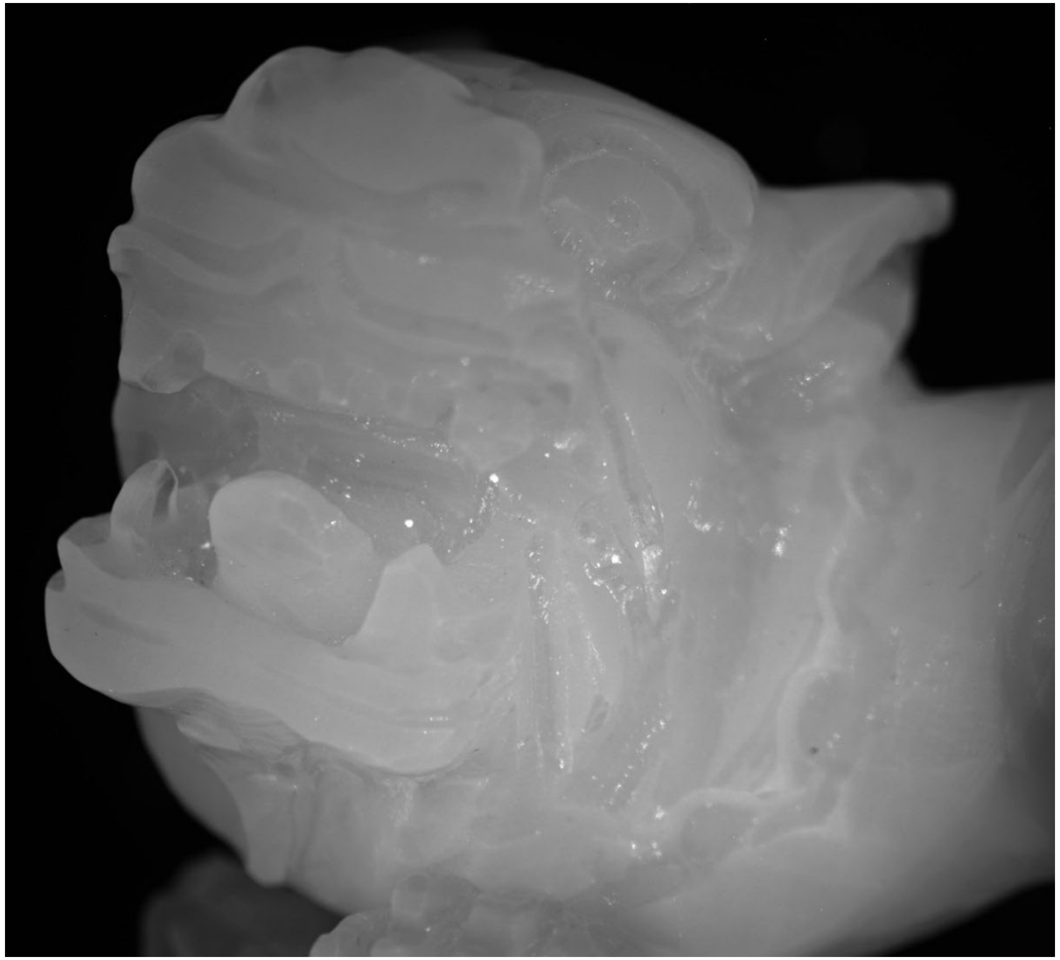
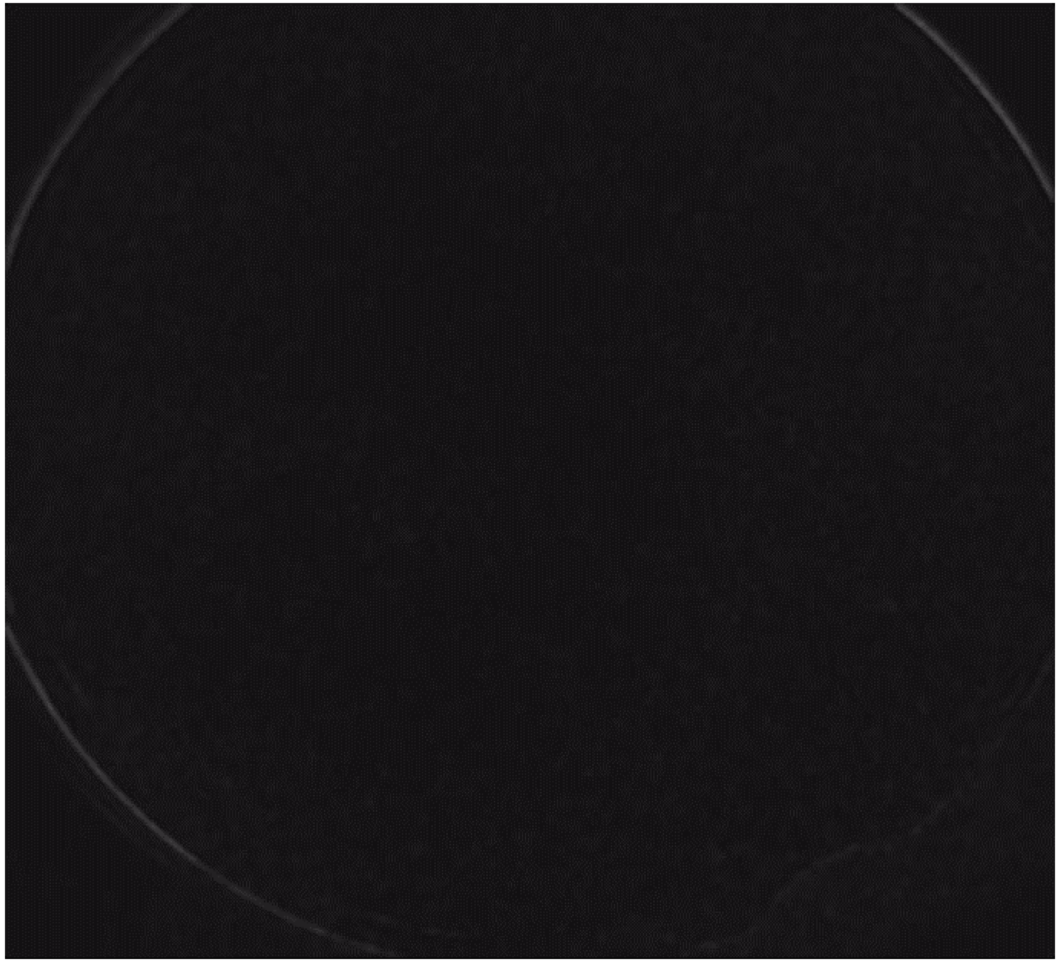
Time-of-flight imaging





15-463, 15-663, 15-862
Computational Photography
Fall 2023, Lecture 17

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

Course announcements

- Homework assignment 6 is due on Friday, December 8th.
  - Do not leave for last minute, you won't have time to complete it.
- Feedback for final project proposals posted.
- If your final project requires special equipment, sign up here: https://docs.google.com/spreadsheets/d/1vbpppfjVQMJ7zGiaJEhxhVi4bW999GeJymeHxxL_0Pk/edit#gid=1109741985
- Vote for preferred date for make-up lecture on Slack.
- Two graphics talks this week—see Slack for details.

Overview of today's lecture

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

Slide credits

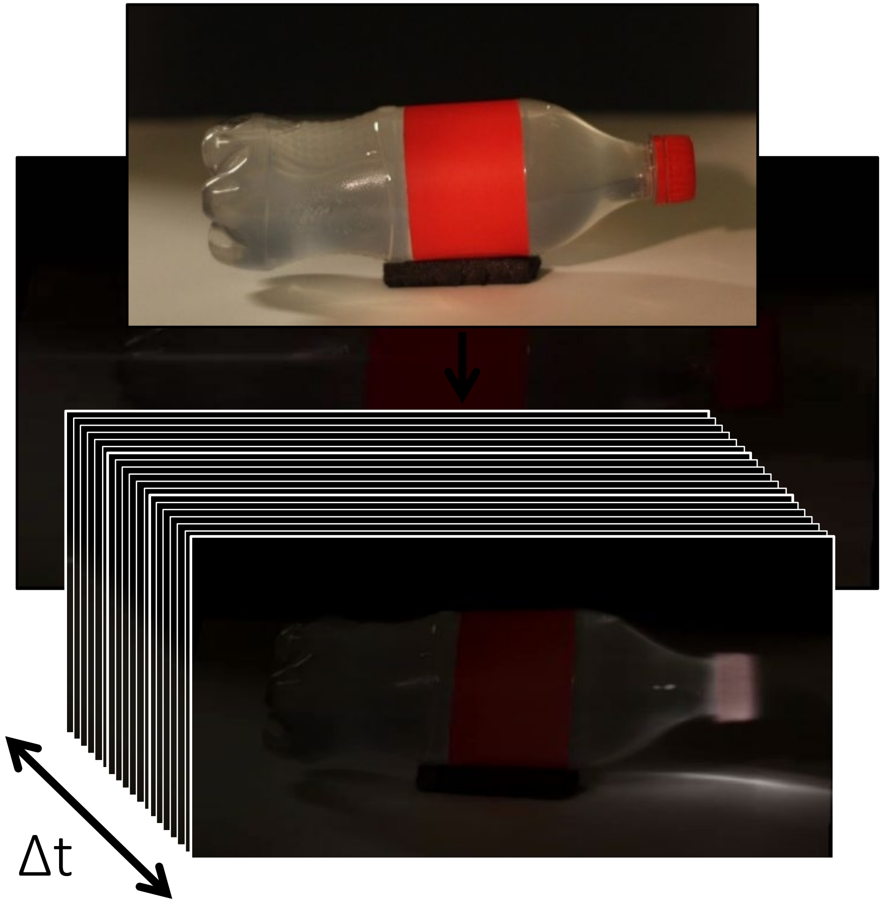
A lot of these slides were adapted from:

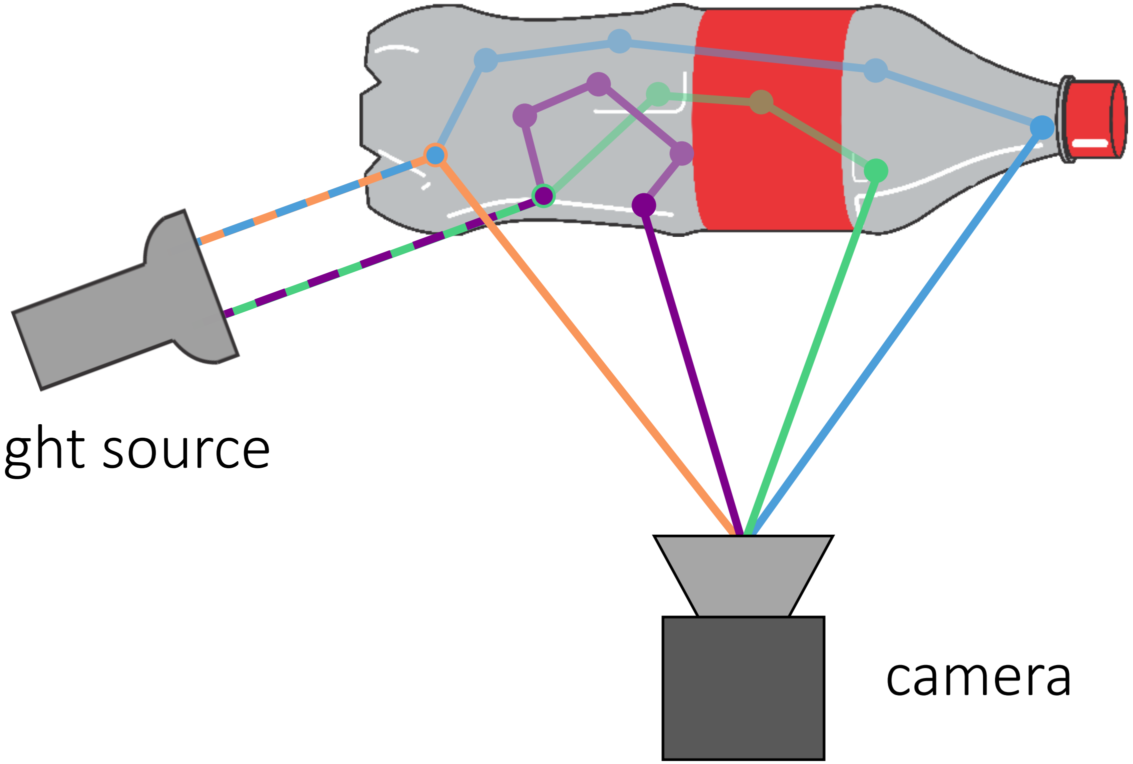
- Mohit Gupta (Wisconsin).
- Supreeth Achar (Google, formerly CMU).

Introduction to time-of-flight (ToF) imaging

Time-of-flight (ToF) imaging

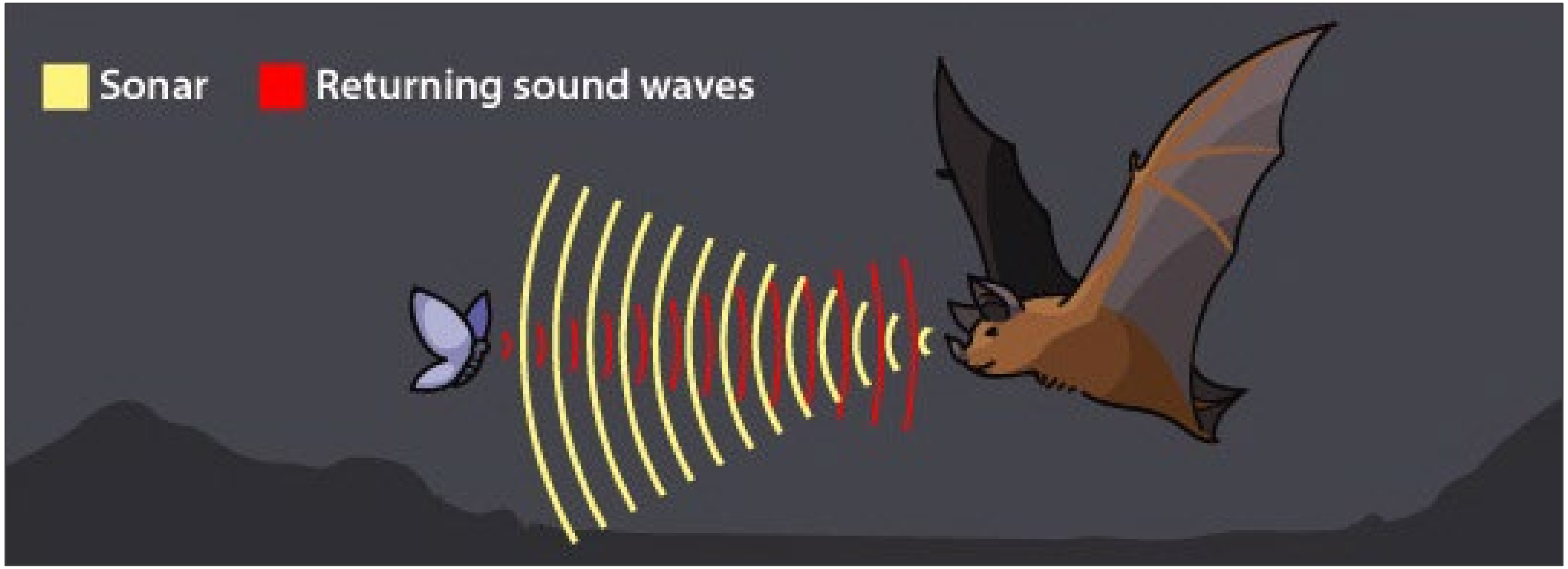
Time-of-flight (ToF) imaging

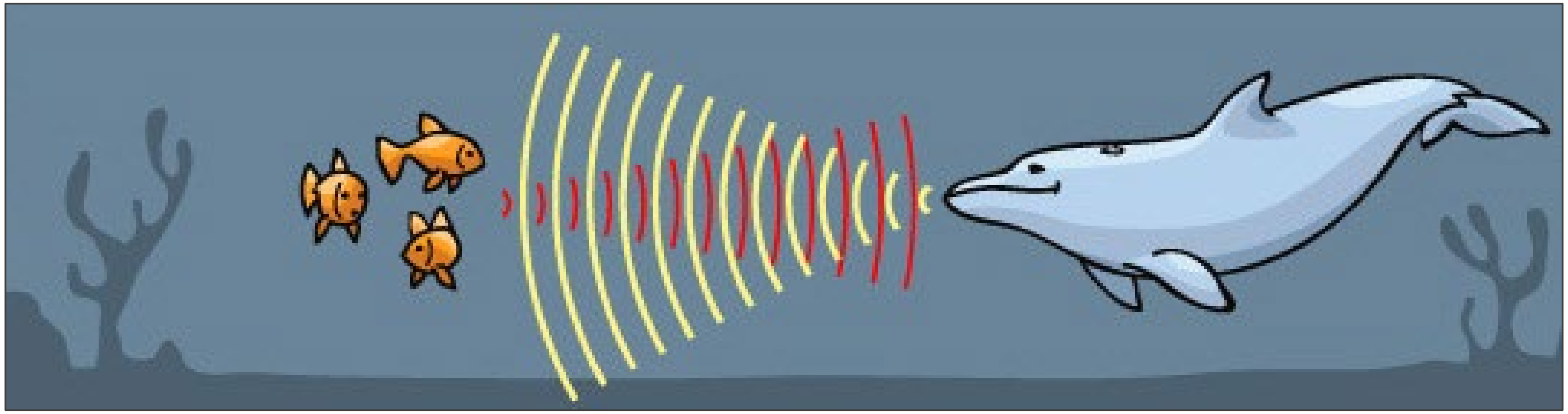




- Conventional imaging: Measure all photons together regardless of time of travel.
- Time-of-flight imaging: Measure photons separately based on time of travel.

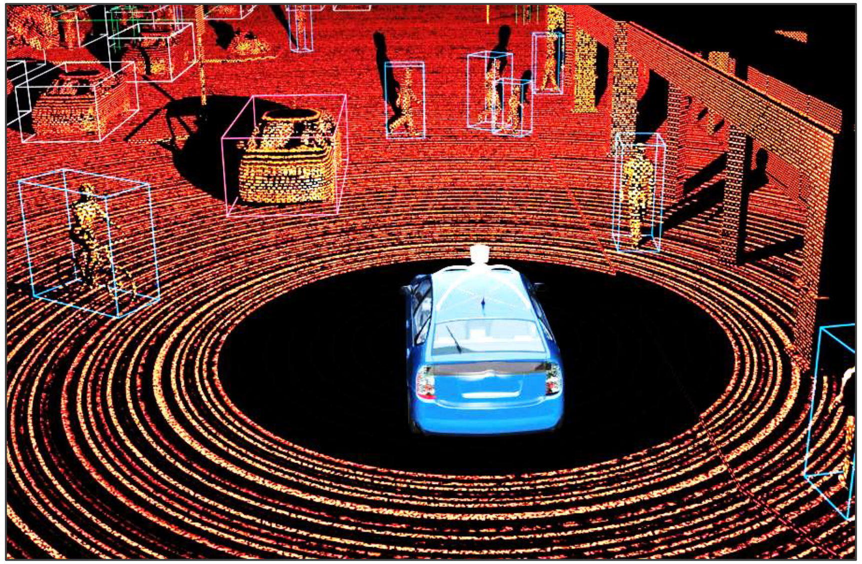
Time-of-flight imaging in nature

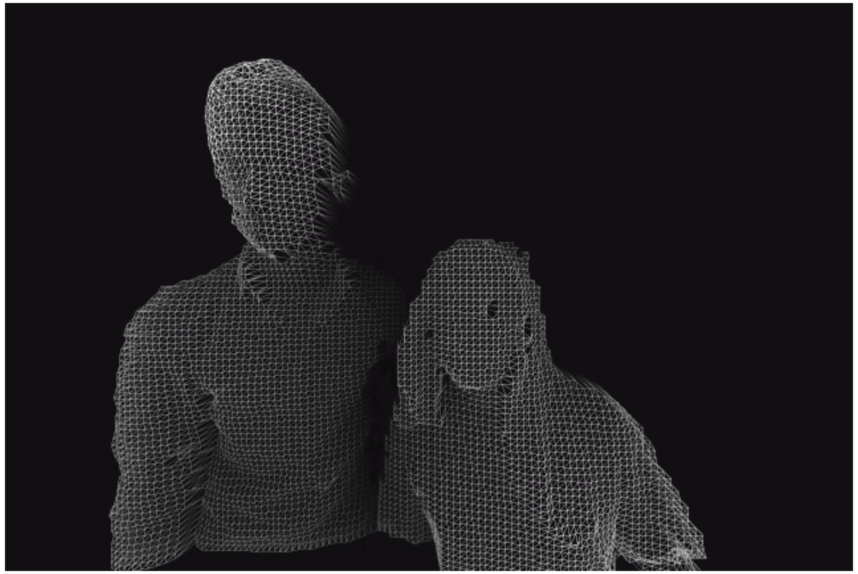




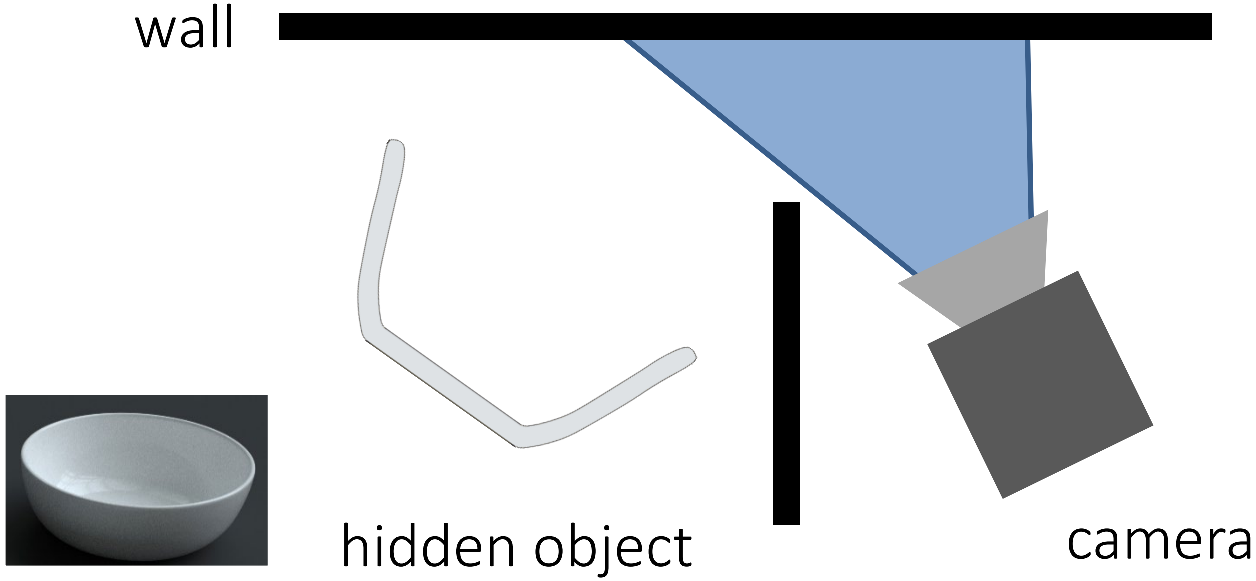
echolocation using sound-wave time-of-flight

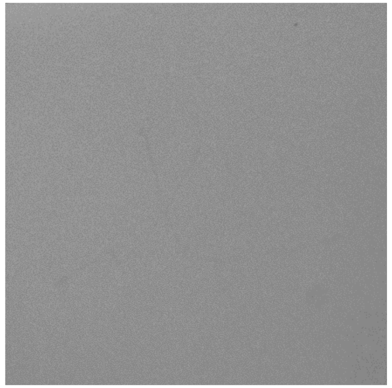
Time-of-flight applications: depth sensing



