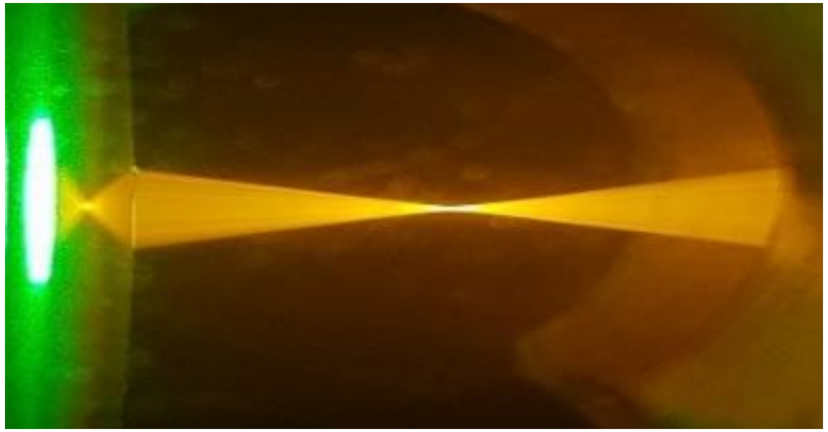
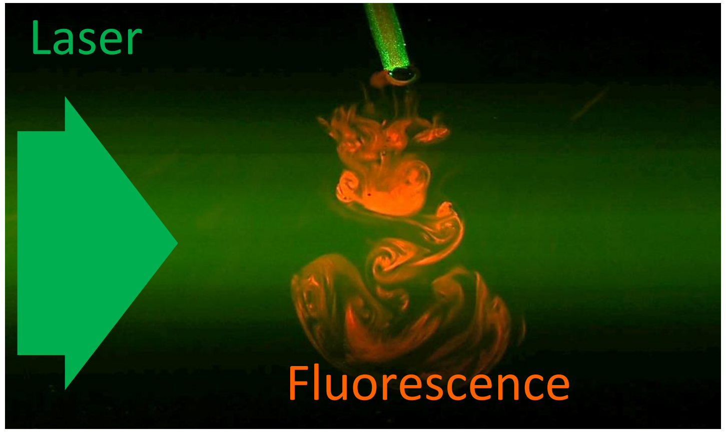
Fluorescence imaging : strength and limits

L'imagerie de fluorescence : forces et limites de l'outil

Romain Collignon, Guillaume Castanet, Ophélie Caballina, Fabrice Lemoine





Why use laser induced fluorescence ?

Spectroscopic method

- Non intrusive
- Low detectivity threshold : only a few ppm of fluorescent species are needed
- Really short response time : $\sim 10^{-9}\ s$

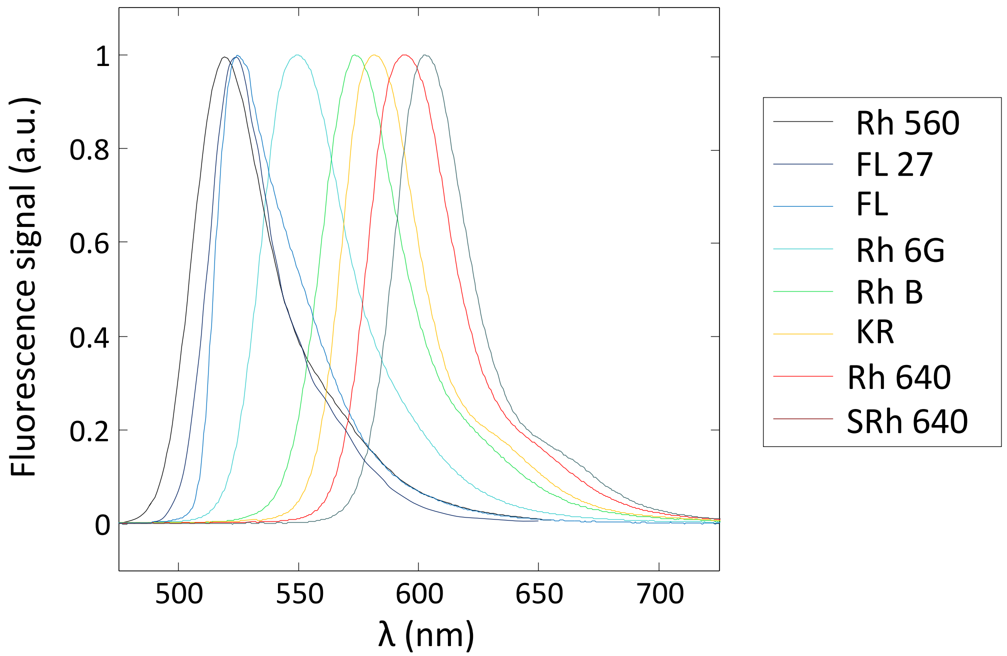
Applications

- Gaseous flow : measurement of concentration, temperature, pressure, presence of a specie
- Liquid flow : measurement of concentration, temperature, separate multiphase flows

Need of a fluorescent dye

Gaseous flow

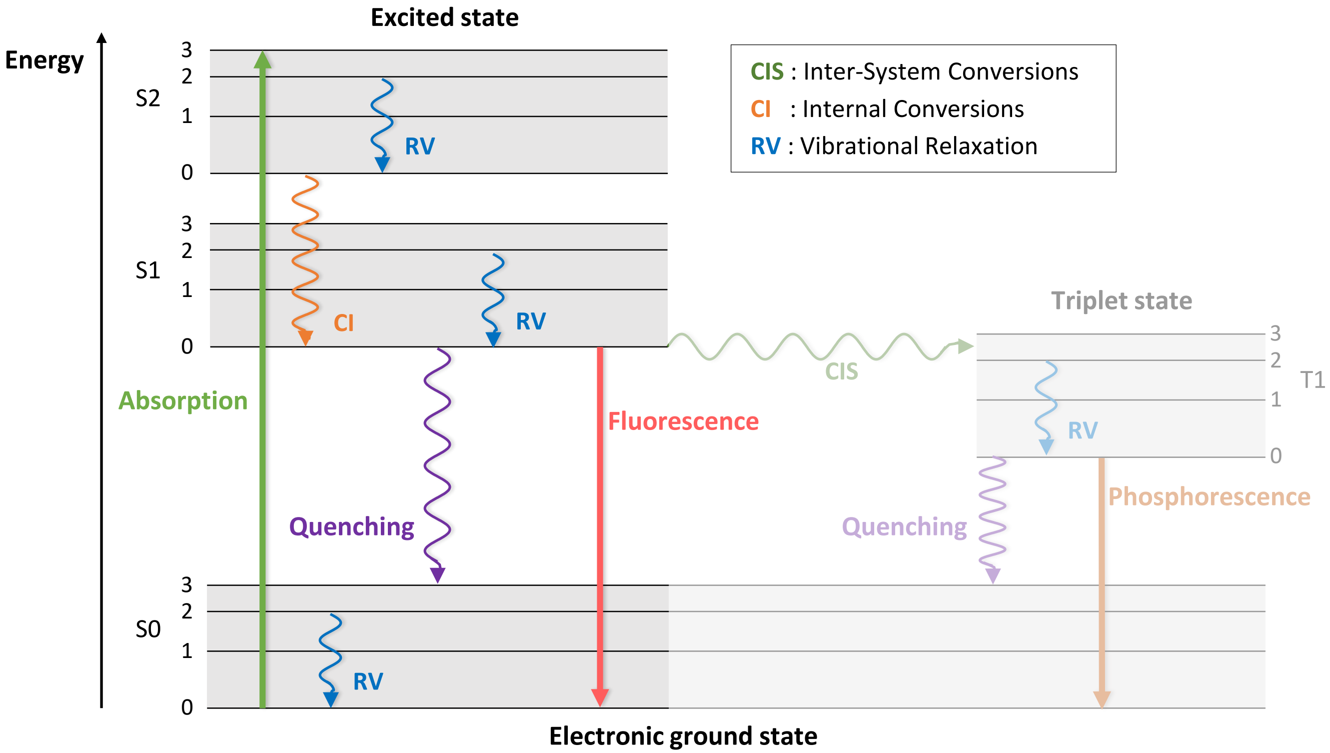
- **Added dyes** : Diacetyl, ketones, benzenes
- **Natural dyes** : OH, NOx (from combustion)

