Computational interferometric imaging

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SIGGRAPH 2023

imaging.cs.cmu.edu/interferometry_siggraph2023

Today's presenters

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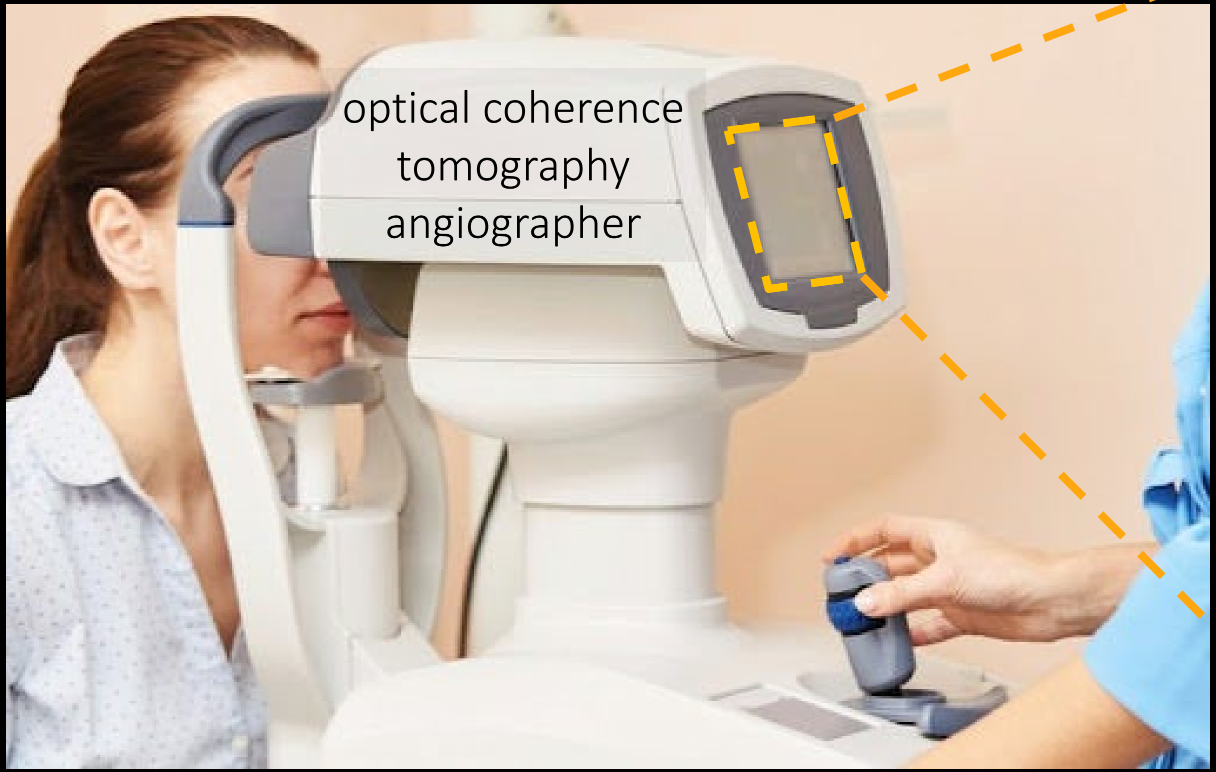
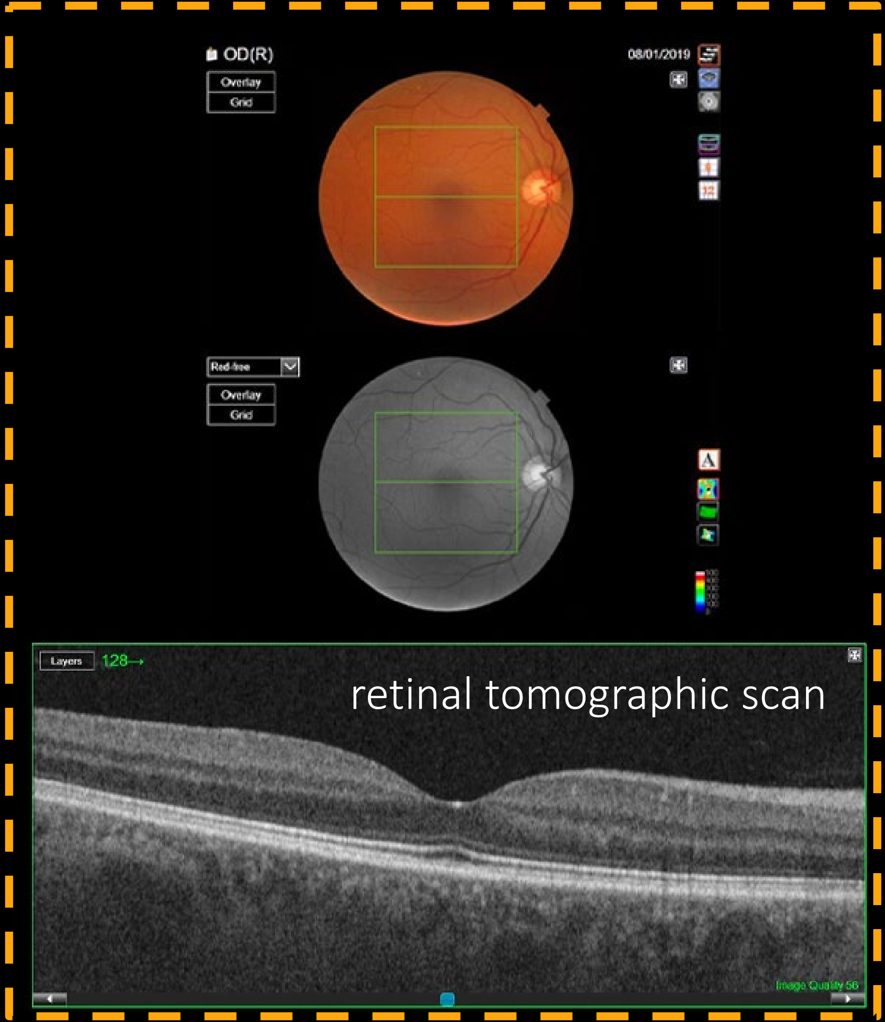
What is interferometry?

OCT eye exam



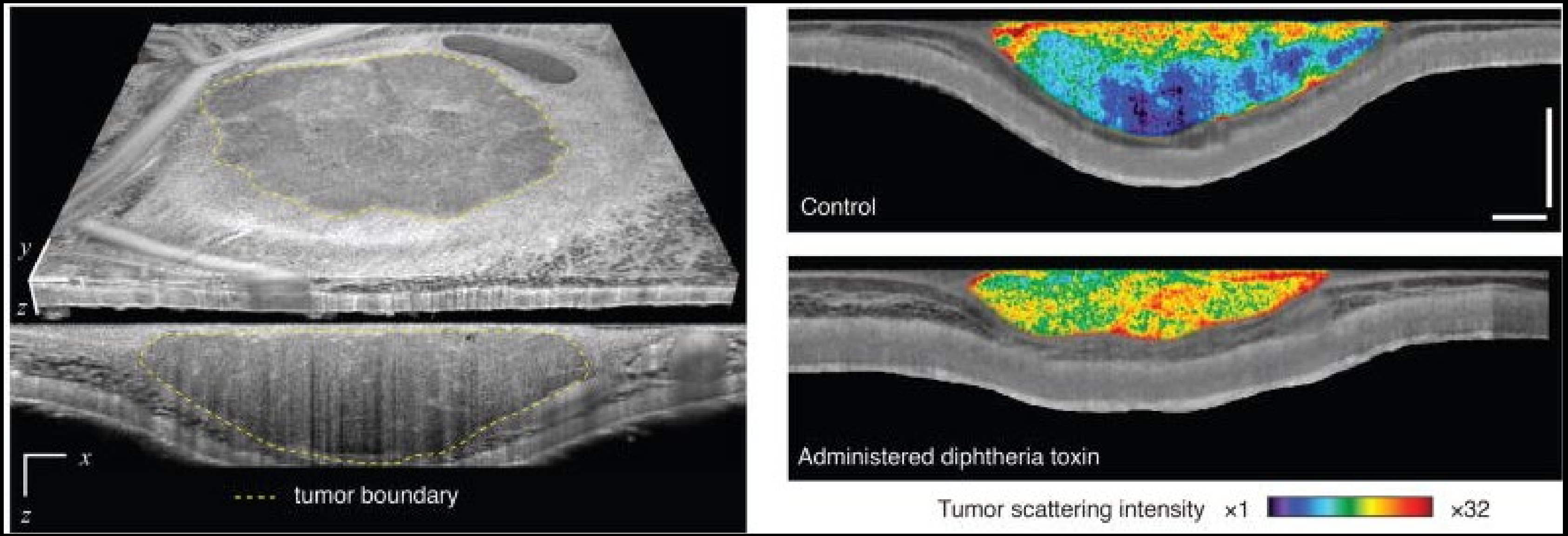


Retinal scanning and angiography to diagnose glaucoma, diabetic retinopathy, macular degeneration, etc.

"Around 64% of adults working in computer and mathematical sciences use some vision correction option" (i.e., glasses, contacts, surgery)
From the Washington Post, May 2023

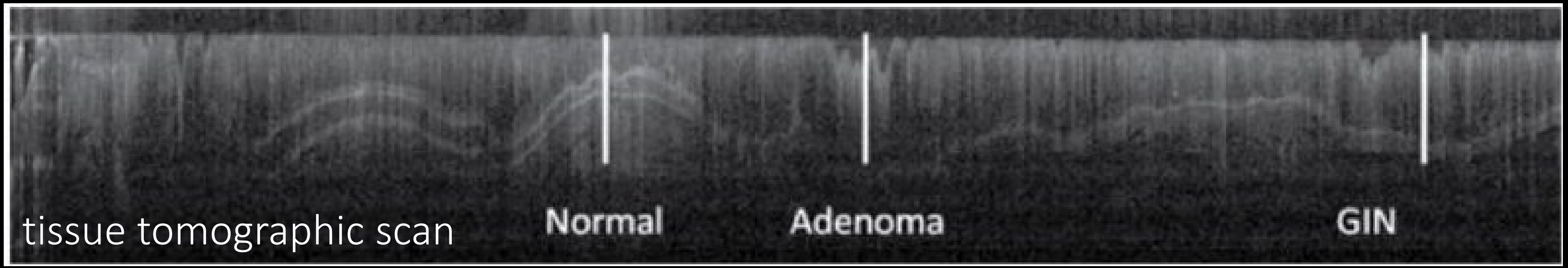
[Images from the American Academy of Ophthalmology]

Skin cancer imaging



Non-invasive imaging of breast and dorsal skin tumors

(Still at the pre-clinical level)



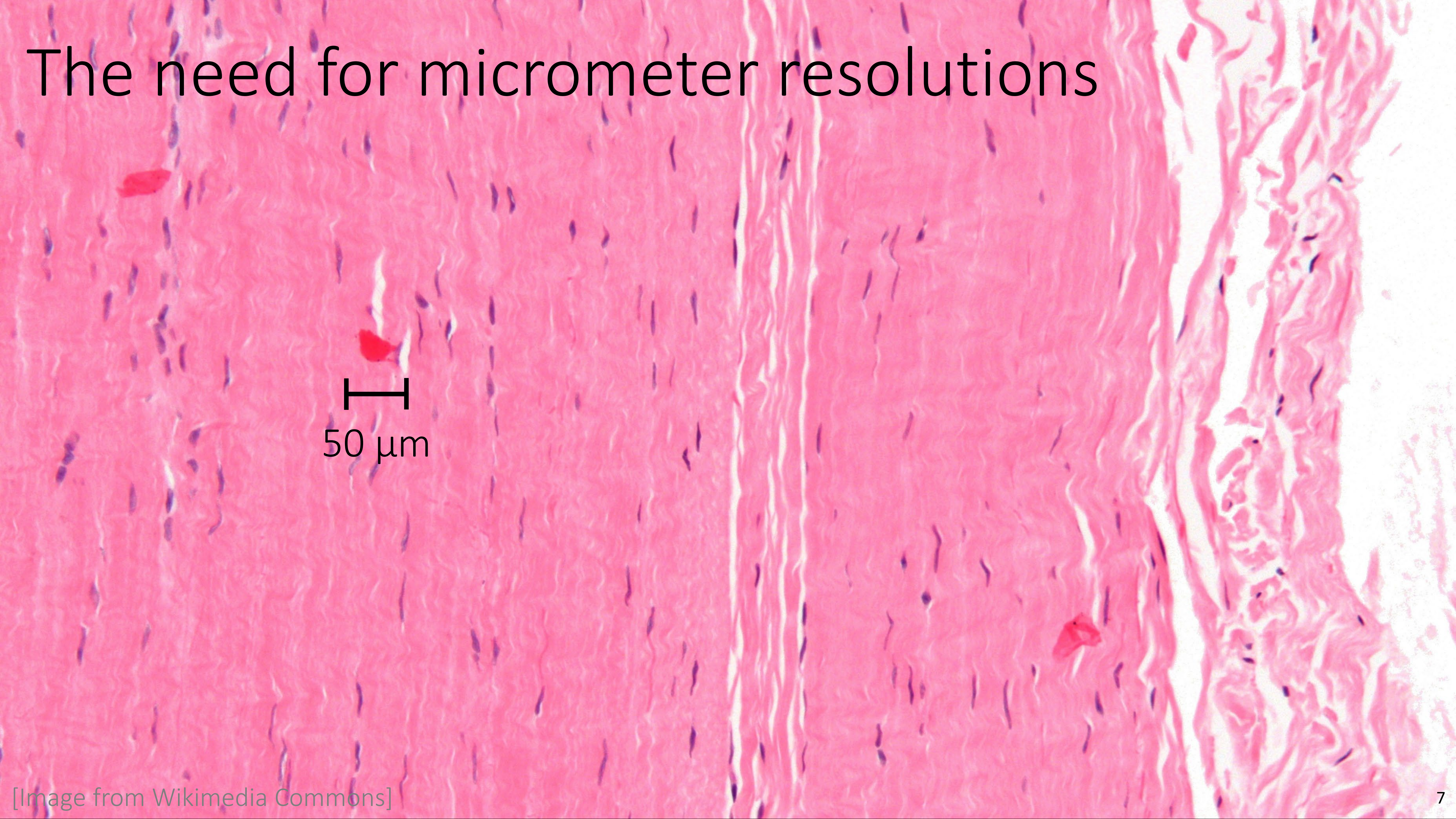
2 mm depth
10 μm resolution

[Images from Vakoc et al. 2012, Nature Reviews Cancer]

Seeing deep inside tissue

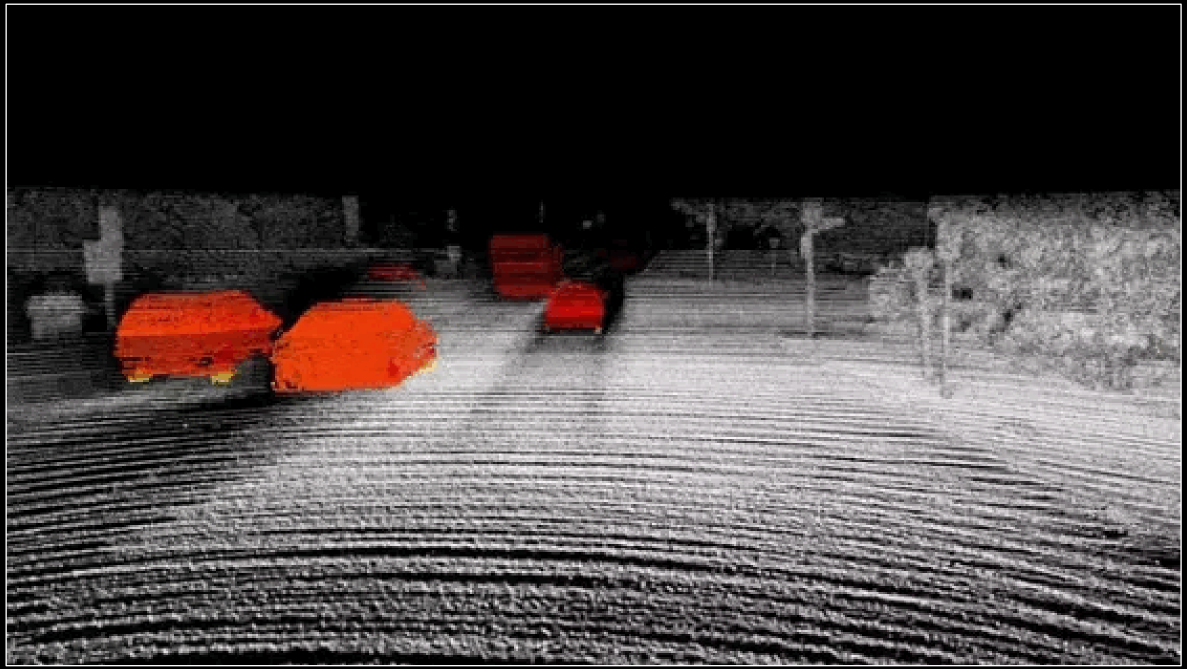
NSF Expedition project, https://seebelowtheskin.org

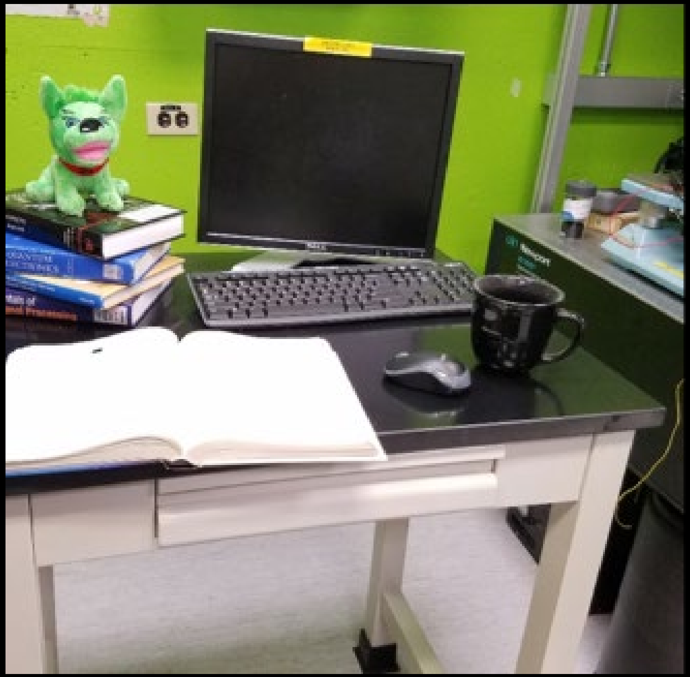
The need for micrometer resolutions



[Image from Wikimedia Commons]

FMCW "4D" lidar





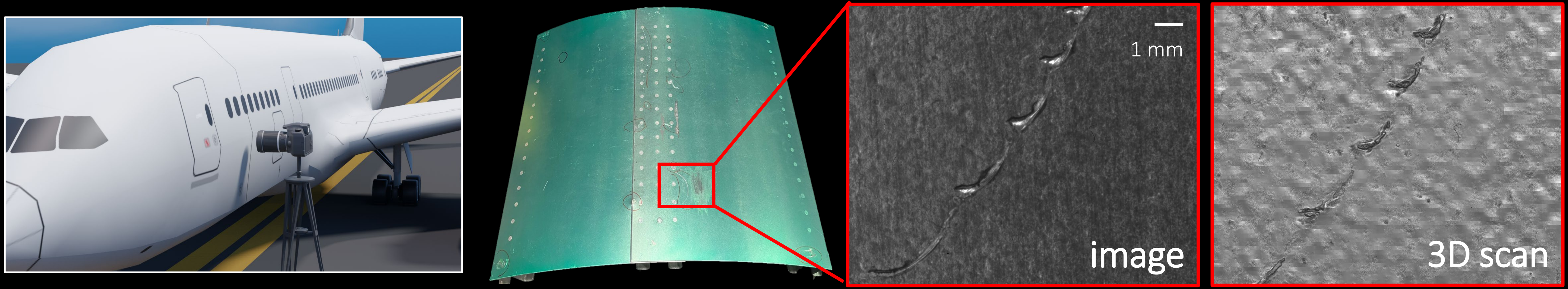
Depth *and* velocity using frequency-modulated continuous-wave lidar
(a.k.a. swept-source optical coherence tomography)

[Images from Aeva, and Zhang et al. 2019]

[Images from Kotwal et al., 2023]

Micrometer 3D sensing

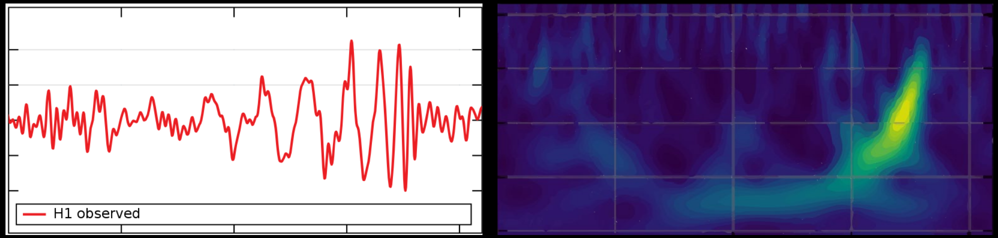
Inspection: aircraft fuselage section



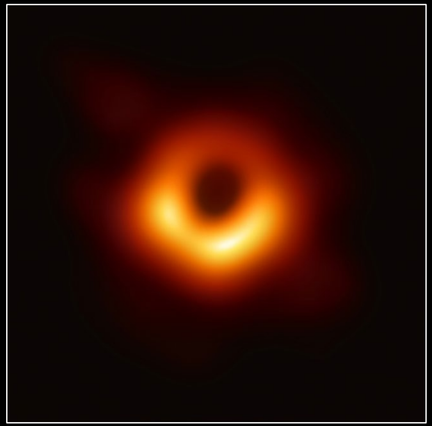
Fabrication: 3D-printed Euro coin

[Images from LIGO and EHT]

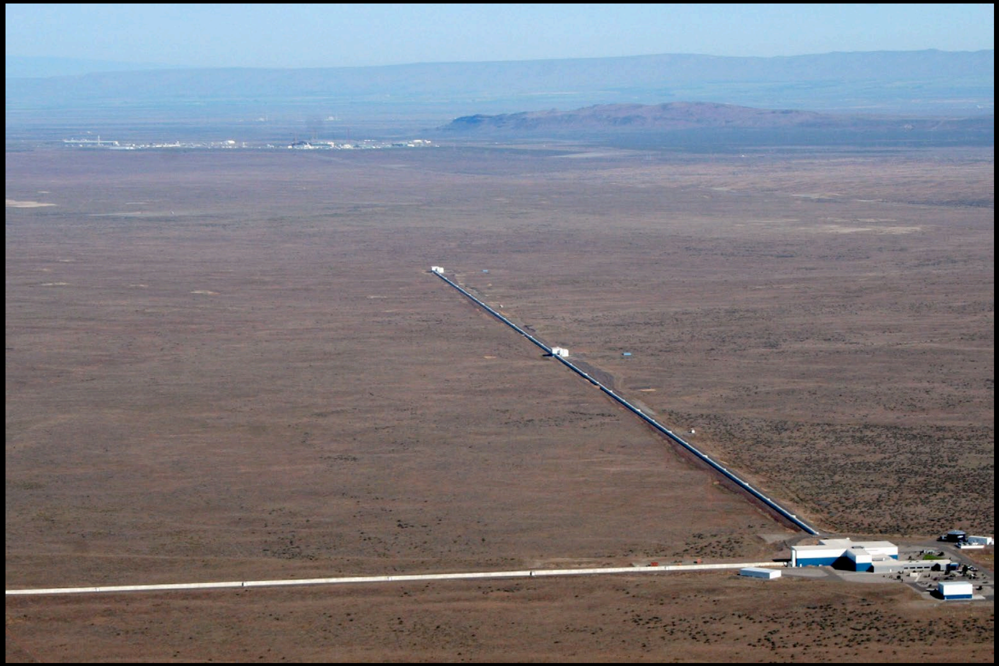
Very large-scale physics



first gravitational wave detection



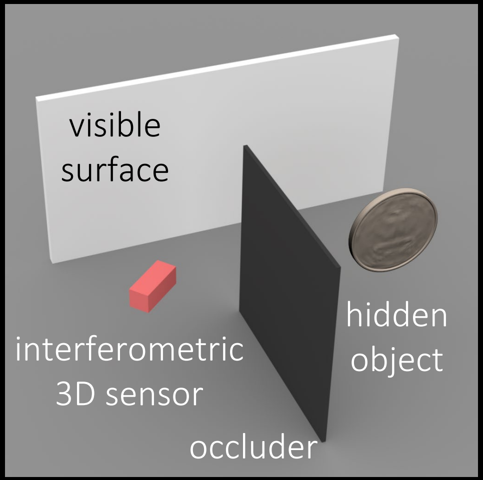
first image of a black hole (center of Messier 87 galaxy)



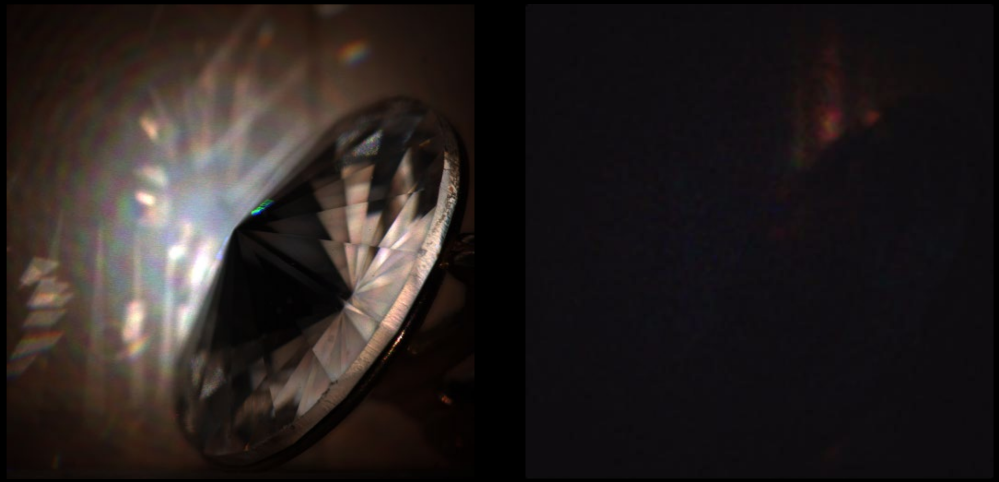
Laser Interferometer Gravitational-wave Observatory (LIGO) at Hanford, WA
(4 km-long Michelson interferometer)

