Artifacts in laser imaging of spray systems

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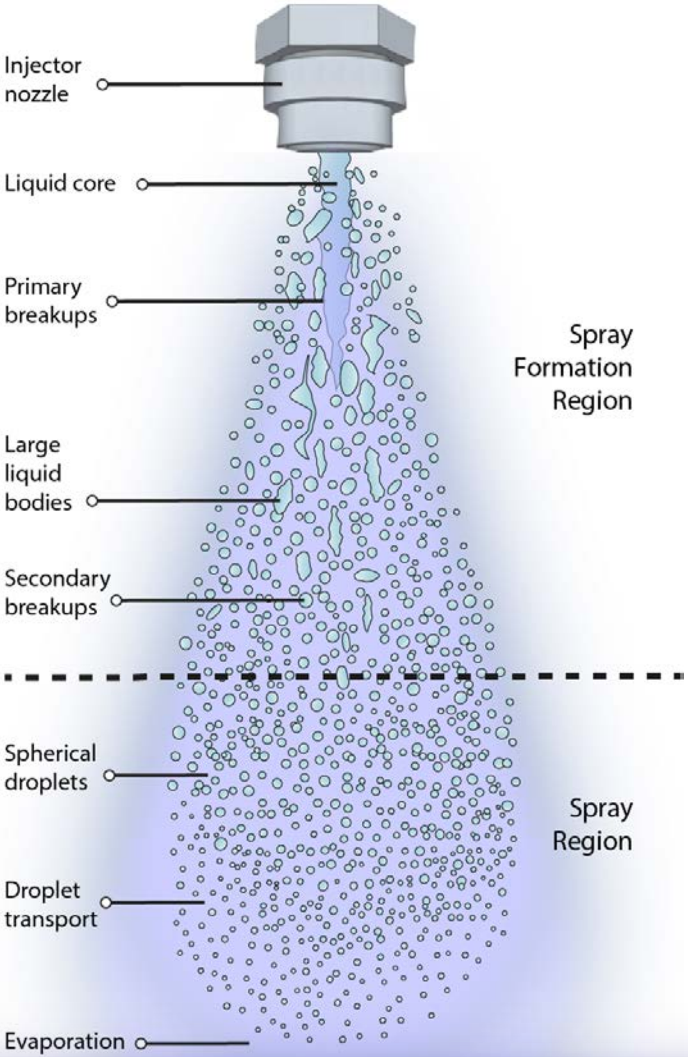
CECOST - Course

Characteristics of spray systems



A spray system is divided into two regions:

- **The spray formation region** which is located directly downstream from the nozzle and is characterized by:

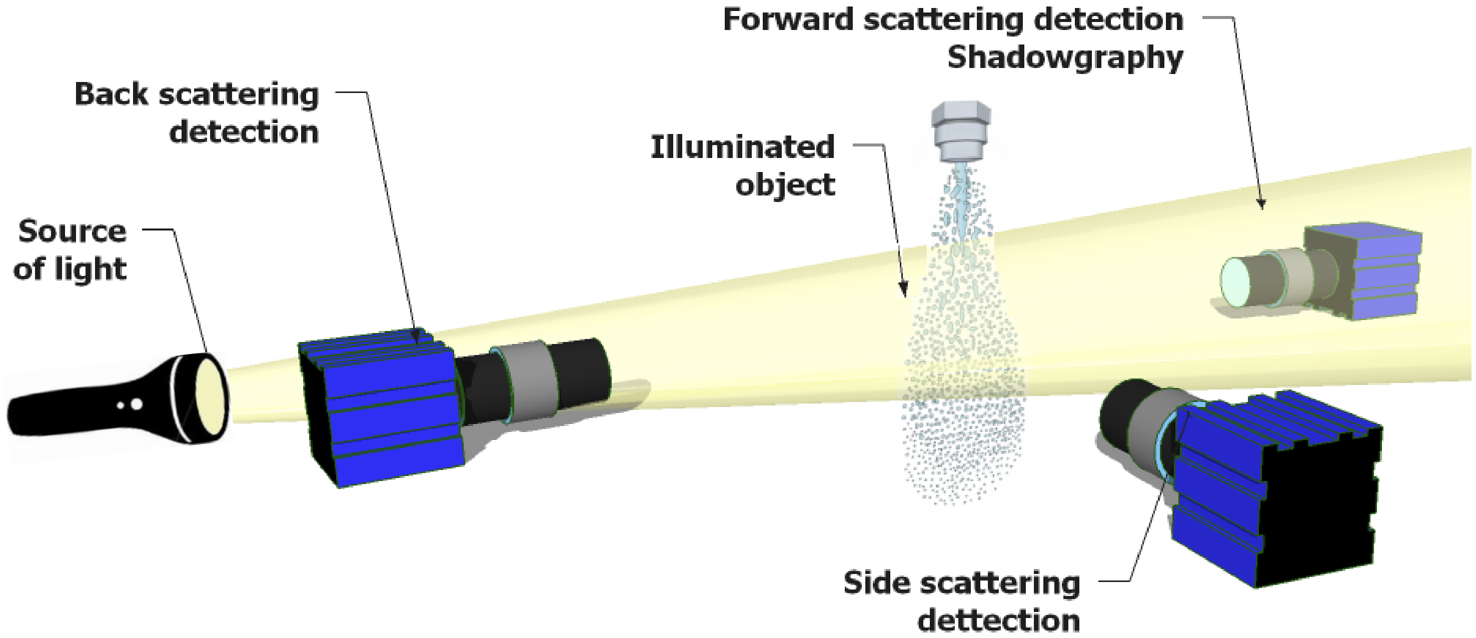
1) The presence of a liquid core or a liquid sheet
2) Primary break-ups where ligaments and large liquid structures are created from the nozzle orifice.
3) Secondary break-ups where the large irregular liquid bodies breakup a second time into spherical droplets.

- **The spray region** is located in the far-field region where the flow is fully dispersed and contains a cloud of round and small droplets.

Those droplets are characterized by their size distribution, number density and velocity. While the smallest droplets have low velocities and rapidly evaporate, the larger droplets keep traveling further with high velocities and can undergo further secondary breakups and possible drop-drop collisions.

At the end of the spray region, the injected liquid has fully evaporated.

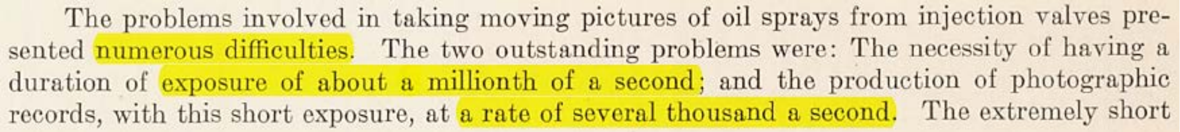
Source/detector configurations



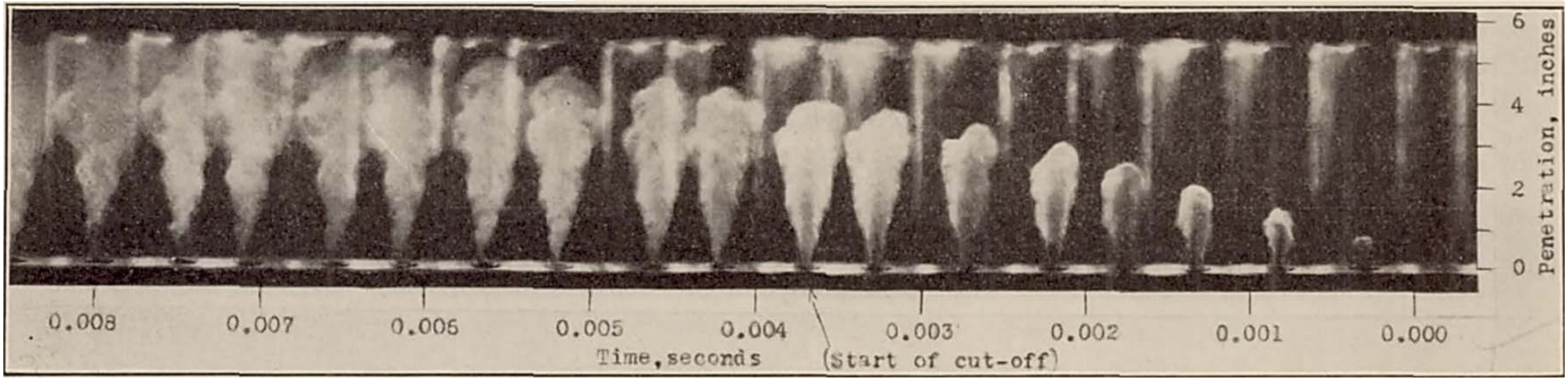
- **Forward scattering detection:** The illumination is located behind the spray, creating a shadow of it. The dark areas where the spray blocks lights provide the desired information.
- **Back scattering detection:** The illumination is in front of the spray on the same side of the camera. Sprays with large number density of drops provide strong back-scattering signals.
- **Side scattering detection:** For this configuration, the camera is usually located at 90° and the illumination most often consists of creating light sheet illuminating a section of the spray.

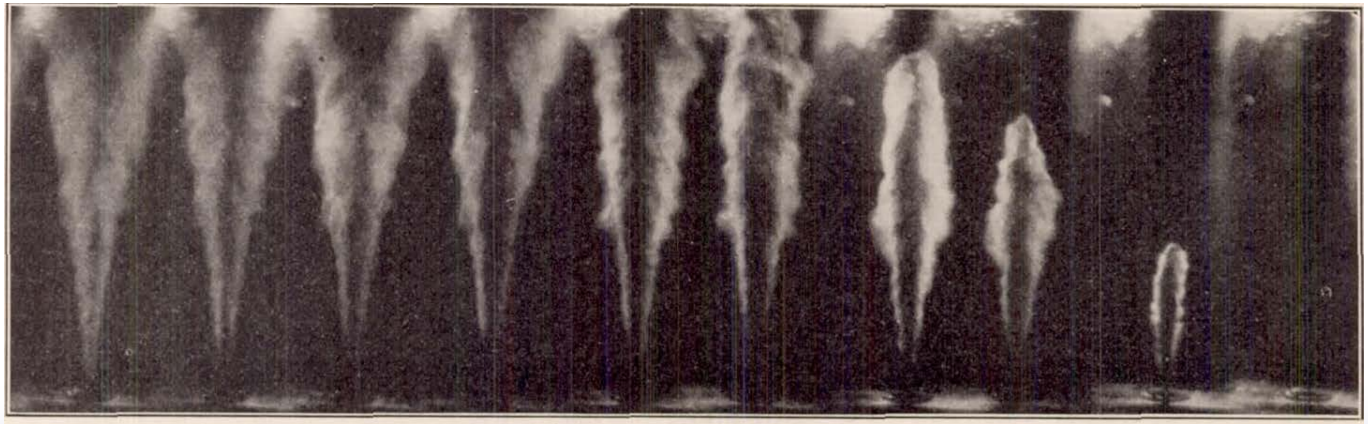
Back-scattered images

- 1927 - Edward Beardsley
  Diesel sprays



The problems involved in taking moving pictures of oil sprays from injection valves presented numerous difficulties. The two outstanding problems were: The necessity of having a duration of exposure of about a millionth of a second; and the production of photographic records, with this short exposure, at a rate of several thousand a second. The extremely short





Injection pressure, 8,000 pounds per square inch

Chamber pressure, 200 pounds per square inch

High-speed series of images recorded at: 2 kHz frame rate

Injection pressure: ~550 bars

Chamber pressure: ~14 bars

Back-scattered images

- 1927 - Edward Beardsley
  Diesel sprays

N. A. C. A. PHOTOGRAPHIC APPARATUS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

The successor agency to NACA is the National Aeronautics and Space Administration - NASA

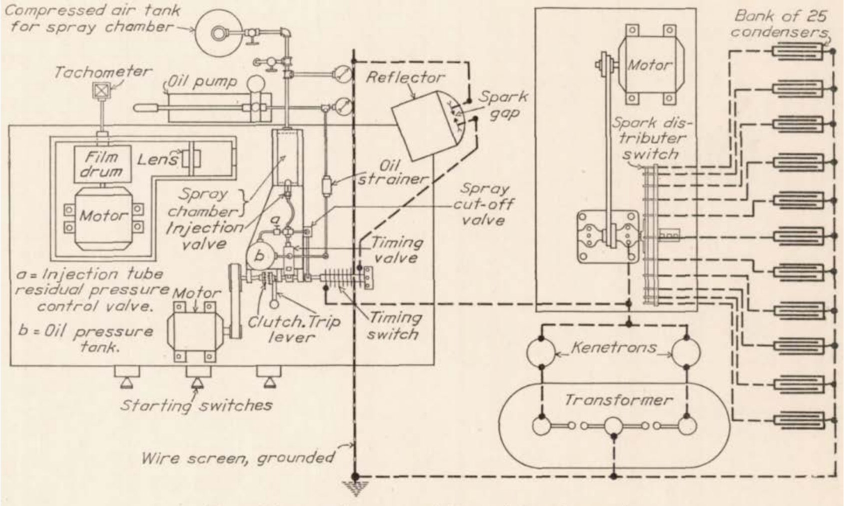


FIG. 1.—Diagrammatic arrangement of spray-photography apparatus

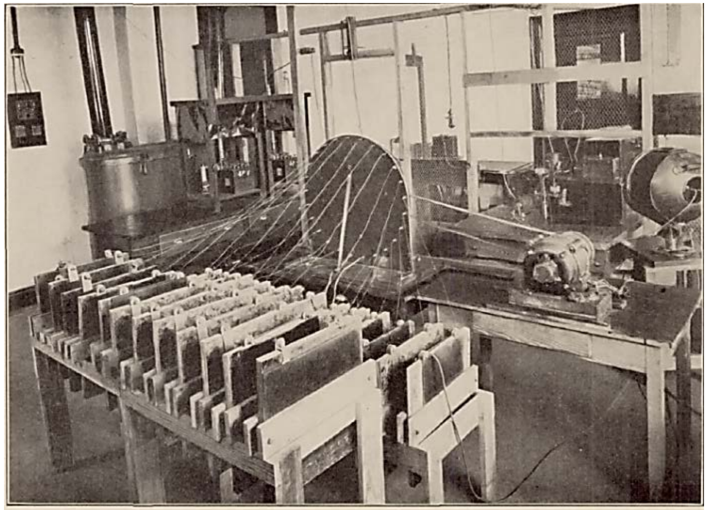


FIG. 2.—GENERAL VIEW OF SPRAY-PHOTOGRAPHY APPARATUS

Apparatus for recording photographically the start, growth, and cut-off of oil sprays from injection valves has been developed at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics. The apparatus consists of a high-tension transformer by means of which a bank of condensers is charged to a high voltage. The controlled discharge of these condensers in sequence, at a rate of several thousand per second, produces electric sparks of sufficient intensity to illuminate the moving spray for photographing. The sprays are injected from various types of valves into a chamber containing gases at pressures up to 600 pounds per square inch.

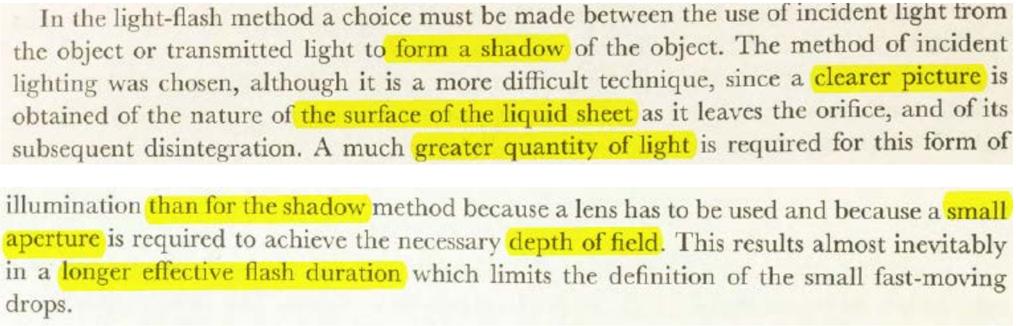
by means of which the 25 condensers are charged to 30,000 volts

The present spray-photography apparatus, so far as is known, was the first apparatus ever built capable of recording by a series of pictures the growth of oil sprays. A diagramatic lay-

the duration of exposure must not be more than one six-hundred-thousandth second.

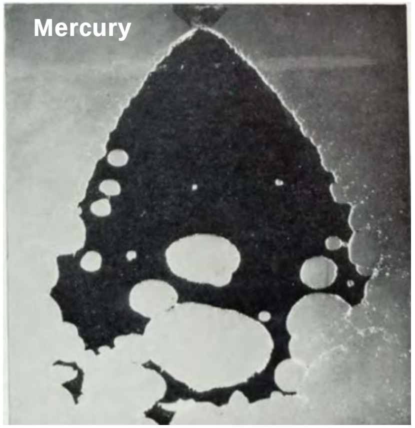
Back-scattered images

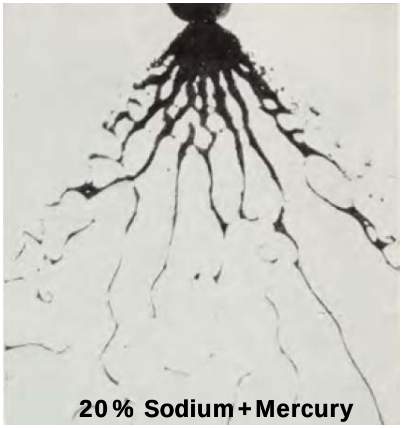
- 1953 - Dombrowski & Fraser
  Disintegration of liquid sheets (London)

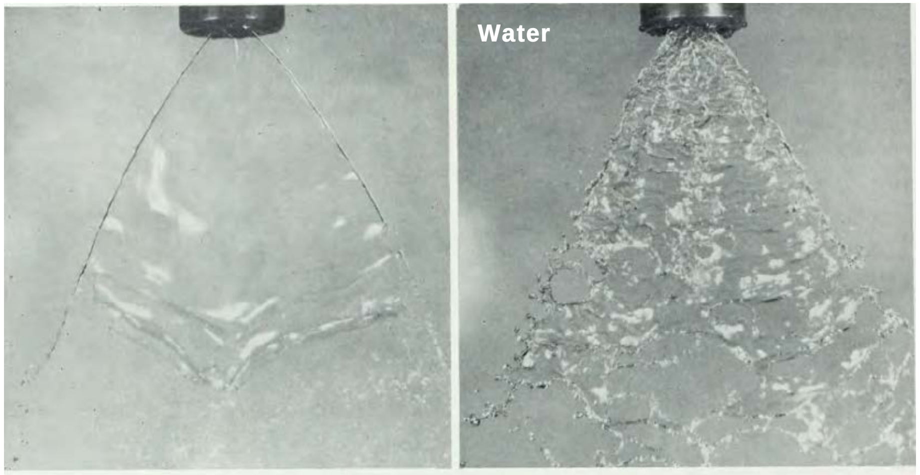


In the light-flash method a choice must be made between the use of incident light from the object or transmitted light to form a shadow of the object. The method of incident lighting was chosen, although it is a more difficult technique, since a clearer picture is obtained of the nature of the surface of the liquid sheet as it leaves the orifice, and of its subsequent disintegration. A much greater quantity of light is required for this form of

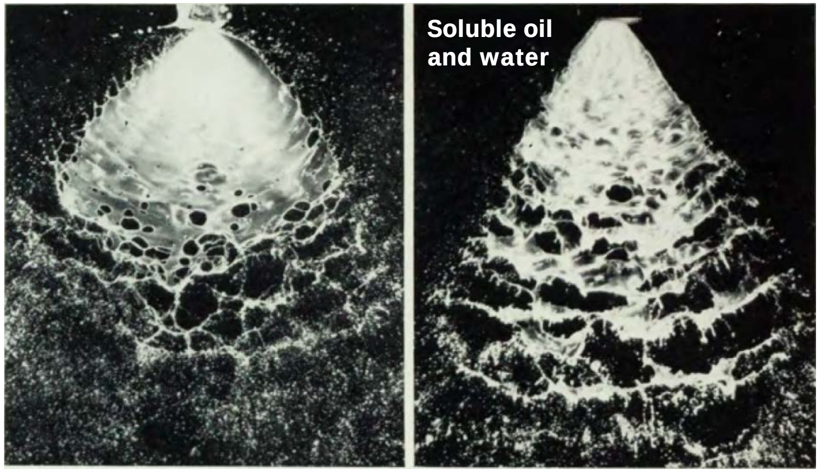
illumination than for the shadow method because a lens has to be used and because a small aperture is required to achieve the necessary depth of field. This results almost inevitably in a longer effective flash duration which limits the definition of the small fast-moving drops.





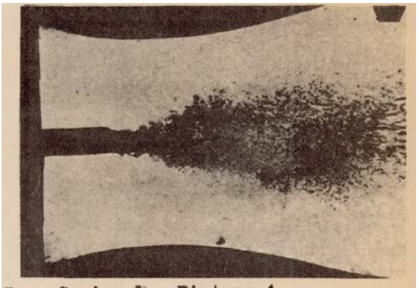


a, $R = 15000$ *b*, $R = 41000$

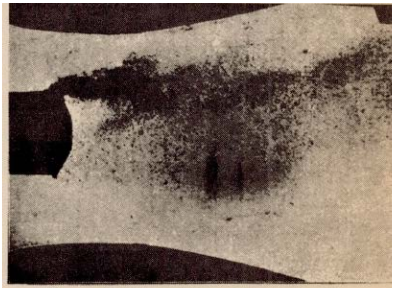


Shadowgraph images

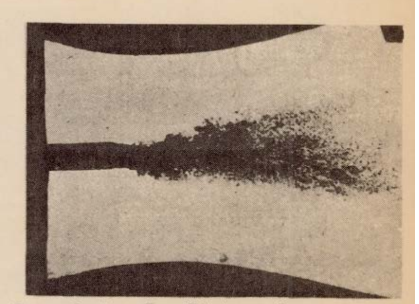
- 1927 - Scheubel (Germany)
  Jet in co-flow and cross-flow



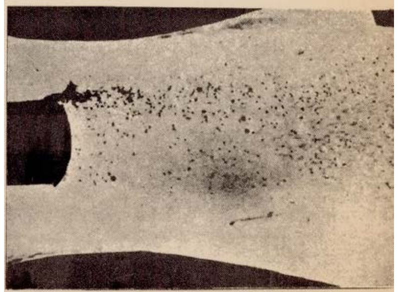
I_4, Series 1, Picture 4,
Alcohol, U= 100 m/s, K= 5020 cm^{-1}



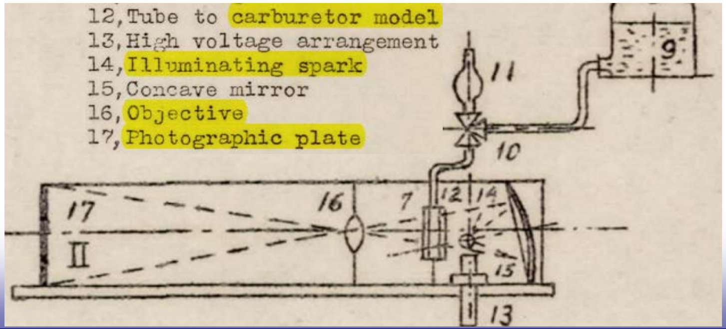
IV_2, Series IV, Picture 2,
U= 104 m/s, K= 5420 cm^{-1}



I_5, Series 1, Picture 5,
Alcohol, U= 55 m/s, K= 1460 cm^{-1}

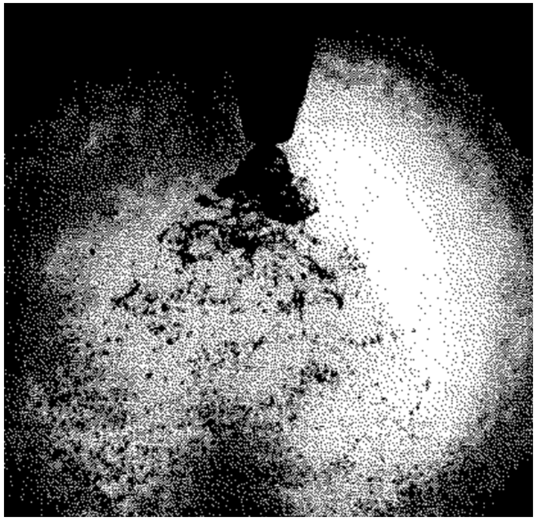


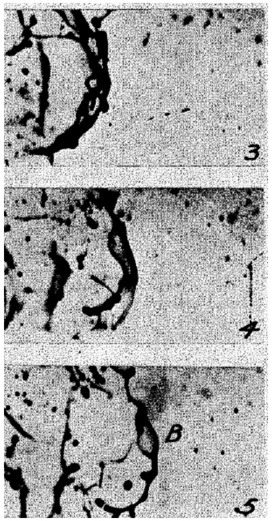
IV_3, Series IV, Picture 3,
U= 58.2 m/s, K= 1700 cm^{-1}

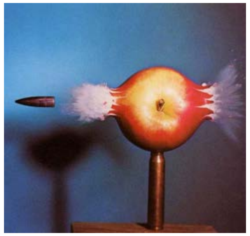


12, Tube to carburetor model
13, High voltage arrangement
14, Illuminating spark
15, Concave mirror
16, Objective
17, Photographic plate

- 1938 - Fogler & Kleninschmidt
  Spray drying



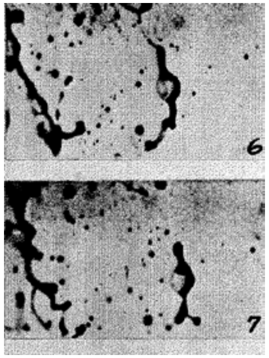




H. Edgerton most famous picture

Edgerton and Germeshausen have succeeded in photographing the formation of a hollow particle by this means.

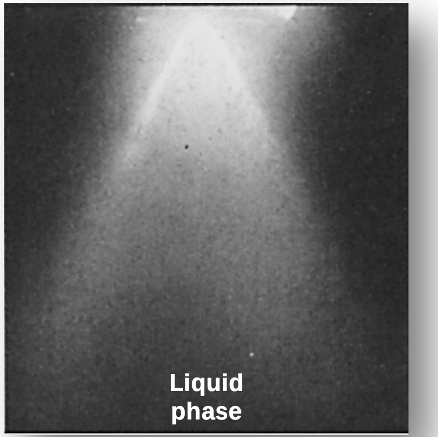
of their motion picture of a nozzle spray taken at six thousand frames per second.

