Measurements of the Near-Wall Region of Pipe Flow at High Reynolds Numbers

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DLR

Outline

- Project aims
- Background on facility
- Implementation of high-speed PIV on facility
- Sample results

- Outlook – including recent developments in high-speed PIV

Motivation

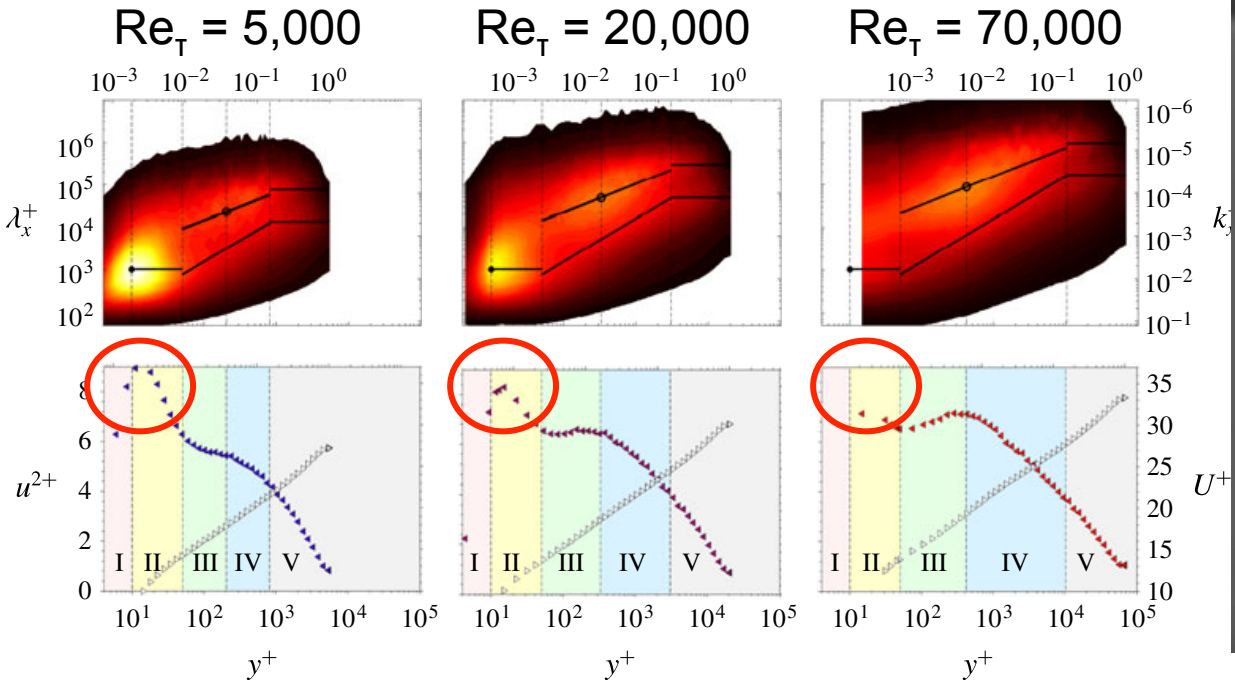
- near wall flow structure of pipe flow so far has not been characterized through measurements, mainly due to finite size of probes
- for high-Re hotwire data is only available for wall distances $y > 20^+$ (*SuperPipe* Princeton)
- DNS only available at low Reynolds numbers
  for pipe flows ($Re_{\tau,max} \leq 1050$, Satake *et al* 2000),
  for channel flow $Re_{\tau,max} = 2000$ (Jimenez *et al.*, 2006)
- DNS difficult to perform using spectral methods due to singularity at center of pipe.
- CICLoPE facility offers combination of high Reynolds number and viscous scales that can be experimentally captured
  → application of PIV becomes possible
- Also: proof-of-concept for planned PIV measurements on inter-compressor-duct in CleanSky2 Project 2-Shaft-Compressor

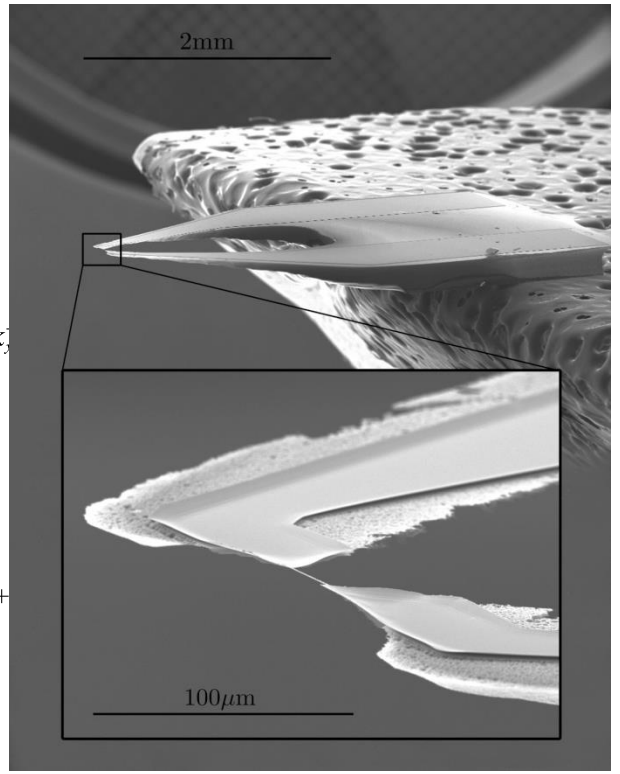
CICLoPE = **C**enter for **I**nternational **C**ooperation in **Lo**ng **P**ipe **E**xperiments
www.ciclope.unibo.it

Existing data / literature

Vallikivi et al. JFM, 2015

Data from Princeton's Super-Pipe Facility using NanoProbe



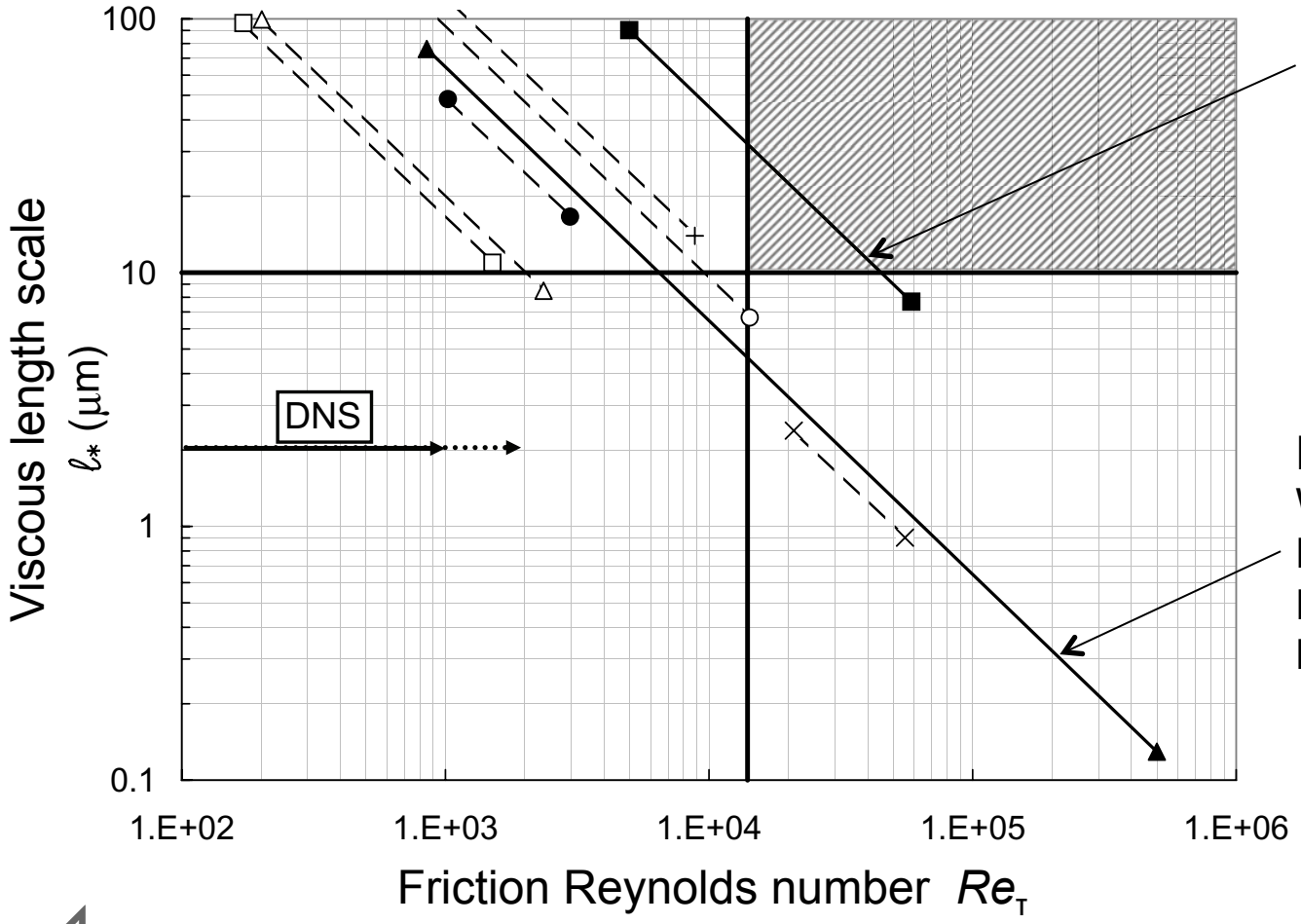


30 µm NSTAP probe

FIGURE 15. Contour plots of spectra in the pipe at $Re_\tau = 5 \times 10^3$, 20×10^3 and 70×10^3. Lines show trends in the loci of peaks shown in figures 8 and 9; (dashed lines), $y^+ = 10$, 67, y^+_{OSP}, $0.15Re_\tau$; ●, location of near-wall spectral peak; ○, location of outer spectral peak.

