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# Structured Laser Illumination Planar Imaging, SLIPI, for imaging of dense sprays

Subtask 3.4D: Application of Laser Techniques for Combustion Diagnostics

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**Combustion Physics**  
**Lund University, Sweden**

IEA-TLM, Nara, Japan, 2010-07-27

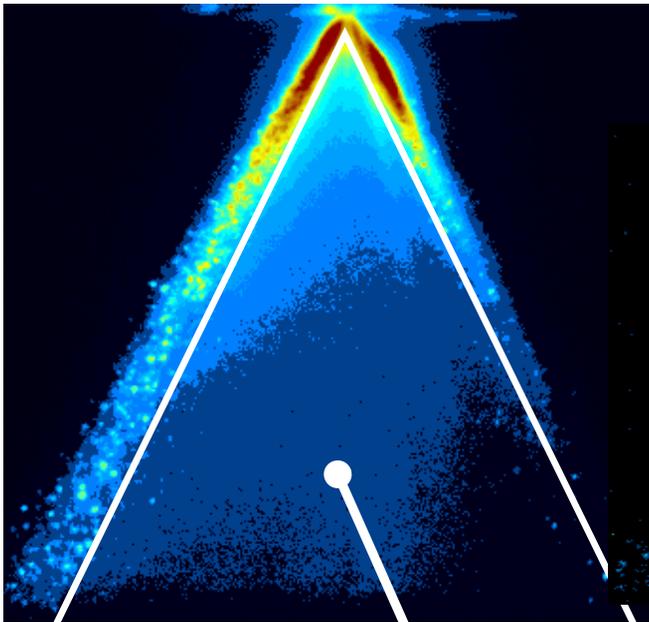
**“Attempts to use conventional laser optical techniques to provide information about the internal structure of high-speed jets have been unsuccessful owing to the multiple scattering by droplets and interfaces”**

**Nature Physics 4, 305 - 309 (2008)**

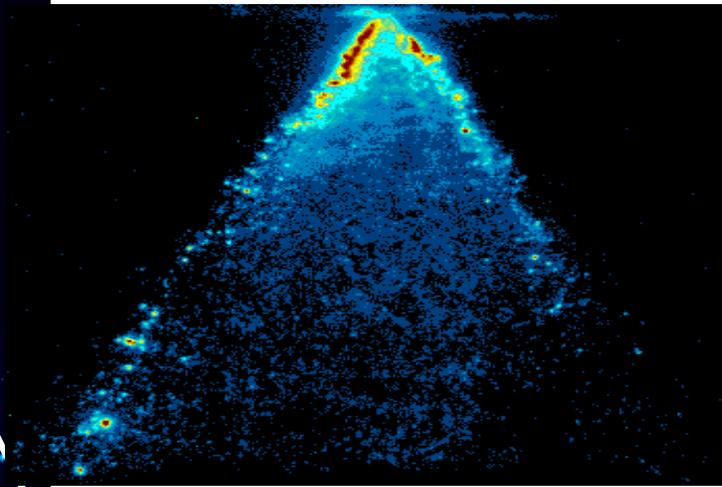


# CONVENTIONAL PLANAR LASER IMAGING

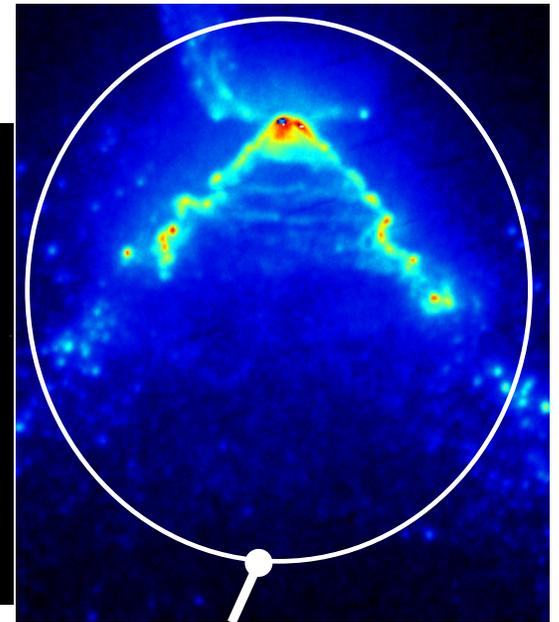
Averaged image



Single shot



Single shot



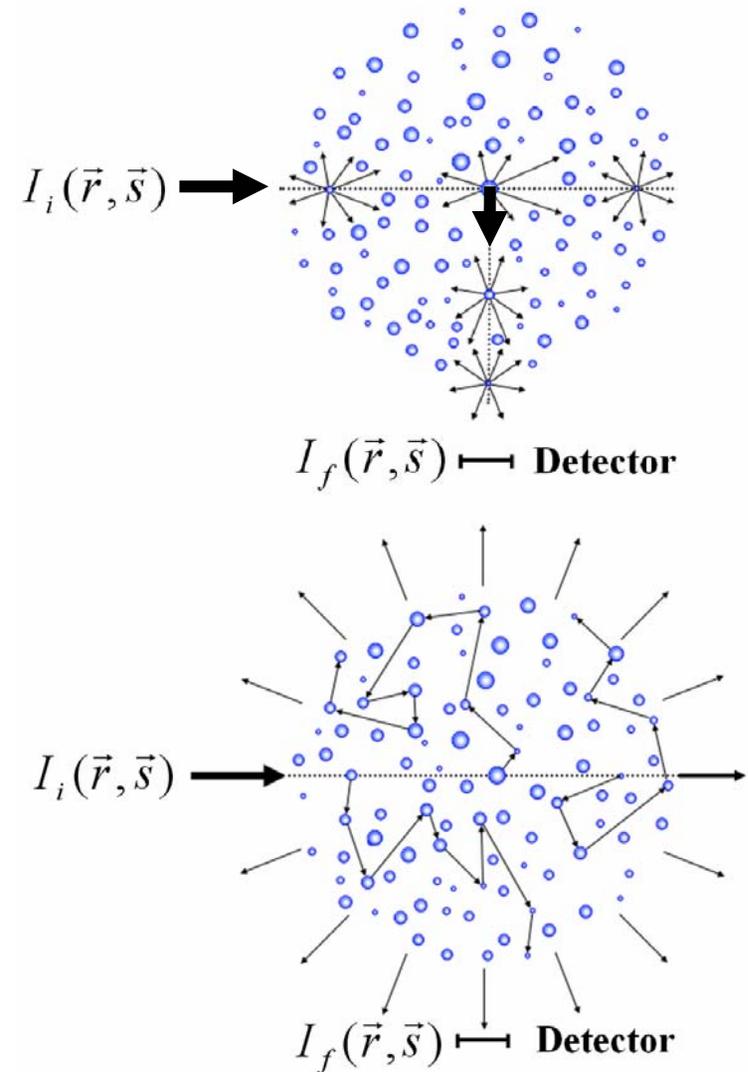
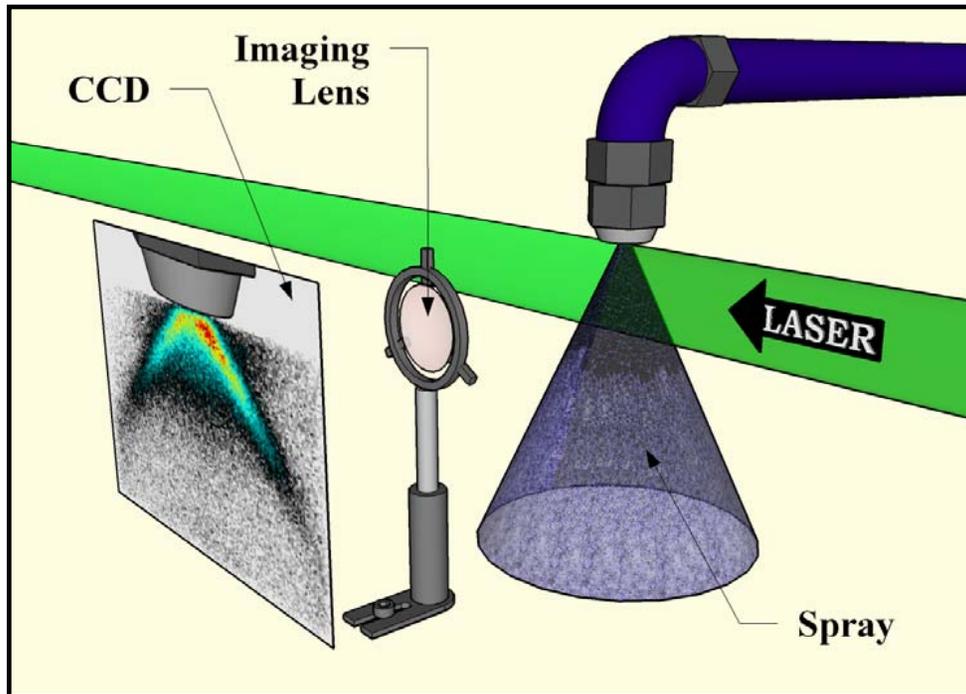
Wrong light intensity contribution

Aureole of light blurring the image

**All Laser Diagnostics of Dense Sprays** based on **Planar Imaging** are strongly restricted by errors introduced by **Multiple Scattering**