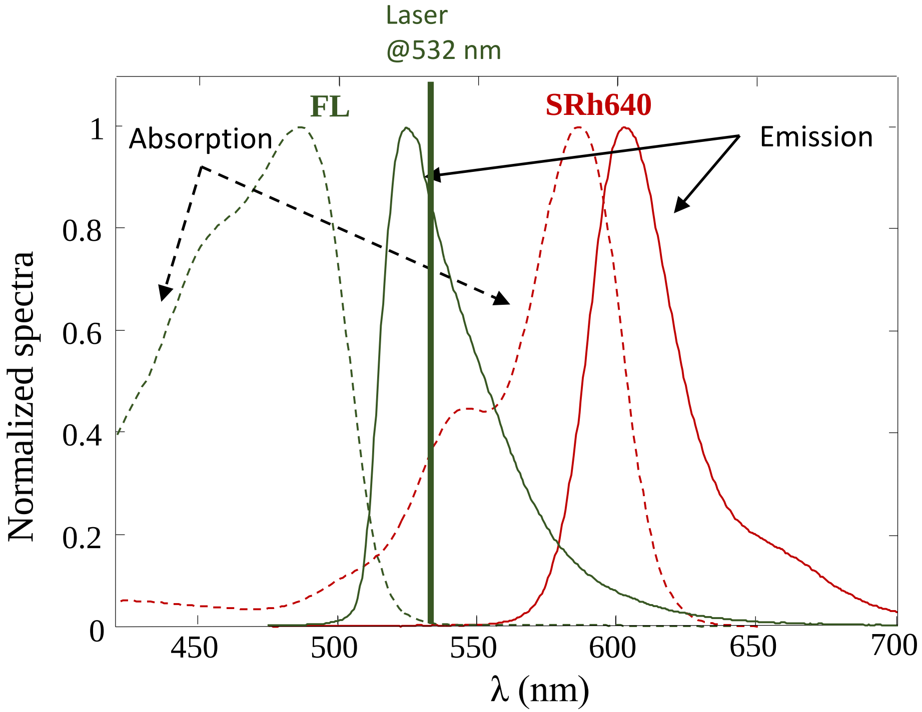


Liquid flow

- **Organic dyes** : rhodamines, fluoresceins, coumarins (mostly for water or alcohols)
- **Aromatic compounds** : ketones, benzenes

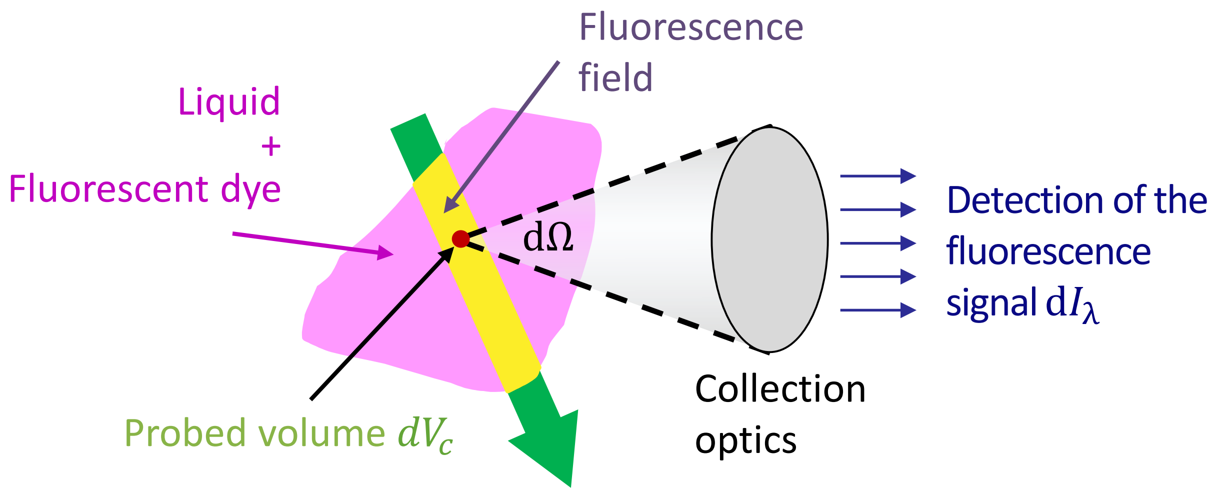
What is fluorescence?





- Fluorescence is one of the means of transition to a more stable electronic state
- Other means include :
  - Vibrating and Rotating conversions
  - Quenching

Laser Induced Fluorescence modeling



LIF principle

- Mixing with a fluorescent dye
- Excitation using a laser
- Measurement of the fluorescence intensity

Fluorescence intensity model

$$dI_\lambda = K_\lambda C I_0 dV_c \varepsilon_{laser} \phi$$

Dye concentration (C)

Laser intensity (I_0)

Probed volume (dV_c)

Absorption coefficient (ε_{laser})

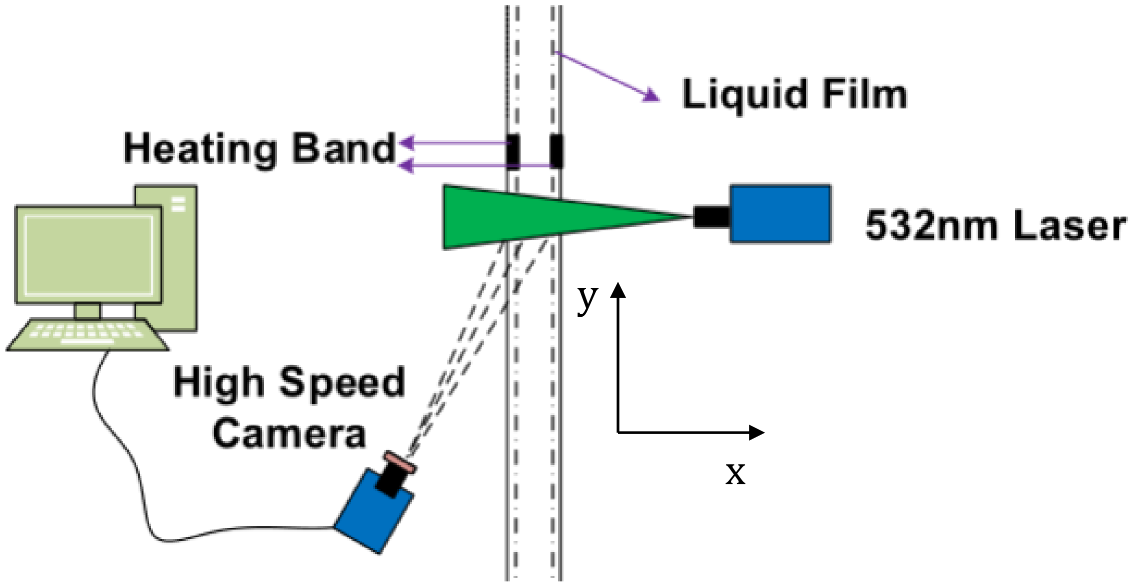
Quantum yield (ϕ)

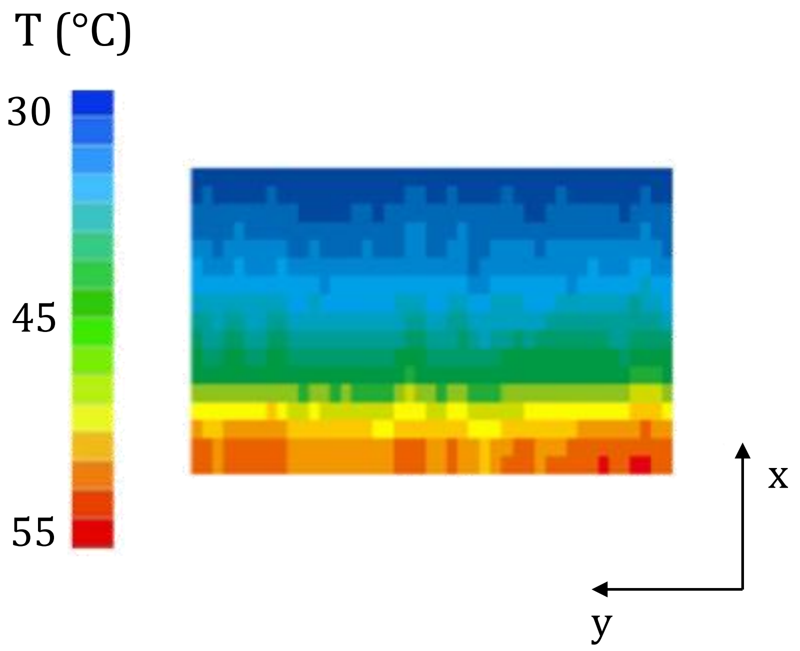
Function of the state of the fluid
(temperature, pressure, mixture)

