Multi-PIV Measurements of an Adverse Pressure Gradient Turbulent Boundary Layer

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Project Motivation and Aims

- Adverse pressure gradient boundary layer very common in aerodynamics

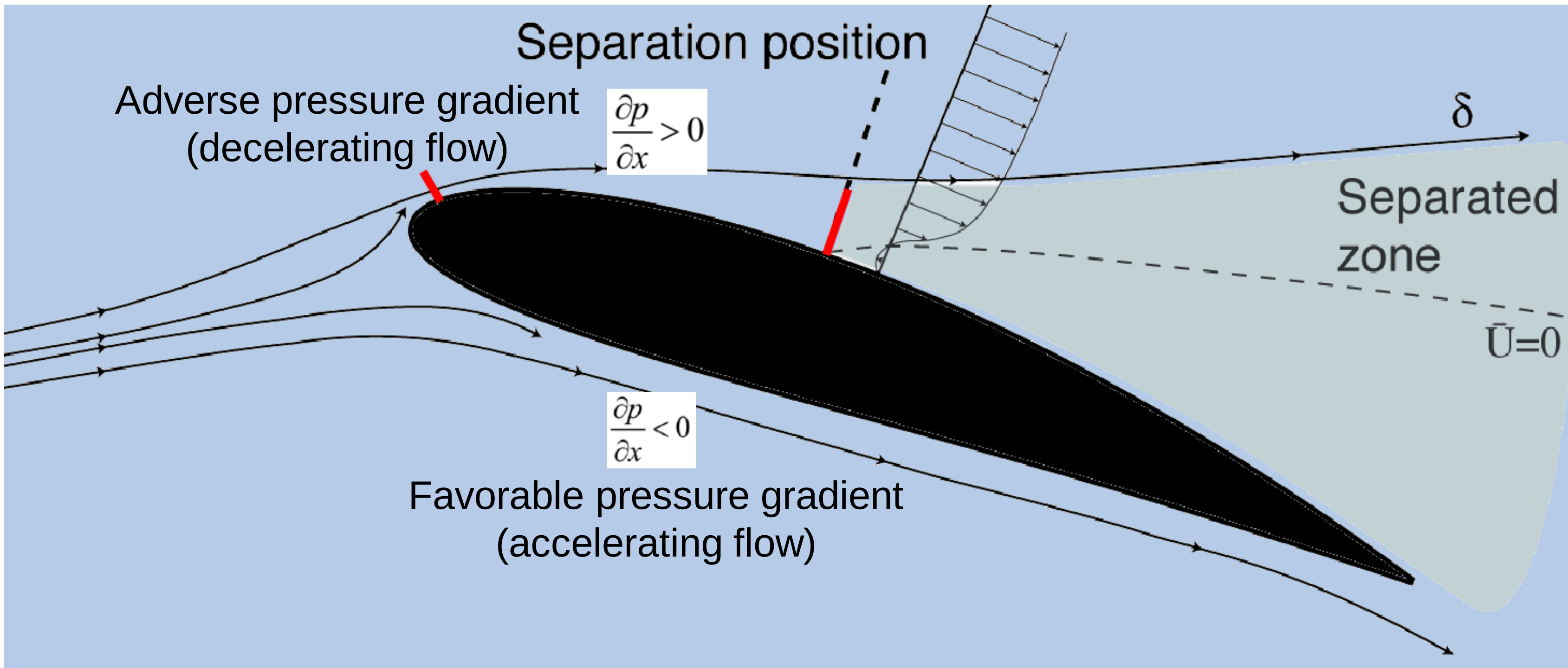
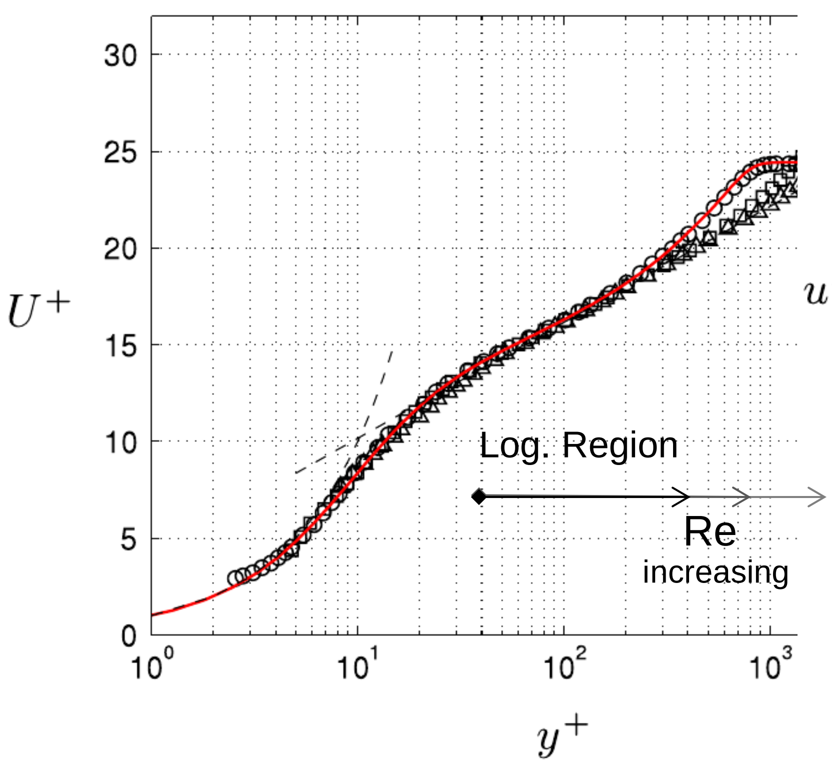
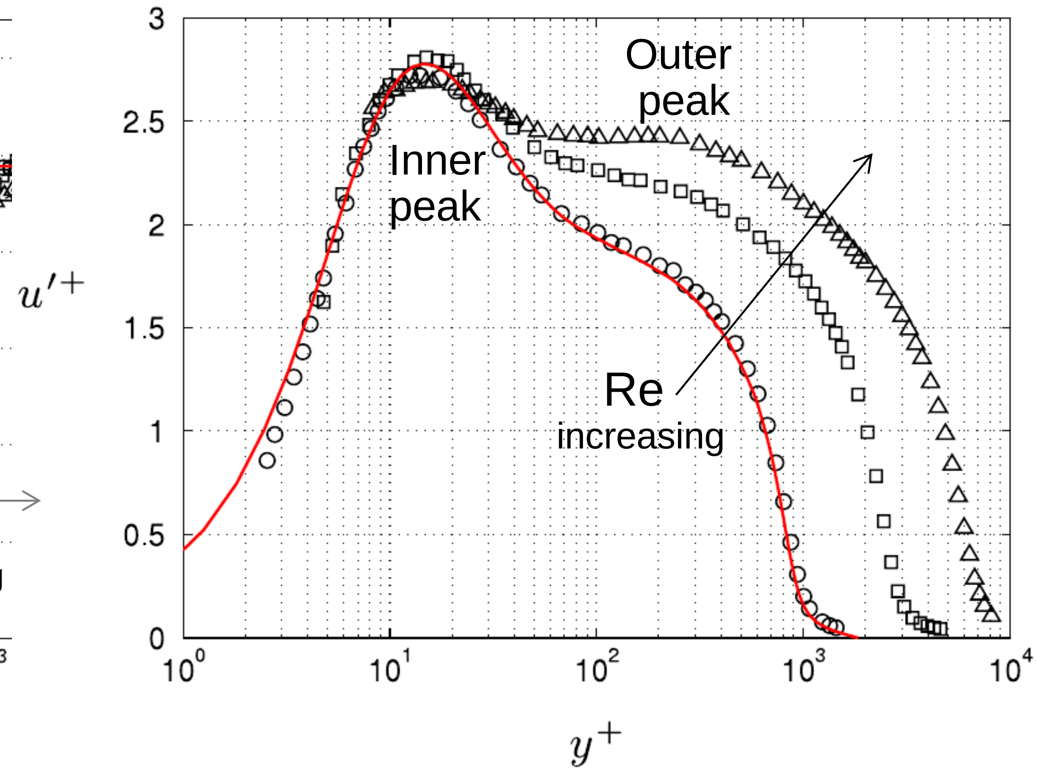


Figure from Yvan Maciel, Laval Univ., Quebec

Project Motivation and Aims

- Large scale turbulent flow structures are primarily found in the log-law region of turbulent boundary layers
- Coherent structures are associated with the outer peak in the stream-wise velocity fluctuations





