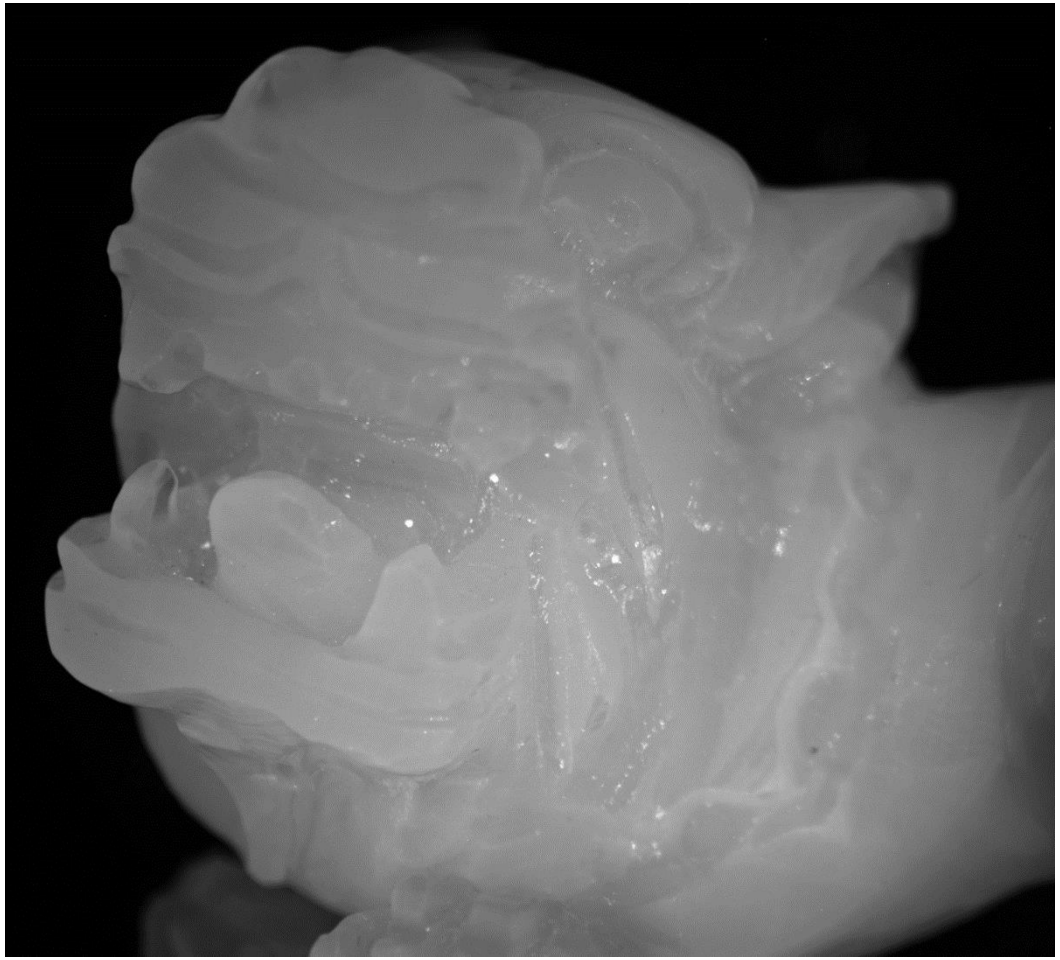
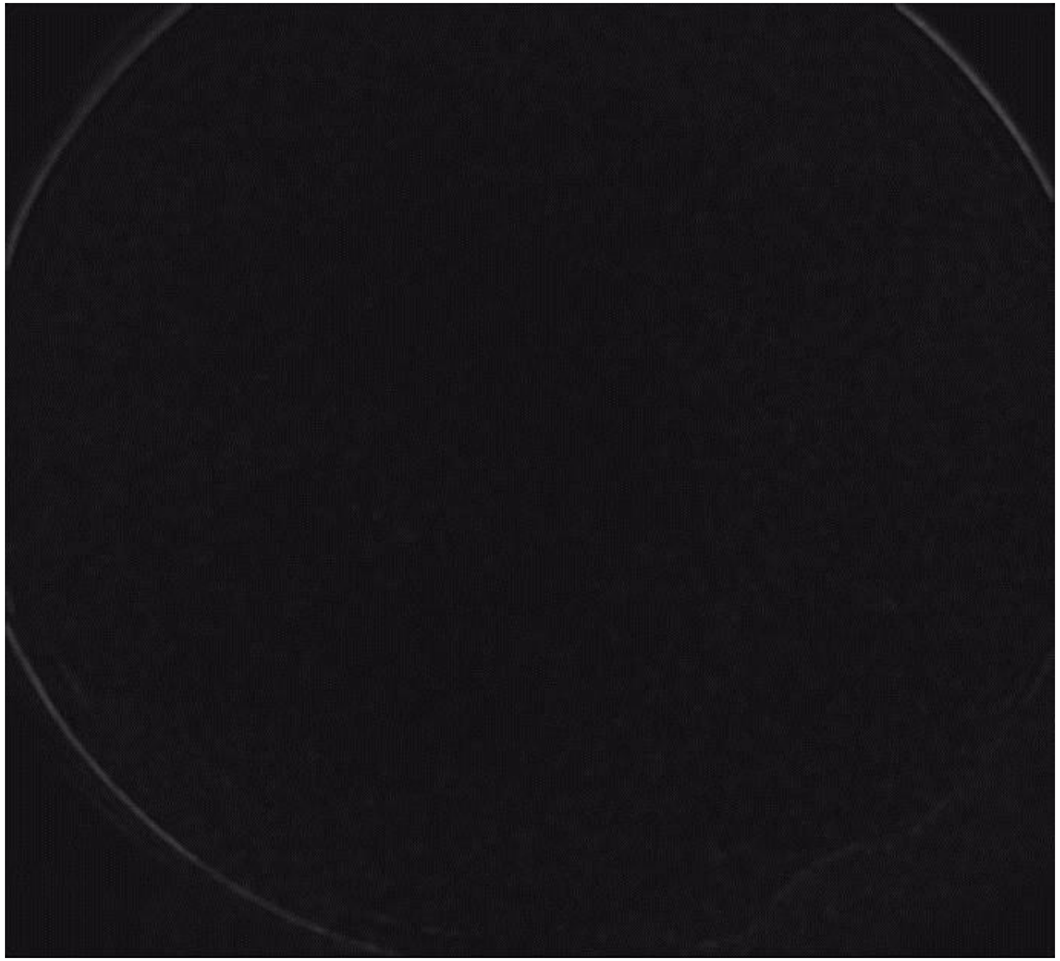
Time-of-flight imaging





15-463, 15-663, 15-862
Computational Photography
Fall 2017, Lecture 24

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

Course announcements

- Homework 5 still ongoing.
  - Any questions?

- Project checkpoint meetings this week.
  - Make sure to sign up for a timeslot if you have not already done so.

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.

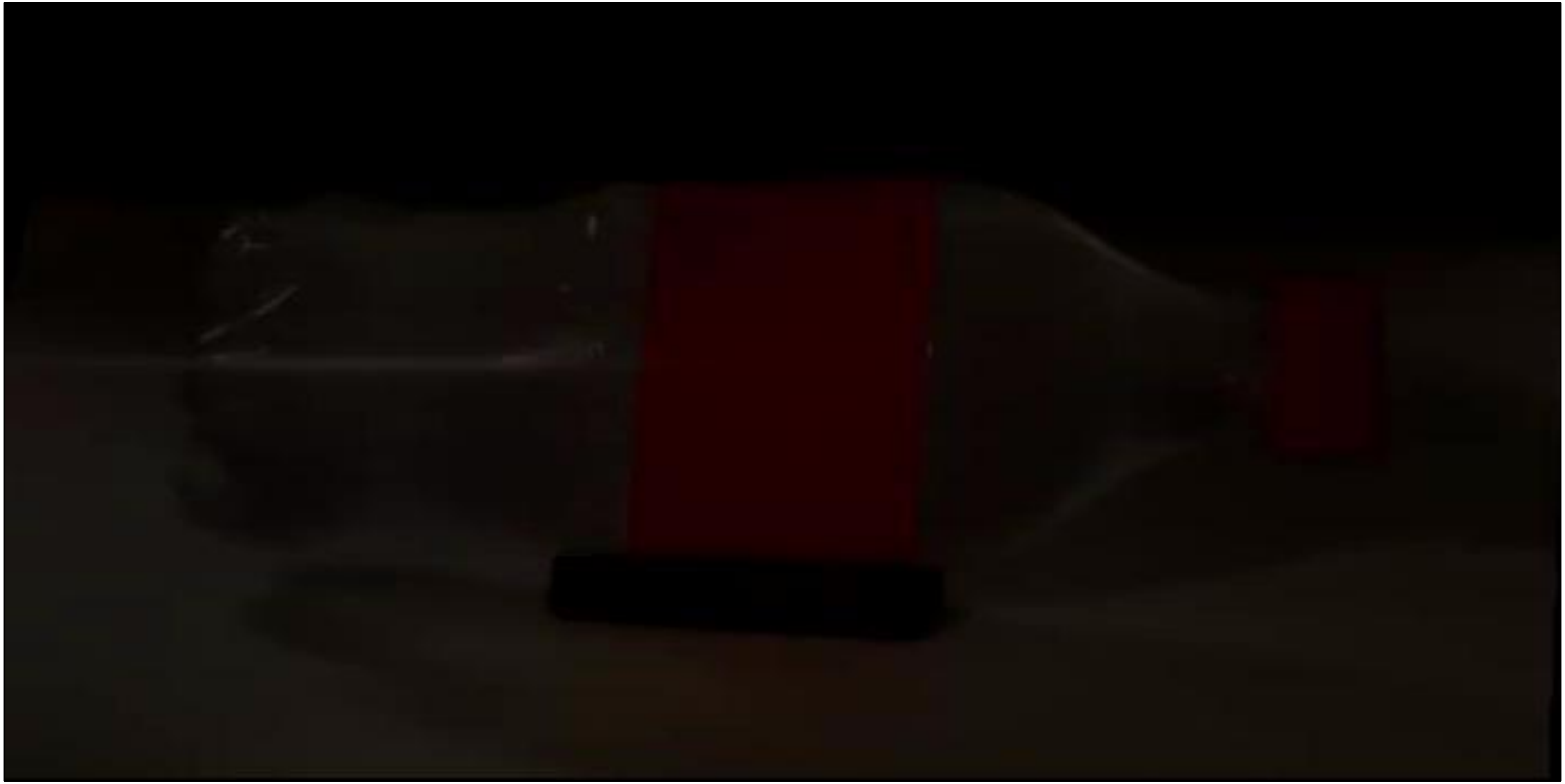
Slide credits

A lot of these slides were adapted from:

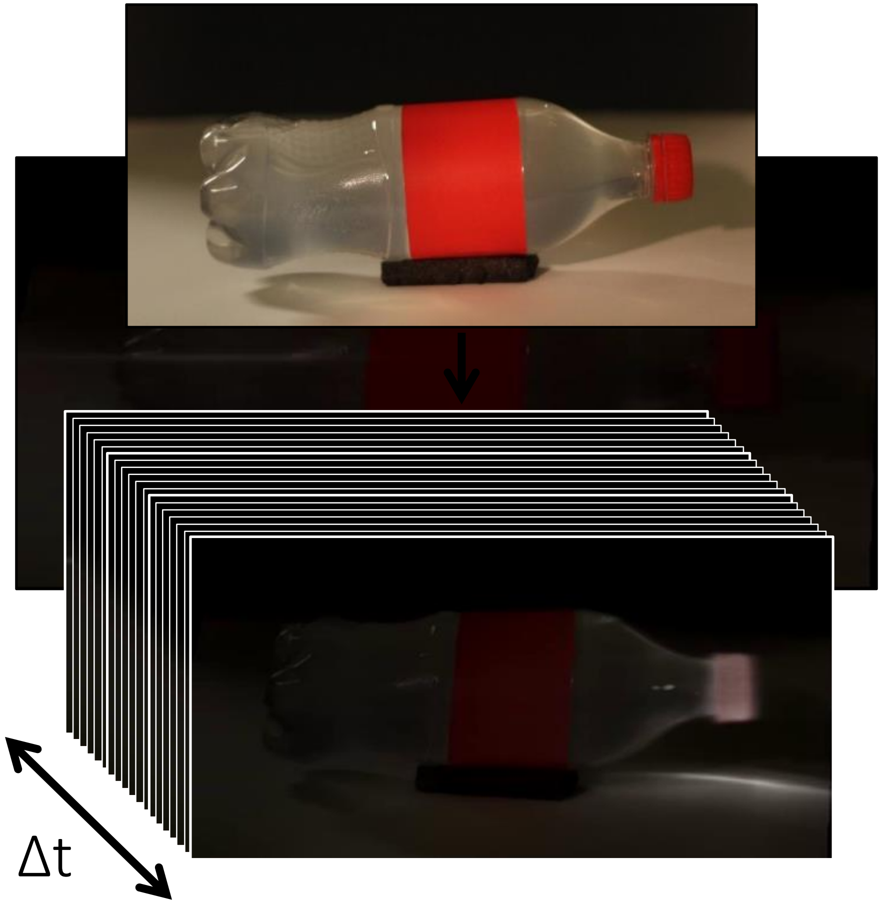
- Mohit Gupta (Wisconsin).
- Supreeth Achar (Google, formerly CMU).

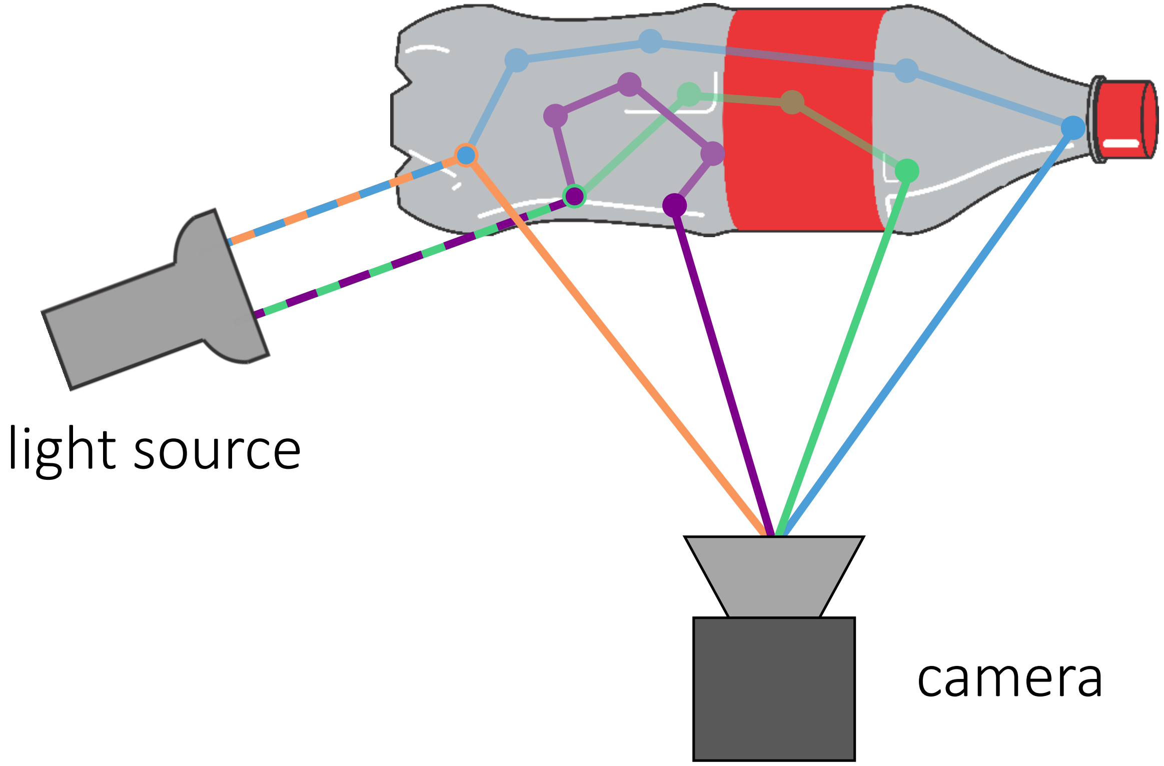
Introduction to time-of-flight (ToF) imaging

Time-of-flight (ToF) imaging



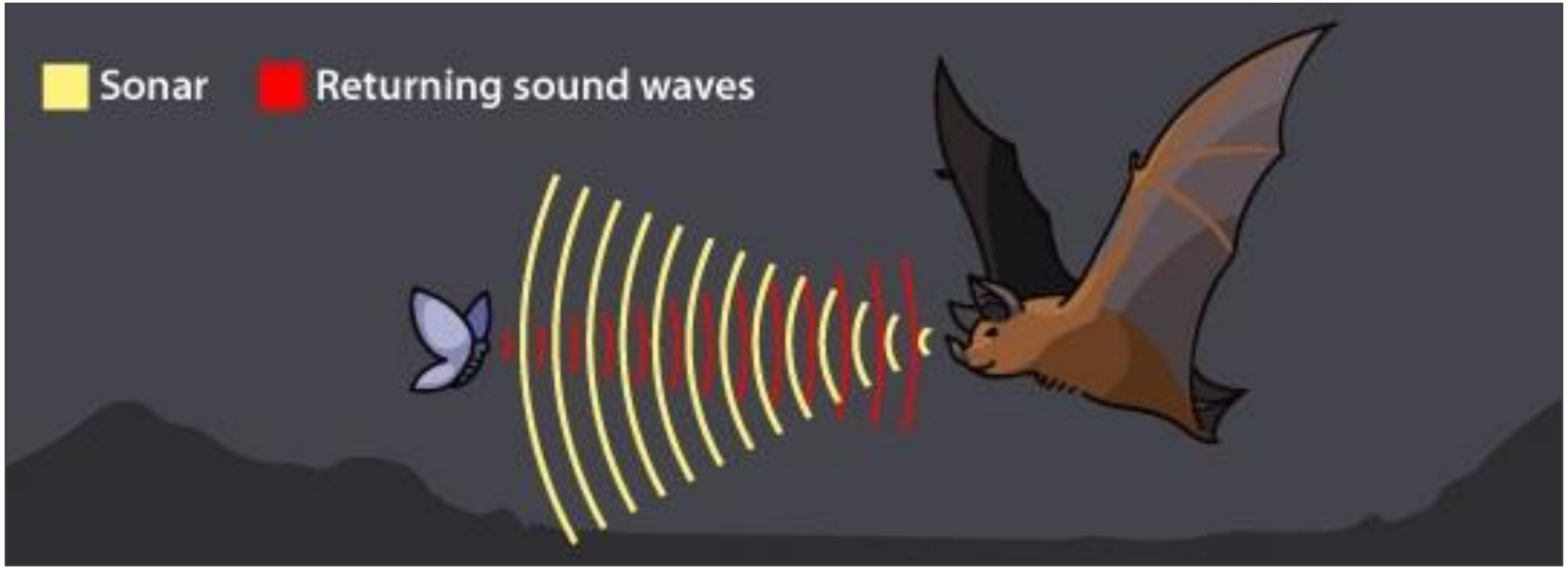
Time-of-flight (ToF) imaging

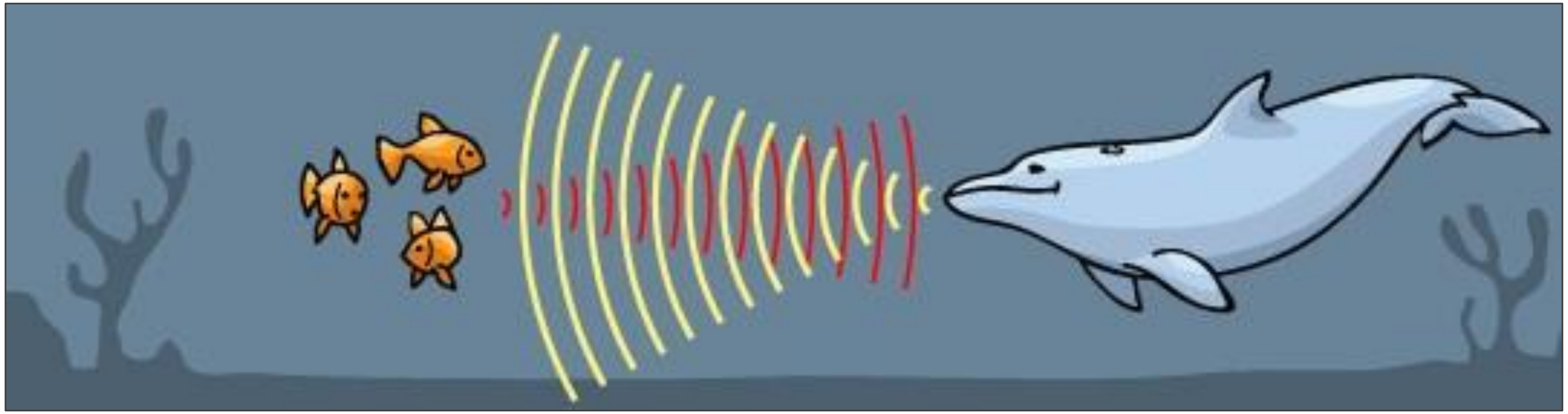




- Conventional imaging: Measure all photons together regardless of time of travel.
- Time-of-flight imaging: Measure photons separately based on time of travel.

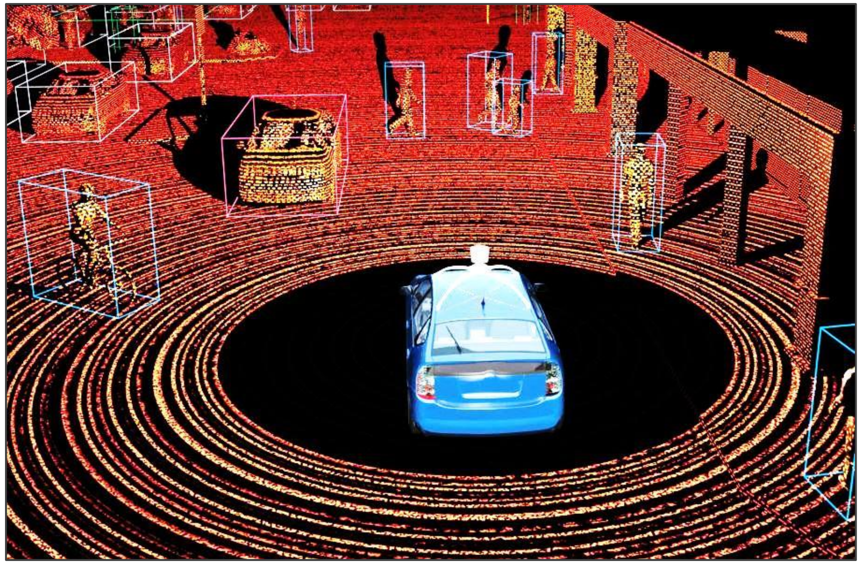
Time-of-flight imaging in nature

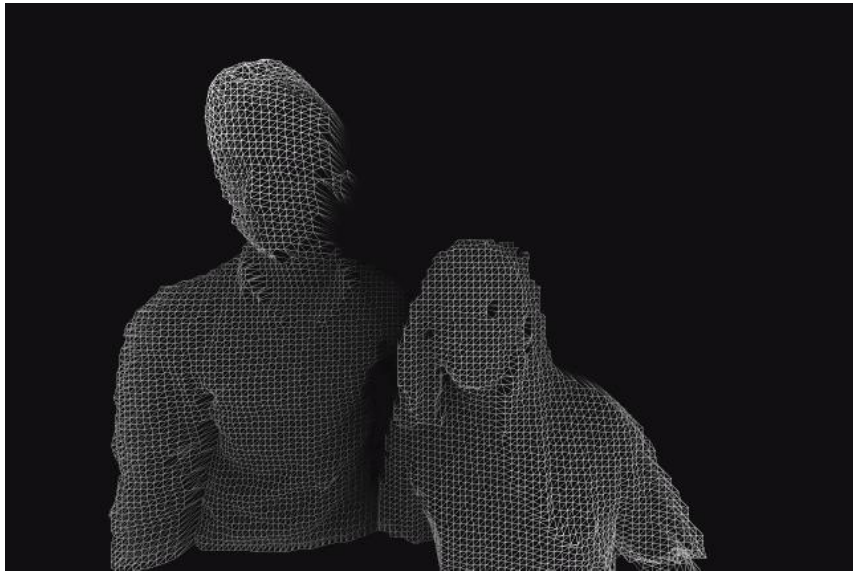




echolocation using sound-wave time-of-flight

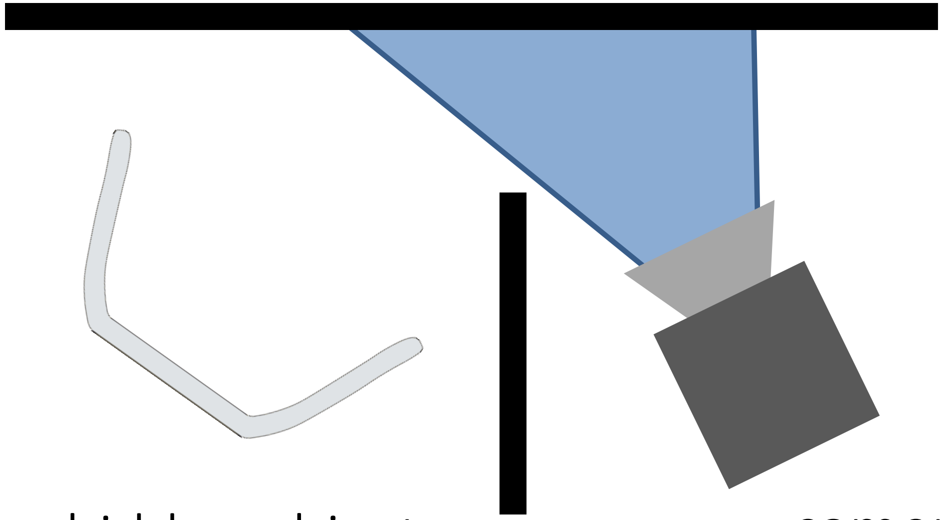
Time-of-flight applications: depth sensing





