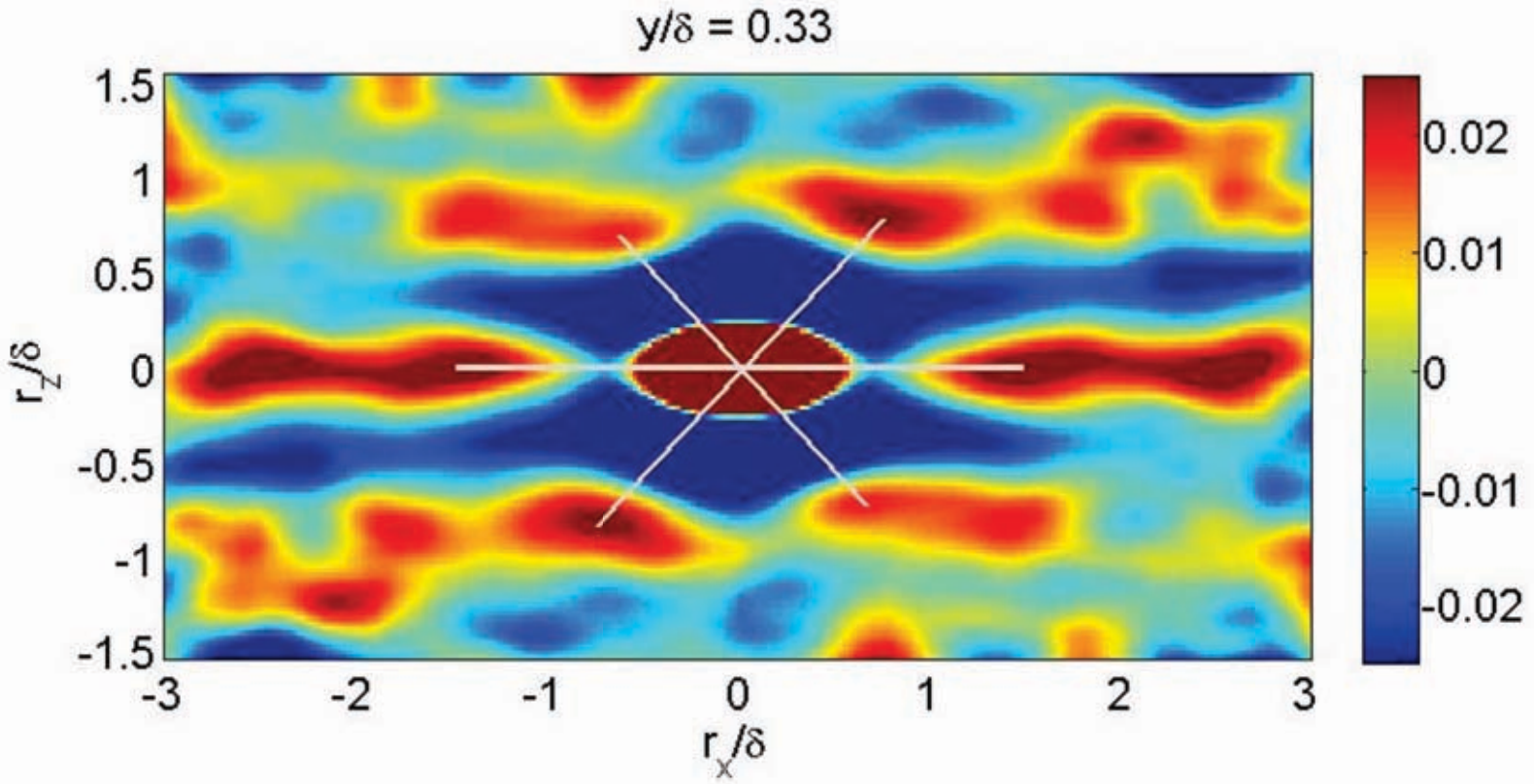
Diagonal arrangement of large-scale hairpins

