Quantitative spray imaging

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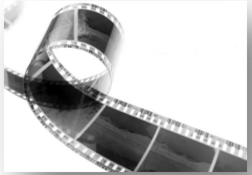
CECOST - Course

The analogue to digital transition

Qualitative imaging

Quantitative imaging

Imaging on photographic films

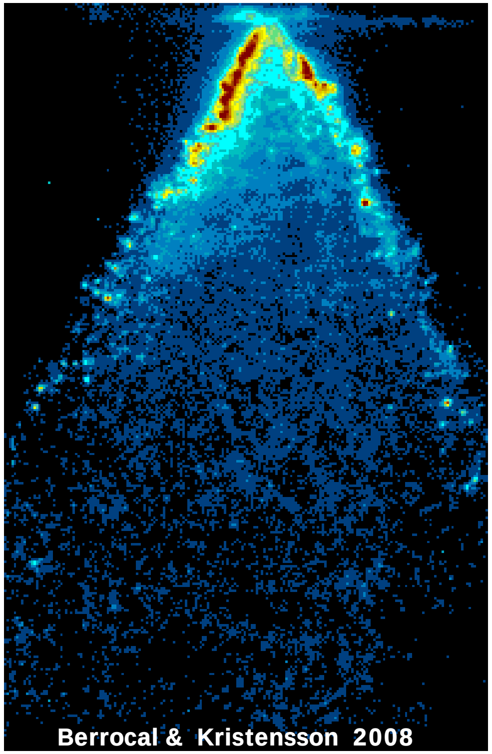


Limited possibilities for image post-processing

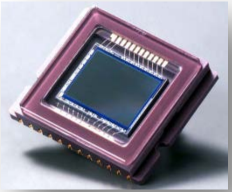
Analogue image

Transition during the 1980th

Digital image



Imaging on electronic sensors (CCD & CMOS)



Micro processors **Storage devices**

Endless possibilities for image post-processing

Relevant spray quantities

Spray formation region

Spray dynamics

Primary breakups

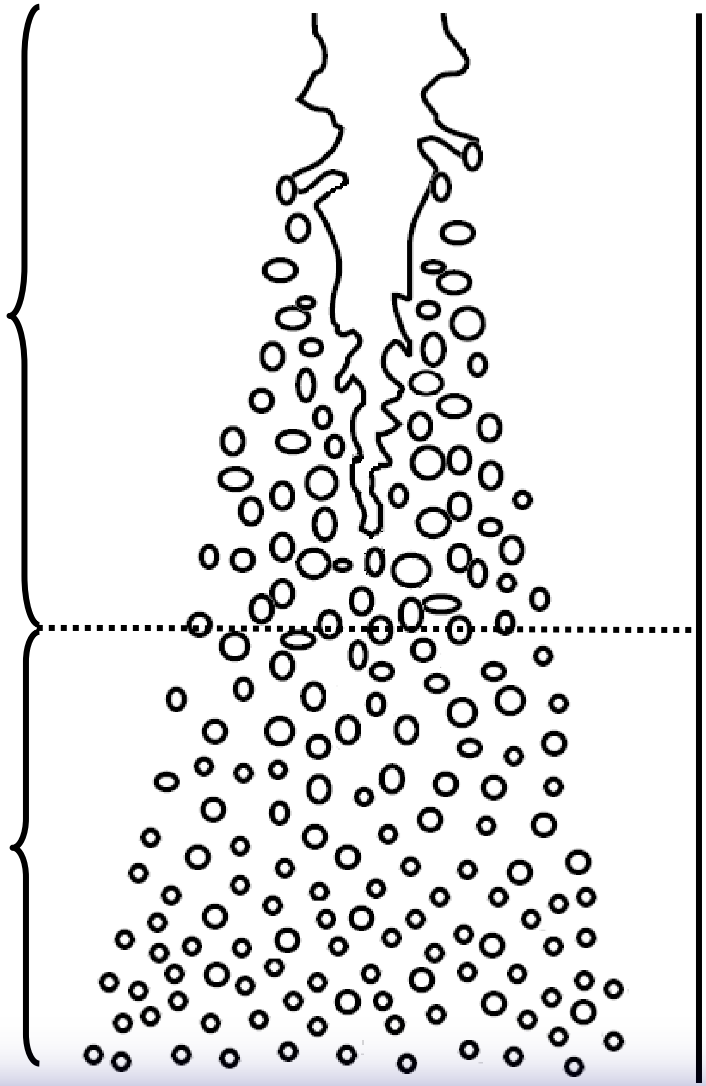
Secondary breakups

Spray region

Droplet transport

Droplet collision

Droplet evaporation



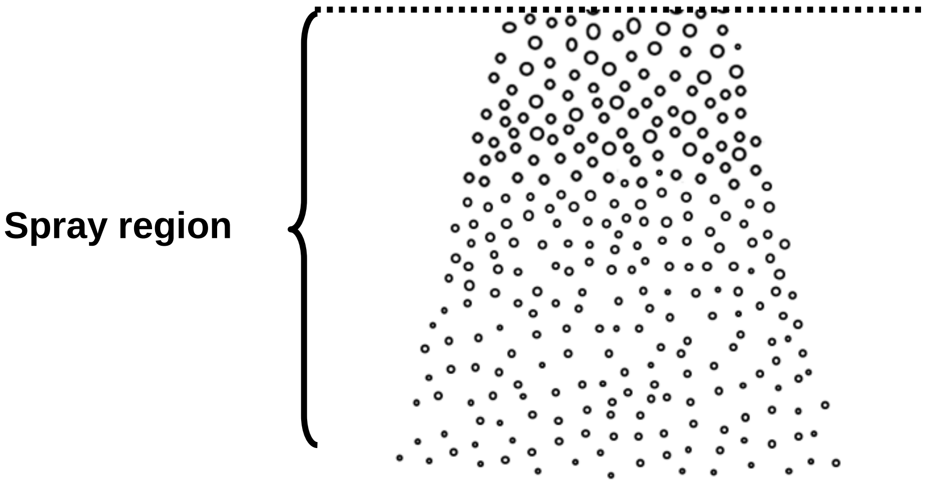
Vector quantities:

- Velocities of liquid bodies
- Acceleration
- Forces acting on the liquid

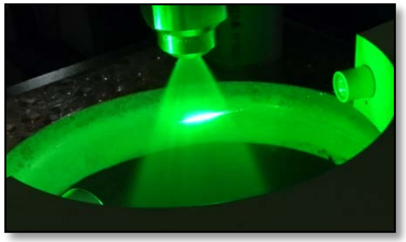
Scalar quantities:

- Droplet size
- Droplet concentration
- Droplet temperature
- Liquid volume fraction

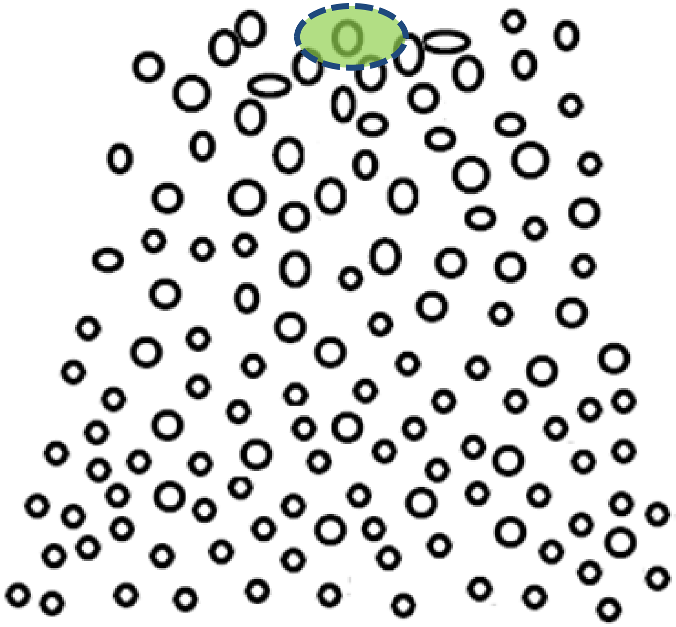
Measument in the spray region



Point measurements



Spray region



Techniques:

- PDA / PDI
- Rainbow refractometry

Main characteristics:

Size & velocity of individual droplets for PDA / PDI

Size & temperature of individual droplets for Rainbow refractometry

Reliable measurements

High measurement dynamic range

Main drawbacks:

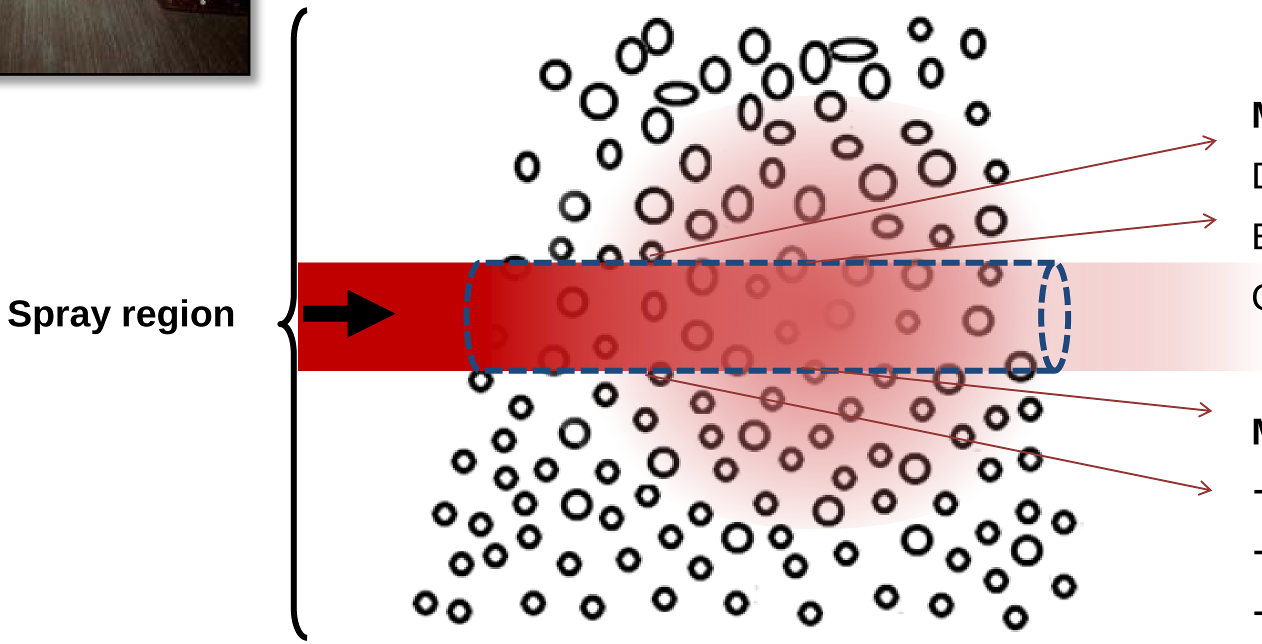
→ Time consumming

→ Limitted to spherical droplets

→ Time averaged measurements

→ Not working in optically dense situations when OD >2

Line-of-sight measurements



Techniques:

- “Laser diffraction”
- Low angle light scattering

Main characteristics:

Droplet size distribution

Ensemble averaged mesurement

Quick measurement

Main drawbacks:

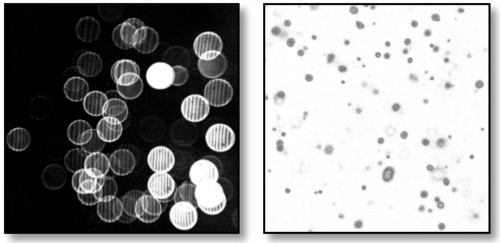
→ Not spatially resolved

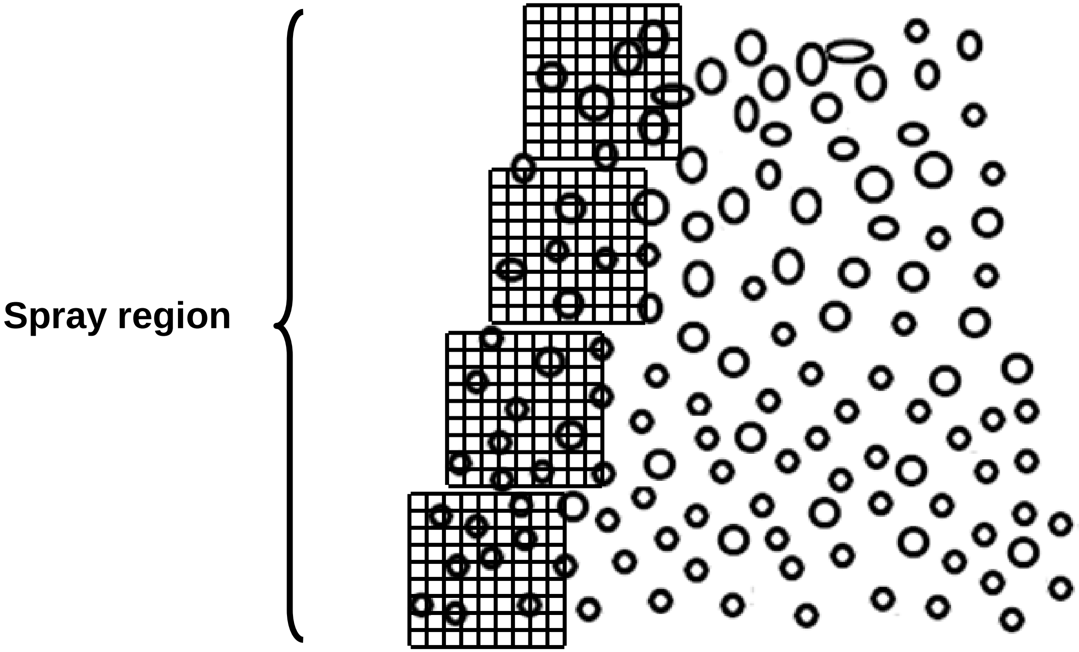
→ Limitted to spherical droplets

→ Time averaged measurements

→ Not working in optically dense situations when OD >2

Small viewed area





Techniques:

- Miroscopic imaging
- Interferometric planar imaging ILIDS technique

Main characteristics:

Droplet size and velocity

Resolved droplets

Single-shot imaging

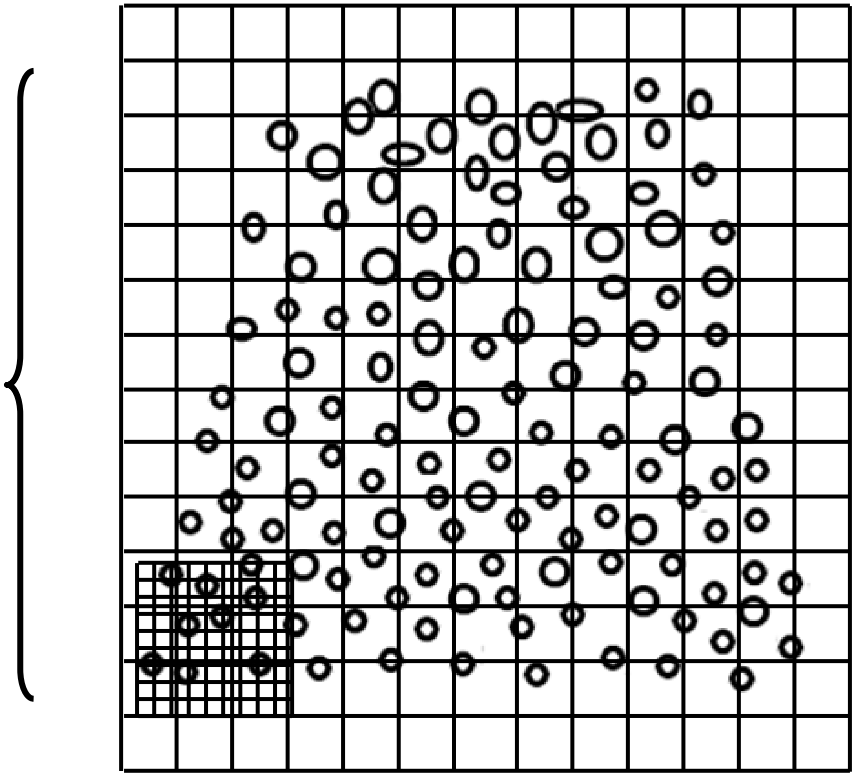
Main drawbacks:

→ ILIDS works for spherical droplets only

→ Time consuming to map the spray region

Large viewed area

Spray region



Techniques:

- LIF/Mie , Raman/Mie, 2-color LIF, Polarisation ratio
- Particle Tracking Velocimetry

Main characteristics:

Non-resolved droplets

Laser sheet imaging

Main drawback:

→ Requires qualibrations for scalar quantities

Advantages:

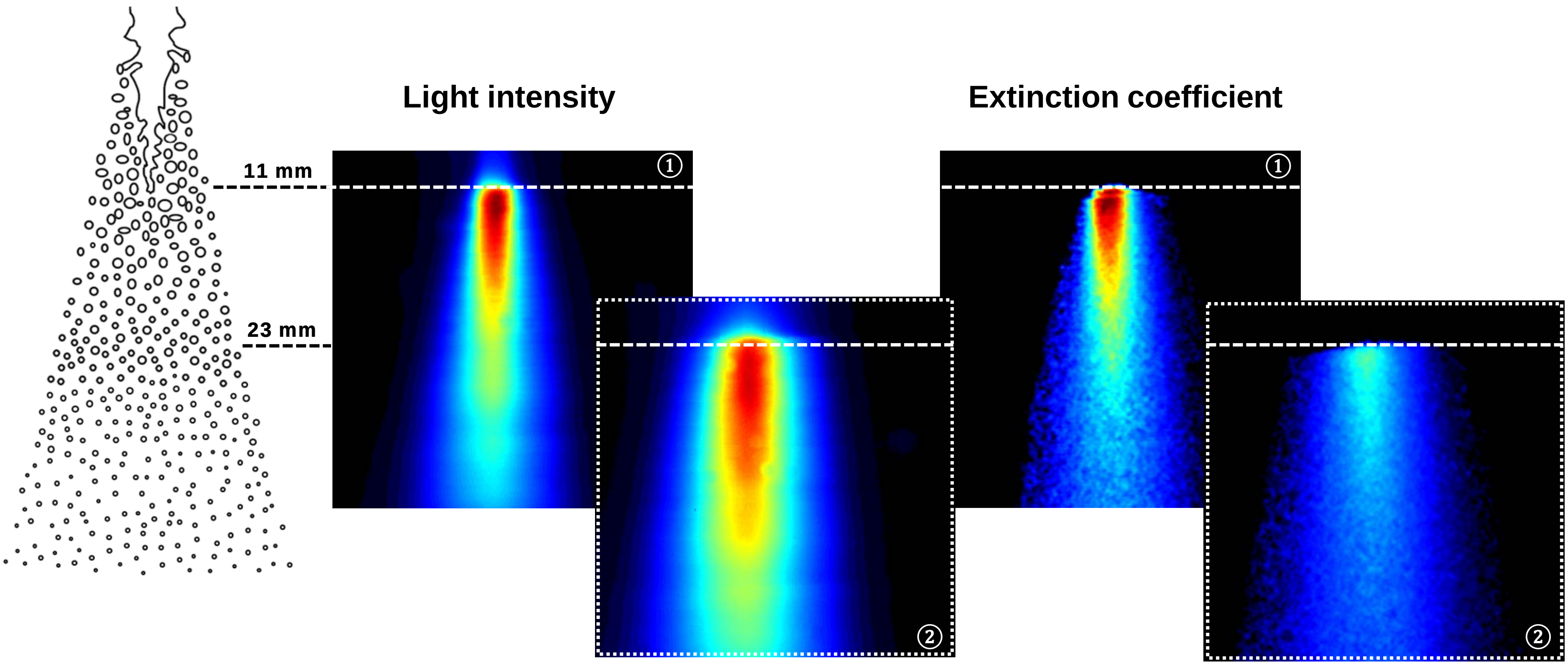
→ Quick 2D mapping

→ Spatially resolved

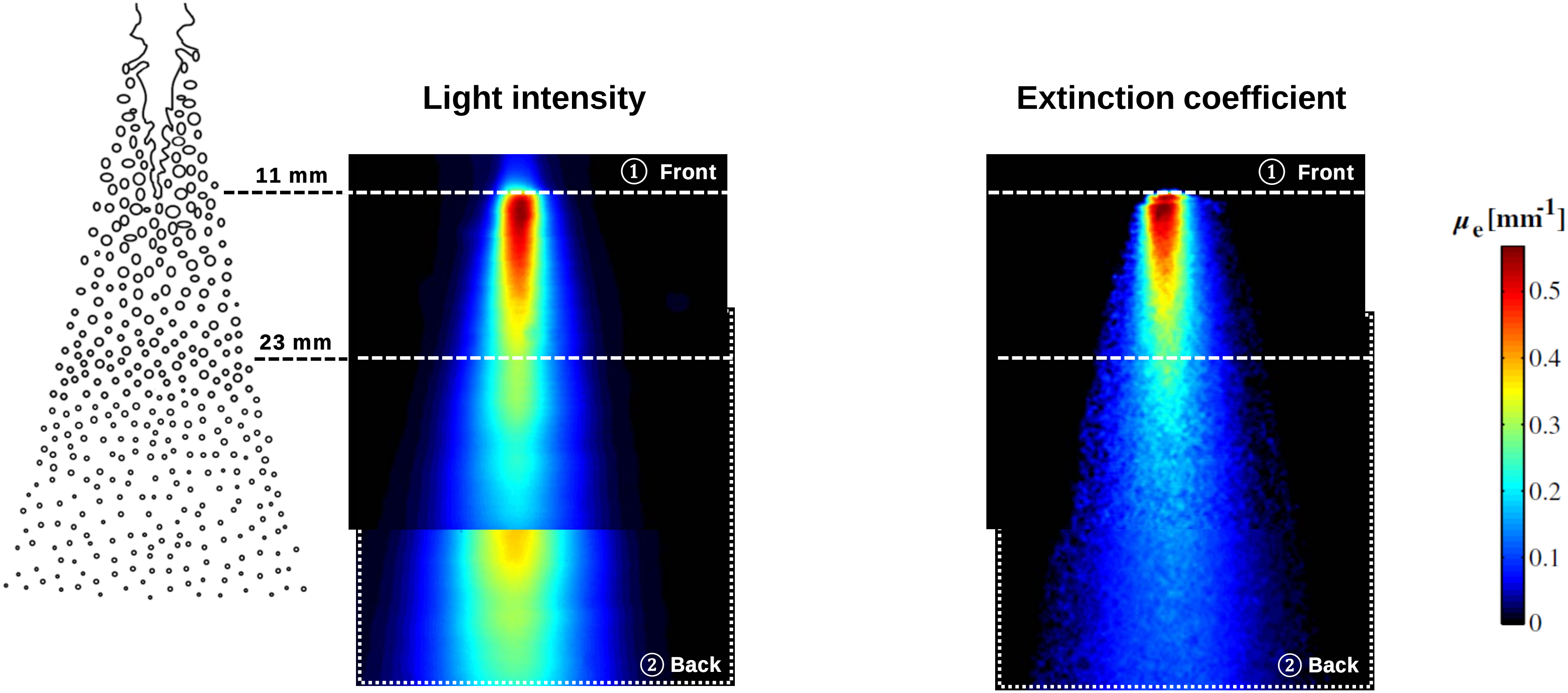
→ Can be time resolved

→ Full structure of the droplet field with possibility for 3D

From qualitative to quantitative imaging

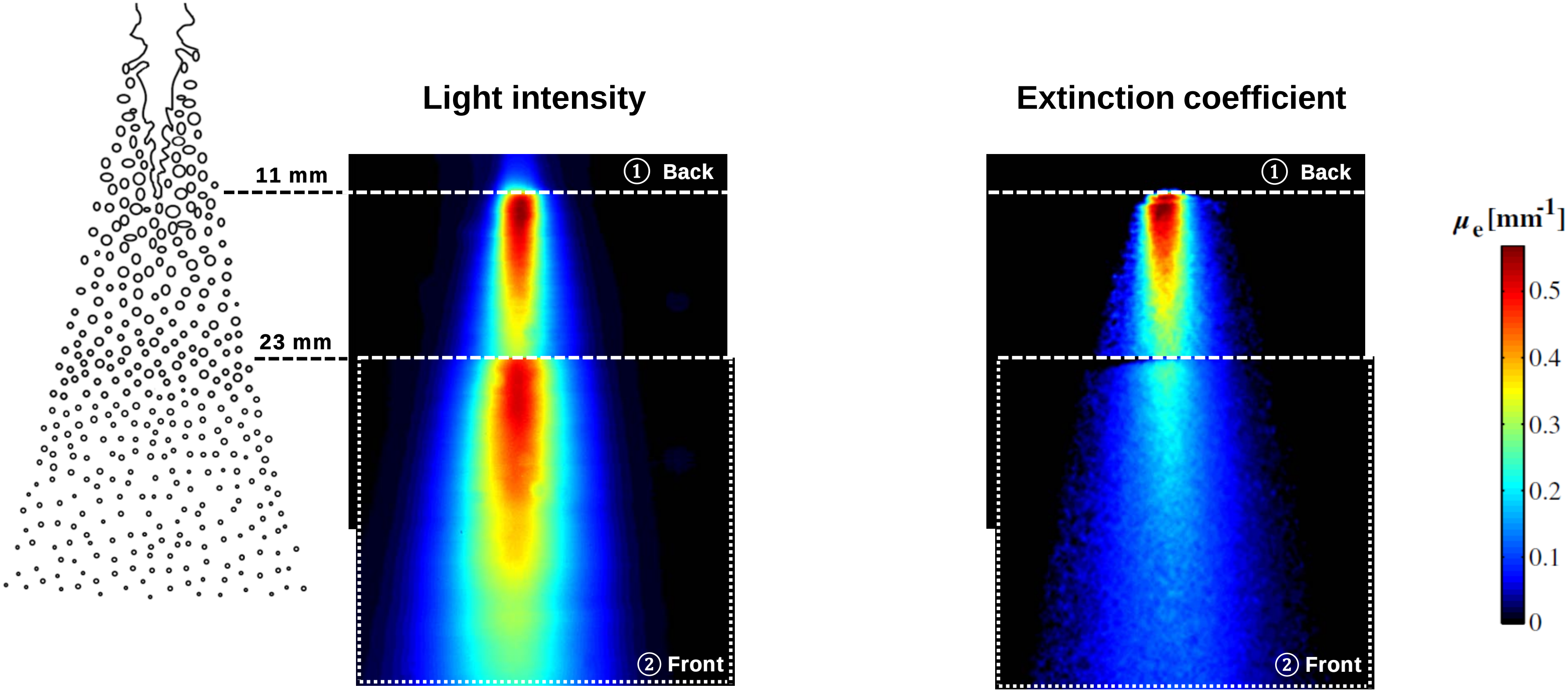


From qualitative to quantitative imaging



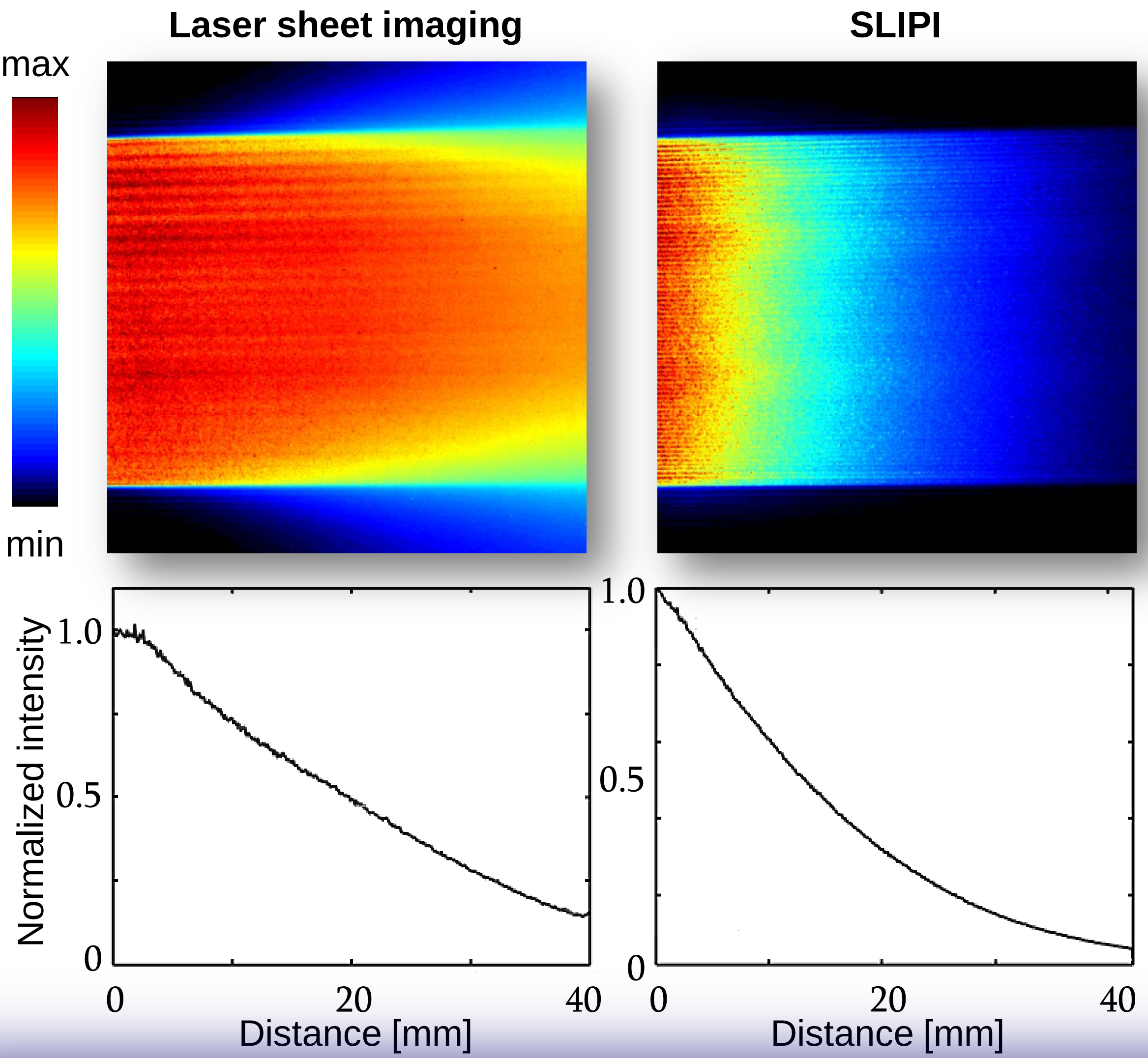
- Deducing spray information directly from light intensities can be misleading.
- Suppressing multiple light scattering effects and correcting for light extinction effects is a necessary requirement to obtain quantitative information from the spray region where the droplets are not spatially resolved.

From qualitative to quantitative imaging

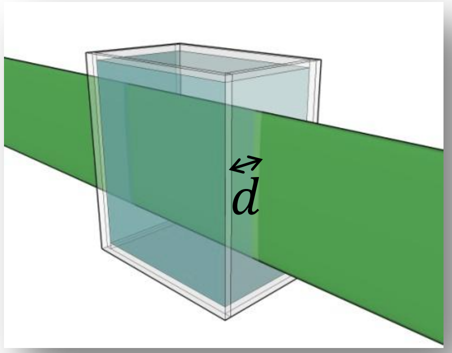


- Deducing spray information directly from light intensities can be misleading.
- Suppressing multiple light scattering effects and correcting for light extinction effects is a necessary requirement to obtain quantitative information from the spray region where the droplets are not spatially resolved.

Can SLIPI extract single light scattering?



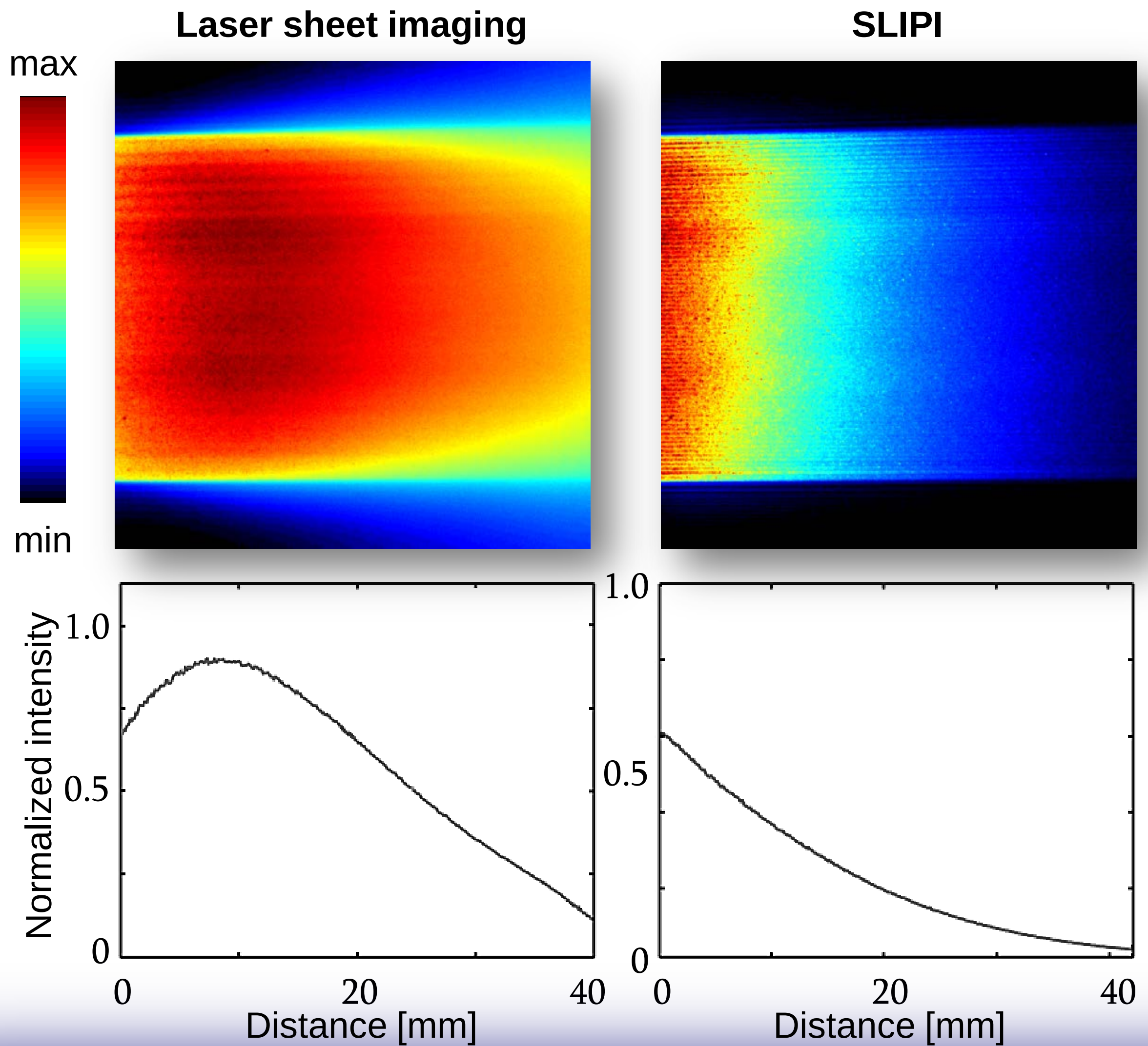
- d = 2 mm



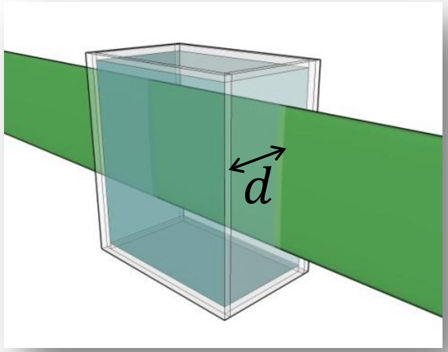
- ∅ = 15 µm
- OD = 4

Homogeneous water dispersion of polystyrene microspheres

Can SLIPI extract single light scattering?



- d = 12 mm



- ∅ = 15 µm
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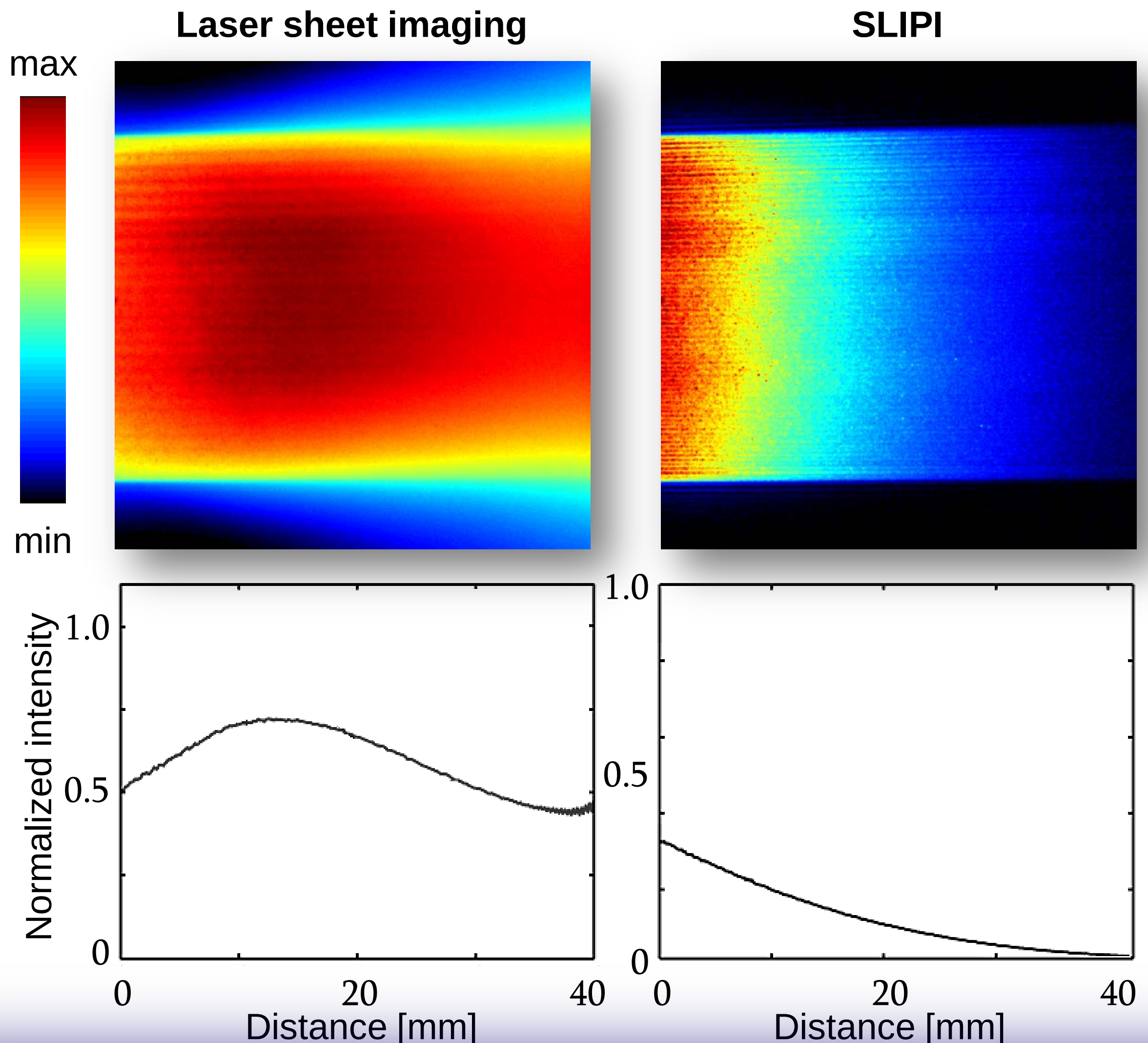
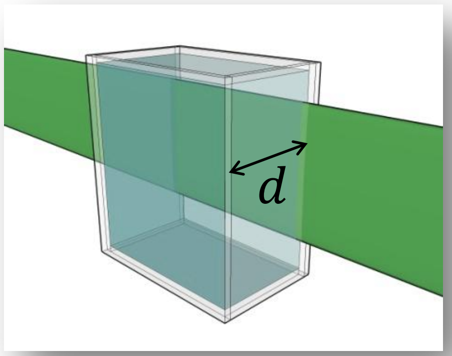
Homogeneous water dispersion of polystyrene microspheres

Can SLIPI extract single light scattering?



- d = 22 mm

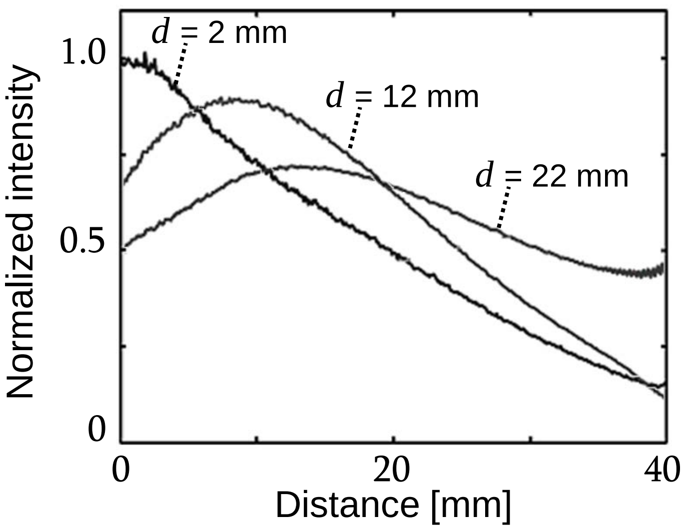


- ∅ = 15 µm
- OD = 4

Homogeneous water dispersion of polystyrene microspheres

Can SLIPI extract single light scattering?

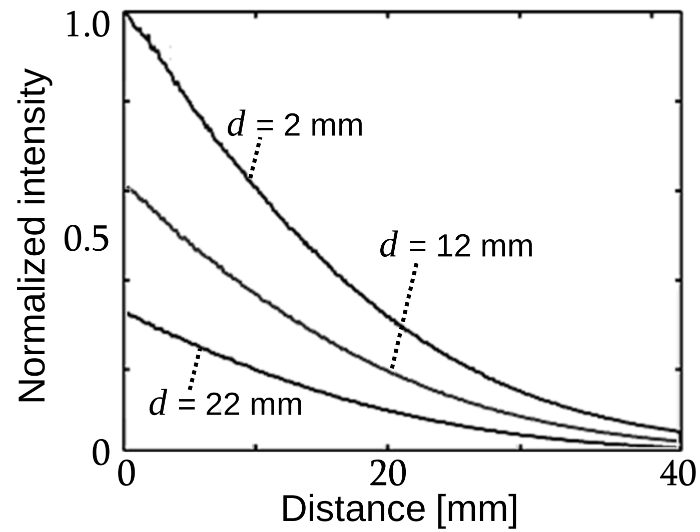
Laser sheet imaging



- Laser extinction not visible
- Signal attenuation not visible
- Intensity increase with distance
- Surrounding medium non-zero intensity

- **Due to multiple scattering**
- **Quantitative measurement not possible**

SLIPI

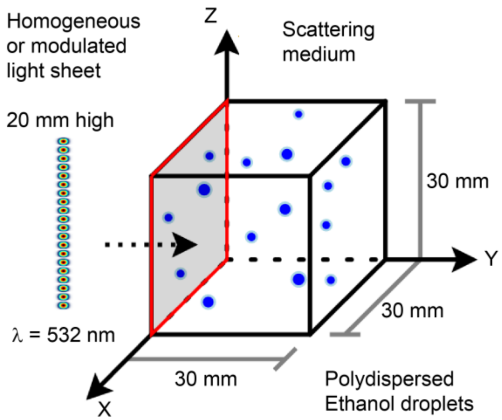


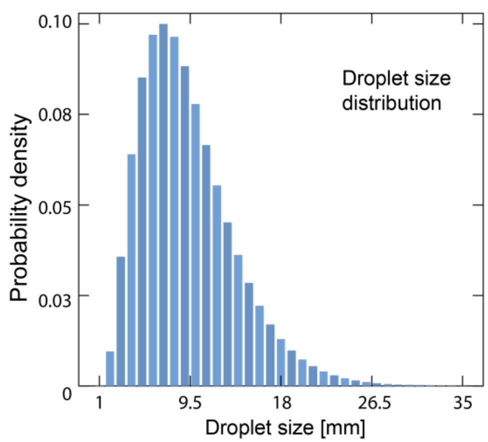
- Laser extinction visible
- Signal attenuation visible
- Intensity decrease with distance
- Surrounding medium ~zero intensity

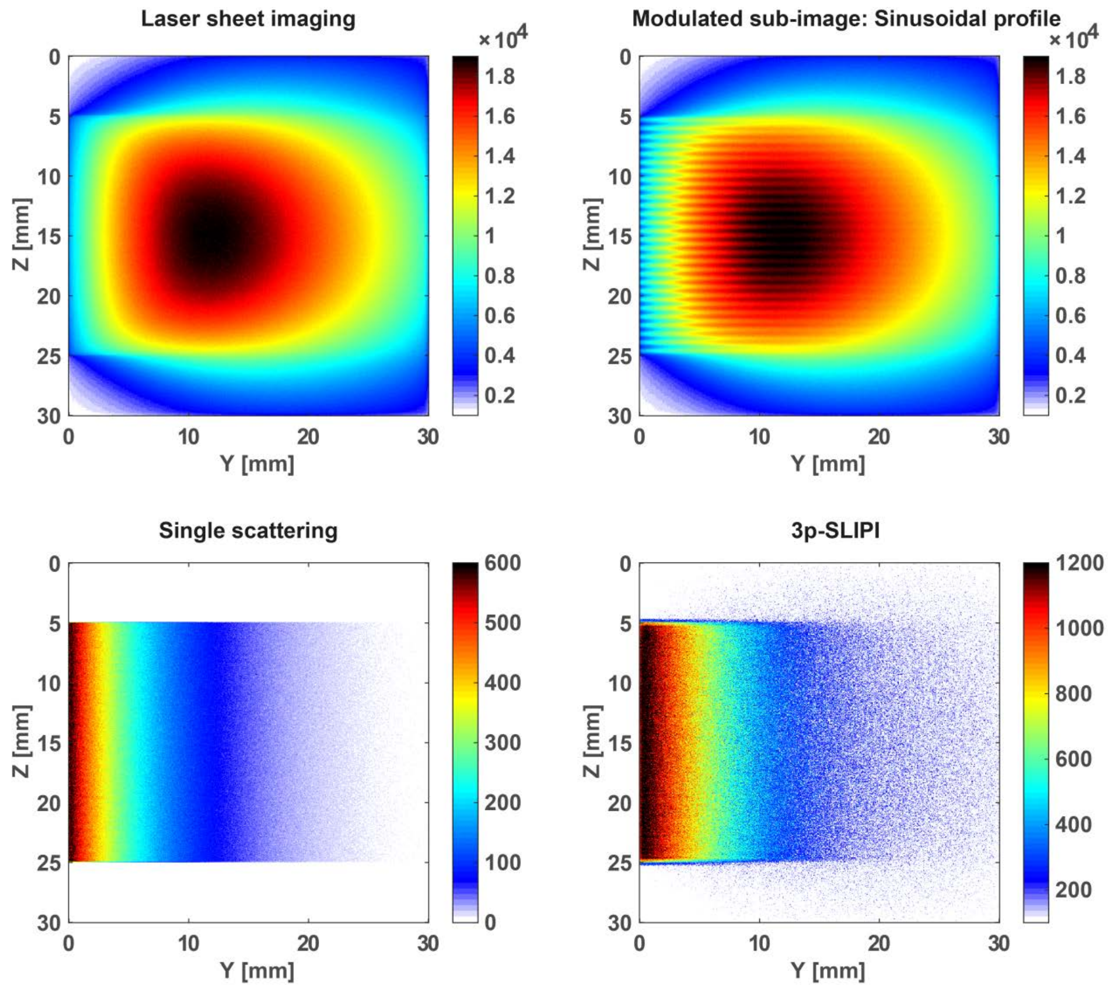
- **Multiple scattering suppressed**
- **Quantitative measurement possible**

Results from MC simulation

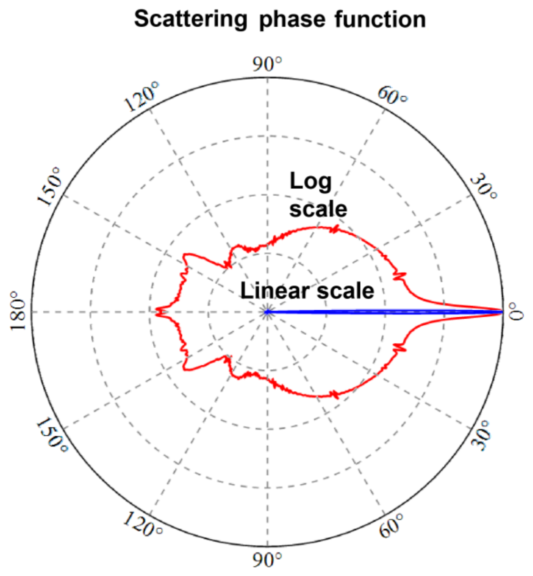
Description of the simulation



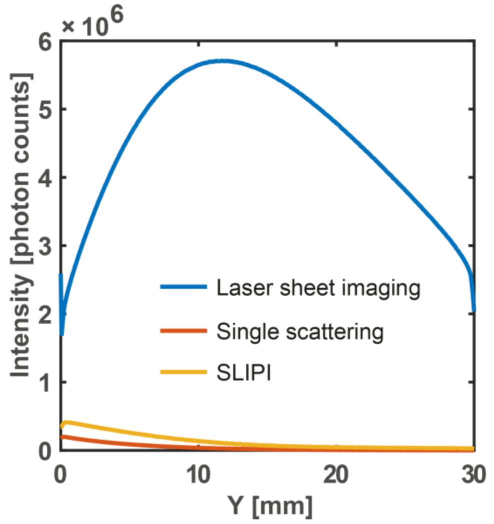


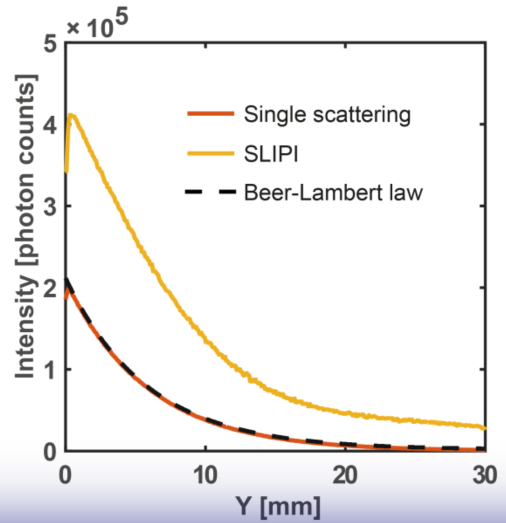


Results from MC simulation



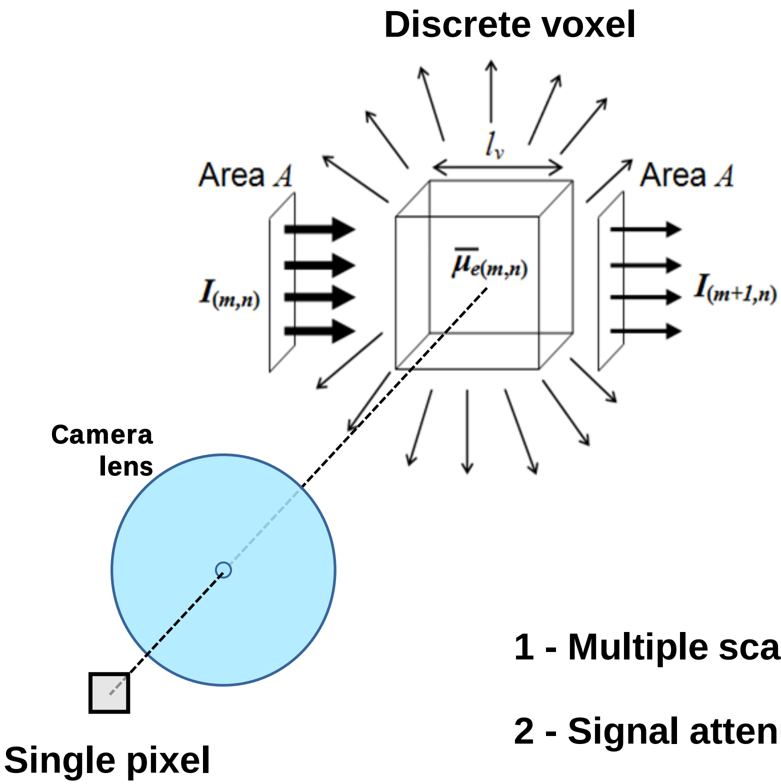
- The droplet size distribution has a mean geometrical diameter of ~10 µm.
- Most light scatters in the forward direction.

