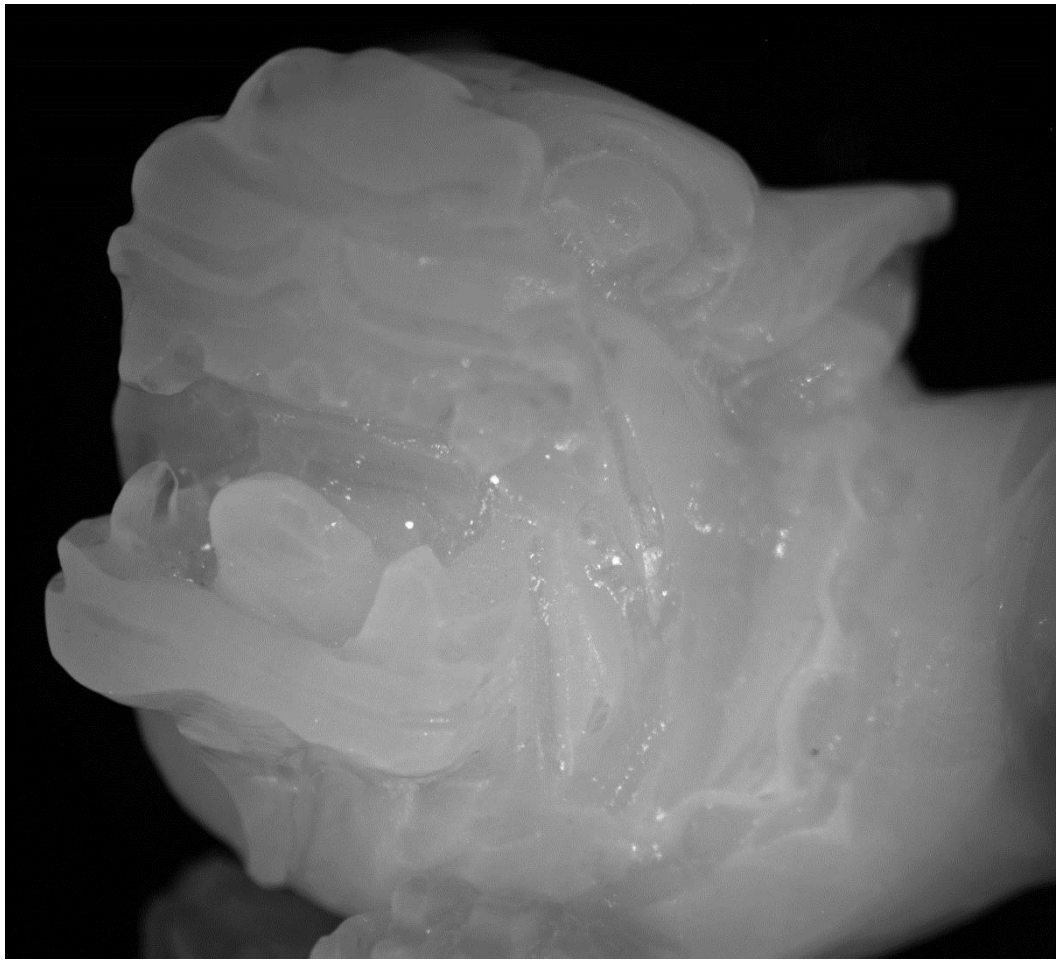
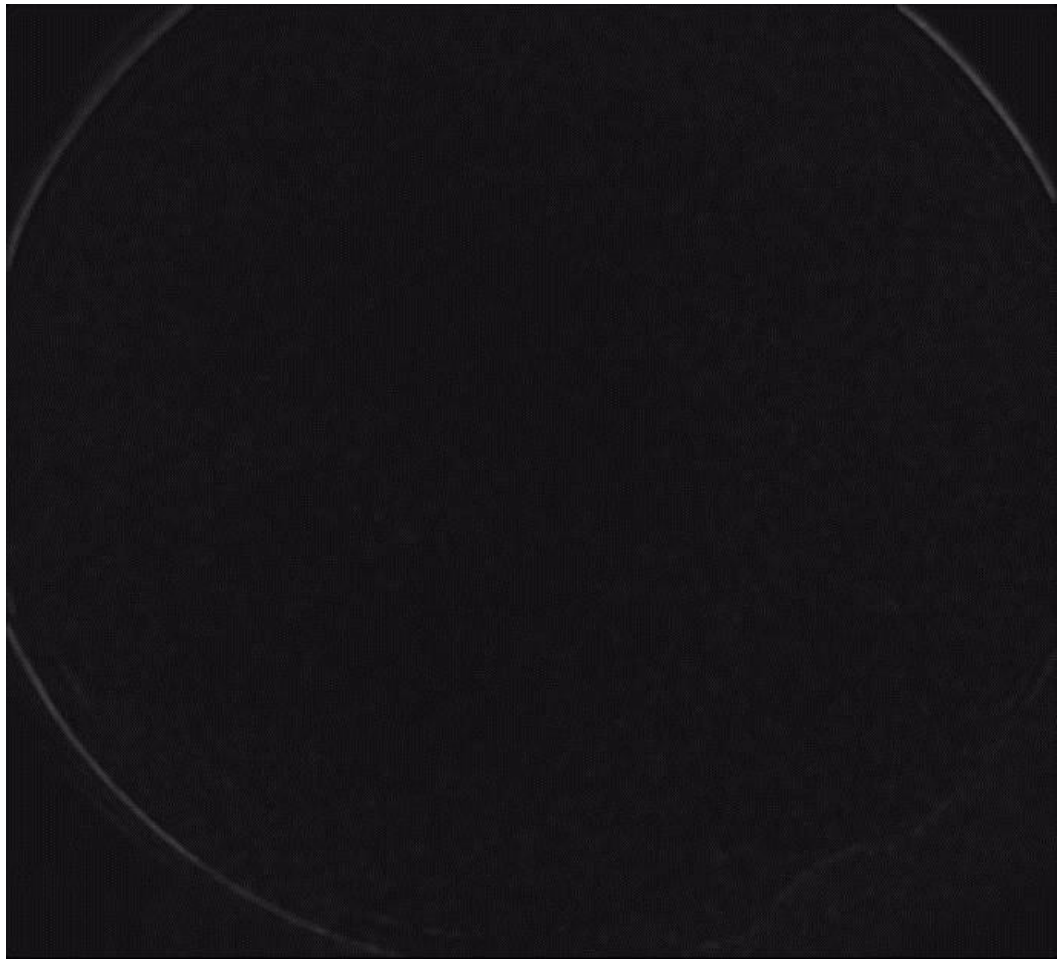
# Time-of-flight imaging





15-463, 15-663, 15-862
Computational Photography
Fall 2018, Lecture 22

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

# Course announcements

- Homework 5 was due yesterday.
  - Any remaining issues?

- Homework 6 posted, due November 30th.
  - Three-week homework.
  - Do not leave for last minute, you won't have time to complete it.
  - Homework 7 will be appropriately shorter so that it can be done in the last week.

- Doodle for scheduling final project presentations was posted on Piazza.
  - https://doodle.com/poll/zf4ur49692m772eg
  - Please make sure to vote!

- Project checkpoint meetings next week.
  - I will post a spreadsheet so that you can sign up for a meeting slot.

# 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.

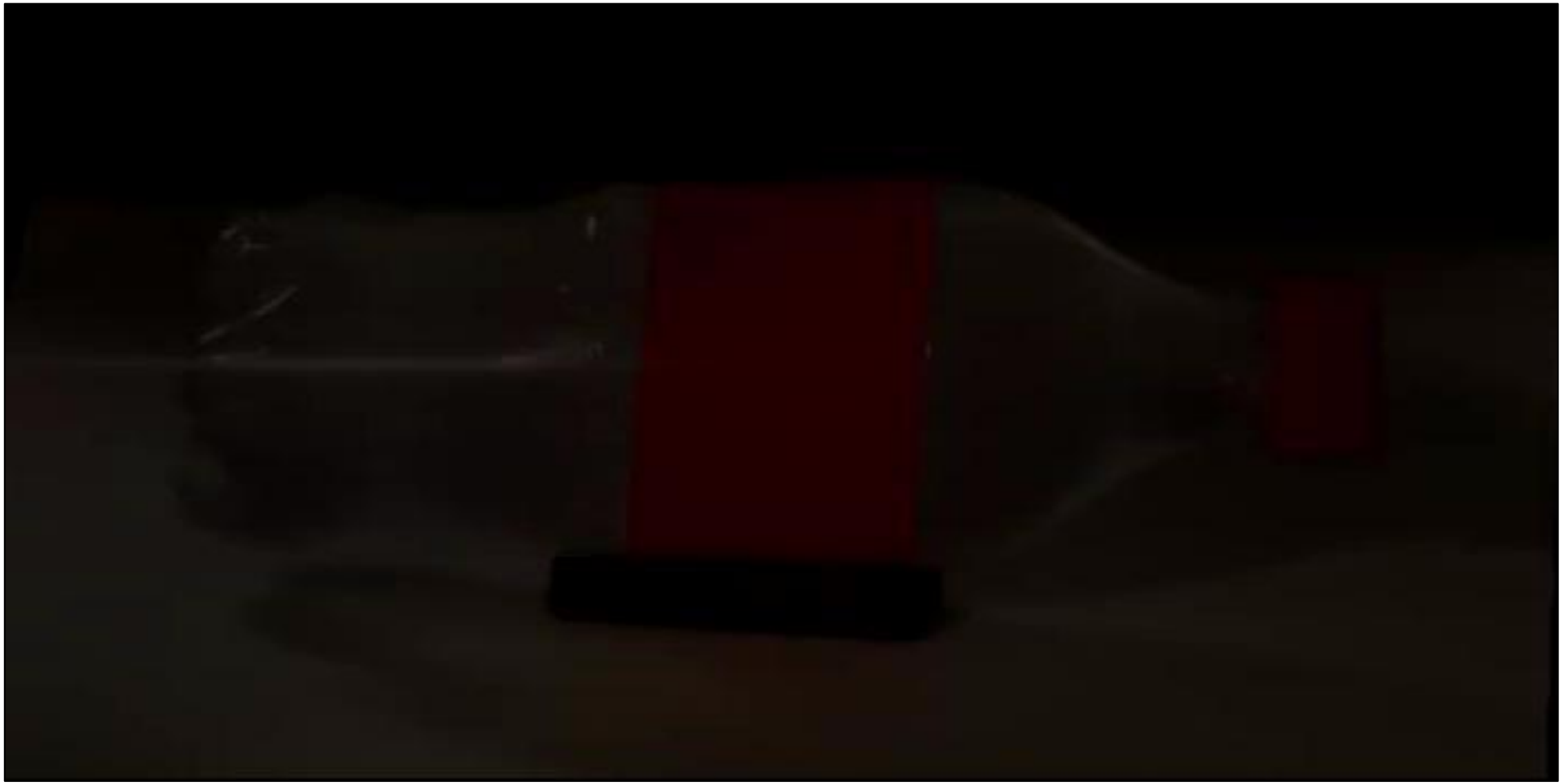
# Slide credits

A lot of these slides were adapted from:

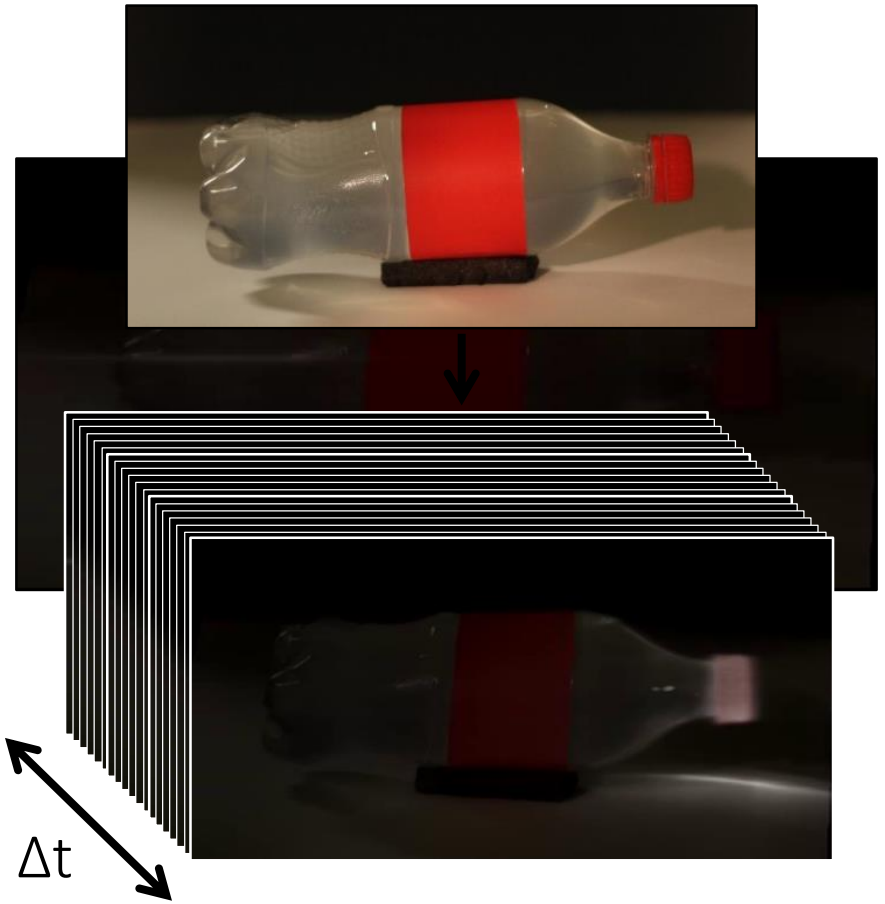
- Mohit Gupta (Wisconsin).
- Supreeth Achar (Google, formerly CMU).

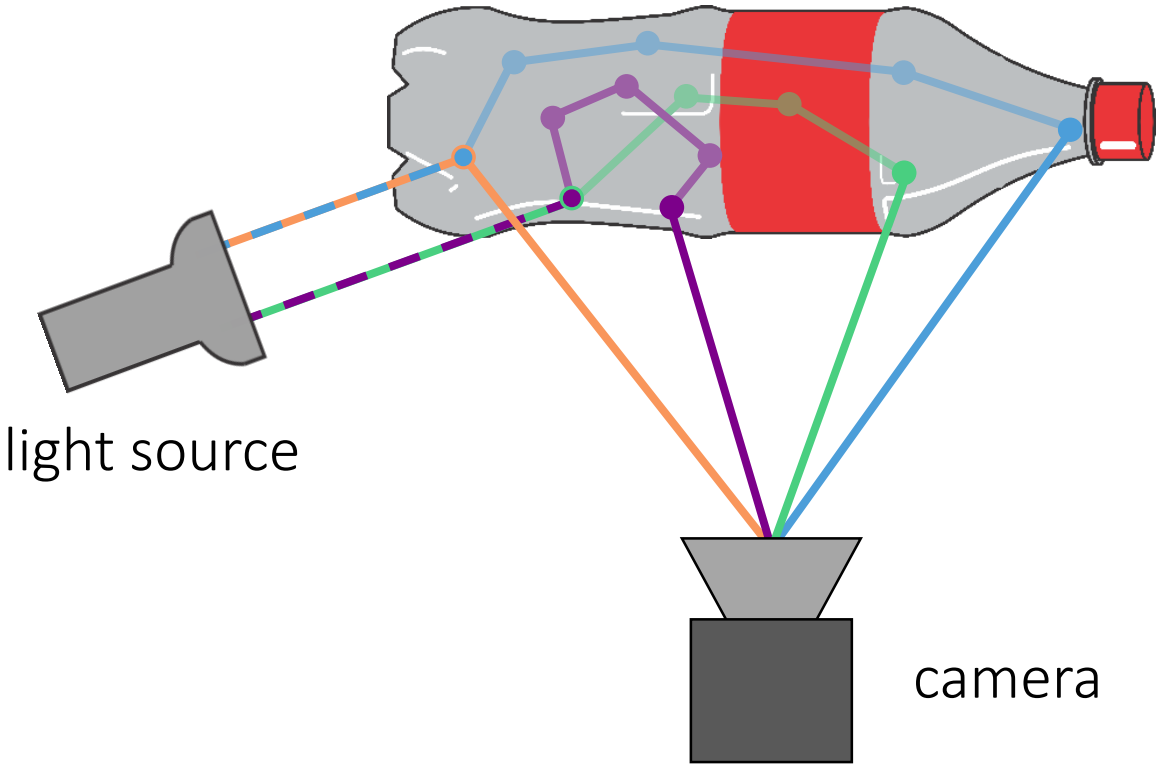
# Introduction to time-of-flight (ToF) imaging

# Time-of-flight (ToF) imaging



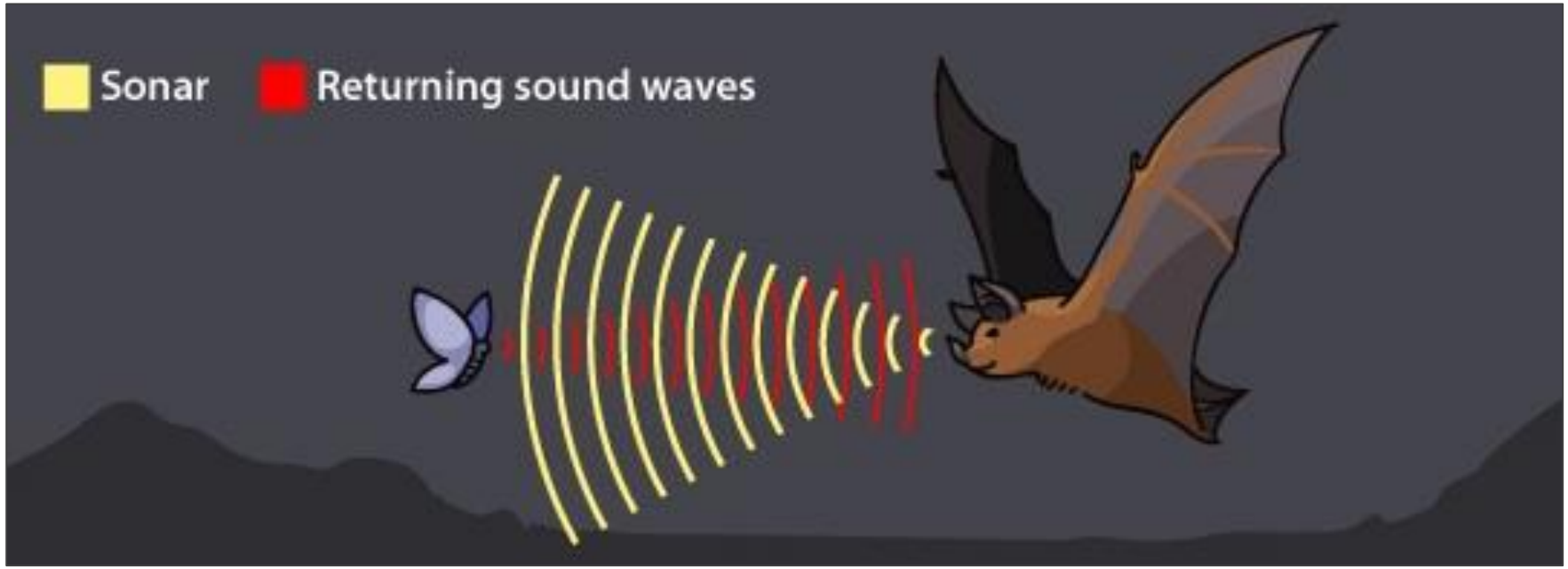
# Time-of-flight (ToF) imaging

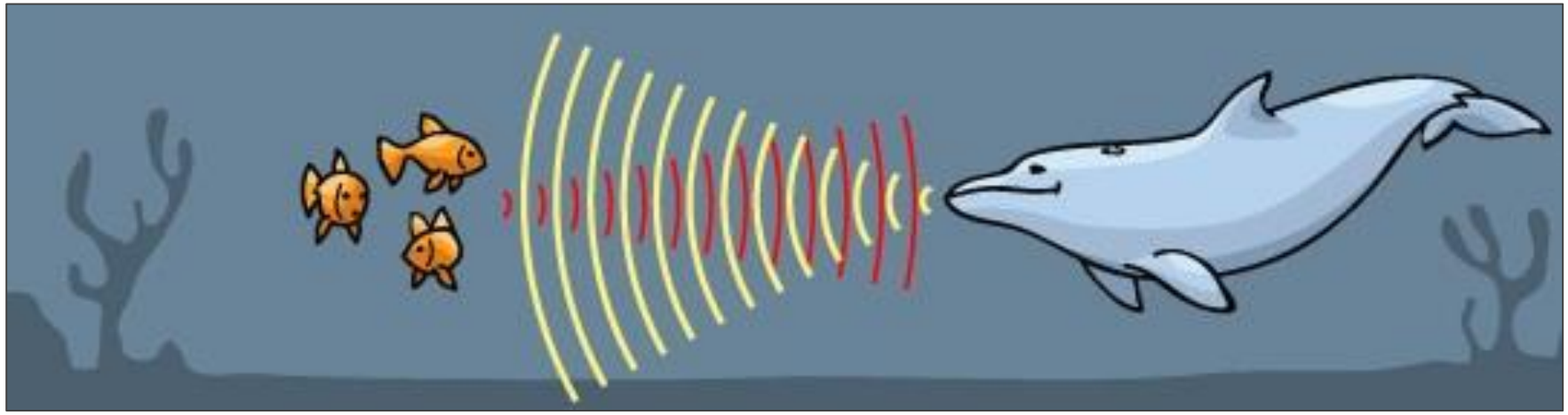



- Conventional imaging: Measure all photons together regardless of time of travel.
- Time-of-flight imaging: Measure photons separately based on time of travel.

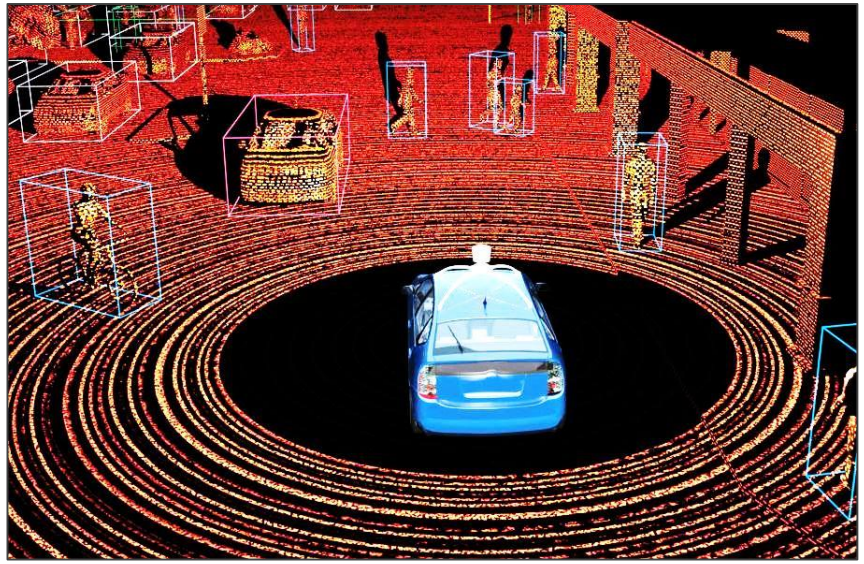
# Time-of-flight imaging in nature

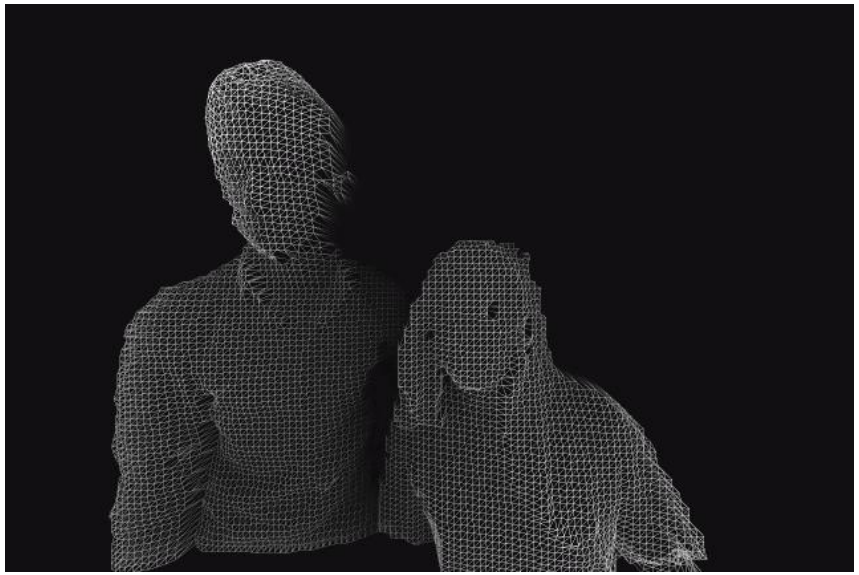


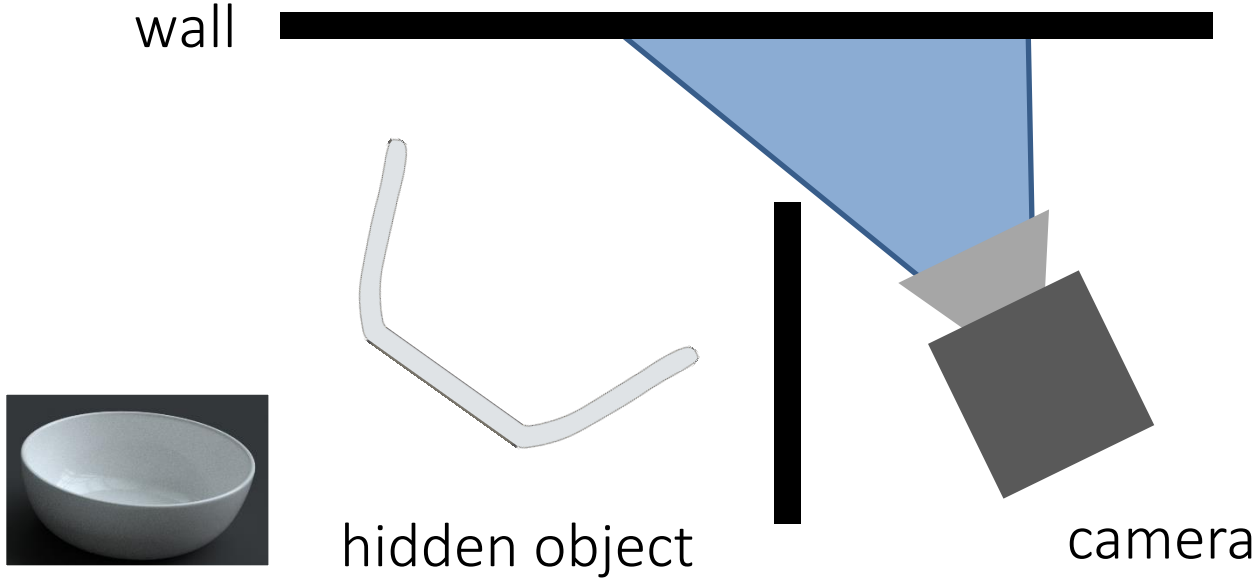
echolocation using sound-wave time-of-flight

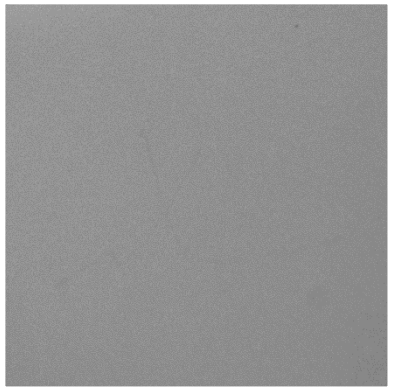
# Time-of-flight applications: depth sensing



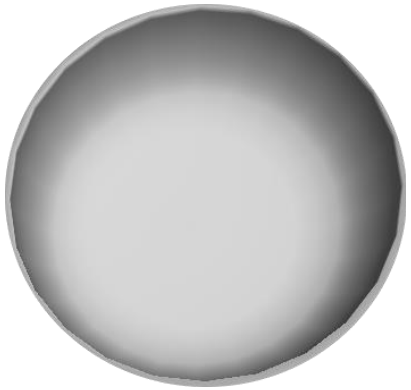



# Time-of-flight applications: non-line of sight imaging

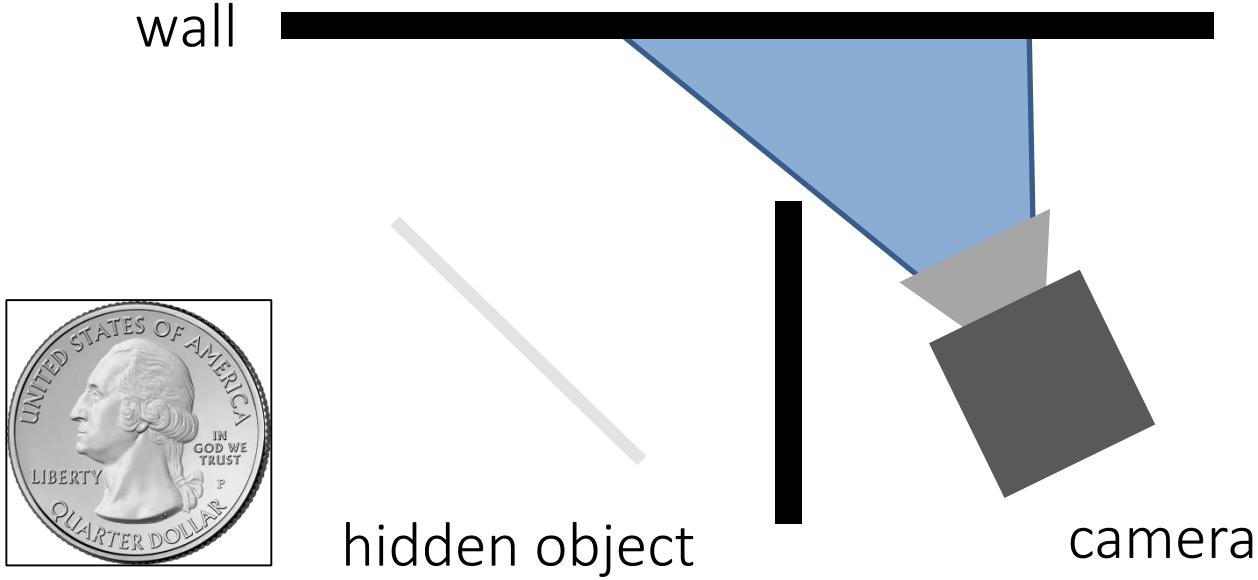


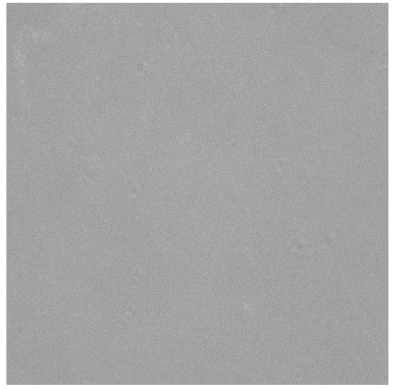



what a regular camera sees



what shape our camera sees

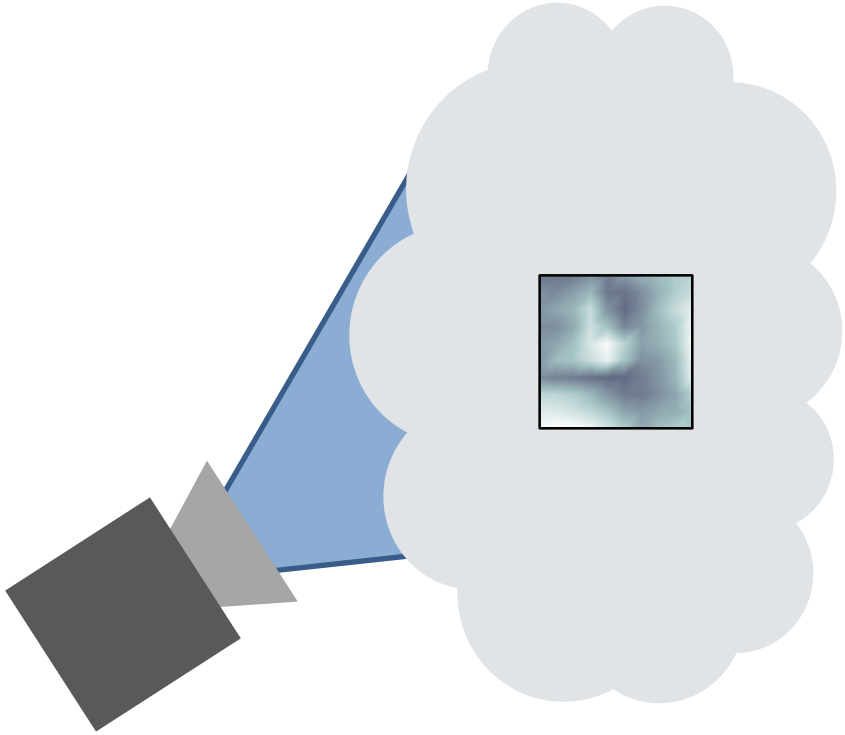


what a regular camera sees

what depth our camera sees

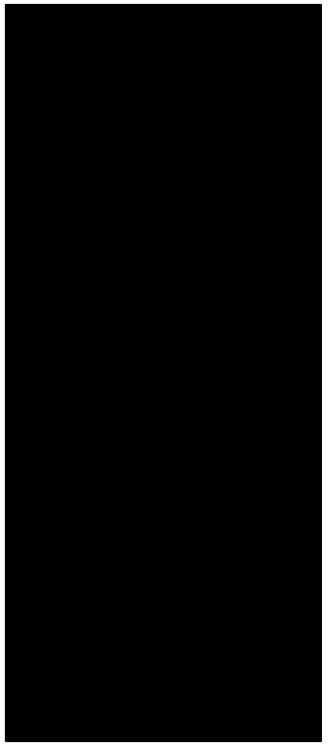
# Time-of-flight applications: seeing inside objects