auto-correlation coefficient wall-normal swirling strength
(480 snapshots)



in low-passed velocity field

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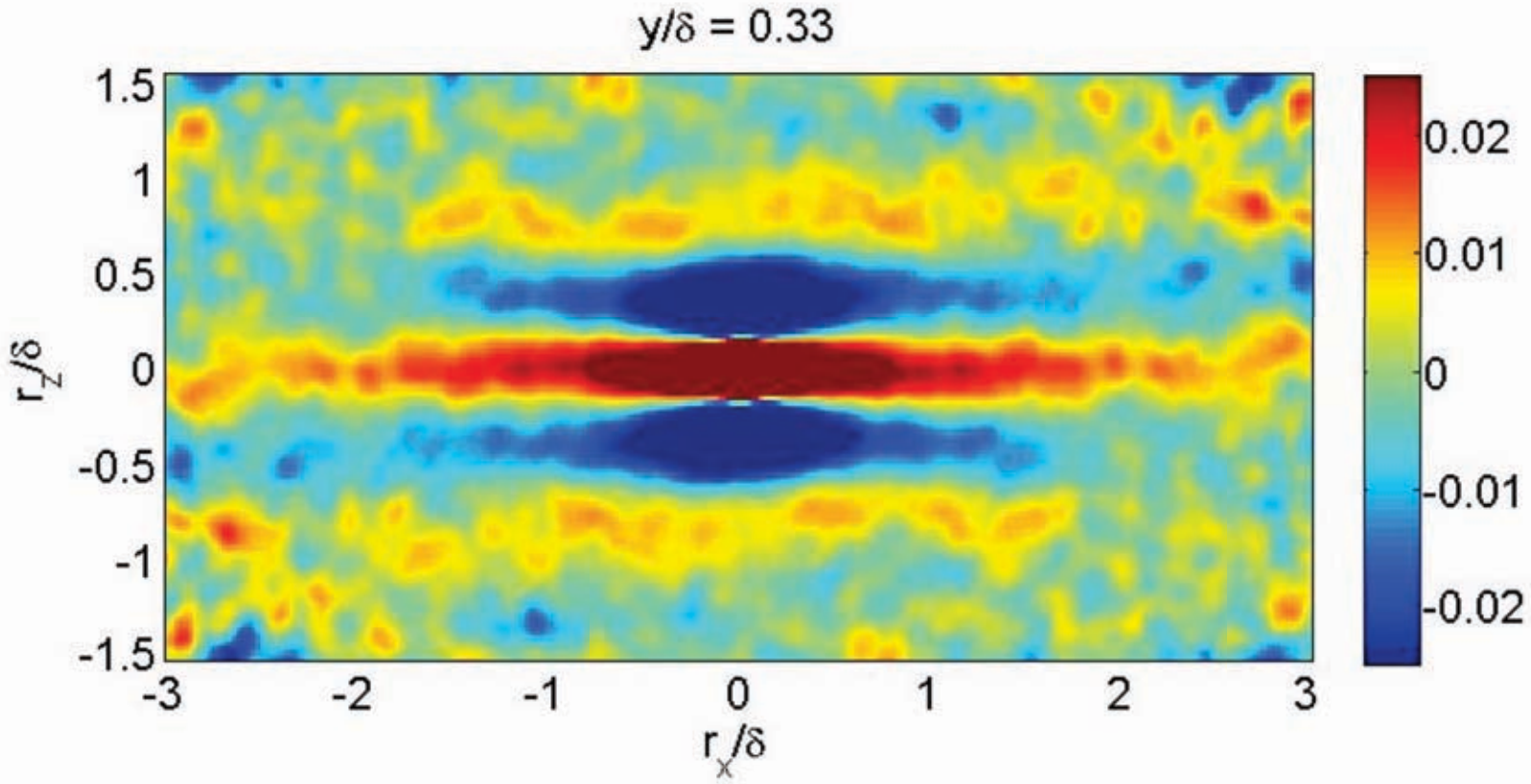
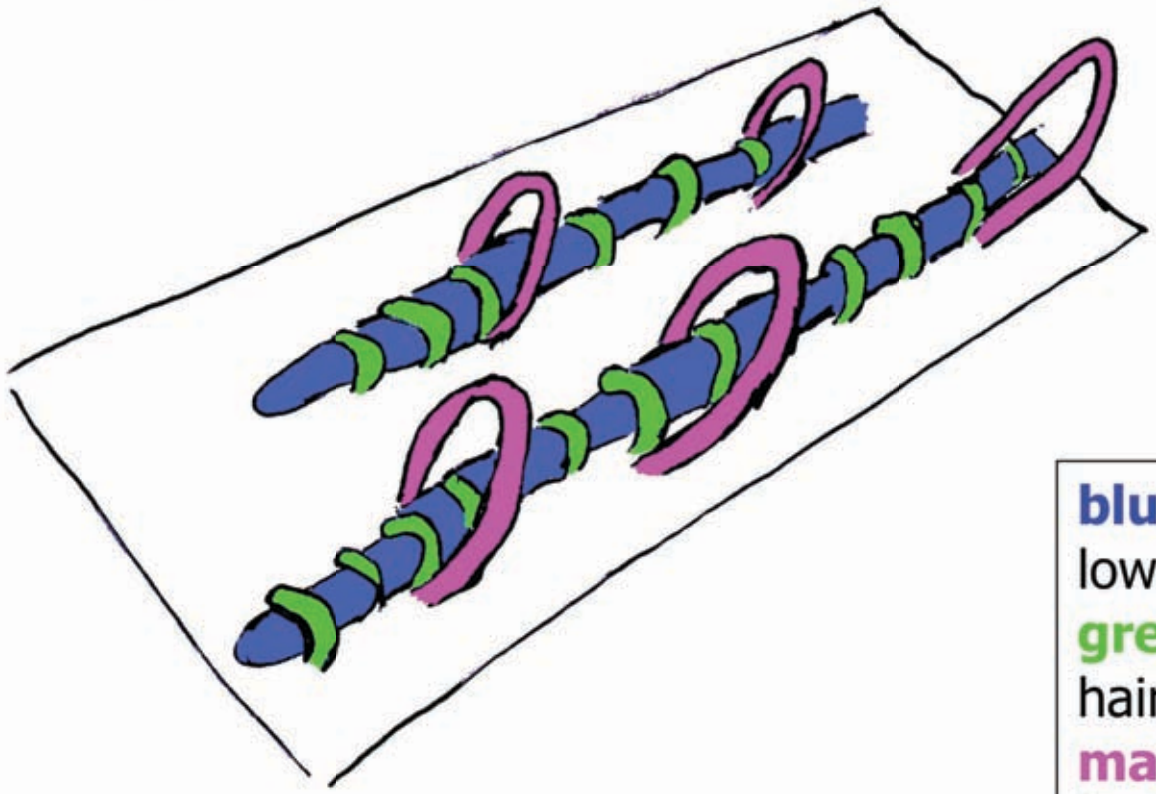
Diagonal arrangement of large-scale hairpins

auto-correlation coefficient wall-normal swirling strength
(for comparison original data, unfiltered, 480 snapshots)



Conceptual sketch of the observed flow pattern



blue:
low speed zones
green:
hairpins
magenta:
large-scale hairpins

TU Delft

Conclusions

1. Tomographic-PIV was applied to measure instantaneous 3-D velocity distribution in the wake-region of a *turbulent boundary layer at Re_θ = 34,000 and M_e = 2.1*

2. *Quantitative visualization of the flow structures*
   - ❑ long (>3δ) low speed zones
   - ❑ hairpins vortices
   - ❑ streamwise vortices and large-scale hairpins in low-pass filtered velocity fields

3. Observation of a preferential *diagonal* and streamwise *arrangement of the large-scale hairpins*