Re$_T$ = 40000 → effective probe size 35 ℓ^+

Reynolds number range for various facilities



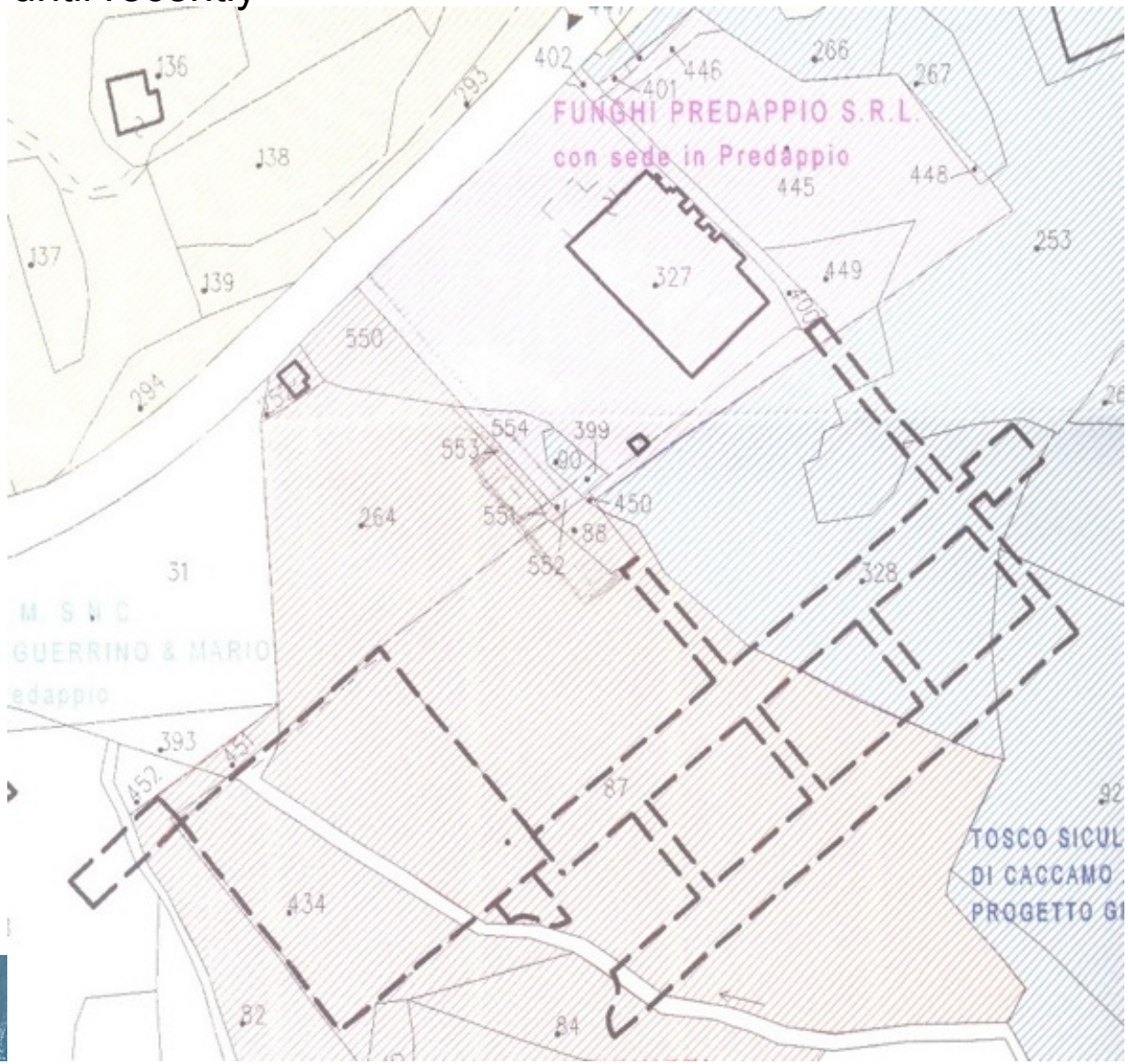
CICLoPE
Working: fluid air
Pressure: ambient
Diameter: 900 mm
Length: 110m (122D)

Princeton *Super-Pipe*
Working: fluid air
Pressure: up to 200 bar
Diameter: 129 mm
Length: 26m (202D)

Blick von Predappio Alta

Caproni tunnel complex

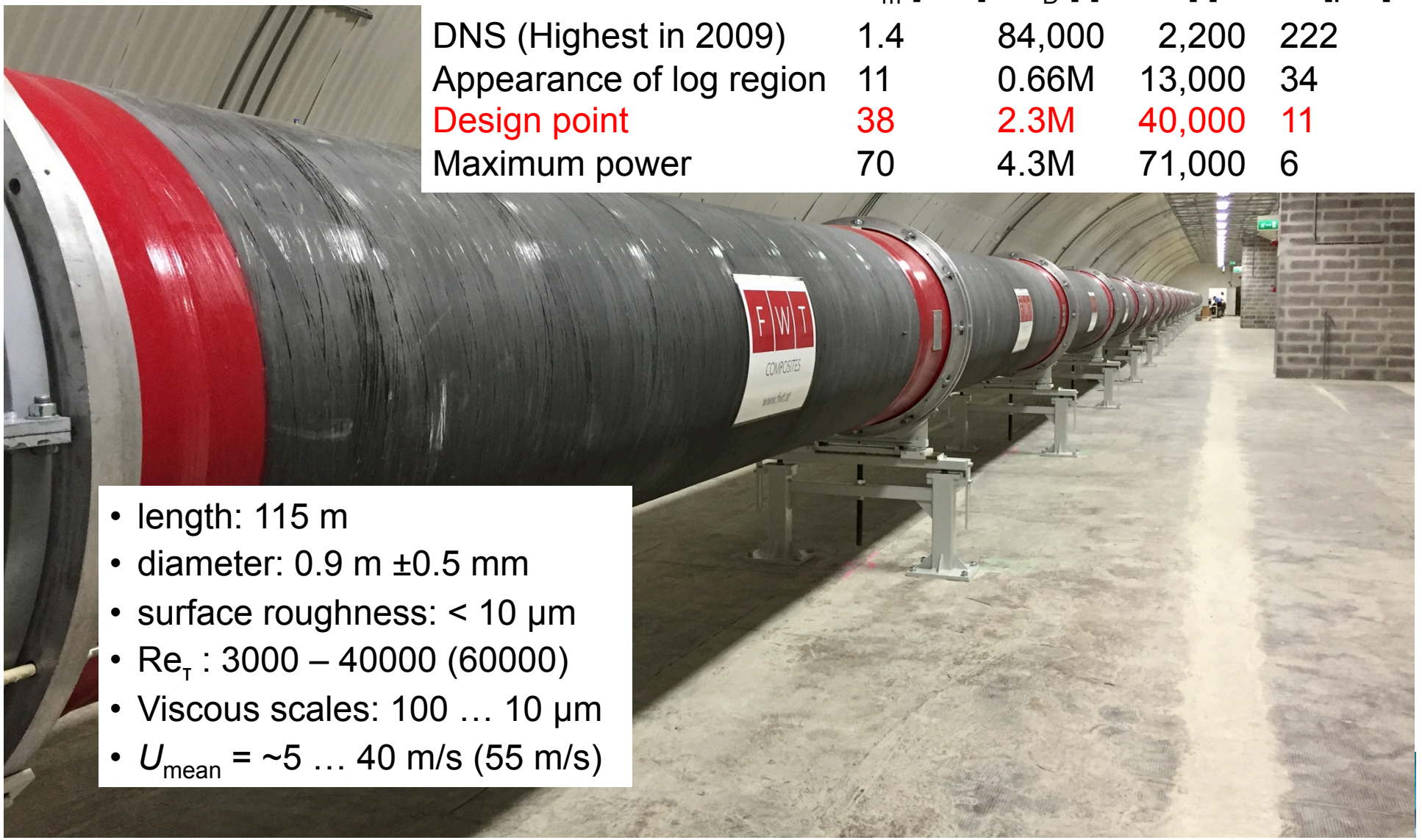
used for Mushroom farming until recently



After the removing the mushrooms…

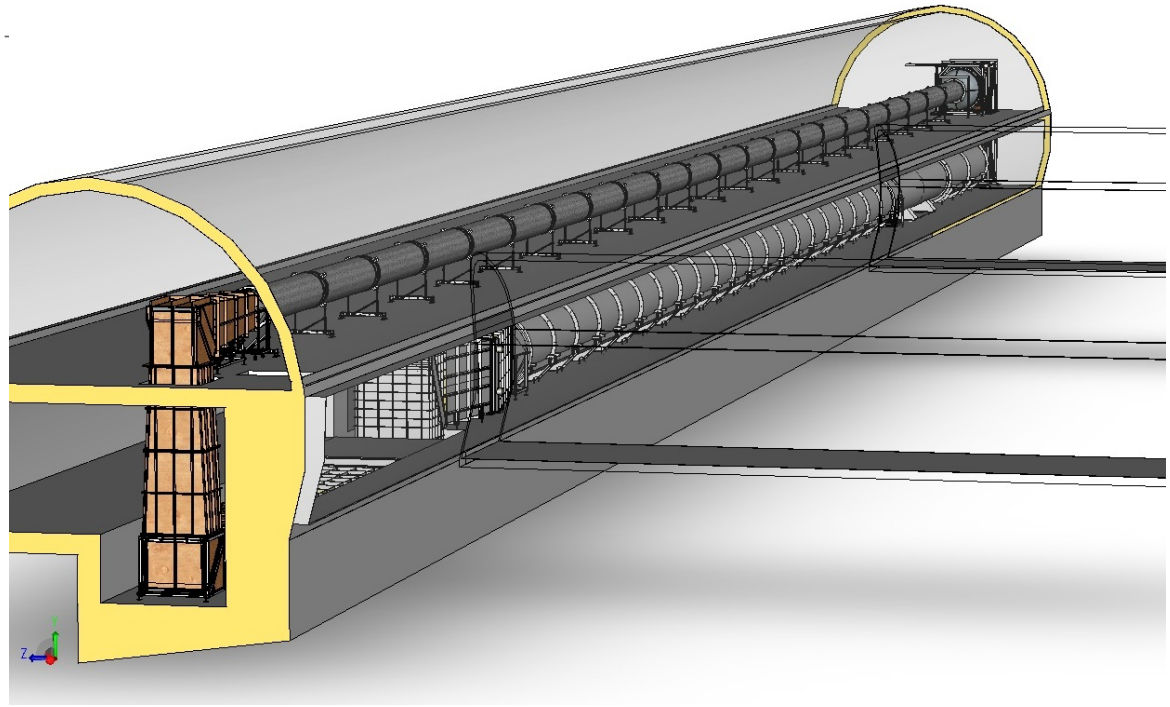
CICLoPE Facility

Conditions	U_m [m/s]	Re_D [-]	R^+ [-]	L^* [µm]
DNS (Highest in 2009)	1.4	84,000	2,200	222
Appearance of log region	11	0.66M	13,000	34
Design point	38	2.3M	40,000	11
Maximum power	70	4.3M	71,000	6



- length: 115 m
- diameter: 0.9 m ±0.5 mm
- surface roughness: < 10 µm
- Re_τ : 3000 – 40000 (60000)
- Viscous scales: 100 … 10 µm
- U_{mean} = ~5 … 40 m/s (55 m/s)

