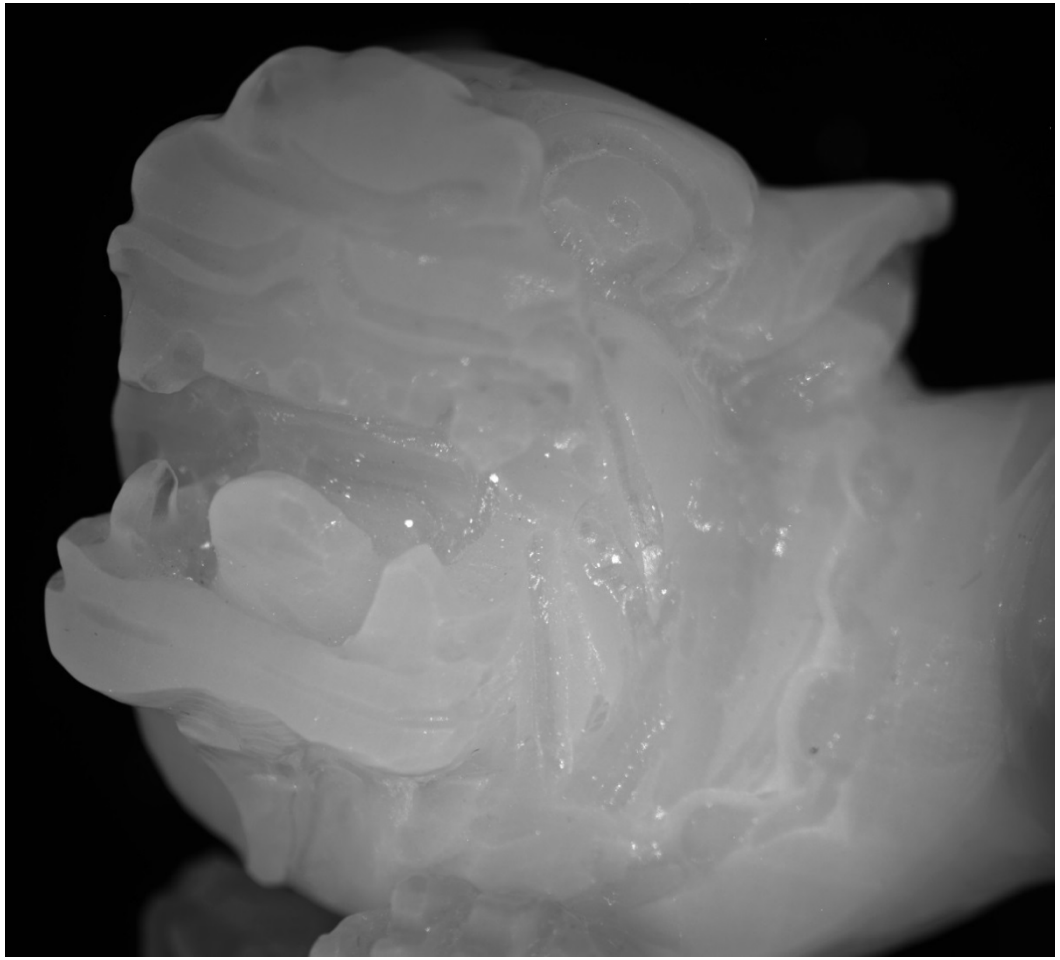
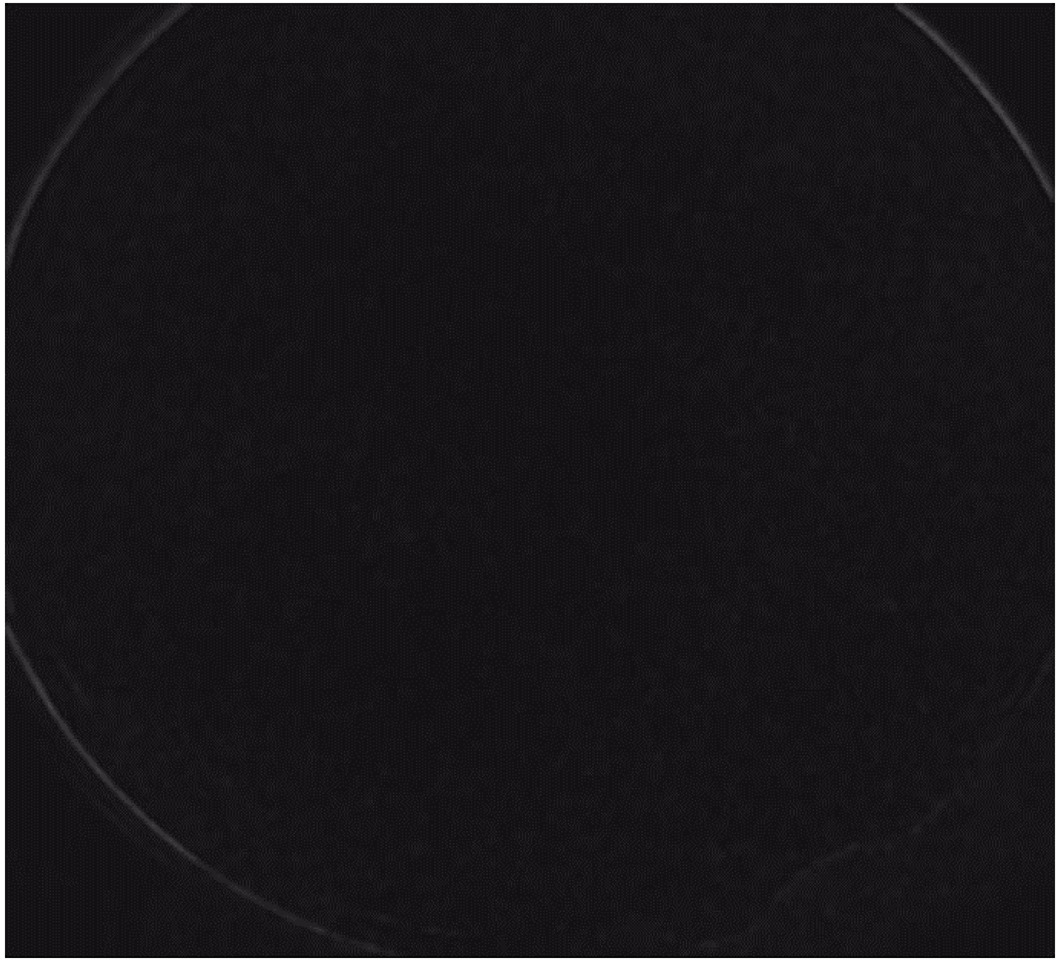
Time-of-flight imaging





15-463, 15-663, 15-862
Computational Photography
Fall 2020, Lecture 23

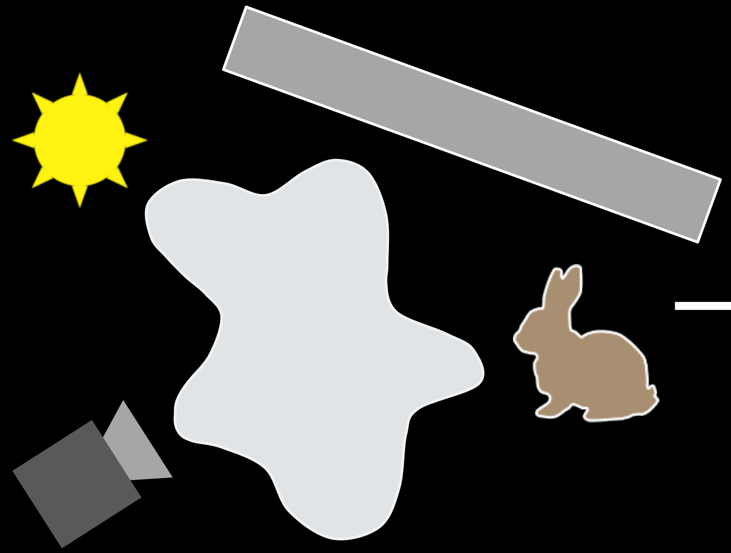
http://graphics.cs.cmu.edu/courses/15-463

Course announcements

- Homework assignment 6 is due on December 11th.
  - Do not leave for last minute, you won't have time to complete it.
- Make sure to sign up for a project checkpoint meeting.
  - Sign up spreadsheet available on Piazza.
- We will have another reading group this Friday, please suggest topics.

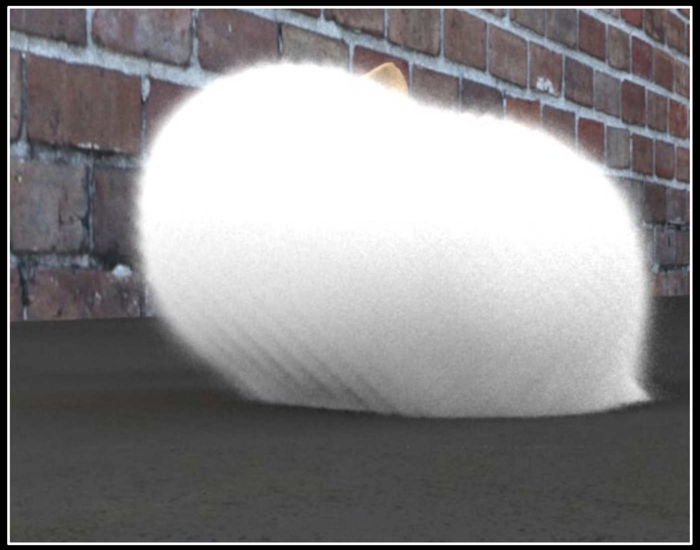
15-468/668/868 Physics-based rendering, Spring 2021

Forward graphics (a.k.a. rendering)



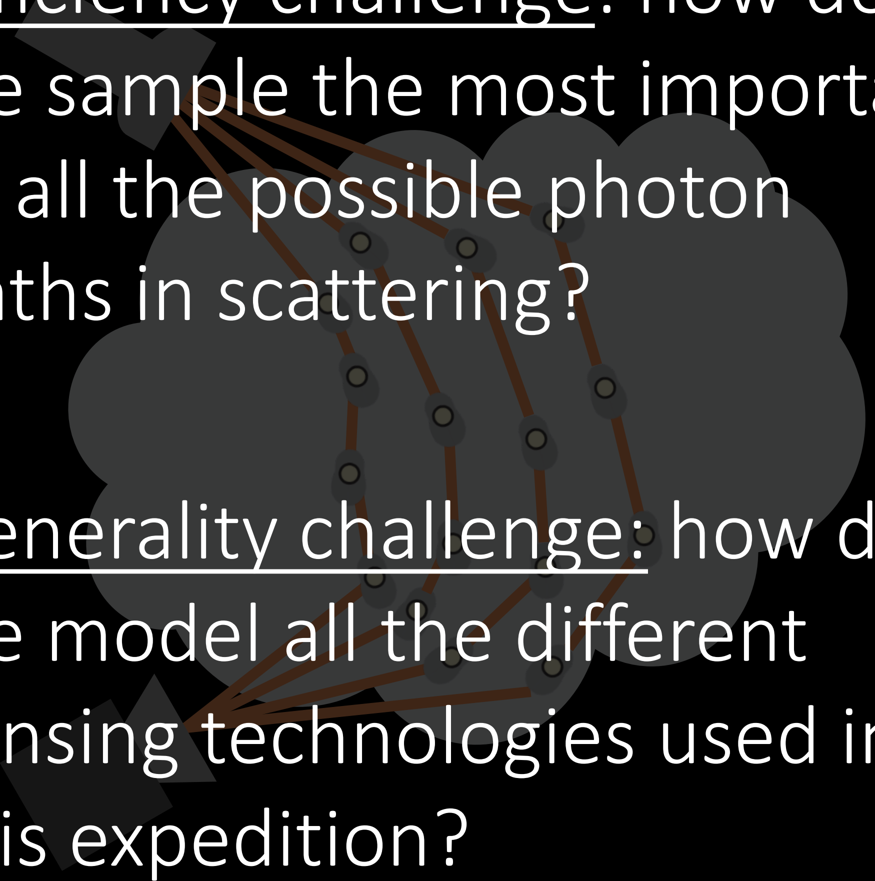
digital scene specification
(geometry, materials,
optics, light sources)

physically-accurate
rendering



photorealistic
simulated image

Physics-based rendering



- Efficiency challenge: how do we sample the most important of all the possible photon paths in scattering?

- Generality challenge: how do we model all the different sensing technologies used in this expedition?

$$\text{Image} = \int_{\text{photon paths}} f(\text{path})$$

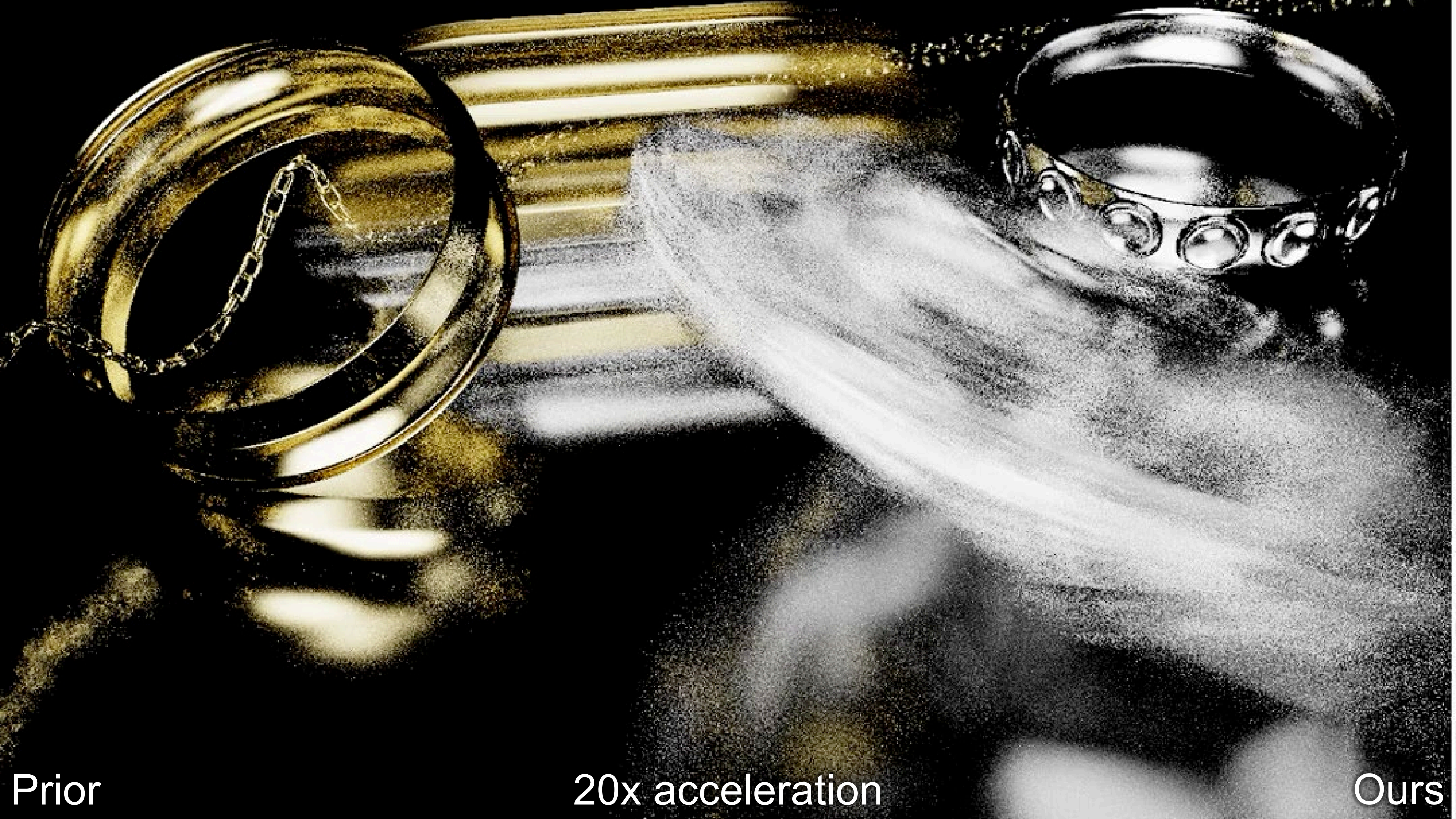
path contribution, depends on tissue properties, light source, and sensor

Monte Carlo rendering:

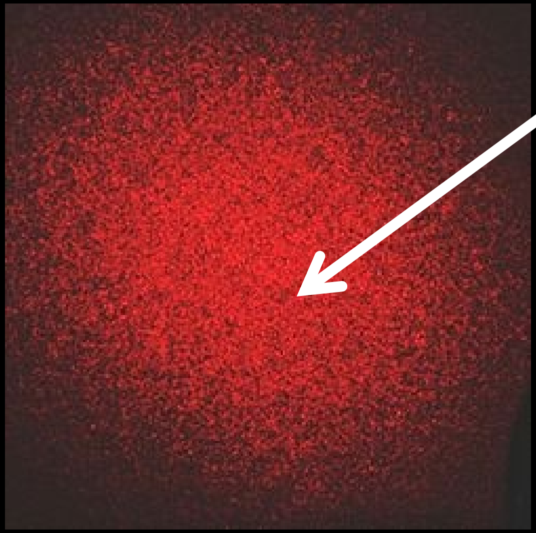
- randomly sample photons: path_1, path_2, …, path_N
- approximate image as:

$$\text{Image} \approx \sum_n \frac{f(\text{path}_n)}{\text{prob}(\text{path}_n)}$$


Prior
10x acceleration
Ours
SIGGRAPH
MCMC
2020
SIGGRAPH

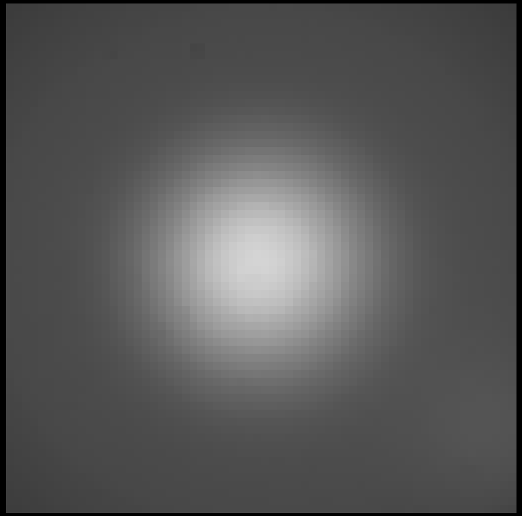

Prior
20x acceleration
Ours

Speckle and memory effect



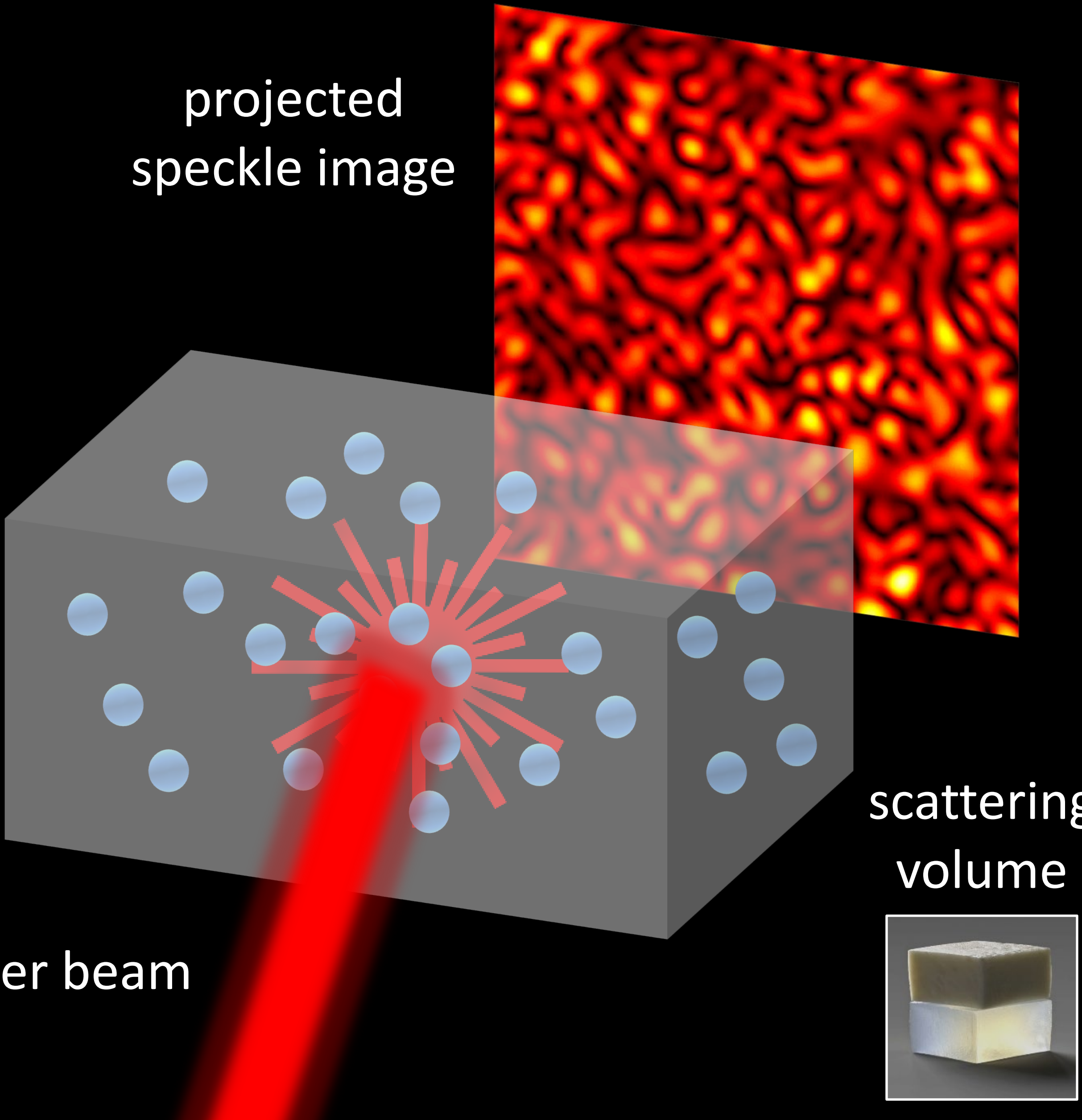
speckle: noise-like pattern

what real laser images look like



what standard rendered images look like

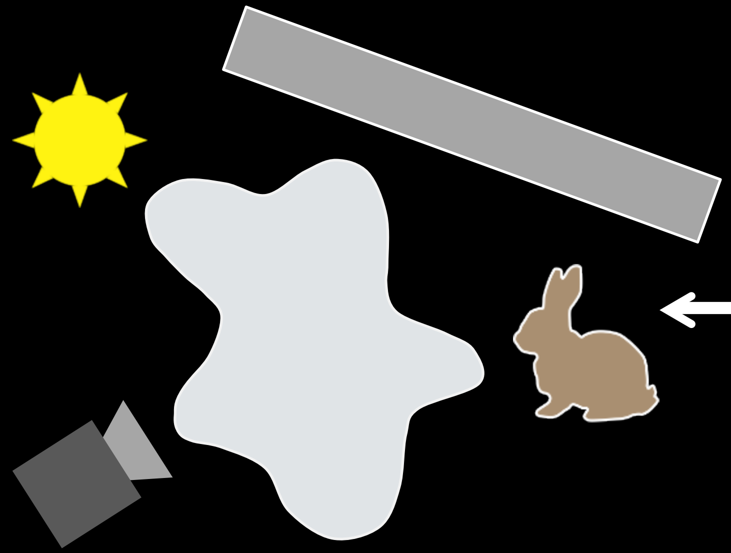
projected speckle image



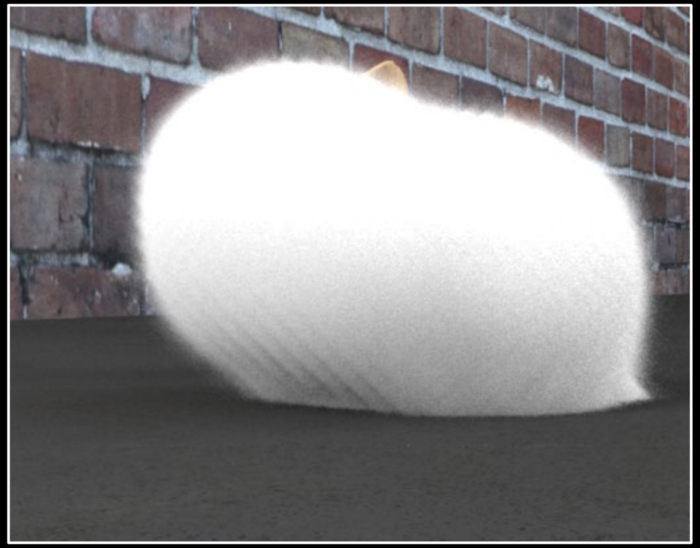
laser beam

scattering volume

Inverse graphics



physically-accurate
inverse rendering



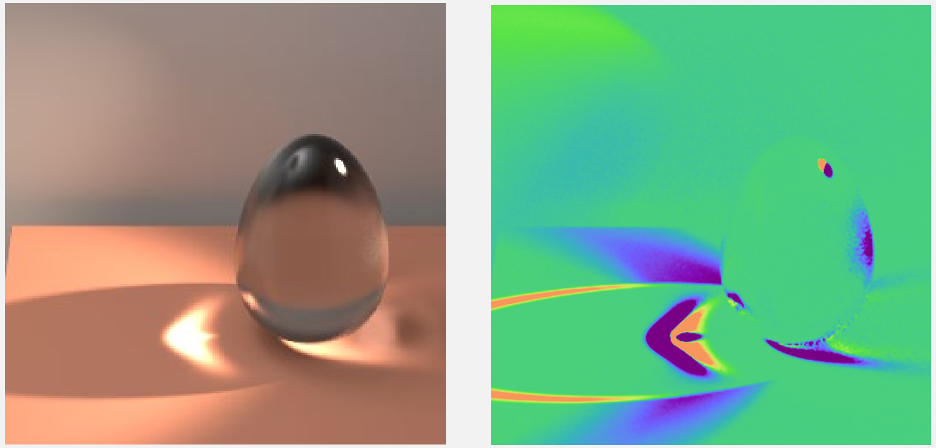
digital scene specification
(geometry, materials,
camera, light sources)

photorealistic
synthetic image

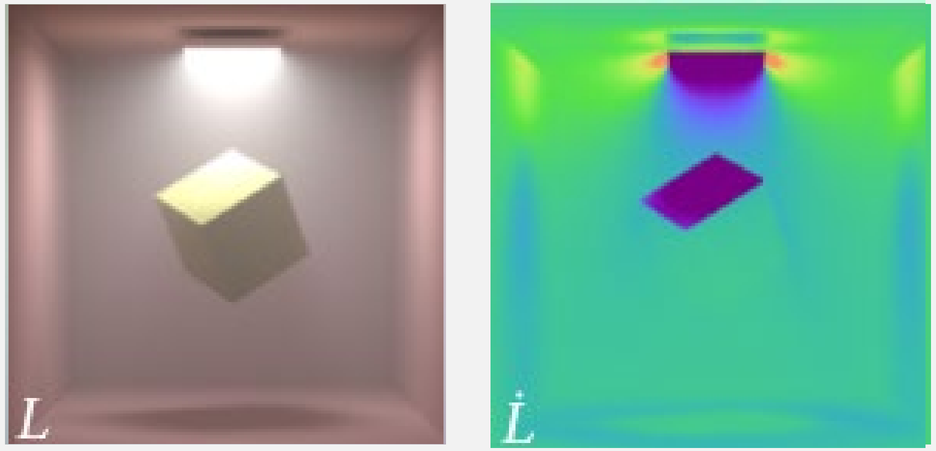
image
measurement

Differentiable rendering

Original image Derivative image

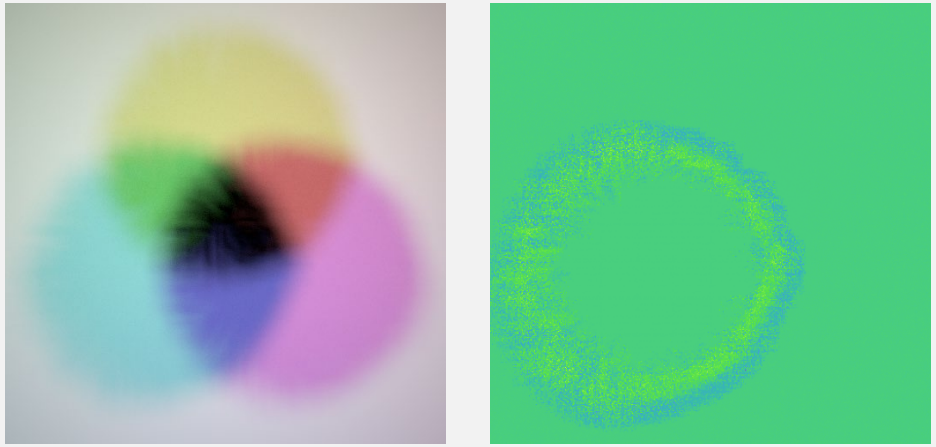


Original image Derivative image



Original image Derivative image

Original image Derivative image



Differentiable rendering this year

Forward rendering

$$I = \int_{\Omega} f(\bar{\boldsymbol{x}})\mathrm{d}\mu(\bar{\boldsymbol{x}})$$

Path integral

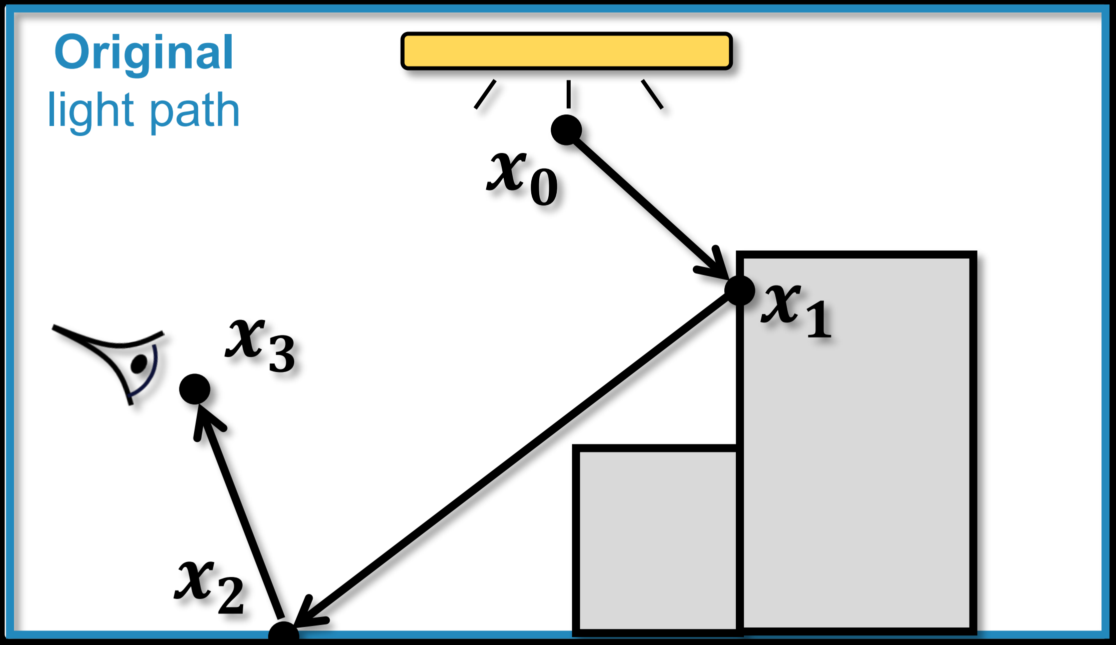
Reynolds theorem →

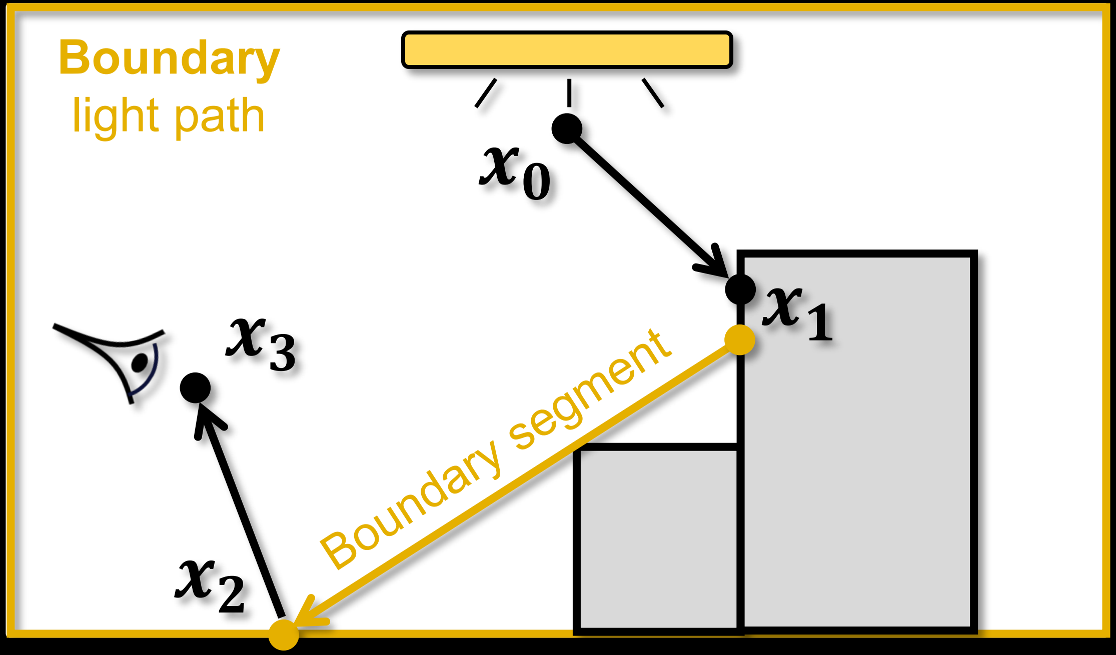
Differentiable rendering

$$\int_{\Omega} \frac{\mathrm{d}}{\mathrm{d}\pi} f(\bar{\boldsymbol{x}})\mathrm{d}\mu(\bar{\boldsymbol{x}}) + \int_{\partial\Omega} g(\bar{\boldsymbol{x}})\mathrm{d}\mu'(\bar{\boldsymbol{x}})$$

