***Masters of Flow Visualization* Short Course**, 08-09 July 2023 , TU-Delft (NL)
https://www.isfv20.org/home/mfv

# EVENT-BASED IMAGING VELOCIMETRY - AN INTRODUCTION

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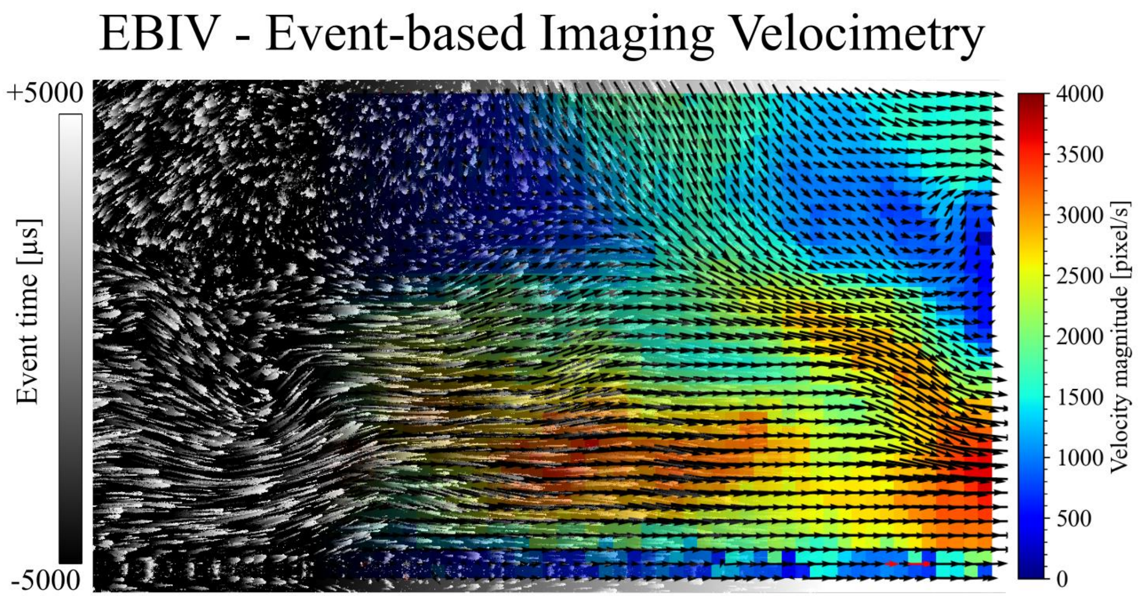
DLR

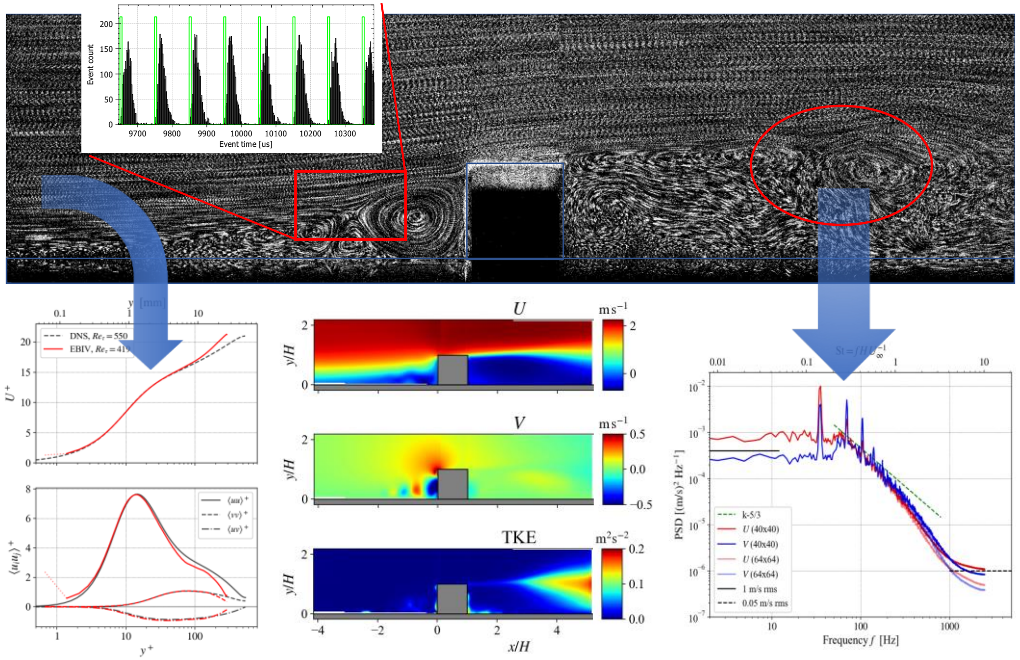
# Outline - Event-based Imaging Flow Velocimetry

- Introduction to concepts of event-based imaging (EBI)
- Application to particle imaging → Event-based imaging velocimetry (EBIV)
- EBIV Applications
  - flow visualization
  - global flow field measurements
  - velocity profile measurement
- Sample results
- Application to TU-Delft Jet Plume
- Summary & Outlook

# Further Reading: Event-based Imaging Velocimetry (EBIV)




Event-based imaging velocimetry using pulsed illumination




Exp.Fluids 63:101 (2022)
https://doi.org/10.1007/s00348-022-03441-6

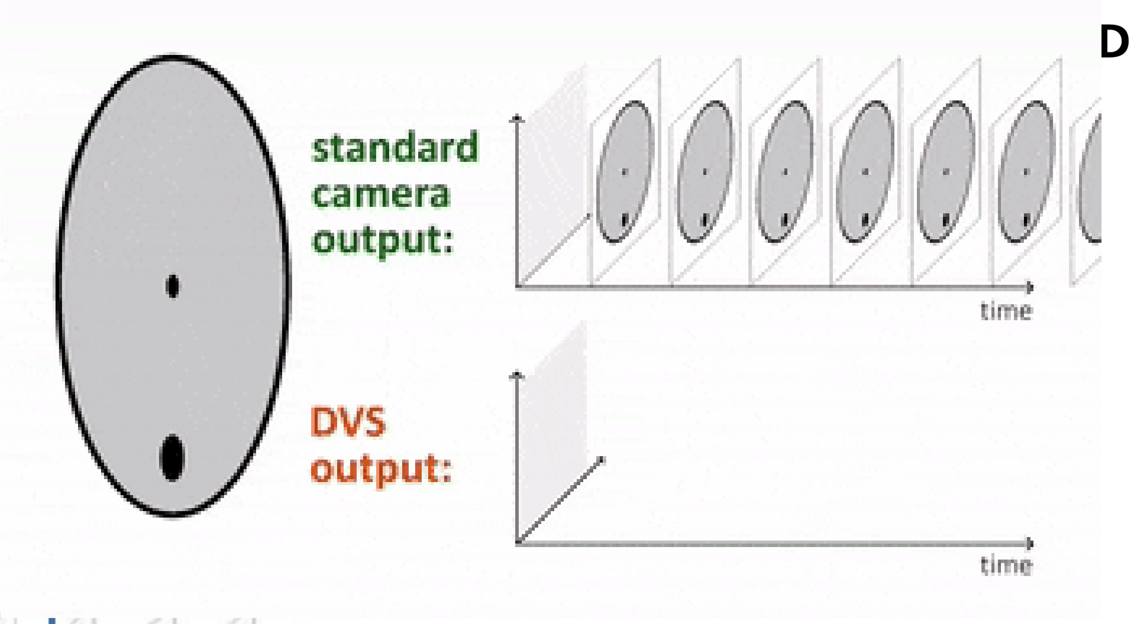
Exp.Fluids 64:98 (2023)
https://doi.org/10.1007/s00348-023-03641-8

# What is Event-based Vision (EBV) ?

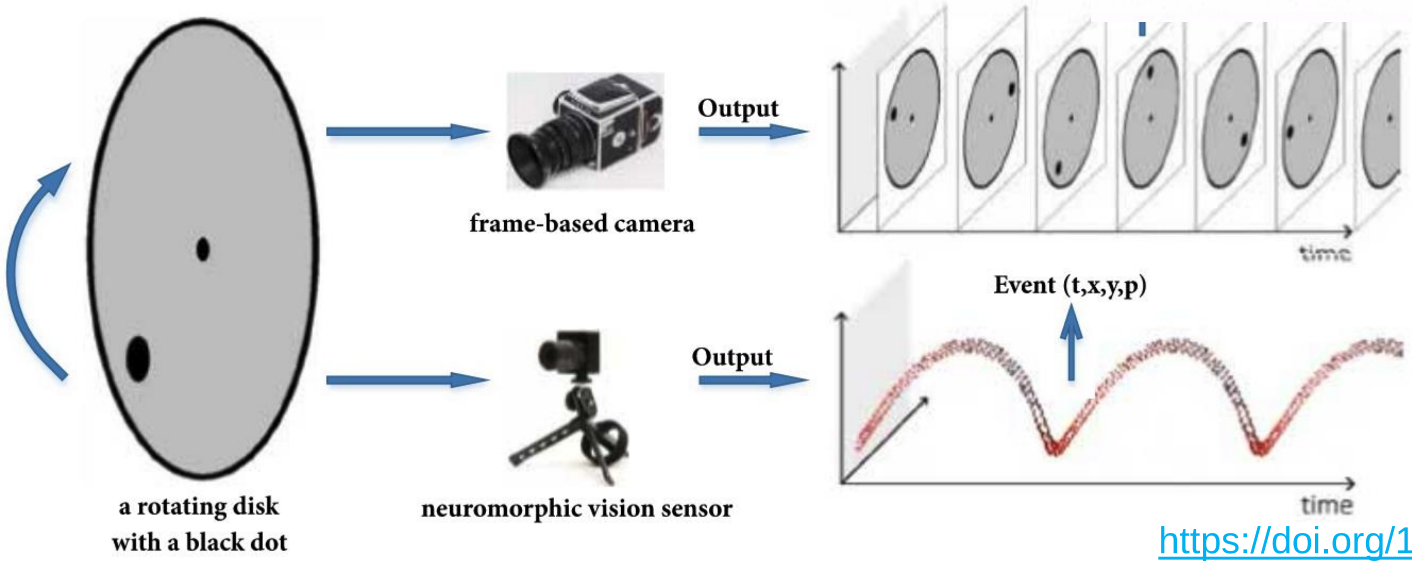
- also known as "Dynamic Vision Sensing" (DVS) or "Neuromorphic Imaging"
  also: "silicon retina", Carver Mead & Misha Mahowald, Caltech, 1990's
- fairly new technology, still under development
  (very active since ~2010, ETHZ/Uni Zurich)
- several commercial vendors
- **records only contrast changes on the pixel level**
  → asynchronous data stream
- does not record image frames (completely different from frame-based imaging)
  → paradigm shift regarding data / "image" processing
- typical applications aimed at real-time processing
  - simultaneous localization and mapping (SLAM)
    visual-inertial odometry
    - autonomous navigation
    - vision and control for UAVs
  - 3-D sensing
  - object counting / machine vision / AI
  - vibration measurement
  - satellite navigation (star tracking)
  - eye tracking
  - ...

http://image-sensors-world.blogspot.com

# Event-based imaging vs. frame-based imaging

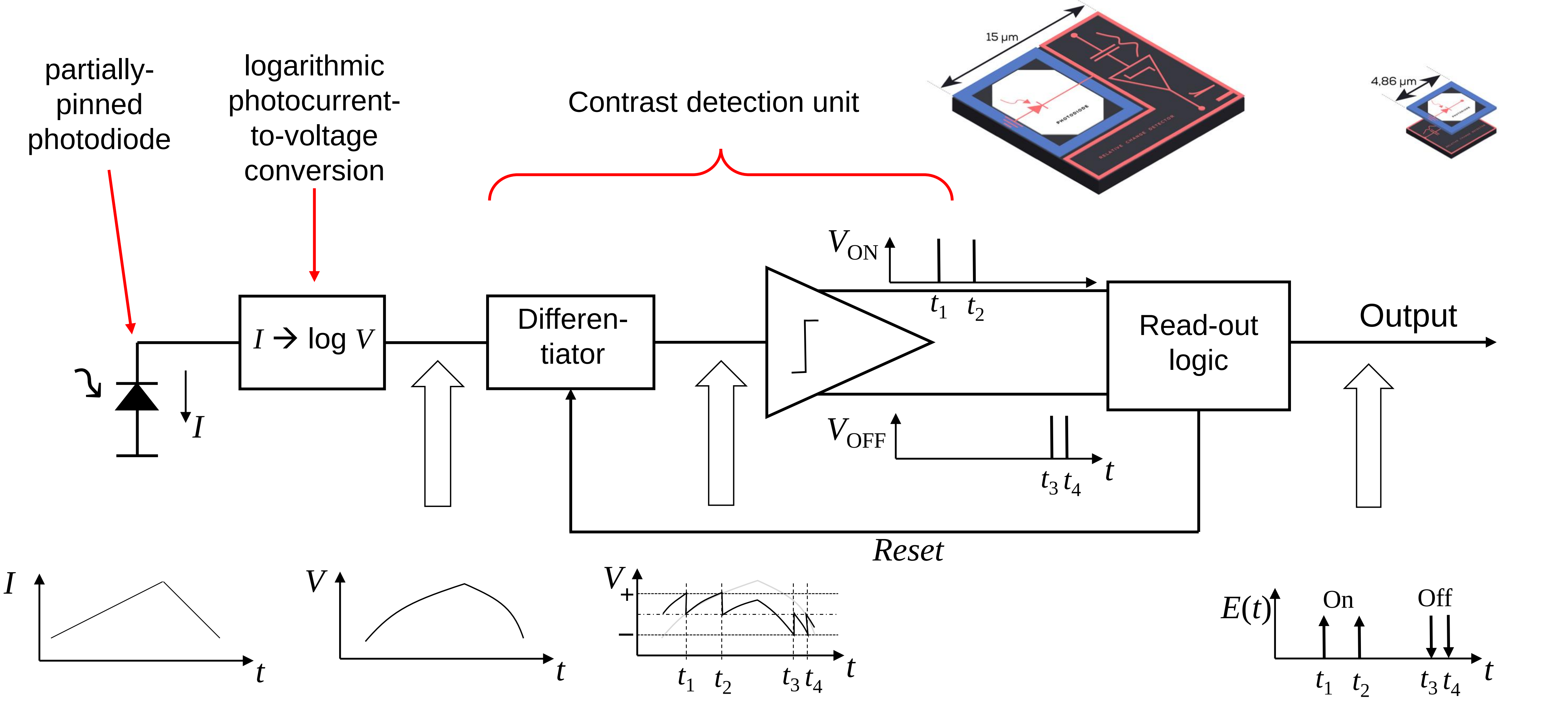



- conventional camera provides individual image frames (for all pixels)
- event-camera produces asynchronous stream of contrast change events (only for affected pixels), time-stamping with 1µs resolution




https://doi.org/10.1155/2018/4815383

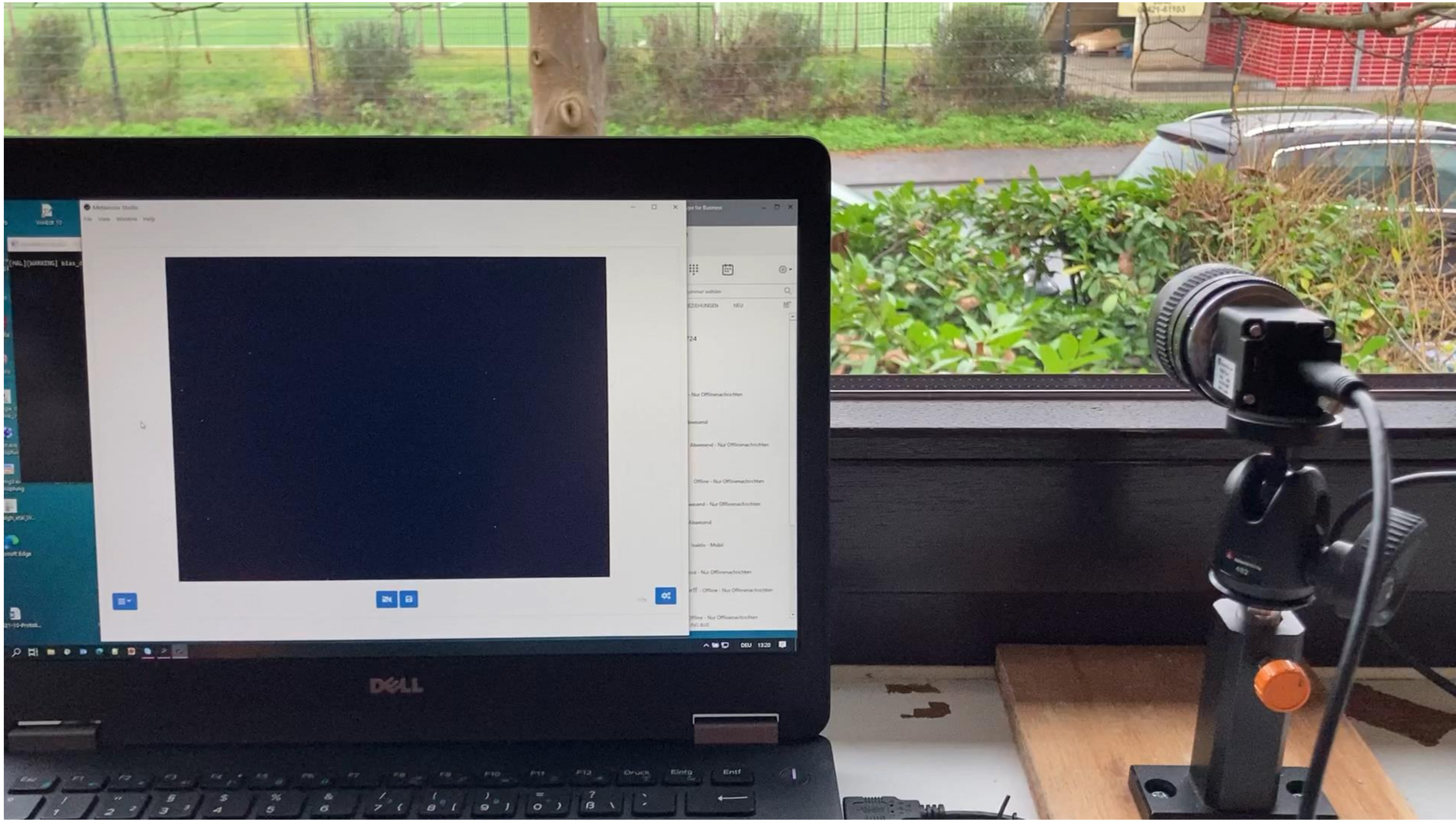
# The Active Pixel of an Event-Camera



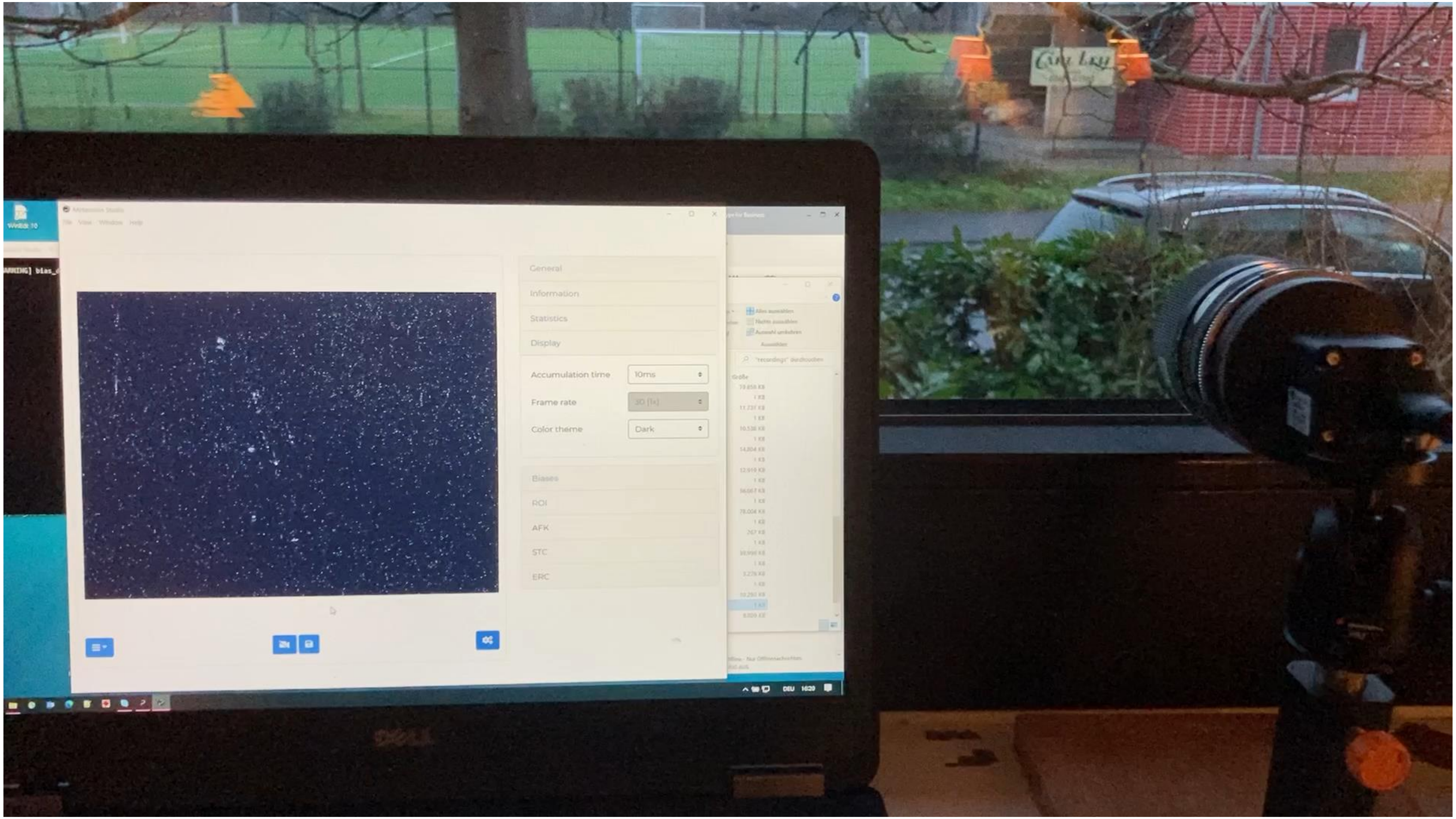
# My first recordings (Dec. 2021)

gloomy, rainy December afternoon

Event-camera with
640 x 480 pixel sensor

# Rain & Insects in the Twilight (dynamic range >120 dB)



# Passing bicycle

Blue = “On” - Events
Black = “Off” - Events

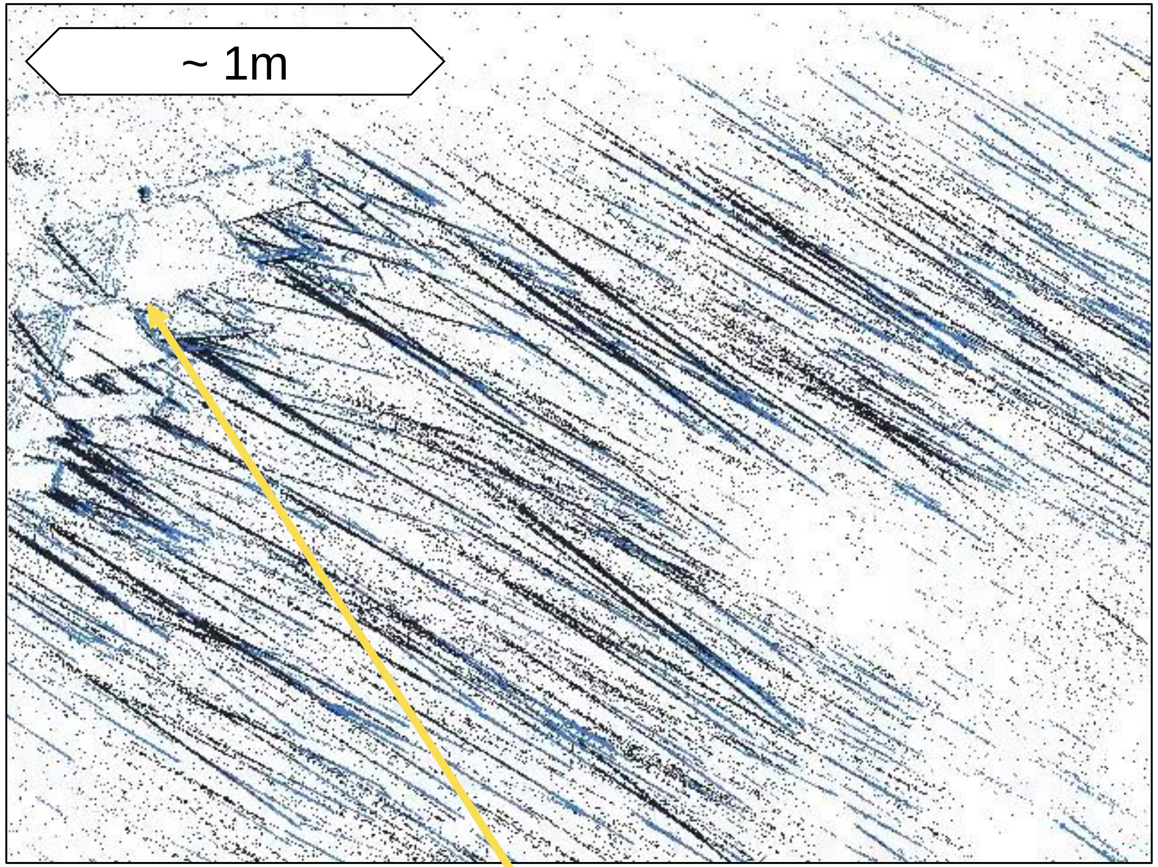
Normal speed (30 fps)