Project Motivation and Aims

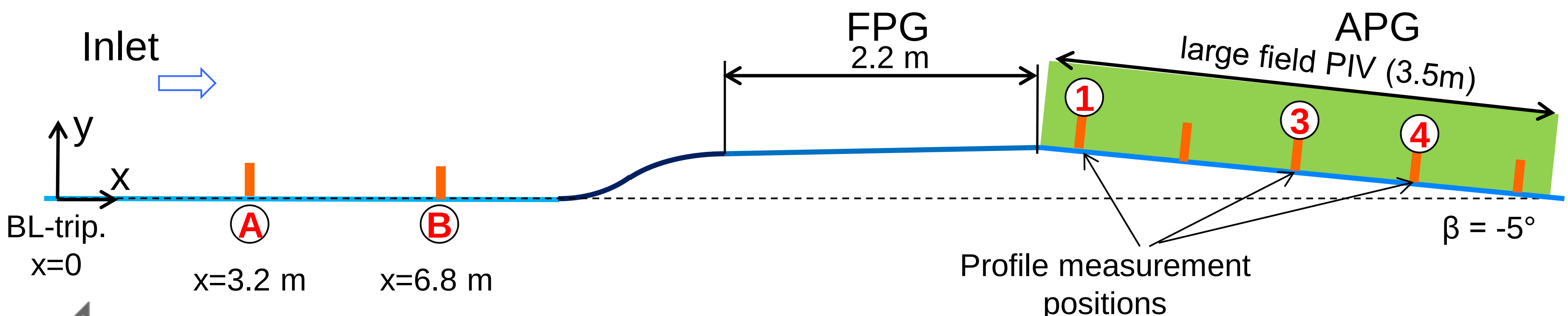
- large scale turbulent flow structures are primarily found in the log-law region of turbulent boundary layers
- coherent structures are associated with the outer peak in the stream-wise velocity fluctuations
- Q1: Are the large scale structures a high Reynolds number effect or just not resolvable at low Reynolds numbers?
- Q2: How do these structures behave in cases with pressure gradients?
- Q3: Shape and dynamics of the large scale turbulent flow structures?
- Q4: Significance of the structures for aerodynamic flows around airfoils?
- Fundamental project aim is to resolve and characterize these structures in an APG boundary layer flow
- Significance of structures for the statistical properties of the flow can be resolved for the first time within the project

Large Scale Structure under Adverse Pressure Gradient

Facility: LML Boundary Layer Wind Tunnel (LML), France

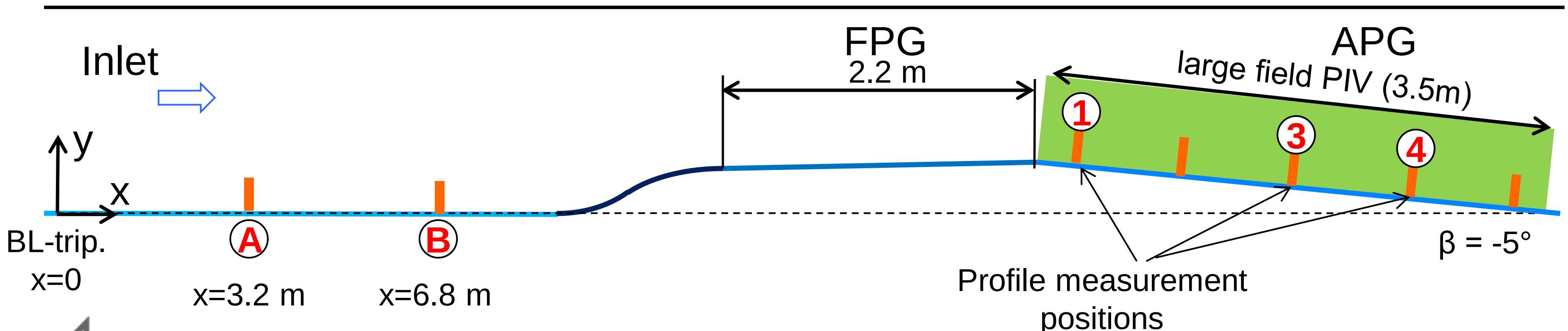
Partners

- LML-Lille
- UniBW-München
- DLR (Gö/KP)
- Monash University

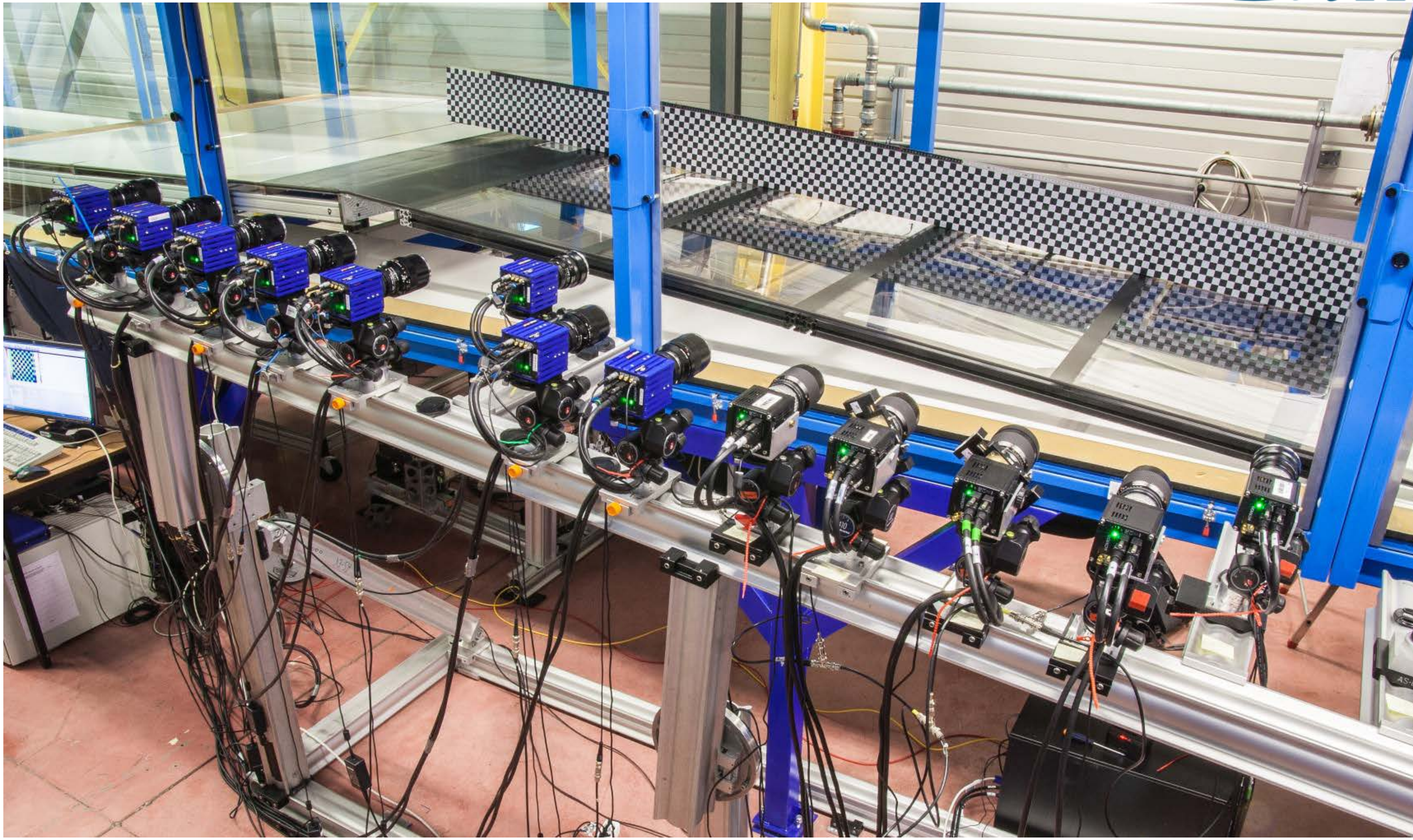


PIV Measurement methods utilized

- **2C 2D PIV** to capture entire APG region (3.5m) using 16 cameras
- 3C 2D PIV (Stereo) of selected spanwise positions in APG (and upstream)
- **High-speed 2C 2D PIV** to measure near wall characteristics (wall shear stress) at selected positions
- 2D wall shear measurements based on shear film
- Long-range microscopy to measure wall shear stress