Different for each dye

Example of 1c-LIF method : vertical film

T. Xue, S. Zhang
International Journal of Heat and Mass Transfer 126, 2018.



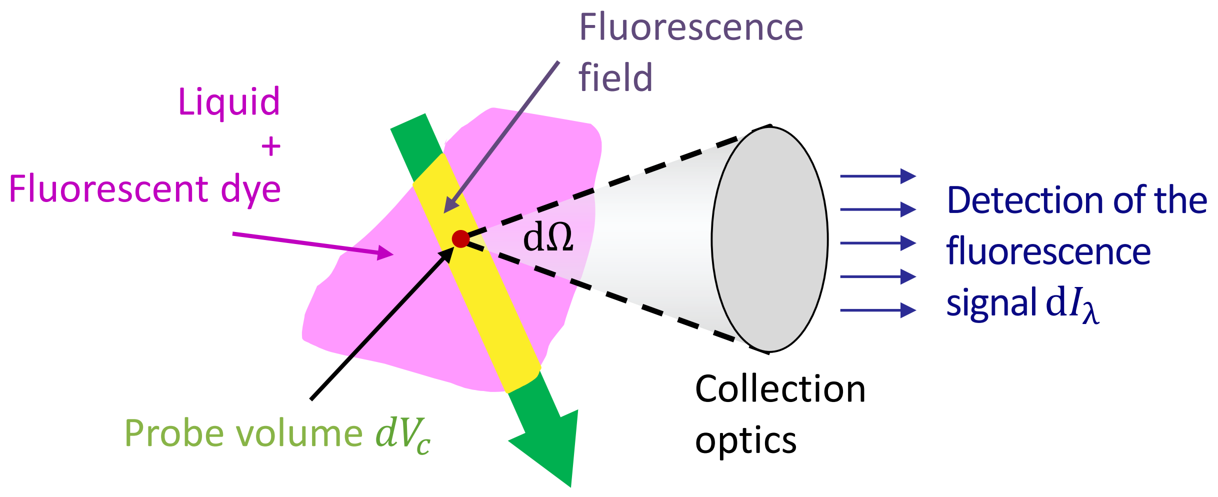


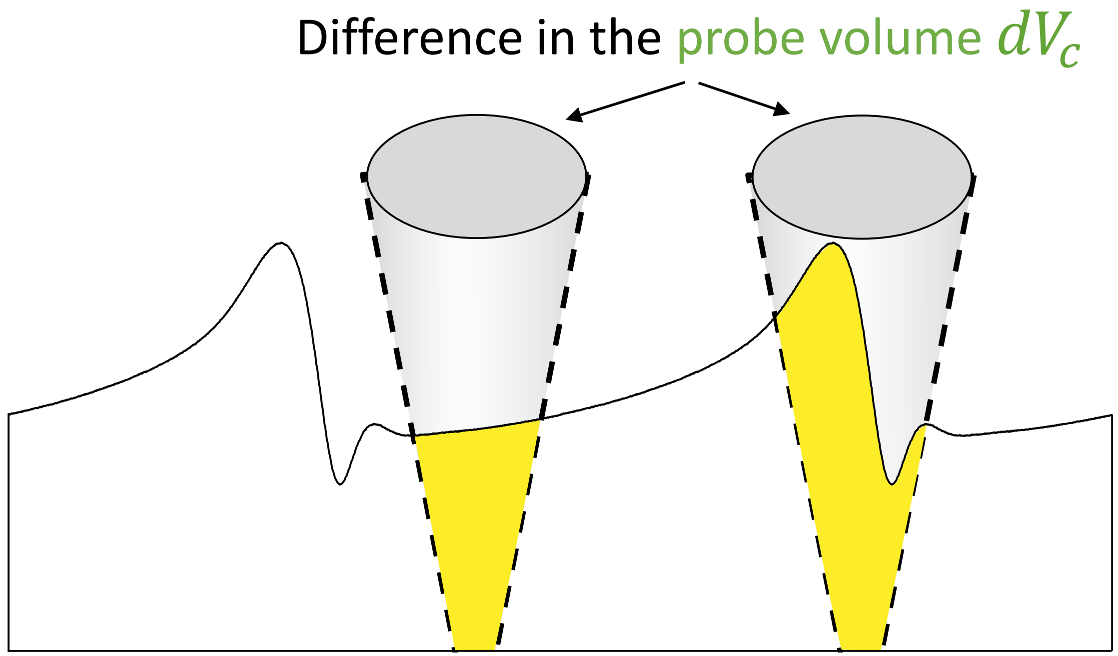
Integrate the full signal of 1 dye (rhodamine B)

Dependency to any geometrical variation

- Limited to flat film

Difficulty with moving interfaces



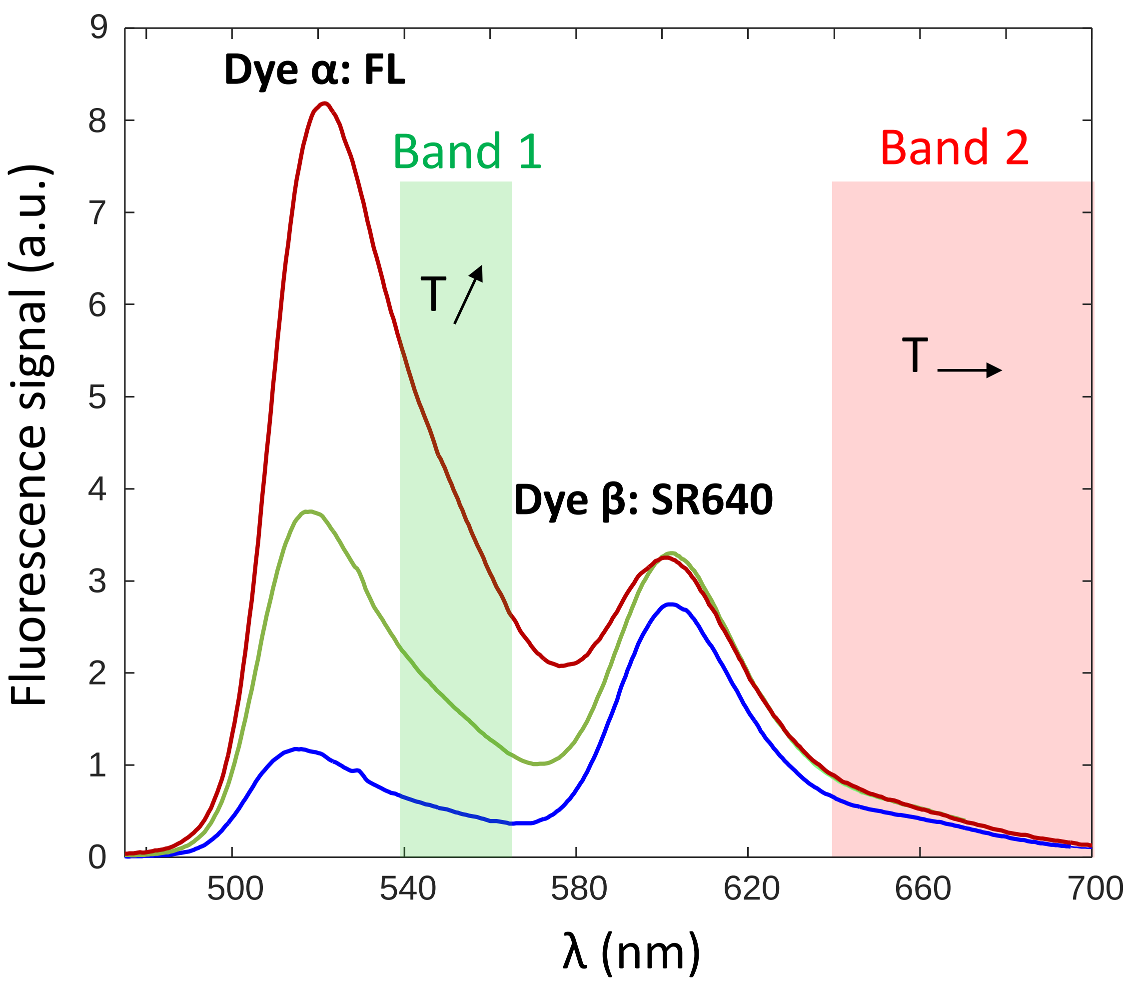


The use of fluorescence intensity dI_λ alone may limit the measurement capacities

⇨ **Ratiometric method**

Two-color ratiometric method for temperature

Dye mixture used in the two-color measurement method : FL and SR640



- Signal intensity on Band 1

$$I_1 = K_1\, I_0\, V_C\, C_\alpha\, f_1(T)$$

- Signal intensity on Band 2

$$I_2 = K_2\, I_0\, V_C\, C_\beta\, f_2(T)$$

- Ratio of the fluorescence intensities

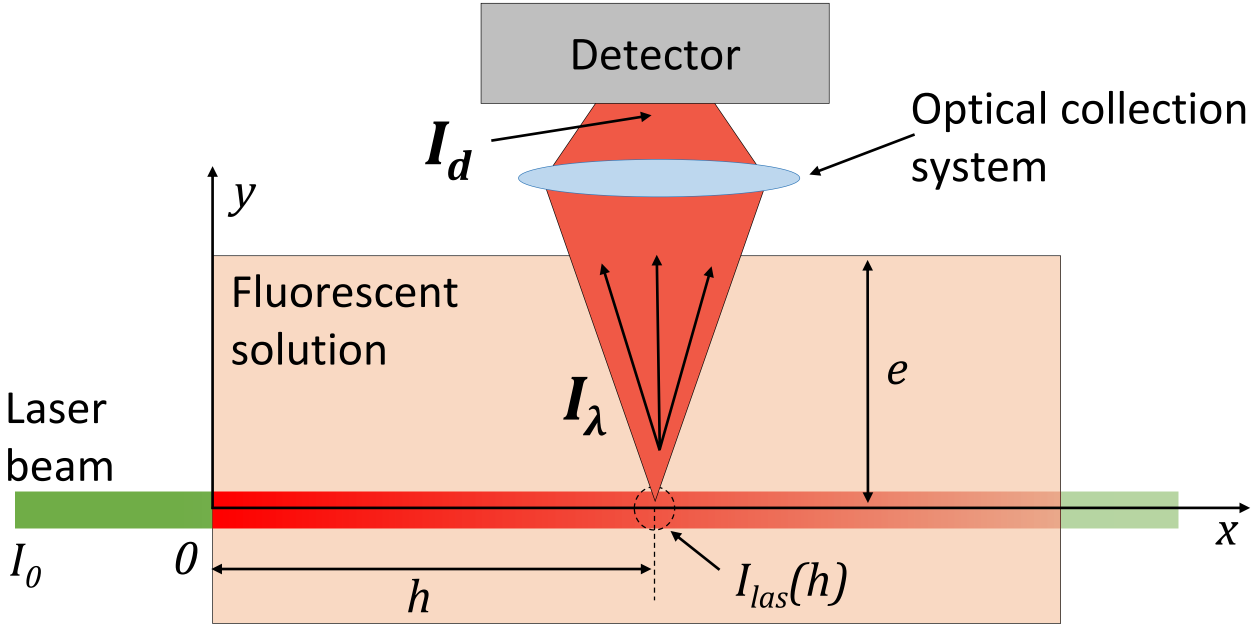
$$R = \frac{I_1}{I_2} = \frac{K_1\, I_0\, V\, C_\alpha\, f_1(T)}{K_2\, I_0\, V\, C_\beta\, f_2(T)}$$

$$R = K\, f_1(T)/f_2(T)$$

(need a reference and a calibration)

