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Towards direct measurement of interfacial momentum & mass transfers

Philippe M Bardet,
Eirini Florou, Charles Fort,
& Corentin Le Houedec
The George Washington University
Mechanical & Aerospace Engineering
Home
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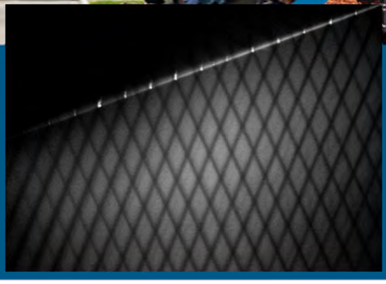
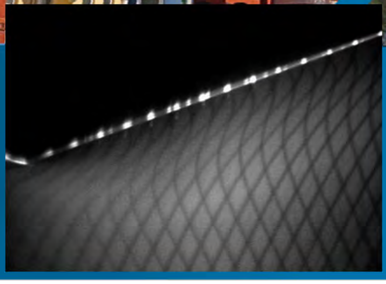
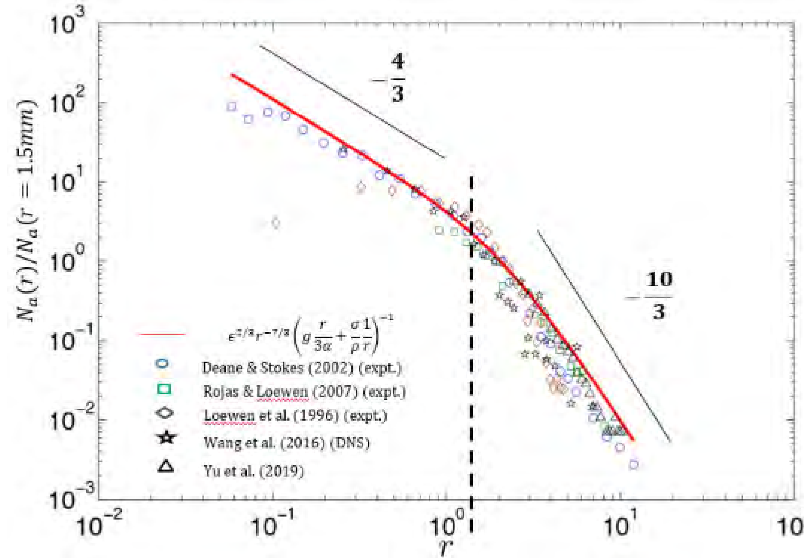
2023 Multiphase Flow Science Workshop

Motivation

- Effect of capillaries missing from most correlations on mass and momentum transfer
- Free surface turbulence (FST) characteristics, bubble entrainment and fragmentation are still not well understood
- Need for more data in sheared regimes
- Lack of experimental evidences
- Need for new experimental tools



Yu et al, 2020

$$r_H = c \left(\frac{\sigma}{\rho} \right)^{\frac{3}{5}} \epsilon^{-\frac{2}{5}} \qquad r_c = \frac{1}{2} \sqrt{\sigma / \rho\, g}$$

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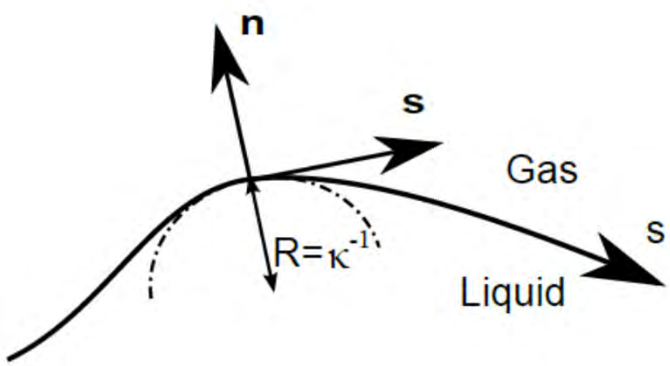
Interface Shear and Vorticity



Stress balance at interface between phase 1 and 2:

Tangential stress

$$\tau = \mu_i \left(\frac{\partial u_s}{\partial n}\bigg|_{n=0} - \kappa u_s + \frac{\partial u_n}{\partial s} \right)$$

Normal stress

$$\sigma = -p + 2\mu \frac{\partial u_n}{\partial n}\bigg|_{n=0}$$

Vorticity at the Surface: $\omega_s = 2u_s\kappa - 2\frac{\partial u_n}{\partial s}$

Stokes layer: $d = \sqrt{\frac{2\nu}{\Omega}}$

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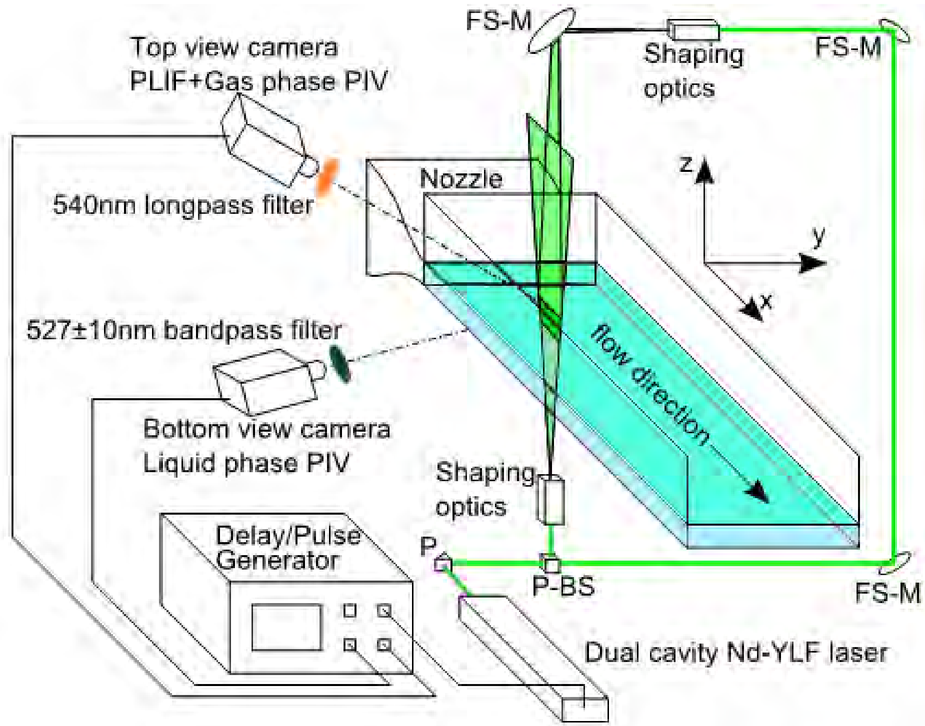
Surface Quantities are Resolved with Two-Phase PIV

$$d = \sqrt{\frac{2\nu}{\Omega}}$$ = 0.04 mm in water

= 0.16 mm in air



André & Bardet (2015a)

Laser: Nd:YLF, 4 pulses, 0 – 20 kHz, 60 mJ/pulses at 1 kHz

Cameras: - 2 CMOS: 1 Mpixels at 7,500 fps, 12 bit, 16 GB → 1×10^4 images

- 2 CMOS: 4 Mpixels at 560 fps, 8 bit, 2 TB → 2×10^6 images

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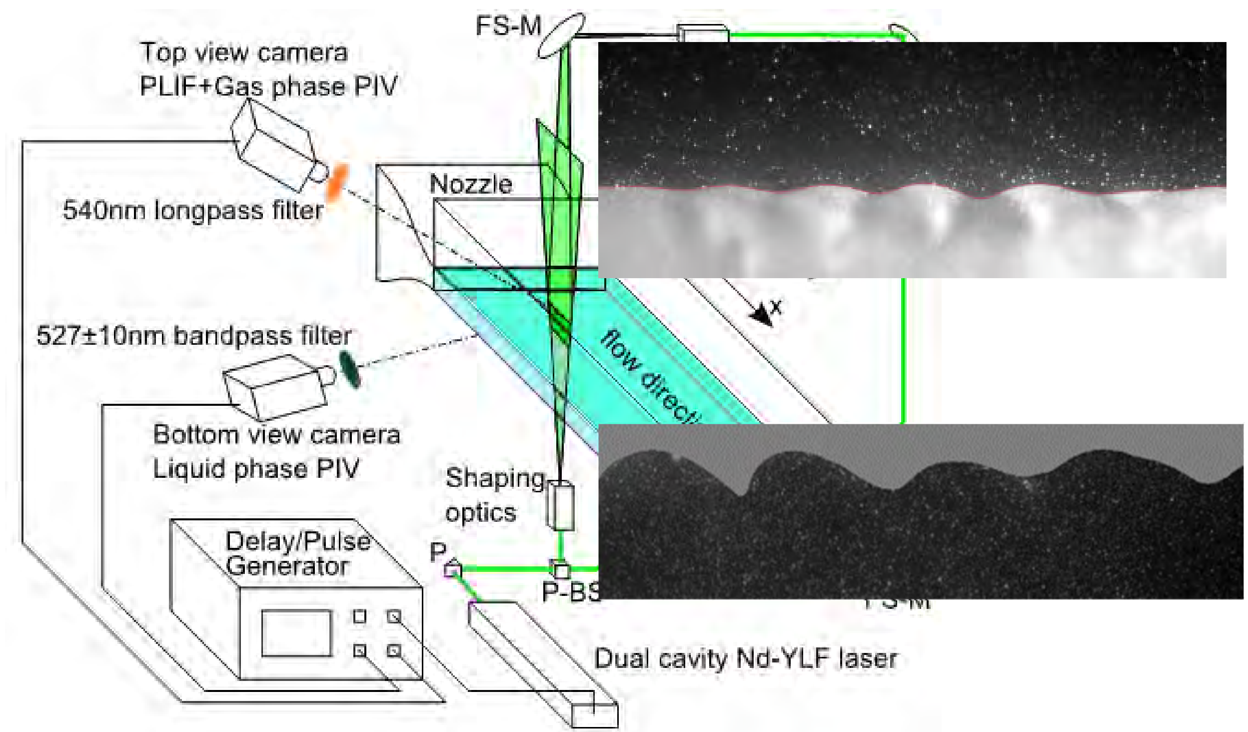

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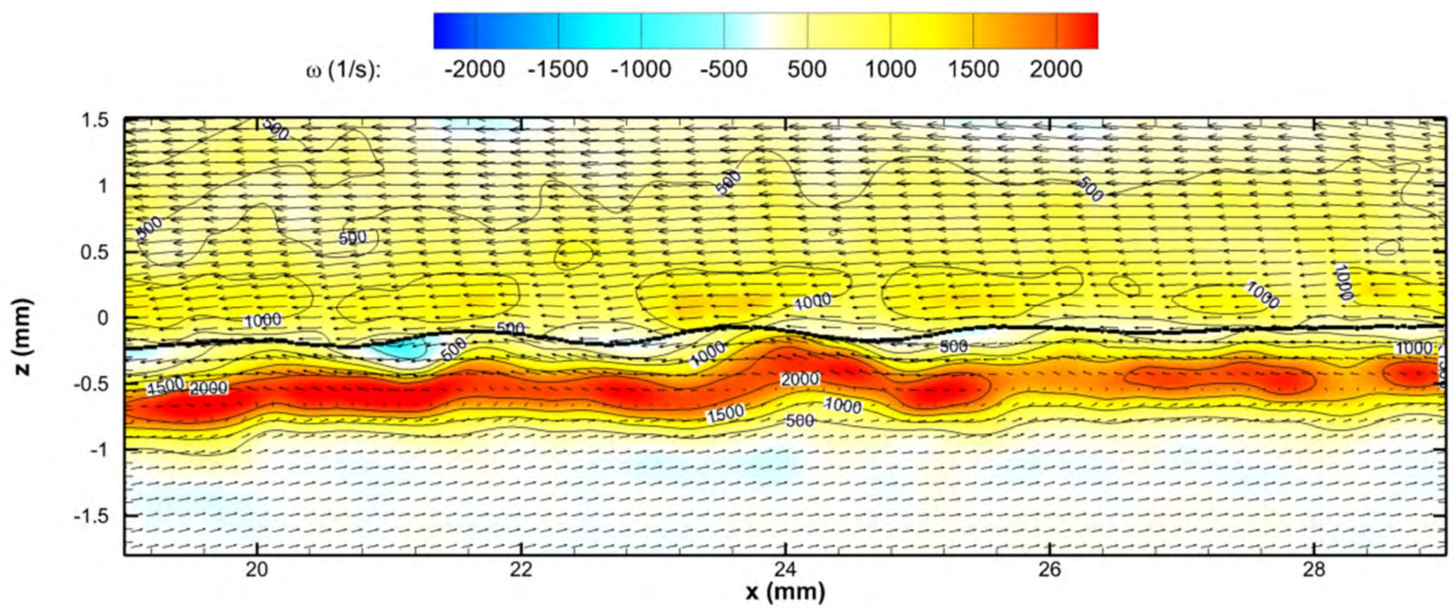
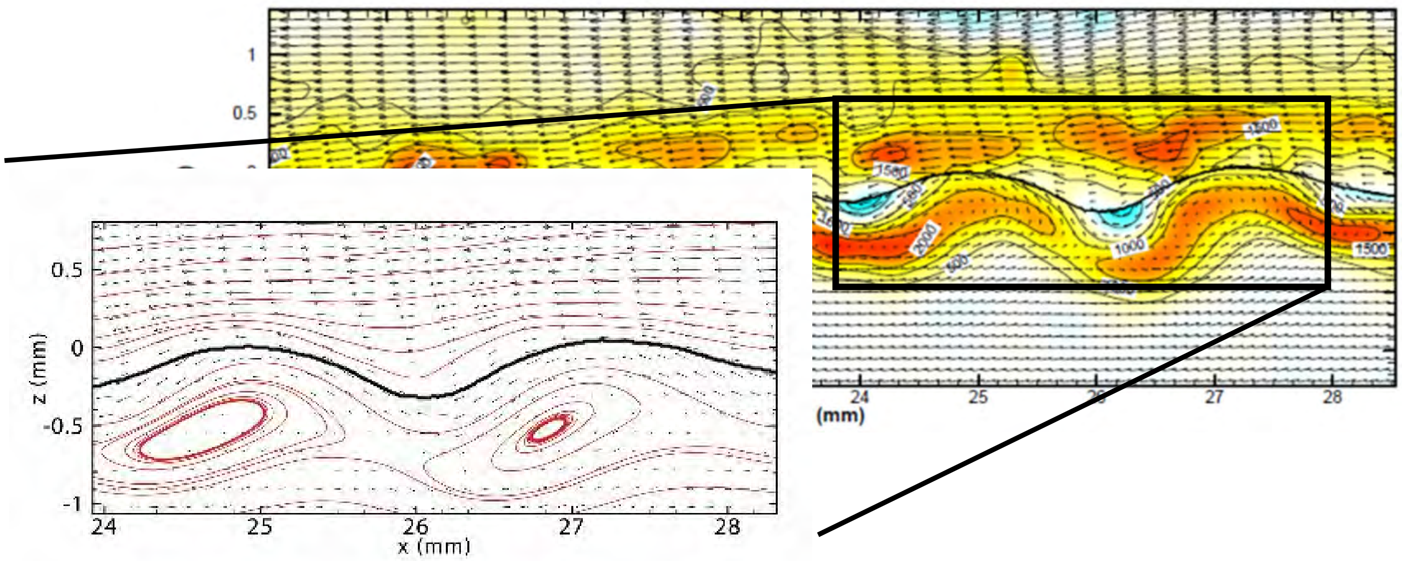
Shear Layer rolls up



André & Bardet (2014b)