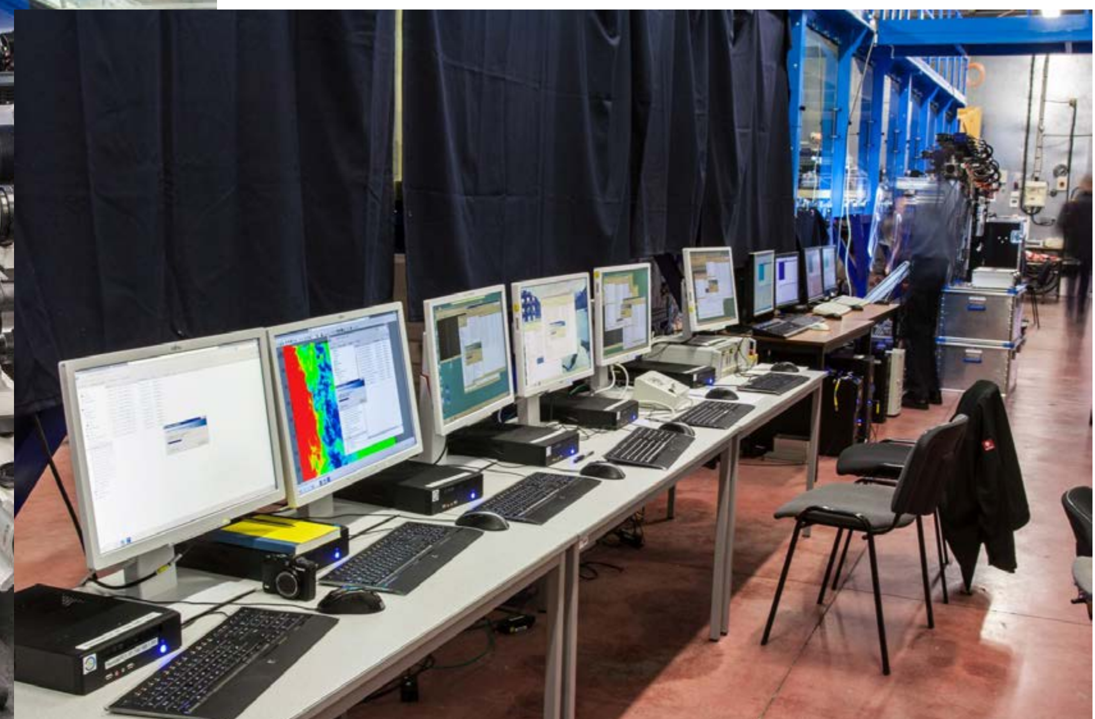


2C-2D Measurement of APG Region



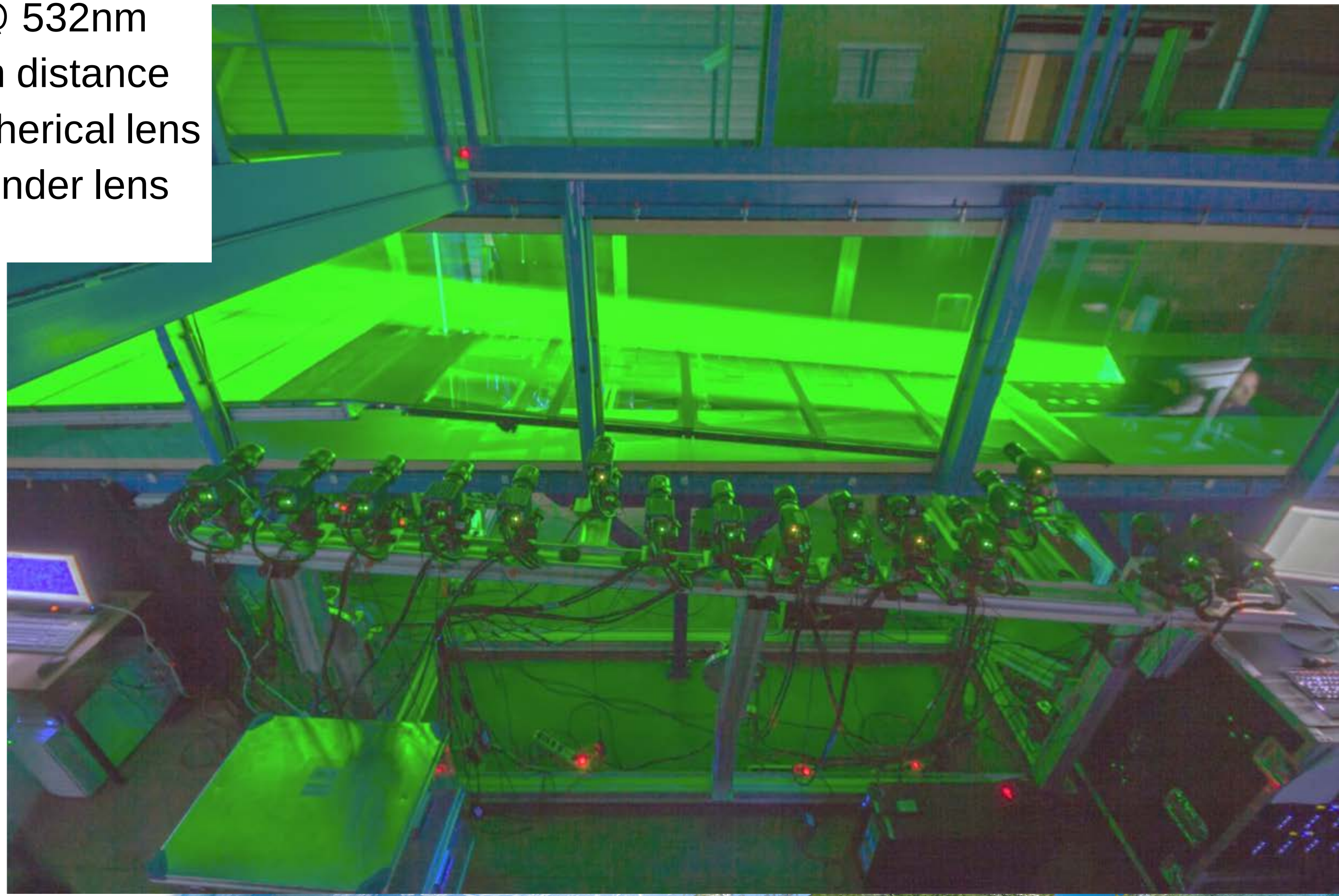
Large Field PIV using 16 sCMOS cameras covering 3.5m

→ image size of about 35,000 x 2500 pixels (87 MPixel)



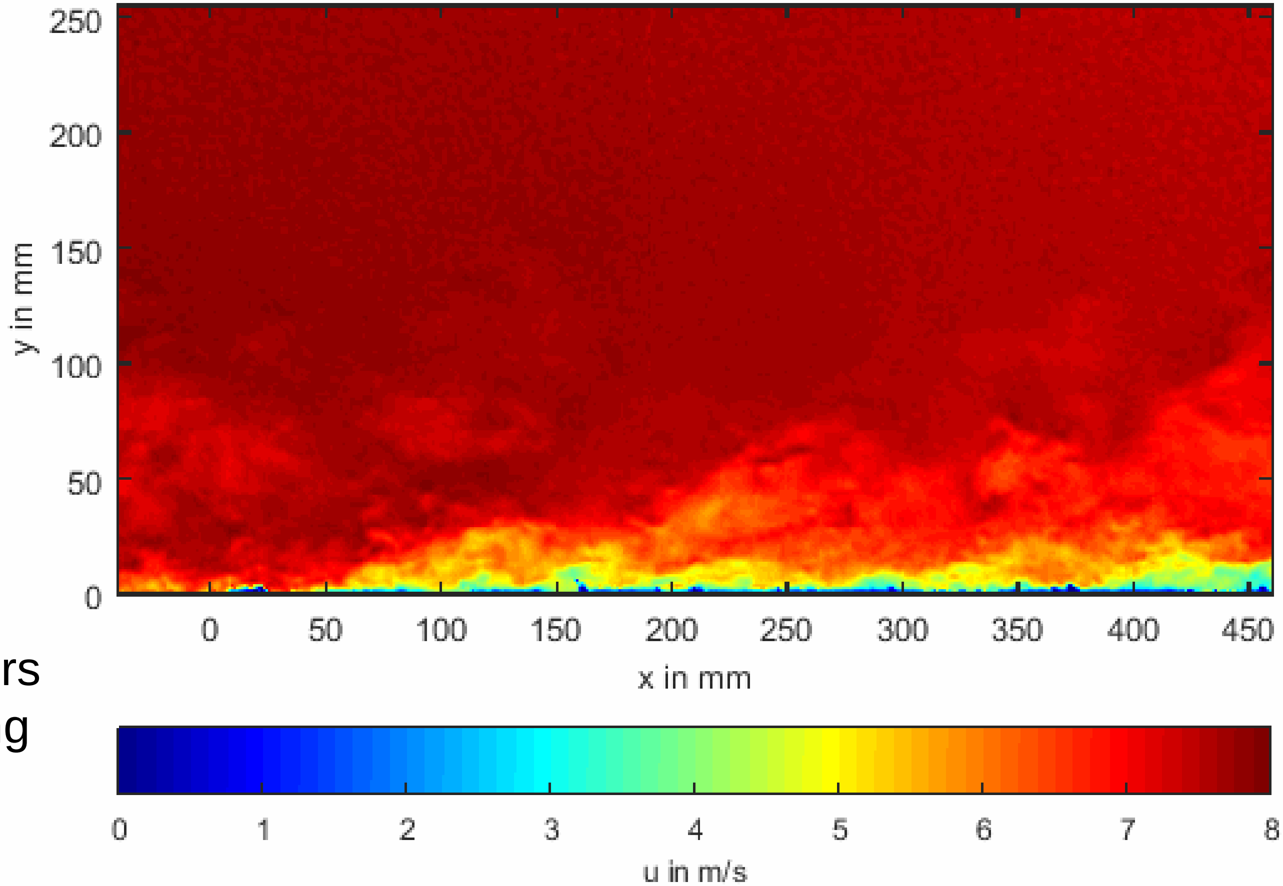
Light sheet generation

- 2x 200mJ @ 532nm
- laser at 10m distance
- 7500mm spherical lens
- -250mm cylinder lens