camera

thick smoke cloud

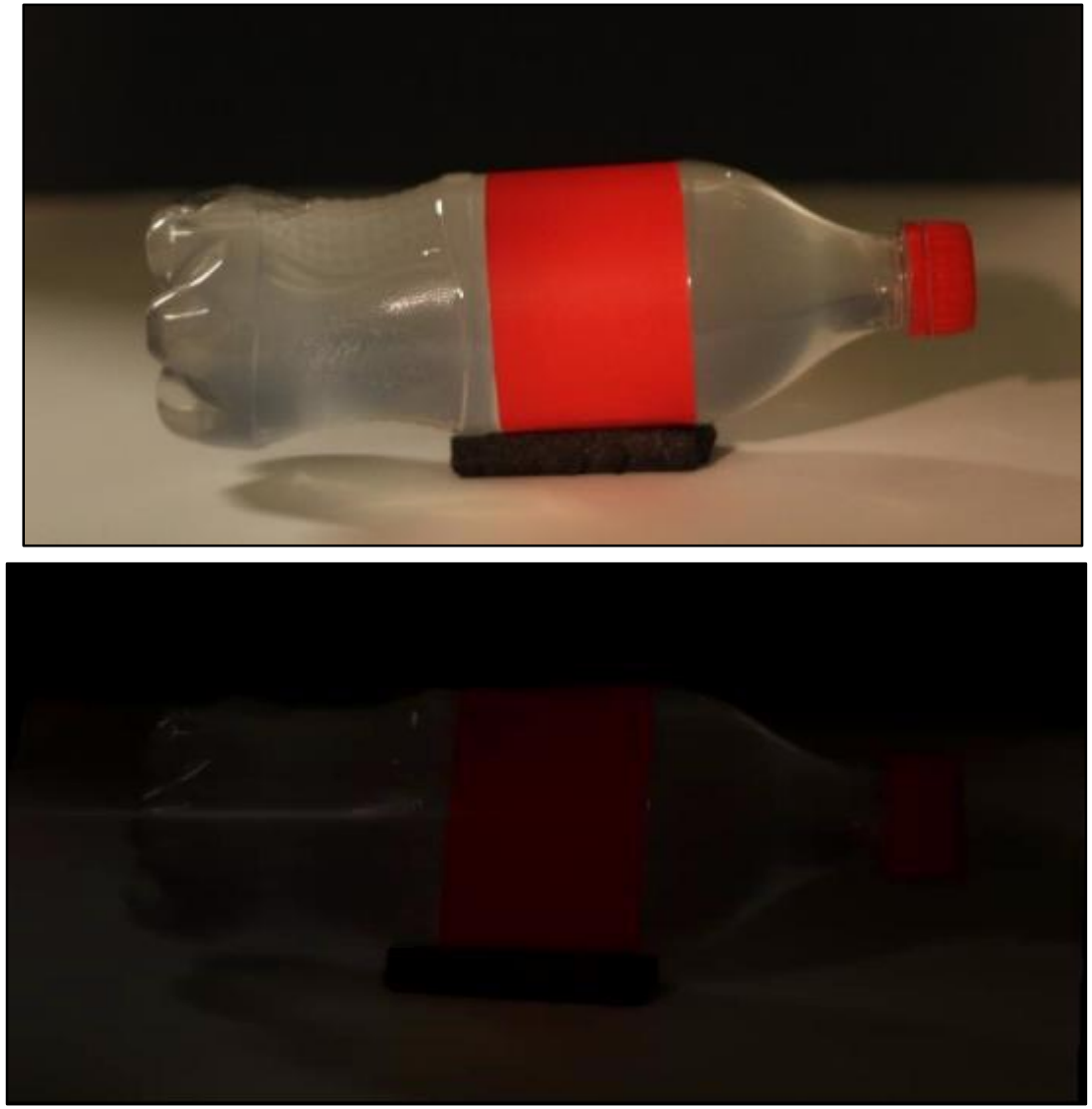
what a regular camera sees



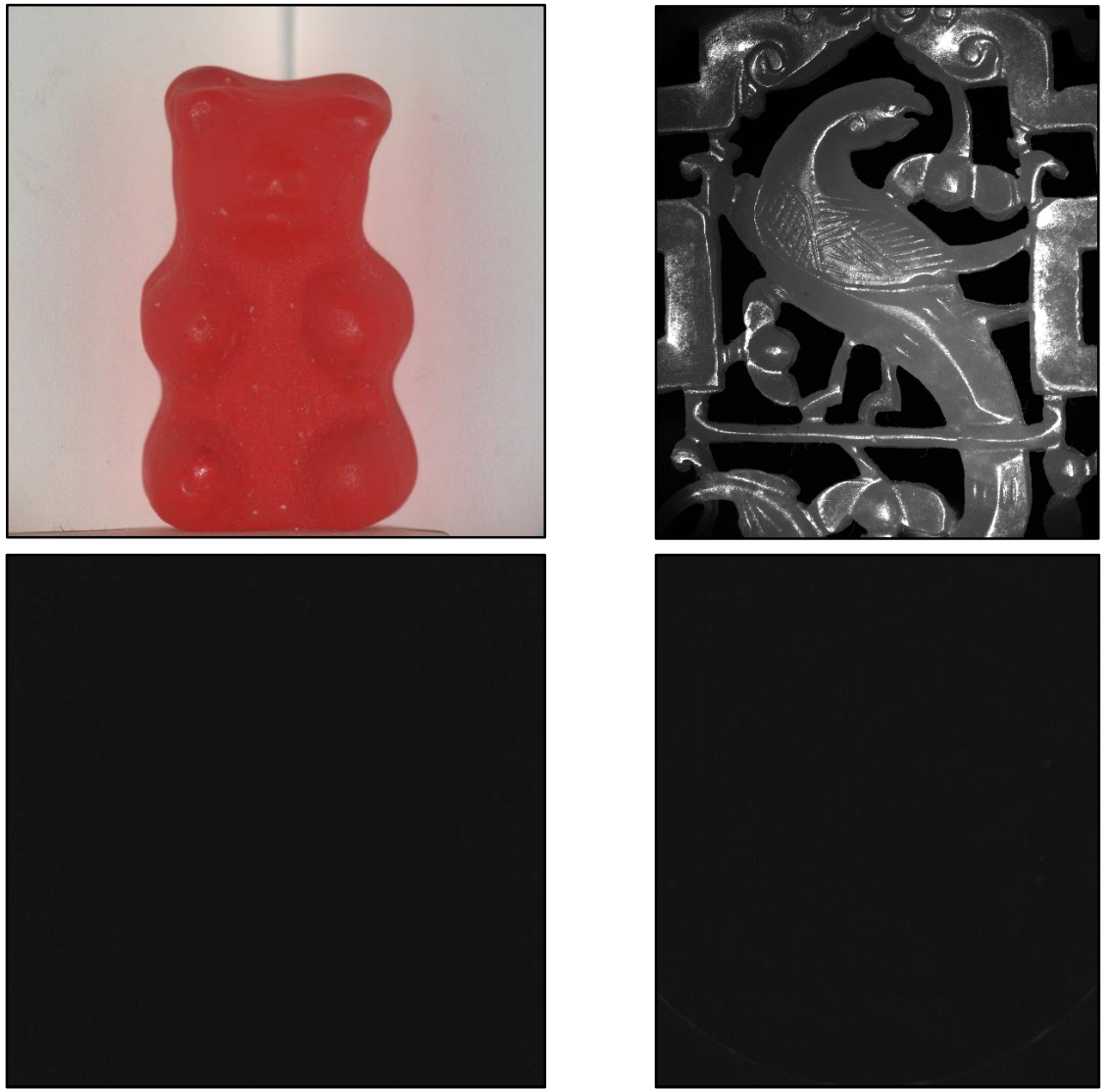
what our camera sees

a slice through the cloud

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



video at $10^{12}$ frames per second

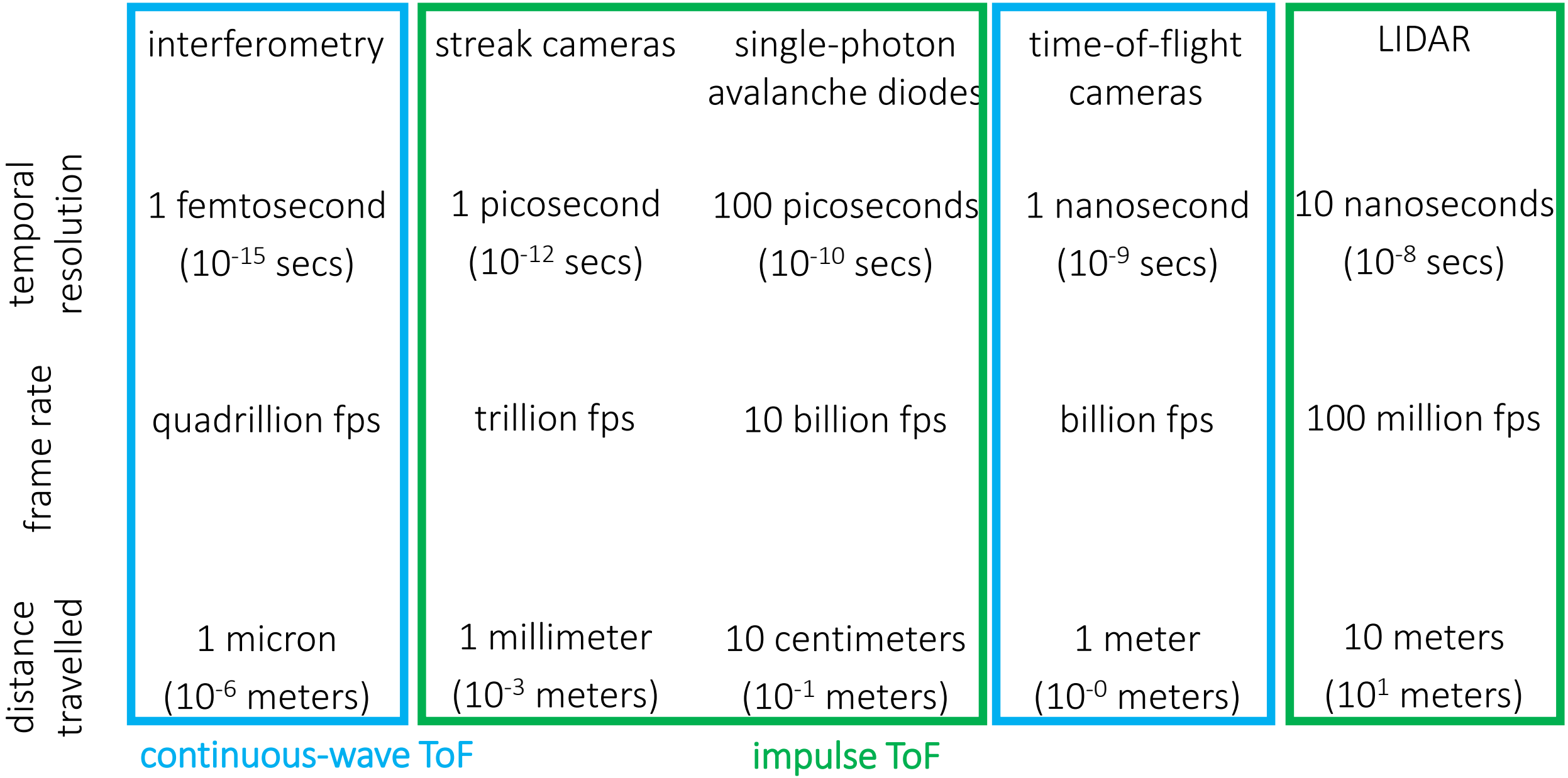


video at $10^{15}$ frames per second

# Time-of-flight imaging technologies

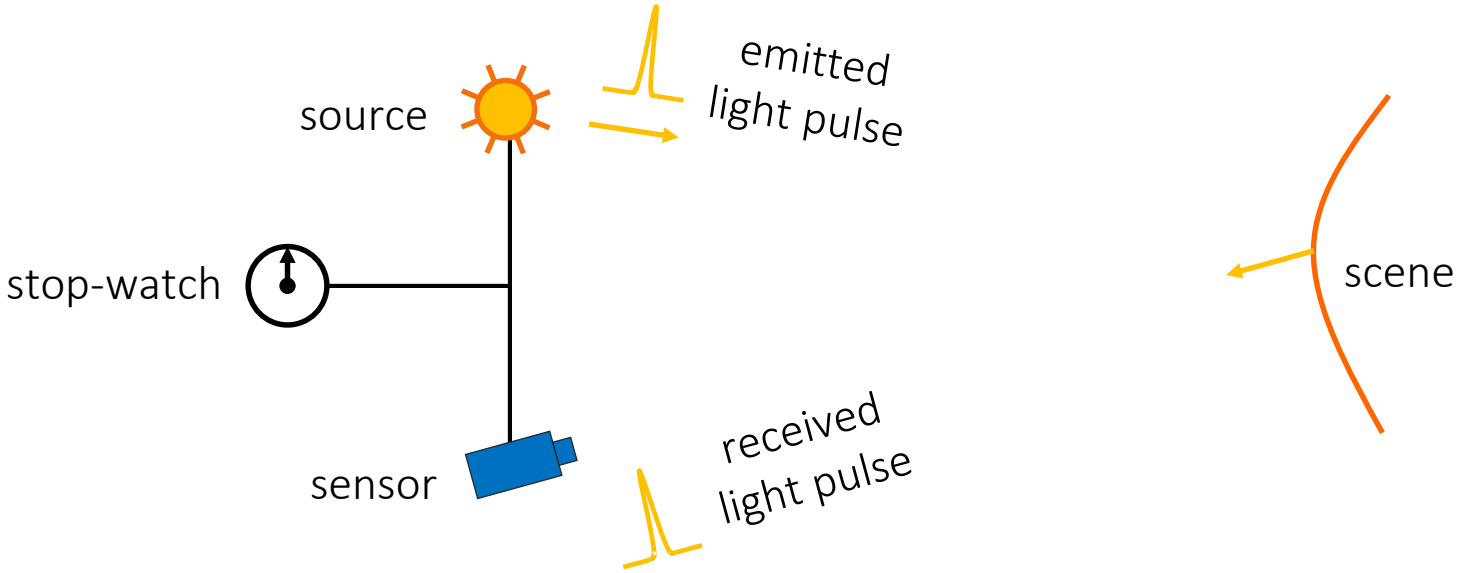
| | interferometry | streak cameras | single-photon avalanche diodes | time-of-flight cameras | LIDAR |
|---|---|---|---|---|---|
| temporal resolution | 1 femtosecond ($10^{-15}$ secs) | 1 picosecond ($10^{-12}$ secs) | 100 picoseconds ($10^{-10}$ secs) | 1 nanosecond ($10^{-9}$ secs) | 10 nanoseconds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



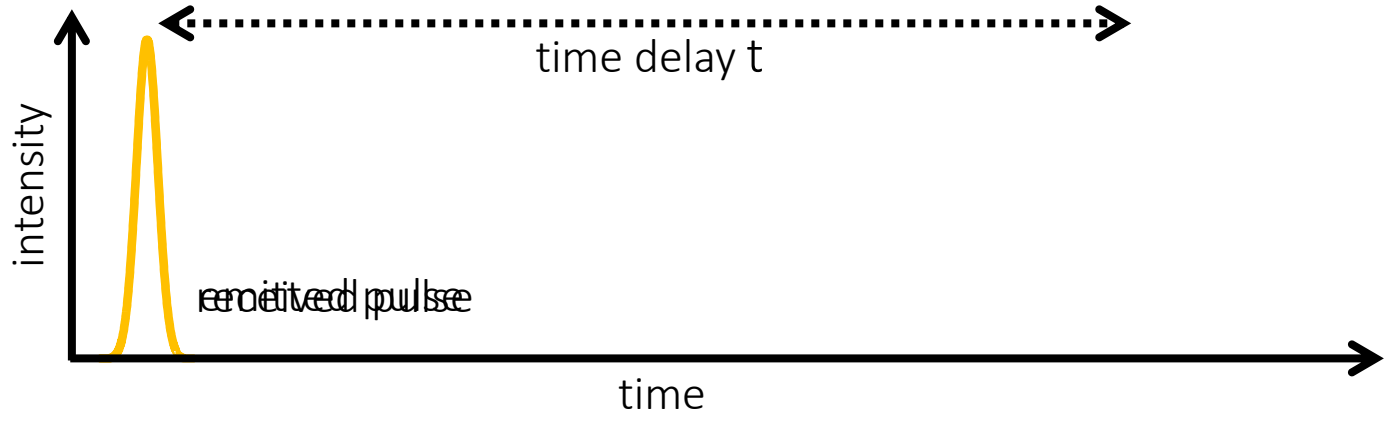
# Impulse ToF imaging and single-photon avalanche diodes

# Impulse time-of-flight imaging

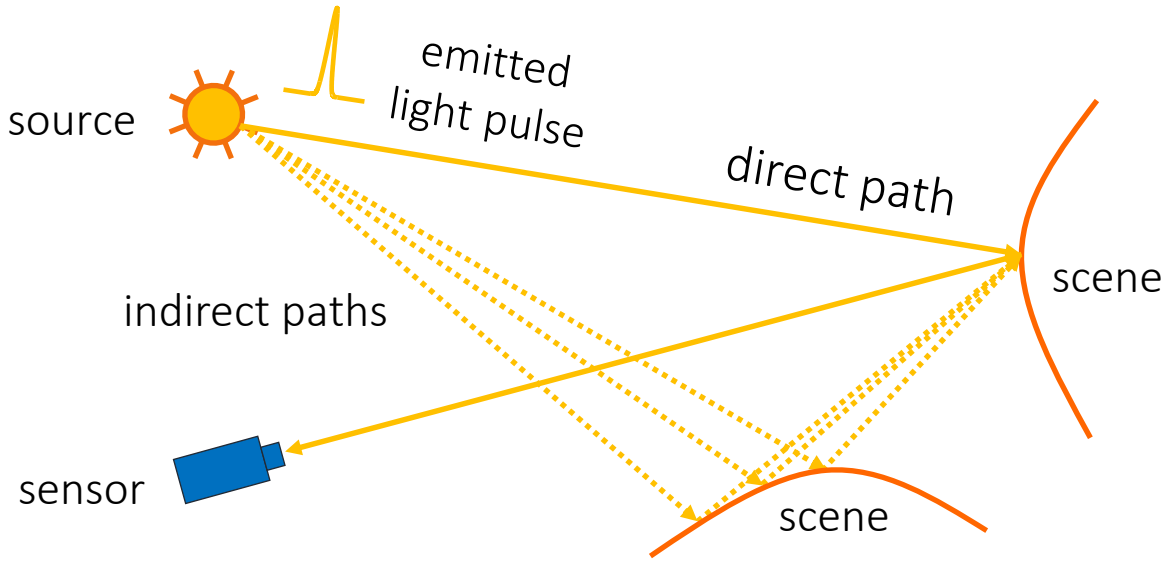


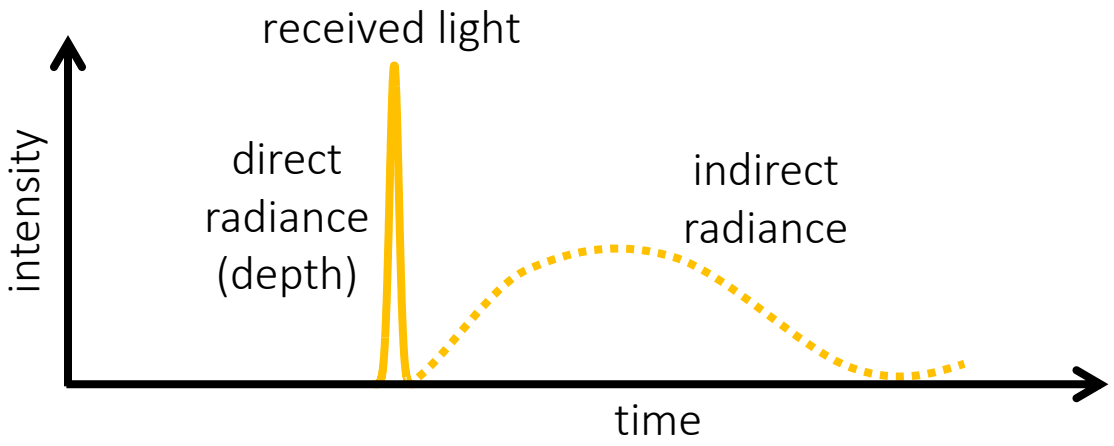

How can we infer depth from this?

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



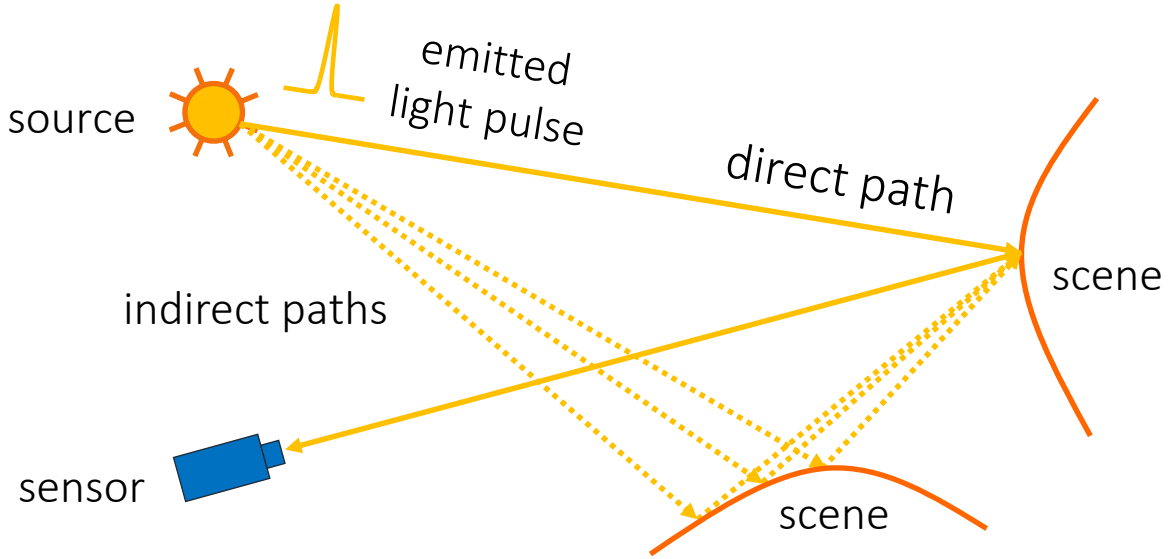
# Impulse time-of-flight imaging

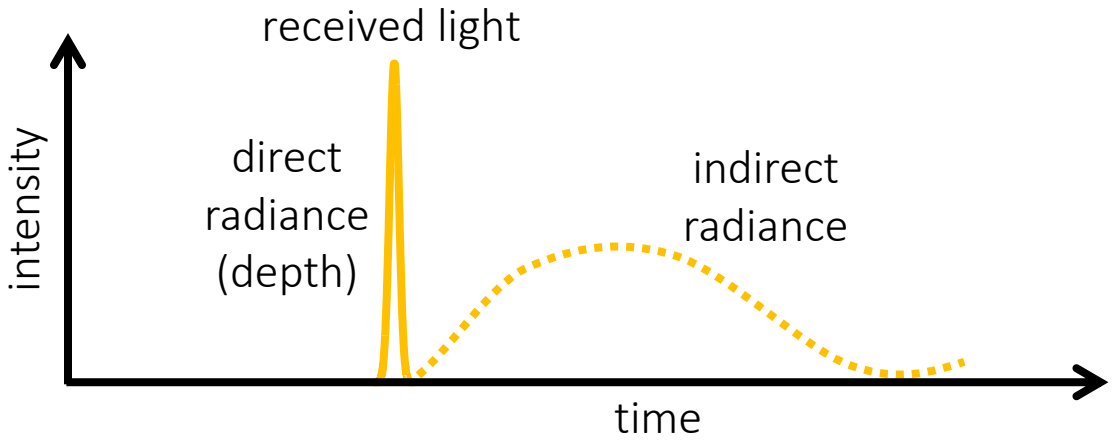



- Indirect paths are nuisance for depth sensing (“multi-path interference”).
- Indirect paths are very informative for other time-of-flight applications.

# Two types of time-of-flight imaging



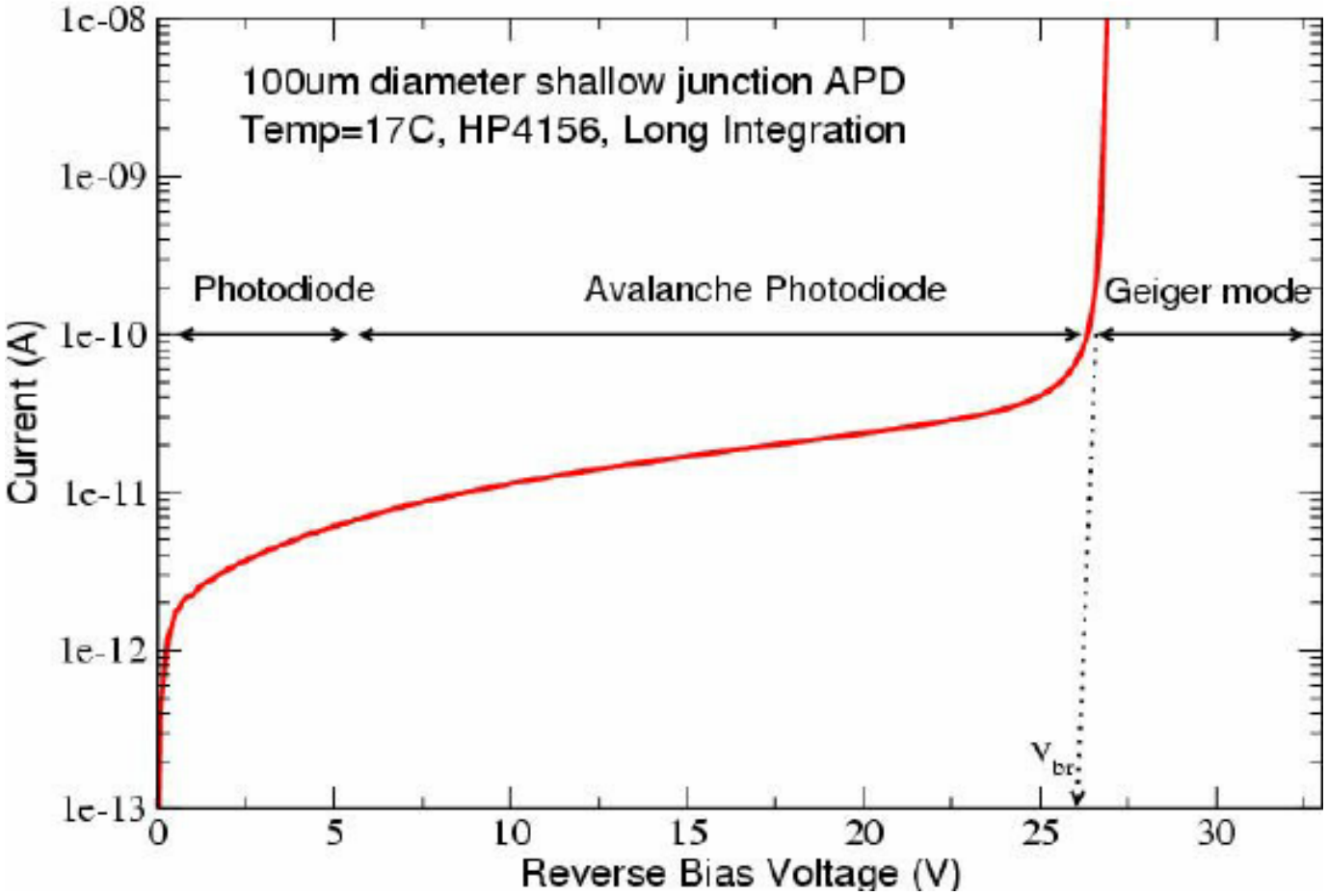

Transient I(t): Time-resolved radiance distribution

- 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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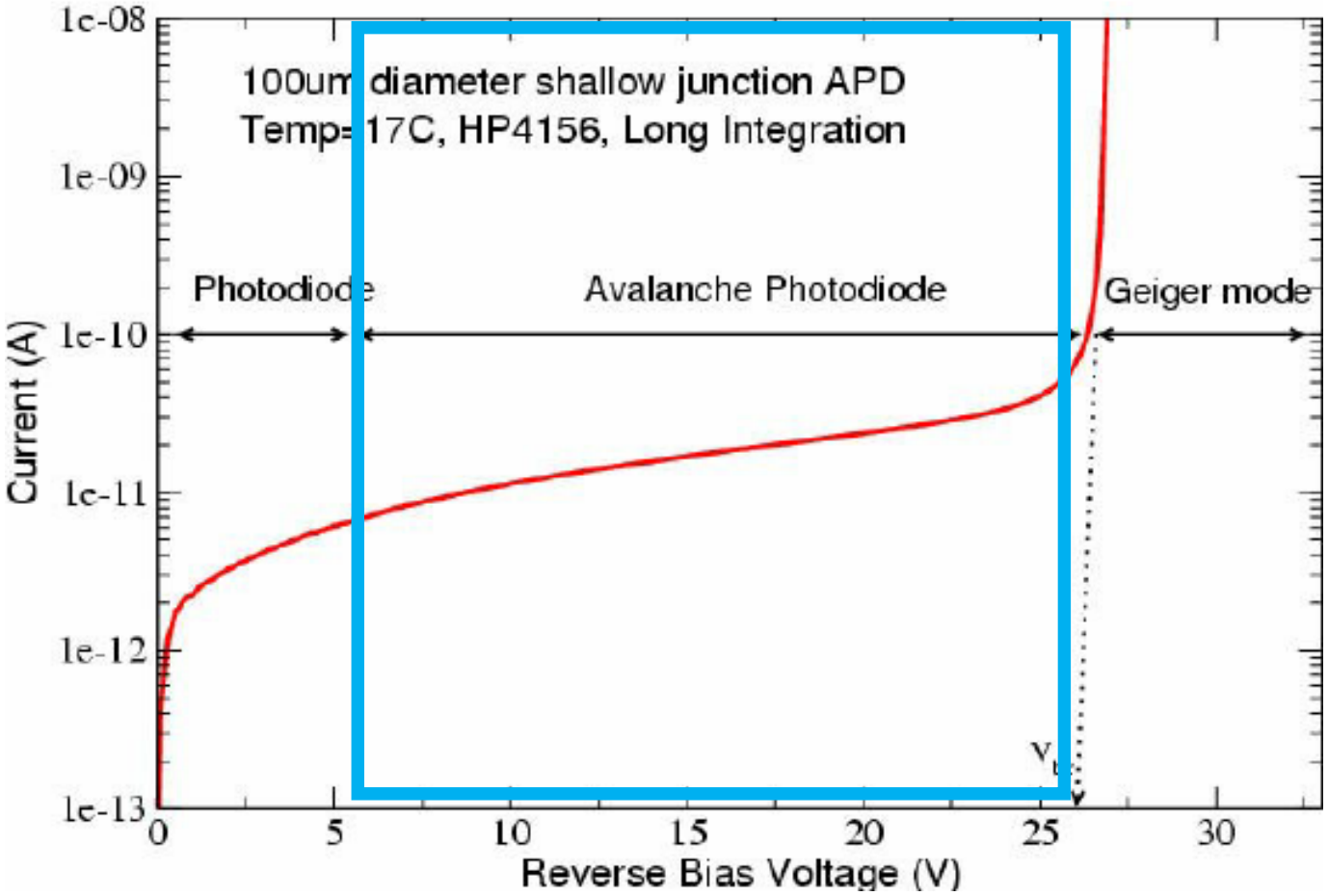


Avalanche photodiode (APD):

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

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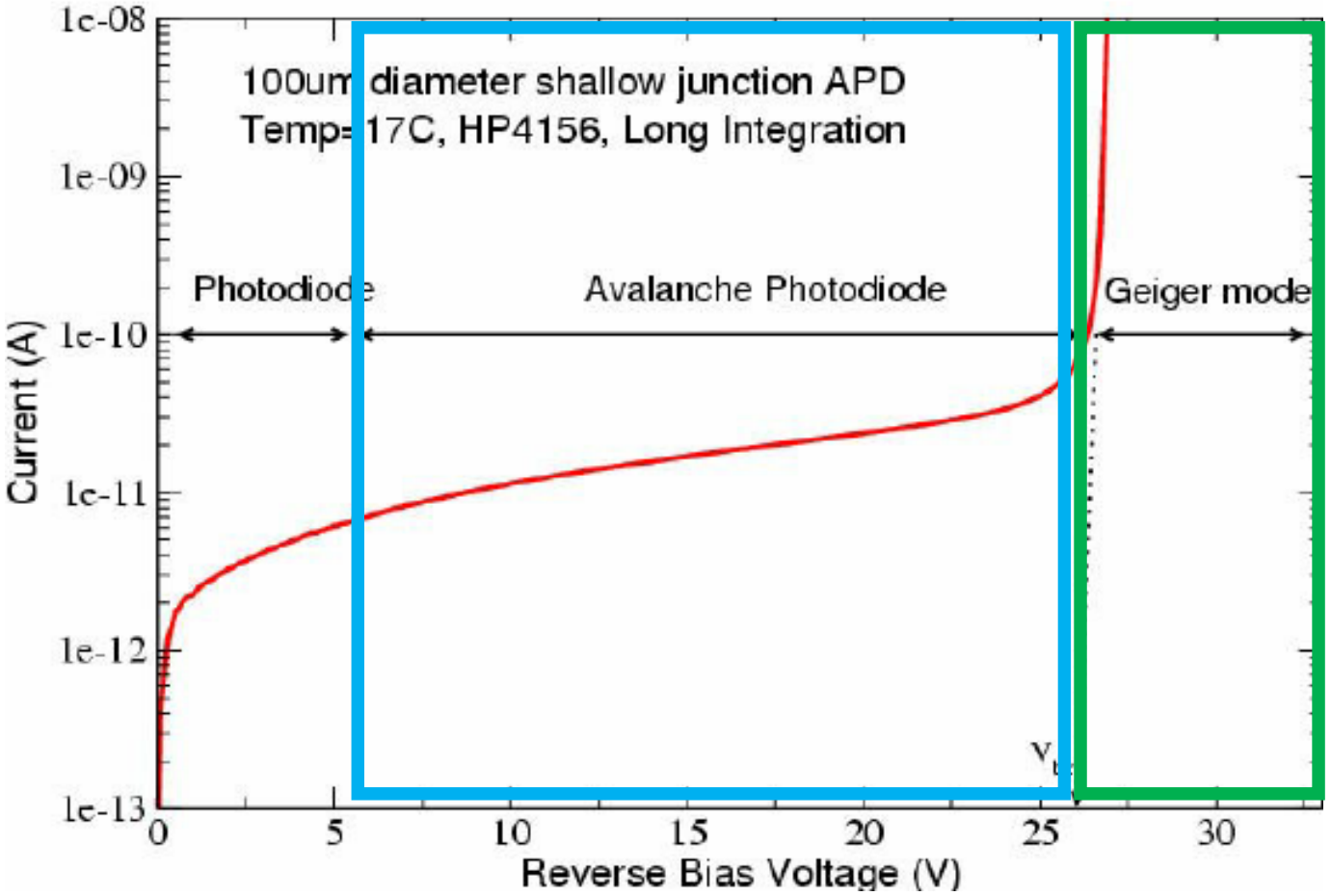



Avalanche photodiode (APD):

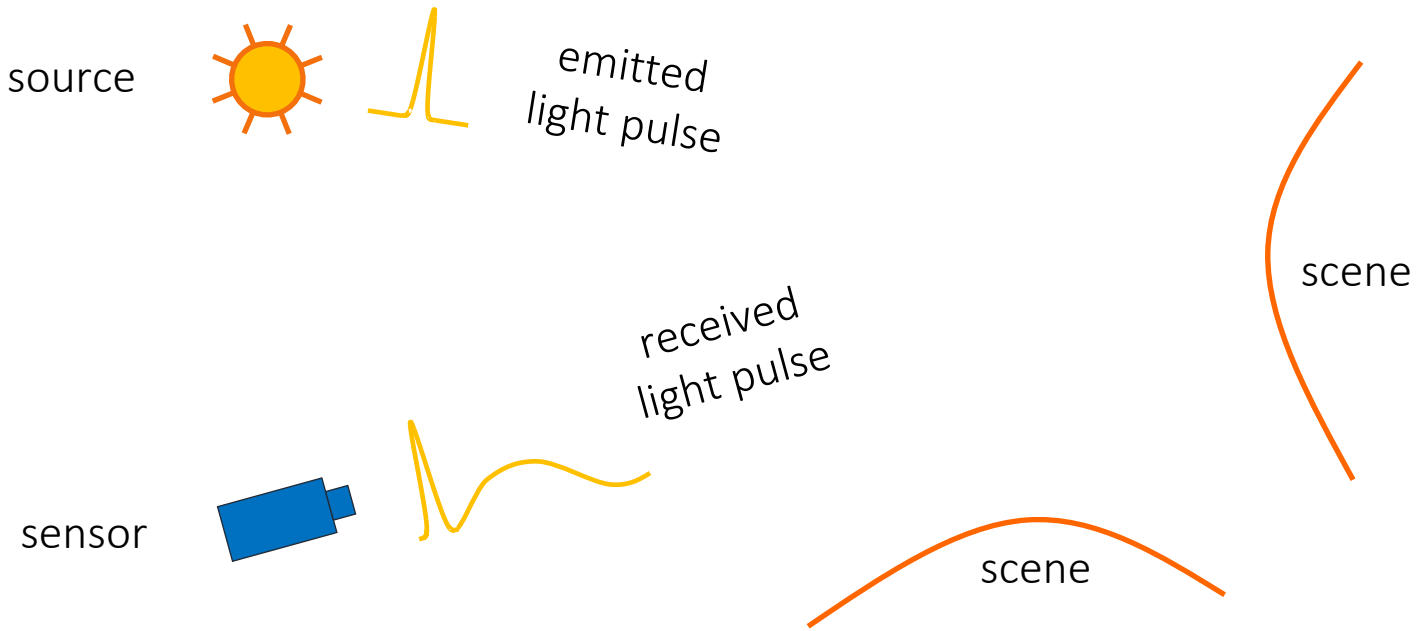
- Current is roughly proportional to number of photons.
- One photon produces tiny current.

