Instantaneous 3D imaging of flame species using coded laser illumination

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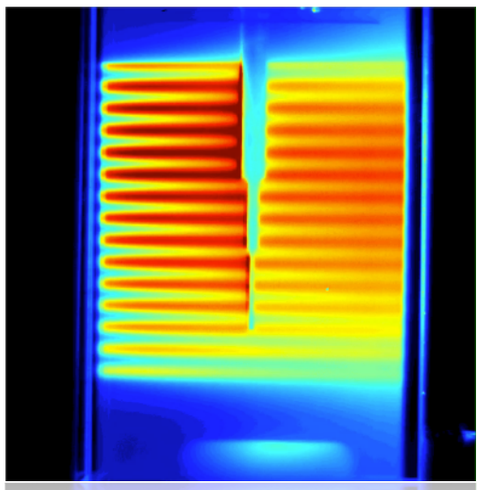
LUND UNIVERSITY

Introduction

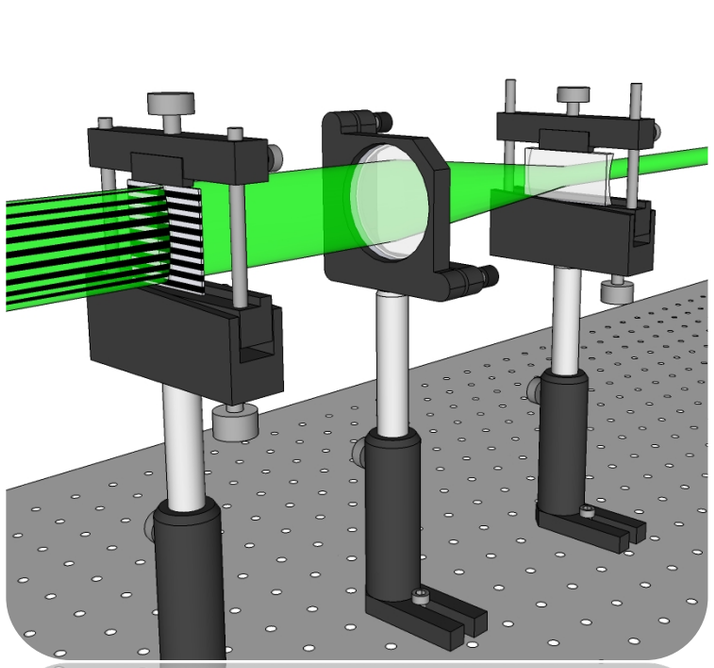
What is coded illumination?



Coded illumination

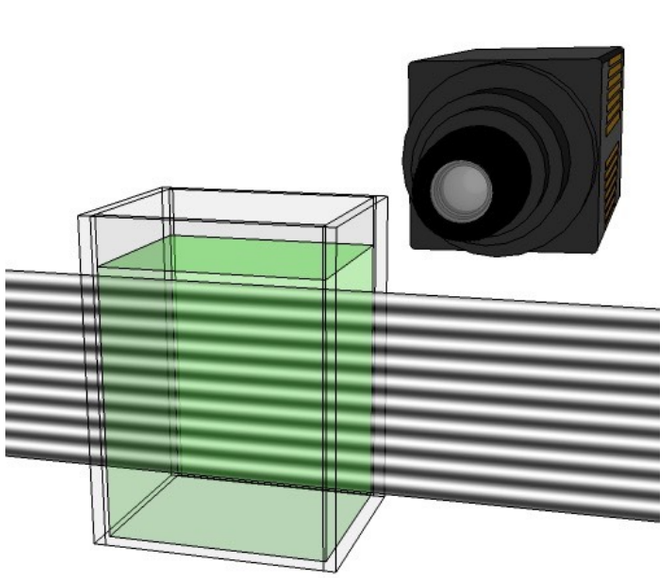
1 Superimpose structure

Guide light through a grid pattern



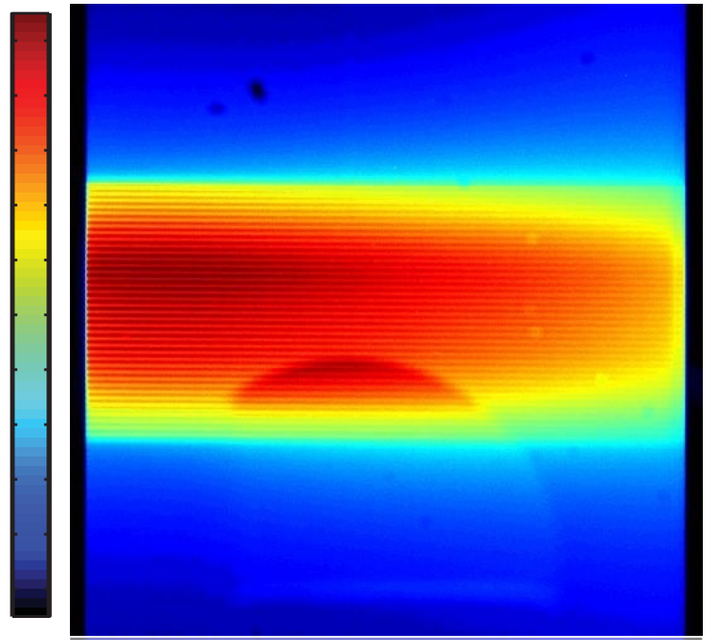
2 Modulated laser sheet

Sinus-modulated laser sheet through a cuvette



3 Camera view

View seen by a camera at 90 degrees



Coded illumination

2 Modulated laser sheet

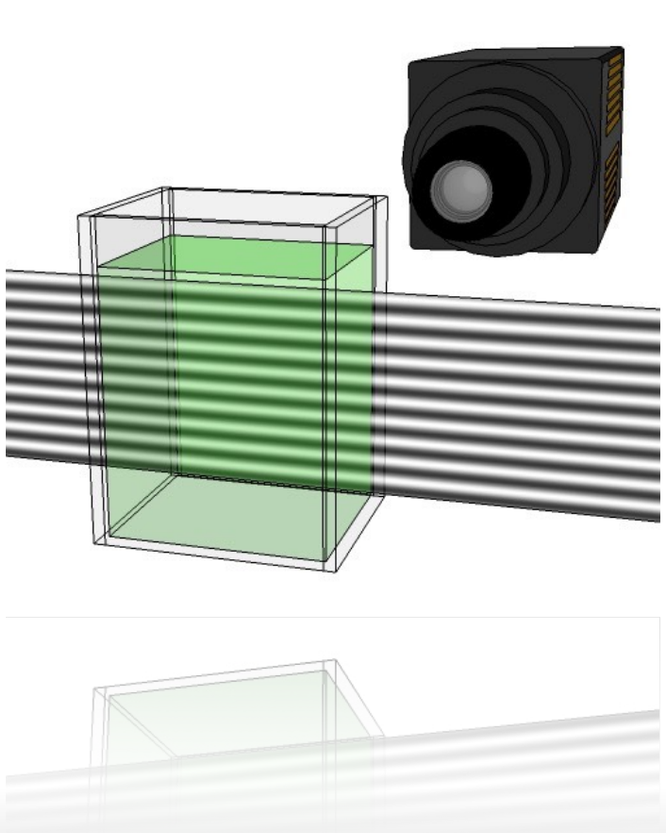
Sinus-modulated laser sheet through a cuvette

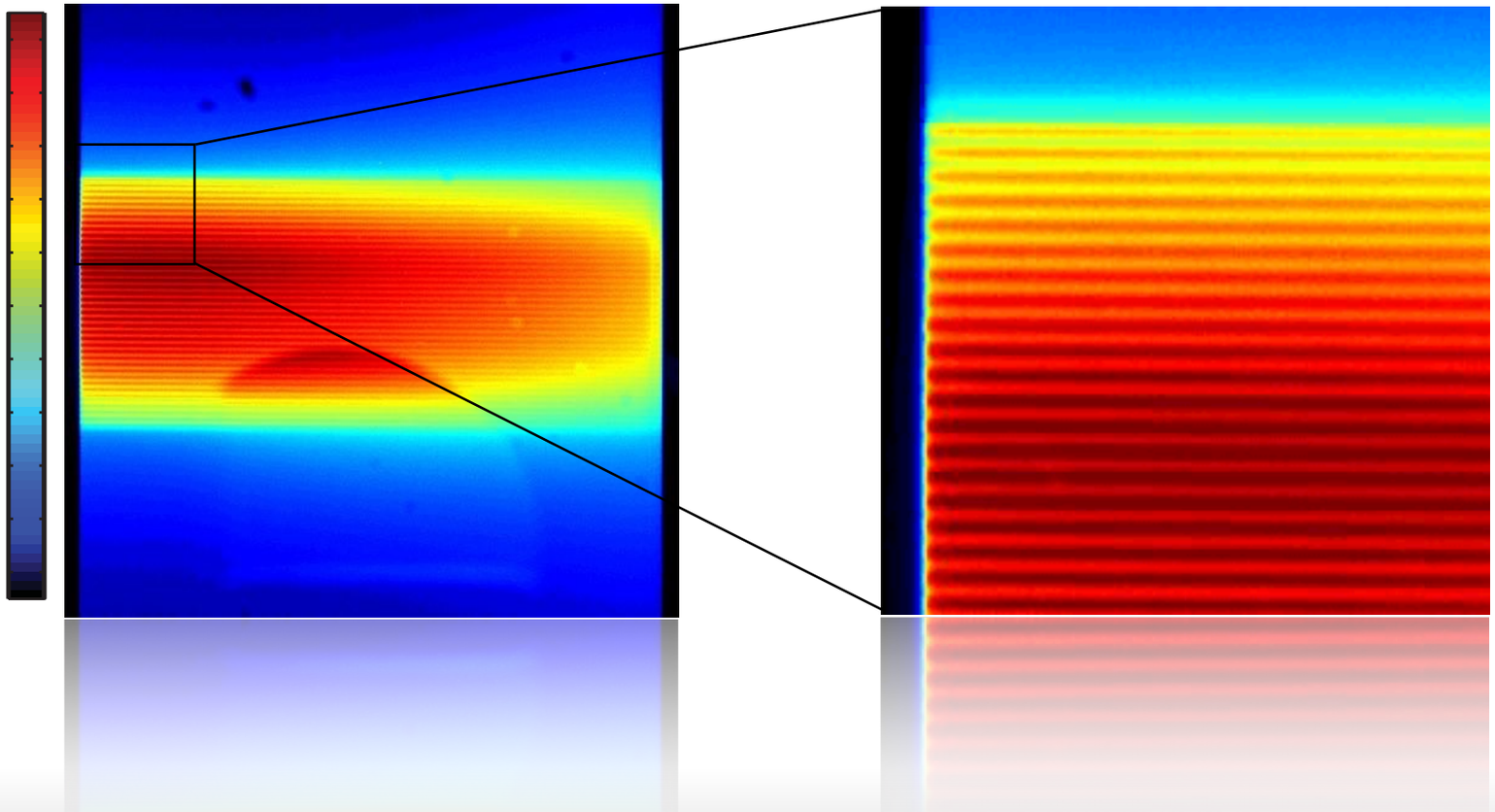
3 Camera view

View seen by a camera at 90 degrees

4 Shift pattern

Distinguish between signal and background interferences





Coded illumination

3 Camera view

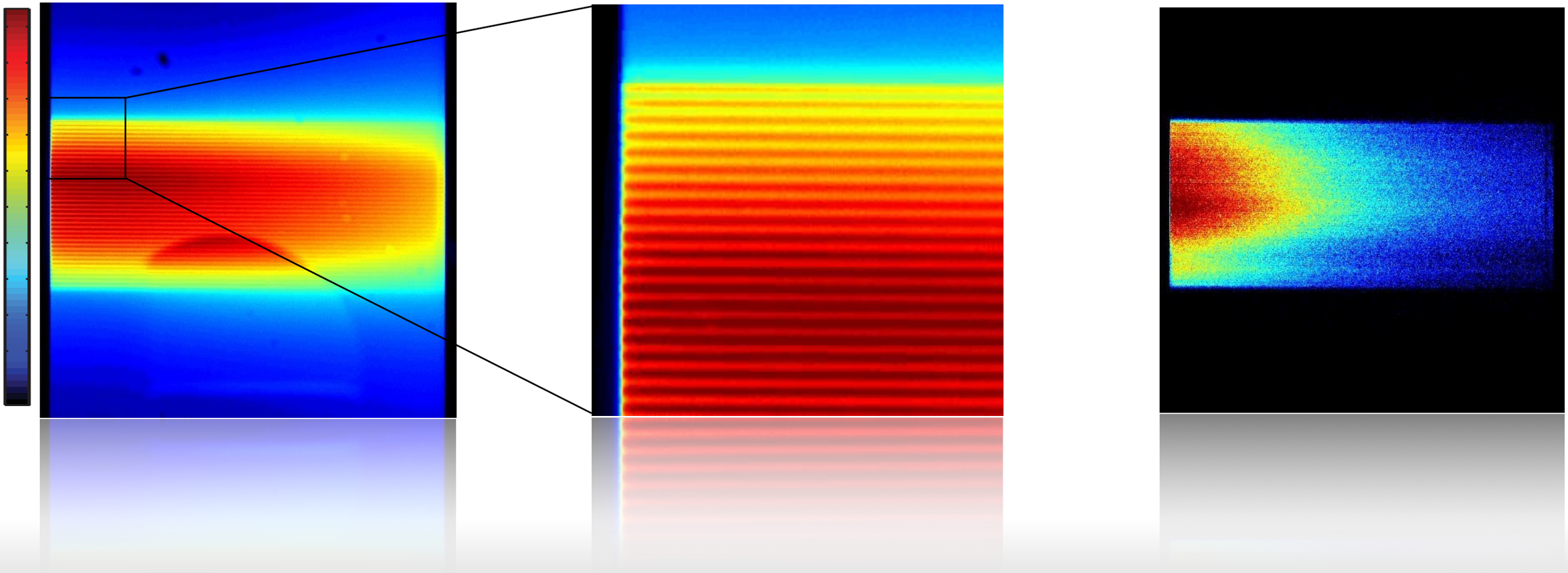
View seen by a camera
at 90 degrees

4 Shift pattern

Distinguish between signal
and background interferences

5 Final image

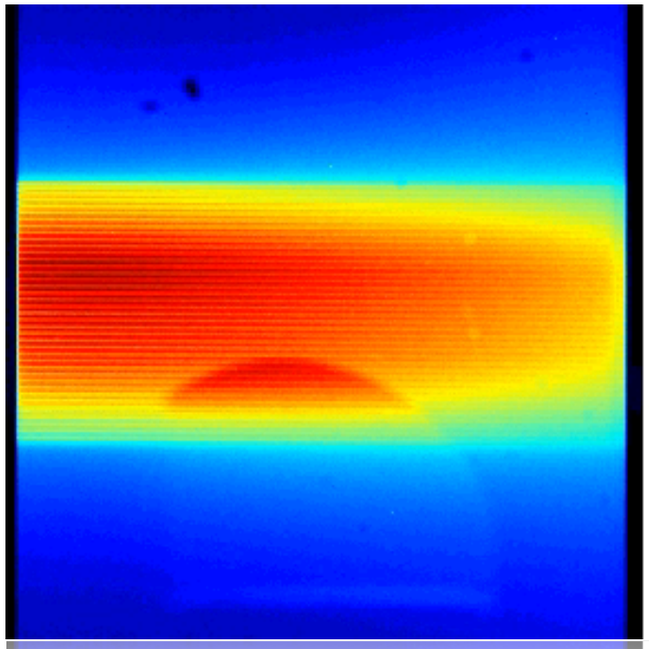
Calculate RMS on a
pixel level



Let's take a Fourier walk

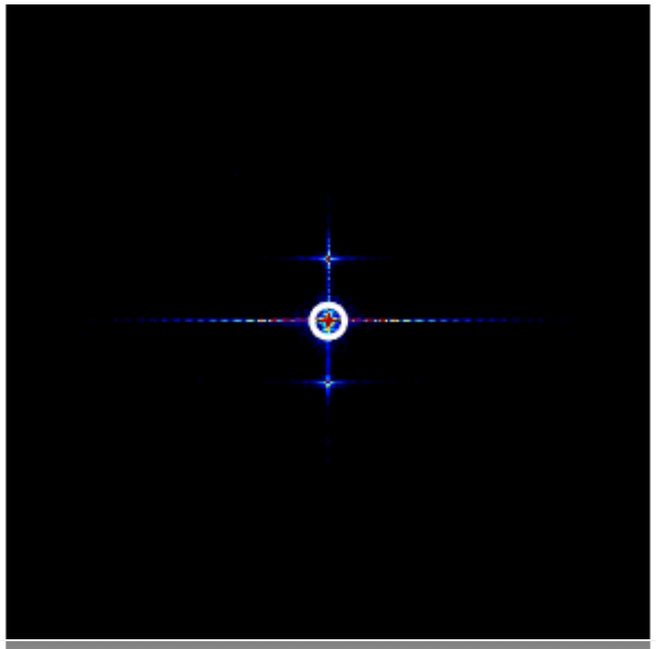
1 Camera view

Sinus-modulated laser sheet through a cuvette



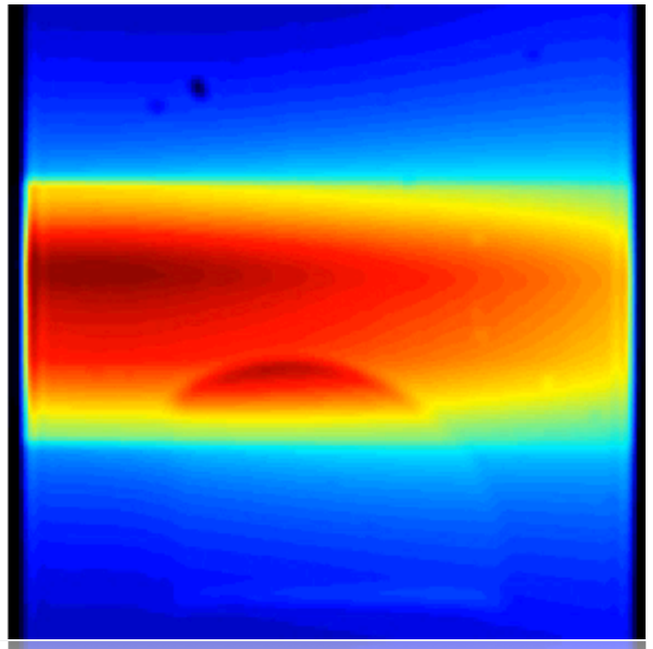
2 Fourier transform

Band-pass filter a small region (0.5% image power)



3 Filtered view

View the information stored locally in the FT



Need for high resolution?

