TIME-RESOLVED 3-D PARTICLE TRACKING VELOCIMETRY COMBINING APERTURE-ENCODED IMAGING AND EVENT- BASED IMAGING

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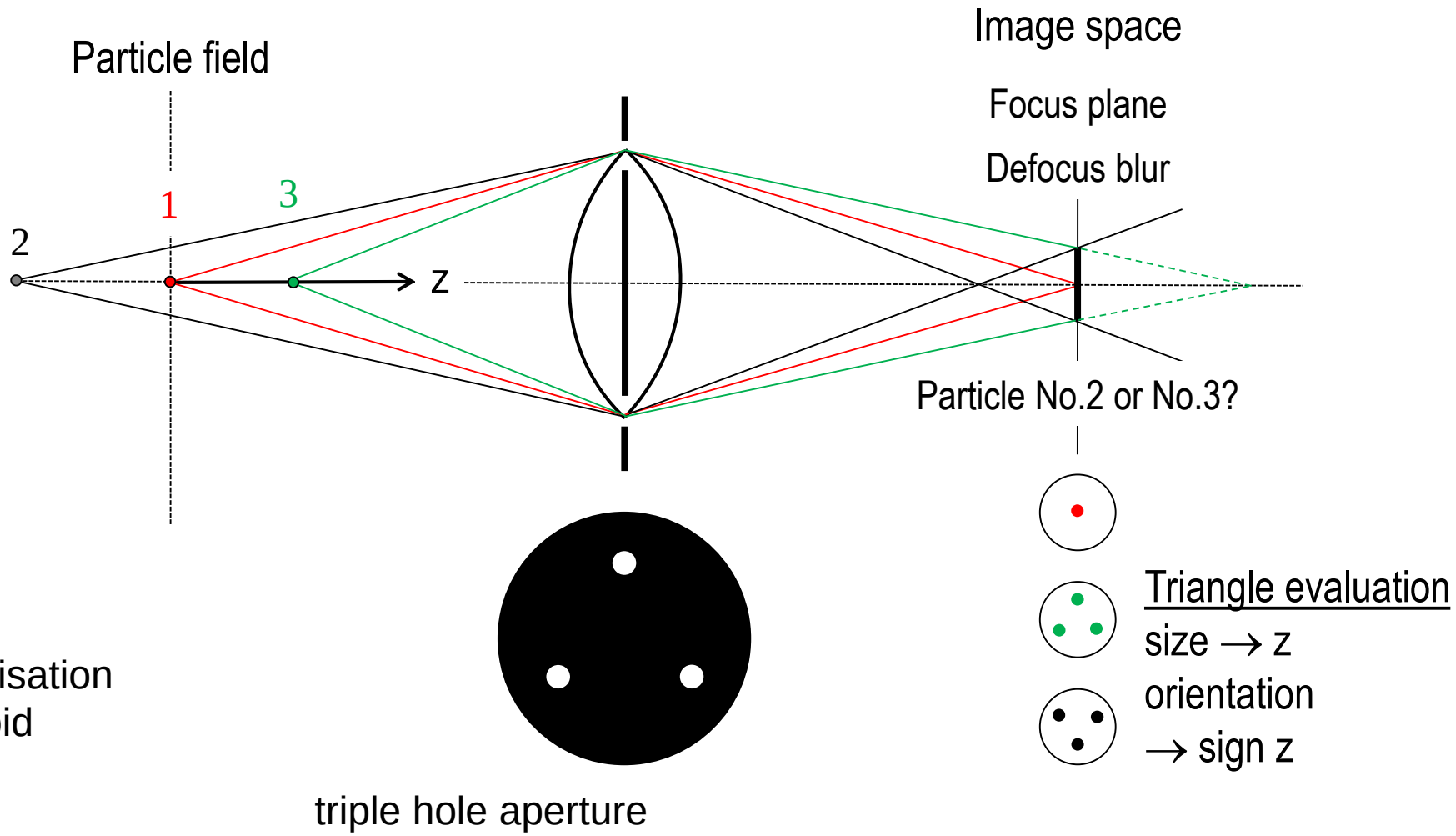
Short Title:
Coded-Aperture Event-based Particle Imaging

Outline

- Aperture-encoded imaging
  → see previous presentation by J. Klinner
- Event-based imaging concepts (EB)
- Various implementations of coded-aperture particle EB-imaging
  - in-line imaging (also see EiF paper by M. Raffel)
  - experiments in air
  - experiments in water
- Current status (Work in progress)

Aperture encoding to recover depth

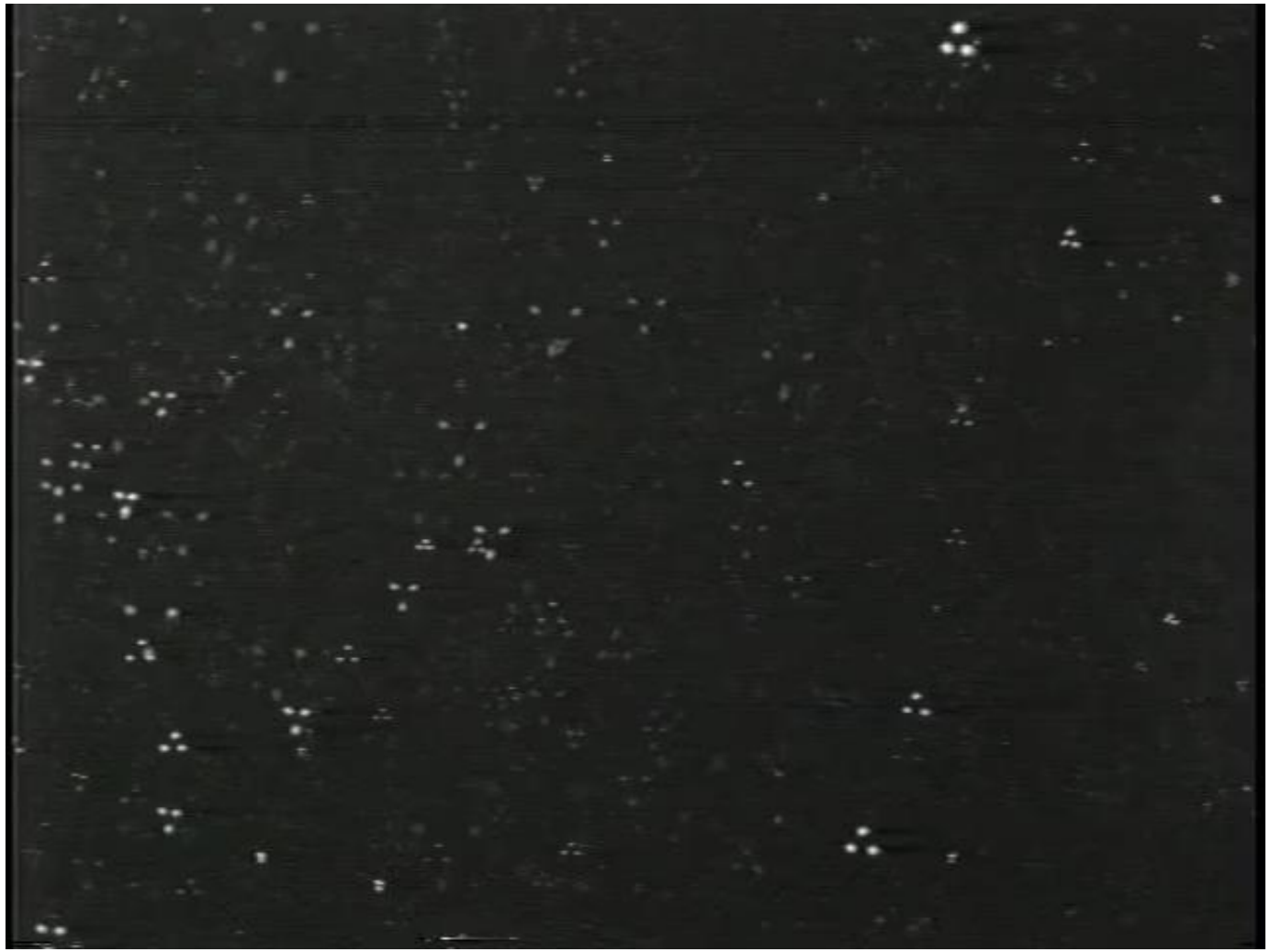


Variants:
color or polarisation coding to avoid mismatching

Willert & Gharib (1992) Exp. Fluids 12, 353–358, https://doi.org/10.1007/BF00193880

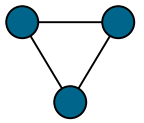
3-D Visualization of Vortex Ring

Video originally shown at APS-DFD Meeting, Cornell, Nov. 1990



- Polystyrene particles in water
- Illumination with xenon strobe light
- 30 Hz video