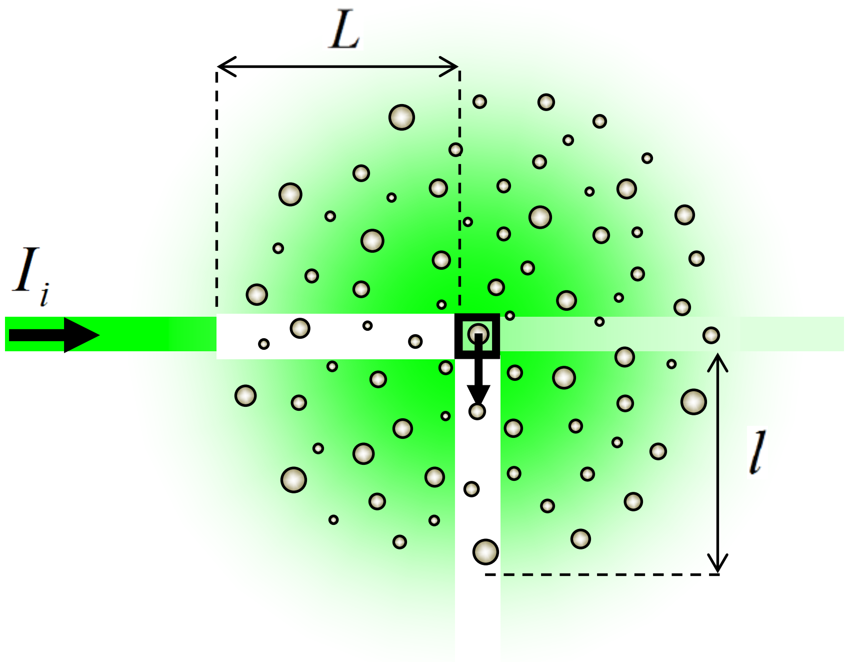




- In this simulated case, the light intensity from multiple scattering is more than one order of magnitude higher than single scattering
- Both the SLIPI and single scattering signals follows a decay as light crosses the homogeneous simulated volume.
- The main difference between the two optical signals shown is related to the higher signal level obtained with 3p-SLIPI.
- This effect is induced by the highly forward scattering lobe of the scattering phase function.
- For particles of sizes comparable or smaller than the wavelength of the light source generate results that are in very close agreement with single light scattering detection.

Correction for light extinction

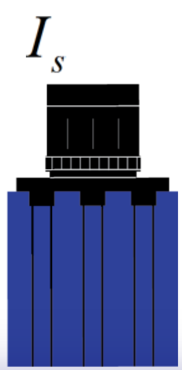




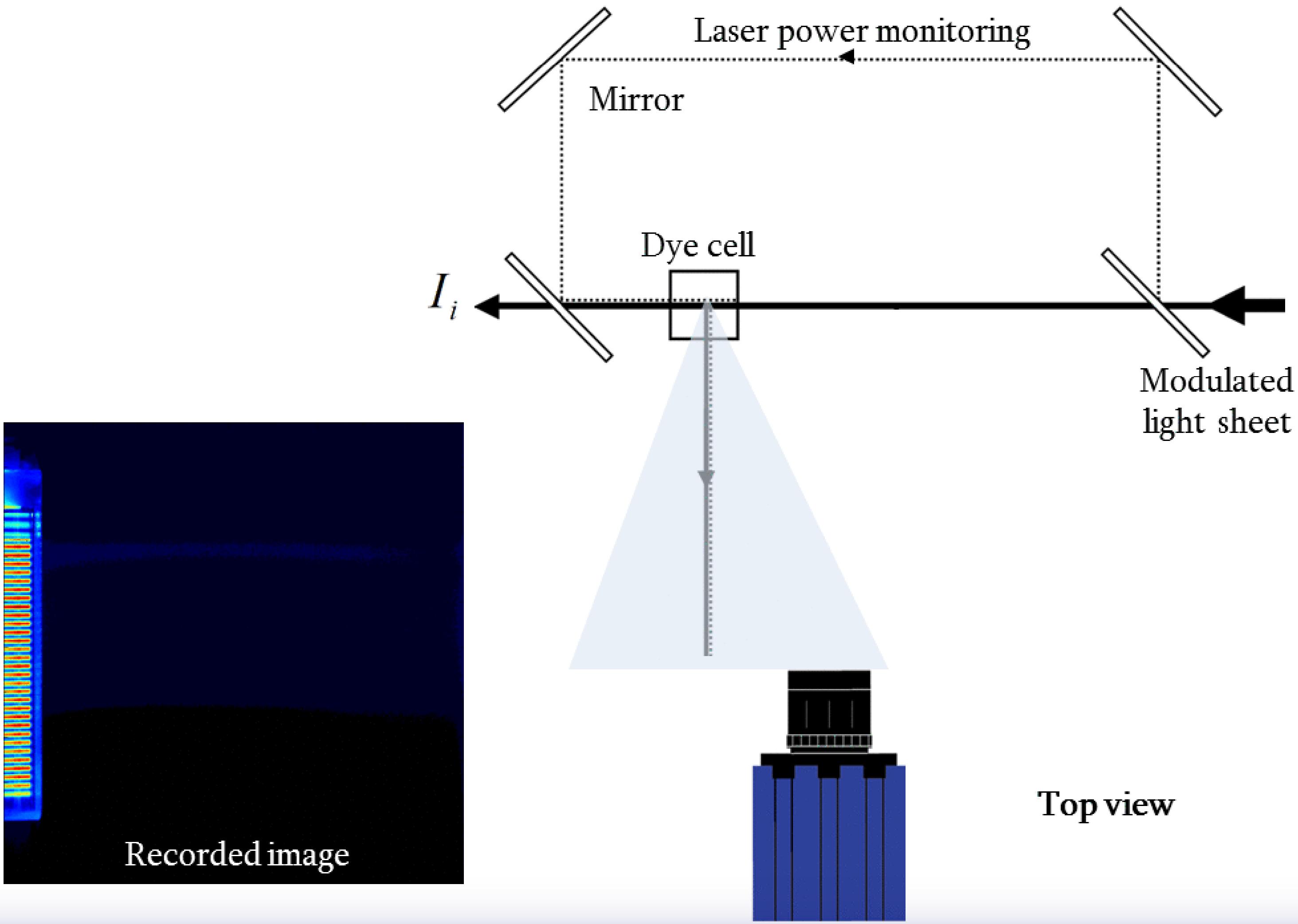
1 - Multiple scattering suppression

2 - Signal attenuation correction

3 - Laser extinction correction

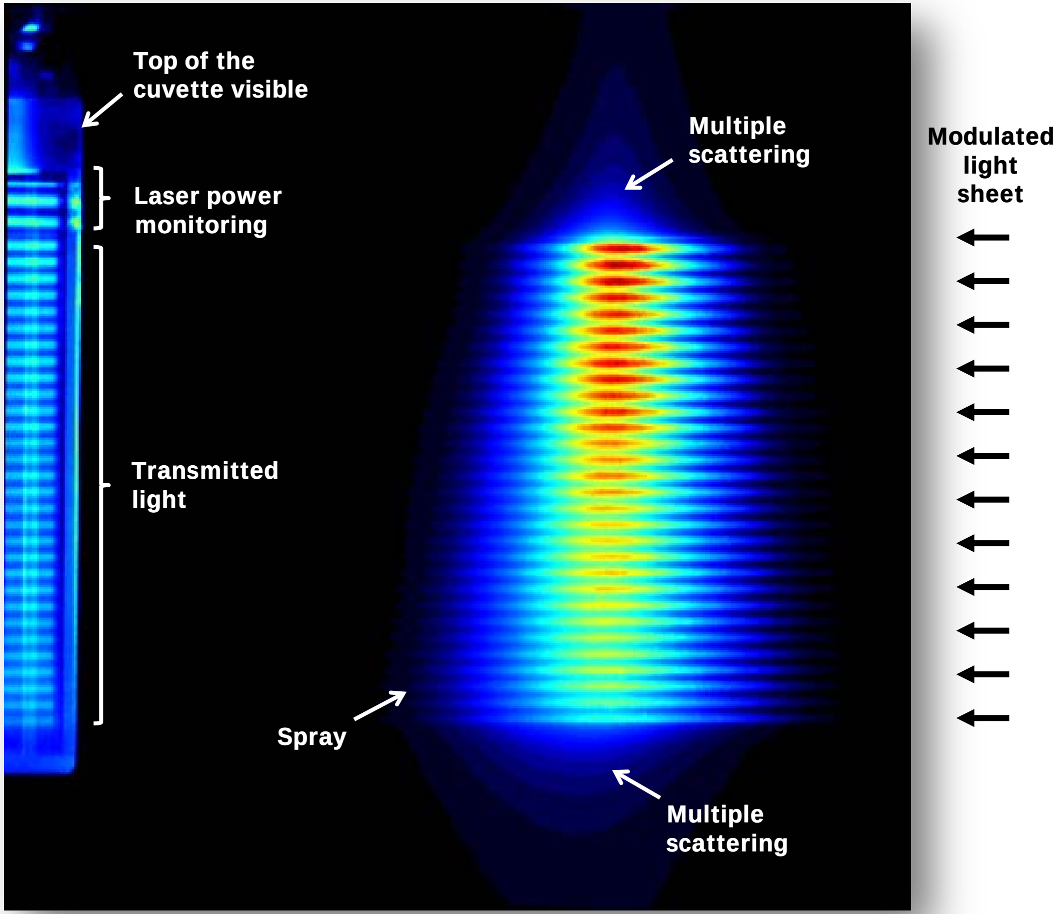


SLIPI - Scan


Laser power monitoring
Mirror
Dye cell
I_i
Modulated light sheet
Recorded image
Top view

SLIPI - Scan

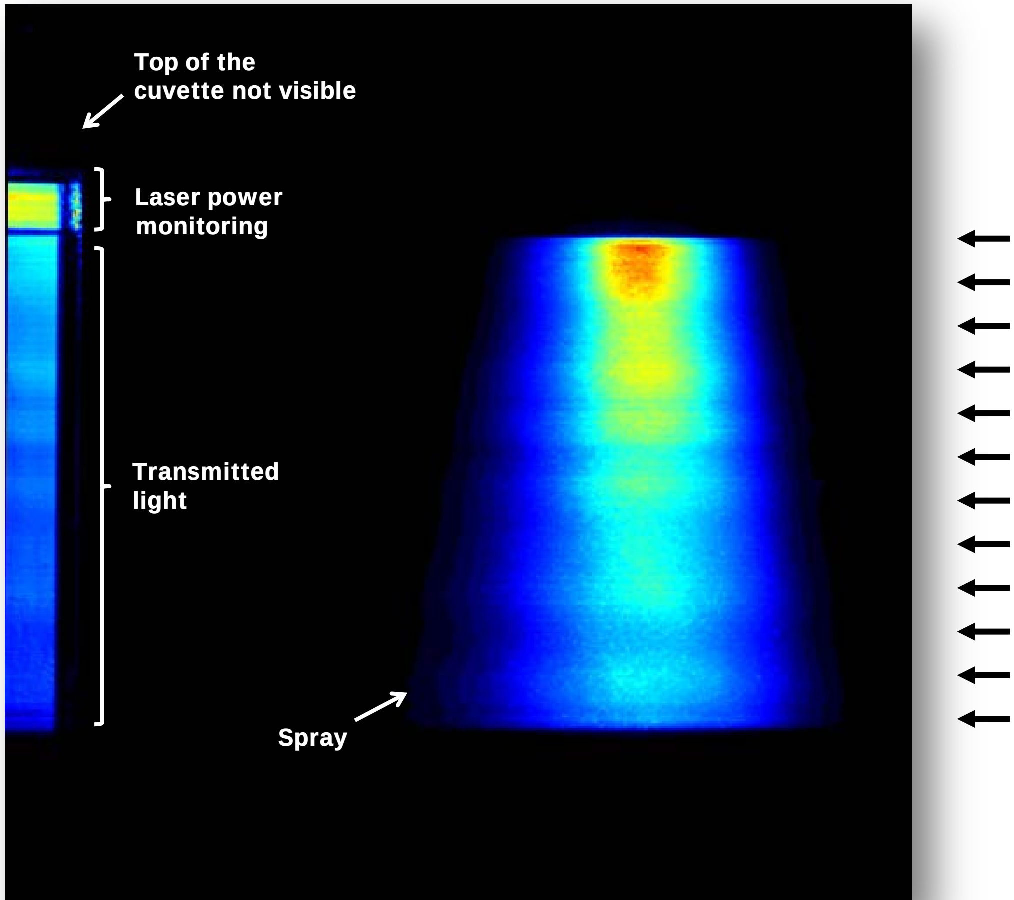
Modulated image I_1



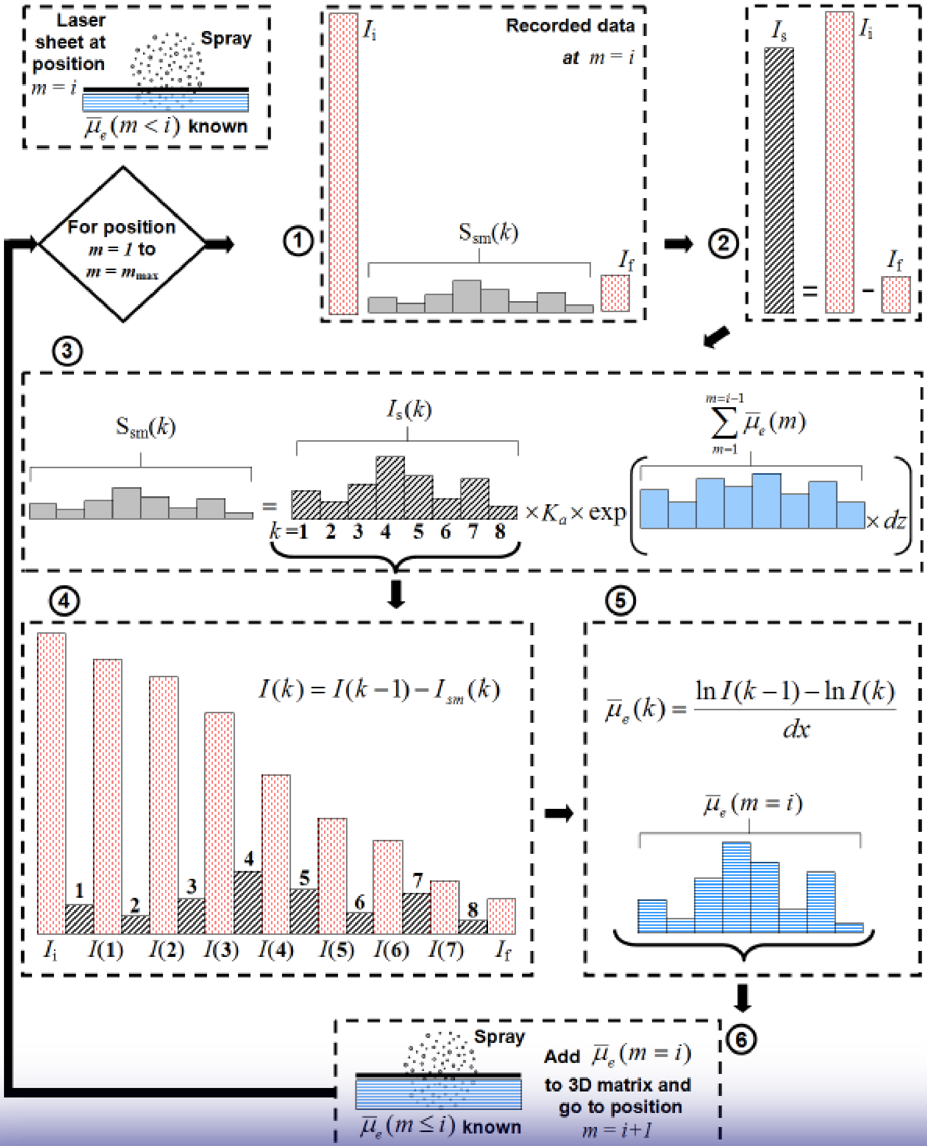
SLIPI - Scan

$$I_s = \frac{\sqrt{2}}{3} \cdot \sqrt{\begin{matrix} [I_1 - I_2]^2 \\ +[I_1 - I_2]^2 \\ +[I_1 - I_2]^2 \end{matrix}}$$

SLIPI image



SLIPI - Scan



Algorithm & procedure

- The initial light intensity I_i is known
- The transmitted light intensity I_f is know
- The SLIPI signal recorded is known S

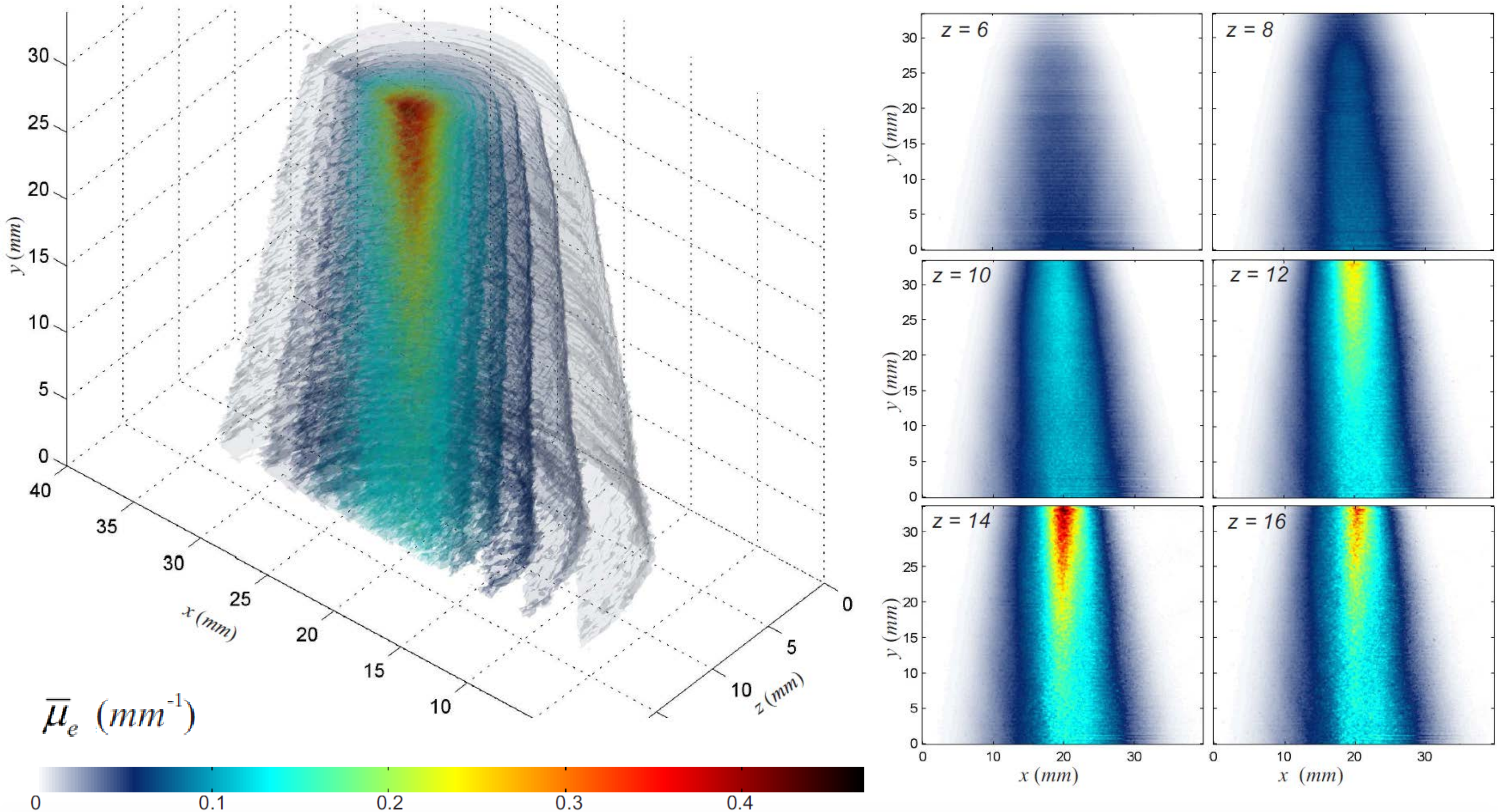
- The light intensity scattered away I_s along one row of pixel corresponds to the subtraction between the incident I_i and the transmitted light intensity I_f .

- The sum of the light intensity scattered by each pixel k equals (I_i - I_f).
- The signal I_s scattered from each voxel is attenuated on its way to the camera.
- The loss of light intensity after crossing each voxel/pixel along the direction of light propagation is deduced.
- The averaged extinction coefficient is extracted for each given layer.

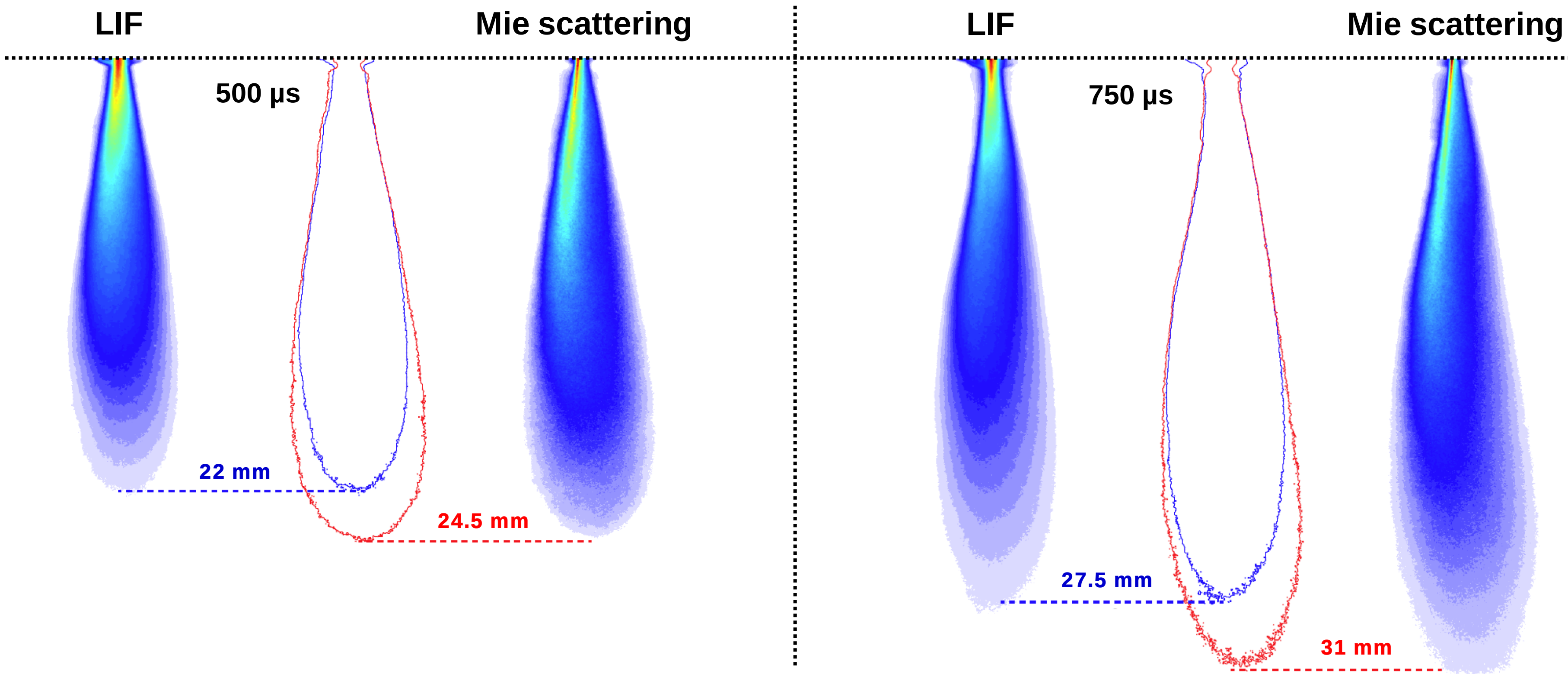
- Detailed information can be found here:

Ref: R. Wellander et al., Measurement Science and Technology **22** (12), 125303, (2011)