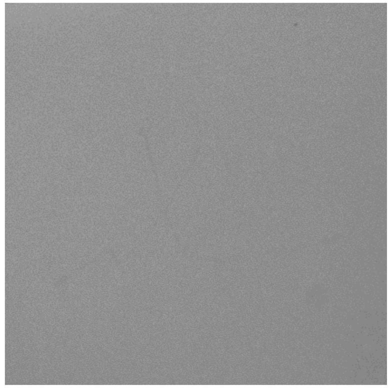
Time-of-flight applications: non-line of sight imaging

wall

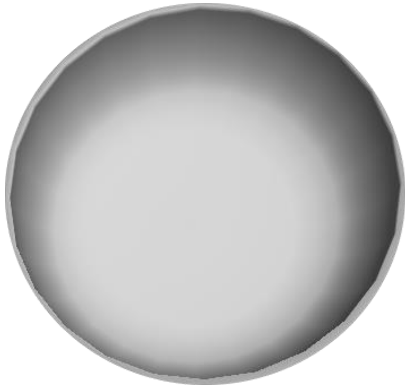


hidden object

camera

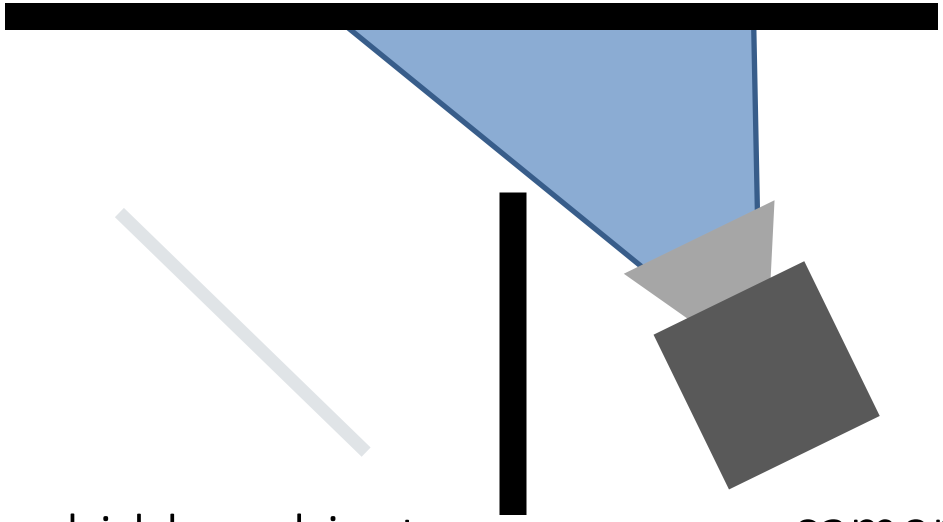


what a regular camera sees



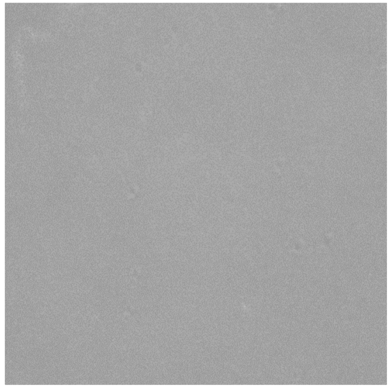
what shape our camera sees

wall



hidden object

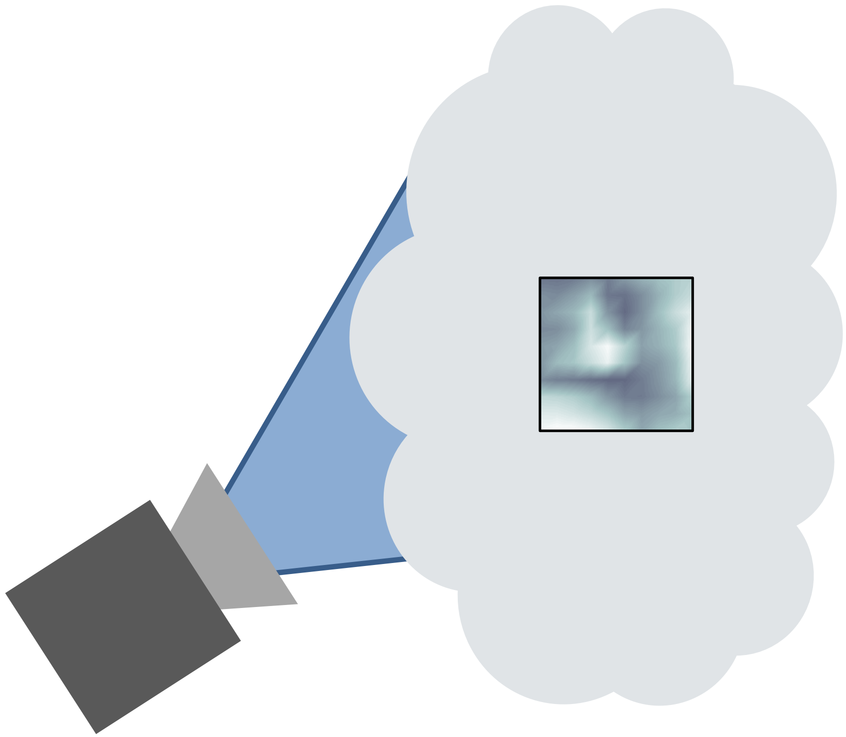
camera



what a regular camera sees

what depth our camera sees

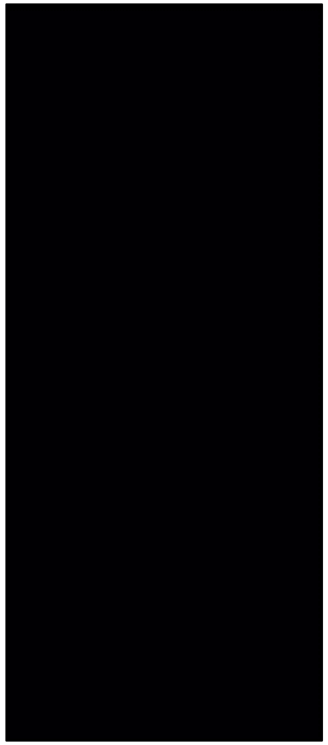
Time-of-flight applications: seeing inside objects



camera

thick smoke cloud

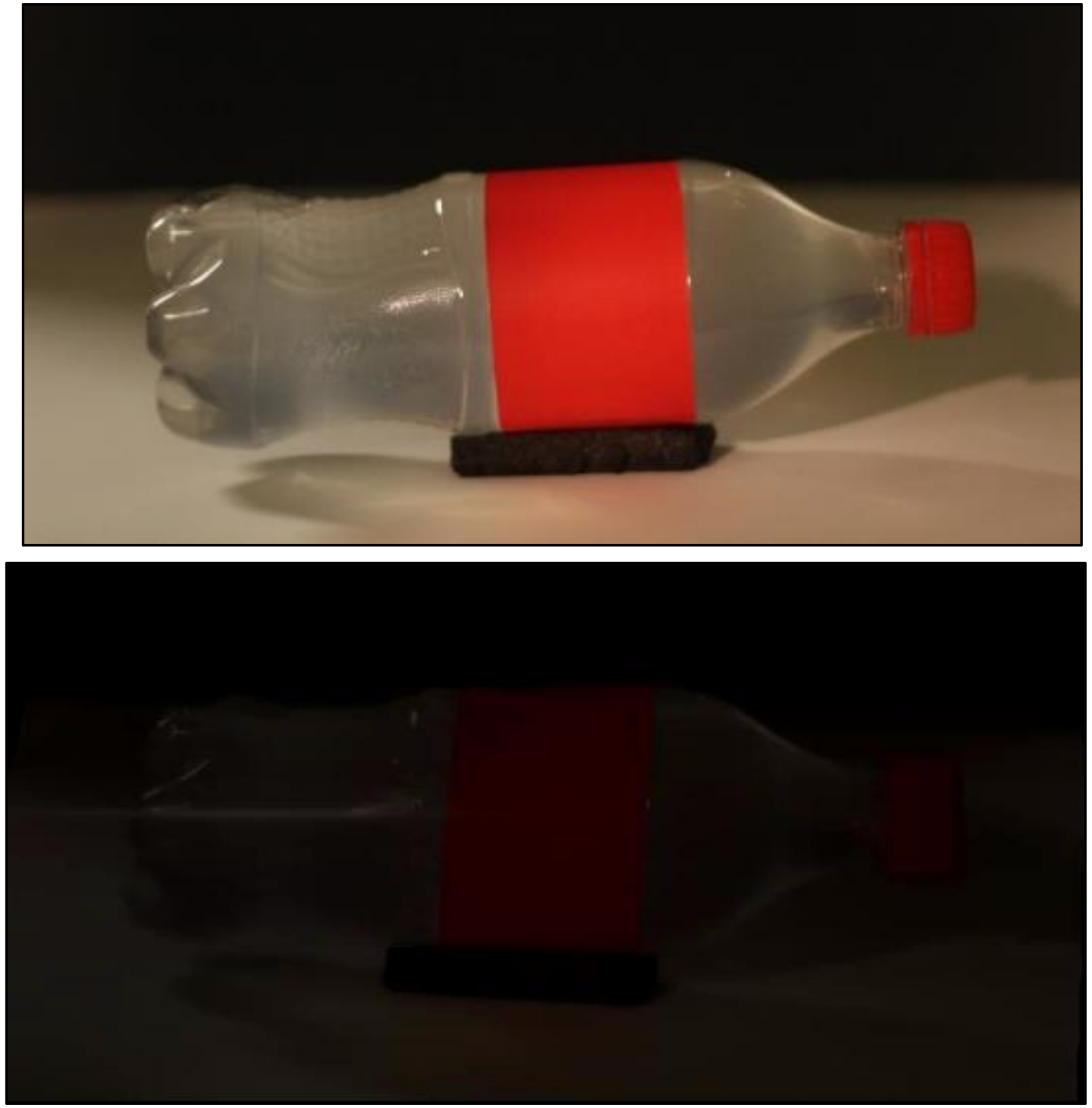
what a regular camera sees



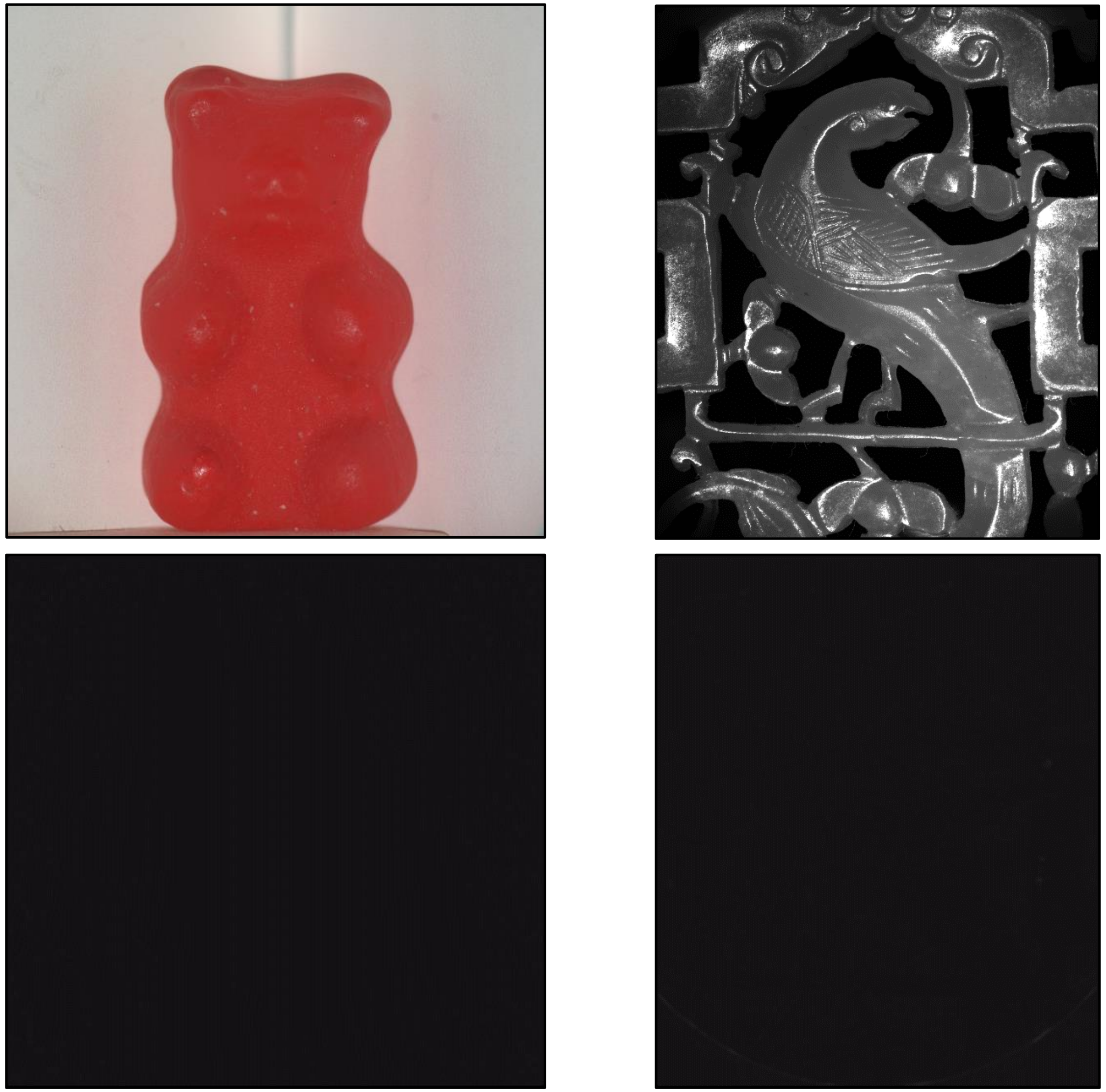
what our camera sees

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)

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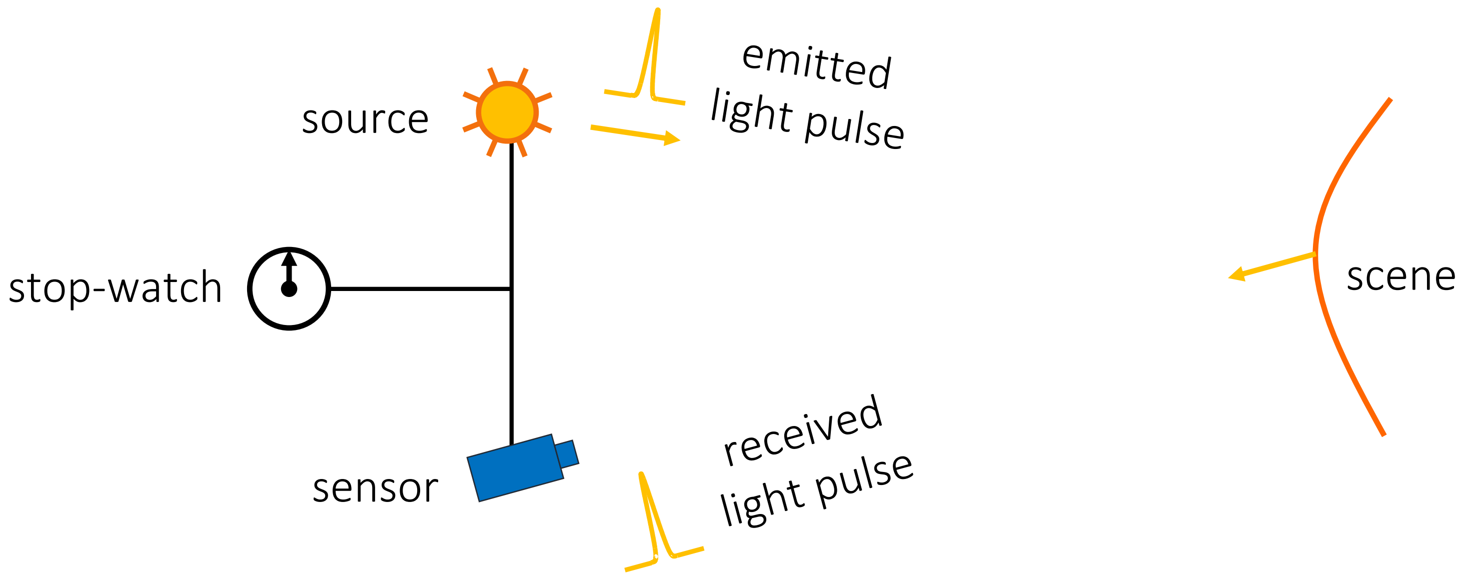
continuous-wave ToF

impulse ToF

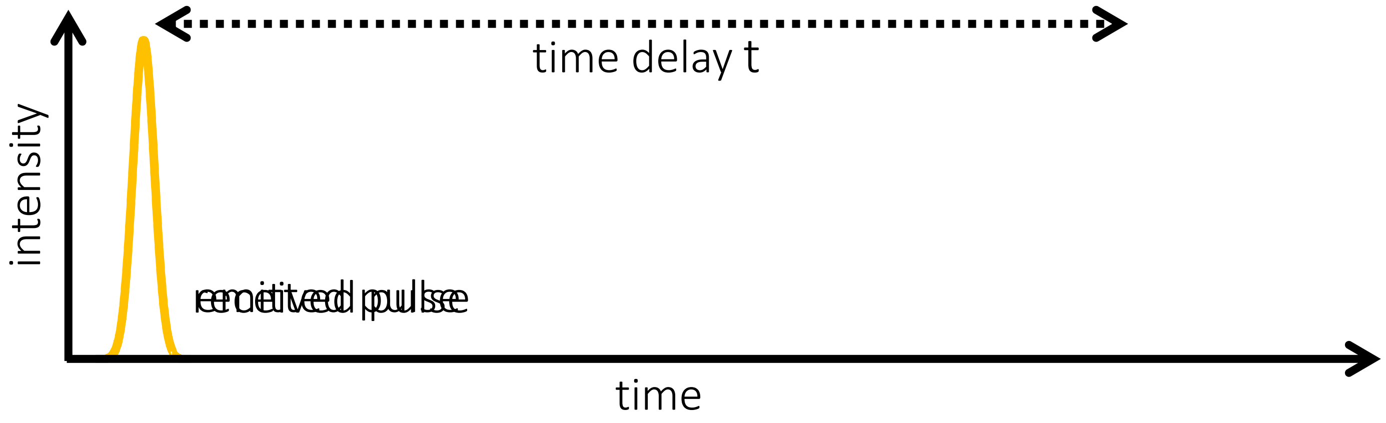
Impulse ToF imaging and single-photon avalanche diodes

Impulse time-of-flight imaging

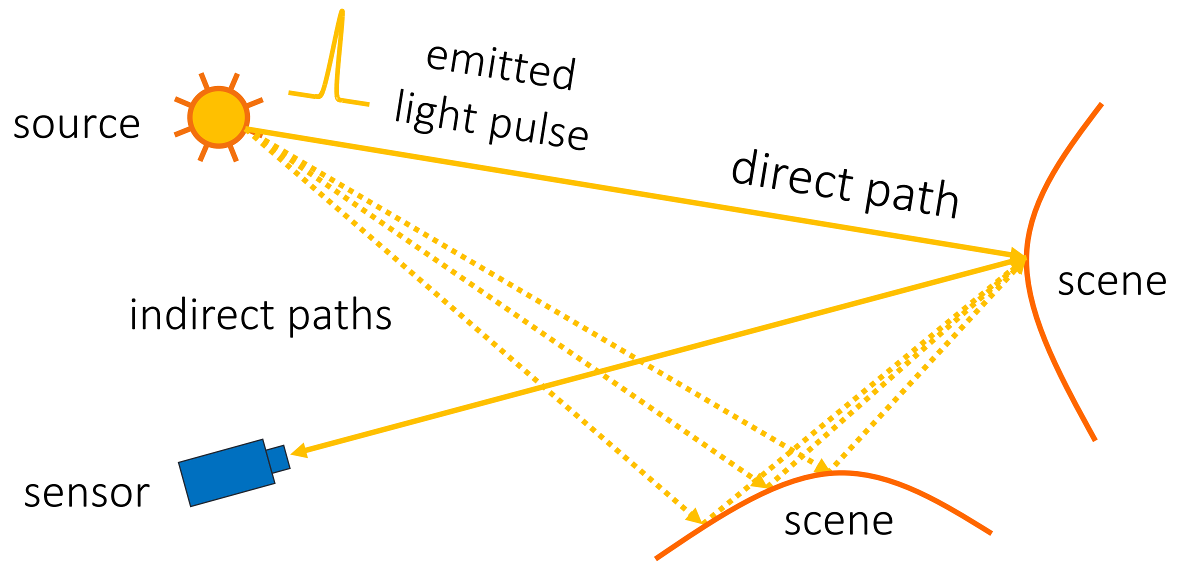


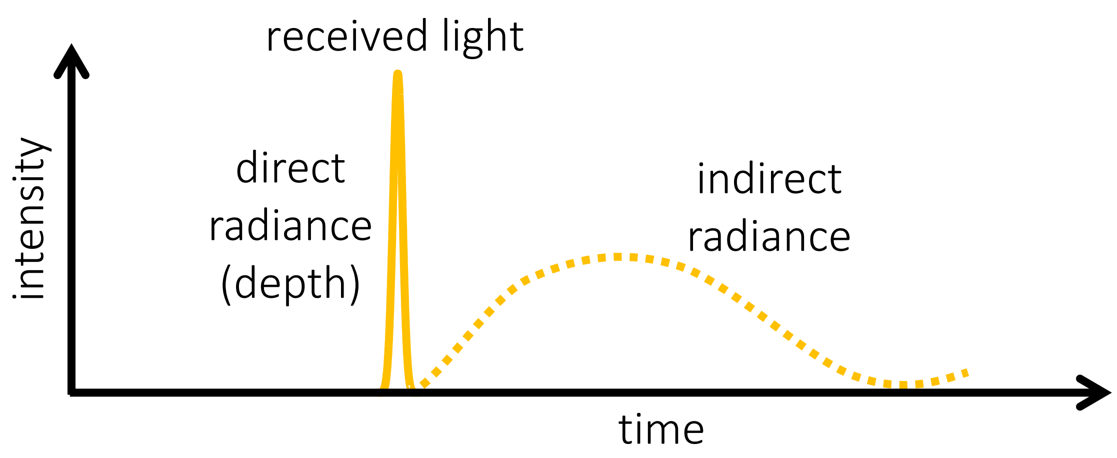
How can we infer depth from this?

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



Impulse time-of-flight imaging



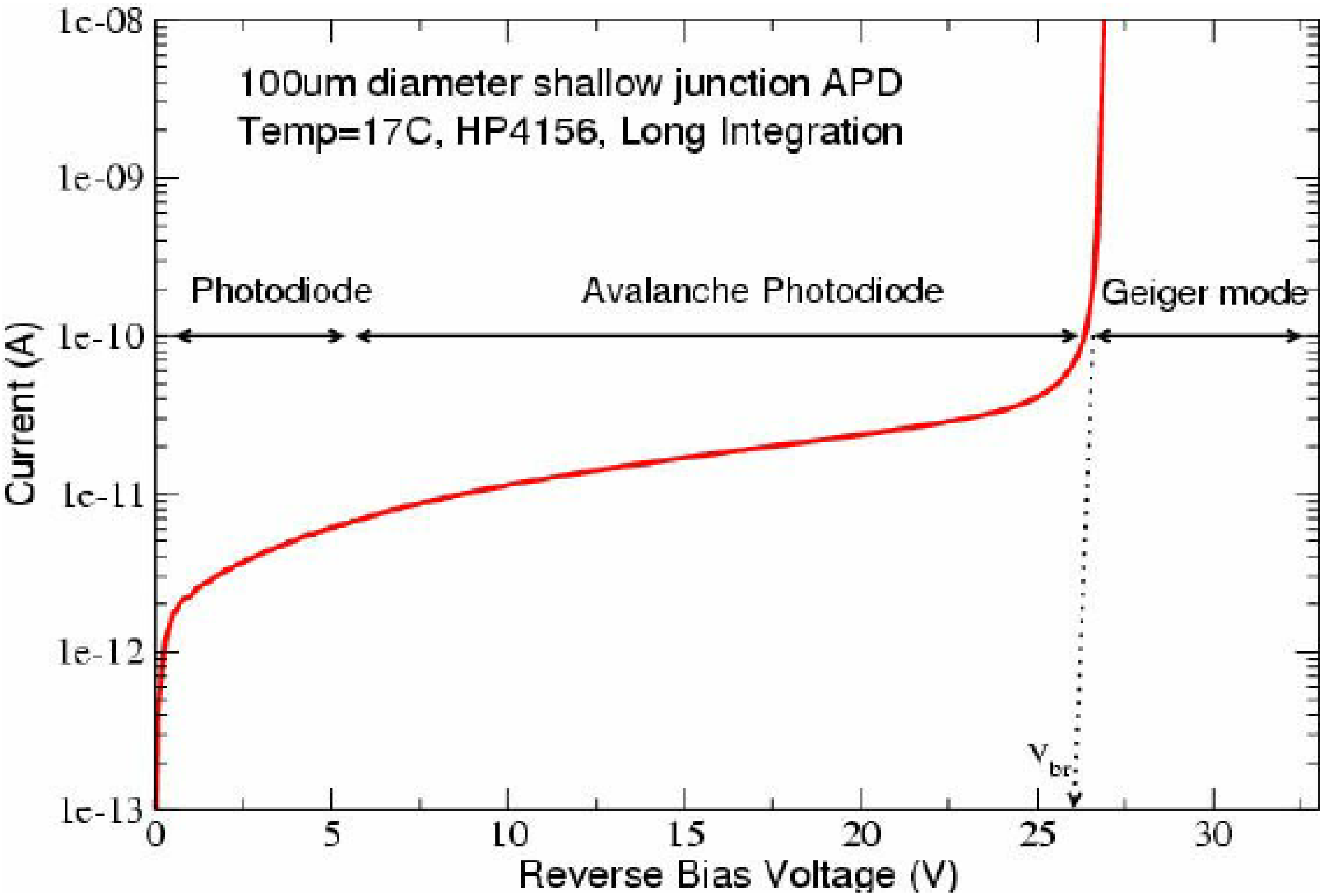


- Indirect paths are nuisance for depth sensing ("multi-path interference").
- Indirect paths are very informative for other time-of-flight applications.

How exactly is the transient formed?

Depends on the kind of sensor we use.

- Here we will examine only photodiodes.



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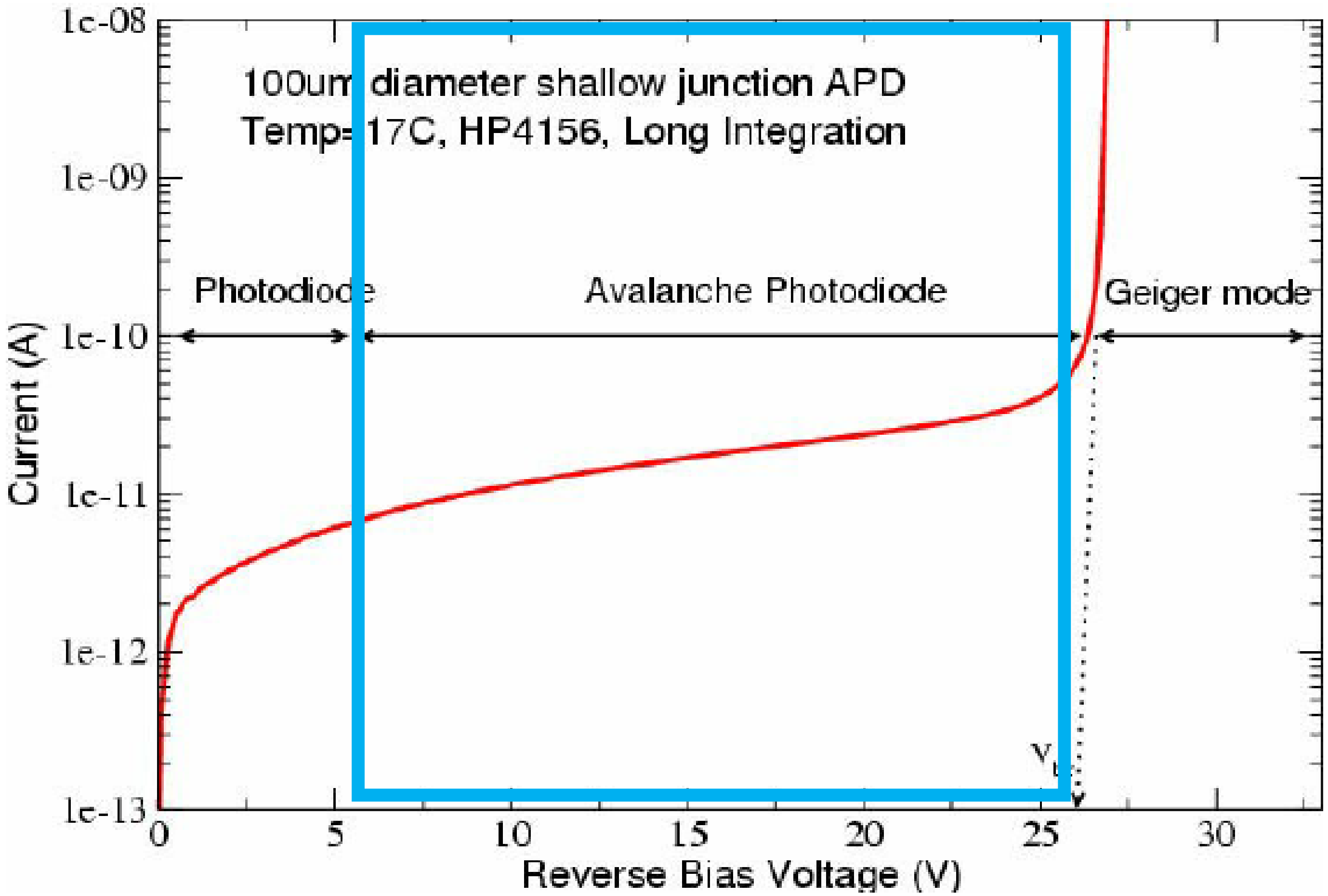

<u>Avalanche photodiode (APD)</u>:

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

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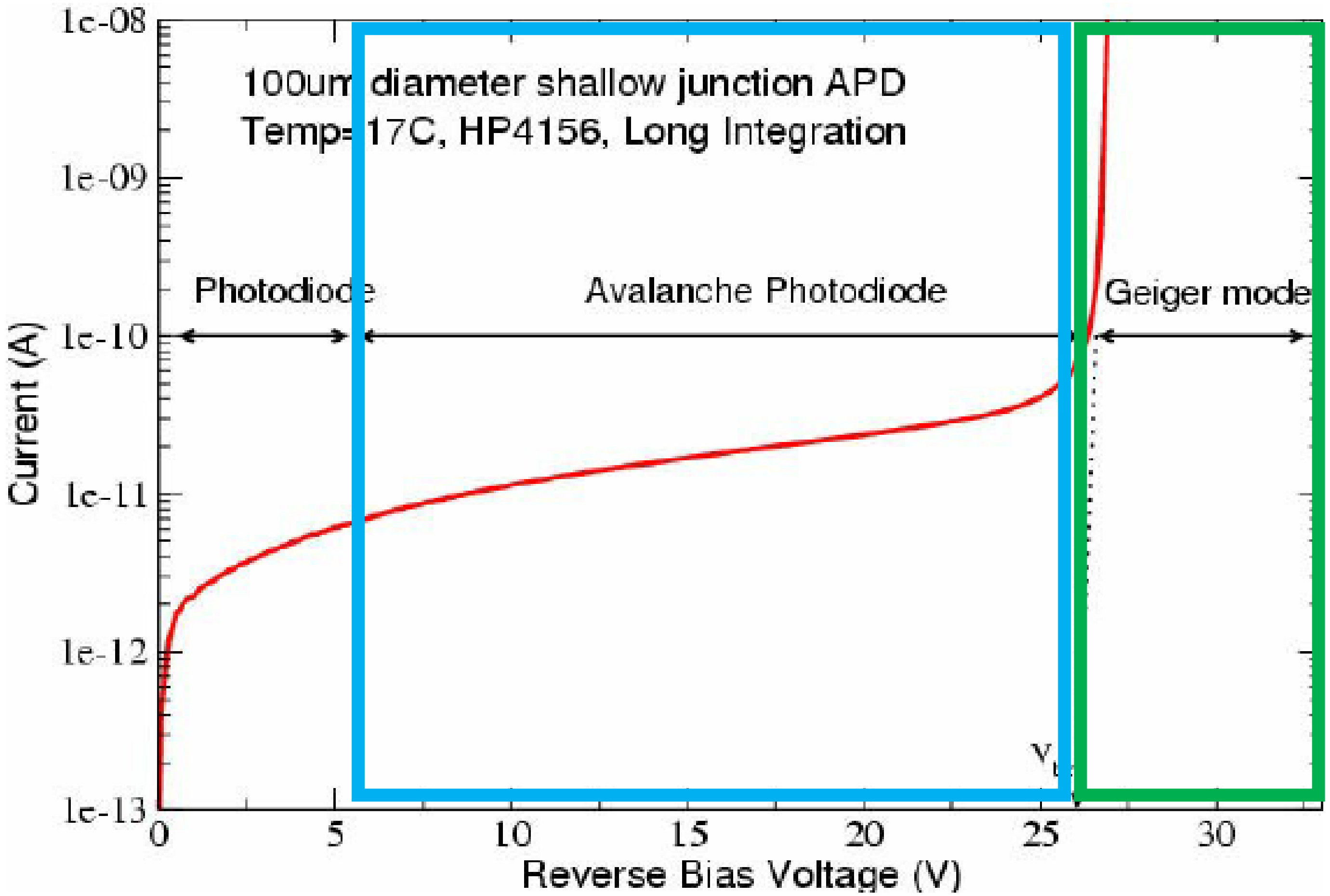