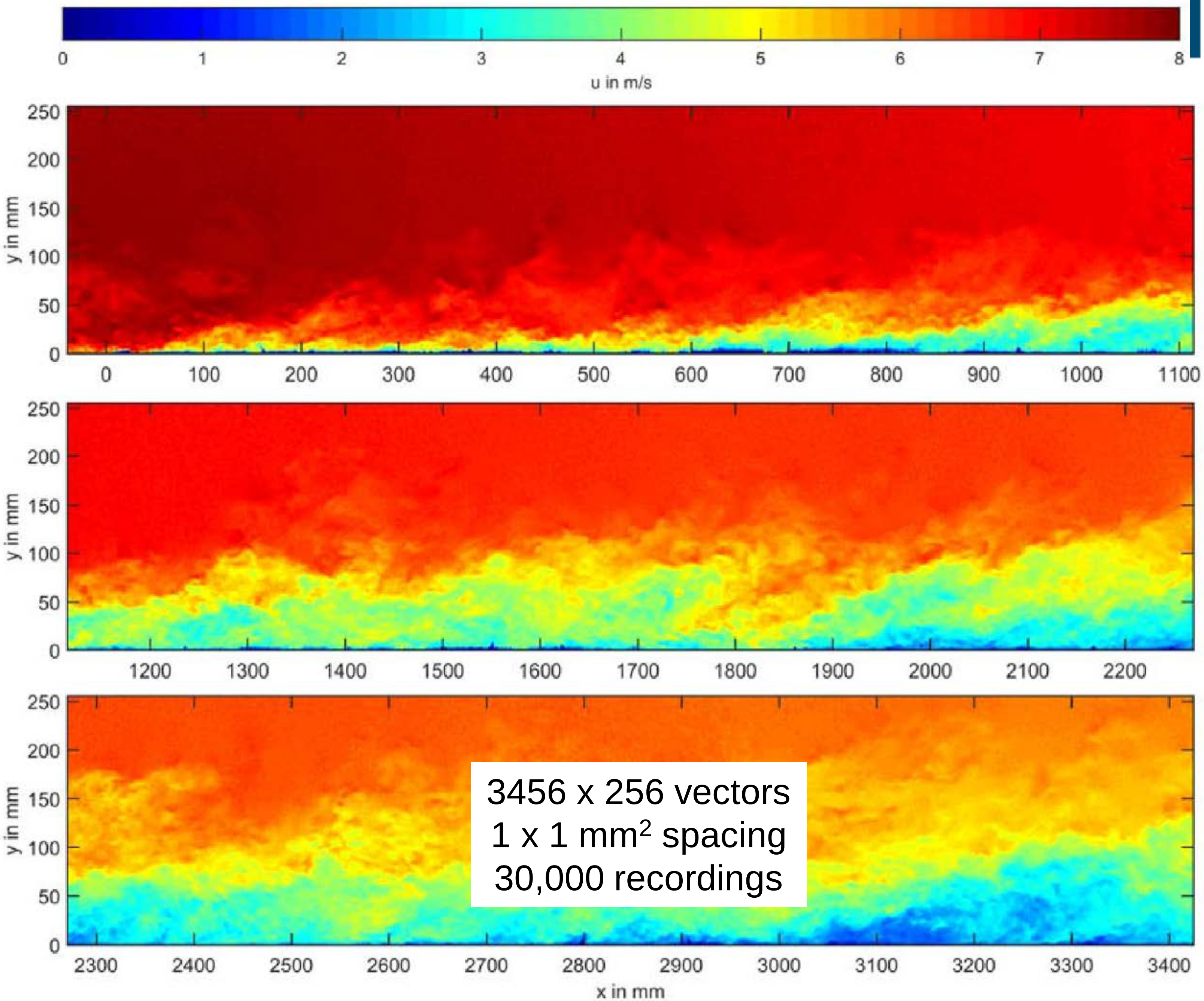
2C-2D Measurement of APG Region

Single PIV recording of 30,000 total samples

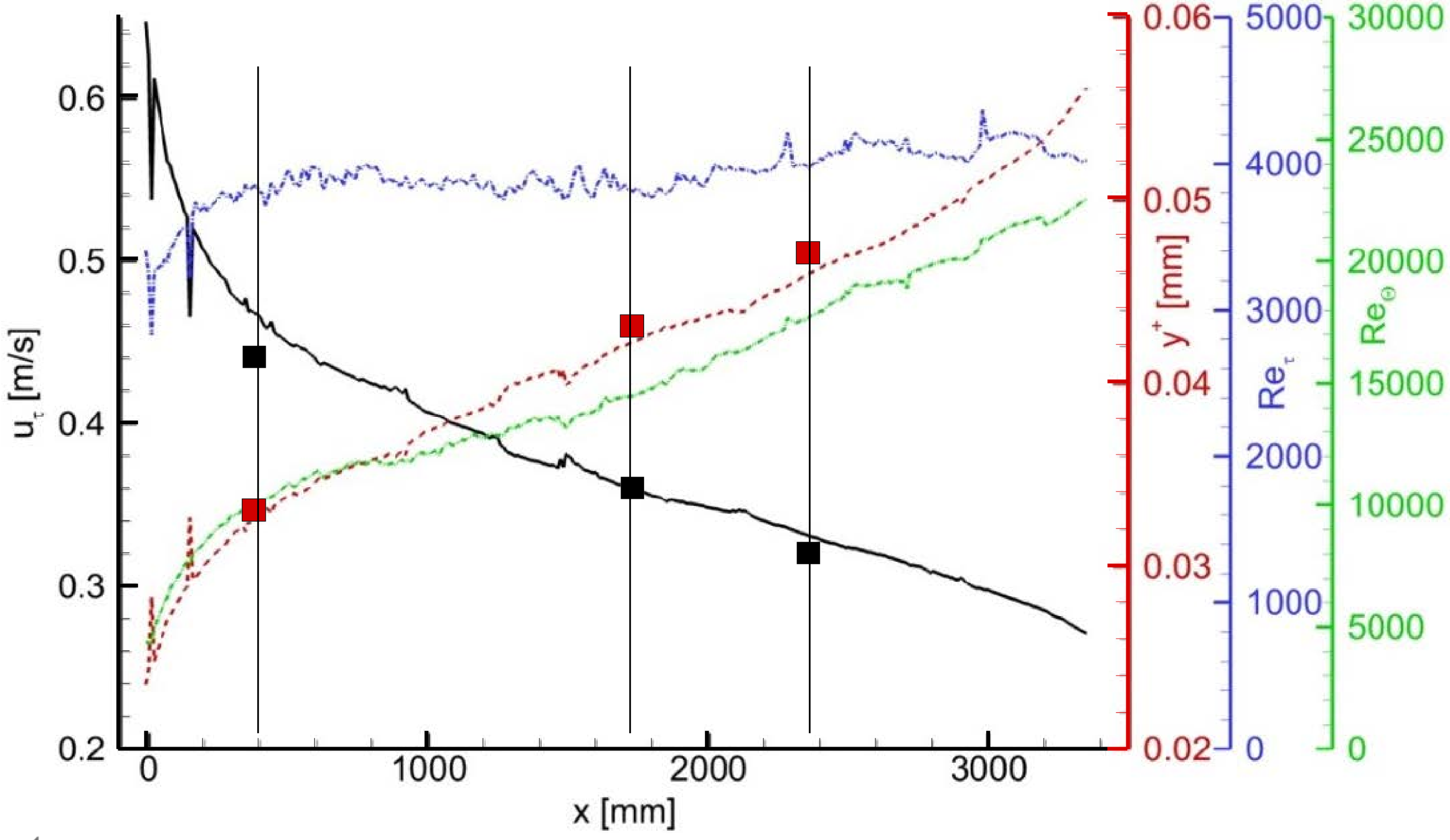


3456 x 256 vectors

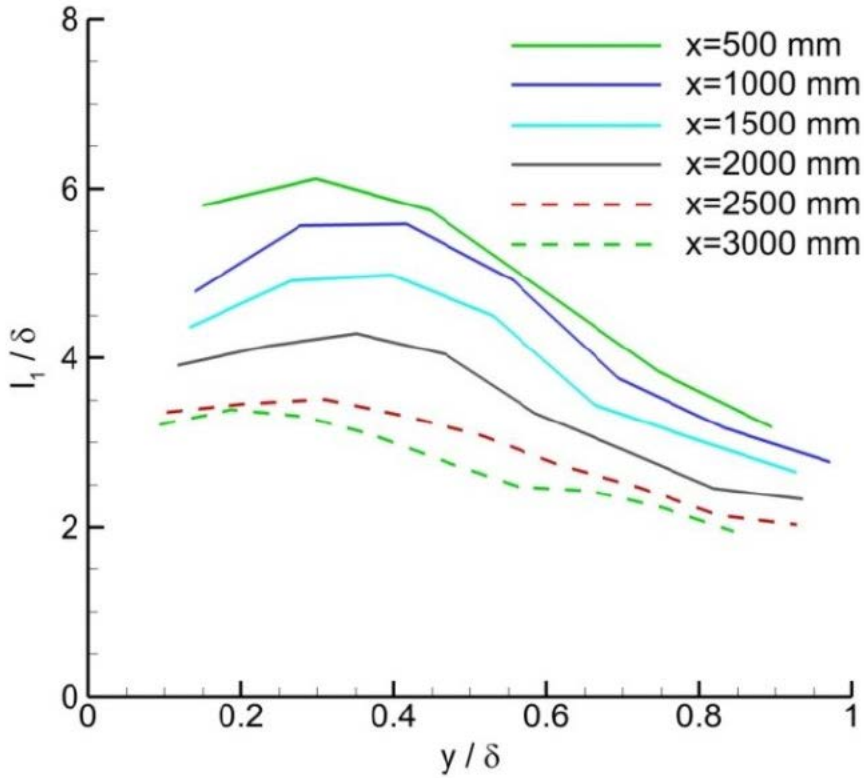
1 x 1 mm^2 spacing


0 1 2 3 4 5 6 7 8
u in m/s
y in mm
x in mm
3456 x 256 vectors
1 x 1 mm² spacing
30,000 recordings