SLIPI - Scan

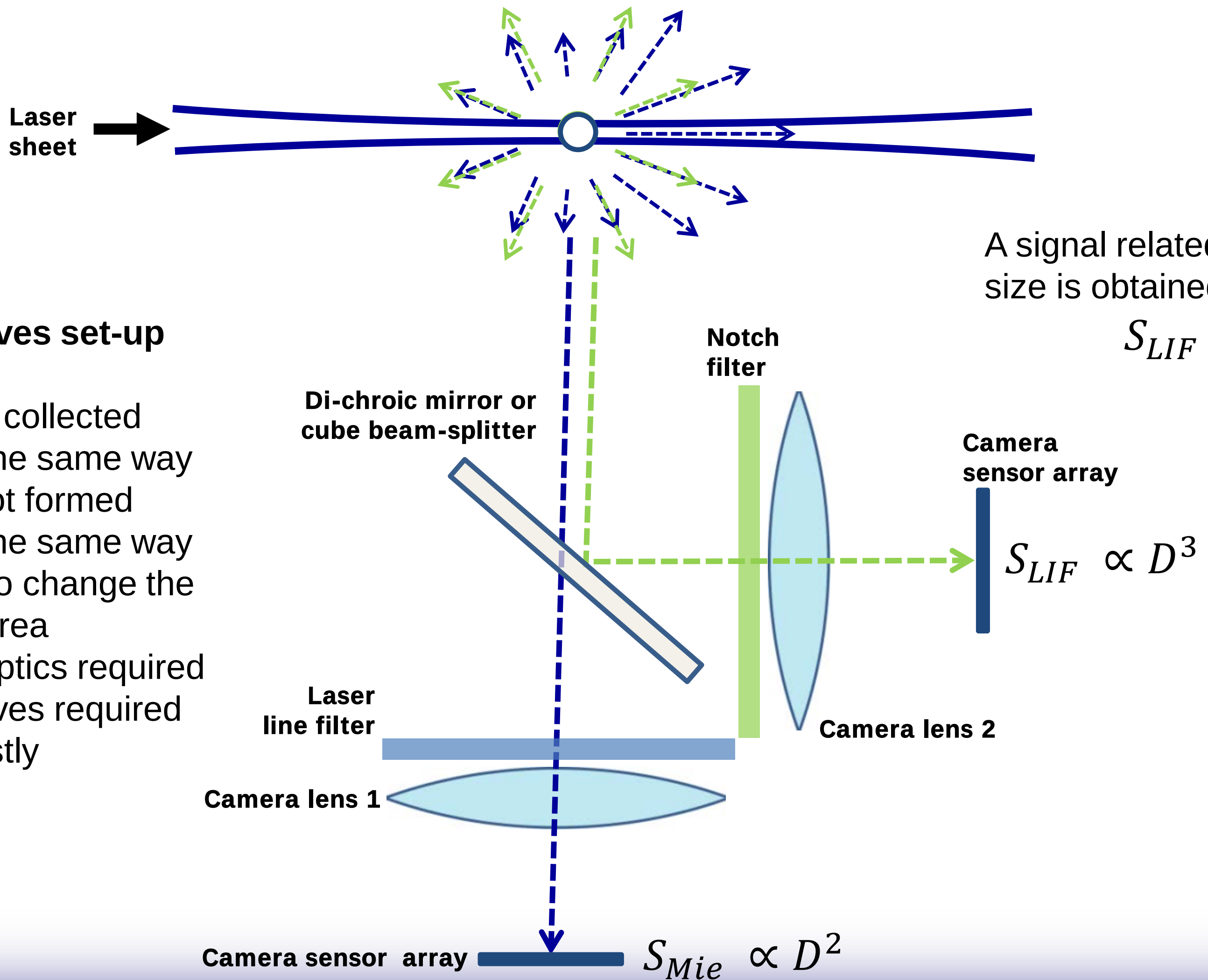


Spray penetration length



- Illustration of the disagreements in the experimental determination of the spray penetration length between LIF and Mie detection. Here a threshold at 5% of the max intensity is used.
- Even though the images have been recorded simultaneously, the estimation of the spray penetration length shows clear discrepancies. Similar discrepancies are likely to occur for images recorded with different cameras and illumination sources.
- Ref: H. Grosshans *et. al.*, International Journal of Multiphase Flow, 72, 218–232, (2015)

LIF/Mie droplet sizing on a single droplet



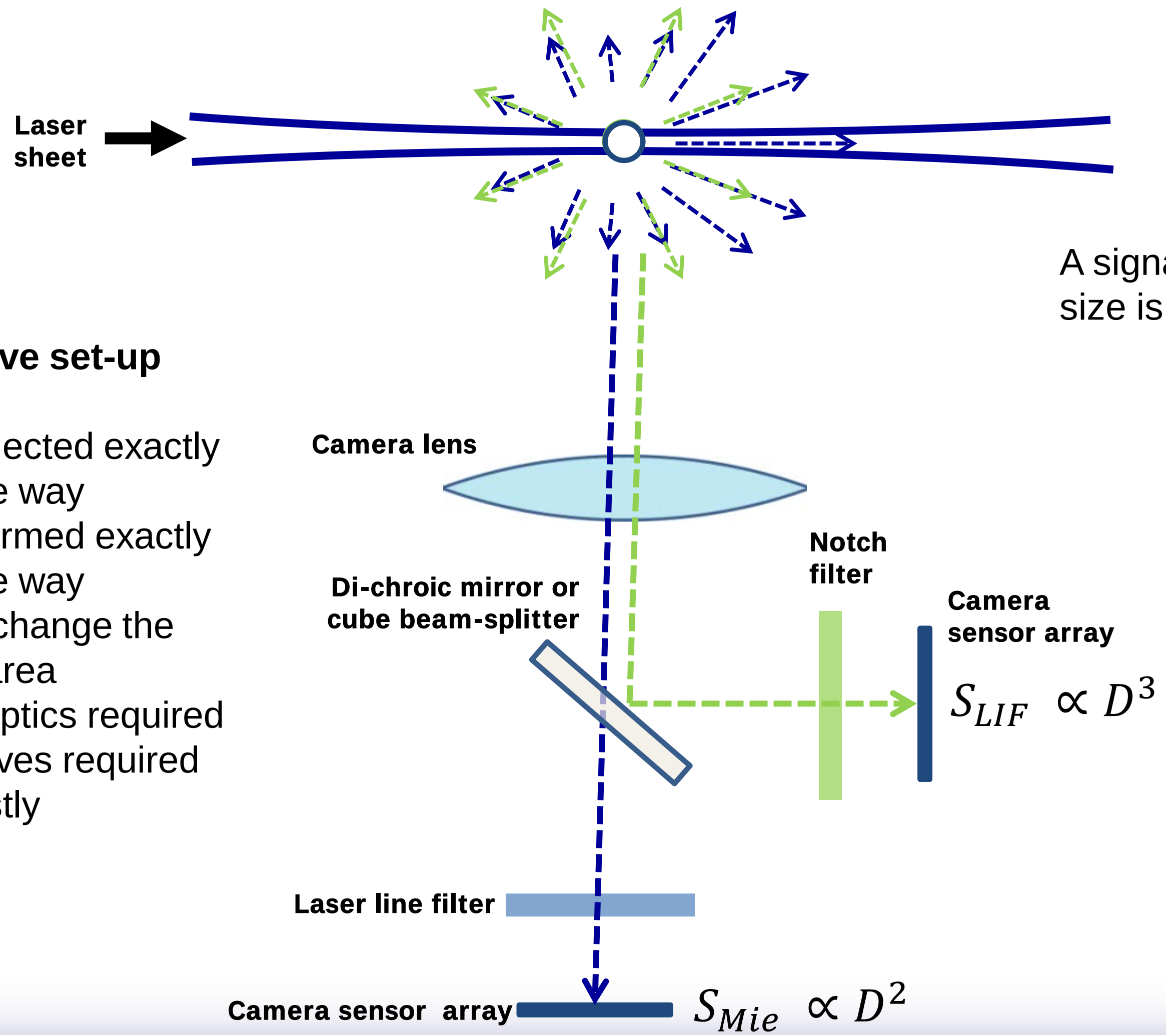
A signal related to the droplet size is obtained from the ratio:

$$S_{LIF} / S_{Mie}$$

Two objectives set-up

- Light not collected exactly the same way
- Image not formed exactly the same way
- Difficult to change the viewed area
- 50 mm optics required
- 2 objectives required
- More costly

LIF/Mie droplet sizing on a single droplet



A signal related to the droplet size is obtained from the ratio:

$$S_{LIF} / S_{Mie}$$

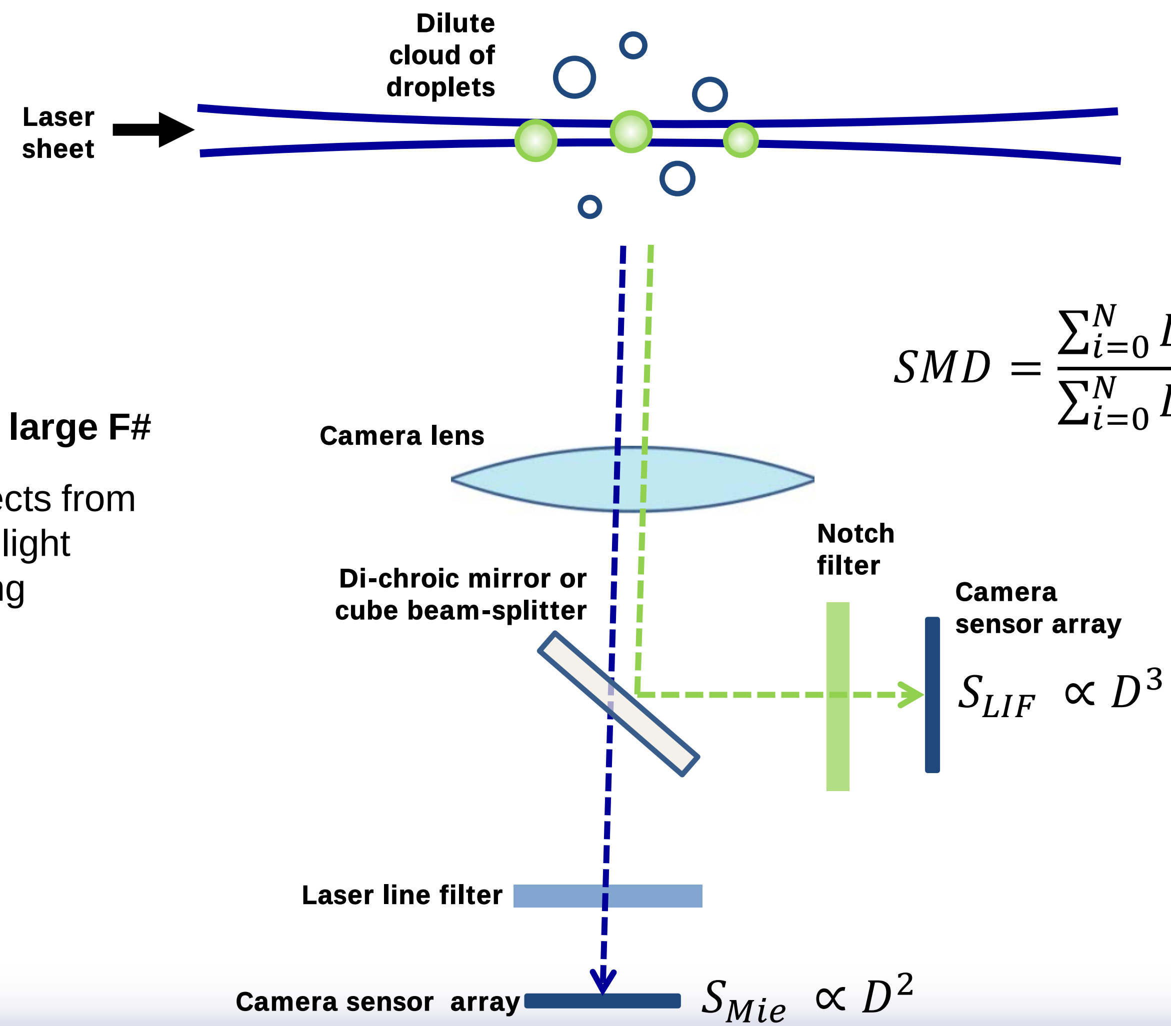
One objective set-up

- Light collected exactly the same way
- Image formed exactly the same way
- Easy to change the viewed area
- 25 mm optics required
- 1 objectives required
- Less costly

LIF/Mie in the single scattering scattering regime

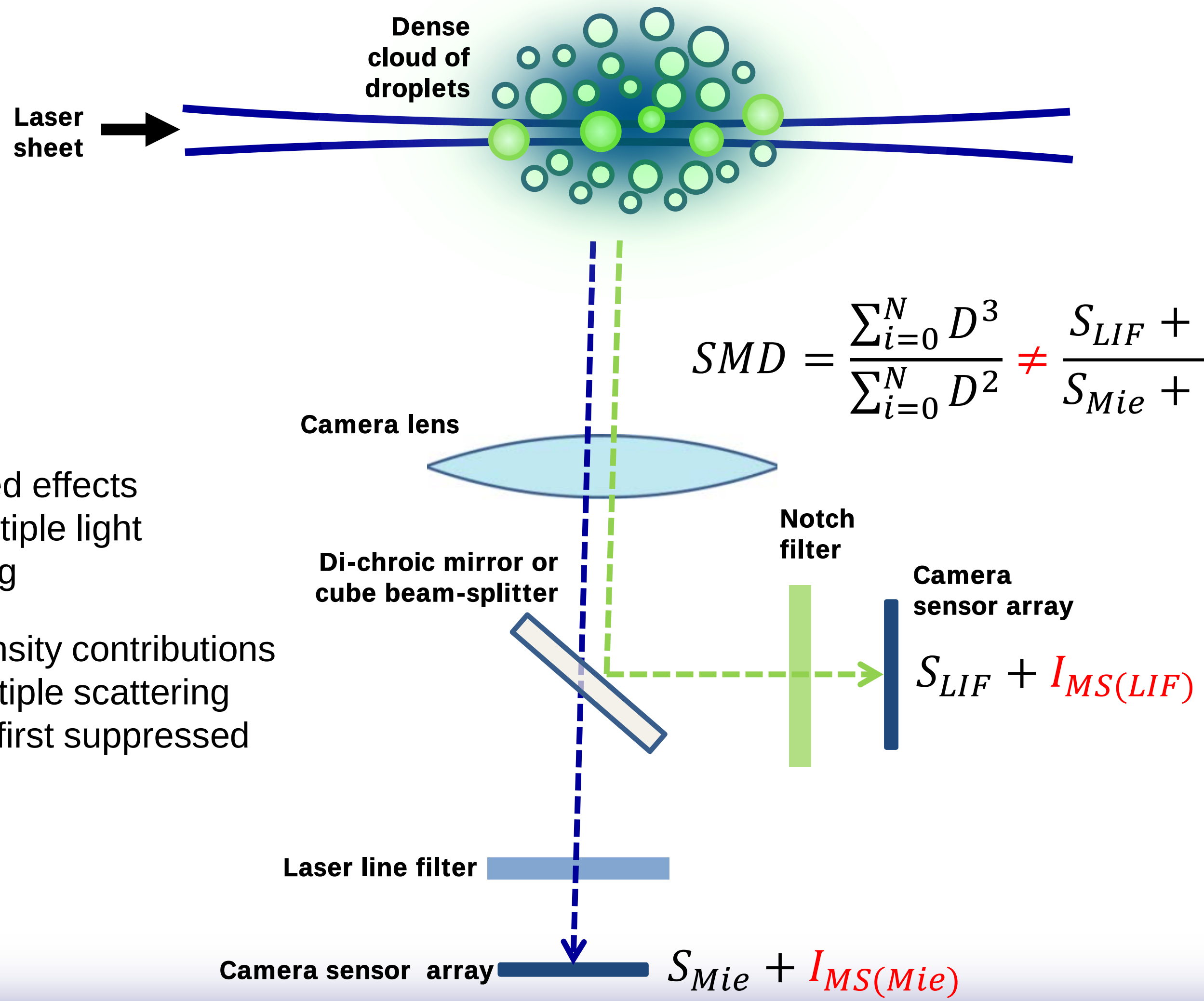
OD << 1 & large F#

- Low effects from multiple light scattering



$$SMD = \frac{\sum_{i=0}^{N} D^3}{\sum_{i=0}^{N} D^2} = \frac{S_{LIF}}{S_{Mie}} \cdot \underbrace{\left[\frac{K_{LIF}}{K_{mie}}\right]}_{\text{Not a constant !! Calibration curve}}$$

LIF/Mie - Multiple scattering effects



$$SMD = \frac{\sum_{i=0}^{N} D^3}{\sum_{i=0}^{N} D^2} \neq \frac{S_{LIF} + I_{MS(LIF)}}{S_{Mie} + I_{MS(Mie)}} \cdot \underbrace{\left[\frac{K_{LIF}}{K_{mie}}\right]}$$

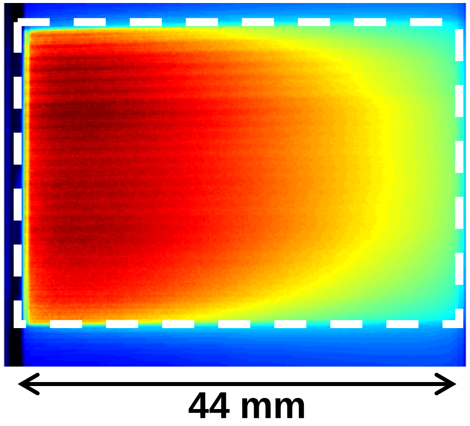
Not a constant !!
Calibration curve

OD ≥ 1

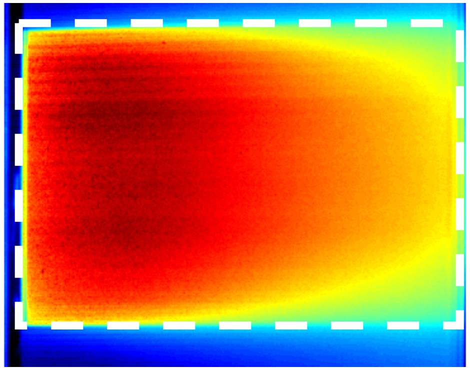
- Unwanted effects from multiple light scattering
- The intensity contributions from multiple scattering must be first suppressed

LIF/Mie - Multiple scattering effects

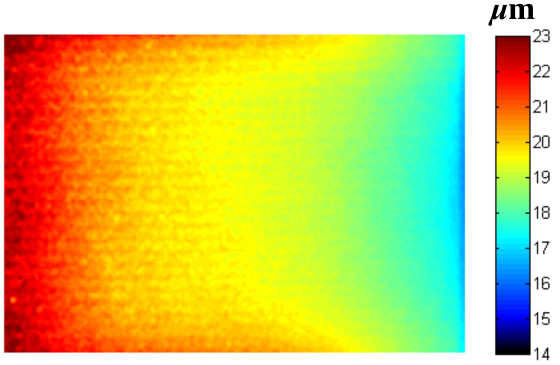
Conv. LIF



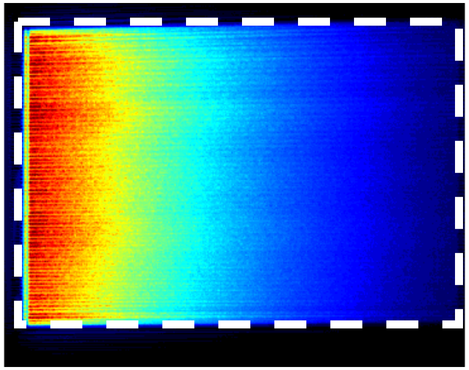
Conv. Mie



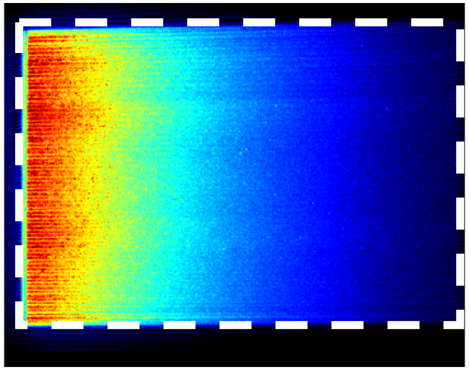
Conv. LIF/Mie: SMD



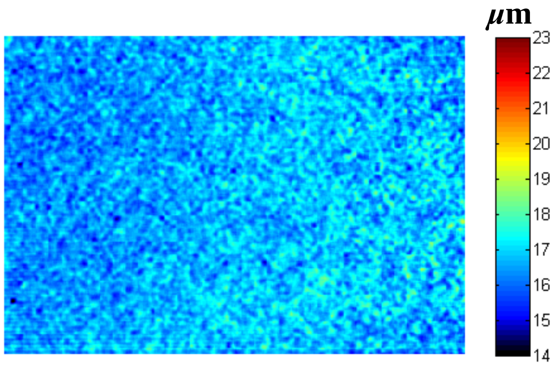
SLIPI LIF



SLIPI Mie



SLIPI - LIF/Mie: SMD

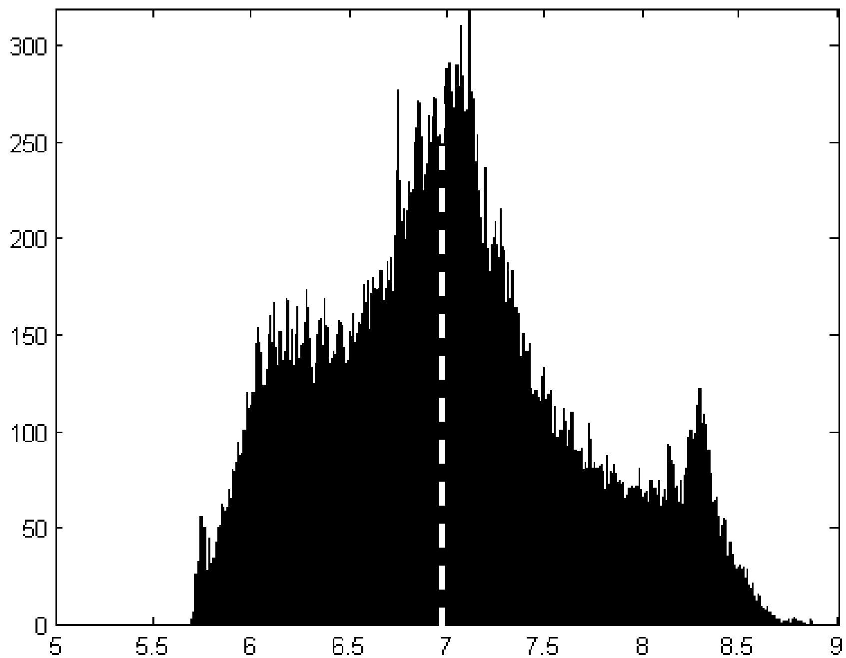


- Cuvette containing fluorescent monodispersed polystyrene microspheres in water - $OD = 4$

LIF/Mie - Multiple scattering effects

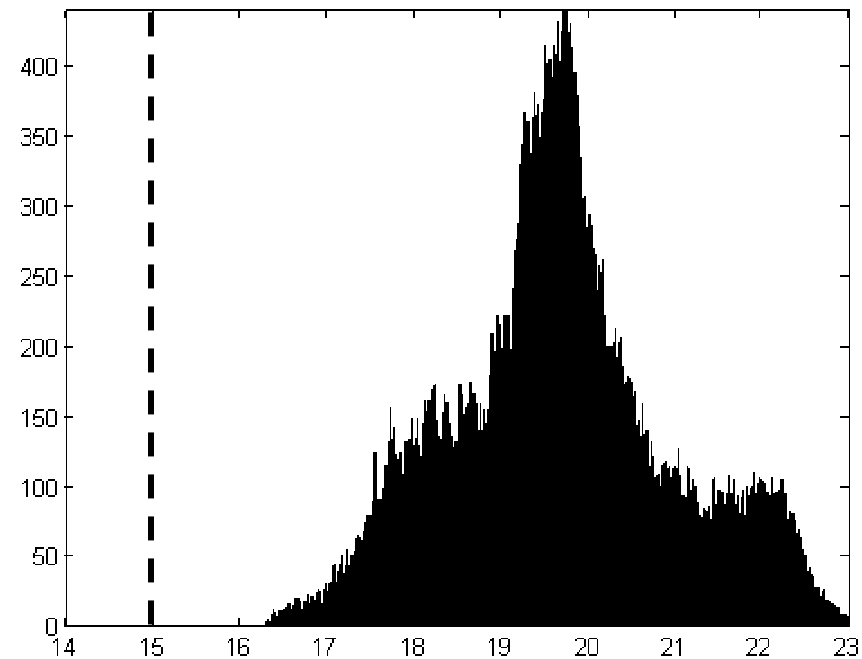
Conv. LIF/Mie ratio

Ø = 7 µm



Sauter Mean Diameter [µm]

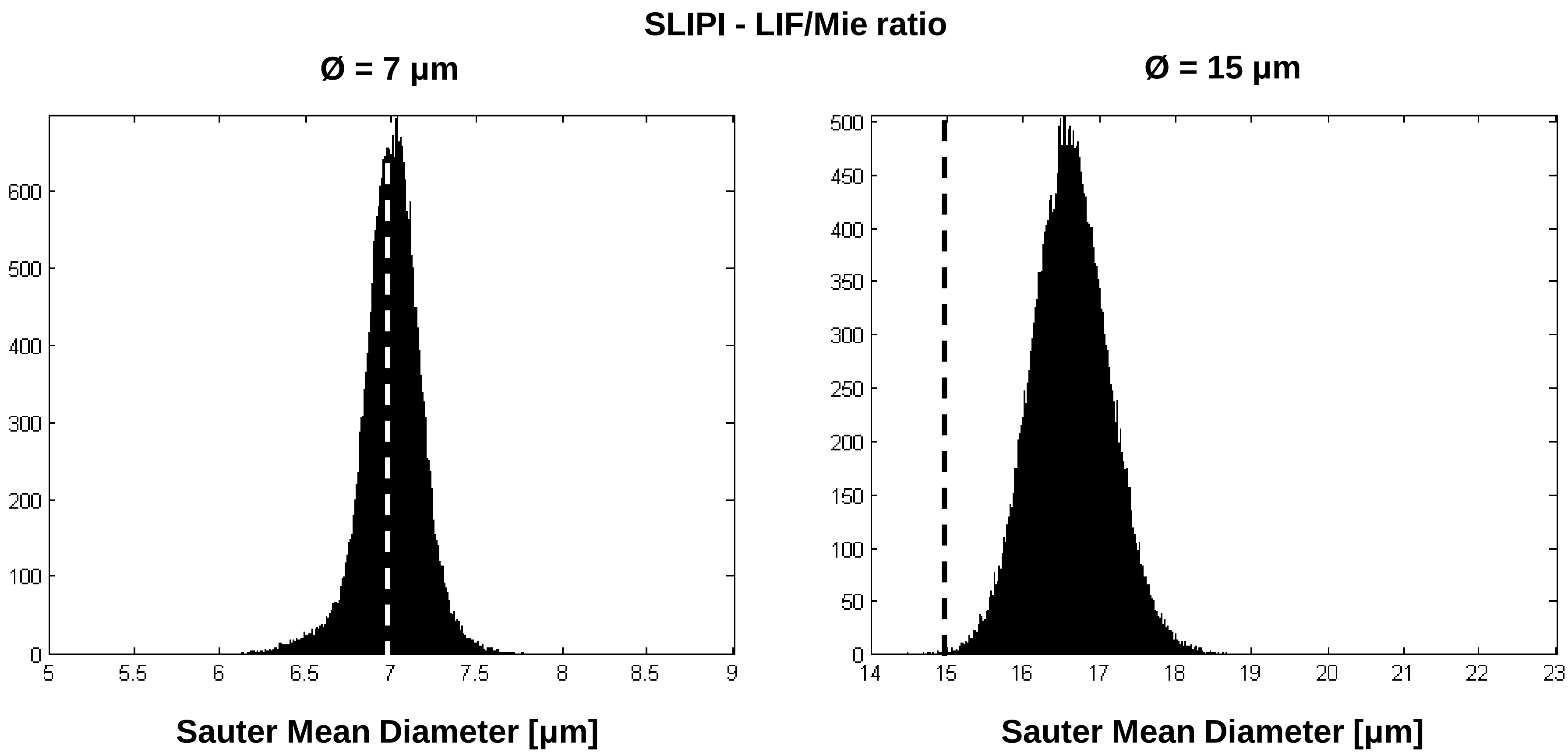
Ø = 15 µm



Sauter Mean Diameter [µm]

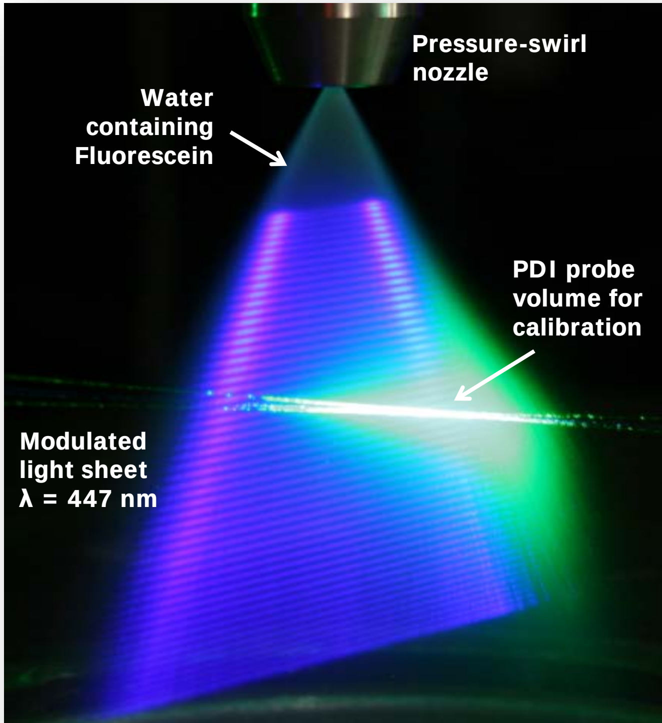
- Particle size distribution over the full image, deduced from the LIF/Mie ratio.
- The 15 microns results are calibrated, here, from the 7 microns results.
- The measurement shows a non-monodispersed particle size distribution.