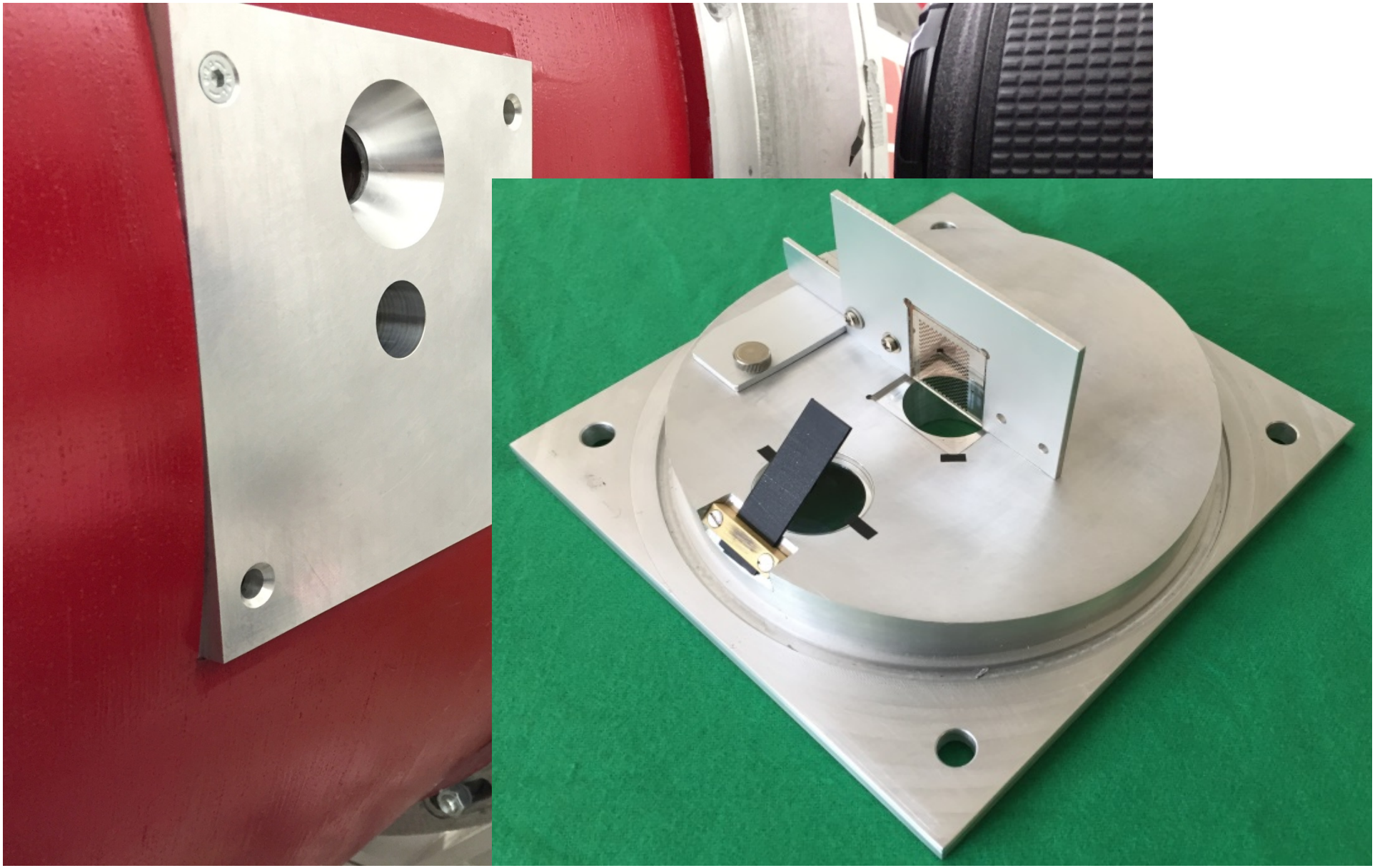
CICLoPE Facility



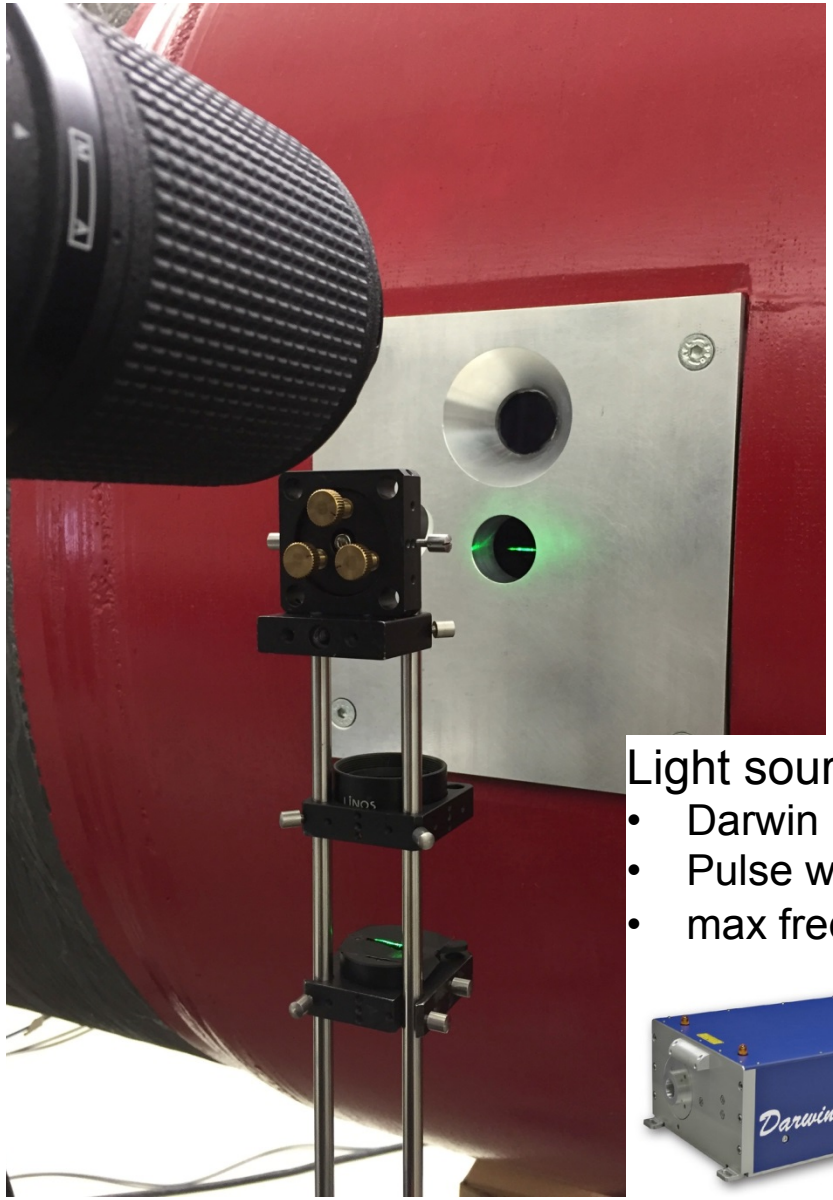
Flow conditioning and contraction

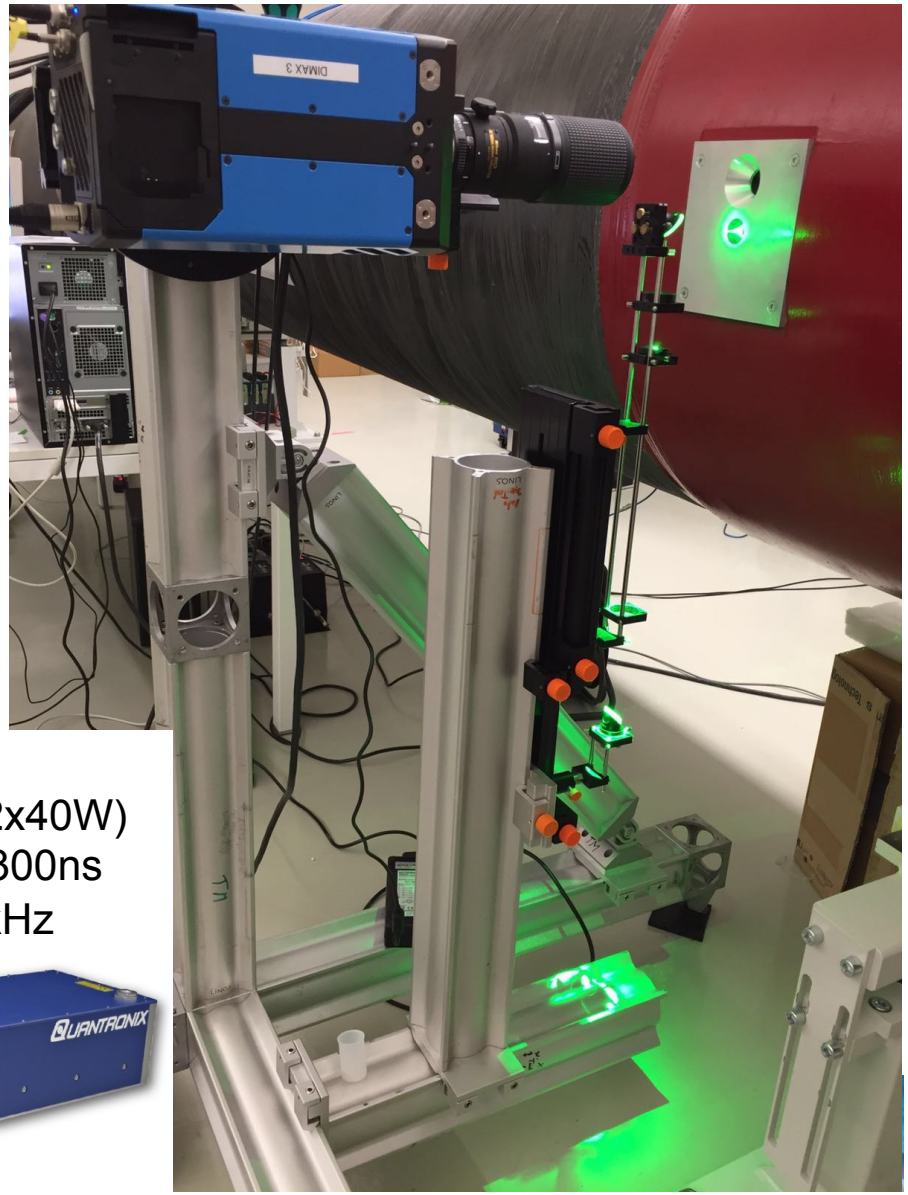
Return duct

Measurement insert