Streamlines in Both Phases correspond



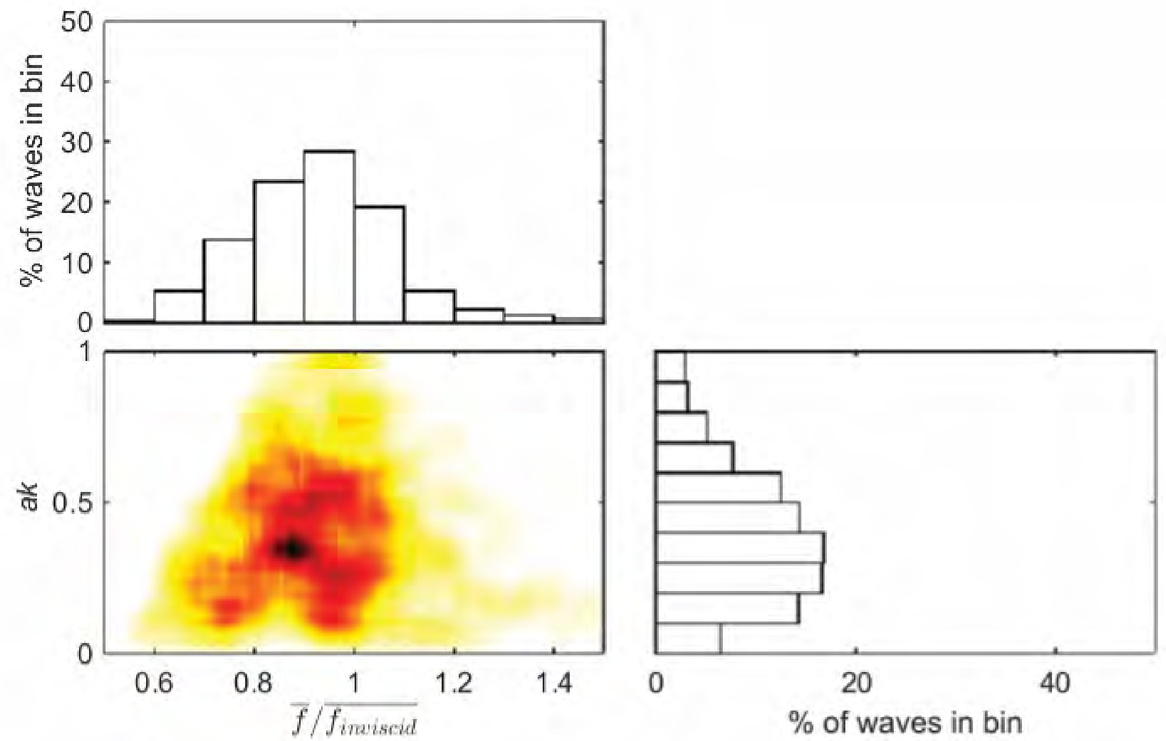
André & Bardet (2015a)

Waves Statistics

6253 waves

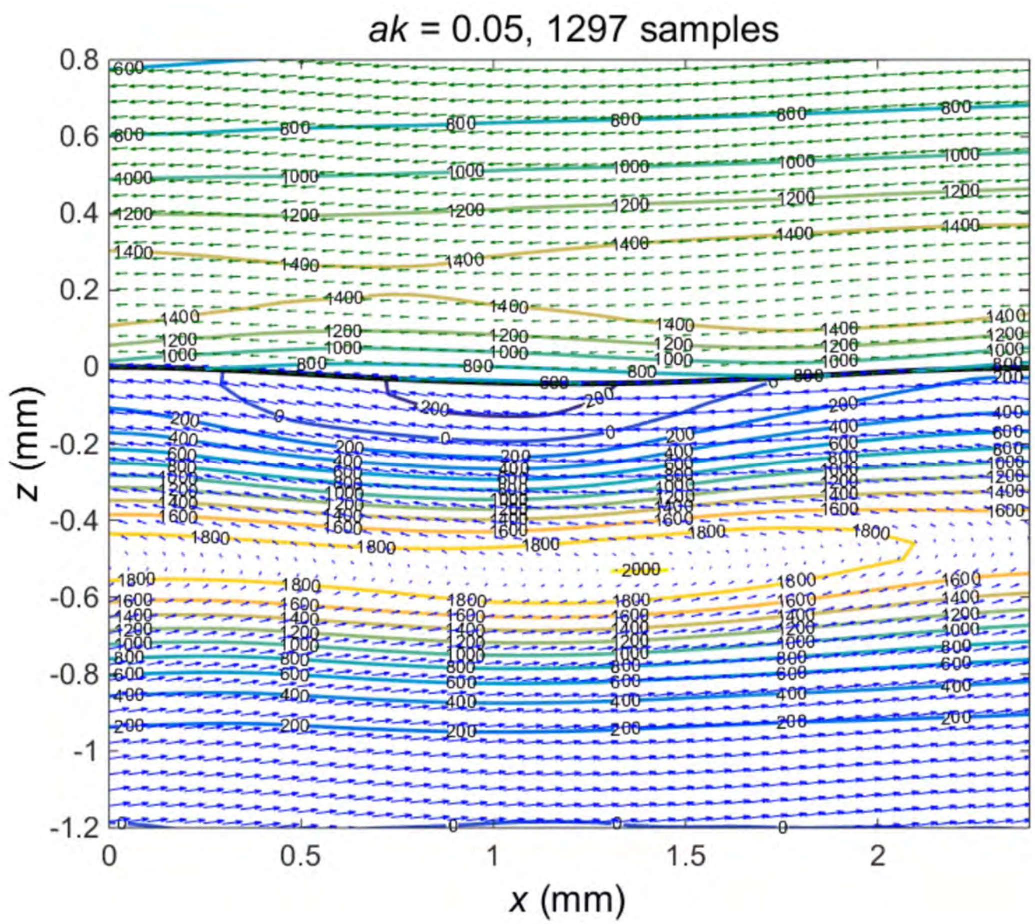
averaged data over 1 λ

wave steepness: $ak = \frac{2\pi \cdot a}{\lambda}$

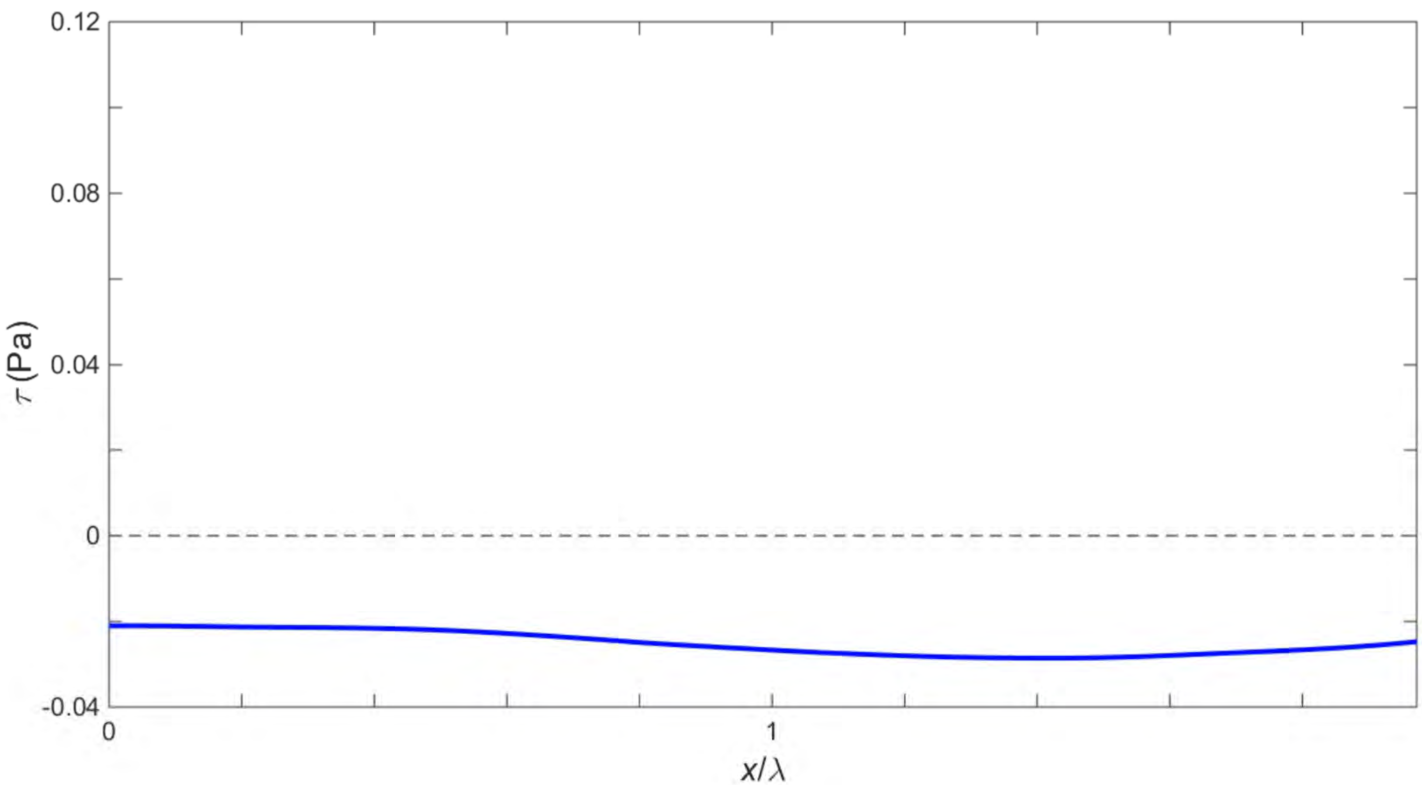


André & Bardet (2015b)