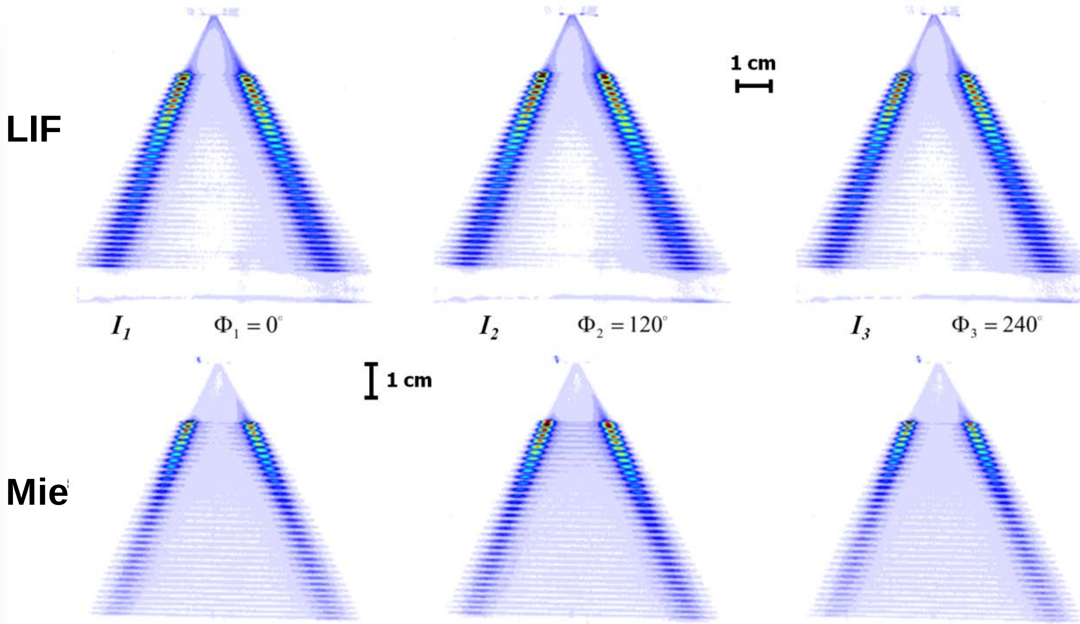
LIF/Mie - Multiple scattering effects

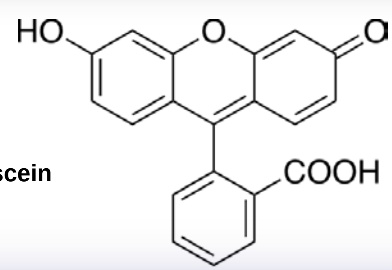


- Particle size distribution over the full image, deduced from the LIF/Mie ratio.
- The 15 microns results are calibrated, here, from the 7 microns results.
- The measurement shows a non-monodispersed particle size distribution.

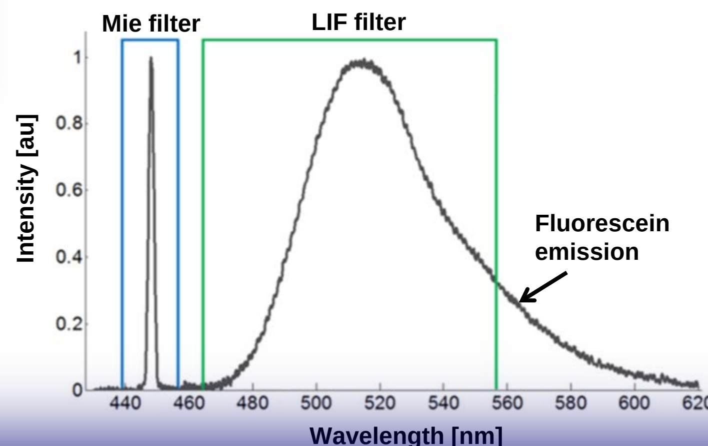
SLIPI - LIF/Mie - Measurement example







Fluorescein

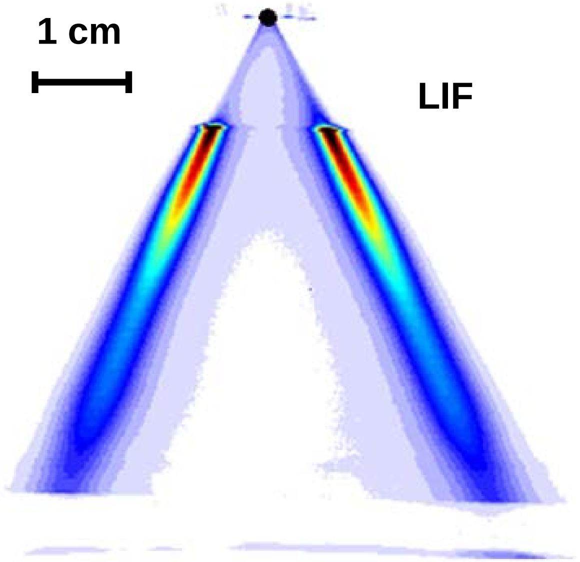


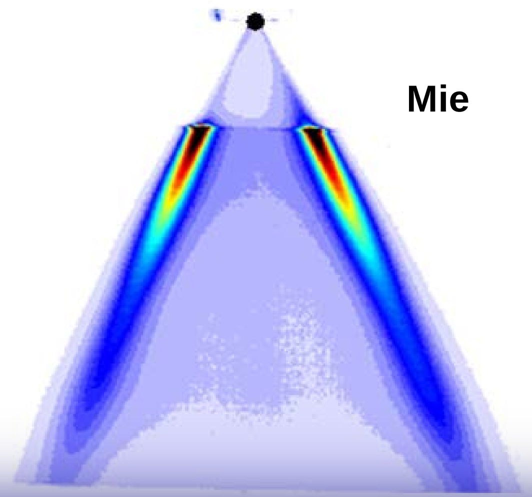
- Fluorescein is an organic dye with high quantum yield when excited in the blue/green spectral region

Conv. LIF/Mie results

- By ratioing the signals, the effects from laser extinction and signal attenuation cancel out

- The effects from multiple light scattering are different between the LIF and Mie signals





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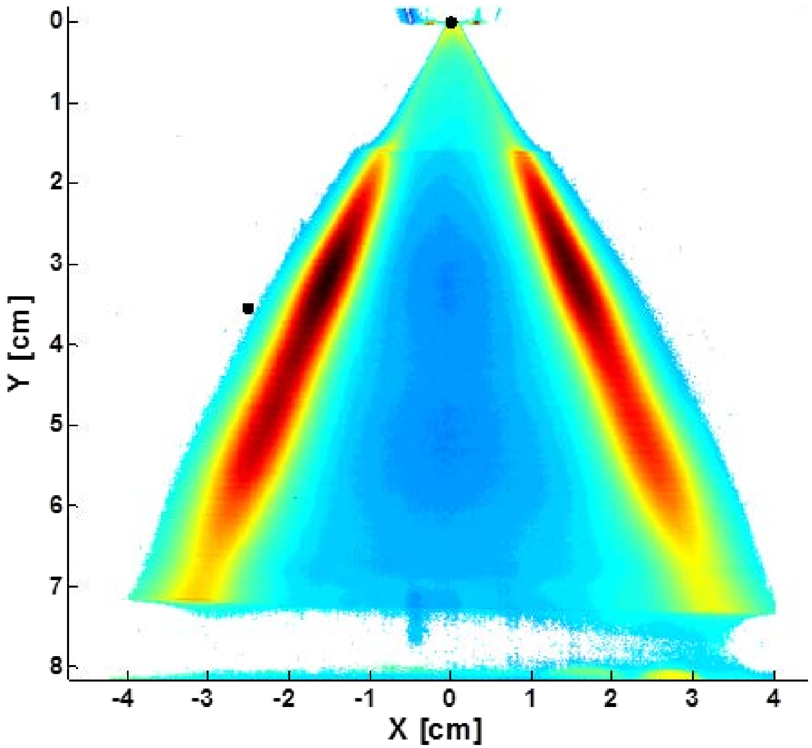
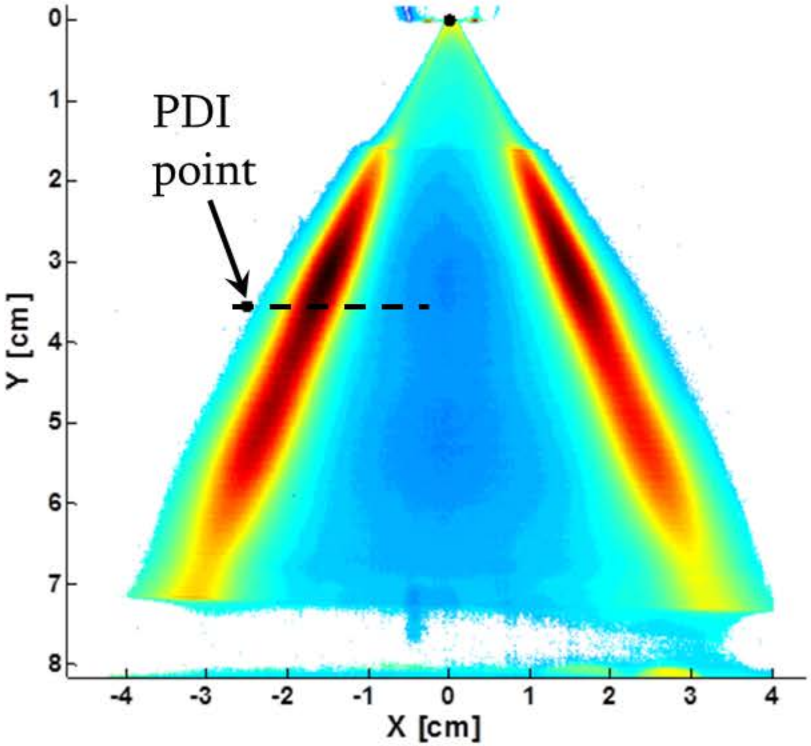
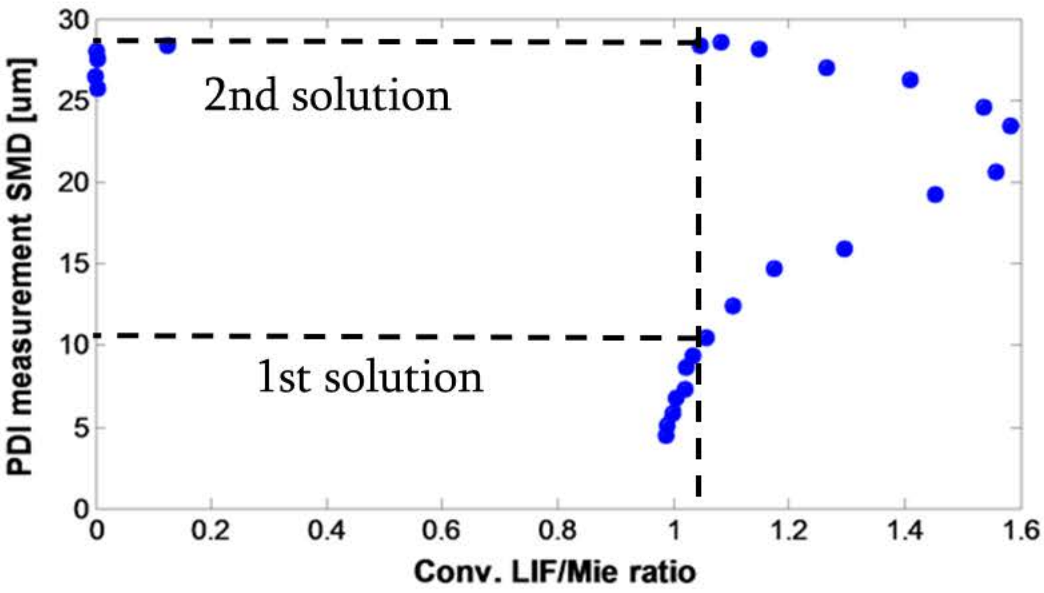


Conv. LIF/Mie results

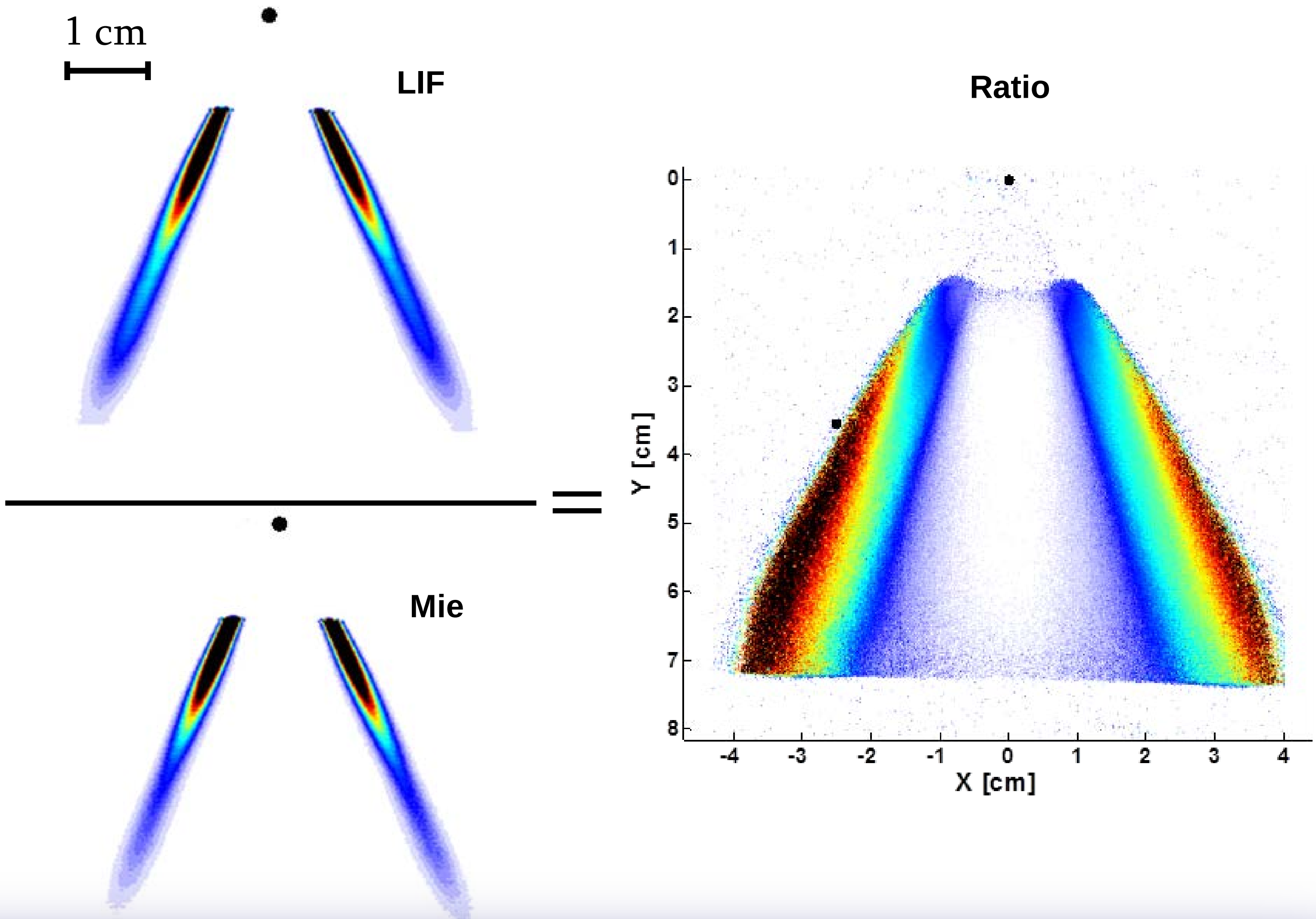


Calibration impossible

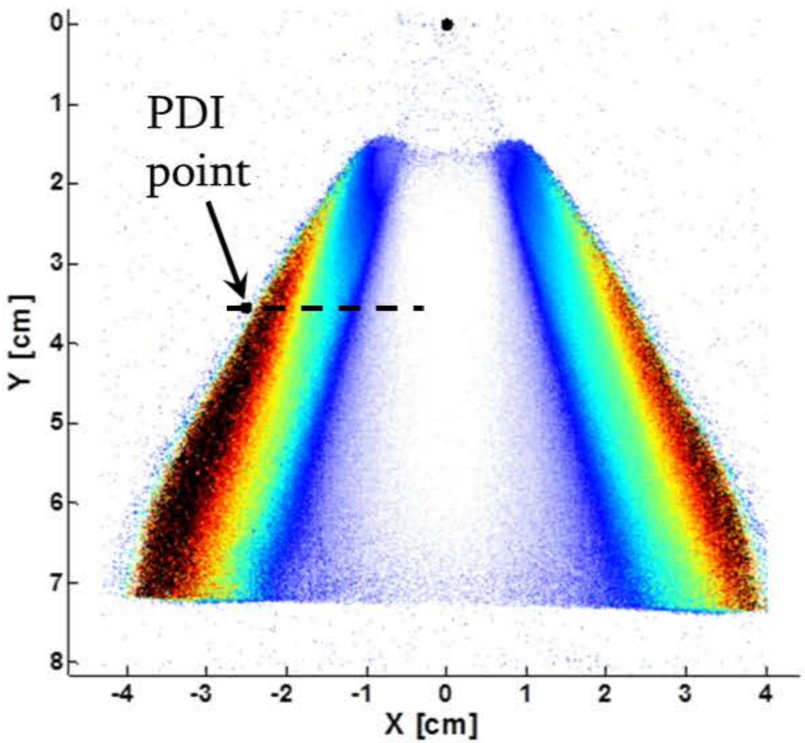


SLIPI - LIF/Mie results

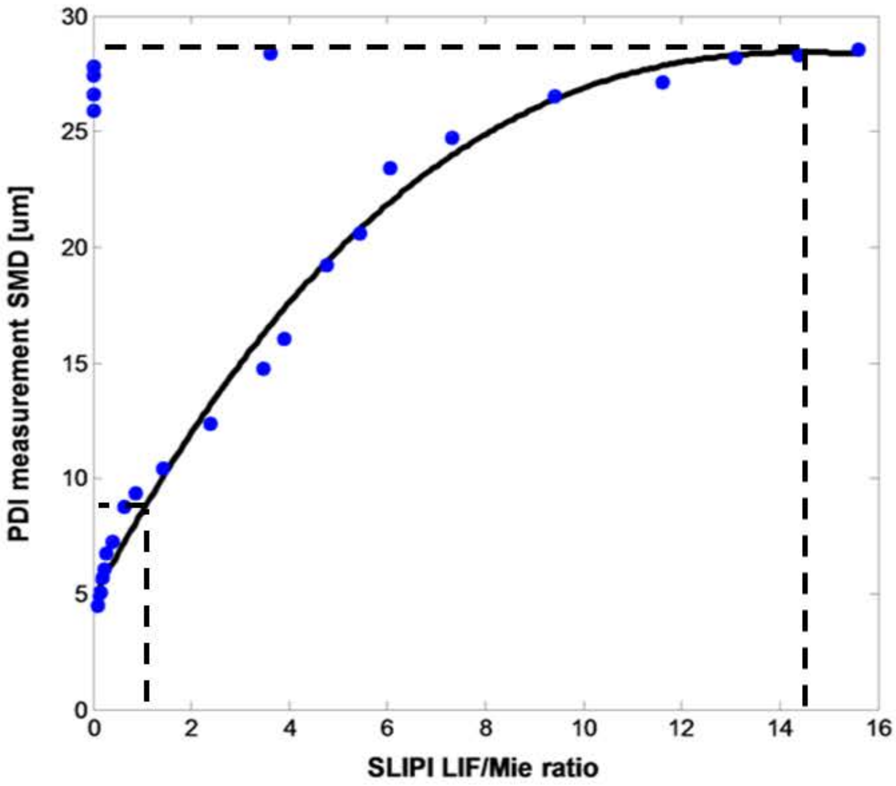
- By ratioing the signals, the effects from laser extinction and signal attenuation cancel out
- The effects from multiple light scattering are suppressed in the LIF and Mie signals