1 2D signal

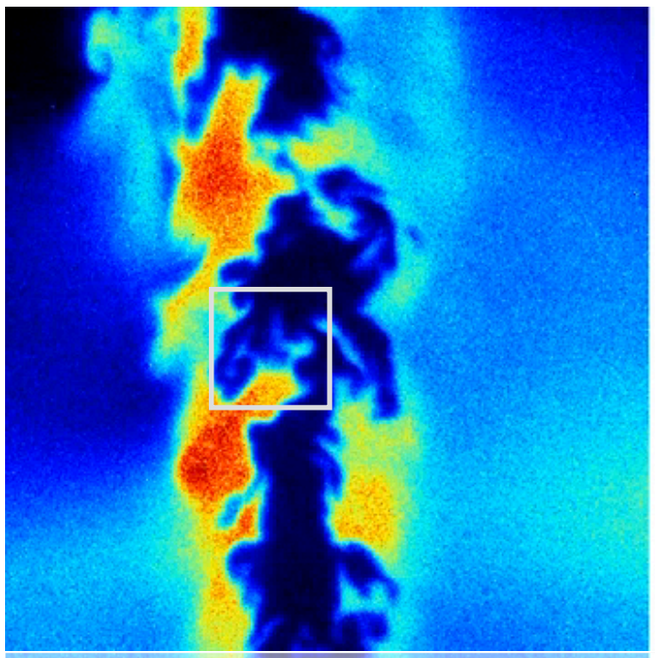
PLIF image of the OH radical

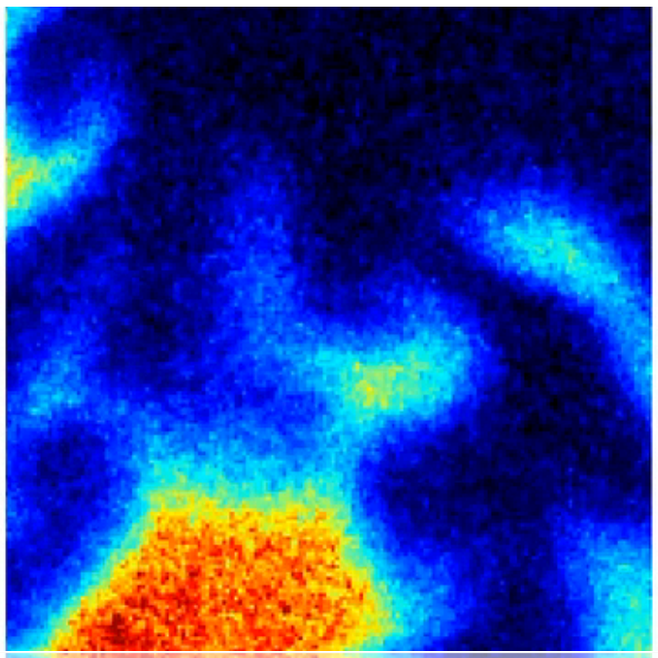
2 Zoomed view

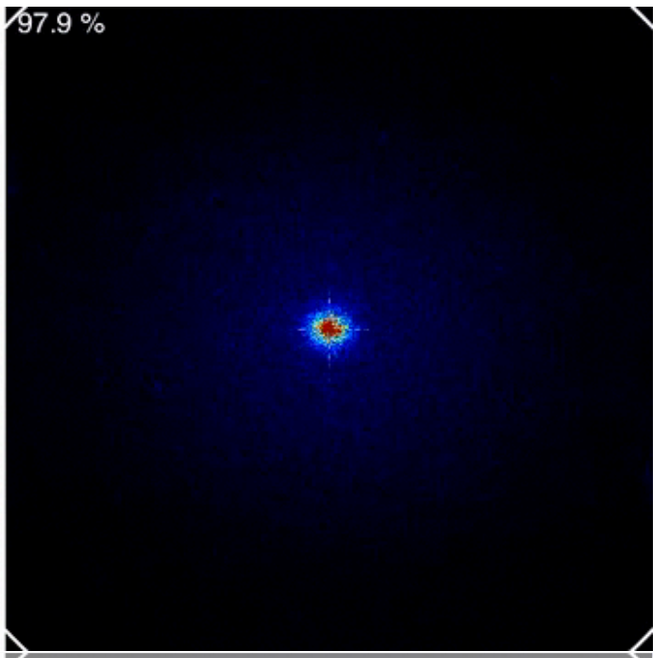
Magnified view to see fine details

3 Fourier transform

Apply a low-pass filter on the image







B. Zhou, *et al.*, Combustion and Flame (162) (2015) 2937-2953.

Simultaneous imaging

1 Signal 1

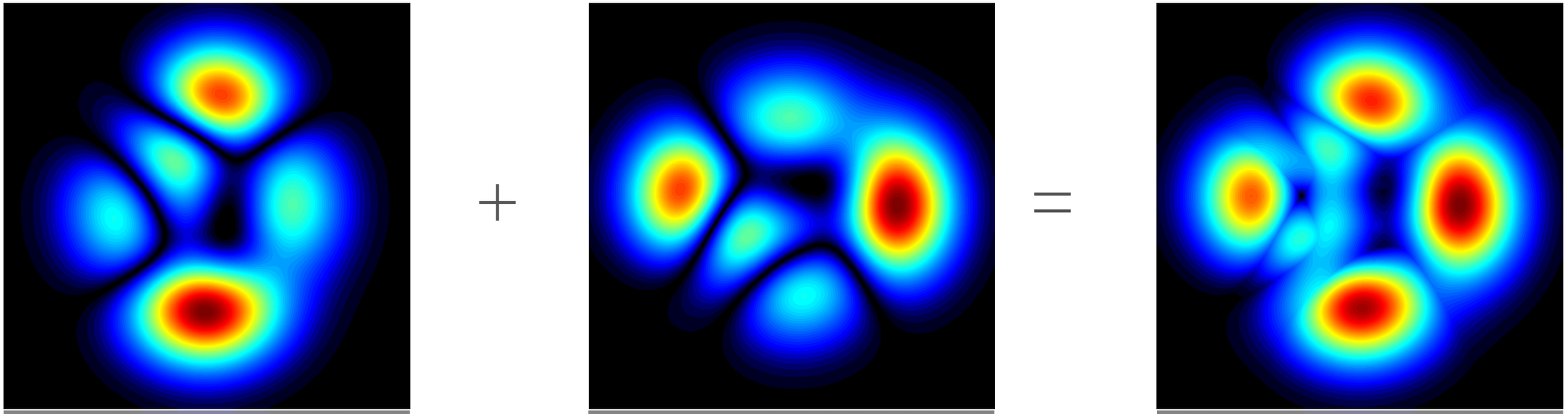
Simulated image of a signal in 2D

2 Signal 2

Simulated image of a signal in 2D

3 Both

Signal 1 + signal 2



Simultaneous imaging

2 Signal 2

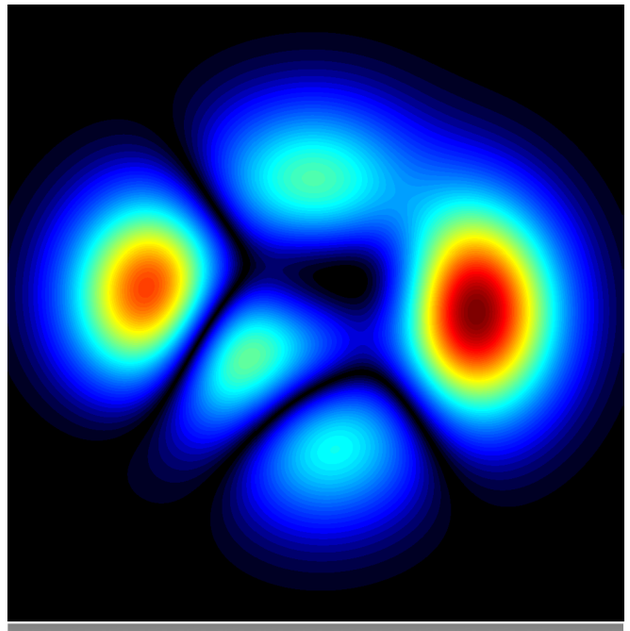
Simulated image of a signal in 2D

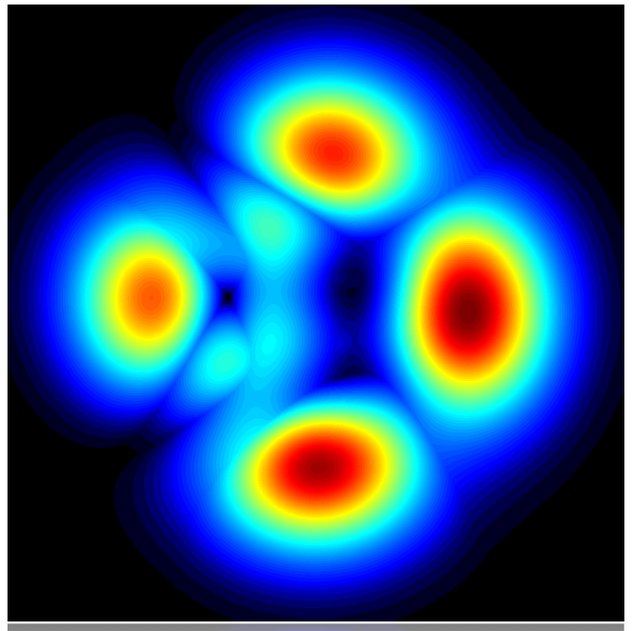
3 Both

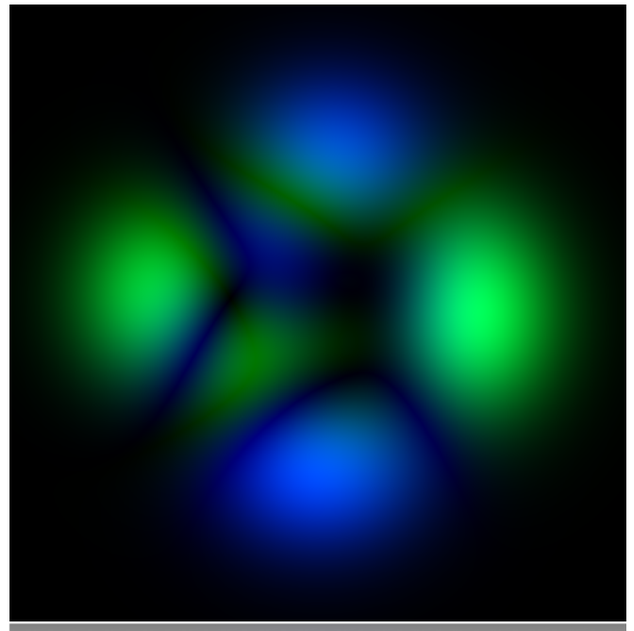
Signal 1 + signal 2

4 Different colors

Spectrally separate signals



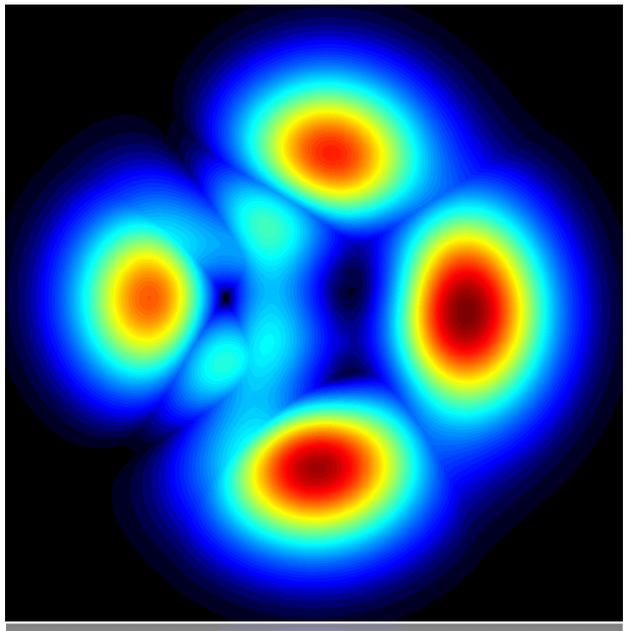




Simultaneous imaging

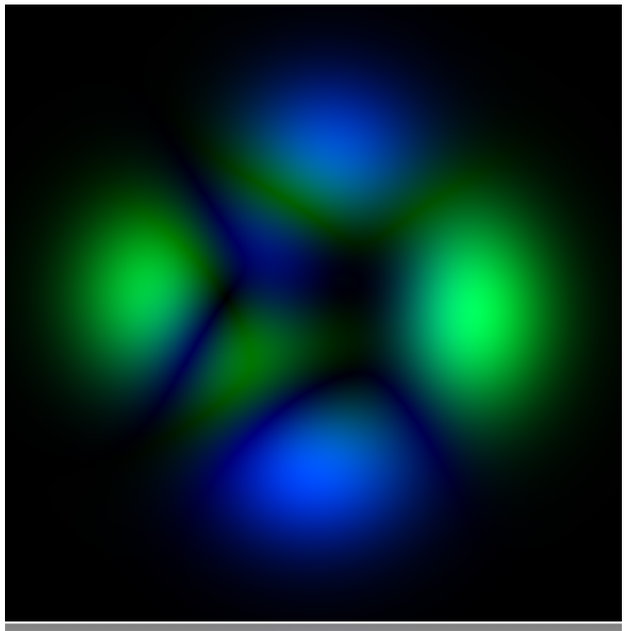
3 Both