1/10 speed (300 fps)

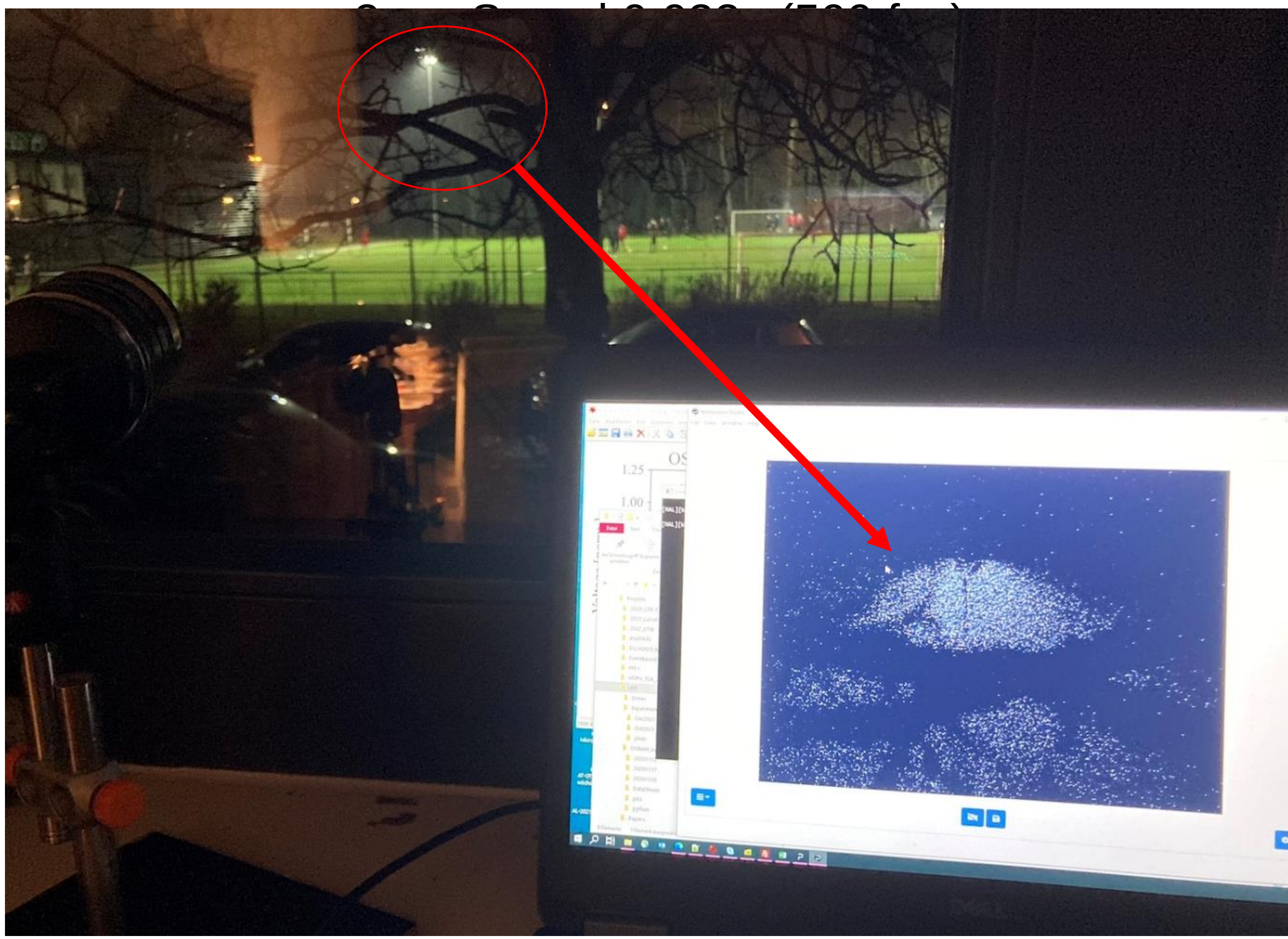
# Rain & wind

imaged with 300mm lens (~30m distance)

20ms, Normal speed (30 fps)



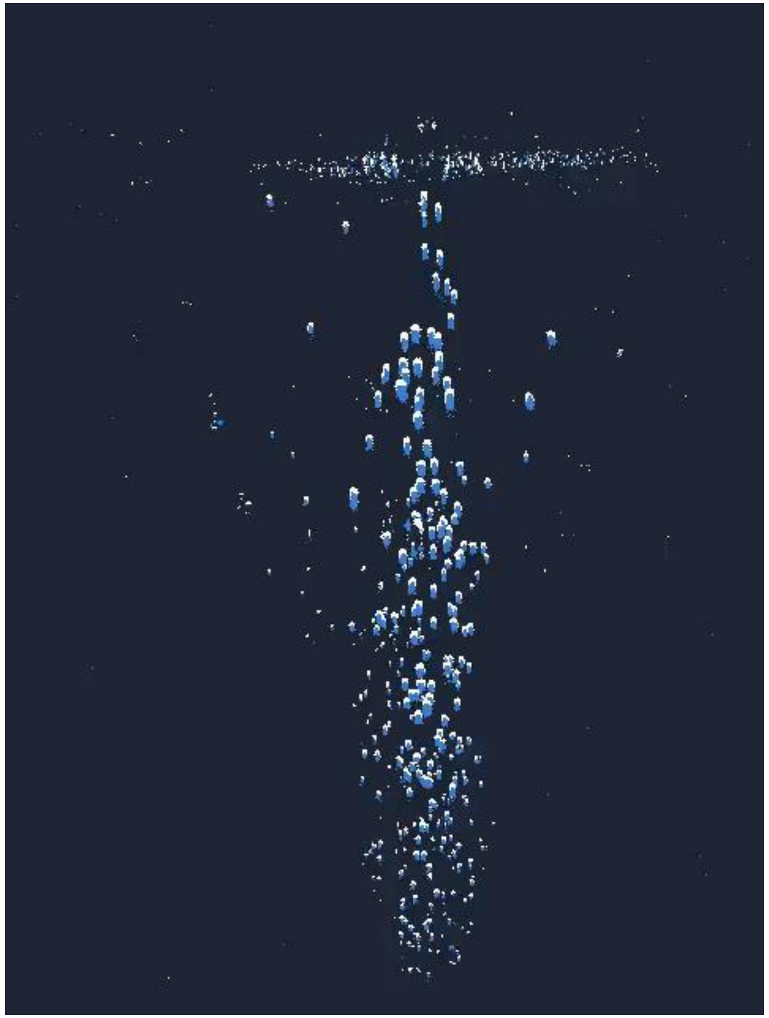

Bright LED flood light



# Crémant ! e bubbles

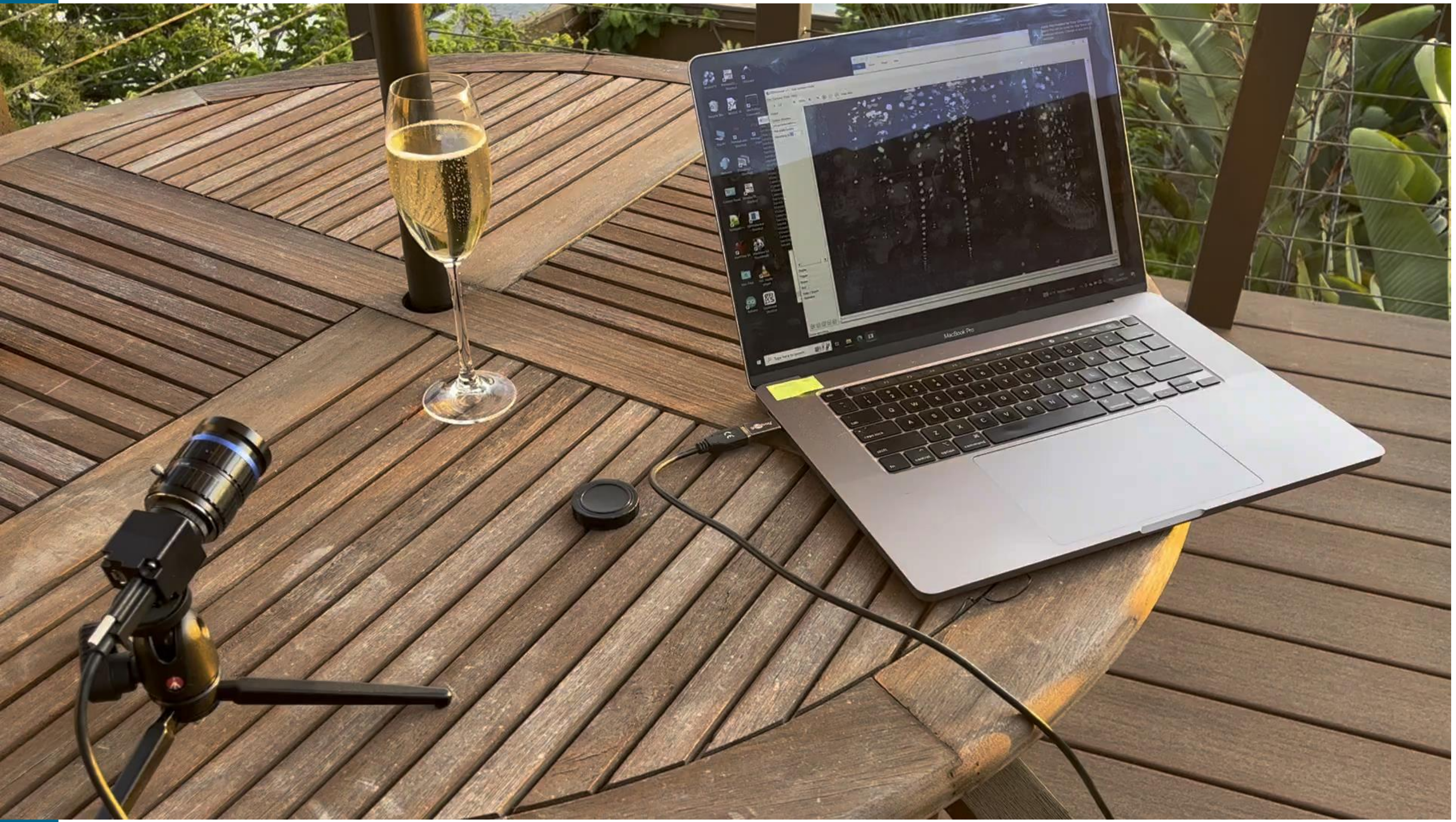
ambient lighting

Normal speed (30 fps)

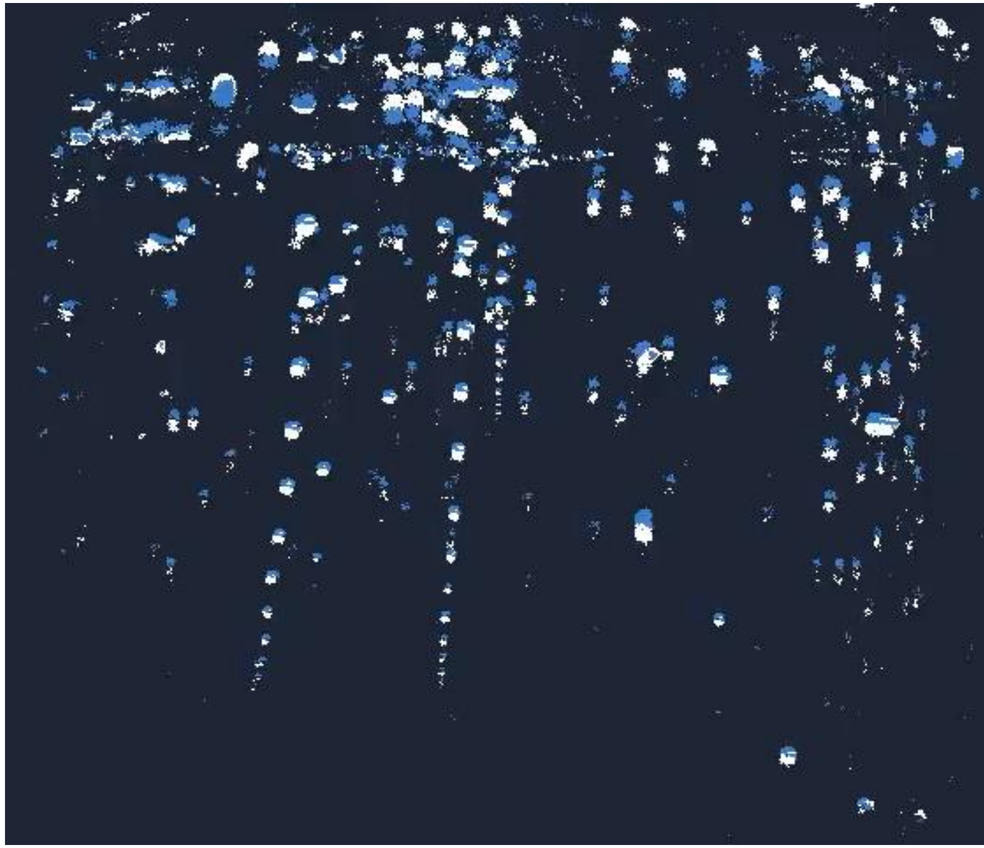


Speed 0.2x (150 fps)

# Now for some real champagne

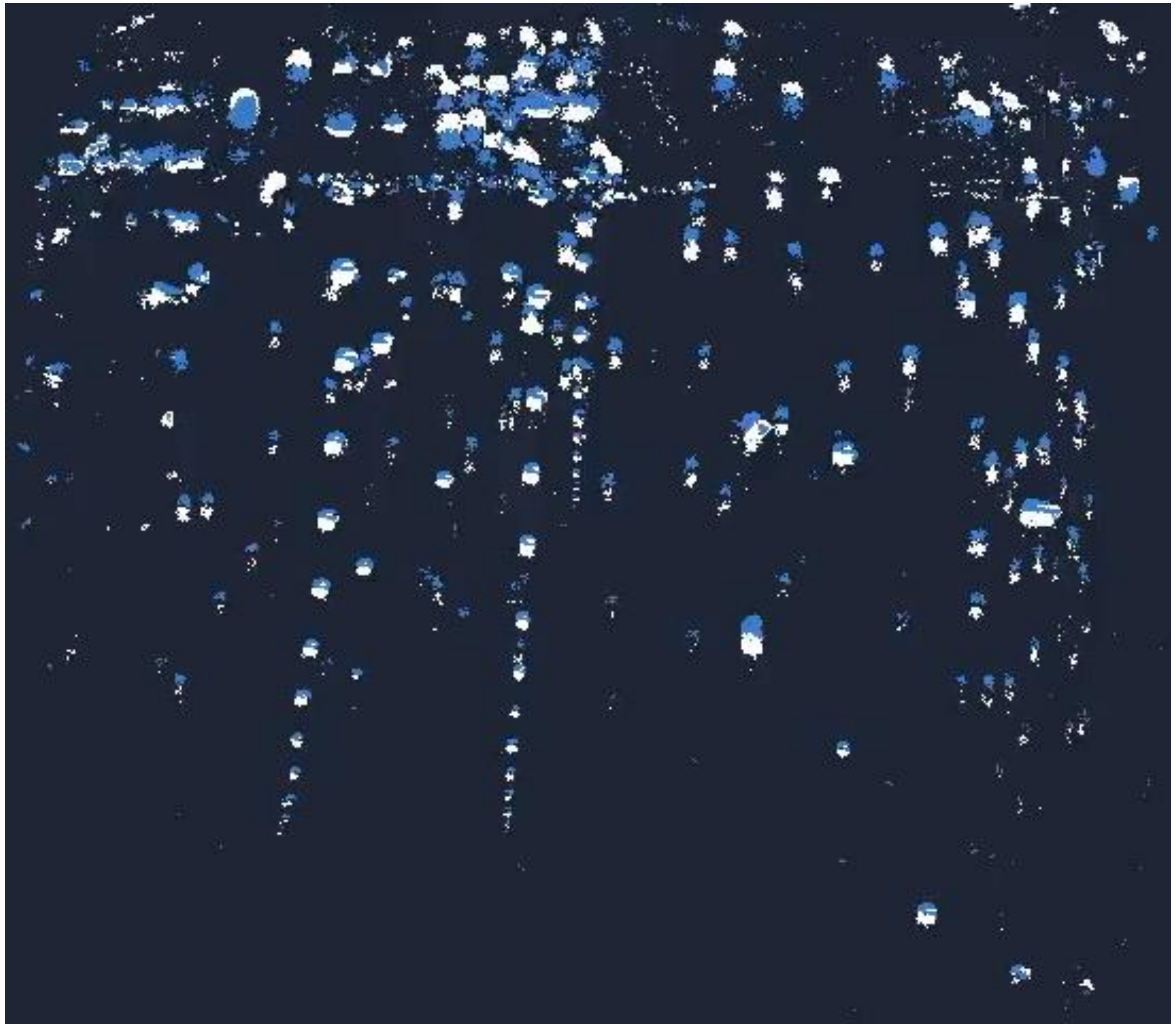


Actual speed (25 fps, 10 ms samples)

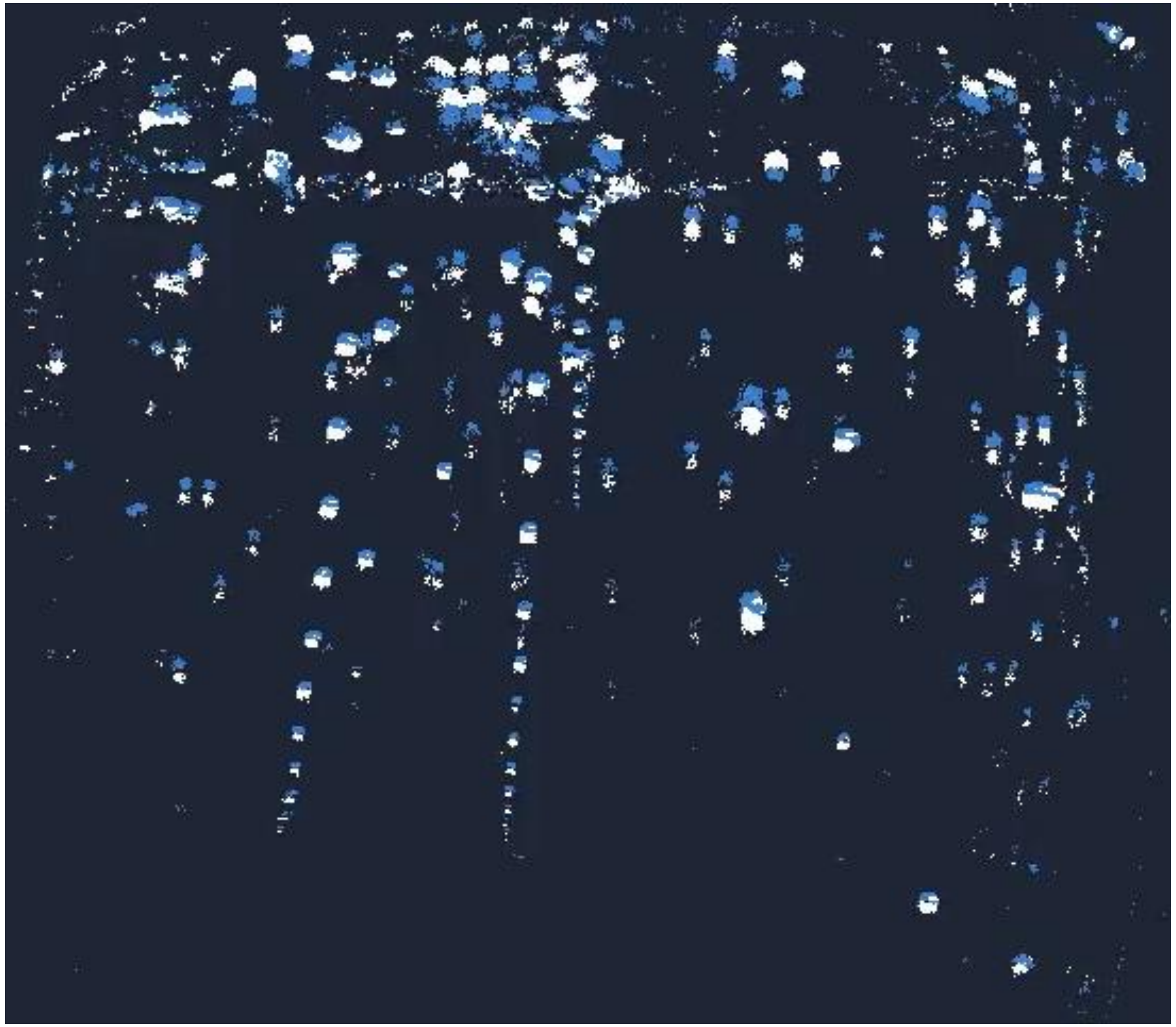


# Champagne bubbles

Actual speed (25 fps, sample time 10 ms)

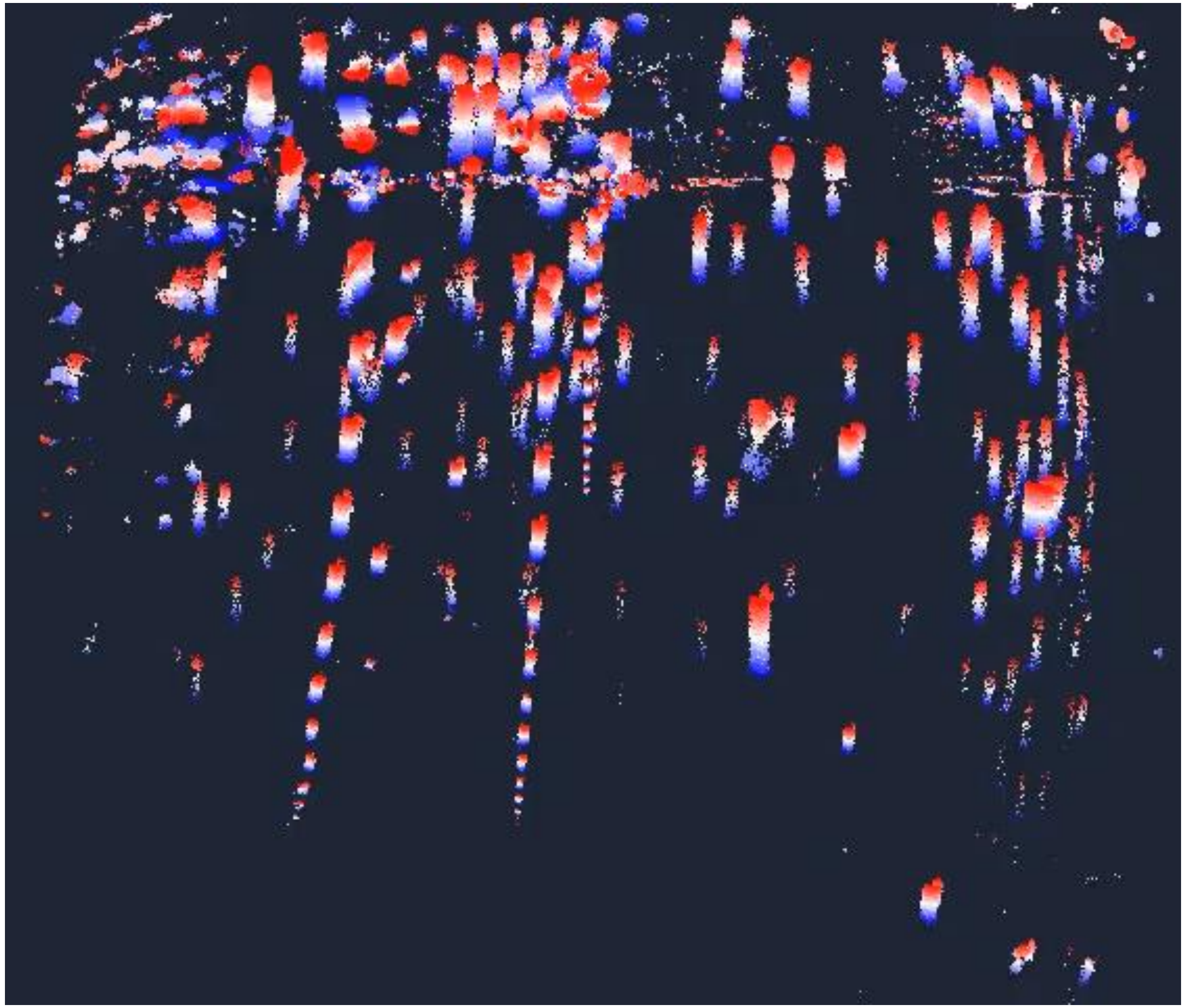


Speed 0.2x (125 fps, sample time 10 ms)

