

# Hyperspectral imaging and holography by dual-comb spectroscopy

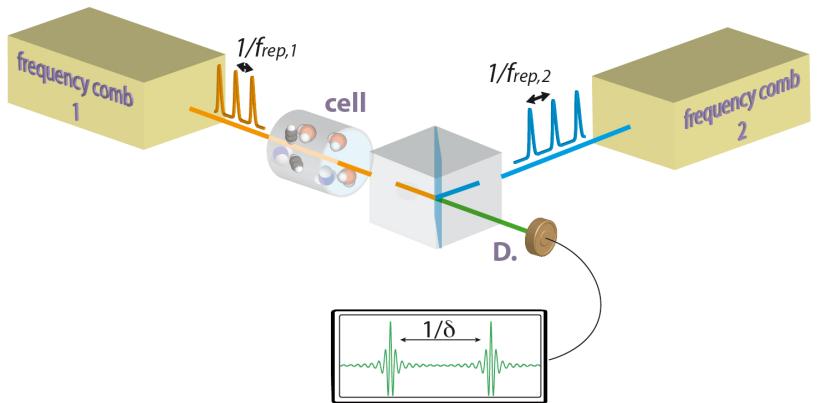
Dr. Edoardo Vicentini - CIC nanoGUNE, San Sebastian (Spain)  
[e.vicentini@nanogune.eu](mailto:e.vicentini@nanogune.eu)

# Motivations

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## Dual-comb spectroscopy

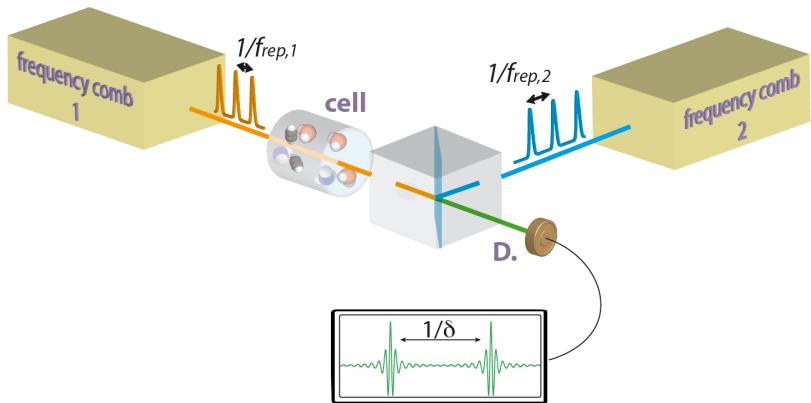
- Ultrahigh resolution
- Broad bandwidth



# Motivations

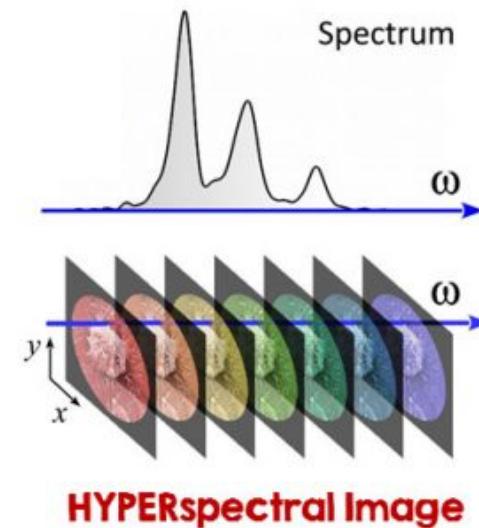
## Dual-comb spectroscopy

- Ultrahigh resolution
- Broad bandwidth



## Hyperspectral imaging

- Imaging with a full spectrum for each pixel
- Characterising chemical and physical properties of different part inside the image

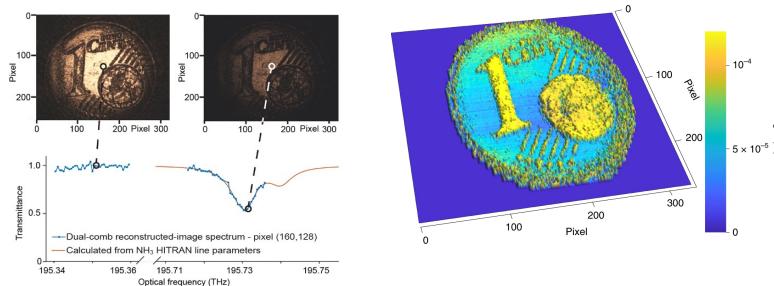


# Motivations

## Dual-comb hyperspectral imaging

- Ultrahigh resolution
- Broad bandwidth
- Image with a full spectrum for each pixel
- Characterising chemical and physical properties of different parts of the image

## New opportunities: Hyperspectral digital holography



Dual-comb hyperspectral imaging and holography

# Outline

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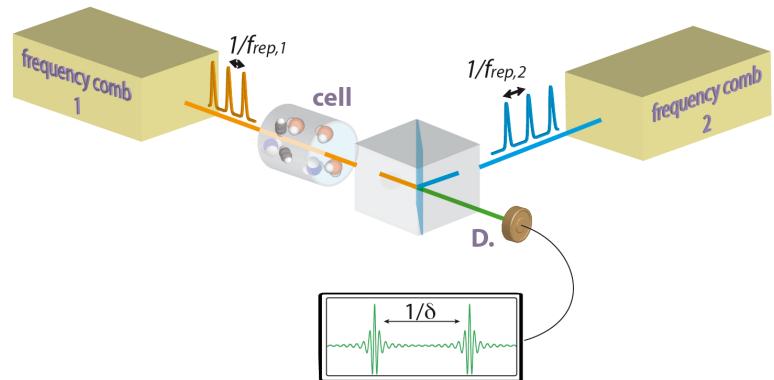
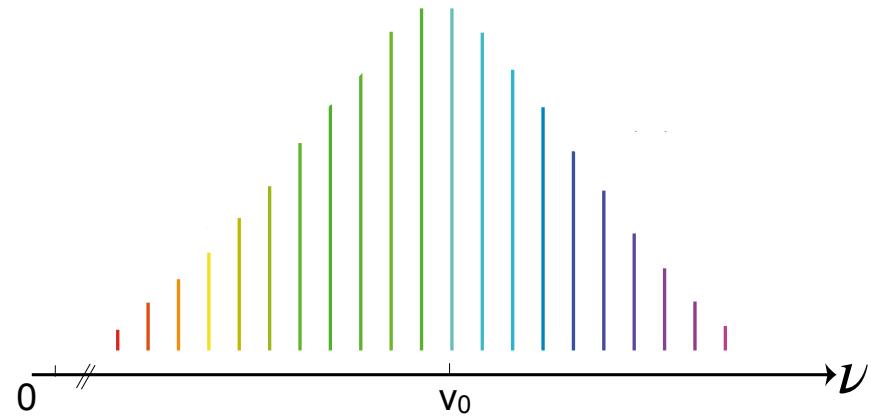
**I. Dual-comb spectroscopy**

**2. Dual-comb hyperspectral imaging**

**3. Dual-comb hyperspectral digital holography**



# Part I: Dual-comb spectroscopy

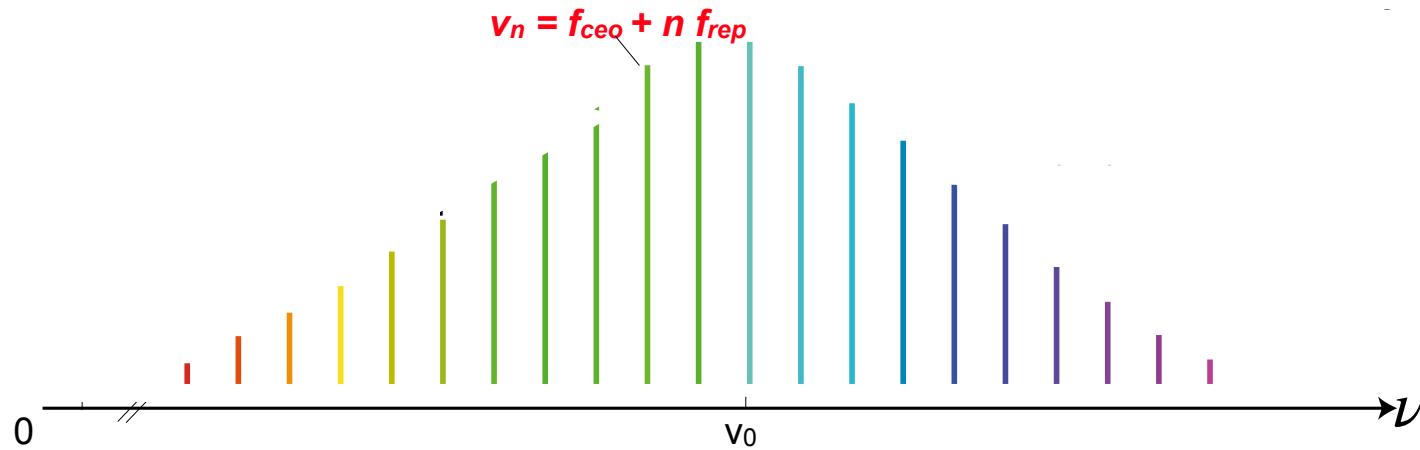




# What is a frequency comb?

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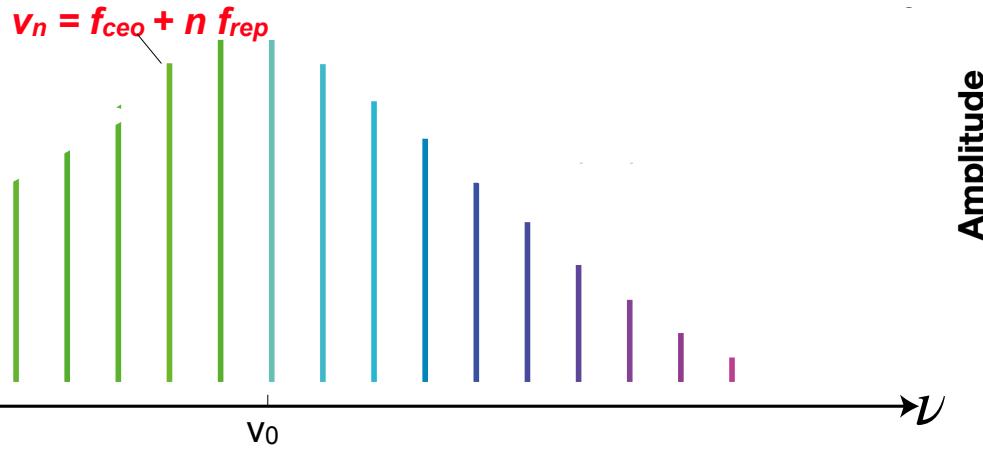
- Frequency domain
- Thousand of CW lasers equally spaced



# What is a frequency comb?

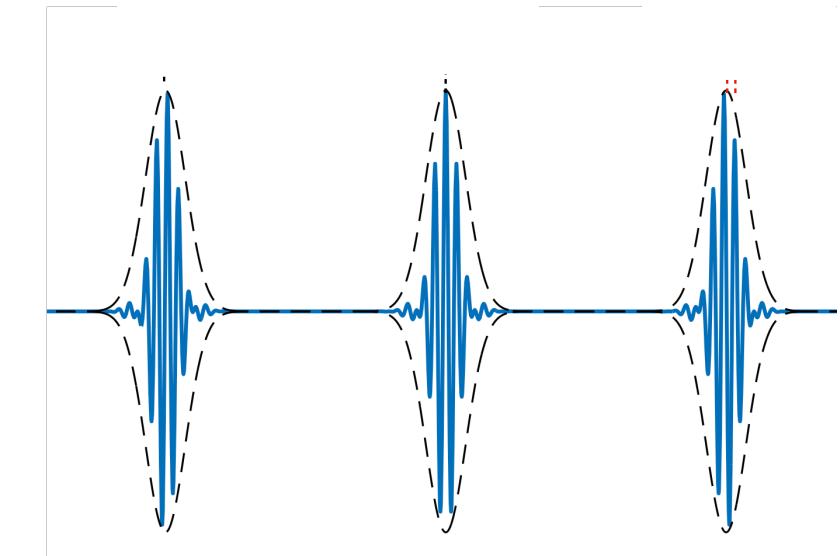
- Frequency domain

- Thousand of CW lasers equally spaced



- Time domain

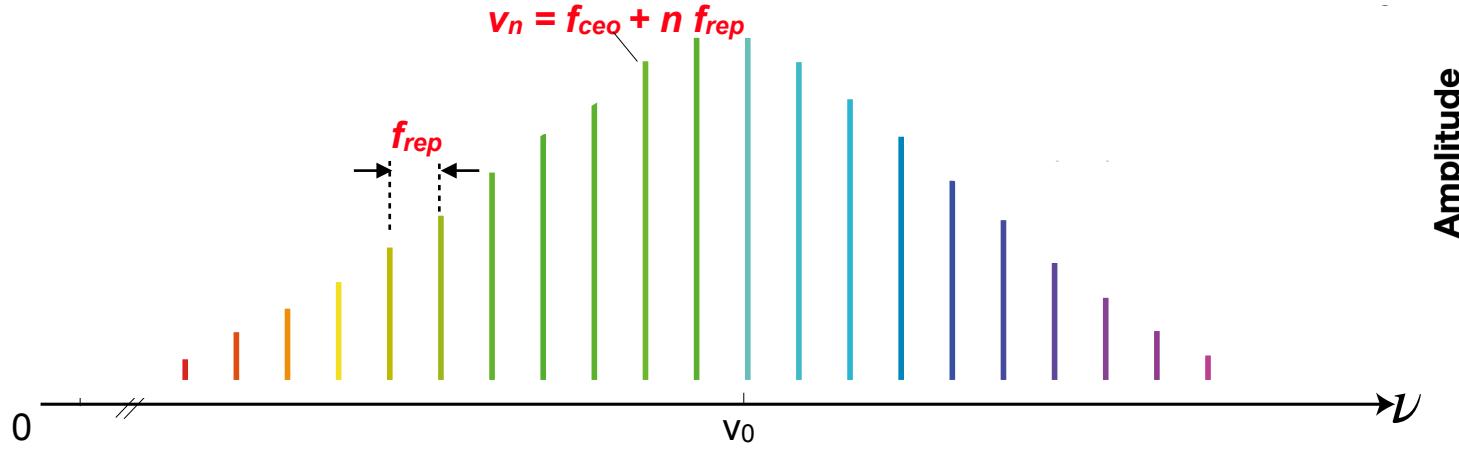
- Stabilised train of laser pulses.



# What is a frequency comb?

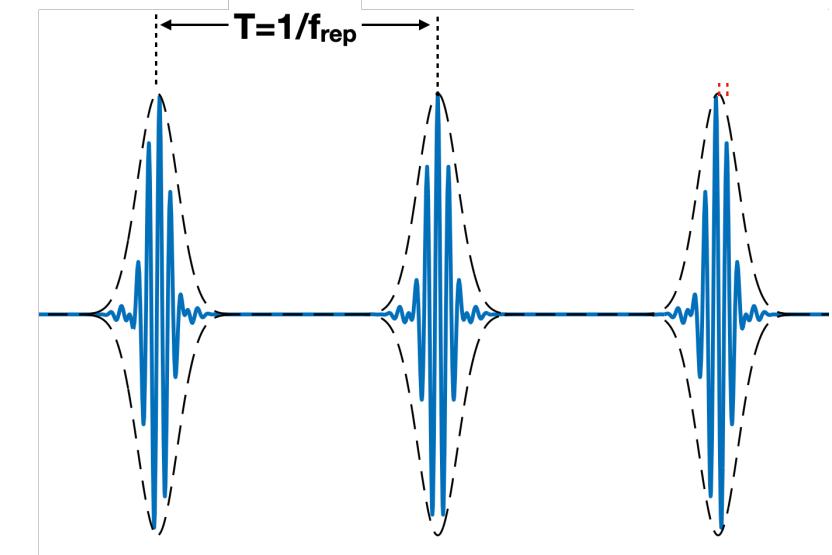
- Frequency domain

- Thousand of CW lasers equally spaced



- Time domain

- Stabilised train of laser pulses.



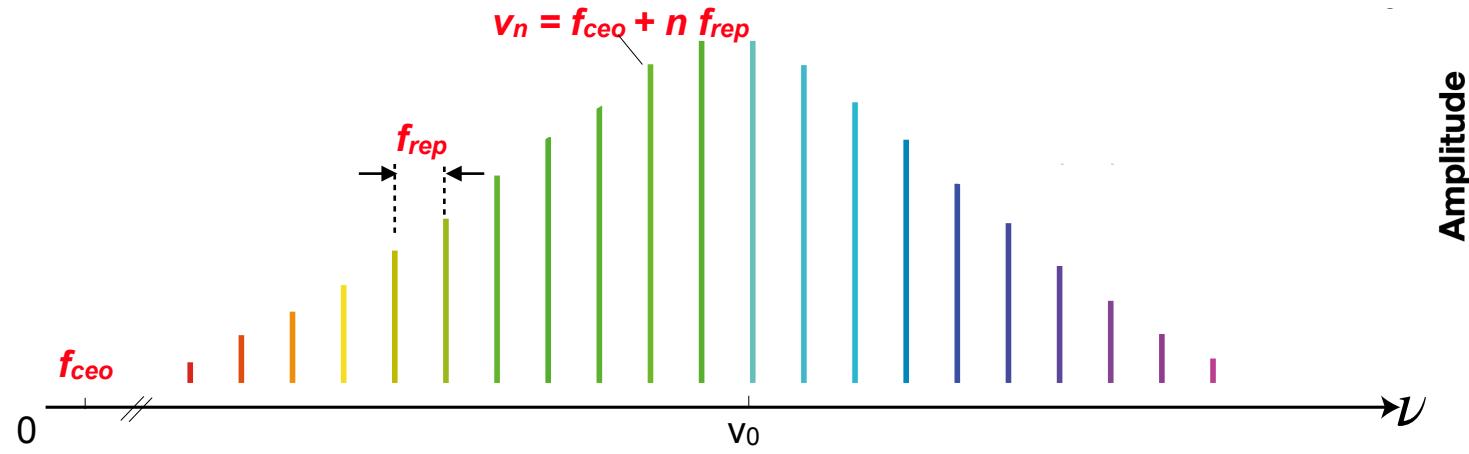
Frequency comb required stabilisation of two quantities

- Repetition frequency of the pulses  $f_{rep}$

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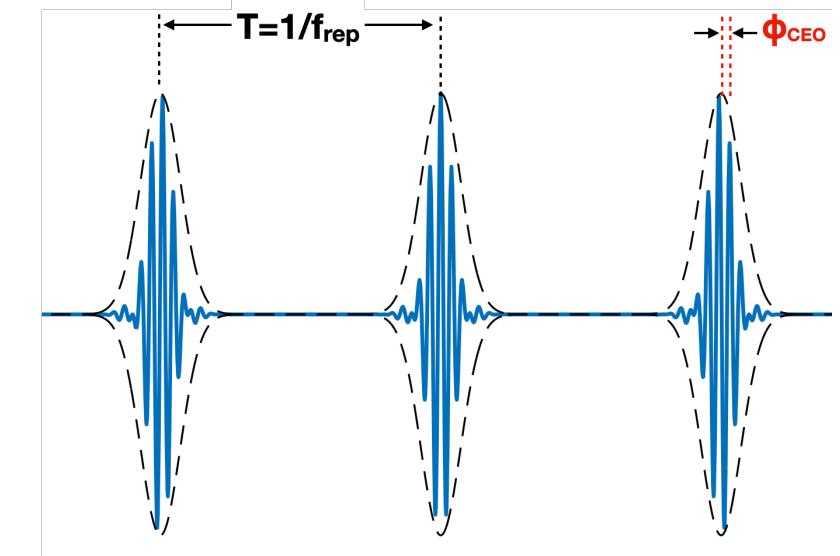
- Frequency domain

- Thousand of CW lasers equally spaced



- Time domain

- Stabilised train of laser pulses.



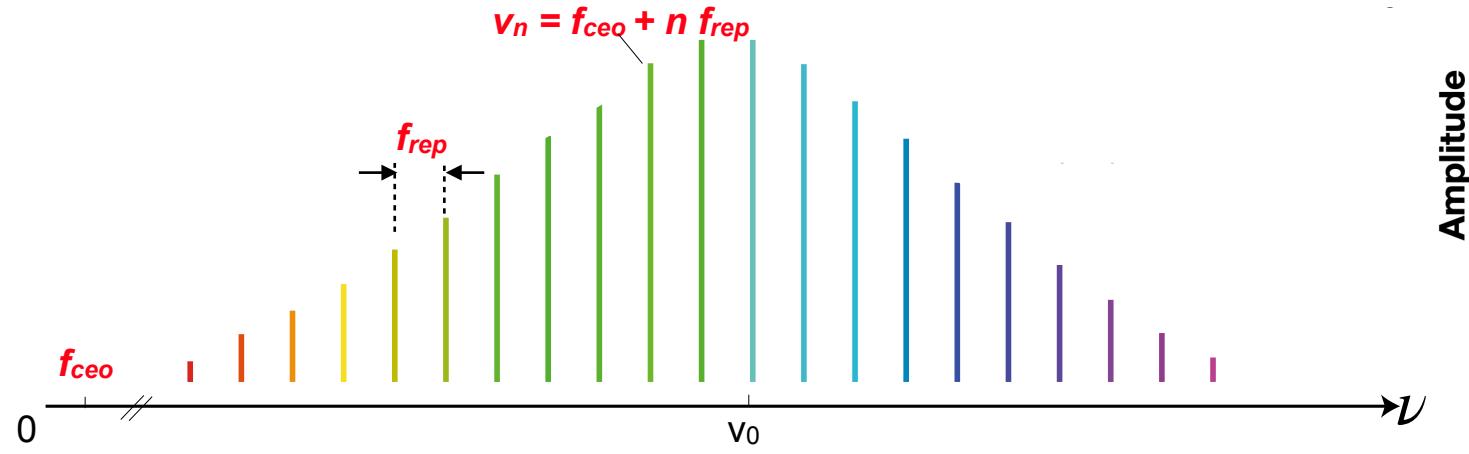
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- Repetition frequency of the pulses  $f_{rep}$
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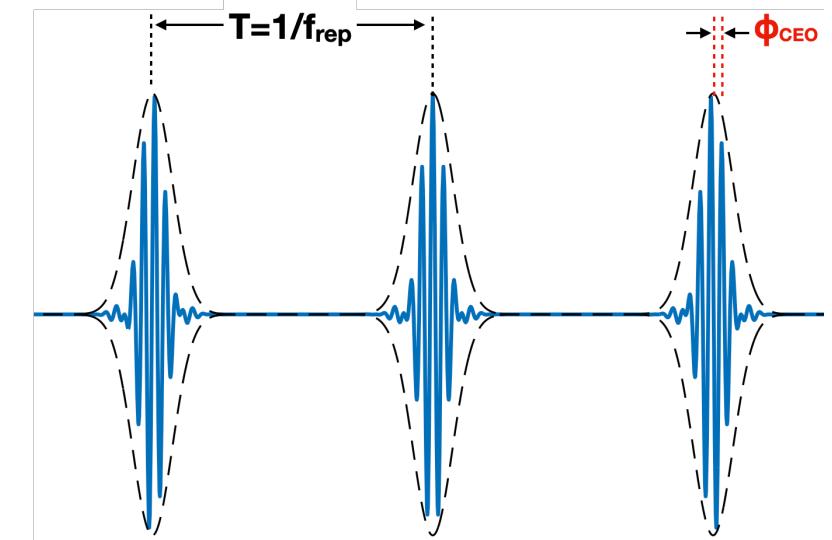
- Frequency domain

- Thousand of CW lasers equally spaced



- Time domain

- Stabilised train of laser pulses.



Frequency comb required stabilisation of two quantities

- Repetition frequency of the pulses  $f_{rep}$
- Carrier-envelop offset frequency  $f_{ceo}$

