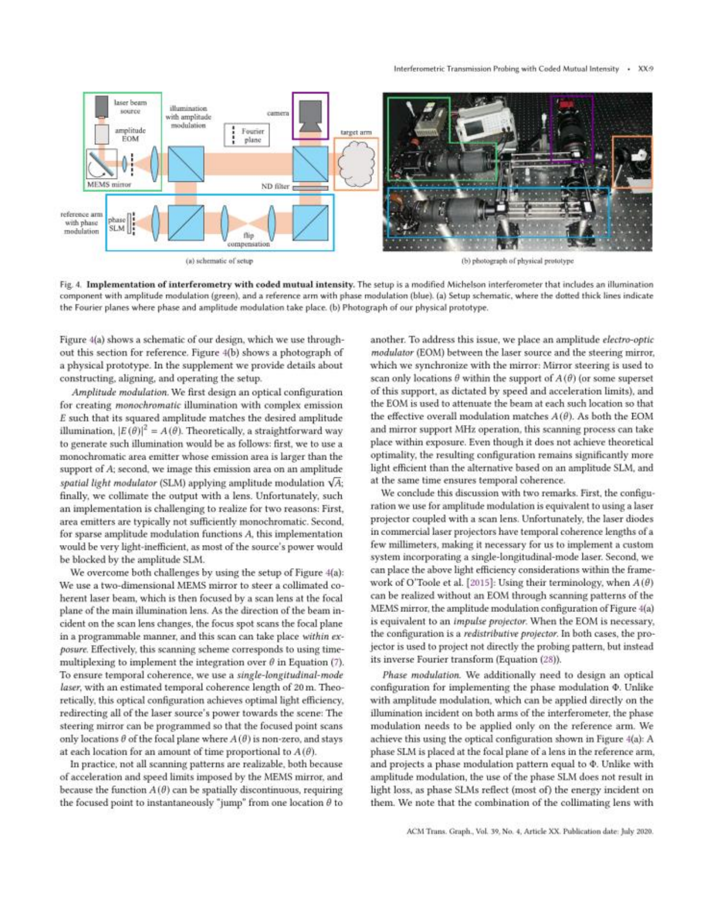
Swept-Angle Synthetic Wavelength Interferometry

Alankar Kotwal

Recap: SIGGRAPH 2020 paper!



(a) schematic of setup

(b) photograph of physical prototype

Fig. 4. **Implementation of interferometry with coded mutual intensity.** The setup is a modified Michelson interferometer that includes an illumination component with amplitude modulation (green), and a reference arm with phase modulation (blue). (a) Setup schematic, where the dotted thick lines indicate the Fourier planes where phase and amplitude modulation take place. (b) Photograph of our physical prototype.

Figure 4(a) shows a schematic of our design, which we use throughout this section for reference. Figure 4(b) shows a photograph of a physical prototype. In the supplement we provide details about constructing, aligning, and operating the setup.

Amplitude modulation. We first design an optical configuration for creating *monochromatic* illumination with complex emission E such that its squared amplitude matches the desired amplitude illumination, $|E(\theta)|^2 = A(\theta)$. Theoretically, a straightforward way to generate such illumination would be as follows: first, we to use a monochromatic area emitter whose emission area is larger than the support of A; second, we image this emission area on an amplitude *spatial light modulator* (SLM) applying amplitude modulation $\sqrt{A}$; finally, we collimate the output with a lens. Unfortunately, such an implementation is challenging to realize for two reasons: First, area emitters are typically not sufficiently monochromatic. Second, for sparse amplitude modulation functions A, this implementation would be very light-inefficient, as most of the source's power would be blocked by the amplitude SLM.

We overcome both challenges by using the setup of Figure 4(a): We use a two-dimensional MEMS mirror to steer a collimated coherent laser beam, which is then focused by a scan lens at the focal plane of the main illumination lens. As the direction of the beam incident on the scan lens changes, the focus spot scans the focal plane in a programmable manner, and this scan can take place *within exposure*. Effectively, this scanning scheme corresponds to using time-multiplexing to implement the integration over θ in Equation (7). To ensure temporal coherence, we use a *single-longitudinal-mode laser*, with an estimated temporal coherence length of 20 m. Theoretically, this optical configuration achieves optimal light efficiency, redirecting all of the laser source's power towards the scene: The steering mirror can be programmed so that the focused point scans only locations θ of the focal plane where $A(\theta)$ is non-zero, and stays at each location for an amount of time proportional to $A(\theta)$.

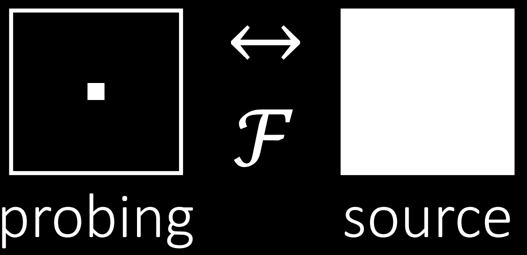
In practice, not all scanning patterns are realizable, both because of acceleration and speed limits imposed by the MEMS mirror, and because the function $A(\theta)$ can be spatially discontinuous, requiring the focused point to instantaneously "jump" from one location θ to another. To address this issue, we place an amplitude *electro-optic modulator* (EOM) between the laser source and the steering mirror, which we synchronize with the mirror: Mirror steering is used to scan only locations θ within the support of $A(\theta)$ (or some superset of this support, as dictated by speed and acceleration limits), and the EOM is used to attenuate the beam at each such location so that the effective overall modulation matches $A(\theta)$. As both the EOM and mirror support MHz operation, this scanning process can take place within exposure. Even though it does not achieve theoretical optimality, the resulting configuration remains significantly more light efficient than the alternative based on an amplitude SLM, and at the same time ensures temporal coherence.

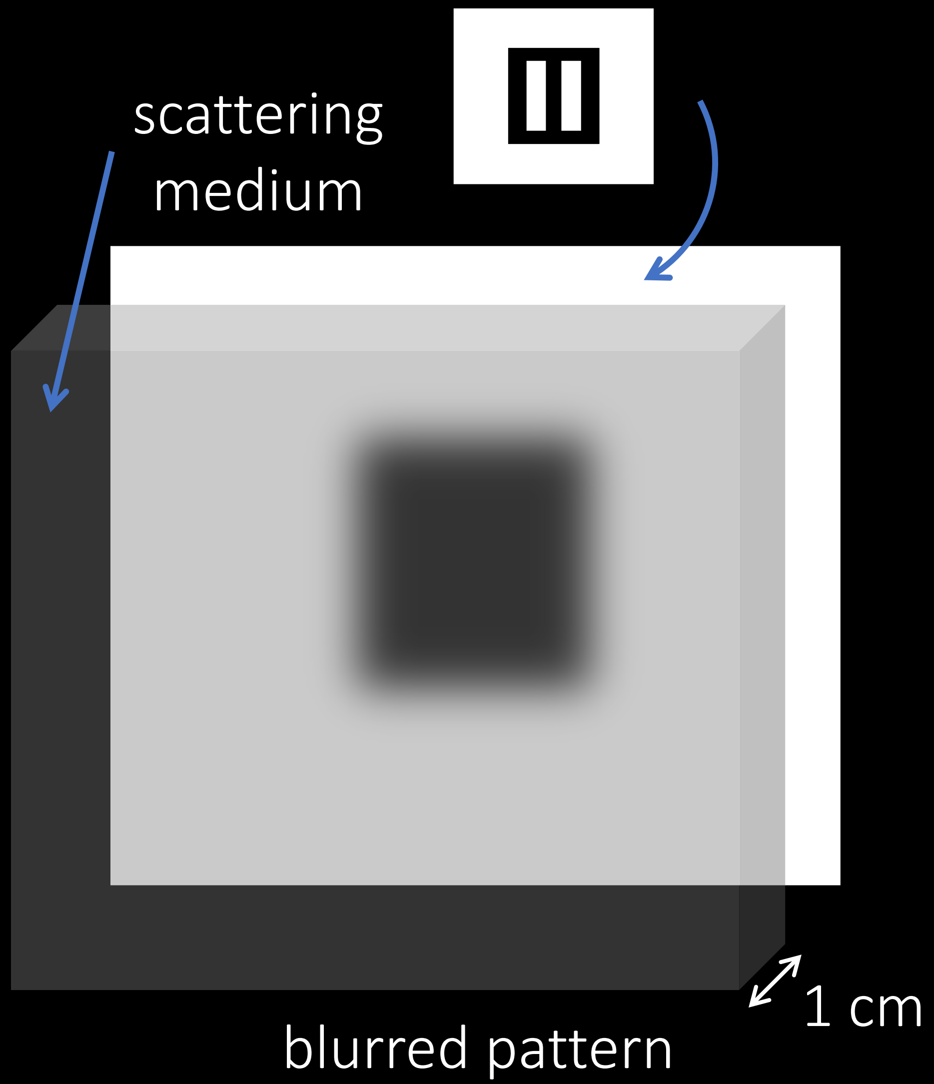
We conclude this discussion with two remarks. First, the configuration we use for amplitude modulation is equivalent to using a laser projector coupled with a scan lens. Unfortunately, the laser diodes in commercial laser projectors have temporal coherence lengths of a few millimeters, making it necessary for us to implement a custom system incorporating a single-longitudinal-mode laser. Second, we can place the above light efficiency considerations within the framework of O'Toole et al. [2015]: Using their terminology, when $A(\theta)$ can be realized without an EOM through scanning patterns of the MEMS mirror, the amplitude modulation configuration of Figure 4(a) is equivalent to an *impulse projector*. When the EOM is necessary, the configuration is a *redistributive projector*. In both cases, the projector is used to project not directly the probing pattern, but instead its inverse Fourier transform (Equation (28)).

Phase modulation. We additionally need to design an optical configuration for implementing the phase modulation Φ. Unlike with amplitude modulation, which can be applied directly on the illumination incident on both arms of the interferometer, the phase modulation needs to be applied only on the reference arm. We achieve this using the optical configuration shown in Figure 4(a): A phase SLM is placed at the focal plane of a lens in the reference arm, and projects a phase modulation pattern equal to Φ. Unlike with amplitude modulation, the use of the phase SLM does not result in light loss, as phase SLMs reflect (most of) the energy incident on them. We note that the combination of the collimating lens with