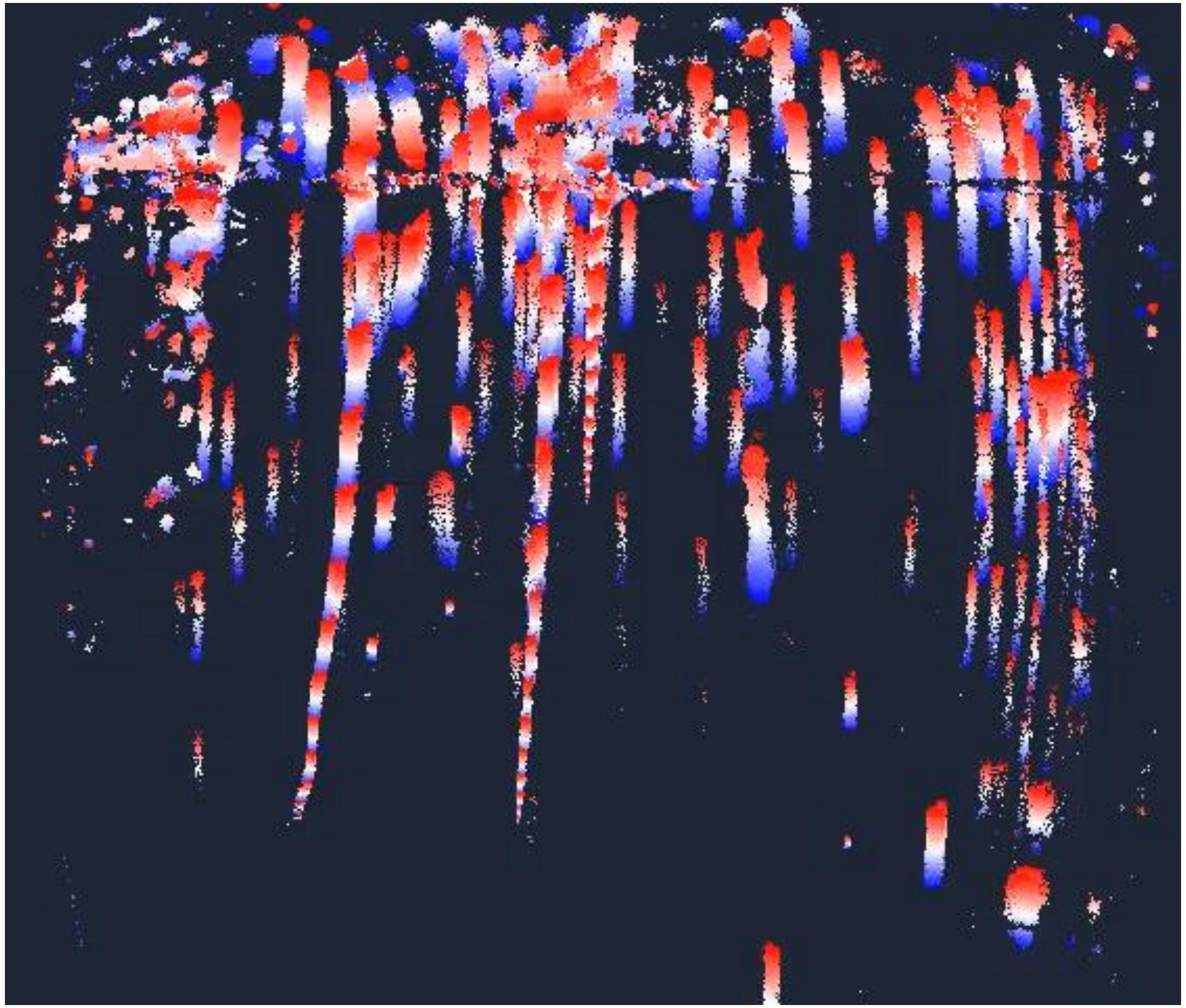


# Bubble Visualization as “Time Surface”

Speed 0.1x (250 fps, **sample time 50 ms**)



Speed 0.1x (250 fps, **sample time 100 ms**)



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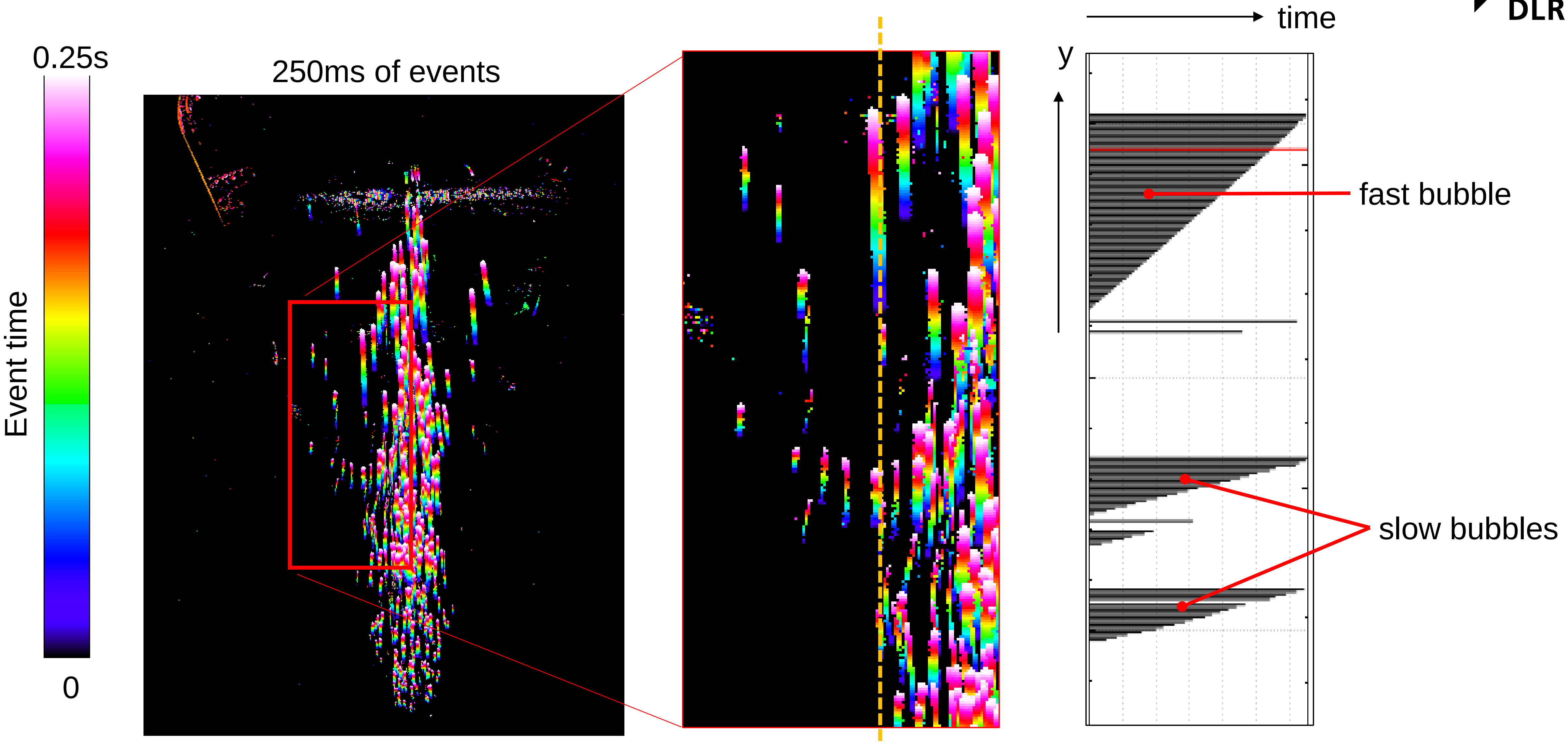
# Champagne bubbles - Time-surface representation

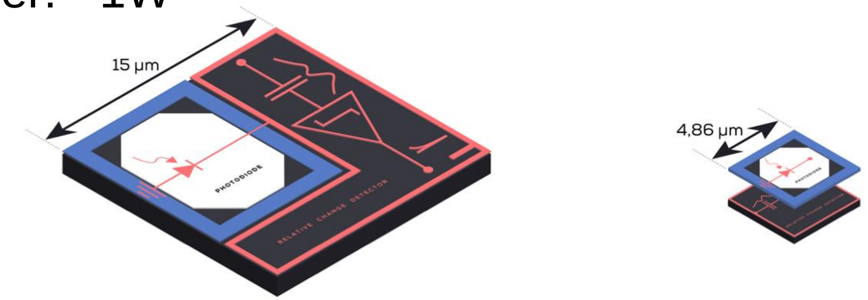


# Event cameras

**Century Arks**

**SilkyCam**

- 640 x 480 pixel (VGA)
- pixel size 15 x 15 µm
- >120 dB dyn. range
- 0.08 lx low-light cutoff
- equiv. 10’000 fps
- USB3.0 interface
- low power: ~1W


**Prophesee.ai**

**Evaluation Kit EVK2-HD**

- back-side illuminated (engineering sample)
- 1280 x 720 pixel (HD)
- pixel size 4.8 x 4.8 µm
- >110 dB dyn. range
- equiv. 10’000 fps
- USB3.1 interface (~150MB/s)
- power: ~7.5W

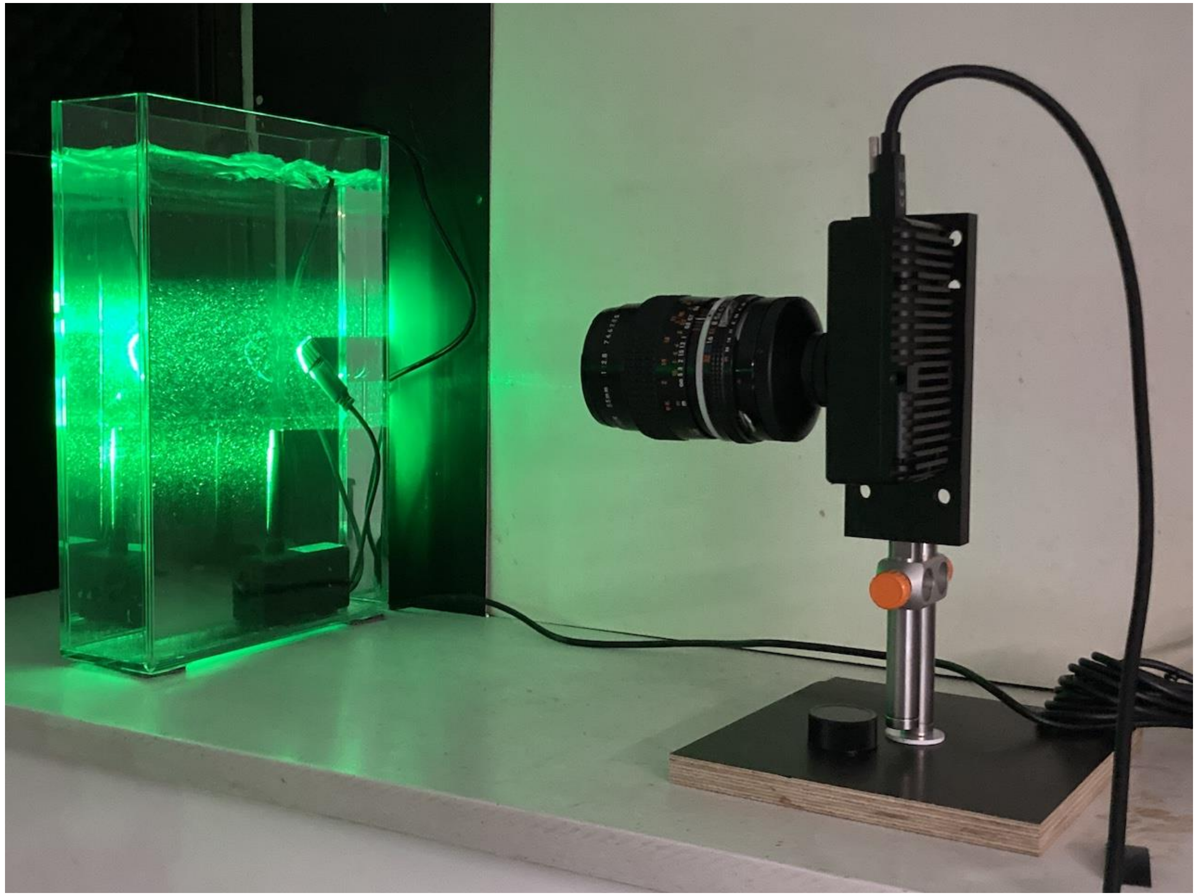

**Evaluation Kit EVK4-HD**

(similar specs as EVK2-HD)

- low power: ~0.5W

# Components for Event-based Imaging Velocimetry (EBIV)

- Event camera (with lens)
- CW laser (1-5 Watts)
- Light sheet optics
- Particles
  - water: ~10 µm (Orgasol)
  - air: ~1 µm (glycerin droplets)
- Software (roll your own...)
- (no synchronizer, no pulsed laser, ...!)



KVANT laser
4W @ $\lambda$ =520 nm
(with OD1 (10%) ND-filter!)

# Simple Water Flow

1ms of events
1/20 speed
→ 1000fps

resolution
1280x720

Wall

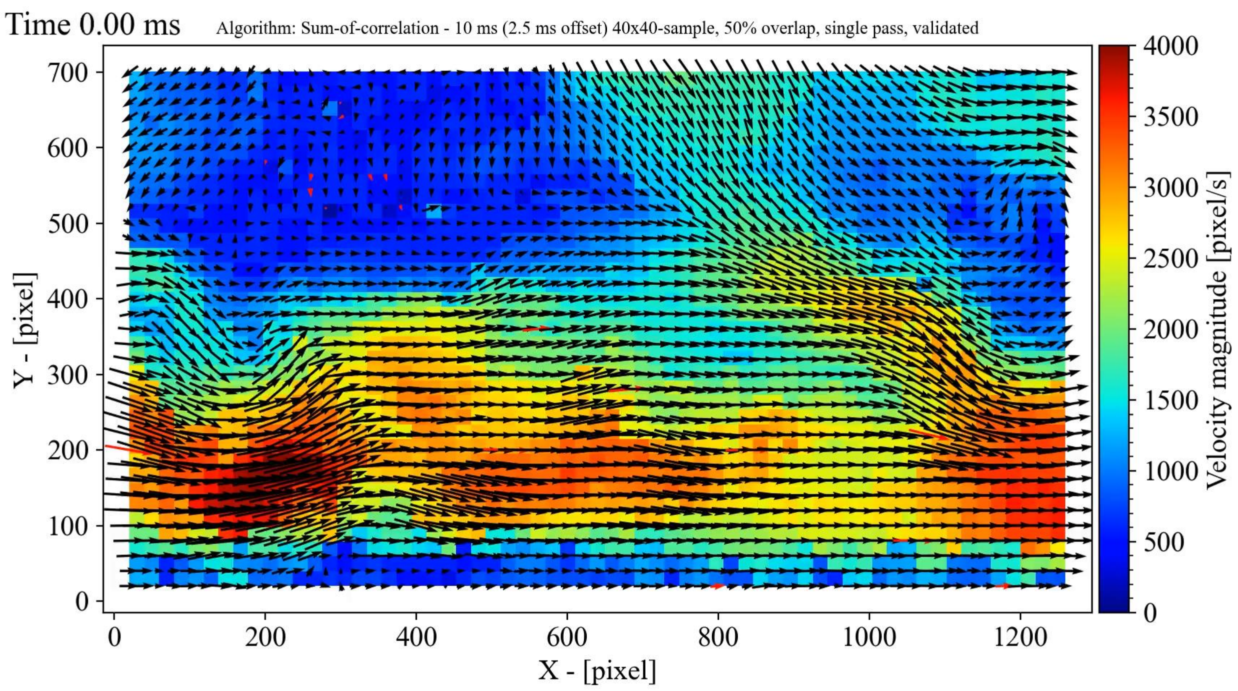
# Simple Water Flow

1ms of events
1/20 speed
→ 1000fps

zoomed portion
(640x360)

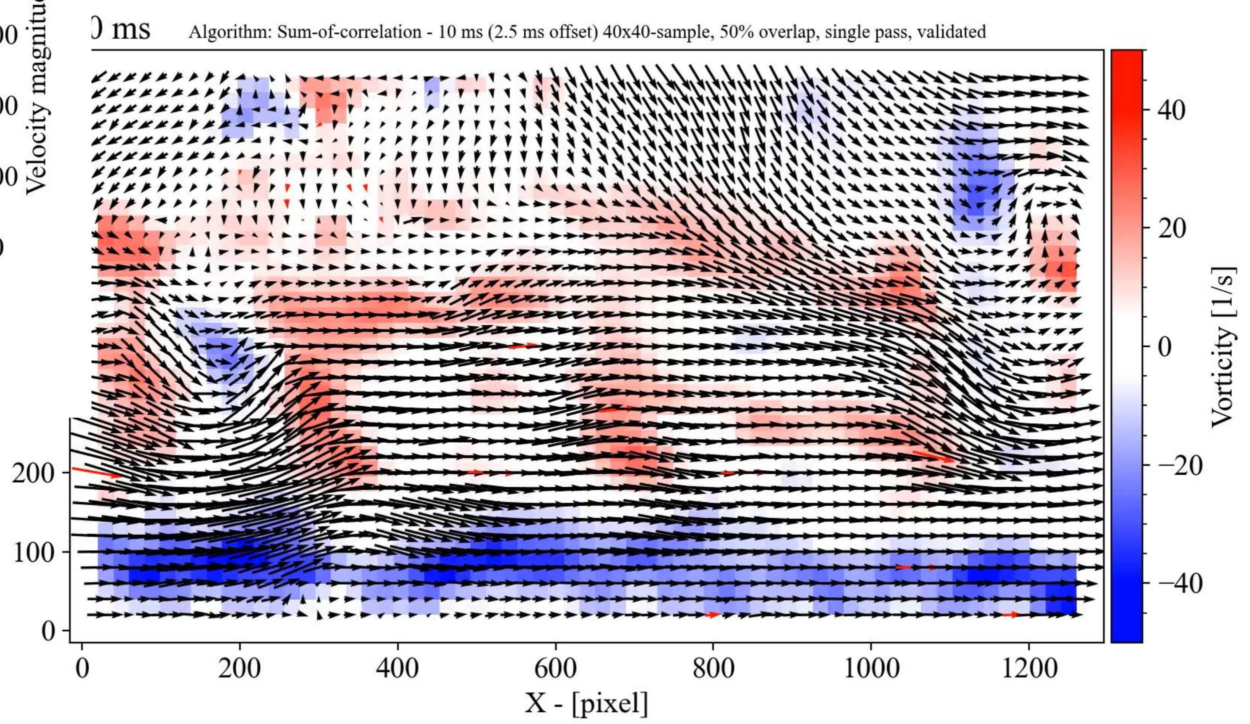
Wall

# EBIV Processing (sum-of-correlation method)




Processing methods investigated:

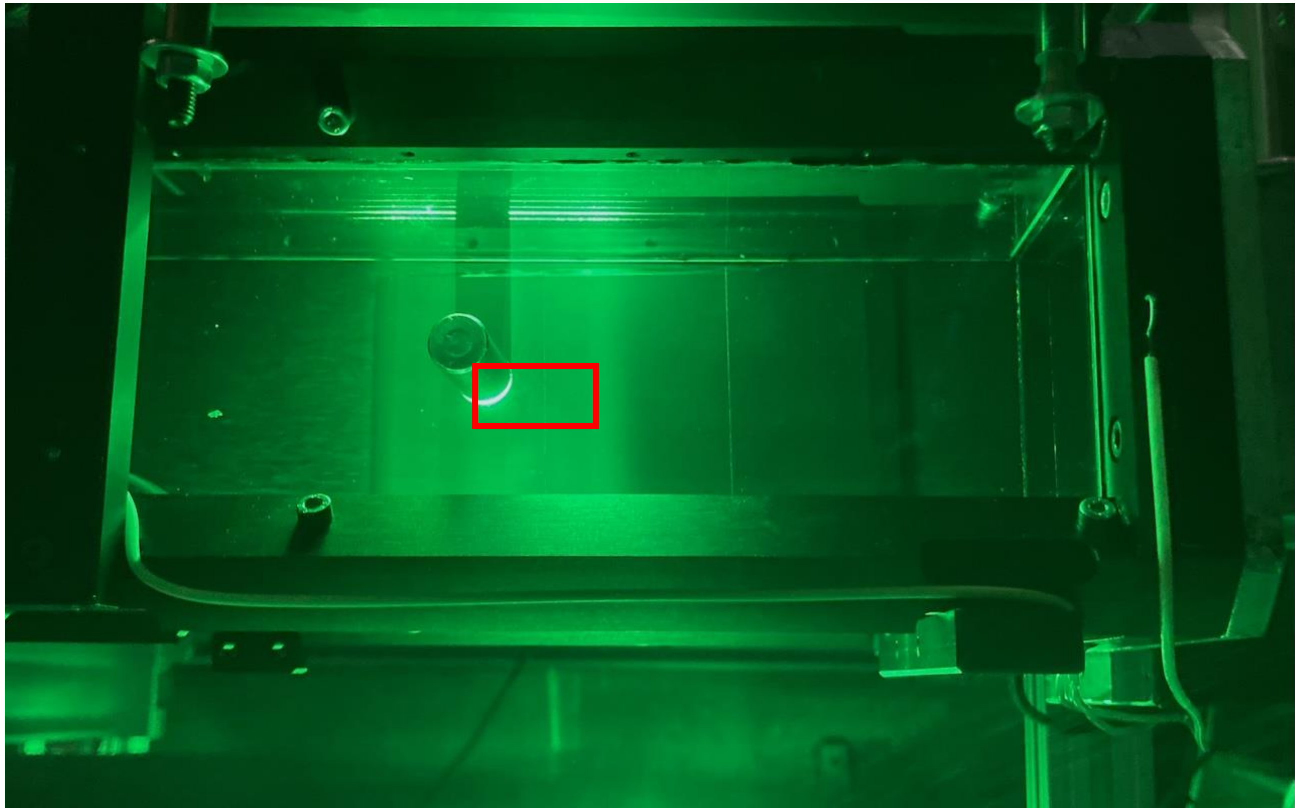
- motion-compensation (from EBI community)
- sum-of-correlation scheme
- **conventional PIV (using pseudo images)**




Further details in: Exp. Fluids 63:101
https://doi.org/10.1007/s00348-022-03441-6

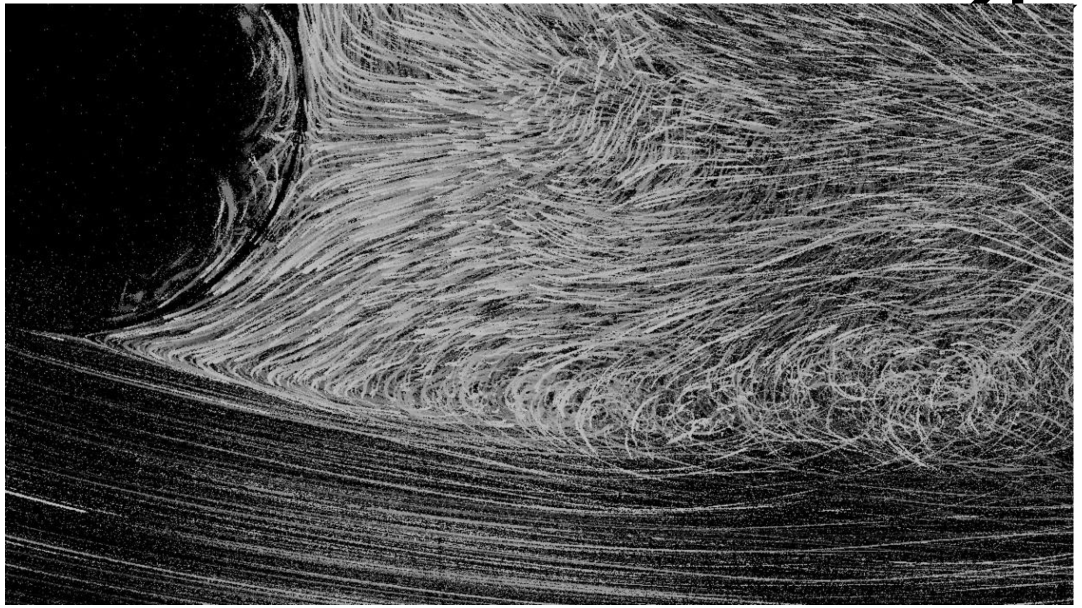
# EBIV in air (cylinder wake)