Signal 1 + signal 2



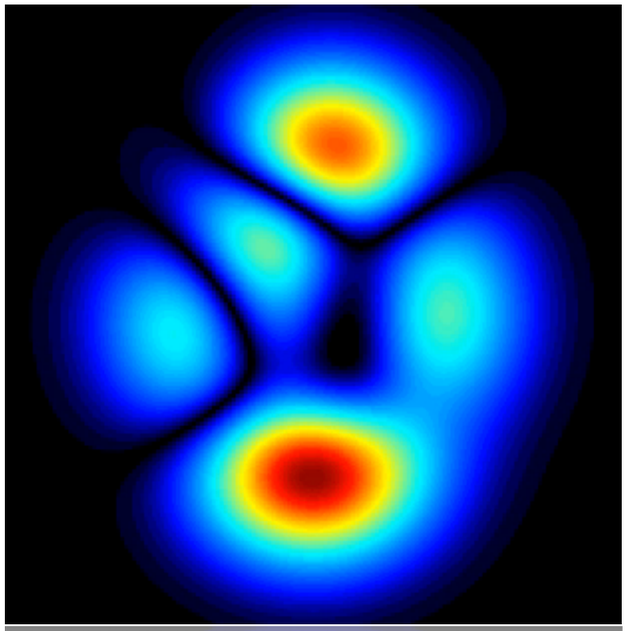
4 Different colors

Spectrally separate signals



5 Time gating

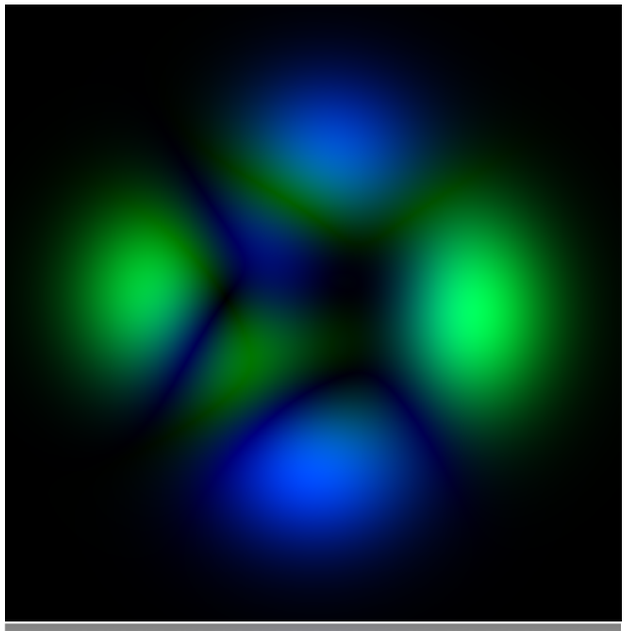
Temporally separate signals



Simultaneous imaging

4 Different colors

Spectrally separate signals



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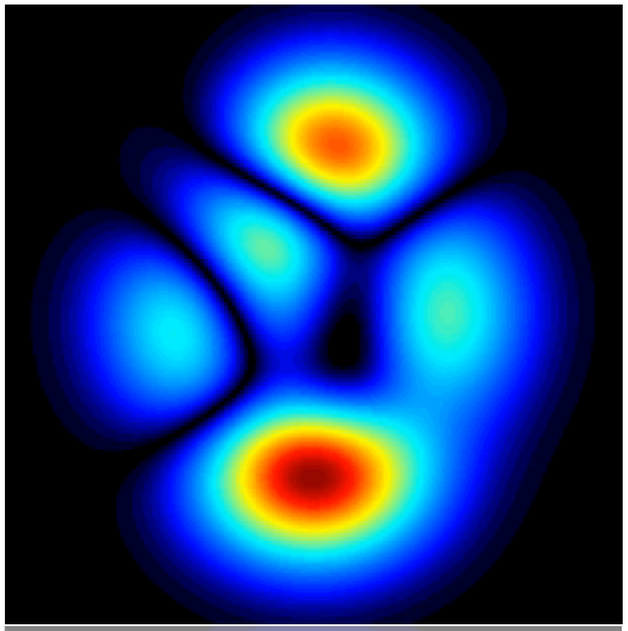
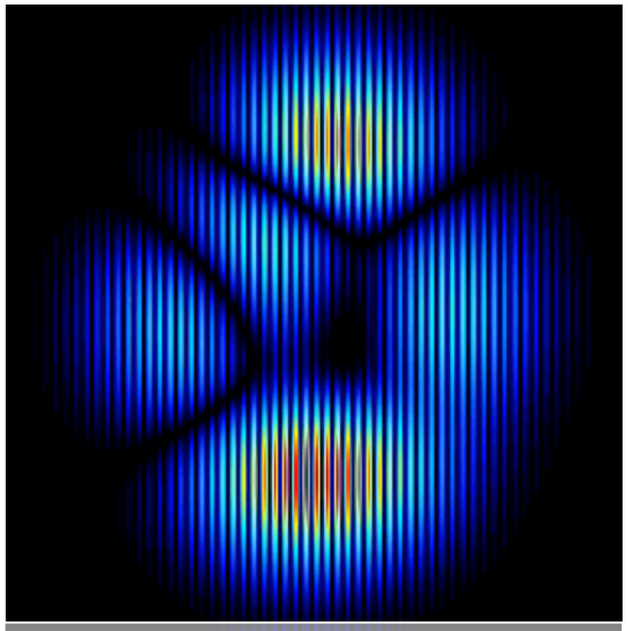
Temporally separate signals



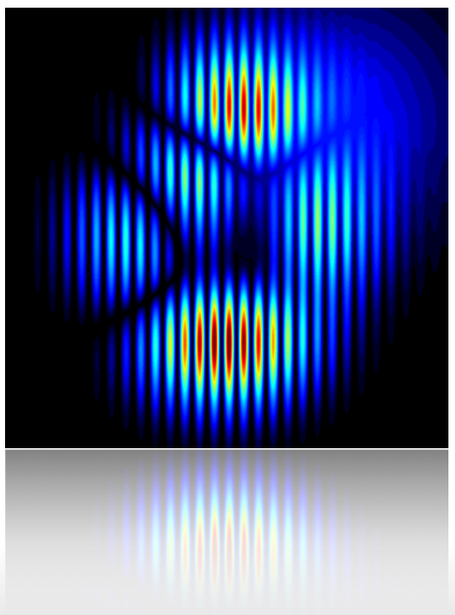
6 Spatial modulation

Modulate each signal in space



Spatial lock-in detection

Theory



Spatial lock-in detection

1 Sample

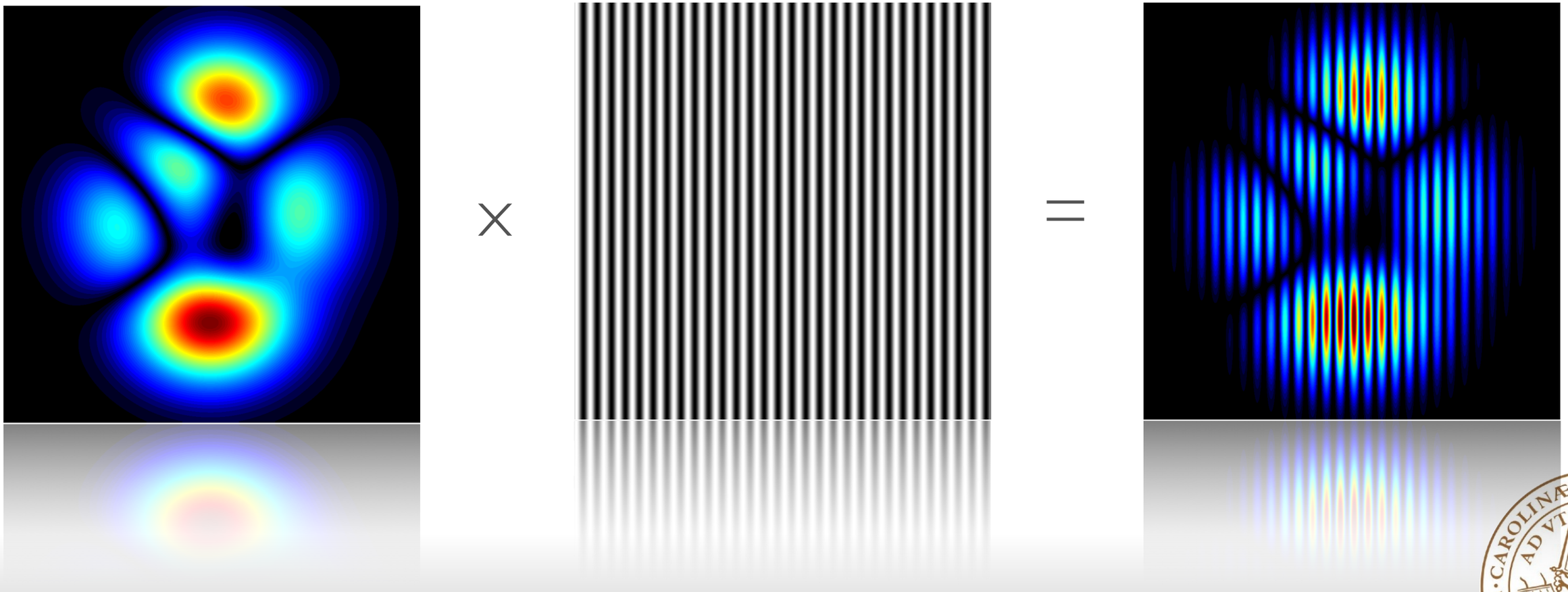
Object structures that we will probe

2 Modulation

An intensity modulated illumination field

3 Modulated signal

Modulated 2D image of the sample



Spatial lock-in detection

2 Modulation

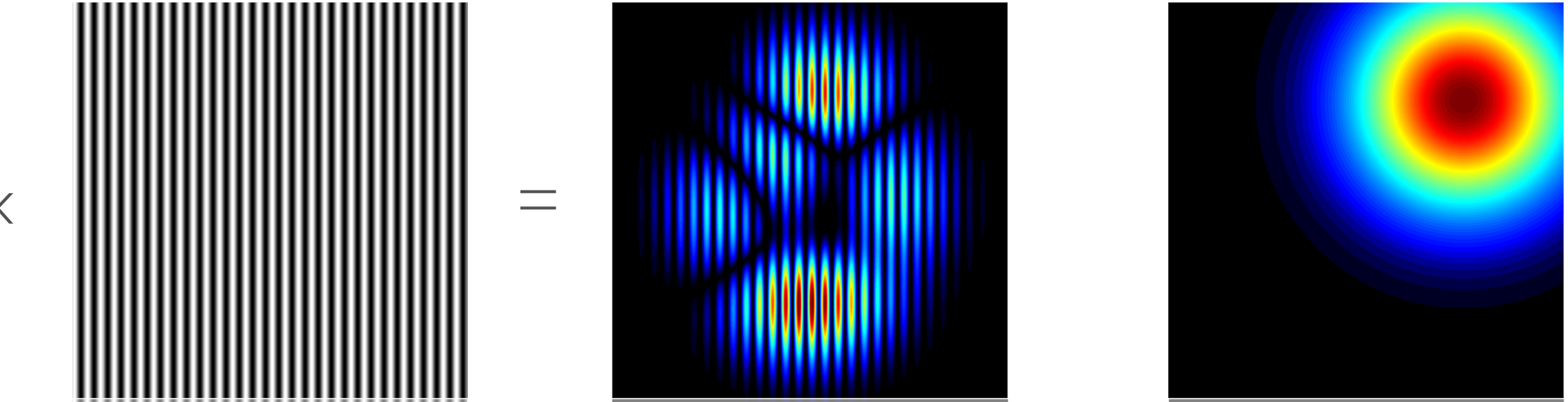
An intensity modulated illumination field