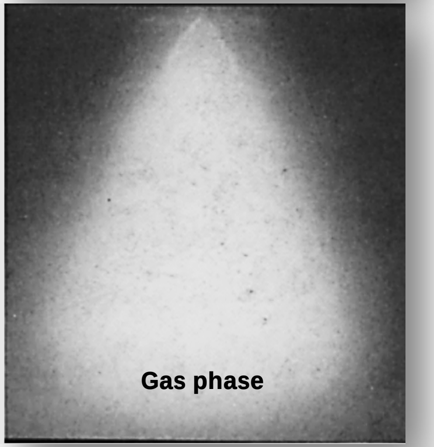


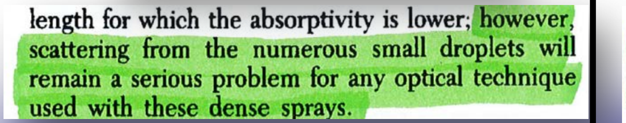
To photograph action at this high rate of speed, it is necessary to secure illumination from behind, which results in silhouette pictures. The dark areas represent either solid

Laser sheet imaging

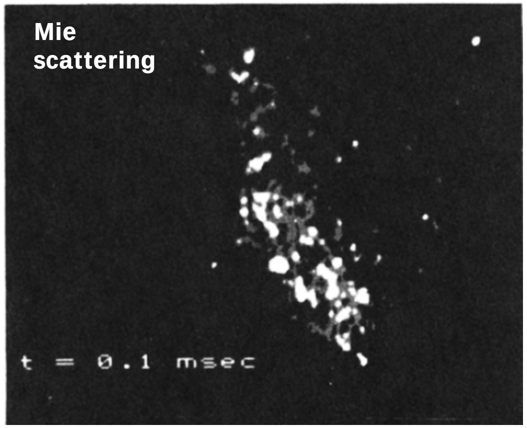
1984 - Melton & Verdieck
Hollow-cone spray

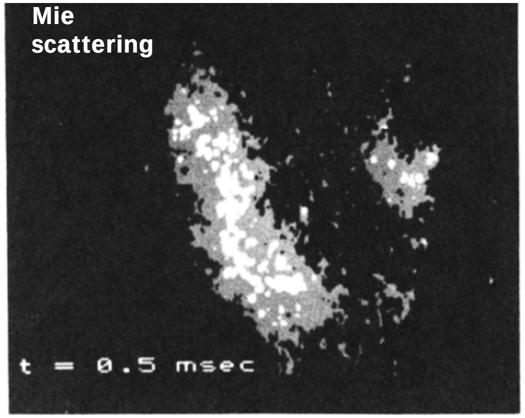


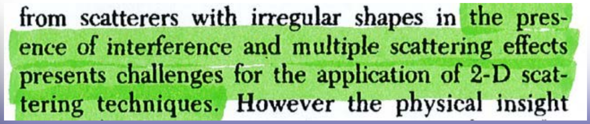



length for which the absorptivity is lower; however, scattering from the numerous small droplets will remain a serious problem for any optical technique used with these dense sprays.

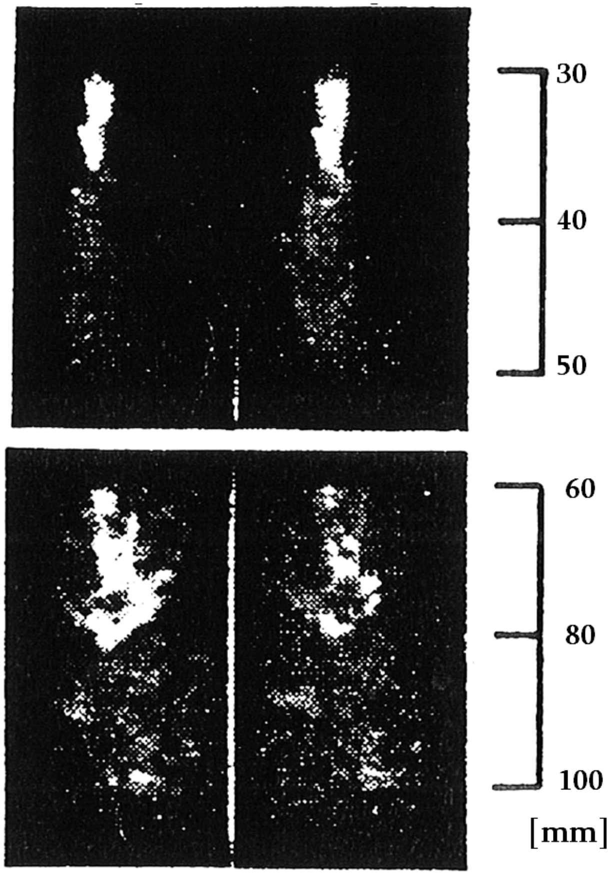
1988 - Cavaliere, Ragucci, D'Alessio & Noviello
Diesel spray






from scatterers with irregular shapes in the presence of interference and multiple scattering effects presents challenges for the application of 2-D scattering techniques. However the physical insight

1993 - Yeh, Kosada & Kamimoto
LIF/Mie droplet sizing



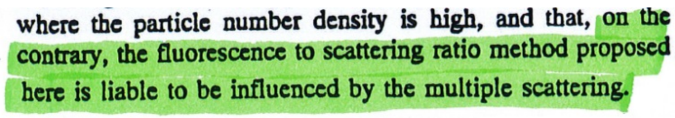
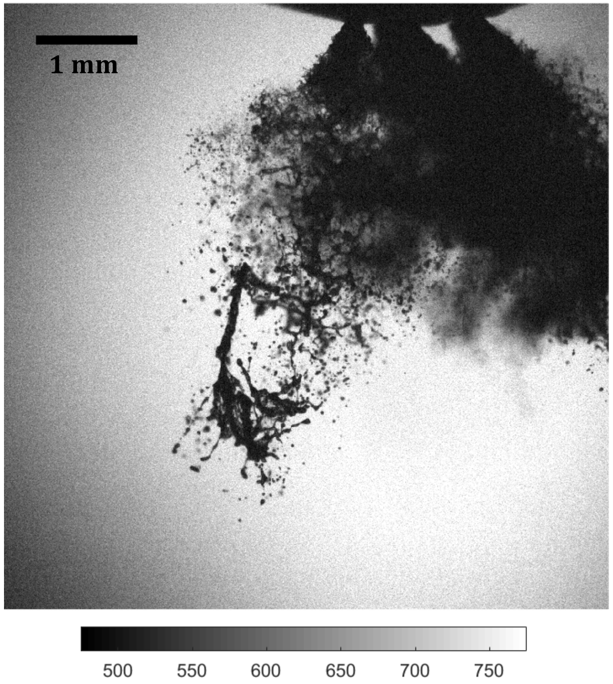
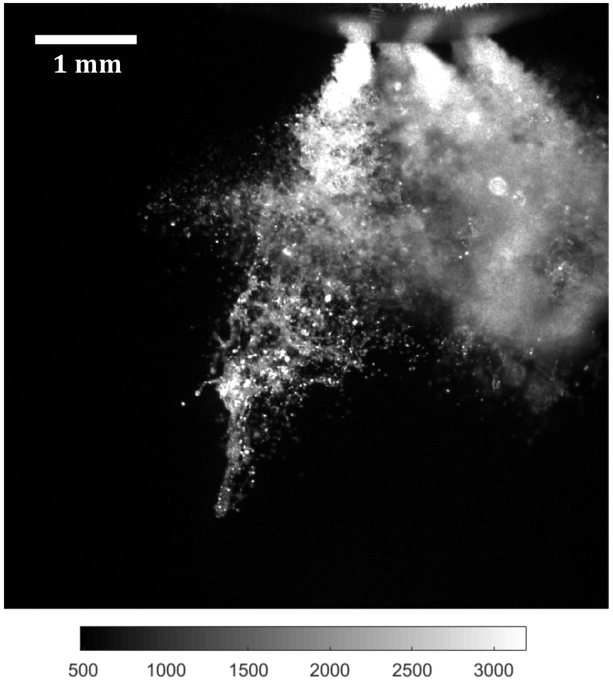

where the particle number density is high, and that, on the contrary, the fluorescence to scattering ratio method proposed here is liable to be influenced by the multiple scattering.

Image comparison

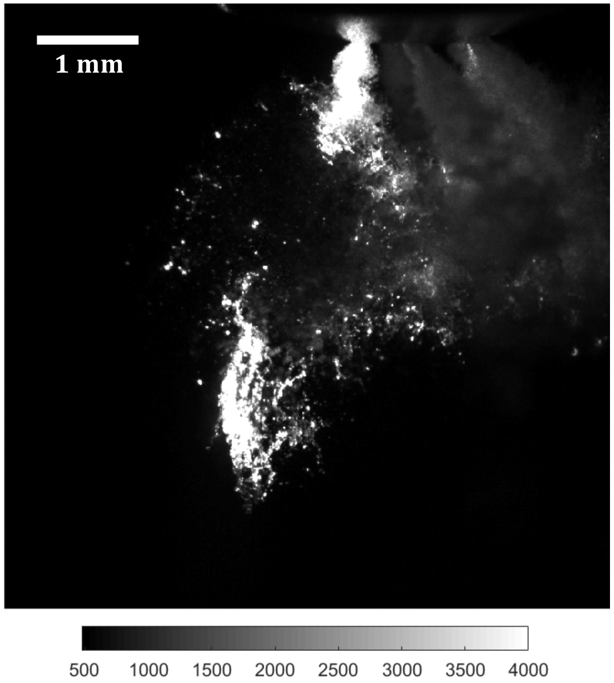
- Shadowgraphy



- Back scattering detection



- Laser sheet imaging



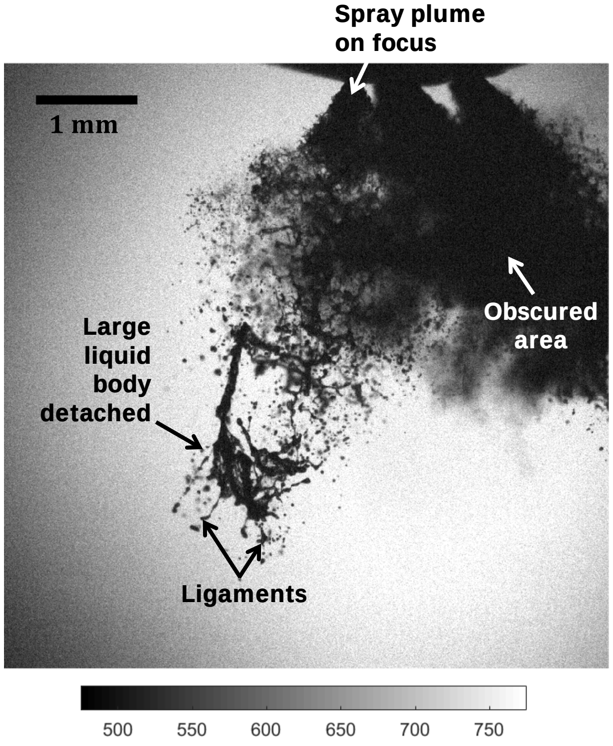
- T = 100 µs

after visible start of injection

- Injector: GDI nozzle 6 holes spray
- Liquid: Water - 200 bars liquid pressure

Image comparison

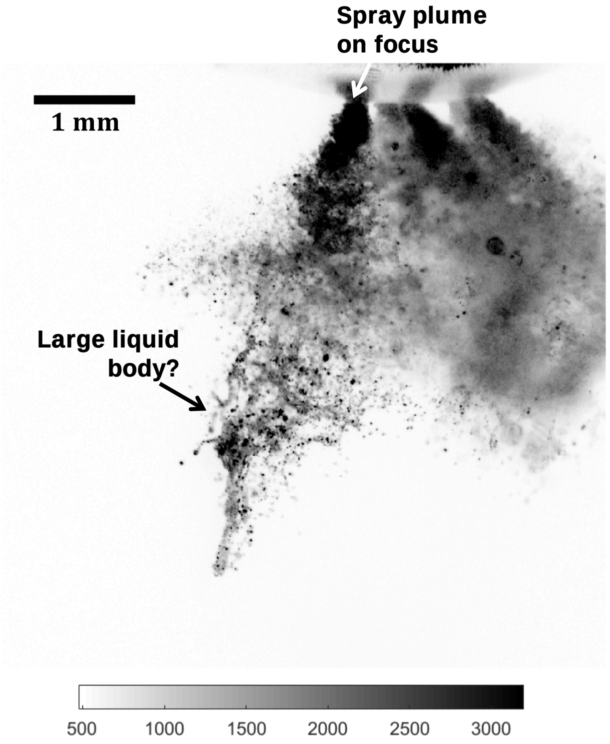
- Shadowgraphy



👍 Isolated liquid structures and ligaments are clearly visible

👎 Line-of-sight technique - Light extinction through large volumes

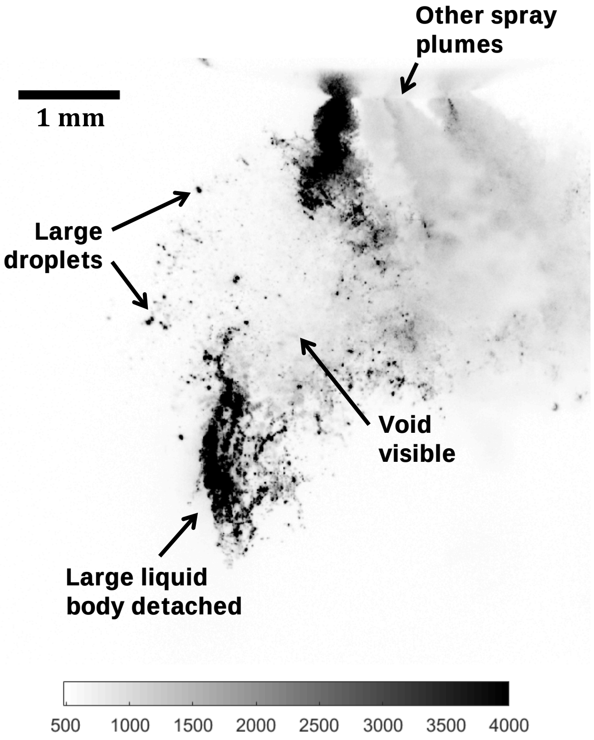
- Back scattering detection



👍 Works on single optical access

👎 Line-of-sight technique
Strong direct reflections

- Laser sheet imaging

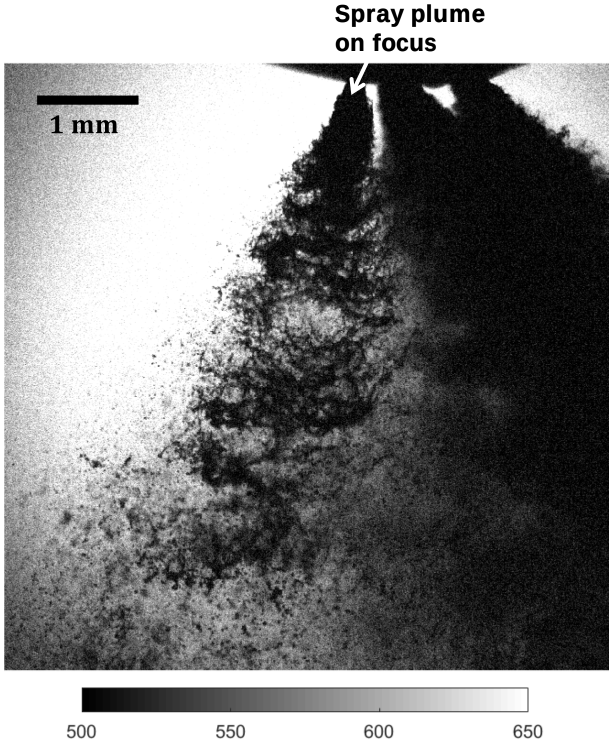


👍 Voids are more visible - Reduced effects from other spray plumes

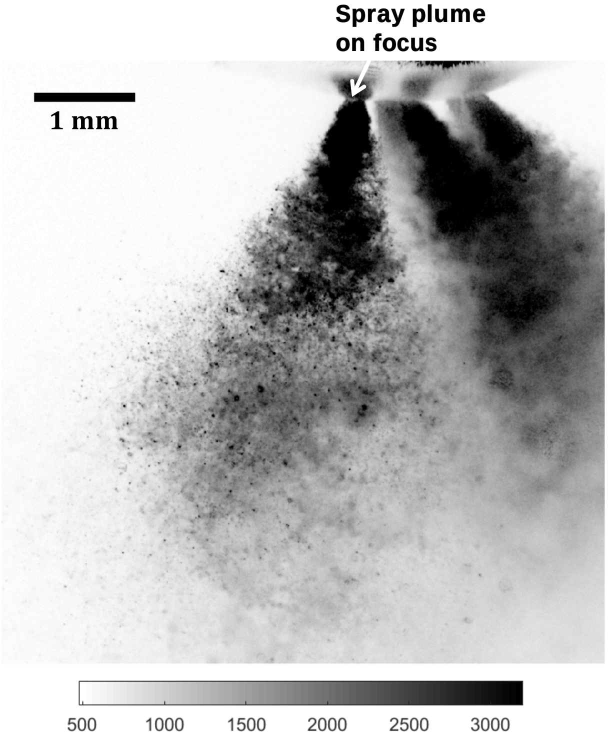
👎 Large liquid structure can be optically cut - Strong reflections

Image comparison

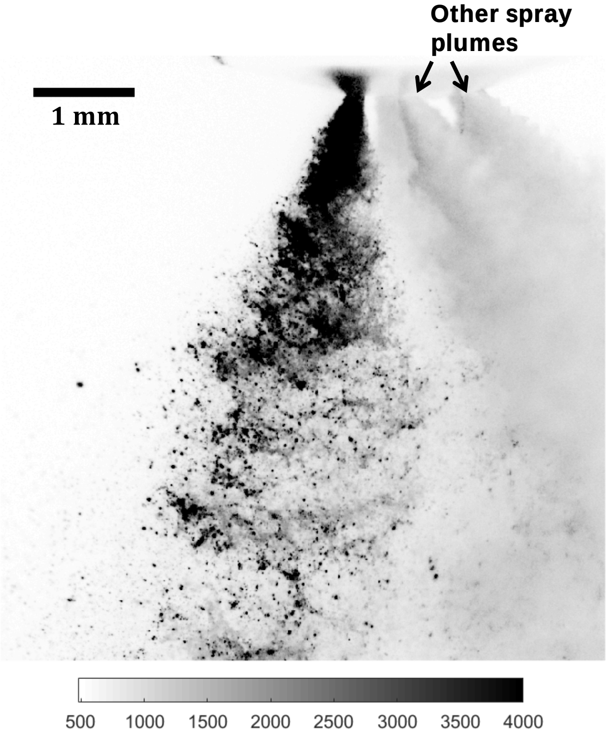
- Shadowgraphy



- Back scattering detection



- Laser sheet imaging

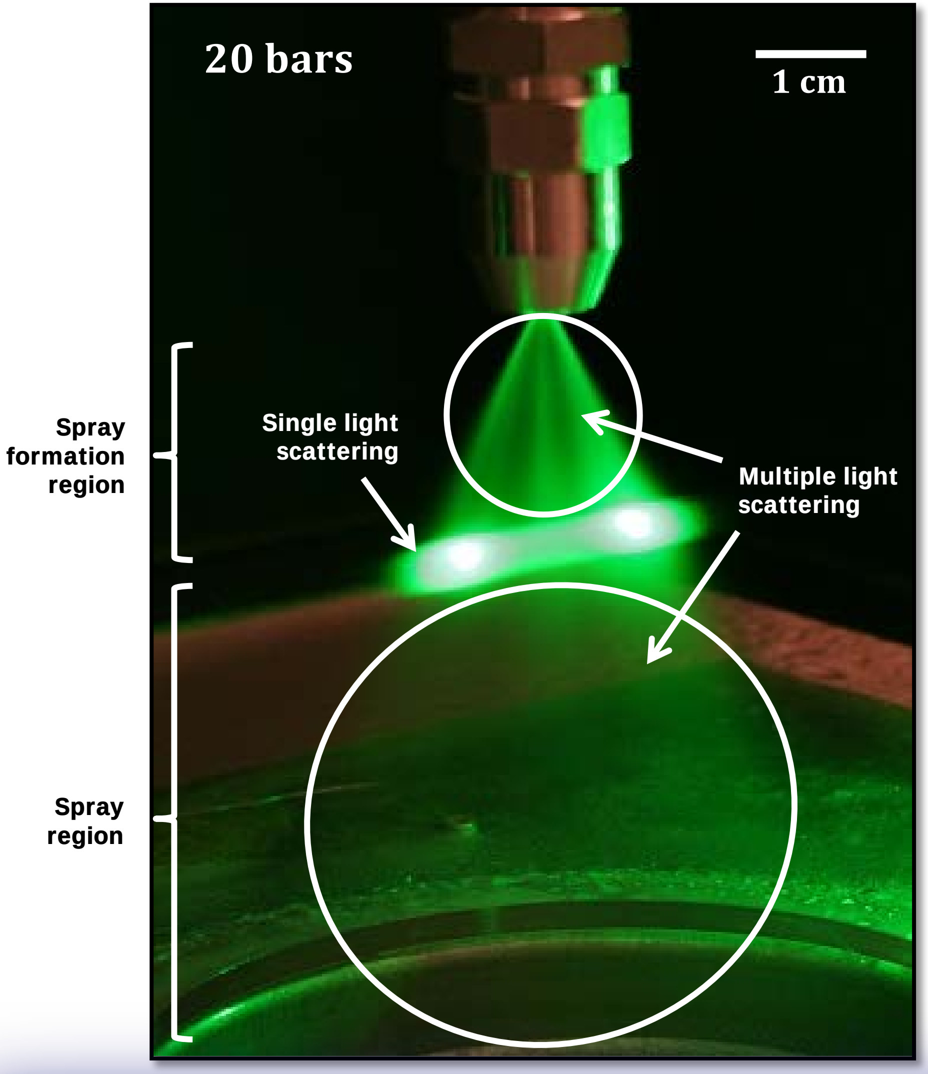


- T = 200 µs

after visible start of injection

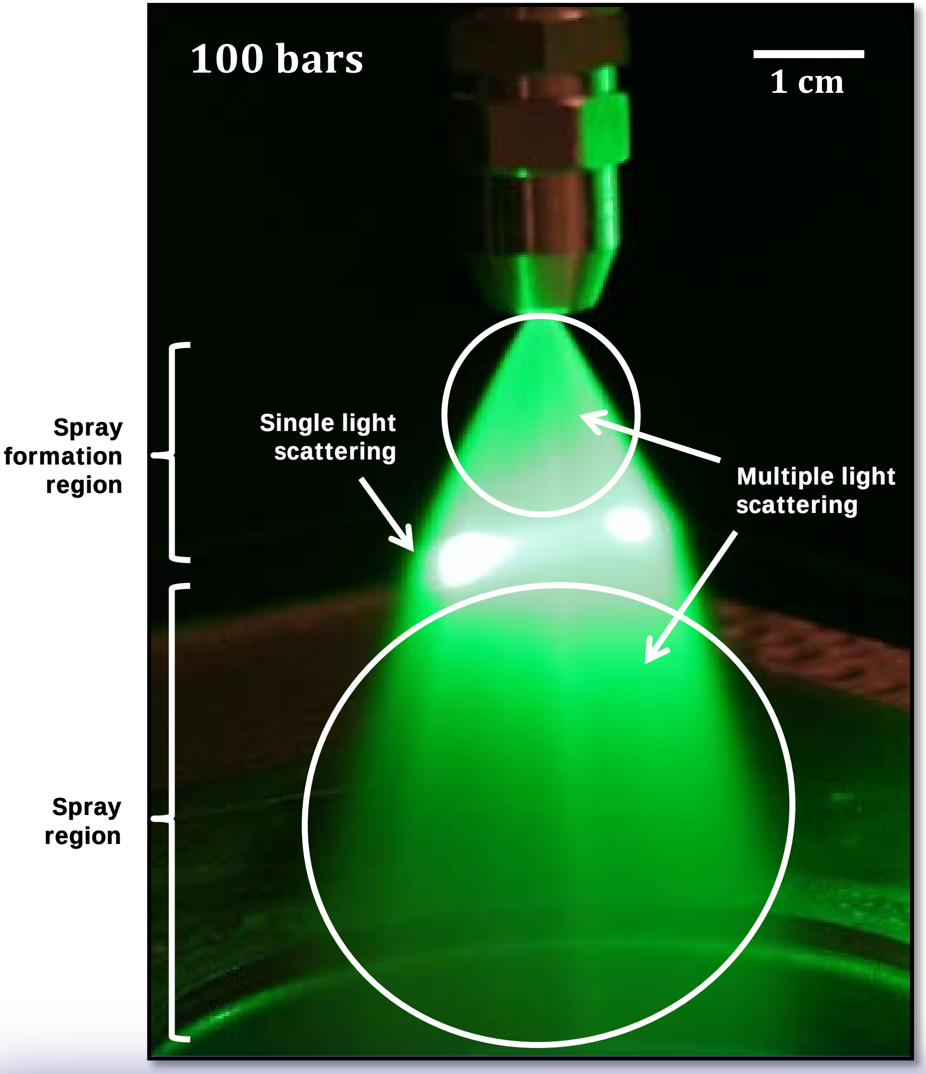
- Injector: GDI nozzle 6 holes spray
- Liquid: Water - 200 bars liquid pressure

Laser beam crossing a spray



- Example of a typical hollow cone water spray generated from a pressure swirl nozzle
- **Single light scattering** is dominant directly at the entrance of the spray system.
- The light visible around the illumination beam results from **multiple light scattering**
- At 20 bars pressure of injection, single light scattering is dominant in comparison to multiple light scattering
- At 100 bars pressure of injection, multiple scattering is dominant in comparison to single light scattering
- The dilute region - in terms of liquid density - of the spray at 100 bars is more **optically dense** than the dense liquid region of the spray injected at 20 bars.