<u>Avalanche photodiode (APD)</u>:

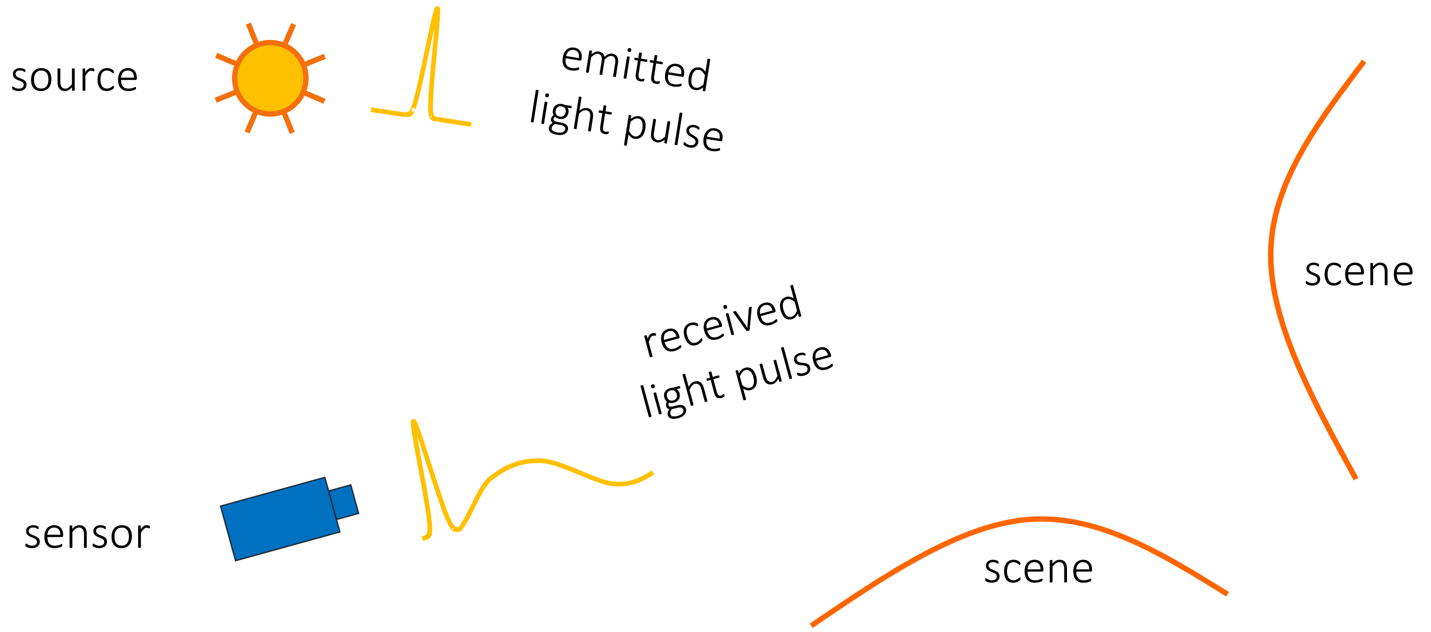
- Current is roughly proportional to number of photons.
- One photon produces tiny current.

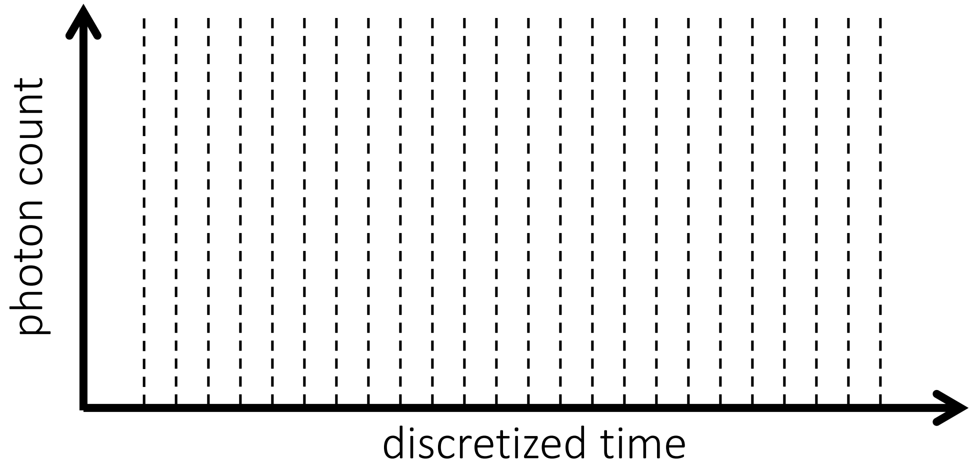
<u>Single-photon avalanche diode (SPAD)</u>:

- 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

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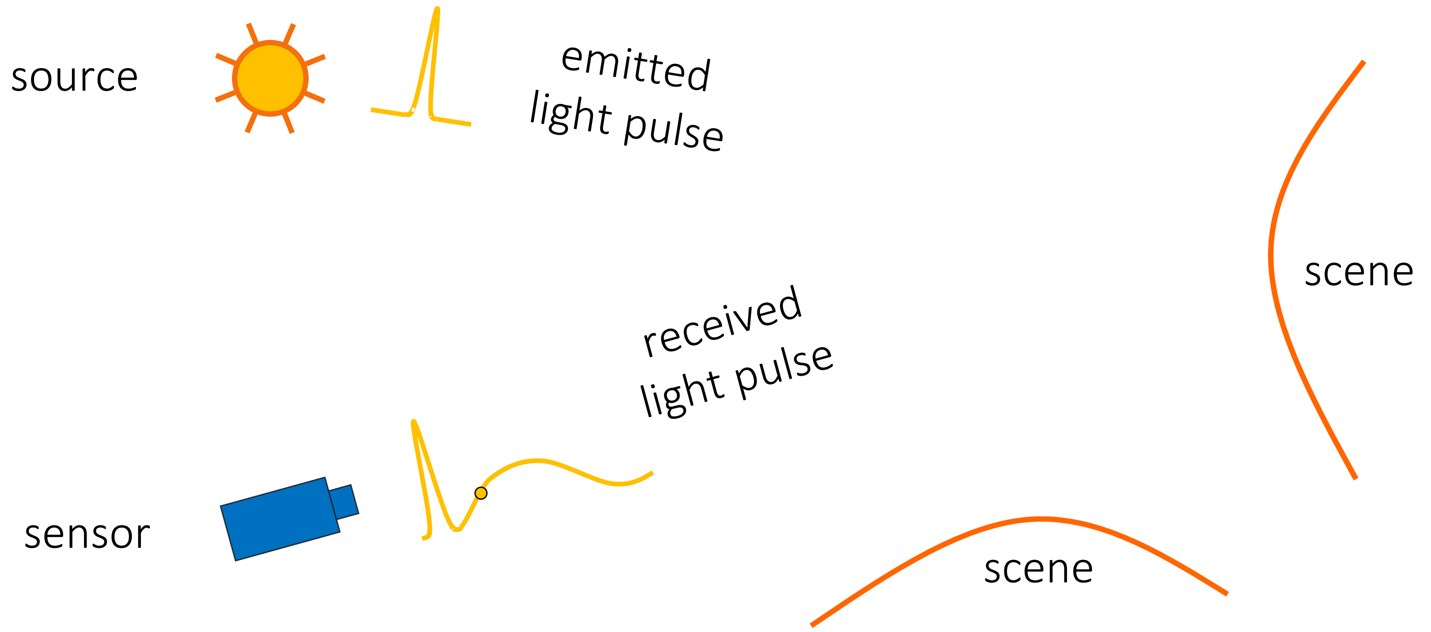

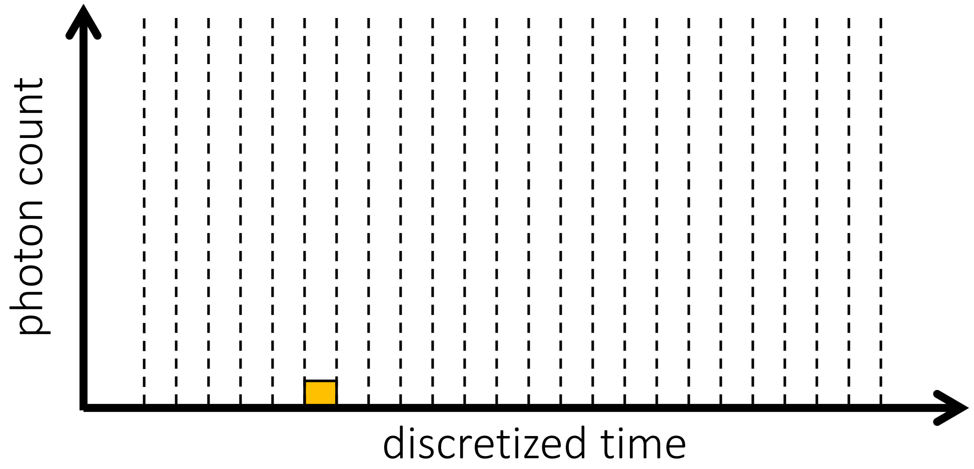

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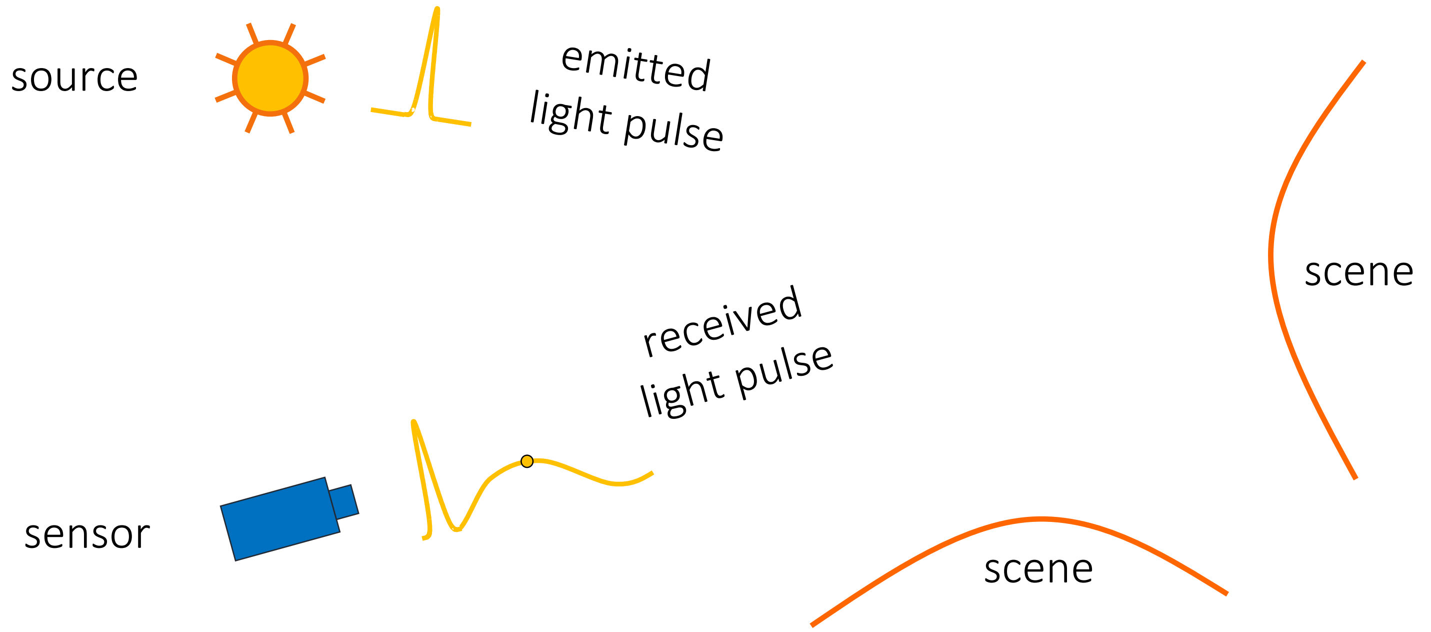

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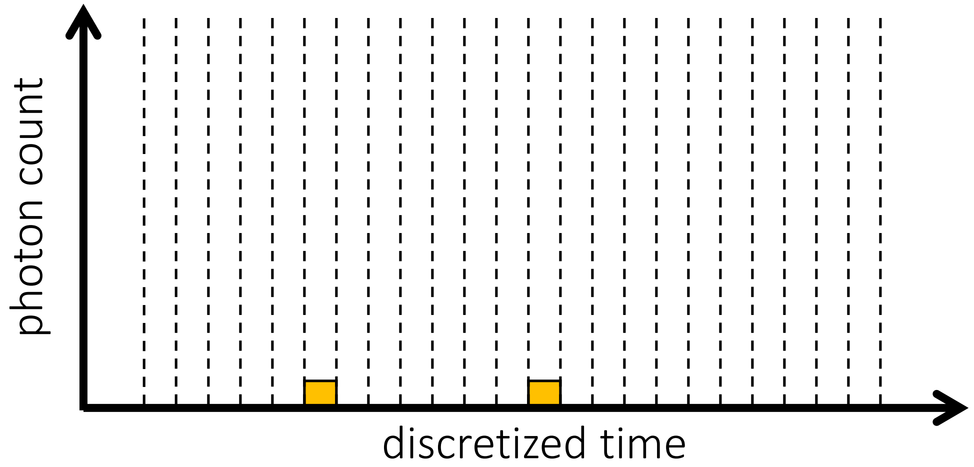

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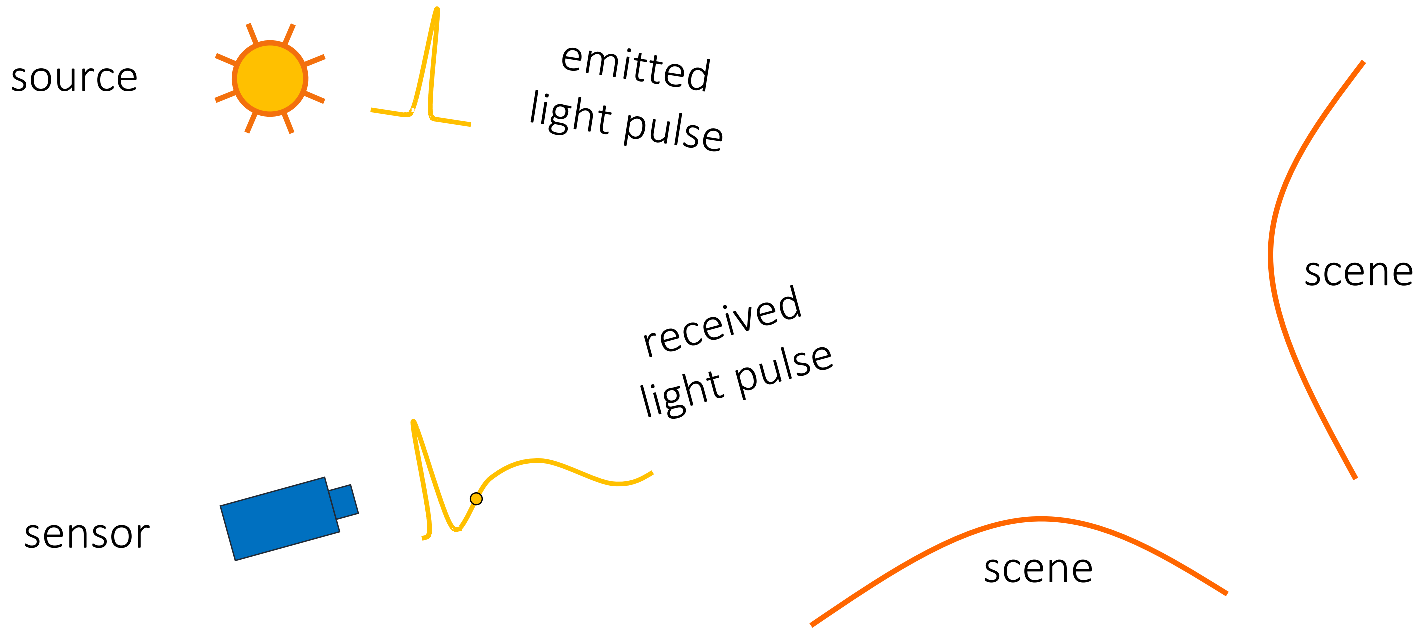

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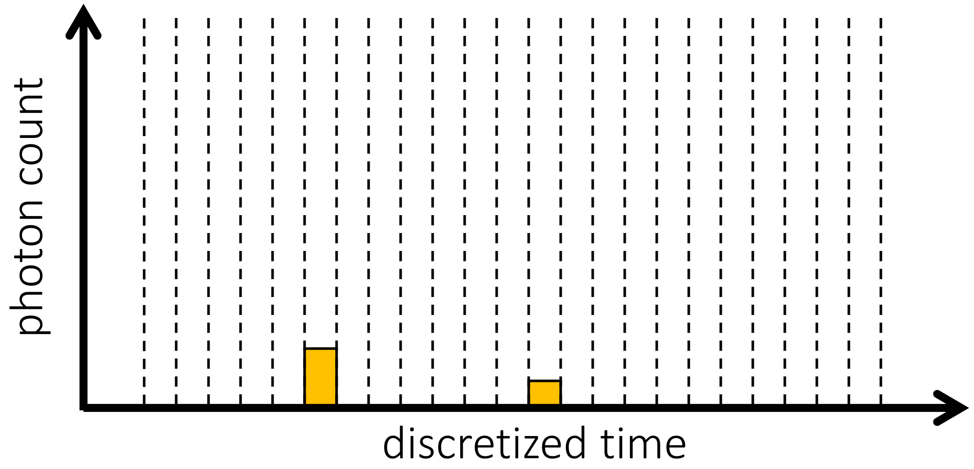

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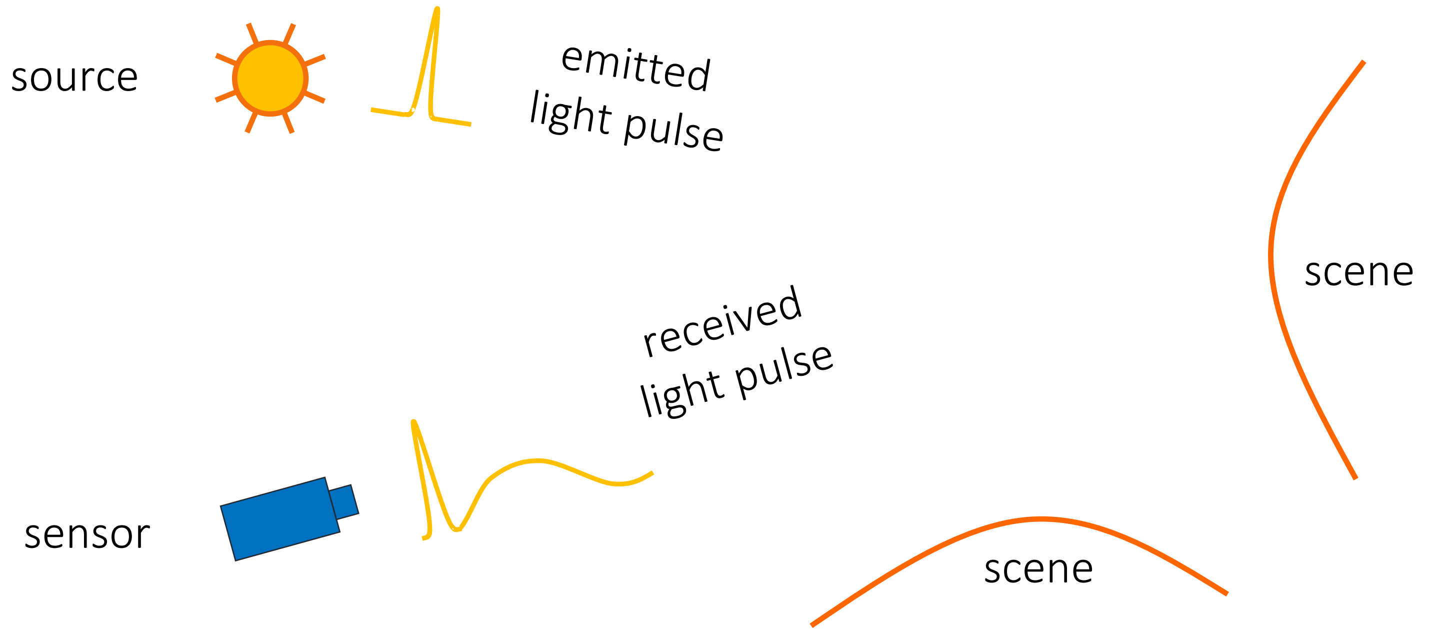
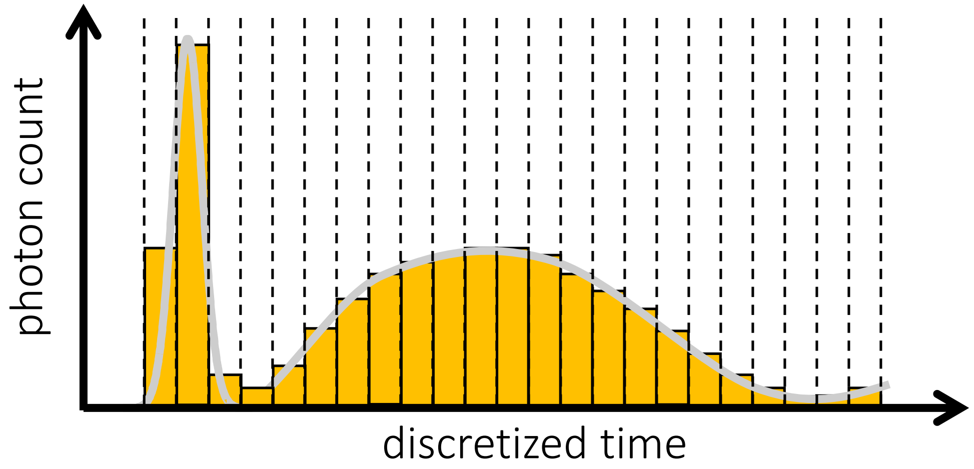


From each received pulse, one photon saturates the SPAD.

What determines which photon gets picked?



- The SPAD records only photon arrival times, no intensity.
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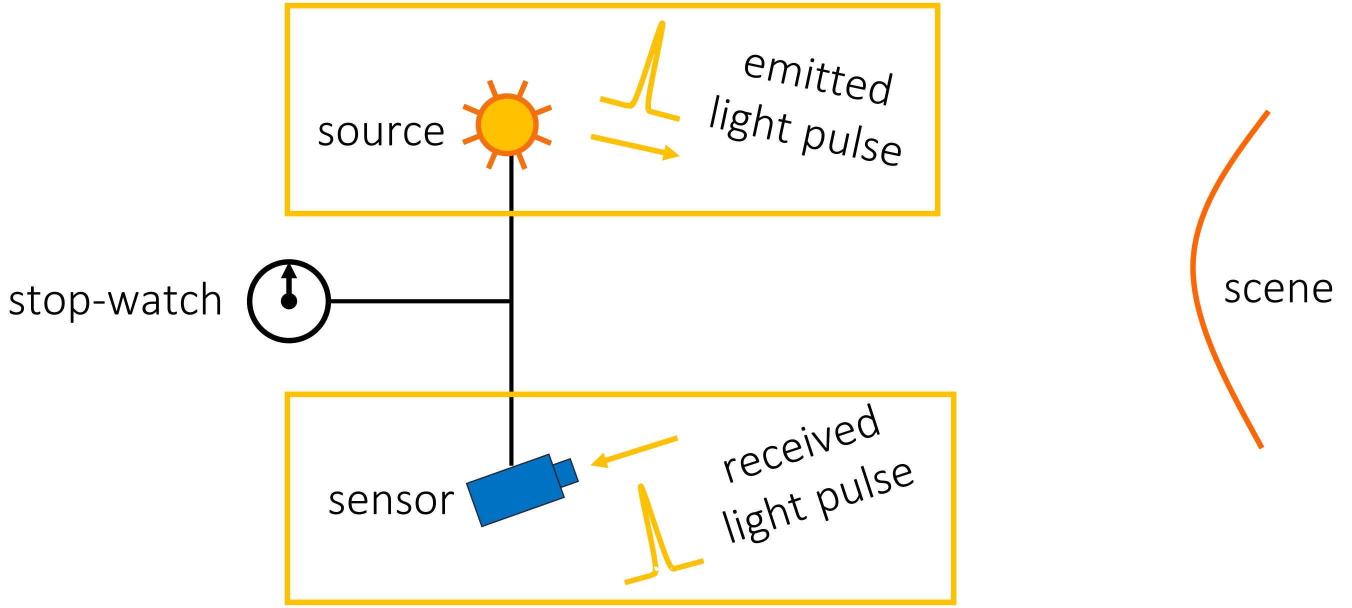
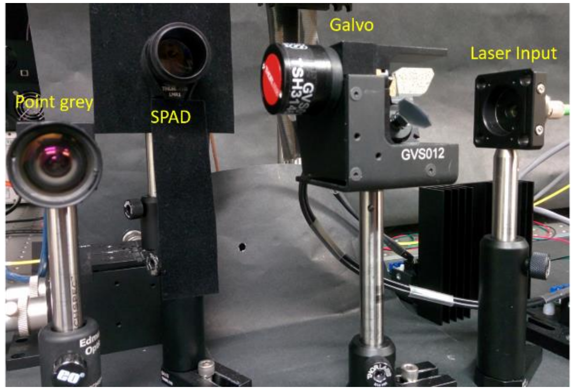
What hardware do we need for impulse ToF?