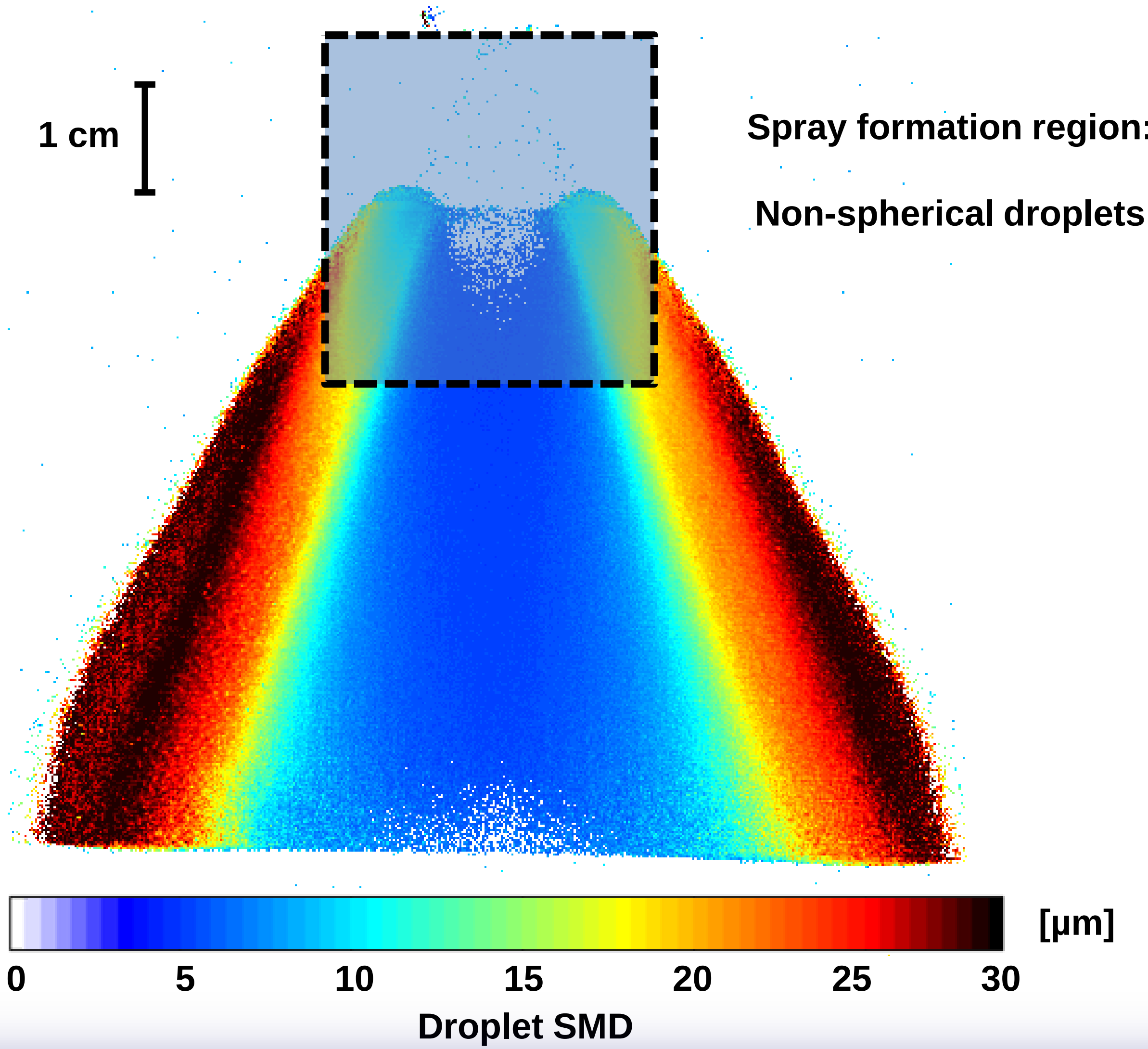
SLIPI LIF/Mie results



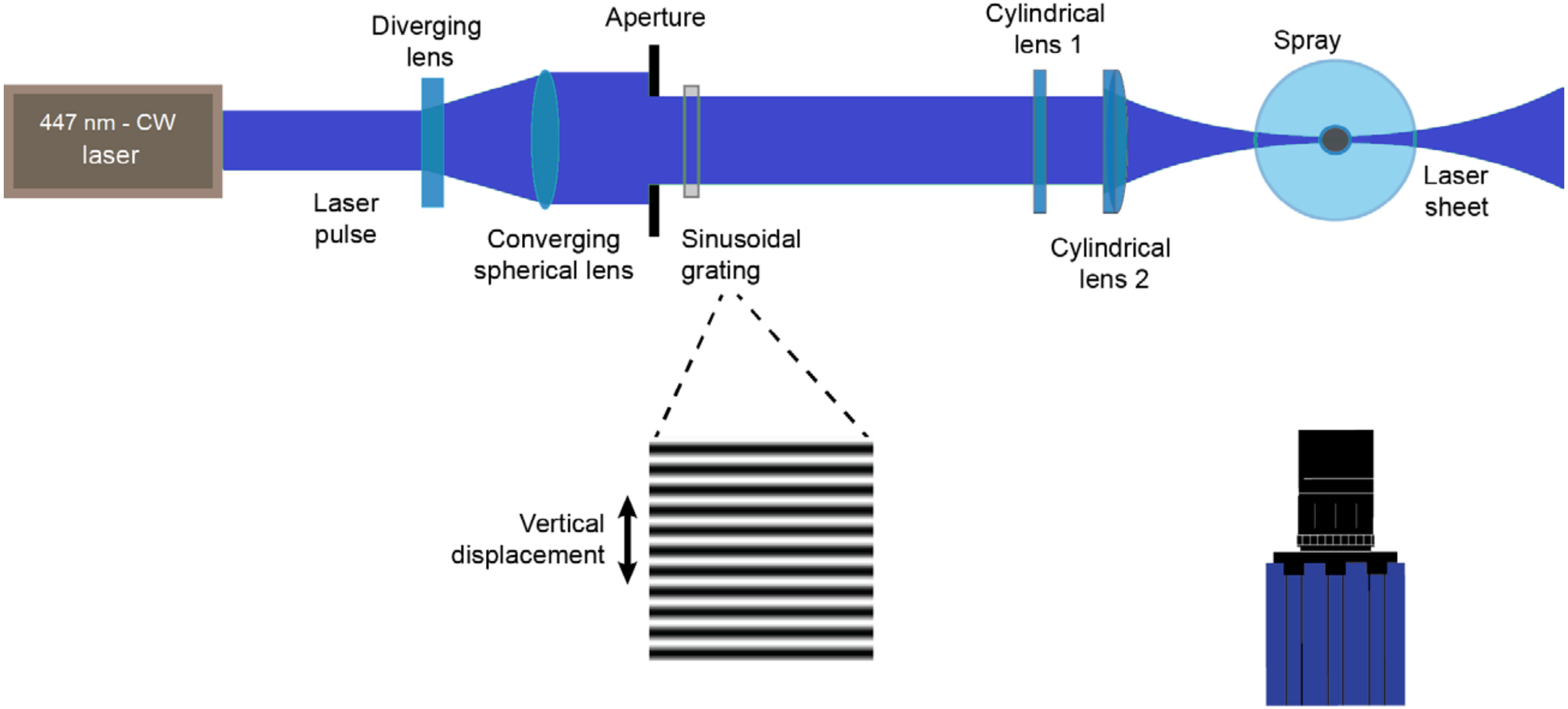
Calibration possible



SLIPI - LIF/Mie results



SLIPI set-up: CW illumination

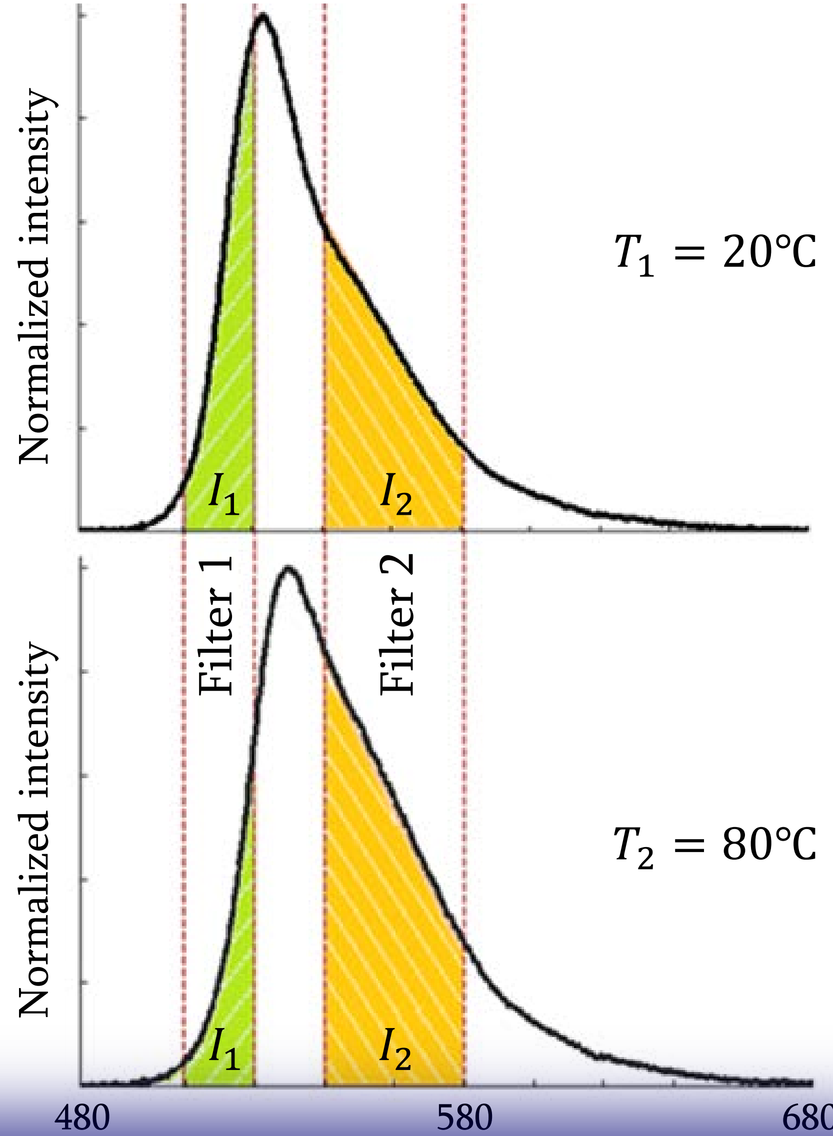


Two-color LIF Thermometry

LIF spectral response

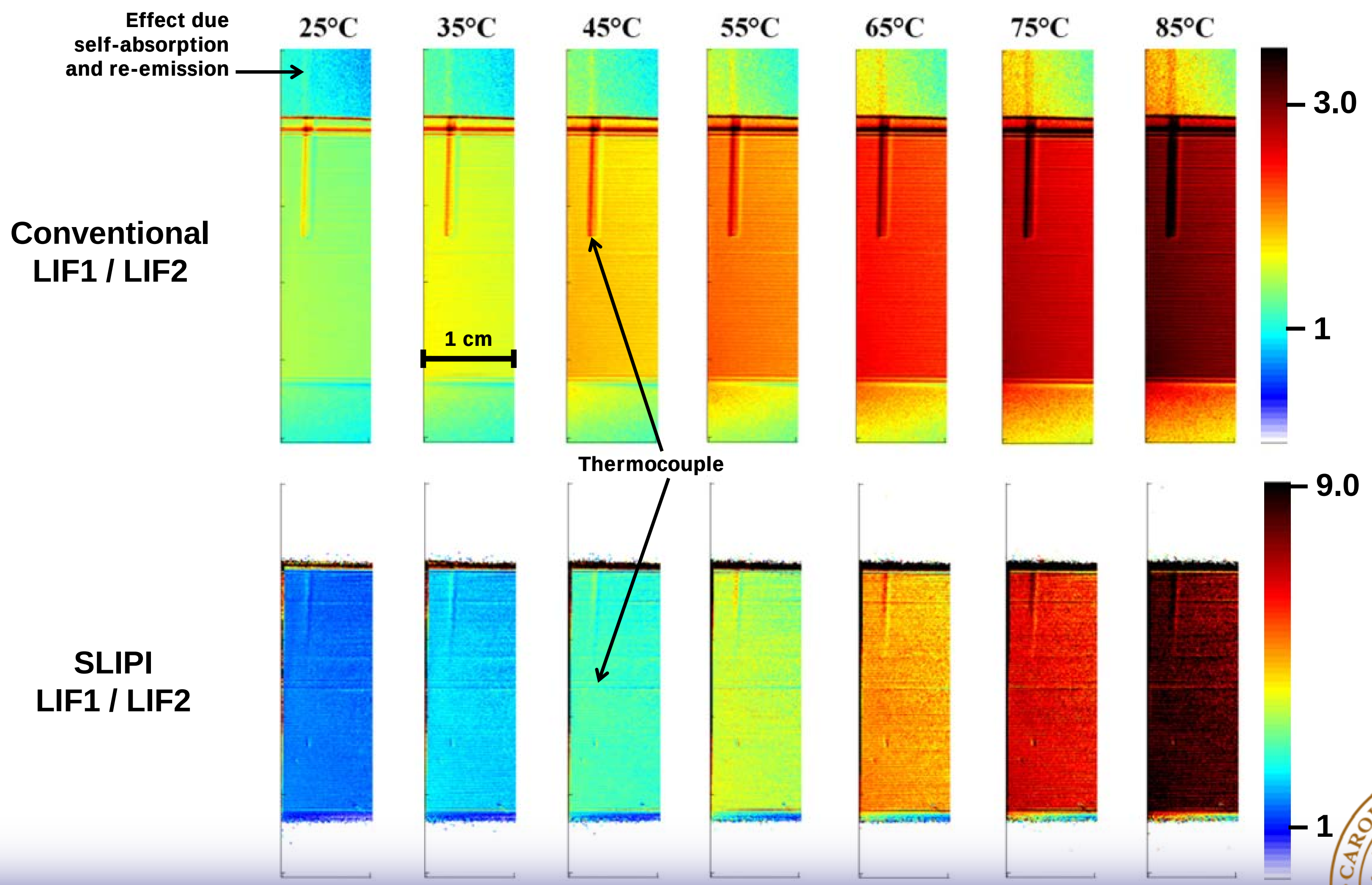
Dye: Fluorescein

Excitation: λ = 447 nm

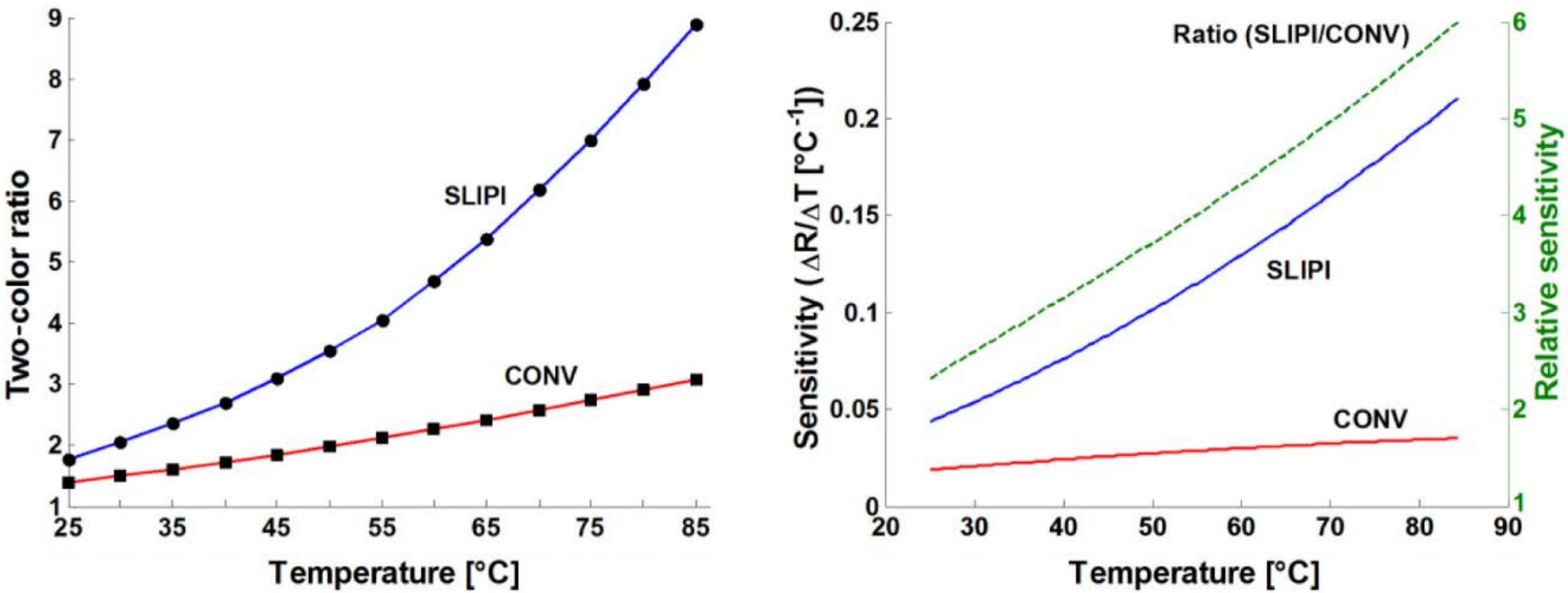


$$\left.\frac{I_2}{I_1}\right|_{T_1} < \left.\frac{I_2}{I_1}\right|_{T_2}$$

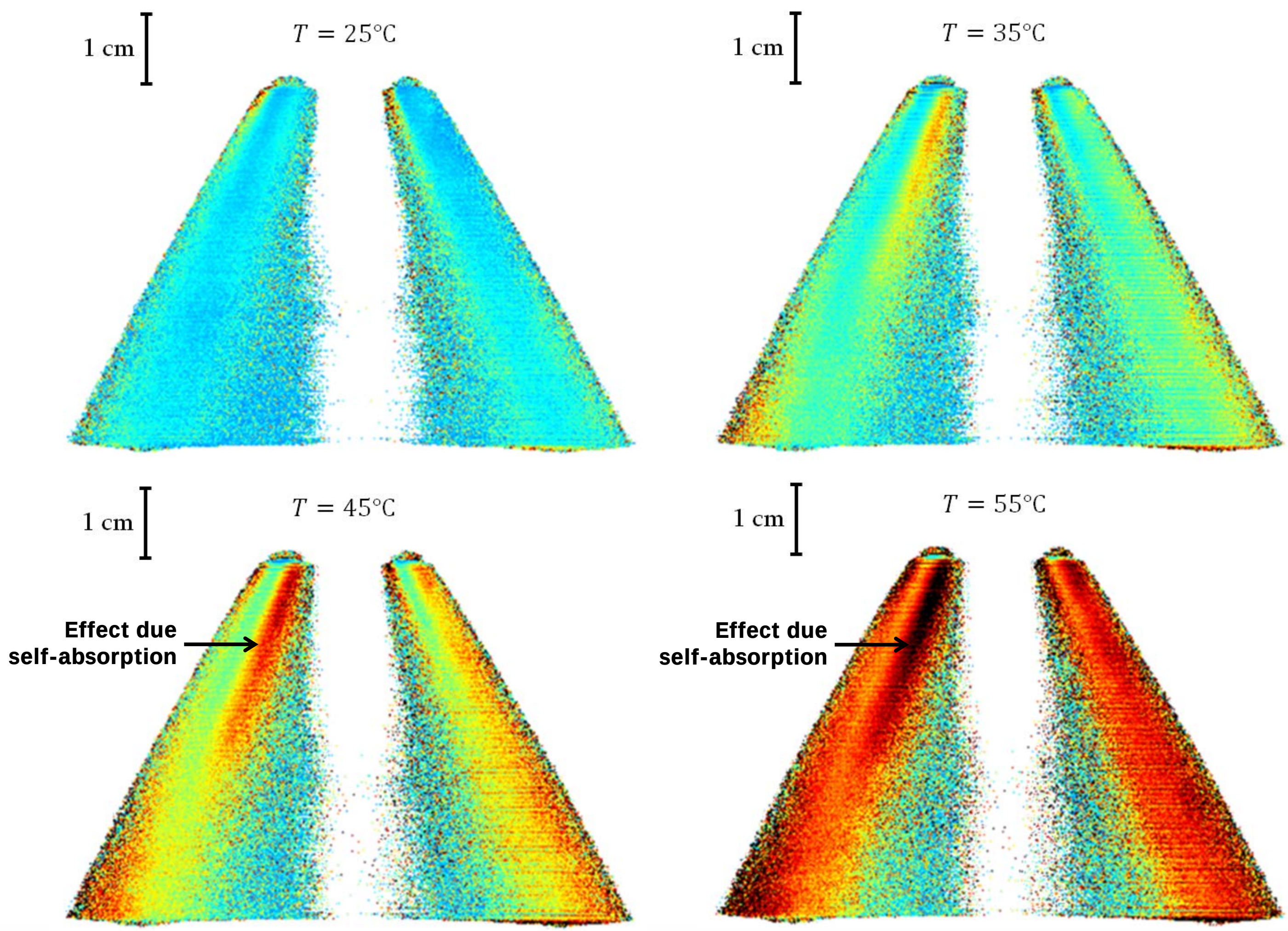
Two-color LIF Thermometry



Two-color LIF Thermometry

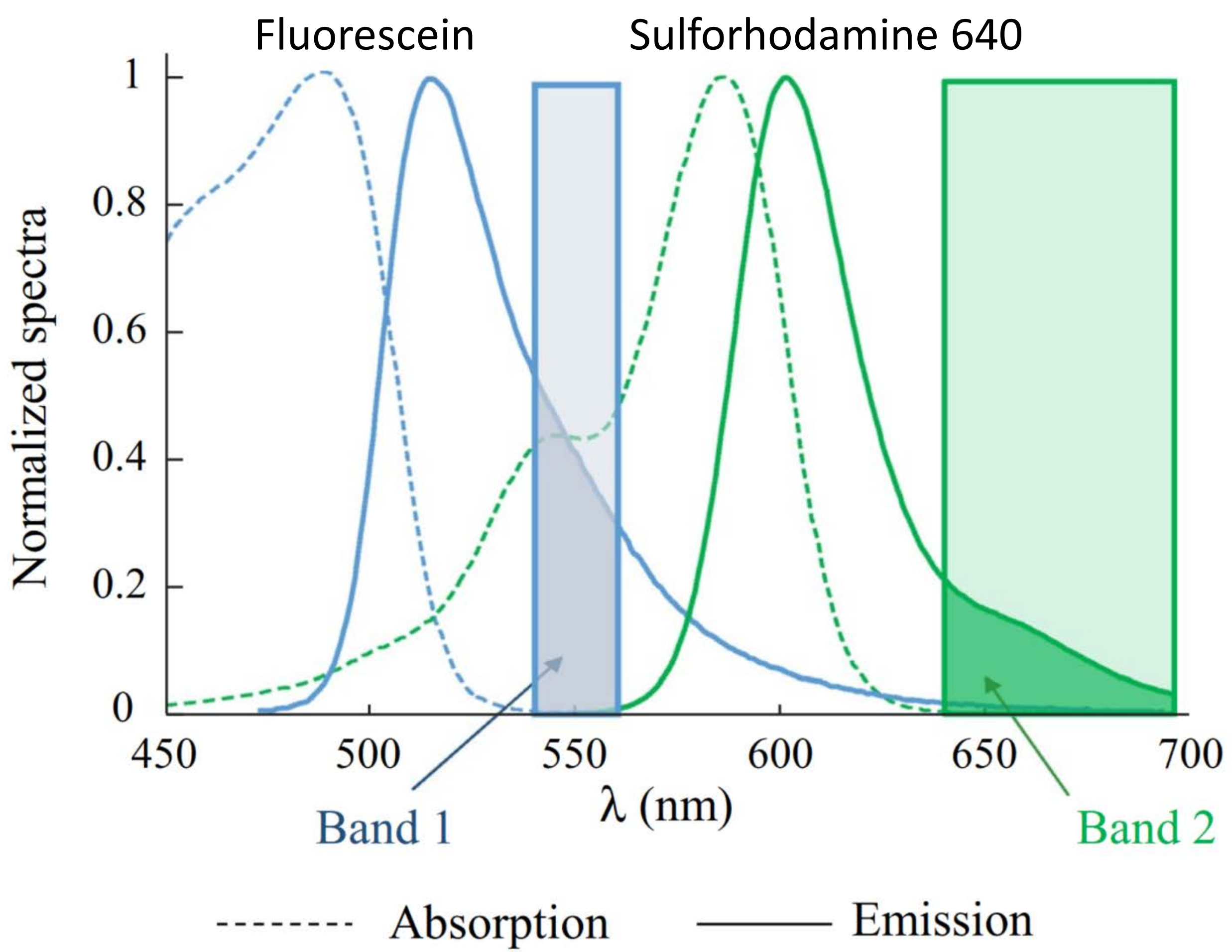


Two-color LIF Thermometry in a spray



- Example of temperature mapping in a hollow-cone spray.
- Changes in liquid temperature are visible.
- However, some unwanted effects can be observed due to self-absorption of the dye.