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

Computational imaging



Non-line-of-sight imaging

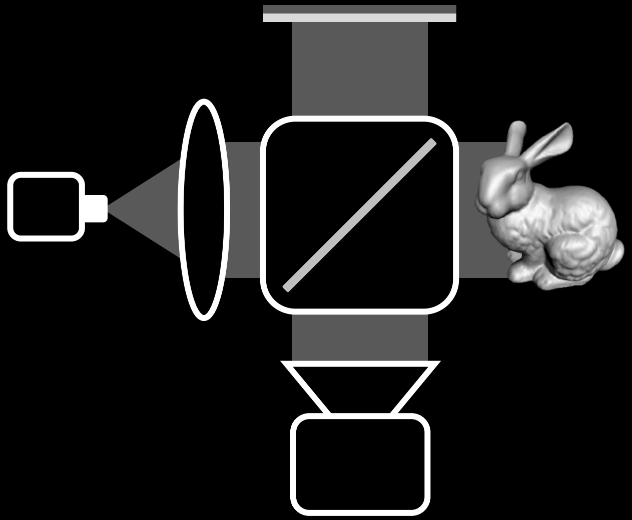


Transient imaging

Separation of direct-indirect illumination

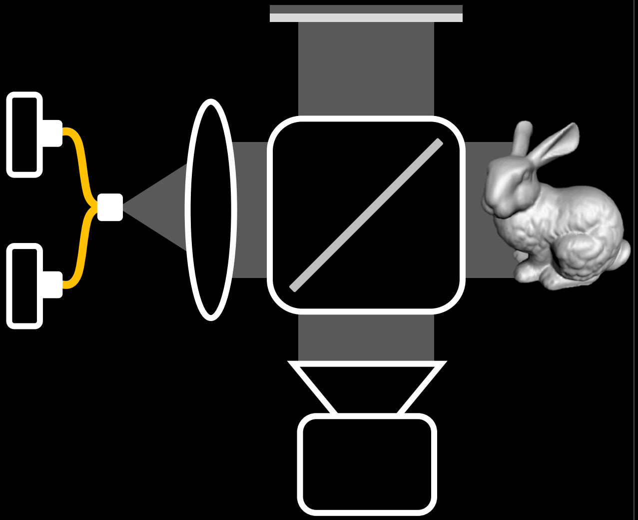
Course overview

introduction to
interferometry



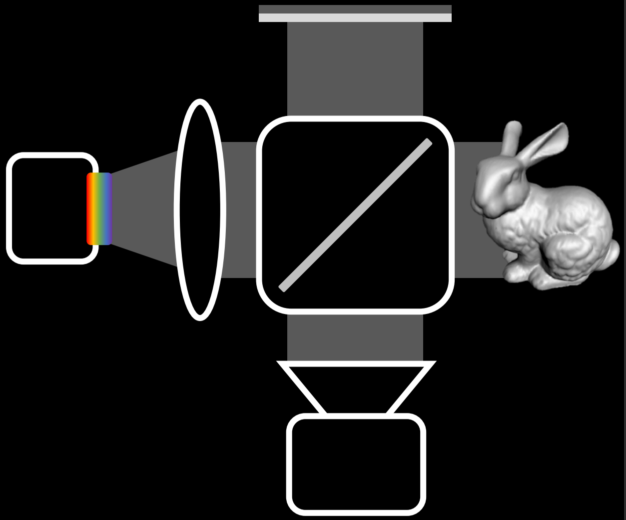
Yannis

two-wavelength
interferometry



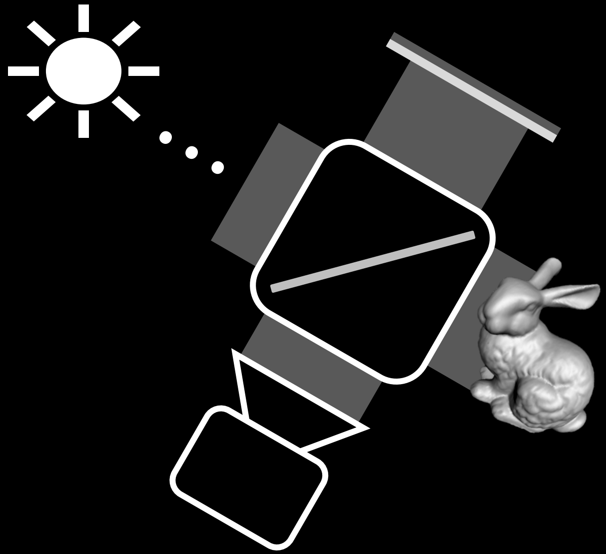
Florian

partially-coherent
interferometry



Alankar

interferometric
computational imaging

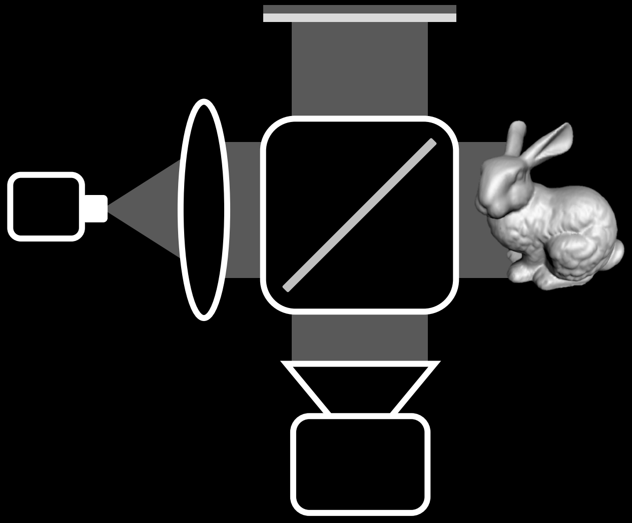


Florian

Yannis

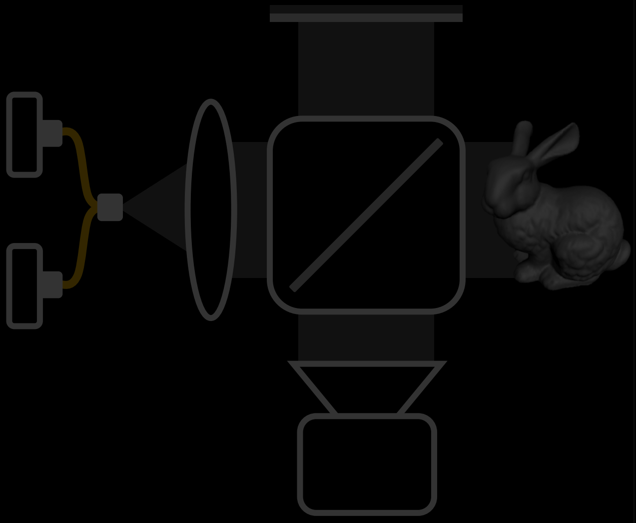
Course overview

introduction to
interferometry



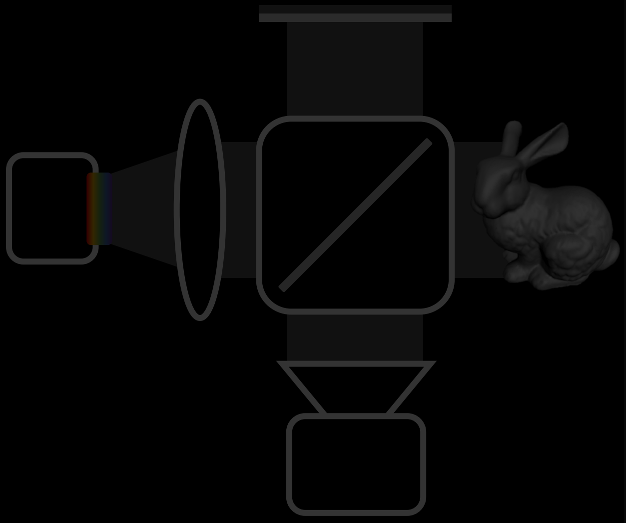
Yannis

two-wavelength
interferometry



Florian

partially-coherent
interferometry



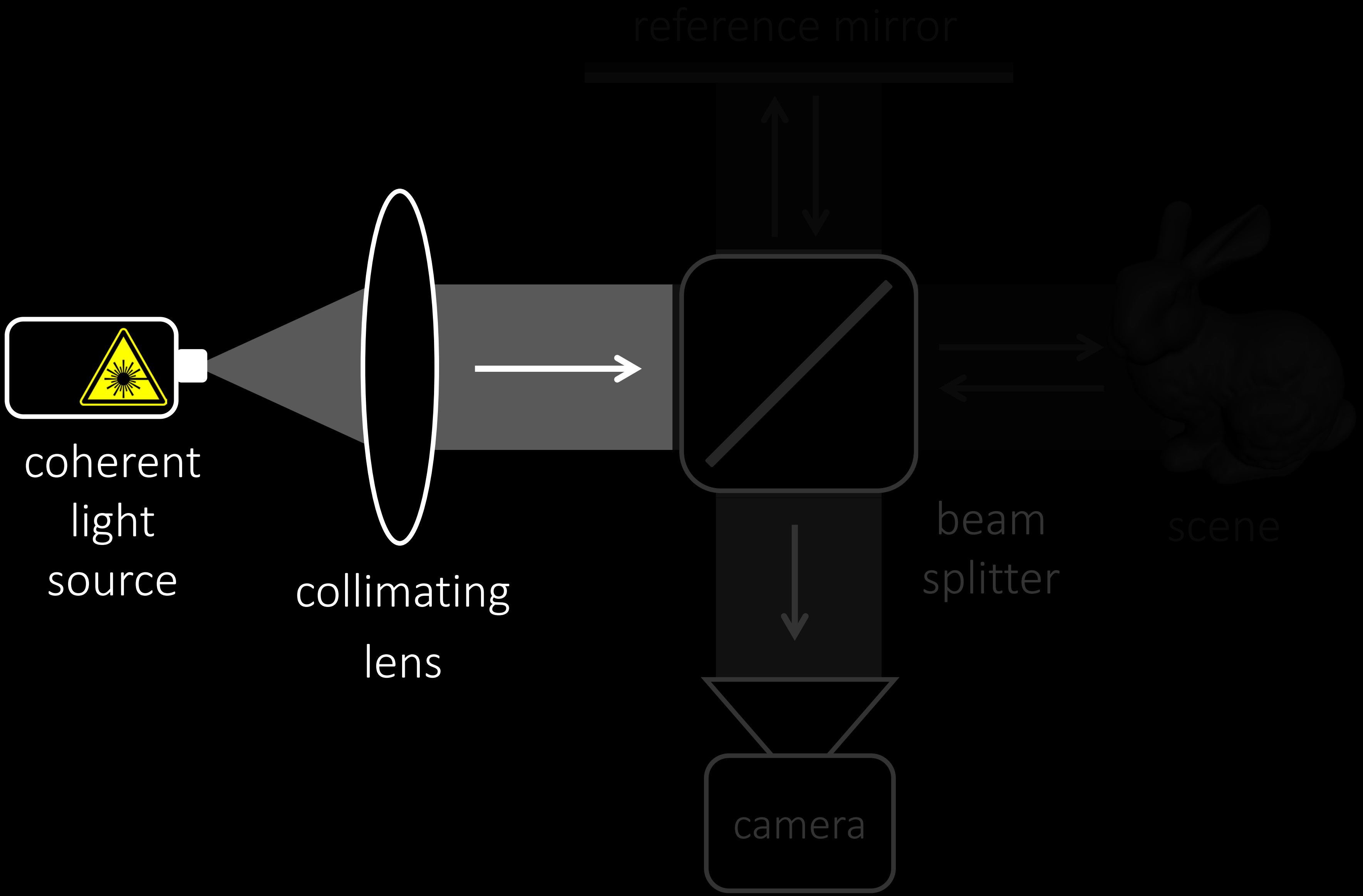
Alankar

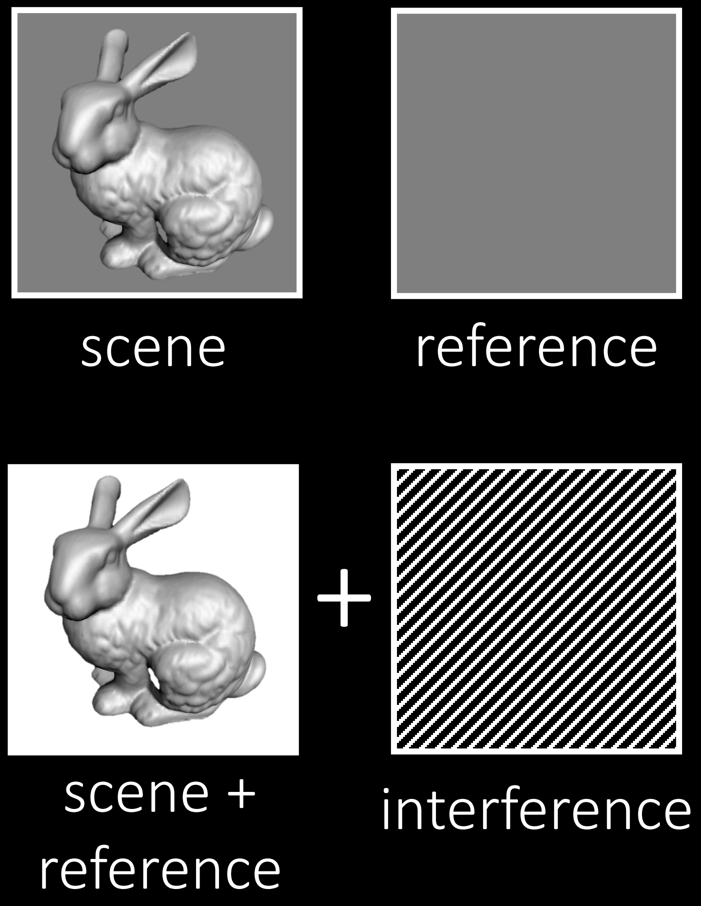
interferometric
computational imaging

Florian

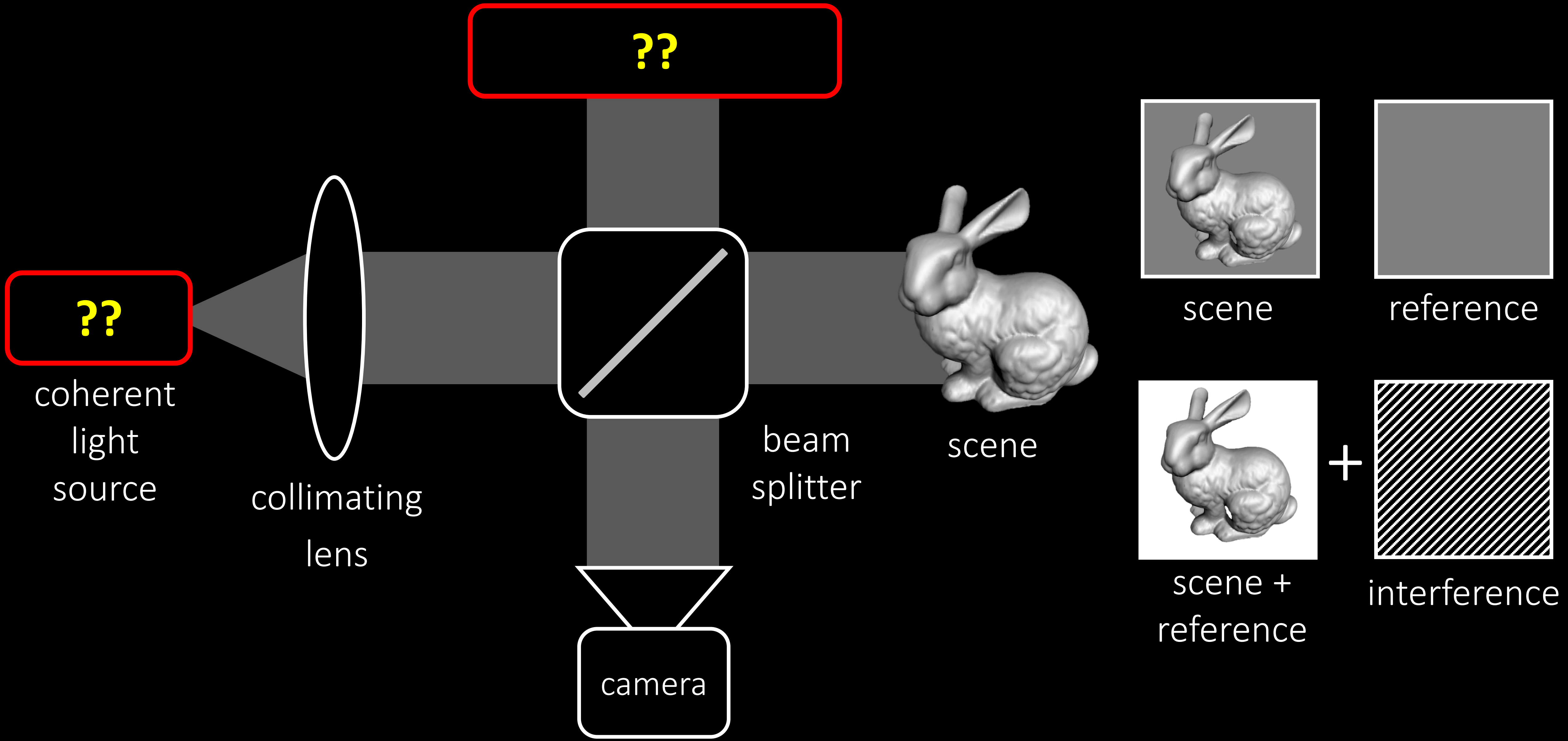
Yannis

Interferometric imaging

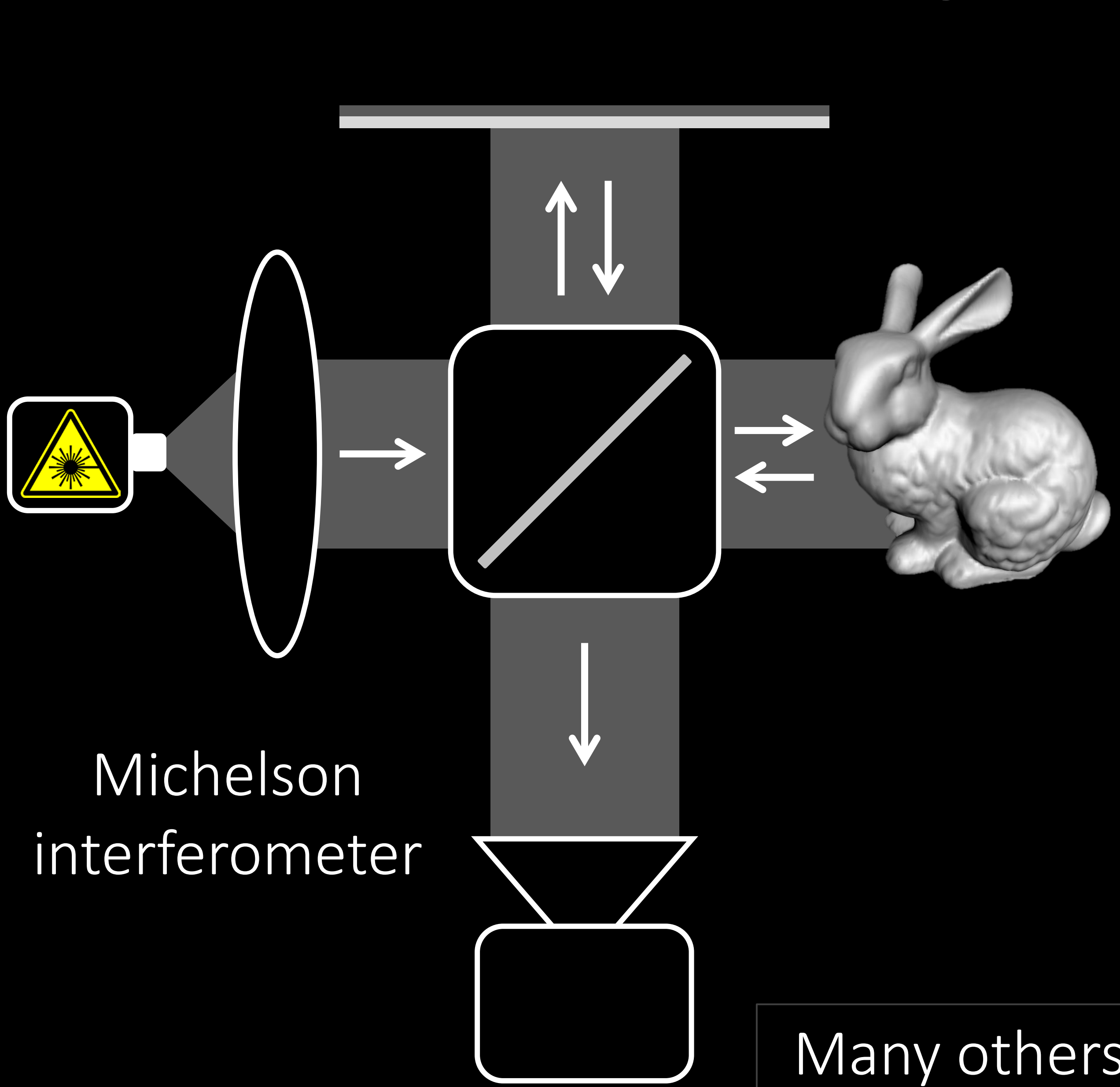




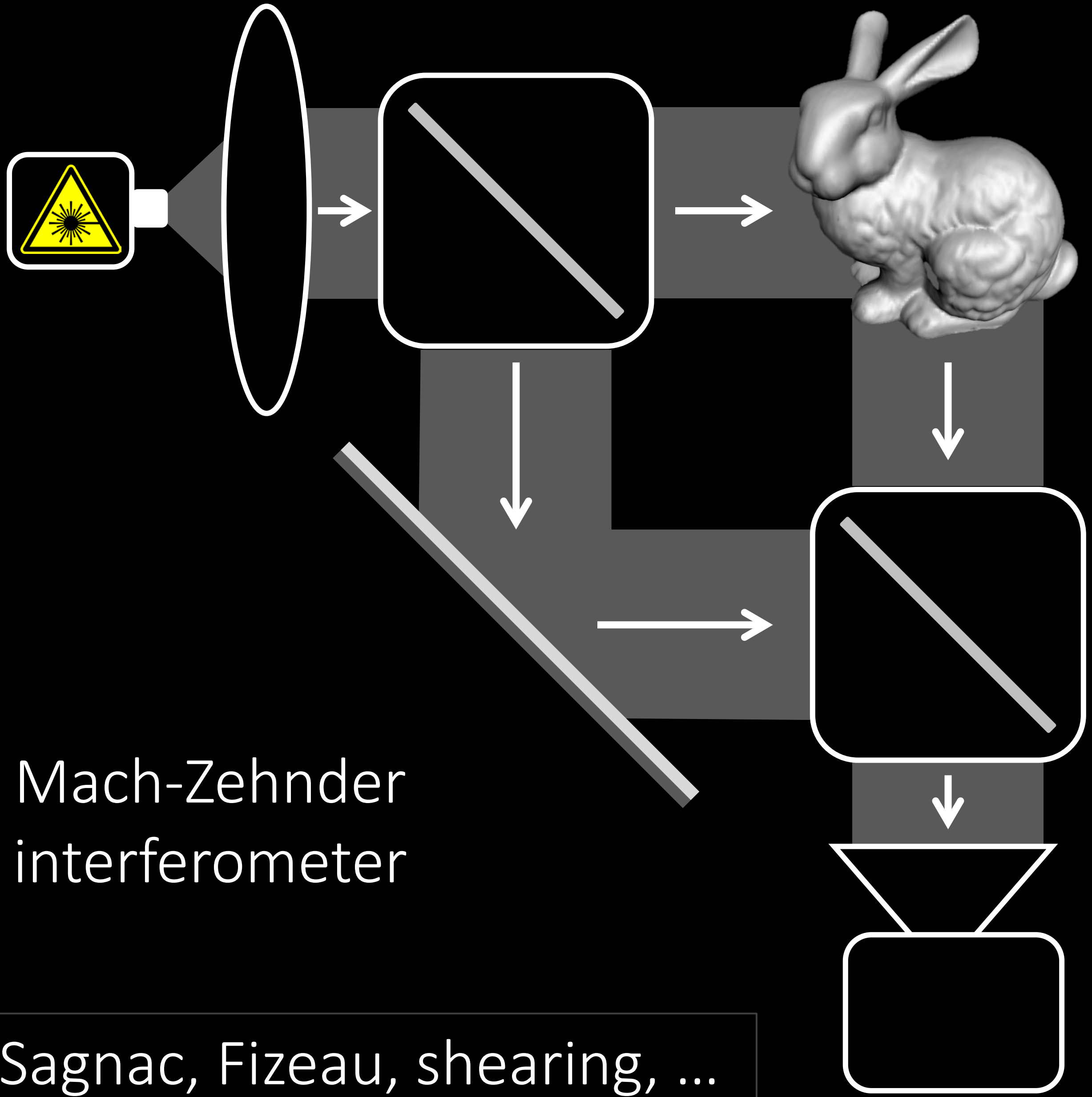
Interferometric imaging



Interferometer designs



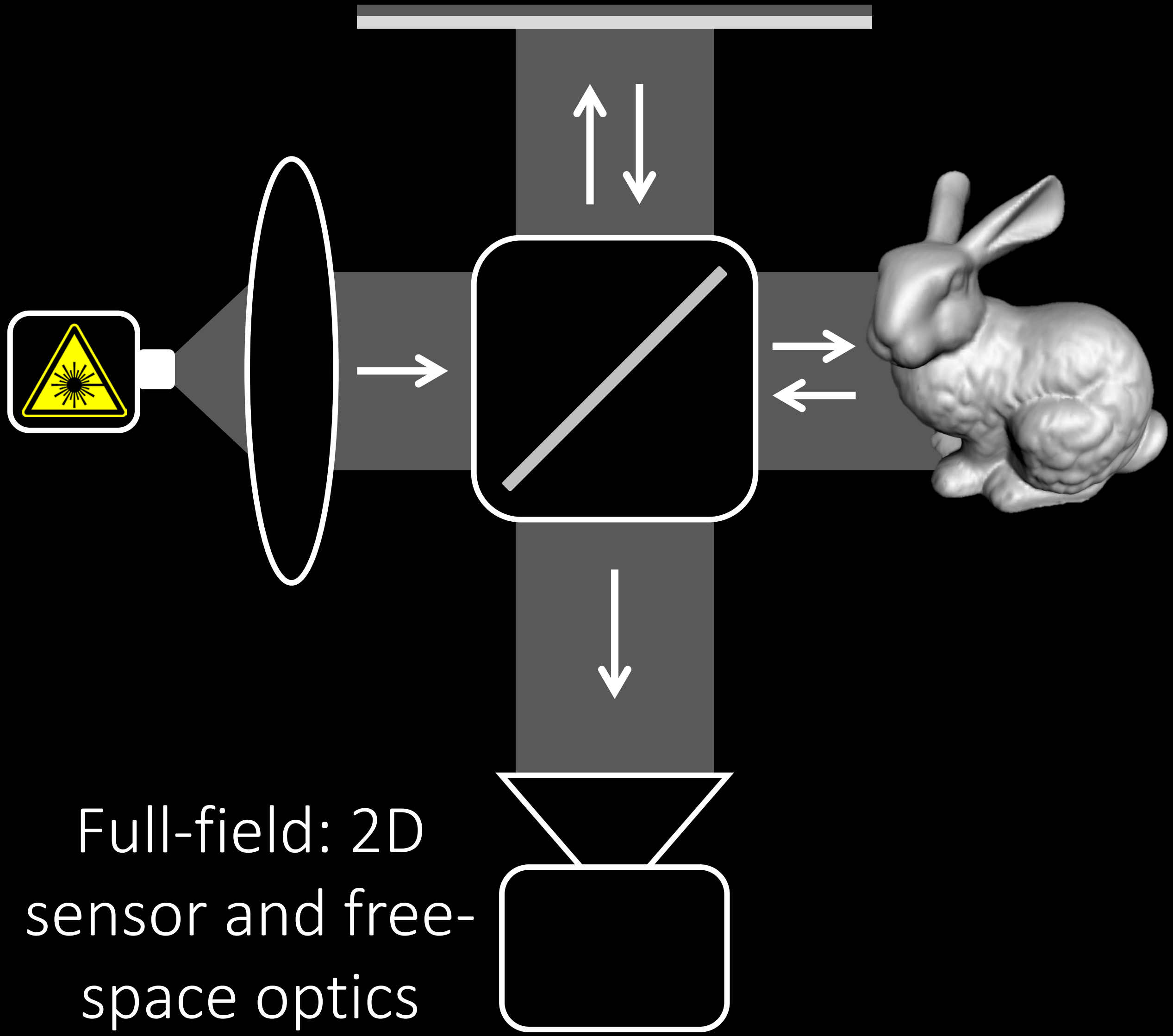
Michelson
interferometer



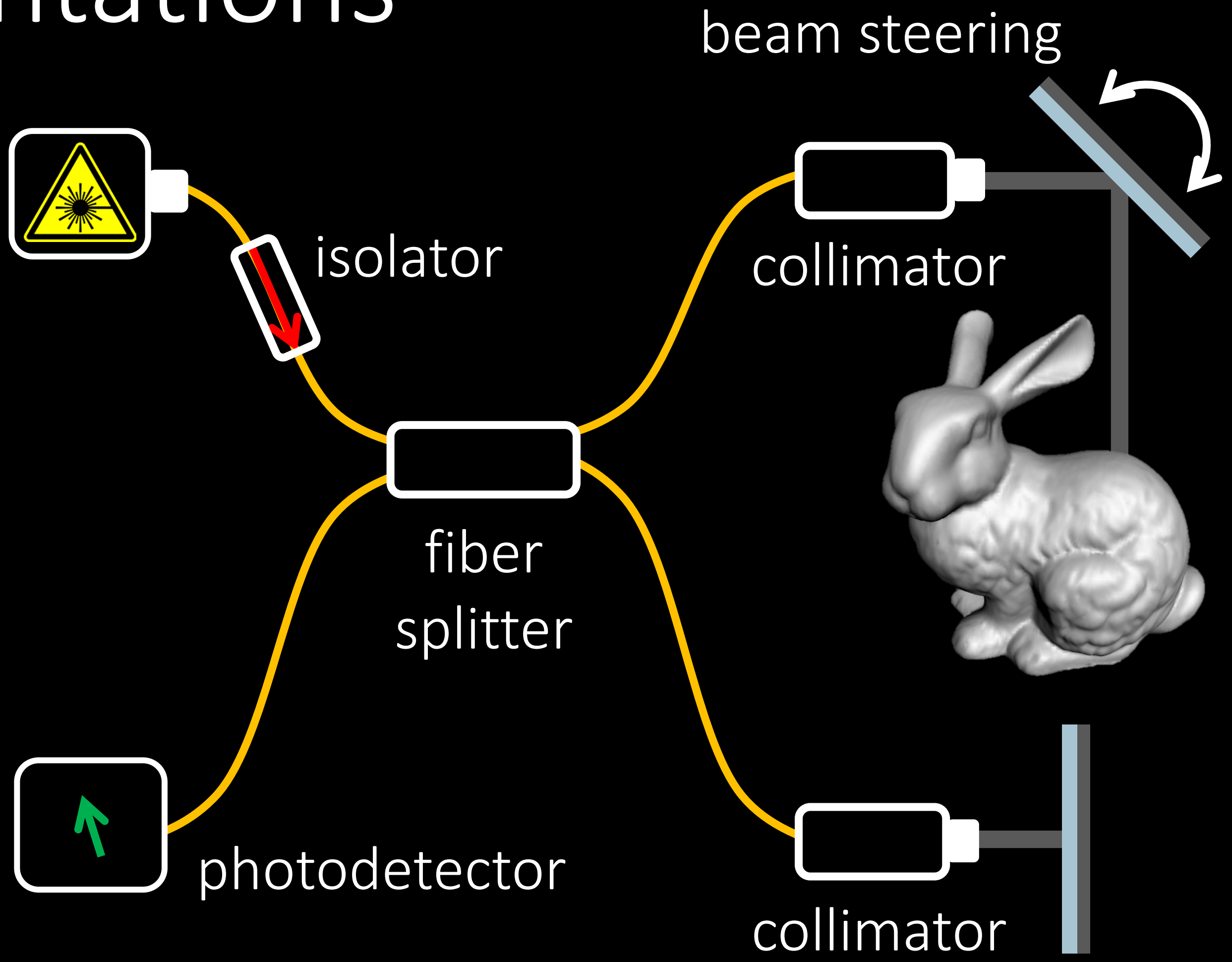
Mach-Zehnder
interferometer

Many others: Sagnac, Fizeau, shearing, …

Interferometer implementations



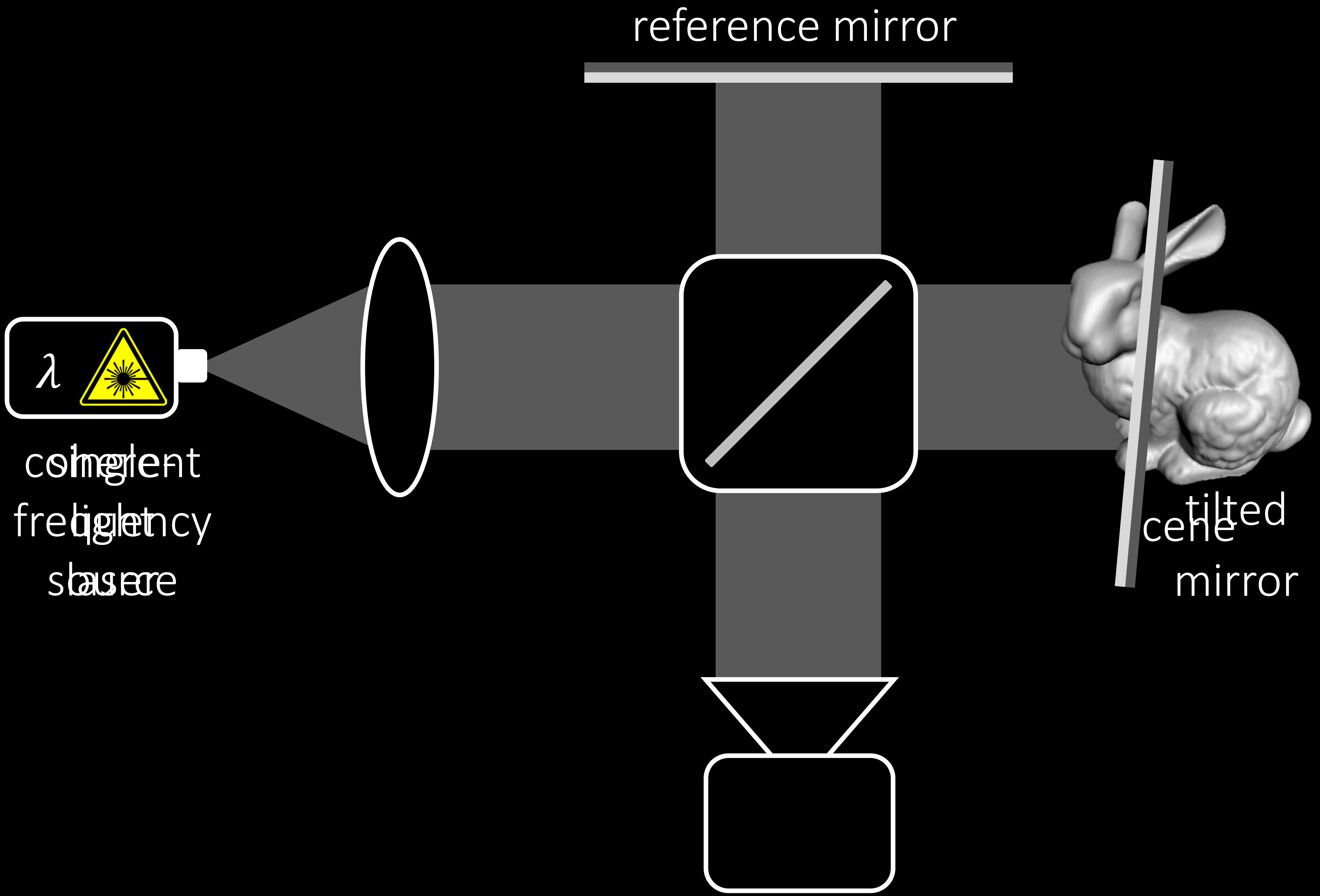
Full-field: 2D sensor and free-space optics



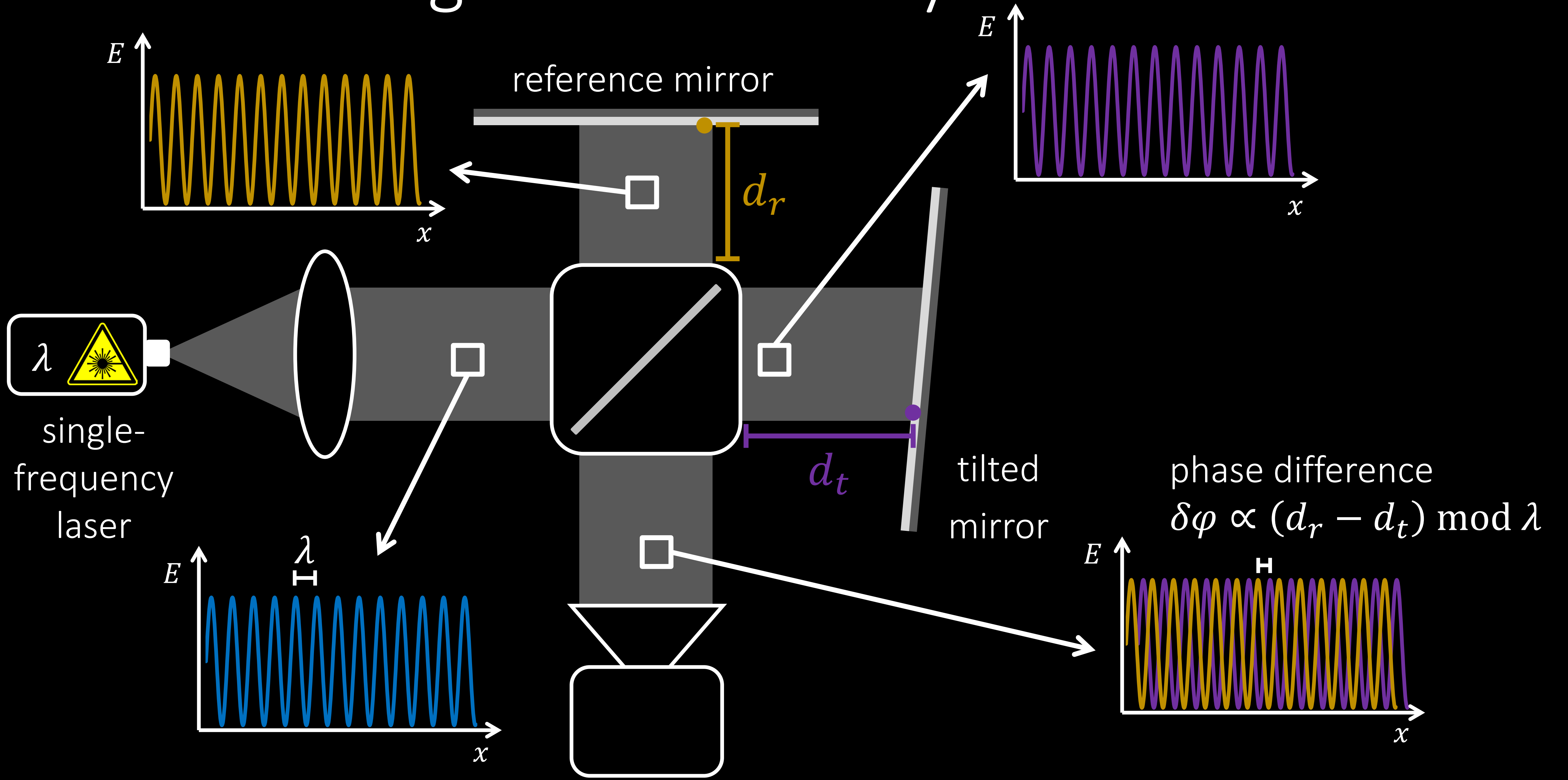
Scanning: single-pixel sensor and fiber optics

Many choices: circulators, balanced detectors

Phase-shifting interferometry

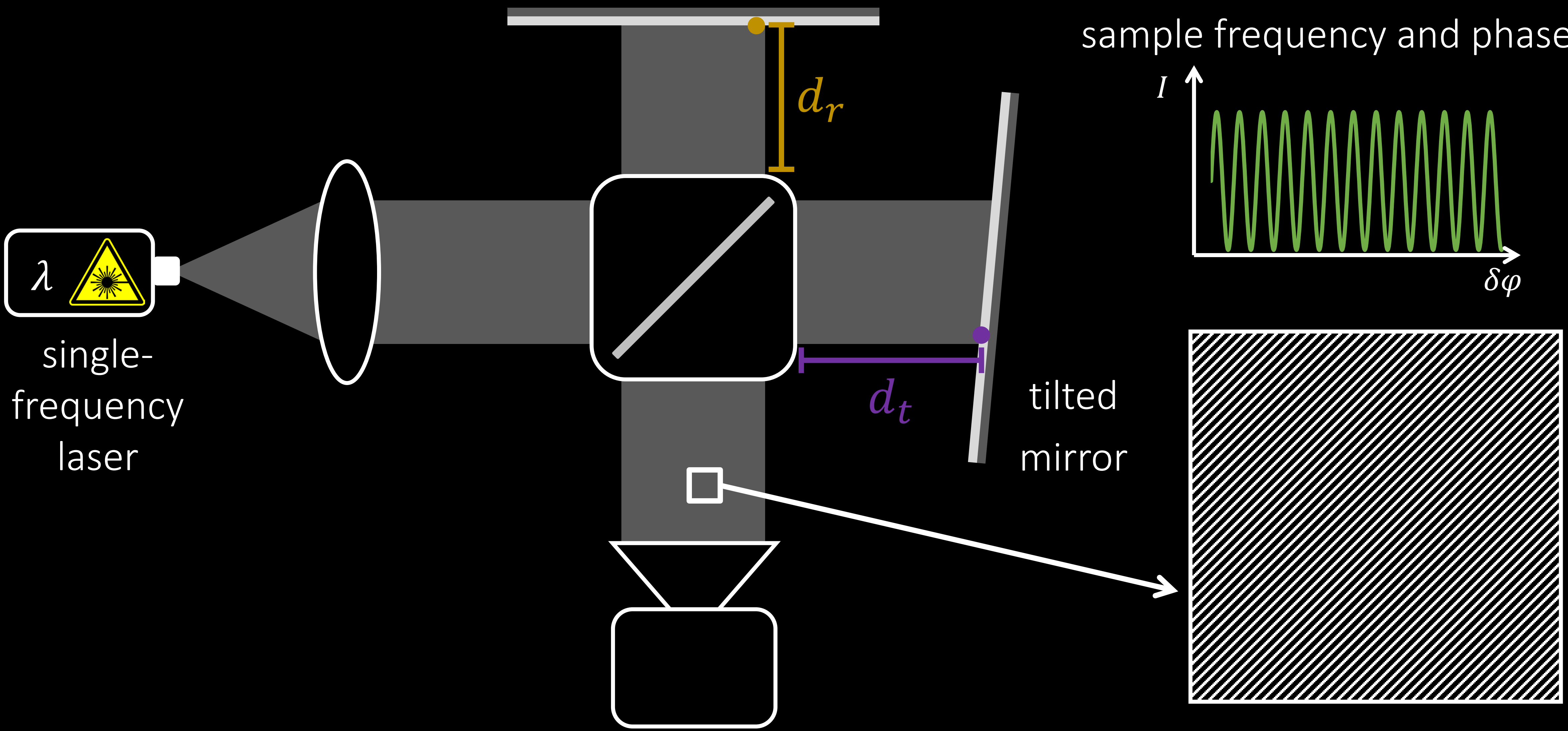


Phase-shifting interferometry

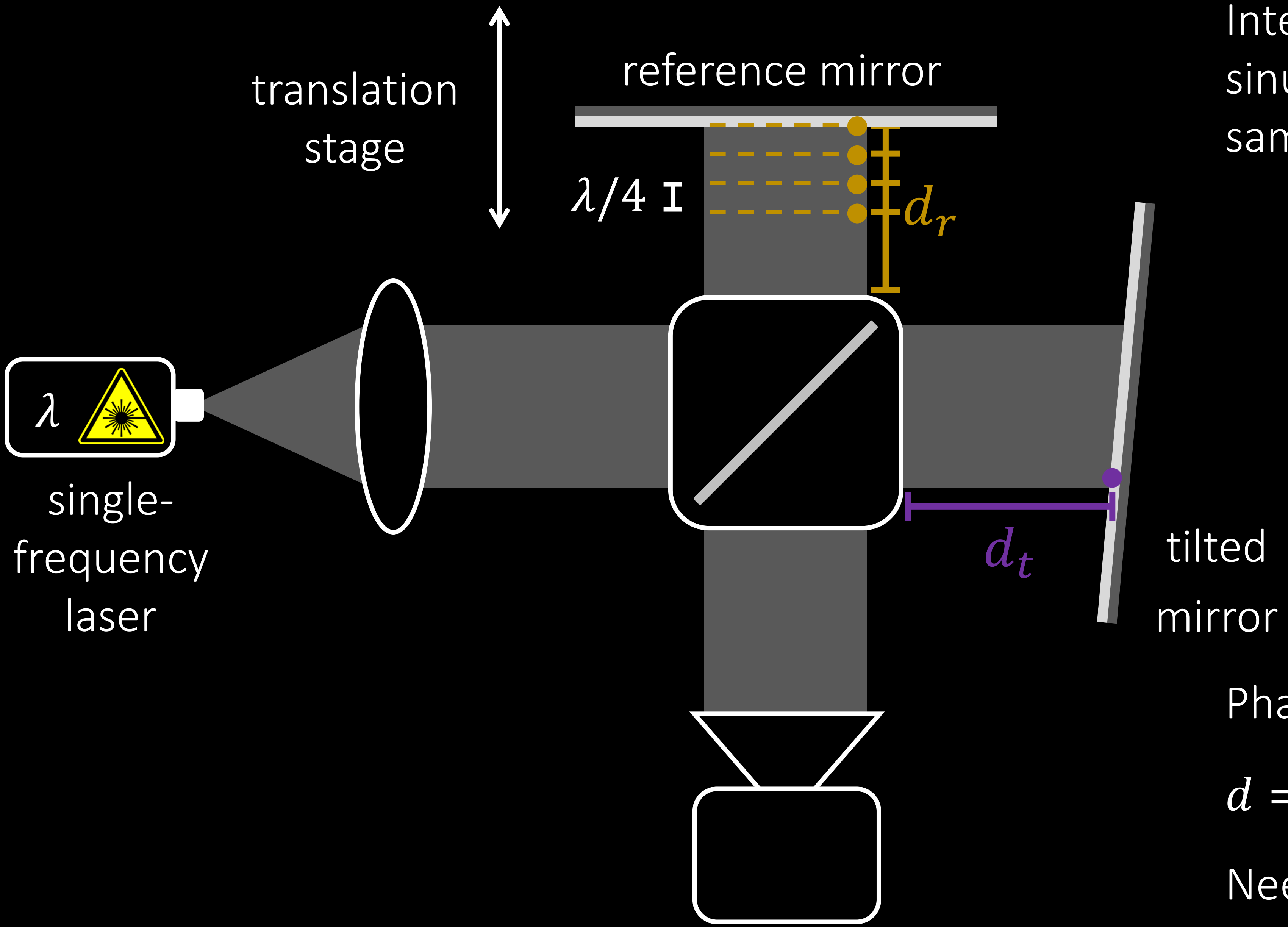


Phase-shifting interferometry

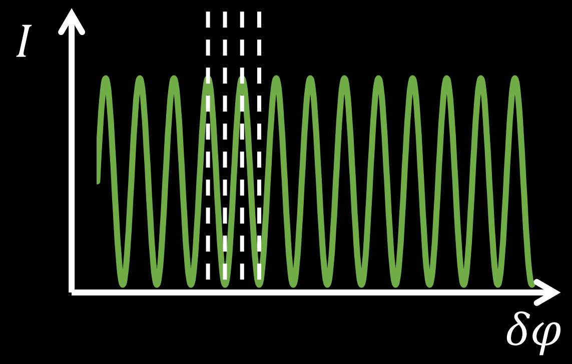
Interference: correlation of two sinusoids → another sinusoid of sample frequency and phase $\delta\varphi$



Phase-shifting interferometry



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

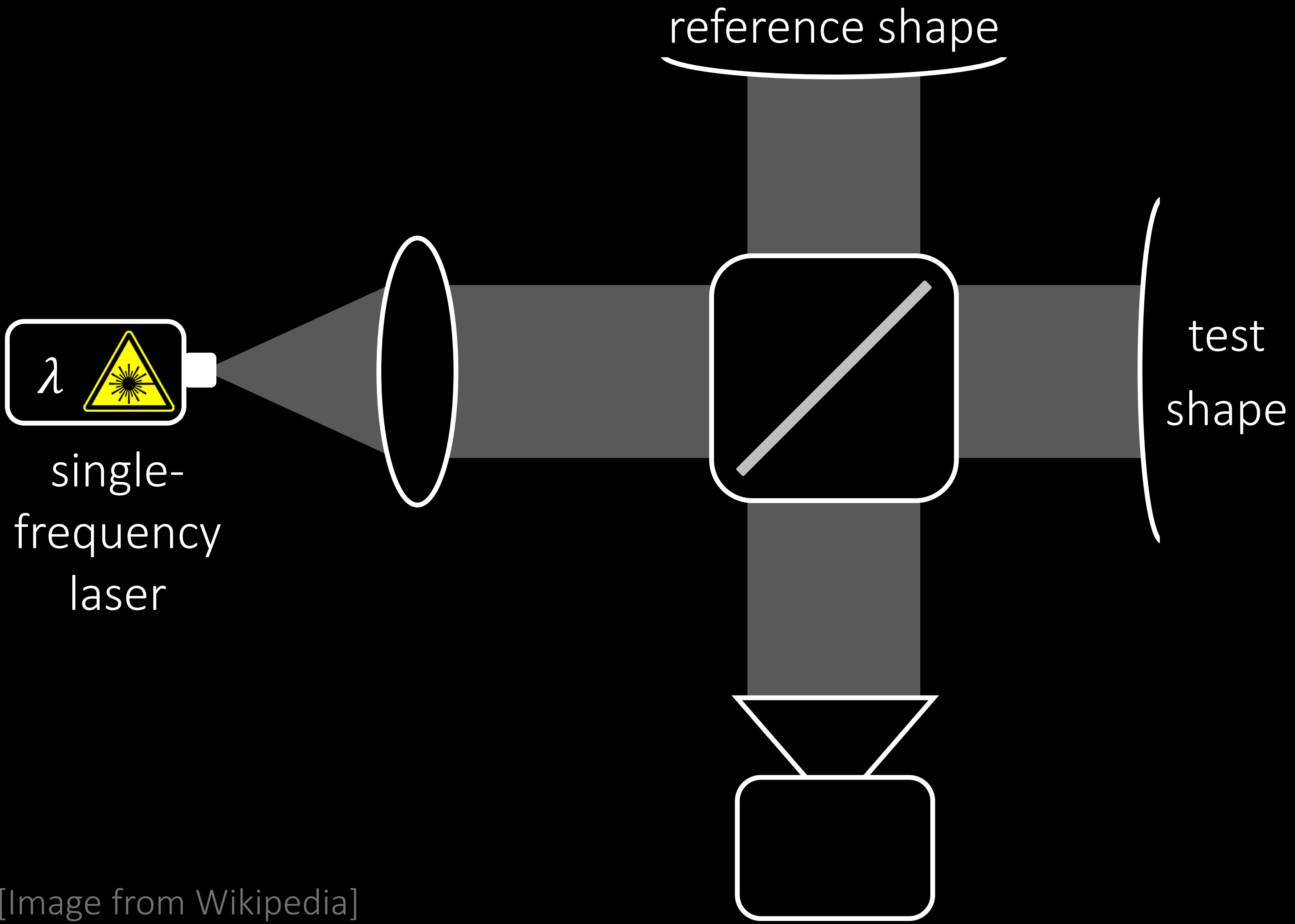


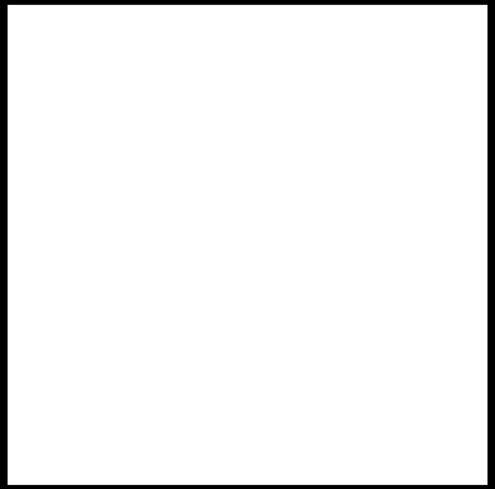
Phase retrieval:

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

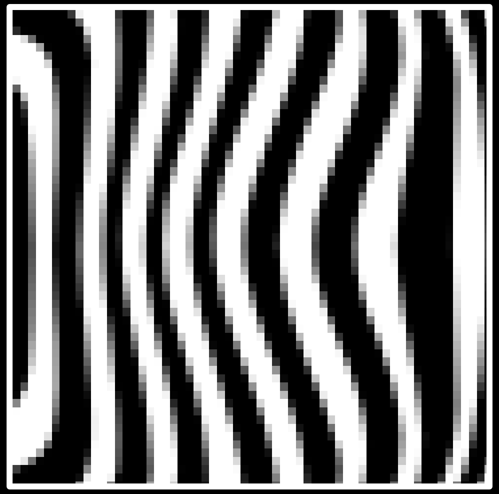
Needs only 4 axial measurements

Example: surface deflectometry with PSI





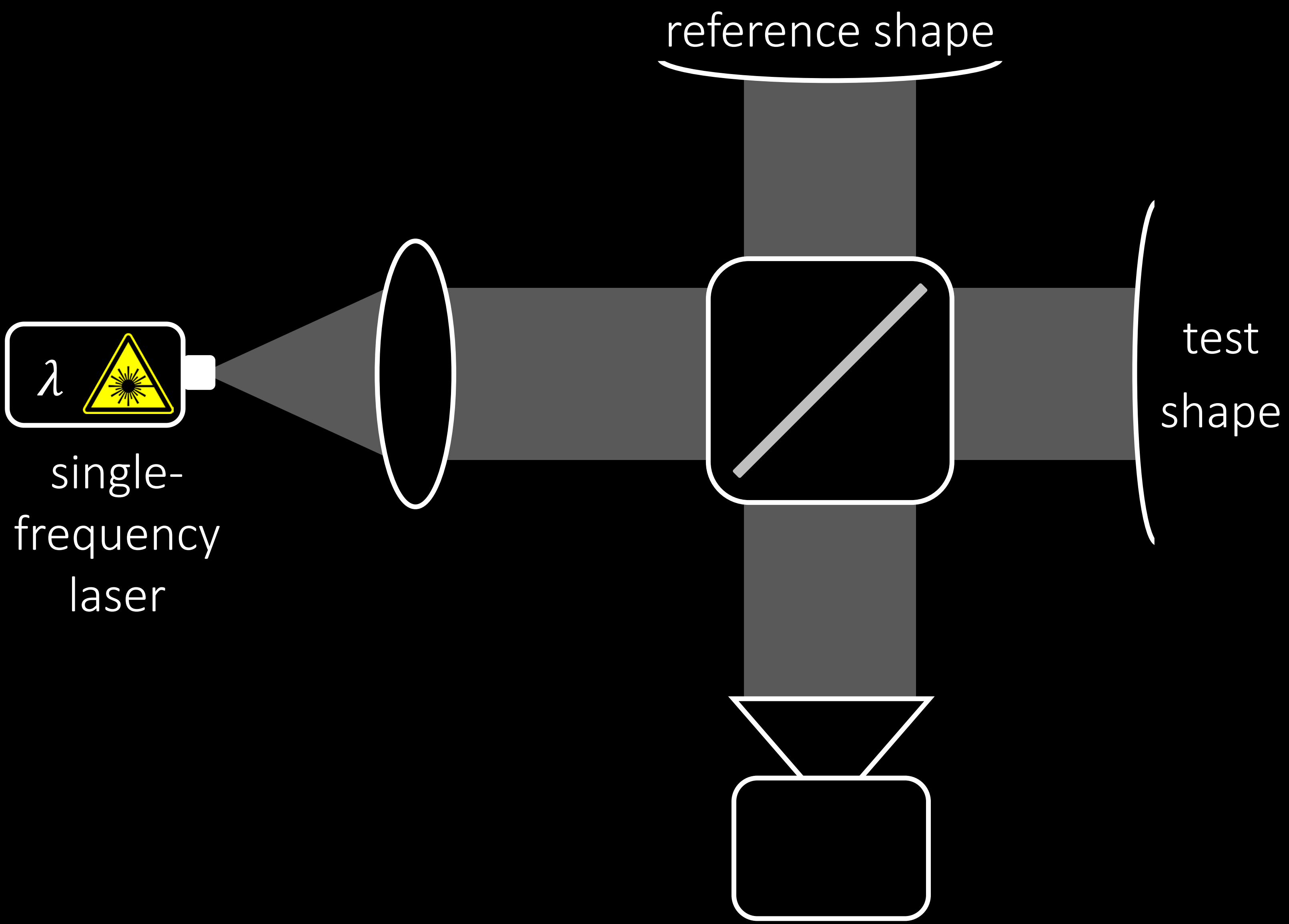
ideal



actual

[Image from Wikipedia]

Example: surface deflectometry with PSI

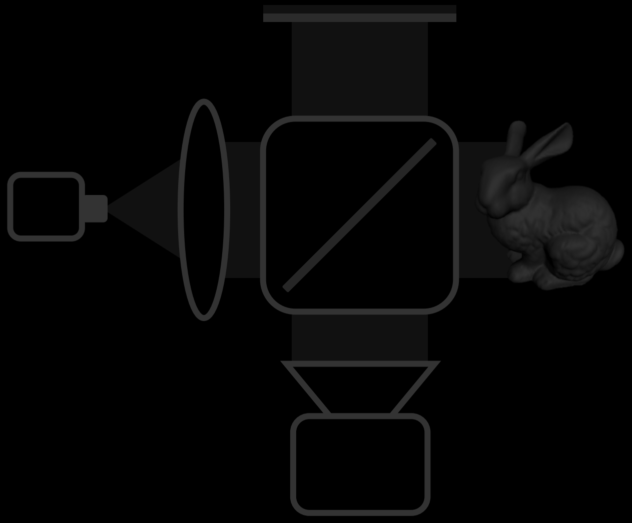


Phase-shifting interferometry:

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

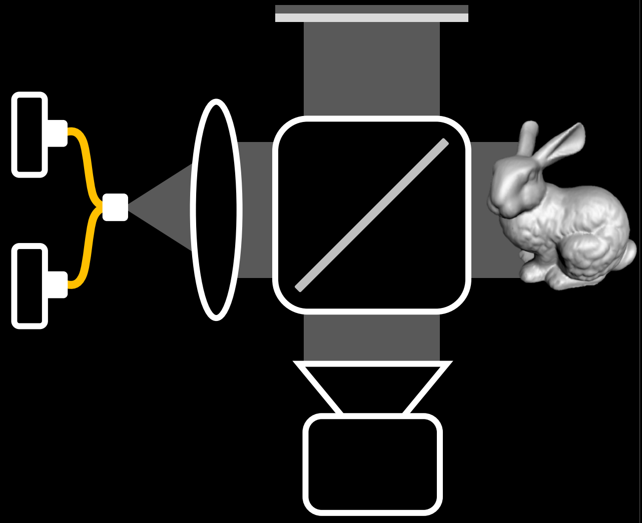
Course overview

introduction to interferometry



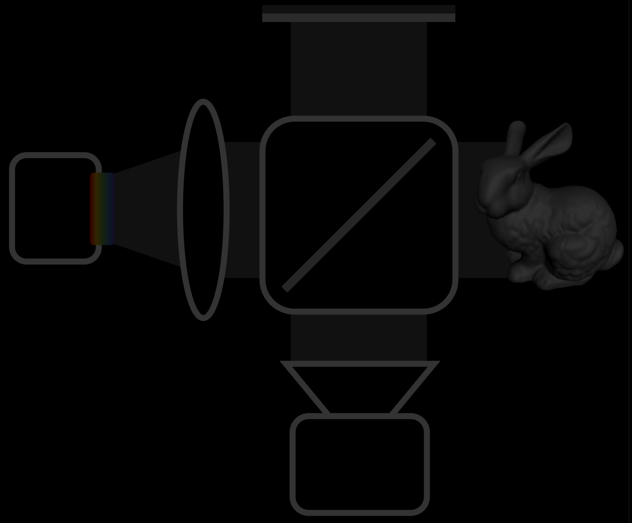
Yannis

two-wavelength interferometry



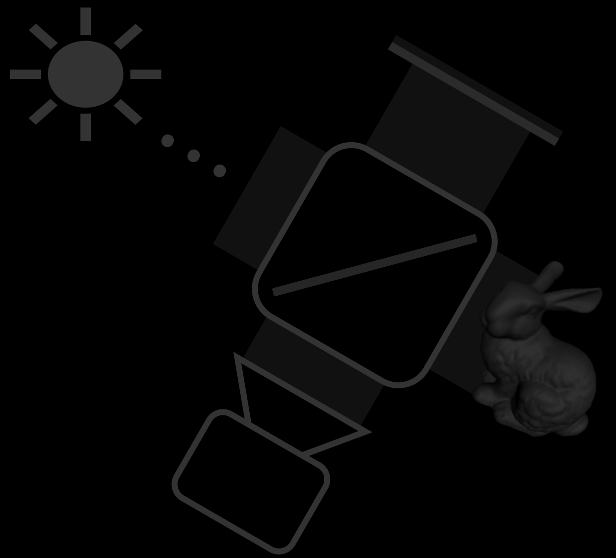
Florian

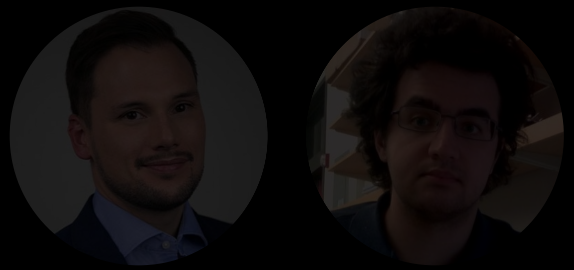
partially-coherent interferometry



Alankar

interferometric computational imaging





Florian Yannis

Computational 3D Imaging and Measurement (3DIM) Lab

Current Members

THE UNIVERSITY OF ARIZONA
Wyant College of Optical Sciences

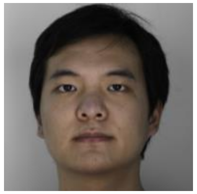
Director

Florian Willomitzer

Students

Jiazhang Wang

Manuel Ballester



Heming Wang

Patrick Cornwall

Yuanxin Guan

Jiwon Choi

Tianfu Wang

James Taylor

John Bass

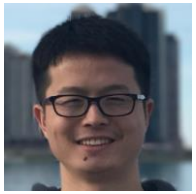
Aniket Dashpute

Contributing collaborators and previous group members:

Northwestern University

SMU

RICE Unconventional Wisdom



Fengqiang Li

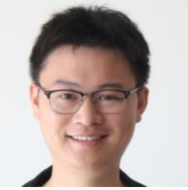
Jiren Li

Oliver Cossairt

Prasanna Rangarajan

Muralidhar Balaji

Marc Christensen



Yicheng Wu

Ashok Veeraraghavan

Part 2:

Interferometry on Rough Surfaces
and
Synthetic Wavelengths

Florian Willomitzer

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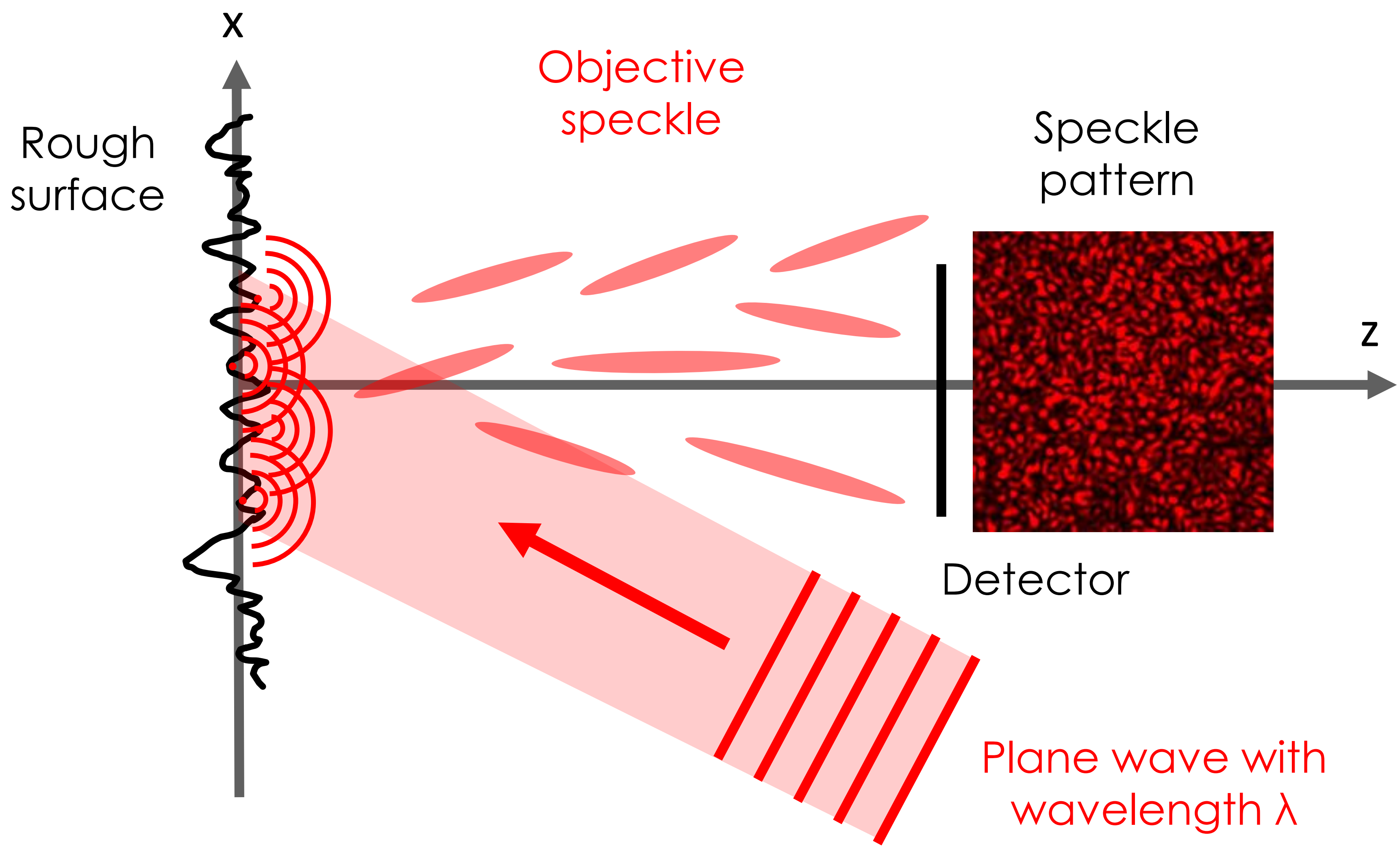
https://www.optics.arizona.edu/3dim

3DIM Lab
Computational 3D Imaging and Measurement Lab
Prof. Florian Willomitzer

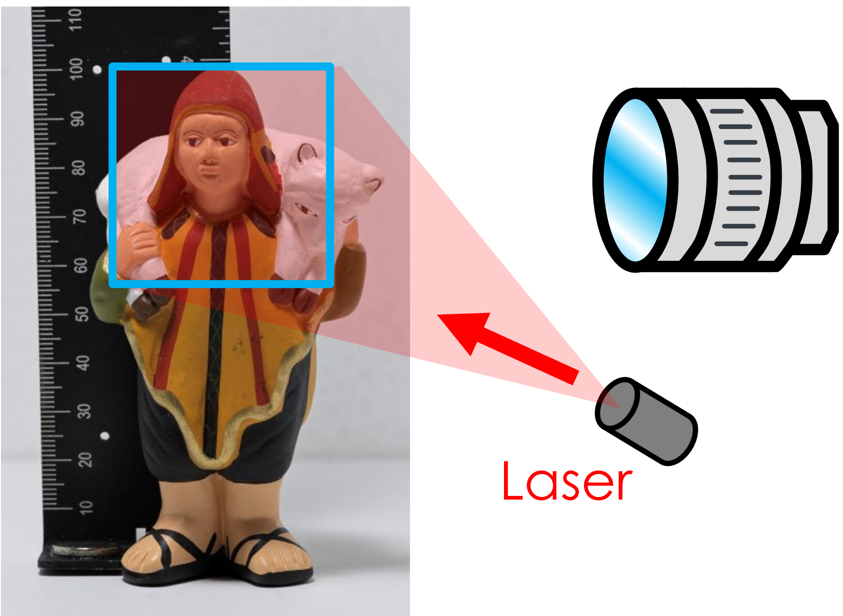
THE UNIVERSITY OF ARIZONA
Wyant College of Optical Sciences

Coherent imaging on rough surfaces - Speckle



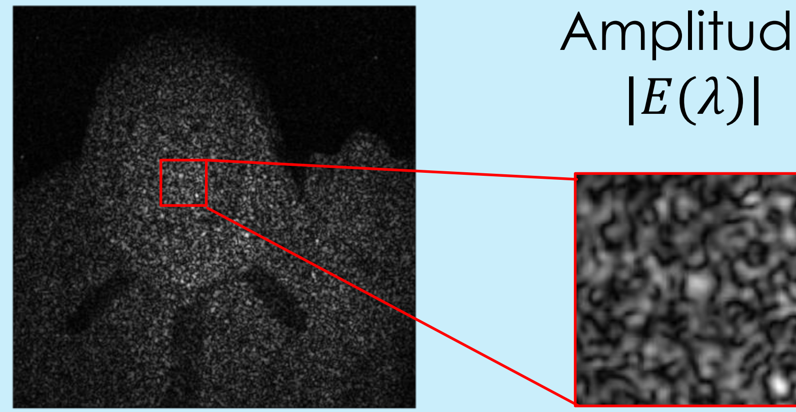
Coherent imaging on rough surfaces - Speckle

Object with rough surface

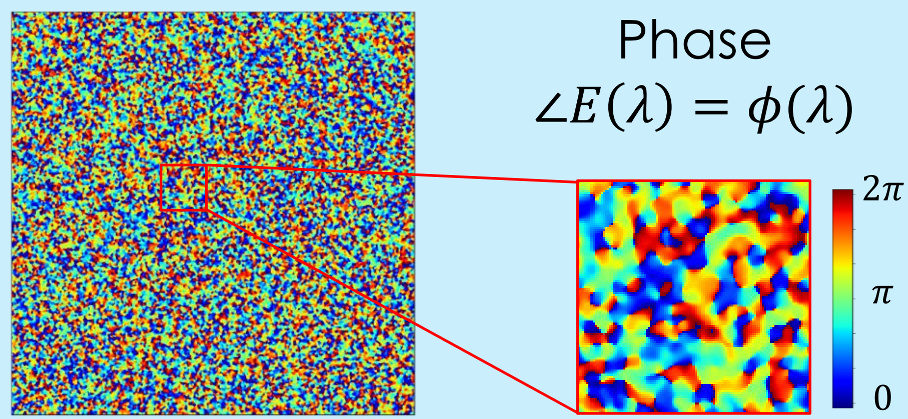


Camera readout

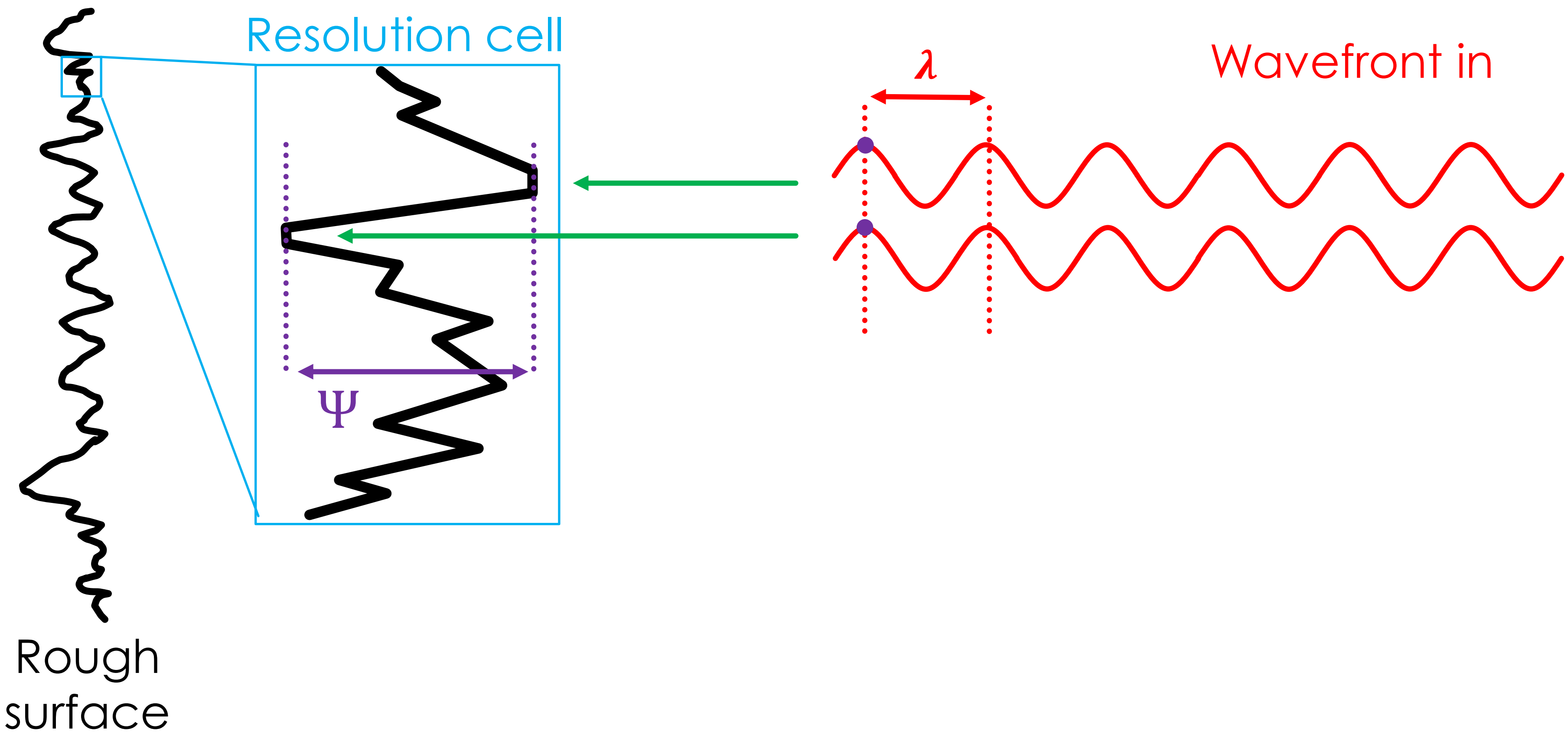
Amplitude
$|E(\lambda)|$



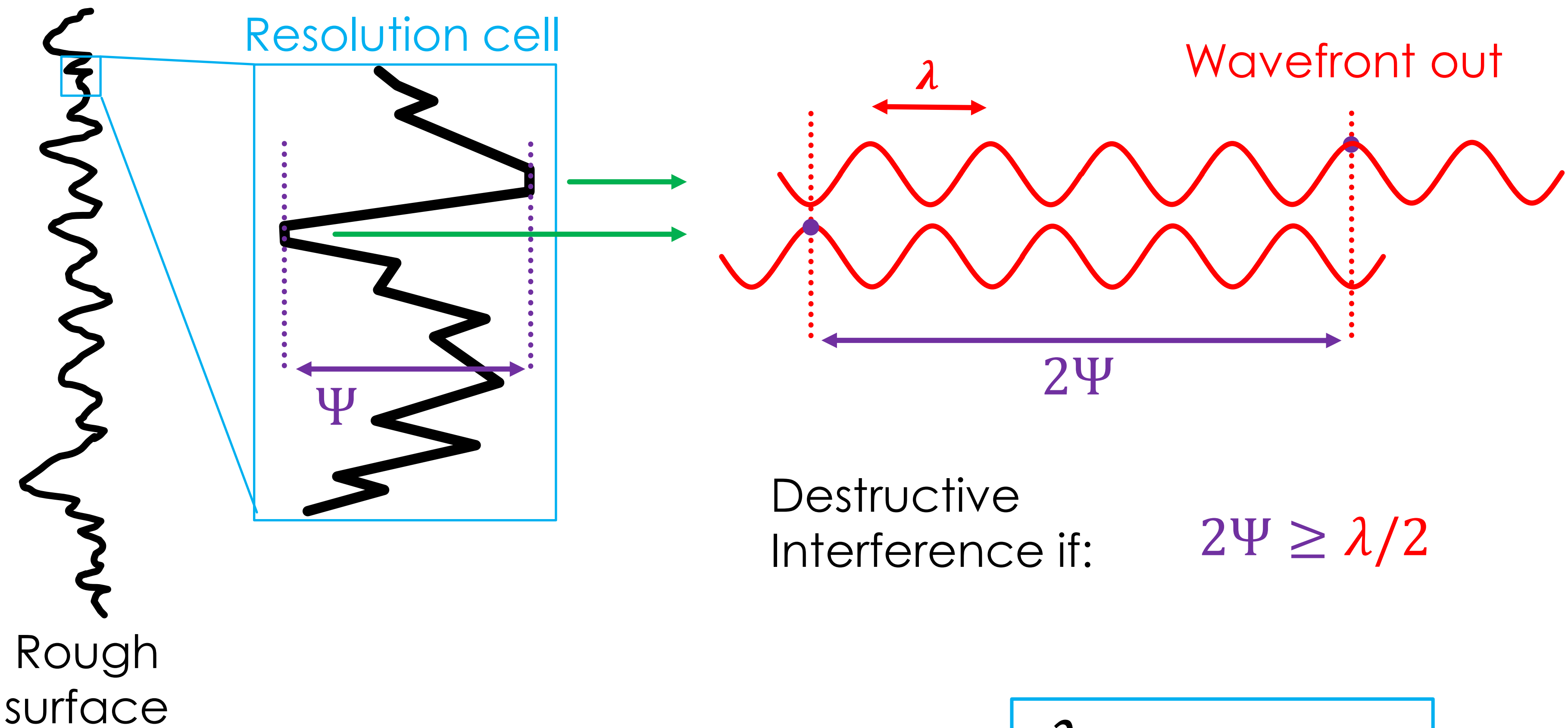
Phase
$\angle E(\lambda) = \phi(\lambda)$



When is a surface "optically rough"?



When is a surface "optically rough"?



Destructive Interference if: $2\Psi \geq \lambda/2$

Speckle-free imaging if: $\boxed{\frac{\lambda}{4} \geq \Psi_{max}}$

Approaches measuring the Time-of-Flight of ligth

$$\delta z \propto \lambda$$

depth resolution

modulation wavelength

Conventional Interferometry (single Wavelength)

Speckle for scattering scenes

Synthetic Wavelength Interferometry

"ToF Cameras" (CW or pulsed)

Poor resolution

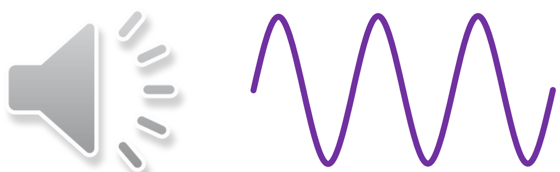
$\sim \mu m$ $\sim m$ λ

Millimeter-sized waves with visible light?