3 Modulated signal

Modulated 2D image of the sample

4 Background

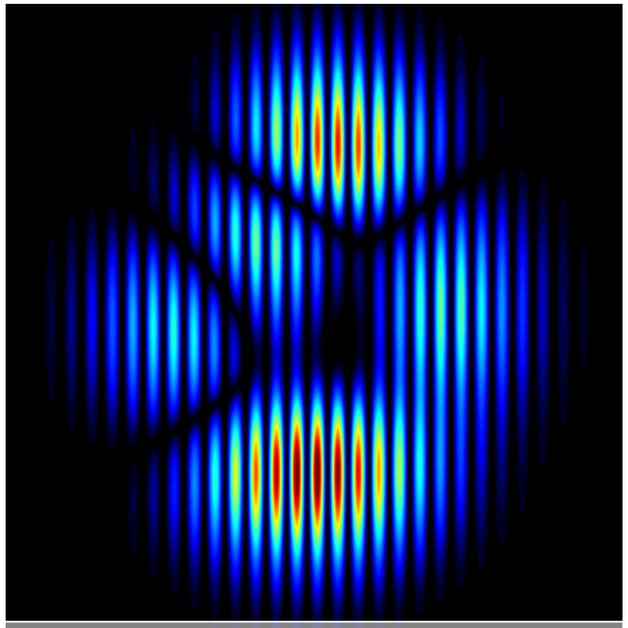
Not induced by the illumination



Spatial lock-in detection

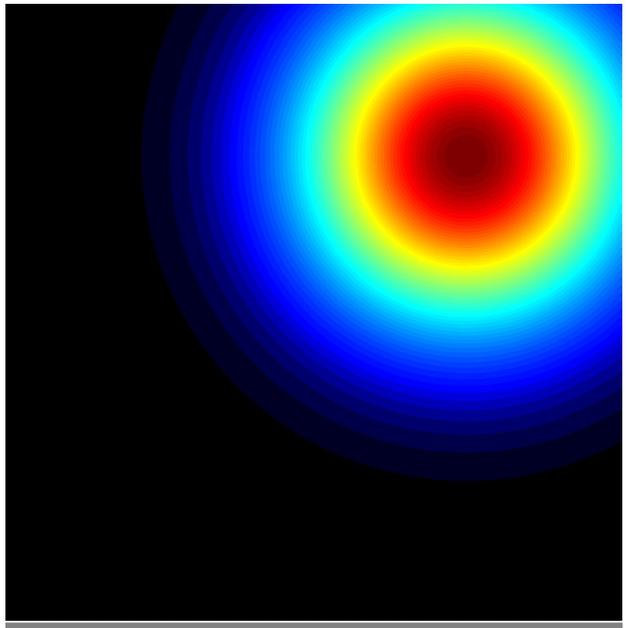
3 Modulated signal

Modulated 2D image of the sample



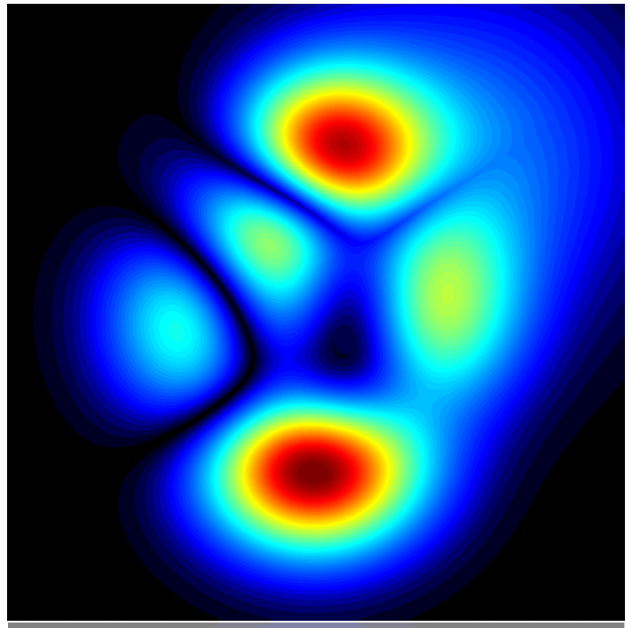
4 Background

Not induced by the illumination



5 Without modulation

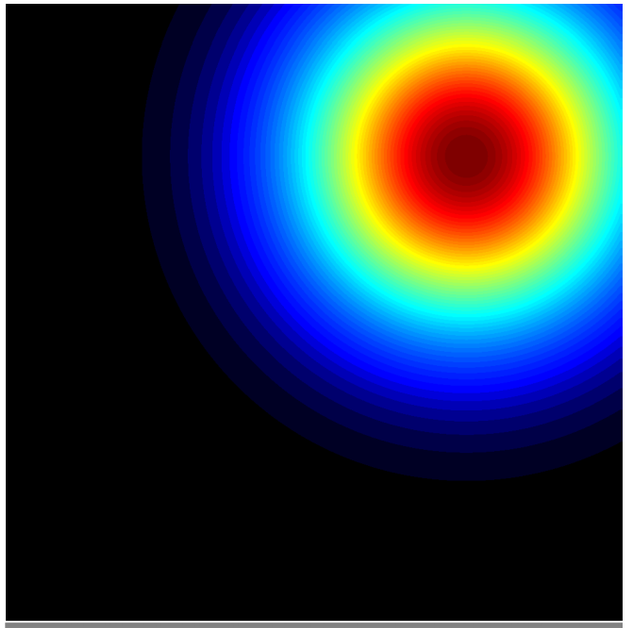
Detected signal without modulation



Spatial lock-in detection

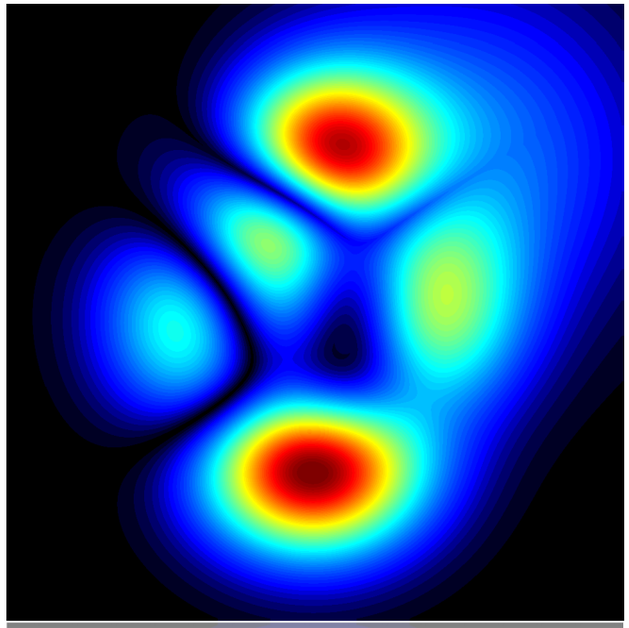
4 Background

Not induced by the illumination



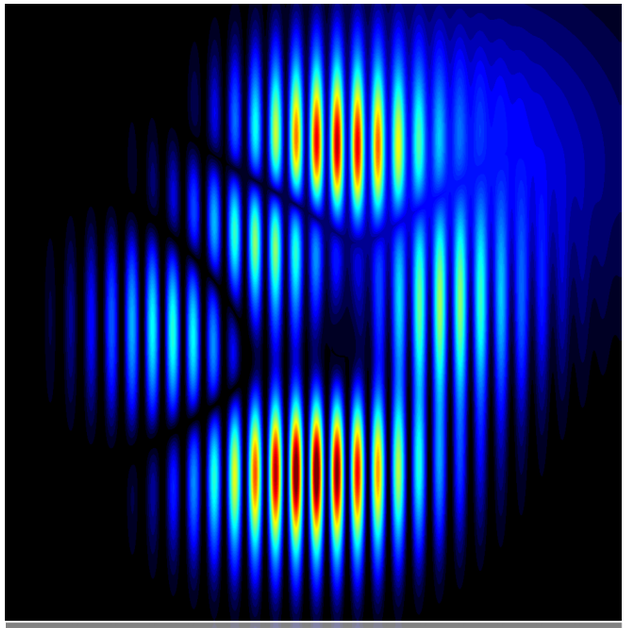
5 Without modulation

Detected signal without modulation



6 With modulation

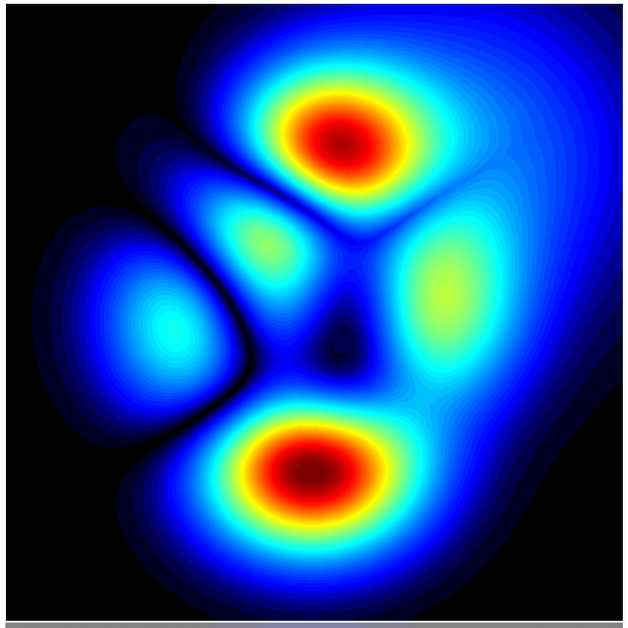
Detected signal with modulation



Spatial lock-in detection

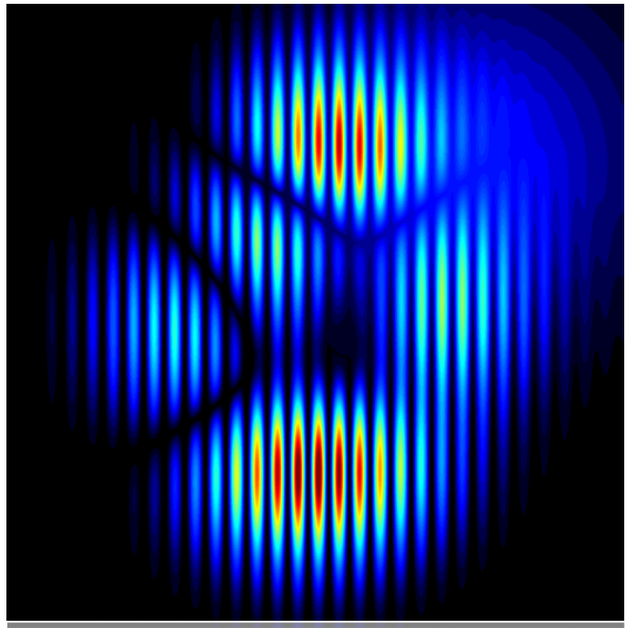
5 Without modulation

Detected signal without modulation



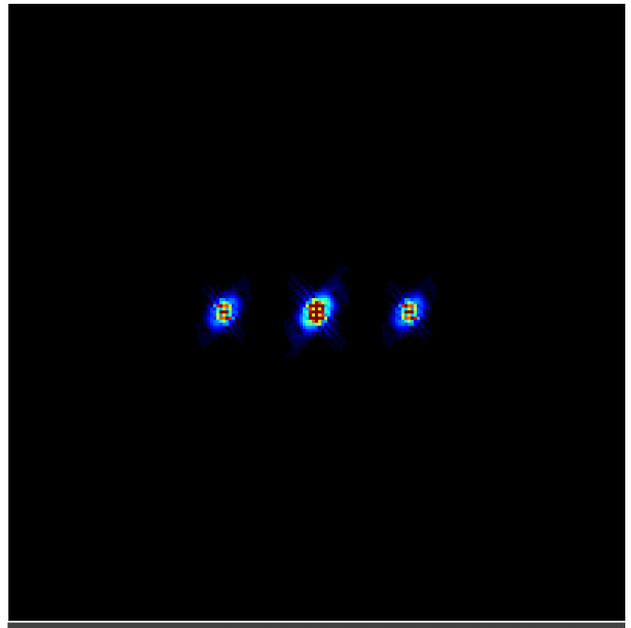
6 With modulation

Detected signal with modulation



7 Fourier transform

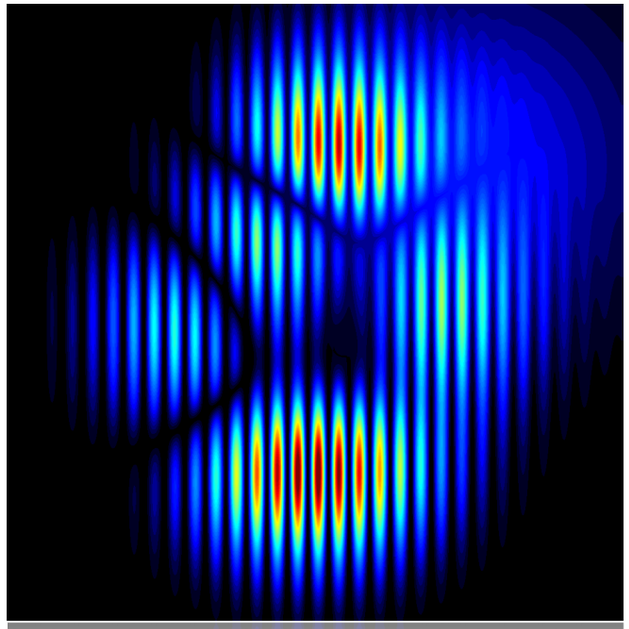
Two peaks corresponding to the modulation



Spatial lock-in detection

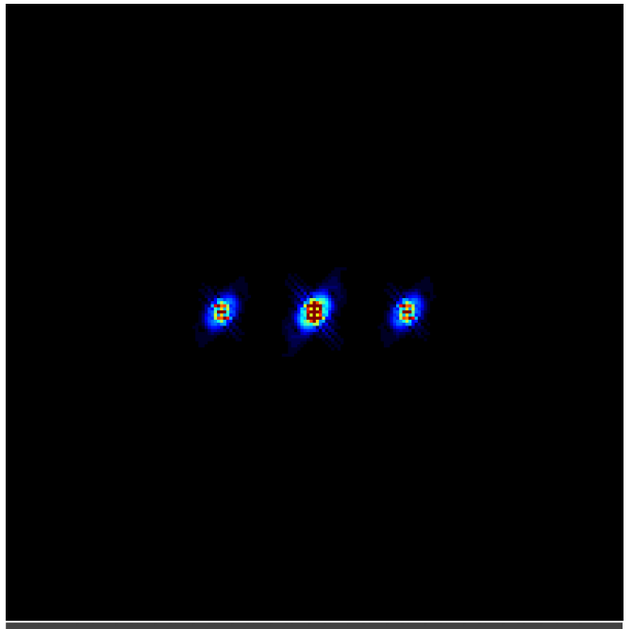
6 With modulation

Detected signal with modulation



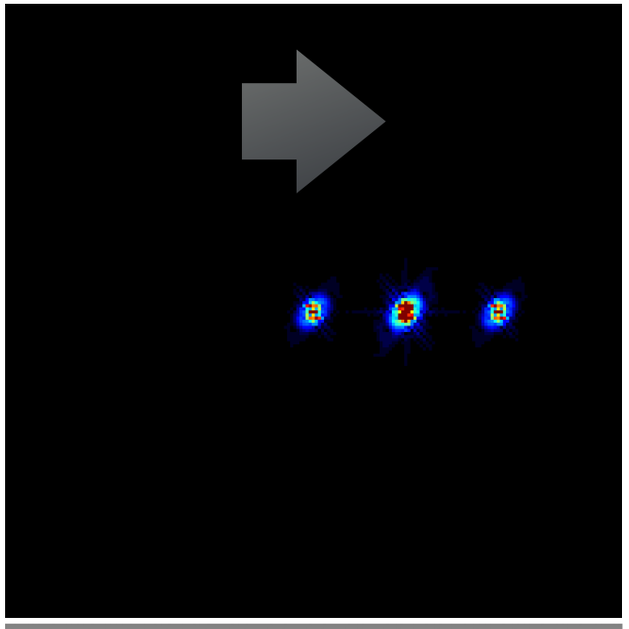
7 Fourier transform

Two peaks corresponding to the modulation



8 Shift FT

Shift modulation peak to origin



Spatial lock-in detection

7 Fourier transform

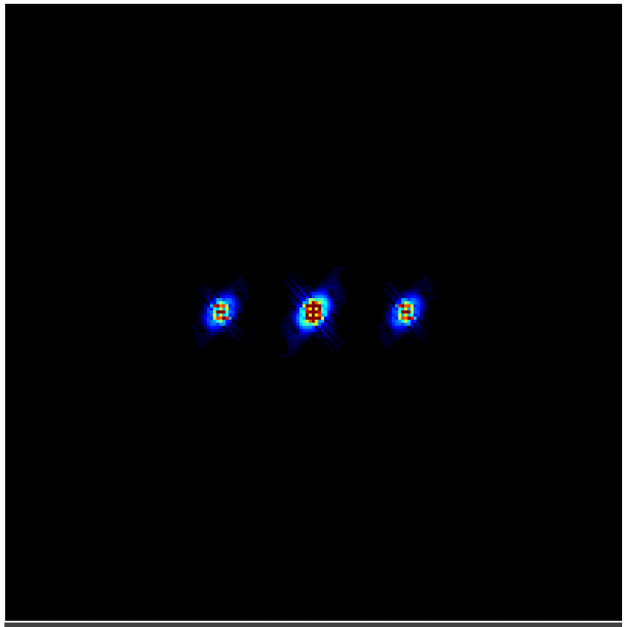
Two peaks corresponding to the modulation

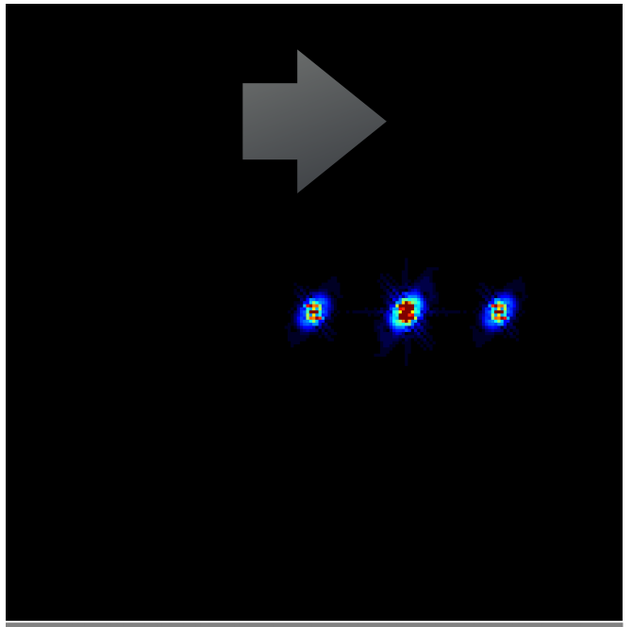
8 Shift FT

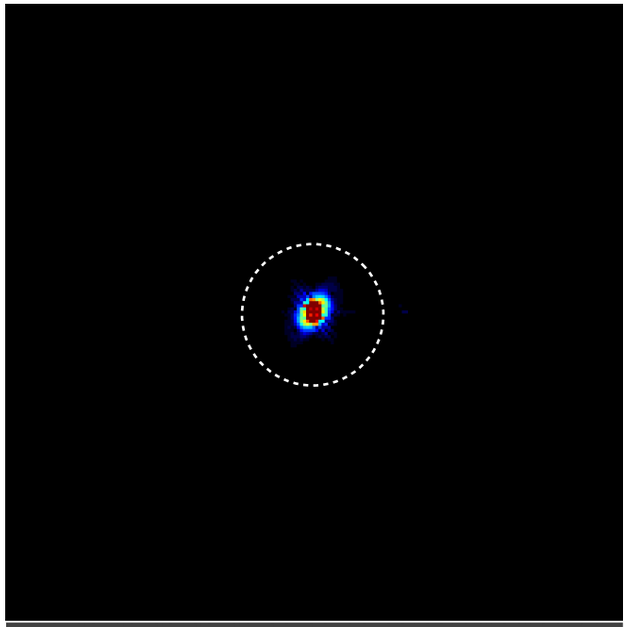
Shift modulation peak to origin

9 Low-pass filter

Apply a low-pass filter on the shifted data







Spatial lock-in detection

8 Shift FT

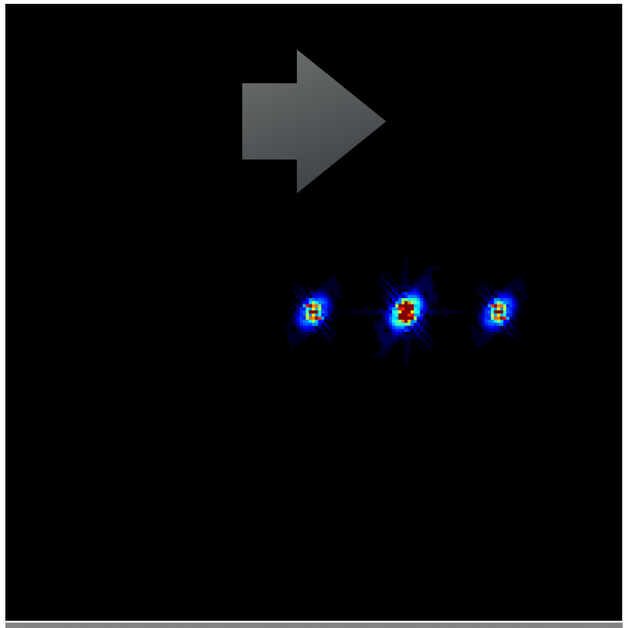
Shift modulation peak to origin

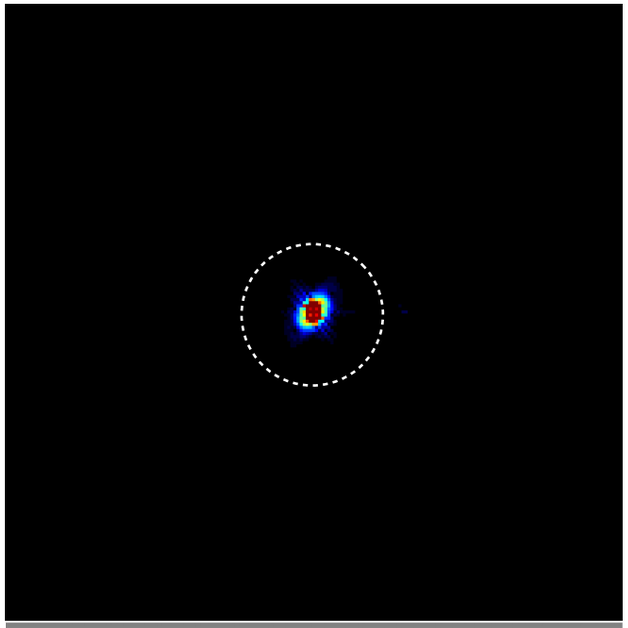
9 Low-pass filter

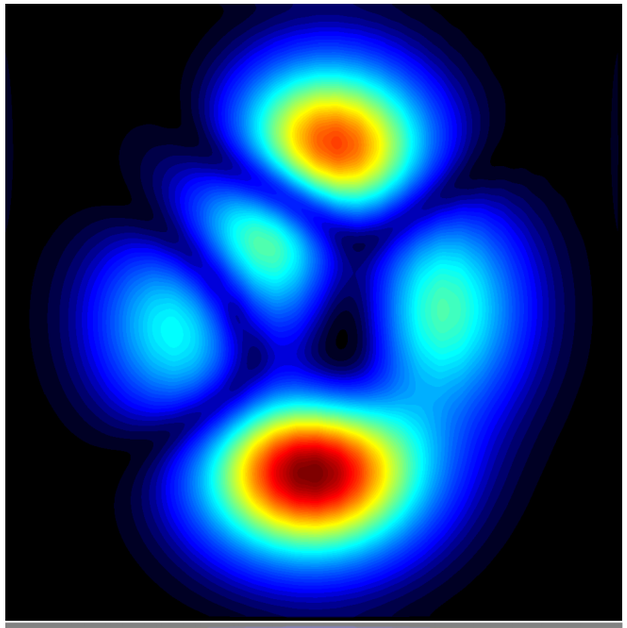
Apply a low-pass filter on the shifted data