https://tinyurl.com/CoherentProbing

Recap: spatial probing result





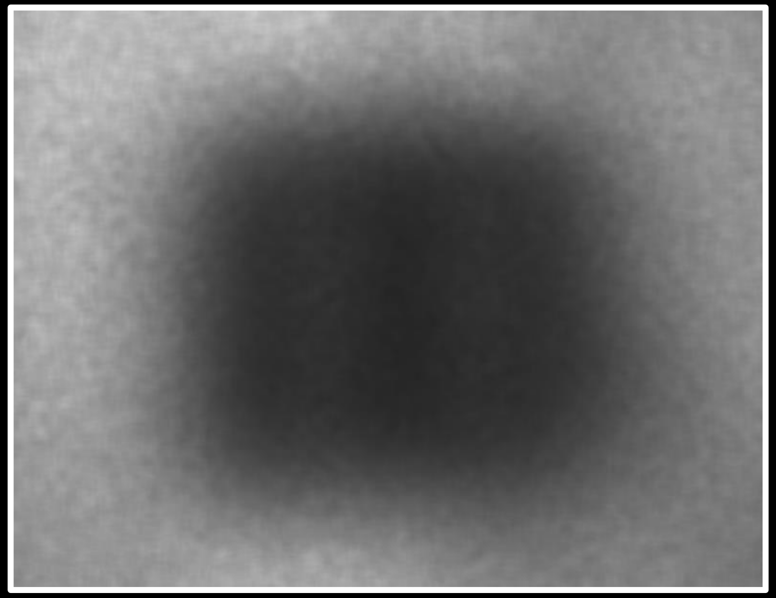


image from a regular camera

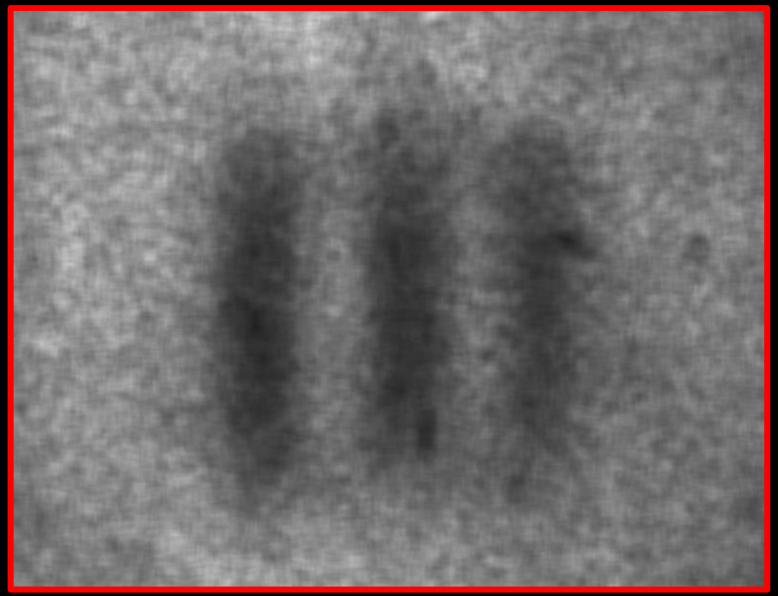
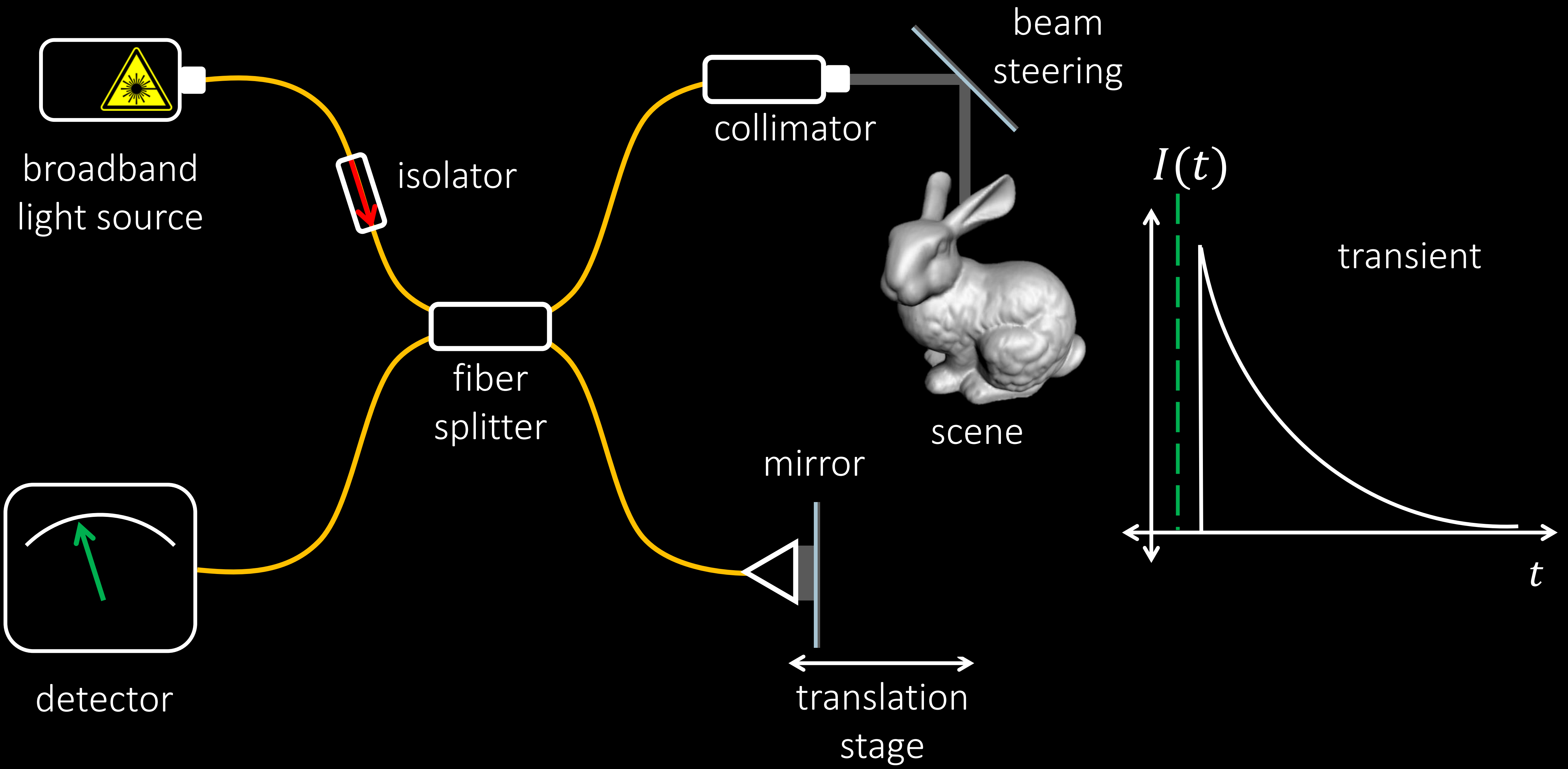
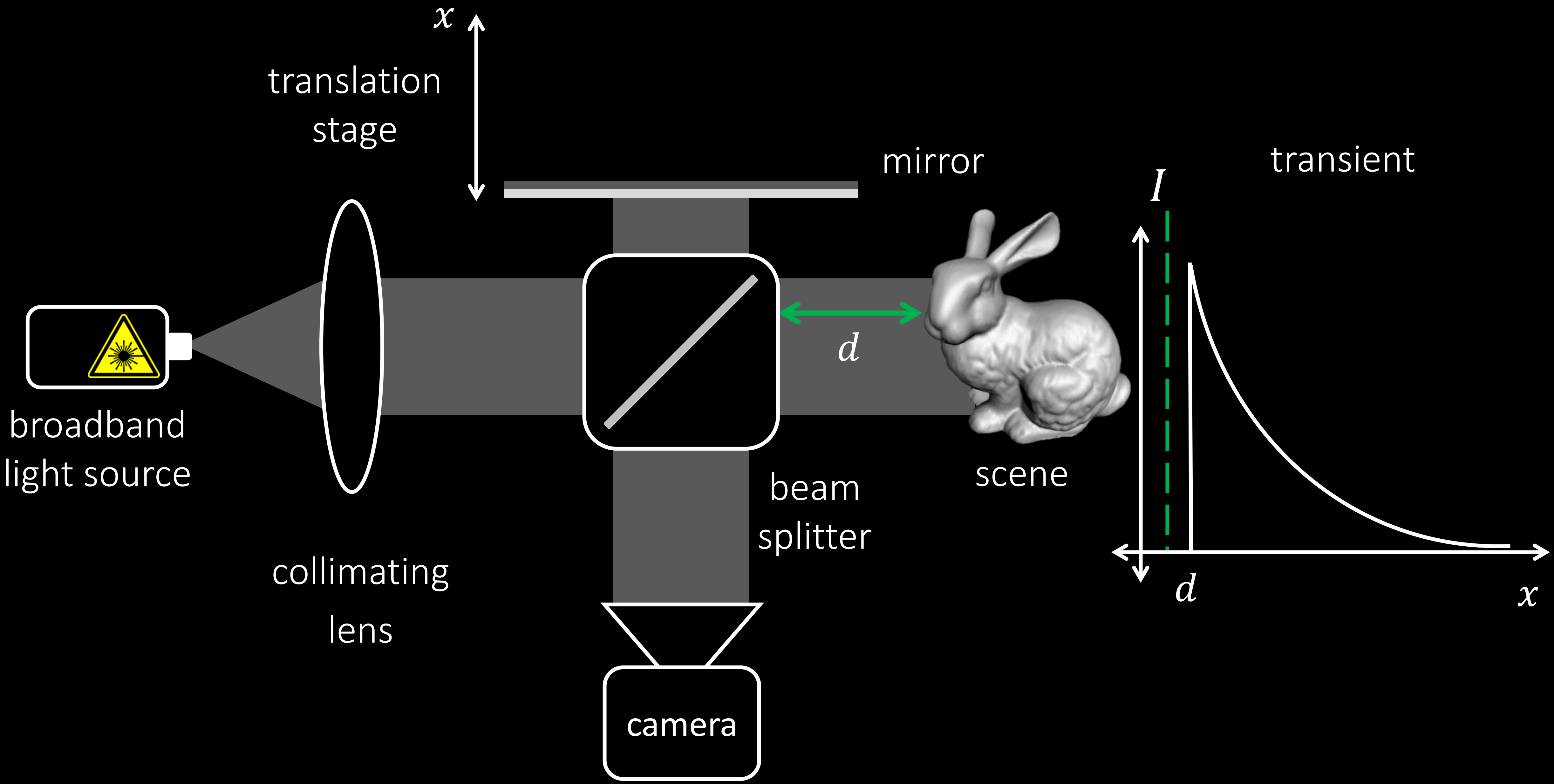


image with direct-only probing

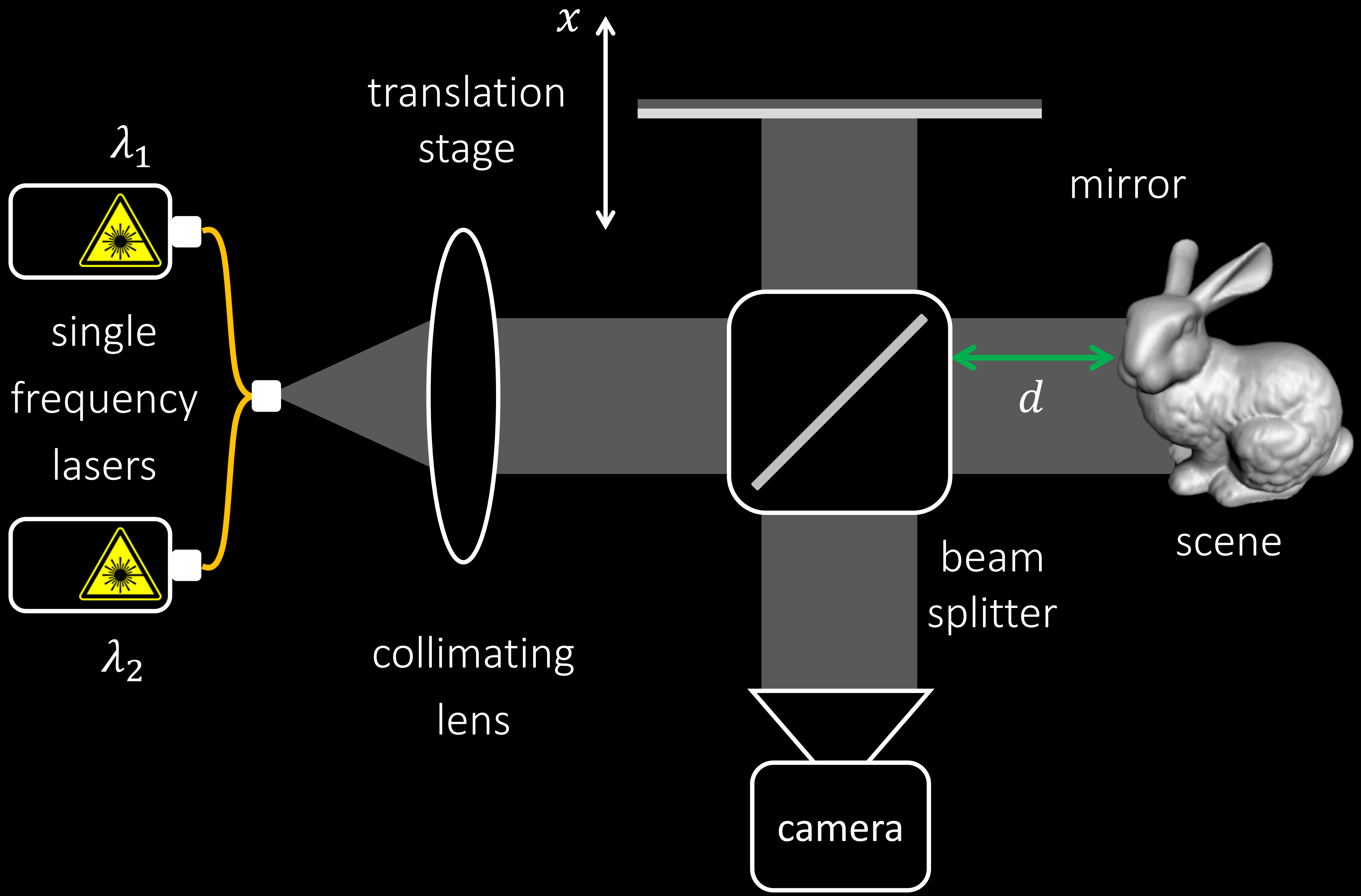
Fiber-based optical coherence tomography