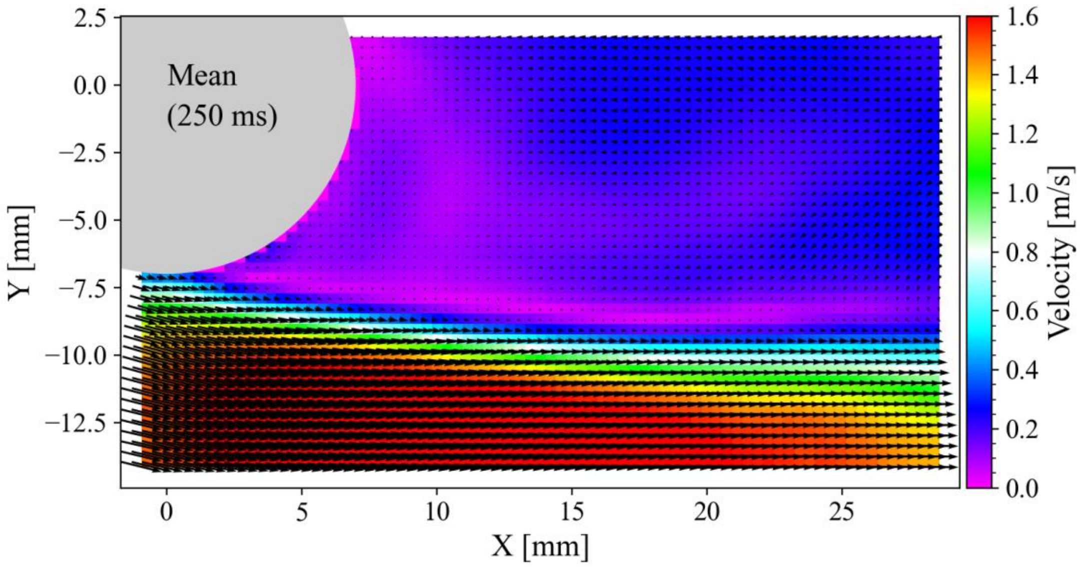
76 x 76 mm$^2$ channel, bulk flow 1-2 m/s



seeding: 1µm aerosol droplets (paraffin oil)
laser: ~4 watts

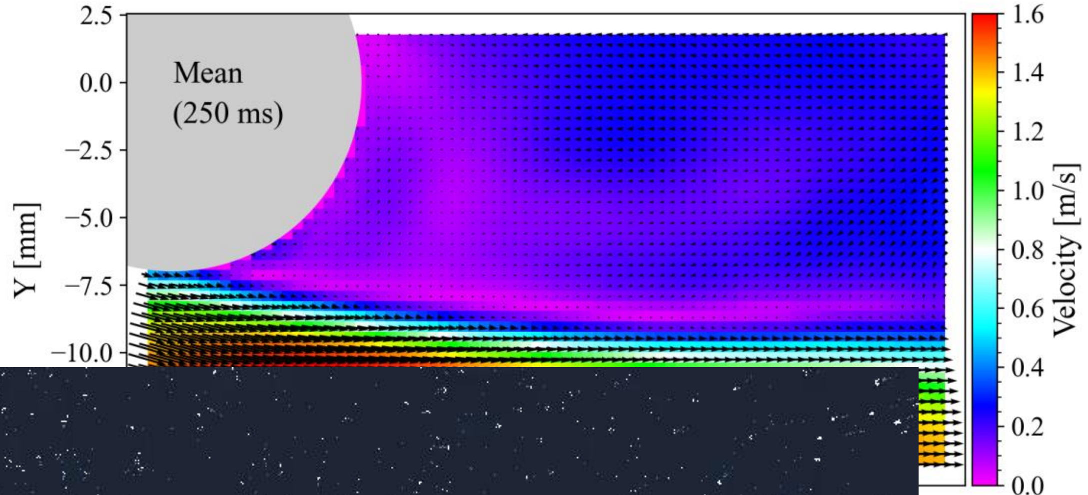
50ms of events

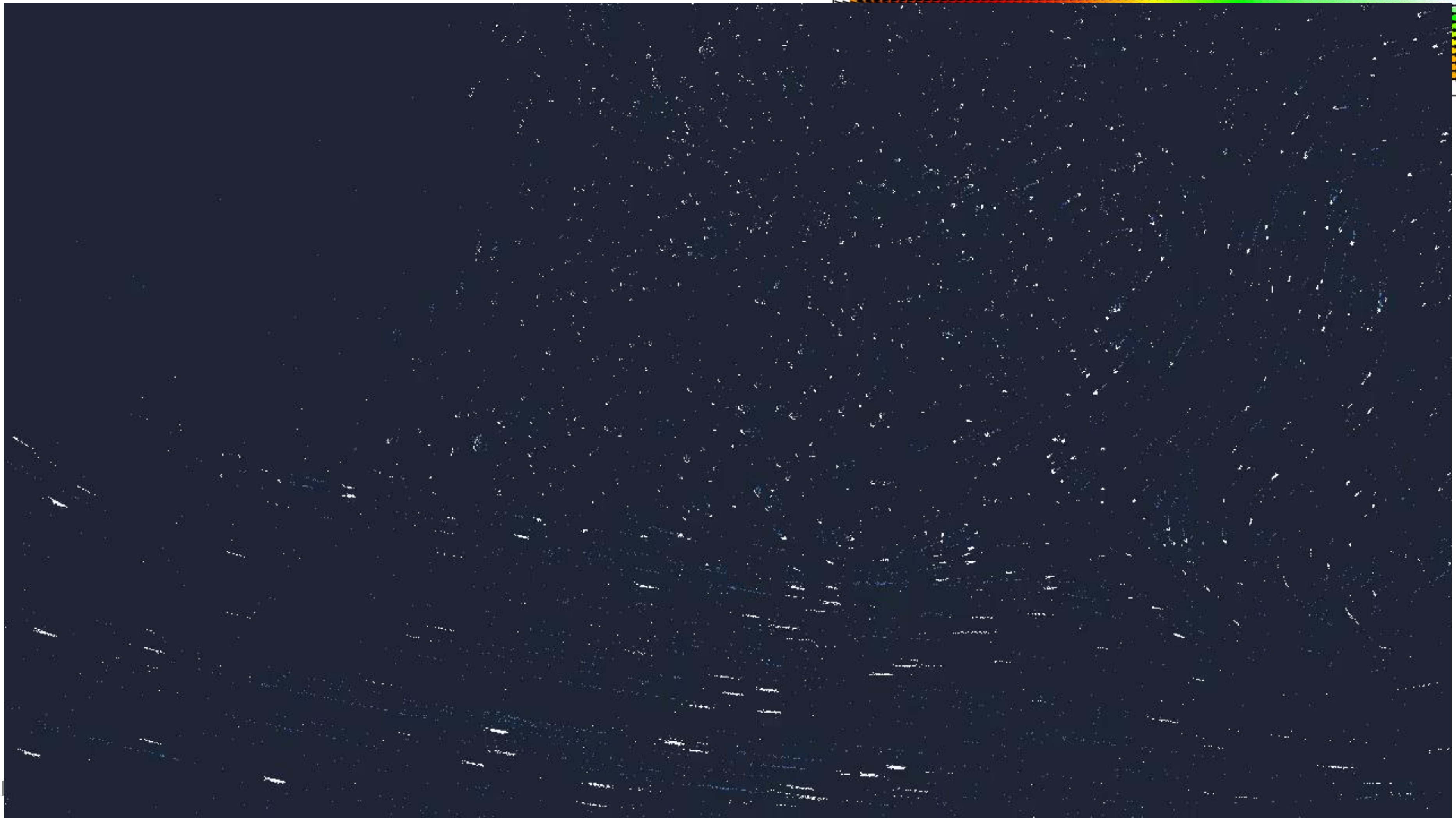




# Near-cylinder wake

| | |
|---|---|
| display: | 2 ms of events/frame |
| play back: | 0.0075x (4000 frames/s) |
| duration: | 250 ms |



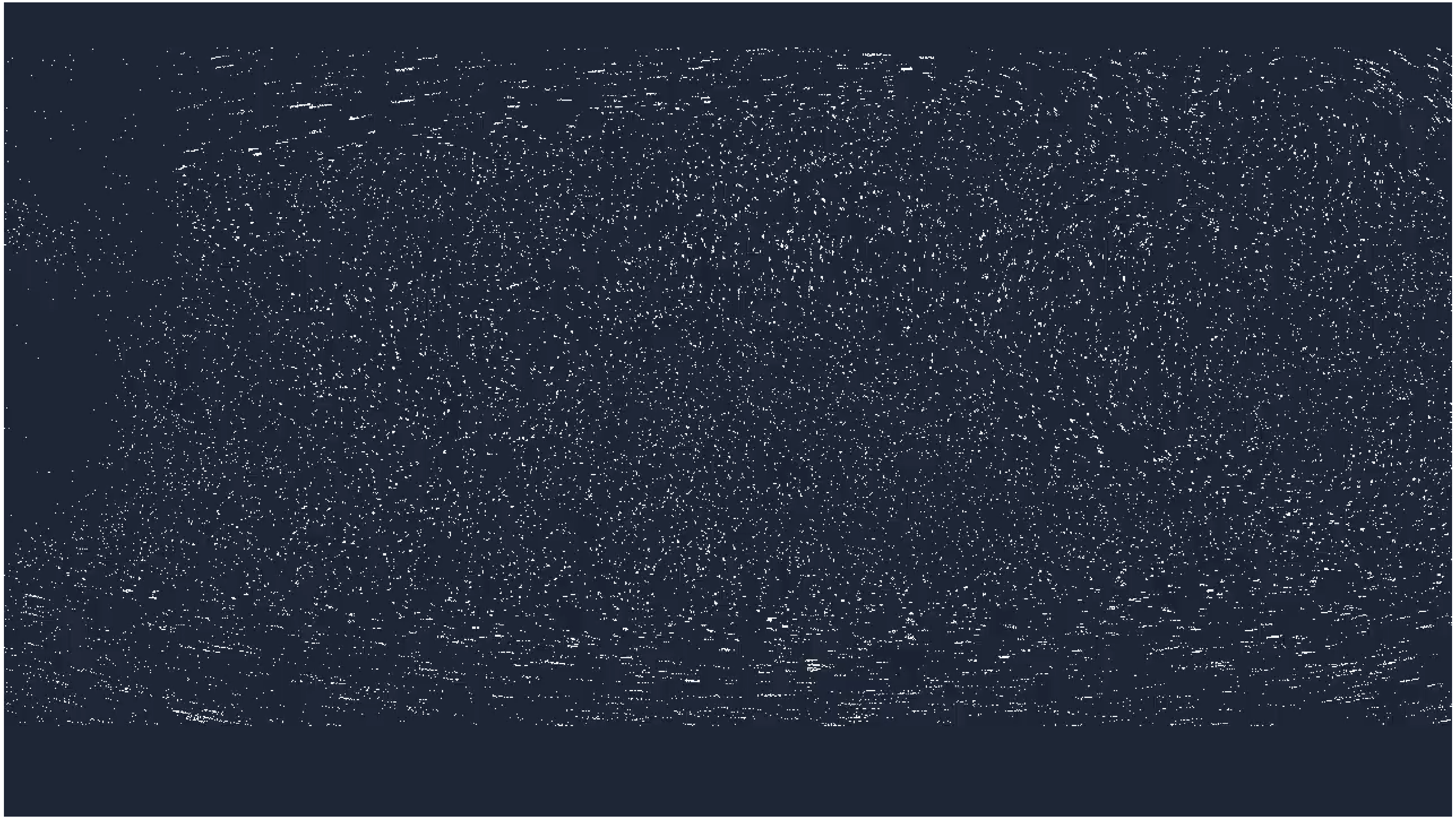



# Measurements of Cylinder Wake Revisited

2 ms/frame

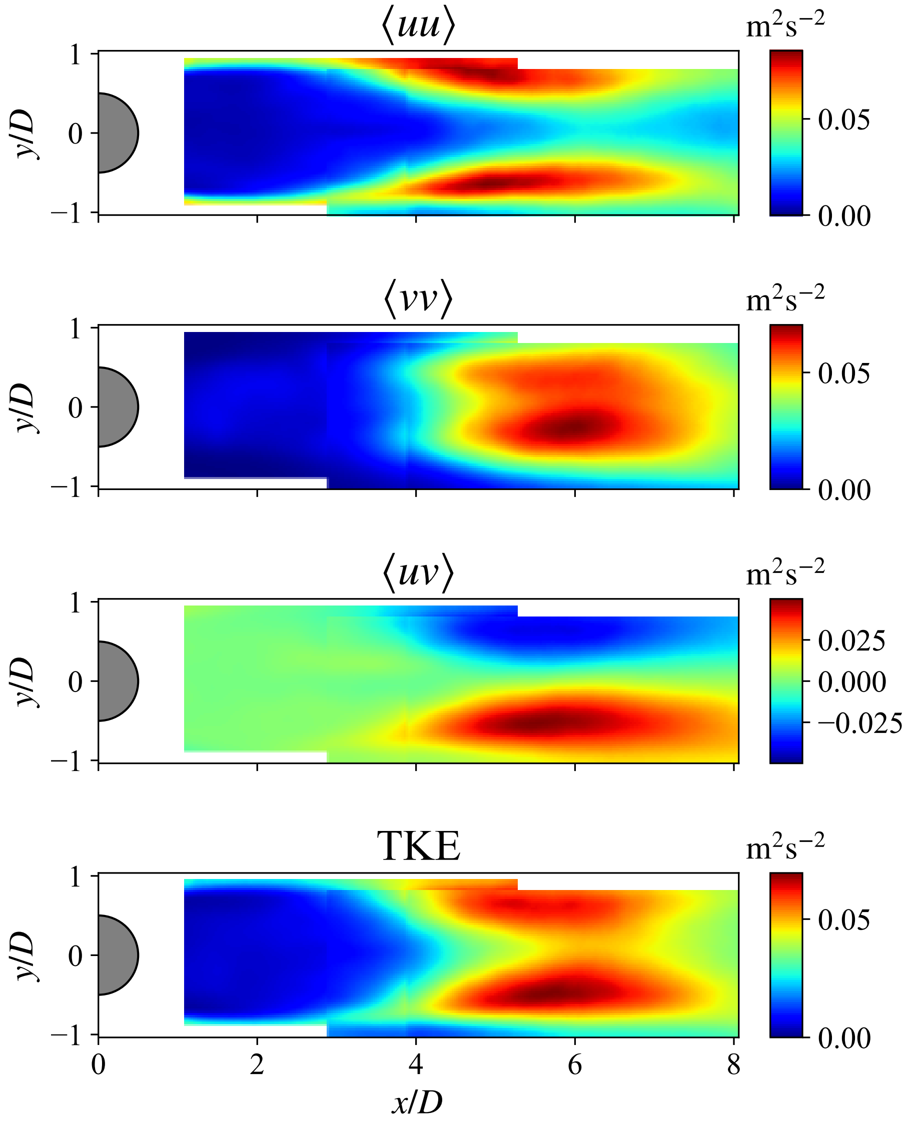
Playback slowed
0.015x (2000 fps)

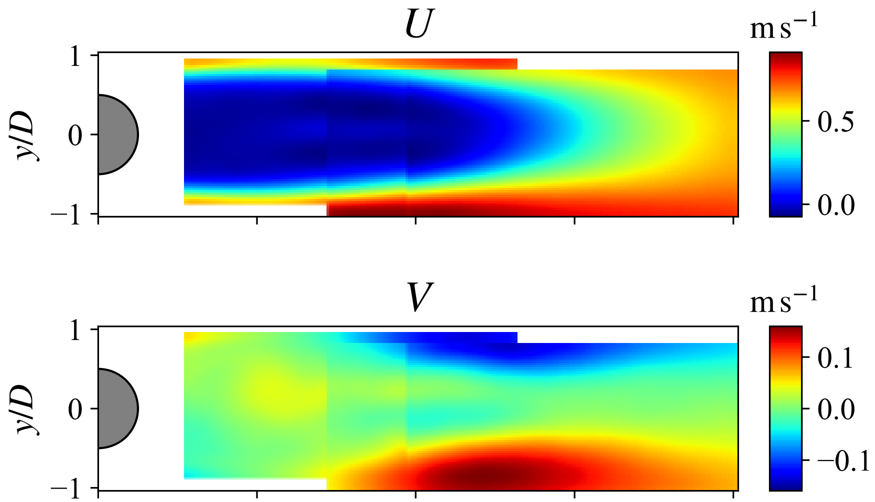
Length 200 ms



# Cylinder wake - velocity statistics

- multiple records of ~10 s duration
- velocity field estimation
  - pseudo-images from time slices of 400 µs
    → 25’000 images @ 2.5 kHz
  - conventional cross-correlation (PIV) processing using 5 frame
  - standard validation schemes
    (normalized median filter)

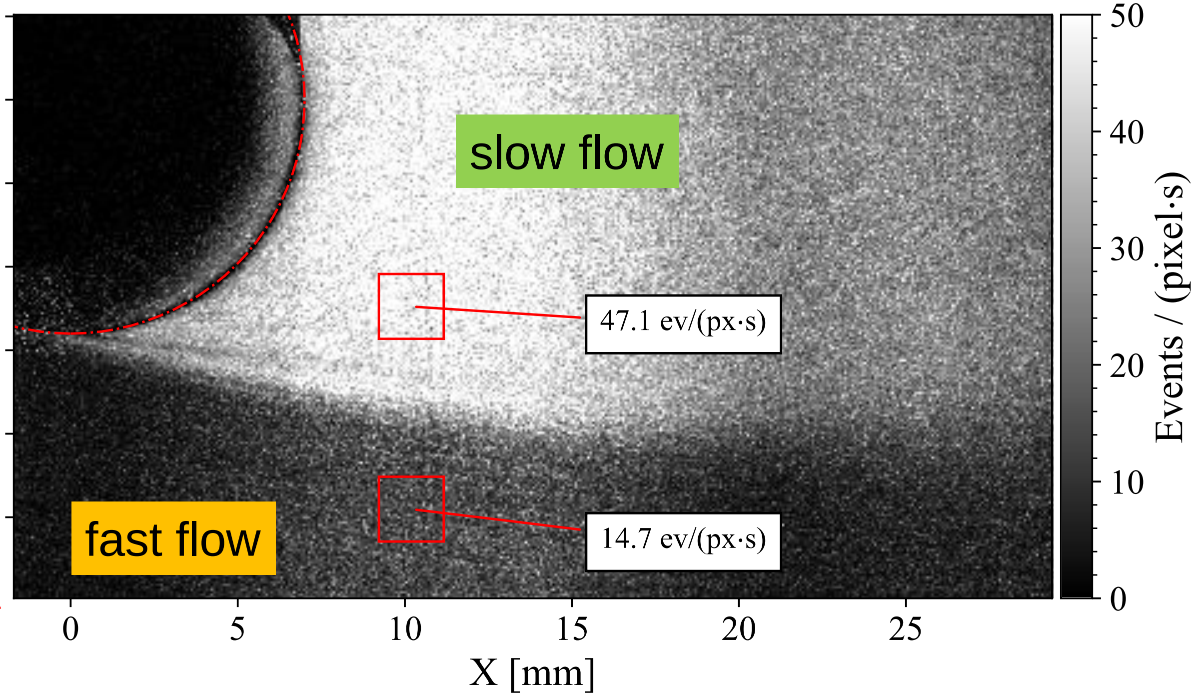


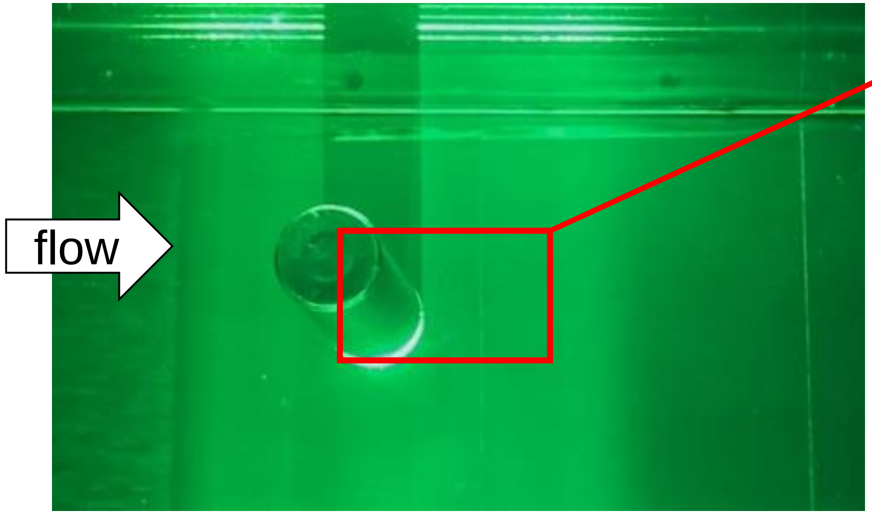



# Another issue: Event rate depends on flow velocity

- **stationary / slow moving particles** become "invisible" by producing no or too few events (constant brightness)
  → loss of data
- **fast moving particles** trigger fewer events (not enough photons collected by pixel)
  → reduction / loss of data rate in fast flow
  (limit ~25,000 pixel/s)

Distribution of event rate




near wake of cylinder

uniform seeding throughout

# EBIV using Pulsed Illumination

**Assume events are triggered by preceding pulse**

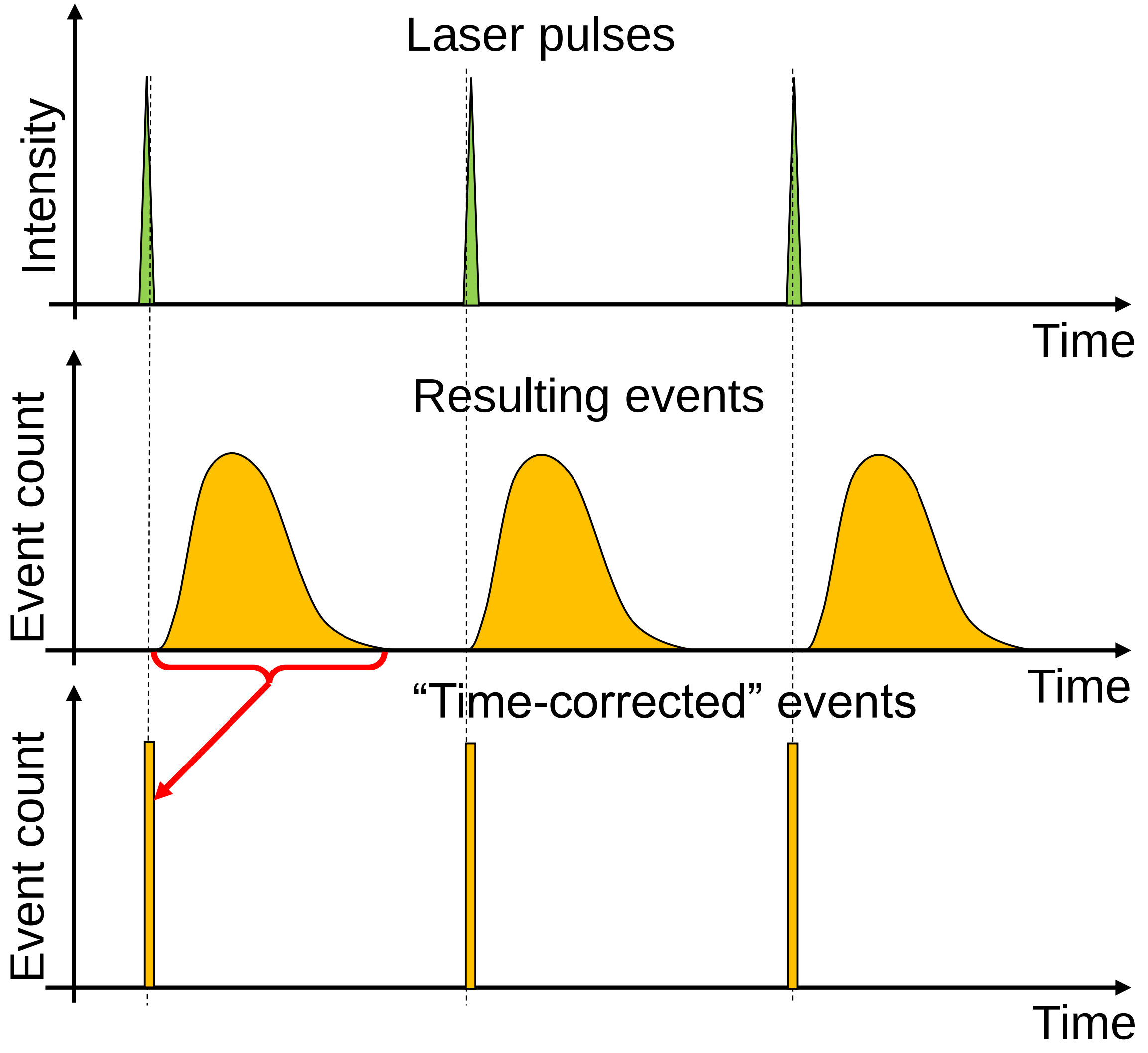
**potentials**

- should make both stationary as well as fast moving objects (= particles) visible
- removes the latency induced event uncertainty (pulse timing is precisely known / controllable)

**risks**

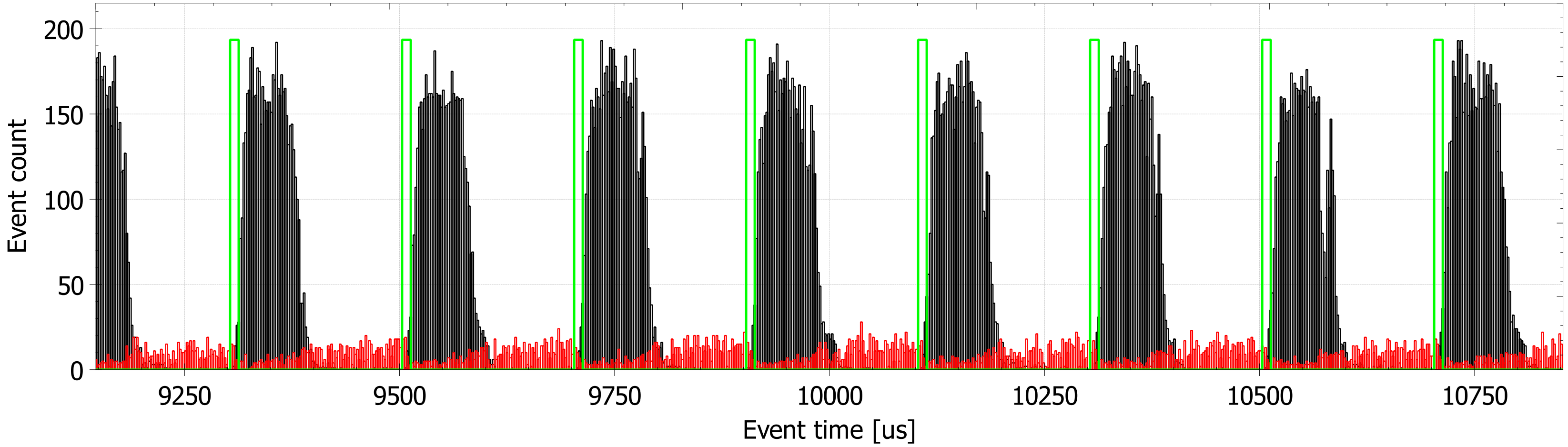
- immediate saturation of detector by flooding the scene with events
- unwanted artefacts (background, laser scatter, ...)