Expensive Lasers
[Short (picosecond) and Powerful (mega joules) Light Pulse]

High Speed and High Dynamic Range Sensors
[Picosecond Time Resolution]



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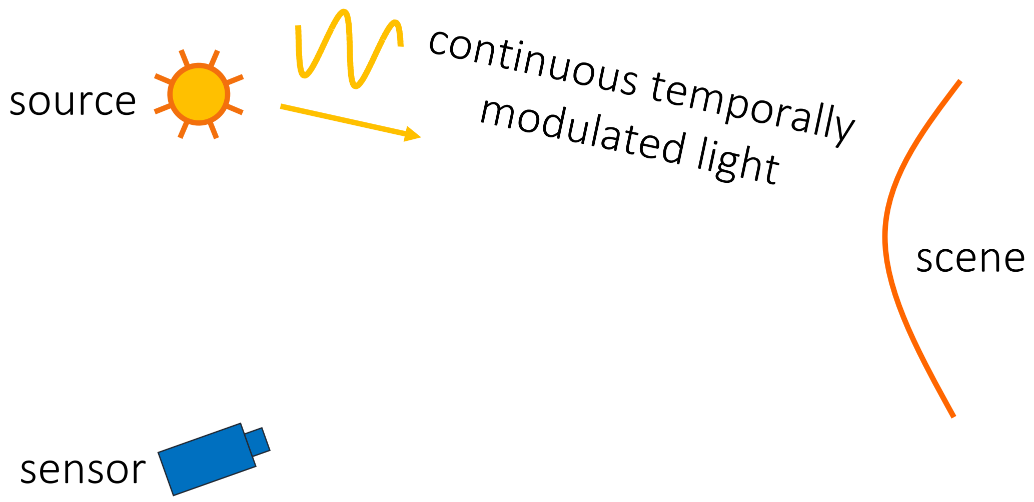
continuous-wave ToF

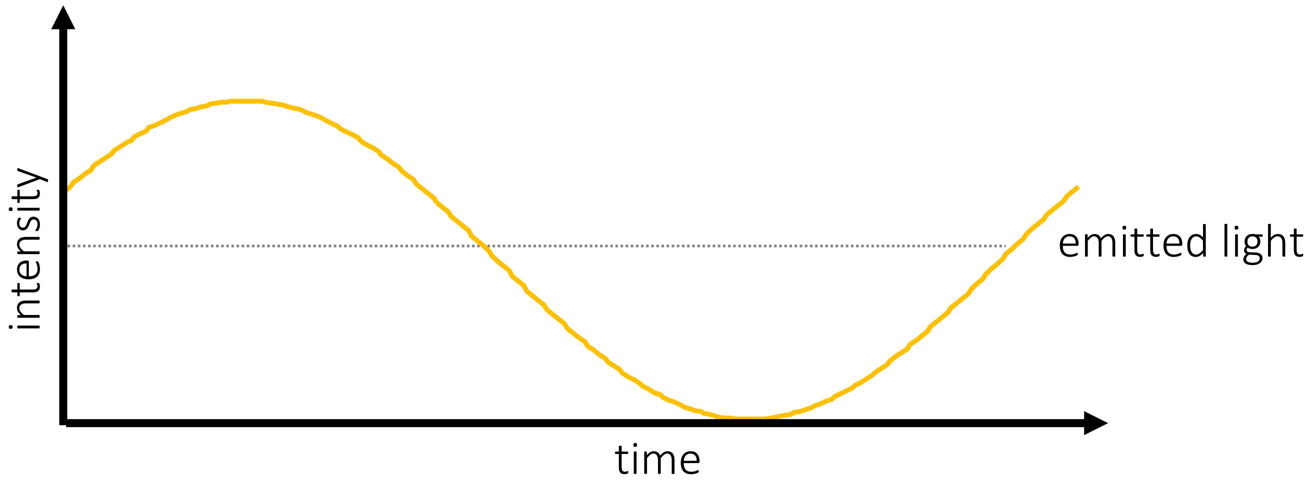
impulse ToF

Continuous-wave ToF imaging

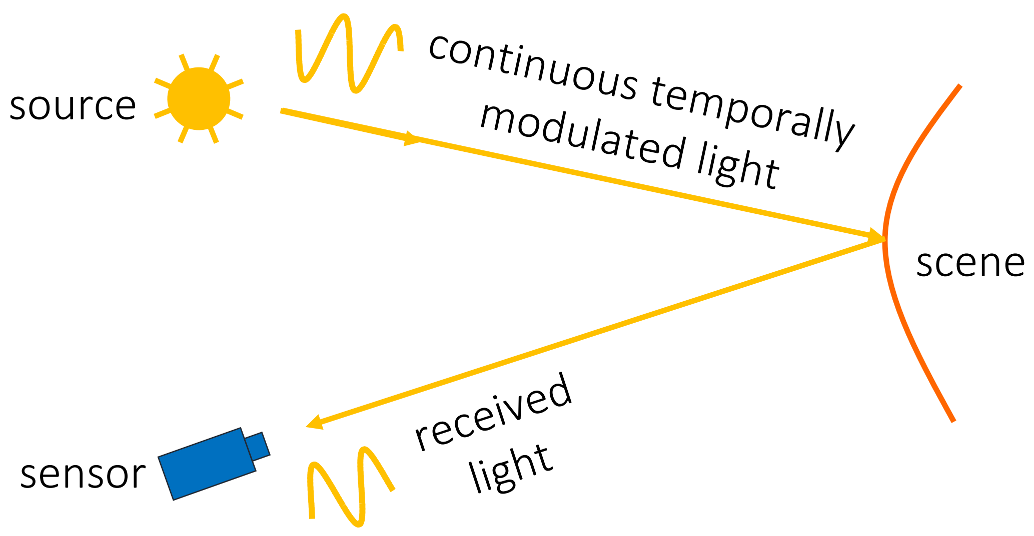
Continuous-wave (CW) time-of-flight imaging

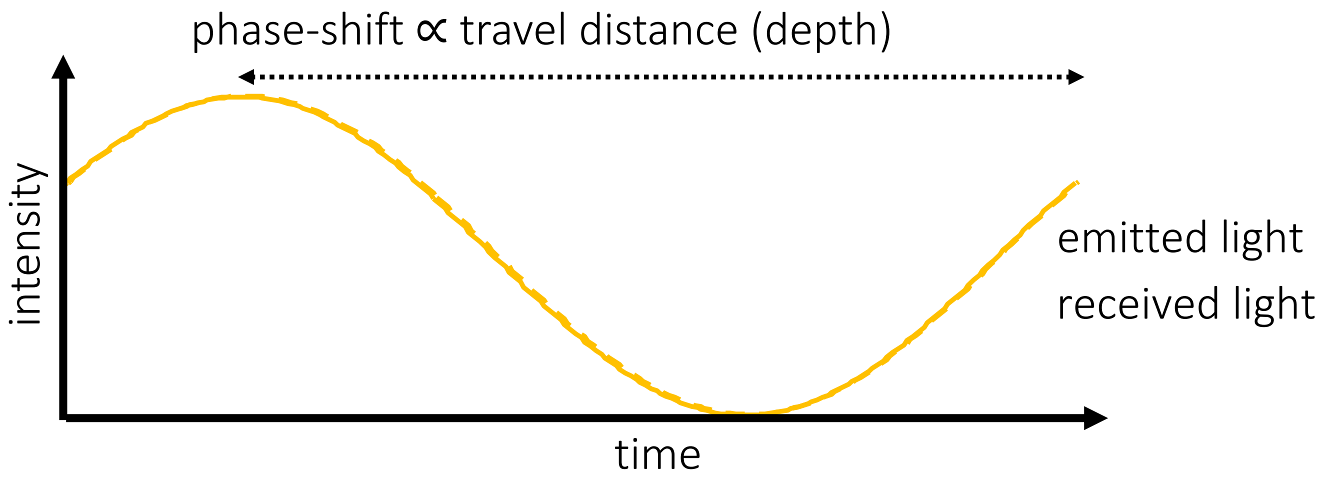


sinusoid

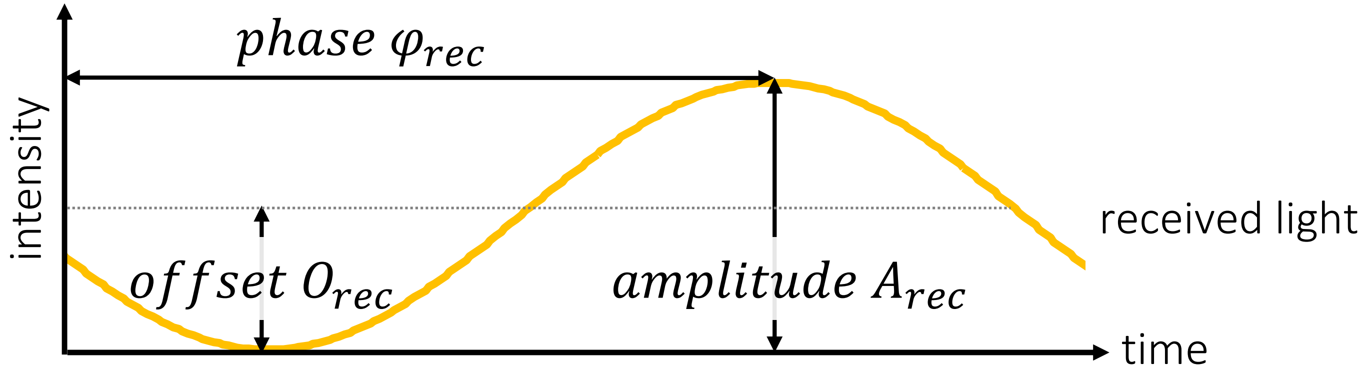


Continuous-wave (CW) time-of-flight imaging





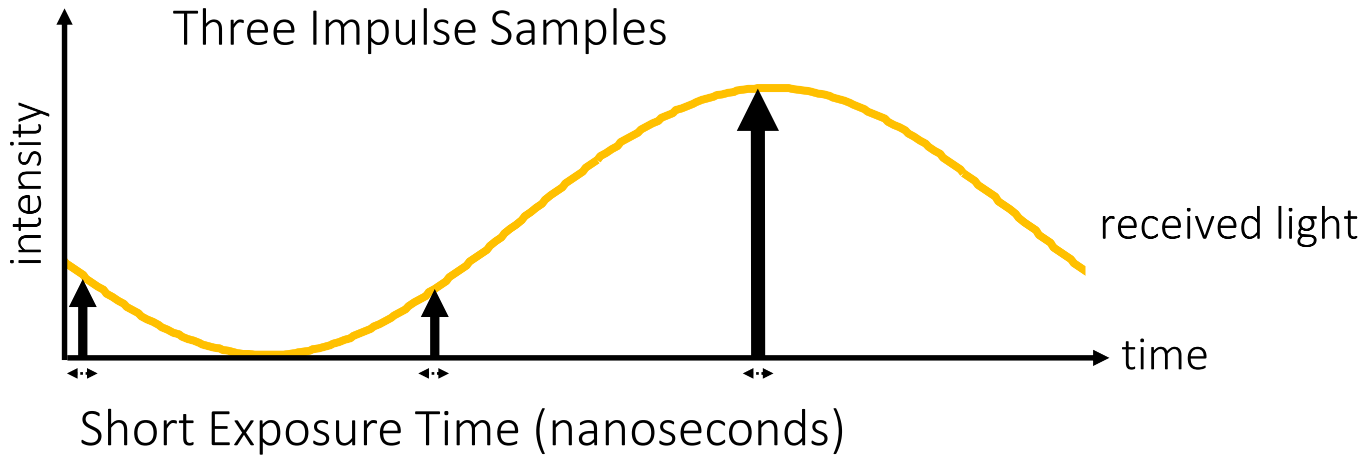
Measuring phase shift



Three Unknowns

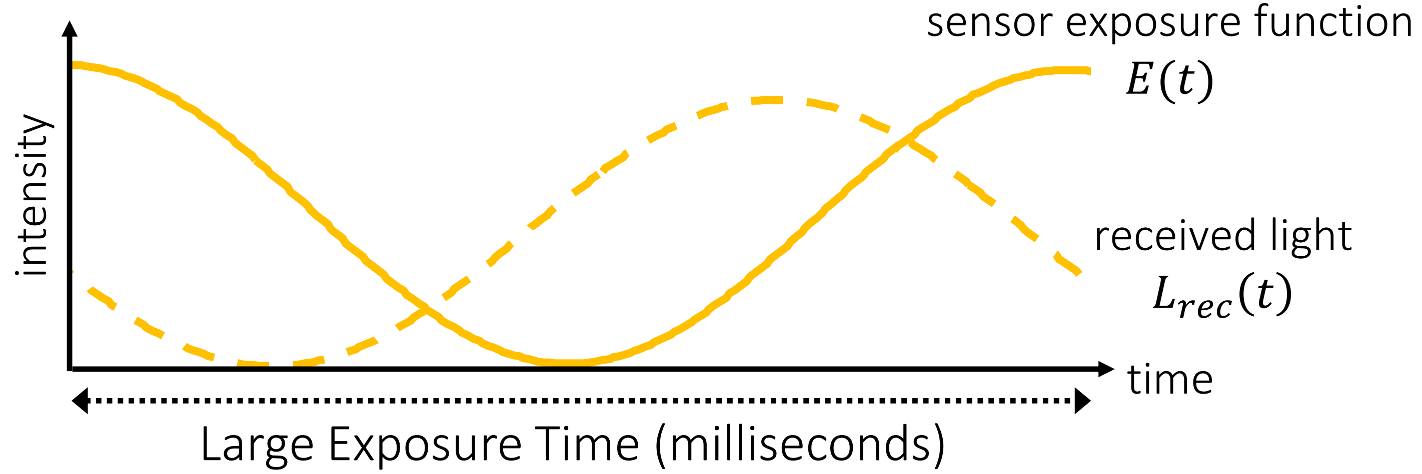
$$L_{rec}(t) = O_{rec} + A_{rec}\cos(\omega t - \phi_{rec})$$

Measuring phase shift: direct



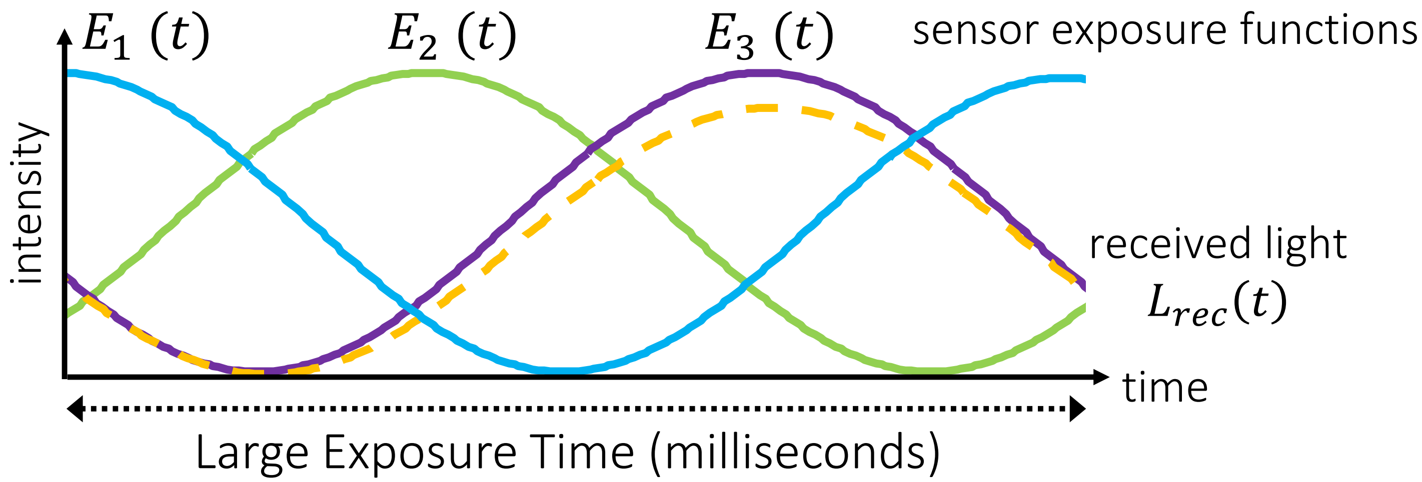
Low Signal-to-Noise-Ratio

Measuring phase shift: correlation



$$\text{Correlation: } \underset{\text{measured brightness}}{I} = \int \underset{\text{exposure function}}{E(t)} \times \underset{\text{received light}}{L_{rec}(t)}\, dt$$

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

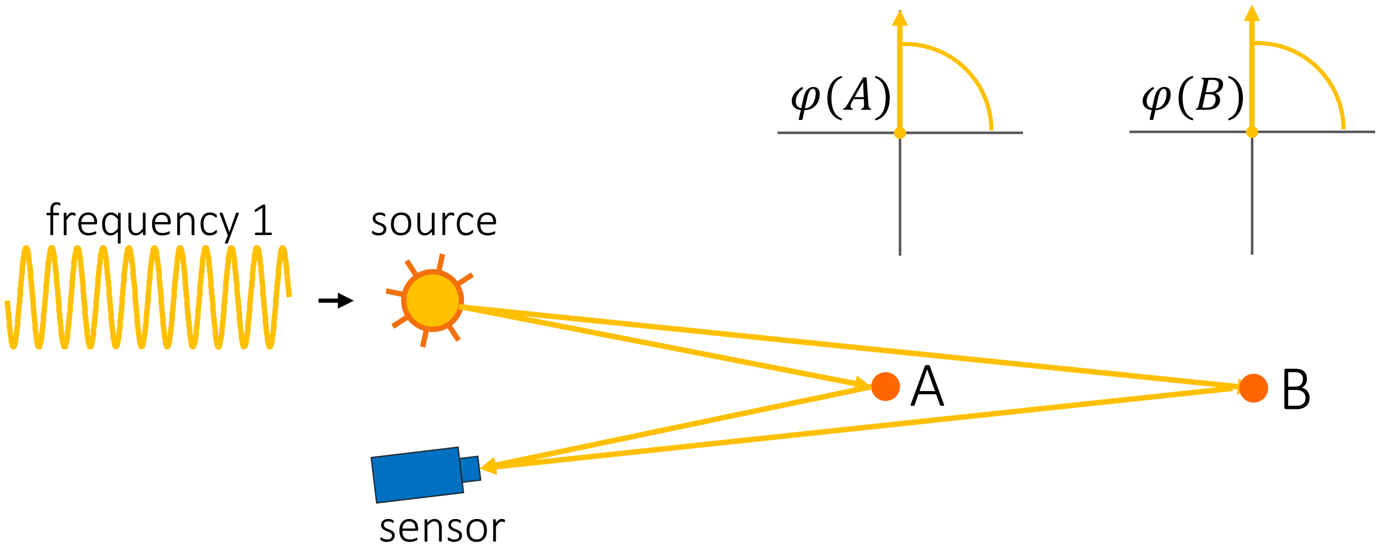
$depth$

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

$offset\ O_{rec}$

$amplitude\ A_{rec}$

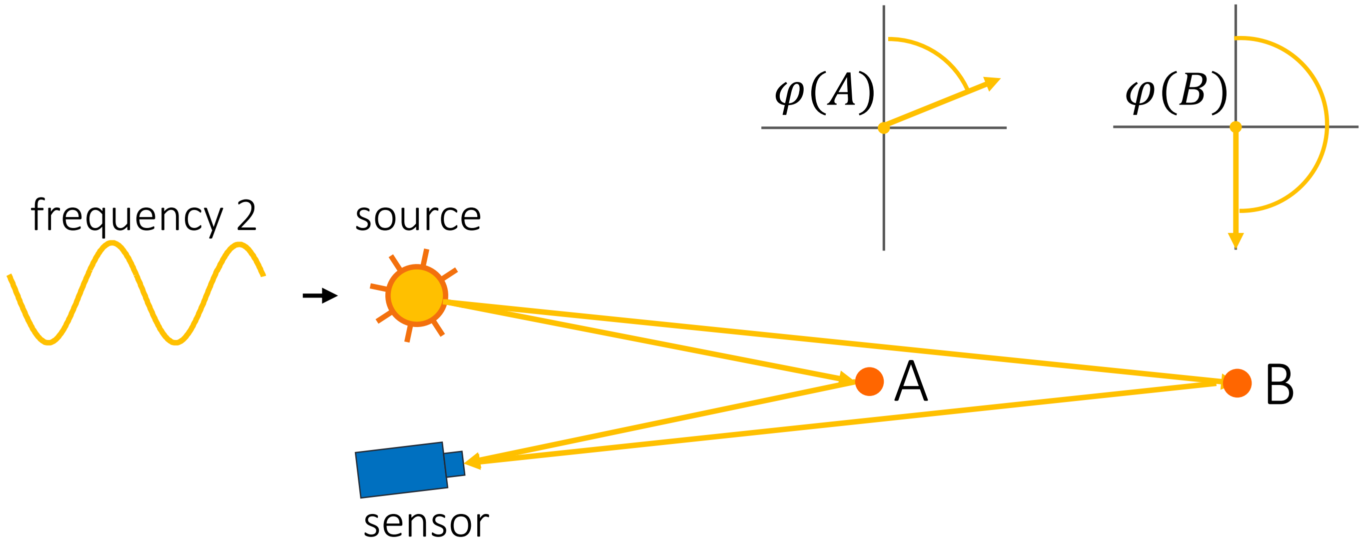
Phase ambiguity



Different Scene Depths Have Same Phase

- Also known as “phase wrapping”.

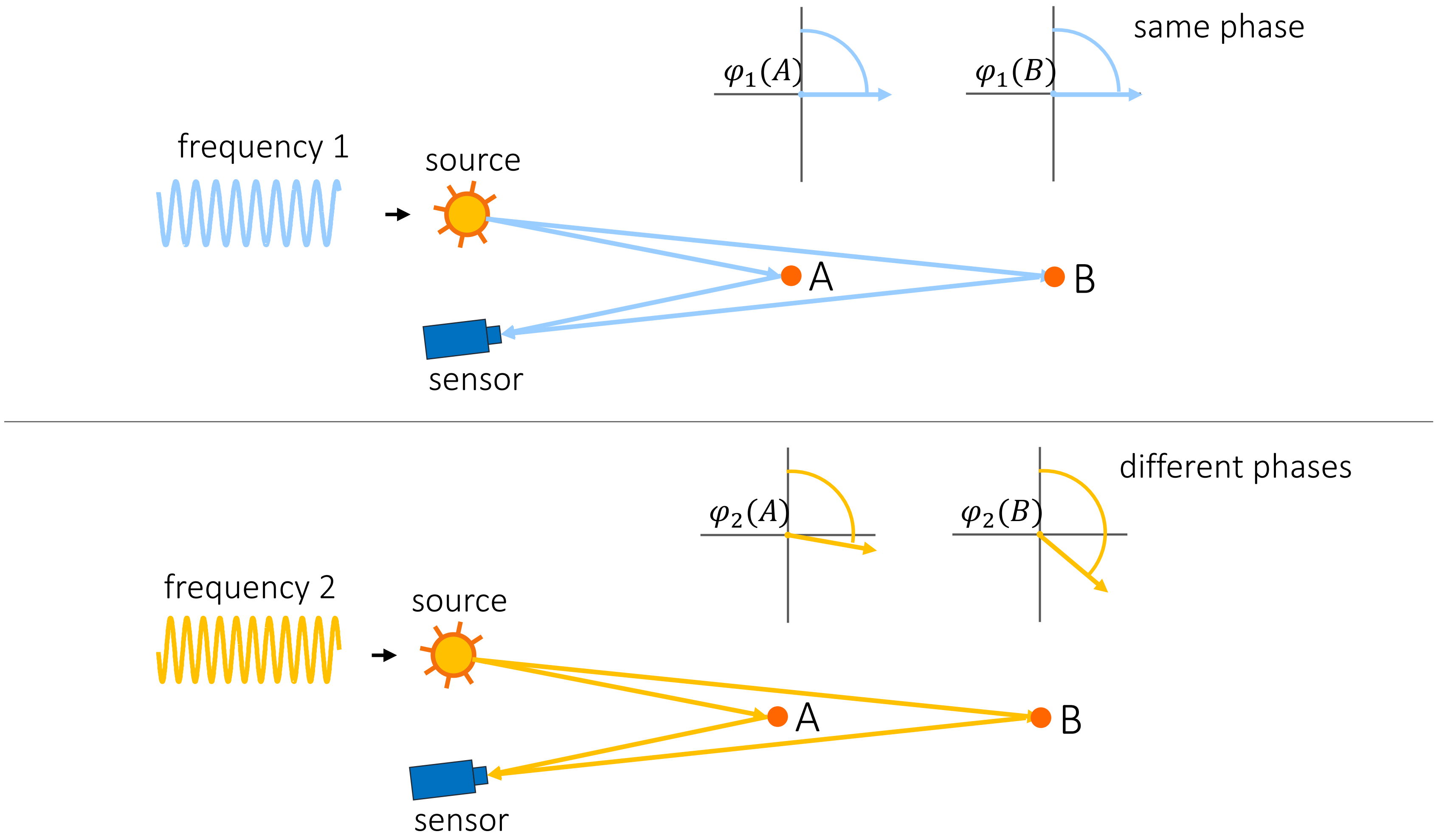
Phase ambiguity



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

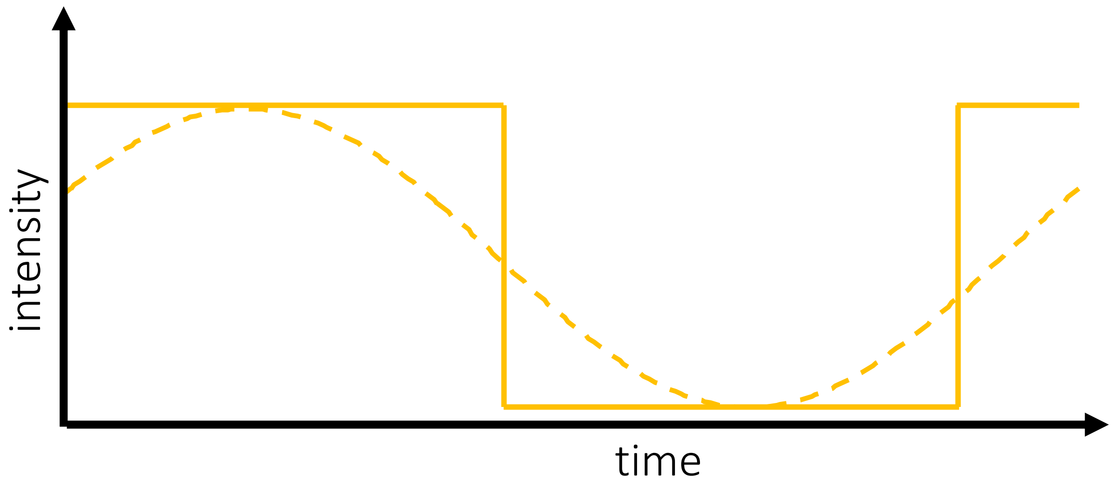
How can we resolve the phase ambiguity?

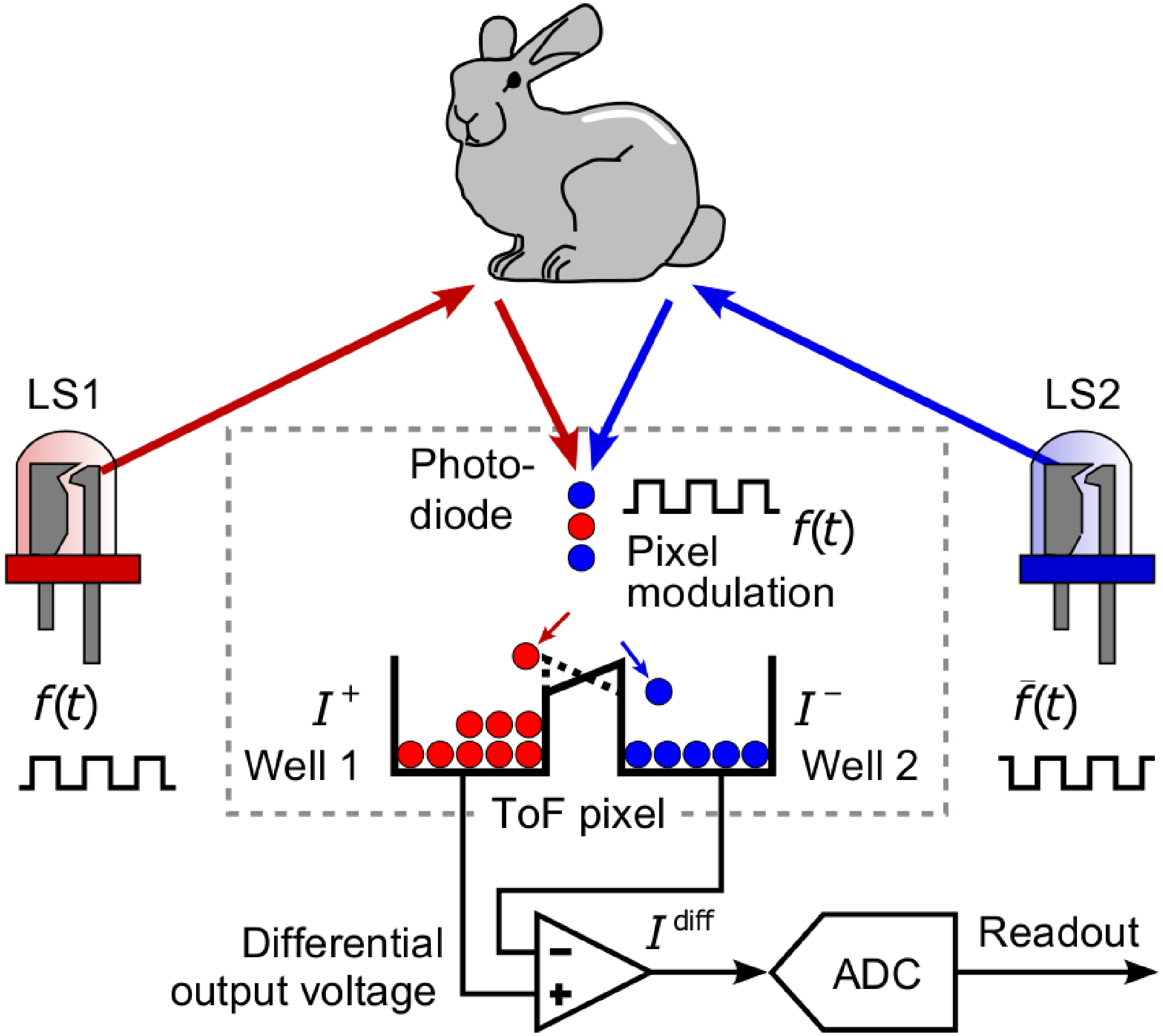
Disambiguating phase



Compute phases at two different frequencies

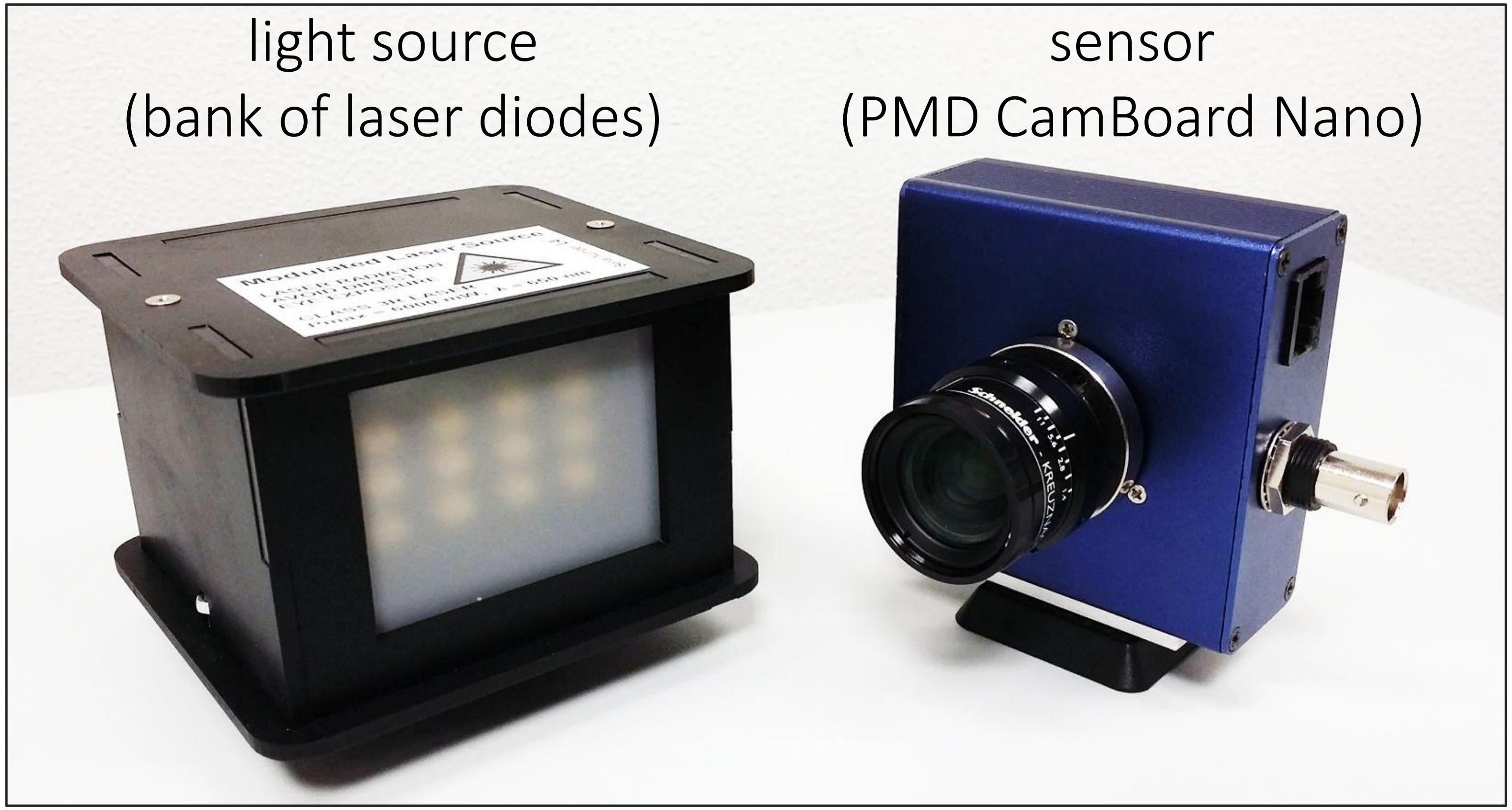
Implementation: two-well architectures



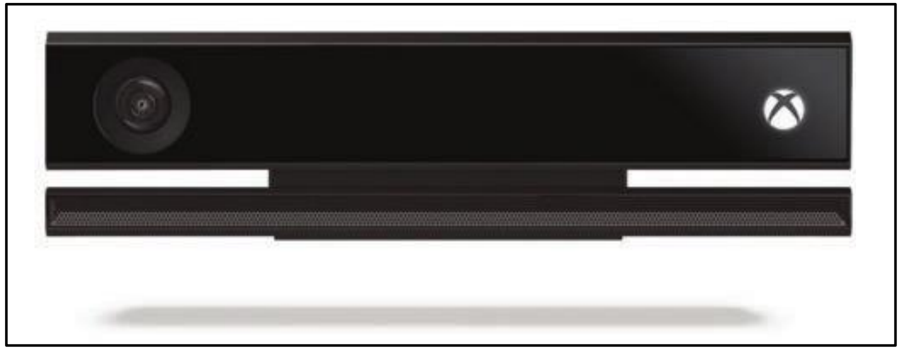


- approximate sinusoid with a square pulse
- store photons in different wells depending on whether they arrive at 1 or 0
- take difference between two wells