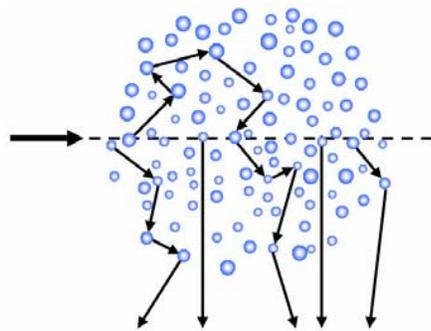
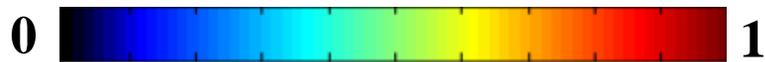
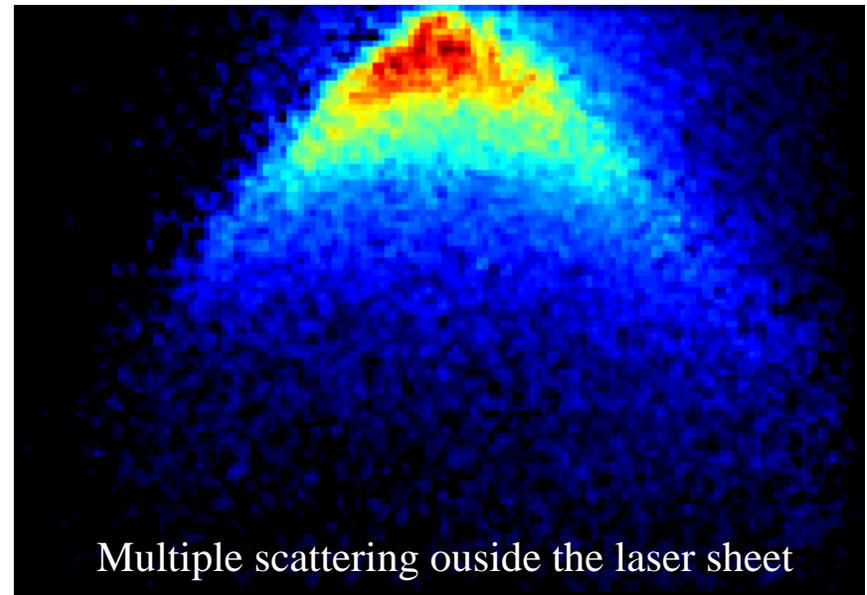
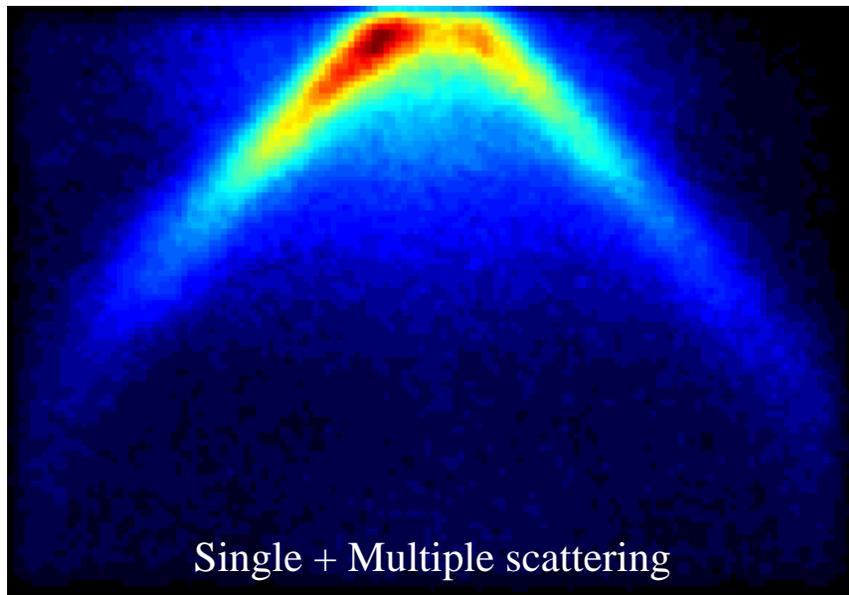
# SOURCES OF ERROR IN PLANAR LASER IMAGING



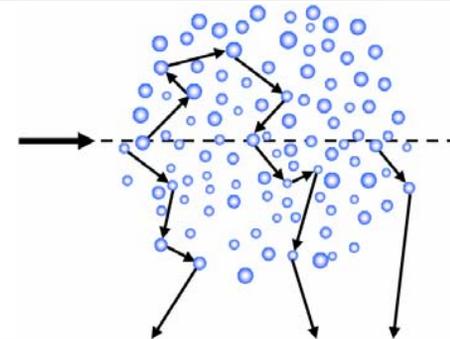
- **Laser Extinction:** Loss of the incident radiation
- **Signal Attenuation:** Loss of the signal
- **Multiple Scattering:** False signal created



# SIMULATION OF LASER SHEET IMAGING VIA MONTE CARLO MODELLING



How can multiple scattering be removed experimentally?

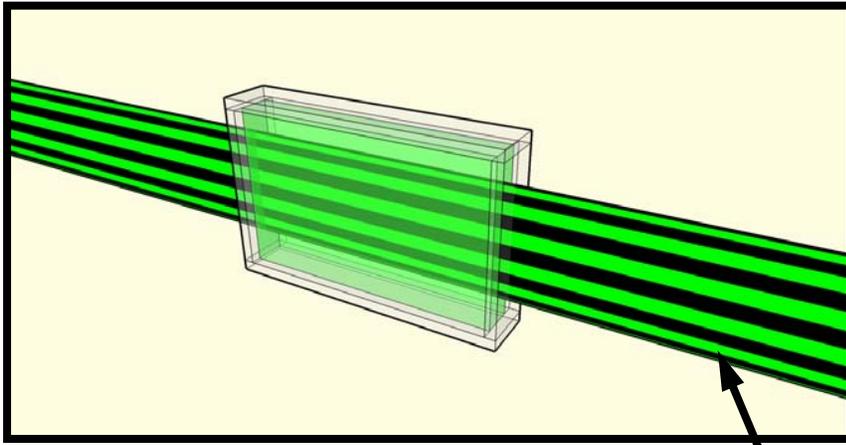


# STRUCTURED LASER ILLUMINATION PLANAR IMAGING

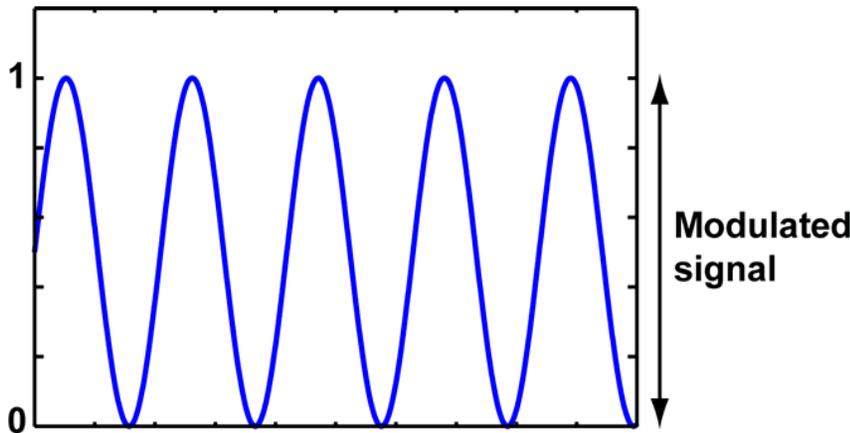
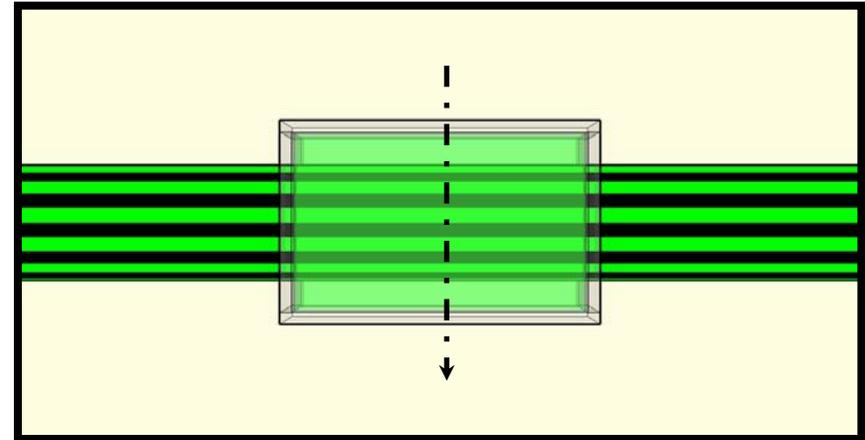
- Part 1: Separation of singly scattered light
- Part 2: Reconstruction of the laser sheet
- Part 3: Suppression of multiple scattering