ak Conditional Averaged Velocity Fields

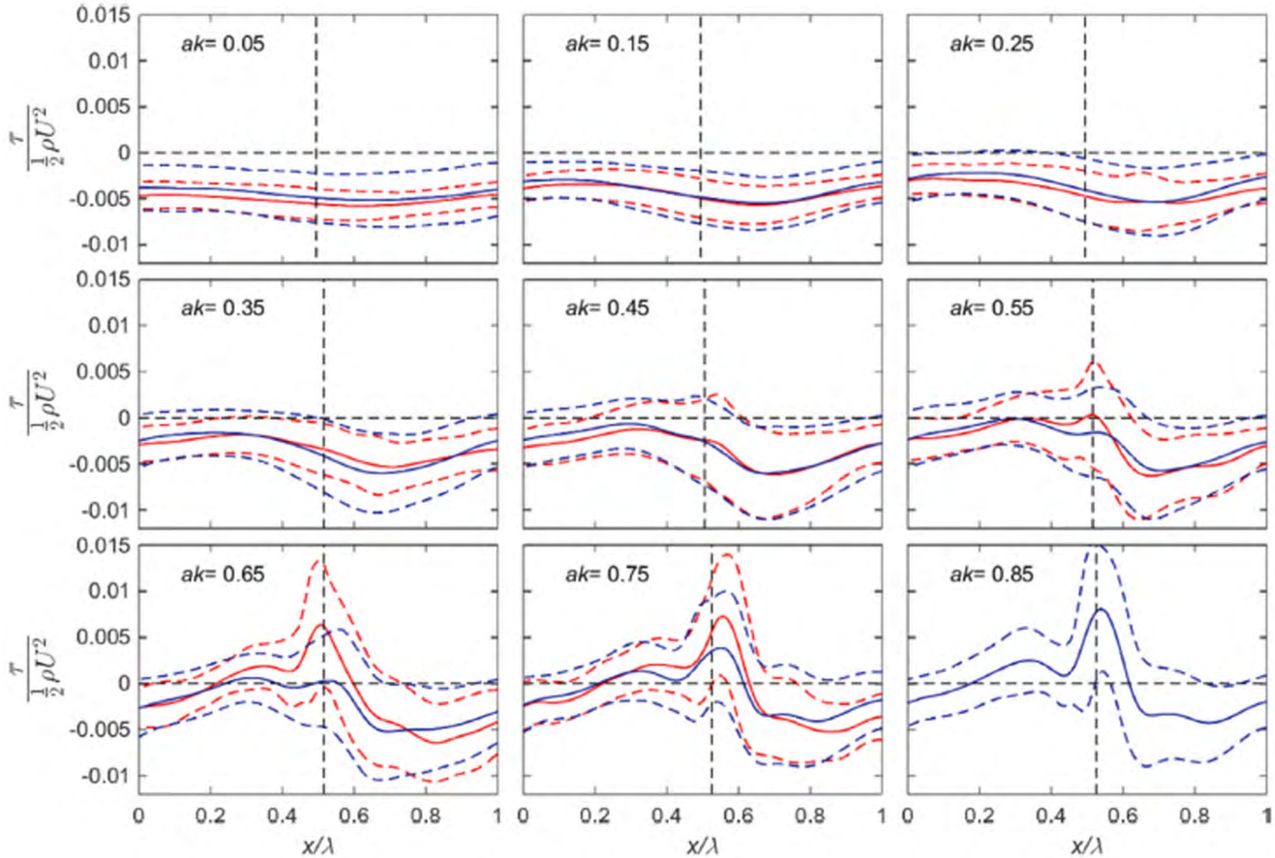


Interface Shear vs *ak*



Conditional Average

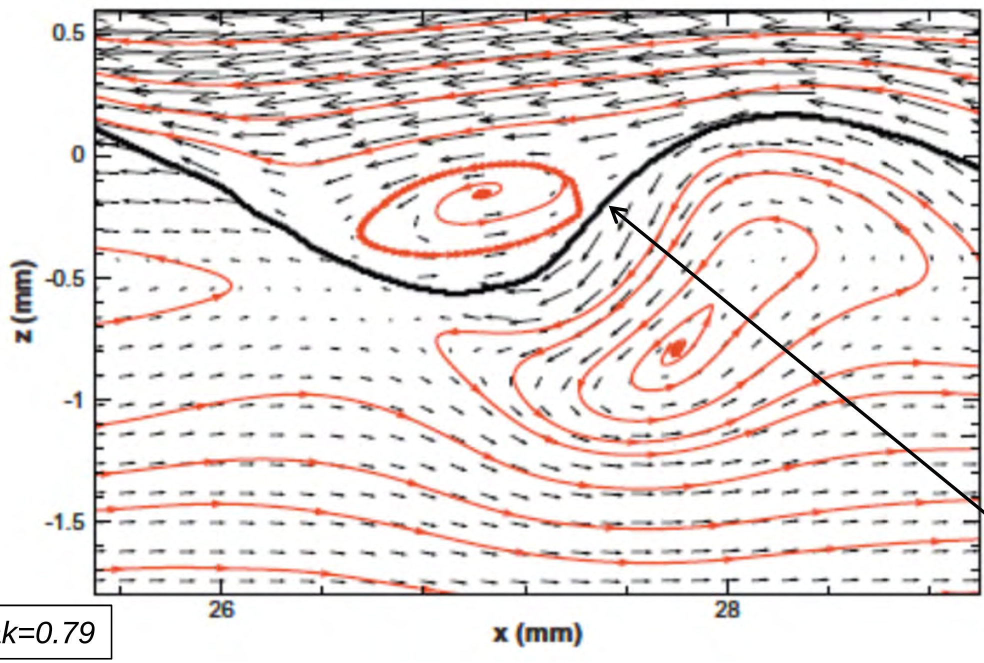
Interface Shear vs *ak*



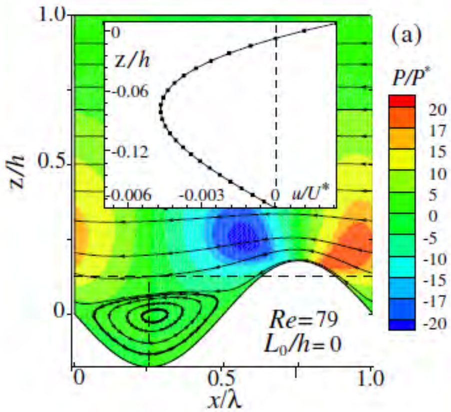
2D wavy surface: Two phase PIV

Interfacial shear stress: Flow separation

$U = 3.00\, m/s \quad Re_\theta = 159 \quad We_\theta = 6.61$



ak=0.79

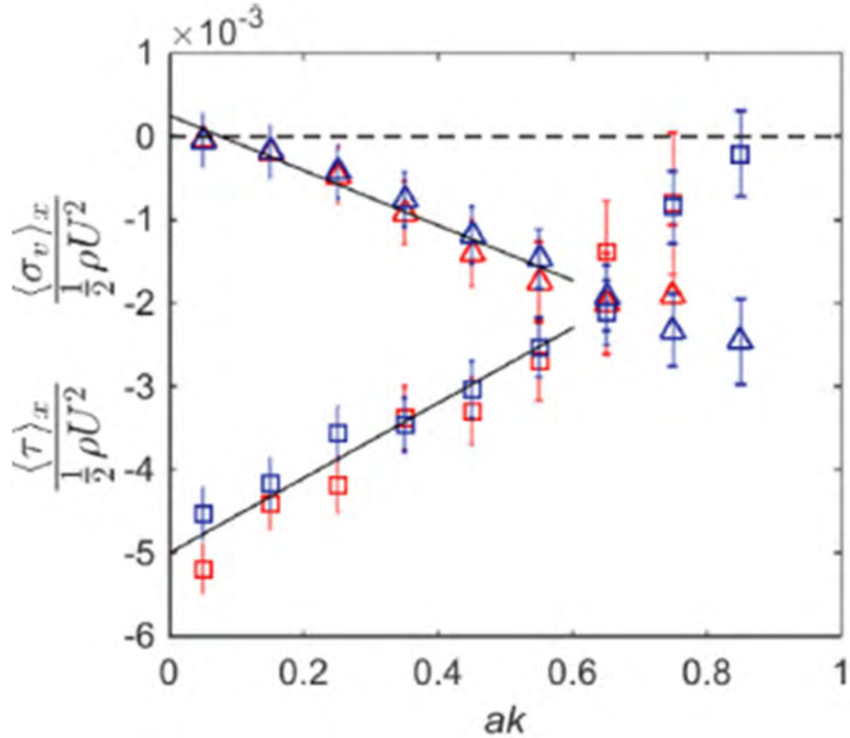


Niavarani et al. 2009
Separation for *ak>0.8*

Separation point: $\tau_s < 0 \;\&\; u_s = 0$

André & Bardet, *in progress*

Mean viscous Shear vs *ak*



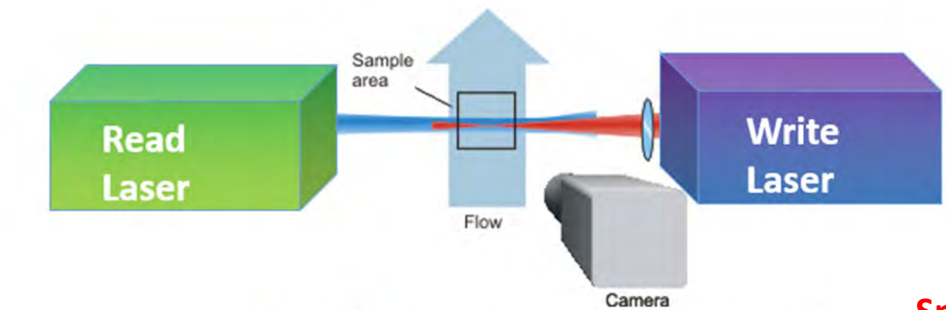
New instrumentation needs

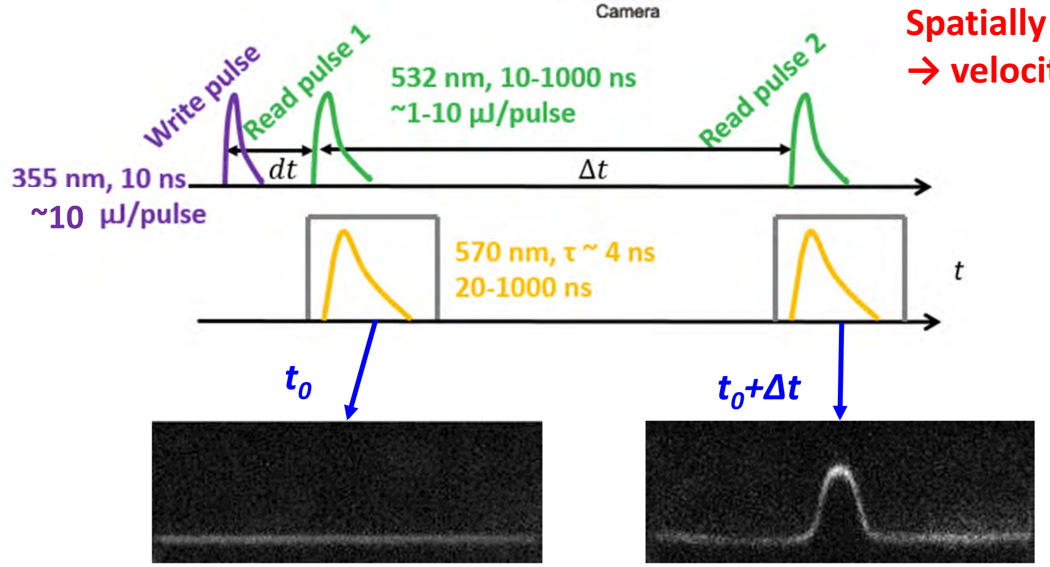
- Velocimetry with higher spatial resolution
- 3D profilometry
- Ability to probe optically high void fraction flows
- Measure mass transfer

- Techniques need to be:
  - Non-intrusive
  - Minimally perturbative

Microscopic Molecular Tagging Velocimetry (µ-MTV)

Operating Principles of µ-MTV





- **Molecular** tracers added or already present
- Tracers activation (tagging) with a first laser (***write***)
- **Lagrangian tracking** of tagged pattern with a 2^{nd} laser (***read***)

Spatially continuous
→ velocity gradients directly resolved at the wall

But historically, MTV in water:

- Limited spatial resolution (500 µm)
- Limited temporal resolution (1 ms)
- Limited laser options

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300-µm-spaced MTV lines at the Talbot plane

Turbulent Channel Flow, Re_τ = 880

$\boldsymbol{l_\nu}$ **~ 11.5 µm**, t_ν ~ 120 µs

Write: 355 nm Nd:YAG (14 ns)
@ **1-2 kHz**

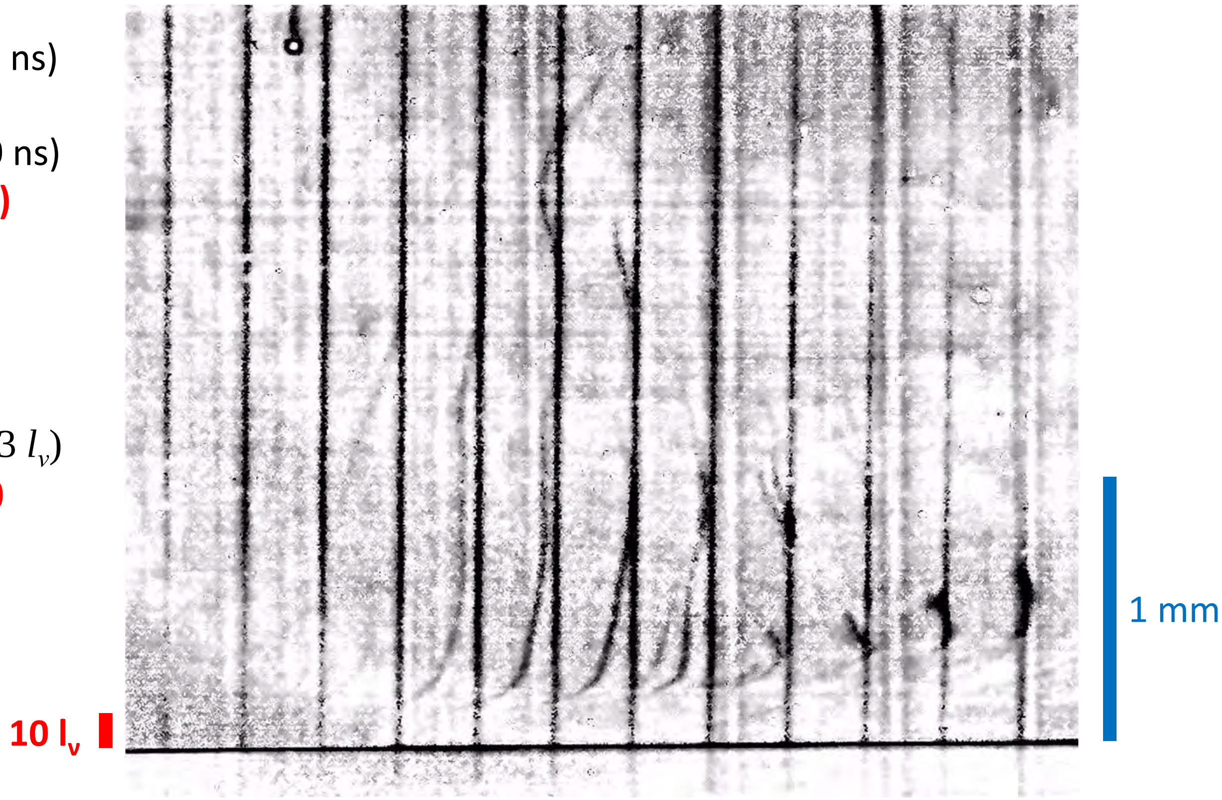
Read: 527 nm Nd:YLF (180 ns)
@ **10 kHz (0.6 t_ν)**

CMOS Camera @ 10 kHz

M = 2.65

Beam spacing = 300 µm (23 l_ν)

Beam width ≈ 25 µm (2 l_ν)



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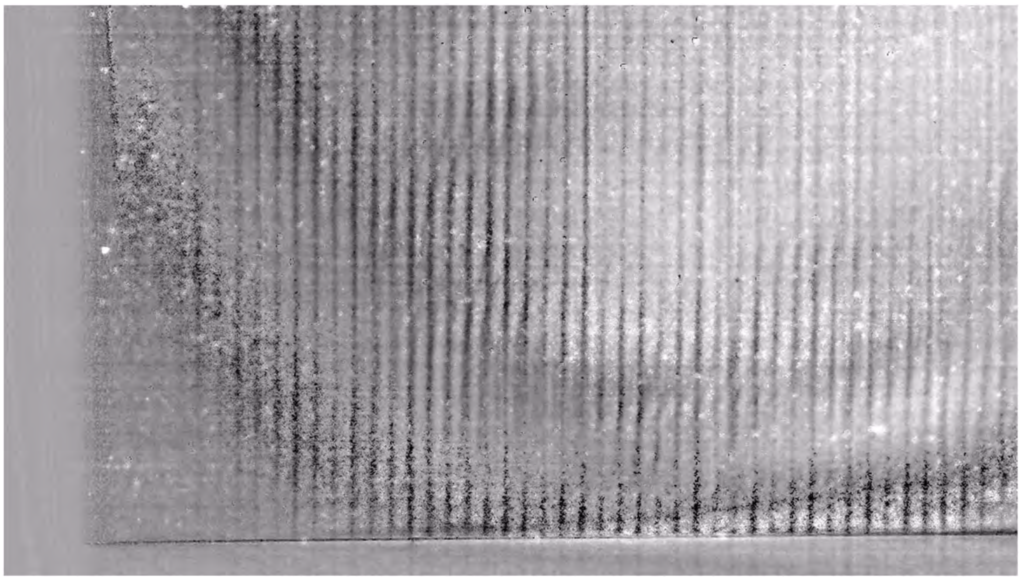
Third fractional plane (p = 100 µm) at high magnification

Δt=100µs
1 kHz *write*
10 kHz *read*

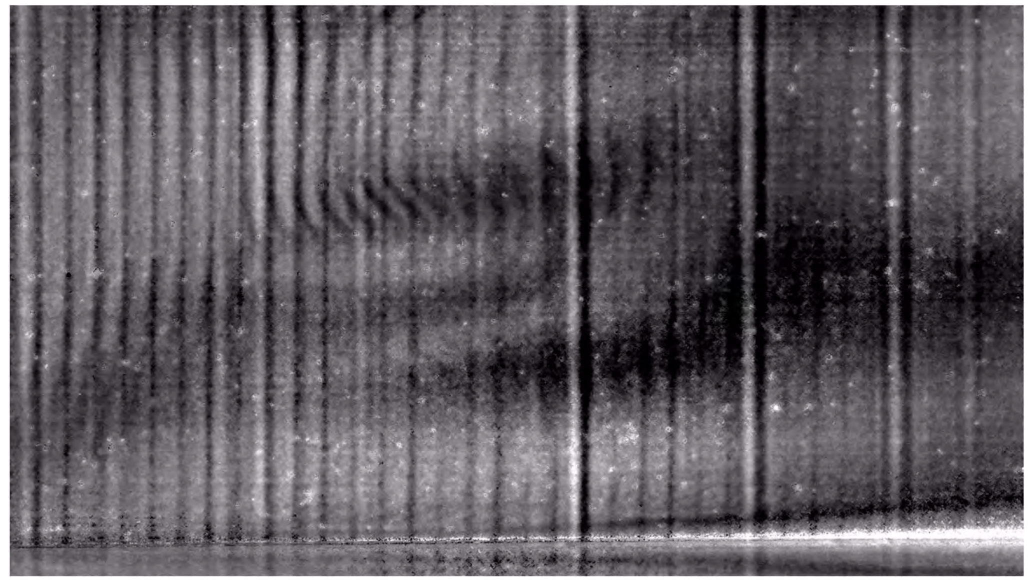
Turbulent Channel Flow, $Re_\tau = 880$

$\boldsymbol{l_\nu} \sim$ **11.5 µm**, $t_\nu \sim 120$ µs

M = 2.65



M = 4.13



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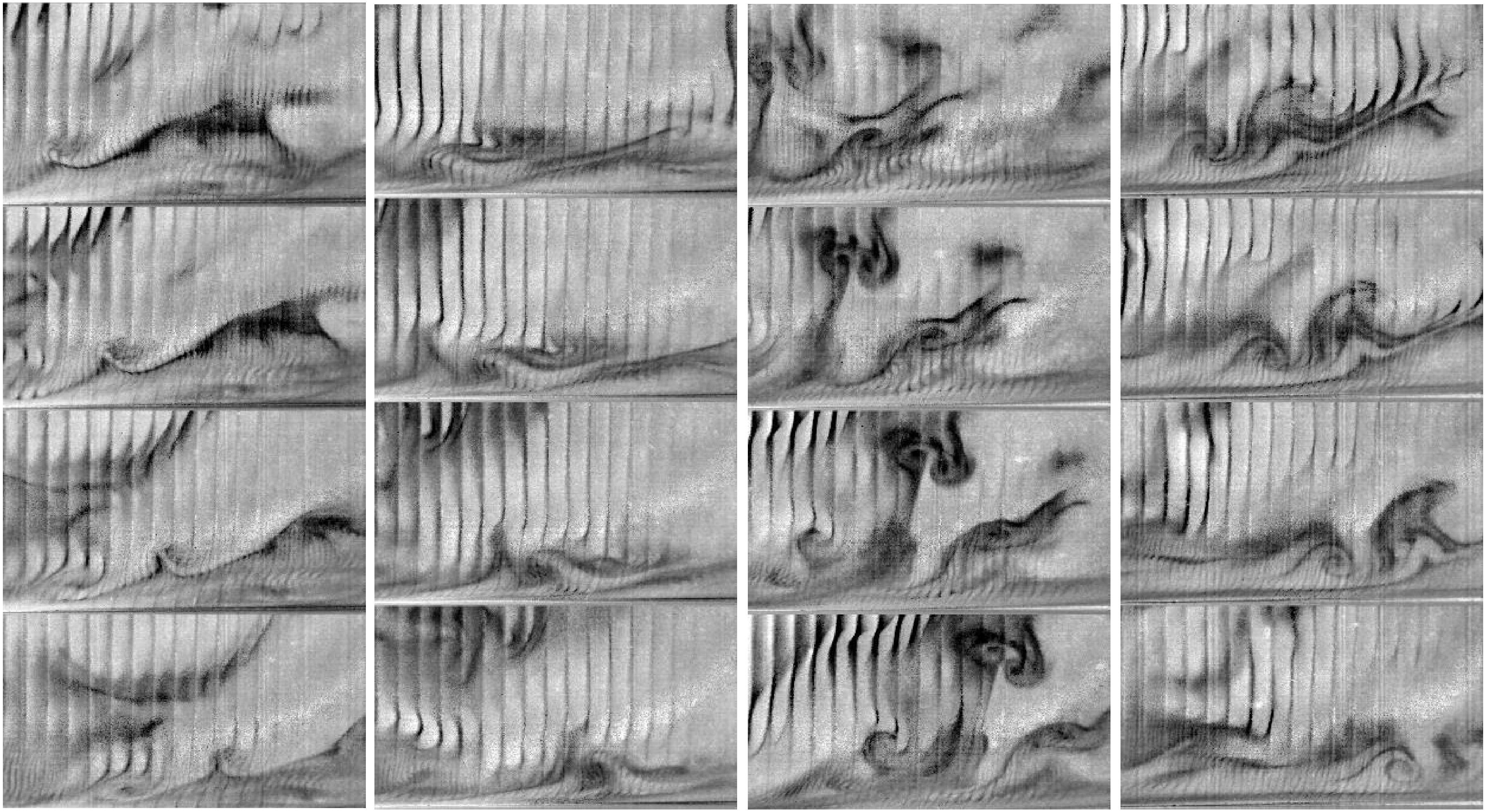