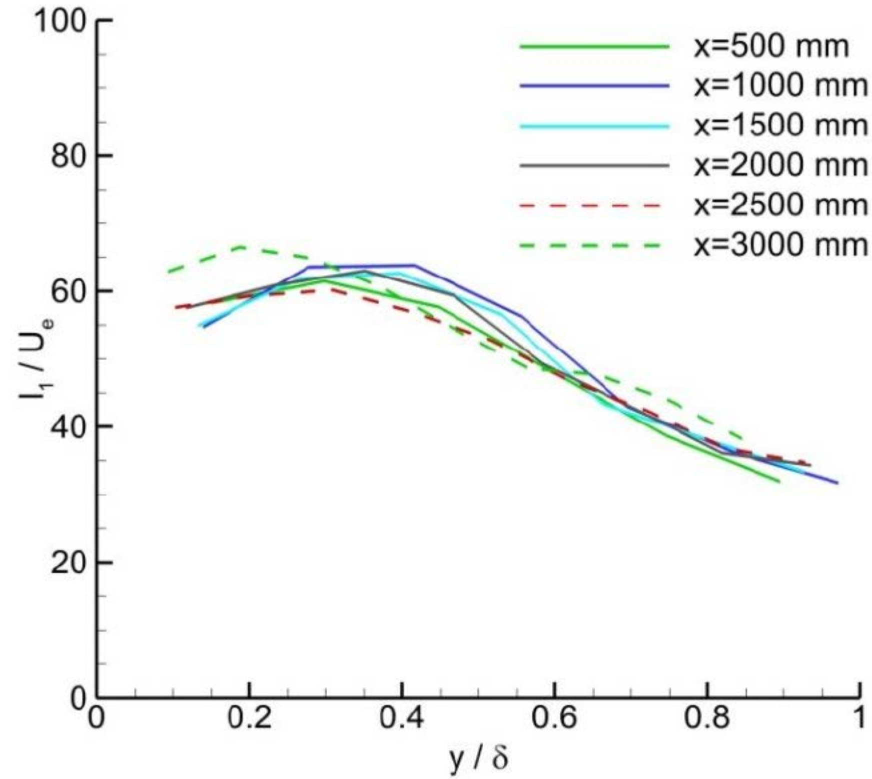
Boundary layer parameters for U_∞ = 9m/s



Two-point correlations of streamwise velocity *u*'
for C = 0.15 and U_∞ = 9 m/s



Length l_1 normalized with the local boundary layer thickness δ



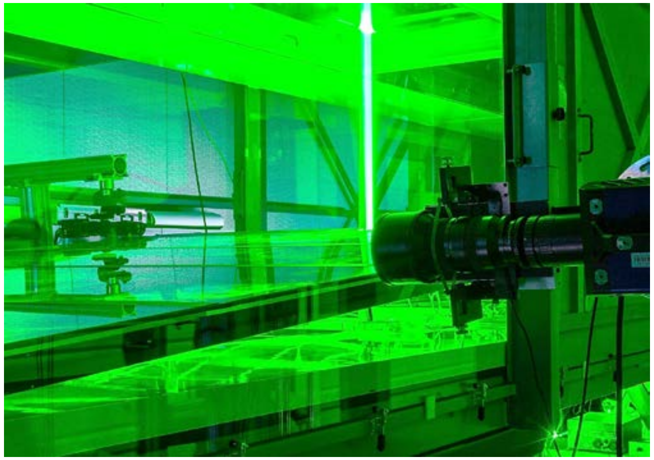
Length l_1 normalized with the edge velocity U_e

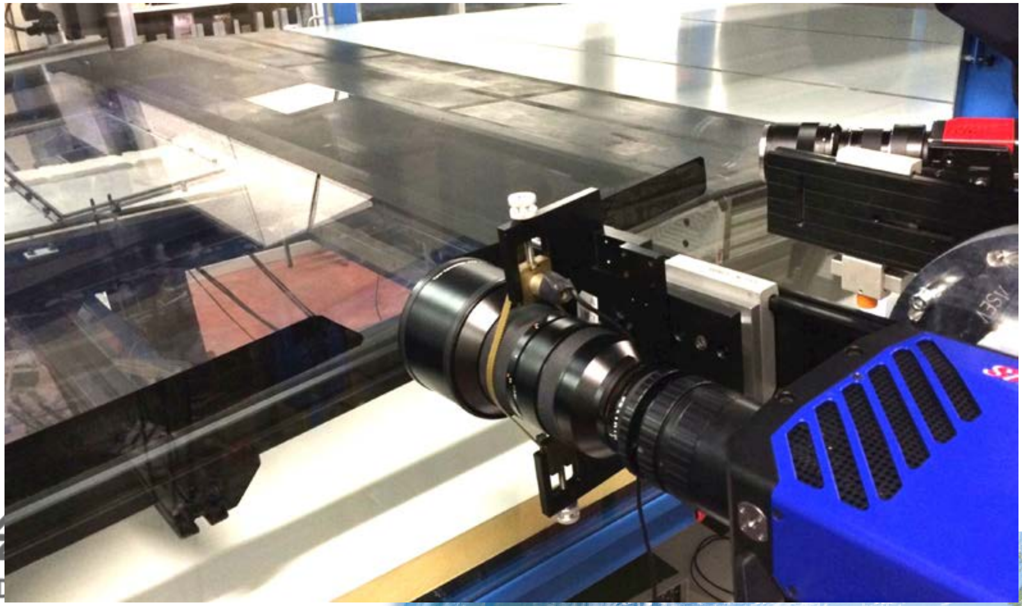
Long-range microscopy and high-speed PIV

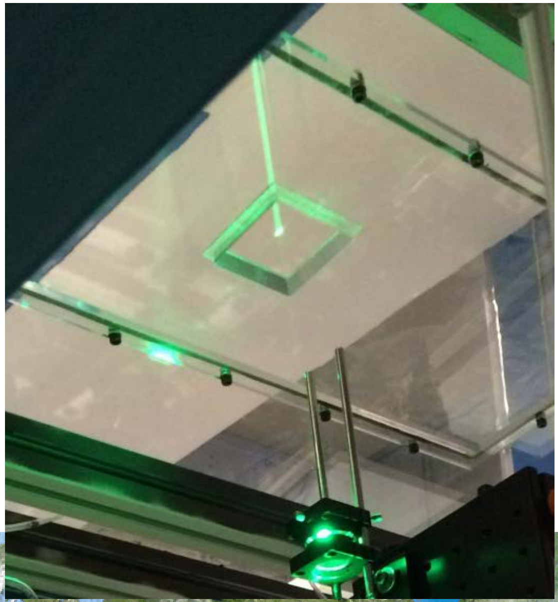
→ wall-shear stress and near wall statistics

~ 1m working distance
(Zeiss ApoTessar 300mm/2.8 lens)
→ m = 0.44 (~25 µm/Pixel) → (> 1y^+ / Pixel)

Camera: PCO Dimax-S4, 36GB
→ up 503,000 images per run (178x288 pixels)