Absorption of incident light by the fluorescent dye

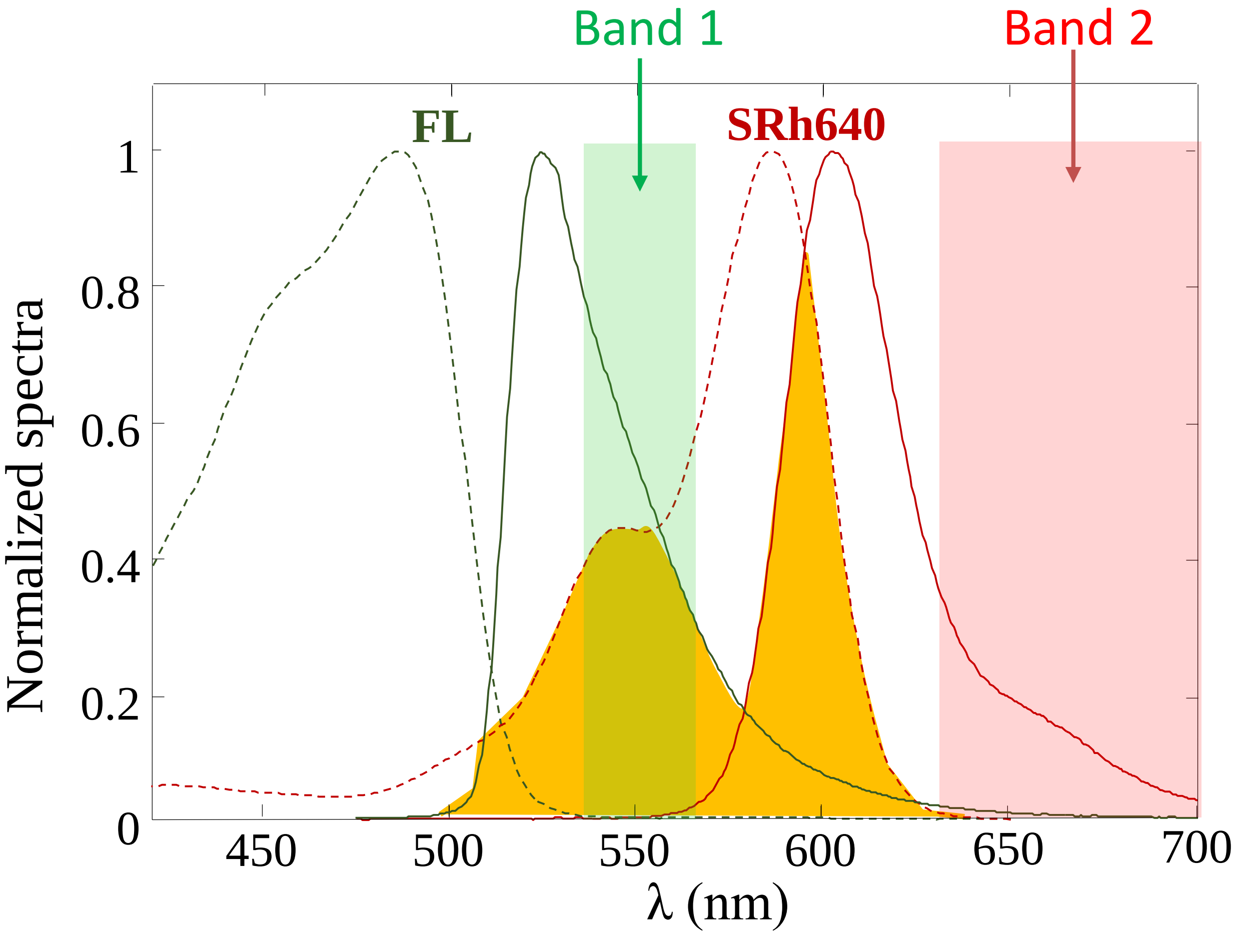
Light travelling in a seeded solution is absorbed following a Beer-Lambert law



$$I_{las}(h) = I_0 \cdot e^{-C \cdot \varepsilon_{laser} \cdot h}$$

$$I_d = K_{opt,\lambda} \cdot I_\lambda(h) \cdot e^{-C \cdot \varepsilon_\lambda \cdot e}$$

Auto-absorption of fluorescence by a dye



SRh640 strongly absorbs both **FL** and **SRh640** emissions

SRh640 absorption is important on **FL** spectral band

Extra care is needed when choosing the dyes concentrations to limit the influence of absorption

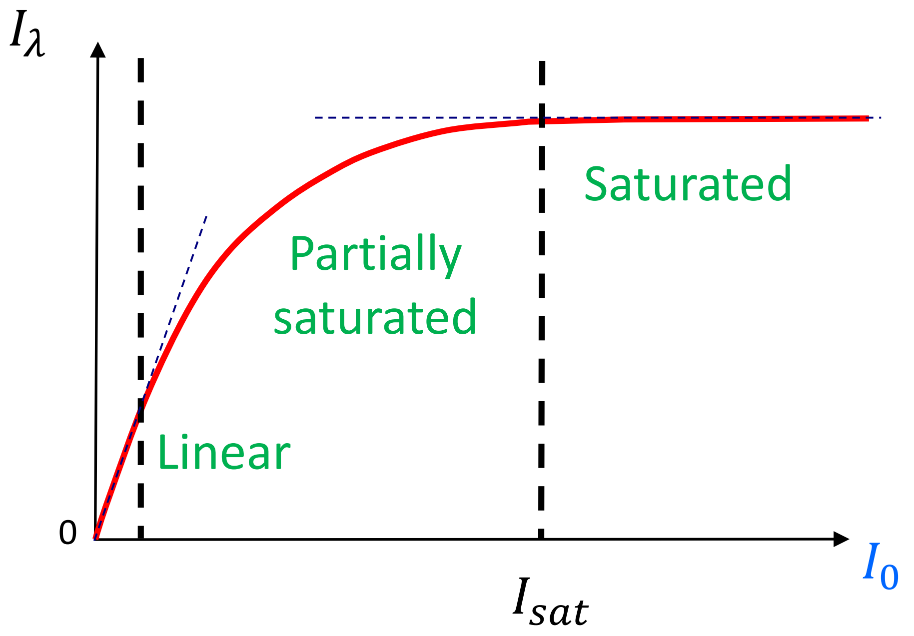
Bound by the length the light has to travel in the absorbing media

- typically ~10^{-5} mol/L for fluid domain of 1 mm

The saturation of the fluorescence

When using a pulsed laser, I_0 becomes really high.

$$dI_\lambda = K_\lambda C I_0 dV_c \varepsilon_{laser} \phi$$

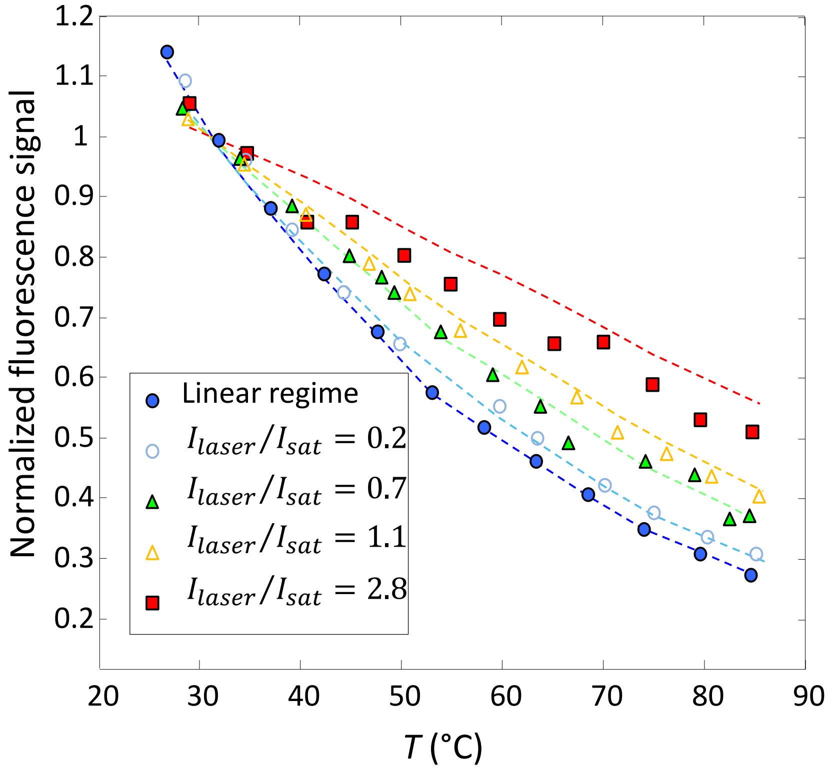


Some dyes lose their dependence to the state of the system, due to the diminishing impact of ϕ, particularly for rhodamines
(e.g. to temperature as a result of increased quenching)