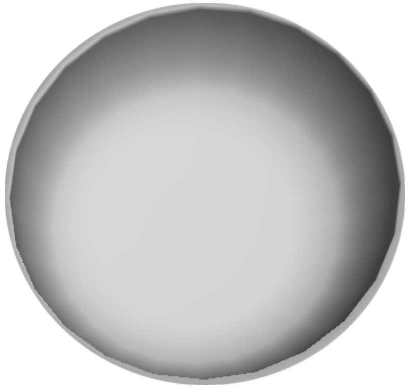


Time-of-flight applications: non-line-of-sight imaging

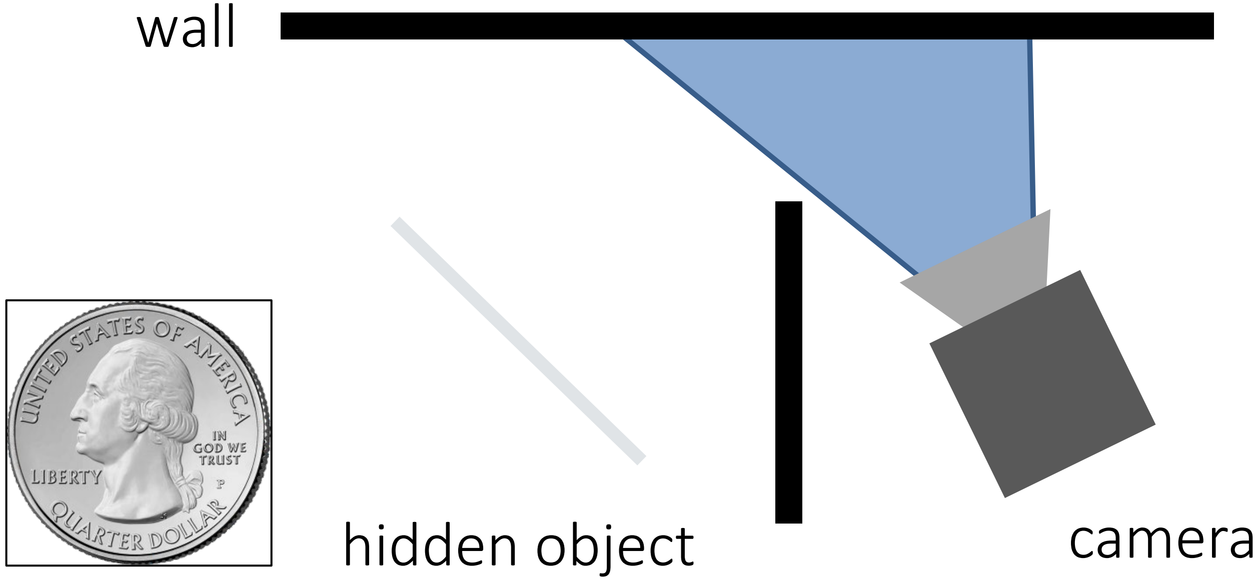


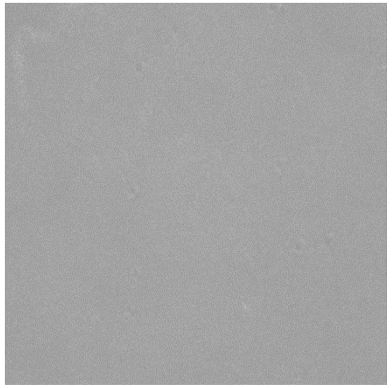


what a regular camera sees



what shape our camera sees

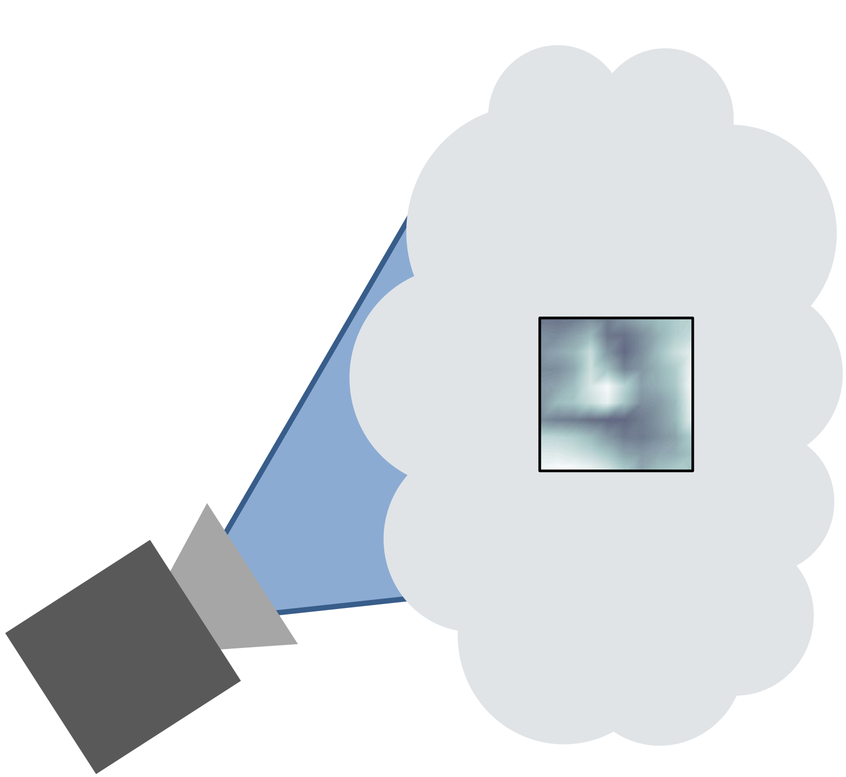




what a regular camera sees

what depth our camera sees

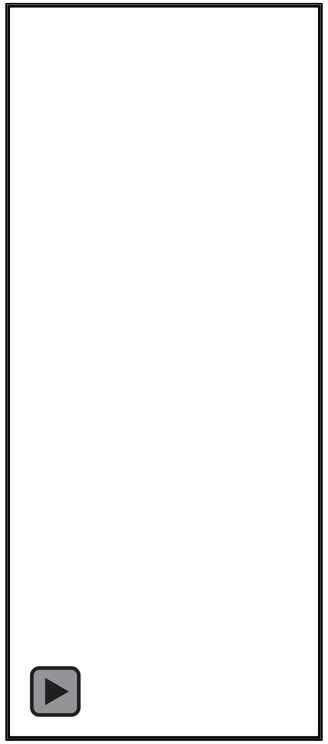
Time-of-flight applications: seeing inside objects



camera

thick smoke cloud

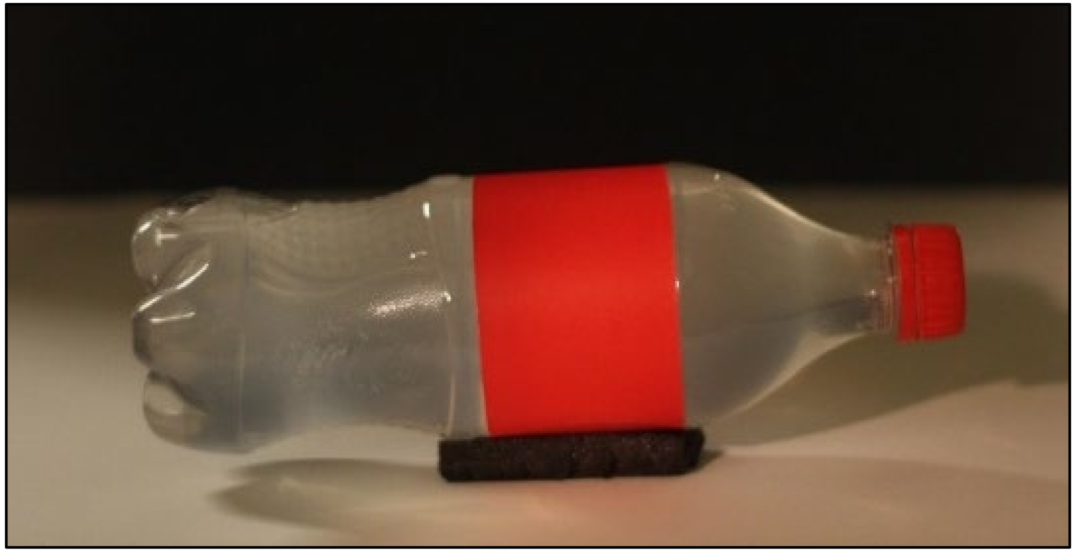
what a regular camera sees



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

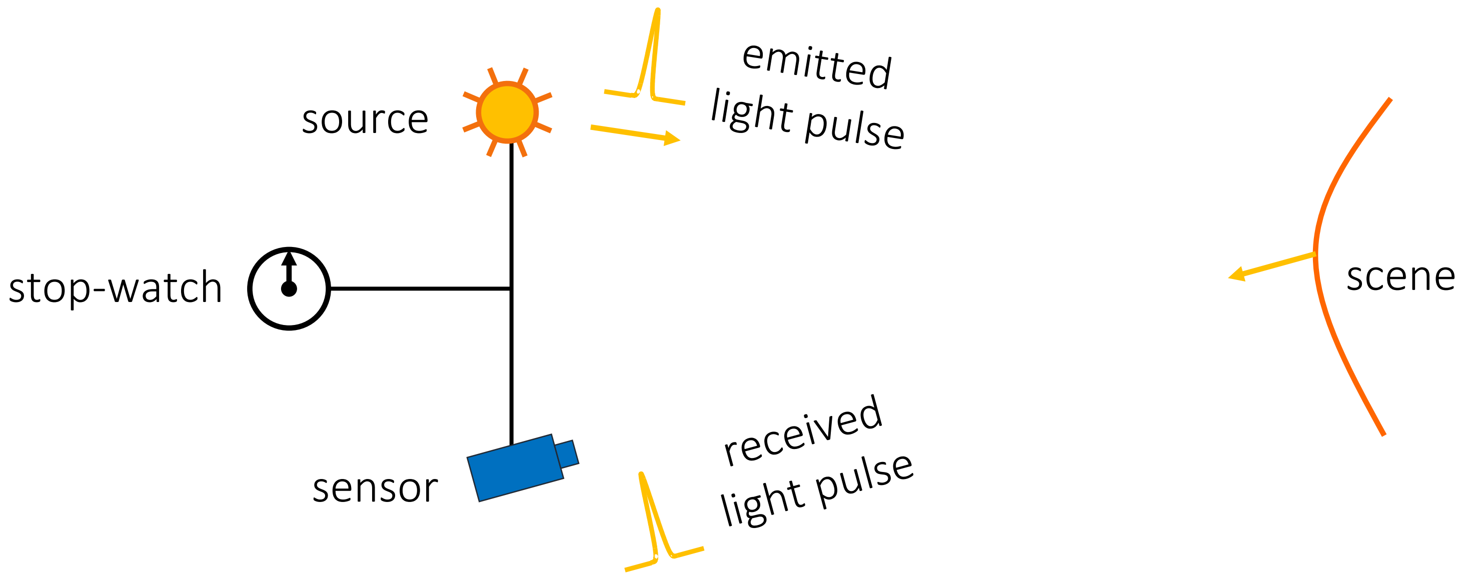
	interferometry	streak cameras	single-photon avalanche diodes	time-of-flight cameras	LIDAR
temporal resolution	1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	100 picoseconds (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)
frame rate	quadrillion fps	trillion fps	10 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

impulse ToF

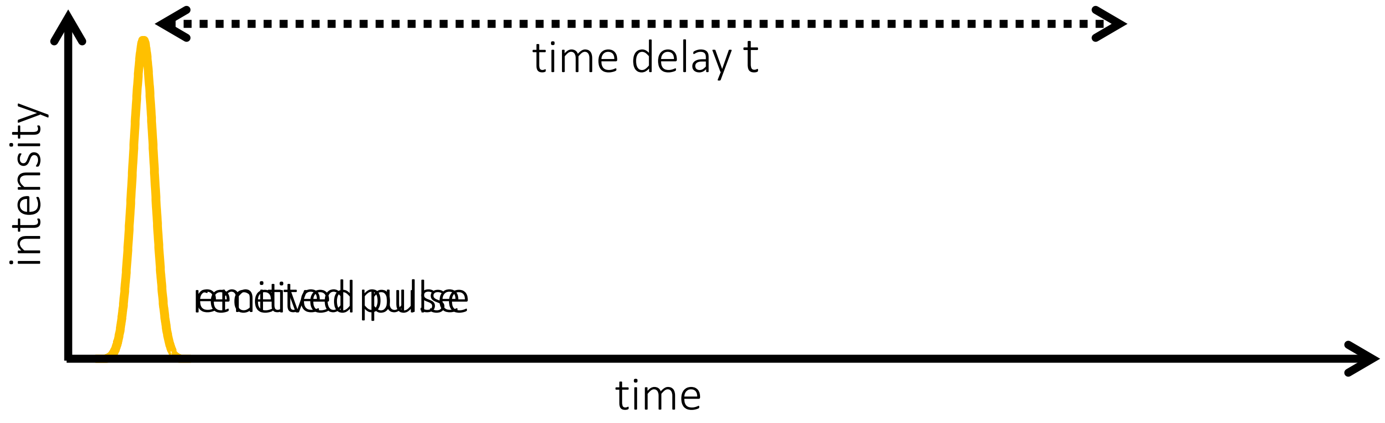
Impulse ToF imaging and single-photon avalanche diodes

Impulse time-of-flight imaging

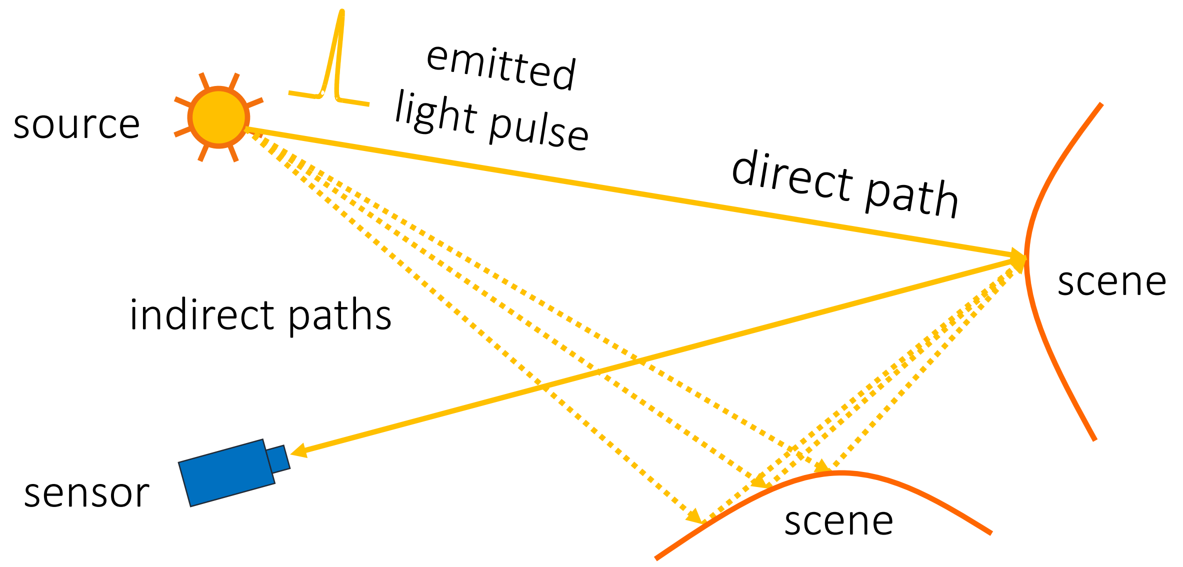


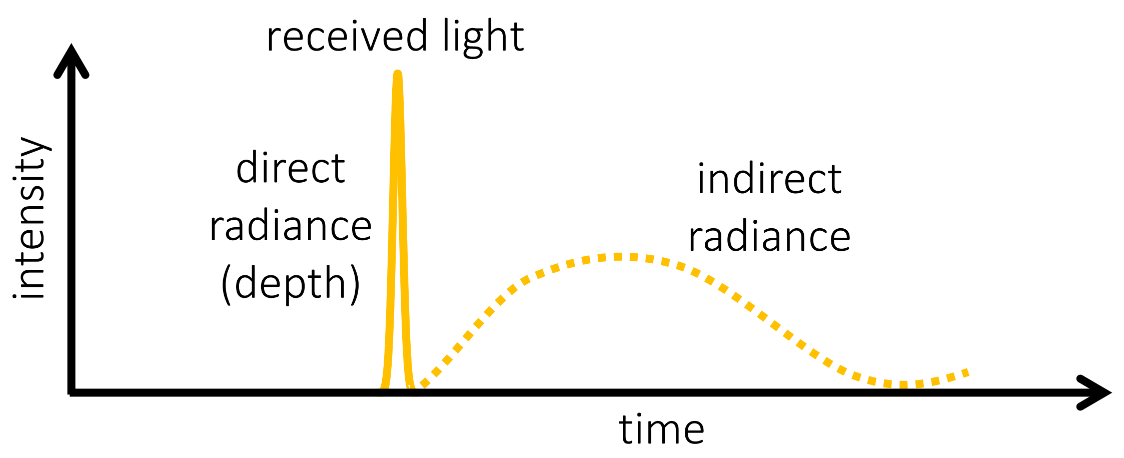
How can we infer depth from this?

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



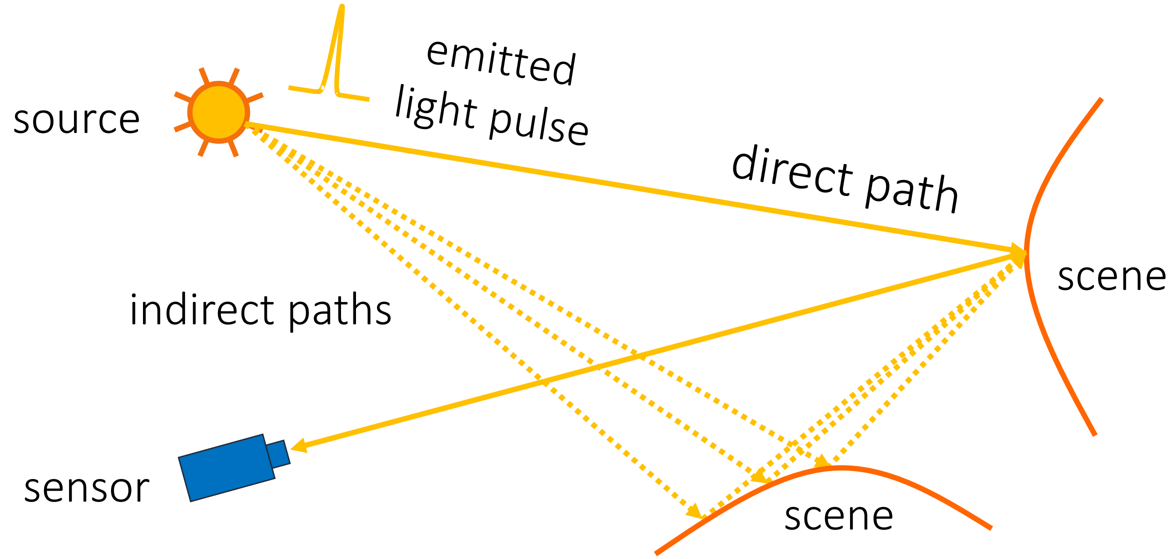
Impulse time-of-flight imaging

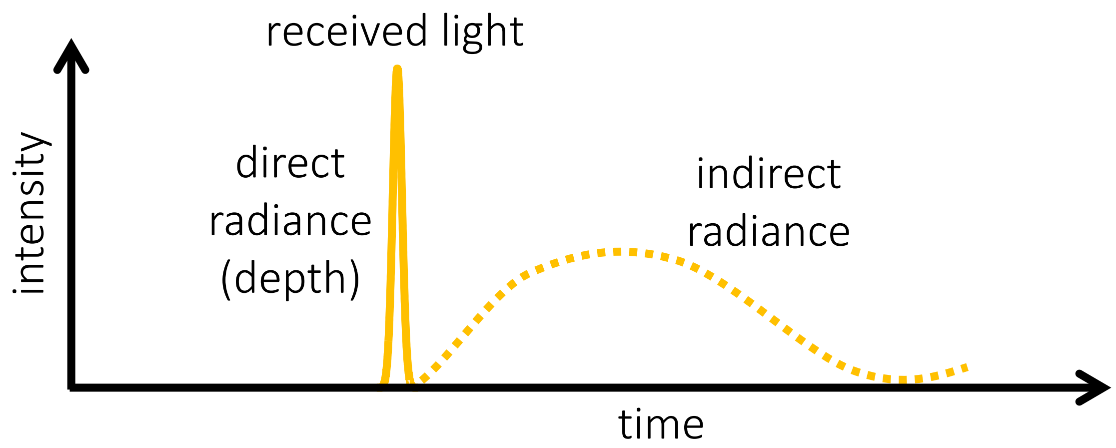




- Indirect paths are nuisance for depth sensing ("multi-path interference").
- Indirect paths are very informative for other time-of-flight applications.

Two types of time-of-flight imaging





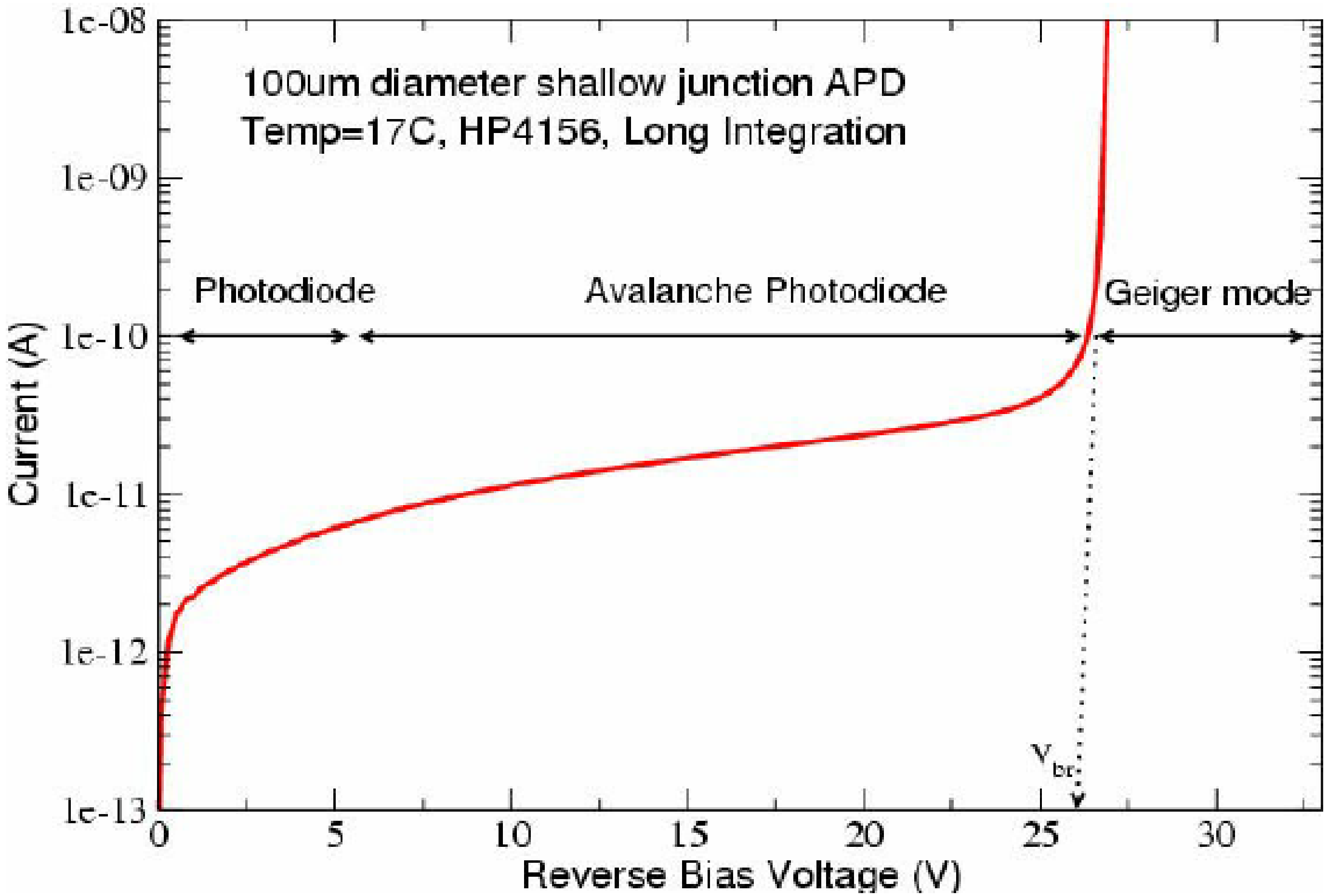
Transient I(t): Time-resolved radiance distribution

- 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.

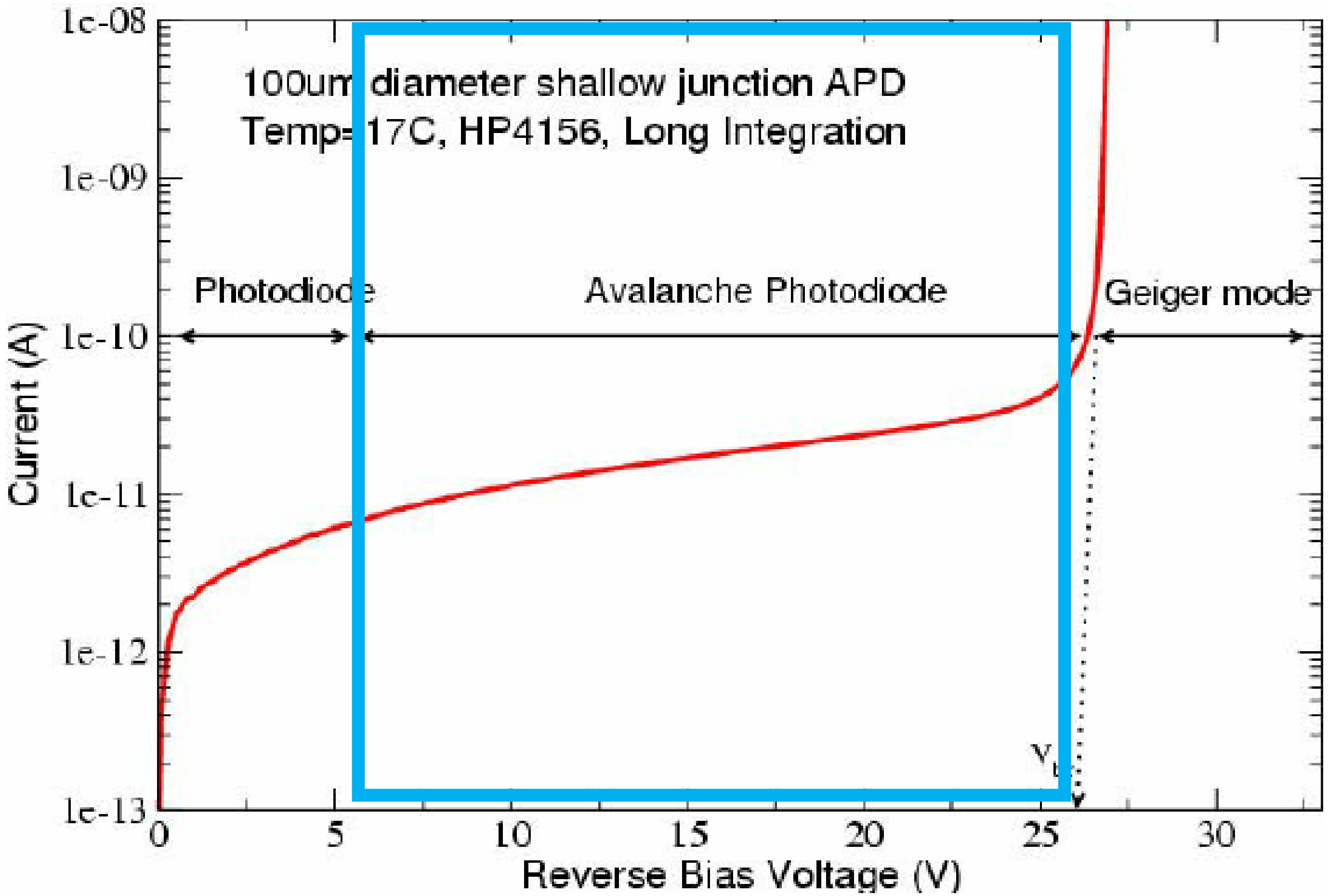
- Here we will examine only photodiodes.



How exactly is the transient formed?

Depends on the kind of sensor we use.

- Here we will examine only photodiodes.