close

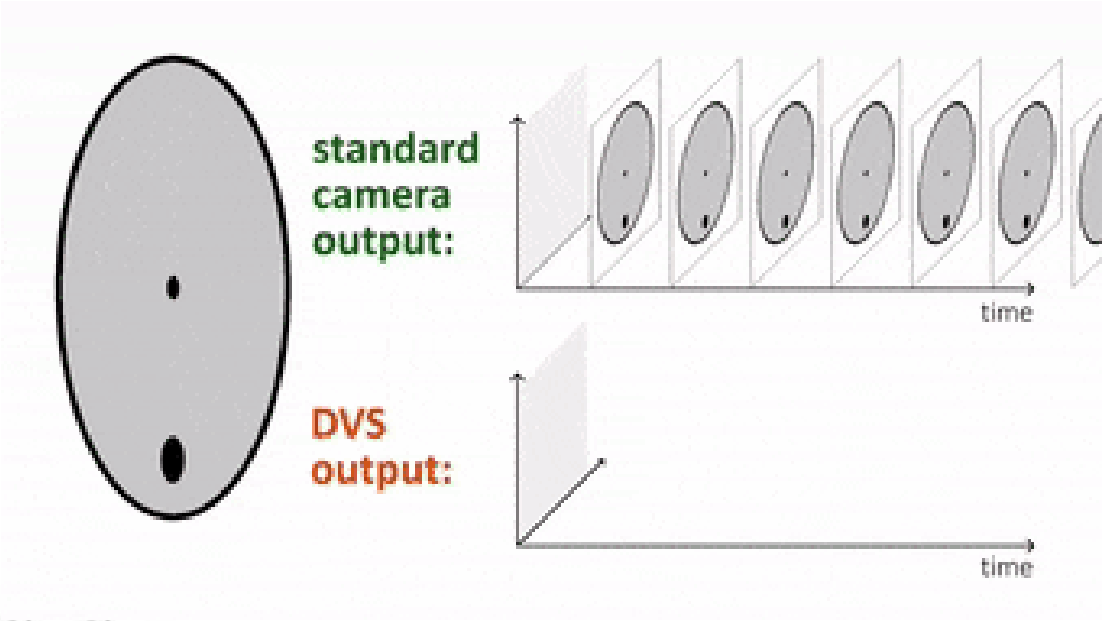


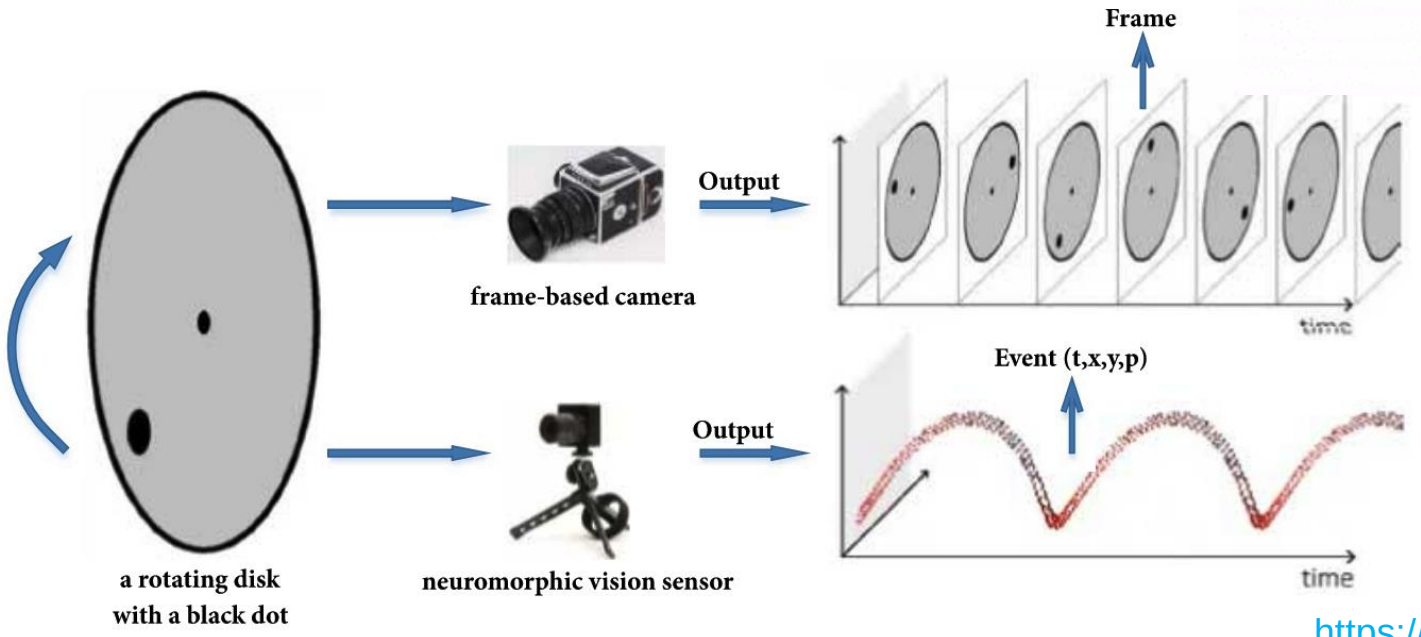
far

Willert & Gharib (1992) Exp. Fluids 12, 353–358, https://doi.org/10.1007/BF00193880

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



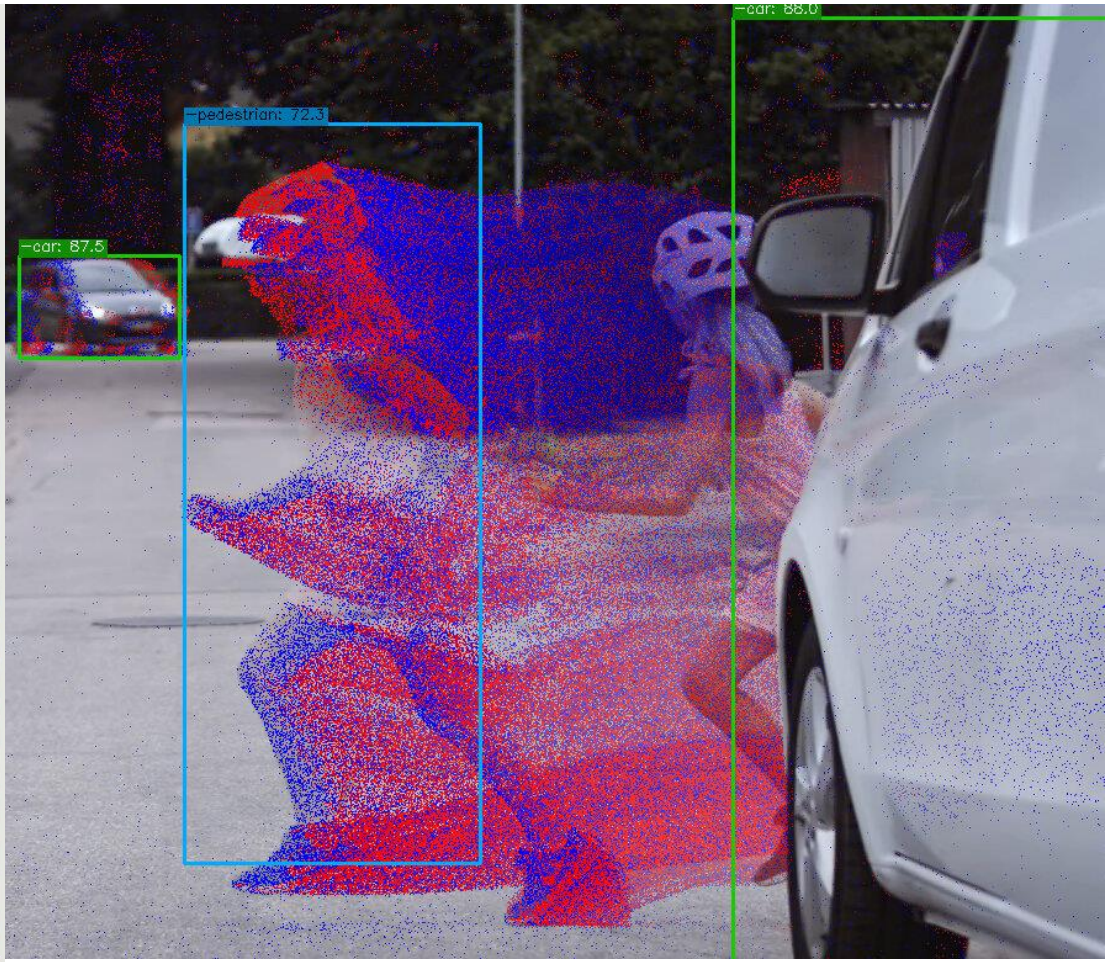


single event consists of 4 values
- Time t [µs]
- Position x [px]
- Position y [px]
- Polarity p ∈ {0,1}

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

Example application of Event-based Vision

By combining a 5,000 frame-per-second (FPS) event camera with a 20-FPS RGB camera, roboticists from the University of Zurich have developed a much more effective vision system that keeps autonomous cars from crashing into stuff, as described in the current issue of *Nature*.

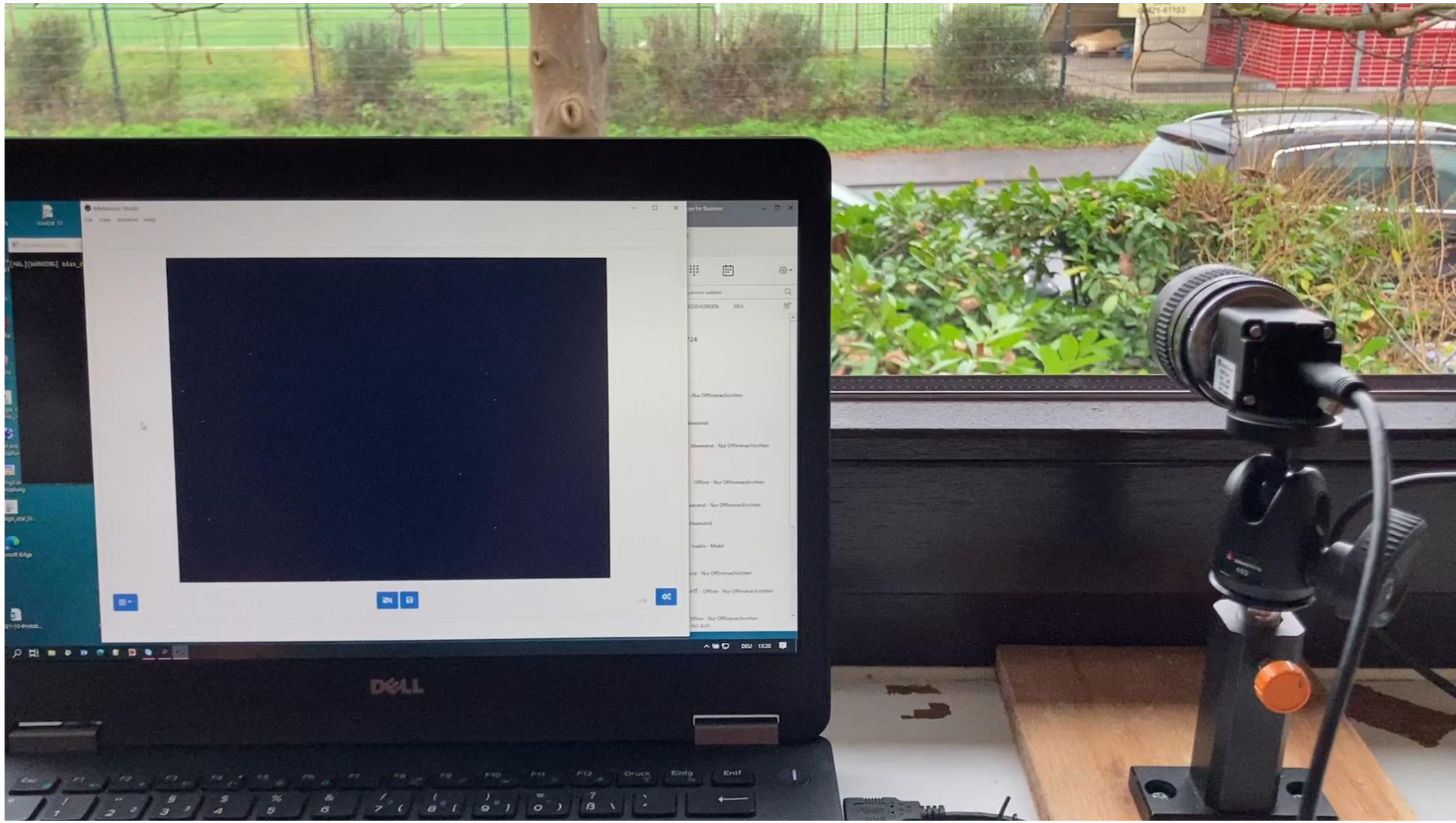


Gehrig, D., Scaramuzza, D. Low-latency automotive vision with event cameras. *Nature* **629**, 1034–1040 (2024). https://doi.org/10.1038/s41586-024-07409-w