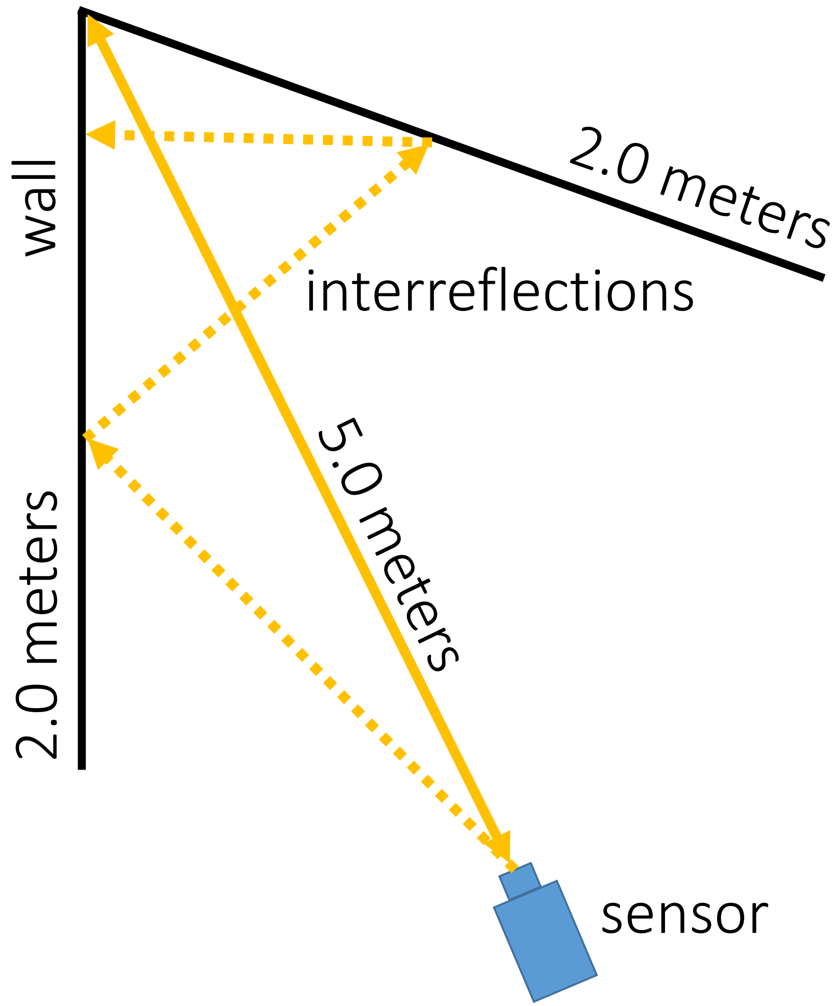
Some examples

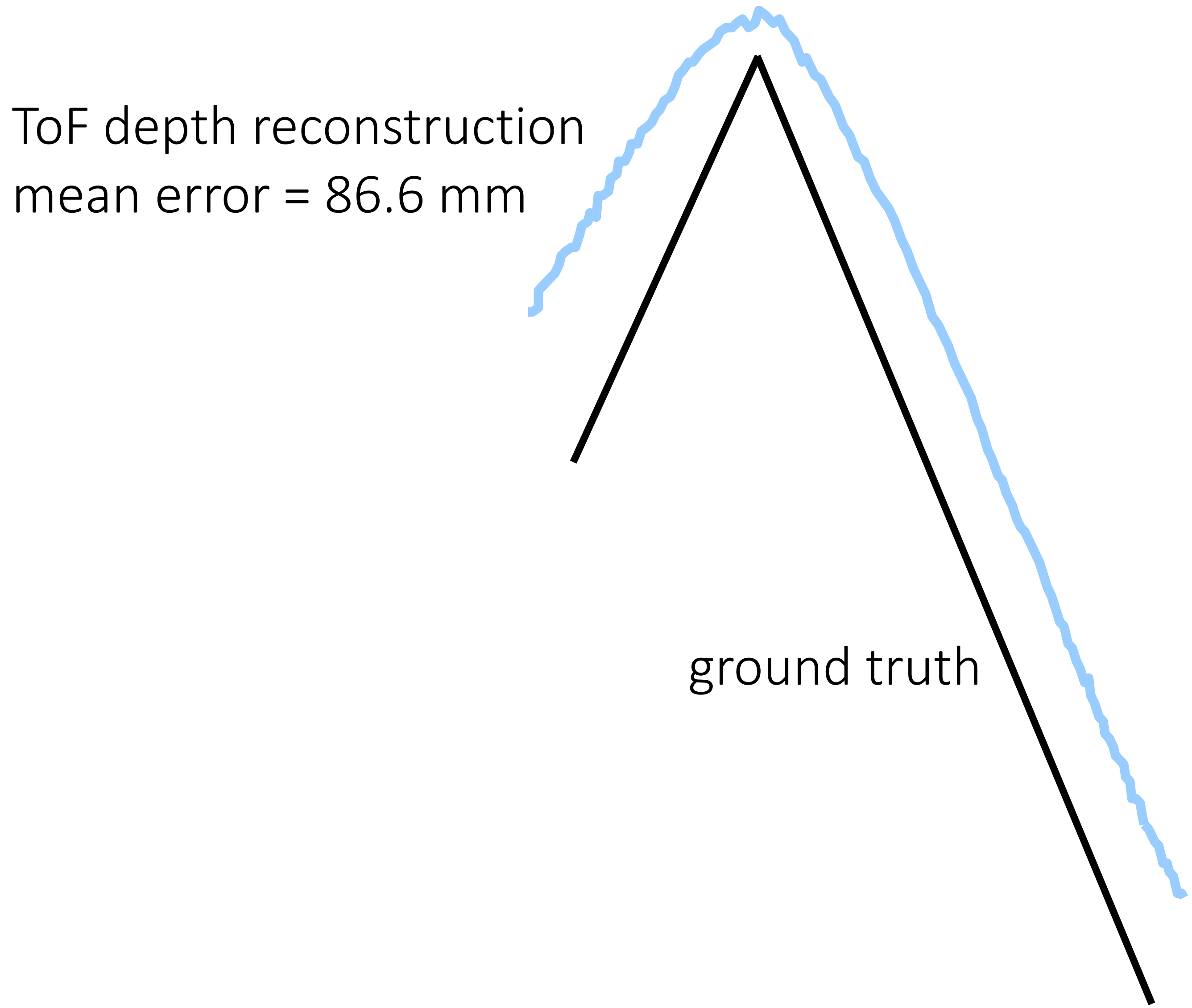


(only second generation of Kinect uses CW ToF)



Multi-path interference





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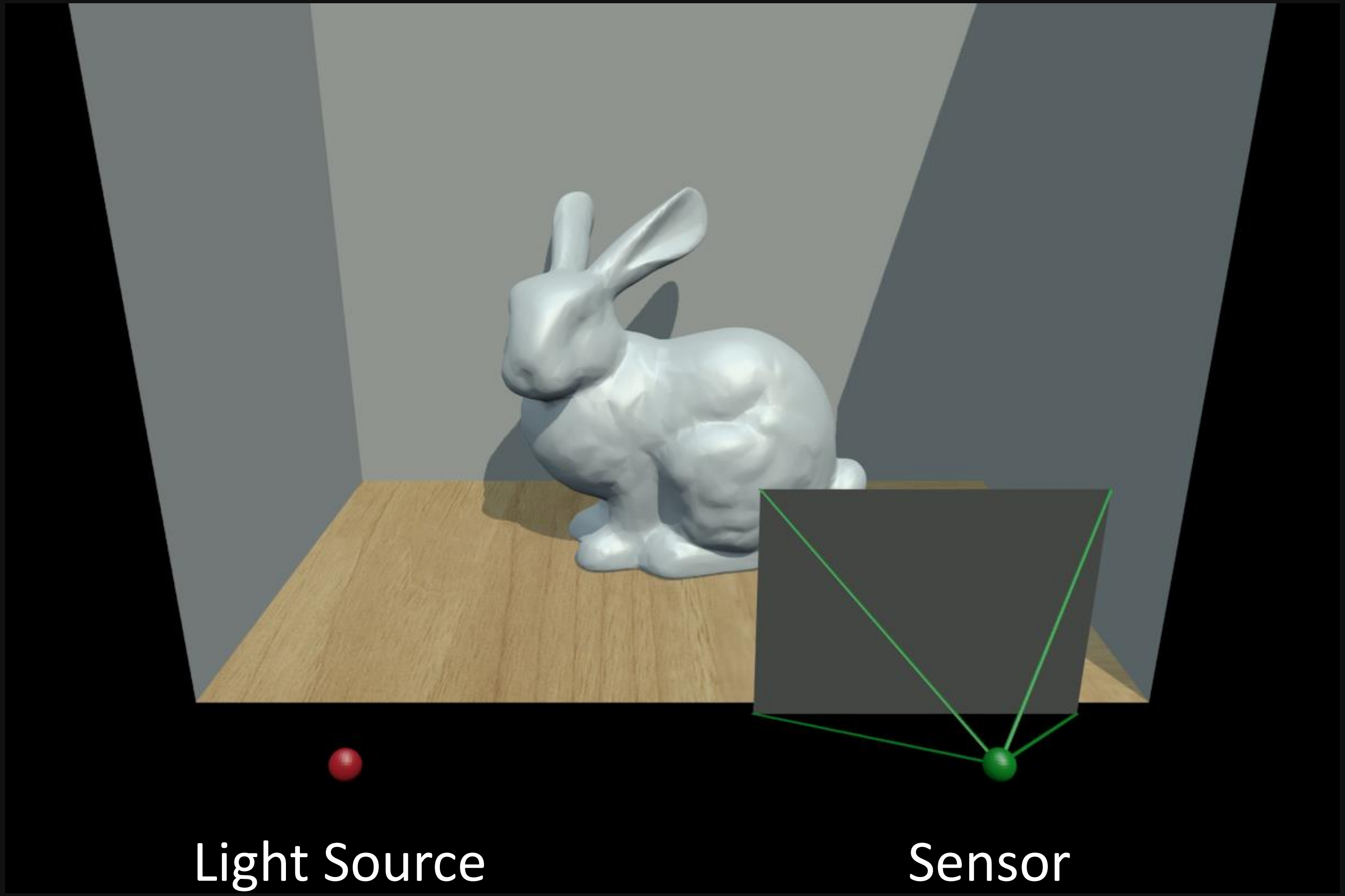
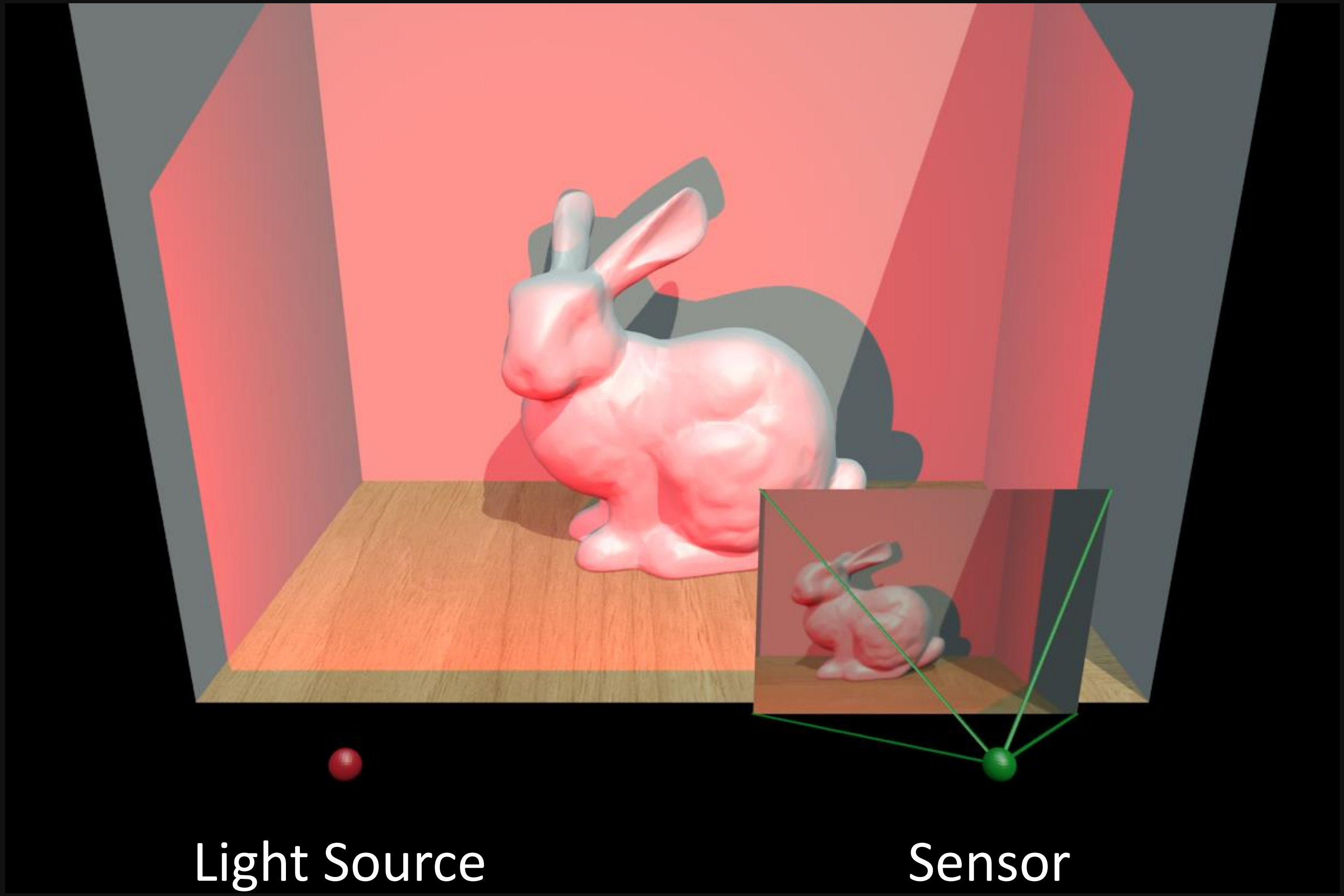
	continuous-wave ToF	impulse ToF	impulse ToF	continuous-wave ToF	impulse ToF