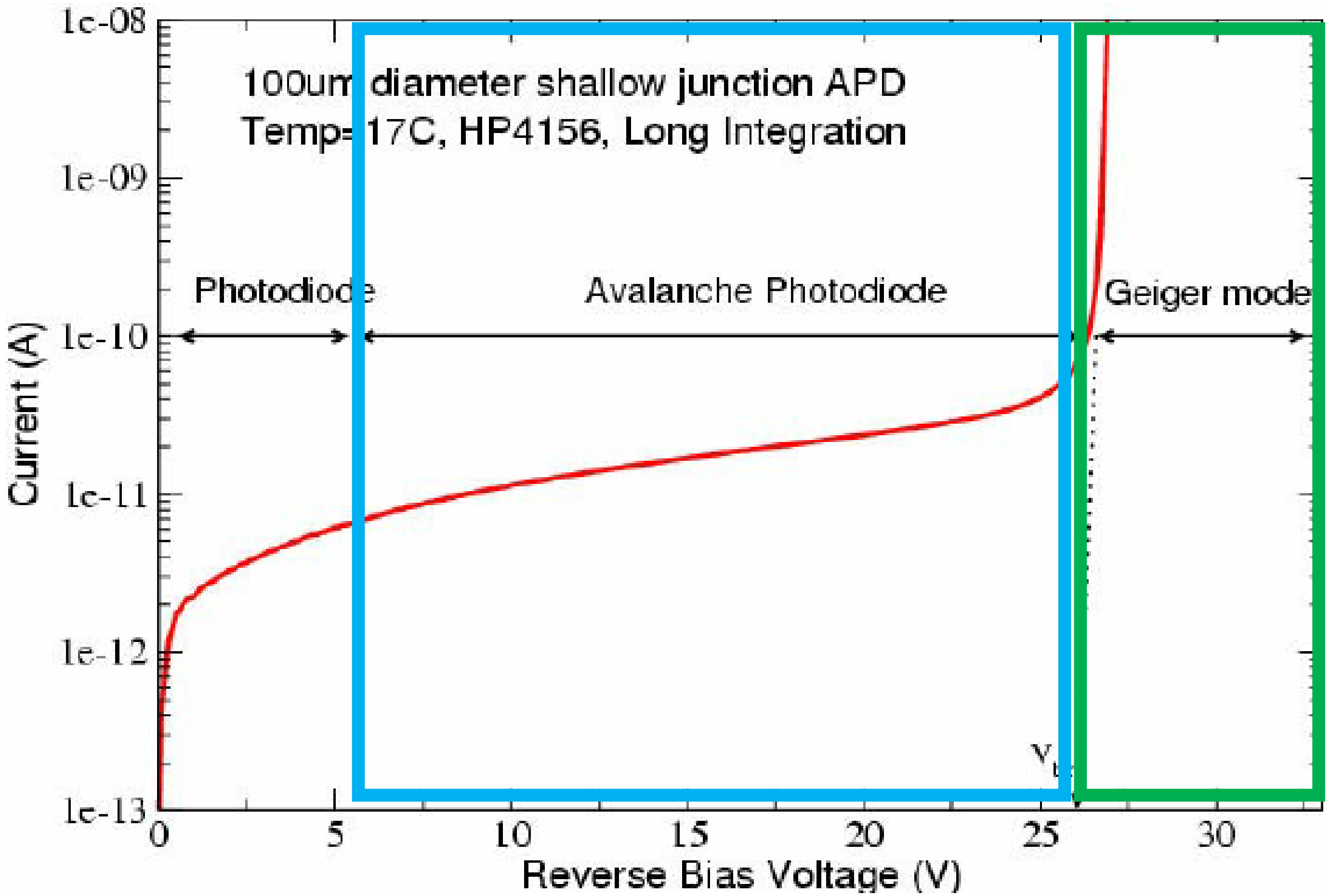
Avalanche photodiode (APD):

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

How exactly is the transient formed?

Depends on the kind of sensor we use.

- Here we will examine only photodiodes.



<u>Avalanche photodiode (APD)</u>:

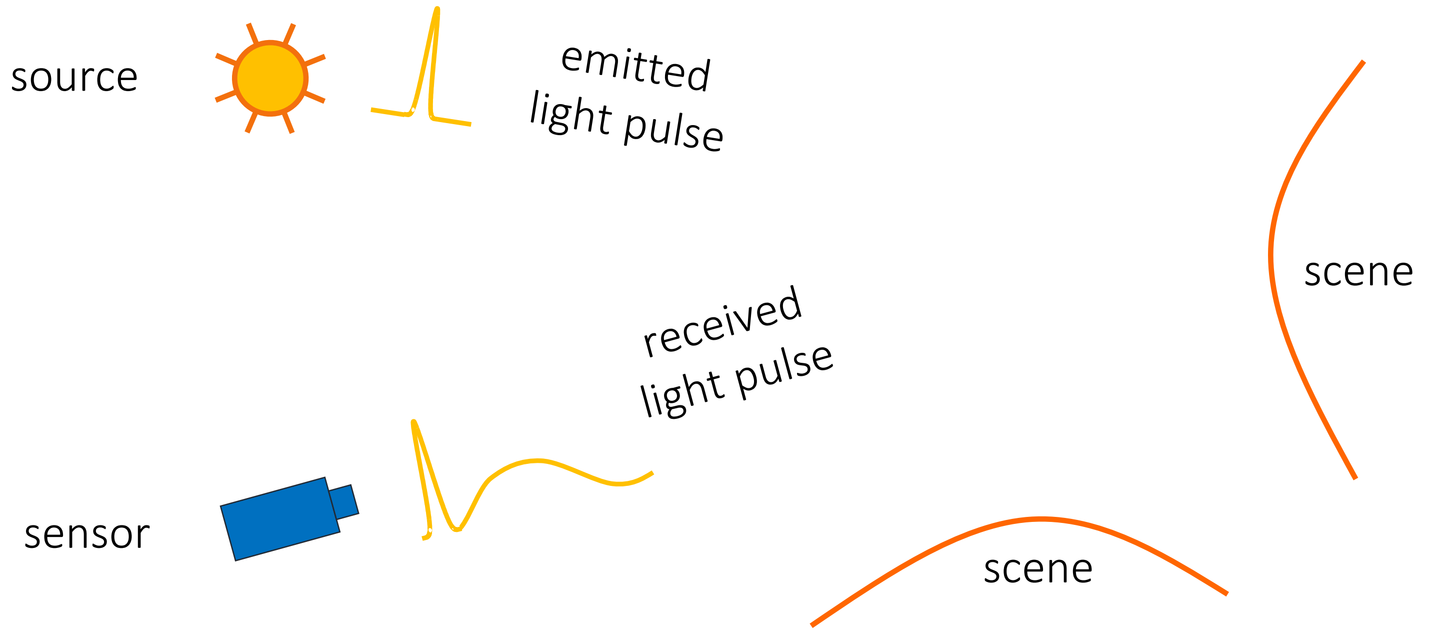
- Current is roughly proportional to number of photons.
- One photon produces tiny current.

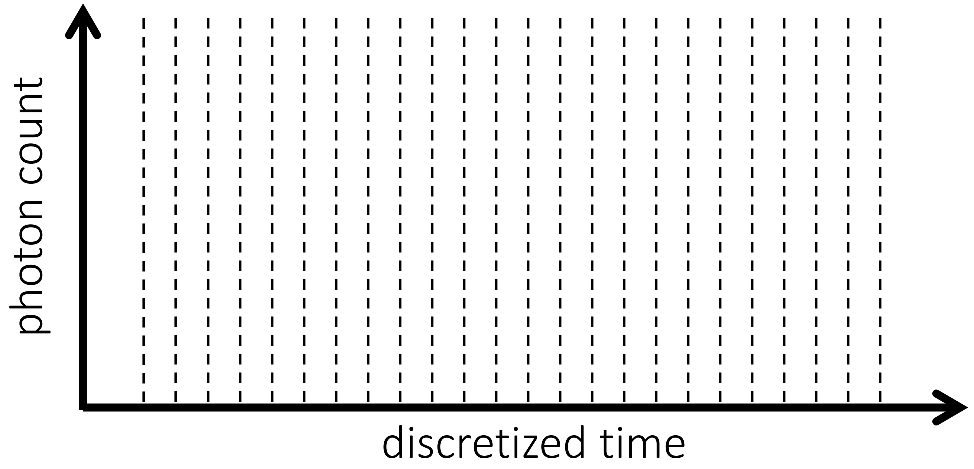
<u>Single-photon avalanche diode (SPAD)</u>:

- One photon produces huge current.
- Requires multiple <u>low power</u> pulses, so that one photon returns from each.

Geiger-mode impulse time-of-flight imaging

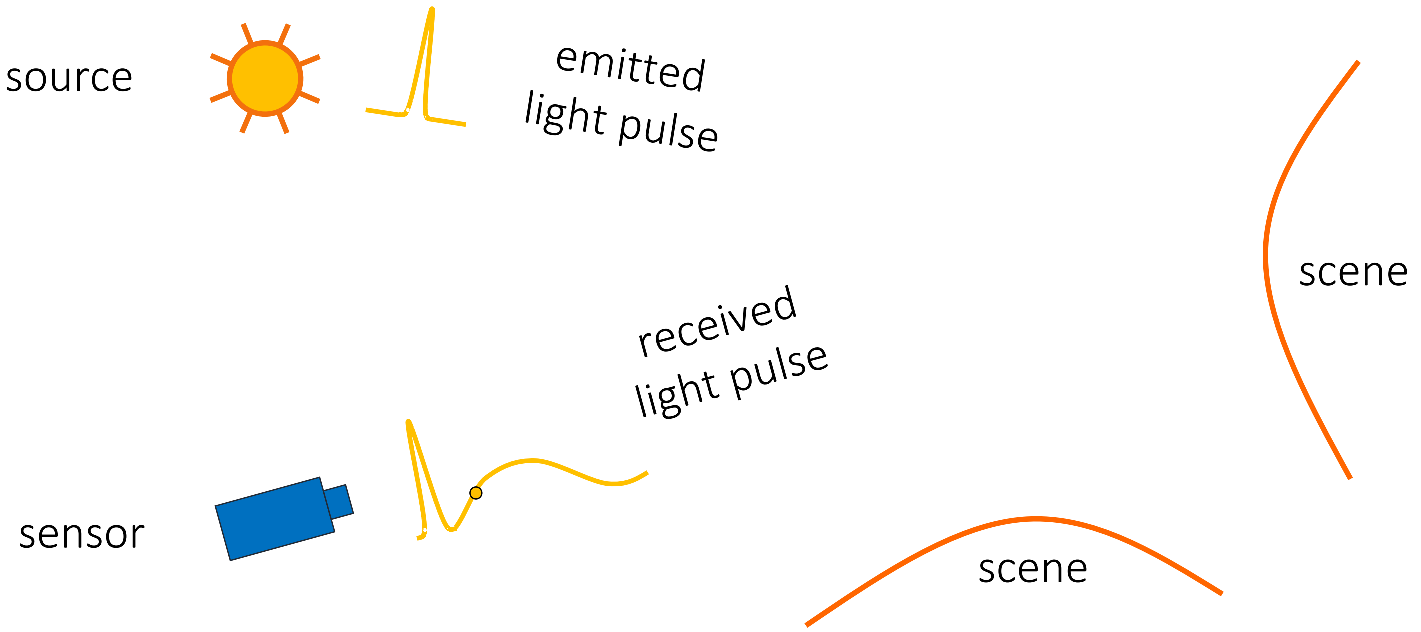
From each received pulse, one photon saturates the SPAD.



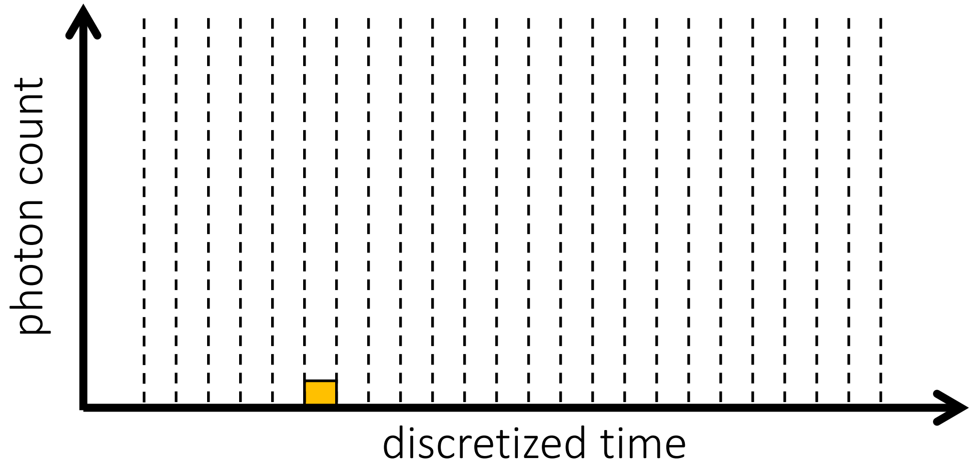


- The SPAD records only photon arrival times, no intensity.
- Additional electronics maintain a histogram of arrival times over multiple pulses

Geiger-mode impulse time-of-flight imaging

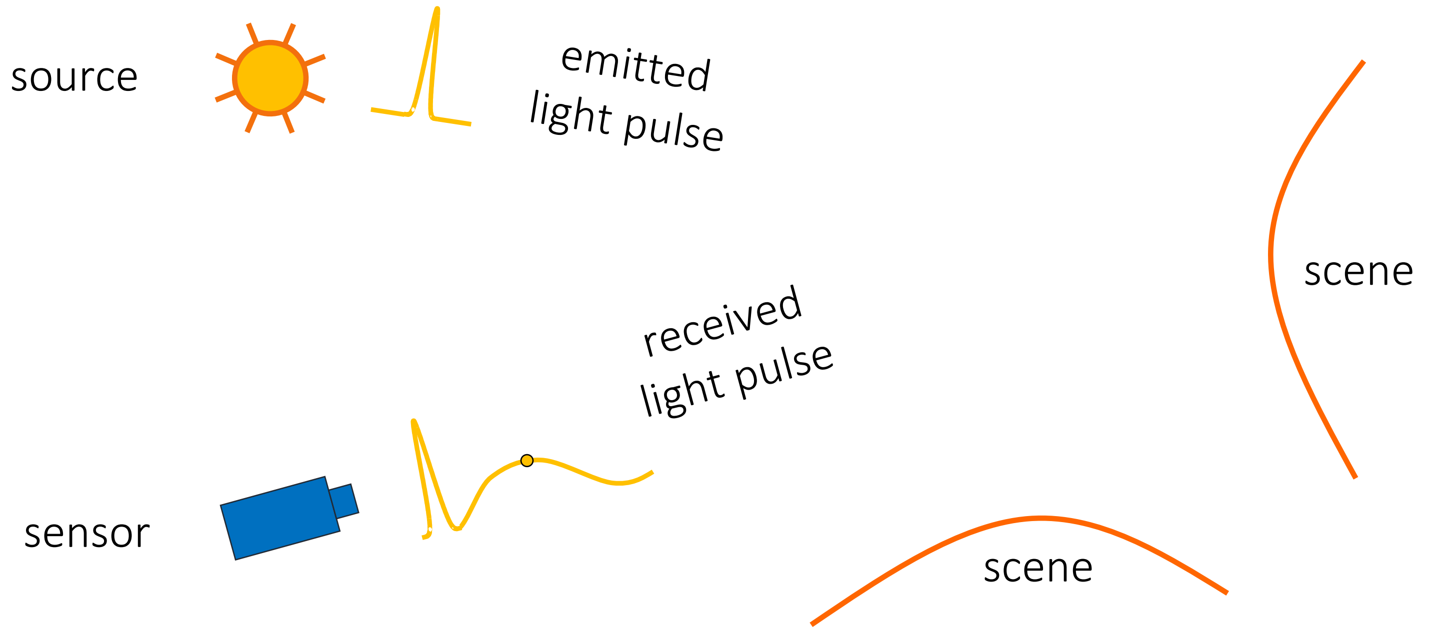


From each received pulse, one photon saturates the SPAD.

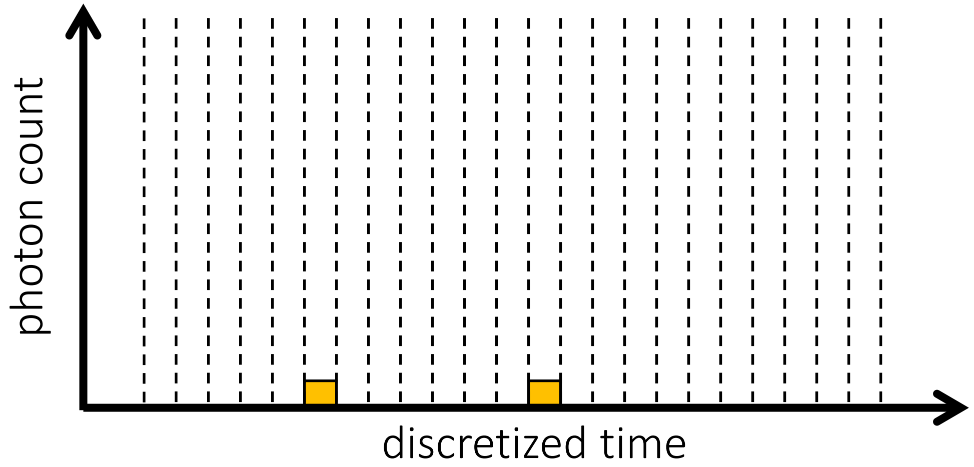


- The SPAD records only photon arrival times, no intensity.
- Additional electronics maintain a histogram of arrival times over multiple pulses

Geiger-mode impulse time-of-flight imaging

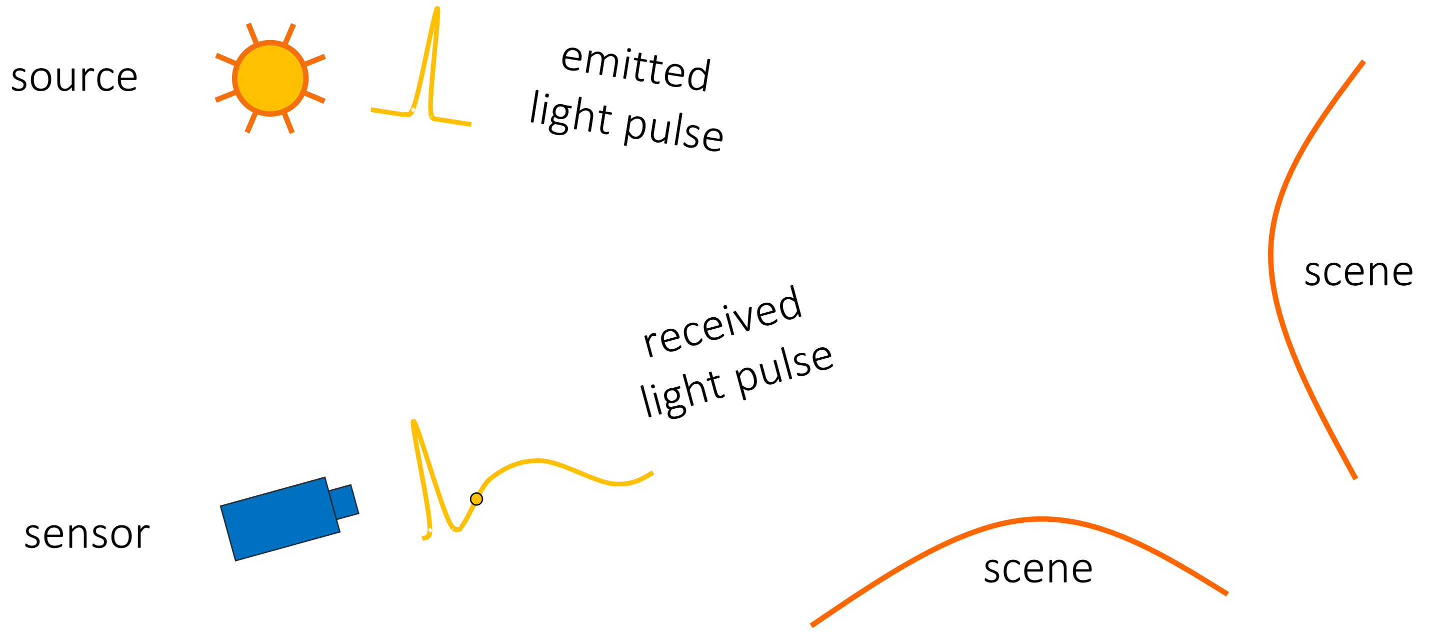


From each received pulse, one photon saturates the SPAD.

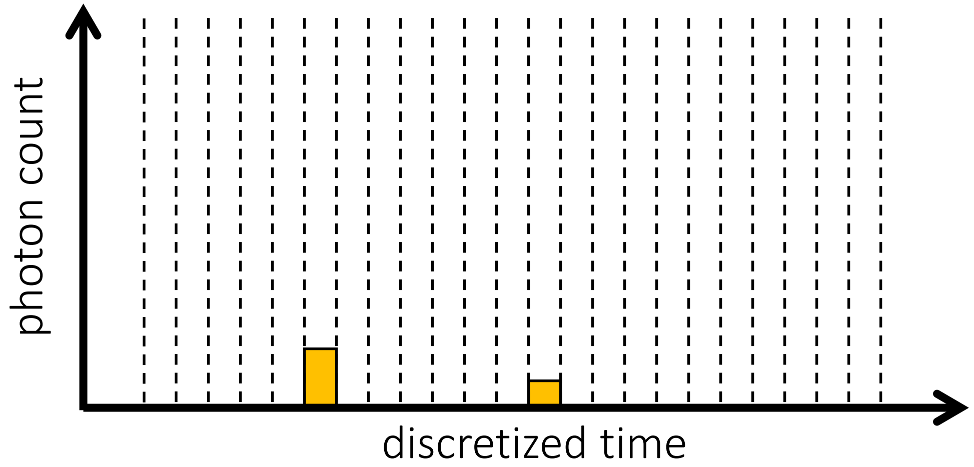


- The SPAD records only photon arrival times, no intensity.
- Additional electronics maintain a histogram of arrival times over multiple pulses

Geiger-mode impulse time-of-flight imaging

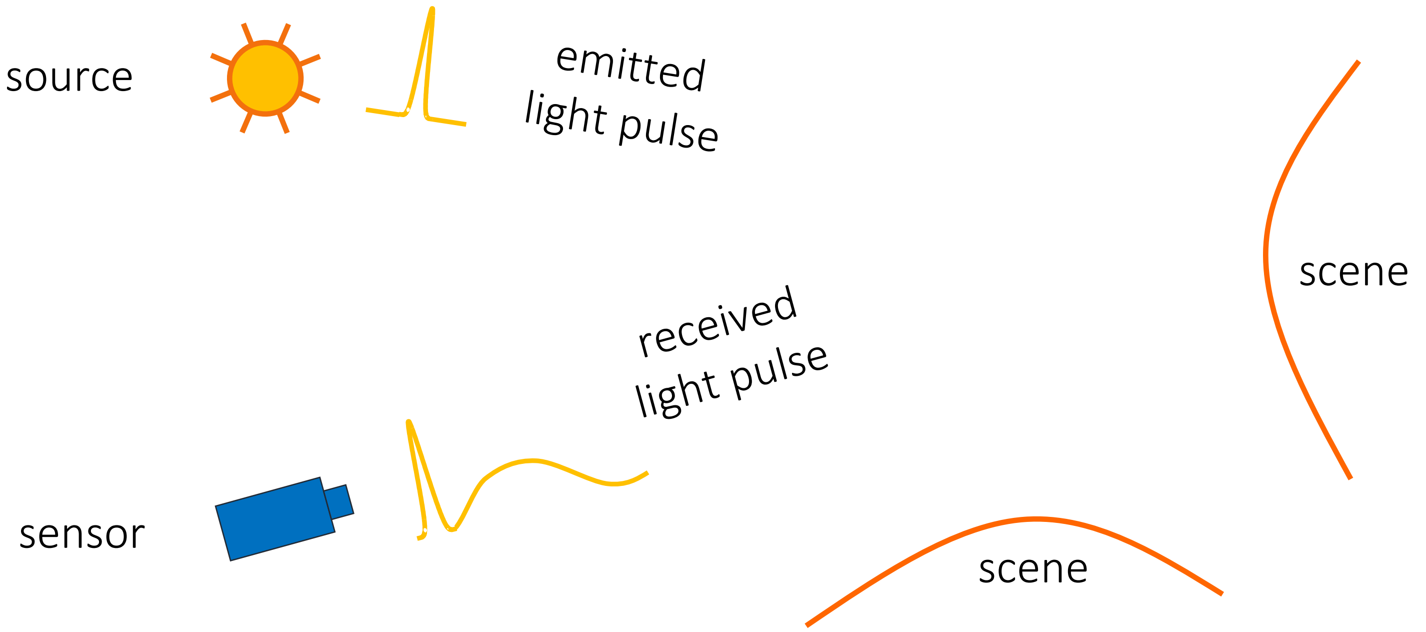


From each received pulse, one photon saturates the SPAD.



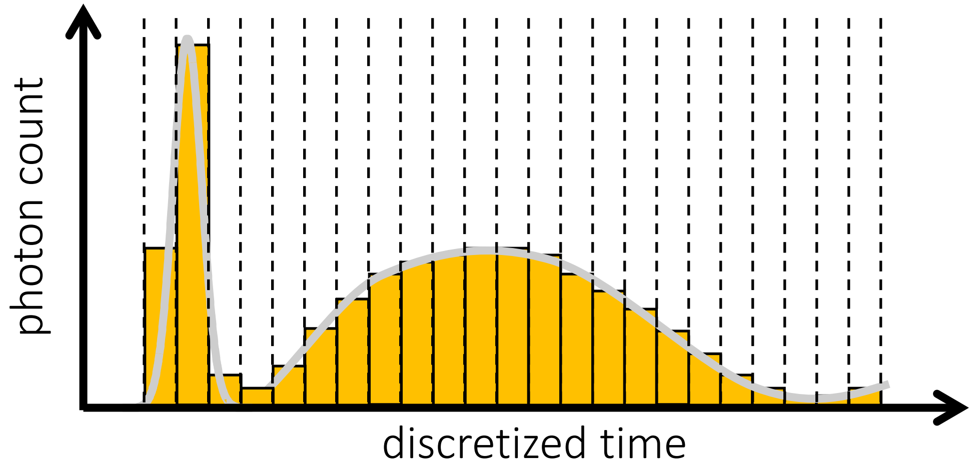
- The SPAD records only photon arrival times, no intensity.
- Additional electronics maintain a histogram of arrival times over multiple pulses

Geiger-mode impulse time-of-flight imaging



From each received pulse, one photon saturates the SPAD.

What determines which photon gets picked?