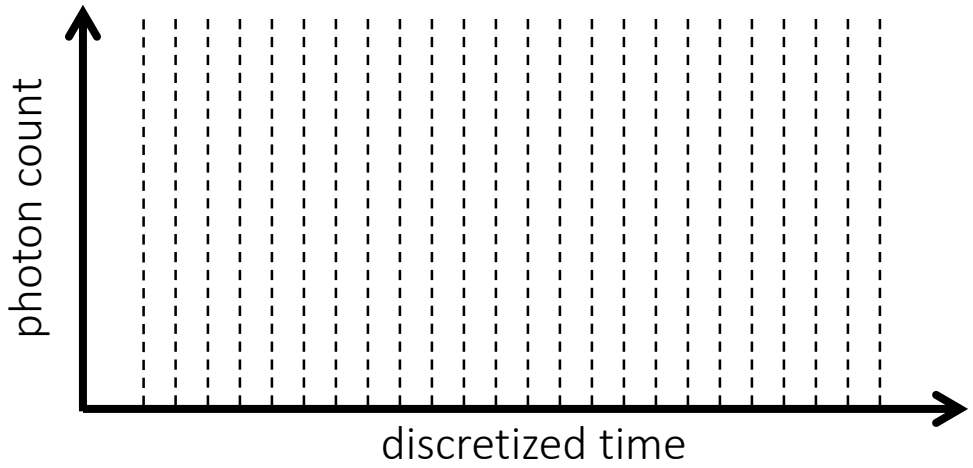
Single-photon avalanche diode (SPAD):

- 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

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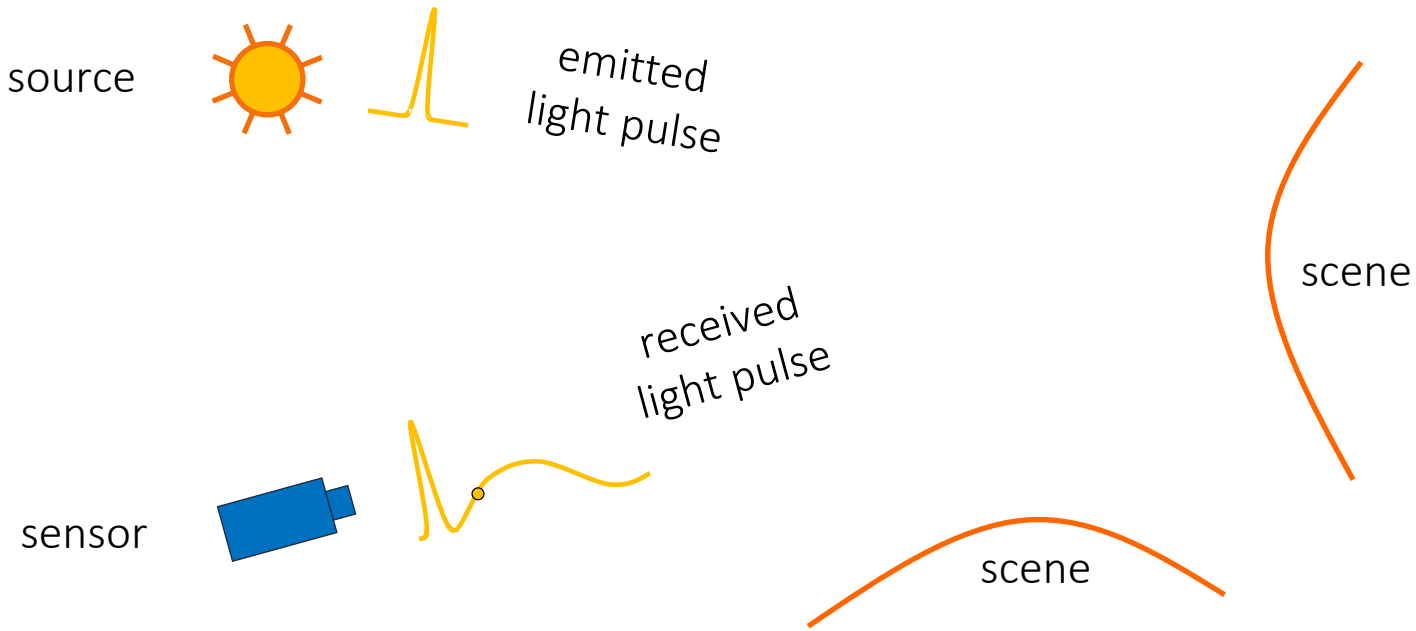


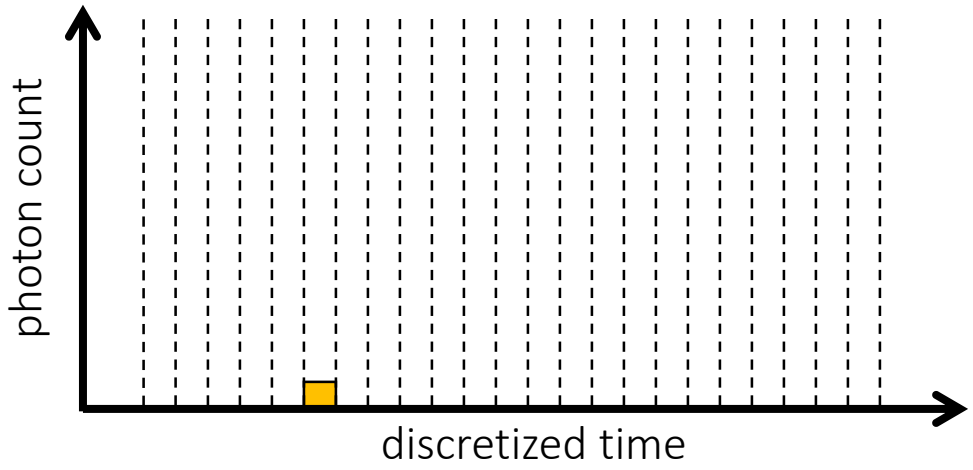


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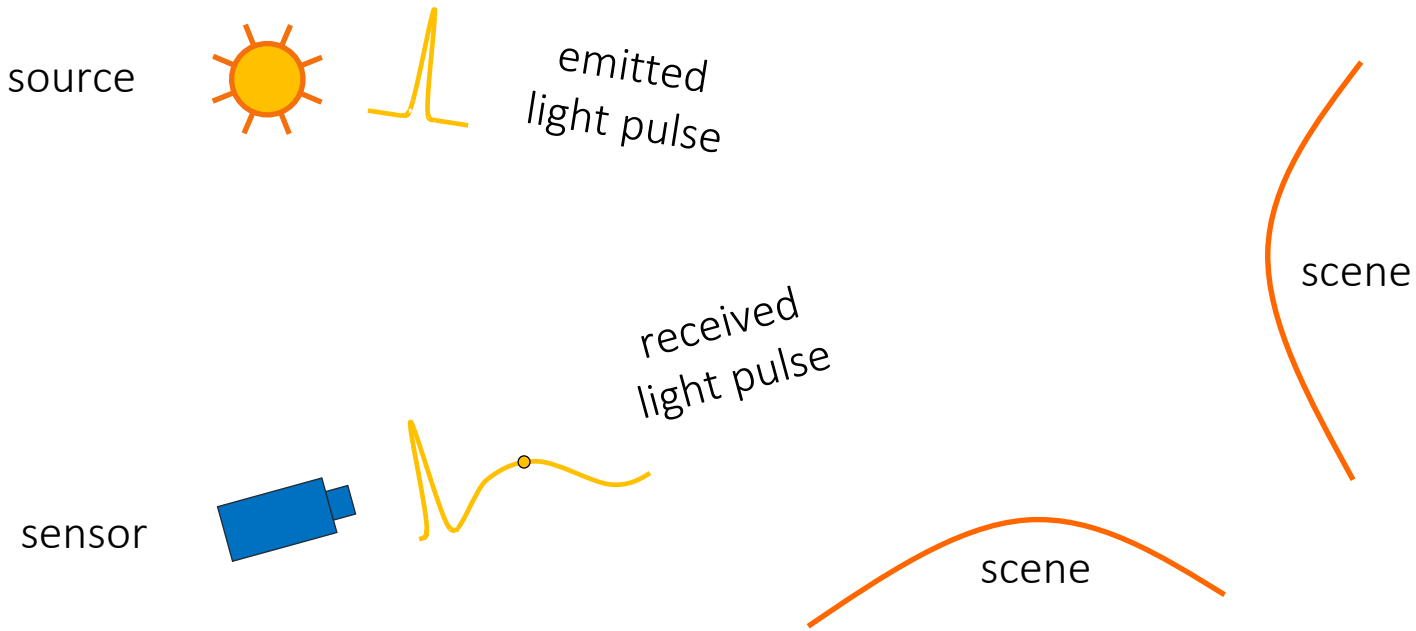


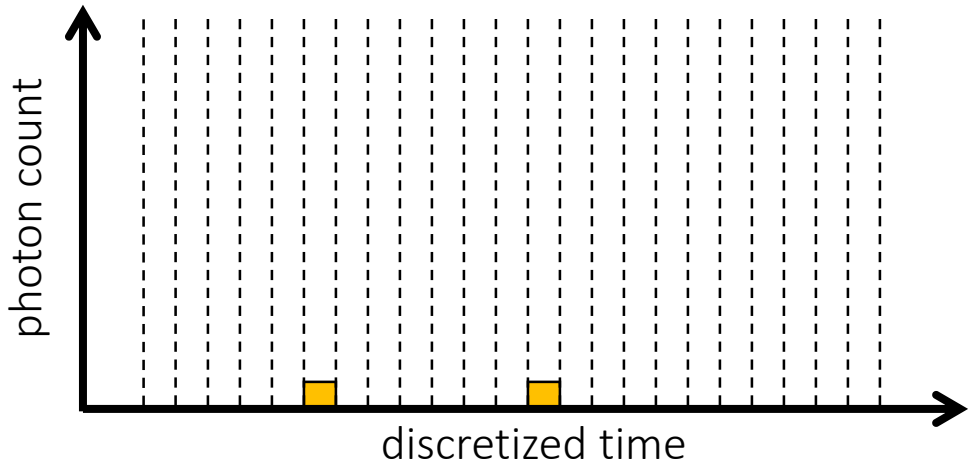


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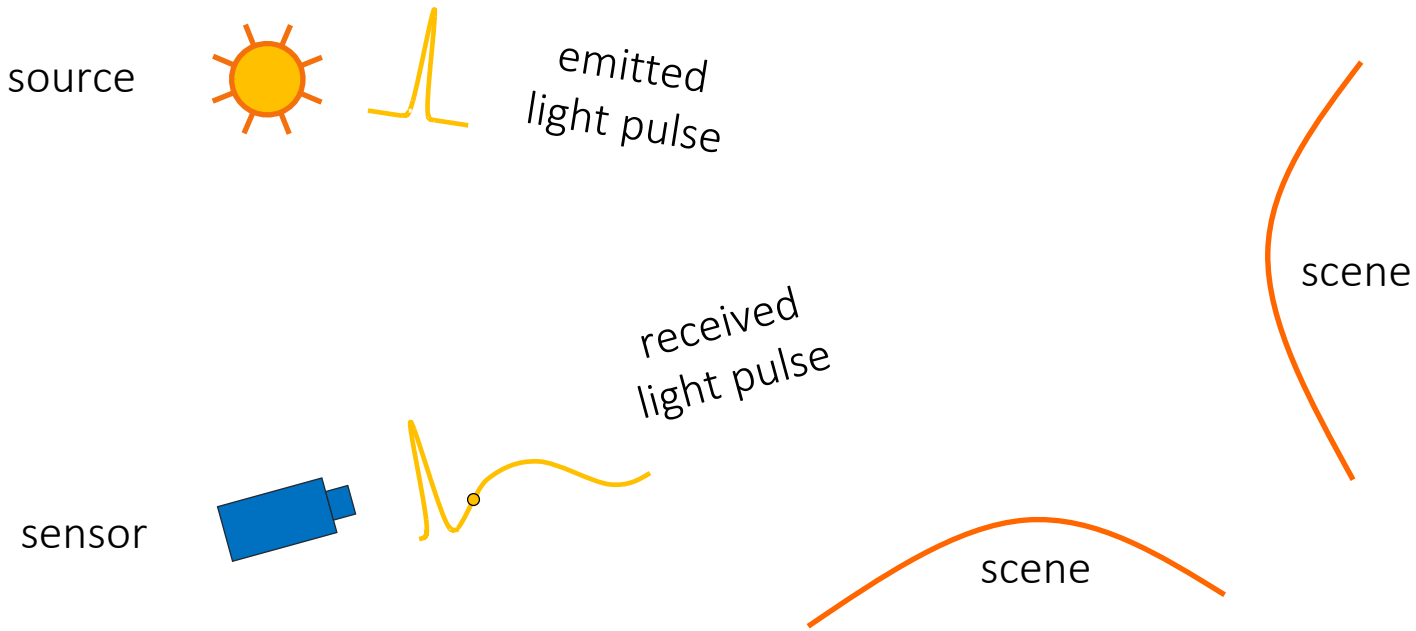
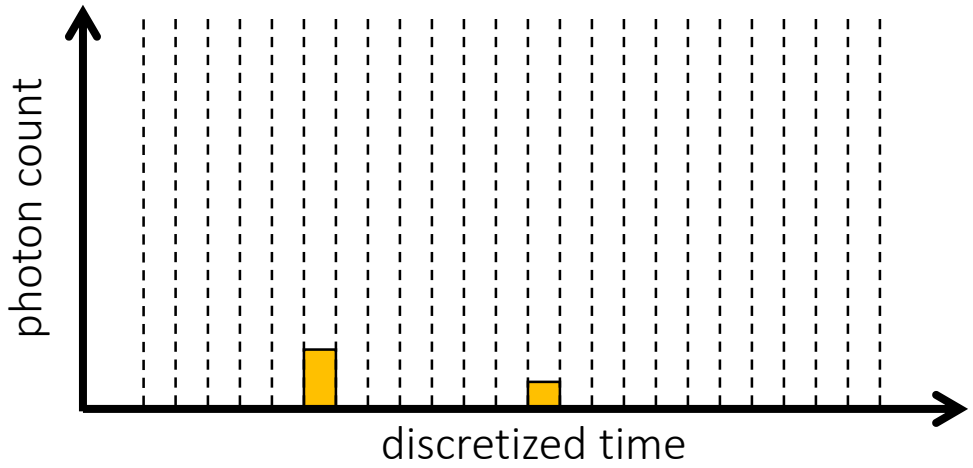


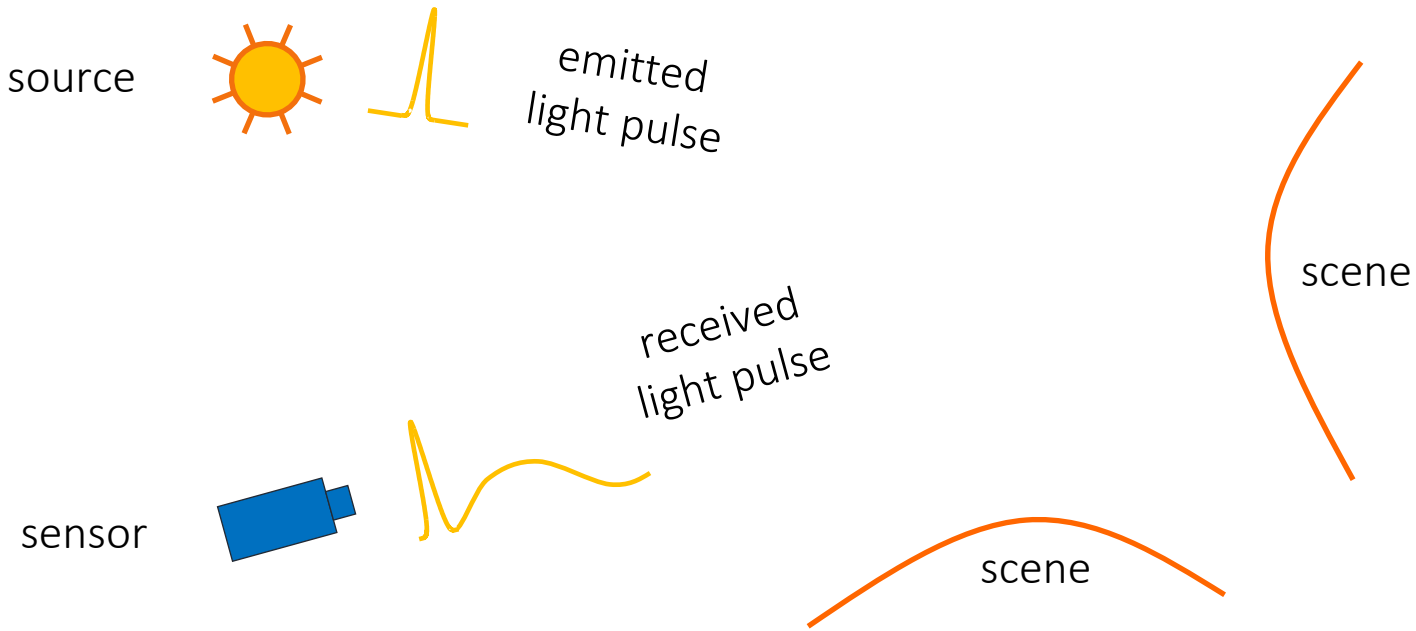



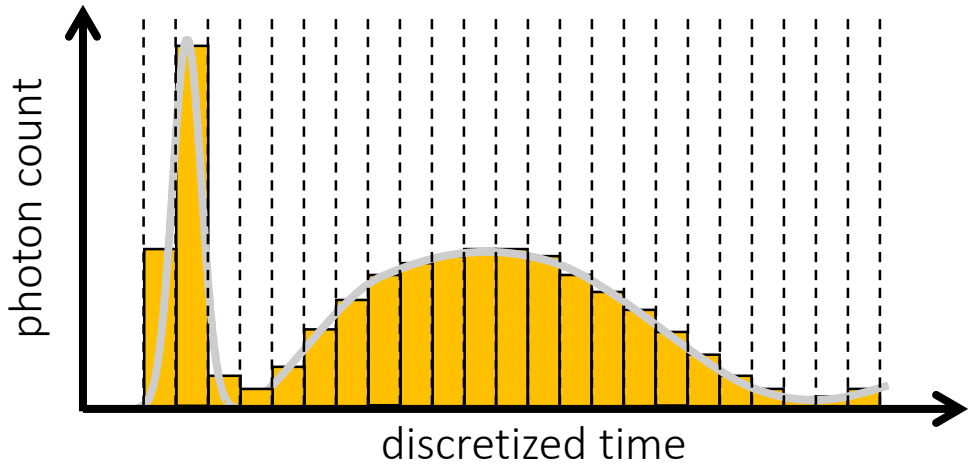

- The SPAD records only photon arrival times, no intensity.
- Additional electronics maintain a histogram of arrival times over multiple pulses

# Geiger-mode impulse time-of-flight imaging

From each received pulse, one photon saturates the SPAD.

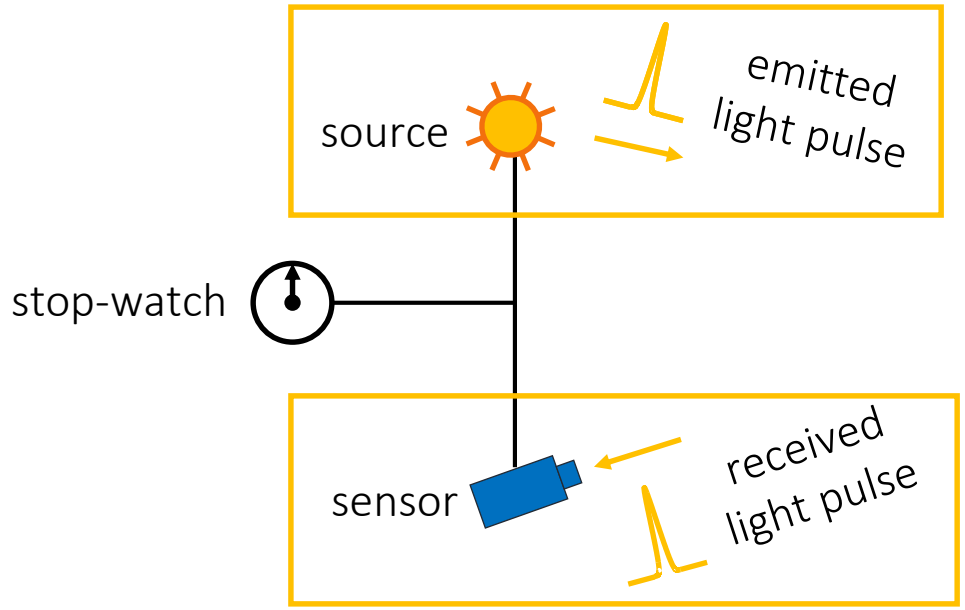
What determines which photon gets picked?




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

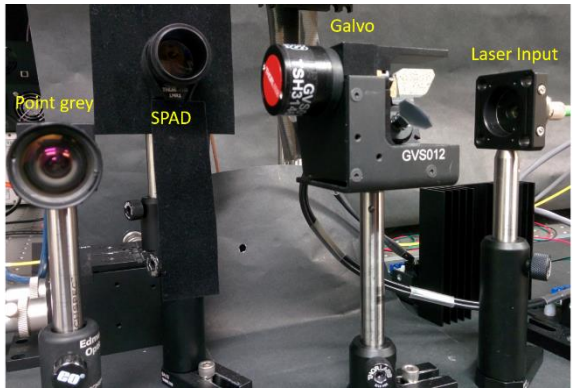
# What hardware do we need for impulse ToF?



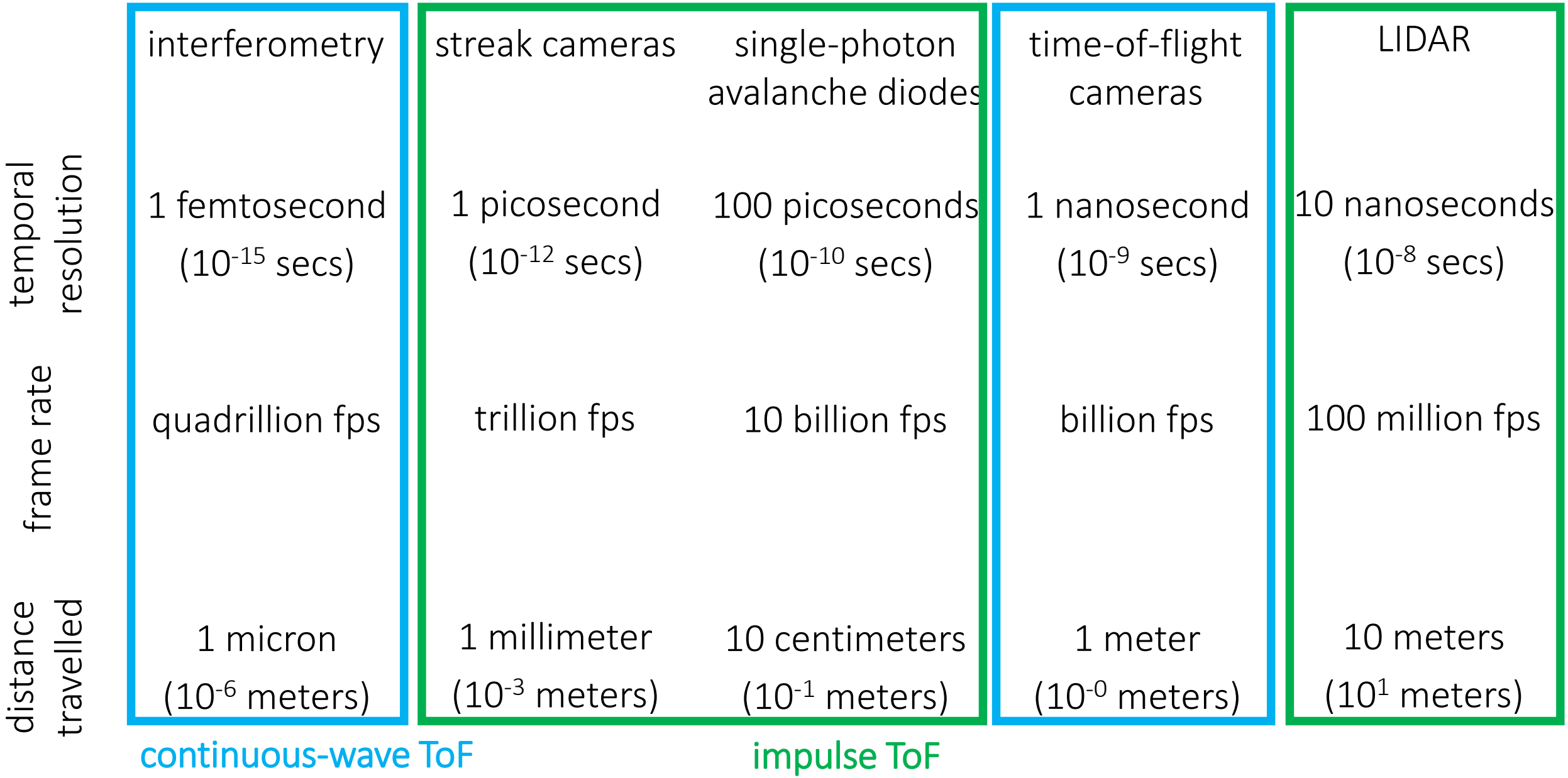


Expensive lasers
[short (picosecond) and powerful (mega joules) light pulses]


High speed and high dynamic range sensors
[picosecond time resolution]

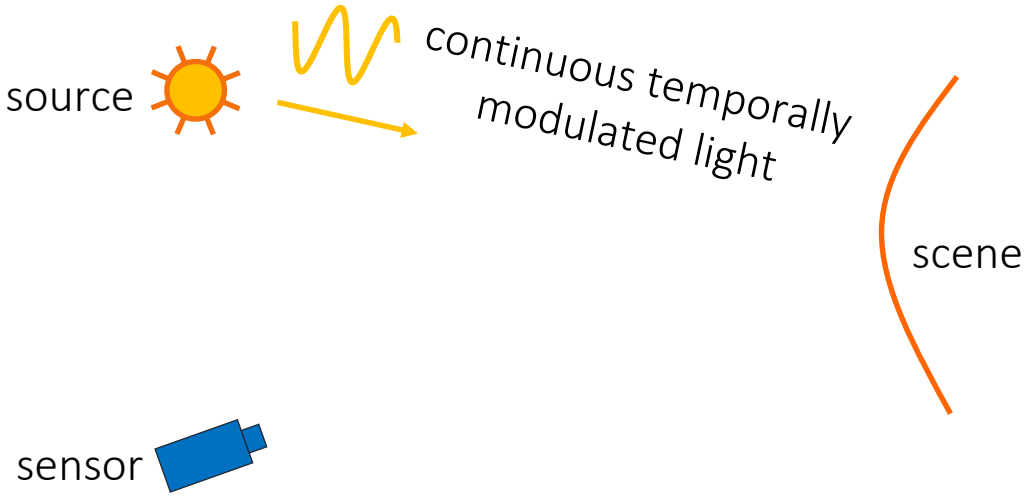


# Time-of-flight imaging technologies

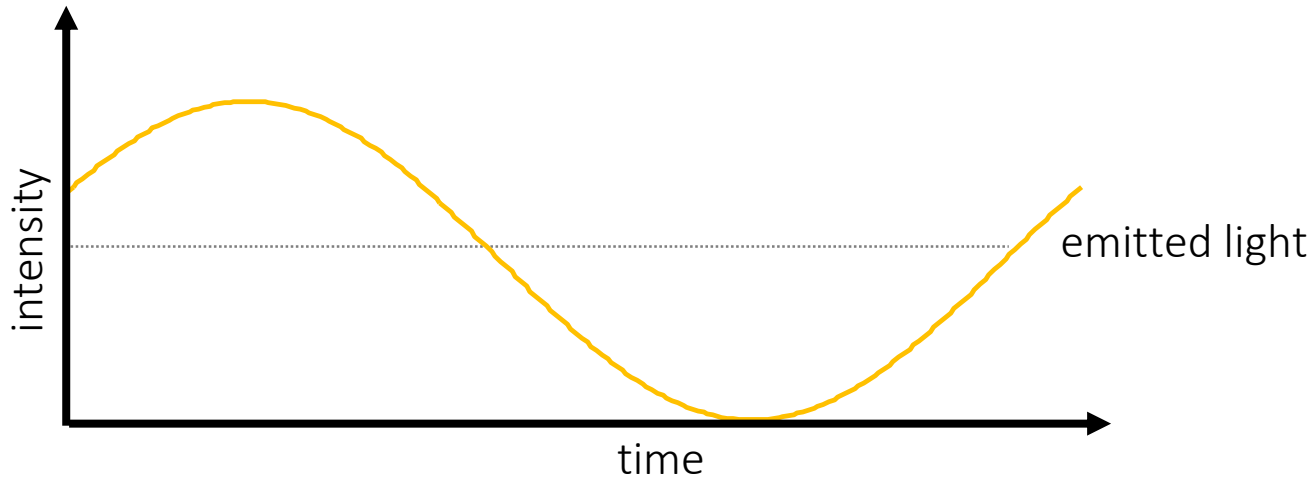


# Continuous-wave ToF imaging

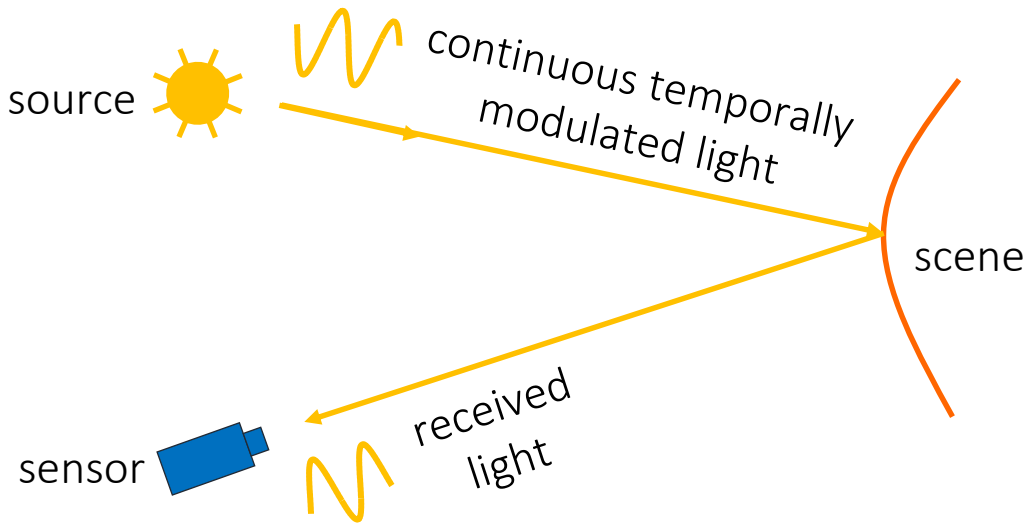
# Continuous-wave (CW) time-of-flight imaging