Interior integral

Boundary integral





Suite of differentiable rendering algorithms

Unidirectional estimator

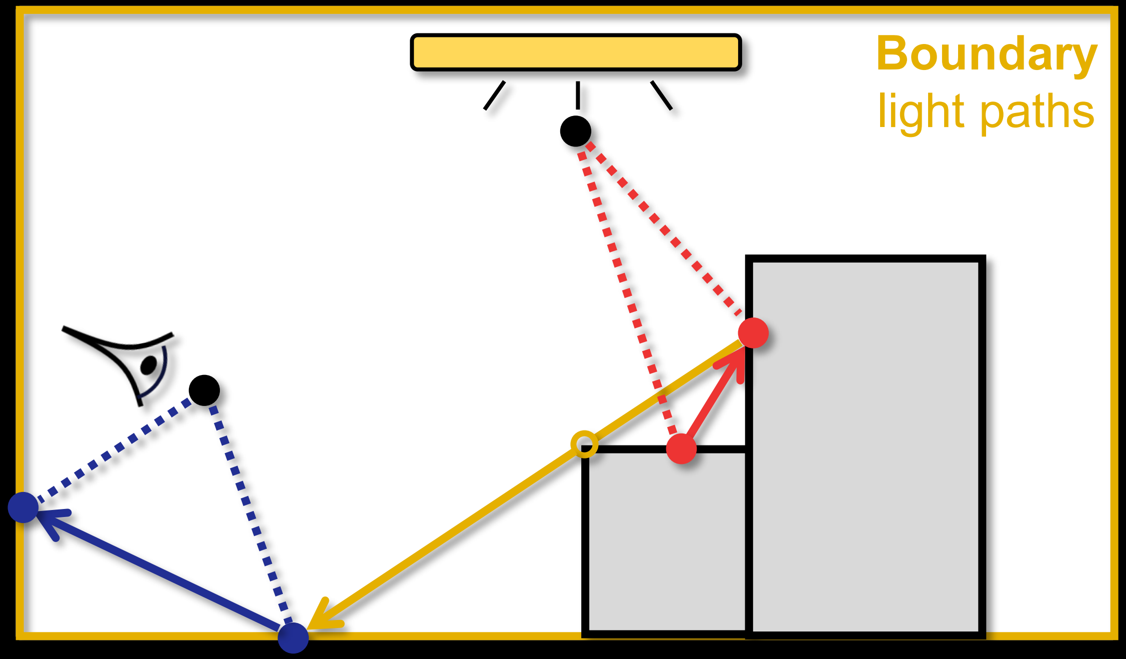
Interior: **unidirectional** path tracing

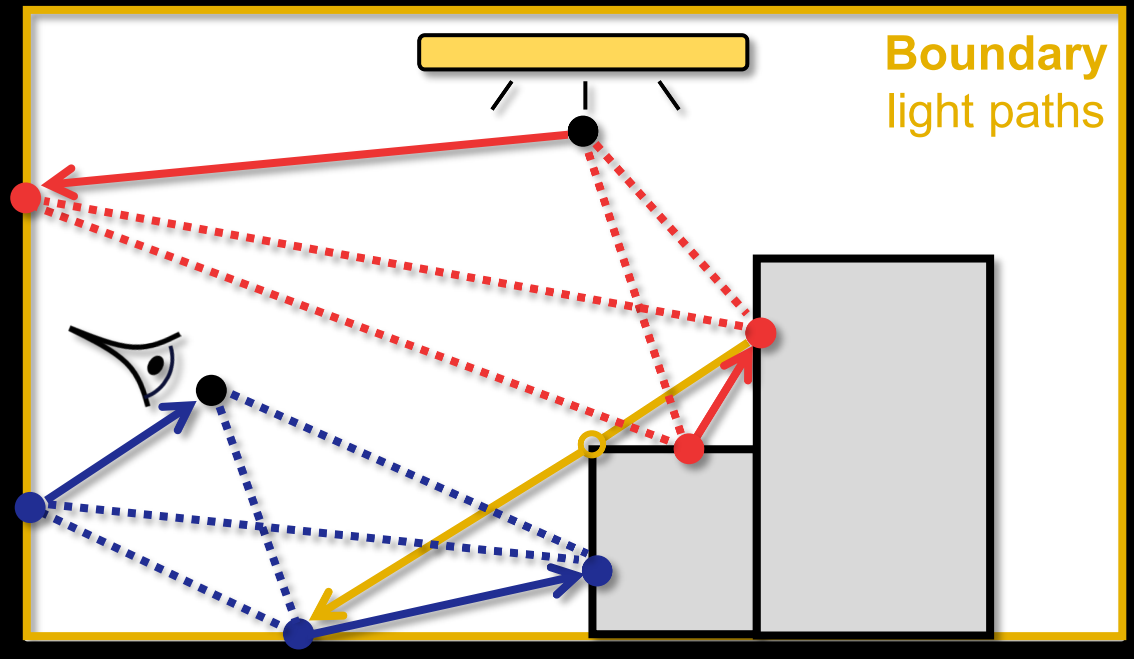
Boundary: **unidirectional** sampling of subpaths

Bidirectional estimator

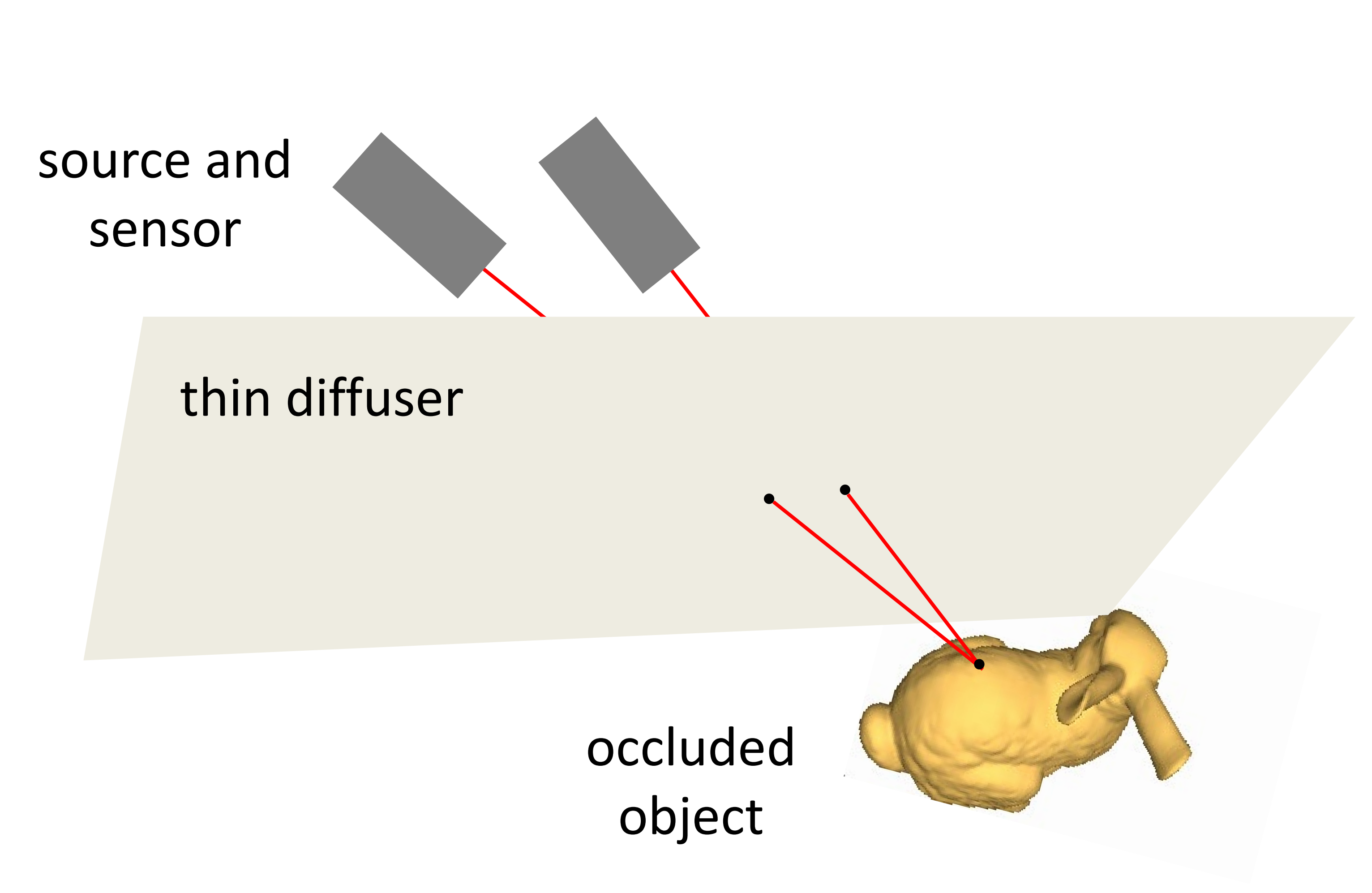
Interior: **bidirectional** path tracing

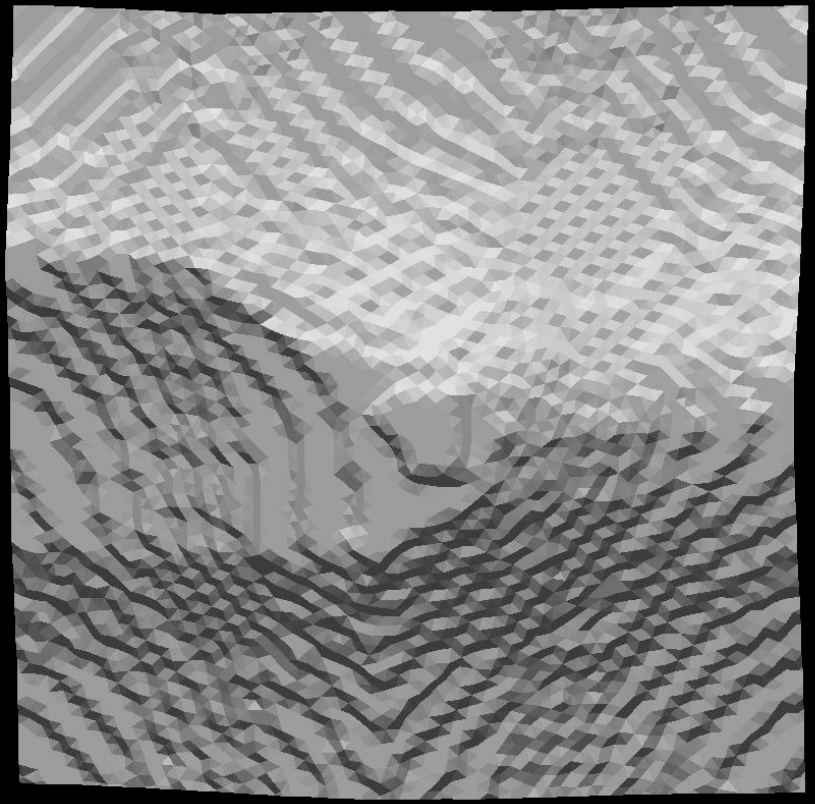
Boundary: **bidirectional** sampling of subpaths





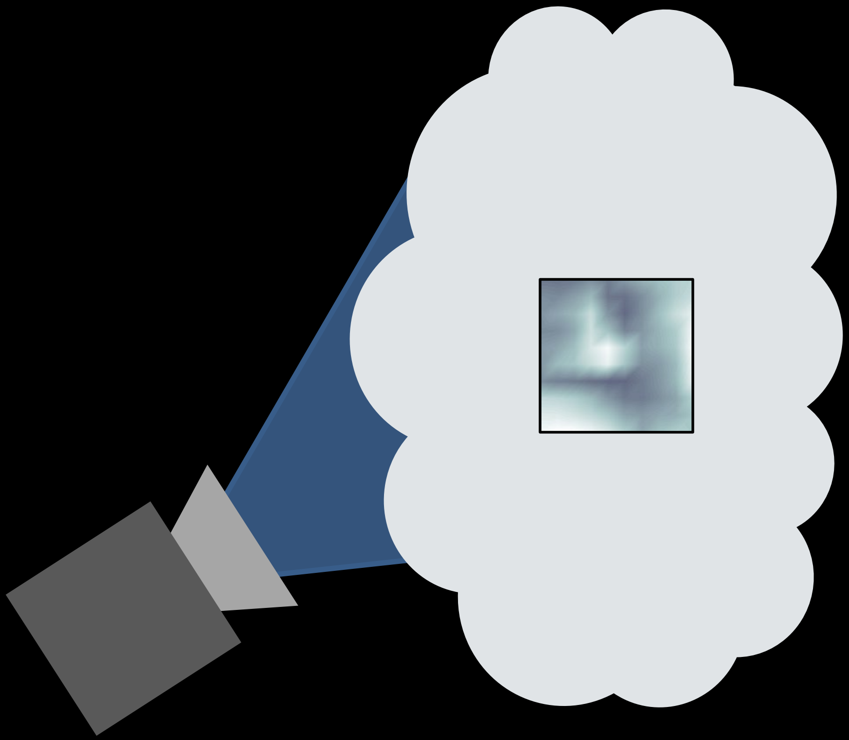
Seeing through diffusers





reconstruction evolution

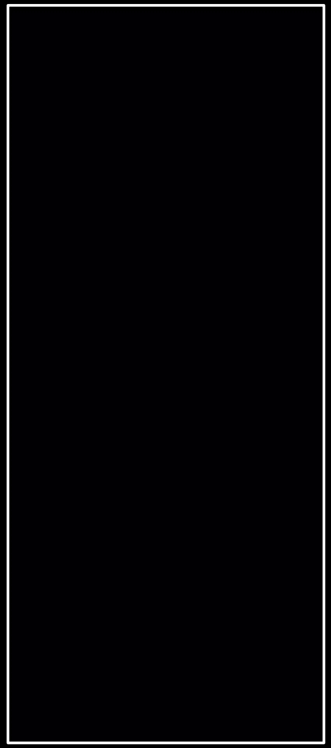
Non-invasive tomography



camera

thick smoke cloud

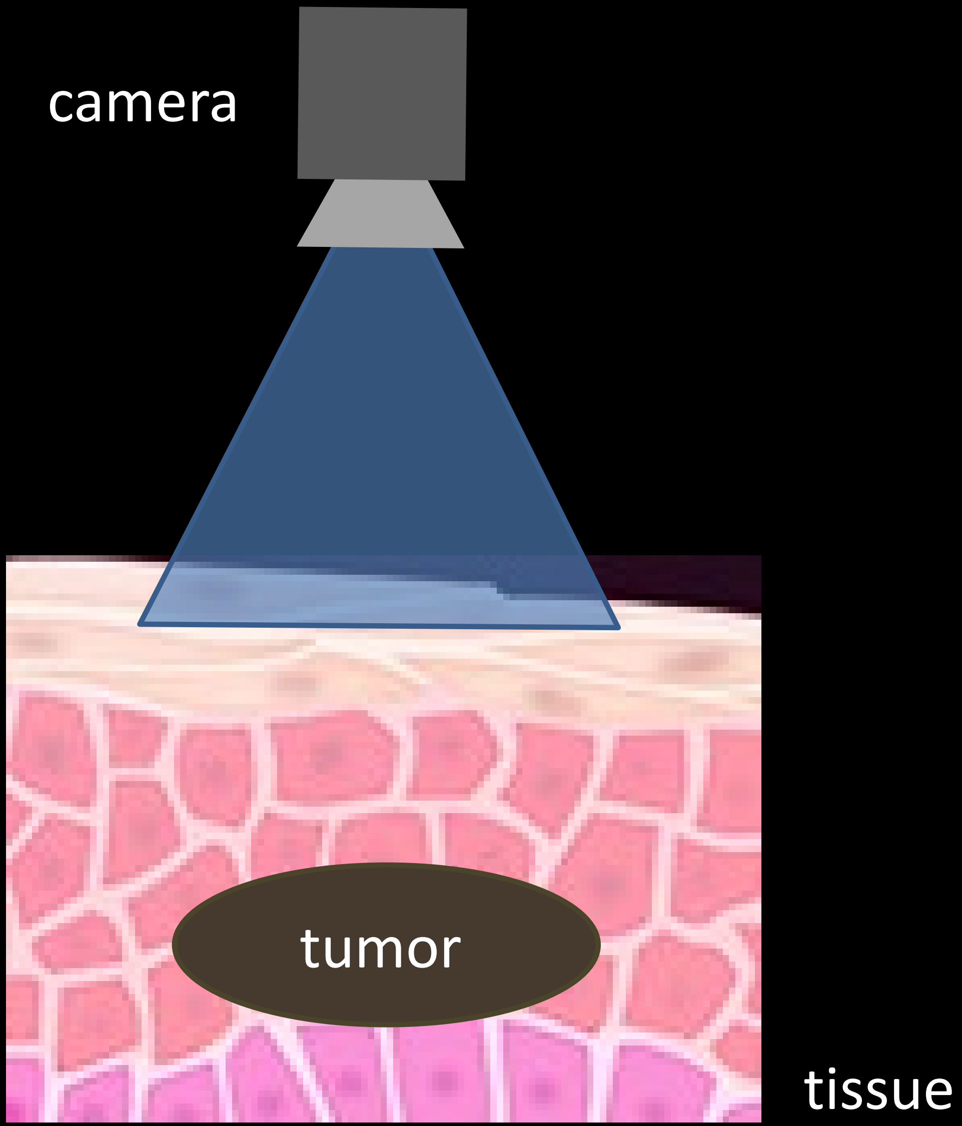
simulated camera measurements

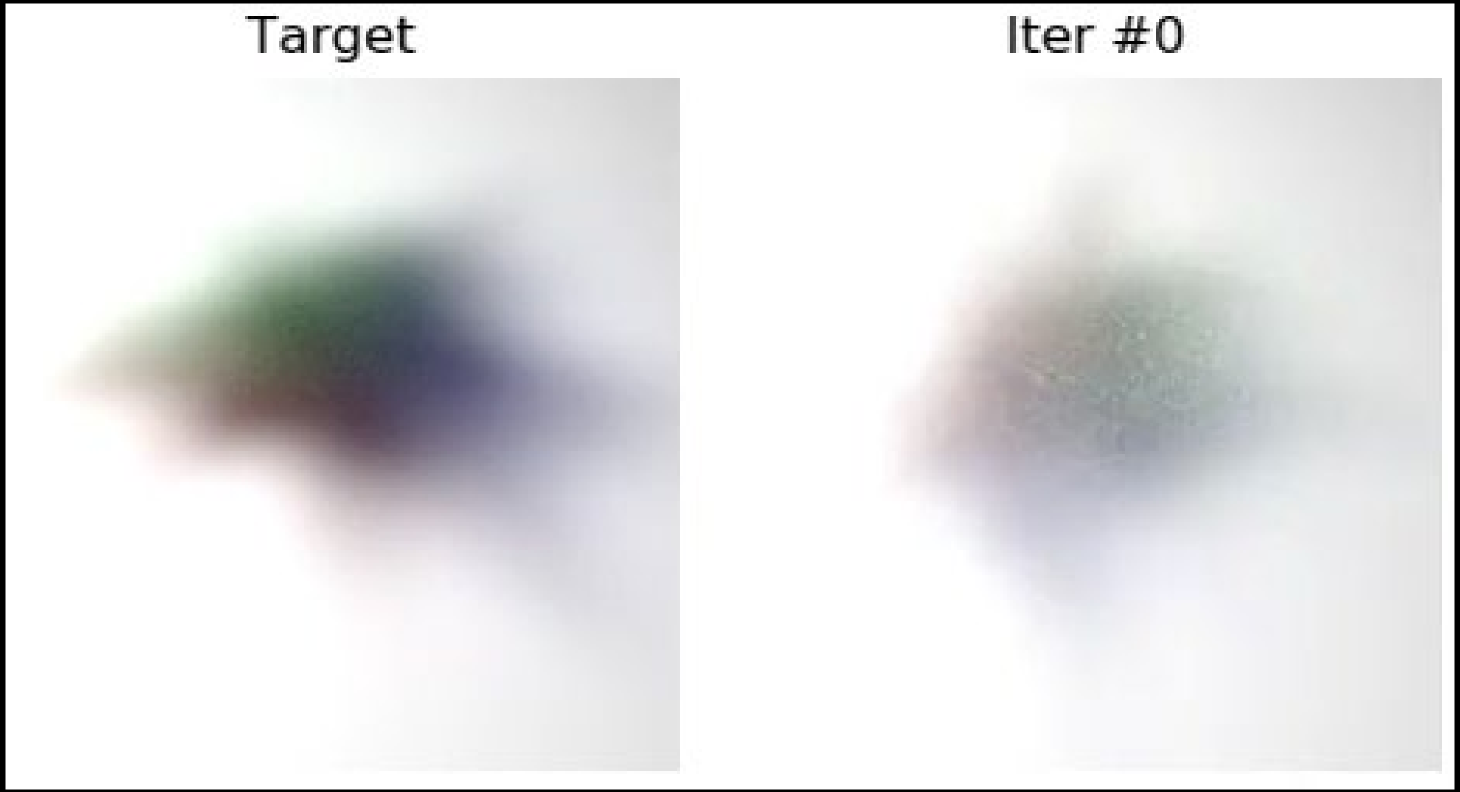


reconstructed cloud volume

slice through the cloud

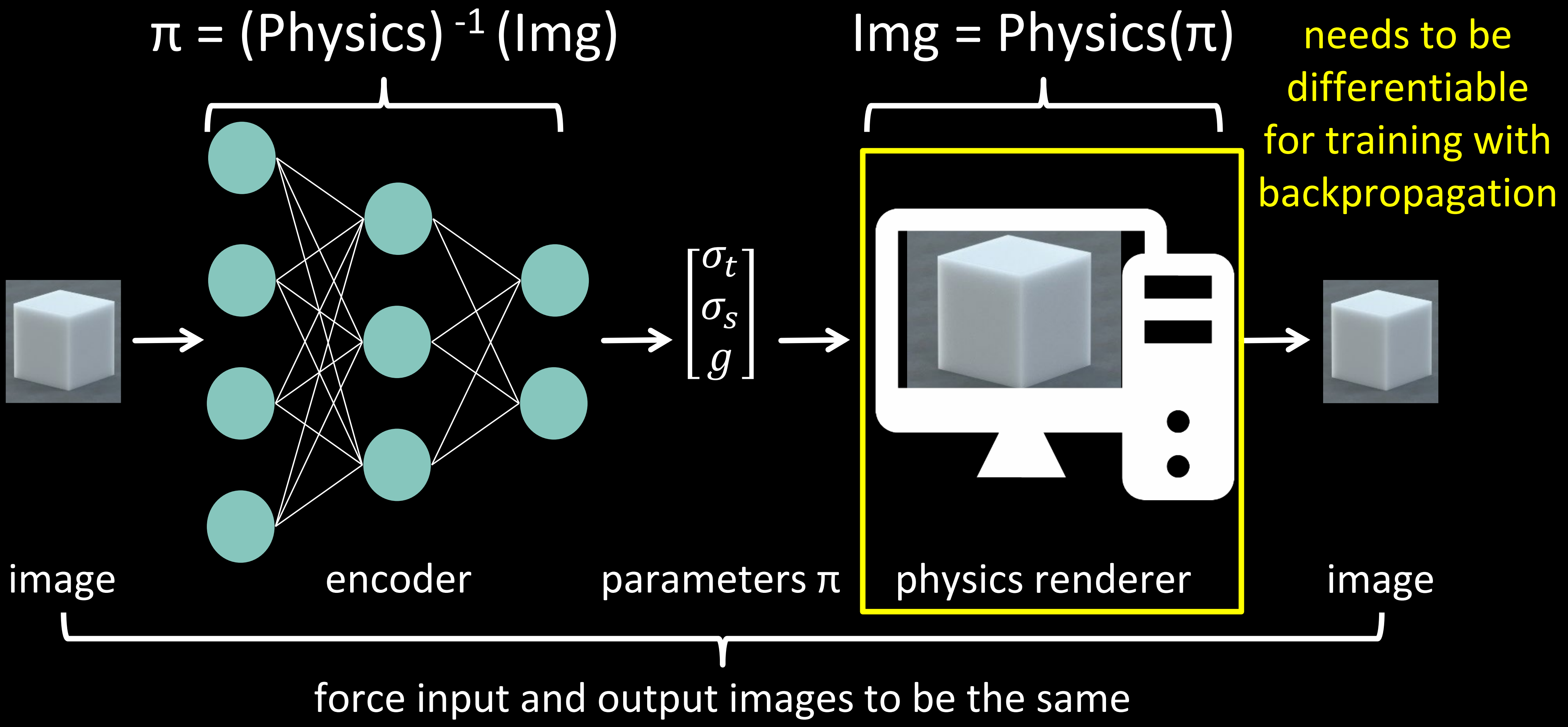
Non-invasive tumor imaging





finding shape and location of a tumor 3 mm below the skin using a single above-the-skin photograph

Physics-aware learning



Overview of today’s lecture

- Introduction to time-of-flight (ToF) imaging.
- Impulse ToF imaging and single-photon avalanche diodes.
- Continuous-wave ToF imaging.
- Epipolar continuous-wave ToF imaging.
- Interferometric ToF imaging.

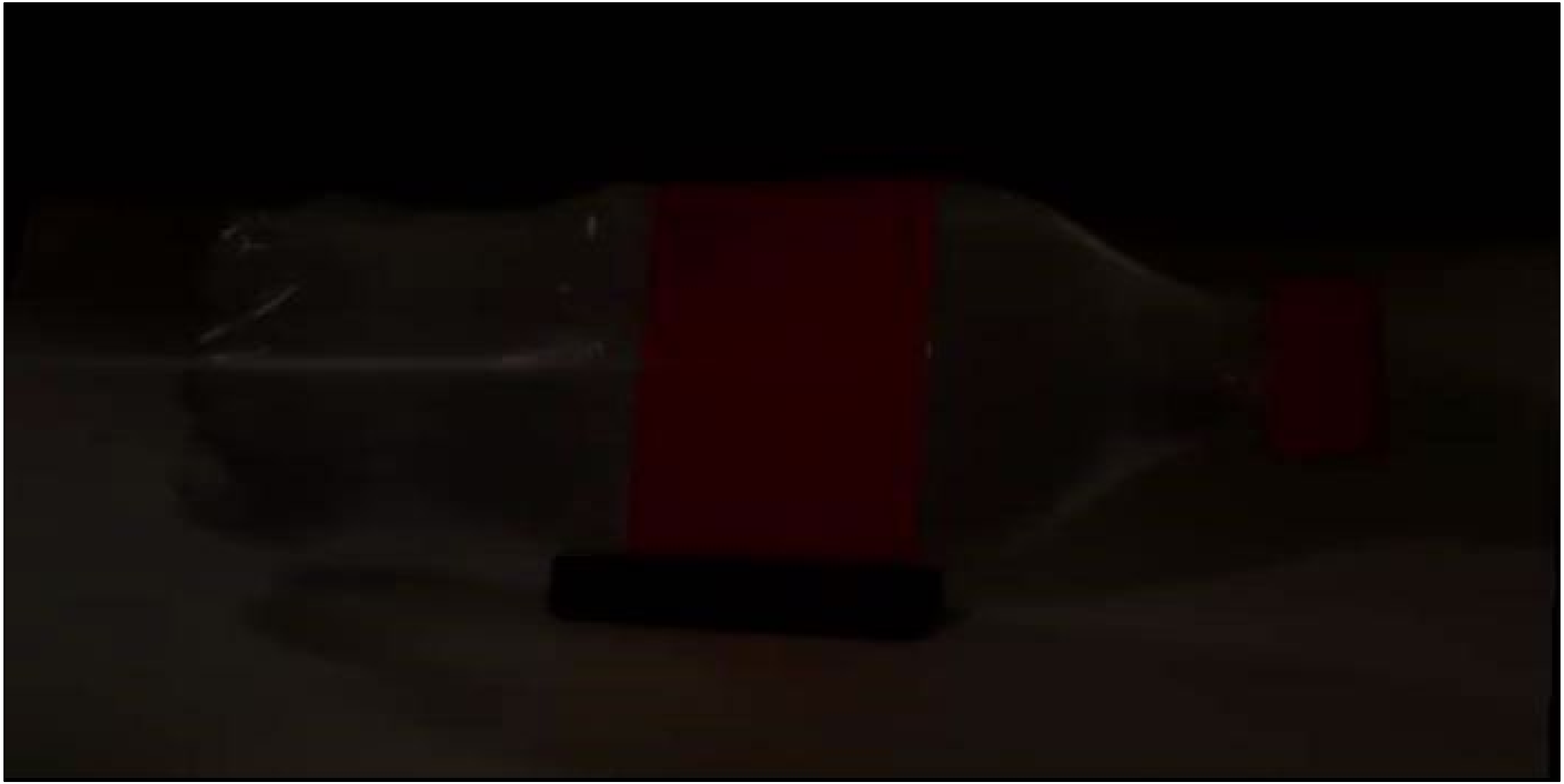
Slide credits

A lot of these slides were adapted from:

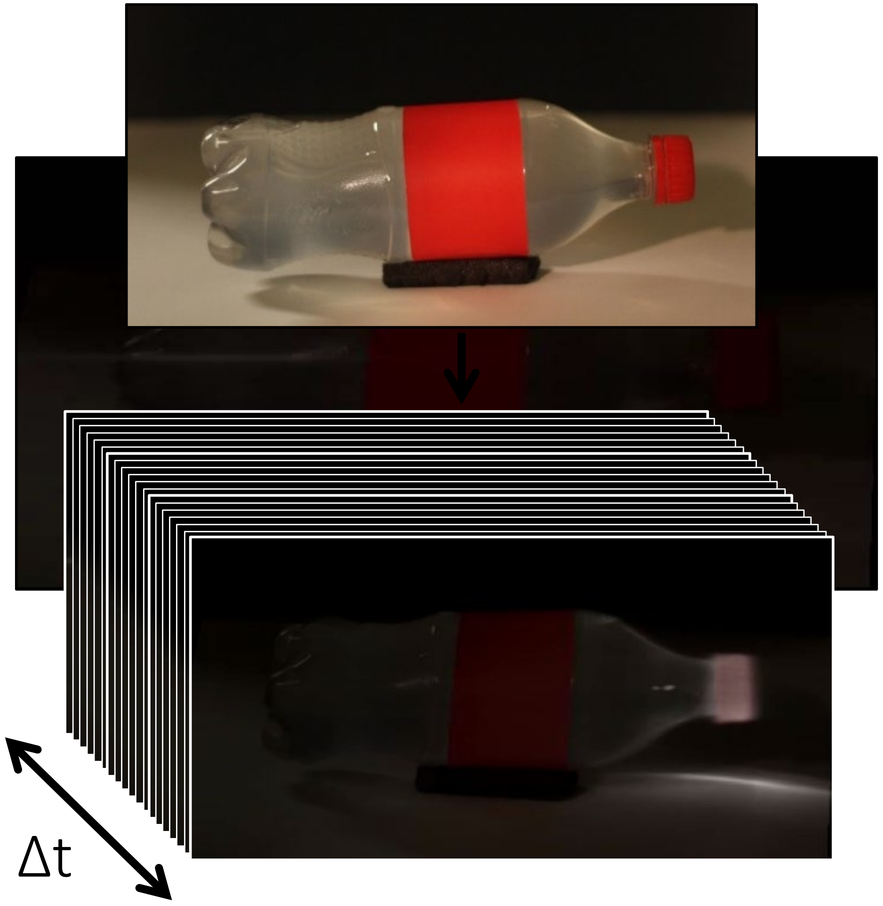
- Mohit Gupta (Wisconsin).
- Supreeth Achar (Google, formerly CMU).

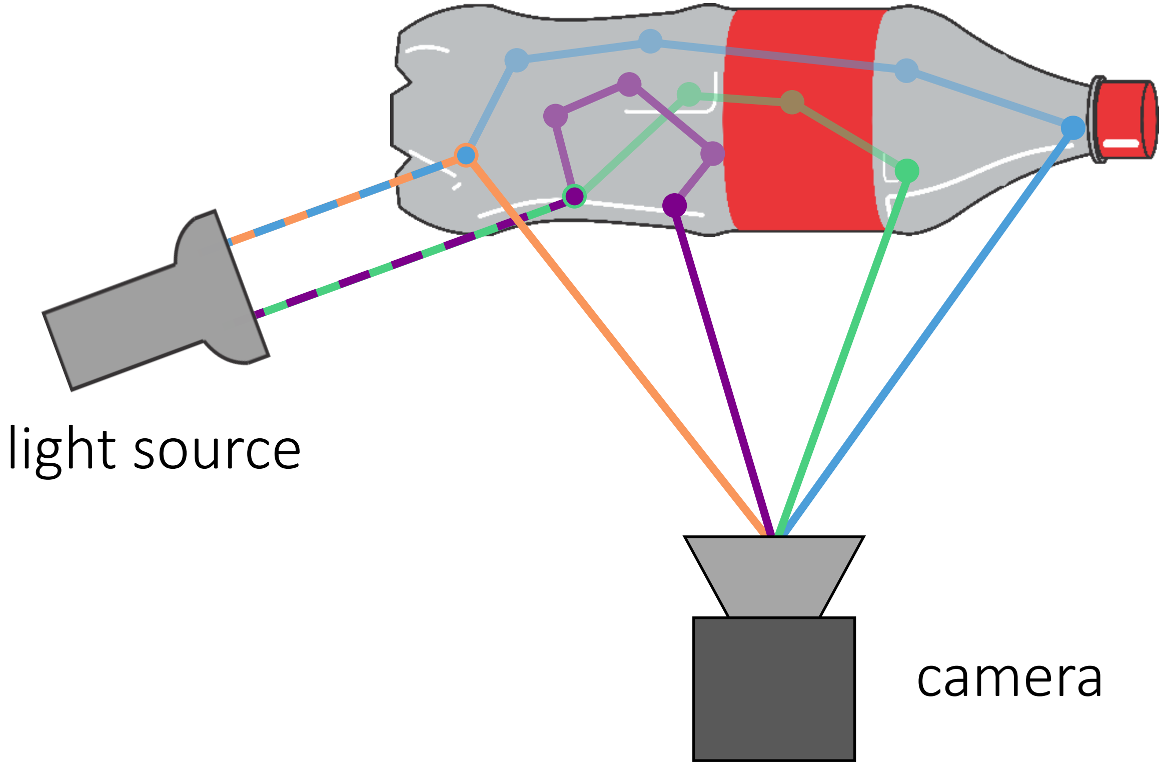
Introduction to time-of-flight (ToF) imaging

Time-of-flight (ToF) imaging



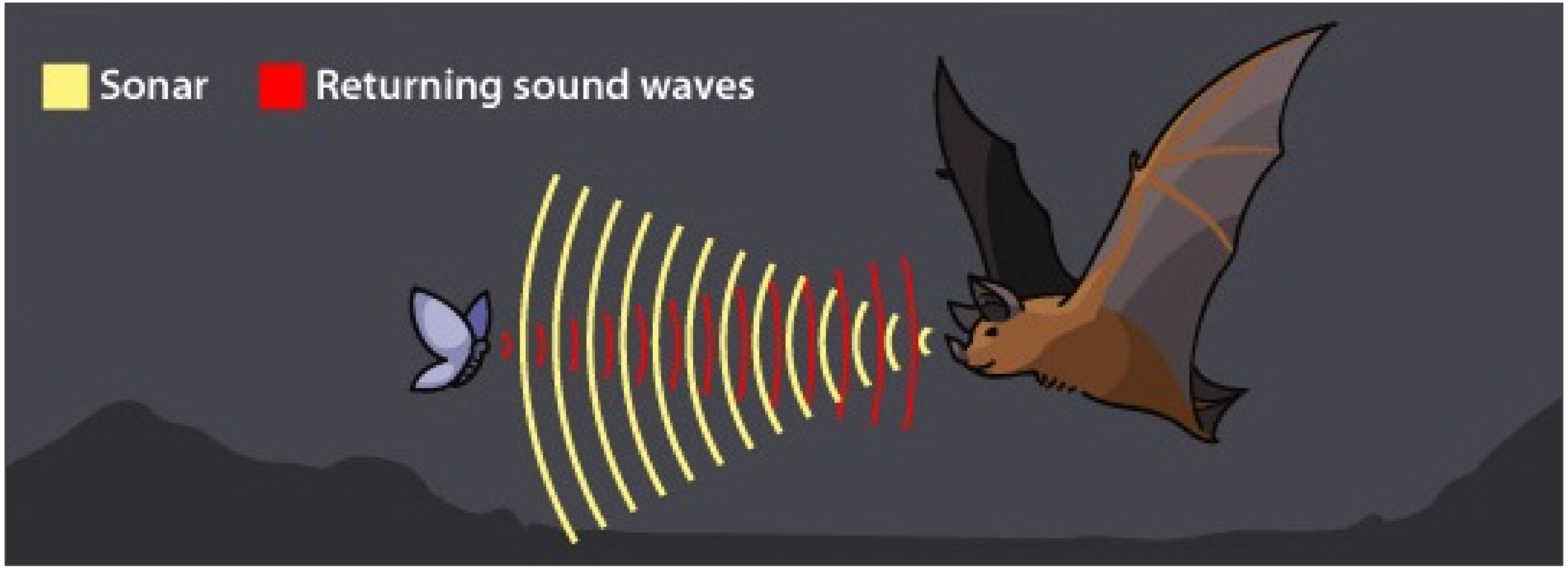
Time-of-flight (ToF) imaging

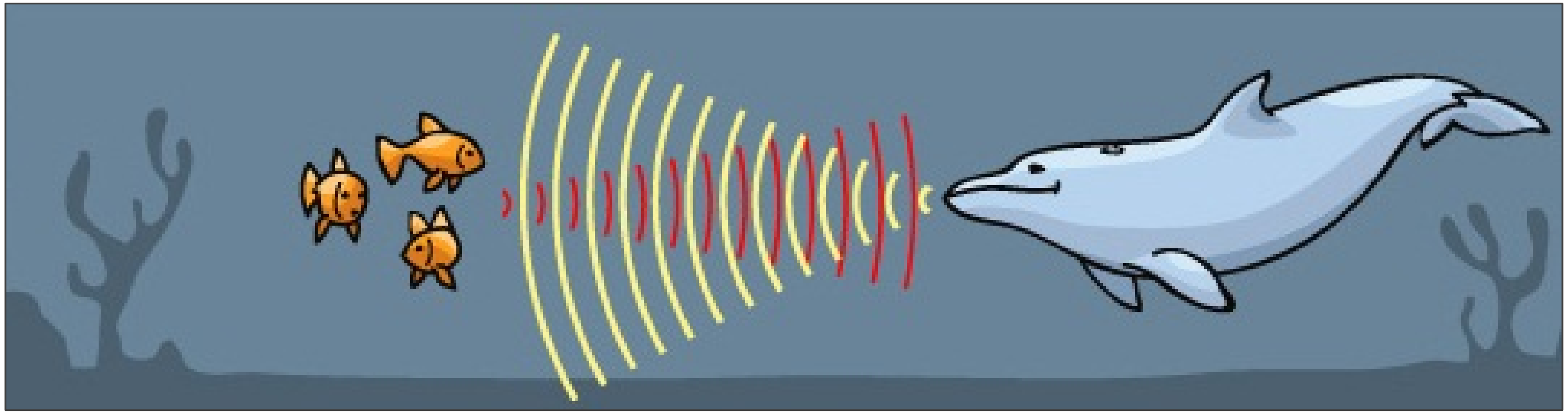




- Conventional imaging: Measure all photons together regardless of time of travel.
- Time-of-flight imaging: Measure photons separately based on time of travel.