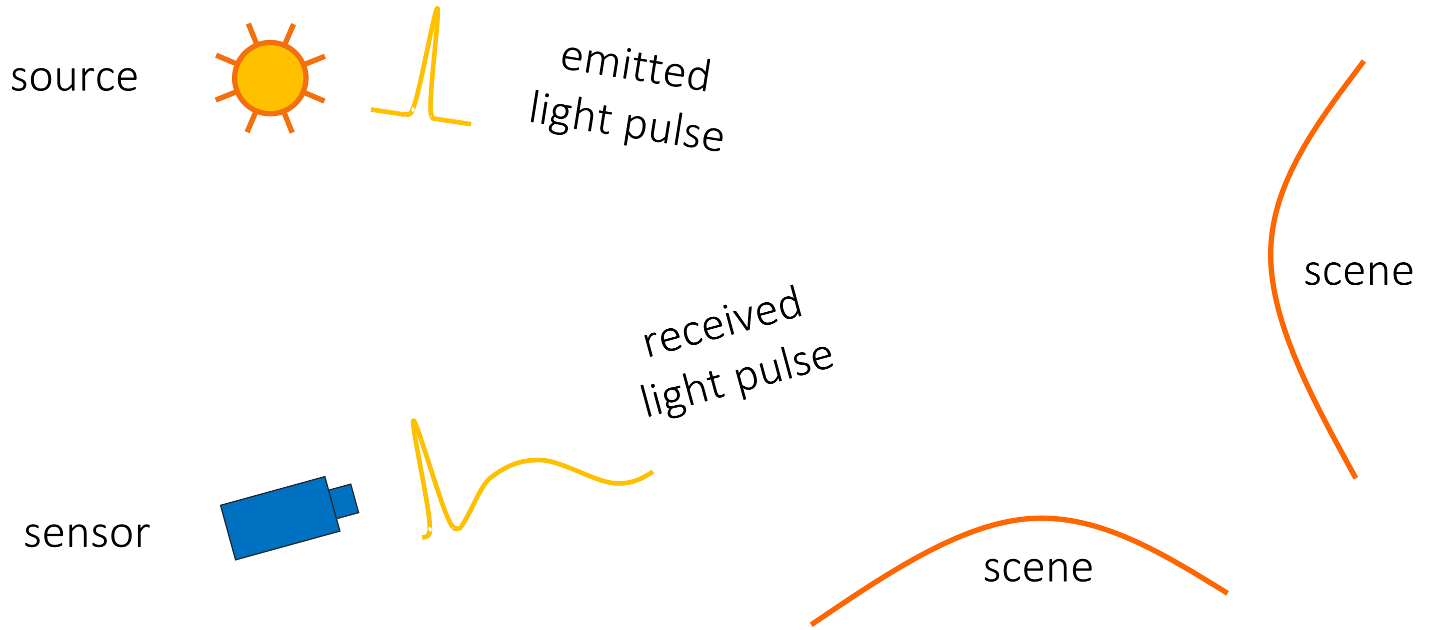


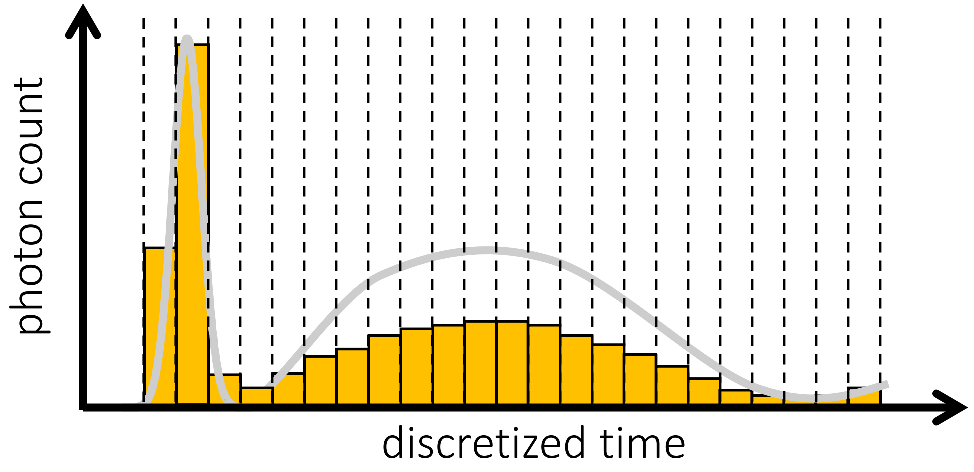
- The SPAD records only photon arrival times, no intensity.
- Additional electronics maintain a histogram of arrival times over multiple pulses

Geiger-mode impulse time-of-flight imaging

From each received pulse, one photon saturates the SPAD.

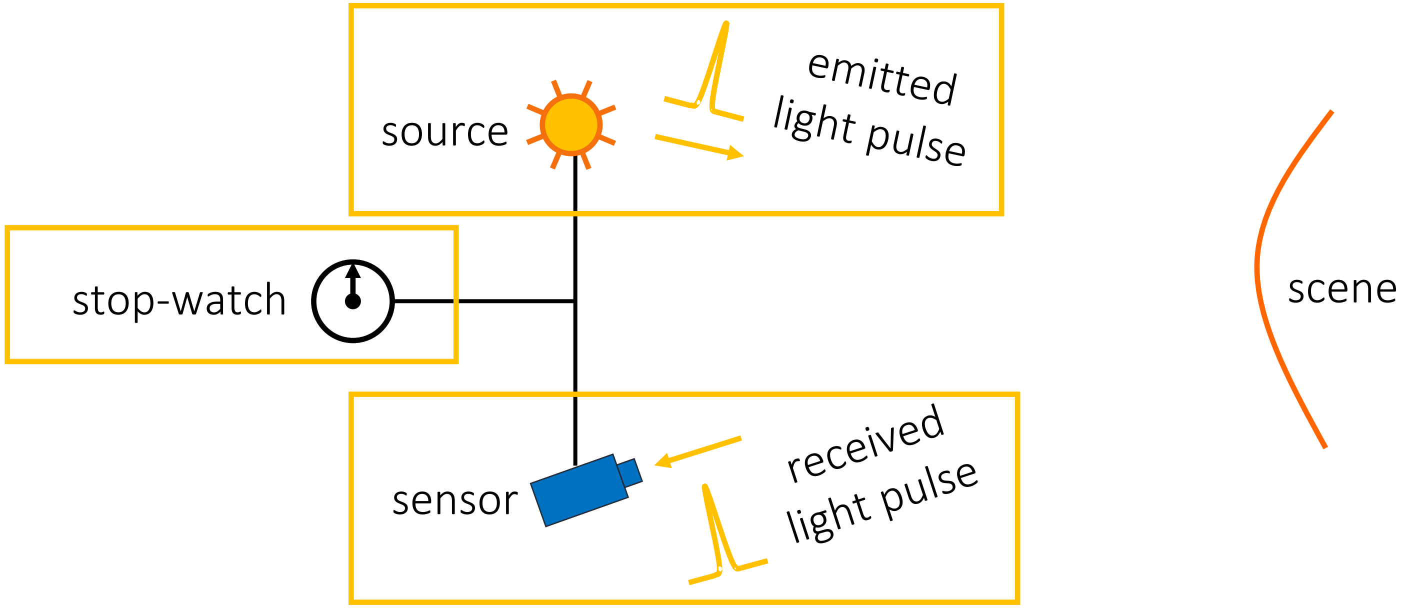
What determines which photon gets picked?





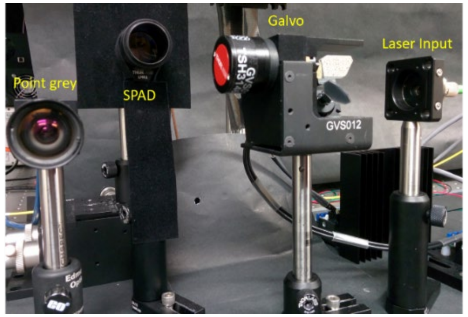
- Photons earlier in the transient have a higher probability of being detected than photons later in the transient.
- As a result, histogram of photon detections underestimates later parts of the transient.
- This effect is called *pile-up* and is very severe under strong light conditions.

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

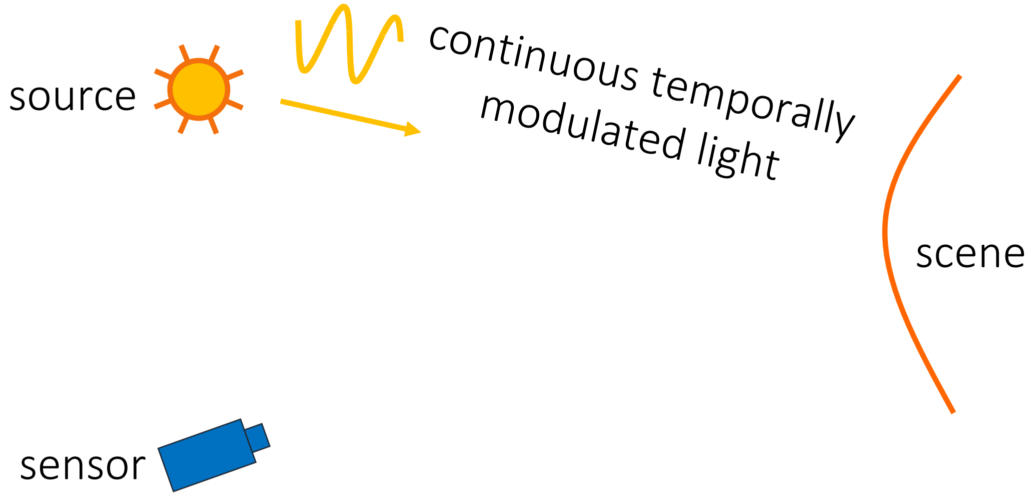
	interferometry	streak cameras	single-photon avalanche diodes	time-of-flight cameras	LIDAR
temporal resolution	1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	100 picoseconds (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)
frame rate	quadrillion fps	trillion fps	10 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

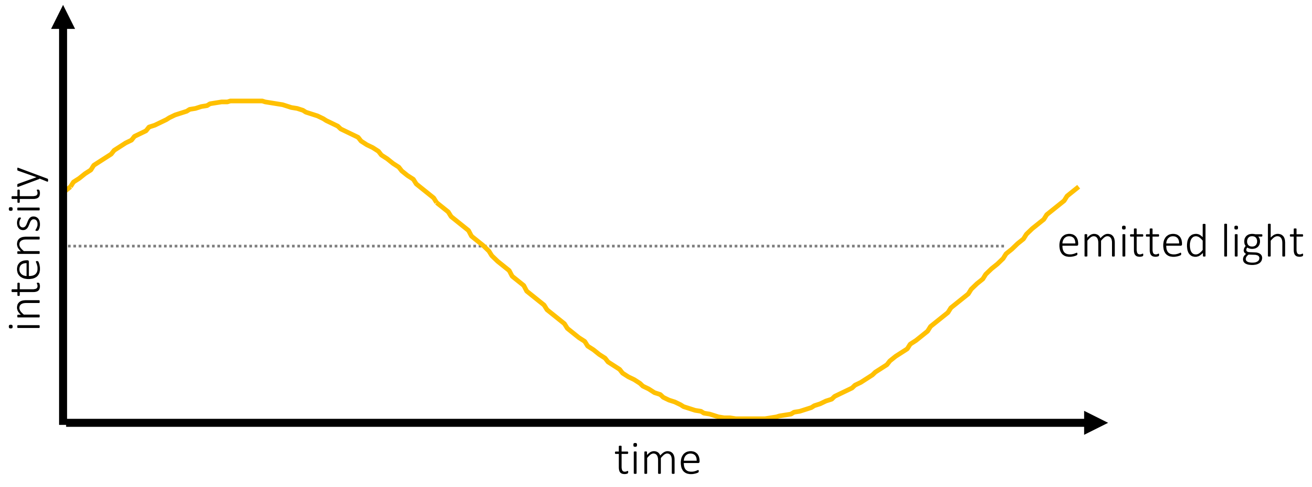
impulse ToF

Continuous-wave ToF imaging

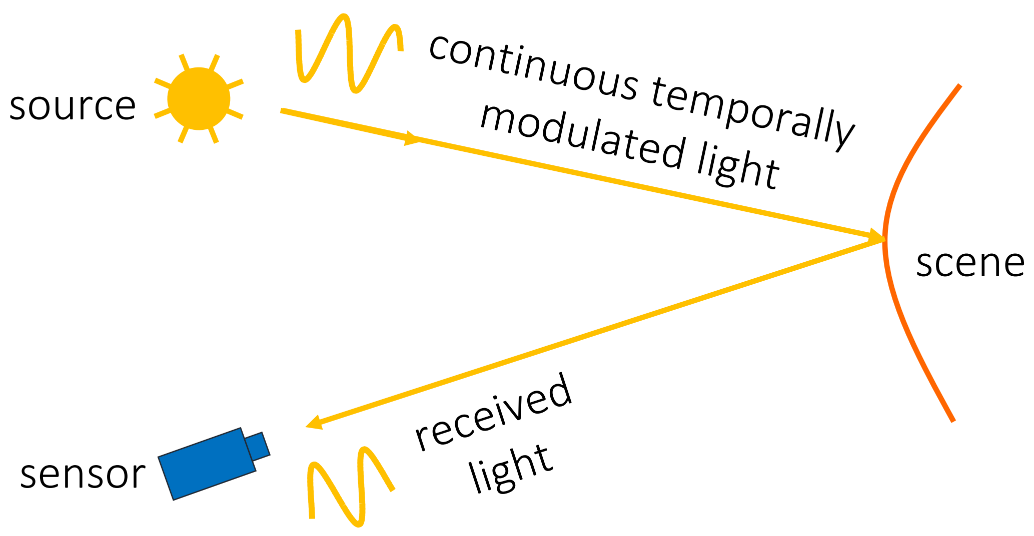
Continuous-wave (CW) time-of-flight imaging

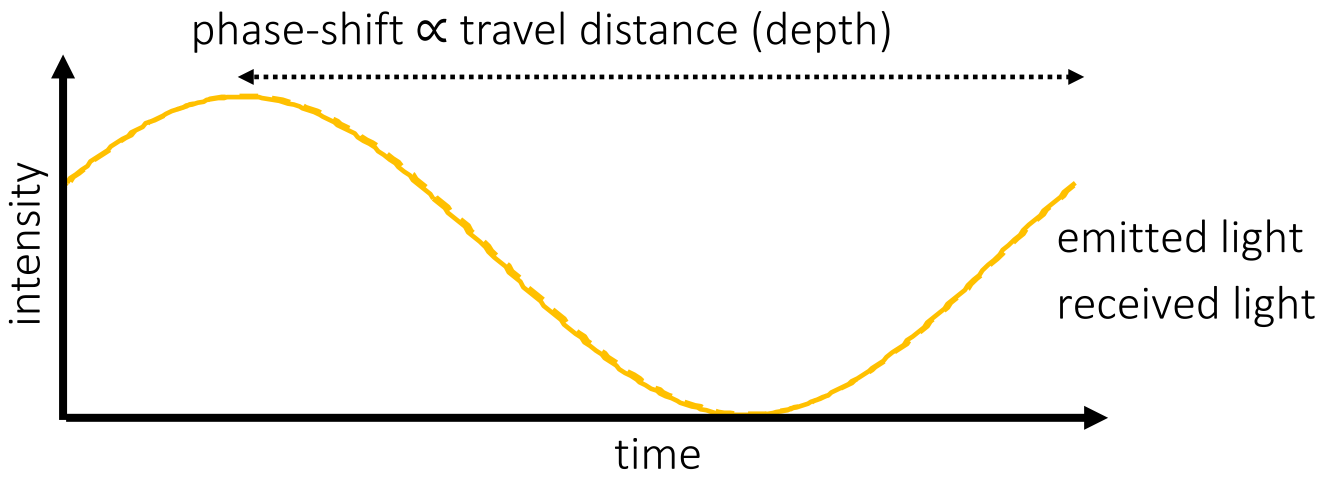


sinusoid

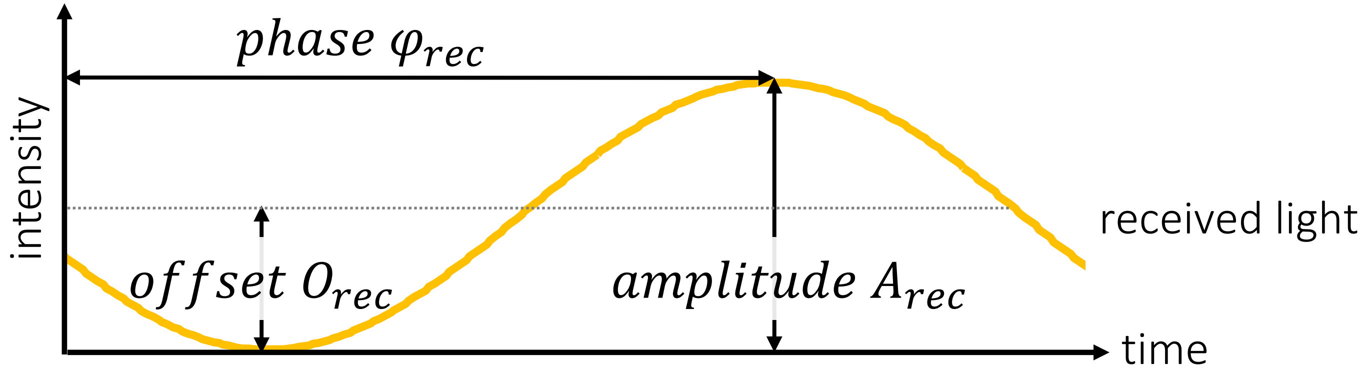


Continuous-wave (CW) time-of-flight imaging





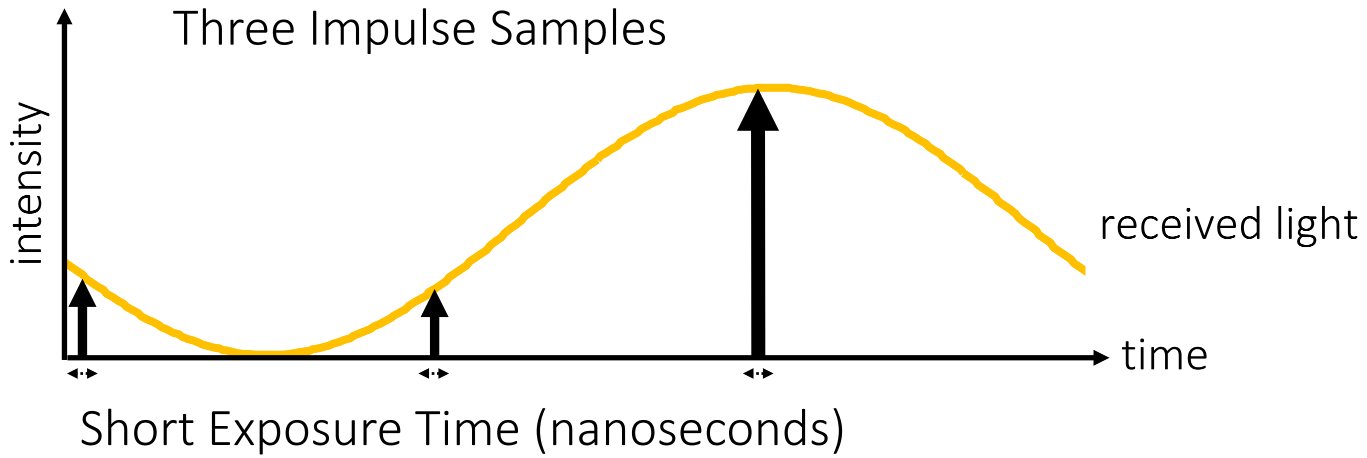
Measuring phase shift



Three Unknowns

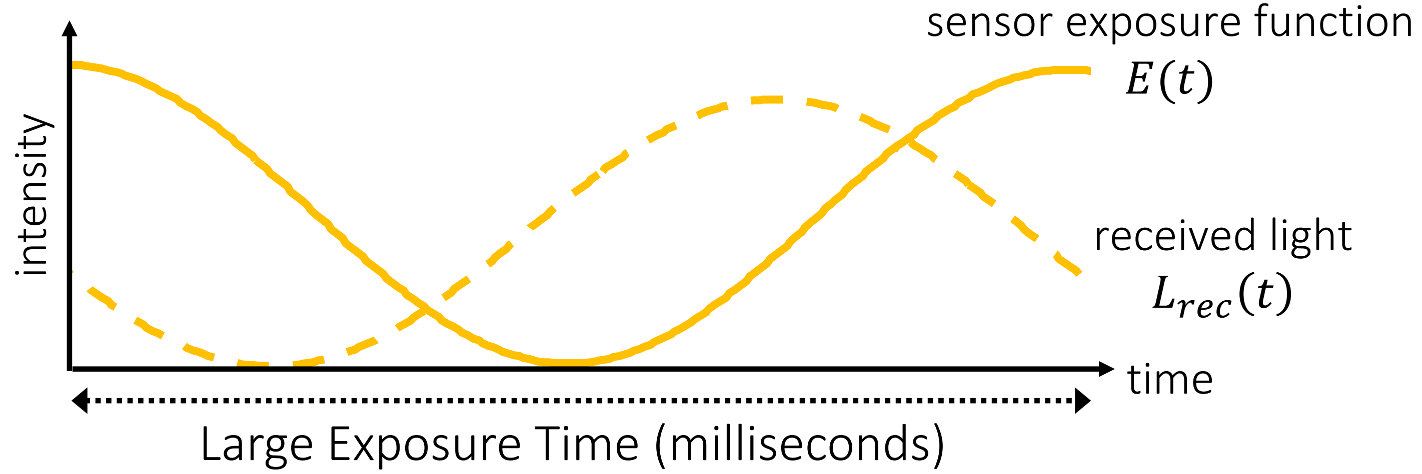
$$L_{rec}(t) = O_{rec} + A_{rec}\cos(\omega t - \phi_{rec})$$

Measuring phase shift: direct



Low Signal-to-Noise-Ratio

Measuring phase shift: correlation



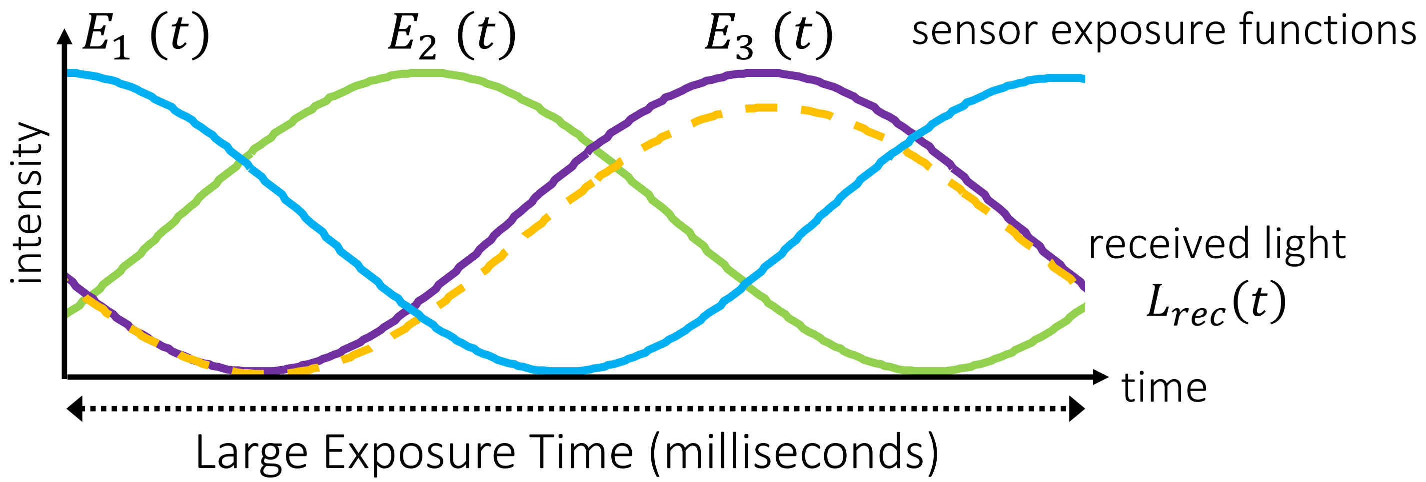
Correlation: $I = \int E(t) \times L_{rec}(t)\, dt$

measured brightness

exposure function

received light

Measuring phase shift: correlation



High Signal-to-Noise Ratio

Real Time Capture

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

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

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

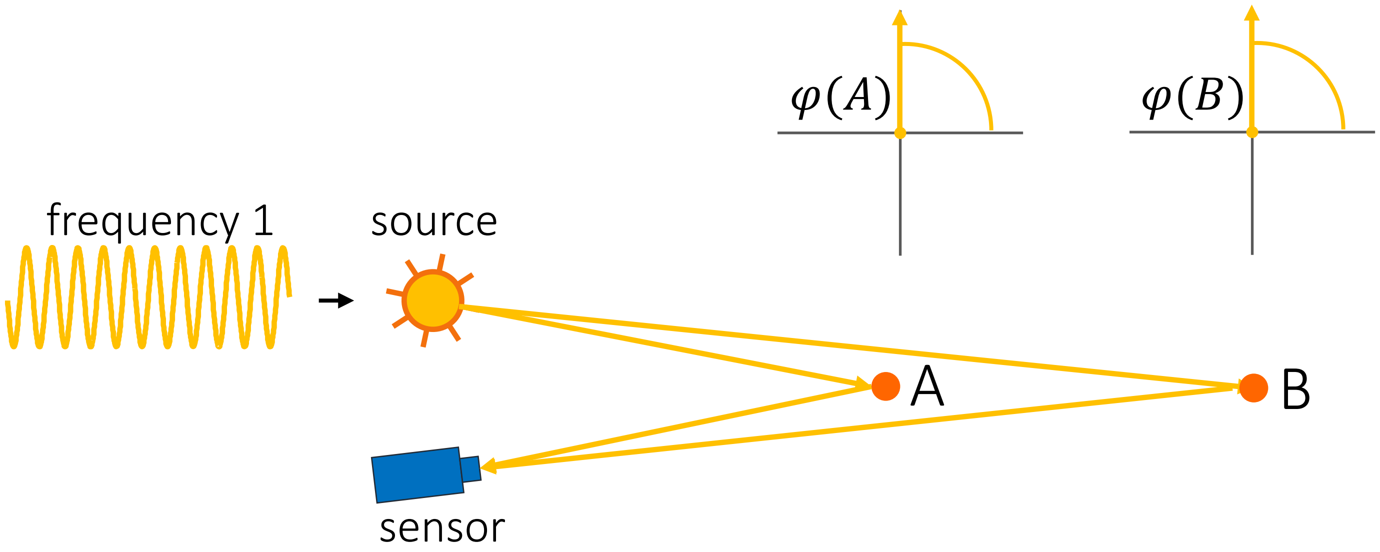
$depth$

$\boxed{phase\ \varphi_{rec}}$

$offset\ O_{rec}$

$amplitude\ A_{rec}$

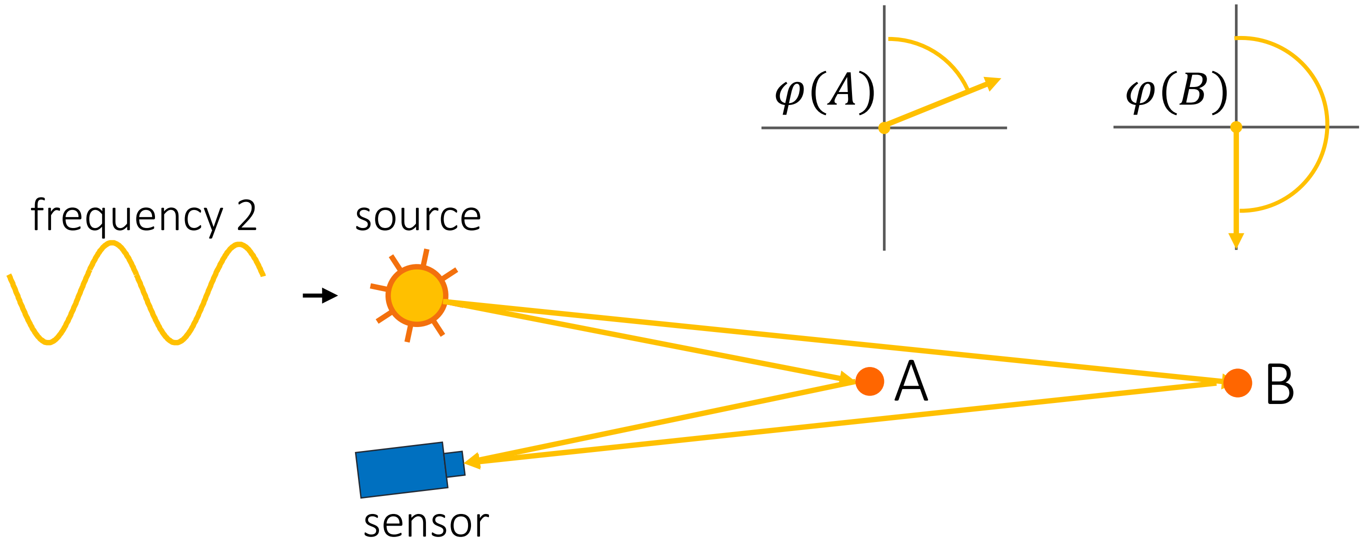
Phase ambiguity



Different Scene Depths Have Same Phase

- Also known as “phase wrapping”.