# Part 1: Separation of singly scattered light



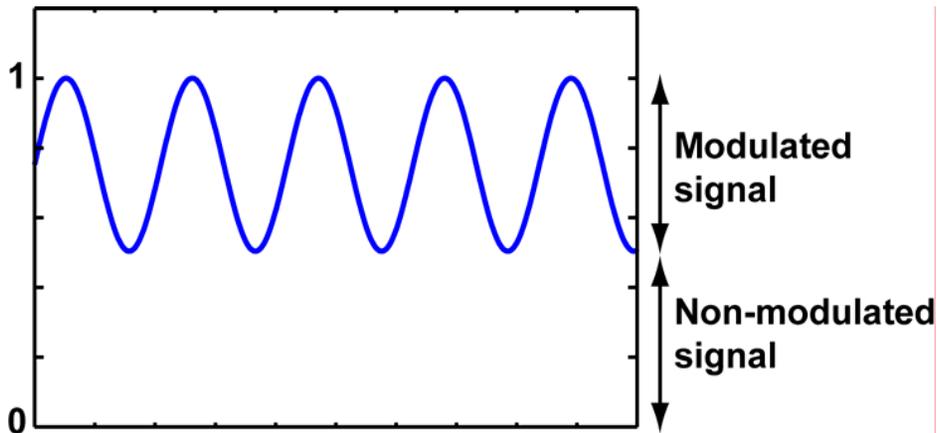
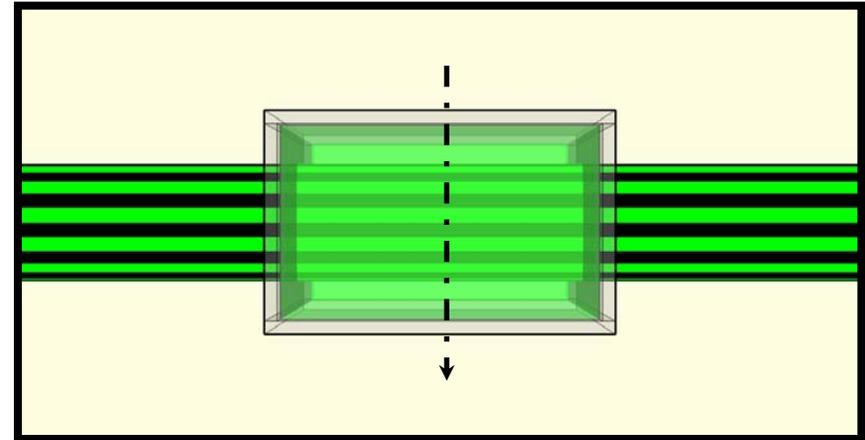
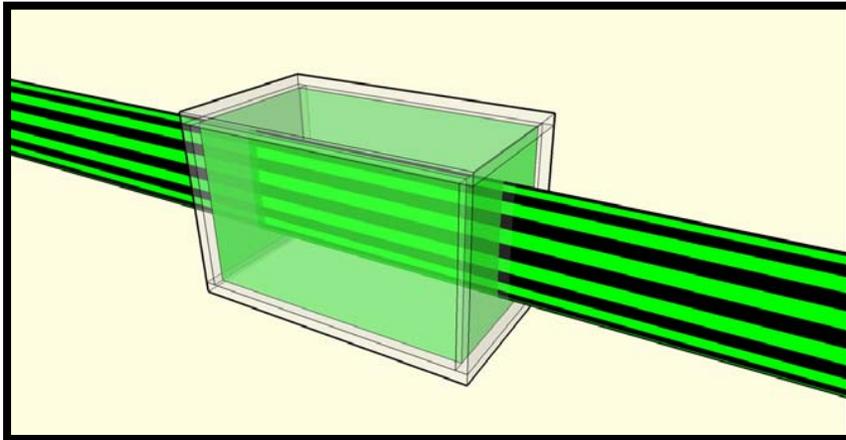
Structured laser sheet



Almost all light is modulated, i.e. directly scattered. No multiple scattering.



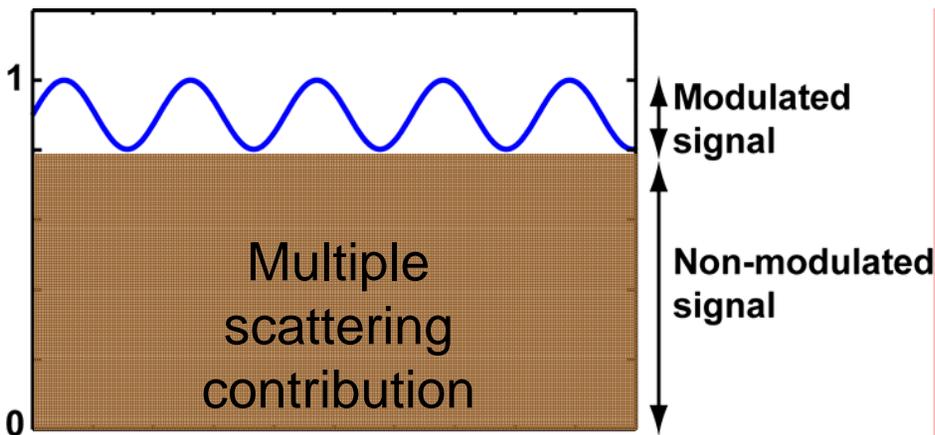
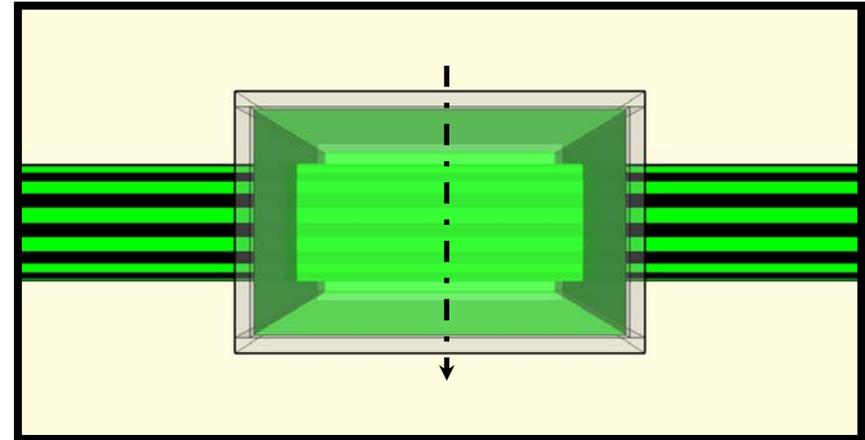
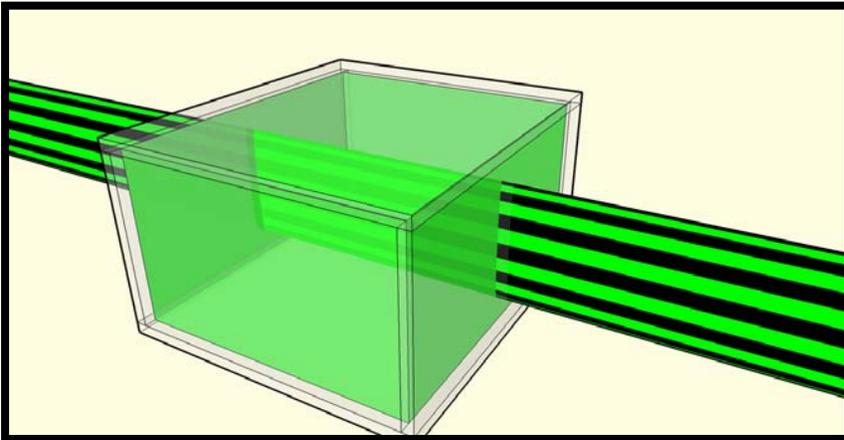
# Part 1: Separation of singly scattered light



Modulation is reduced,  
due to light being  
multiply scattered.



# Part 1: Separation of singly scattered light



Almost no light is modulated, only a small portion is directly scattered.

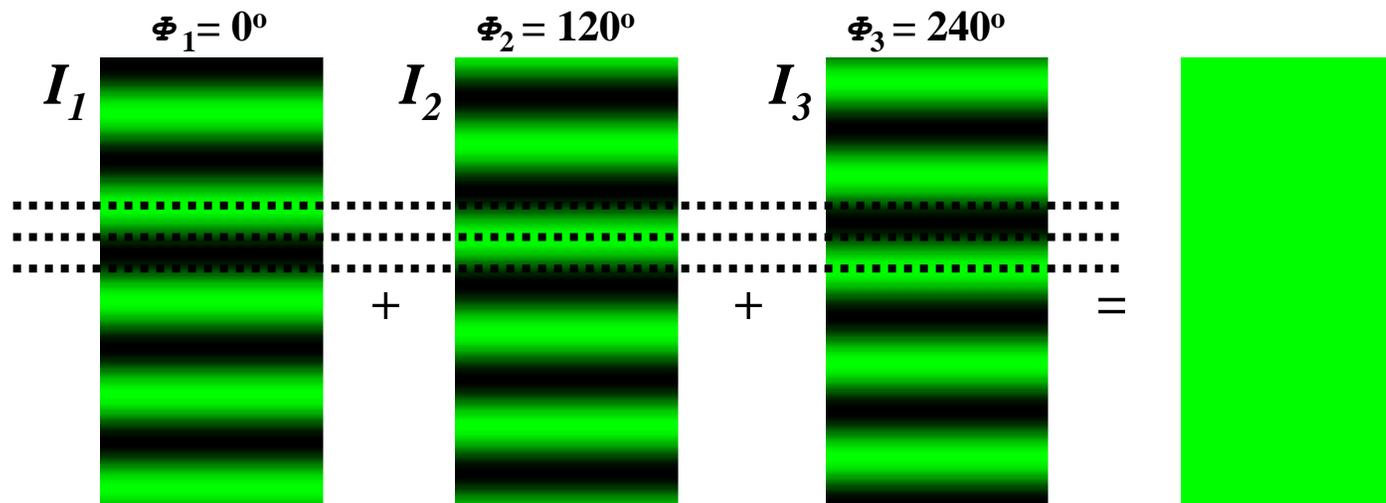


# STRUCTURED LASER ILLUMINATION PLANAR IMAGING

- Part 1: Separation of singly scattered light
- Part 2: Reconstruction of the laser sheet
- Part 3: Suppression of multiple scattering