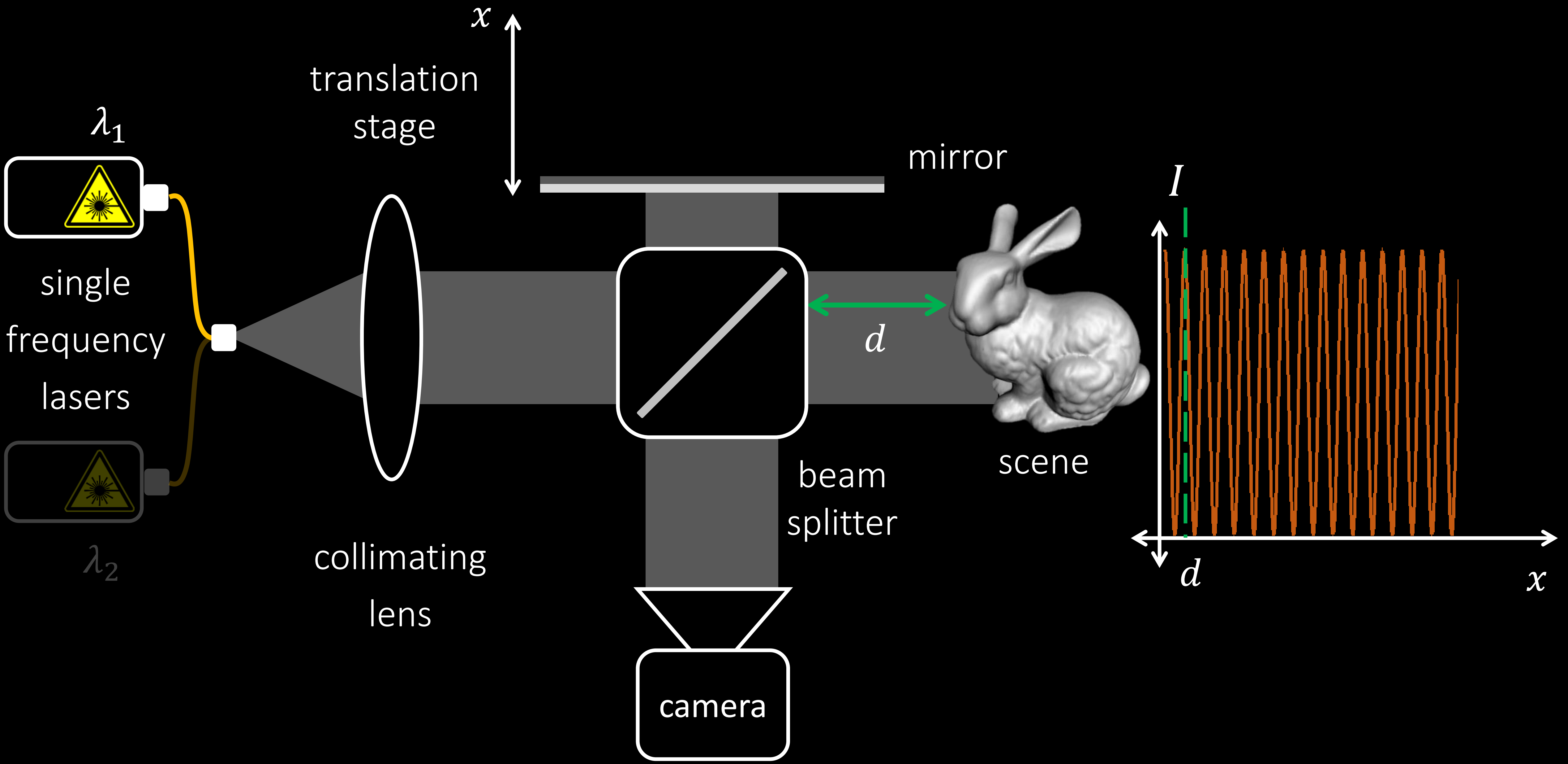
Full-field optical coherence tomography



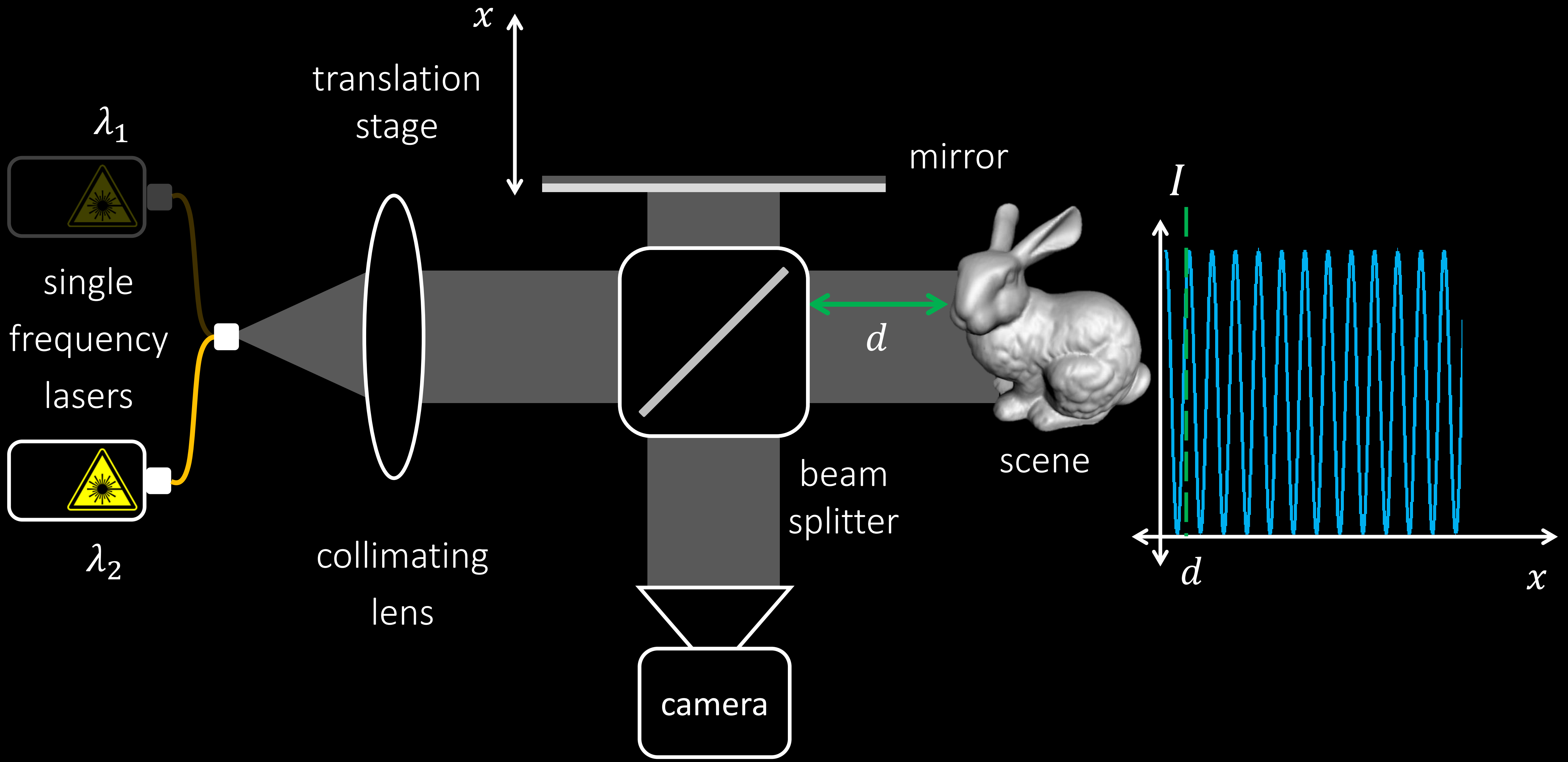
Synthetic wavelength interferometry



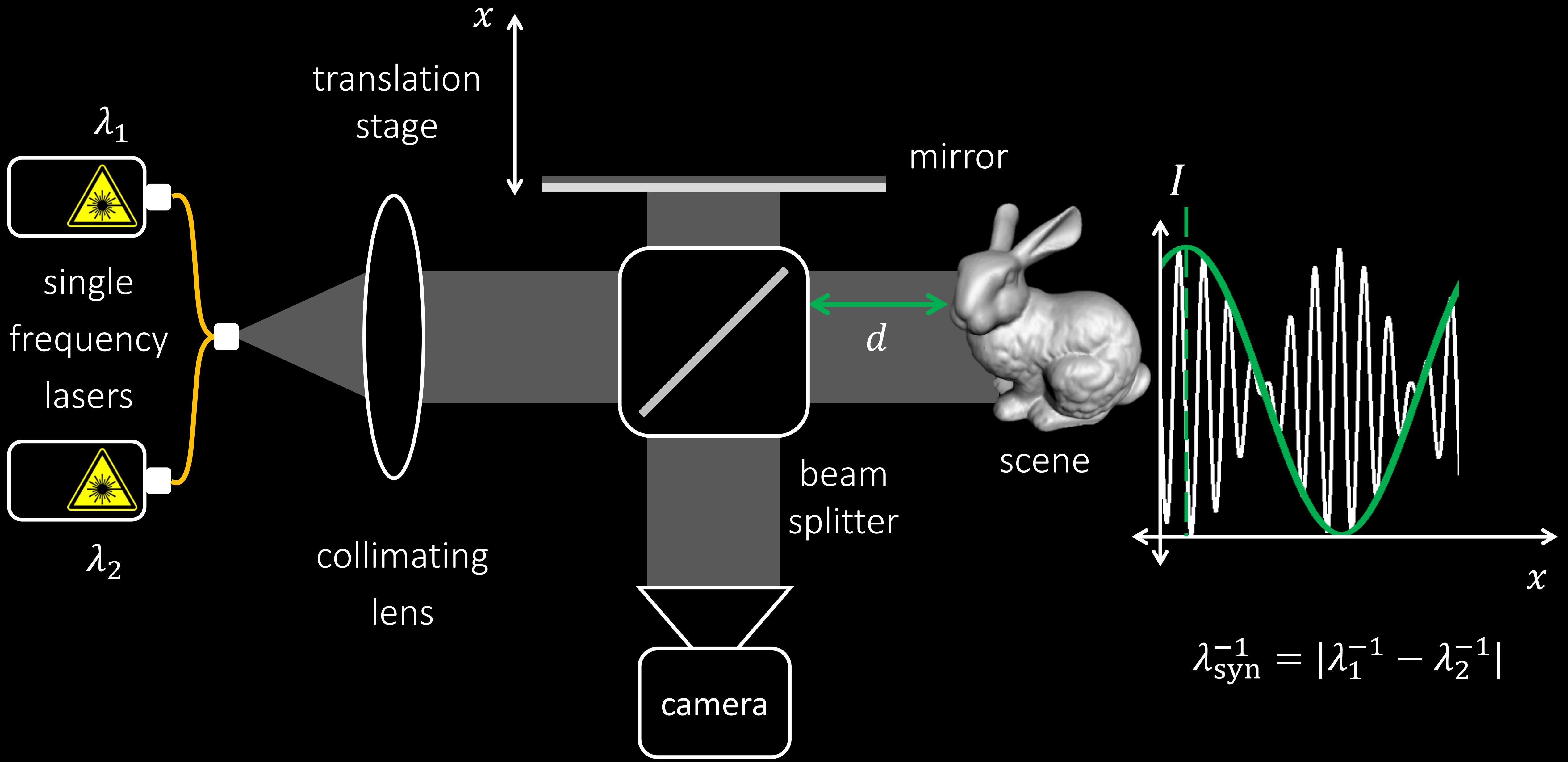
Synthetic wavelength interferometry



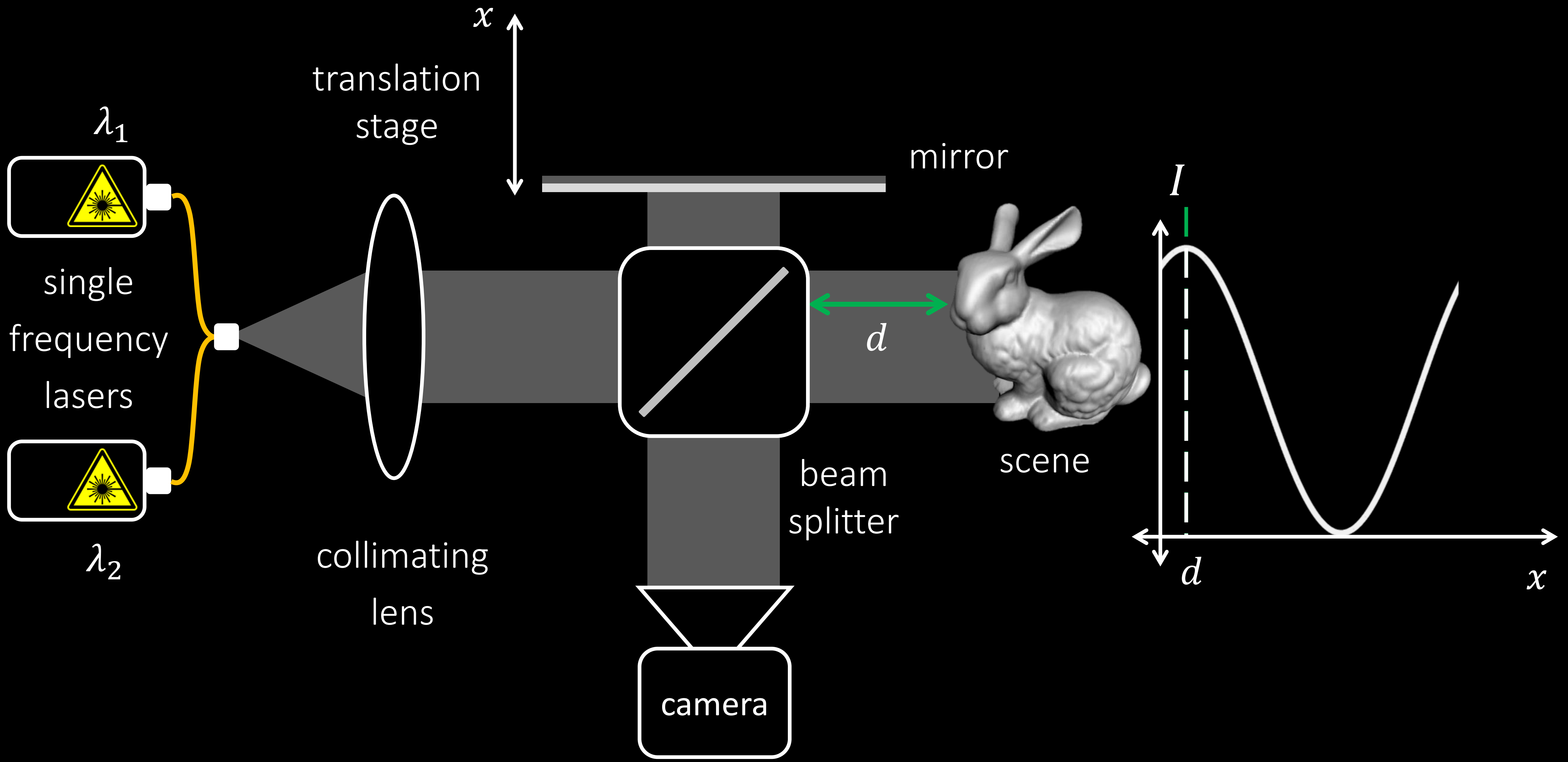
Synthetic wavelength interferometry