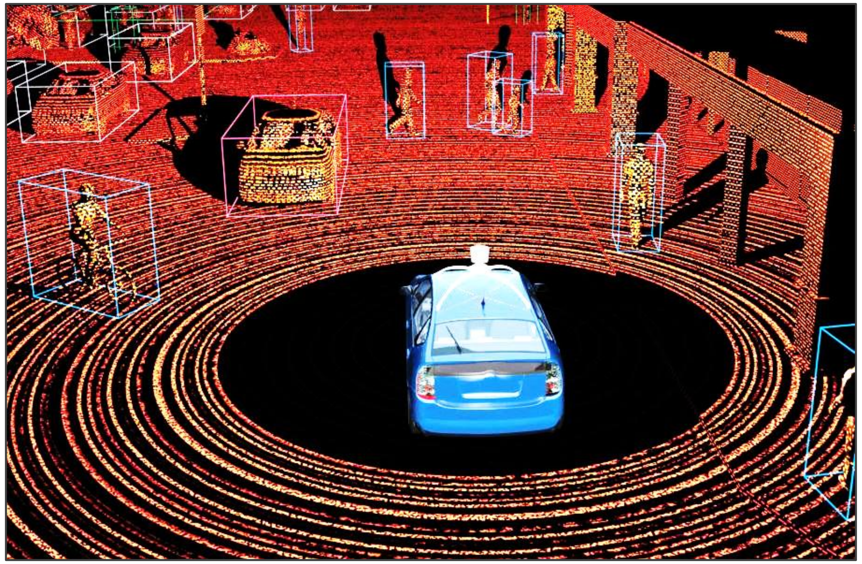
Time-of-flight imaging in nature

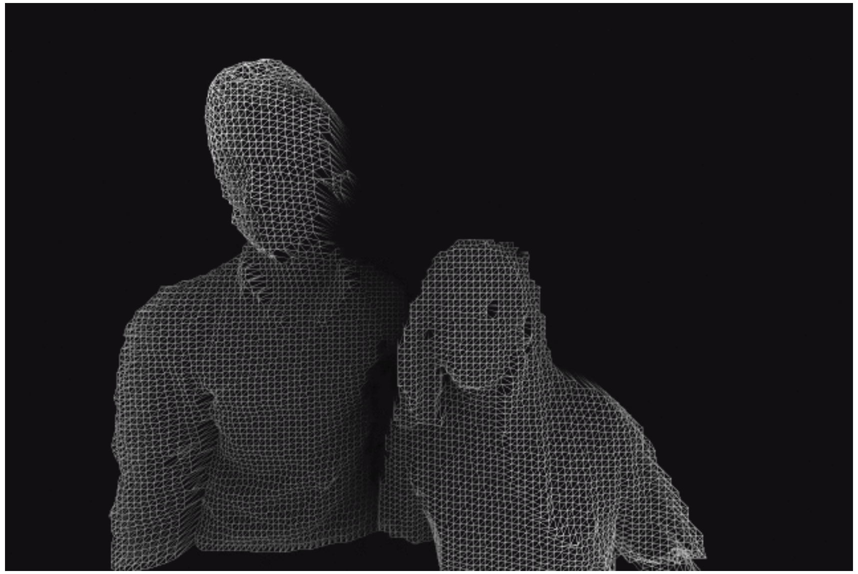




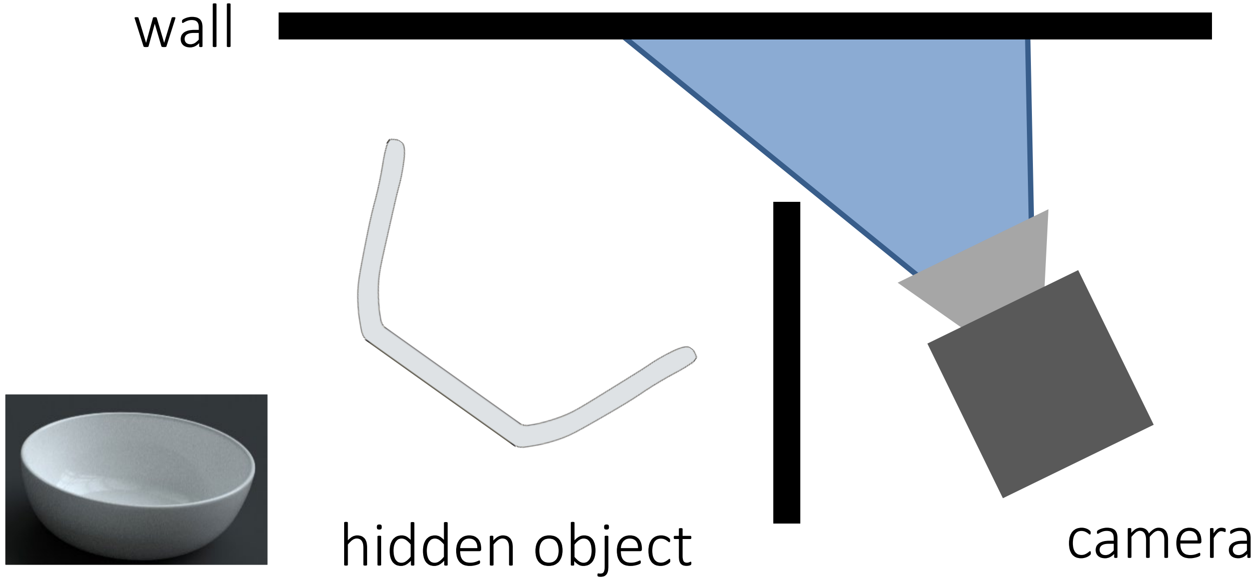
echolocation using sound-wave time-of-flight

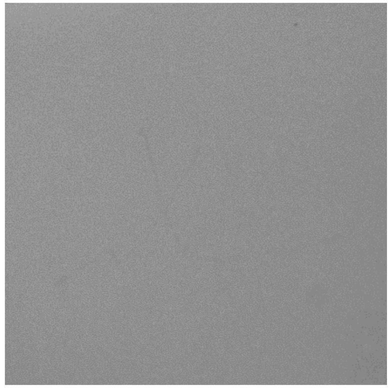
Time-of-flight applications: depth sensing

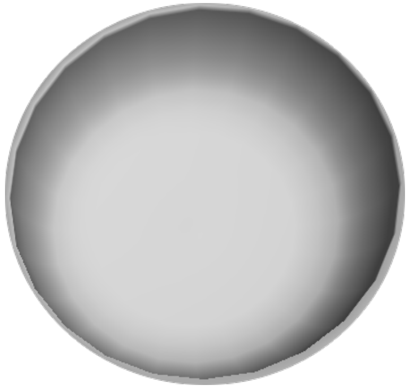


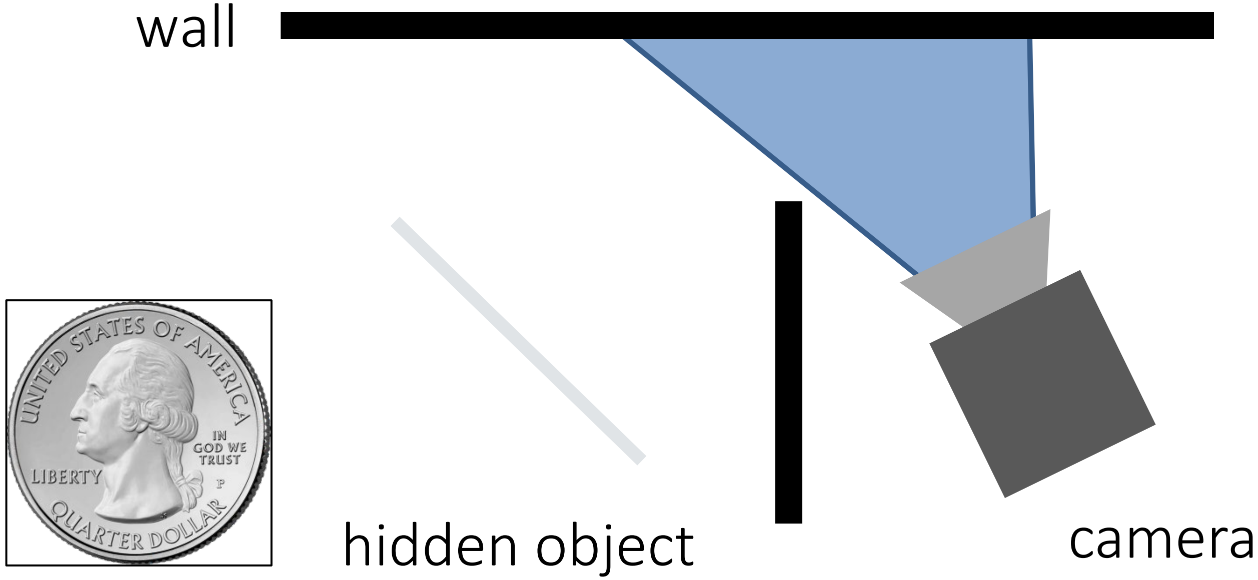


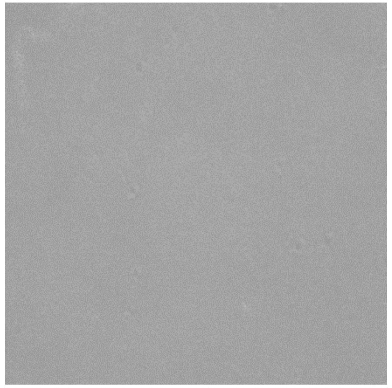
Time-of-flight applications: non-line-of-sight imaging




what a regular camera sees

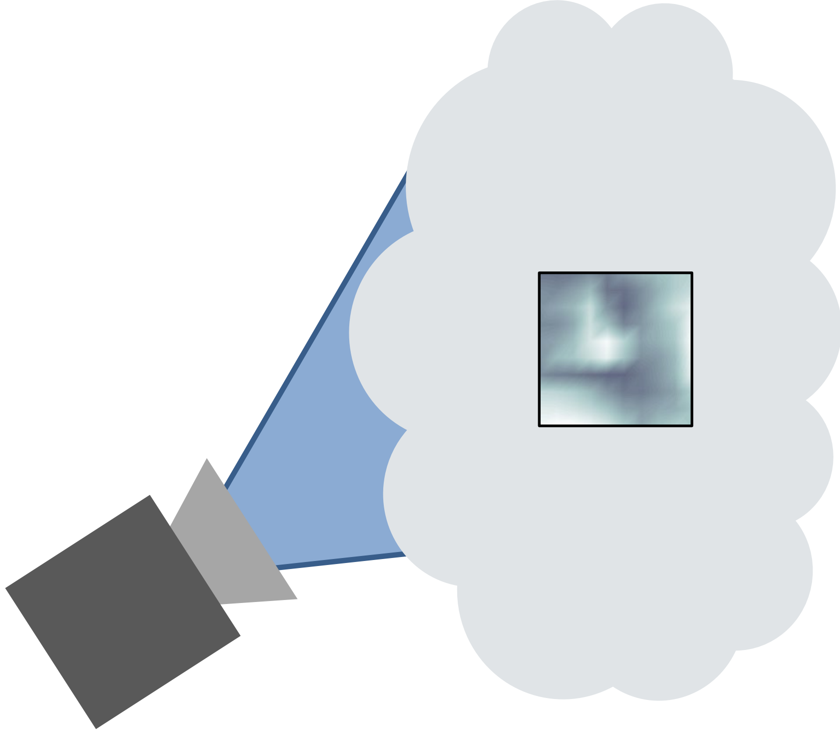

what shape our camera sees




what a regular camera sees


what depth our camera sees

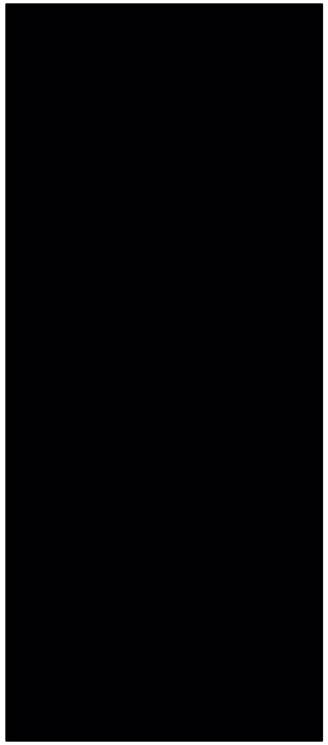
Time-of-flight applications: seeing inside objects



camera

thick smoke cloud

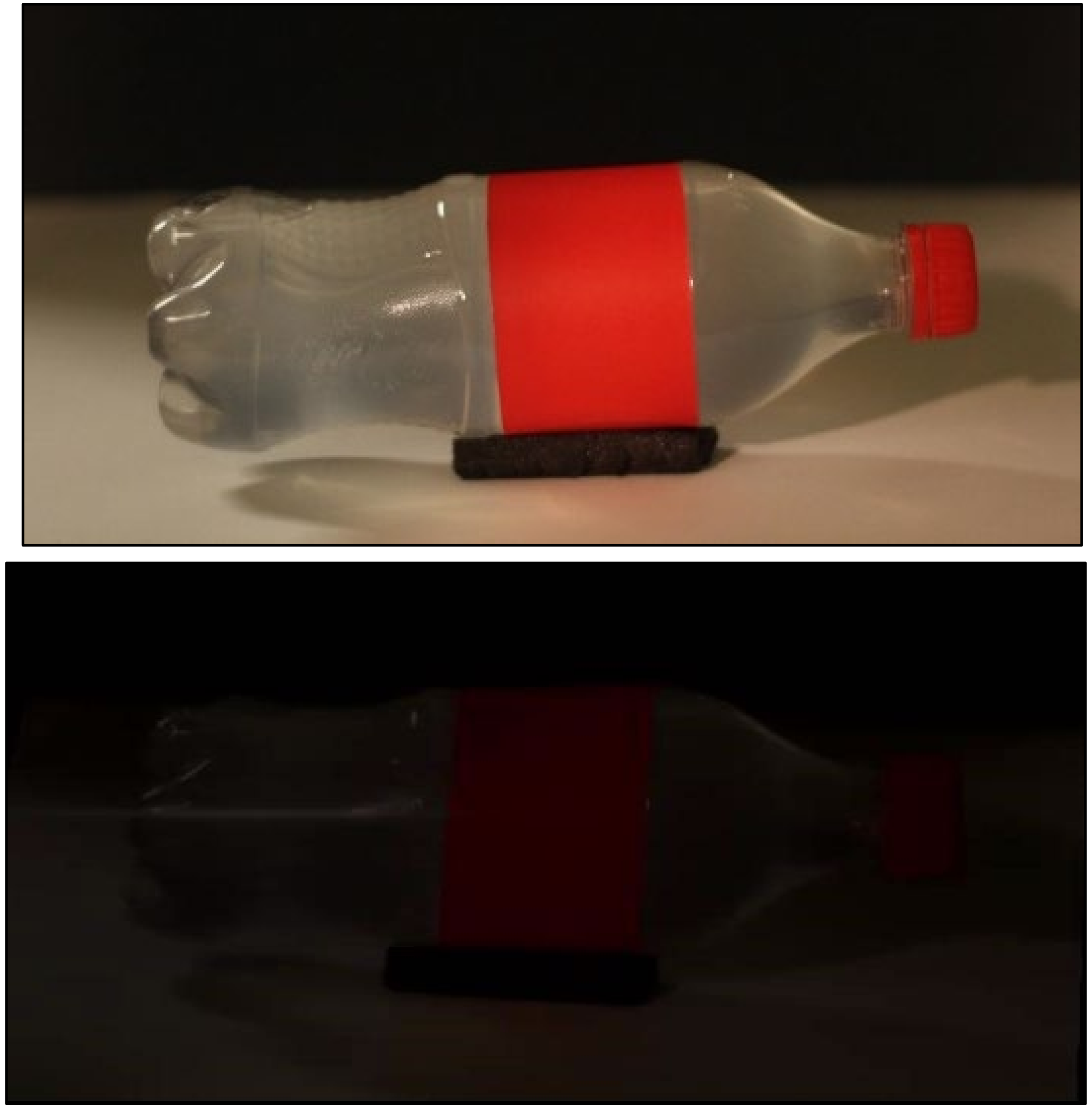
what a regular camera sees



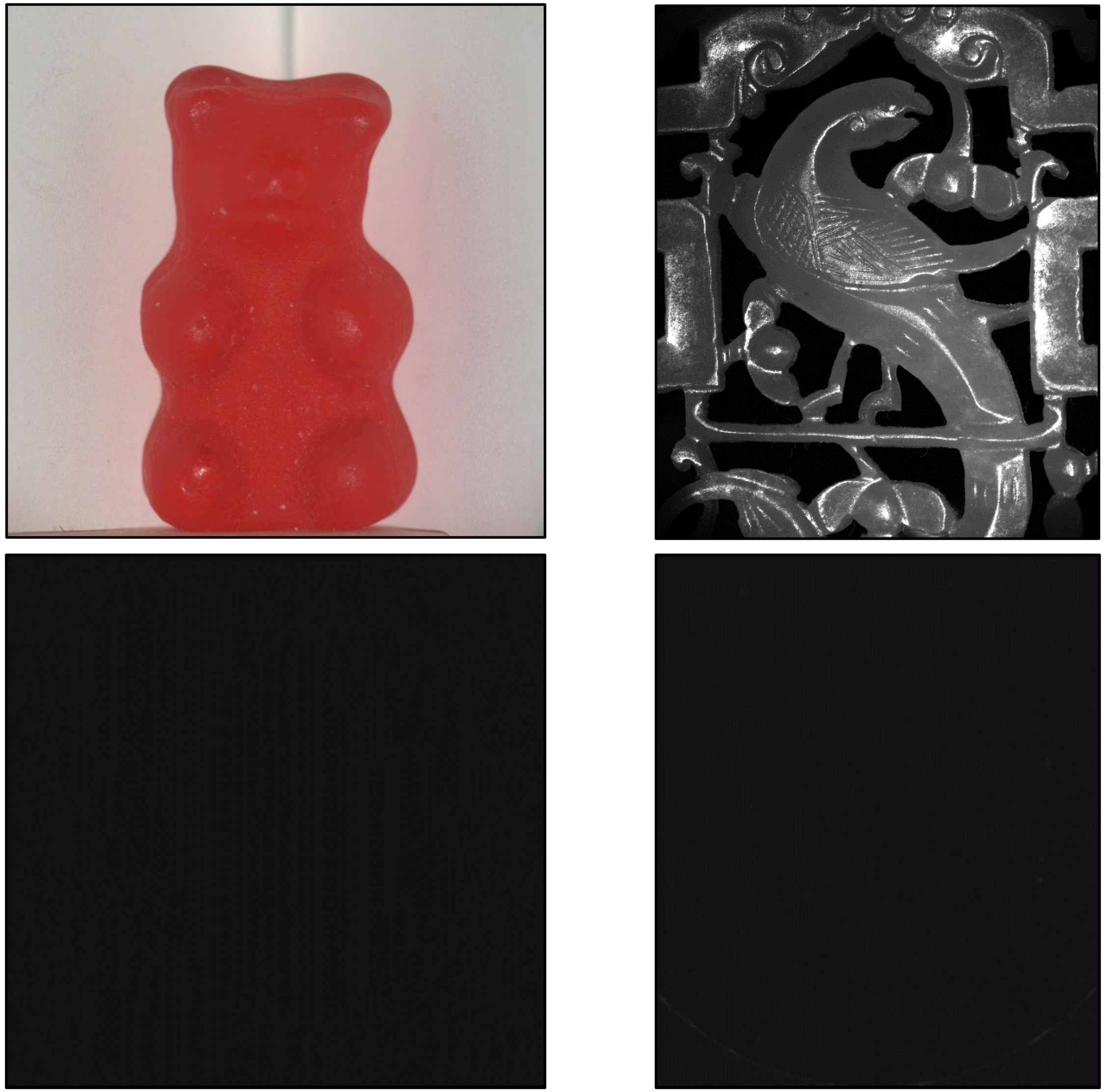
what our camera sees

a slice through the cloud

Time-of-flight applications: light-in-flight visualization



video at 10^{12} frames per second



video at 10^{15} frames per second

Time-of-flight imaging technologies

	interferometry	streak cameras	single-photon avalanche diodes	time-of-flight cameras	LIDAR
temporal resolution	1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	100 picoseconds (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)
frame rate	quadrillion fps	trillion fps	10 billion fps	billion fps	100 million fps
distance travelled	1 micron (10^{-6} meters)	1 millimeter (10^{-3} meters)	10 centimeters (10^{-1} meters)	1 meter (10^{-0} meters)	10 meters (10^{1} meters)

Time-of-flight imaging technologies

	interferometry	streak cameras	single-photon avalanche diodes	time-of-flight cameras	LIDAR
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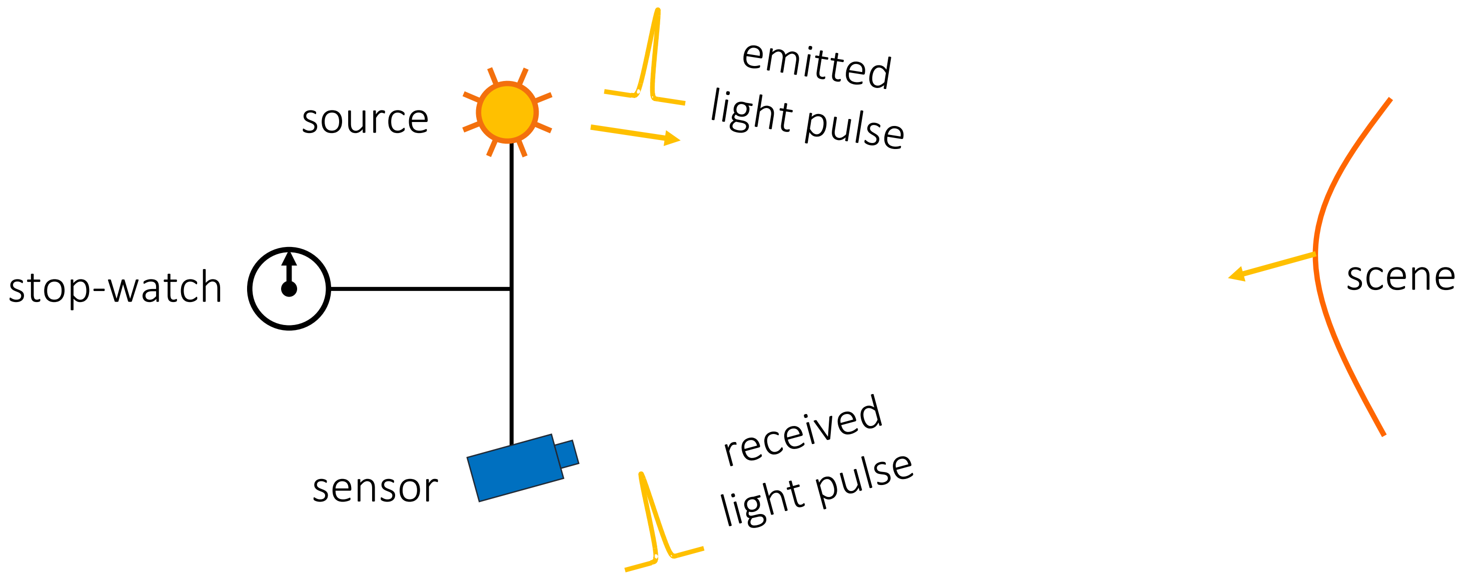
distance travelled	1 micron (10^{-6} meters)	1 millimeter (10^{-3} meters)	10 centimeters (10^{-1} meters)	1 meter (10^{-0} meters)	10 meters (10^{1} meters)

continuous-wave ToF (interferometry, time-of-flight cameras)

impulse ToF (streak cameras, single-photon avalanche diodes, LIDAR)

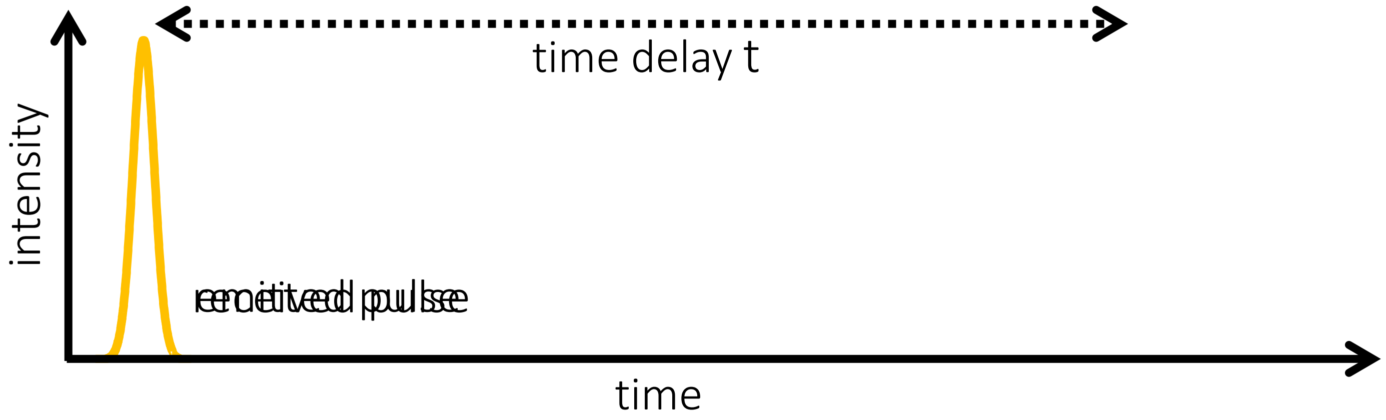
Impulse ToF imaging and single-photon avalanche diodes

Impulse time-of-flight imaging

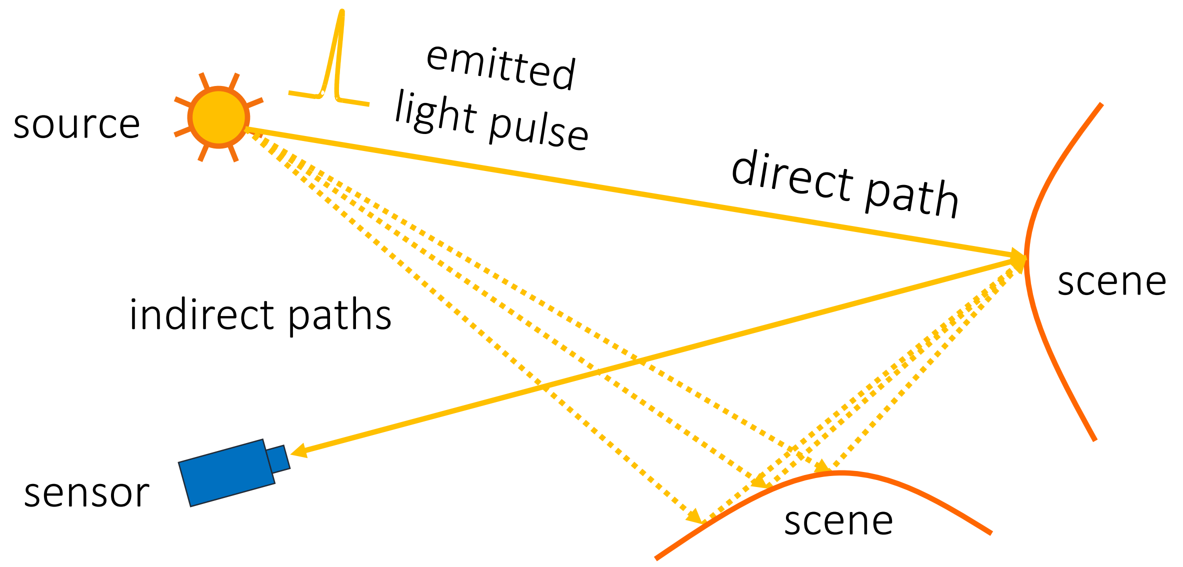


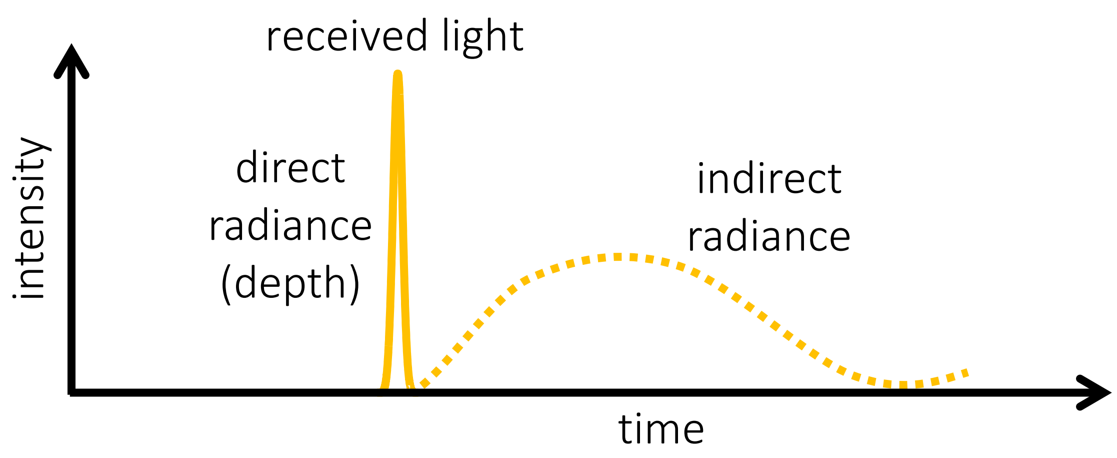
How can we infer depth from this?

$$depth = \frac{c}{2\tau}$$



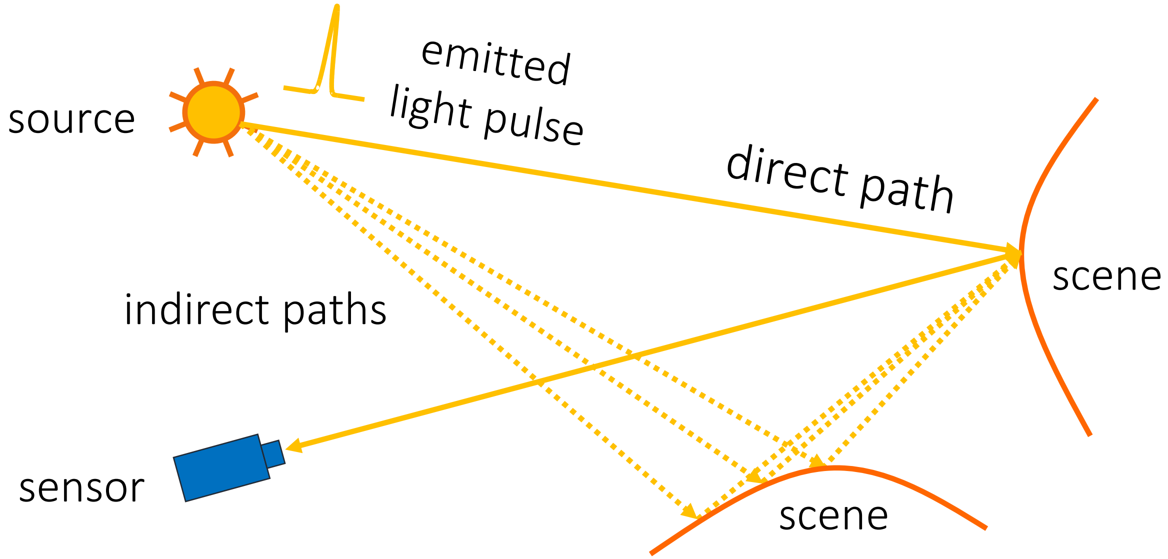
Impulse time-of-flight imaging

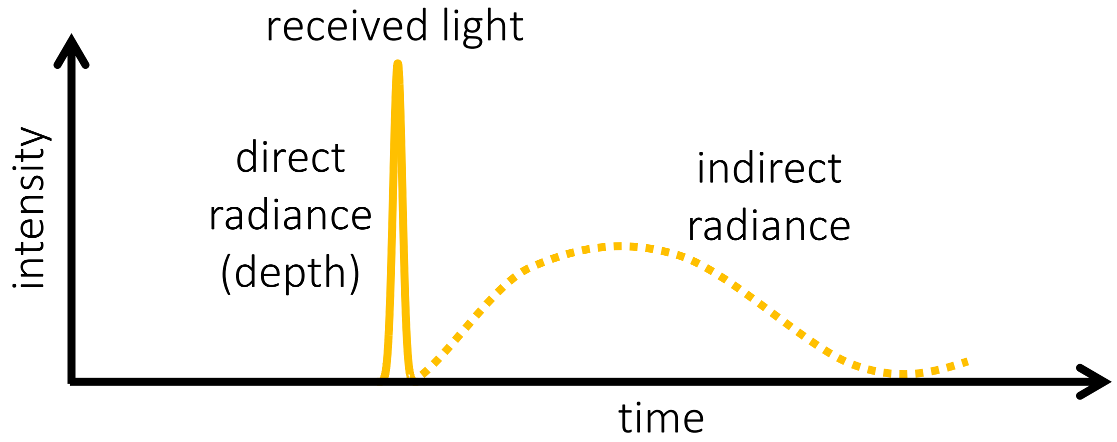




- Indirect paths are nuisance for depth sensing ("multi-path interference").
- Indirect paths are very informative for other time-of-flight applications.