## Part 2: Reconstruction of the laser sheet



Record three images, with a phase shift of a third of a period between each image

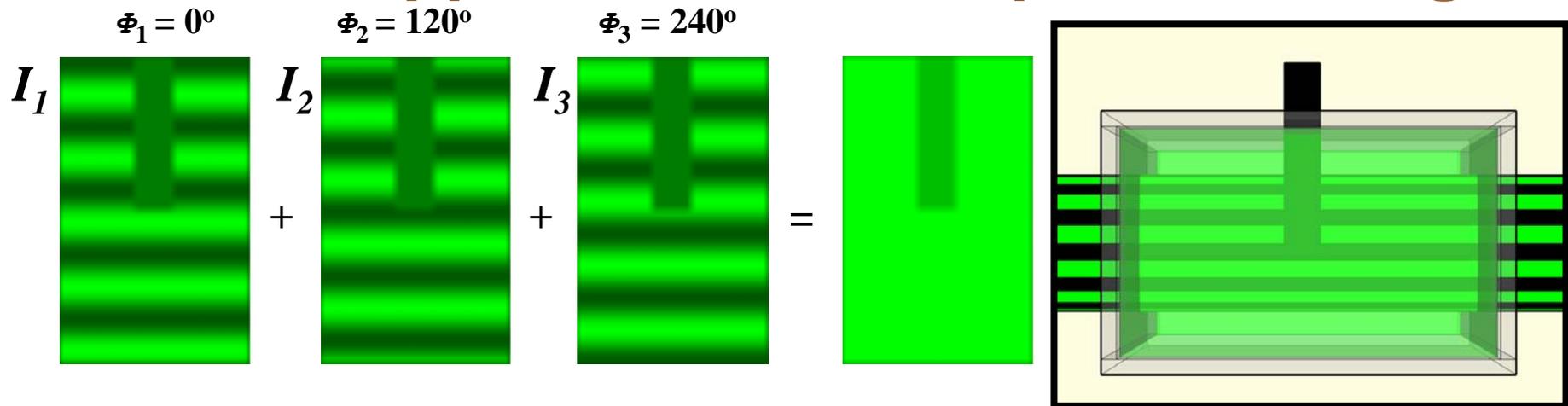


# STRUCTURED LASER ILLUMINATION PLANAR IMAGING

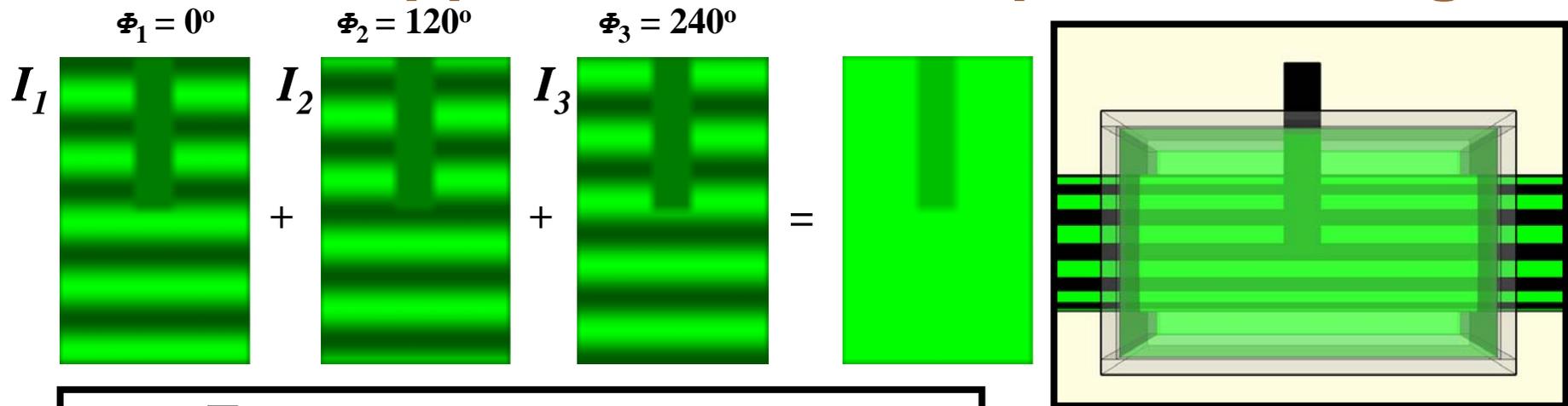
- Part 1: Separation of singly scattered light
- Part 2: Reconstruction of the laser sheet
- Part 3: Suppression of multiple scattering



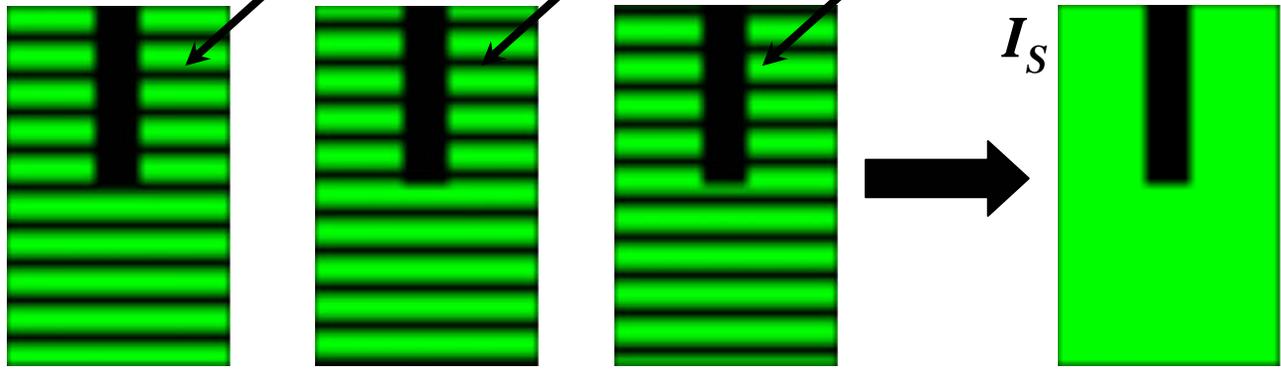
# Part 3: Suppression of multiple scattering



# Part 3: Suppression of multiple scattering



$$I_S = \frac{\sqrt{2}}{3} \cdot \left[ \underline{(I_1 - I_2)}^2 + \underline{(I_1 - I_3)}^2 + \underline{(I_2 - I_3)}^2 \right]^{1/2}$$

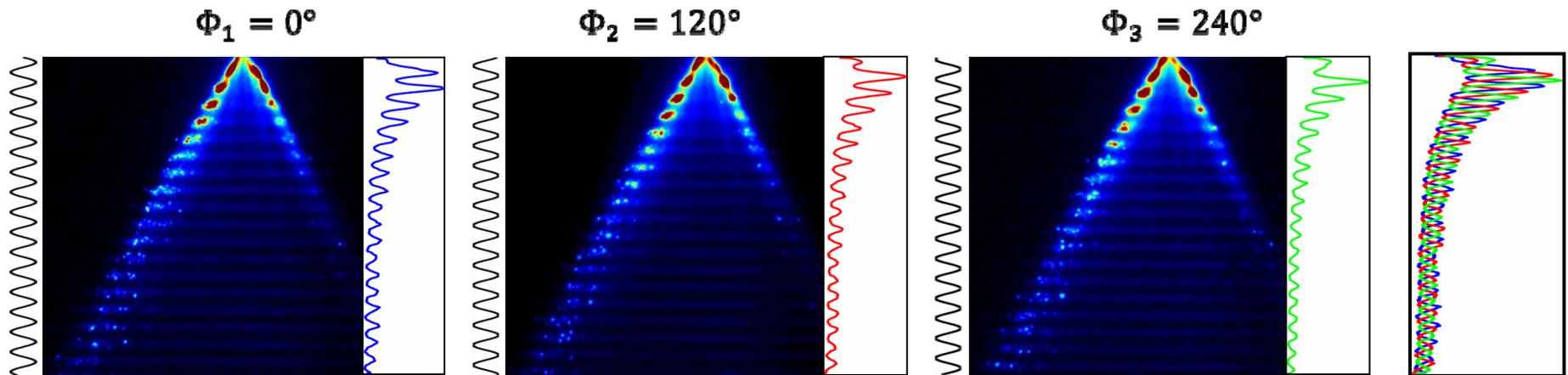


Signal in blocked area

SLIPI Technique

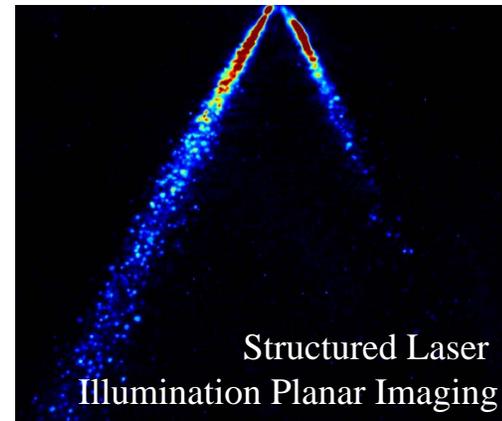
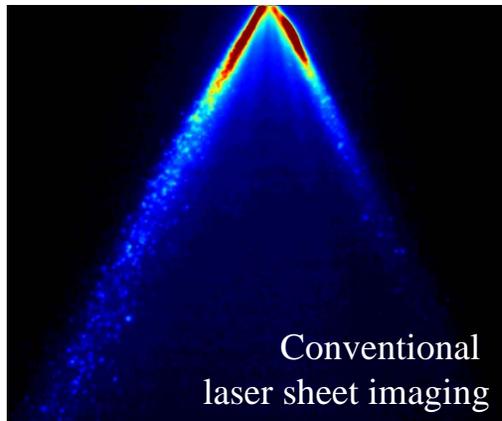