Aufbau für Wandnahe PIV Messungen

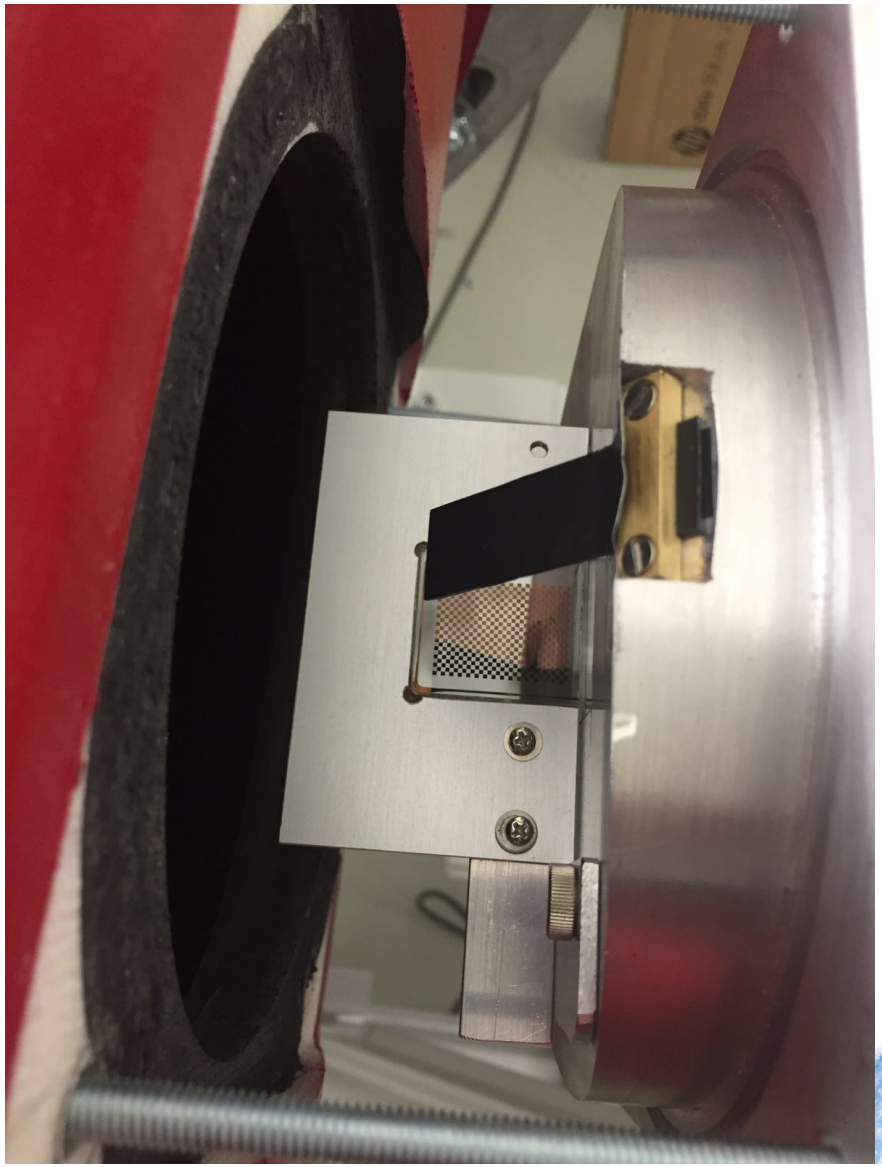


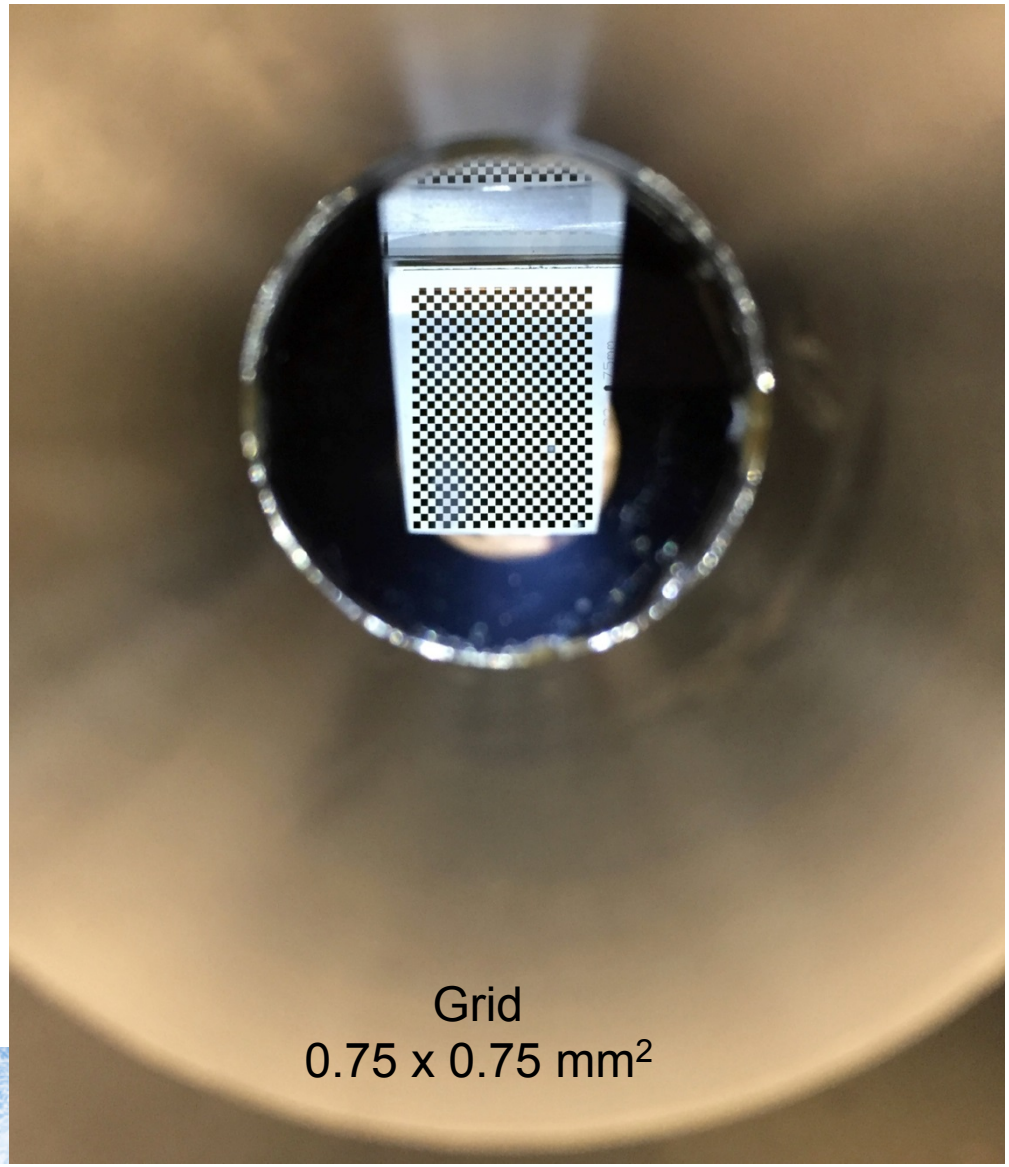


Light source:

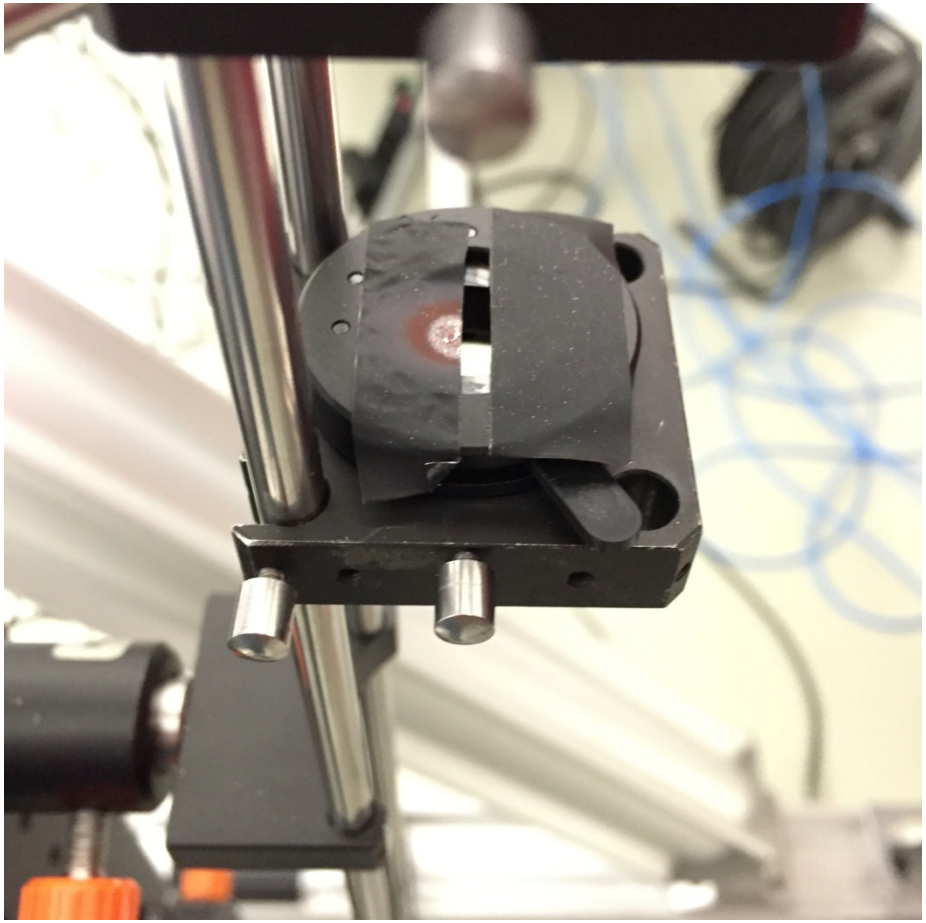
- Darwin Duo (2x40W)
- Pulse width ~300ns
- max freq. 10 kHz