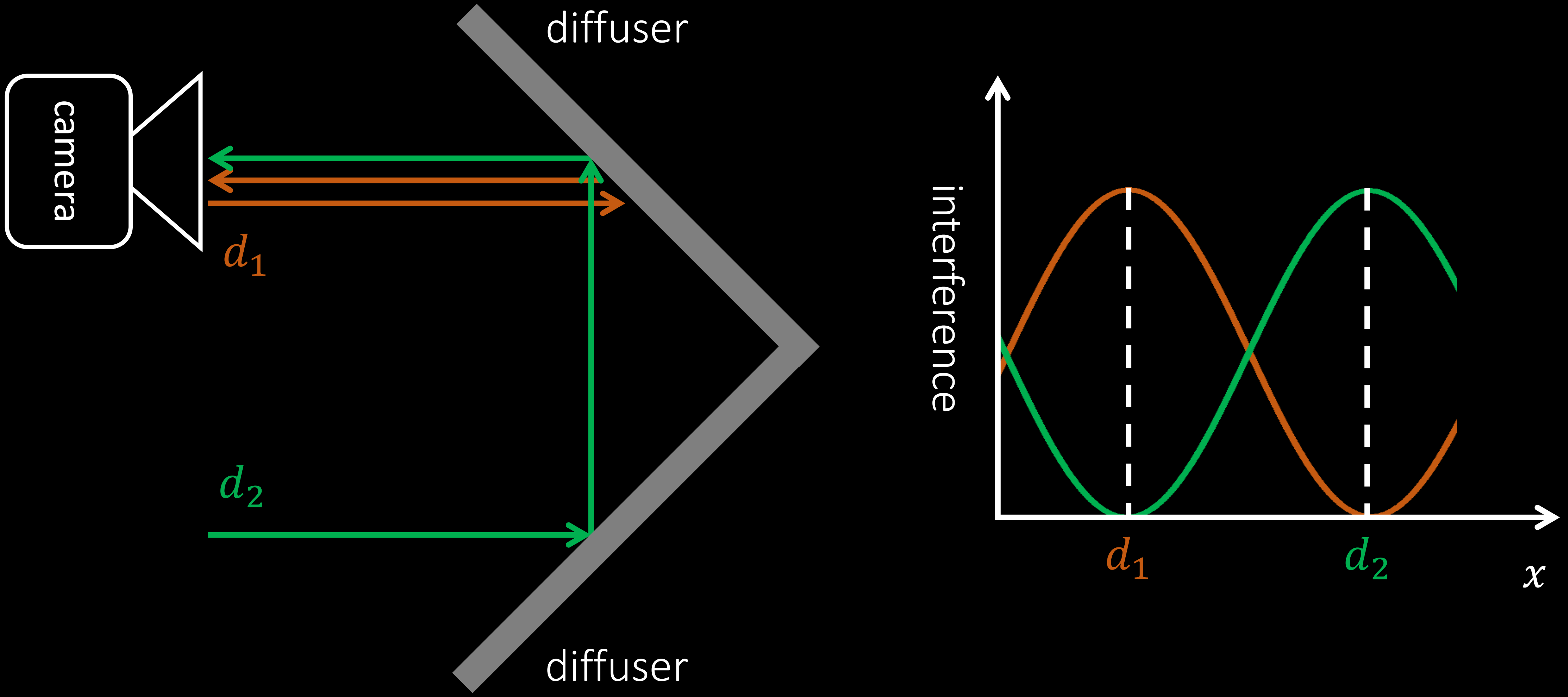
Synthetic wavelength interferometry



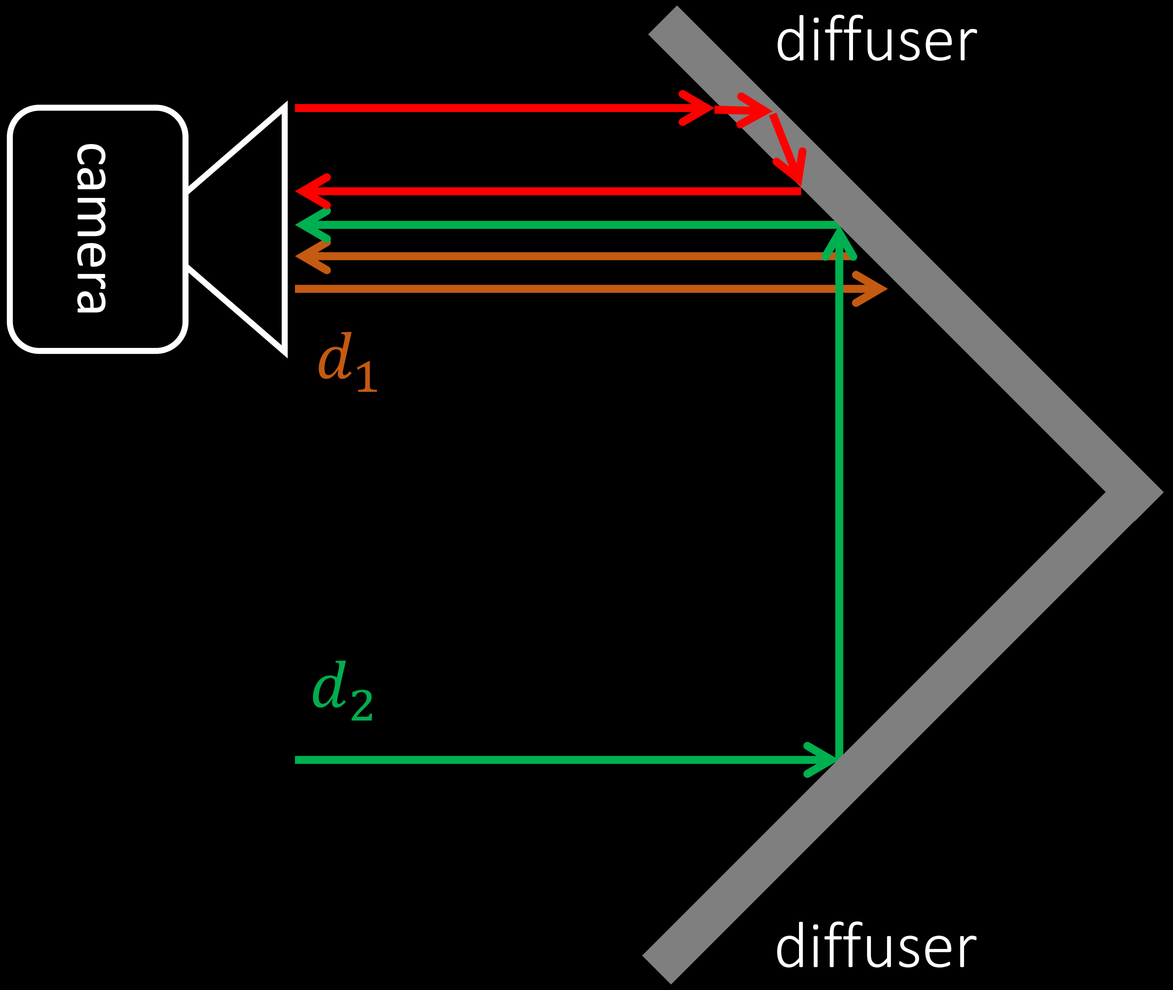
Synthetic wavelength interferometry

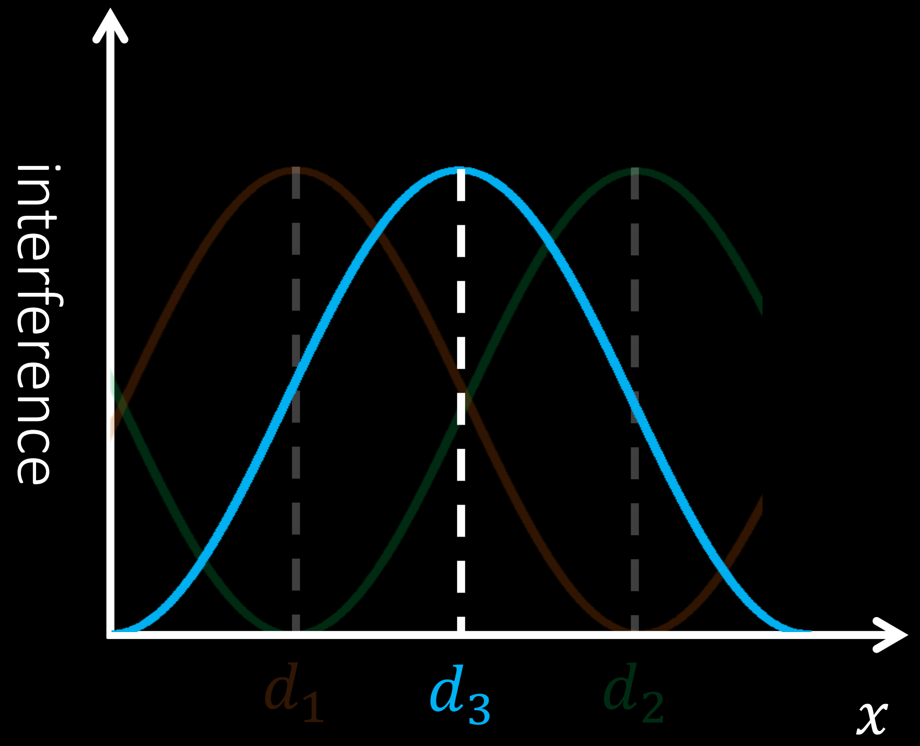


Effects of global illumination

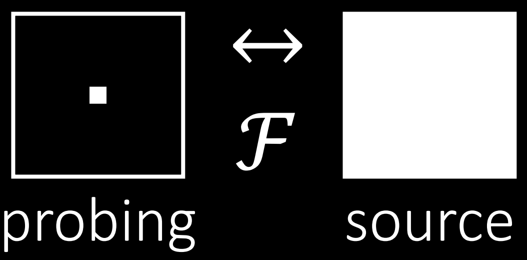


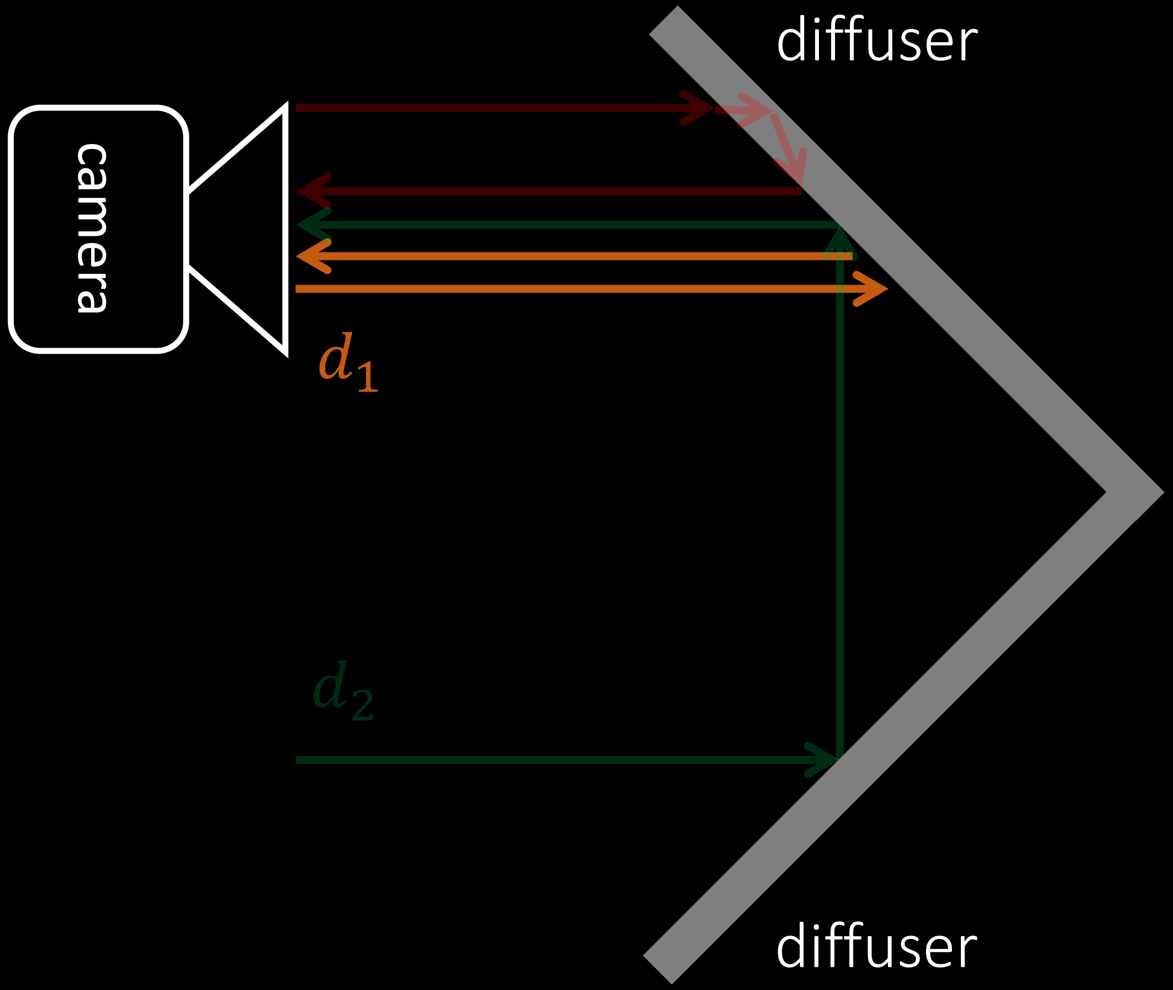
