

# Computational interferometric imaging

Alankar Kotwal

Florian Willomitzer

Ioannis Gkioulekas

SIGGRAPH 2023

[imaging.cs.cmu.edu/interferometry\\_siggraph2023](https://imaging.cs.cmu.edu/interferometry_siggraph2023)



# Today's presenters



Alankar Kotwal

University of Texas Medical Branch  
[alankarkotwal13@gmail.com](mailto:alankarkotwal13@gmail.com)  
[alankarkotwal.github.io](http://alankarkotwal.github.io)



Florian Willomitzer

University of Arizona  
[fwillomitzer@arizona.edu](mailto:fwillomitzer@arizona.edu)  
[www.optics.arizona.edu/3dim](http://www.optics.arizona.edu/3dim)

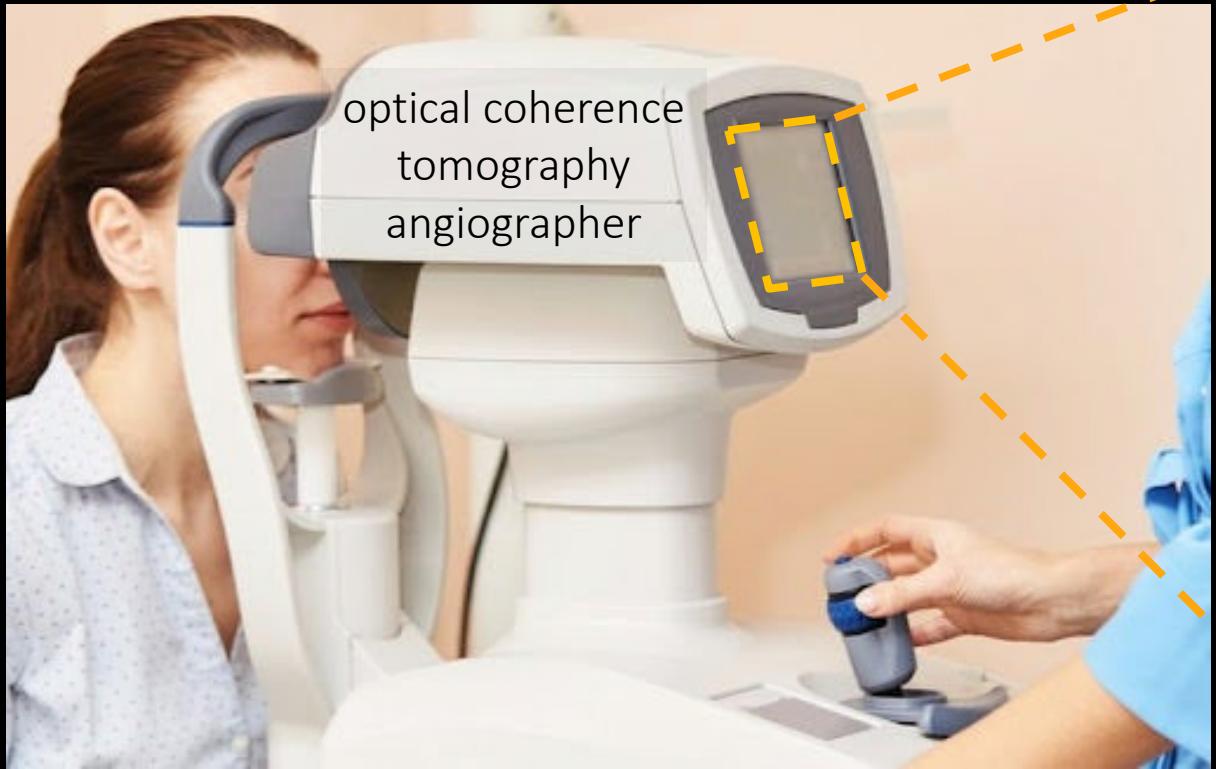


Ioannis Gkioulekas

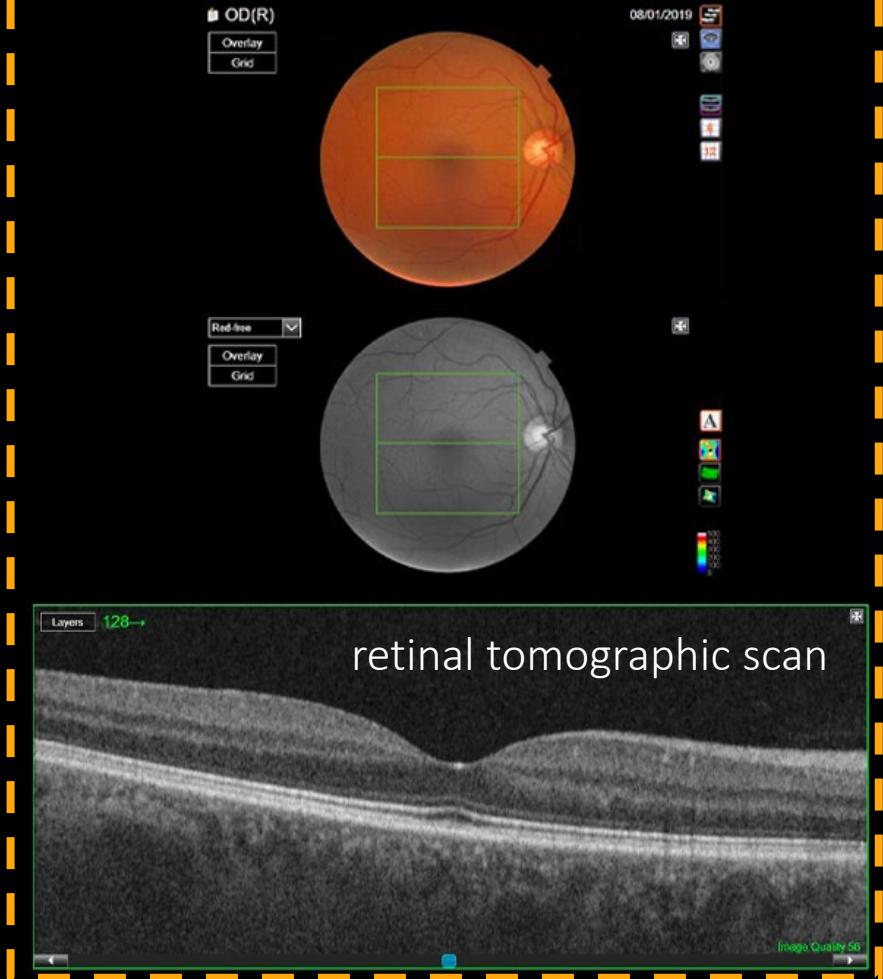
Carnegie Mellon University  
[igkioule@andrew.cmu.edu](mailto:igkioule@andrew.cmu.edu)  
[imaging.cs.cmu.edu](http://imaging.cs.cmu.edu)

# What is interferometry?

# OCT eye exam



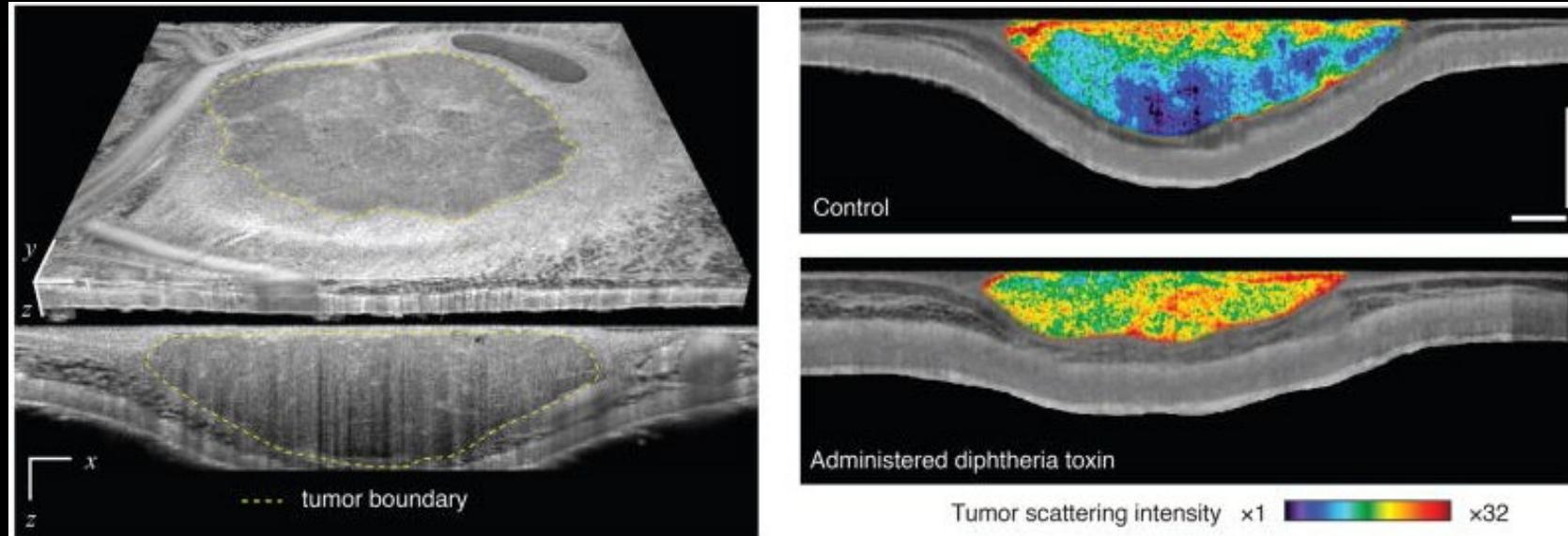
optical coherence  
tomography  
angiographer



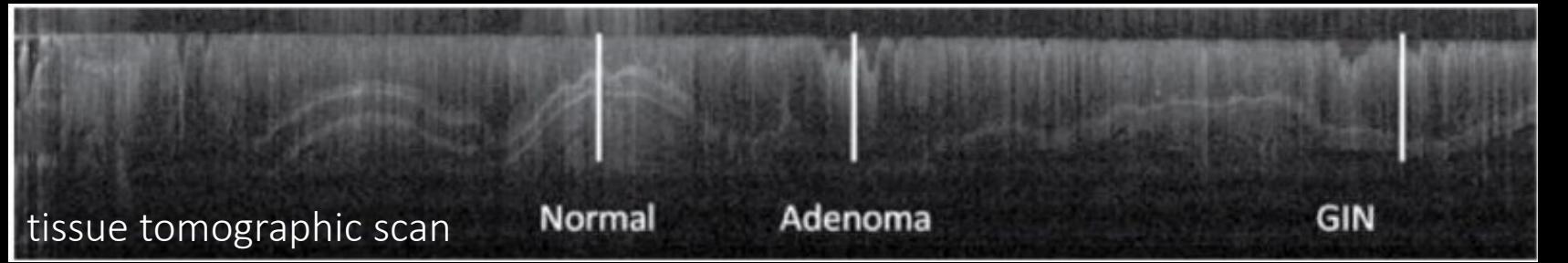
Retinal scanning and angiography to diagnose glaucoma, diabetic retinopathy, macular degeneration, etc.

*"Around 64% of adults working in computer and mathematical sciences use some vision correction option" (i.e., glasses, contacts, surgery)*

# Skin cancer imaging



Non-invasive imaging of  
breast and dorsal skin tumors  
(Still at the pre-clinical level)

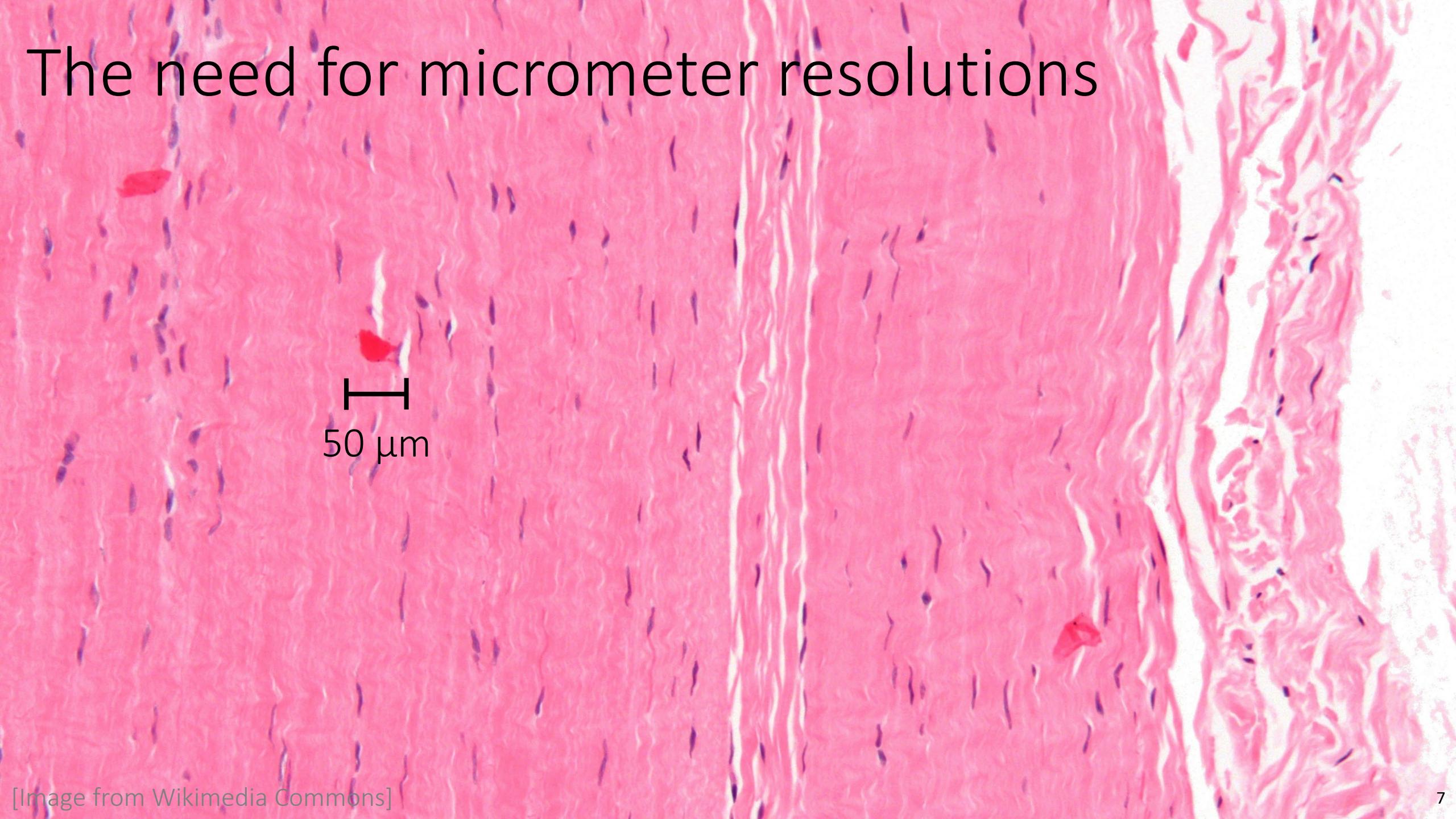


2 mm depth  
10  $\mu\text{m}$  resolution

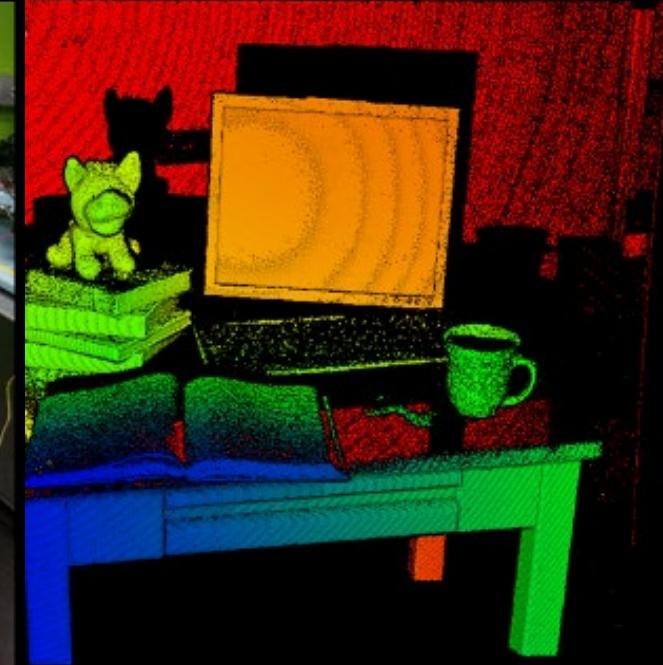
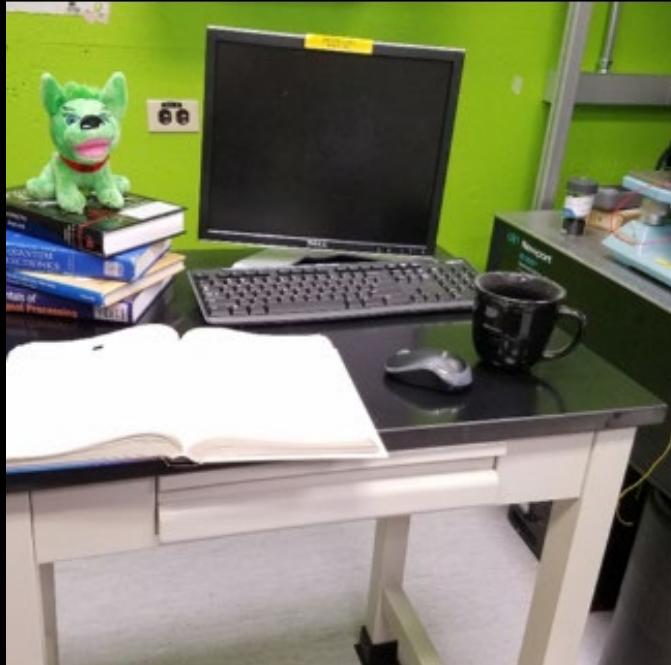
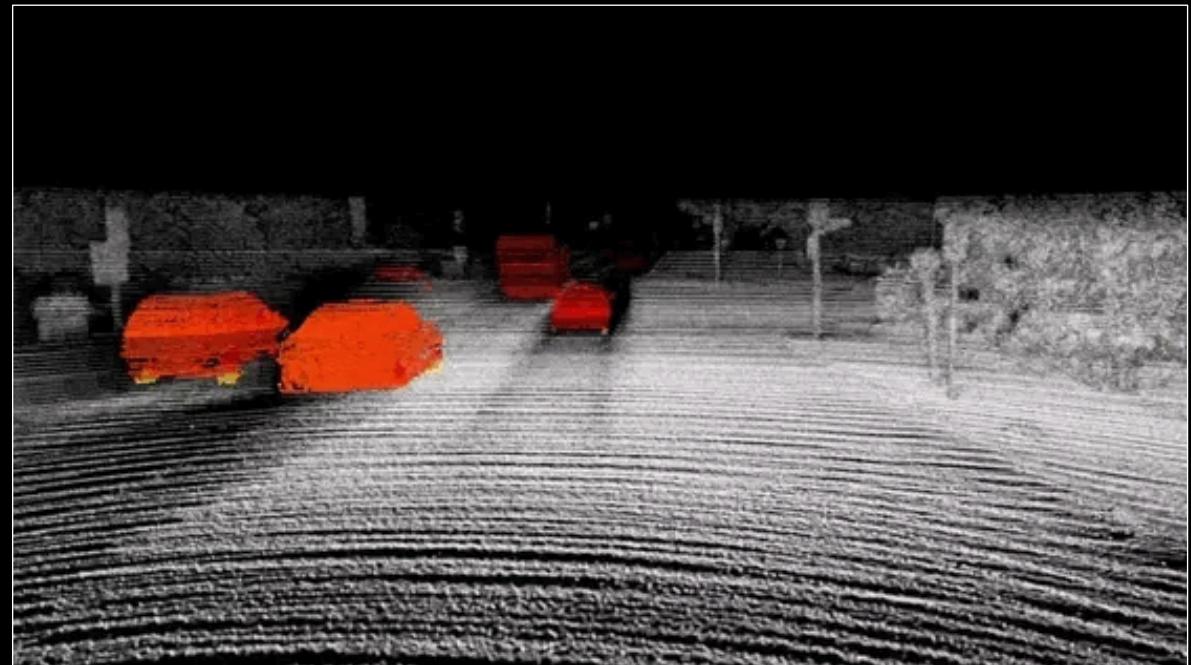
# Seeing deep inside tissue



# The need for micrometer resolutions



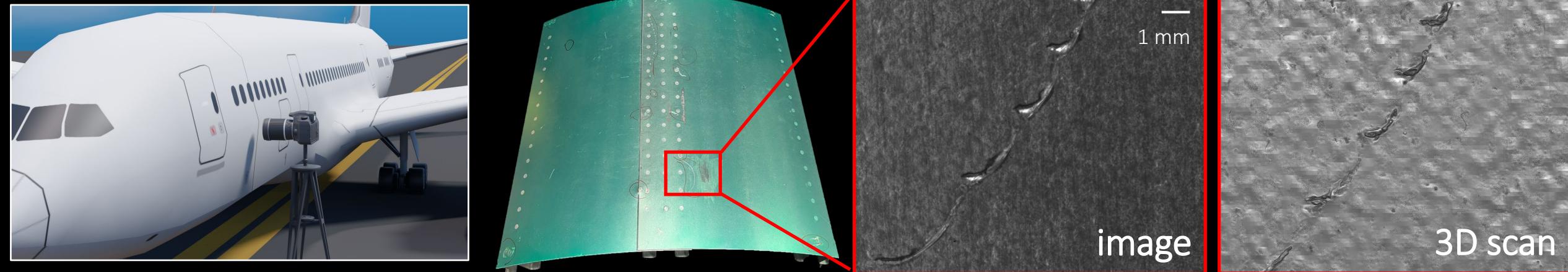
# FMCW “4D” lidar



Depth *and* velocity using frequency-modulated continuous-wave lidar  
(a.k.a. swept-source optical coherence tomography)

# Micrometer 3D sensing

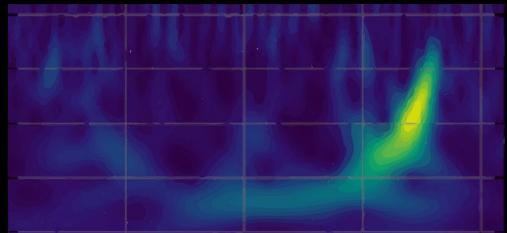
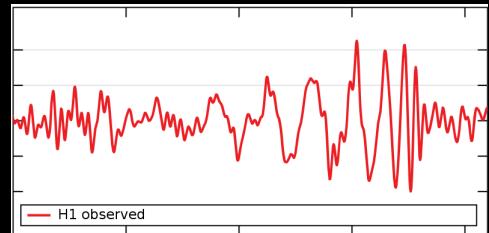
Inspection: aircraft fuselage section



Fabrication: 3D-printed Euro coin



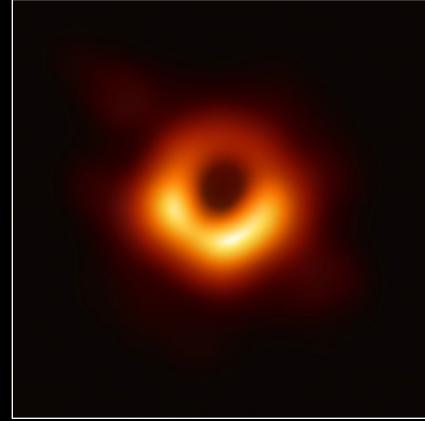
# Very large-scale physics



first gravitational wave detection



Laser Interferometer Gravitational-wave Observatory (LIGO) at Hanford, WA  
(4 km-long Michelson interferometer)

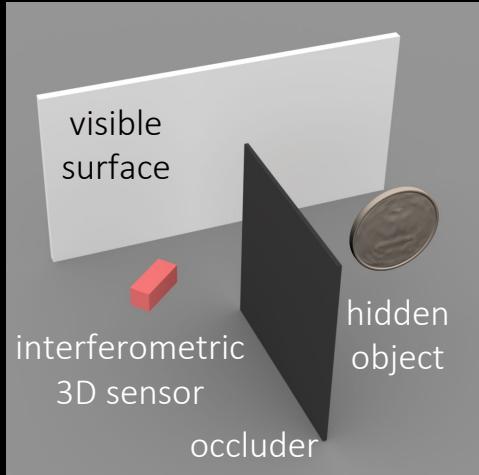


first image of a black hole (center of Messier 87 galaxy)

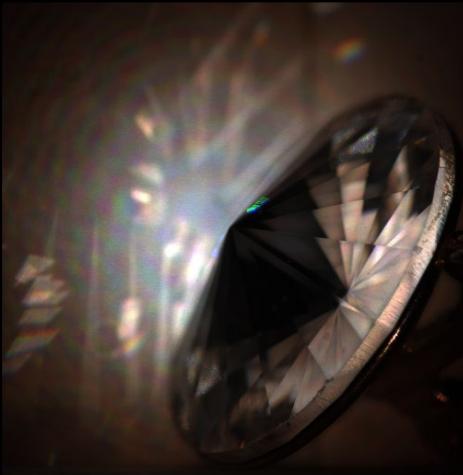


Location of observatories making up the Event Horizon Telescope (EHT)  
(very-long-baseline interferometry)

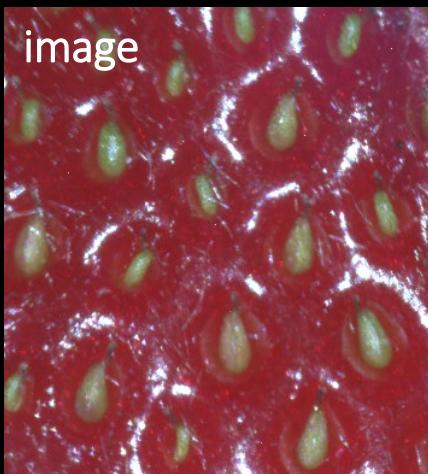
# Computational imaging



Non-line-of-sight imaging



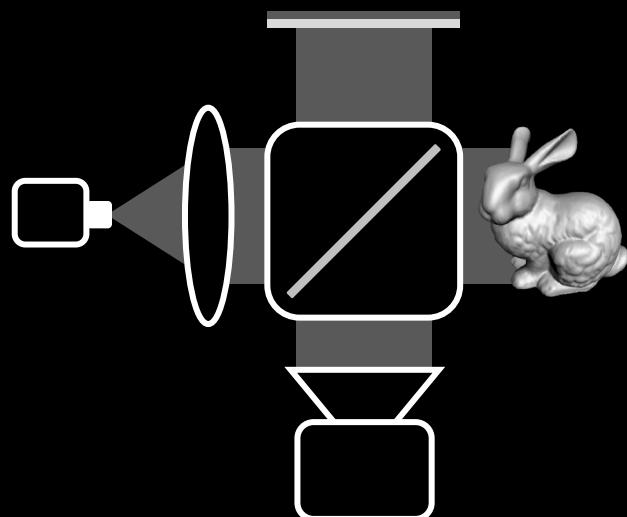
Transient imaging



Separation of direct-indirect illumination

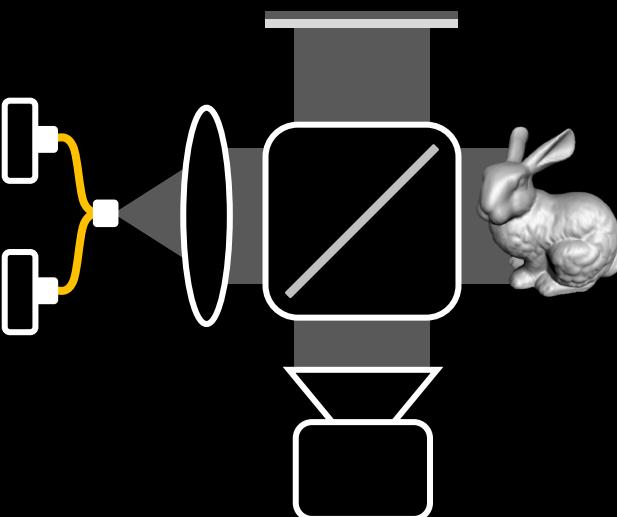
# Course overview

introduction to  
interferometry



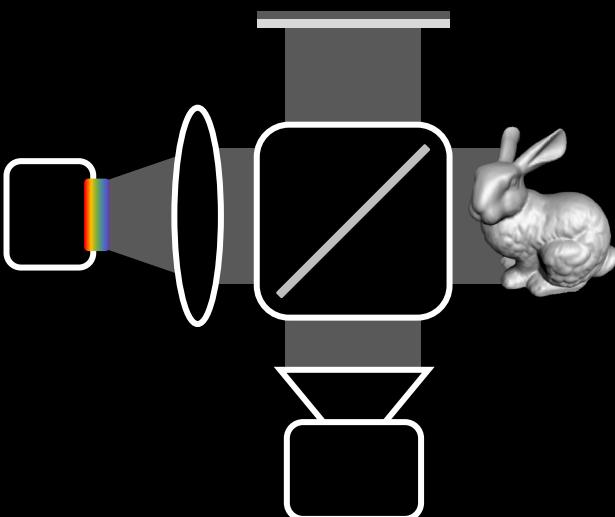
Yannis

two-wavelength  
interferometry



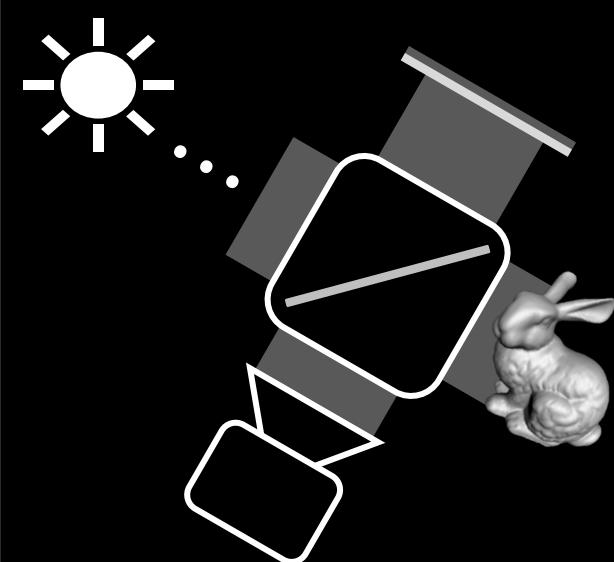
Florian

partially-coherent  
interferometry



Alankar

interferometric  
computational imaging



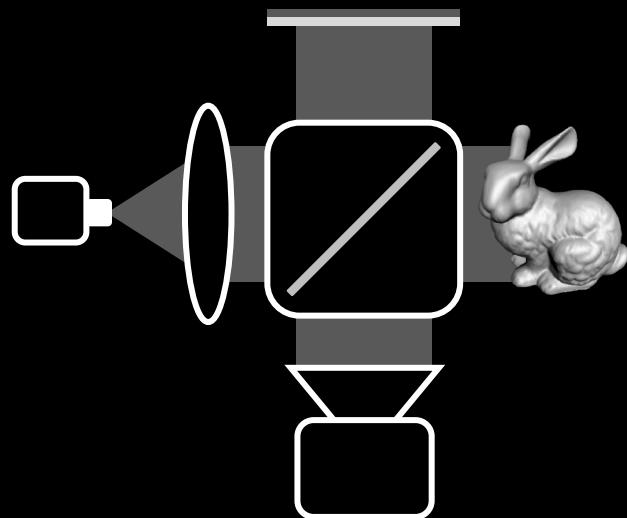
Florian



Yannis

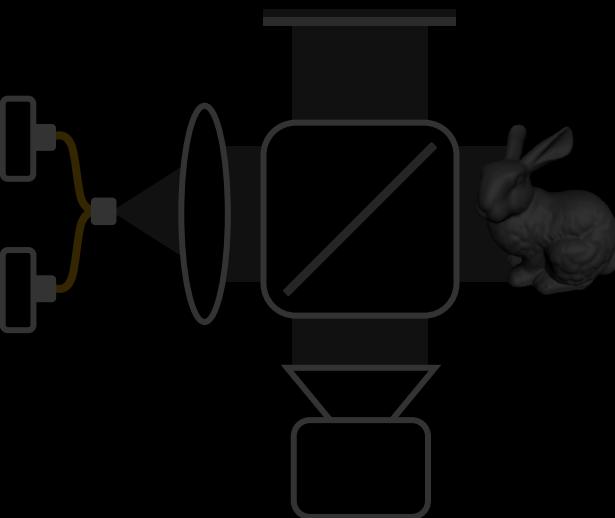
# Course overview

introduction to  
interferometry



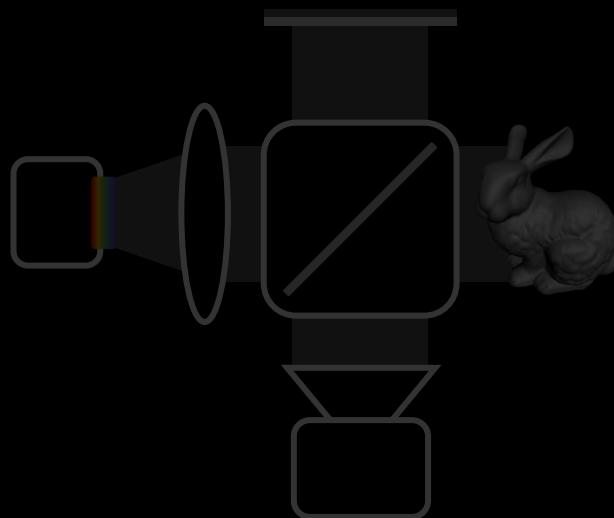
Yannis

two-wavelength  
interferometry



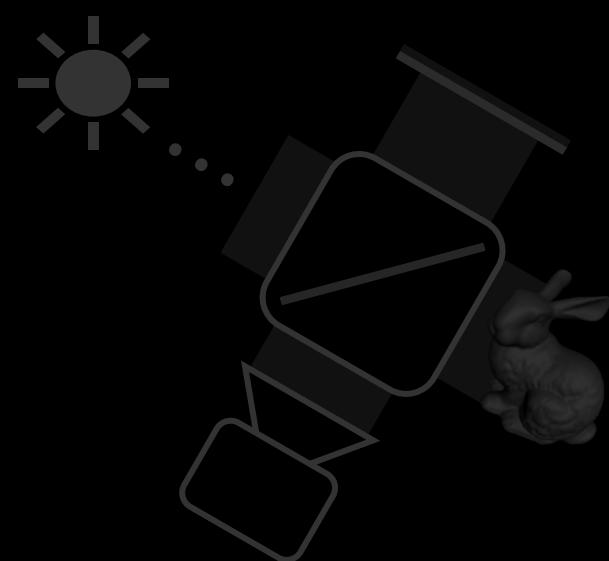
Florian

partially-coherent  
interferometry



Alankar

interferometric  
computational imaging

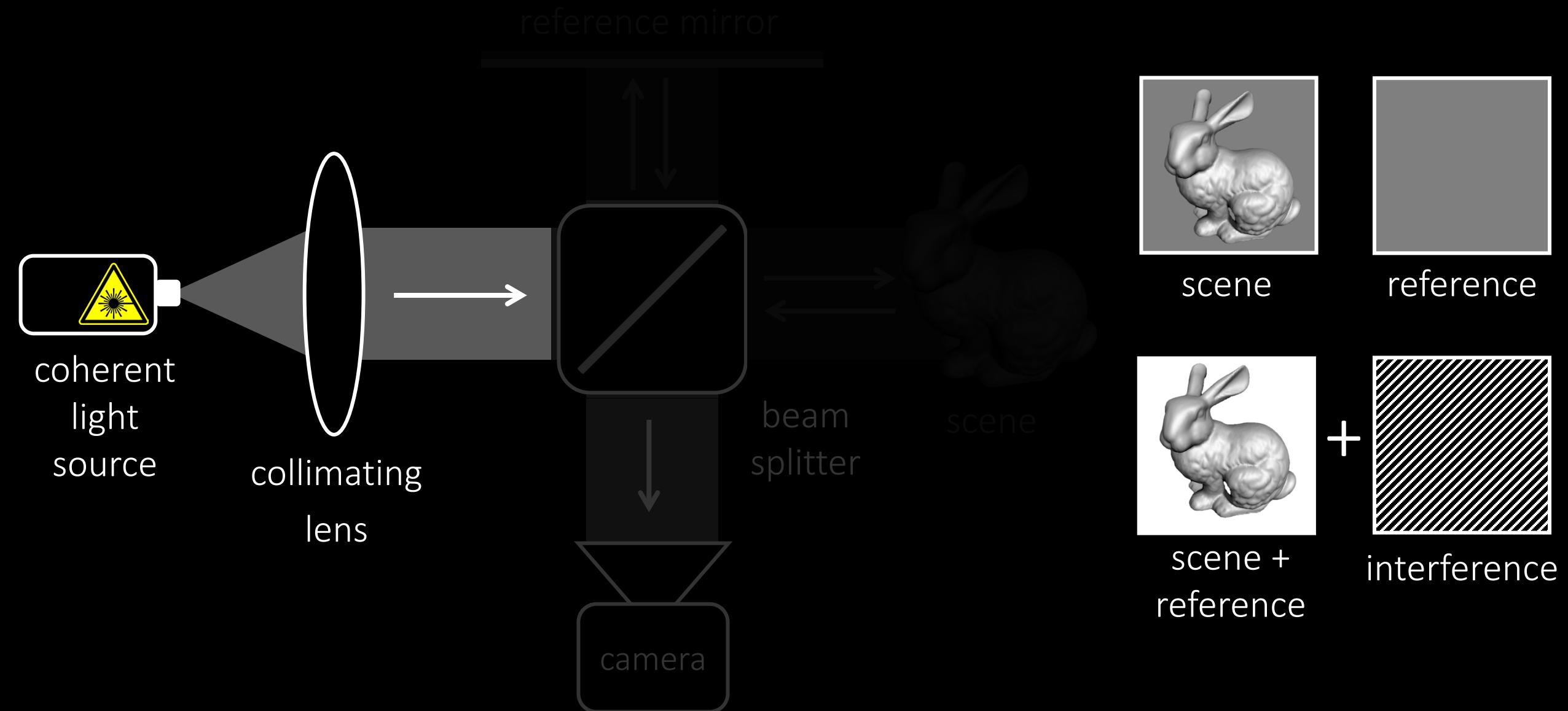


Florian

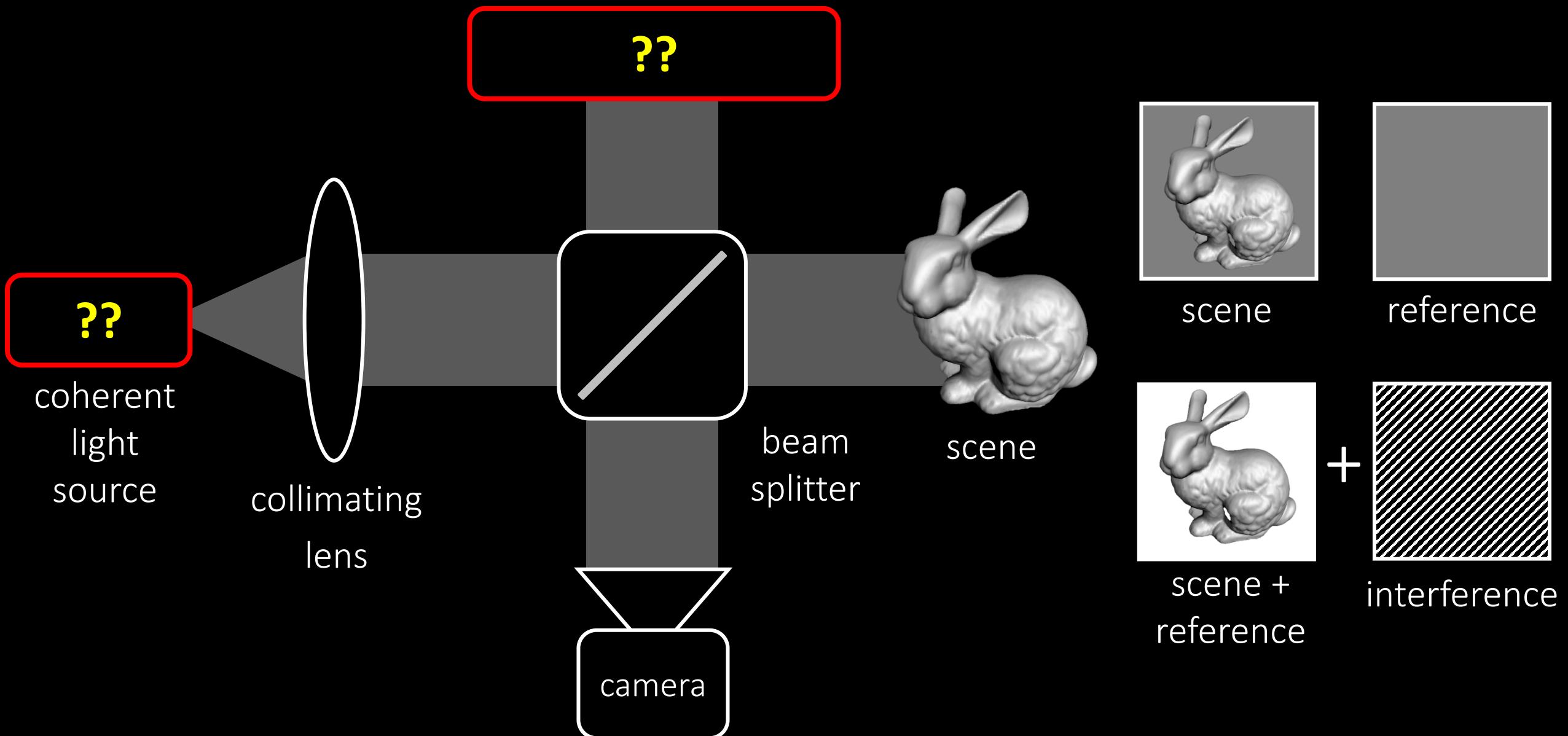


Yannis

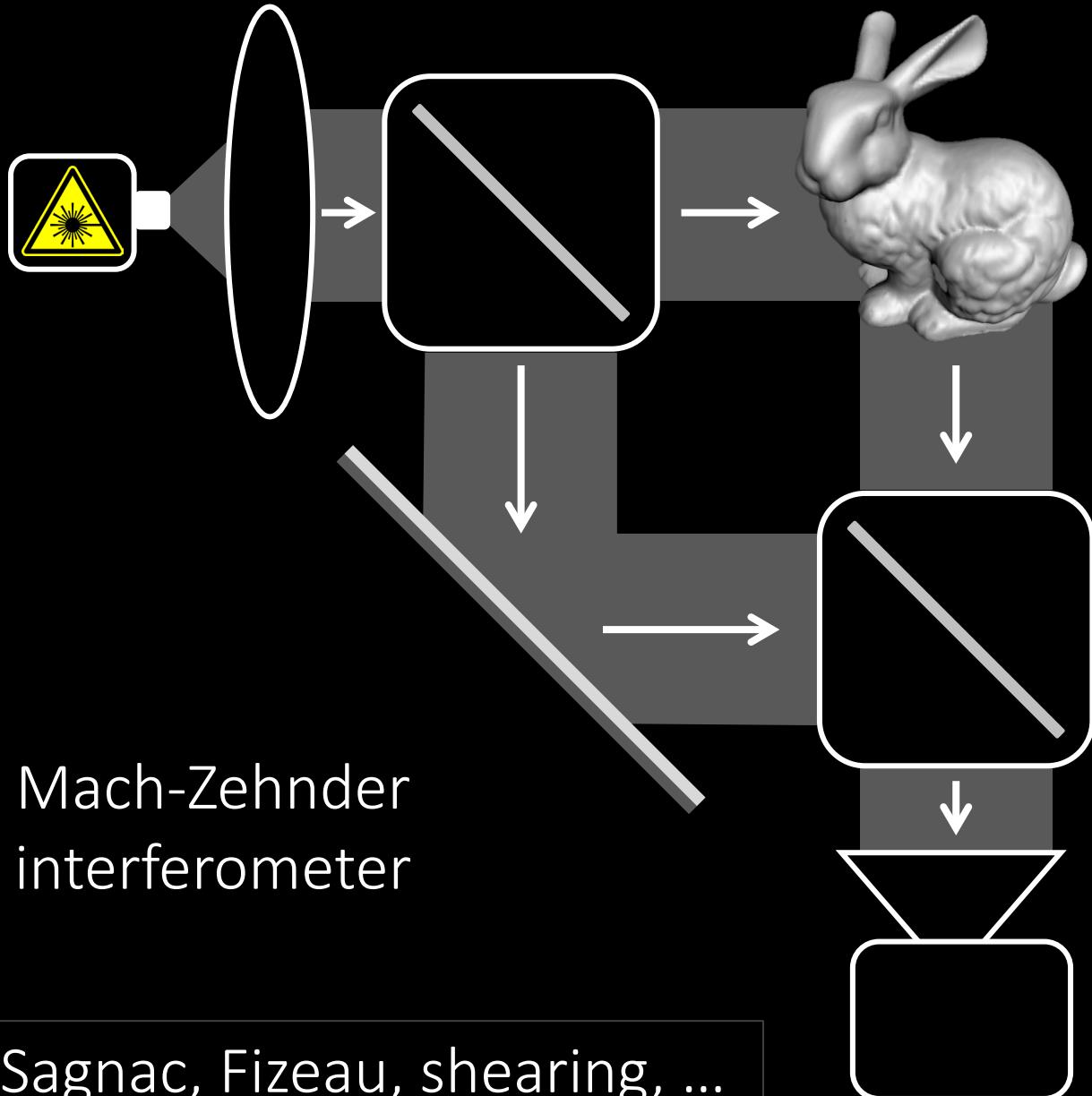
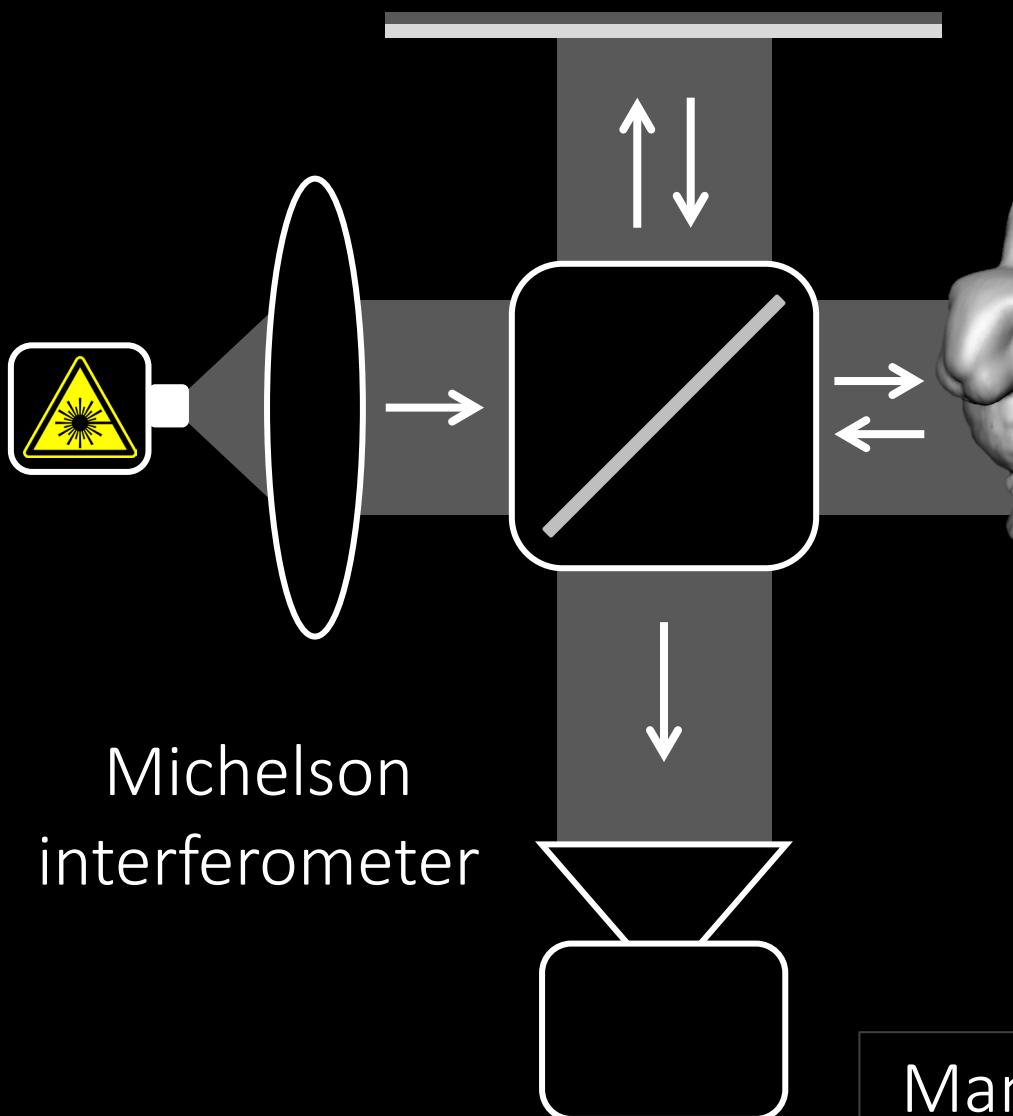
# Interferometric imaging