Two types of time-of-flight imaging





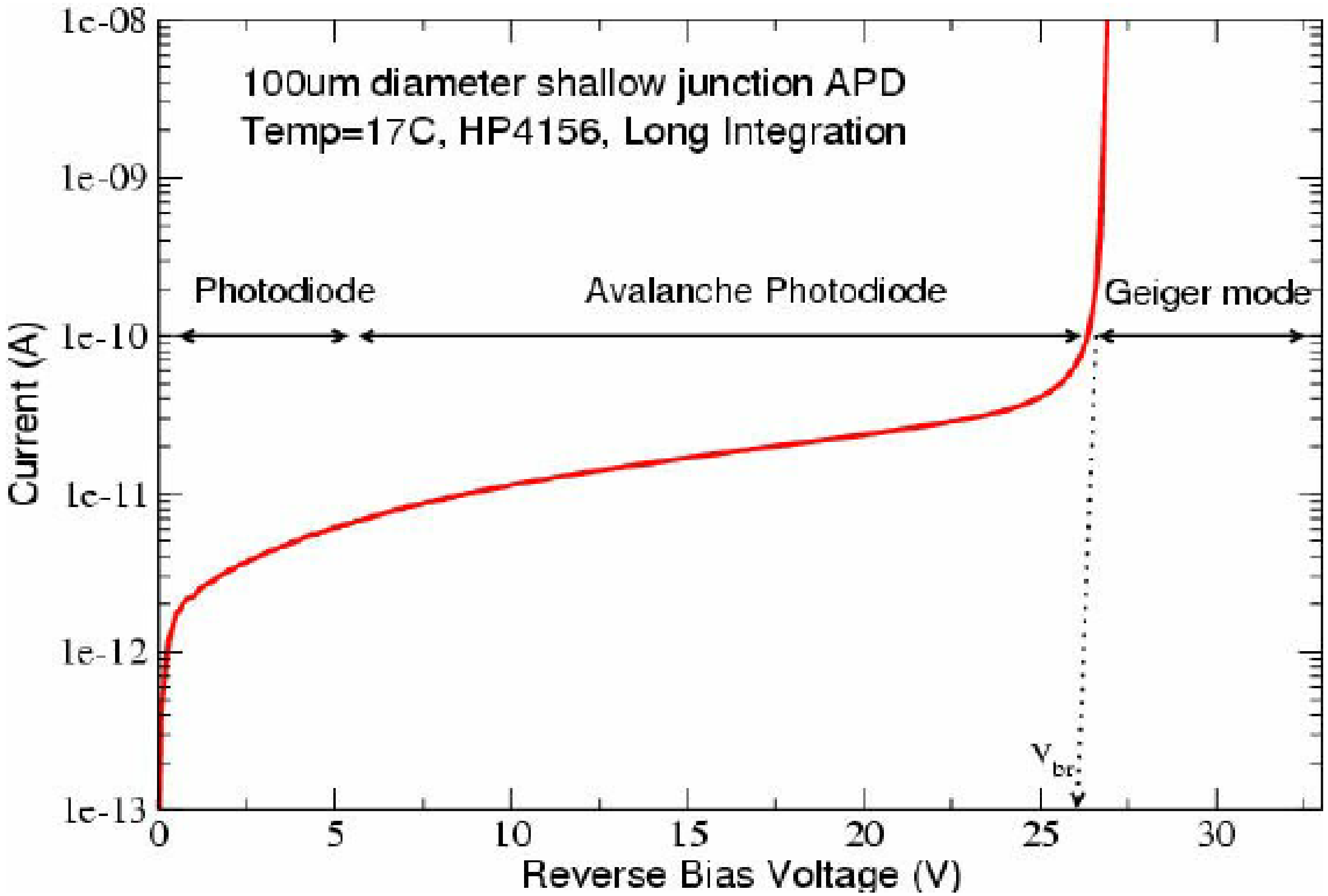
Transient I(t): Time-resolved radiance distribution

- Range imaging: Measuring only first returning photons (e.g., LIDAR).
- Transient imaging: Measuring entire transient (e.g., SPAD).

How exactly is the transient formed?

Depends on the kind of sensor we use.

- Here we will examine only photodiodes.



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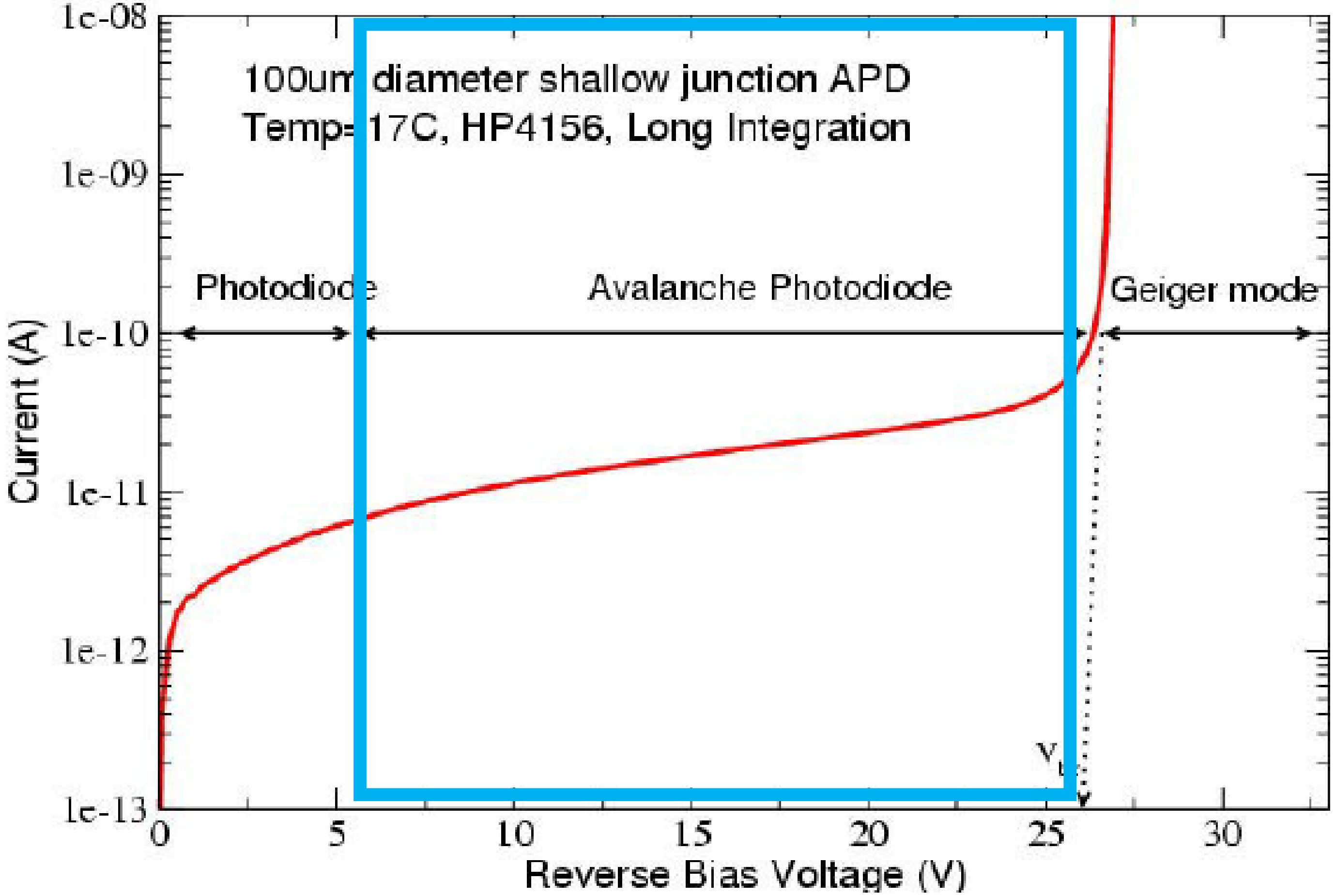

Avalanche photodiode (APD):

- Current is roughly proportional to number of photons.
- One photon produces tiny current.

How exactly is the transient formed?

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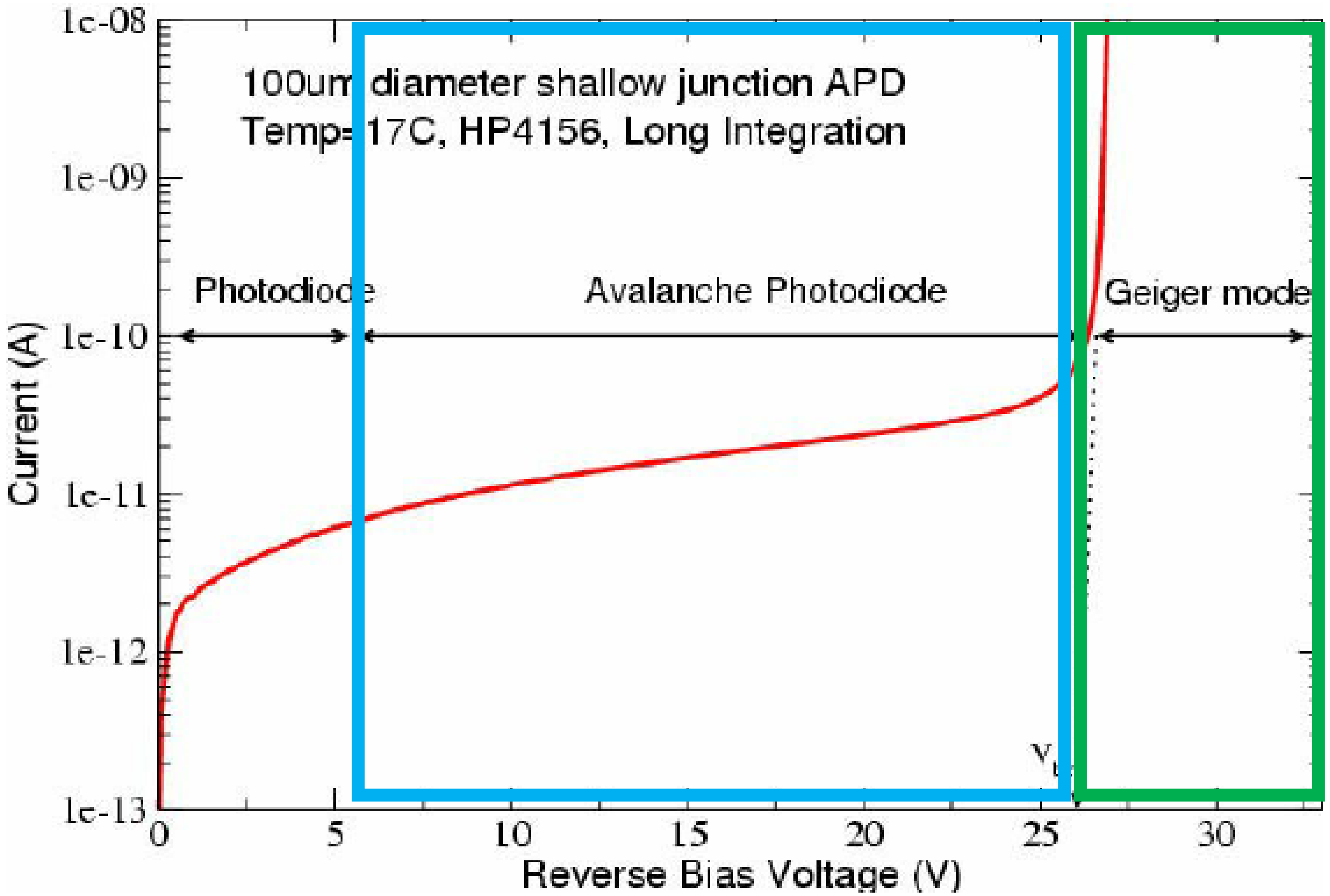
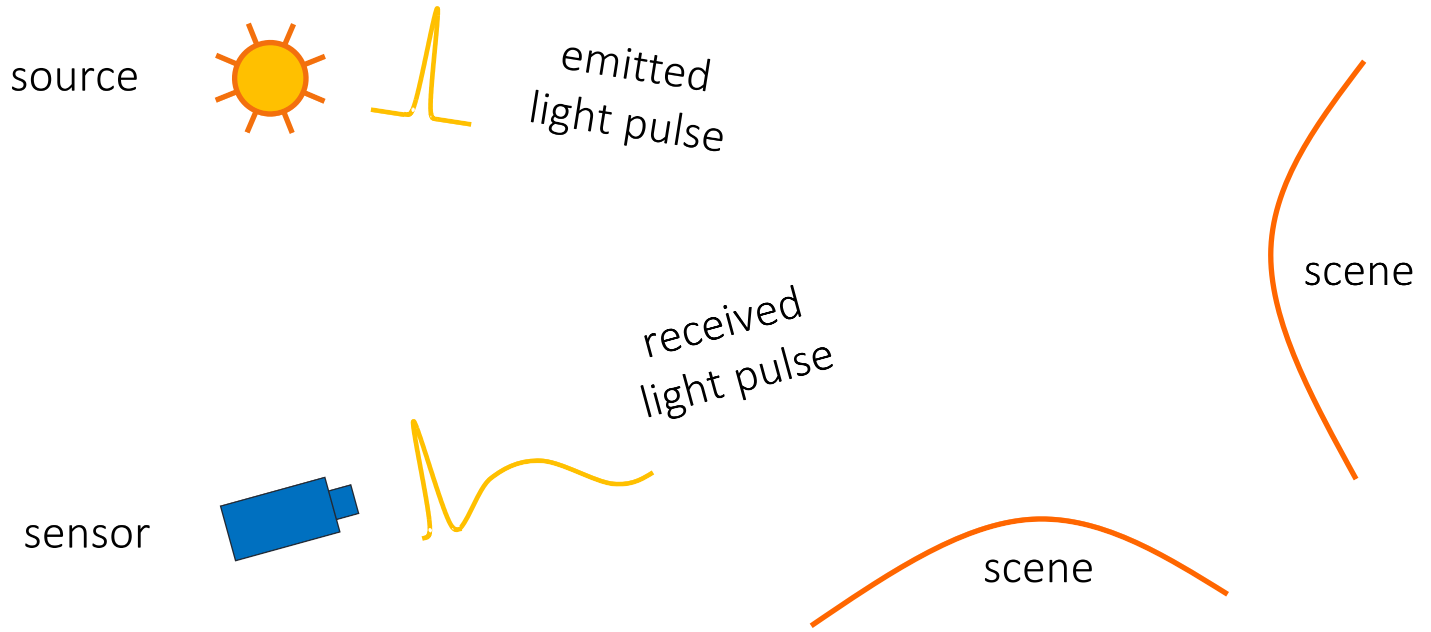


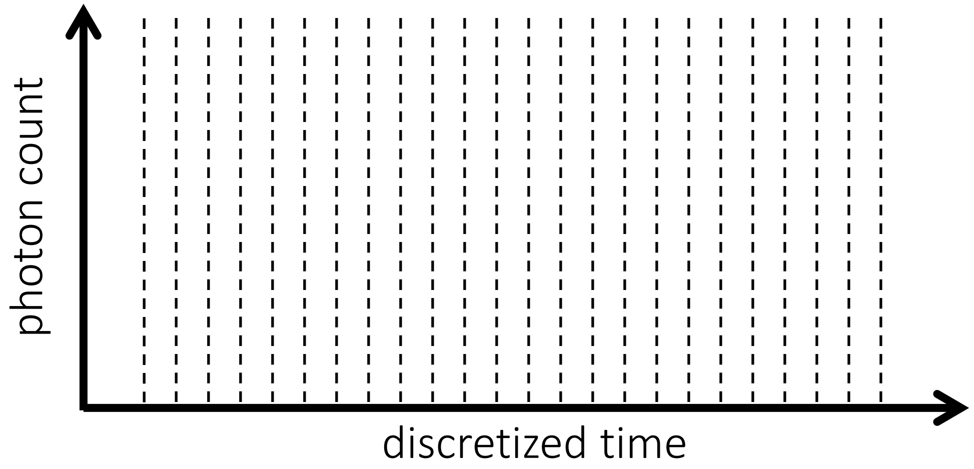
Avalanche photodiode (APD):
- Current is roughly proportional to number of photons.
- One photon produces tiny current.

Single-photon avalanche diode (SPAD):
- One photon produces huge current.
- Requires multiple low power pulses, so that one photon returns from each.

Geiger-mode impulse time-of-flight imaging

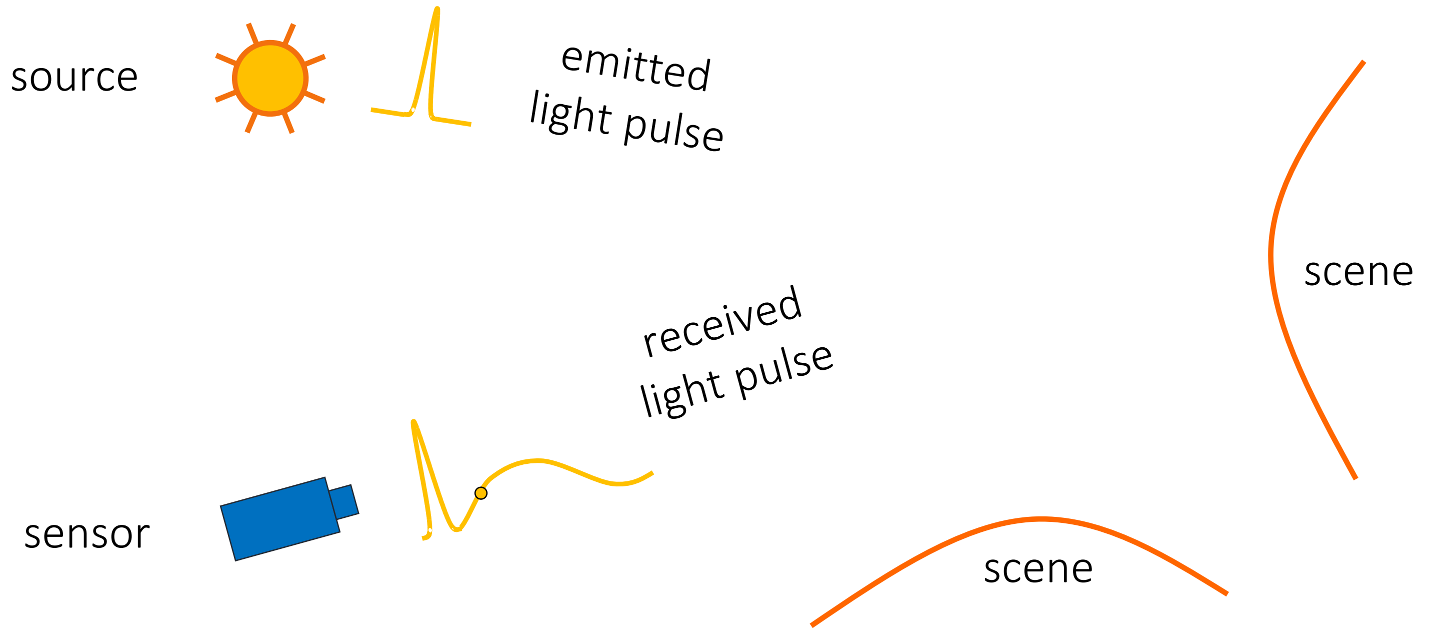


From each received pulse, one photon saturates the SPAD.



- The SPAD records only photon arrival times, no intensity.
- Additional electronics maintain a histogram of arrival times over multiple pulses

Geiger-mode impulse time-of-flight imaging



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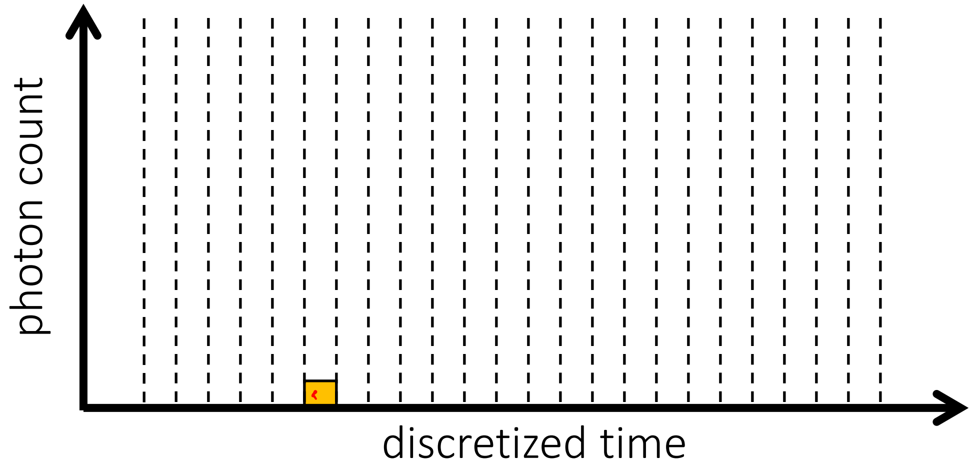

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Geiger-mode impulse time-of-flight imaging

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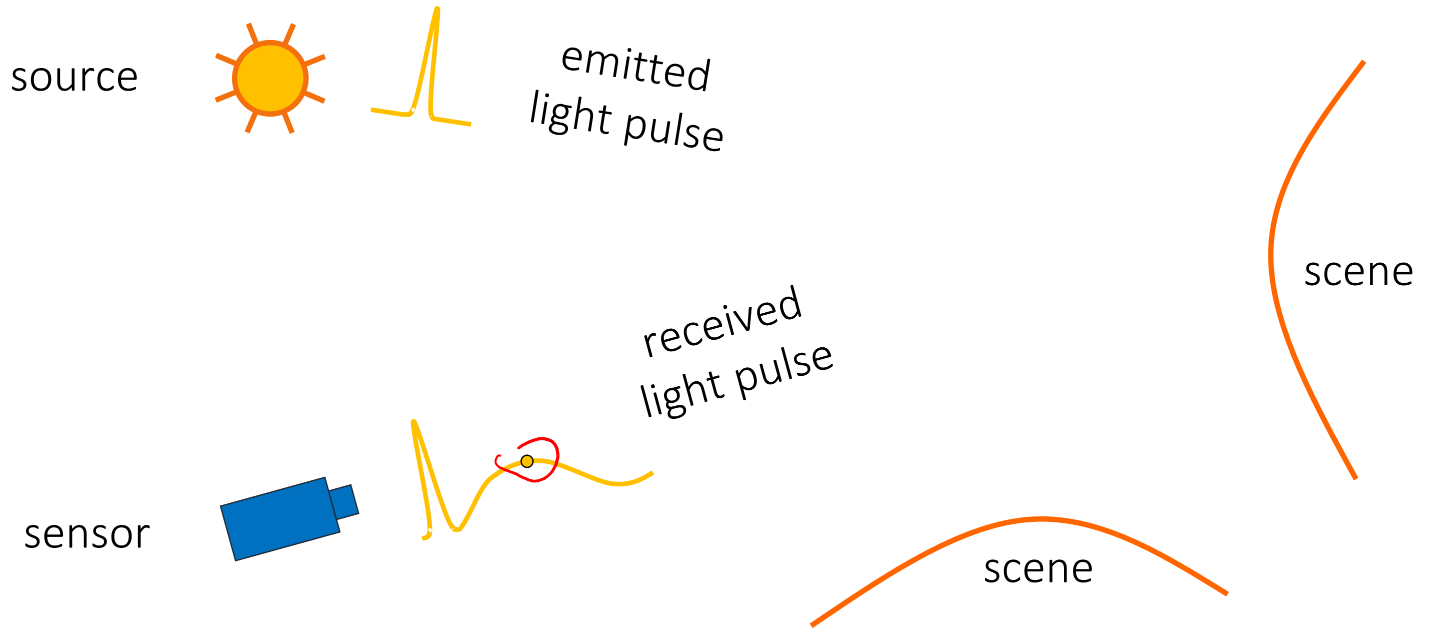

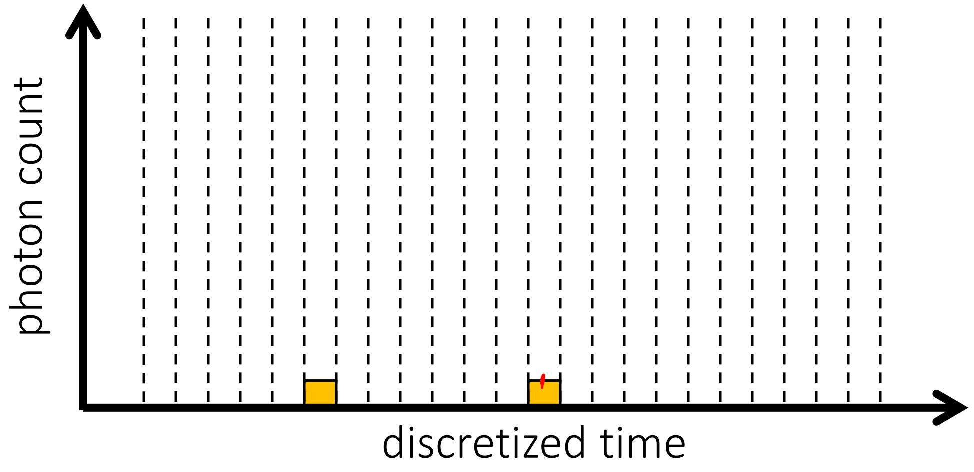

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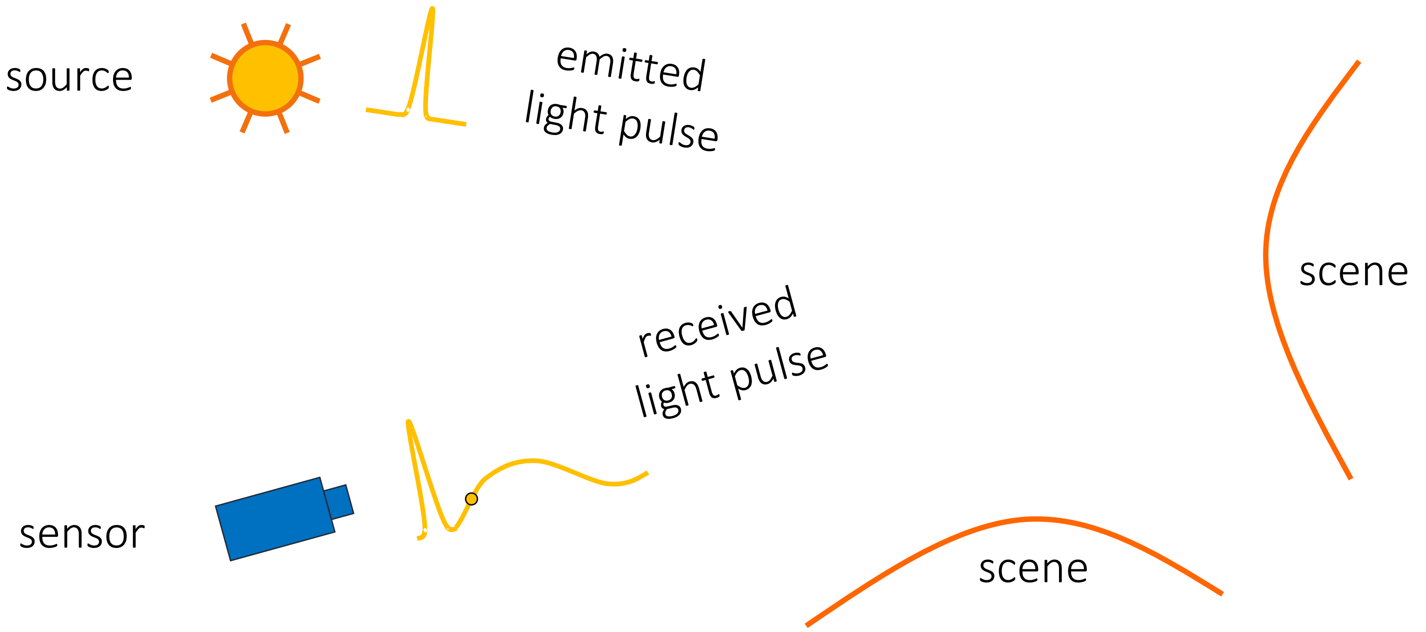
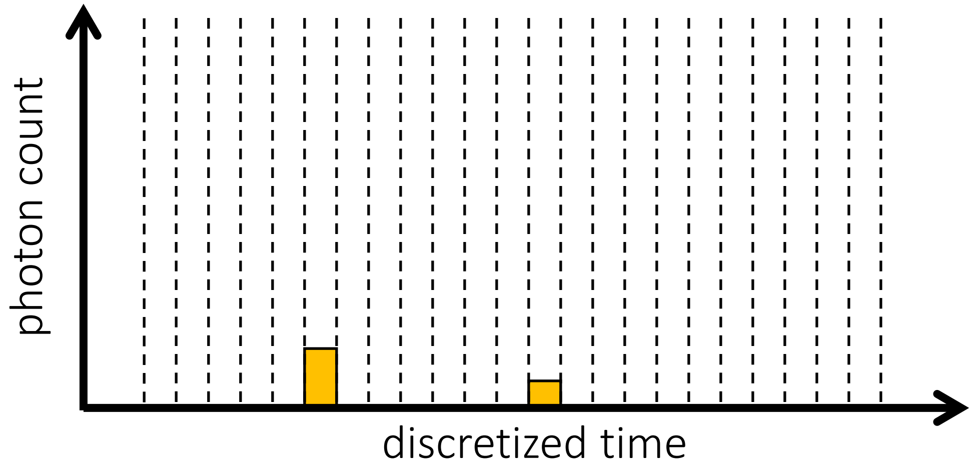
Geiger-mode impulse time-of-flight imaging

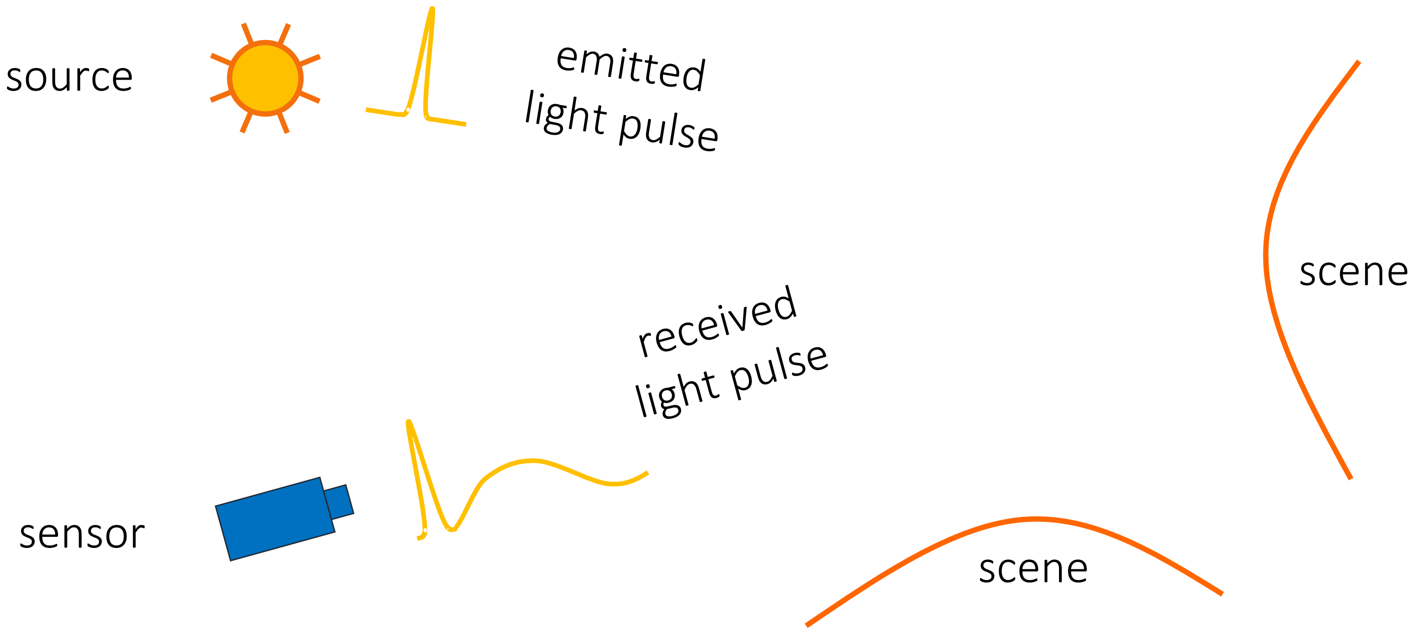
From each received pulse, one photon saturates the SPAD.