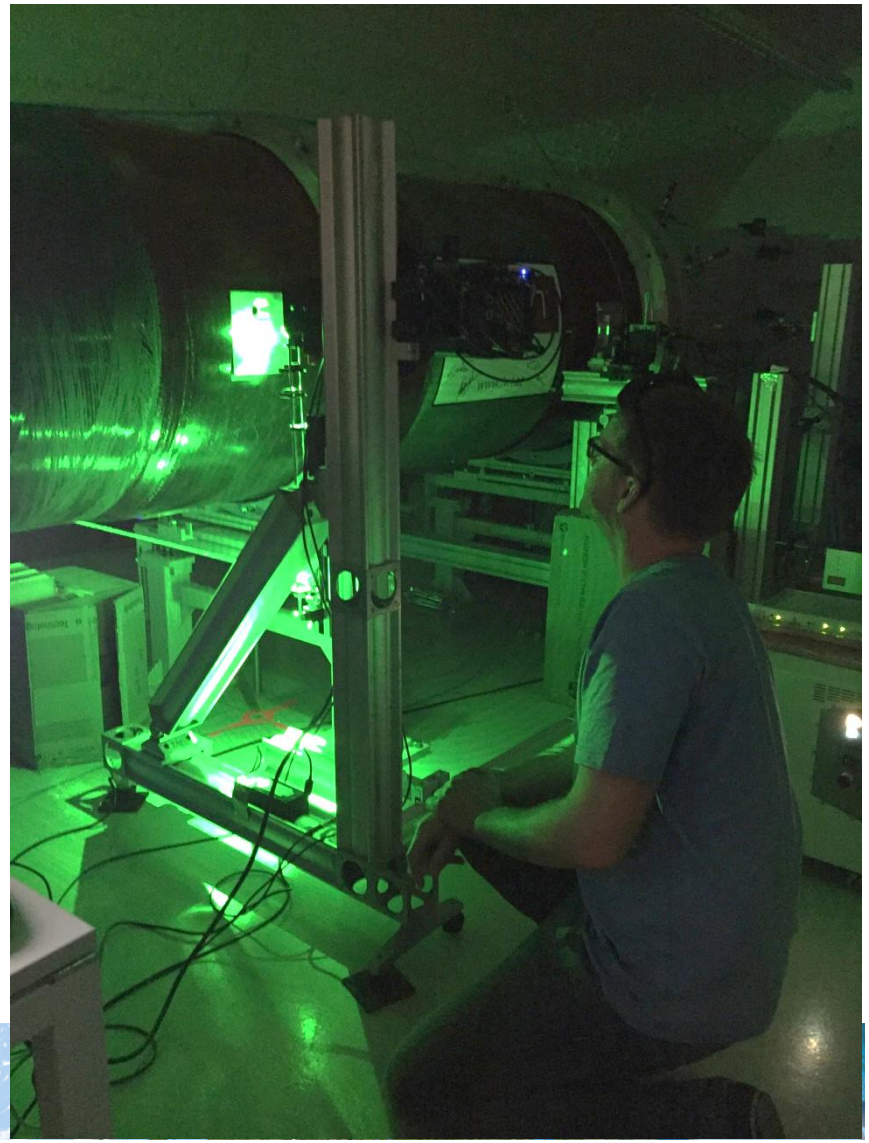
Calibration target





Up to 25W of laser power…

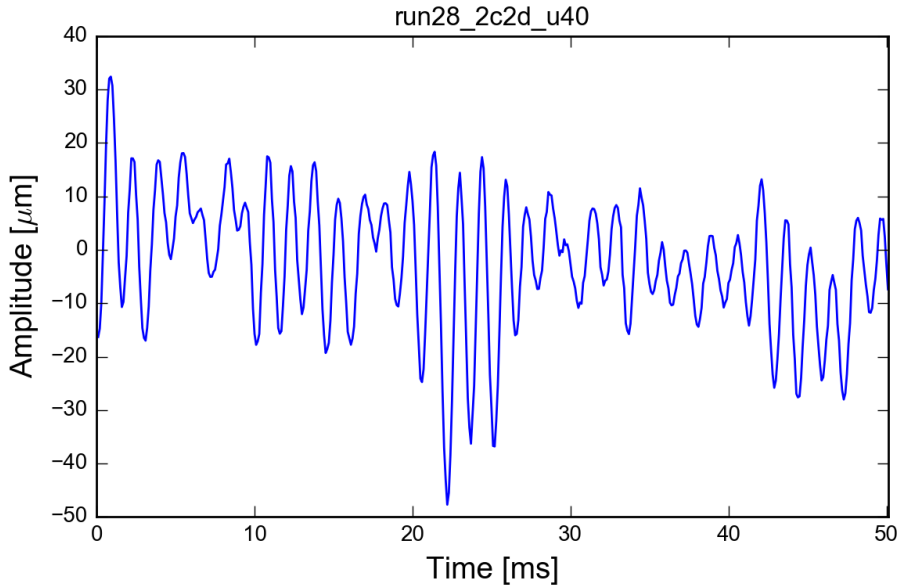


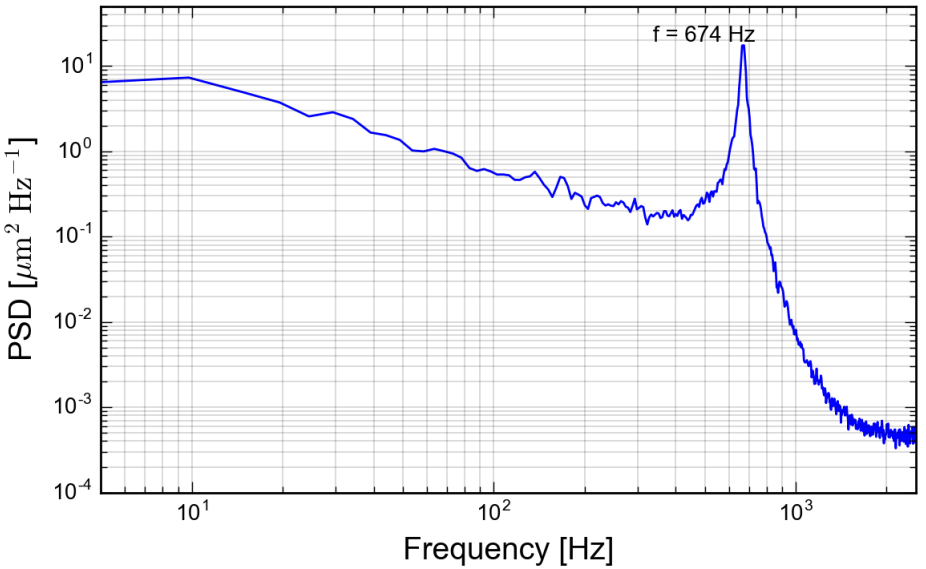


Seeding

Vibrations

- present at U ≥ 30 m/s
- tracked using correlation approach
- image shifting before PIV analysis





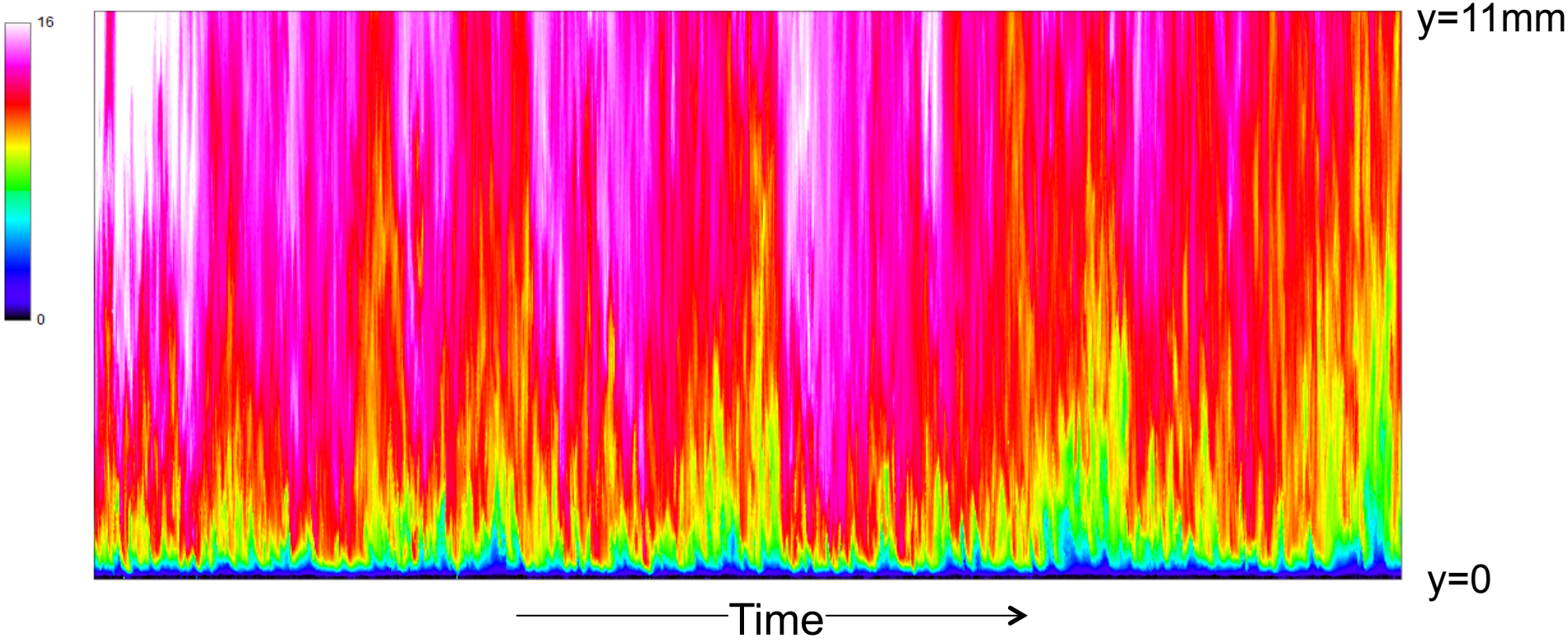
Acquired data

- 47 sequences of 48 GB each (ca. 2.2TB)
- acquisition frequency: 100 Hz to 10 kHz
- sequence length: 32,000 – 71,000 double images
- image size: 200 x 1008, 200 x 2016, 178 x 1008, 178 x 2016
- free stream velocities: 5, 10, 20, 30, 40 m/s
- magnification factor 1:1 (11µm / pixel)
- aperture $f_{\#}$ 8 – 11
- pulse separation 8 … 60 µs
- average laser power 0.7W – 24.2W (double pulses)