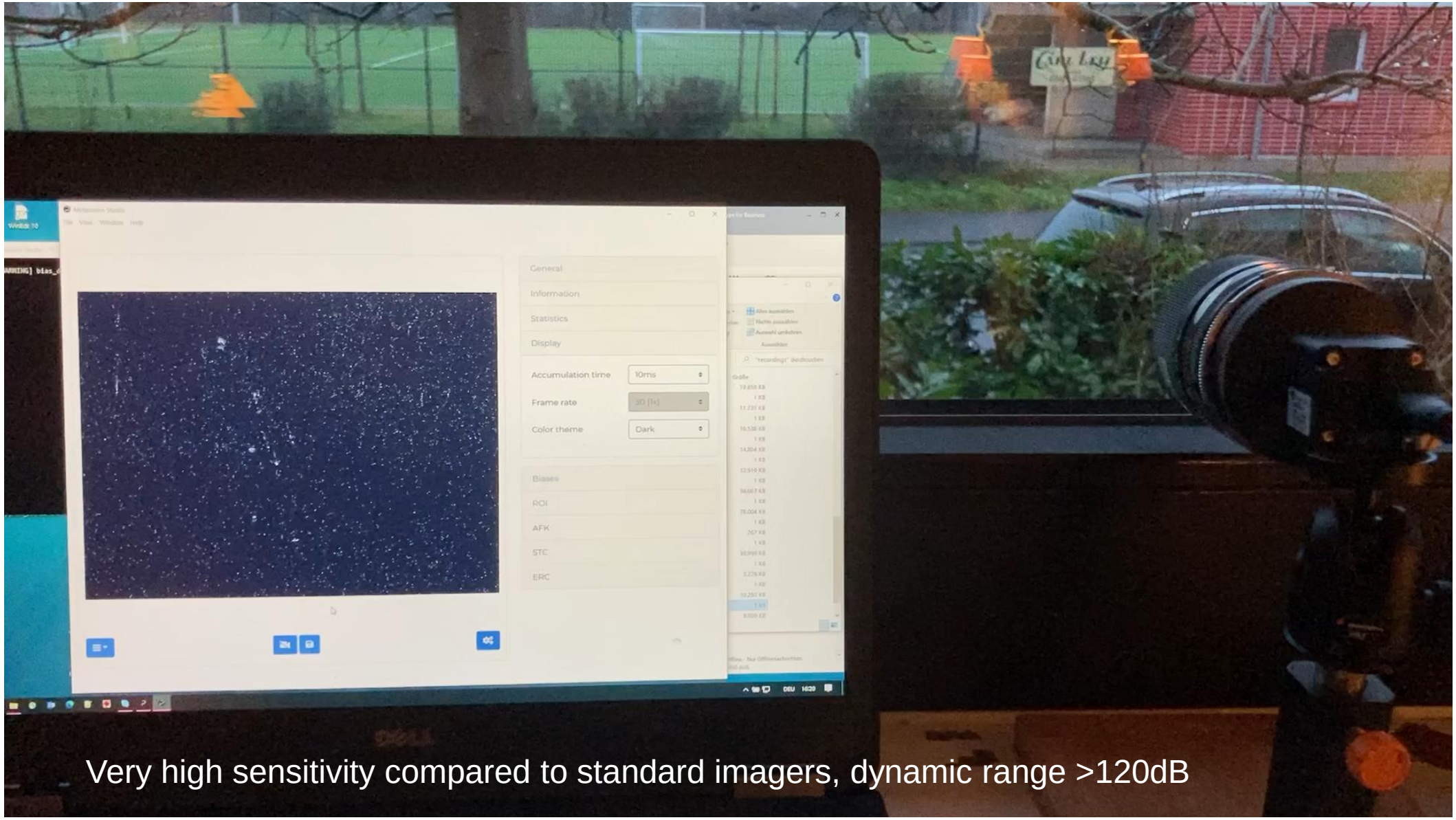
First recordings

on a rainy afternoon in December 2021

Event-camera with 640 x 480 pixel sensor



Rain & Insects in the Twilight

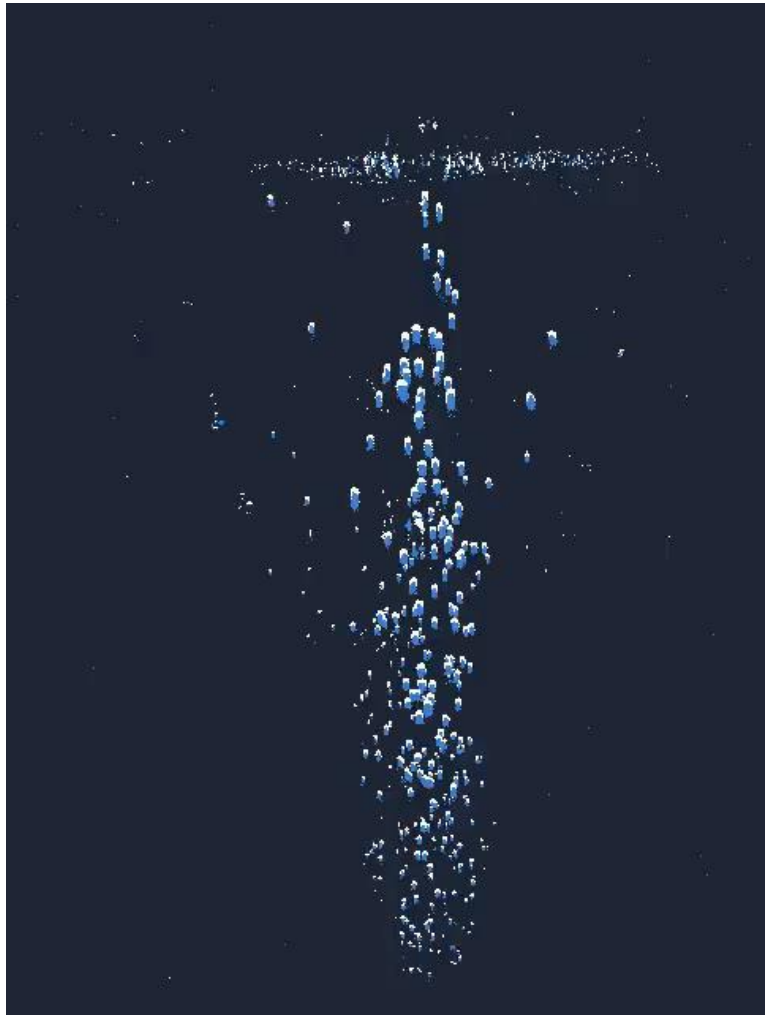


Very high sensitivity compared to standard imagers, dynamic range >120dB

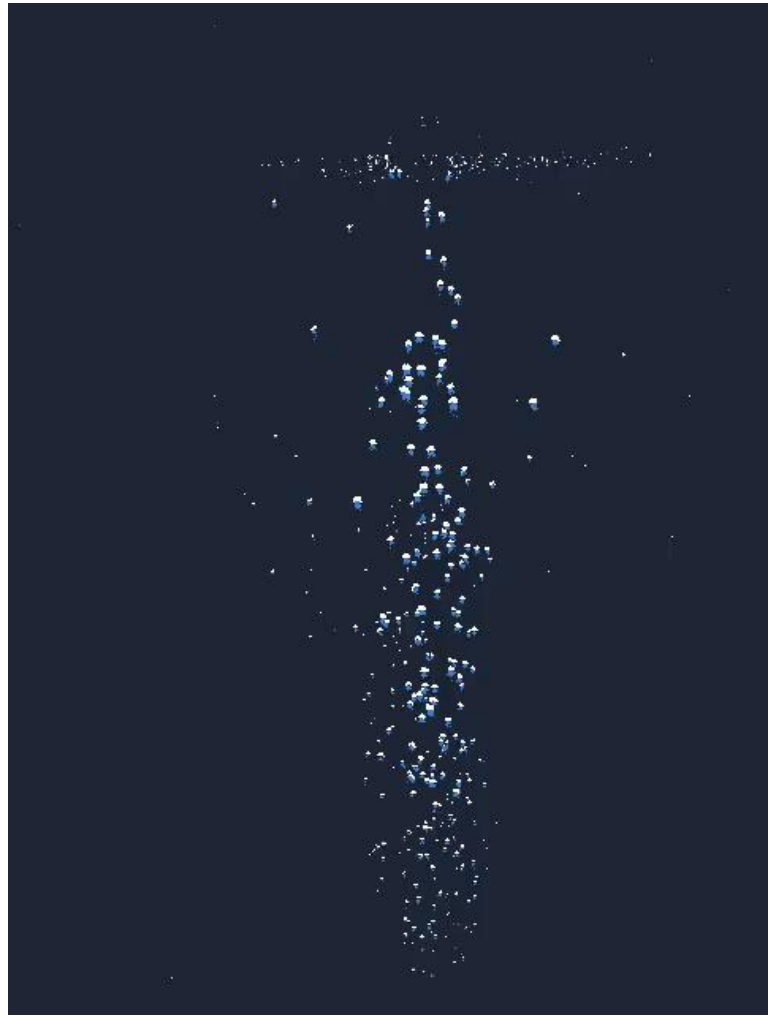
Champagne bubbles

Crémant !

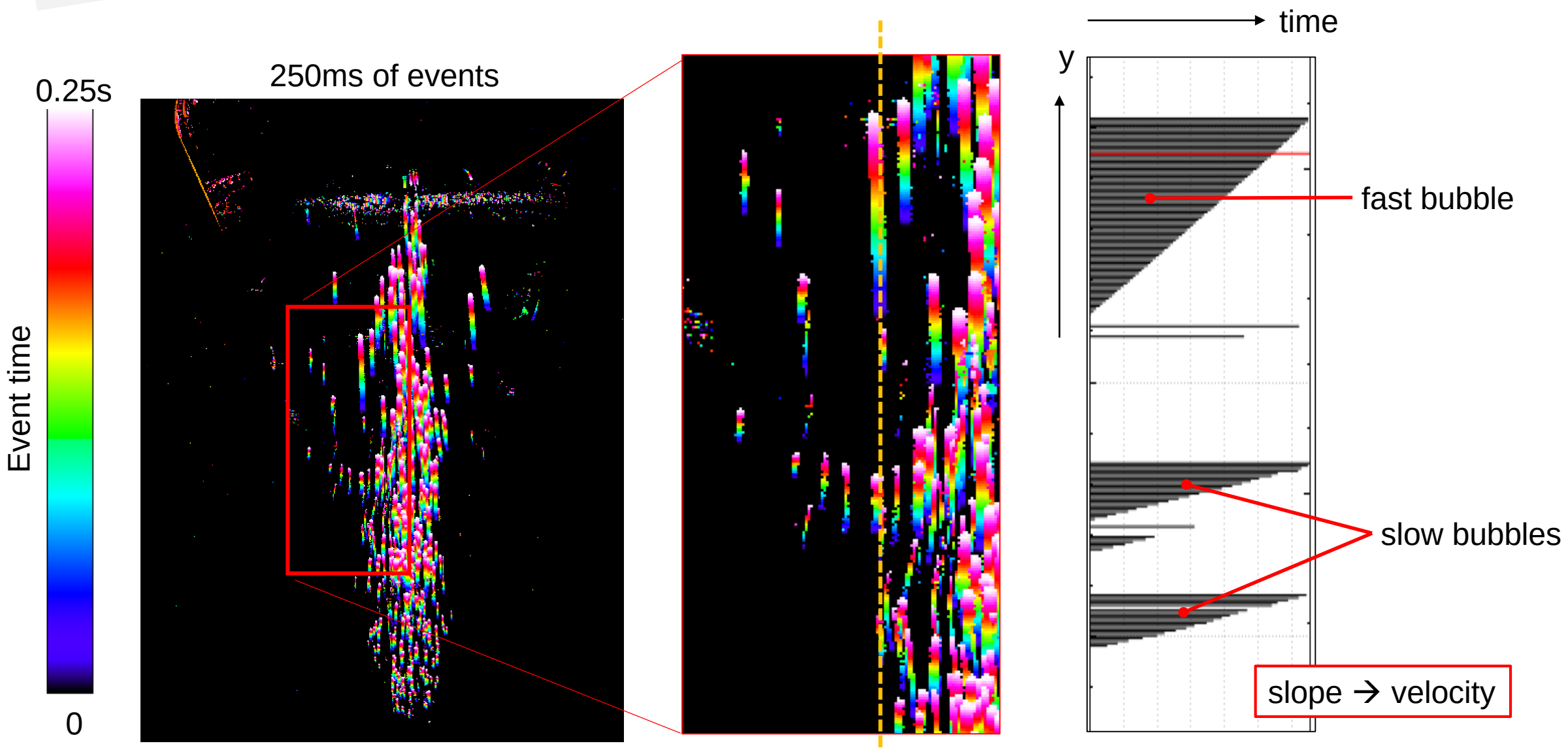
Normal speed (30 fps)



Speed 0.2x (150 fps)