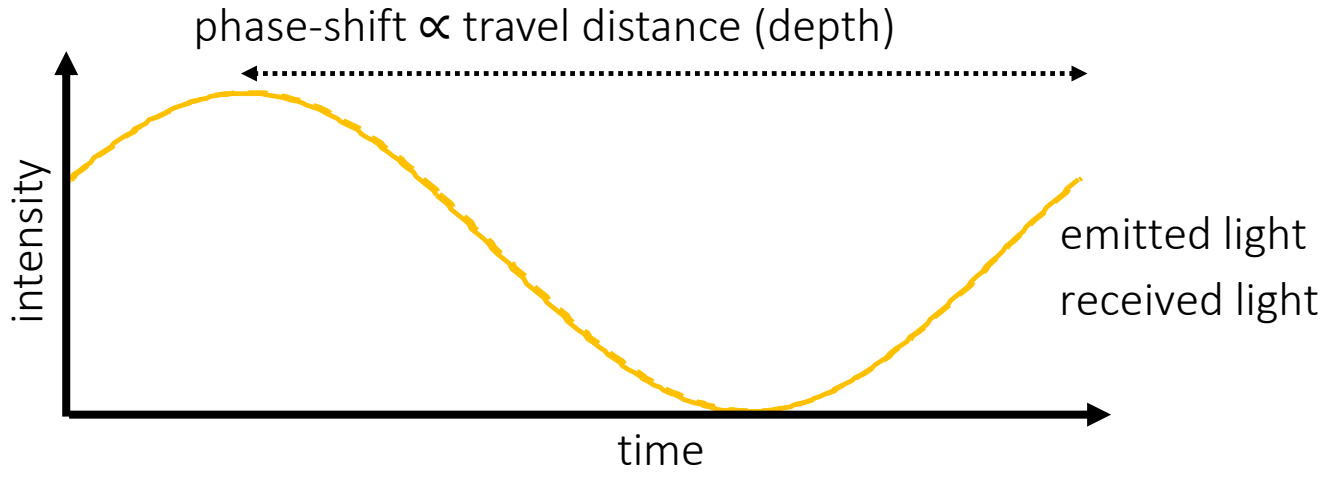



sinusoid

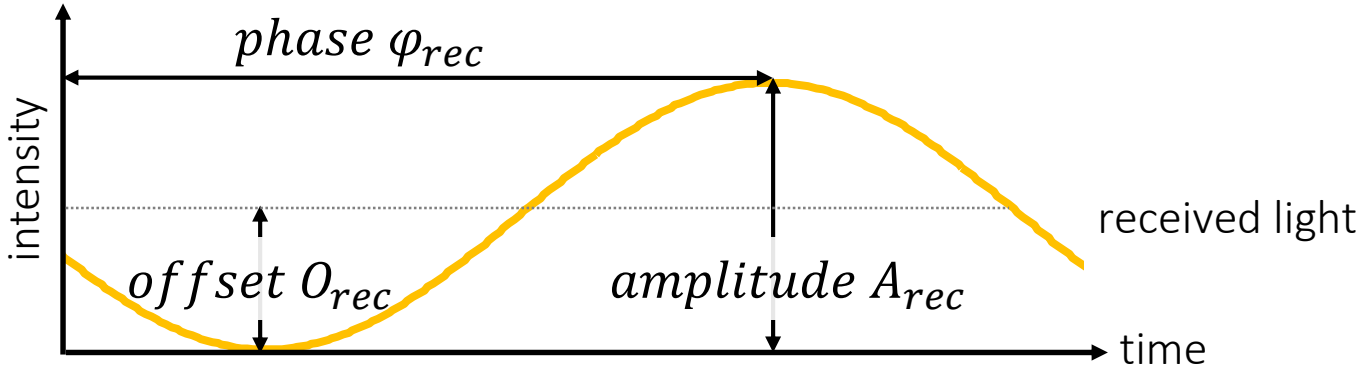


# Continuous-wave (CW) time-of-flight imaging



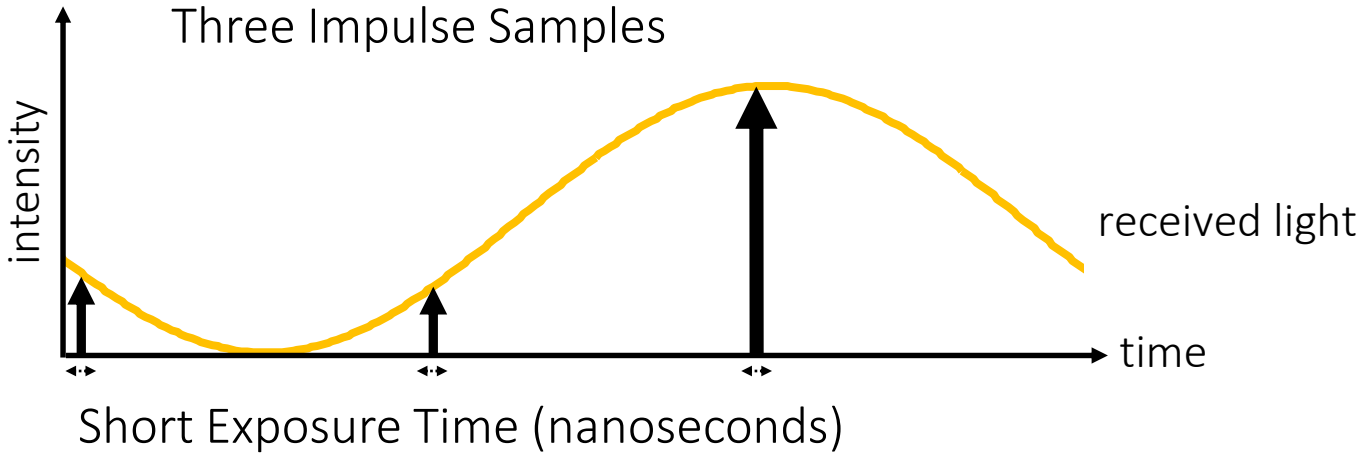
# Measuring phase shift




Three Unknowns

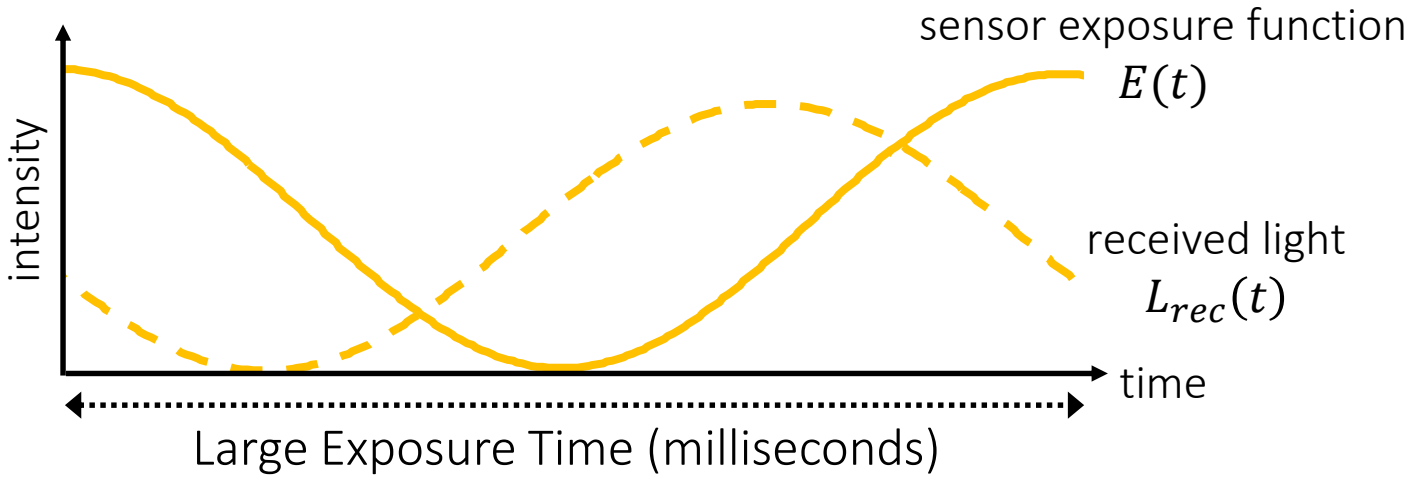
$$L_{rec}(t) = O_{rec} + A_{rec}\cos(\omega t - \phi_{rec})$$

# Measuring phase shift: direct




Low Signal-to-Noise-Ratio

# Measuring phase shift: correlation



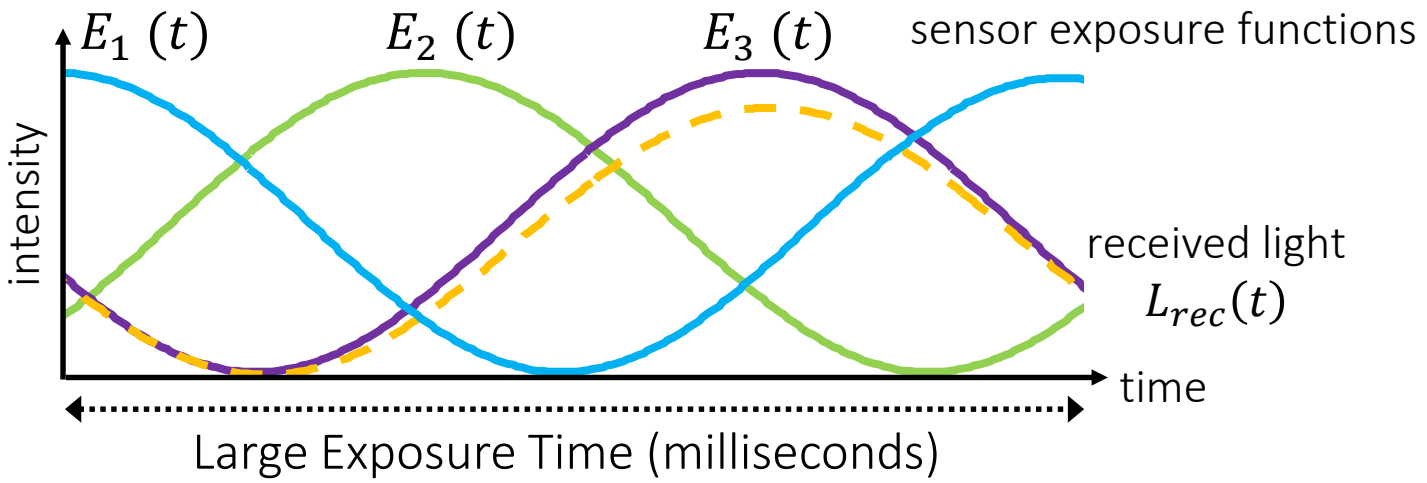

Correlation: $I = \int E(t) \times L_{rec}(t)\, dt$

measured brightness

exposure function

received light

# Measuring phase shift: correlation




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

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

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

→ $depth$

$phase\ \varphi_{rec}$

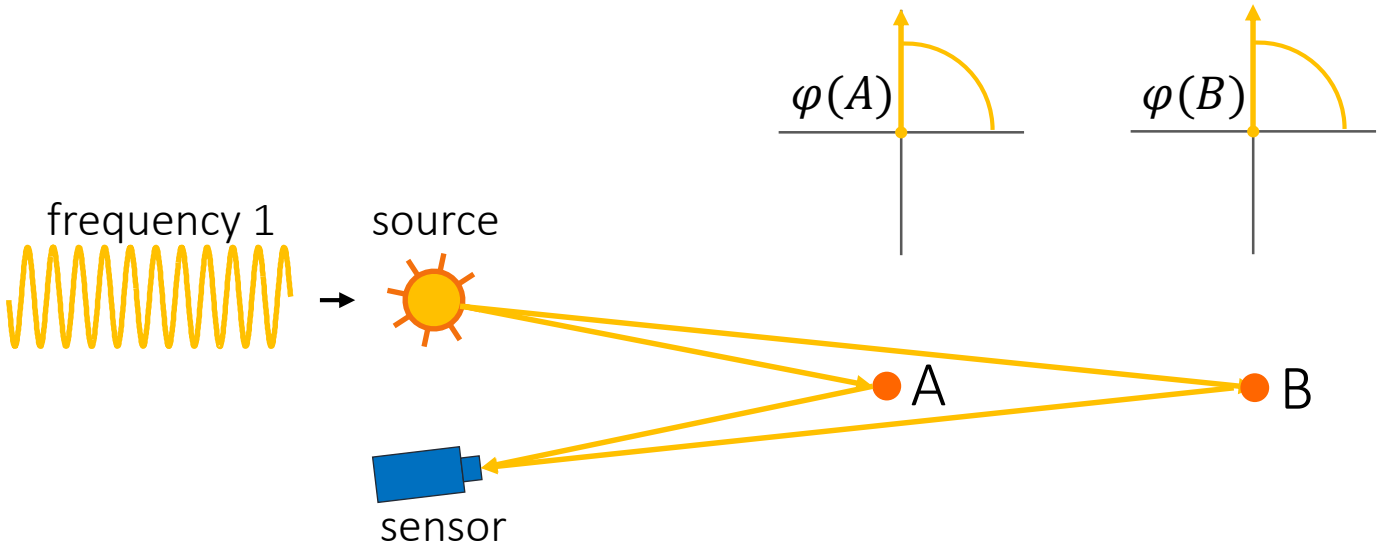
$offset\ O_{rec}$

$amplitude\ A_{rec}$

~~High Signal-to-Noise Ratio~~

~~Real Time Capture~~

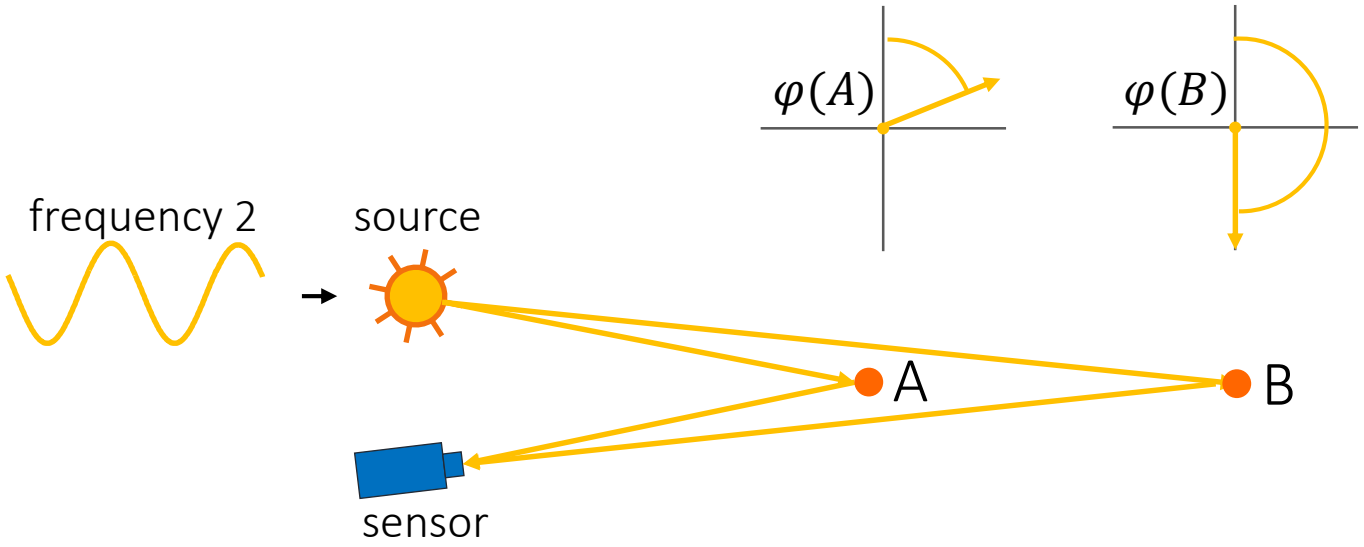
# Phase ambiguity




Different Scene Depths Have Same Phase

- Also known as “phase wrapping”.

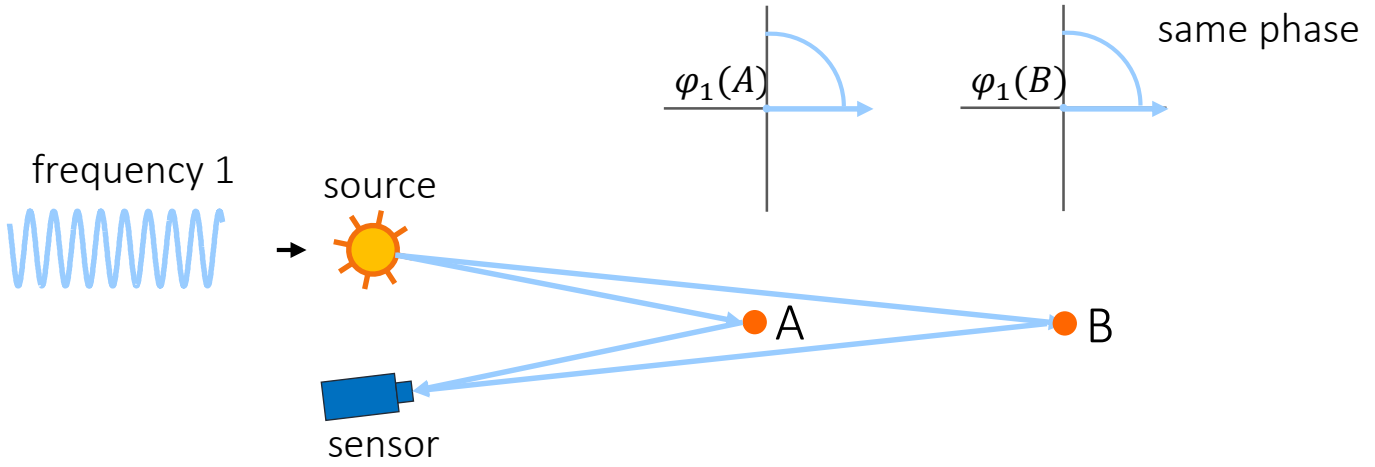
# Phase ambiguity

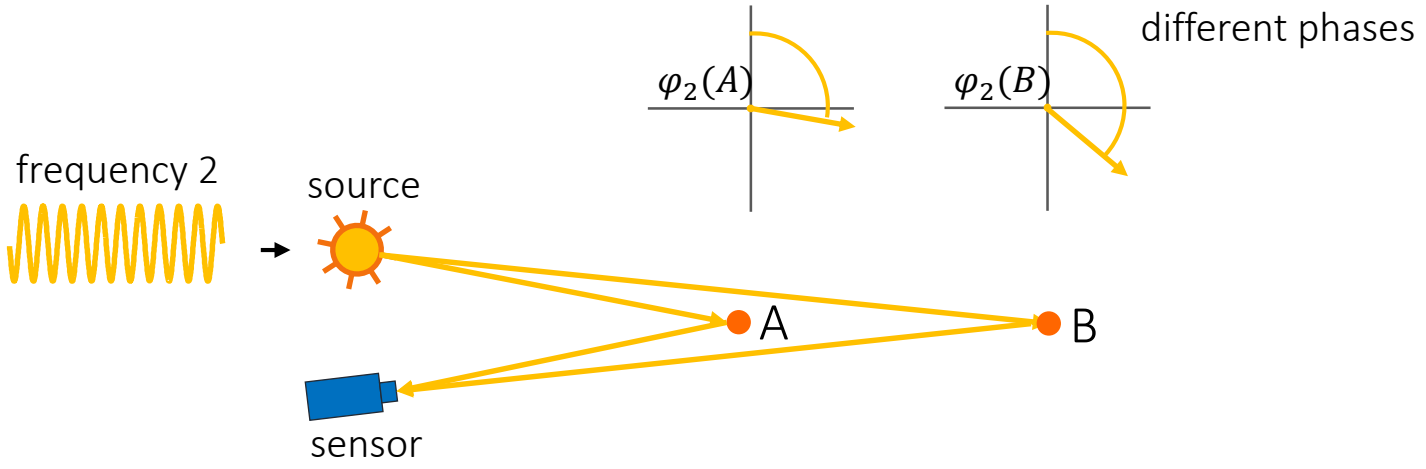



Unambiguous Depth Range: $R_{unambiguous} = \frac{1}{2\omega}$

How can we resolve the phase ambiguity?

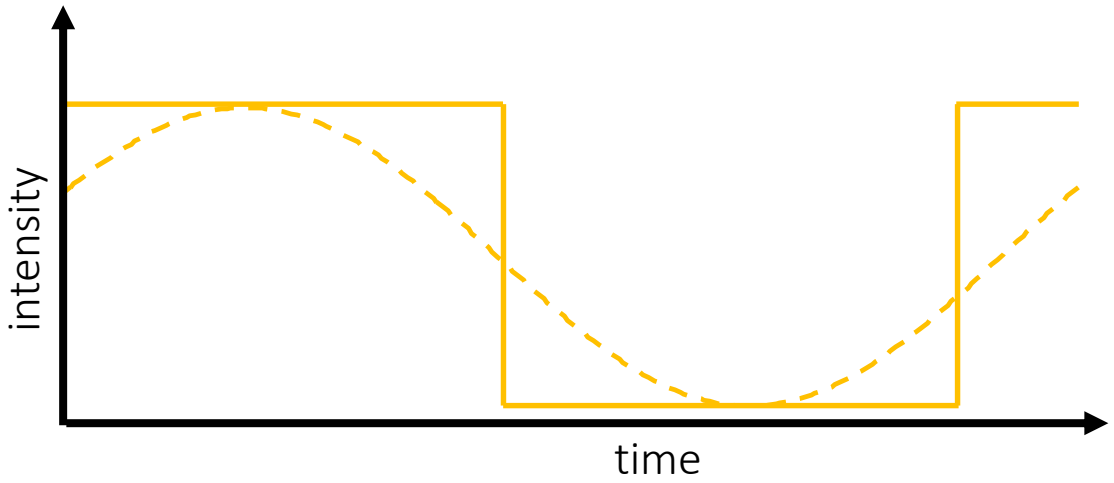
# Disambiguating phase



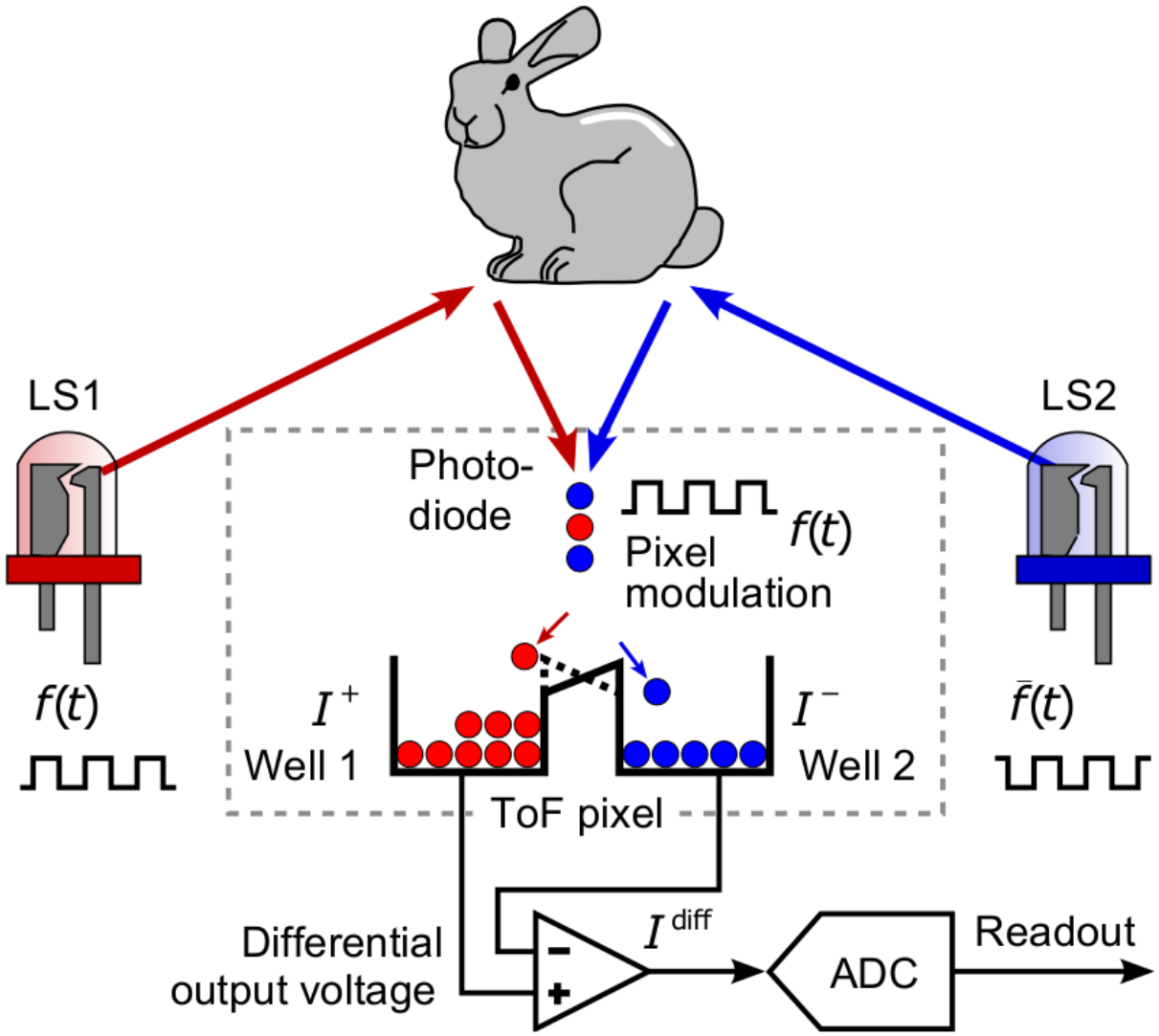




Compute phases at two different frequencies

# 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

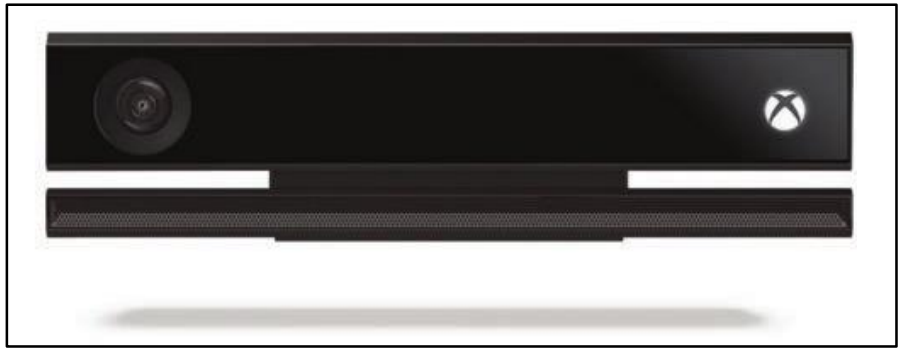


# Some examples

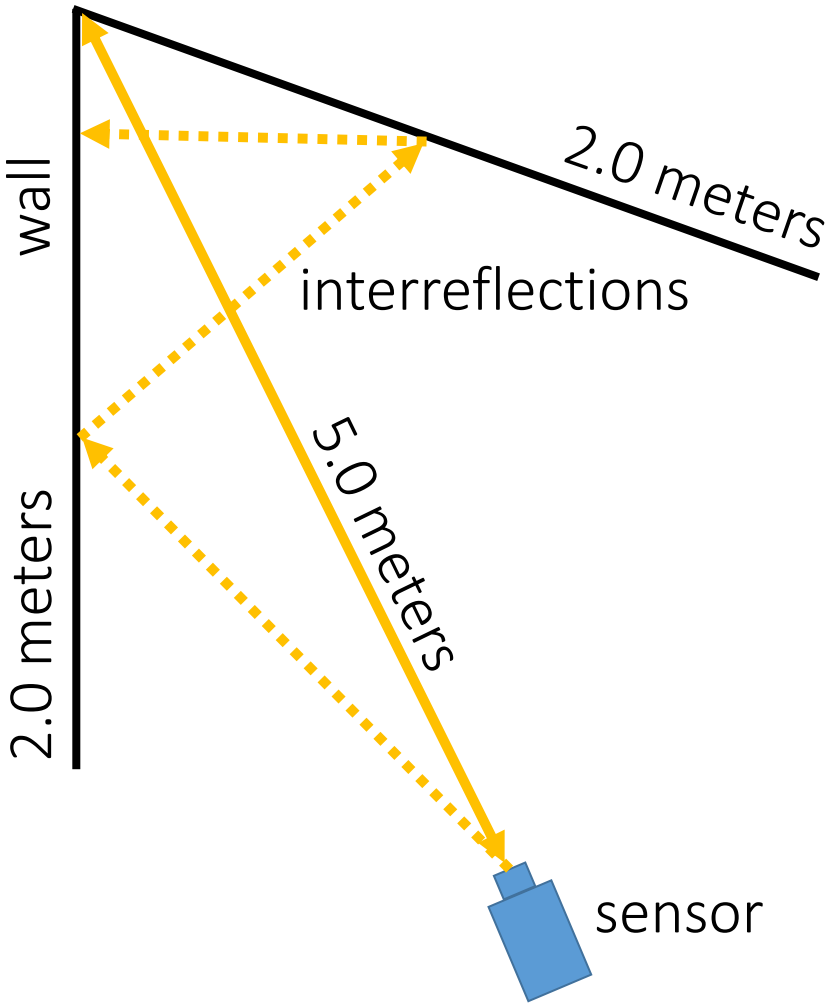
light source
(bank of laser diodes)

sensor
(PMD CamBoard Nano)

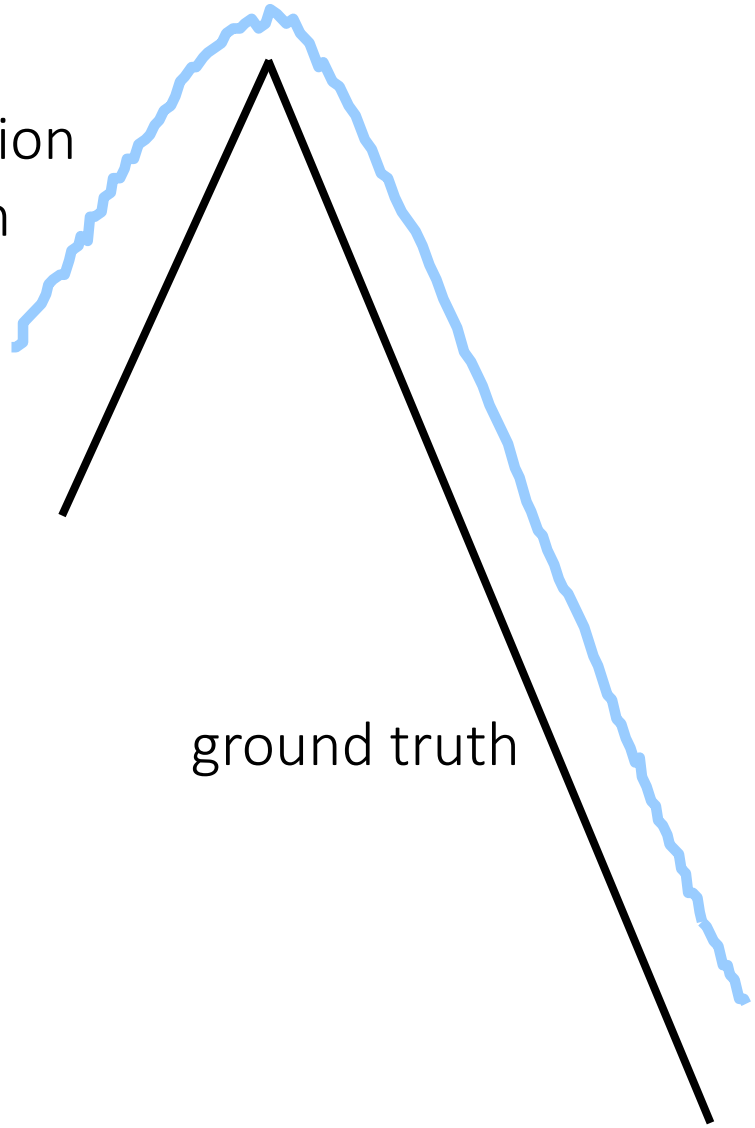
(only second generation of Kinect uses CW ToF)



# Multi-path interference

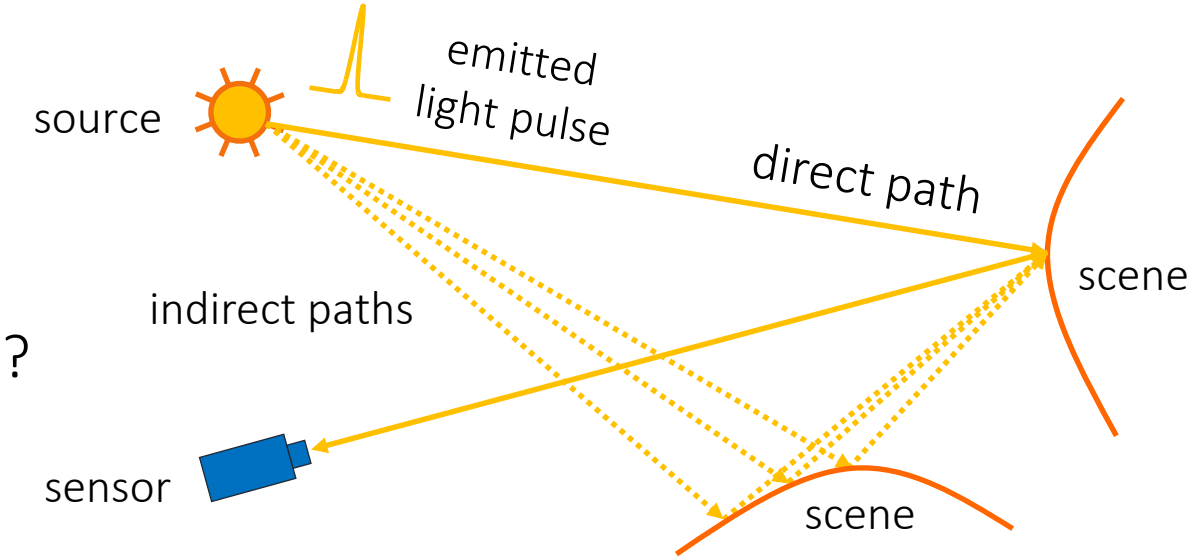


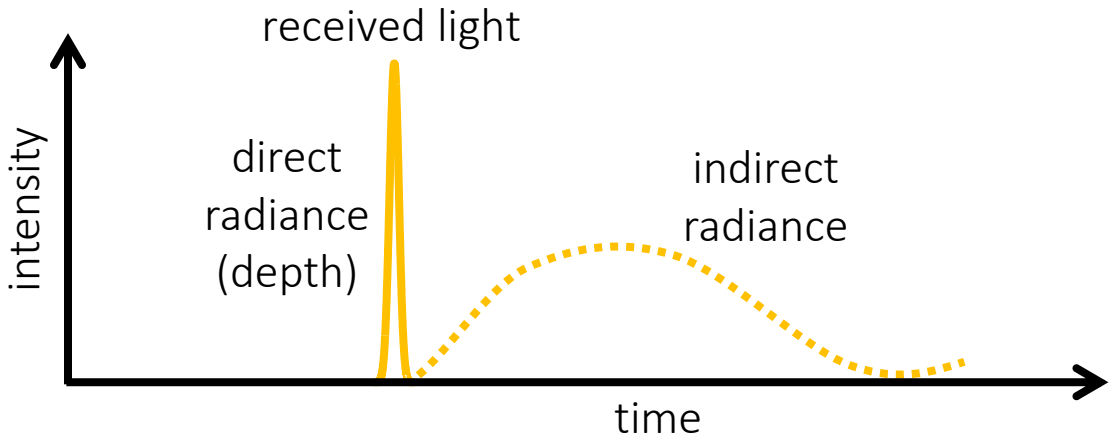

ToF depth reconstruction
mean error = 86.6 mm



# Transient imaging with continuous-wave ToF

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



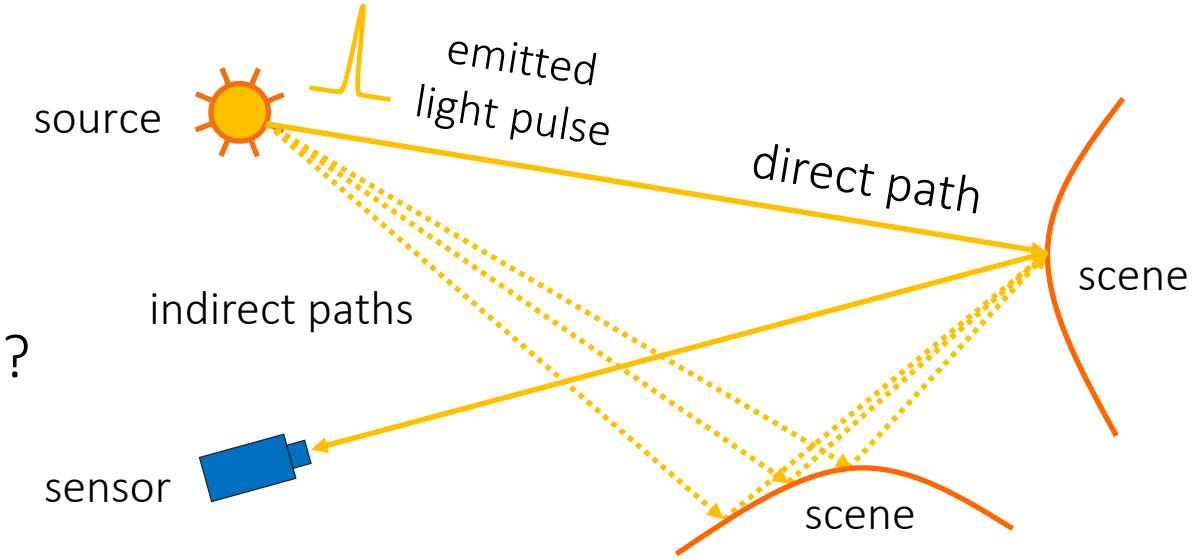



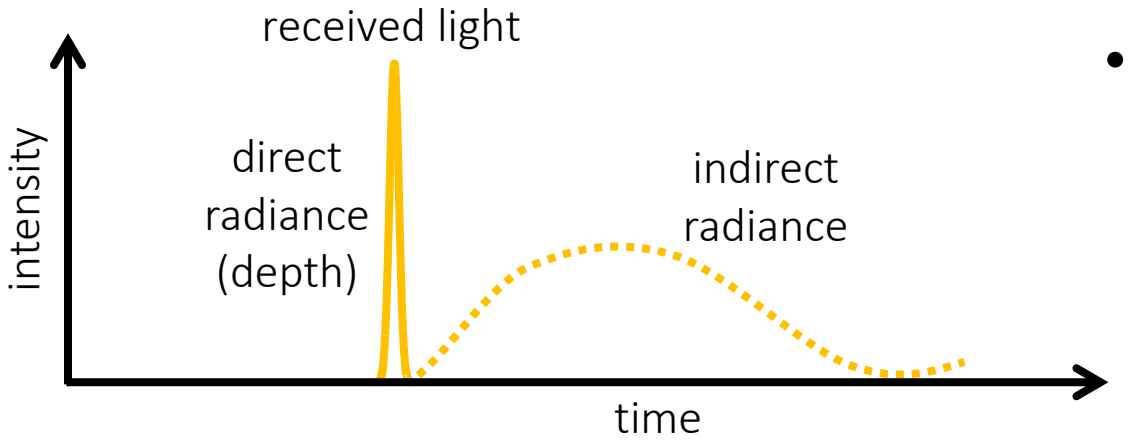

Transient I(t): Time-resolved radiance distribution

- 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?