$$\nu_n = f_{ceo} + n f_{rep}$$

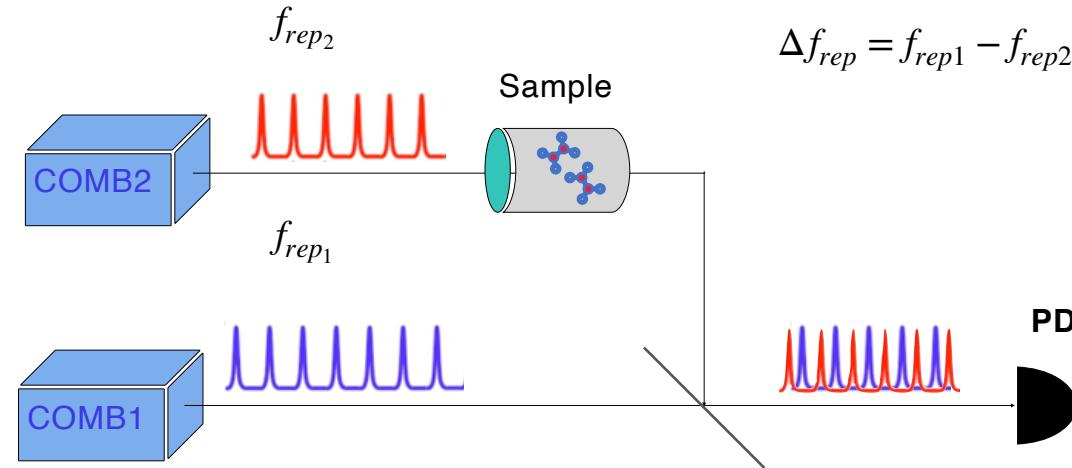


J. L. Hall T.W. Hänsch  
2005 Nobel prize

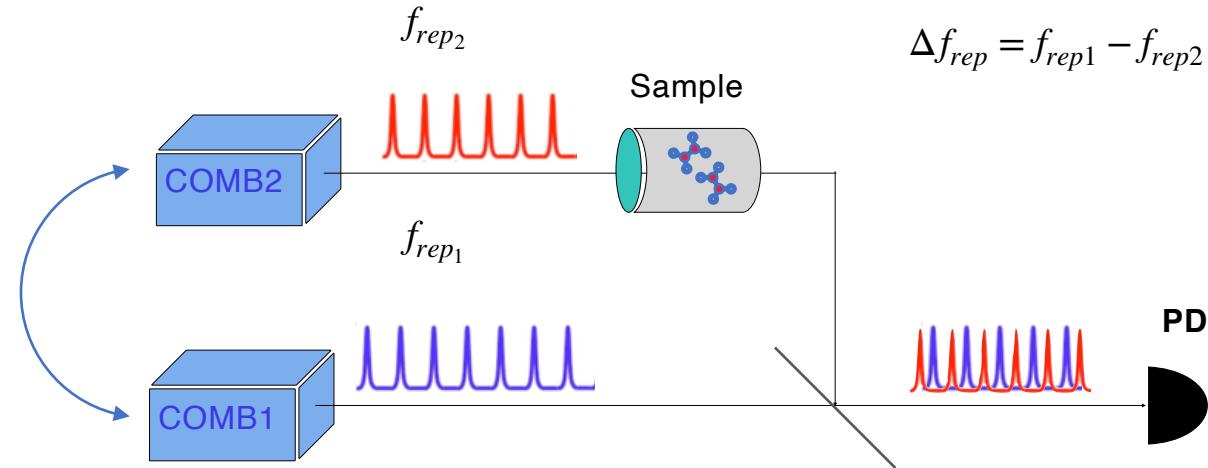




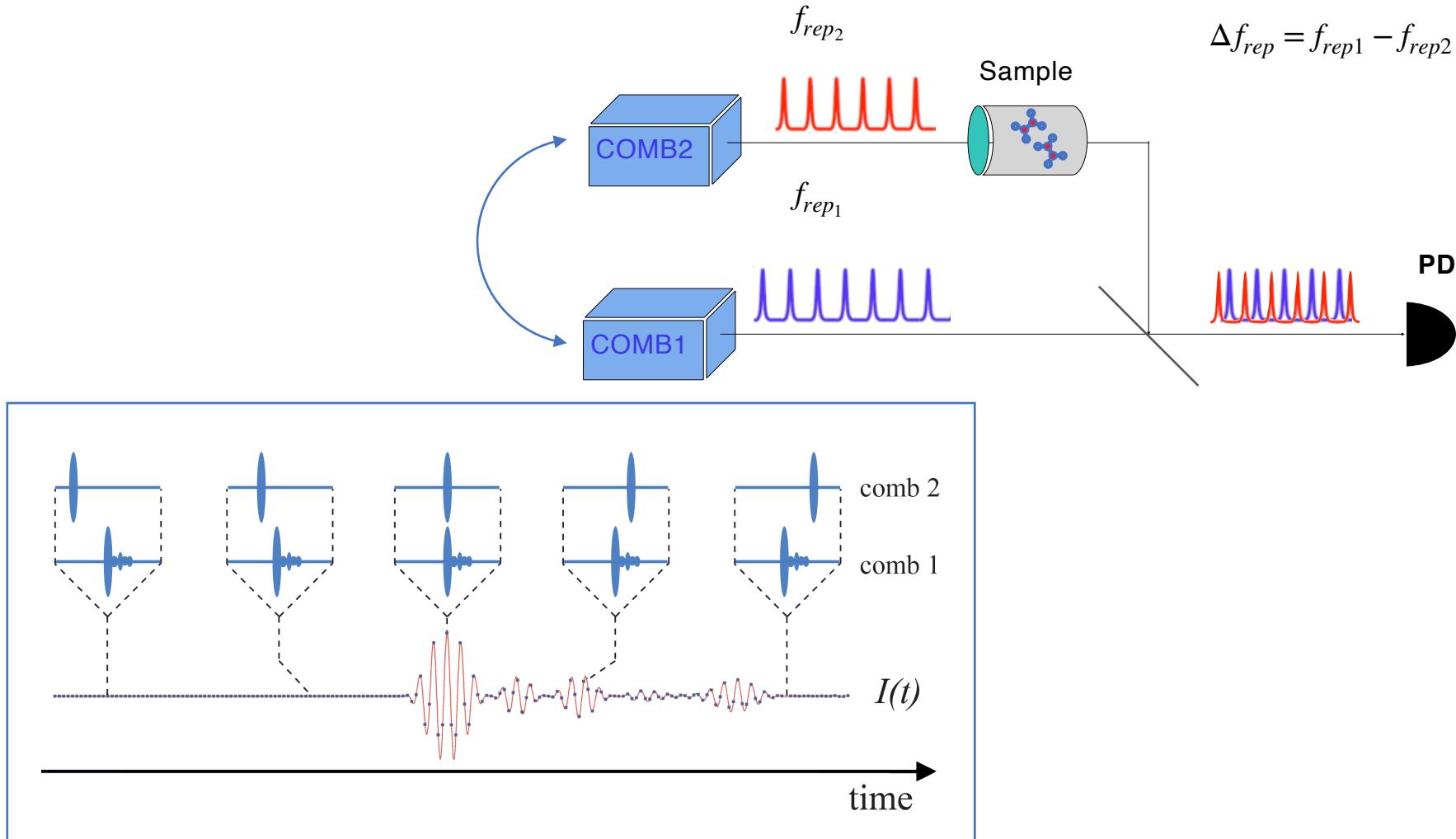
# Dual-comb spectroscopy: principle



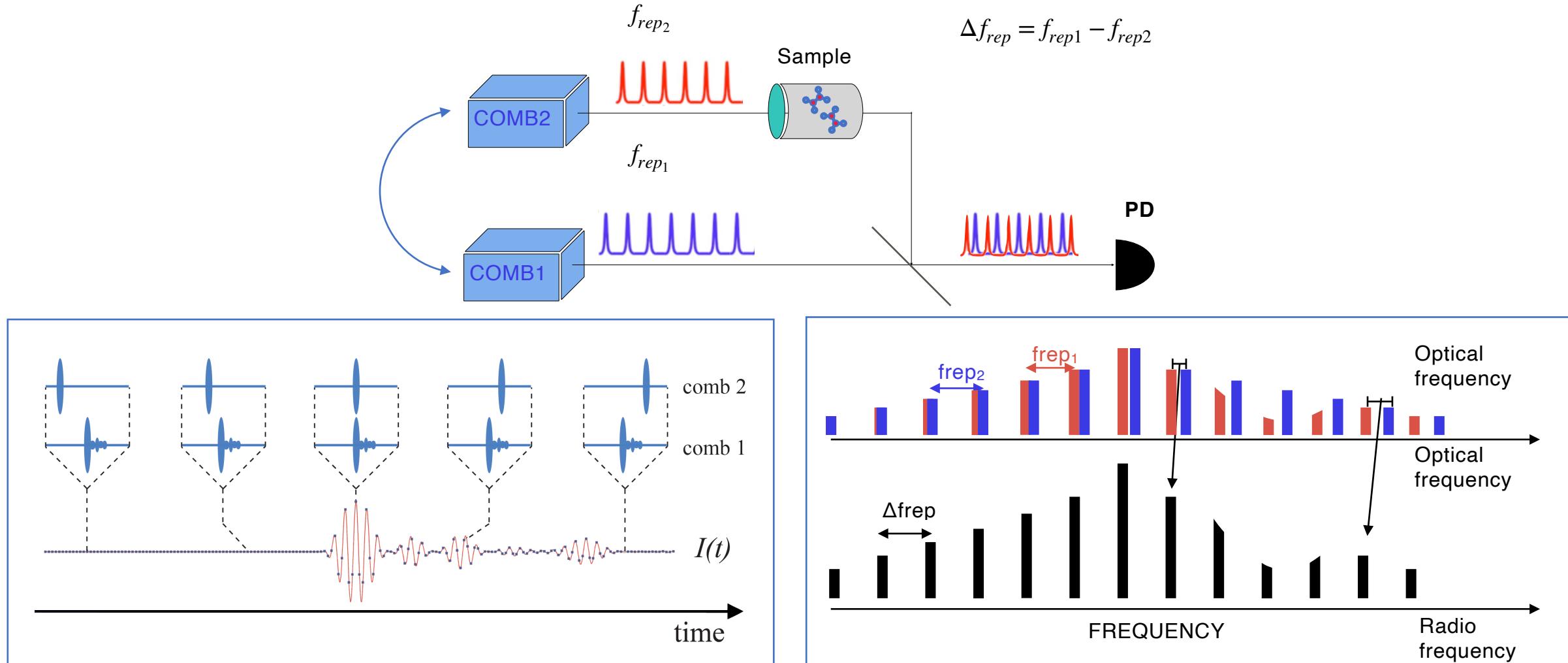
# Dual-comb spectroscopy: principle



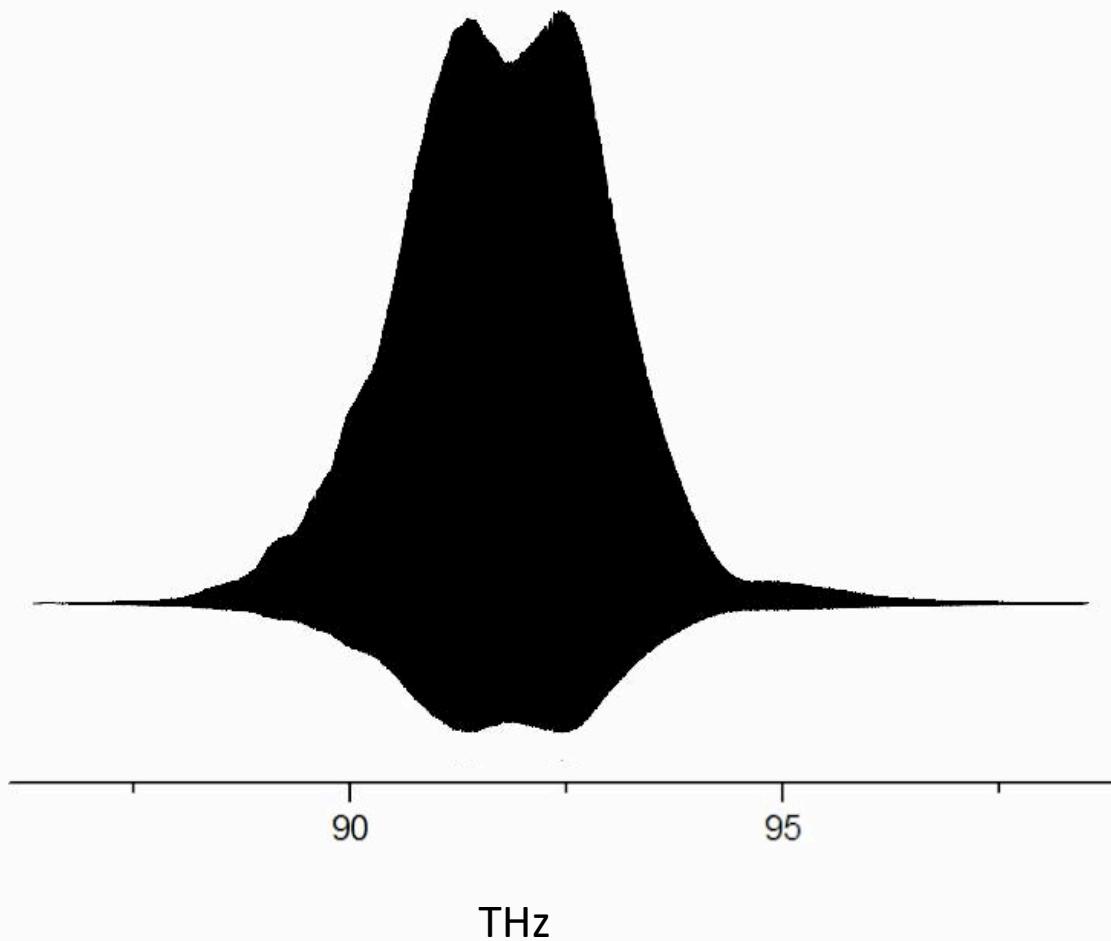
# Dual-comb spectroscopy: principle



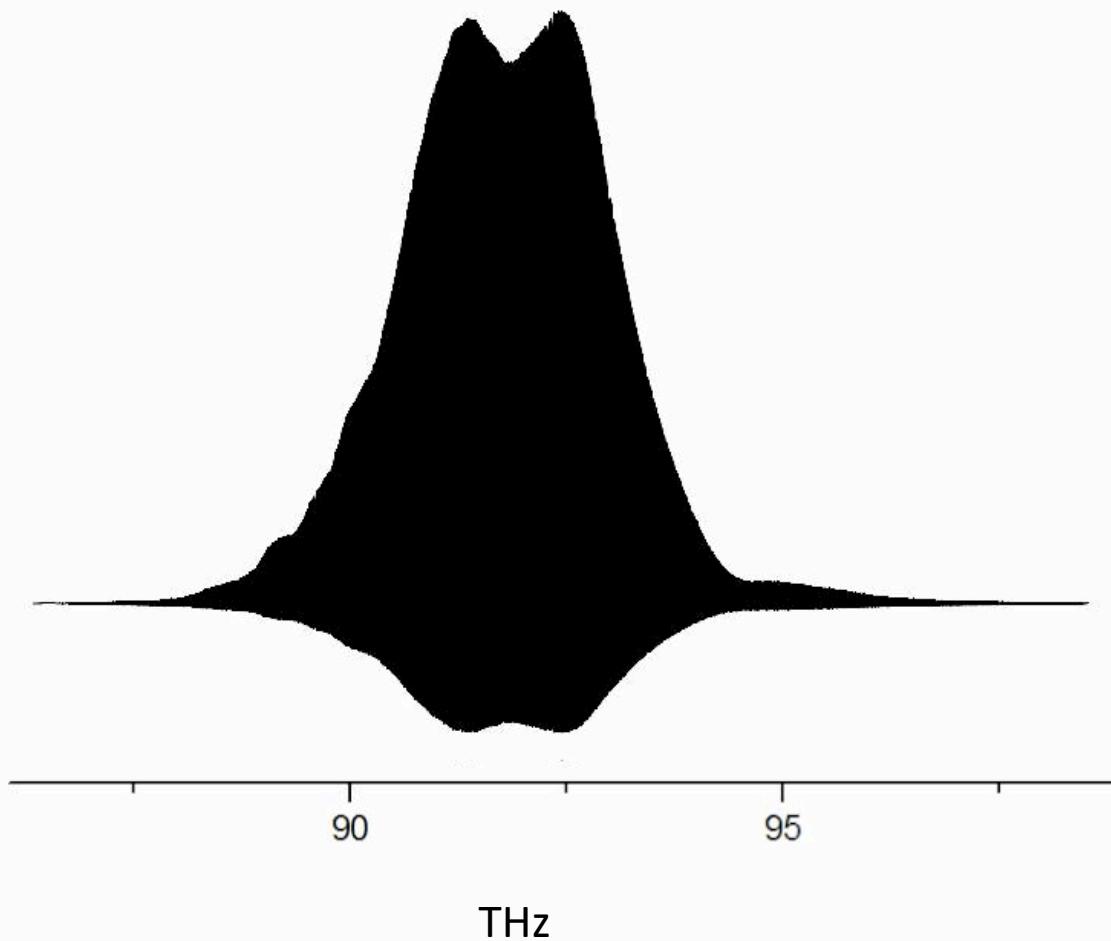
# Dual-comb spectroscopy: principle



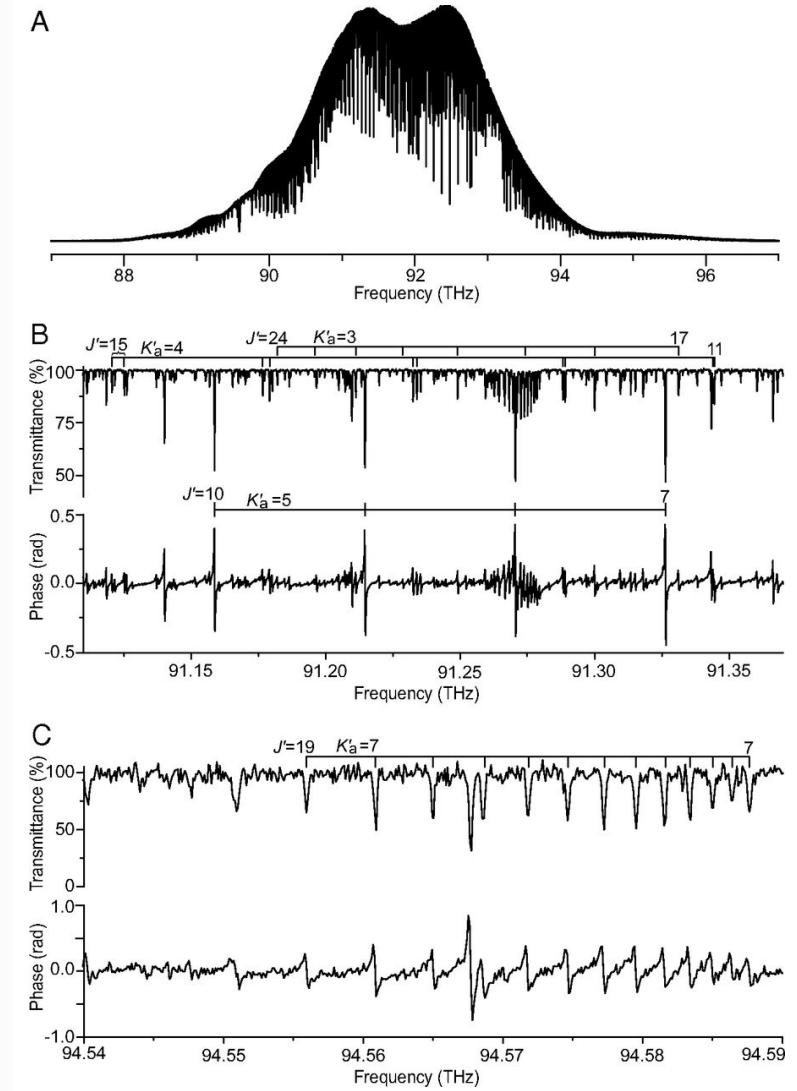
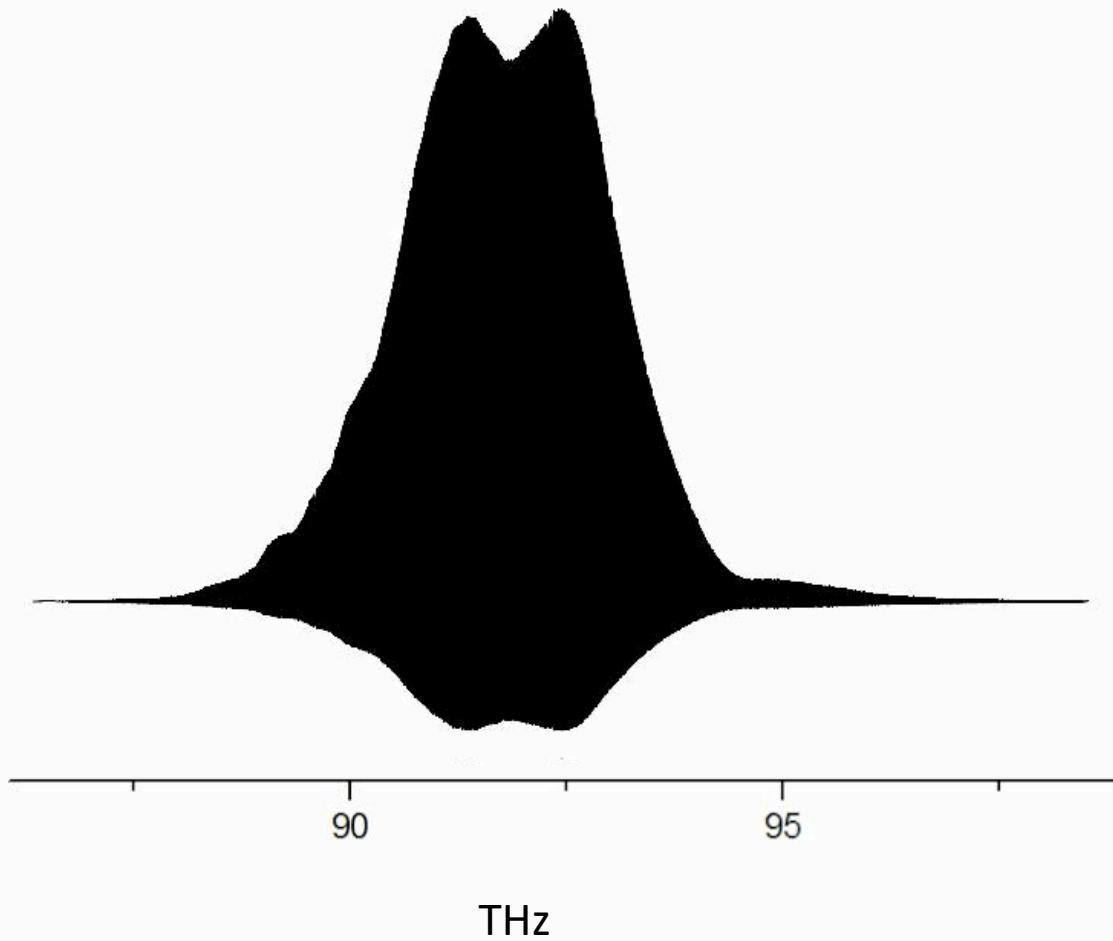
# Dual-comb spectroscopy



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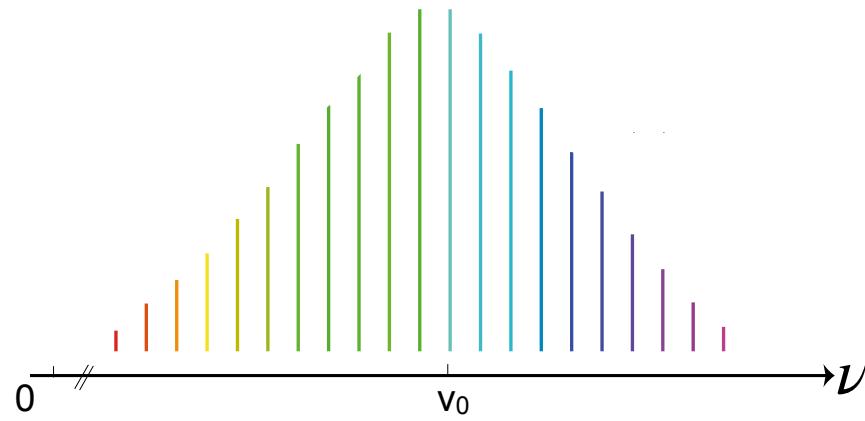


# Dual-comb spectroscopy

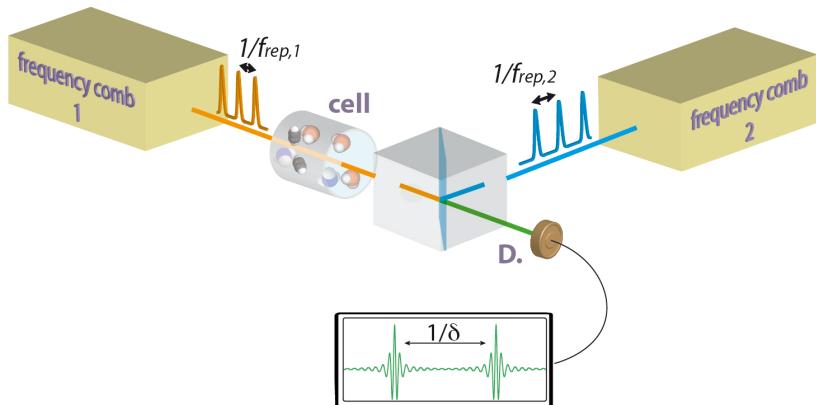


# **Part I: Dual-comb spectroscopy**

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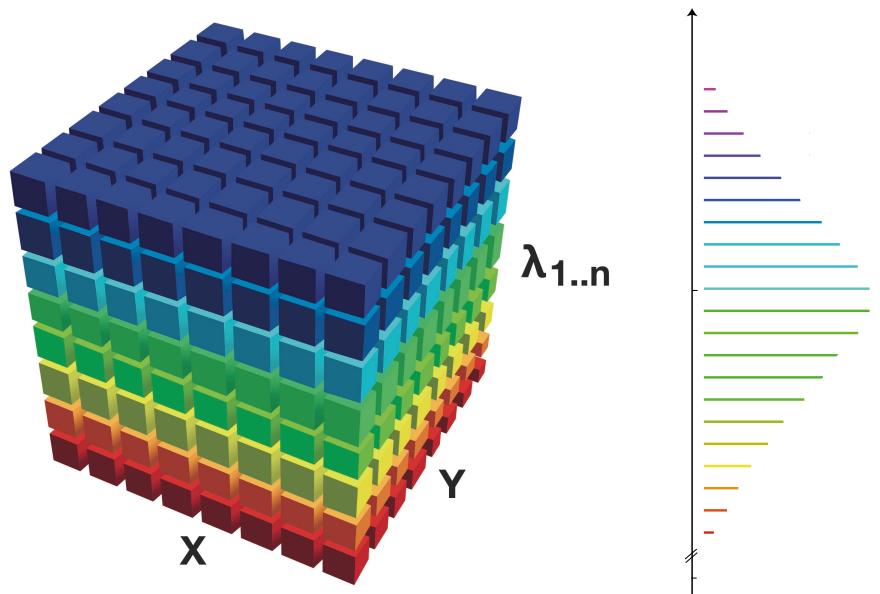


- Frequency comb is a series of narrow mode equally spaced
- Dual-comb makes possible to measure broad bandwidth with high resolutions without moving part



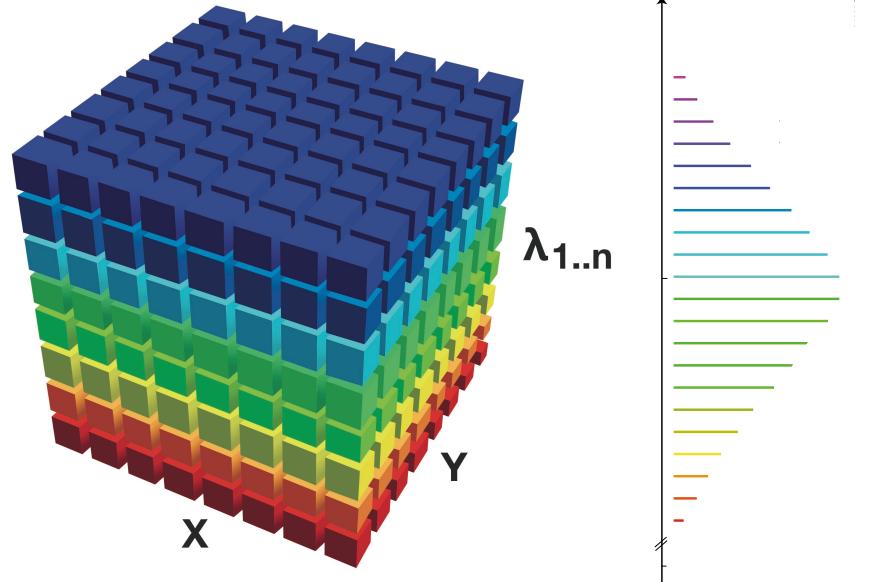


## Part 2: Dual-comb hyperspectral imaging

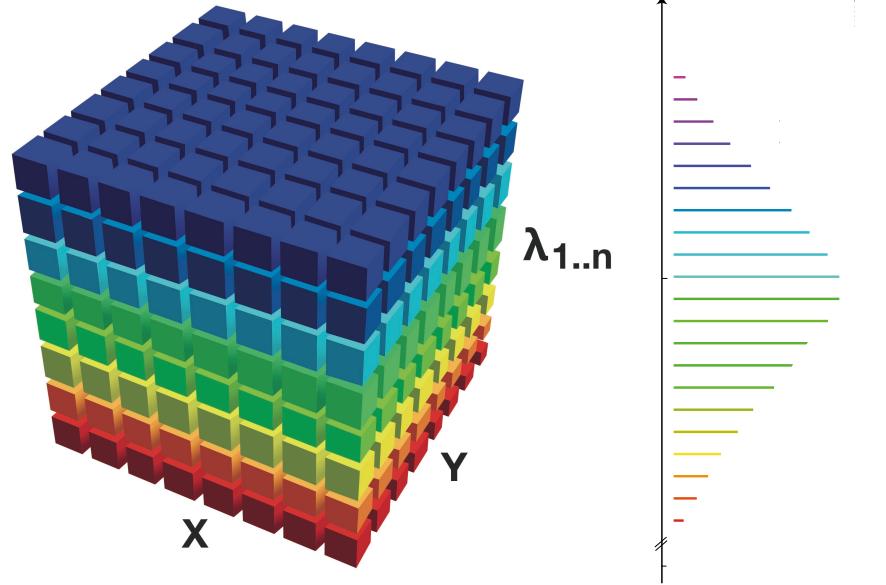


# Hyperspectral imaging: what is?

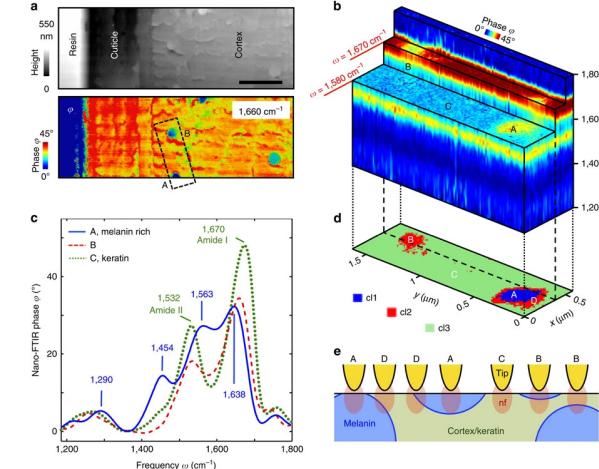
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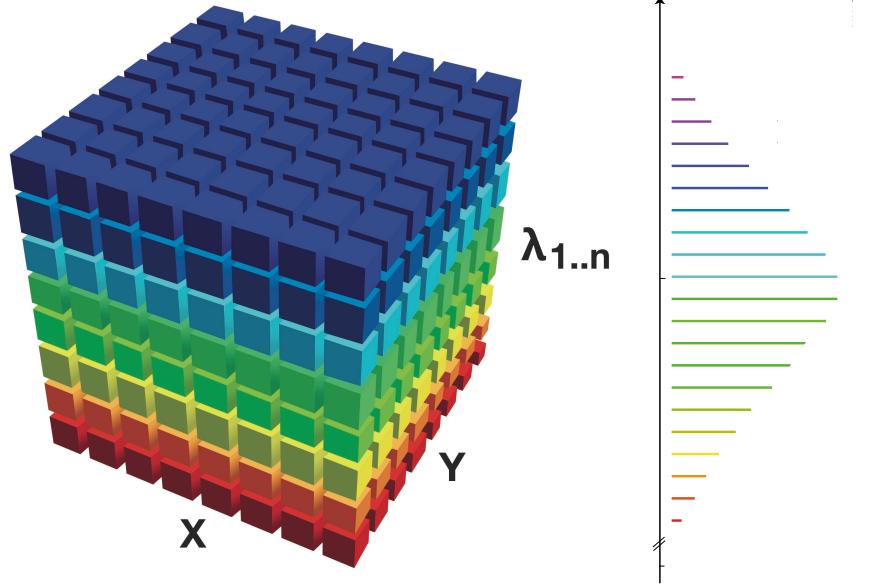


Nanoscale hyperspectral-imaging



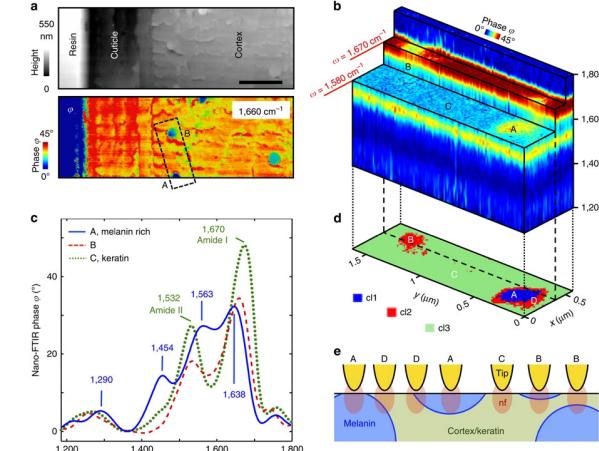
I. Amenabar, et al. *Nat Commun* 8, 14402 (2017)

# Hyperspectral imaging: what is?



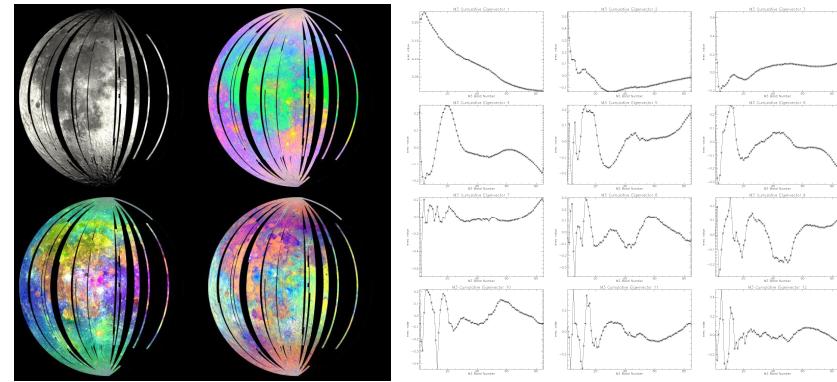
Dual-comb hyperspectral imaging and holography

## Nanoscale hyperspectral-imaging



I. Amenabar, et al. *Nat Commun* 8, 14402 (2017)

## Planet-scale hyperspectral-imaging



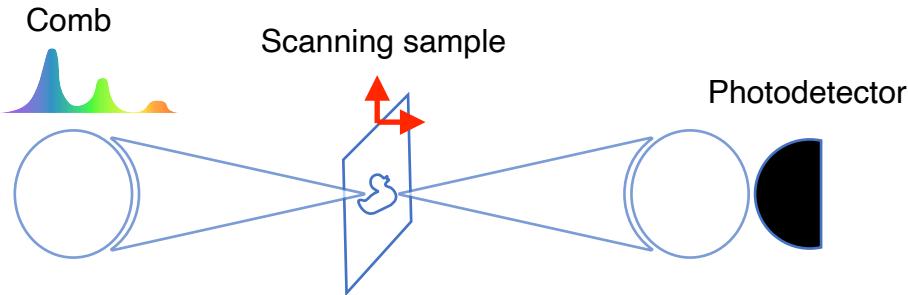
R.O. Gree, et al. *KAGUYA/Chandrayaan-1 Cross-Calibration Meeting*. No. M10-0330. (2010).



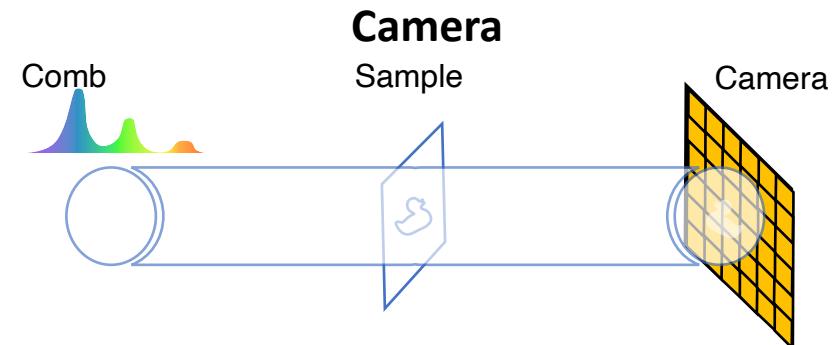
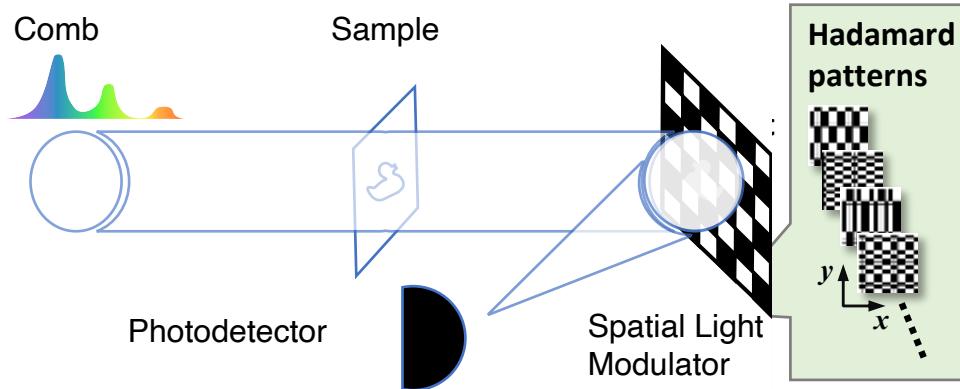
# Dual-comb hyperspectral imaging: how?

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Scanning sample

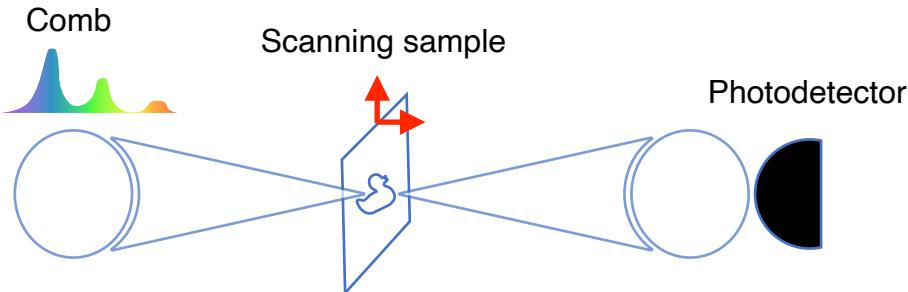


Spatial field decomposition

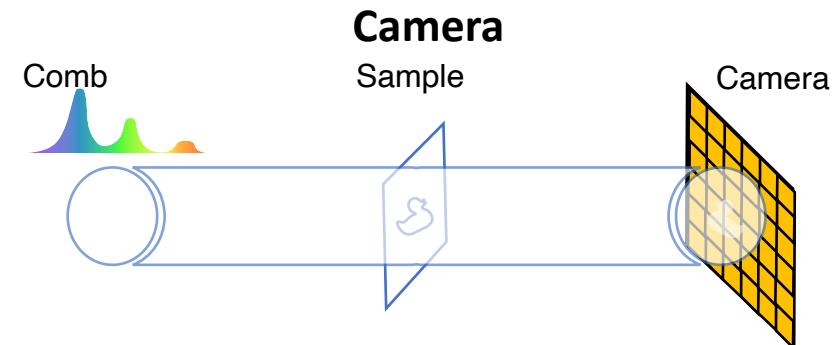
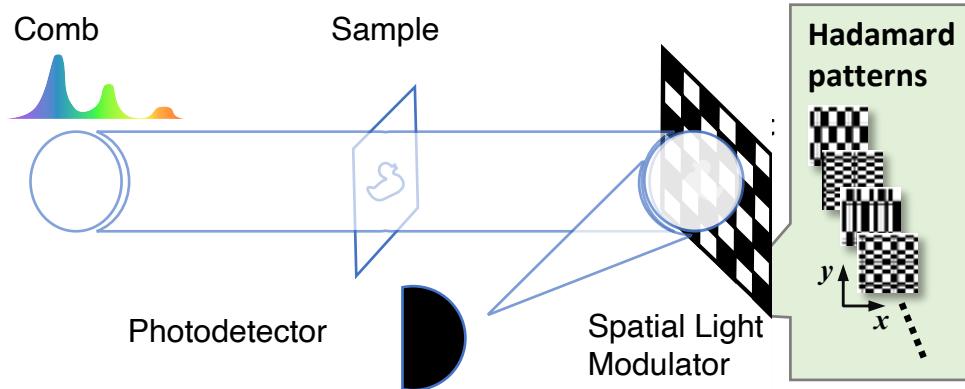


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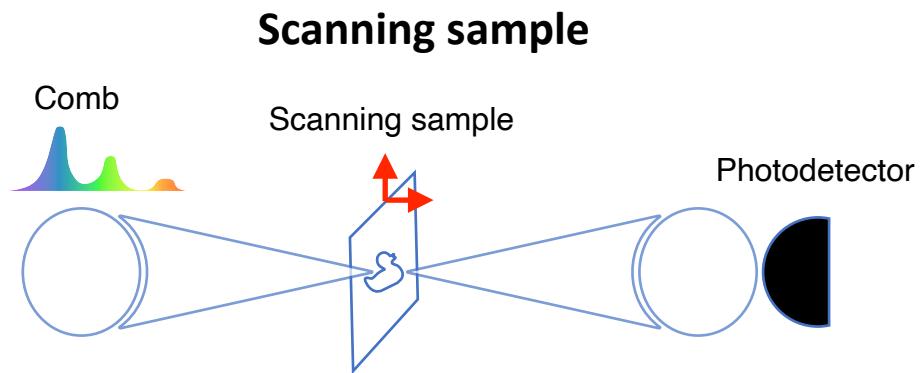
Scanning sample



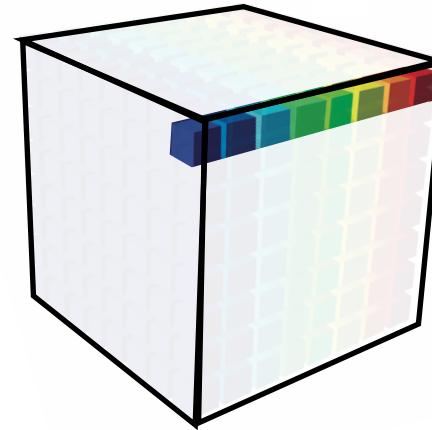
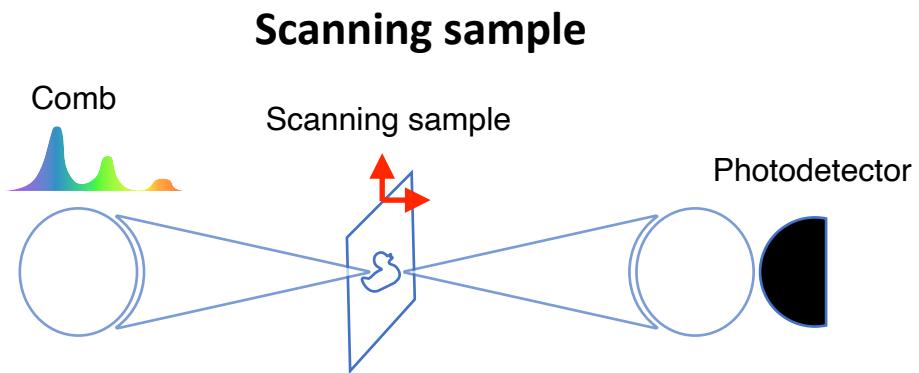
Spatial field decomposition



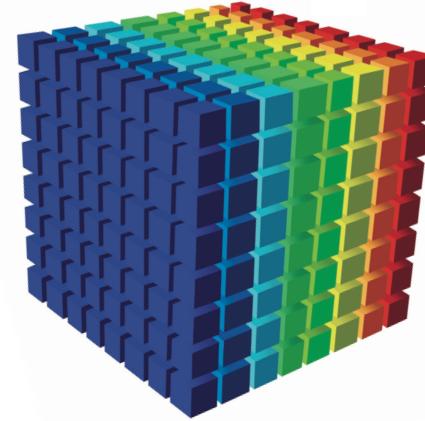
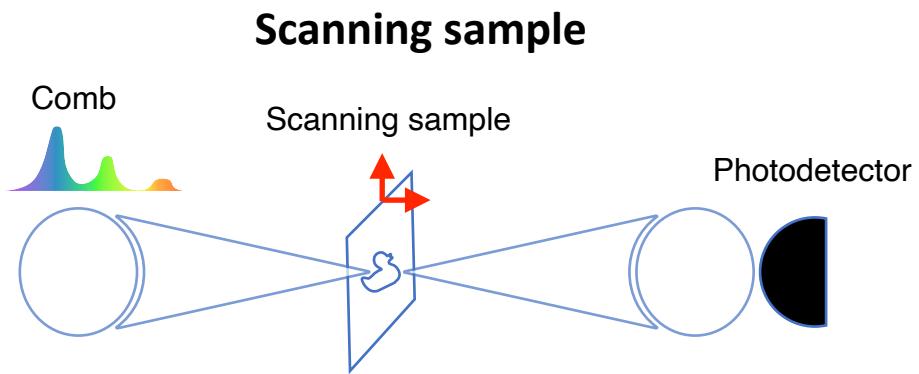
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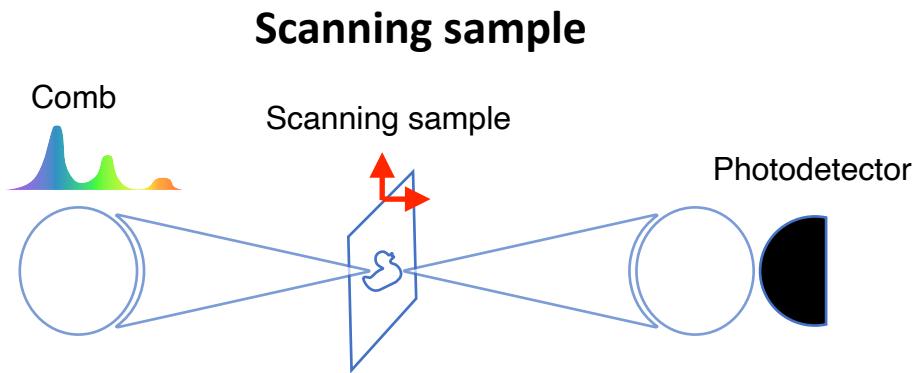
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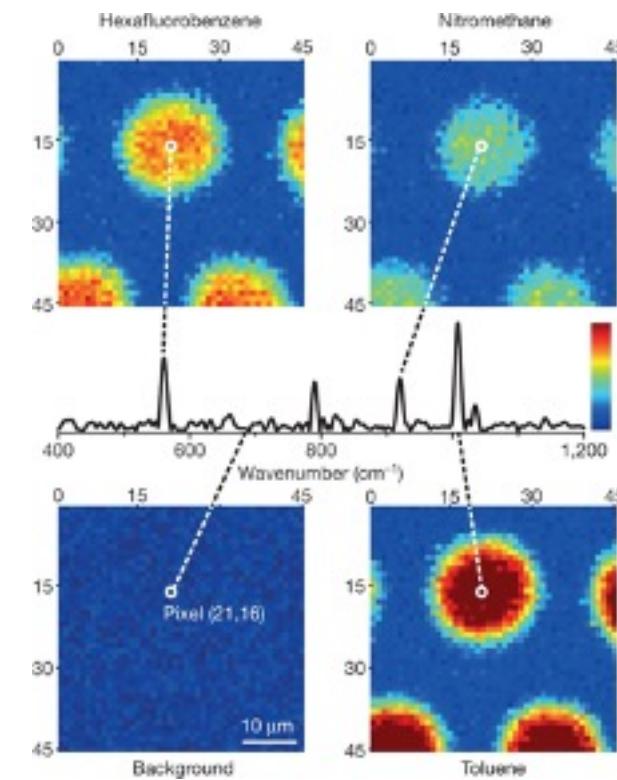
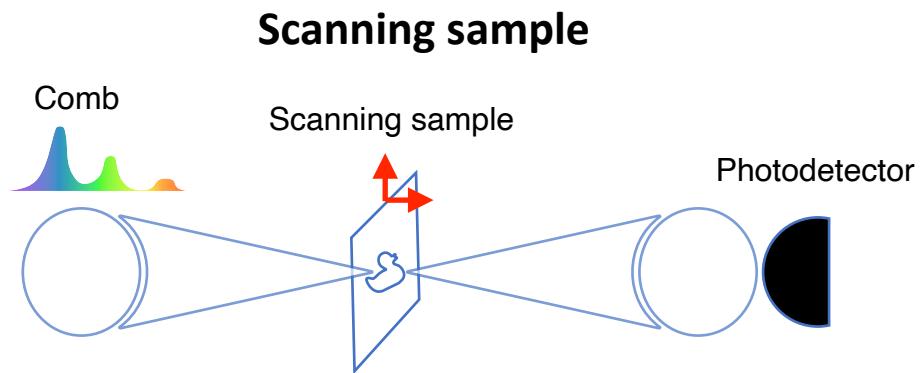
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# Dual-comb hyperspectral imaging