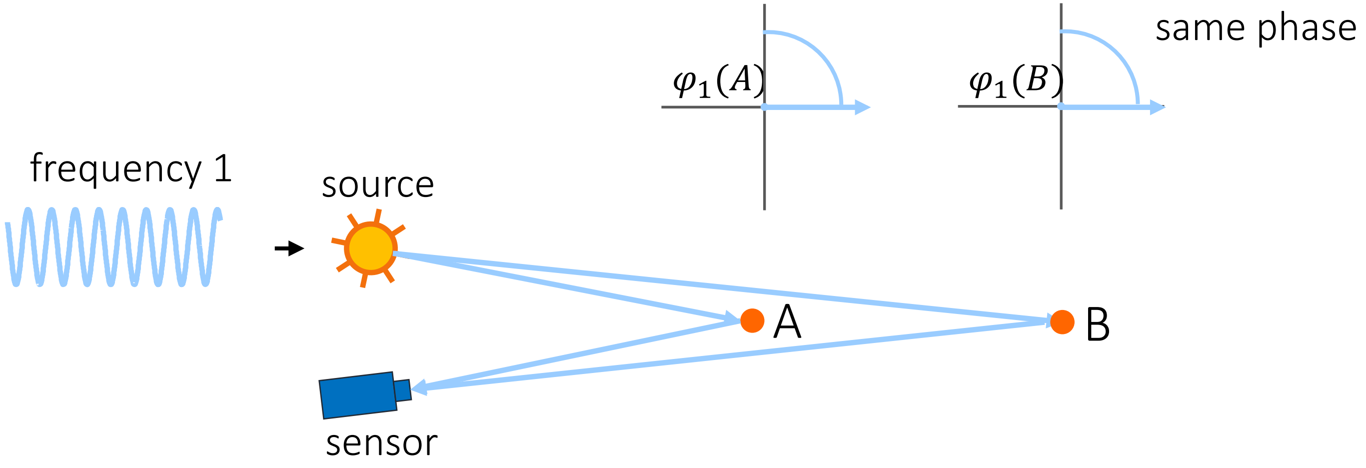
Phase ambiguity

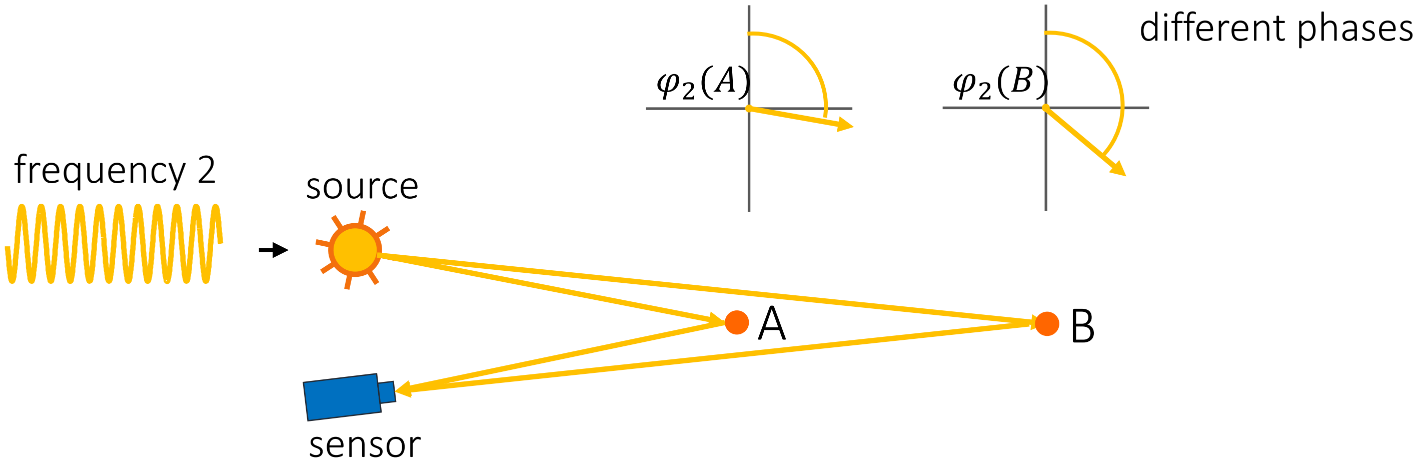


Unambiguous Depth Range: $R_{unambiguous} = \frac{1}{2\omega}$

How can we resolve the phase ambiguity?

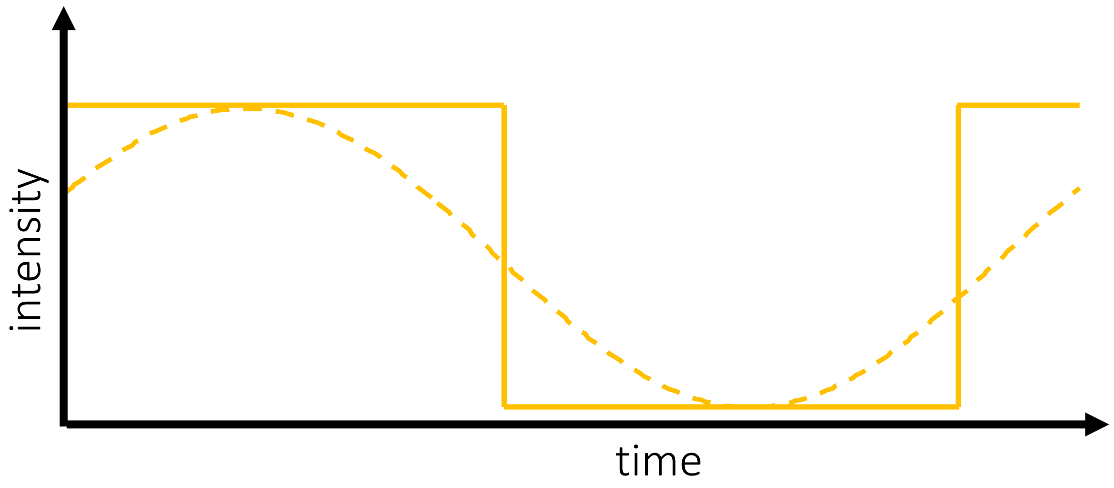
Disambiguating phase

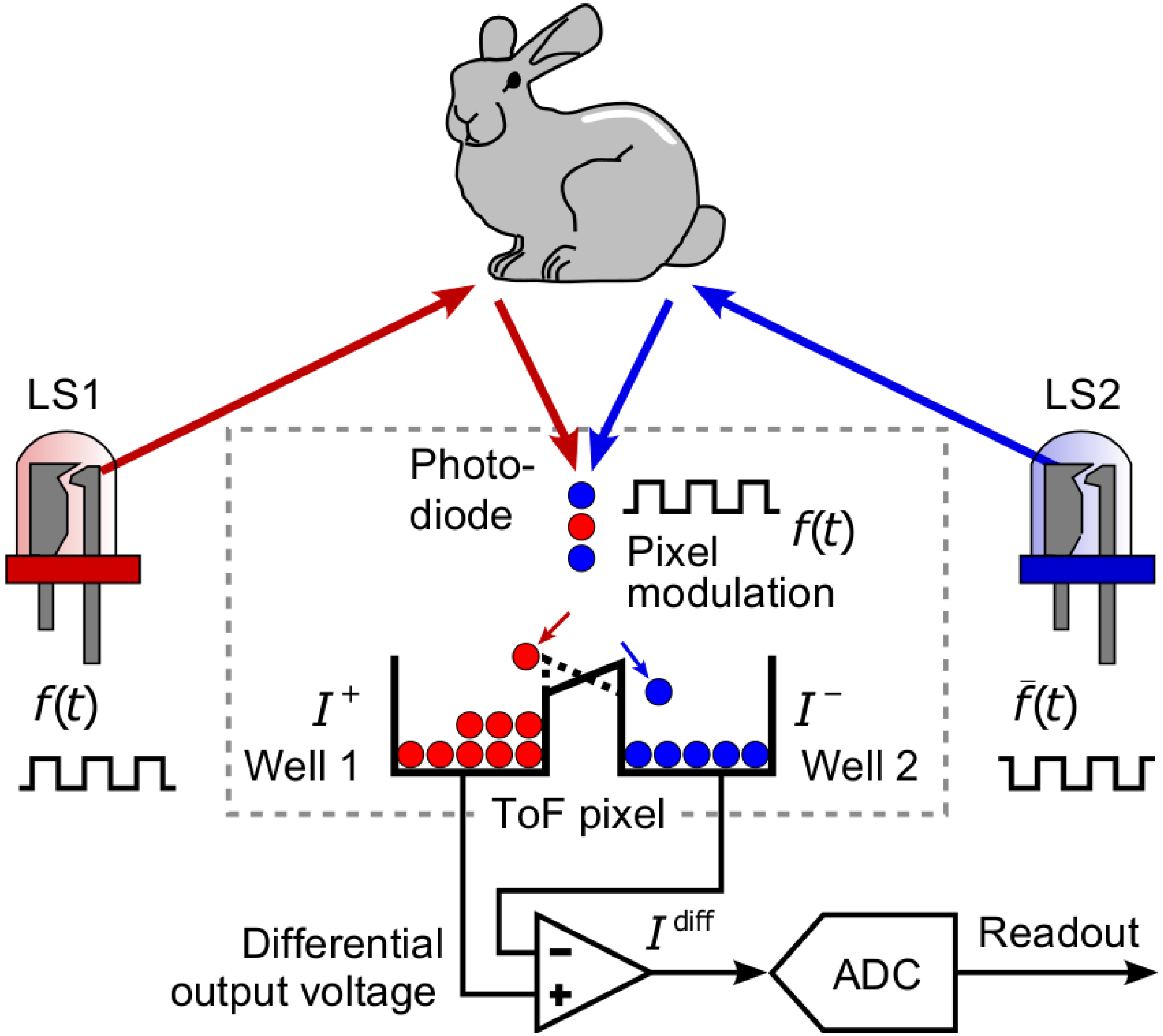




Compute phases at two different frequencies

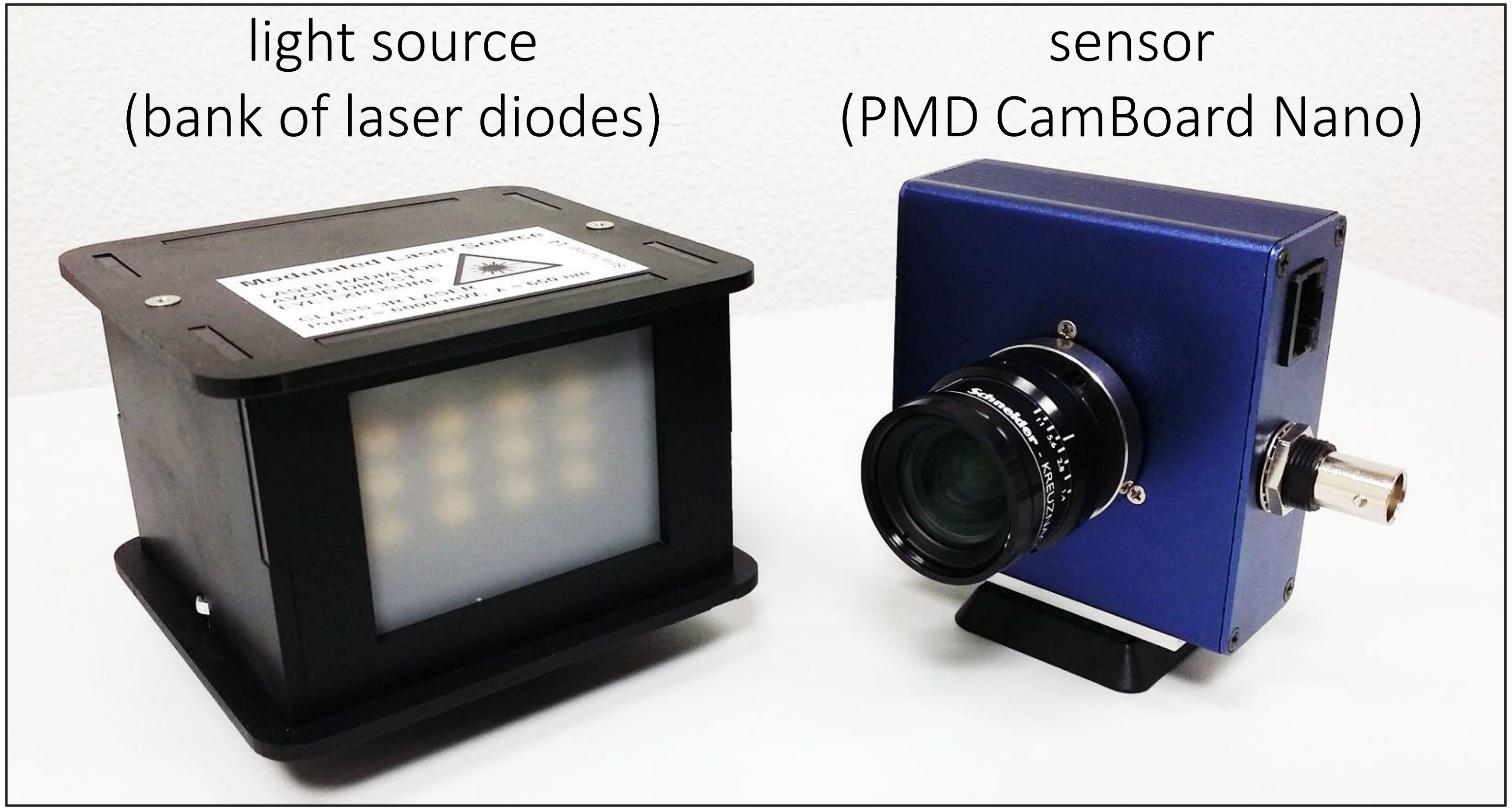
Implementation: two-well architectures



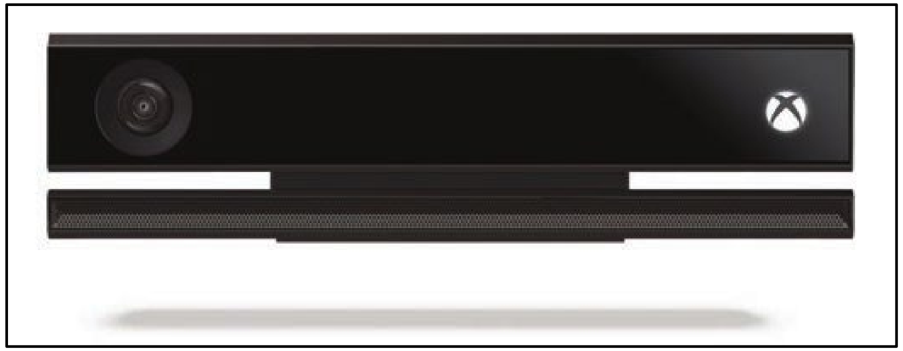


- approximate sinusoid with a square pulse
- store photons in different wells depending on whether they arrive at 1 or 0
- take difference between two wells

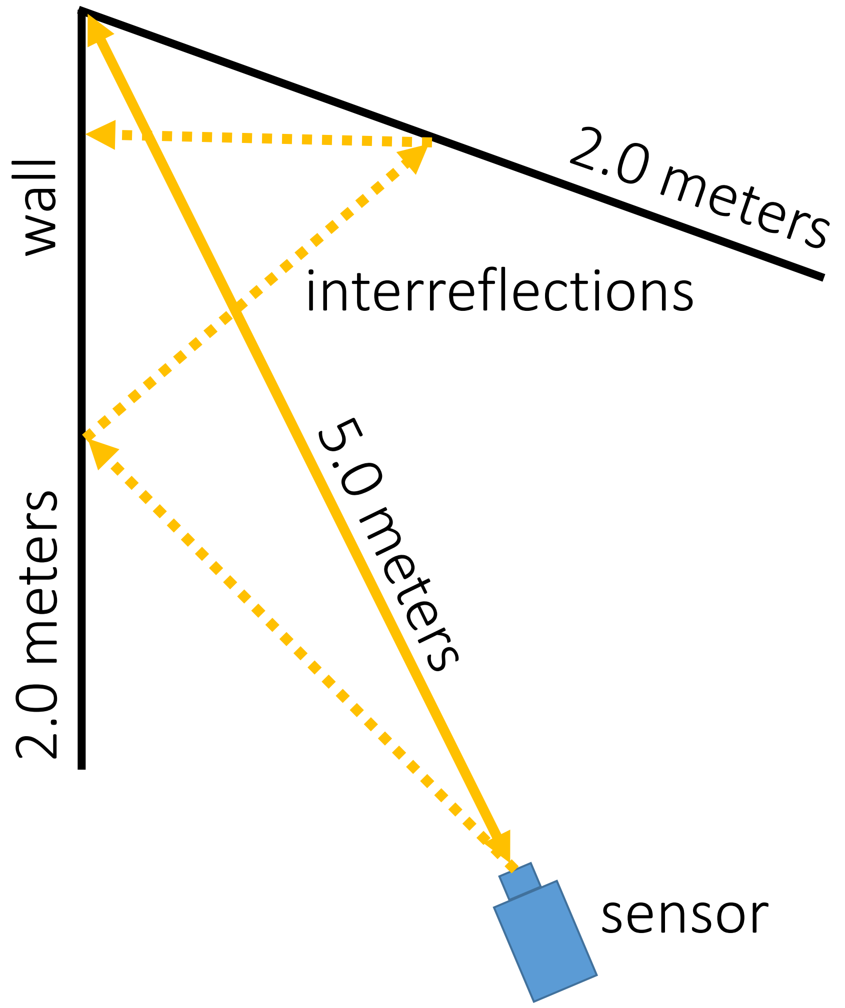
Some examples

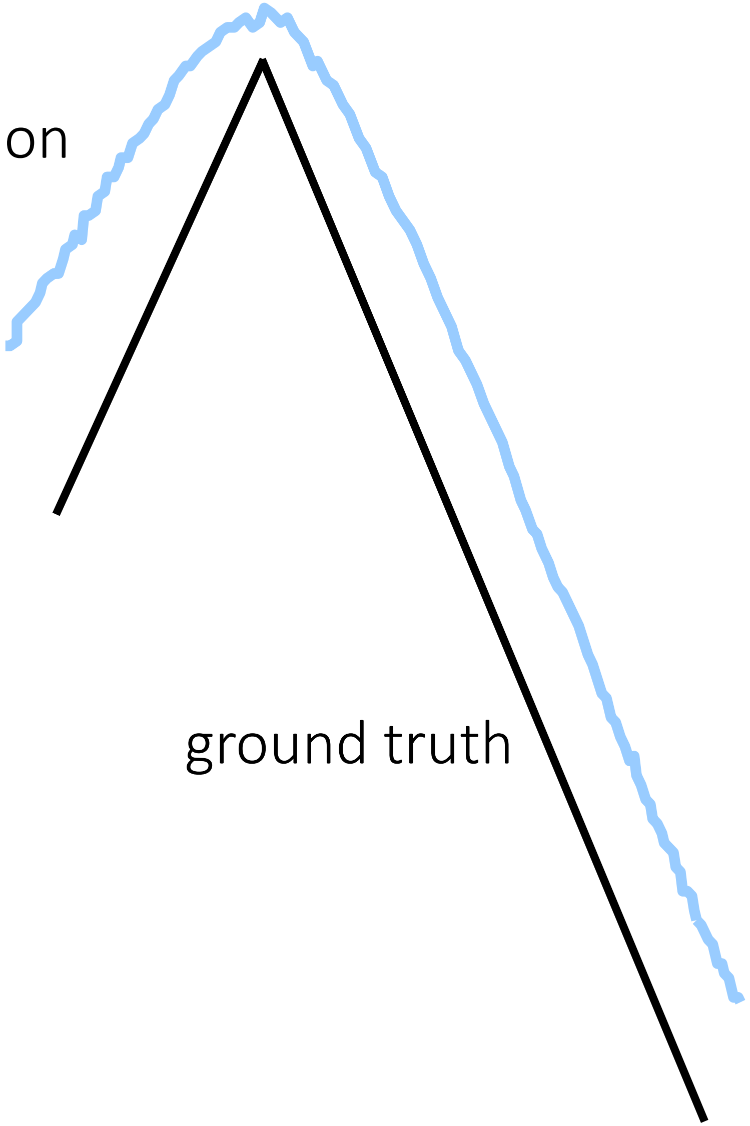


(only second generation of Kinect uses CW ToF)



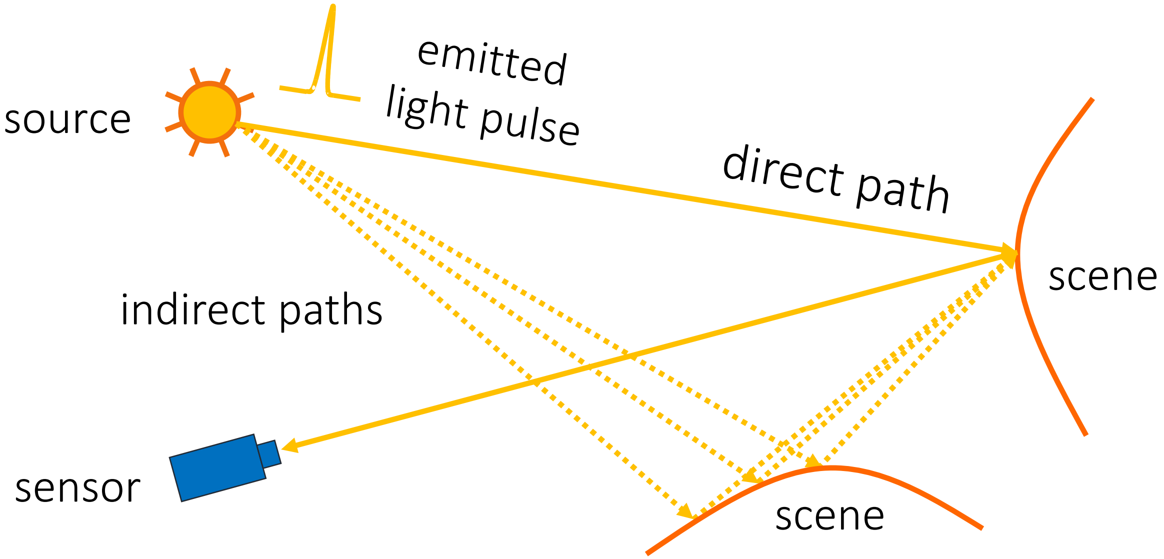
Multi-path interference

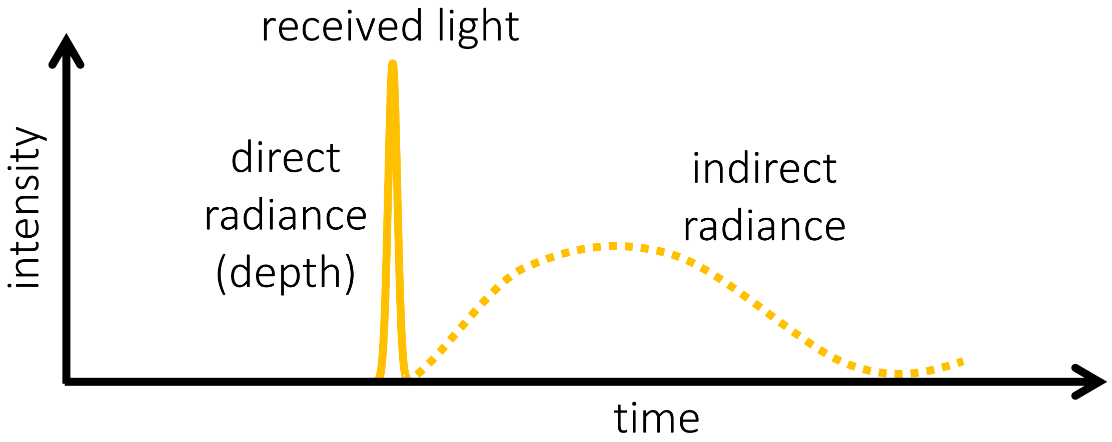




Transient imaging with continuous-wave ToF

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



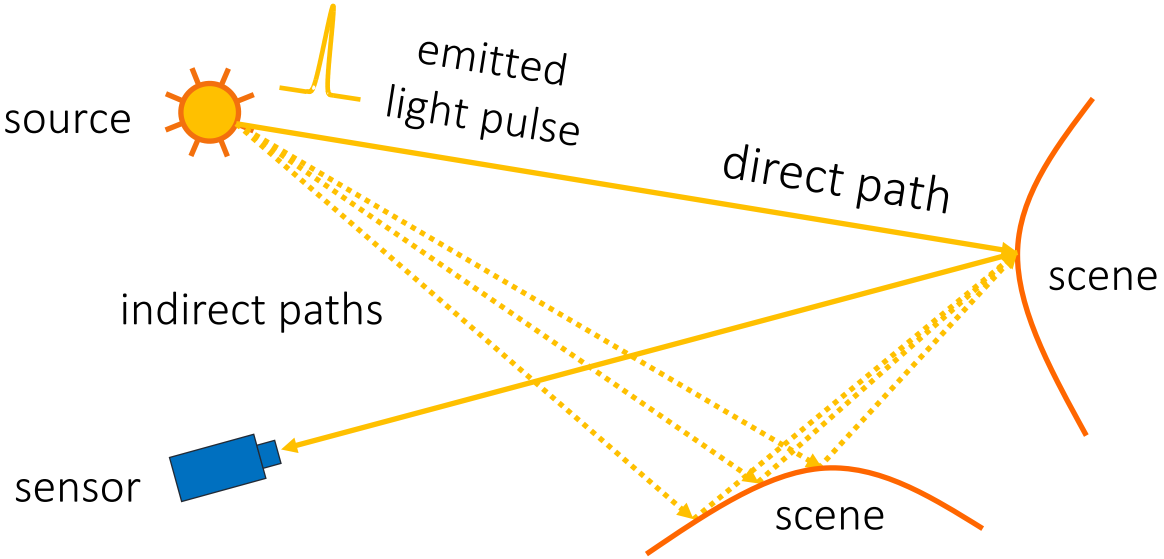


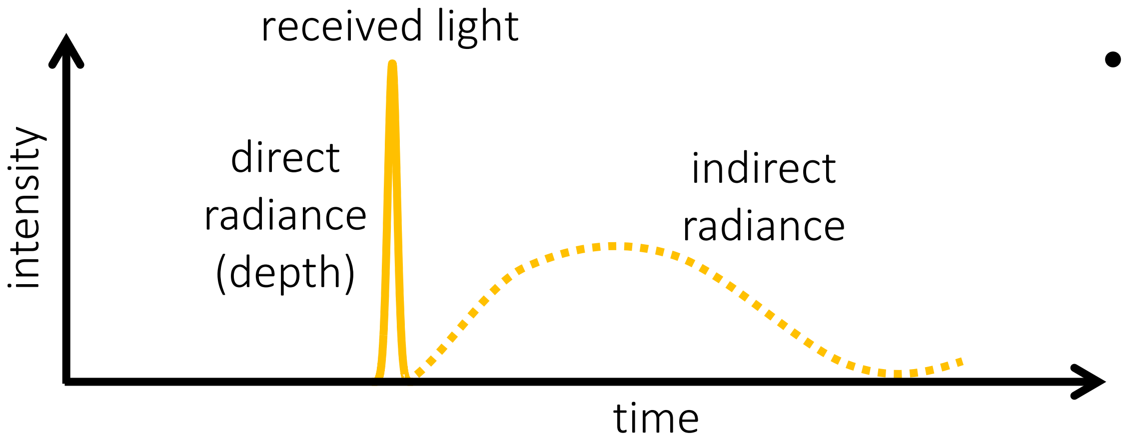
Transient I(t): Time-resolved radiance distribution

- 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?