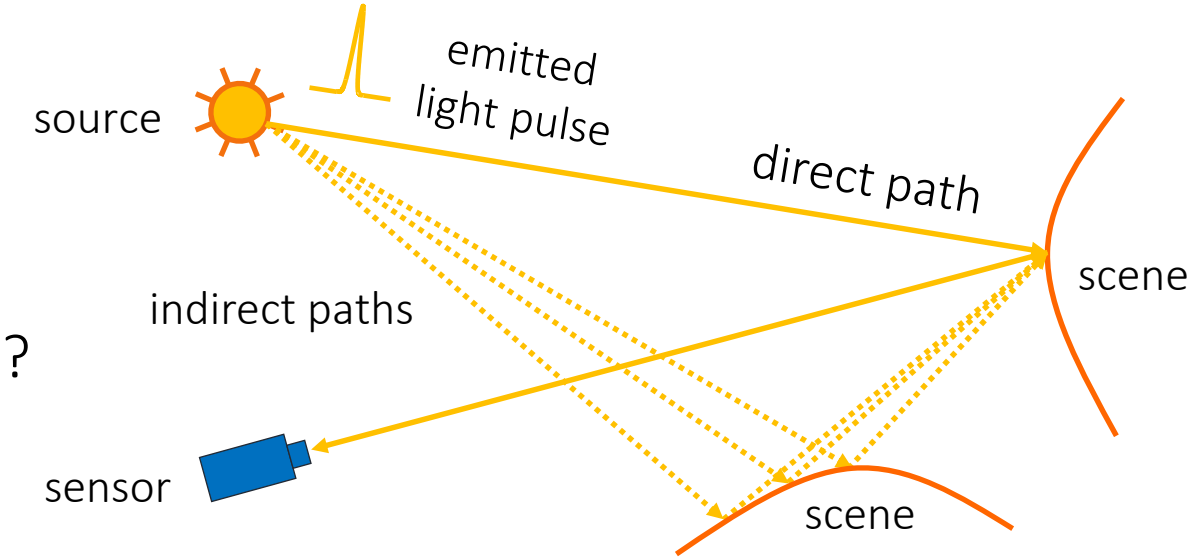

Transient I(t): Time-resolved radiance distribution

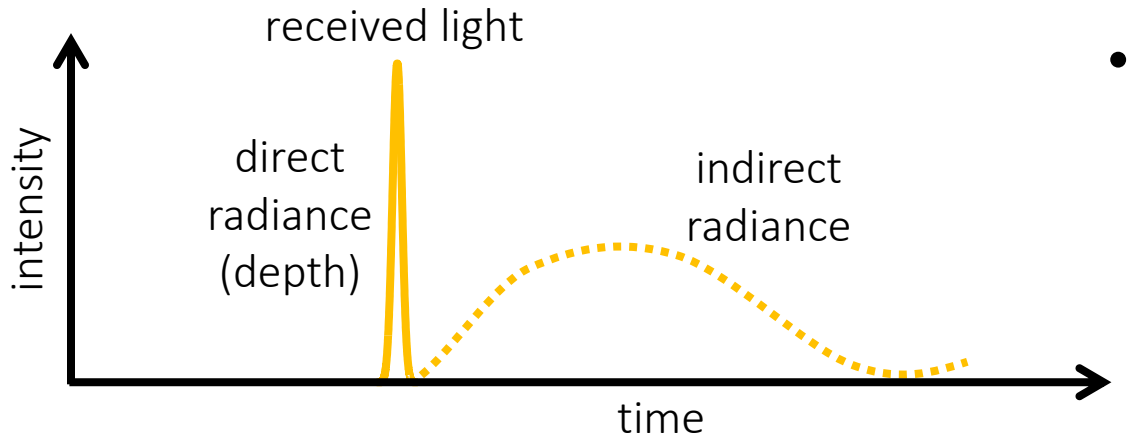
- Each measurement we capture is of the form:

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

# Transient imaging with continuous-wave ToF

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




Transient I(t): Time-resolved radiance distribution

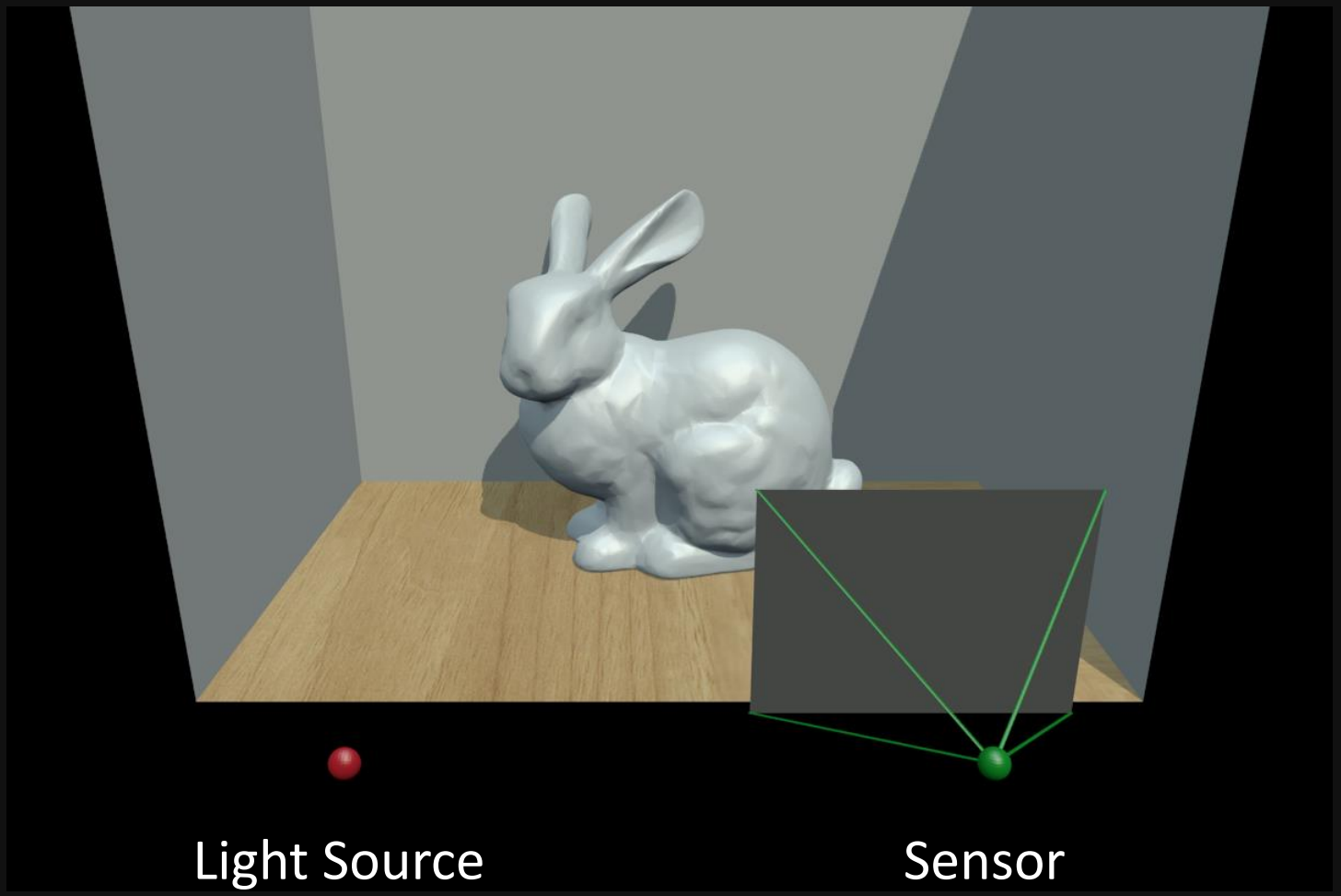
- Each measurement we capture is of the form:

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

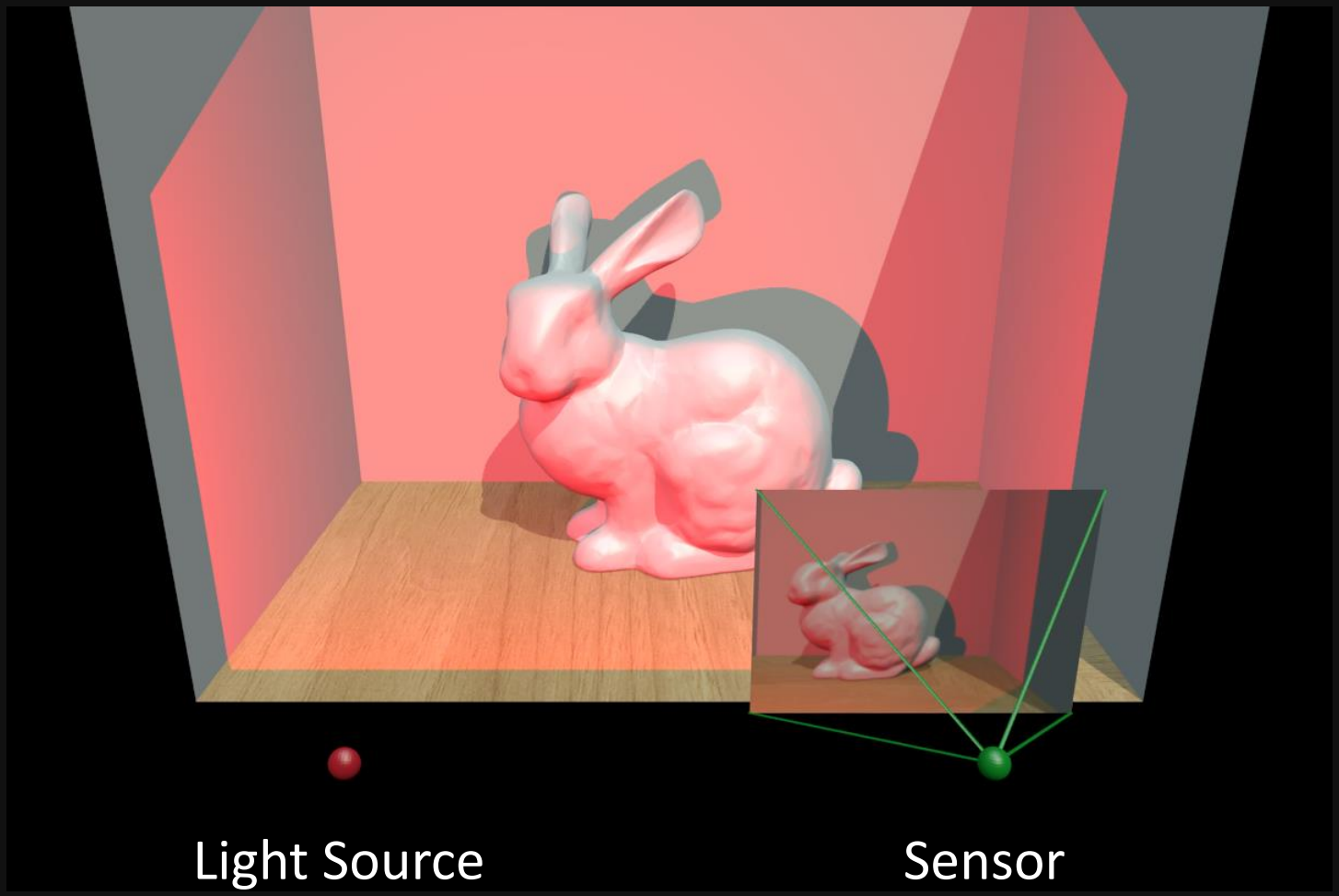
We can do transient imaging by taking measurements at multiple frequencies ω, then doing an inverse Fourier transform