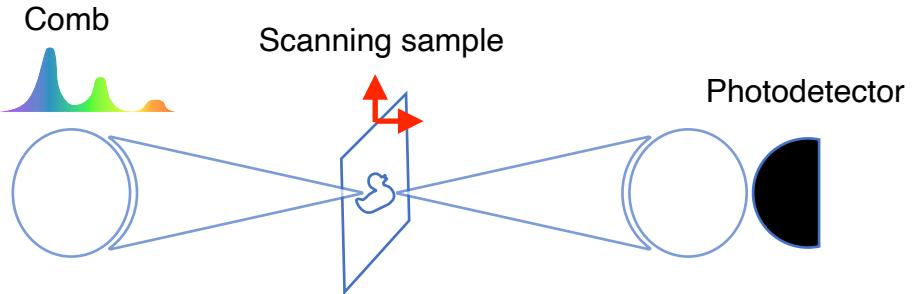


# Dual-comb hyperspectral imaging

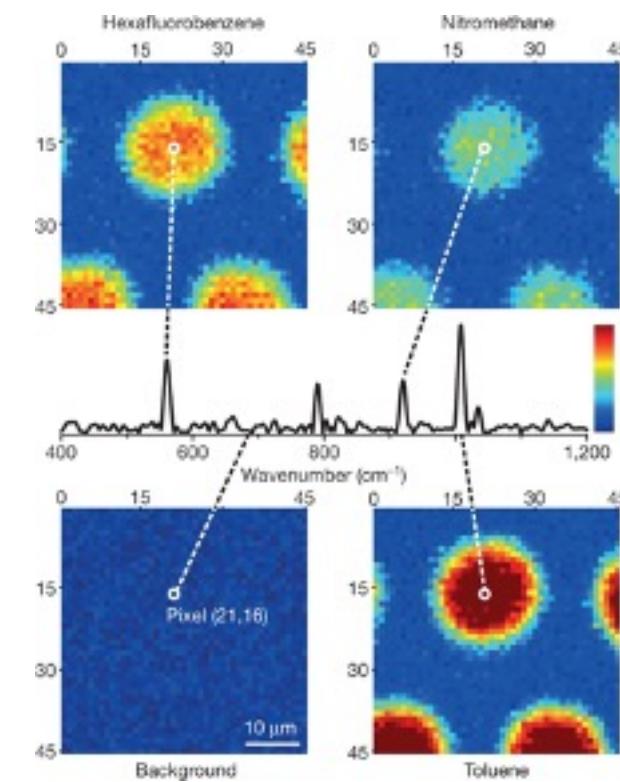
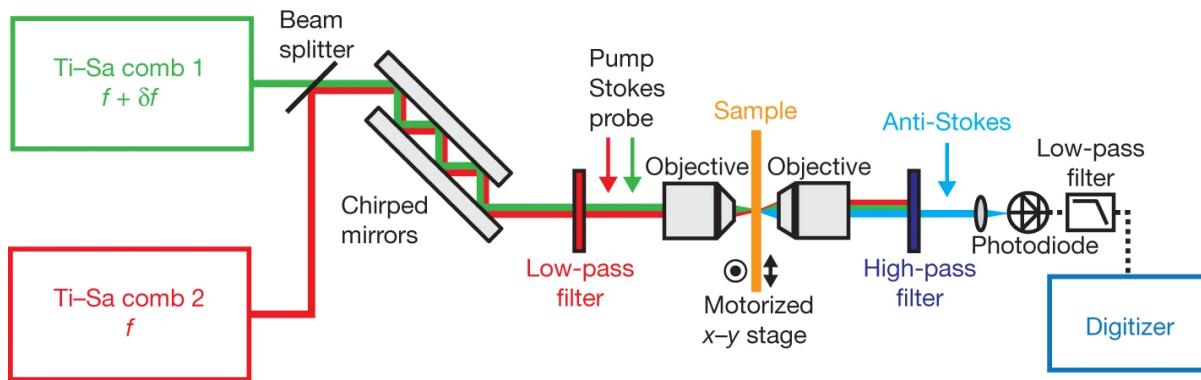


# Dual-comb hyperspectral imaging

Scanning sample

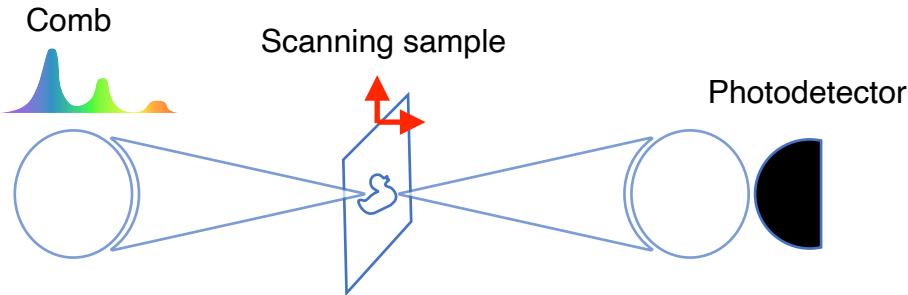


High-speed broadband CARS

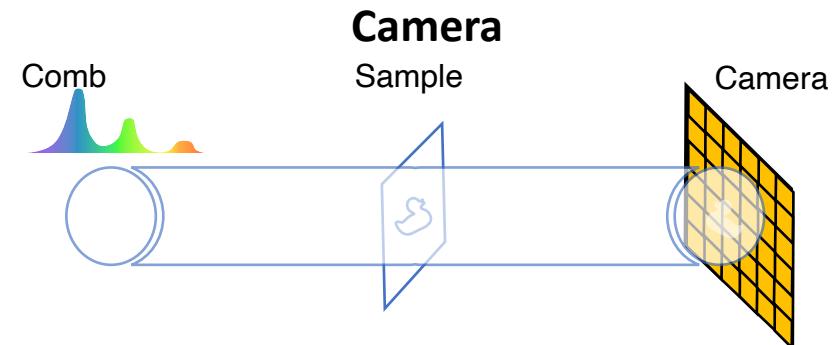
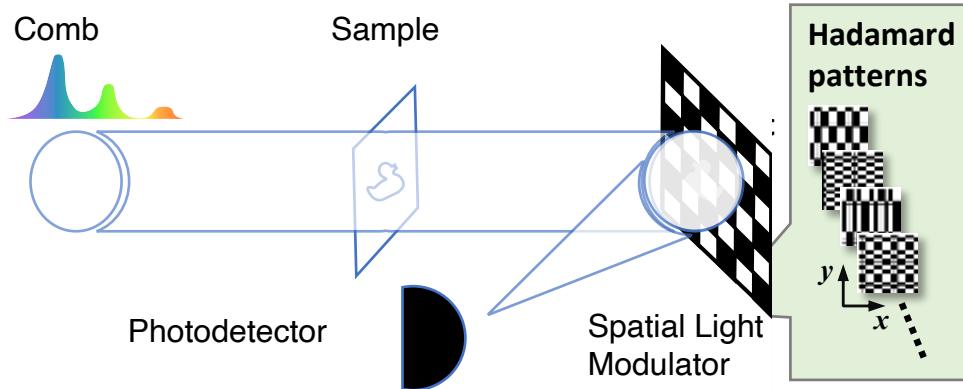


# Dual-comb hyperspectral imaging: how?

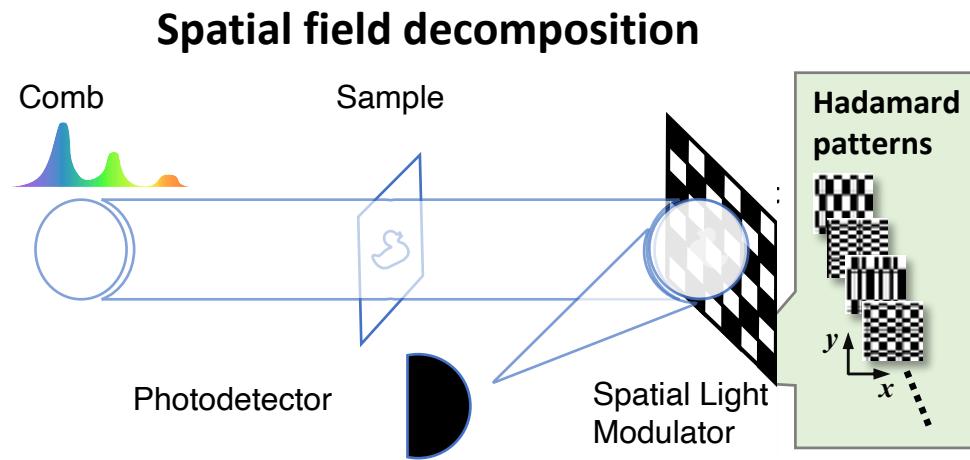
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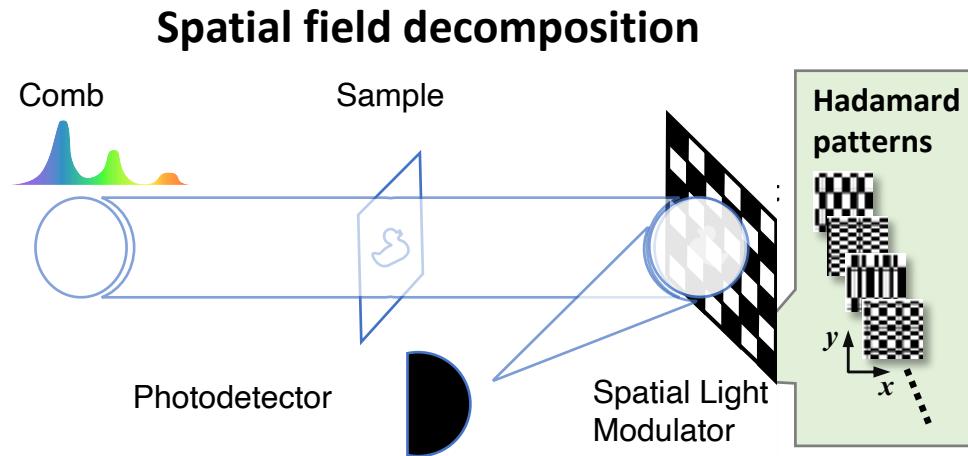
Spatial field decomposition



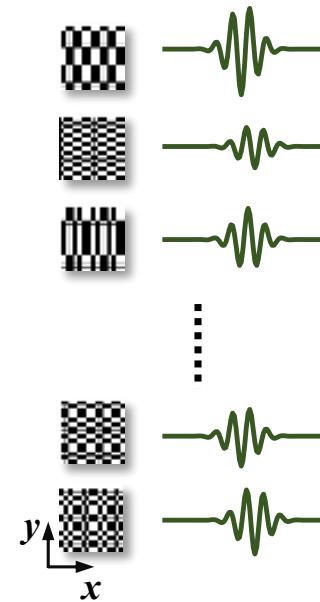
# Dual-comb hyperspectral imaging: how?



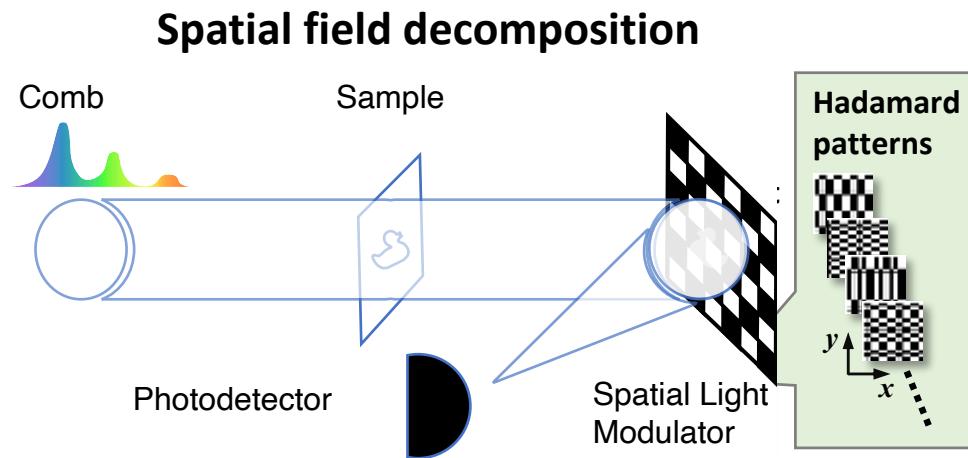
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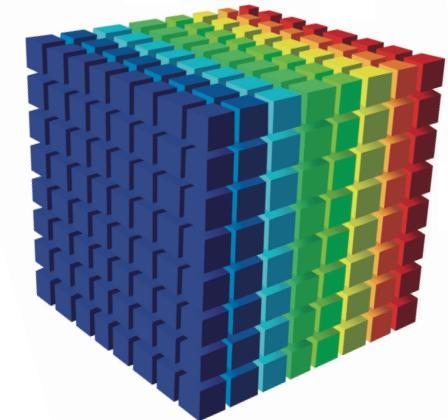
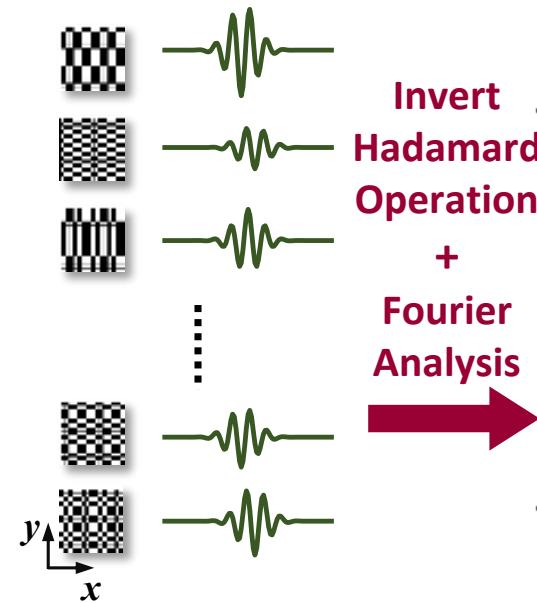
Pattern-dependent  
interferograms



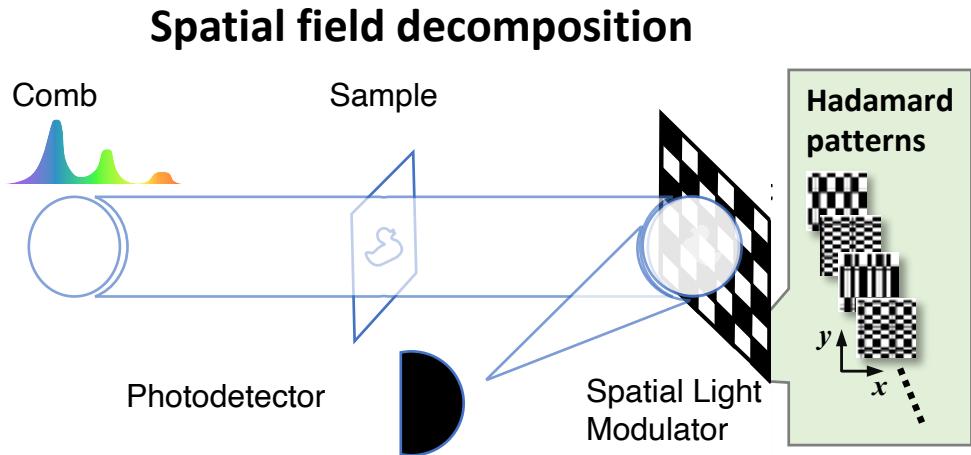
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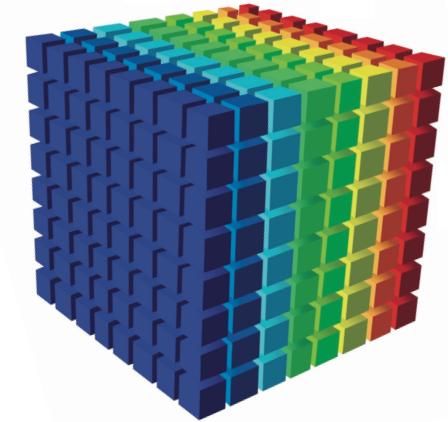
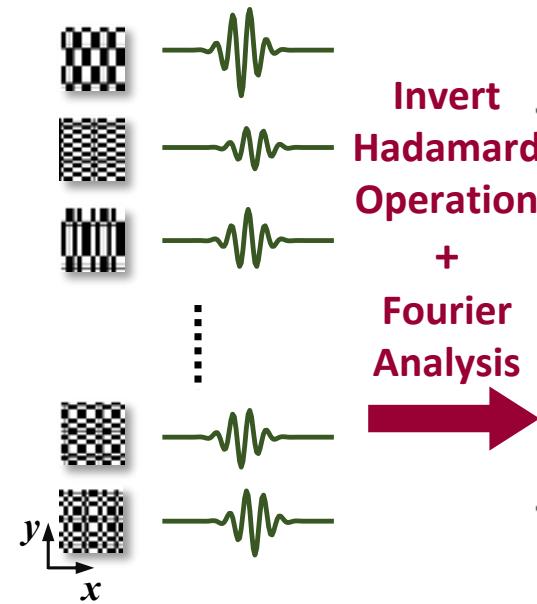
Pattern-dependent  
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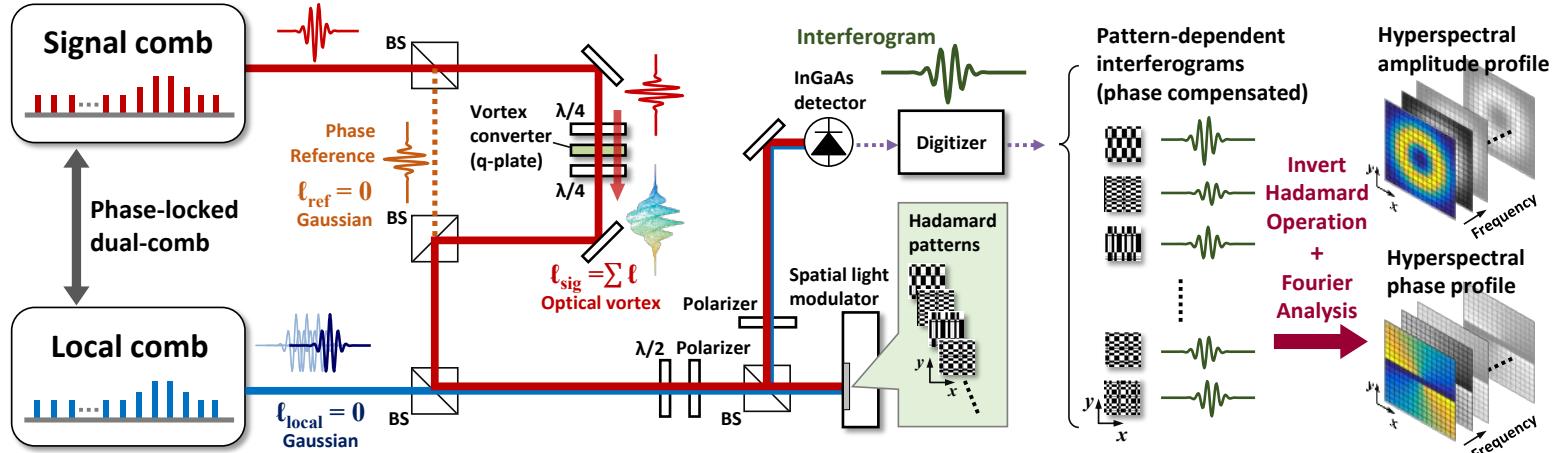
# Dual-comb hyperspectral imaging



Pattern-dependent  
interferograms

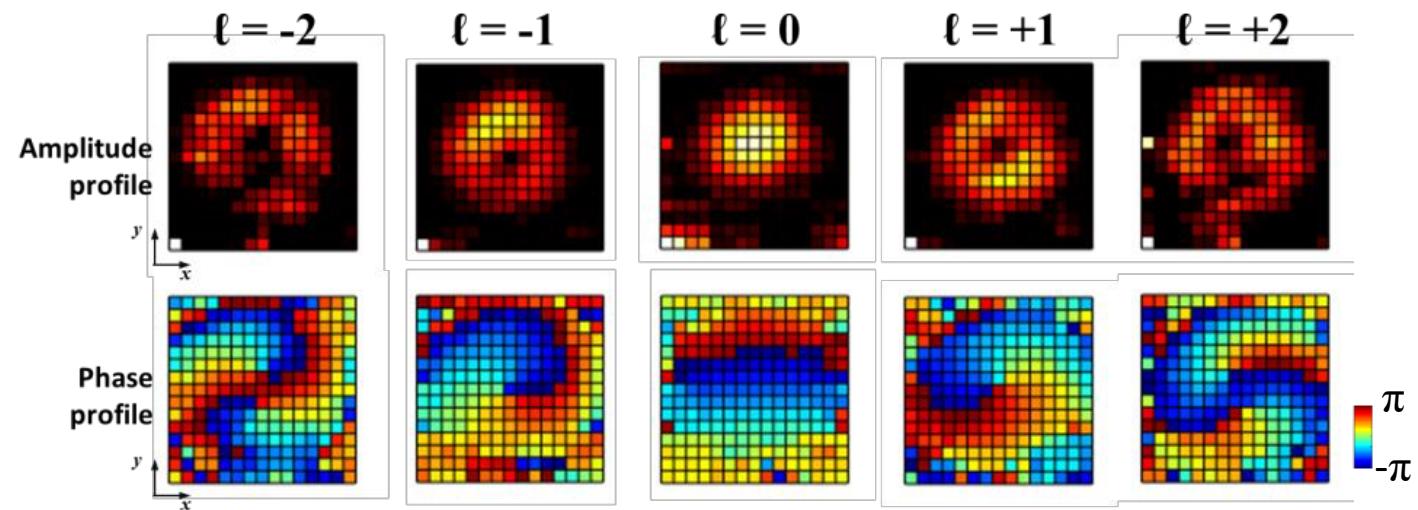
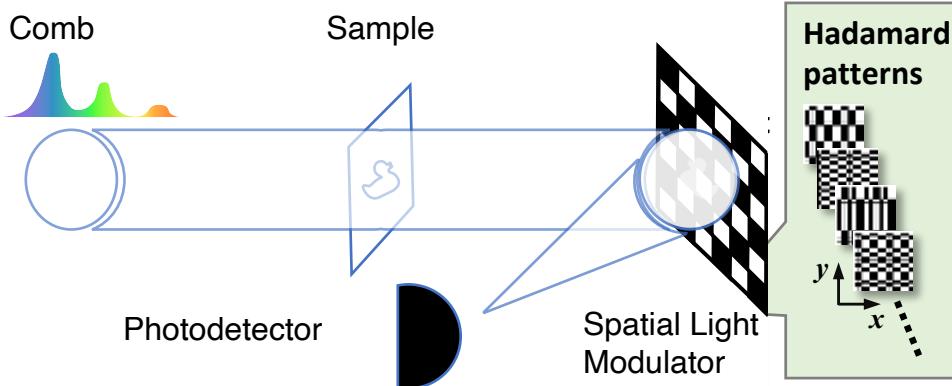


# Dual-comb hyperspectral imaging



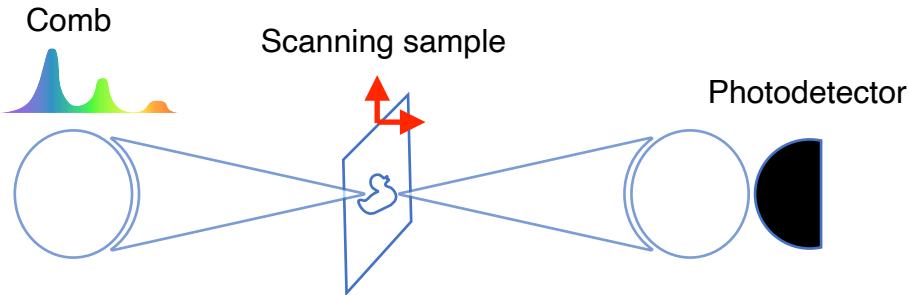
Spatiotemporal characterization of optical vortex light-wave

## Spatial field decomposition

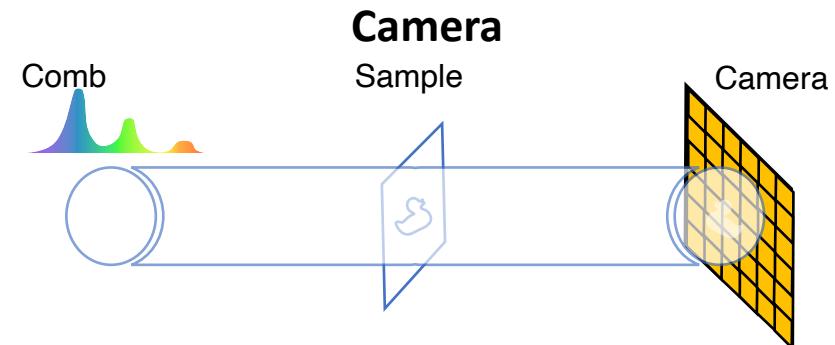
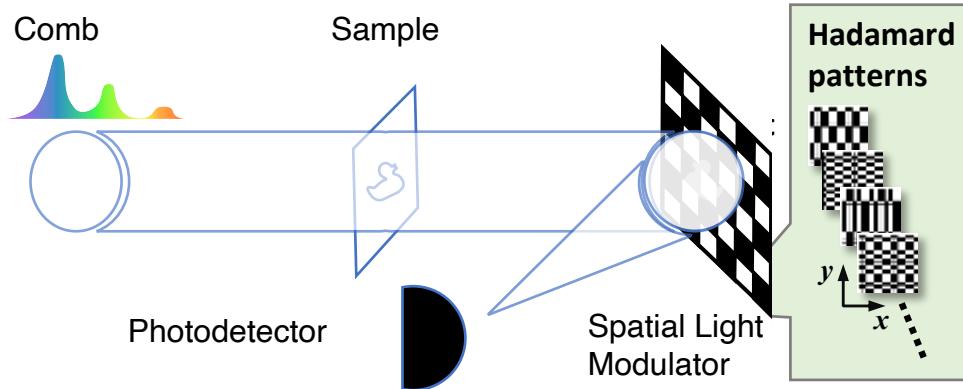


# Dual-comb hyperspectral imaging: how?

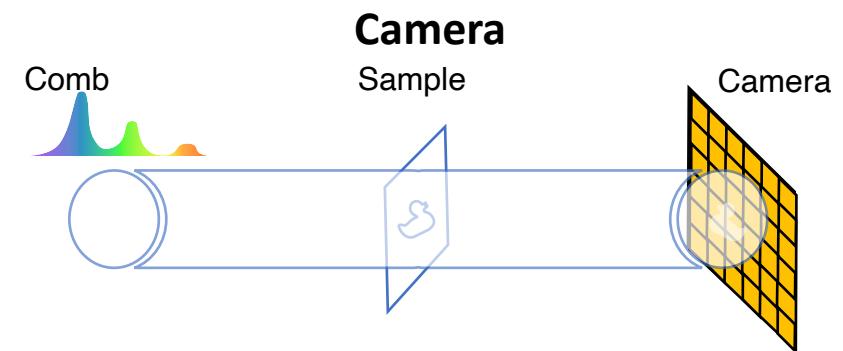
Scanning sample



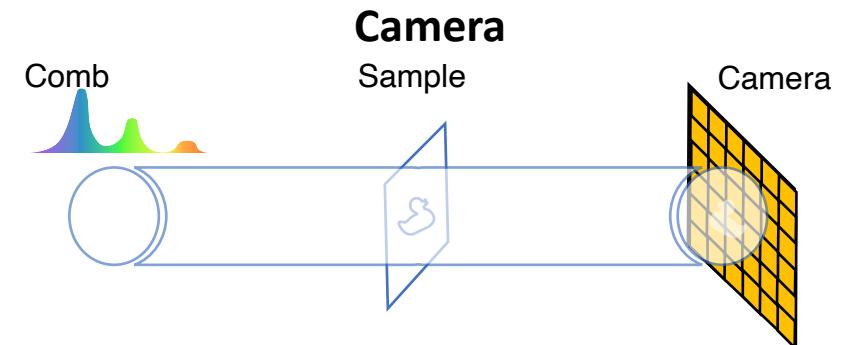
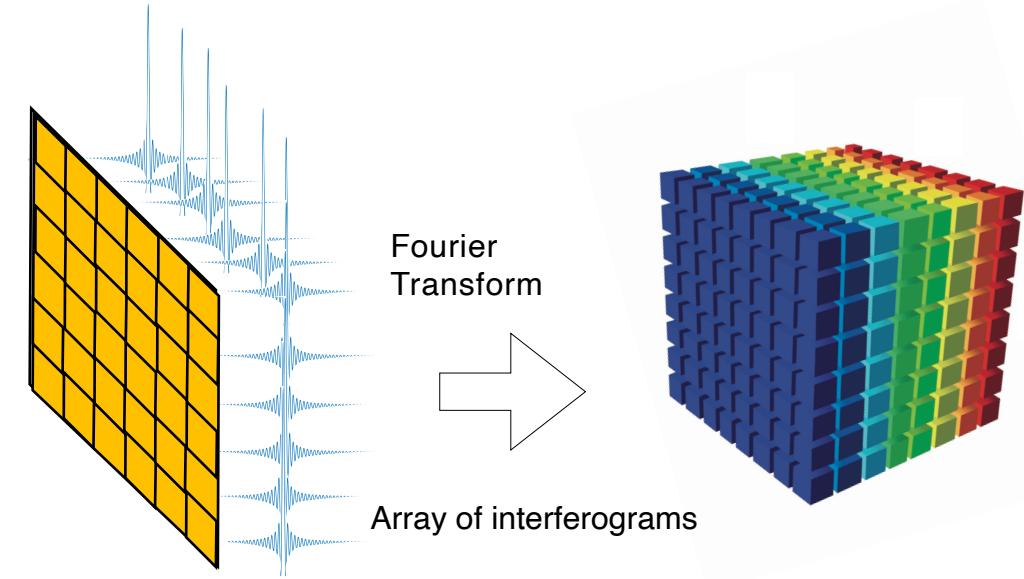
Spatial field decomposition



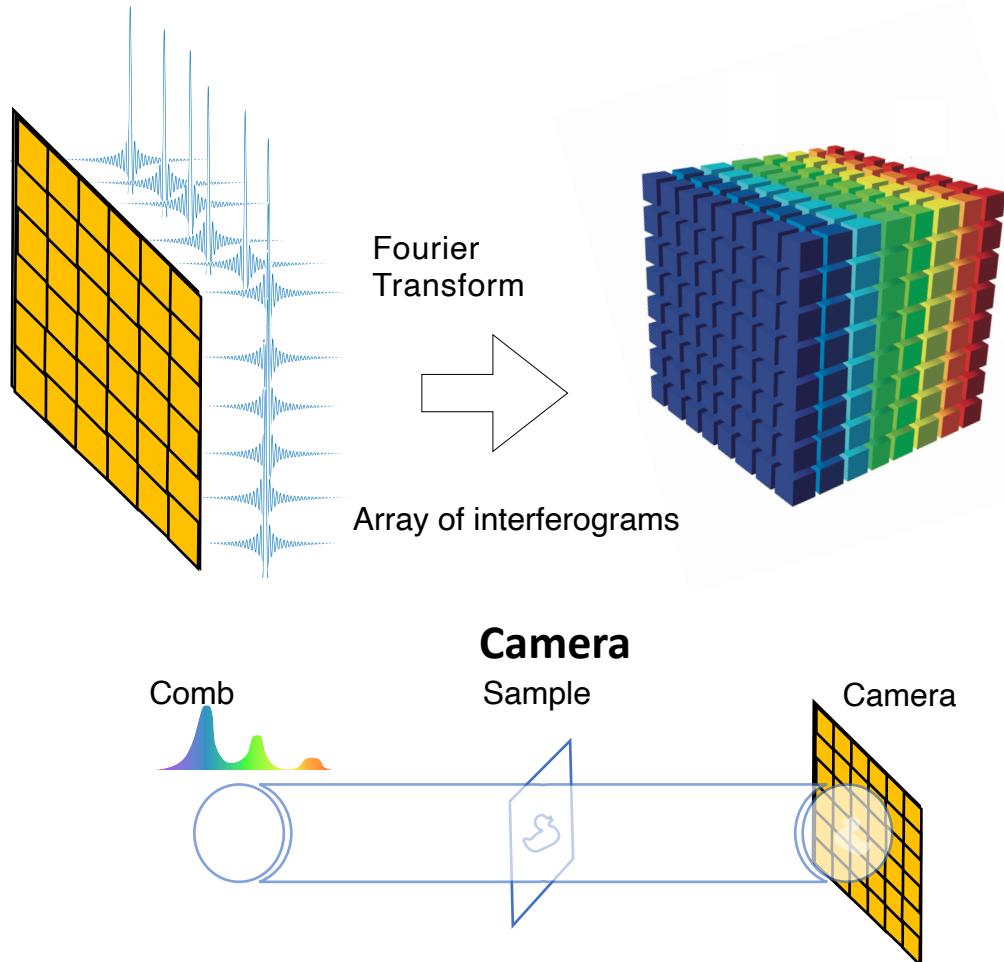
# Dual-comb hyperspectral imaging: how?