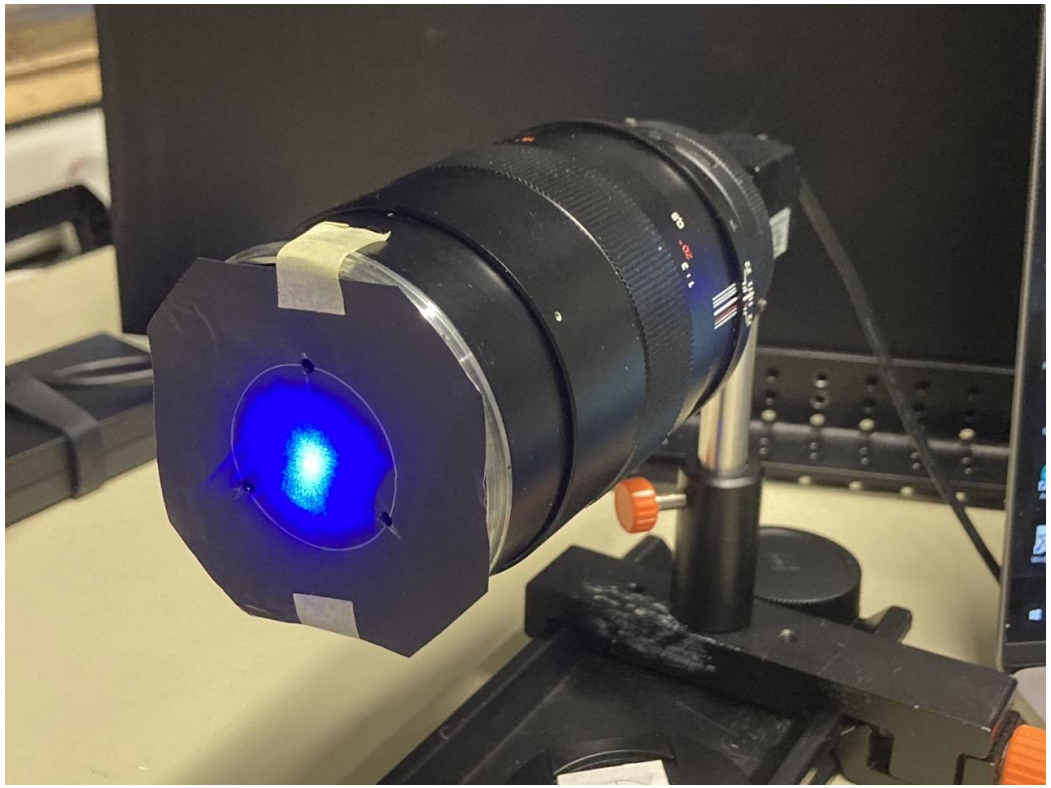


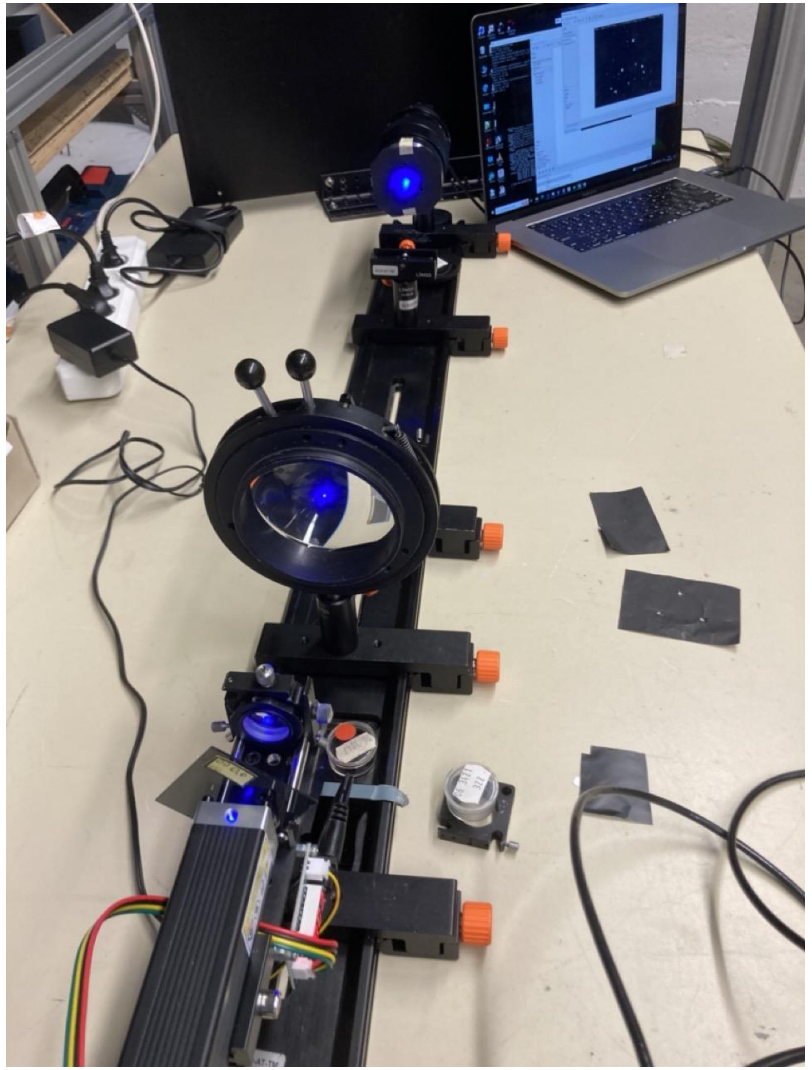
Crémant ! bubbles



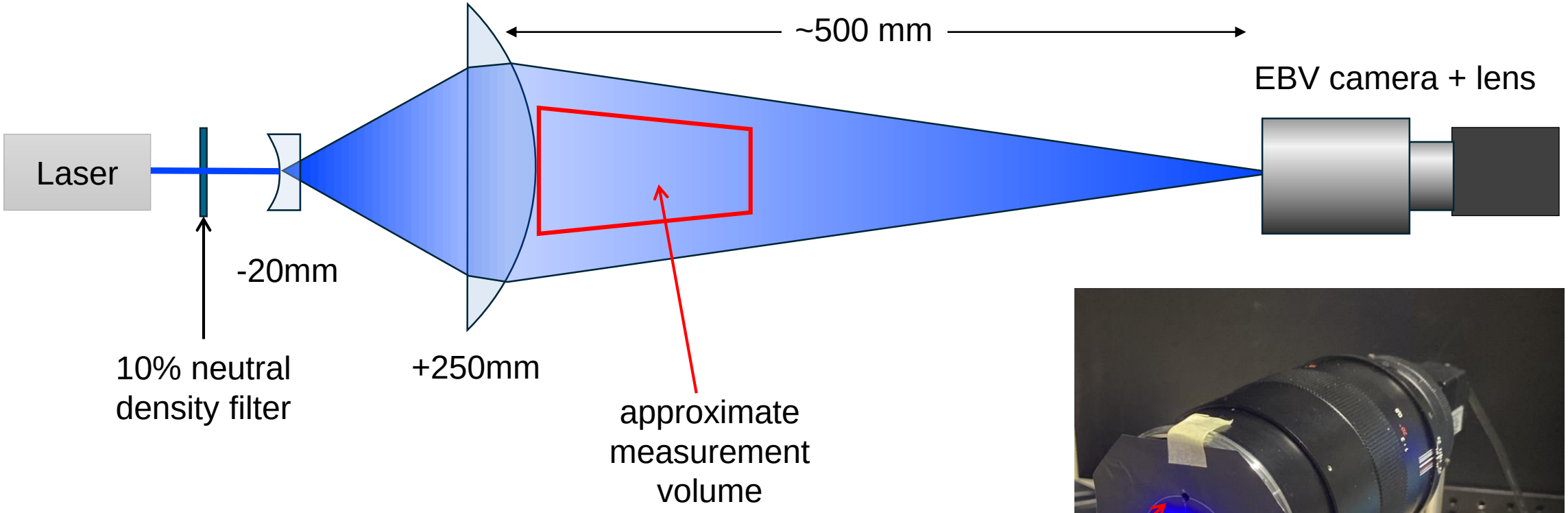
Aperture-encoded event-based imaging in air

- Inline-imaging setup (Raffel et al. 2024, https://doi.org/10.1007/s00348-024-03766-4)



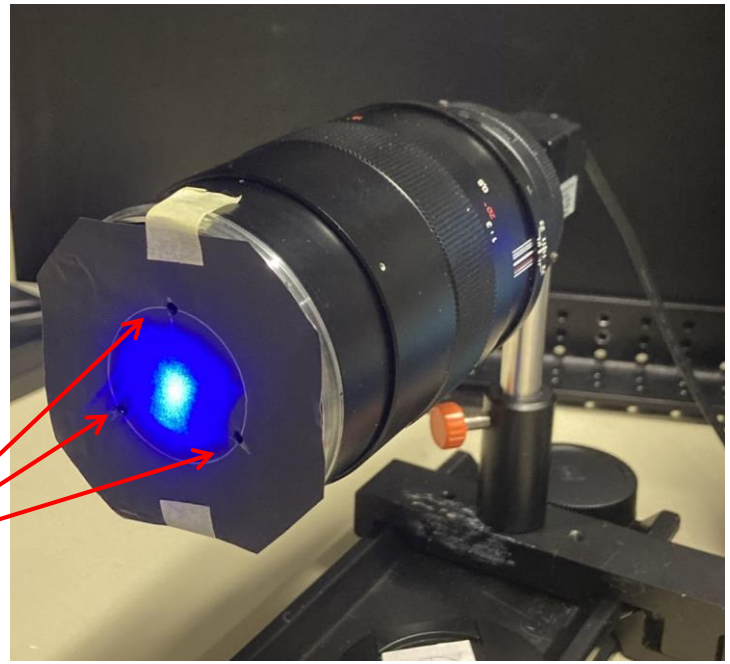


Setup - inline illumination

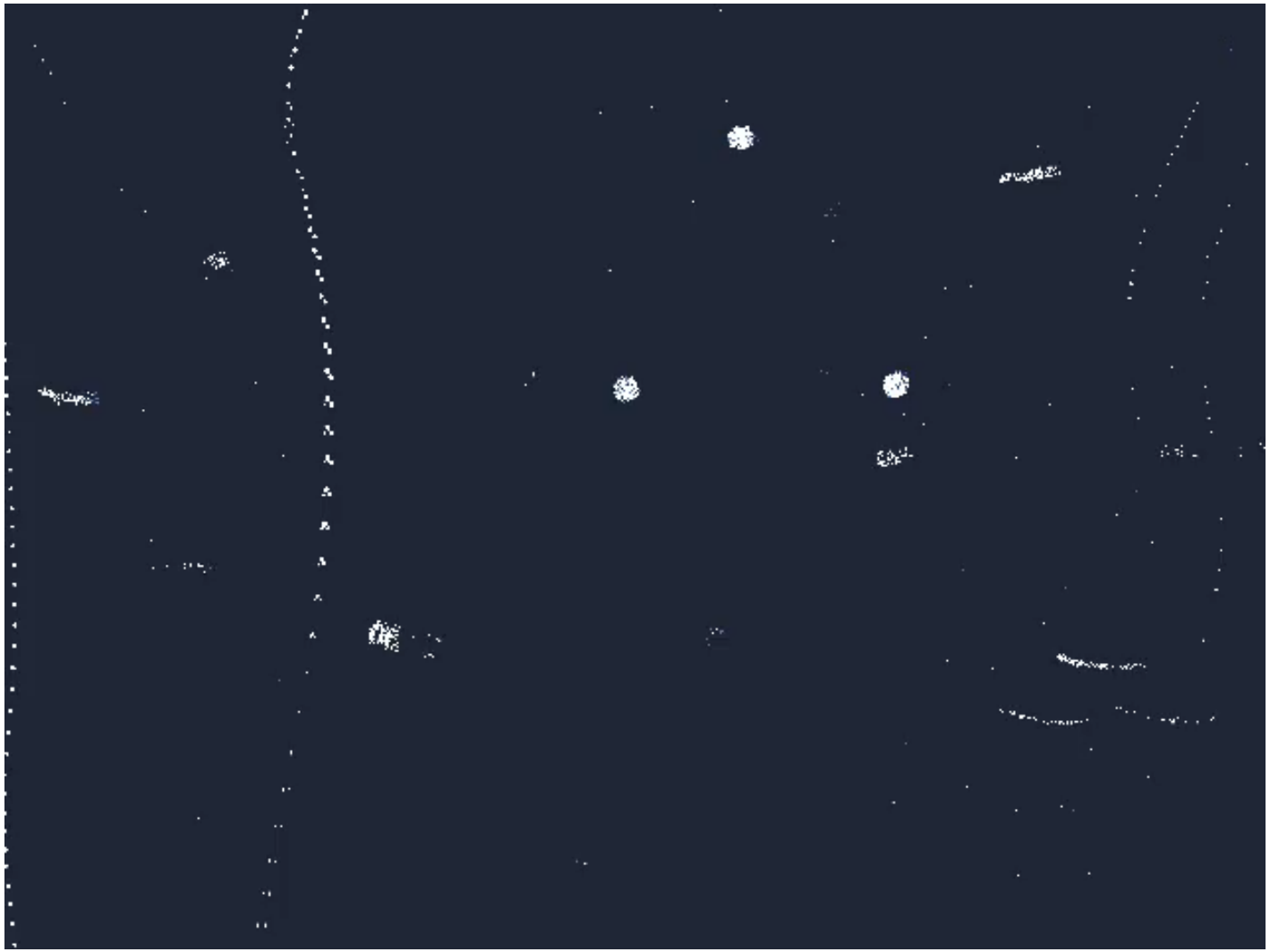


- EBV camera: 640x480 px
  Century Arks, SilkyEvCam
- Lens: 100 mm f/2
  Zeiss Makro Planar 100/2