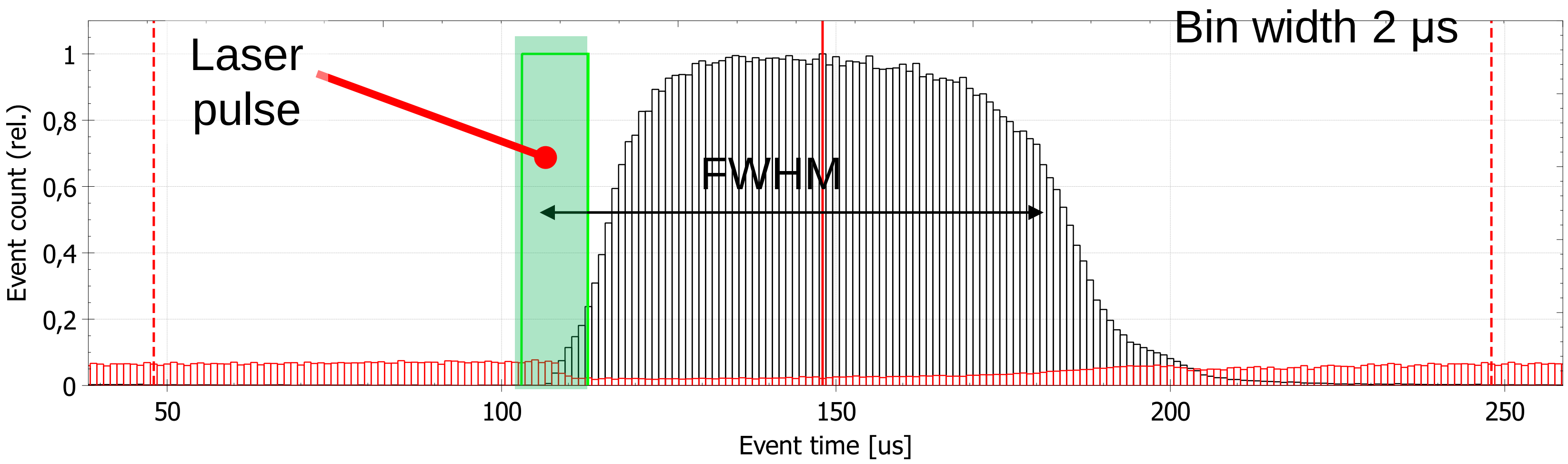
concept previously used for 3-D reconstruction of objects (laser line scanning) → "structured light"



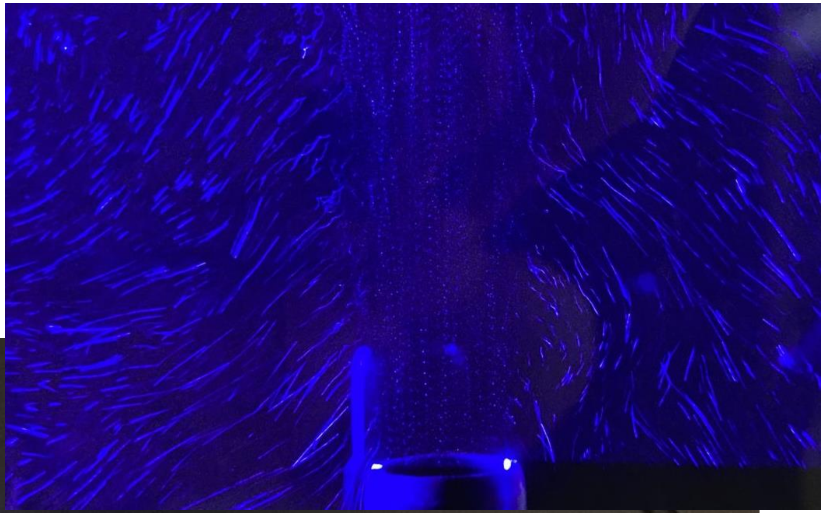
# Events in response to pulsed illumination (actual data)

- Laser pulse rate:
  5 kHz at 10 µs width
  (modulated CW laser)
- events: 70 µs (FWHM)
- black: "on" events
- red: "off" events

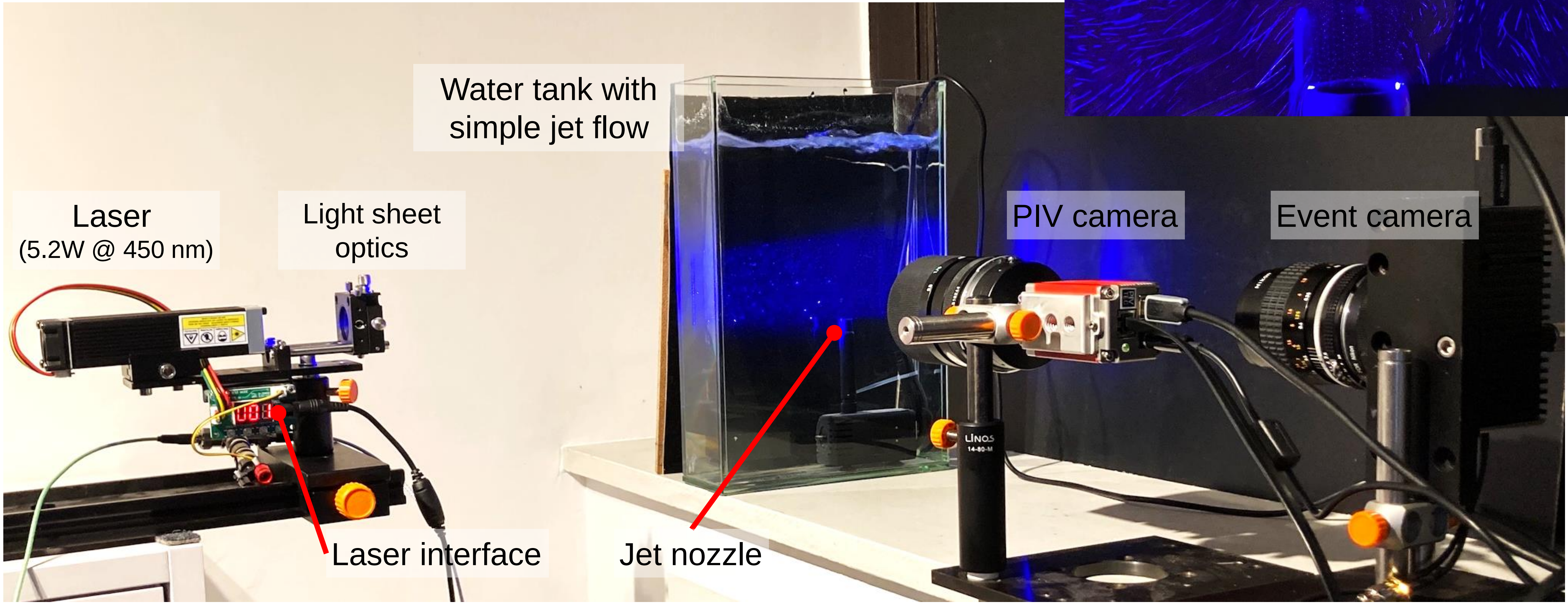


# Pulsed EBIV on simple water flow



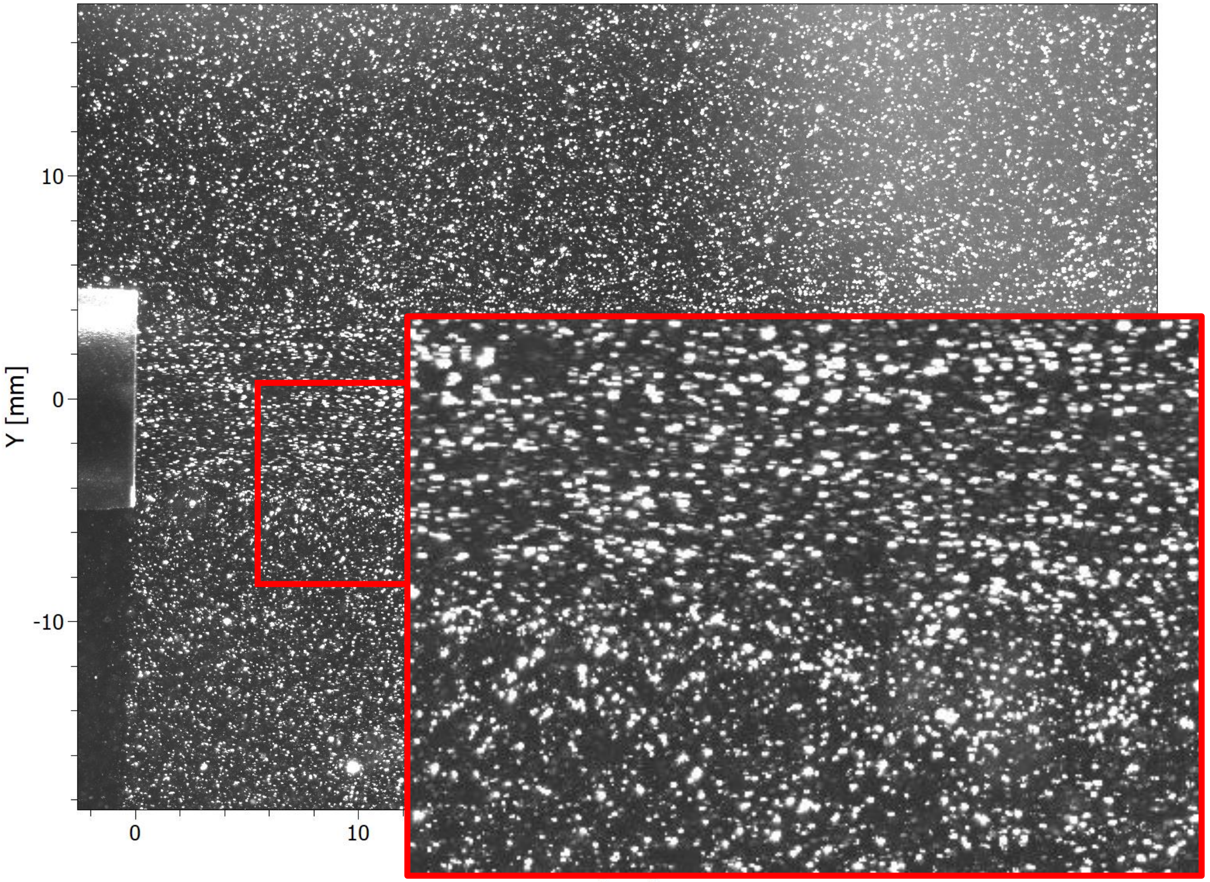
combined with PIV for comparison



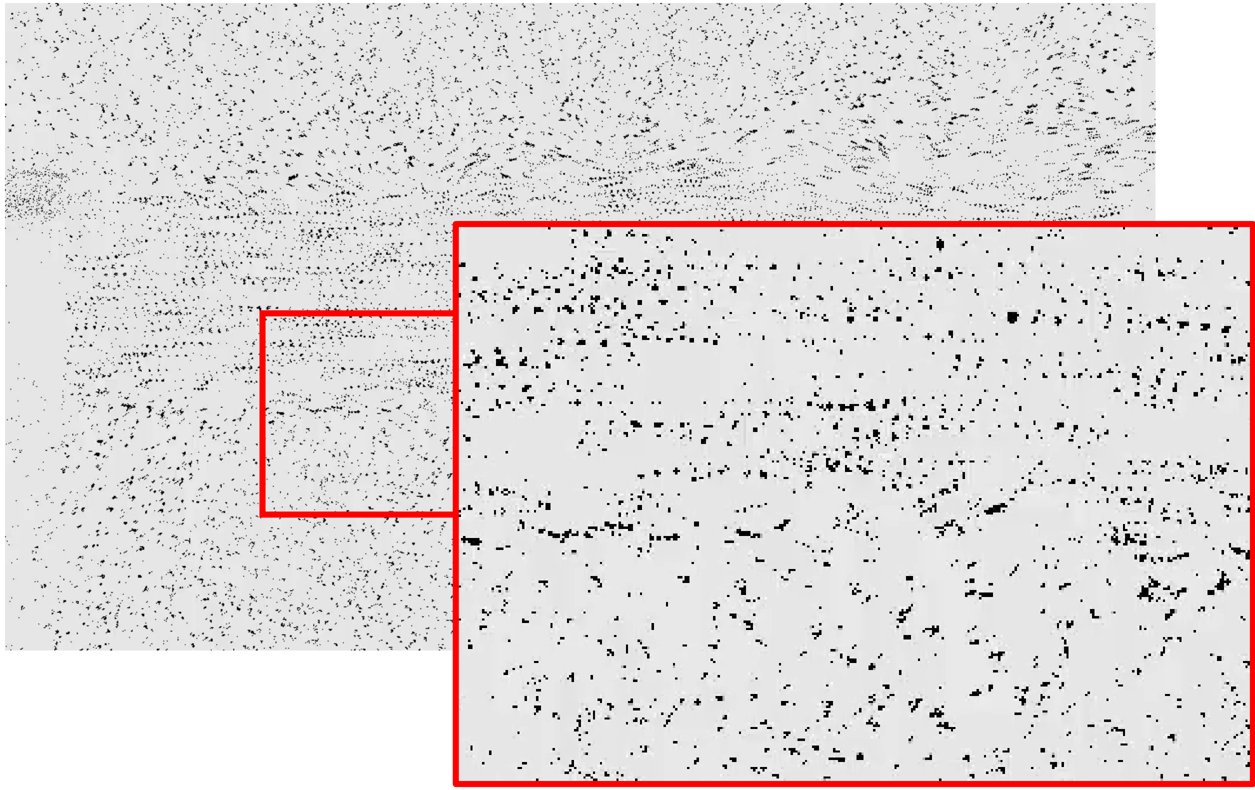
# PIV and EBIV on a small turbulent water jet

(same laser/light-sheet, same seeding)

**PIV recording** (overlaid image pair)
pulse delay: 500 µs, pulse width: 100 µs




**Event based imaging** with pulsed illumination at 4 kHz (→ pulse delay: 250 µs), pulse width: 7.5 µs



# Comparison PIV and EBIV on a small turbulent water jet

**PIV**

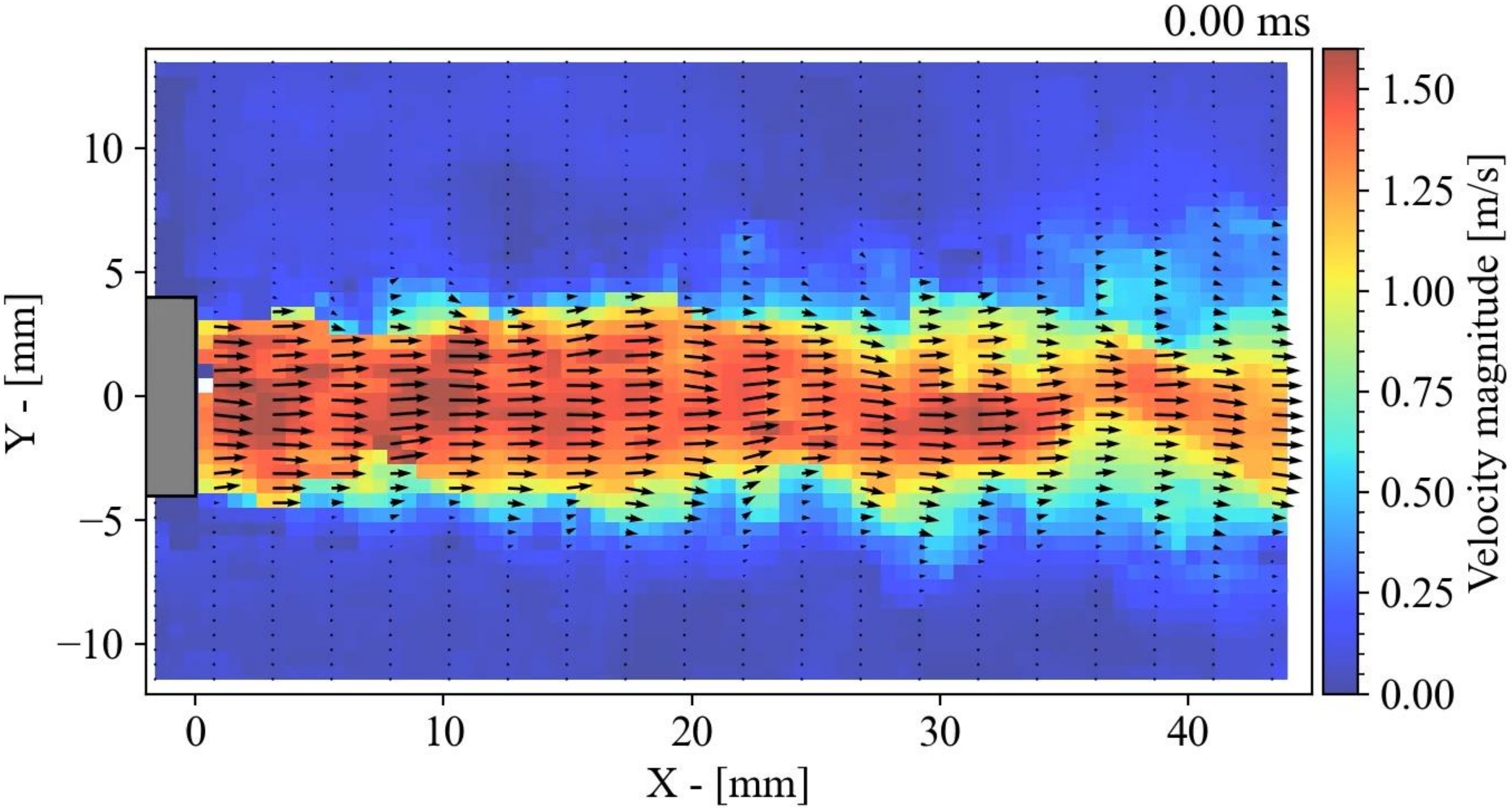
- double pulses at 4 Hz
- pulse delay: 500 µs
- pulse width: **100 µs**
- lens: 55mm Nikon Micro-Nikkor 55/2.8, **f#2.8**
- magnification: 28.7 pixel/mm
- 1000 recordings at 4 Hz (~4 min)
  → 1000 uncorrelated snap shots (12 bit)
  → **3.25 GB** (compressed)
- correlation processing using 2 frames

**EBIV**

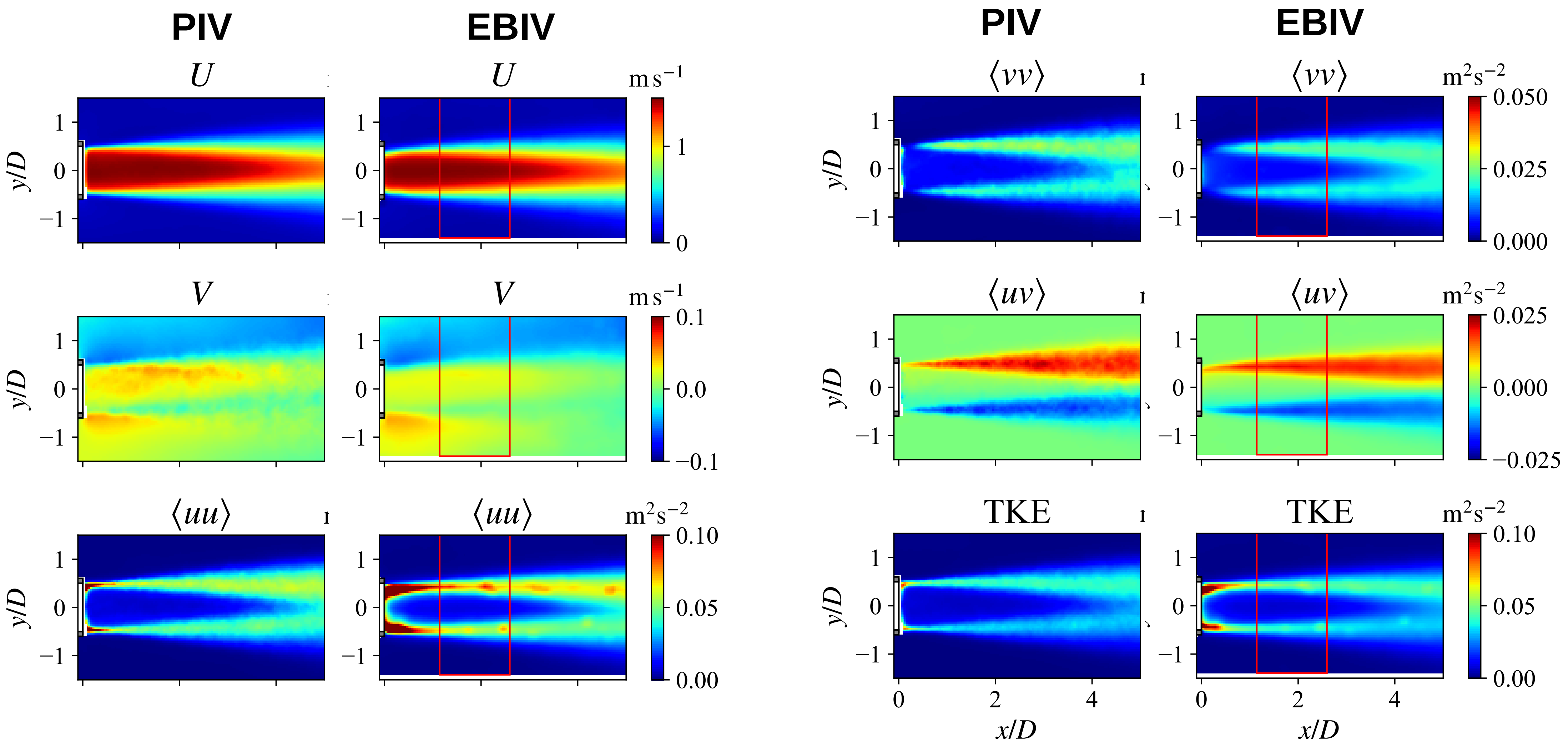
- laser pulses at 4 kHz
- (pulse delay 250 µs)
- pulse width: **7.5 µs**
- lens: 55mm Nikon Micro-Nikkor 55/2.8, **f#4.0**
- magnification: 27.0 pixel/mm
- 10 seconds of event data
  → 40,000 correlated "pseudo"-images (1 bit)
  → **0.95 GB** (compressed) ~ 100 MB/s
- correlation processing using 5 frames / time step
  → low-pass filtering at 800 Hz (1/1250 $\mu s^{-1}$)

same laser/light-sheet, same seeding

# Result obtained from event data (5 kHz pulse rate)

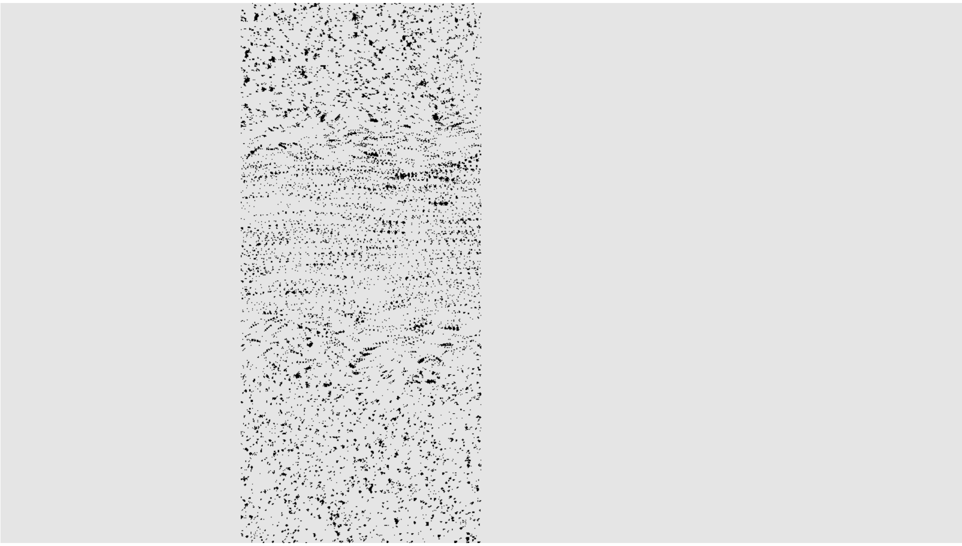


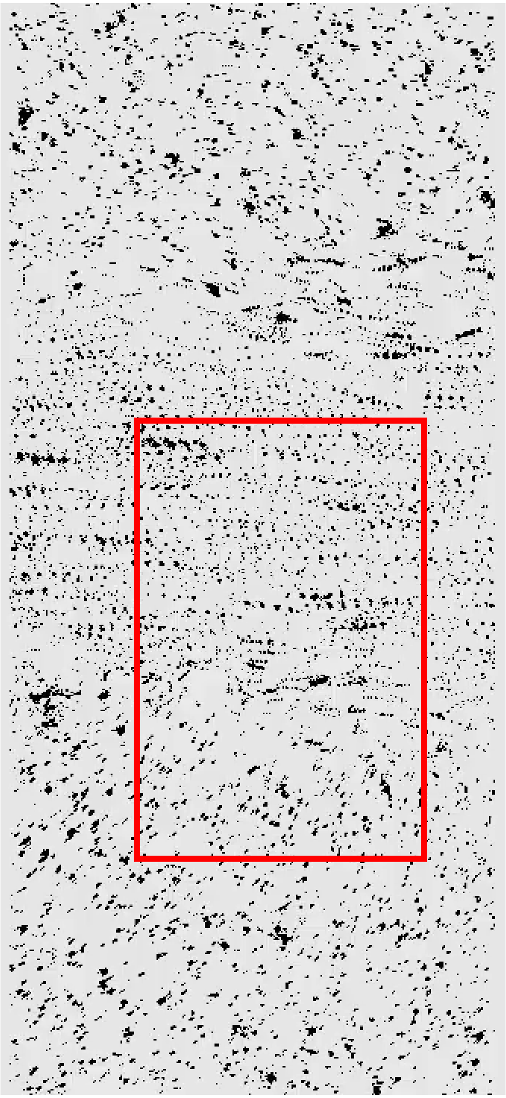
# Comparison PIV and EBIV - velocity statistics