Laser beam crossing a spray



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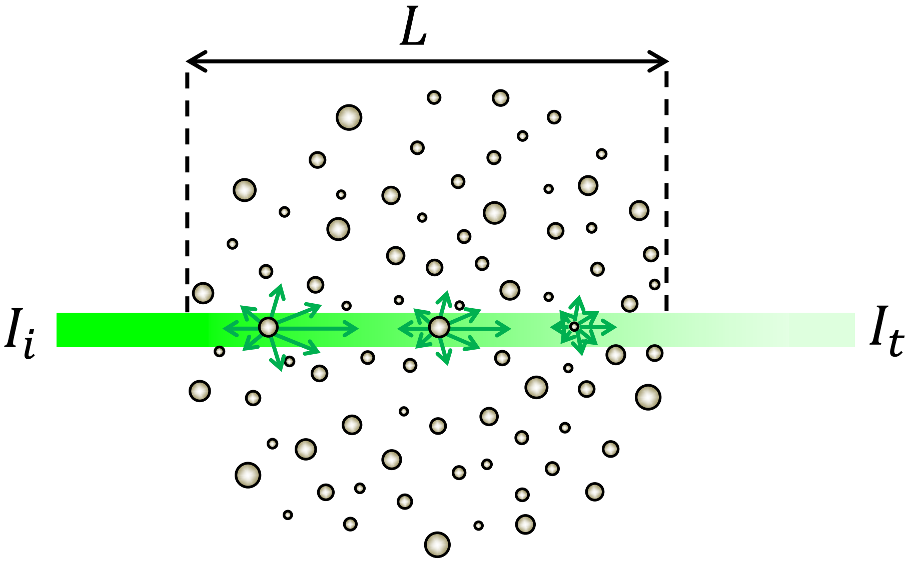
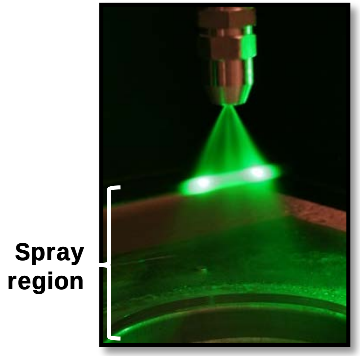
Light transmission through the spray region



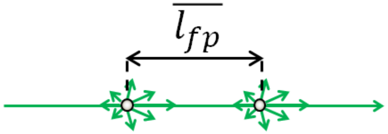


The loss of the incident radiation follows the Beer-Lambert relation:

$$I_t = I_i \cdot \exp(-L \cdot N \cdot \overline{\sigma_e})$$

Droplet number density

Mean extinction cross-section

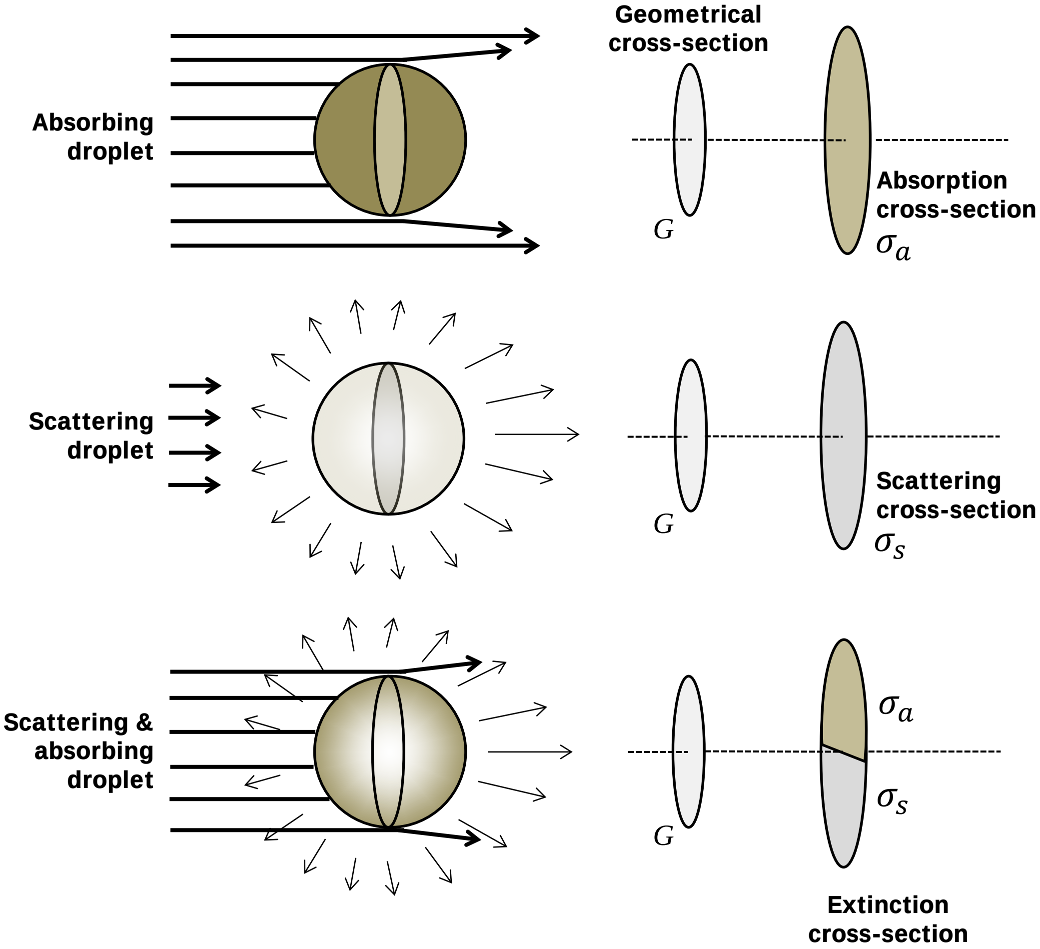


Mean free path length: $\overline{l_{fp}} = \dfrac{1}{N \cdot \overline{\sigma_e}}$

Optical Depth: $OD = L/\overline{l_{fp}} = L \cdot N \cdot \overline{\sigma_e}$

- The Optical Depth corresponds to the average number of scattering events along the distance L

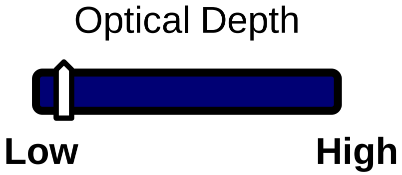
Extinction cross-section

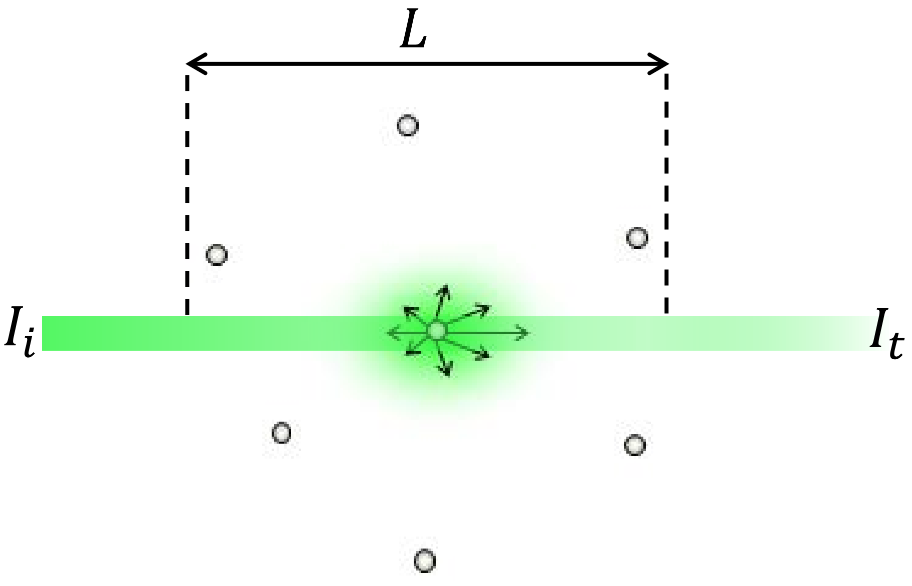


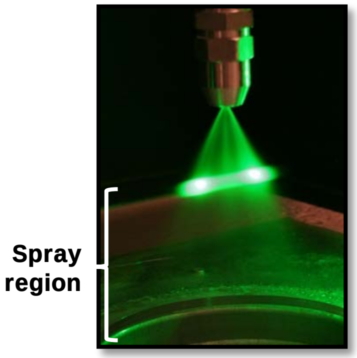
Extinction = scattering + absorption $\sigma_e = \sigma_s + \sigma_a$

- Considering one absorbing droplet illuminated by a light beam; the droplet casts a shadow of given area.
- The absorbed energy may be set equal to the energy of the incident wave falling on the area σ_a. This area is the absorption cross-section
- Similarly, the scattering cross-section, σ_s, corresponds to a surface-area where the energy of the incident wave falling on this area equals the total energy scattered in all direction.
- The total energy removed from the original beam is the sum of the scattering energy and the absorbed energy, the extinction cross-section σ_e.
- In the case of spherical droplets, the scattering cross-section is linearly dependent on D^2

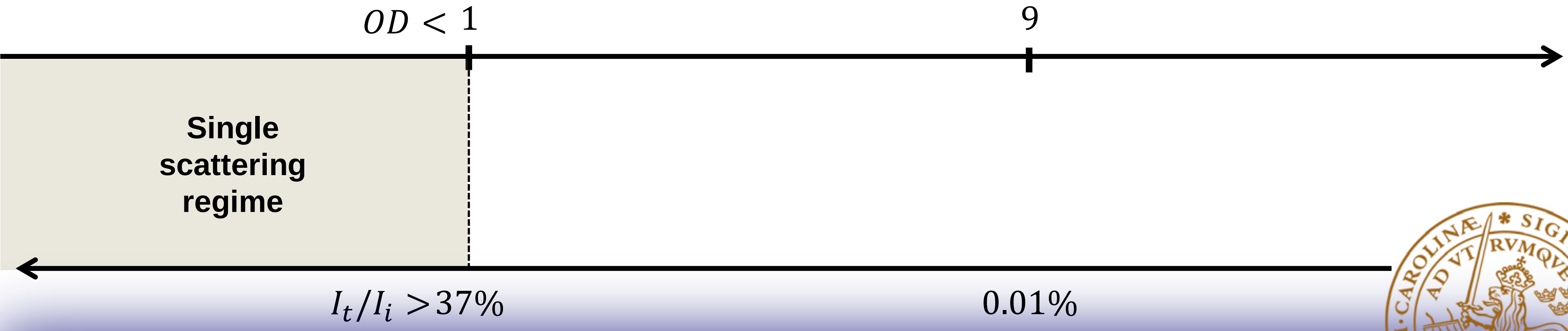
Scattering regimes







Transmission: $I_t/I_i = \exp(-OD)$



$OD < 1$

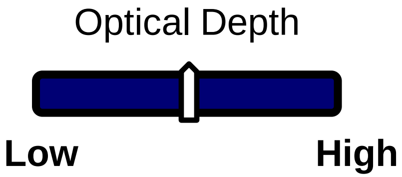
9

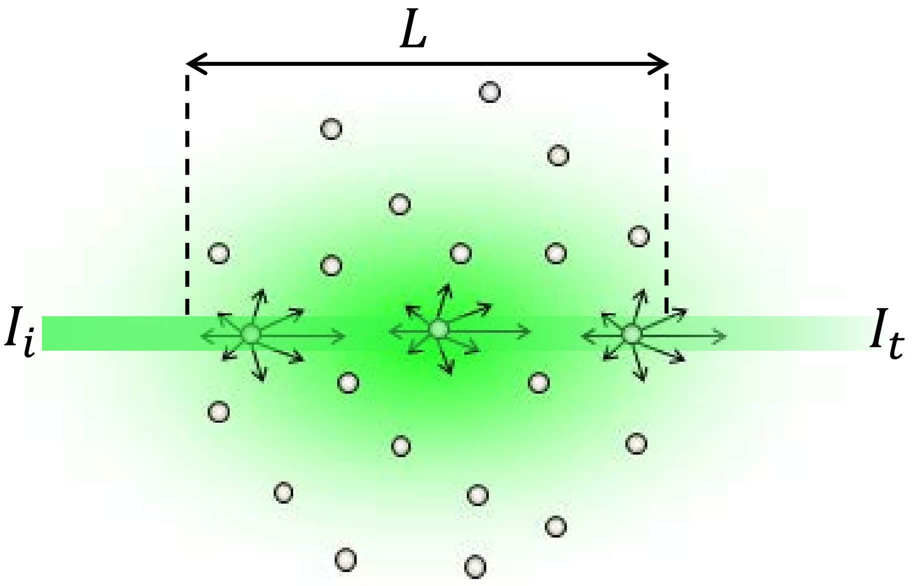
Single scattering regime

$I_t/I_i > 37\%$

0.01%

Scattering regimes





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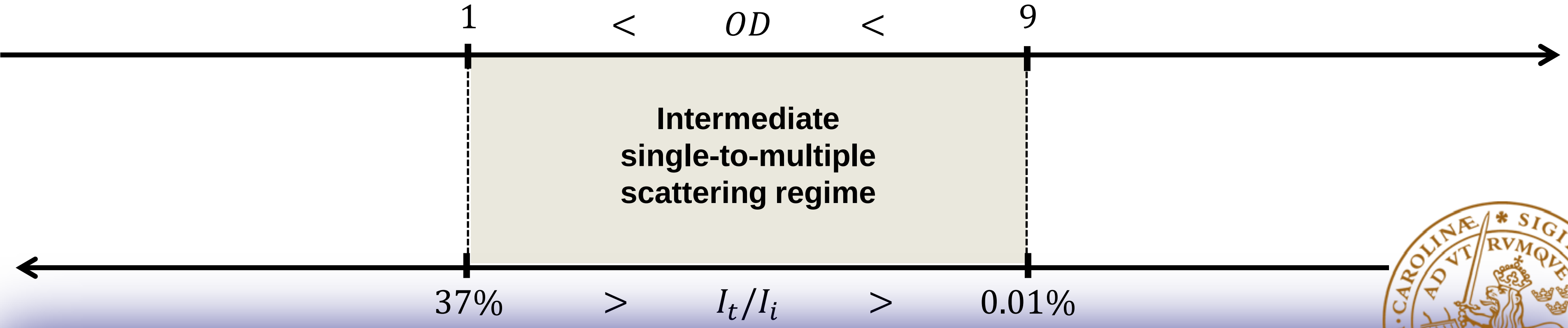


$1 < OD < 9$

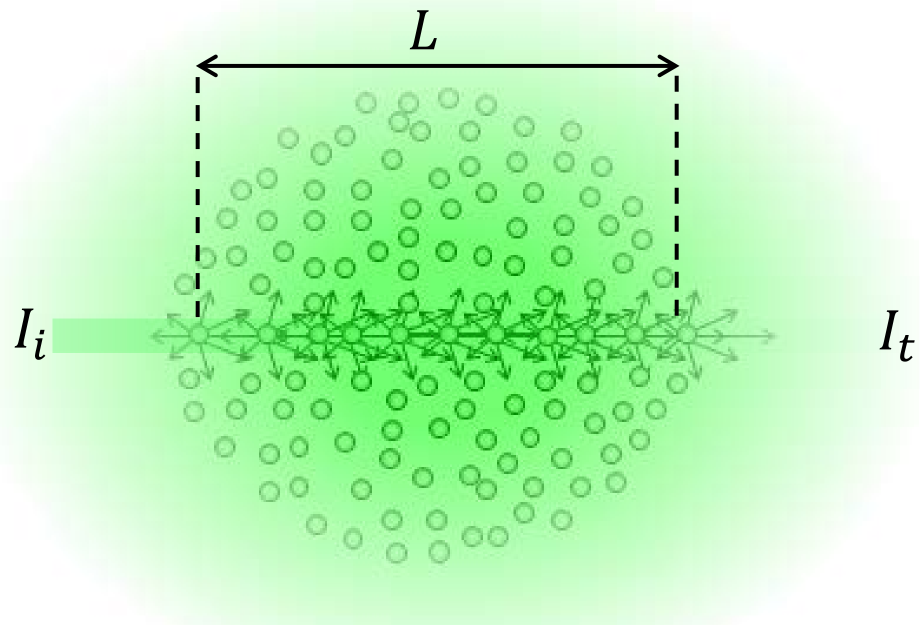
Intermediate single-to-multiple scattering regime

$37\% > I_t/I_i > 0.01\%$

Scattering regimes

Optical Depth

Low **High**



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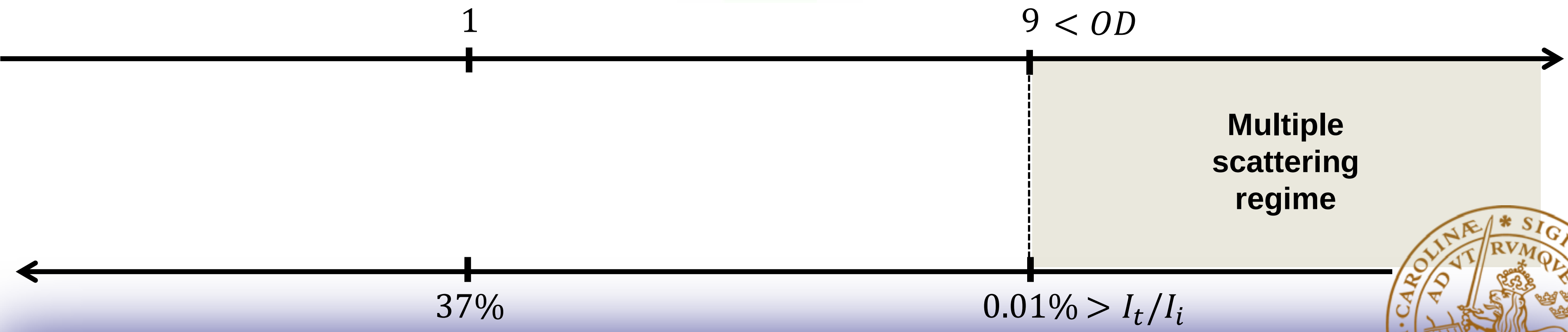
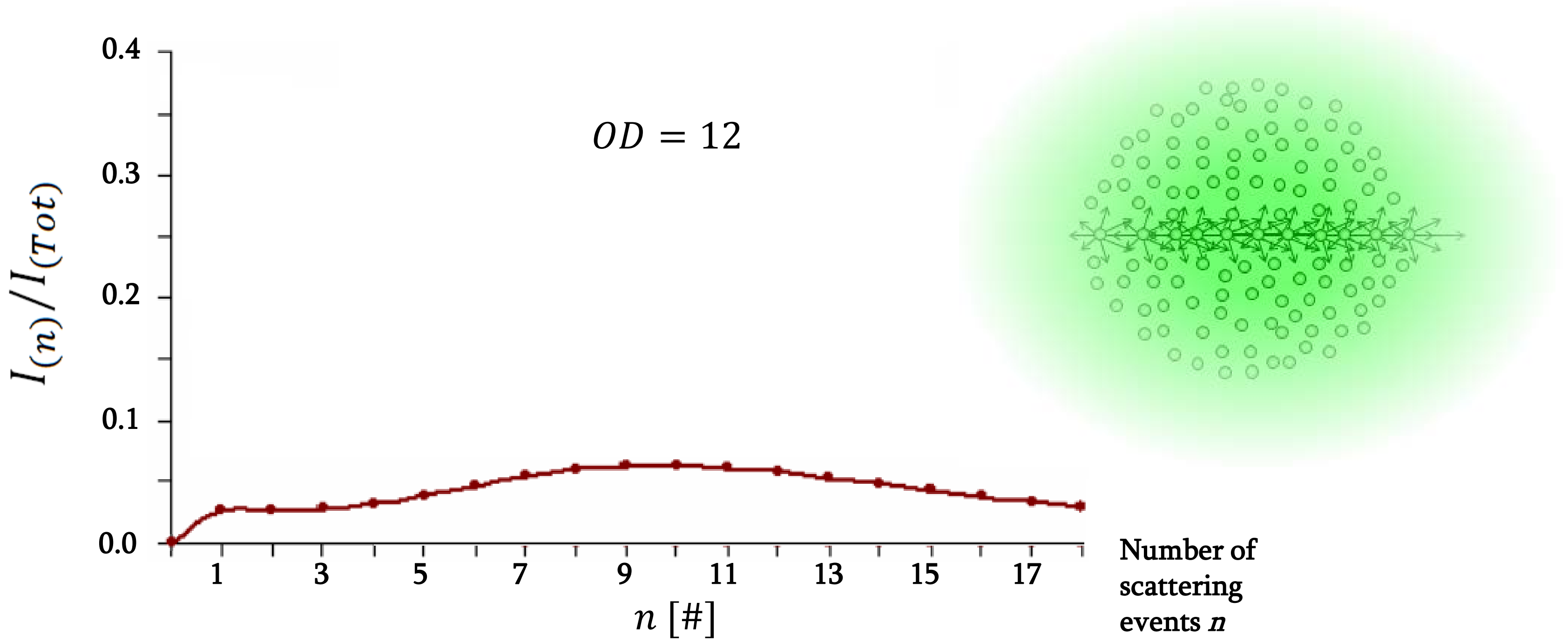
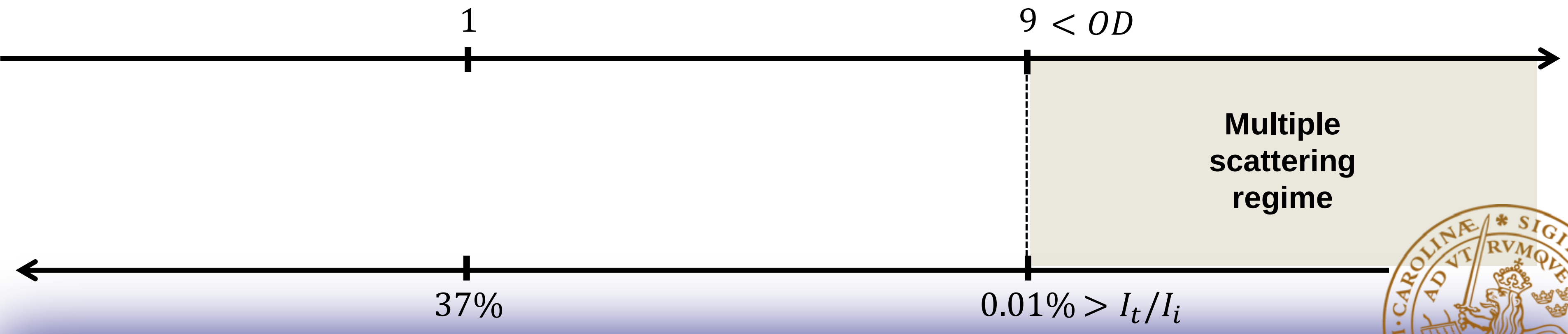


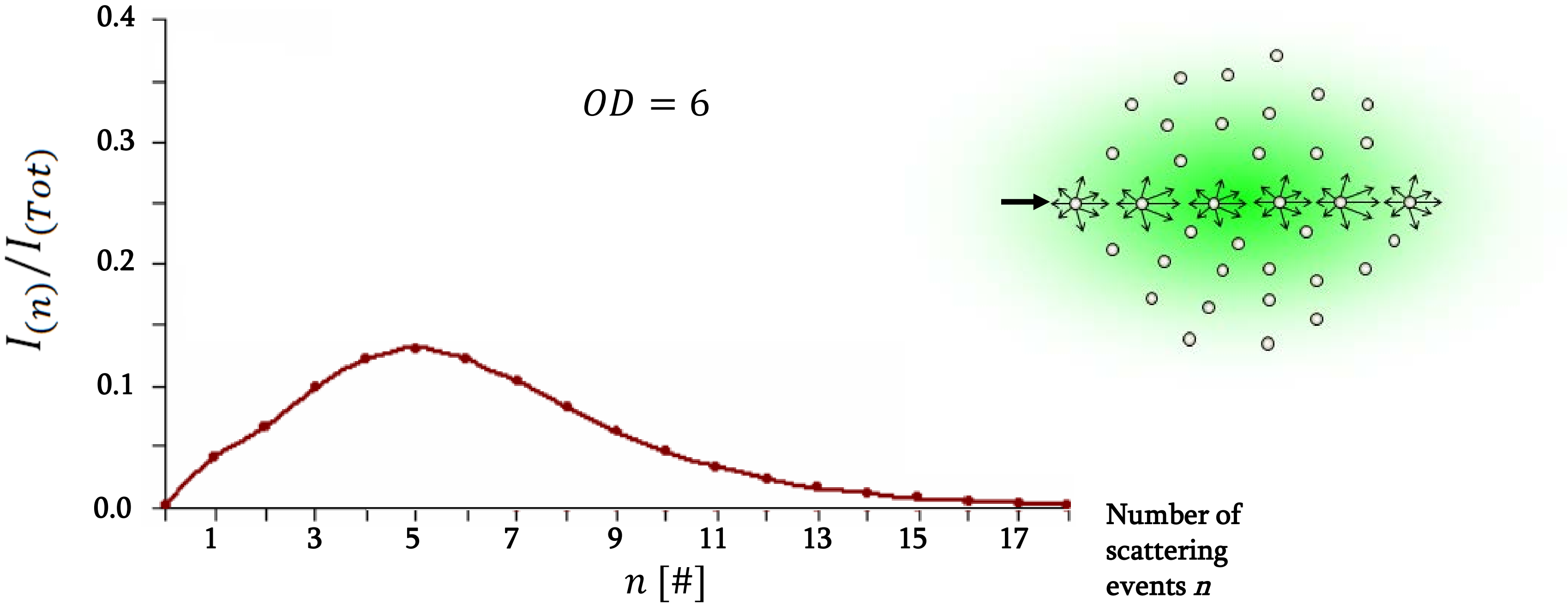
Scattering regime transition



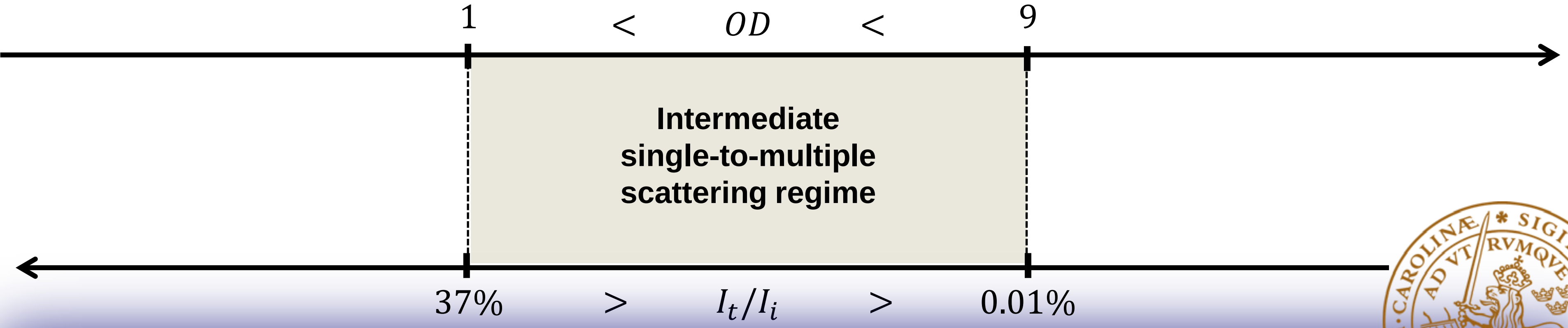


Multiple scattering regime

Scattering regime transition



Number of scattering events *n*

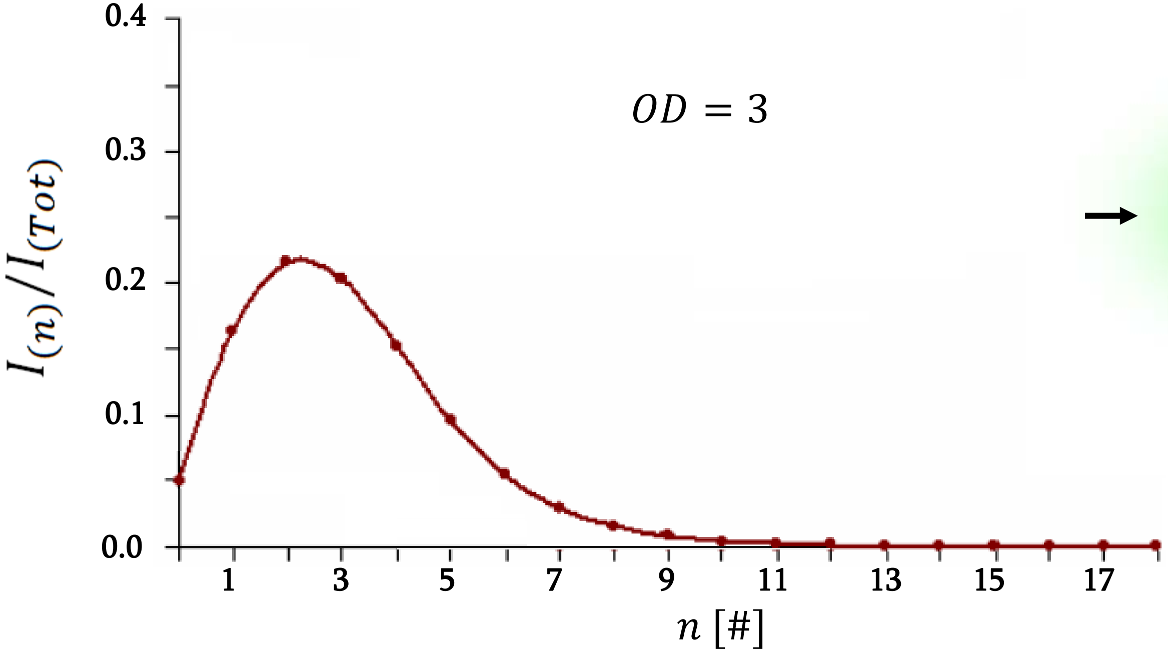


$1 < OD < 9$

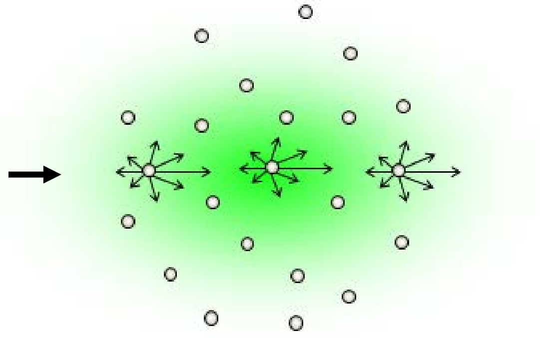
Intermediate single-to-multiple scattering regime