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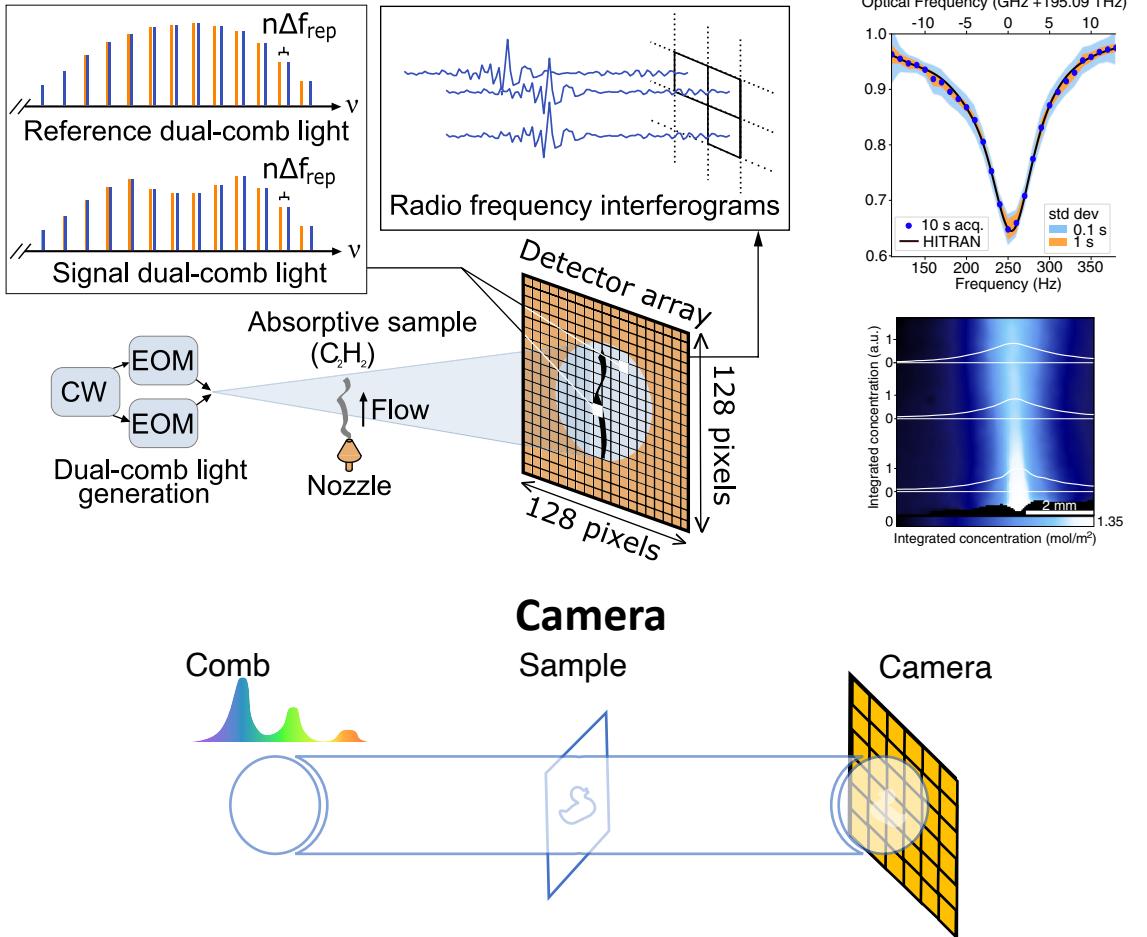


# Dual-comb hyperspectral imaging



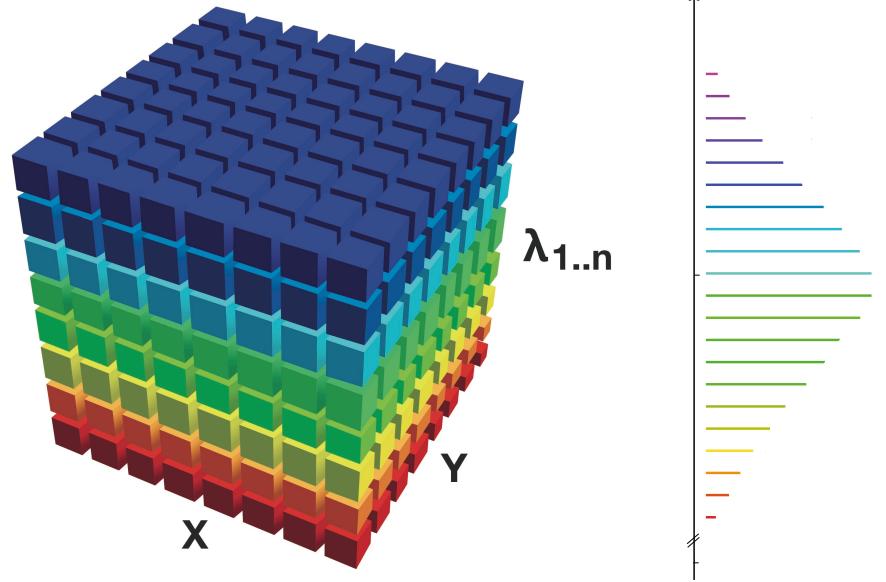
# Dual-comb hyperspectral imaging

Real time C<sub>2</sub>H<sub>2</sub> concentration  
by AI spectra computing



T. Voumard et al. Opt. Lett. 45, 6583-6586 (2020)

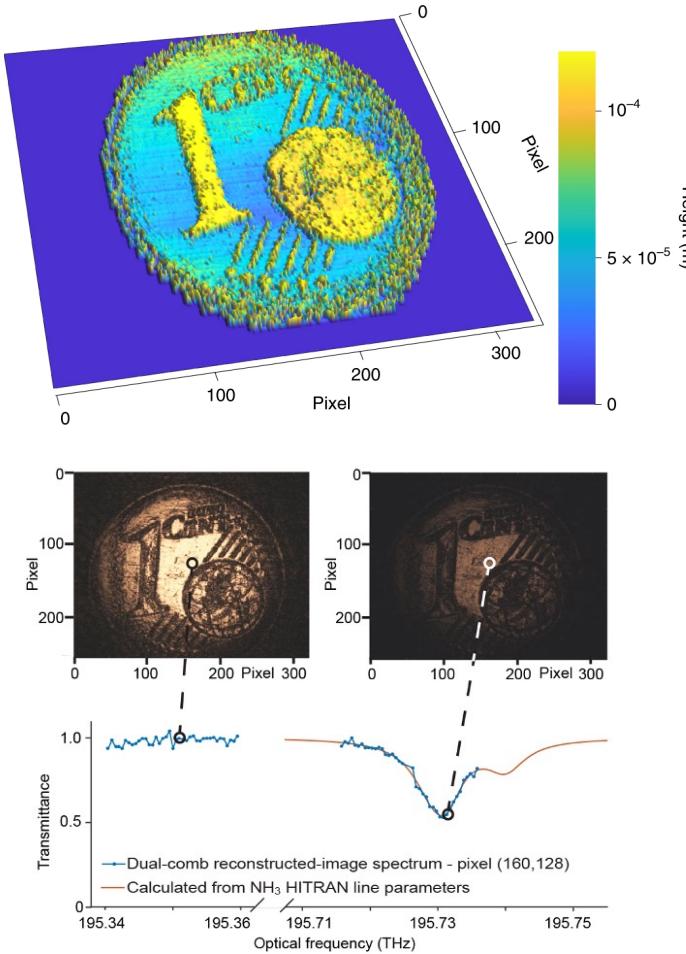
## Part 2: Dual-comb hyperspectral imaging applications



Different configuration are possible:

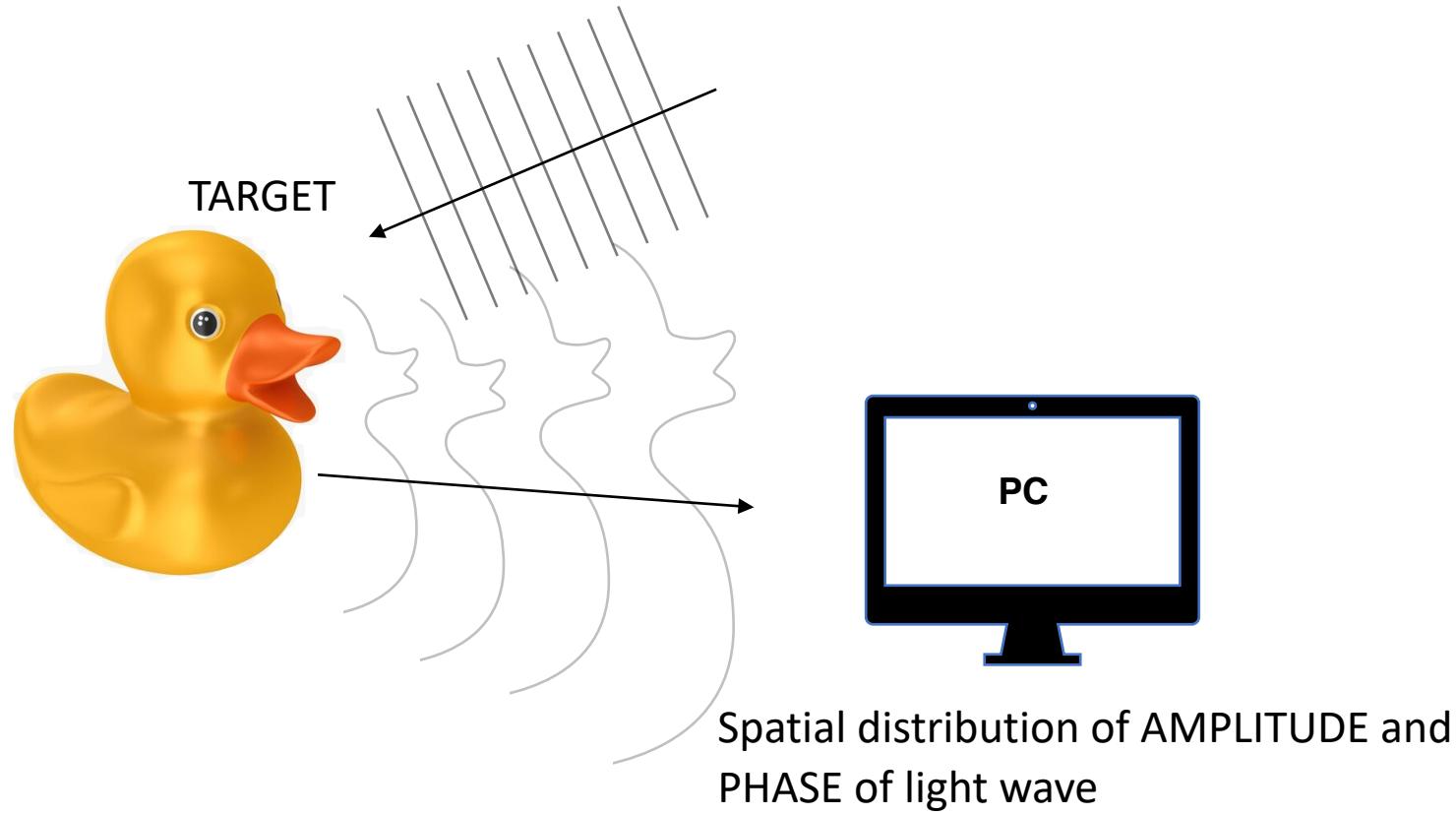
- Point scanning
- Spatial field decomposition
- Camera imaging

# Part 3: Dual-comb hyperspectral digital holography

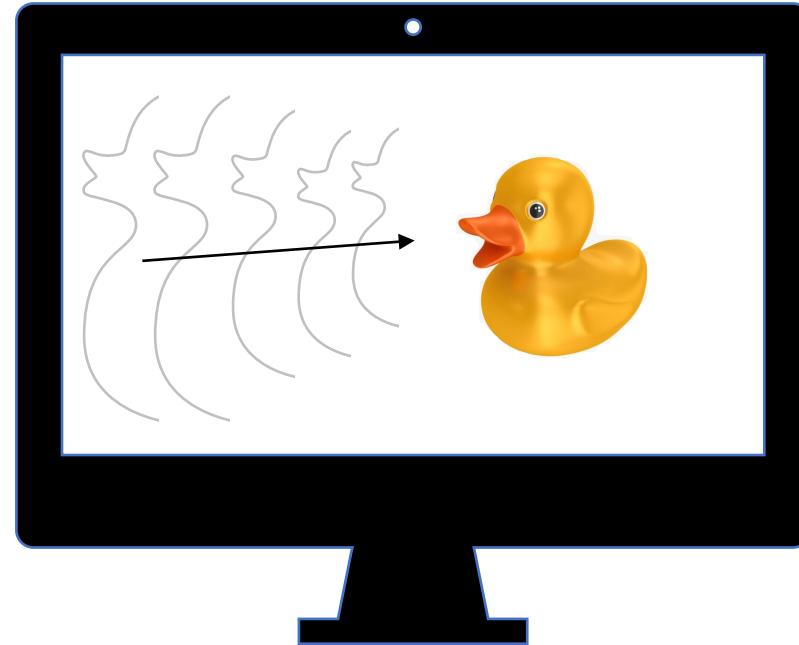
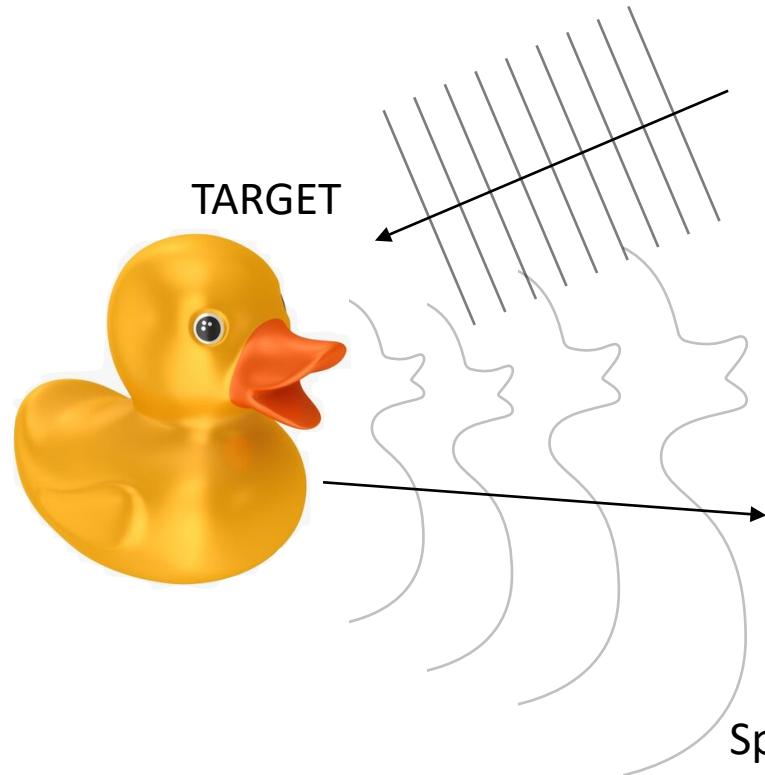




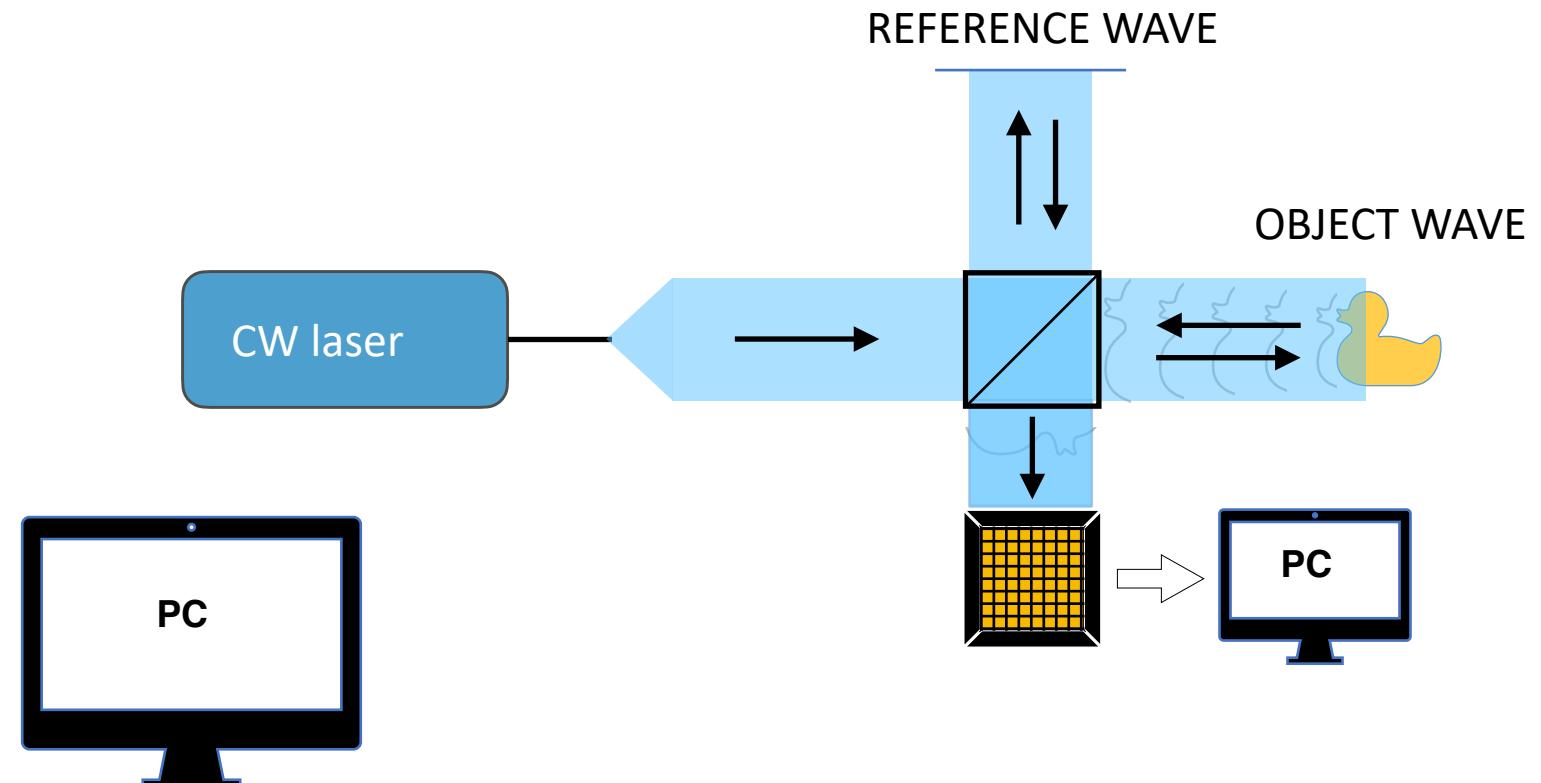
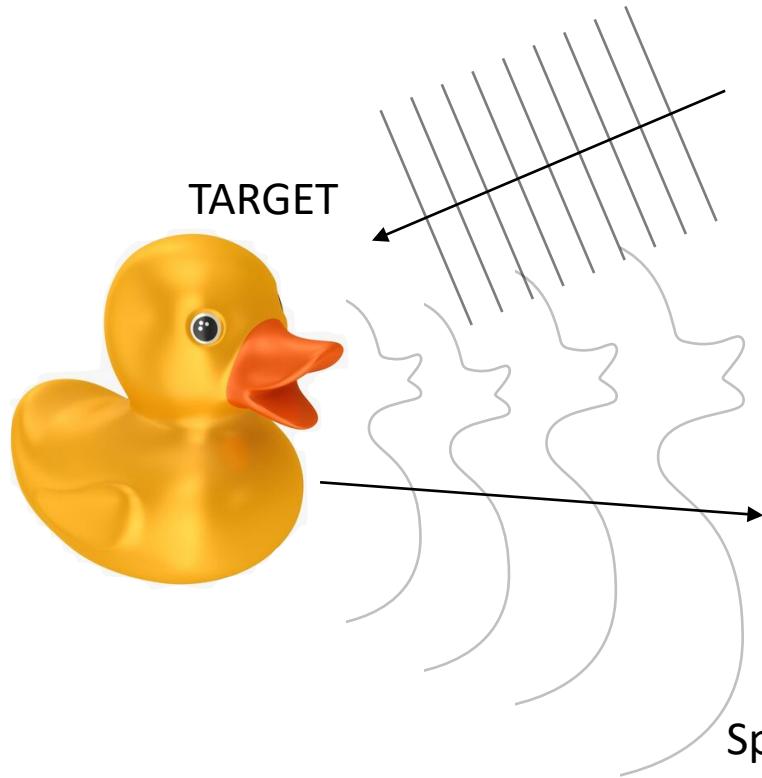
# Digital holography



# Digital holography

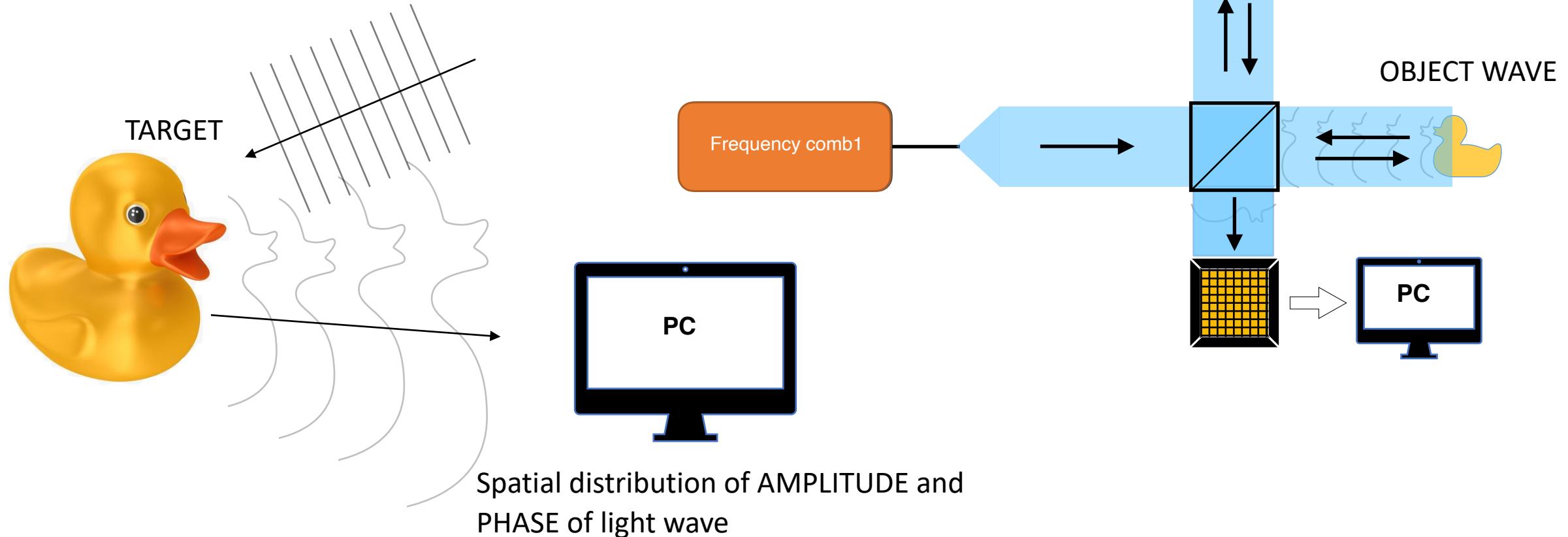


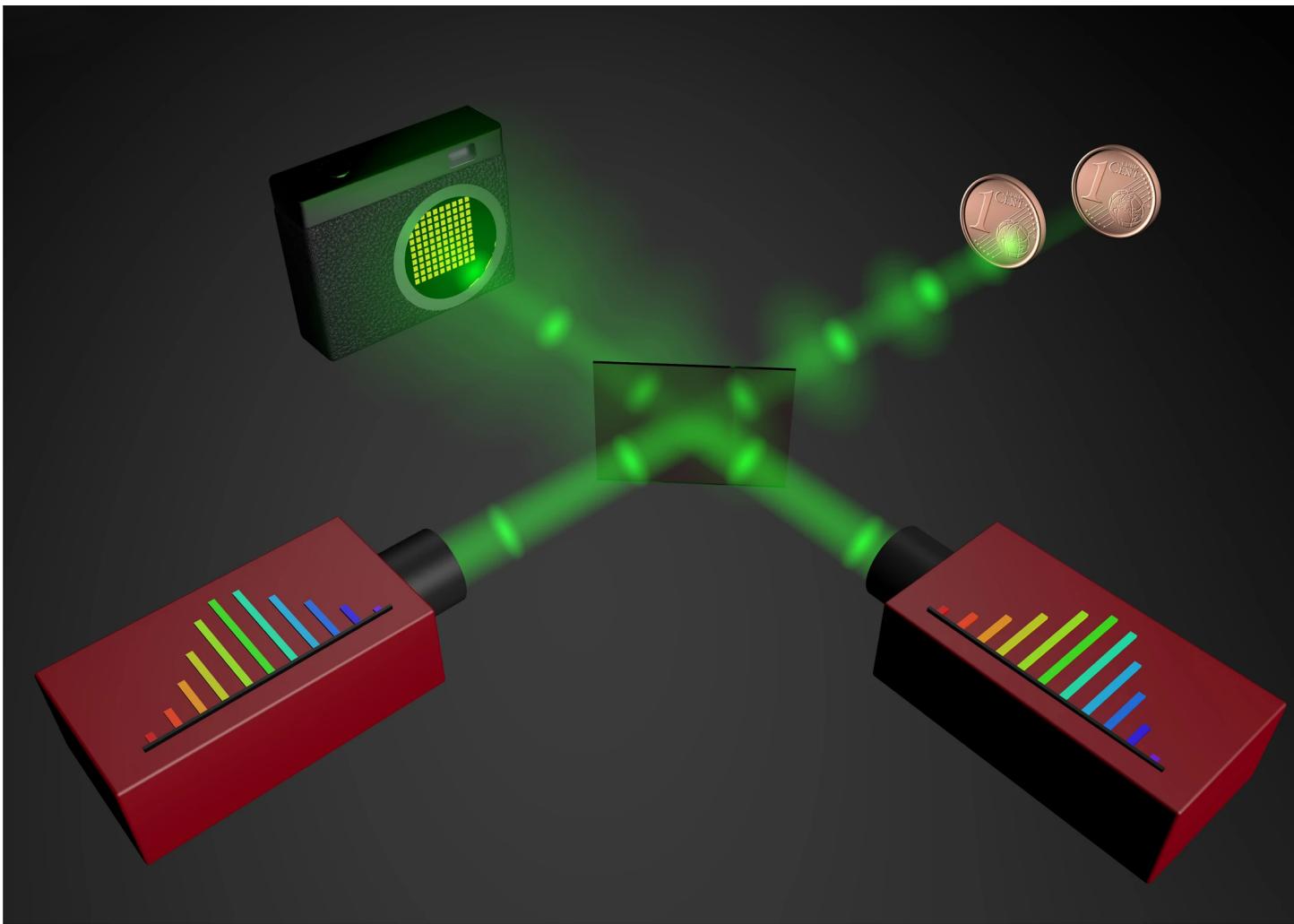
# Digital holography



Spatial distribution of AMPLITUDE and  
PHASE of light wave

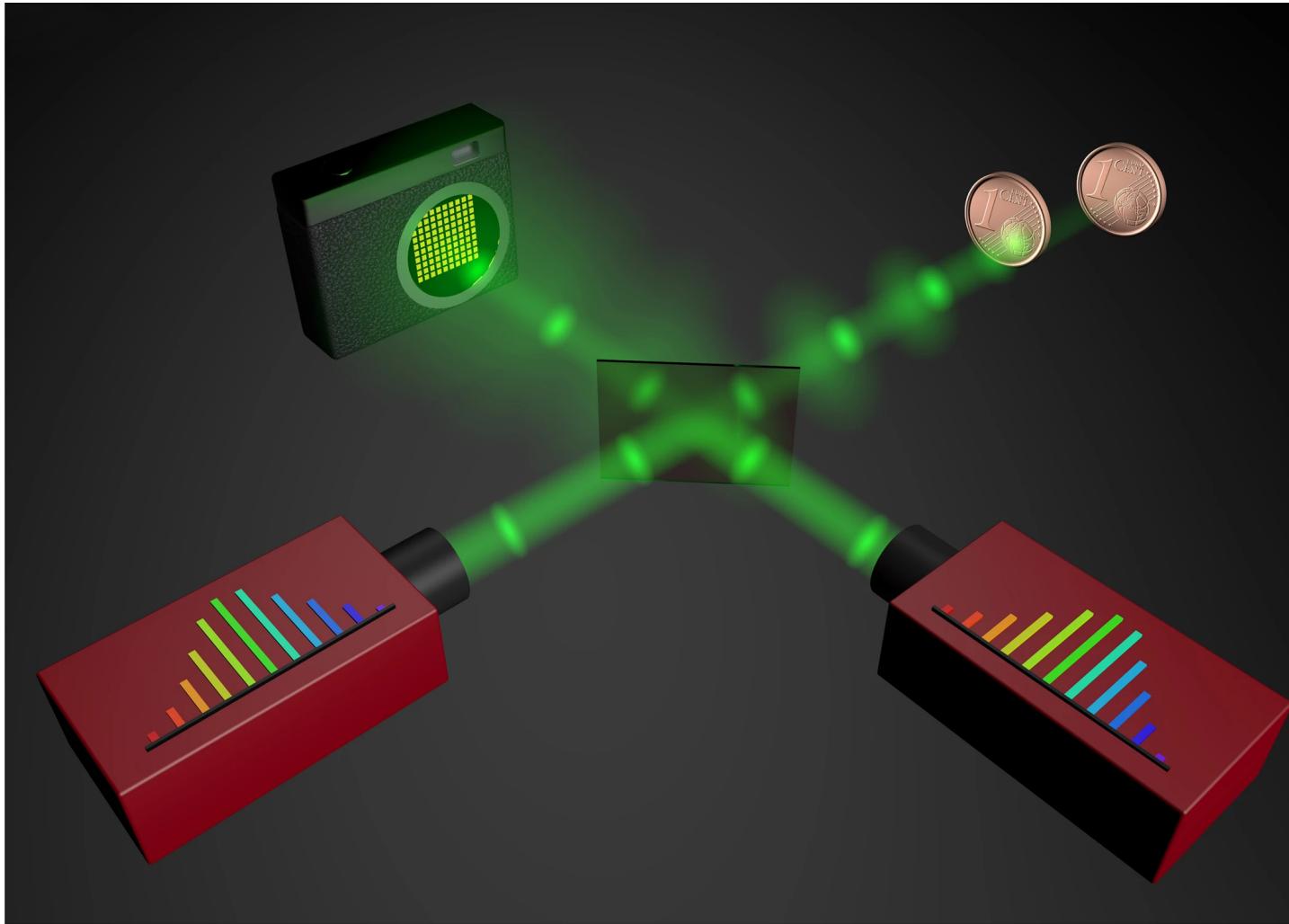
# Digital holography





E. Vicentini, et al. Nat. Photonics  
15, 890 (2021)

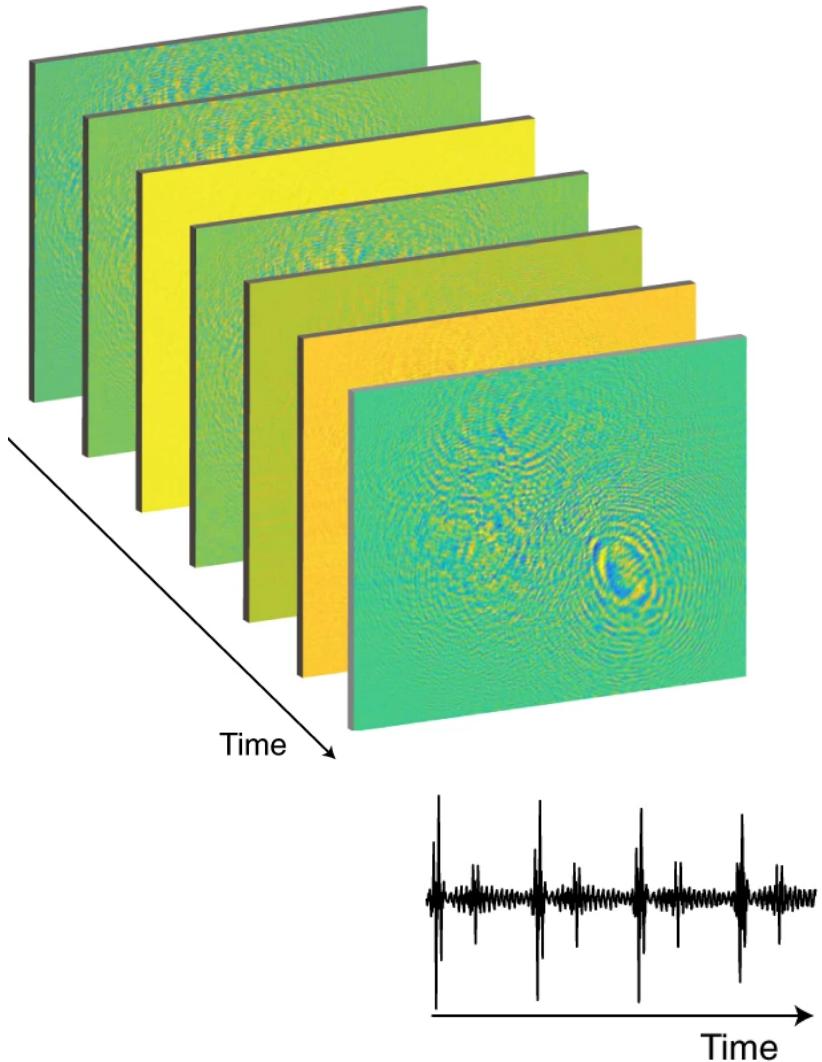
# Dual-comb digital holography: setup



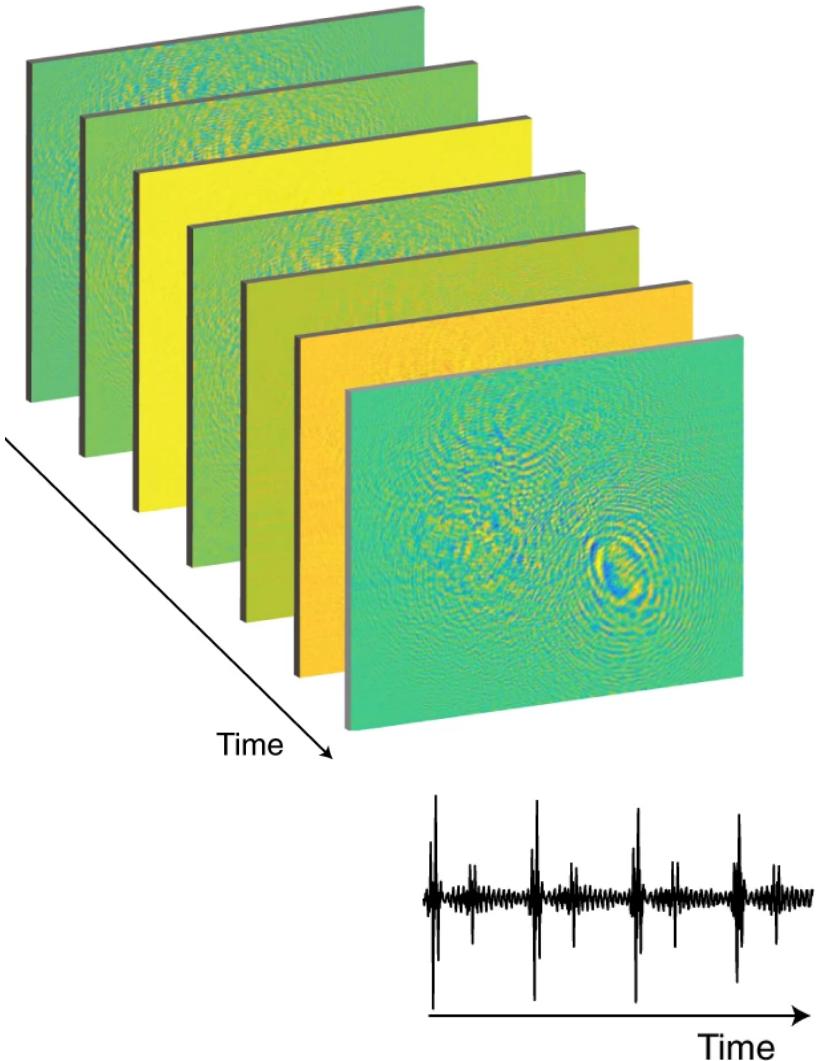
E. Vicentini, et al. Nat. Photonics  
15, 890 (2021)