# Epipolar continuous-wave ToF imaging

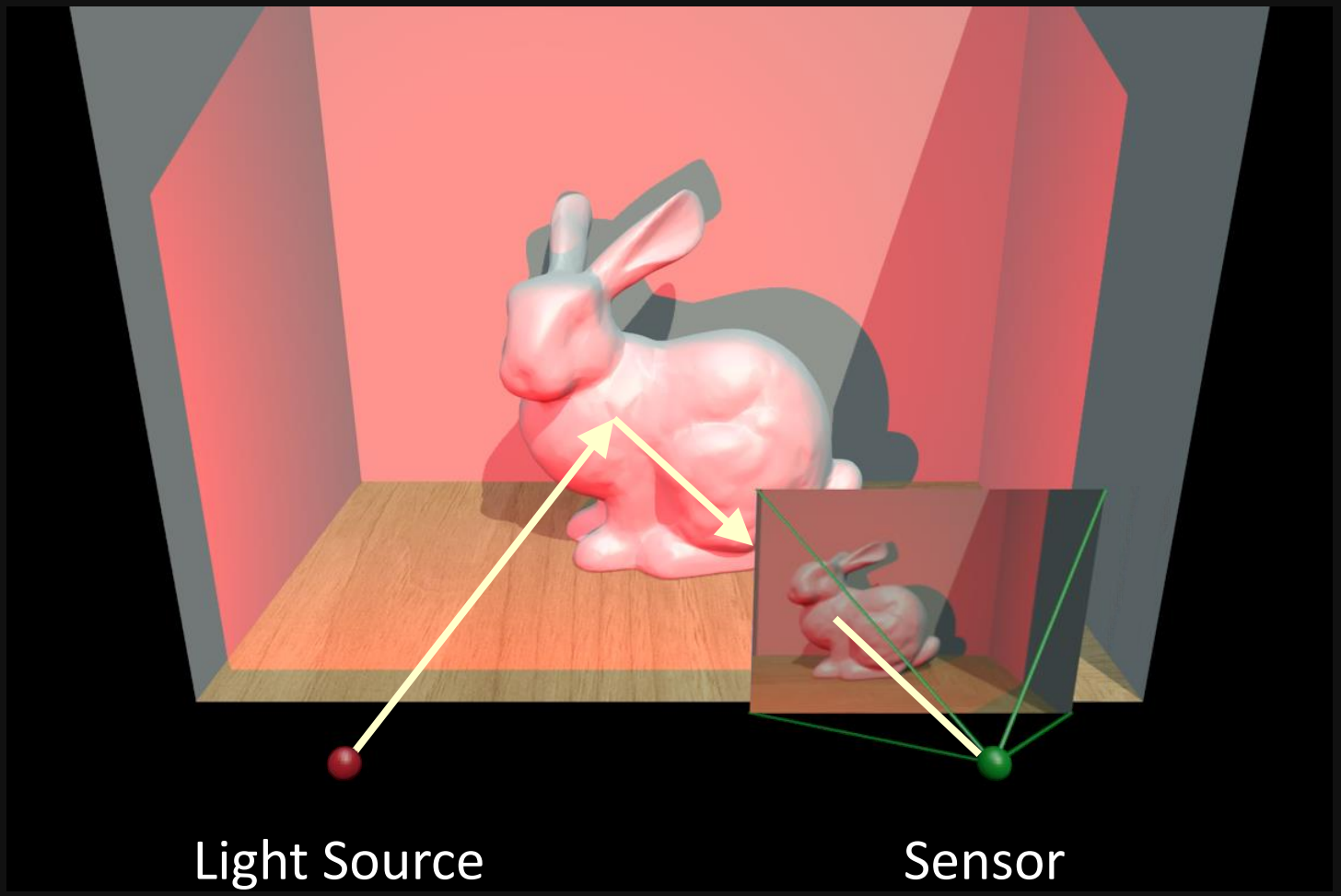
# Regular Imaging



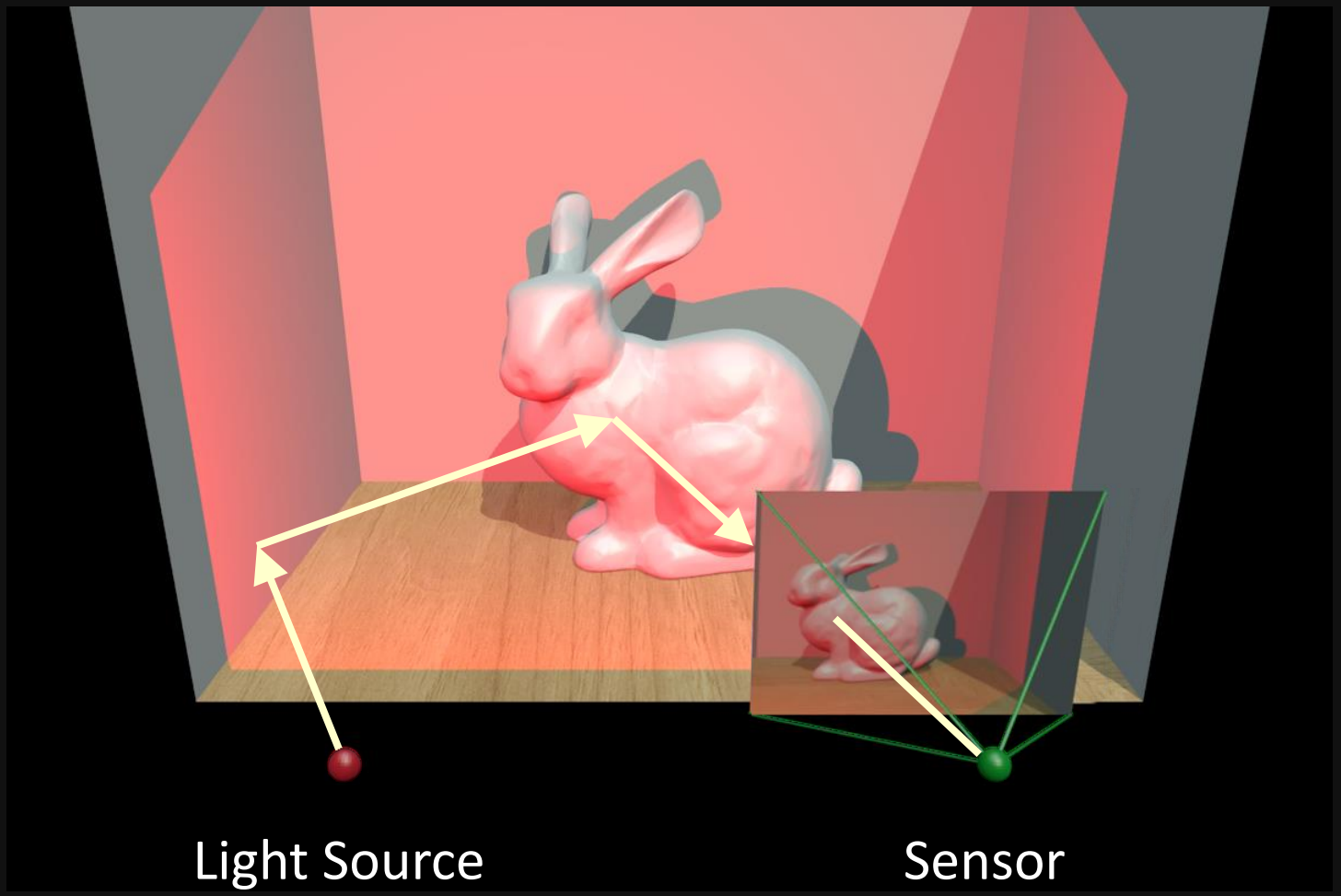
# Regular Imaging



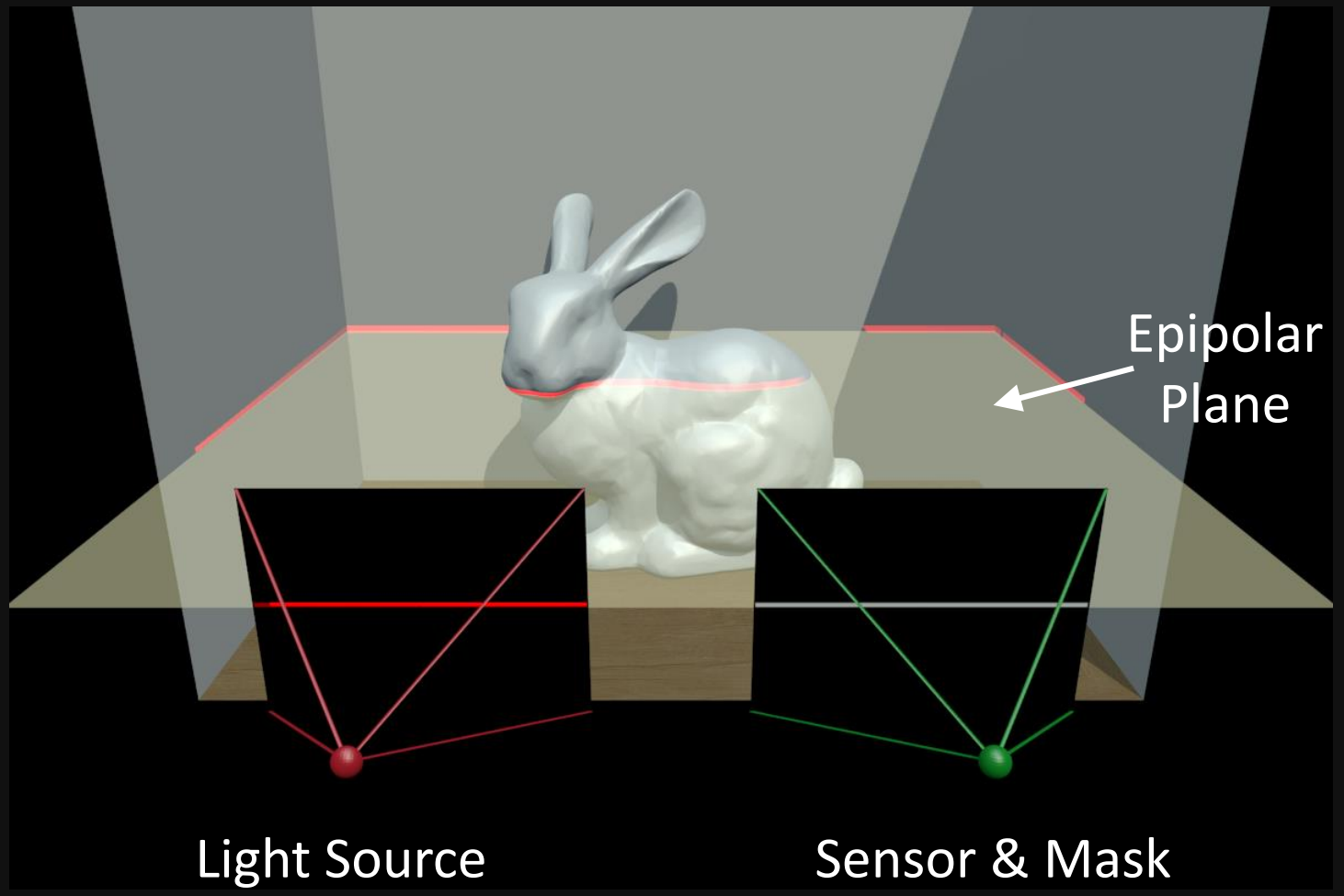
# Regular Imaging



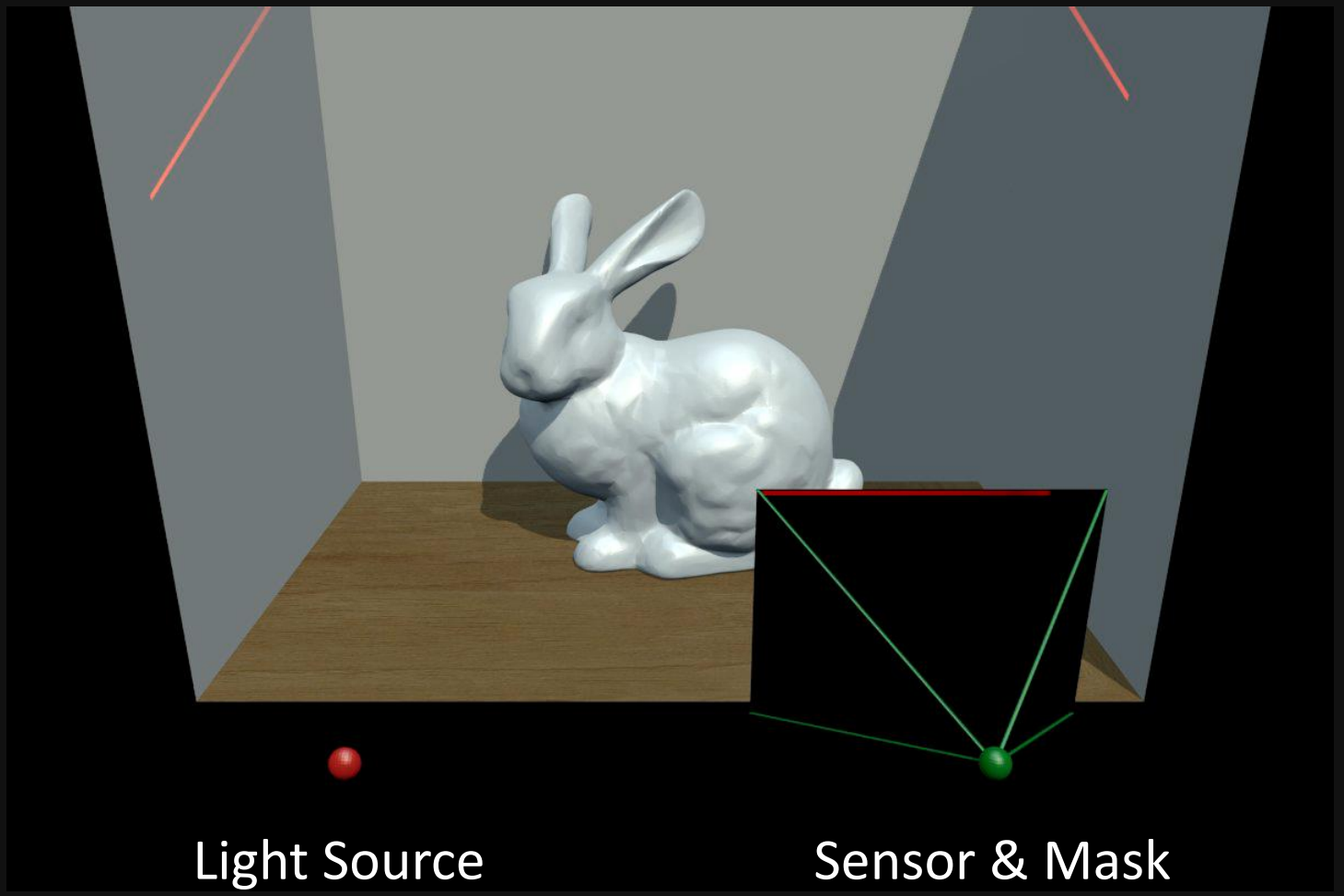
# Regular Imaging



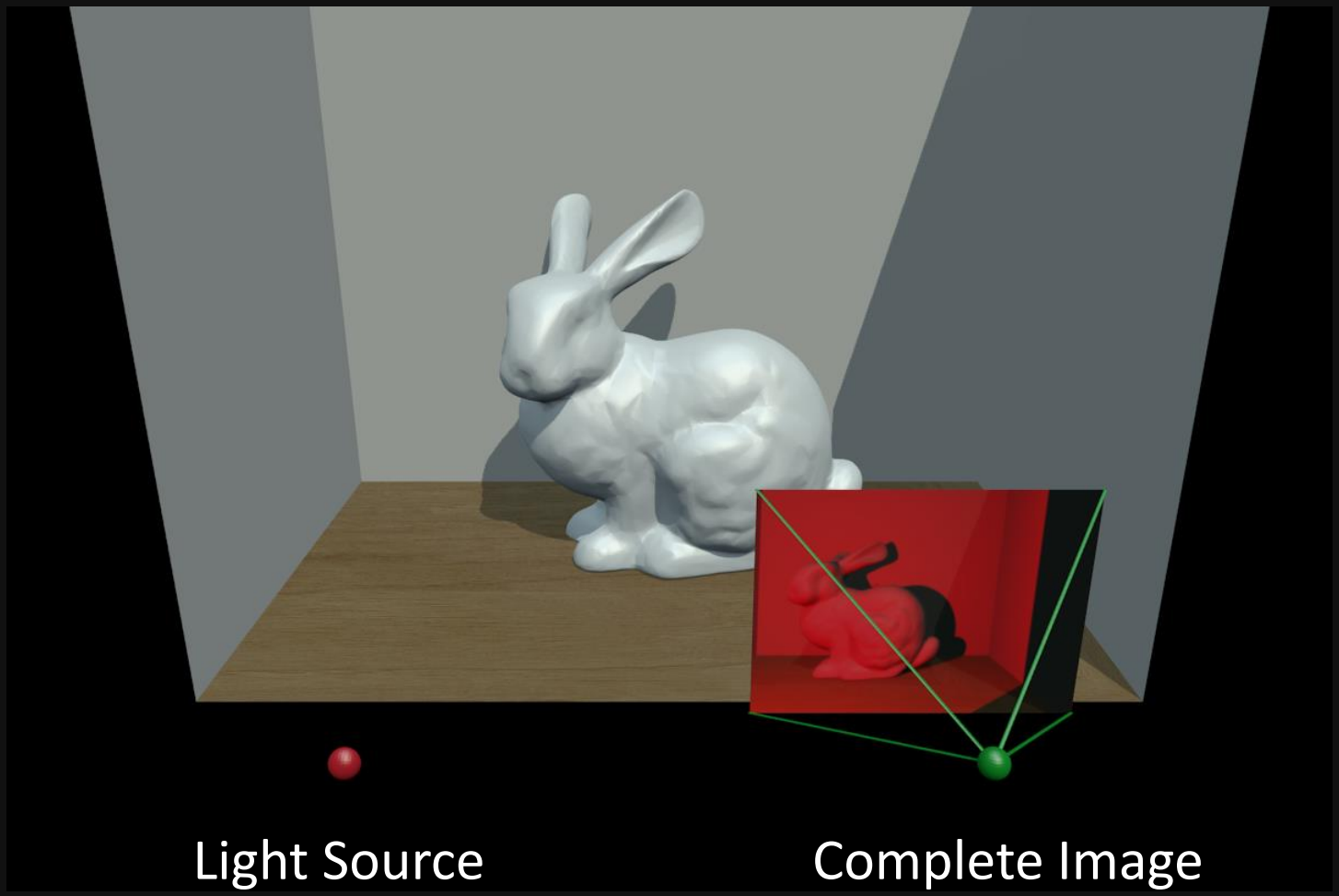
# Epipolar Imaging



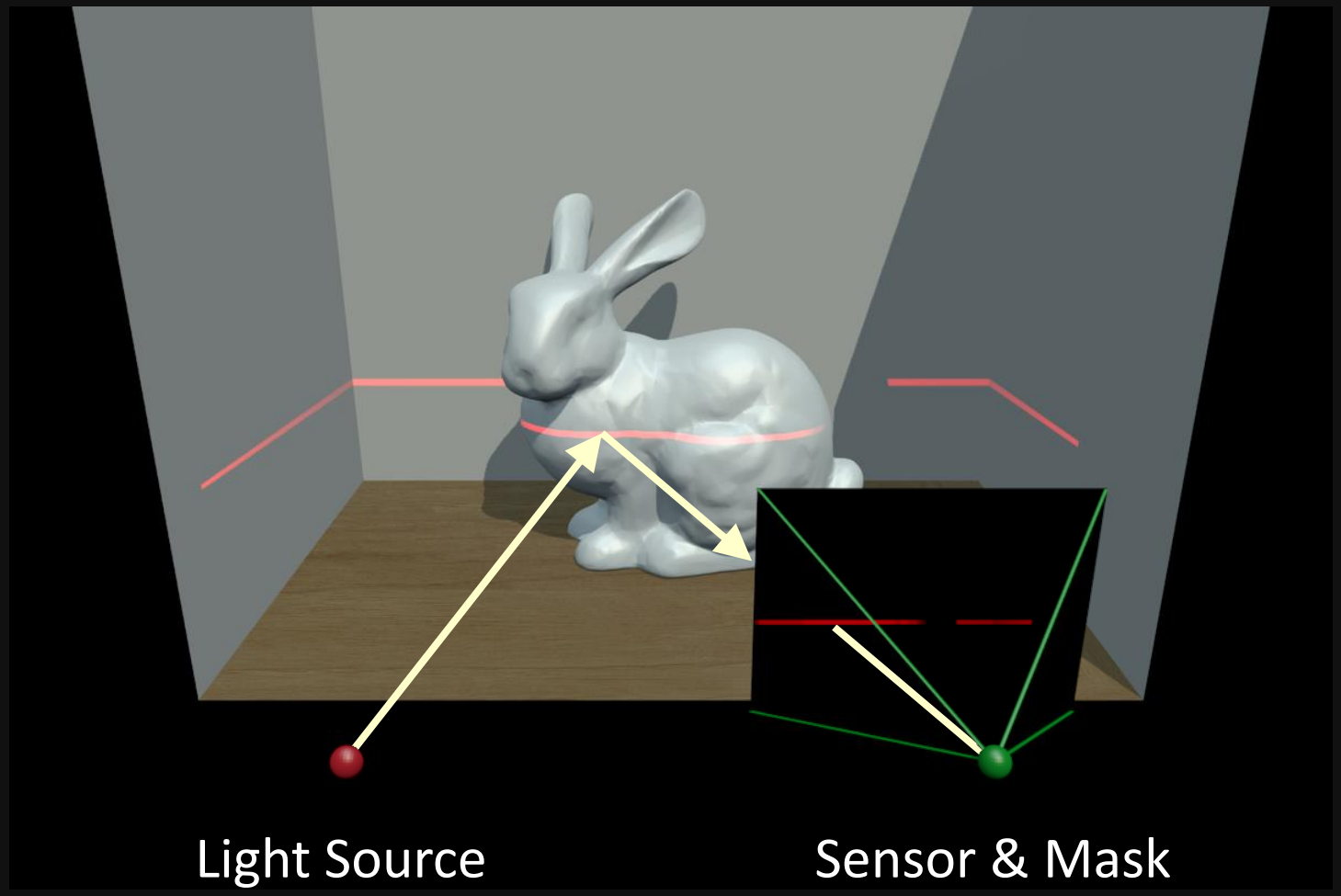
# Epipolar Imaging



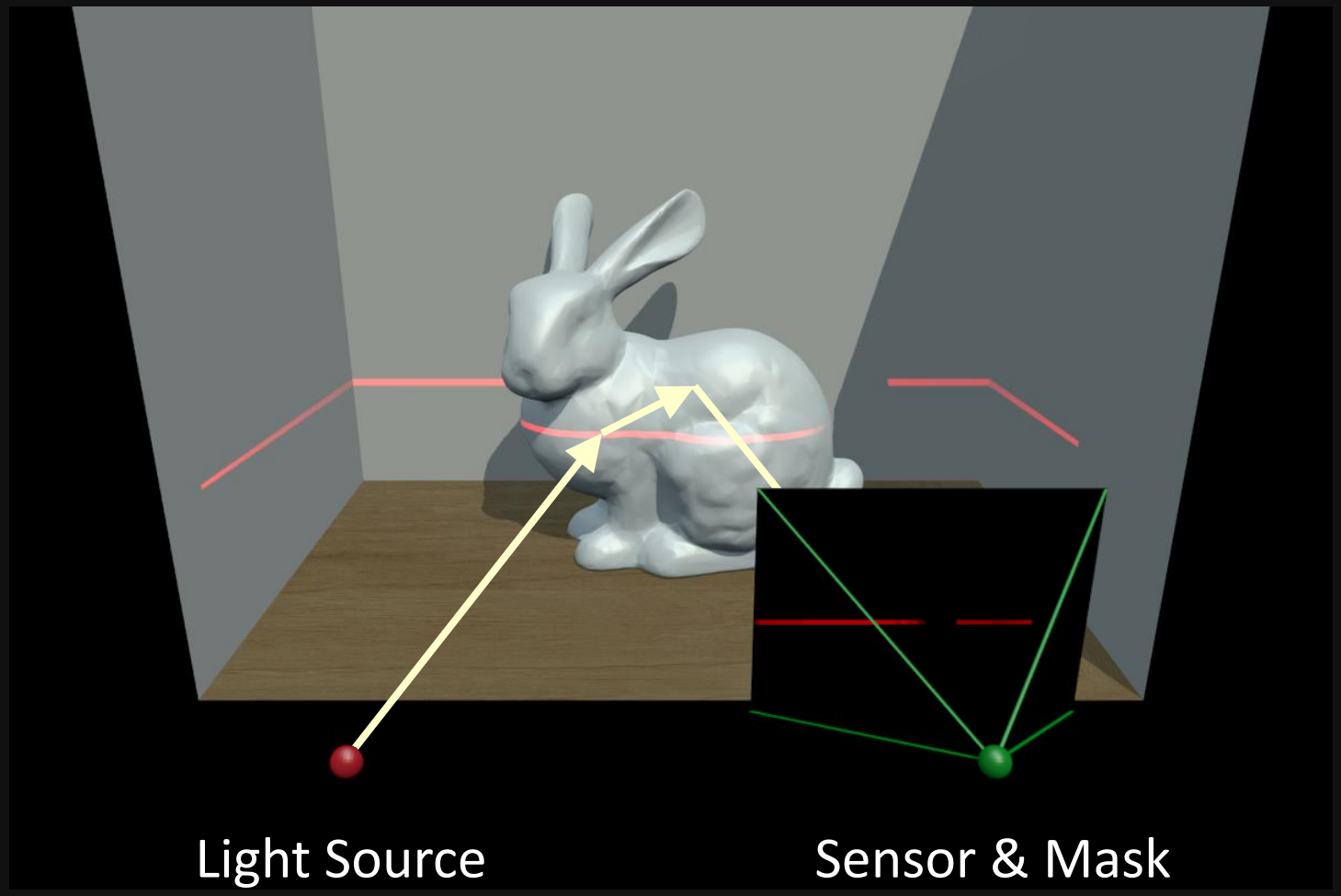
# Epipolar Imaging



# Epipolar Imaging

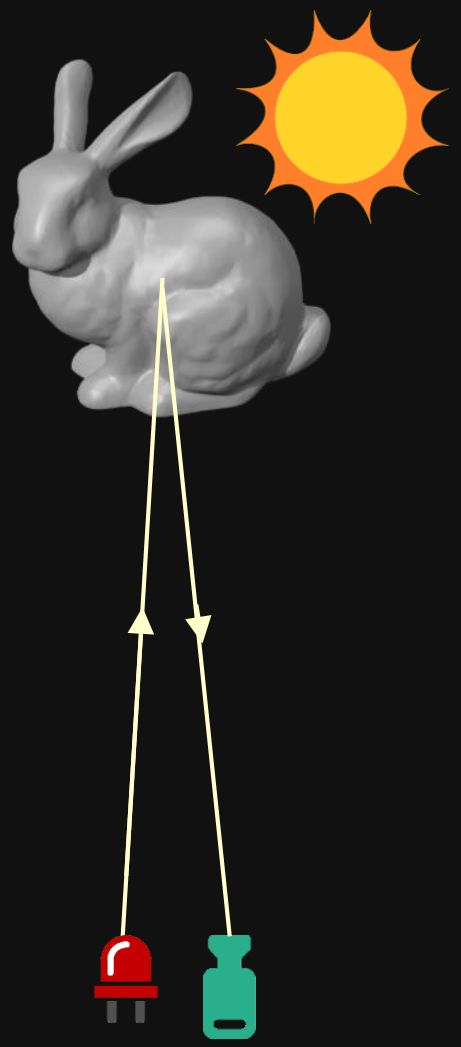


# Epipolar Imaging

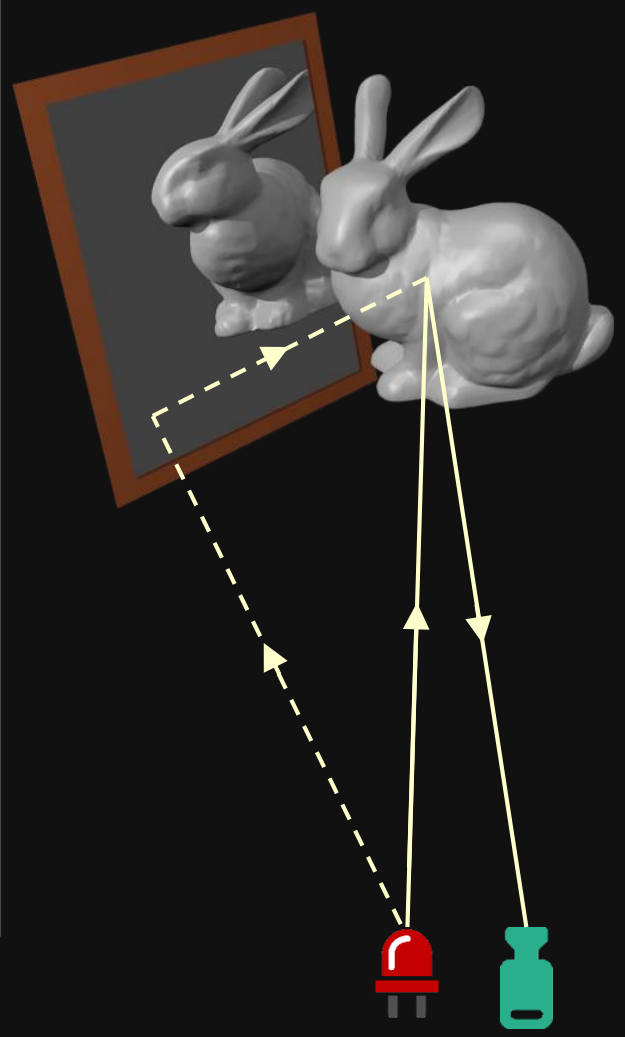


# Benefits of Epipolar ToF Imaging

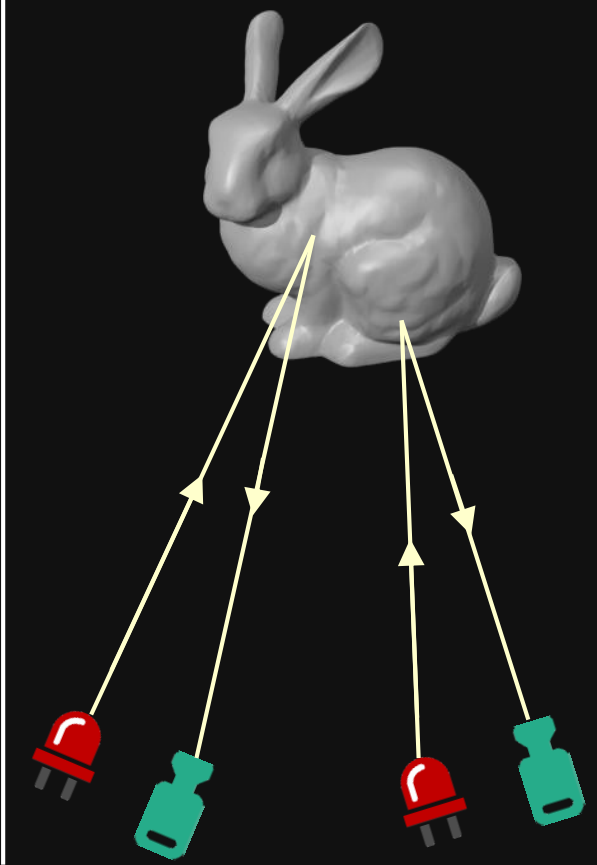
Ambient Light



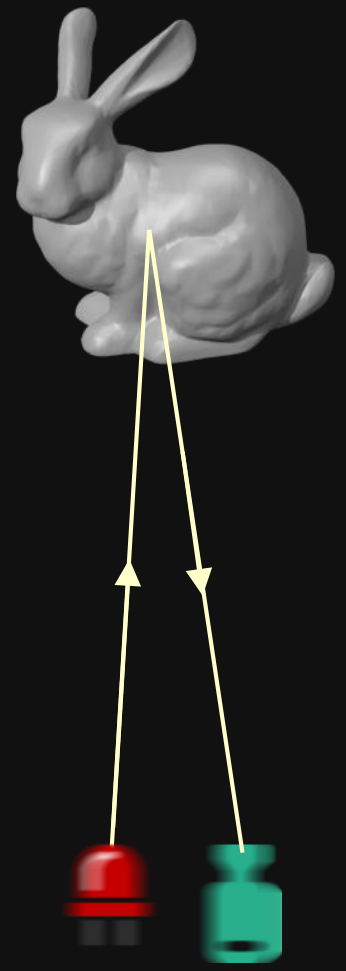
Multi-Path Interference



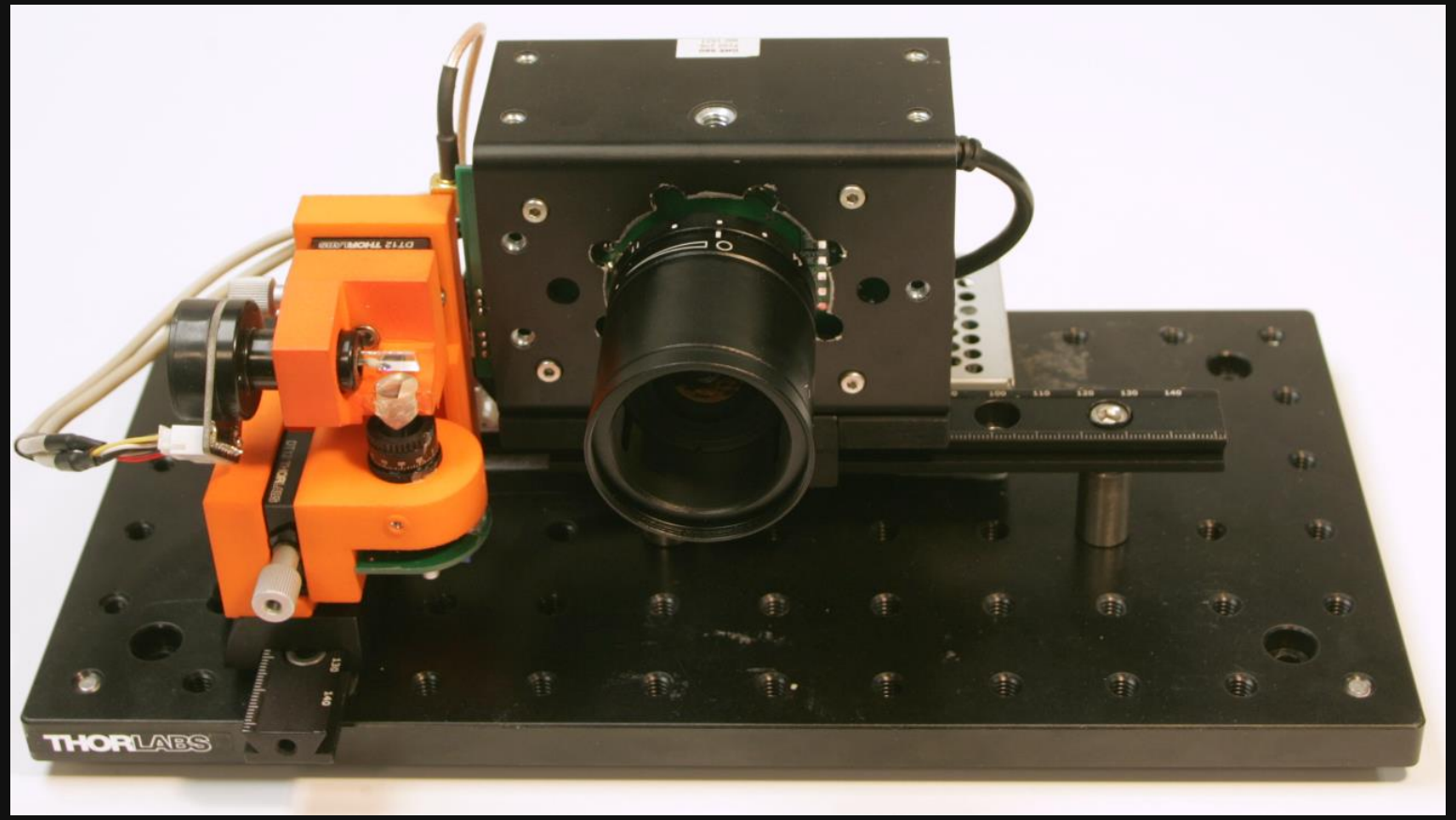
Multi-Device Interference



Camera Motion

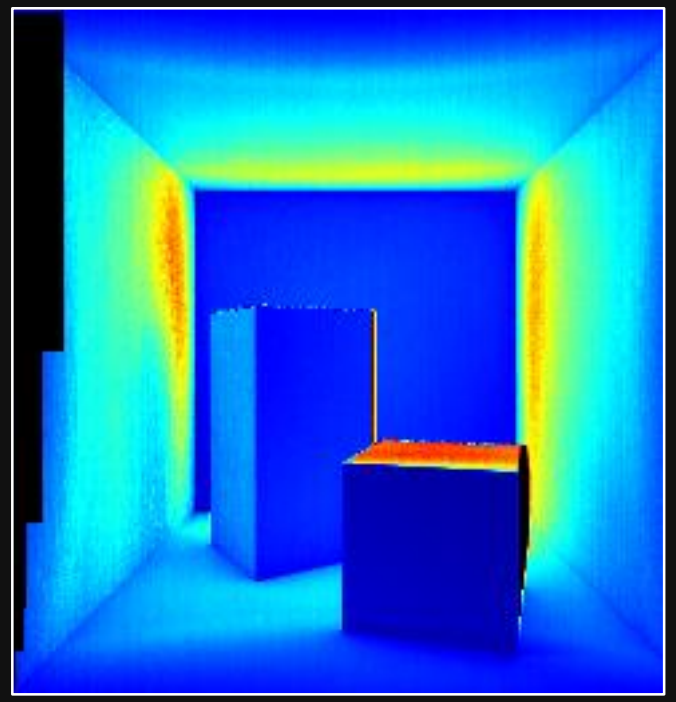


# Epipolar ToF Prototype

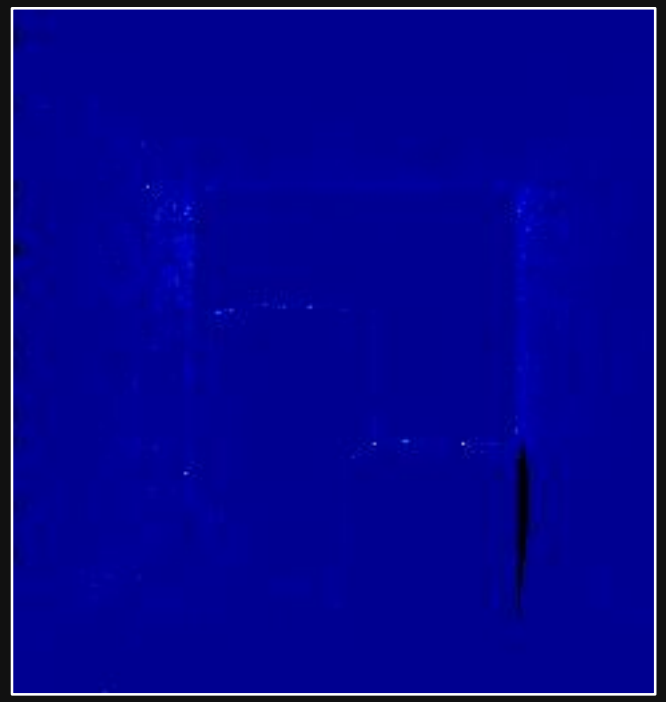


# Epipolar ToF and Global Illumination

Depth Errors (in meters)