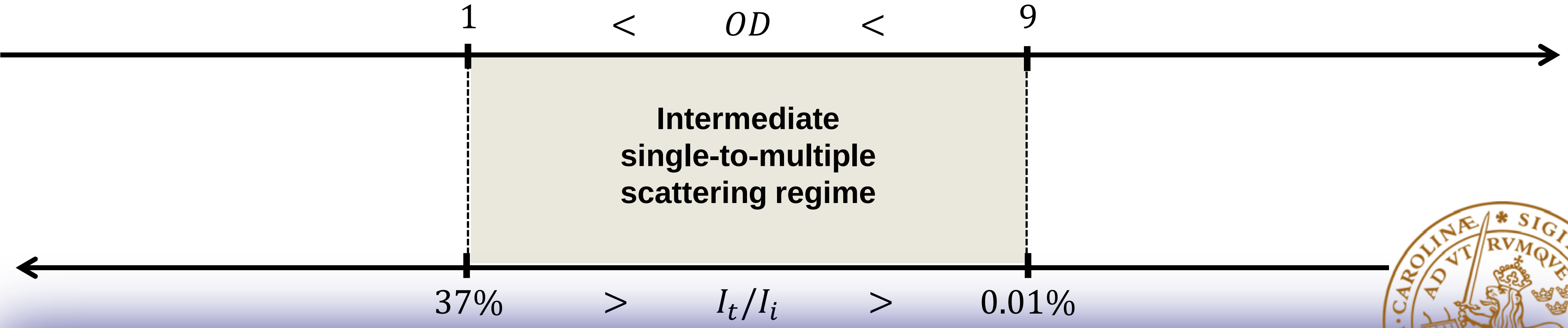
$37\% > I_t/I_i > 0.01\%$

Scattering regime transition



Number of scattering events *n*





$$1 < OD < 9$$

Intermediate single-to-multiple scattering regime

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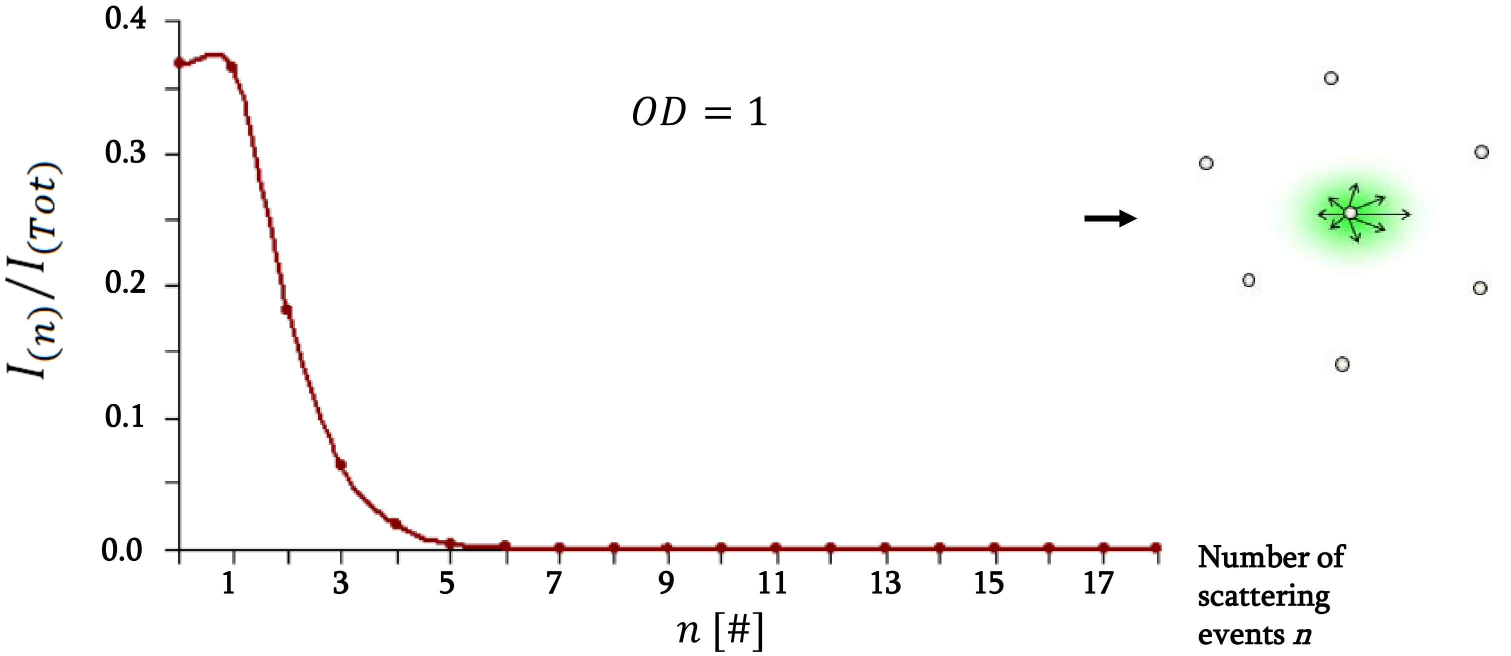
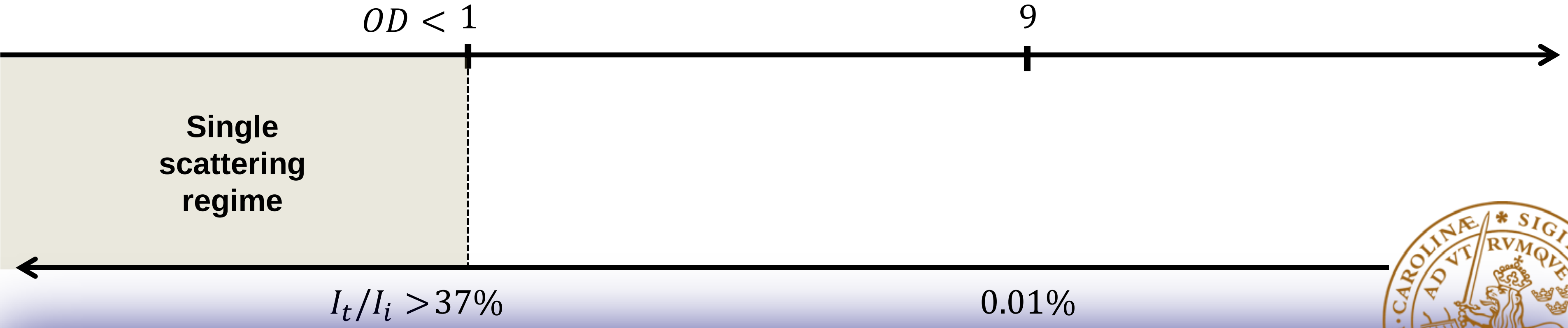
Scattering regime transition





$OD < 1$

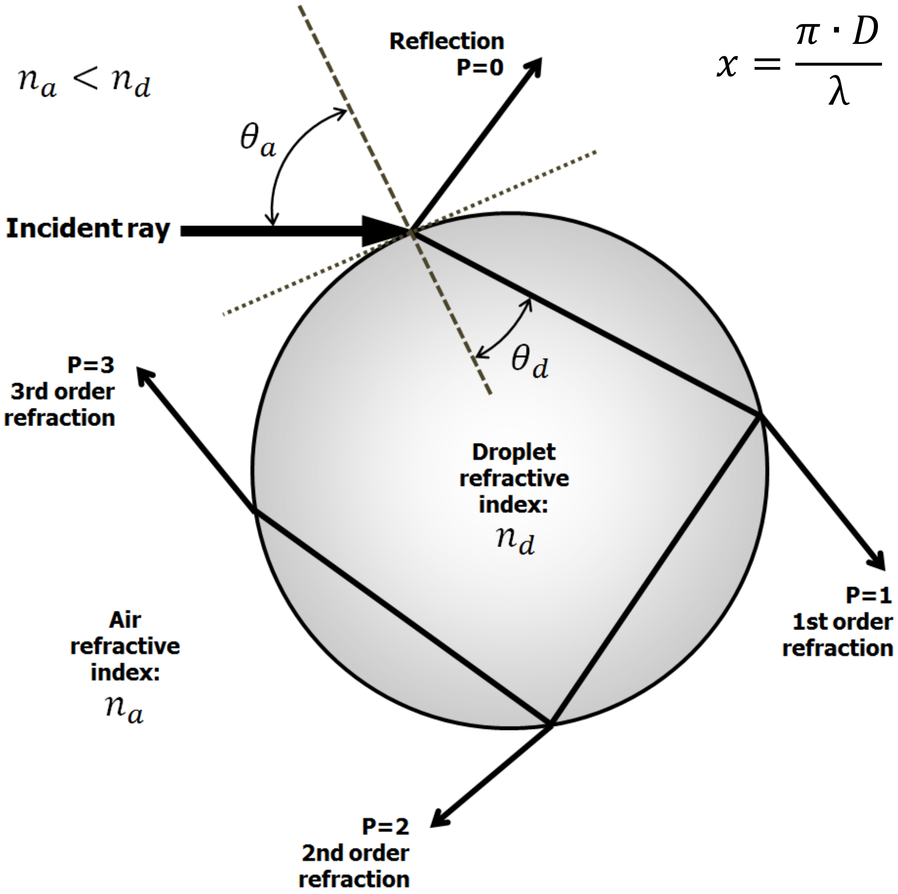
9

Single scattering regime

$I_t/I_i > 37\%$

0.01%

Single light scattering by spherical droplets



Scattering parameter:

$$x = \frac{\pi \cdot D}{\lambda}$$

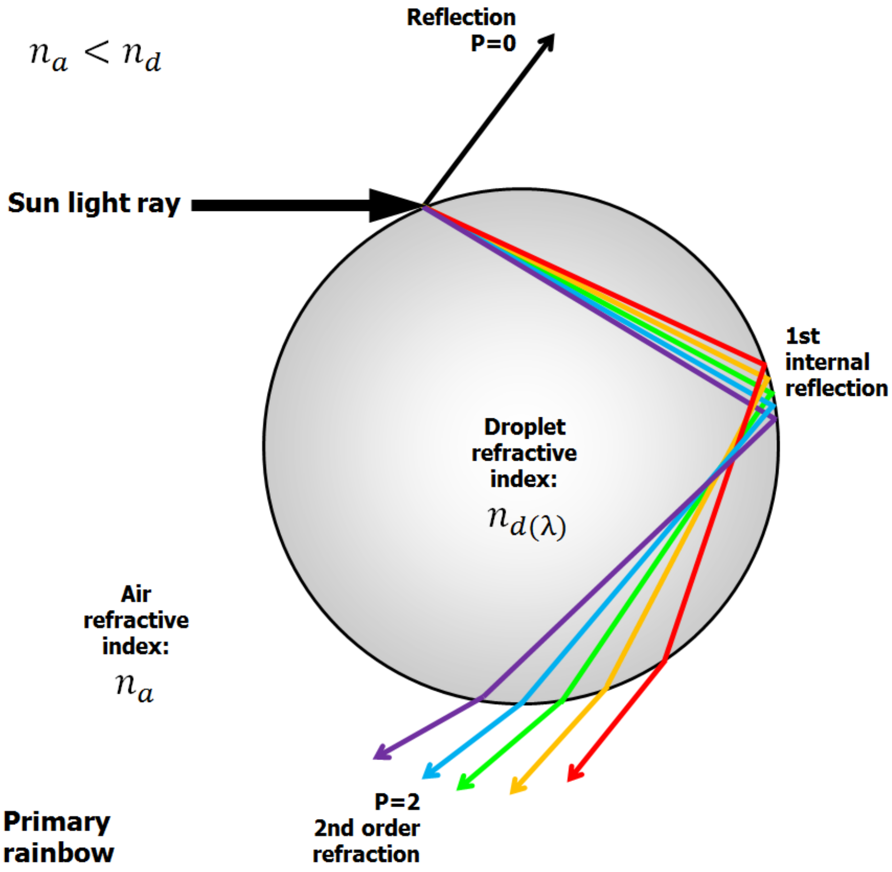
Geometrical Optics

- For $100 < x$ and real refractive indices, the Geometrical Optics (GO) theory can be used.
- In GO, the reflected and refracted rays are separated at each refractive index changes. The intensity and directions of the new refracted and reflected rays are then calculated from the Snell-
- Descartes law:

$$n_a \cdot \sin\theta_a = n_d \cdot \sin\theta_d$$

- An order of refraction P is attributed for each new refracted ray. The method is termed “ray tracing”.
- Note that GO applies for particles much bigger than the incident wavelength and that diffraction as well as interference phenomena are not considered in the method.

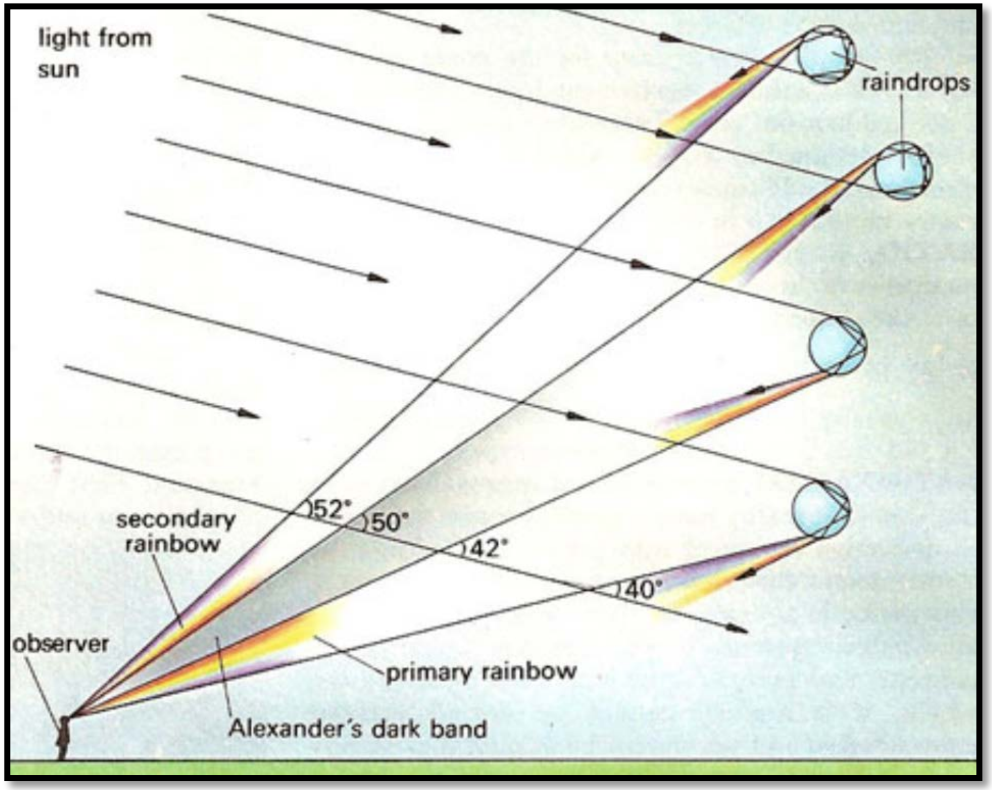
Single light scattering by spherical droplets



Rainbows explained by Geometrical Optics

Recoubeau-Jansac , France - 2016

Single light scattering by spherical droplets



Rainbows explained by Geometrical Optics

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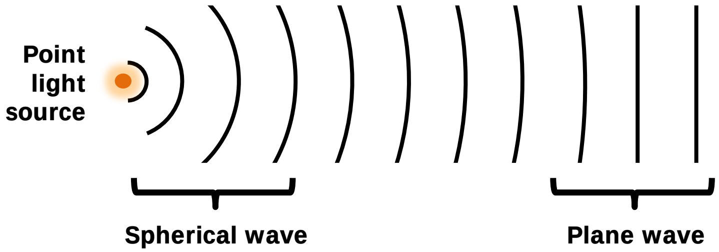
Single light scattering by spherical droplets

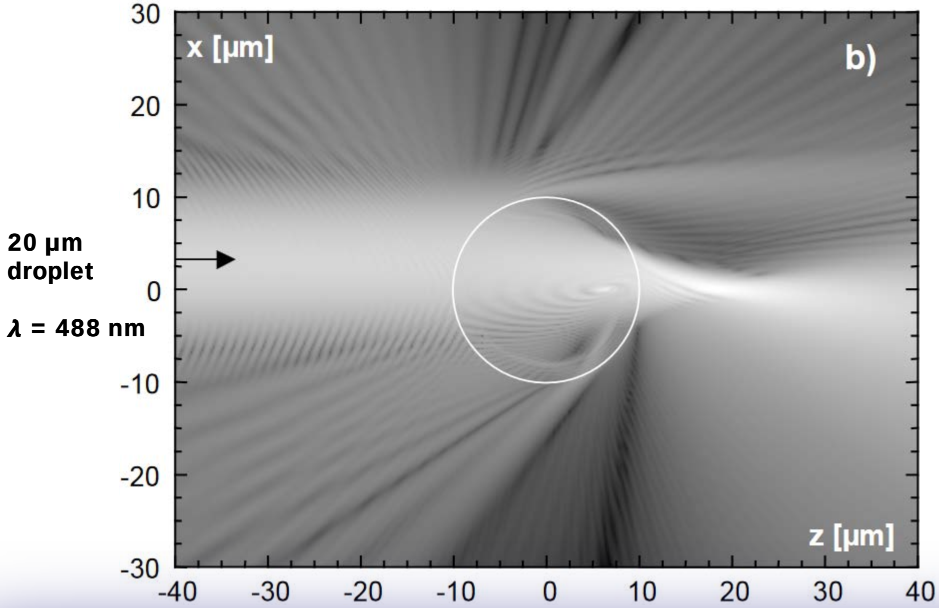


Scattering parameter:

$$x = \frac{\pi \cdot D}{\lambda}$$

Albrecht, Borys, Damashke & Tropea - 1999

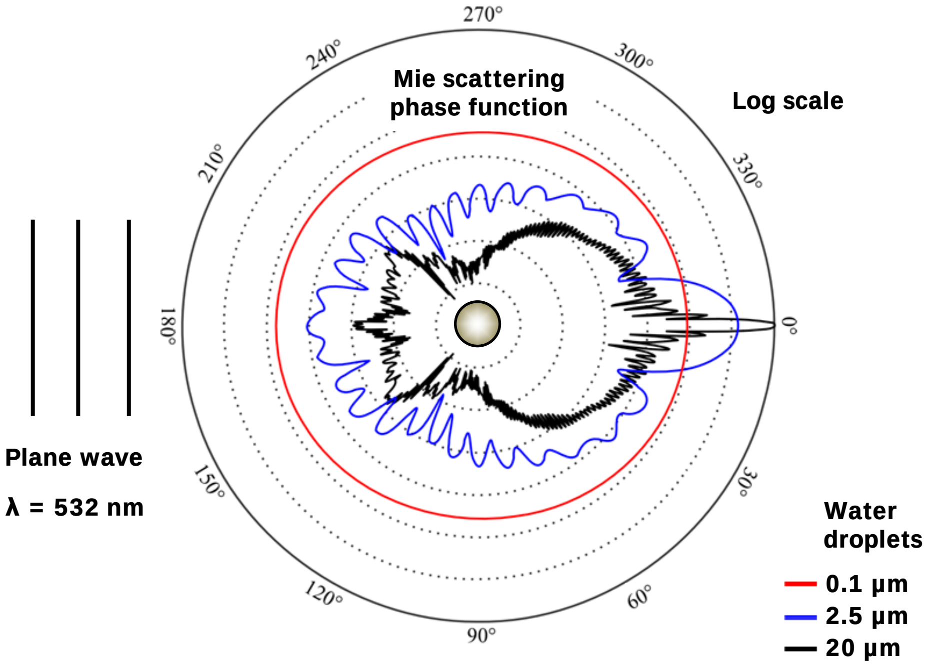
Scattered intensities of the near field and inner field of a droplet

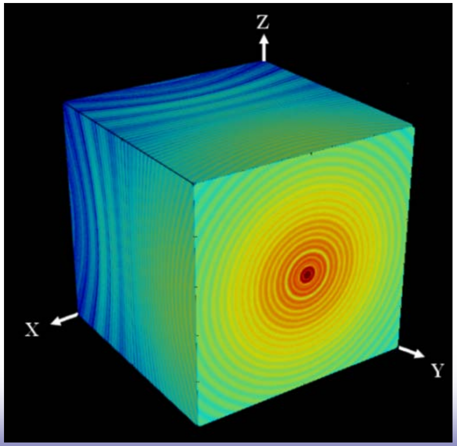


Lorenz-Mie theory

- For $0.1 < x < 100$ the Geometrical Optics theory is not a good approximation anymore and the Lorenz-Mie theory should be used.
- The Lorenz-Mie theory consists in resolving the Maxwell’s equations for the case of a plane wave interacting with a homogeneous sphere.
- The Maxwell’s equations are a set of partial differential equations describing how fluctuating electric and magnetic fields propagate at the speed of light – light is an electromagnetic wave
- In “Mie scattering” situations the size of the particles is comparable to the wavelength producing a patterns like an antenna lobe and where larger droplets produce sharper and more intense forward lobe.
- The Lorenz-Mie theorie has been generalized for arbitrary shaped particles and illumination wave.

Far-field Mie scattering





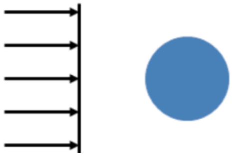
Scattering phase function

- The scattering phase function is the angular distribution of light intensity scattered by a particle at a given wavelength..
- It is given at an angle θ_s relative to the incident beam. It gives the scattered light intensity distribution in the far-field.
- The scattering phase function is the probability of a photon to be scattered from an incident direction to another direction and is given under its normalized form.
- For a number n of droplets of various diameter D, the averaged scattering phase function $\overline{f}(\theta_s)$ can be calculated such as:

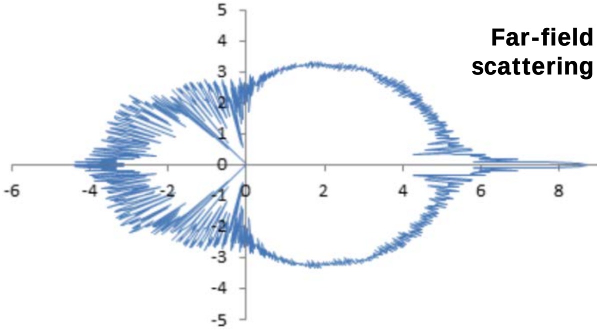
$$\bar{f}(\theta_s) = \frac{\int_{D=0}^{\infty} n(D) \cdot \sigma_s(D) \cdot f(D, \theta_s) dD}{\int_{D=0}^{\infty} n(D) \cdot \sigma_s\,(D)}$$