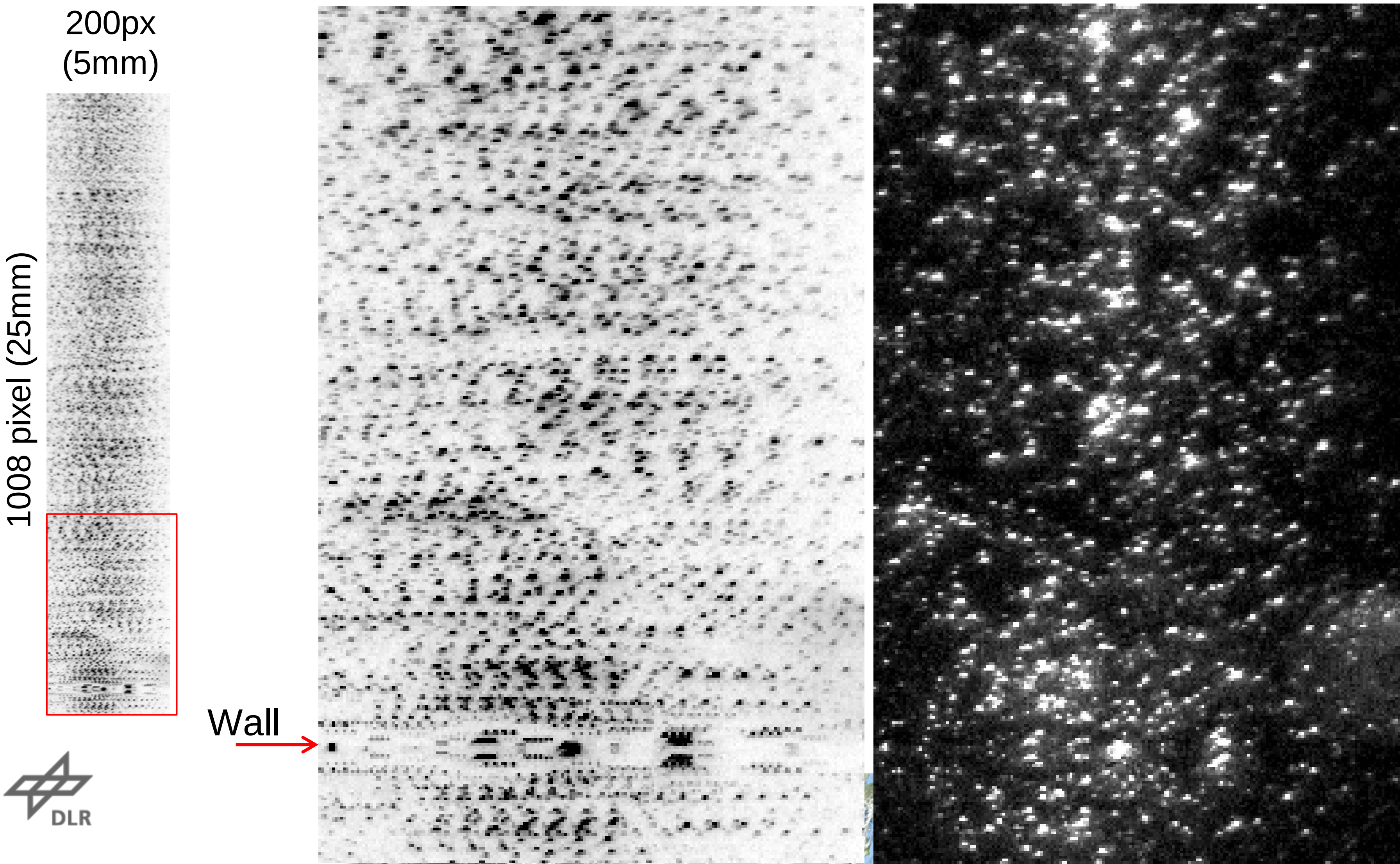






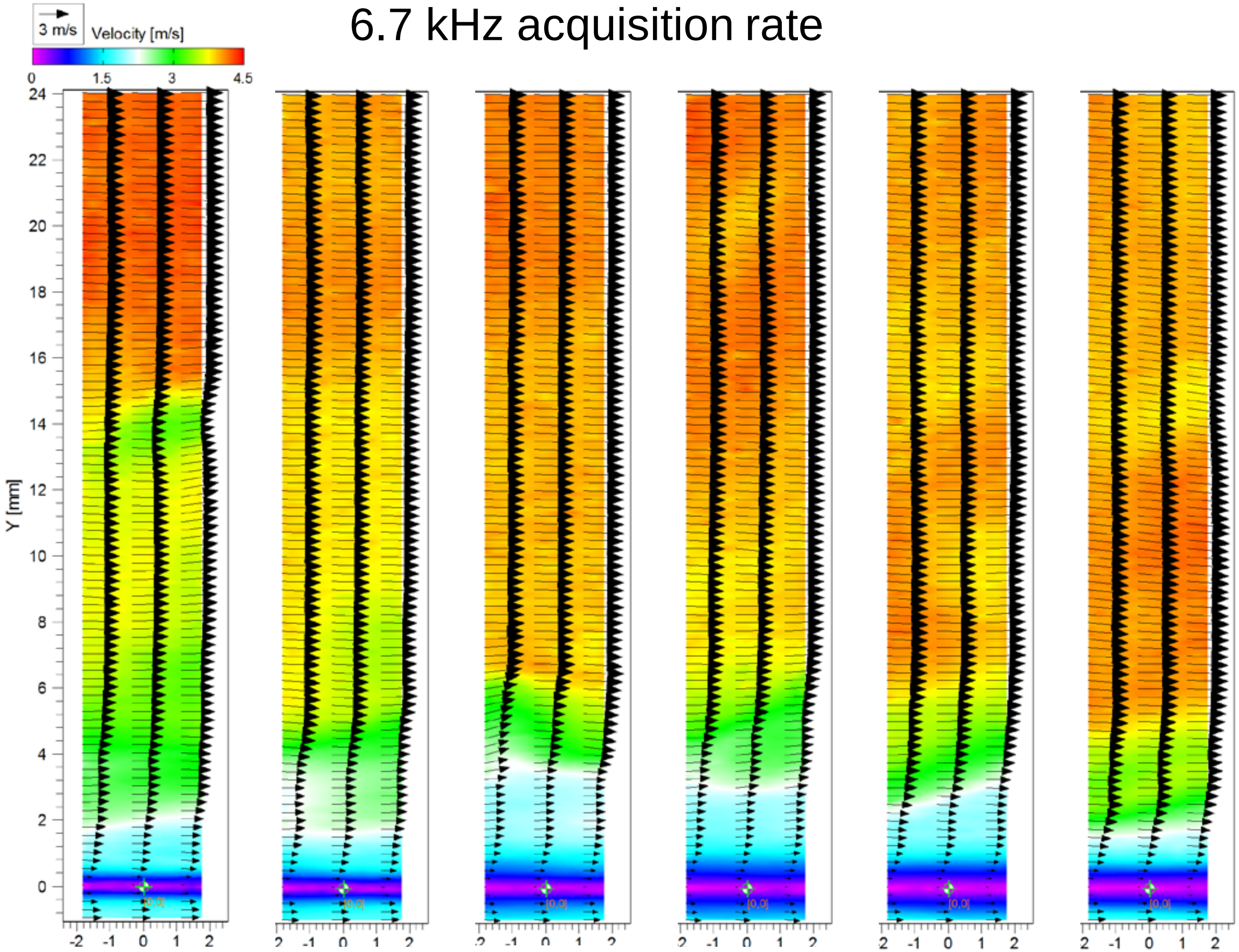
Position 0 – Upstream of model, U_∞ = 5 m/s

6.7 kHz acquisition rate (Δt = 150µs) 125,000 images (~19 s)



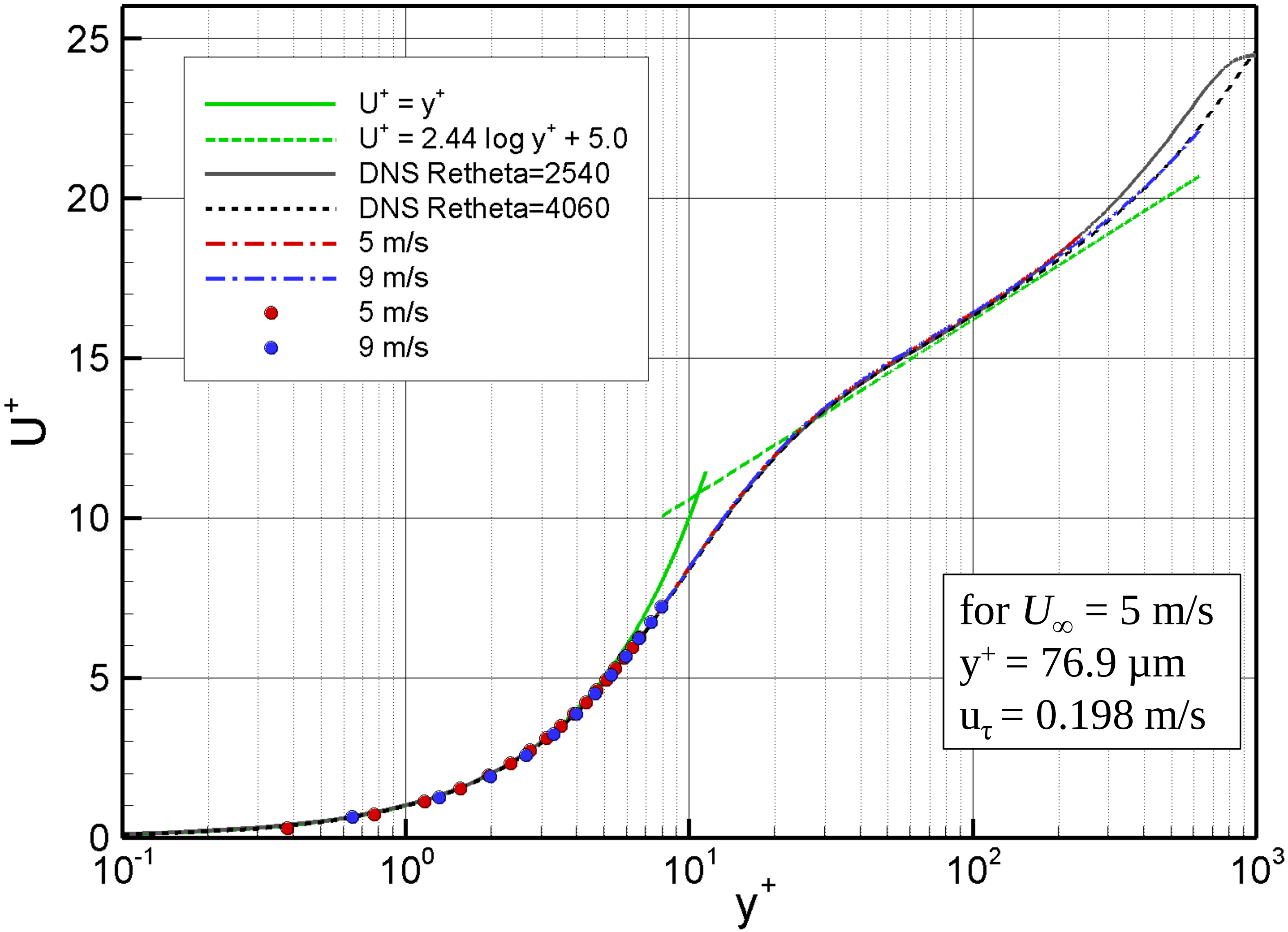
Single snapshots of time resolved profile data