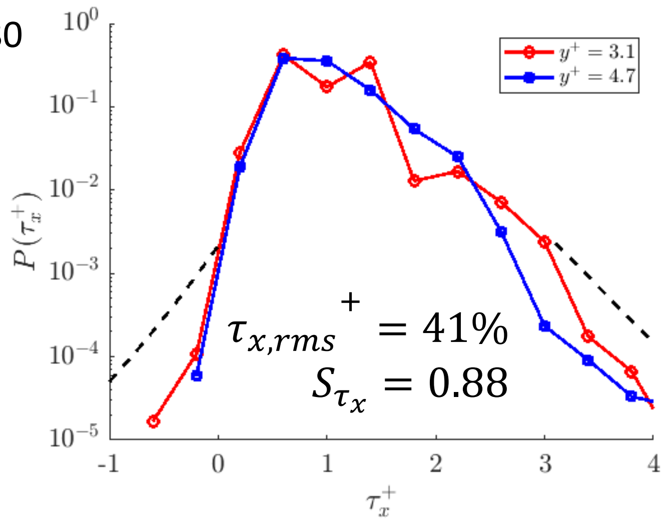
MTV accuracy – to date

WSS from pressure gradient: $\tau_w = -\frac{H}{2}\frac{dP}{dx}$

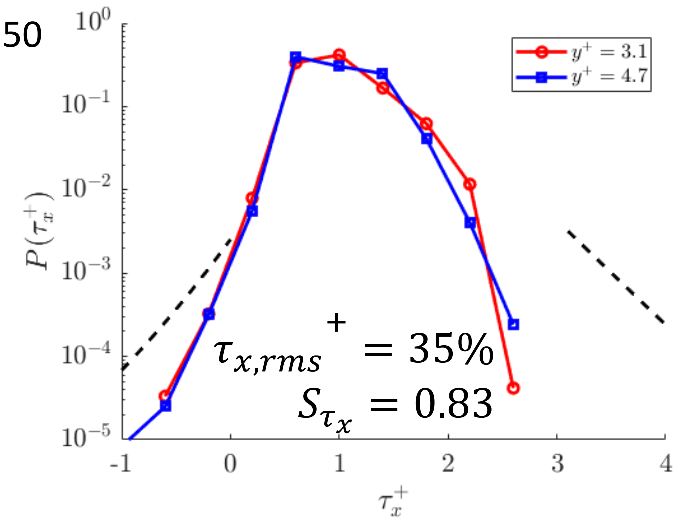
MTV: 120,000 frames @1 kHz (2 min sample)

U_b (m/s)	Re_τ	l_ν (μm)	M (l_ν /pxl)	$\Delta t_{write/read}$ (μs)	τ_w (Pa)	$\overline{\tau_x}$ (%)
1.8	880	11.5	0.2	122 (≈ t_ν)	7.52 ± 0.06	< 1%
2.6	1250	8.1	0.3	62 (≈ t_ν)	15.10 ± 0.10	

Re_τ = 880



Re_τ = 1,250



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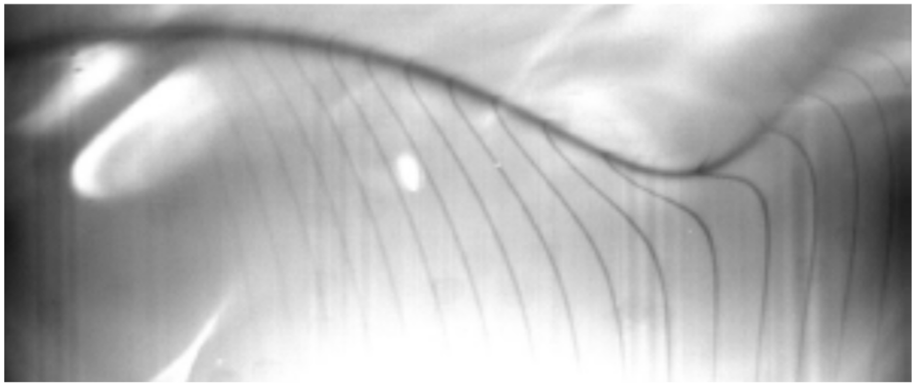
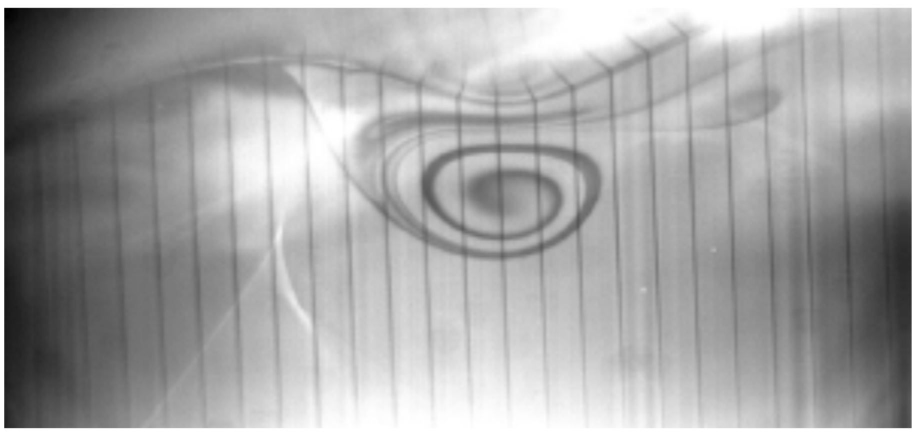
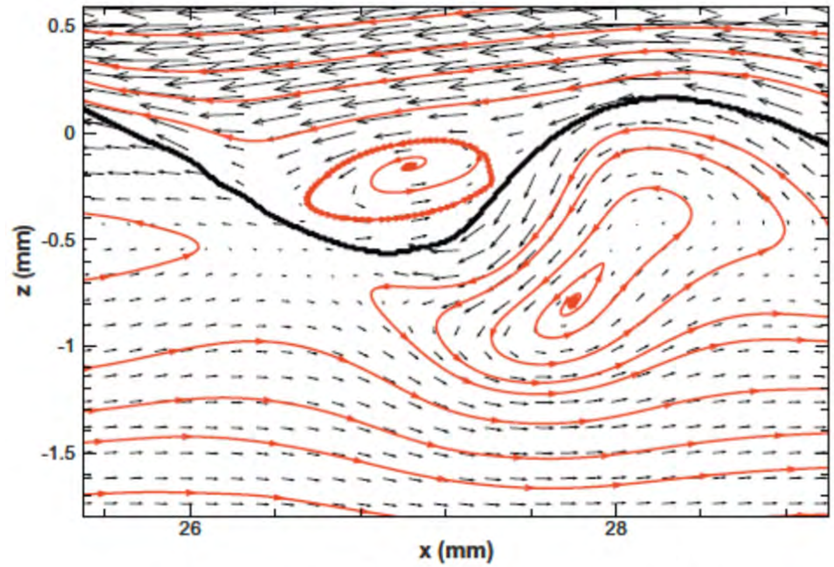
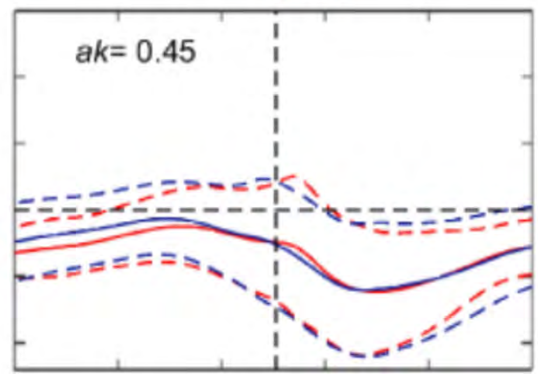
MTV below capillary waves









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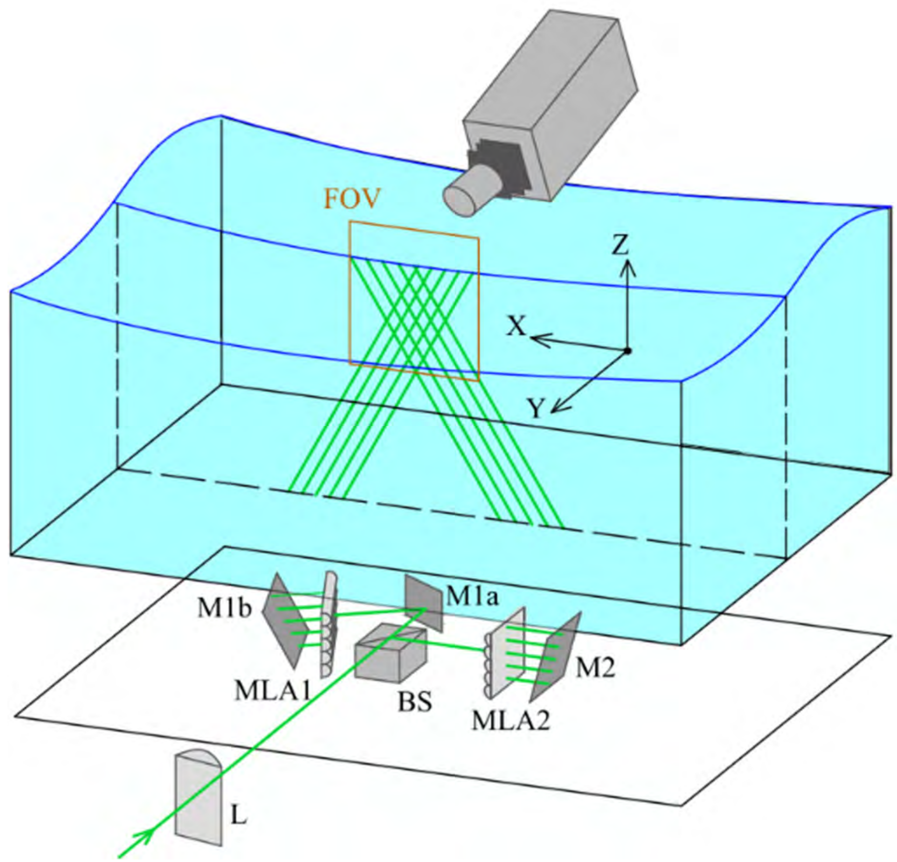
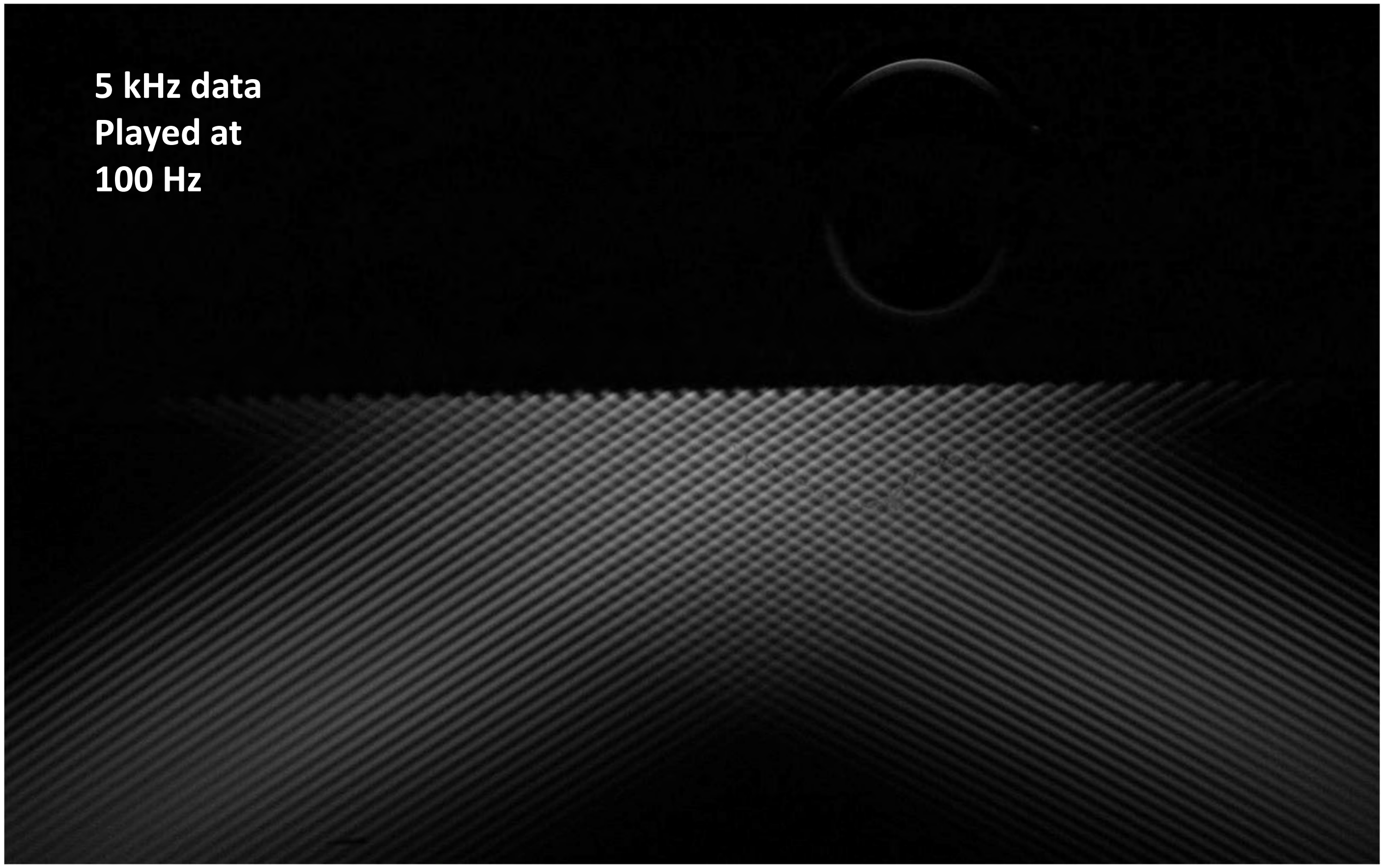
3- 3D + t Profilometry