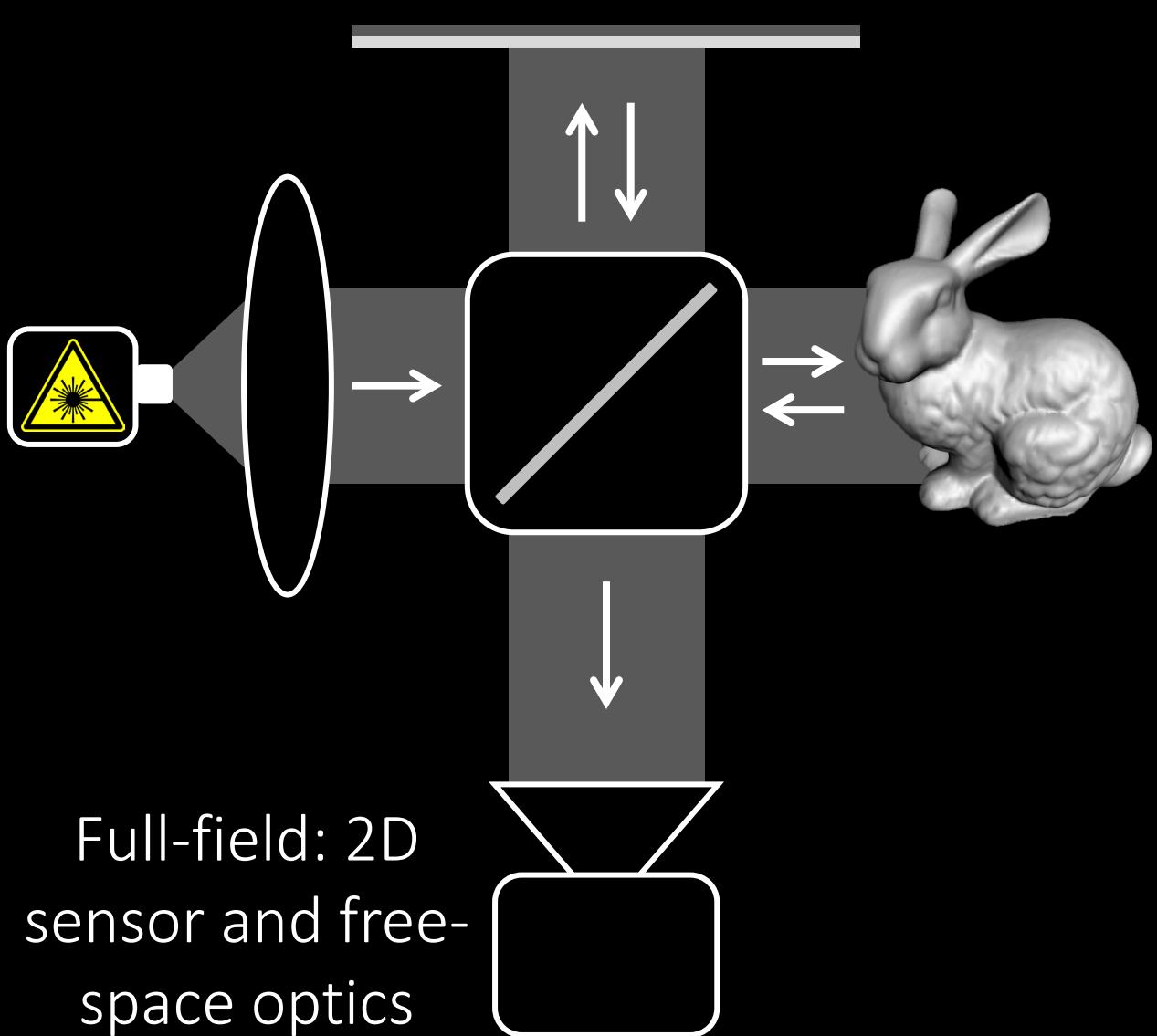
# Interferometric imaging



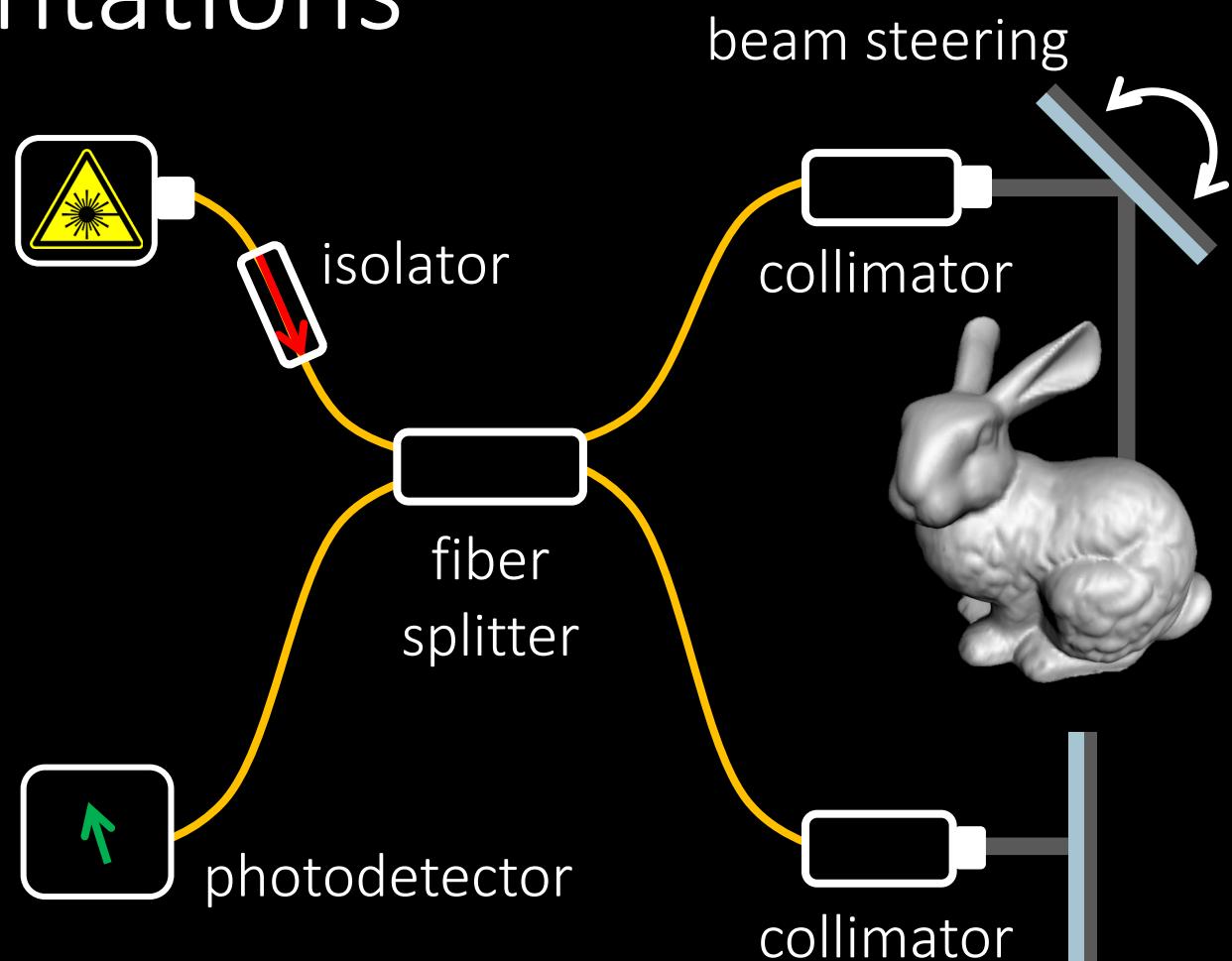
# Interferometer designs



# Interferometer implementations



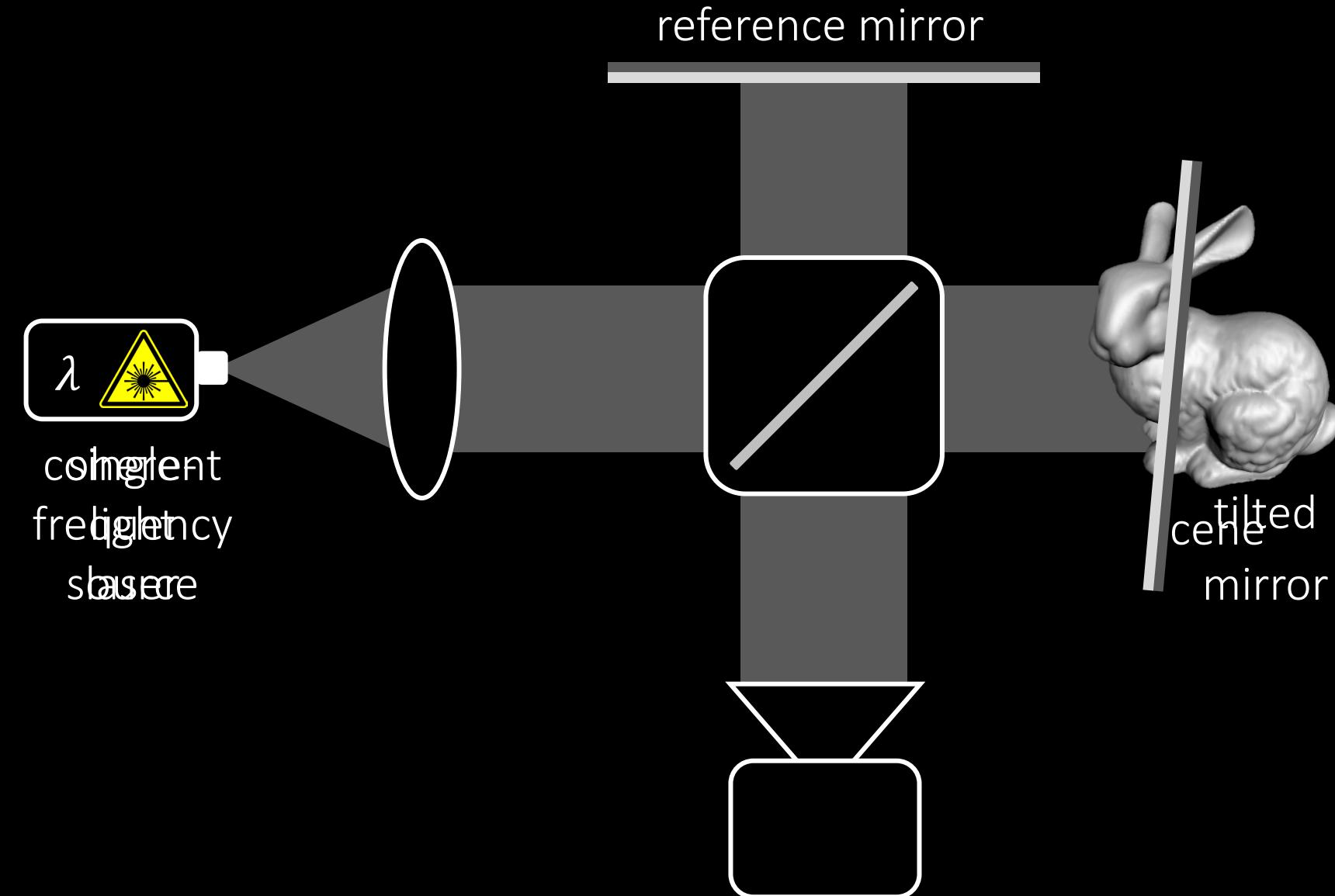
# Full-field: 2D sensor and free- space optics



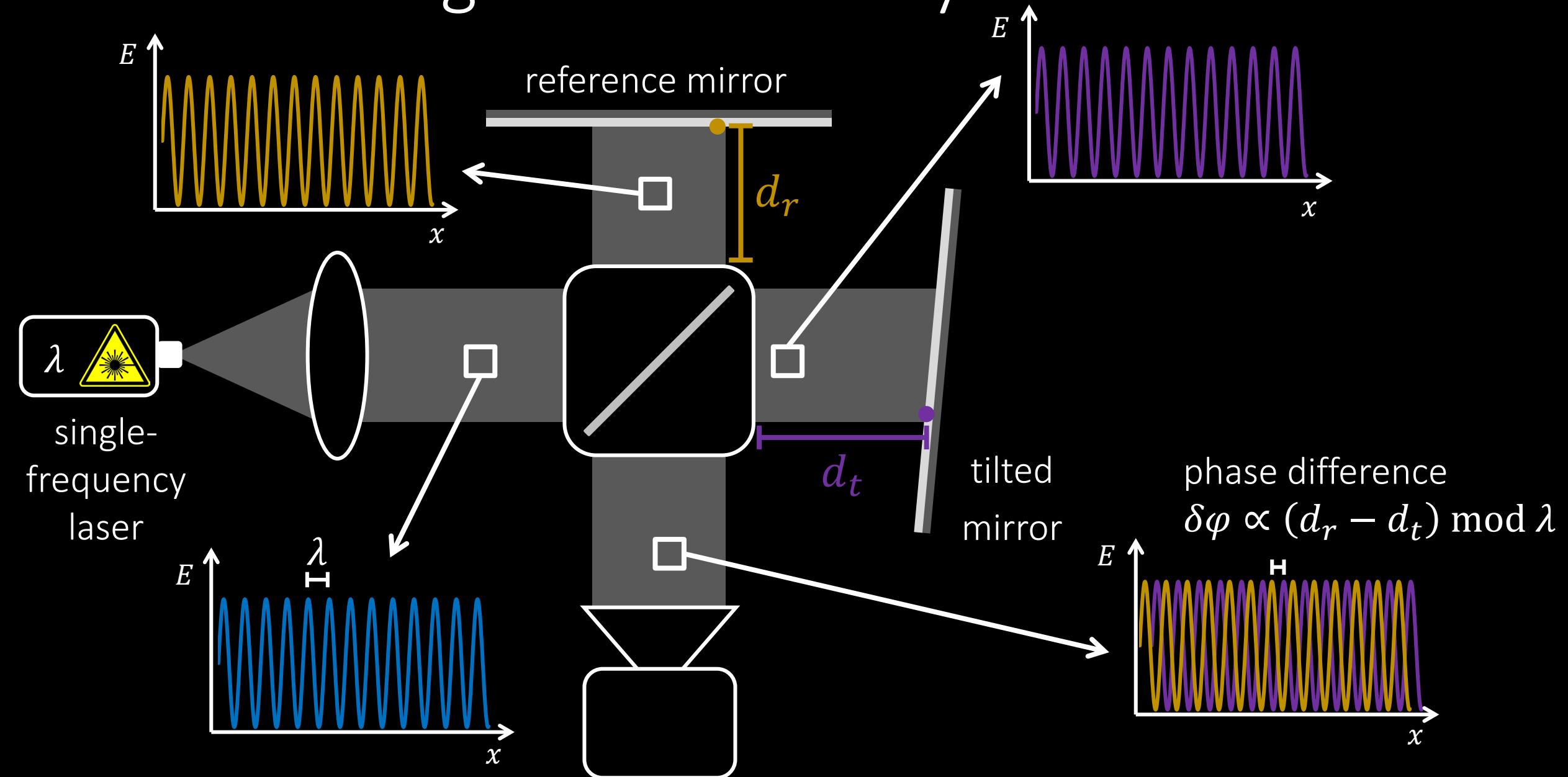
# Scanning: single-pixel sensor and fiber optics

Many choices:  
circulators,  
balanced detectors

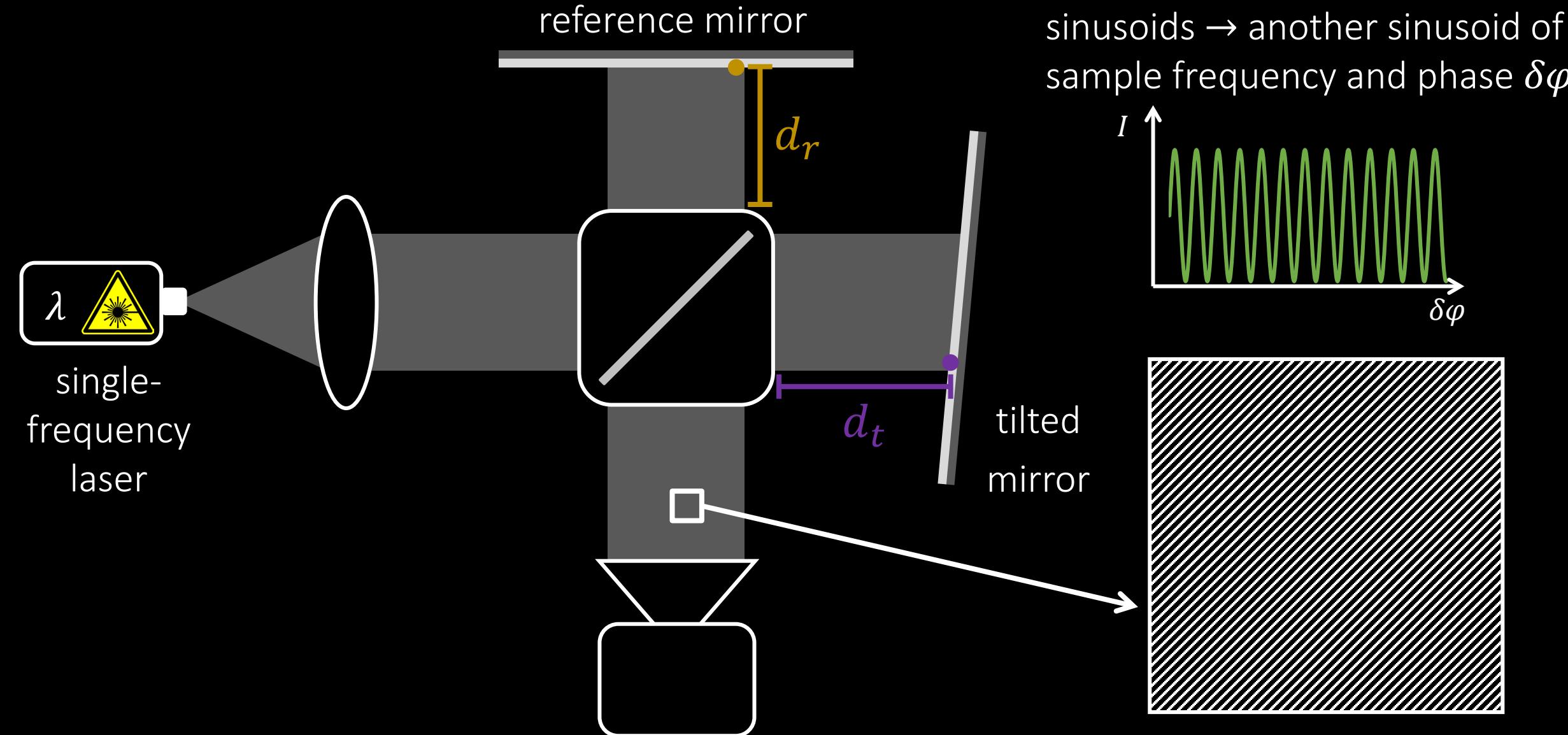
# Phase-shifting interferometry



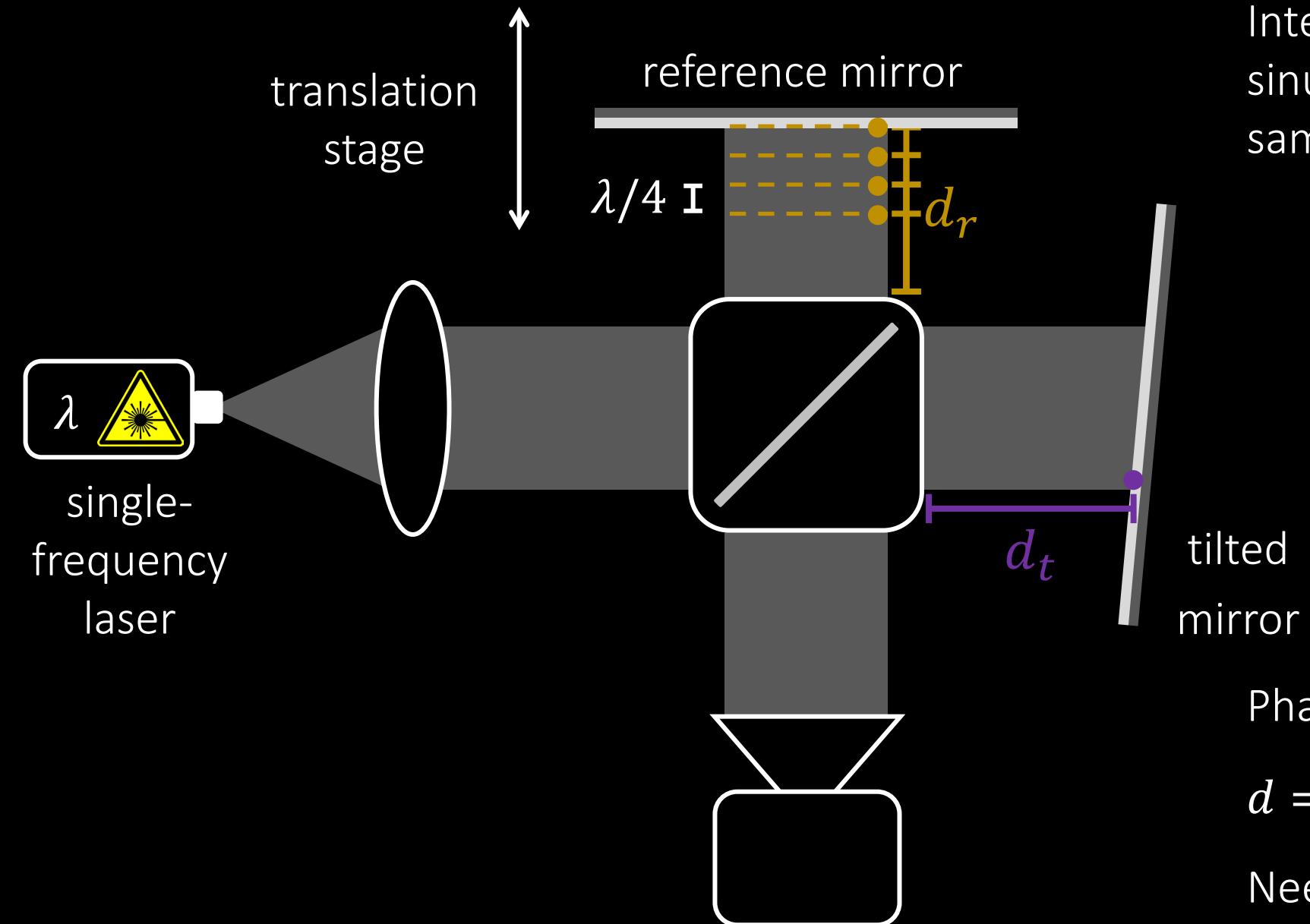
# Phase-shifting interferometry



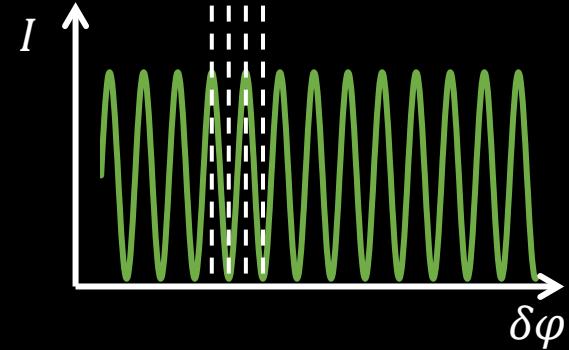
# Phase-shifting interferometry



# Phase-shifting interferometry



Interference: correlation of two sinusoids  $\rightarrow$  another sinusoid of sample frequency and phase  $\delta\varphi$

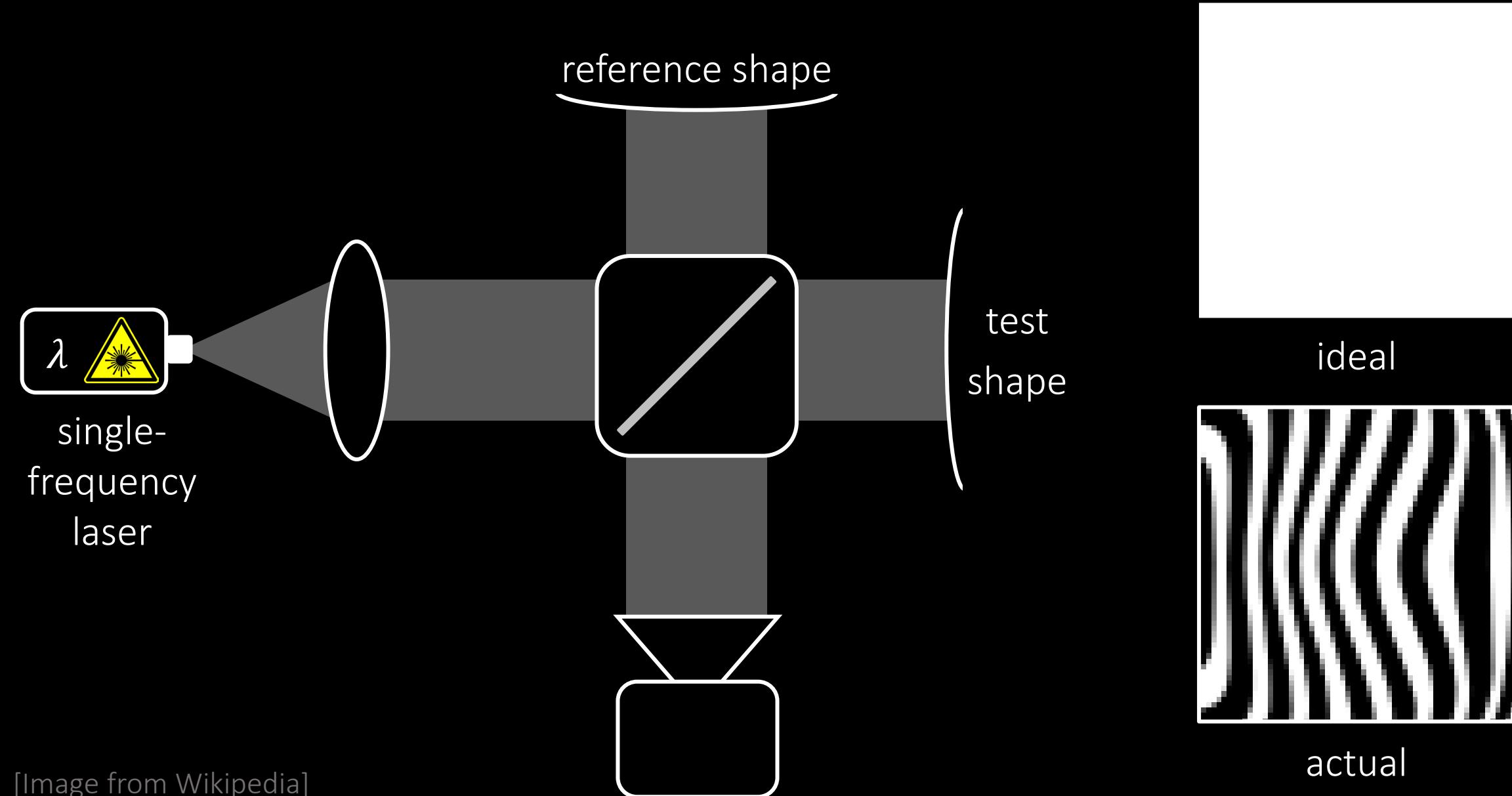


Phase retrieval:

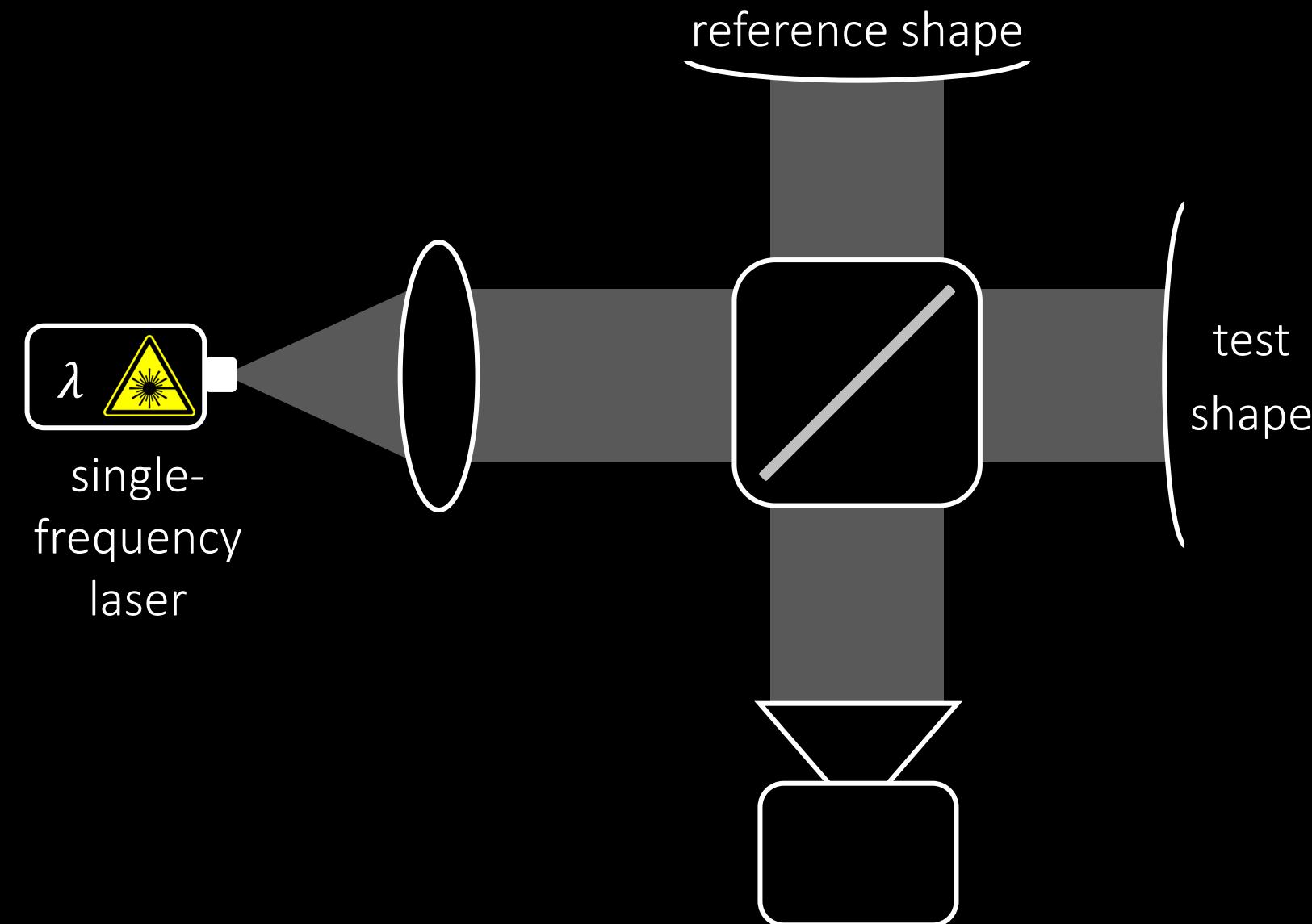
$$d = \frac{\lambda}{2\pi} \tan^{-1} \frac{E_4 - E_2}{E_1 - E_3} + n\lambda$$

Needs only 4 axial measurements

# Example: surface deflectometry with PSI



# Example: surface deflectometry with PSI

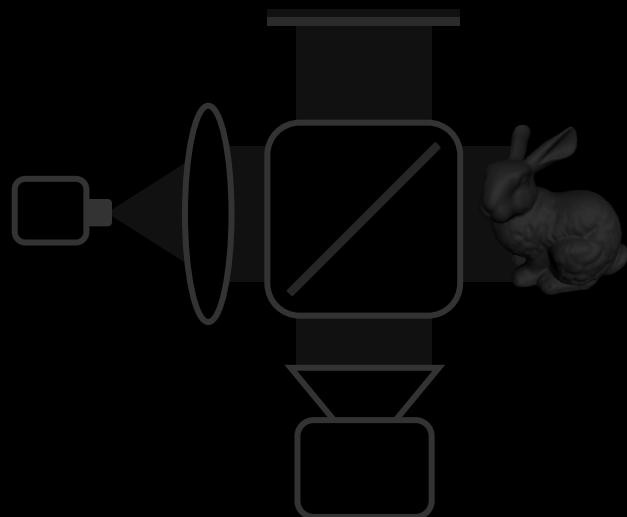


Phase-shifting interferometry:

- ✓ sub-wavelength resolution
- ✗ wavelength depth range
- ✗ only for smooth surfaces
- ✗ very sensitive to vibrations
- ✗ very sensitive to aberrations

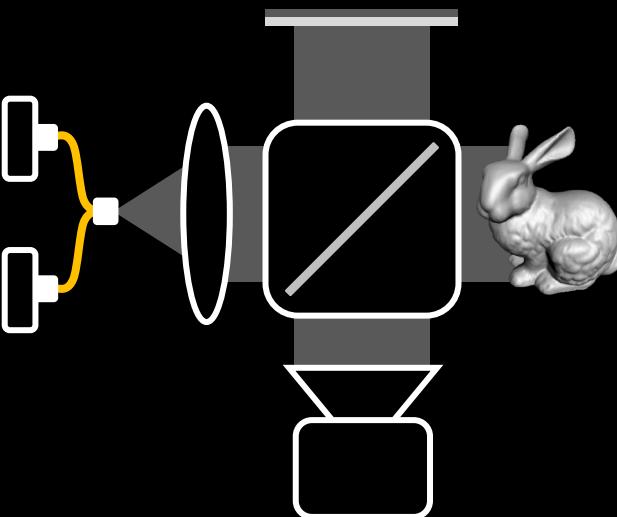
# Course overview

introduction to  
interferometry



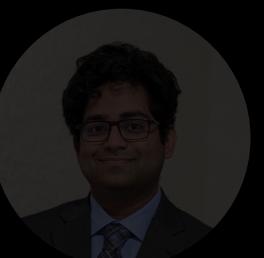
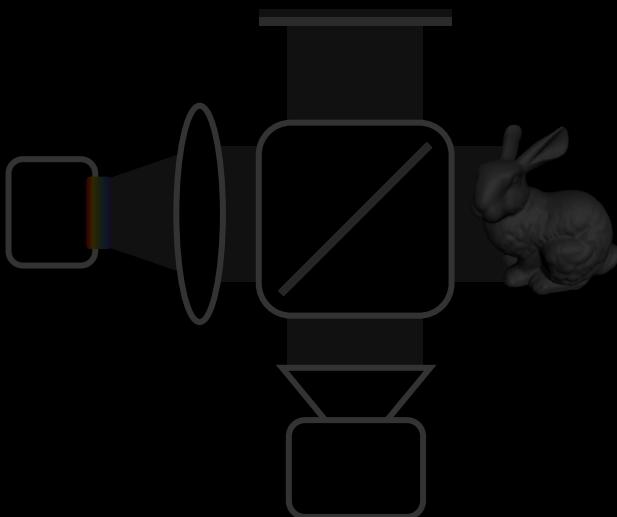
Yannis

two-wavelength  
interferometry



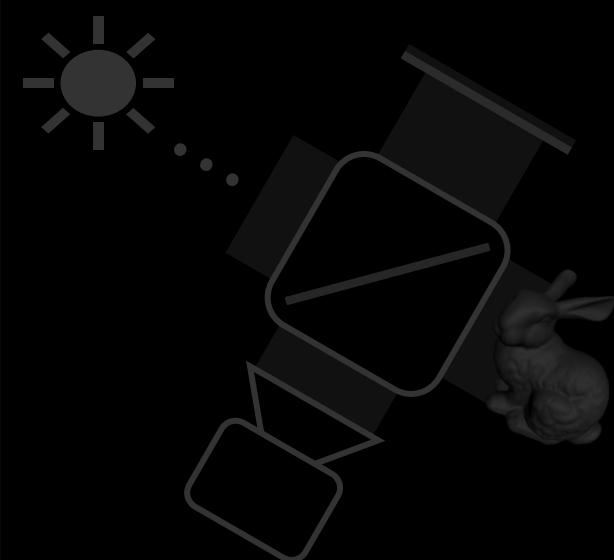
Florian

partially-coherent  
interferometry



Alankar

interferometric  
computational imaging



Florian



Yannis

# Computational 3D Imaging and Measurement (3DIM) Lab

## Current Members

### Director

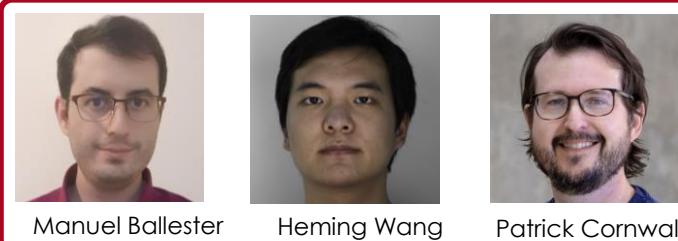


Florian Willomitzer

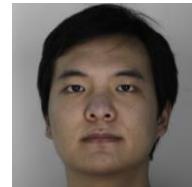
### Students



Jiazhang Wang



Manuel Ballester



Heming Wang



Patrick Cornwall



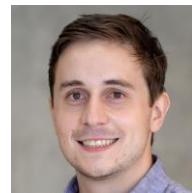
Yuanxin Guan



Jiwon Choi



Tianfu Wang



James Taylor



John Bass

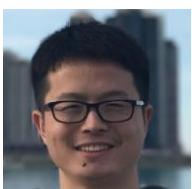


Aniket Dashpute

### Contributing collaborators and previous group members:



Northwestern  
University



Fengqiang Li



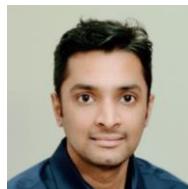
Jiren Li



Oliver Cossairt



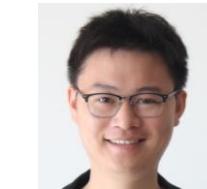
SMU.

Prasanna  
Rangarajan

Muralidhar Balaji



Marc Christensen



Yicheng Wu

Ashok  
Veeraraghavan

RICE<sup>®</sup>  
Unconventional Wisdom

# Part 2:

## Interferometry on Rough Surfaces and Synthetic Wavelengths

---

Florian Willomitzer

Associate Professor  
Wyant College of Optical Sciences  
University of Arizona, USA

<https://www.optics.arizona.edu/3dim>

**3DIM Lab**

Computational 3D Imaging  
and Measurement Lab

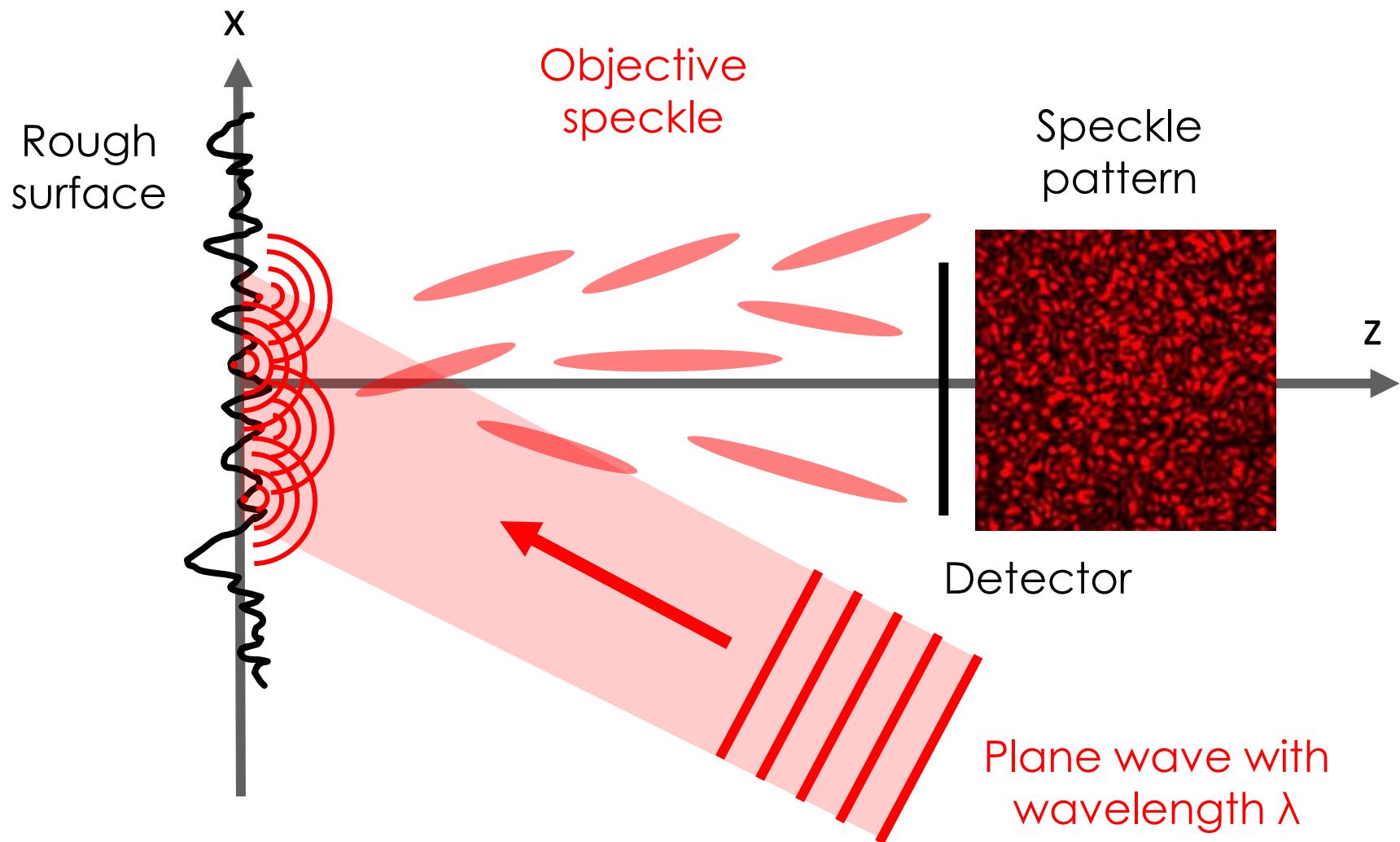
Prof. Florian Willomitzer



THE UNIVERSITY OF ARIZONA  
**Wyant College  
of Optical Sciences**

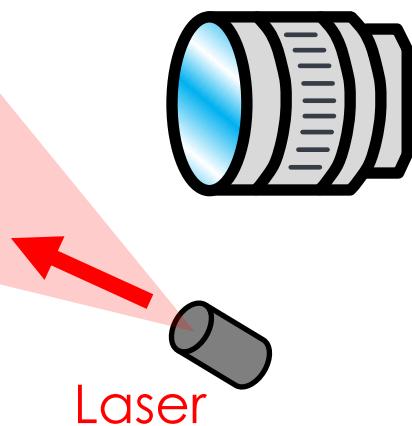


# Coherent imaging on rough surfaces - Speckle



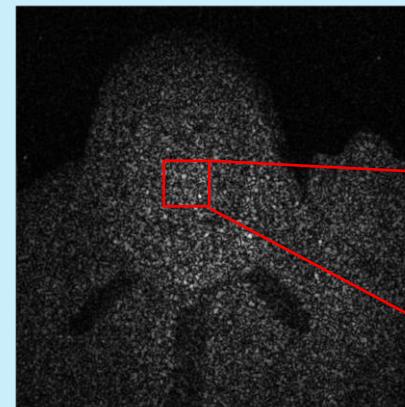
# Coherent imaging on rough surfaces - Speckle

Object with  
rough surface

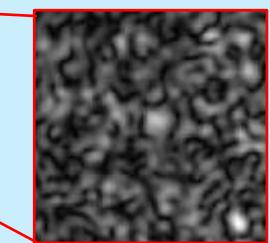


Laser

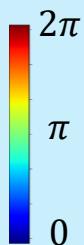
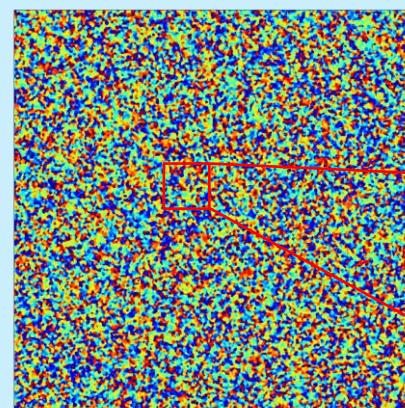
Camera readout



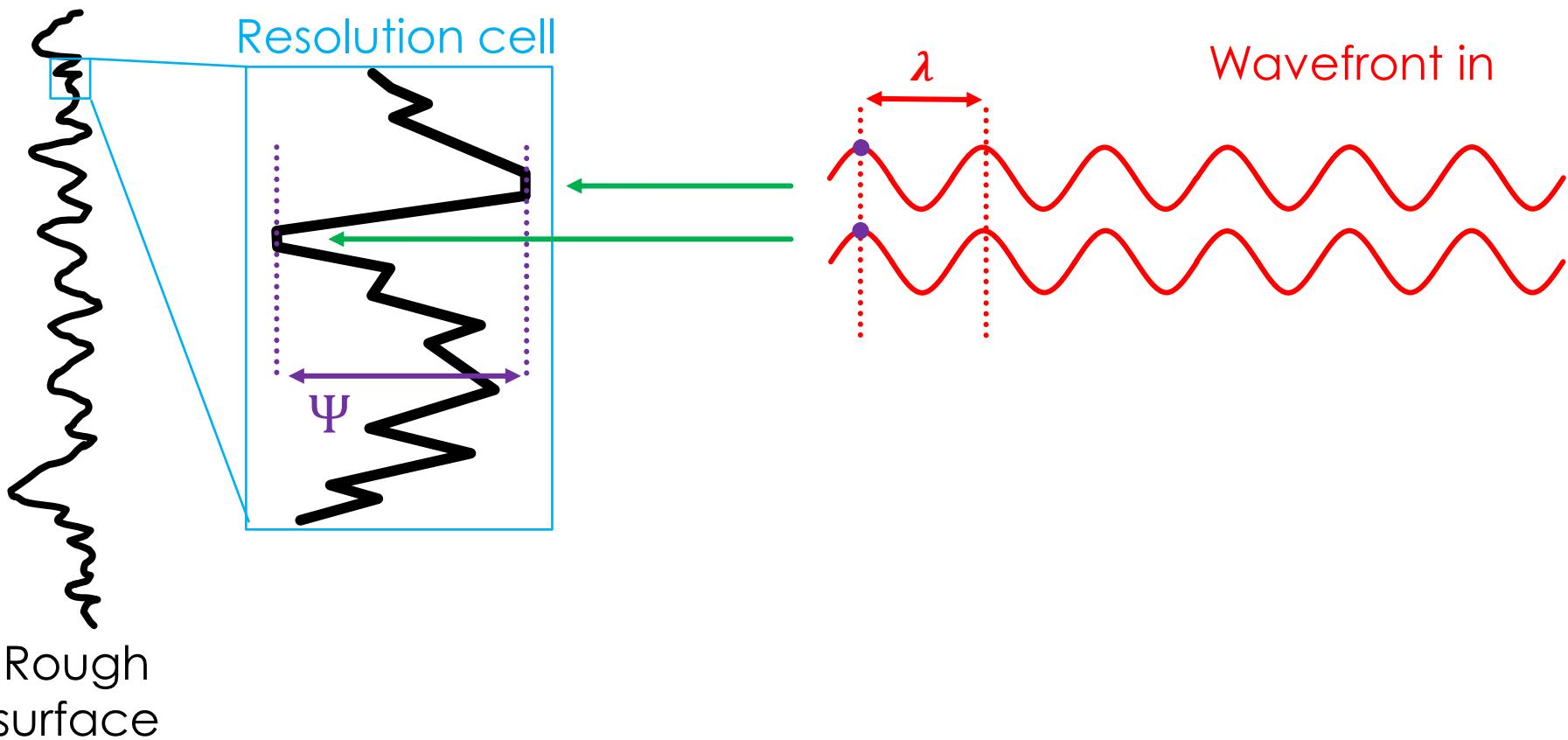
Amplitude  
 $|E(\lambda)|$



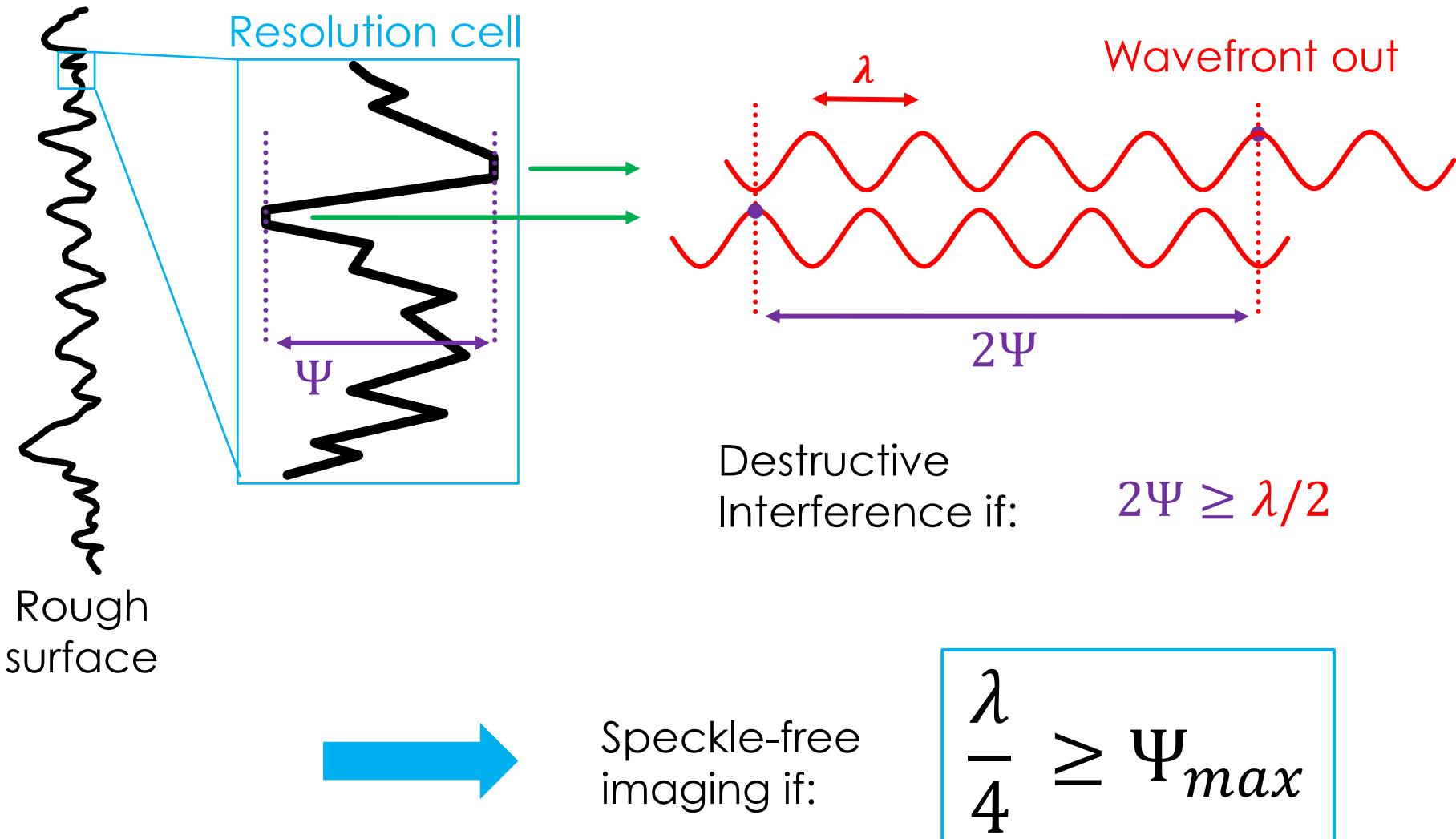
Phase  
 $\angle E(\lambda) = \phi(\lambda)$



# When is a surface “optically rough”?



# When is a surface “optically rough”?



# Approaches measuring the Time-of-Flight of light

$$\delta z \propto \lambda$$

depth modulation  
resolution wavelength

Conventional  
Interferometry  
(single Wavelength)

Speckle for  
scattering  
scenes

"ToF Cameras"  
(CW or pulsed)

**Synthetic  
Wavelength  
Interferometry**

$\sim \mu\text{m}$

$\sim \text{m}$

Poor  
resolution

$\lambda$

# Millimeter-sized waves with visible light?

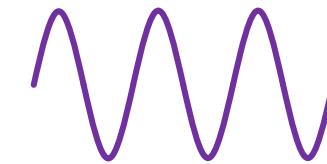
NO!

... well

... let's look at sound waves!