Time-record of stream-wise velocity profile

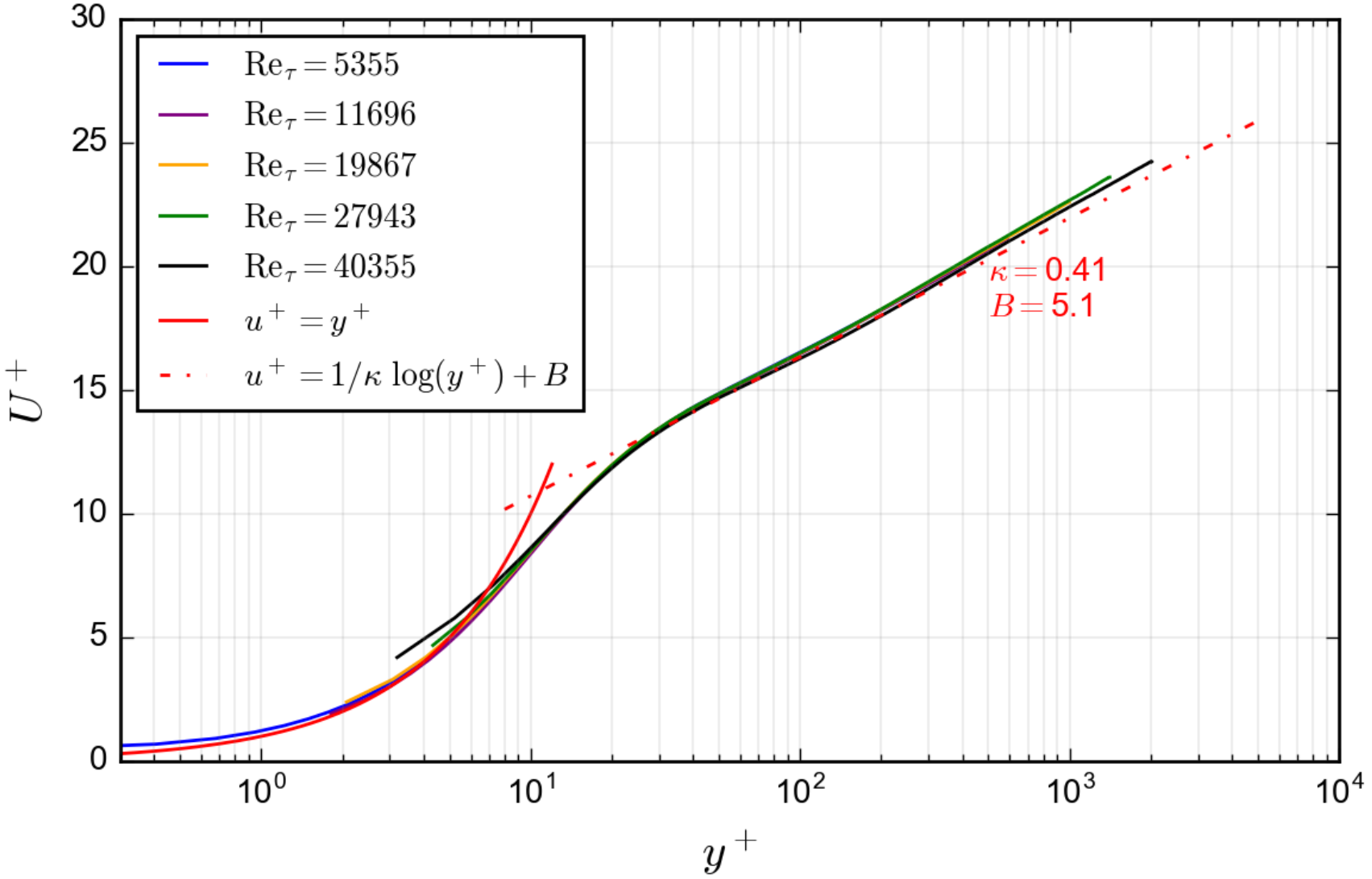
Re_T = 20,000

U_o = 22 m/s 1000 of 70000 samples 10 kHz sample rate

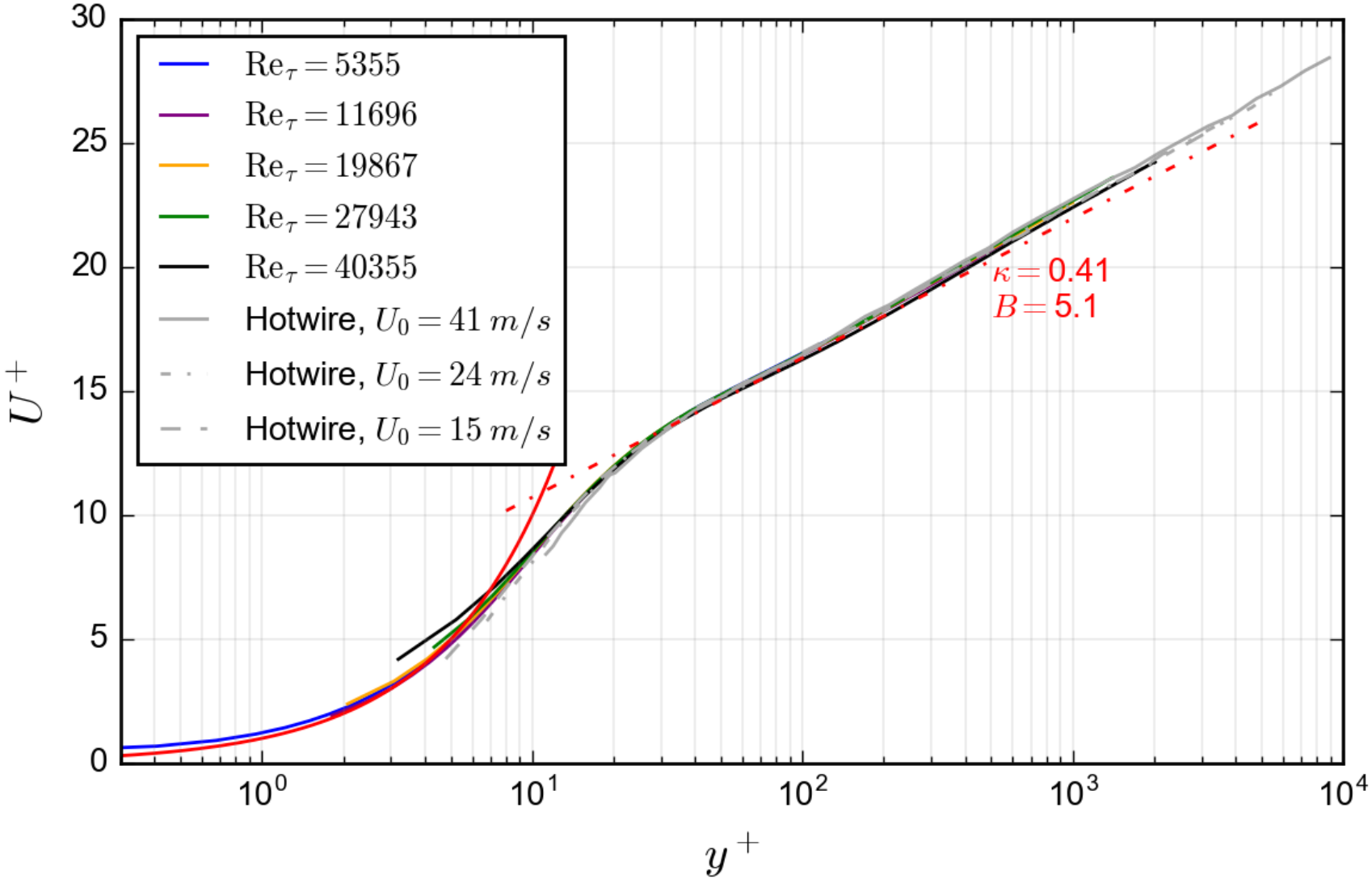


also have wall-normal velocity component (and vorticity ω_z)