Florou, et al, *Exp Fluids (2023)*

2 mm drop on quiescent water



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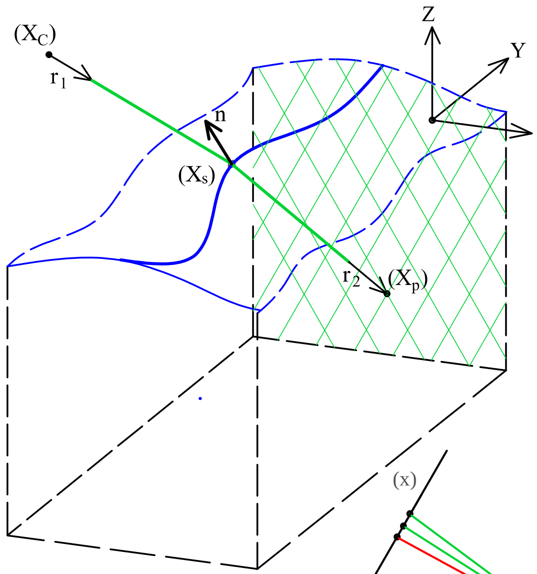
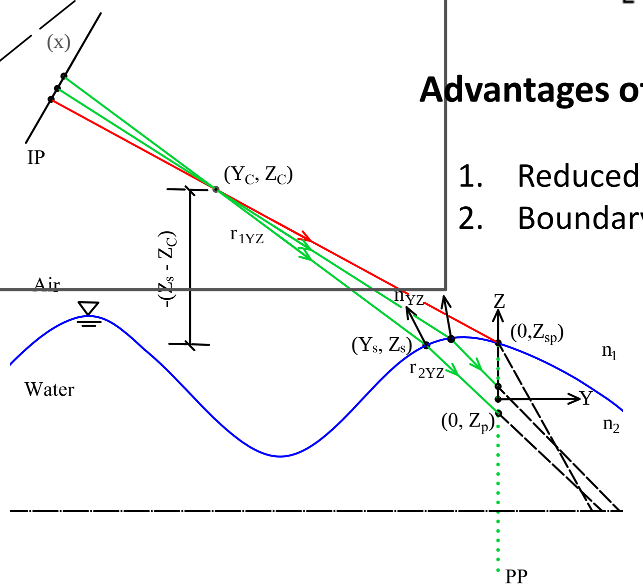
Florou, et al, *Exp Fluids (2023)*

Profilometer relies on ray tracing





Basic equations:

$$X_s = X_C + \frac{Z_s - Z_C}{\boldsymbol{Z} \cdot \boldsymbol{r_1}} \boldsymbol{r_1}$$

$$X_p = X_s + \frac{Y_p - Y_s}{\boldsymbol{Y} \cdot \boldsymbol{r_2}} \boldsymbol{r_2}$$

$$\mathbf{r_2} = \frac{n_1}{n_2}\mathbf{r_1} + \left[\frac{n_1}{n_2}(-\mathbf{n}\cdot\mathbf{r_1}) - \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 (1 - (\mathbf{n}\cdot\mathbf{r_1})^2)}\right]\mathbf{n}$$ *Snell's law*

Advantages of vertical pattern plane:

1. Reduced risk of ambiguities -> resolution of stronger surface curvature and slope
2. Boundary conditions for initialization of the free surface reconstruction

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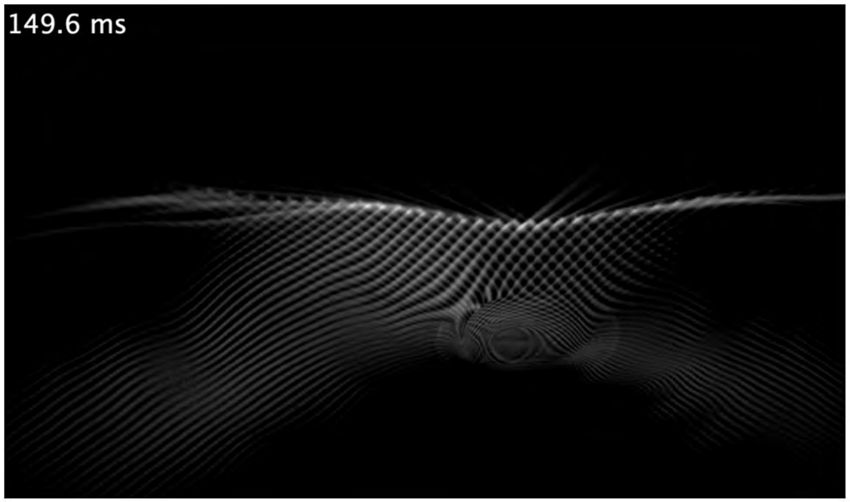
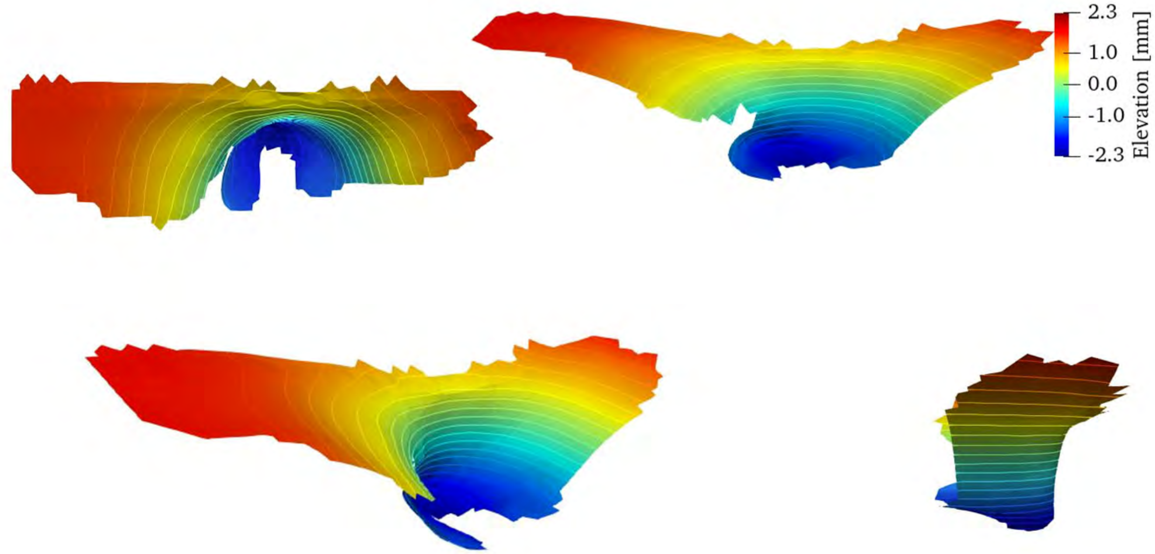
Florou, et al, *Exp Fluids (2023)*

Sample raw data and corresponding 3D surfaces





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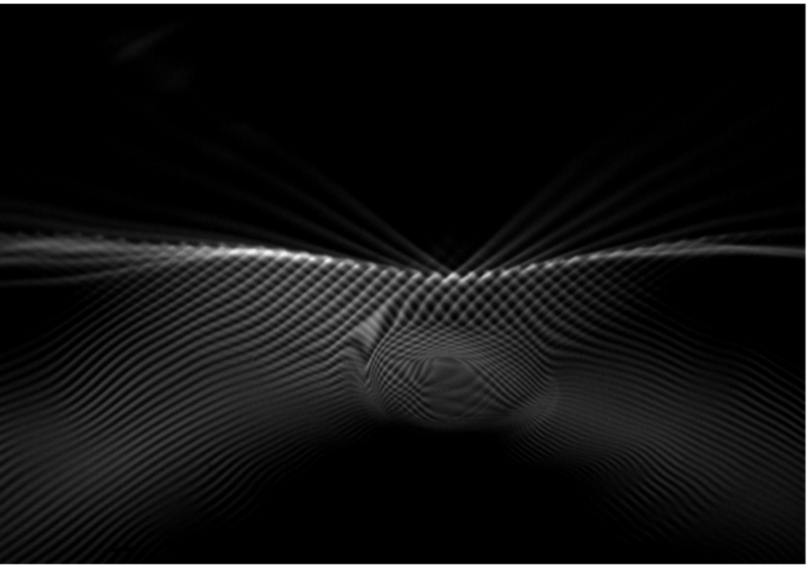
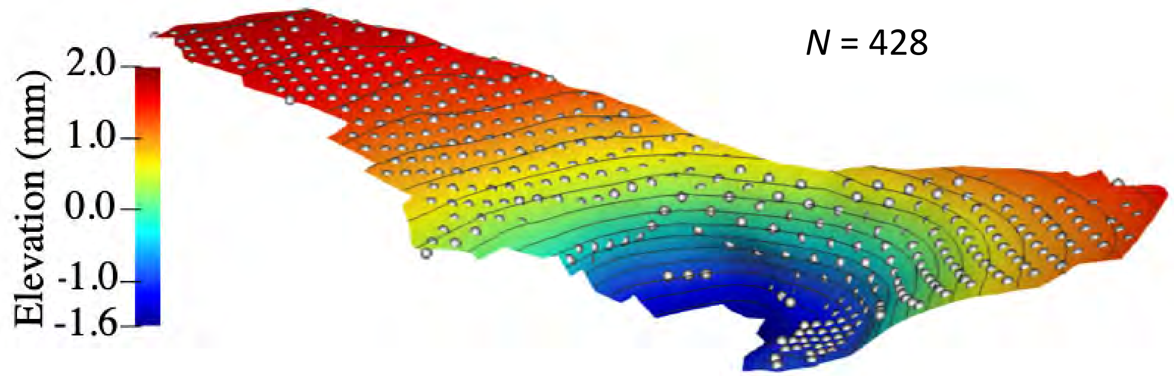
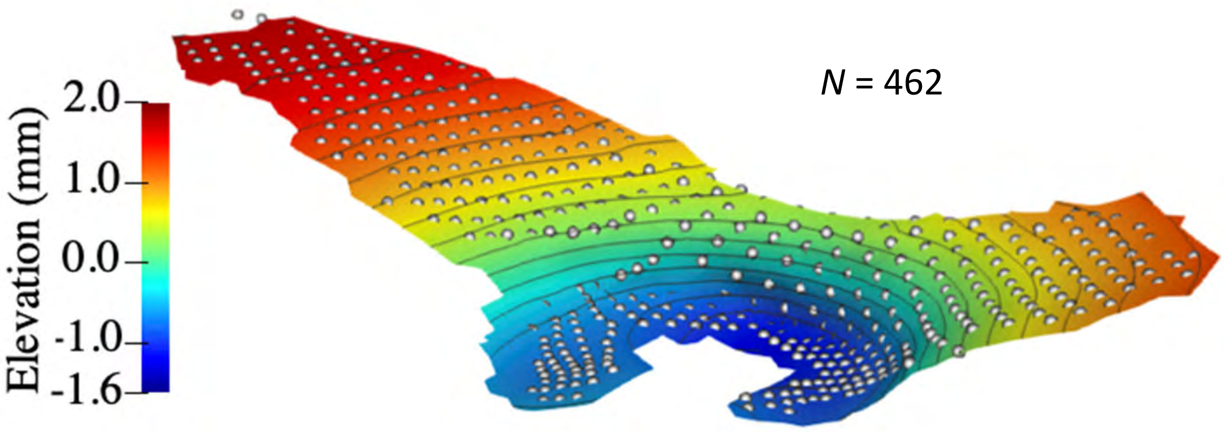
Florou, et al, *Exp Fluids (2023)*

Independent vs Time-dependent processing – Surface reconstruction

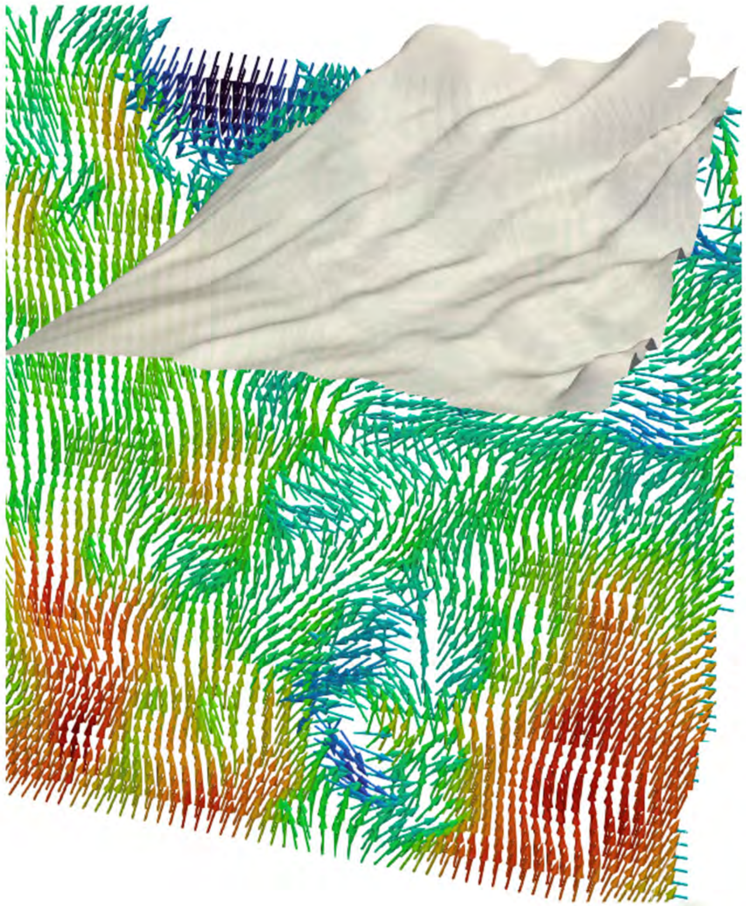






Florou, et al, *Exp Fluids (2023)*

Polarimetric Slope Sensing combined with PIV



Complimentary to TESI-PLIF

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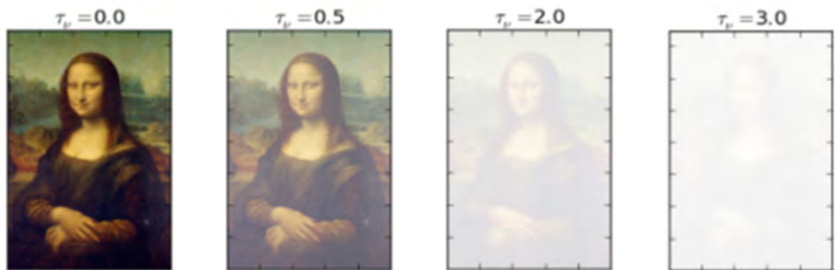
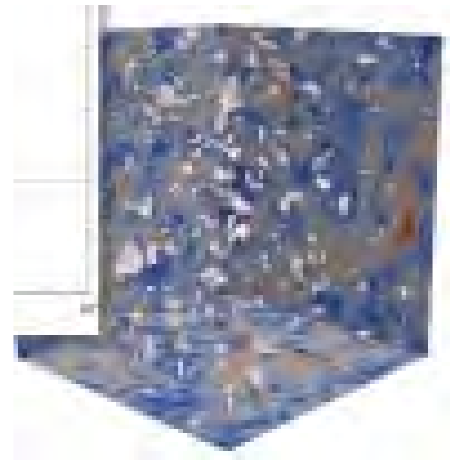
Le Houedec, et al *(in preparation)*

4- Bubble statistics with UFOs

Optical thickness (τ): amount of absorbed light through a medium of thickness *L*





- Numerical examples of optical thickness for bubbly flows:
  - L: 0.15m, bubble diameter: 100µm, void fraction: 0.55% ➔ τ = 25
  - L: 0.15m, bubble diameter: 200µm, void fraction: 1.1% ➔ τ = 25