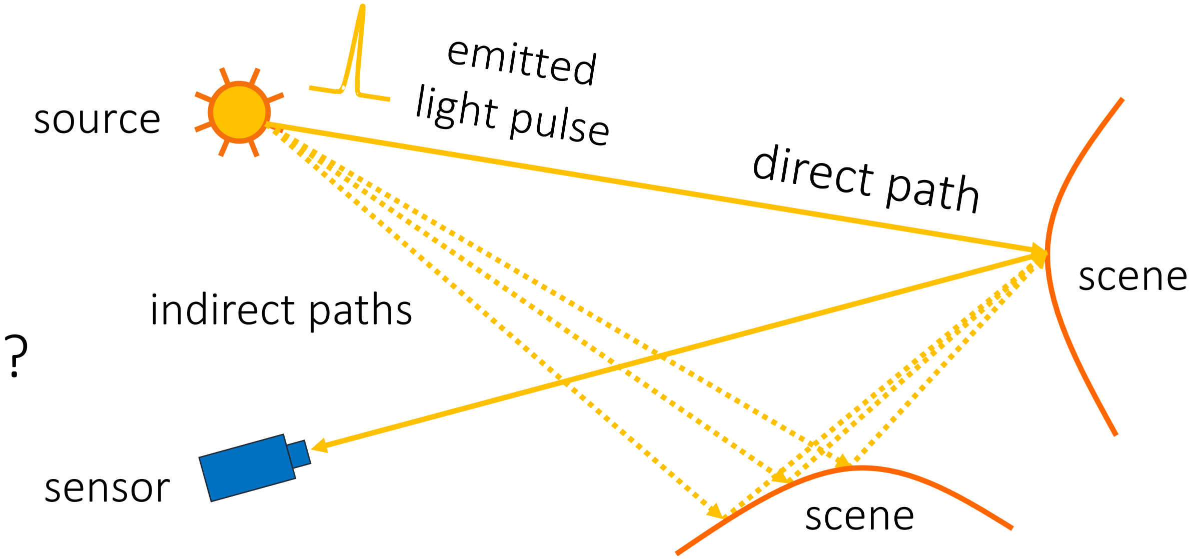
Transient I(t): Time-resolved radiance distribution

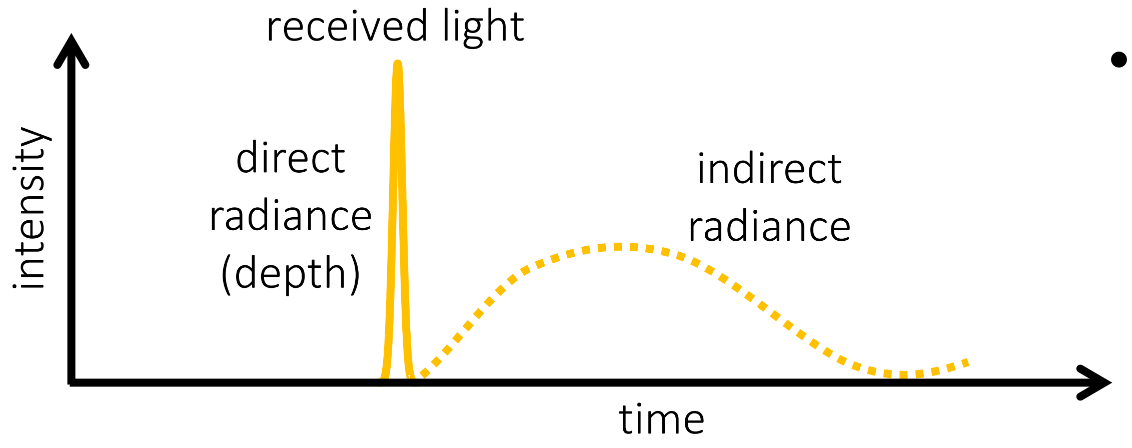
- Each measurement we capture is of the form:

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

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

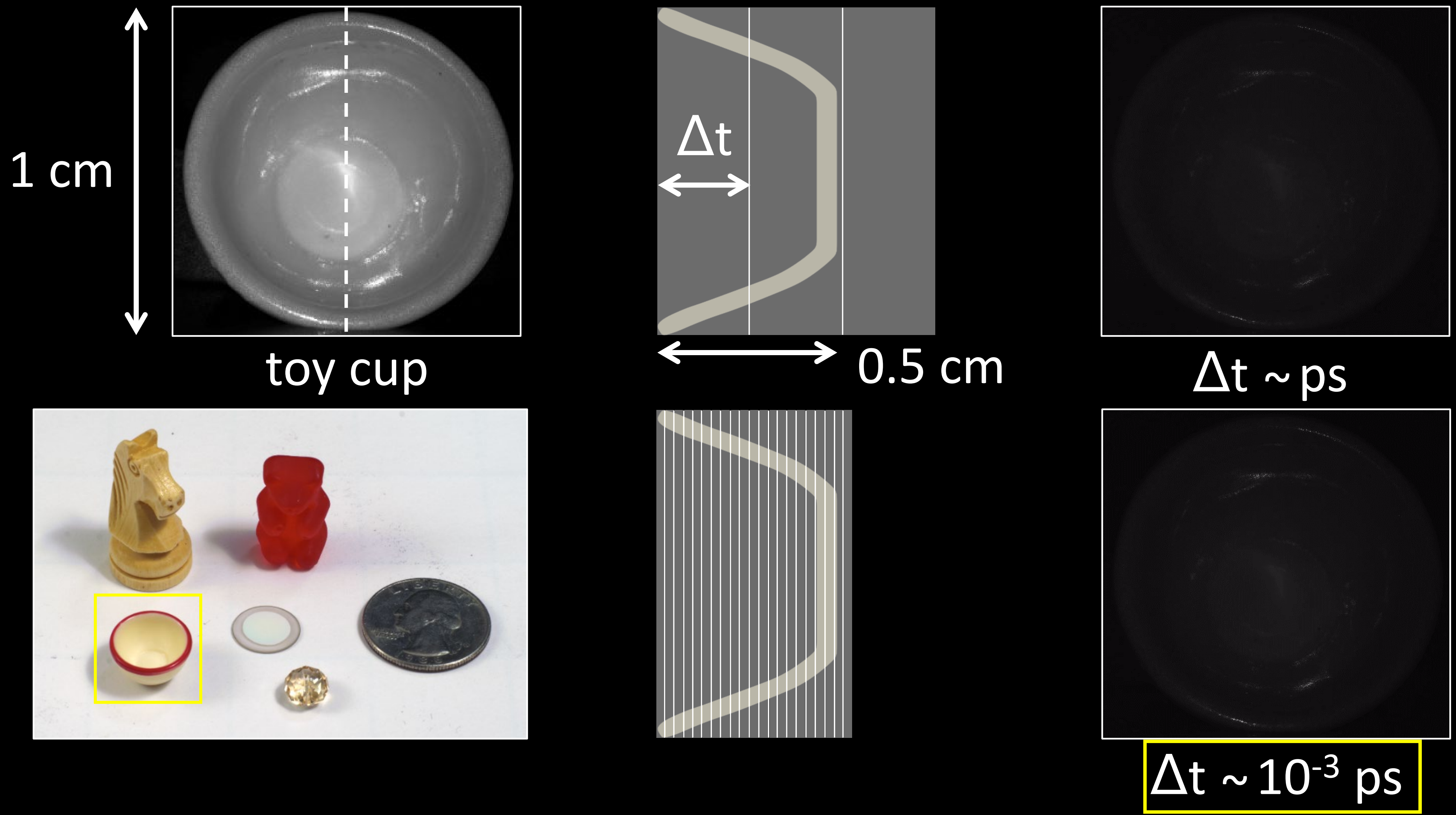
Time-of-flight imaging technologies

	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)