Triplet aperture
on 25 mm circle,
each ~2mm diameter



Aperture-encoded particle imaging with inline illumination



- Ambient room flow
- 0.8 µm DEHS tracer particles
- Low-coherent pulsed laser light at 1% duty cycle attenuated
- Laser pulsed at 5 kHz
- Output up to 40 Mevents/s

- Large depth field (small apertures in mask)

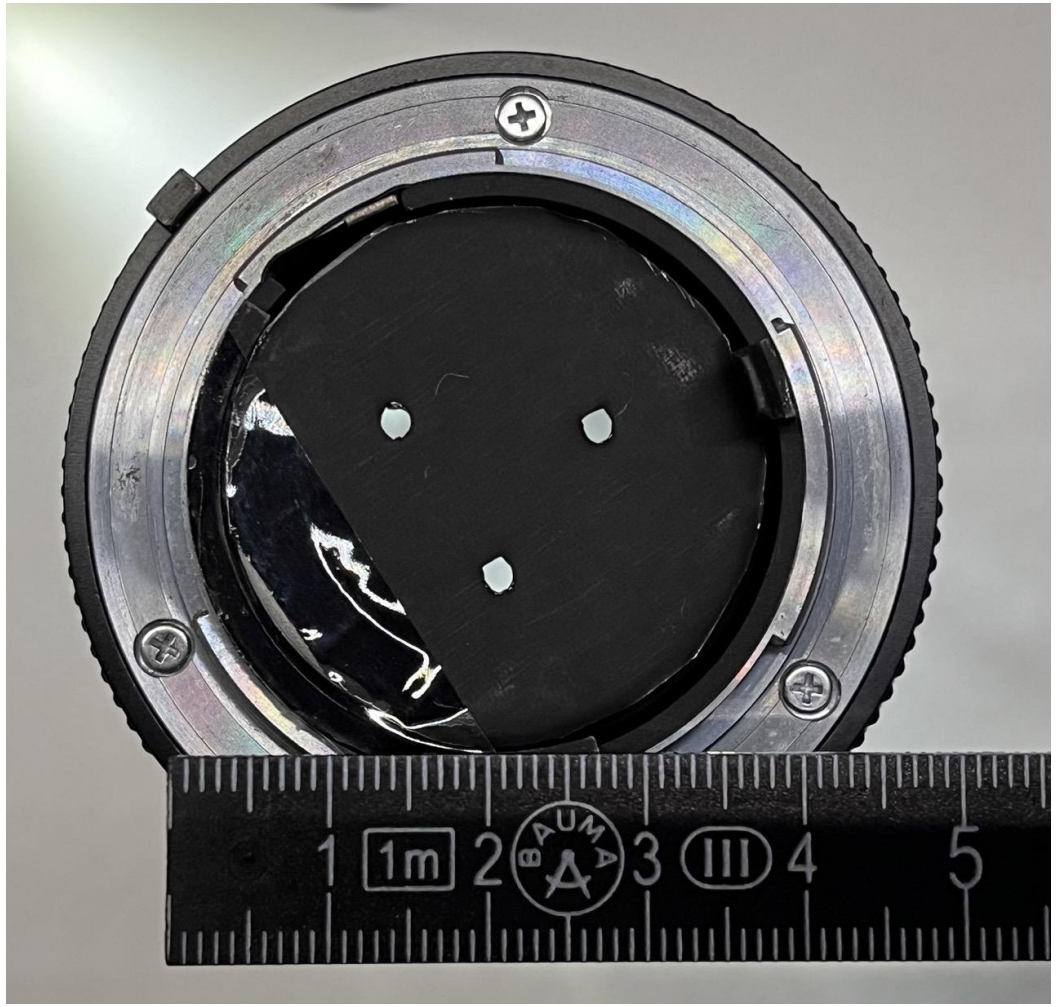
Major challenges with inline illumination

- high background intensity
  → event imager is less likely to trigger events
- event trigger requires 20% intensity change
  → increasing overall light intensity does not help
- issues with intermediate surfaces (e.g. windows, lens)
  → strong signal from scratches and dust → reduced/obscured events

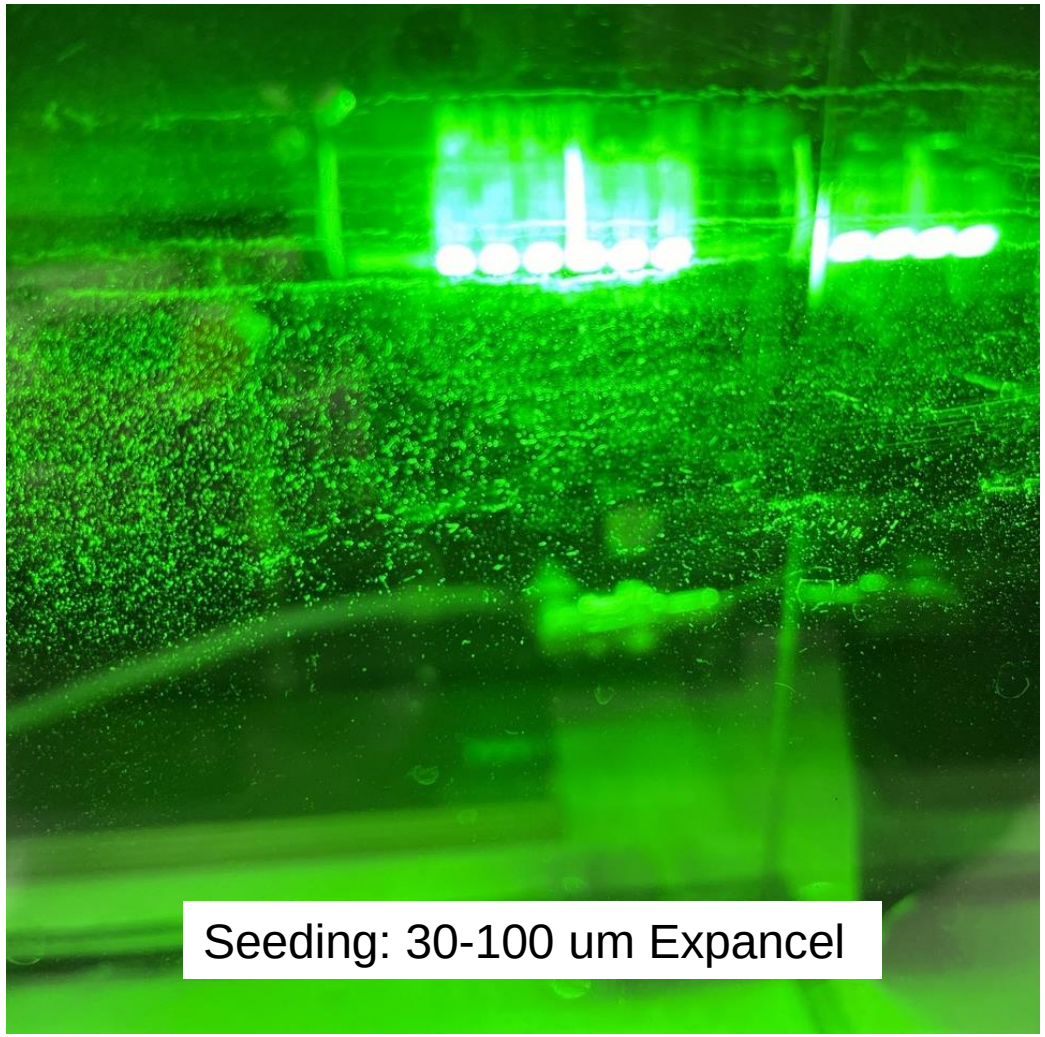
Triplet aperture lens

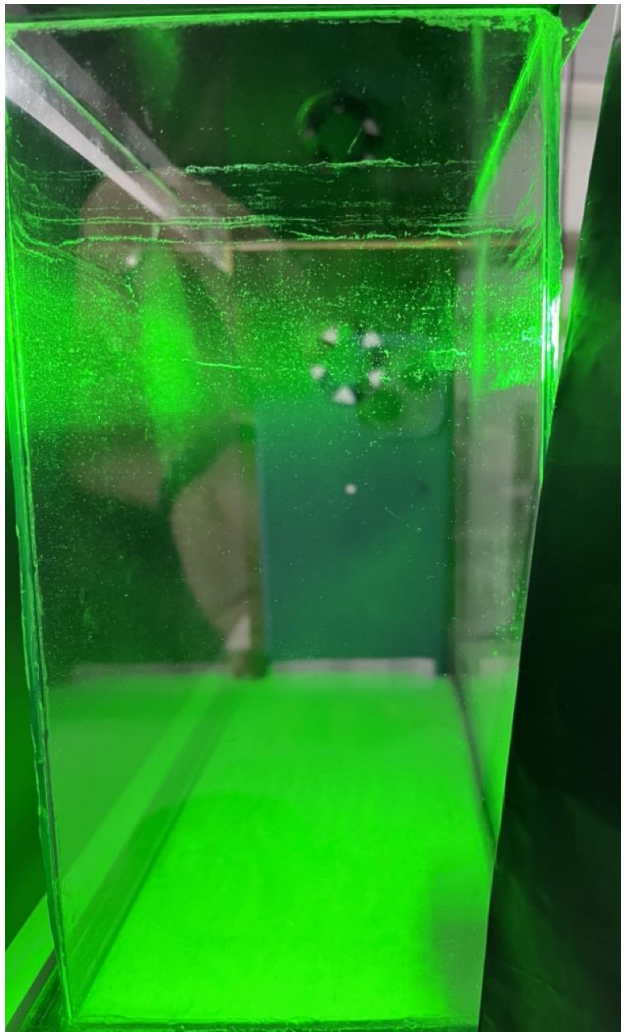
- lens: Nikon Nikkor 35 mm / 1.4
- triplet aperture holes spaced ~12 mm diameter ~2 mm
- placed at lens exit plane (could also be placed in front)
- ideal location is at iris (difficult to access)

- Note: not all lenses are suitable (unless you can access the iris area)