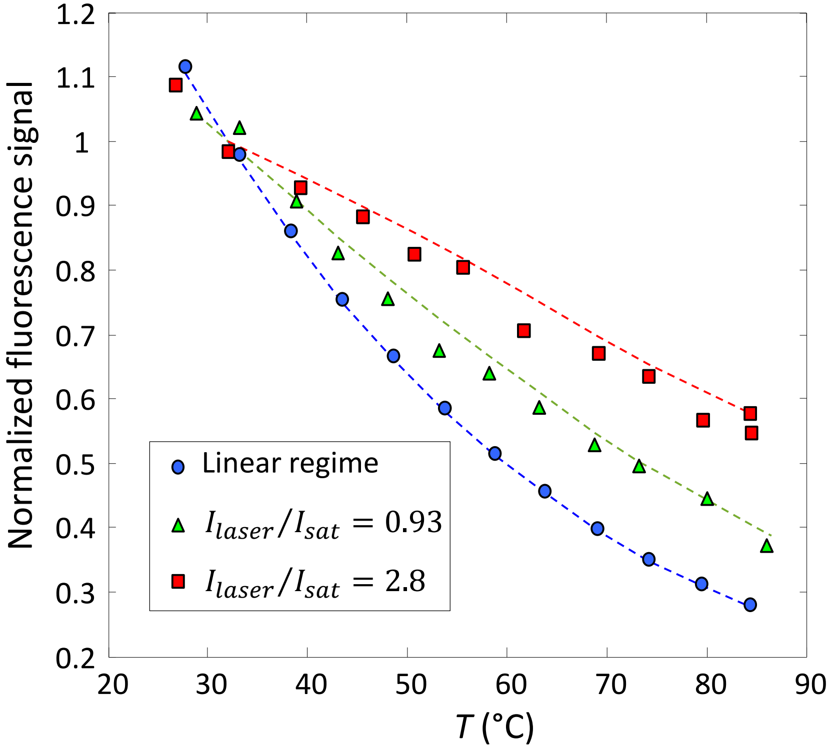
The choice of dye is reduced for LIF imaging when using high power laser source

Influence of laser intensity saturation on the dyes : loss of sensitivity

Rhodamine B



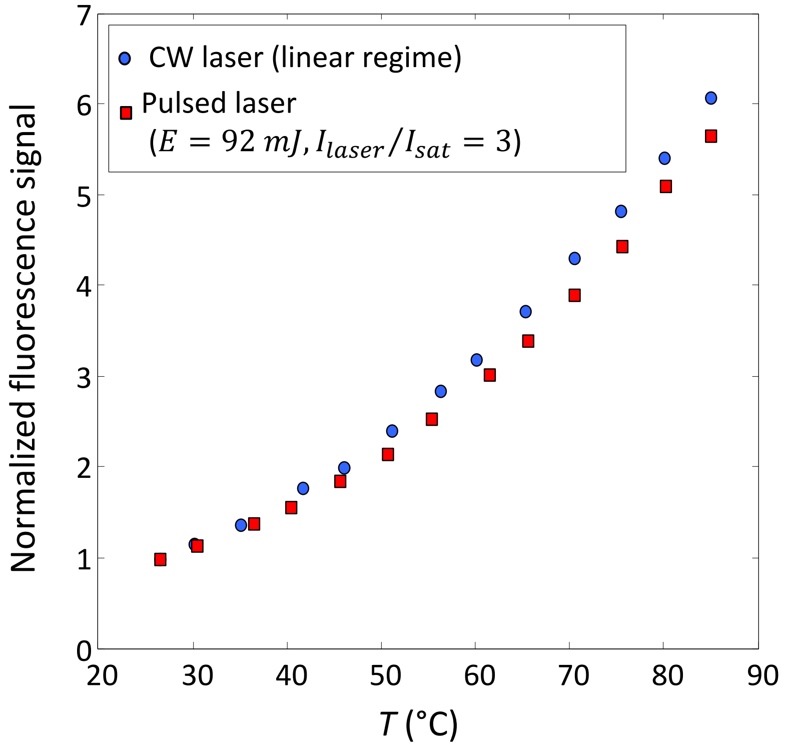
Kiton Red



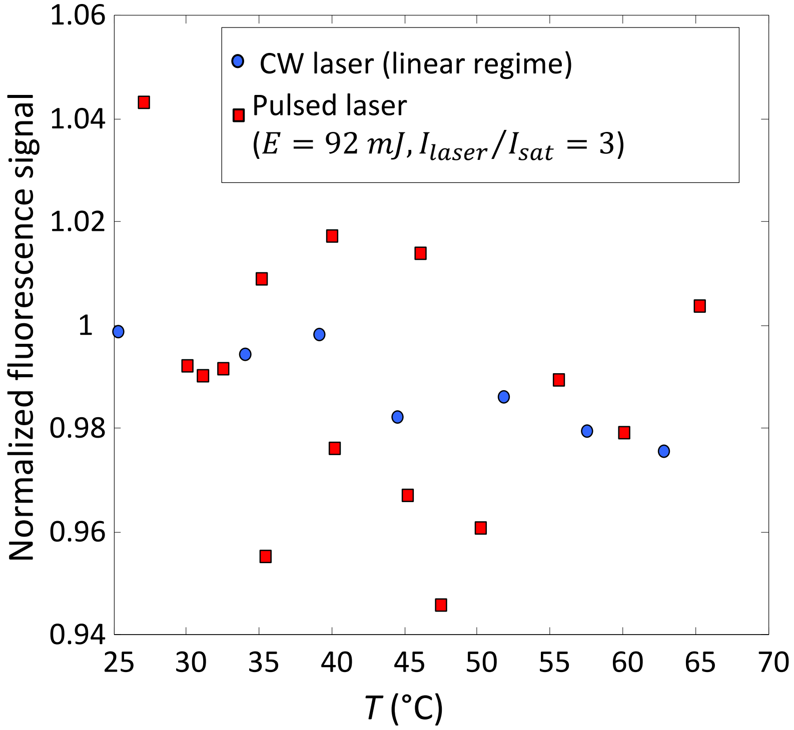
$\varepsilon_{laser}(T) \approx$cst $\qquad I_{sat}(T) \nearrow \qquad \phi(\mathrm{T}) \searrow$