Sine wave

$$\nu = 240\text{Hz} \rightarrow \lambda \approx 1.429\text{m}$$



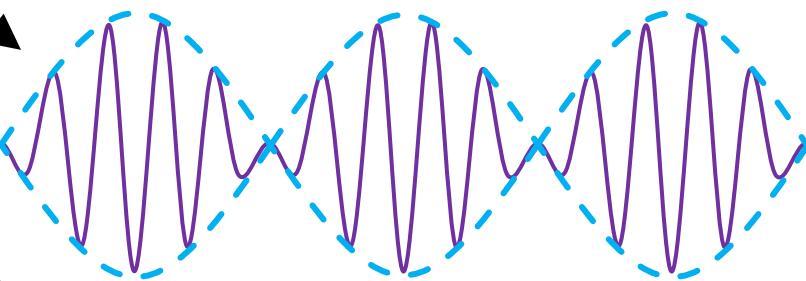
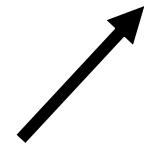
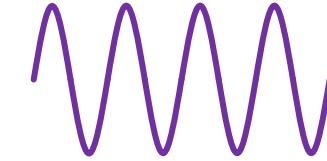
Beat note

$$\Lambda_{beat} \approx 171.5\text{m}$$

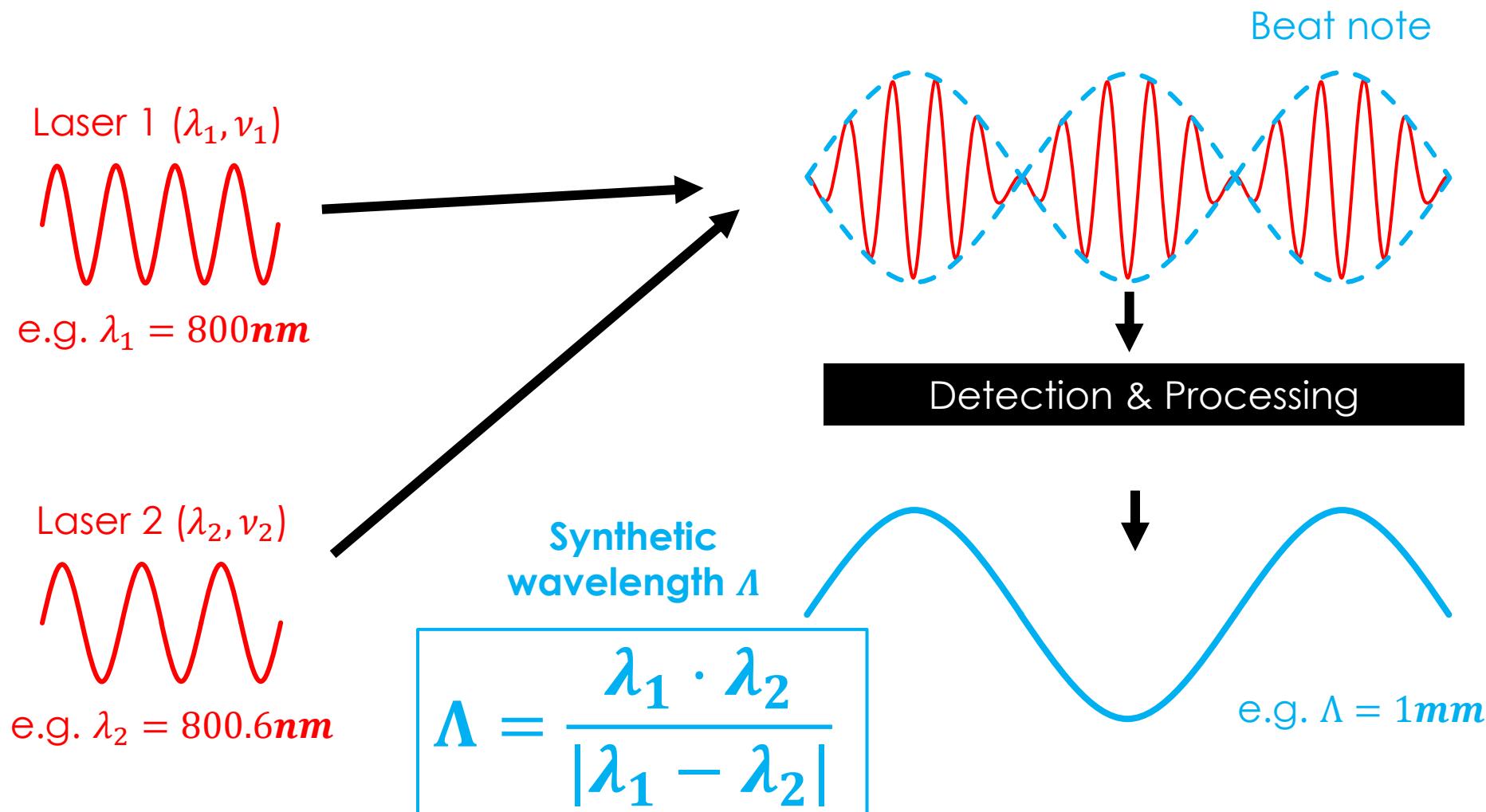


Sine wave

$$\nu = 242\text{Hz} \rightarrow \lambda \approx 1.417\text{m}$$

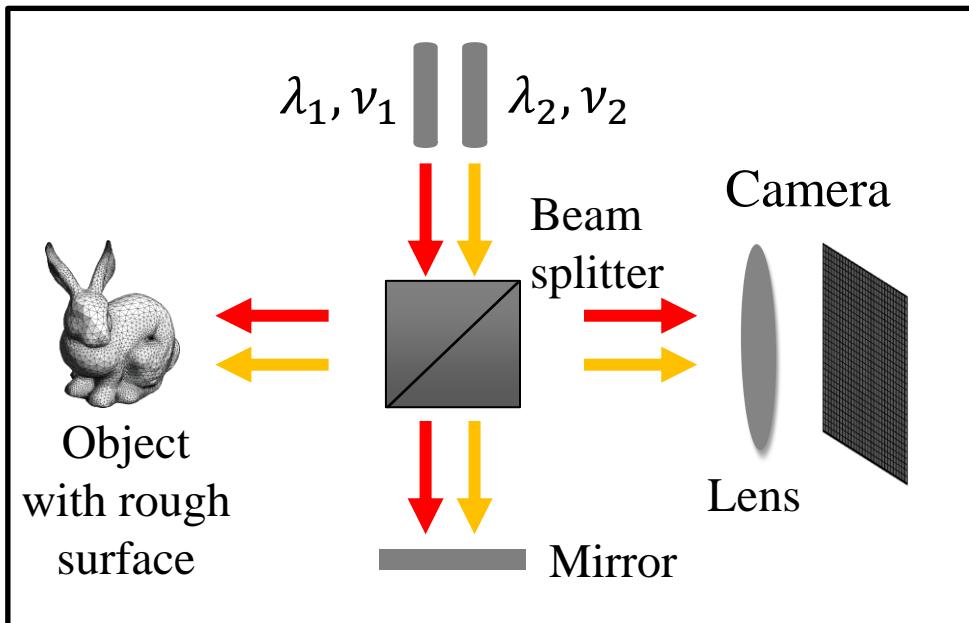


# Synthetic Waves



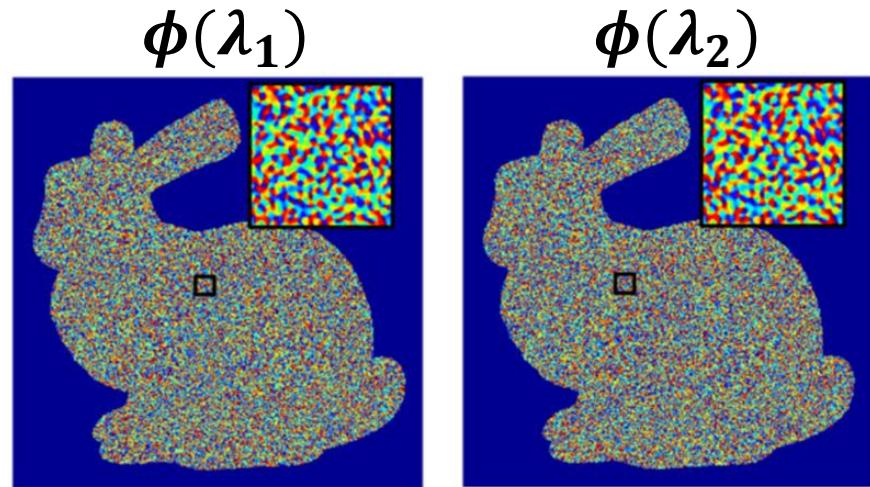
Fercher et al., Applied Optics 24(14) (1985)  
Dändliker et al., Optics Letters 13(5) (1988)

# High-precision “ToF Camera”

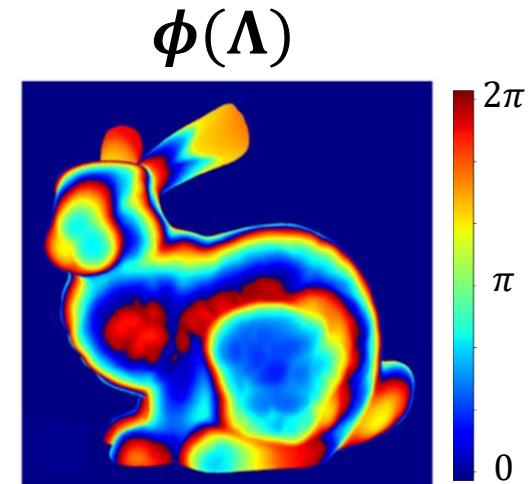


$$E(\lambda_1) = A_1 \cdot e^{i\phi(\lambda_1)}$$

$$E(\lambda_2) = A_2 \cdot e^{i\phi(\lambda_2)}$$

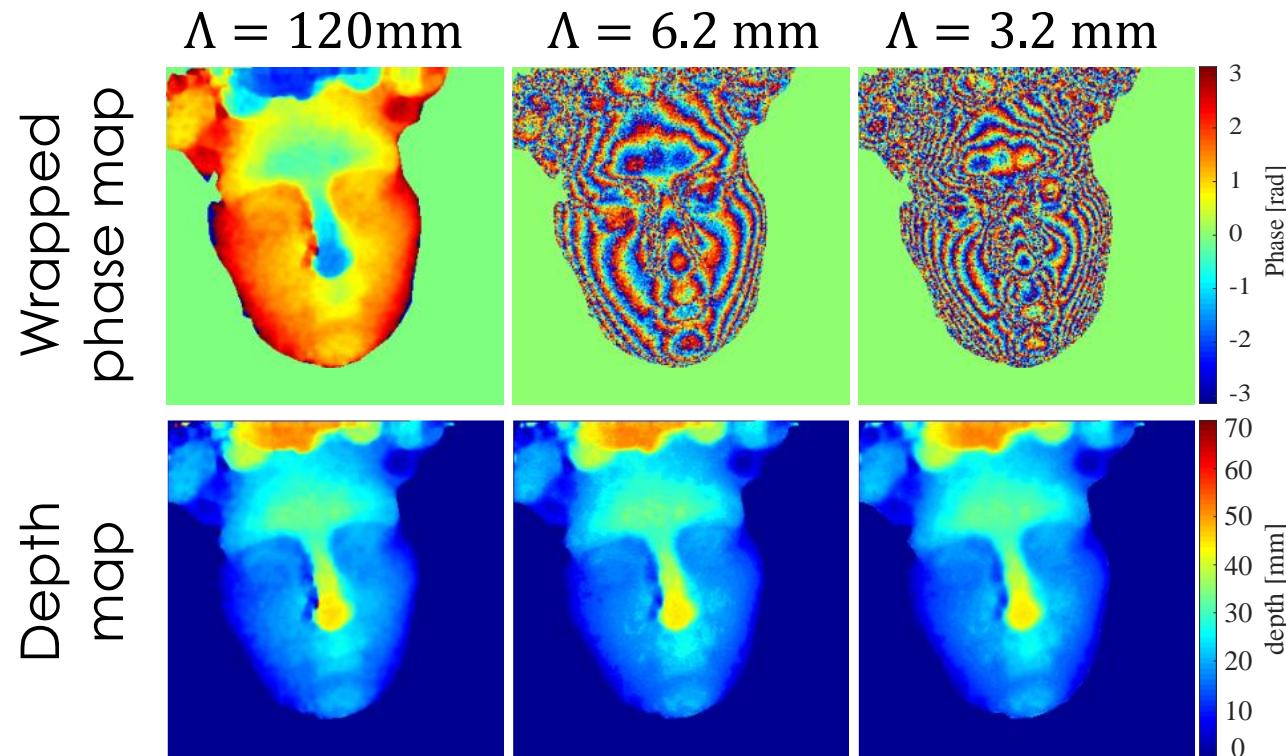


$$\begin{aligned} E(\Lambda) &= E(\lambda_1) \cdot E^*(\lambda_2) \\ &= A_1 A_2 \cdot \exp(i(\phi(\lambda_1) - \phi(\lambda_2))) \end{aligned}$$



F. Li\*, F. Willomitzer\*, M. Balaji, P. Rangarajan, O. Cossairt, Exploiting Wavelength Diversity for High Resolution Time-of-Flight 3D Imaging, IEEE Transactions on Pattern Analysis and Machine Intelligence (TPAMI), 2021

# High-precision “ToF Camera”



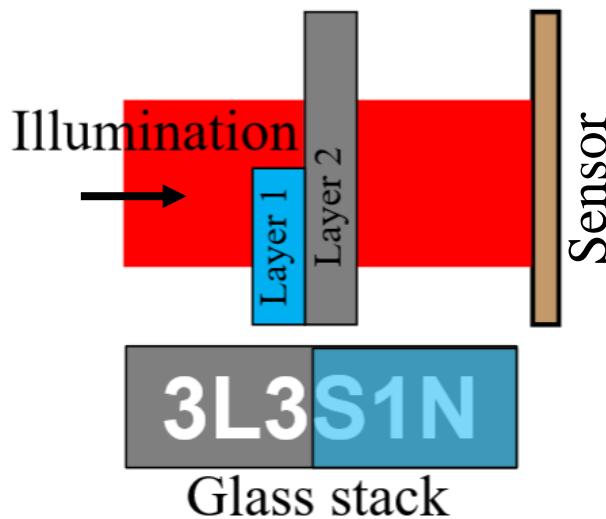
Sub-mm depth resolution easily achievable!

F. Li\*, F. Willomitzer\*, M. Balaji, P. Rangarajan, O. Cossairt, Exploiting Wavelength Diversity for High Resolution Time-of-Flight 3D Imaging, IEEE Transactions on Pattern Analysis and Machine Intelligence (TPAMI), 2021

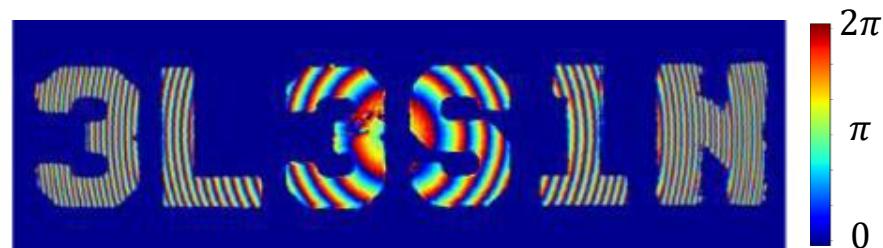
# Sidenote

Synthetic wavelengths are also useful in absence of scattering!

Schematic setup



Optical phase → strong wrapping!  
 $\lambda = 854.3 \text{ nm}$



Synthetic phase → no wrapping!  
 $\Lambda = 1.29 \text{ mm}$



Y. Wu\*, F. Li\*, F. Willomitzer, A. Veeraraghavan, O. Cossairt, WISHED: Wavefront Imaging Sensor with High resolution and Depth ranging, EEE International Conference on Computational Photography (ICCP), 2020

# How to detect the synthetic field $E(\Lambda)$ ?

(or the two optical fields  $E(\lambda_1), E(\lambda_2)$ )

- Phase shifting
- Temporal heterodyning
- Spatial heterodyning
- Iterative phase retrieval
- Deep learning
- .....

→ Vast playfield!

→ No free lunch!

Better question to ask by an “adopter”:

## **What are important modalities for your application?**



- Full field



- Single-shot

- Reference-less



- No prior object knowledge

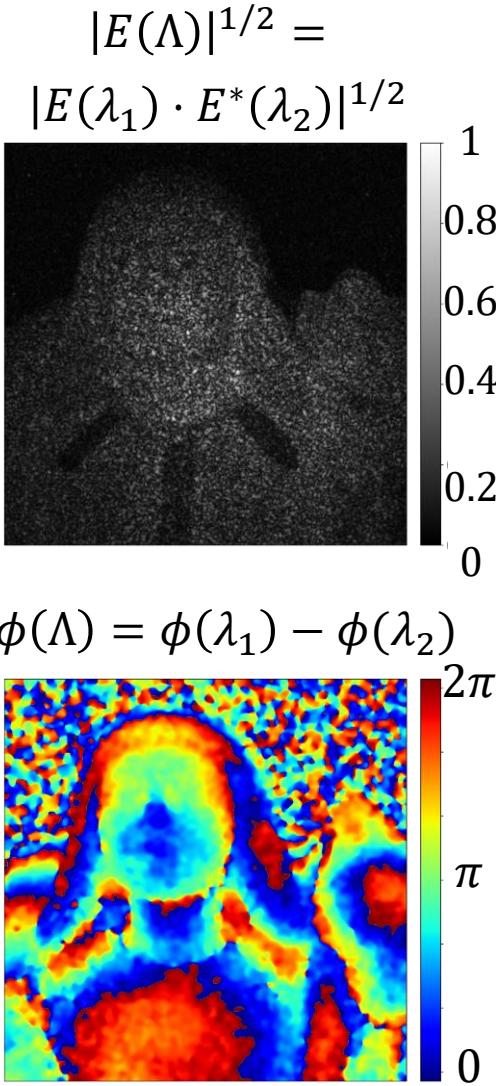
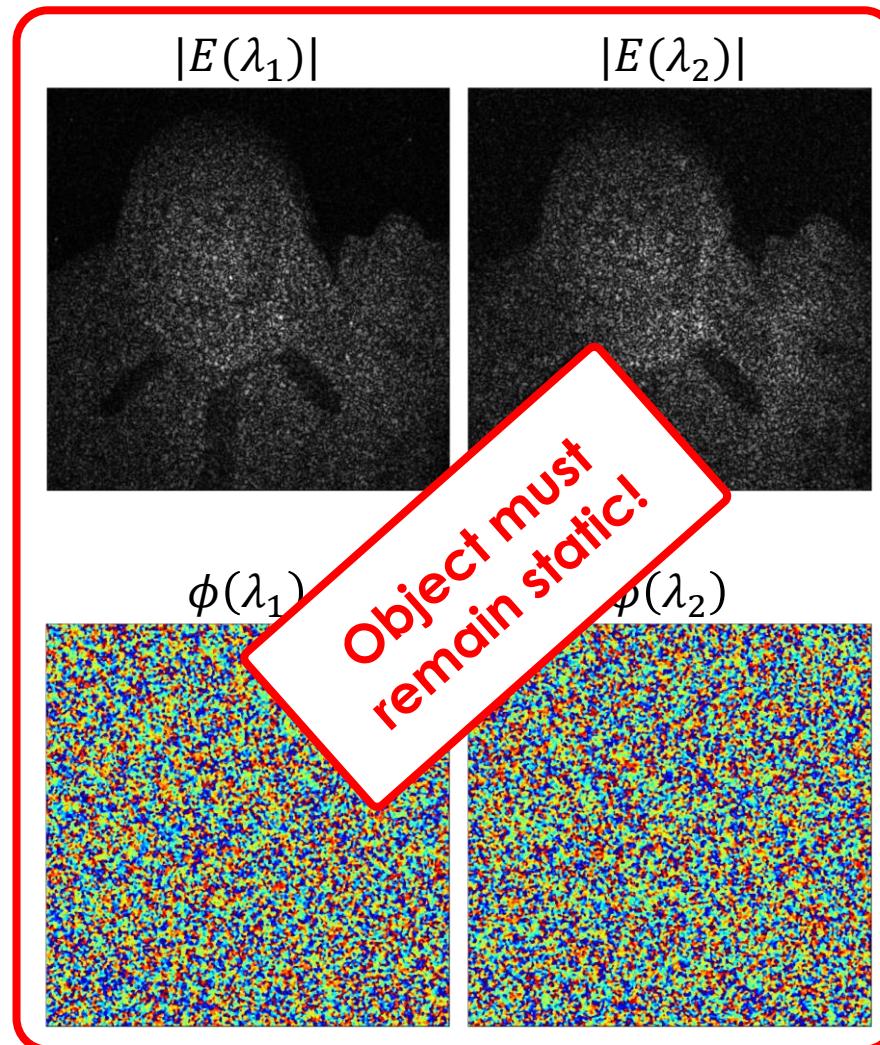


- COTS CCD/CMOS cameras

- ....

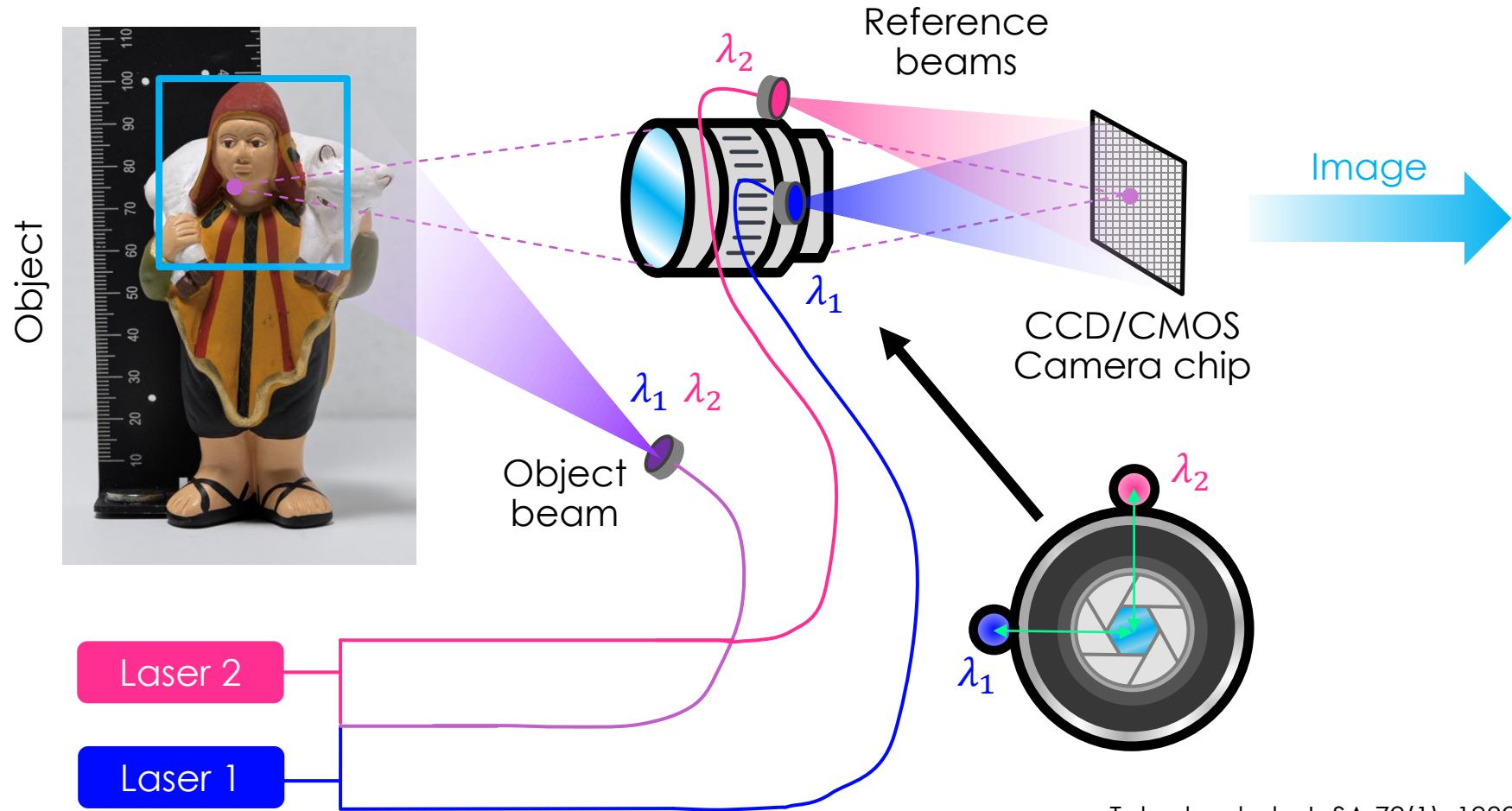
\* Coming up now...

# Susceptibility to motion



M. Ballester\*, H. Wang\*, J. Li, O. Cossairt, F. Willomitzer.  
 'Single-shot ToF sensing with sub-mm precision using conventional CMOS sensors', Arxiv Preprint, 2022

# Solution: Single-shot acquisition



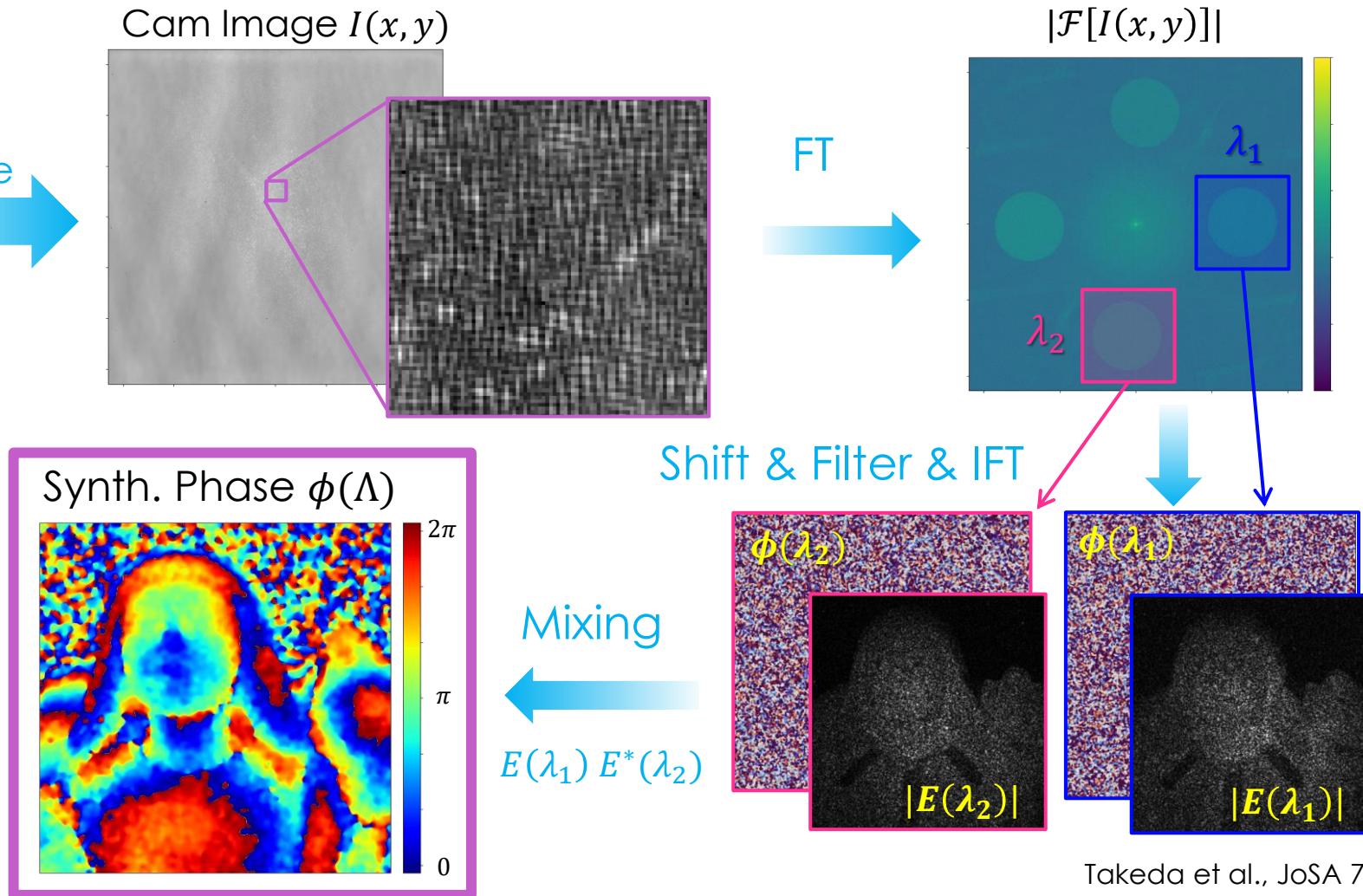
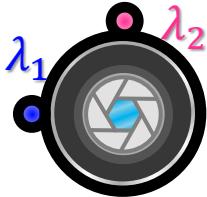
Takeda et al., JoSA 72(1), 1982

M. Ballester\*, H. Wang\*, J. Li, O. Cossairt, F. Willomitzer.

'Single-shot ToF sensing with sub-mm precision using conventional CMOS sensors', Arxiv Preprint, 2022

# Solution: Single-shot acquisition

Reminder  
last slide:



M. Ballester\*, H. Wang\*, J. Li, O. Cossairt, F. Willomitzer.

'Single-shot ToF sensing with sub-mm precision using conventional CMOS sensors', Arxiv Preprint, 2022

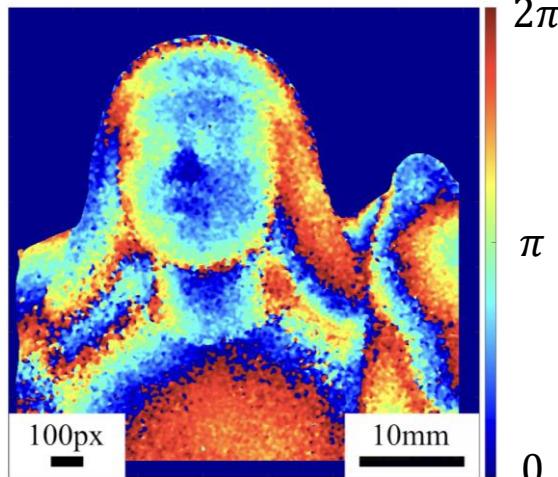
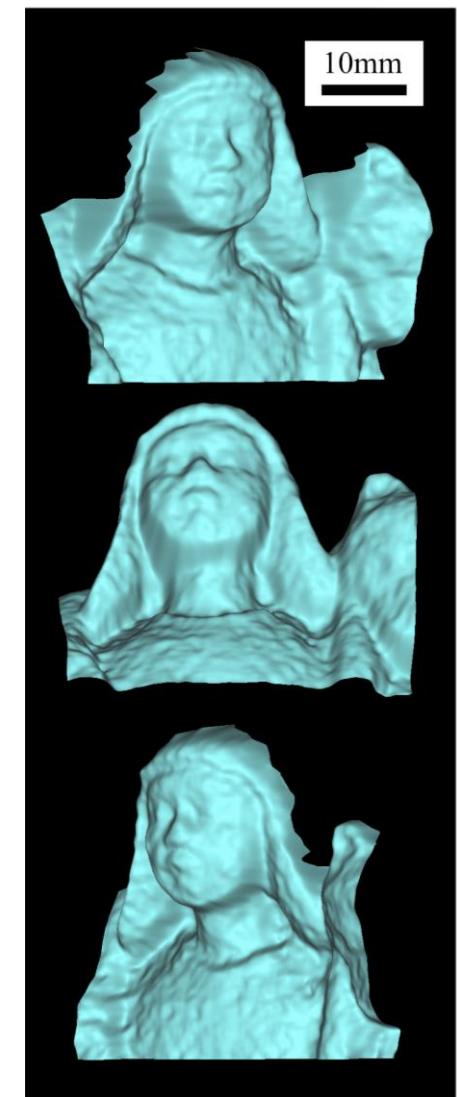
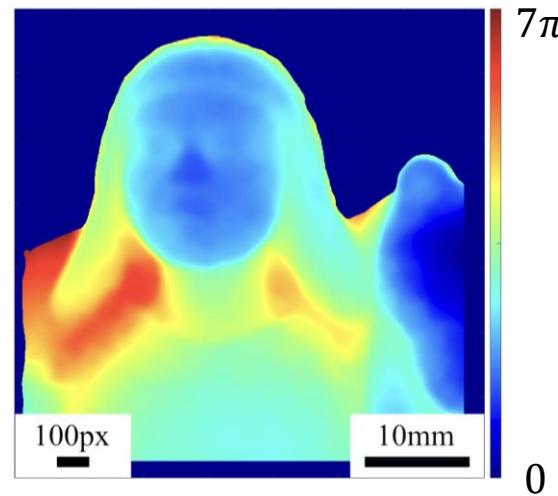
# Results

(single-shot)

Object



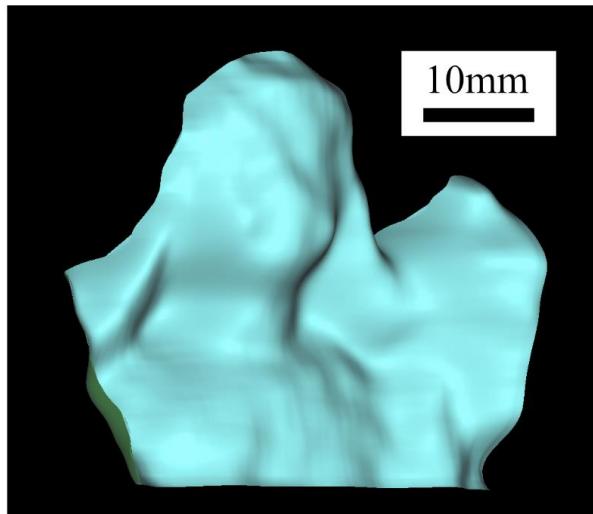
Small figure

 $\phi_{wrapped}(\Lambda = 10mm)$ 3D model  
 $\Lambda = 10mm$   
 $\delta z \approx 1.8mm$  $\phi_{unwrapped}(\Lambda = 10mm)$ 

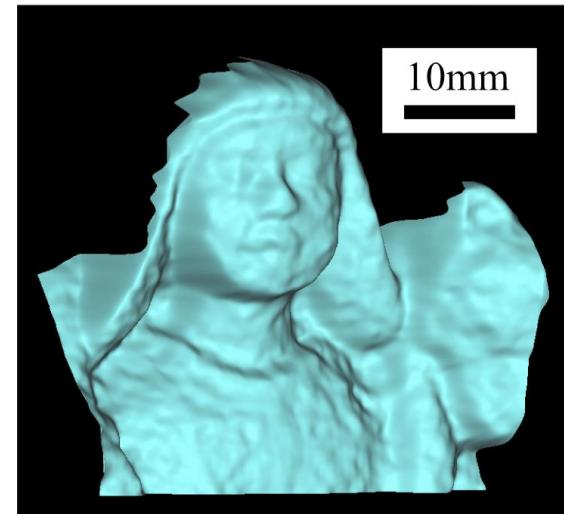
EXPERIMENT

# Quantitative analysis of distance precision $\delta z$

$\Lambda$ [mm]	40	10	5	3	1
$\delta z_{\text{single}}$ [mm]	5.56	1.78	1.64	0.79	0.33



$\Lambda = 50mm$



$\Lambda = 10mm$

M. Ballester\*, H. Wang\*, J. Li, O. Cossairt, F. Willomitzer.  
'Single-shot ToF sensing with sub-mm precision using conventional CMOS sensors', Arxiv Preprint, 2022

# Results

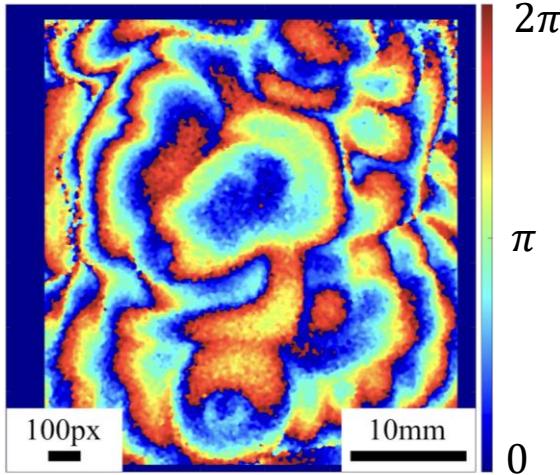
(dual shot)

Object

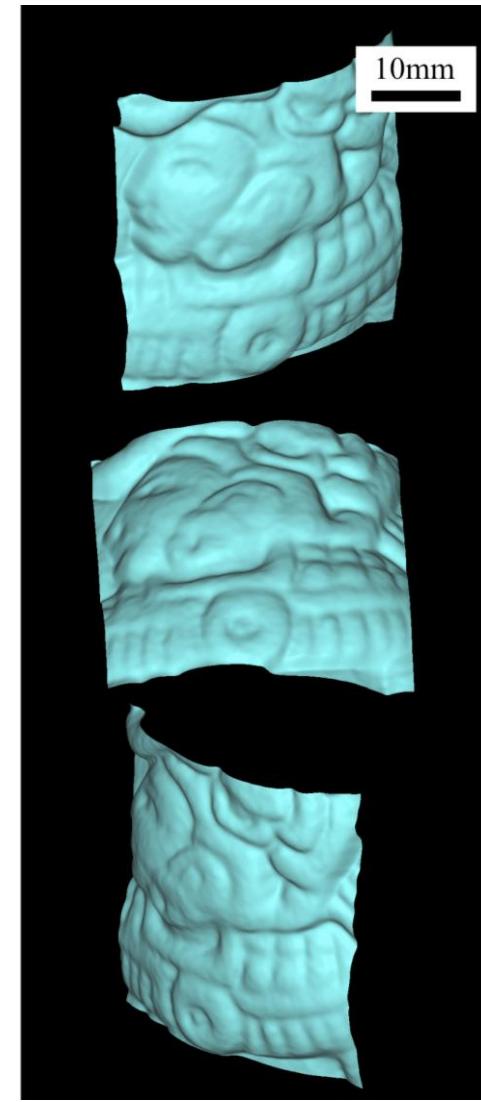


Clay pot

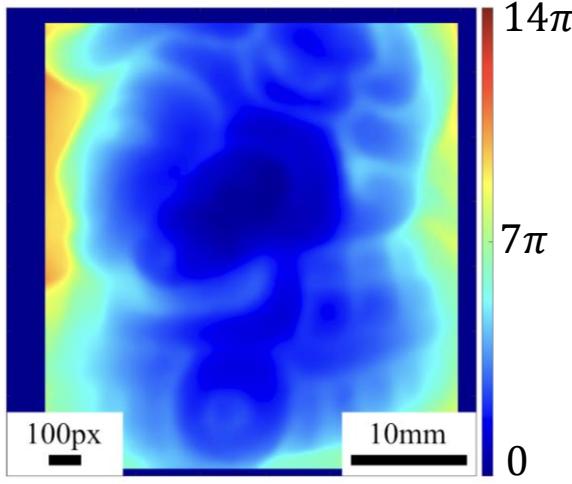
$\phi_{wrapped}(\Lambda = 3mm)$



3D model  
 $\Lambda = 3mm$   
 $\delta z \approx 0.8mm$



$\phi_{unwrapped}(\Lambda = 3mm)$



EXPERIMENT

# Results

Object

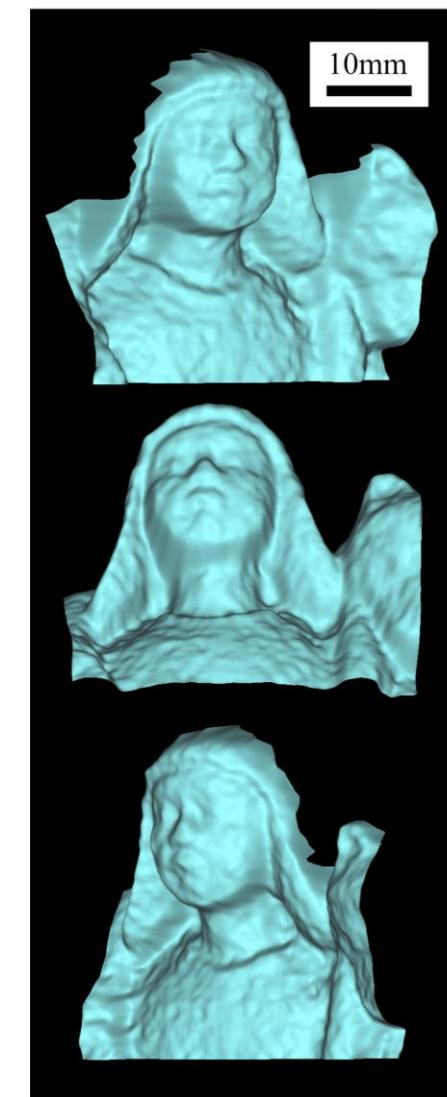
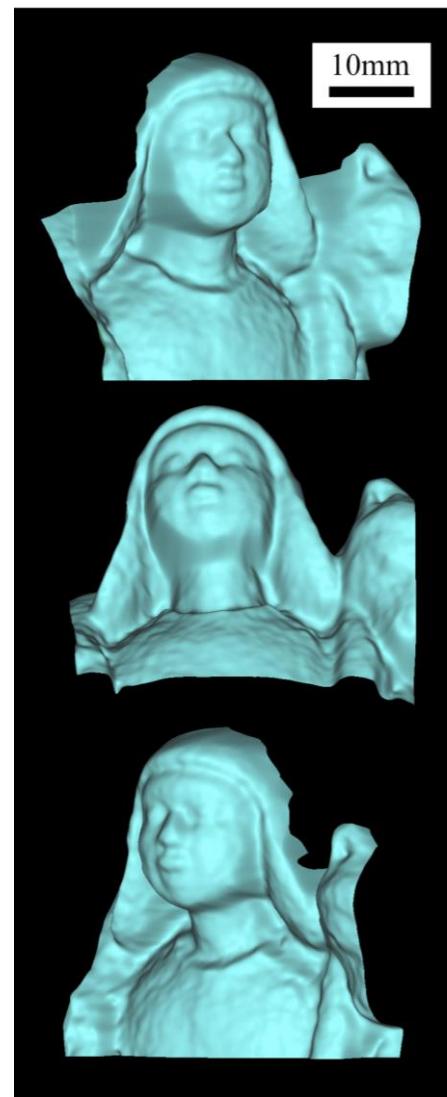


Small figure

3D model  $\Lambda = 10\text{mm}$

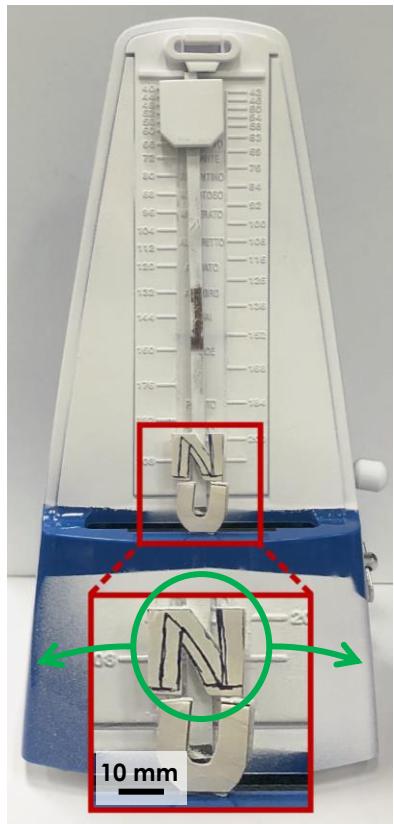
Dual-shot

vs. Single-shot

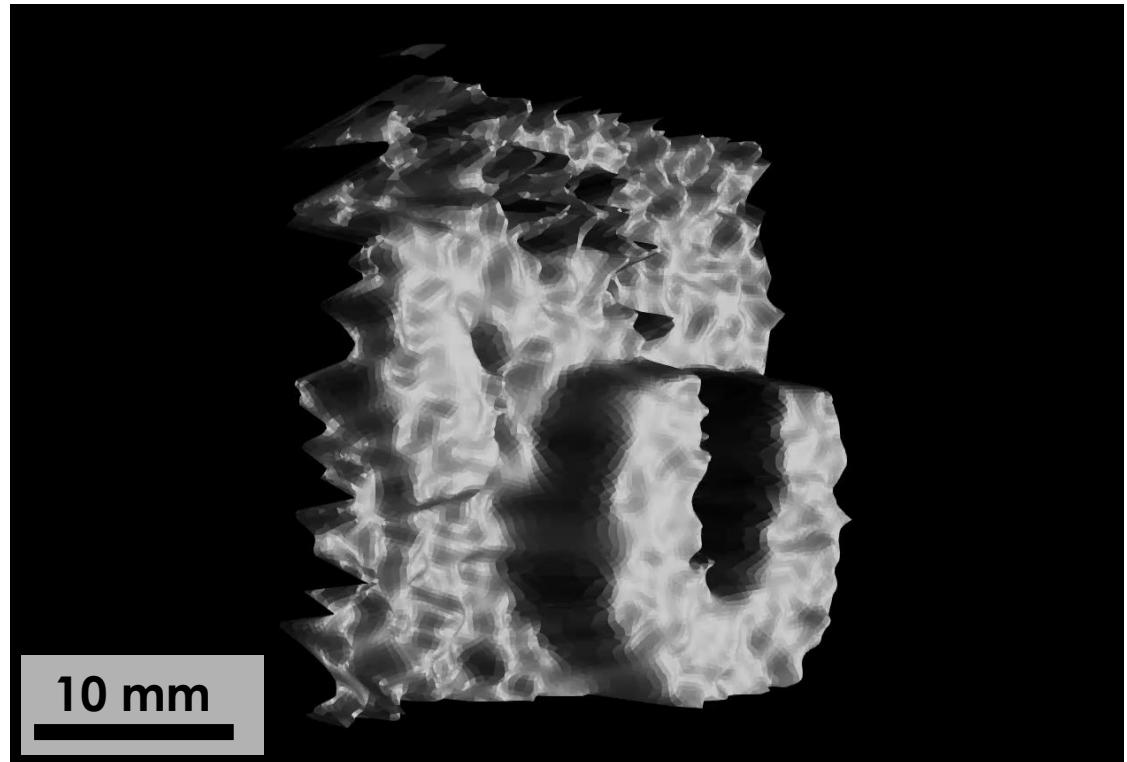


# Video acquisition

Object:  
metronome



3D Video

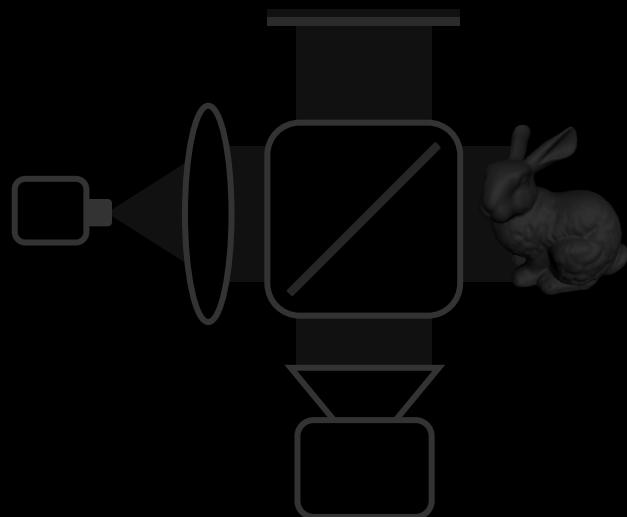


M. Ballester\*, H. Wang\*, J. Li, O. Cossairt, F. Willomitzer.  
'Single-shot ToF sensing with sub-mm precision using conventional CMOS sensors', Arxiv Preprint, 2022