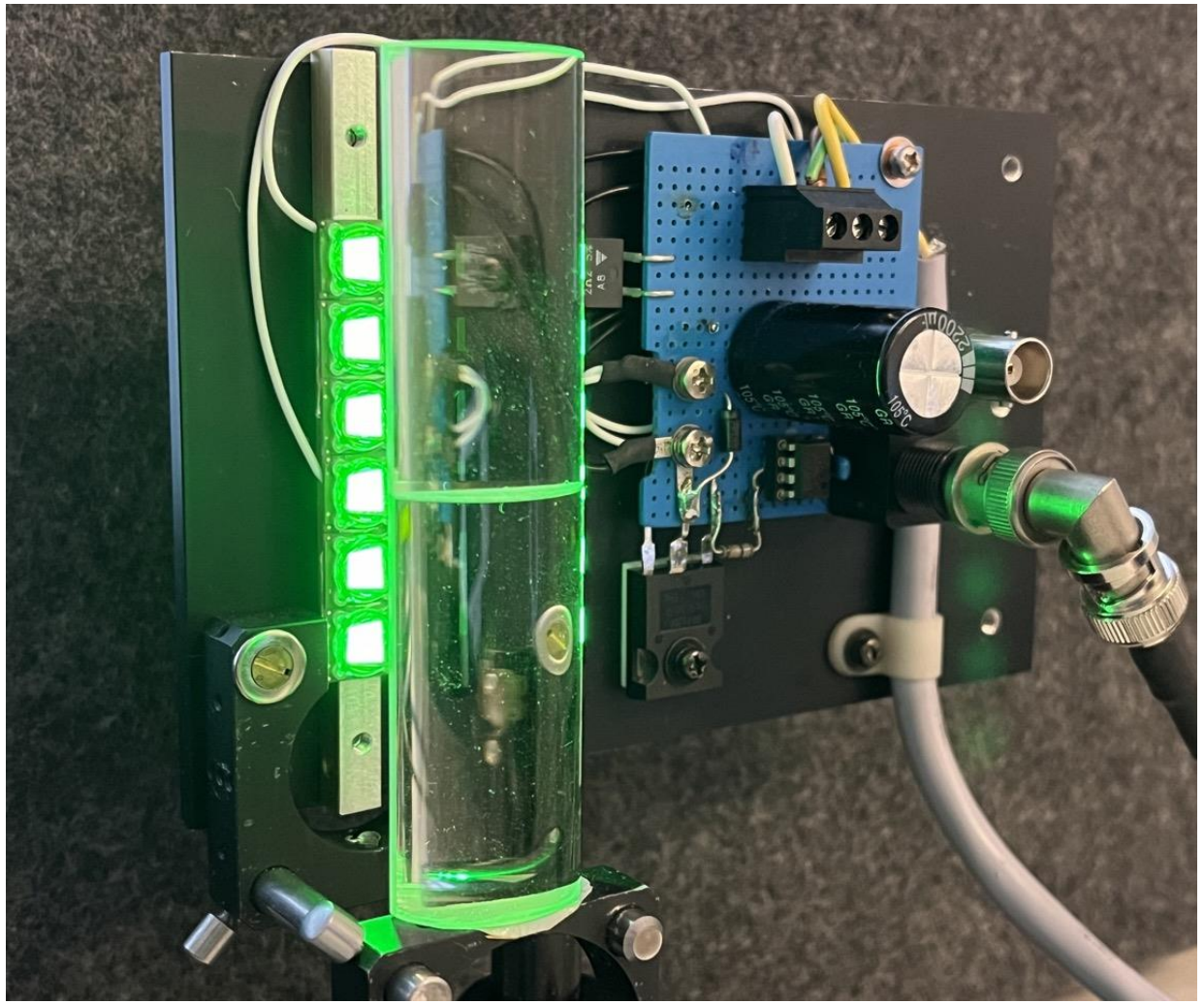
Aperture-encoded event-based particle imaging in air

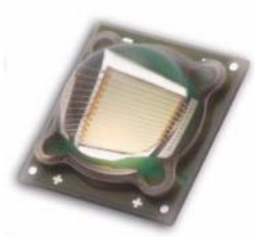




Aperture-encoded event-based particle imaging in air

- pulsed LED light source
- 6x Luminus SST90 (9 mm^2 die)
- collimation into 20-30mm thick volume



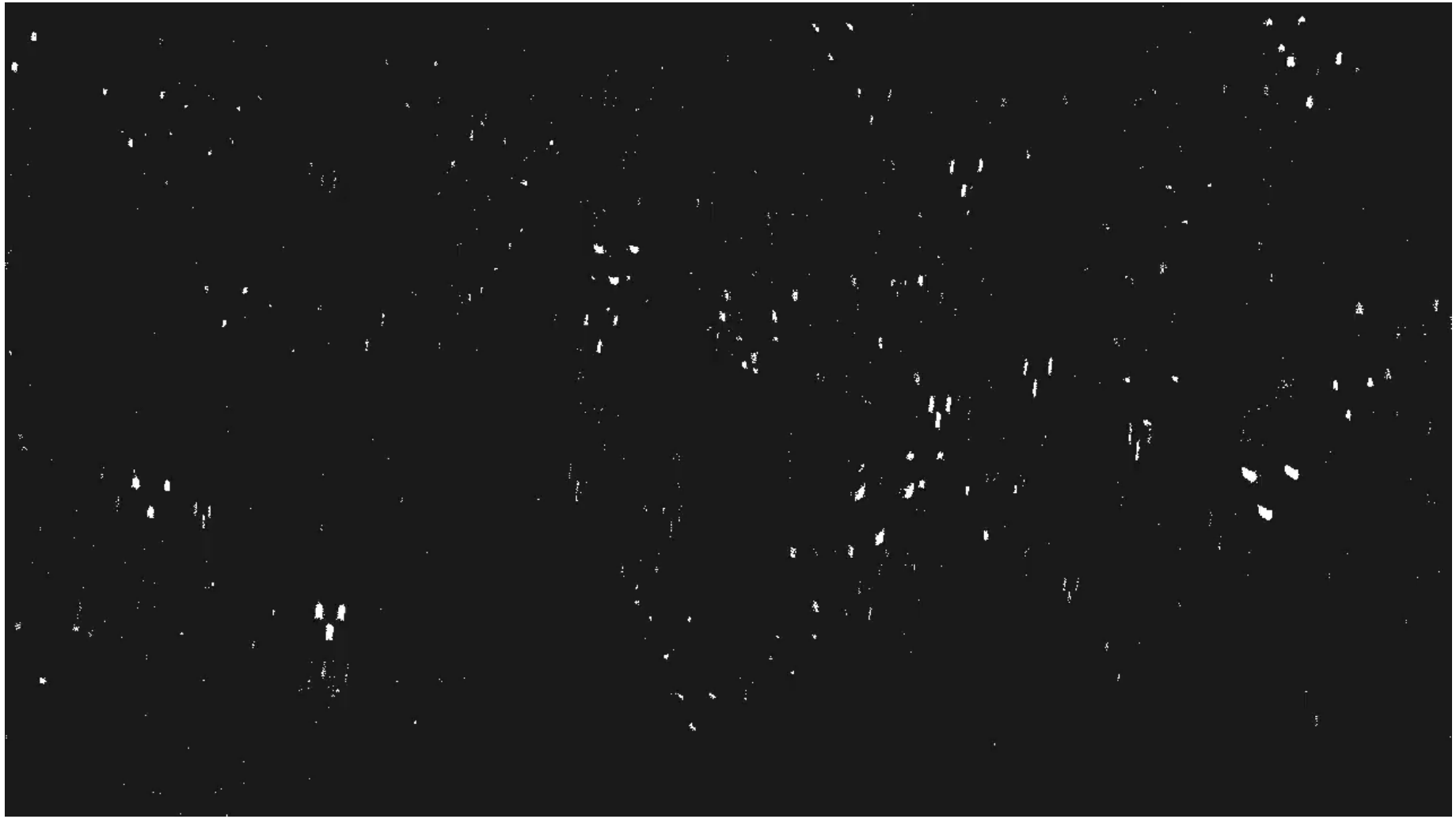


1500 lm @ 9A P_{LED} ~3W
Absolute max. current: 27A
(~4000 lm)

Event recordings in air - Pulsed LED @ 1 kHz

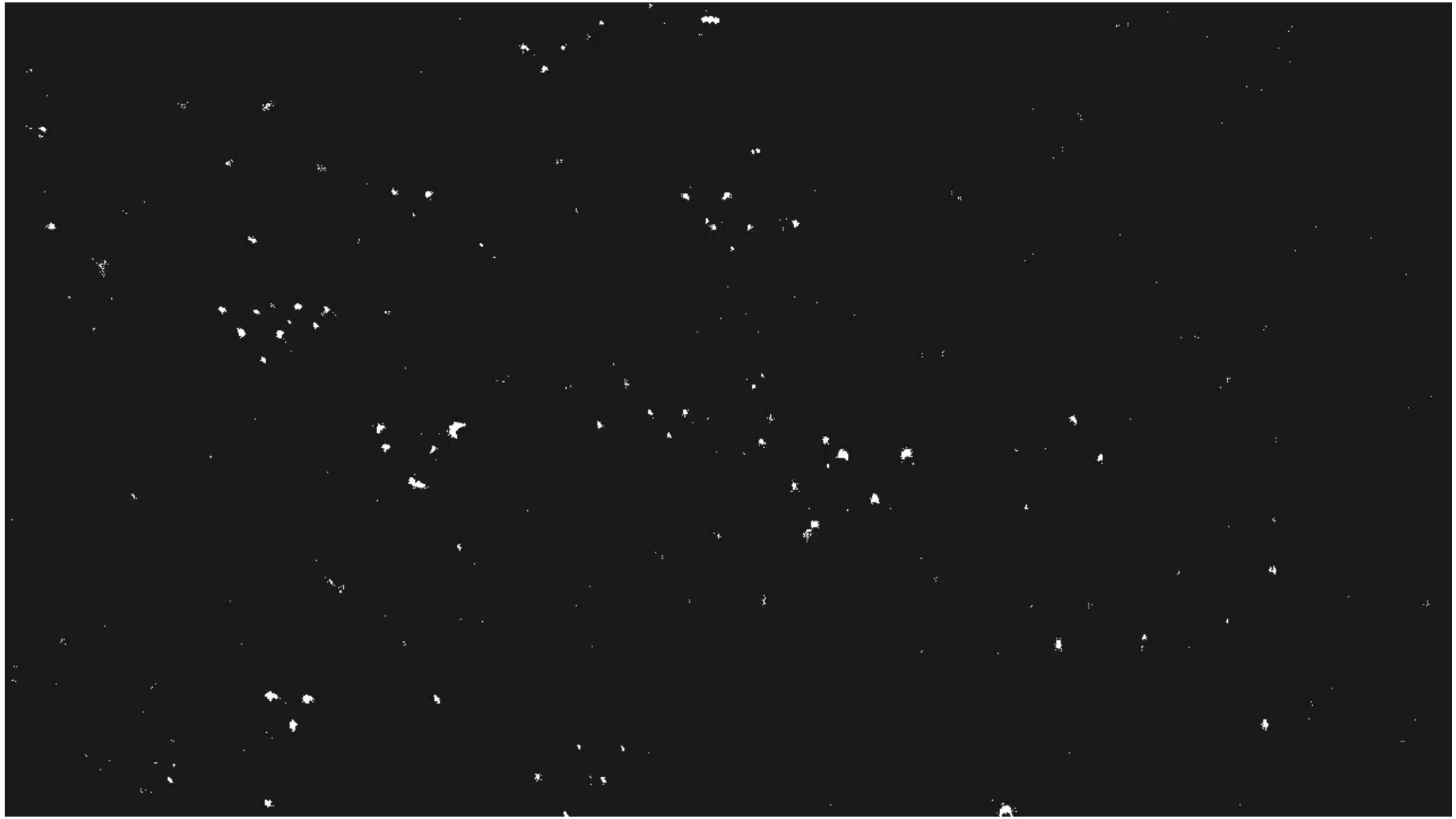
Real-time, 50ms time-slice (convection / residual flow)

Volume: ~60 x 35 x 80 mm^3 (W x H x D)