Influence of laser intensity saturation on the dyes : no loss

Fluorescein

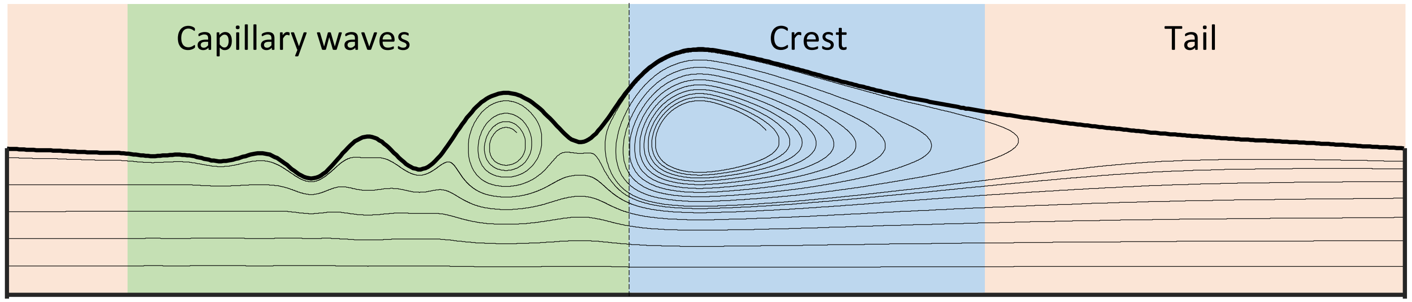


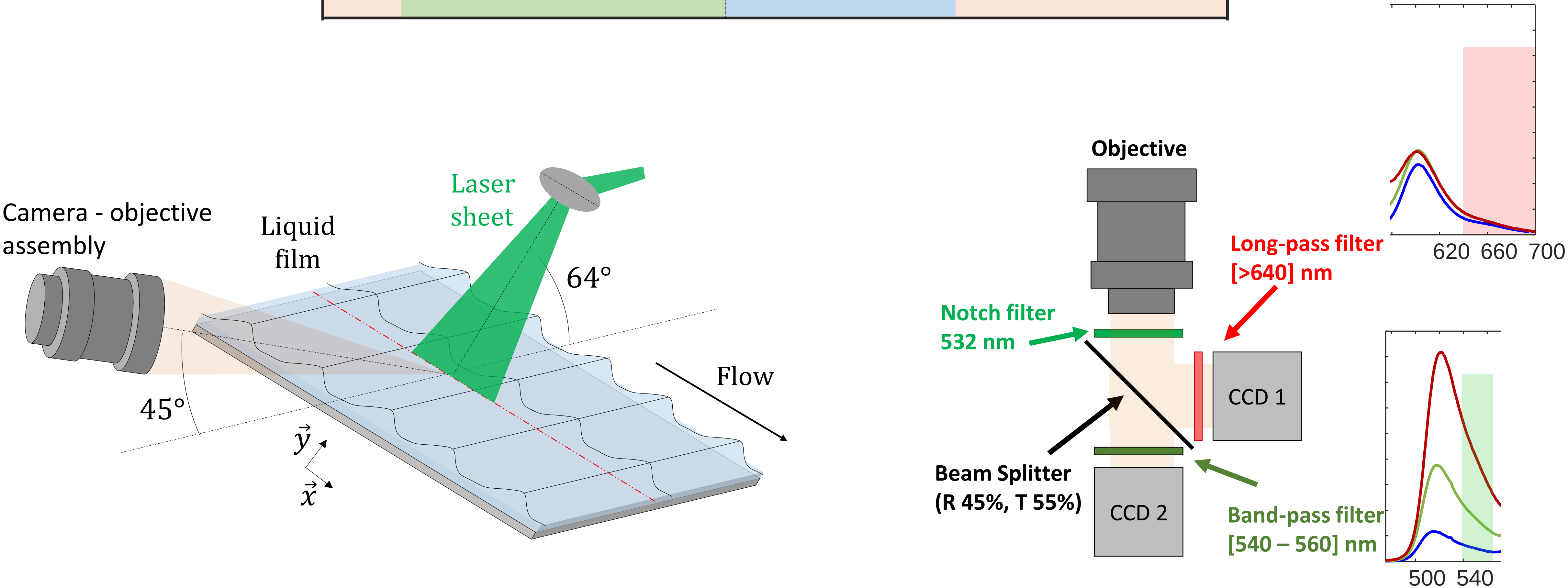
Sulforhodamine 640



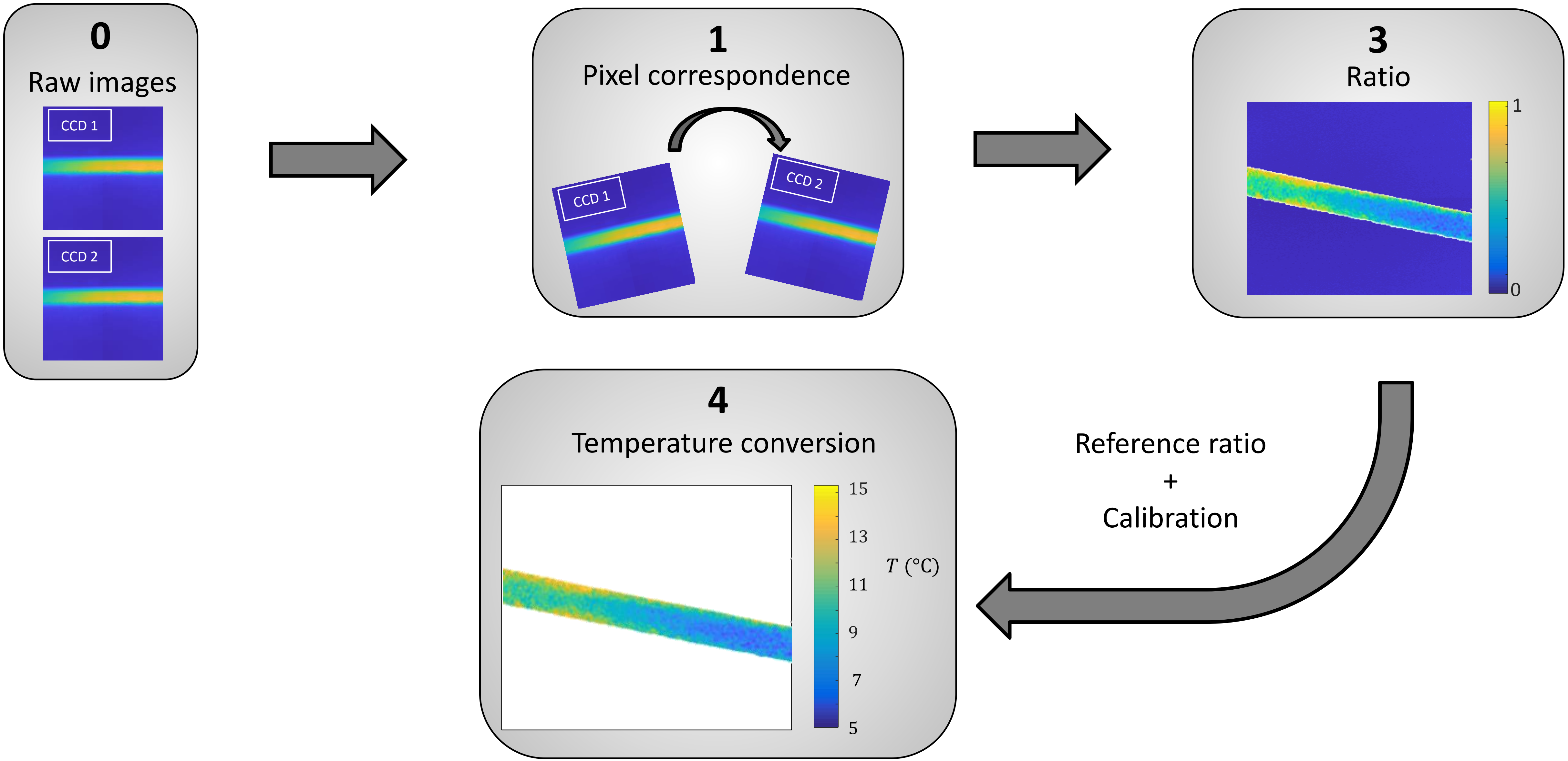
$$I_{sat}(T) \approx cst \qquad \phi(\mathrm{T}) \approx cst$$