# Dual-comb digital holography: time domain

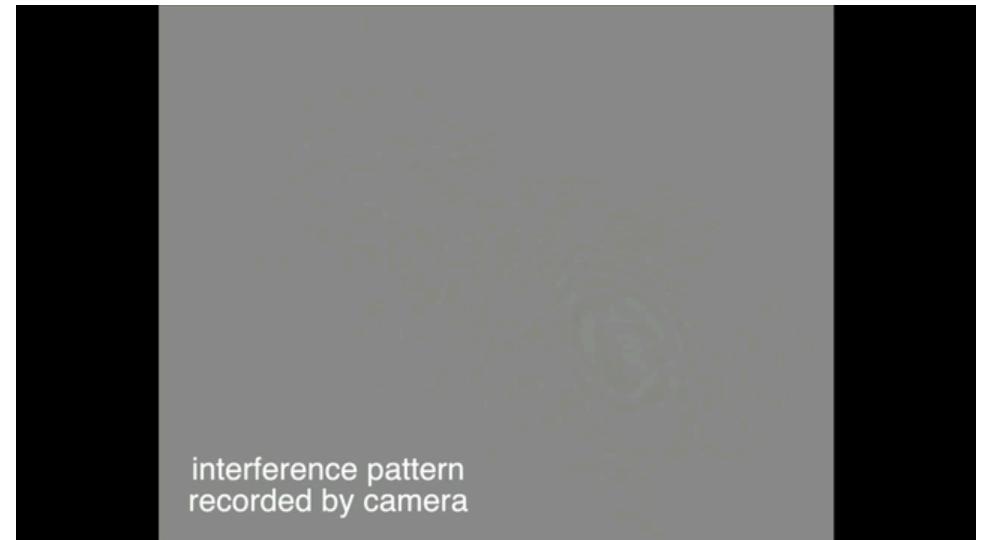
# Dual-comb digital holography: time domain



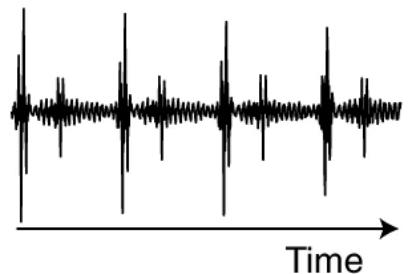
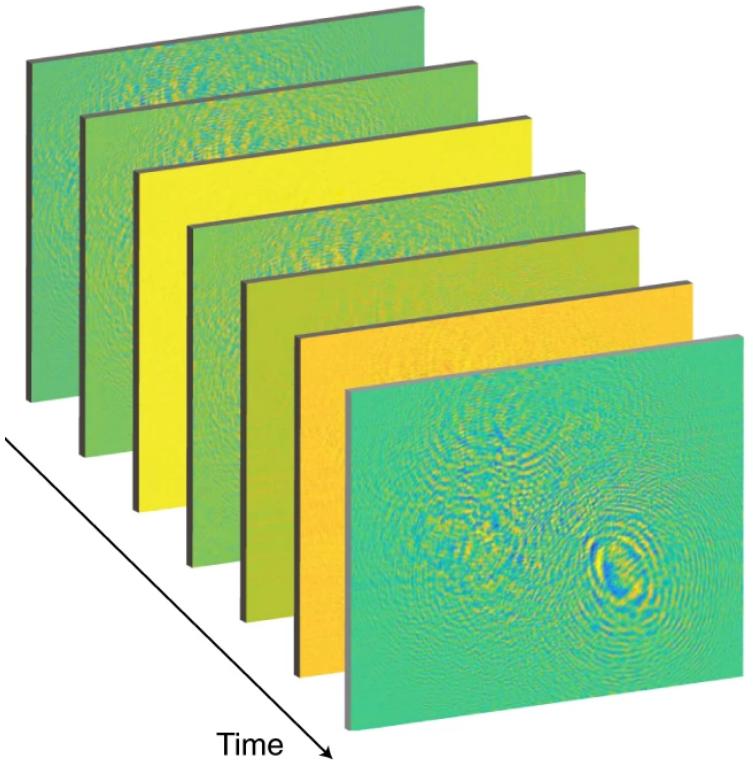
# Dual-comb digital holography: time domain



One frame - one time

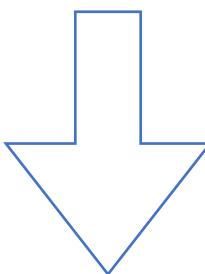
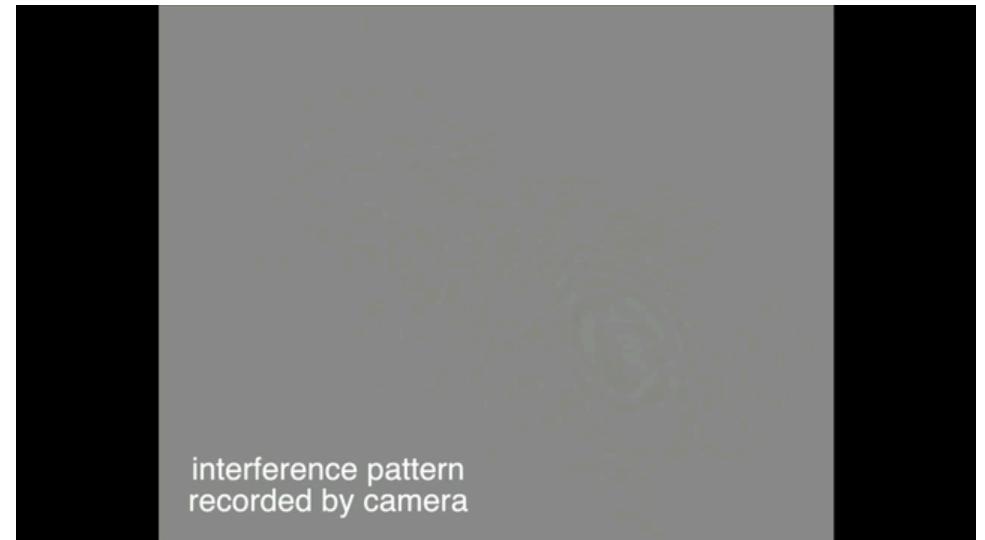


# Dual-comb digital holography: time domain



Dual-comb hyperspectral imaging and holography

One frame - one time

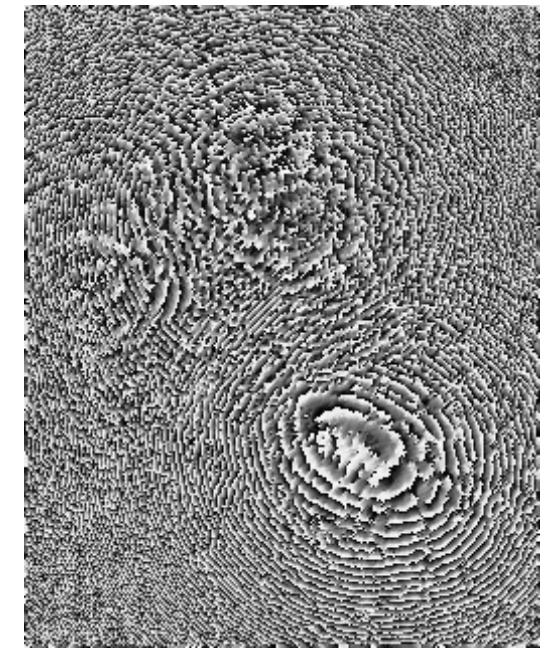
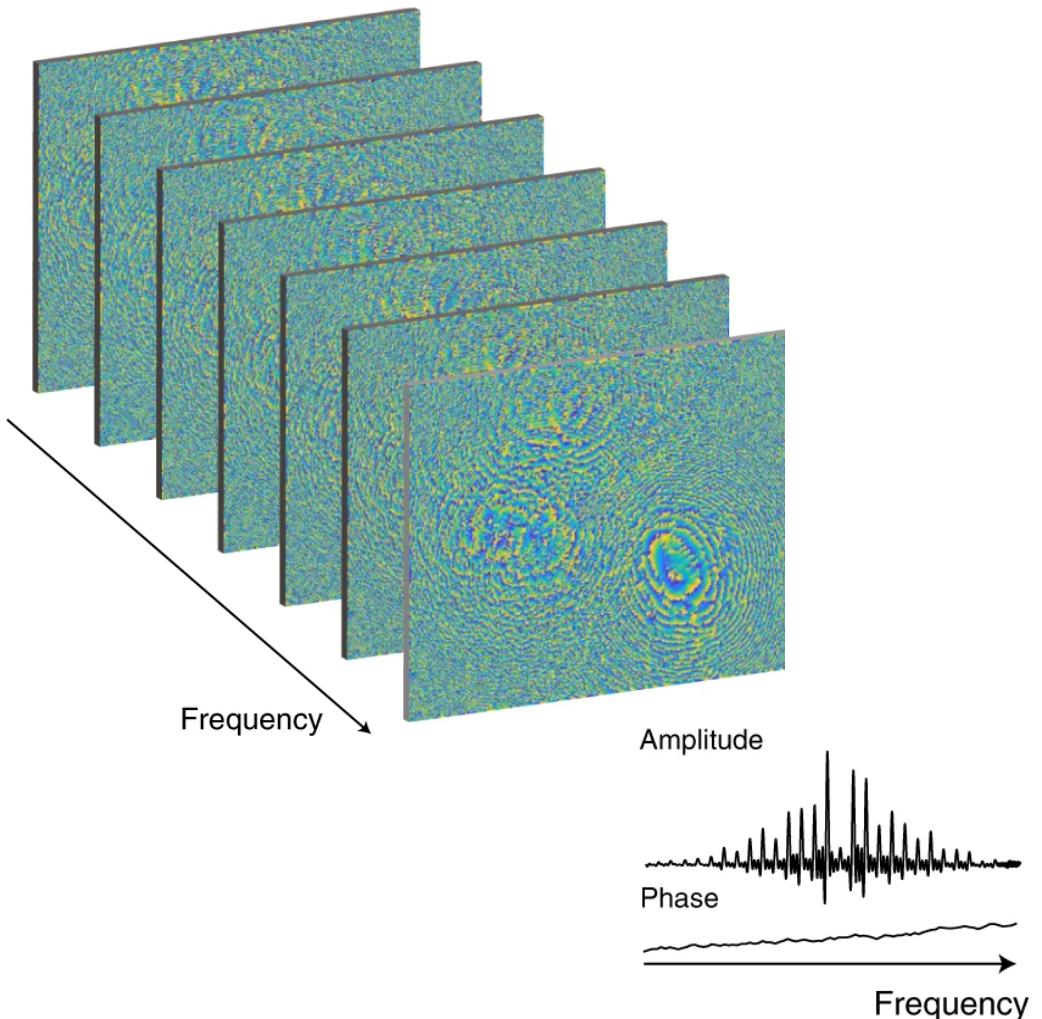


TIME-DOMAIN  
FOURIER  
TRANSFORM

# Dual-comb digital holography: frequency domain

# Dual-comb digital holography: frequency domain

One frame - one frequency

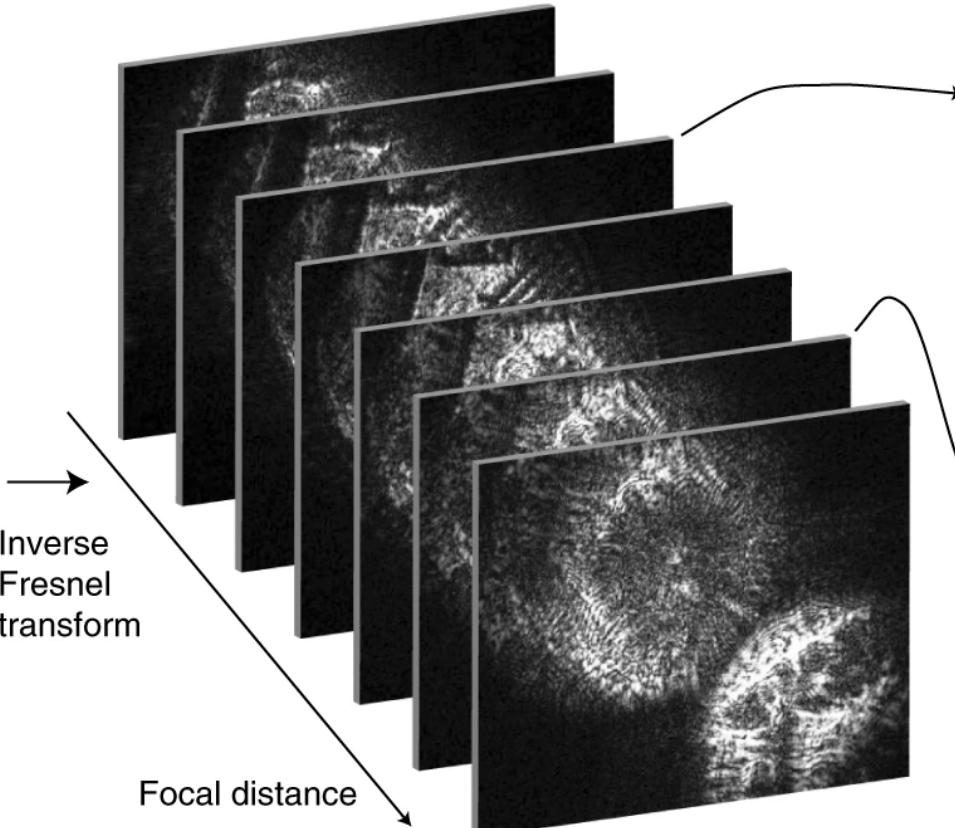
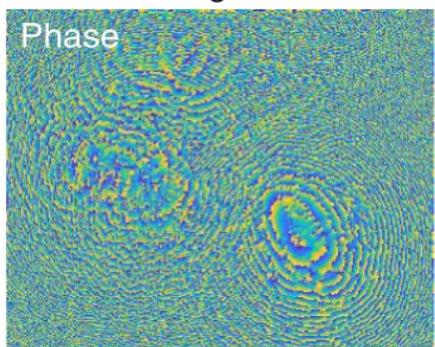
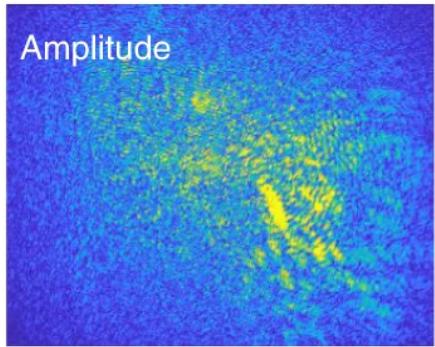


Phase

# Dual-comb digital holography: single frequency spatial reconstruction

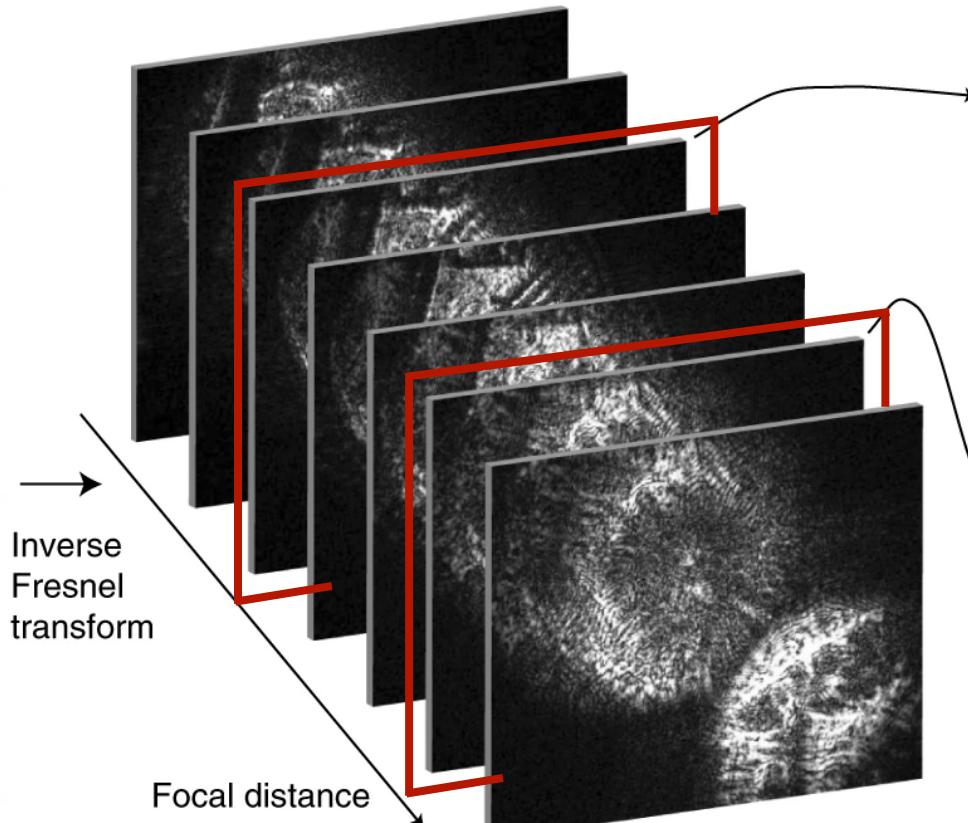
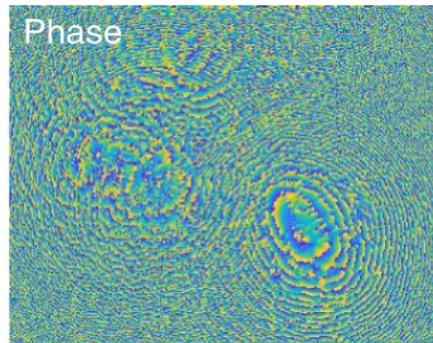
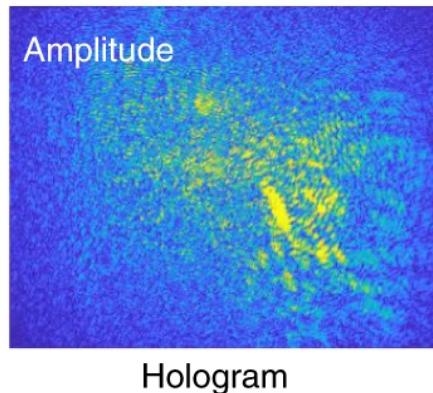
# Dual-comb digital holography: single frequency spatial reconstruction

d



# Dual-comb digital holography: single frequency spatial reconstruction

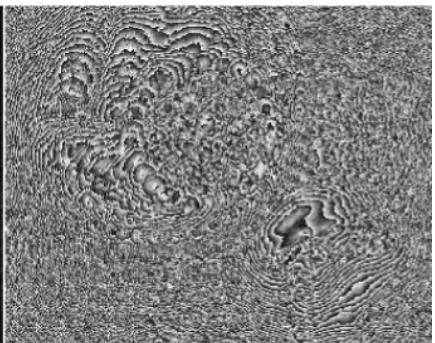
d



Amplitude

Phase

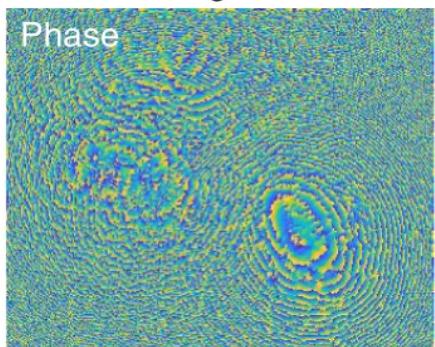
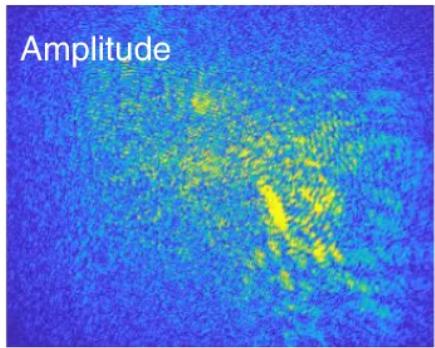
Reconstructed image



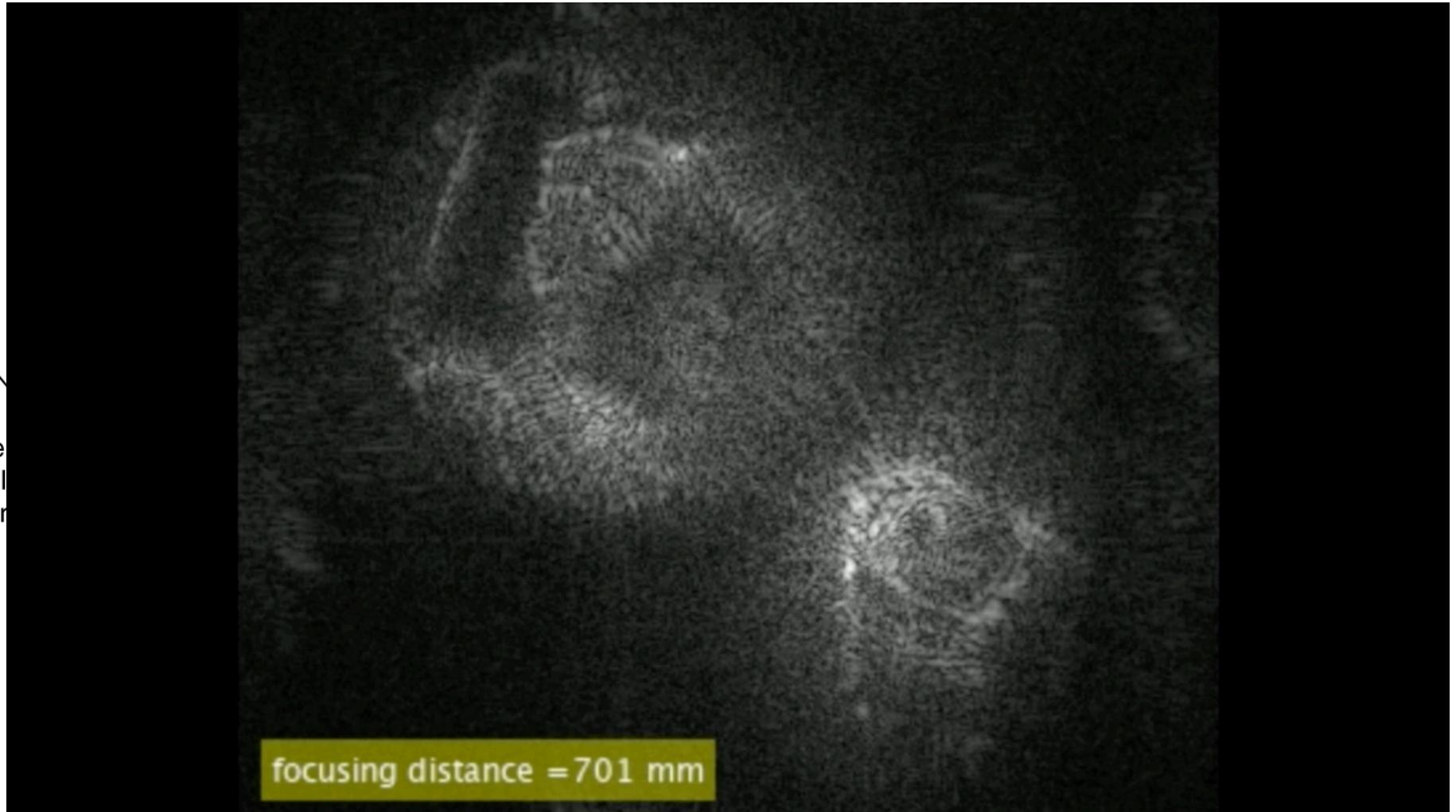
# Dual-comb digital holography: single frequency spatial reconstruction

One frame - one distance

d



Inverse  
Fresnel  
transform

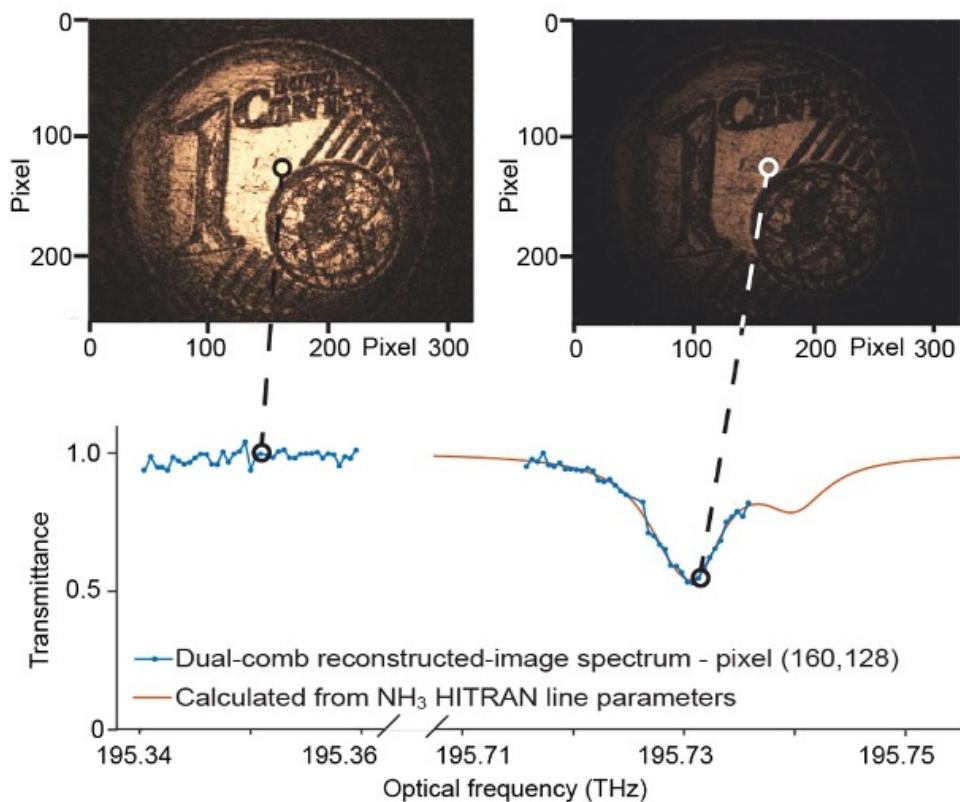


# Dual-comb digital holography: 4D information

# Dual-comb digital holography: 4D information

From amplitude at different frequency

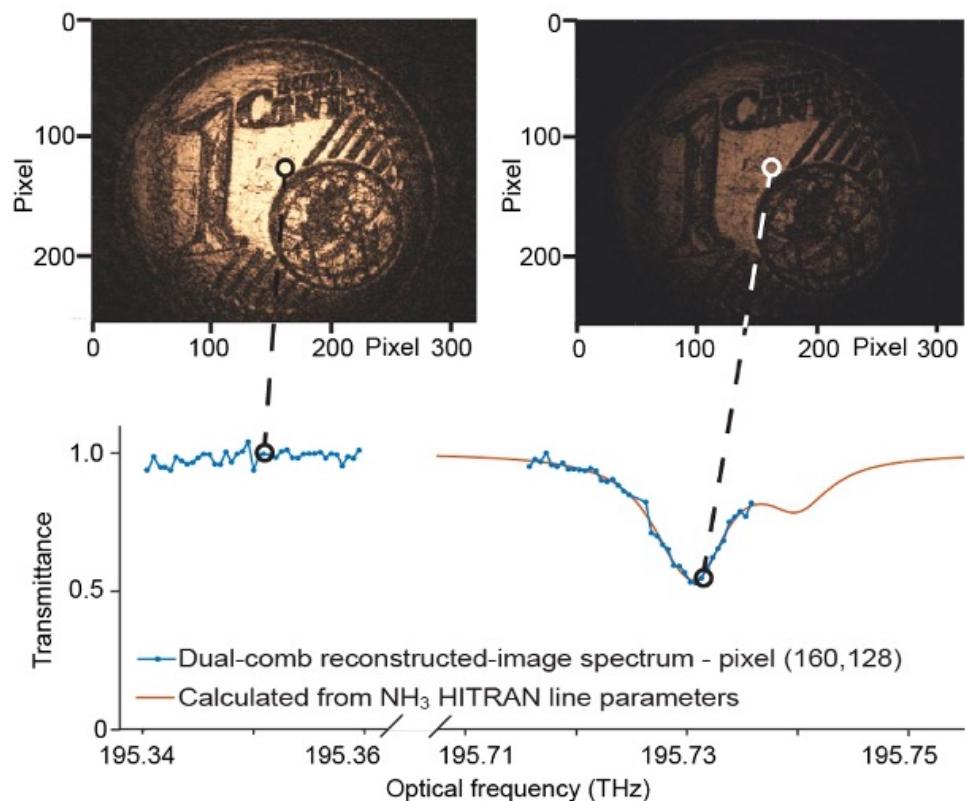
## Hyperspectral imaging



# Dual-comb digital holography: 4D information

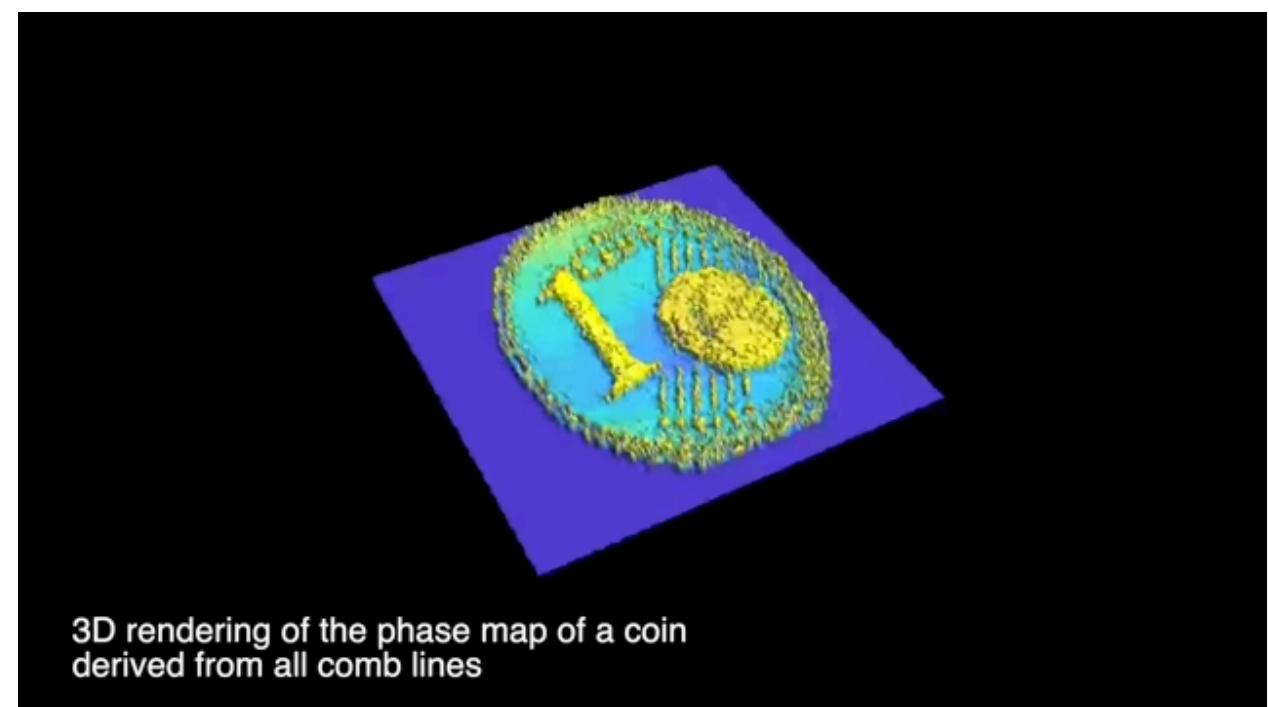
From amplitude at different frequency

## Hyperspectral imaging

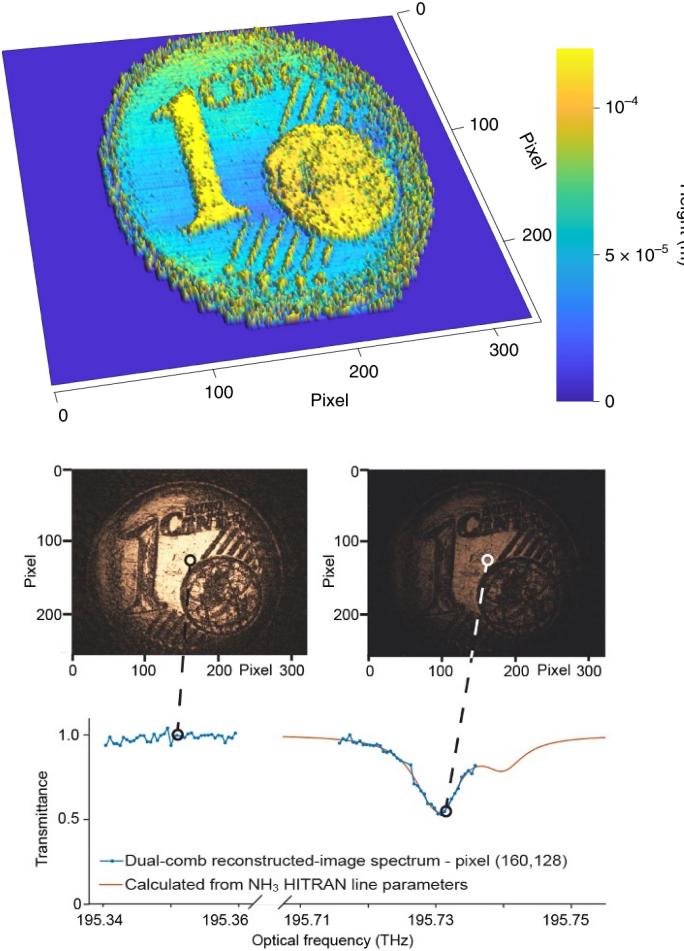


From Phase at different frequency

## 3D profile



# Part 3: Dual-comb hyperspectral digital holography



## Perspectives

### Faster acquisition

- Larger spectral bandwidth
- Characterisation of faster dynamics
- Larger ambiguity range
- Higher 3d imaging precision