Generalized Lorenz-Mie theory

Plane wave

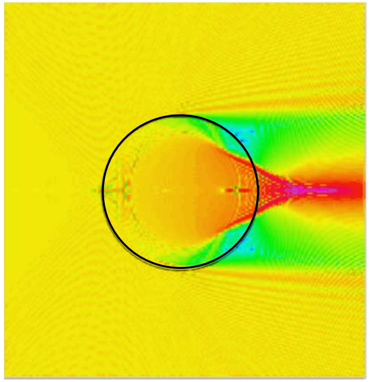


- $\lambda=0.6\ \mu m$
- $d=40\ \mu m$
- $n=1.33+0.i$

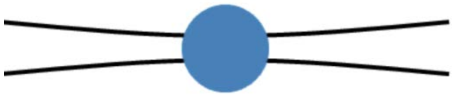


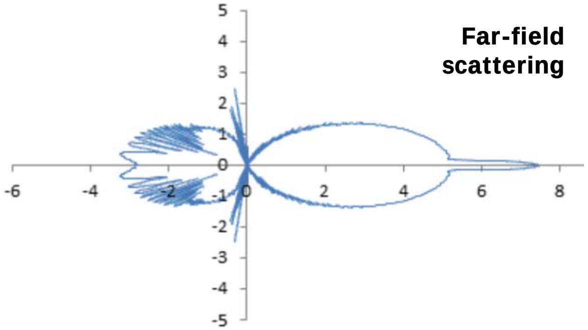
Far-field scattering

Internal & near-field scattering



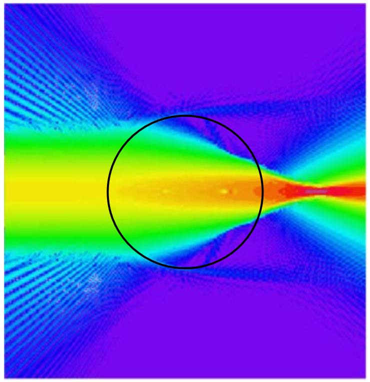
Centered focused beam



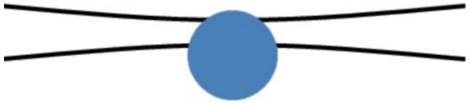


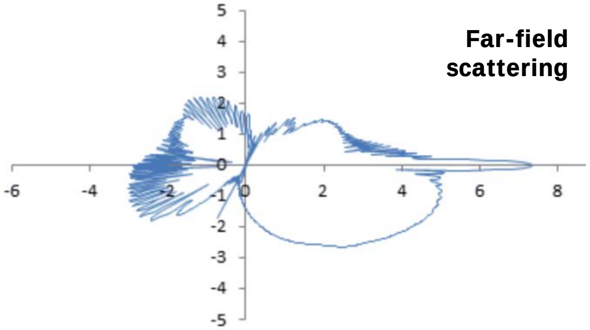
Far-field scattering

Internal & near-field scattering



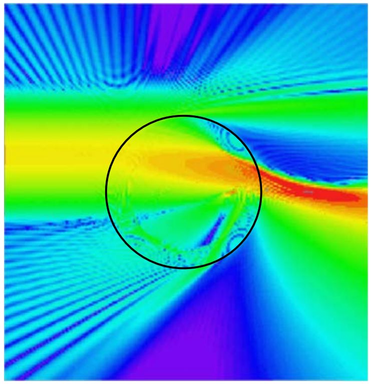
Off-axis focused beam





Far-field scattering

Internal & near-field scattering



Source: © 2012 L. Méès

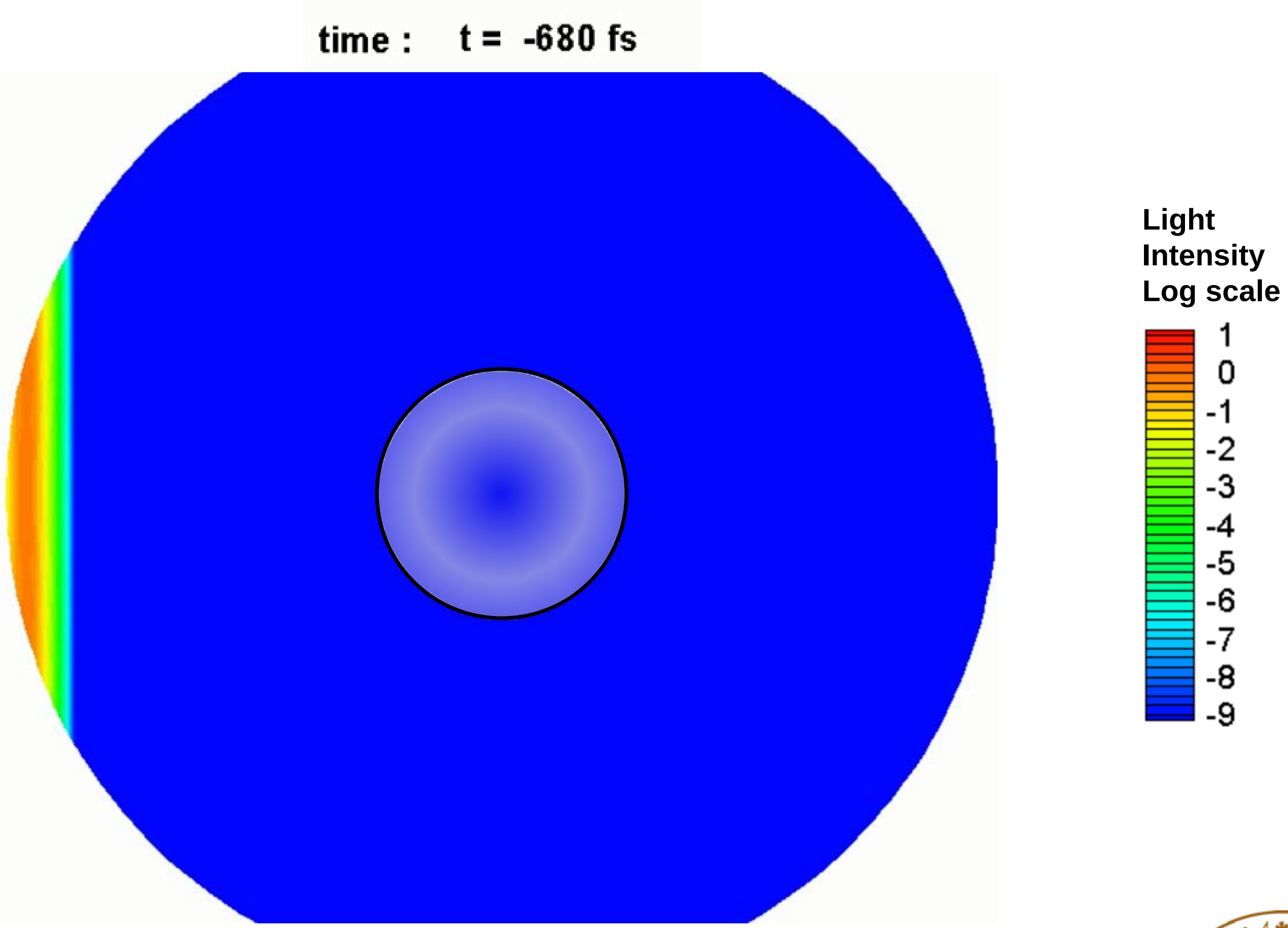
Generalized Lorenz-Mie theory

Femtosecond laser pulse crossing a water droplet

40 µm
water droplet

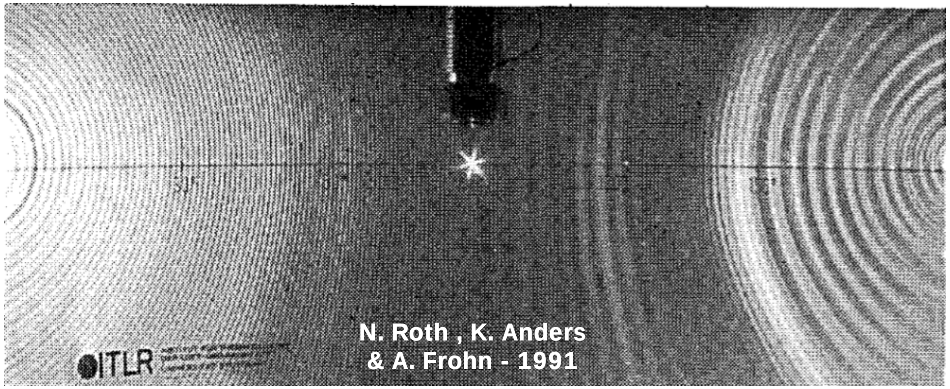
Δt = 35 fs
pulse duration

λ = 800 nm
wavelength

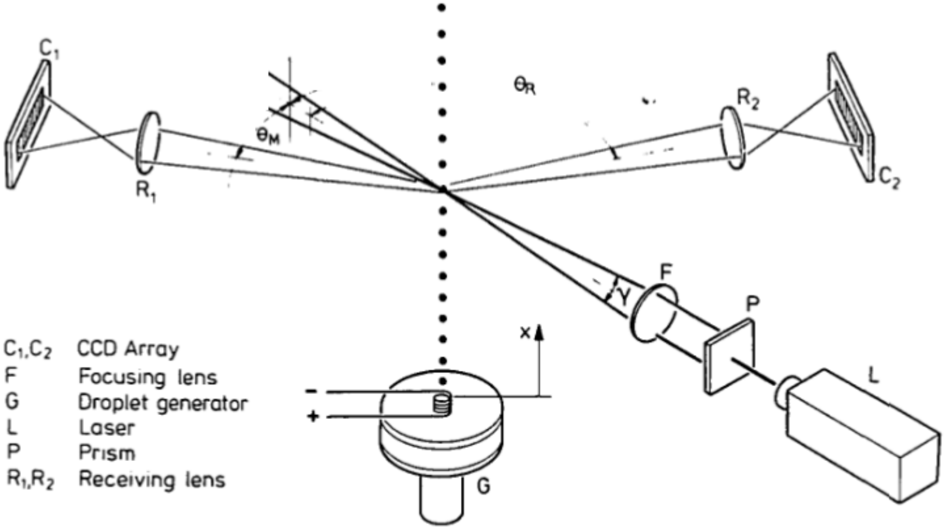


Source: © 2012 L. Méès

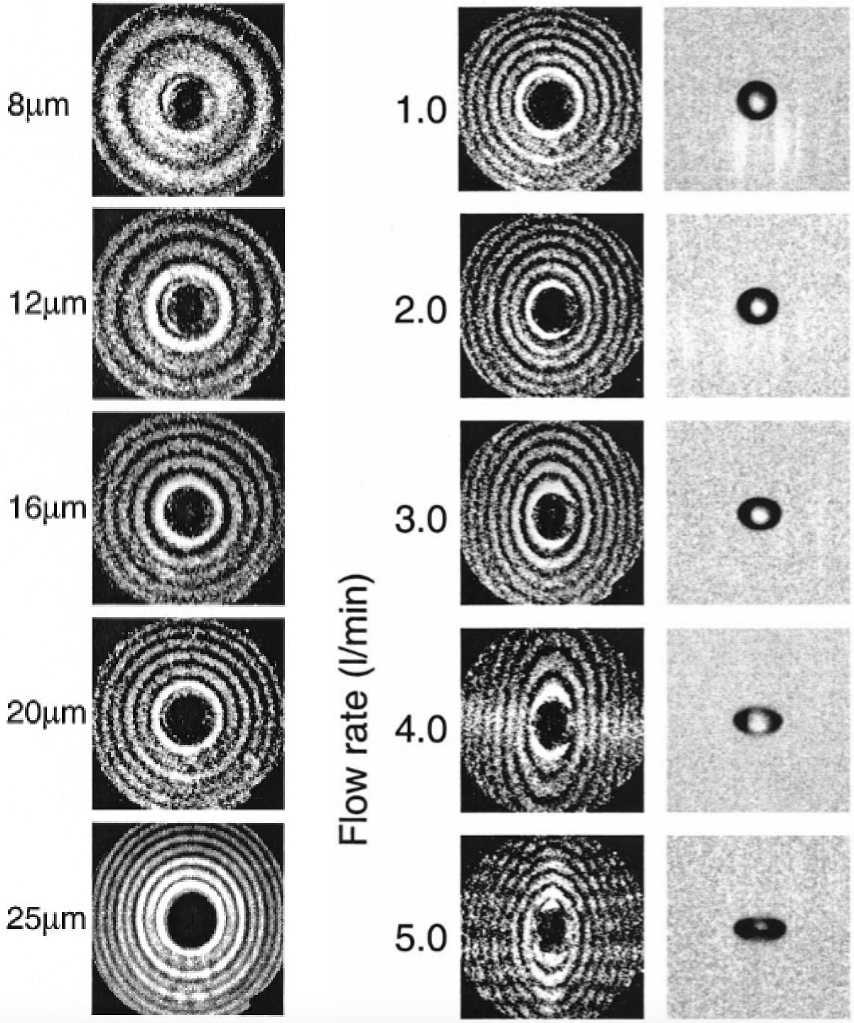
Light scattering by single droplets



N. Roth , K. Anders
& A. Frohn - 1991

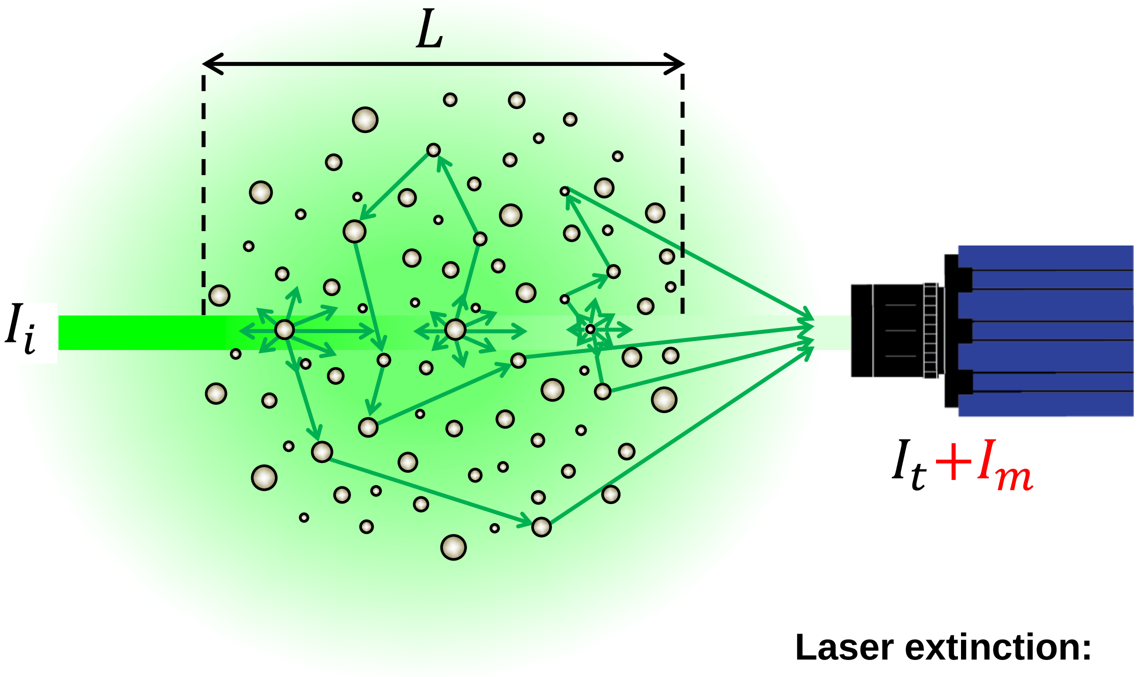


Optical set-up



Secker, Kaye, Greenaway, Hirst, Bartley & Videen - 2000

Transmission imaging through the spray region



Laser extinction:

$$I_t = I_i \cdot \exp(-L \cdot N \cdot \overline{\sigma_e})$$

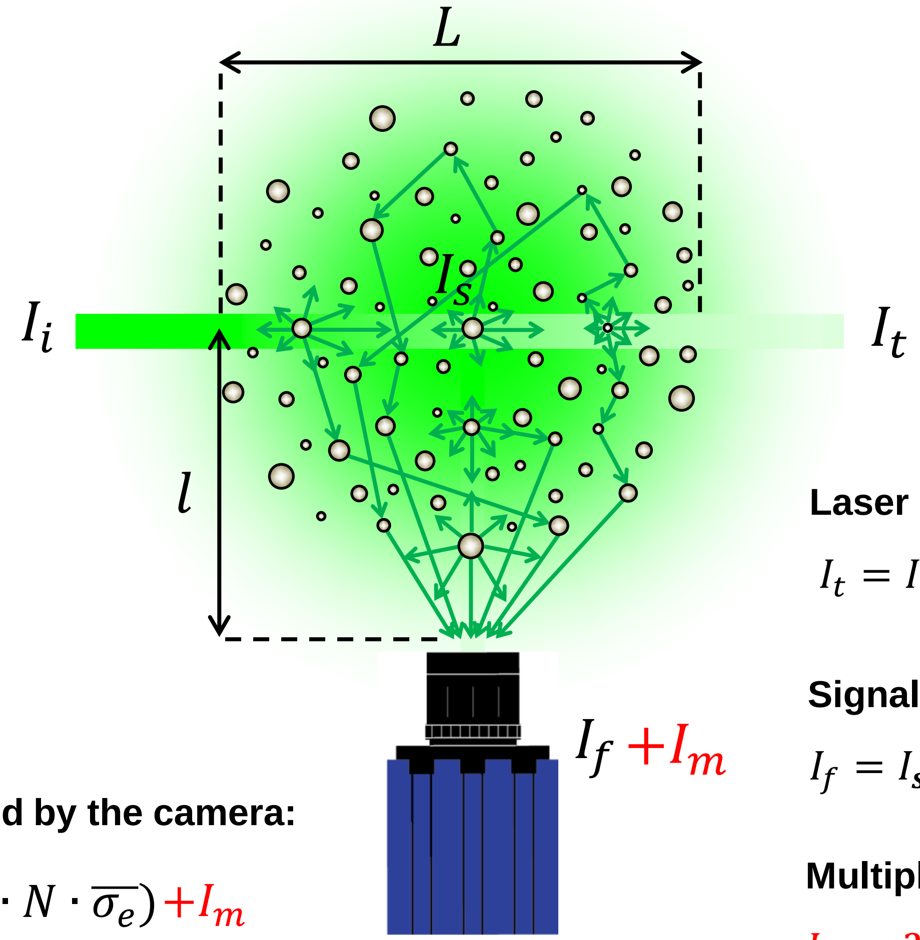
Light intensity detected by the camera:

$$I_d = I_{\boldsymbol{i}} \cdot \exp(-L \cdot N \cdot \overline{\sigma_e}) + I_m$$

Multiple scattering:

$$I_m = ???$$

Laser sheet imaging through the spray region



Light intensity detected by the camera:

$$I_d = I_s \cdot \exp(-L \cdot N \cdot \overline{\sigma_e}) + I_m$$

Laser extinction:

$$I_t = I_i \cdot \exp(-L \cdot N \cdot \overline{\sigma_e})$$

Signal attenuation:

$$I_f = I_s \cdot \exp(-l \cdot N \cdot \overline{\sigma_e})$$

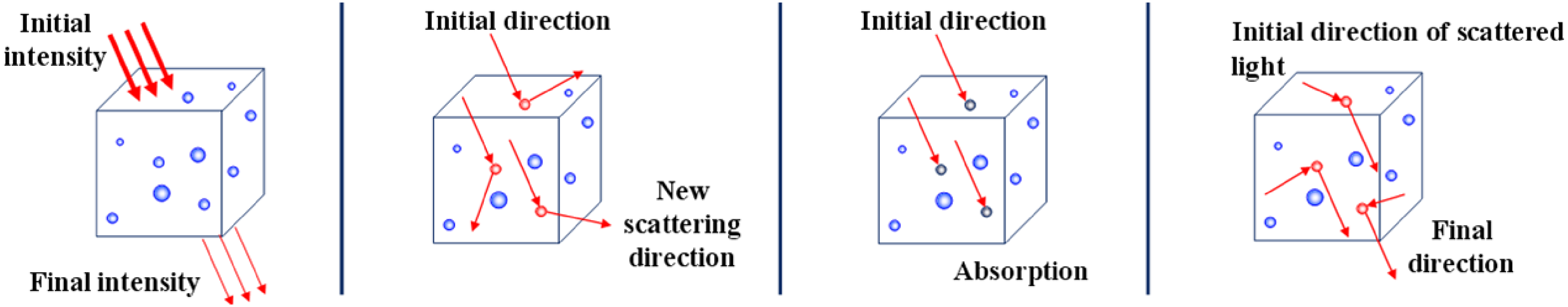
Multiple scattering:

$$I_m = ???$$

Quantifying light intensity from multiple scattering

This is essentially the solution of the **Radiative Transport Equation (RTE)**:

$$\frac{1}{C}\frac{\partial I(\vec{r},\vec{s},t)}{\partial t} = -\mu_s I(\vec{r},\vec{s},t) - \mu_a I(\vec{r},\vec{s},t) + \mu_s \int_{4\pi} f(\vec{s}',\vec{s}) I(\vec{r},\vec{s},t)\, d\Omega'$$



Change of light intensity in a volume V equals = Loss of intensity due to scattering in other directions (negative value) + Loss of intensity due to absorption (negative value) + Increase of the light intensity scattered from other directions into the initial direction (positive value)

- Analytic solutions to the radiative transfer equation (RTE) exist for simple cases but for more realistic media, with complex multiple scattering effects, numerical methods are required.
- The most versatile solution to solve the RTE is to use the Monte Carlo approach

Monte Carlo simulation (MC)

Optical Radiation is defined by photon packets:

- Photons are sent through the scattering medium with an initial direction

Trajectory of each photon is governed by Probability Density Functions:

- Probability to be absorbed along the path length l
- Probability to be scattered along the path length l
- Probability to change direction depending on the appropriate scattering phase function

Detected photons are characterized by:

- Number of scatter events occurred
- Final photon position and direction
- Total path length and time of flight

Exact solution of the RTE:

- If an infinite number of photons could be sent

MC - Photon path length and scattering angle

ξ_n : Random numbers

Free path length:

$$l_{fp} = \frac{\ln(\xi_1)}{\mu_s + \mu_a}$$

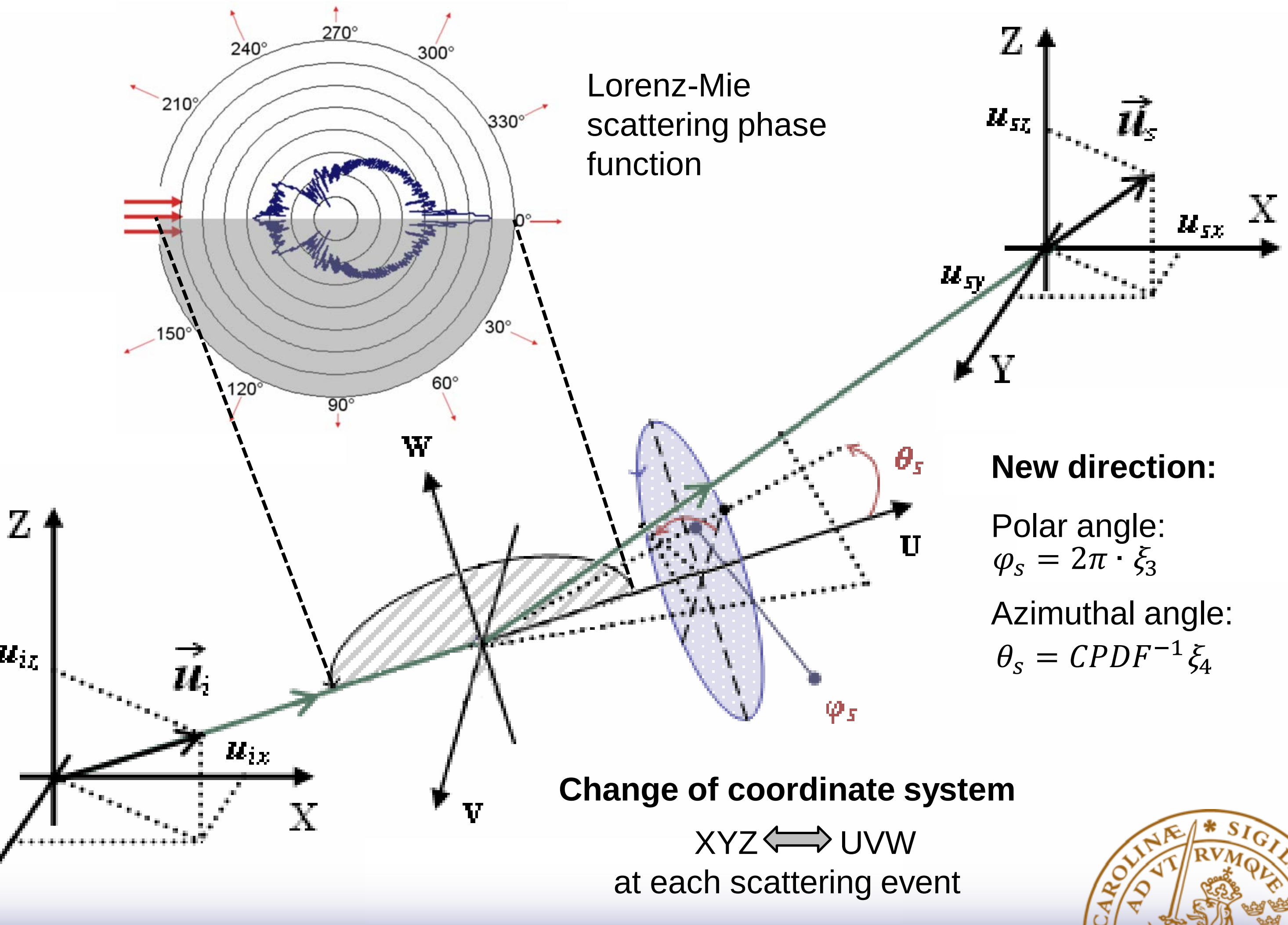
Scattering probability:

If $\xi_2 < A$, scattering

If $\xi_2 > A$, absorption

where the albedo A is:

$$A = \frac{\mu_s}{\mu_s + \mu_a}$$



Lorenz-Mie scattering phase function

New direction:

Polar angle:
$\varphi_s = 2\pi \cdot \xi_3$

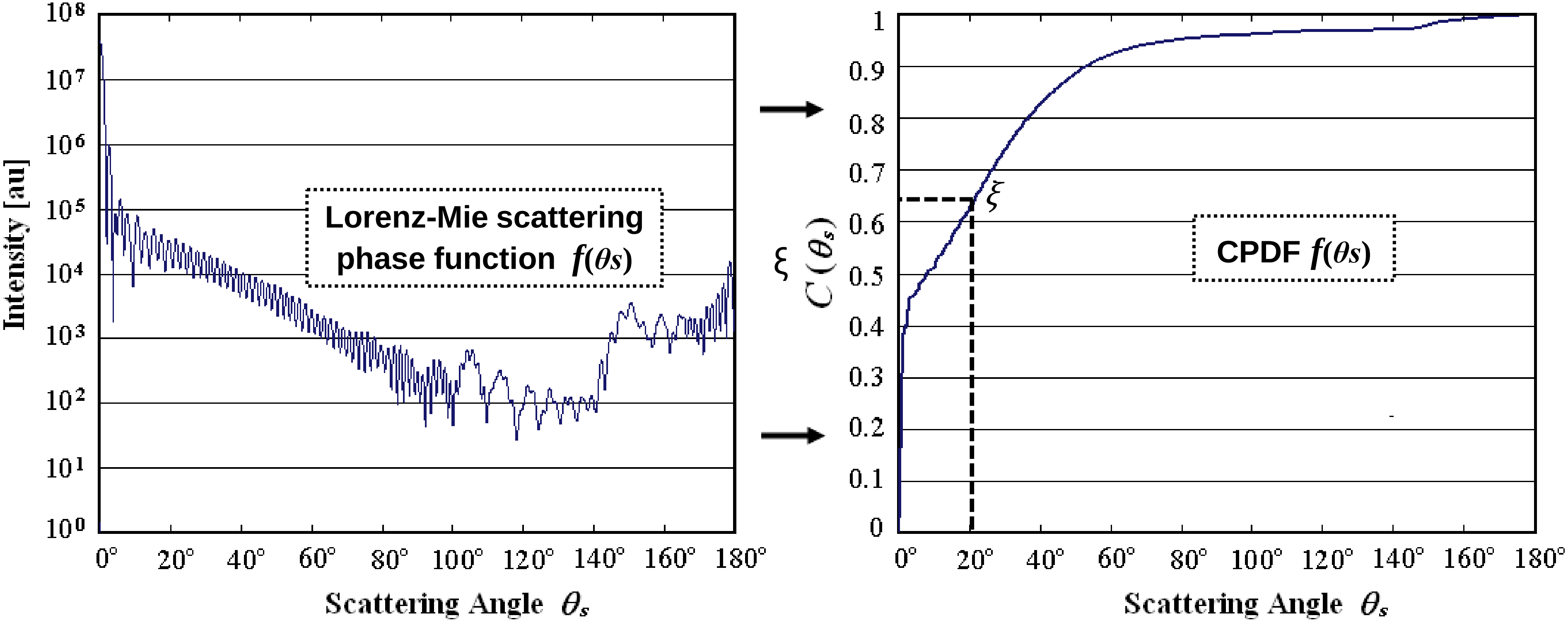
Azimuthal angle:
$\theta_s = CPDF^{-1}\xi_4$