Example of LIF temperature imaging : falling film



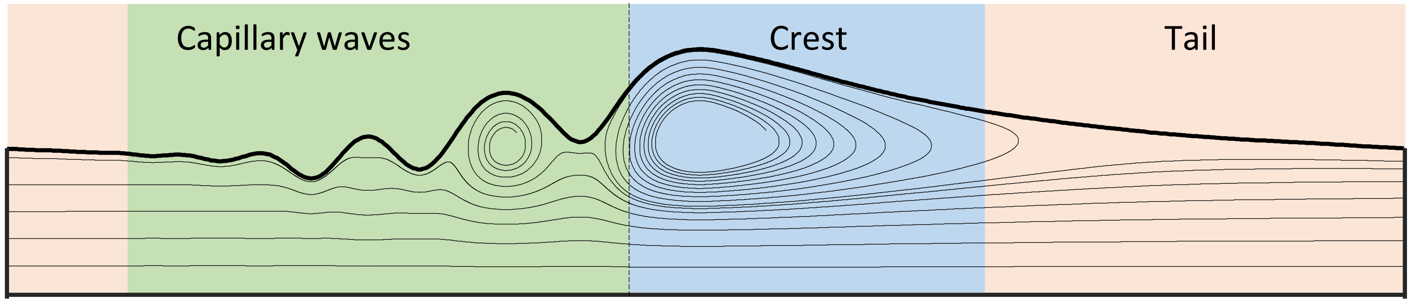


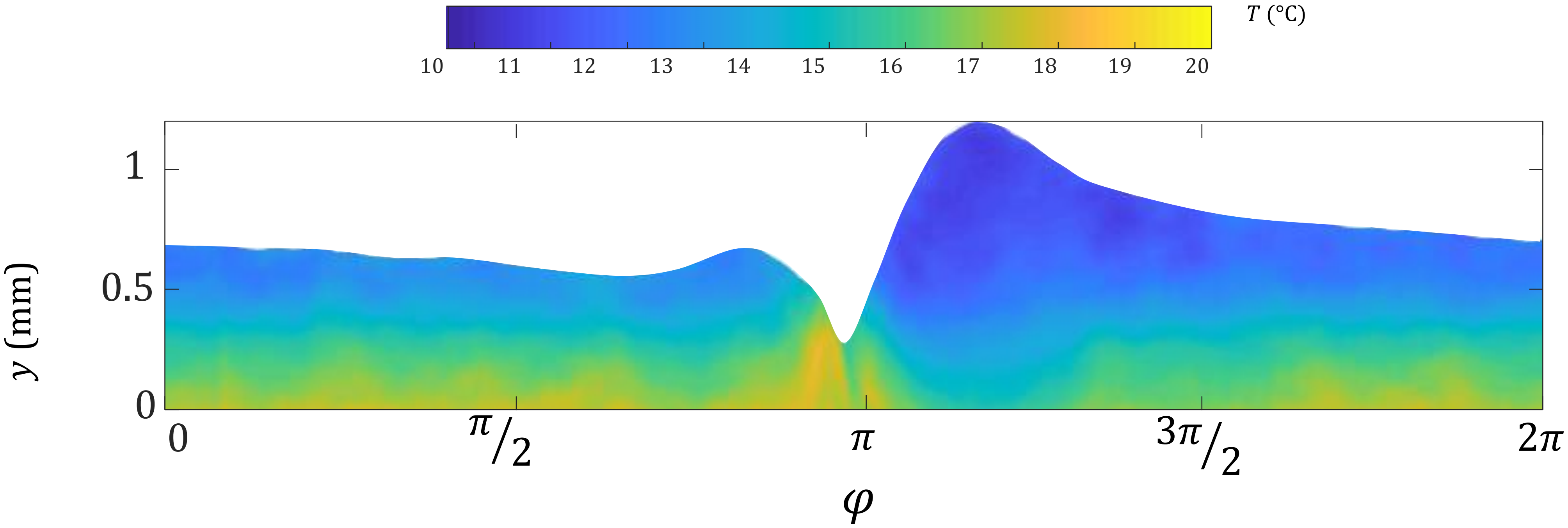
Pixel correspondence and temperature calculation



Example of 2c-LIF temperature imaging : falling film

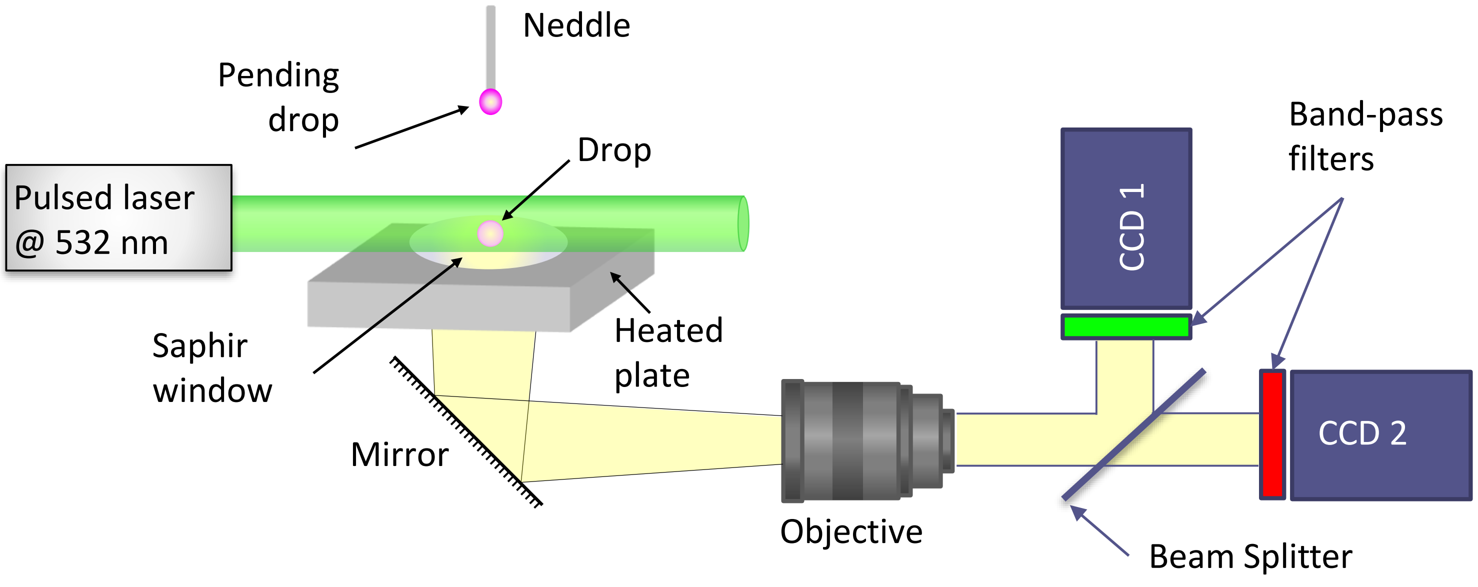
R. Collignon et al.
Experiments in Fluids 62, 2021.

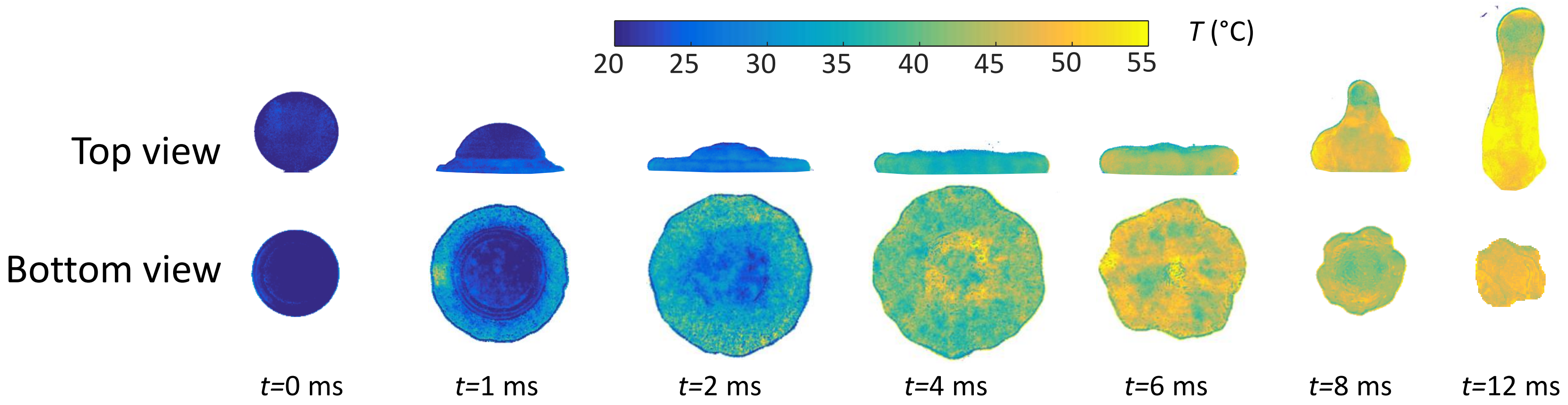




Example of 2c-LIF temperature imaging : drop impact

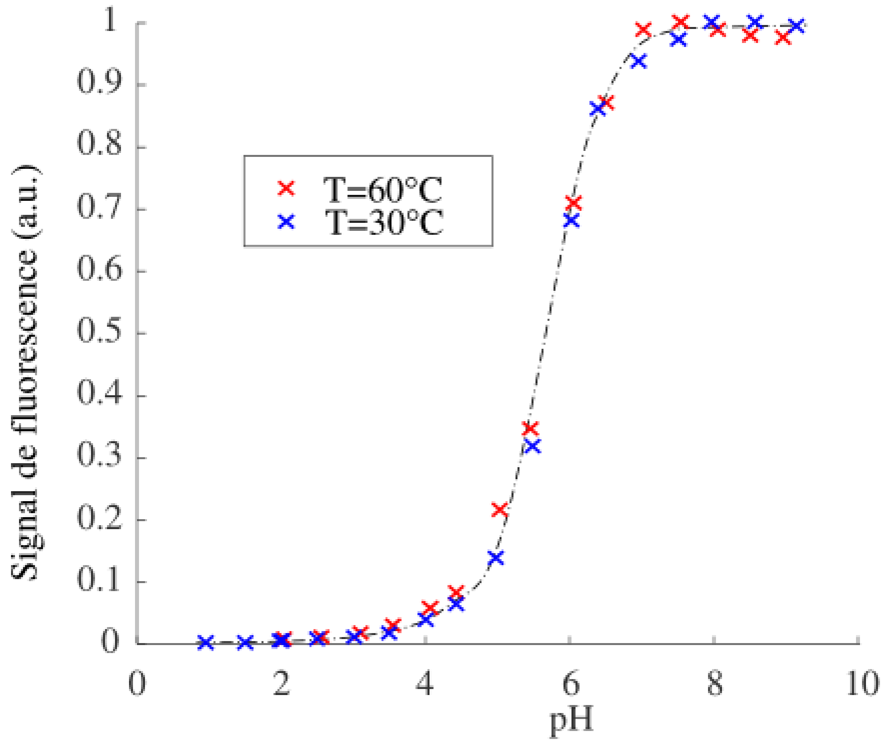
W. Chaze et al.
Experiments in Fluids 58, 2017.