Effects of global illumination

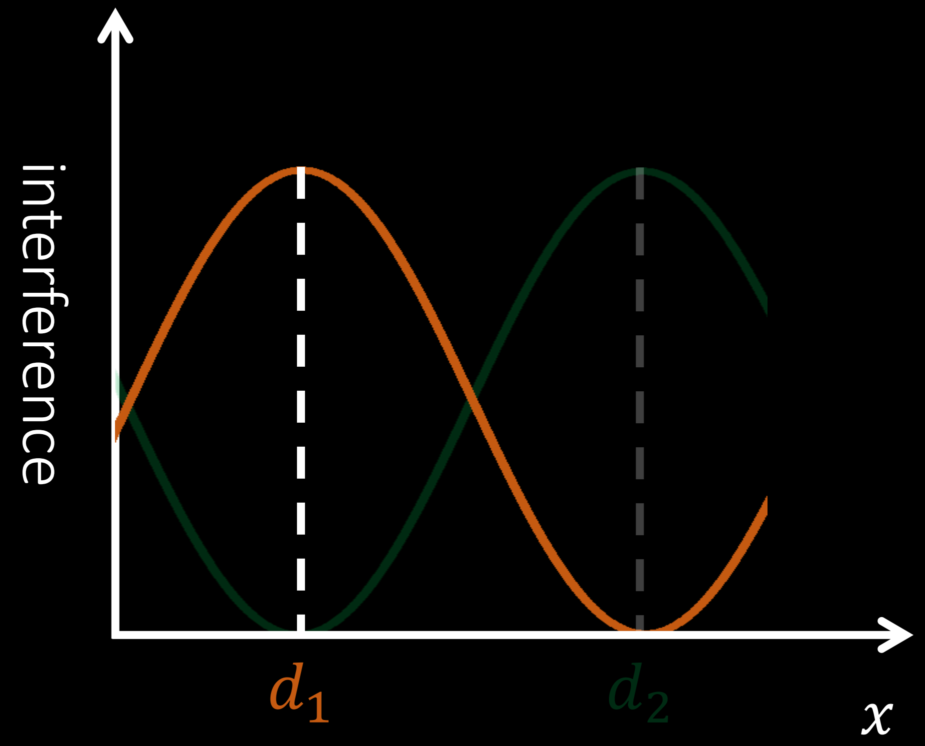




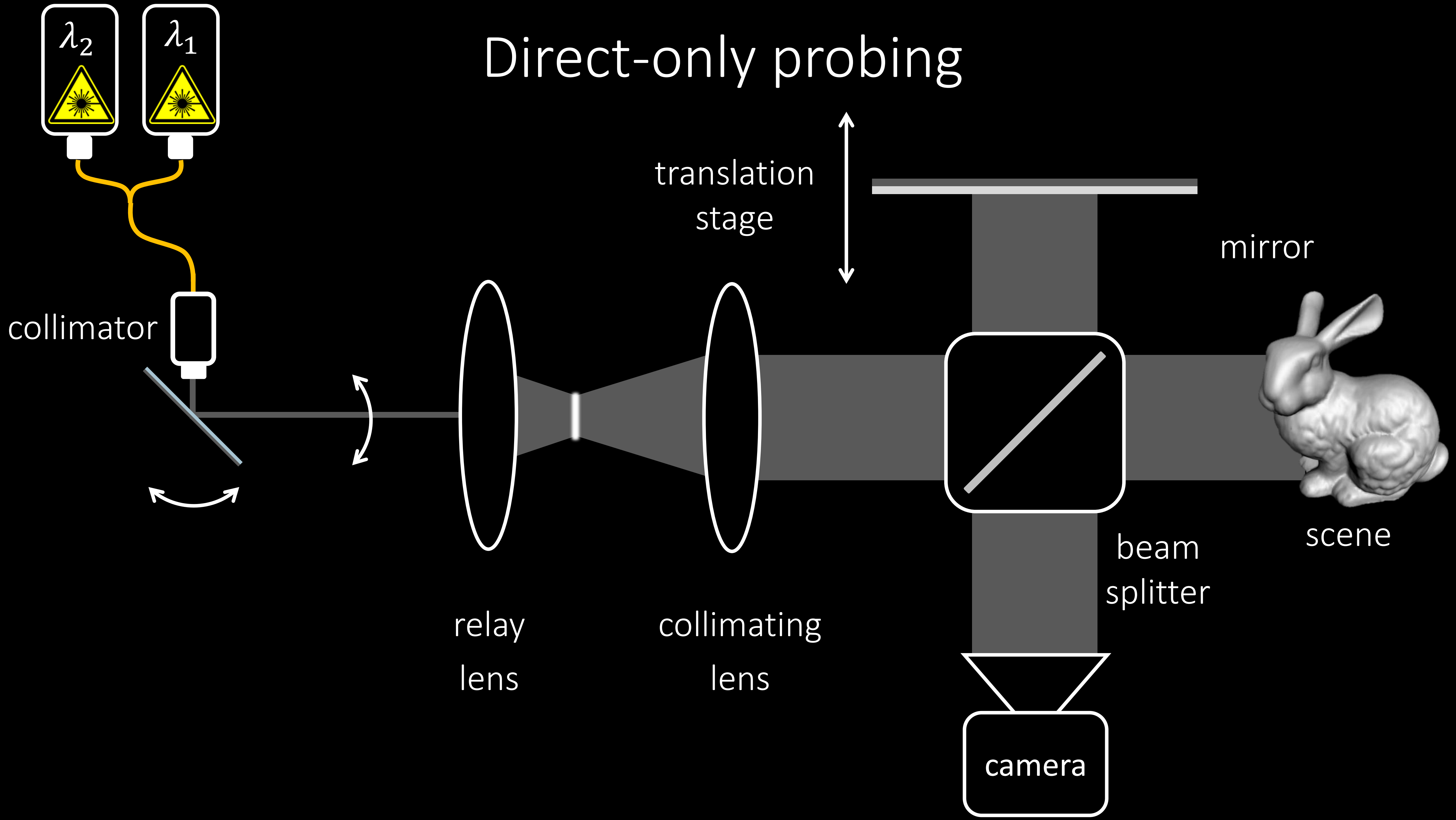
With direct-only probing



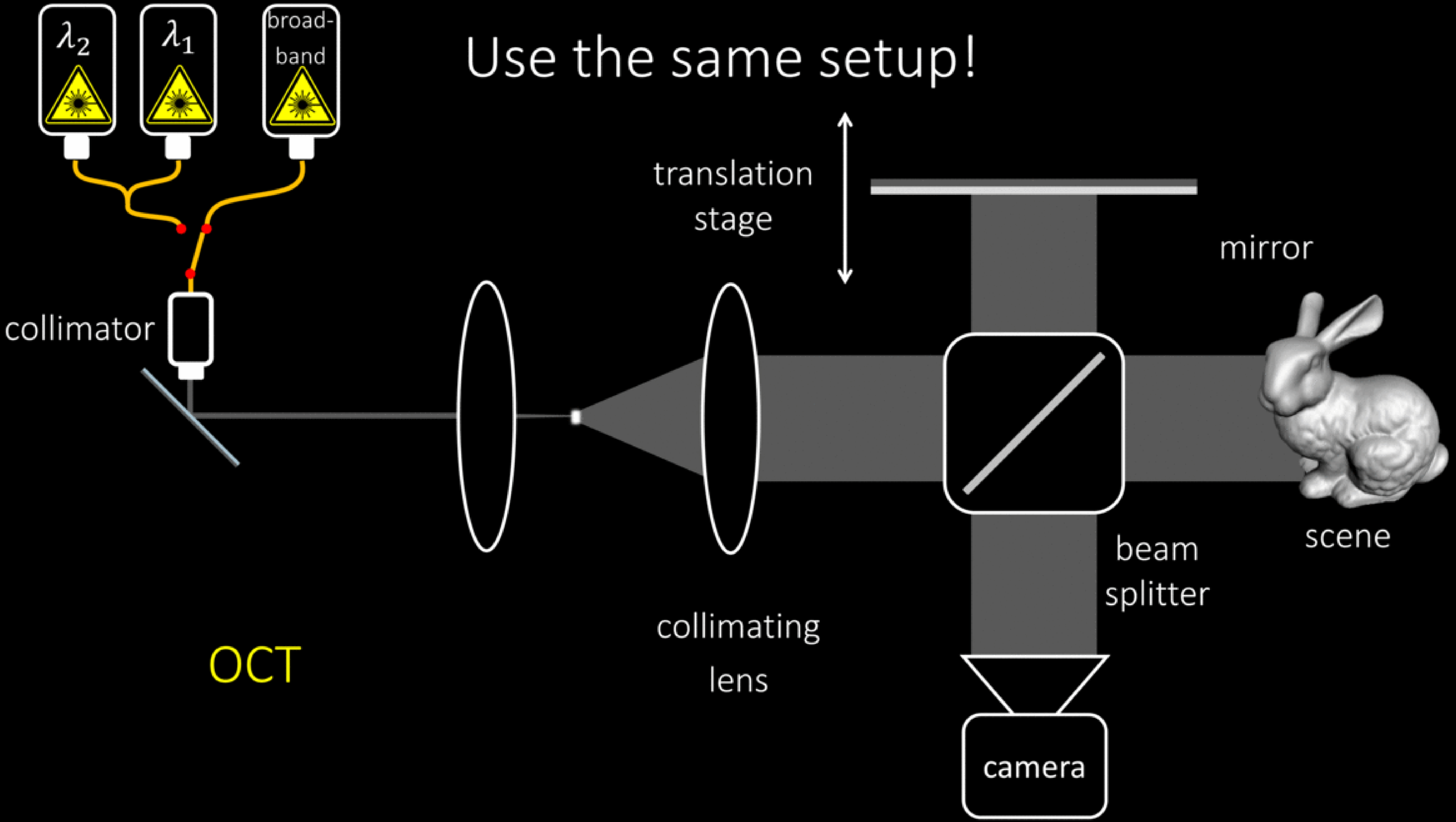




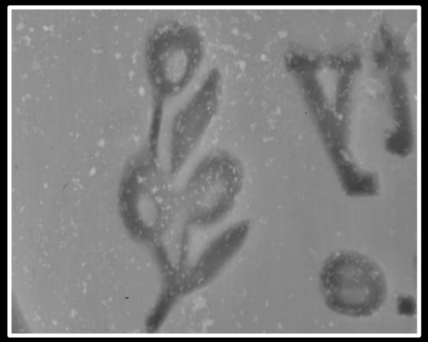
Direct-only probing

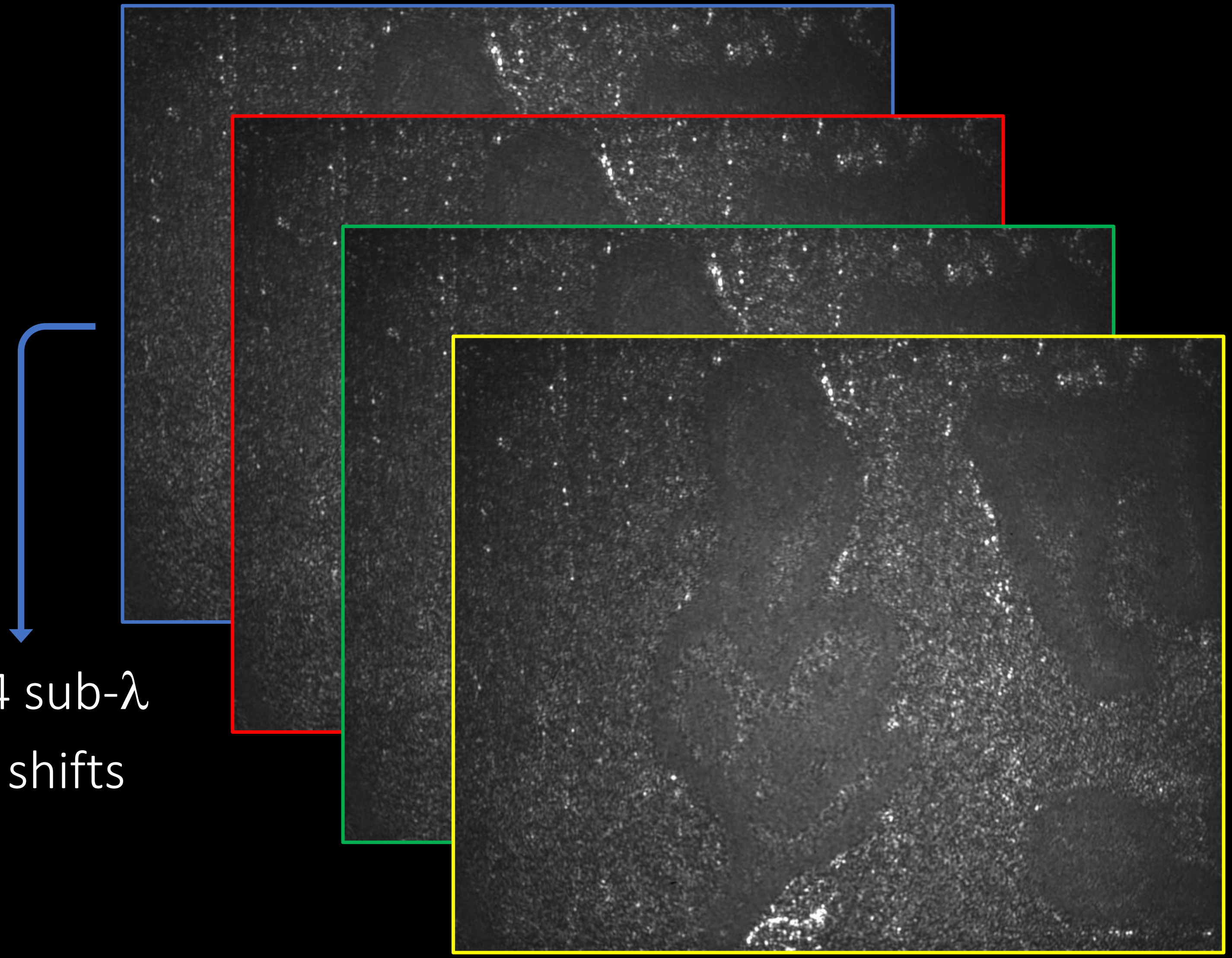


Use the same setup!