Change of coordinate system

XYZ ⟺ UVW
at each scattering event

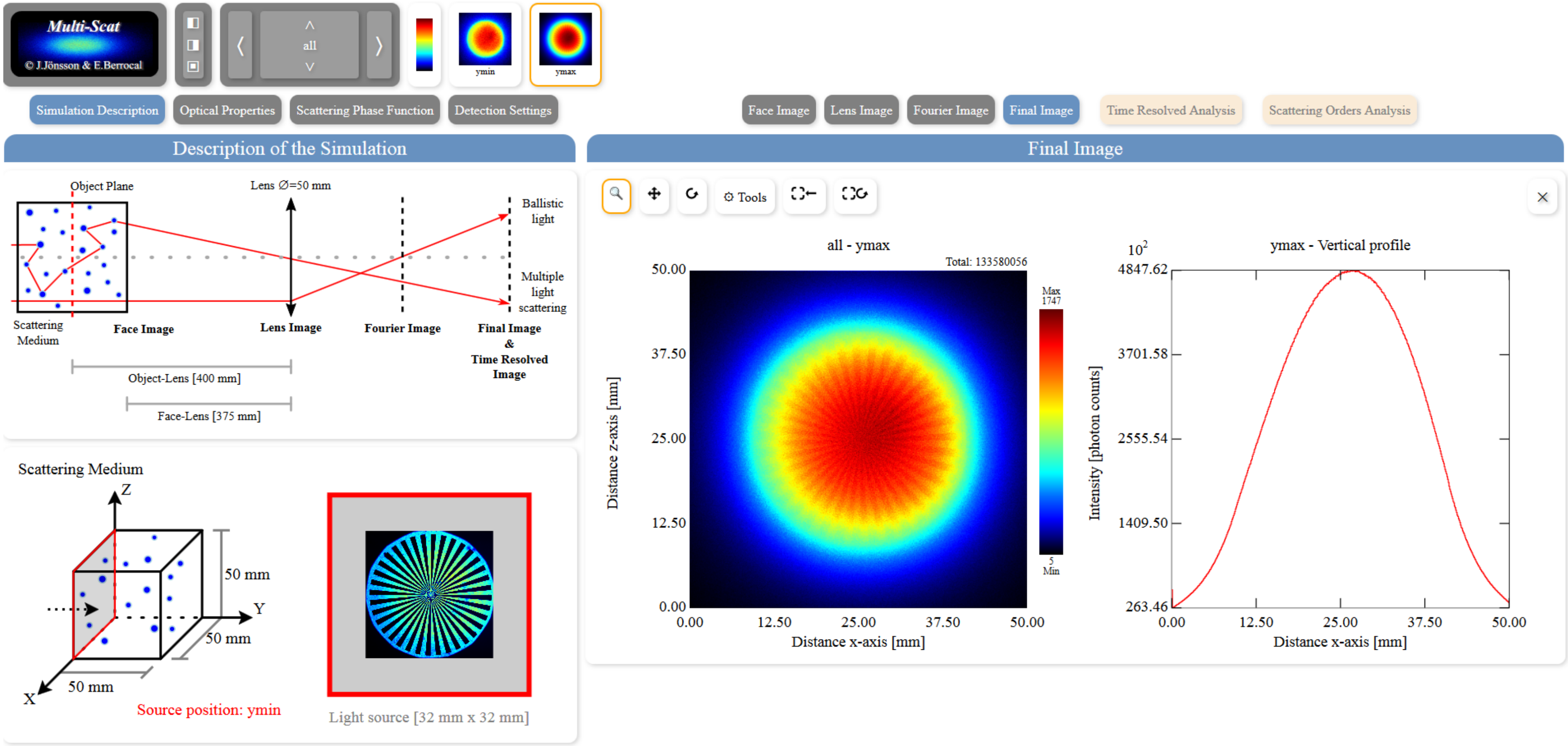
MC - Scattering angle determination

Non-absorbing fuel droplet: ***n* = 1.4+0.0i - D = 20 μm**

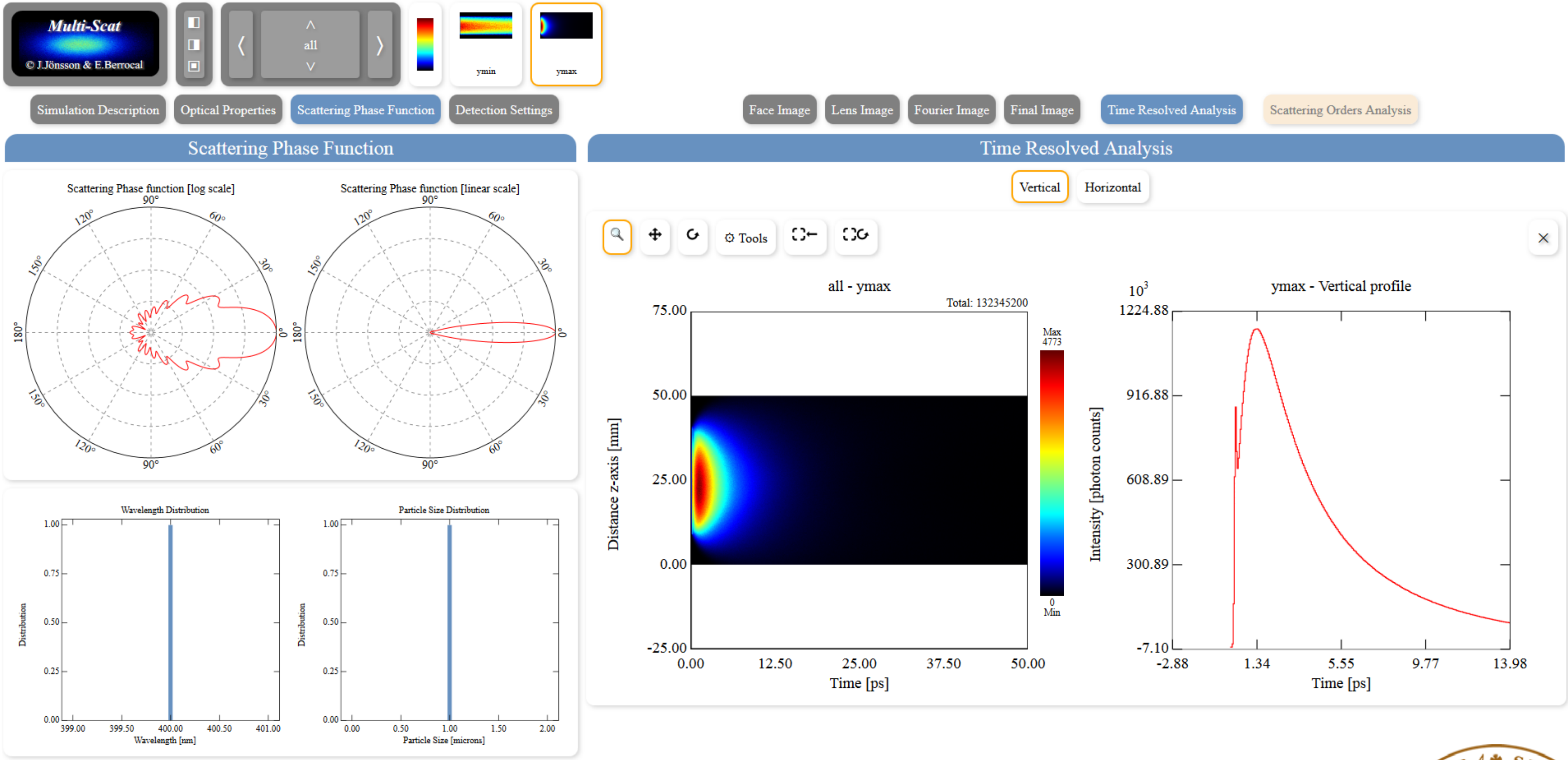


- The azimuthal angle is extracted using a random number and the Cumulative Probability Density Function (CPDF) of the scattering phase function such as: $\theta_s = CPDF^{-1}\xi$

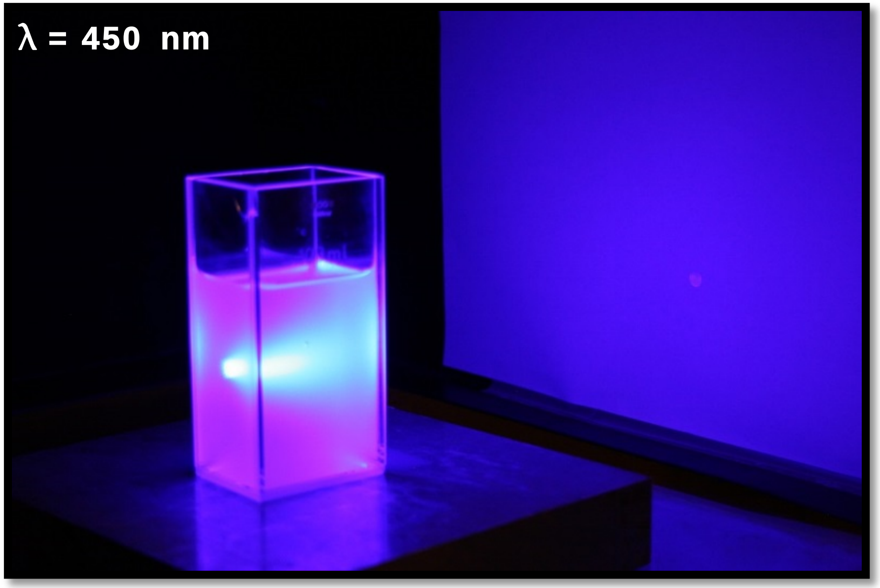
MC - *Multi-Scat* online software

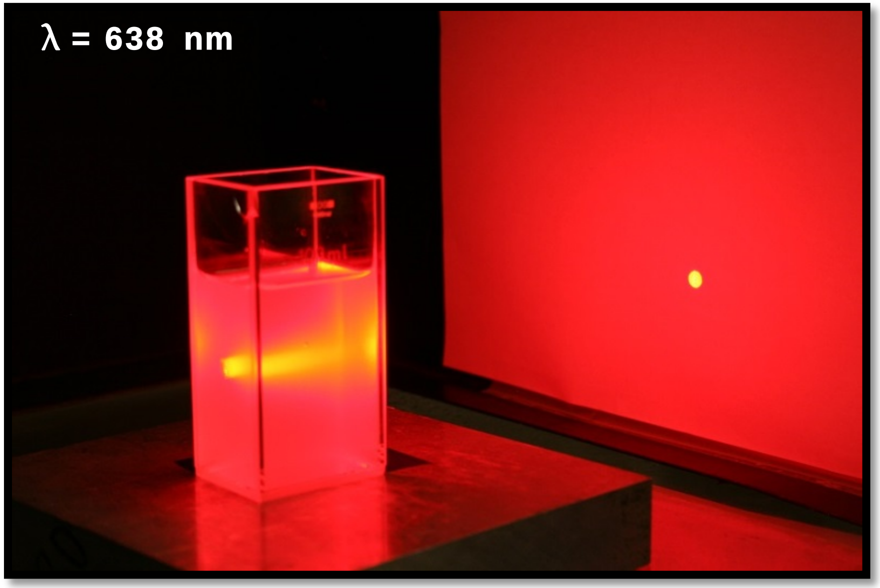


MC - ***Multi-Scat*** online software

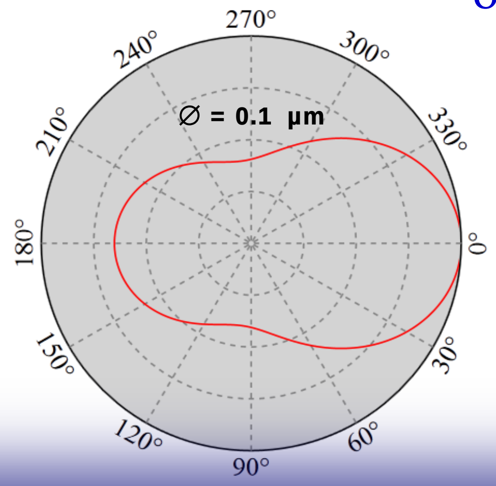


Reducing multiple light scattering (MS)



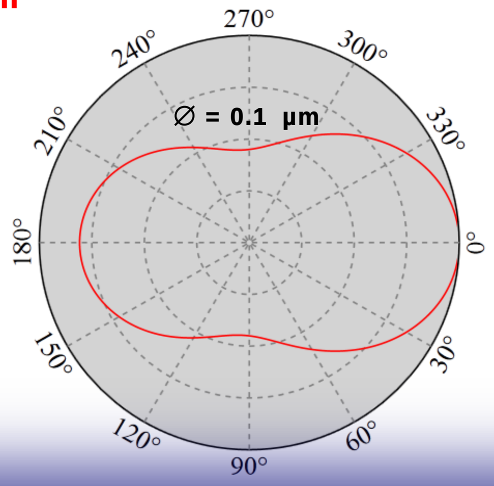


σ_e **= 1.95 E-10 mm^2** < σ_e **= 5.00 E-11 mm^2**

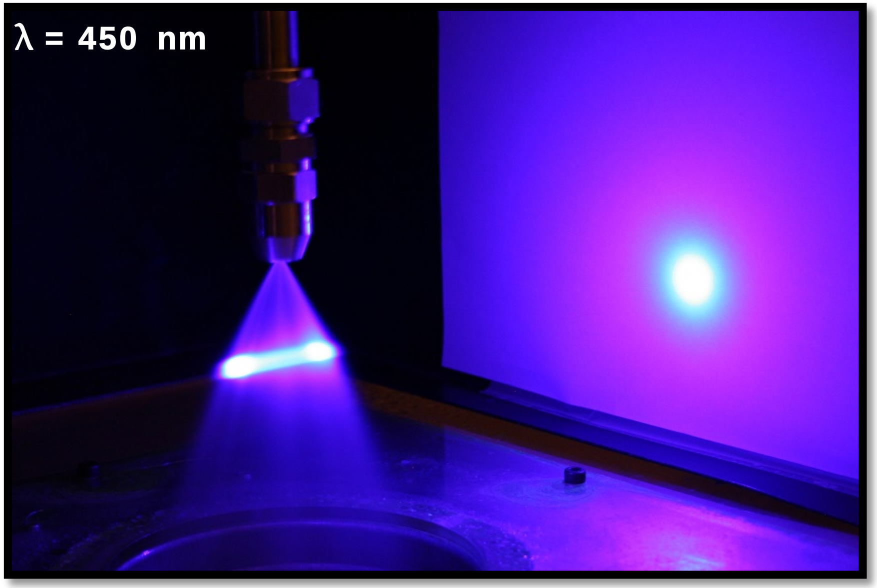


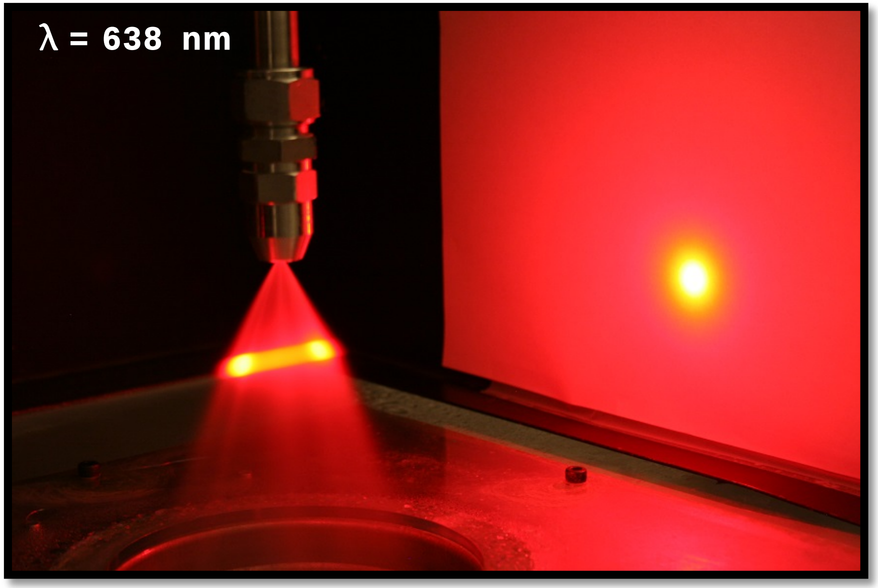
Wavelength effect: ∅ < λ

- For particles smaller than the wavelength, the extinction cross-section changes with wavelength in the visible.
- Longer wavelengths generate significantly smaller extinction cross-section.

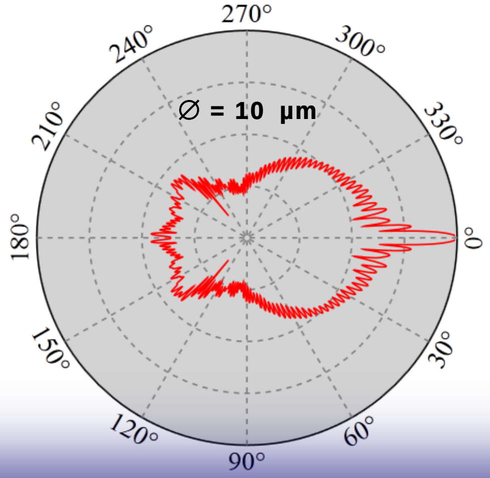


Reducing multiple light scattering (MS)



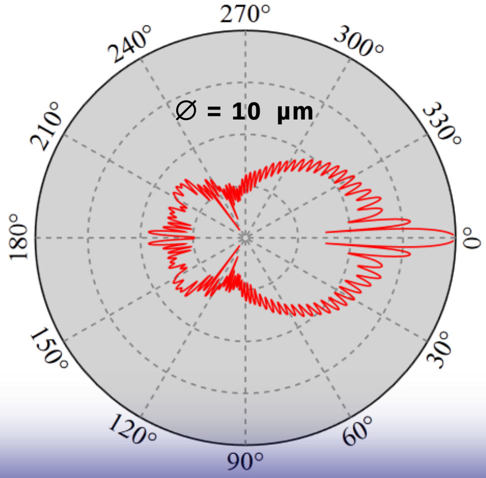


σ_e = **1.60 E-4 mm²** ≈ σ_e = **1.56 E-4 mm²**



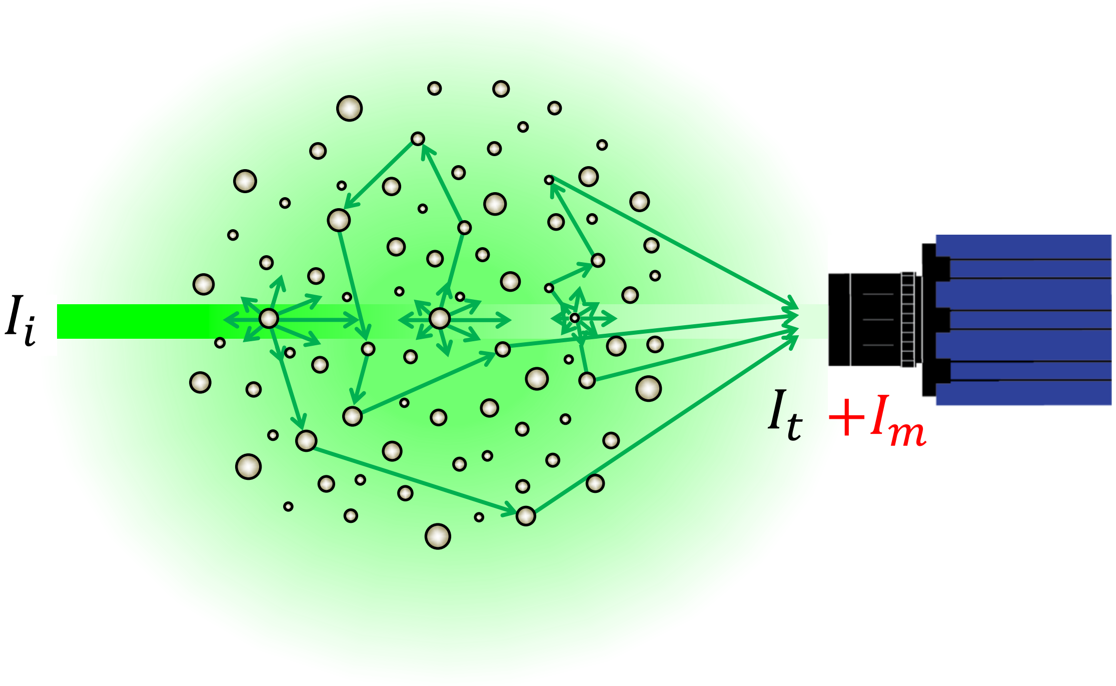
Wavelength effect: ∅ > λ

- For micrometric droplets, the extinction cross-section does not change much with wavelength in the visible.
- Adding absorbers in the liquid reduces the amount of scattering in favor of absorption



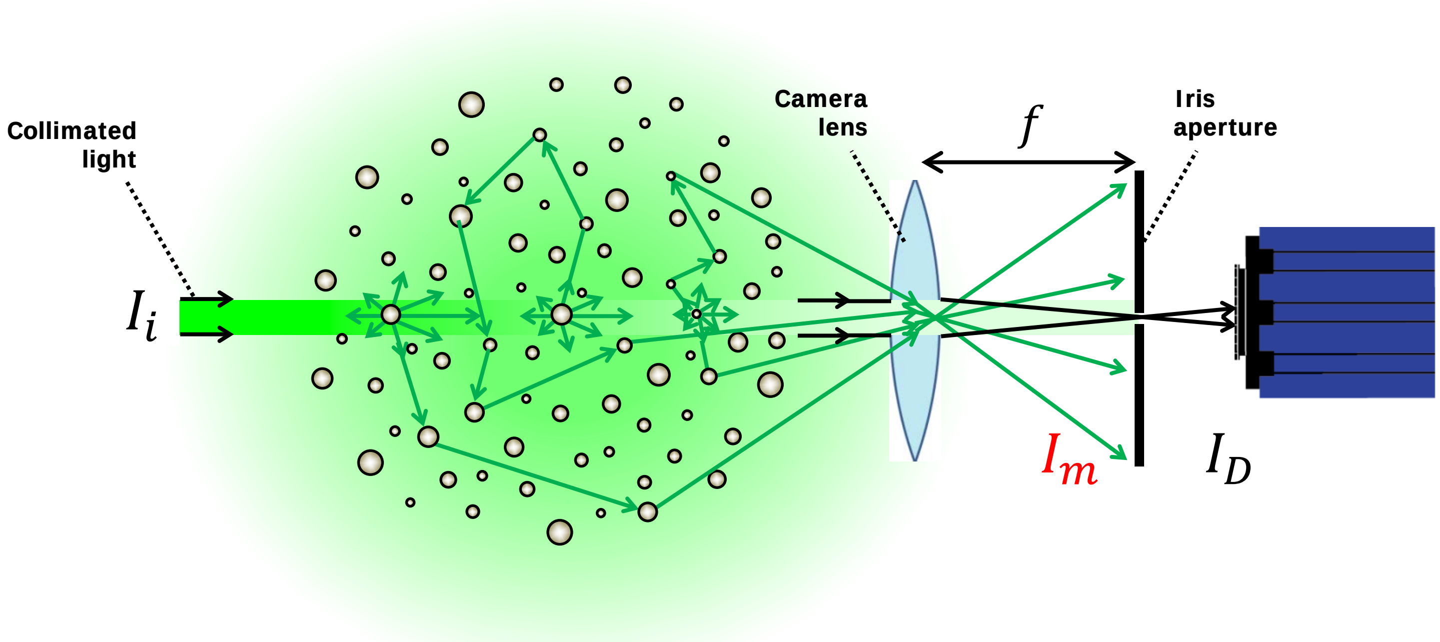
Reducing MS - Spatial Fourier filtering

Initial optical configuration



Reducing MS - Spatial Fourier filtering

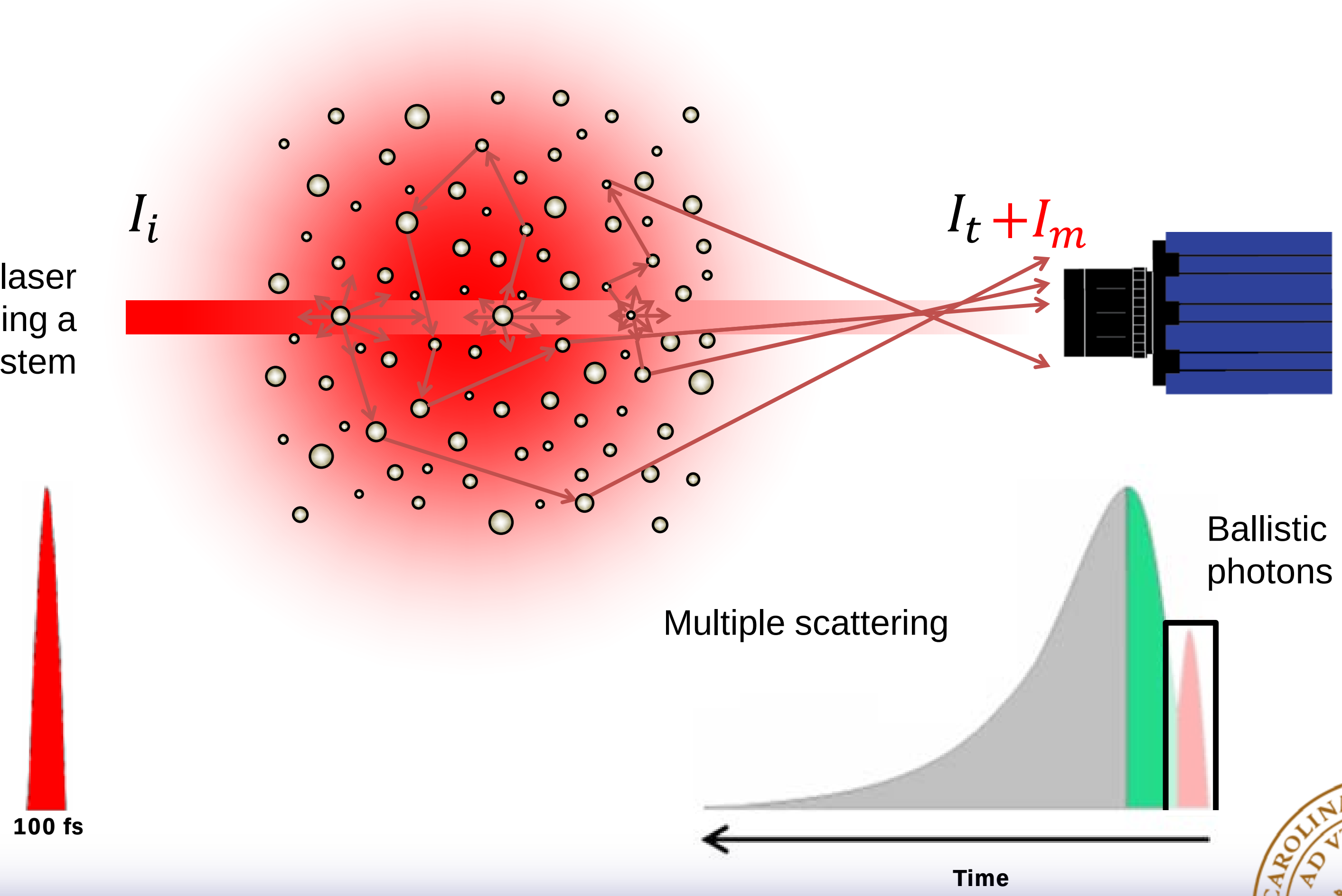
Fourier filtering optical configuration



- In spatial Fourier filtering a small aperture is located at the focal distance of a spherical converging lens. This optical configuration allows preserving the collimated light will suppressing photons arriving at large angles onto the collecting lens.
- However, image details are obtained at some angles - light being diffracted from edges.
- Closing the aperture down to ~2 mm is usually a good trade-off between preserving most of the image information while suppressing a large part of scattered photons.