6.7 kHz acquisition rate

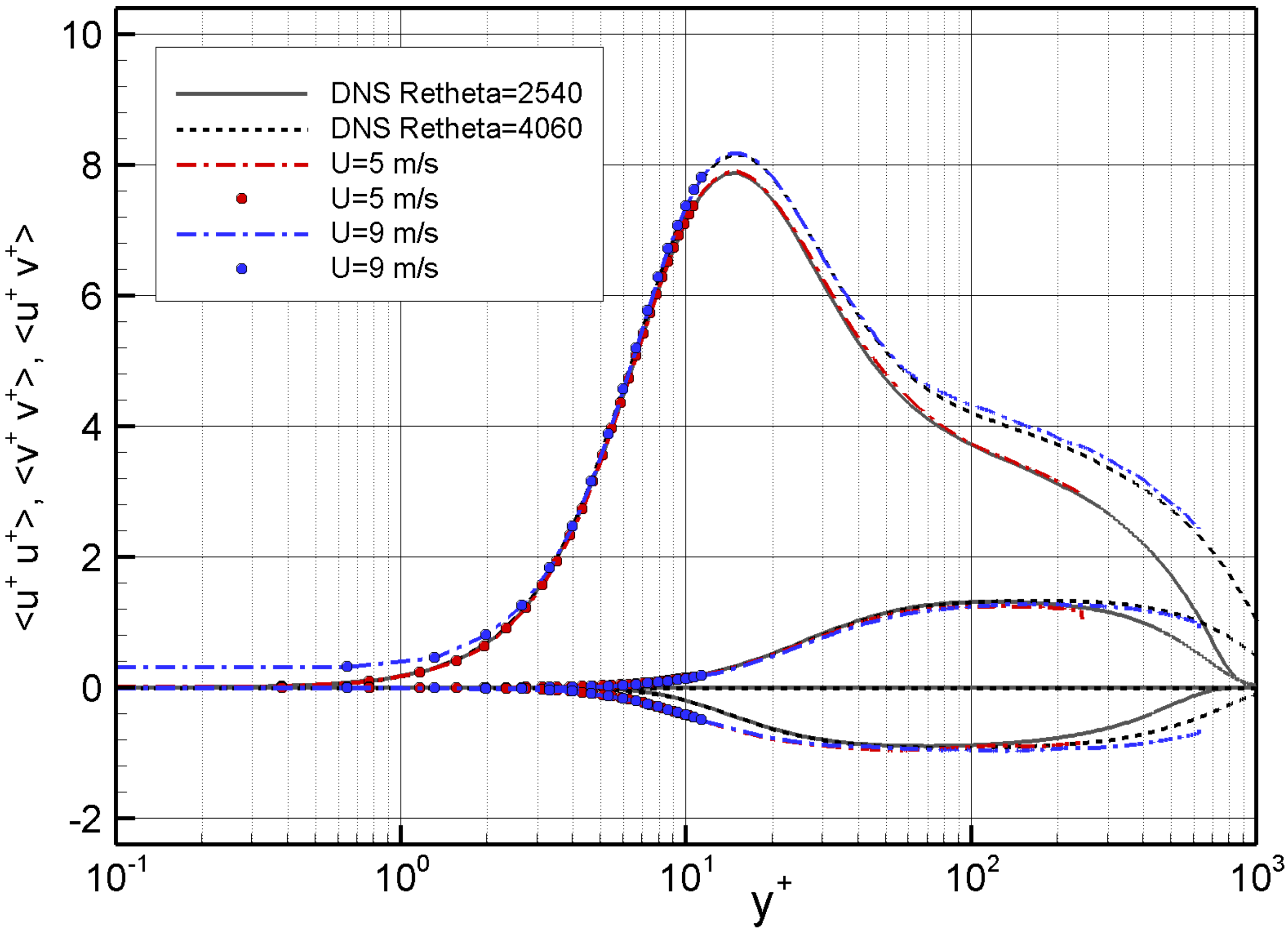


t_0 t_0+1.5ms t_0+3.0ms t_0+4.5ms t_0+6.0ms t_0+7.5ms

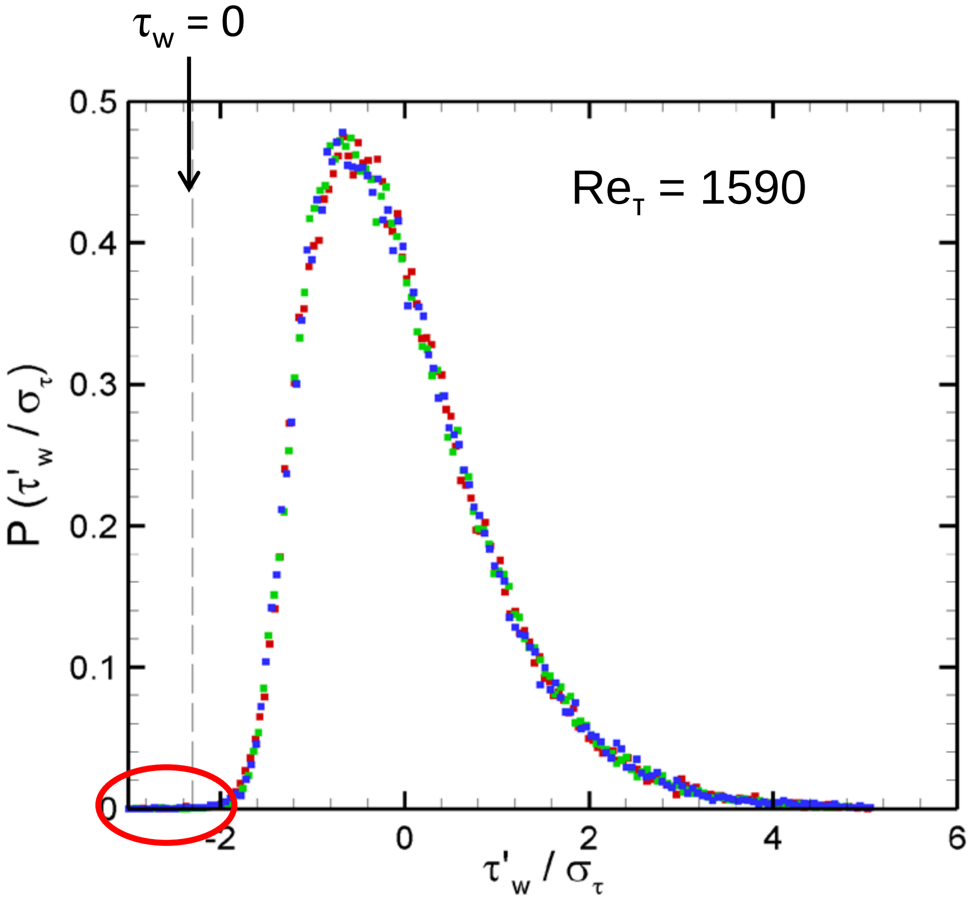
Mean velocity profiles upstream of model