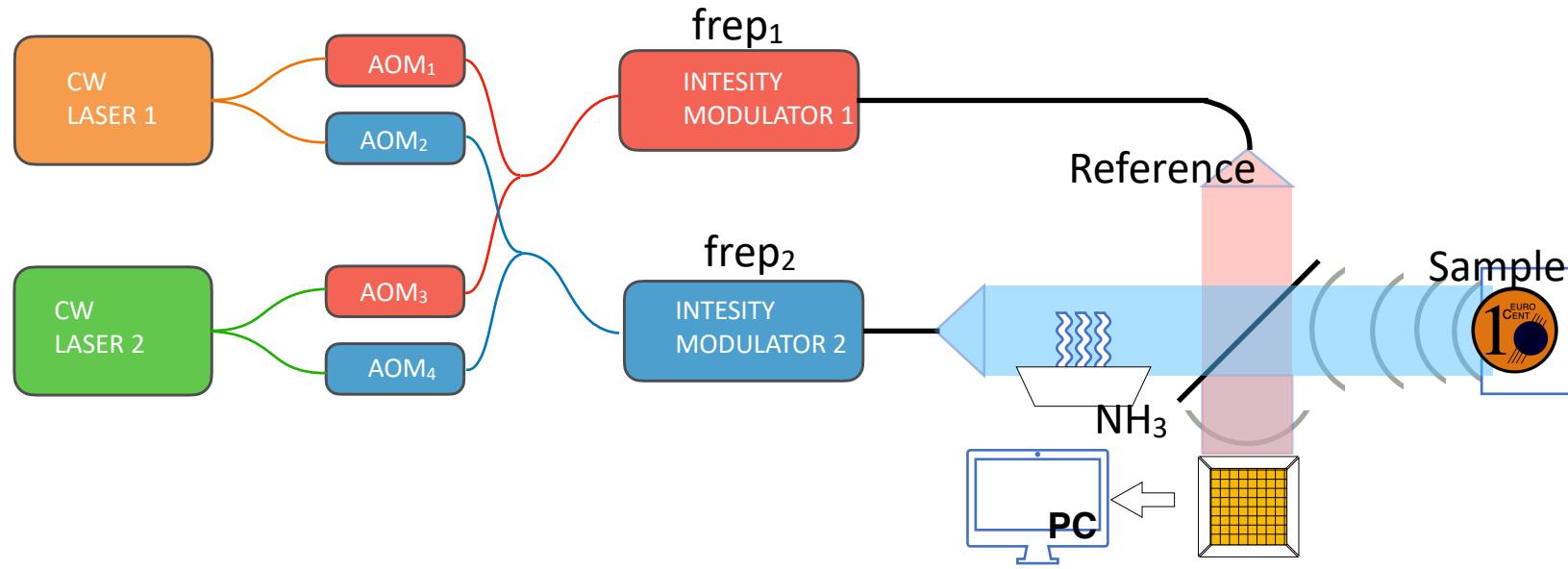
### Localised absorption

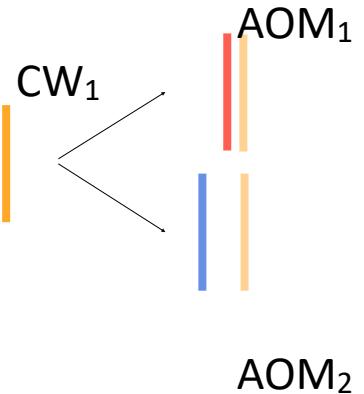
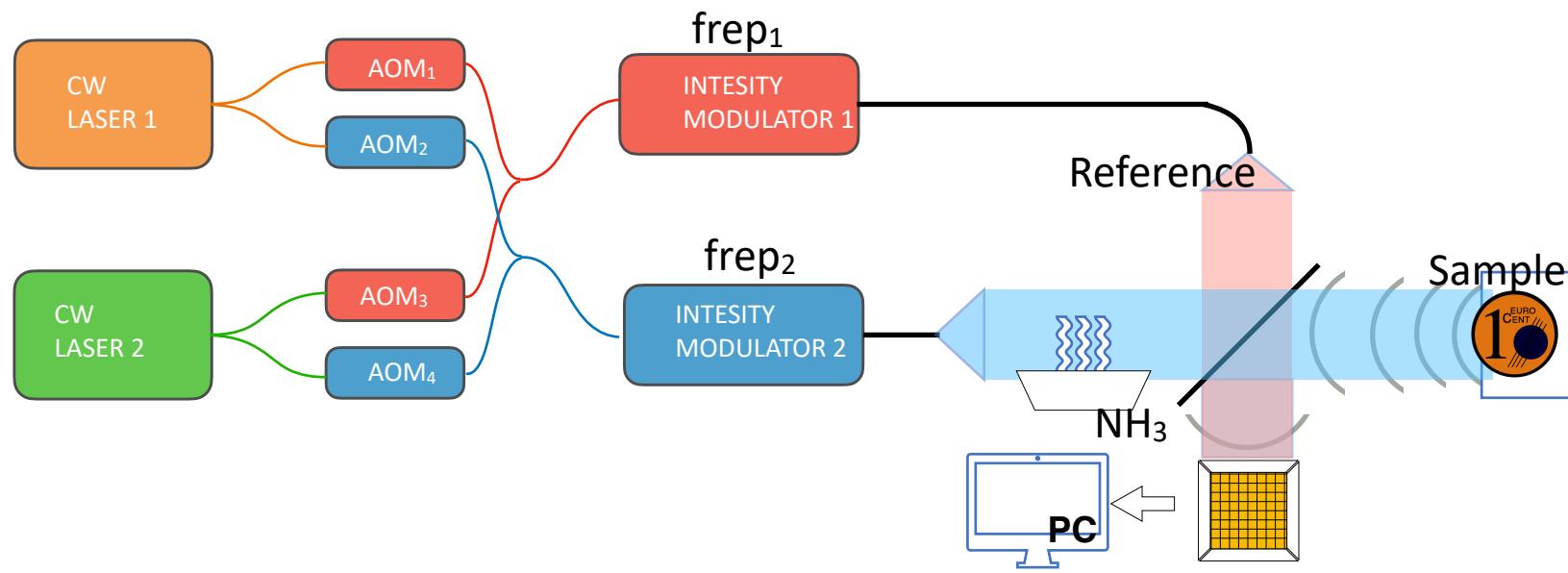


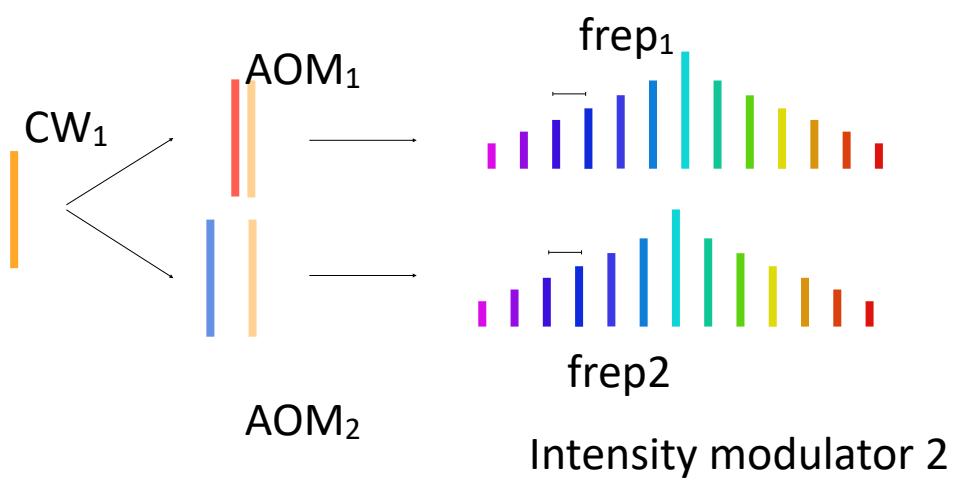
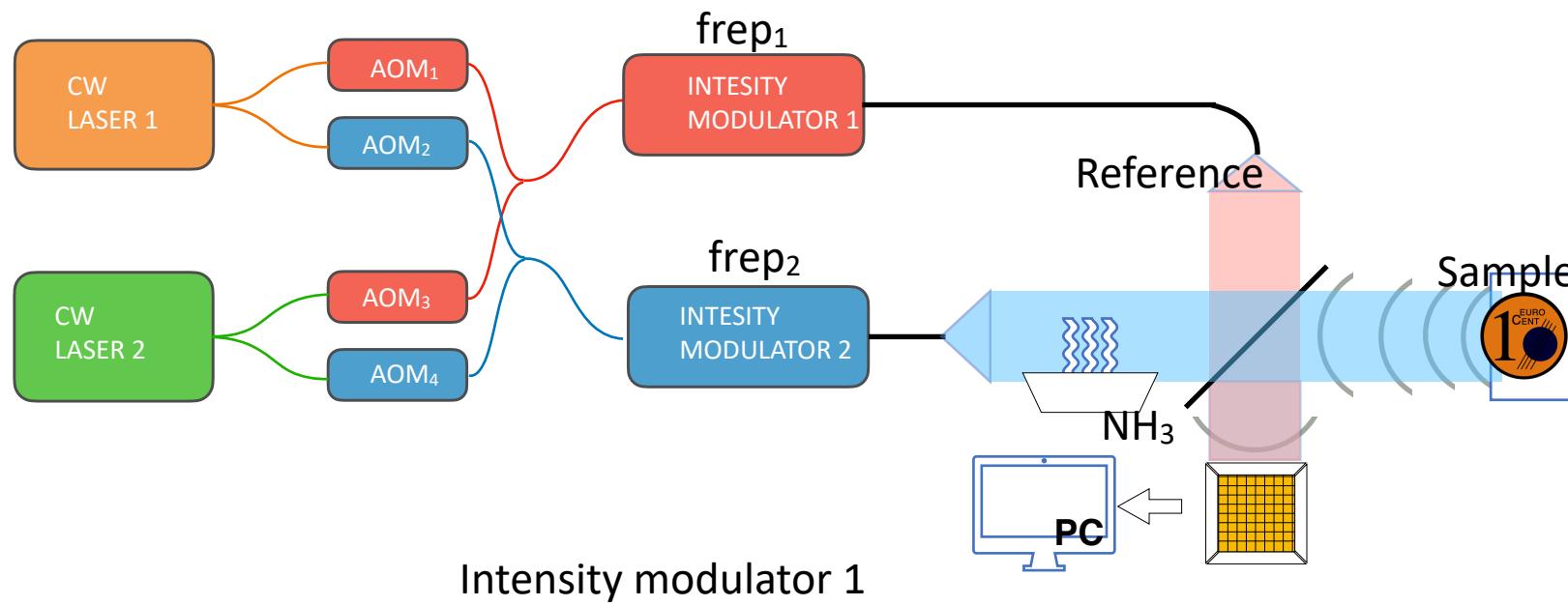
# Thank you for your attention

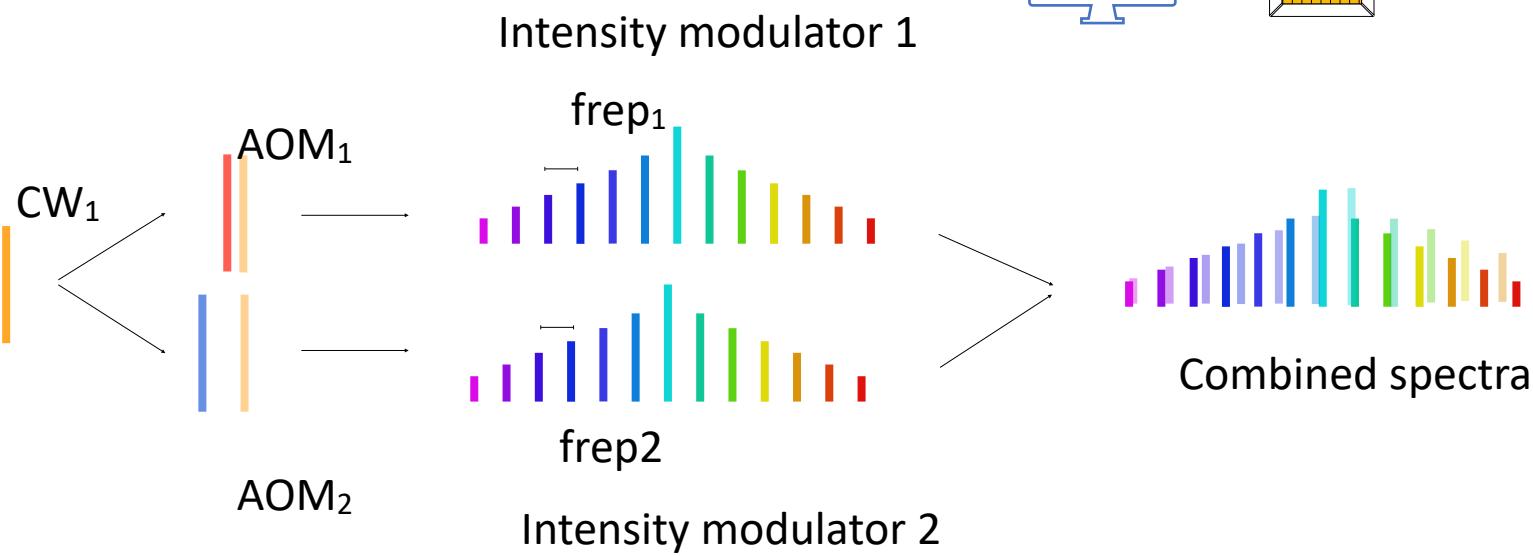
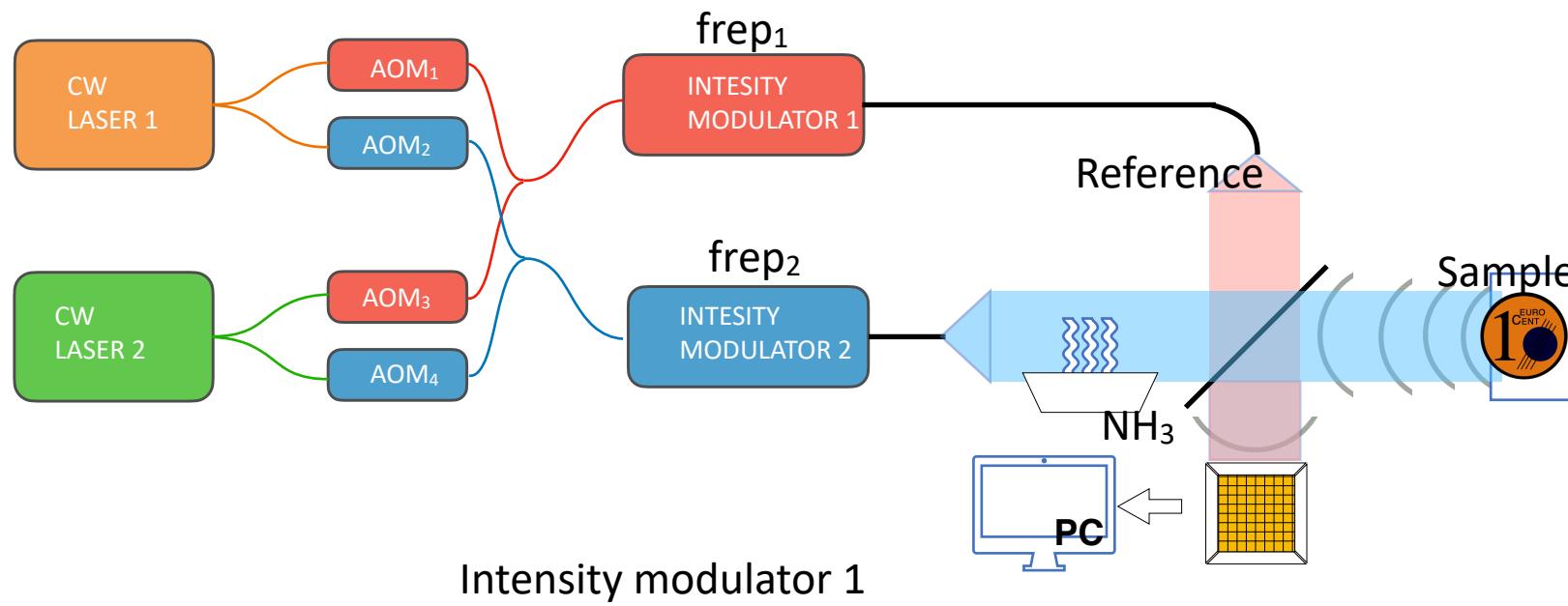


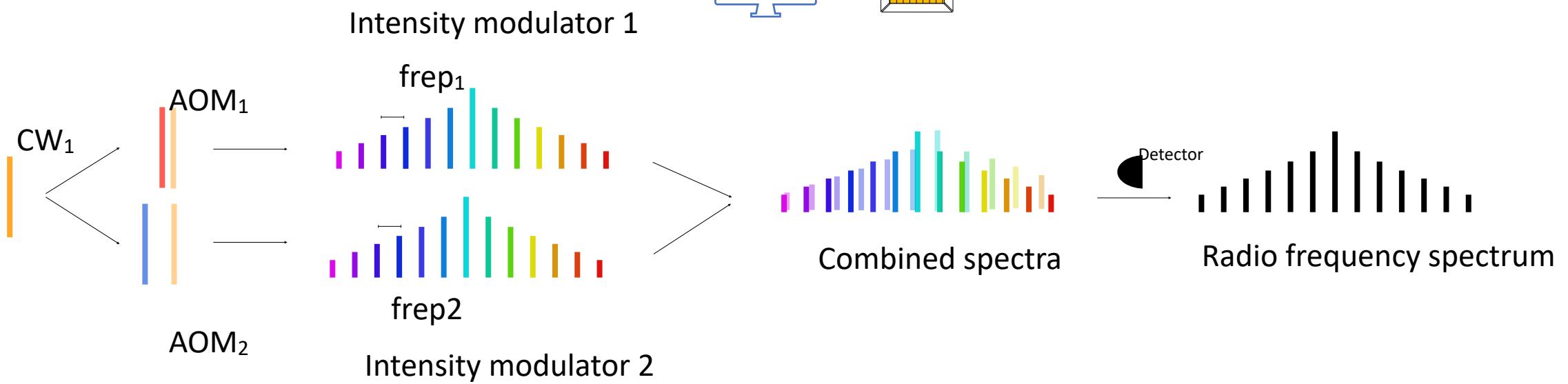
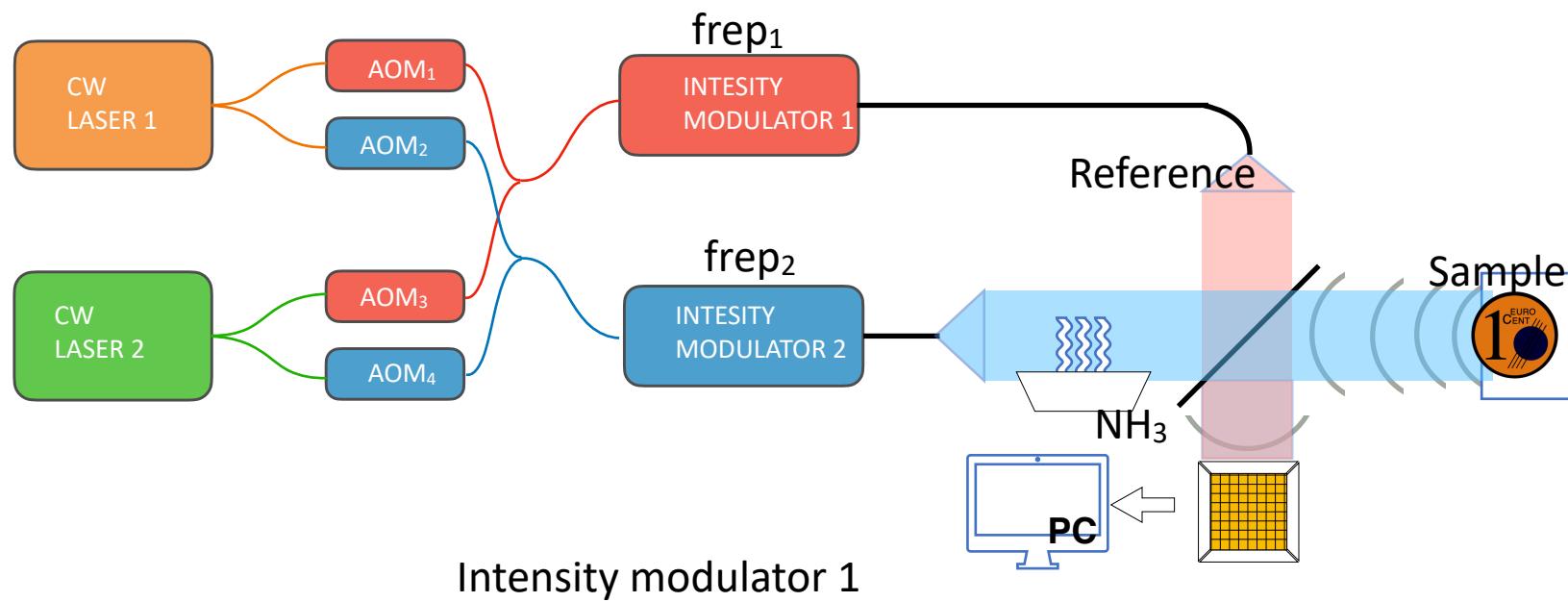


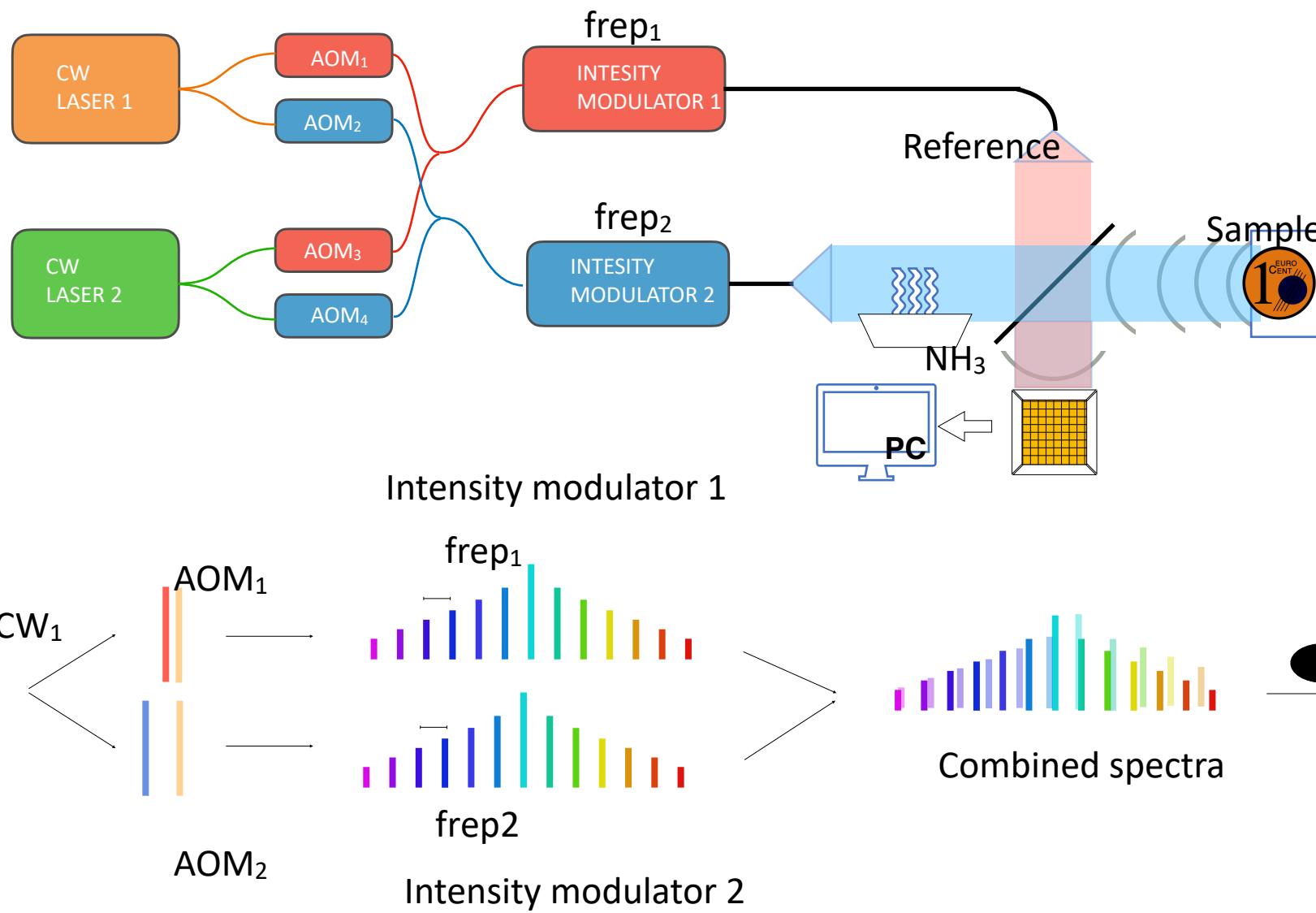






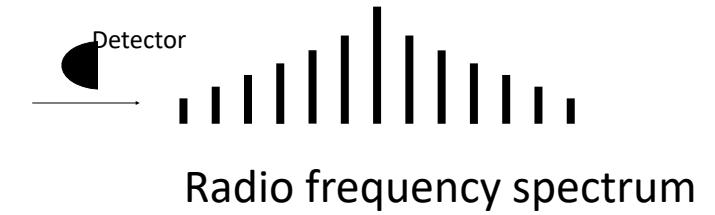


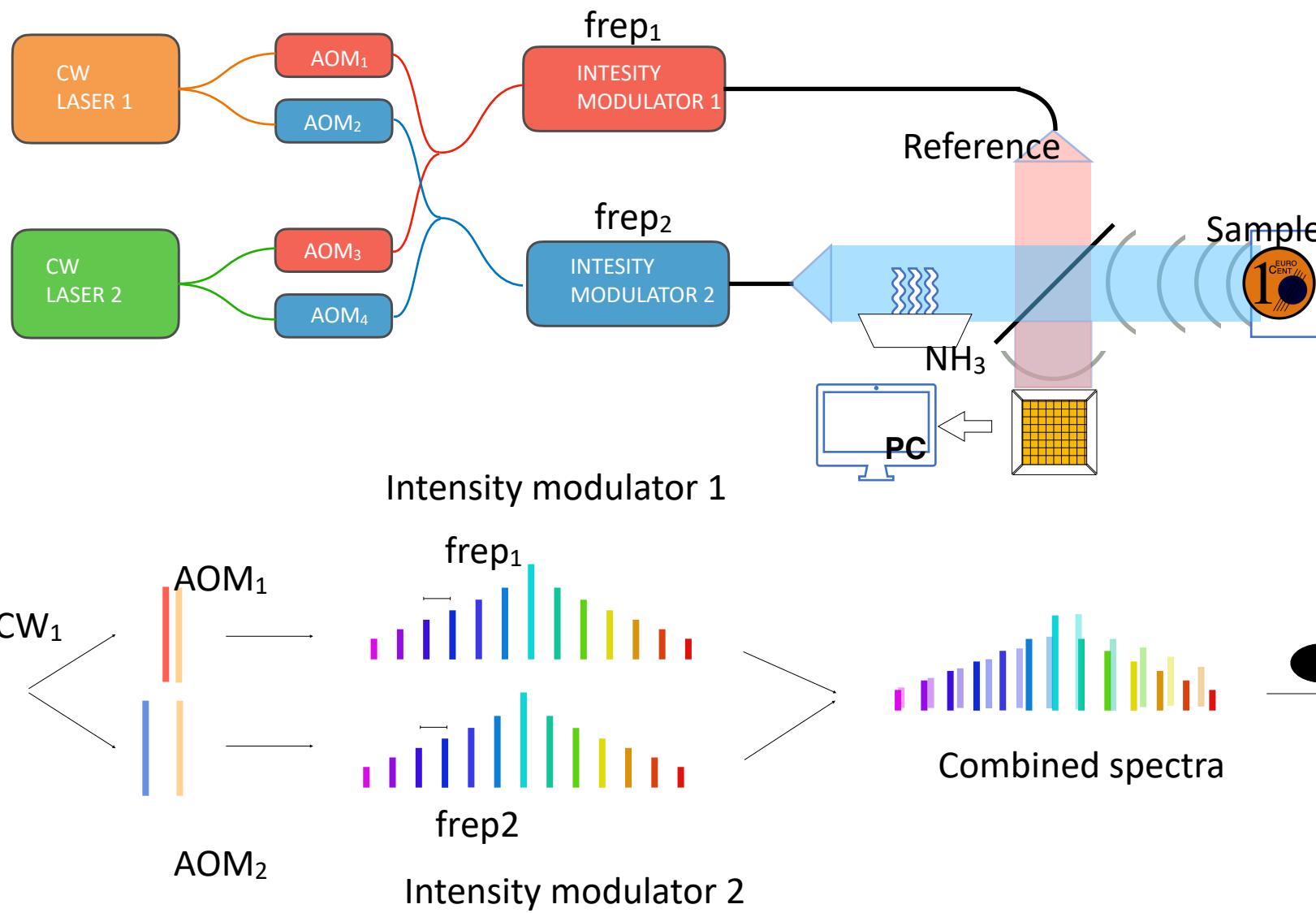




$CW_1 = 195.353 \text{ THz}$   
 $AOM_1 = 25 \text{ MHz}$   
 $AOM_2 = 25 \text{ MHz} + 40 \text{ Hz}$   
 $f_{\text{rep}1} = 500 \text{ MHz}$

$CW_2 = 195.736 \text{ THz}$   
 $AOM_3 = 40 \text{ MHz}$   
 $AOM_4 = 40 \text{ MHz} + 120 \text{ Hz}$   
 $f_{\text{rep}2} = 500 \text{ MHz} + 1 \text{ Hz}$



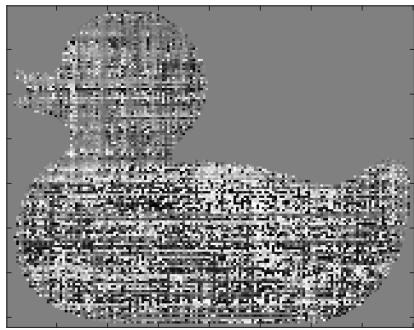


$CW_1 = 195.353 \text{ THz}$   
 $AOM_1 = 25 \text{ MHz}$   
 $AOM_2 = 25 \text{ MHz} + 40 \text{ Hz}$   
 $f_{\text{rep}1} = 500 \text{ MHz}$

$CW_2 = 195.736 \text{ THz}$   
 $AOM_3 = 40 \text{ MHz}$   
 $AOM_4 = 40 \text{ MHz} + 120 \text{ Hz}$   
 $f_{\text{rep}2} = 500 \text{ MHz} + 1 \text{ Hz}$

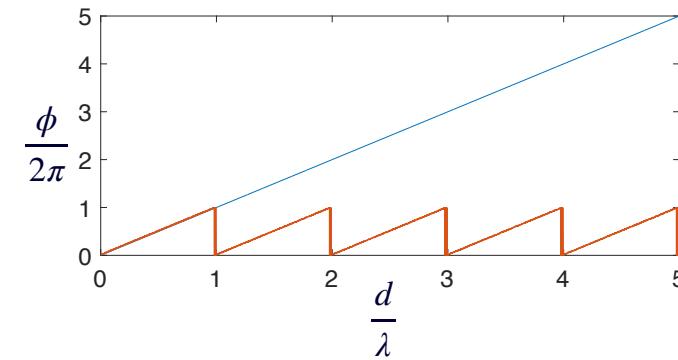




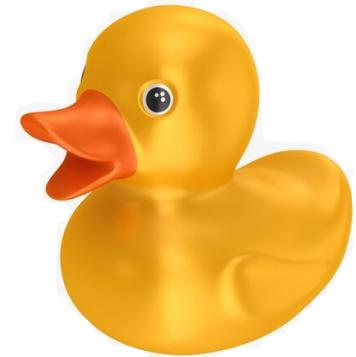


PHASE

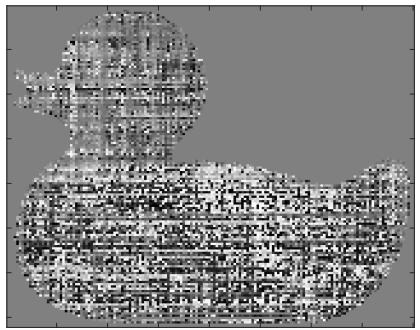
Phase  
unwrap



3D  
profile

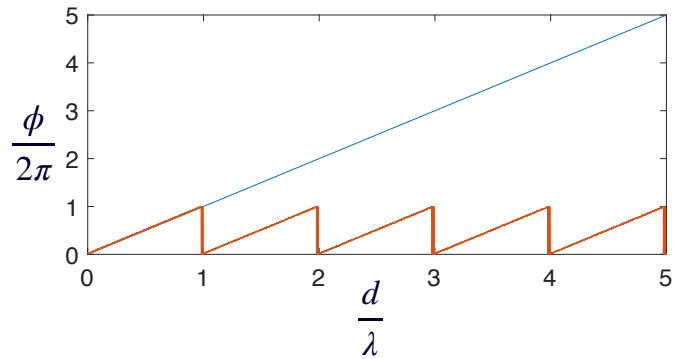


TARGET

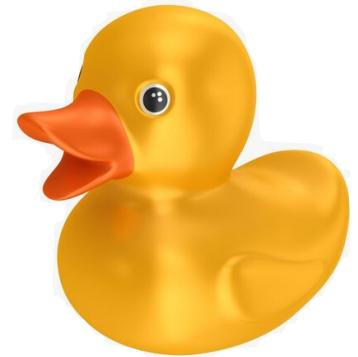


PHASE

Phase  
unwrap

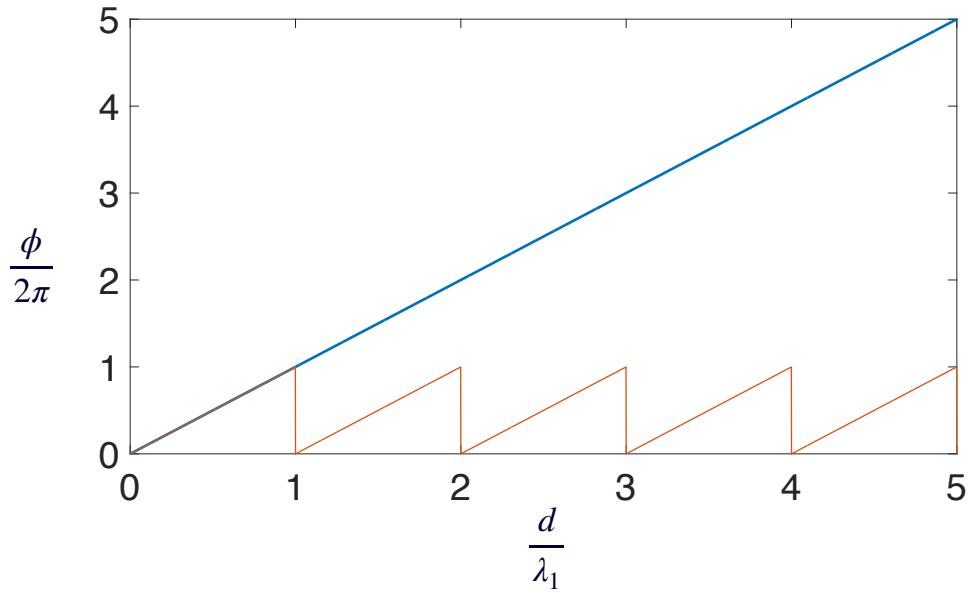


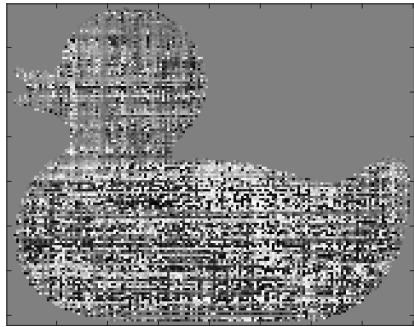
3D  
profile



$\lambda_1$

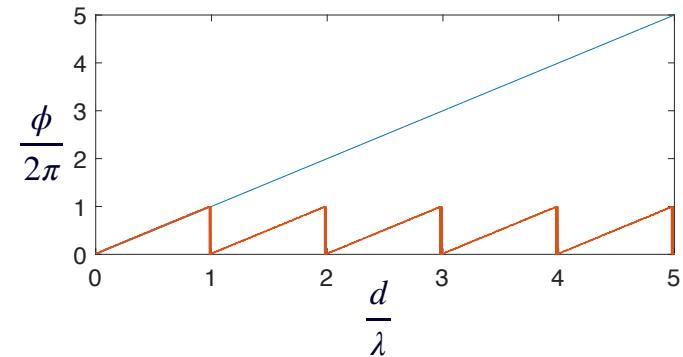
$$d_{MIN} \approx \frac{\lambda_1}{SNR} \quad d_{MAX} \approx \frac{\lambda_1}{2}$$



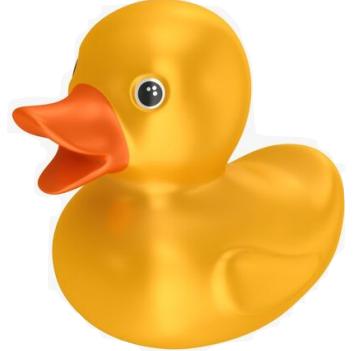


PHASE

Phase  
unwrap



3D  
profile

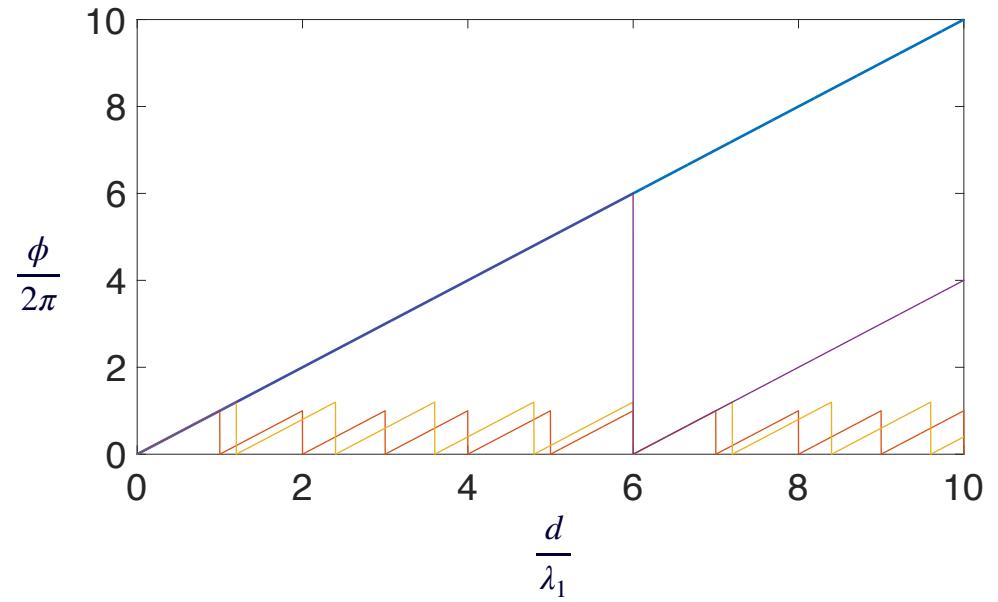


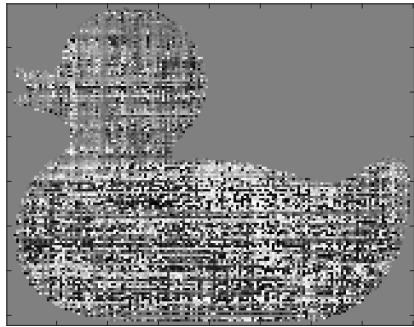
$$\lambda_1$$

$$d_{MIN} \approx \frac{\lambda_1}{SNR} \quad d_{MAX} \approx \frac{\lambda_1}{2}$$