Epipolar continuous-wave ToF imaging

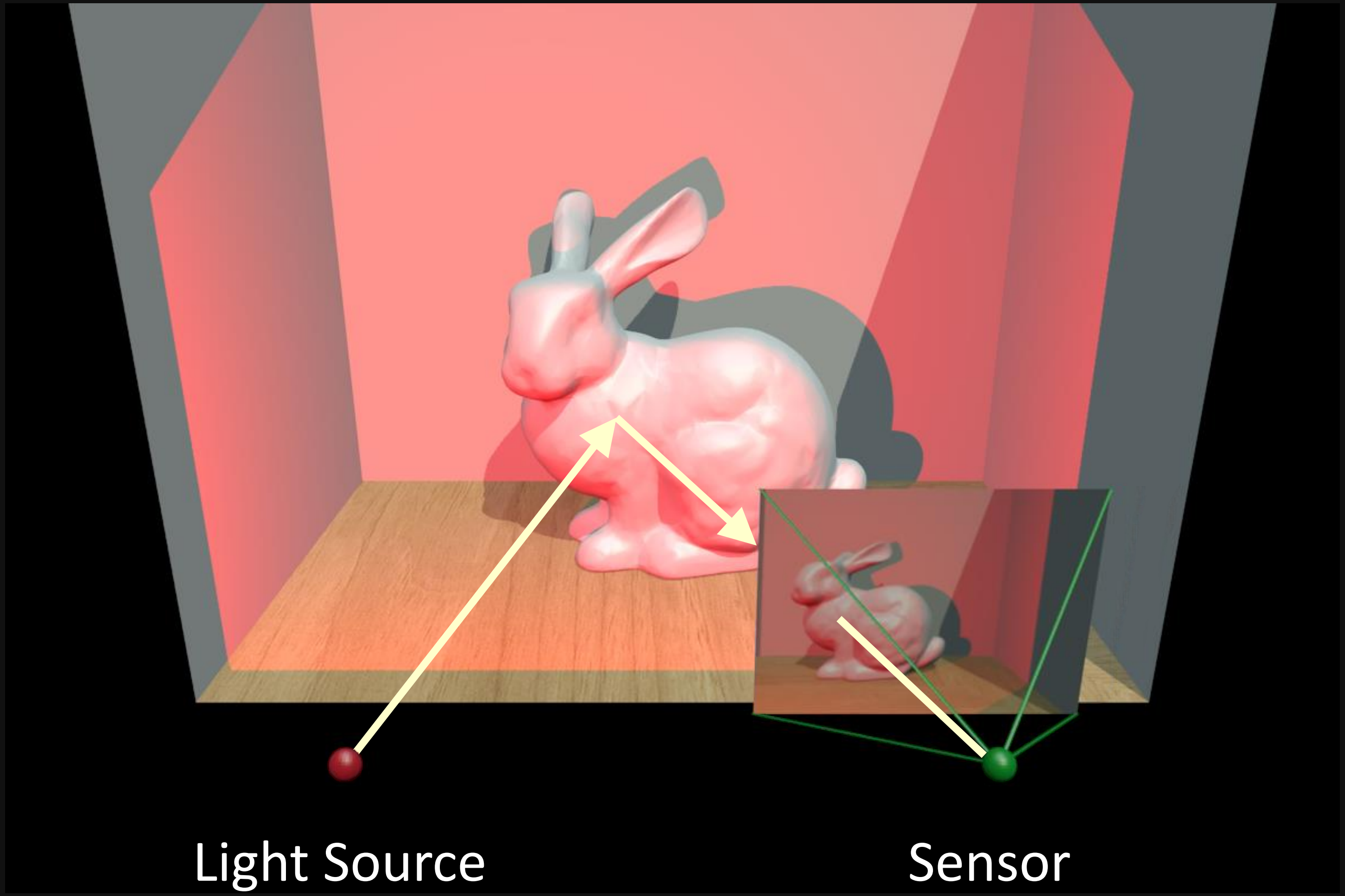
Regular Imaging



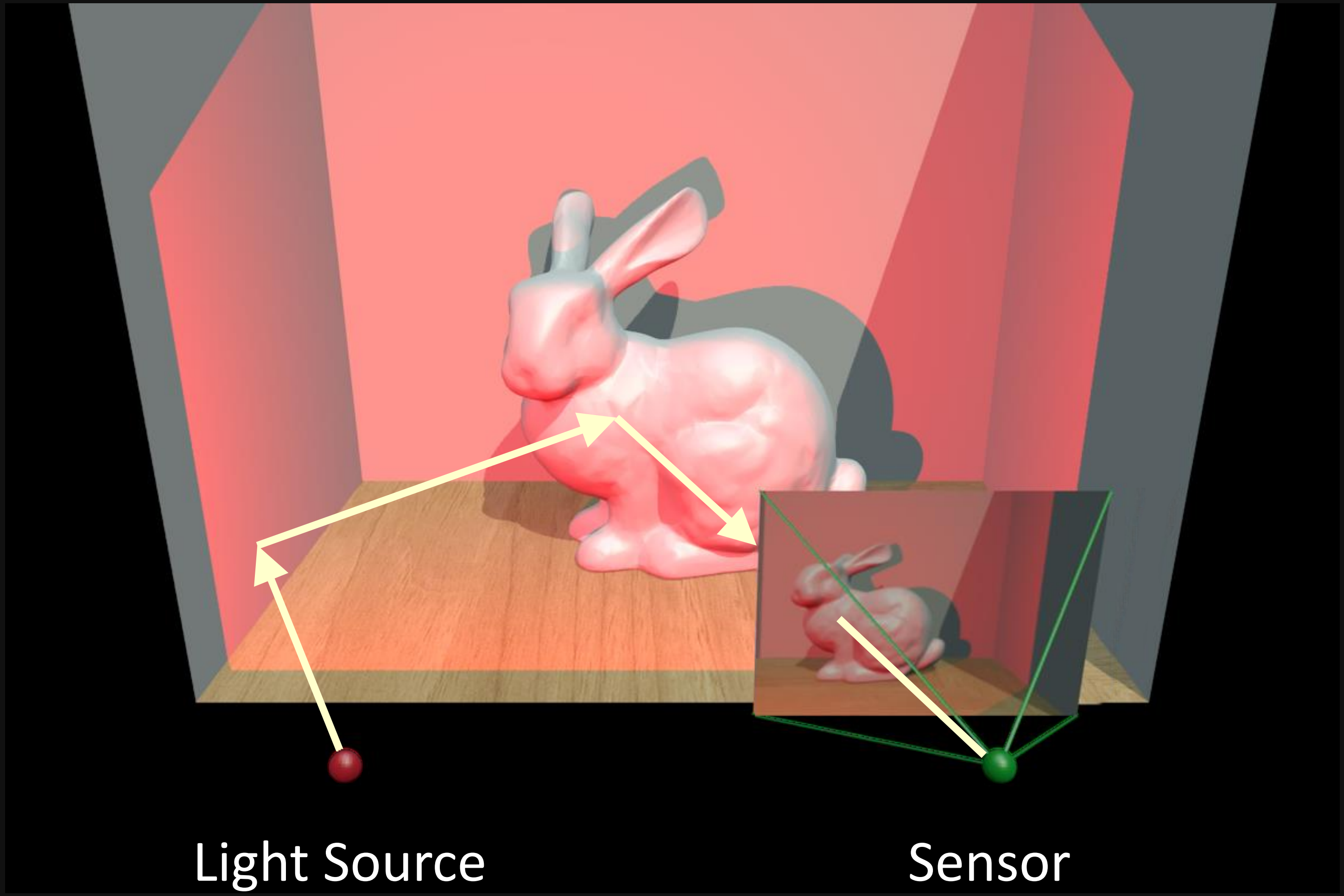
Regular Imaging



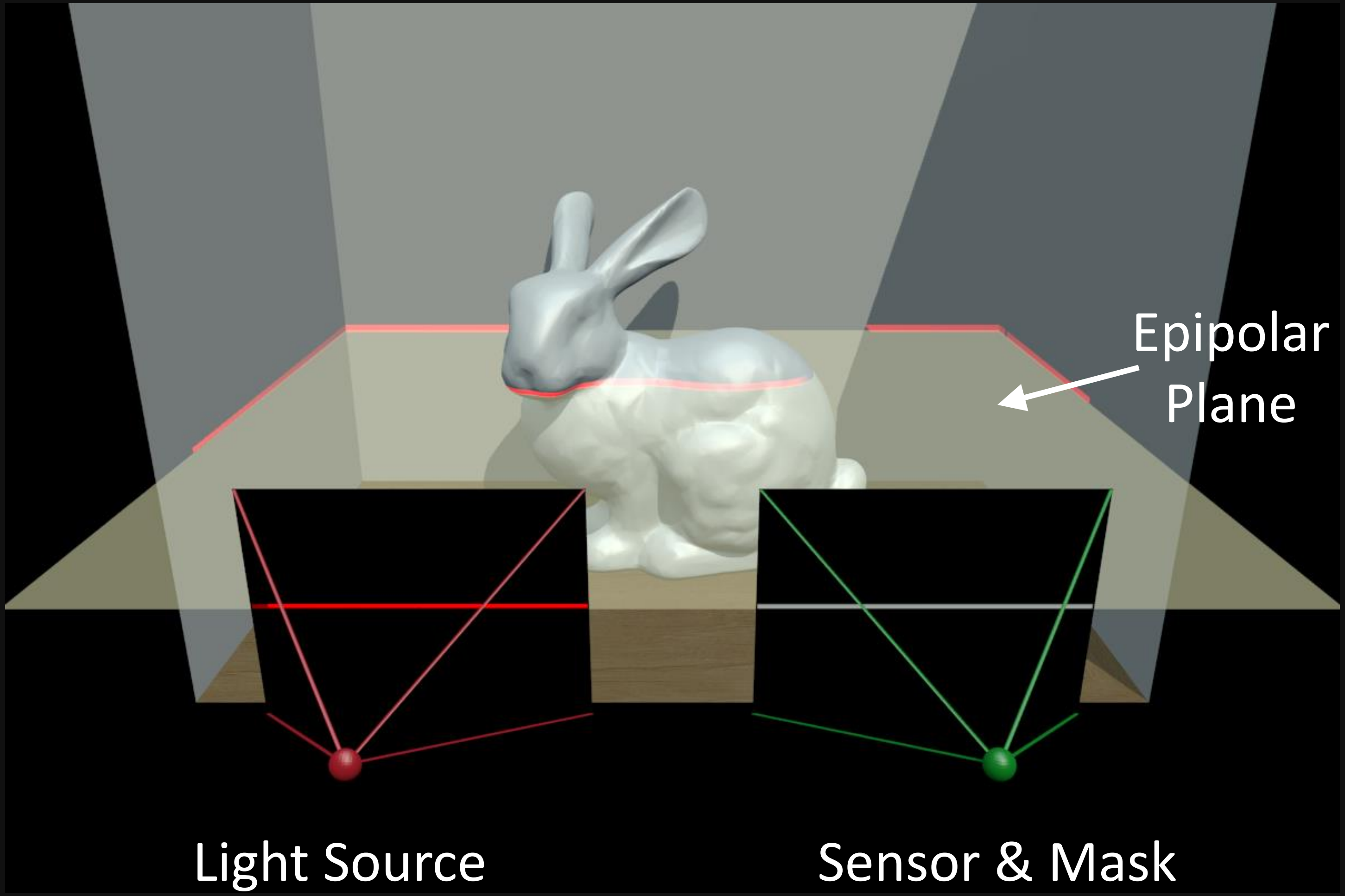
Regular Imaging



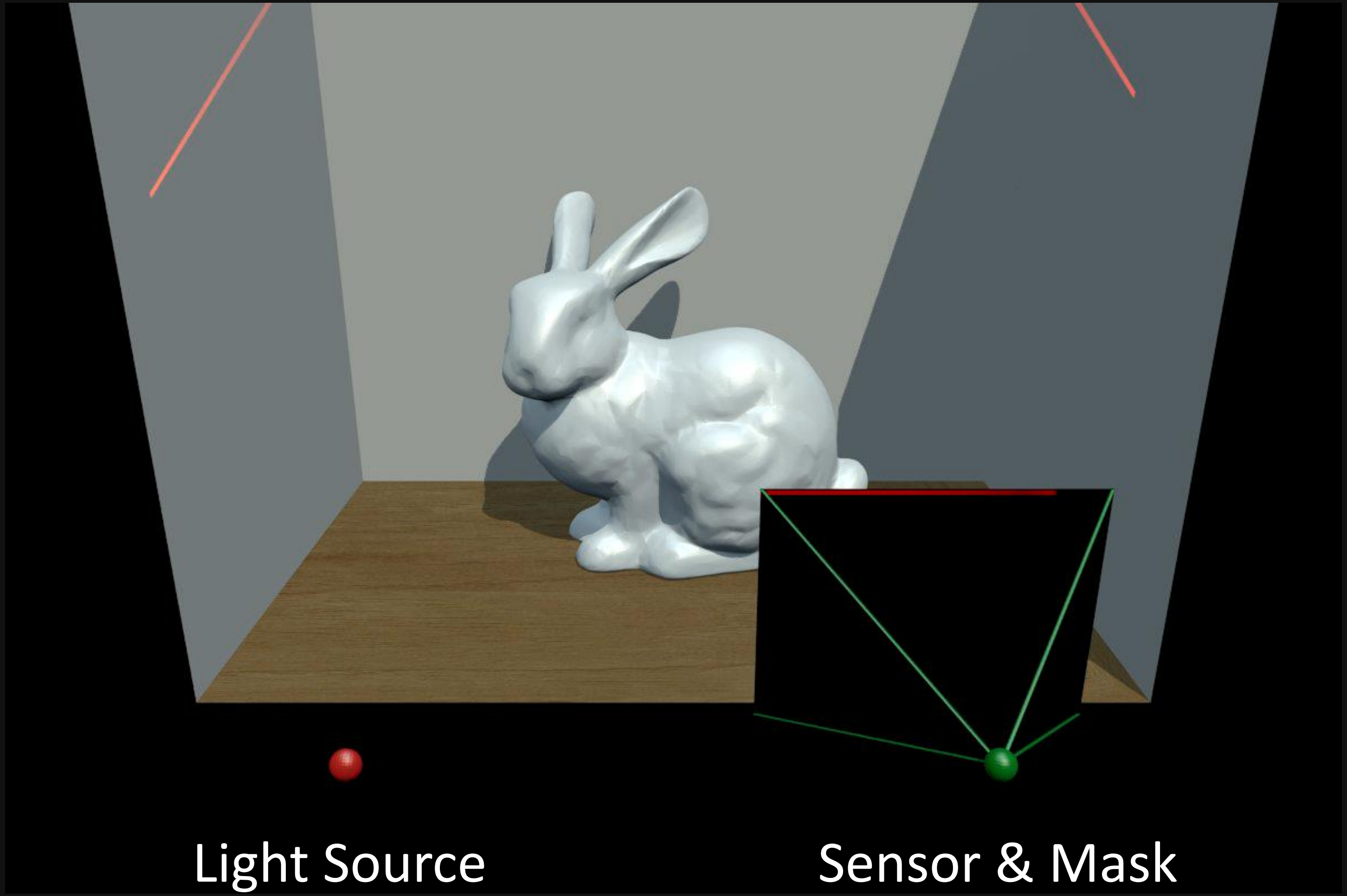
Regular Imaging



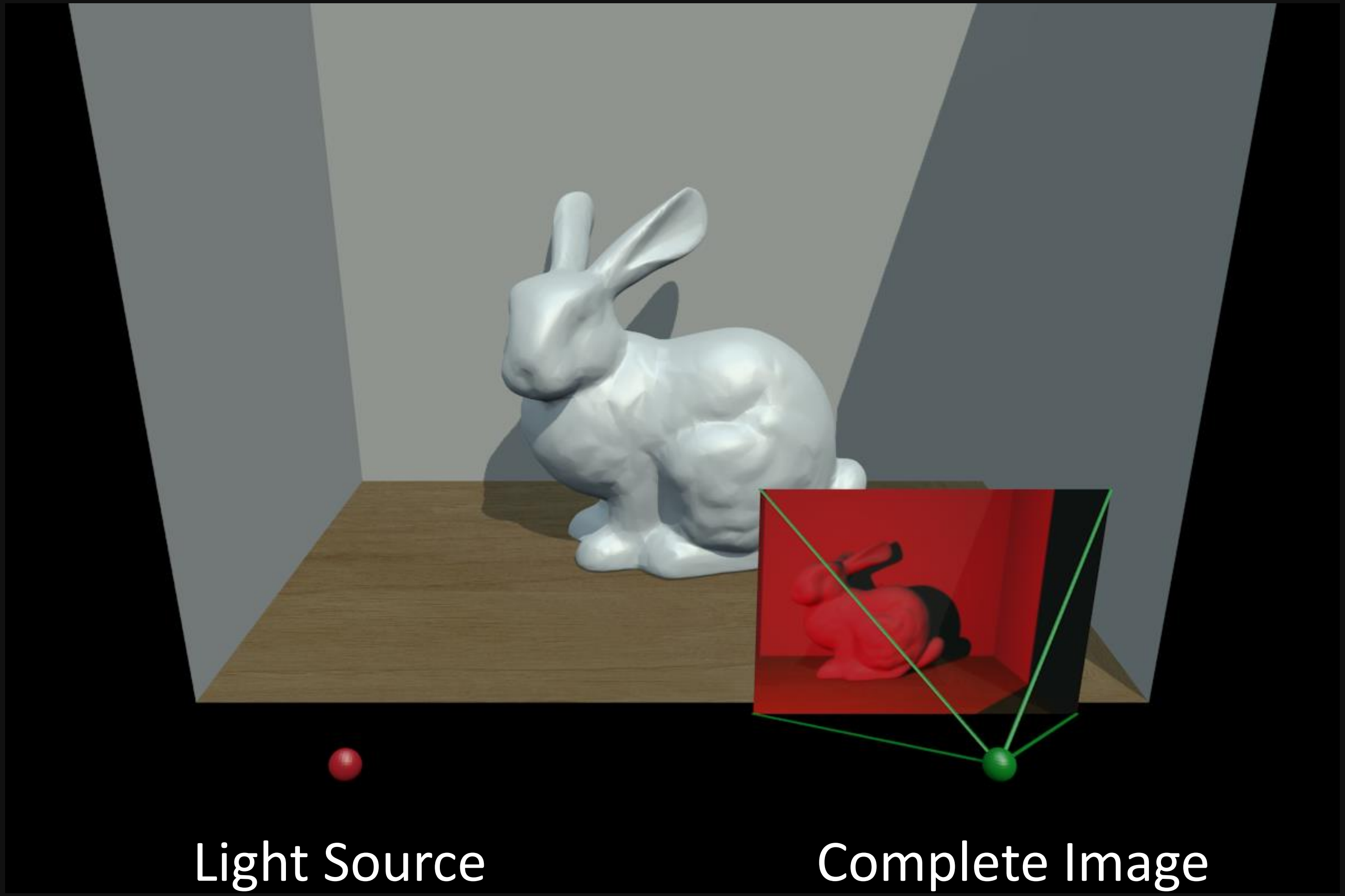
Epipolar Imaging



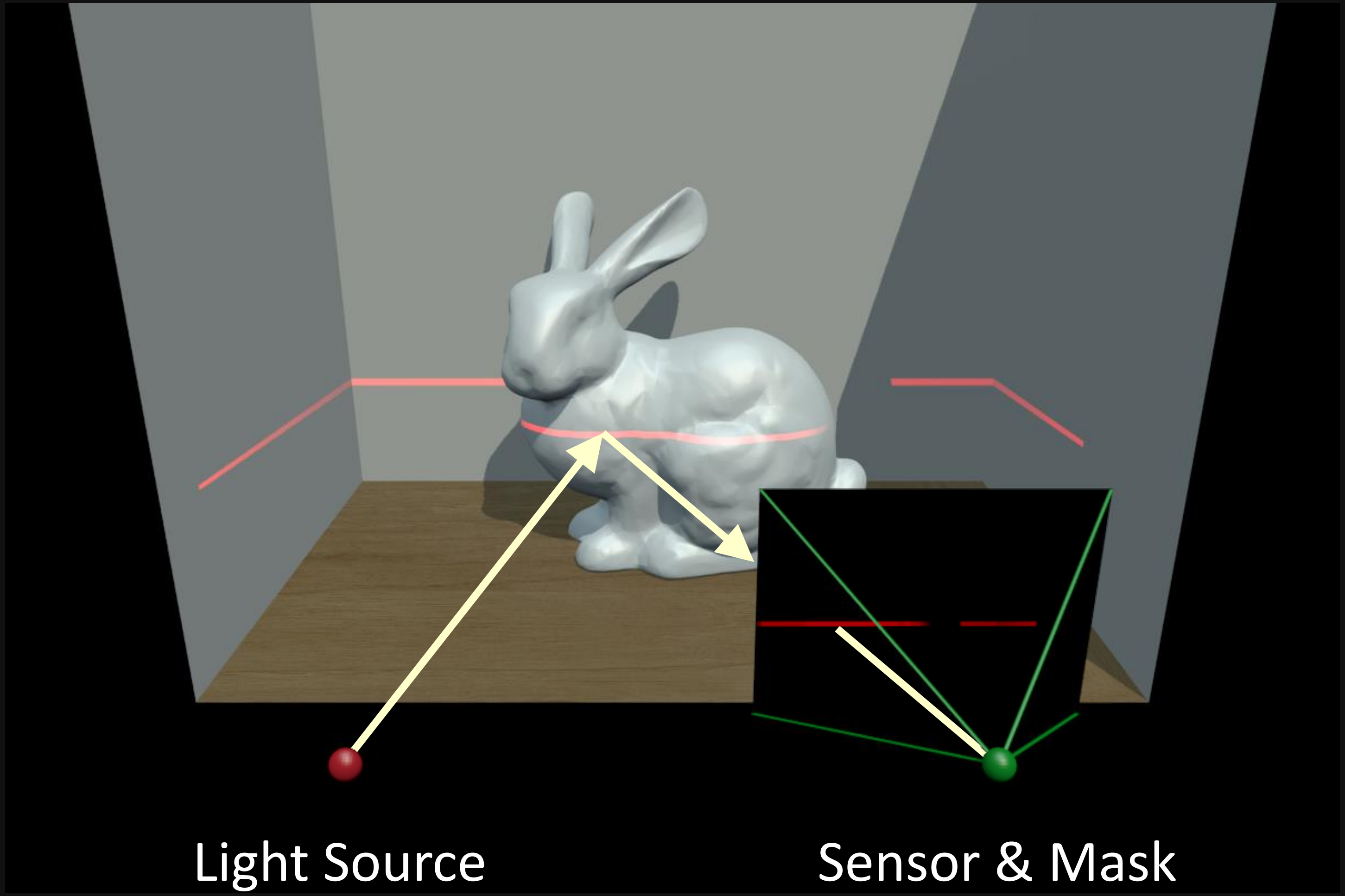
Epipolar Imaging



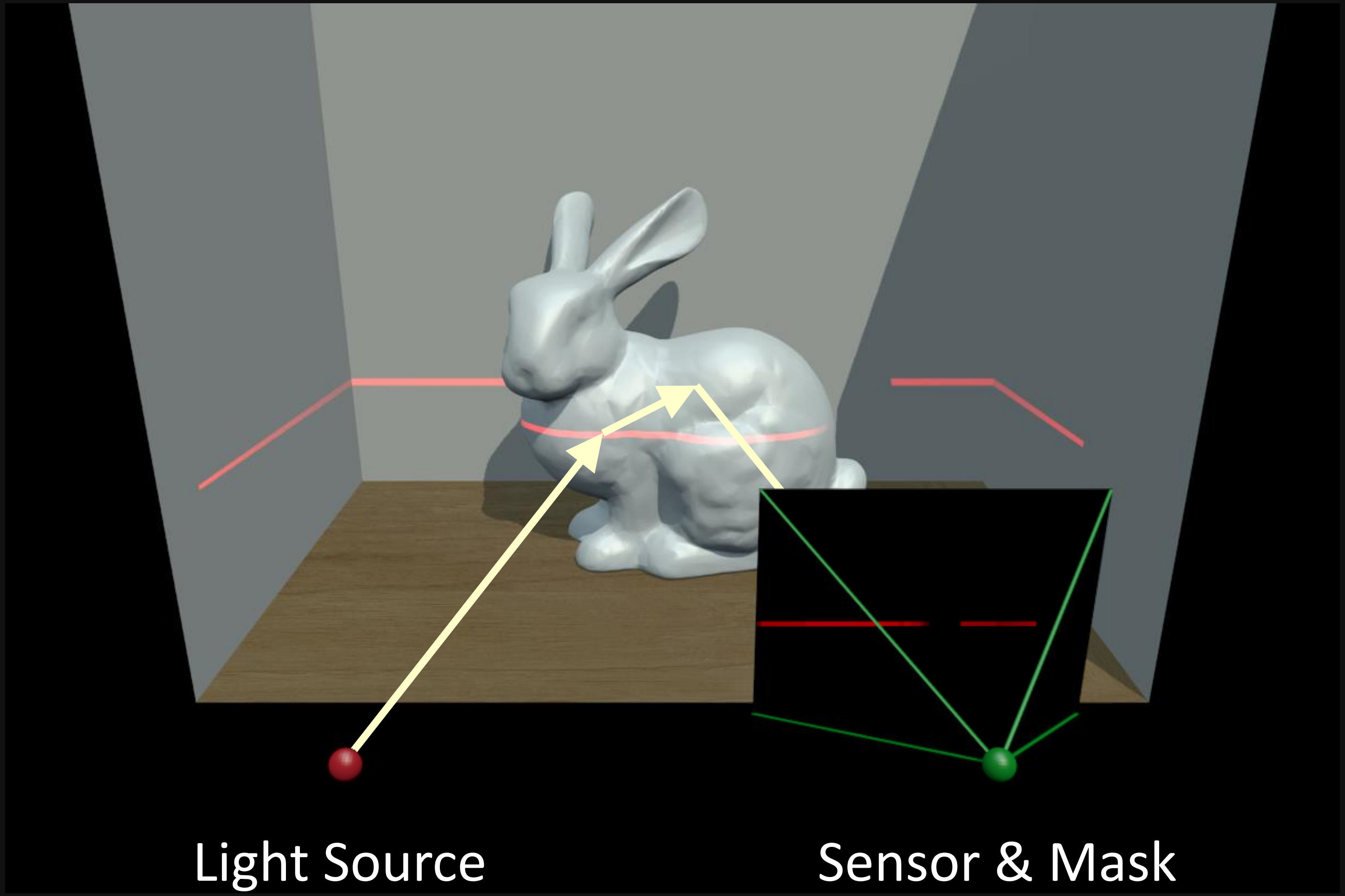
Epipolar Imaging



Epipolar Imaging

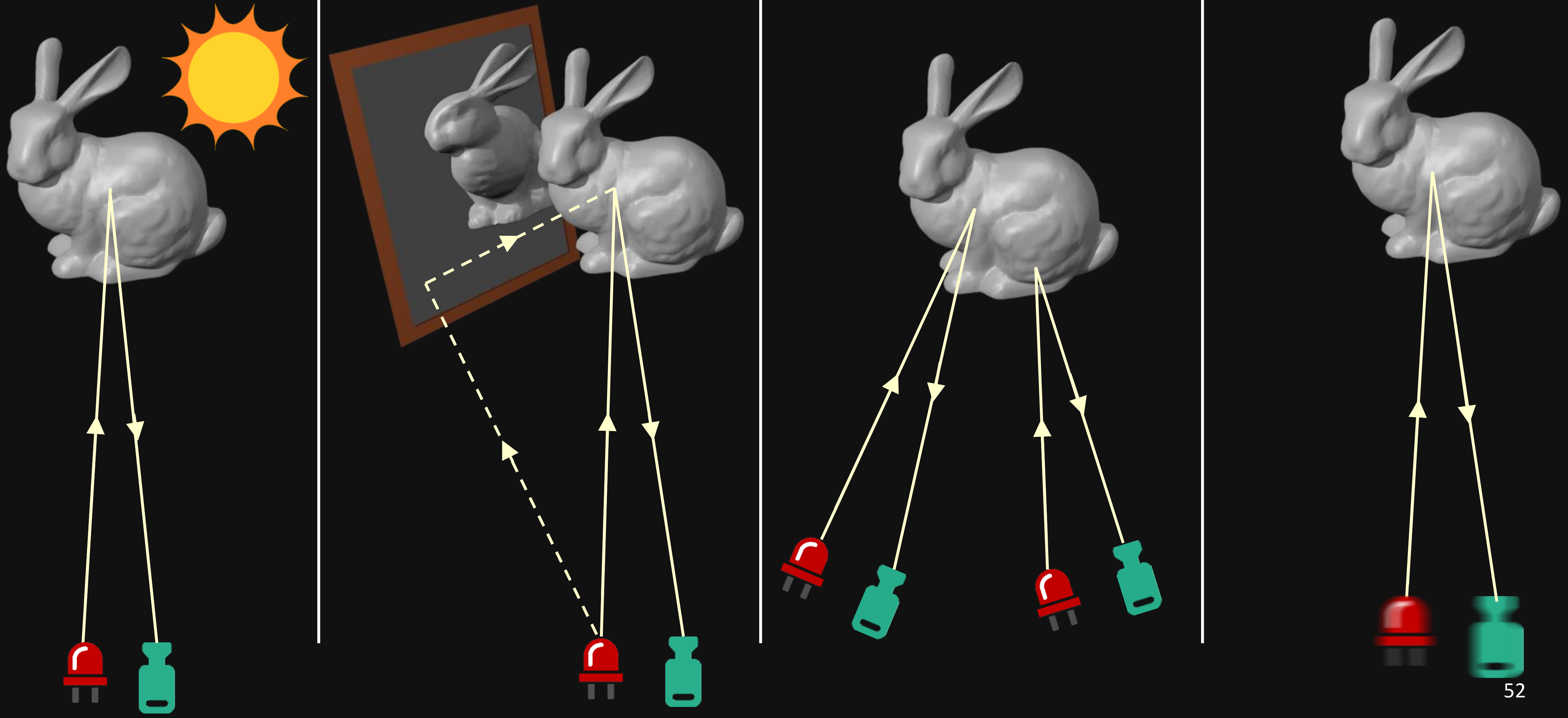


Epipolar Imaging

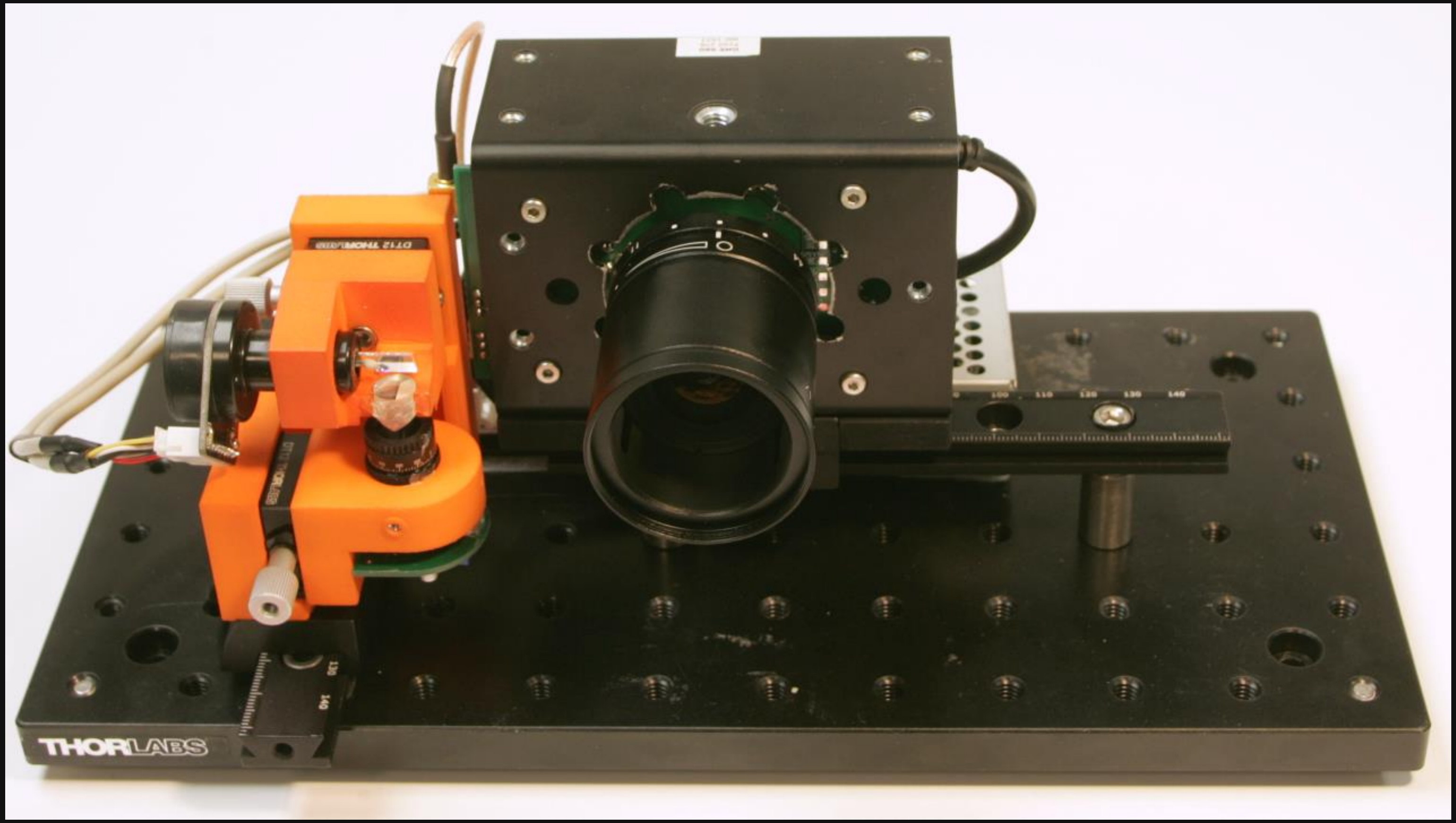


Benefits of Epipolar ToF Imaging

Ambient Light	Multi-Path Interference	Multi-Device Interference	Camera Motion

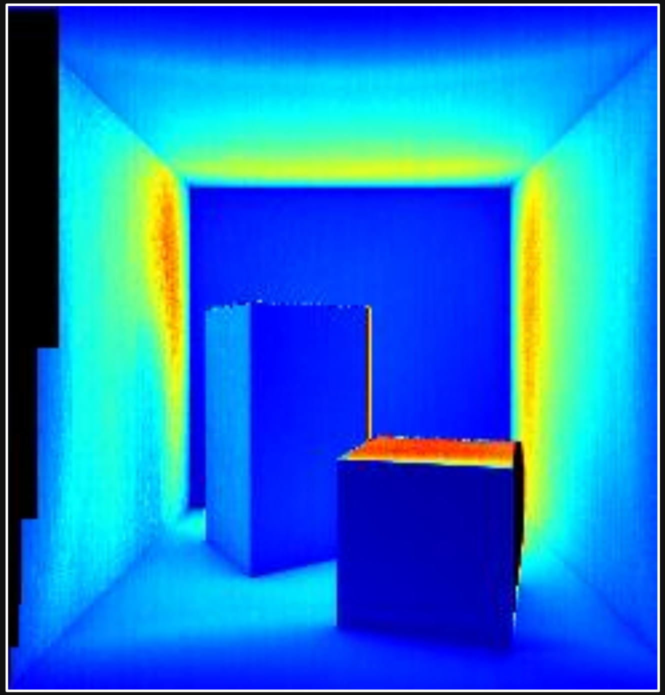


Epipolar ToF Prototype

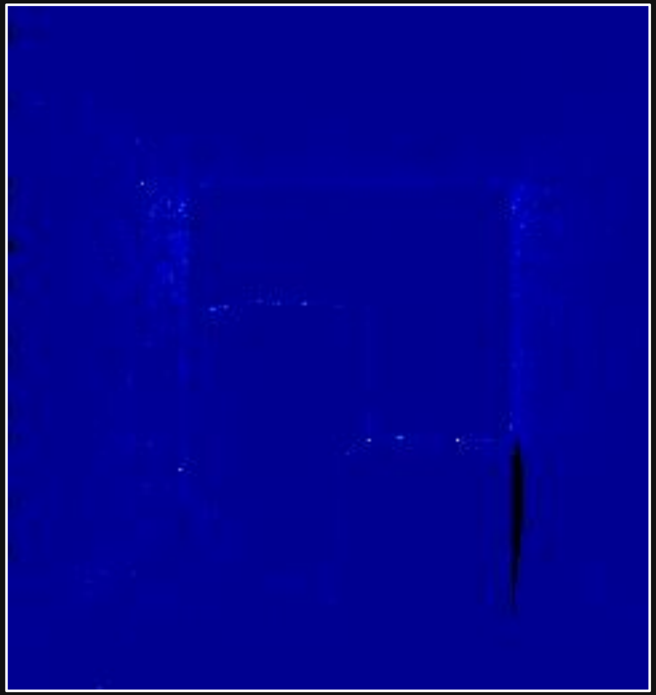


Epipolar ToF and Global Illumination

Depth Errors (in meters)