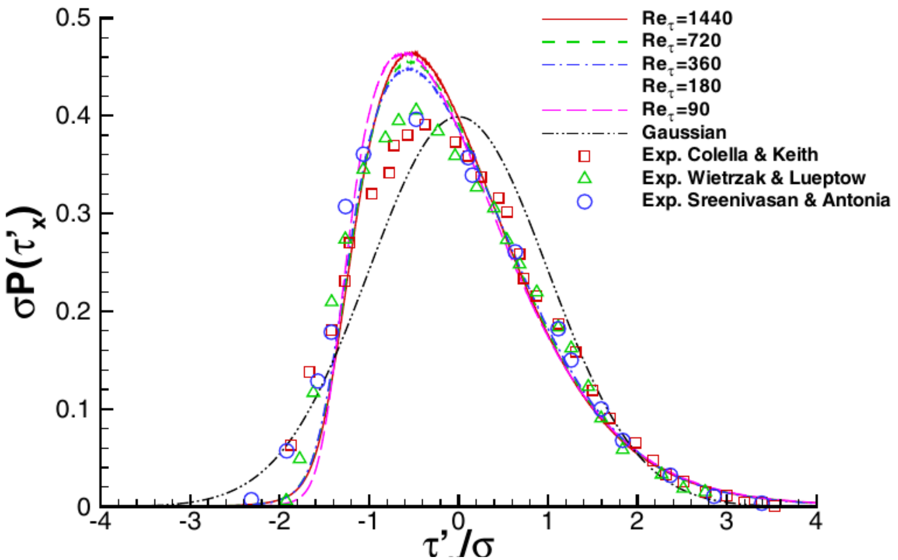
Reynolds Stresses upstream of model

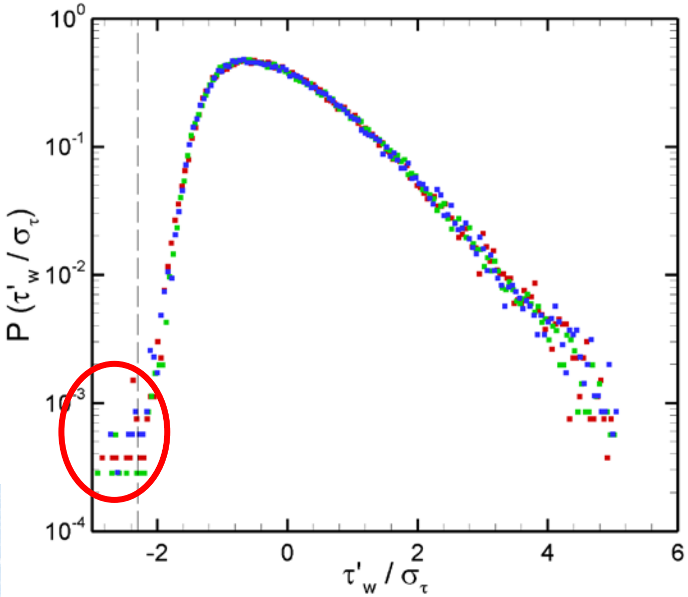


PDF of Wall-Shear Stress



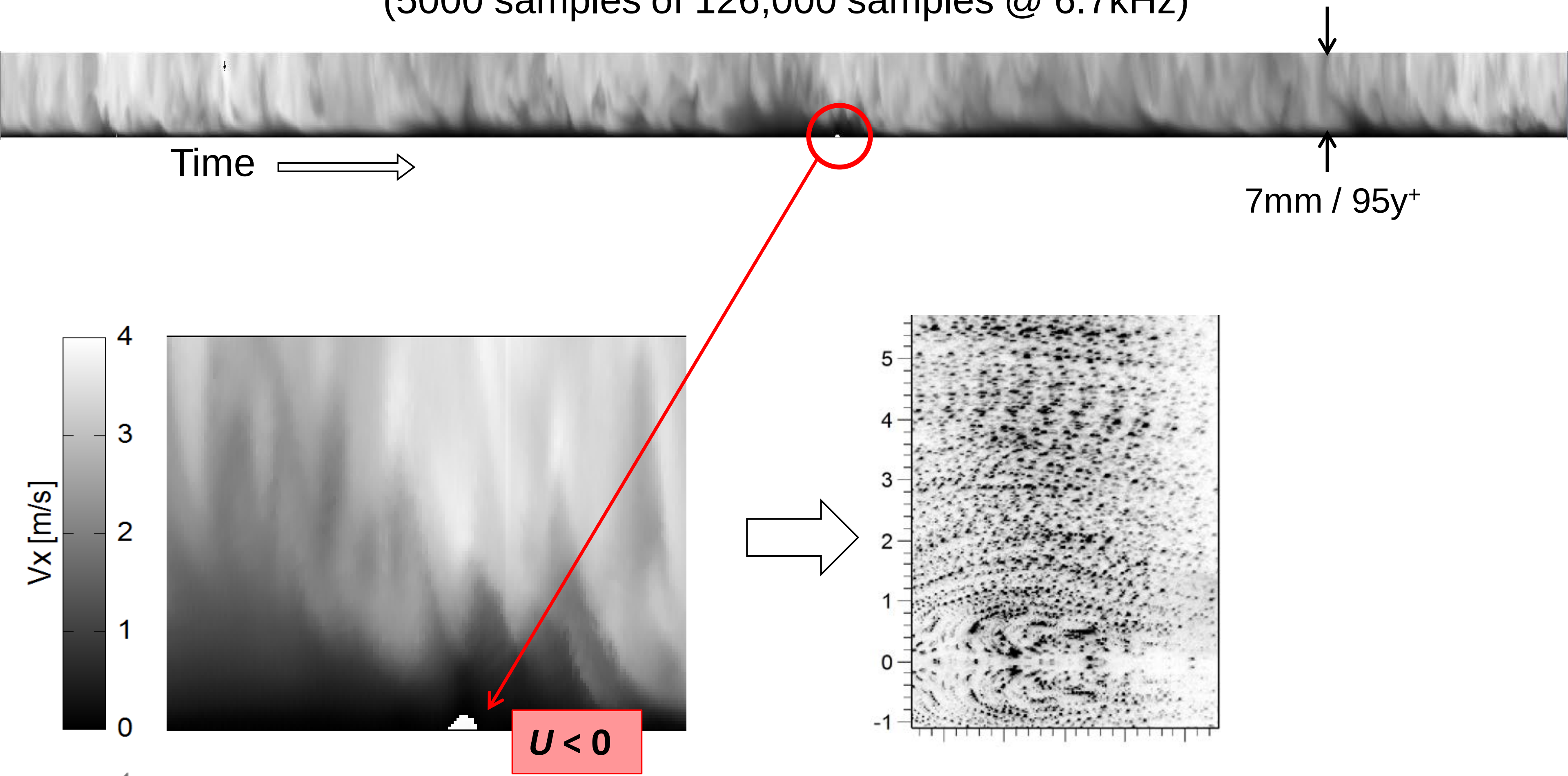
Hu, Morfey & Sandham, AIAA J 44(7) 2006



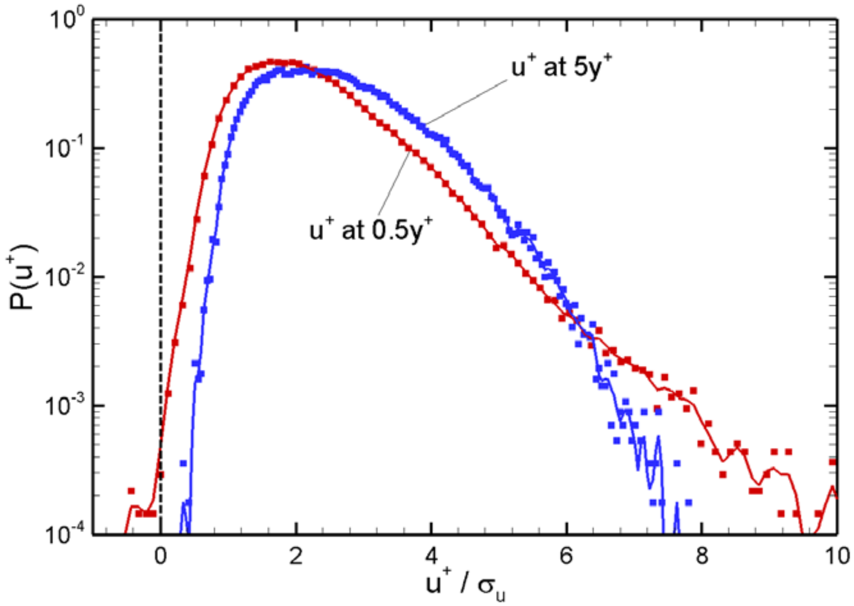


Evidence of rare back-flow events (ZPG Turb-BL)

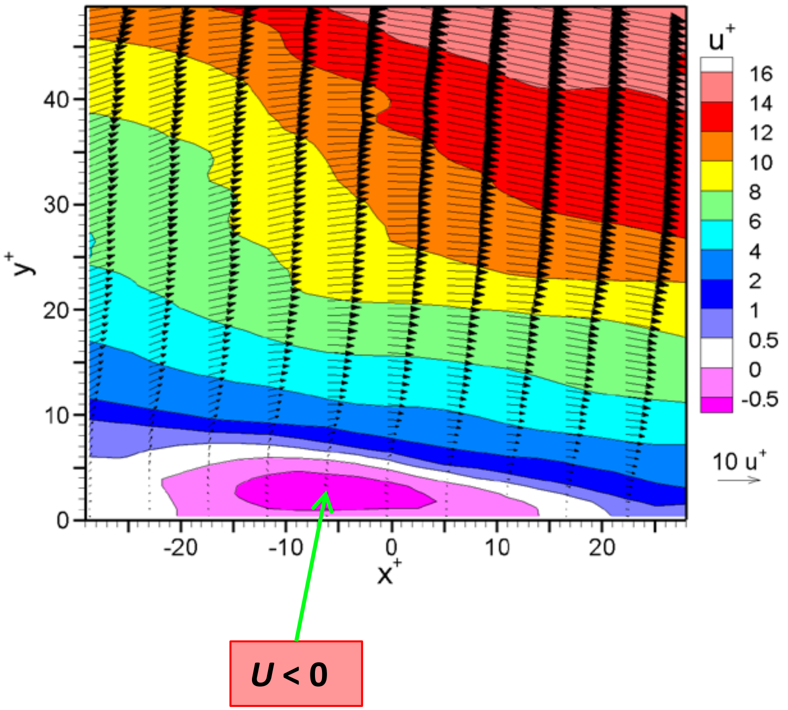
Time-trace of wall-normal profile of streamwise velocity U
(5000 samples of 126,000 samples @ 6.7kHz)



Evidence of rare back-flow events



Probability density functions of streamwise velocity u^+ at wall distances of $0.5y^+$ and $5y^+$ (Re_τ = 1070, U_∞= 5m/s)



Good agreement with DNS reported in:
Lenaers, P., Li, Q., Brethouwer, G., Schlatter, P., Örlü, R. (2012): Rare backflow and extreme wall-normal velocity fluctuations in near-wall turbulence. Phys. Fluids **24**, 035110

Events ~5-10x more frequent in APG region (detailed investigation pending)

Summary

- Large data base of a turbulent boundary layer with adverse pressure gradient has been acquired with high spatial resolution
  - raw data >25TByte
  - Re_θ up to 20,000
  - spatial resolution 1x1mm^2
  - time-resolved velocity near-wall profiles with resolution O(y^+)
- Initial PIV processing completed
- Data to be archived on / provided by CINECA servers (Italy)
- Ongoing analysis:
  - two-point correlations $R(u_\tau, u'_i)$
  - joint PDFs of velocity components
  - …

- Funding provided through EuHIT – *European High performance Infrastructures in Turbulence*

DLR

Thank you for your attention