Regular ToF @ 30MHz



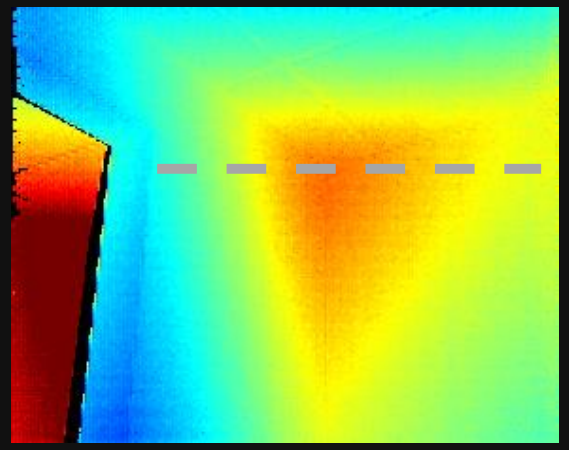
**Epipolar ToF @ 30MHz**

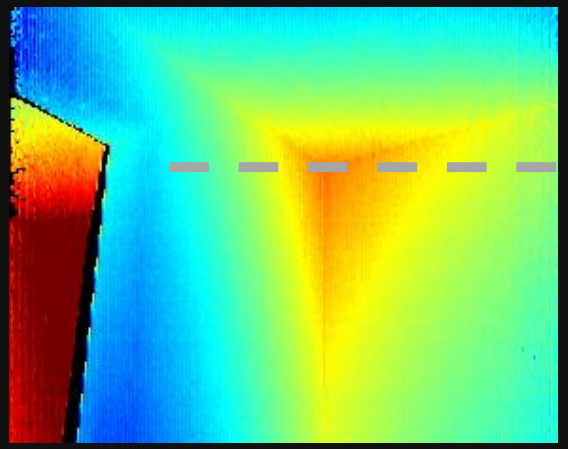
# Epipolar ToF and Global Illumination

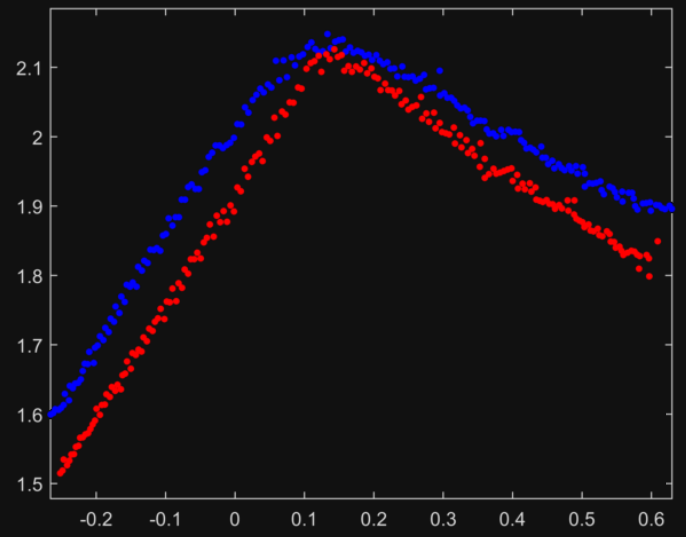
Regular ToF

Epipolar ToF

Corner of Room







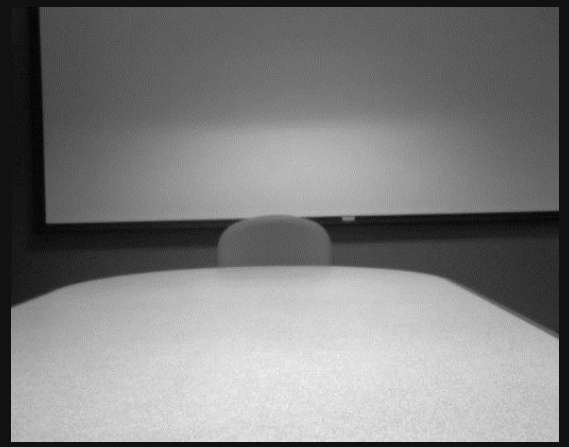

Regular ToF

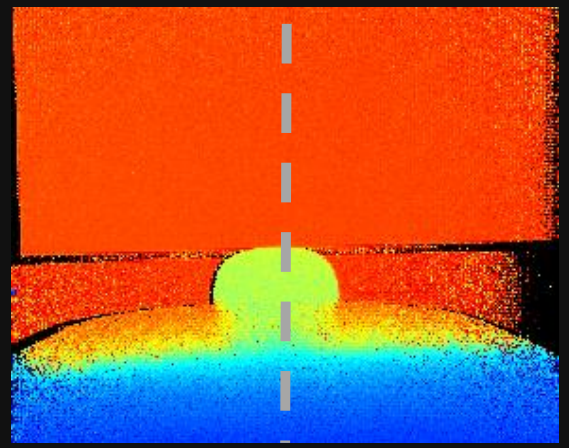
Epipolar ToF

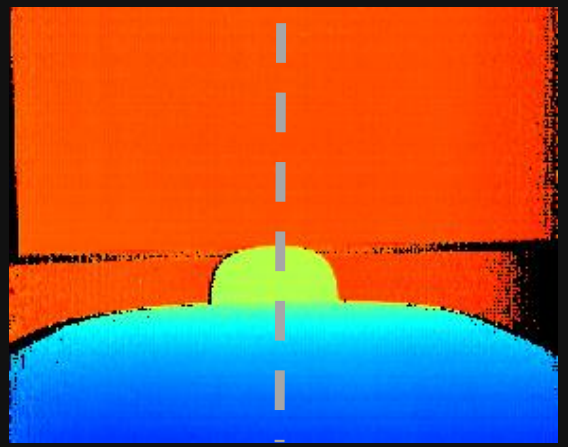
# Epipolar ToF and Global Illumination

Regular ToF

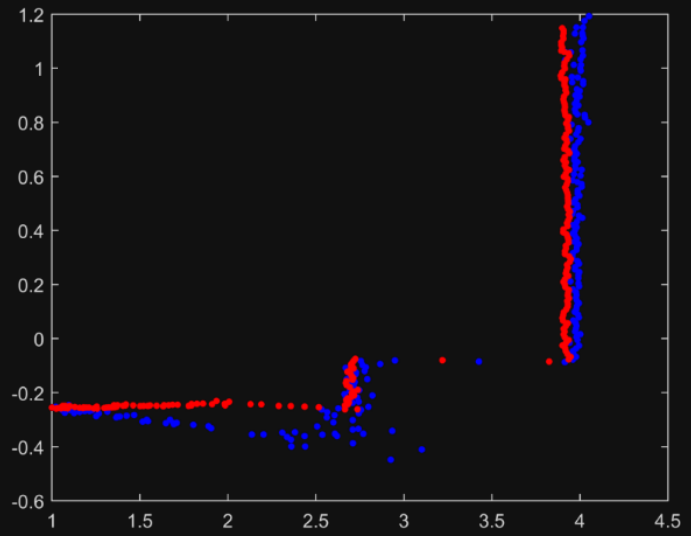
Epipolar ToF







Conference Room




Regular ToF

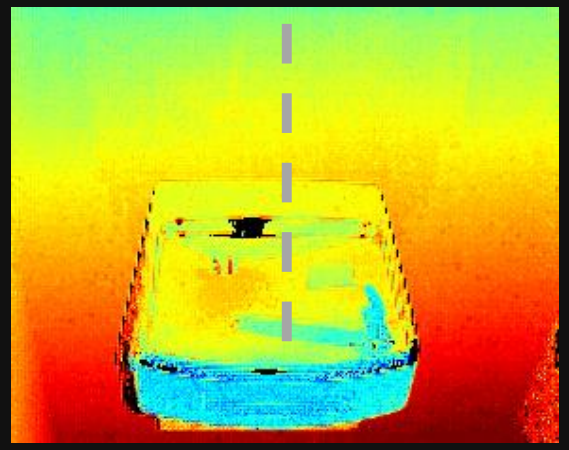
Epipolar ToF

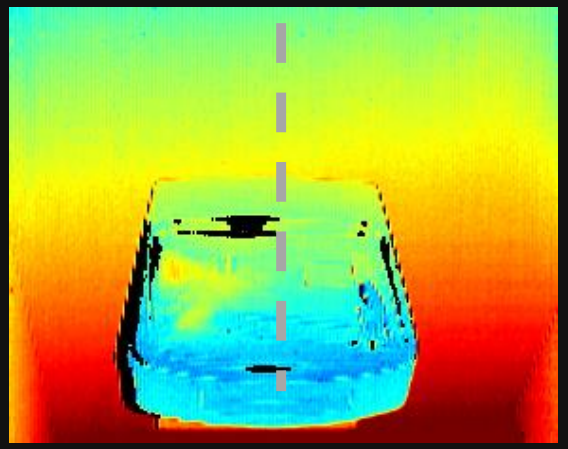
# Epipolar ToF and Global Illumination

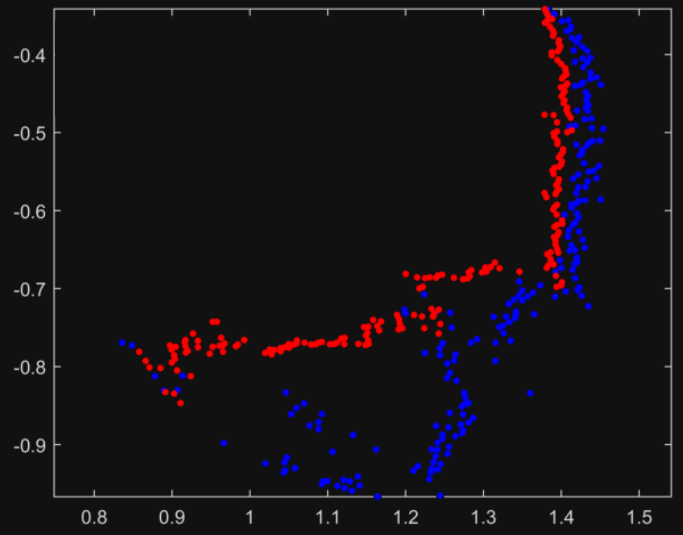
Regular ToF

Epipolar ToF

Water Fountain



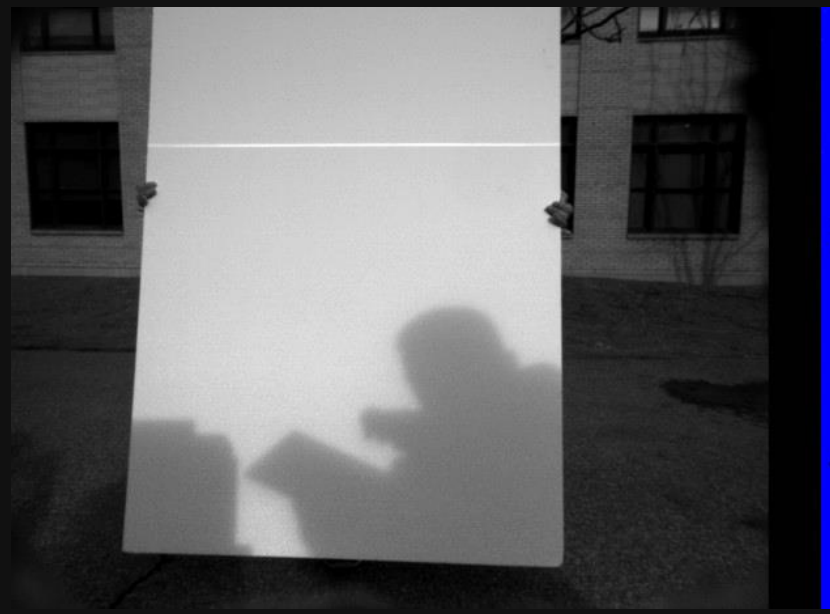




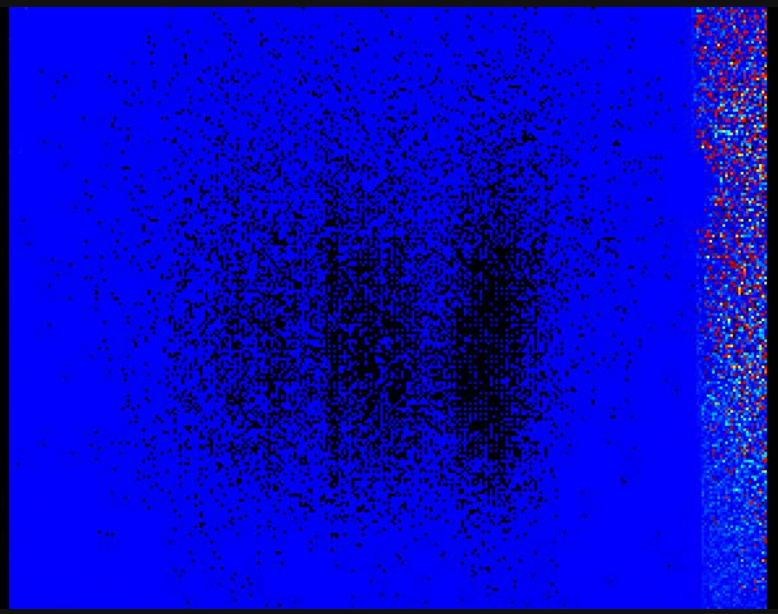

- Regular ToF
- Epipolar ToF

# Outdoors (Cloudy – 10 kilolux)

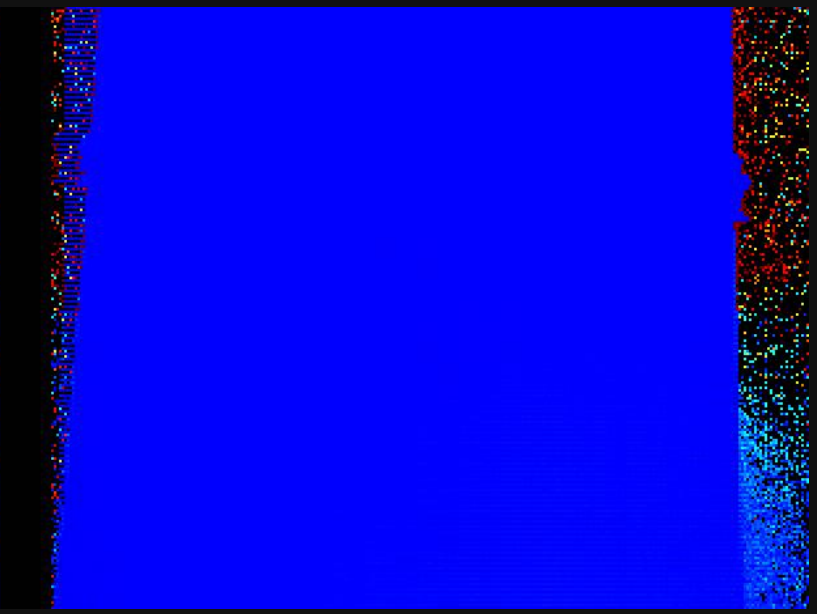
Scene

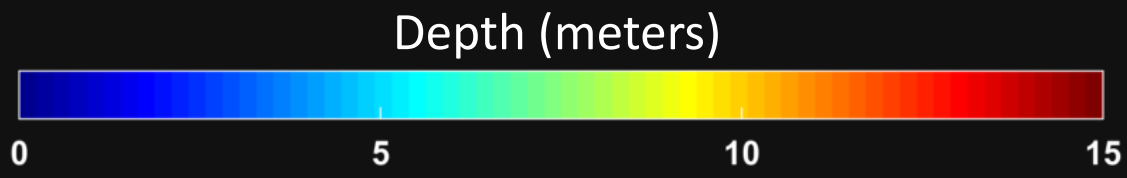


Regular ToF



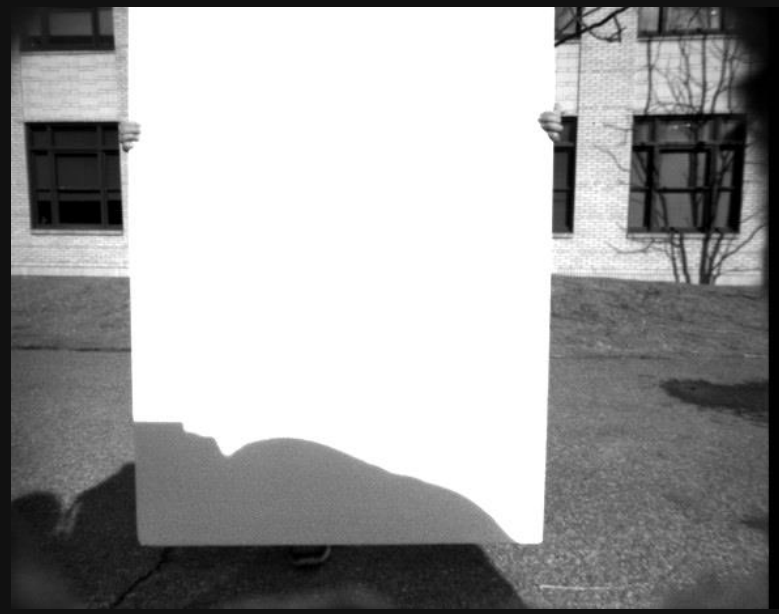
Epipolar ToF



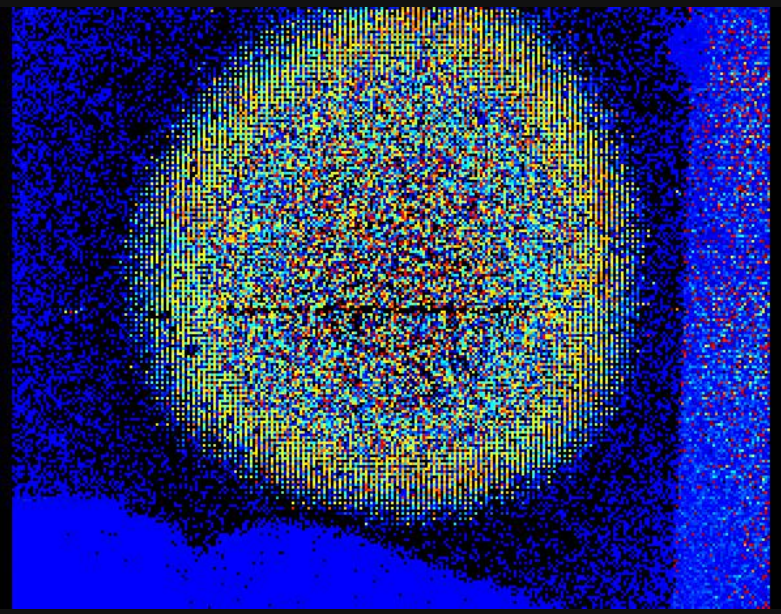


# Outdoors (Sunny – 70 kilolux)

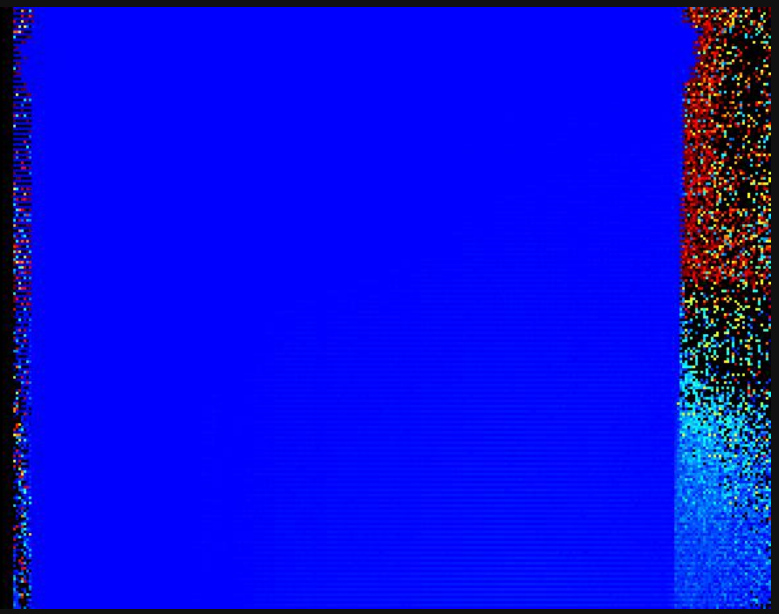
Scene

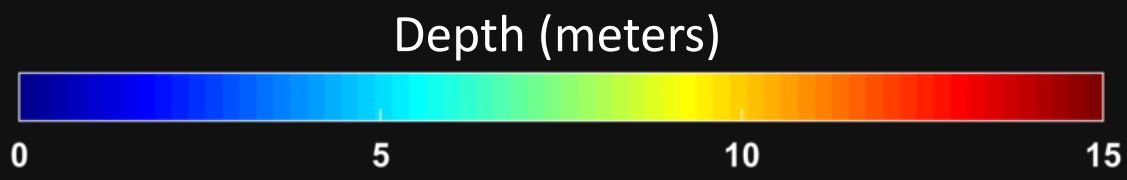


Regular ToF

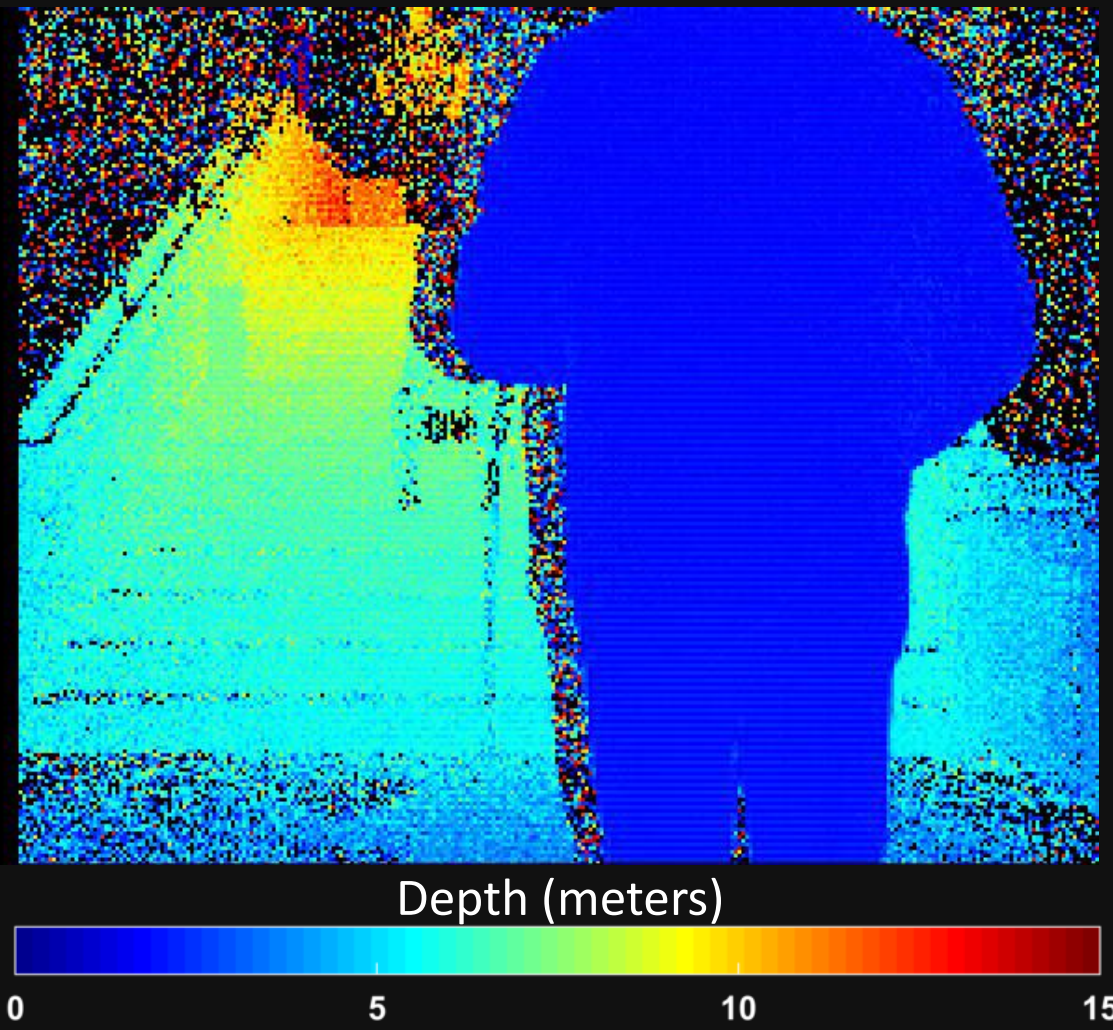


Epipolar ToF

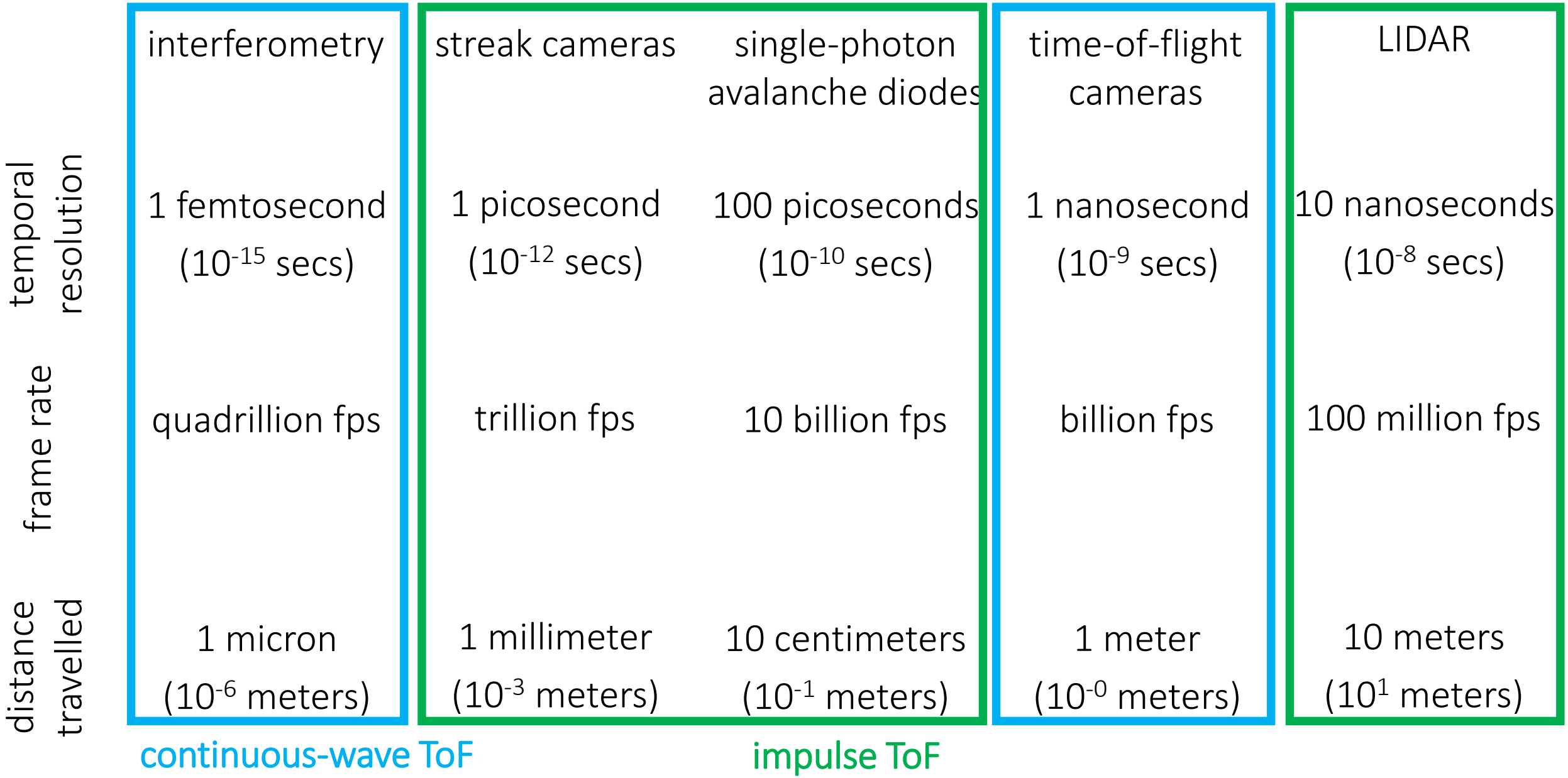




# Outdoors (Sunny – 70 kilolux)

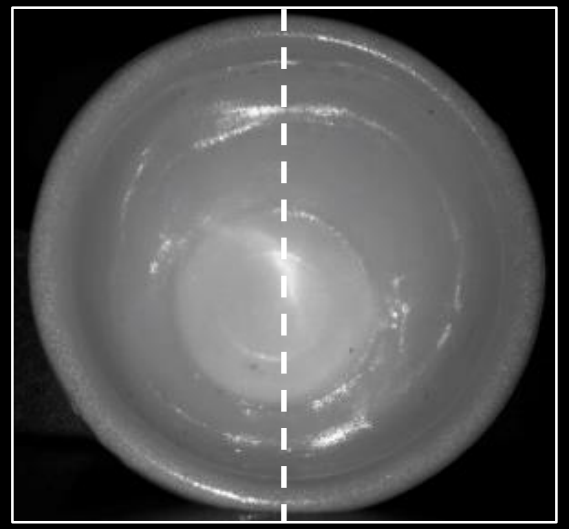


# Time-of-flight imaging technologies



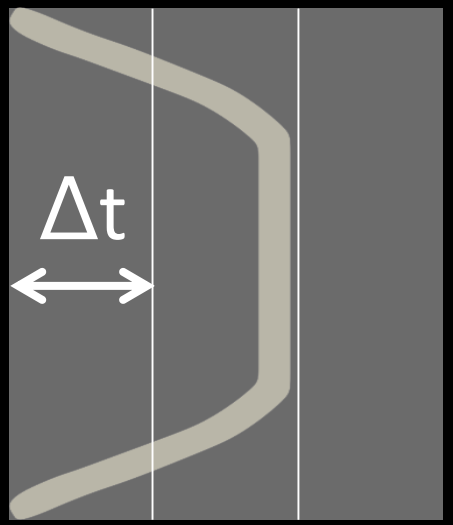
# Interferometric ToF imaging

# Tiny scenes



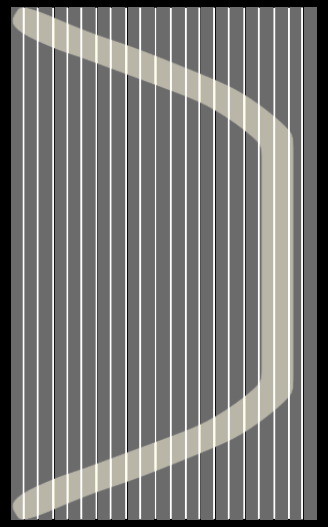
1 cm

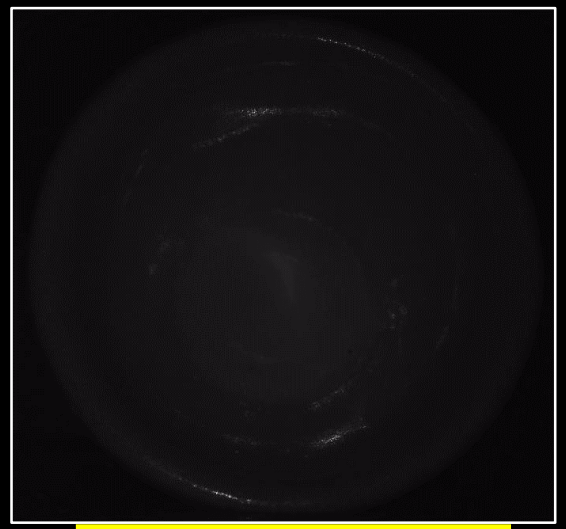
toy cup




0.5 cm

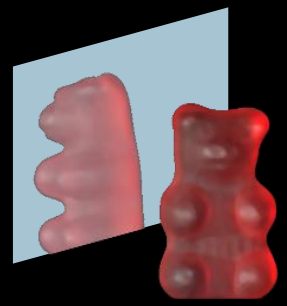
Δt ~ ps





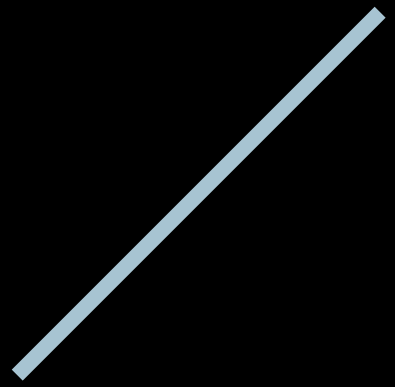
Δt ~ $10^{-3}$ ps

# Interferometry example



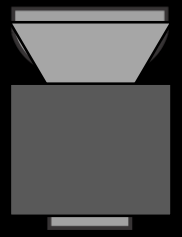
scene

light source



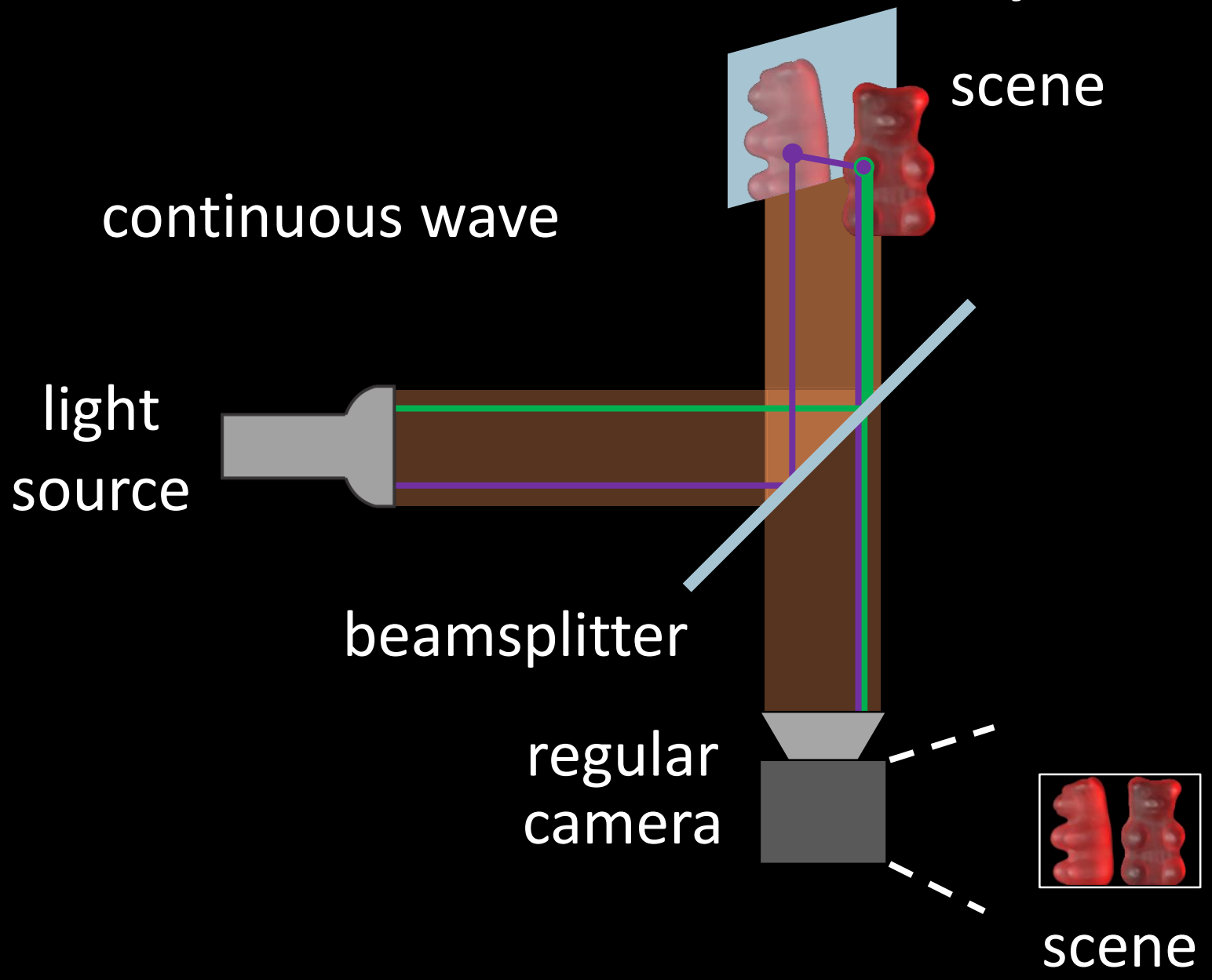
beamsplitter

regular camera

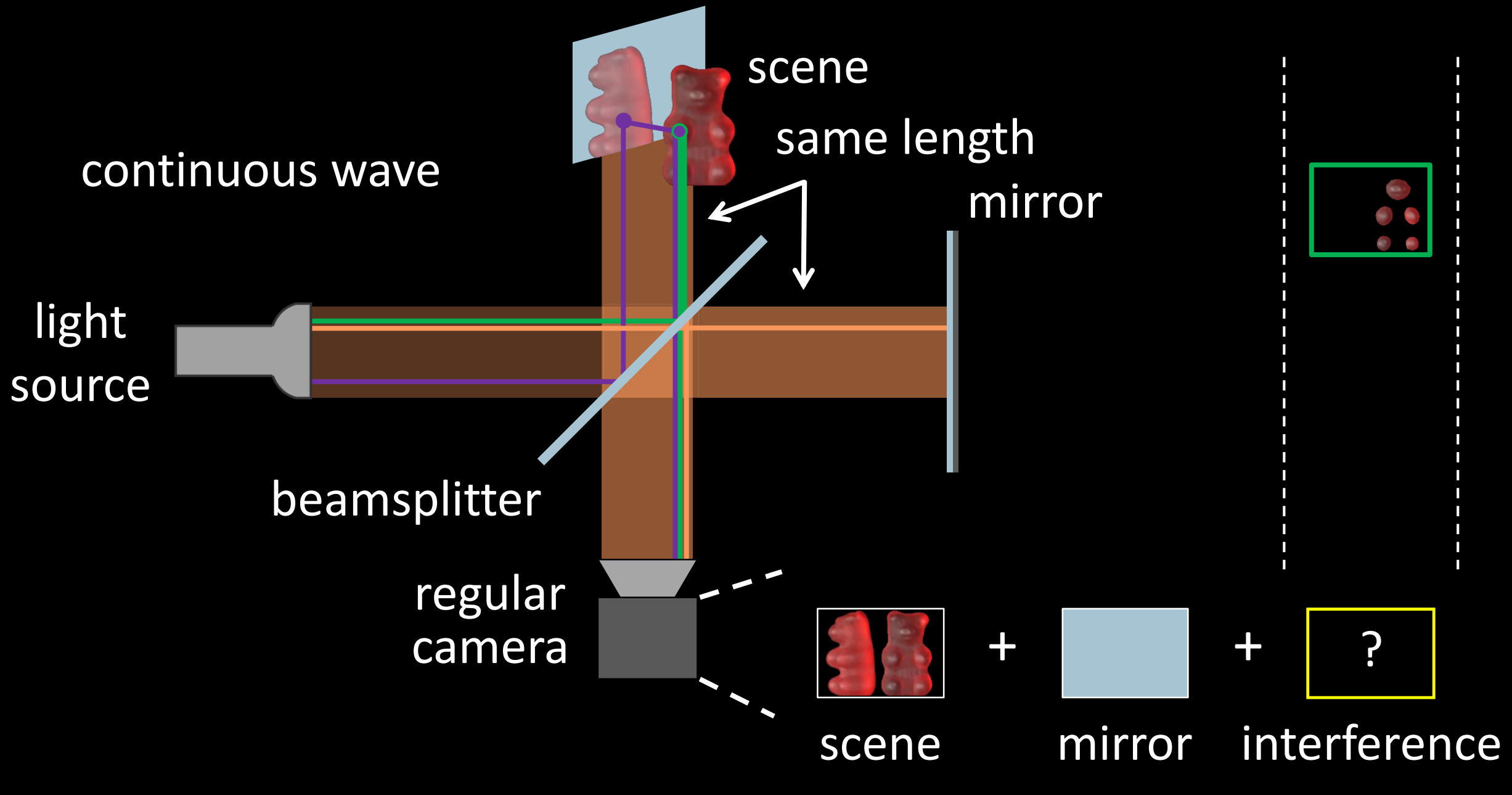


light source

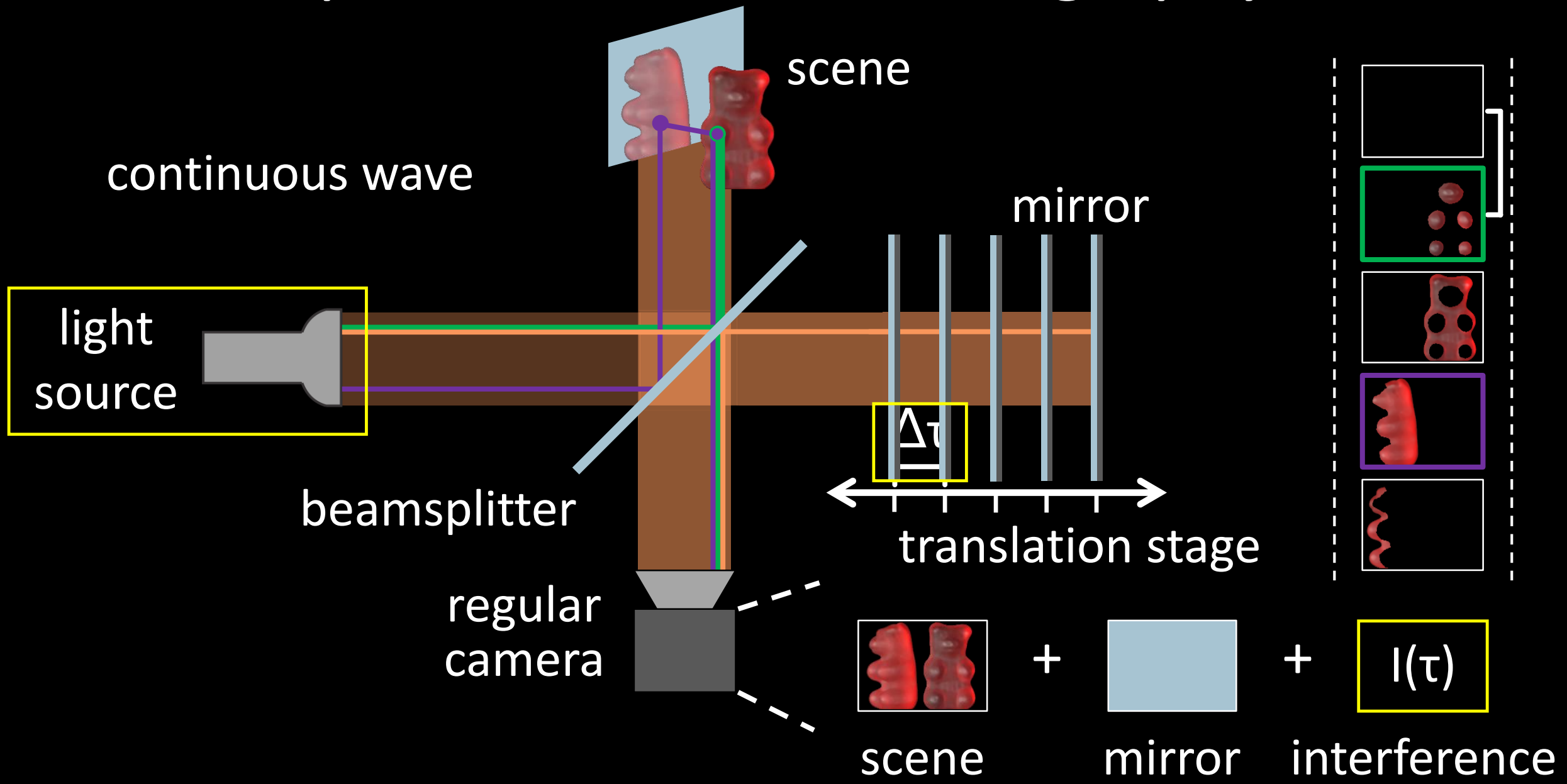
# Interferometry example



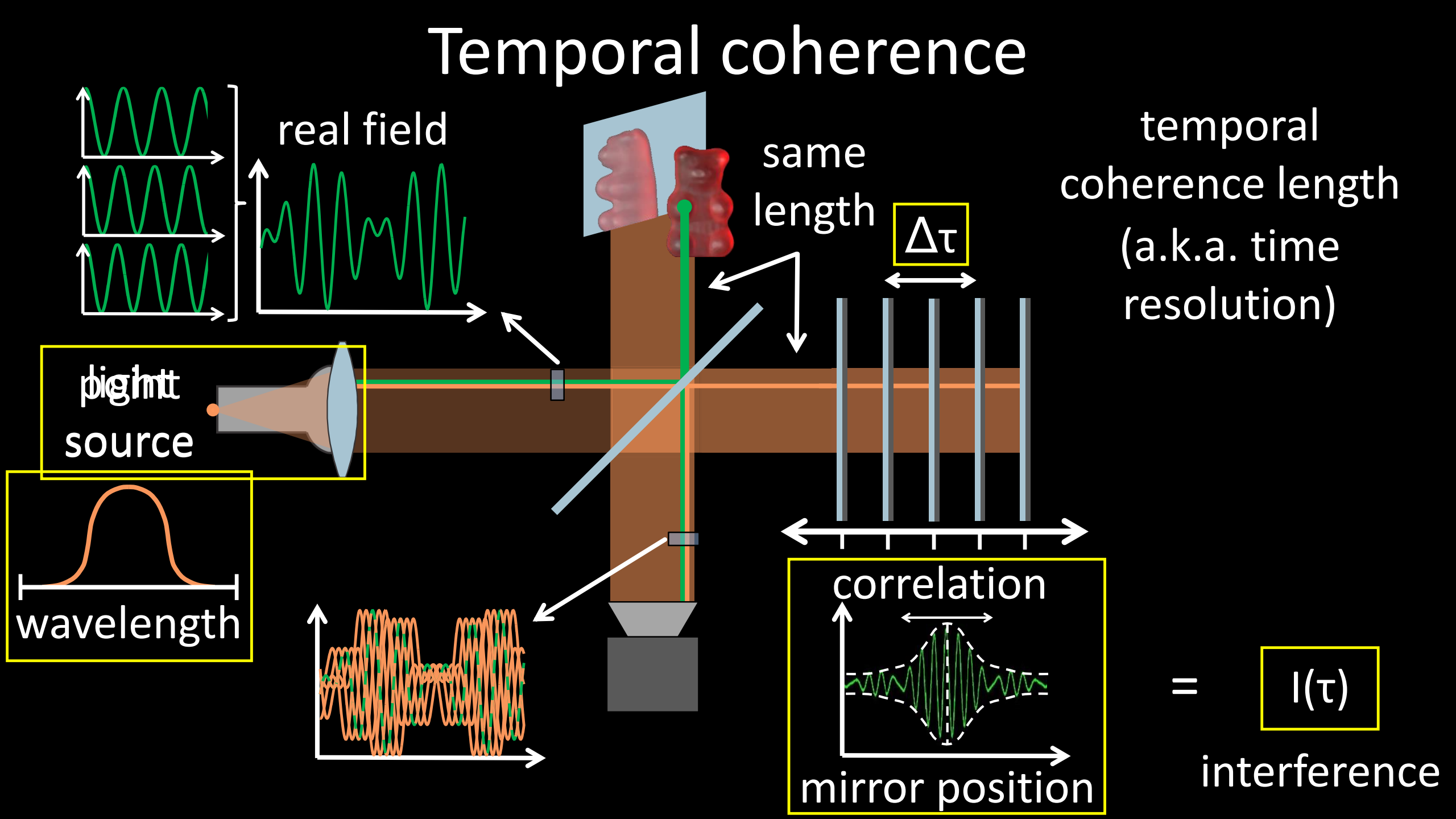
# Michelson interferometer



# Optical coherence tomography



# Temporal coherence



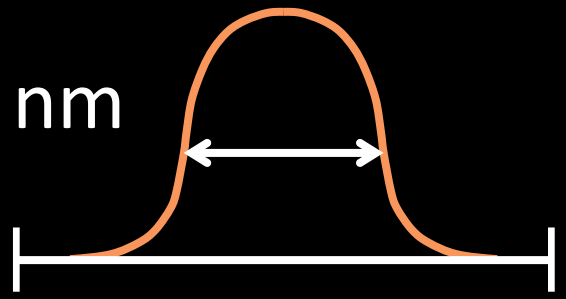
# Temporal coherence length

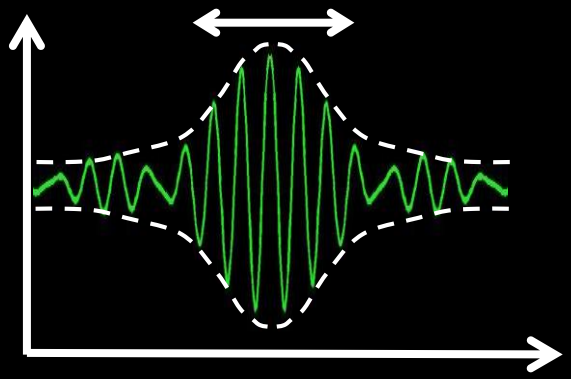
bandwidth

correlation

broadband

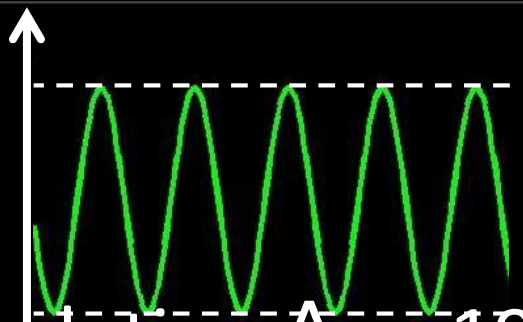
25 nm





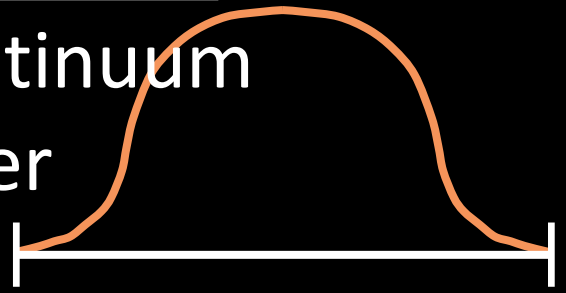
monochromatic

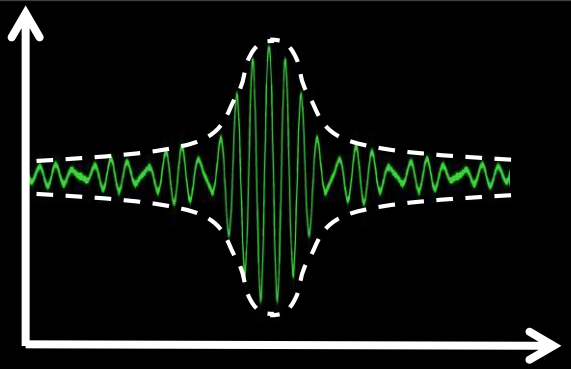

pathlength resolution $\Delta\tau \sim 10\,\mu m$



very broadband superluminescent diode

supercontinuum laser





# Optical setup

superluminescent diode

supercontinuum laser

broadband LED

sodium lamp

camera + imaging lens

light source

collimating lens

filter wheel

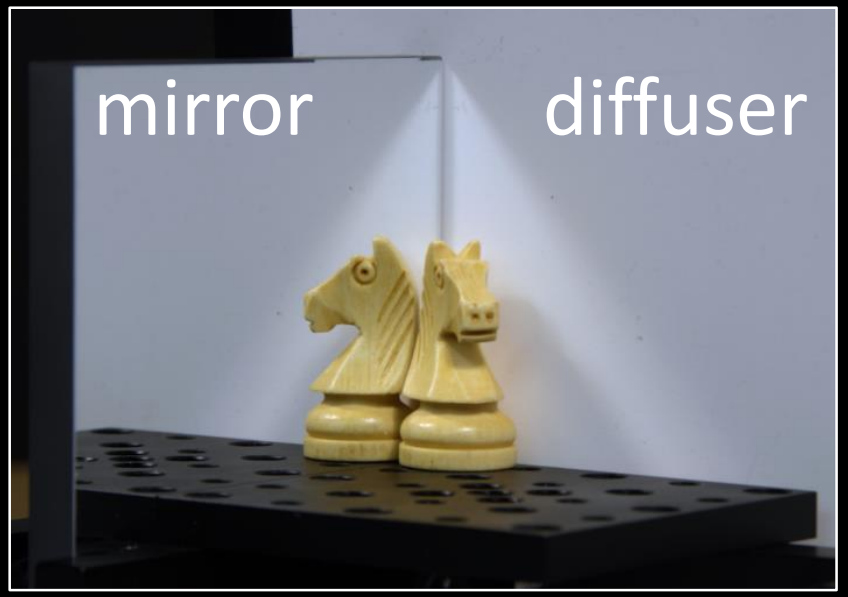
beamsplitter

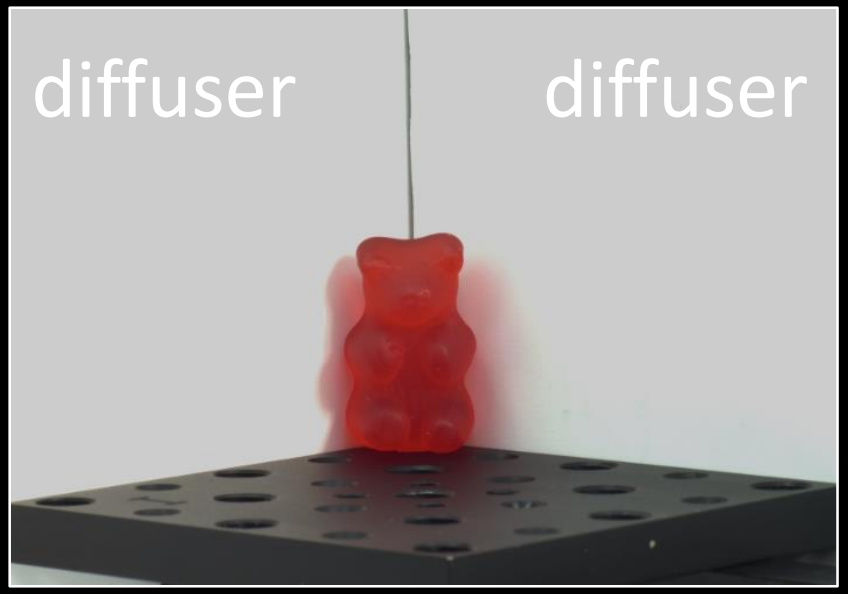
translating mirror

scene

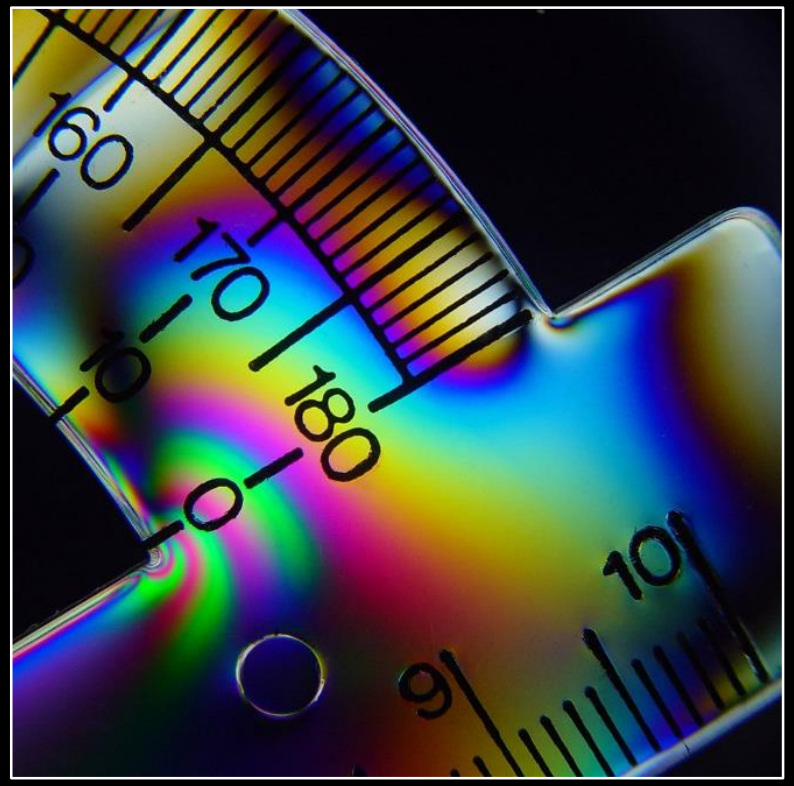
# Some transient images

centimeter-sized objects



# Material properties



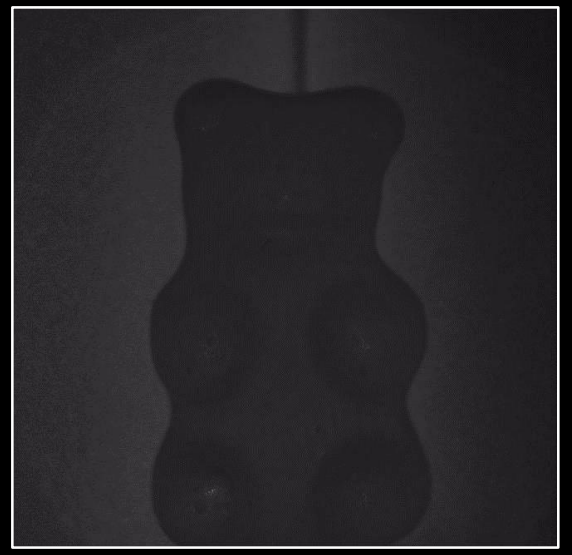

birefringence

dispersion

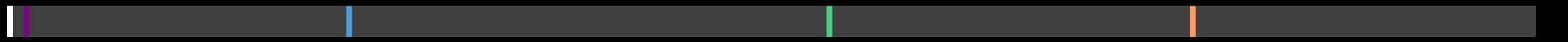
scattering

# Gummy bear and diffuse corner

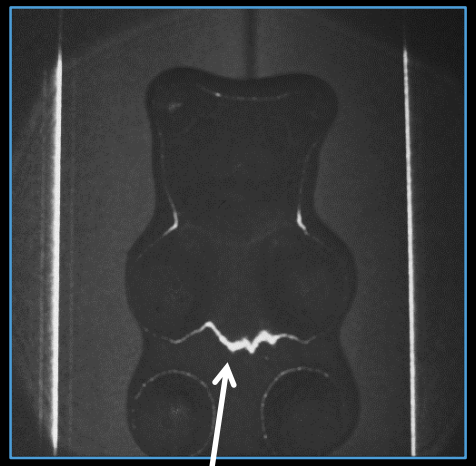

2 cm



pathlength
($\Delta\tau$ = 10 µm)



dark frame



surface reflections

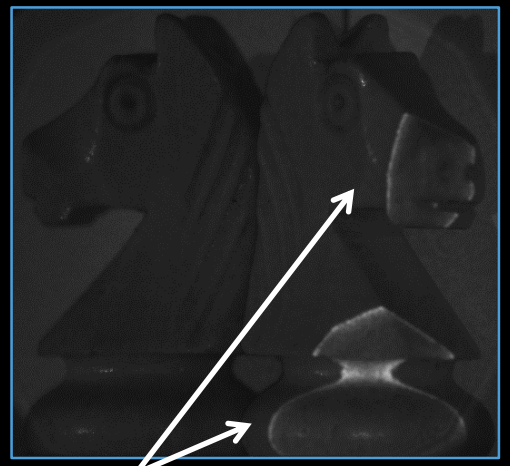
paths through gummy bear

very highly scattered paths

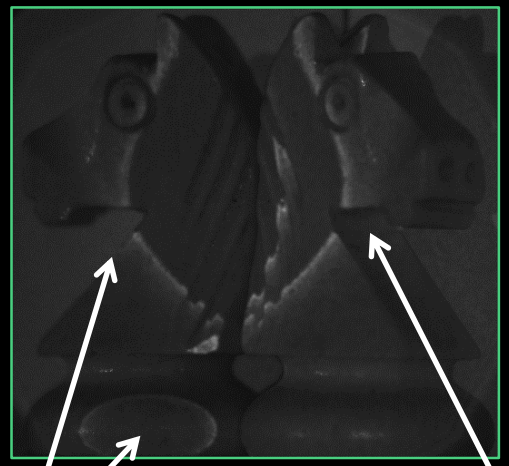
# Chess knight and mirror


3 cm

pathlength
($\Delta\tau$ = 10 µm)