# Comparison PIV and EBIV - velocity statistics at reduced ROI

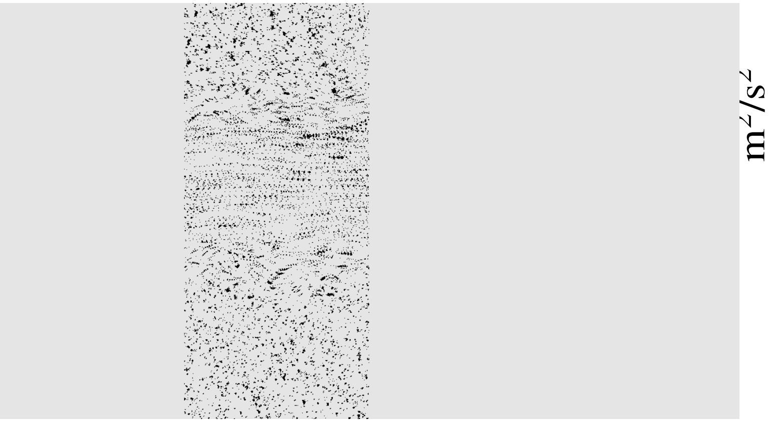
- region of interest (ROI)
  reduced to 320(W) x 720(H)
- event data rate increased proportionally
  (increased particle image density)
- laser pulse rate up to 10 kHz

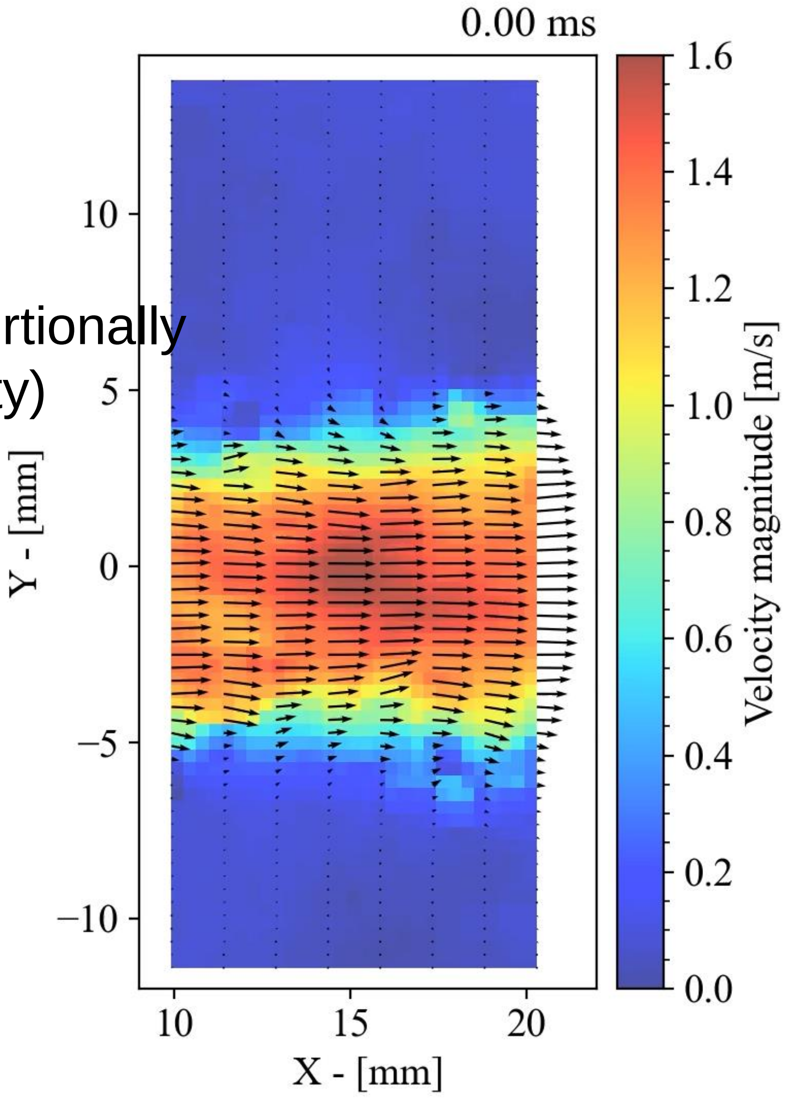


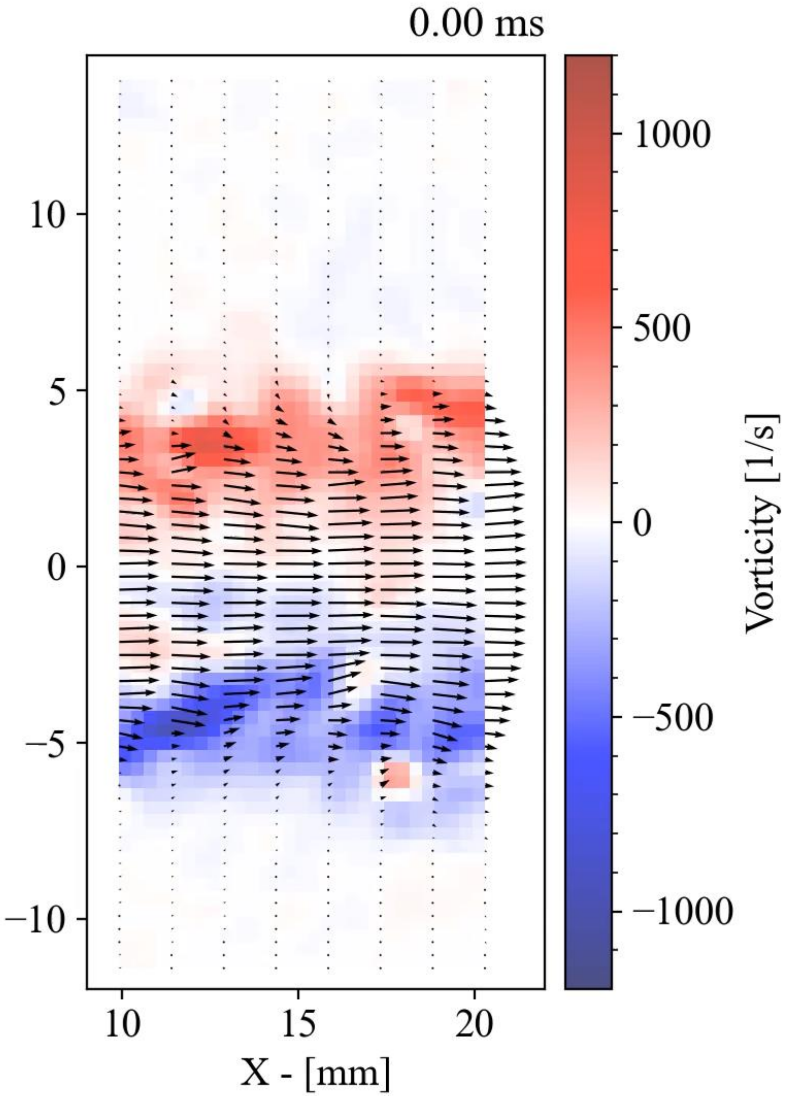


# Comparison PIV and EBIV - velocity statistics at reduced ROI

- region of interest (ROI)
  reduced to 320(W) x 720(H)
- event data rate increased proportionally
  (increased particle image density)
- laser pulse rate up to 10 kHz
- improved match with PIV result

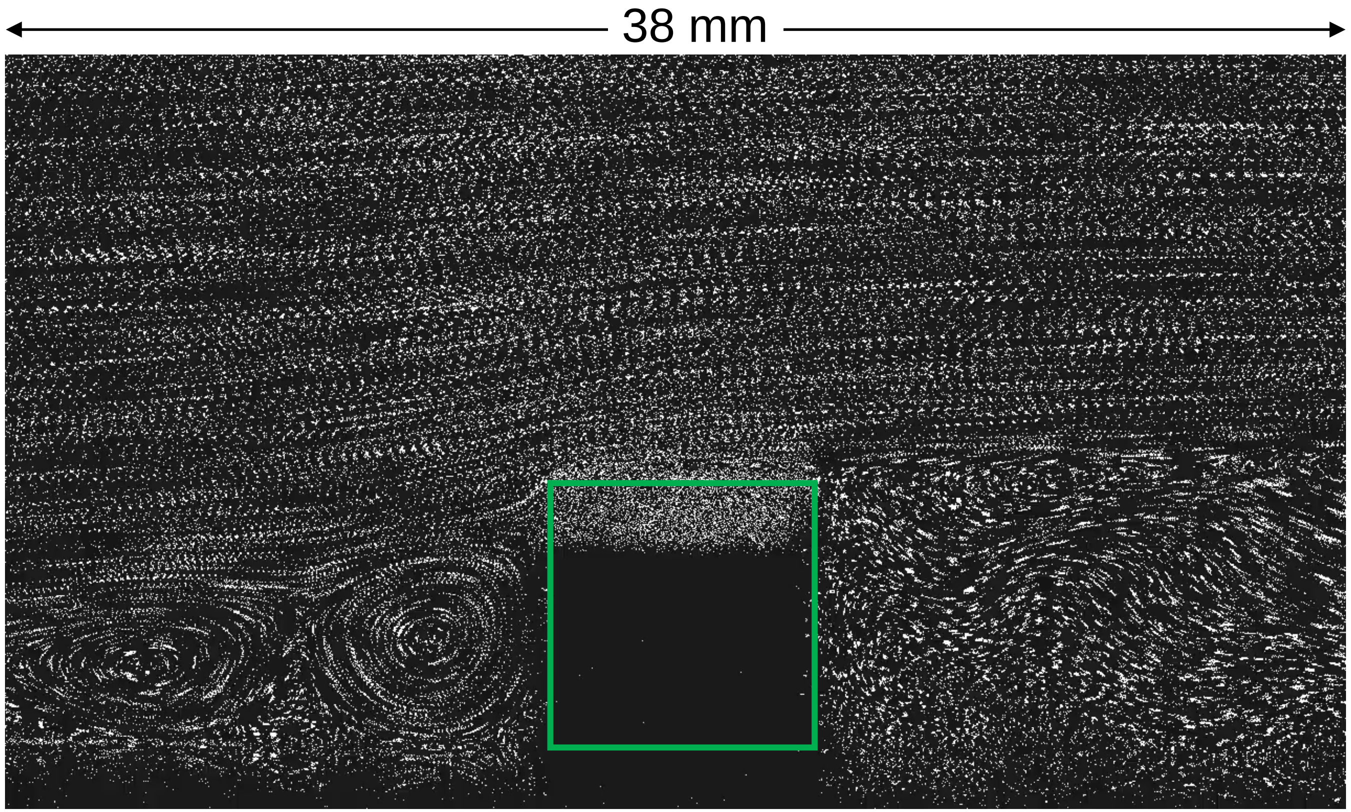


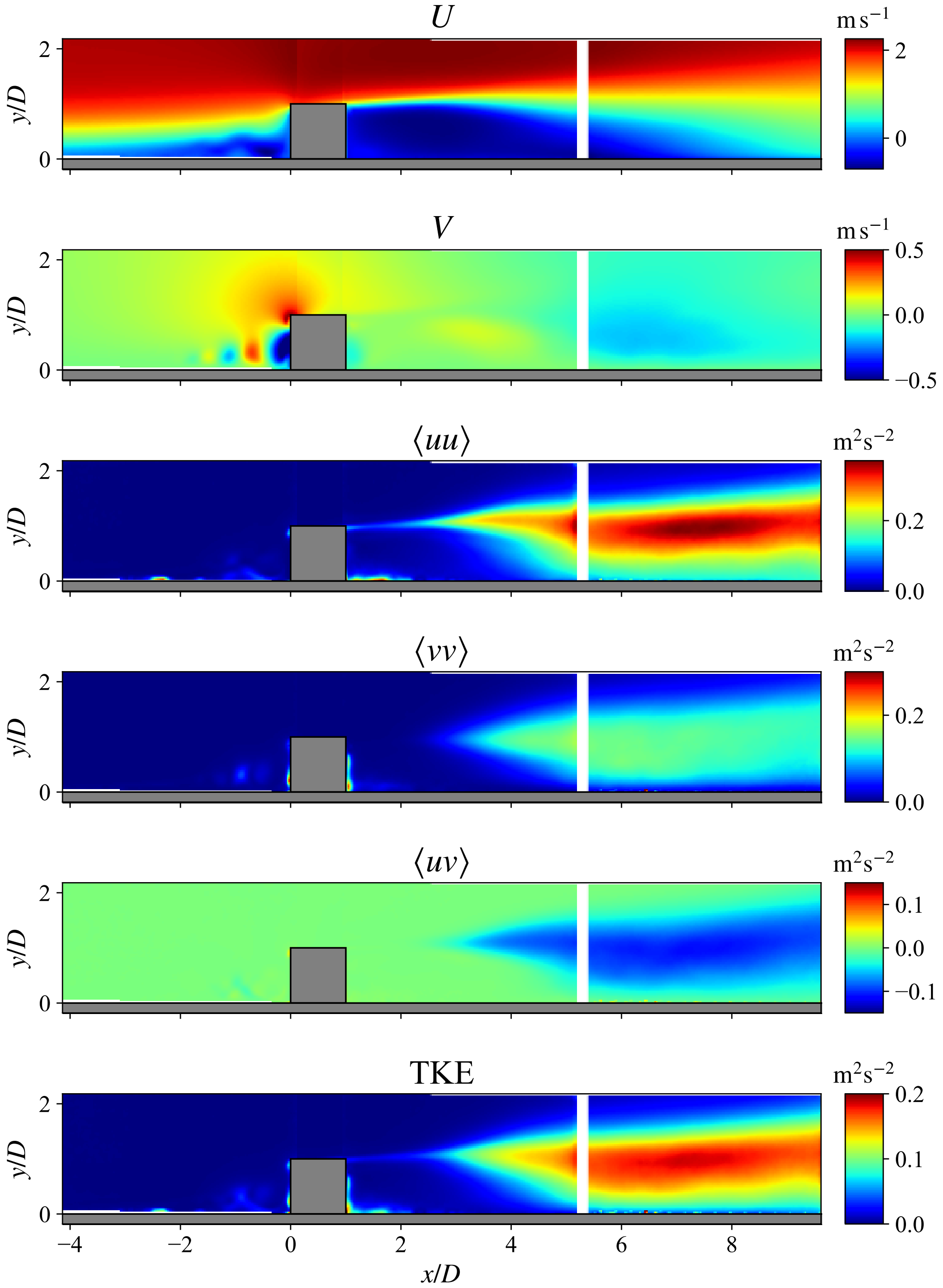


# Flow around a square rib

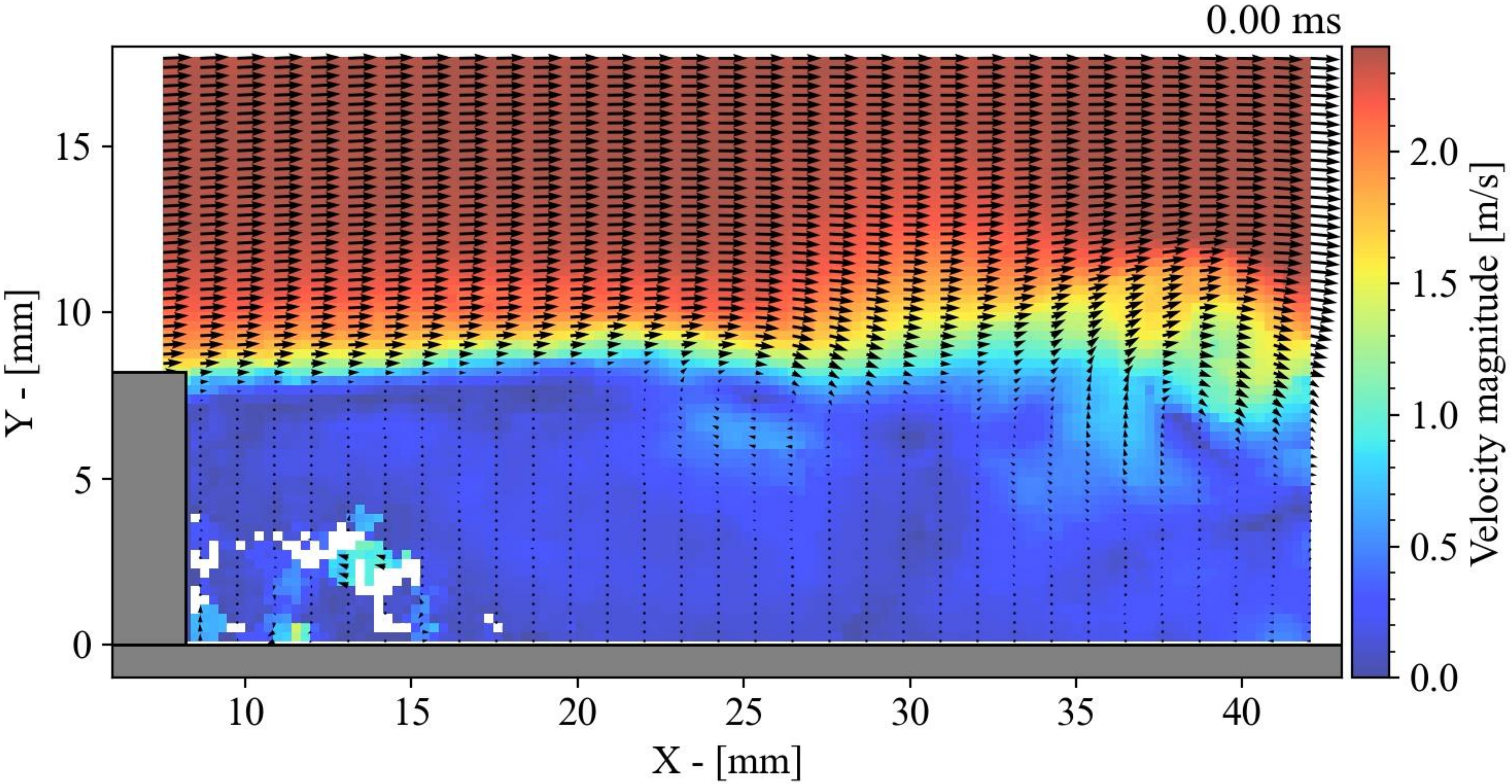
- laminar inflow at 2 m/s
- 5 kHz pulse rate
- *D* = 8.17 mm



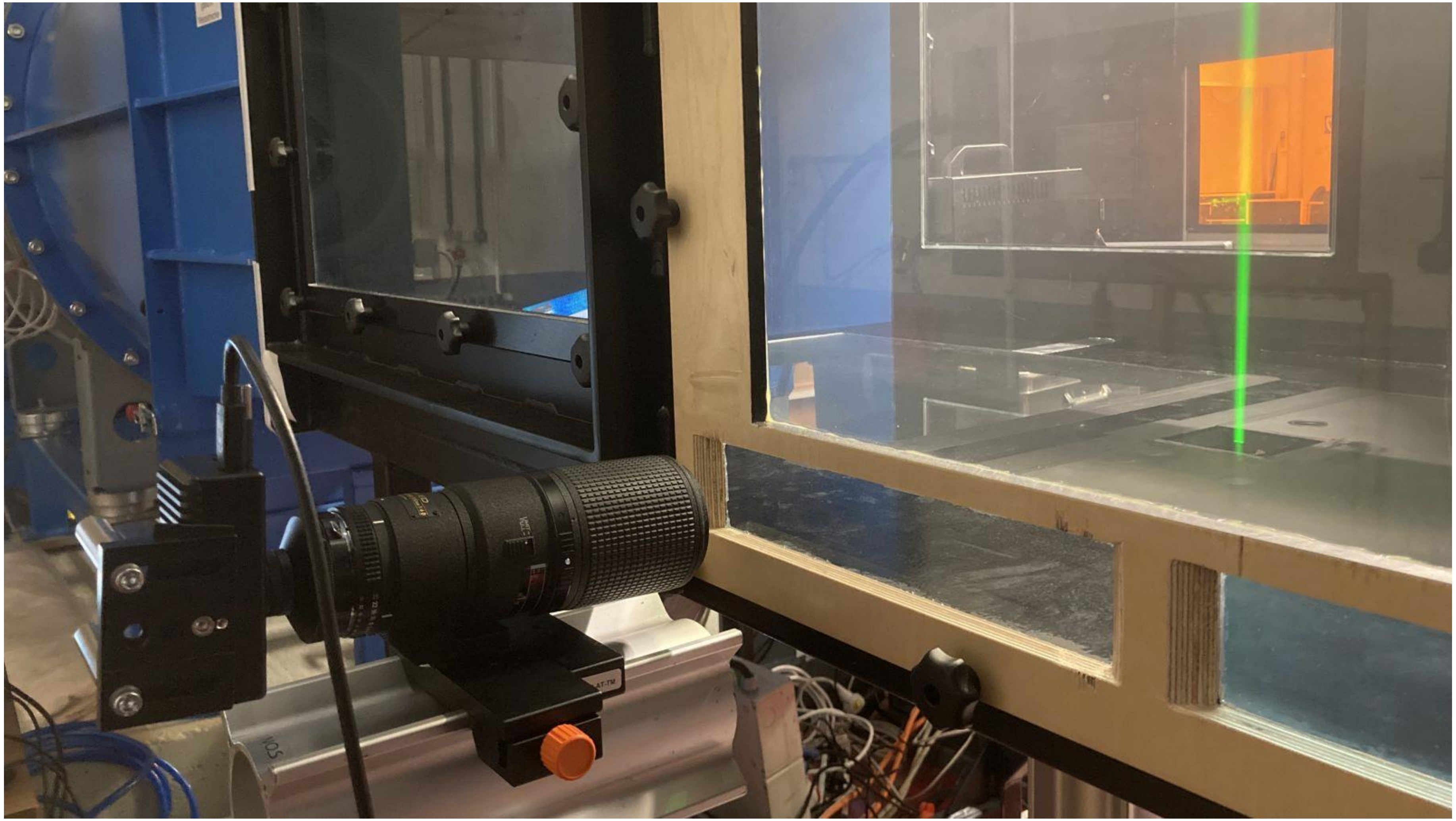



# Flow downstream of square rib

- 5 kHz pulse rate

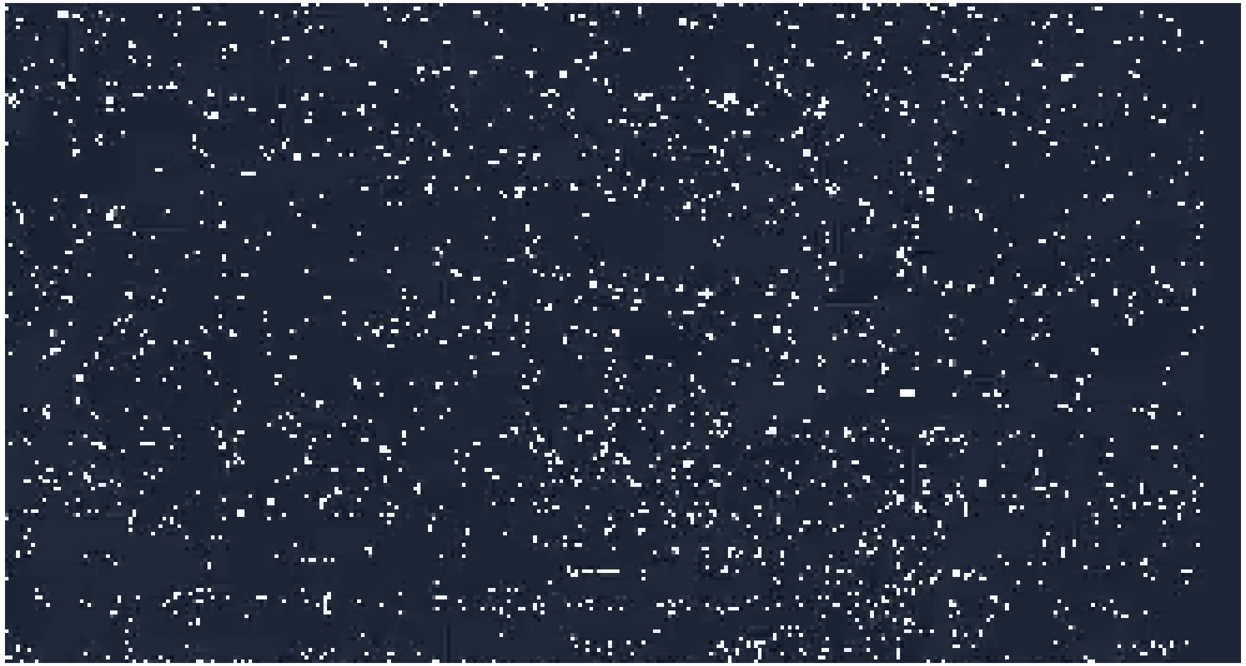


# EBIV Setup in 1m Windtunnel of DLR Göttingen



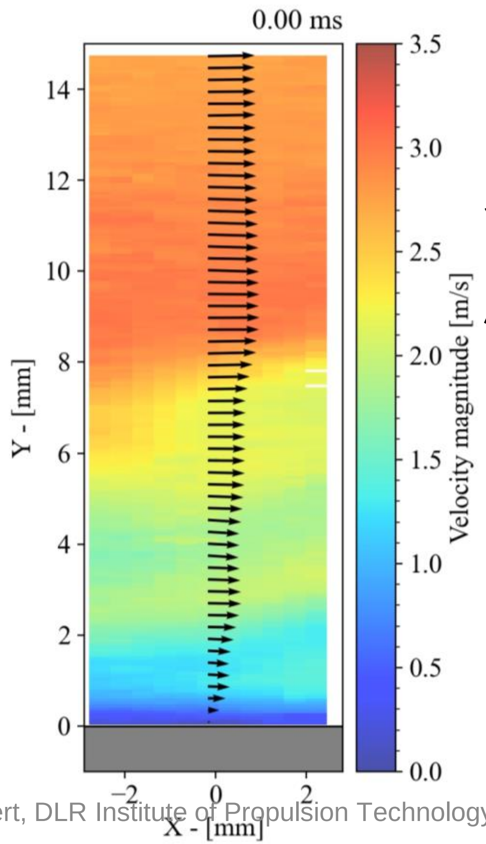
# Pulsed EBIV on turbulent boundary layer in air