# STRUCTURED LASER ILLUMINATION PLANAR IMAGING

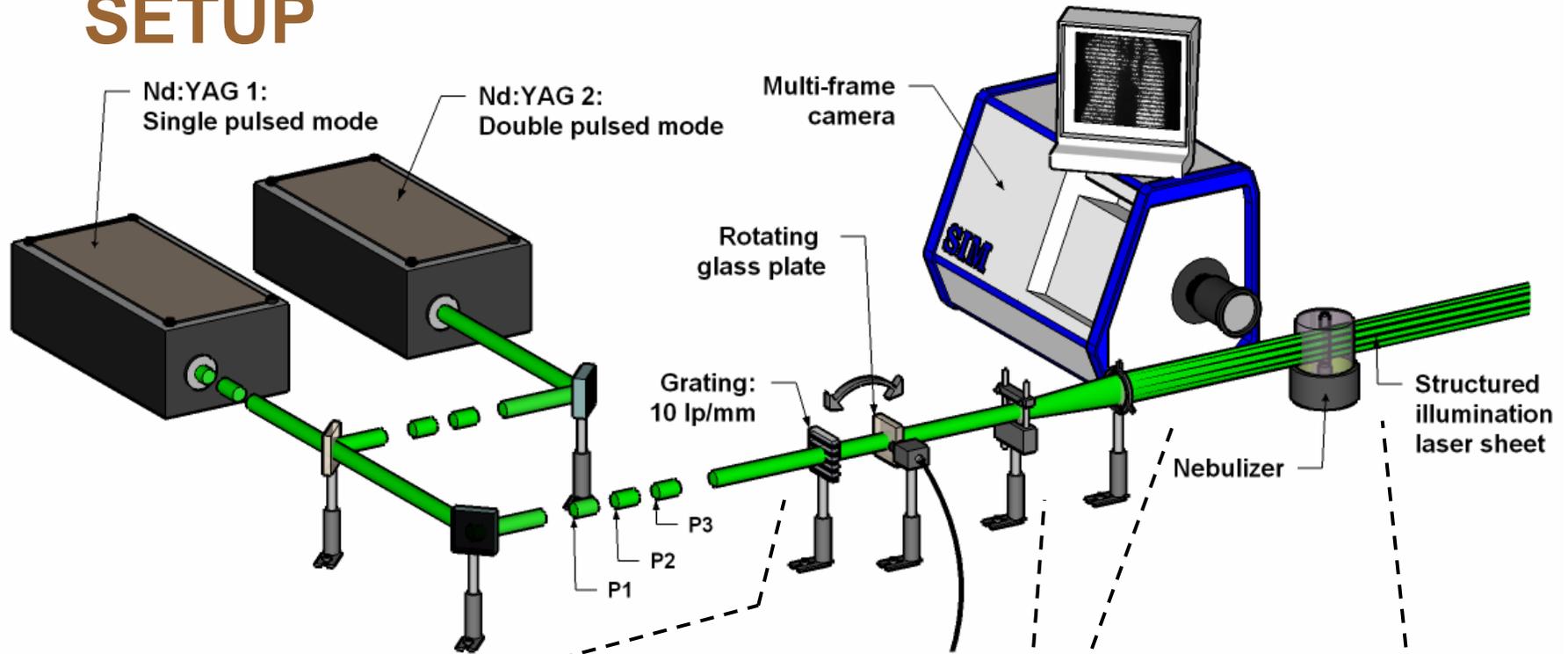


$$I_C = \frac{I_1 + I_2 + I_3}{3}$$

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

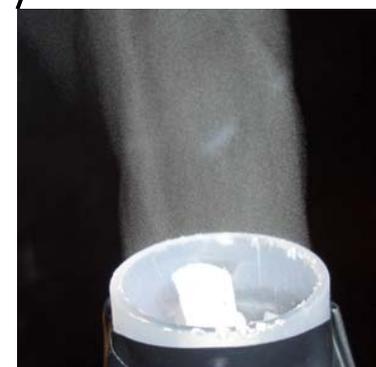
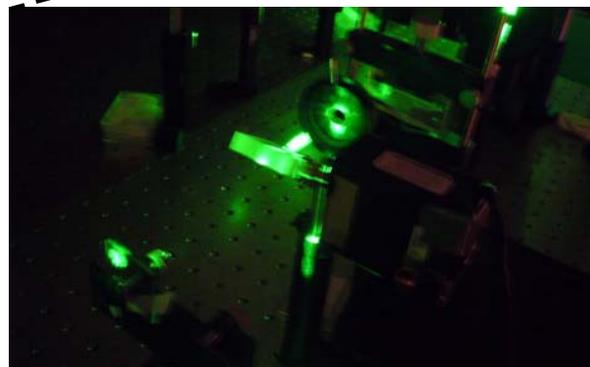


# FIRST SINGLE-SHOT EXPERIMENTAL SETUP



## Capabilities:

- Single-shot imaging
- Flows up to 25 cm/s
- Study of a nebulizer
- Limit: Rotating glass plate
- 12-bit intensified CCDs

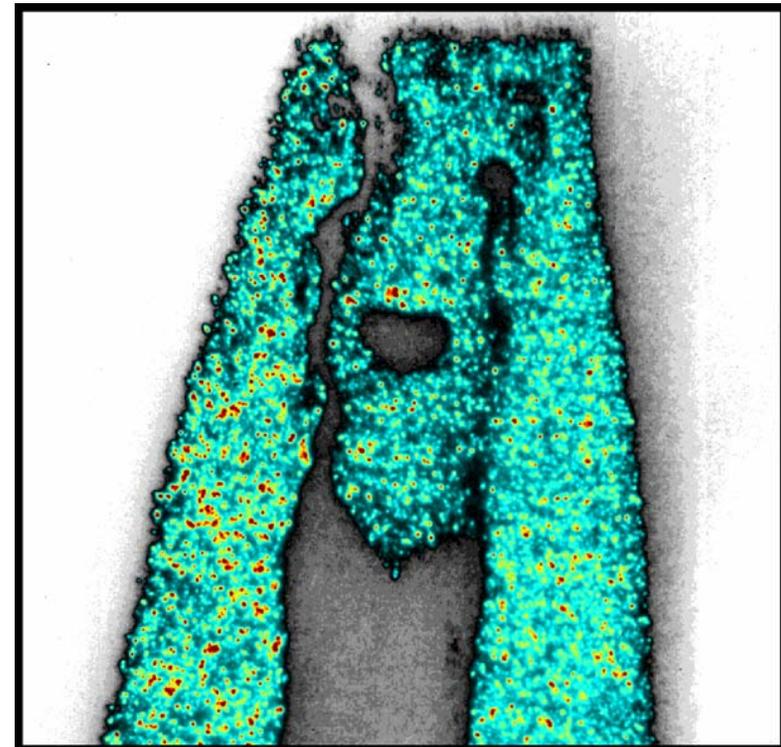


# FIRST SINGLE-SHOT SLIPI

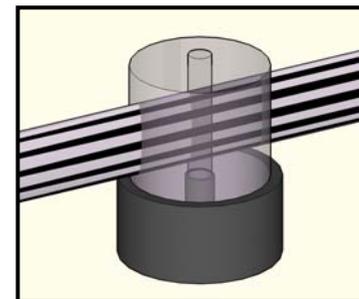
SLIPI



Conventional Laser Sheet

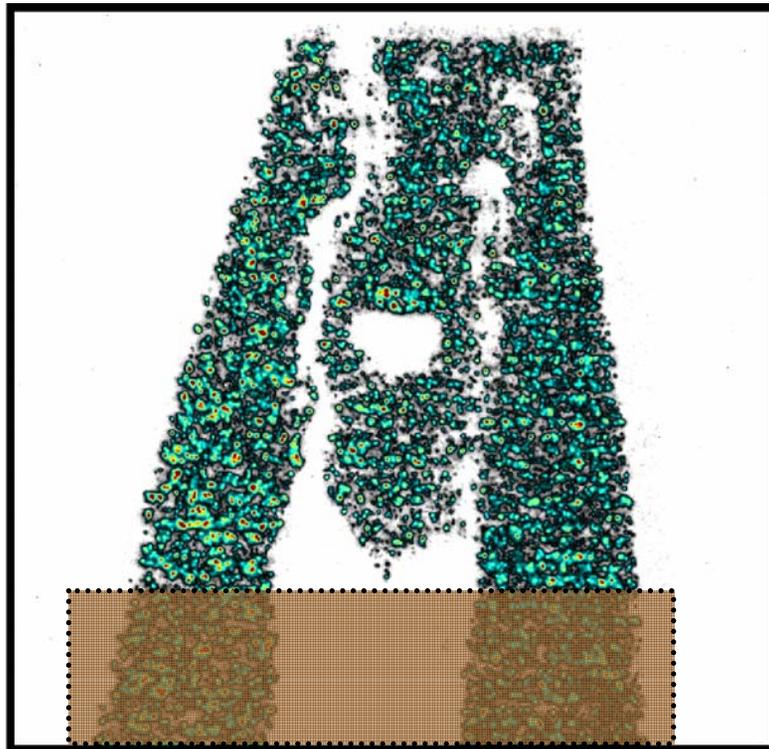


- **Slow flow** of water droplets
- Additional inner **flow of nitrogen** for quantification
- **55  $\mu$ s** pulse separation, velocities up to **25 cm/s**
- Separated liquid structures, **voids** more visible