10 Inverse Fourier transform

Reveals the information carried by the modulation







Spatial lock-in for multiple detection

1 Signal 1

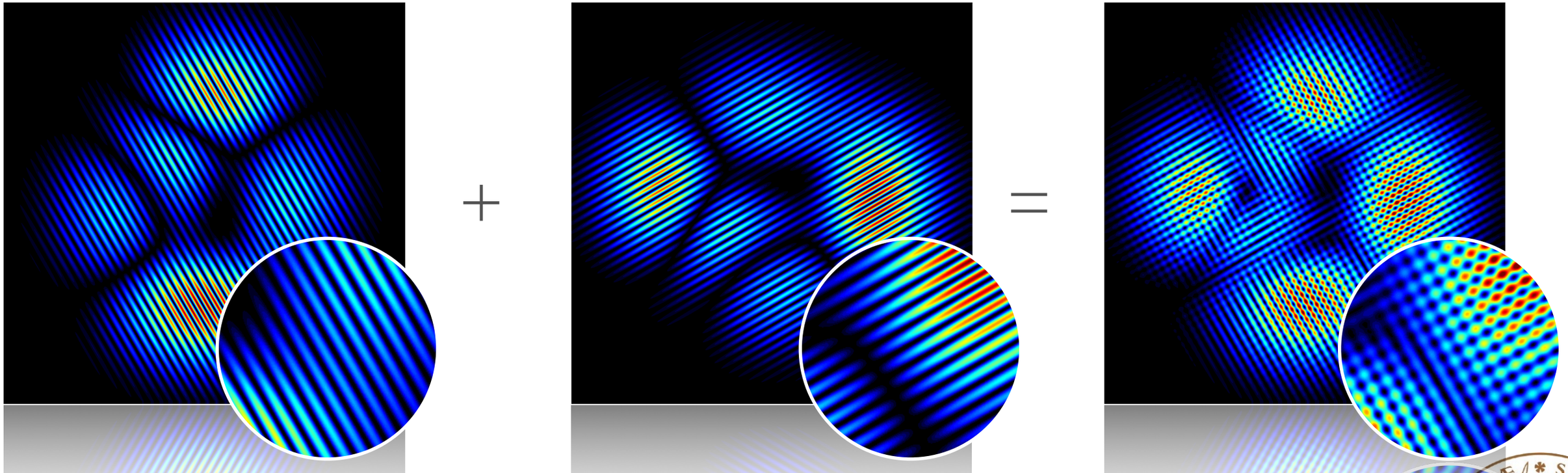
Sample 1 illuminated with modulation

2 Signal 2

Sample 2 illuminated with different modulation

3 Camera view

Camera sees both signals simultaneously



Spatial lock-in for multiple detection

2 Signal 2

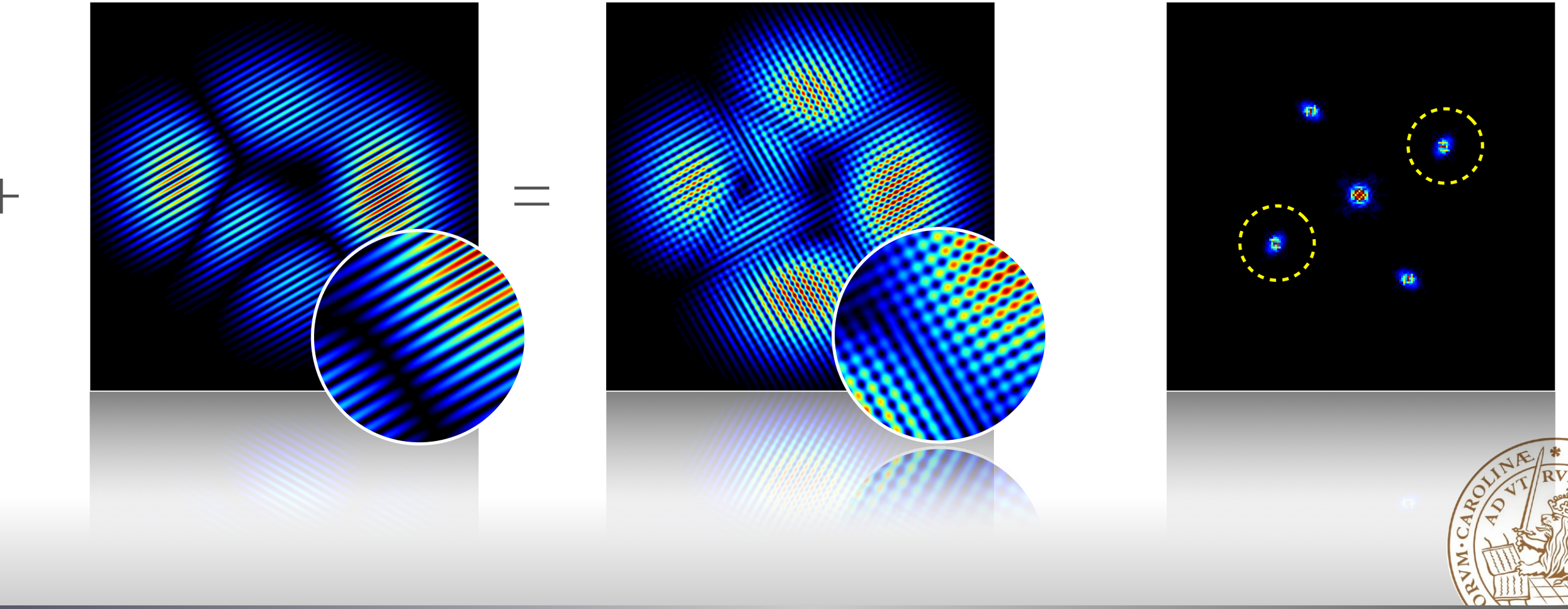
Sample 2 illuminated with different modulation

3 Camera view

Camera sees both signals simultaneously

4 Fourier transform

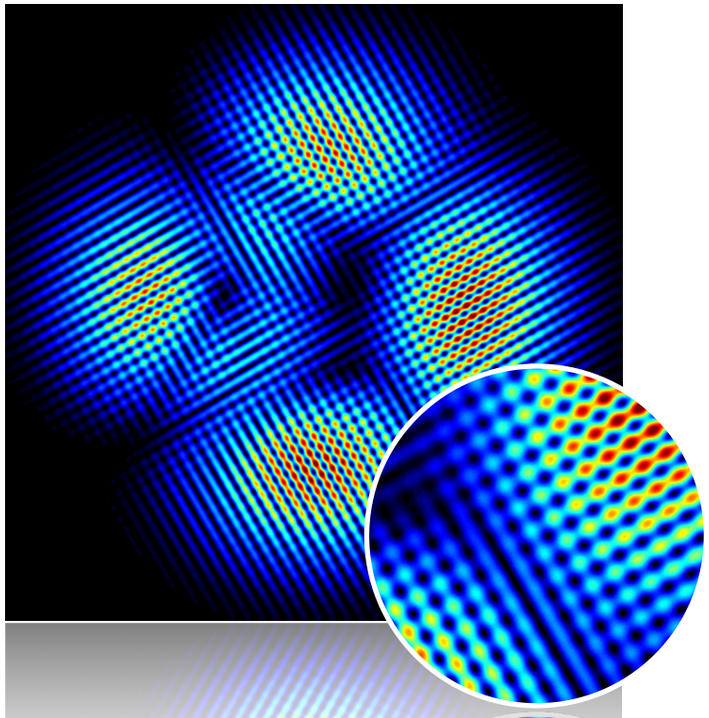
Signal peaks are isolated from each other



Spatial lock-in for multiple detection

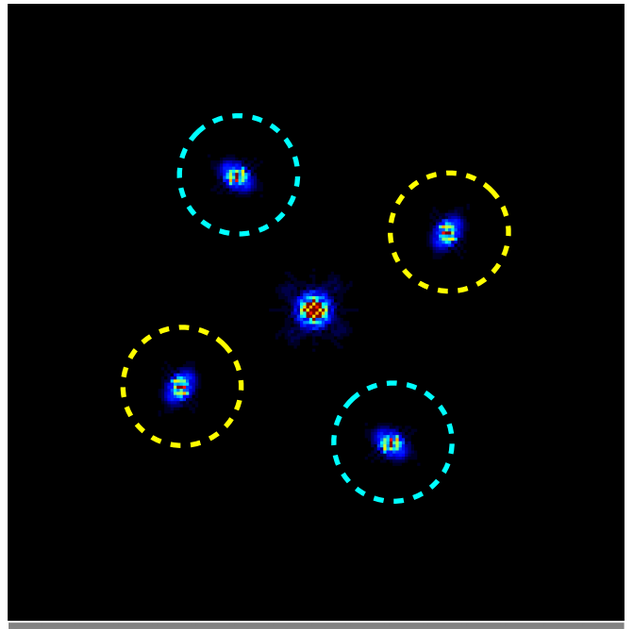
3 Camera view

Camera sees both signals simultaneously



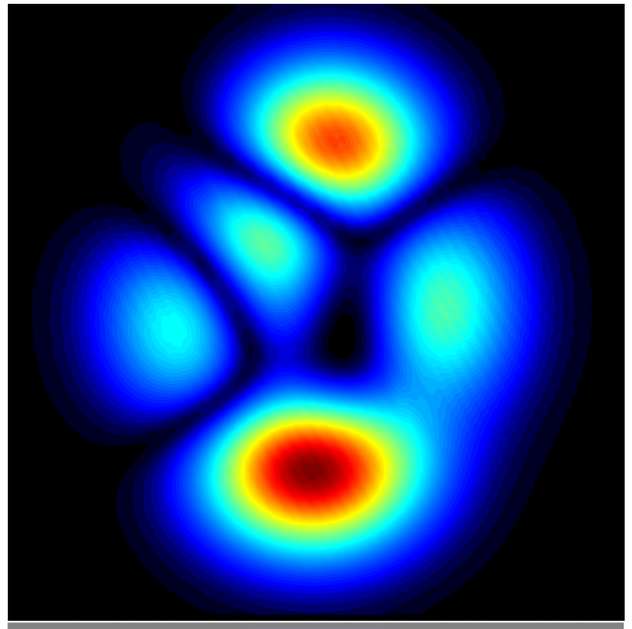
4 Fourier transform

Signal peaks are isolated from each other



5 Inverse transform

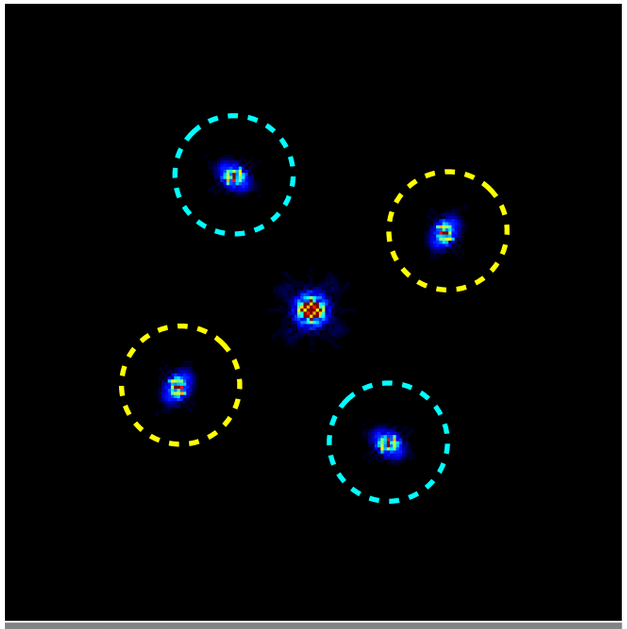
Signal 1 extracted from inverse Fourier transform



Spatial lock-in for multiple detection

4 Fourier transform

Signal peaks are isolated from each other



5 Inverse transform

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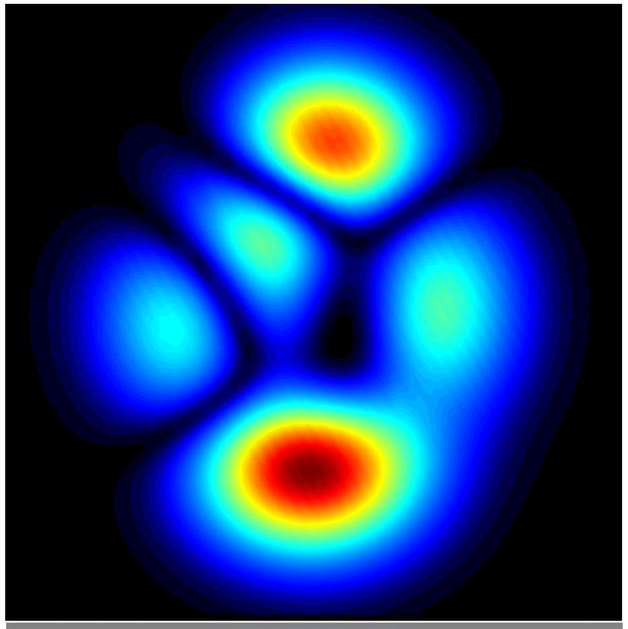
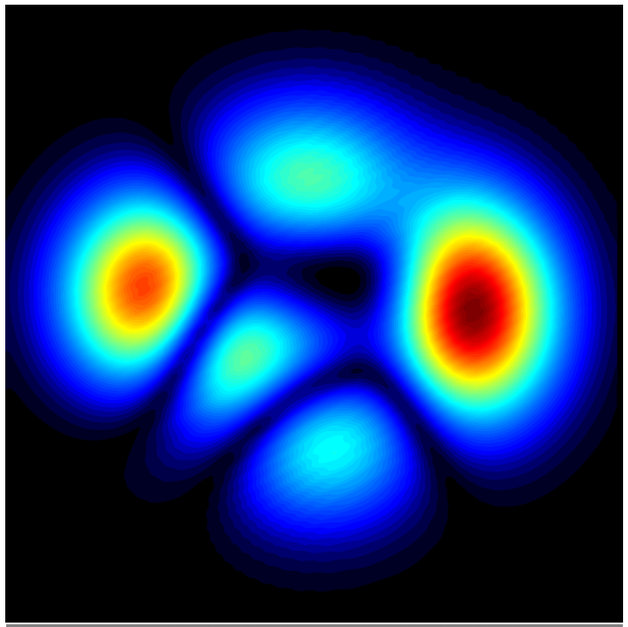