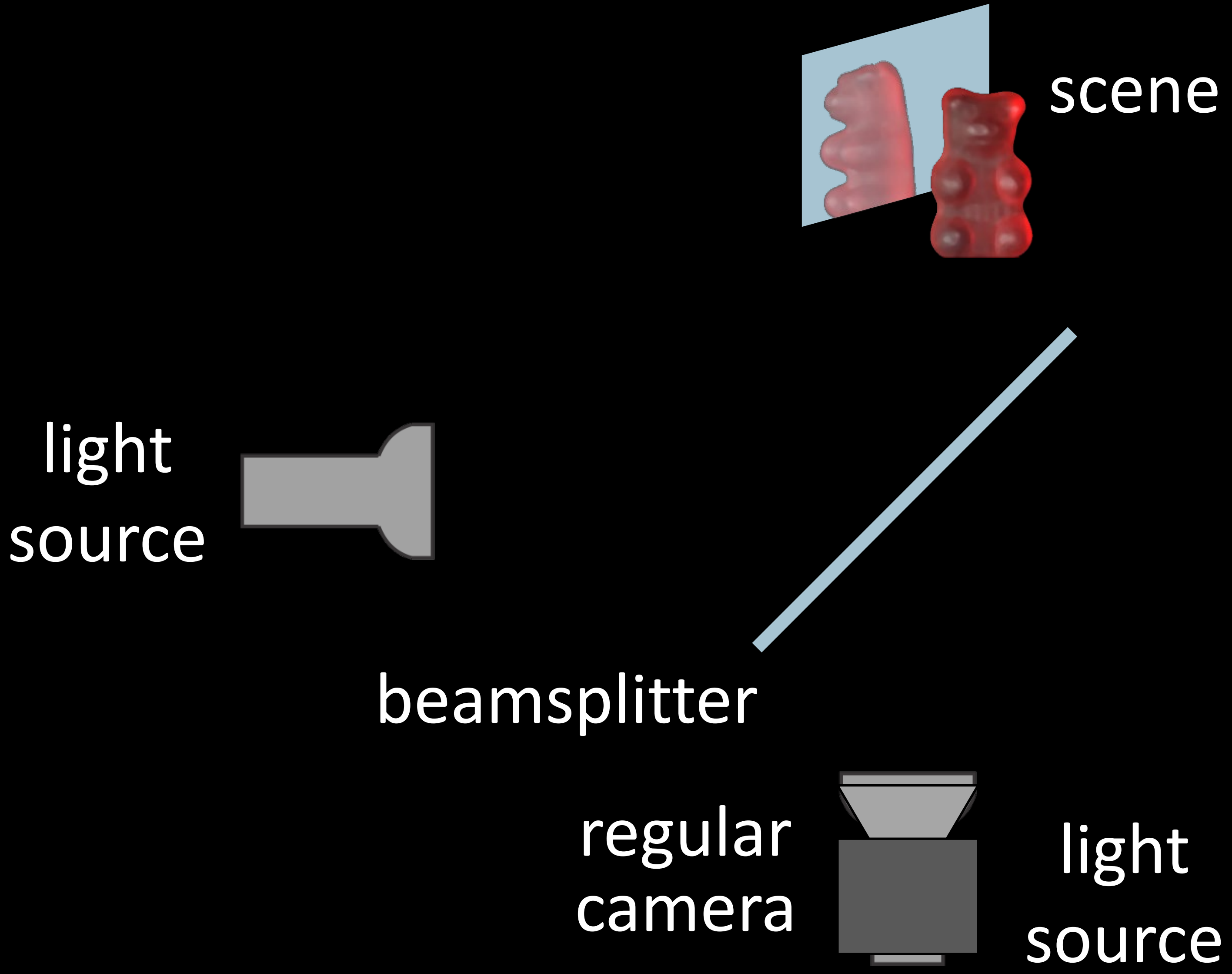
continuous-wave ToF

impulse ToF

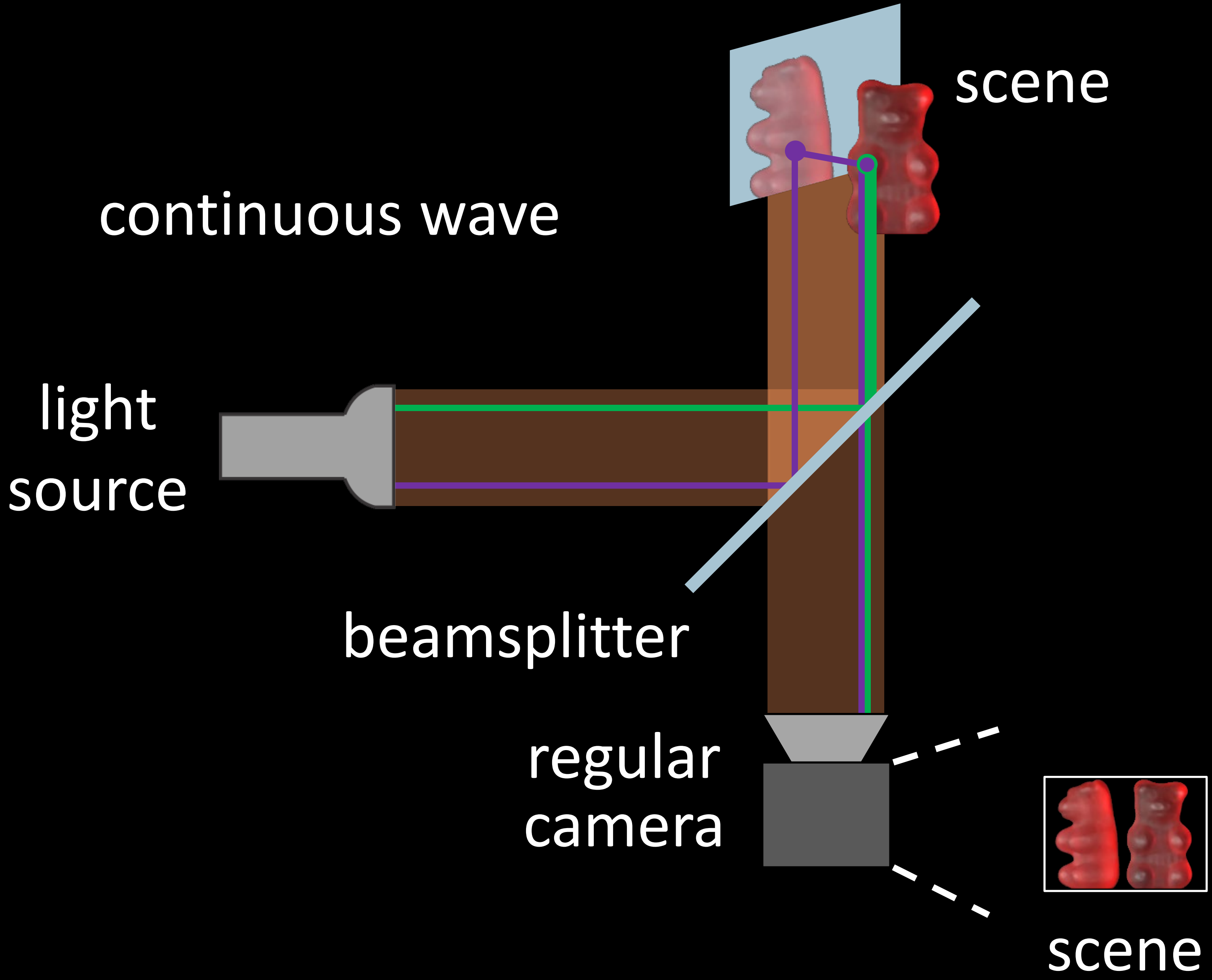
Tiny scenes



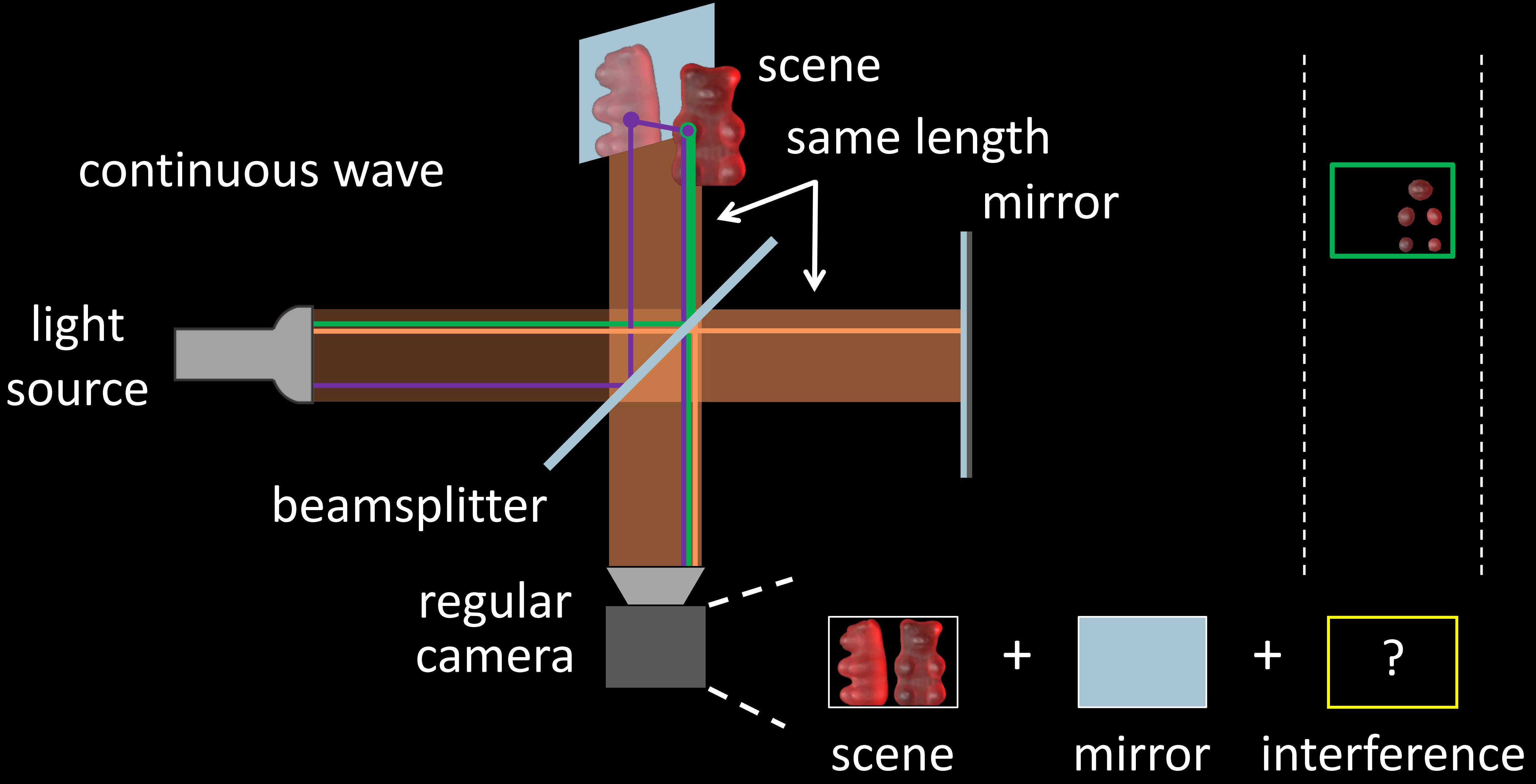
Interferometry example



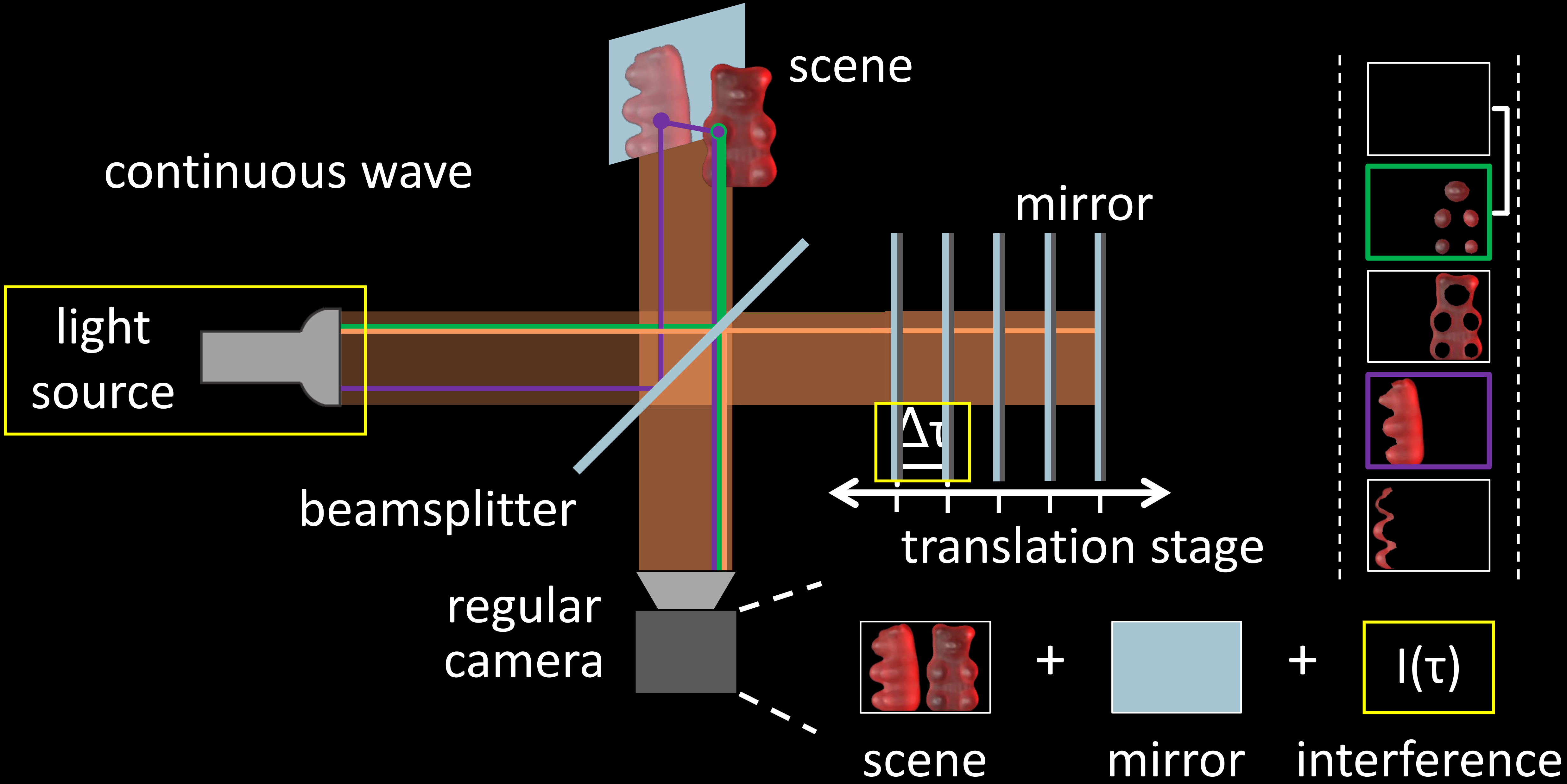
Interferometry example



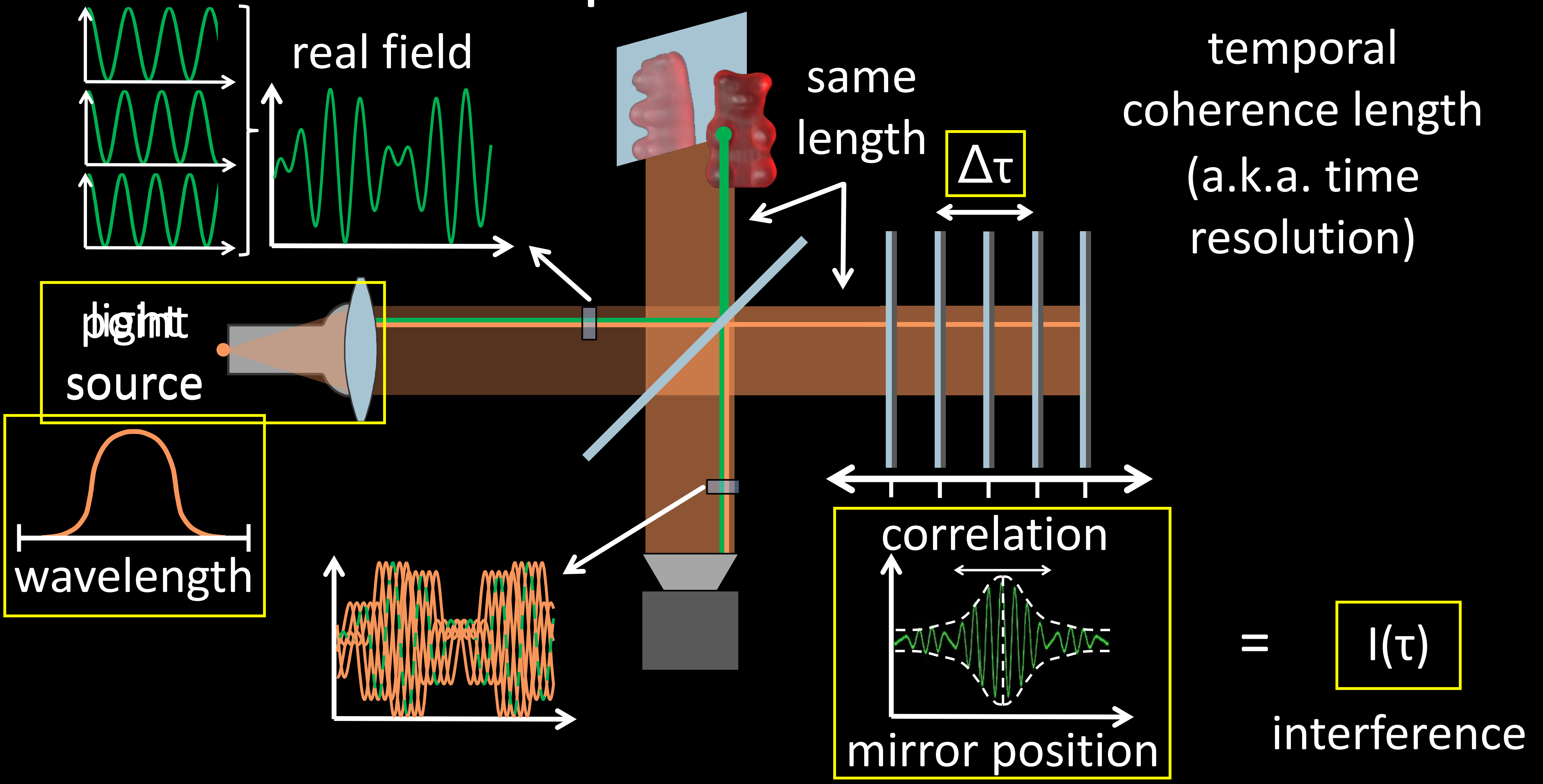
Michelson interferometer



Optical coherence tomography



Temporal coherence



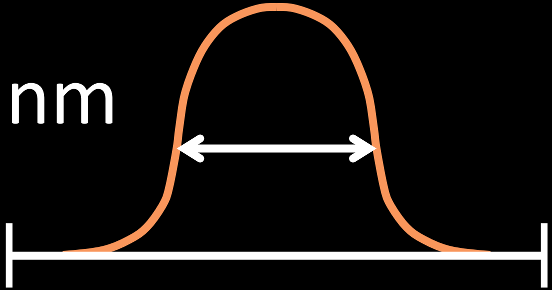
Temporal coherence length

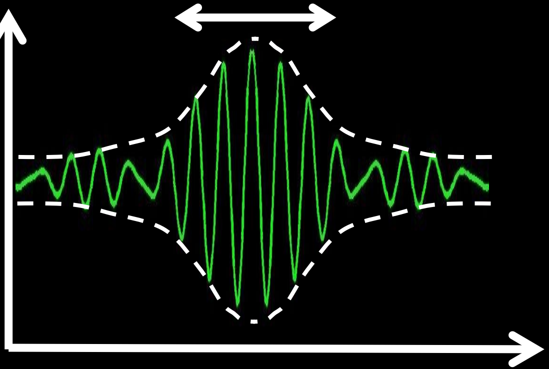
bandwidth

correlation

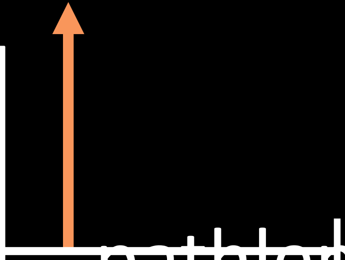
broadband

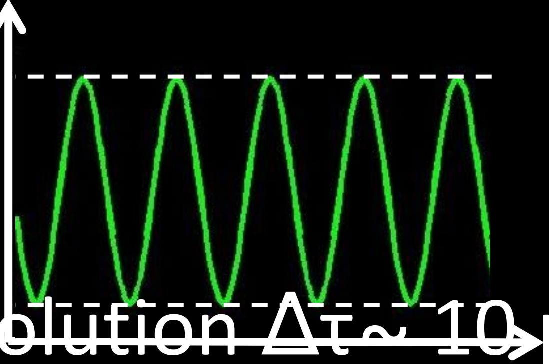
25 nm





monochromatic



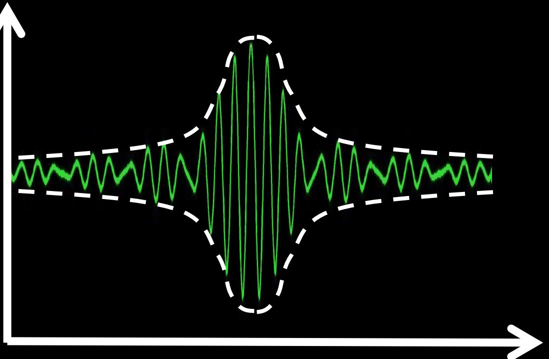


pathlength resolution Δτ ~ 10 µm

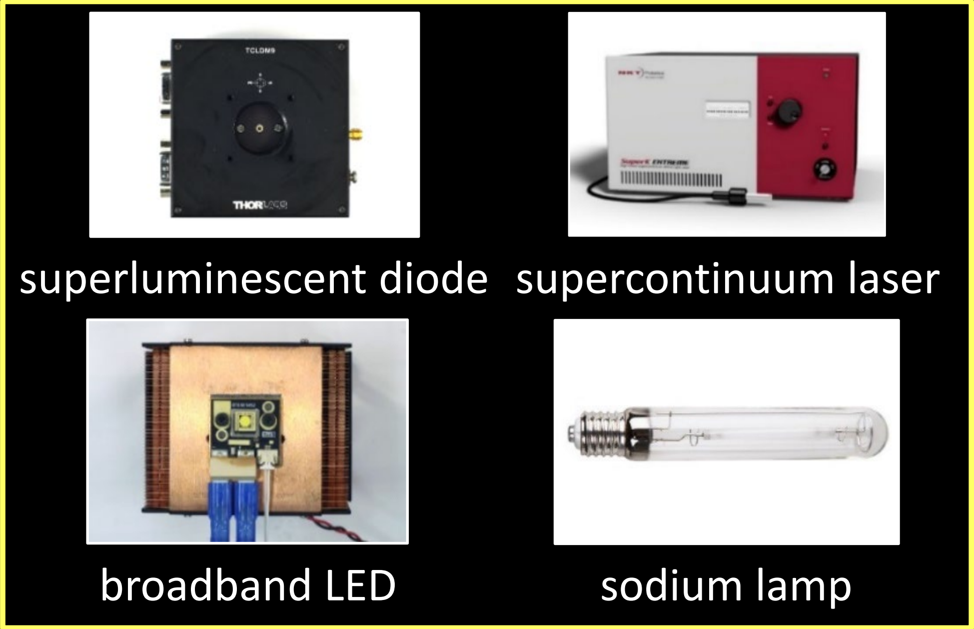
very broadband

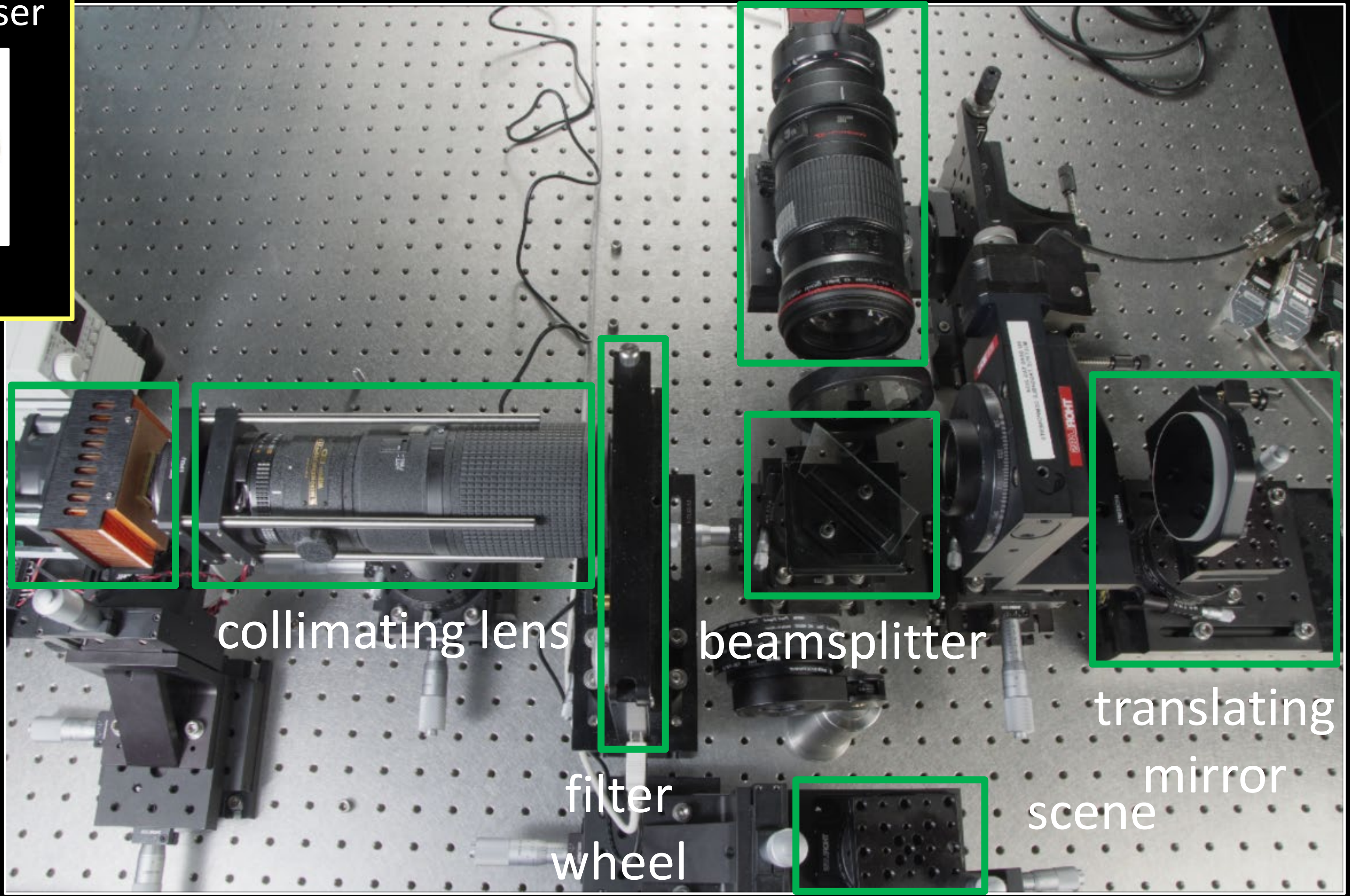
superluminescent diode

supercontinuum laser



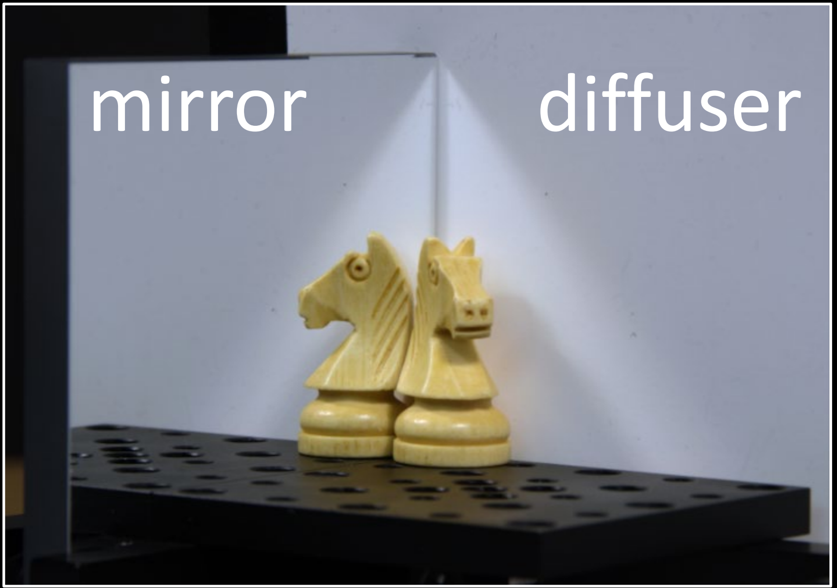
Optical setup

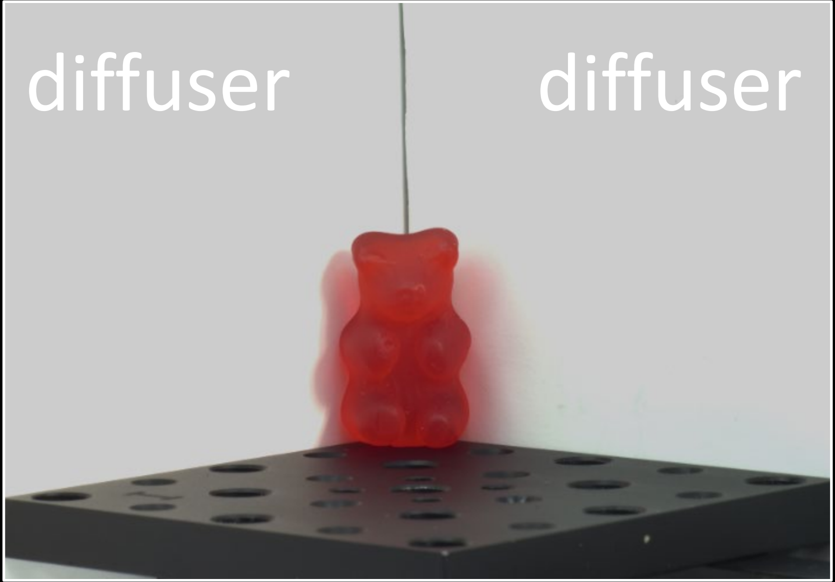




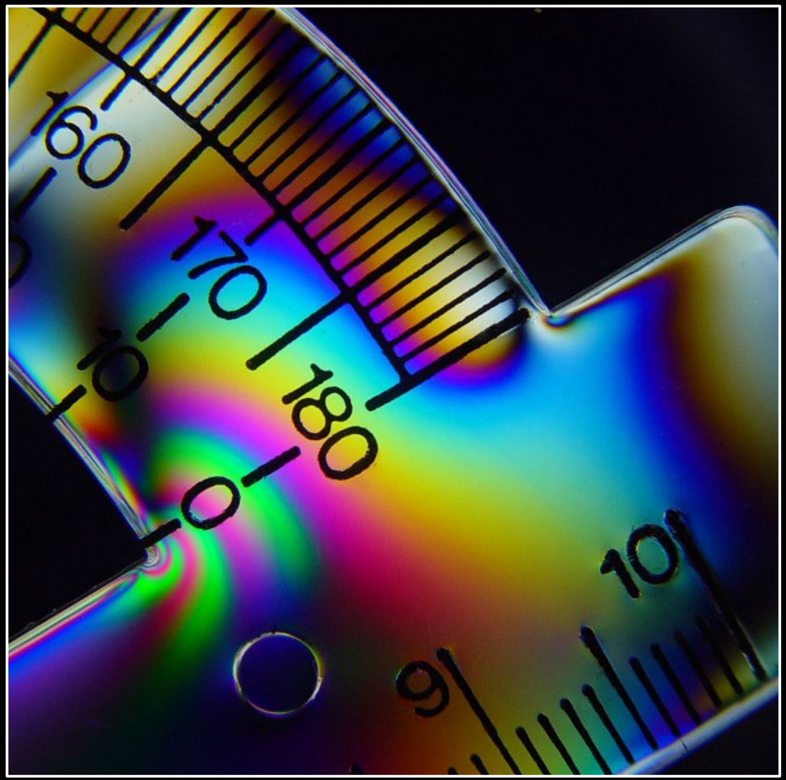
Some transient images

centimeter-sized objects





Material properties

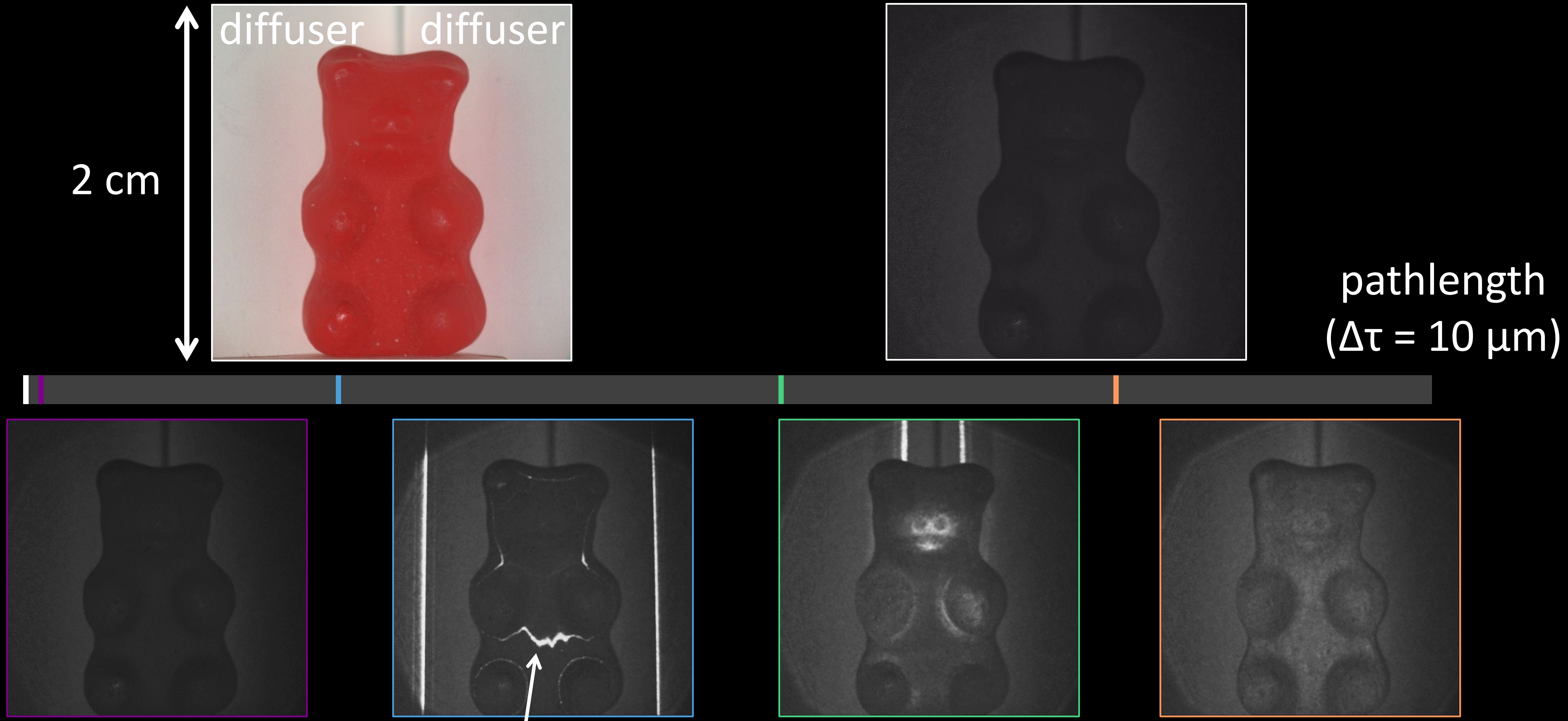


birefringence

dispersion

scattering

Gummy bear and diffuse corner



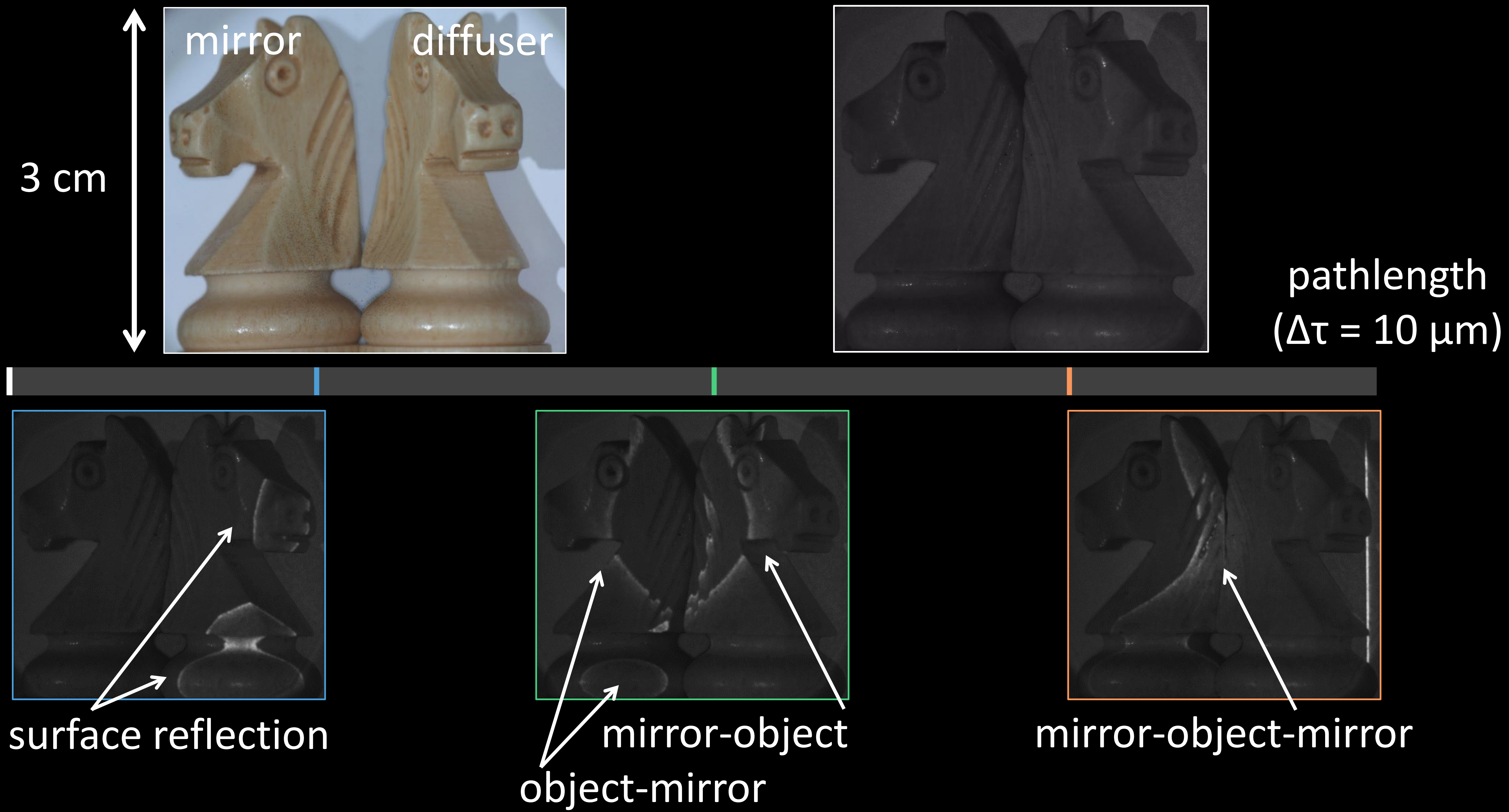
dark frame

surface reflections

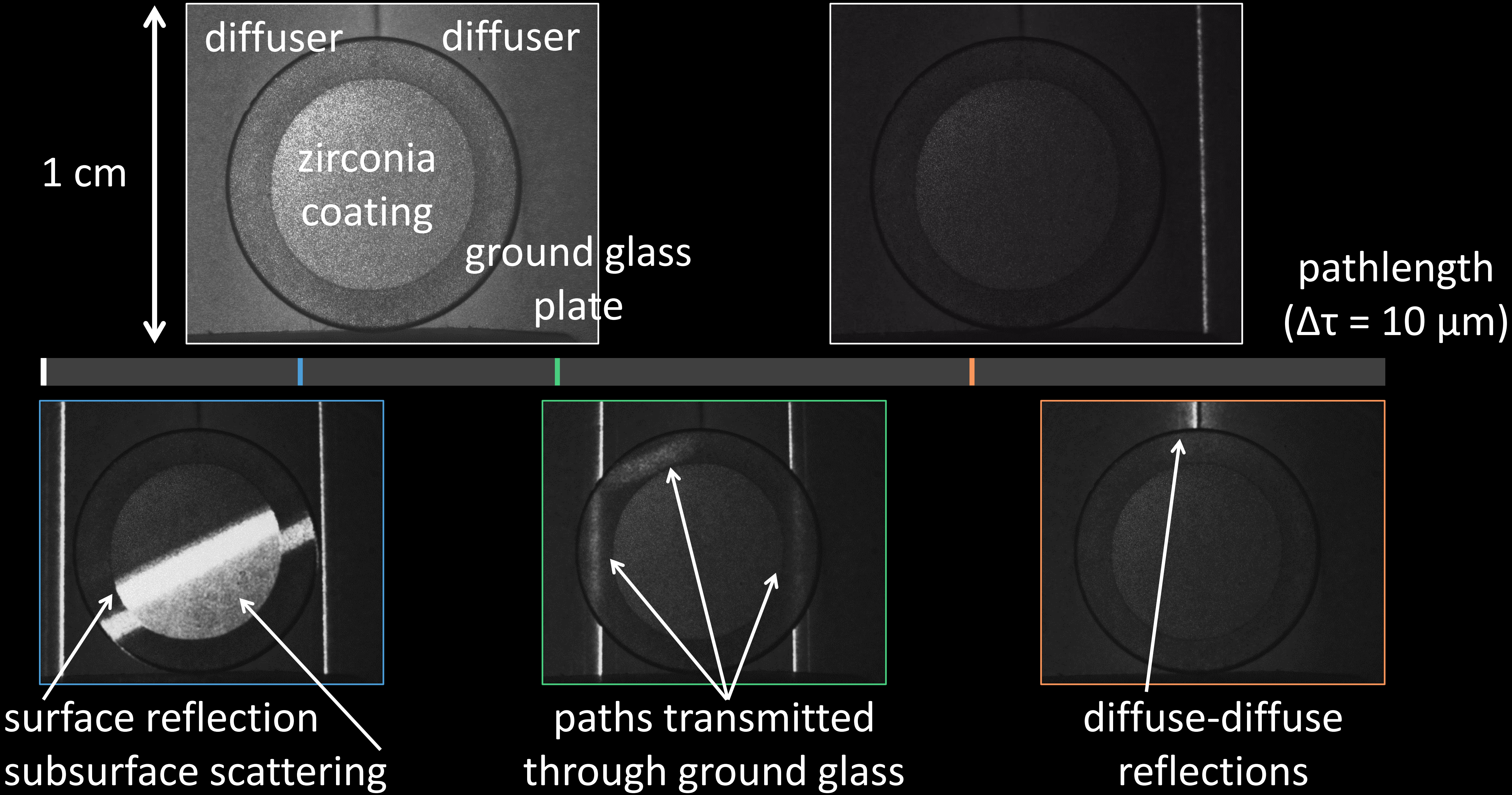
paths through gummy bear

very highly scattered paths

Chess knight and mirror



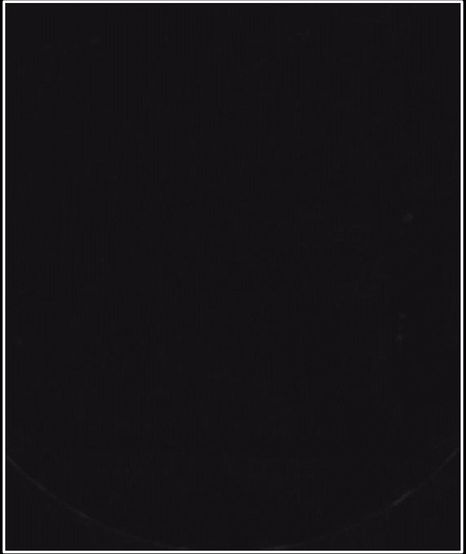
Subsurface scattering



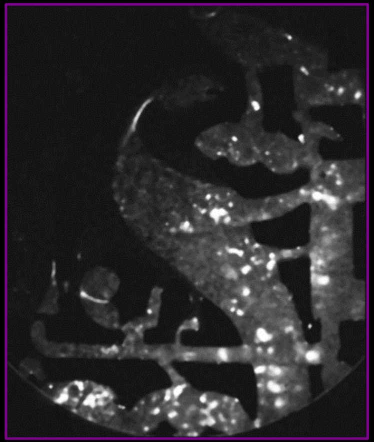
White jade

3 cm

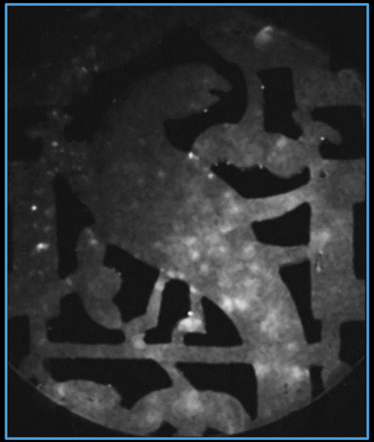
exquisite
white jade



time (10^{-15} seconds)