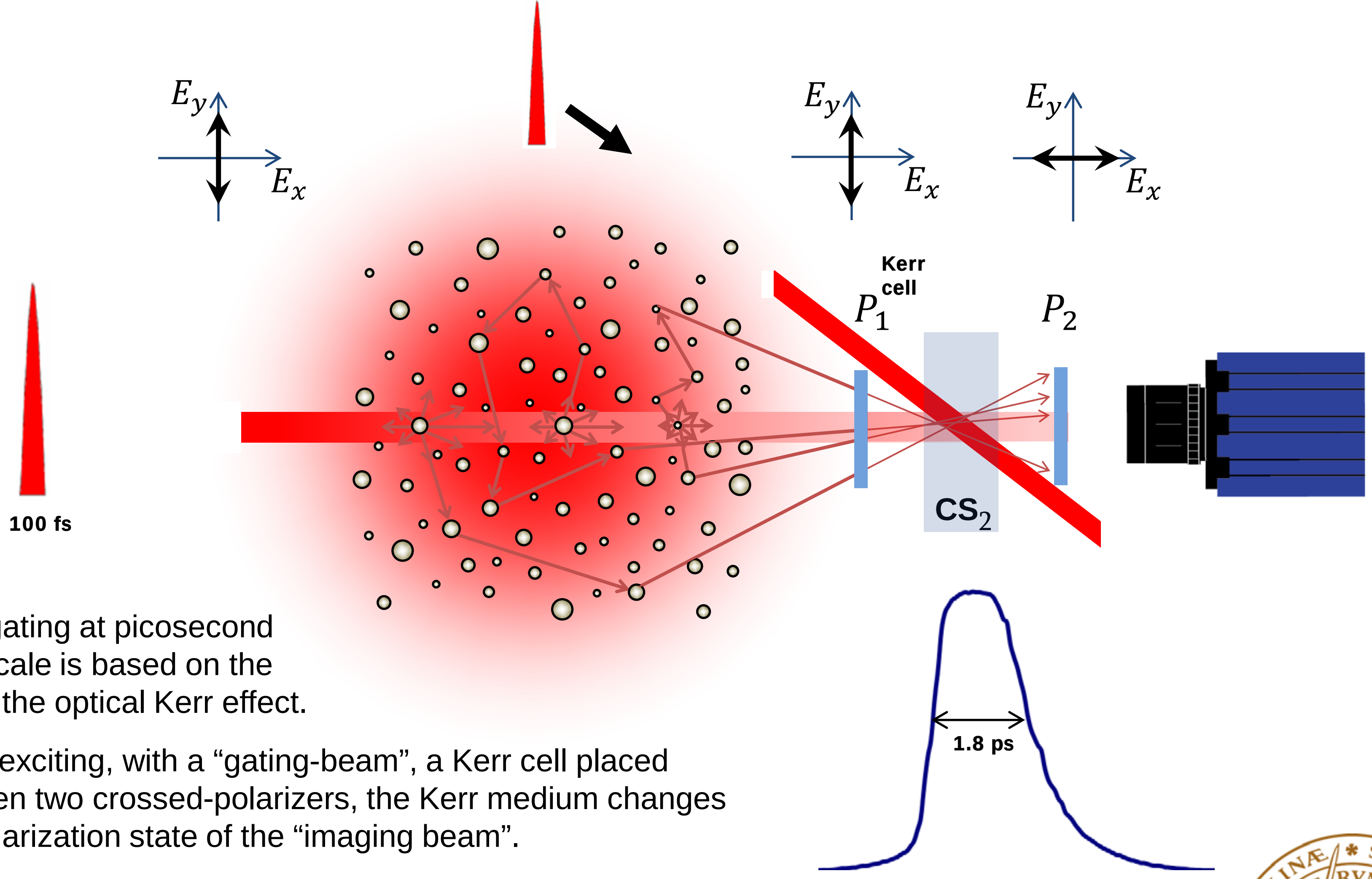
Reducing MS - Time Gating

Initial optical configuration



Femtosecond laser pulse crossing a spray system

Reducing MS - Time Gating

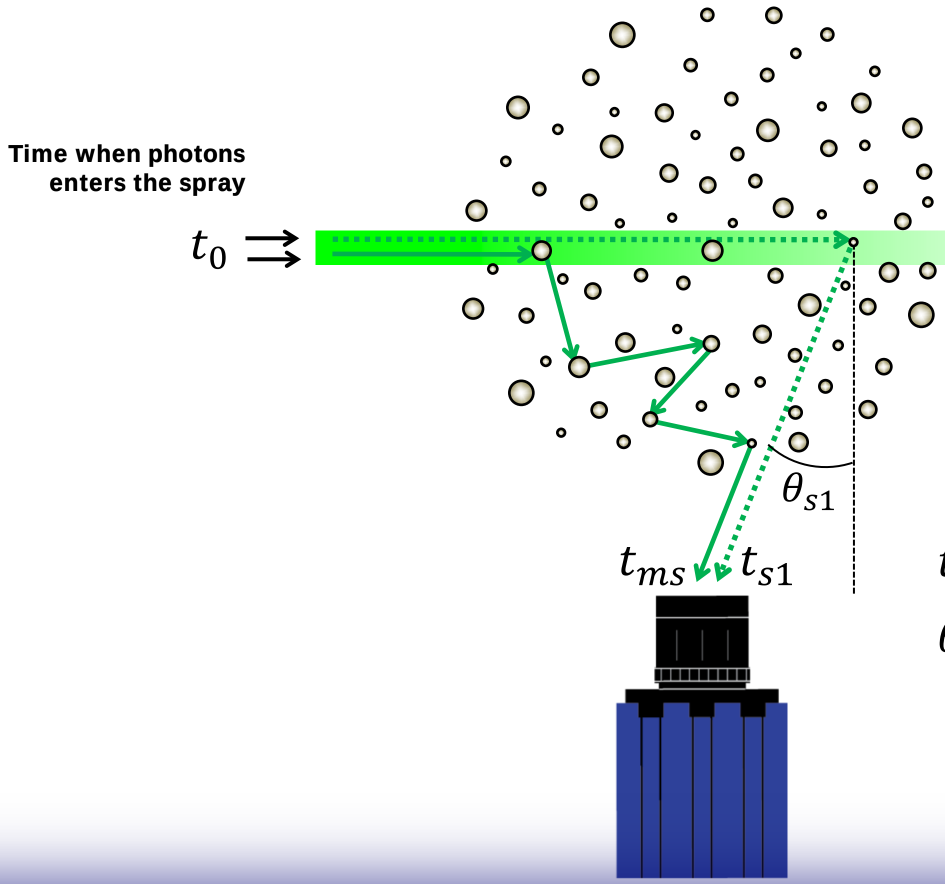


Carbon disulfide relaxation time

- Time gating at picosecond time-scale is based on the use of the optical Kerr effect.
- When exciting, with a “gating-beam”, a Kerr cell placed between two crossed-polarizers, the Kerr medium changes the polarization state of the “imaging beam”.
- This allows light to cross the second polarizer over a period of time corresponding to the relaxation time of the Kerr material.

How to remove MS in laser sheet imaging?

→	Example of a photon being scattered multiple times	Time at camera: t_{ms}	Angle at camera: θ_{ms}
⇢	Example of a photon being scattered one time only	Time at camera: t_{s1}	Angle at camera: θ_{s1}



$t_{ms} \approx t_{s1}$

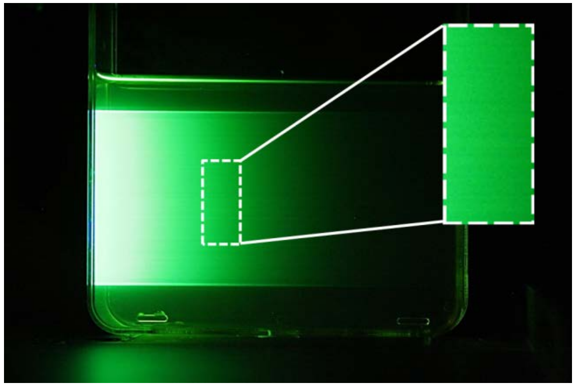
$\theta_{ms} \approx \theta_{s1}$

- Fourier filtering
- Time gating

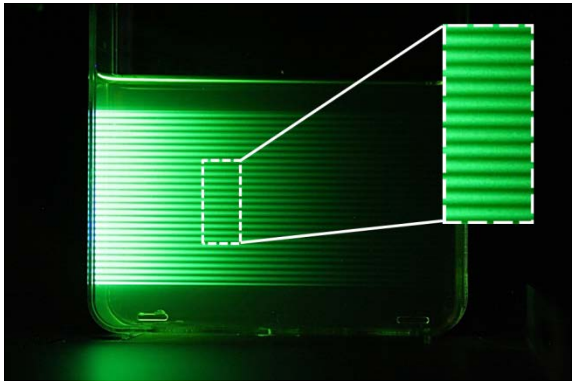
Does not work for laser sheet imaging

How to remove MS in laser sheet imaging?

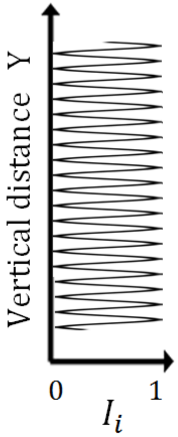
Conventional laser sheet
-
Homogeneous spatial intensity profile

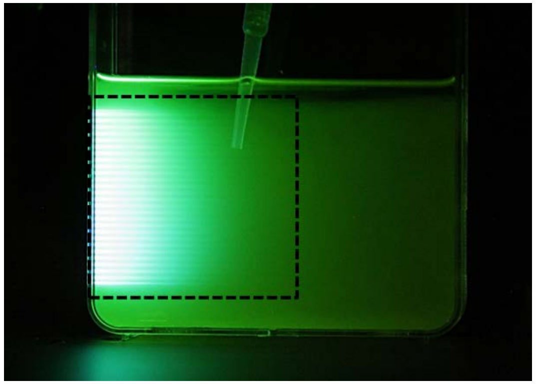


Structured laser sheet
-
Spatially modulated intensity profile

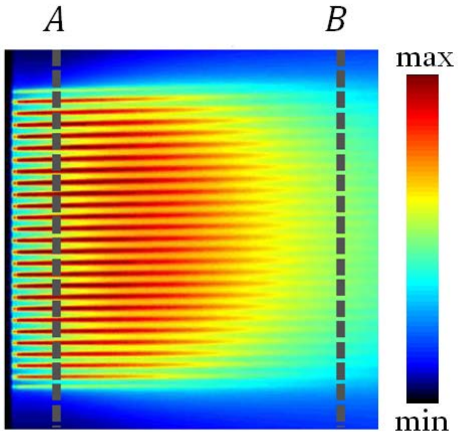


Incident modulation

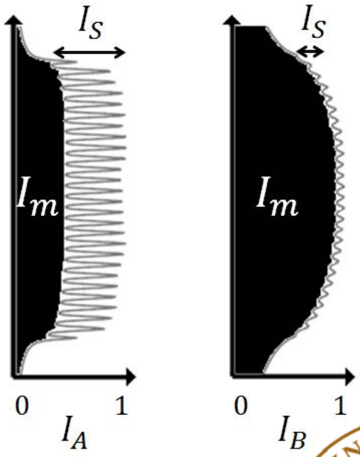




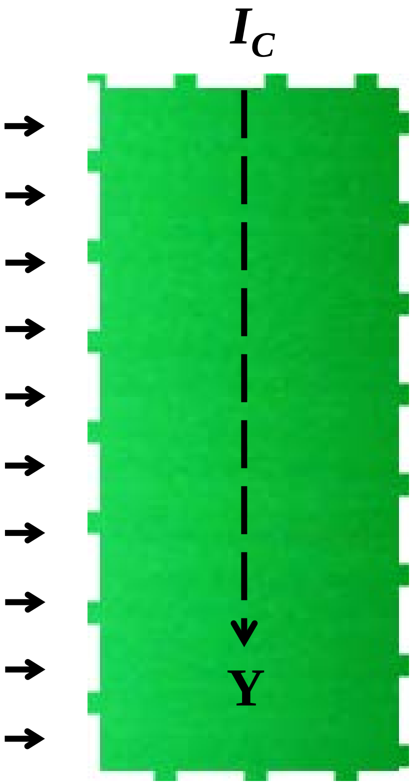
Structured laser sheet through a scattering medium

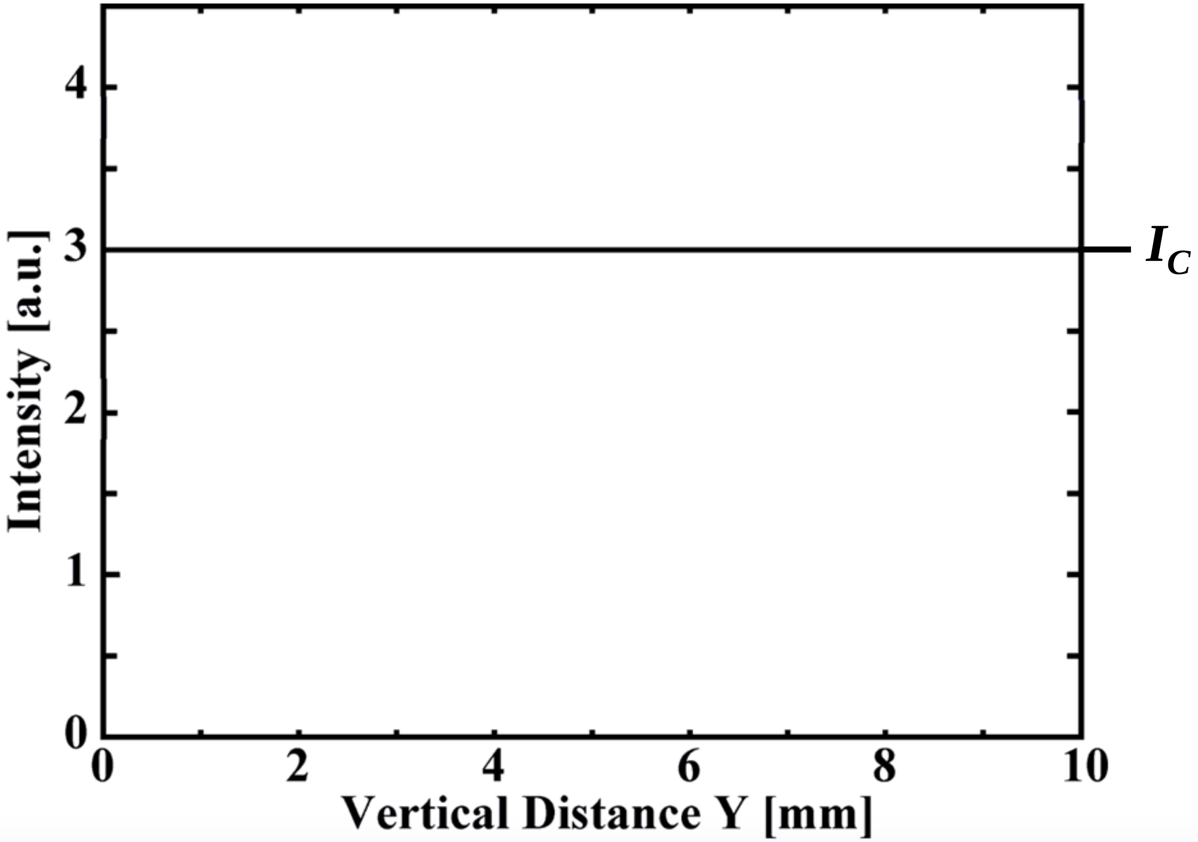


Imaged modulations



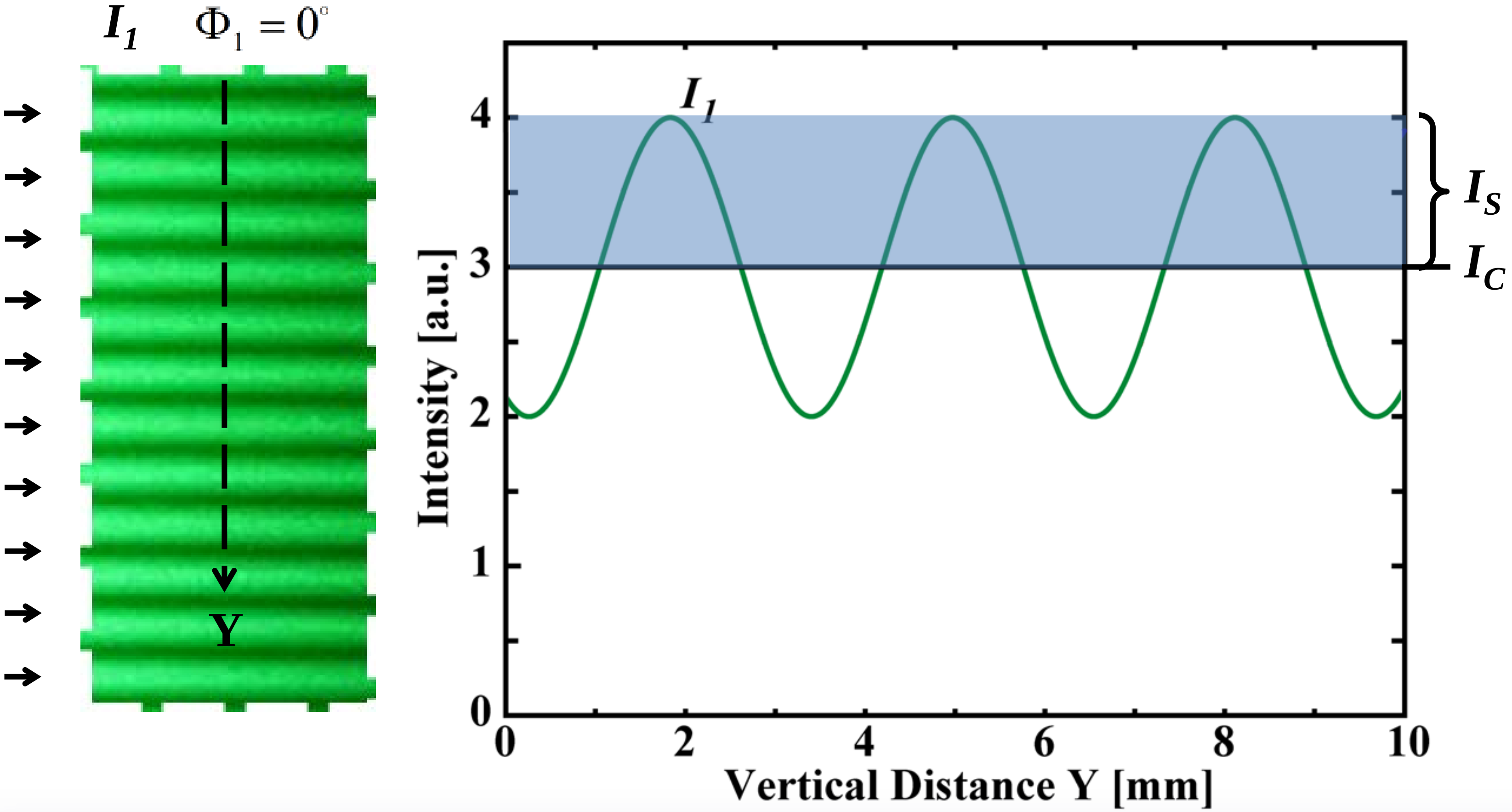
How to remove MS in laser sheet imaging?





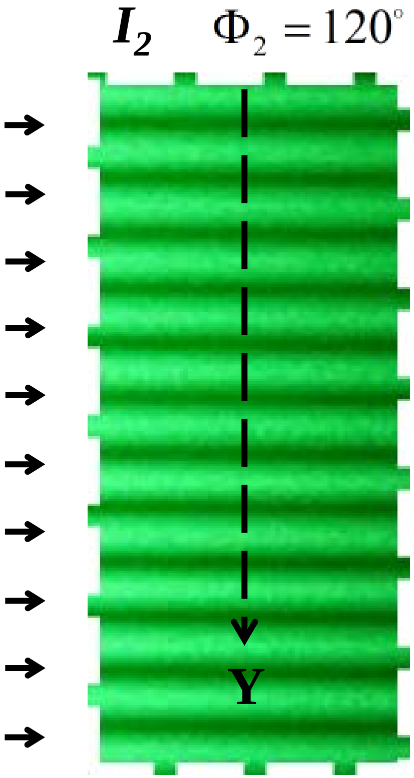
How to remove MS in laser sheet imaging?

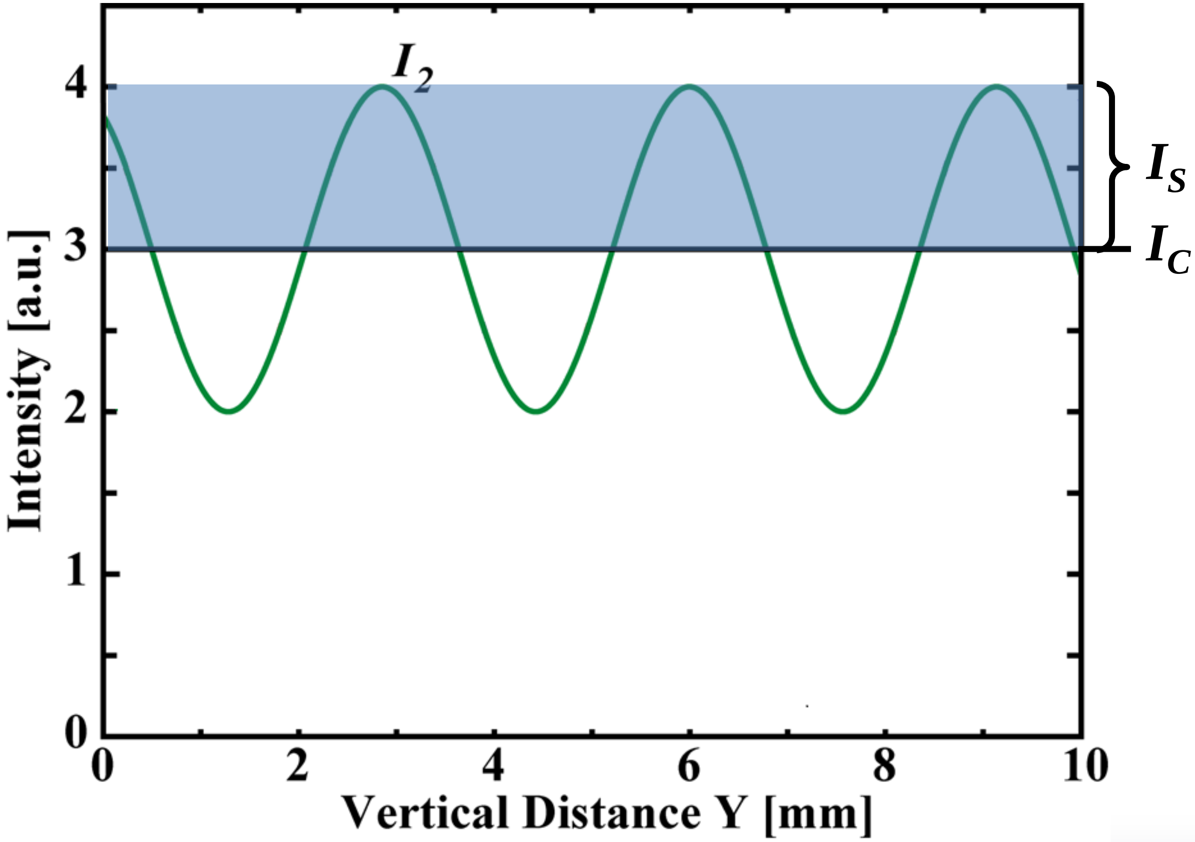
$$I_1 = I_C + I_S \cdot \cos(2\pi\nu y + \Phi_1)$$



How to remove MS in laser sheet imaging?