**End Part 2**

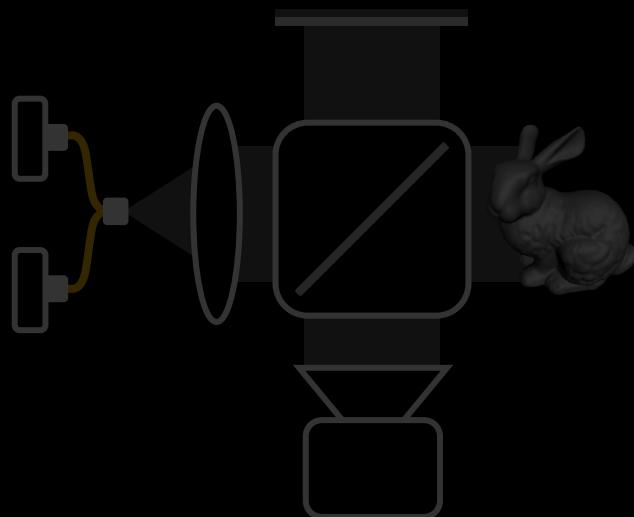
# Course overview

introduction to  
interferometry



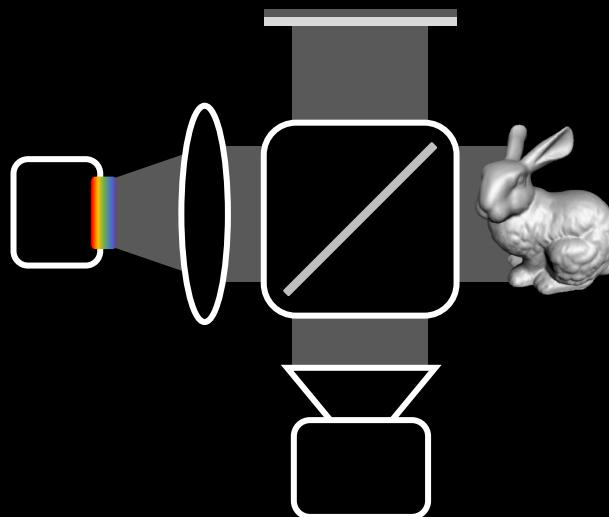
Yannis

two-wavelength  
interferometry



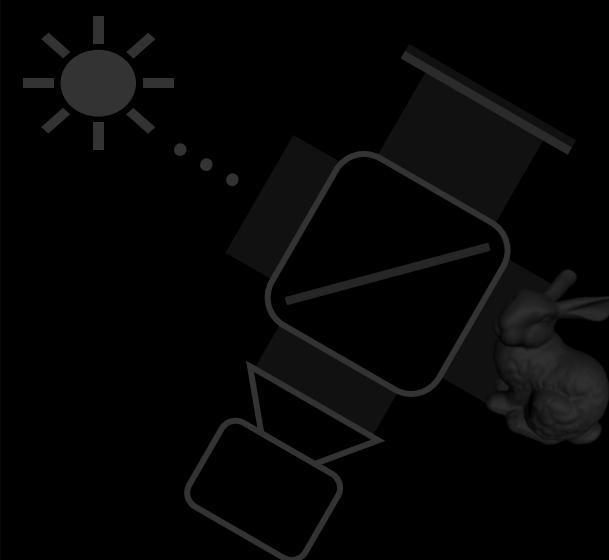
Florian

partially-coherent  
interferometry



Alankar

interferometric  
computational imaging

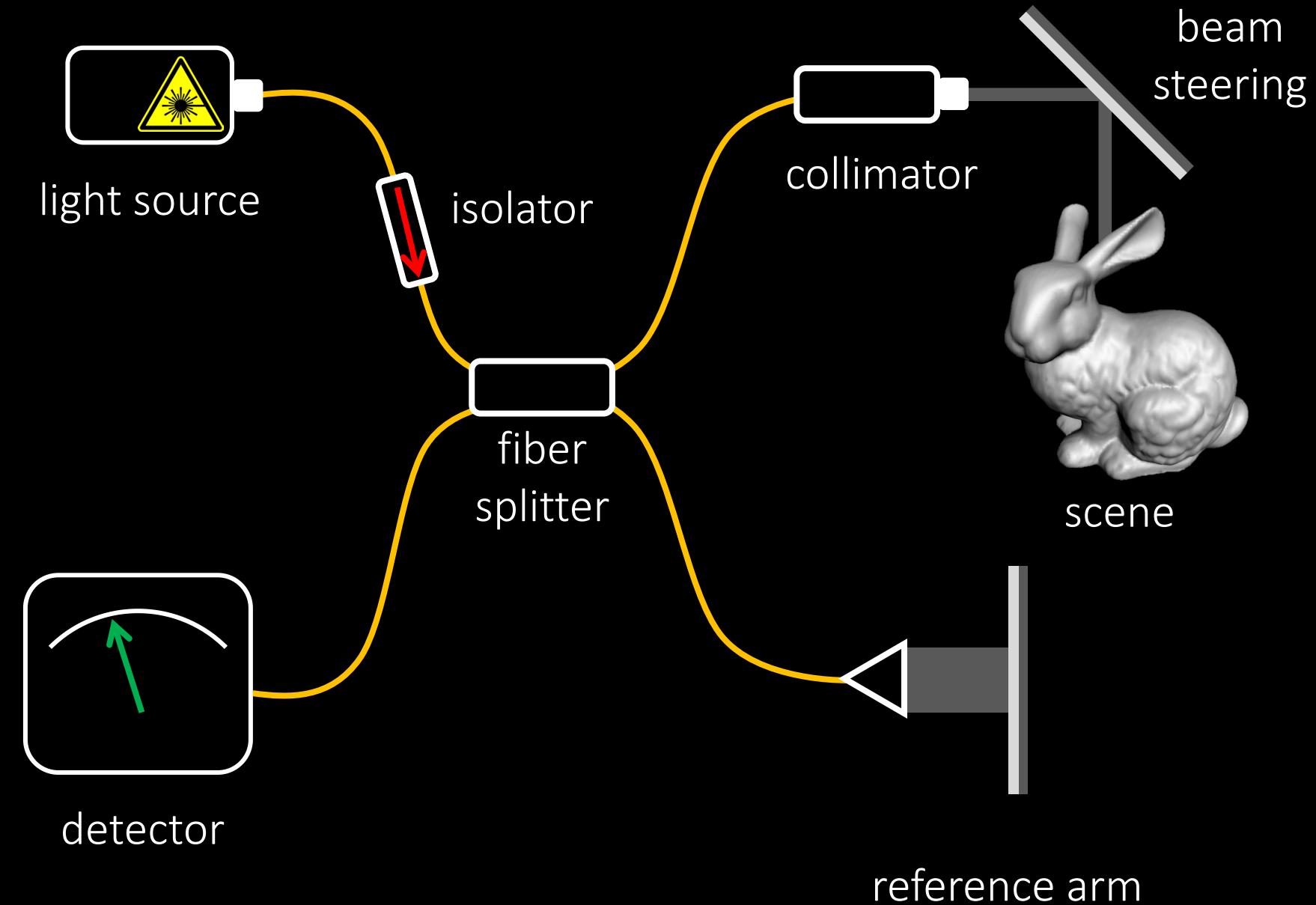


Florian

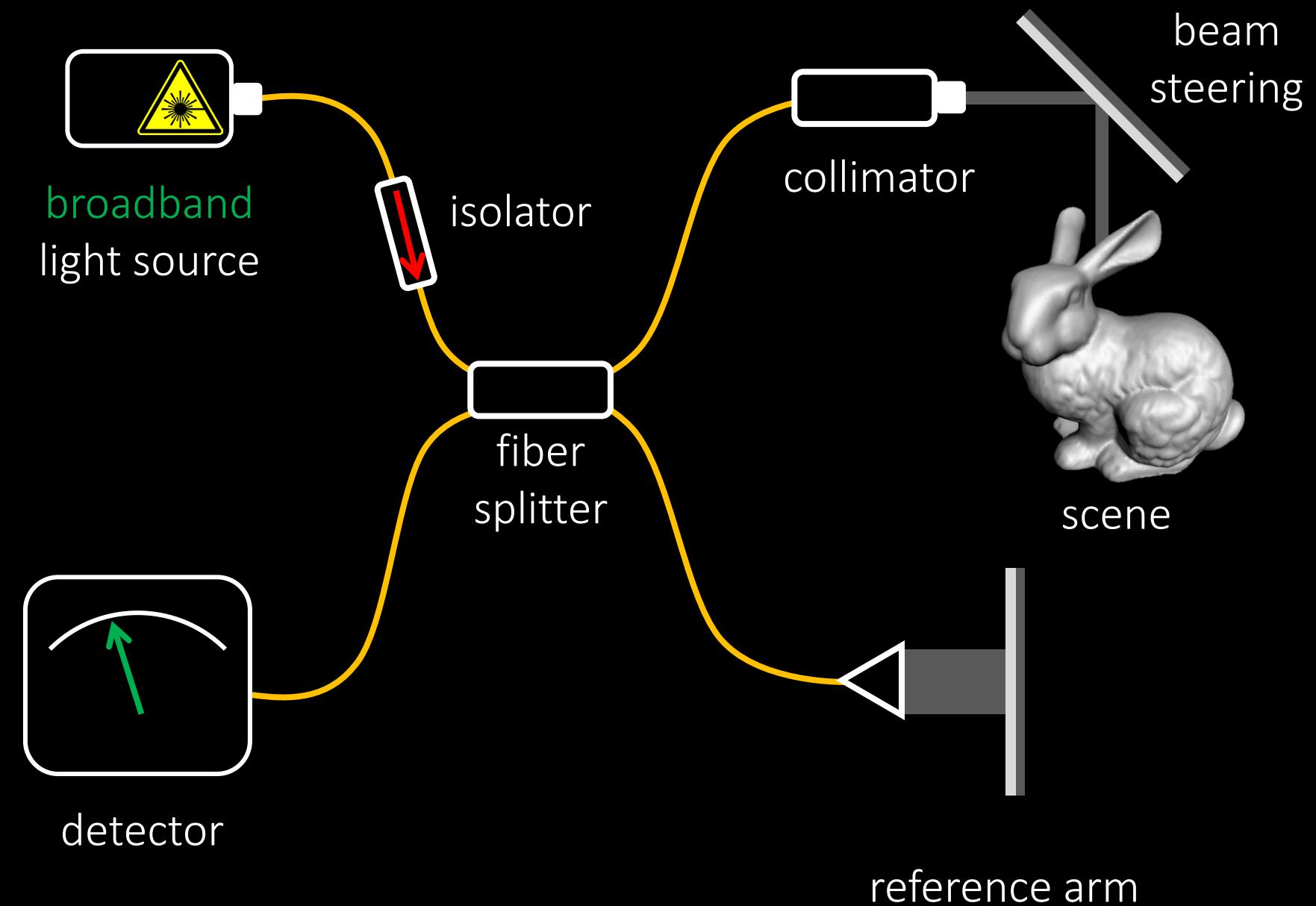


Yannis

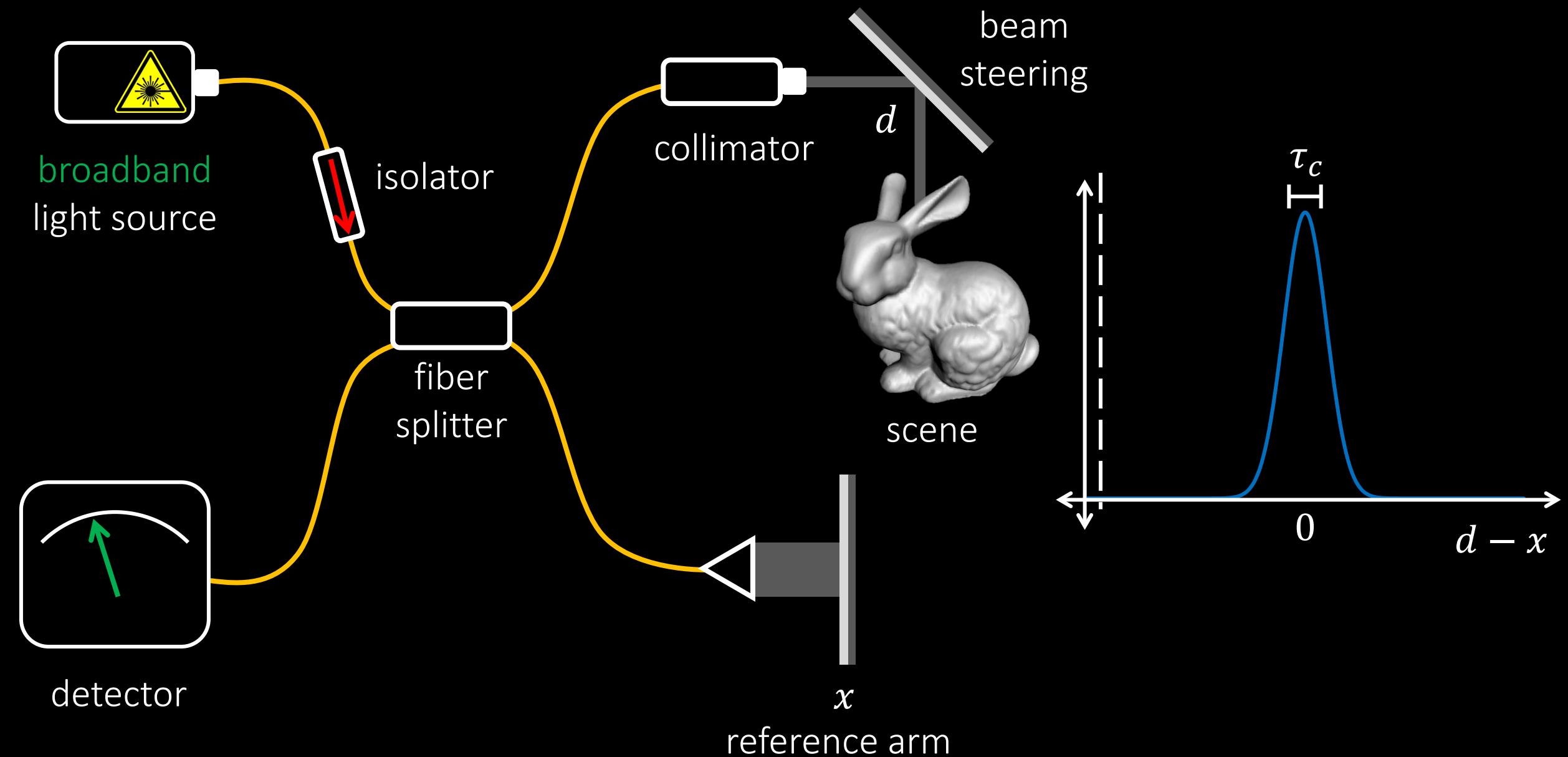
# Fiber-based interferometry



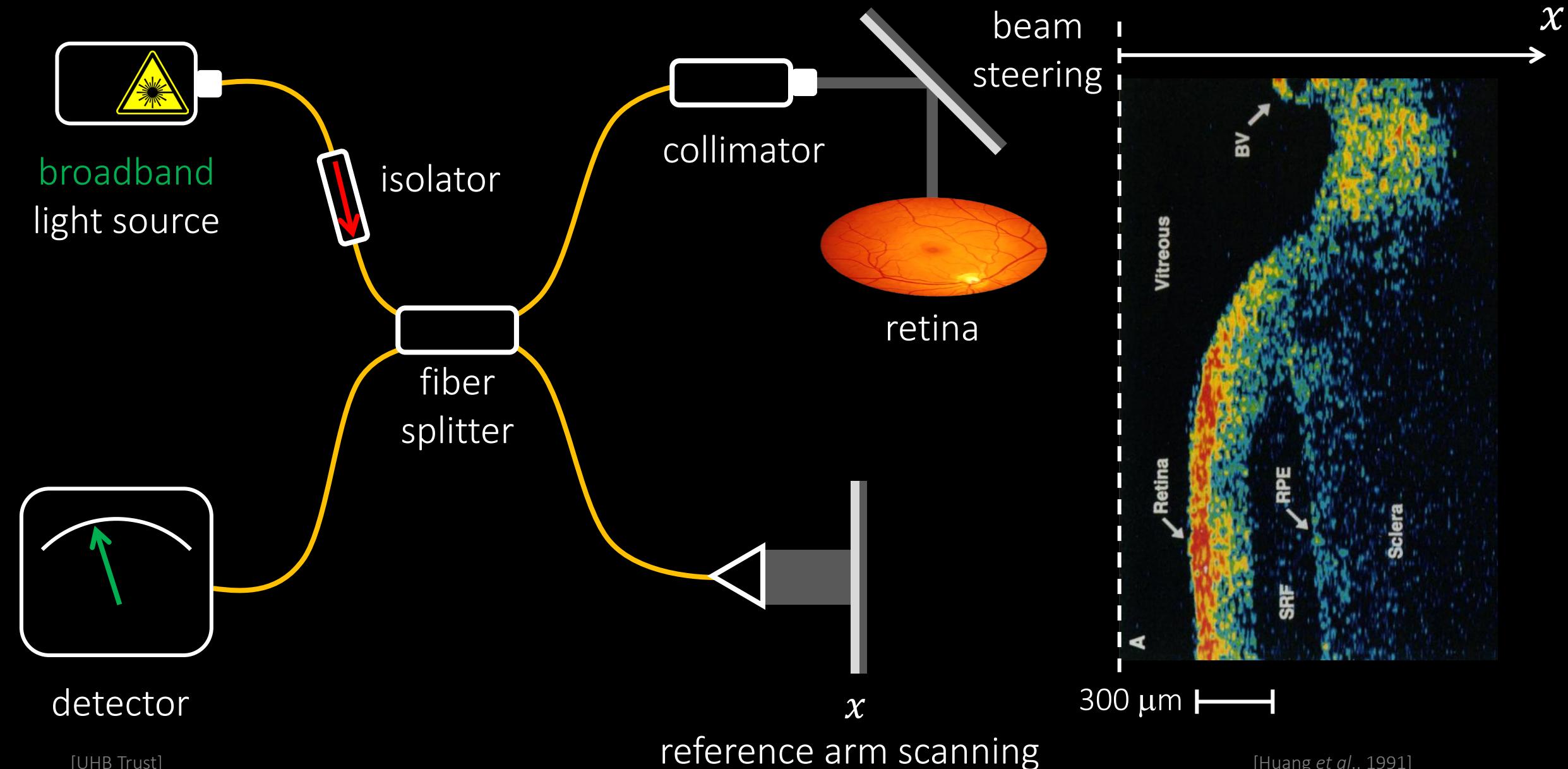
# Time-domain optical coherence tomography



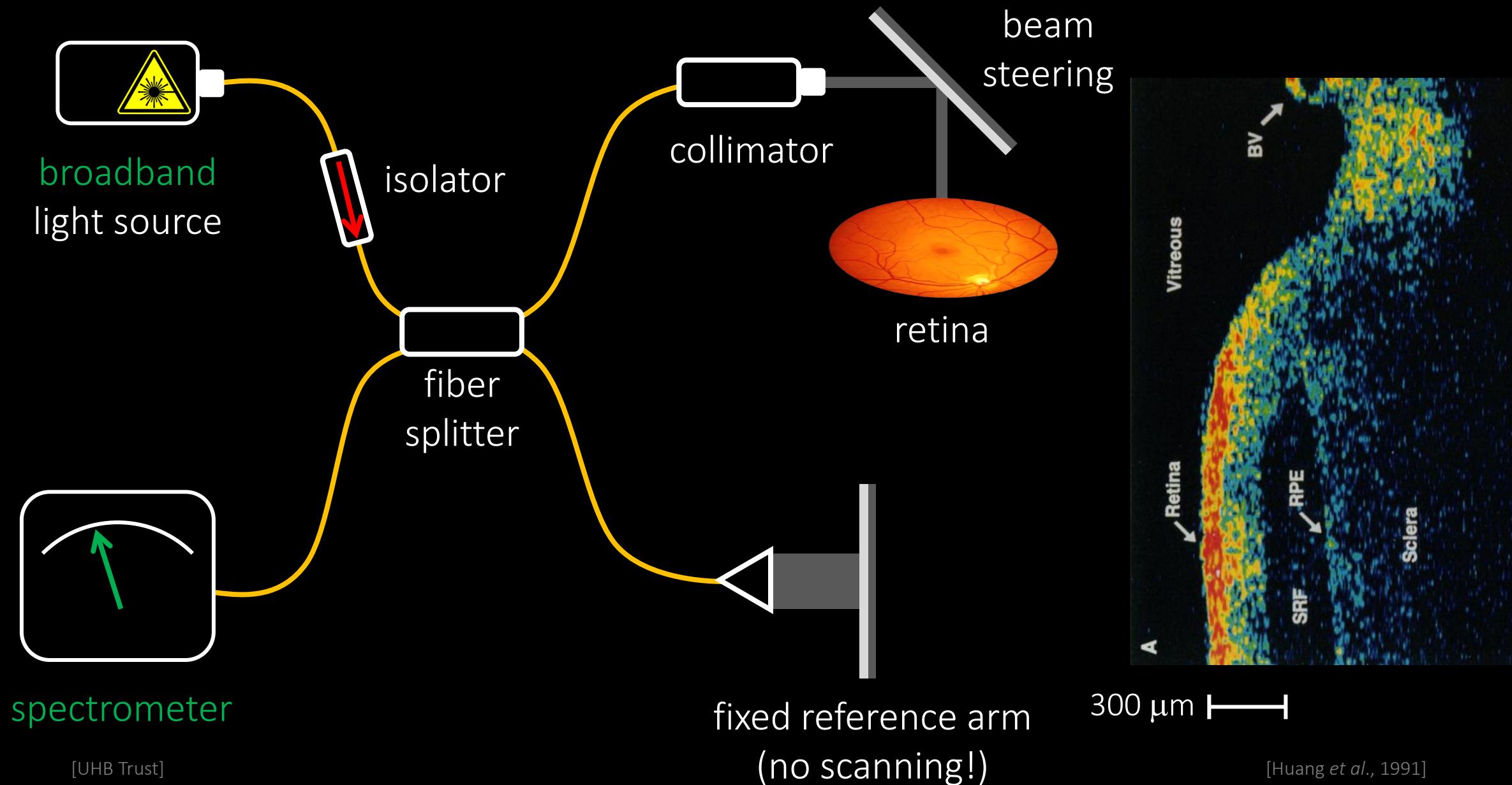
# Time-domain optical coherence tomography



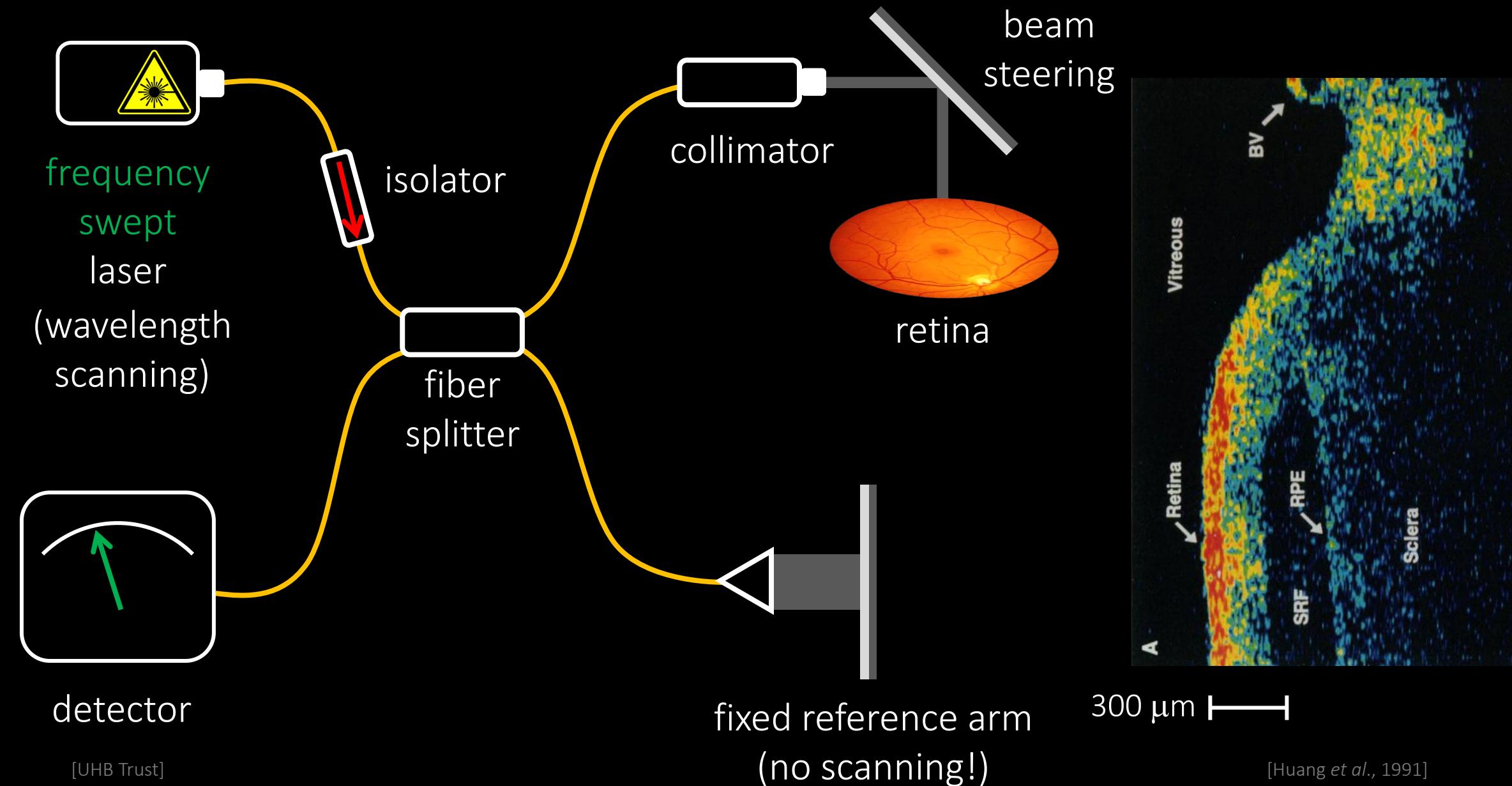
# Time-domain optical coherence tomography



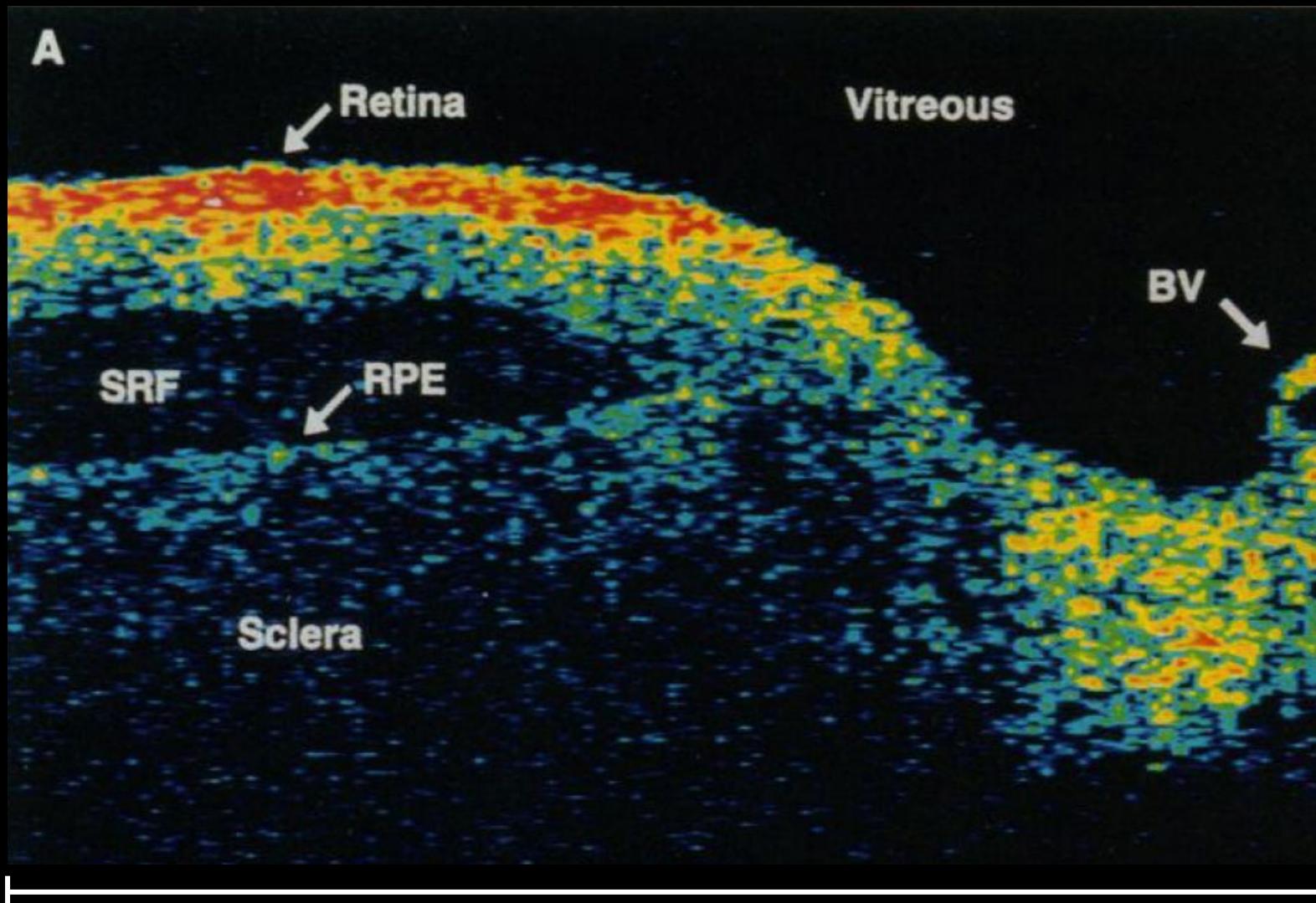
# Frequency-domain optical coherence tomography



# Swept-source optical coherence tomography



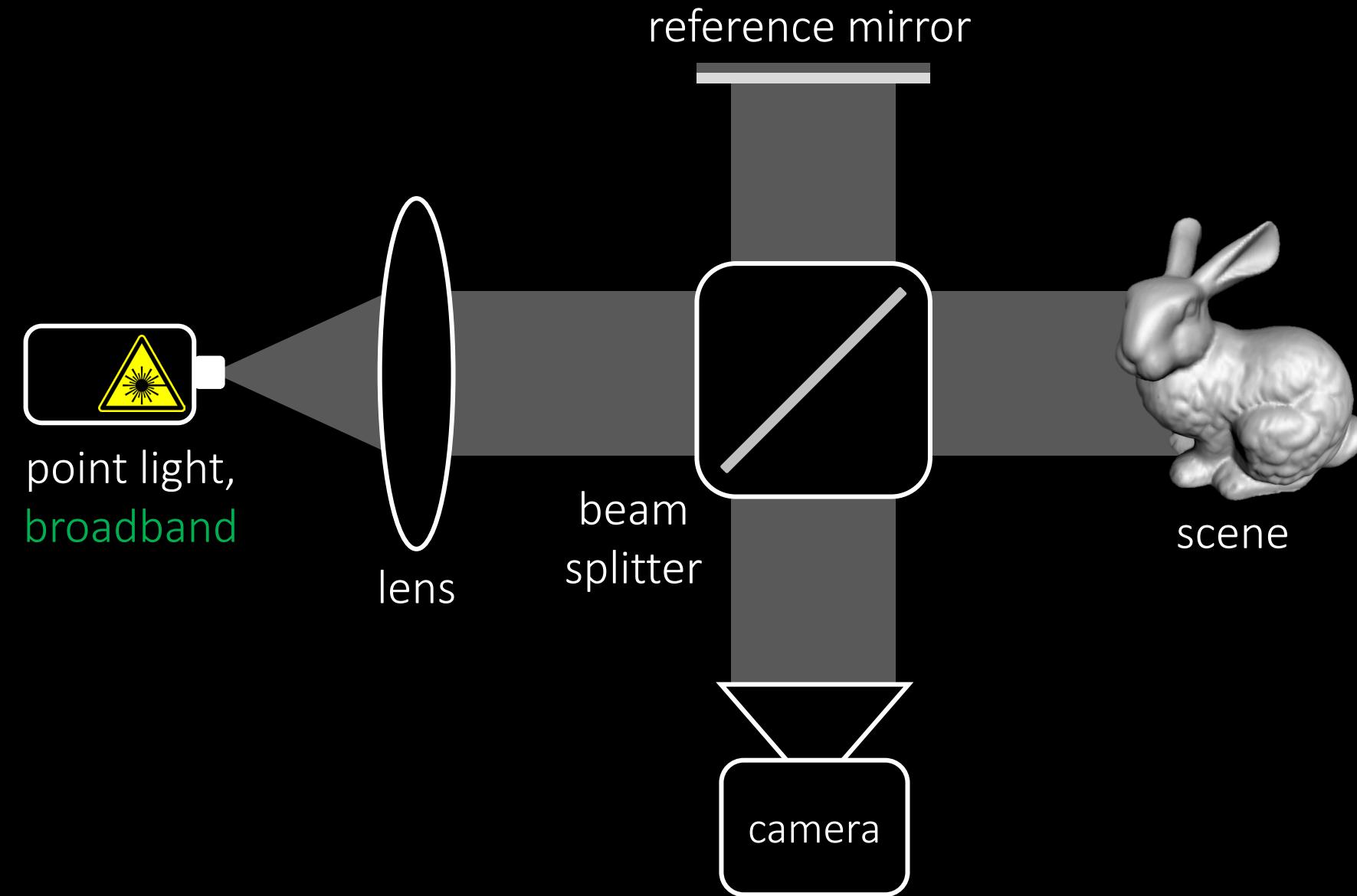
# Swept-source optical coherence tomography



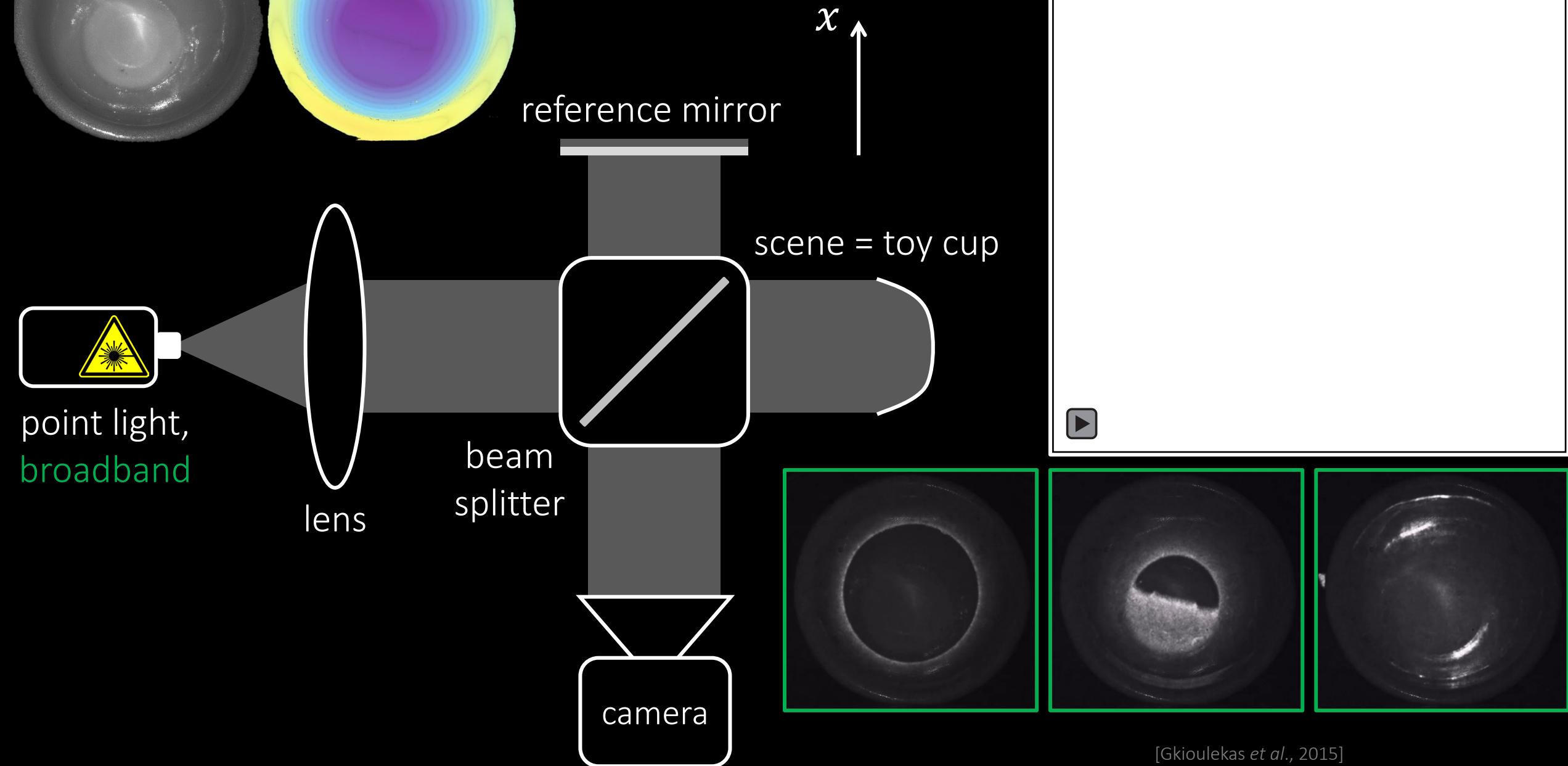
2 mm

[Huang *et al.*, 1991]

# Full-field OCT



# Full-field TD-OCT



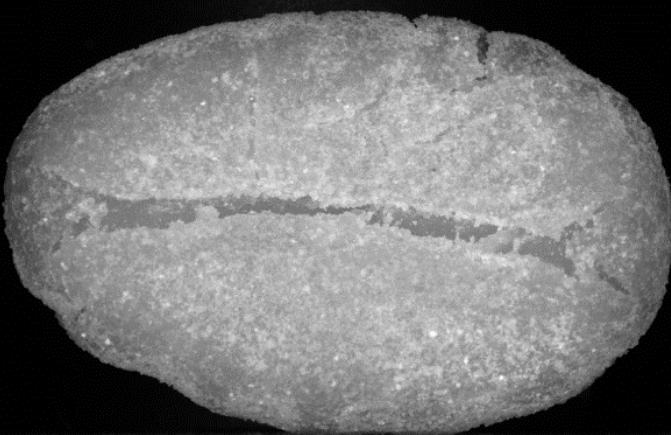
# Micron-scale shape scanning

depth resolution  $\sim 5 \mu\text{m}$

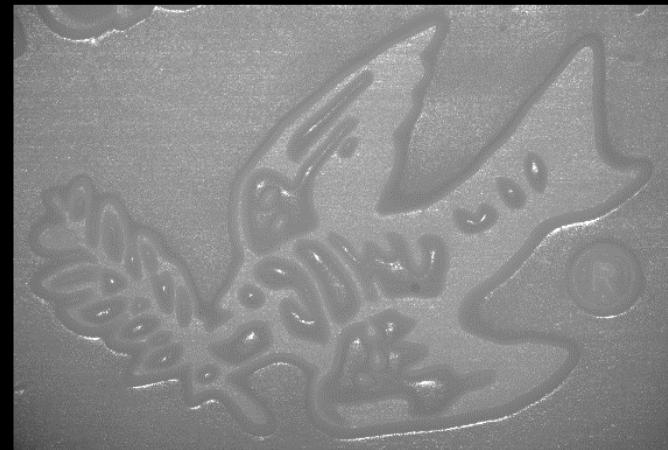
coin



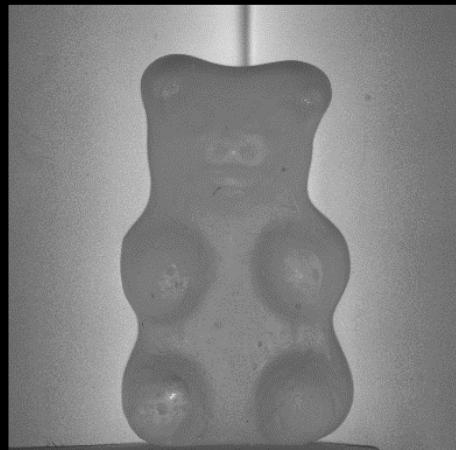
gnocchi



soap carving

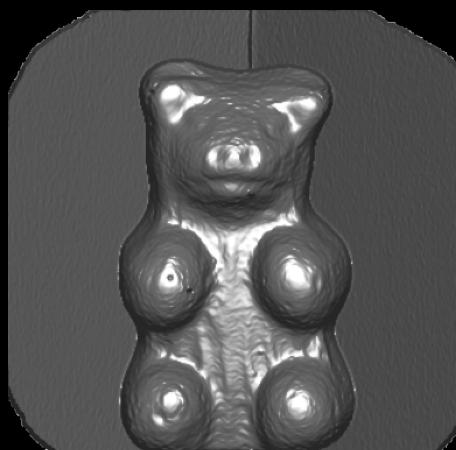


gummy bear



captured image

scanned shape



# OCT v/s SWI

full-field OCT

full-field SWI

# OCT v/s SWI

	full-field OCT	full-field SWI
depth range	constrained by reference translation	synthetic wavelength (separation between wavelengths)
phase wrapping	no	yes

# OCT v/s SWI

	full-field OCT	full-field SWI
depth range	constrained by reference translation	synthetic wavelength (separation between wavelengths)
phase wrapping	no	yes
depth resolution	spectral bandwidth	separation between wavelengths

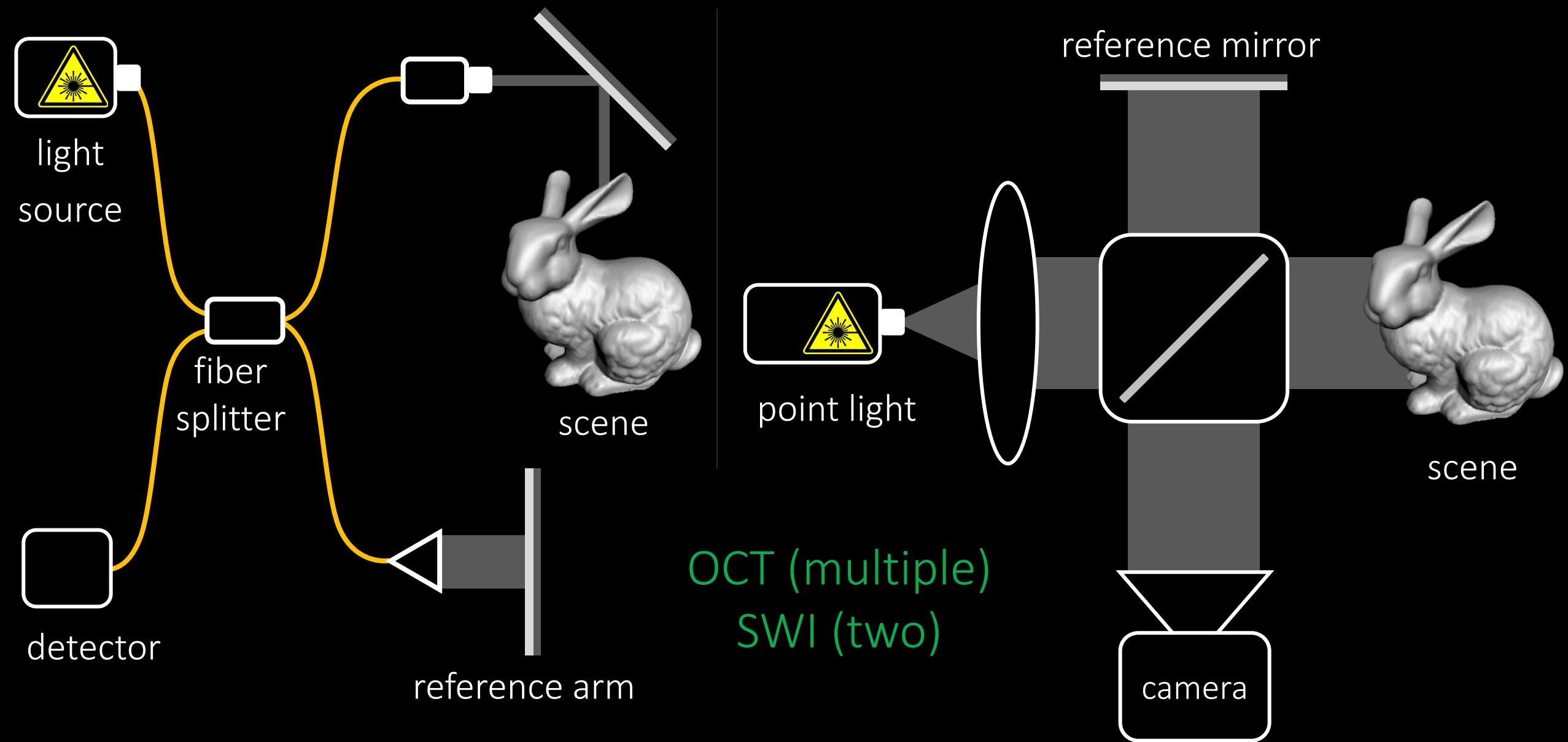
# OCT v/s SWI

	full-field OCT	full-field SWI
depth range	constrained by reference translation	synthetic wavelength (separation between wavelengths)
phase wrapping	no	yes
depth resolution	spectral bandwidth	separation between wavelengths
scanning	axial proportional to depth range OR lateral proportional to scene size	fixed axial scanning possibly single shot!

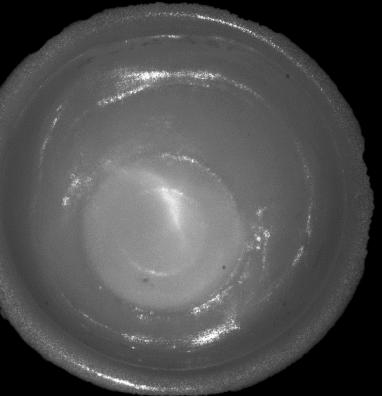
# OCT v/s SWI

	full-field OCT	full-field SWI
depth range	constrained by reference translation	synthetic wavelength (separation between wavelengths)
phase wrapping	no	yes
depth resolution	spectral bandwidth	separation between wavelengths
scanning	axial proportional to depth range OR lateral proportional to scene size	fixed axial scanning possibly single shot!
measurement	full tomography	surface-only

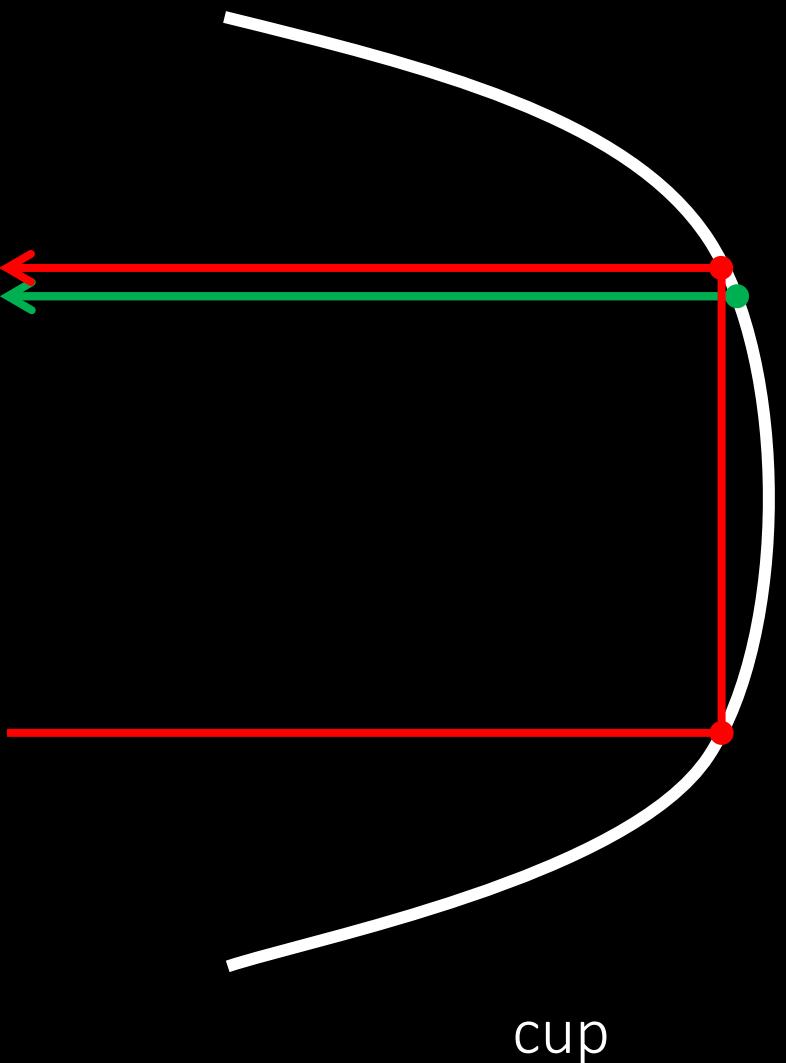
# Fiber v/s full-field



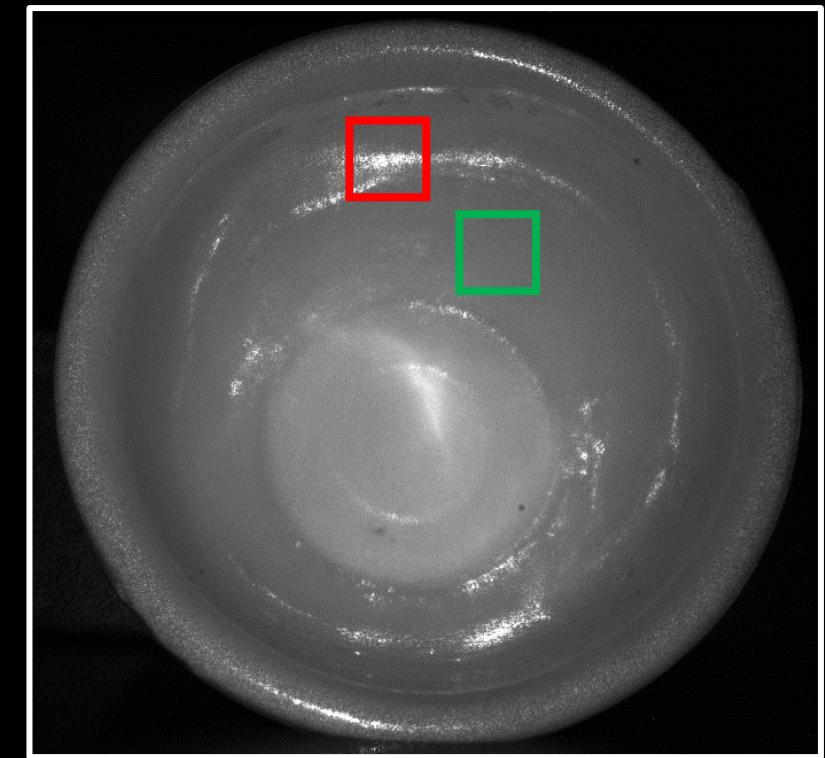
# Cup: image formation



'direct'  
+  
'retroreflective  
specular'

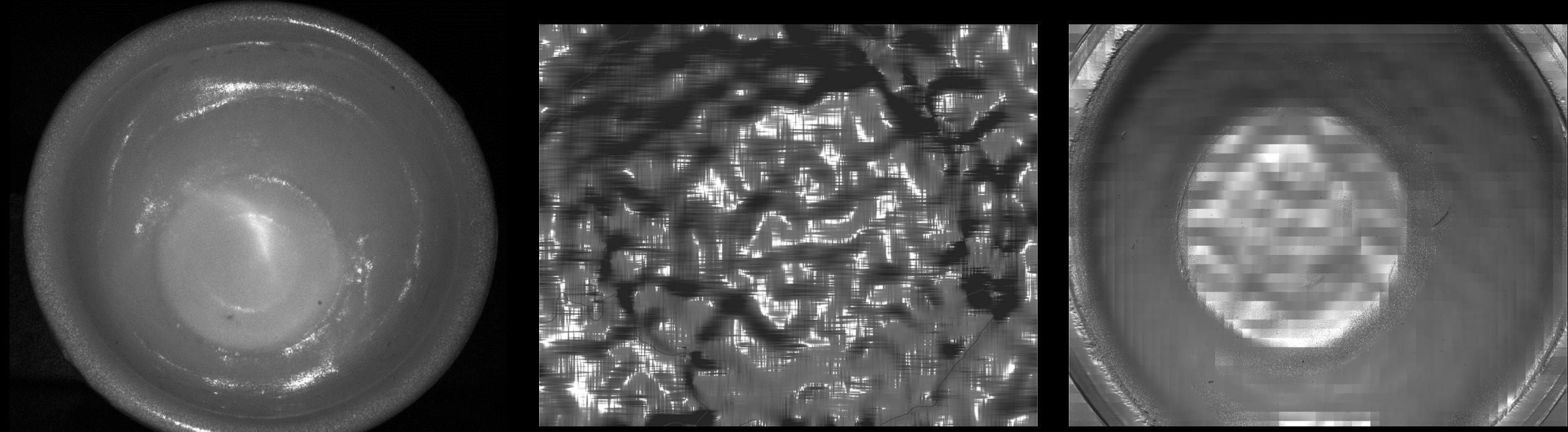


=



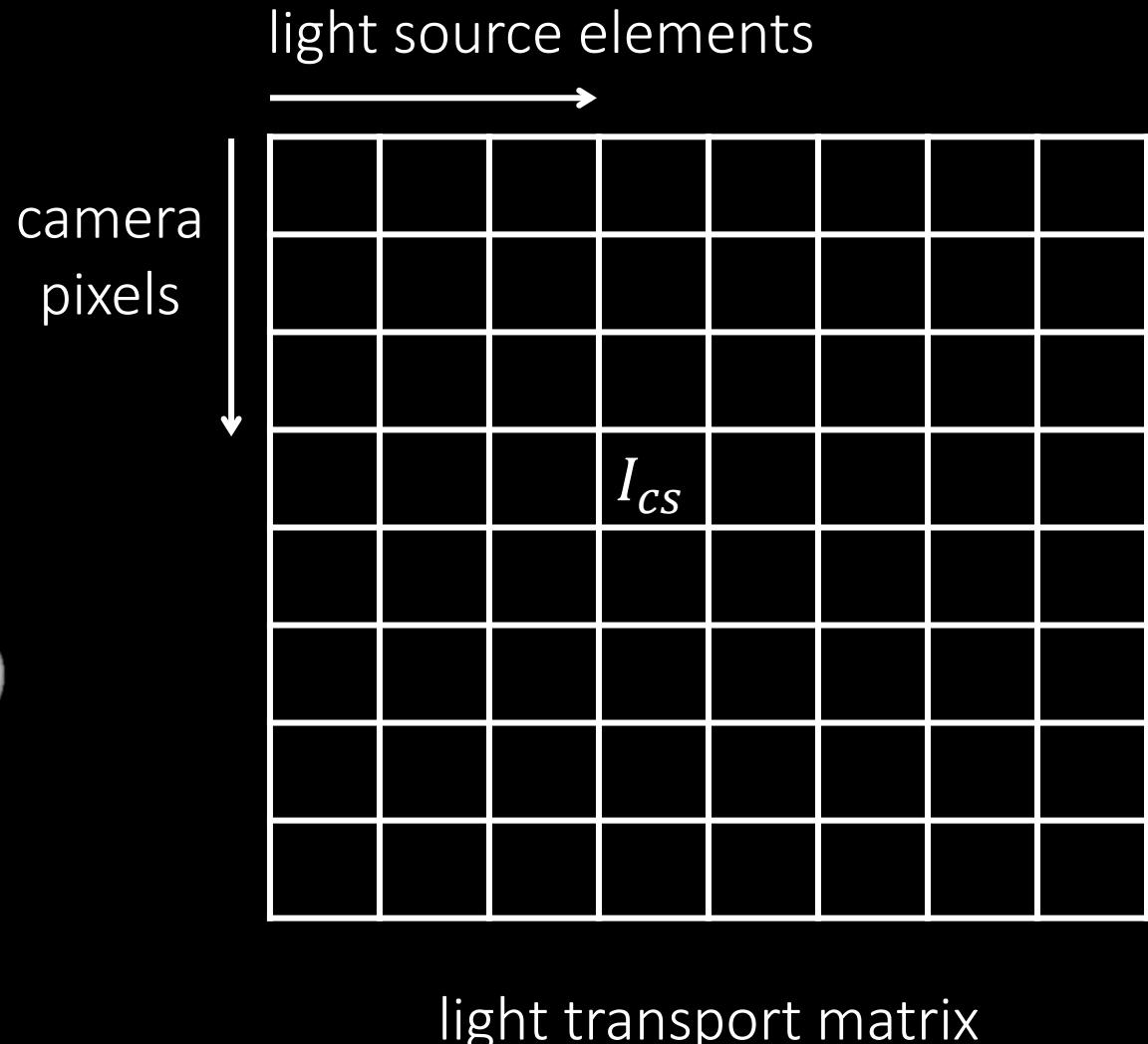
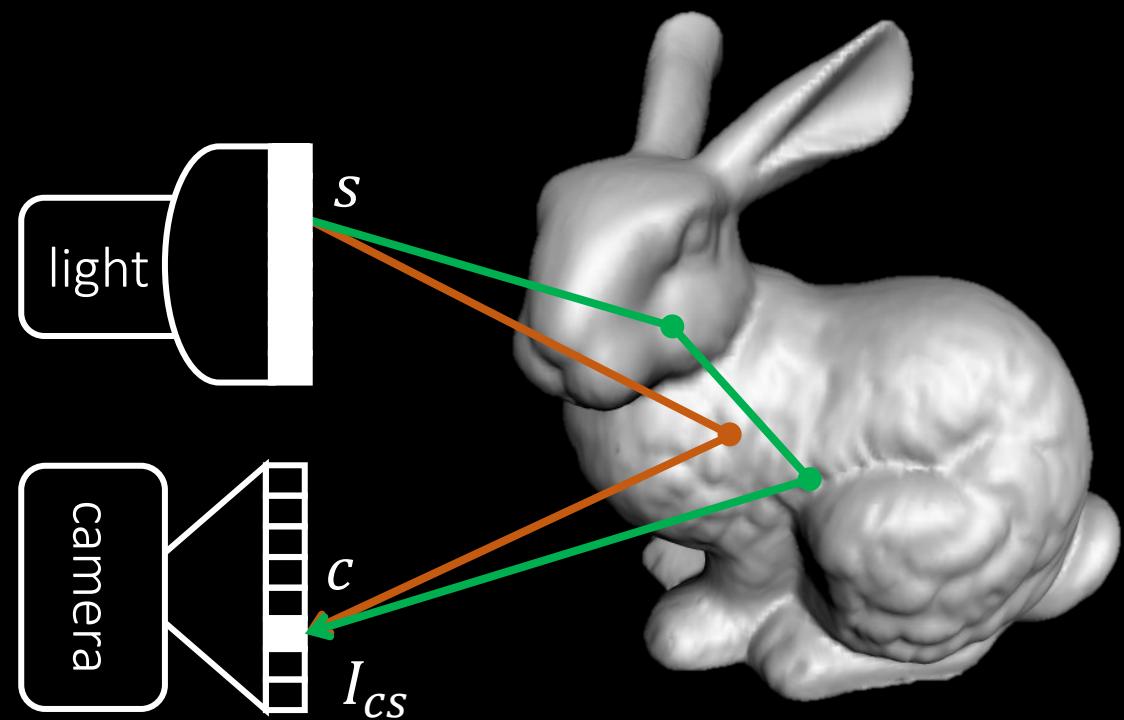
scene-only image