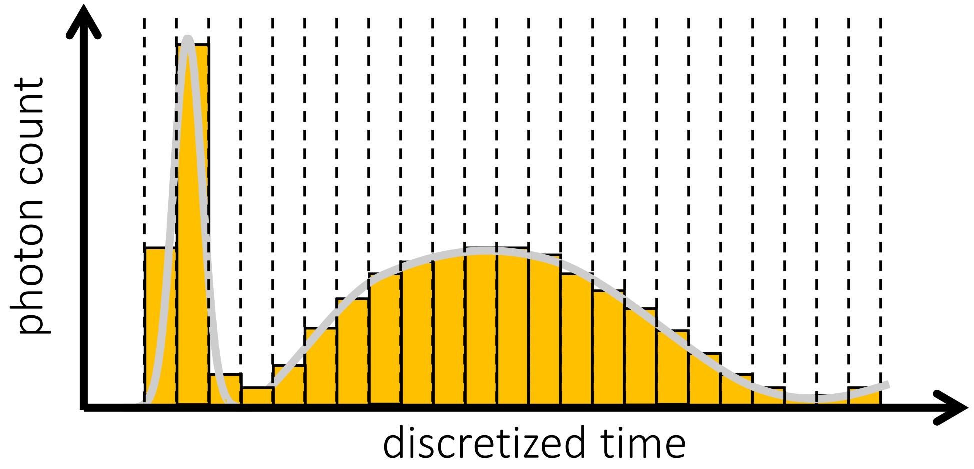
- The SPAD records only photon arrival times, no intensity.
- Additional electronics maintain a histogram of arrival times over multiple pulses

Geiger-mode impulse time-of-flight imaging



From each received pulse, one photon saturates the SPAD.

What determines which photon gets picked?



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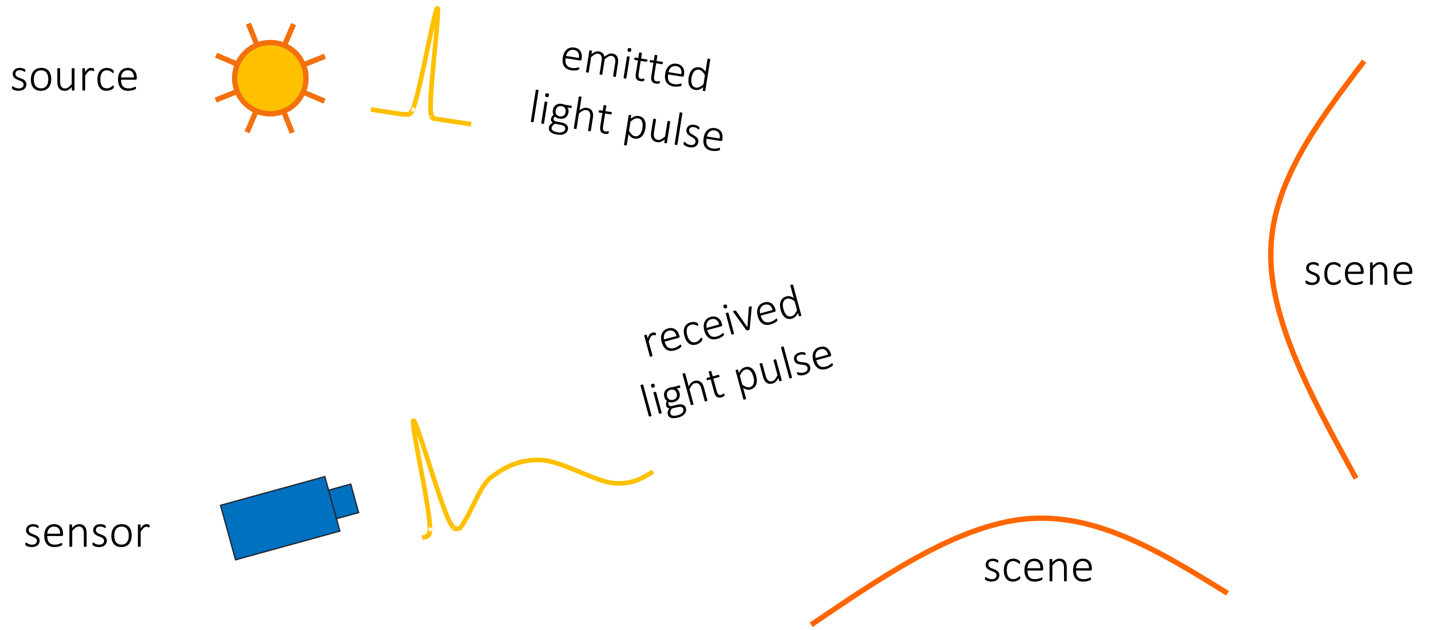
Geiger-mode impulse time-of-flight imaging



From each received pulse, one photon saturates the SPAD.

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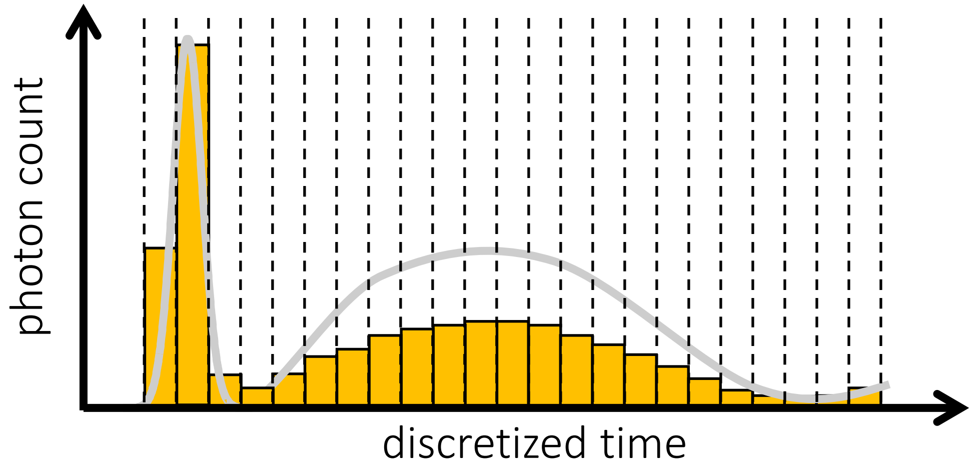
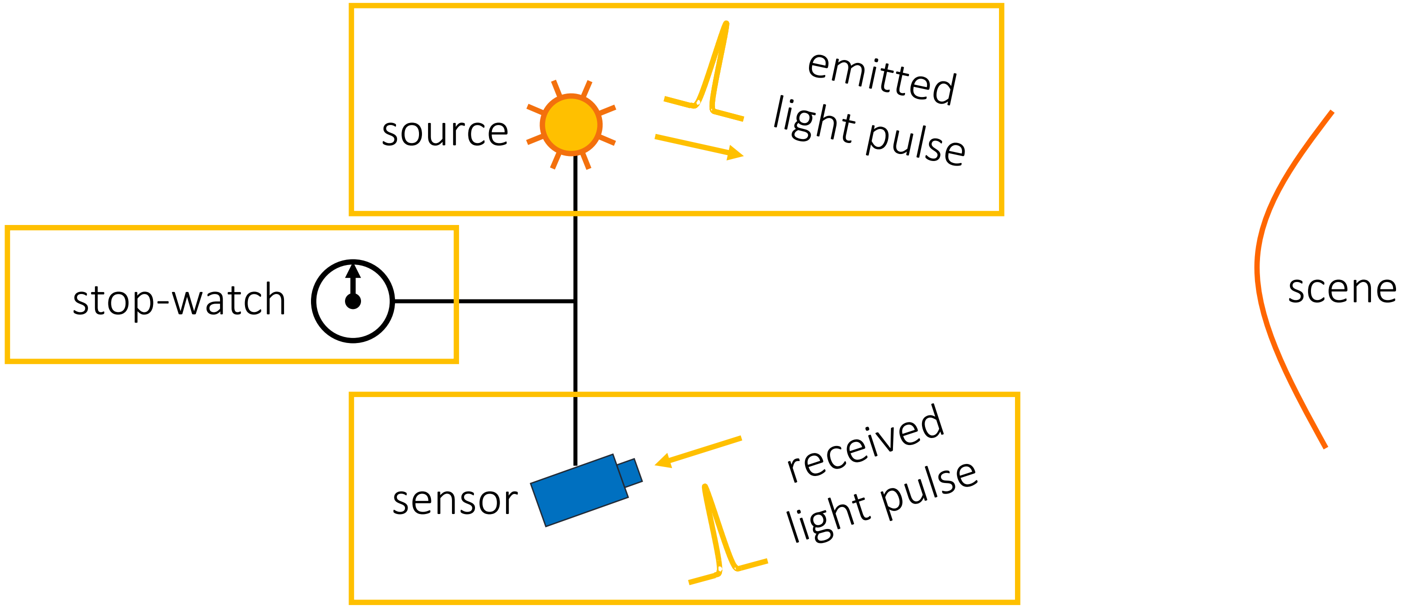


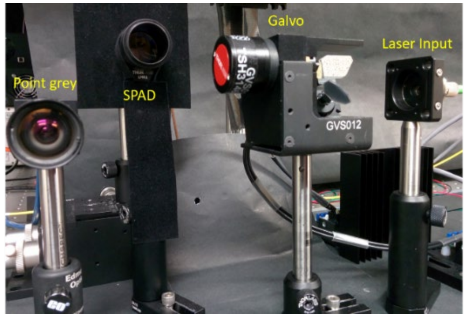
- Photons earlier in the transient have a higher probability of being detected than photons later in the transient.
- As a result, histogram of photon detections underestimates later parts of the transient.
- This effect is called *pile-up* and is very severe under strong light conditions.

What hardware do we need for impulse ToF?



Expensive lasers
[short (picosecond) and powerful
(mega joules) light pulses]

High speed and high
dynamic range sensors
[single-photon sensitivity]



Expensive syncing and
photon-counting electronics
[picosecond time resolution]

Time-of-flight imaging technologies

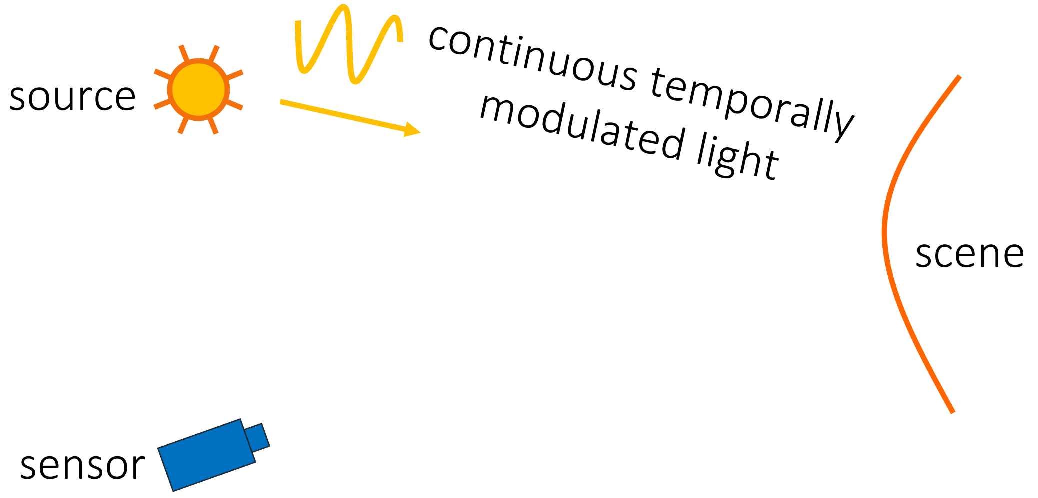
	interferometry	streak cameras	single-photon avalanche diodes	time-of-flight cameras	LIDAR
temporal resolution	1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	100 picoseconds (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)
frame rate	quadrillion fps	trillion fps	10 billion fps	billion fps	100 million fps
distance travelled	1 micron (10^{-6} meters)	1 millimeter (10^{-3} meters)	10 centimeters (10^{-1} meters)	1 meter (10^{-0} meters)	10 meters (10^{1} meters)

continuous-wave ToF: interferometry, time-of-flight cameras

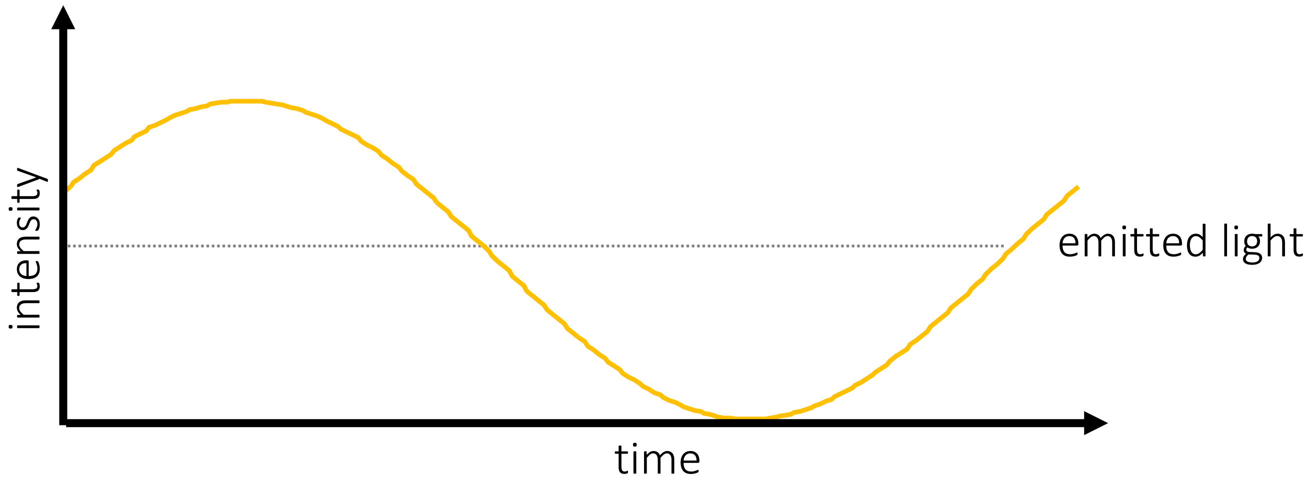
impulse ToF: streak cameras, single-photon avalanche diodes, LIDAR

Continuous-wave ToF imaging

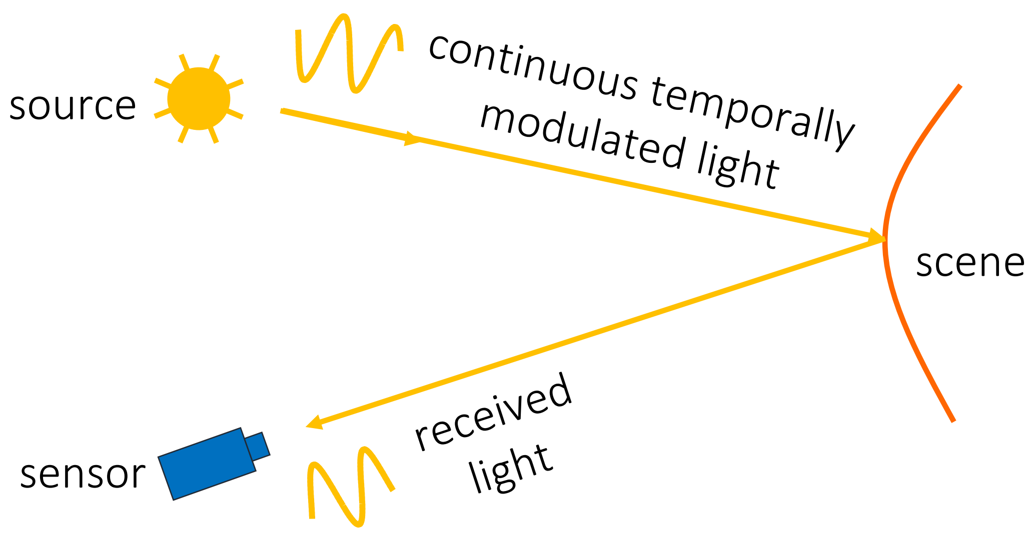
Continuous-wave (CW) time-of-flight imaging

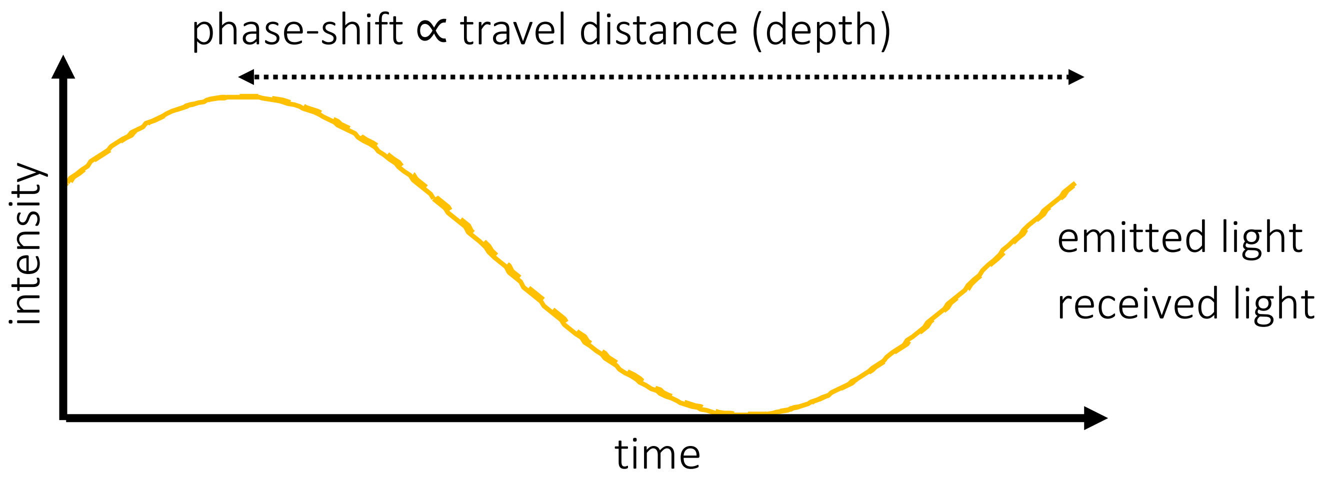


sinusoid

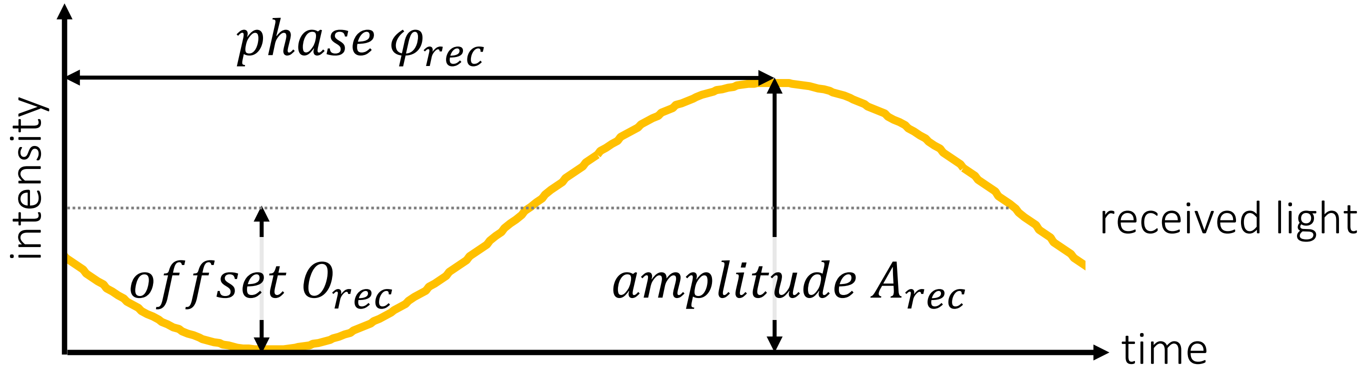


Continuous-wave (CW) time-of-flight imaging





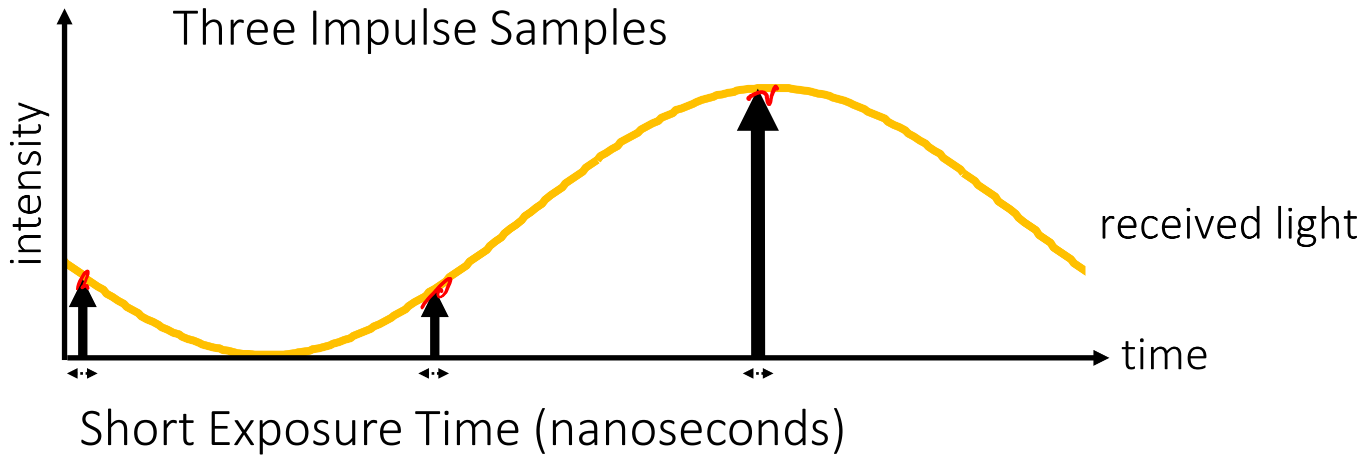
Measuring phase shift



Three Unknowns

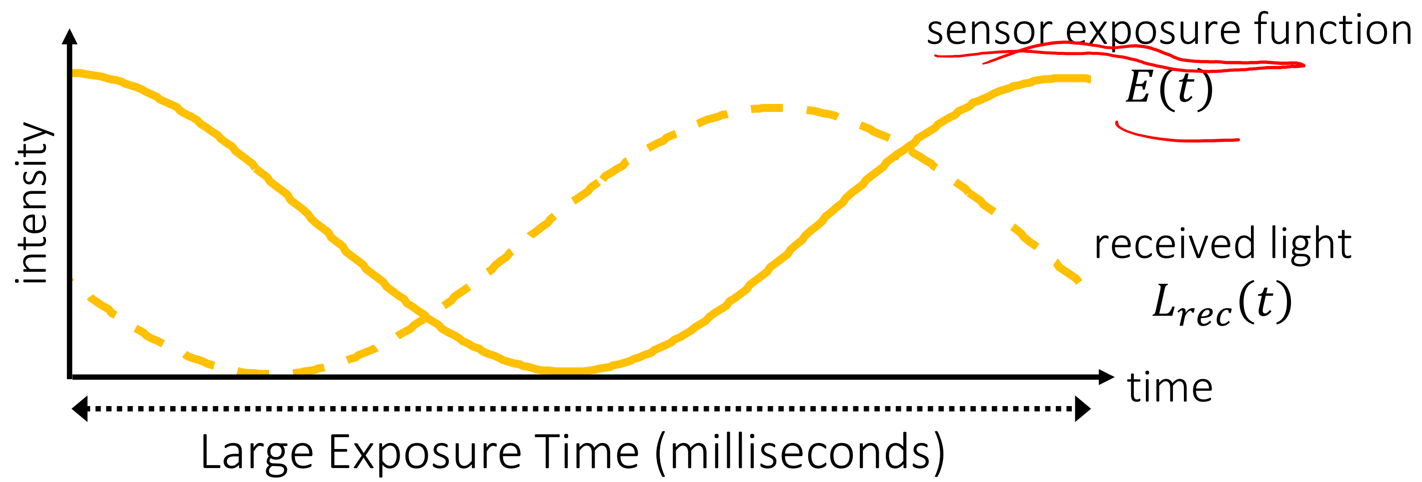
$$L_{rec}(t) = O_{rec} + A_{rec}\cos(\omega t - \phi_{rec})$$

Measuring phase shift: direct



Low Signal-to-Noise-Ratio

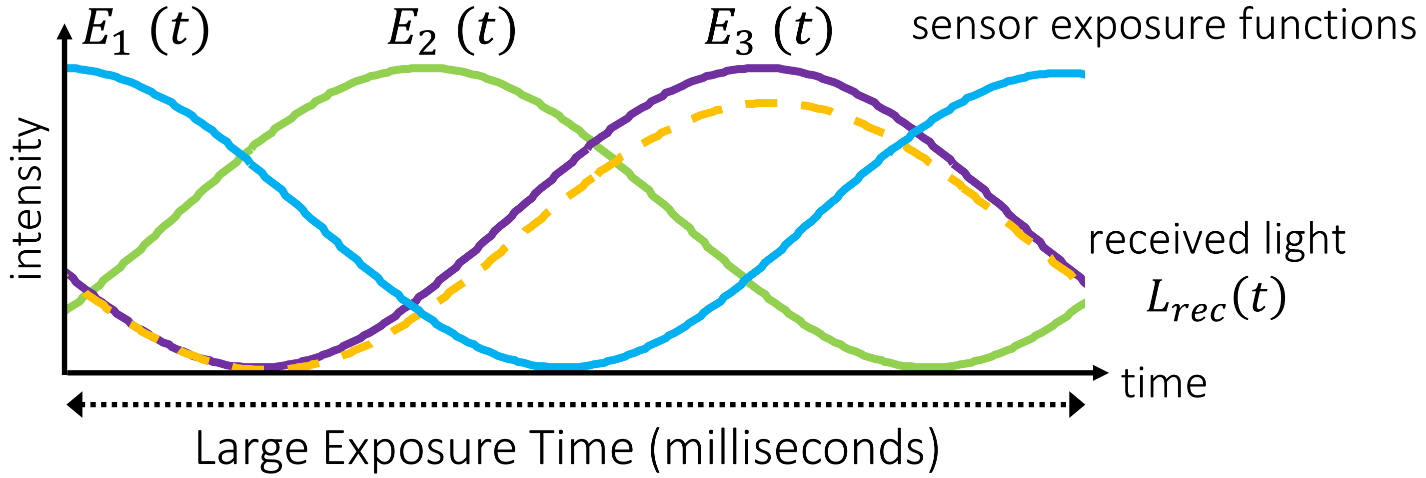
Measuring phase shift: correlation



Correlation: $I = \int E(t) \times L_{rec}(t)\, dt$

measured brightness — exposure function — received light

Measuring phase shift: correlation



Correlation 1: $I_1 = \int E_1\ (t) \times L_{rec}(t)\ dt$

High Signal-to-Noise Ratio

Correlation 2: $I_2 = \int E_2\ (t) \times L_{rec}(t)\ dt$

Real Time Capture

Correlation 3: $I_3 = \int E_3\ (t) \times L_{rec}(t)\ dt$

$\rightarrow$

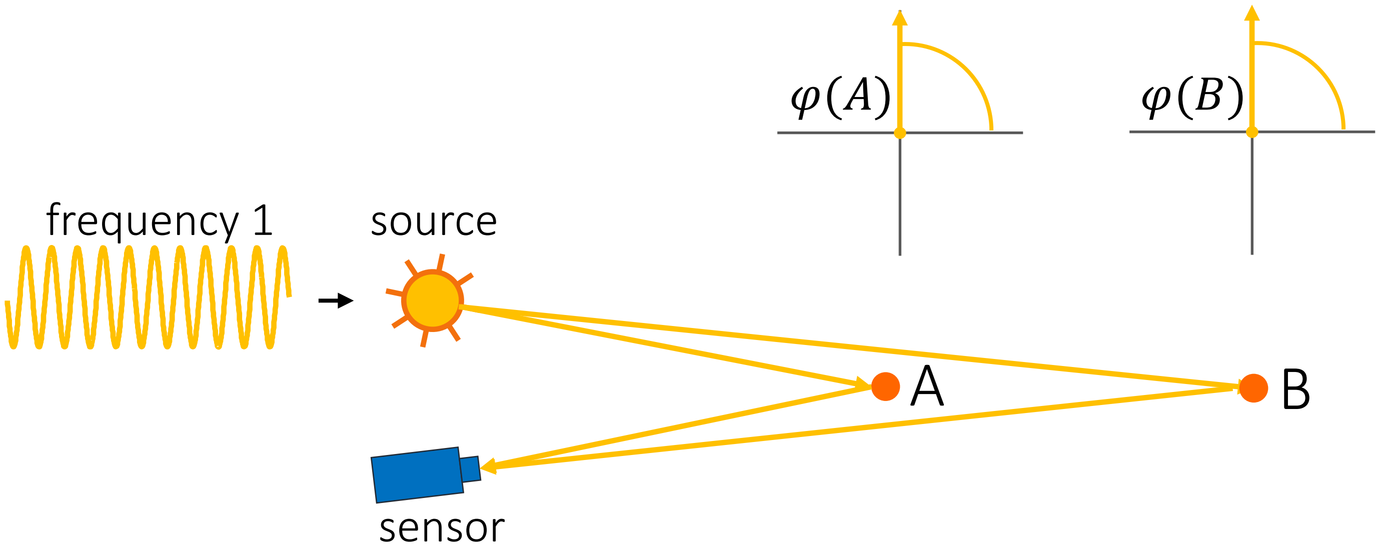
$depth$

$phase\ \varphi_{rec}$

$offset\ O_{rec}$

$amplitude\ A_{rec}$

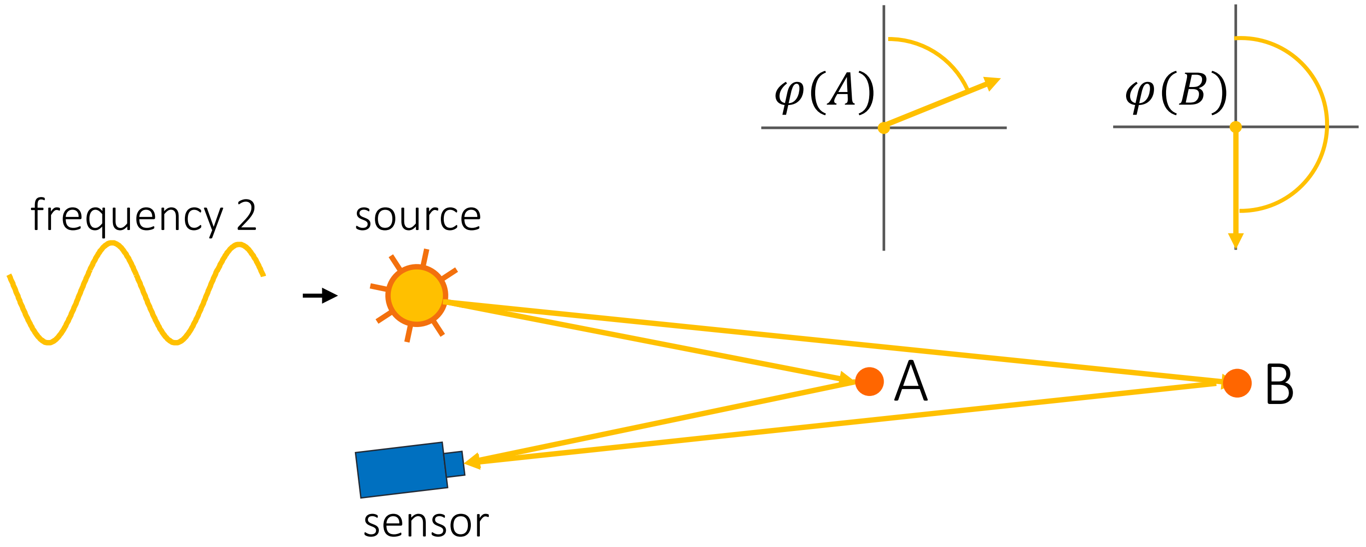
Phase ambiguity



Different Scene Depths Have Same Phase

- Also known as “phase wrapping”.

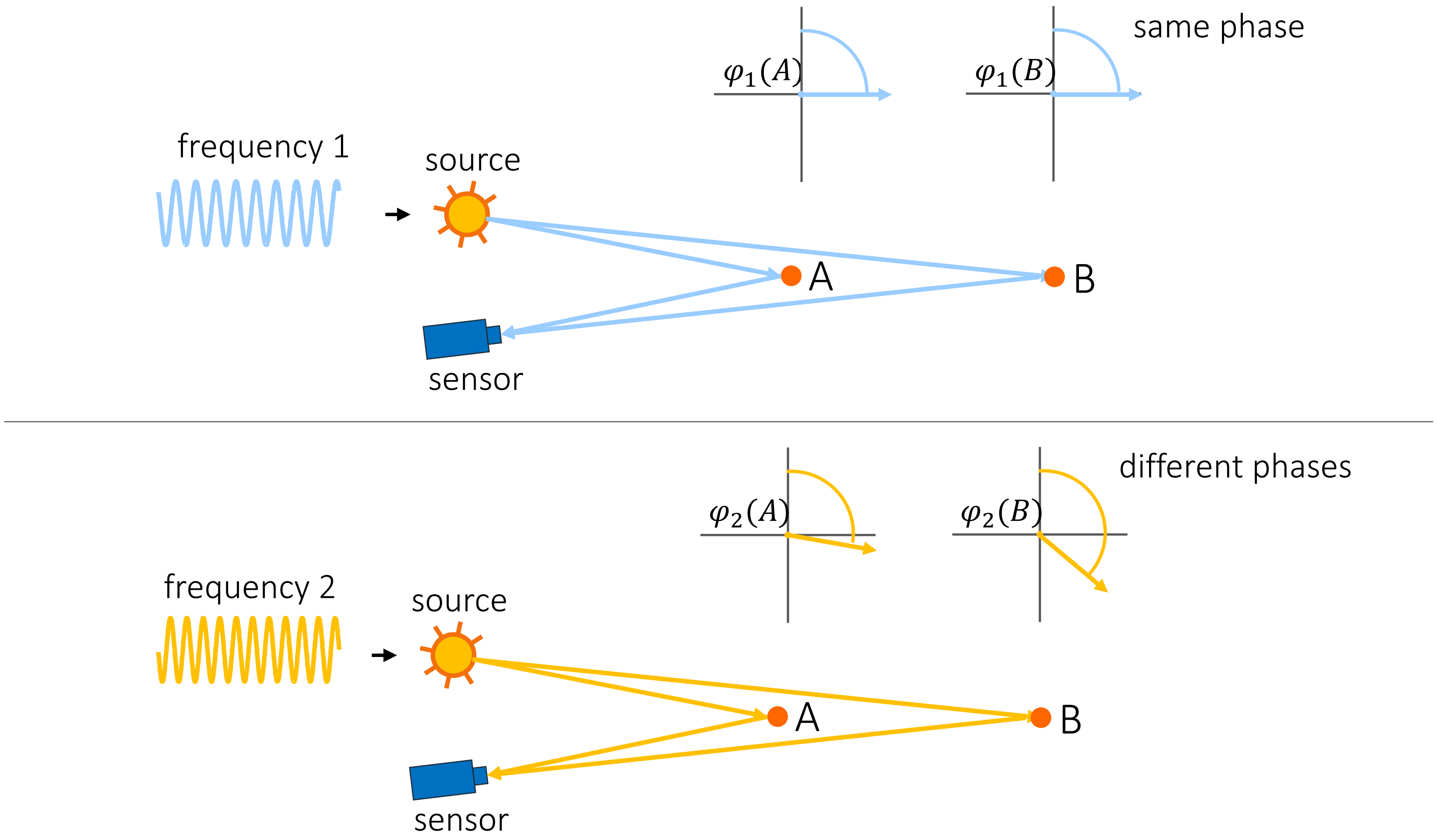
Phase ambiguity



Unambiguous Depth Range: $R_{unambiguous} = \frac{1}{2\omega}$

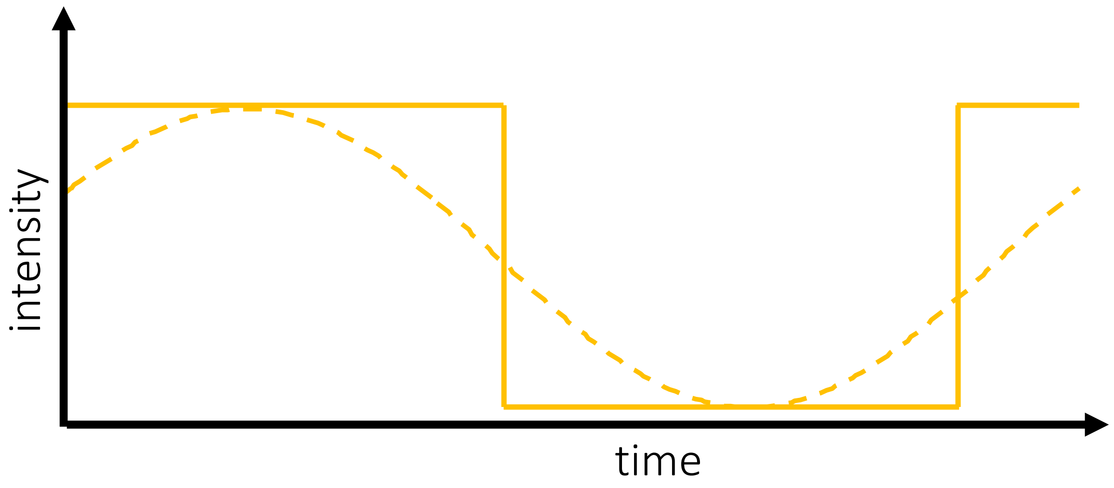
How can we resolve the phase ambiguity?