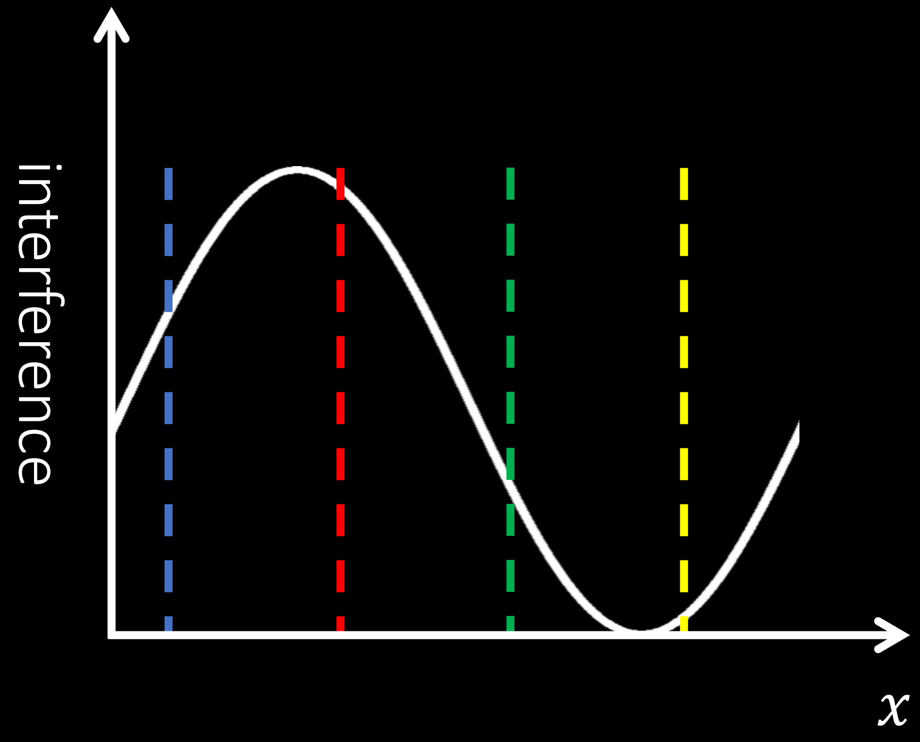
Measurements



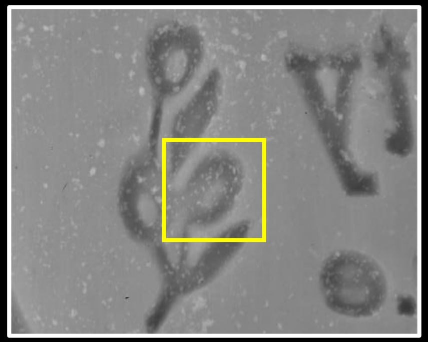


4 sub-λ shifts

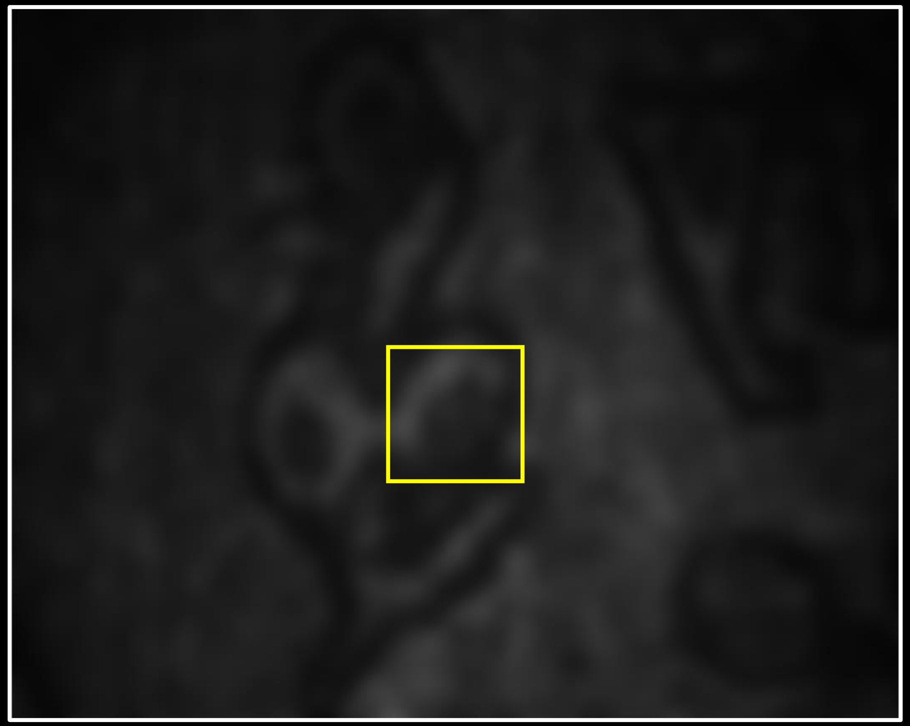
4-bucket positions



Post-processing measurements

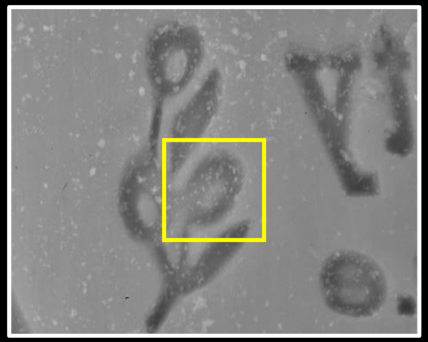


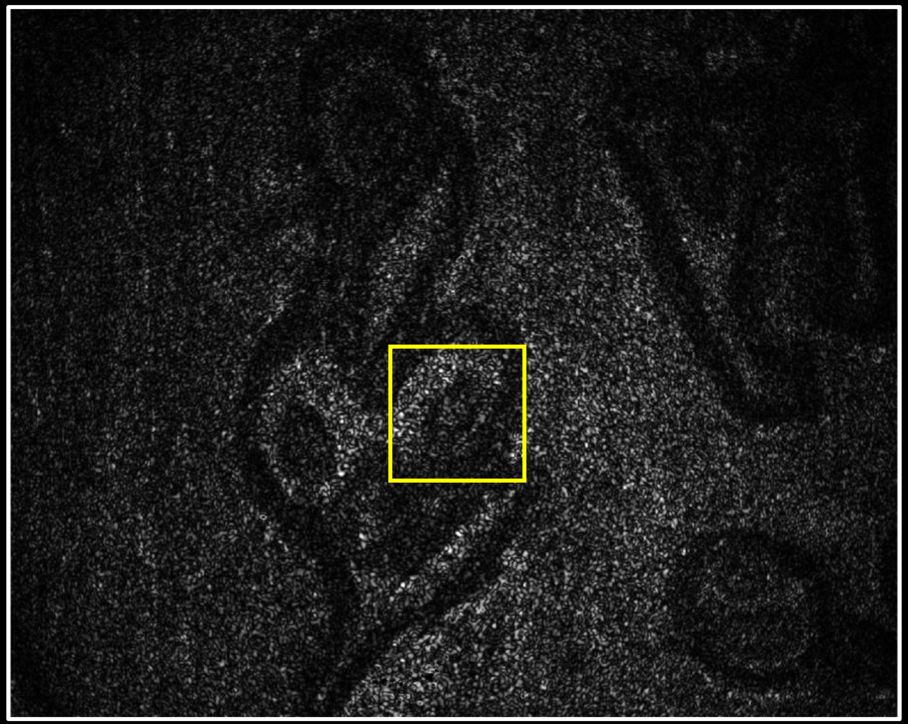
speckle



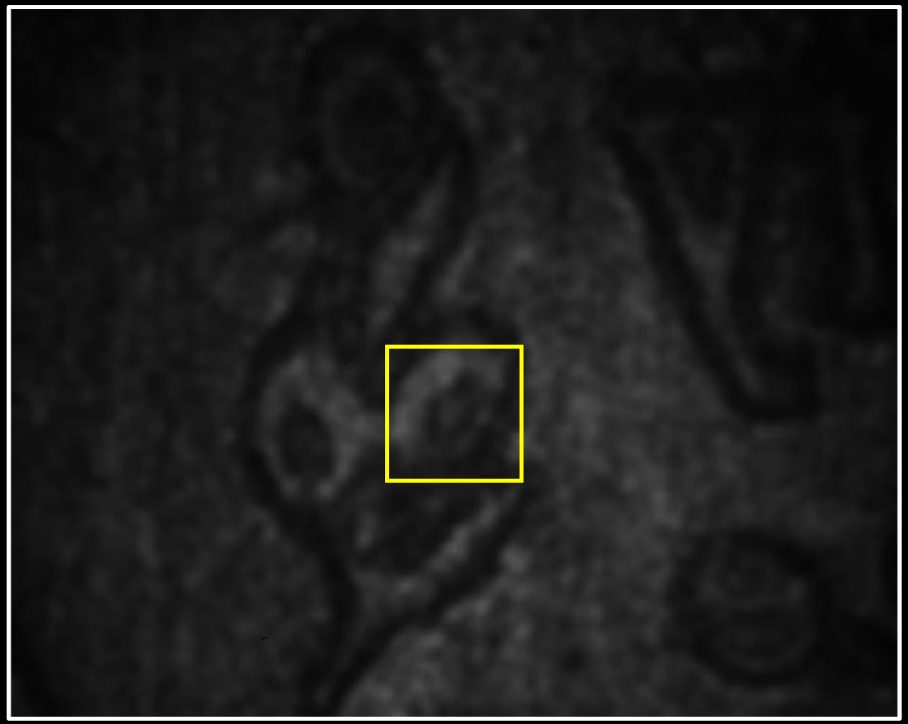
with Gaussian blurring

Bilateral filtering



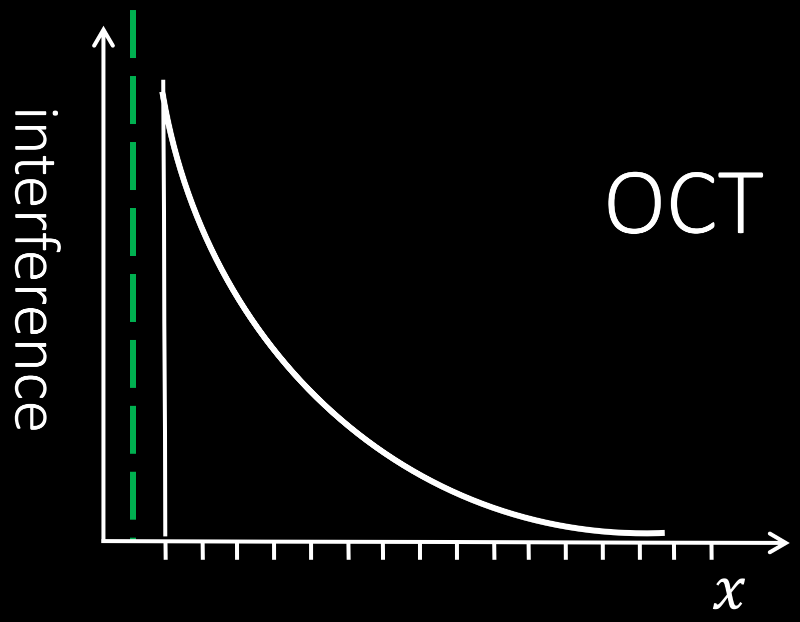


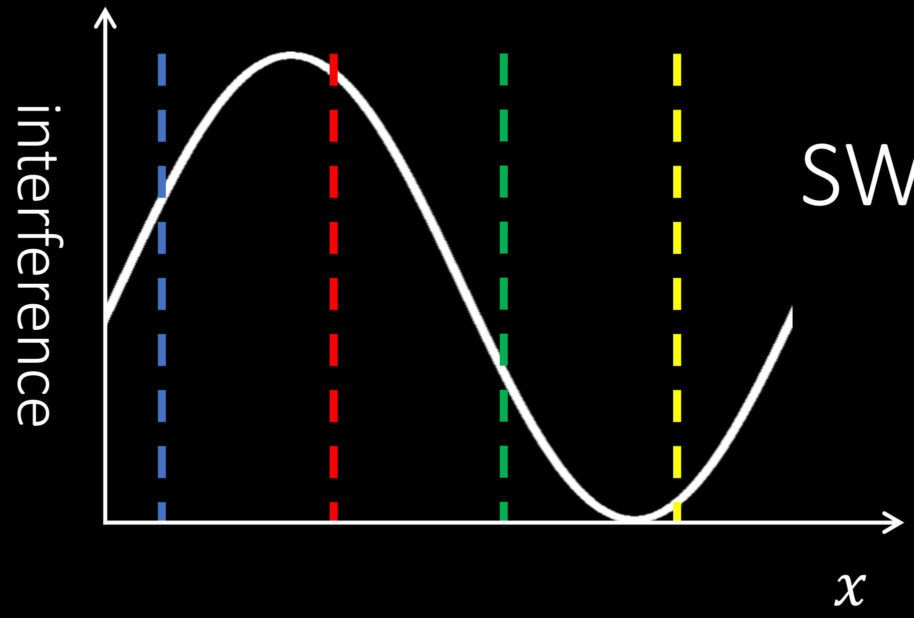
speckle



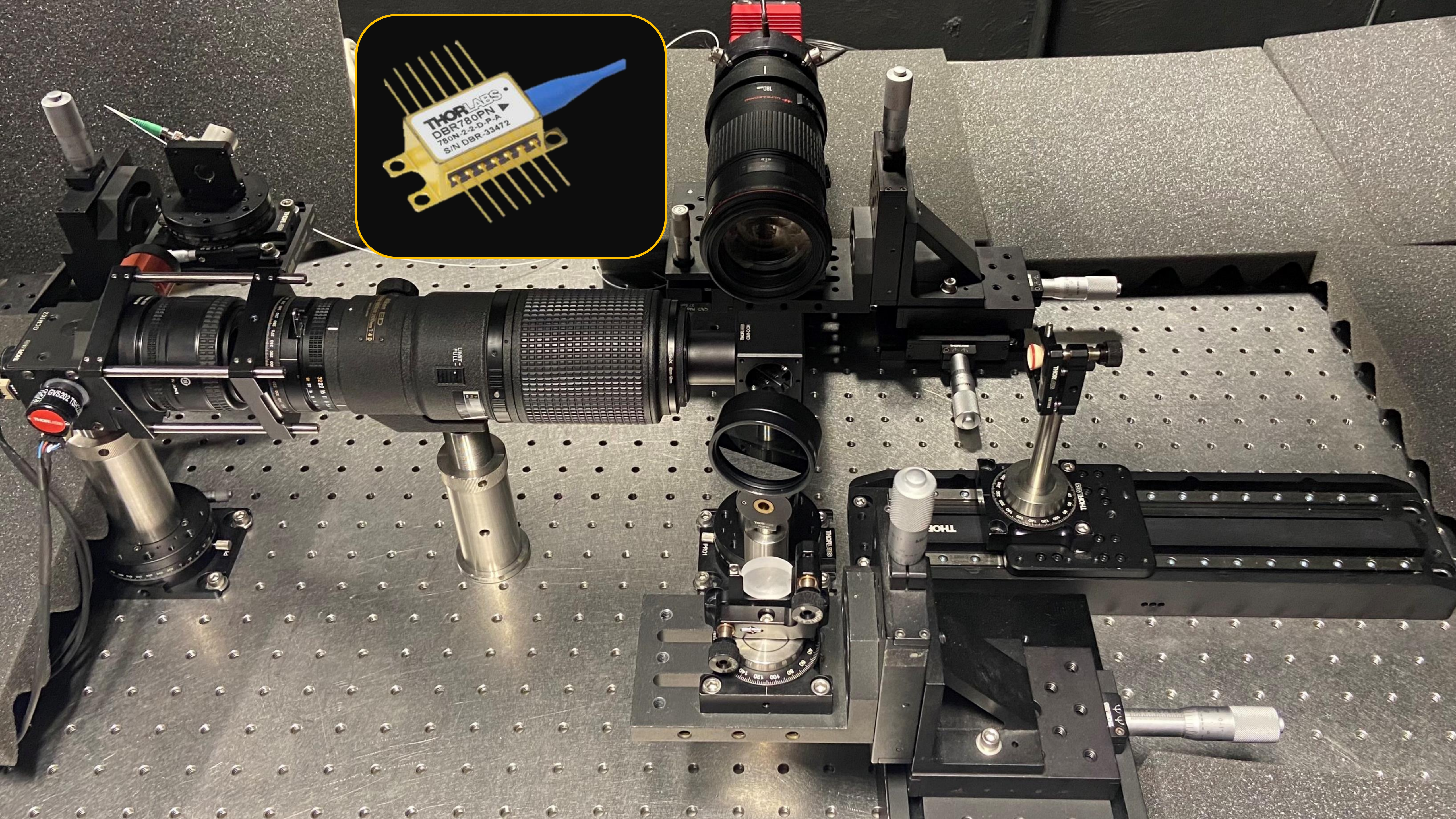
with bilateral filtering

Depth range and resolution

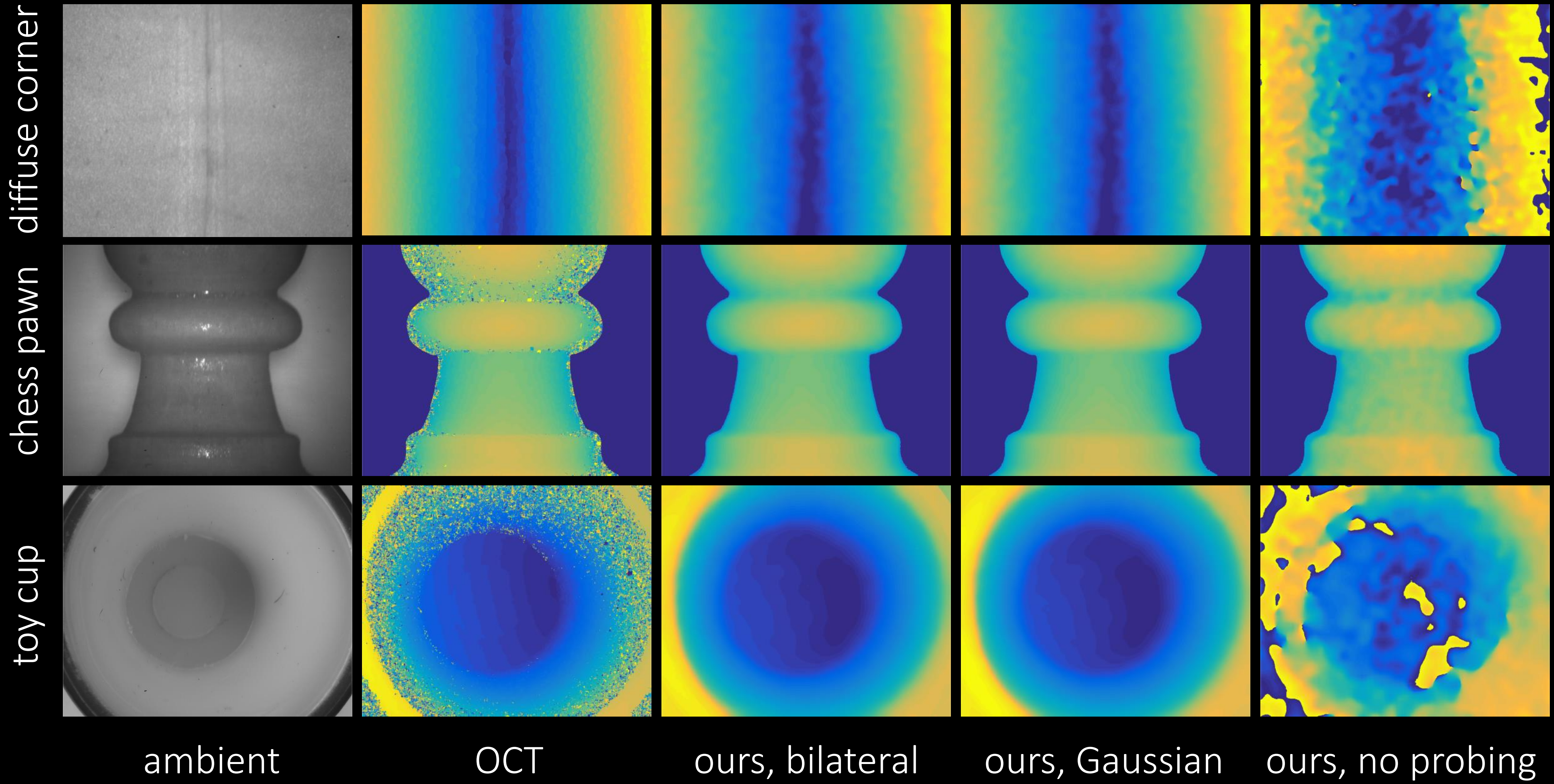




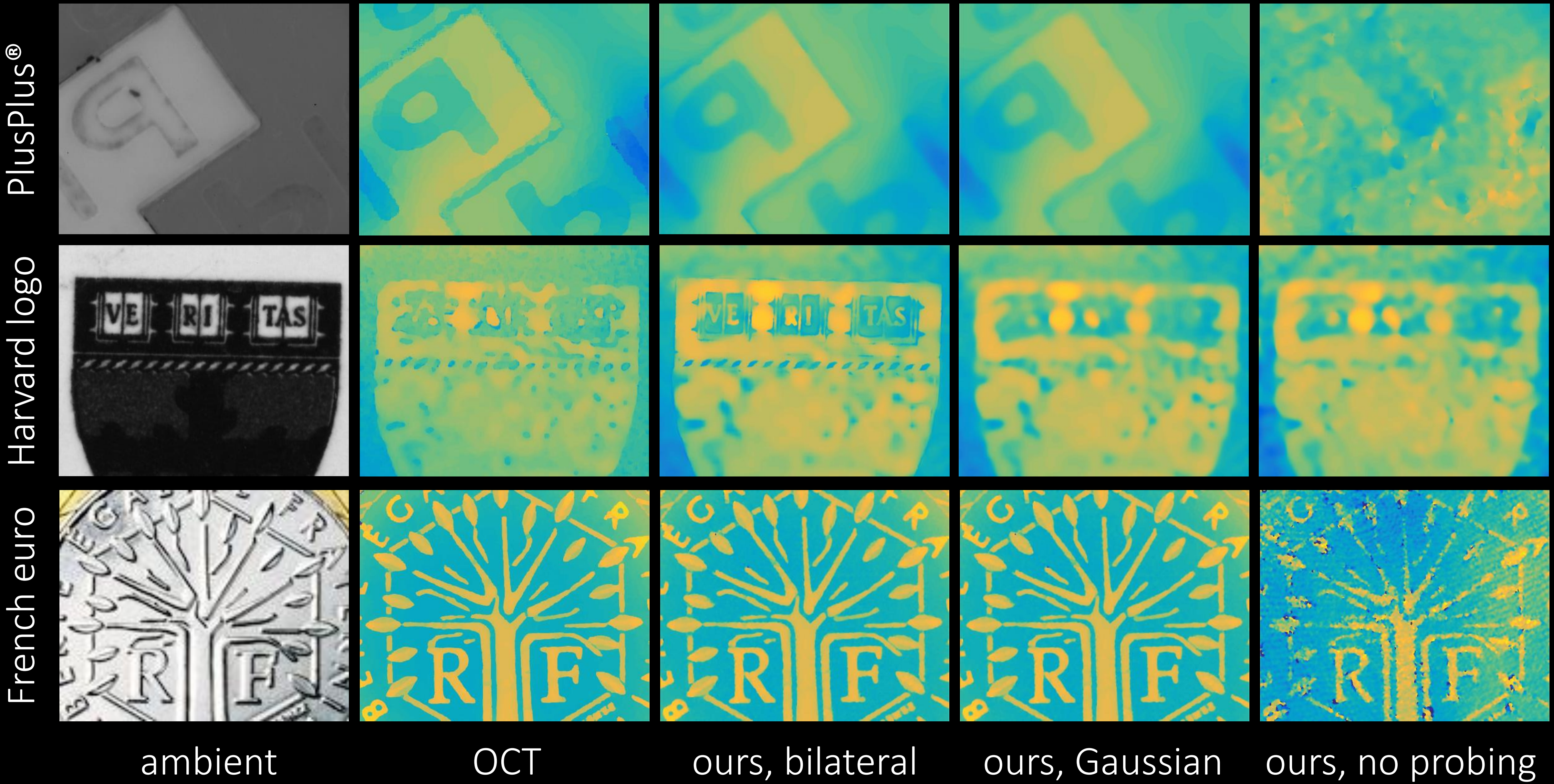