- Traditional methods fail with optical thickness > 1

τ

PIV, LIF, LDA/PDA, Shadowgraphy | **1** | SLIPI (Structured Laser Illumination Planar Imaging), **Ballistic Imaging** | **10** | X-rays

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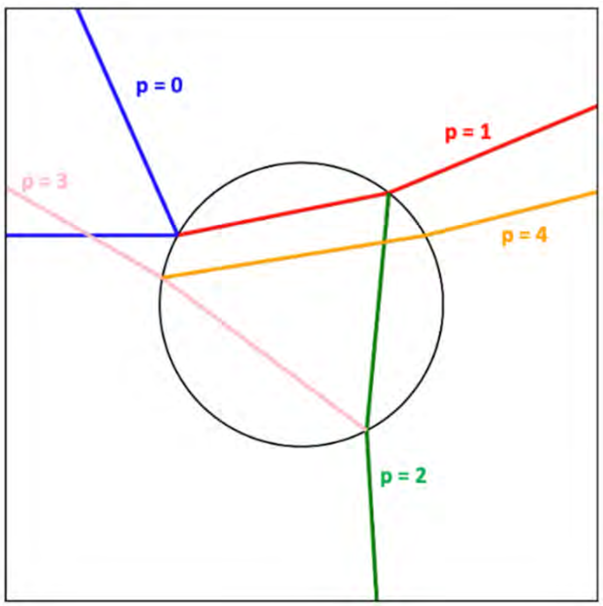
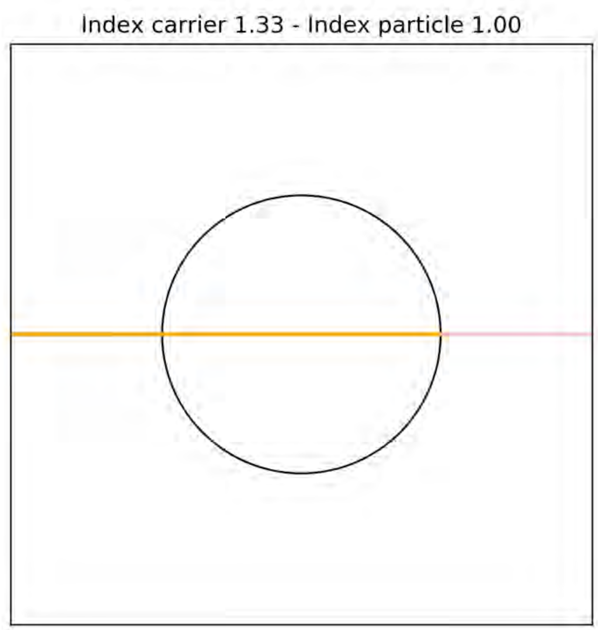
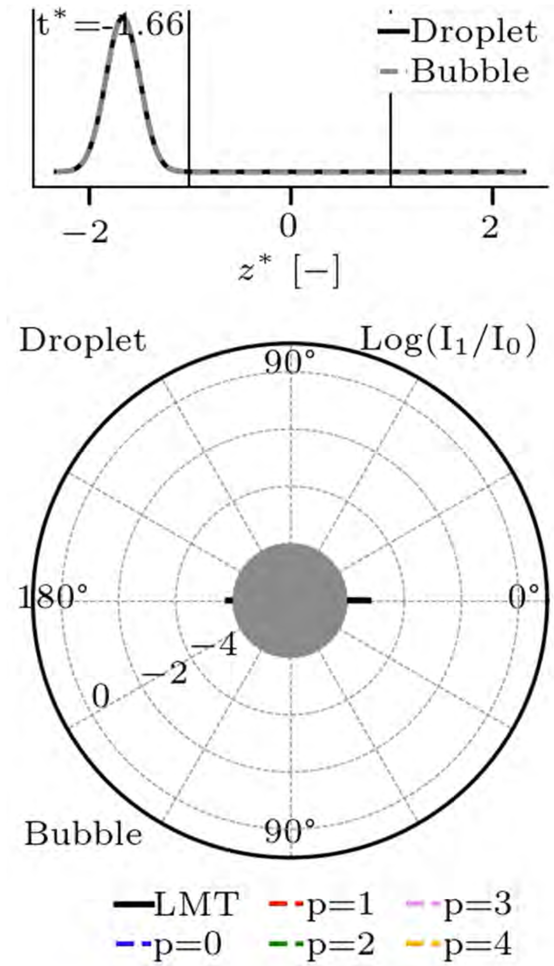
Comparison droplet/bubble

- Water droplet in air vs. Air bubble in water
- Speed of light depends on the medium: $C_{water} < C_{air}$



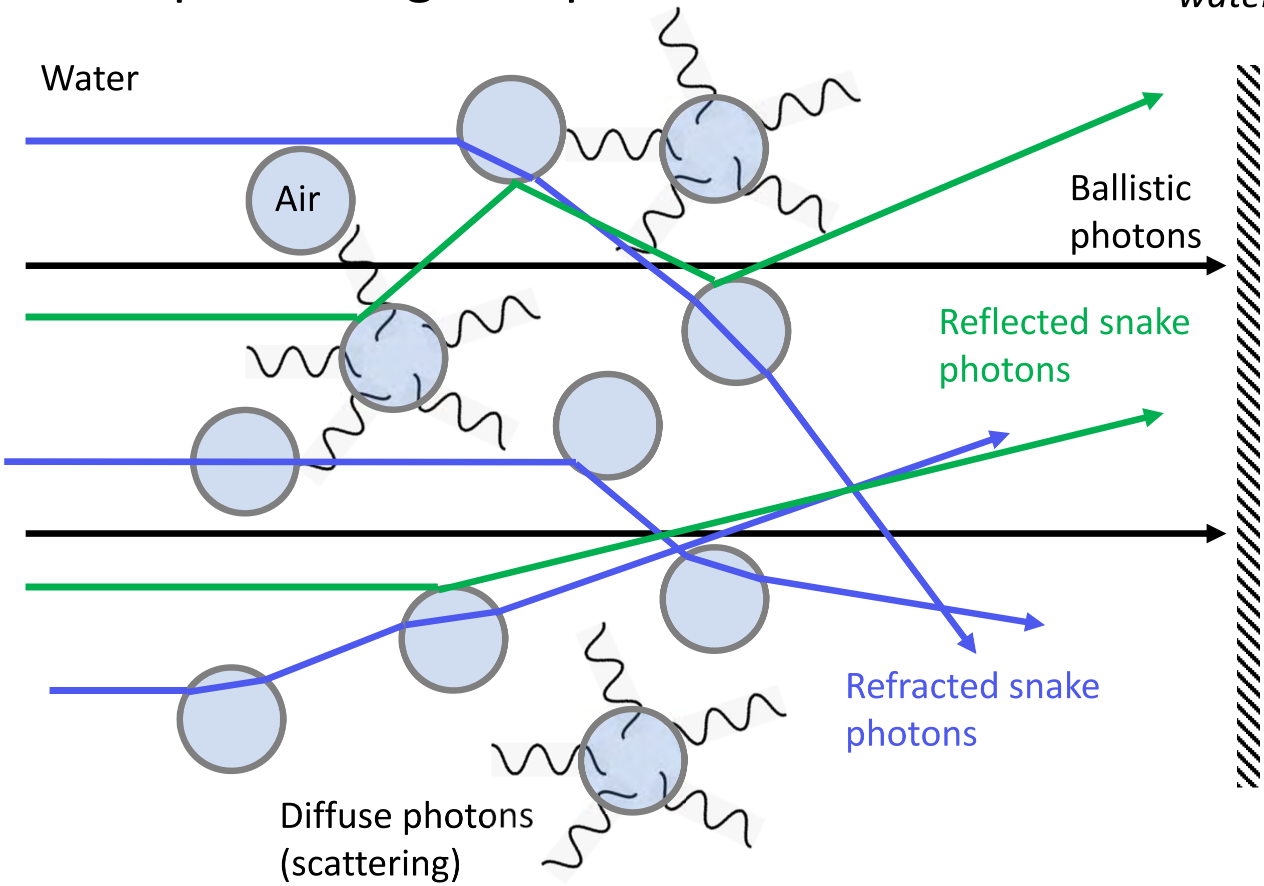


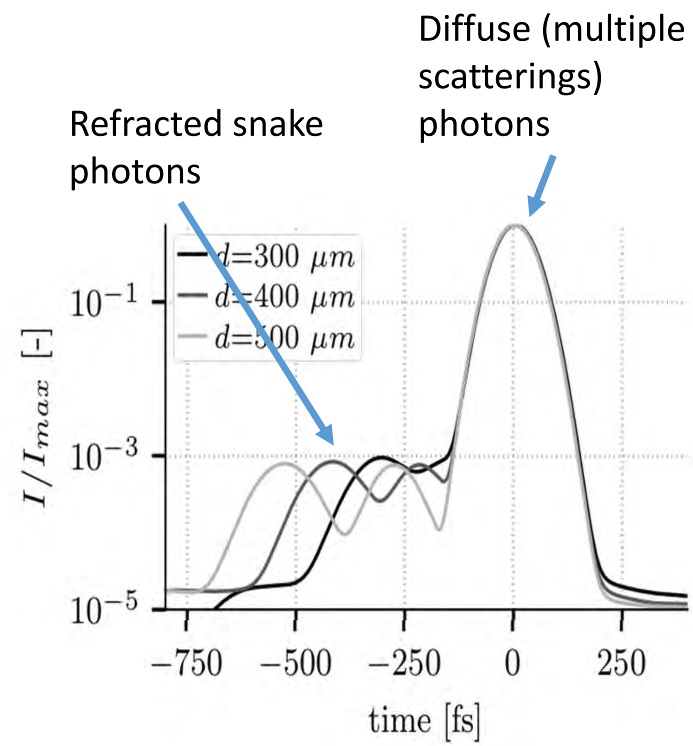


Chaussonnet & Bardet, *Optics Express* (2021)

Ballistic imaging for droplets

- Speed of light depends on the medium: $C_{water} < C_{air}$





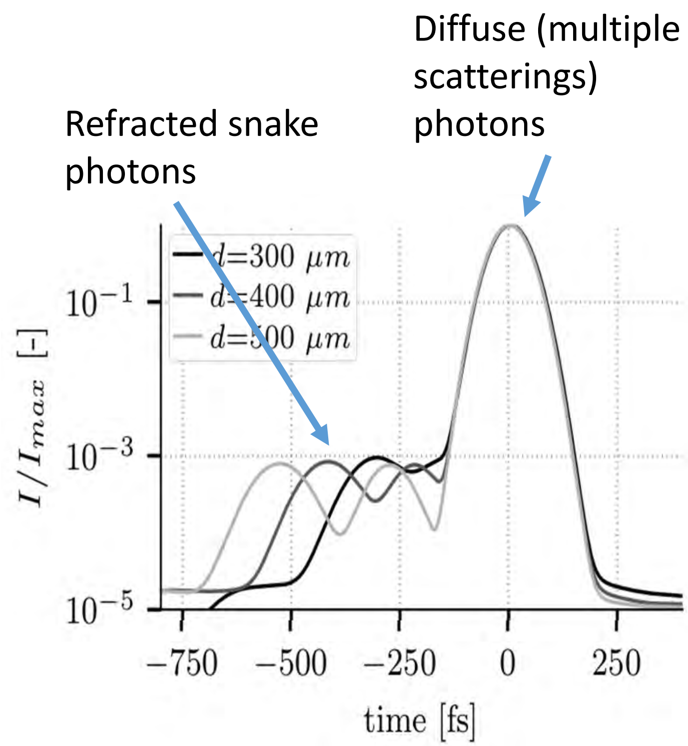
Chaussonnet & Bardet, *J Comp Physics* (2022)

Ballistic imaging for droplets

- Speed of light depends on the medium: $C_{water} < C_{air}$

Wa

Diffuse photons
(scattering)



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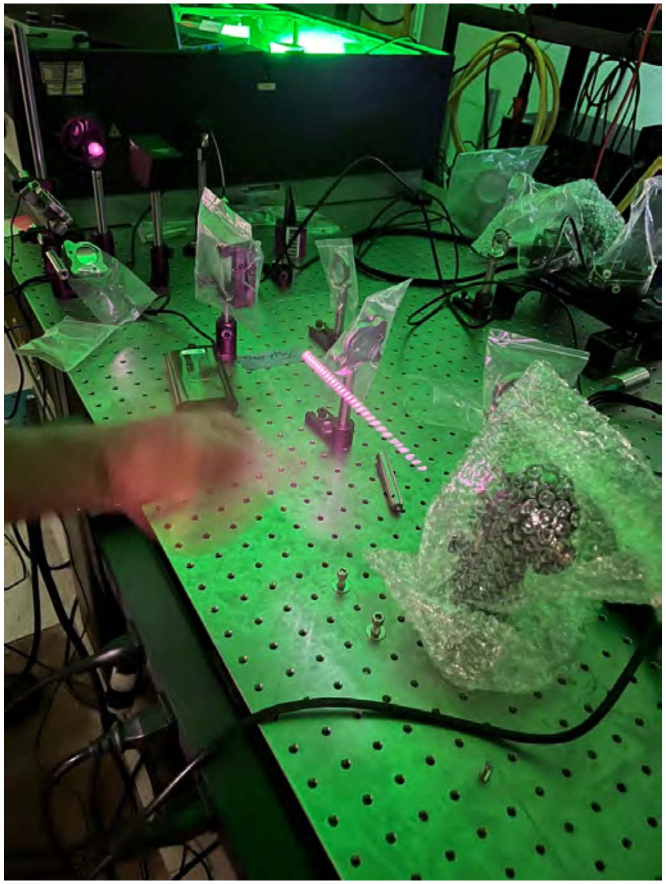
Chaussonnet & Bardet, *J Comp Physics* (2022)

Need Ultrafast laser



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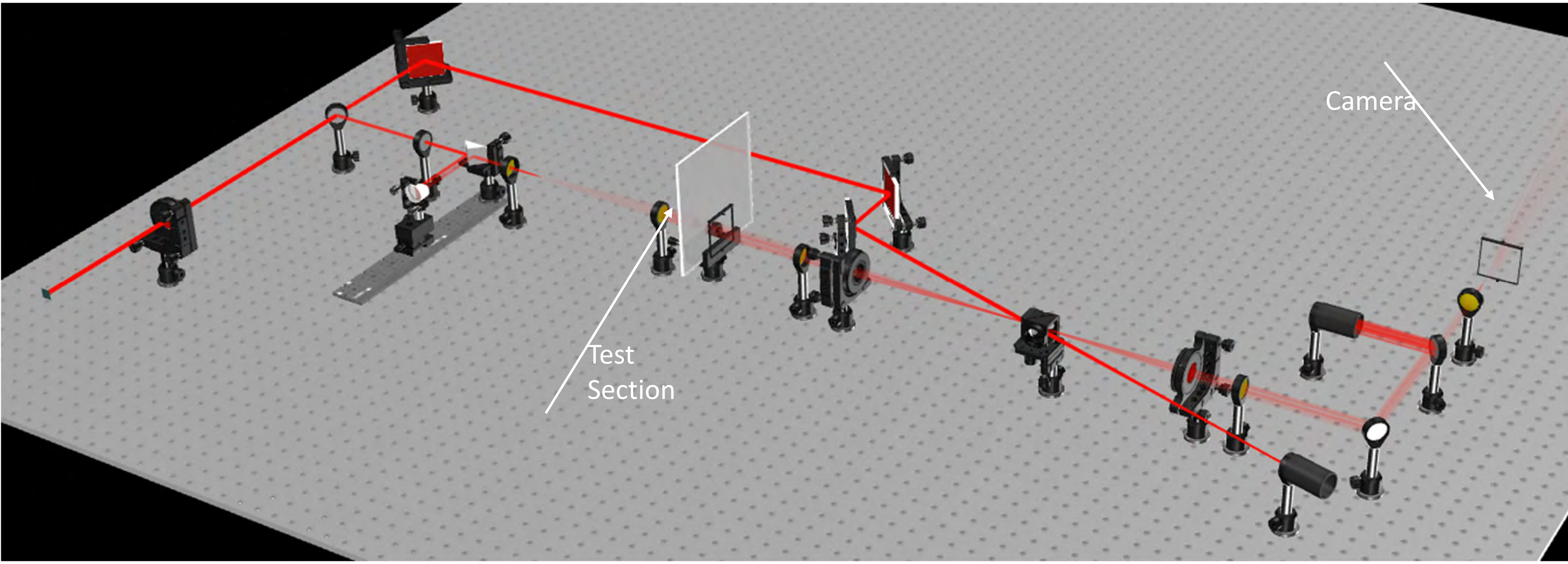
Test Setup