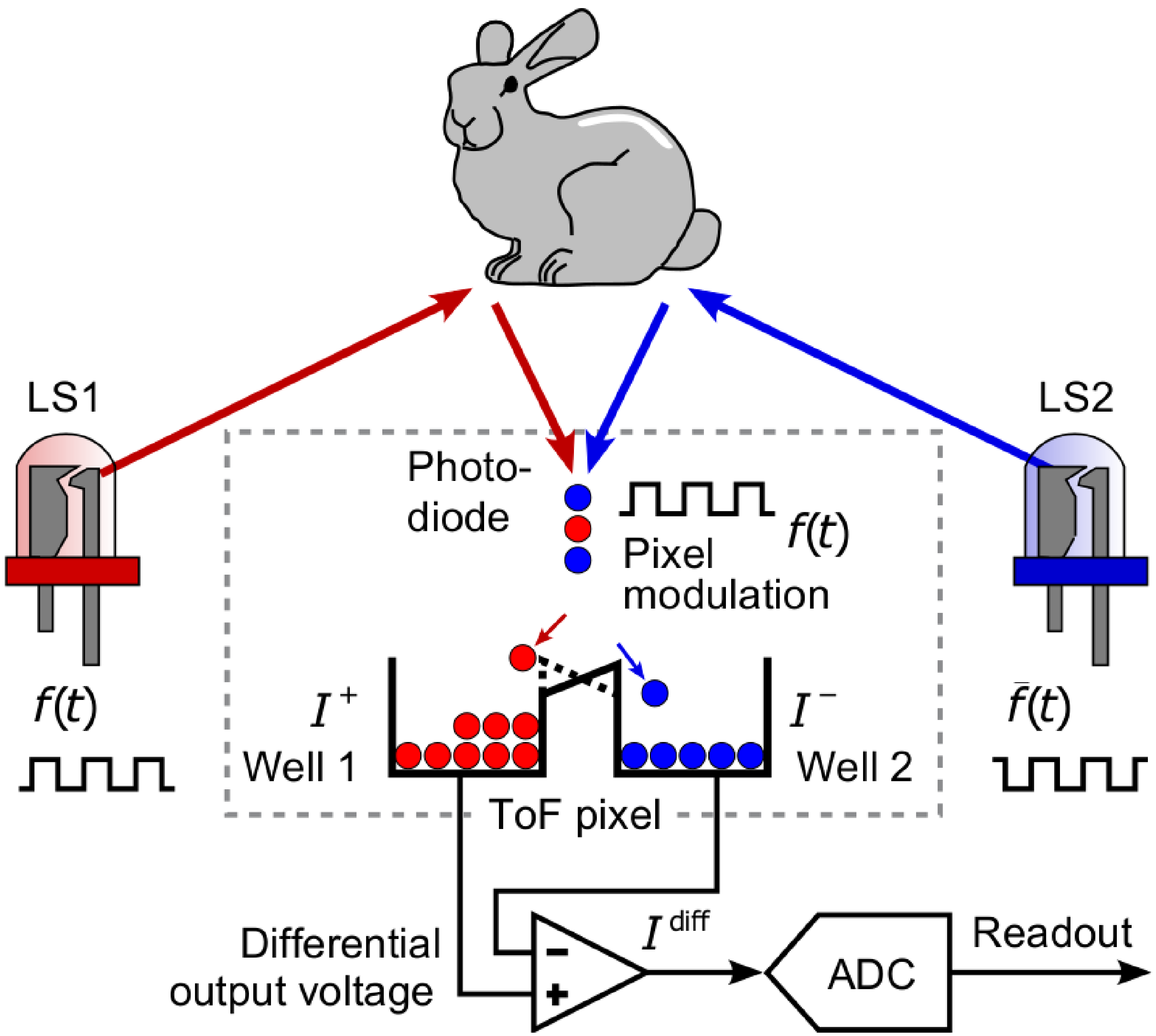
Disambiguating phase



Compute phases at two different frequencies

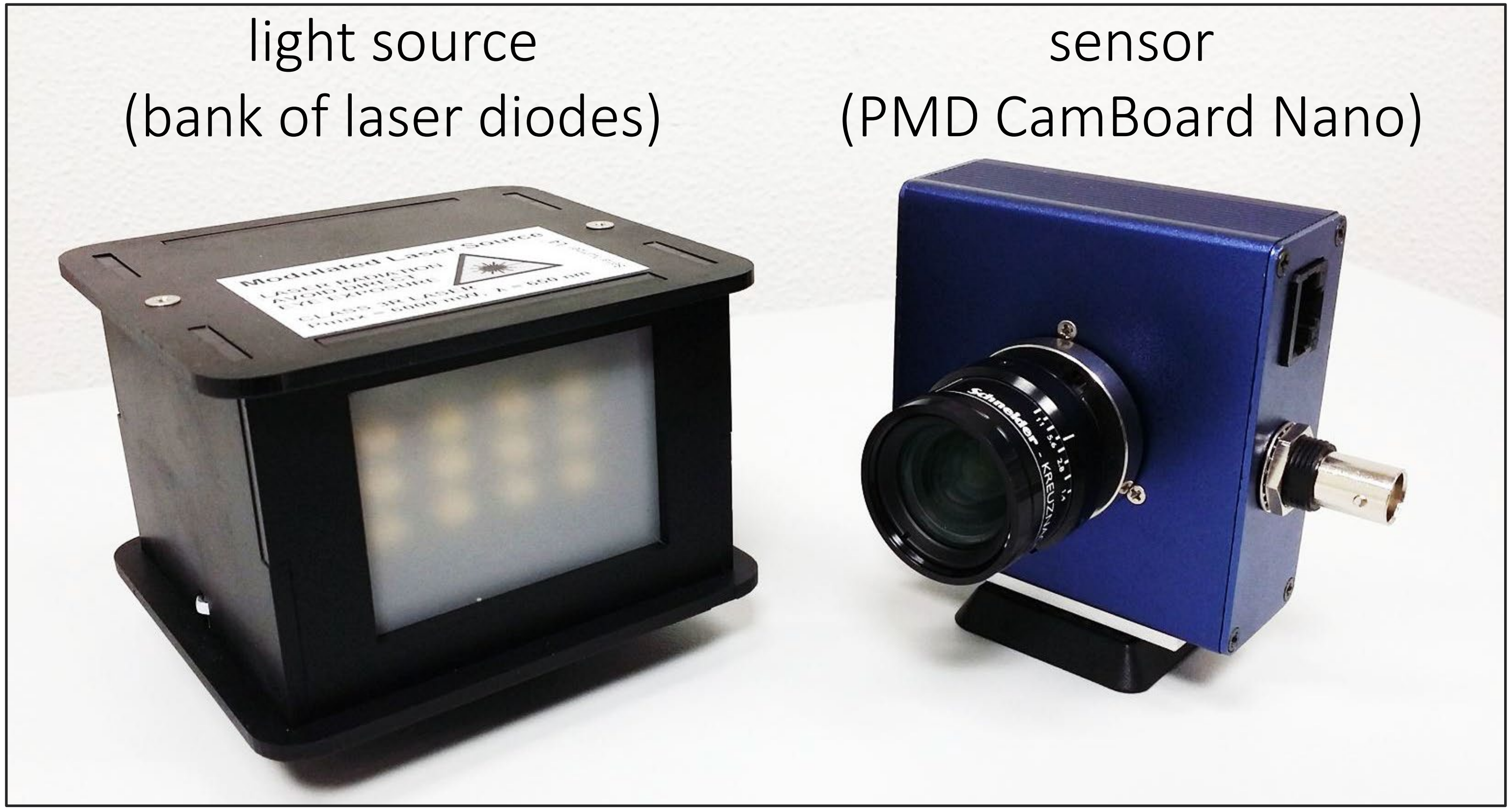
Implementation: two-well architectures



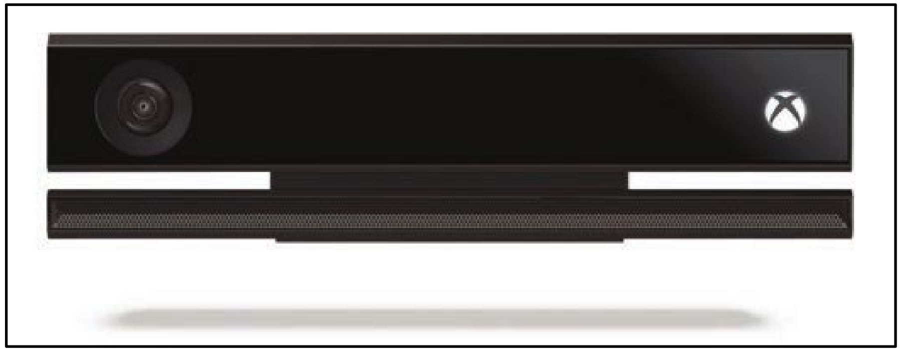


- approximate sinusoid with a square pulse
- store photons in different wells depending on whether they arrive at 1 or 0
- take difference between two wells

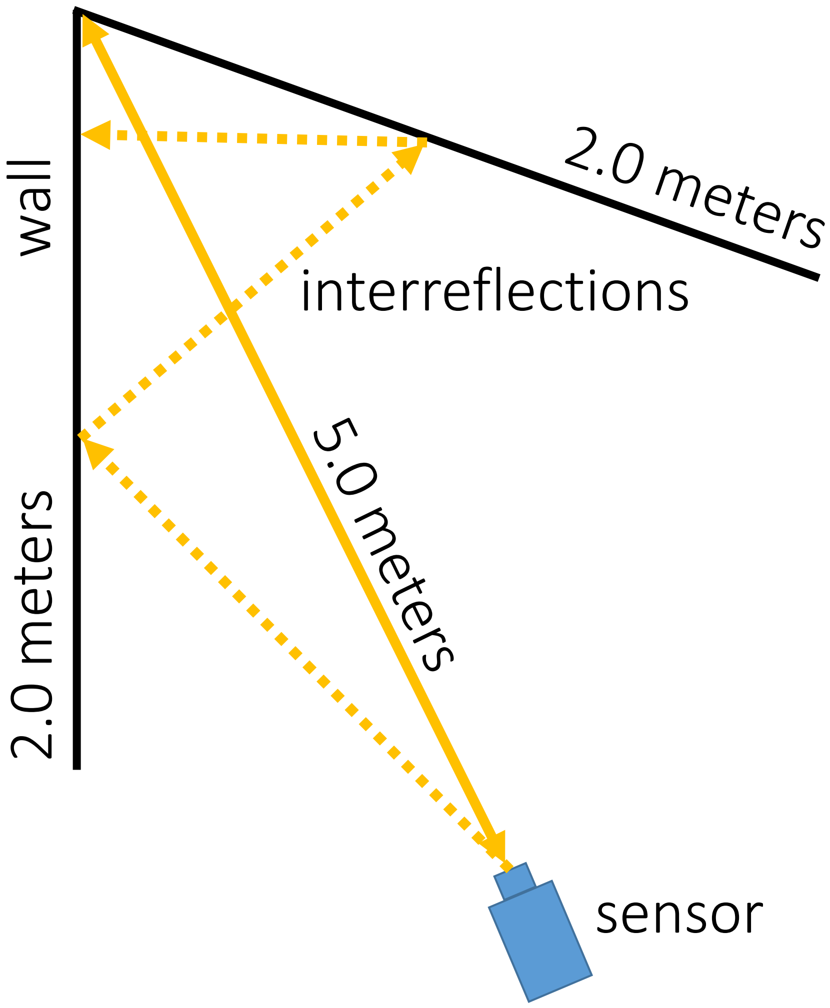
Some examples



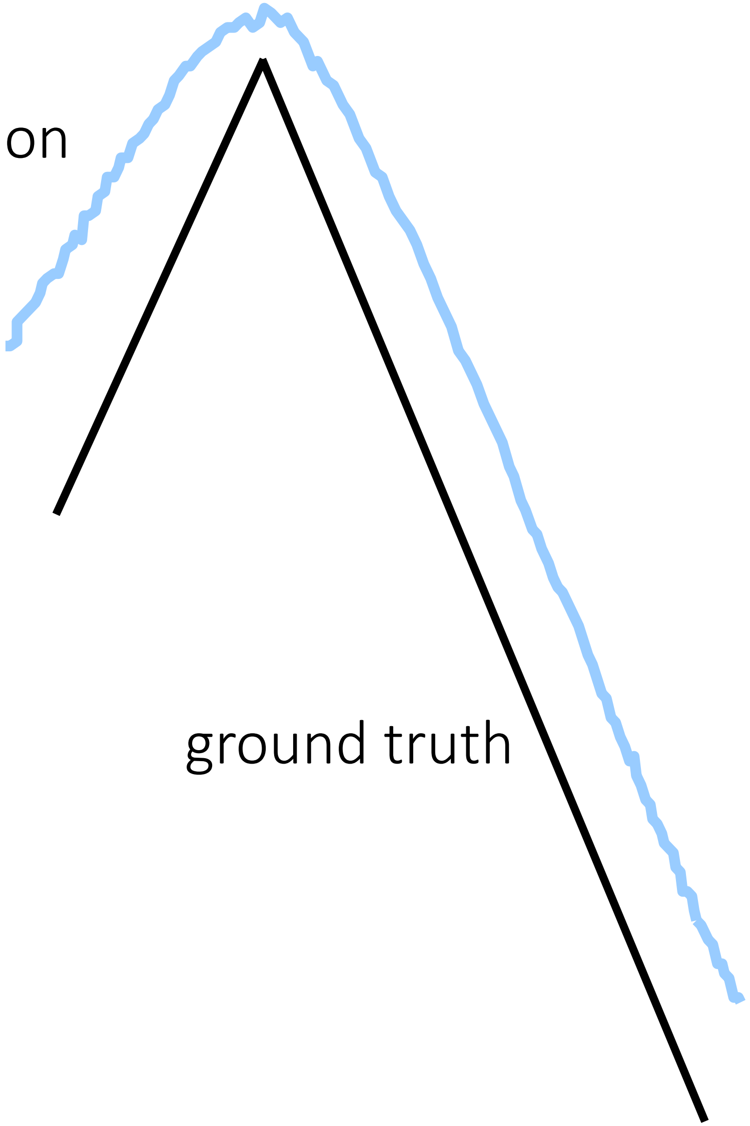
(only second generation of Kinect uses CW ToF)



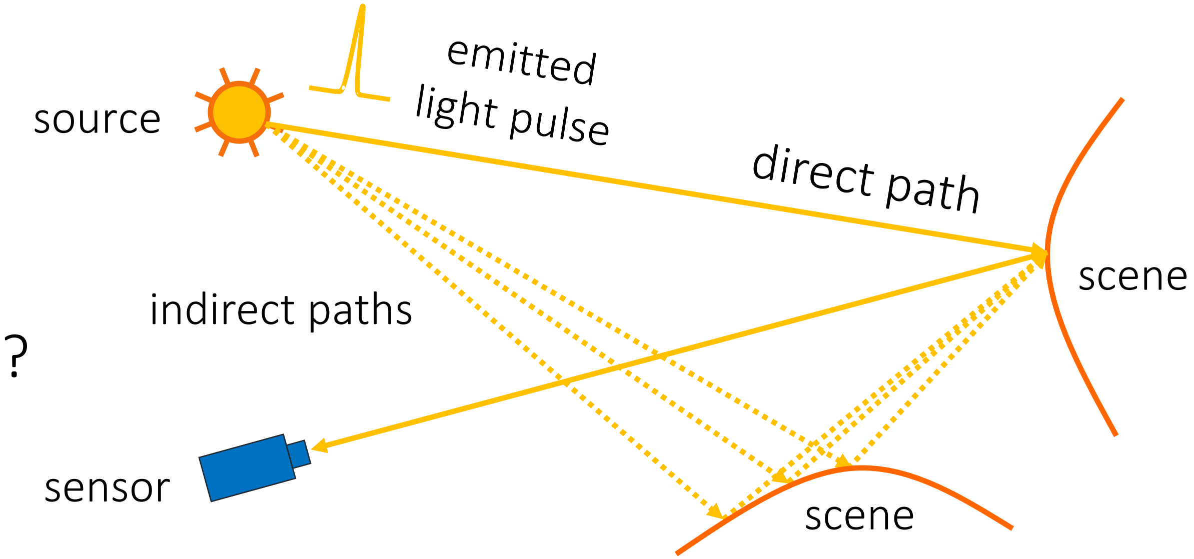
Multi-path interference



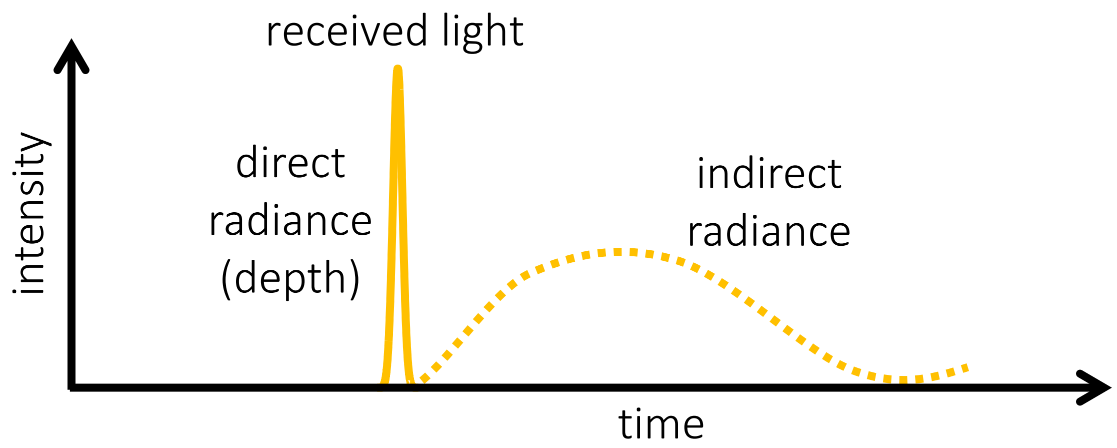
ToF depth reconstruction
mean error = 86.6 mm



Transient imaging with continuous-wave ToF



How do we do transient imaging in the CW-ToF case?

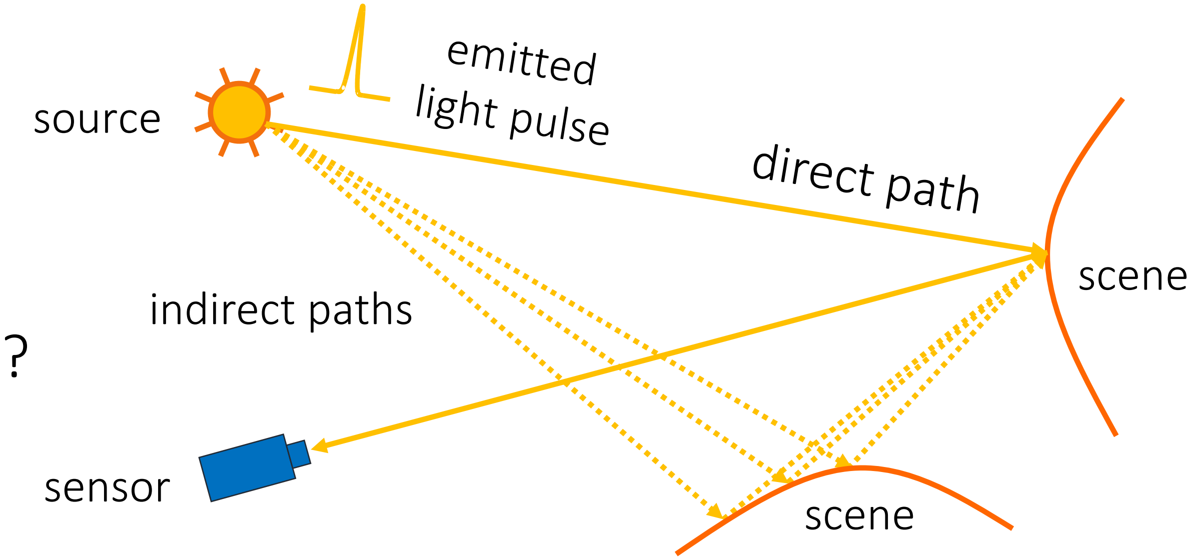


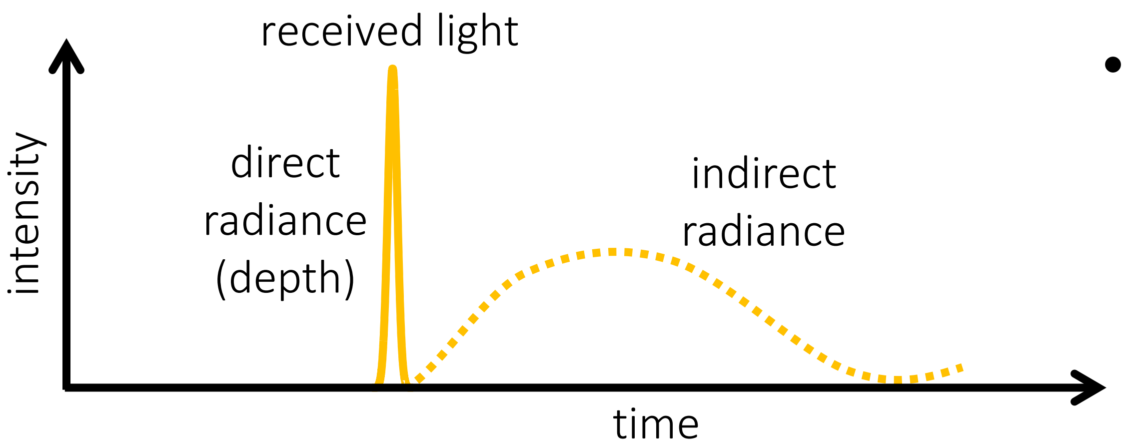
Transient I(t): Time-resolved radiance distribution

- Range imaging: Measuring only first returning photons (e.g., LIDAR).
- Transient imaging: Measuring entire transient (e.g., SPAD).

Transient imaging with continuous-wave ToF

How do we do transient imaging in the CW-ToF case?





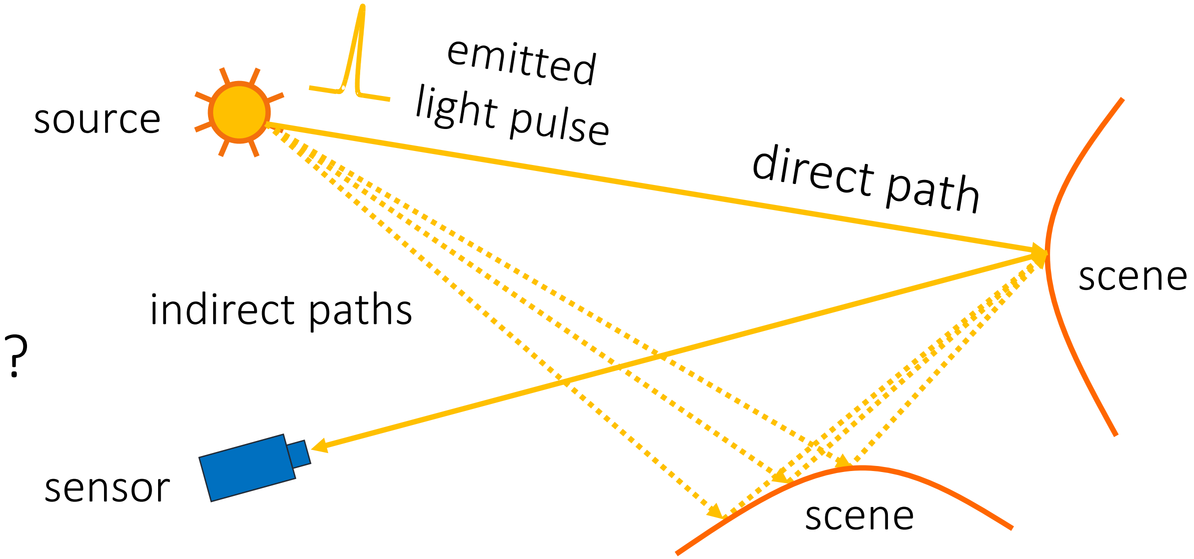
Transient I(t): Time-resolved radiance distribution

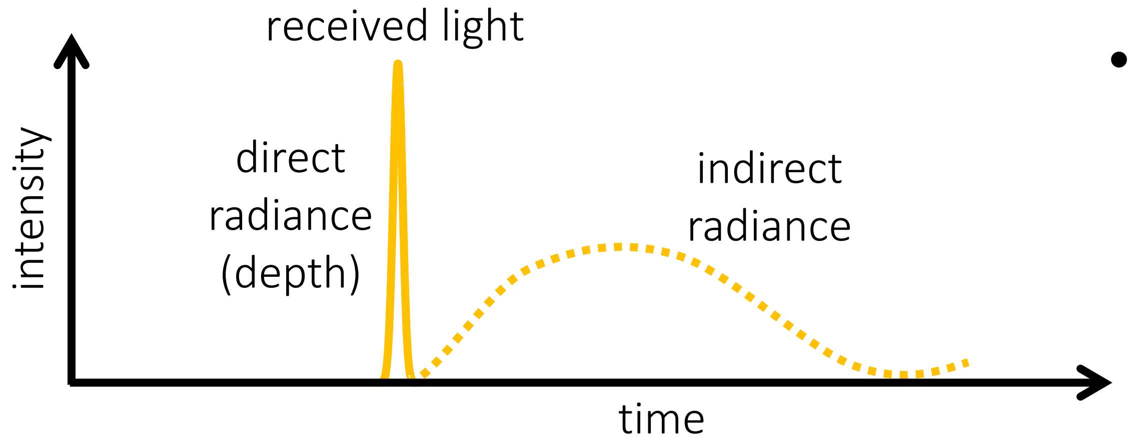
- Each measurement we capture is of the form:

$$I(\omega) = \int \sin(\omega t) \cdot I(t) dt$$

Transient imaging with continuous-wave ToF

How do we do transient imaging in the CW-ToF case?





Transient I(t): Time-resolved radiance distribution

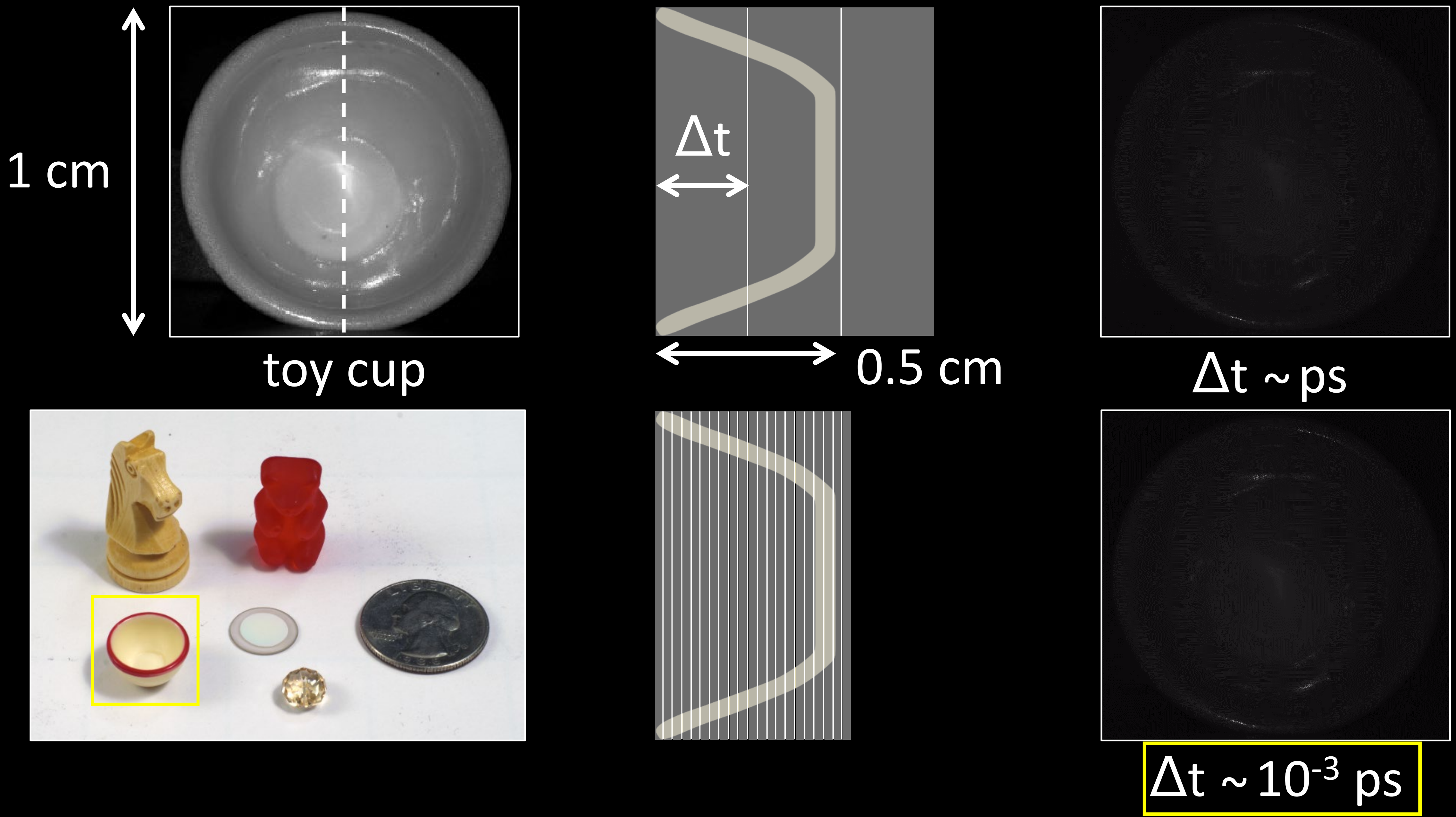
- Each measurement we capture is of the form:

$$I(\omega) = \int \sin(\omega t) \cdot I(t) dt$$

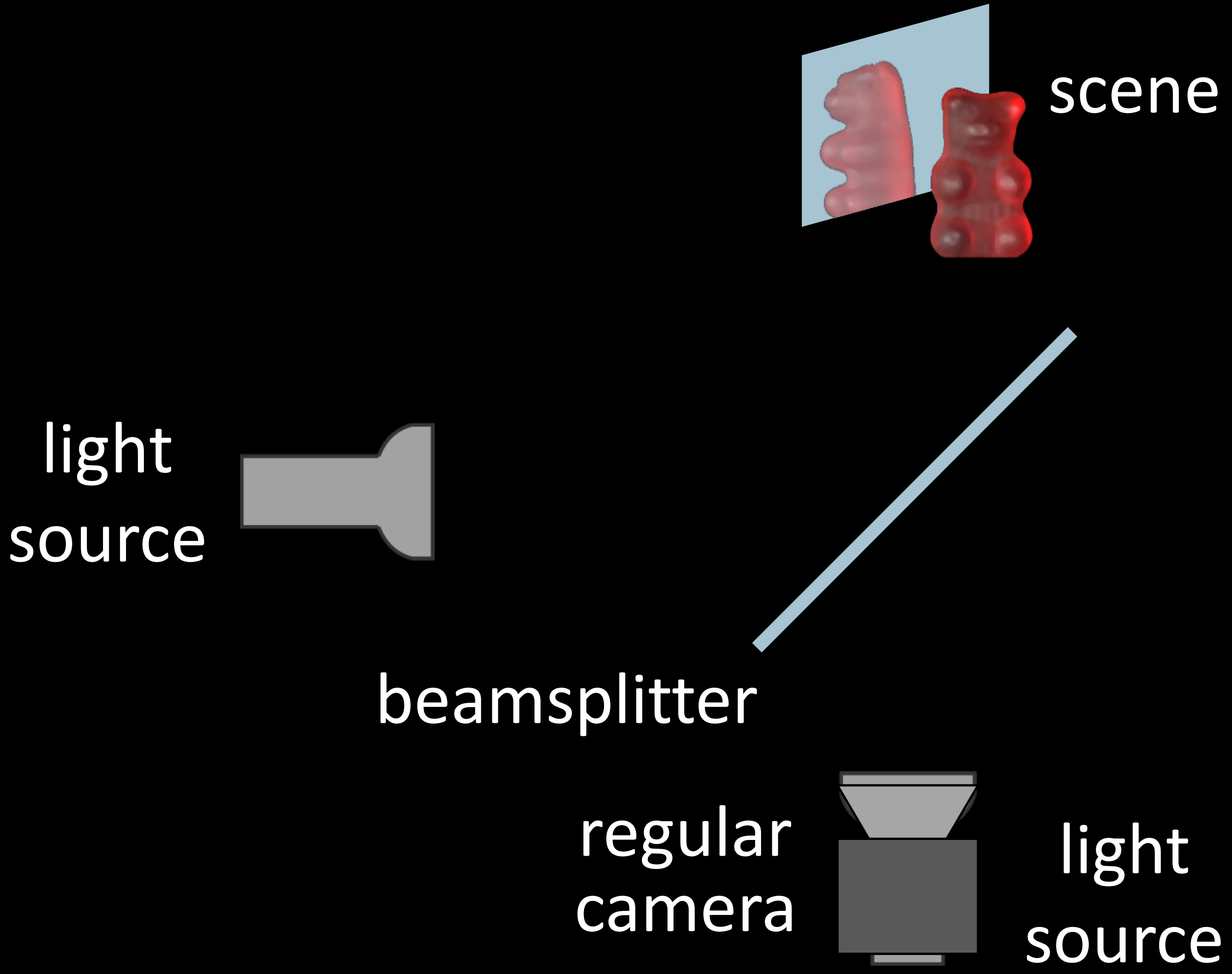
We can do transient imaging by taking measurements at multiple frequencies ω, then doing an inverse Fourier transform