	OCT	SWI
range	translation stage scan length	synthetic wavelength
depth resolution	user-specified (coherence length)	tied into range
measurements	range / resolution (x 2, empirically)	16


THORLABS
DBR780PN
780N-2-2-D-P-A
S/N DBR-33472

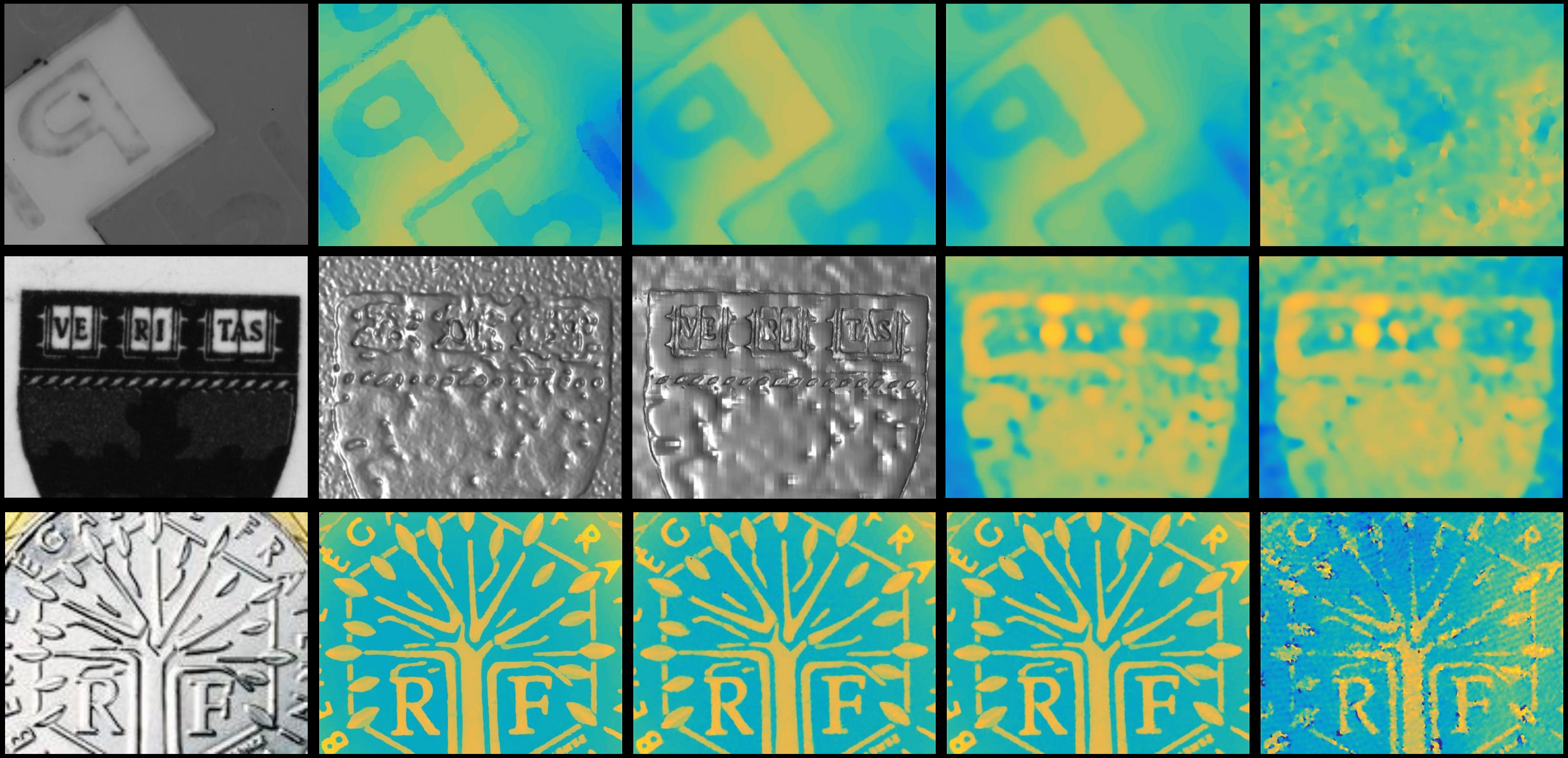
Results: macroscopic scenes



Results: microscopic scenes

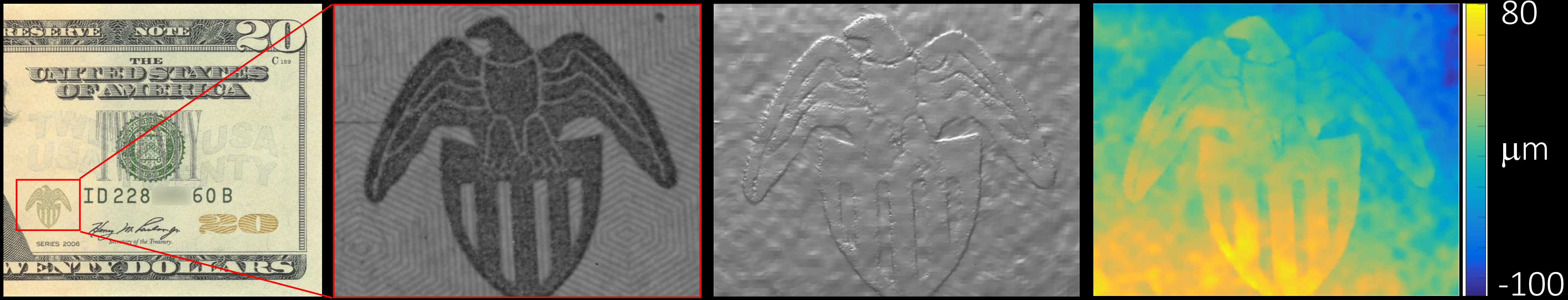


Results: microscopic scenes



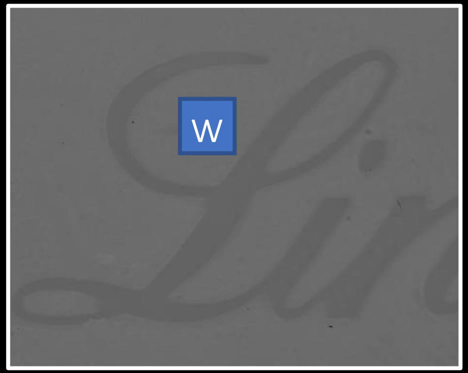
Results: microscopic scenes

Results: $20 bill eagle

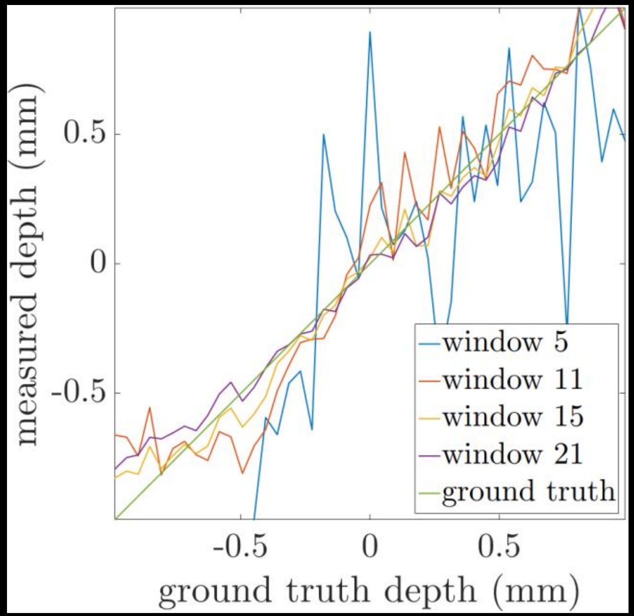


dollar bill | ambient light image | recovered depth surface | recovered depth map