NO! **… well** **… let's look at sound waves!**

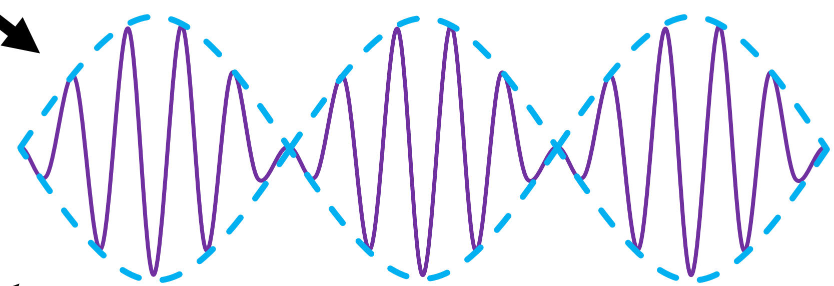
Sine wave
$\nu = 240Hz \rightarrow \lambda \approx 1.429m$

ON



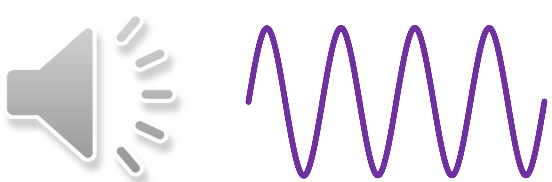
Beat note

$\Lambda_{beat} \approx 171.5m$



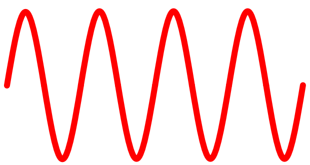
Sine wave
$\nu = 24\mathbf{2}Hz \rightarrow \lambda \approx 1.417m$

ON



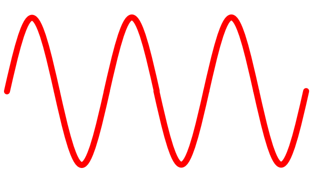
Synthetic Waves

Laser 1 (λ_1, ν_1)



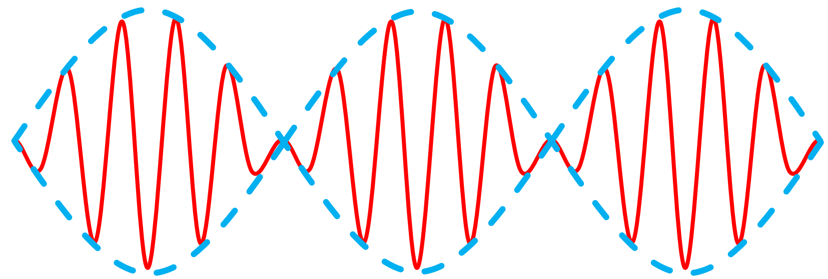
e.g. $\lambda_1 = 800\boldsymbol{nm}$

Laser 2 (λ_2, ν_2)



e.g. $\lambda_2 = 800.6\boldsymbol{nm}$

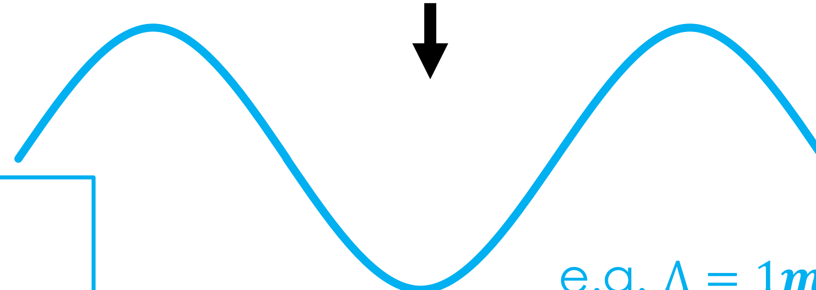
Beat note



Detection & Processing

Synthetic wavelength Λ

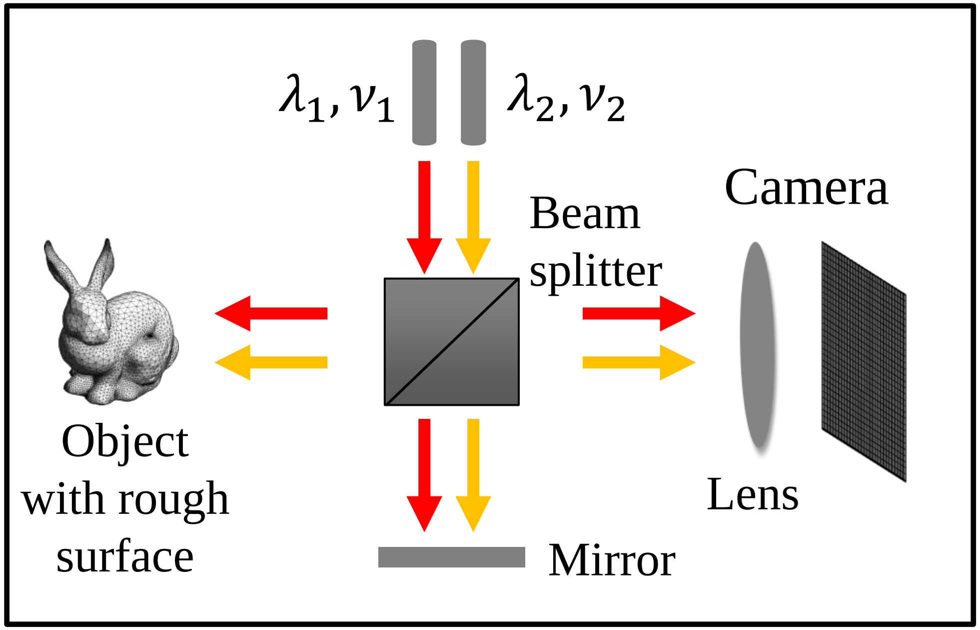
$$\boxed{\Lambda = \frac{\lambda_1 \cdot \lambda_2}{|\lambda_1 - \lambda_2|}}$$



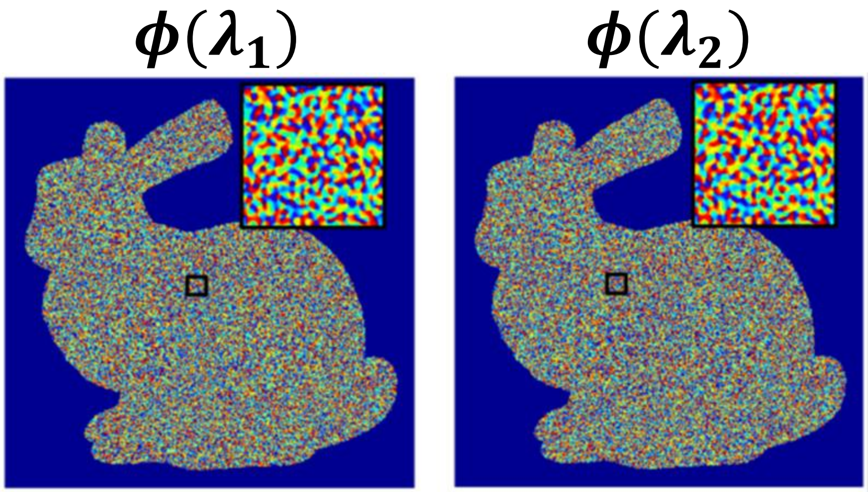
e.g. $\Lambda = 1\boldsymbol{mm}$

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

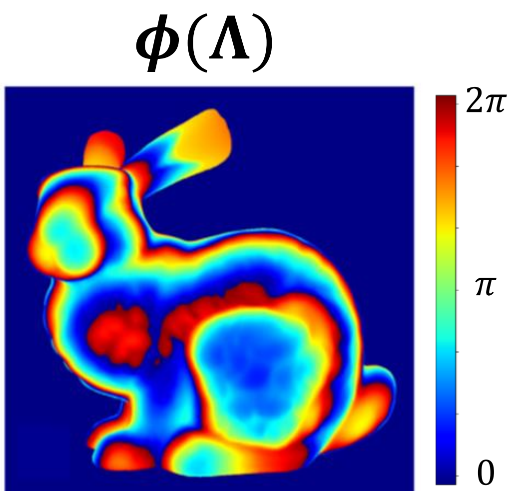
High-precision "ToF Camera"



$$E(\lambda_1) = A_1 \cdot e^{i\phi(\lambda_1)}$$
$$E(\lambda_2) = A_2 \cdot e^{i\phi(\lambda_2)}$$



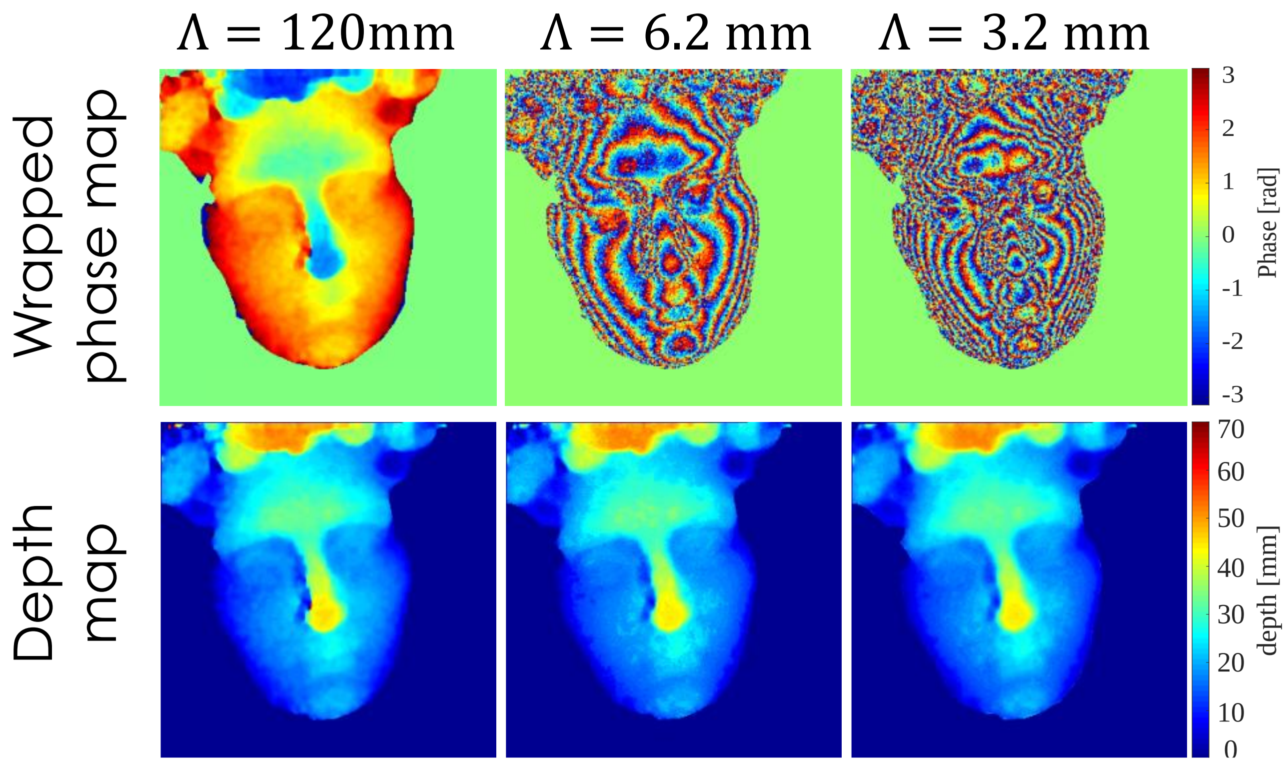
$$E(\Lambda) = E(\lambda_1) \cdot E^*(\lambda_2)$$
$$= A_1 A_2 \cdot \exp(i(\phi(\lambda_1) - \phi(\lambda_2)))$$



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”

Object



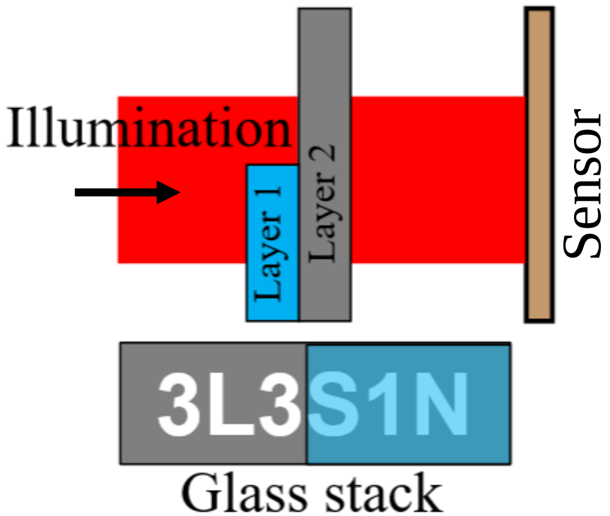
Sub-mm depth resolution easily achievable!

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

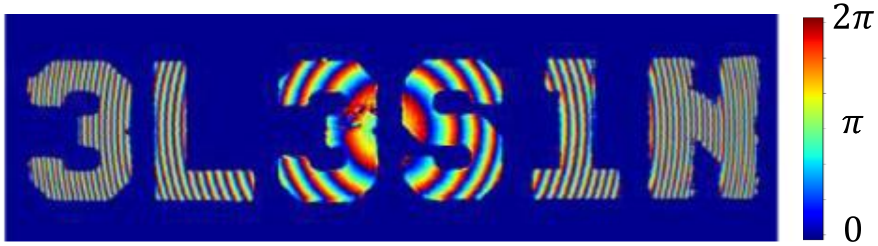
Synthetic wavelengths are also useful in absence of scattering!

Schematic setup



Optical phase → strong wrapping!

$\lambda = 854.3\ nm$



Synthetic phase → no wrapping!

$\Lambda = 1.29\ mm$

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!**

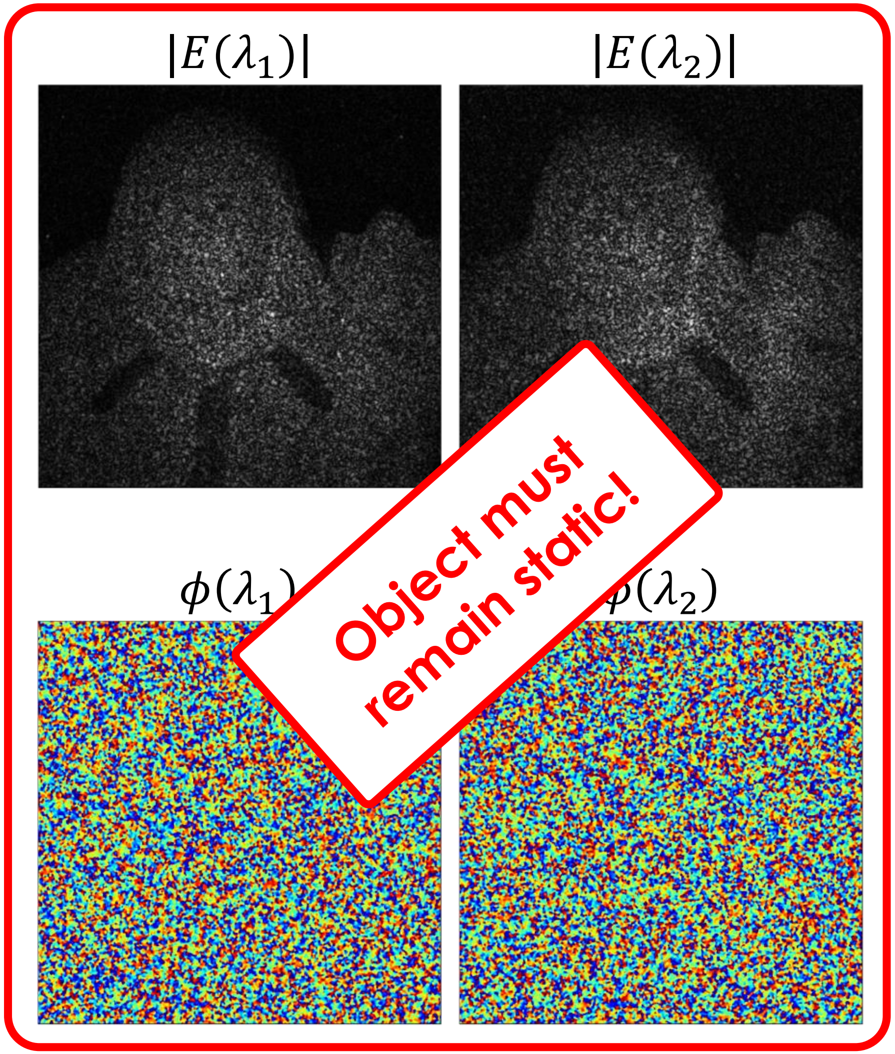
Better question to ask by an "adopter":

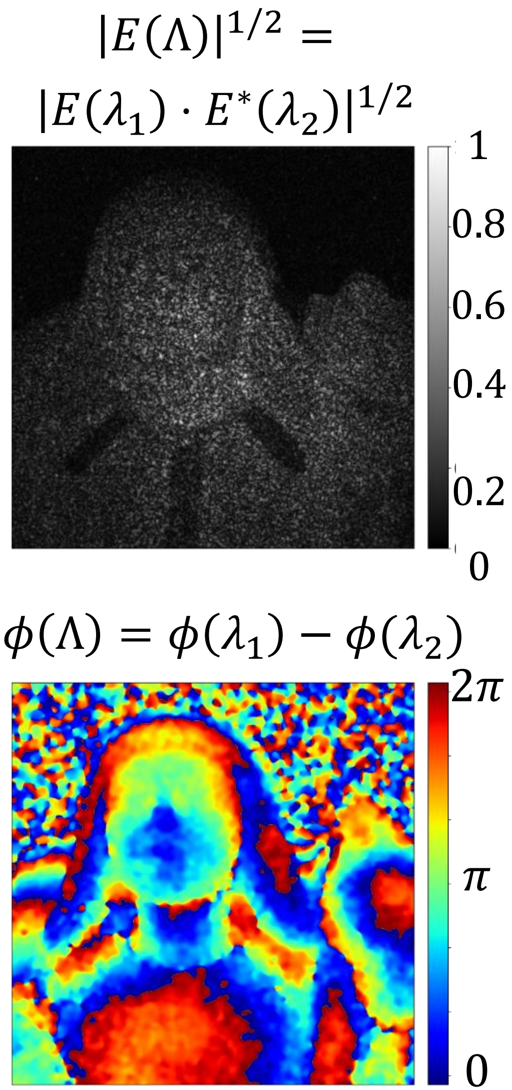
What are important modalities for your application?

- ✅ Full field
- ✅ Single-shot
- Reference-less
- ✅ No prior object knowledge
- ✅ COTS CCD/CMOS cameras
- ....

*** Coming up now…**

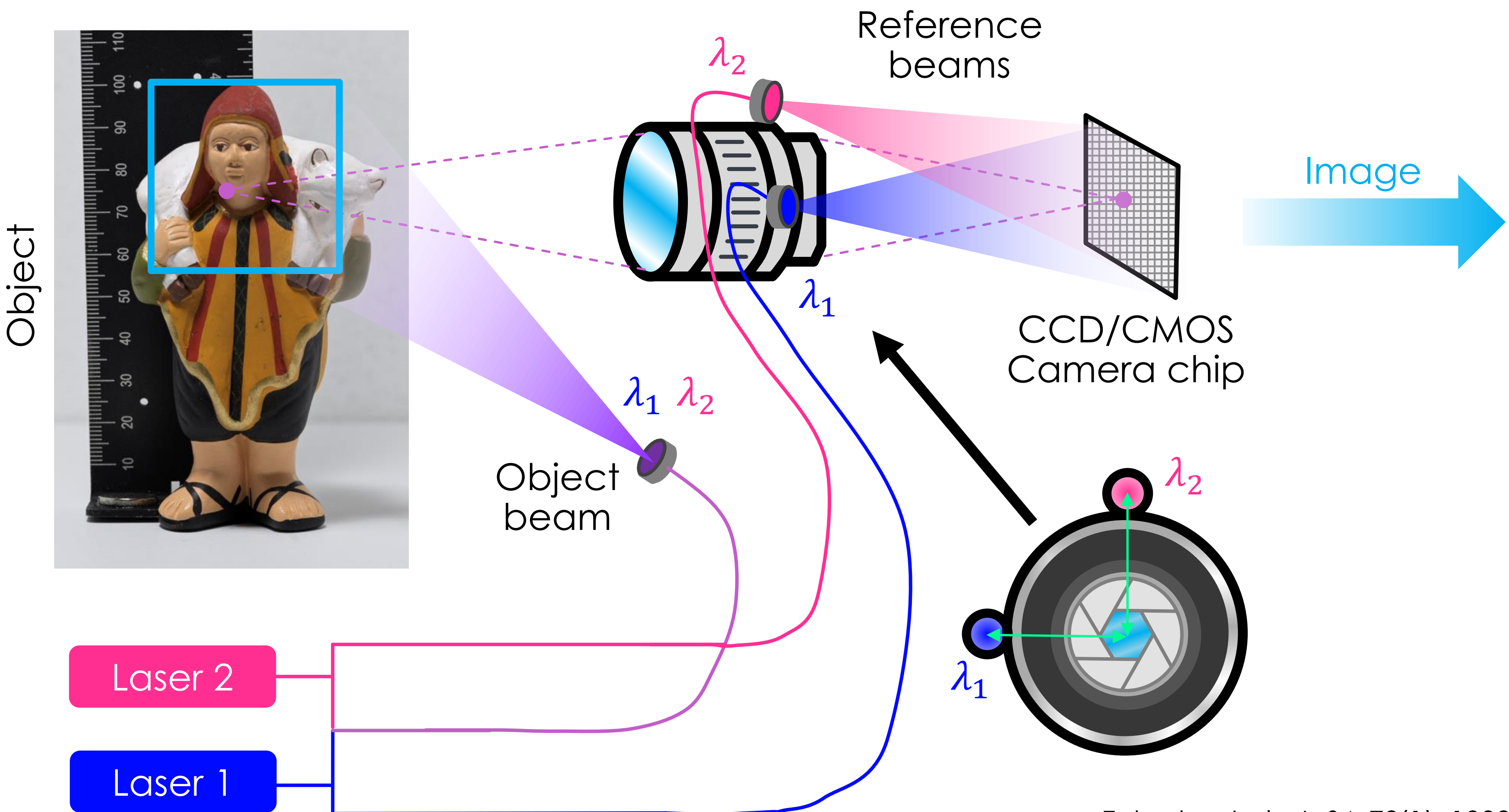
Susceptibility to motion





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

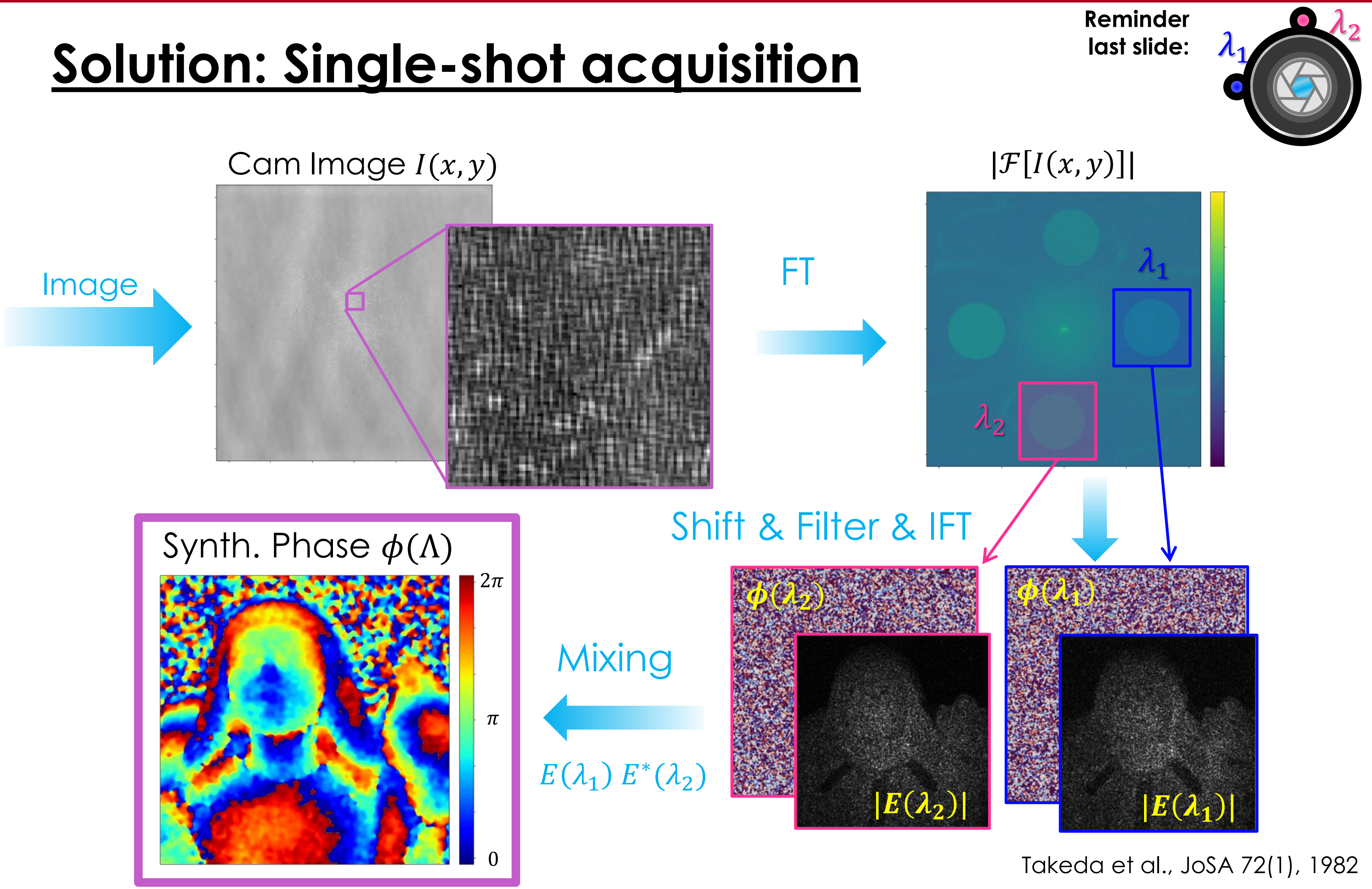
Solution: Single-shot acquisition



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



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

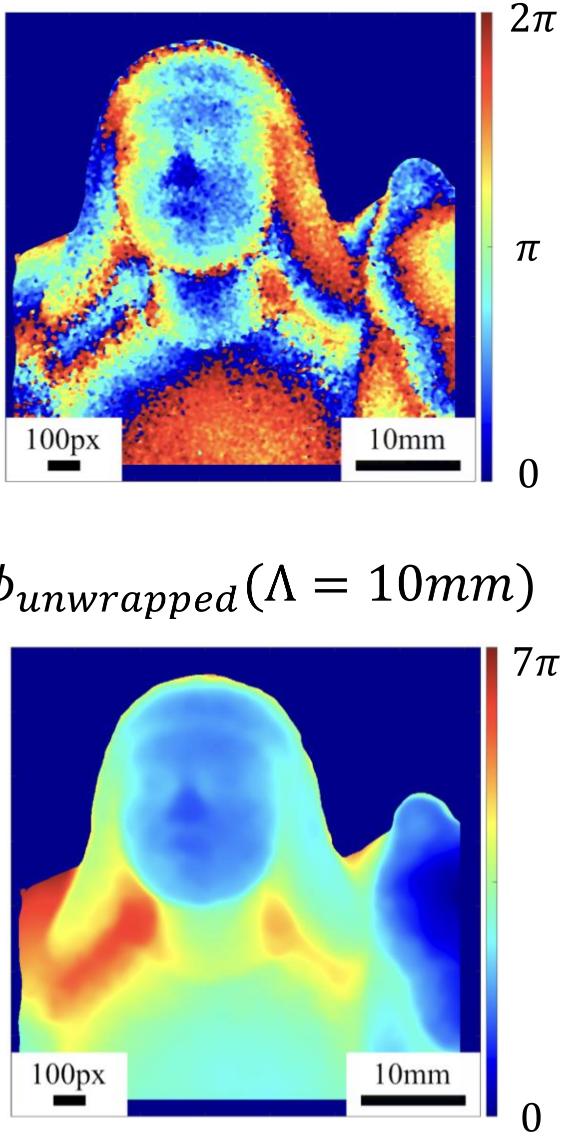
Results
(single-shot)

Object

Small figure

$\phi_{wrapped}(\Lambda = 10mm)$

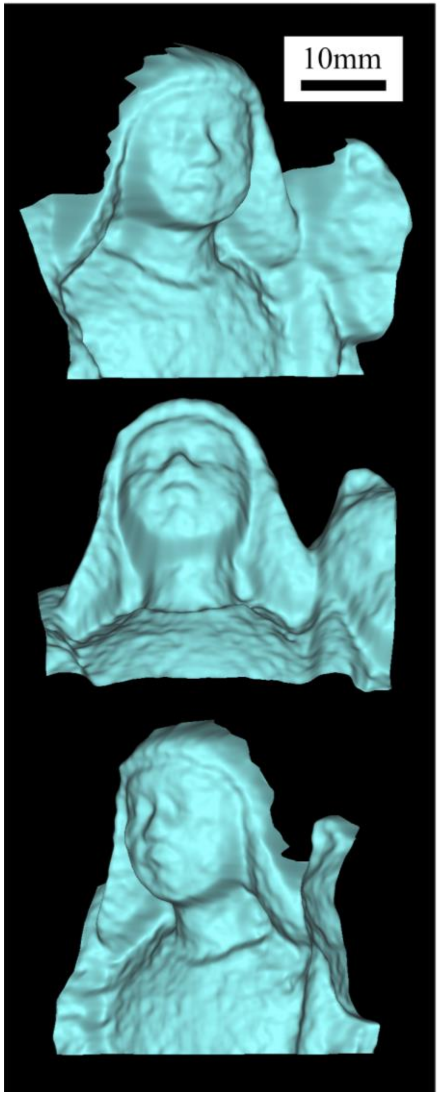
$\phi_{unwrapped}(\Lambda = 10mm)$



3D model

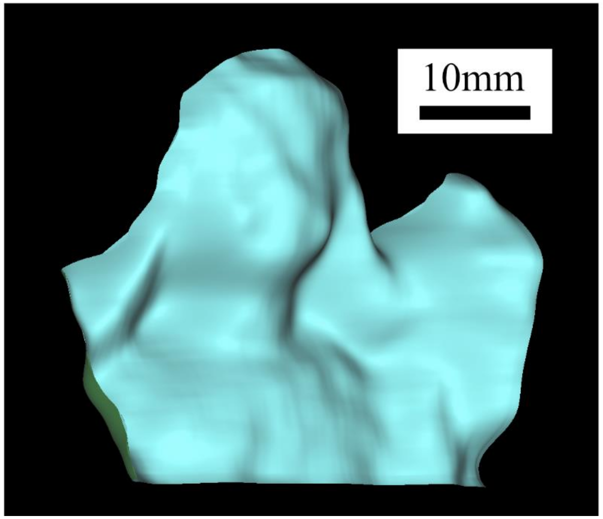
$\Lambda = 10mm$

$\delta z \approx 1.8mm$

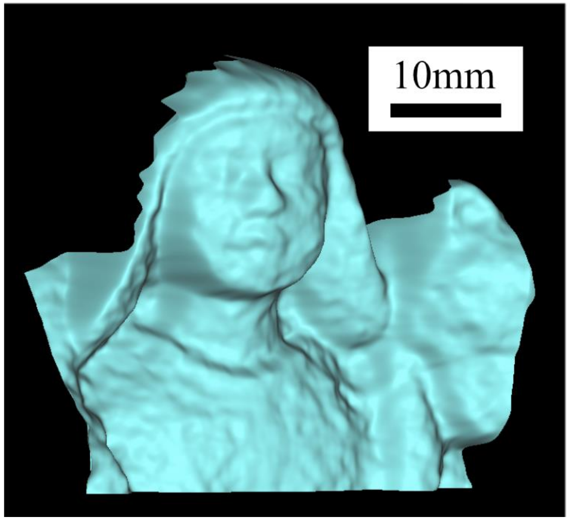


Quantitative analysis of distance precision δz

Λ [mm]	40	10	5	3	1
δz_{single} [mm]	5.56	1.78	1.64	0.79	0.33



$\Lambda = 50mm$

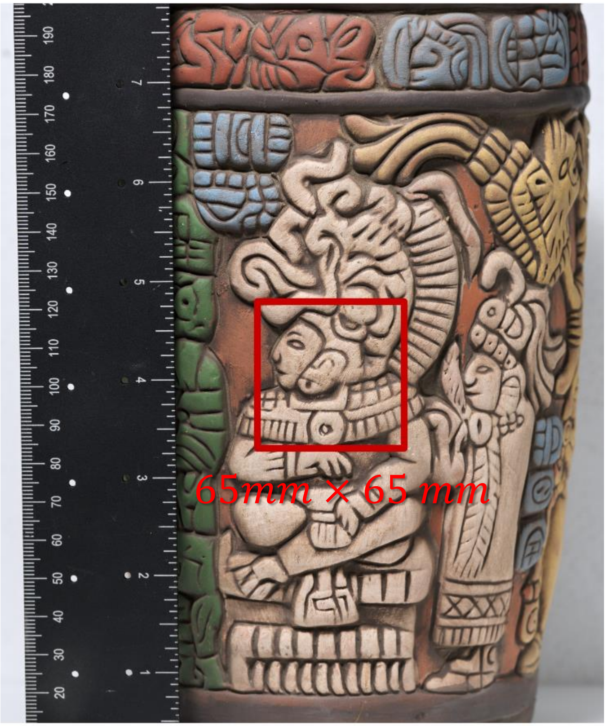


$\Lambda = 10mm$

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

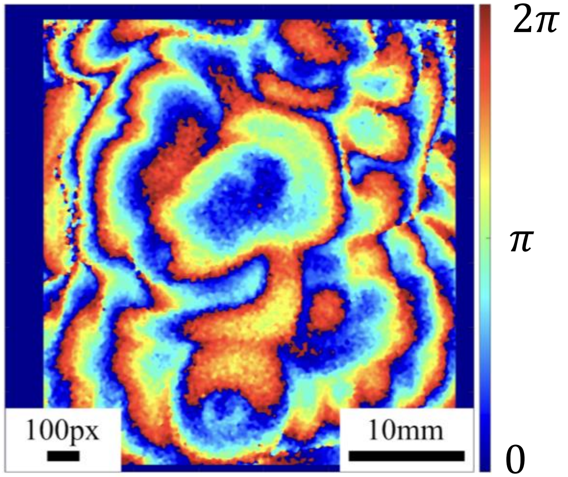
Results
(dual shot)

Object

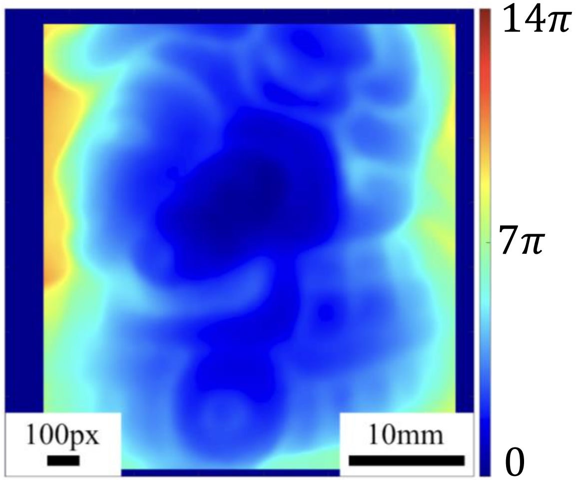


Clay pot

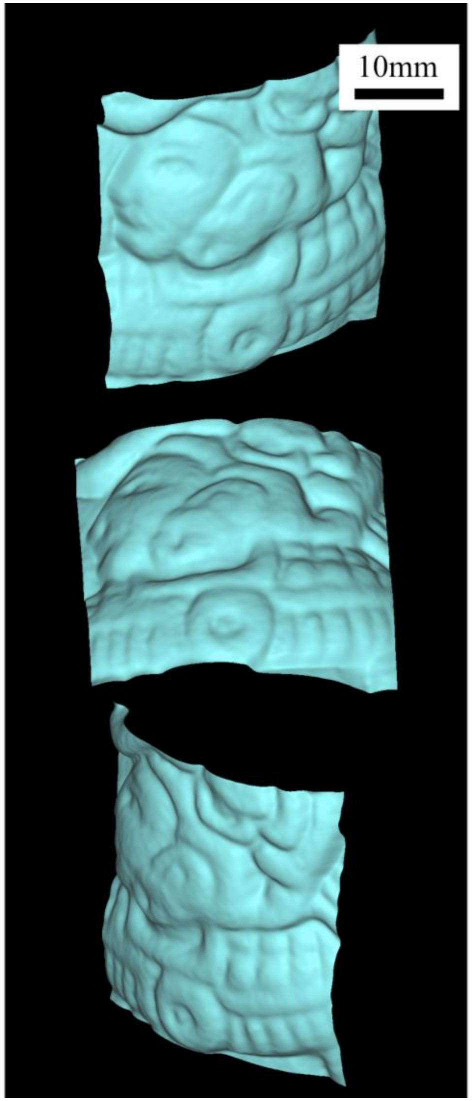
$\phi_{wrapped}(\Lambda = 3mm)$



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



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



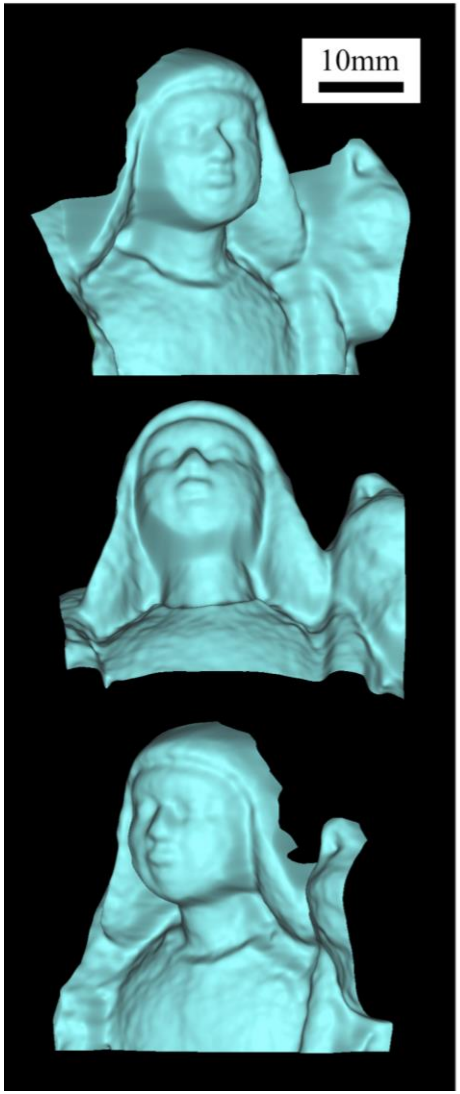
Results

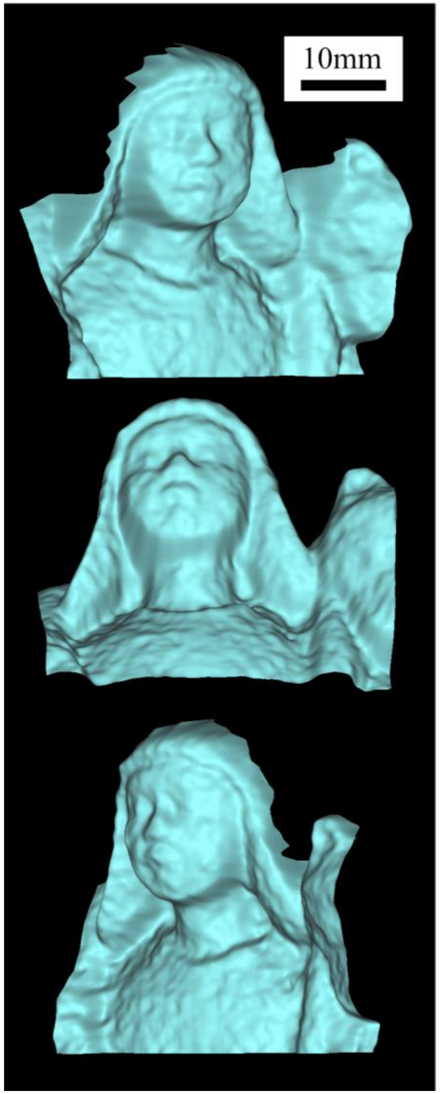
3D model $\Lambda = 10mm$

Object

Small figure

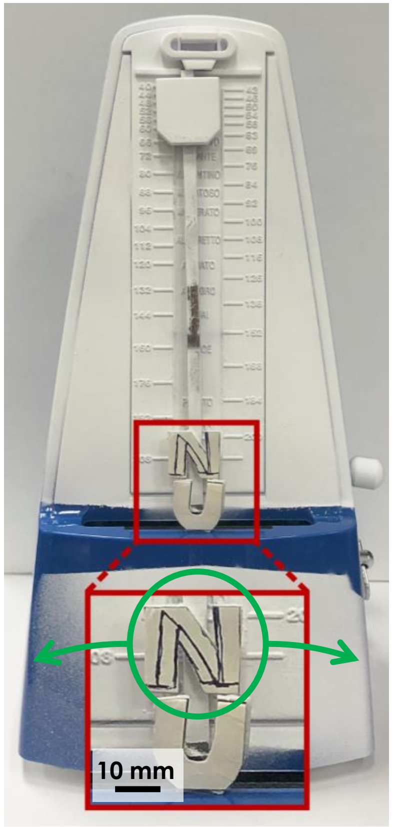
Dual-shot vs. Single-shot



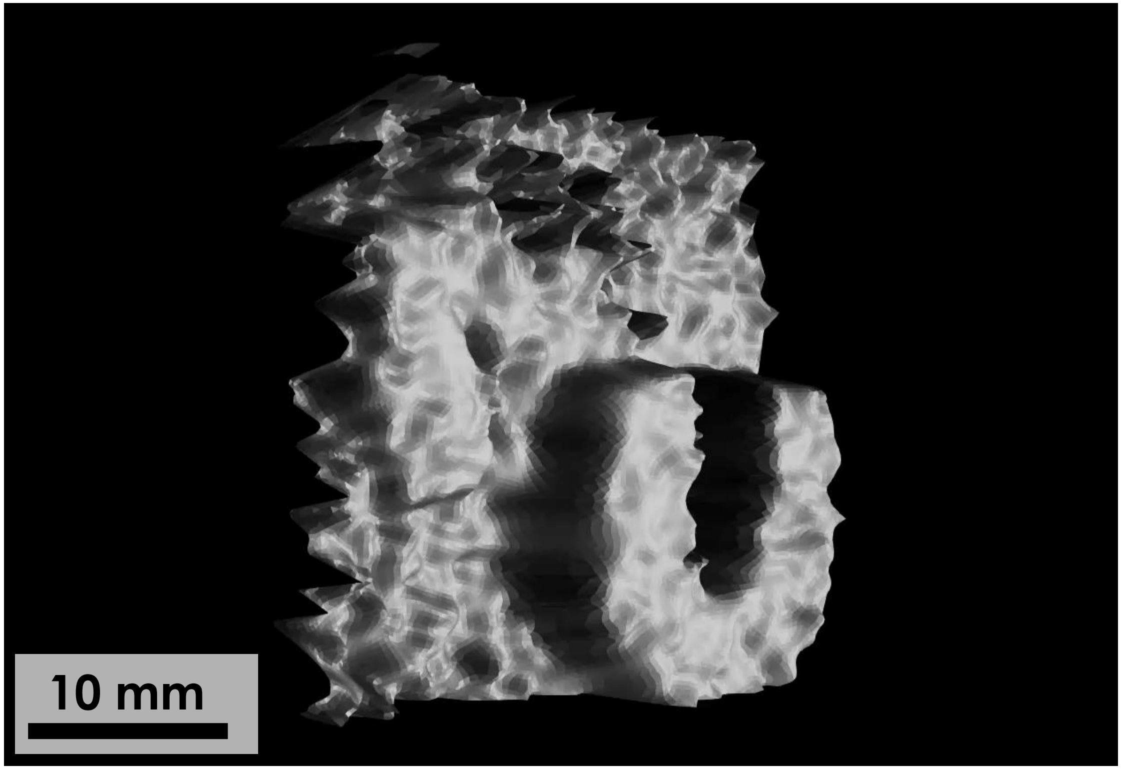


Video acquisition

Object:
metronome



3D Video

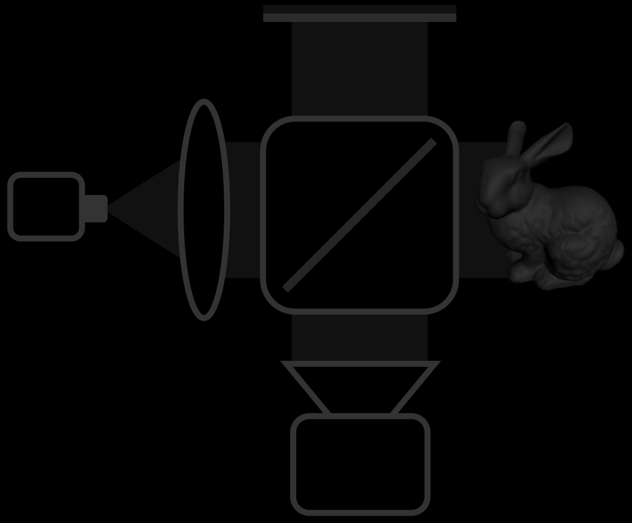


M. Ballester*, H. Wang*, J. Li, O. Cossairt, F. Willomitzer.
'Single-shot ToF sensing with sub-mm precision using conventional CMOS sensors', Arxiv Preprint, 2022

End Part 2

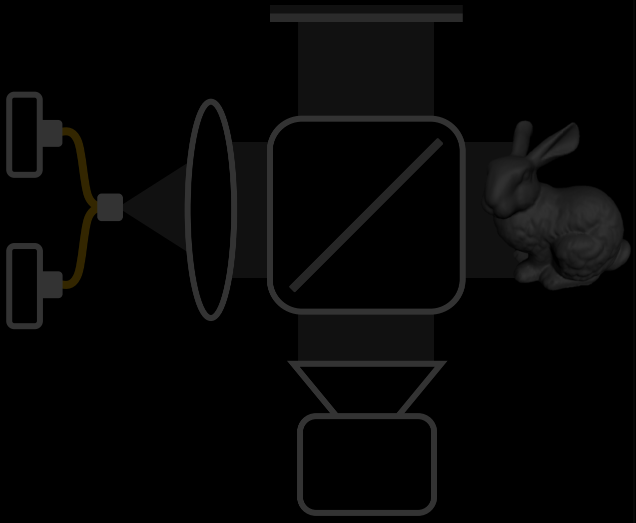
Course overview

introduction to
interferometry



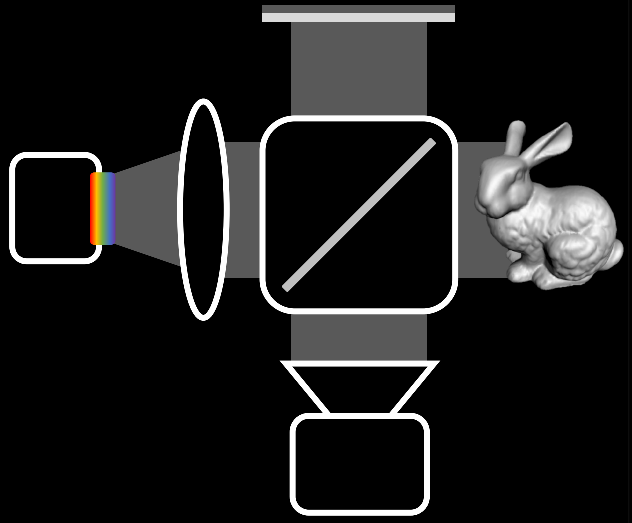
Yannis

two-wavelength
interferometry



Florian

partially-coherent
interferometry



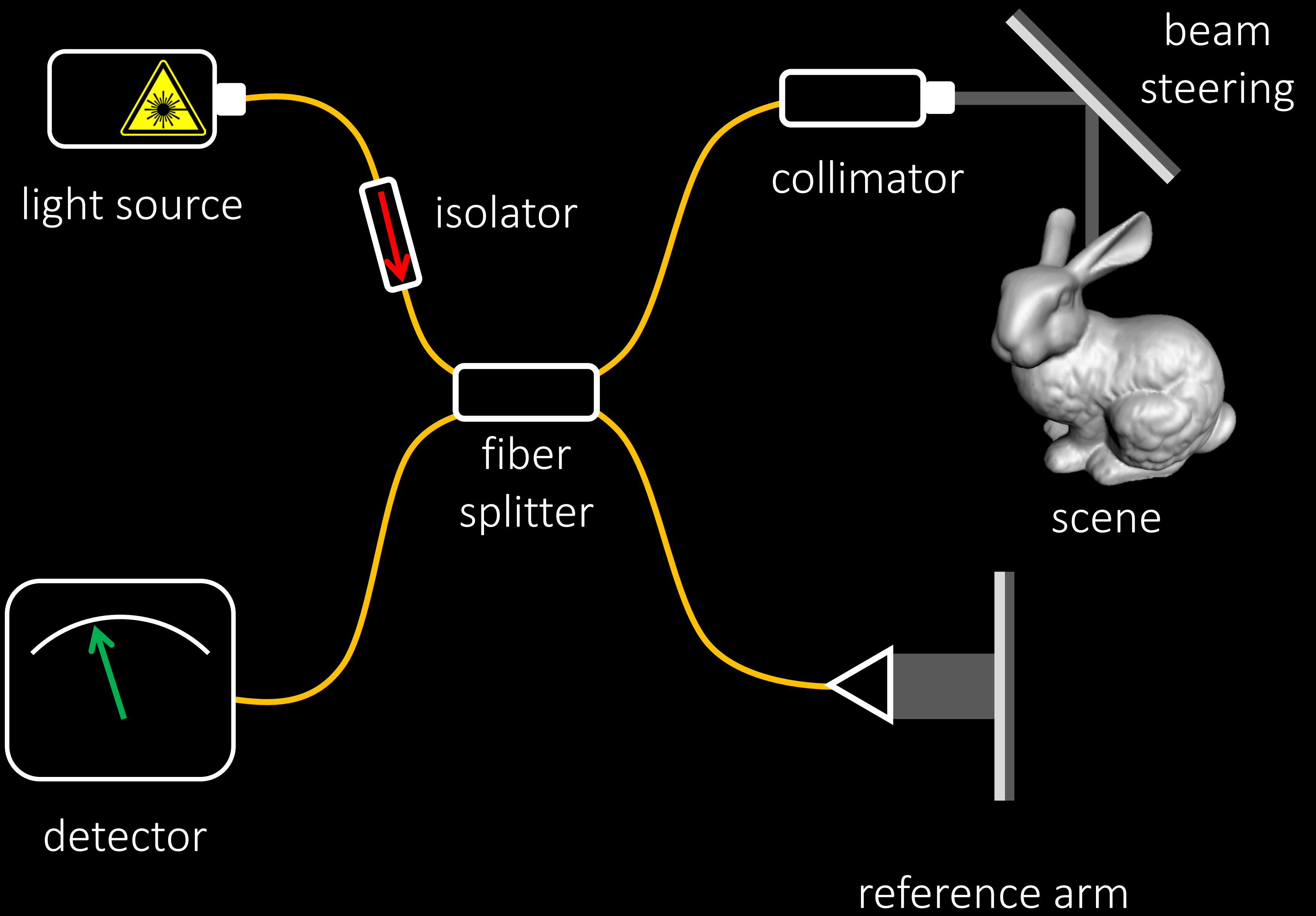
Alankar

interferometric
computational imaging

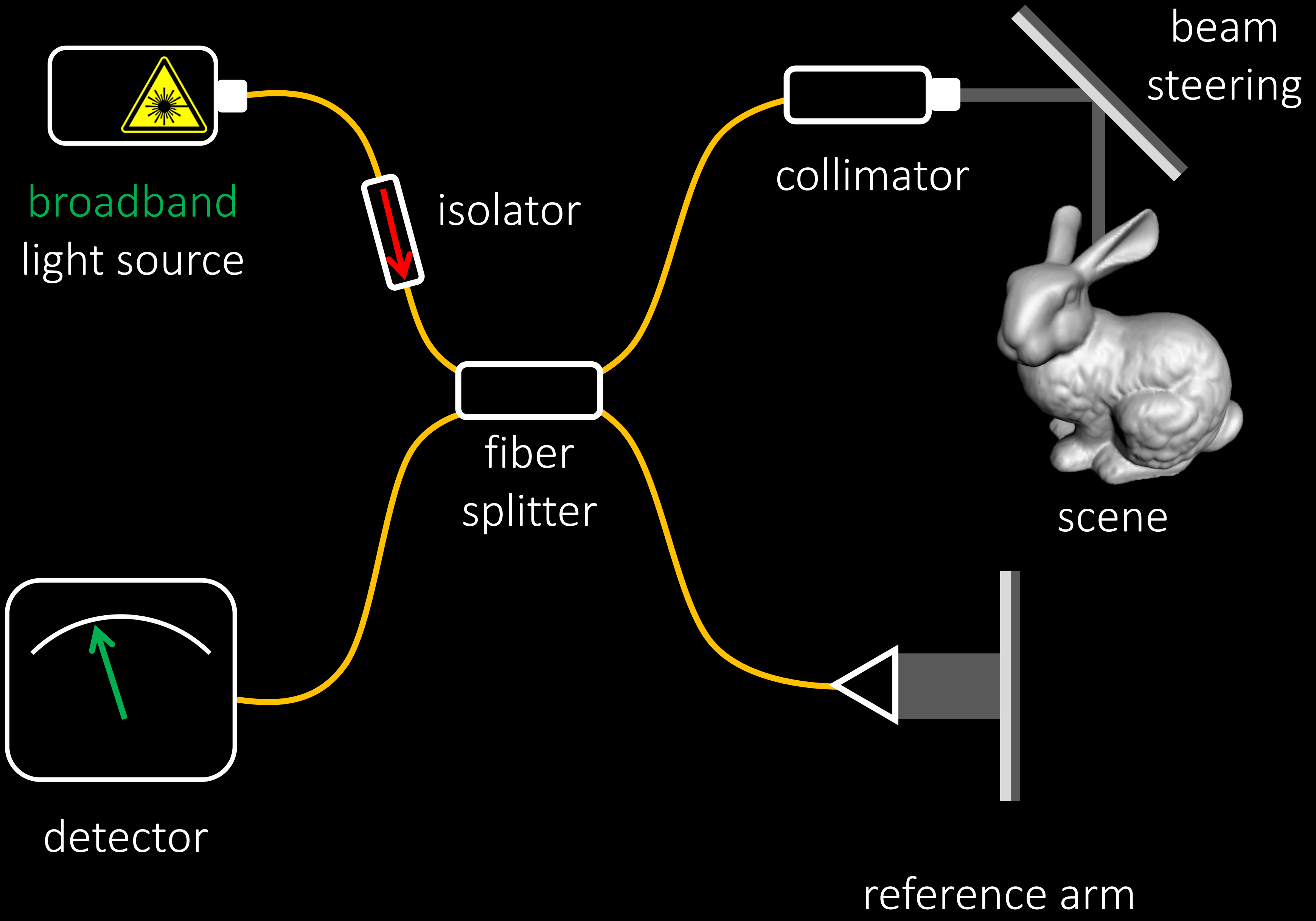
Florian

Yannis

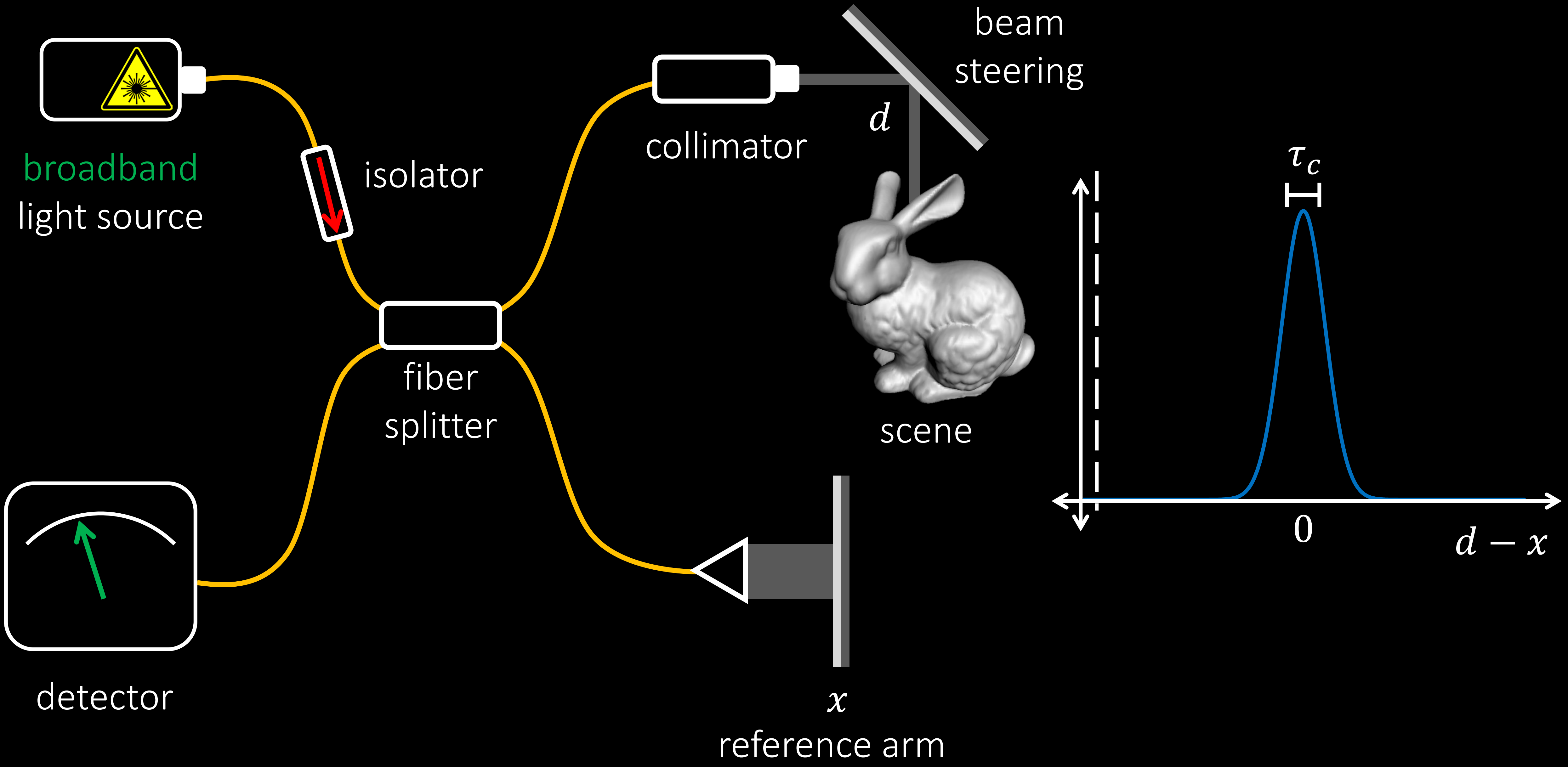
Fiber-based interferometry



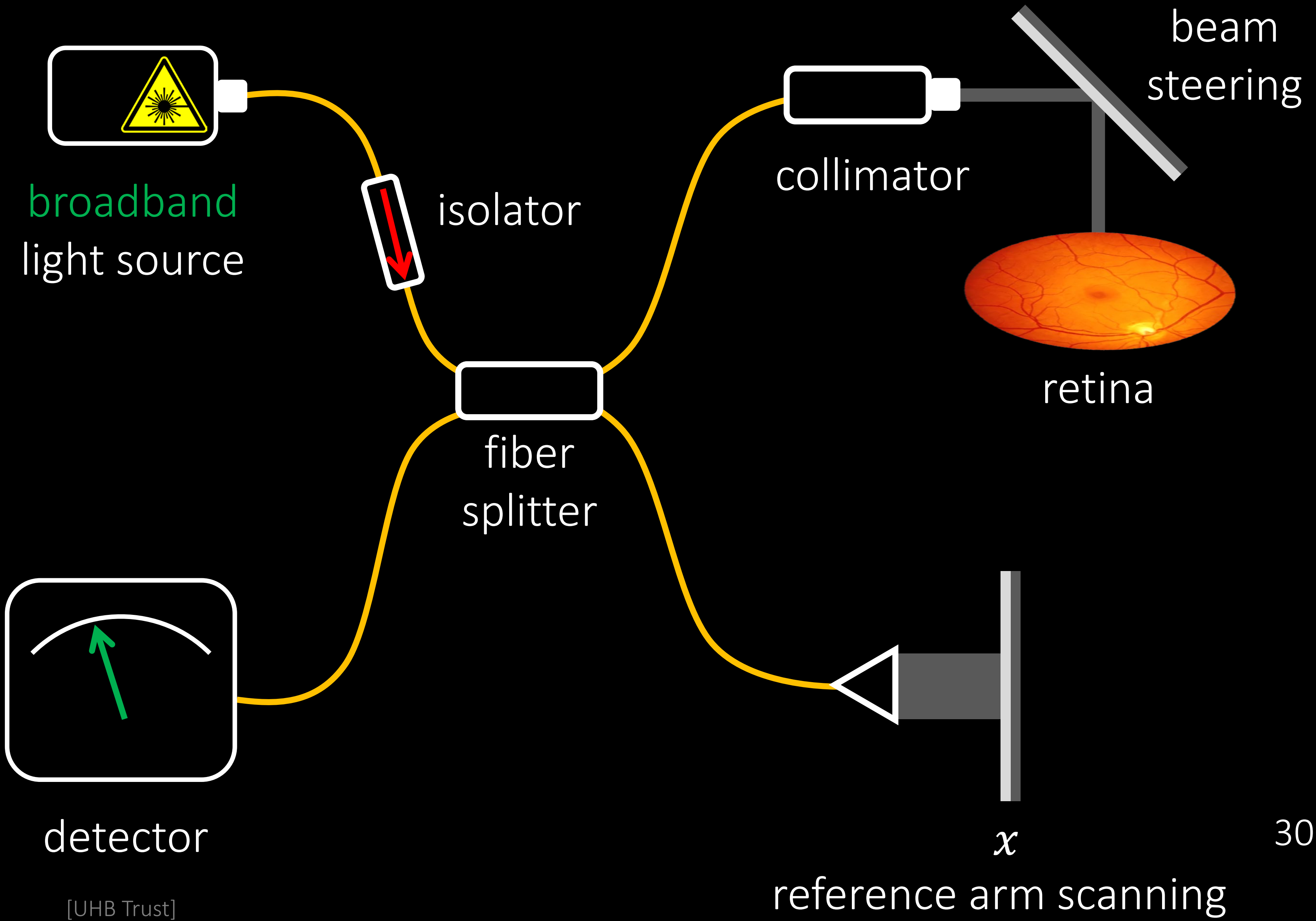
Time-domain optical coherence tomography