# Depth corruption due to indirect light

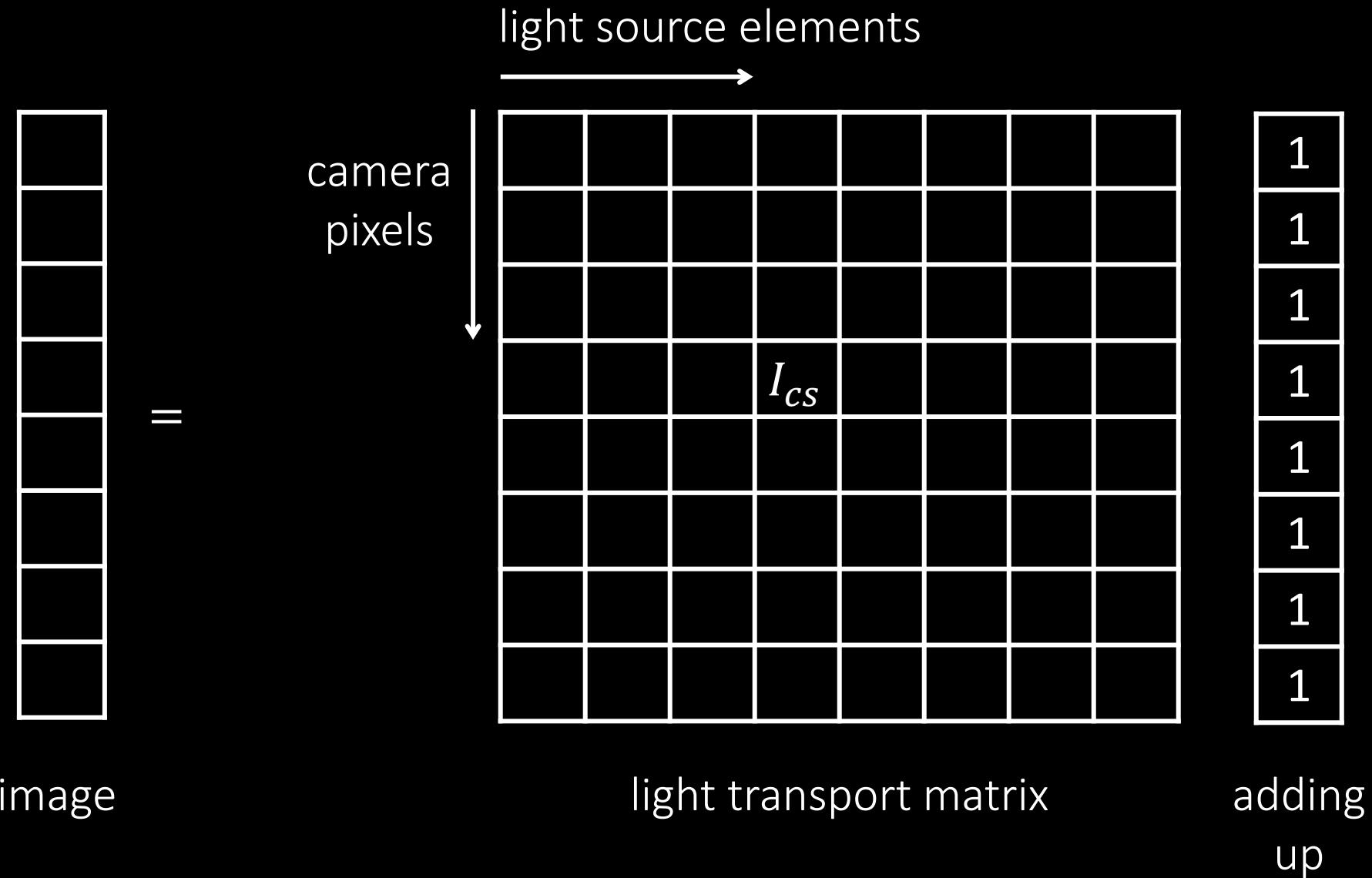


depth corruption

# Image formation and light transport

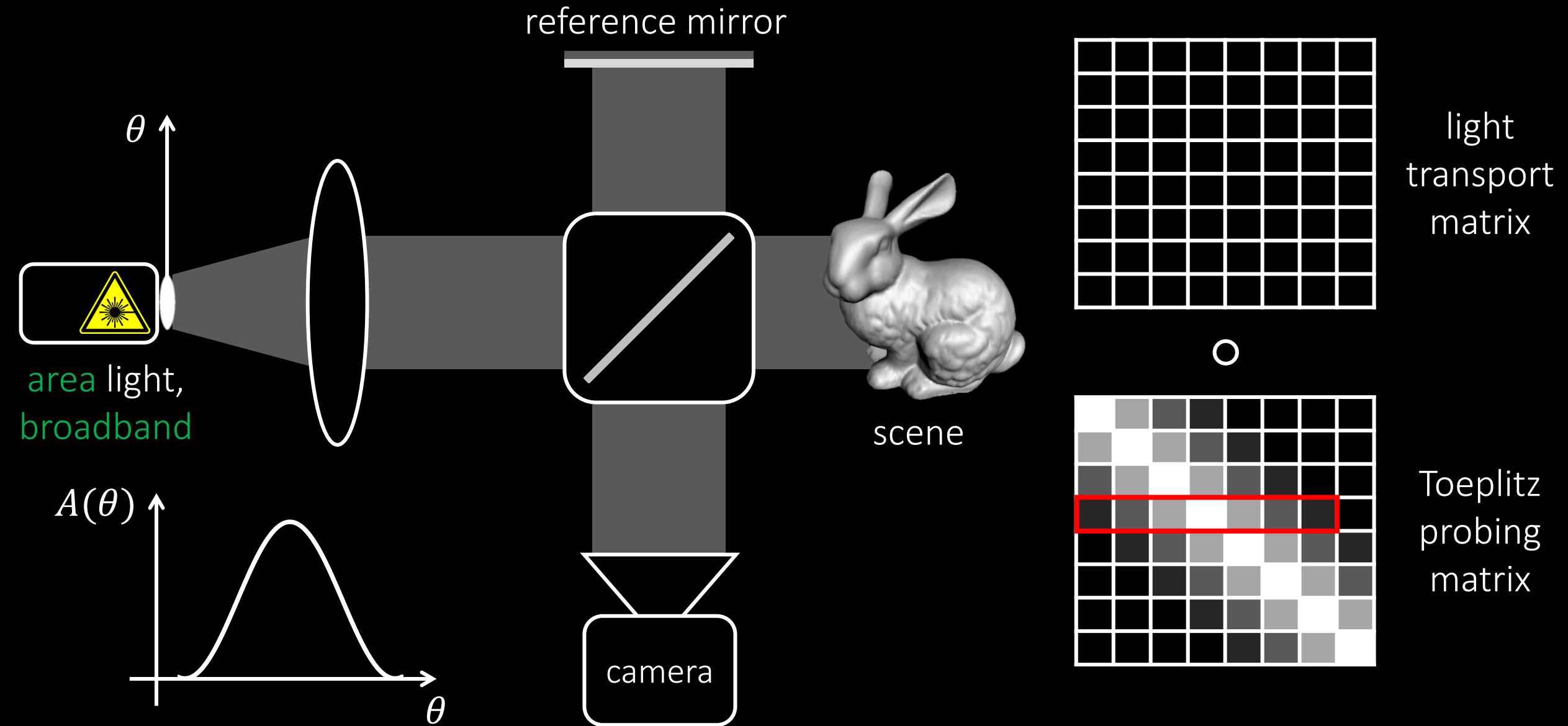


# Image formation and light transport

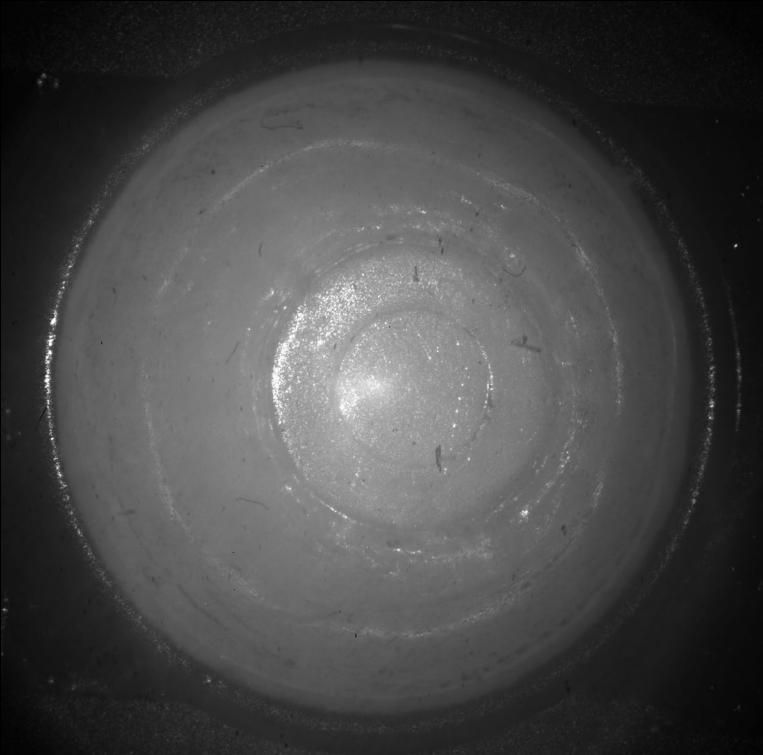


# Probing

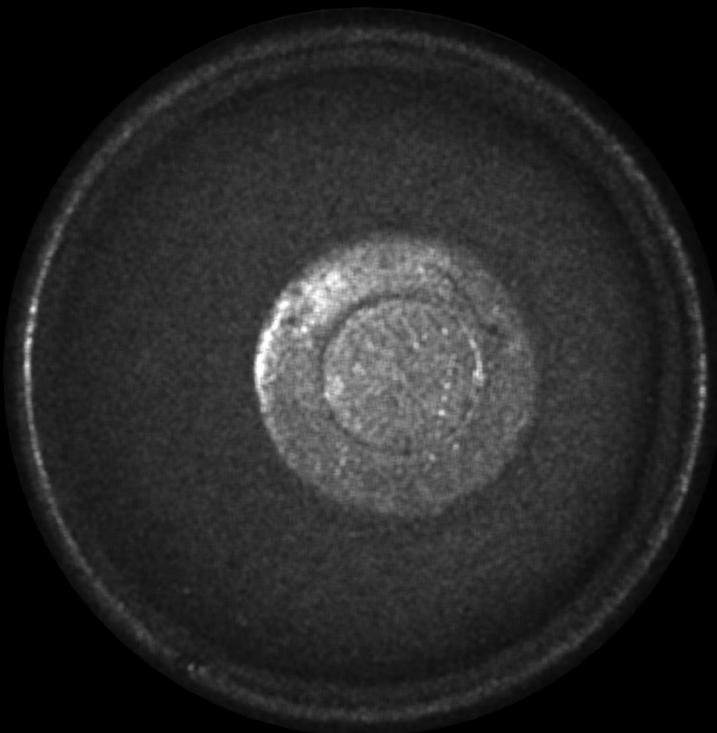
# Interferometric probing



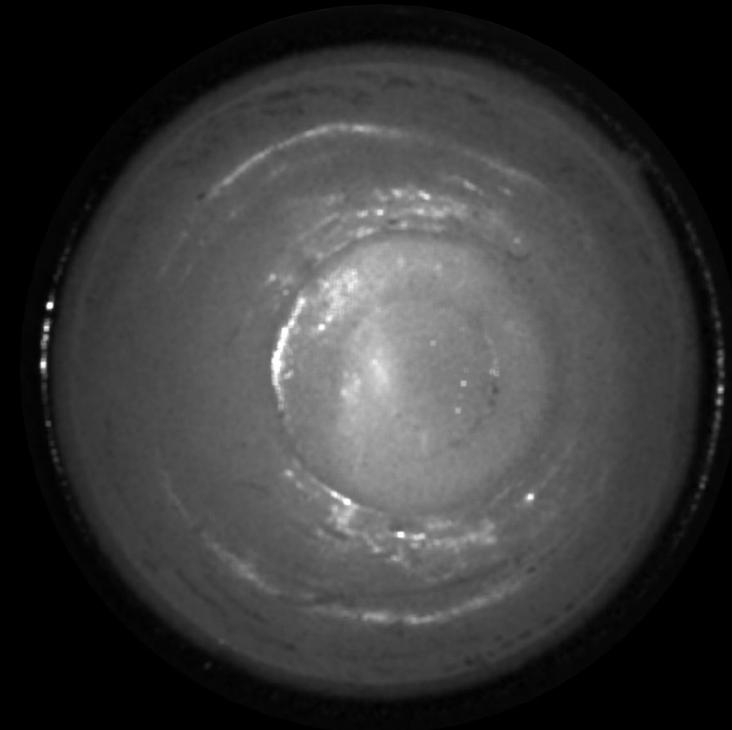
# Direct-indirect separation



scene

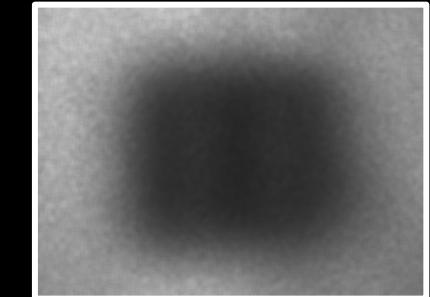
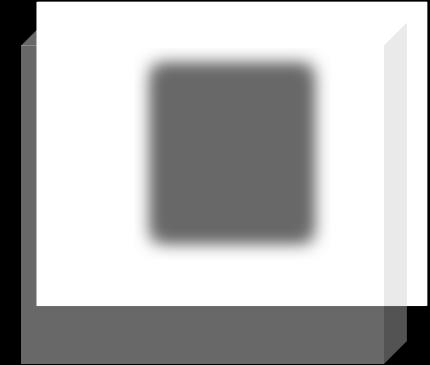


direct-only

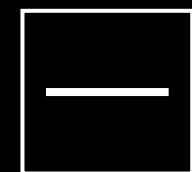
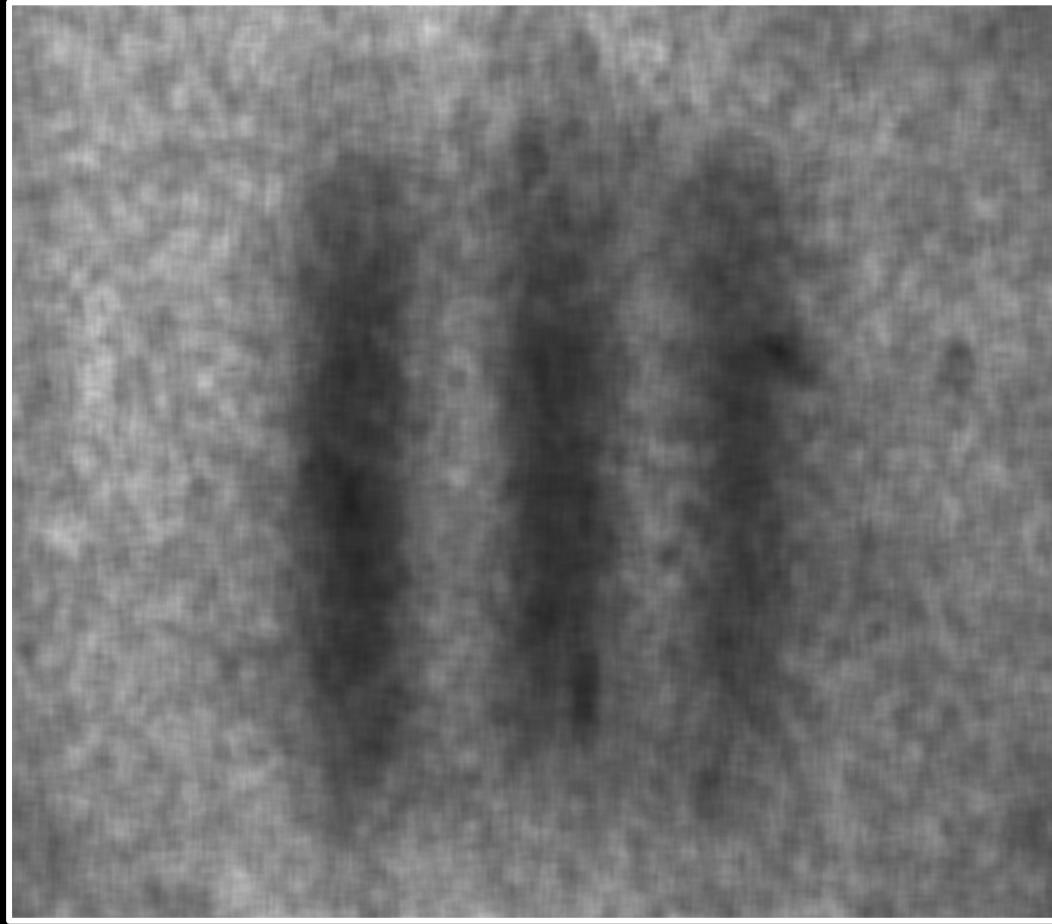


indirect-only

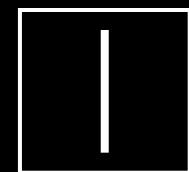
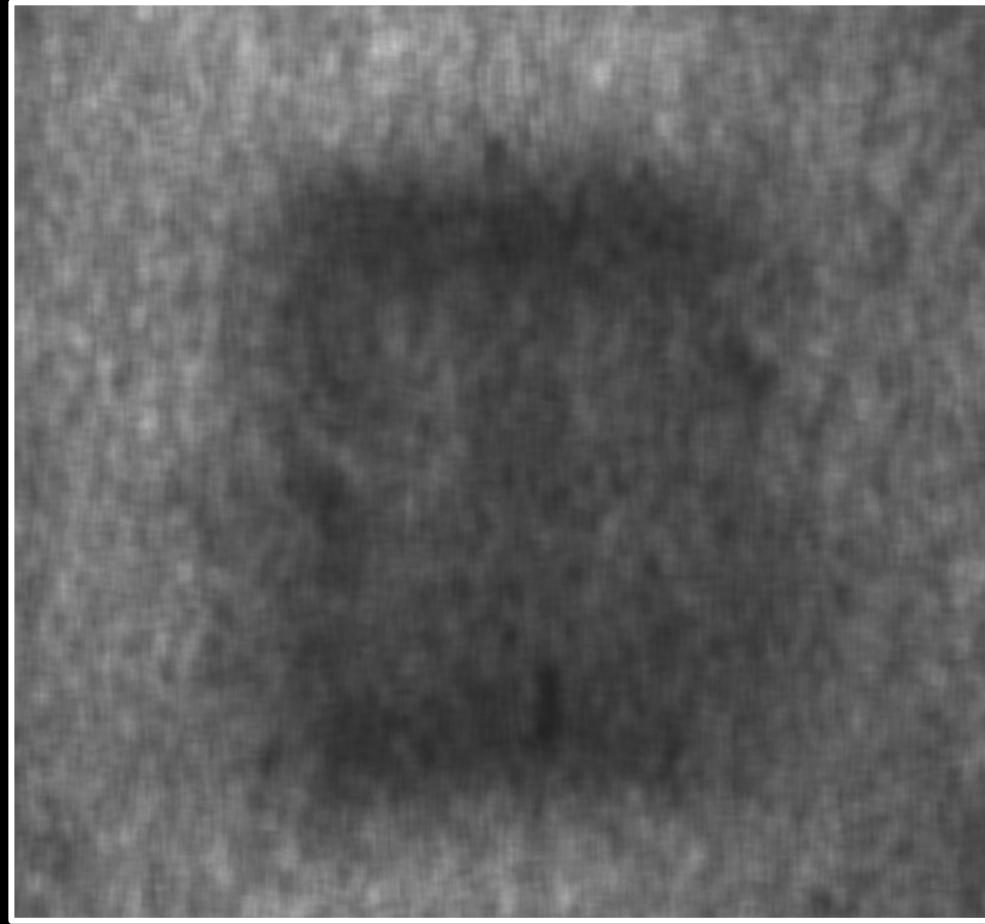
# Seeing through scattering



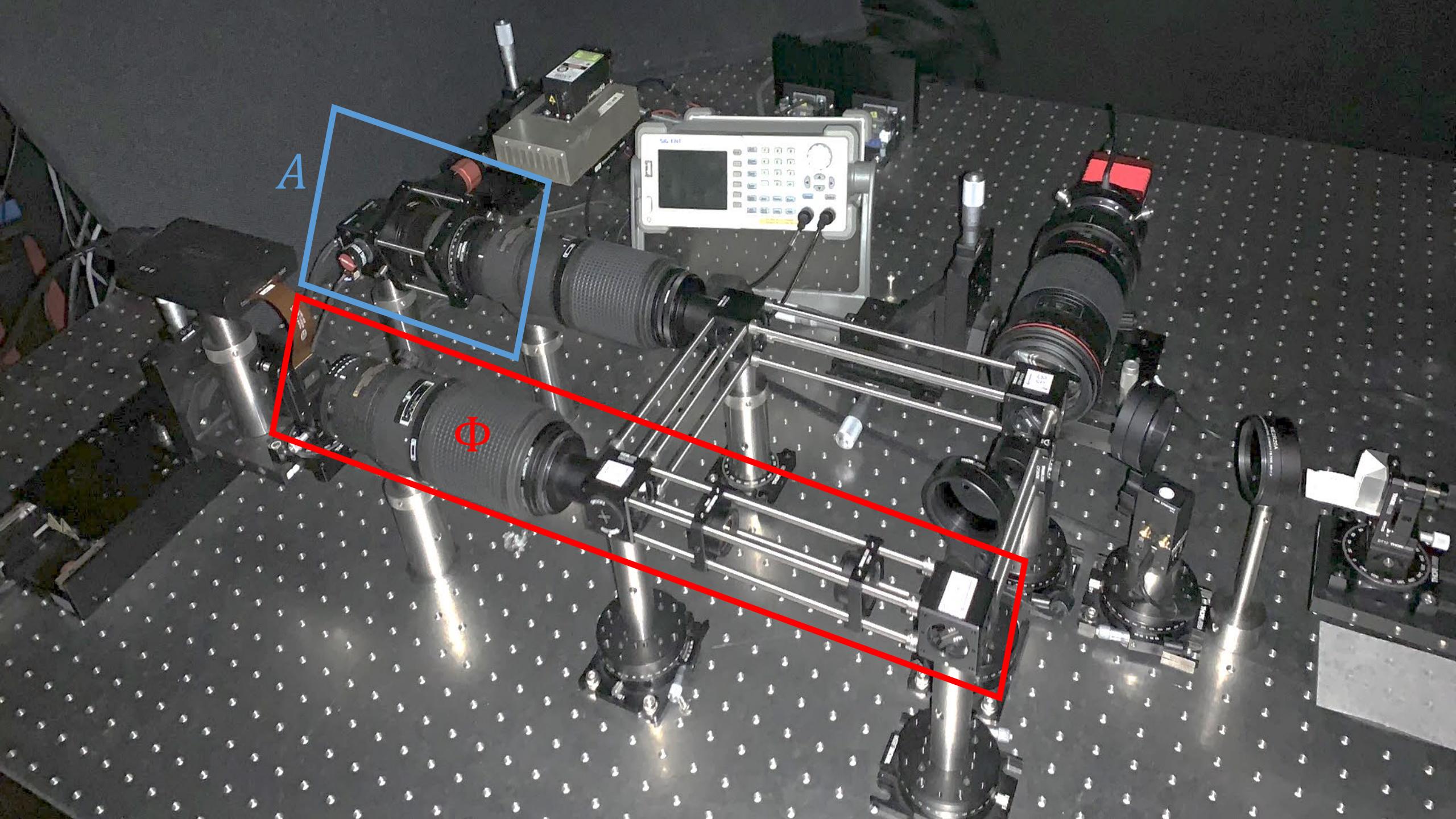
camera



source



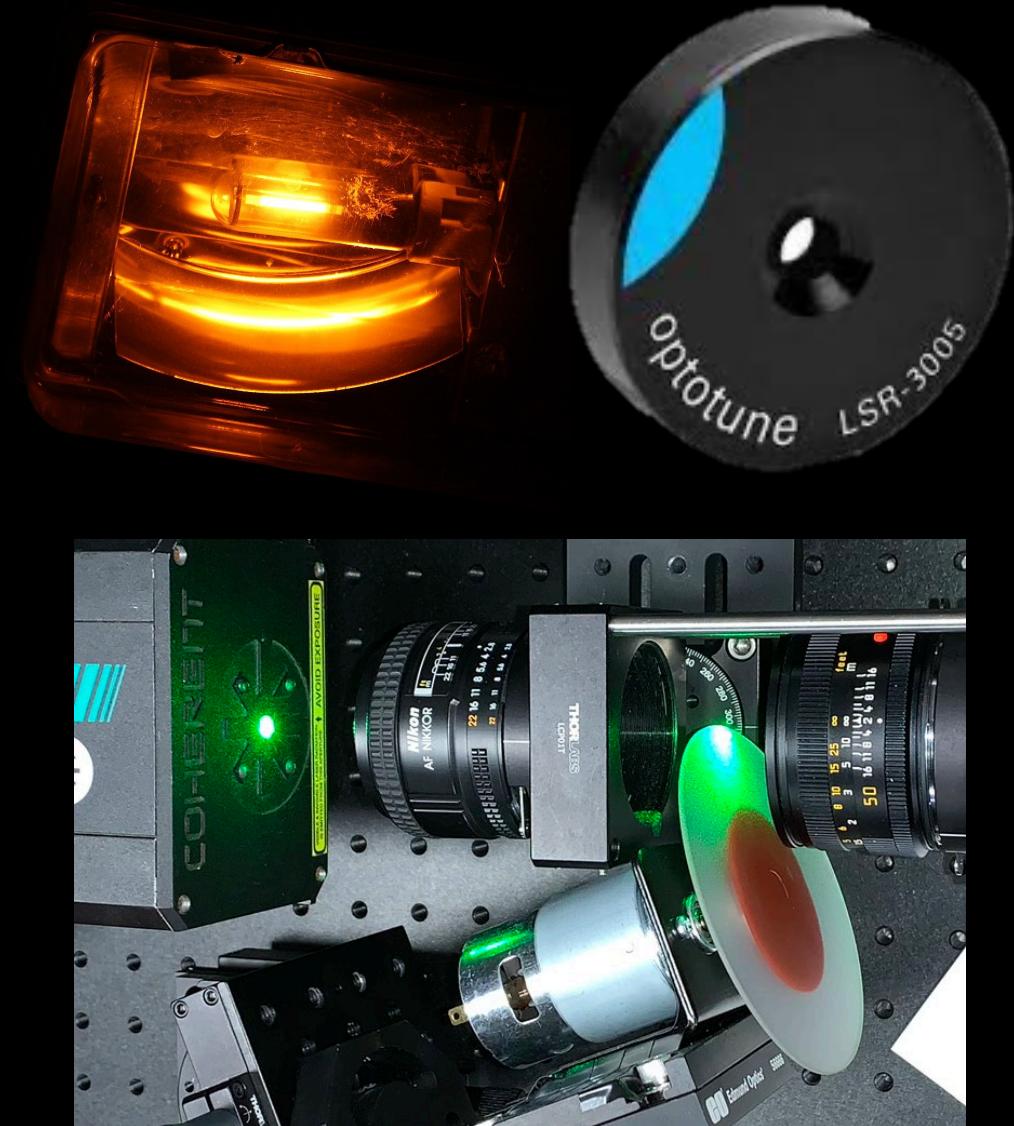
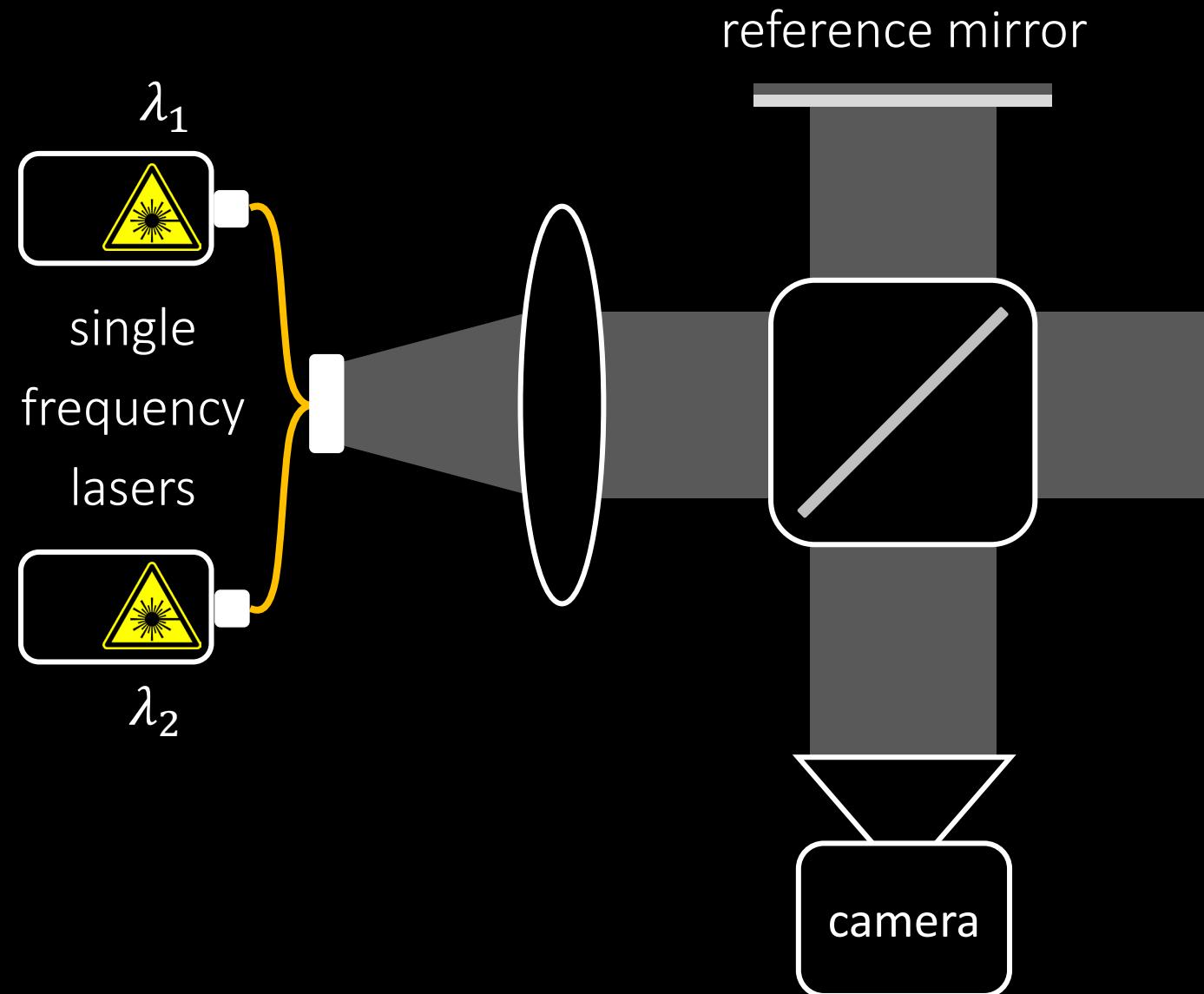
source



A

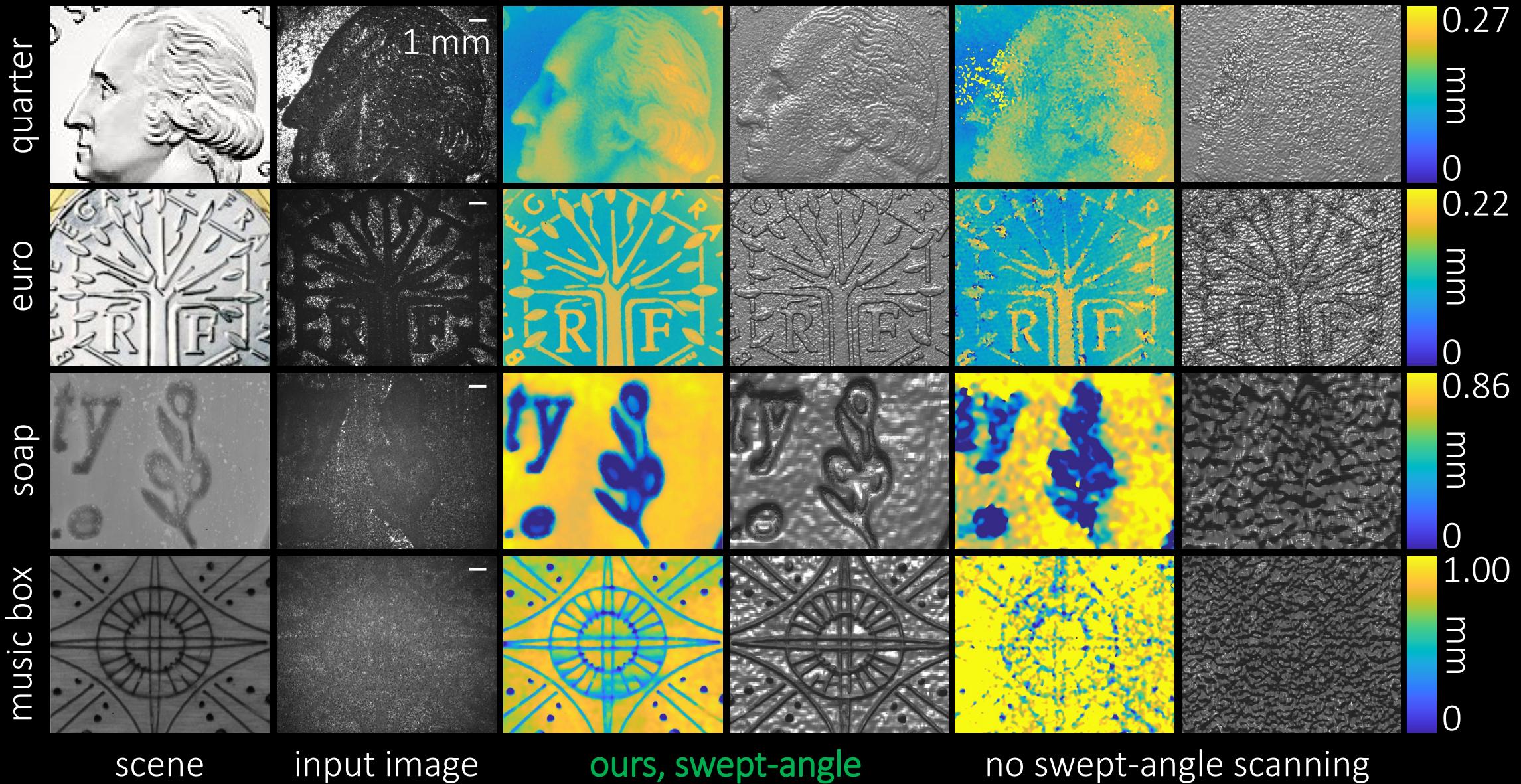
$\Phi$

# Dichromatic area light?

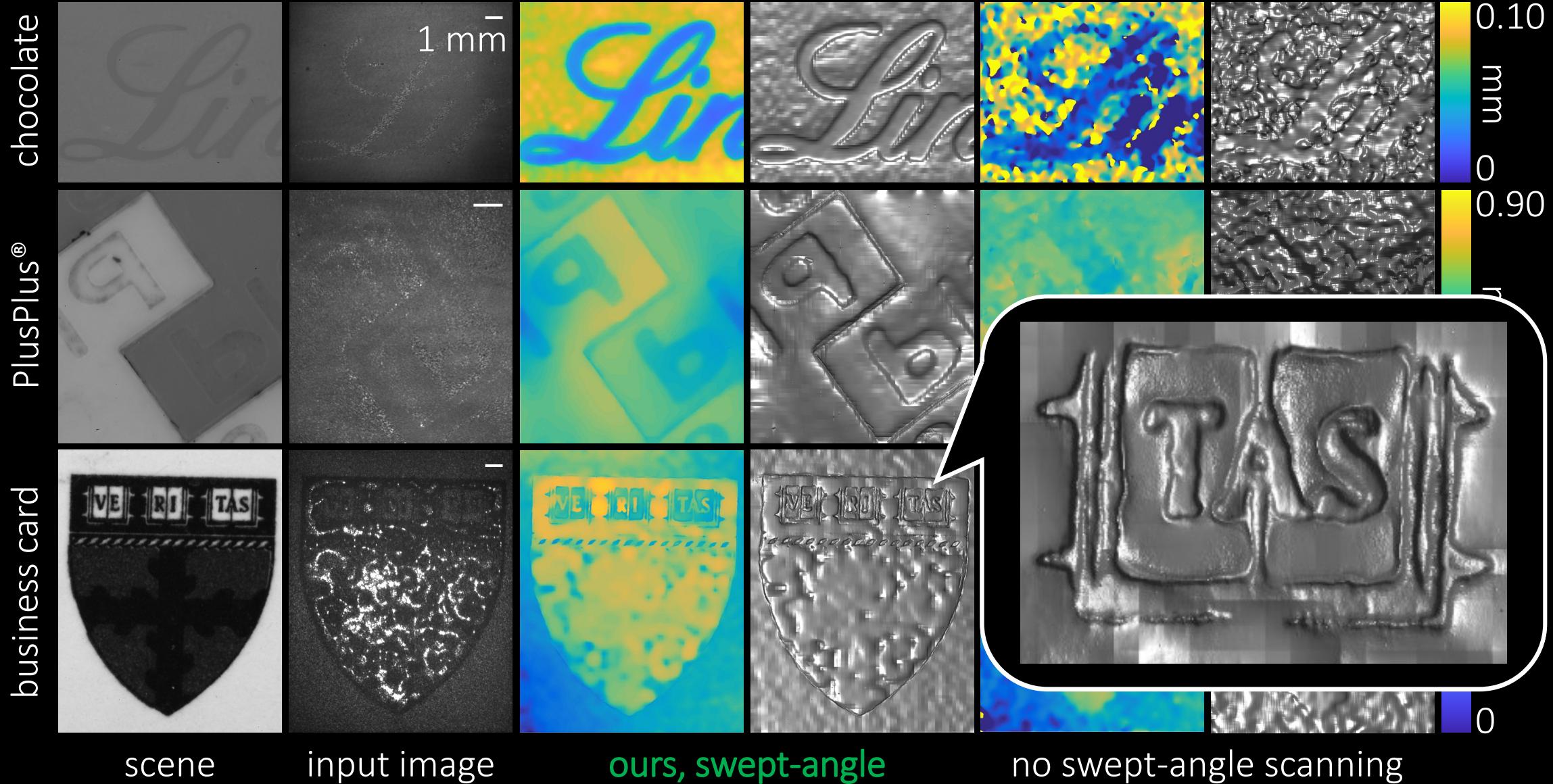


# *Swept-angle* synthetic wavelength interferometry

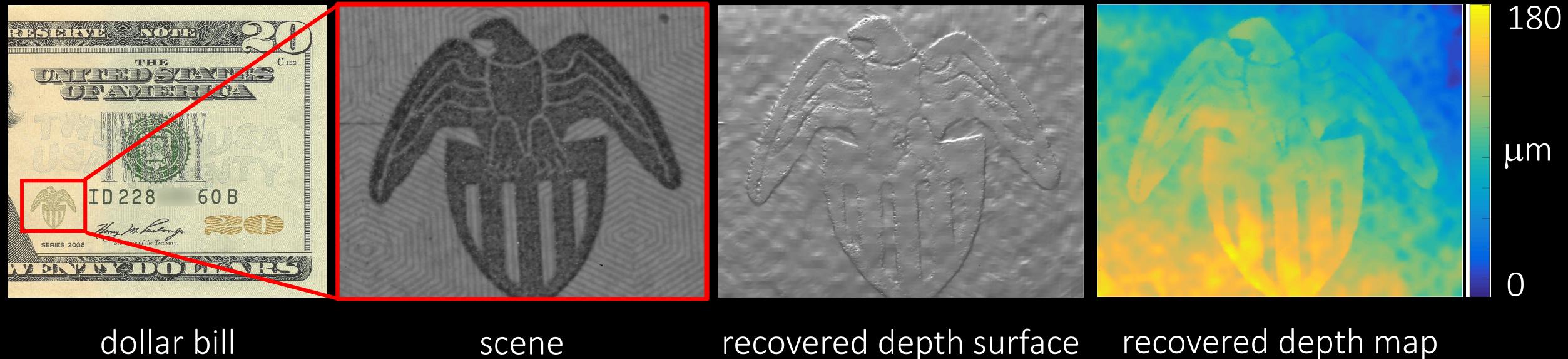
# Swept-angle SWI results: 1 mm depth range



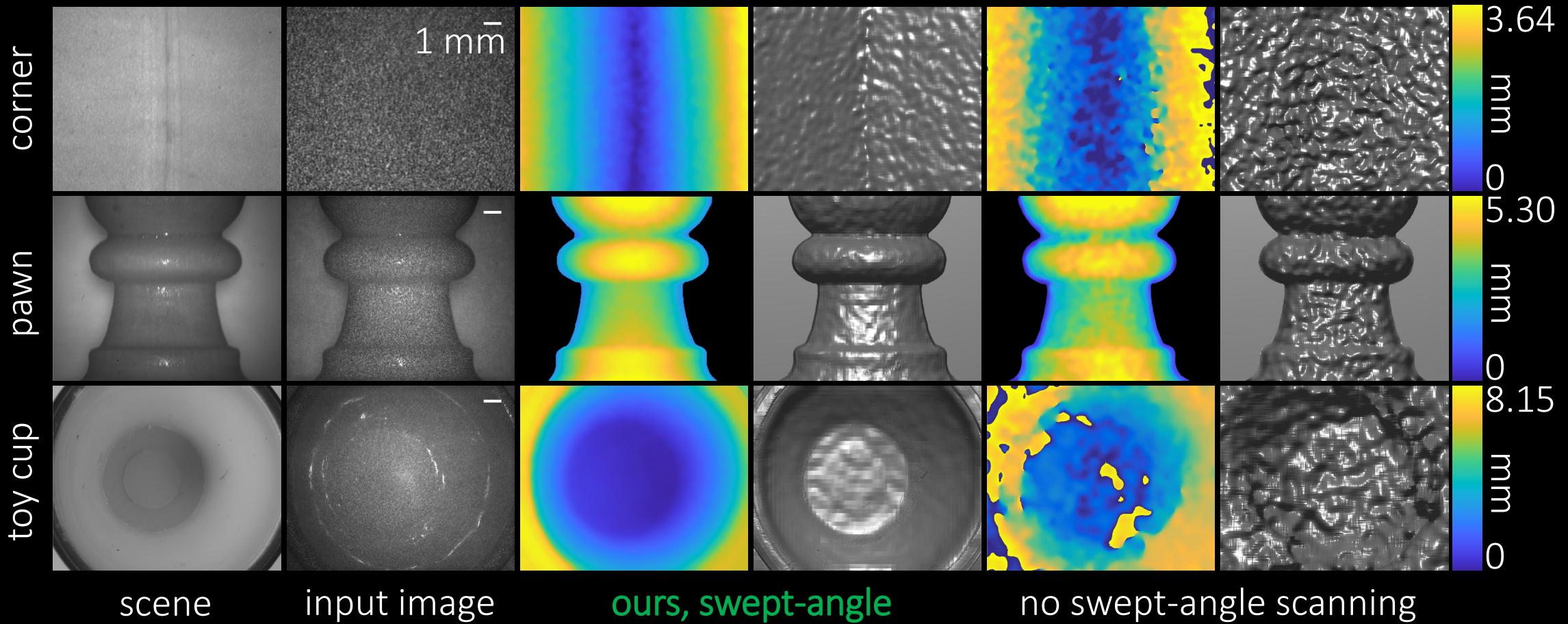
# Swept-angle SWI results: 1 mm depth range



# Swept-angle SWI results: \$20 bill eagle



# Swept-angle SWI results: 1 cm depth range



# Applications: industrial inspection

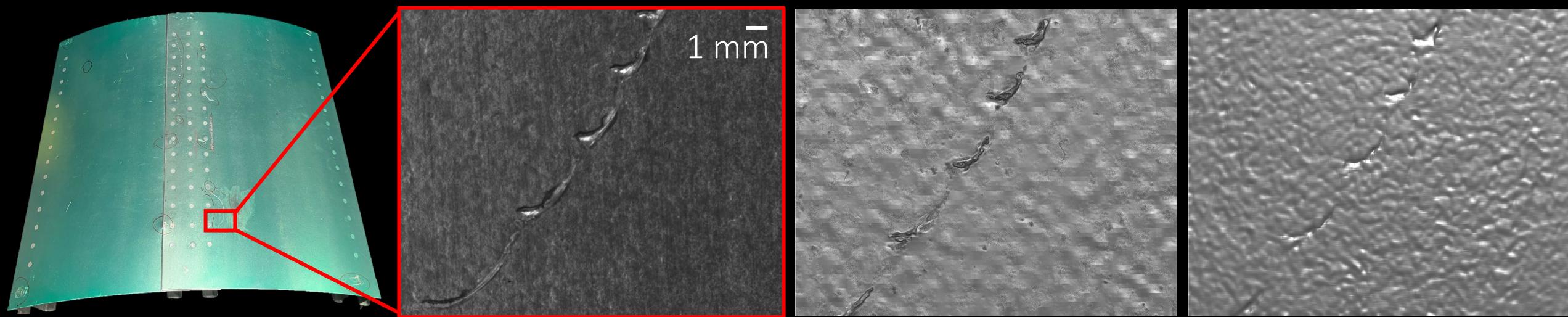


photo of scanned object

image of scanned scene

ours, swept-angle

without swept-angle

# Applications: precision fabrication

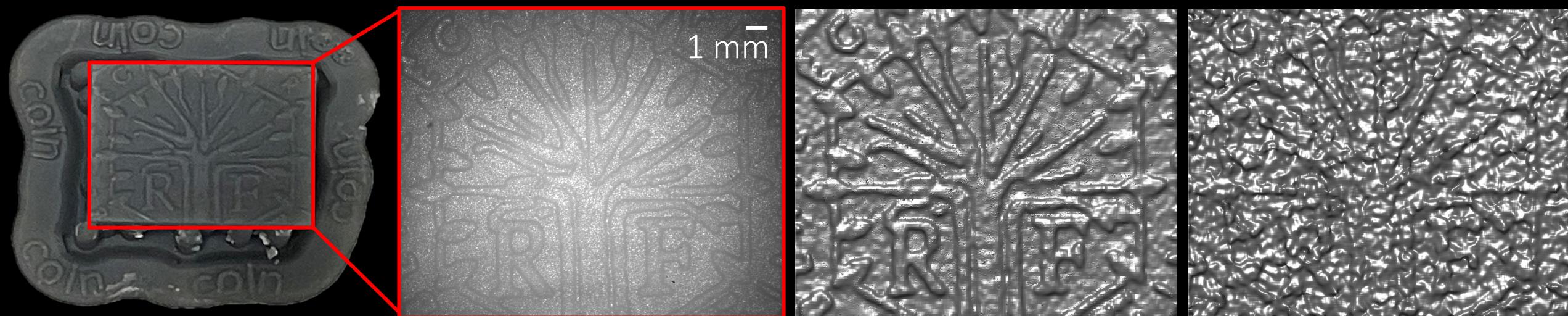
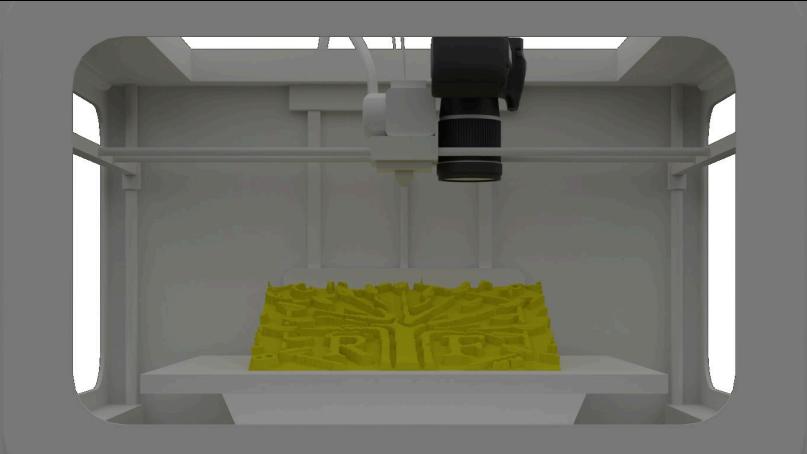
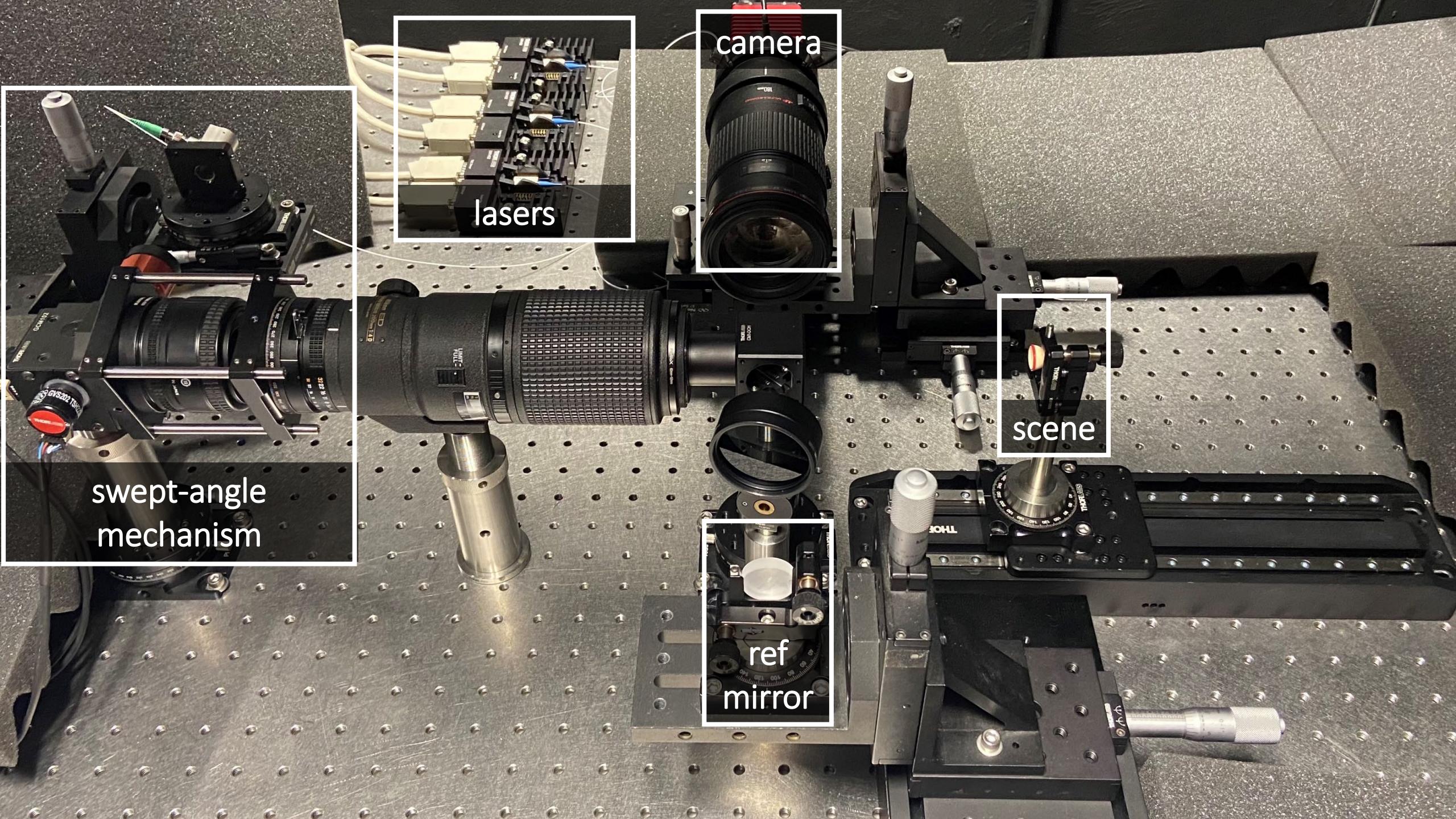


photo of scanned object

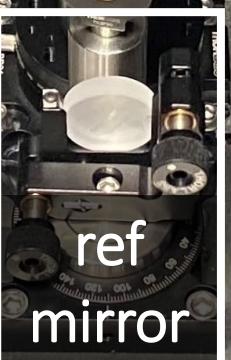
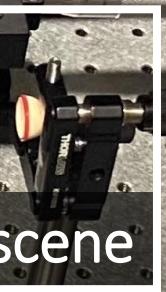
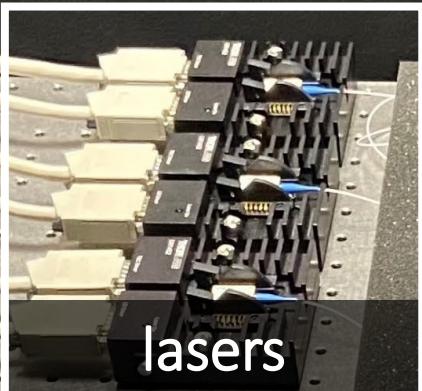
image of scanned scene

ours, swept-angle

without swept-angle

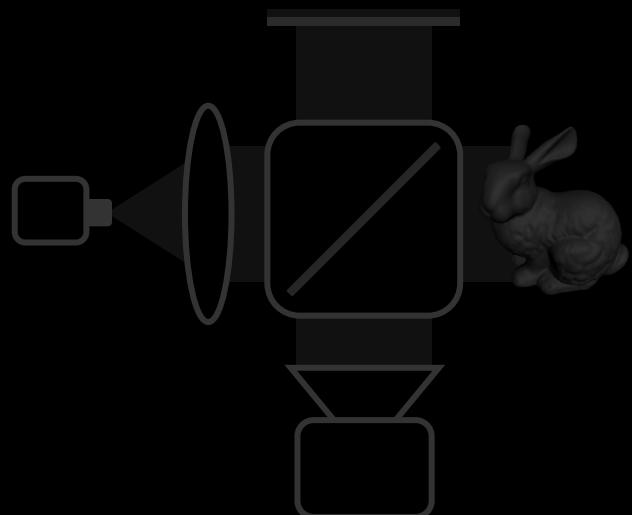


swept-angle  
mechanism



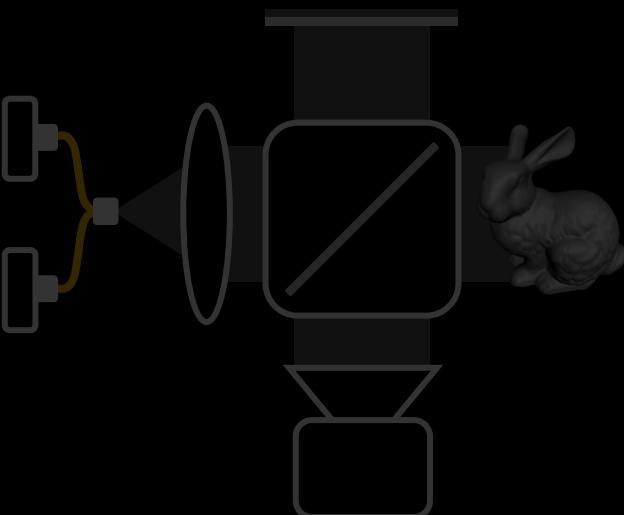
# Course overview

introduction to  
interferometry



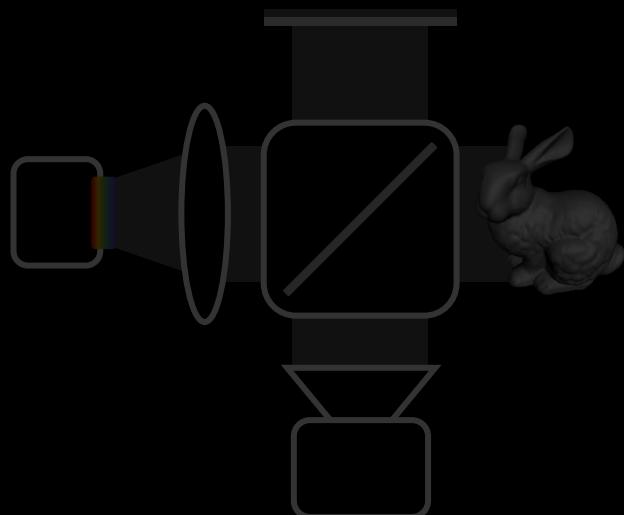
Yannis

two-wavelength  
interferometry



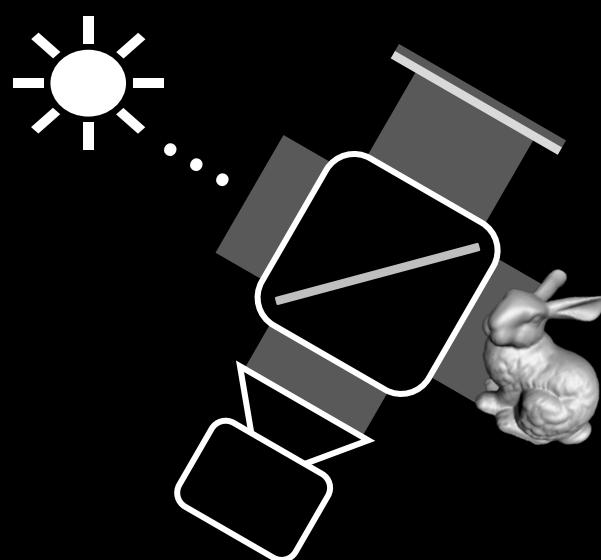
Florian

partially-coherent  
interferometry



Alankar

interferometric  
computational imaging



Florian



Yannis

# Part 4:

## Non-Line-of-Sight imaging using Synthetic Wavelengths

---

Florian Willomitzer

Associate Professor  
Wyant College of Optical Sciences  
University of Arizona, USA