Event-recordings obtained in water

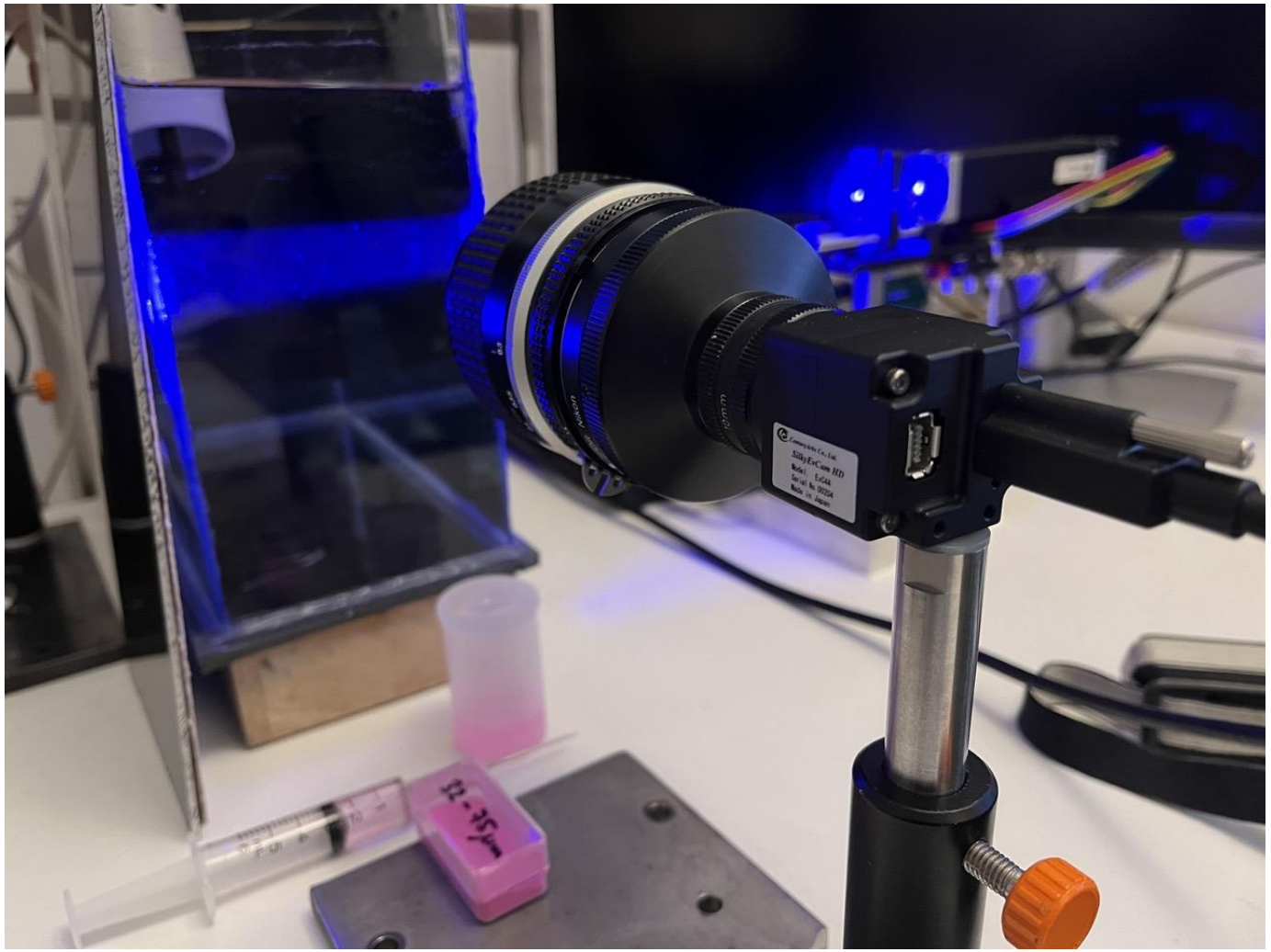
Seeding: “fluorescent” beads (35-75 µm)

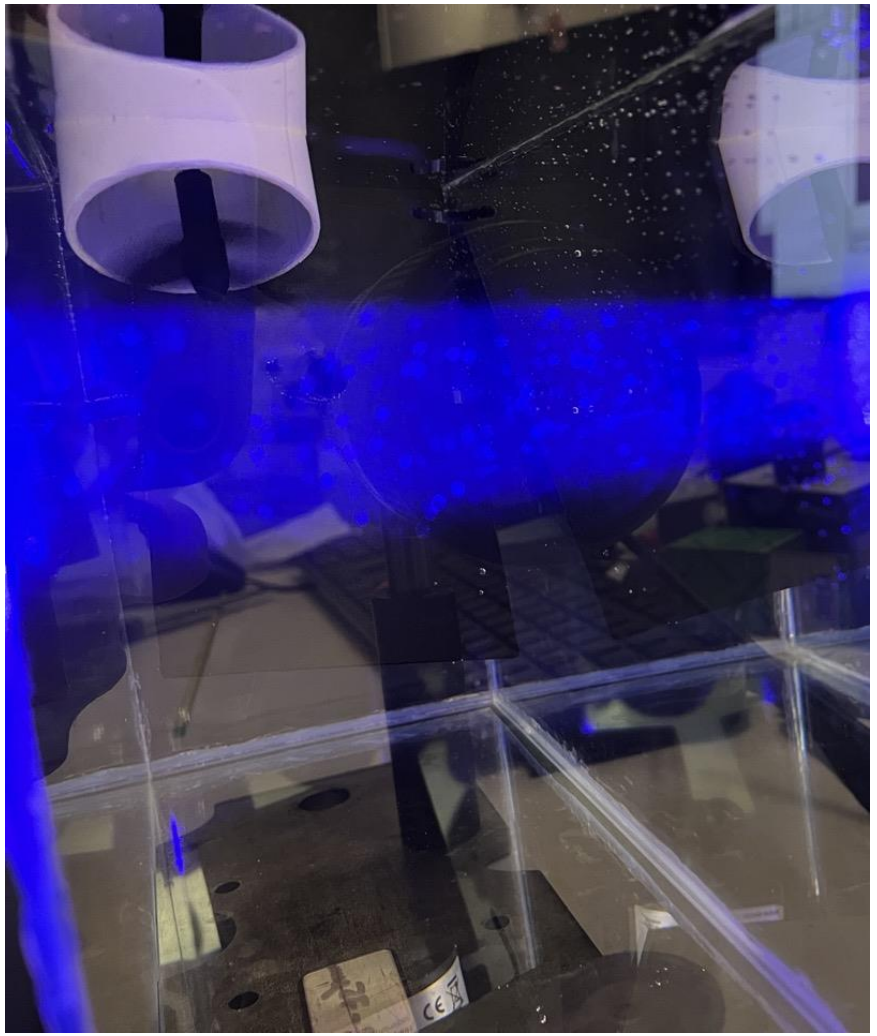


Time-surface display

Time-slice 1s, Playback speed 0.25x
LED pulse rate: 1 kHz @ 50 µs

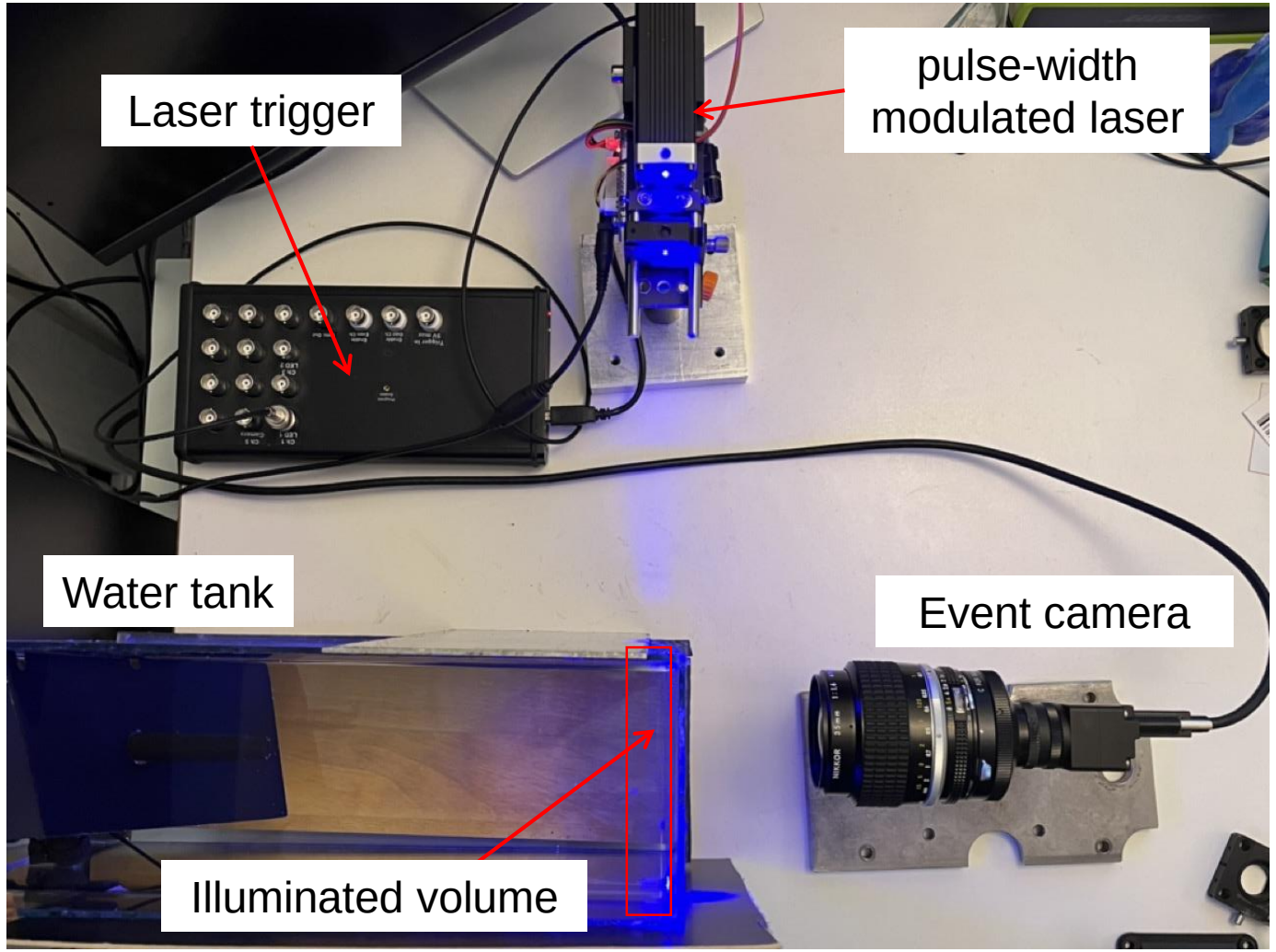
Aperture-encoded event imaging in water flow





Aperture-encoded event imaging in water

- Laser illumination
  at 100 Hz, 1 kHz, 10 kHz,
  duty cycle: 1% - 10%
  → 50mW - 0.5W
- Measurement volume
  ~15-20mm
- Measurements
  - without seeding (tap water)
  - “fluorescent” particles
    (32-75 µm)