6 Inverse transform

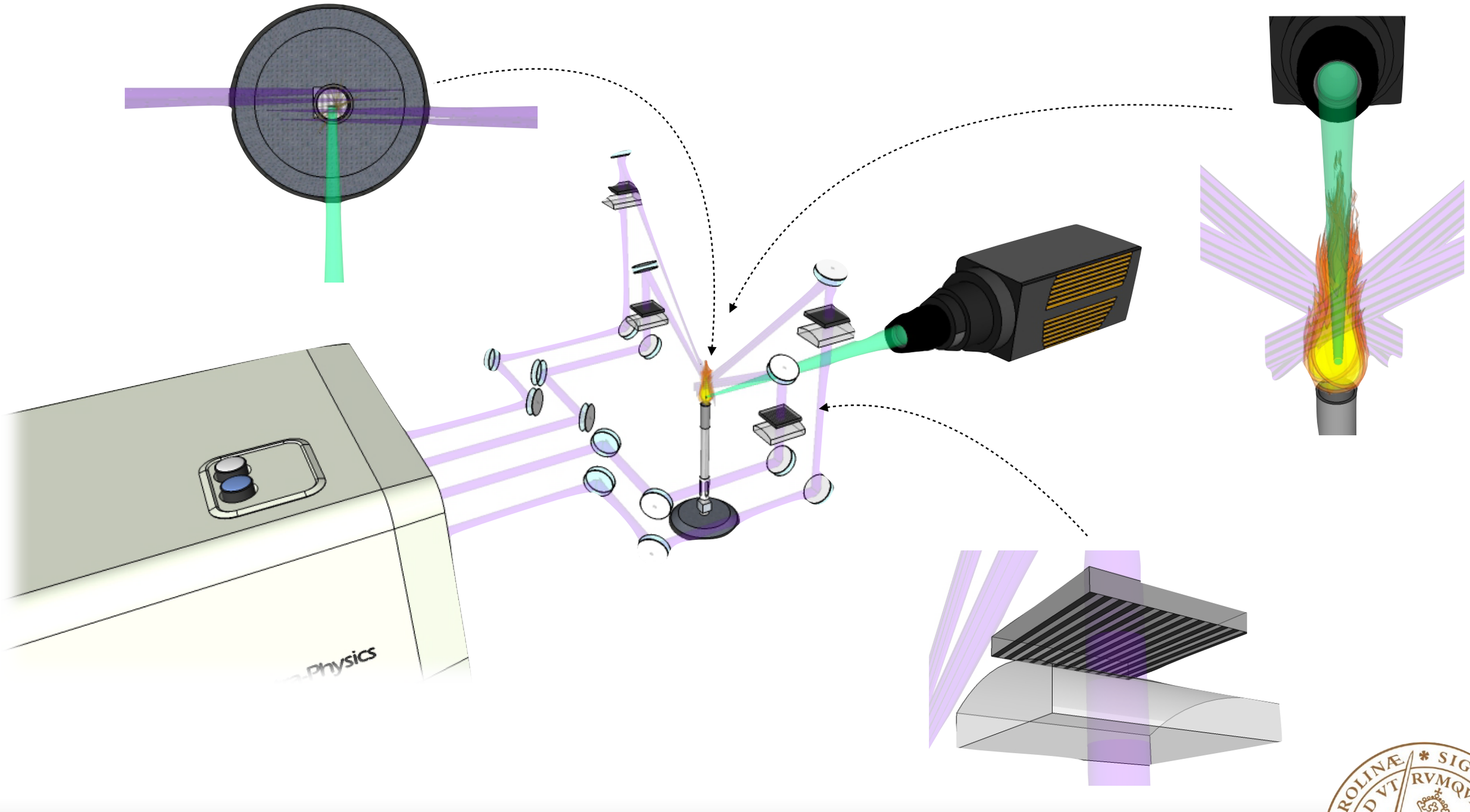
Signal 2 extracted from inverse Fourier transform



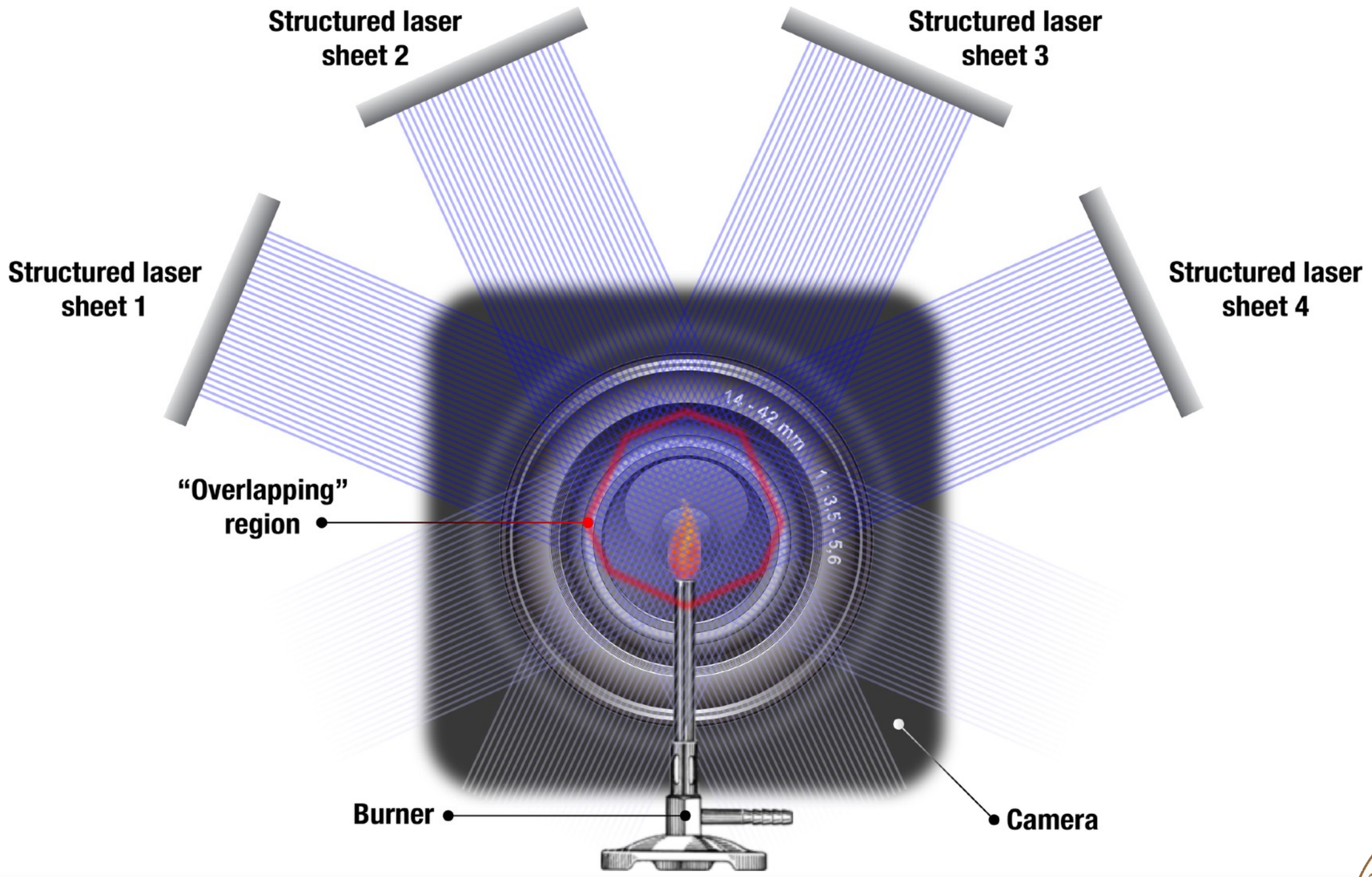
Experimental setup

Modulated illumination for multiple exposures

Experimental setup



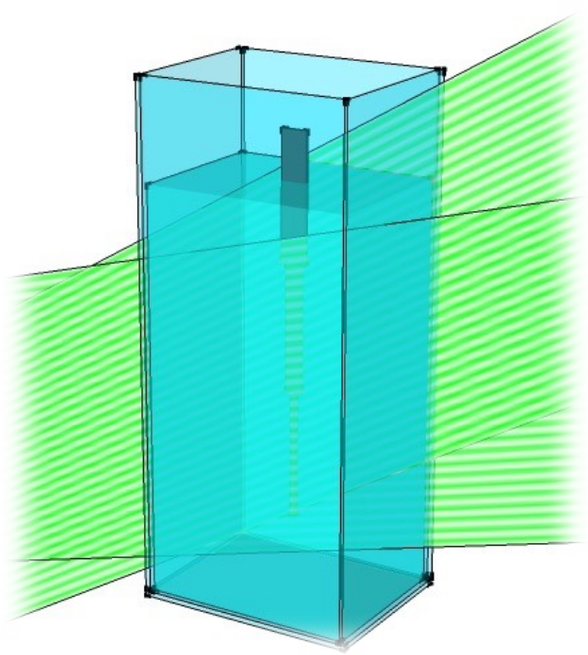
Camera view


Structured laser sheet 2
Structured laser sheet 3
Structured laser sheet 1
Structured laser sheet 4
"Overlapping" region
Burner
Camera