<https://www.optics.arizona.edu/3dim>

**3DIM Lab**

Computational 3D Imaging  
and Measurement Lab

Prof. Florian Willomitzer

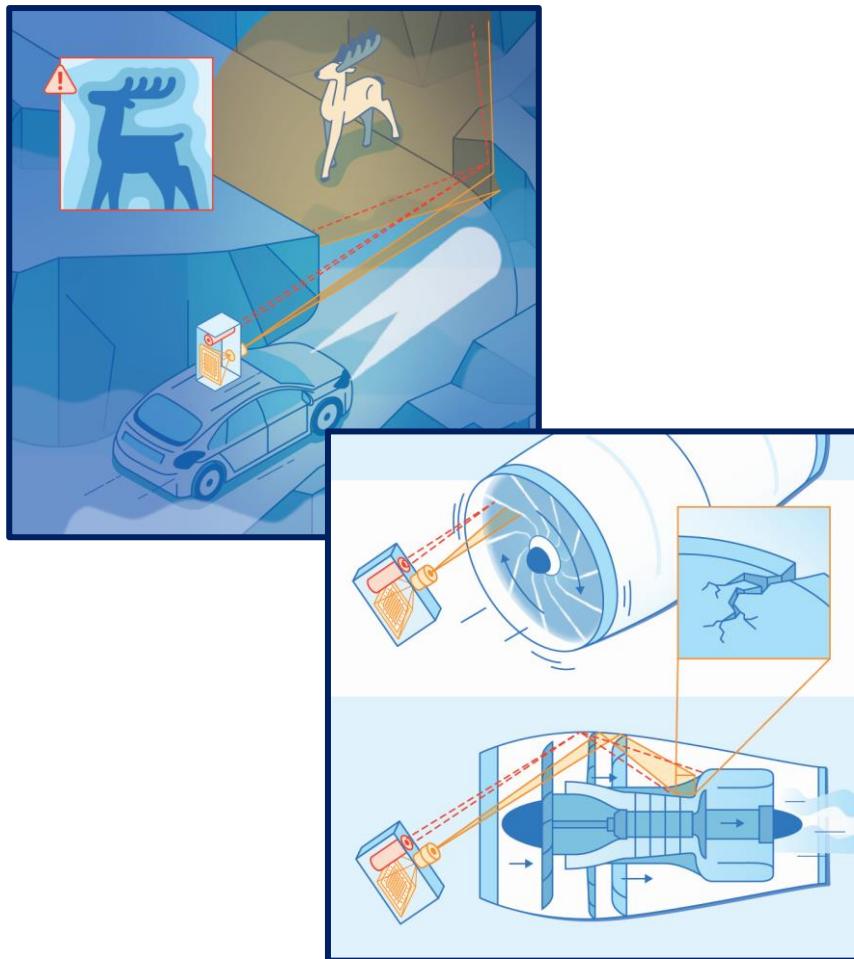


THE UNIVERSITY OF ARIZONA  
**Wyant College  
of Optical Sciences**

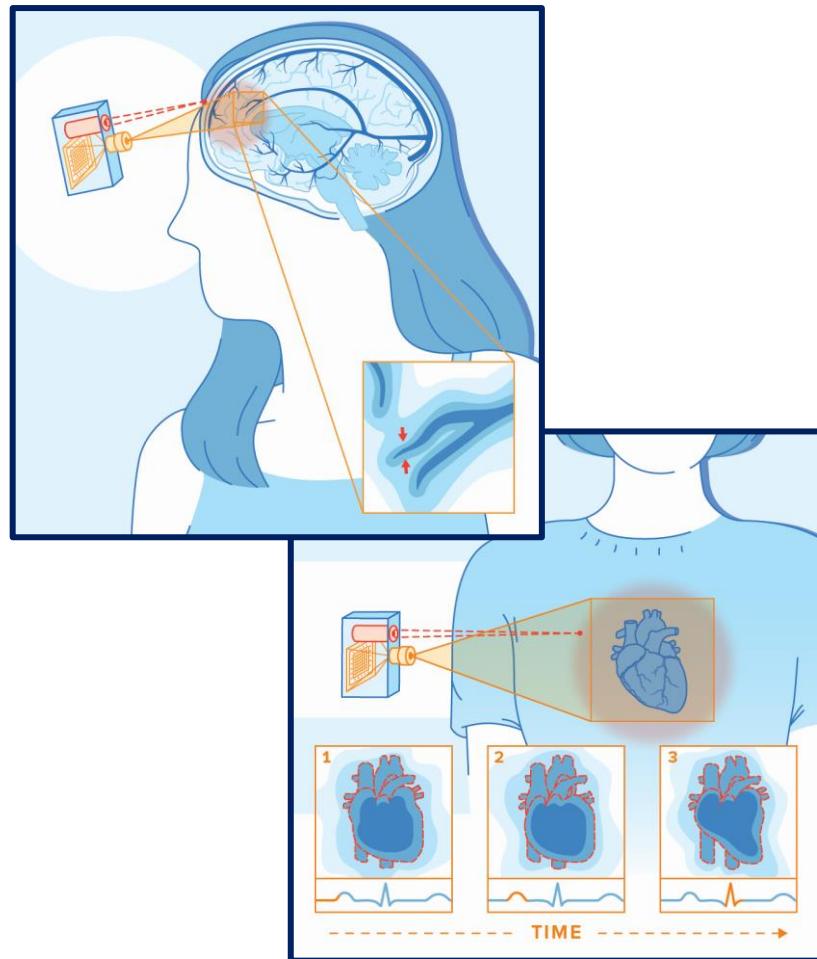


# Non-Line-of-Sight Imaging – Potential Applications

## Imaging around Corners



## Imag. through Scattering Media



F. Willomitzer et al., Nature Communications 12, 6647 (2021)

# Approaches measuring the Time-of-Flight of light

$$\delta z \propto \lambda$$

depth error

modulation  
wavelength

**RECAP**

Conventional  
Interferometry  
(single Wavelength)

Speckle for  
scattering  
scenes

"ToF Cameras"  
(CW or pulsed)

**Dual-Wavelength  
Interferometry**

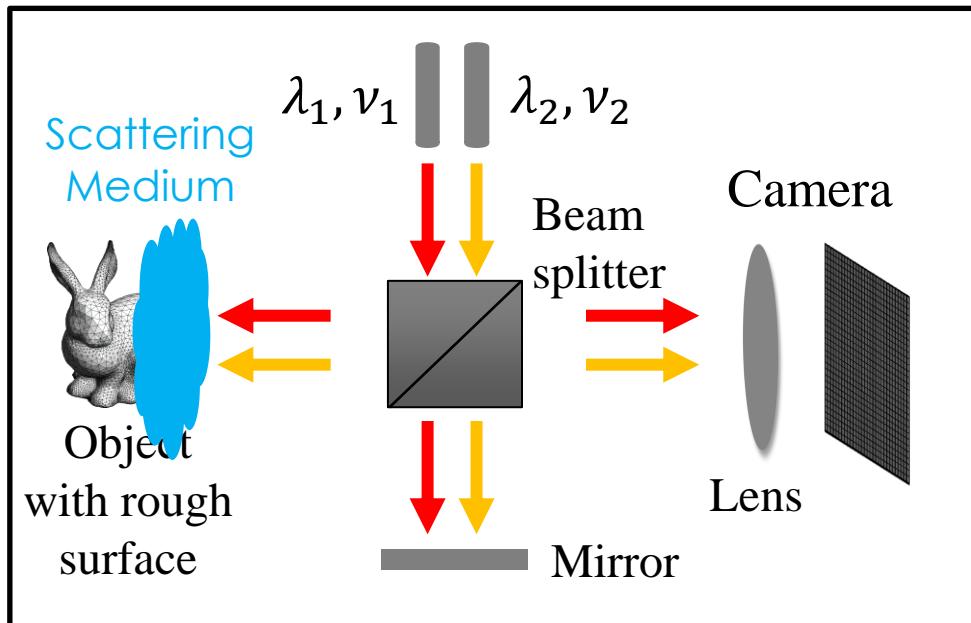
$\sim \mu\text{m}$

$\sim 10\text{cm}$

Poor  
resolution

$\lambda$

# High-precision “ToF Camera”

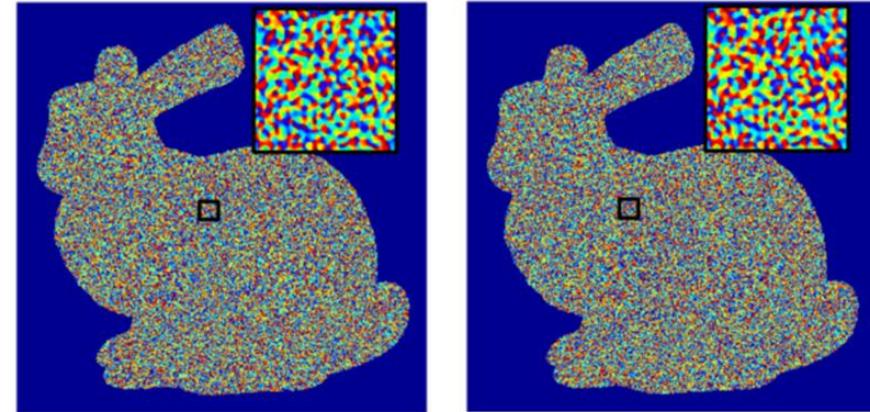


$E(\Lambda) = E(\lambda_1) \cdot E^*(\lambda_2)$

$E(\lambda_1) = A_1 \exp(i\phi(\lambda_1))$

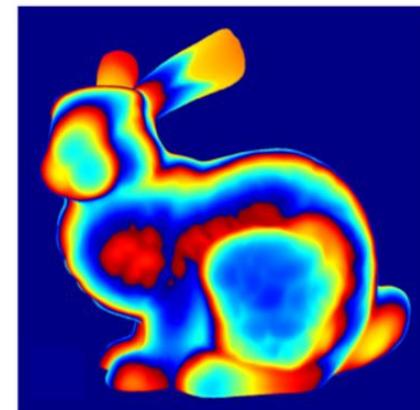
$E(\lambda_2) = A_2 \exp(i\phi(\lambda_2))$

**RECAP**



$$\begin{aligned} E(\Lambda) &= E(\lambda_1) \cdot E^*(\lambda_2) \\ &= A_1 A_2 \cdot \exp(i(\phi(\lambda_1) - \phi(\lambda_2))) \end{aligned}$$

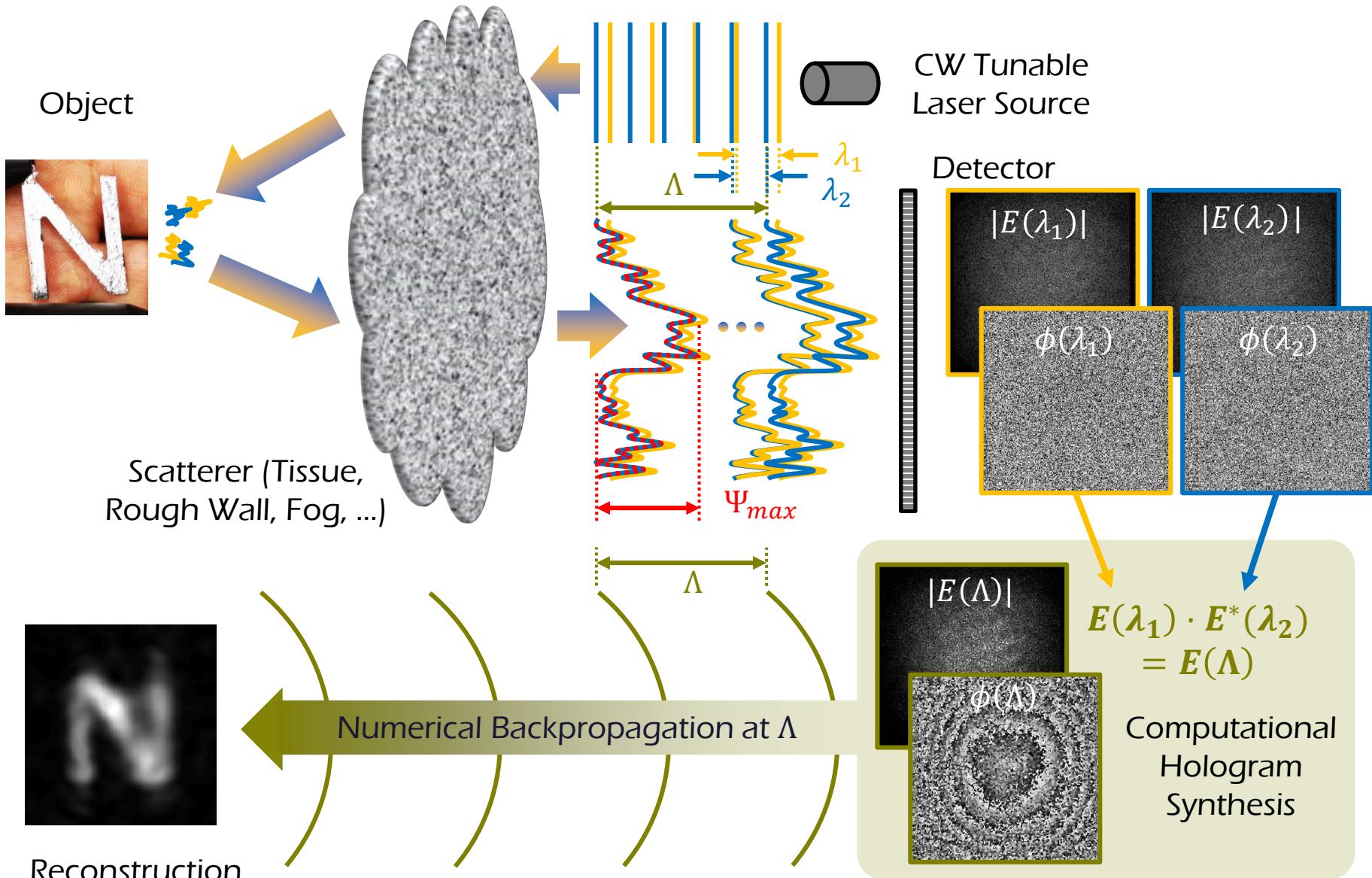
$\phi(\Lambda)$



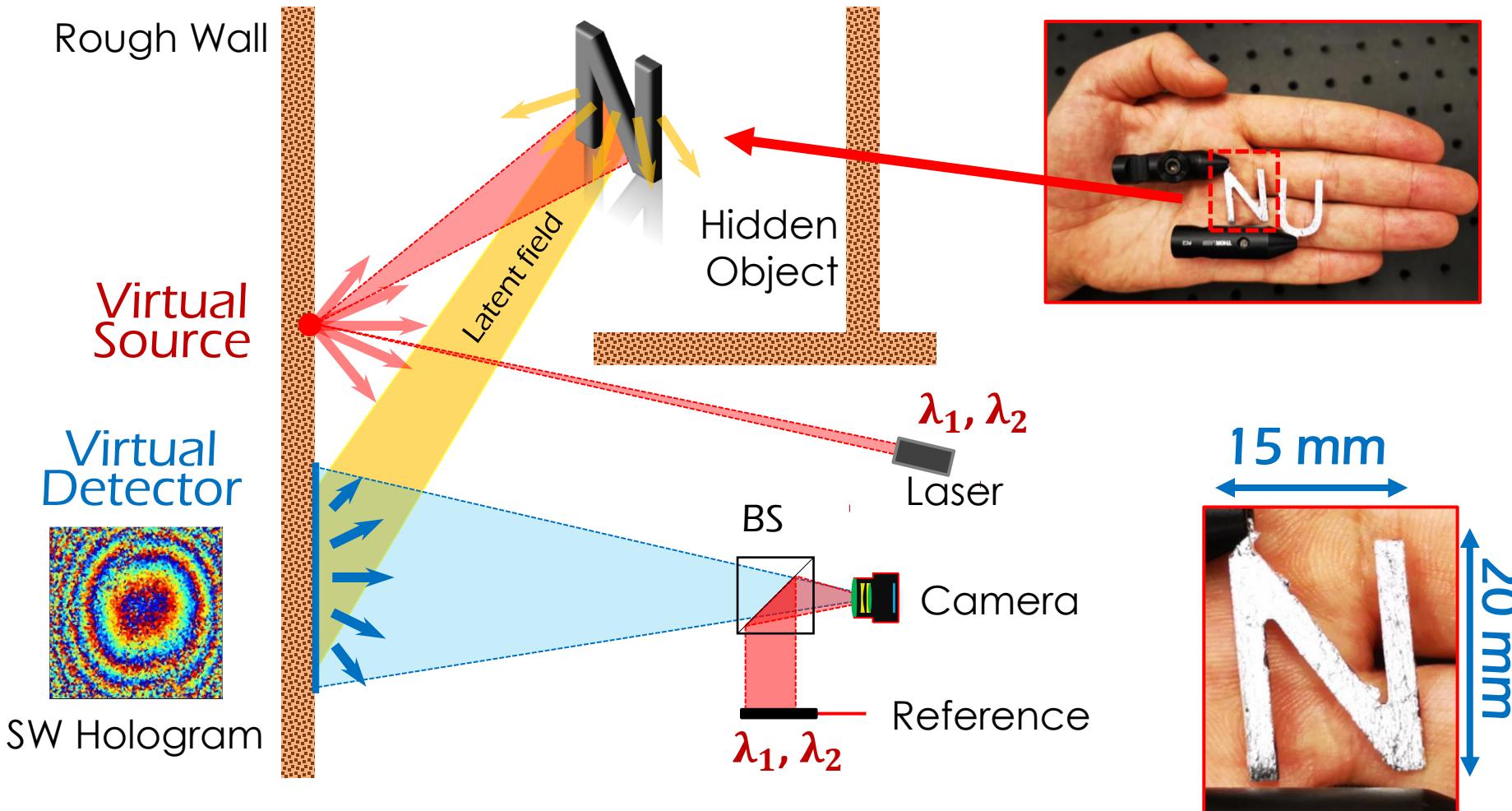
F. Li\*, F. Willomitzer\*, M. Balaji, P. Rangarajan, O. Cossairt, Exploiting Wavelength Diversity for High Resolution Time-of-Flight 3D Imaging, IEEE Transactions on Pattern Analysis and Machine Intelligence (TPAMI), 2021

# Synthetic Wavelength Holography

Willomitzer et al., Nature Communications 12, 6647, 2021

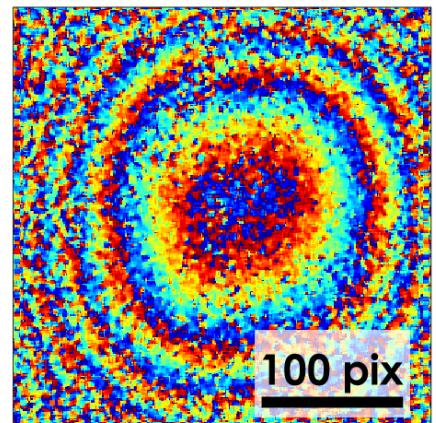


# Experiment: Looking around corners

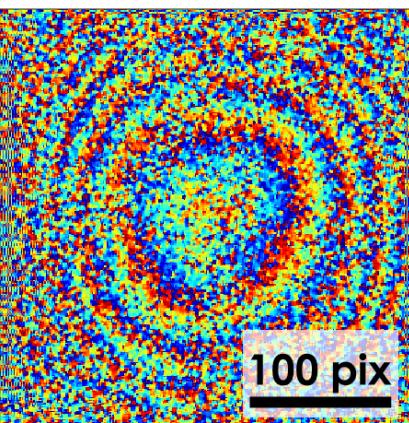


# Imaging around corners at multiple SWLs

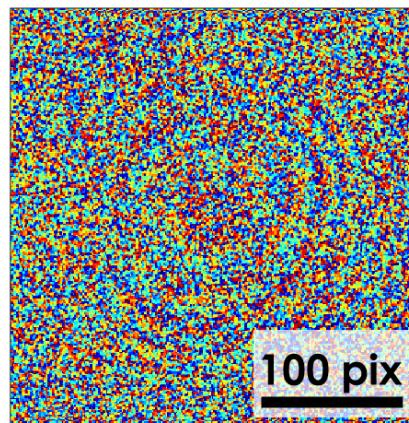
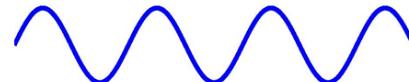
$$\Lambda = 1.30 \text{ mm}$$



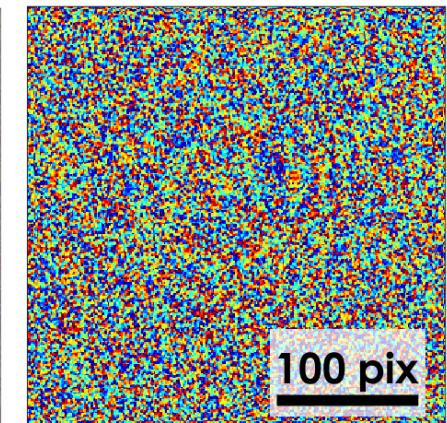
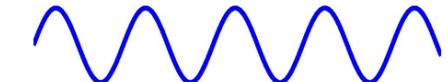
$$\Lambda = 0.92 \text{ mm}$$



$$\Lambda = 0.56 \text{ mm}$$



$$\Lambda = 0.44 \text{ mm}$$



Phase  $\phi(\Lambda)$

Reconstruction

10 mm

10 mm

10 mm

10 mm

Fundamental limit

# Where is the limit?

Fundamental limit:

$$\Lambda \geq 4 \Psi_{max}$$

Tunable!

## How to estimate the performance of our system?

Space-Bandwidth Product (SBP):

Field of view width

$$SBP = \frac{W}{\delta x} \leq \frac{D_{VD}}{2 \Psi_{max}}$$

Smallest laterally  
resolvable distance

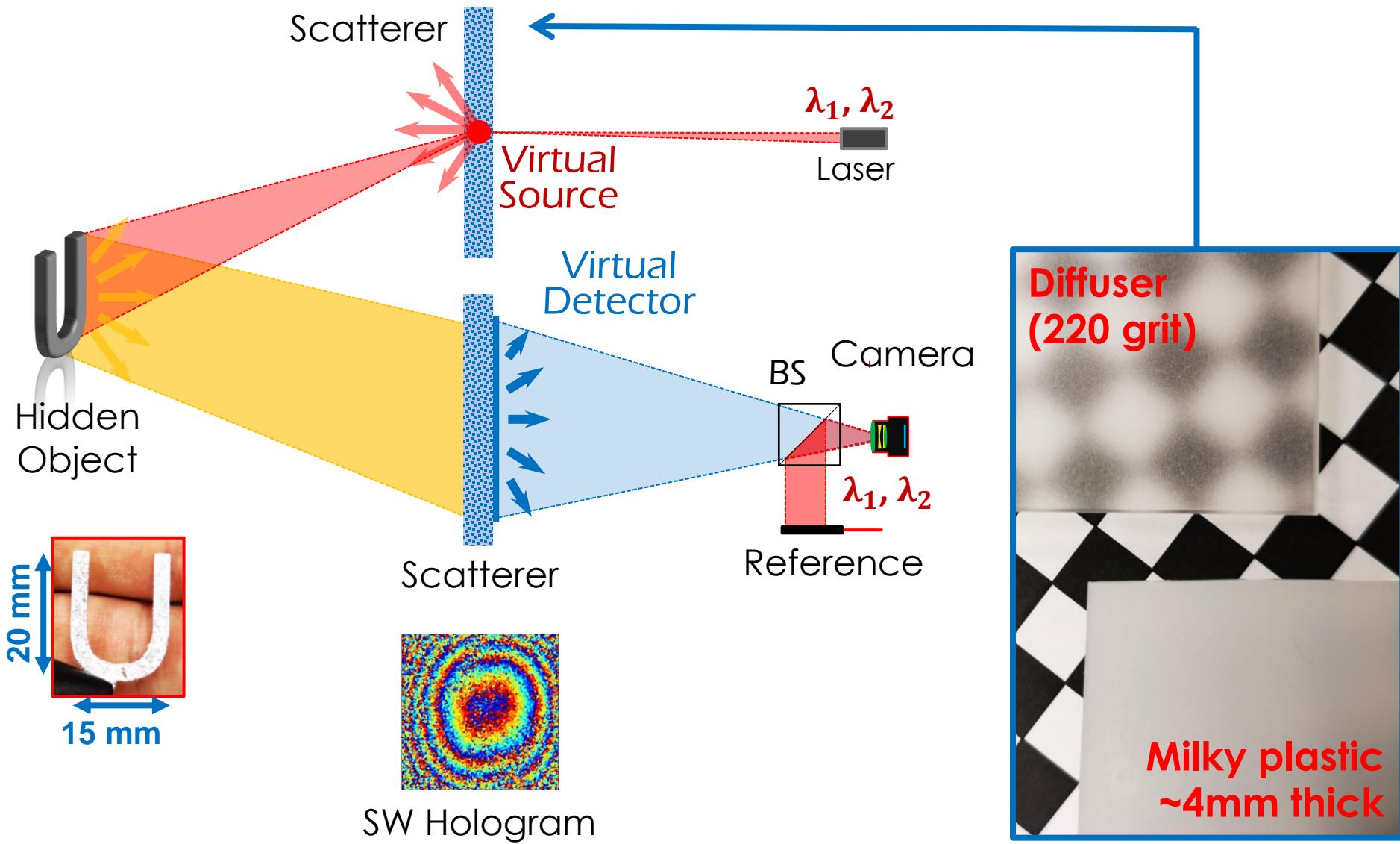
System constants

\*

\* Related calculations given in:

F. Willomitzer, P. Rangarajan, F. Li, M. Balaji, M. Christensen, O. Cossairt, 'Synthetic Wavelength Holography: An Extension of Gabor's Holographic Principle to Imaging with Scattered Wavefronts', Arxiv 1912.11438 (2019)

# Experiment: Imaging through Scattering Media

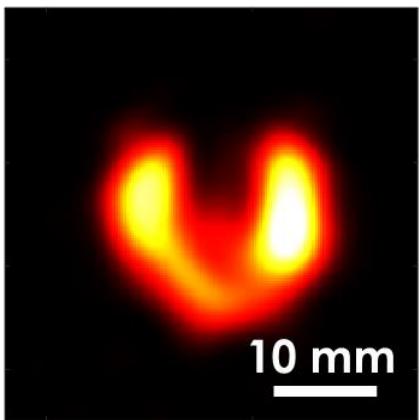


# Imaging through scatterers - Results

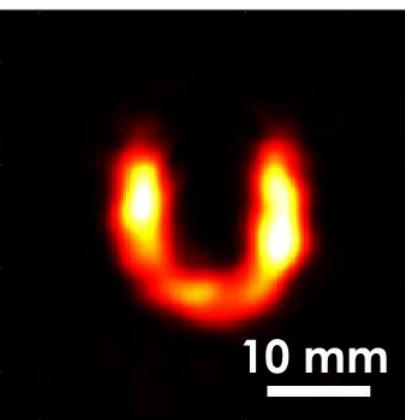
$$\Lambda \approx 4 \Psi_{max}$$

Reconstructions through  
Diffuser

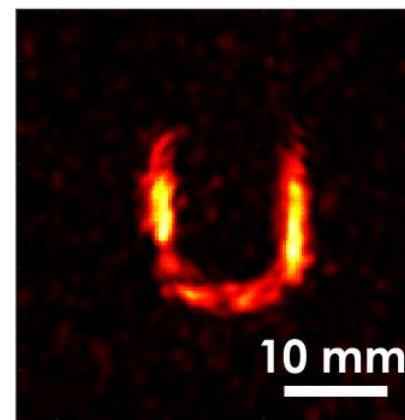
$$\Lambda = 1.30 \text{ mm}$$



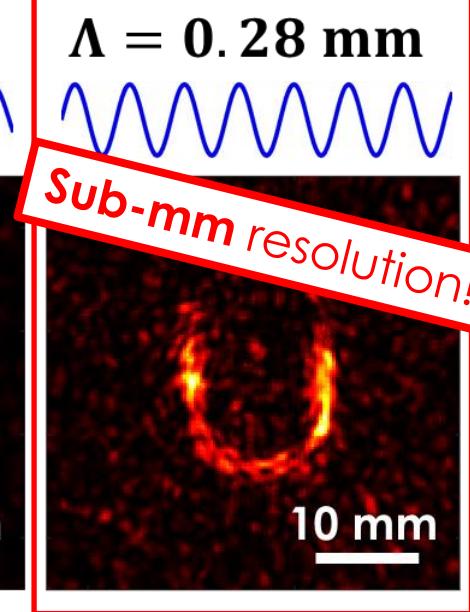
$$\Lambda = 0.80 \text{ mm}$$



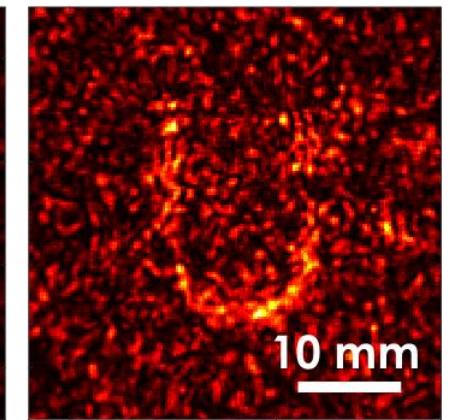
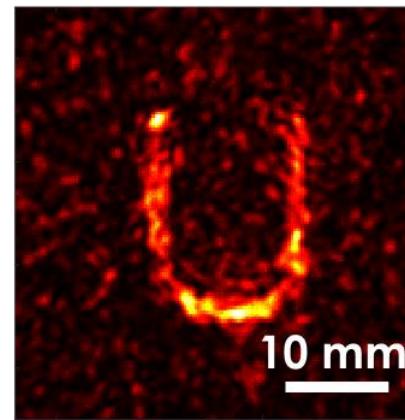
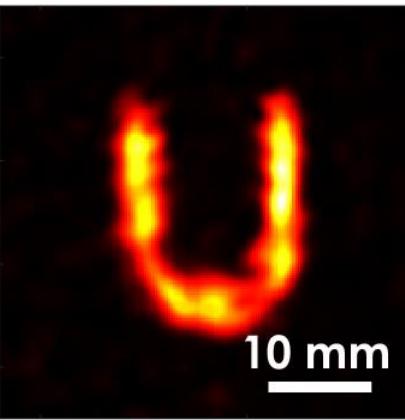
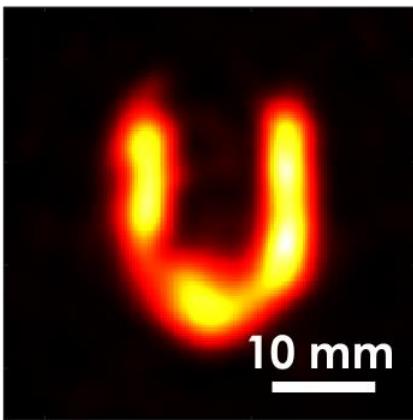
$$\Lambda = 0.36 \text{ mm}$$



$$\Lambda = 0.28 \text{ mm}$$

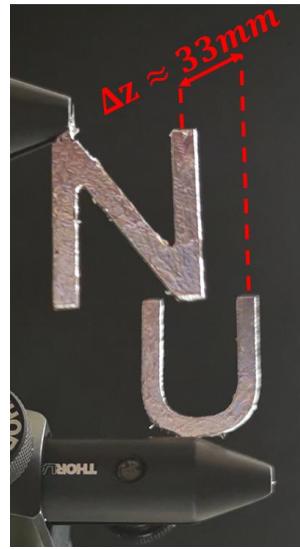


Reconstructions through  
Milky Plastic



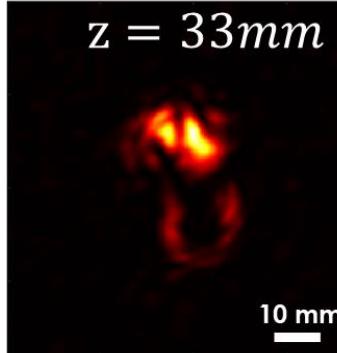
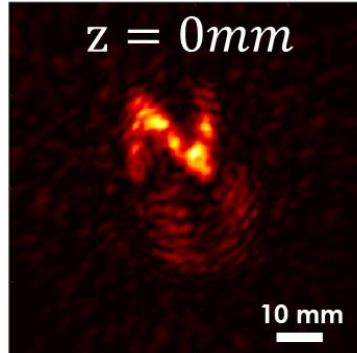
# Synthetic Pulse Holography/Interferometry

Computational coherent superposition of multiple synthetic holograms → “synthetic pulse”

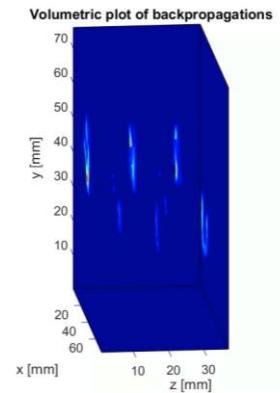
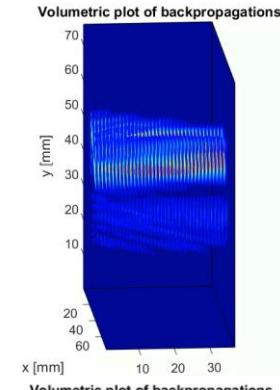
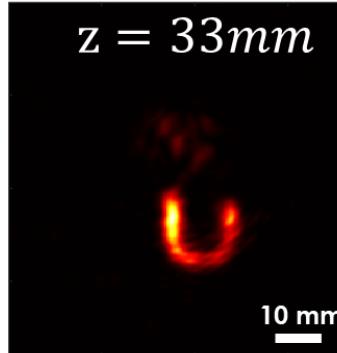
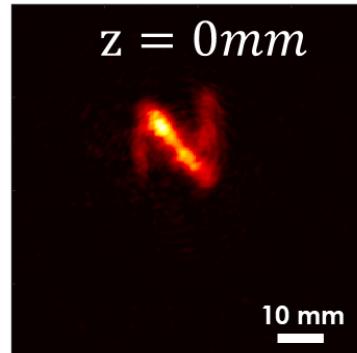


Hidden Object

$$N_A = 1$$



$$N_A = 23$$

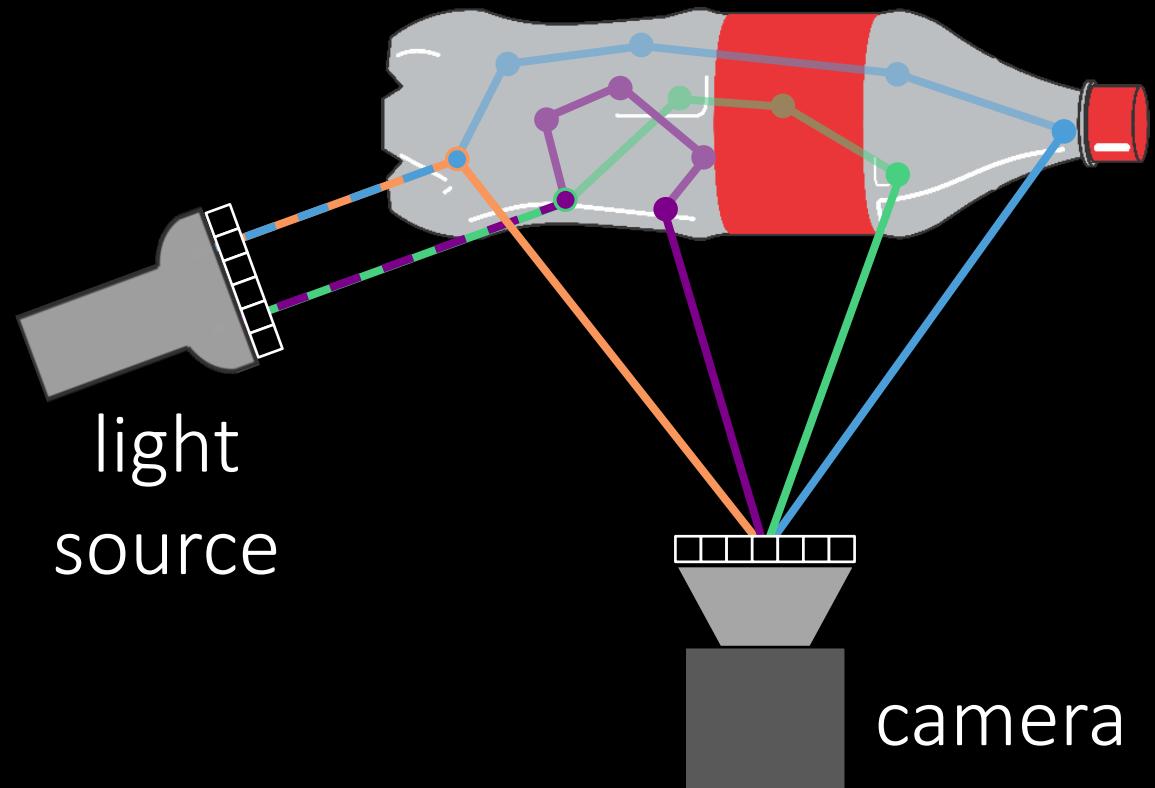


→ Similarity to OCT, WLI, light-in-flight imaging, transient imaging

F. Willomitzer, P. Rangarajan, F. Li, M. Balaji, M. Christensen, O. Cossairt, ‘Fast Non-Line-of-Sight Imaging with High-Resolution and Wide Field of View using Synthetic Wavelength Holography’, Nature Communications 12, 6647 (2021)

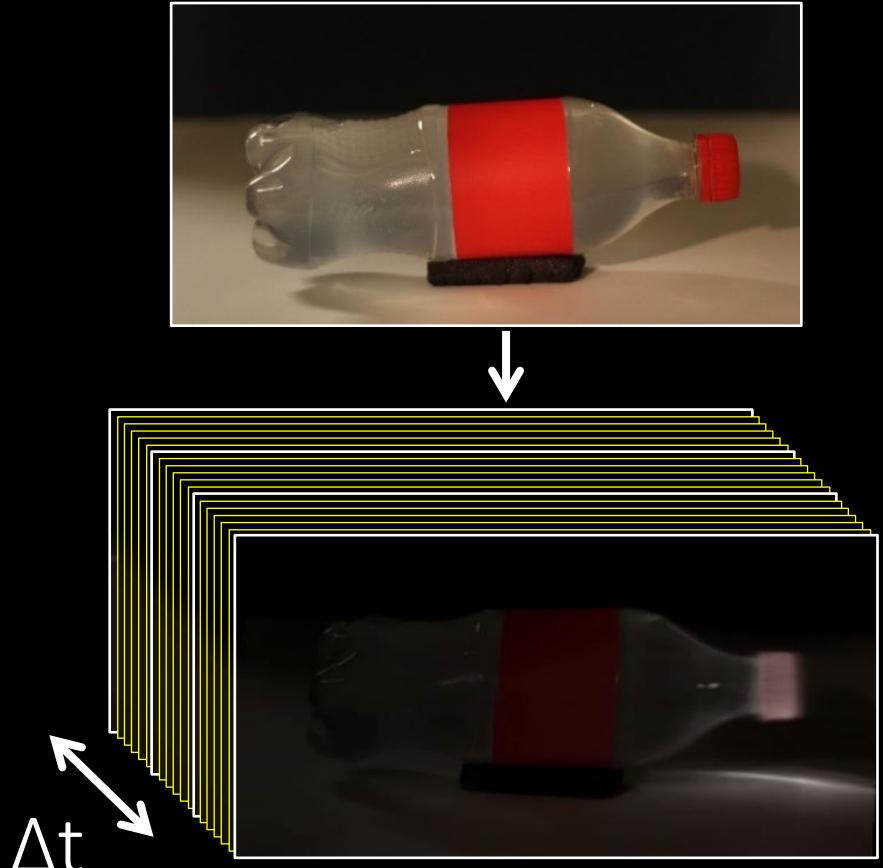
P. Cornwall, M. Ballester, H. Wang, F. Willomitzer, ‘Towards Synthetic Light-in-Flight’, Optica Comp. Optical Sensing and Imaging (2023)

# Transient imaging

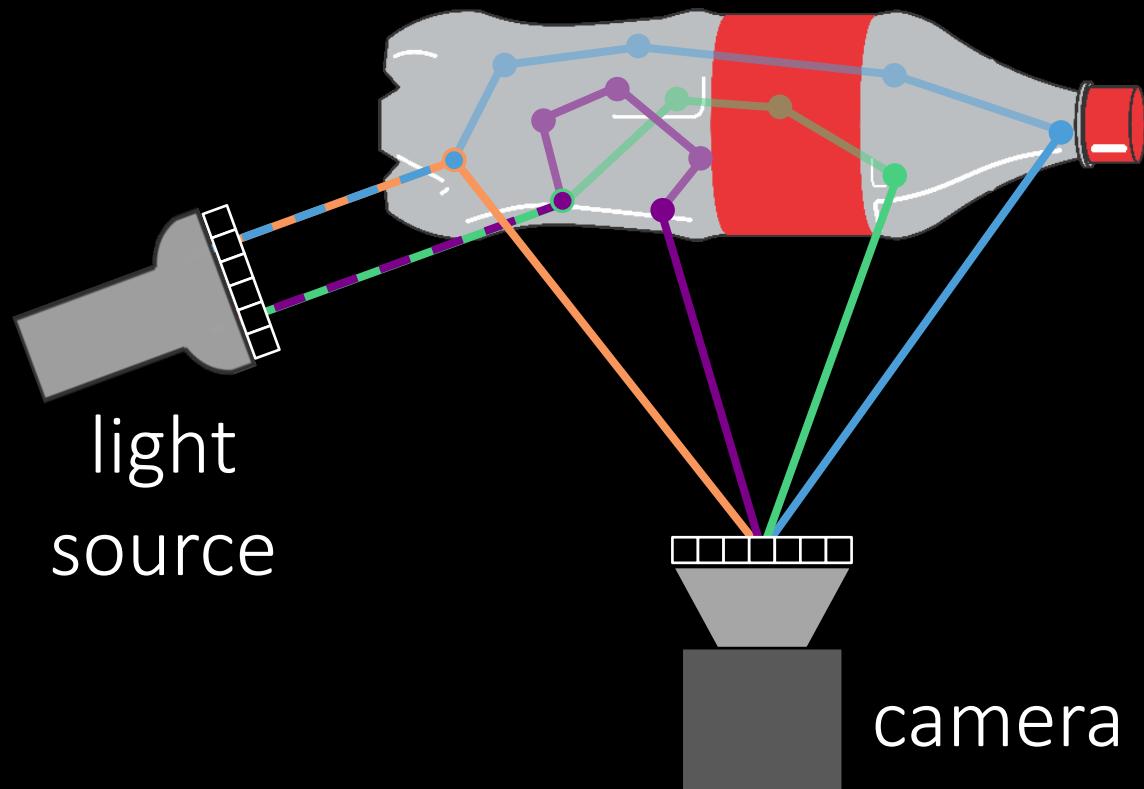


transient imaging using interferometry  
at 1000x larger temporal resolution

# Transient imaging

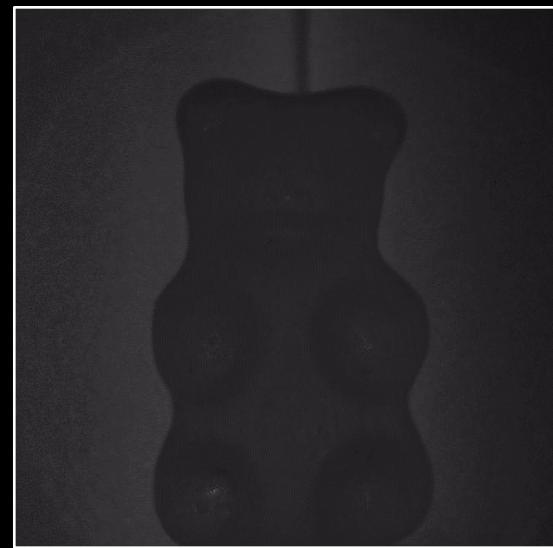


[Velten et al. 2013]

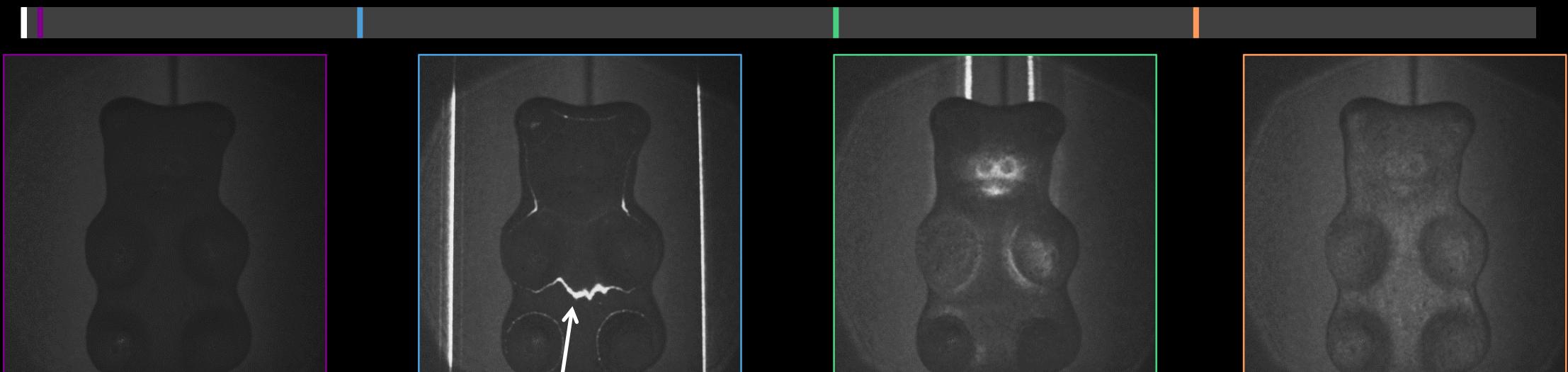


transient imaging using interferometry  
at 1000x larger temporal resolution

# Gummy bear and diffuse corner



resolution  
 $10^{-15}$  s



dark frame

surface reflections

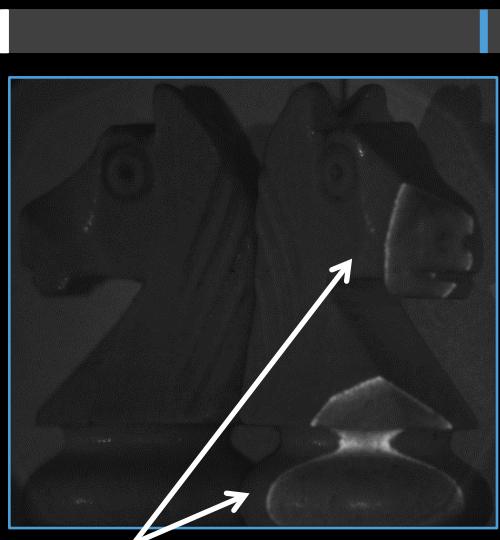
paths through  
gummy bear

very highly  
scattered paths

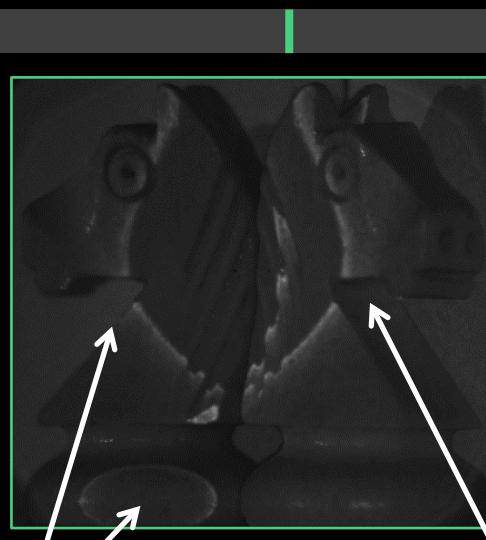
# Chess knight and mirror



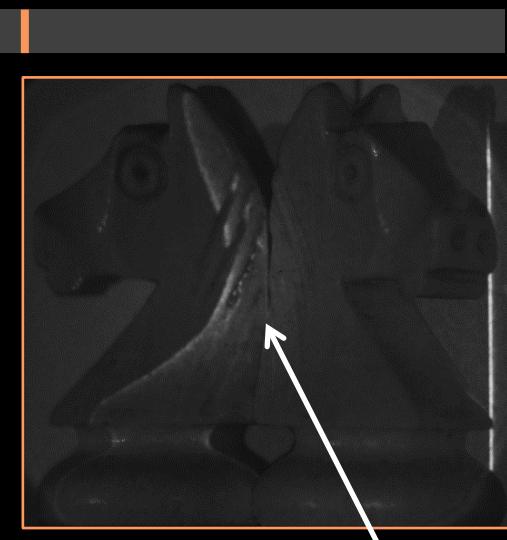
resolution  
 $10^{-15}$  s



surface reflection

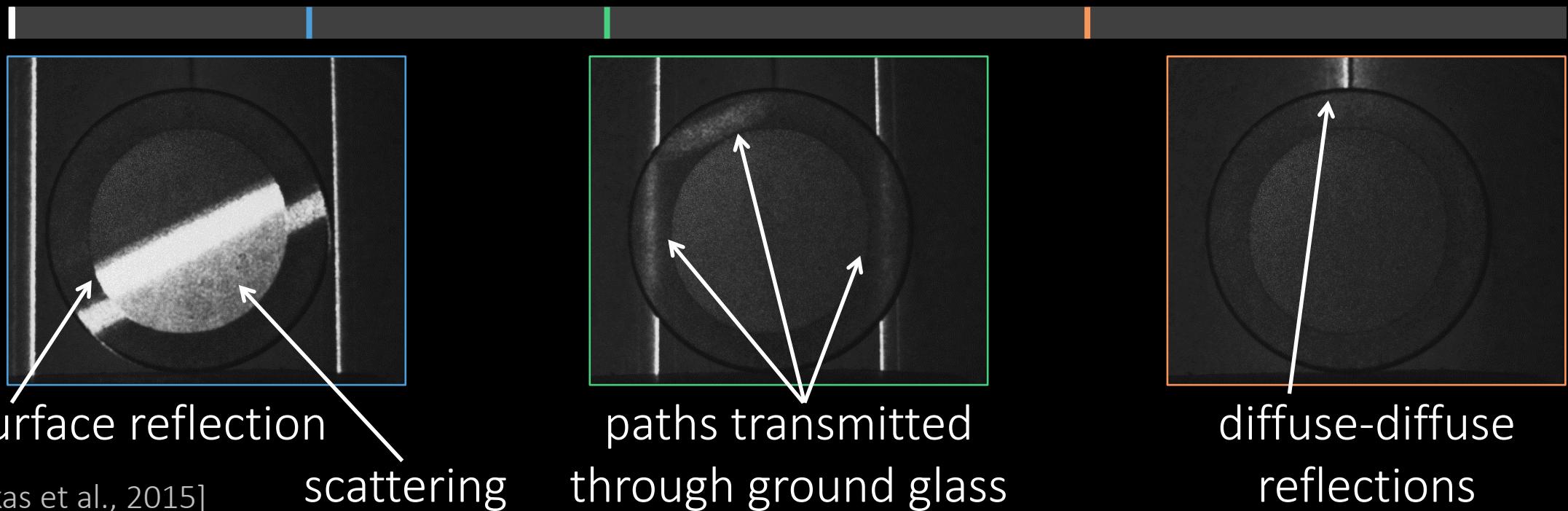
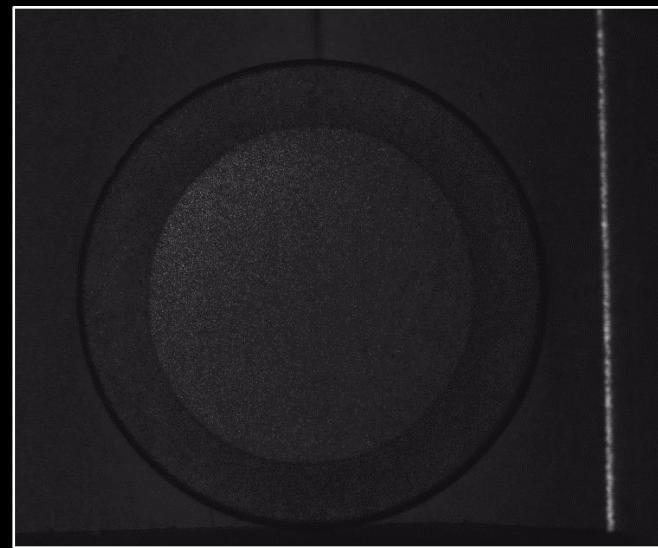
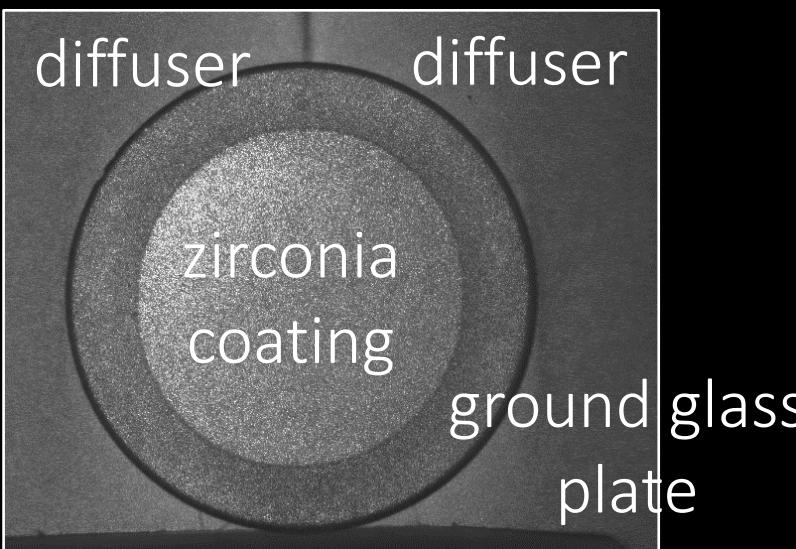