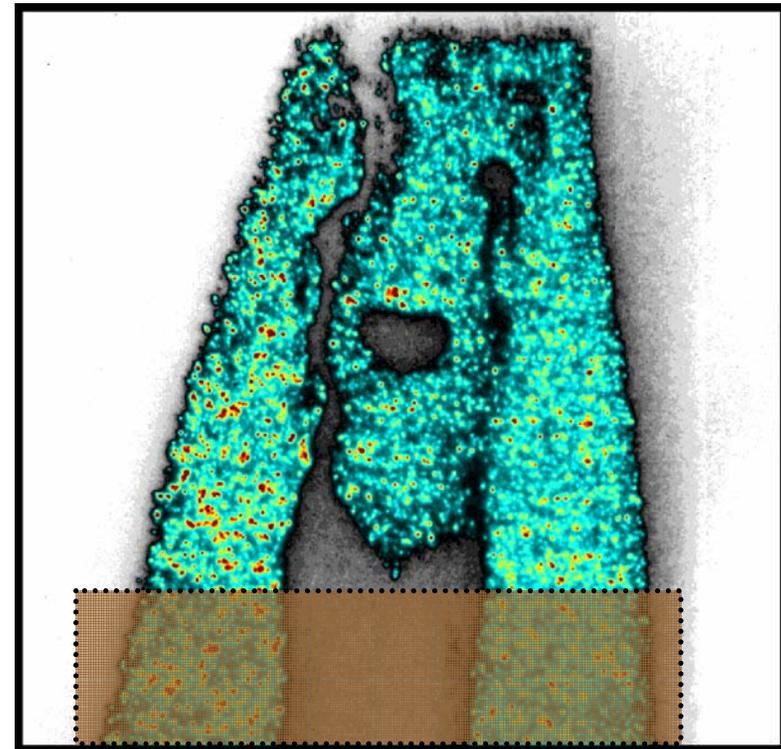


# FIRST SINGLE-SHOT SLIPI

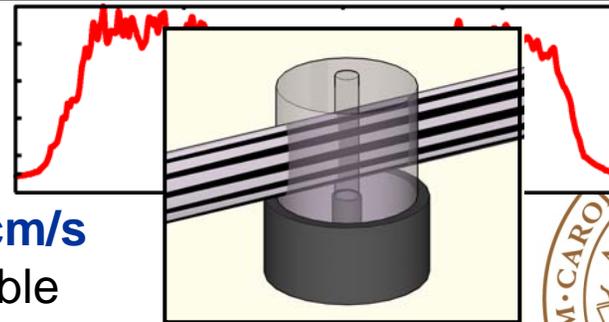
## SLIPI



## Conventional Laser Sheet

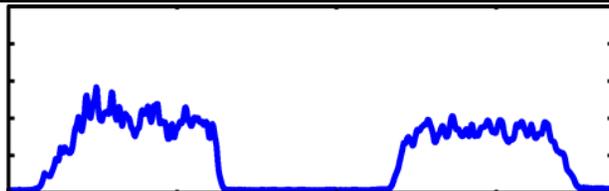
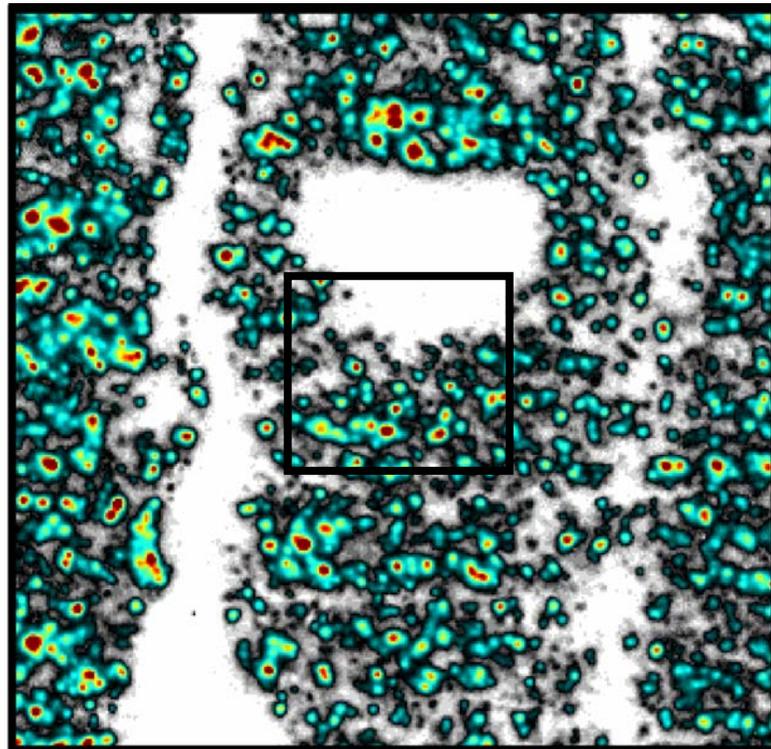


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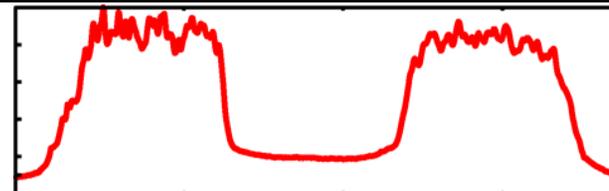
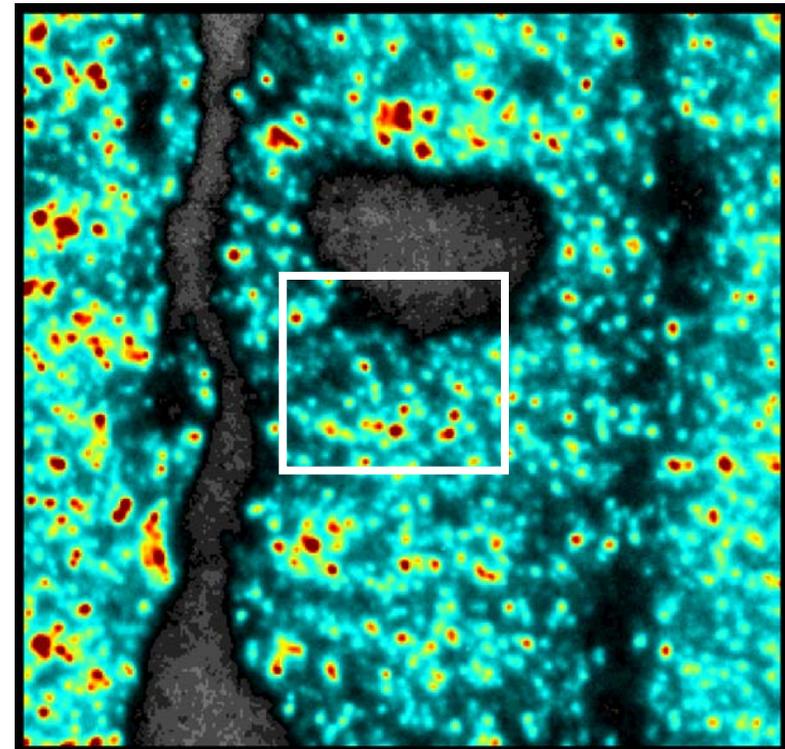


# FIRST SINGLE-SHOT SLIPI

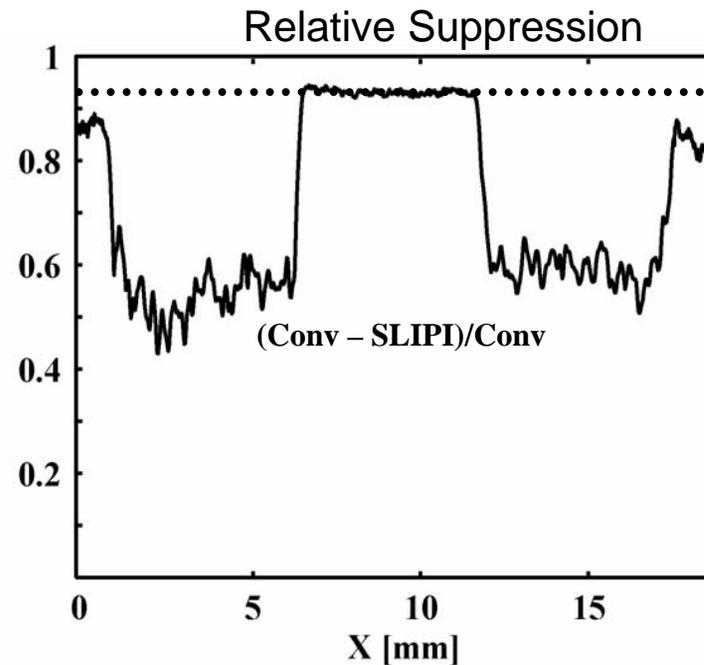
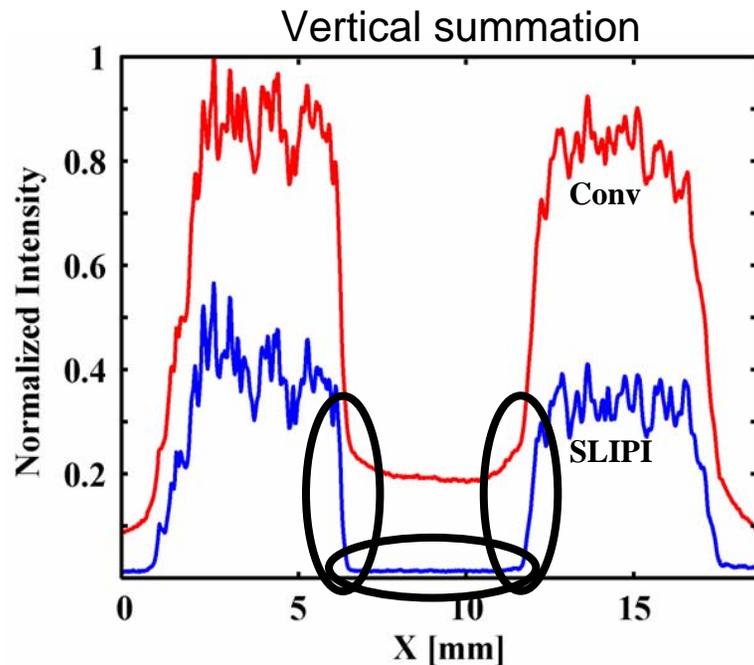
SLIPI