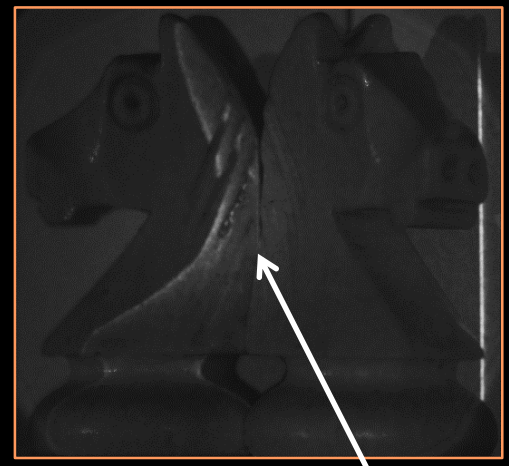


surface reflection



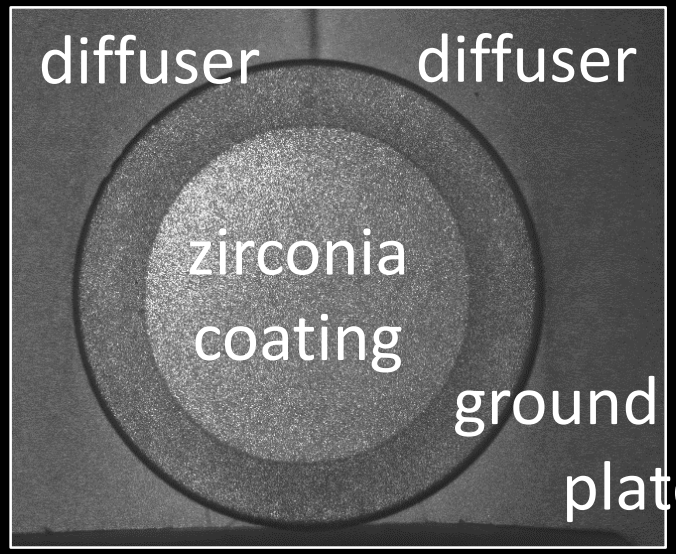
mirror-object

object-mirror

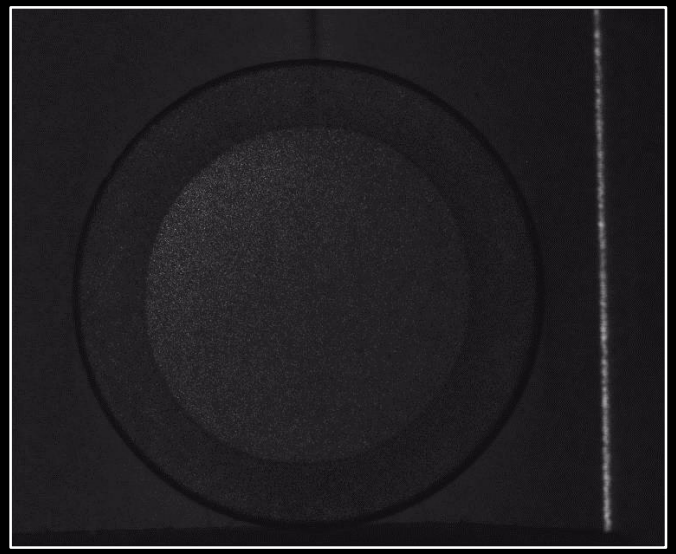


mirror-object-mirror

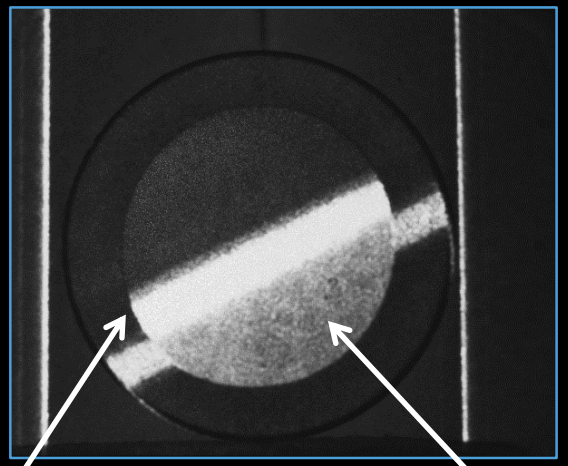
# Subsurface scattering



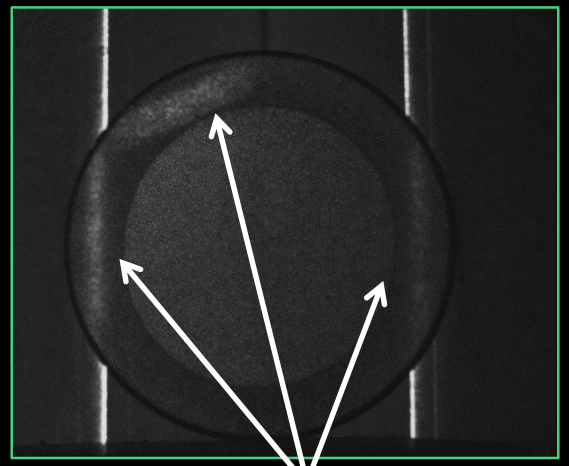

1 cm



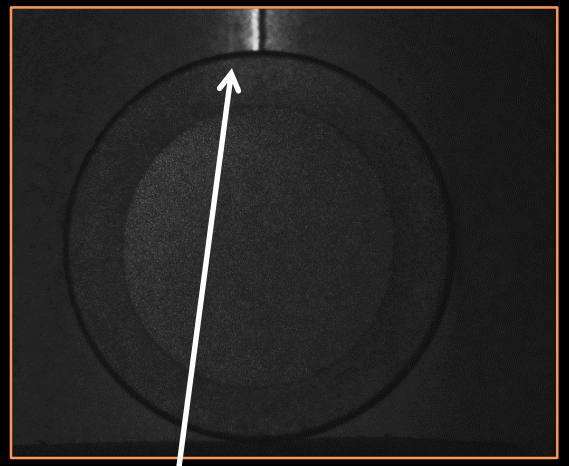
pathlength
($\Delta\tau$ = 10 μm)



surface reflection
subsurface scattering



paths transmitted
through ground glass

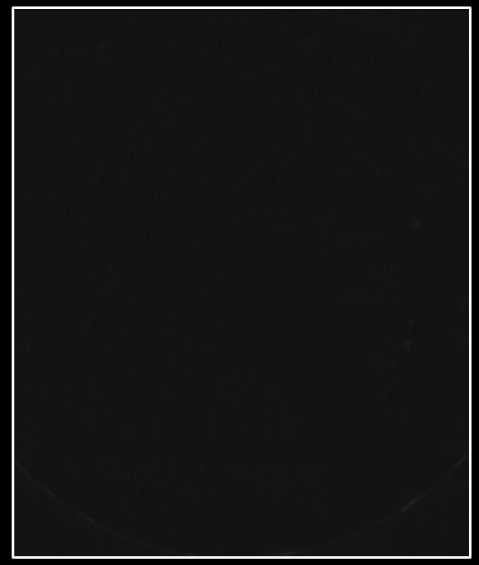


diffuse-diffuse
reflections

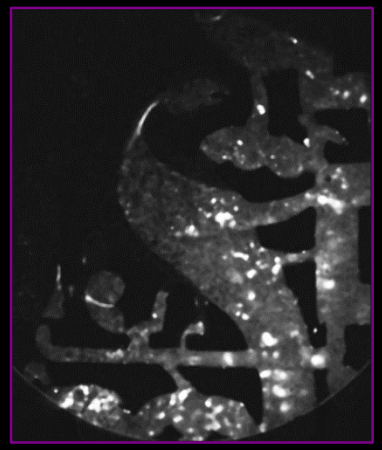
# White jade

3 cm

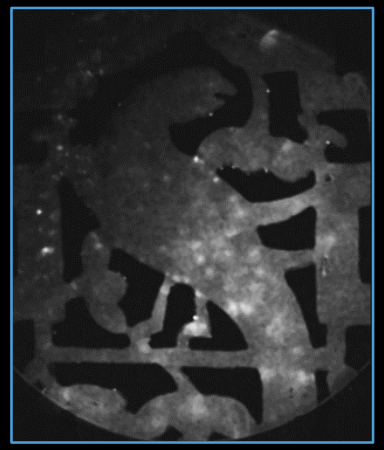
exquisite white jade



time ($10^{-15}$ seconds)



specular reflections



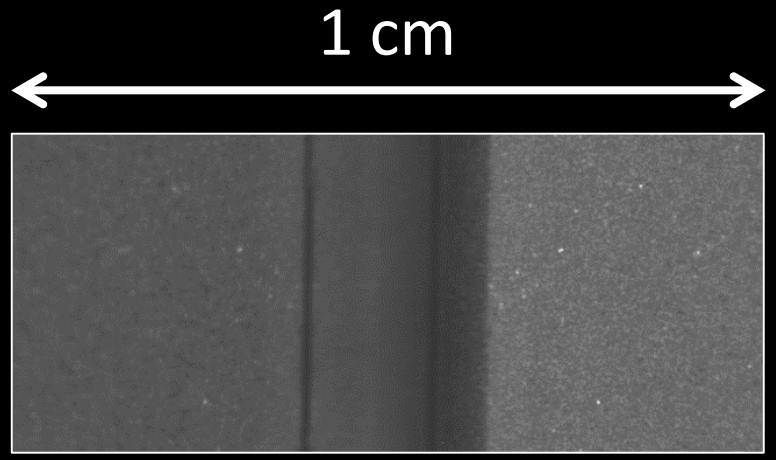
low-order scattering

mid-order scattering

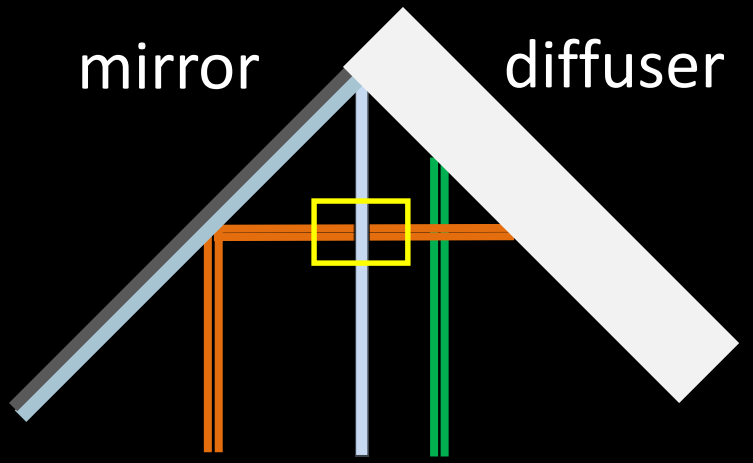
high-order scattering

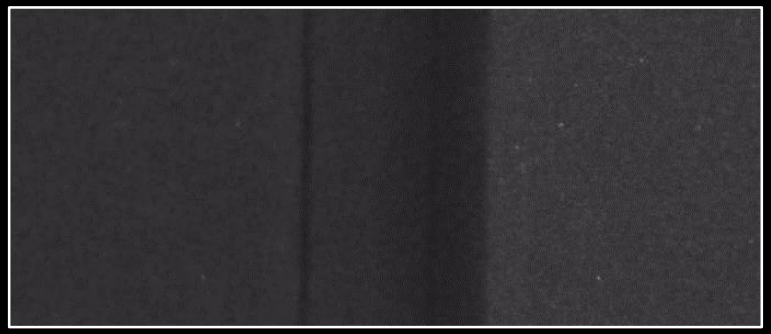
[TOG 2015]

# Dispersion

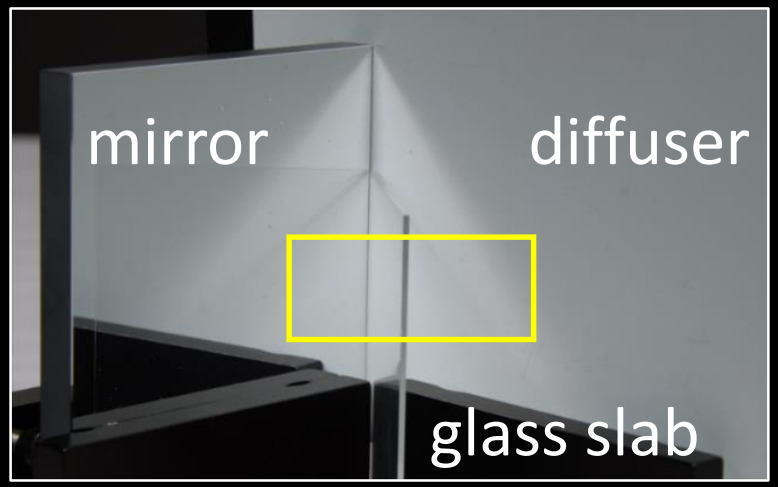


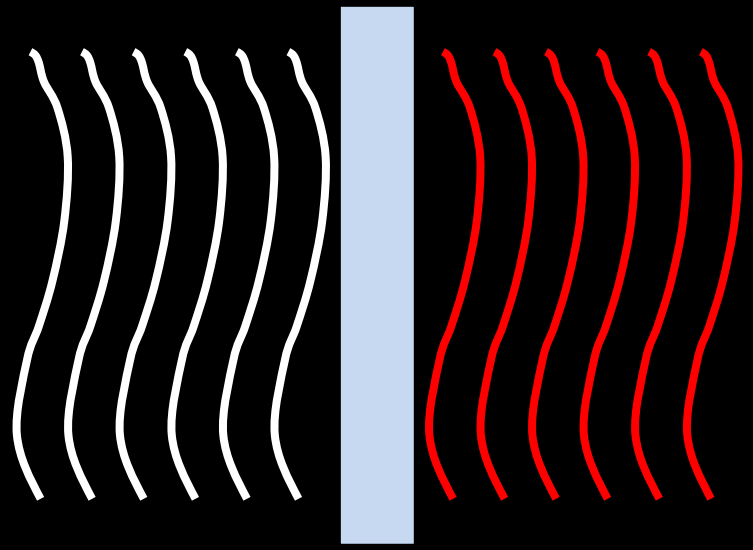

cropped frame

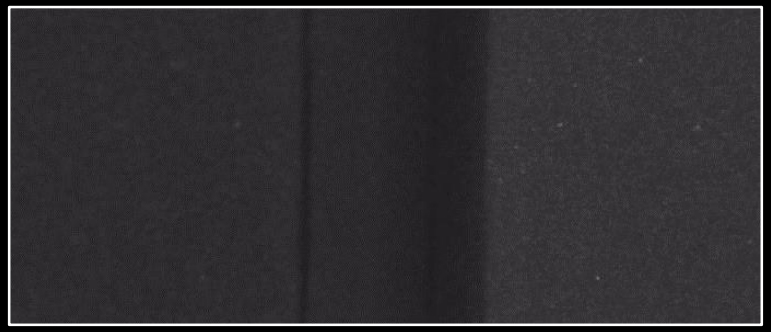


$\Delta t \sim$ ns



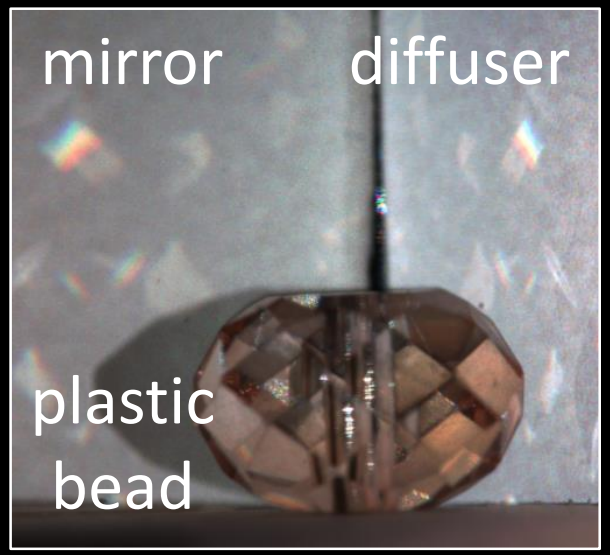





$\Delta t \sim 10^{-3}$ ns

refractive index η(wavelength)

# Dispersion




1 cm

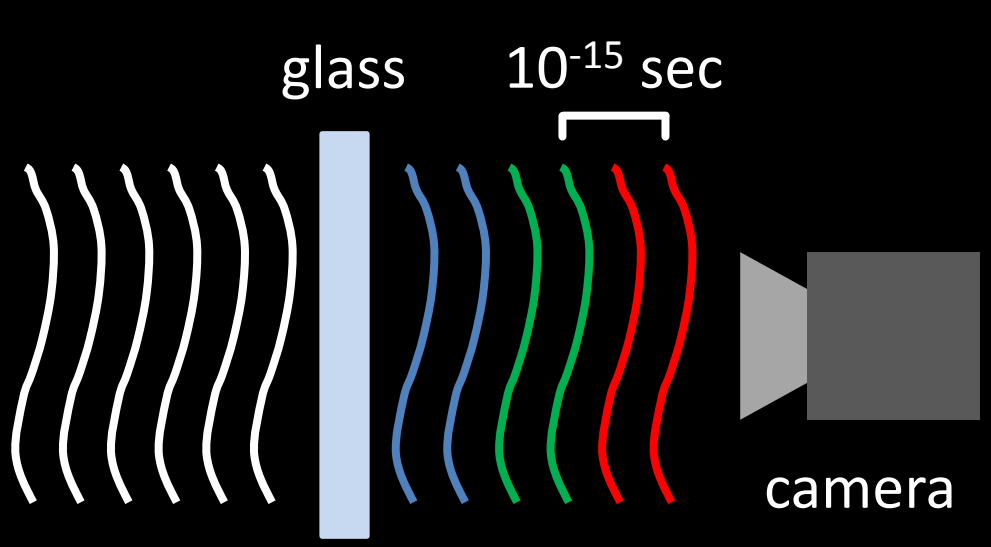
pathlength
($\Delta\tau$ = 10 µm)

facets changing color

surface reflections
surface-wall reflections

rainbow

# Visualizing dispersion



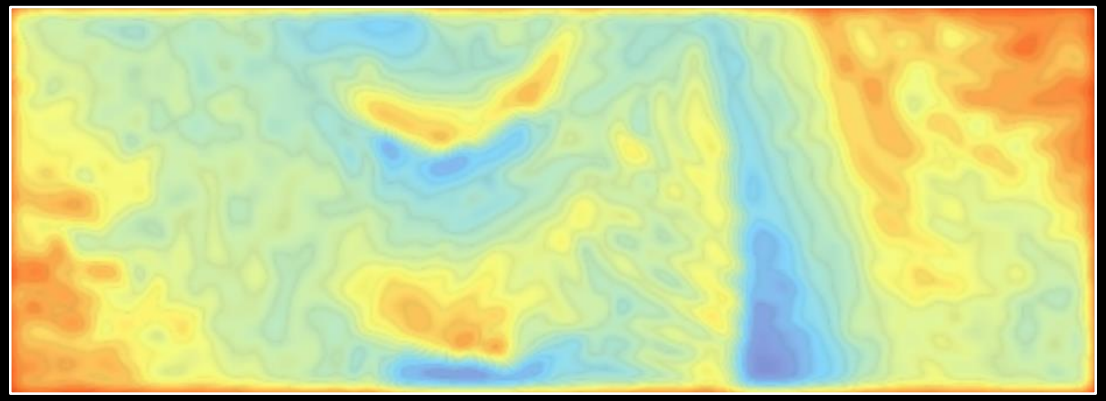

what a regular camera sees

what our camera sees

# Visualizing photoelasticity

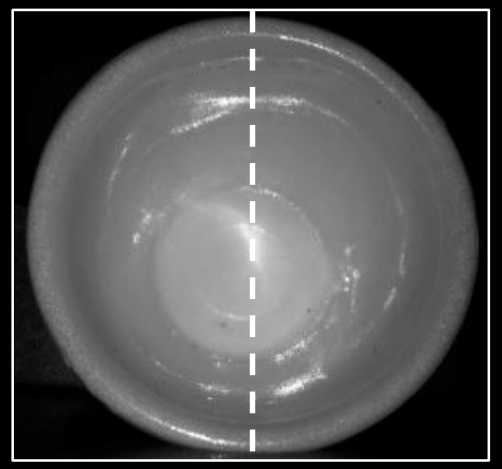
detail under cross-polarized light

low resolution Δτ = 1 mm

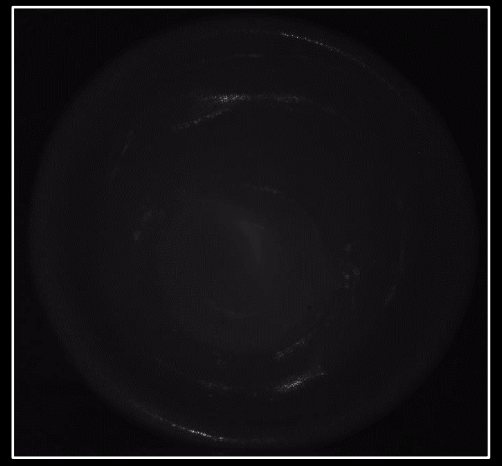


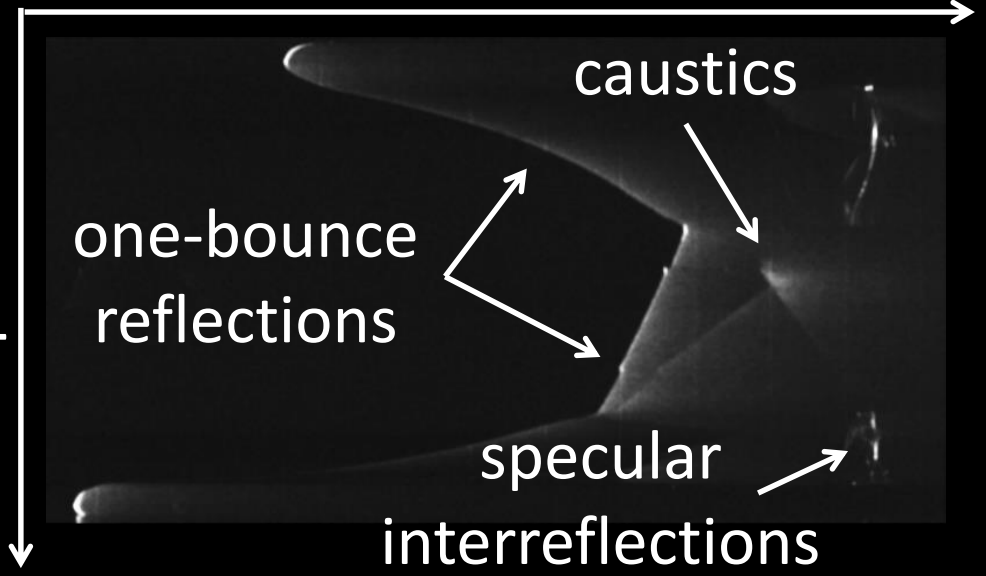
high resolution Δτ = 10 µm

# Toy cup

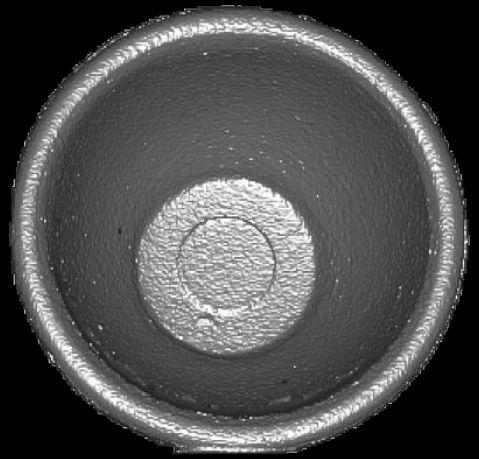


full transient

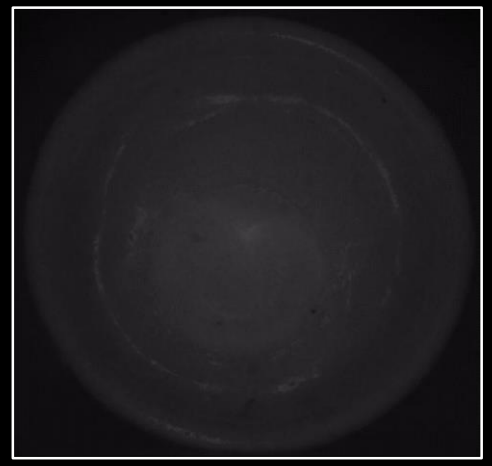


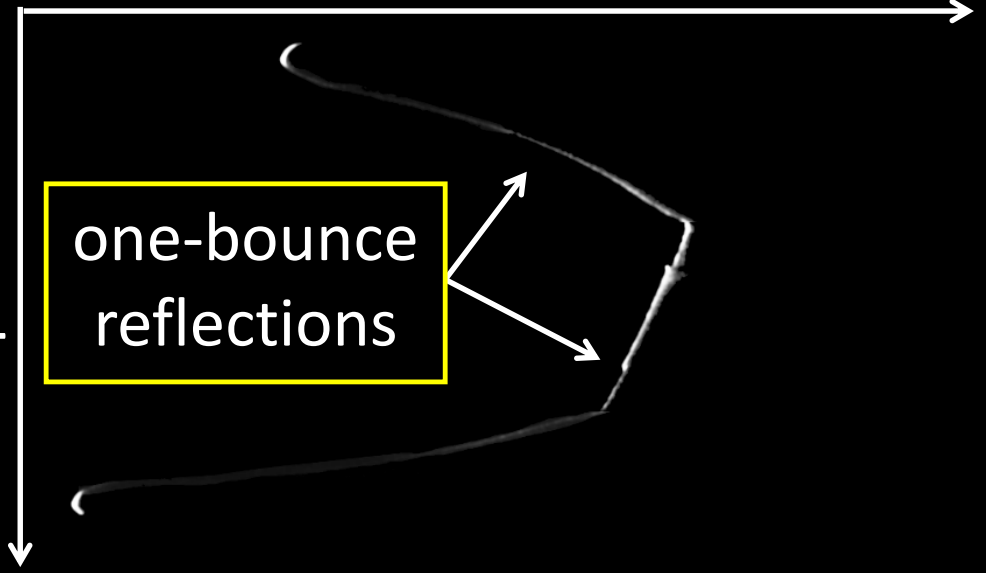



measured depth



direct-only transient





# Depth scanning

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

coin


2.5 cm

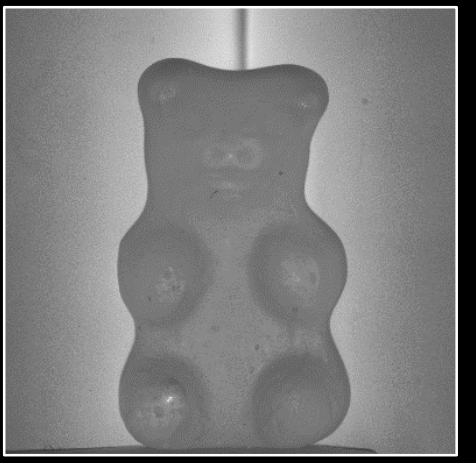

gnocchi

1 cm

soap carving

1.5 cm

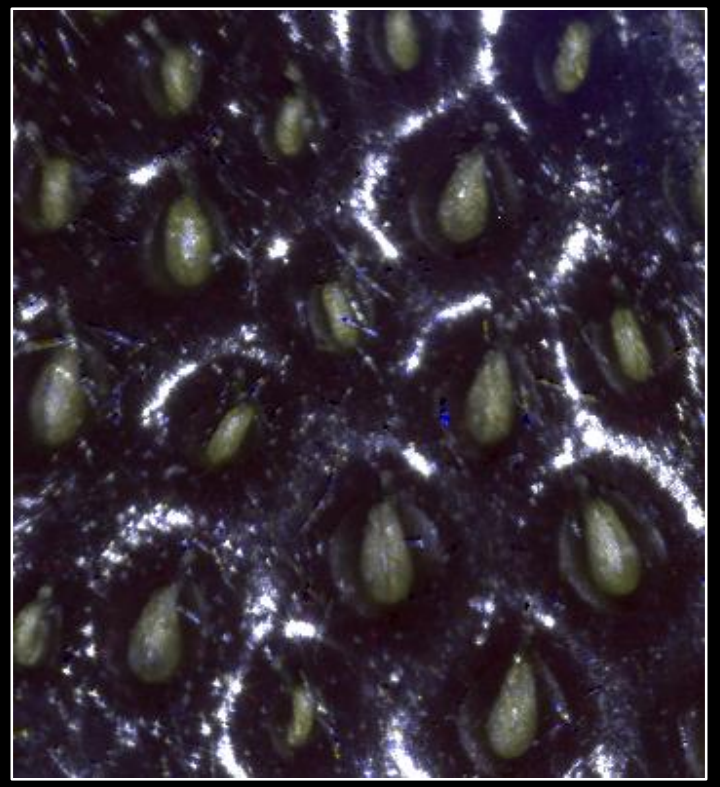
gummy bear and diffusers



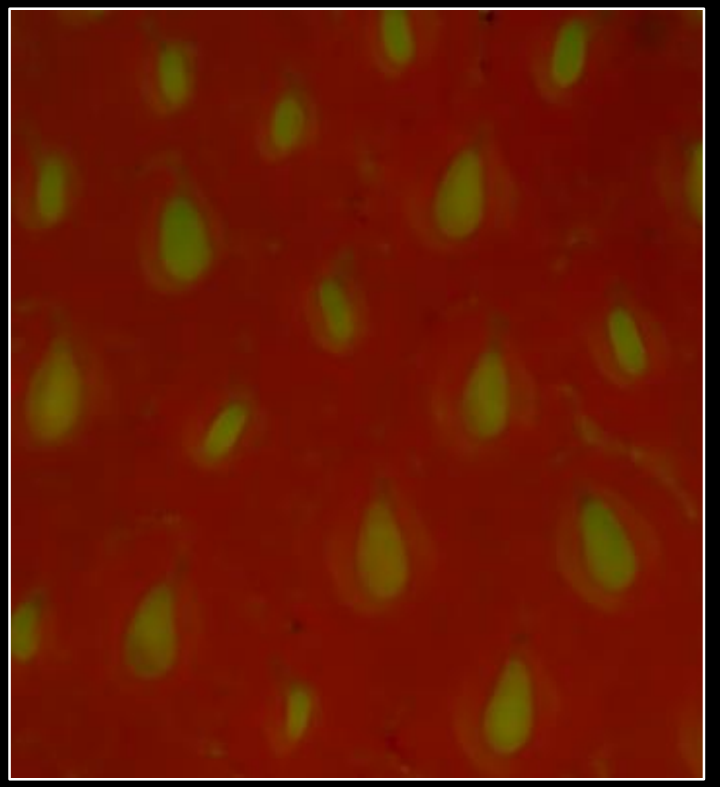
3 cm

# Direct-global separation

strawberry close-up



direct component



global component

# 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.
  a paper 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.
- Achar et al., “Epipolar time-of-flight imaging,” SIGGRAPH 2017.
  the paper on epipolar ToF.
- 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.

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.