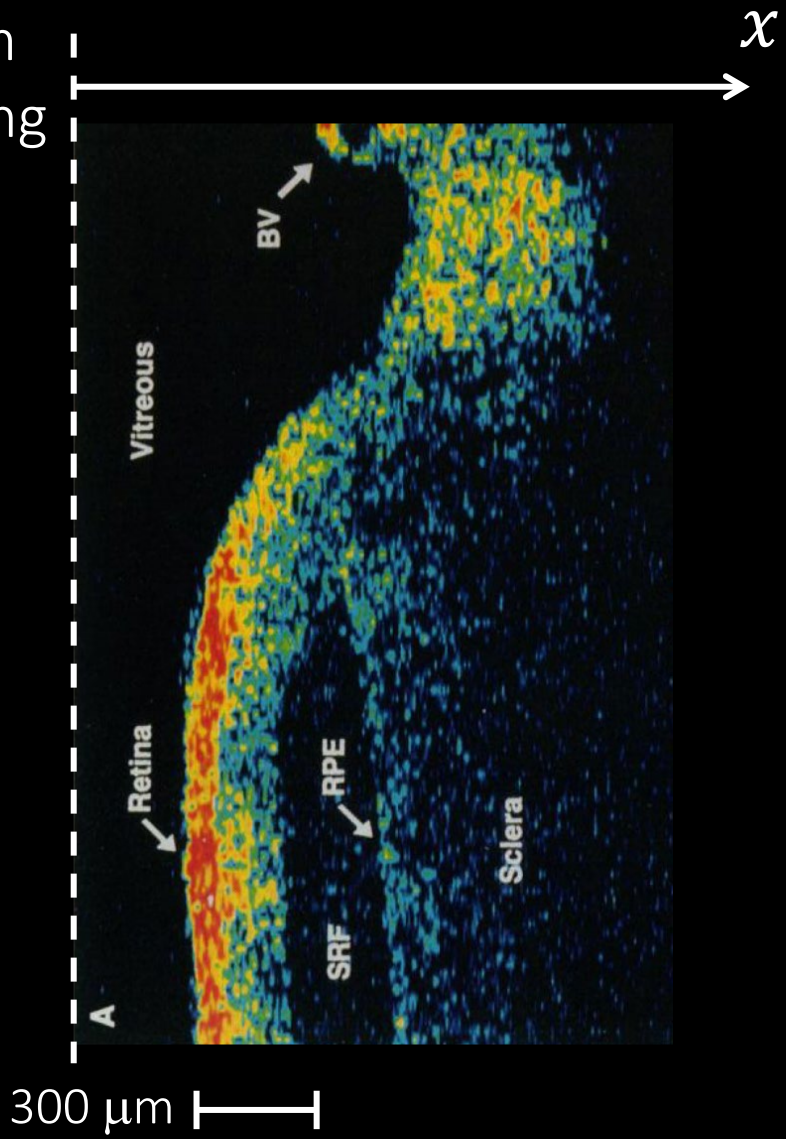
Time-domain optical coherence tomography



Time-domain optical coherence tomography

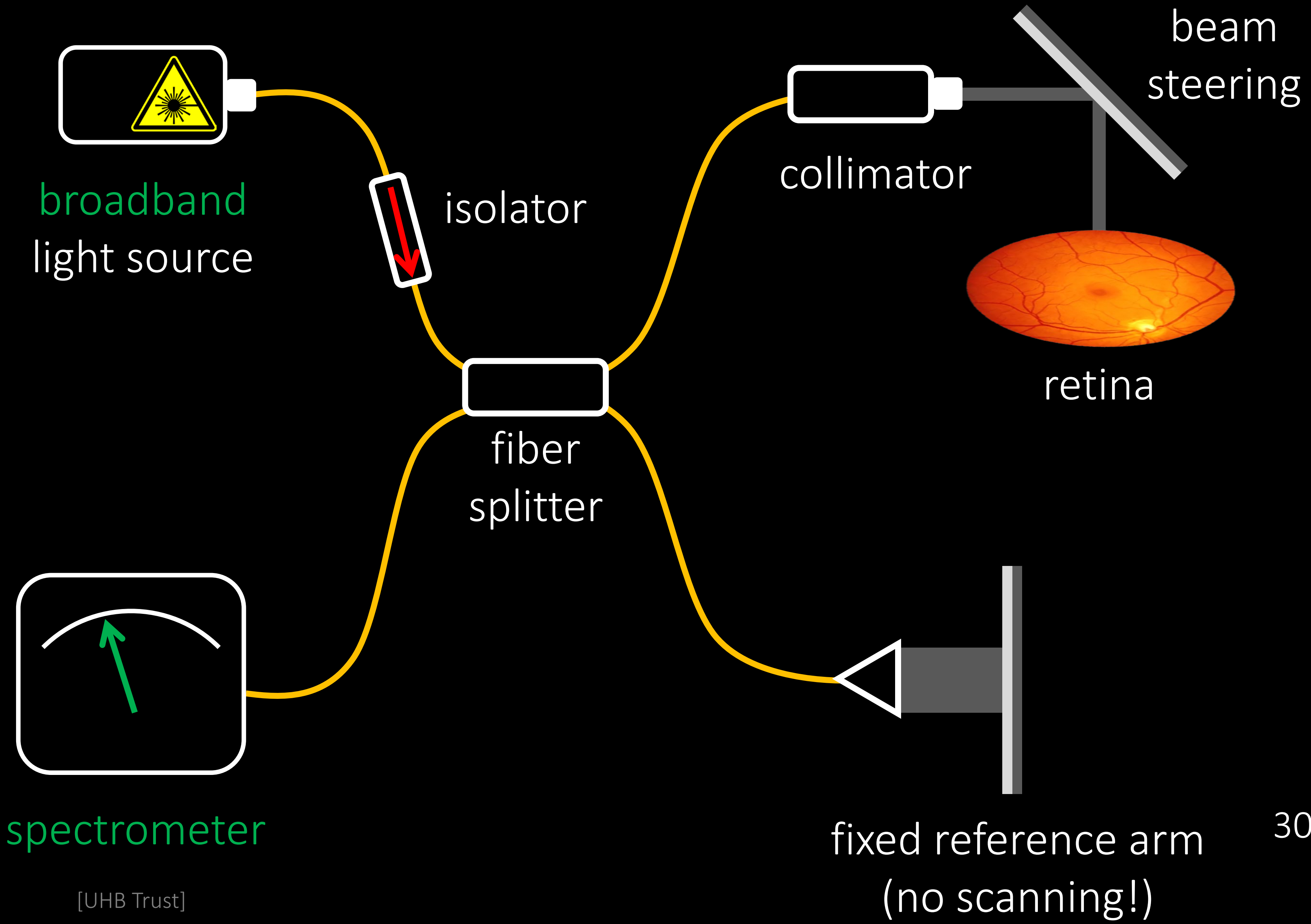


[UHB Trust]

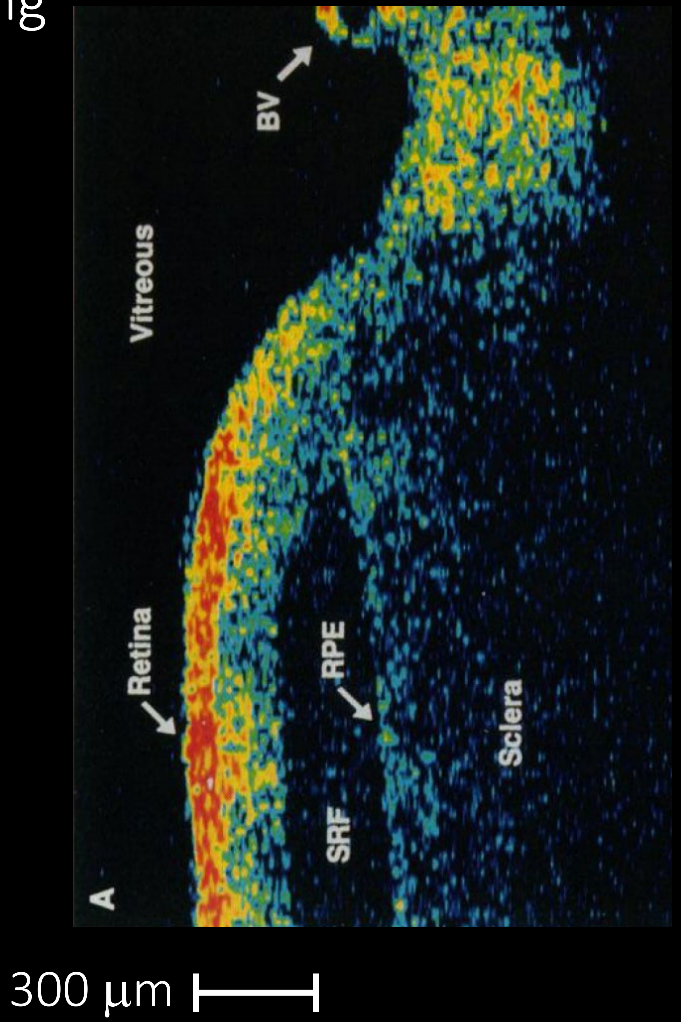


[Huang *et al.*, 1991]

Frequency-domain optical coherence tomography

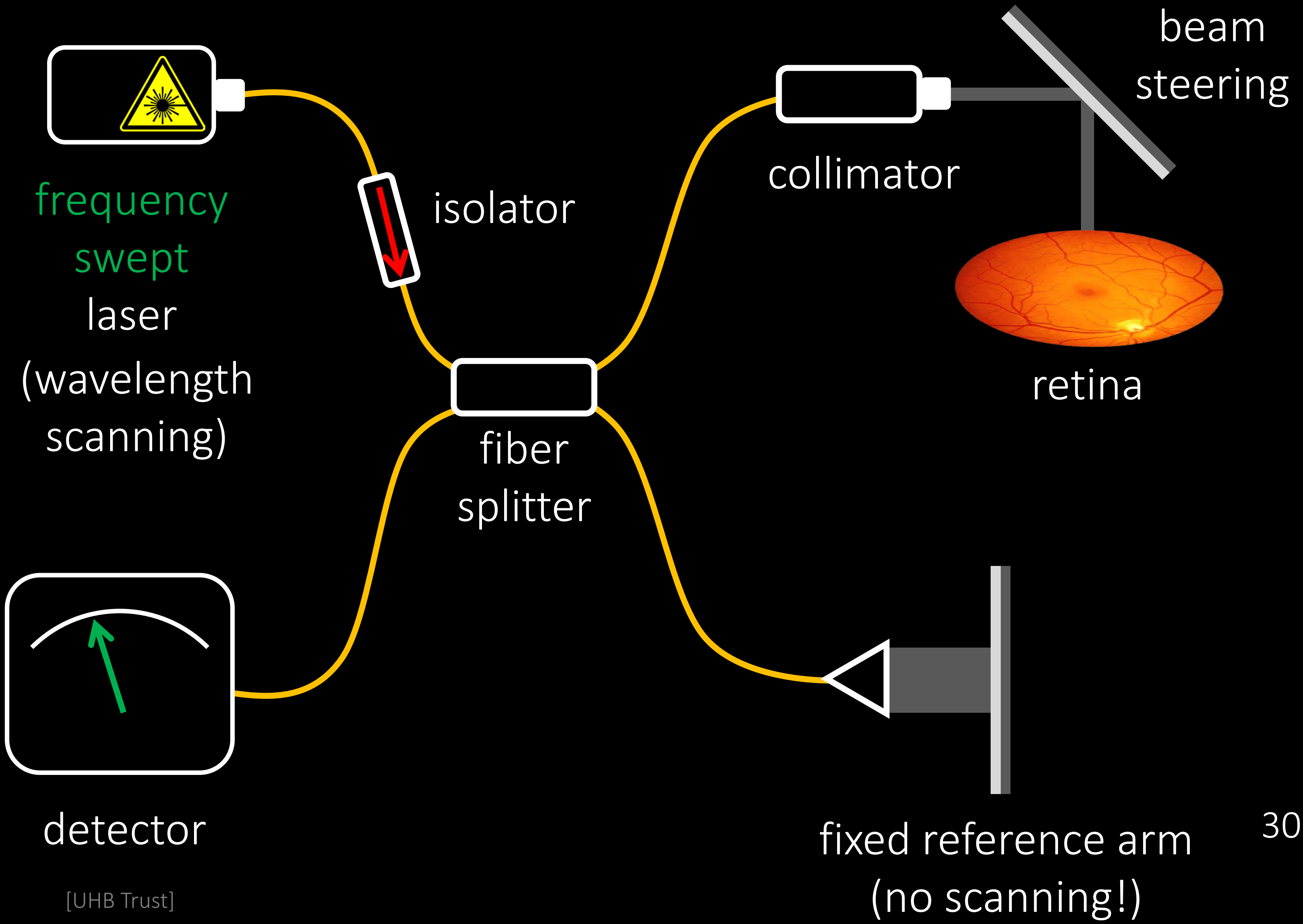


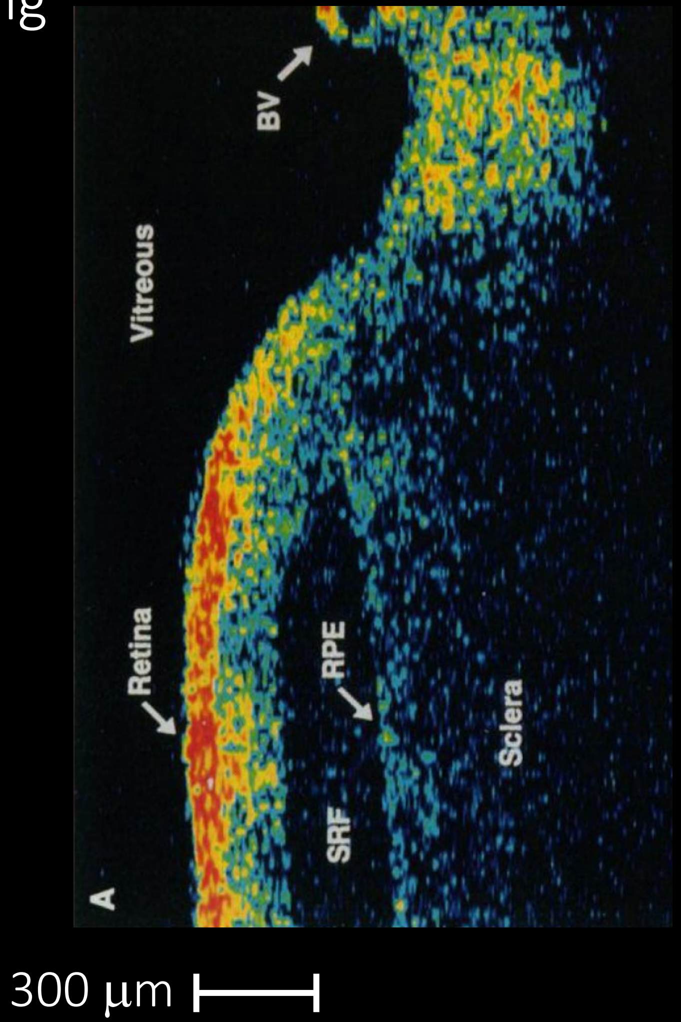
[UHB Trust]



[Huang *et al.*, 1991]

Swept-source optical coherence tomography

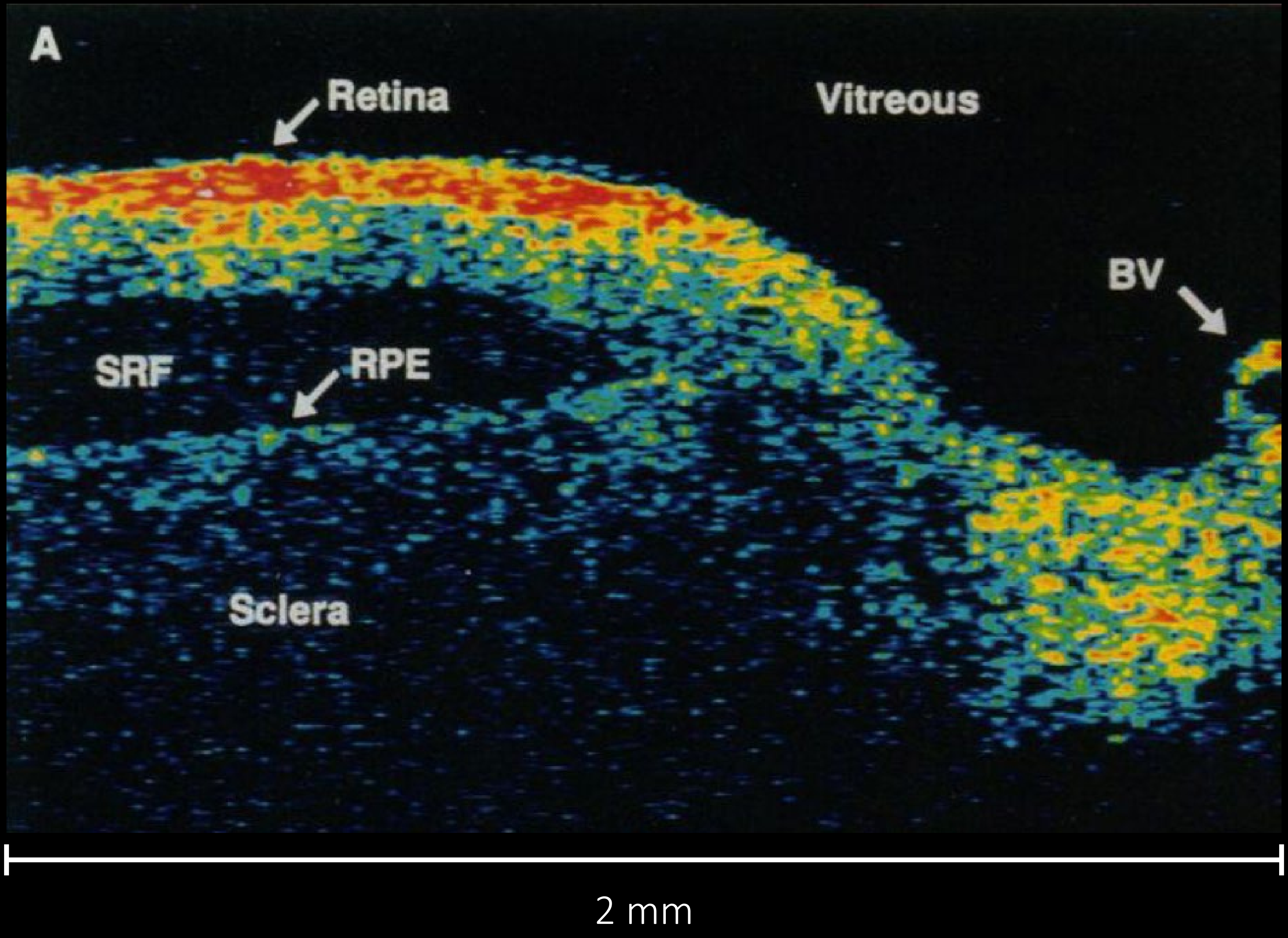




[UHB Trust]

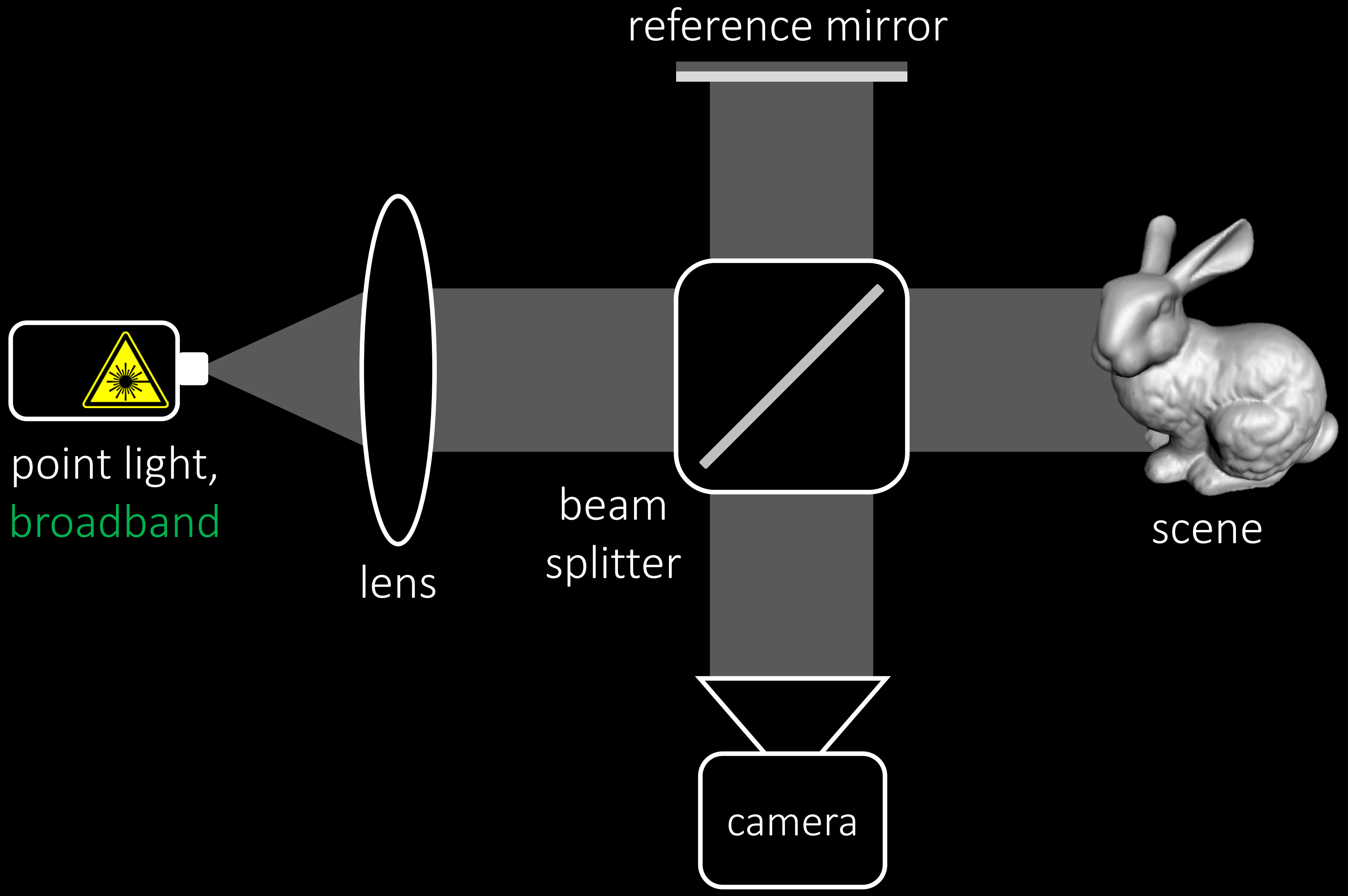
[Huang *et al.*, 1991]

Swept-source optical coherence tomography

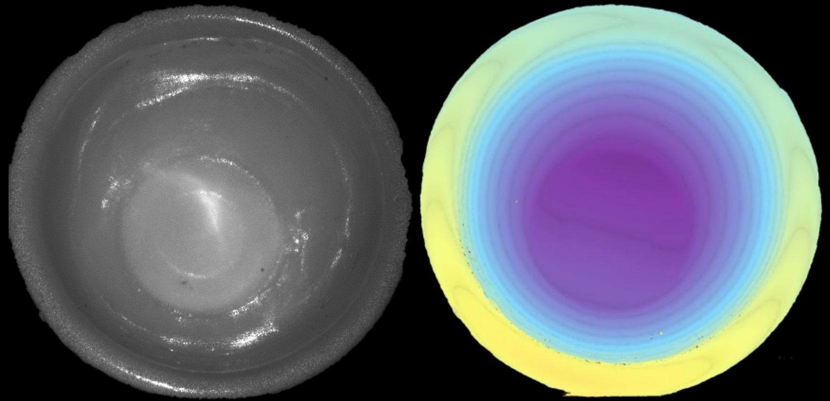


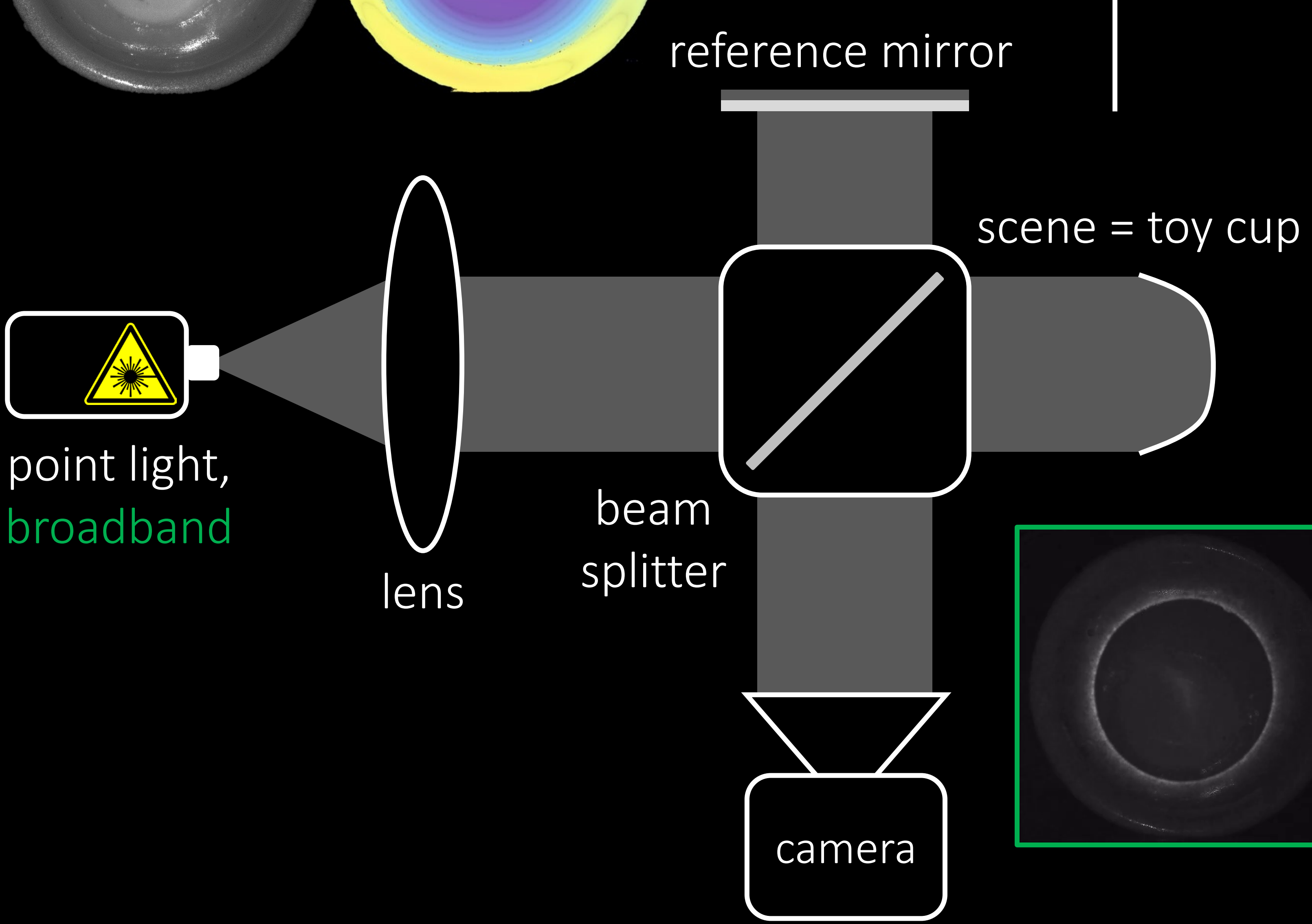
[Huang *et al.*, 1991]

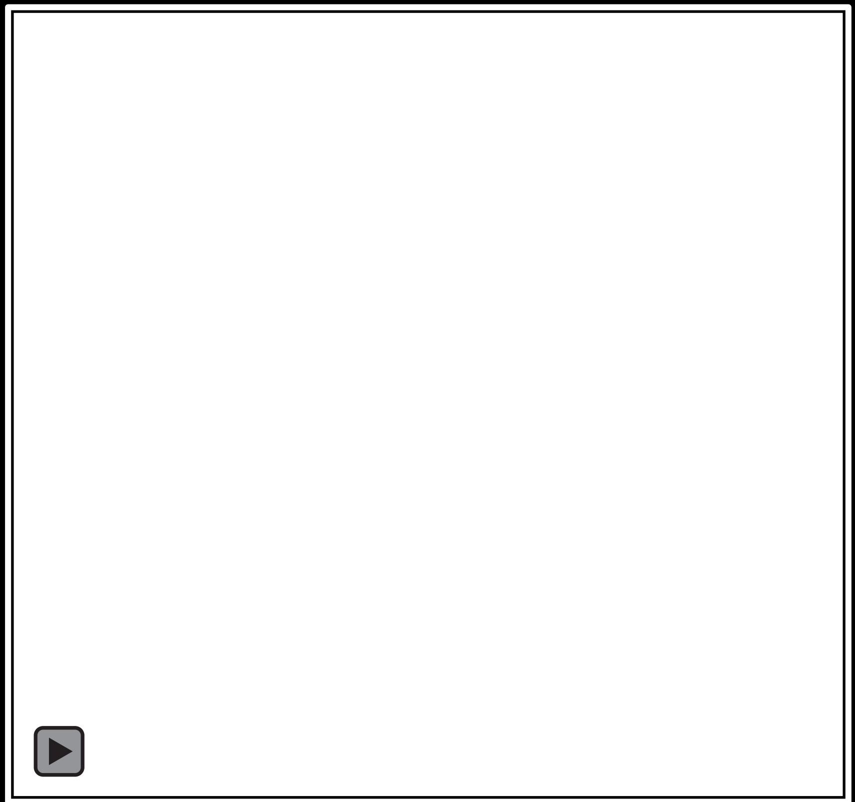
Full-field OCT

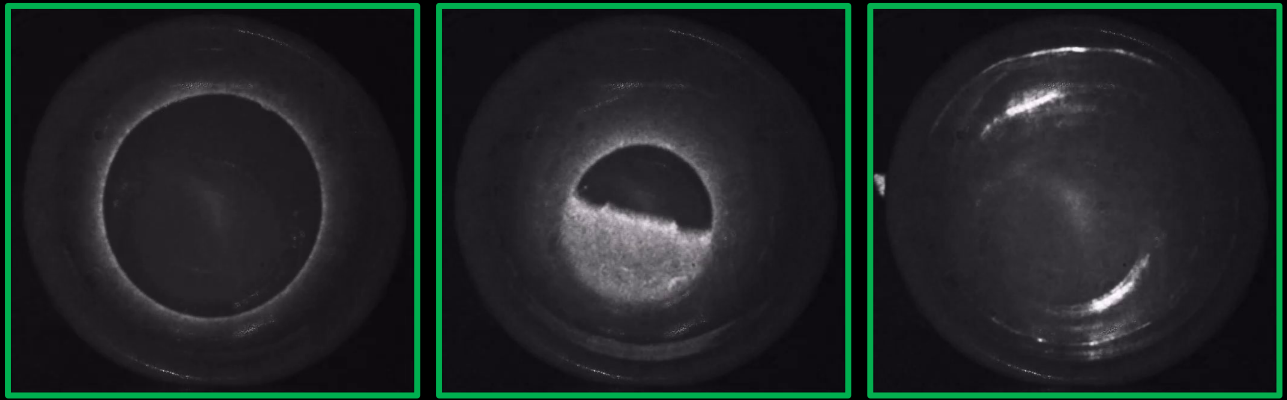


Full-field TD-OCT





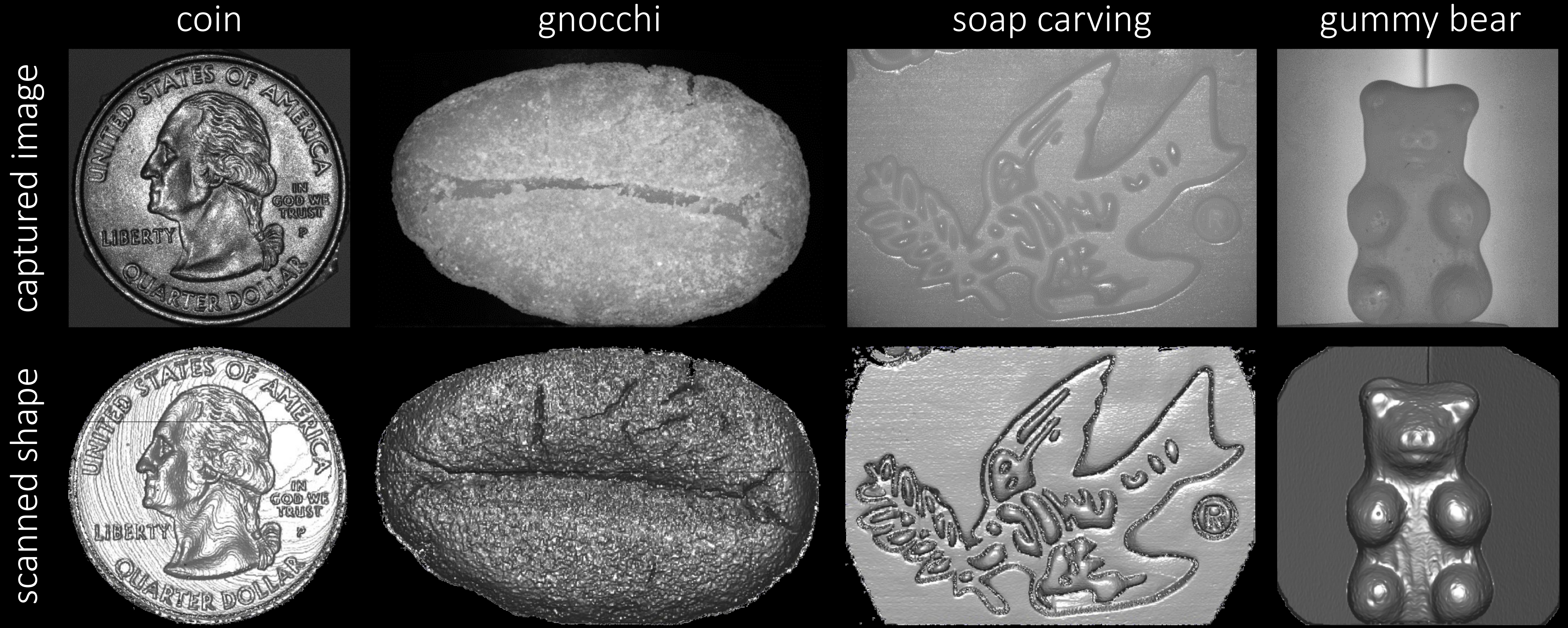




[Gkioulekas *et al.*, 2015]

Micron-scale shape scanning

depth resolution ~5 µm



[Gkioulekas *et al.*, 2015]

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

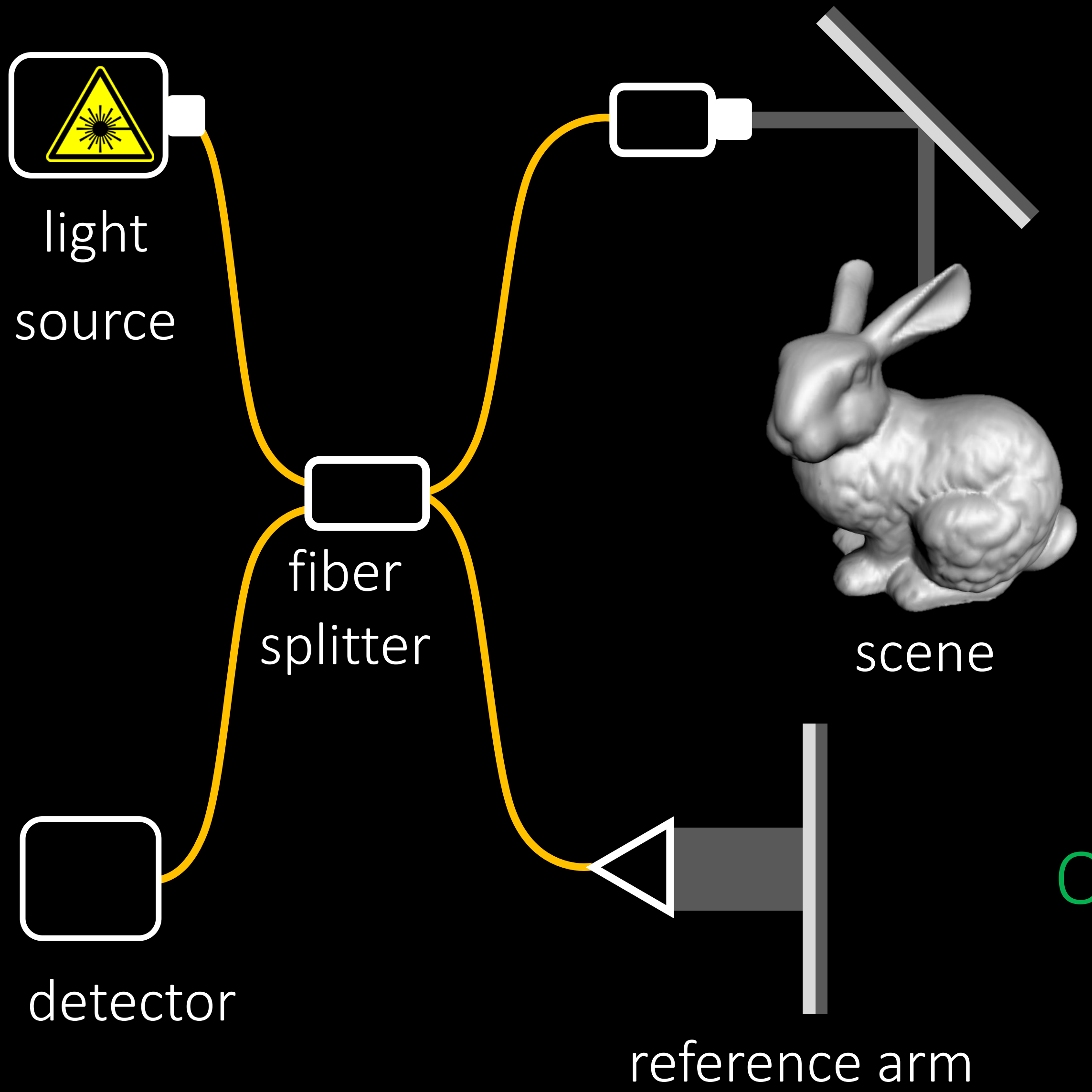
OCT v/s SWI

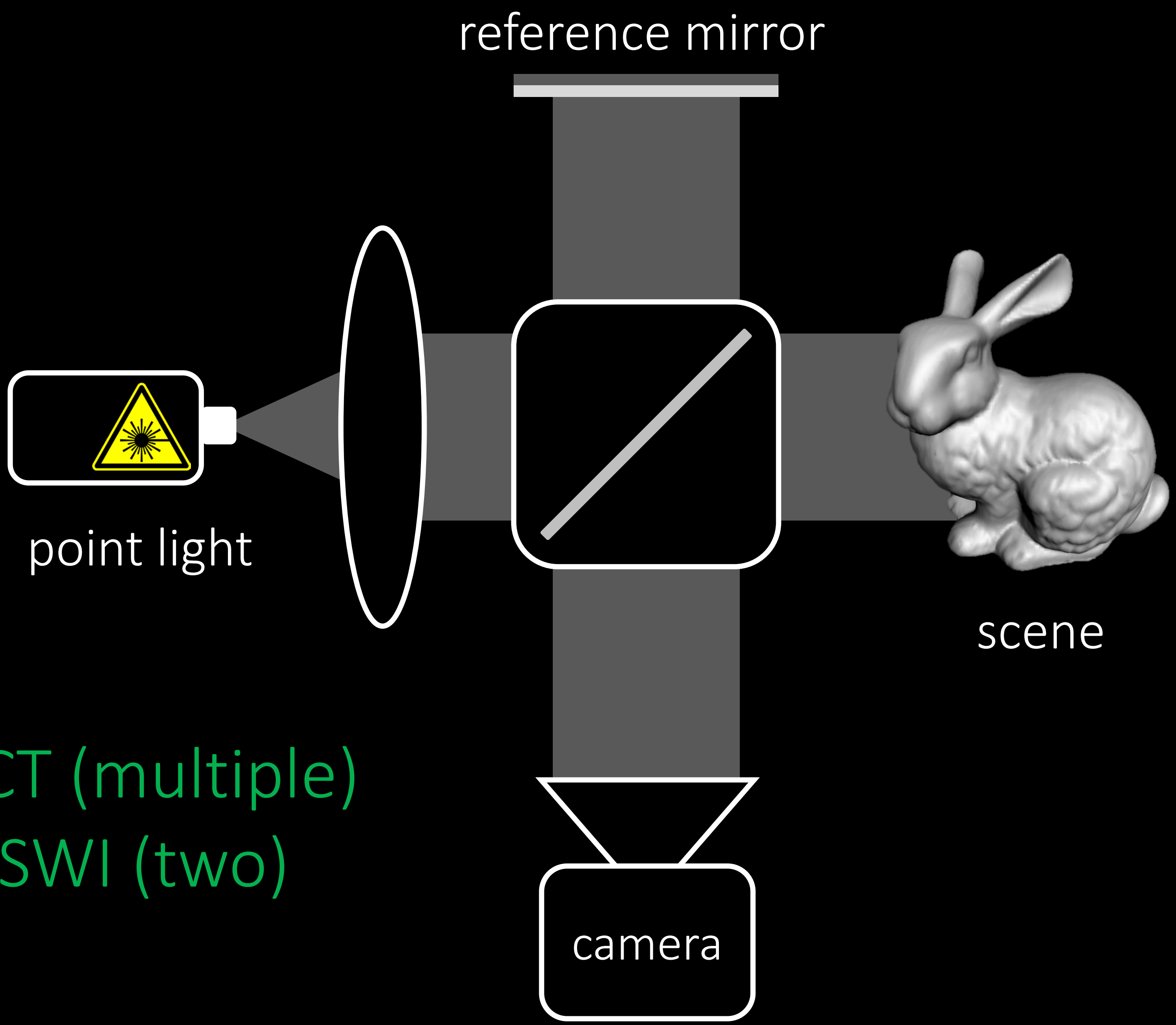
	full-field OCT	full-field SWI
depth range	constrained by reference translation	synthetic wavelength (separation between wavelengths)
phase wrapping	no	yes
depth resolution	spectral bandwidth	separation between wavelengths
scanning	axial proportional to depth range **OR** lateral proportional to scene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

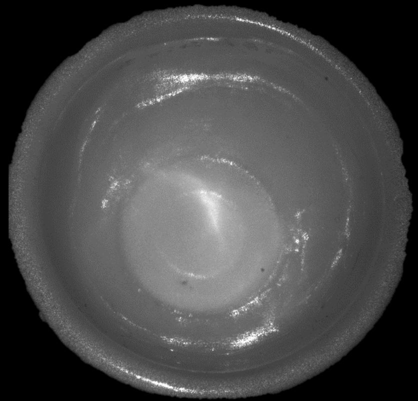
Fiber v/s full-field

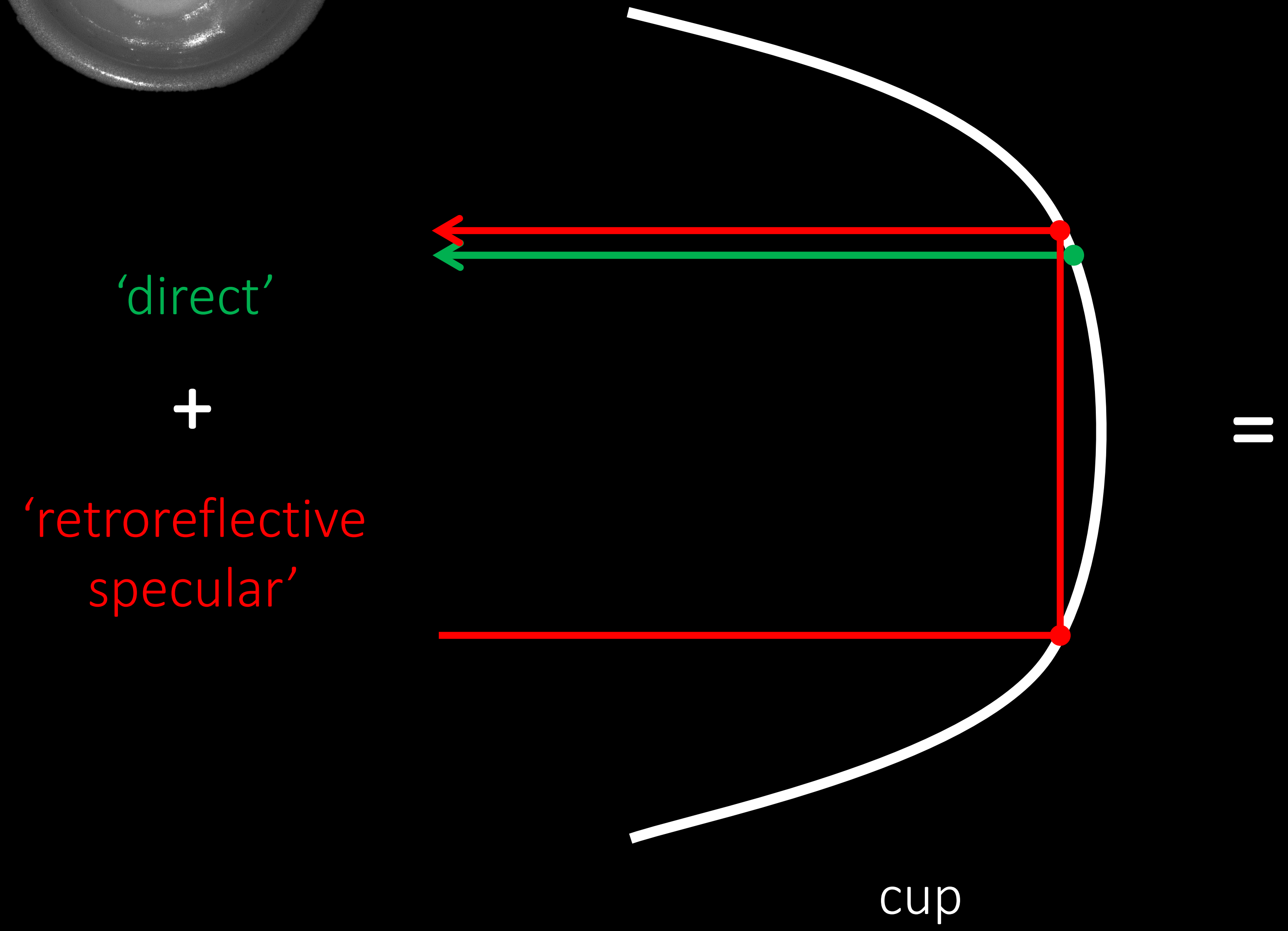


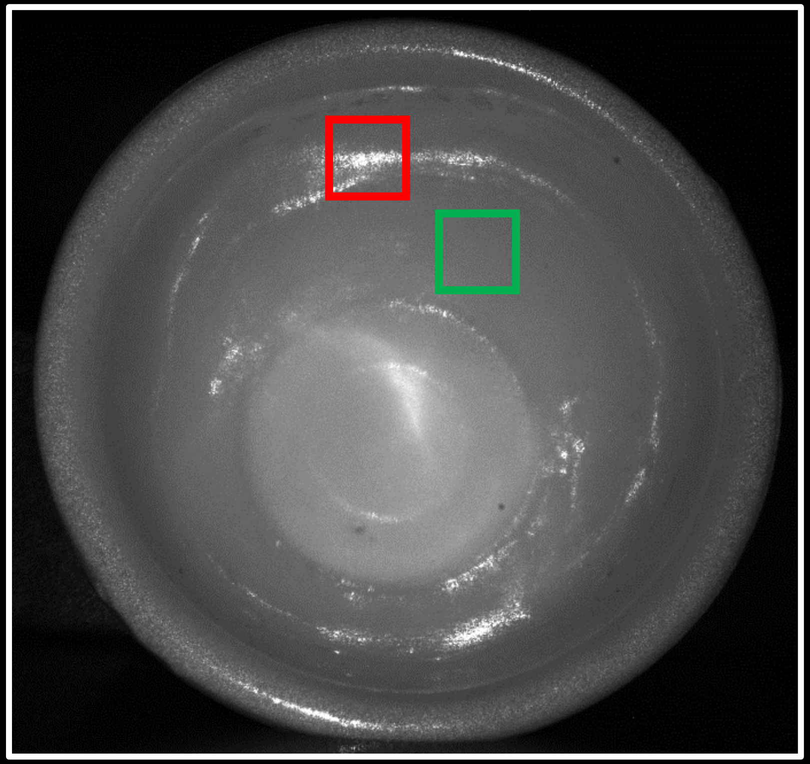


OCT (multiple)
SWI (two)