First test

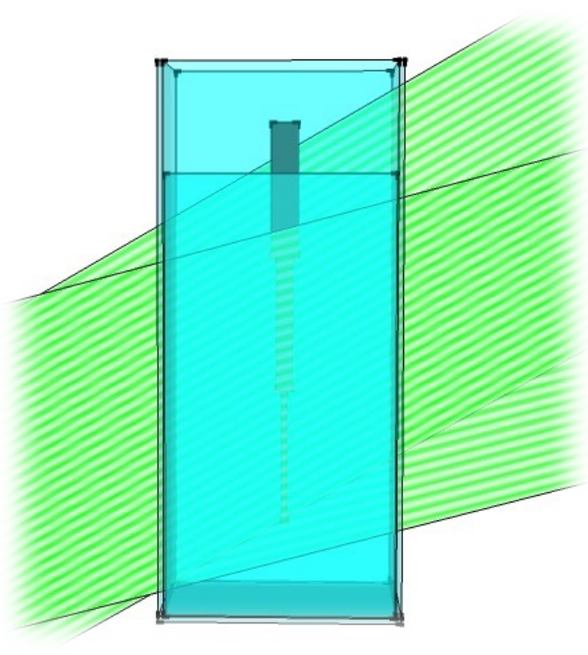
1 Cuvette

Cuvette with dye illuminated with 2 sheets



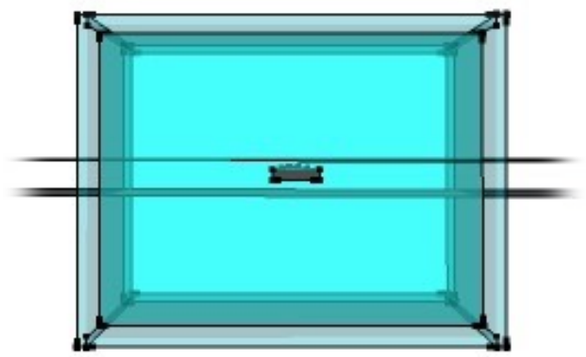
2 Camera view

Metal piece in front of one sheet



3 Top view

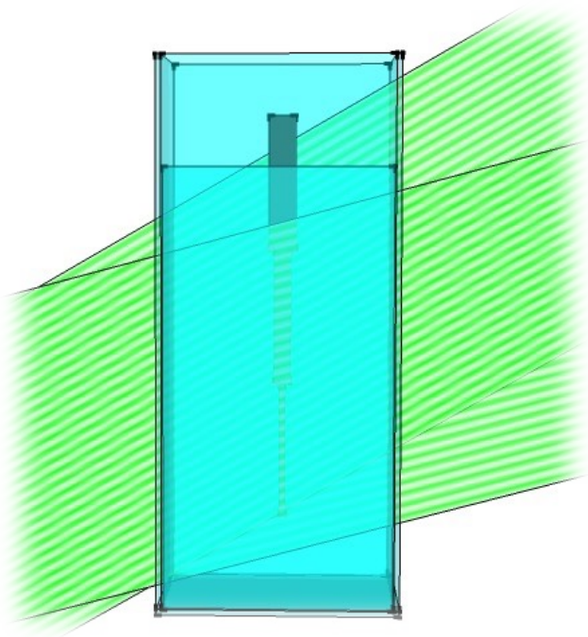
Sheets separated ~4 mm



First test

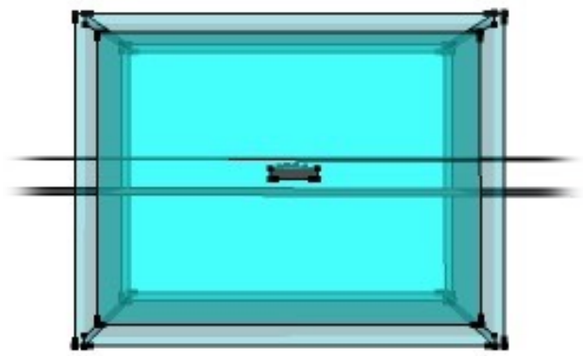
2 Camera view

Metal piece in front of one sheet



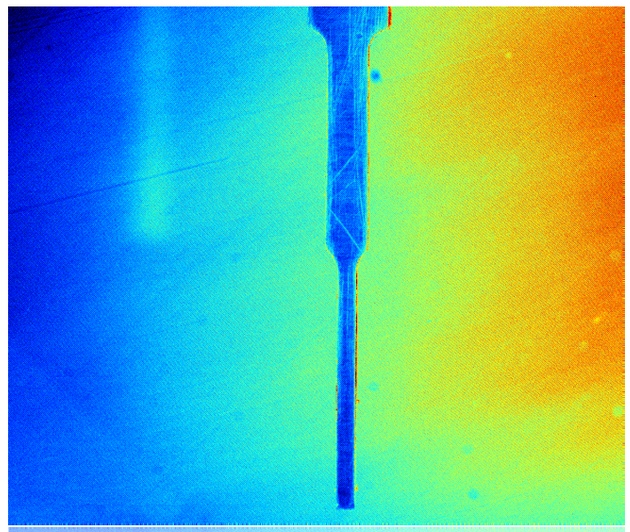
3 Top view

Sheets separated ~4 mm



4 Raw data

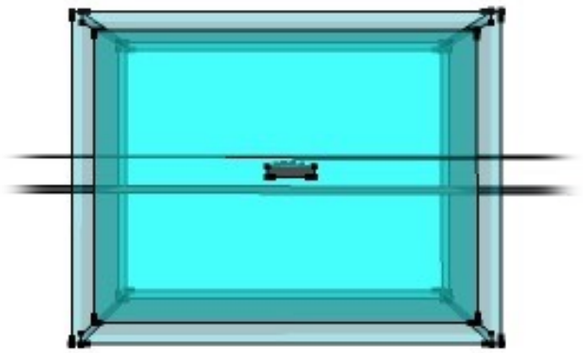
Image acquired with camera



First test

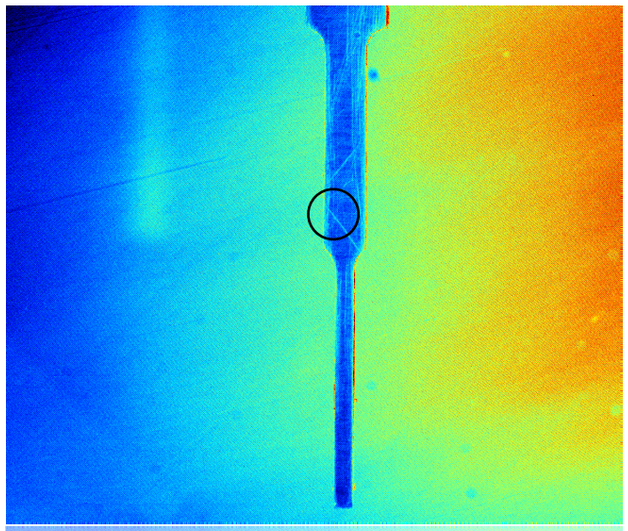
3 Top view

Sheets separated
~4 mm



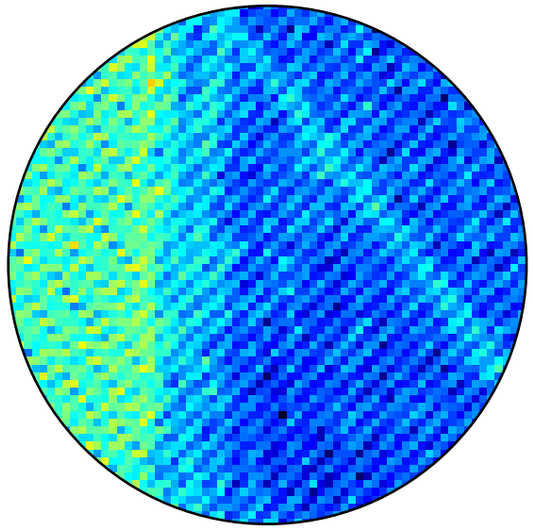
4 Raw data

Image acquired with
camera



5 Magnified region

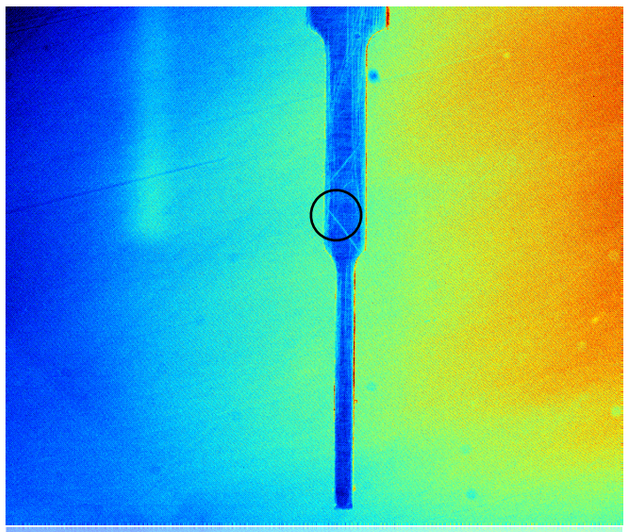
Modulation
frequencies different



First test

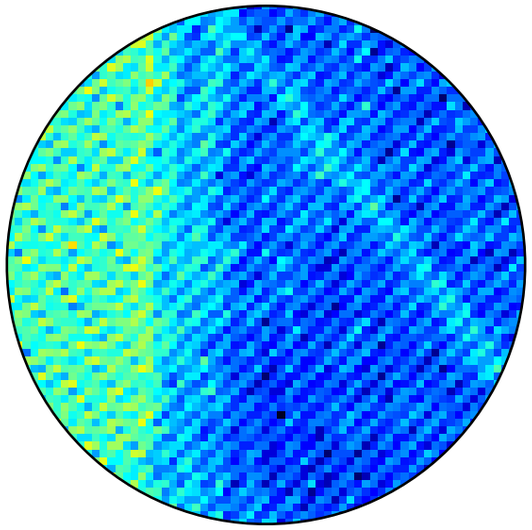
4 Raw data

Image acquired with camera



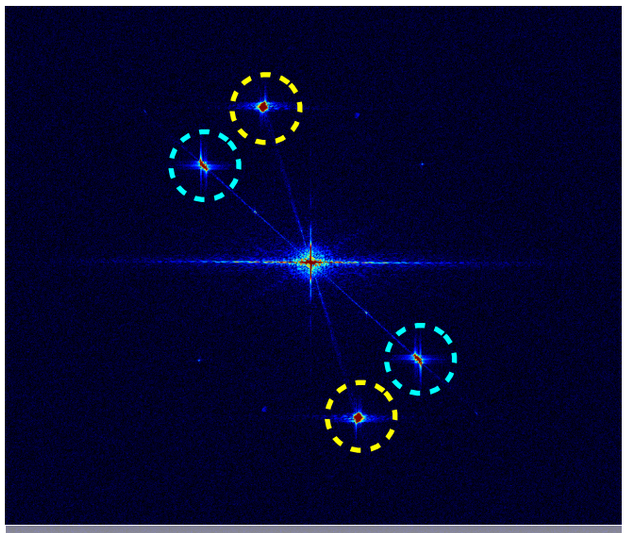
5 Magnified region

Modulation frequencies different



6 Fourier transform

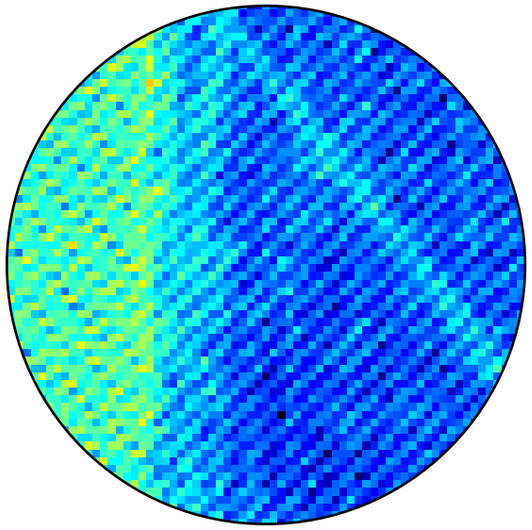
Each signal as peaks in Fourier domain



First test

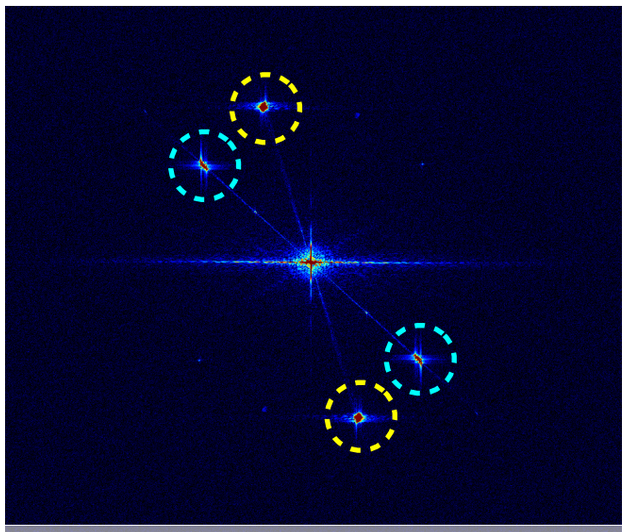
5 Magnified region

Modulation frequencies different



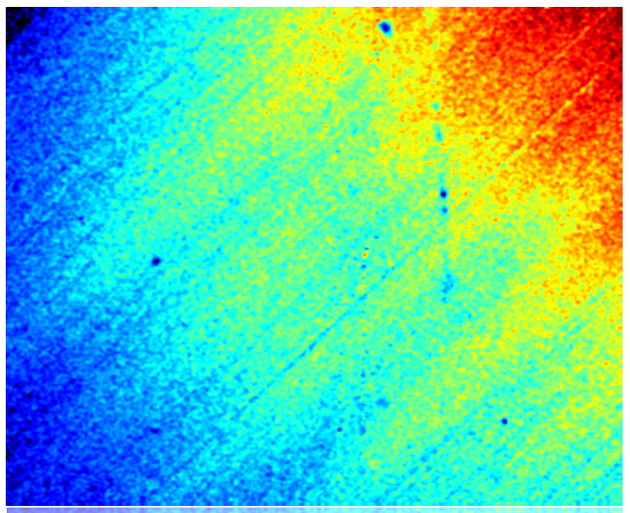
6 Fourier transform

Each signal as peaks in Fourier domain



7 Subimage 1

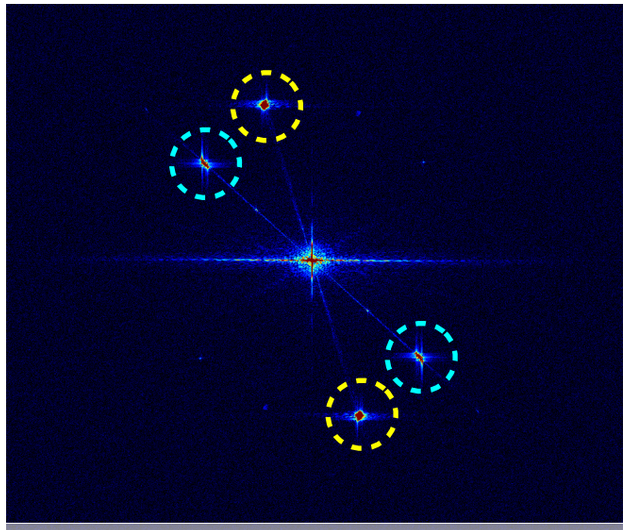
Information in band-pass filter #1



First test

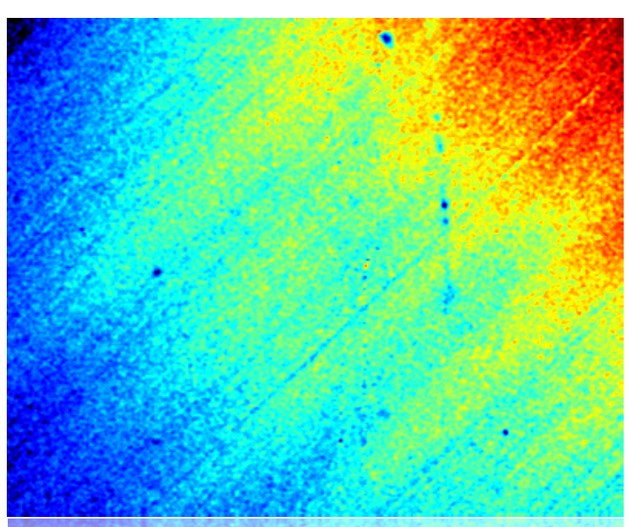
6 Fourier transform

Each signal as peaks in Fourier domain



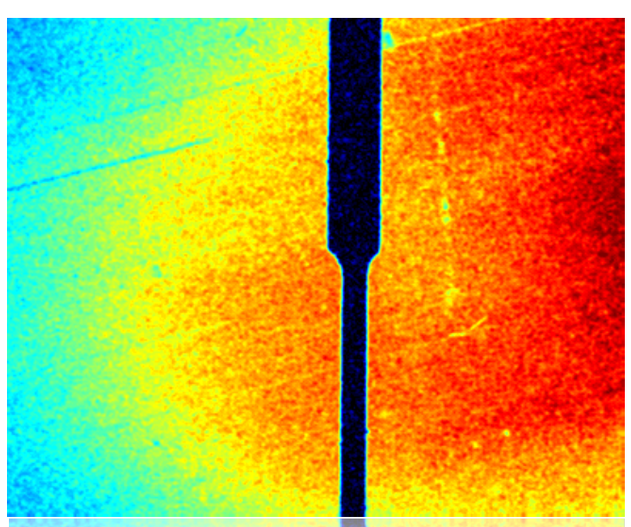
7 Subimage 1

Information in band-pass filter #1



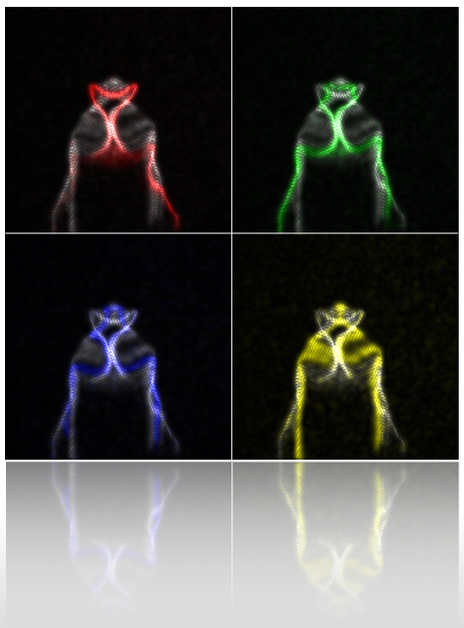
8 Subimage 2

Information in band-pass filter #2



Results

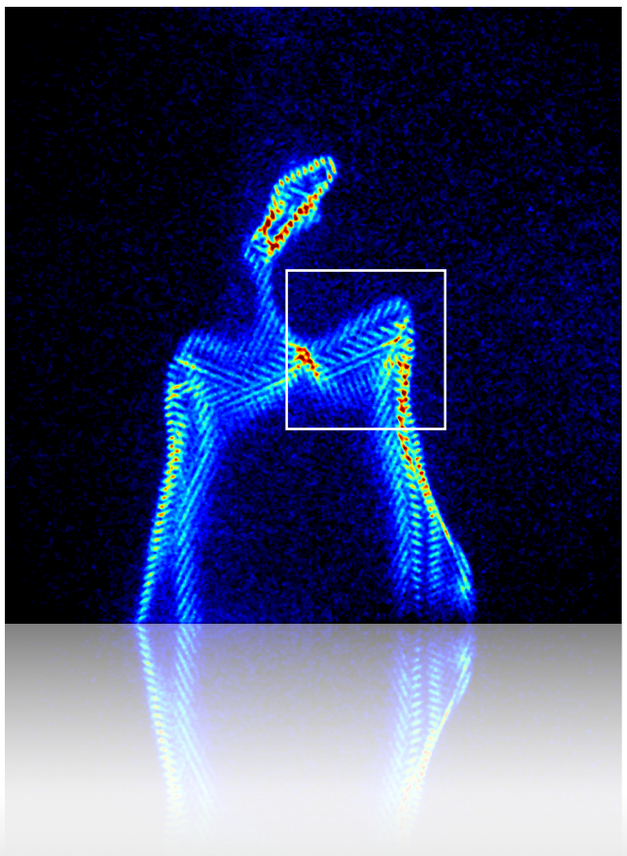
Modulated PLIF images of formaldehyde distribution