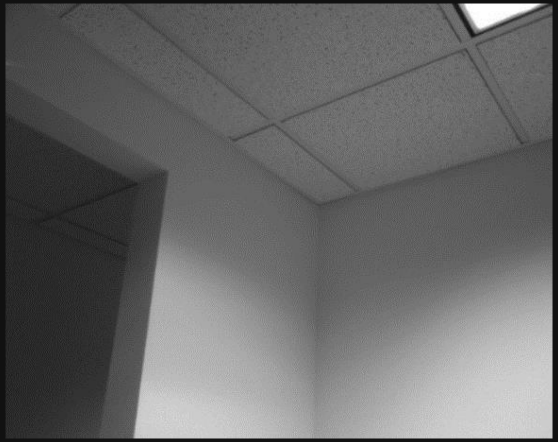


Regular ToF @ 30MHz



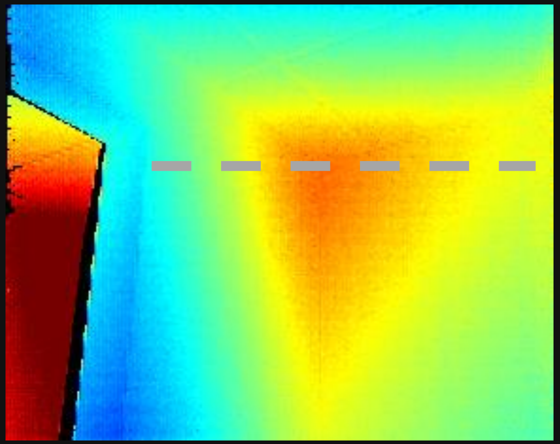
Epipolar ToF @ 30MHz

Epipolar ToF and Global Illumination

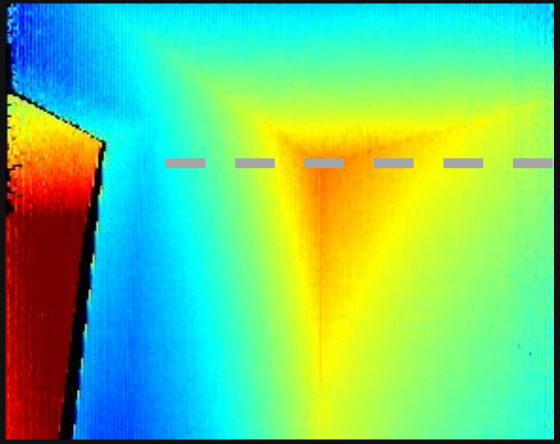


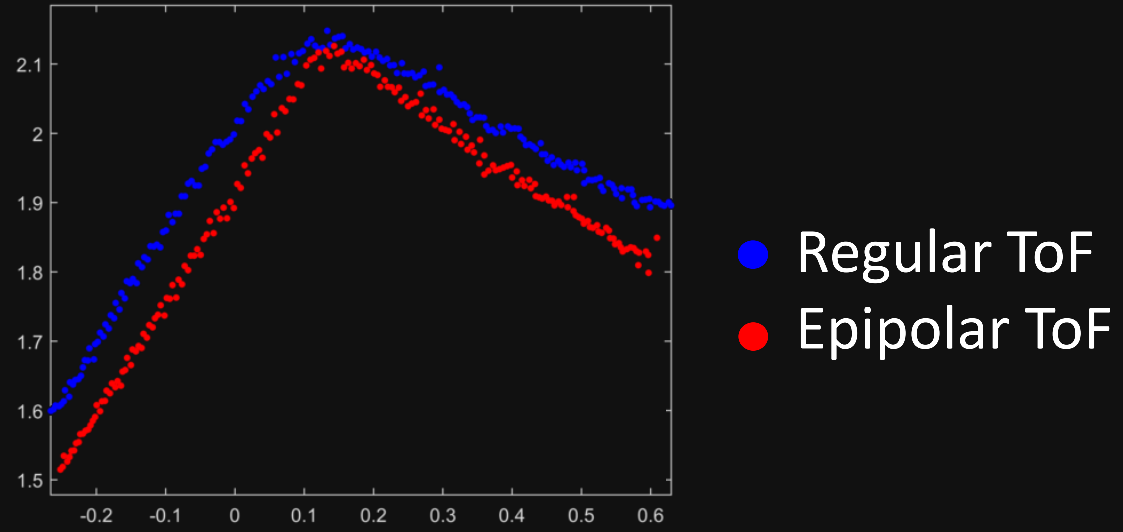
Corner of Room

Regular ToF

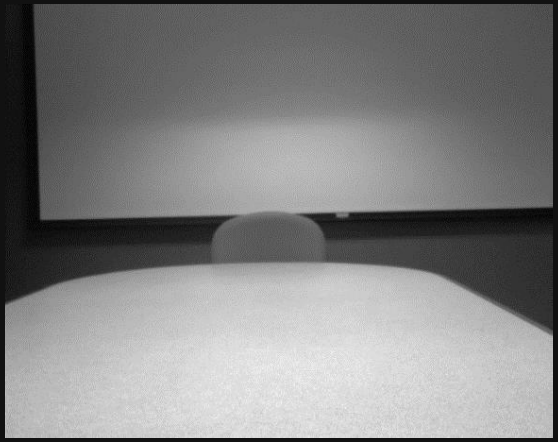


Epipolar ToF



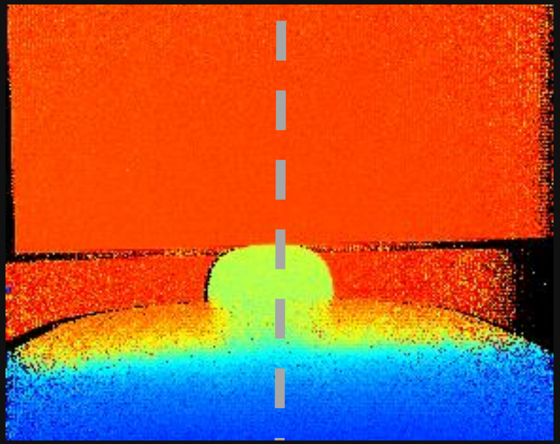


Epipolar ToF and Global Illumination

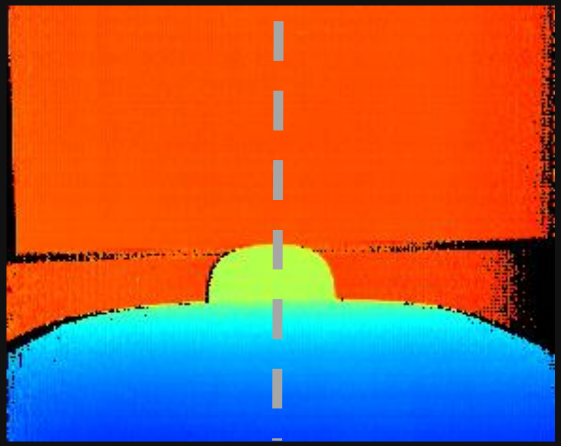


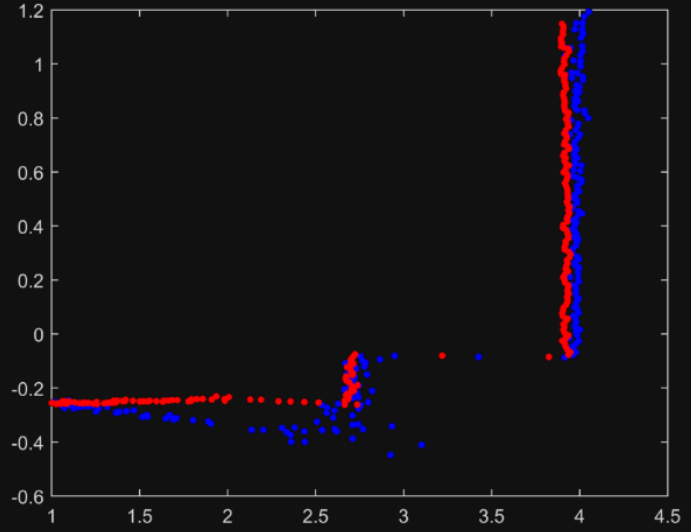
Conference Room

Regular ToF



Epipolar ToF





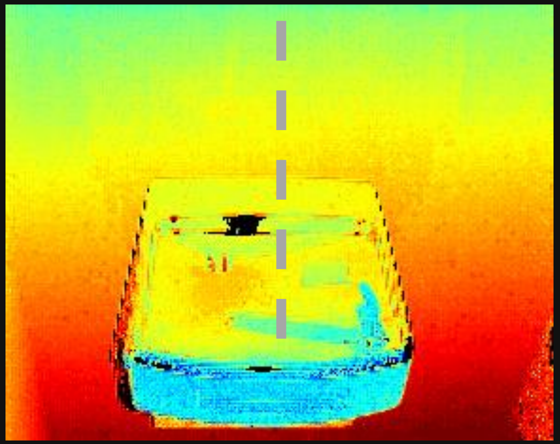
Regular ToF

Epipolar ToF

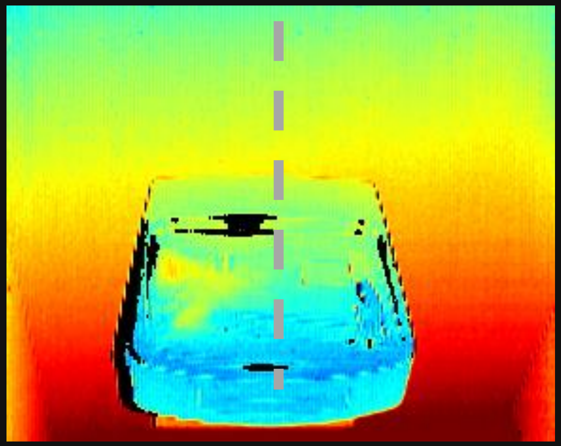
Epipolar ToF and Global Illumination

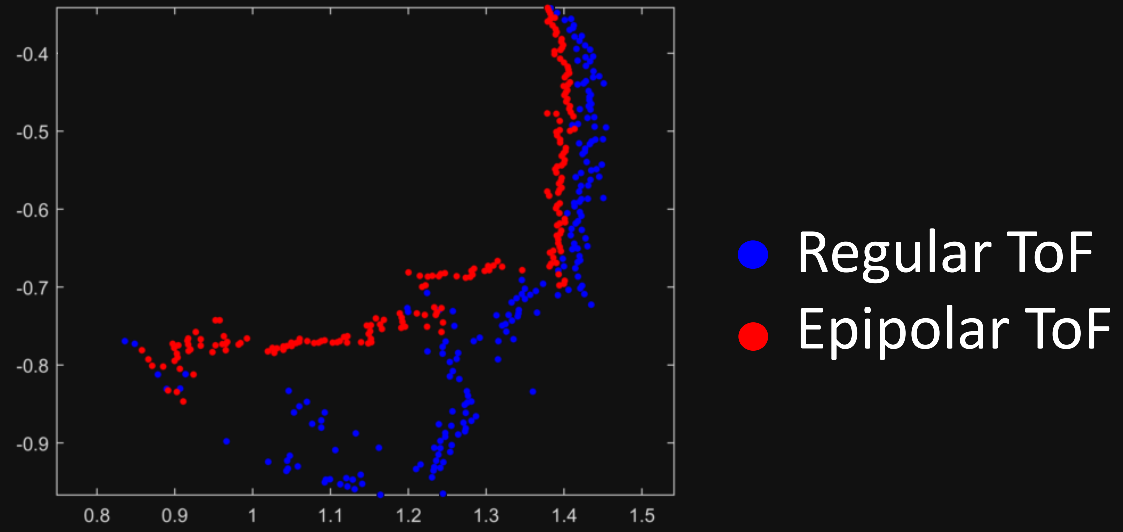
Water Fountain

Regular ToF



Epipolar ToF



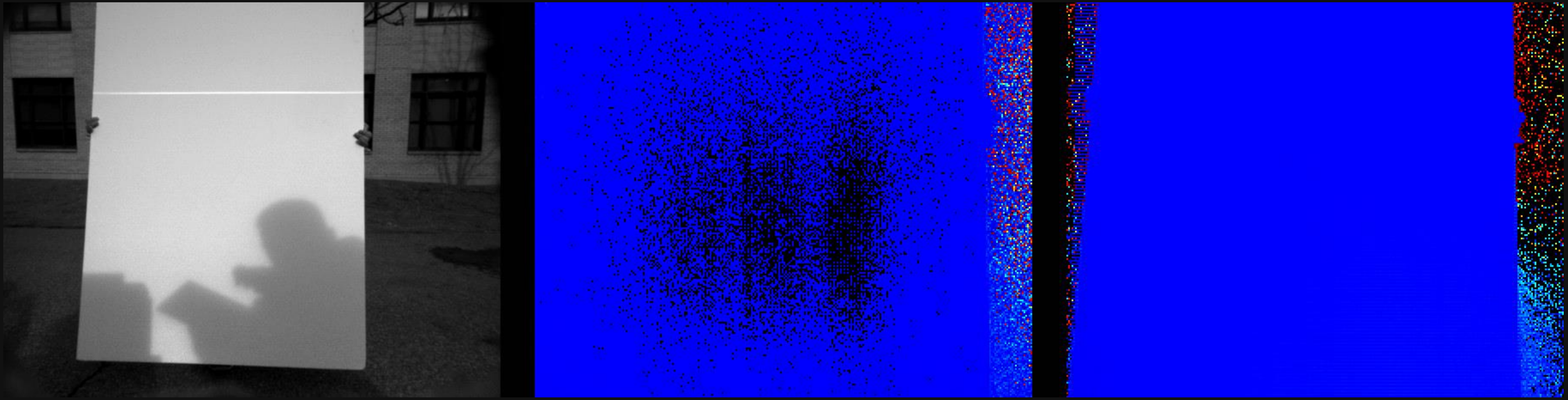


Outdoors (Cloudy – 10 kilolux)

Scene

Regular ToF

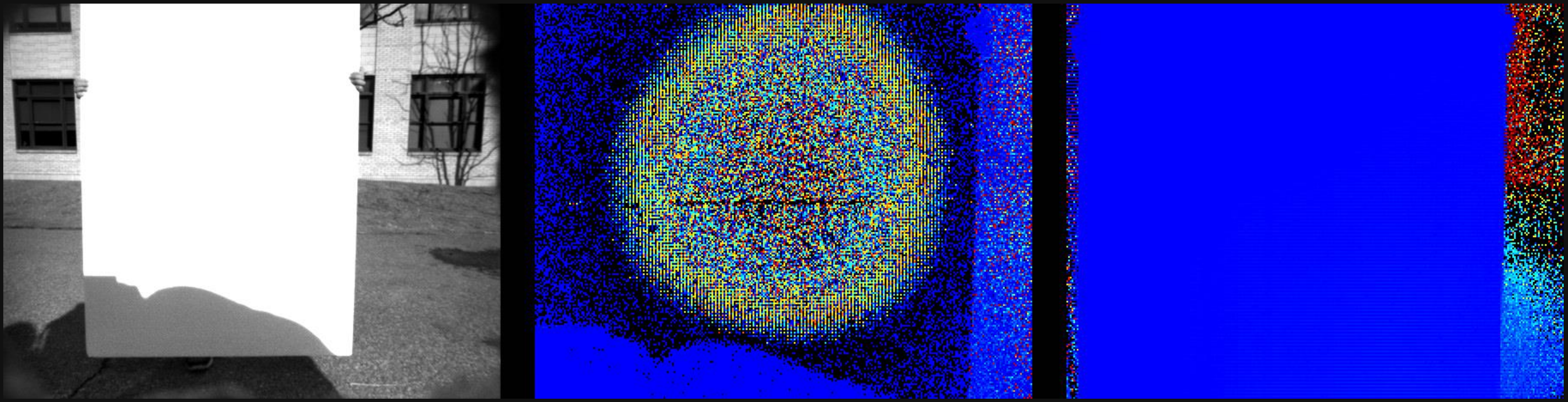
Epipolar ToF



Depth (meters)

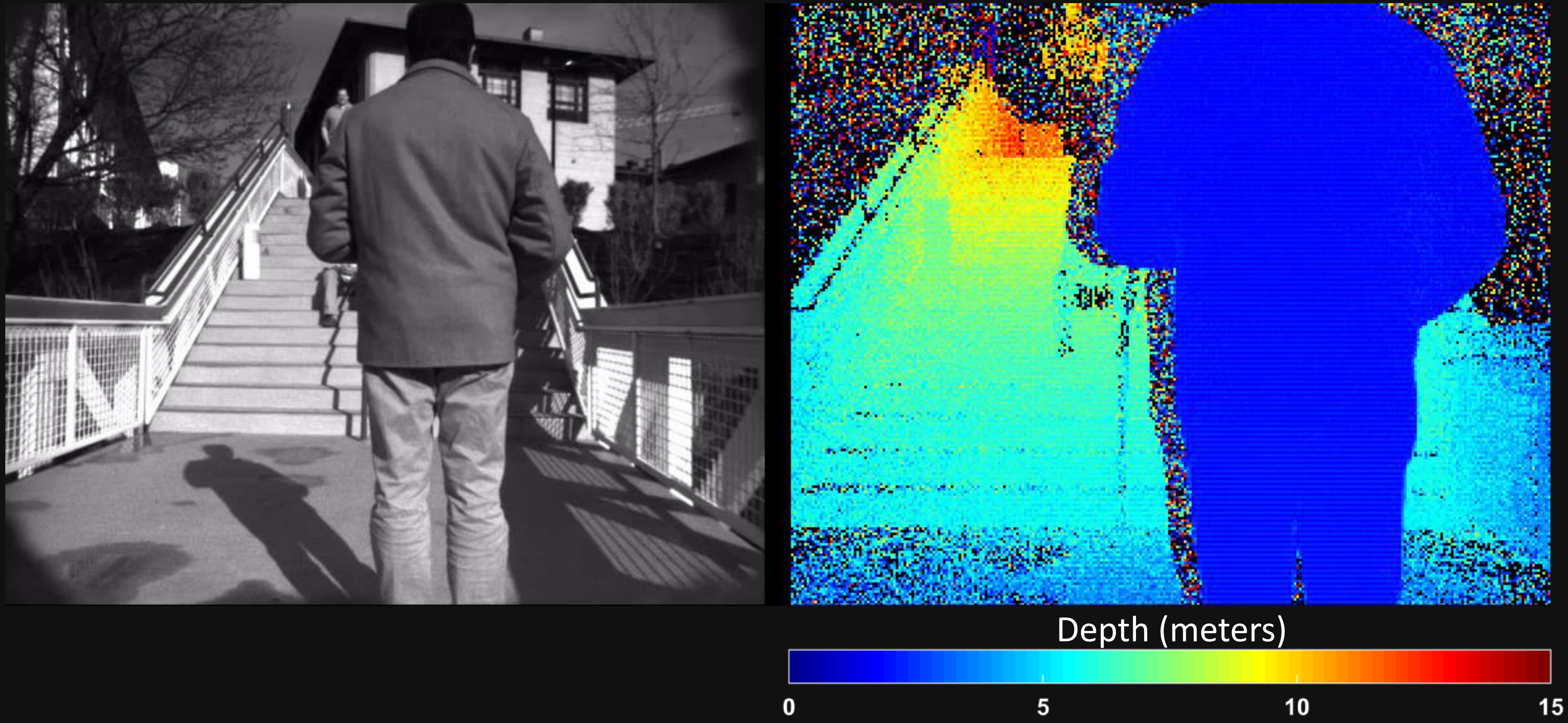
Outdoors (Sunny – 70 kilolux)

Scene | Regular ToF | Epipolar ToF



Depth (meters)

Outdoors (Sunny – 70 kilolux)



Time-of-flight imaging technologies

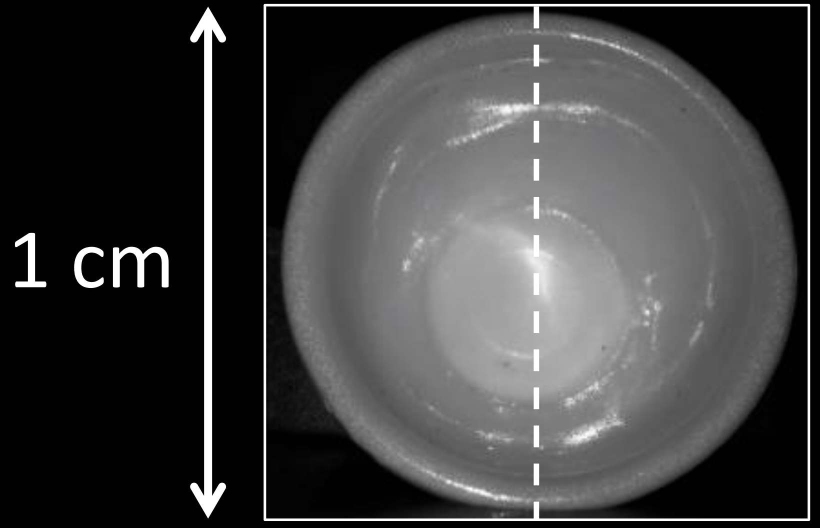
	interferometry	streak cameras	single-photon avalanche diodes	time-of-flight cameras	LIDAR
temporal resolution	1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	100 picoseconds (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)
frame rate	quadrillion fps	trillion fps	10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