Cup: image formation

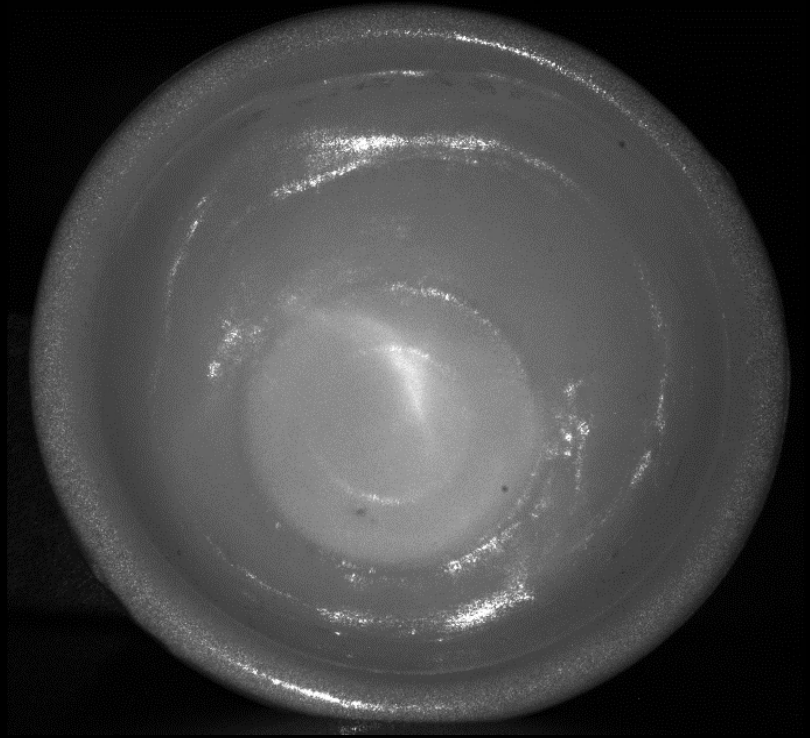


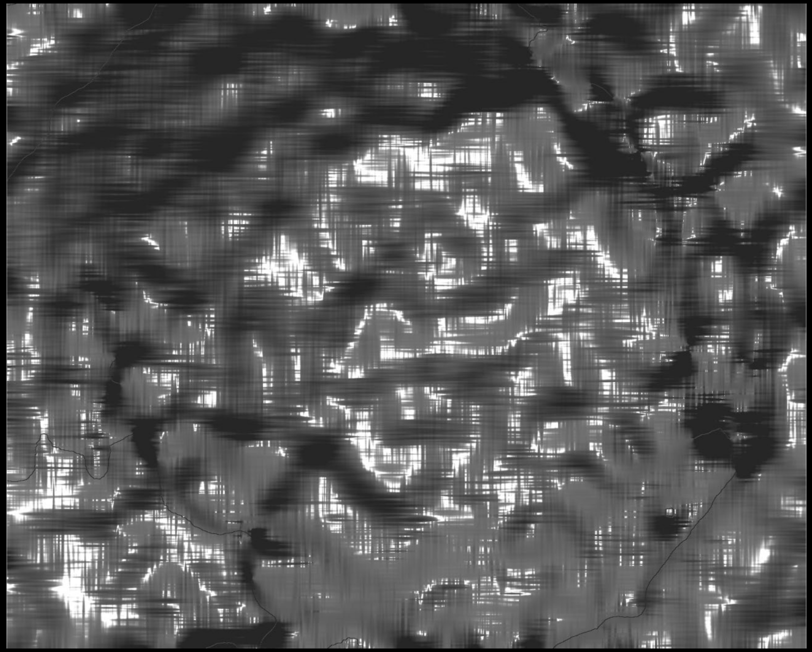




scene-only image

Depth corruption due to indirect light





depth corruption

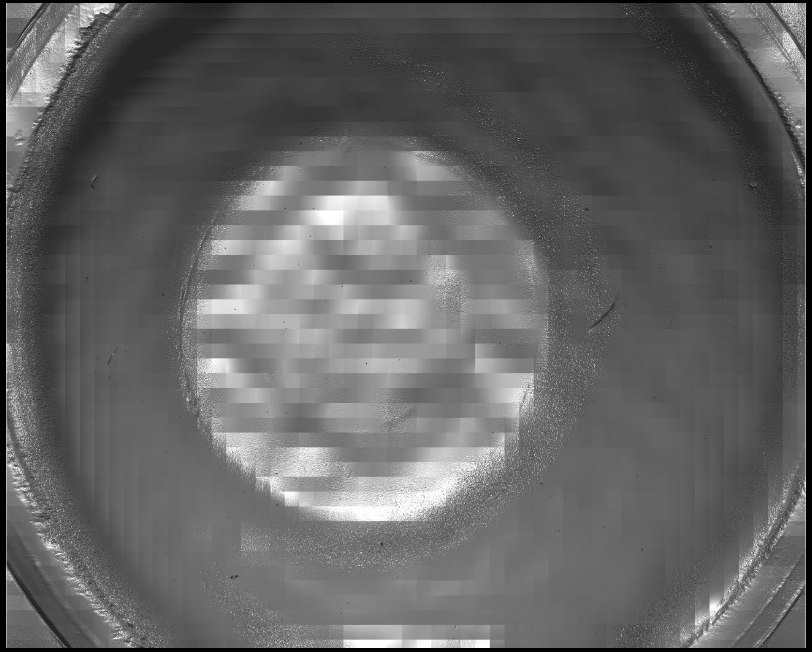
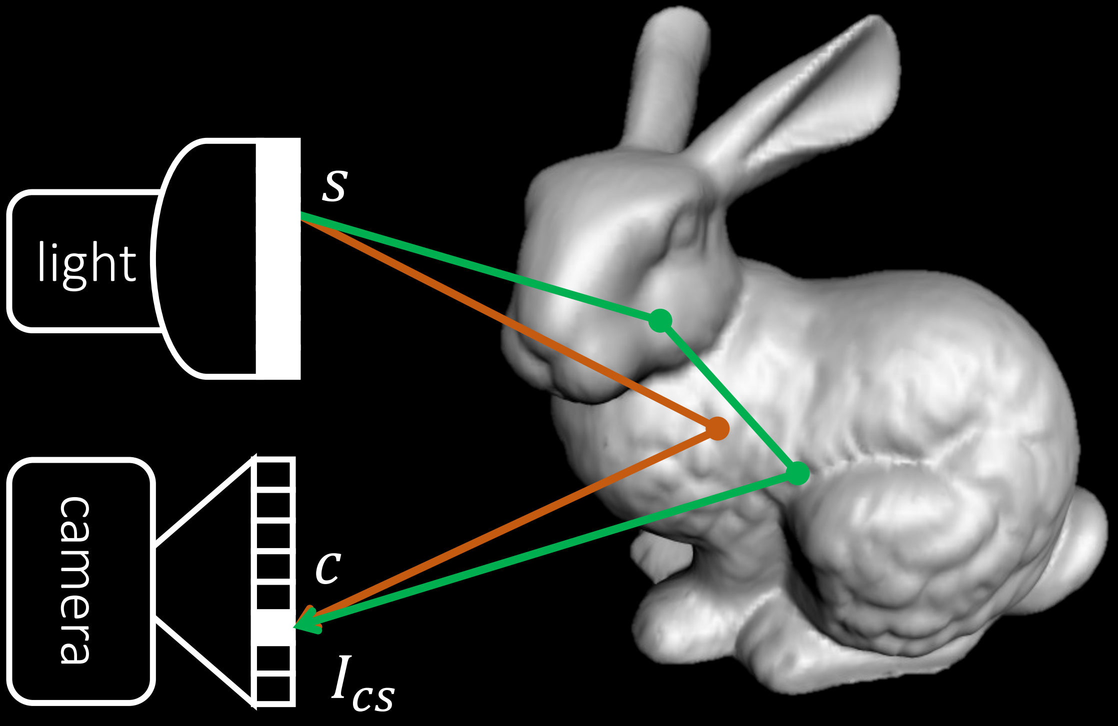
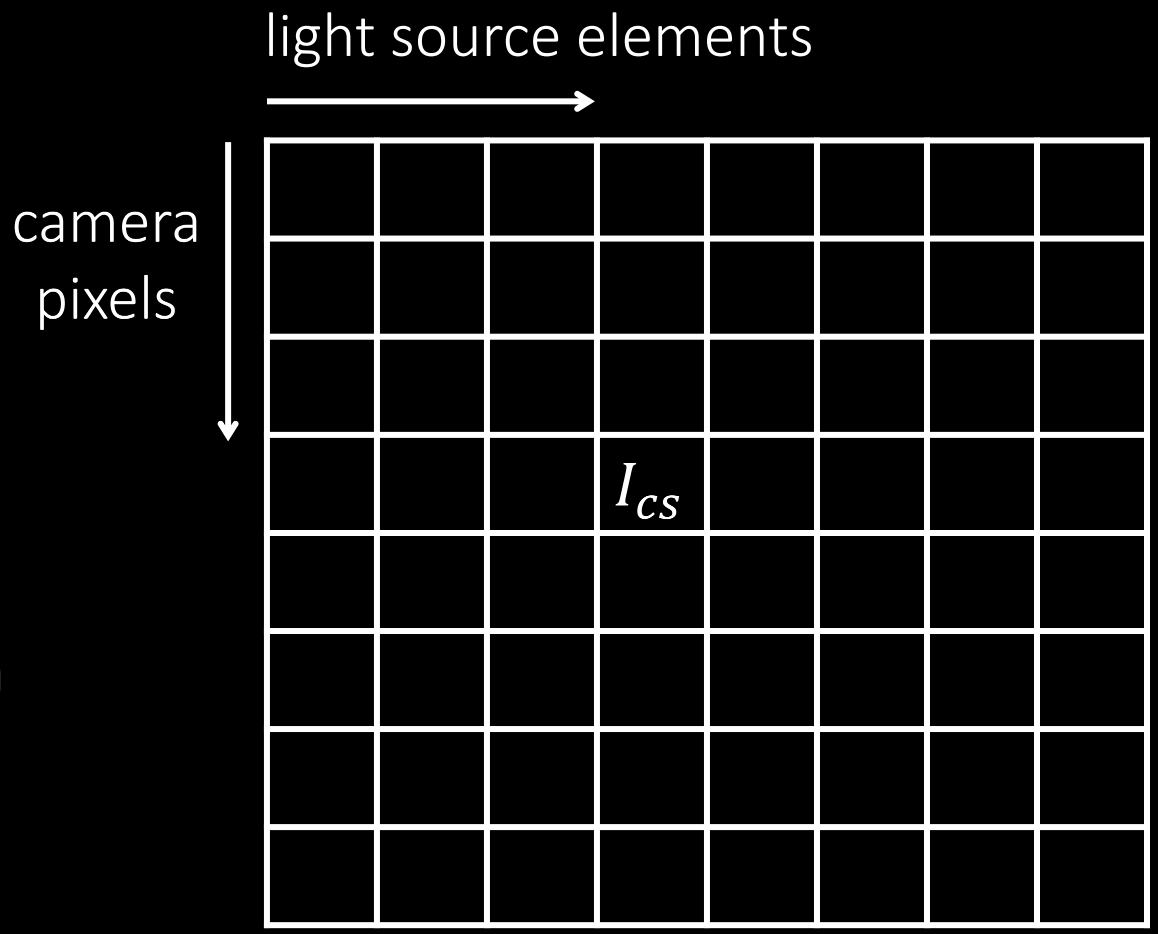


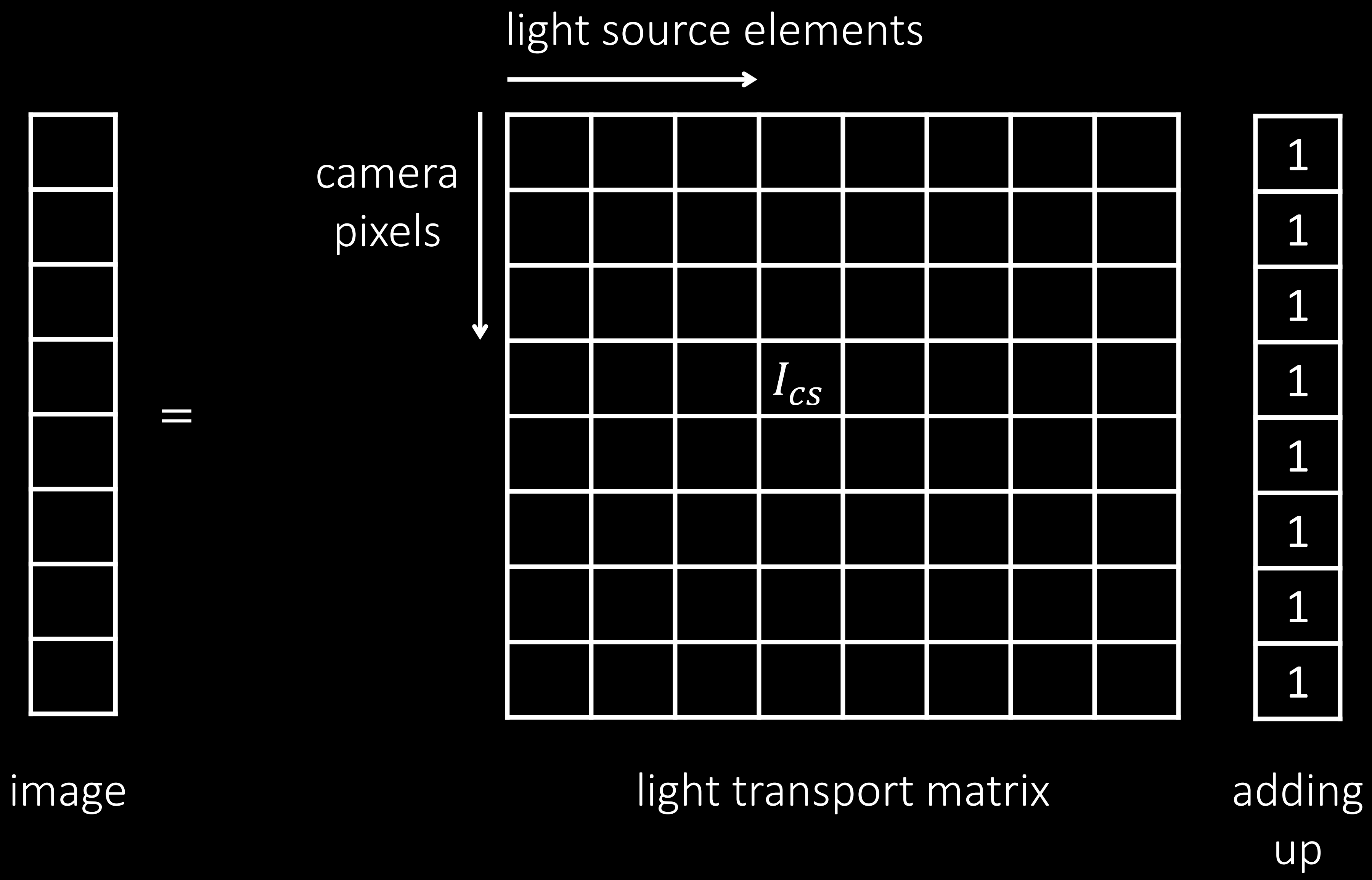
Image formation and light transport



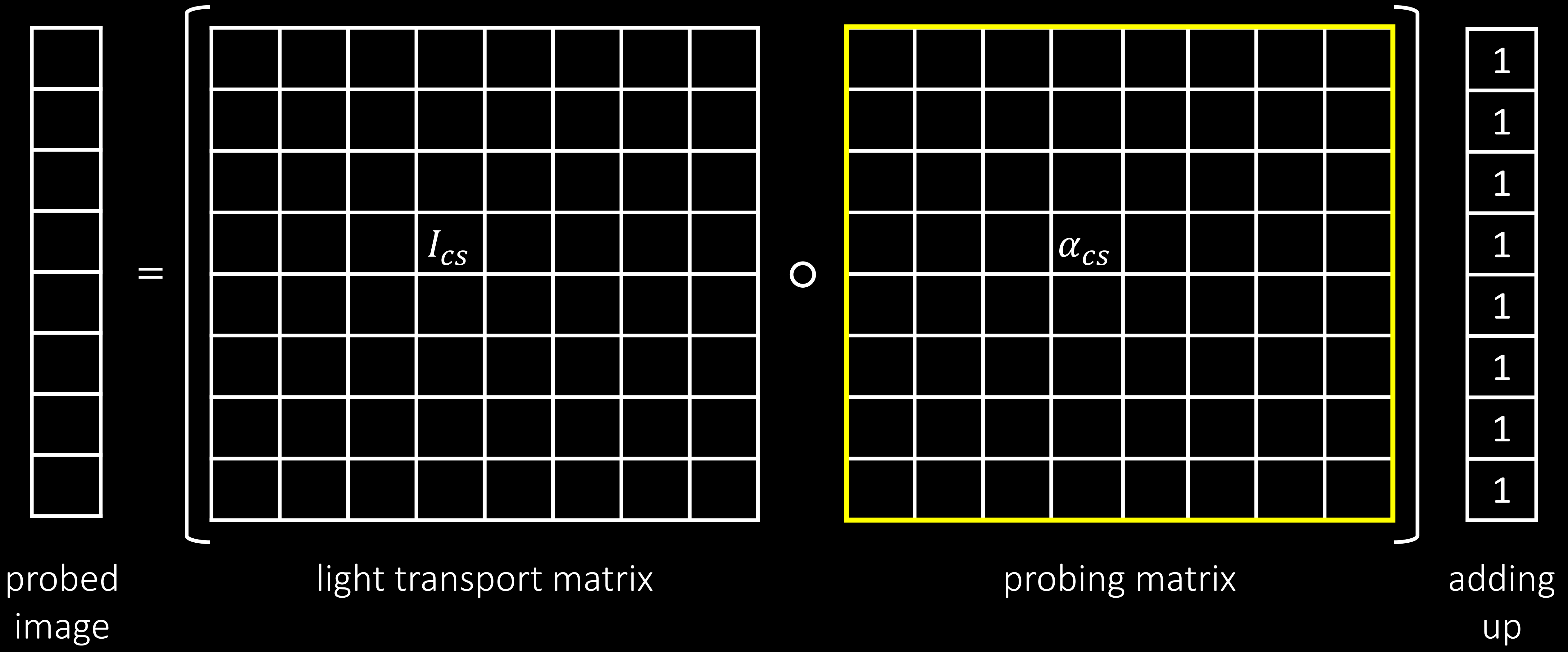


light transport matrix

Image formation and light transport



Probing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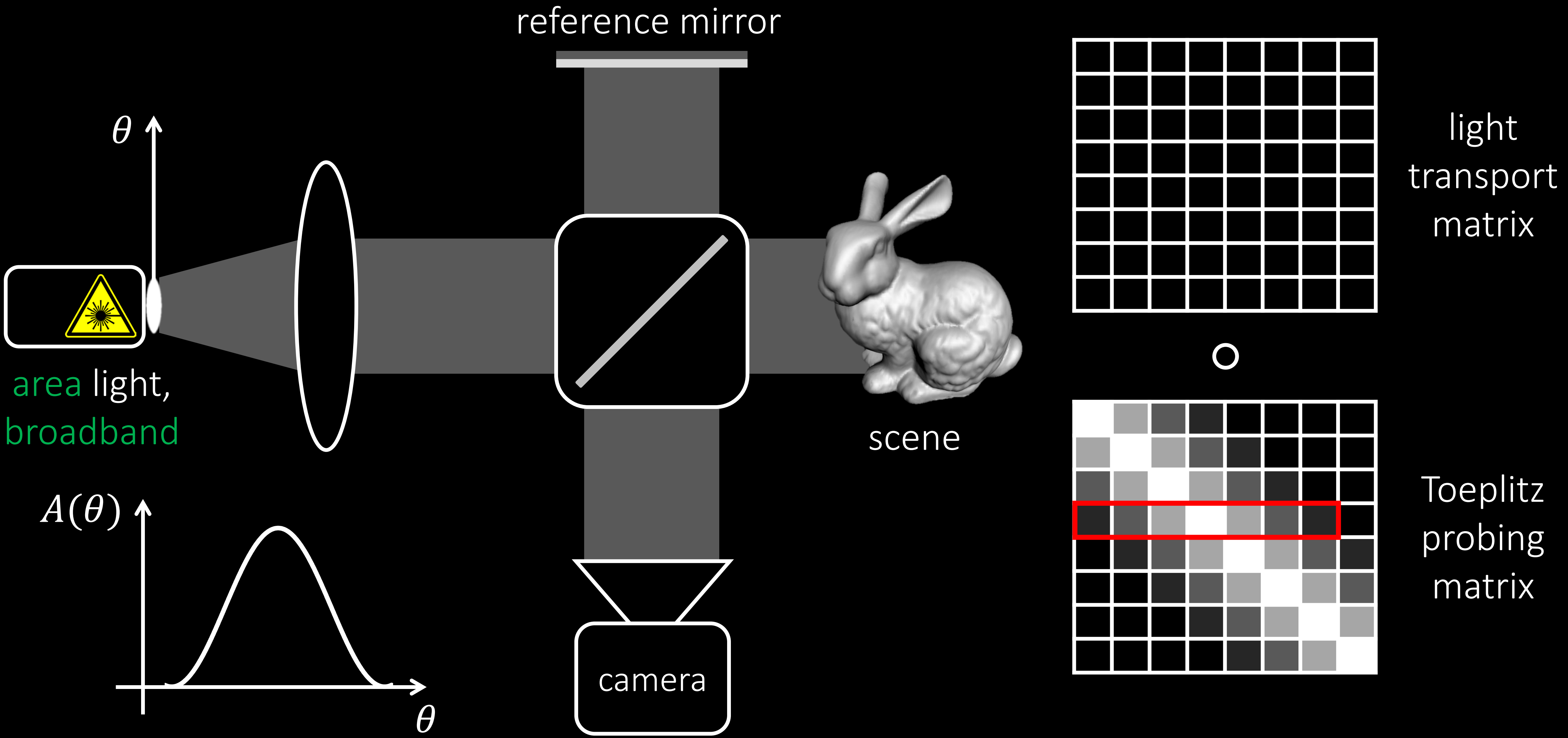
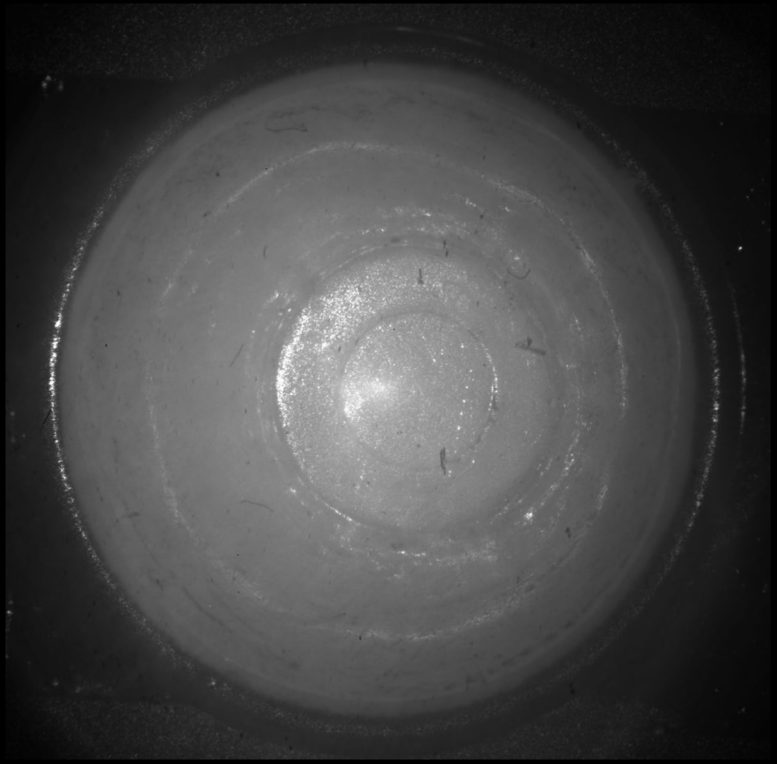
1
1
1
1
probed image
light transport matrix
probing matrix
adding up

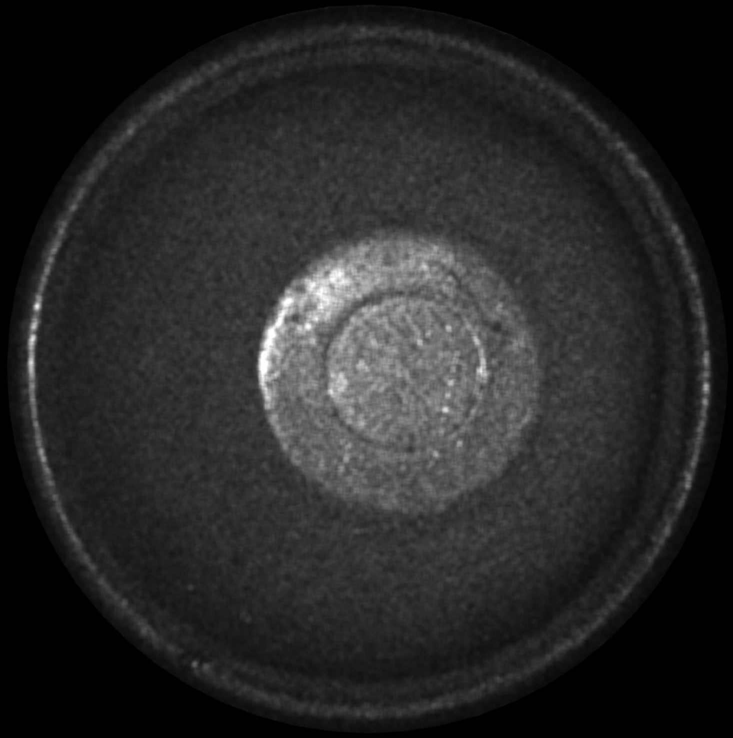
Interferometric probing



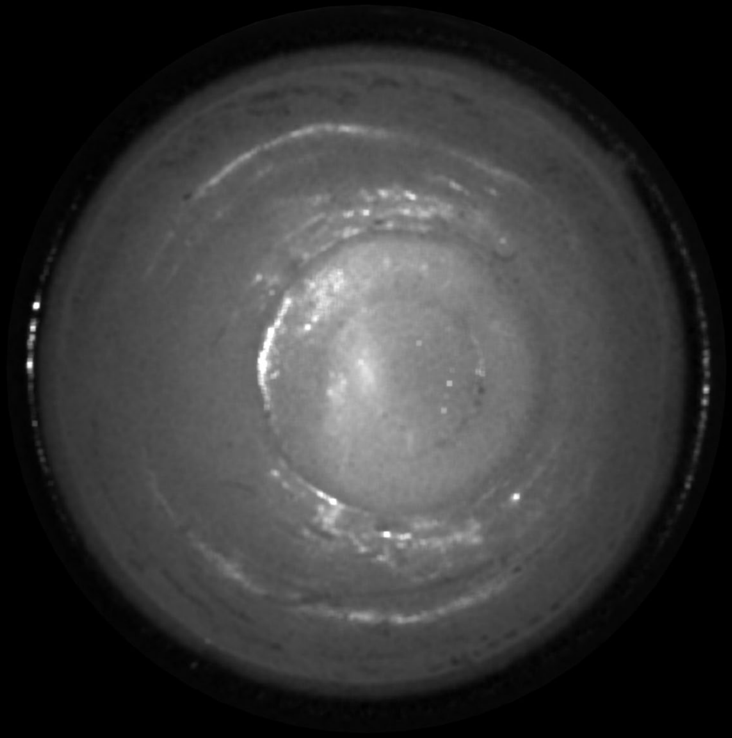
Direct-indirect separation



scene

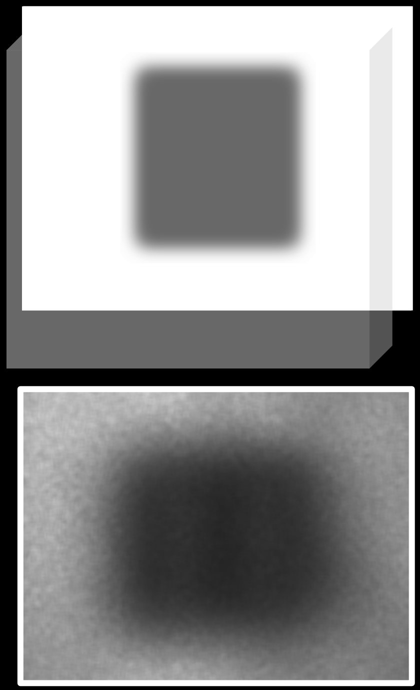


direct-only

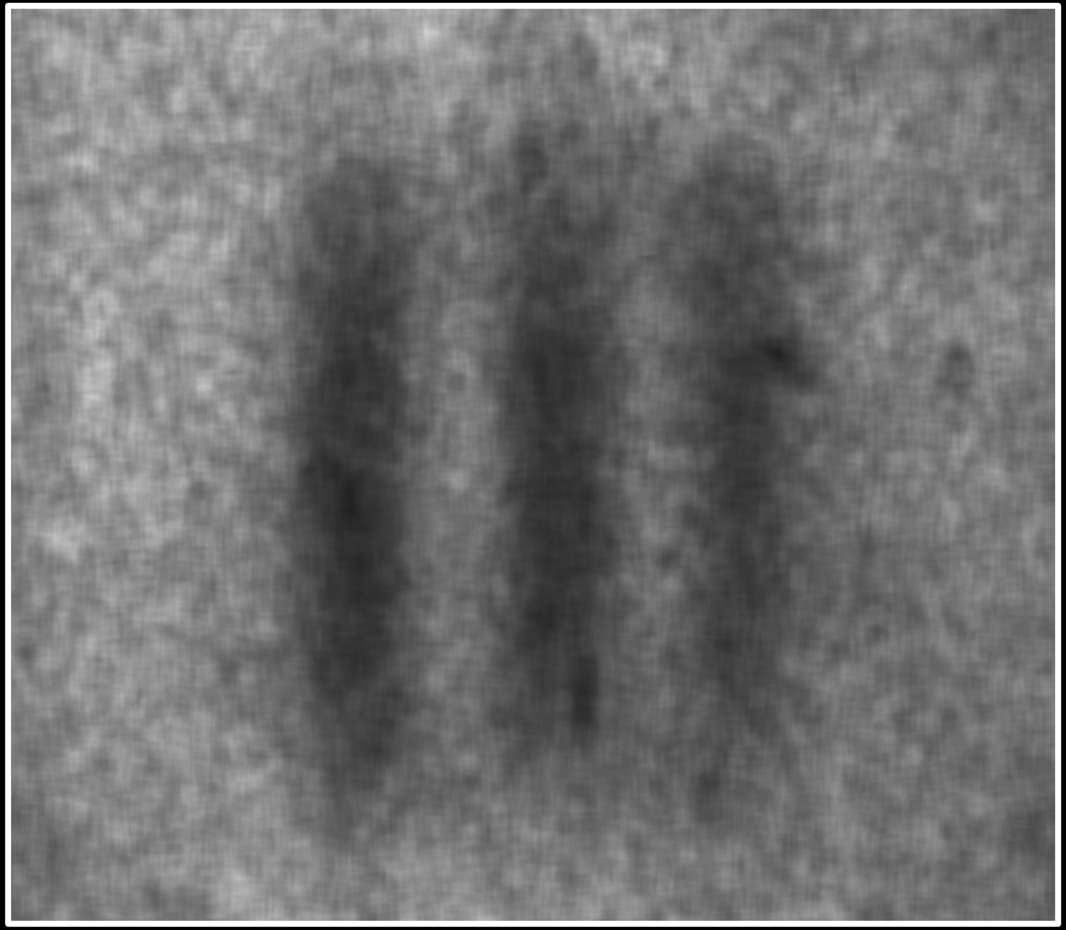


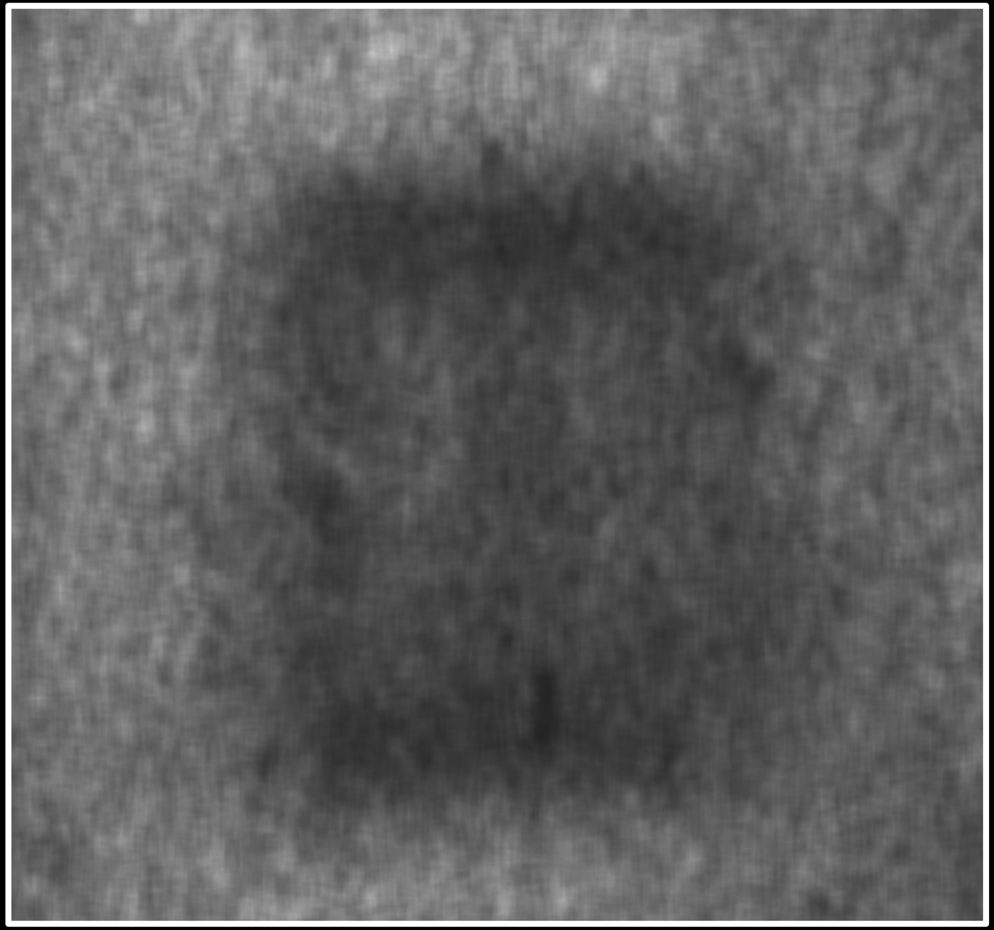
indirect-only

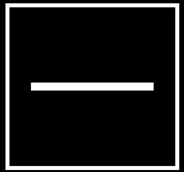
Seeing through scattering



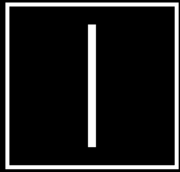
camera



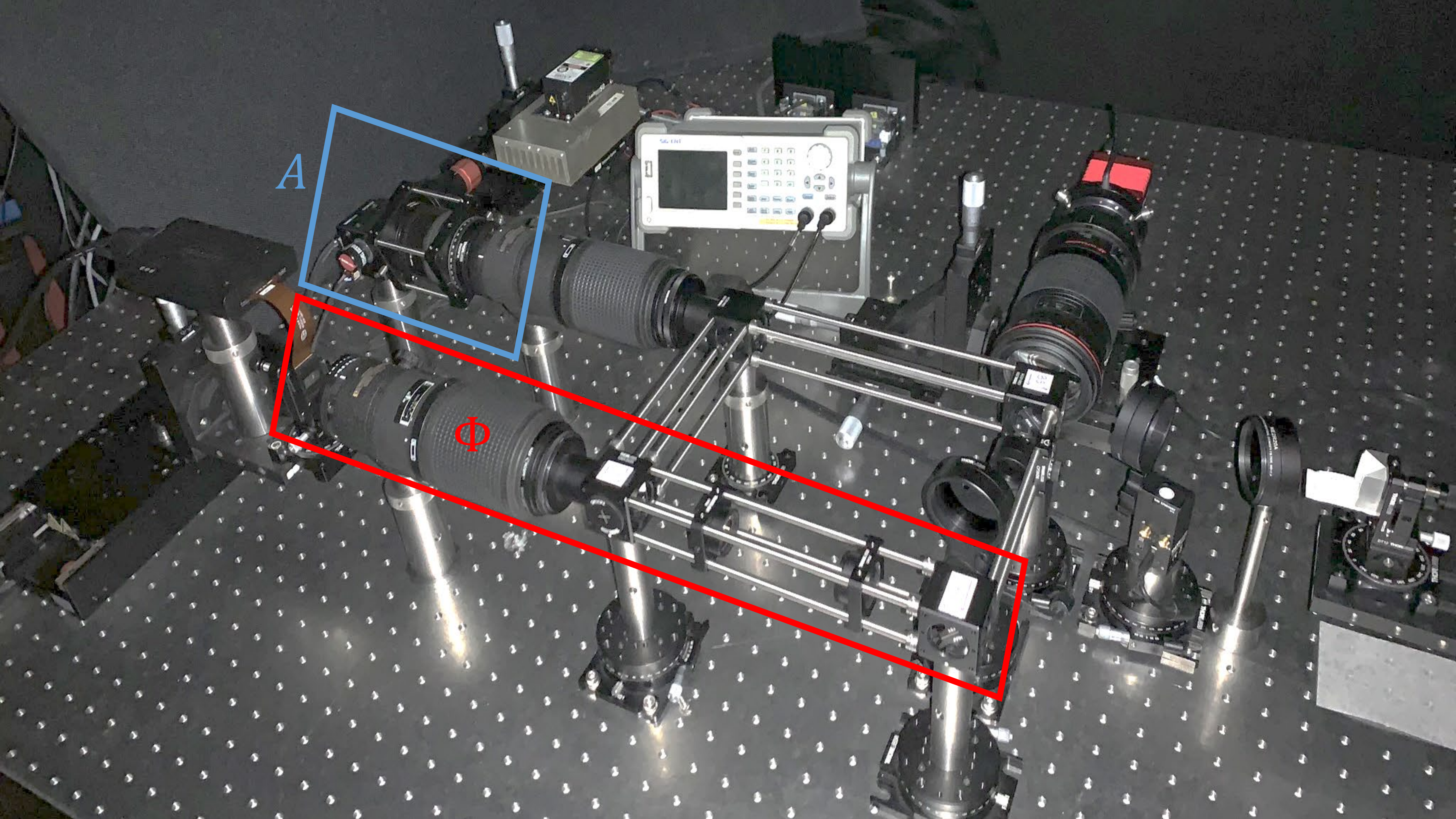




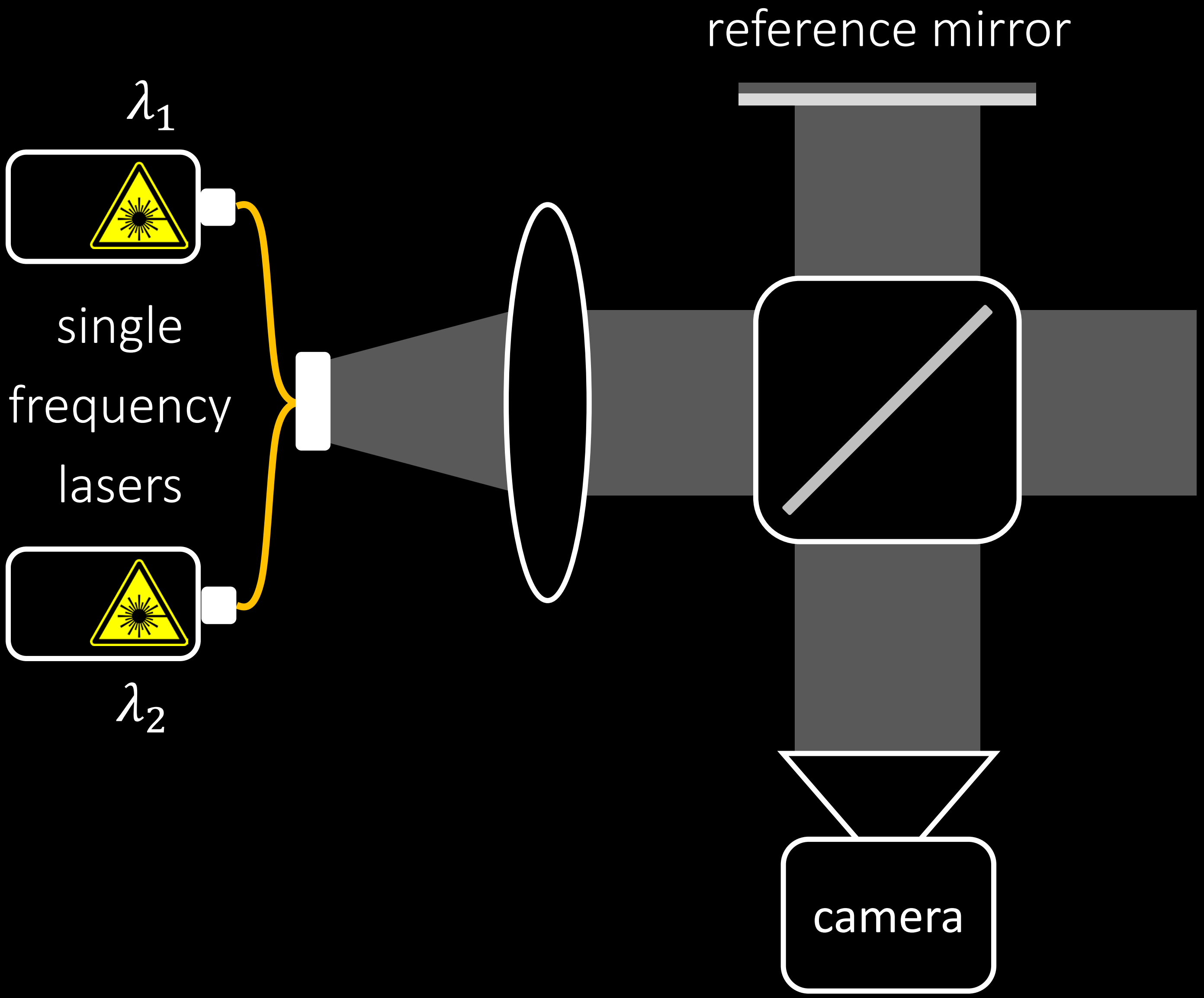
source

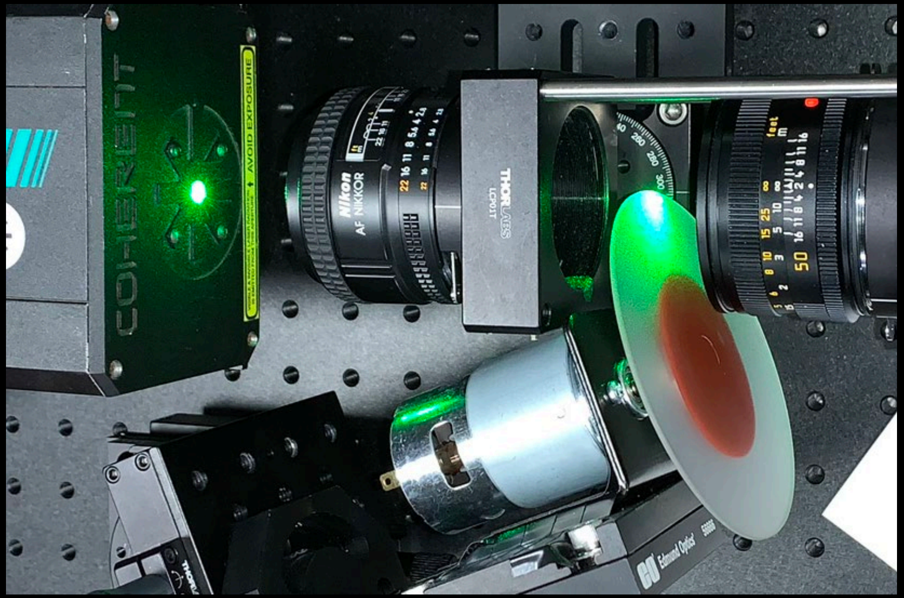


source


A
Φ

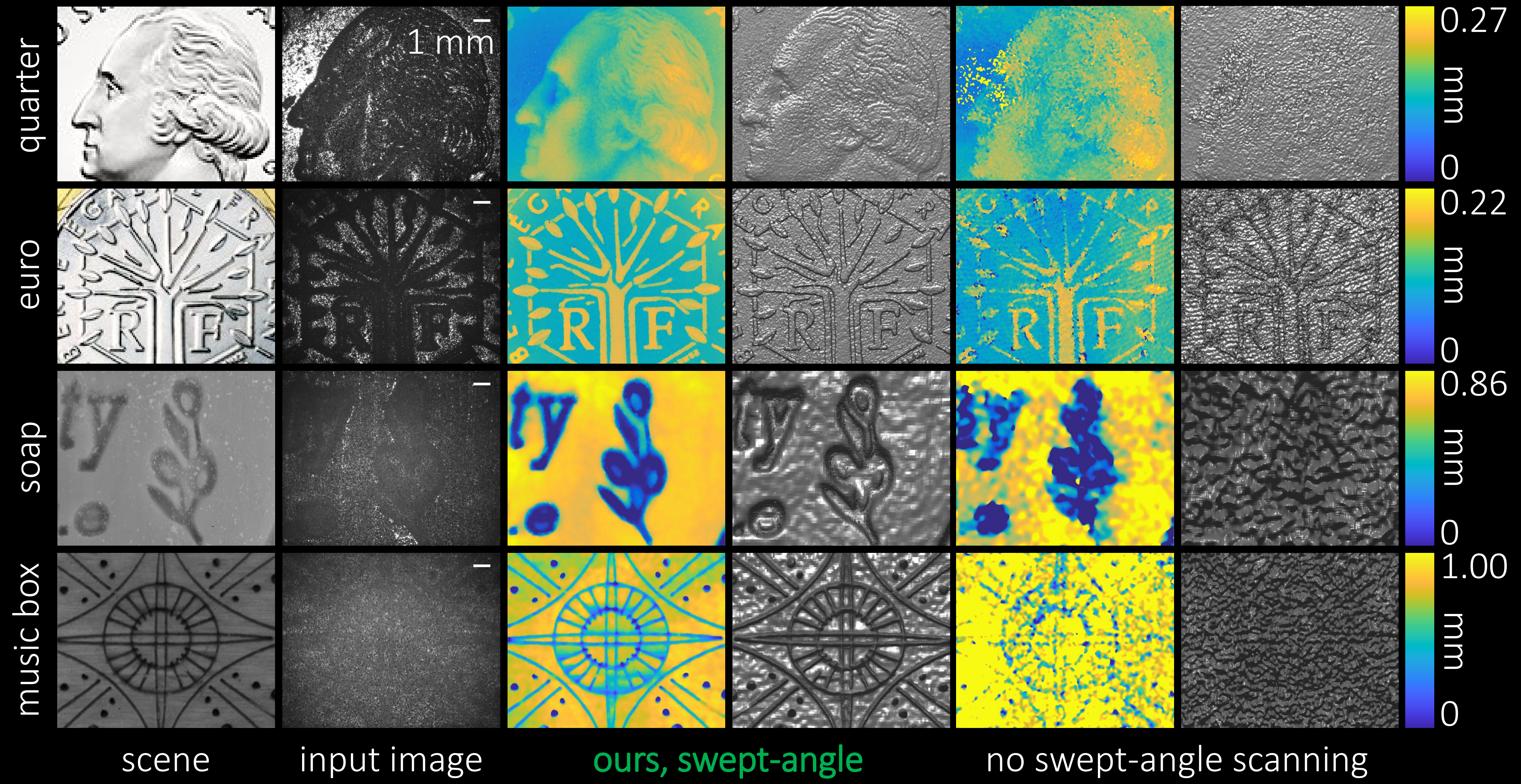
Dichromatic area light?