Conventional Laser Sheet

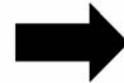


# SUPPRESSION ANALYSIS



- Droplet-free region **tends to zero** for SLIPI
- Sharper "on-off" **gradient**
- **~93 %** suppression in droplet-free region

Laser sheet



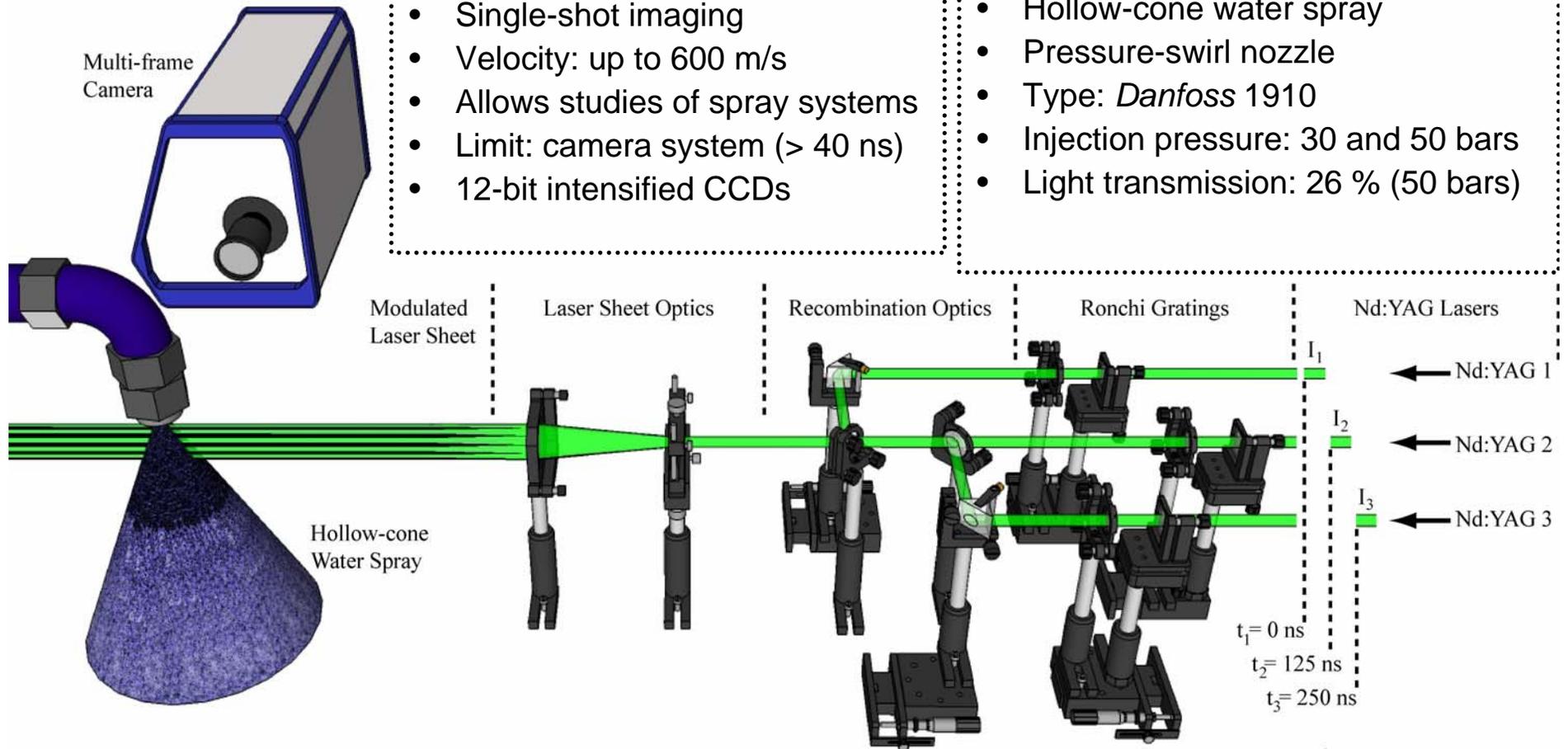
# ULTRA-FAST SLIPI – OPTICAL ARRANGEMENT

## Capabilities:

- Single-shot imaging
- Velocity: up to 600 m/s
- Allows studies of spray systems
- Limit: camera system ( $> 40$  ns)
- 12-bit intensified CCDs

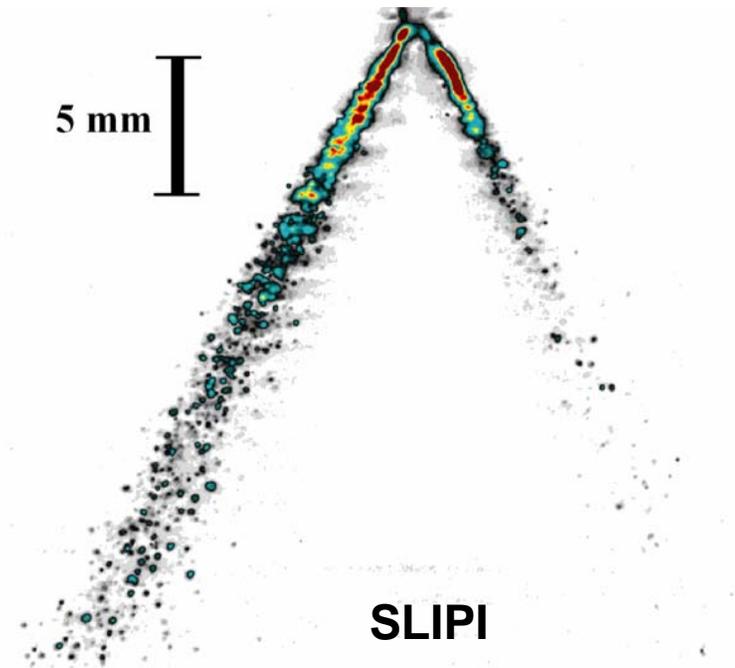
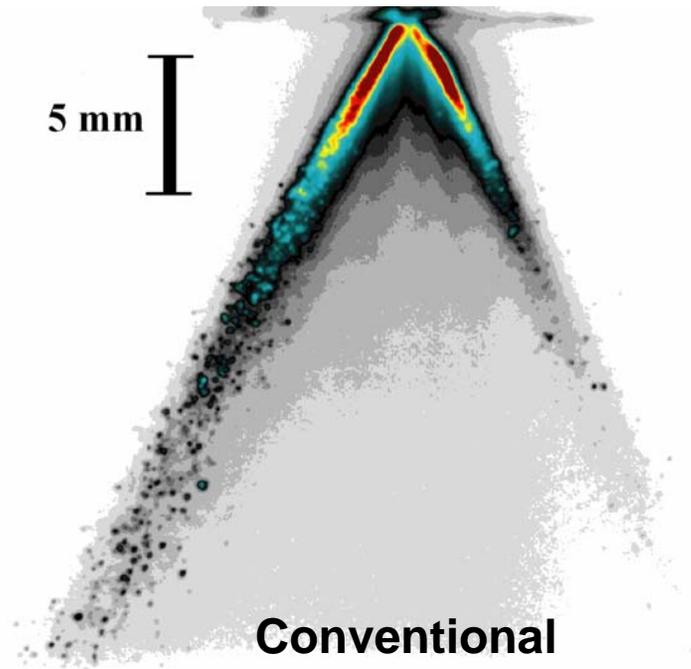
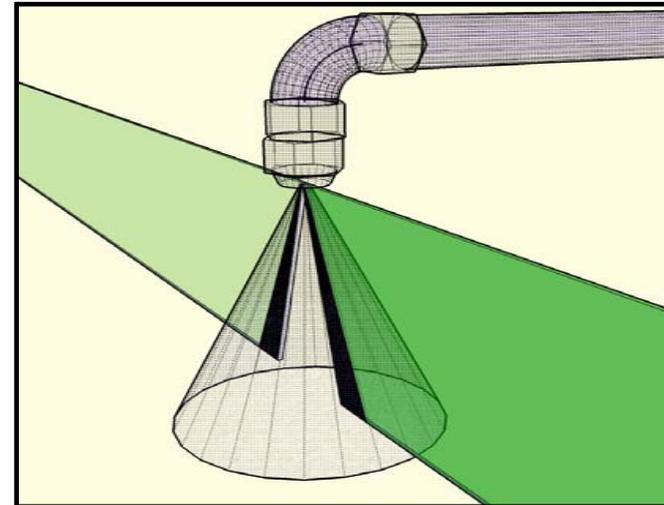
## Spray information:

- Hollow-cone water spray
- Pressure-swirl nozzle
- Type: *Danfoss 1910*
- Injection pressure: 30 and 50 bars
- Light transmission: 26 % (50 bars)

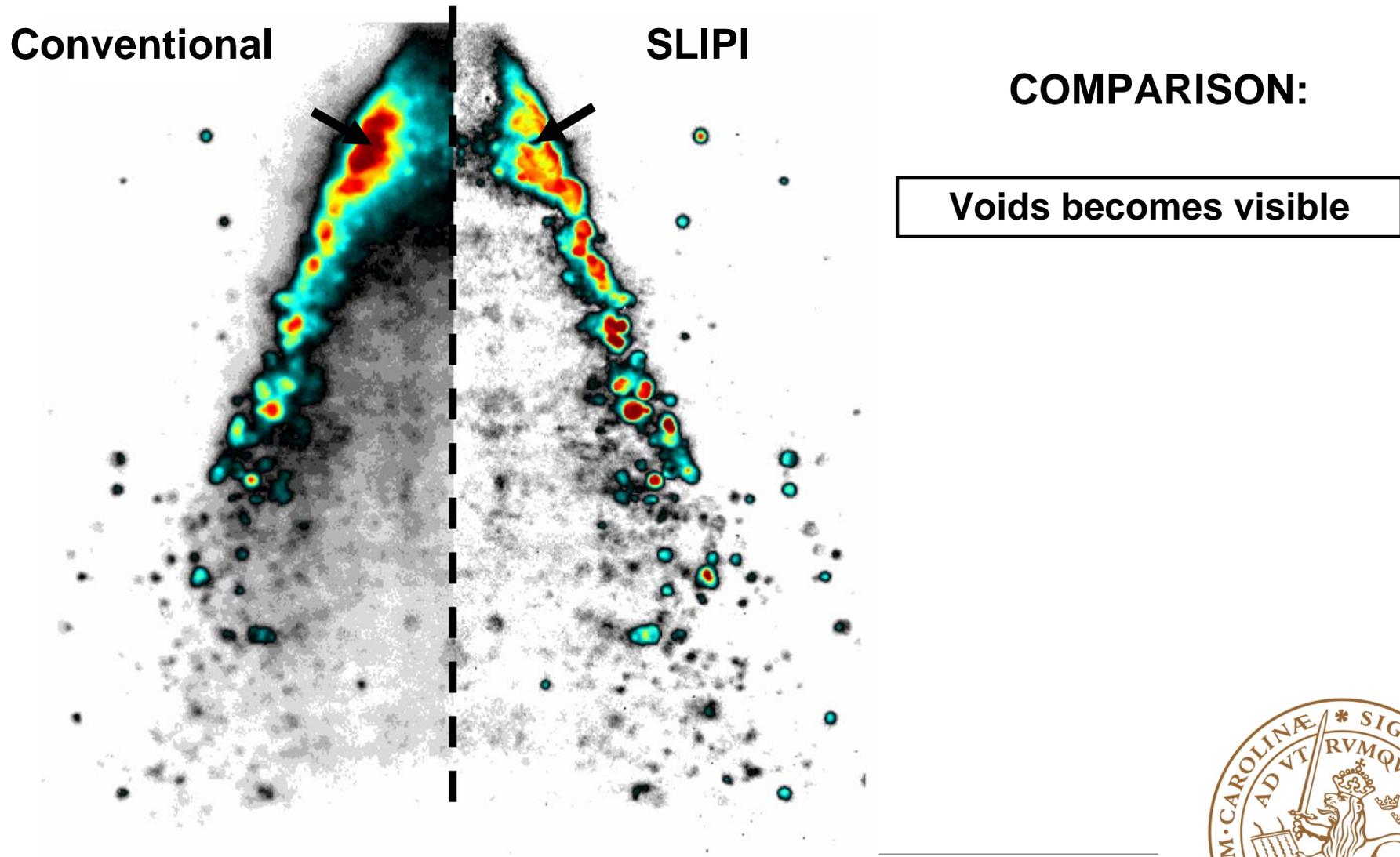


# AVERAGED IMAGES Hollow-Cone Spray

**OFF-AXIS ILLUMINATION**



# SINGLE-SHOT - Hollow-Cone Spray



# SINGLE-SHOT - Hollow-Cone Spray

Conventional

SLIPI

COMPARISON:

Voids becomes visible

Droplets more enhanced



# SINGLE-SHOT - Hollow-Cone Spray

Conventional

SLIPI

COMPARISON:

Voids becomes visible

Droplets more enhanced

Central region appears hollow



# SINGLE-SHOT - Hollow-Cone Spray

Conventional

SLIPI

COMPARISON:

Voids becomes visible

Droplets more enhanced

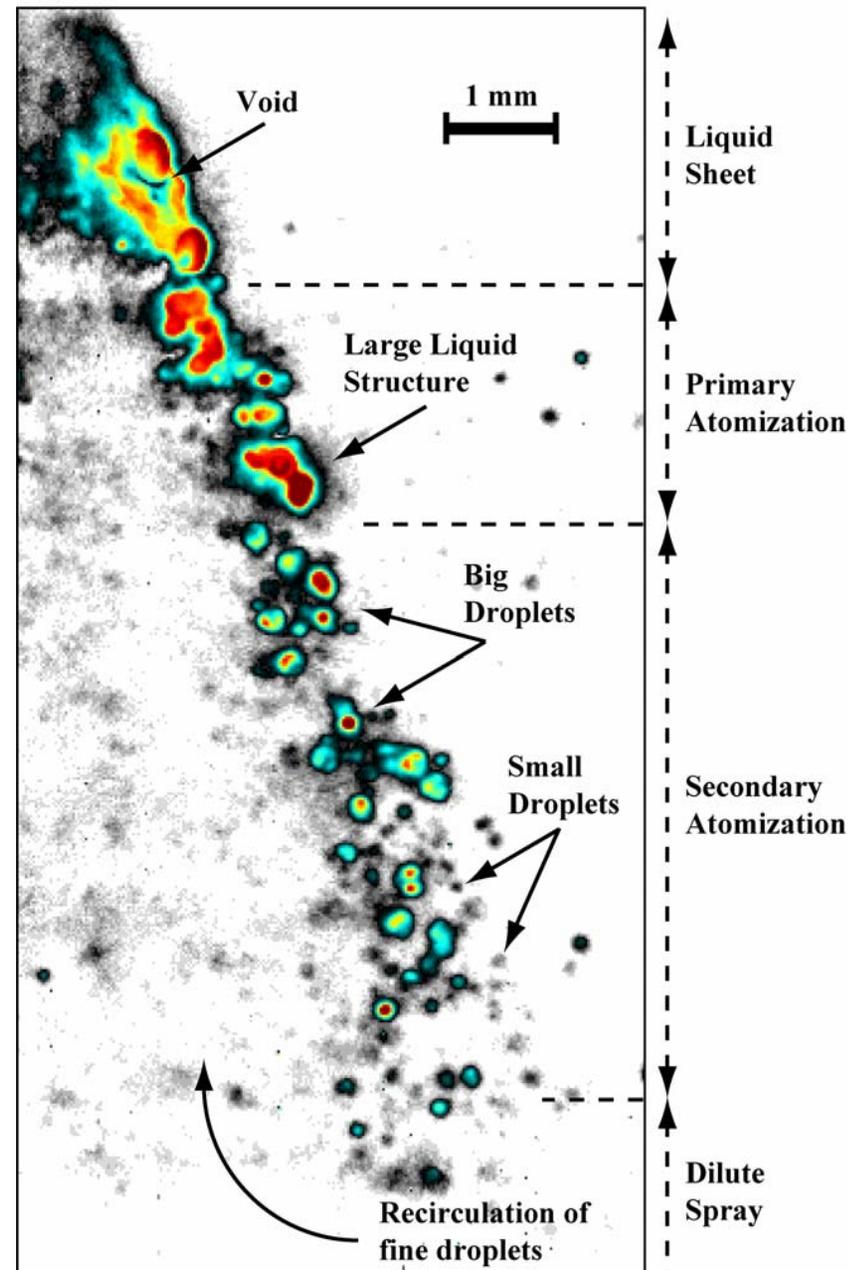
Central region appears hollow

Interfaces become sharp



**SPRAY  
BREAKUPS  
ANALYSIS  
FROM HIGH  
RESOLUTION  
IMAGES**

**PROVIDE  
VALUABLE DATA  
FOR THE VALIDATION  
OF CFD MODELS**



# CONCLUSIONS

- Novel technique for **multiple scattering suppression** in planar laser imaging
- First time applied for **single-shot** imaging of a spray
- Provide visualization of primary and secondary **atomizations** in the **dense spray** region
- Allows a better estimation of the **liquid sheet/liquid core** length
- Direct application for **PIV** and **PLIF**



# ACKNOWLEDGEMENTS

Thanks to the Linné Centre within the Lund Laser Centre (LLC), SSF and STEM through CECOST for financial support



# Presentation at 33rd Symposium on Combustion in Beijing:

E. Kristensson et al.: Structured illumination for 3D Mie imaging and 2D attenuation measurements in optically dense sprays