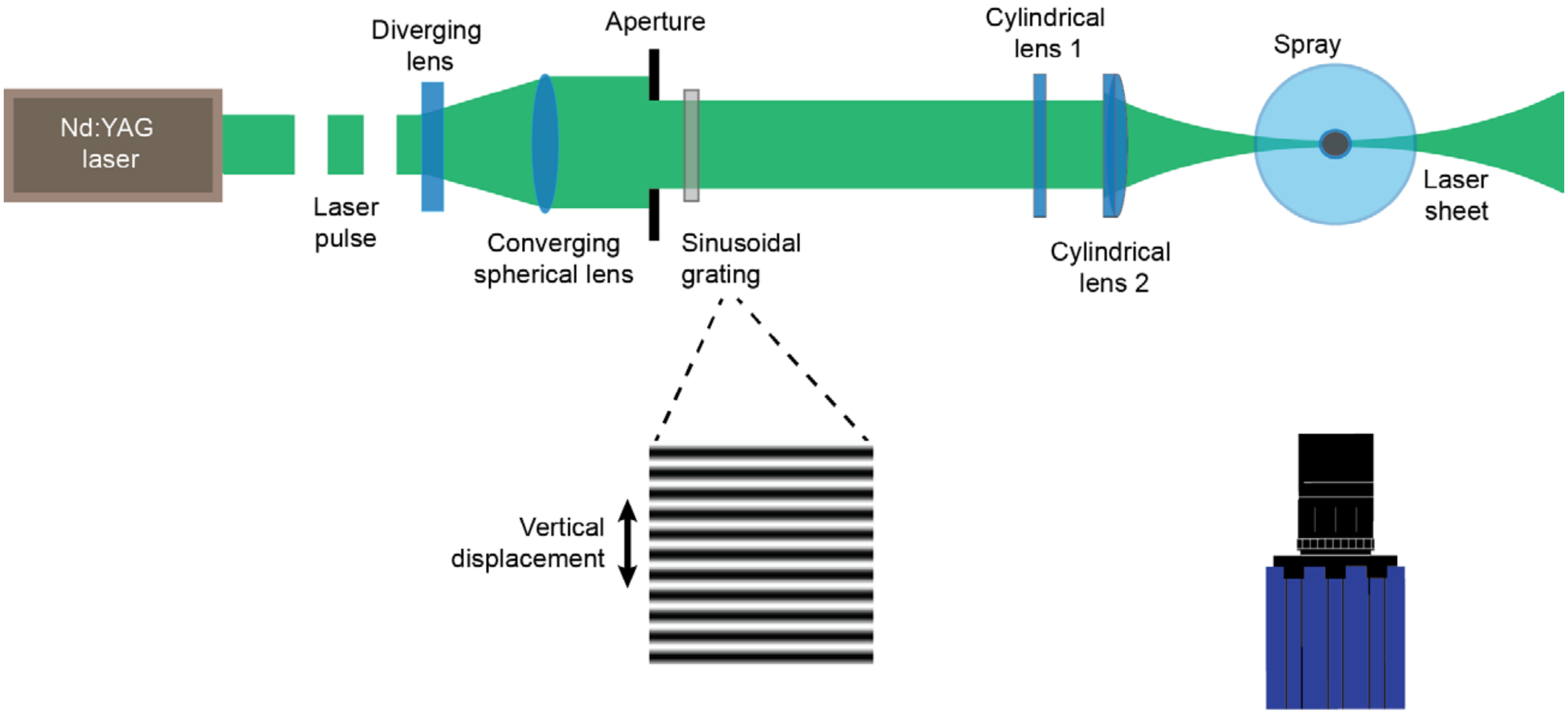
Two-color LIF Thermometry: Self-absorption



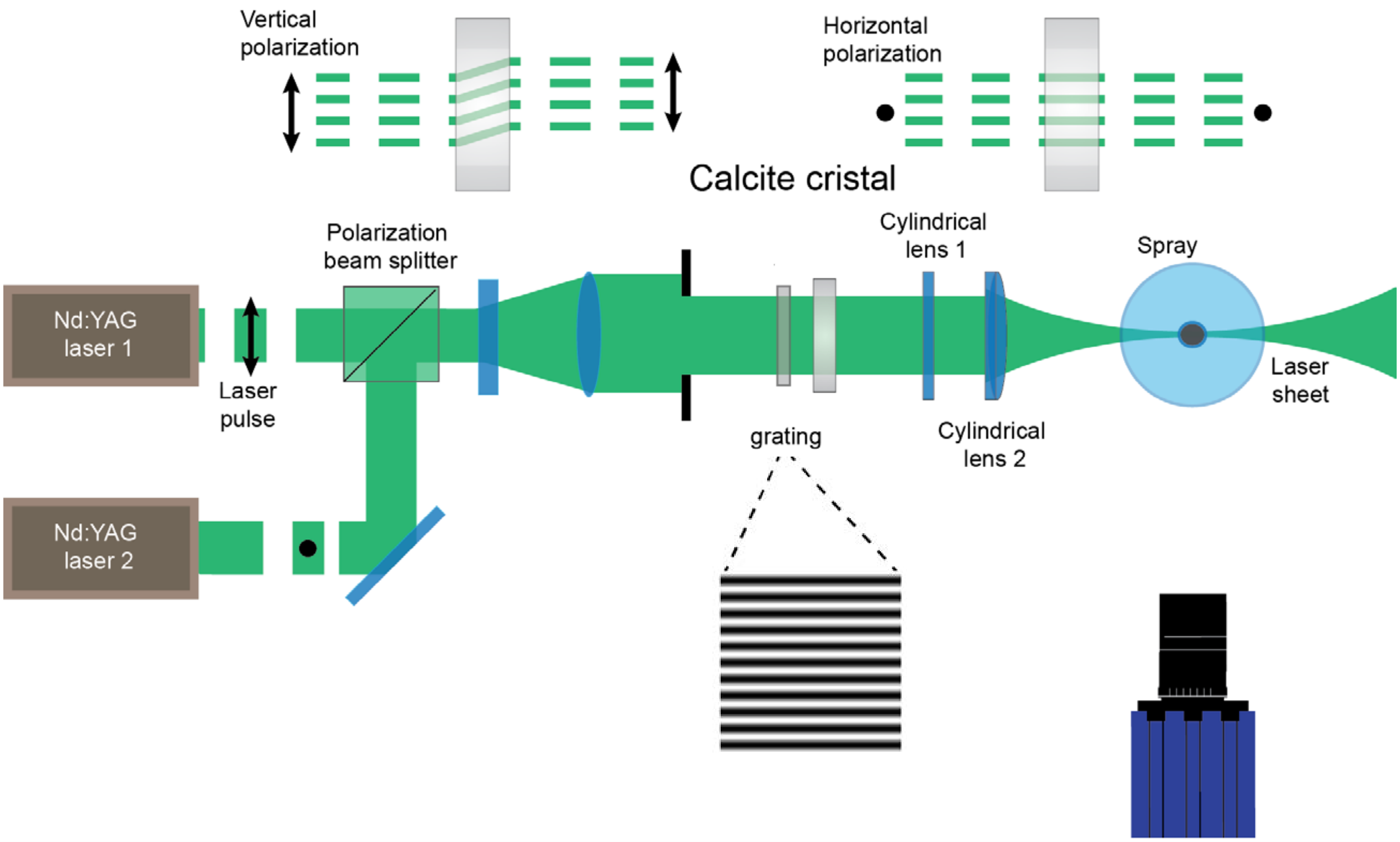
- To avoid effects due to self-absorption, a two-dye approach has been recently investigated by Chaze *et al.*
- The idea is to extract a spectral band ”away” from the absorption spectrum.
- In the best case, one dye decreases with temperature and the other one increases.

Ref: William Chaze, et al., Experiments in Fluids, 2017. **58**(8): p. 96.

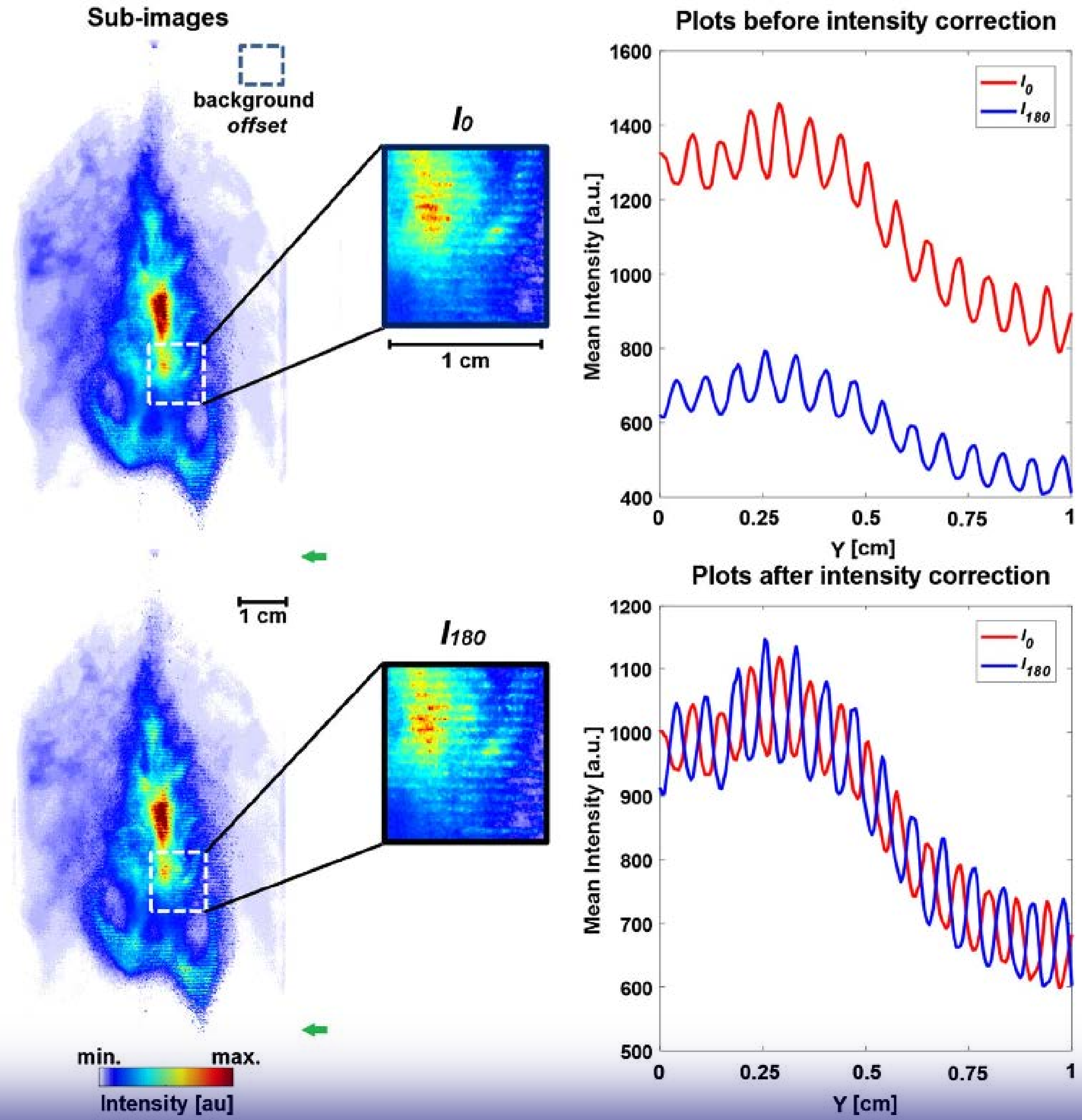
SLIPI set-up: Pulsed laser illumination



SLIPI set-up: Pulsed laser illumination

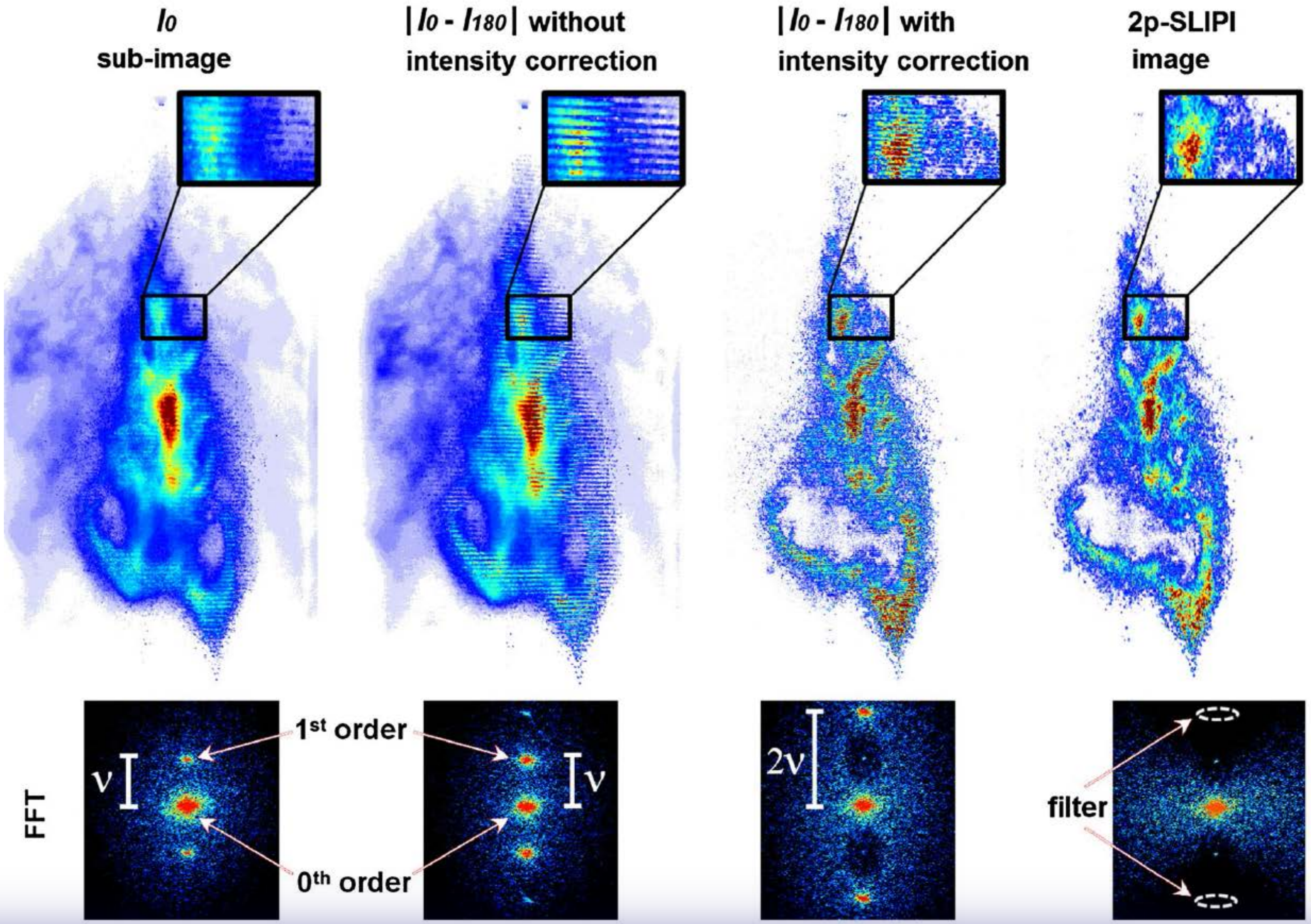


Two-phase SLIPI for instantaneous imaging

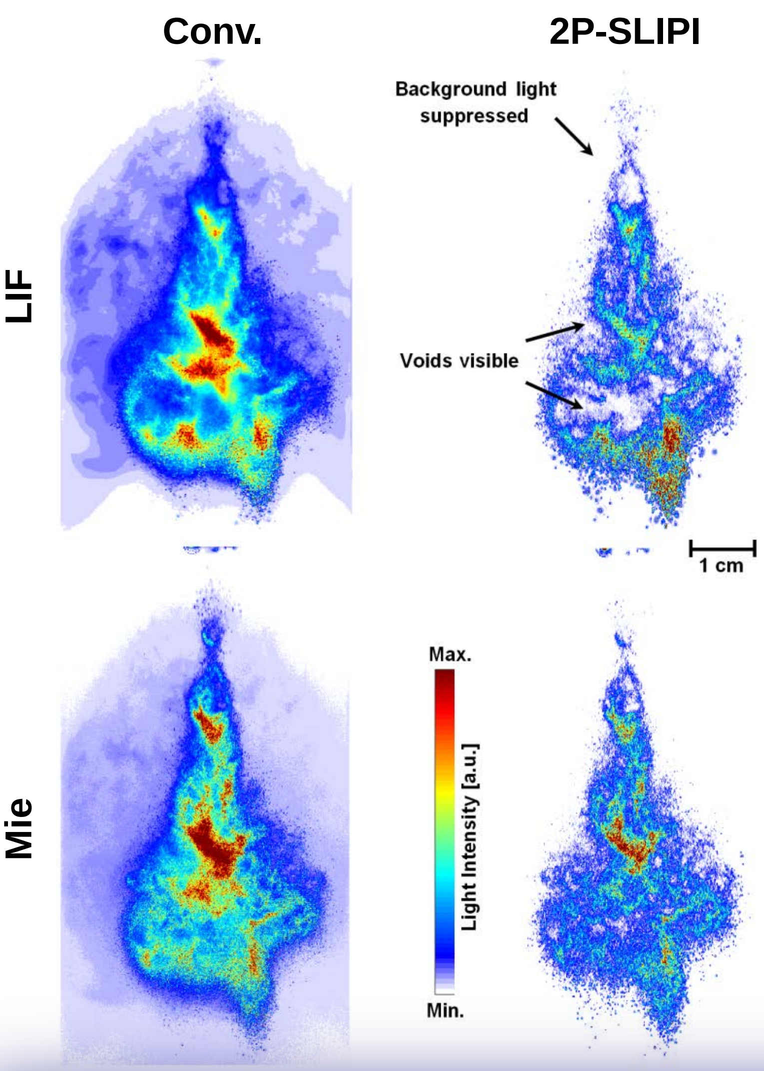


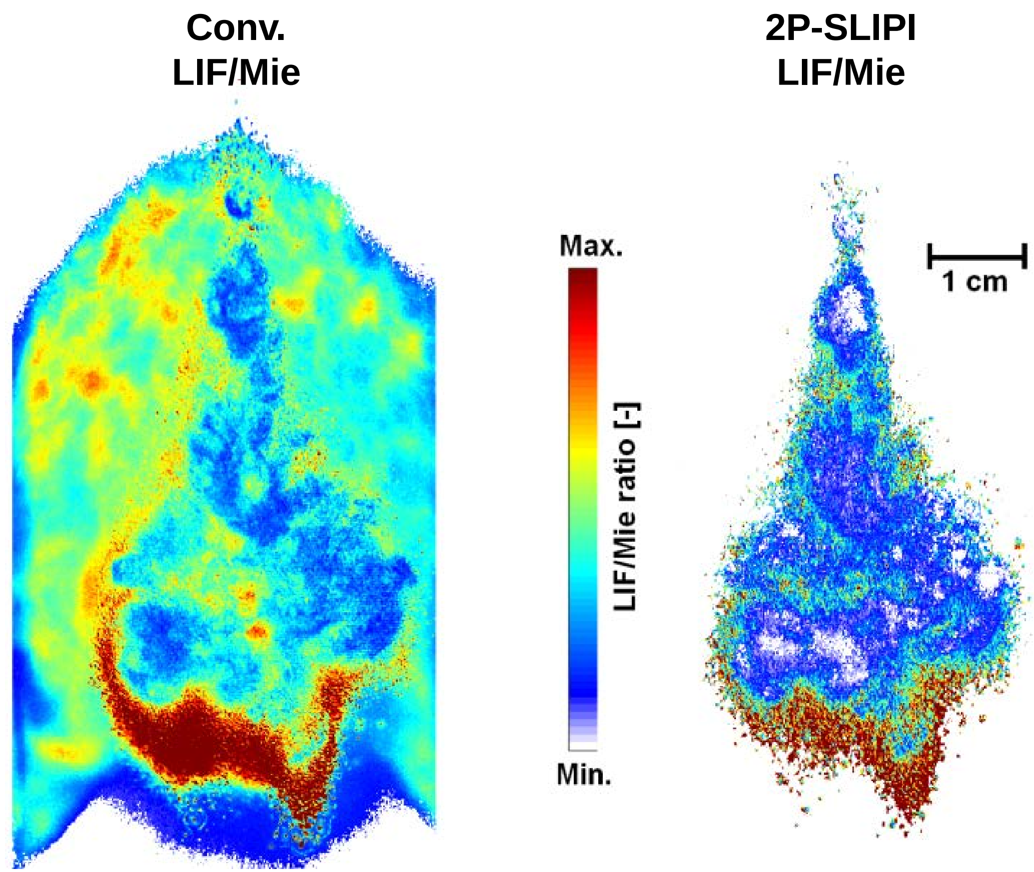
- The two laser pulses most probably have different energy profiles.
- It is important to normalize the intensity levels before subtracting the images.

Two-phase SLIPI for instantaneous imaging



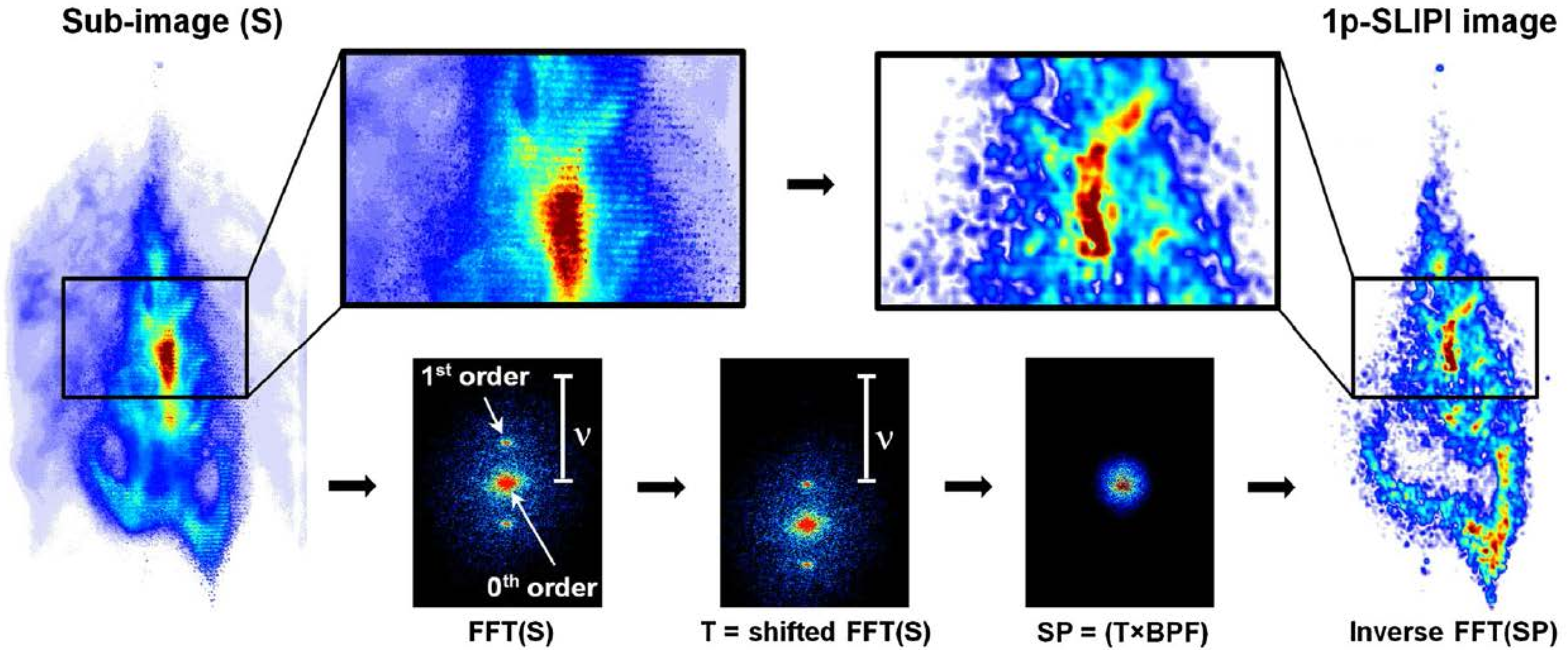
Two-phase SLIPI for instantaneous LIF/Mie





Ref: Yogeshwar Mishra, et al., Optics Letters, 2017. **58**(9): p. 110.

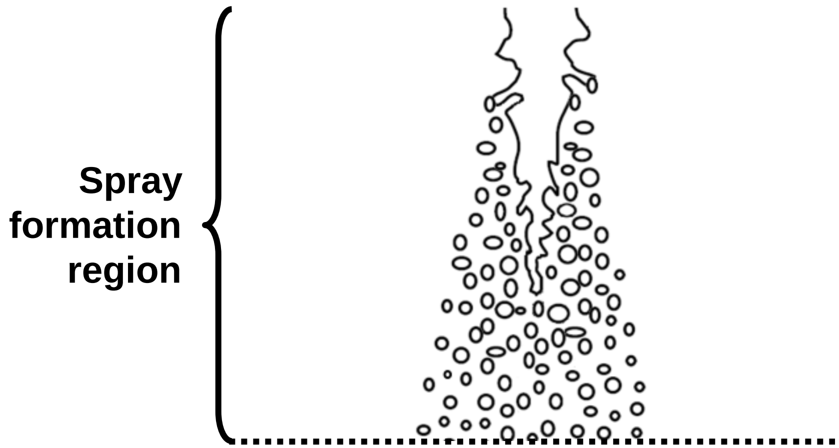
One-phase SLIPI for instantaneous imaging



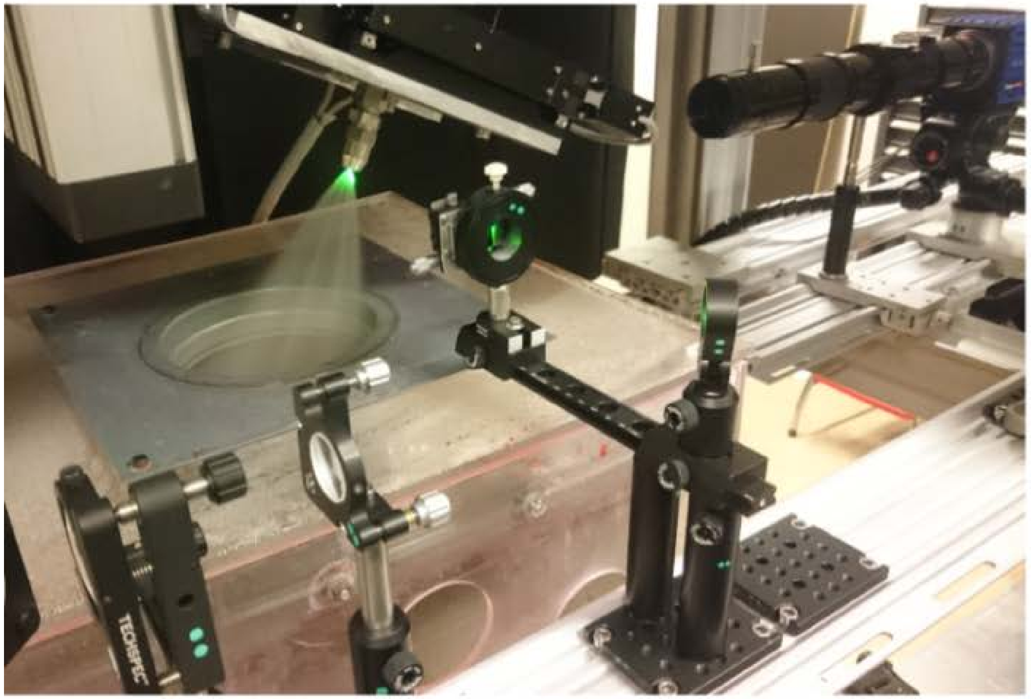
- In one-phase SLIPI, the image resolution is reduced due to the fact that half of the spray is not illuminated
- The approach is easy to implement and can be used in situations where spray details are not required

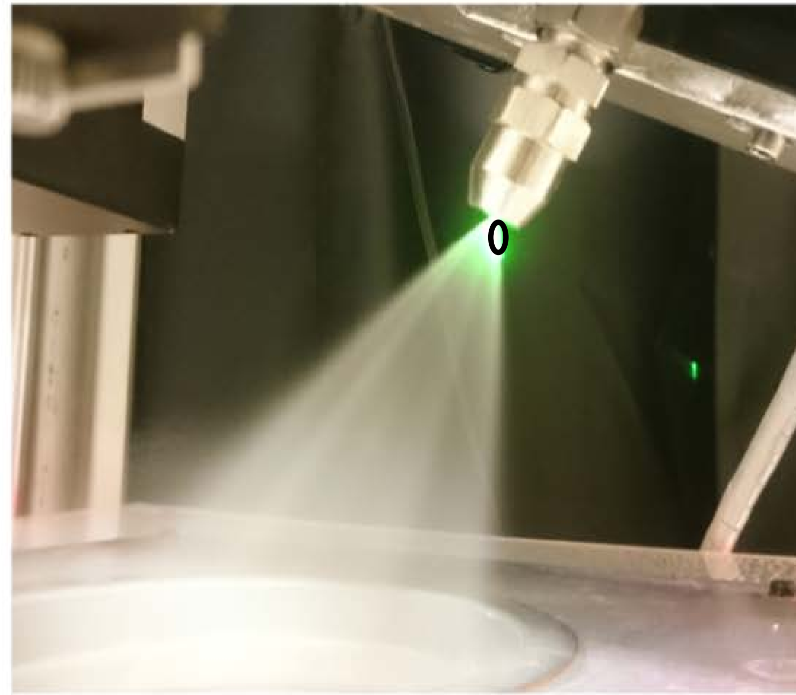
Ref: Yogeshwar Mishra, et al., Experiments in Fluids, 2017. **58**(9): p. 110.