$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$$

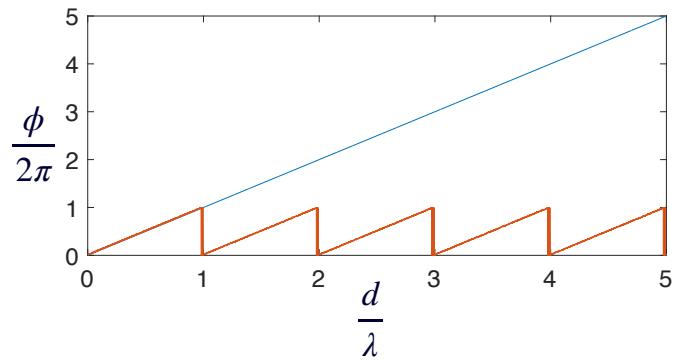
$$d_{MIN} \approx \frac{\lambda_c}{SNR} \quad d_{MAX} \approx \frac{\lambda_c}{2}$$



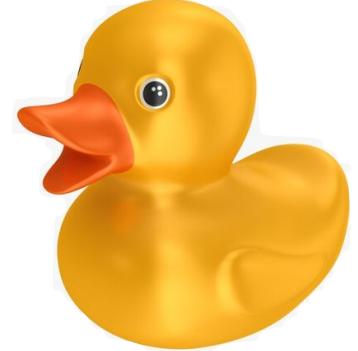


PHASE

Phase  
unwrap



3D  
profile



$$\lambda_1$$

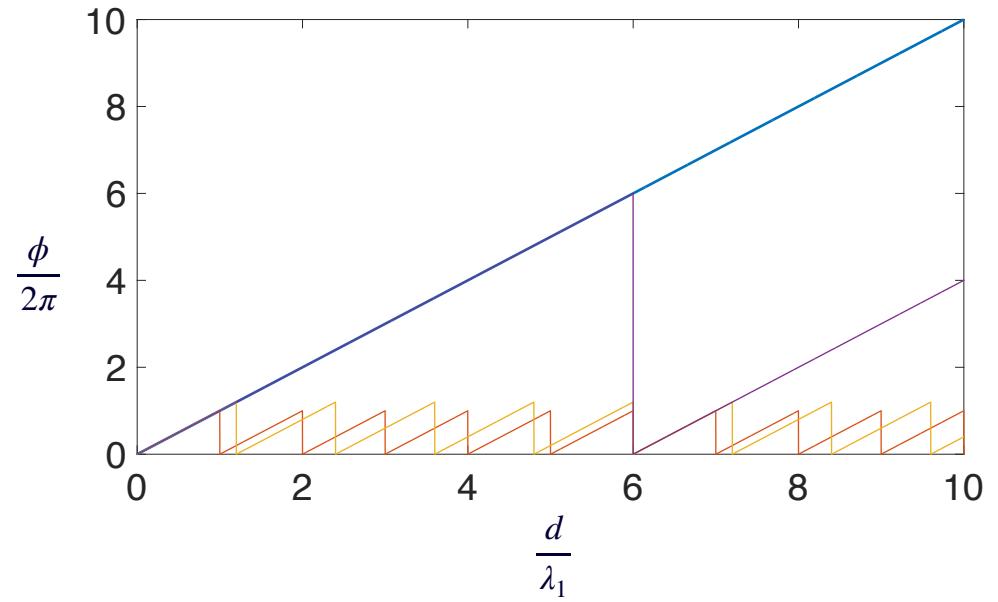
$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$$

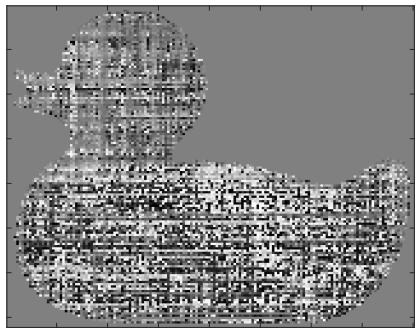
$$d_{MIN} \approx \frac{\lambda_1}{SNR}$$

$$d_{MIN} \approx \frac{\lambda_c}{SNR}$$

$$d_{MAX} \approx \frac{\lambda_1}{2}$$

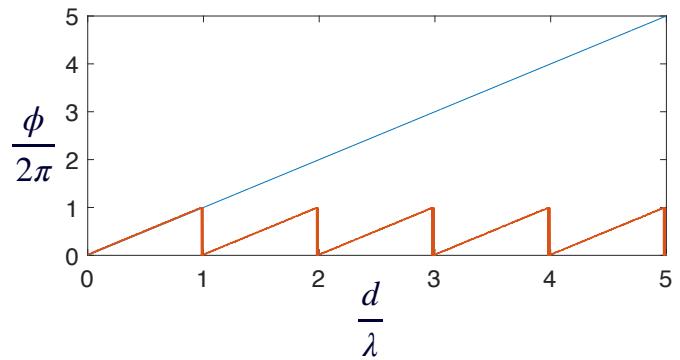
$$d_{MAX} \approx \frac{\lambda_c}{2}$$



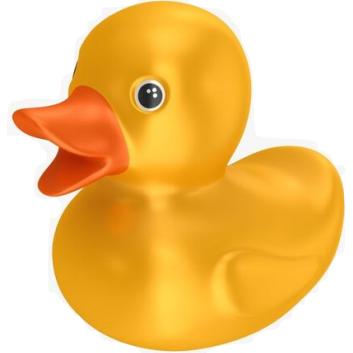


PHASE

Phase  
unwrap



3D  
profile



$$\lambda_1$$

$$d_{MIN} \approx \frac{\lambda_1}{SNR}$$

$$d_{MAX} \approx \frac{\lambda_1}{2}$$

$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$$

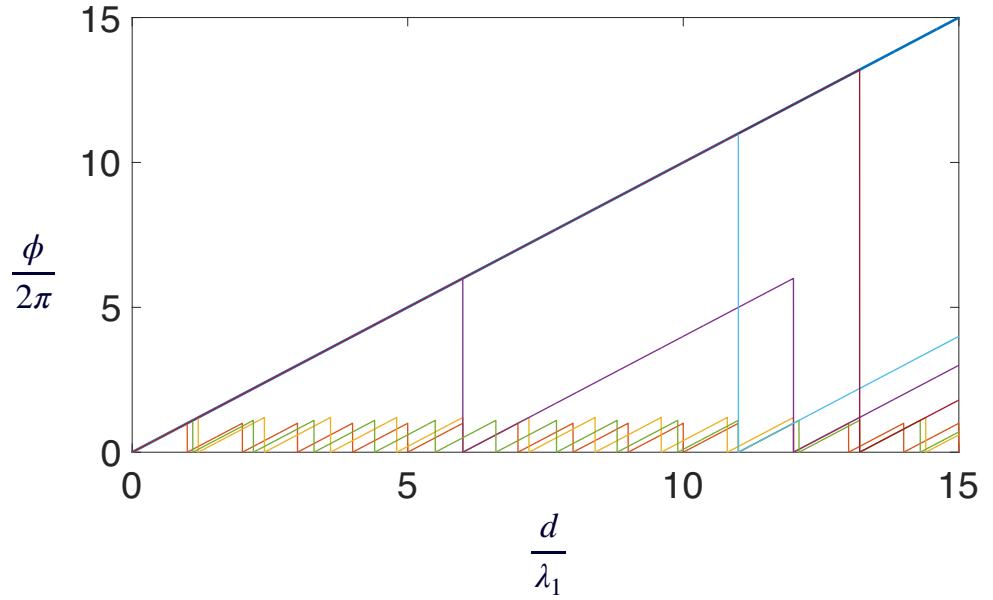
$$d_{MIN} \approx \frac{\lambda_c}{SNR}$$

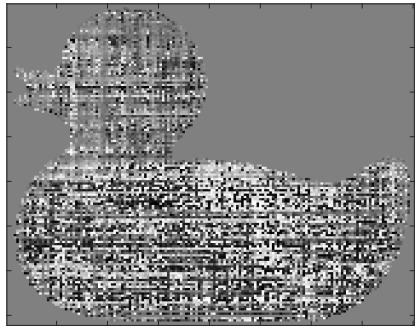
$$d_{MAX} \approx \frac{\lambda_c}{2}$$

$$\lambda_K = \frac{\lambda_{c_1} \lambda_{c_2}}{\lambda_{c_1} - \lambda_{c_2}}$$

$$d_{MIN} \approx \frac{\lambda_K}{SNR}$$

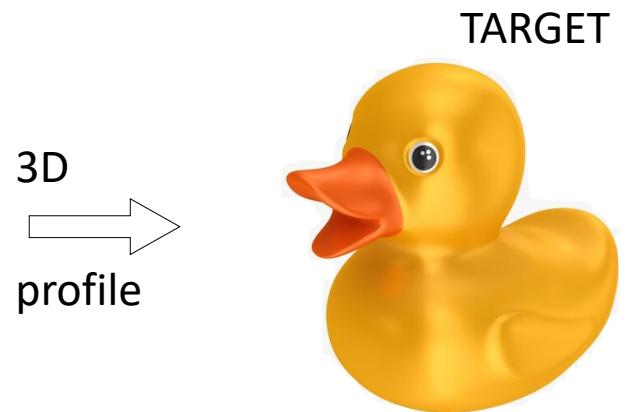
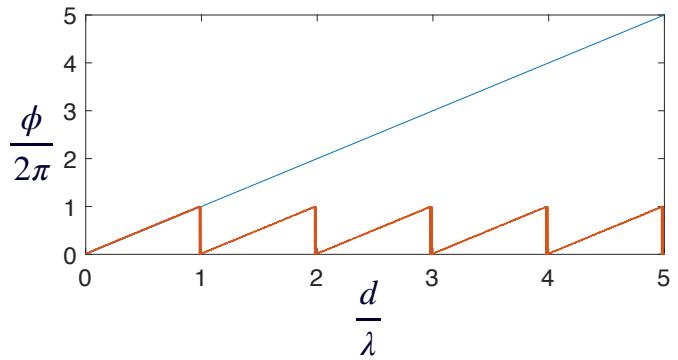
$$d_{MAX} \approx \frac{\lambda_K}{2}$$





PHASE

Phase  
unwrap



3D  
profile

$$\lambda_1$$

$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$$

$$\lambda_K = \frac{\lambda_{c_1} \lambda_{c_2}}{\lambda_{c_1} - \lambda_{c_2}}$$

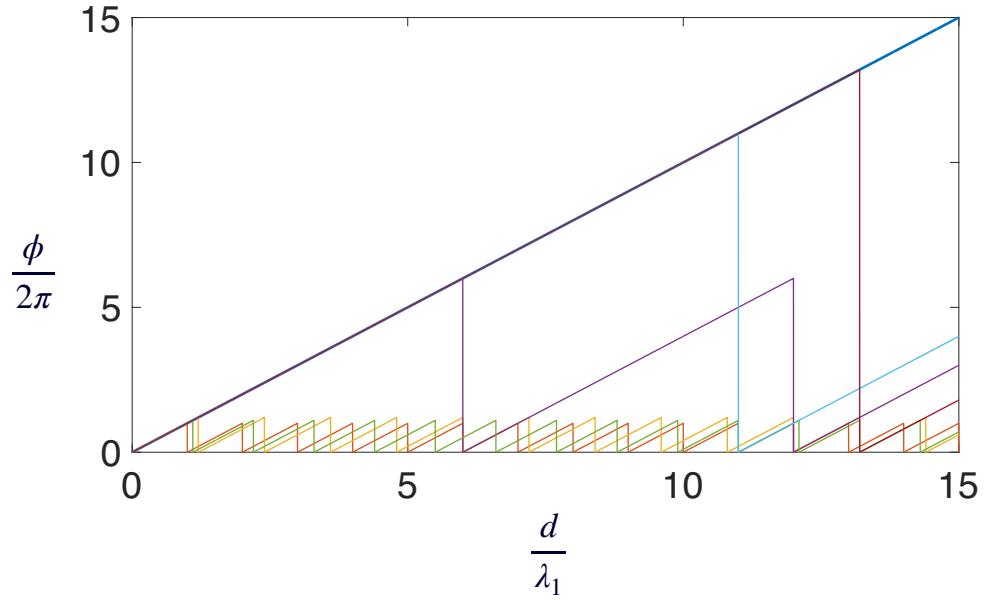
$$d_{MIN} \approx \frac{\lambda_1}{SNR}$$

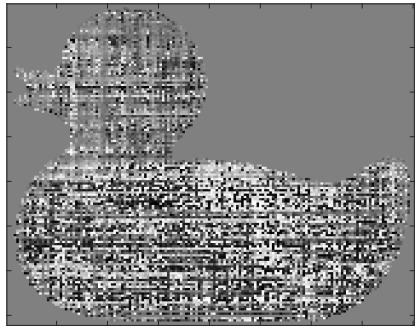
$$d_{MIN} \approx \frac{\lambda_c}{SNR}$$

$$d_{MAX} \approx \frac{\lambda_1}{2}$$

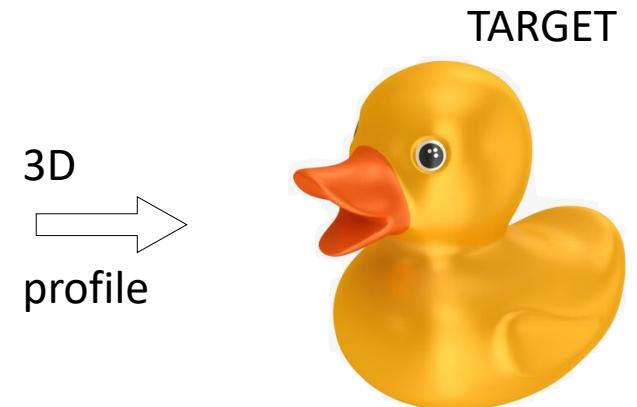
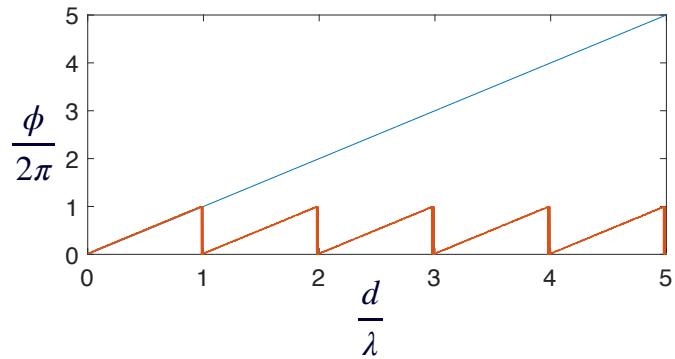
$$d_{MAX} \approx \frac{\lambda_c}{2}$$

$$d_{MAX} \approx \frac{\lambda_K}{2}$$





PHASE  
Phase  
unwrap



$$\lambda_1$$

$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$$

$$\lambda_K = \frac{\lambda_{c_1} \lambda_{c_2}}{\lambda_{c_1} - \lambda_{c_2}}$$

$$d_{MIN} \approx \frac{\lambda_1}{SNR}$$

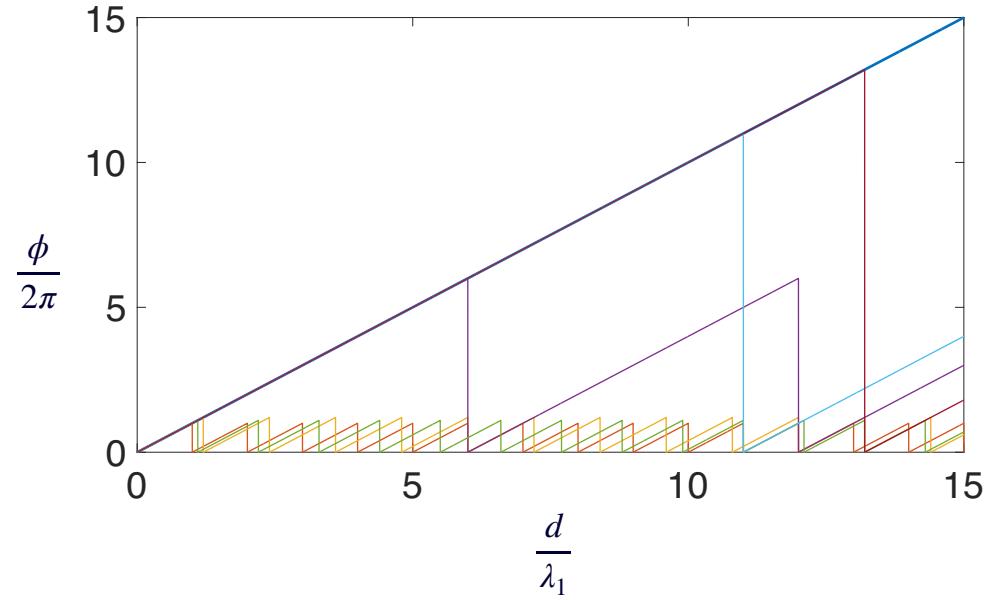
$$d_{MAX} \approx \frac{\lambda_1}{2}$$

$$d_{MIN} \approx \frac{\lambda_c}{SNR}$$

$$d_{MAX} \approx \frac{\lambda_c}{2}$$

$$d_{MIN} \approx \frac{\lambda_K}{SNR}$$

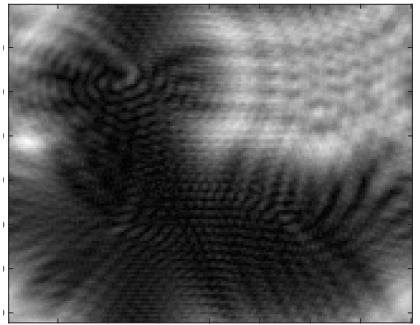
$$d_{MAX} \approx \frac{\lambda_K}{2}$$



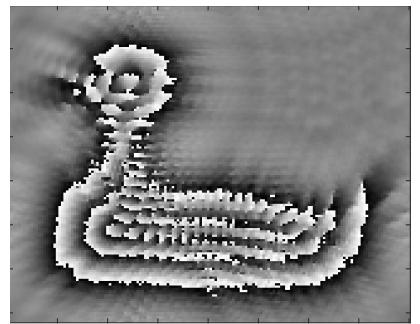


Digital hologram

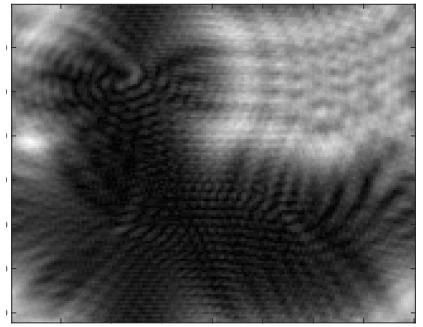
AMPLITUDE



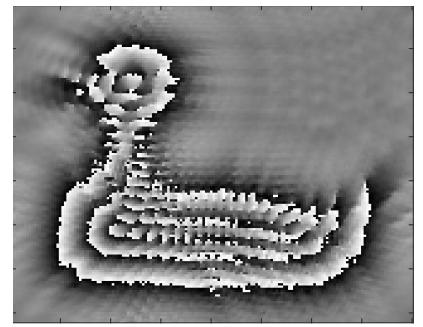
PHASE



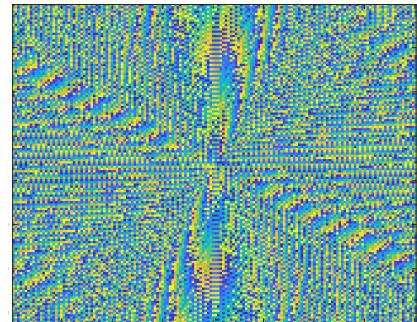
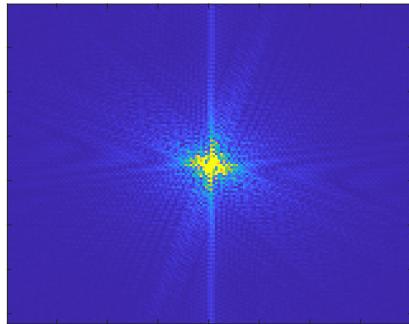
AMPLITUDE



2D  
Fourier  
transform

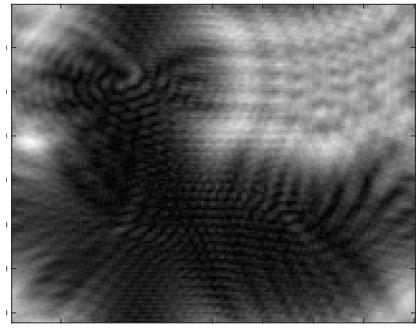


Fourier hologram

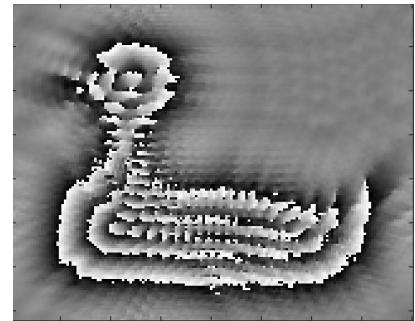


AMPLITUDE

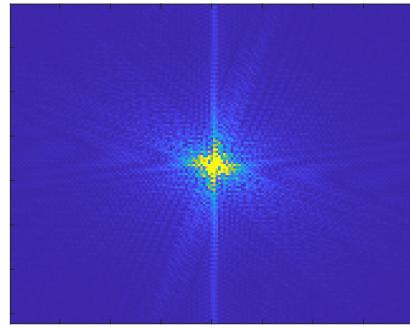
Digital hologram



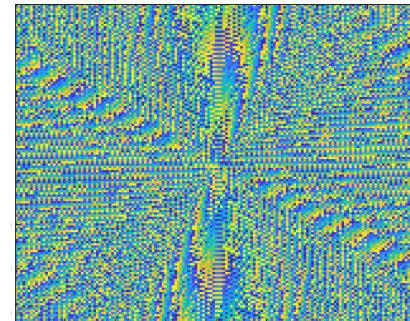
2D  
Fourier  
transform  
 $m$



Fourier hologram



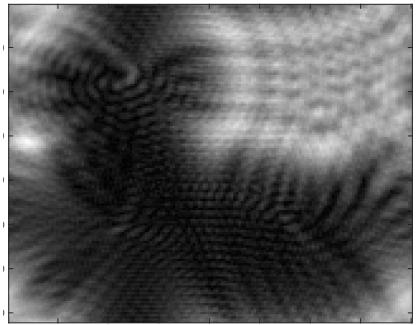
Data  
Processing



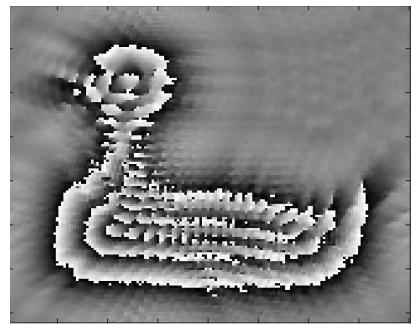
2D  
inverse  
Fourier  
transform  
 $m$

AMPLITUDE

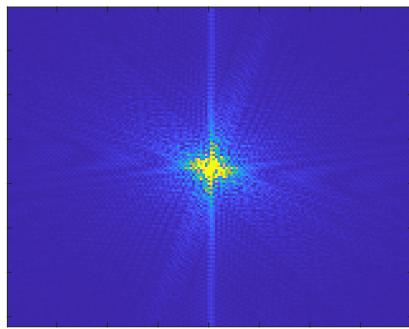
Digital hologram



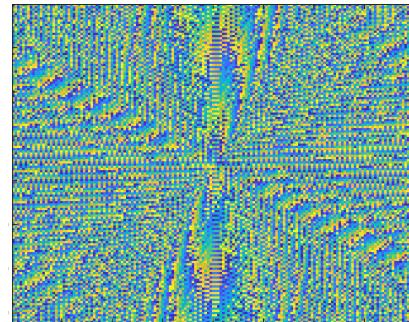
2D  
Fourier  
transform  
 $m$



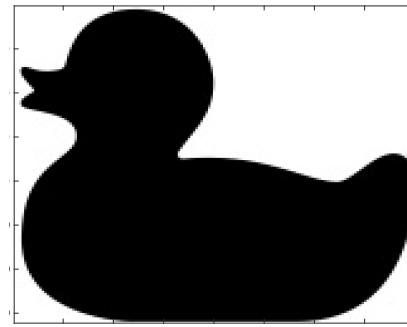
Fourier hologram



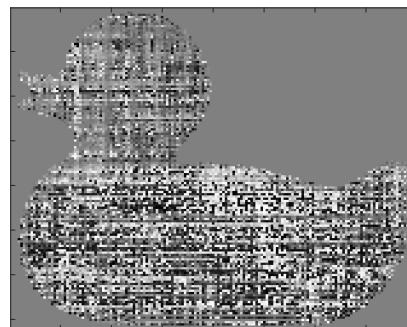
Data  
Processing



Reconstructed image



AMPLITUDE

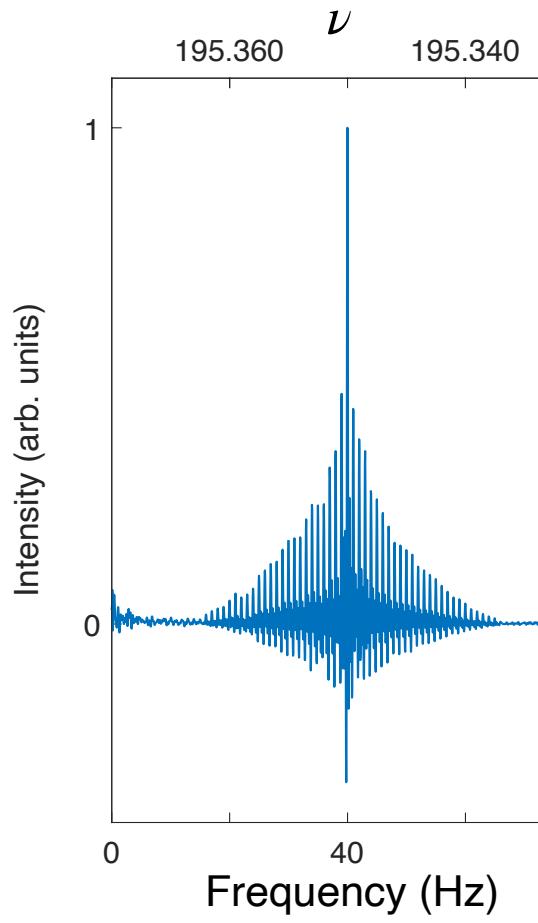
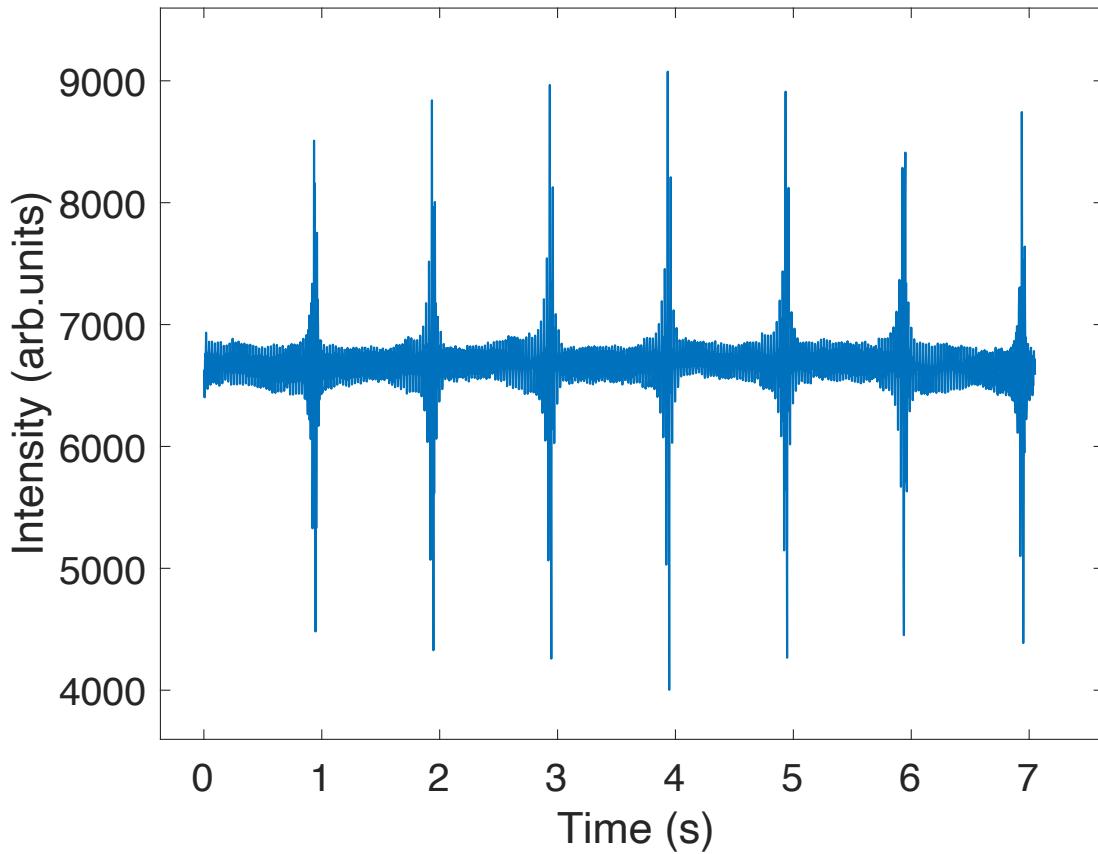


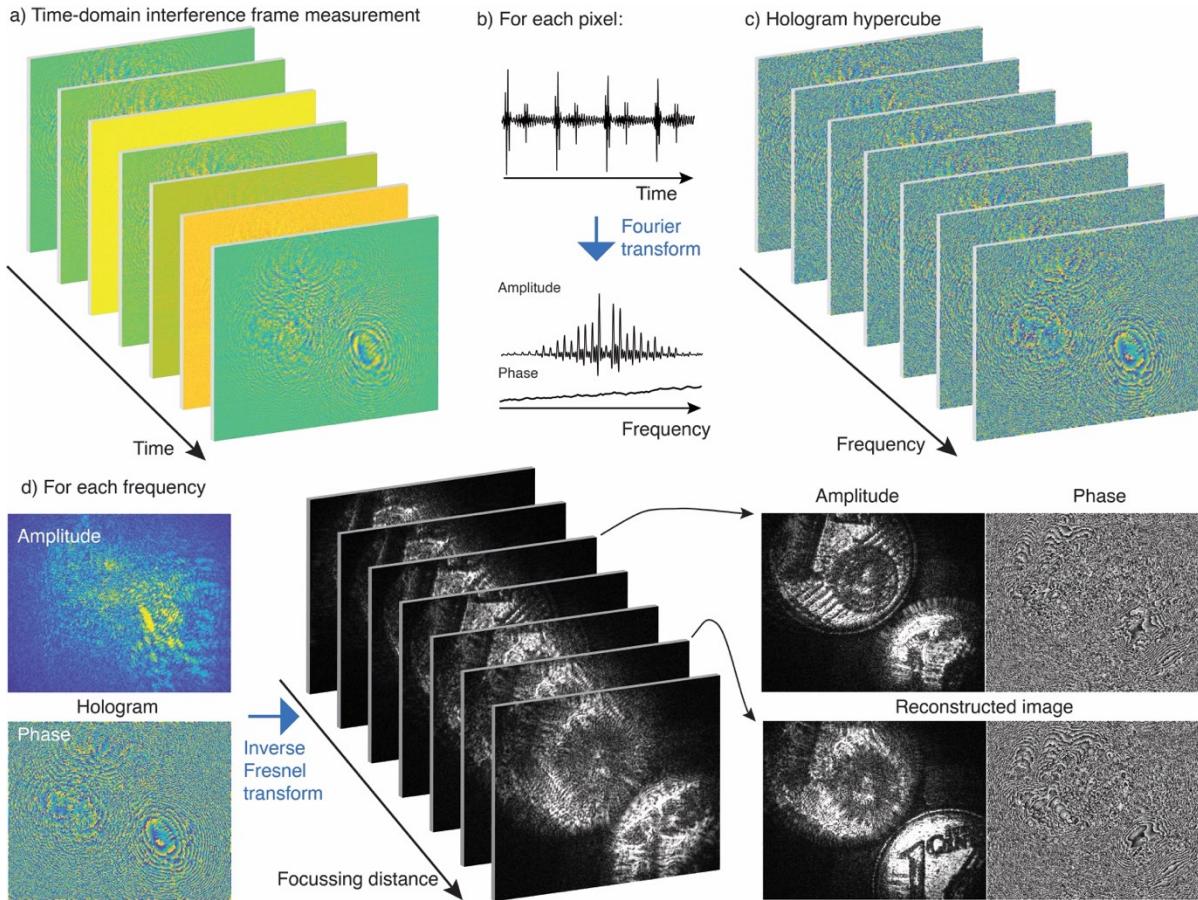
PHASE

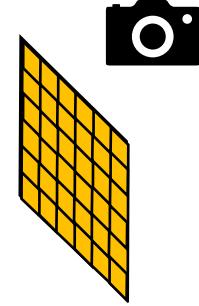
# Dual-comb digital holography

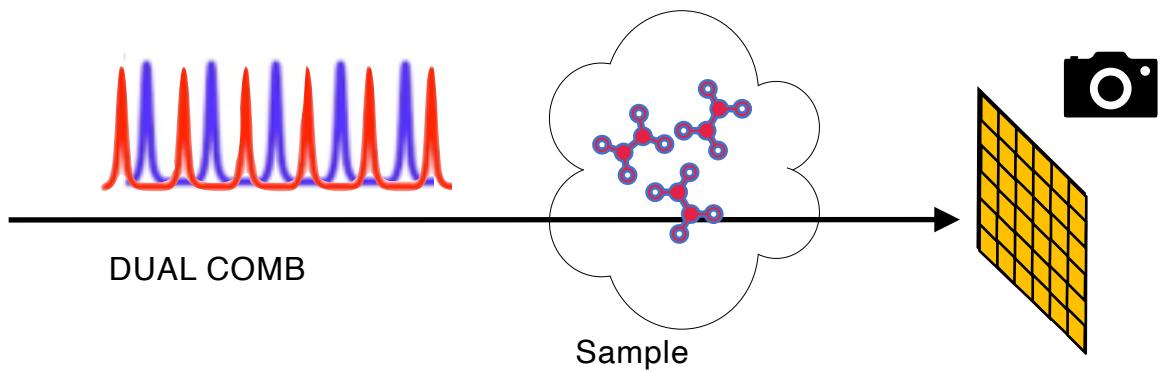
# Dual-comb digital holography

Single pixel

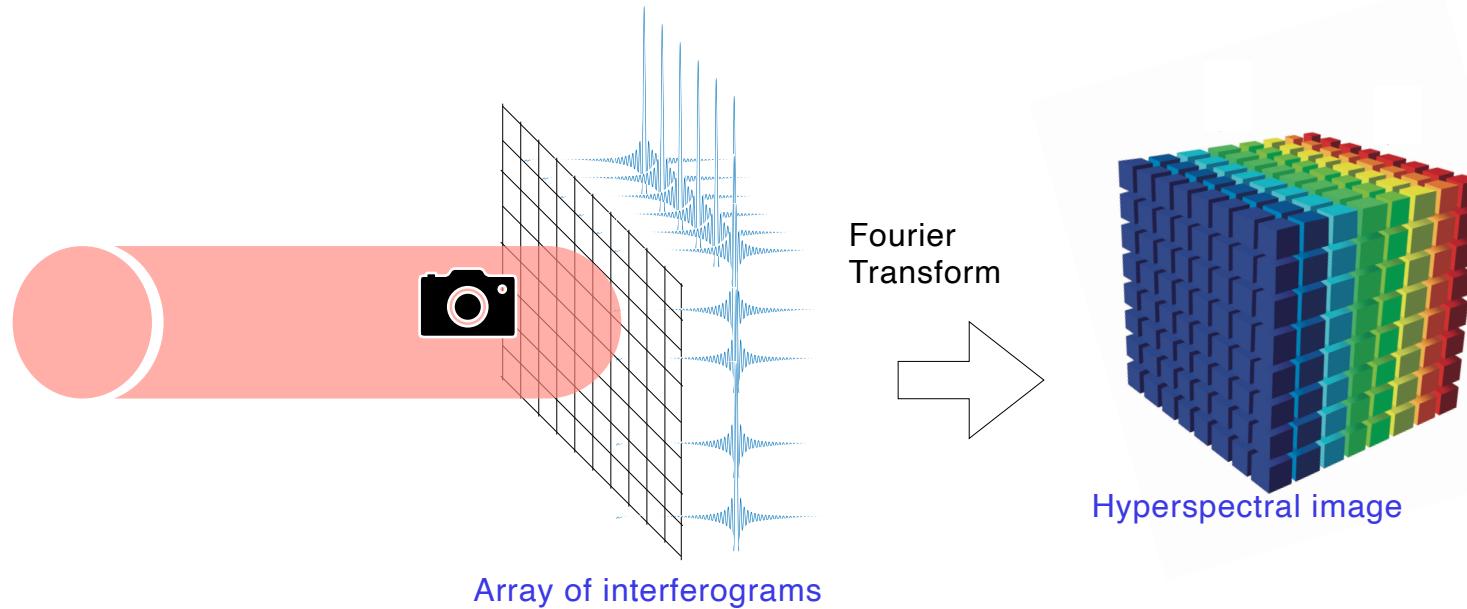
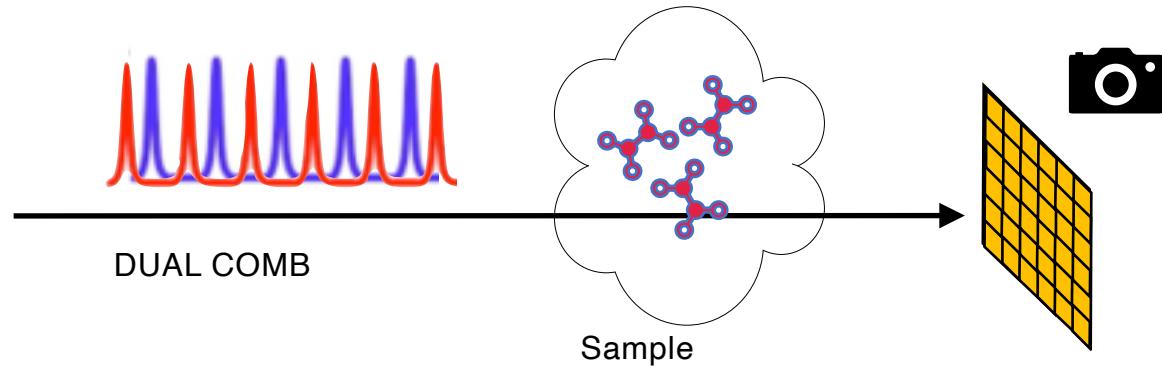