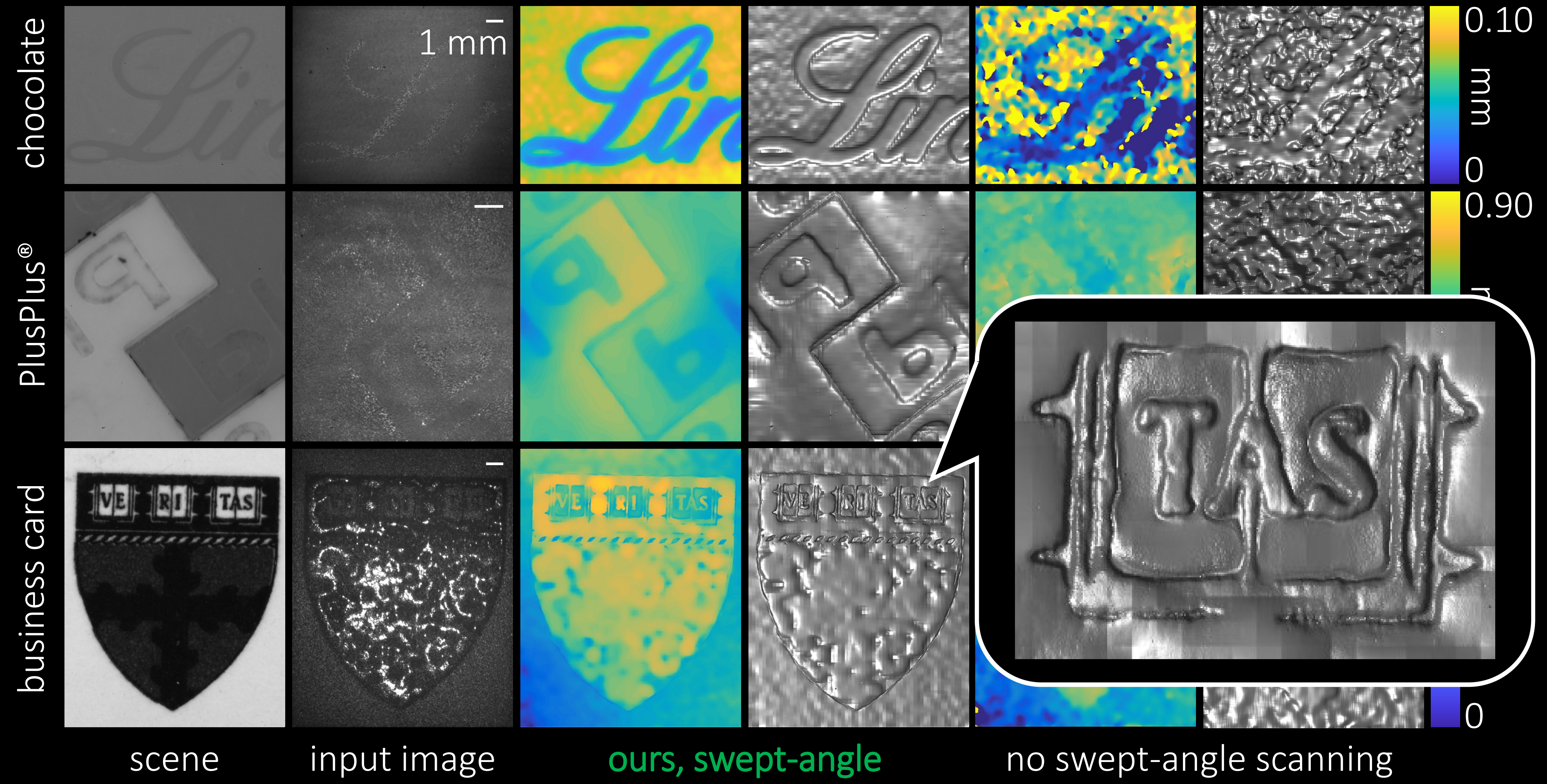


Swept-angle synthetic wavelength interferometry

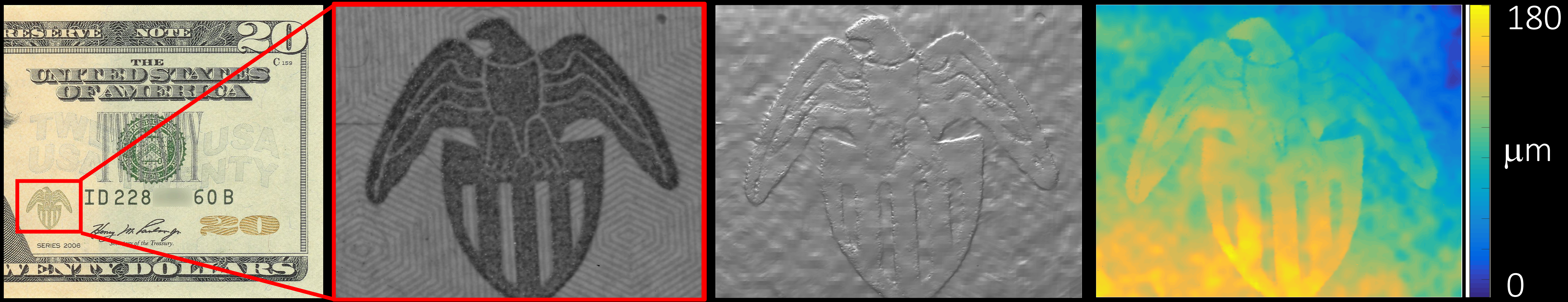
Swept-angle SWI results: 1 mm depth range



Swept-angle SWI results: 1 mm depth range

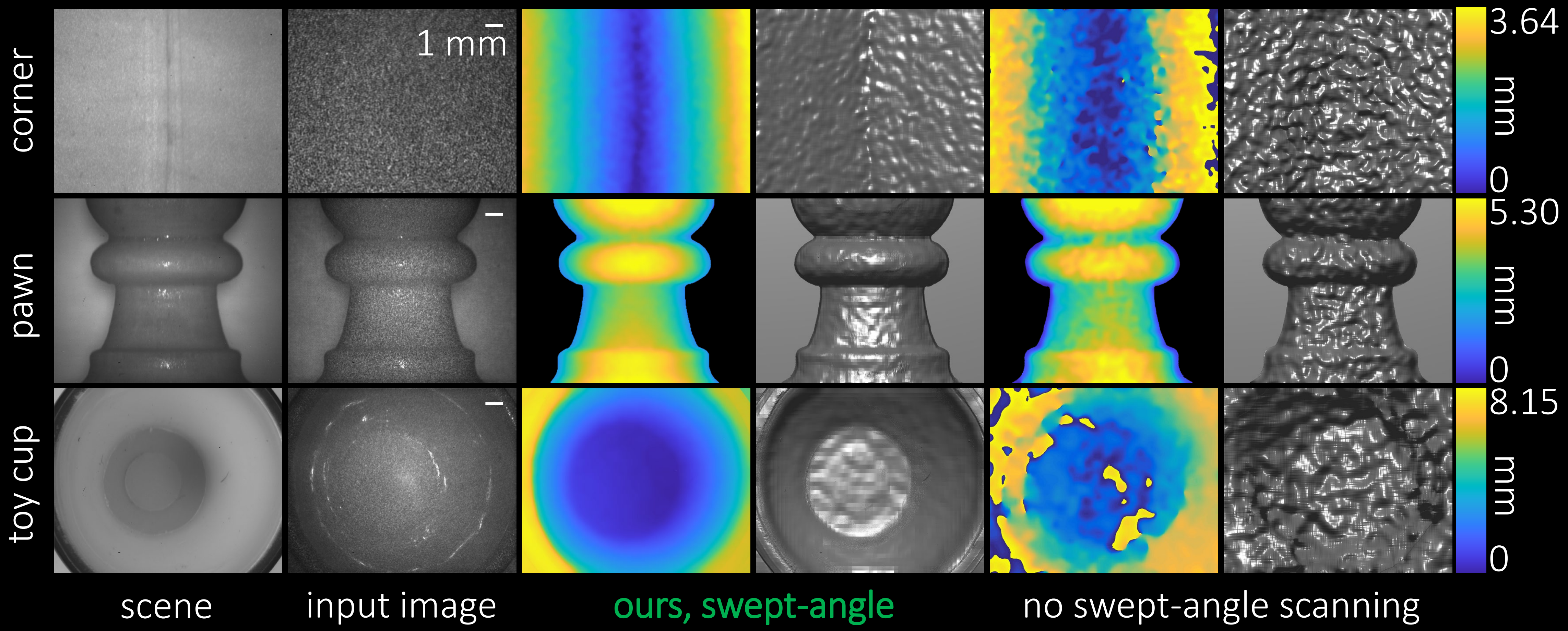


Swept-angle SWI results: $20 bill eagle



dollar bill — scene — recovered depth surface — recovered depth map

Swept-angle SWI results: 1 cm depth range



Applications: industrial inspection

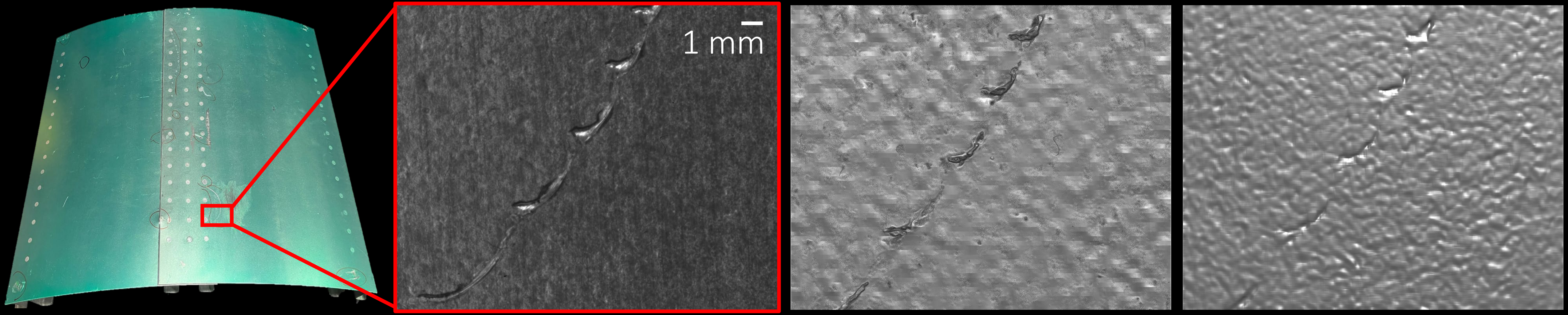
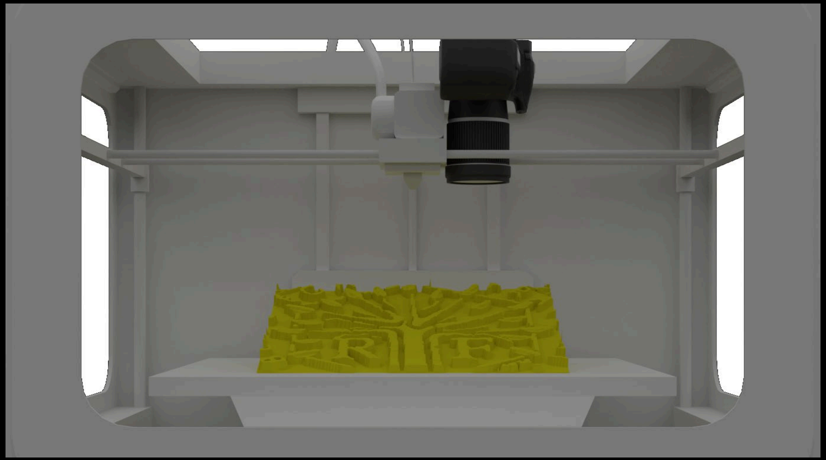


photo of scanned object | image of scanned scene | ours, swept-angle | without swept-angle



Applications: precision fabrication

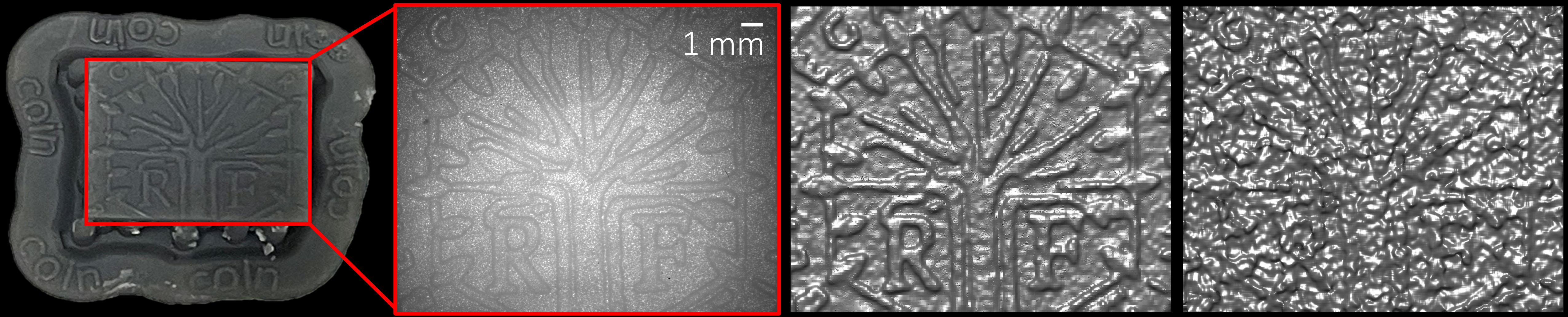
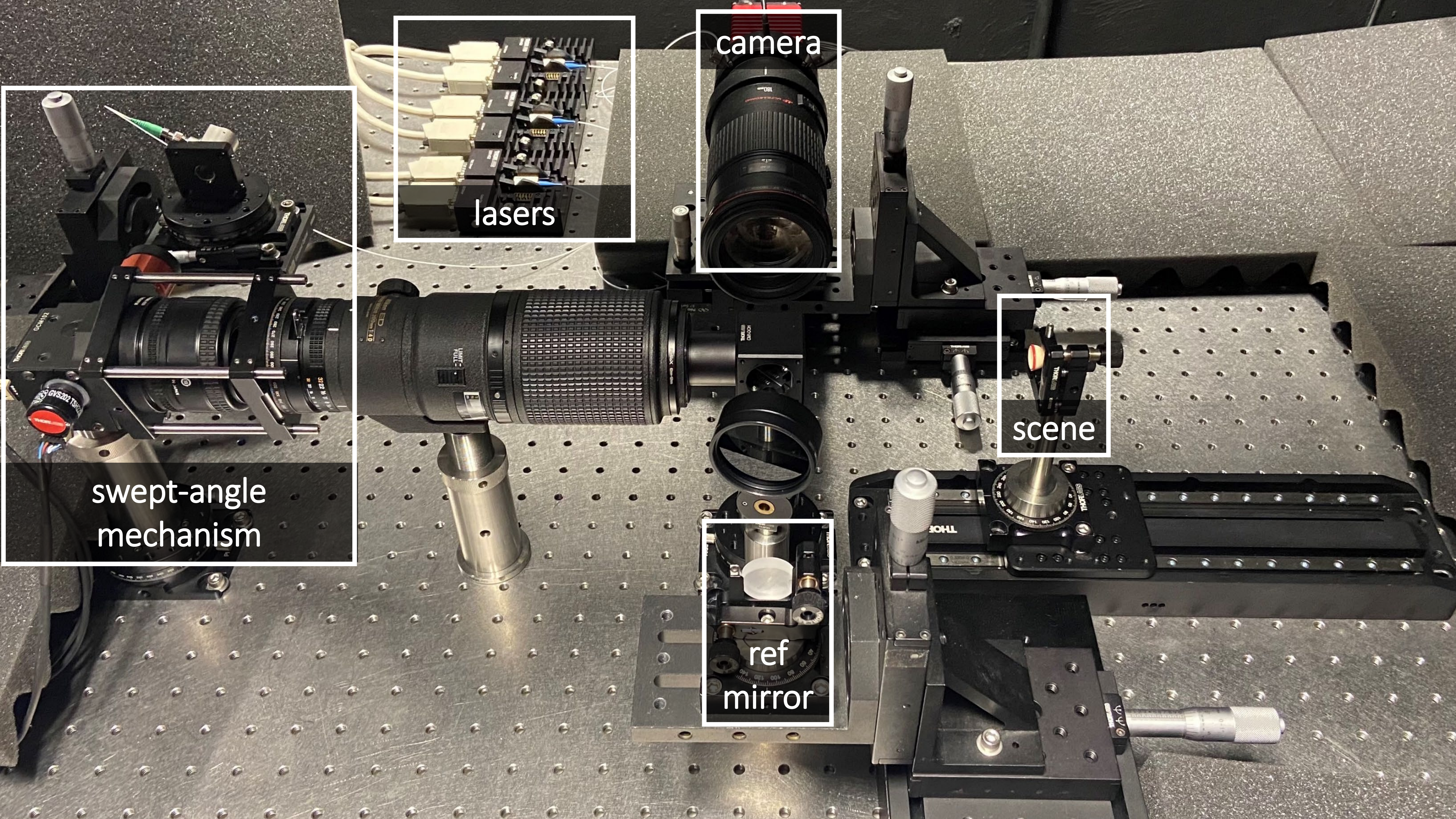
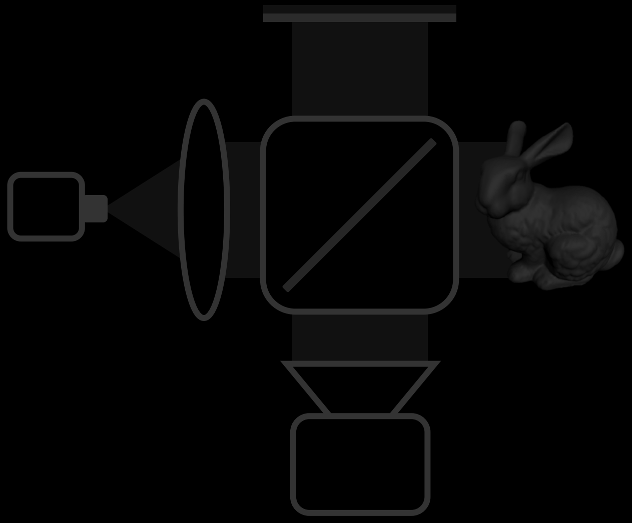


photo of scanned object | image of scanned scene | ours, swept-angle | without swept-angle


lasers
camera
swept-angle
mechanism
scene
ref
mirror

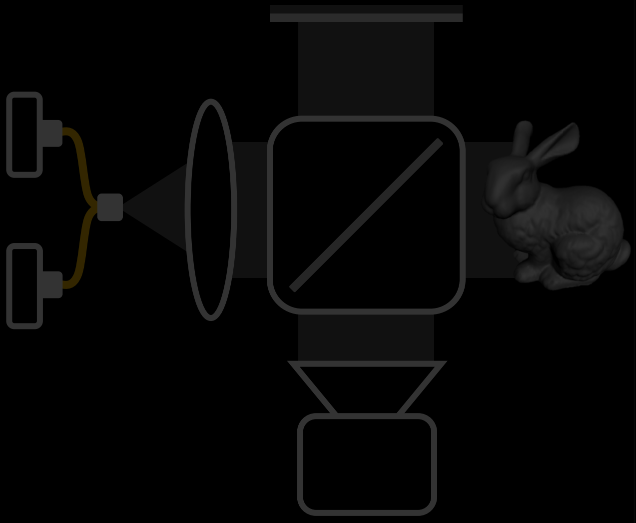
Course overview

introduction to interferometry



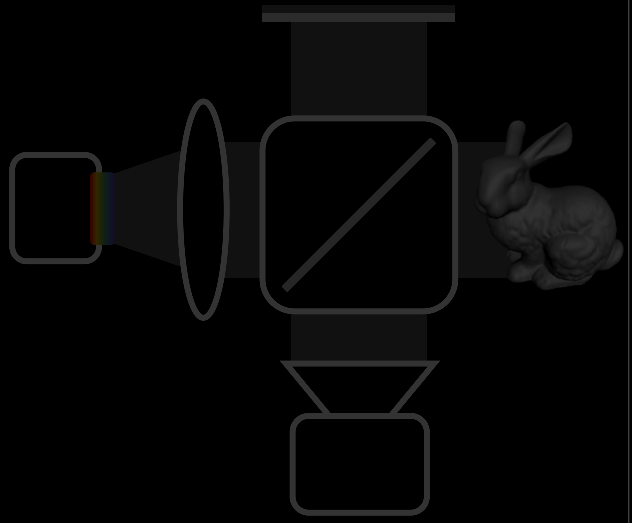
Yannis

two-wavelength interferometry



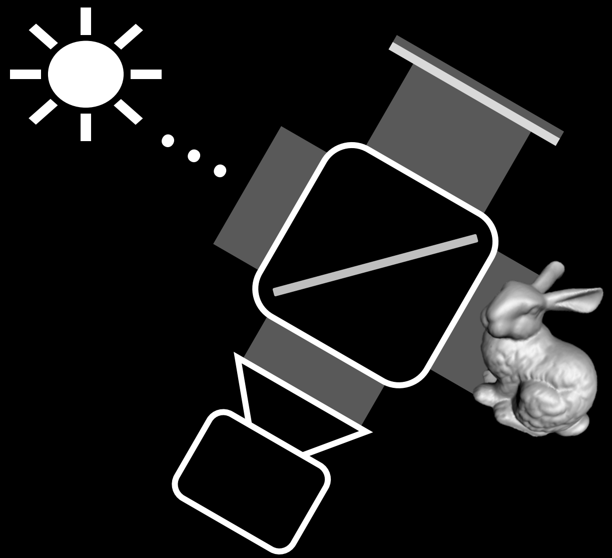
Florian

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

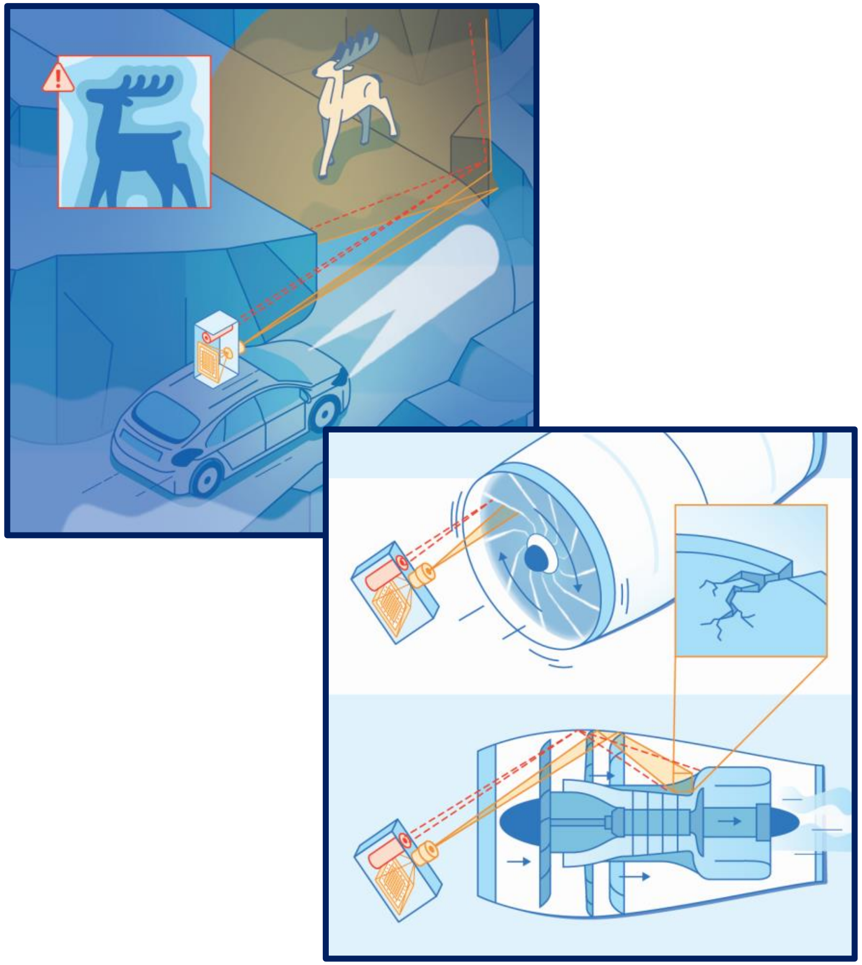
https://www.optics.arizona.edu/3dim

3DIM Lab
Computational 3D Imaging and Measurement Lab
Prof. Florian Willomitzer

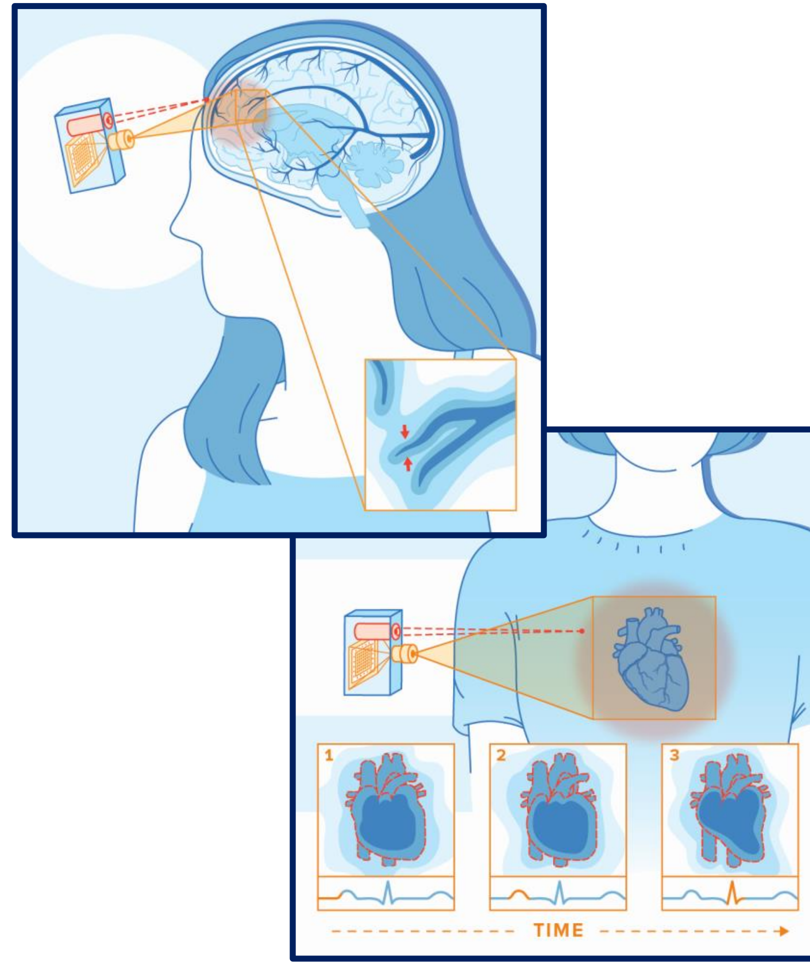
THE UNIVERSITY OF ARIZONA
Wyant College of Optical Sciences

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 ligth

RECAP

$$\delta z \propto \lambda$$

depth error

modulation wavelength

Conventional Interferometry (single Wavelength)

Speckle for scattering scenes

Dual-Wavelength Interferometry

"ToF Cameras" (CW or pulsed)

Poor resolution

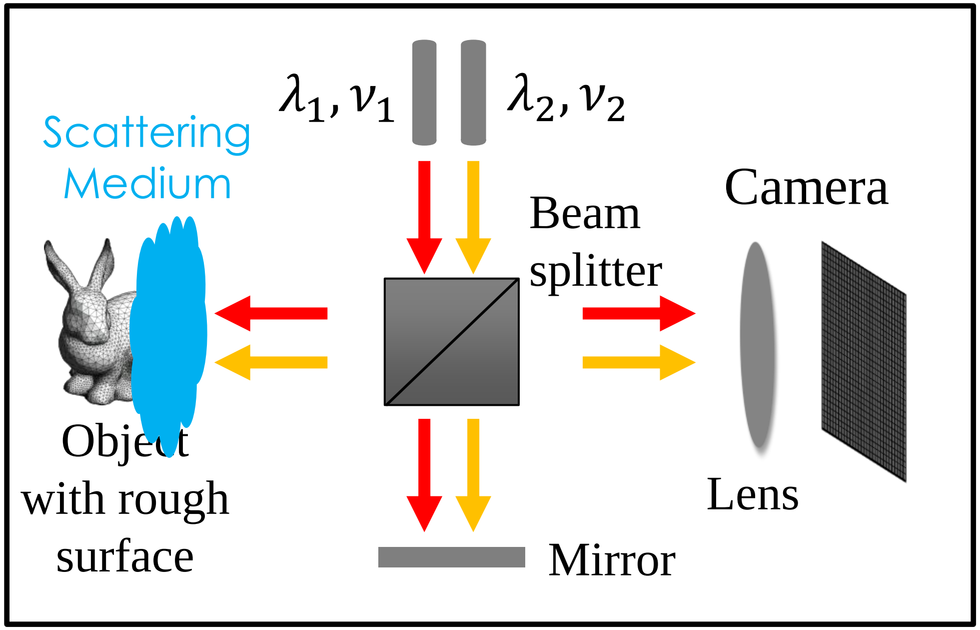
$\sim \mu m$ $\sim 10cm$ λ

High-precision "ToF Camera"

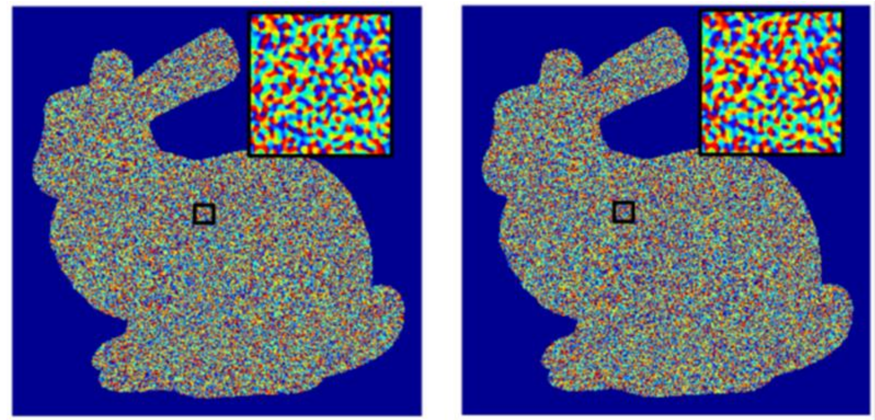
RECAP

$\ldots i\phi(\lambda_1)$

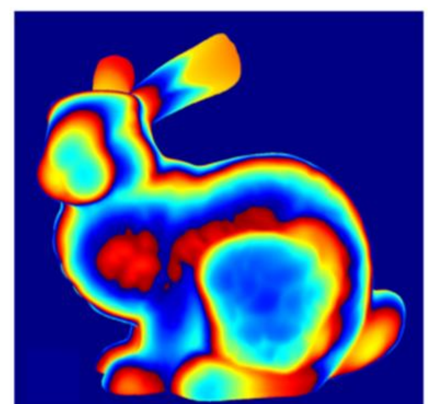
$E(\lambda_2) = A_2 \ldots$



$\boldsymbol{\phi(\lambda_1)}$ $\boldsymbol{\phi(\lambda_2)}$



$\boldsymbol{\phi(\Lambda)}$

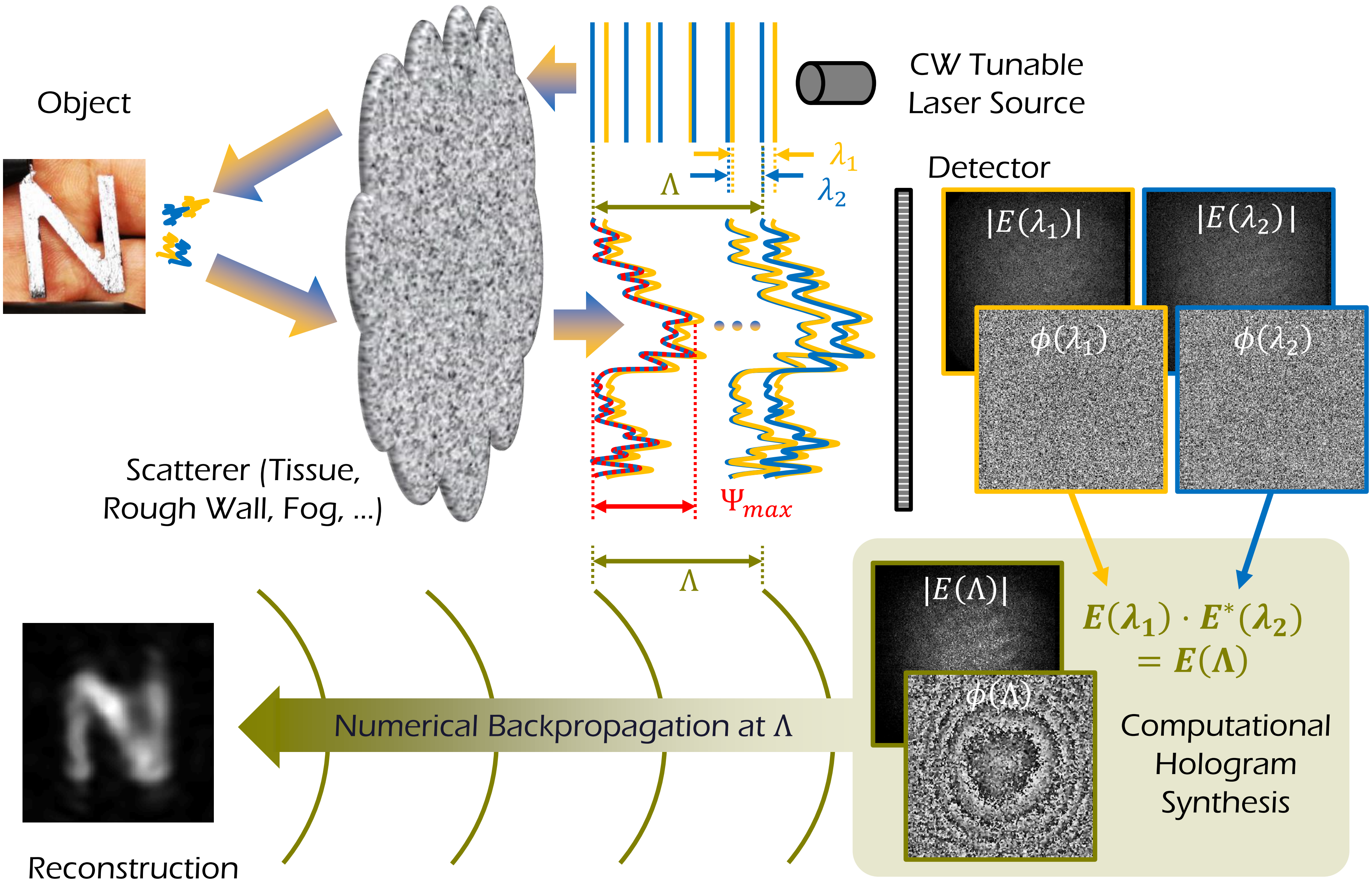


$$E(\Lambda) = E(\lambda_1) \cdot E^*(\lambda_2)$$
$$= A_1 A_2 \cdot \exp(i(\phi(\lambda_1) - \phi(\lambda_2)))$$

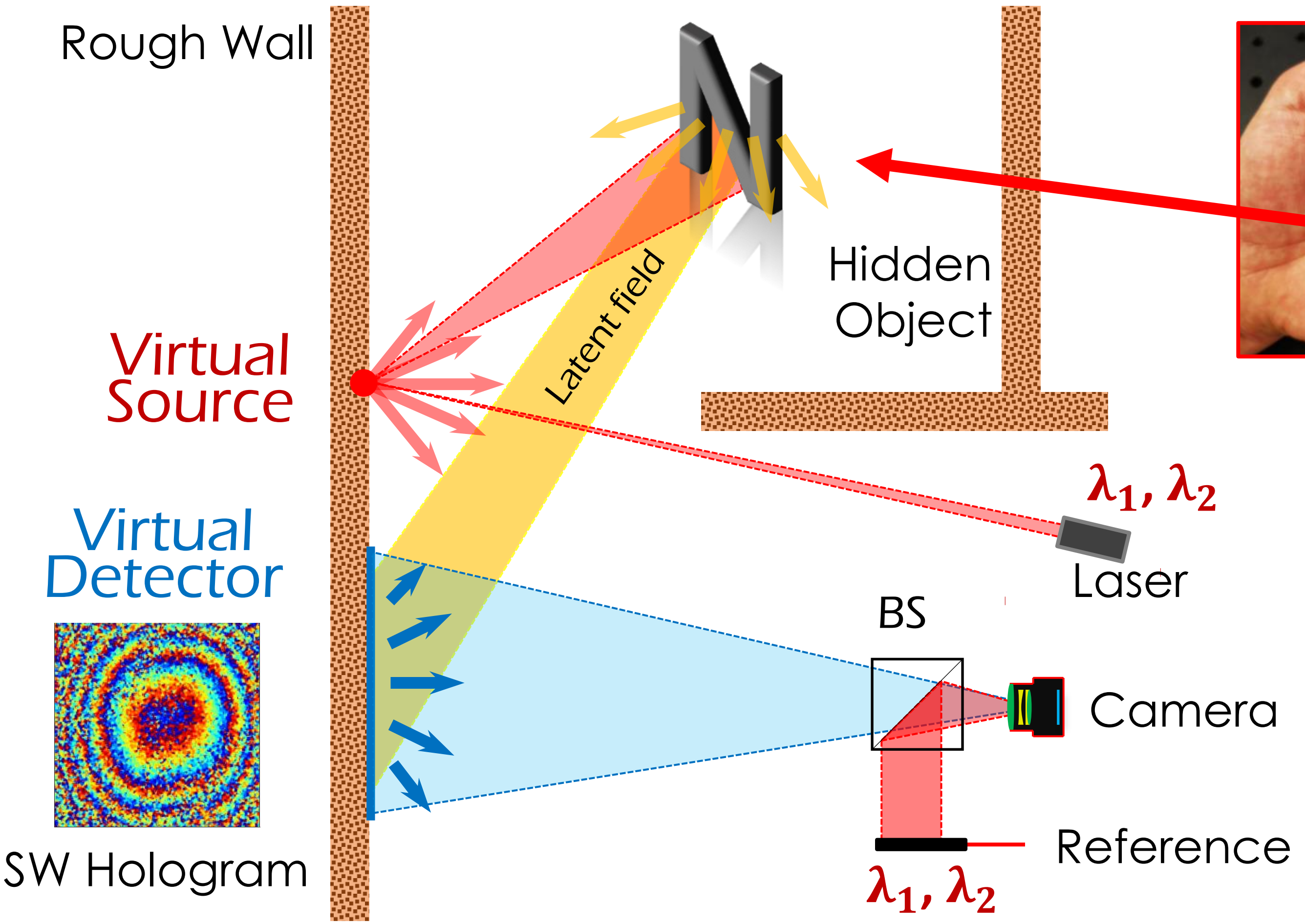
F. Li*, F. Willomitzer*, M. Balaji, P. Rangarajan, O. Cossairt, Exploiting Wavelength Diversity for High Resolution Time-of-Flight 3D Imaging, IEEE Transactions on Pattern Analysis and Machine Intelligence (TPAMI), 2021

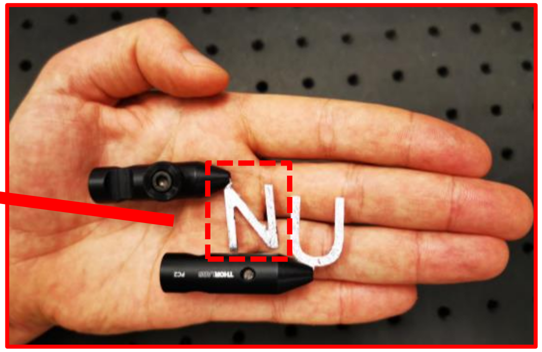
Synthetic Wavelength Holography

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

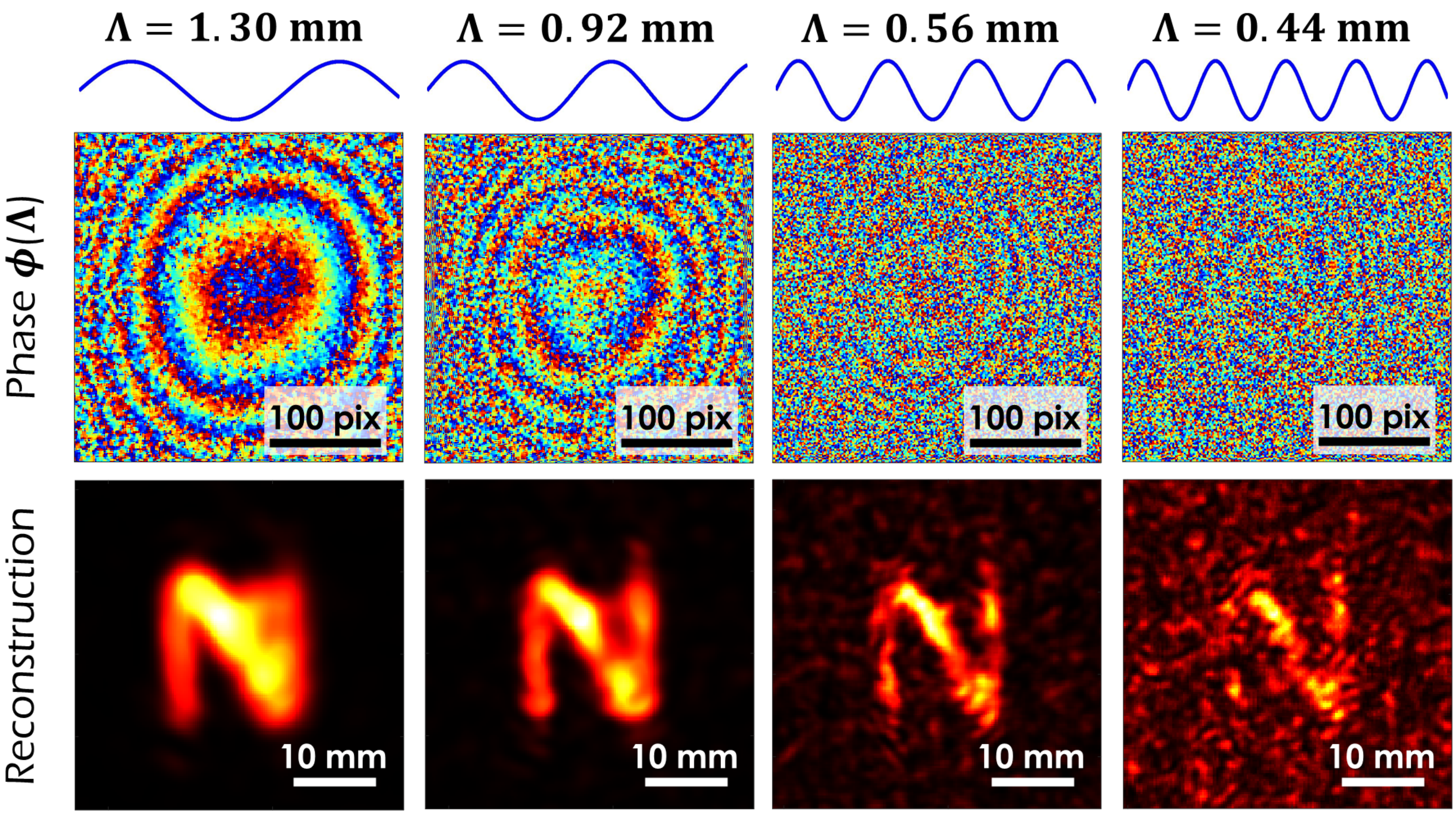


Experiment: Looking around corners





Imaging around corners at multiple SWLs



Fundamental limit

Where is the limit?

Tunable!

Fundamental limit: $\boxed{\Lambda \geq 4\,\Psi_{max}}$ *

How to estimate the performance of our system?

Space-Bandwidth Product (SBP):

Field of view width

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

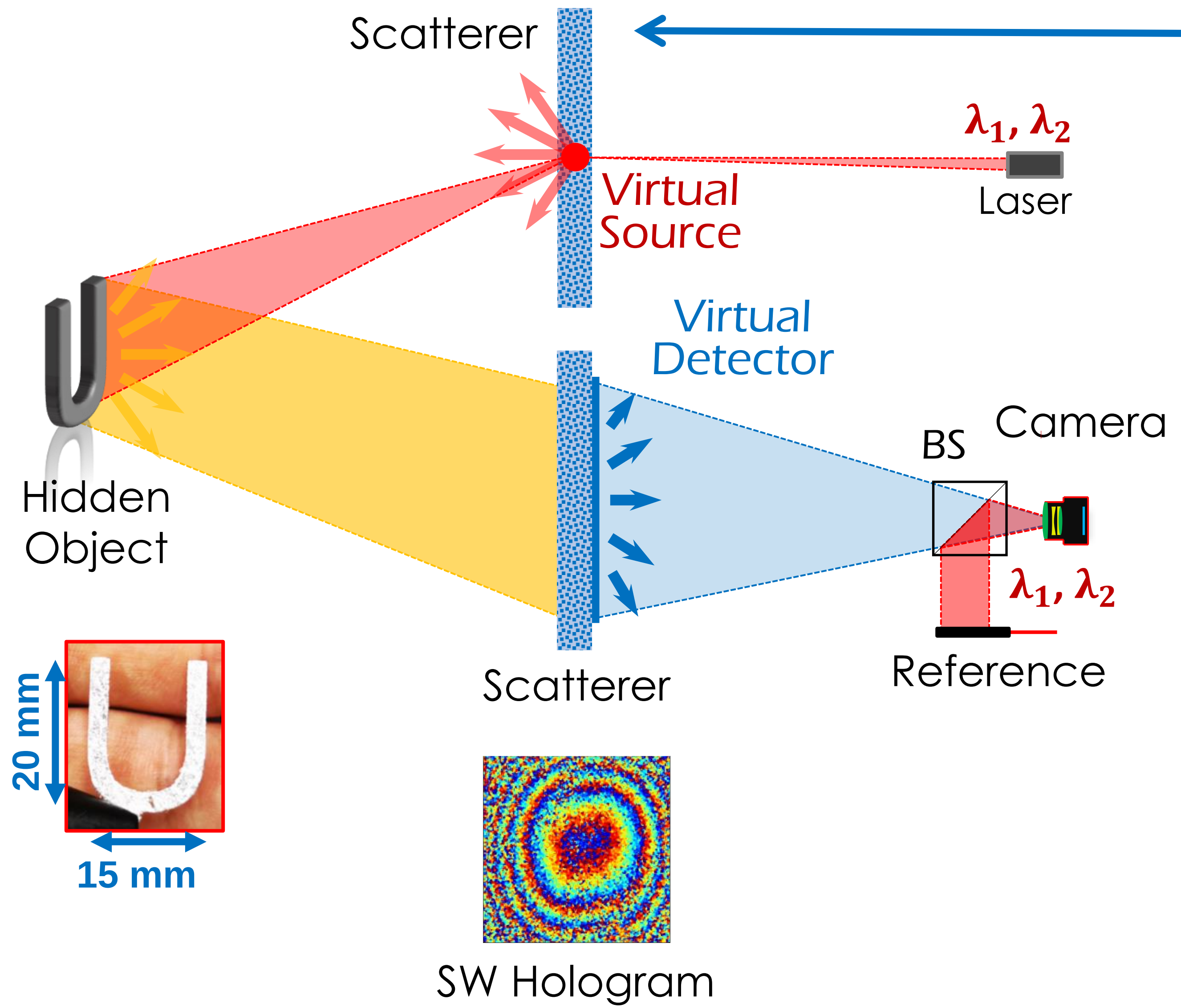
Smallest laterally resolvable distance

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)

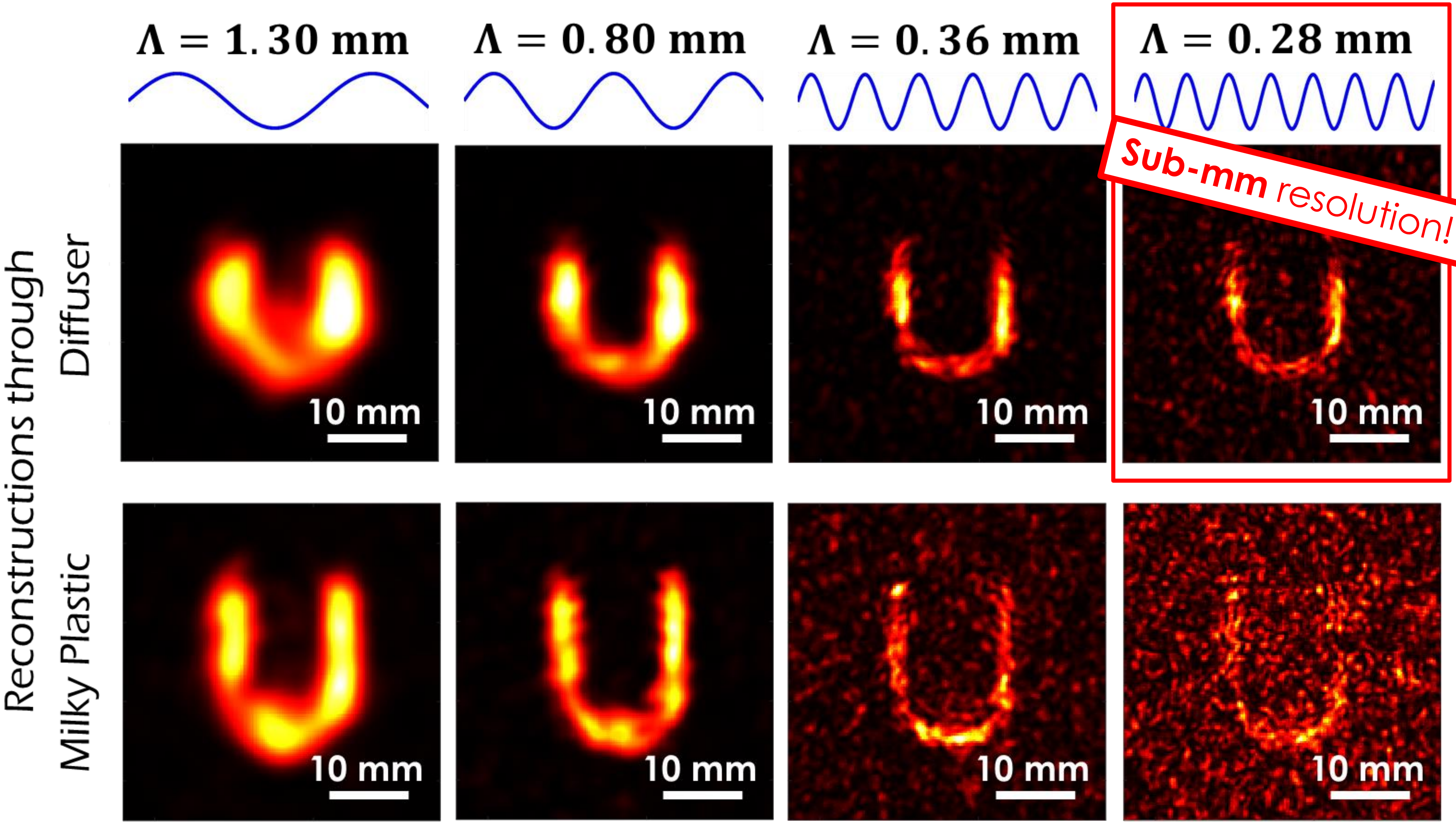
Experiment: Imaging through Scattering Media



Willomitzer et al., 2021

Imaging through scatterers - Results

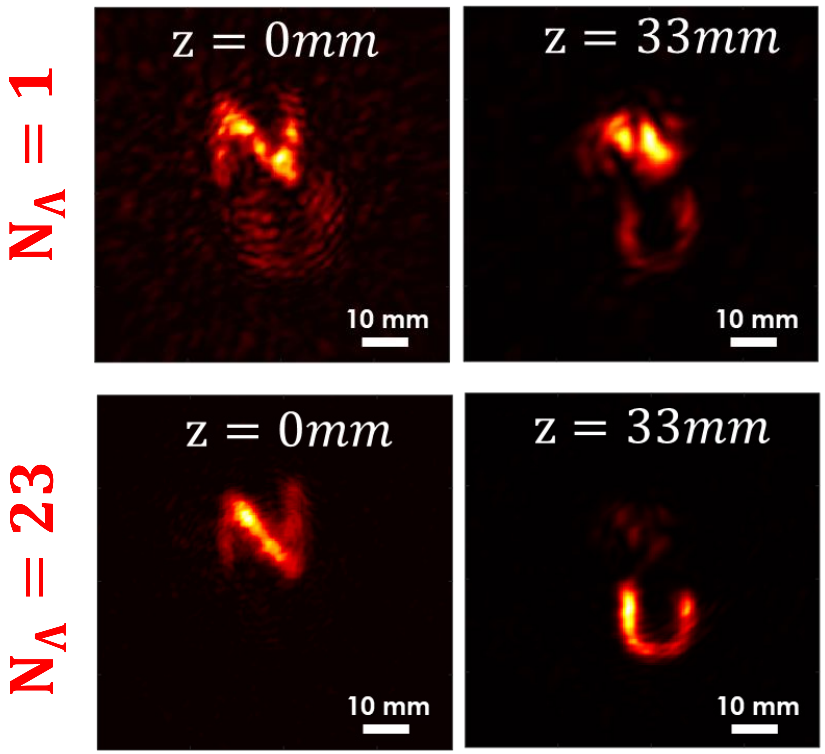
$\Lambda \approx 4\,\Psi_{max}$

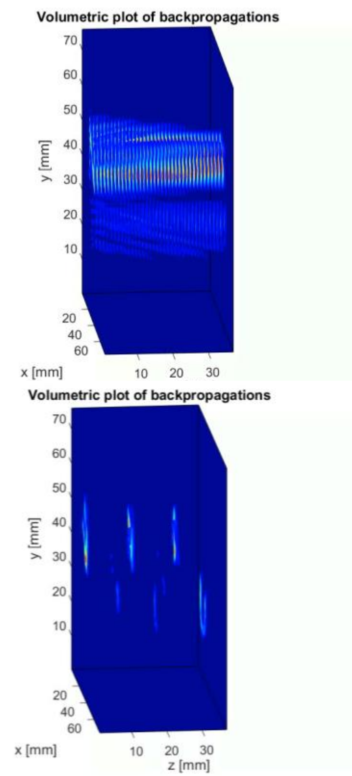


Synthetic Pulse Holography/Interferometry

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

Hidden Object



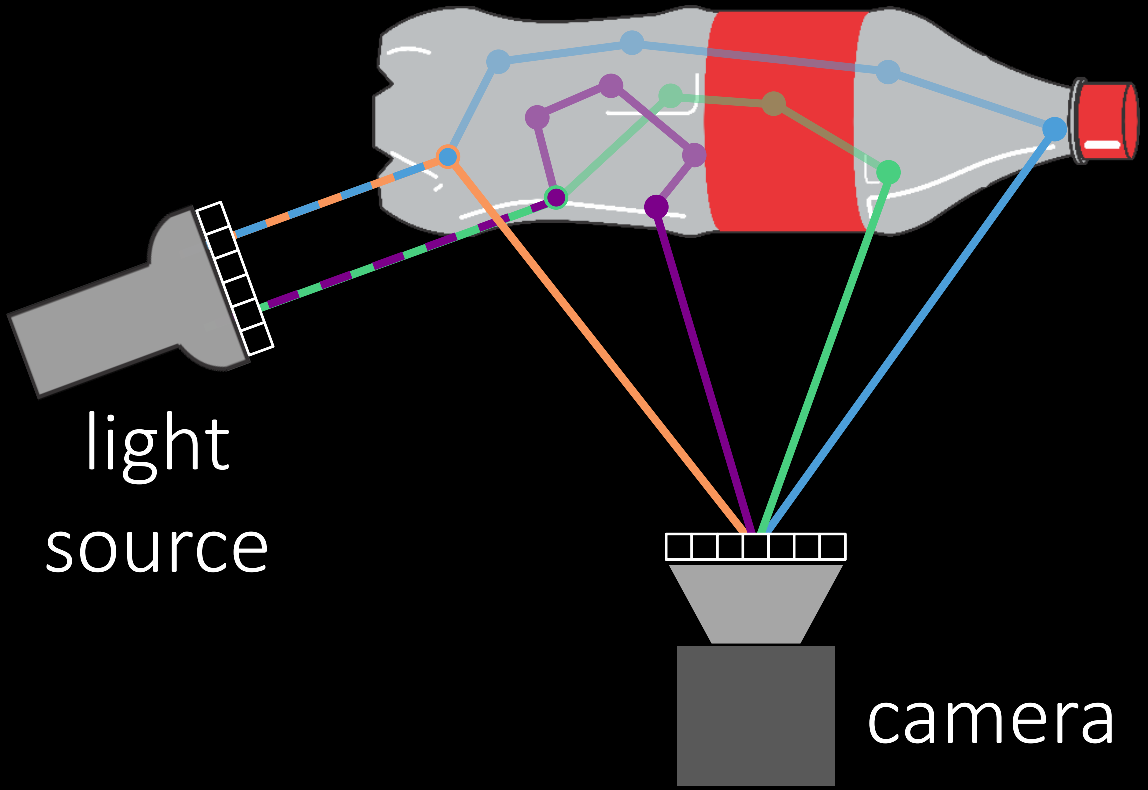


→ Similarity to OCT, WLI, light-in-flight imaging, transient imaging

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)

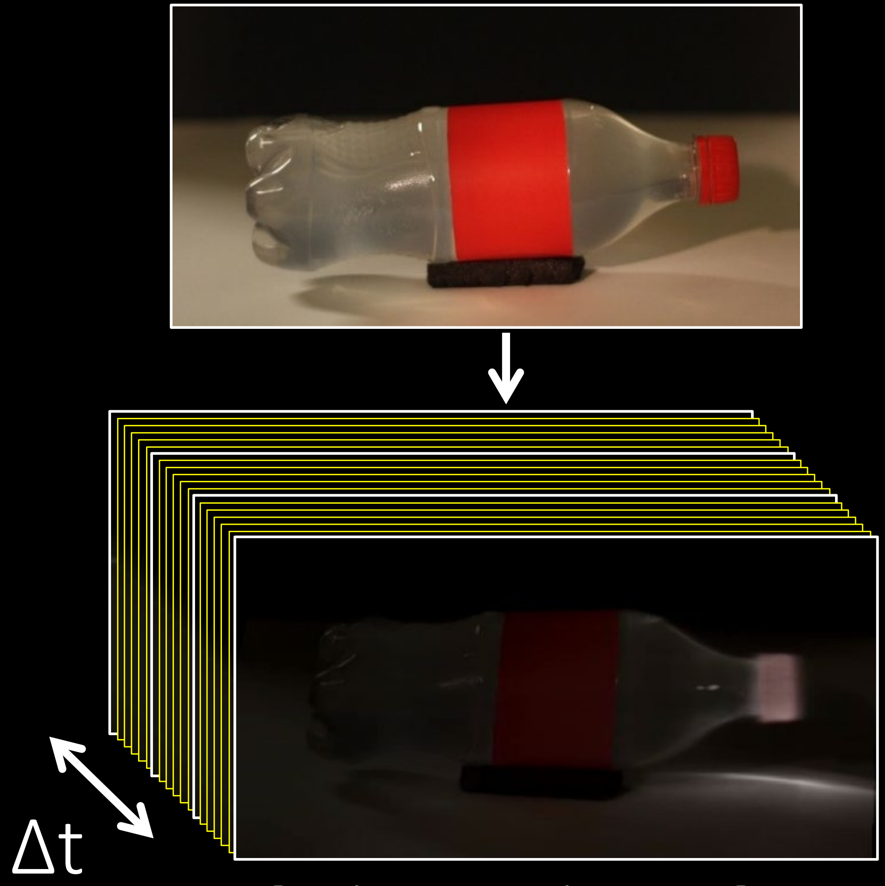
P. Cornwall, M.Ballester, H. Wang, F.Willomitzer, ‘Towards Synthetic Light-in-Flight’, Optica Comp. Optical Sensing and Imaging(2023)