Measument in the spray formation region

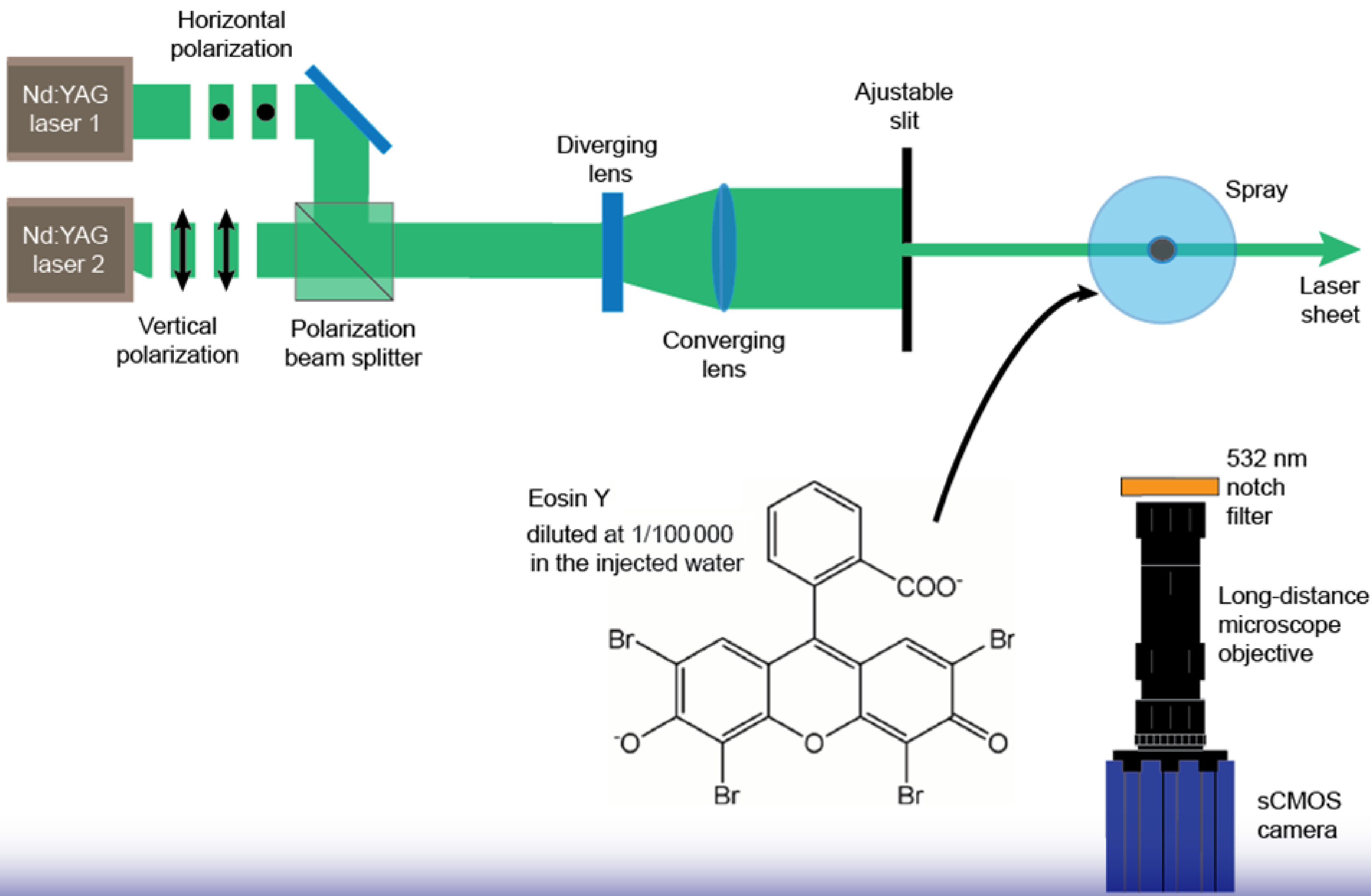


LSFM: Laser Sheet Fluorescence Microscopy





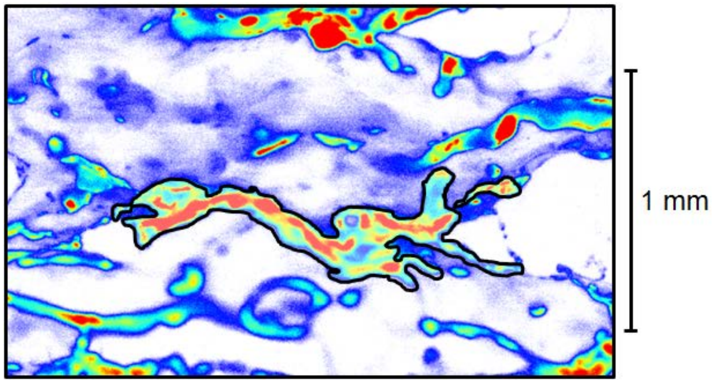
LSFM: Laser Sheet Fluorescence Microscopy

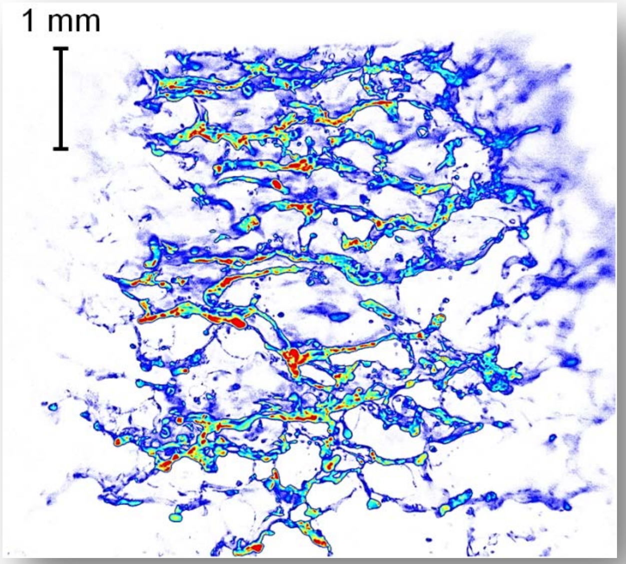


LSFM: Laser Sheet Fluorescence Microscopy

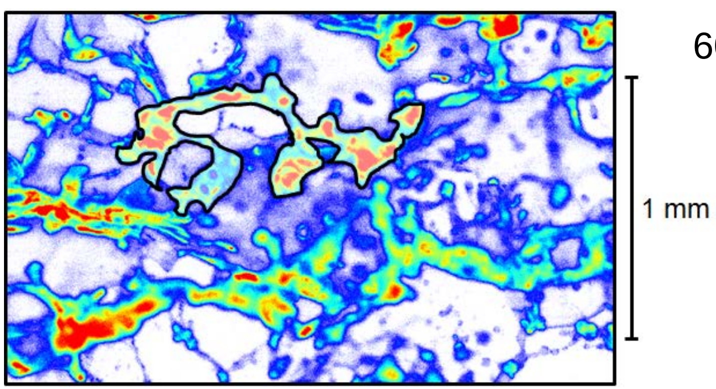
t_0

20 bars

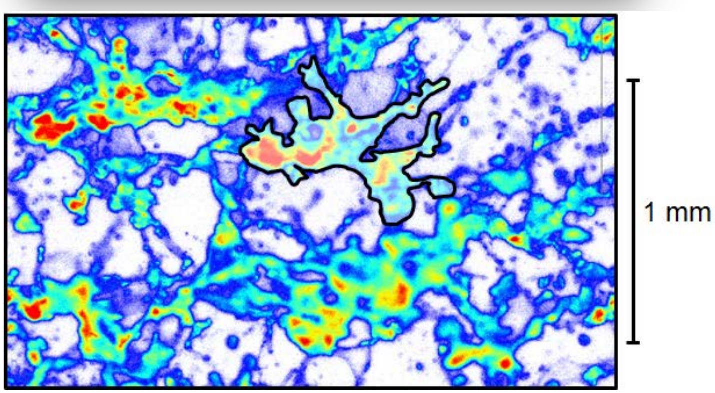




40 bars



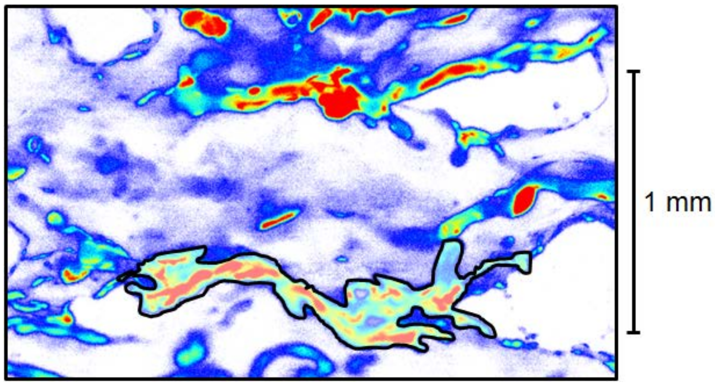
60 bars



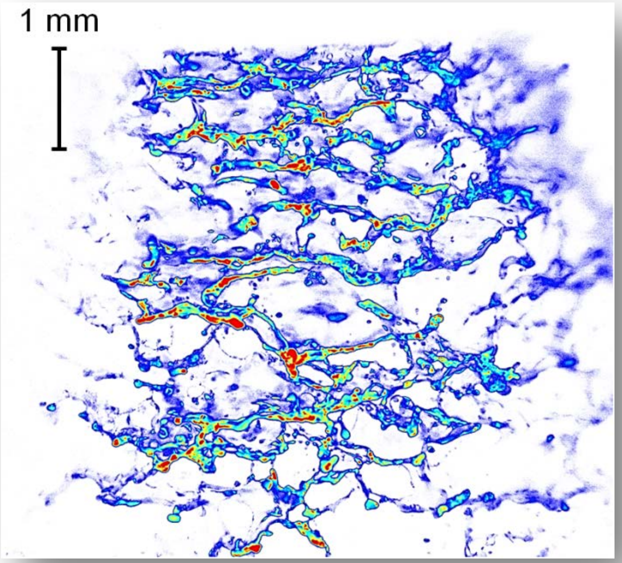
LSFM: Laser Sheet Fluorescence Microscopy

$t_1 = t_0 + 5\ \mu s$

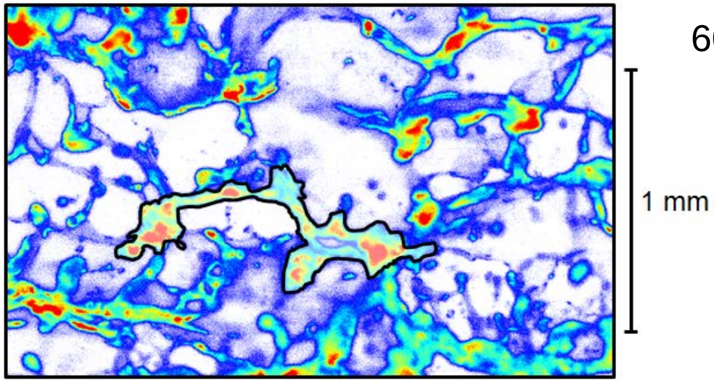
20 bars



$\Delta d = 0.25$ mm V ~ 50 m/s

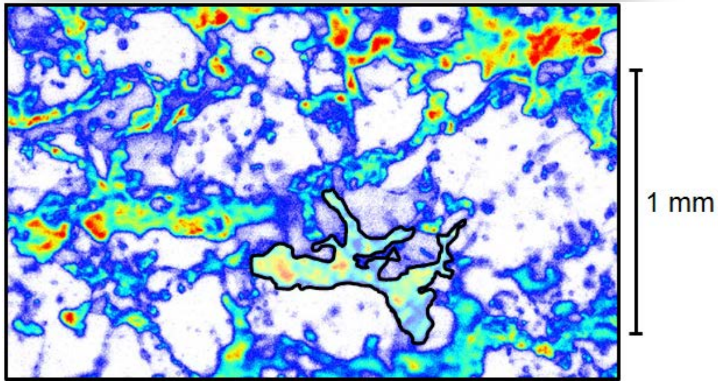


40 bars



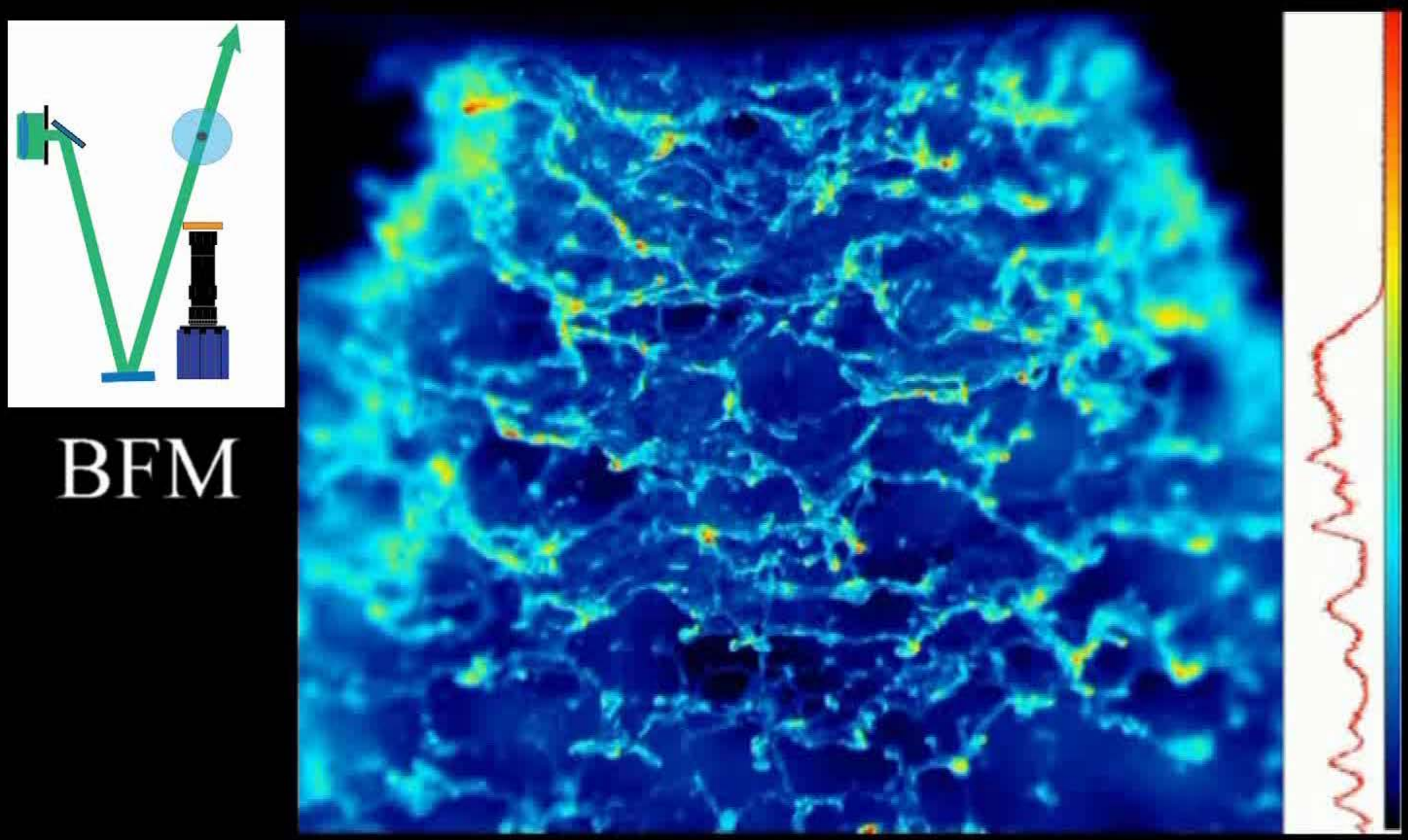
$\Delta d = 0.40$ mm V ~ 80 m/s

60 bars



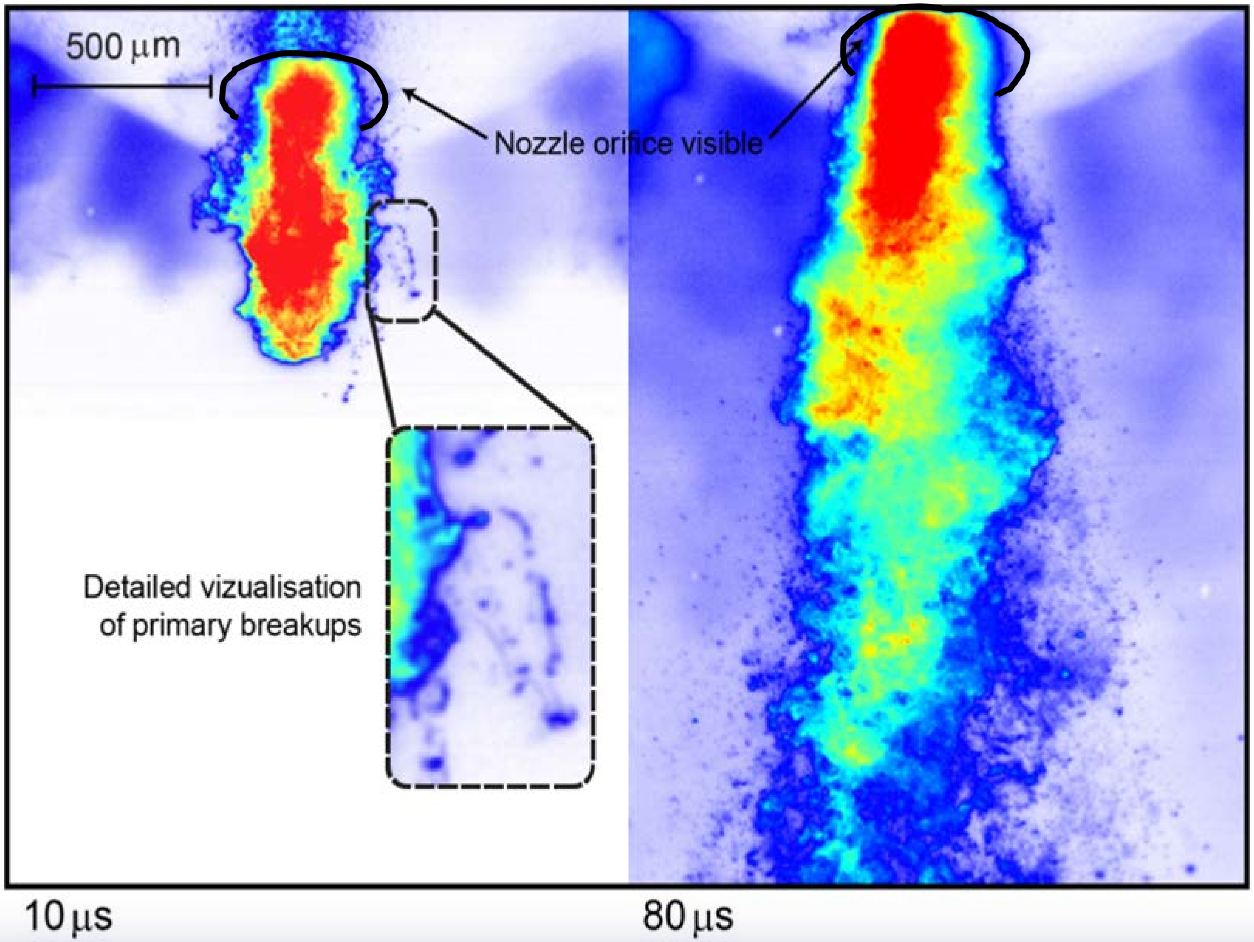
$\Delta d = 0.51$ mm V ~ 100 m/s

LSFM and Back Fluorescence comparison



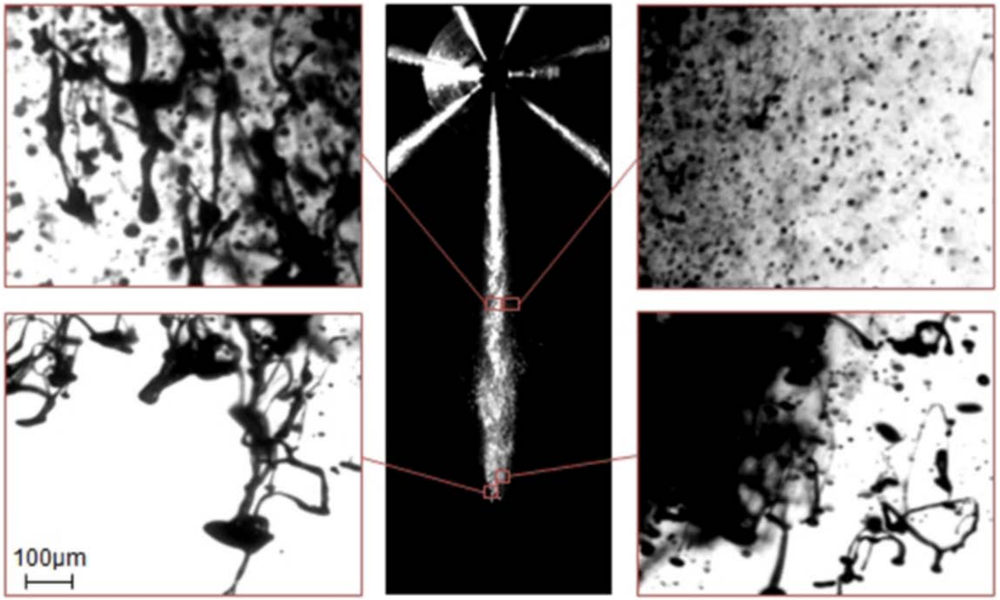
LSFM detection for GDI injection imaging

- Microscopic images of a DISI spray injected at 80 bars pressure of injection

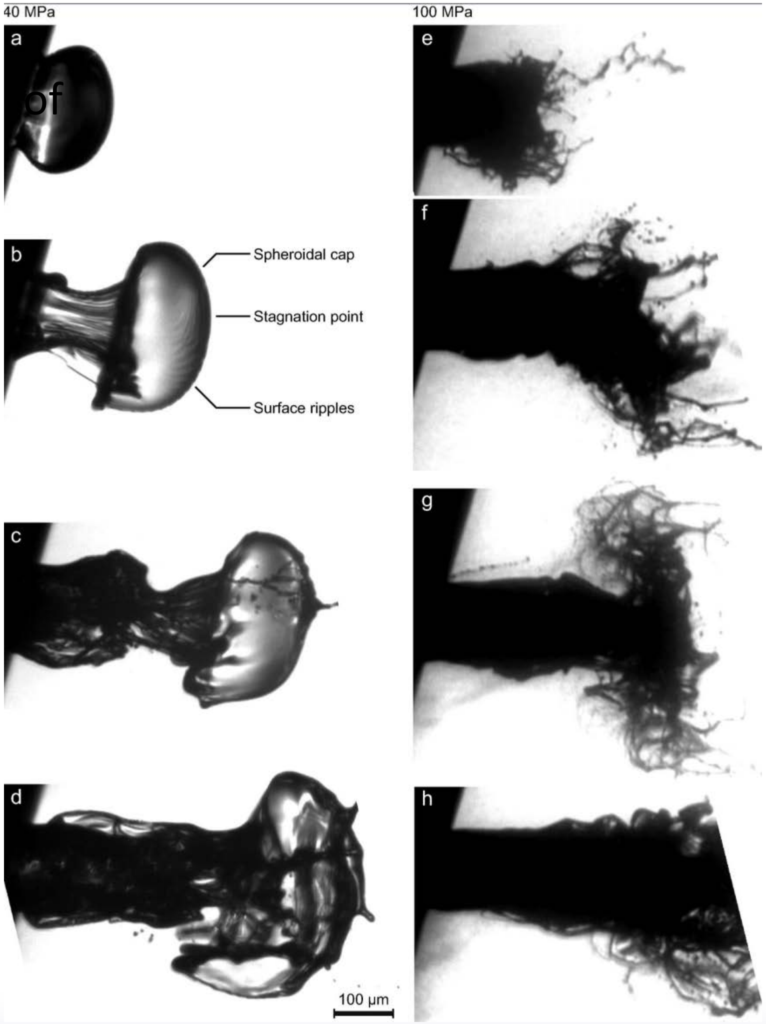


Microscopic shadowgraphy

Ref: Crua C, Heikal MR and Gold, MR 2015 “Microscopic imaging of the initial stage of diesel spray formation”, Fuel 157



https://www.brighton.ac.uk/advanced-engineering/research-projects/non-spherical-droplets-in-high-pressure-sprays.aspx



Summary

- Quantitative spray imaging developed together with the creation of digital sensors in the 1980th.
- Large viewed areas are practical but they rely on light intensity levels to extract spray information as droplets are not resolved.
- By correcting for laser extinction and signal attenuation after multiple scattering suppression one can obtained spray images without artifacts.
- The extinction coefficient should be used to define the spray penetration length.
- Ratios techniques are practical as the extinction effects cancel out in the ratio; but they require cautious calibration.
- LIF/Mie ratio provides information about the droplet Sauter Mean Diameter.
- Two-color LIF provides information about the temperature of the liquid.
- Two-color LIF is sensitive to self-absorption effects.
- Ratio techniques are very sensitive to multiple light scattering contributions.
- Two-phase and one-phase SLIPI can be used for instantaneous imaging of transient sprays.
- One phase SLIPI loose image resolution but can be easily implemented.
- Microscopic imaging techniques are used to study in detail the spray formation region.