mirror-object  
object-mirror

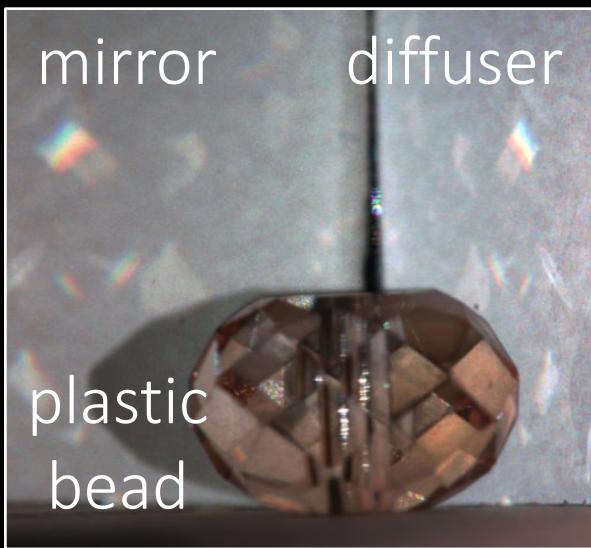


mirror-object-mirror

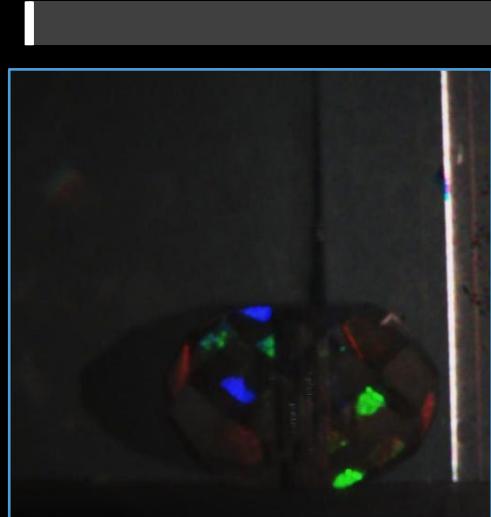
# Subsurface scattering



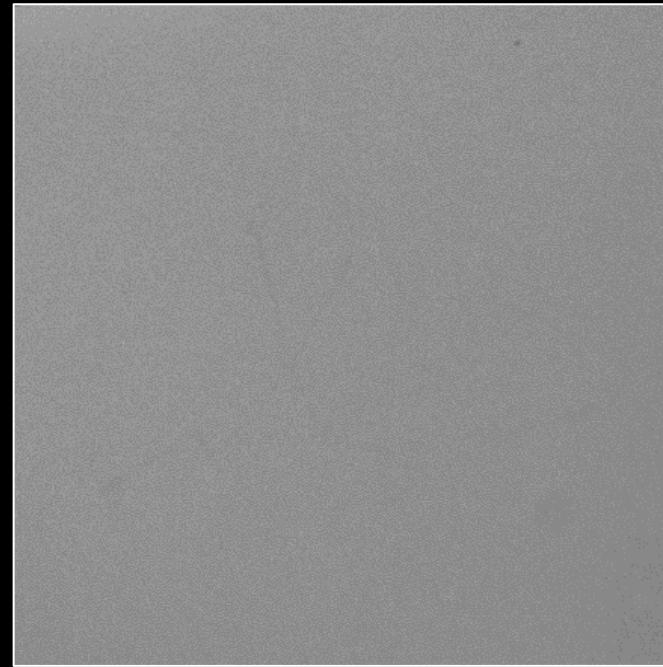
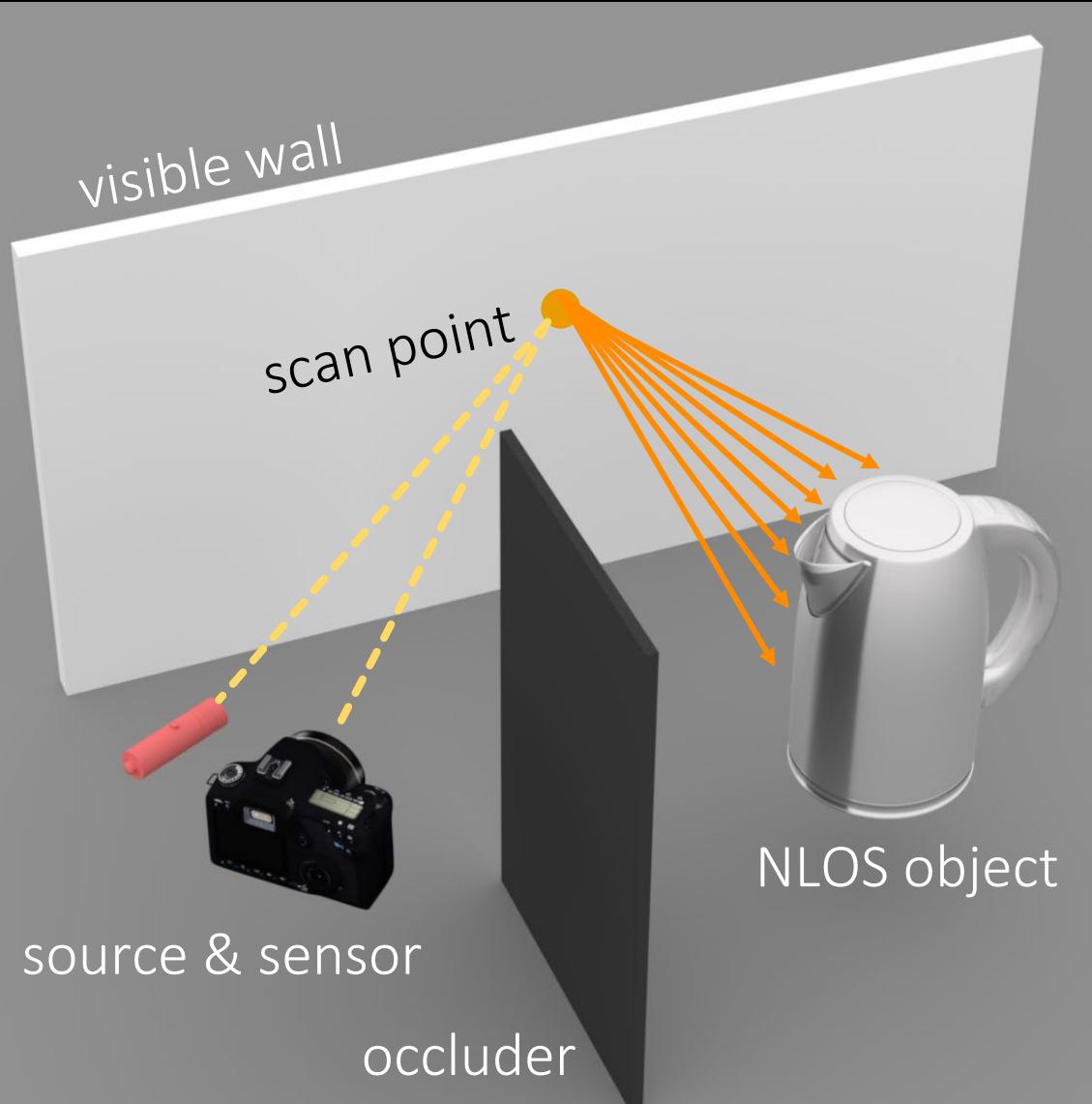
# Dispersion



resolution  
 $10^{-15} \text{ s}$

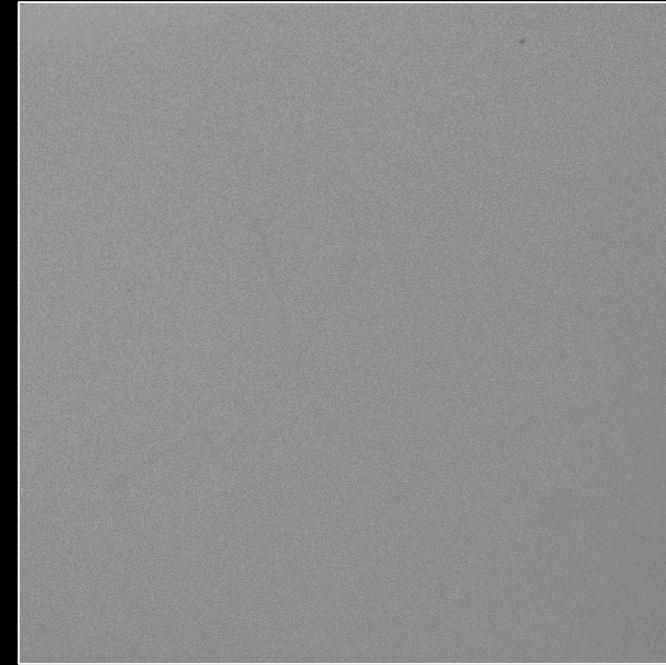
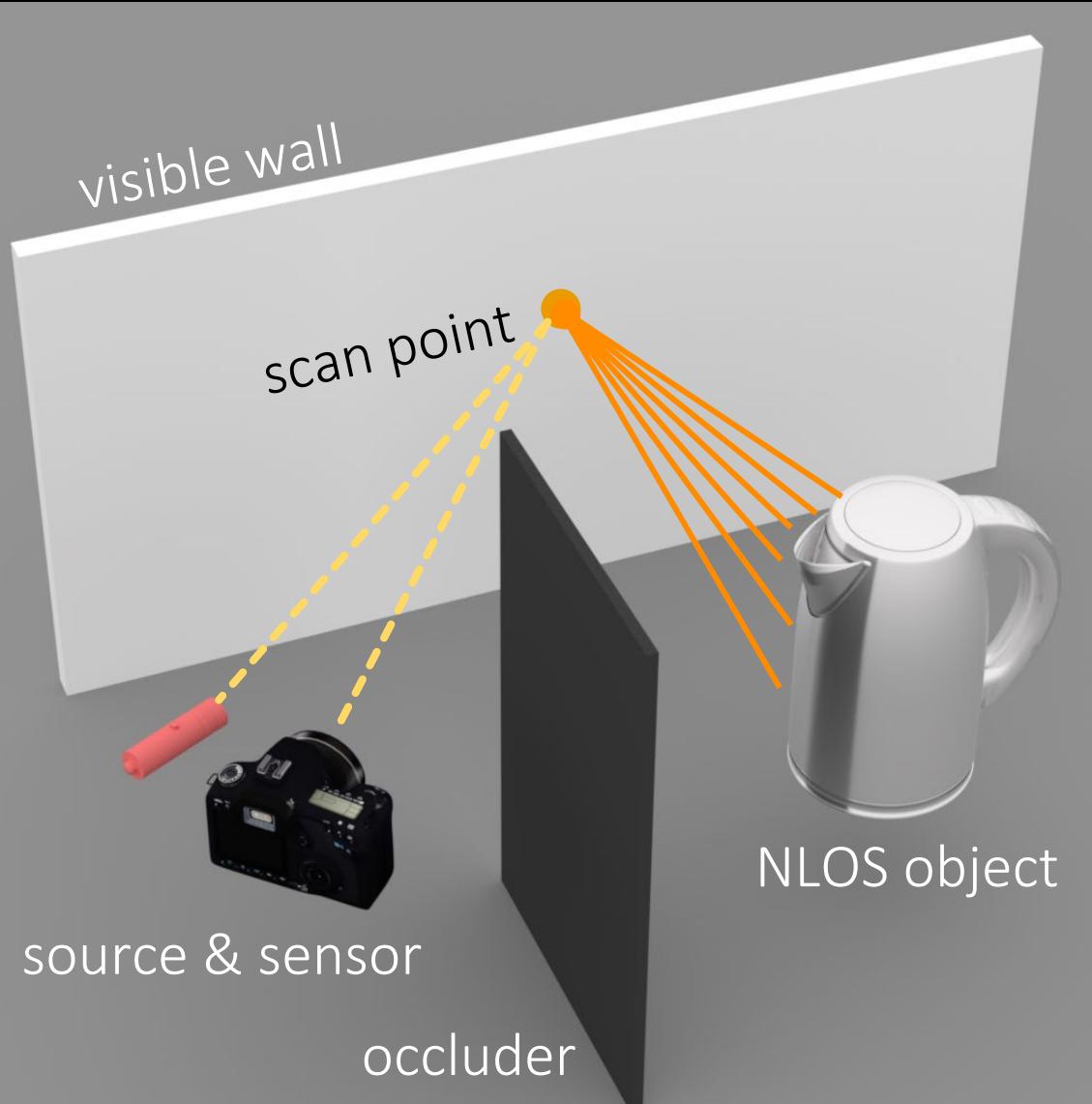


# Non-line-of-sight (NLOS) imaging



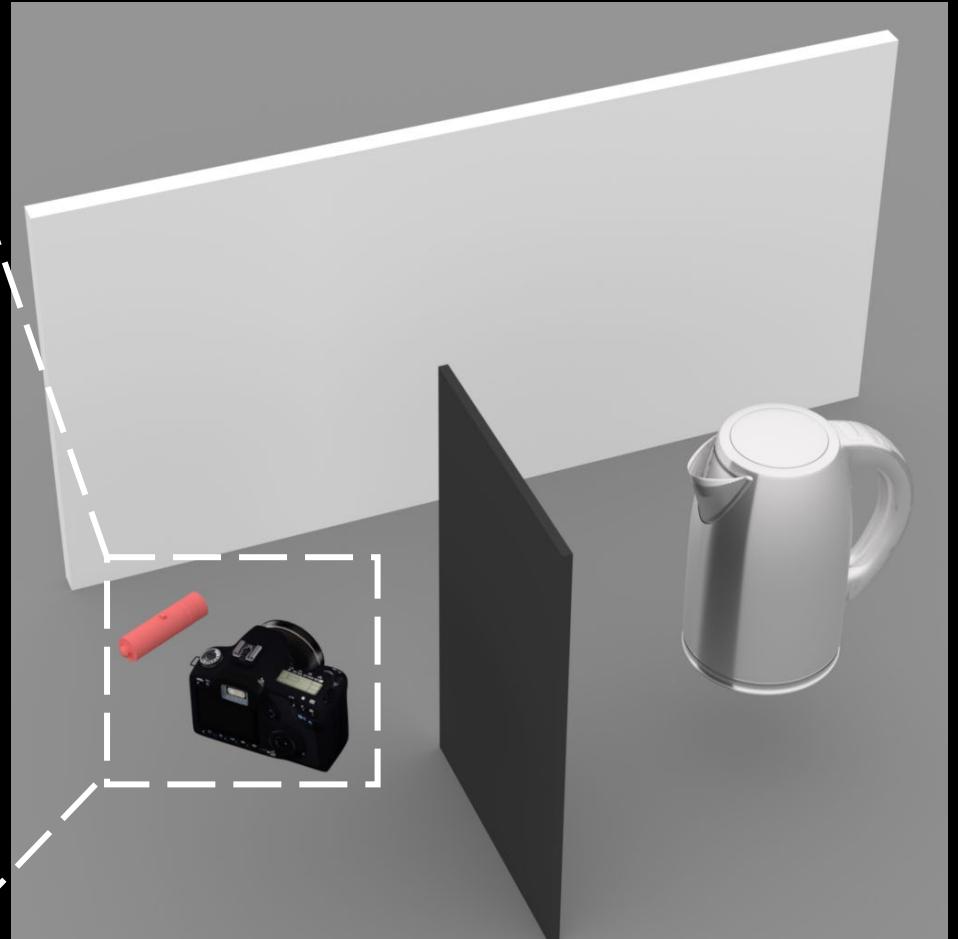
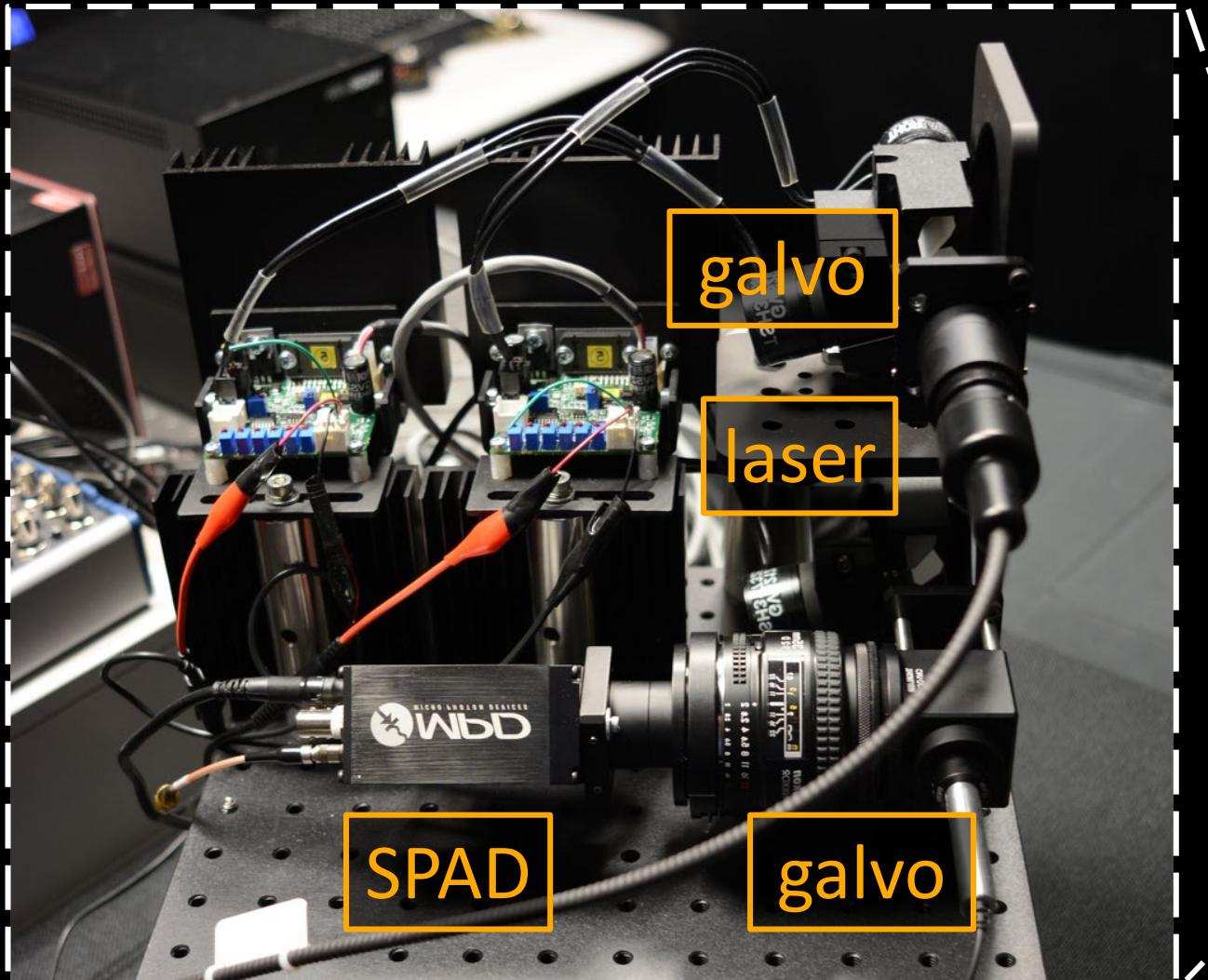
what a regular  
camera sees

# Non-line-of-sight (NLOS) imaging



what a regular  
camera sees

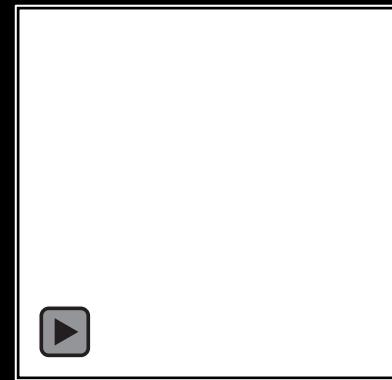
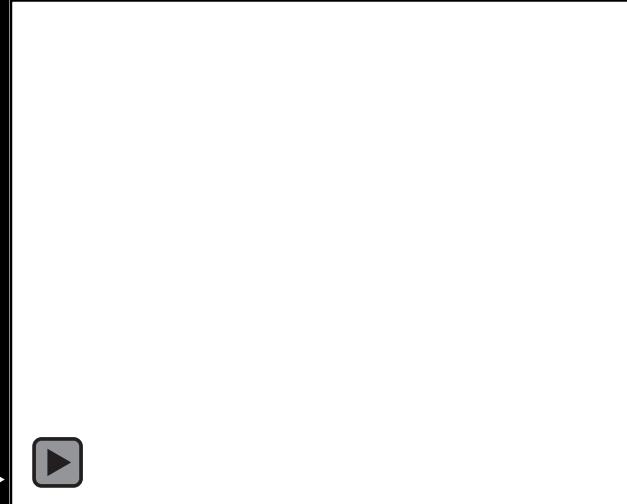
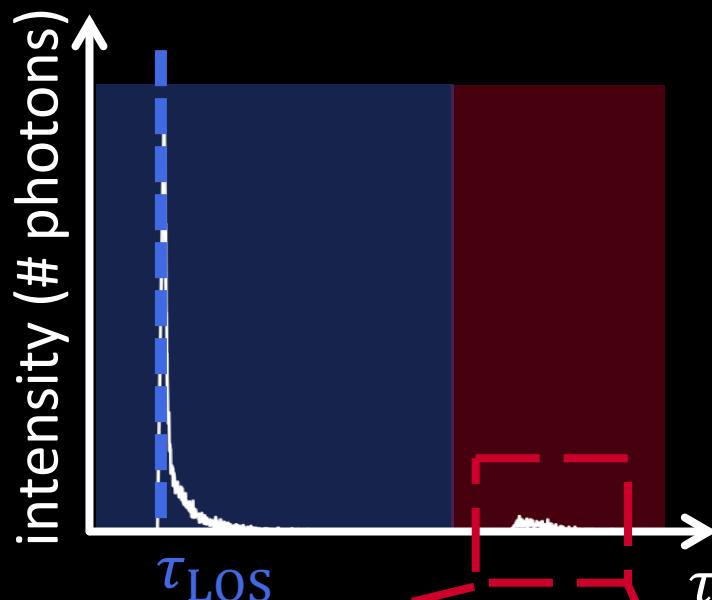
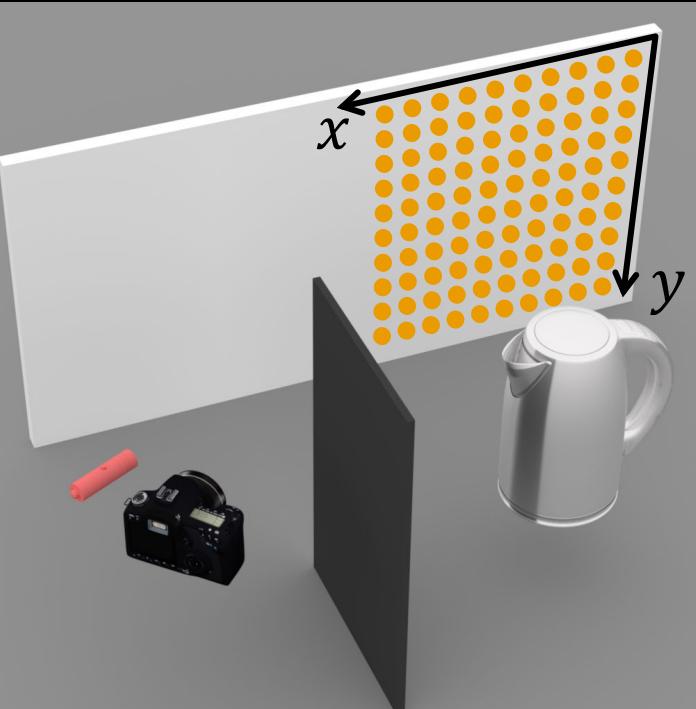
# Picosecond-scale setup



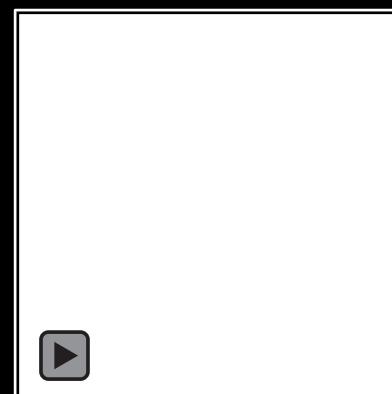
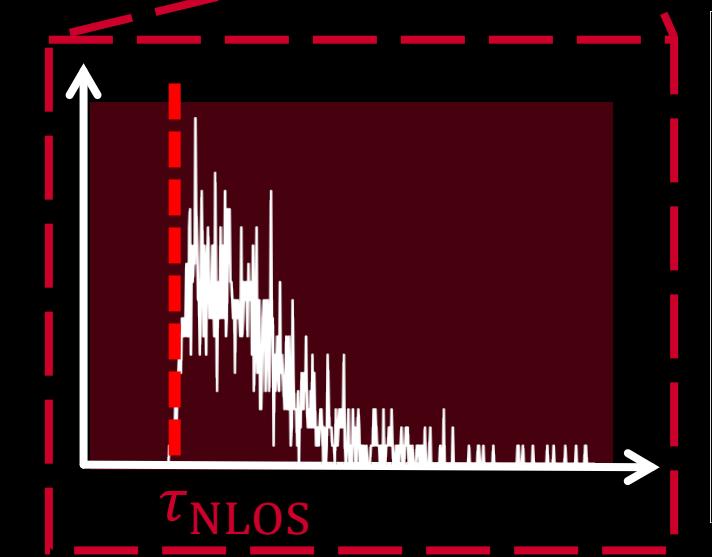
ultra-sensitive lidar capturing later returns  
(single-photon avalanche diode)

# Lidar scanning procedure

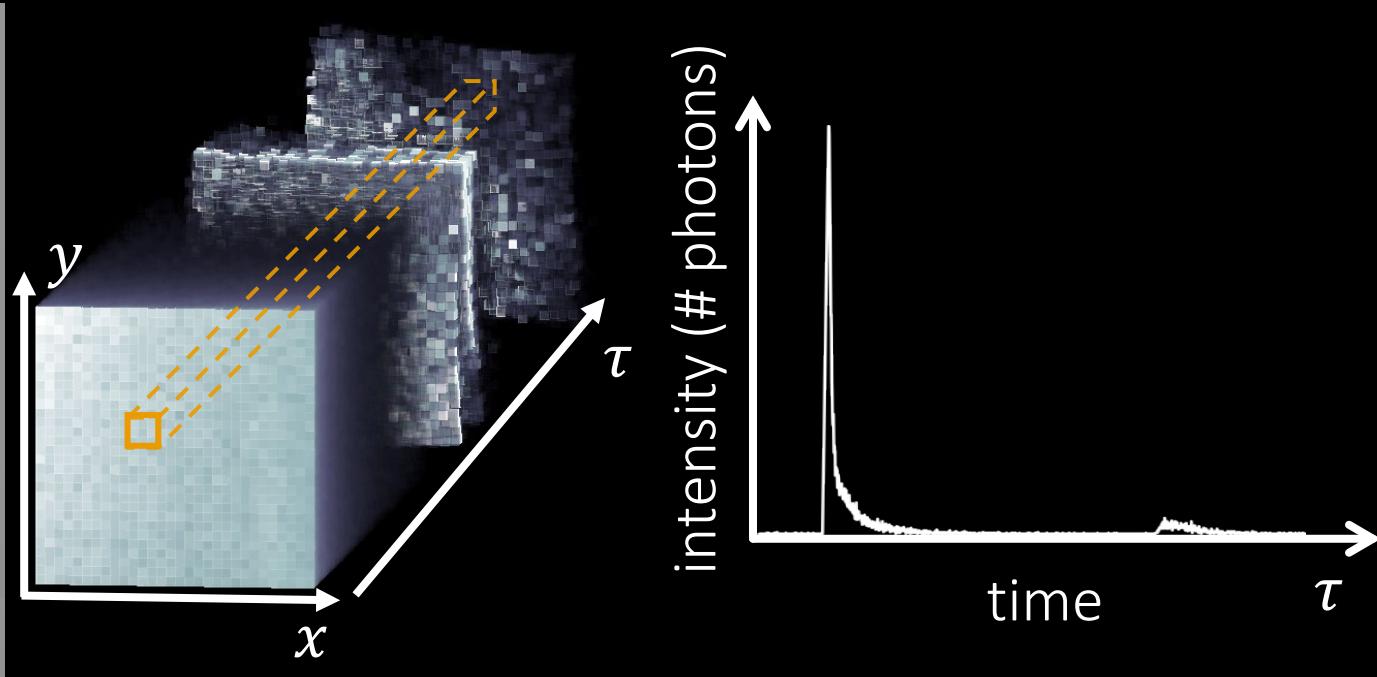
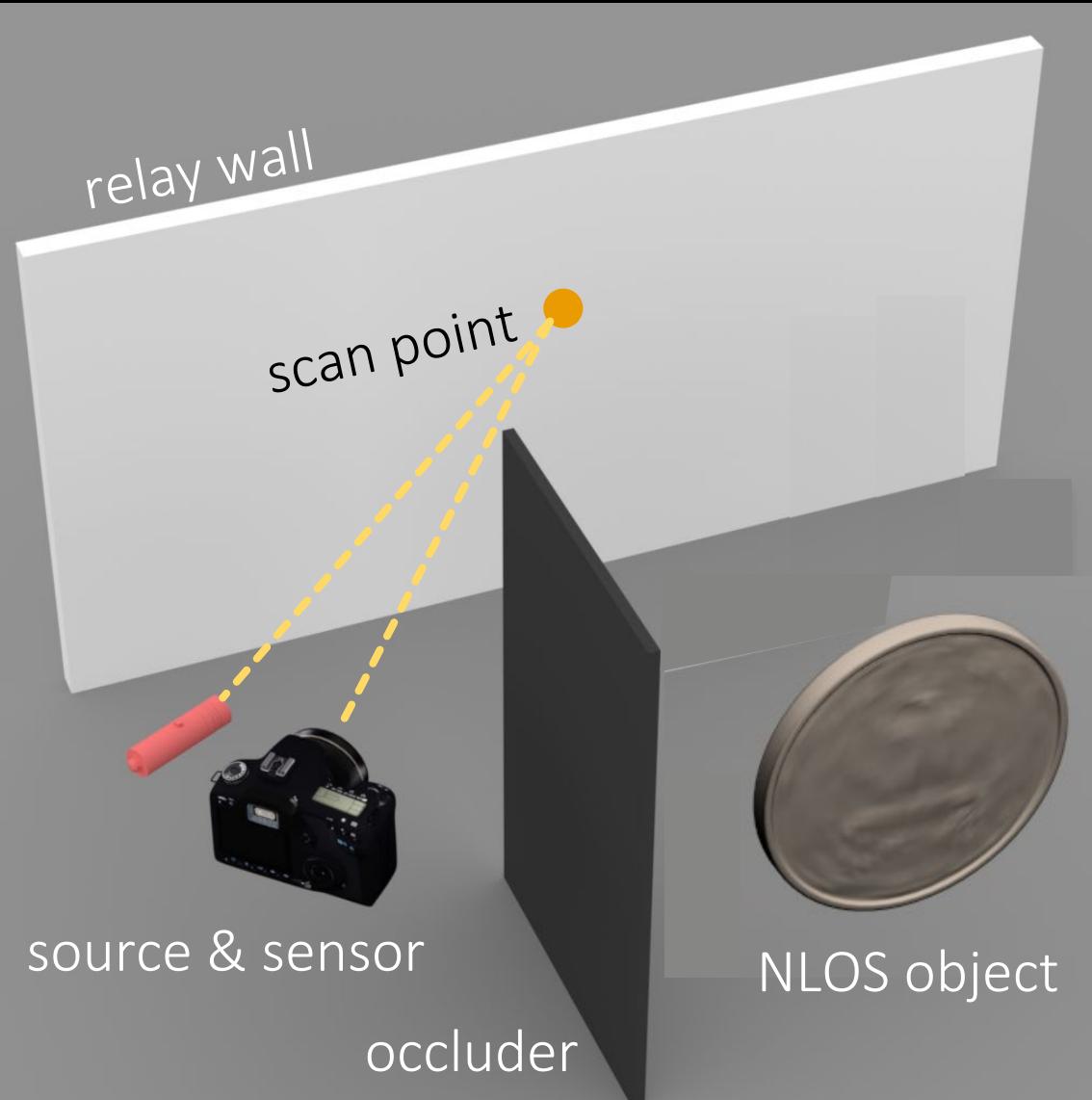
LOS Reconstruction



NLOS Reconstruction



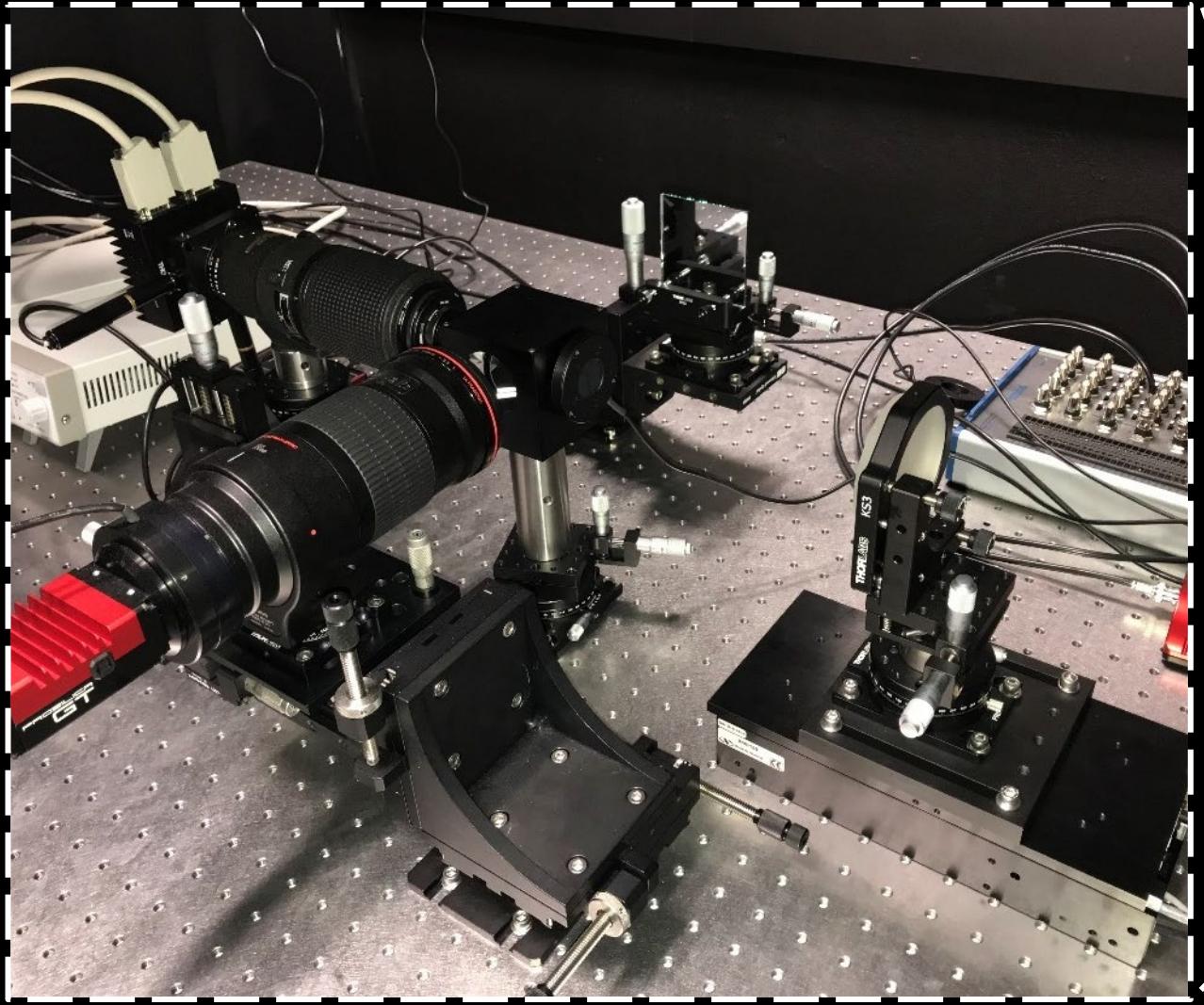
# Non-line-of-sight (NLOS) imaging



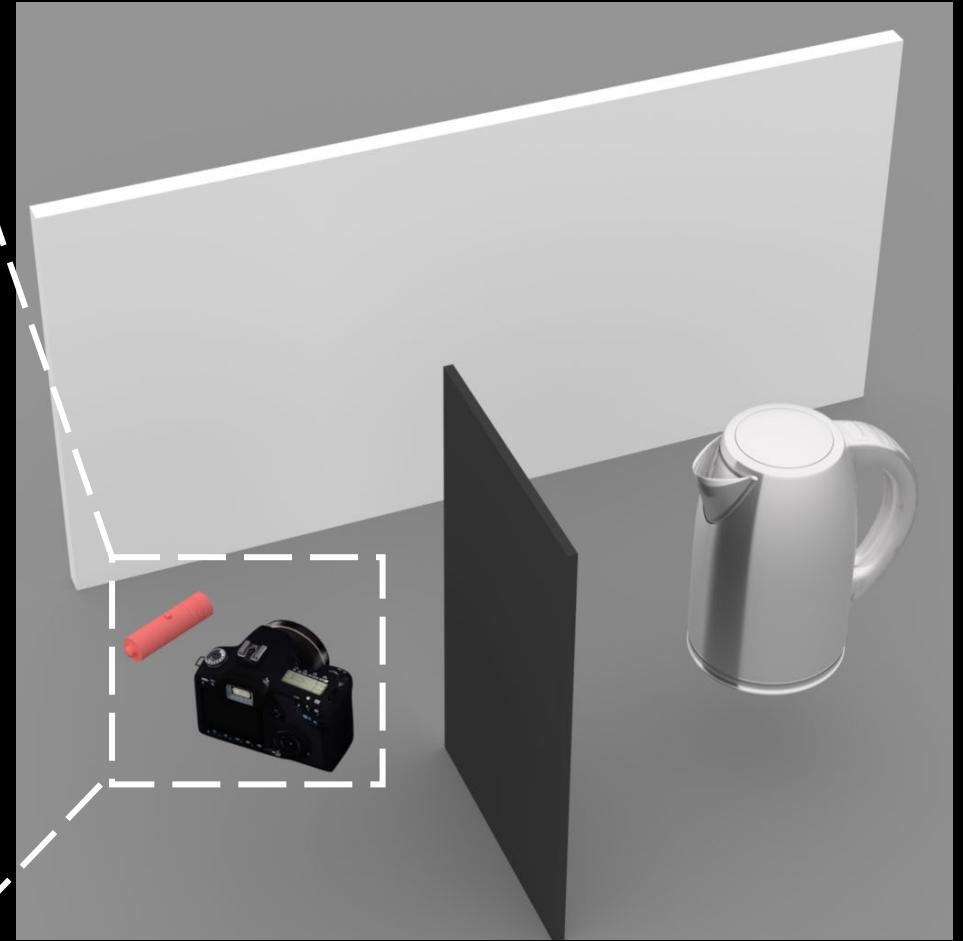
- Room-scale scanning ( $2 \text{ m} \times 2\text{m}$ )
- Object-scale scanning ( $0.5 \text{ m} \times 0.5 \text{ m}$ )

Can we do this at micron scales?

# Femtosecond-scale setup



interferometric time-of-flight setup



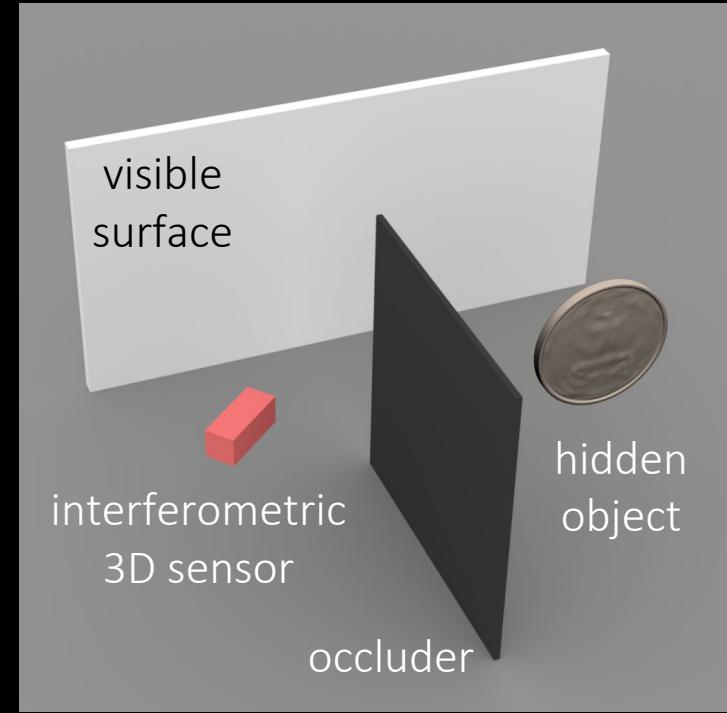
# Micron-scale NLOS imaging



ground truth (LOS scan)

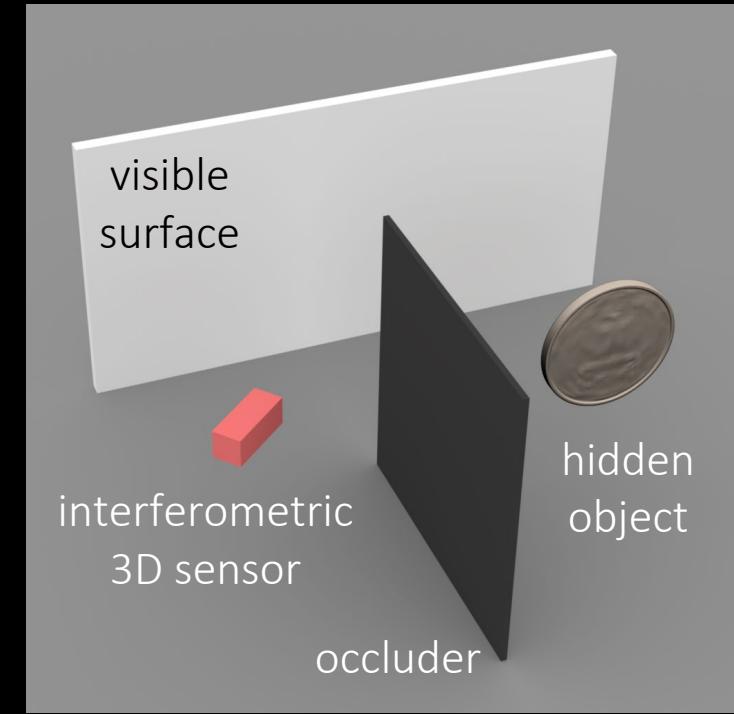
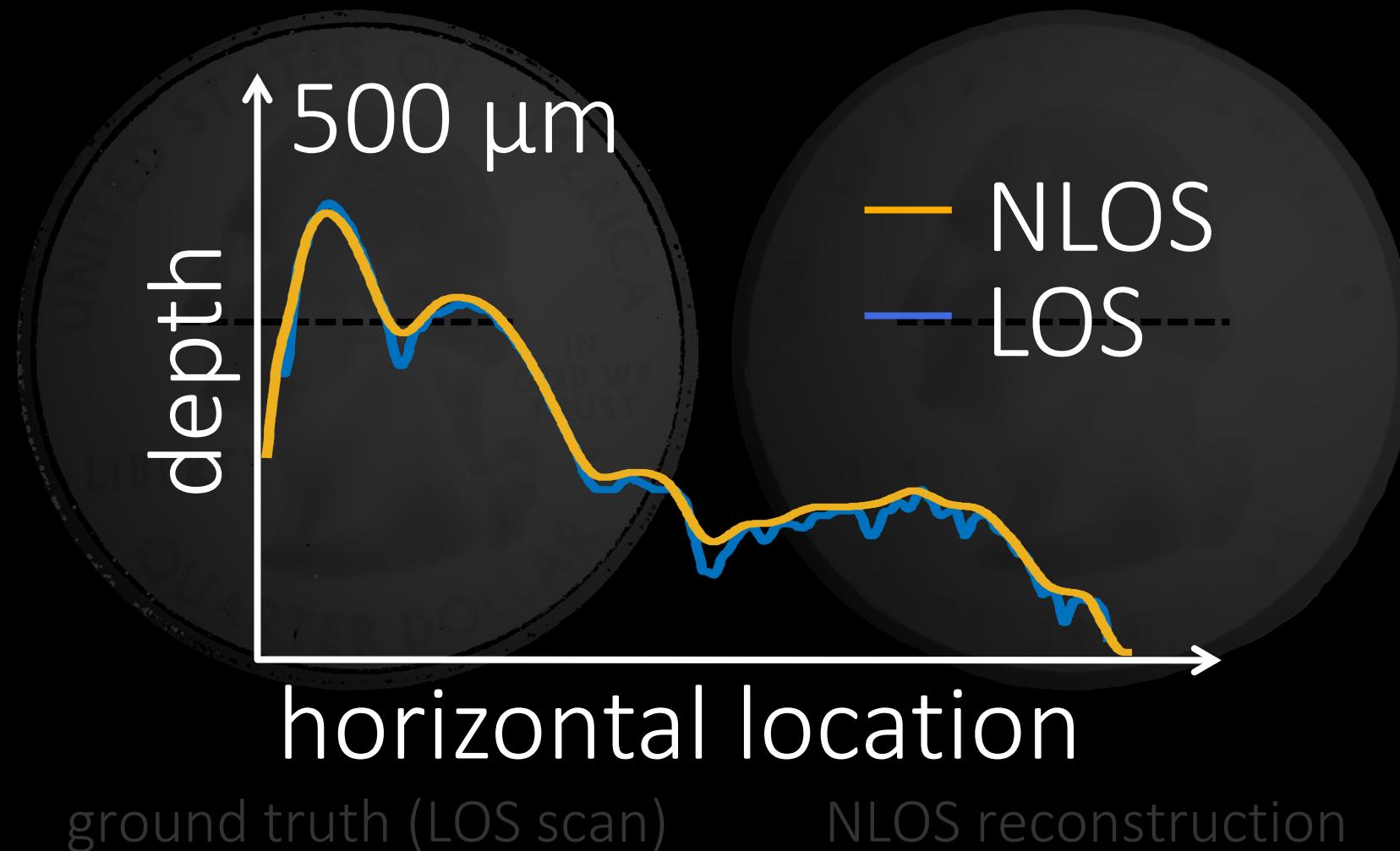


NLOS reconstruction



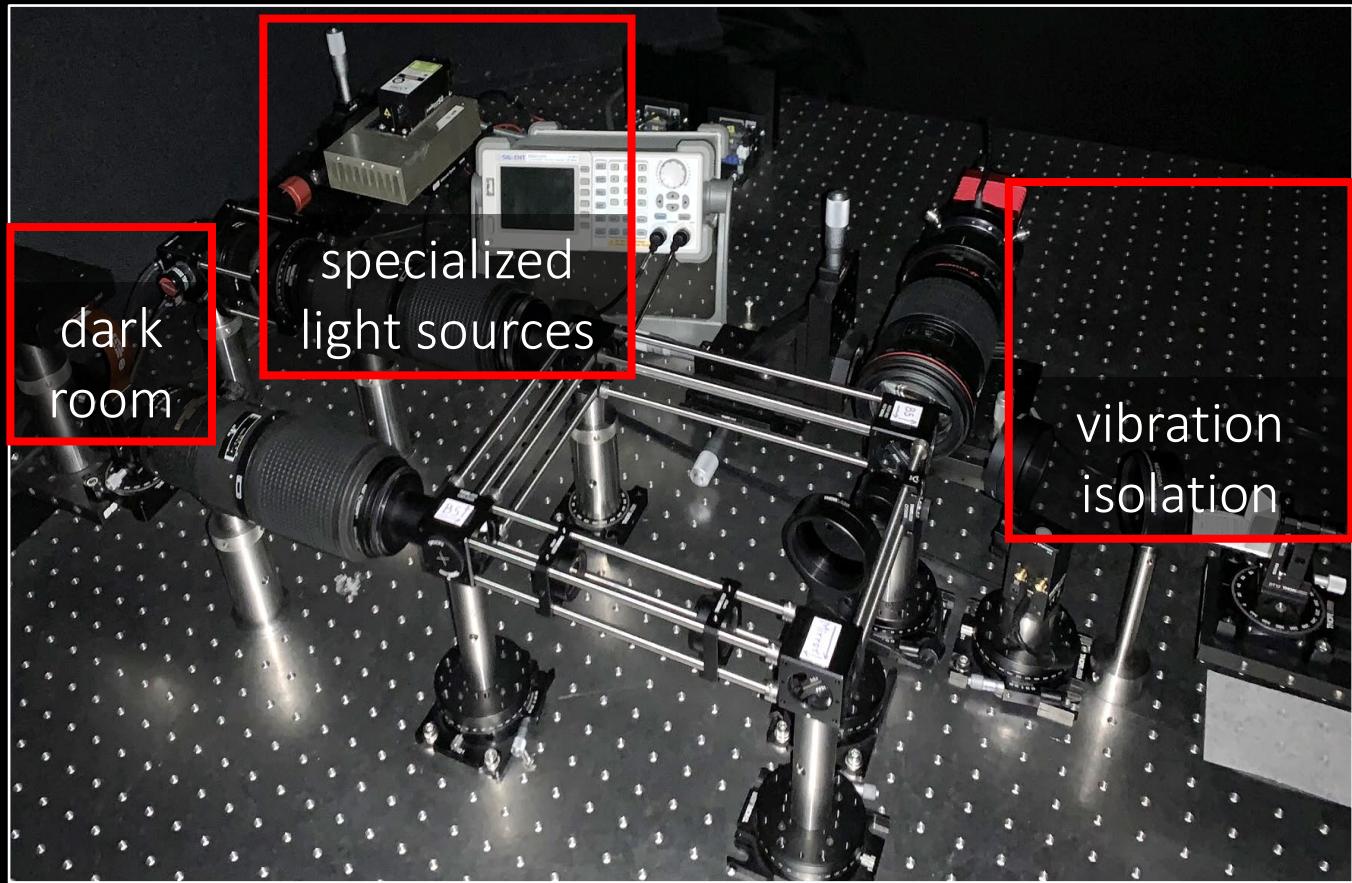
interferometric setup  
resolution: 10  $\mu\text{m}$  (33 fs)

# Micron-scale NLOS imaging

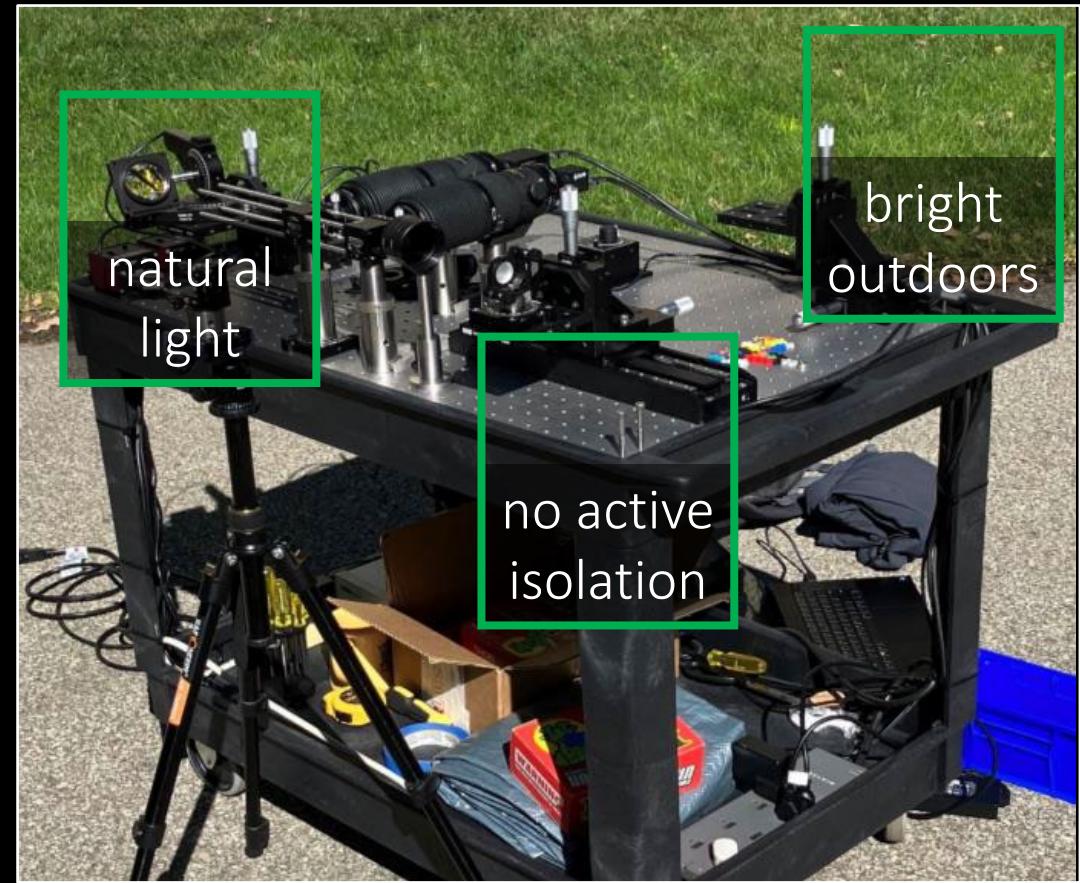


interferometric setup  
resolution: 10  $\mu\text{m}$  (33 fs)