Transient imaging

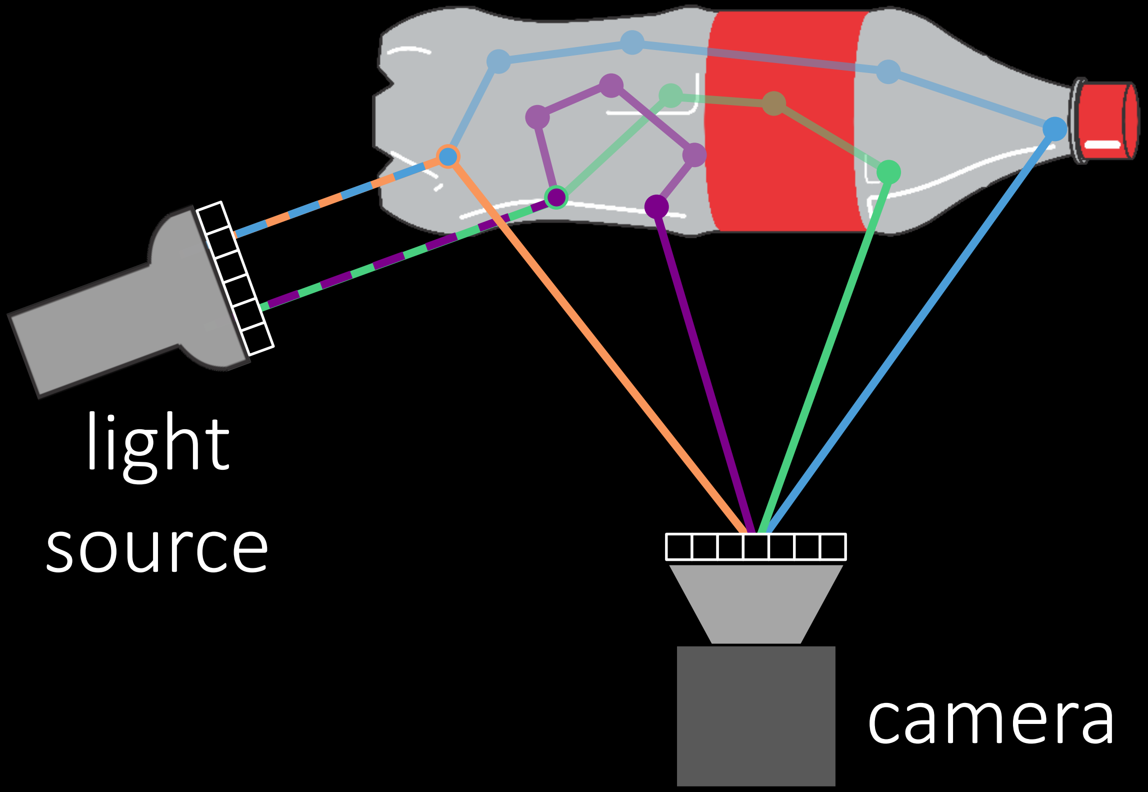


transient imaging using interferometry
at 1000x larger temporal resolution

Transient imaging

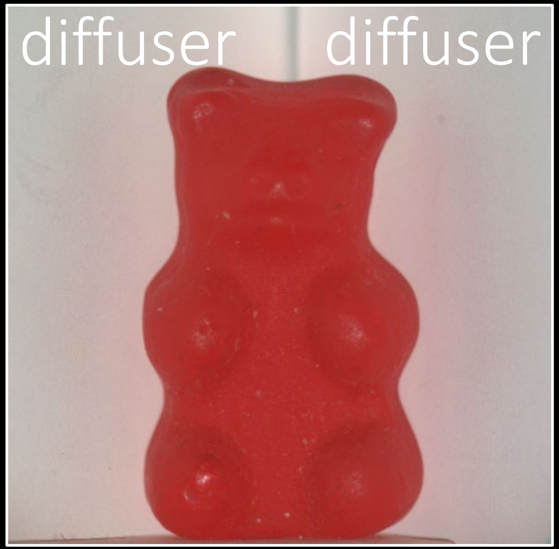


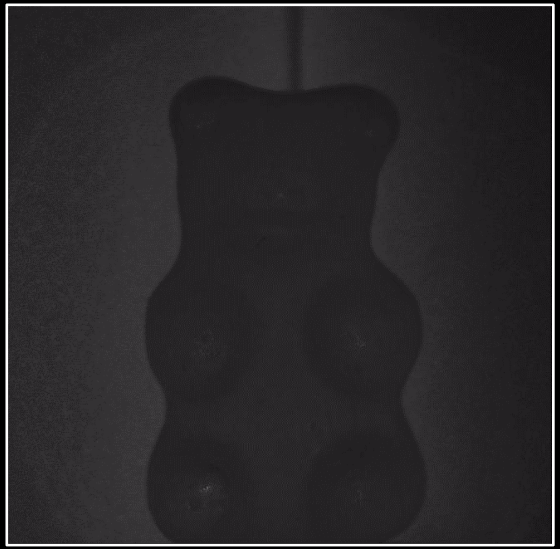
[Velten et al. 2013]



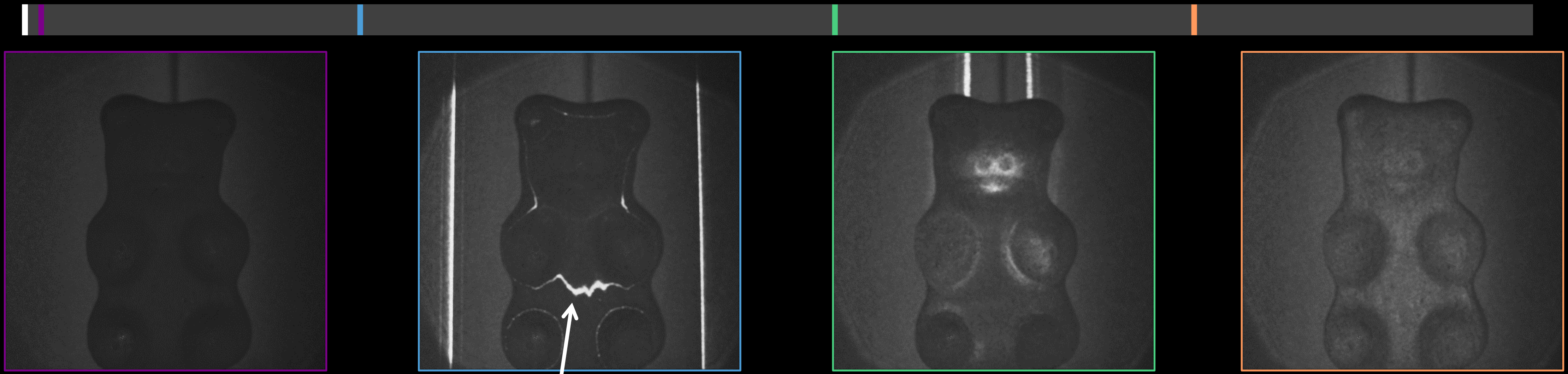
transient imaging using interferometry at 1000x larger temporal resolution

Gummy bear and diffuse corner





resolution
10^{-15} s



dark frame

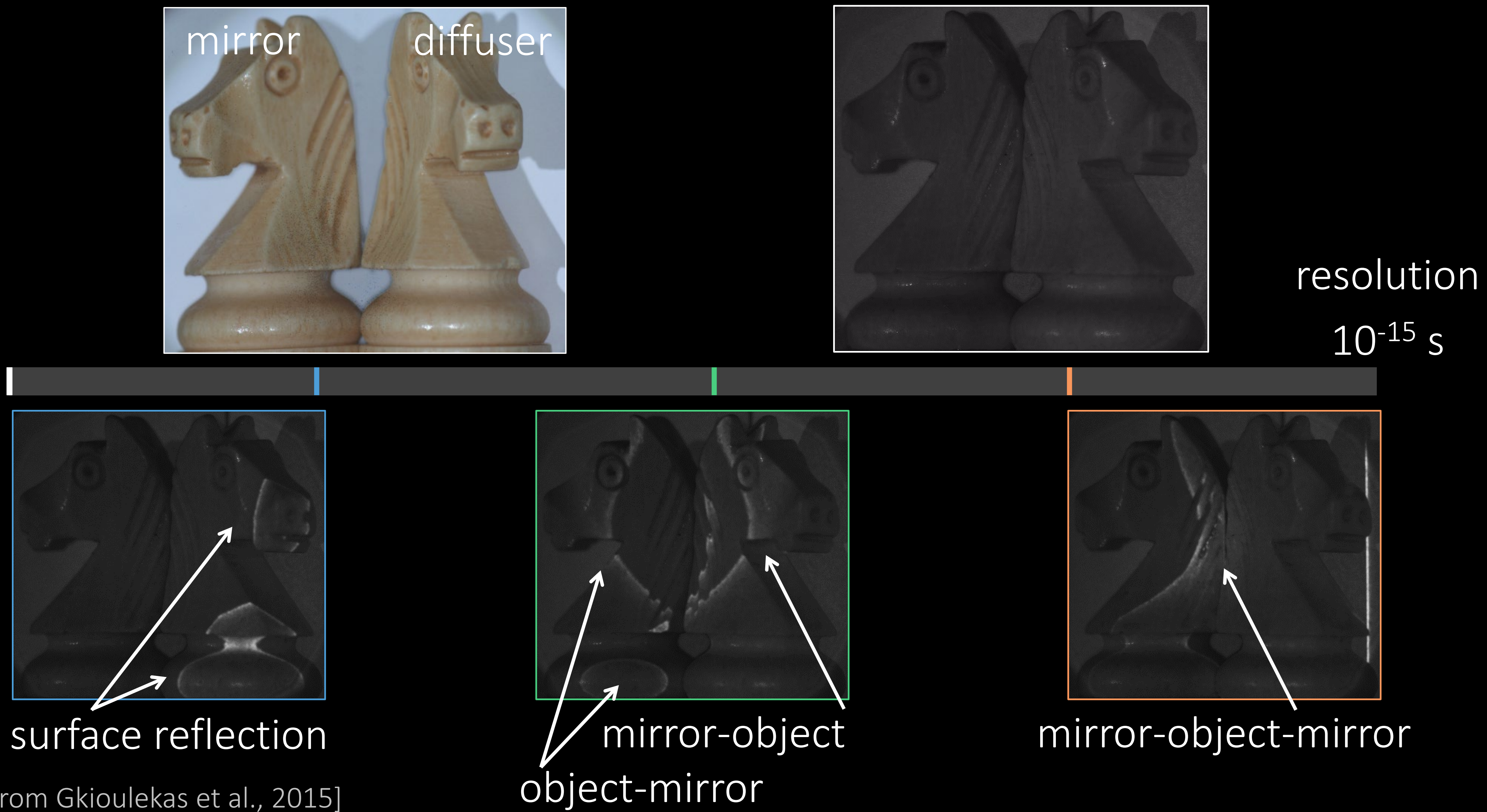
surface reflections

paths through gummy bear

very highly scattered paths

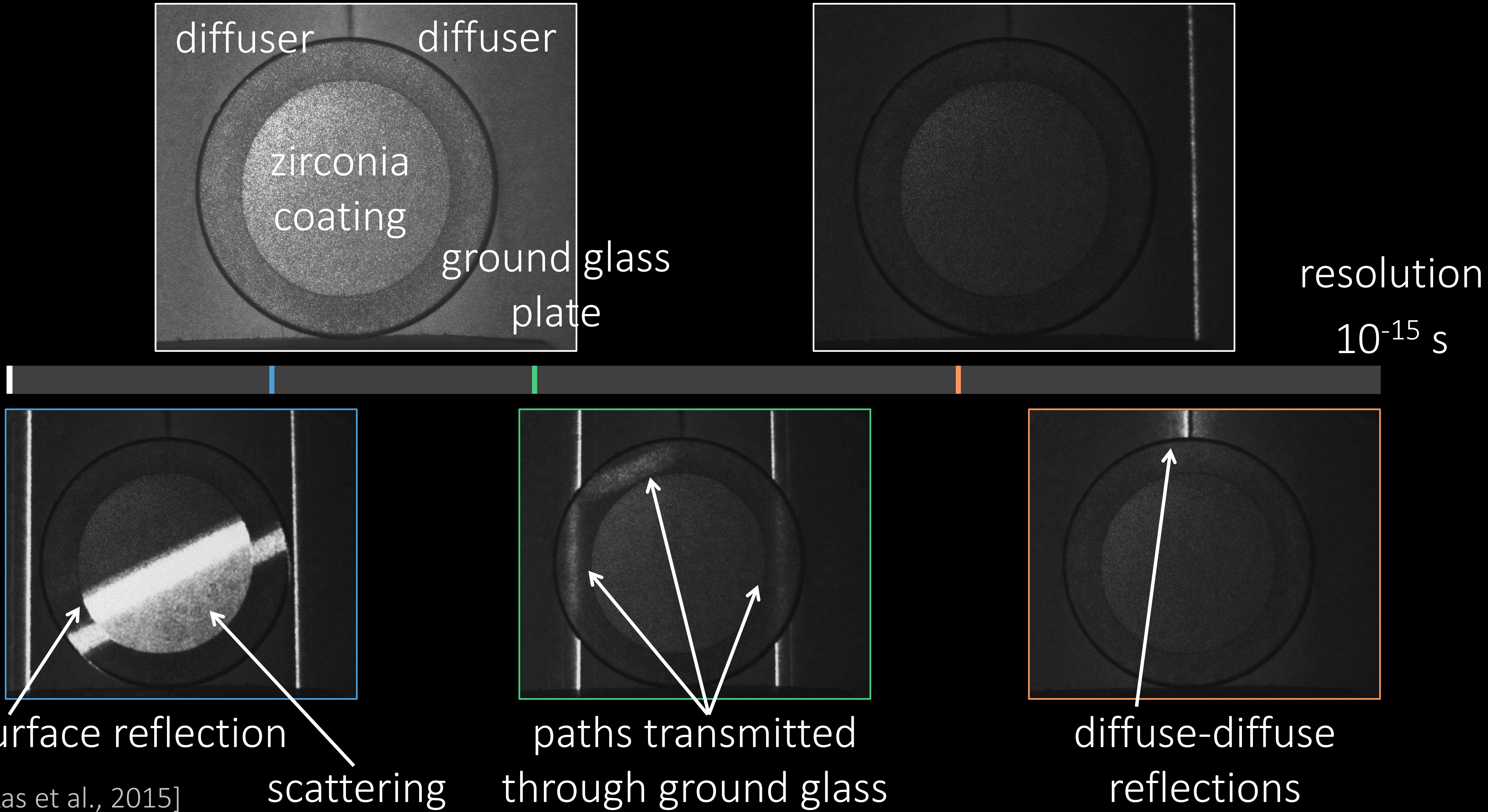
[Images from Gkioulekas et al., 2015]

Chess knight and mirror



[Images from Gkioulekas et al., 2015]

Subsurface scattering



[Gkioulekas et al., 2015]

Dispersion

resolution 10^{-15} s

facets changing color

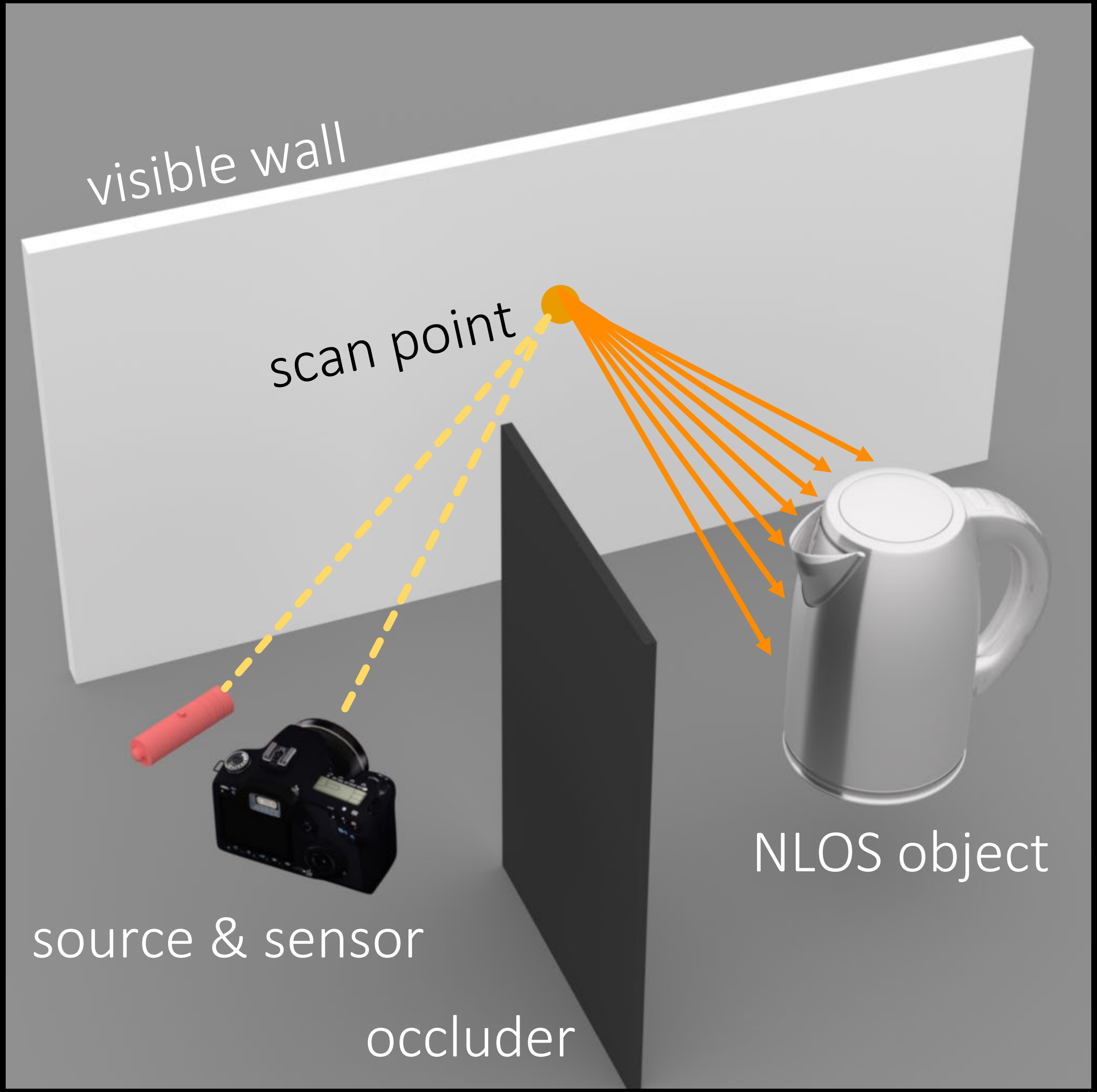
surface reflections

surface-wall reflections

rainbow

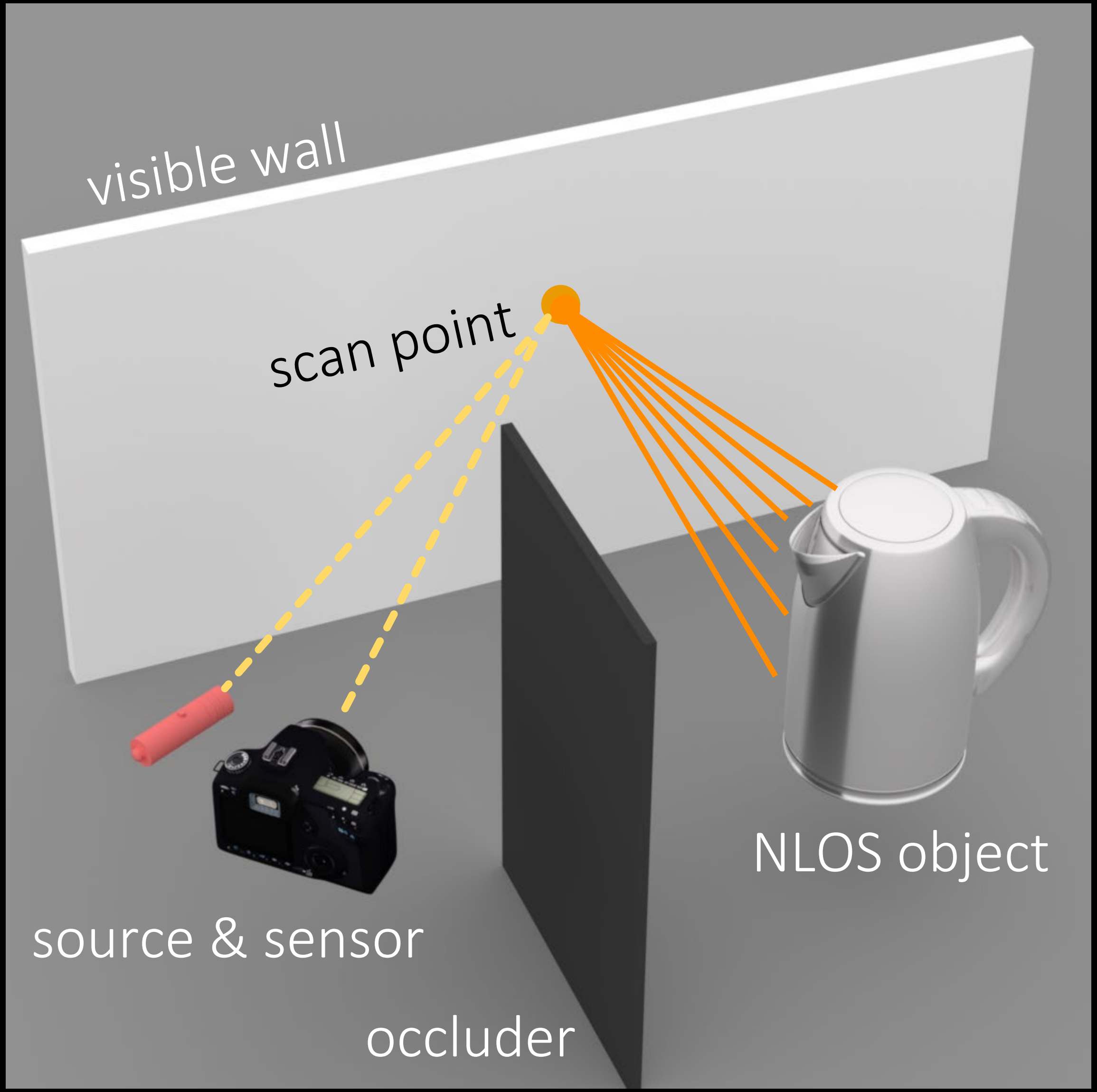
[Images from Gkioulekas et al., 2015]

Non-line-of-sight (NLOS) imaging



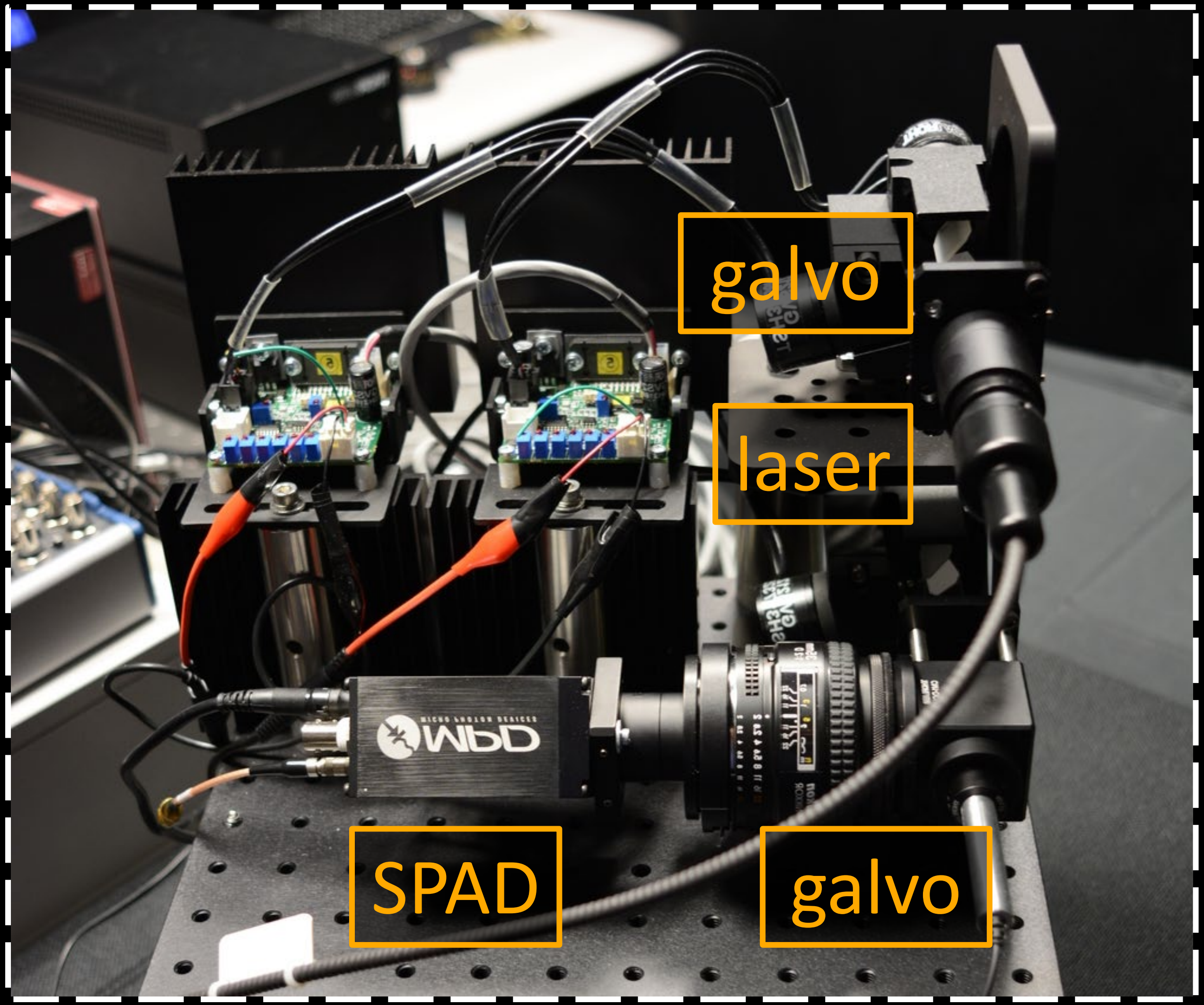
what a regular camera sees

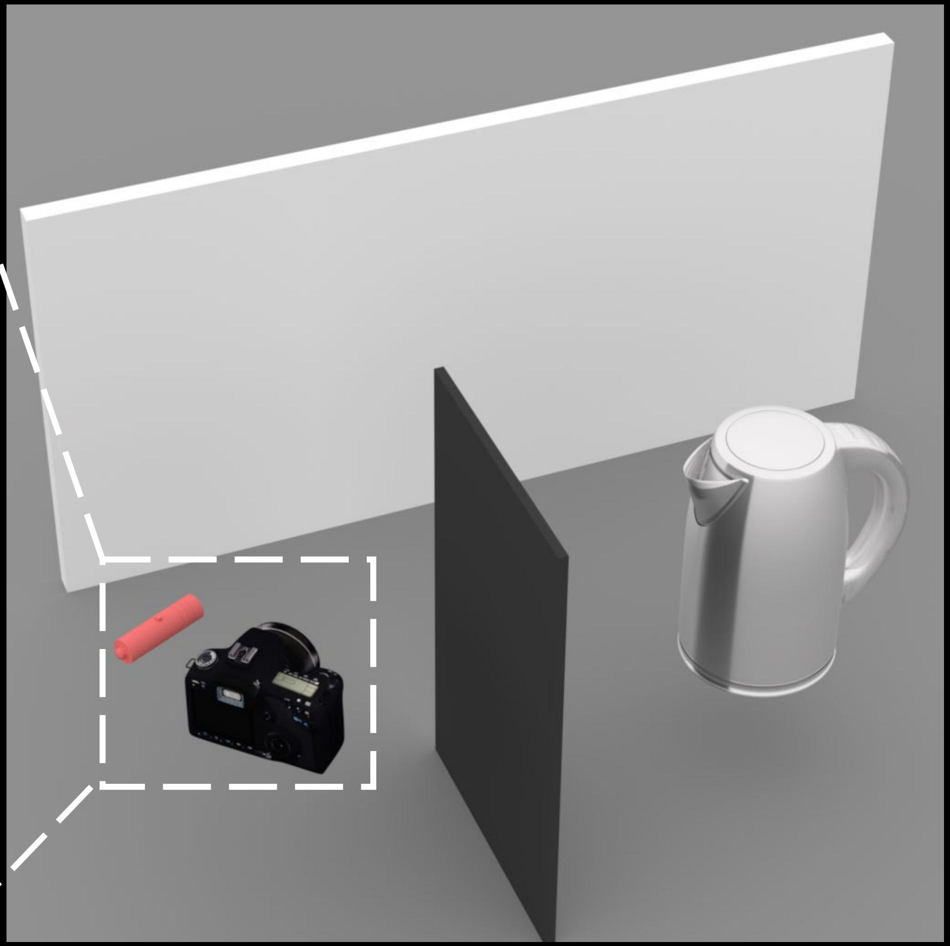
Non-line-of-sight (NLOS) imaging



what a regular camera sees

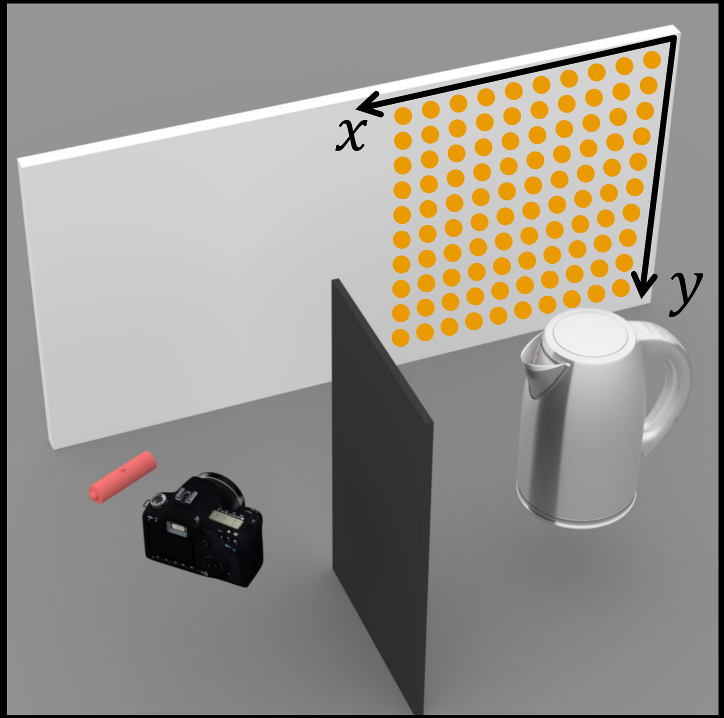
Picosecond-scale setup

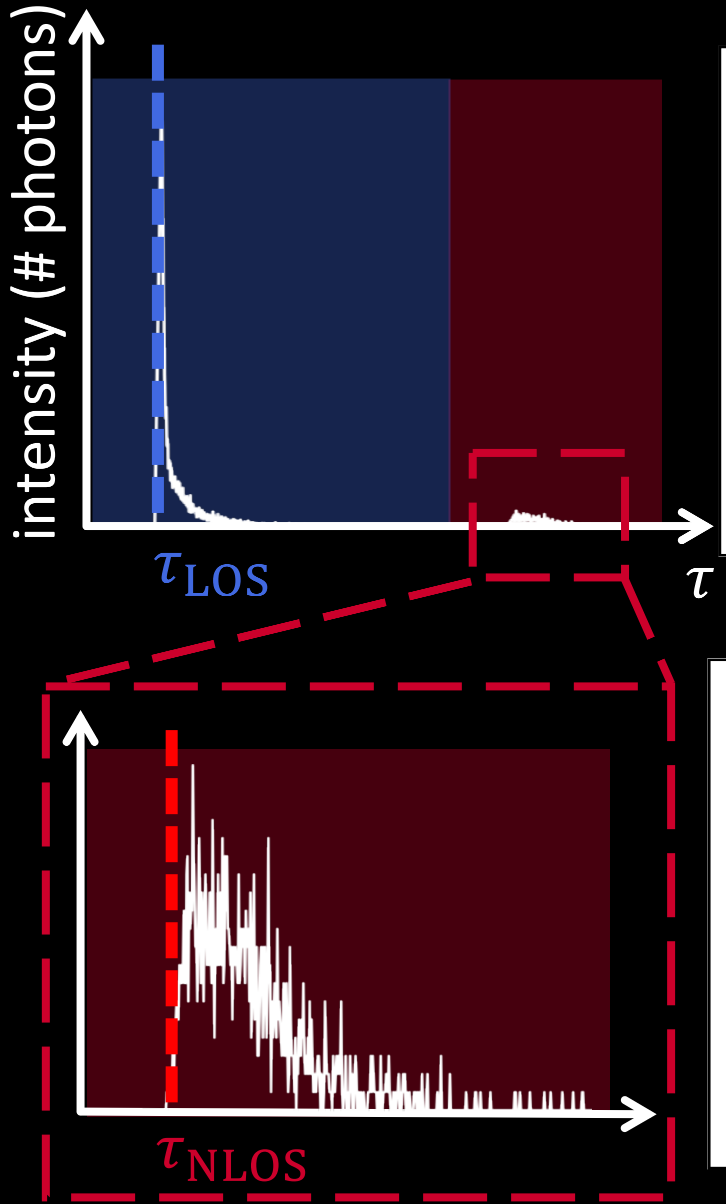




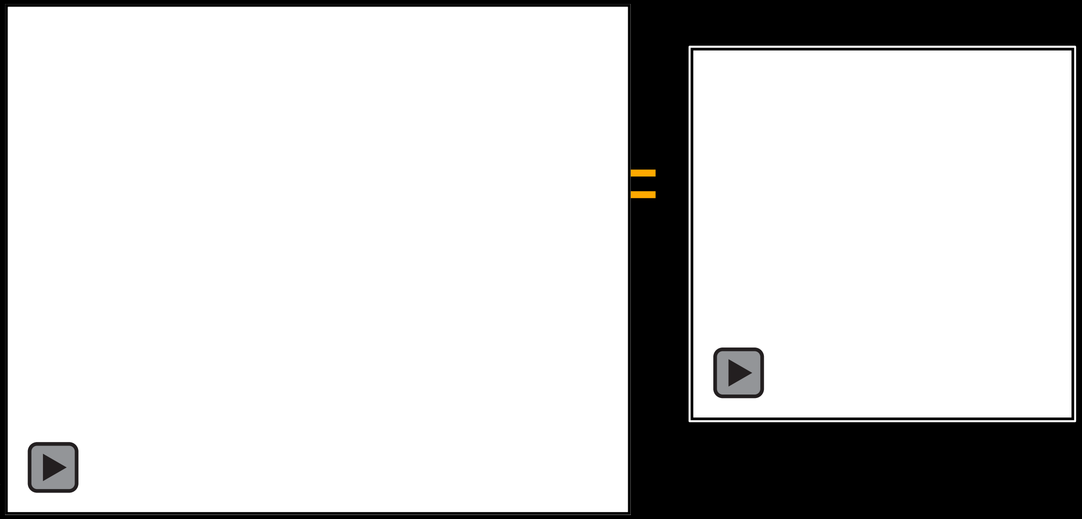
ultra-sensitive lidar capturing later returns
(single-photon avalanche diode)

Lidar scanning procedure

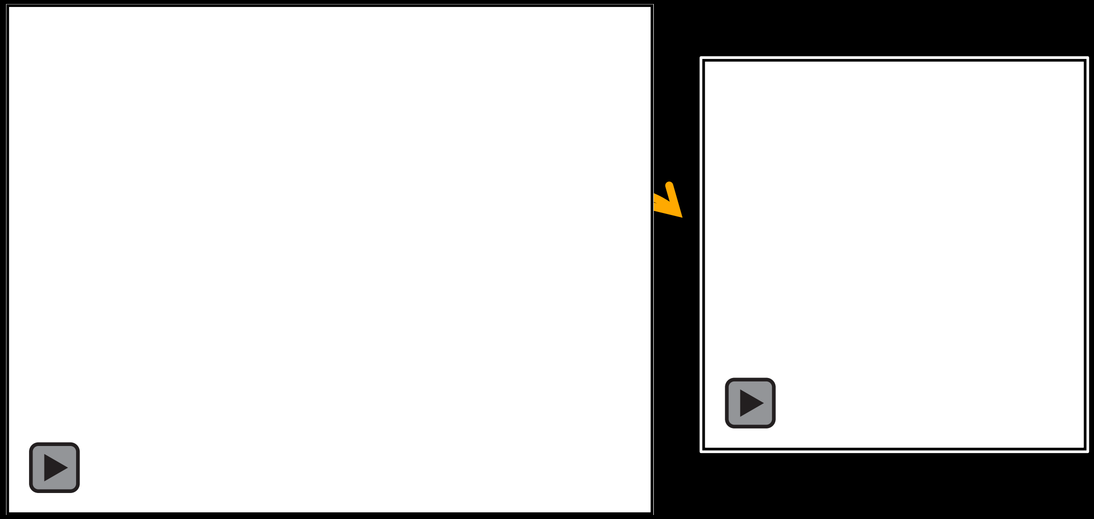




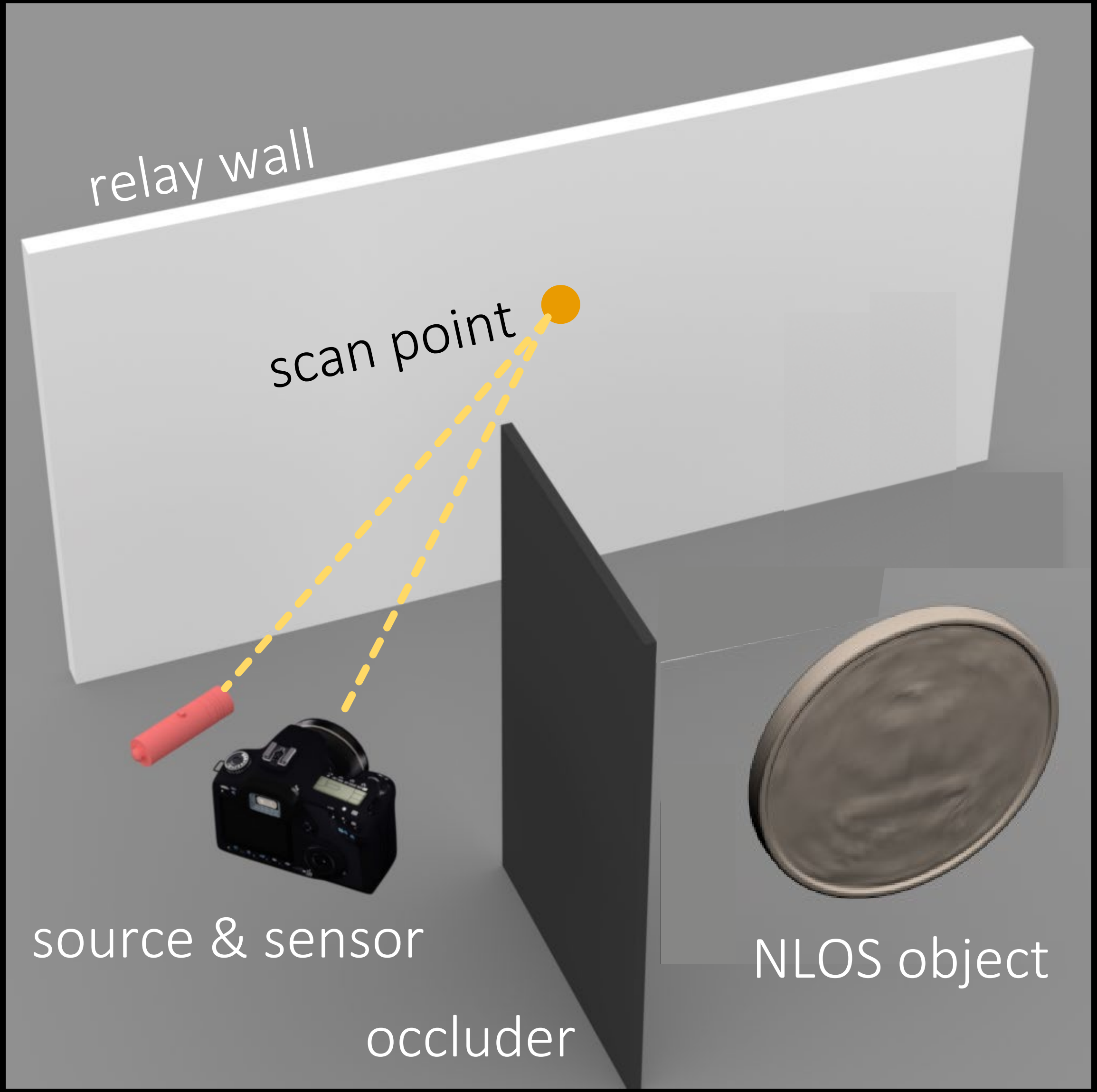
LOS Reconstruction

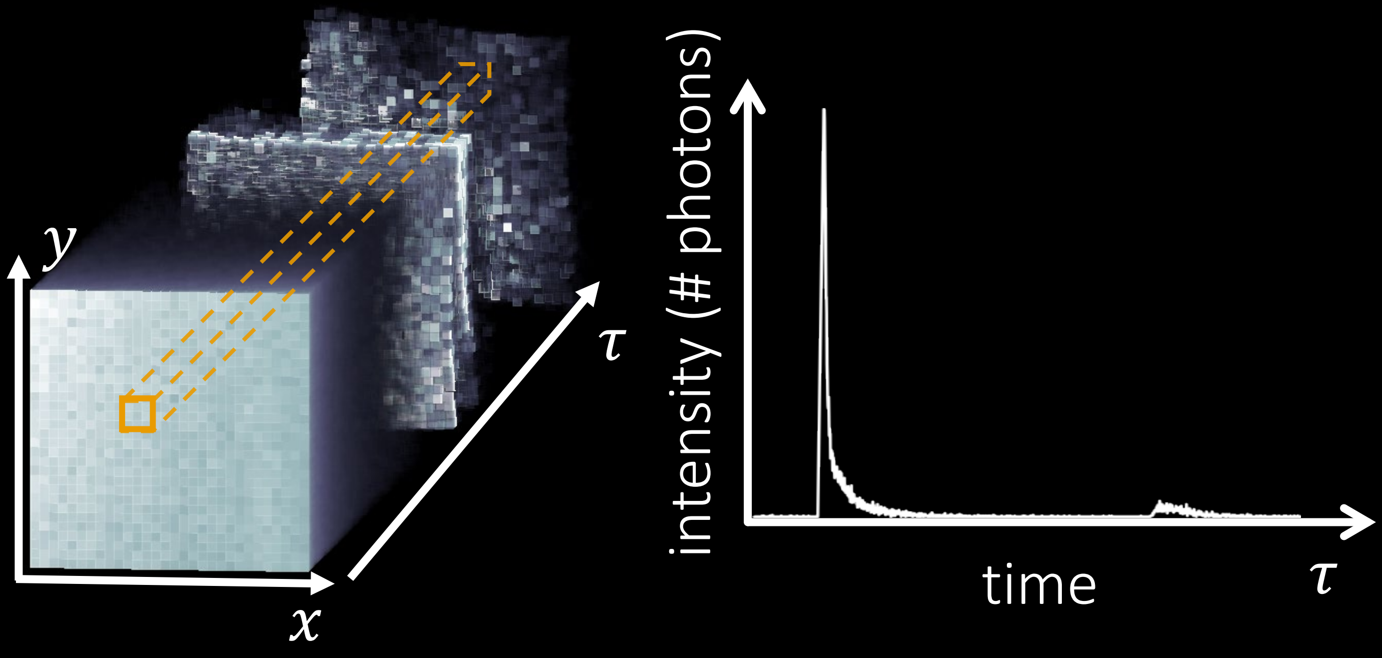


NLOS Reconstruction



Non-line-of-sight (NLOS) imaging

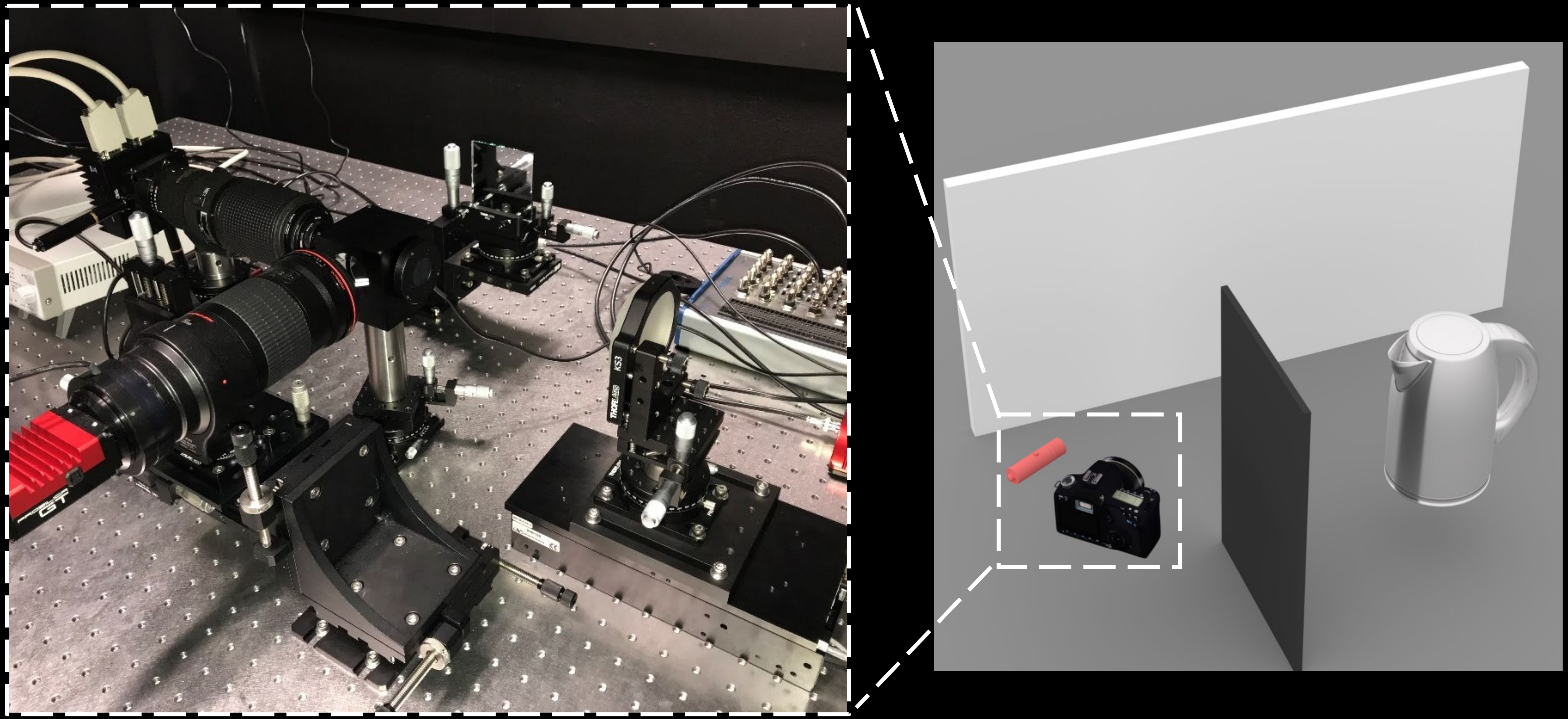




- Room-scale scanning (2 m x 2m)
- Object-scale scanning (0.5 m x 0.5 m)

Can we do this at micron scales?