specular
reflections



low-order
scattering

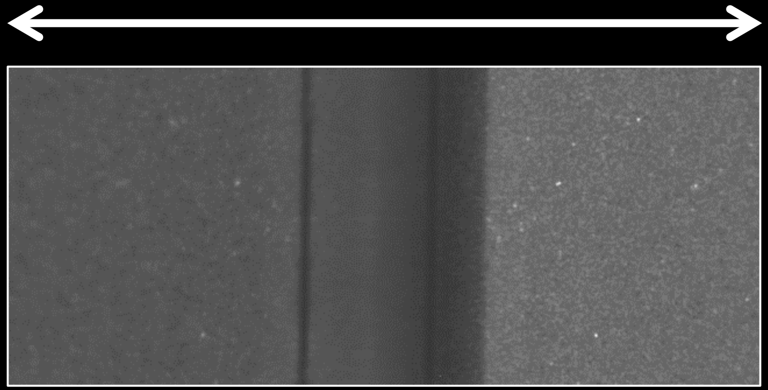
mid-order
scattering

high-order scattering

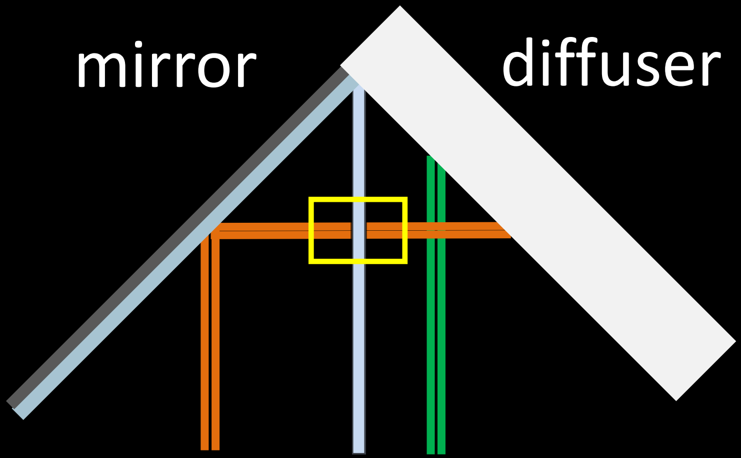
[TOG 2015]

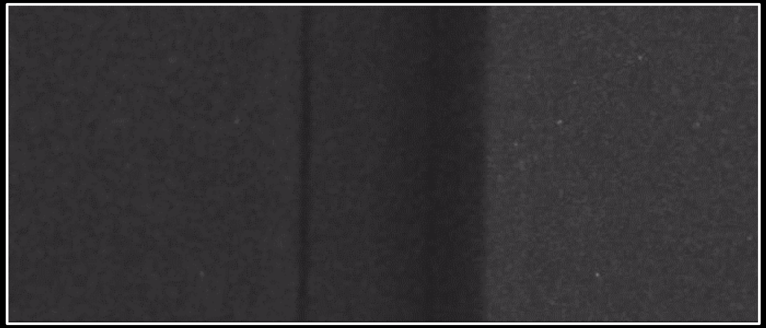
Dispersion

1 cm

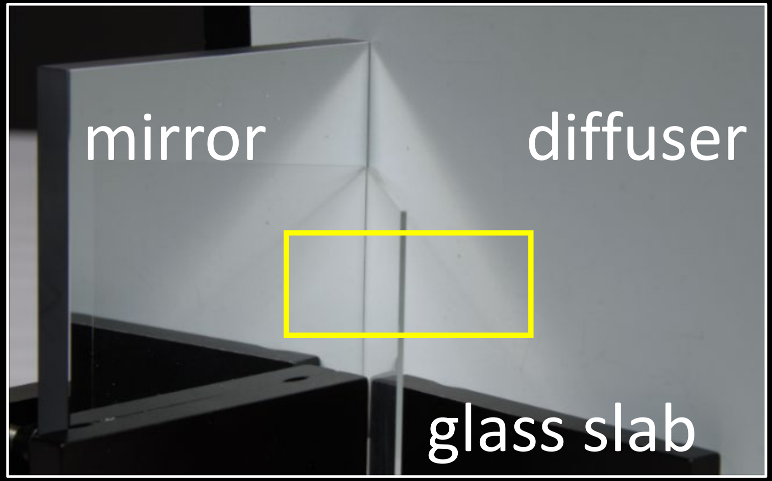


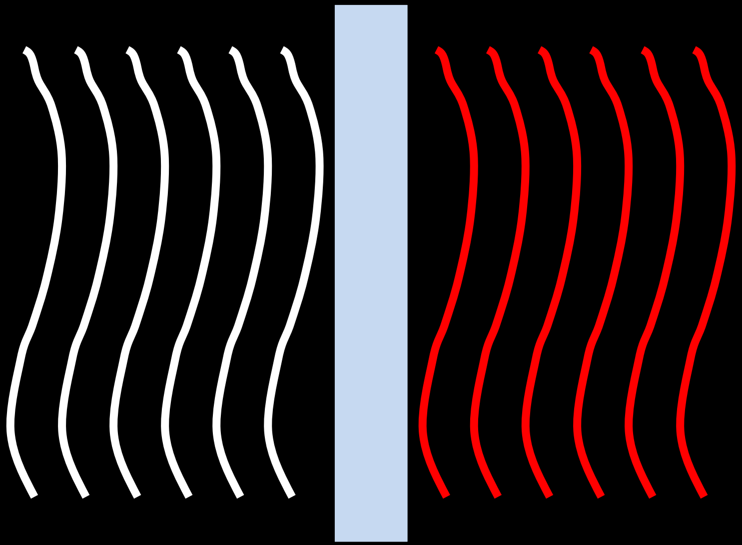
cropped frame



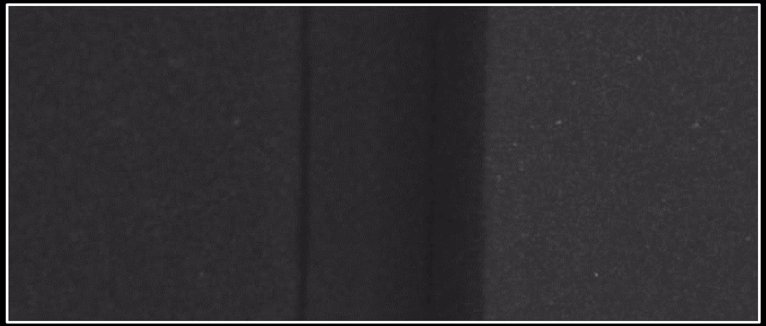


$\Delta t \sim$ ns



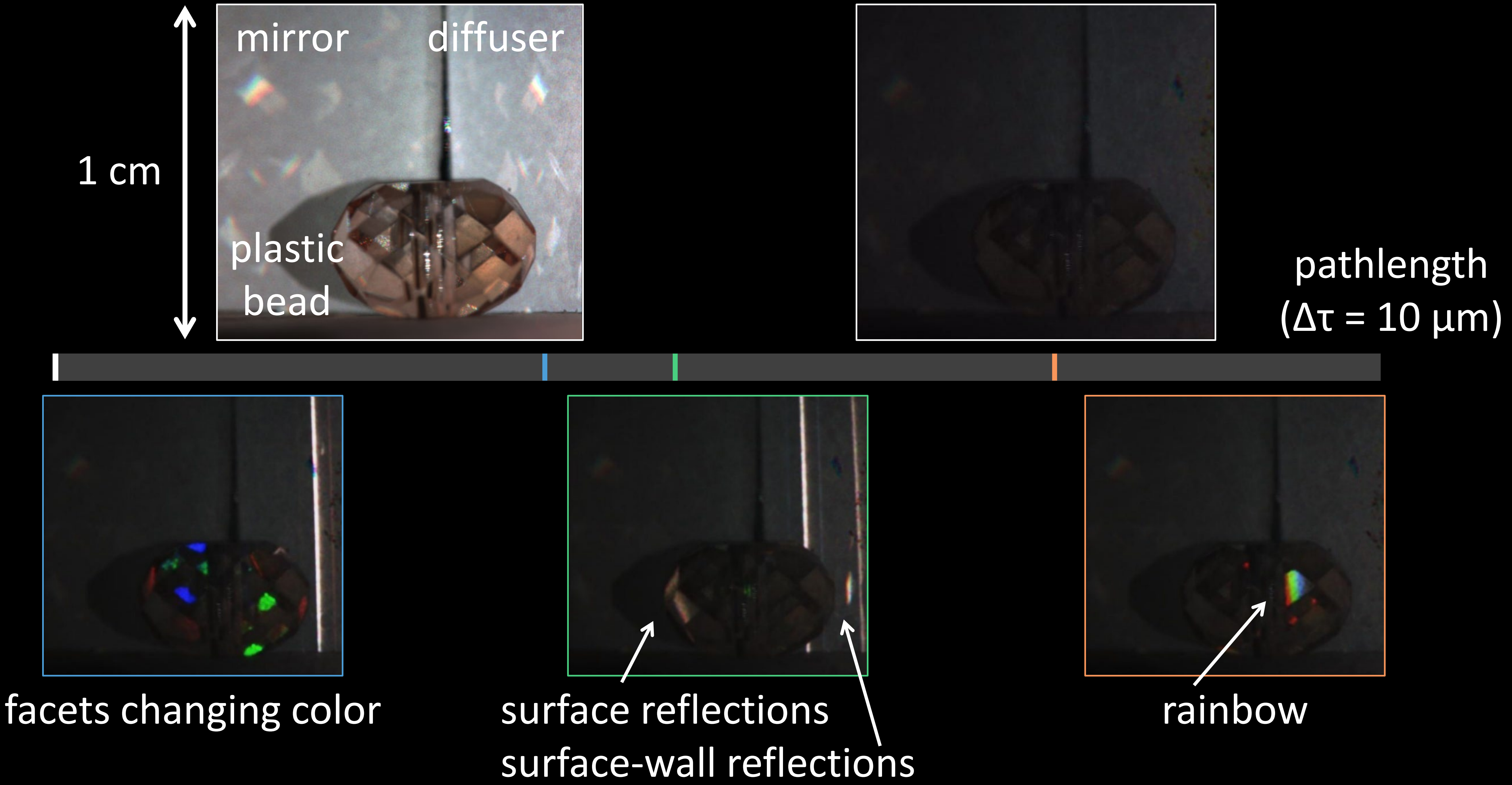


refractive index η(wavelength)



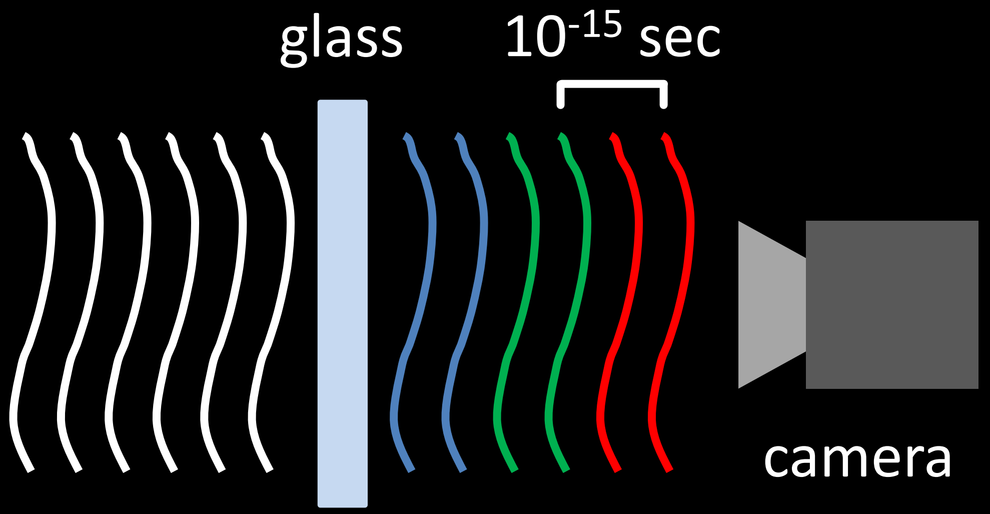
$\boxed{\Delta t \sim 10^{-3}\ \text{ns}}$

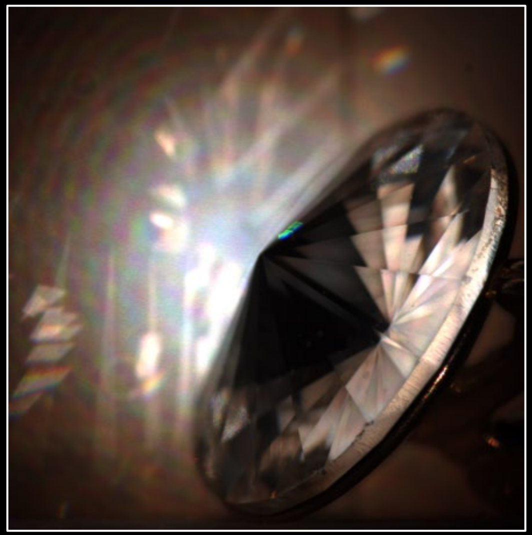
Dispersion



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

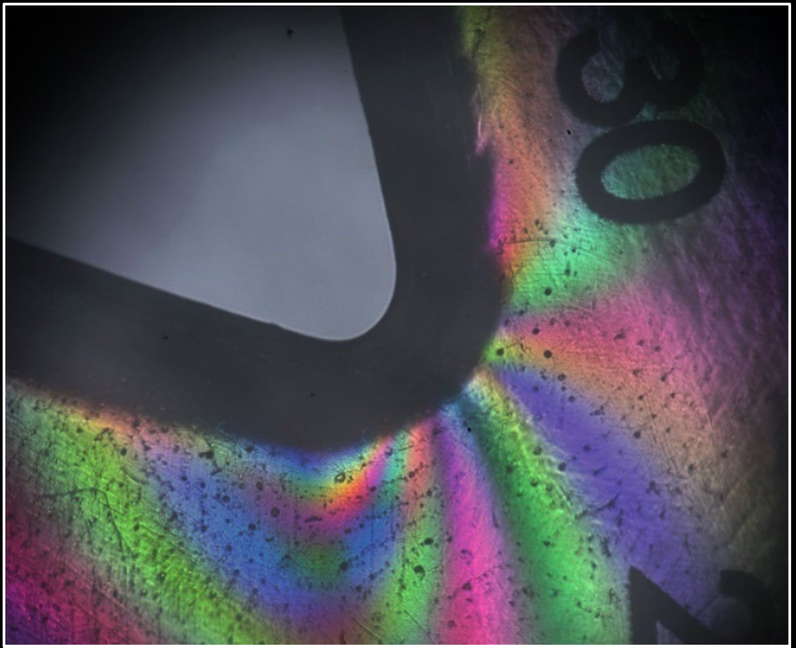
Visualizing dispersion




what a regular camera sees

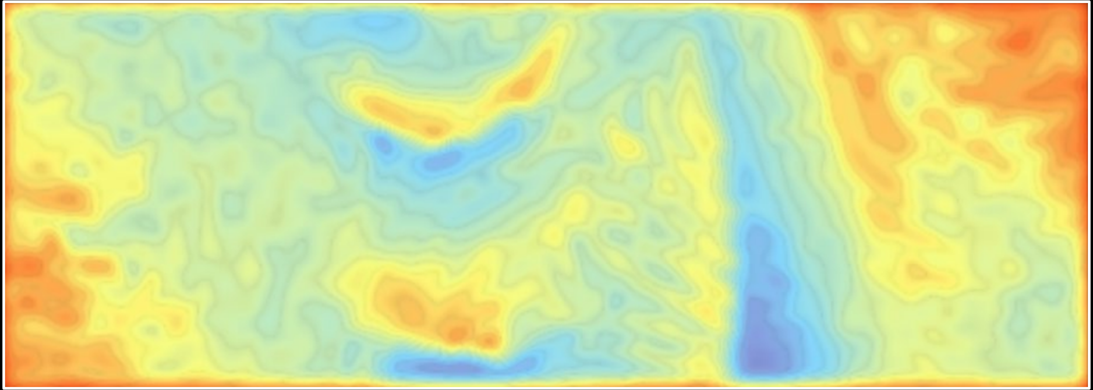

what our camera sees

Visualizing photoelasticity



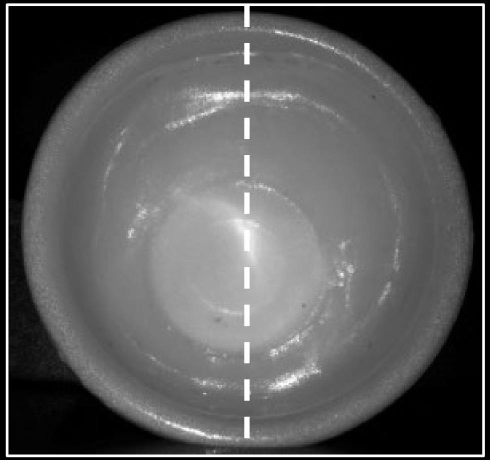
detail under polarized light

low resolution $\Delta\tau = 1$ mm

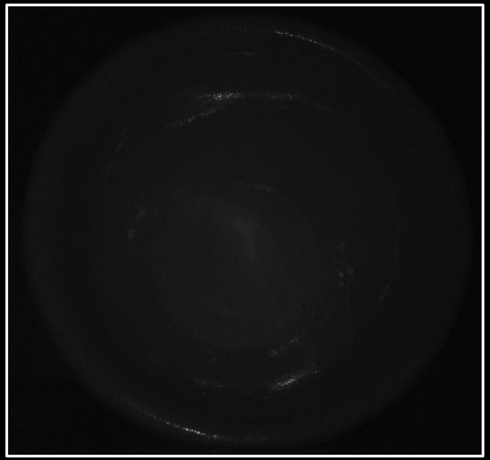


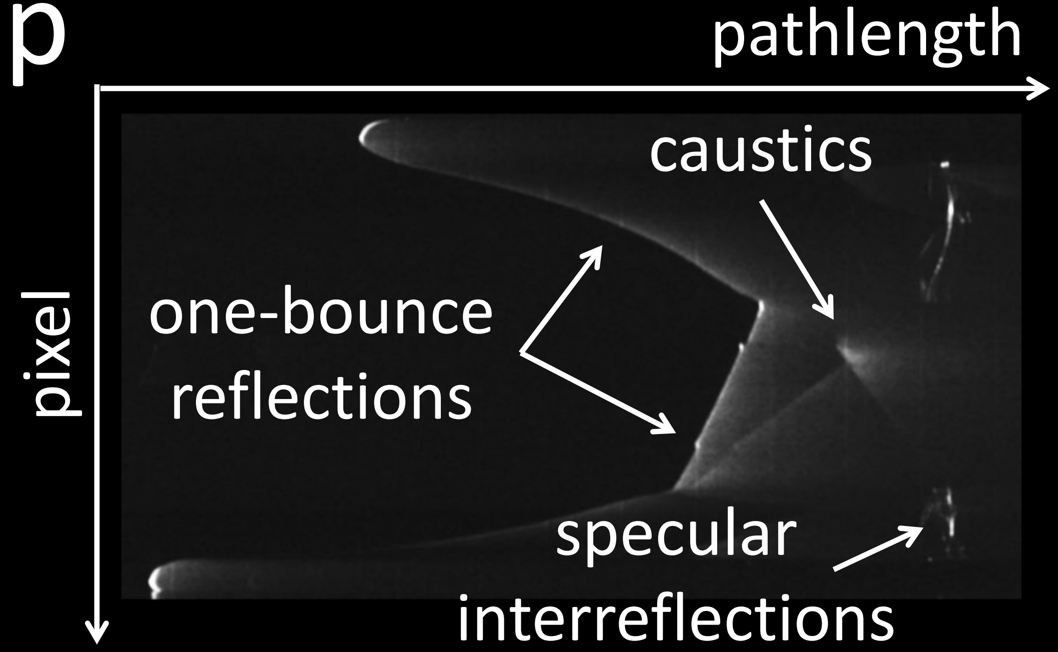
high resolution $\Delta\tau = 10$ µm

Toy cup

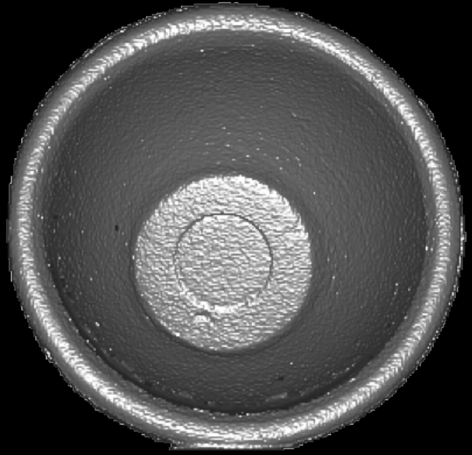


full transient

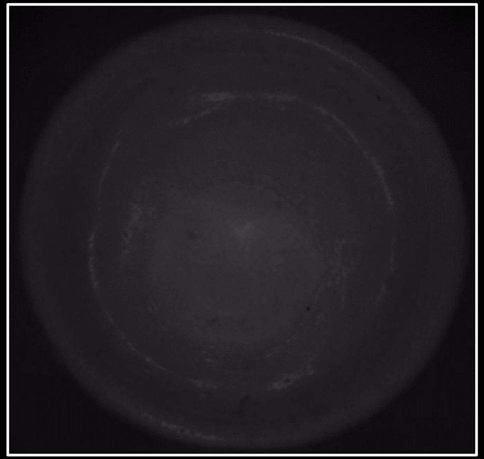


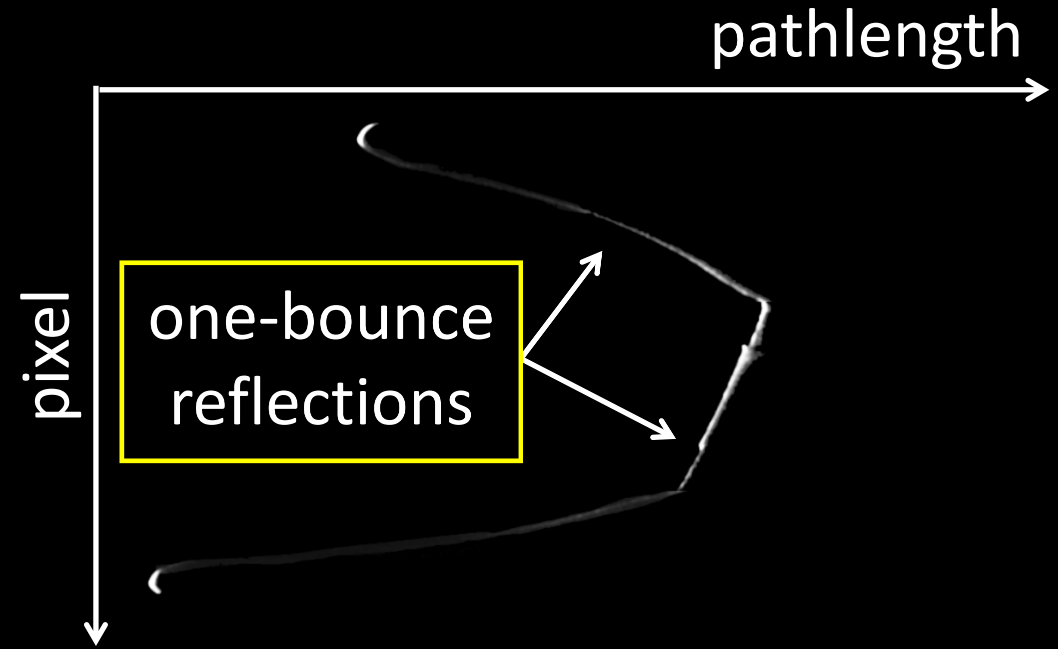


measured depth



direct-only transient





Depth scanning

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

coin

2.5 cm

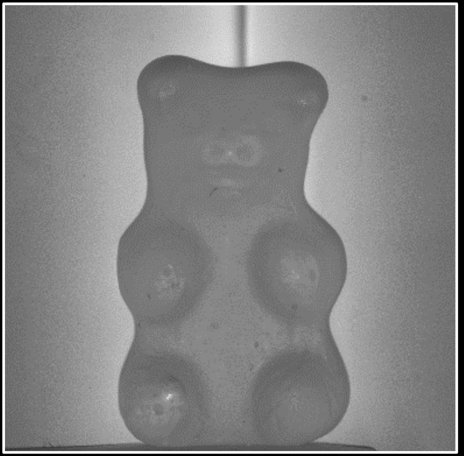
gnocchi

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.