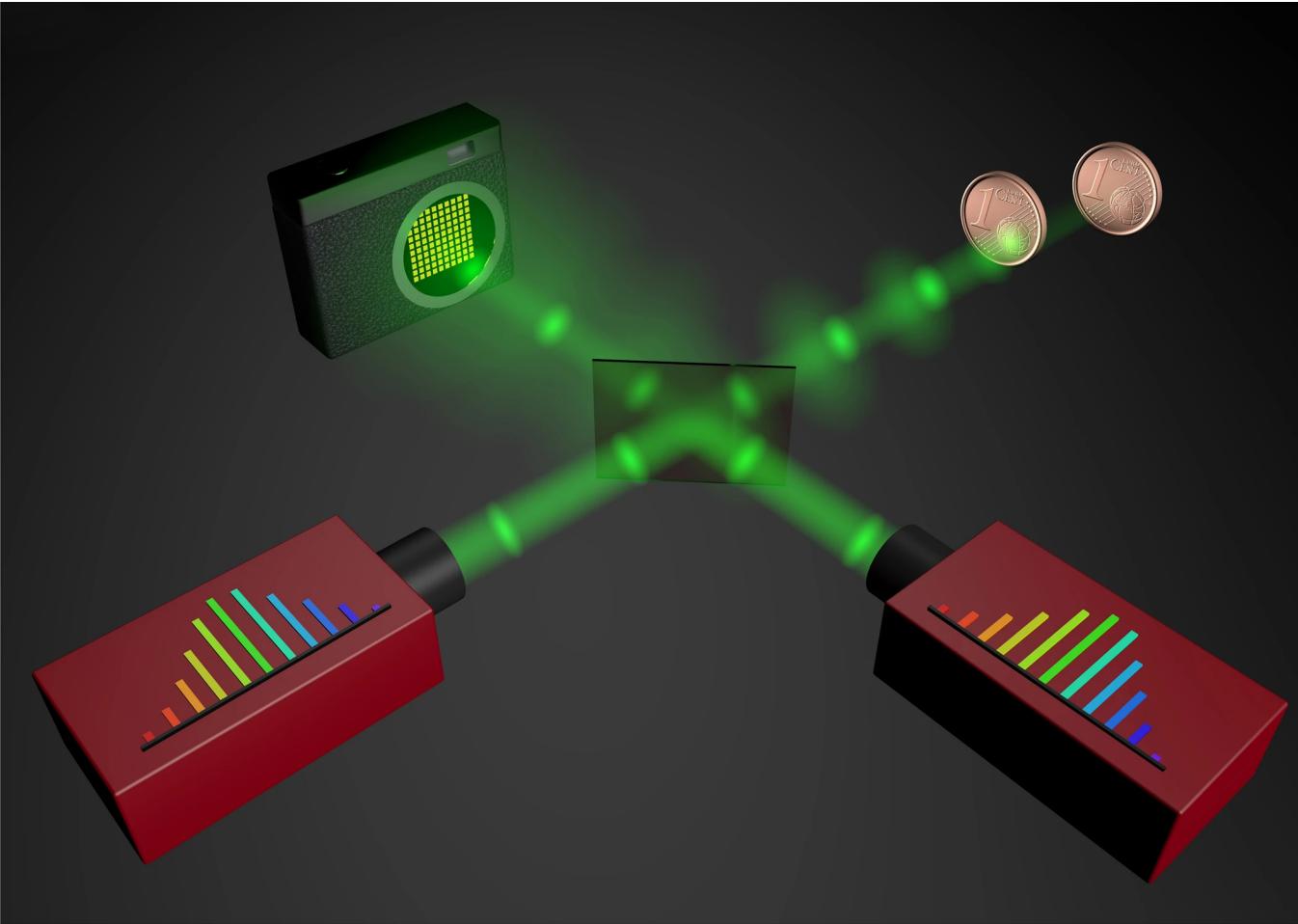




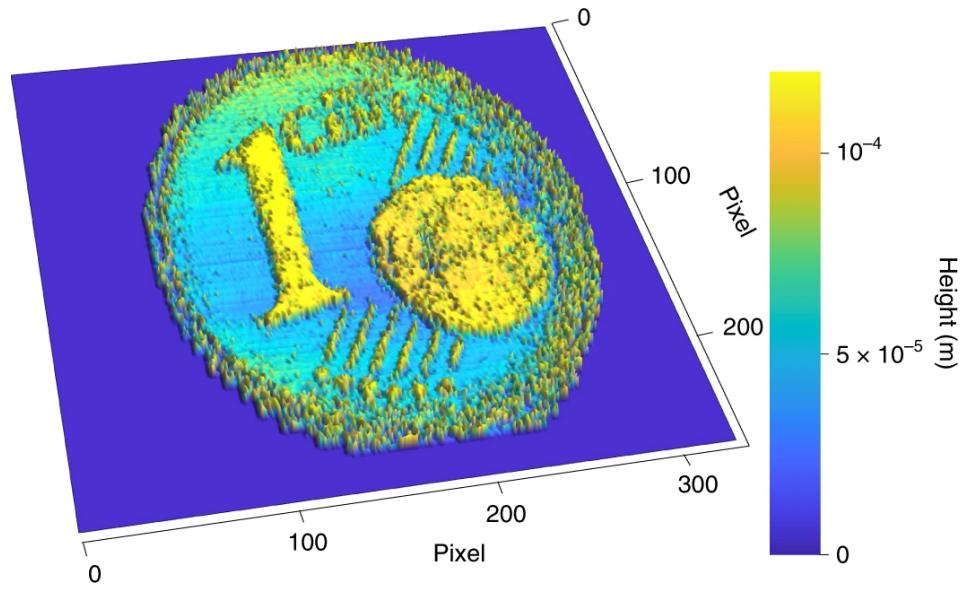


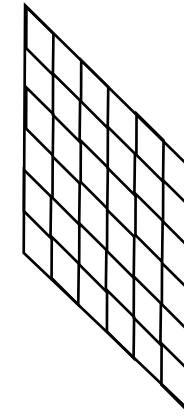
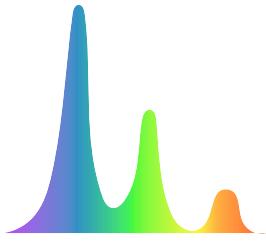
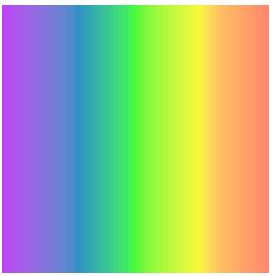
# Dual-comb hyperspectral imaging



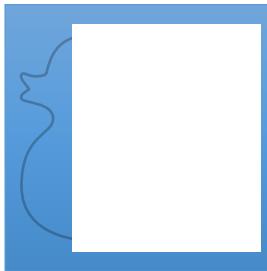
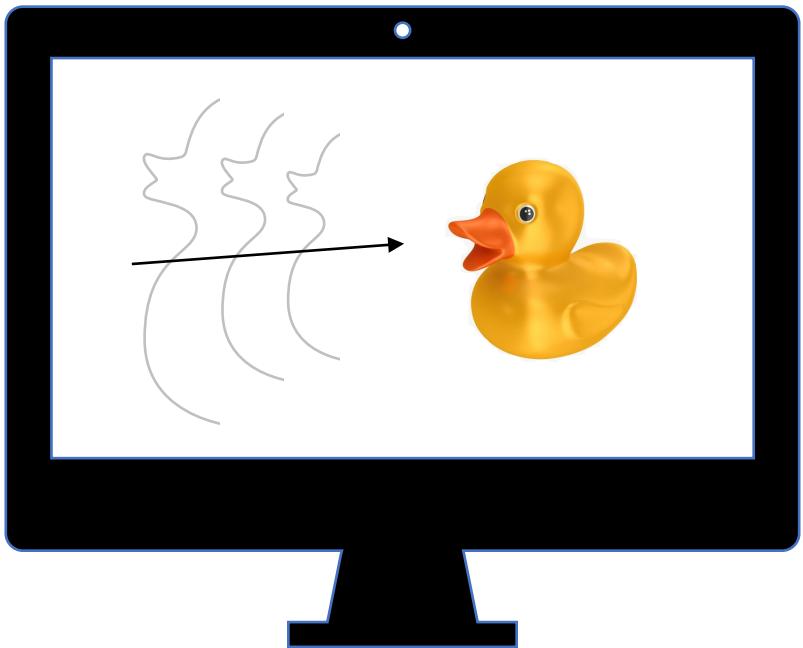


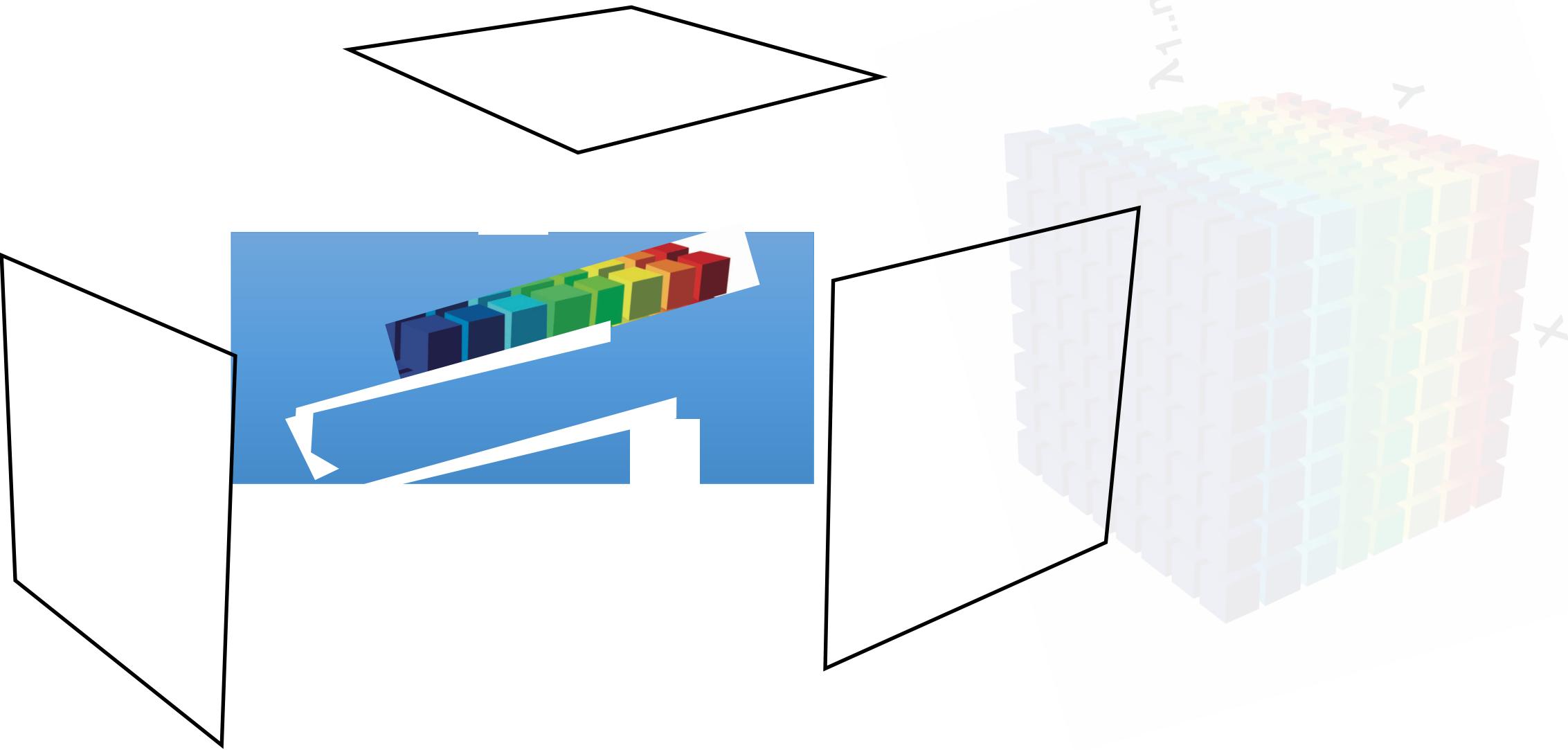
Dual-comb hyperspectral imaging and holography



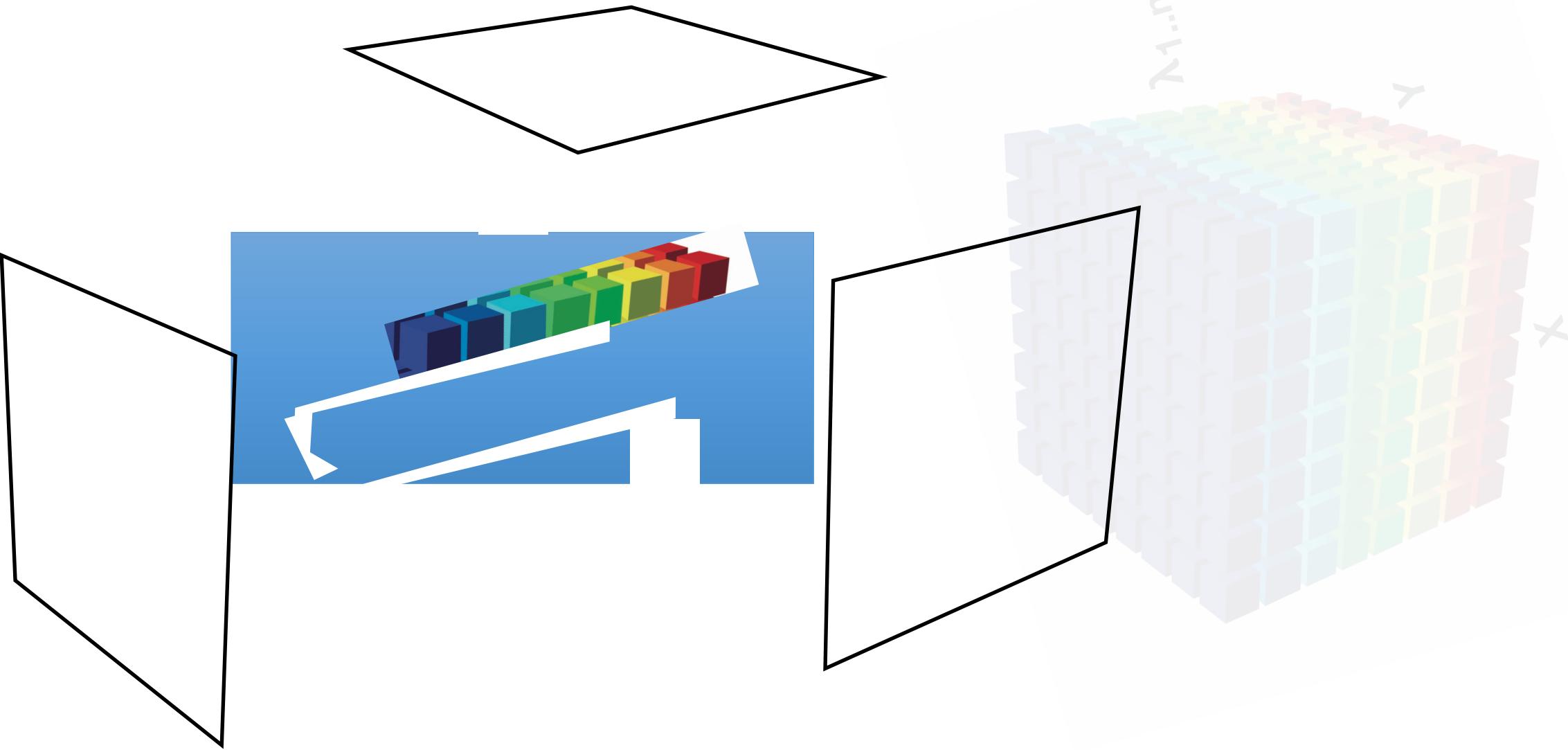




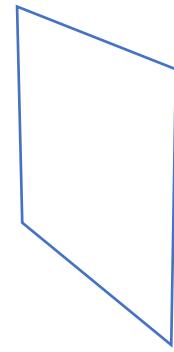
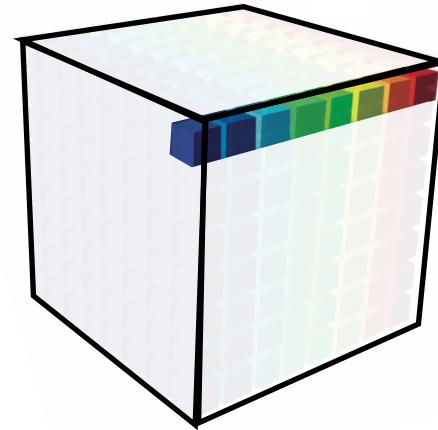




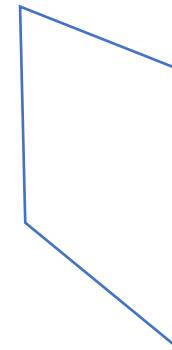
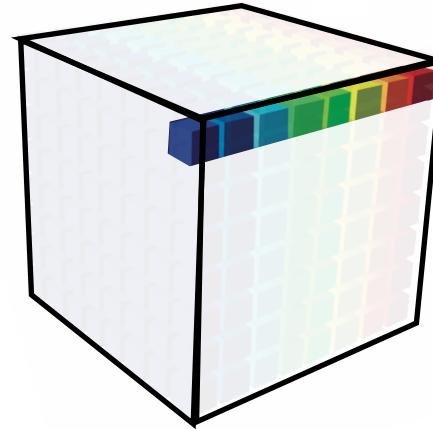
Dual-comb hyperspectral imaging and holography



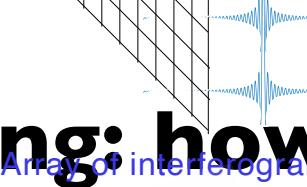
Dual-comb hyperspectral imaging and holography



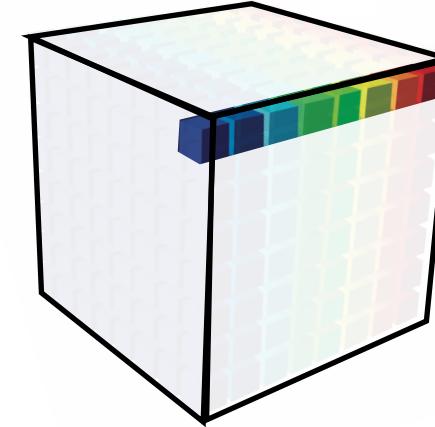
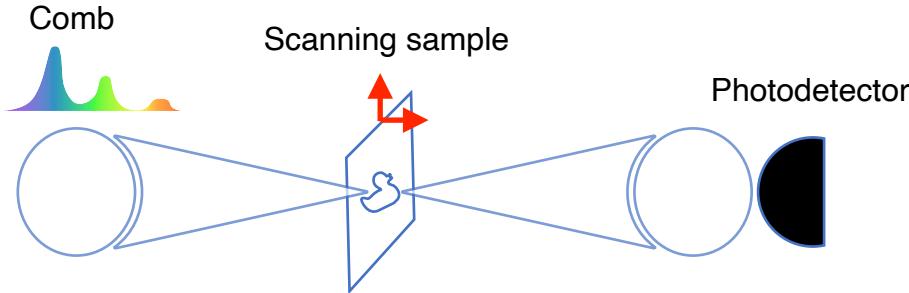
# Dual-comb hyperspectral imaging: how?



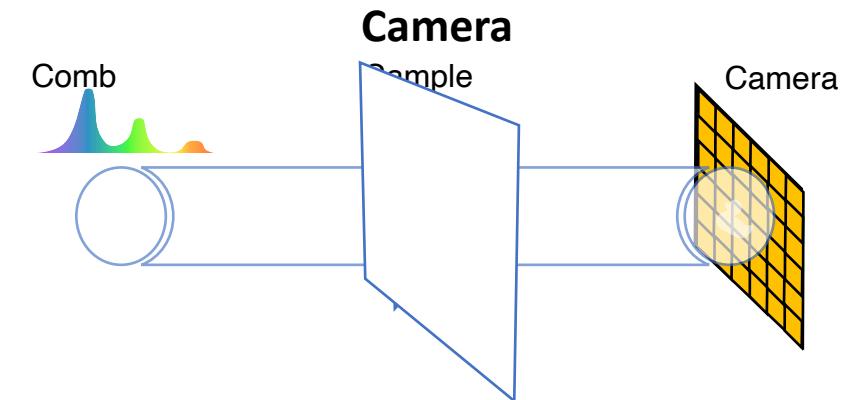
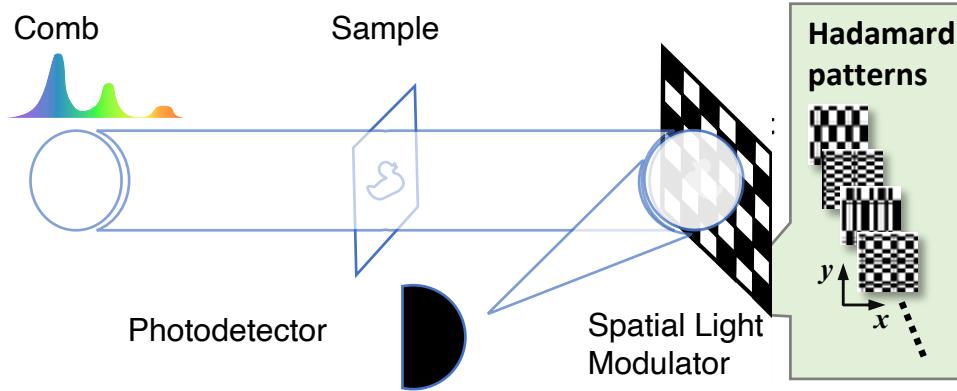
# Dual-comb hyperspectral imaging: how?



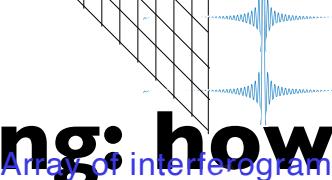
Scanning sample



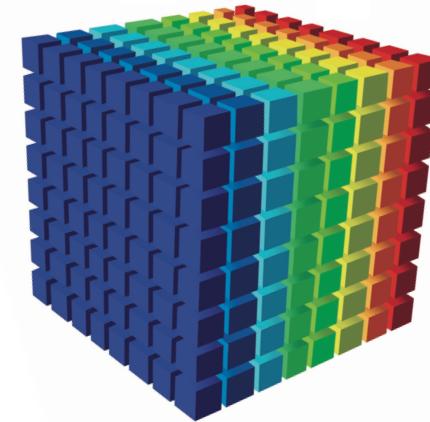
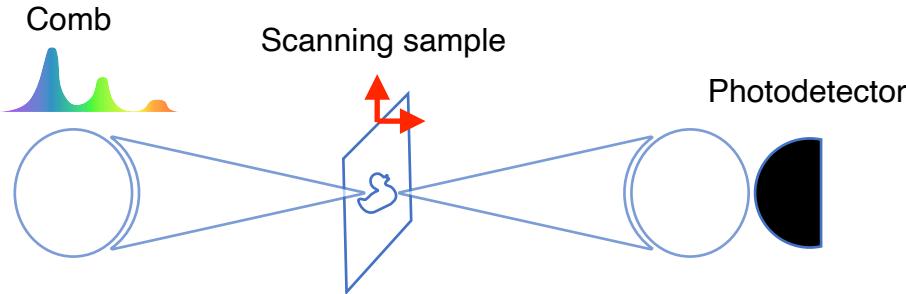
Hadamard decomposition



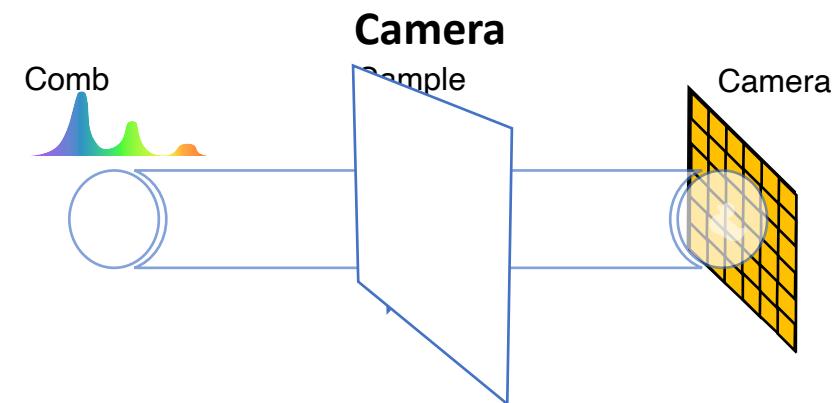
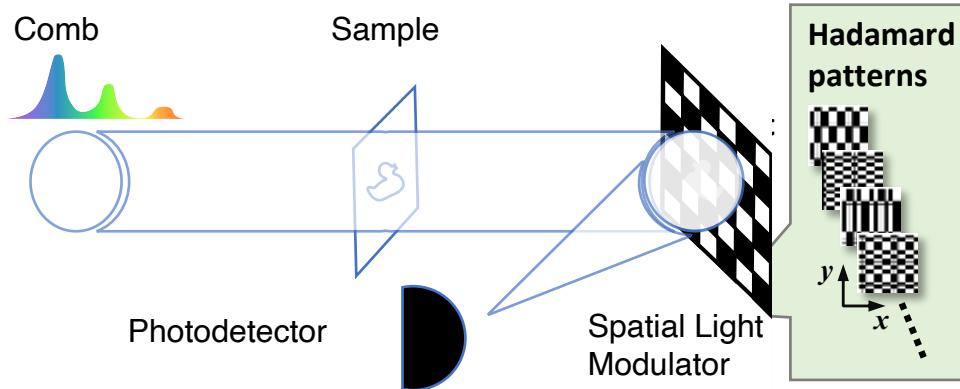
# Dual-comb hyperspectral imaging: how?



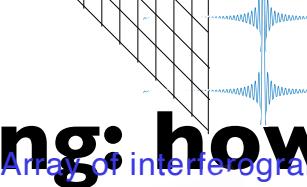
Scanning sample



Hadamard decomposition

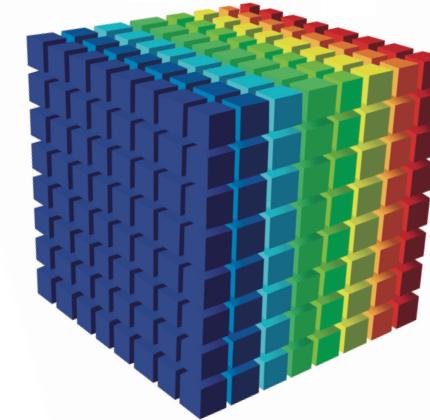
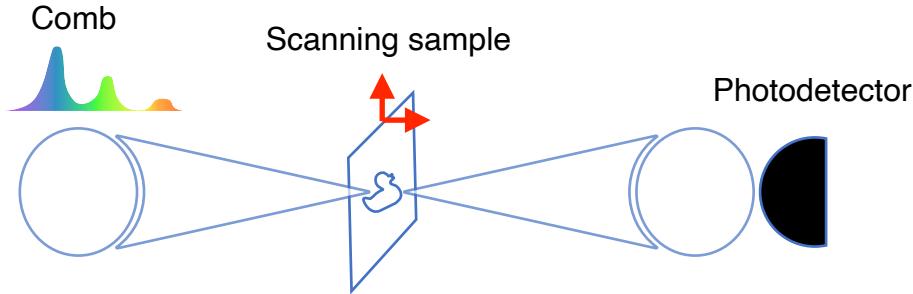


# Dual-comb hyperspectral imaging: how?

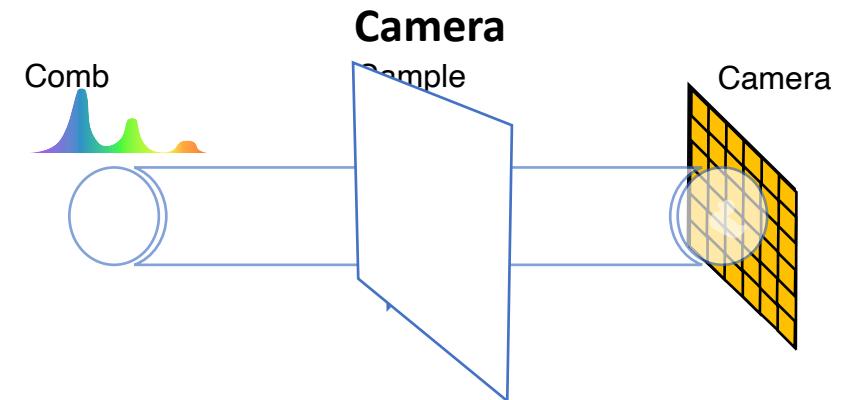


Array of interferograms

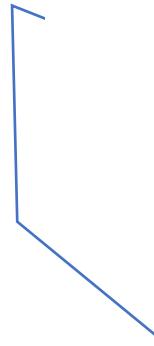
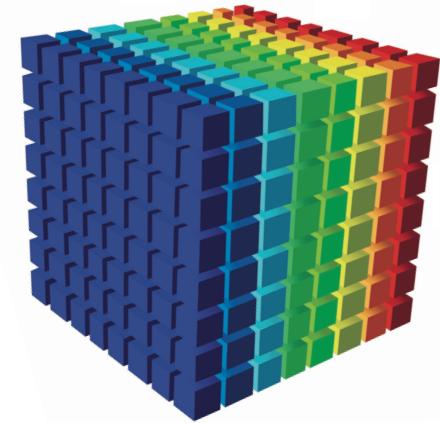
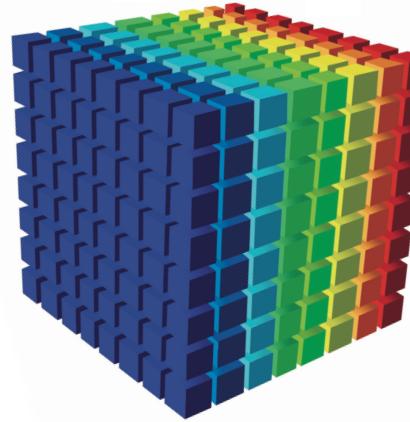
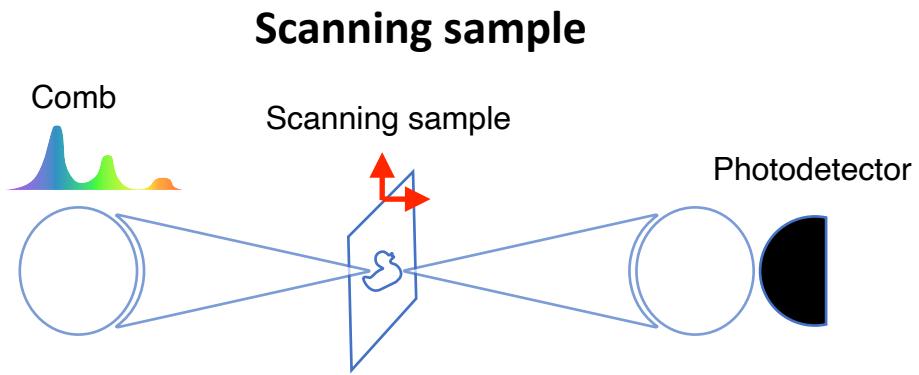
Scanning sample



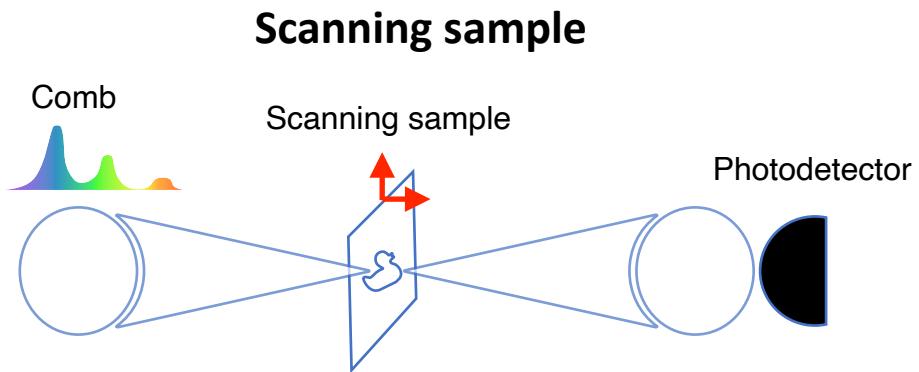
Camera



# Dual-comb hyperspectral imaging: how?



# Dual-comb hyperspectral imaging: how?



Pattern-dependent  
interferograms  
(phase compensated)