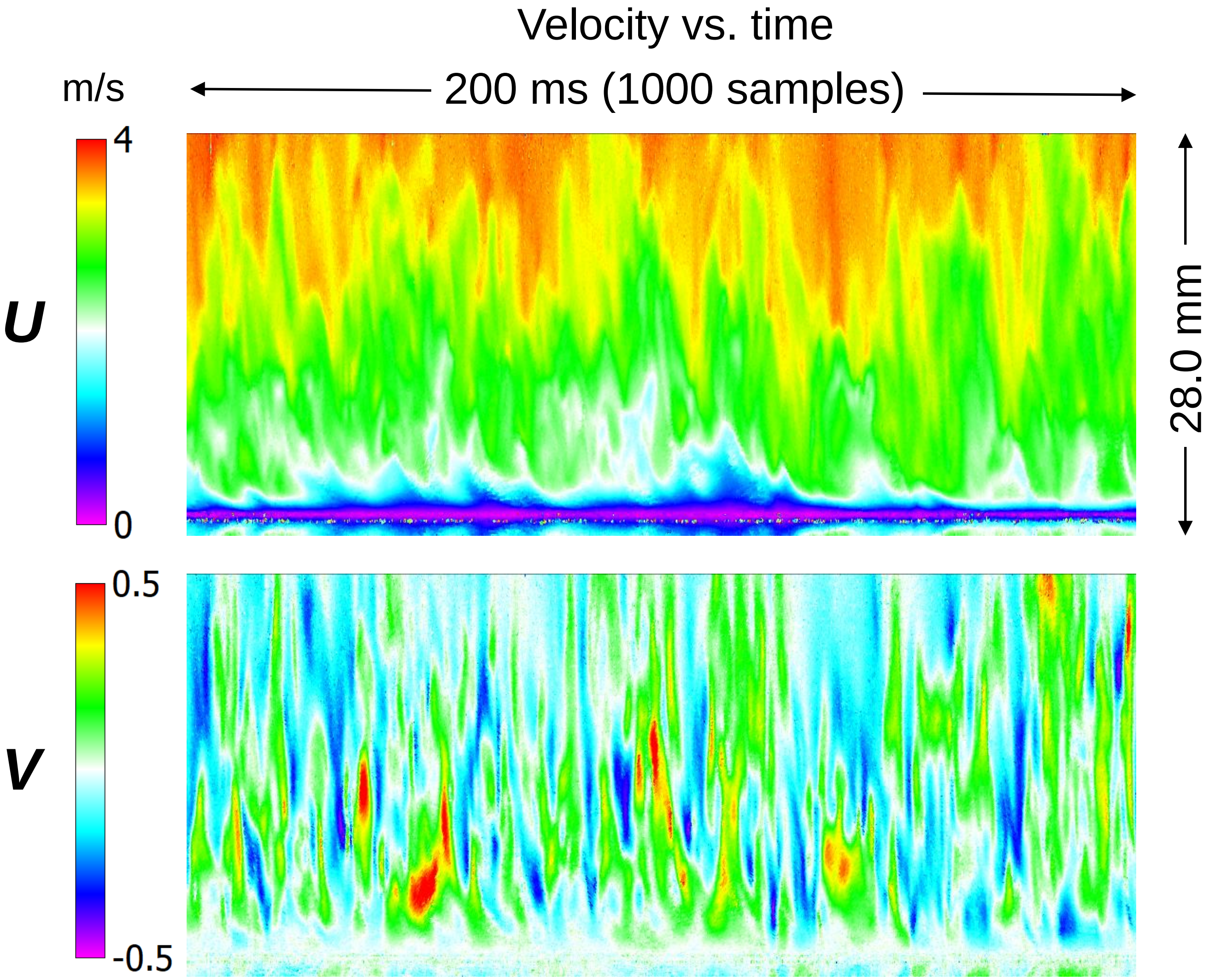
- Laser pulsing rate: 5 kHz at 12 µs width
- eff. pulse width ~70 µs FWHM (events)
- Reduced field of view: 1280W x 320H (camera rotated)
- Data rate: 32.5 Mev/s (94 MB/s)
  or 6500 events / “frame” (200 µs)




# Pulsed EBIV on turbulent boundary layer in air

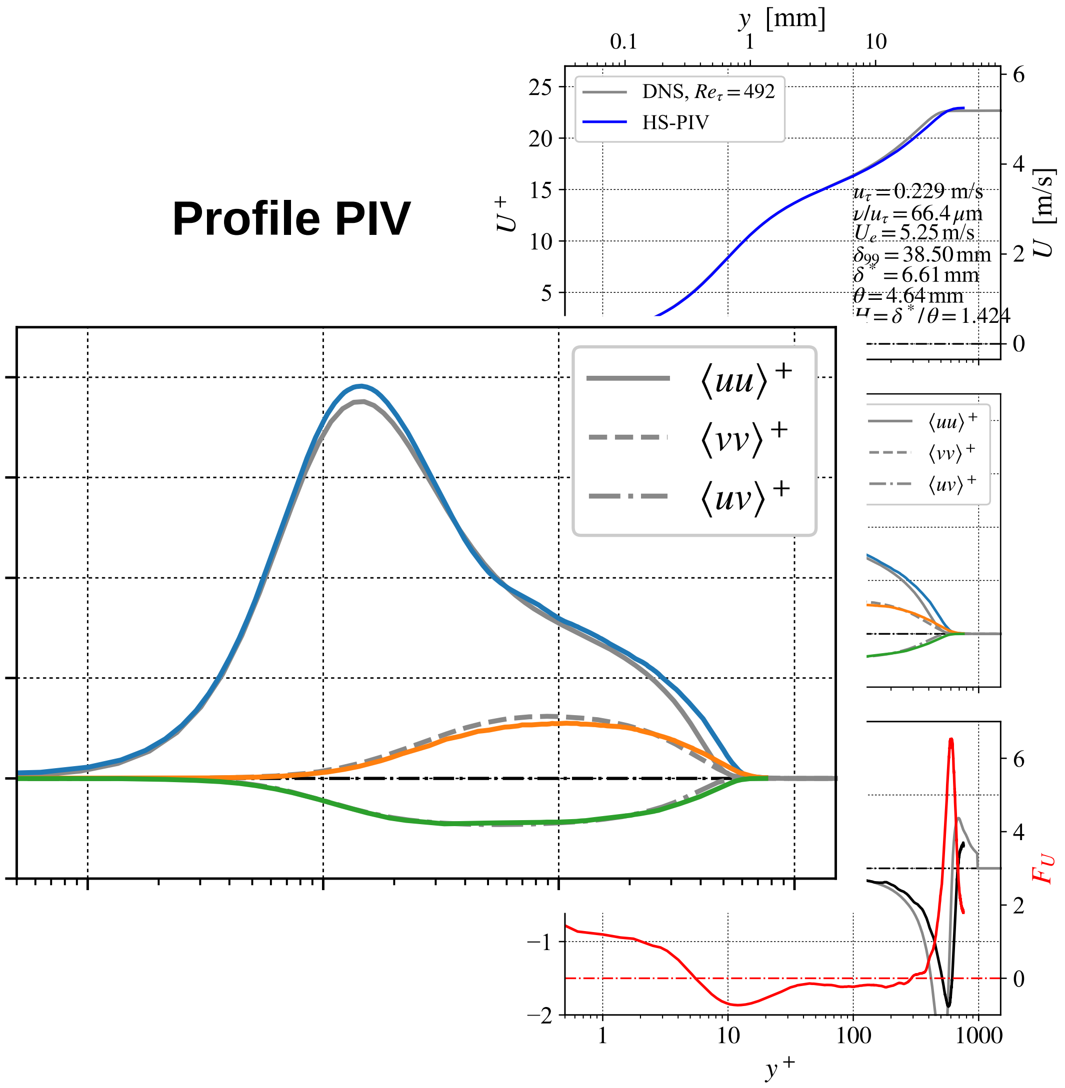
- total record length 2x 10 s (2x 50,000 pulses)
- processing using 5-frames per time step
- sampling (64 x 8 pixel) → (1.4 x 0.175 mm²)



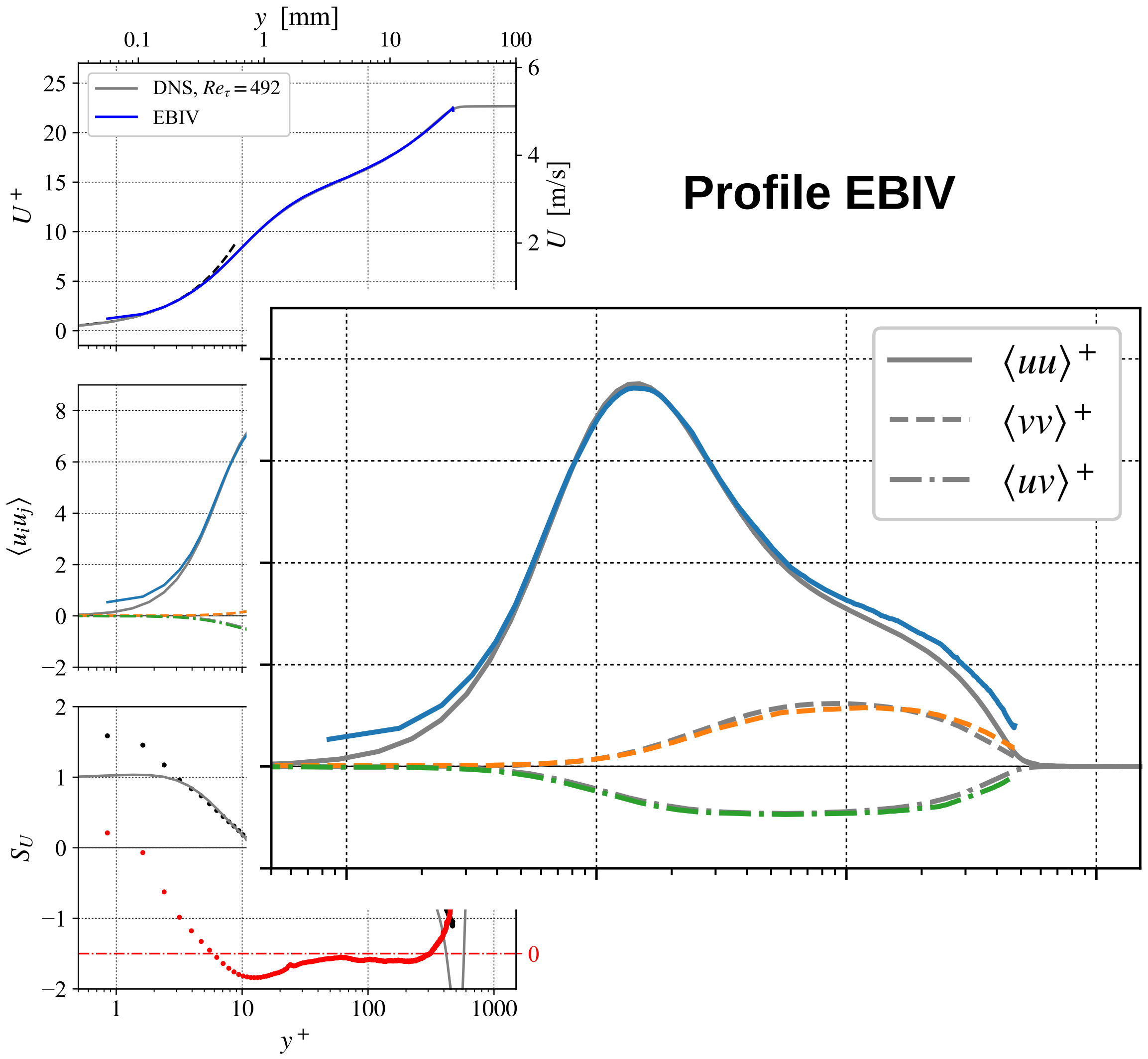



# Comparison: Profile-PIV vs Profile-EBIV

## Profile PIV

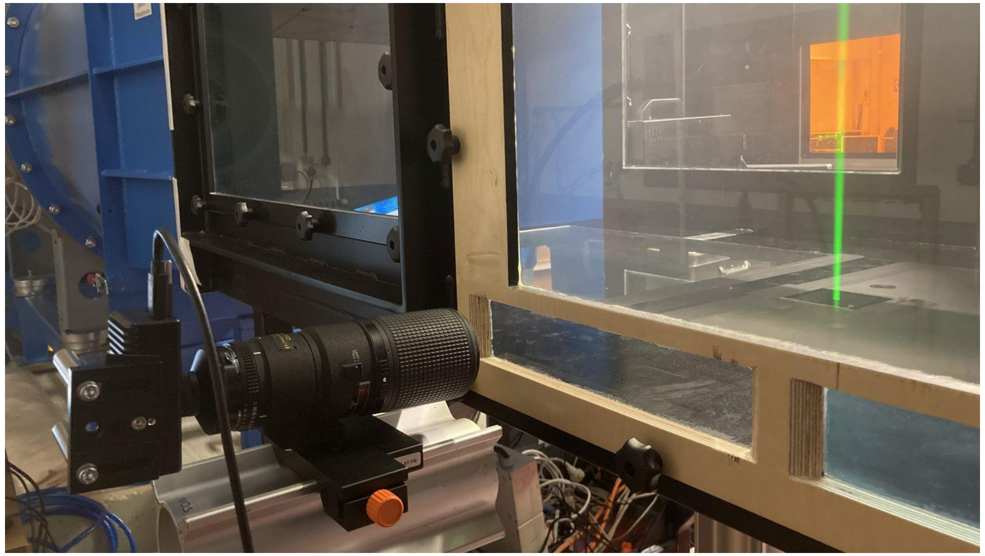


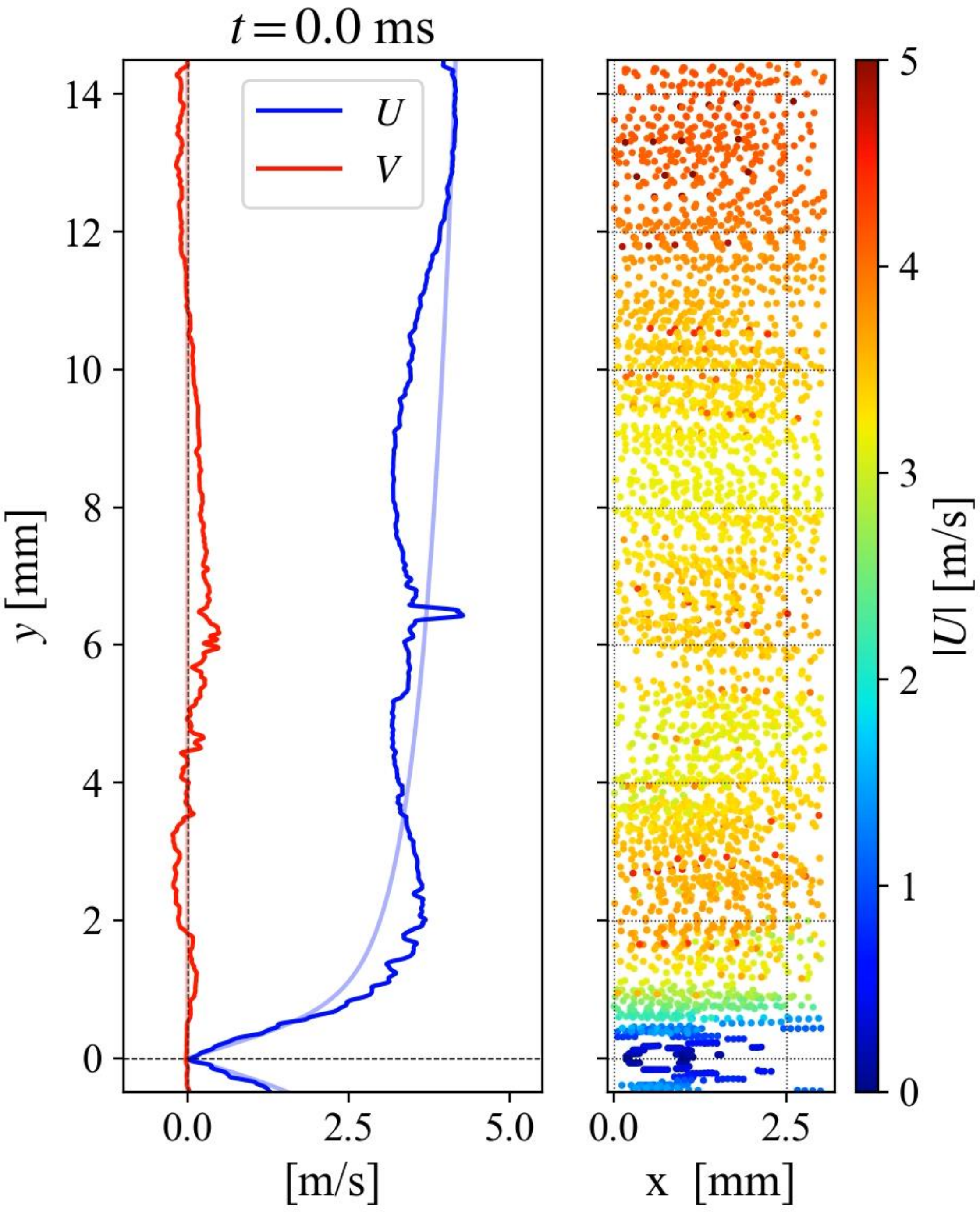

## Profile EBIV



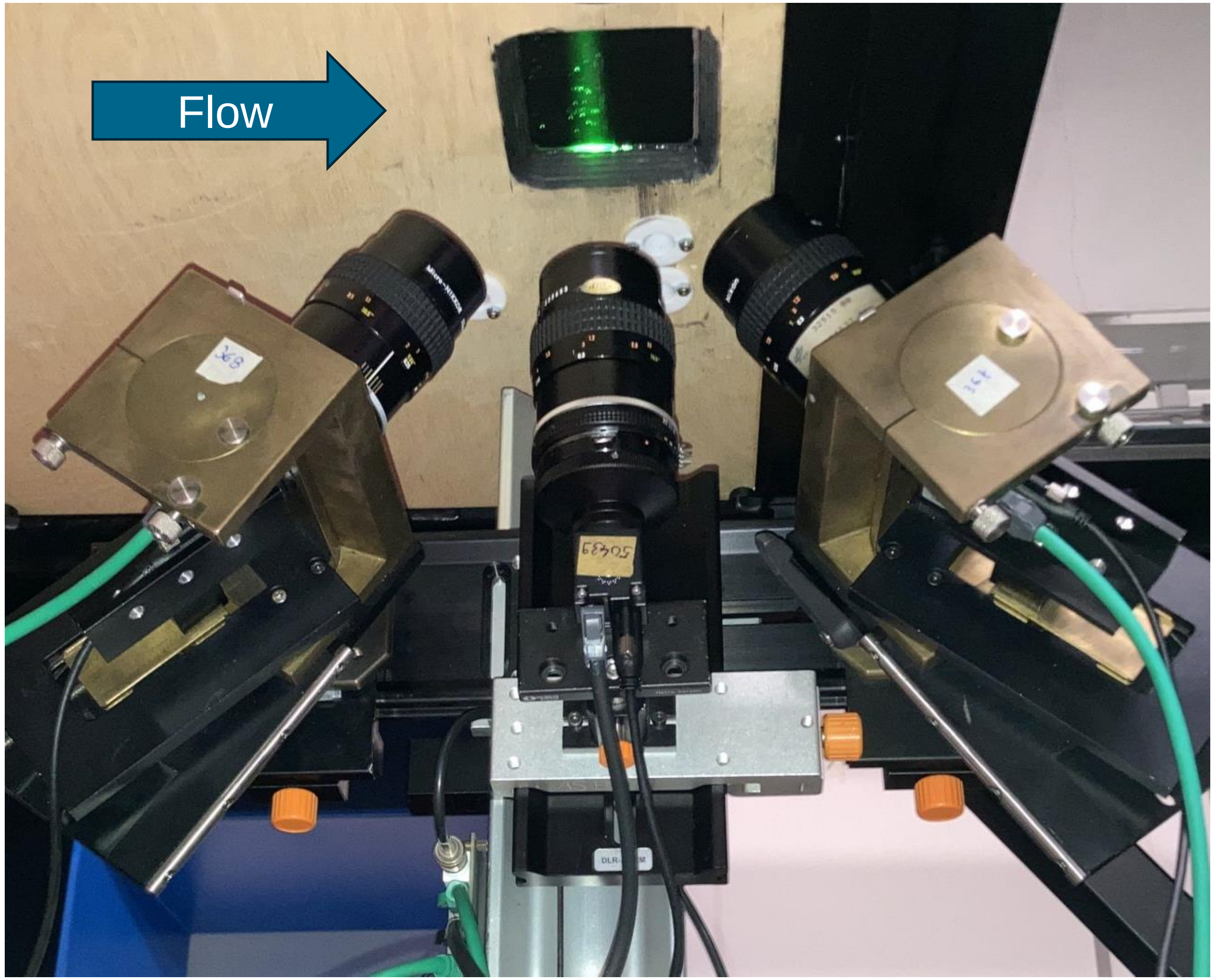
# Event-based PTV (EB-PTV)