Interferometric ToF imaging

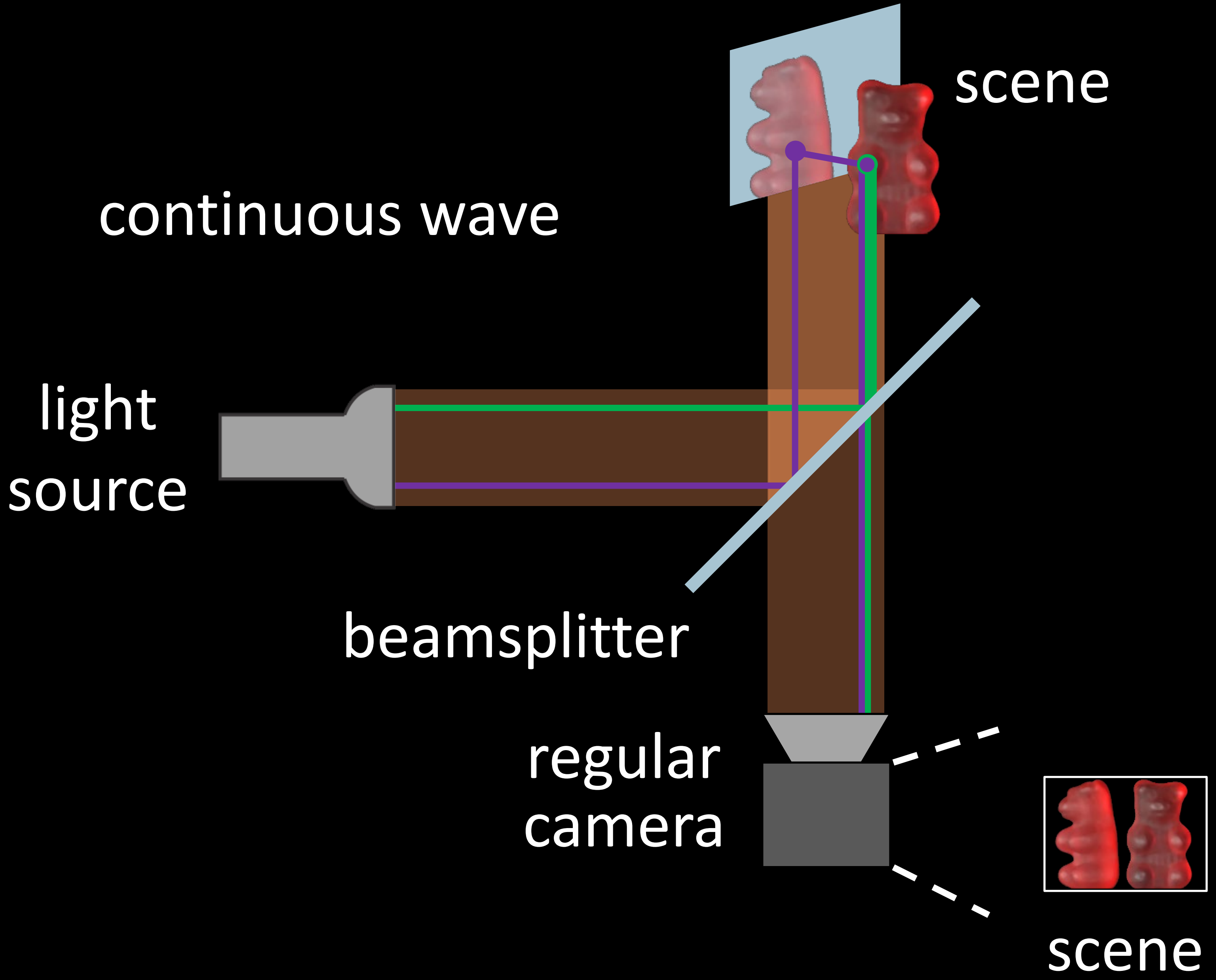
Tiny scenes



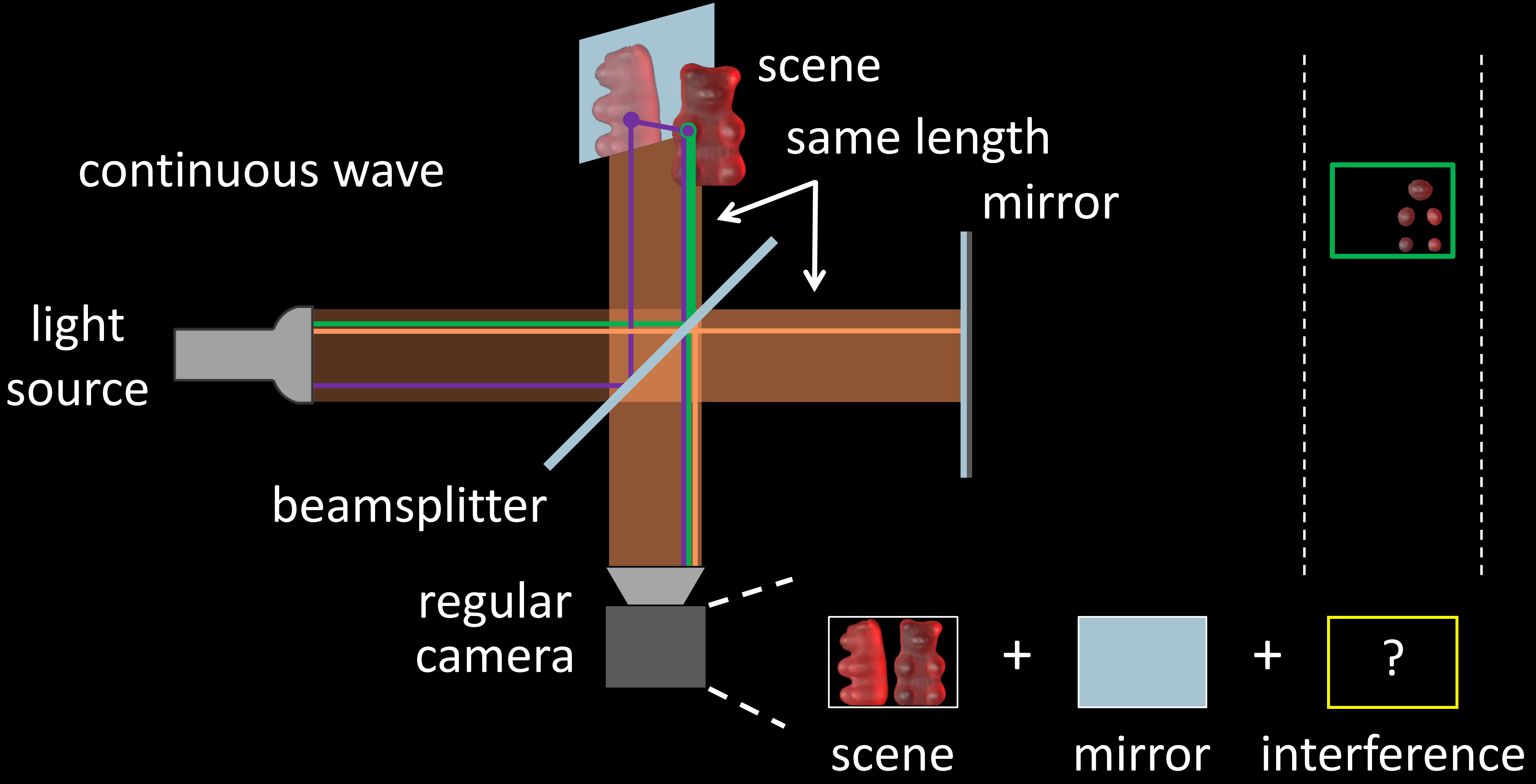
Interferometry example



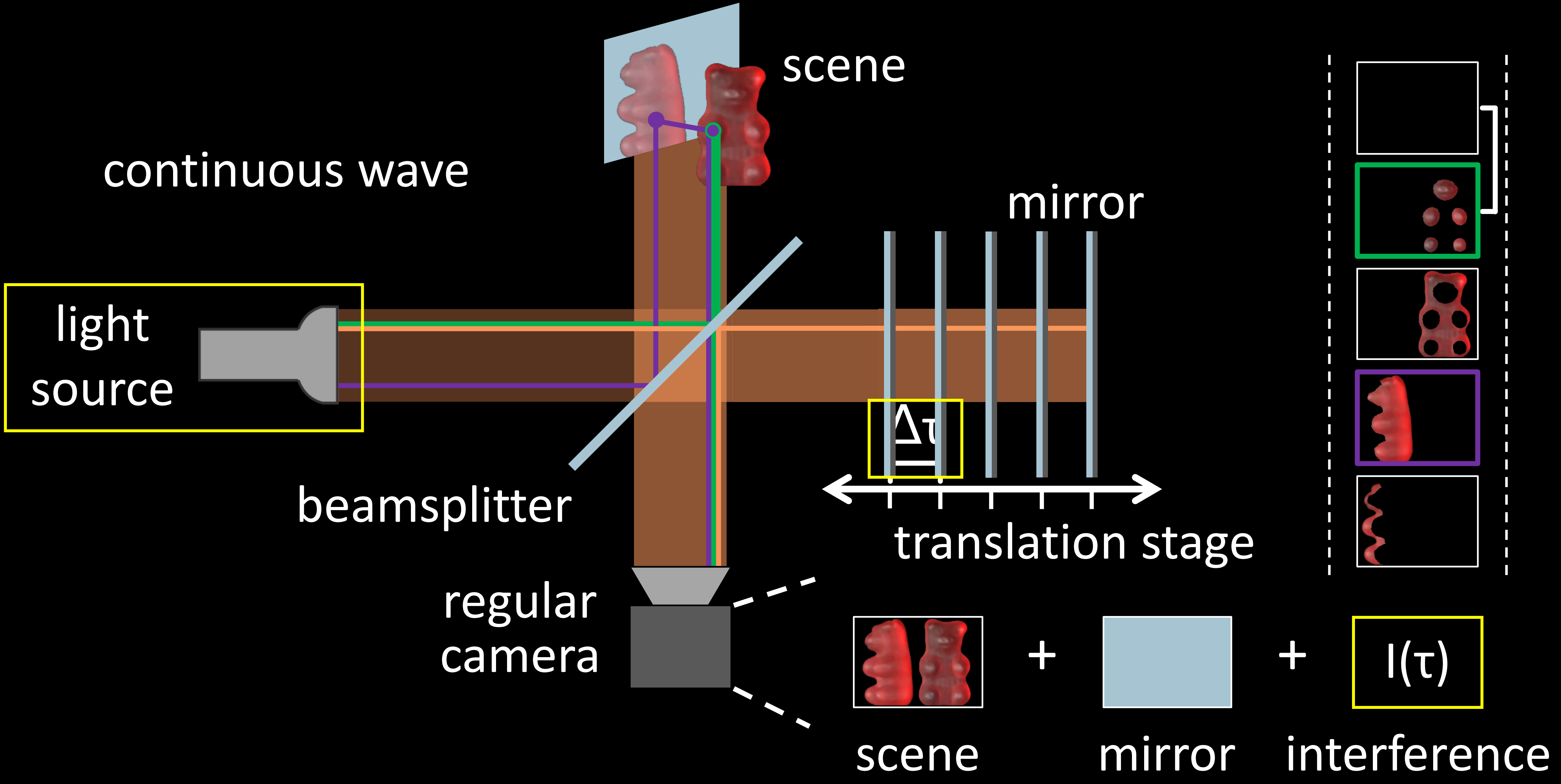
Interferometry example



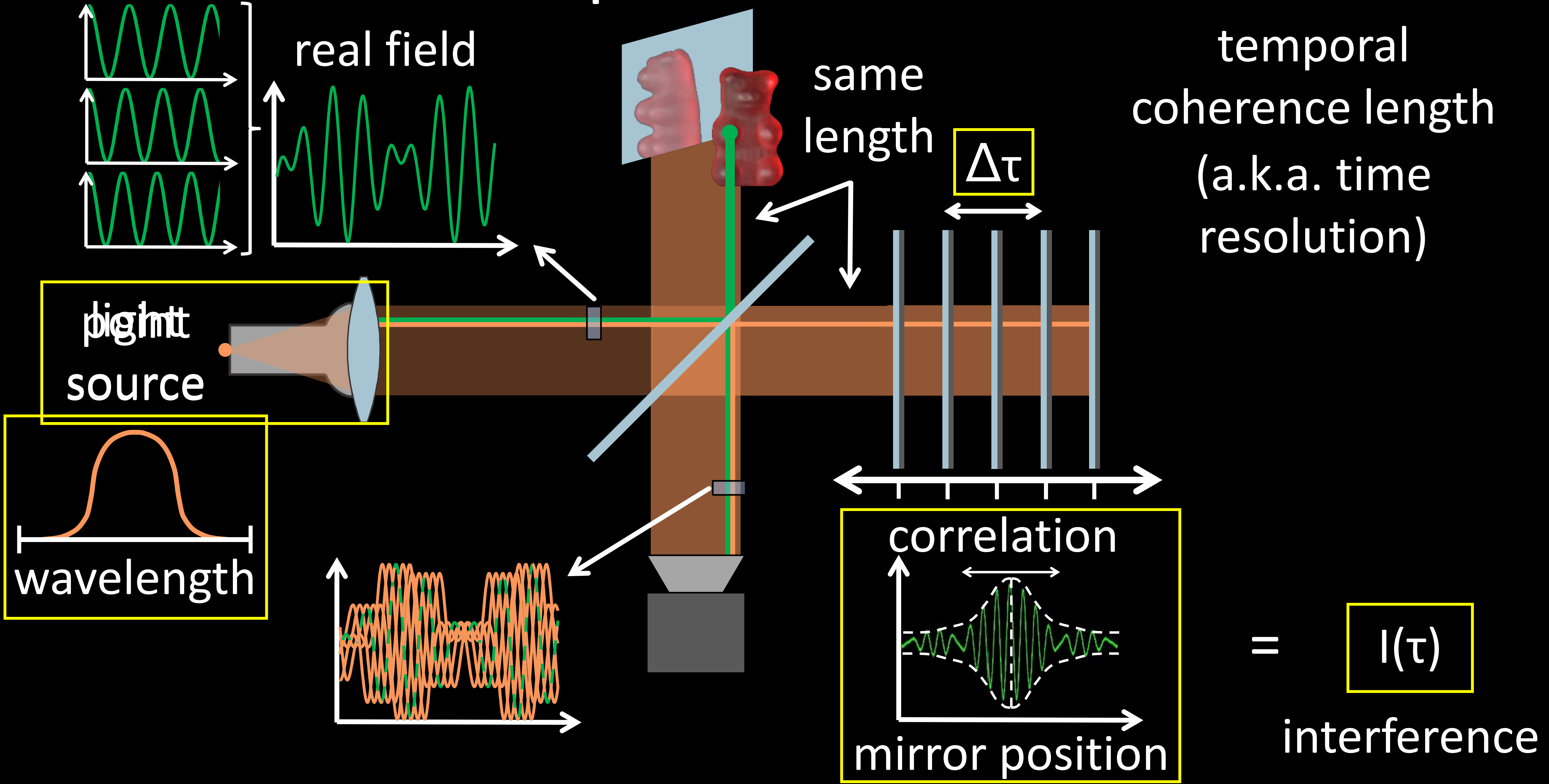
Michelson interferometer



Optical coherence tomography



Temporal coherence



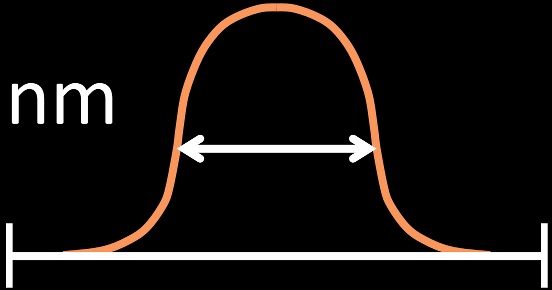
Temporal coherence length

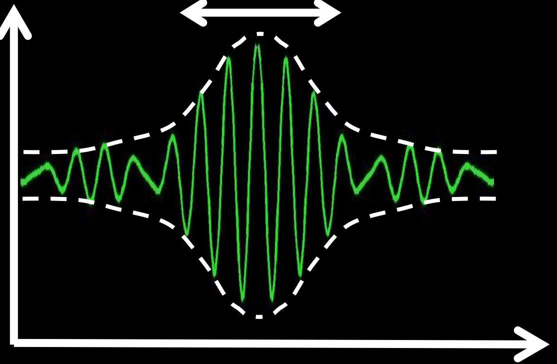
bandwidth

correlation

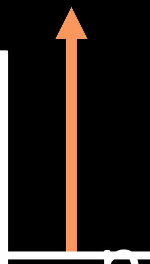
broadband

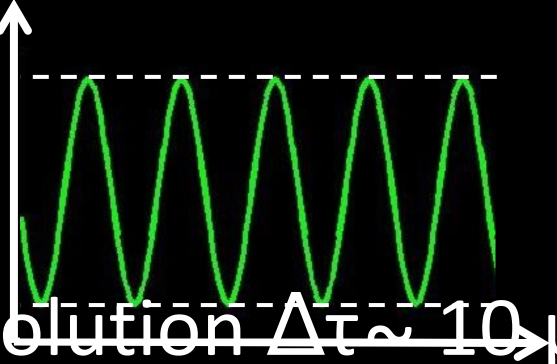
25 nm





onochro tic



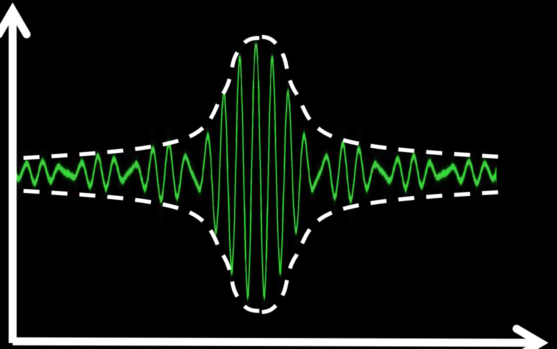


pathlength resolution Δτ~ 10 μm

very broadband

superluminescent diode

supercontinuum laser



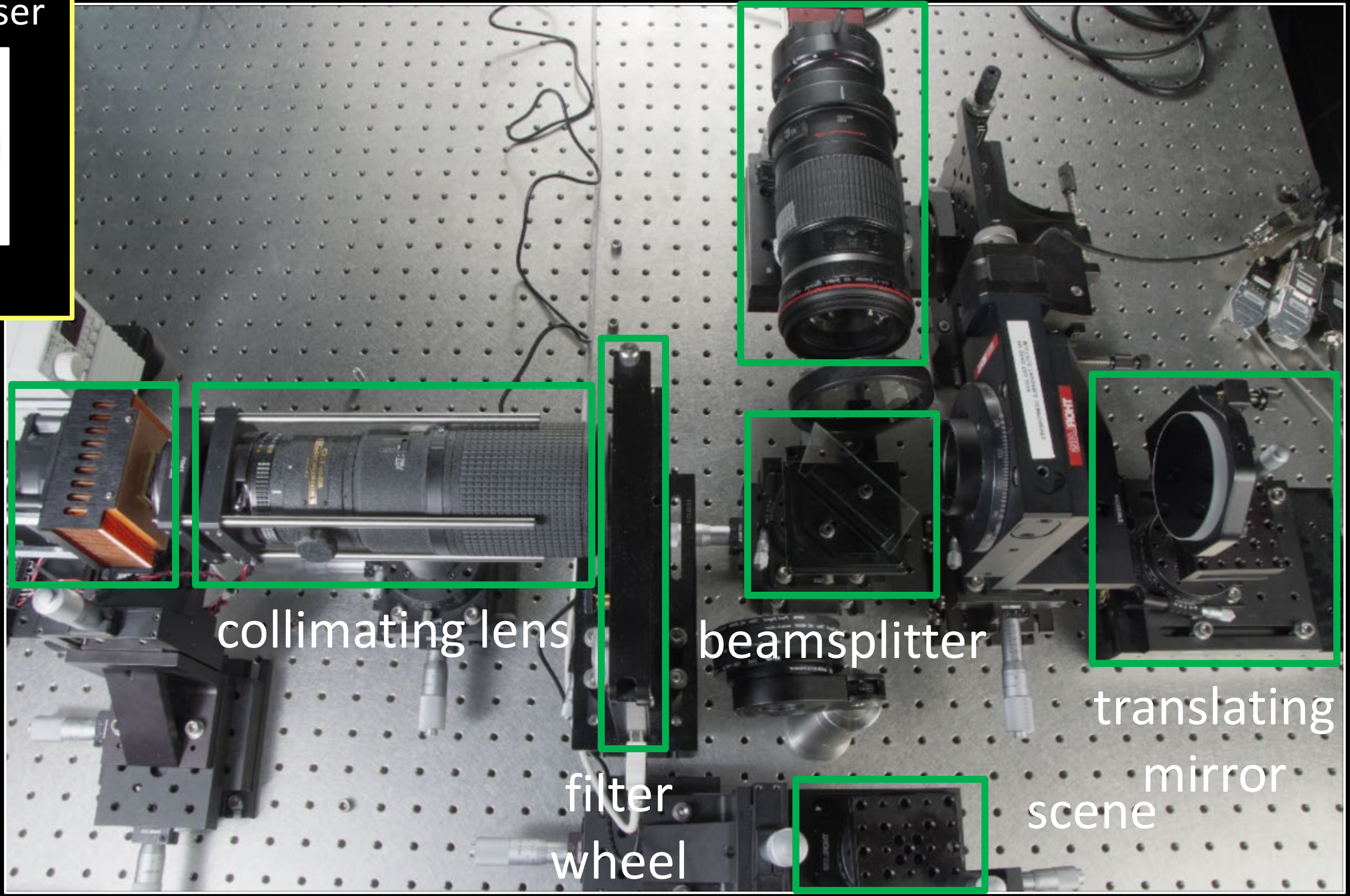
Optical setup


superluminescent diode


supercontinuum laser

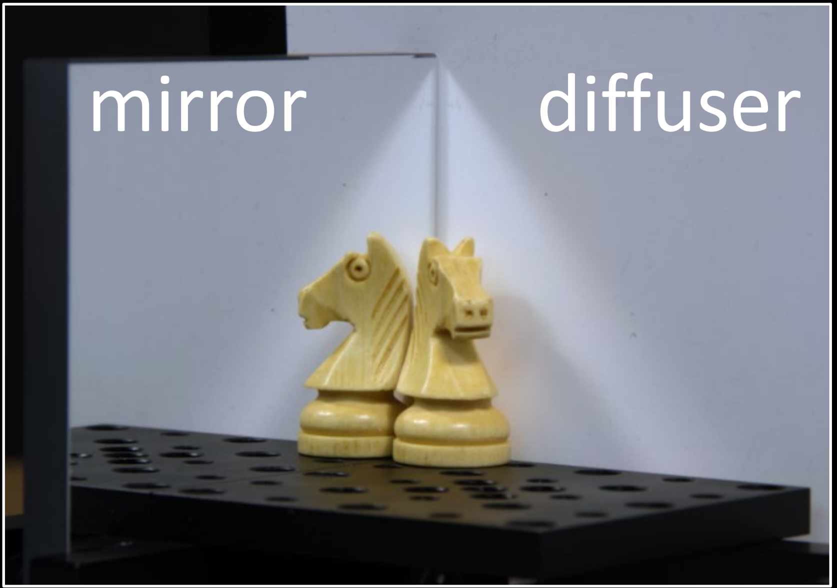

broadband LED

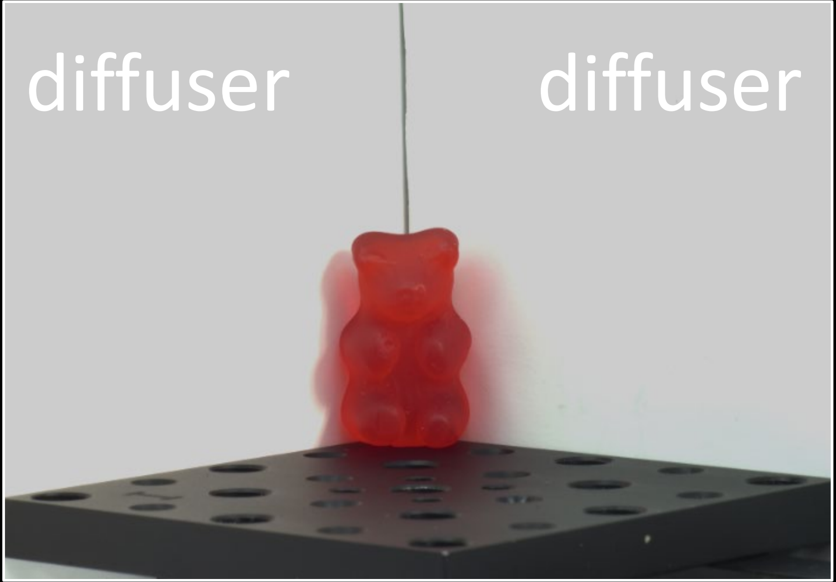

sodium lamp



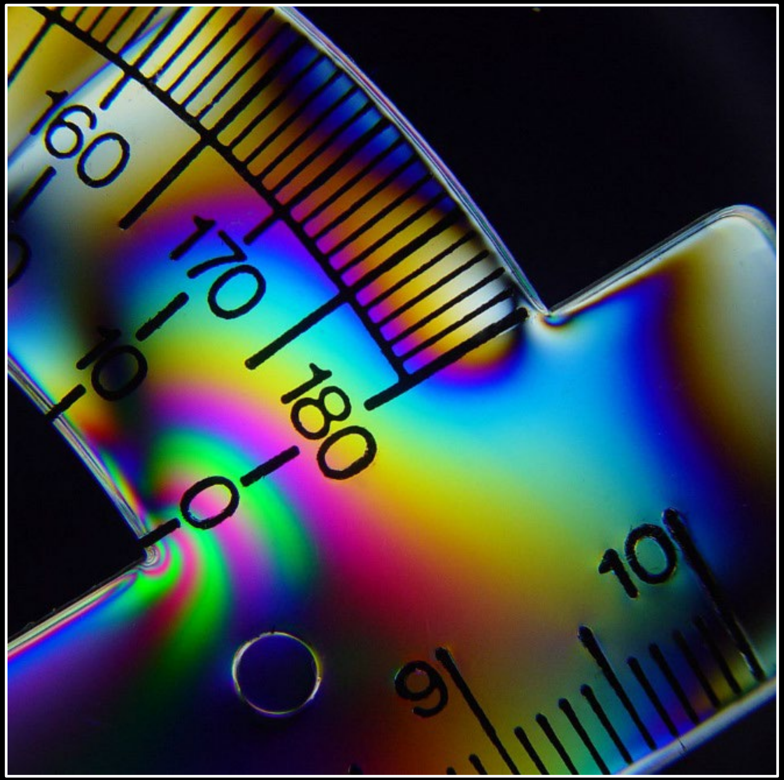
Some transient images

centimeter-sized objects





Material properties

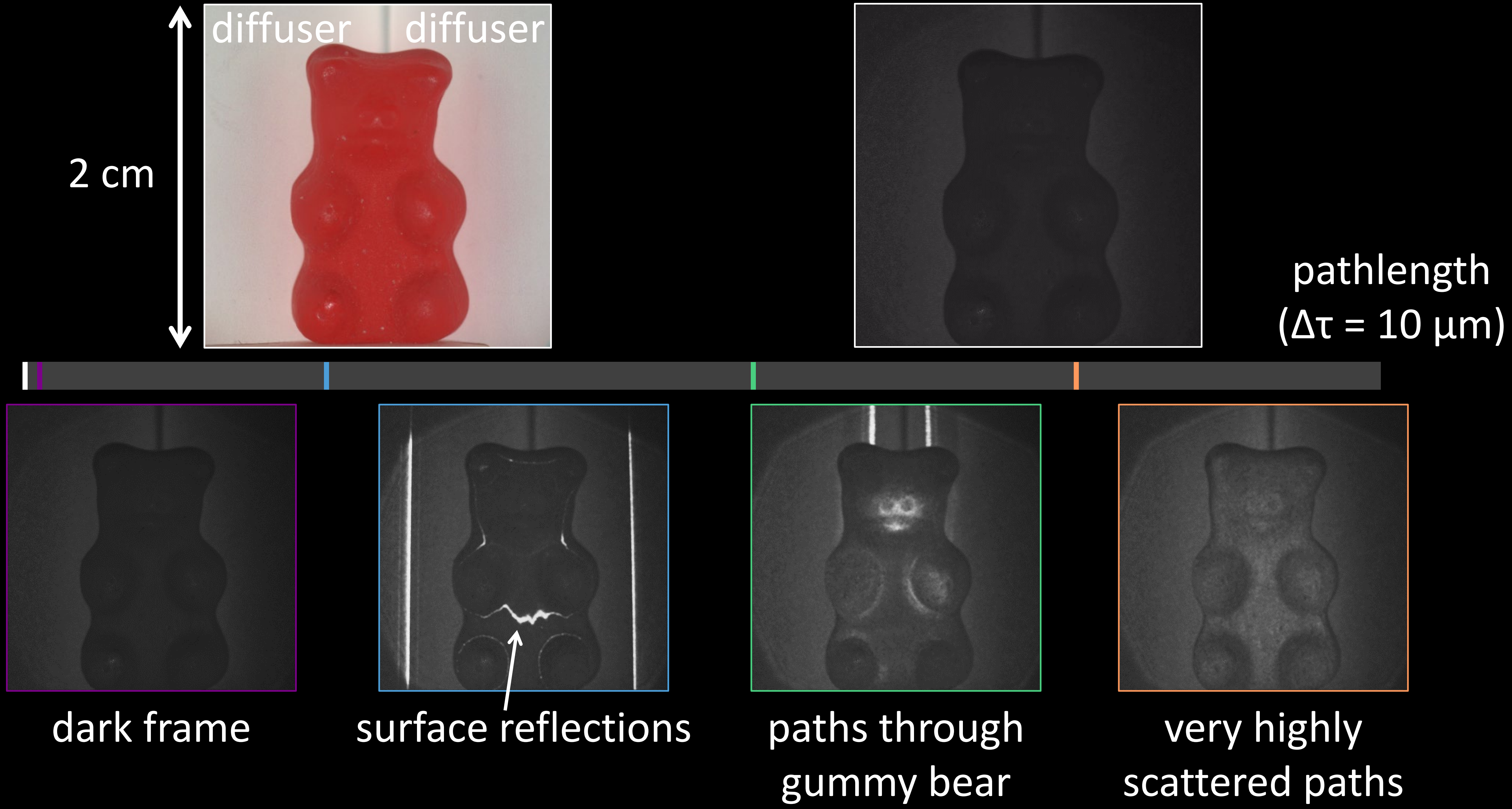


birefringence

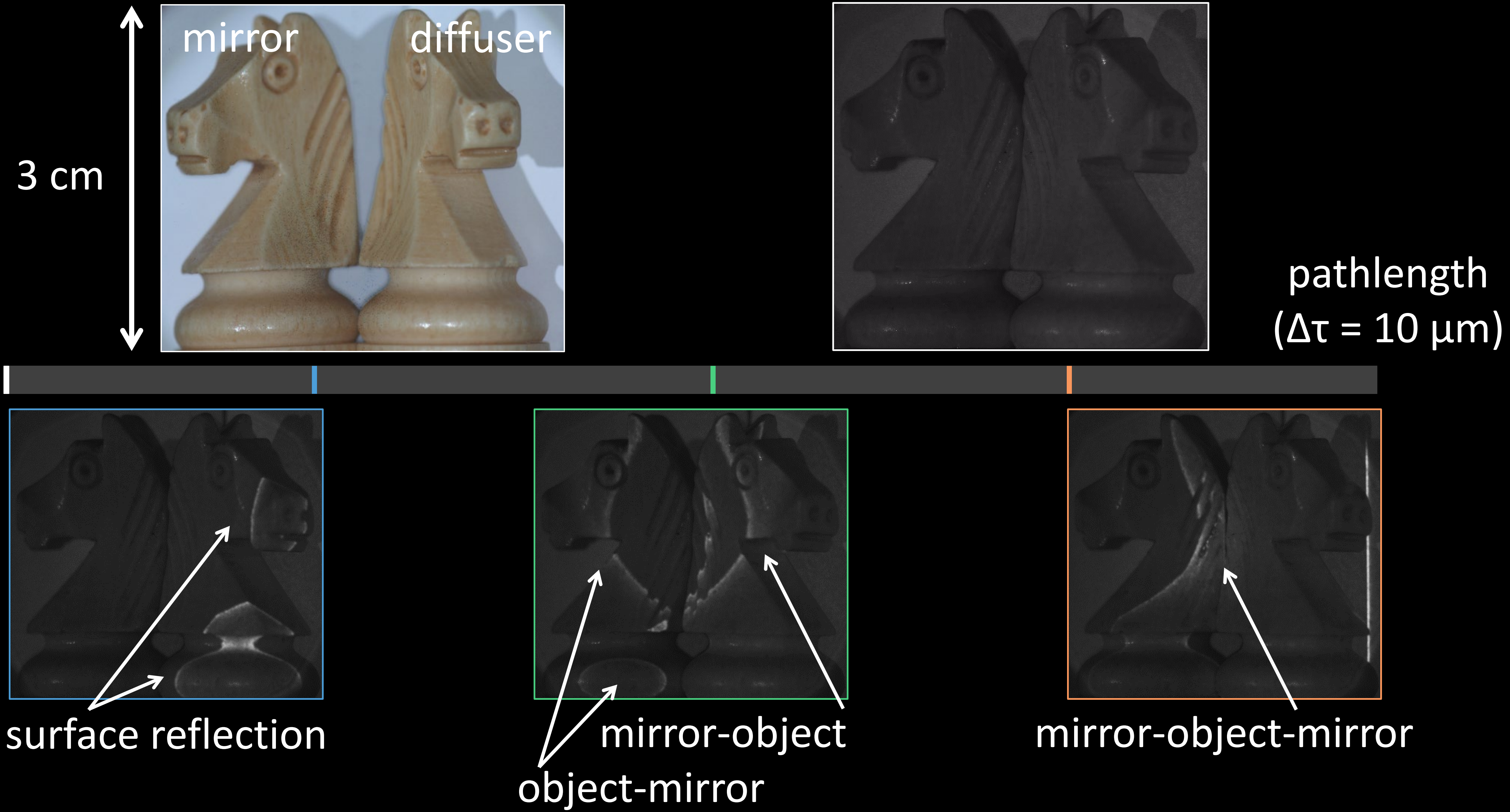
dispersion

scattering

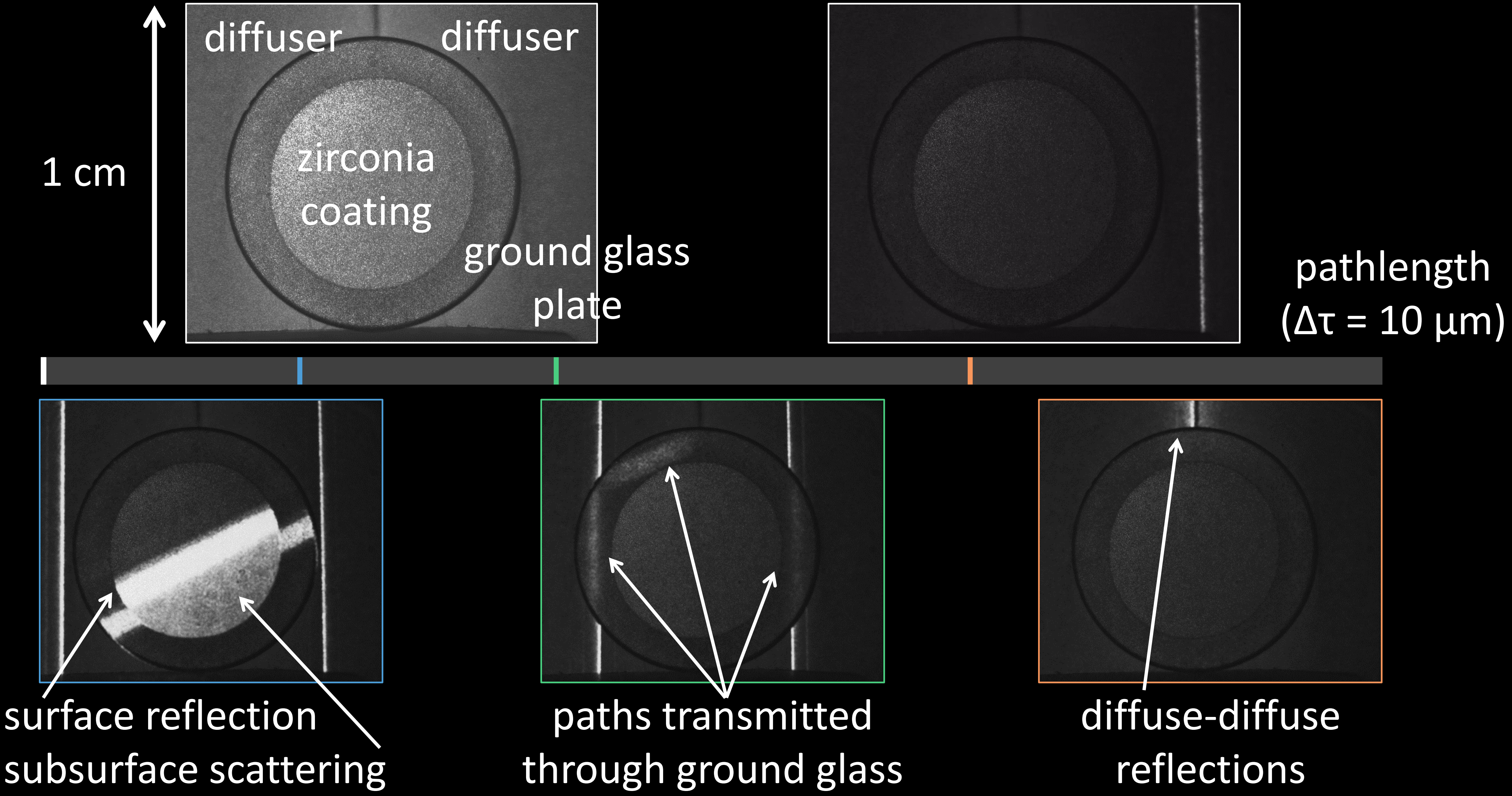
Gummy bear and diffuse corner



Chess knight and mirror

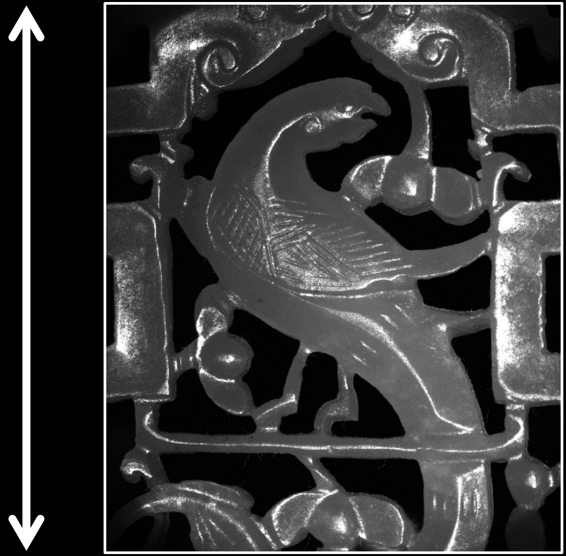


Subsurface scattering

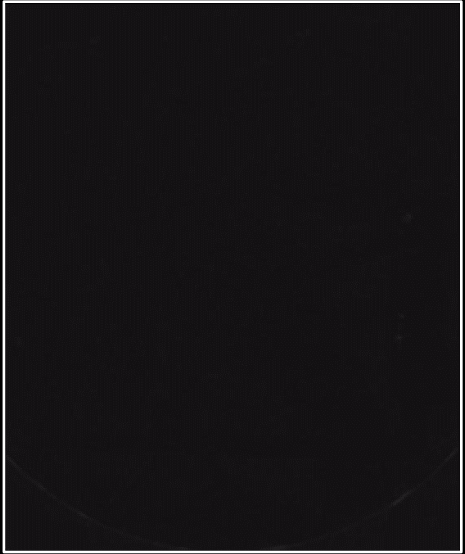


White jade

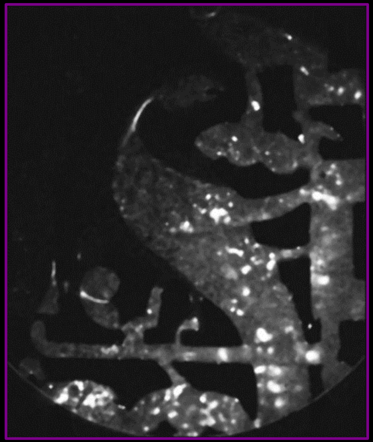
3 cm



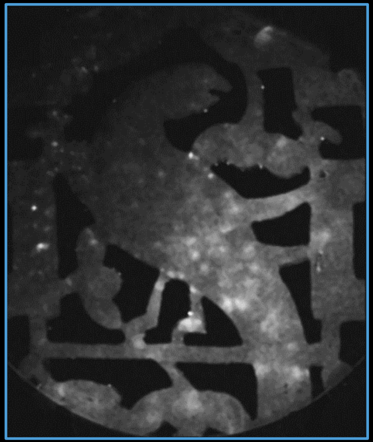
exquisite
white jade



time (10^{-15} seconds)



specular
reflections

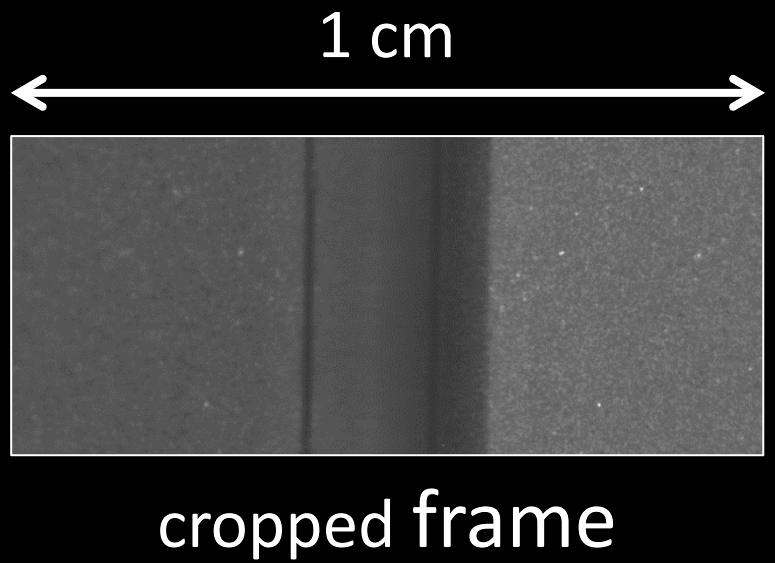


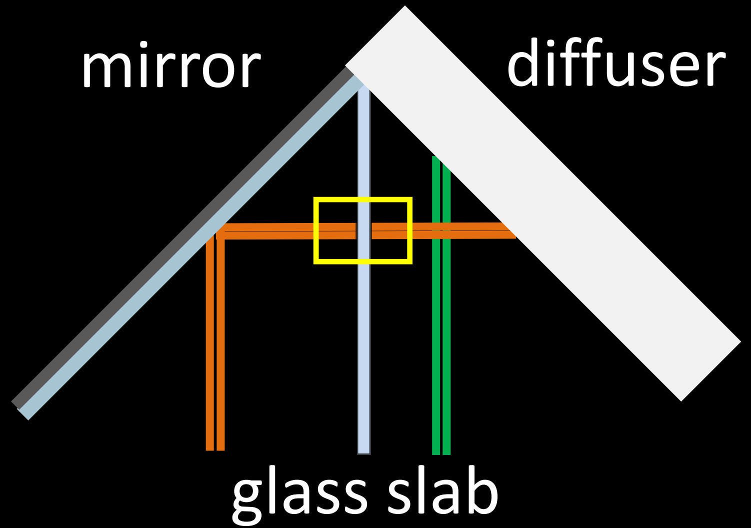
low-order
scattering

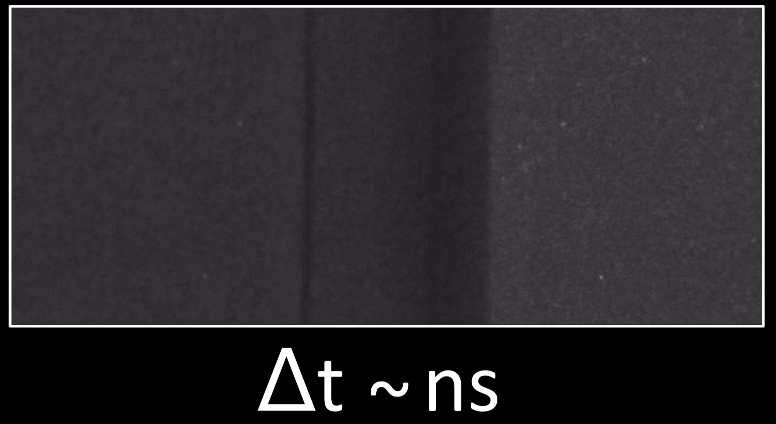
mid-order
scattering

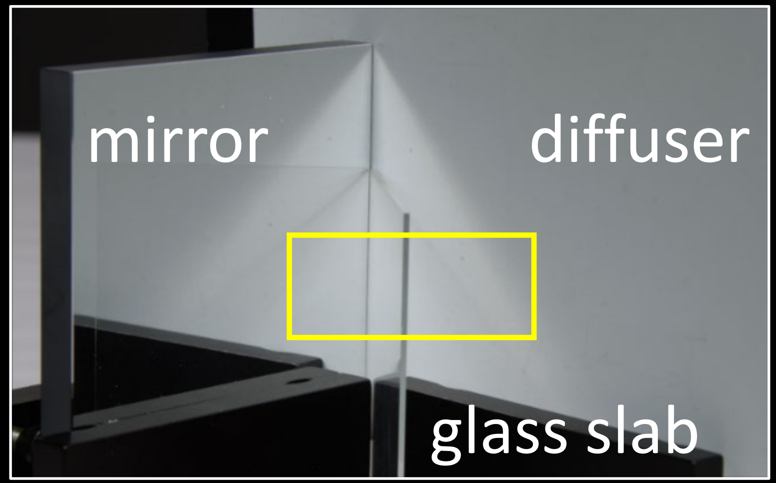
high-order scattering
[TOG 2015]

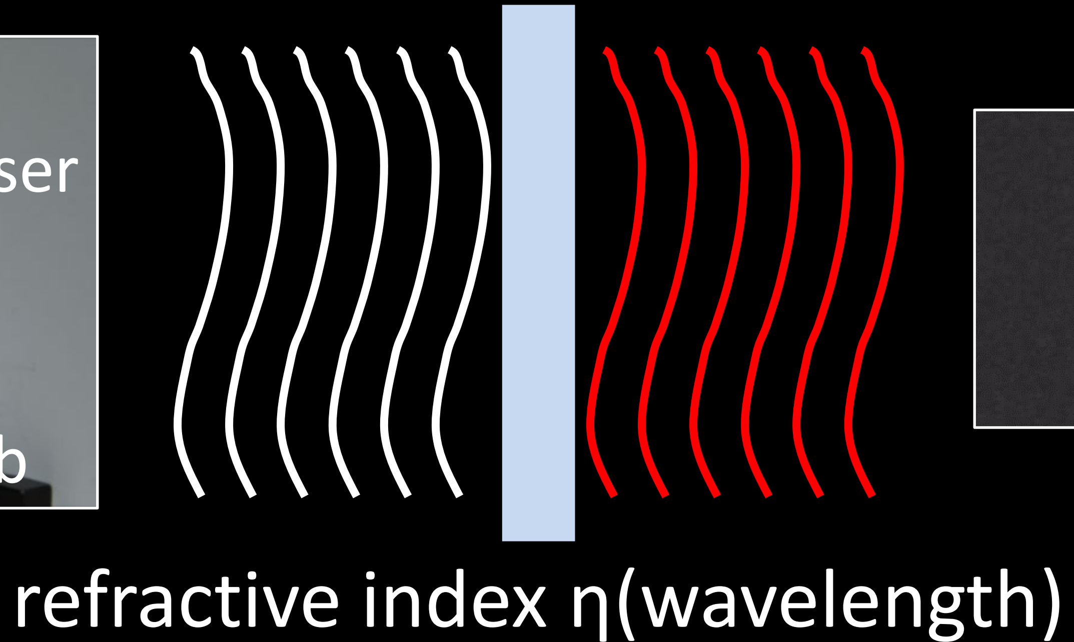
Dispersion

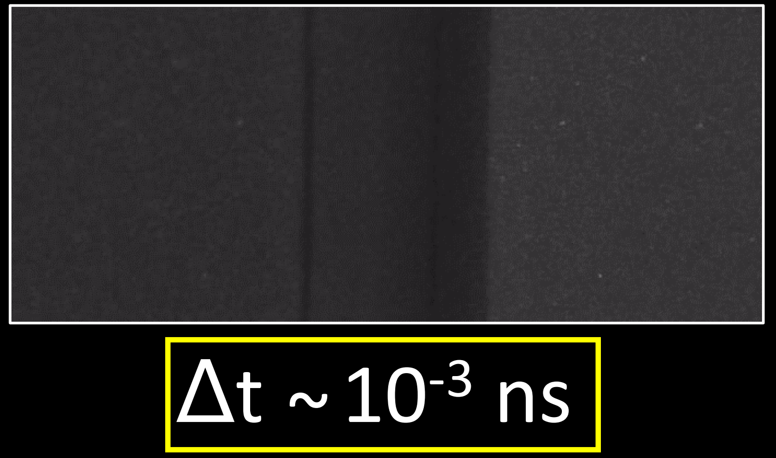

1 cm
cropped frame


mirror
diffuser
glass slab

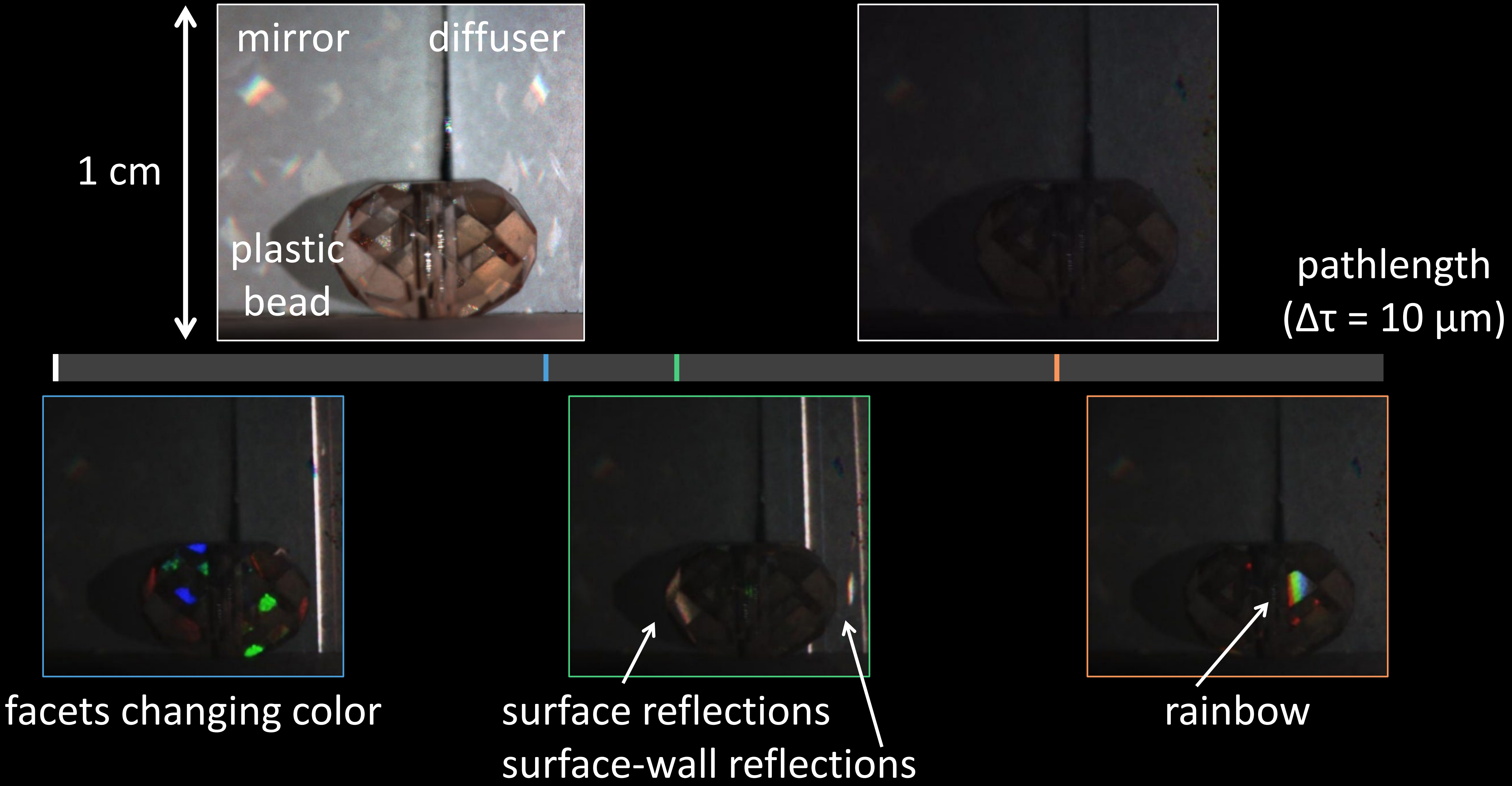

Δt ~ ns


mirror
diffuser
glass slab


refractive index η(wavelength)

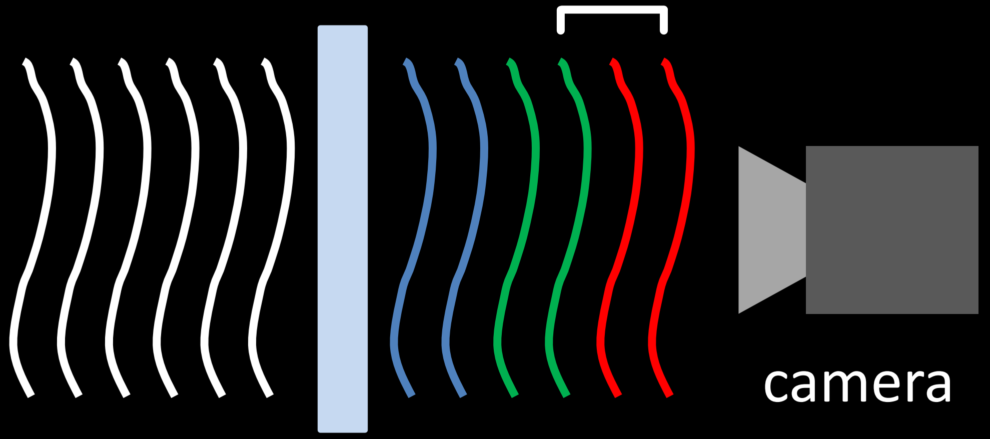

Δt ~ 10-3 ns

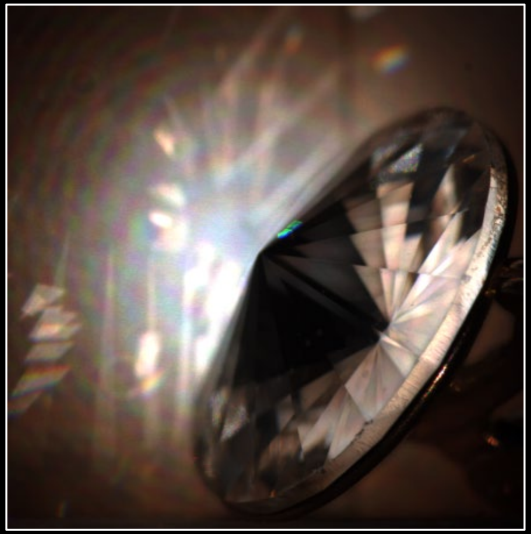
Dispersion



1 cm
mirror
diffuser
plastic
bead
pathlength
(Δτ = 10 μm)
facets changing color
surface reflections
surface-wall reflections
rainbow

Visualizing dispersion

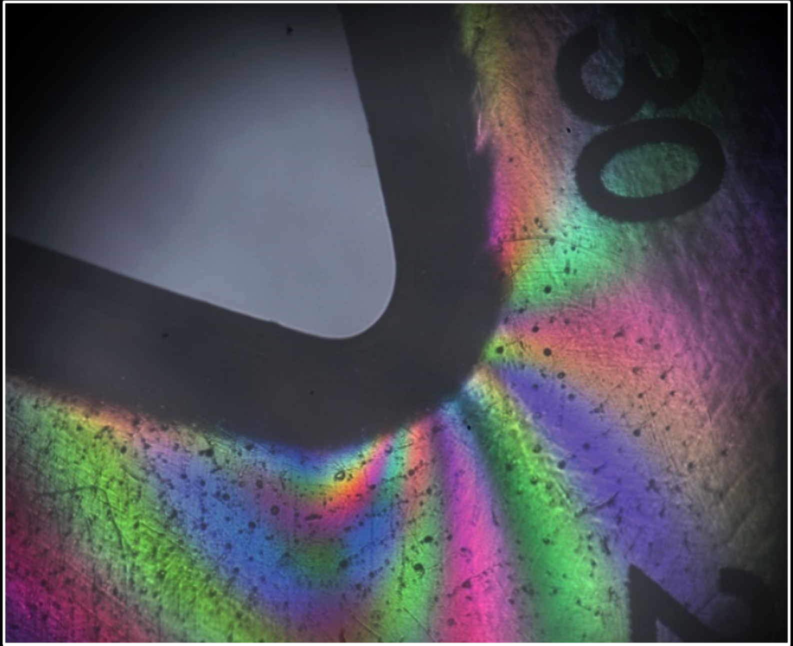




what a regular camera sees

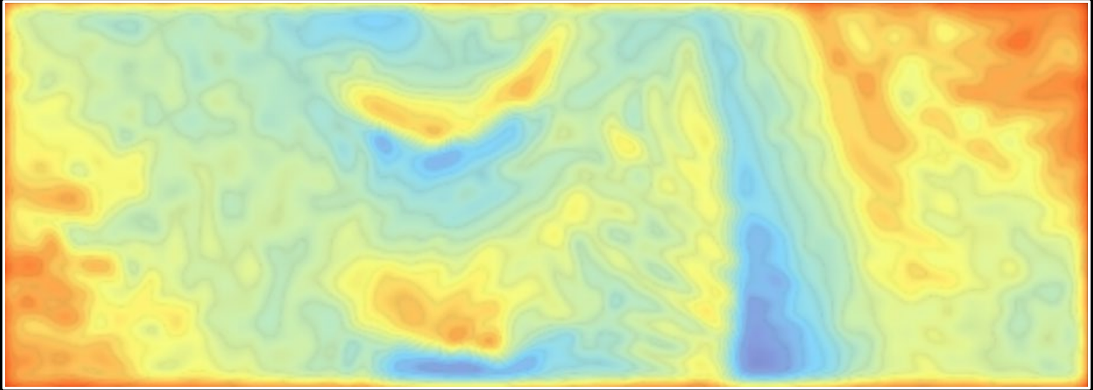
what our camera sees

Visualizing photoelasticity



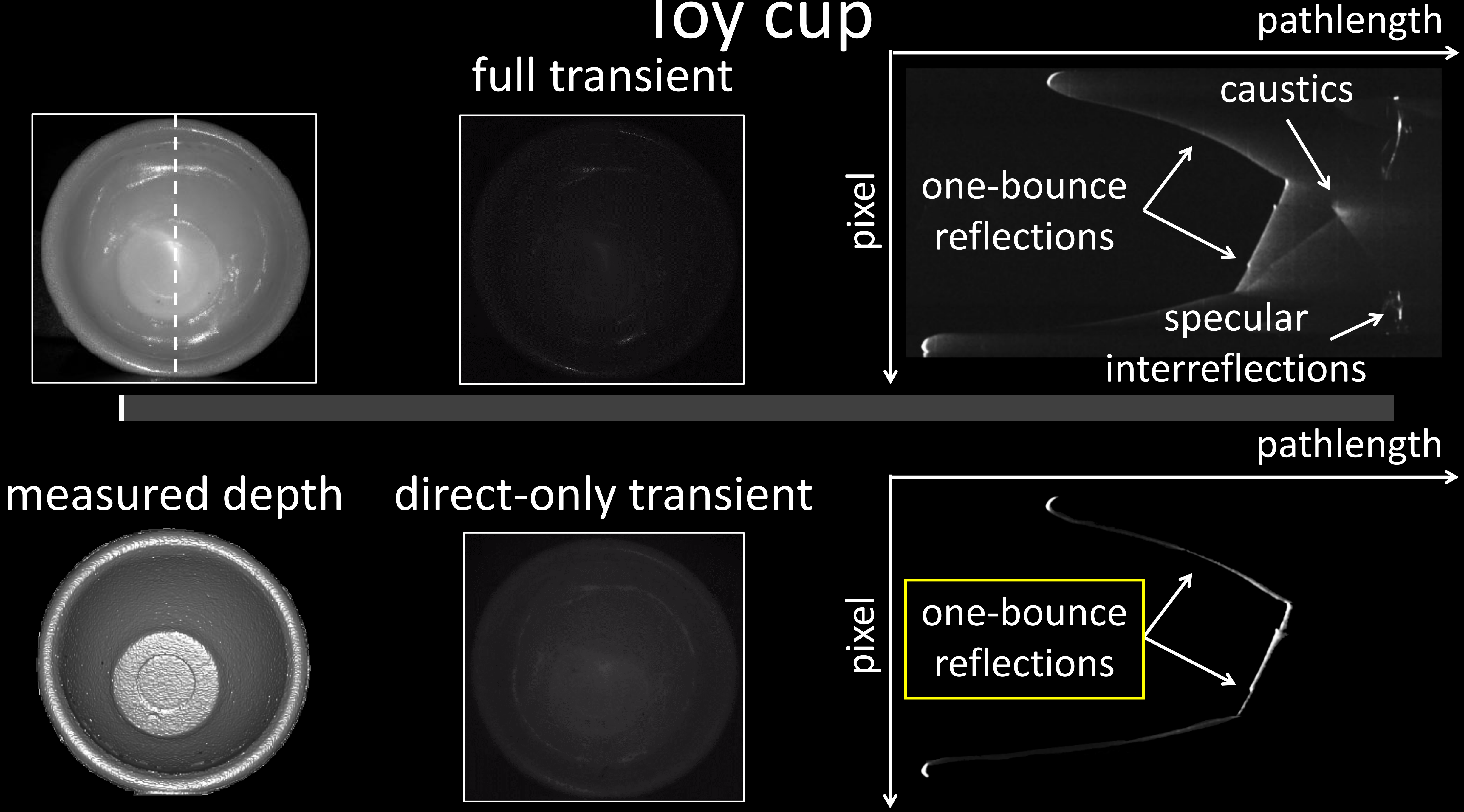
detail under polarized light
scene

low resolution $\Delta\tau$ = 1 mm



high resolution $\Delta\tau$ = 10 µm

Toy cup


full transient
pathlength
pixel
caustics
one-bounce
reflections
specular
interreflections
pathlength
measured depth
direct-only transient
pixel
one-bounce
reflections

Depth scanning

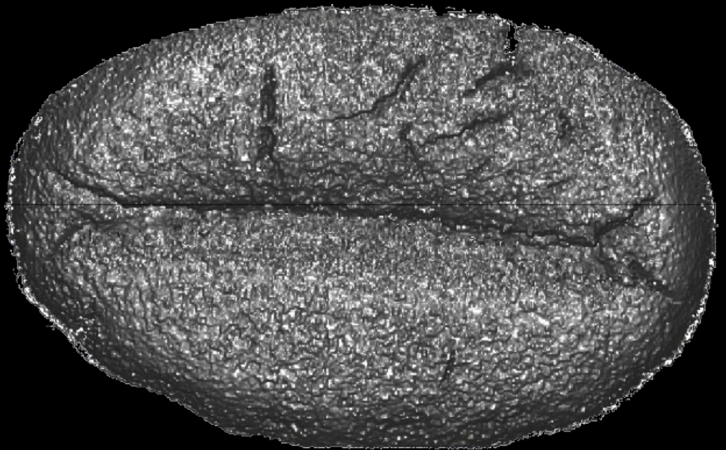
depth resolution $\Delta\tau \sim 10\ \mu m$

coin

2.5 cm

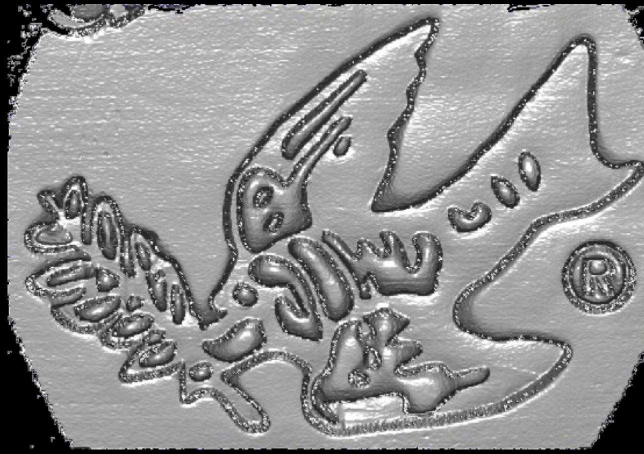
gnocchi

1 cm

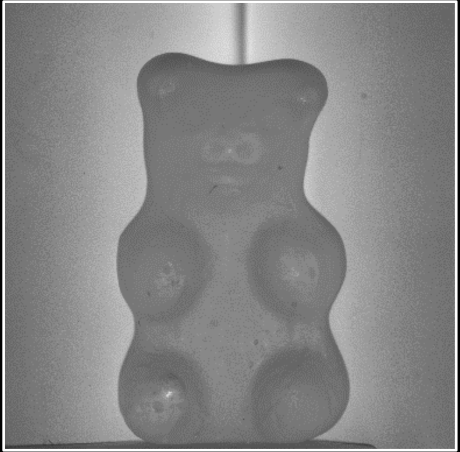


soap carving

1.5 cm



gummy bear and diffusers



3 cm

References

Basic reading:

- Gupta et al., “Computational Time-of-Flight,” ICCV 2015 tutorial, http://web.media.mit.edu/~achoo/iccvtoftutorial/
  this tutorial provides an overview of many of the topics covered in this lecture, with a focus on continuous-wave ToF imaging.
- Jarabo et al., “Recent Advances in Transient Imaging: A Computer Graphics and Vision Perspective,” Visual Informatics 2017
  a great review paper for ToF imaging.
- Velten et al., “Femto-photography: capturing and visualizing the propagation of light,” SIGGRAPH 2013, CACM 2016.
  the paper that introduced the idea of transient imaging to the computational imaging community, and an explanation of how streak cameras work.
- Lange et al., “Solid-state time-of-flight range camera,” JQE 2001.
  a standard reference on continuous-wave ToF sensors.
- Heide et al., “Low-budget transient imaging using photonic mixer devices,” SIGGRAPH 2013.
- Lin et al., “Fourier analysis on transient imaging with a multifrequency time-of-flight camera,” CVPR 2014.
- Peters et al., “Solving trigonometric moment problems for fast transient imaging,” SIGGRAPH 2015.
  three papers showing how continuous-wave ToF sensors can be used for transient imaging.
- Gupta et al., “Phasor imaging: A generalization of correlation-based time-of-flight imaging,” TOG 2015.
  a more recent paper that provides nice insights into how continuous-wave ToF works, as well as a way to deal with MPI.
- Abramson, “Light-in-flight recording by holography,” Optics Letters 1978.
  a very early paper showing visualization of light-in-flight, i.e., transient imaging.
- Huang et al., “Optical Coherence Tomography,” Science 1991.
  the paper introducing optical coherence tomography.
- Gkioulekas et al., “Micron-scale light transport decomposition using interferometry,” SIGGRAPH 2014.
  the paper showing how interferometry can be used for time-of-flight imaging.
- Gariepy et al., “Single-photon sensitive light-in-fight imaging,” Nature Communications 2015.
  the paper describing how SPADs can be used for ToF imaging.
- O’Toole et al., “Reconstructing Transient Images from Single-Photon Sensors,” CVPR 2017.
  a paper explaining the operation of SPADs in a more accessible manner to computer science backgrounds.
- Pediredla et al., “Signal processing based pile-up compensation for gated single-photon avalanche diodes,” 2018.
- Heide et al., “Sub-picosecond photon-efficient 3D imaging using single-photon sensors,”
- Gupta et al., “Photon-flooded single-photon 3d cameras,” CVPR 2019.
  three papers discussing the pile-up issue and proposing ways to overcome it.
- Mark Itzler, “Single-photon LiDAR imaging: from airborne to automotive platforms,” ICCP 2020 keynote, https://www.youtube.com/watch?v=4tEfVr6fKqw
  a keynote discussing advantages and current state of SPAD LiDAR technology.

Additional reading:

- Kirmani et al., “Looking around the corner using ultrafast transient imaging,” ICCV 2009 and IJCV 2011.
- Velten et al., “Recovering three-dimensional shape around a corner using ultrafast time-of-flight imaging,” Nature Communications 2012.
  the first two papers showing how ToF imaging can be used for looking around the corner.