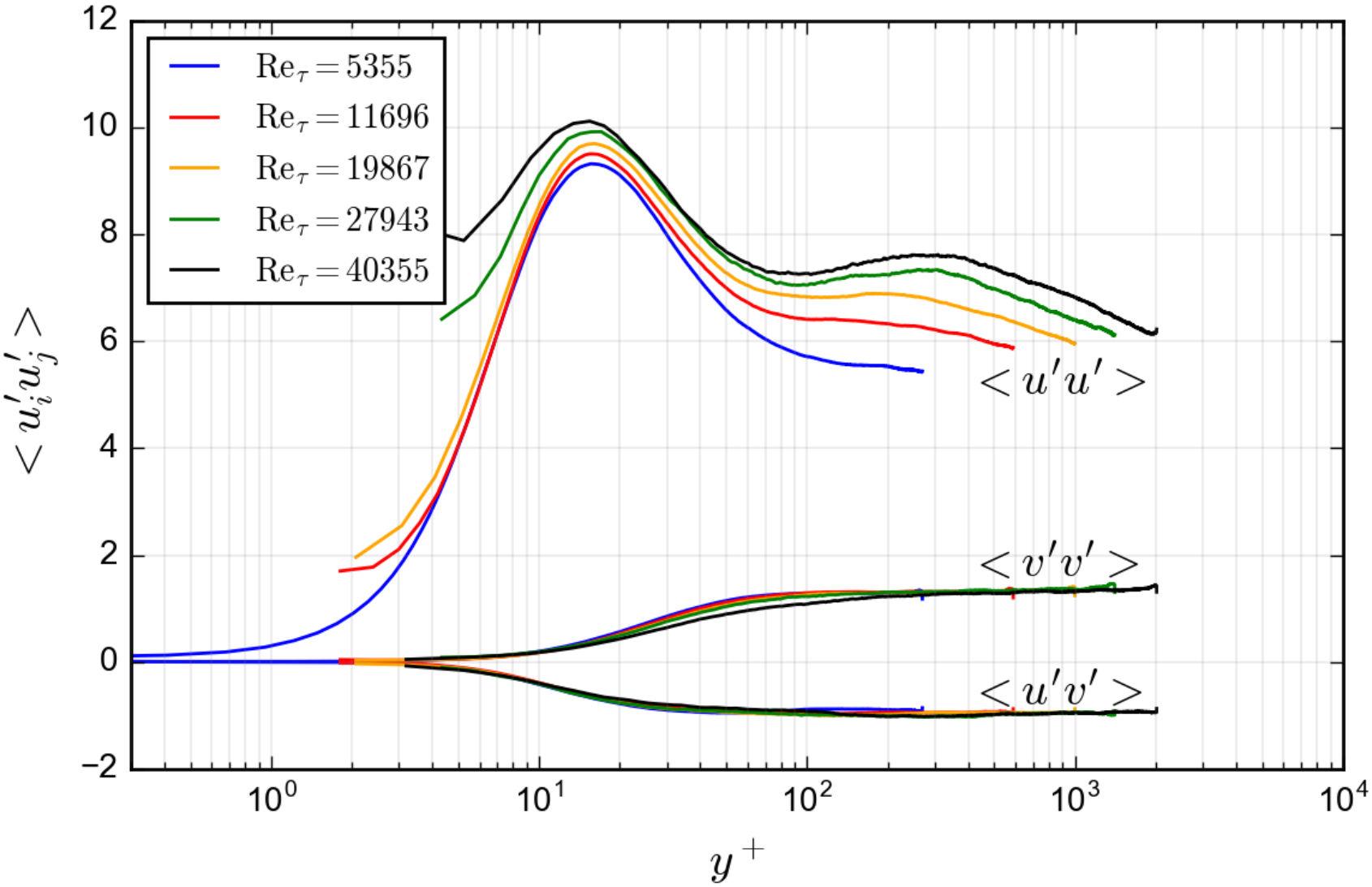
Mean velocity profiles



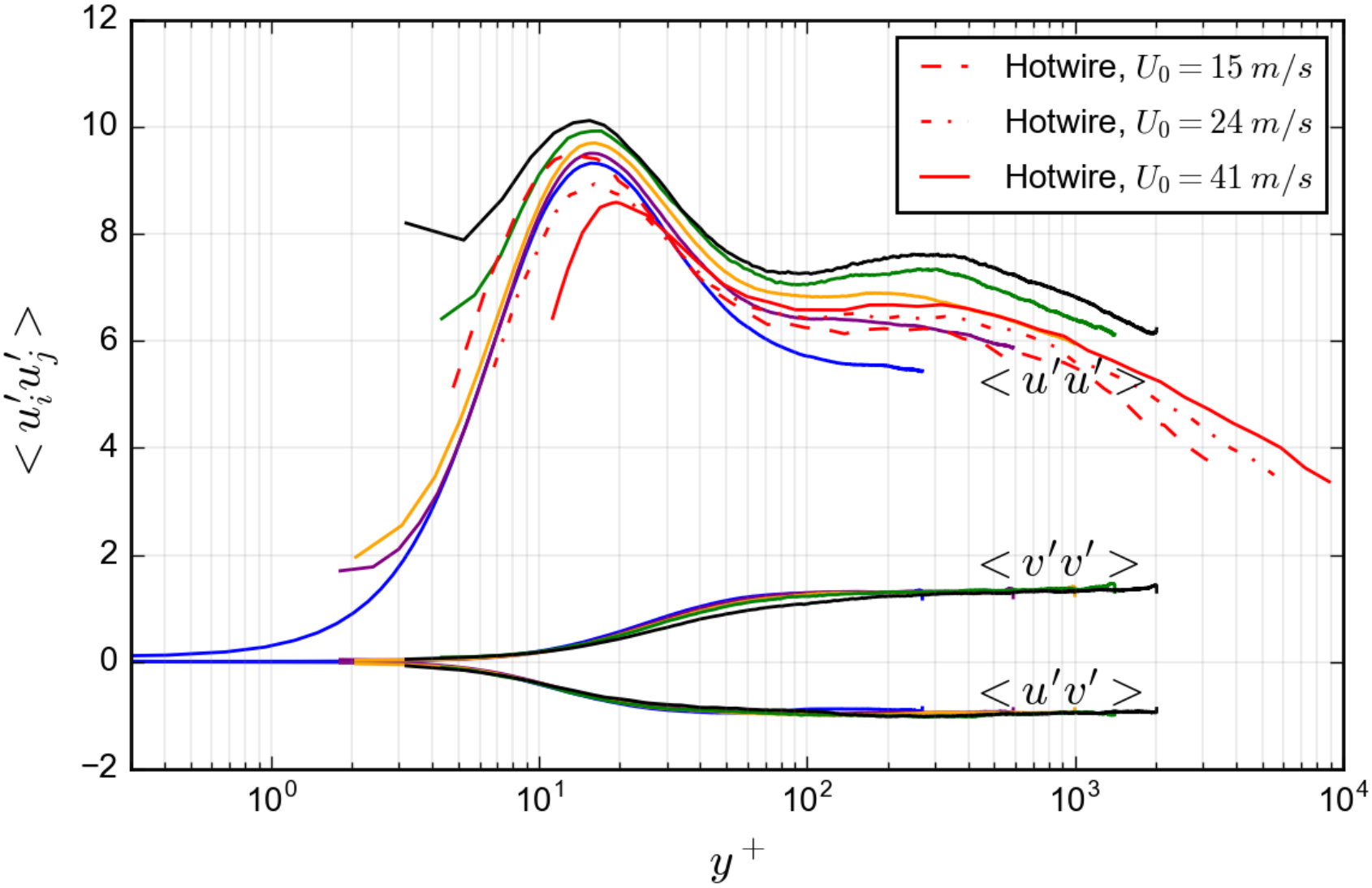
Mean velocity profiles



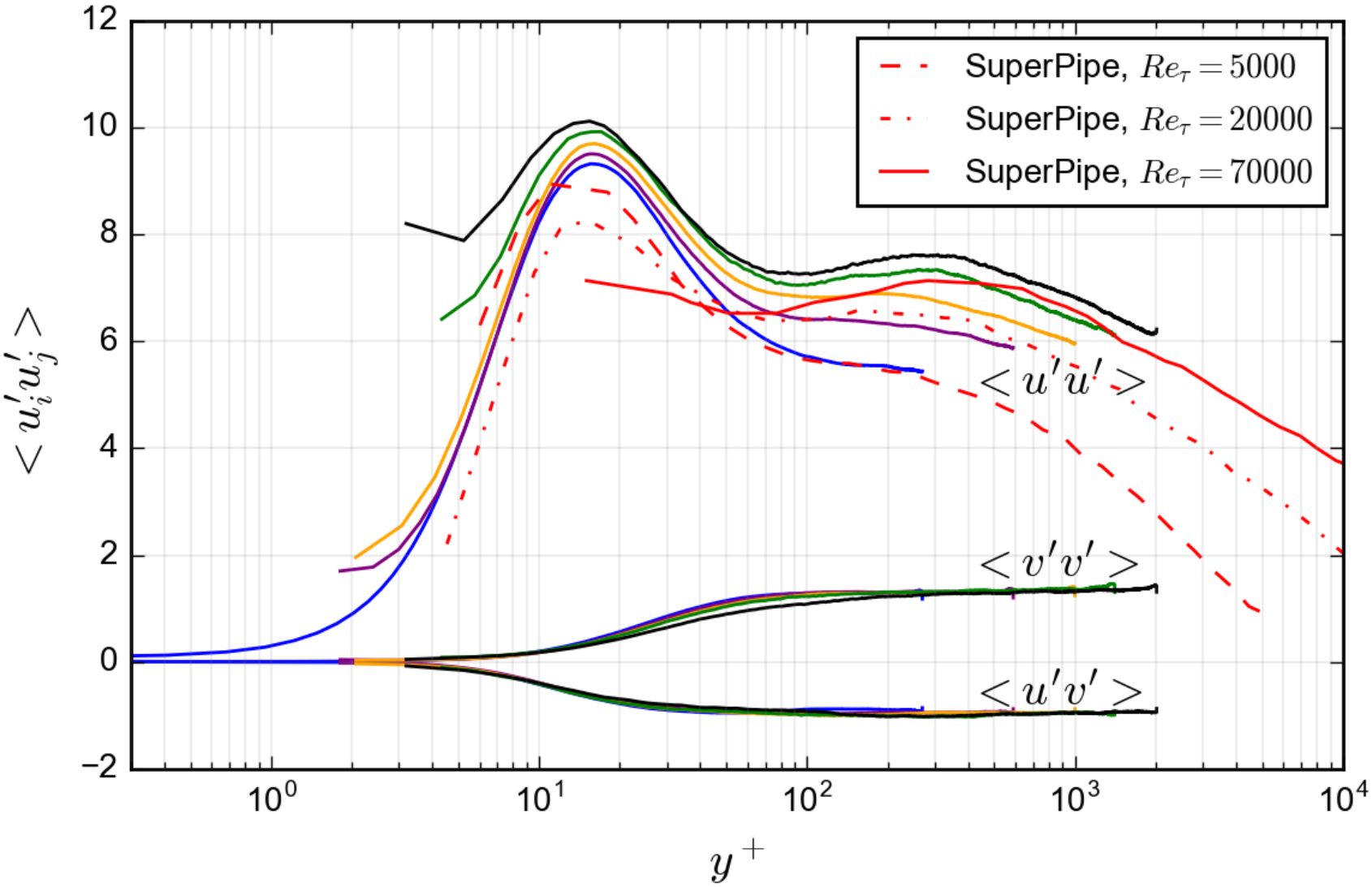
Reynolds stress profiles



Reynolds stress profiles, incl. hotwire data



Reynolds stress profiles, incl. SuperPipe data (NSTAP)



Comparison to existing data

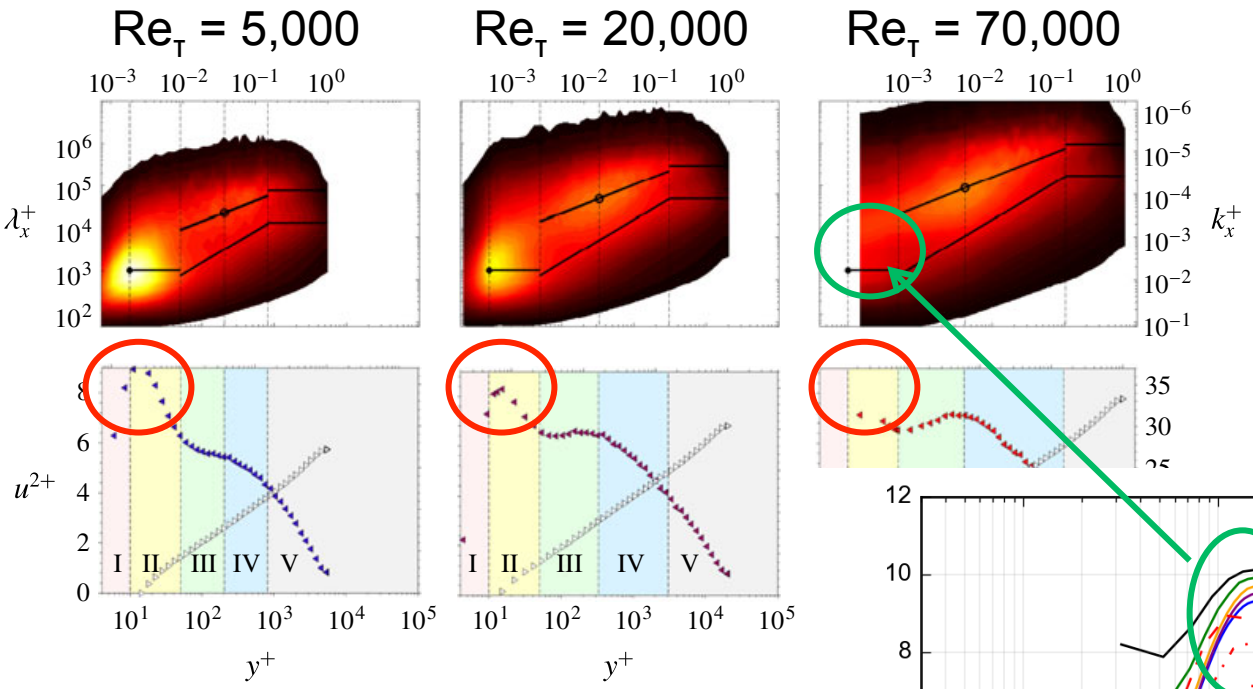
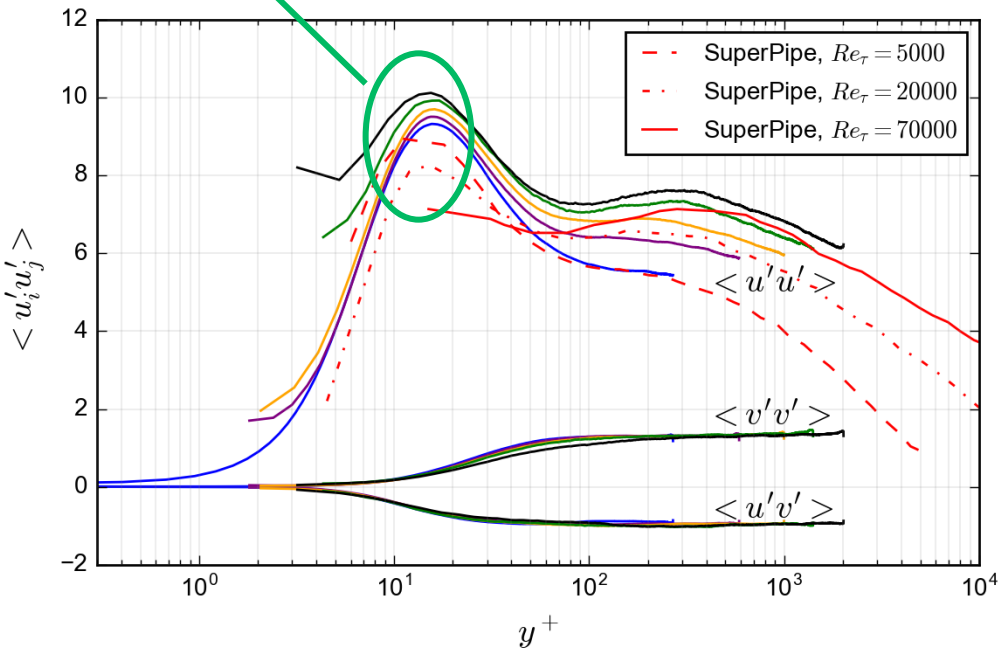