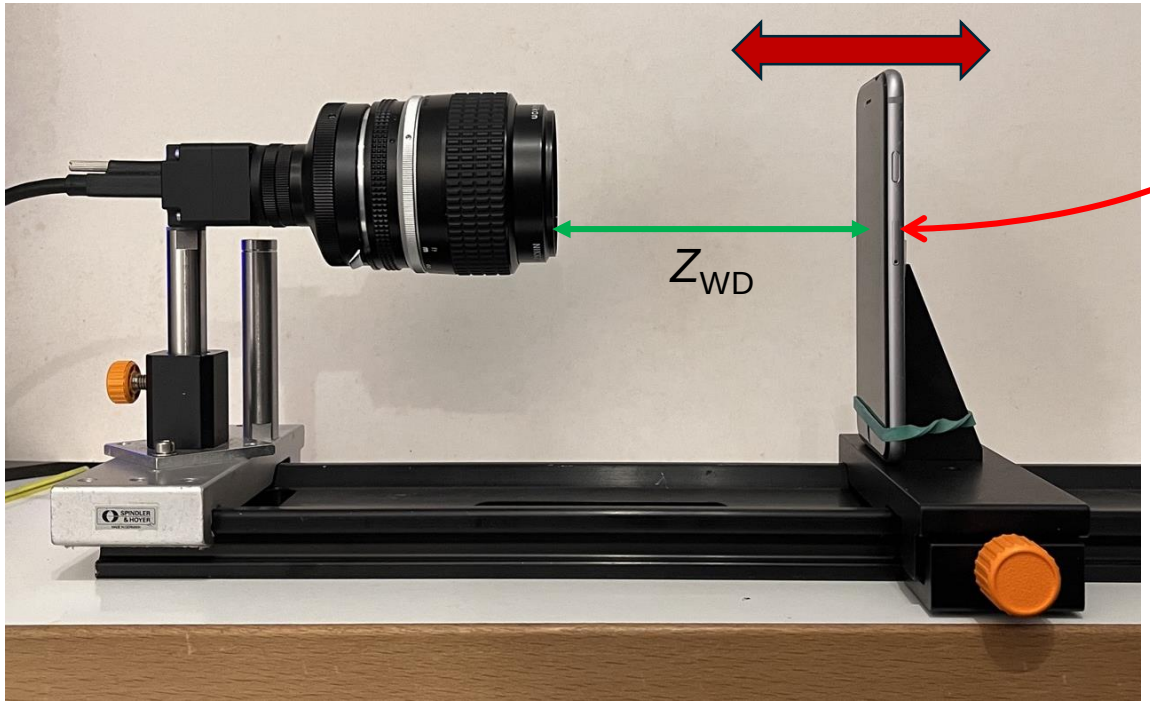


Event-recordings obtained in water with laser illumination

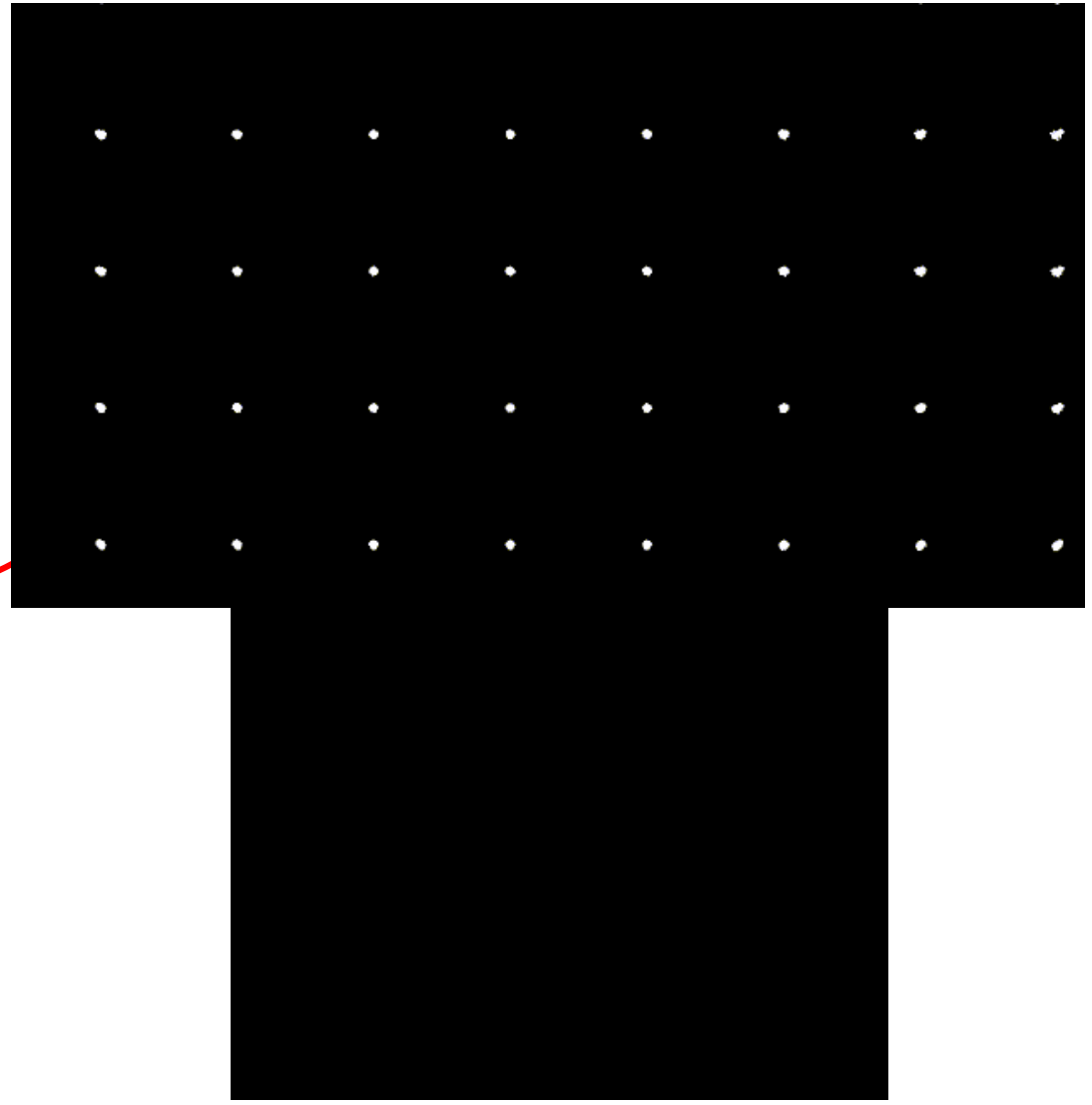
1 kHz @ 40 µs → 2.5% duty cycle (25 mW)

Calibration

- Blinking grid of dots
- FOV 21 x 12 mm² (W x H)
- Working distance Z_{WD} = 112 mm

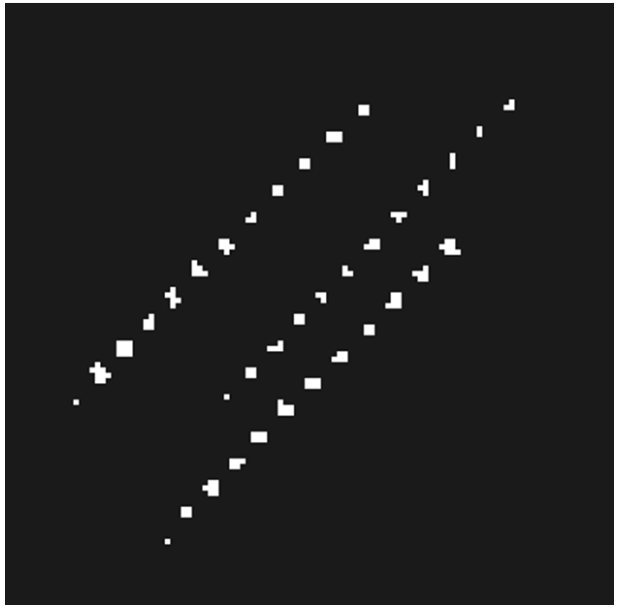


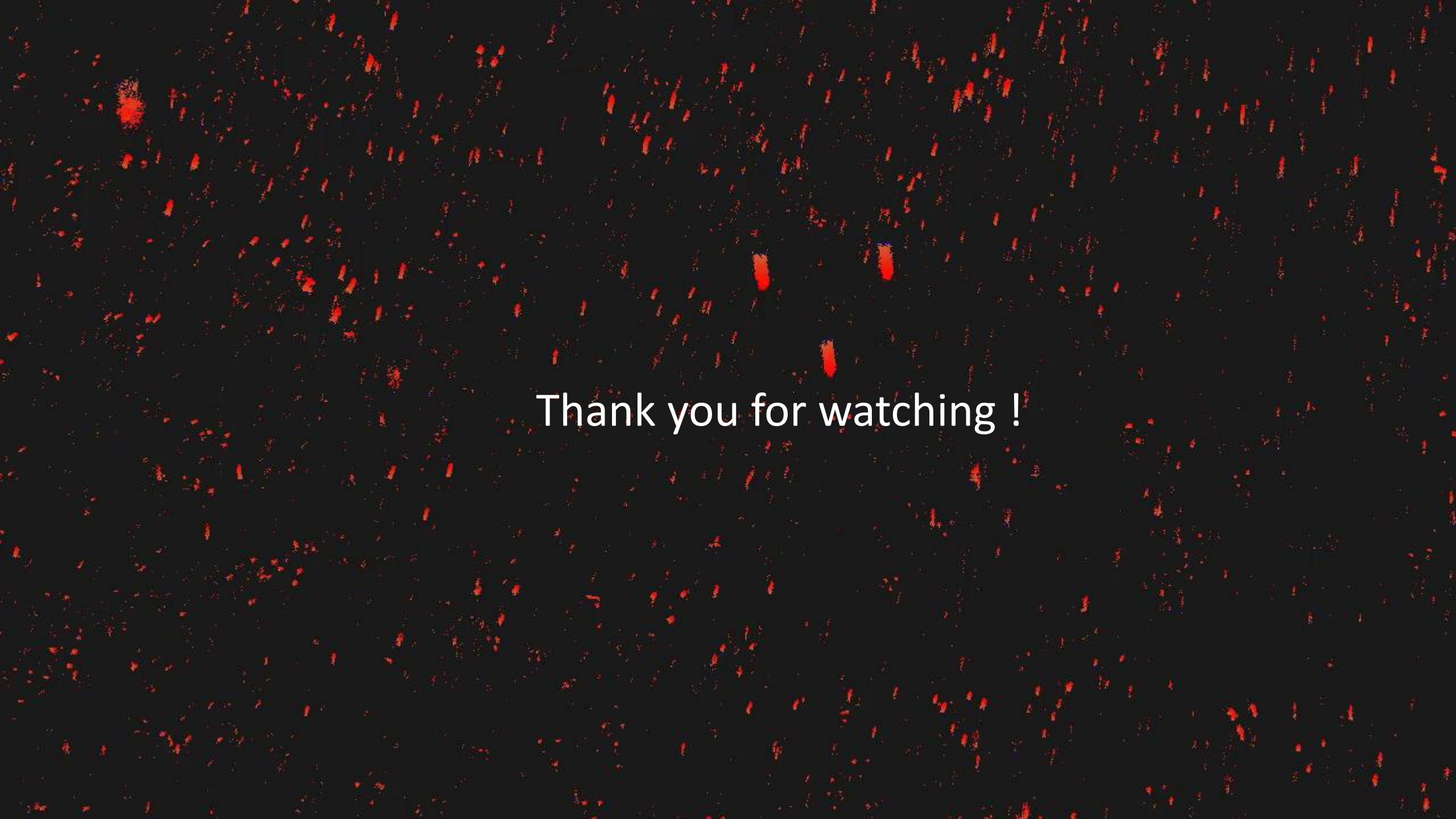
Scan depth 17 mm



Summary - Coded Aperture Event-Based Particle Imaging

- combination of event-based imaging and aperture encoding concept (“defocusing”) produces suitable raw data
- binary data → triplet matching and tracking could be simpler compared to standard MA-PTV
- higher sensitivity of EB camera permits smaller apertures → reduced blurring of triplets
- inline illumination holds potential but suffers from dust and scratches on surfaces along optical path
- reasonable results with LED side illumination using ~3-10 µm particles in air
- pulsed laser provides better control of illuminated volume (sharper edges)
- Work in progess!




Thank you for watching !