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First UFO data

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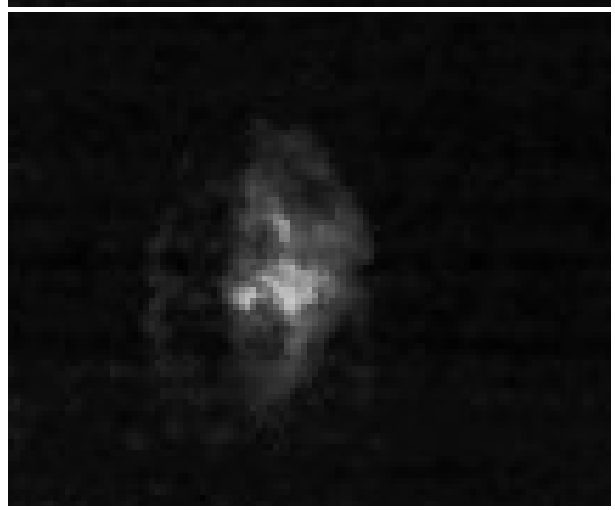
First UFO data

Path in air



Path in water, probed after

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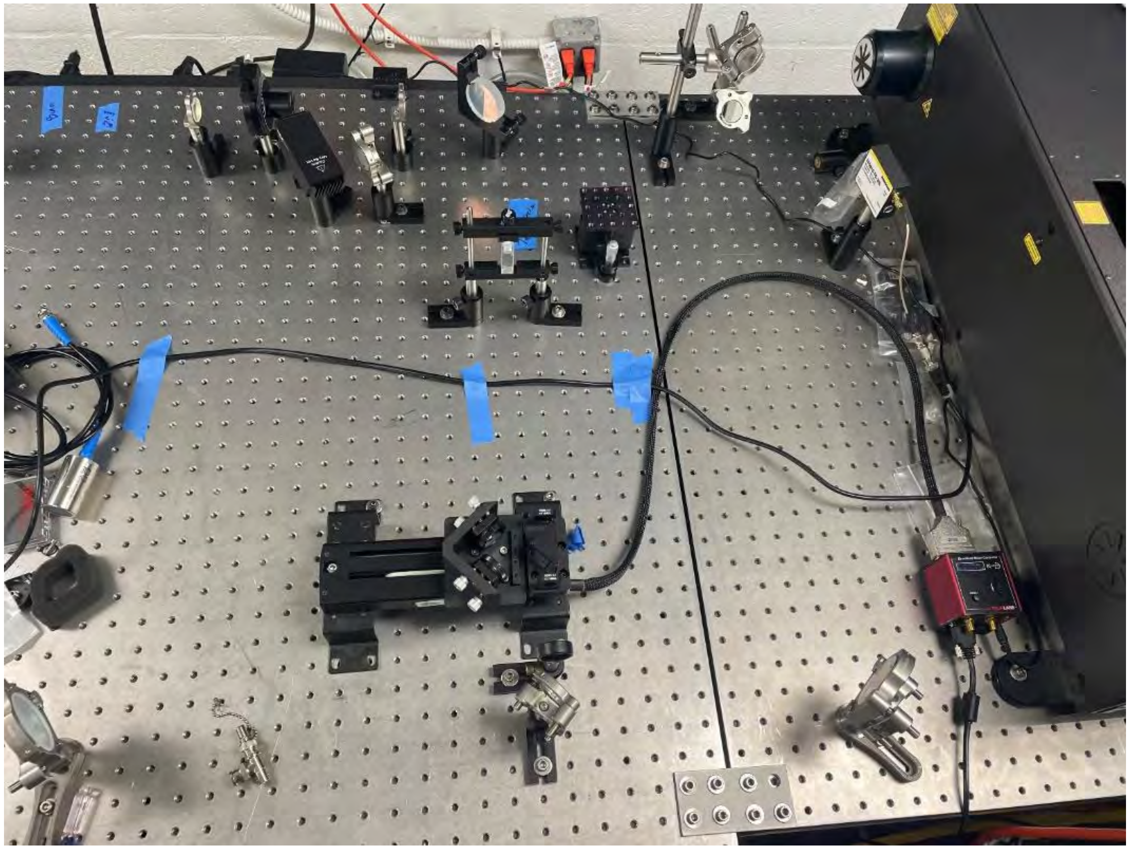
Actual setup



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Frozen bubbles

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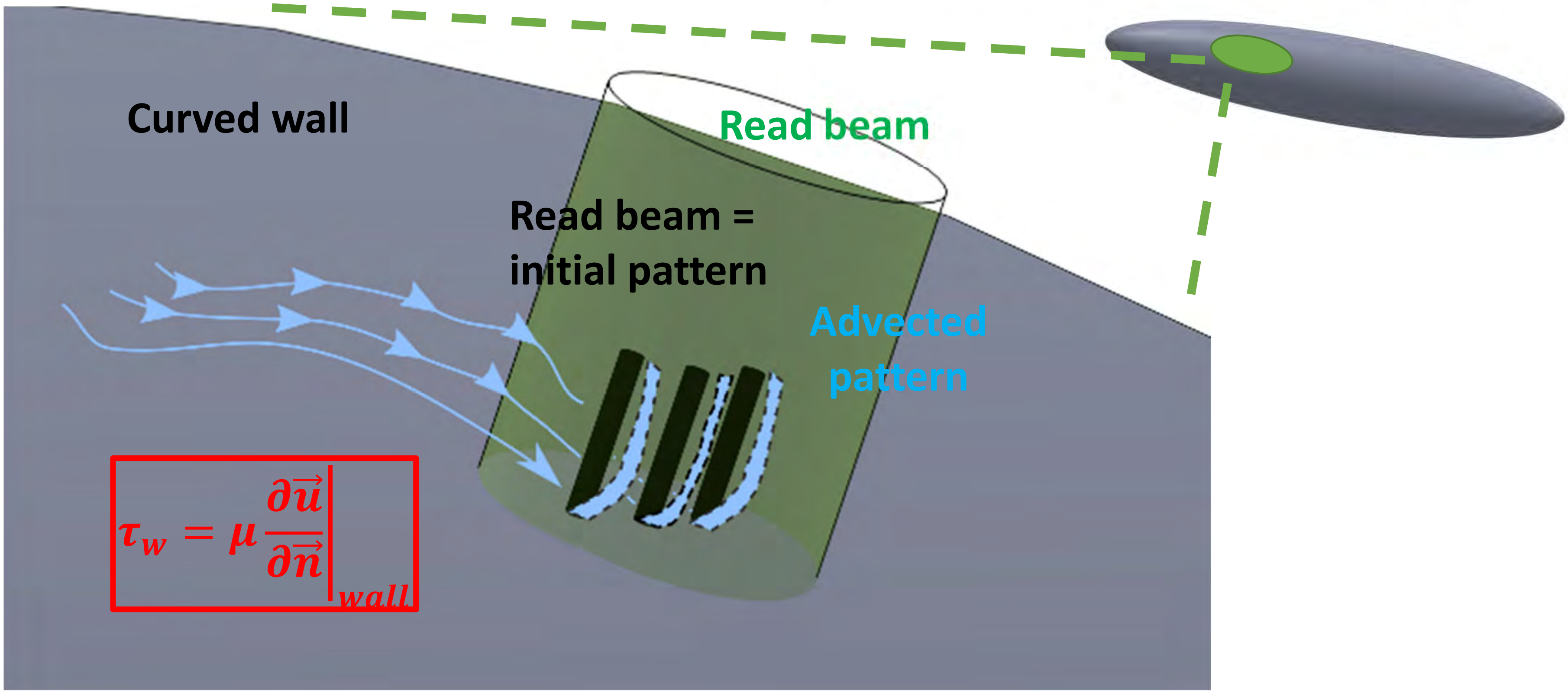
“Distributed” WSS: with confocal microscope



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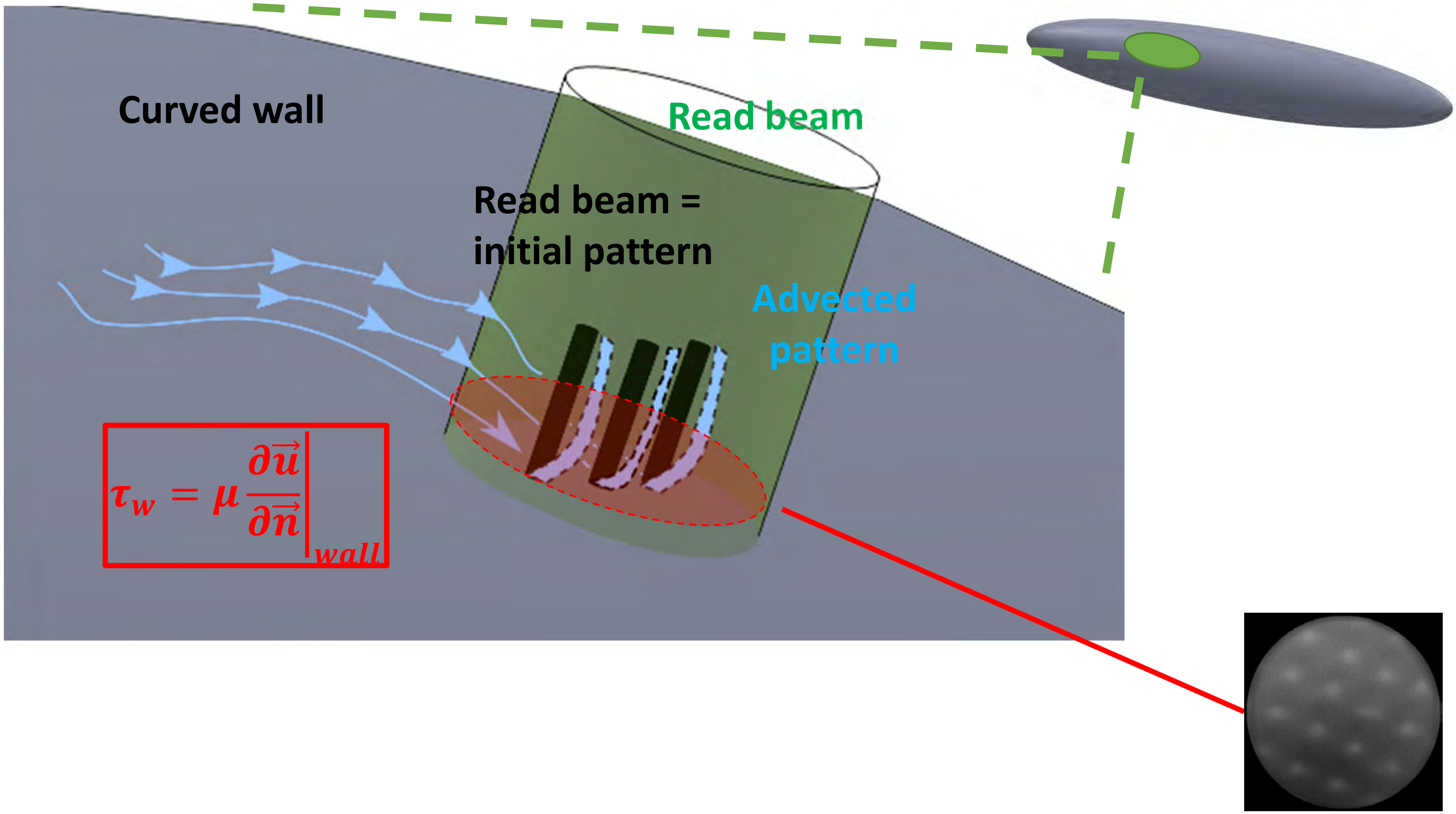
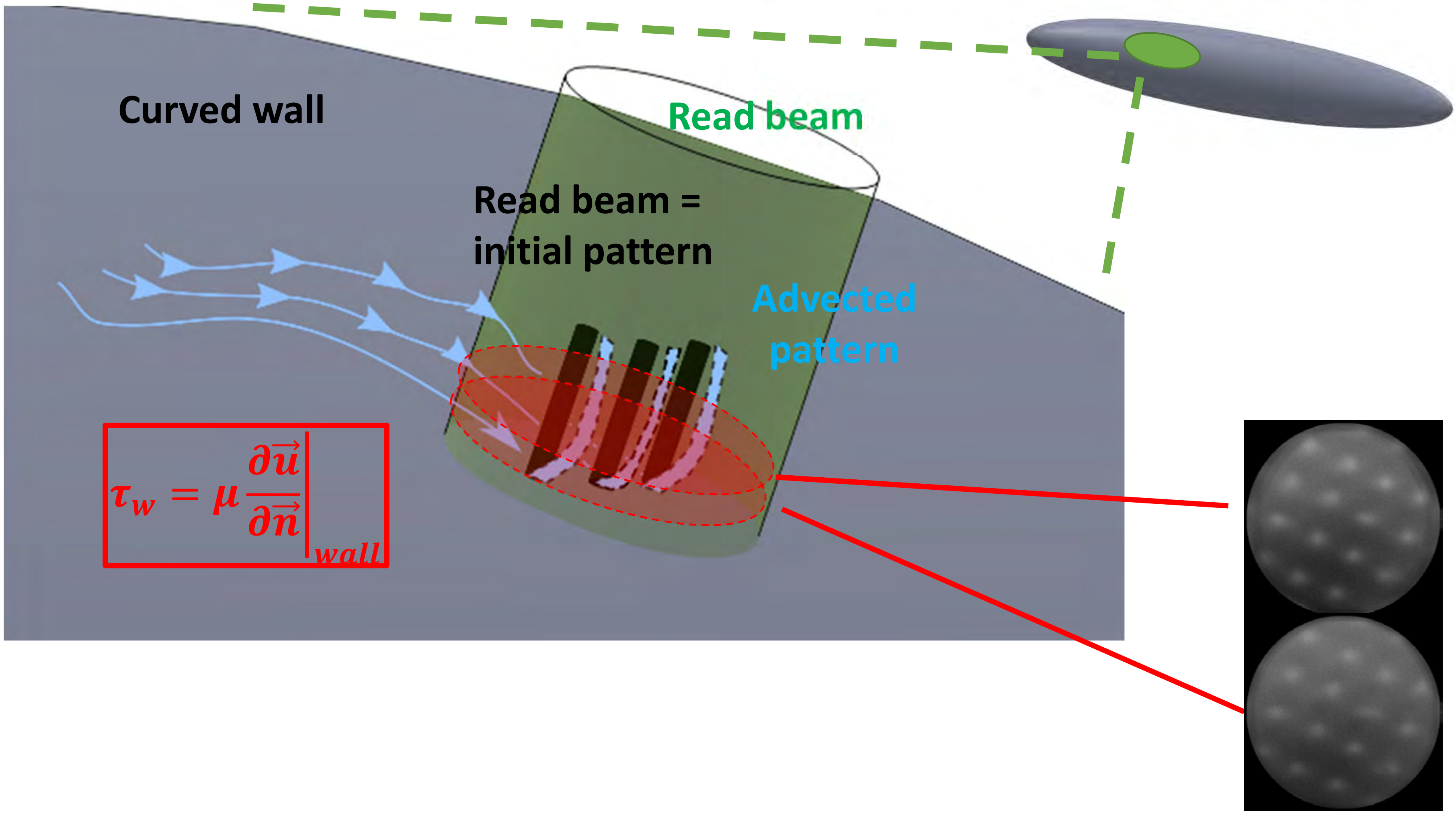
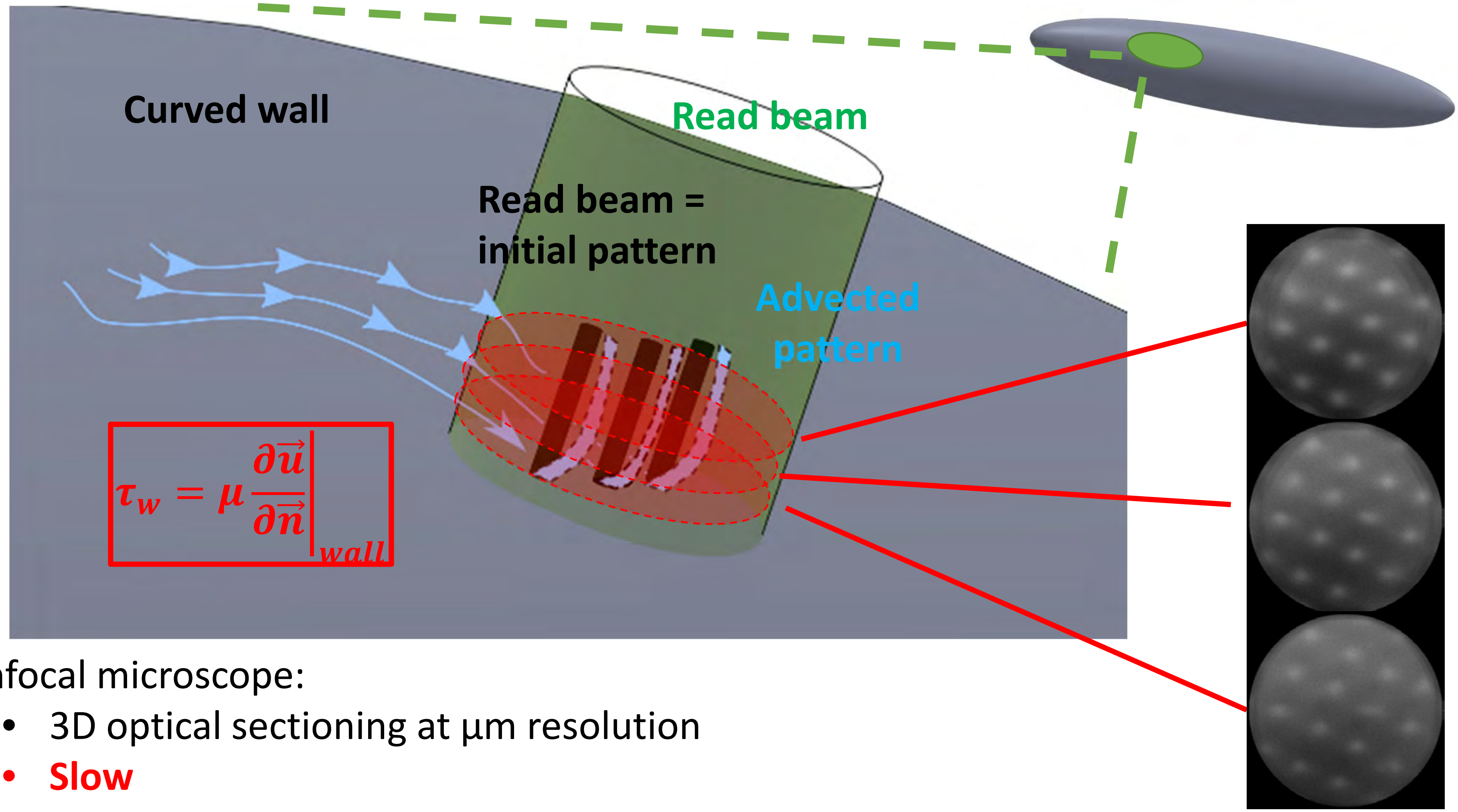
“Distributed” WSS: with confocal microscope