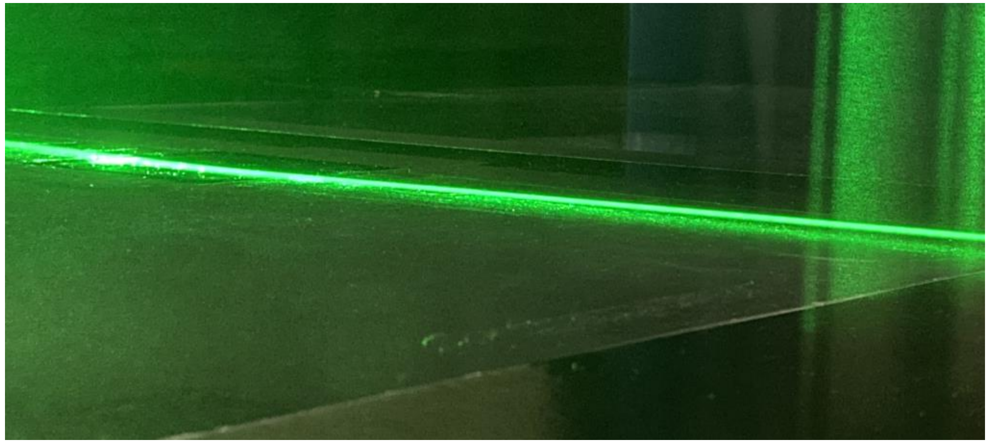
- laser pulse frequency: 10 kHz
- simple tracker scheme
- initial predictor required (Musker, 1979)
- processing rate: >200 frames/s
- density: ~2000 particles/frame





# Extension to 3D Event-based PTV

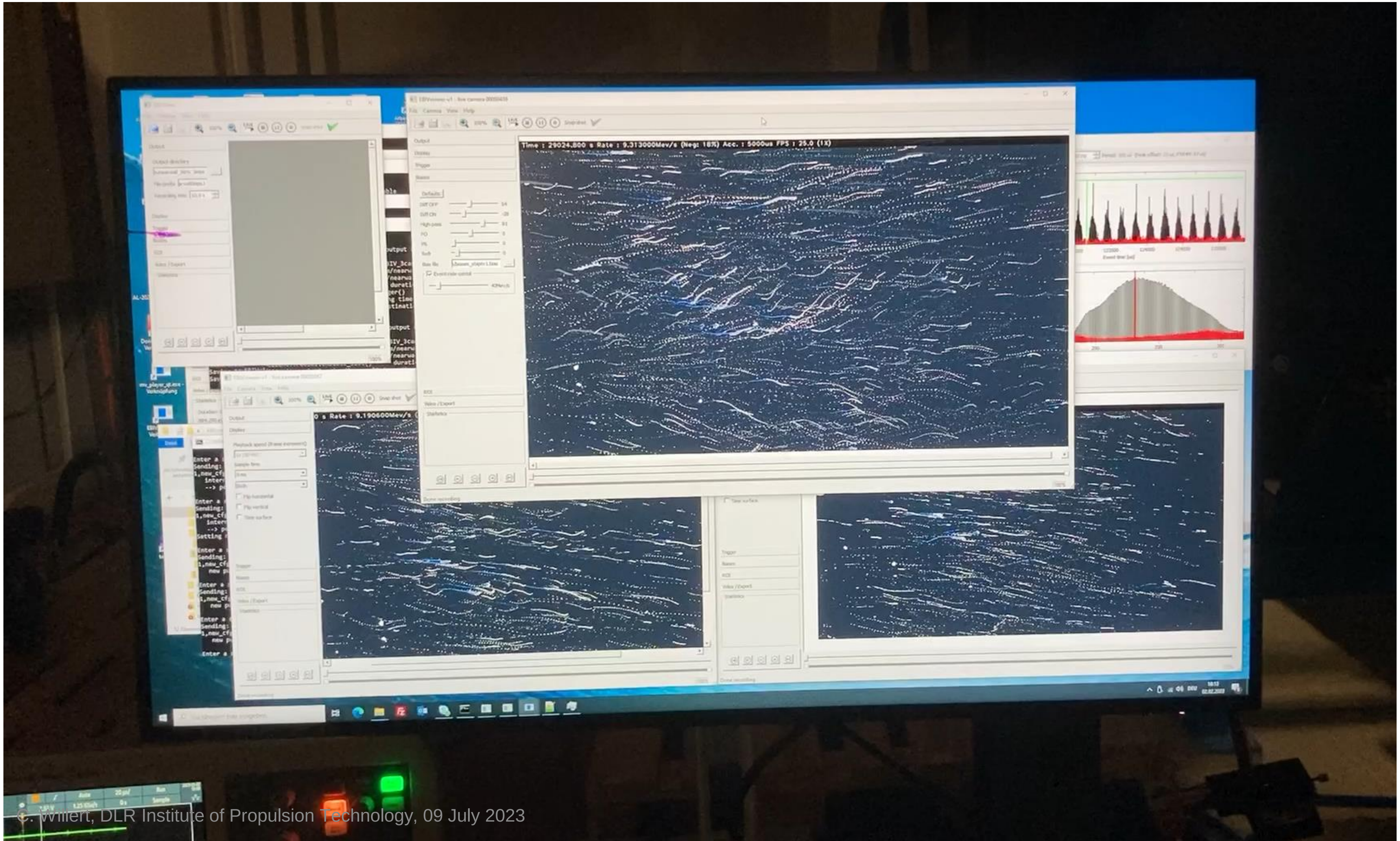


Wall-parallel light sheet
thickness < 0.5 mm
grazing angle ~1 deg

Subject of ISFV 2023
contribution on Tuesday

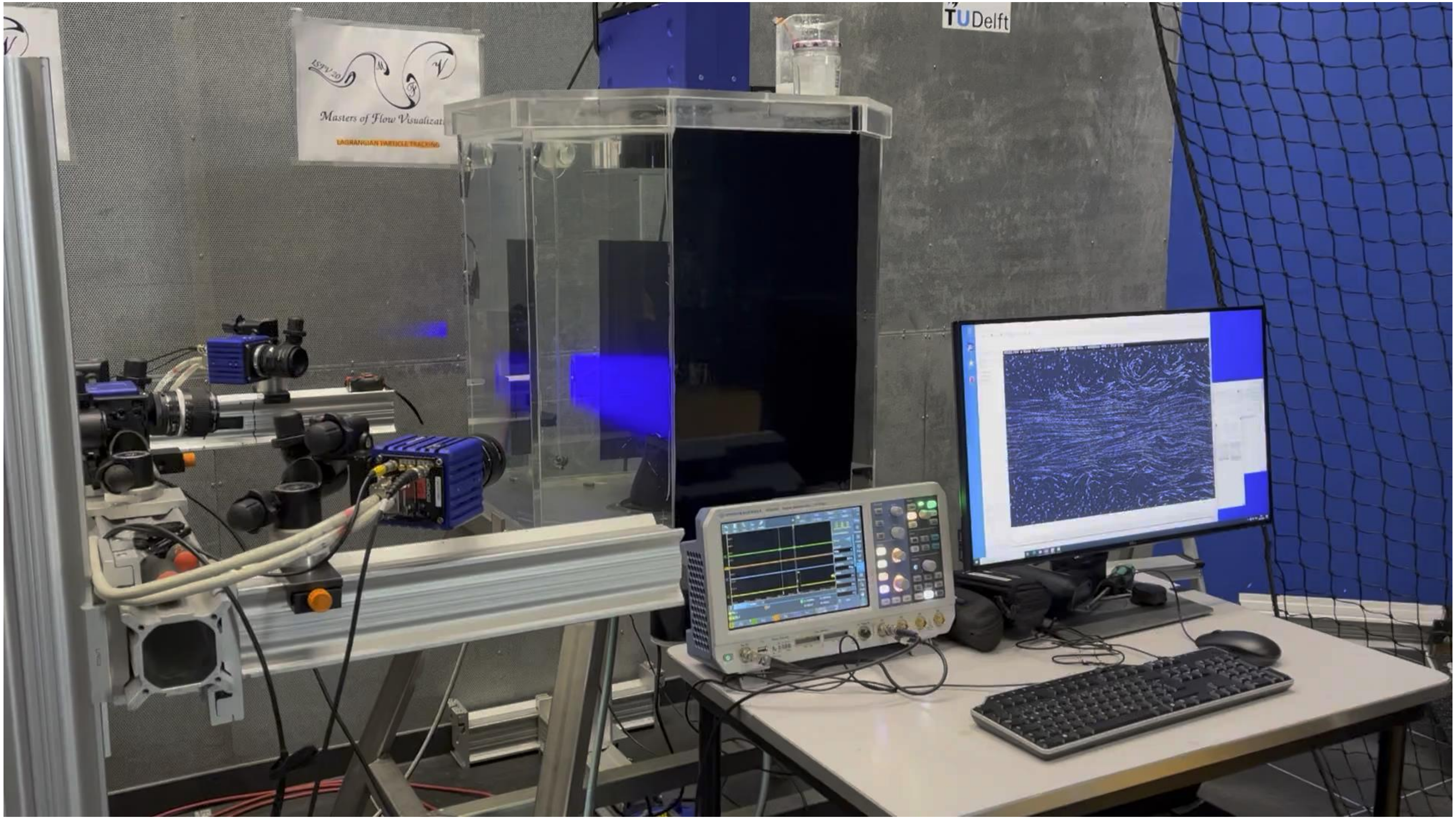
# 3D-Event-based PTV System in Operation



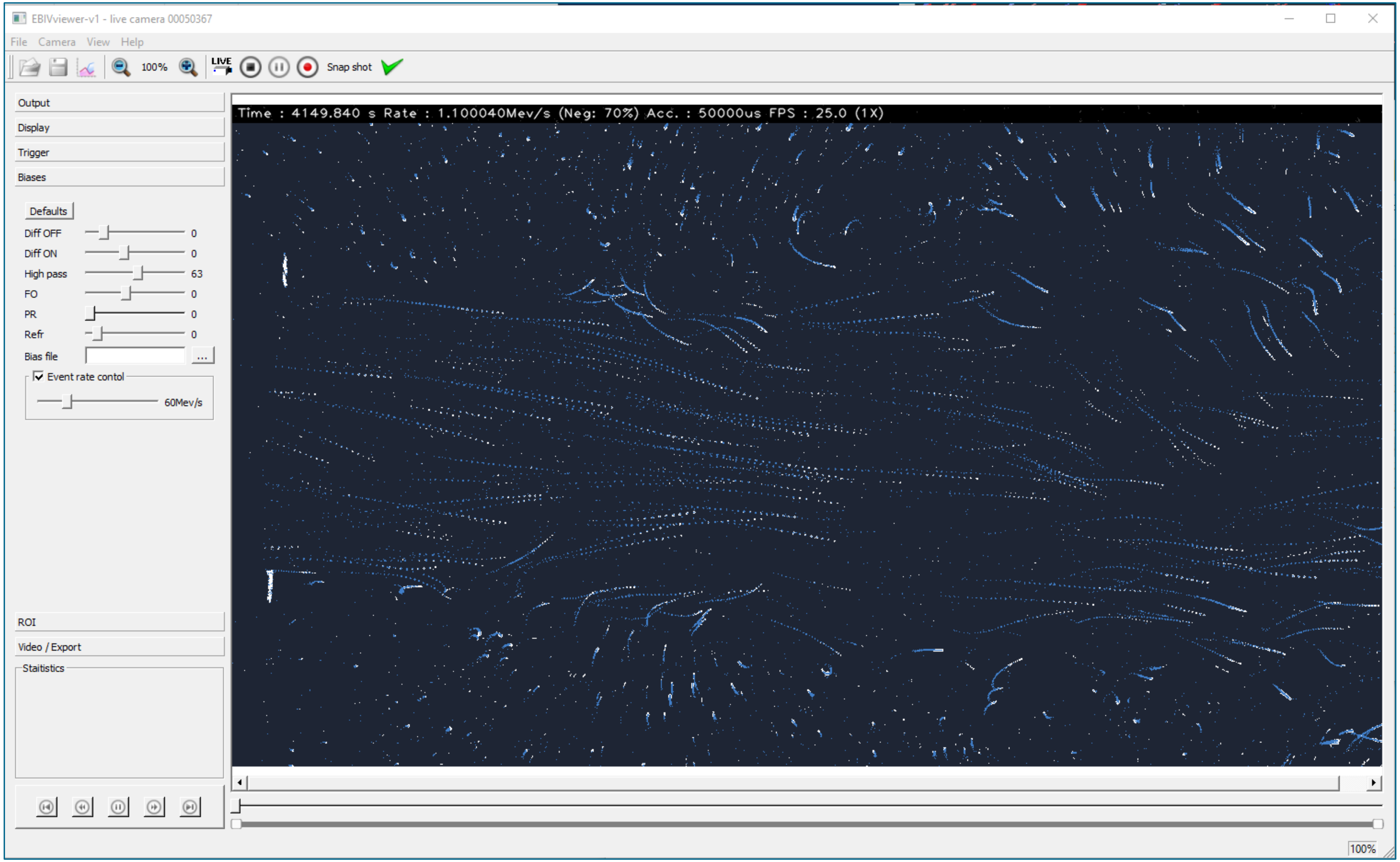
# Summarizing Remarks - Event-Based Imaging Velocimetry

- event-based imaging offers new approaches to flow visualization and measurement
  - real-time visualization of particle tracks (or anything that moves)
  - flow field measurements possible in both water and air using CW laser and standard PIV particles
    → time-resolved measurements at >1 kHz for <3T€
  - particle tracking velocimetry (PTV) → on-going activity
  - variety of other applications yet to be explored
- paradigm shift on the acquisition and processing side
  (e.g. new algorithms are necessary to extract particle track info)
- current limitations:
  - sensor-level limitations (arbiter) → latency, bandwidth → next generation sensors
  - reduced event generation for fast moving objects (particles)
- partially solved using pulsed illumination (→ pulsed EBIV)
- need for characterization of error sources (strongly dependent on hardware):
  - simulation of event-generation (probabilistic process)

# EBIV Setup “Masters of Flow Visualization 2023” TU-Delft



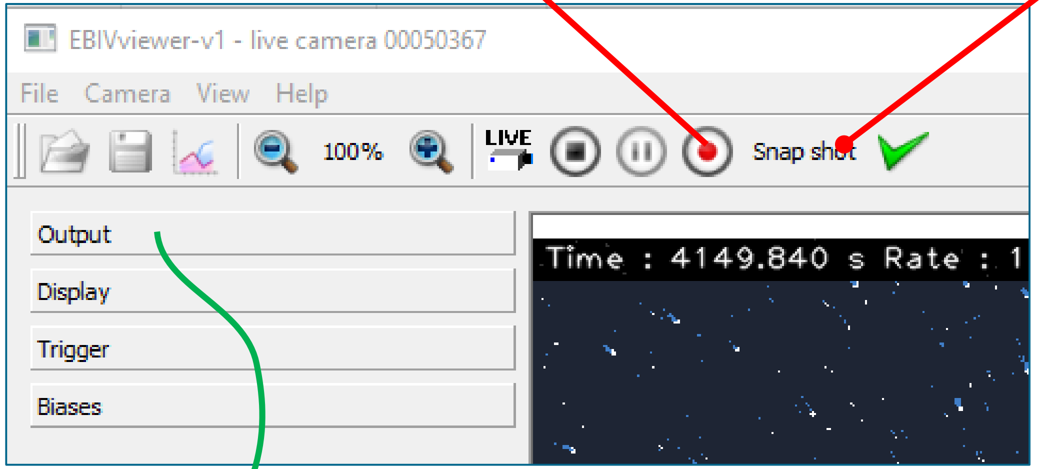
# EBIVview - Software

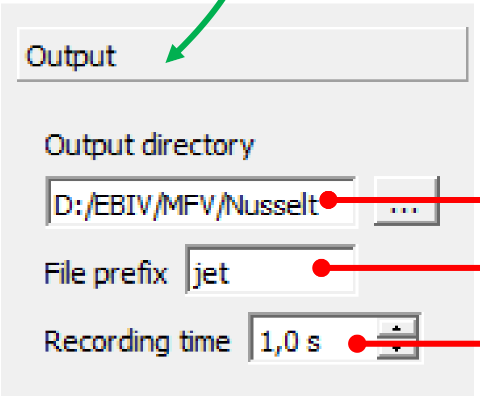


# EBIVview - Software

**Record button**: streams data of given duration to specified directory

Creates a snapshot of screen




Destination directory

Identifier placed at beginning of file (date & time added automatically)

Duration of event capture

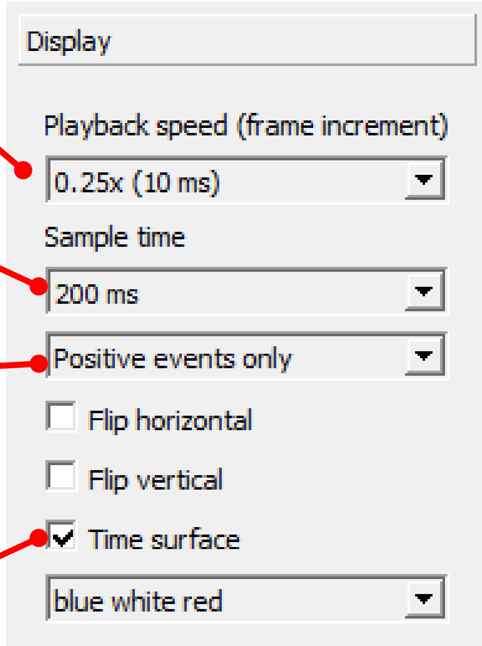
# EBIVview - Display and Export

Determines video speed
(frame increment is 10 ms)

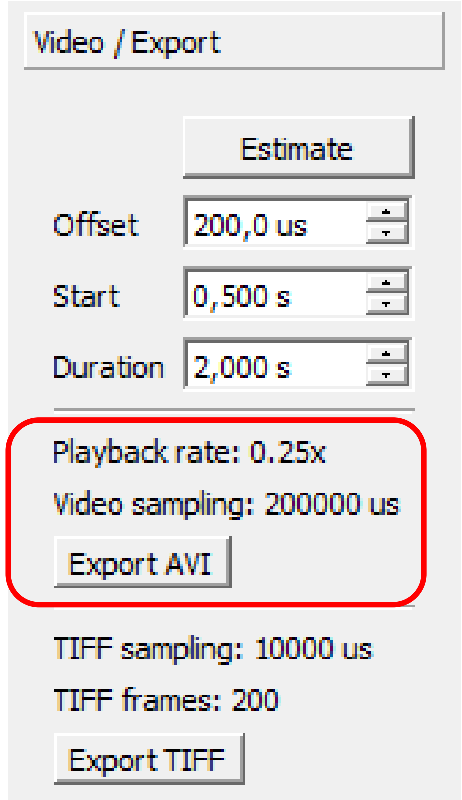
Duration of “time-slices”

Event display:
ON, OFF or both

Events are displayed
in color code

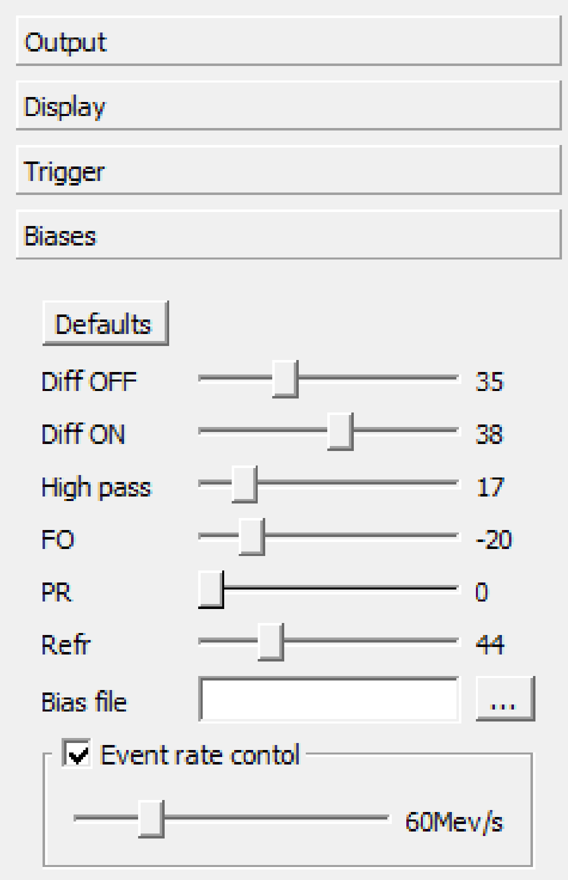



Controls the video export



# What about those “biases” ?

- Diff ON / Diff OFF - controls the positive / negative comparator thresholds. The further away the positive/negative threshold is from the reference level, the more noise can be tolerated on positive/negative events, the less sensitive the pixel becomes to detect ON / OFF events.
- High pass - controls the pixel high-pass cut-off frequency. It is a trade-off between the change detection's sensitivity, noise reduction and low light sensitivity. Filters out slow events such as background rate. Decreased values worsen the contrast detection probability.
- FO - controls the pixel low-pass cut-off frequency. It is a trade-off between pixel bandwidth (referring to pixel speed or pixel latency) and pixel background noise.
- PR - controls the front-end part of the pixel, the photoreceptor (no longer accessible in new cameras)
- Refr - controls the so-called refractory period, representing a dead time for which the pixel will be kept in reset mode after an event acknowledged. Pixel is not responsive during this time.



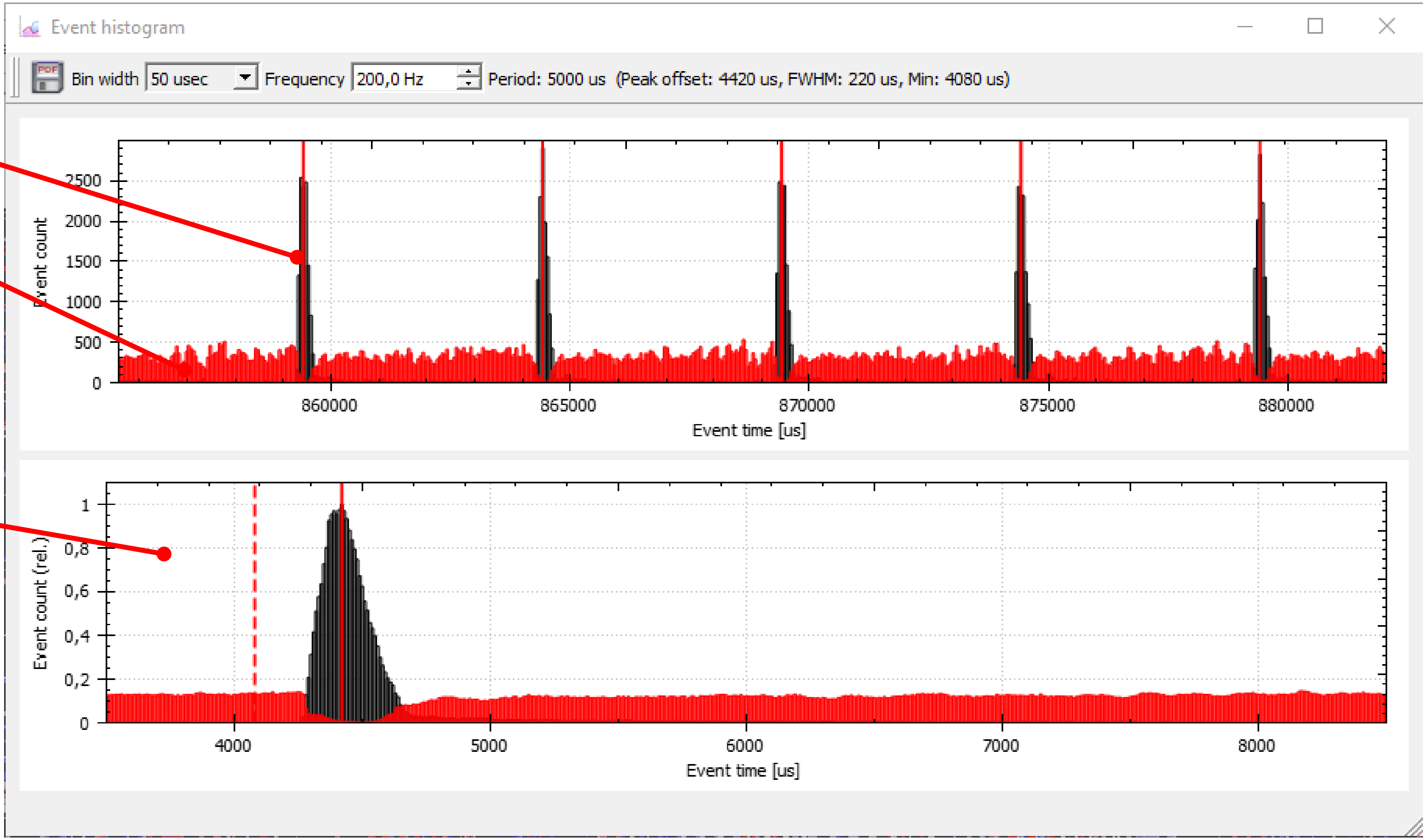

(Source: Prophesee technical documentation)

# EBIVview - Time-record of events

Black: ON events

Red: OFF events

“Mean” event distribution
(obtained from ~1s of data)



# Challenges for Masters of Flow Visualization Exercise

- Adjust biases to get good signal, minimal noise
  (adjust favoring positive or negative events)
- Adjust seeding density to suit visualization or velocity field measurement
- Prevent sensor overload (arbiter overload at >80 Mev/s)
- **Capture vortex formation, steady flow vs. impulse**
  **→ visualize using AVI export or single images**
- Velocity field measurement
  → export multi-frame TIFF sequence suitable for PIV processing
- Record reference length scale

# Starting vortex - Visualization using “Time Surface”