Results

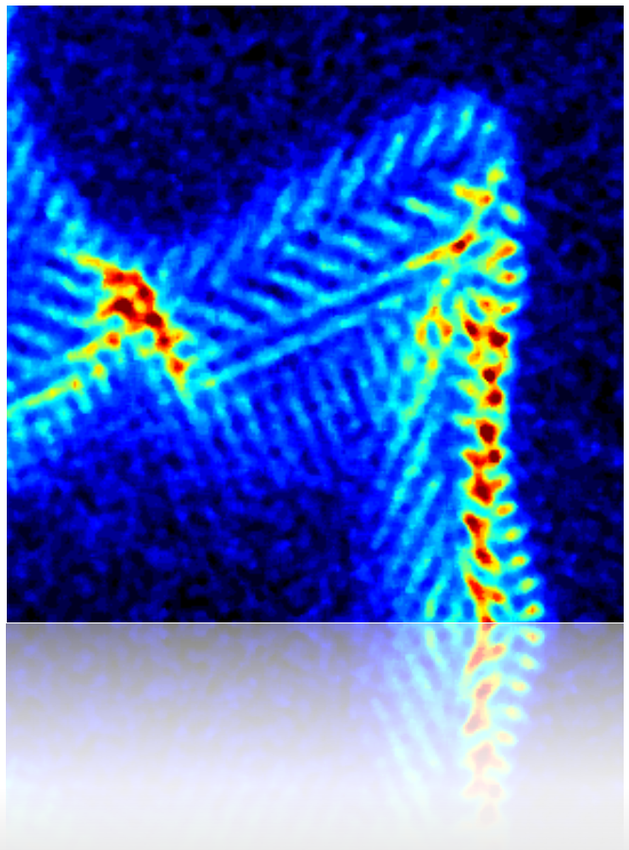
1 Camera view

4 superimposed images of CH_2O



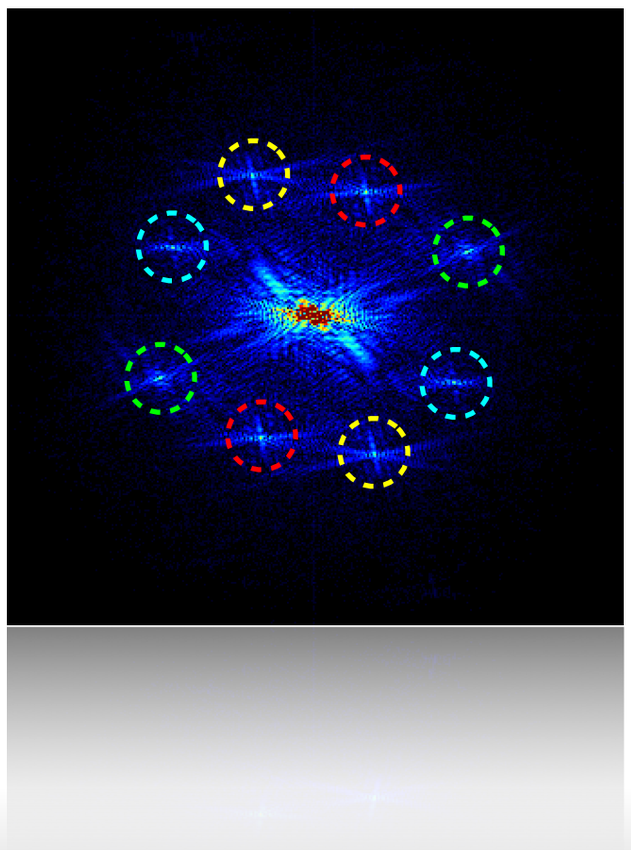
2 Zoomed view

Different modulation patterns visible



3 Fourier transform

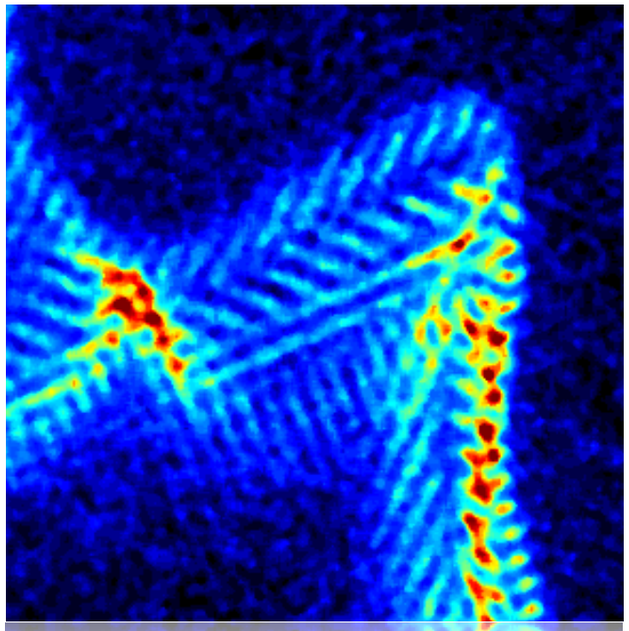
Signal components seen as peaks



Results

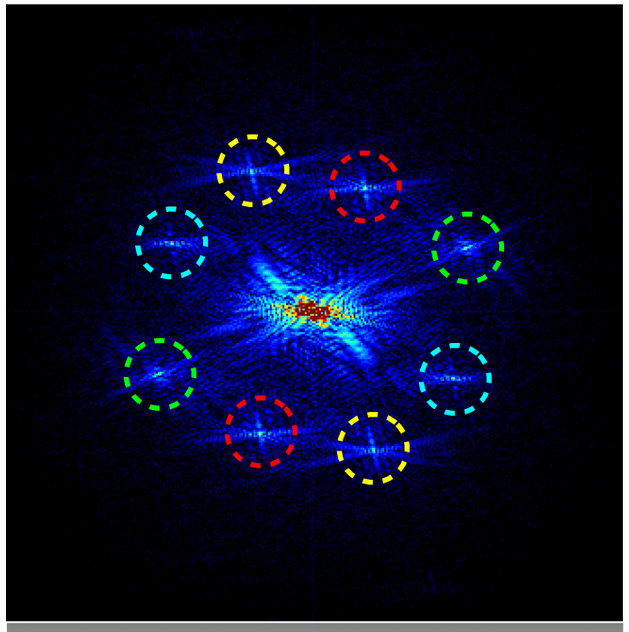
2 Zoomed view

Different modulation patterns visible



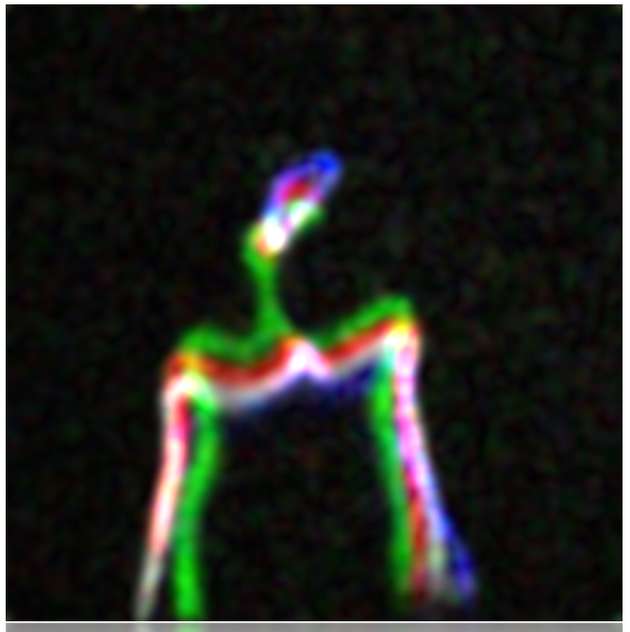
3 Fourier transform

Signal components seen as peaks



4 Decoded

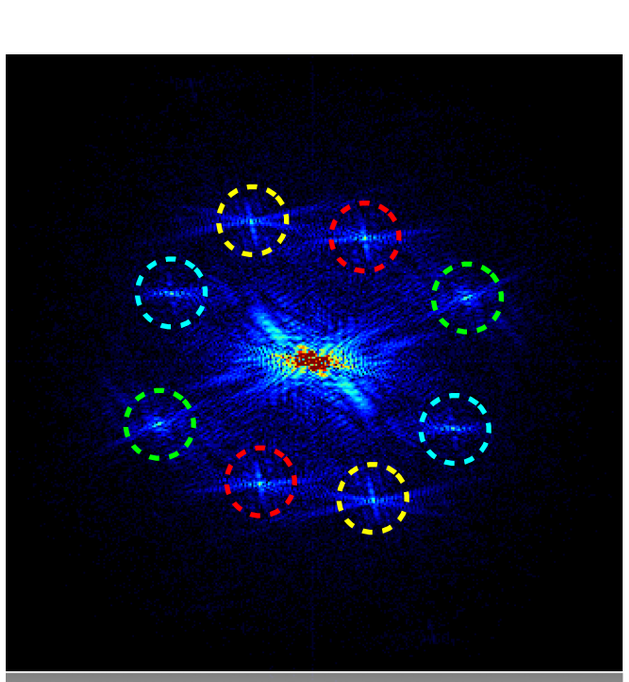
Each signal component decoded



Results

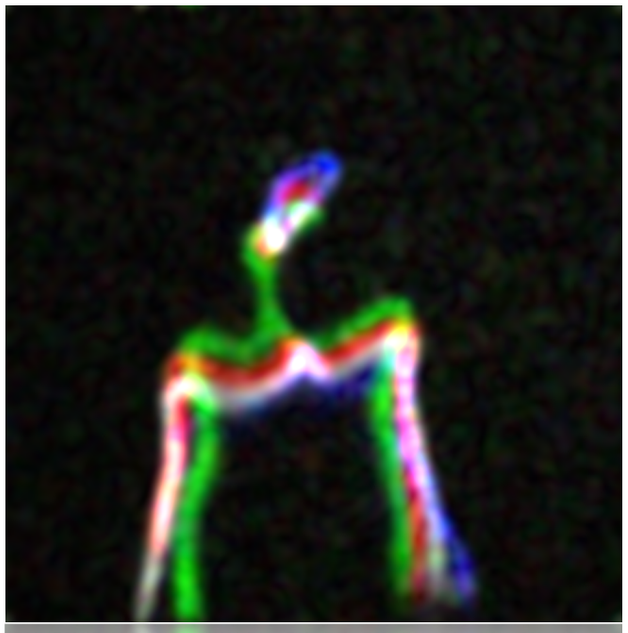
3 Fourier transform

Signal components seen as peaks



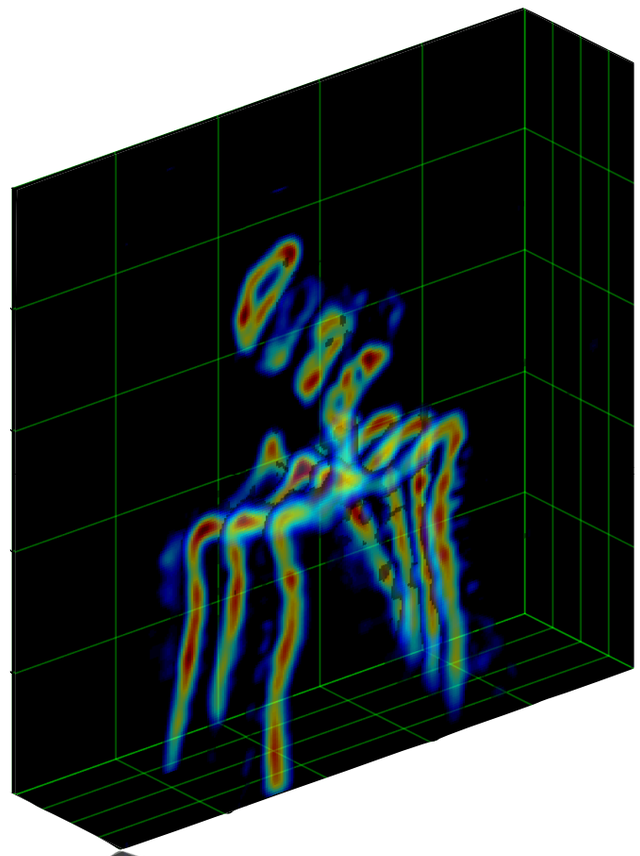
4 Decoded

Each signal component decoded



5 Distributed in 3D

Each signal is positioned in space



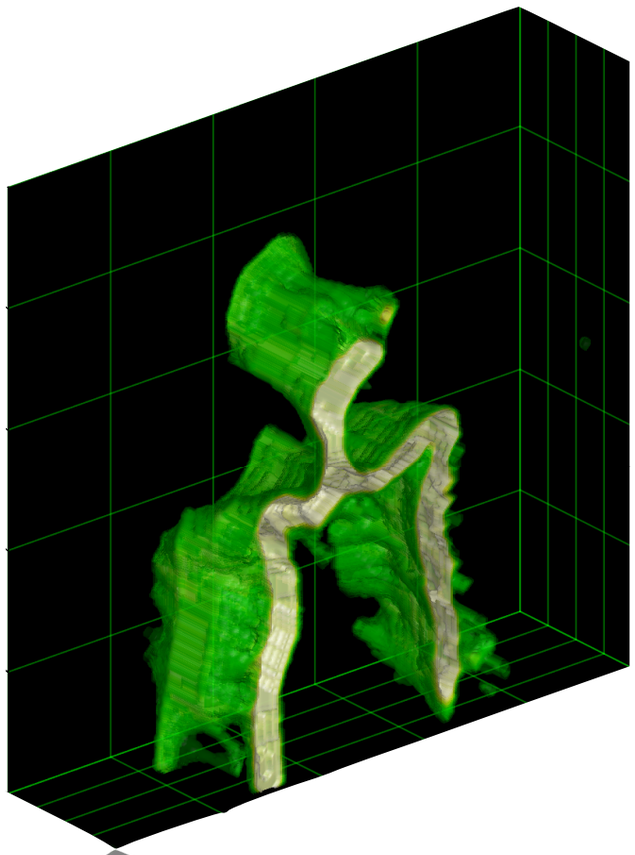
Results

4 Decoded

Each signal component decoded

5 Distributed in 3D

Each signal is positioned in space



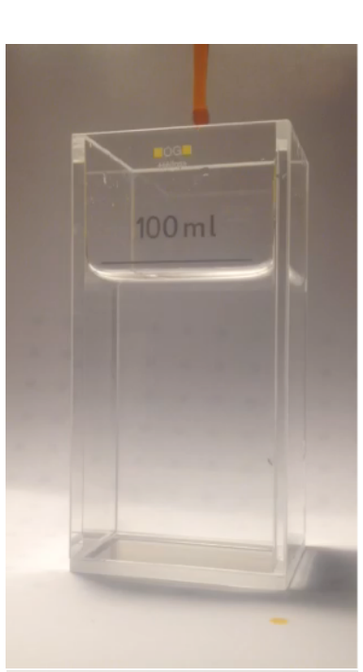
6 3D rendering

Instantaneous 3D view of flame

4D imaging?

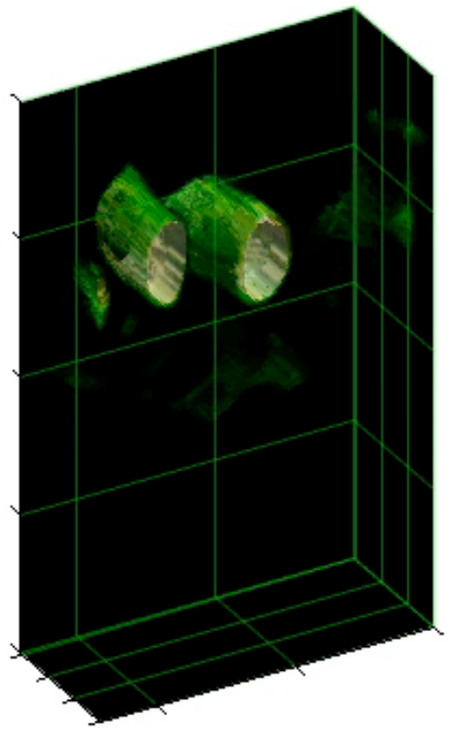
1 Droplets of dye

Dye taking the shape of a donut



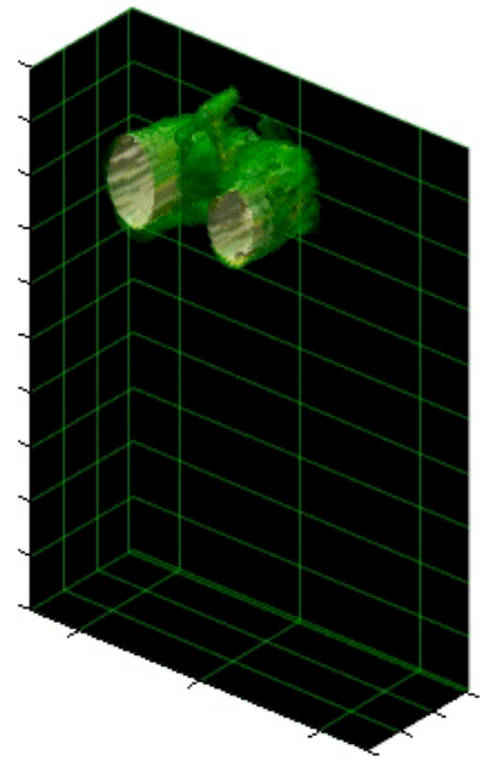
2 "4D" view

Motion tracked in time



3 "4D" view

Motion tracked in time



Summary

*

Simultaneous detection of several images

Images given different structural "codes"

Spatial lock-in demodulation

\+

One camera solution

Perfect pixel-to-pixel overlap

Potential for 4D imaging

Benefit from technological development

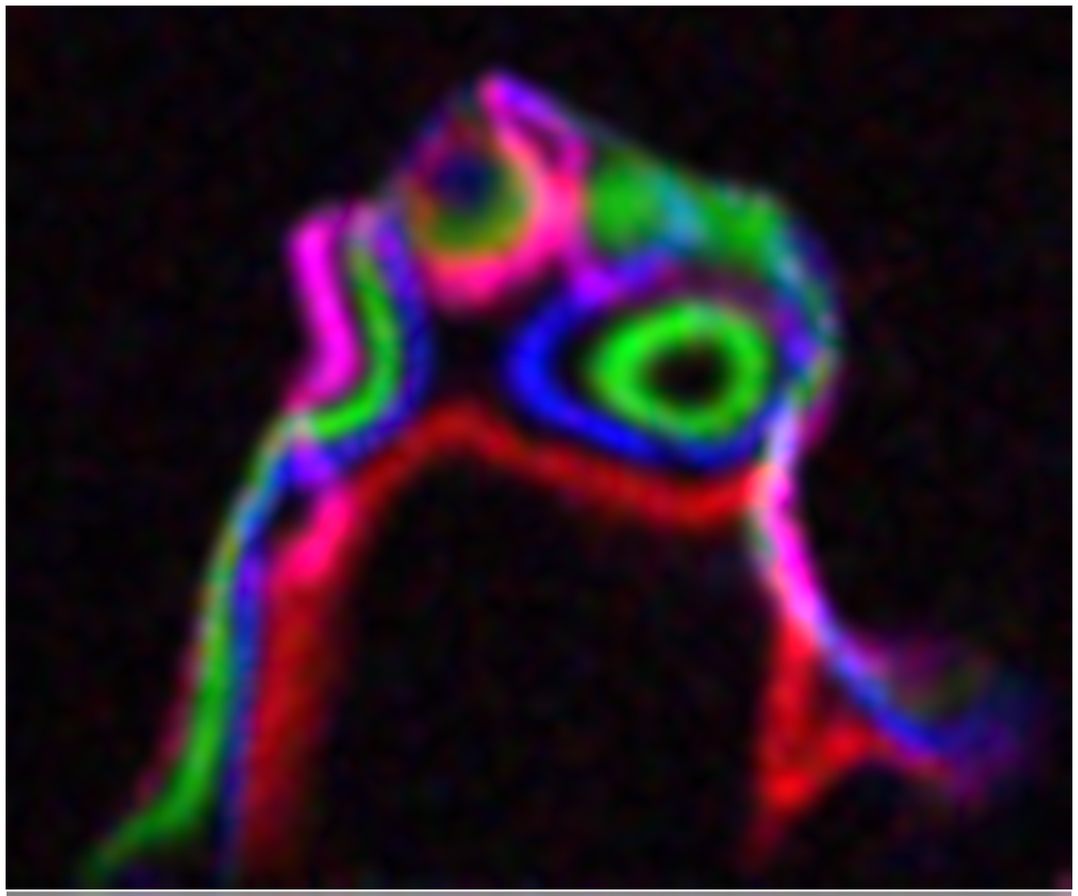
\-

Optical access

Trade resolution for simultaneous detection

Signals share dynamic range

Thank you for your attention!



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tel: +46 46 222 4756