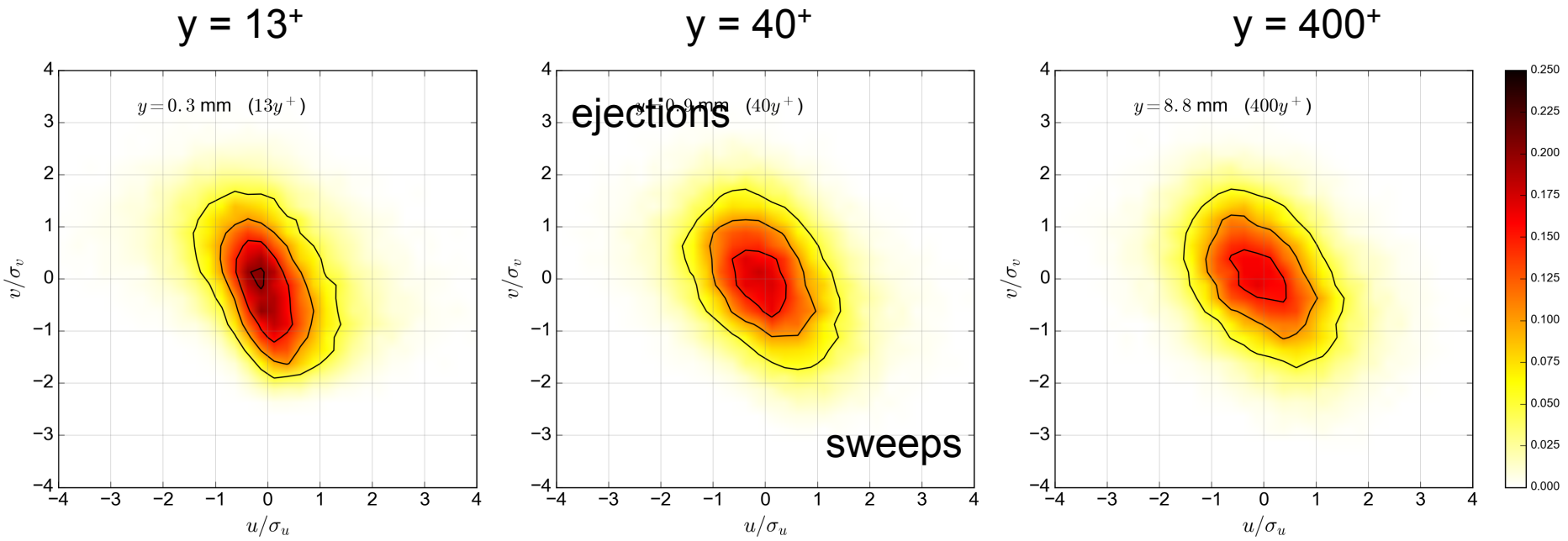
FIGURE 15. Contour plots of spectra in the pipe at $Re_\tau =$ Lines show trends in the loci of peaks shown in figures 8 67, y^+_{OSP}, $0.15Re_\tau$; ●, location of near-wall spectral peak peak.

PIV data clearly shows that inner peak increases with Re



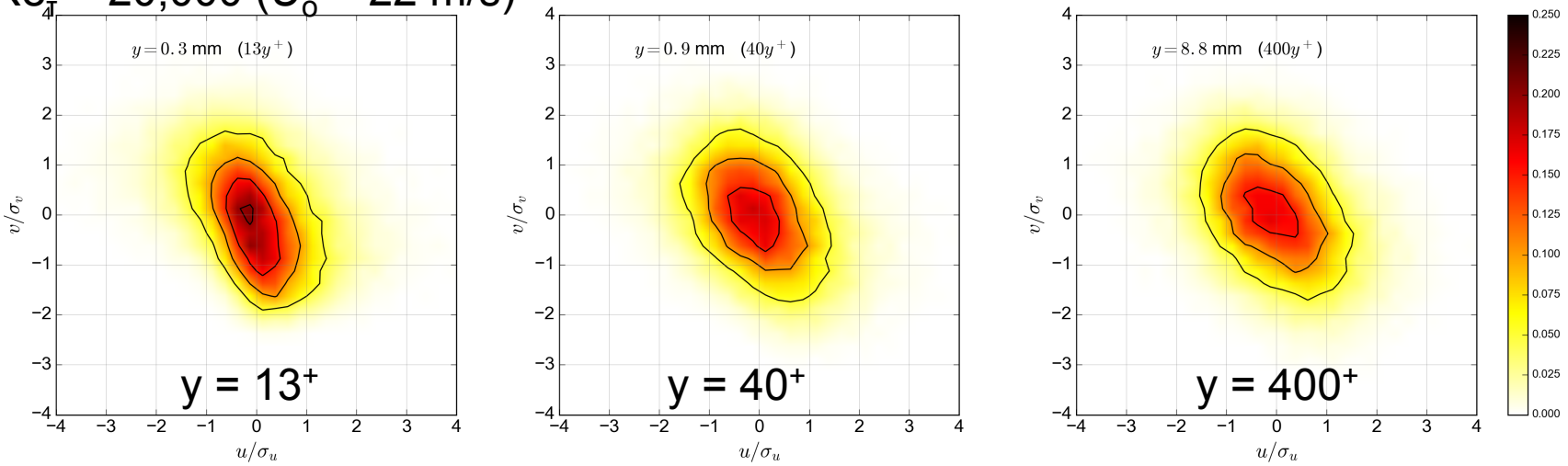
Joint Probability Density functions (Joint-PDF)

Re_T = 20,000 (U_o = 22 m/s)

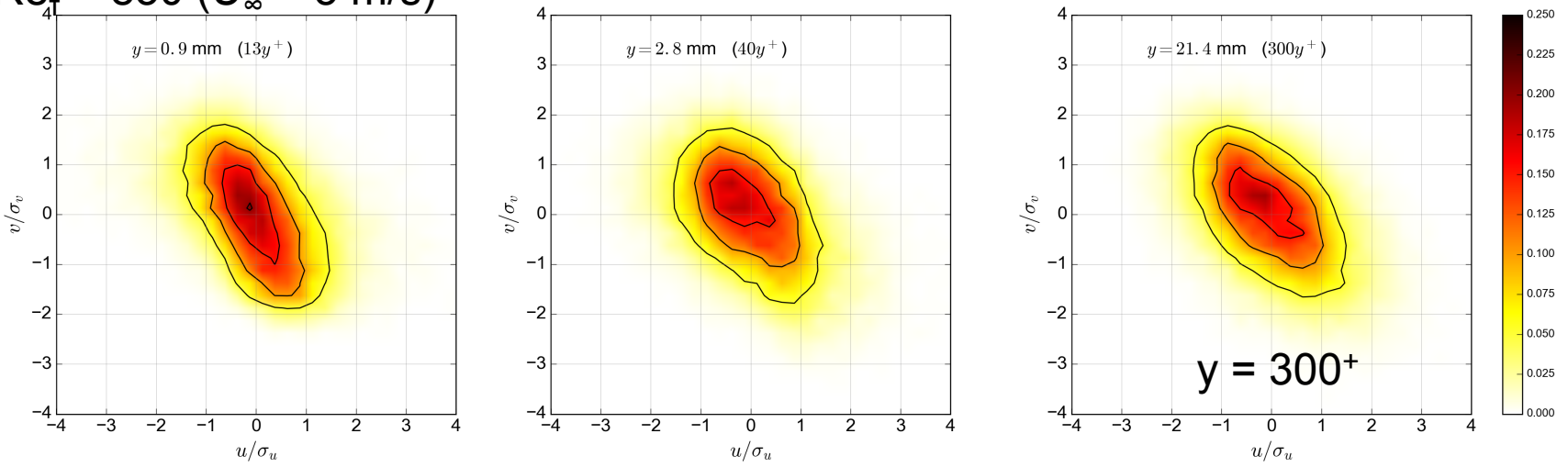


Joint-PDFs : Pipe vs. Flate Plate Turbulent BL

Re_τ = 20,000 (U_o = 22 m/s)



Re_τ = 830 (U_∞ = 5 m/s)



Summary – Turbulent pipe flow measurements

- First application of PIV in new pipe flow facility CICLoPE (in operation since 2015)
- imaging with spatial resolution of O(10µm) → resolves viscous sublayer
- statistical convergence through time-records of up to 70,000 samples
- todo:
  - extract unsteady wall-shear rate
  - detailed spectral analysis
  - stereo-PIV measurements in the future

- spin-off: mirror-based imaging approach found suitable for application in CleanSky2 Project 2-Shaft-Compressor