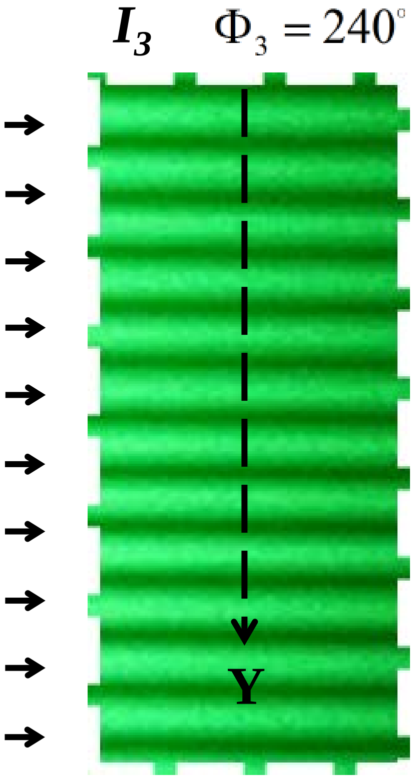
$$I_2 = I_C + I_S \cdot \cos(2\pi \nu y + \Phi_2)$$

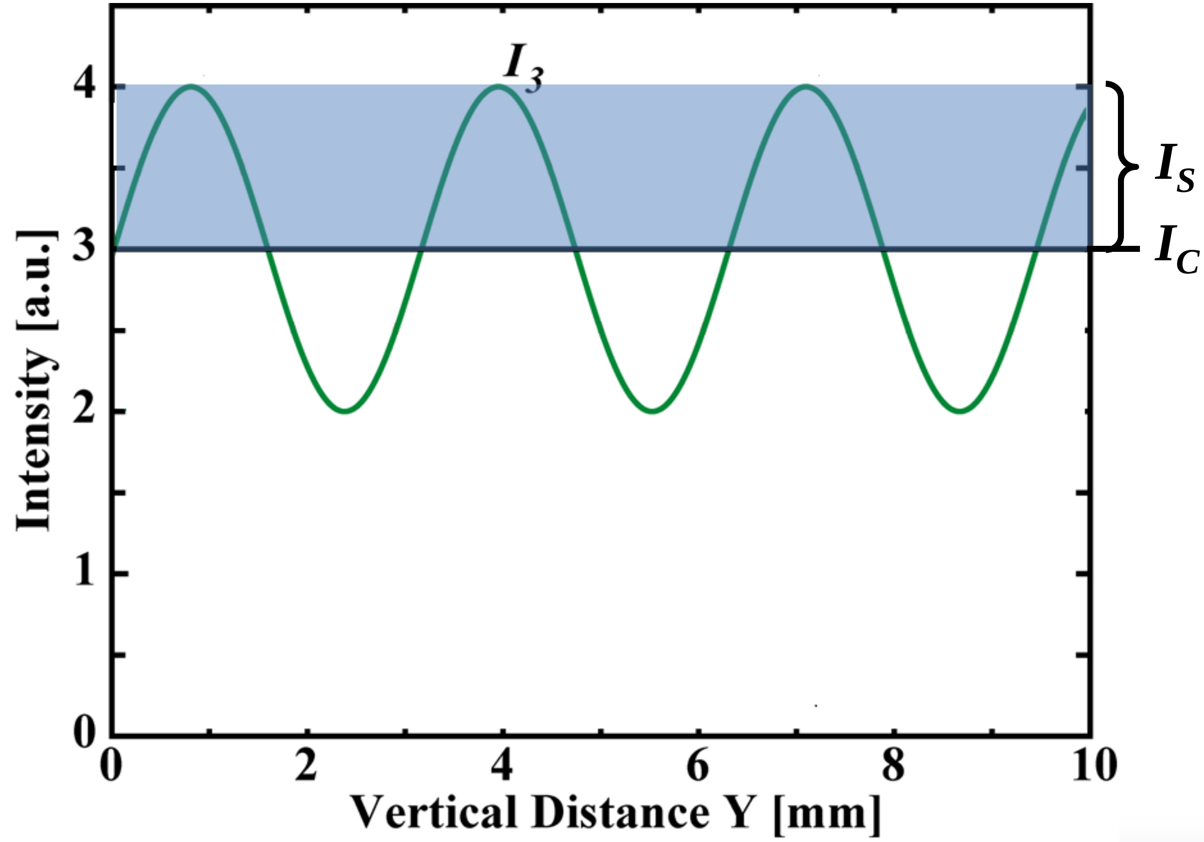




How to remove MS in laser sheet imaging?

$$I_3 = I_C + I_S \cdot \cos(2\pi \nu y + \Phi_3)$$

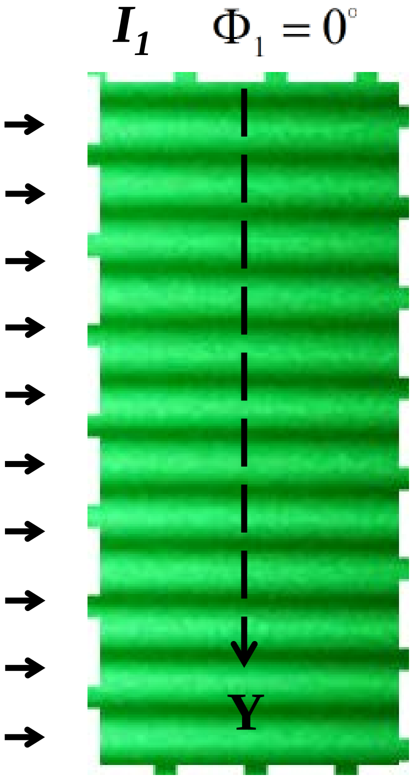


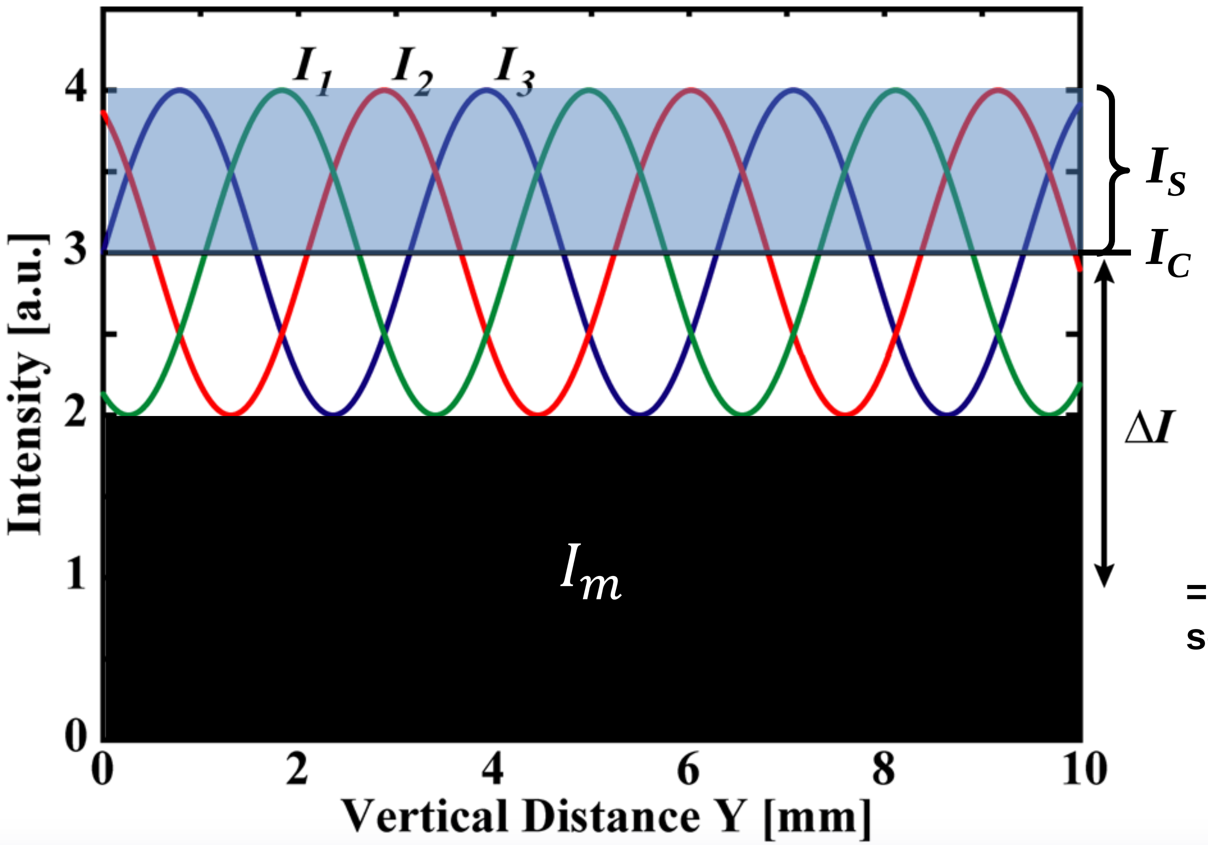


How to remove MS in laser sheet imaging?

$$I_1 = I_C + I_S \cdot \cos(2\pi \nu y + \Phi_1)$$

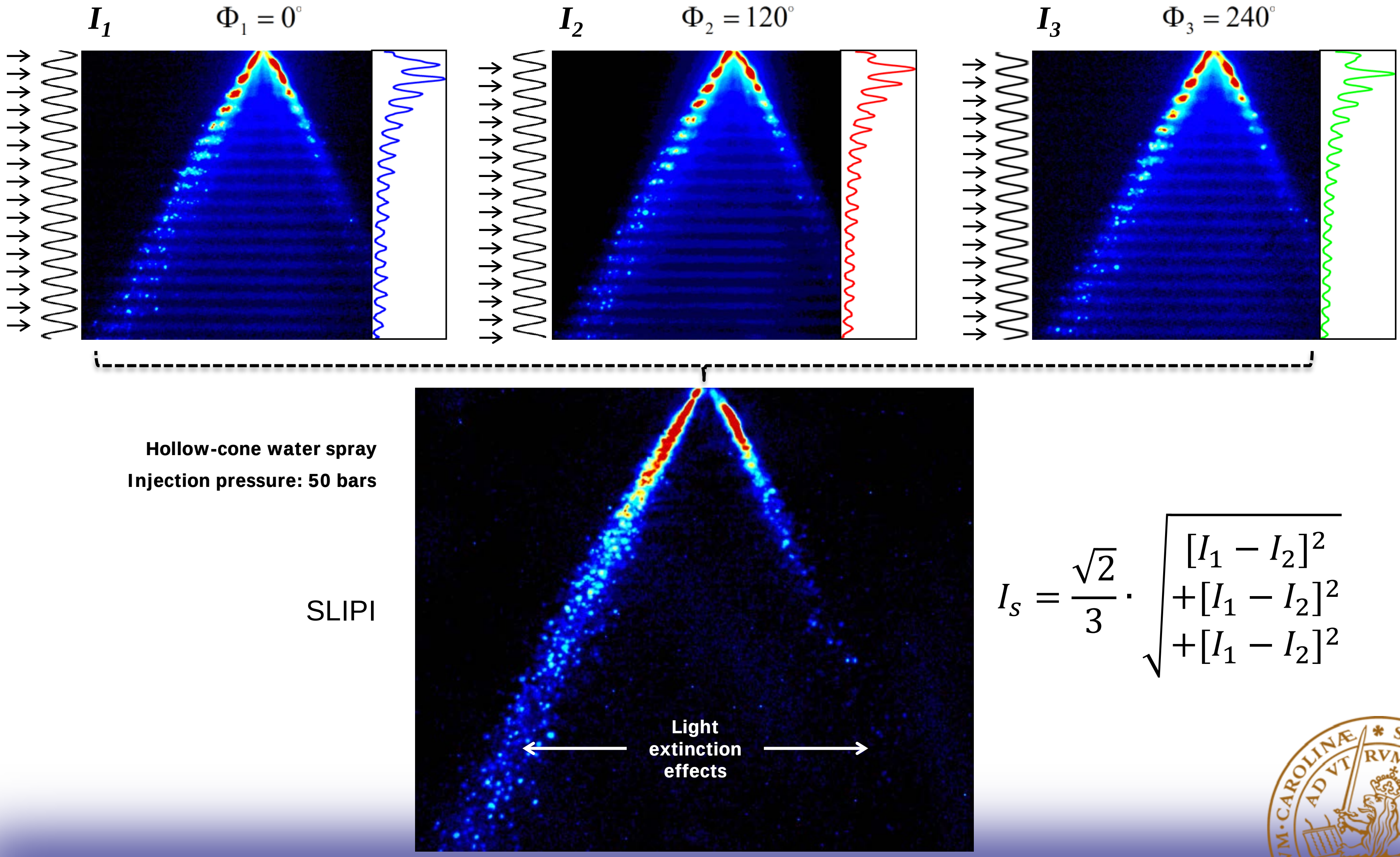
$$I_S = \frac{\sqrt{2}}{3} \cdot \sqrt{[(I_1 - I_2)^2 + (I_1 - I_3)^2 (I_2 - I_3)^2]}$$





= Multiple scattering

Structured Laser Illumination Planar Imaging



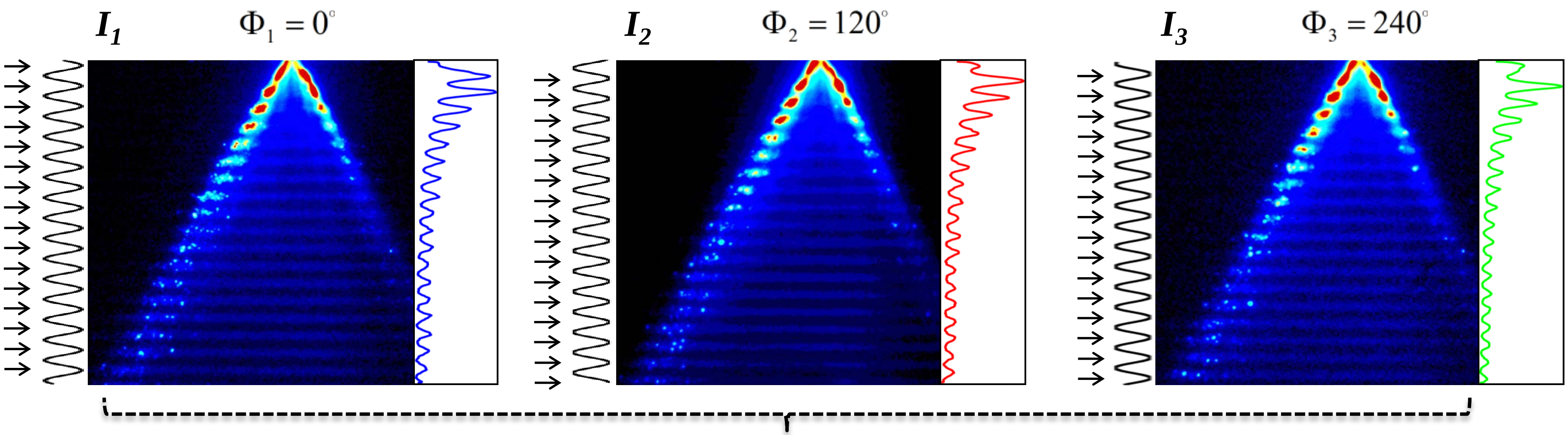
Hollow-cone water spray

Injection pressure: 50 bars

SLIPI

$$I_S = \frac{\sqrt{2}}{3} \cdot \sqrt{\begin{array}{l}[I_1 - I_2]^2 \\ +[I_1 - I_2]^2 \\ +[I_1 - I_2]^2\end{array}}$$

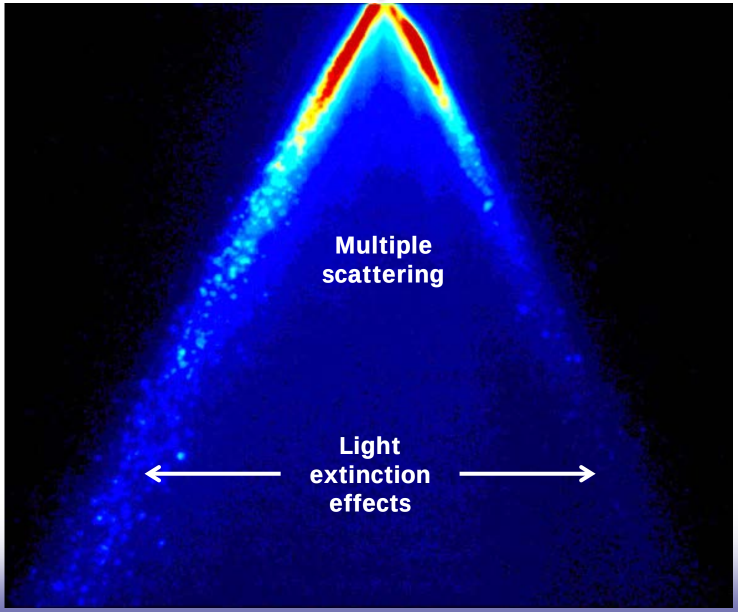
Structured Laser Illumination Planar Imaging



Hollow-cone water spray

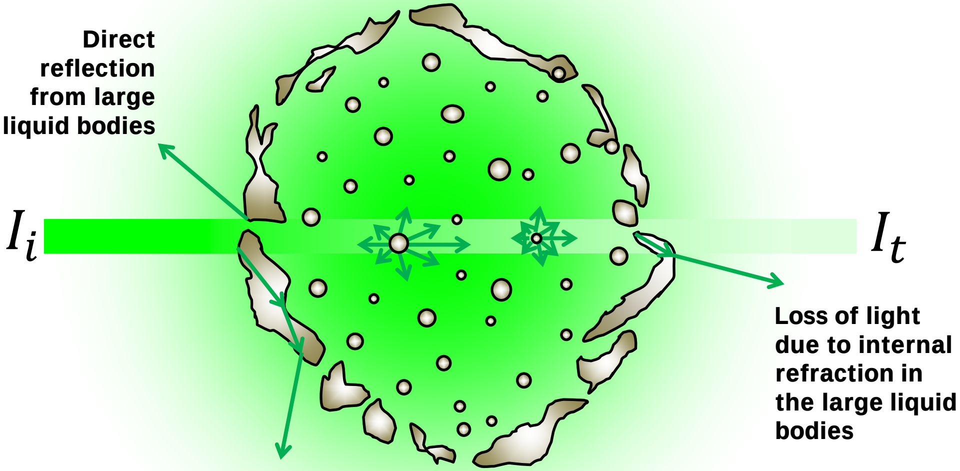
Injection pressure: 50 bars

Conventional laser sheet imaging



$$I_c = \frac{I_1 + I_2 + I_3}{3}$$

Light transmission in the spray formation region



Direct reflection from large liquid bodies

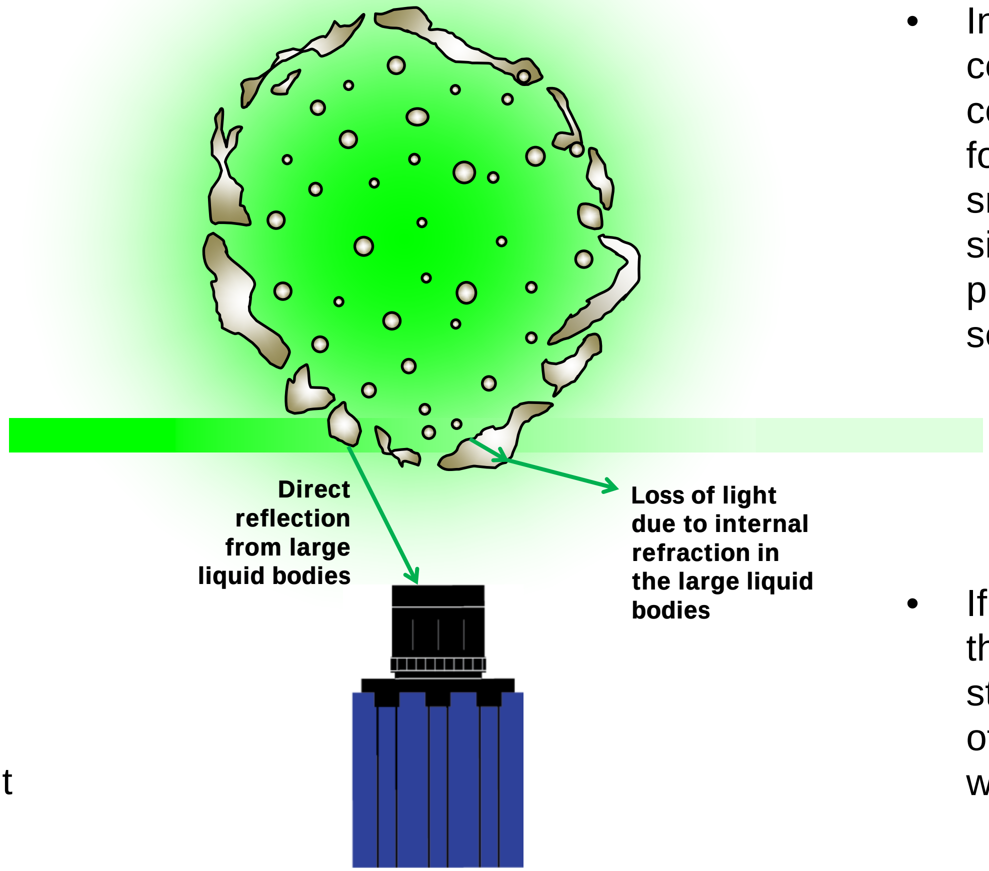
Loss of light due to internal refraction in the large liquid bodies

Spray formation region

Transmission: $I_t/I_i = ???$

- In the spray formation region, light is strongly reflected and refracted by the presence of large liquid bodies and ligaments; creating distinct shadows of those structures
- However, the system cannot be considered as a cloud of spherical droplet with well-defined extinction cross section.
- Thus, the loss of light intensity is not related to the extinction cross-section from spherical droplets. Thus, the light transmission cannot be deduces from the Beer-Lambert law and the optical depth has, in this case, “no meaning”.

Laser sheet imaging in the spray formation region



- In such optical configuration, the contribution of out-of-focus light is much smaller than for line-of-sight detection, thus providing clearly sectioned images

- By positioning the light sheet on the spray periphery, toward the camera objective, the effects due to multiple light scattering can be reduced

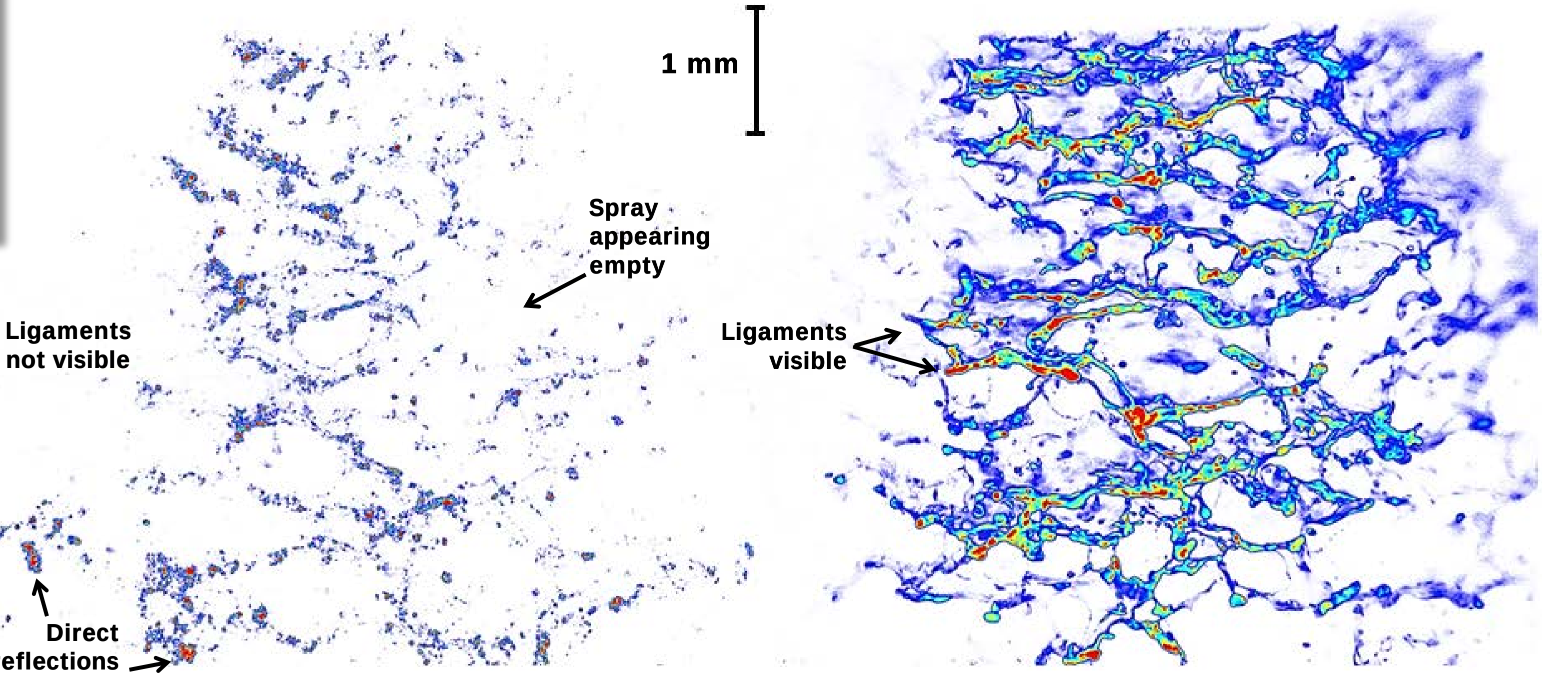
- If the light sheet is thinner than the liquid structures, then a “cut” of those structures would be obtained

Laser sheet imaging in the spray formation region

Scattered light

P=20 bars

Liquid fluorescence



Spray appearing empty

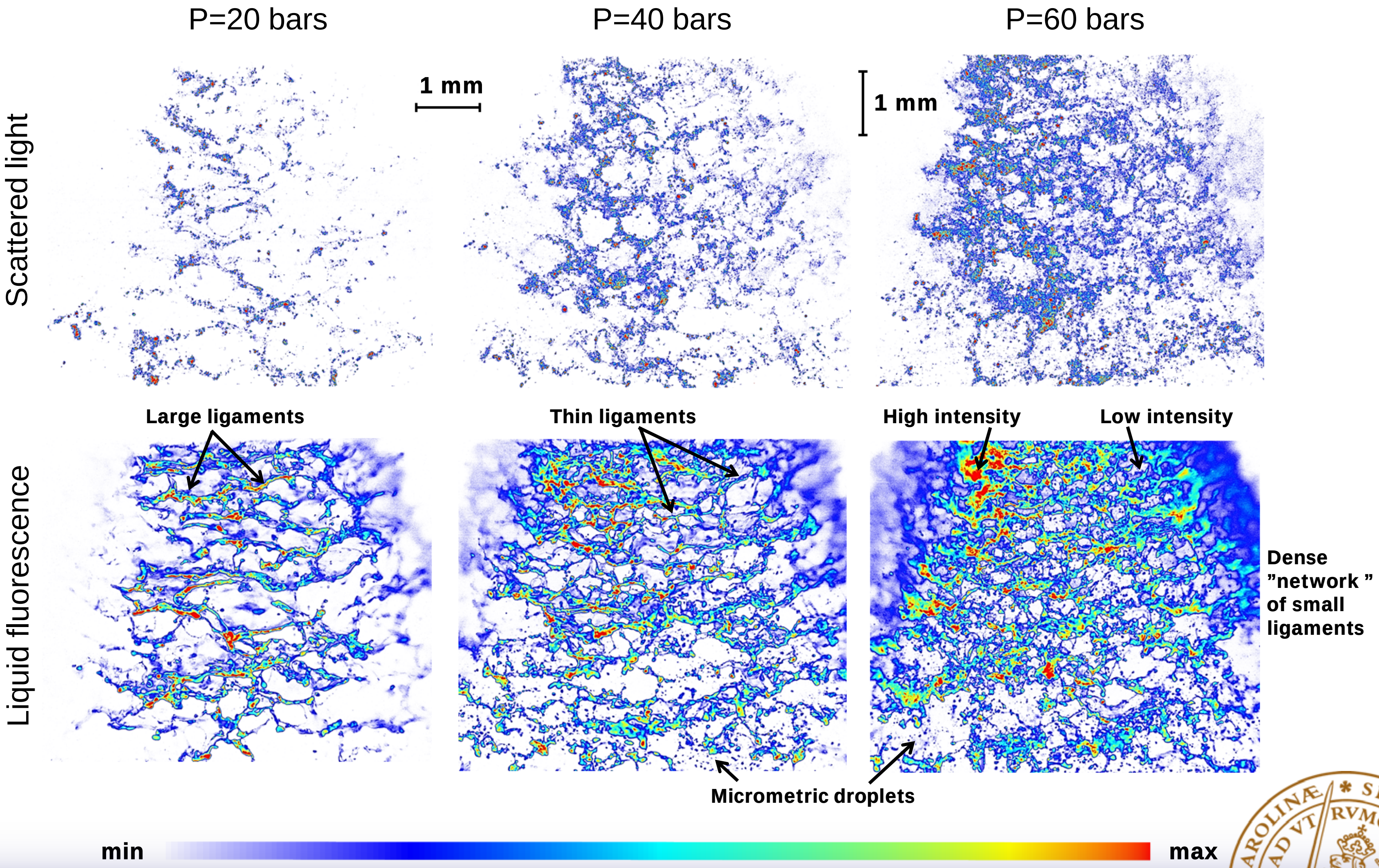
Ligaments not visible

Ligaments visible

Direct reflections saturating the camera

- The scattered light is generated at the air-liquid interfaces. In laser sheet imaging, the scattered light does not provide a faithful representation of the irregular liquid structures.
- The fluorescence signal is emitted by the fluorescing dye molecules inside the liquid itself. Liquid fluorescence gives, in laser sheet imaging, a faithful representation of the structure of liquid bodies and ligaments.

Laser sheet imaging in the spray formation region



Summary

- **Spray imaging is a topic of strong interest since 1920th**
- **Back scattering, shadowgraphy and laser sheet imaging configurations have been compared**
- **Light propagation in the spray region has been described**
- **Three scattering regimes have been identified depending on the value of the optical depth - OD**
- **Approaches to describe light scattering by a single droplet have been summarized**
- **The effects of multiple light scattering have been highlighted**
- **Strategies to reduce or suppress multiple scattering effects have been mentioned**
- **The effects of laser extinction and signal attenuation have been highlighted**
- **The Monte Carlo approach has been introduced for simulating light propagation through a cloud of droplets**
- **The *Multi-Scat* software been mentioned**
- **Artifacts induced by direct reflection and refraction in the spray formation have been shown**
- **Liquid fluorescence is more faithful to the spray structures for imaging the spray formation region with laser sheet imaging**