Femtosecond-scale setup

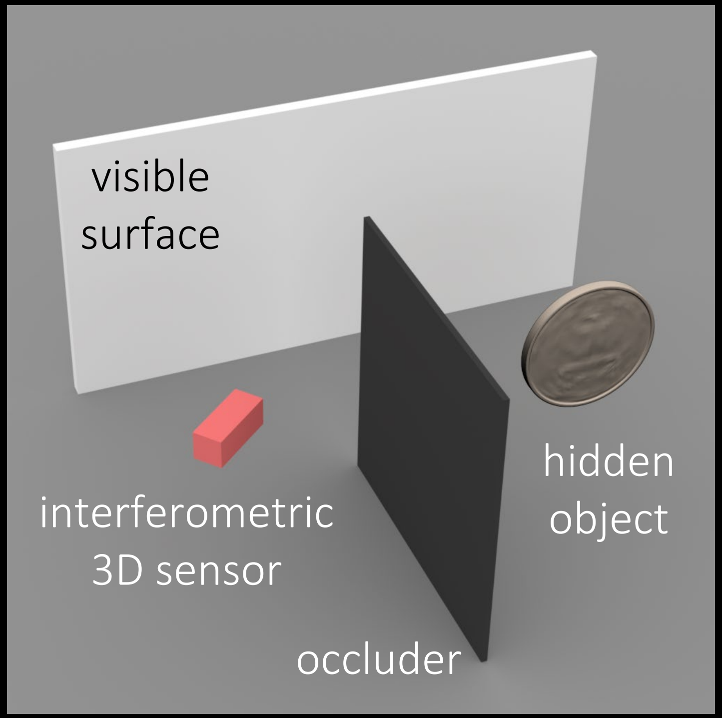


interferometric time-of-flight setup

Micron-scale NLOS imaging

ground truth (LOS scan)

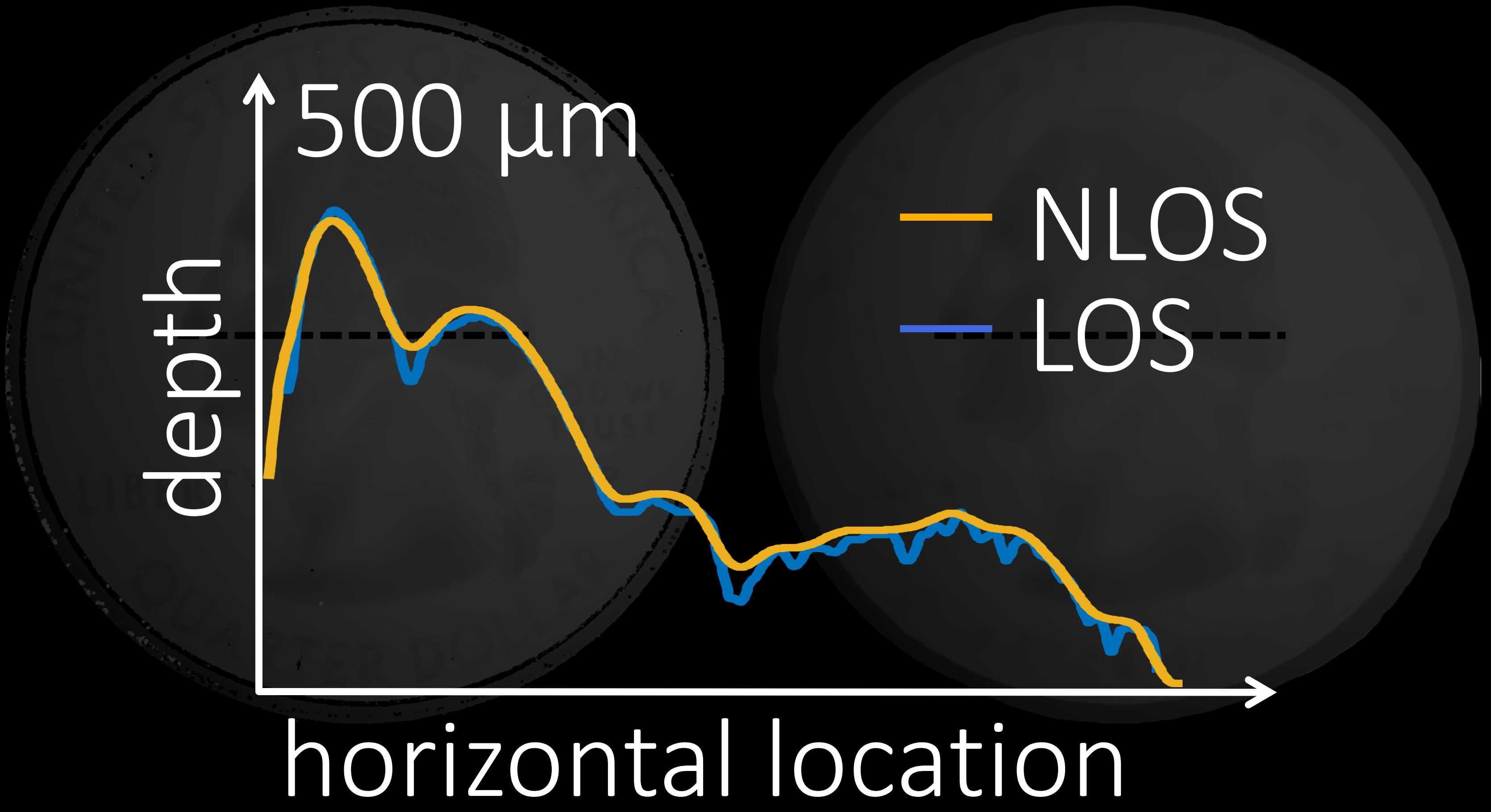
NLOS reconstruction



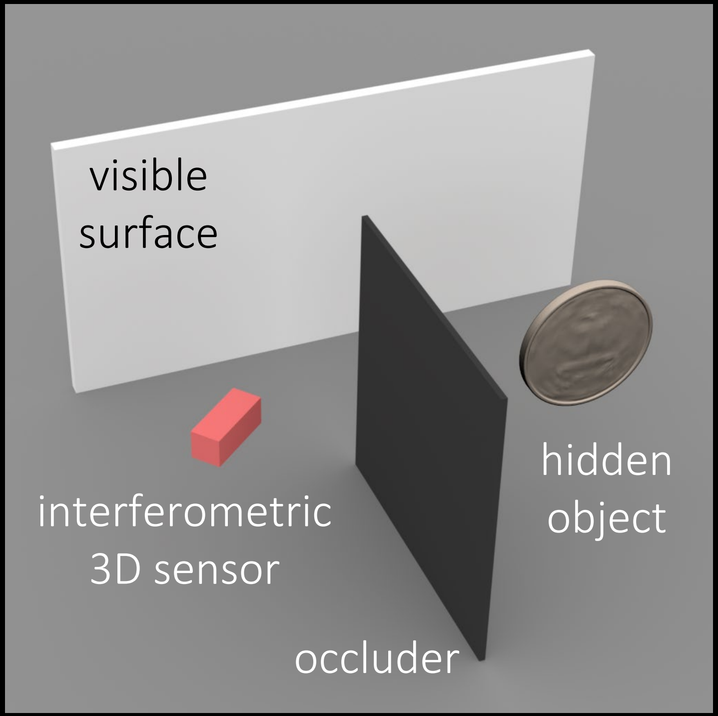
interferometric setup
resolution: 10 μm (33 fs)

[Images from Xin et al., 2019]

Micron-scale NLOS imaging



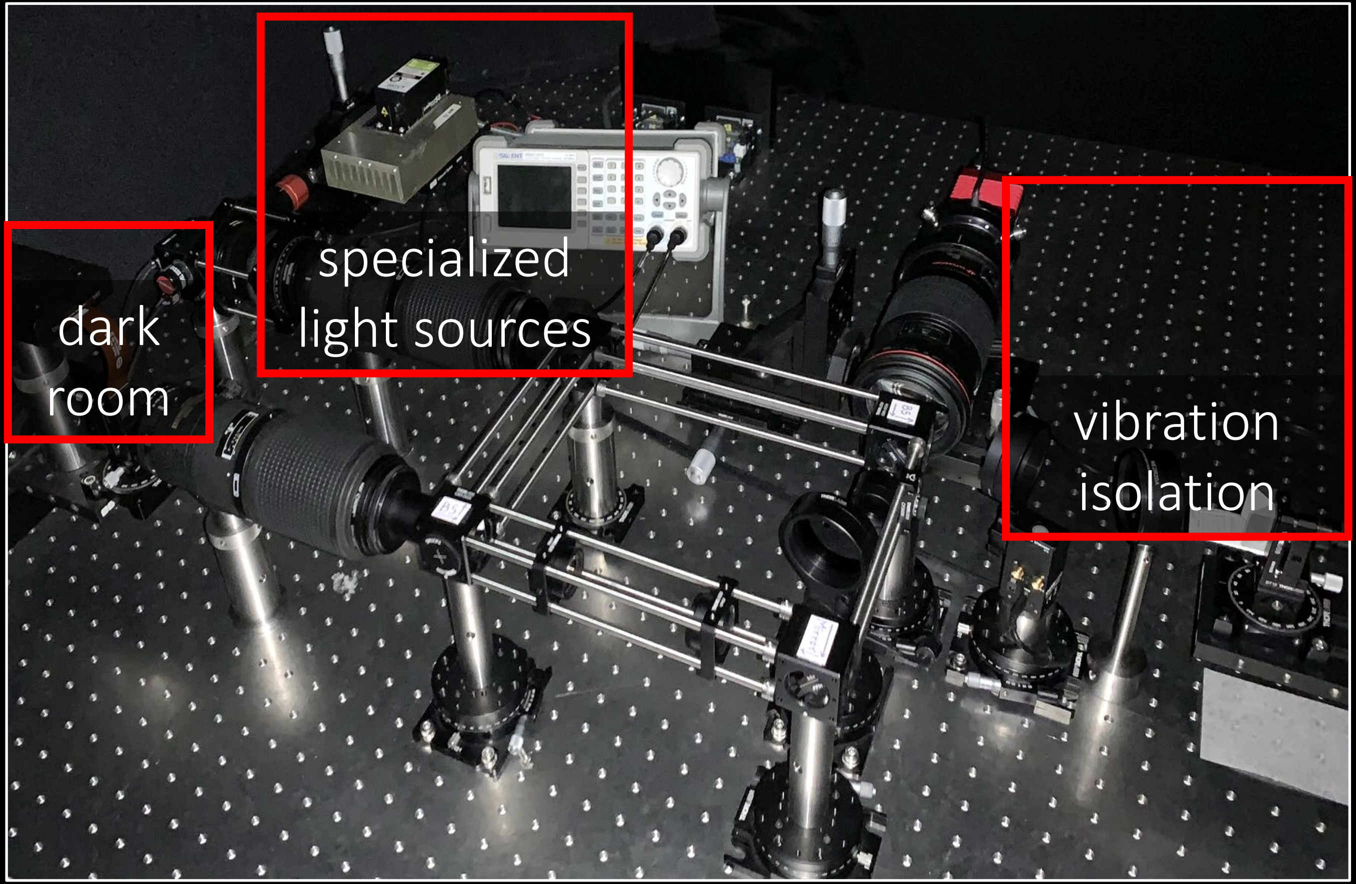
ground truth (LOS scan) NLOS reconstruction



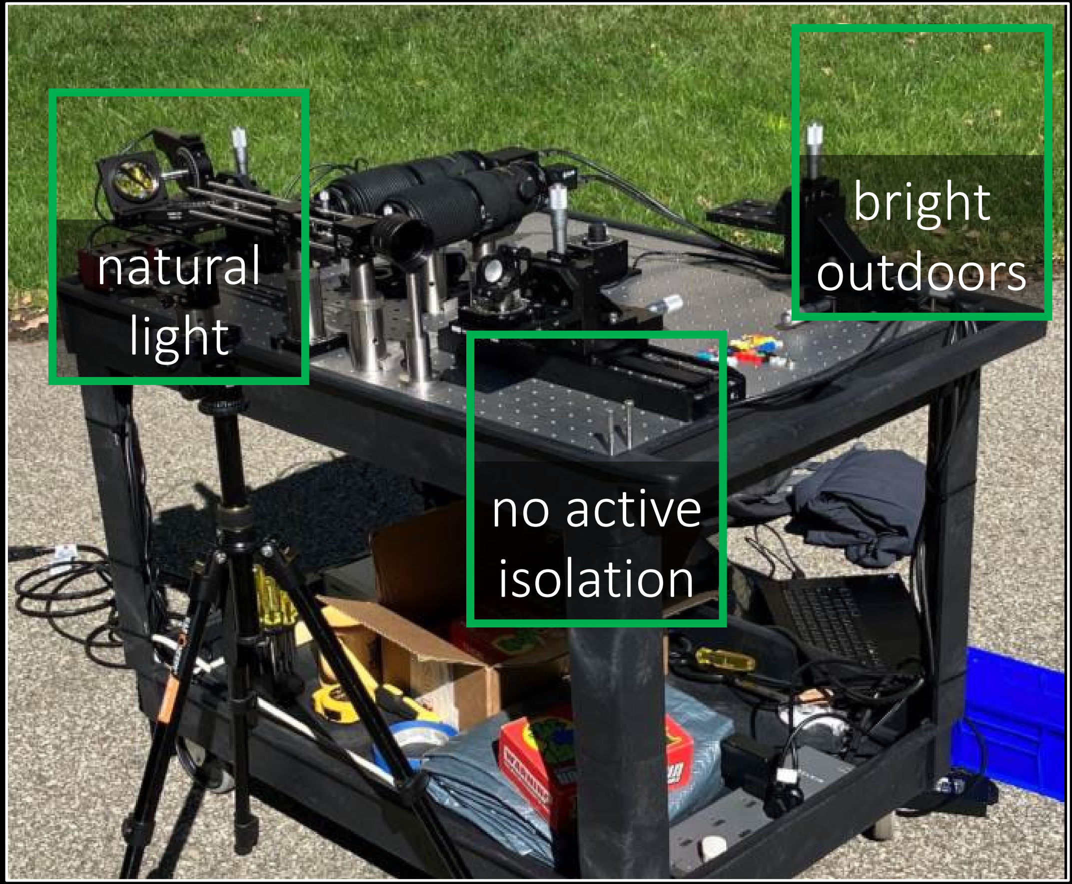
interferometric setup
resolution: 10 µm (33 fs)

[Images from Xin et al., 2019]

Deploying interferometric systems is hard

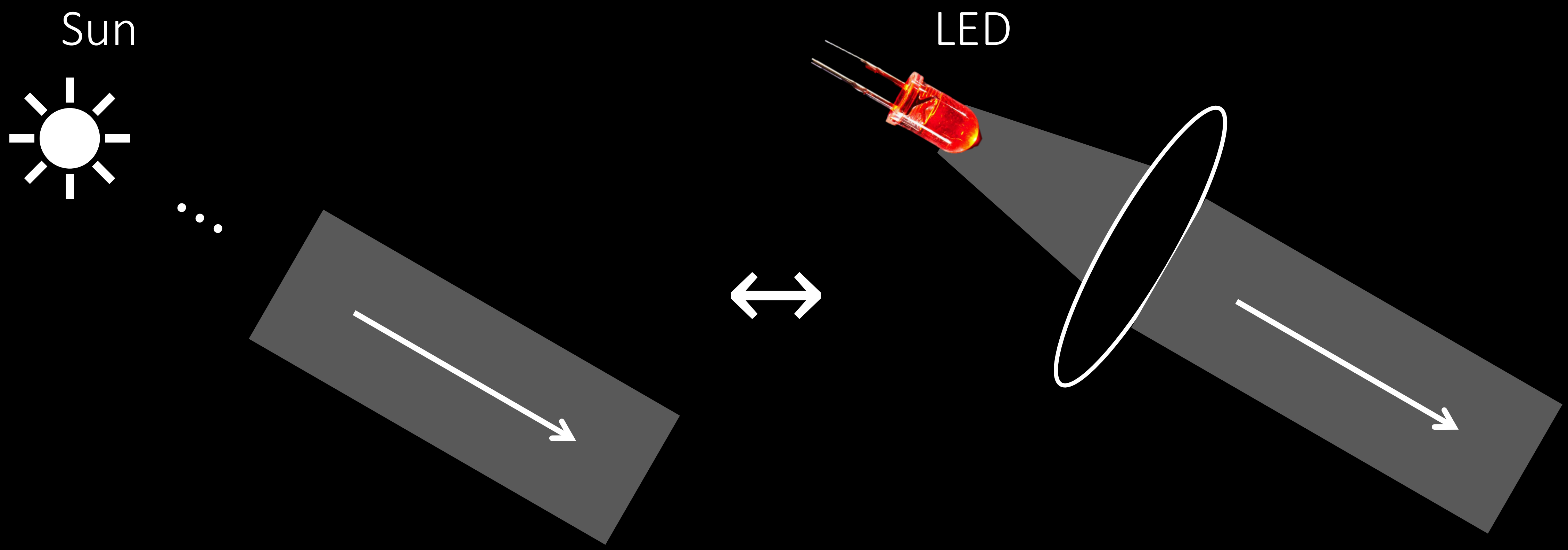


typical interferometry setup

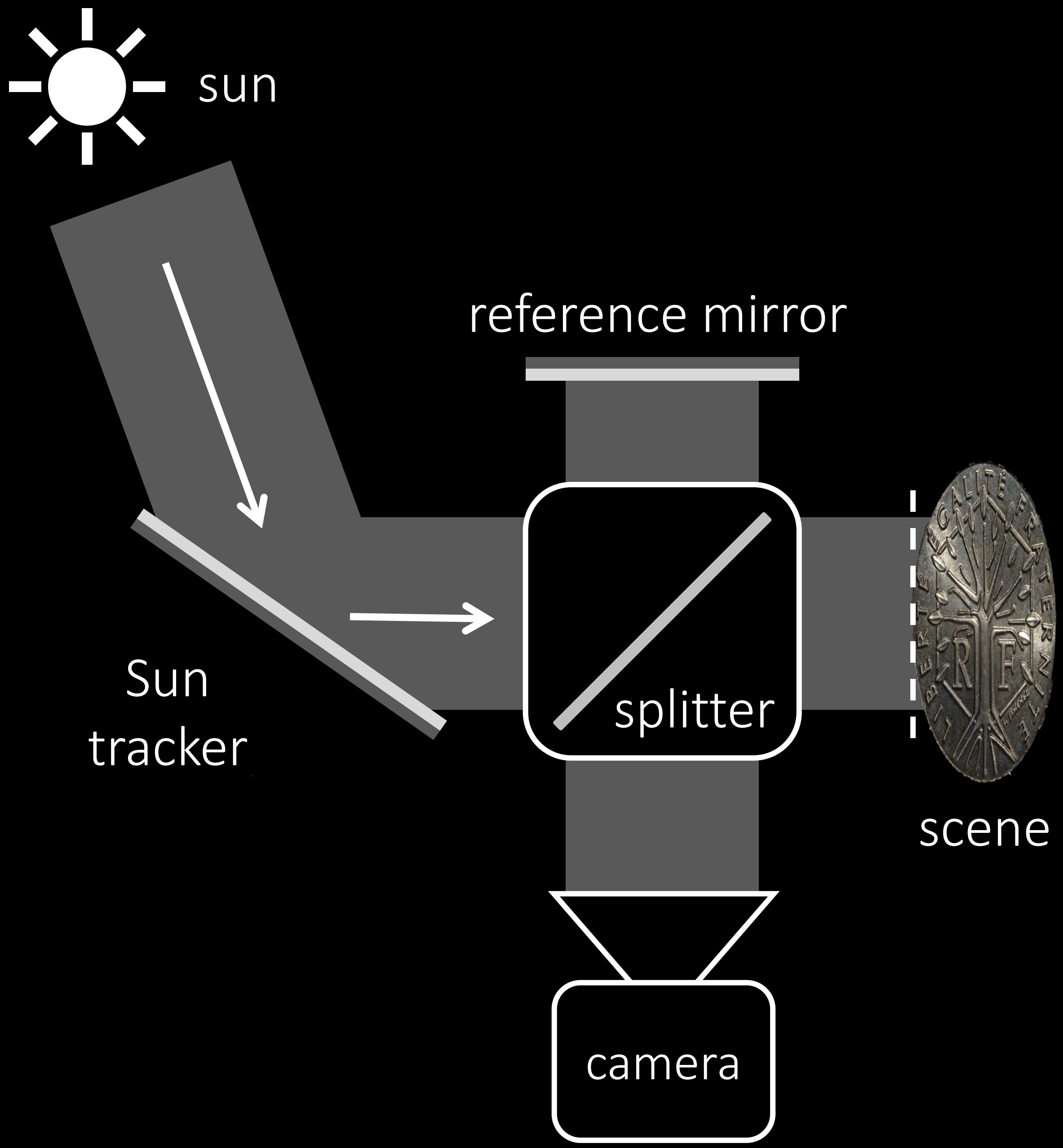


sunlight interferometry

Passive interferometry with sunlight



Sunlight interferometry

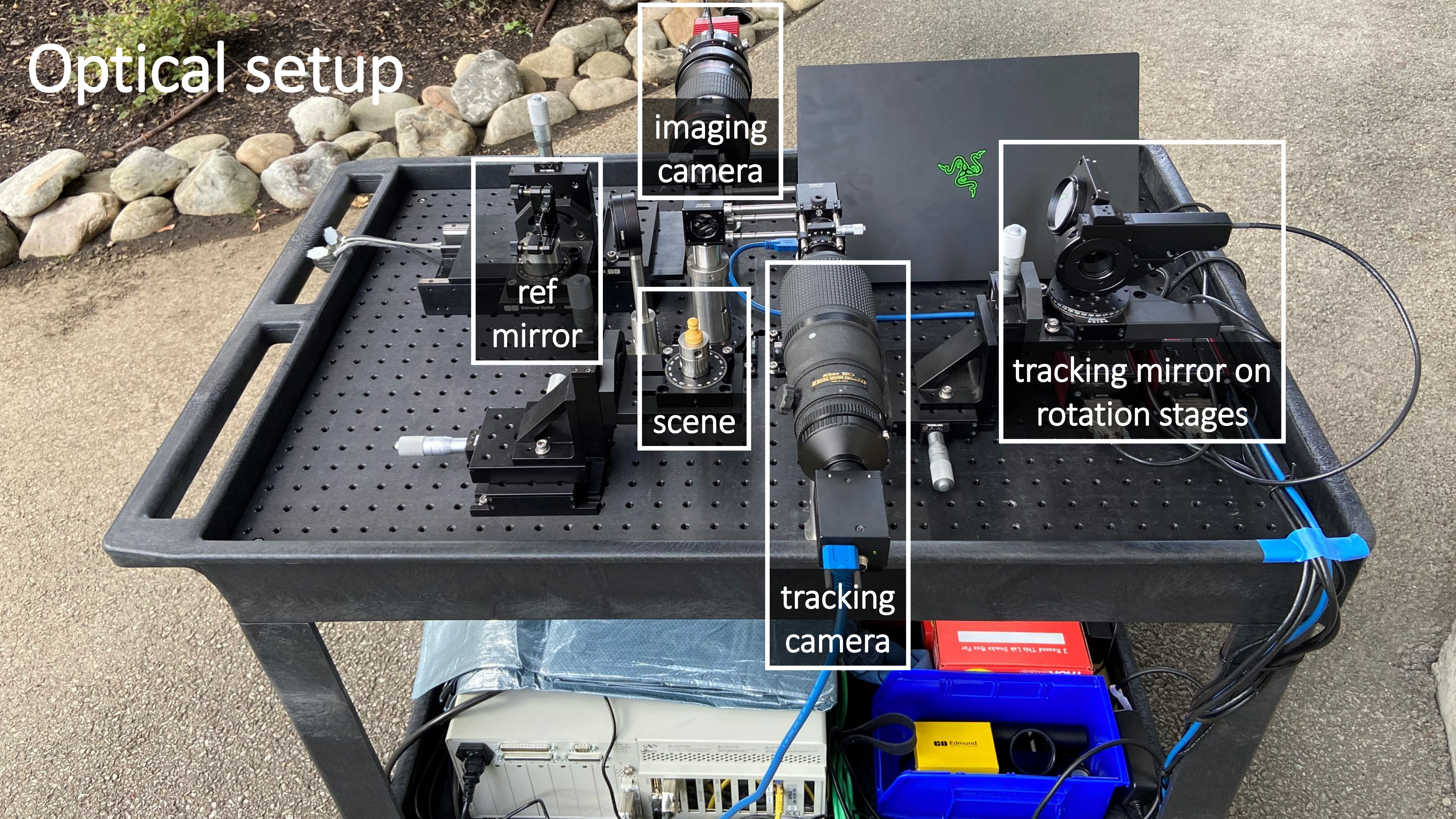


scene

depth map

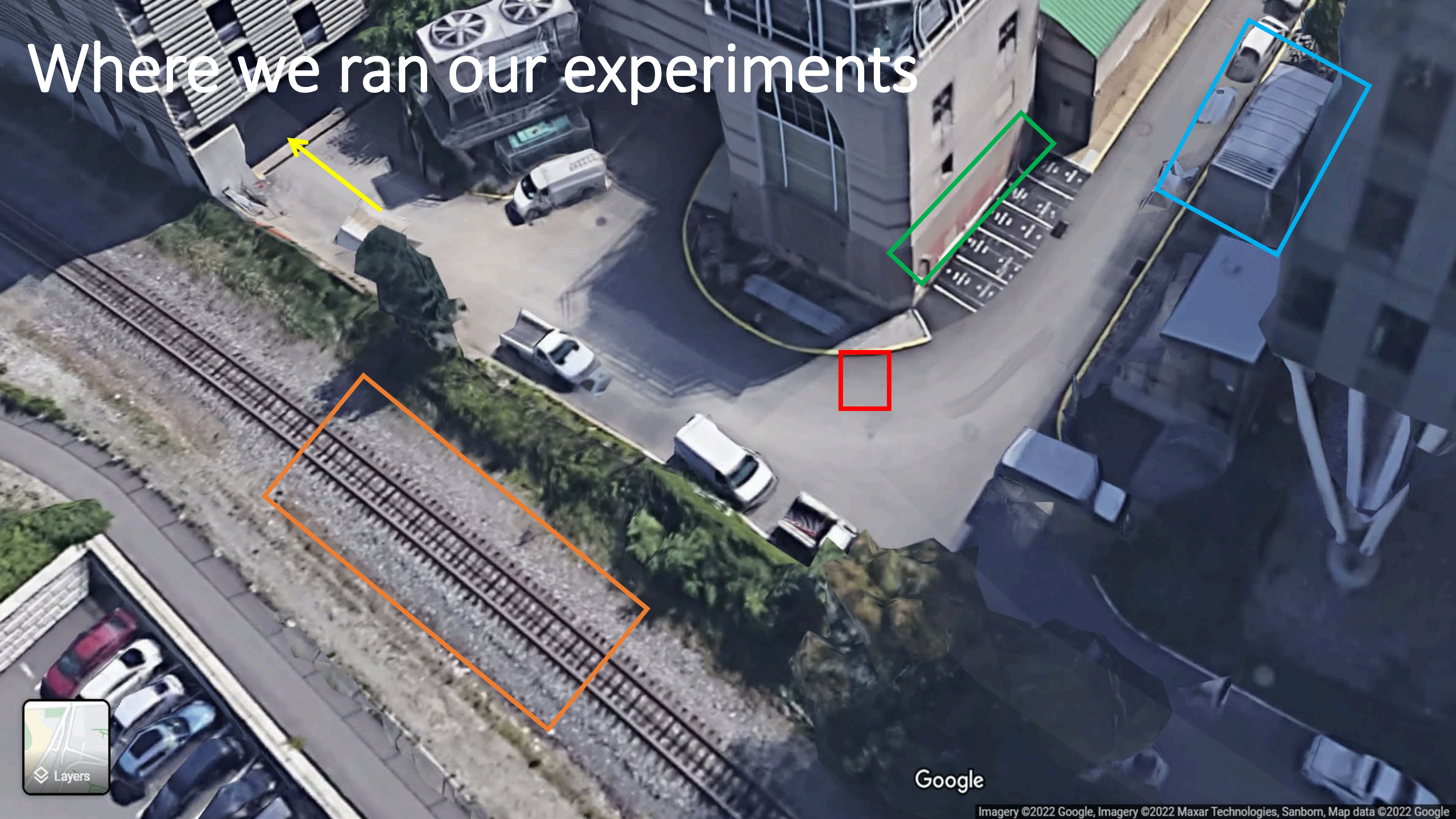
input images

scene transient

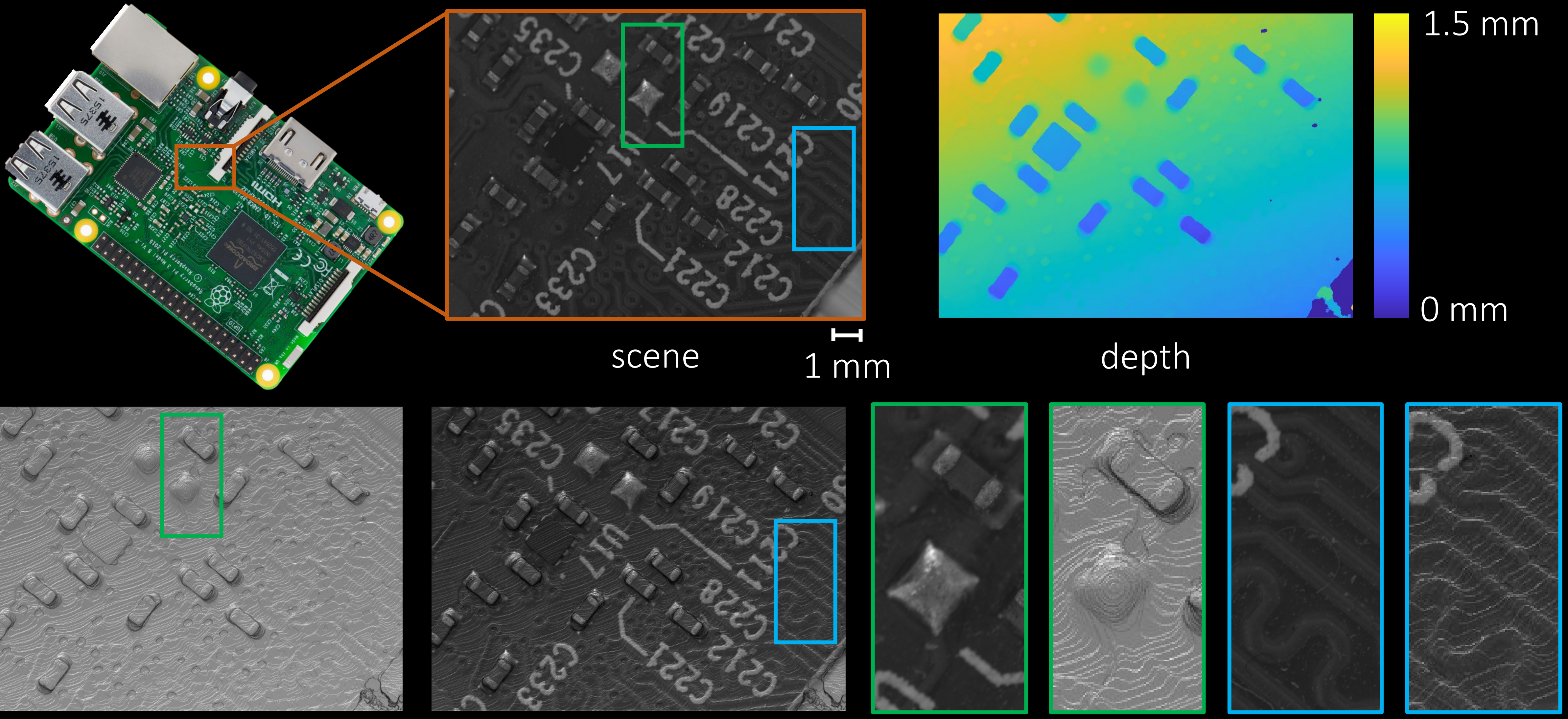


Optical setup
imaging camera
ref mirror
scene
tracking camera
tracking mirror on rotation stages

Where we ran our experiments



Passive 3D sensing: Raspberry Pi



rendered depth | texture-mapped | resistor and pad | conducting tracks

Passive transient imaging: metallic coin

scene

transient response

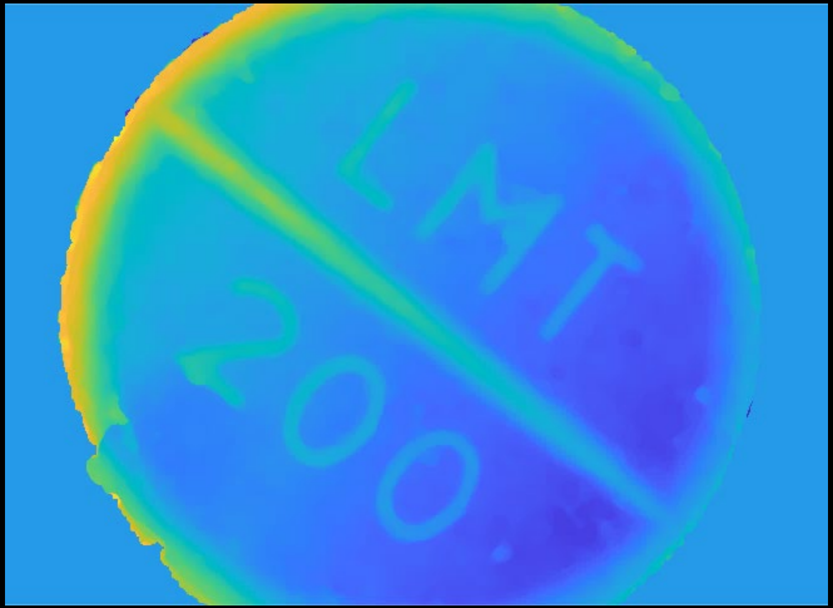
depth

[Images from Kotwal et al., 2023]

Passive transient imaging: diffuse pill

scene

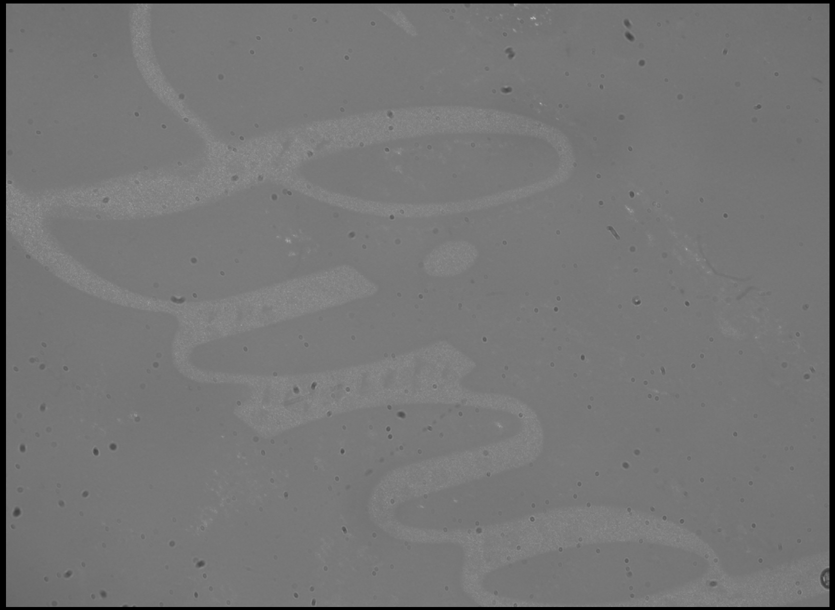
transient response



depth

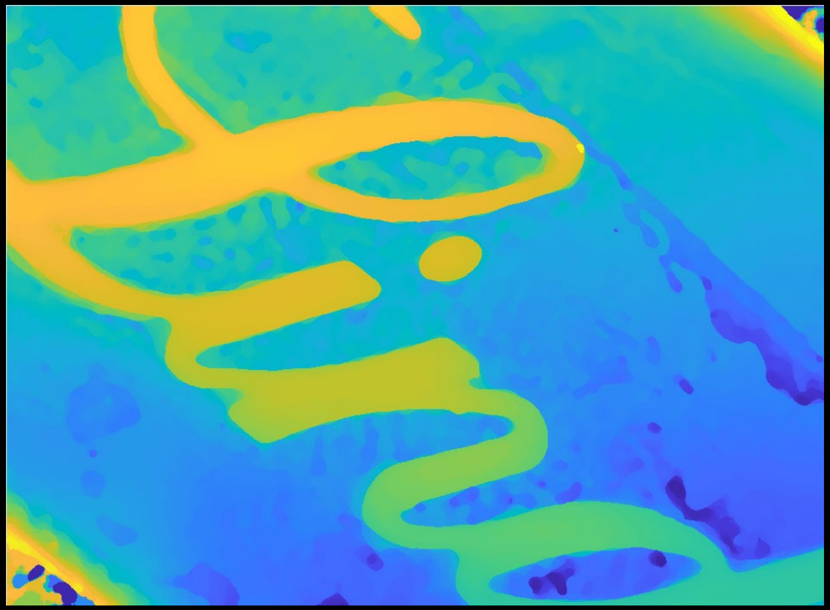
[Images from Kotwal et al., 2023]

Passive transient imaging: scattering chocolate



scene

transient response



depth

[Images from Kotwal et al., 2023]

Passive NLOS imaging

direct imaging

scene

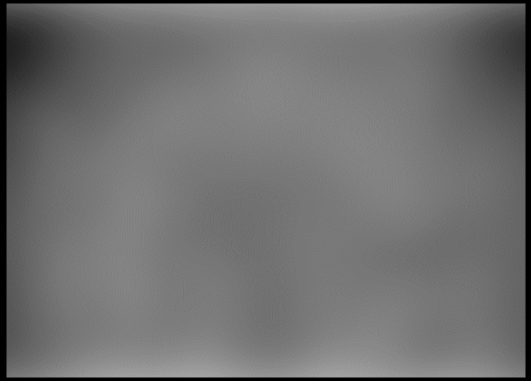
image

depth

descattered image

occluded imaging

scene



image

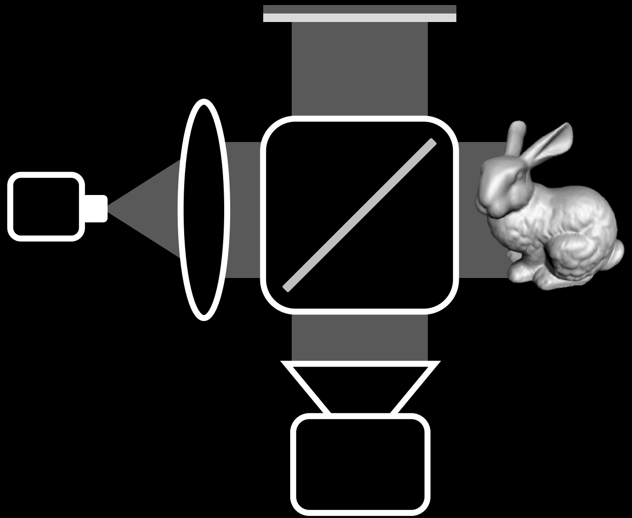
depth

descattered image

[Images from Kotwal et al., 2023]

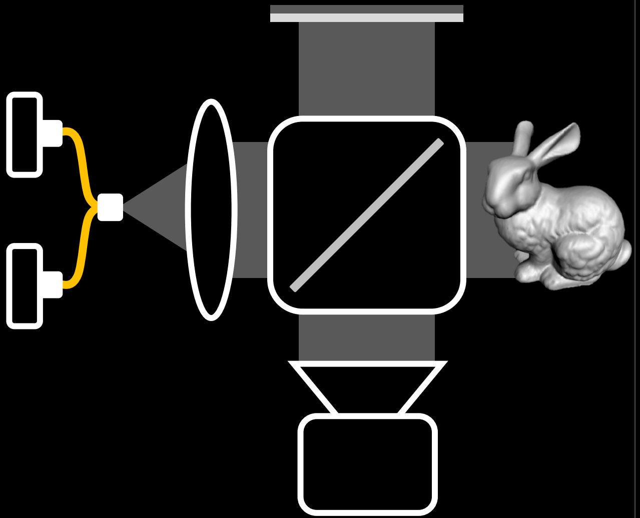
Course overview

introduction to interferometry



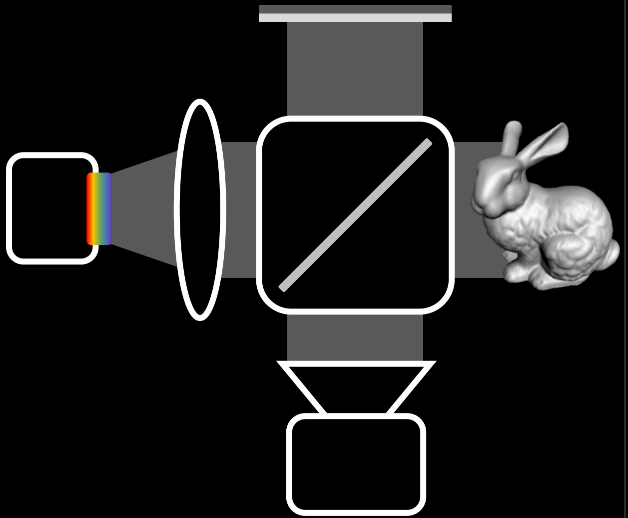
Yannis

two-wavelength interferometry



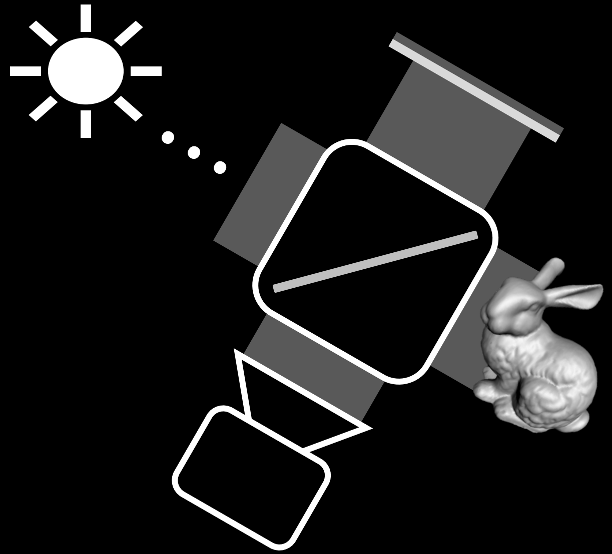
Florian

partially-coherent interferometry



Alankar

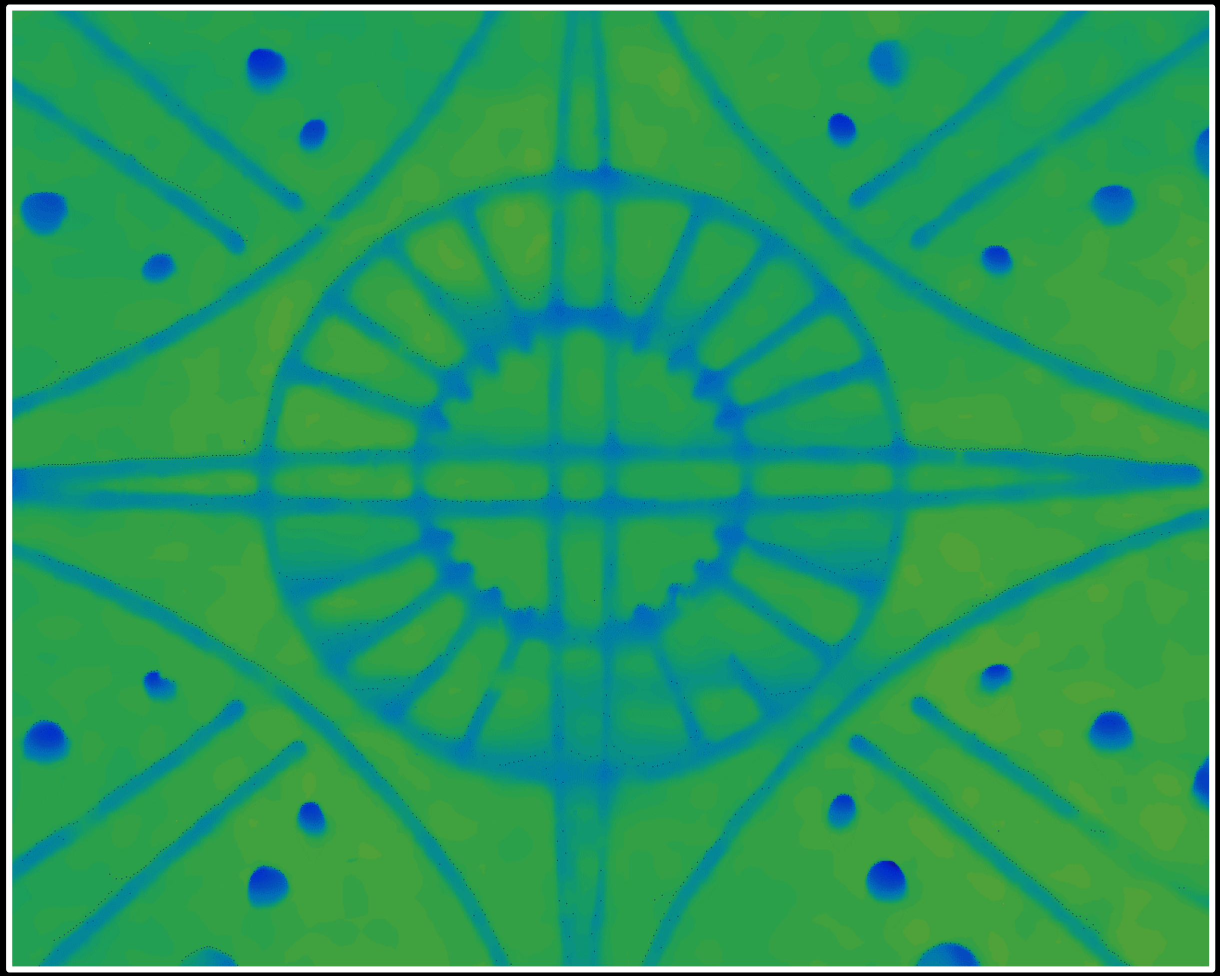
interferometric computational imaging

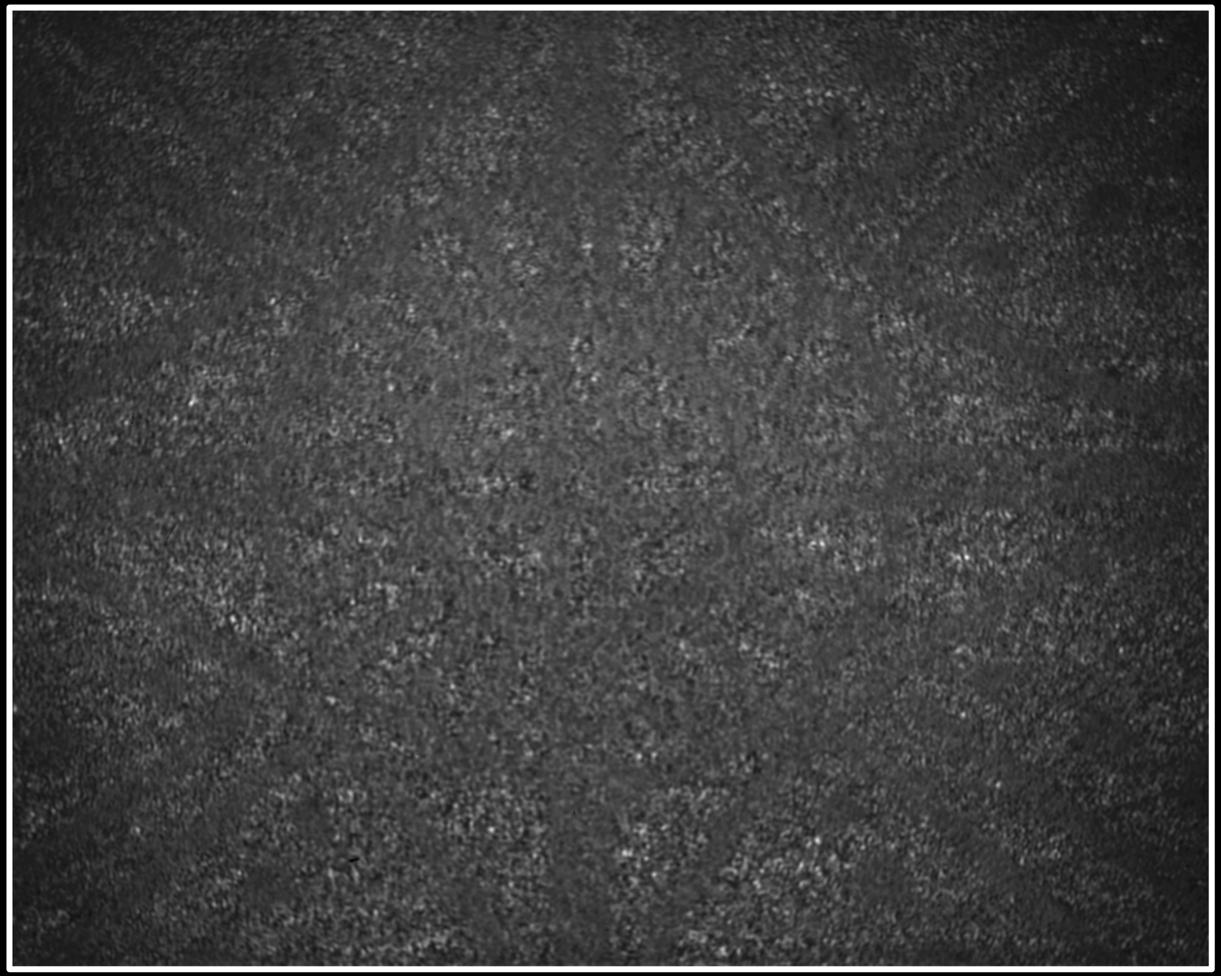


Florian

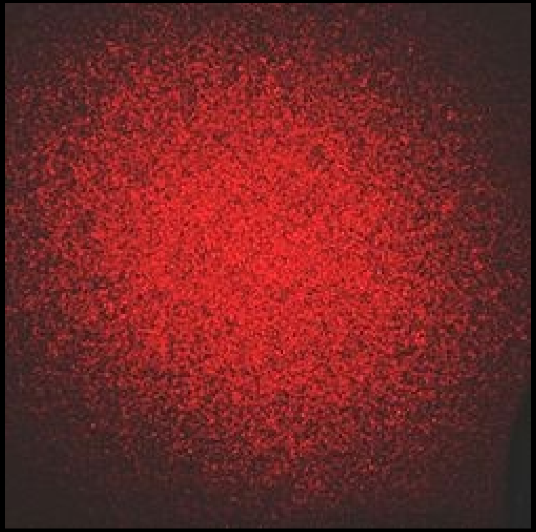
Yannis

A coherent world...

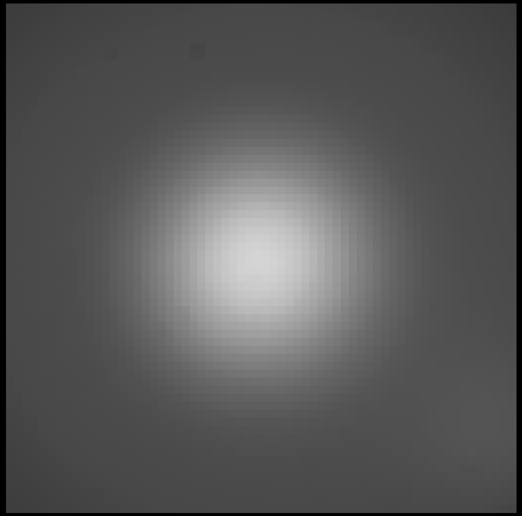




Speckle rendering



what real laser images look like



what standard Monte Carlo renderings look like

A Monte Carlo Framework for Rendering Speckle Statistics in Scattering Media

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MARINA ALTERMAN, Department of Electrical Engineering, Technion, Israel
IOANNIS GKIOULEKAS, Robotics Institute, Carnegie Mellon University, USA
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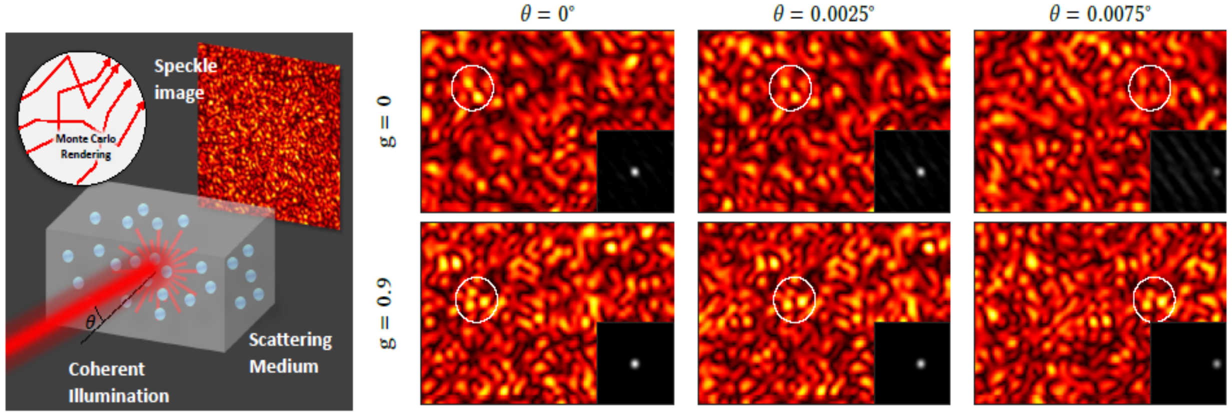
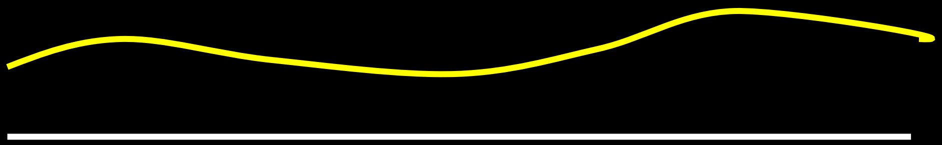


Fig. 1. **Simulation of memory effect in scattering.** Coherent images of translucent materials typically involve highly-fluctuating speckle structure. Despite their semi-random structure, speckles have strong statistical properties. For example, the memory effect property states that, as one tilts the 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.

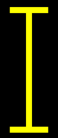
Other coherent effects

https://en.wikipedia.org/wiki/Thin-film_interference

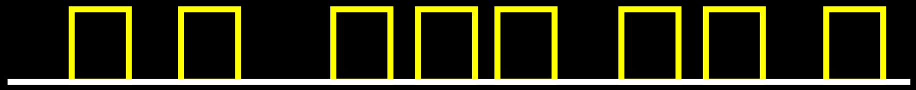
https://en.wikipedia.org/wiki/CD-ROM



thin film interference



$\approx 1\ \mu m$



diffraction

Some work in this area

A Generic Framework for Physical Light Transport

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

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

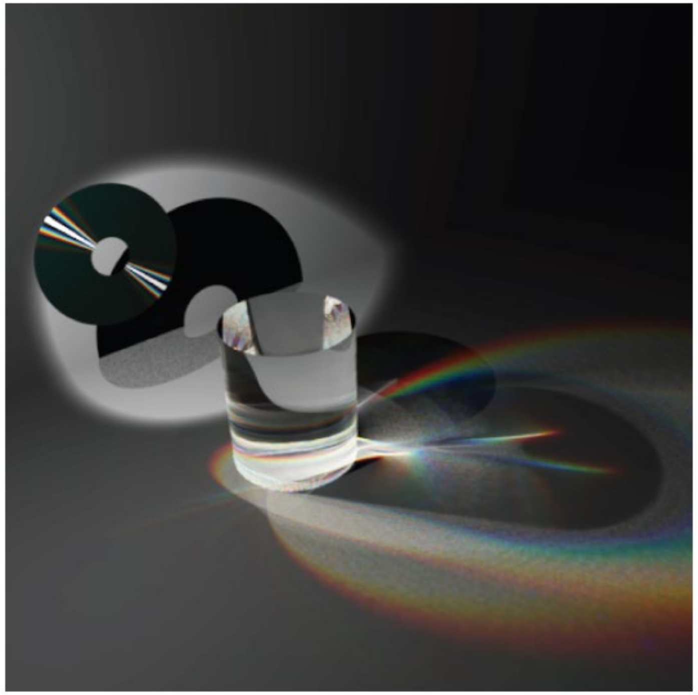
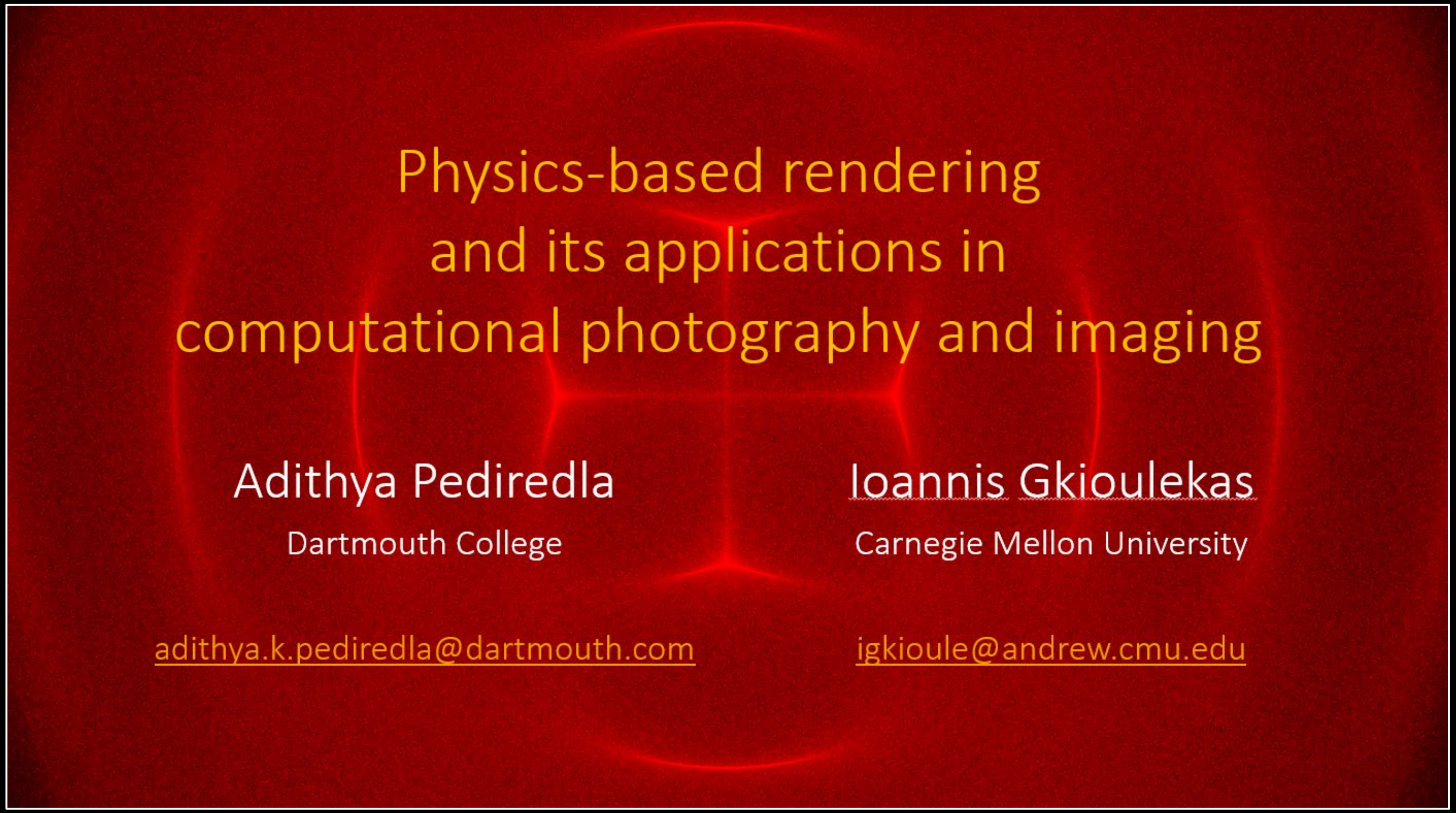


Fig. 1. We generalize the rendering equation and the BSDF to simulate wave phenomena. The new Wave BSDF behaves like a local scattering function, creates interference globally, and allows easy integration into traditional ray-based methods.

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

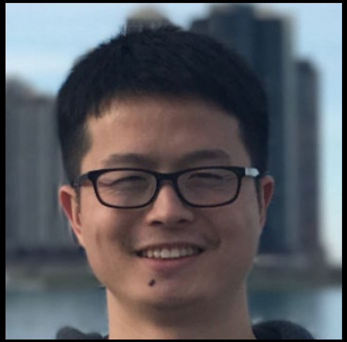
But it would be awesome if we could!



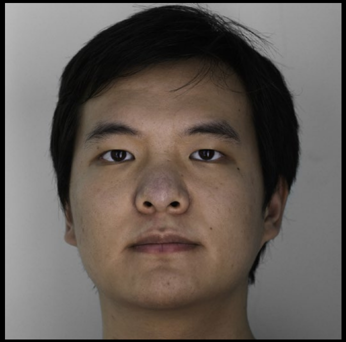
Many thanks to our collaborators!


Anat Levin


Ashok Vee-raraghavan


Fengqiang Li


Fredo Durand


Heming Wang


Jiren Li


Manuel Ballester


Marc Christensen

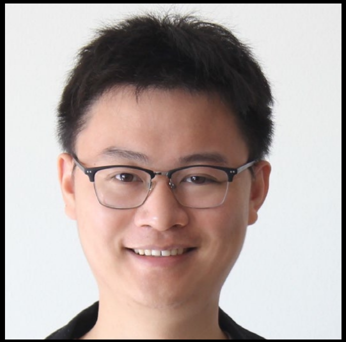

Muralidhar Balaji


Oliver Cossairt


Patrick Cornwall


Prasanna Rangarajan


Todd Zickler


Yicheng Wu

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