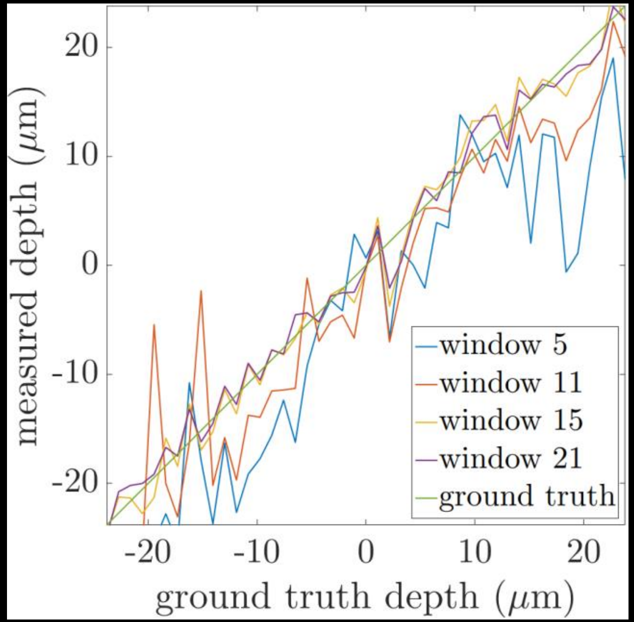
Results: depth accuracy



type	window w	with direct-only probing MAE	with direct-only probing MedAE	with direct-only probing RMSE	without direct-only probing MAE	without direct-only probing MedAE	without direct-only probing RMSE
micro-scopic (400 μm)	5	6.5	4.8	8.2	15.2	13.2	18.9
	11	4.1	3.6	5.1	9.5	9.5	11.2
	15	1.7	1.6	2.0	8.5	7.3	10.5
	21	1.3	1.0	1.6	8.6	6.7	11.1
macro-scopic (16 mm)	5	381.3	300.3	471.4	1130.4	1351.0	1267.2
	11	137.6	120.5	167.1	490.4	501.9	577.9
	15	62.7	50.9	78.7	479.3	412.2	609.5
	21	60.9	49.6	81.7	484.9	334.4	605.7

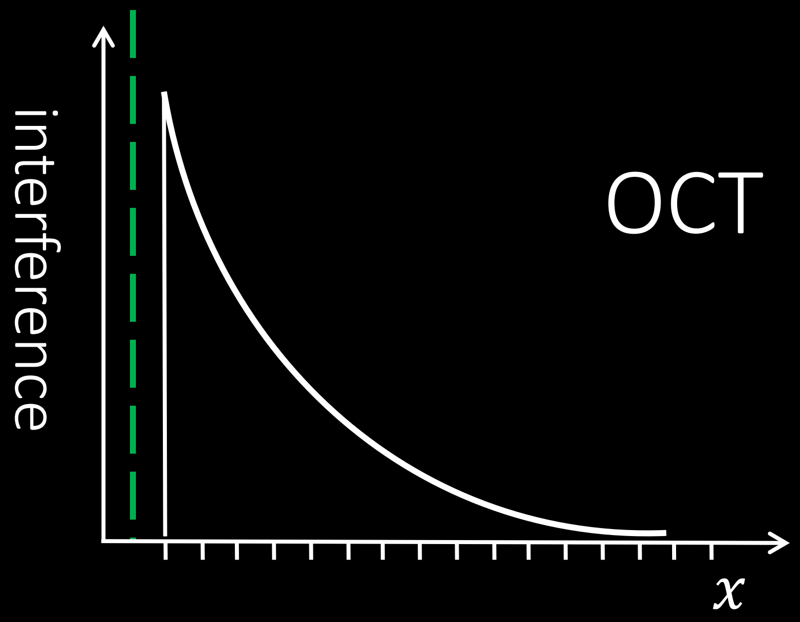


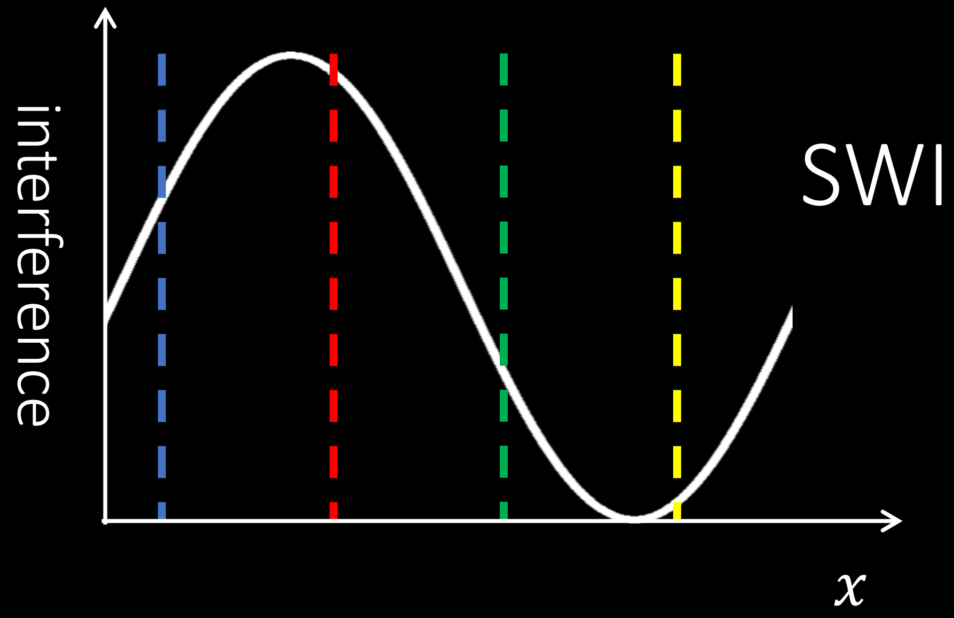
microscopic range



macroscopic range

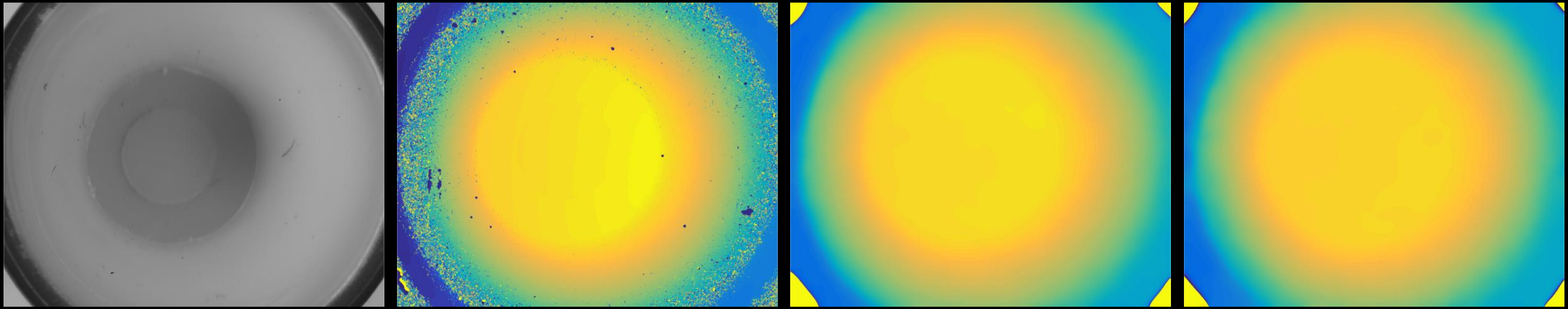
Depth range and resolution





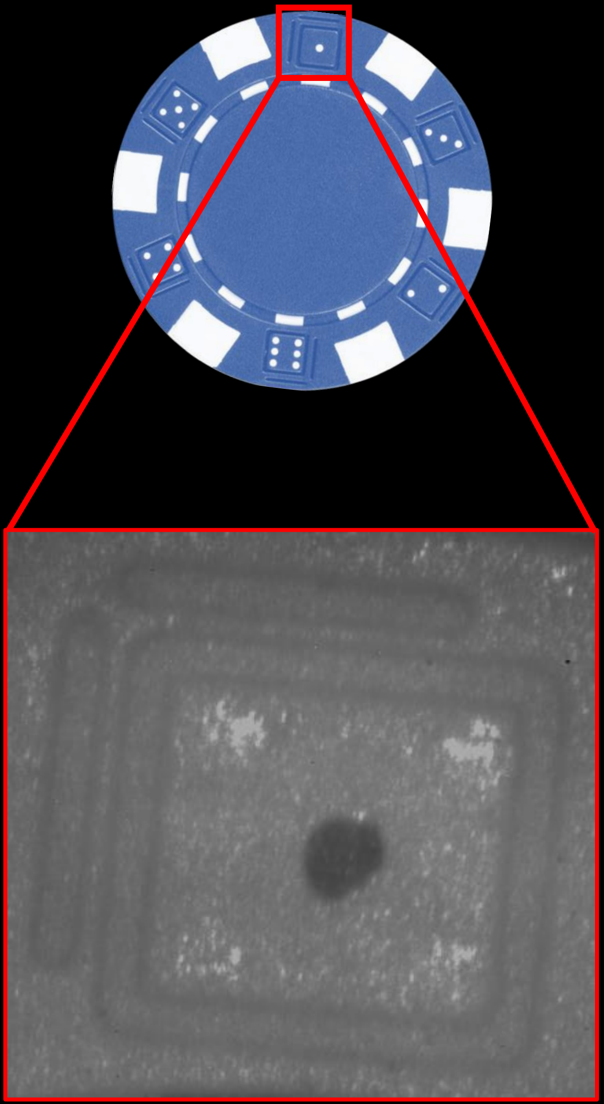
range	400 μm micro / 16 mm macro	
depth resolution	1 μm micro / 50 μm macro	
measurements	800 micro / 640 micro	16

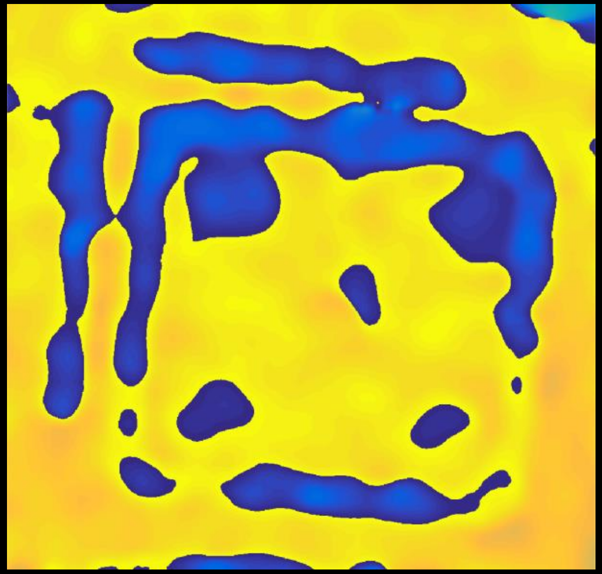
Results: robustness to environmental conditions



scene | OCT | no background | 10% SBR

Extending depth range



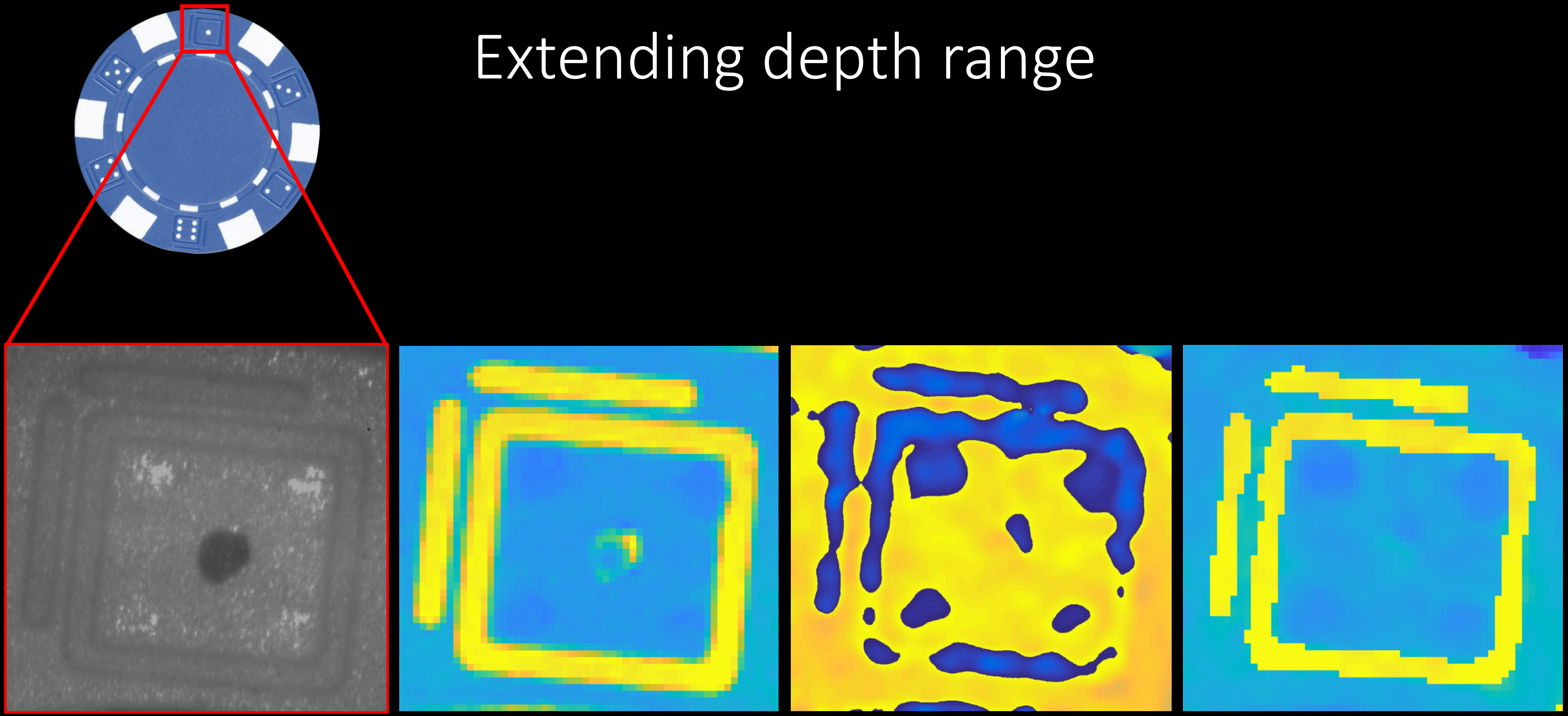


scene

OCT

wrapped SWI depth

Extending depth range



scene | OCT | wrapped SWI depth | unwrapped SWI depth

Swept-Angle Synthetic Wavelength Interferometry

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