# Deploying interferometric systems is hard

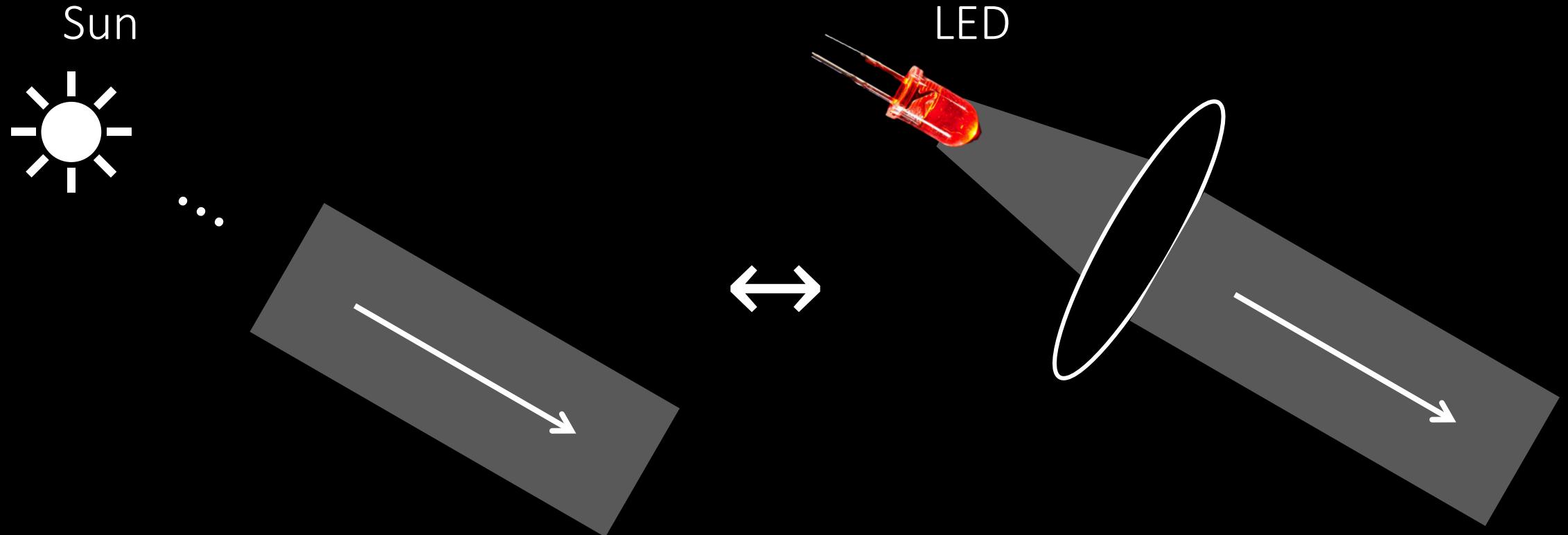


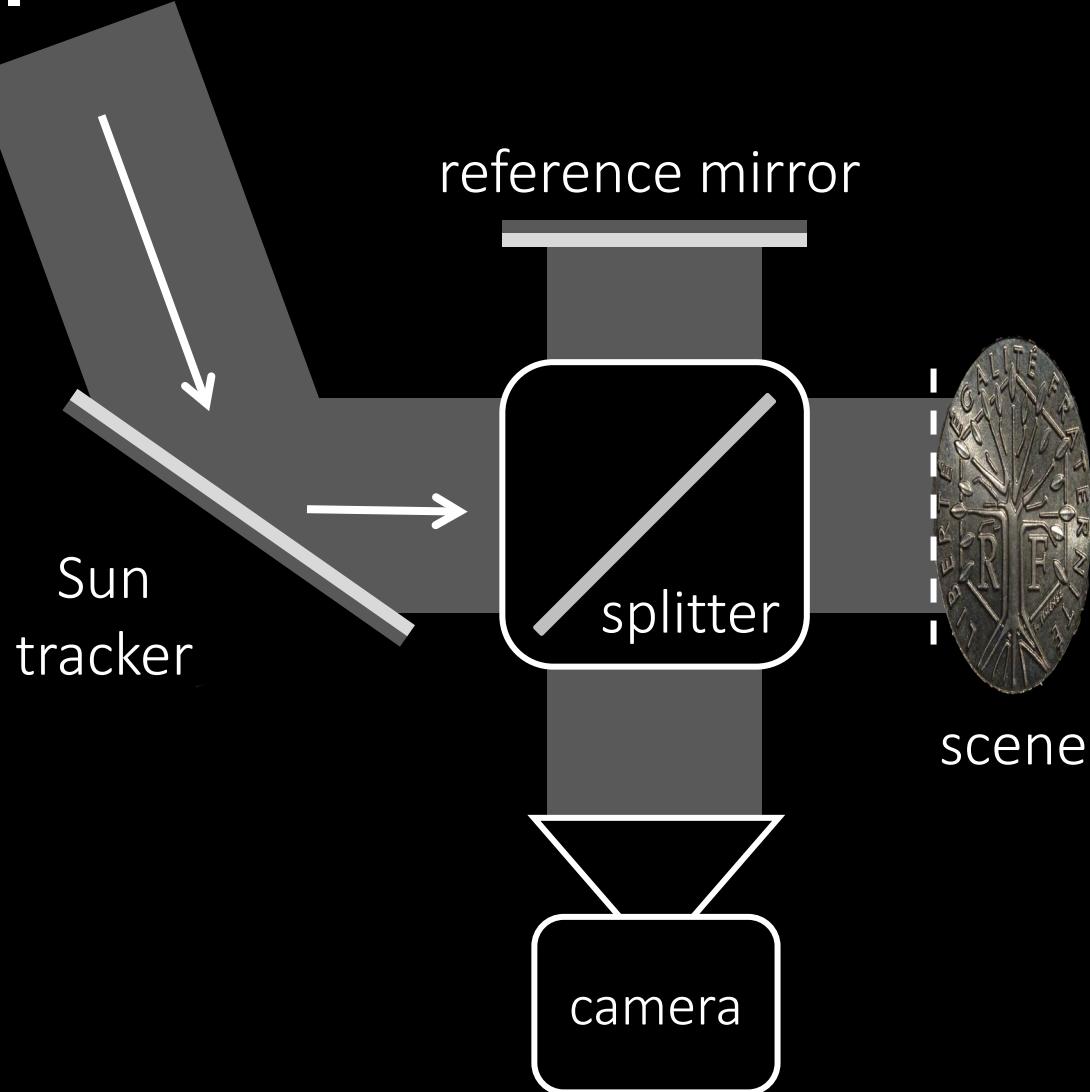
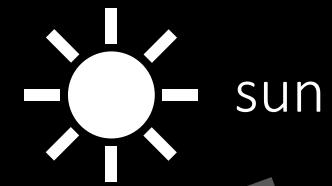
typical interferometry setup



sunlight interferometry

# Passive interferometry with sunlight





# Sunlight interferometry



scene



depth map

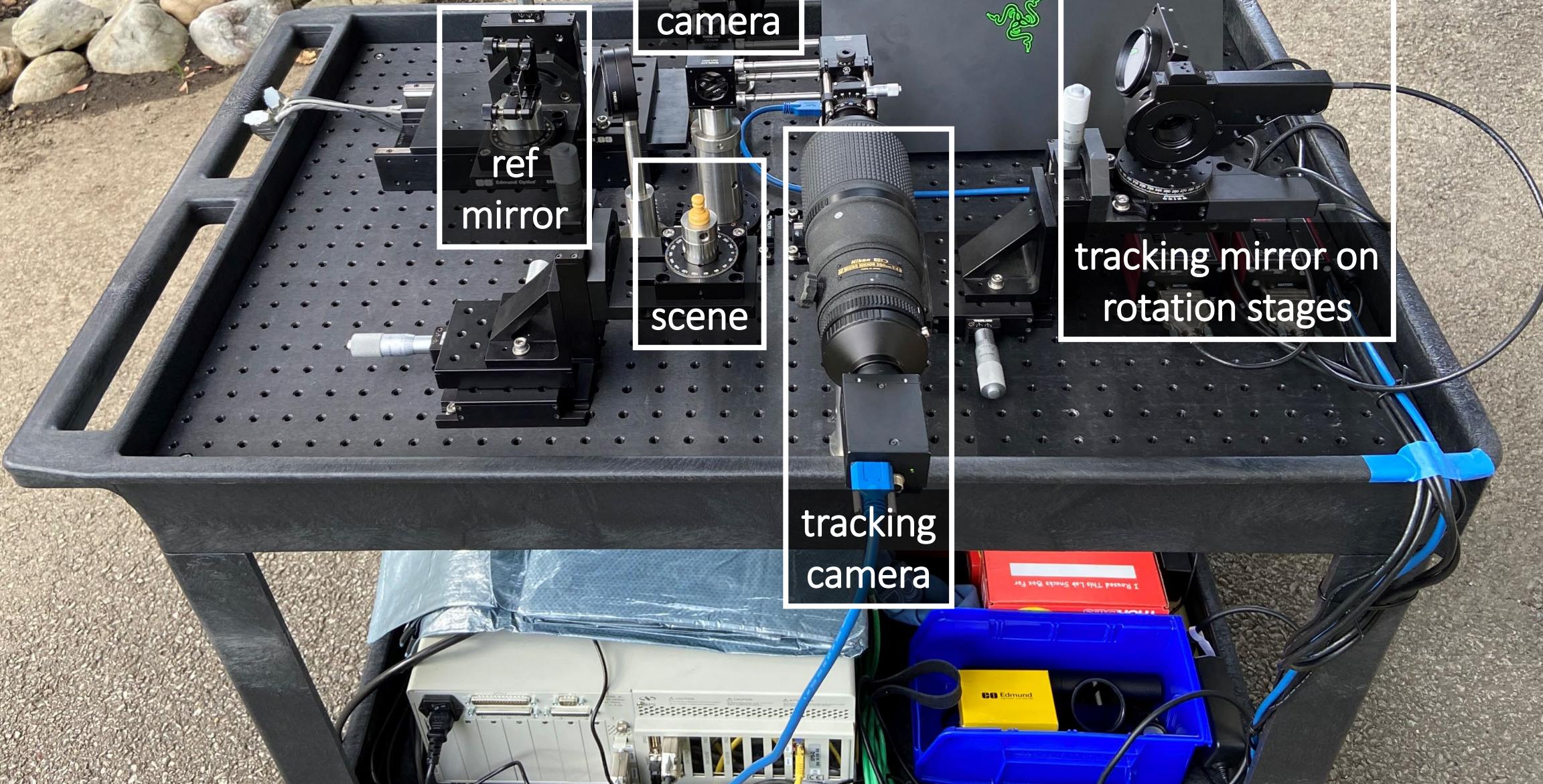


input images

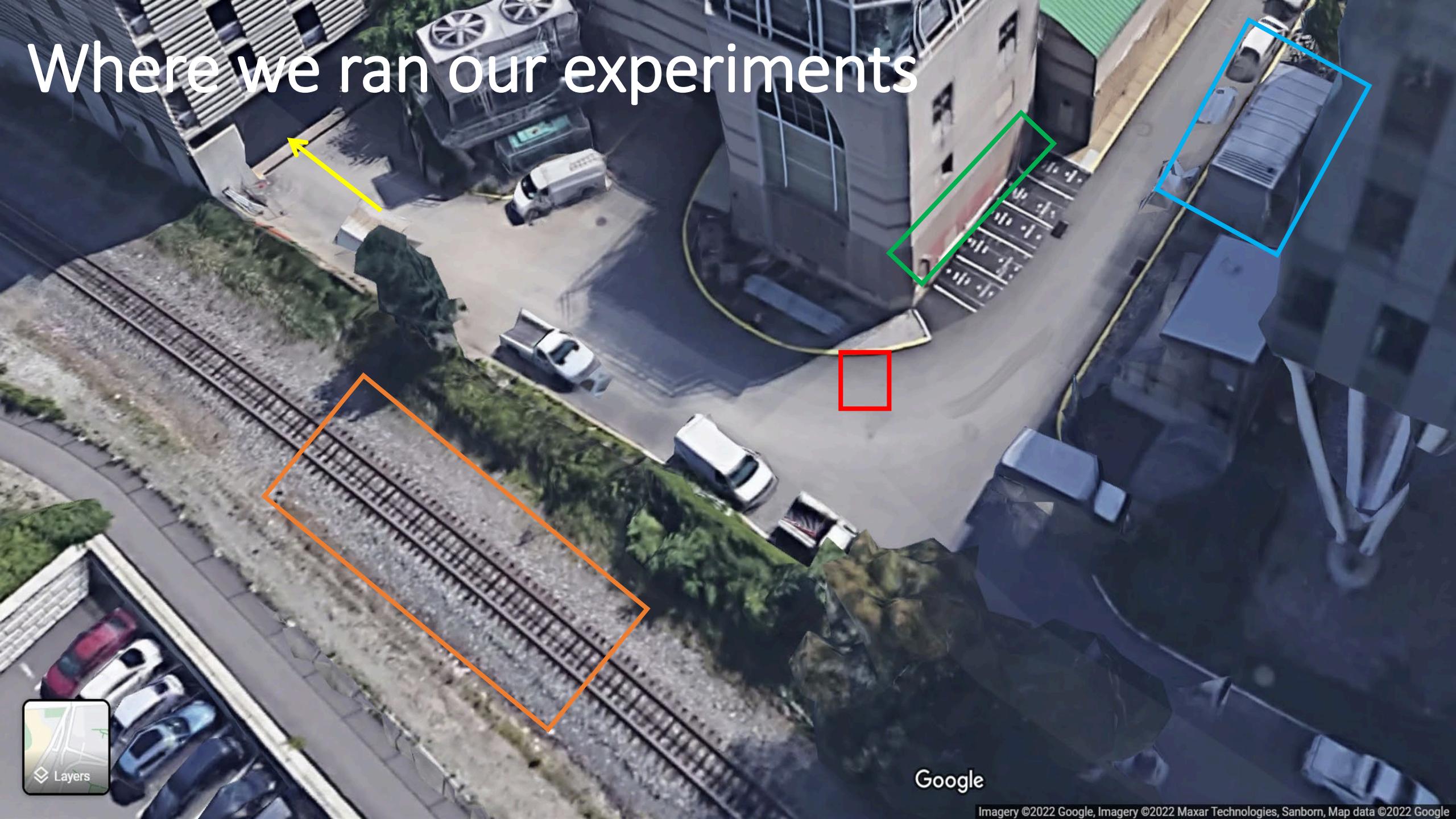


scene transient

# Optical setup

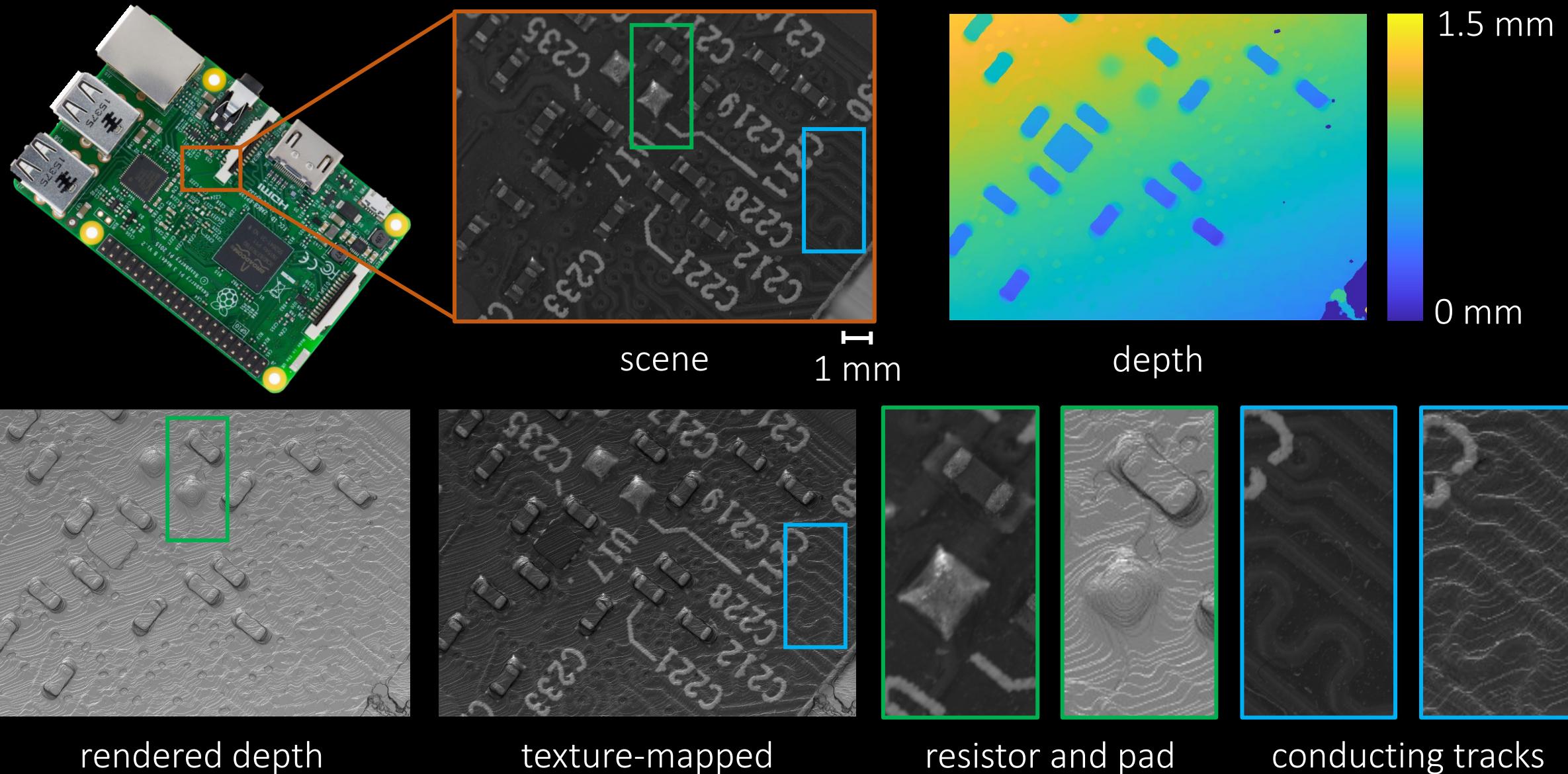


# Where we ran our experiments



Google

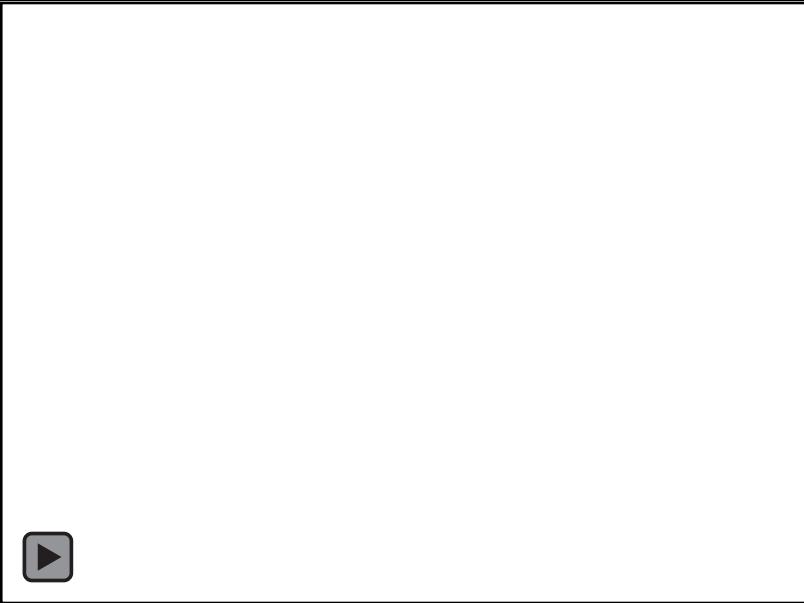
# Passive 3D sensing: Raspberry Pi



# Passive transient imaging: metallic coin



scene



transient response

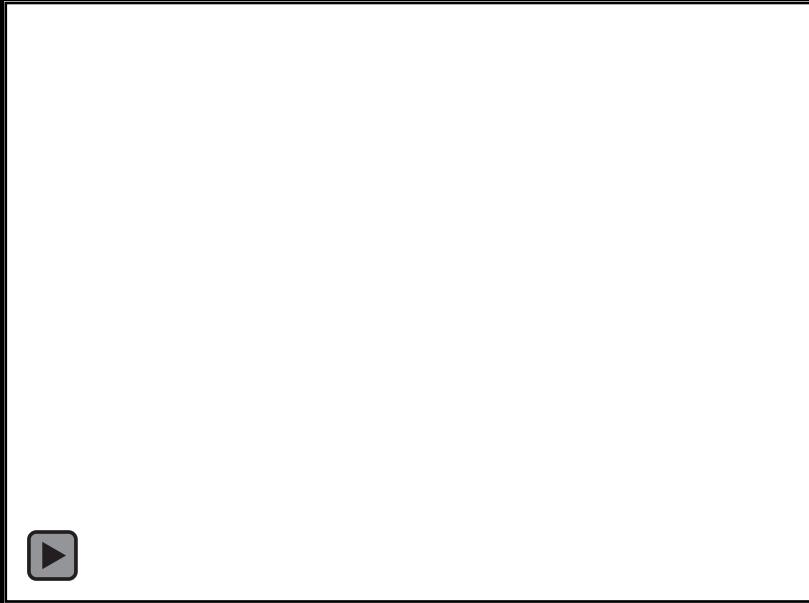


depth

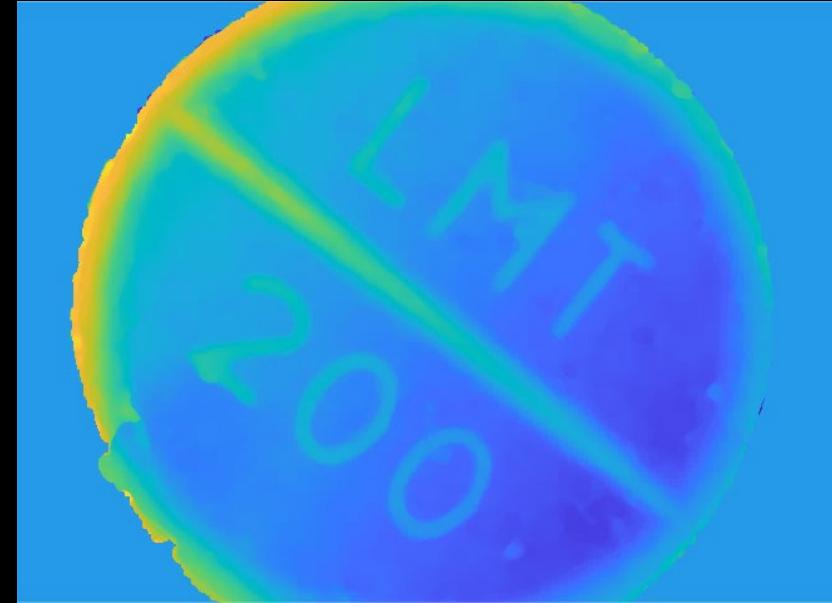
# Passive transient imaging: diffuse pill



scene

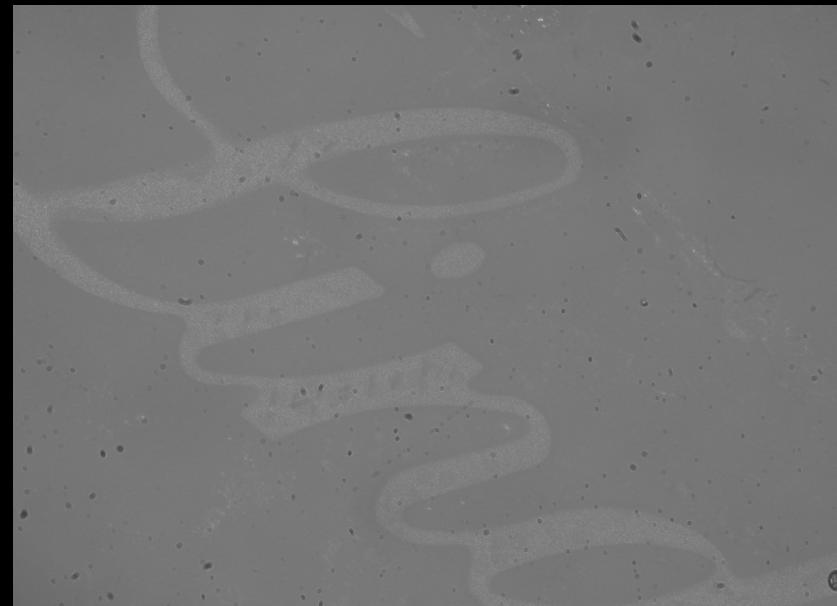


transient response

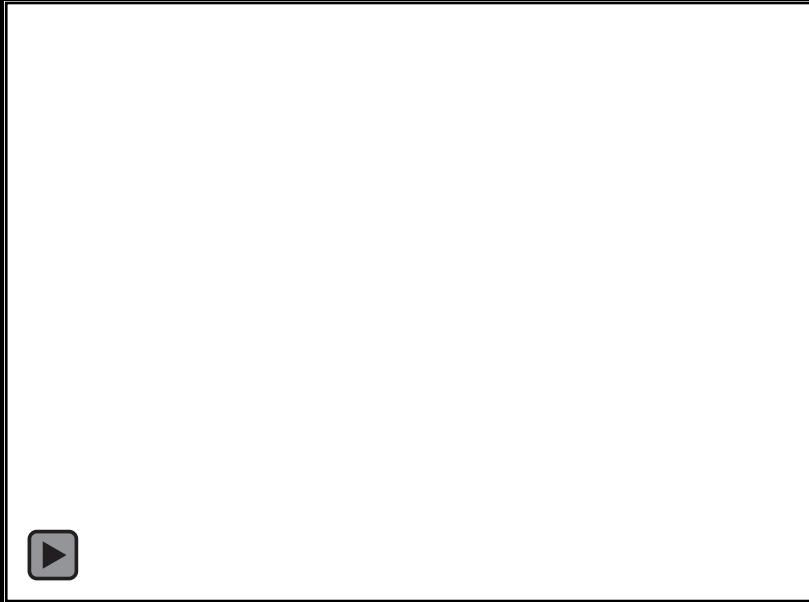


depth

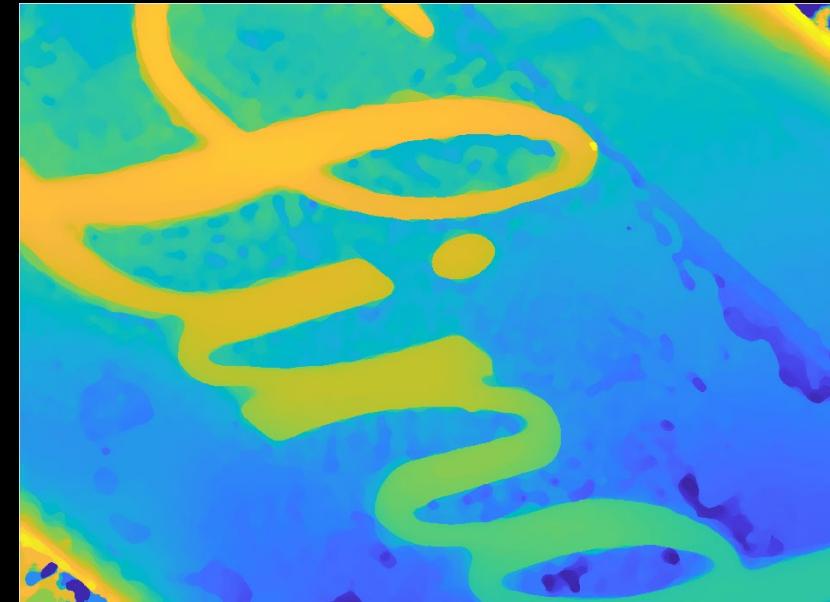
# Passive transient imaging: scattering chocolate



scene



transient response



depth

# Passive NLOS imaging

direct imaging



scene



image

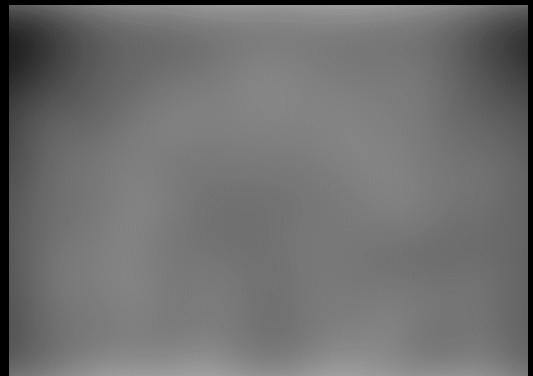


depth

occluded imaging



scene



image



depth



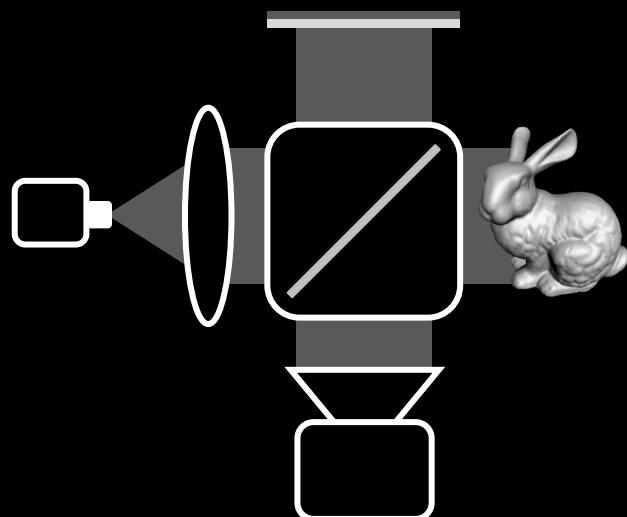
descattered image



descattered image

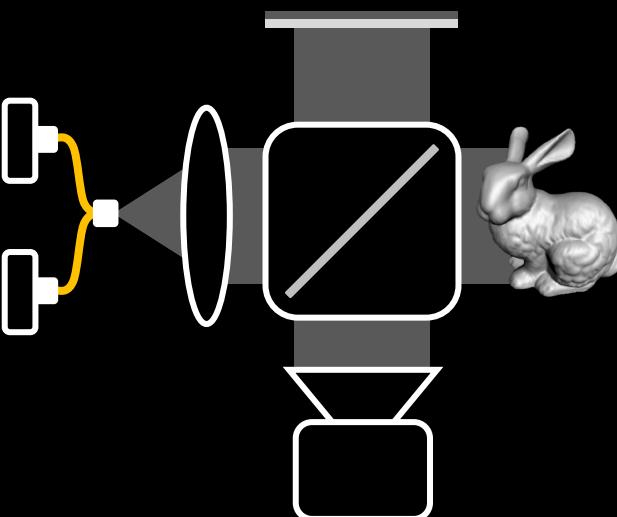
# Course overview

introduction to  
interferometry



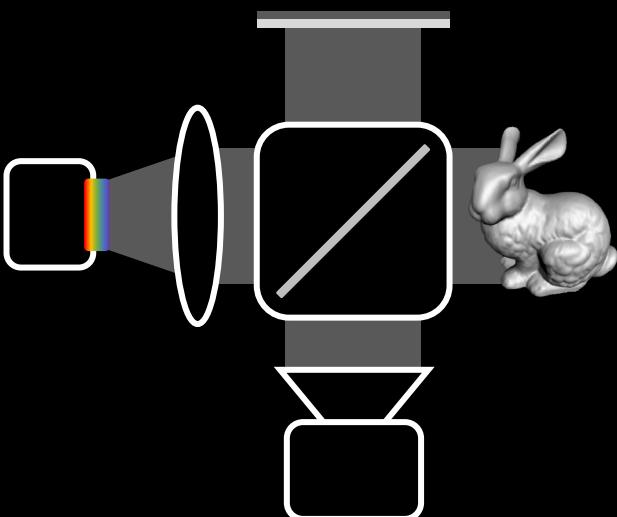
Yannis

two-wavelength  
interferometry



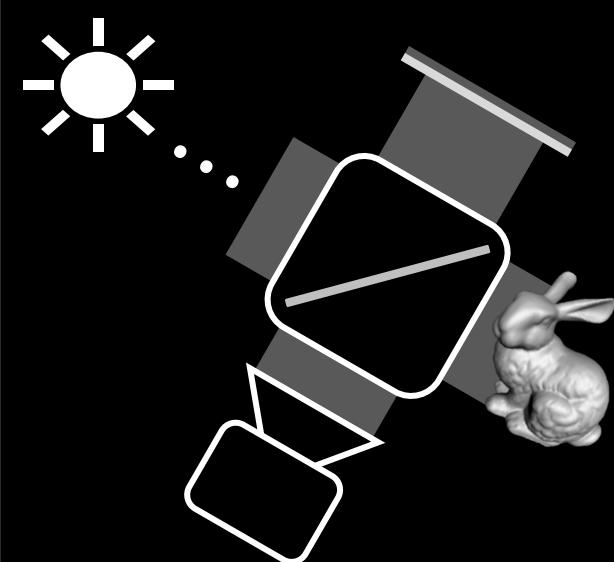
Florian

partially-coherent  
interferometry



Alankar

interferometric  
computational imaging



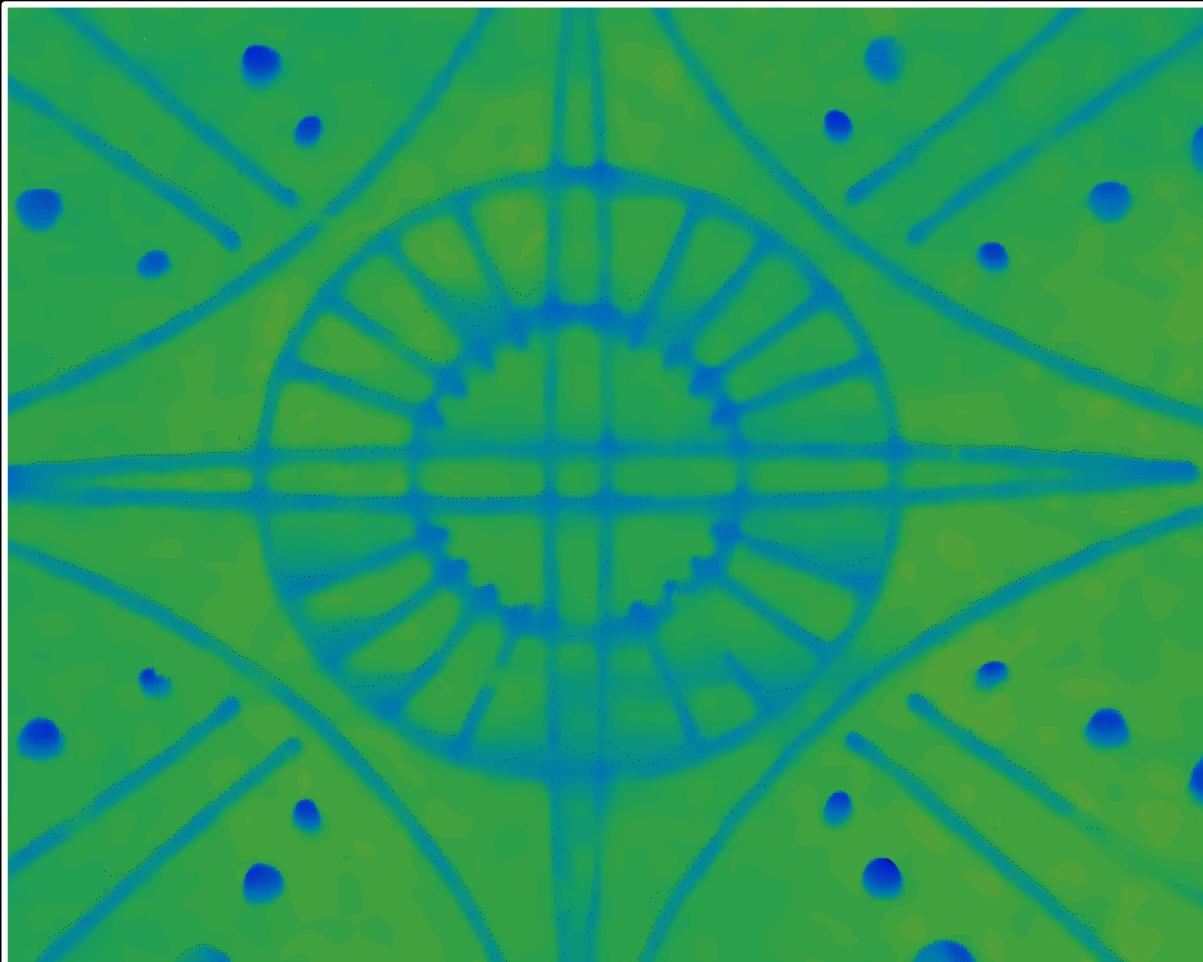
Florian



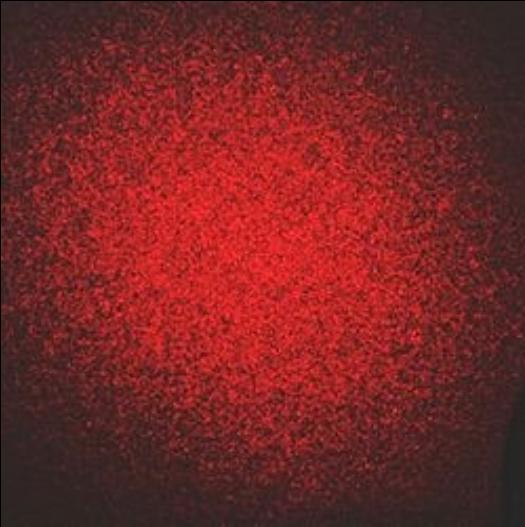
Yannis



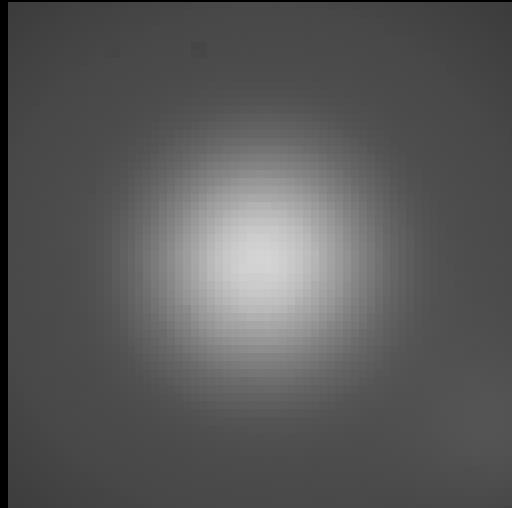
A coherent world...



# Speckle rendering



what real laser  
images look like



what standard  
Monte Carlo  
renderings look like

## A Monte Carlo Framework for Rendering Speckle Statistics in Scattering Media

CHEN BAR, Department of Electrical Engineering, Technion, Israel

MARINA ALTERMAN, Department of Electrical Engineering, Technion, Israel

IOANNIS GKIOULEKAS, Robotics Institute, Carnegie Mellon University, USA

ANAT LEVIN, Department of Electrical Engineering, Technion, Israel

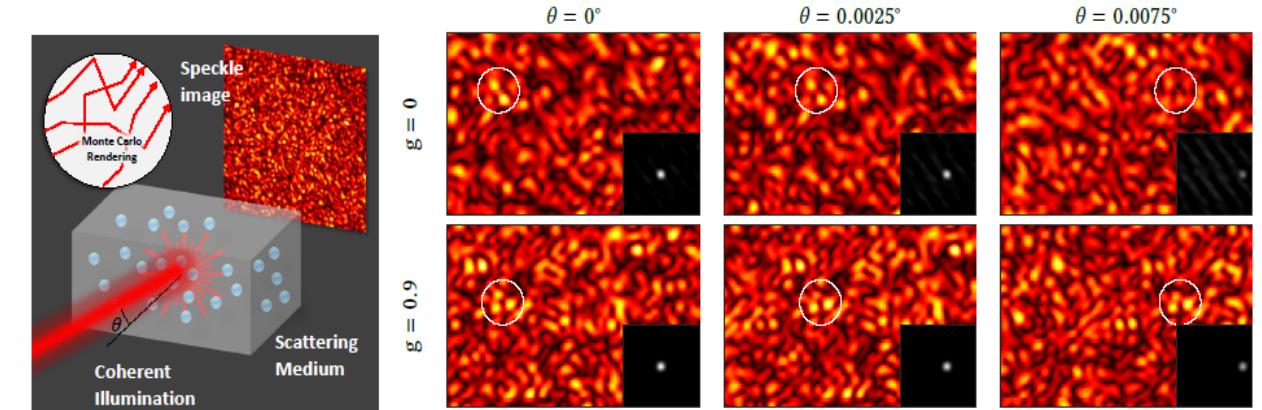
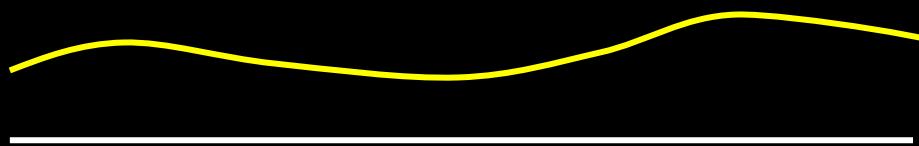


Fig. 1. Simulation of memory effect in scattering. Coherent images of translucent materials typically involve highly-fluctuating speckle structure. Despite their semi-random structure, speckles have strong statistical properties. For example, the memory effect property states that, as one tilts the illumination direction (setup at left), the resulting speckles shift. This property is at the core of multiple computational imaging applications. The memory effect is valid over a limited angular range that depends on material properties. Due to the absence of analytical formulas, it is generally necessary to measure this angular range for materials of interest empirically in the lab. We present a Monte Carlo rendering approach for simulating physically-accurate speckle images, as well as their statistics, as a function of material parameters. The figure shows speckle images rendered by our algorithm for a few illumination directions, as well as their auto-correlation (black insets), demonstrating the speckle shift property. As the angle difference increases, the correlation decays, and the decay rate is different for different material parameters—in this case, materials with Henyey-Greenstein (HG) phase functions of different parameters  $g$ . For the isotropic scattering case,  $g = 0$ , the pattern similarity is lost at the third column, whereas for the forward scattering case,  $g = 0.9$ , correlation is preserved. We verify the accuracy of our algorithm against an exact, yet computationally heavy, wave solver, as well as against analytical formulas derived under limiting assumptions.

# Other coherent effects



[https://en.wikipedia.org/wiki/Thin-film\\_interference](https://en.wikipedia.org/wiki/Thin-film_interference)



thin film interference

I  
 $\approx 1 \mu\text{m}$



<https://en.wikipedia.org/wiki/CD-ROM>



diffraction

# Some work in this area

## Reflectance Model for Diffraction

TOM CUYPERS, TOM HABER and PHILIPPE BEKAERT

Hasselt University

and

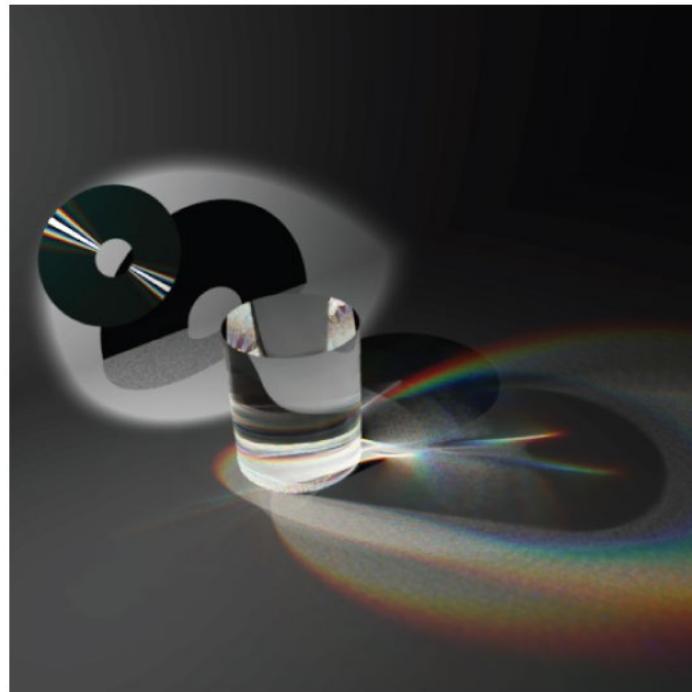
SE BAEK OH and RAMESH RASKAR

MIT

We present a novel method of simulating wave effects in graphics using ray-based renderers with a new function: the Wave BSDF (Bidirectional Scattering Distribution Function). Reflections from neighboring surface patches represented by local BSDFs are mutually independent. However, in many surfaces with wavelength-scale microstructures, interference and diffraction requires a joint analysis of reflected wavefronts from neighboring patches. We demonstrate a simple method to compute the BSDF for the entire microstructure, which can be used independently for each patch. This allows us to use traditional ray-based rendering pipelines to synthesize wave effects. We exploit the Wigner Distribution Function (WDF) to create transmissive, reflective, and emissive BSDFs for various diffraction phenomena in a physically accurate way. In contrast to previous methods for computing interference, we circumvent the need to explicitly keep track of the phase of the wave by using BSDFs that include positive as well as negative coefficients. We describe and compare the theory in relation to well-understood concepts in rendering and demonstrate a straightforward implementation. In conjunction with standard raytracers, such as PBRT, we demonstrate wave effects for a range of scenarios such as multibounce diffraction materials, holograms, and reflection of high-frequency surfaces.

Categories and Subject Descriptors: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—*Physically based modeling*

General Terms: Algorithms, Theory



## A Generic Framework for Physical Light Transport

SHLOMI STEINBERG, University of California, Santa Barbara, USA

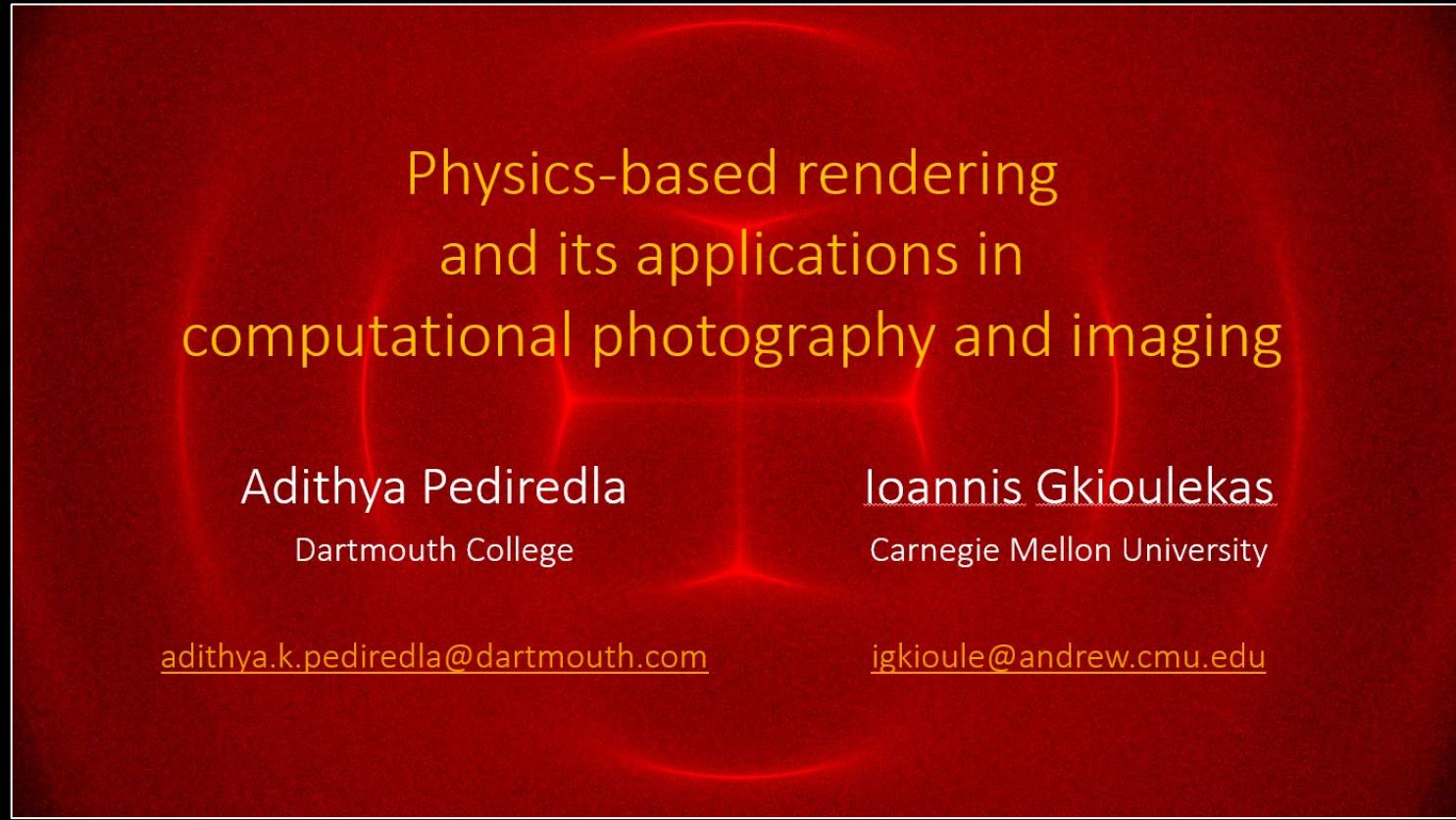
LING-QI YAN, University of California, Santa Barbara, USA



Fig. 1. We generalize the rendering equation and the BSDF to simulate wave phenomena. The new Wave BSDF behaves like a local scattering function, creates interference globally, and allows easy integration into traditional ray-based methods.

We still can't render an interferometer  
(for general scenes)

But it would  
be awesome  
if we could!



Physics-based rendering  
and its applications in  
computational photography and imaging

Adithya Pediredla  
Dartmouth College

[adithya.k.pediredla@dartmouth.edu](mailto:adithya.k.pediredla@dartmouth.edu)

Ioannis Gkioulekas  
Carnegie Mellon University

[igkioule@andrew.cmu.edu](mailto:igkioule@andrew.cmu.edu)



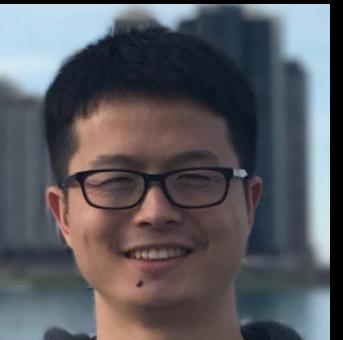
# Many thanks to our collaborators!



Anat  
Levin



Ashok Veeraraghavan



Fengqiang  
Li



Fredo  
Durand



Heming  
Wang



Jiren  
Li



Manuel  
Ballester



Marc  
Christensen



Muralidhar  
Balaji



Oliver  
Cossairt



Patrick  
Cornwall



Prasanna  
Rangarajan



Todd  
Zickler



Yicheng  
Wu

# Many thanks to our sponsors!



**OPTICA**  
Formerly OSA



 **ALFRED P. SLOAN**  
FOUNDATION

**SEE BELOW THE SKIN**

# Questions?



Alankar Kotwal

University of Texas Medical Branch  
[alankarkotwal13@gmail.com](mailto:alankarkotwal13@gmail.com)  
[alankarkotwal.github.io](http://alankarkotwal.github.io)



Florian Willomitzer

University of Arizona  
[fwillomitzer@arizona.edu](mailto:fwillomitzer@arizona.edu)  
[www.optics.arizona.edu/3dim](http://www.optics.arizona.edu/3dim)



Ioannis Gkioulekas

Carnegie Mellon University  
[igkioule@andrew.cmu.edu](mailto:igkioule@andrew.cmu.edu)  
[imaging.cs.cmu.edu](http://imaging.cs.cmu.edu)

Course website



[imaging.cs.cmu.edu/interferometry\\_siggraph2023](https://imaging.cs.cmu.edu/interferometry_siggraph2023)