Example of 2c-LIF mixing imaging : turbulent jet

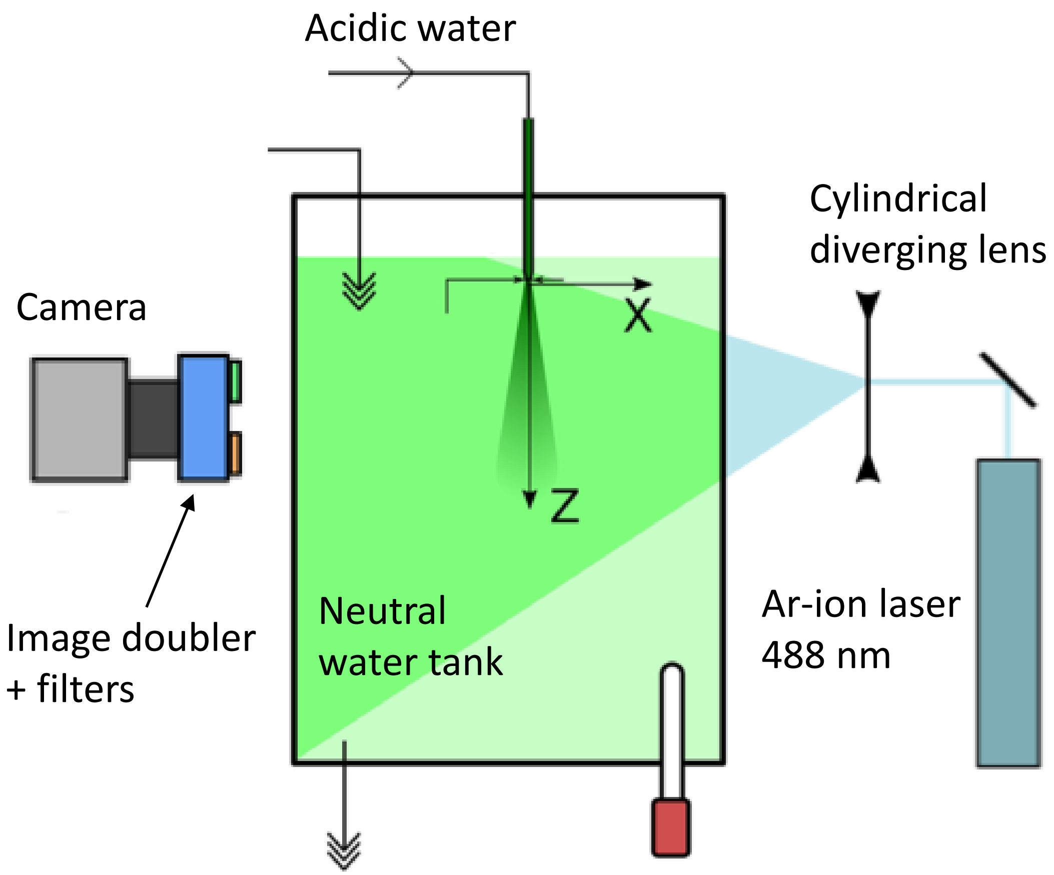
Fluorescein is a dye whose fluorescent emission depends on the **pH of the solvent**

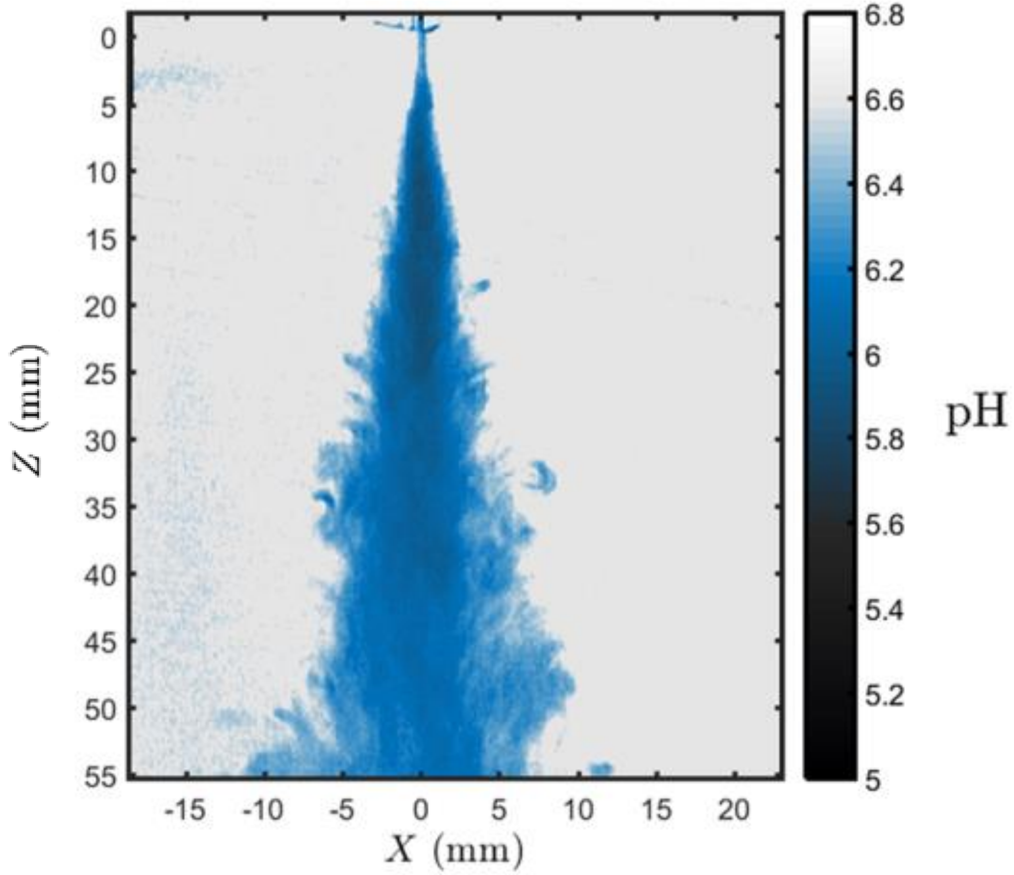


Example of 2c-LIF mixing imaging : turbulent jet

T. Lacassagne et al.
Experiments in Fluids 59, 2017.

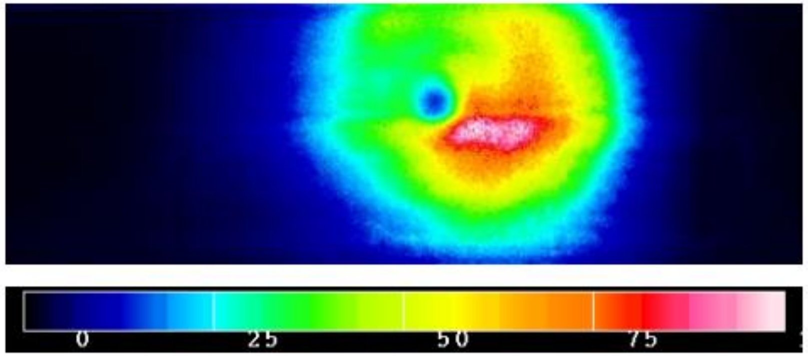
Fluorescein is a dye whose fluorescent emission depends on the **pH of the solvent**



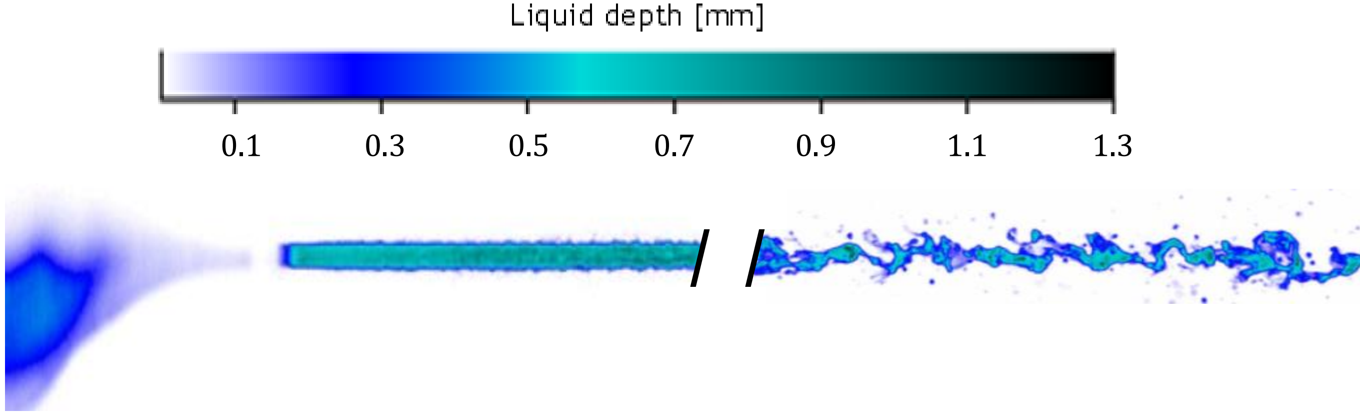


Conclusion and perspectives

- Short introduction on LIF and it’s potential for imaging scalar quantities
- Awareness of some limitations for the technique (dye selection, spectral conflicts, laser power)
- A few examples of research applications



Kerosene distribution in a combustion chamber
R.D. Lockett and D.A. Greenhalgh, *ILASS* 2010



Thickness of a vertical jet stream
A. Roth et al., *International Journal of Multiphase Flow*, 2021

➢ Extend LIF and PLIF imaging to 3 colors to study coupled heat and mass transfer
  Temperature and LiBr concentration for falling film evaporators