“Distributed” WSS: with confocal microscope



“Distributed” WSS: with confocal microscope



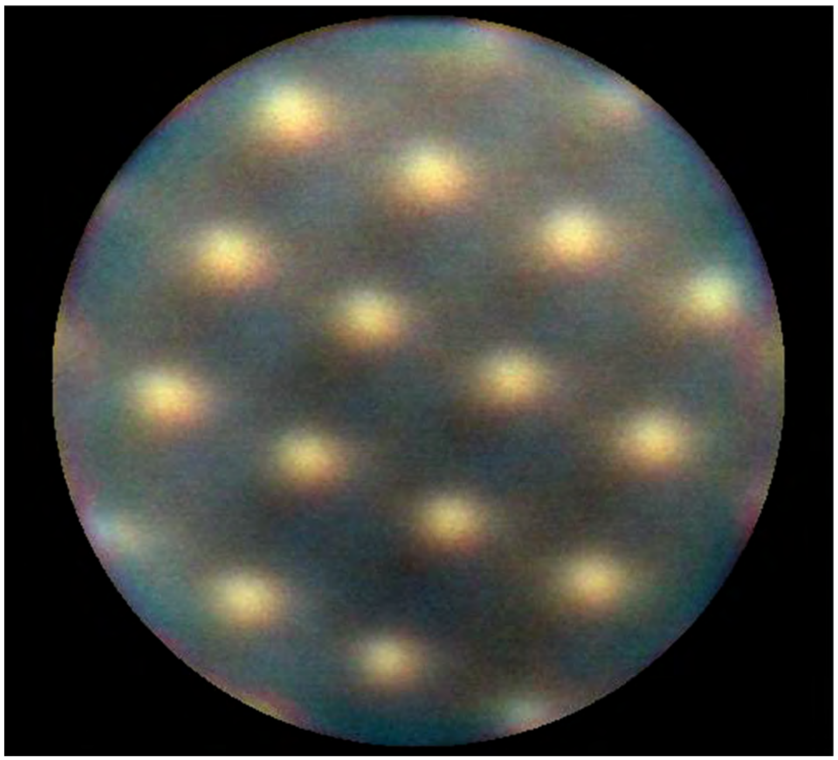
Confocal microscope:

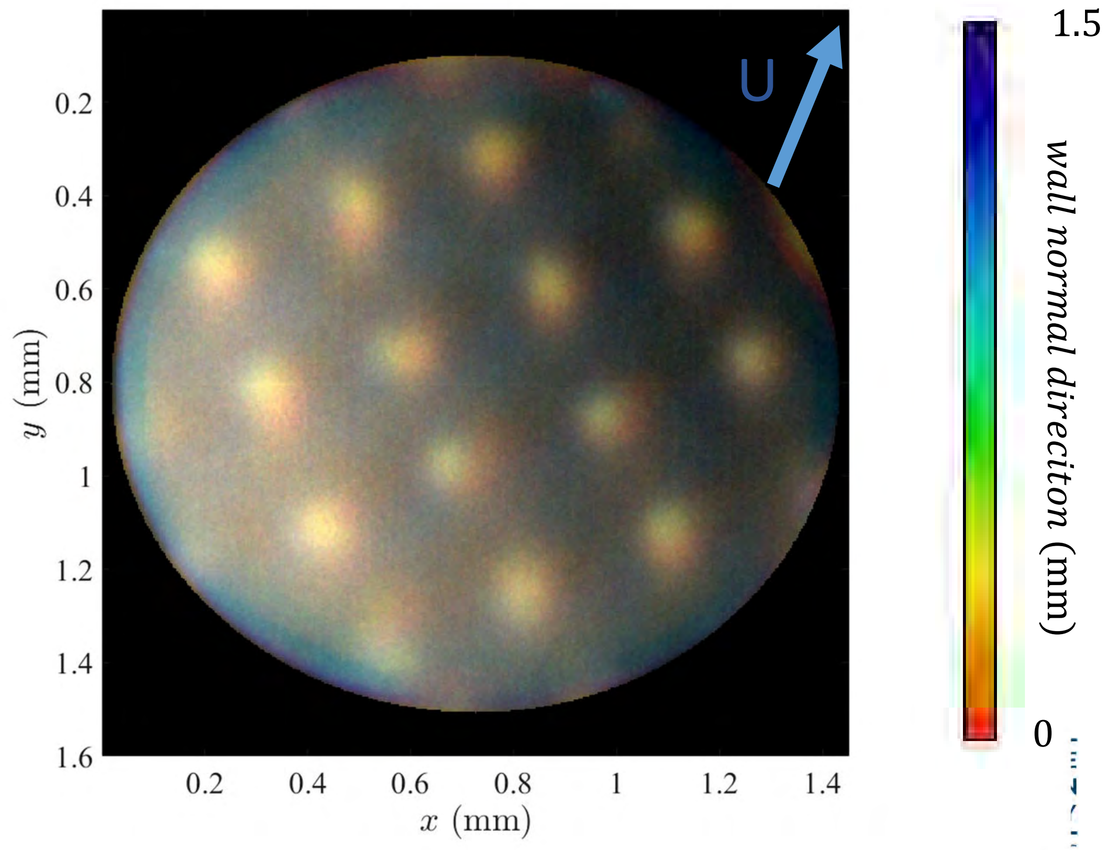
- 3D optical sectioning at μm resolution
- **Slow**

First approach to rendering

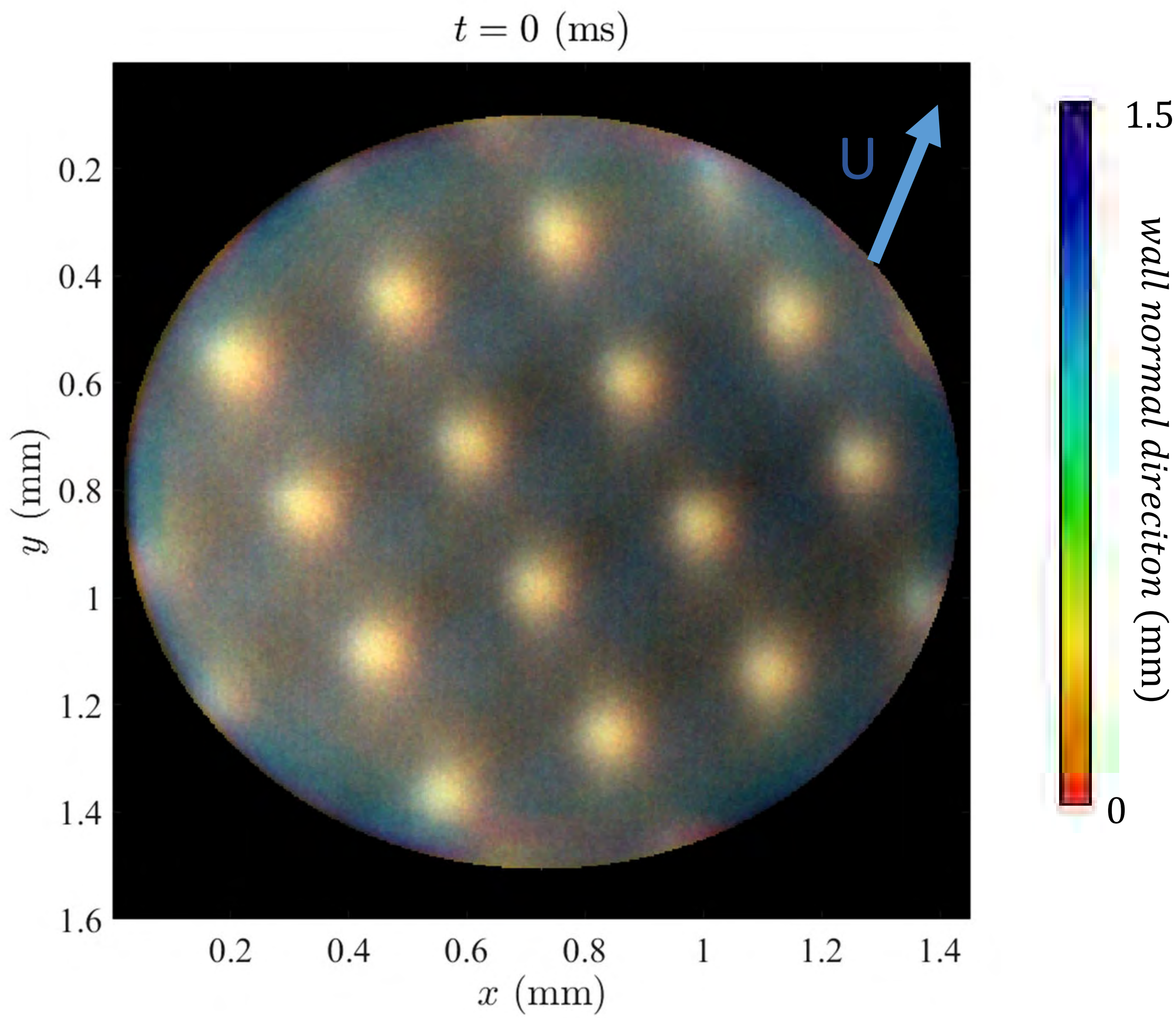
$\Delta_{zF} = 260\mu m$
$R_{zF} = 33\mu m$

$t = 0\ \mu s$





$\Delta_{zF} = 260\mu m$
$R_{zF} = 33\mu m$



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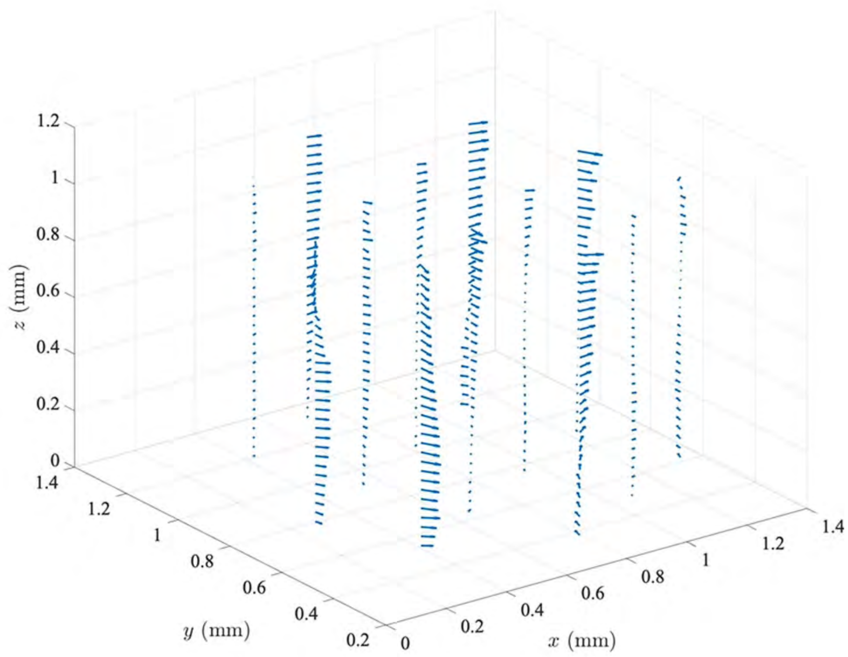
First Displacement Vectors



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Conclusions

- MTV has improved tremendously and getting ready to tackle “real” flows:
  - 2D + time
  - Direct measurement of interface shear
  - Moving to 3D…
  - Moving to active dyes
- 3D profilometry is advancing
  - 1st paper on iid processing is nearly finalized
  - Time-resolved processing algorithm is operational
    - Adds one channel of information -> adds robustness
  - First results from PSS
    - It is all about the slope integration scheme
- UFO
  - Viable route to probe bubbly flows

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