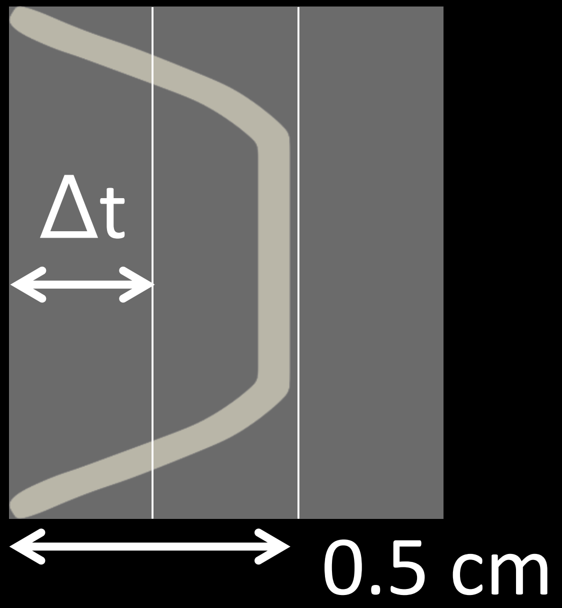
impulse ToF

Interferometric ToF imaging

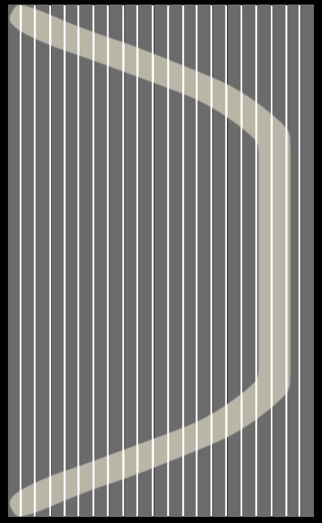
Tiny scenes



toy cup

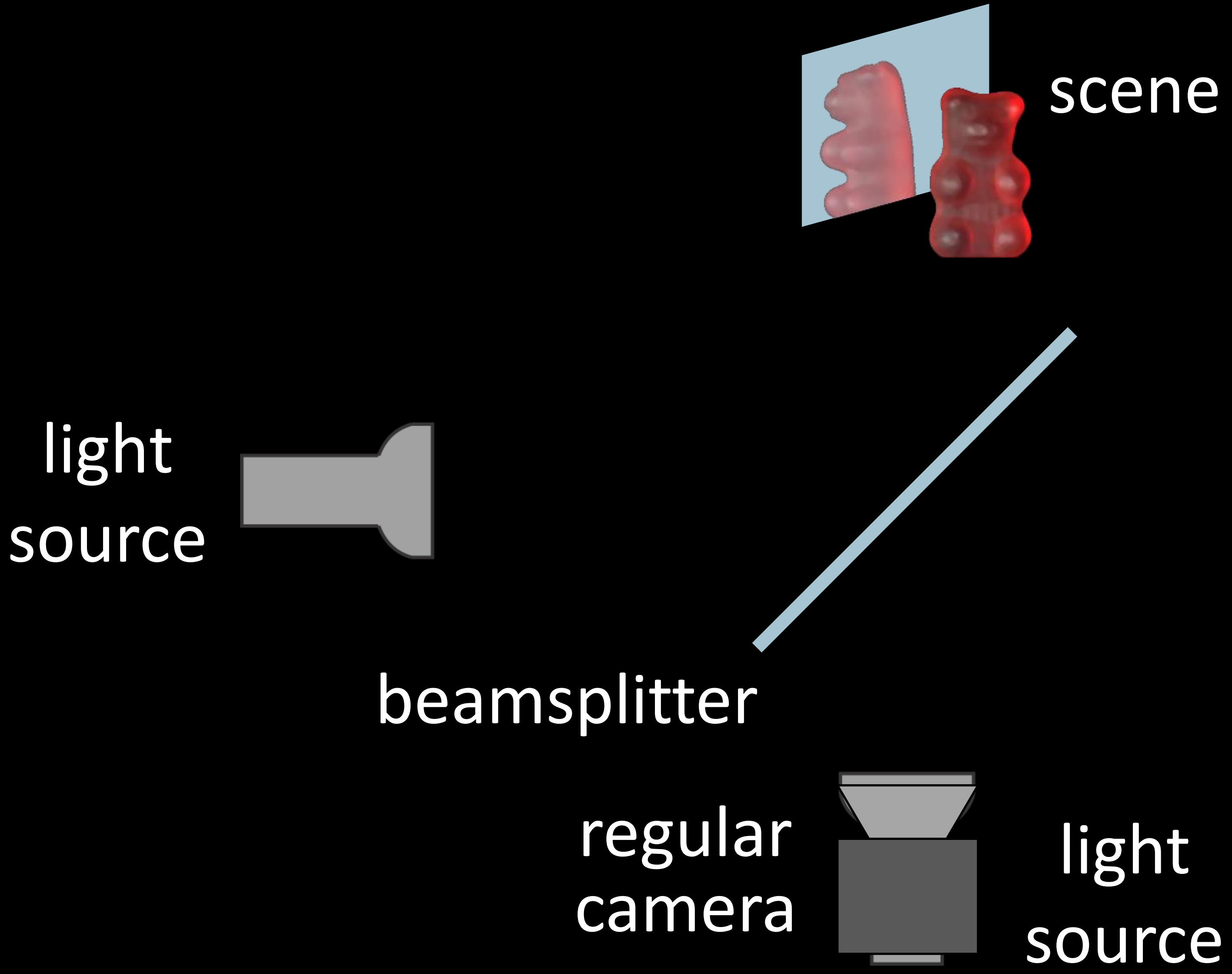


$\Delta t \sim$ ps

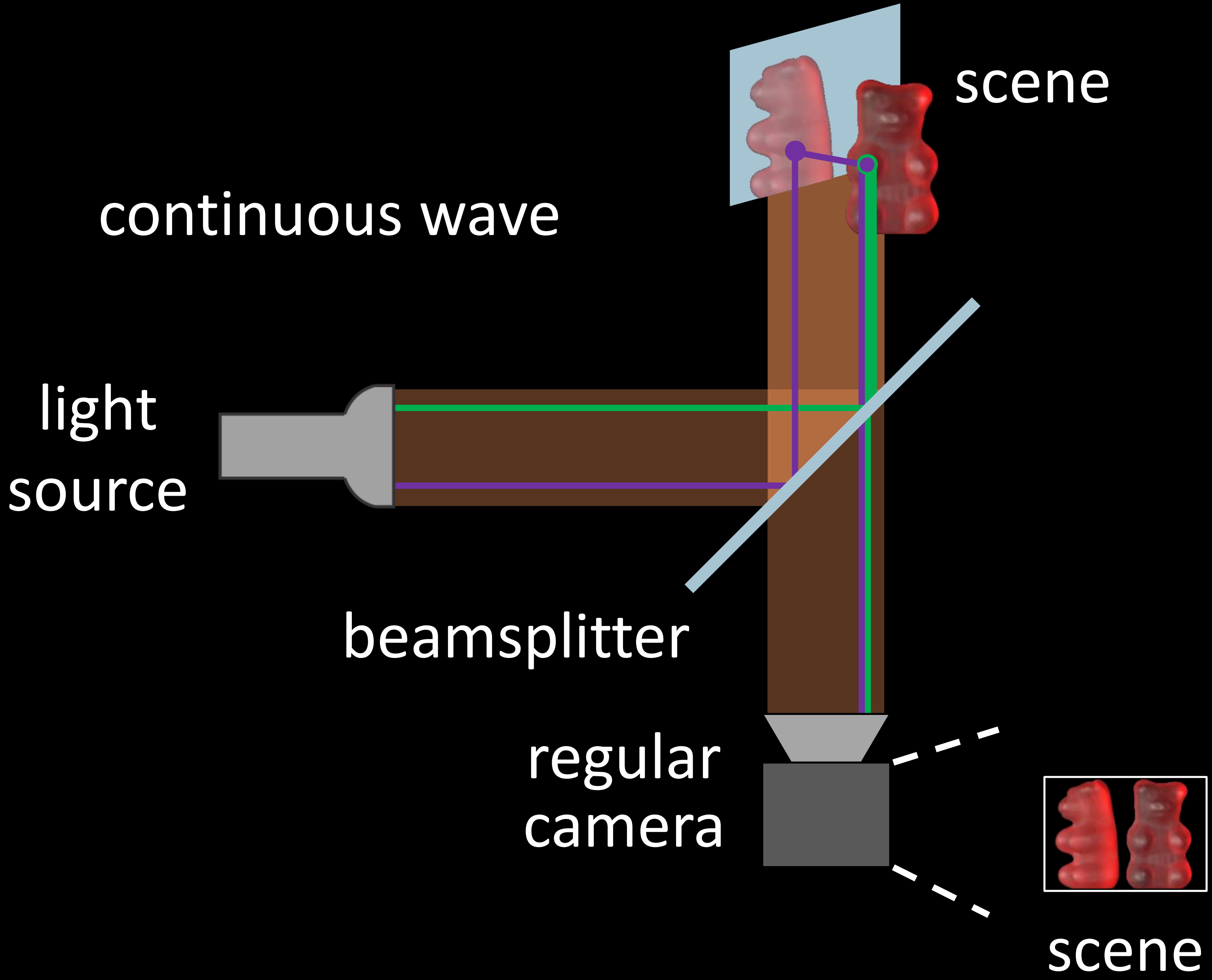


$\Delta t \sim 10^{-3}$ ps

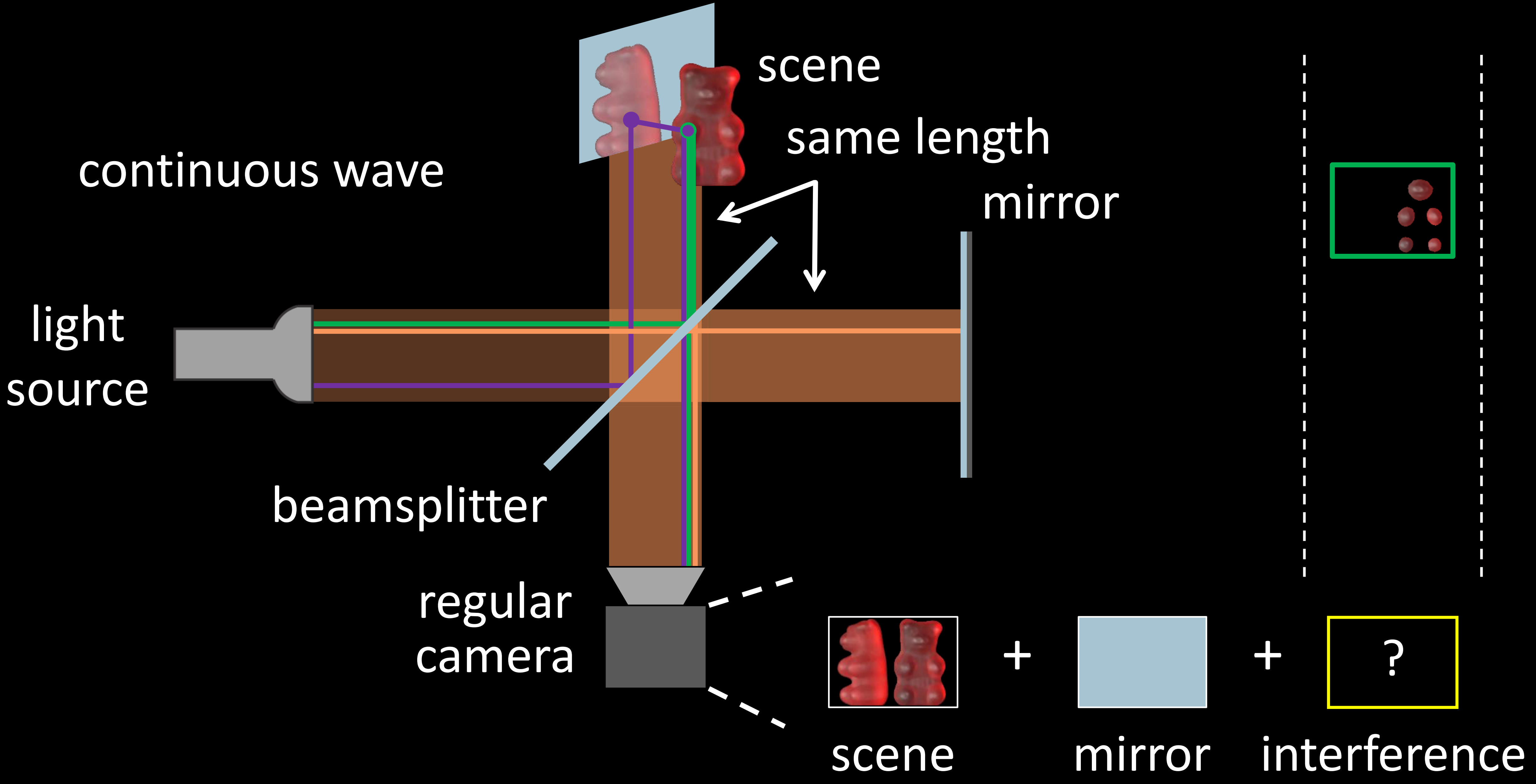
Interferometry example



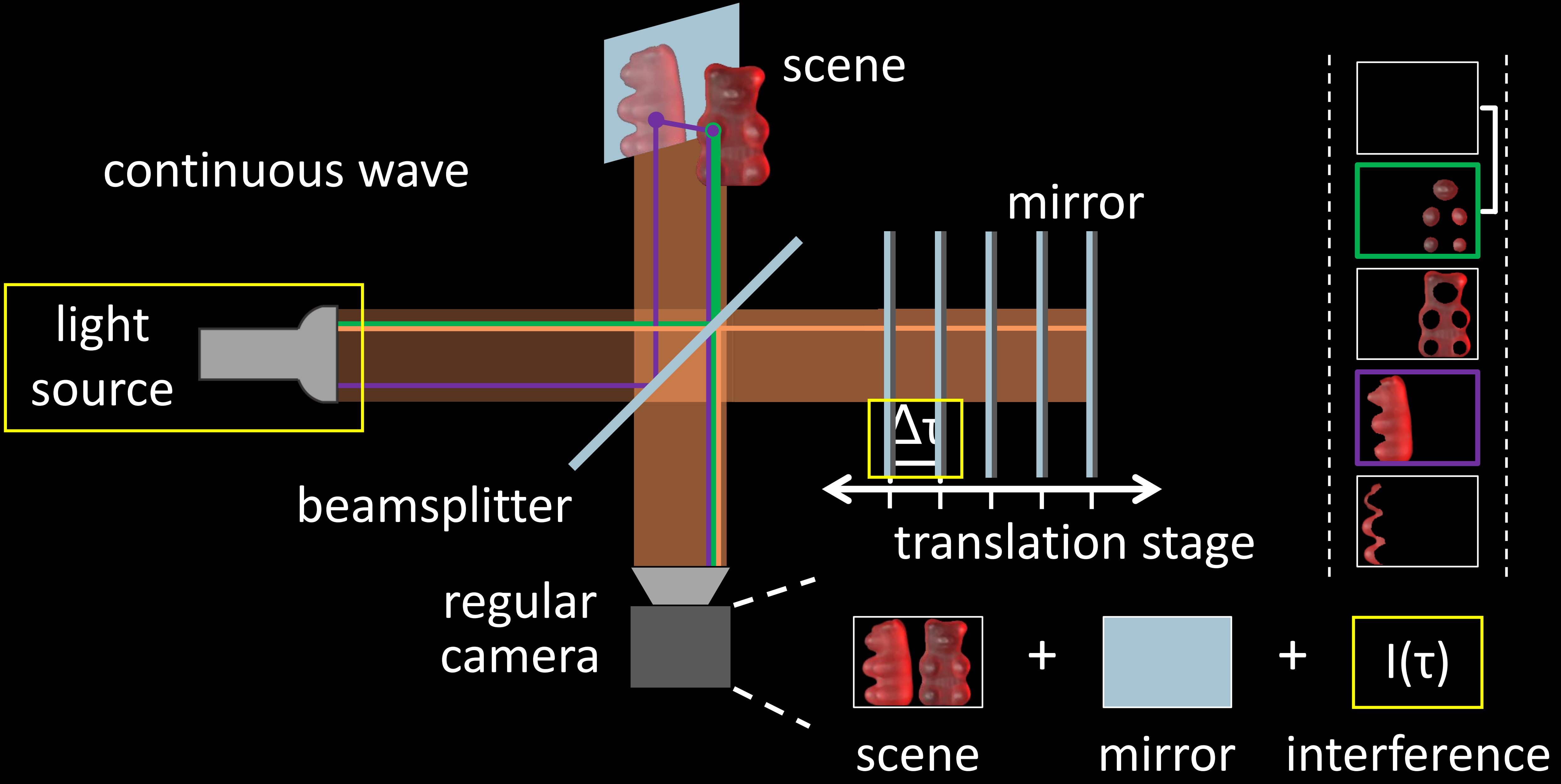
Interferometry example



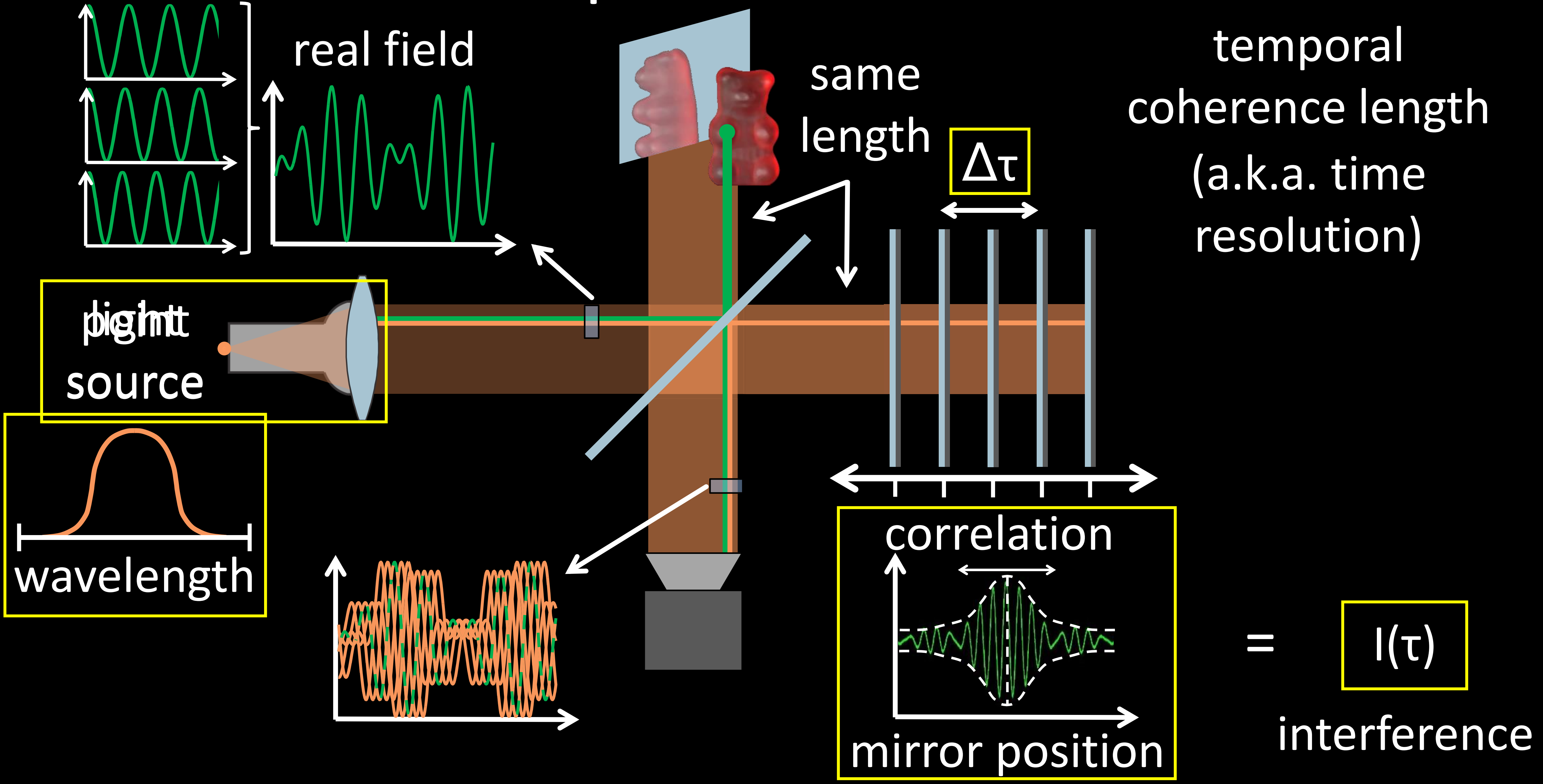
Michelson interferometer



Optical coherence tomography



Temporal coherence



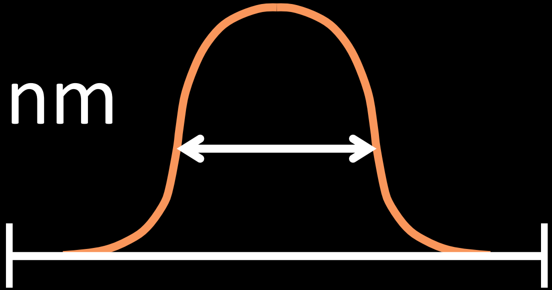
Temporal coherence length

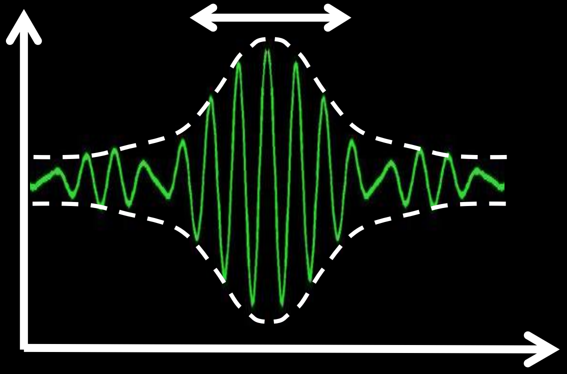
bandwidth

correlation

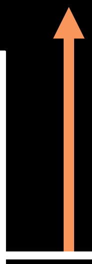
broadband

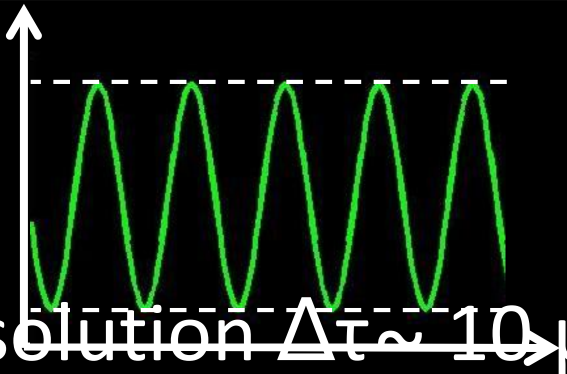
25 nm





onochro tic



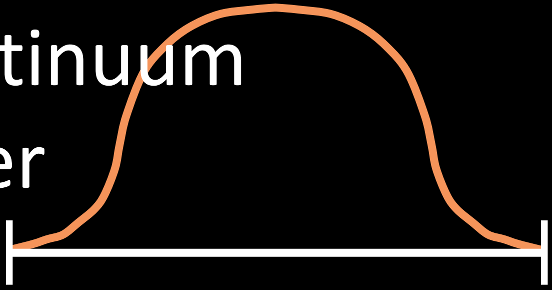


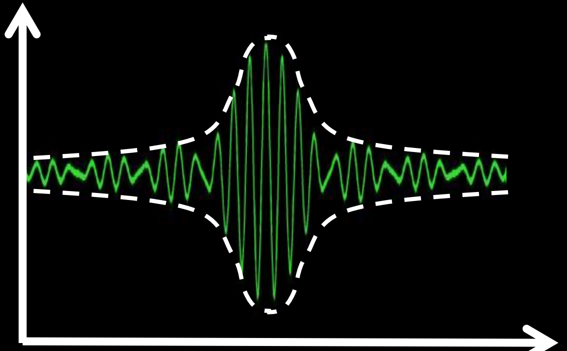
pathlength resolution $\Delta\tau \sim 10\ \mu m$

very broadband

superluminescent diode

supercontinuum laser





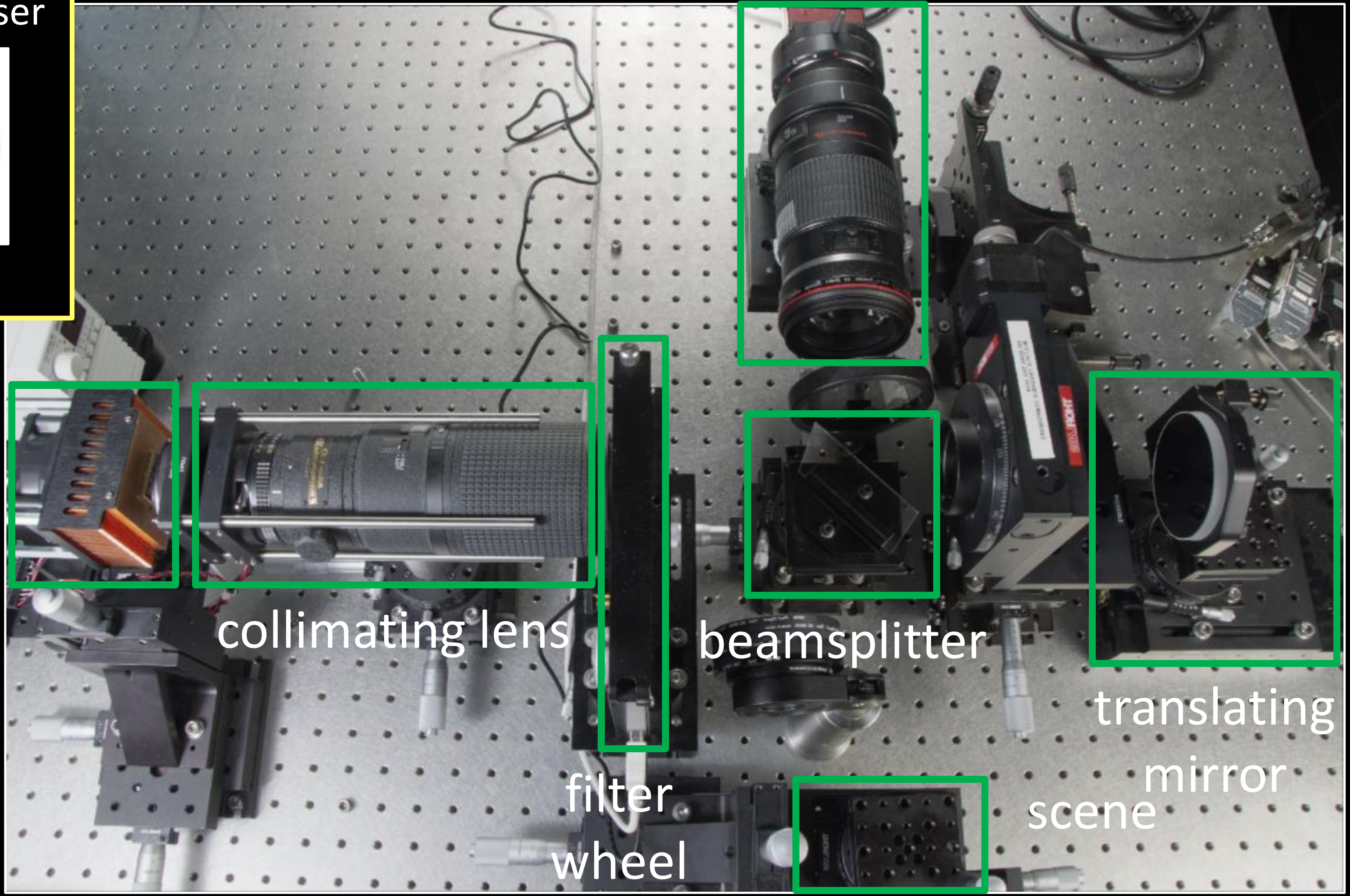
Optical setup

superluminescent diode

supercontinuum laser

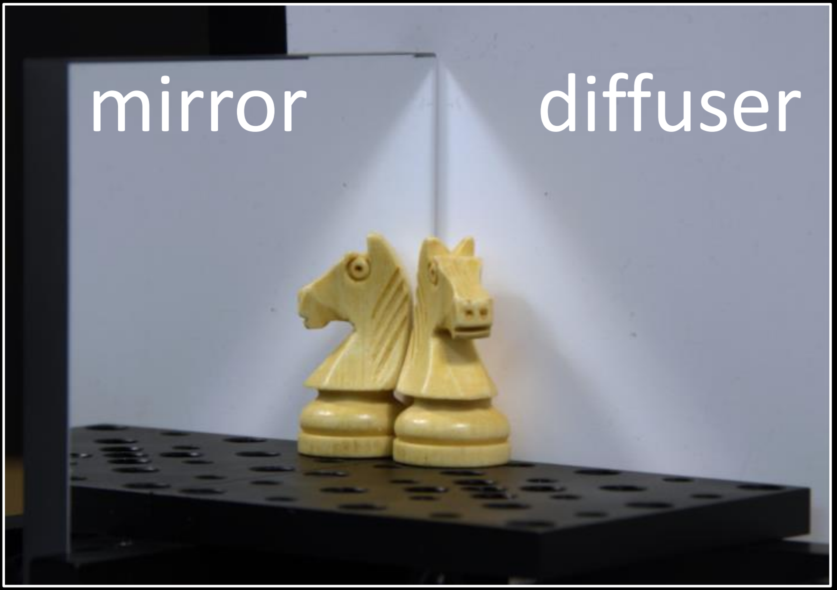
broadband LED

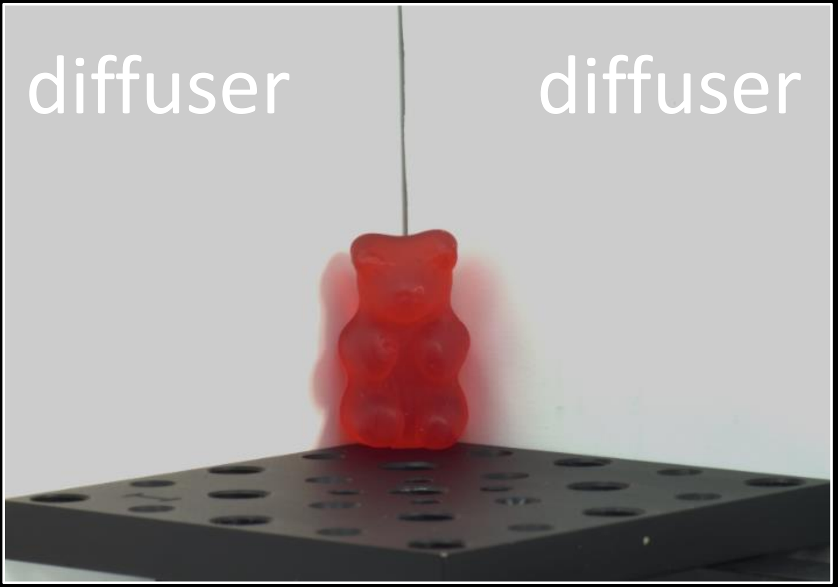
sodium lamp



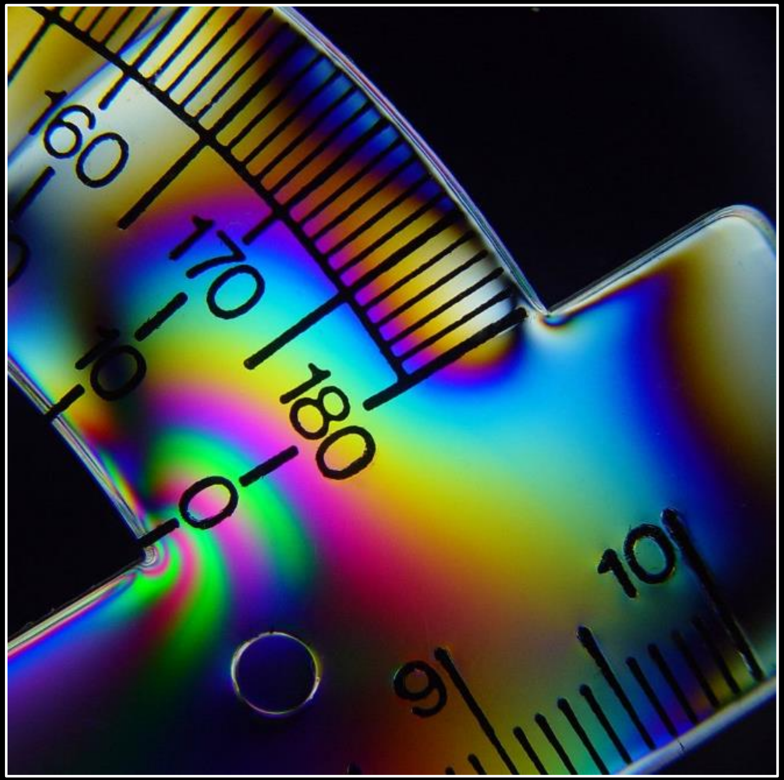
Some transient images

centimeter-sized objects





Material properties

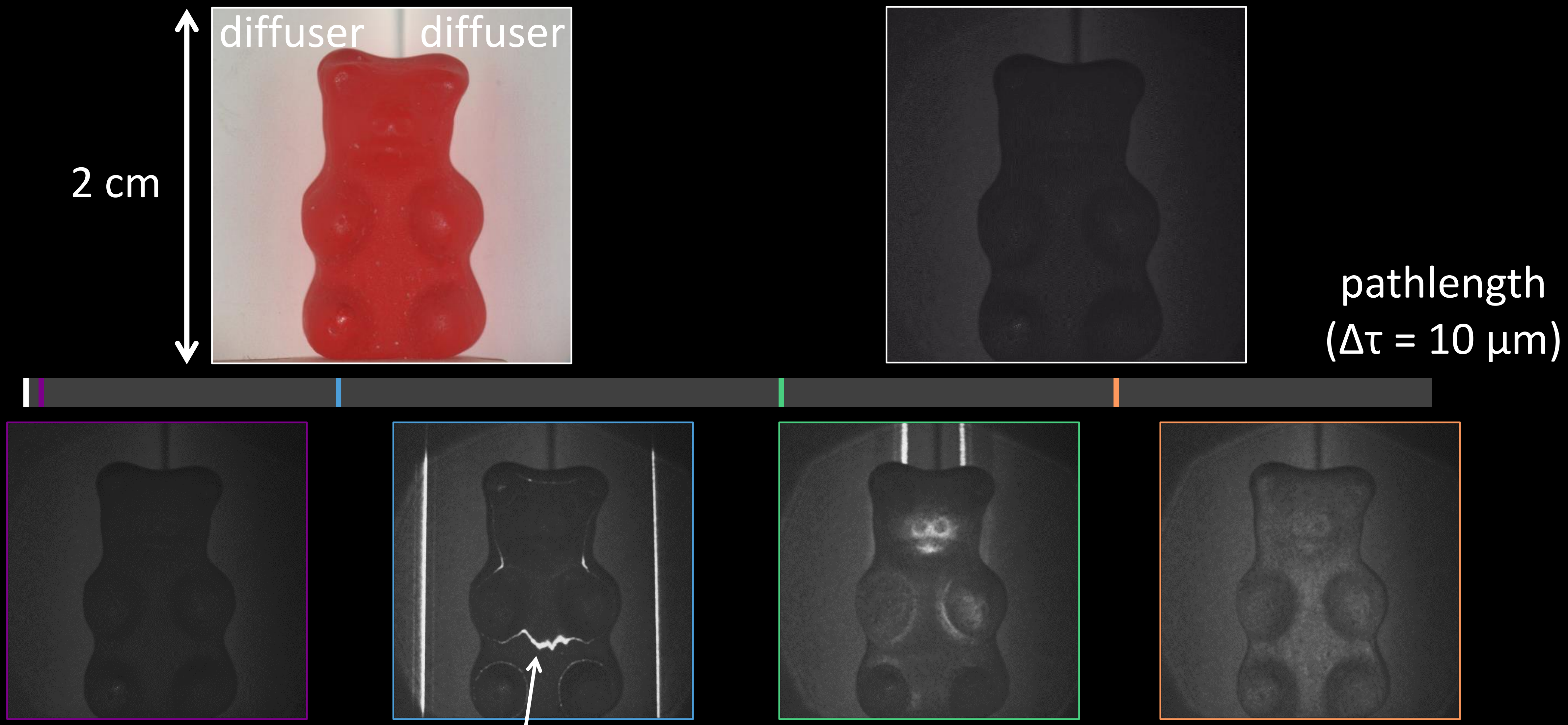


birefringence

dispersion

scattering

Gummy bear and diffuse corner



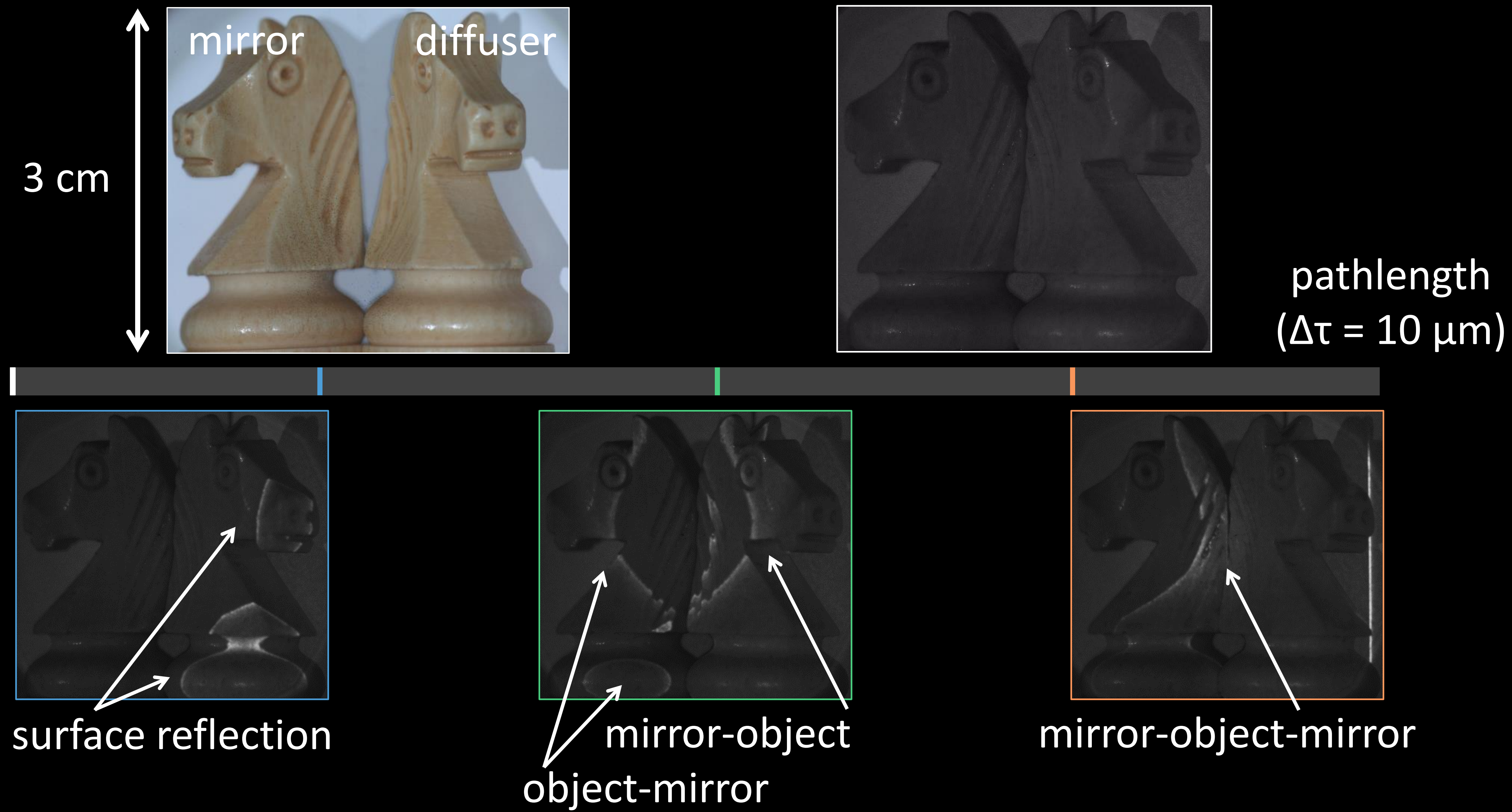
dark frame

surface reflections

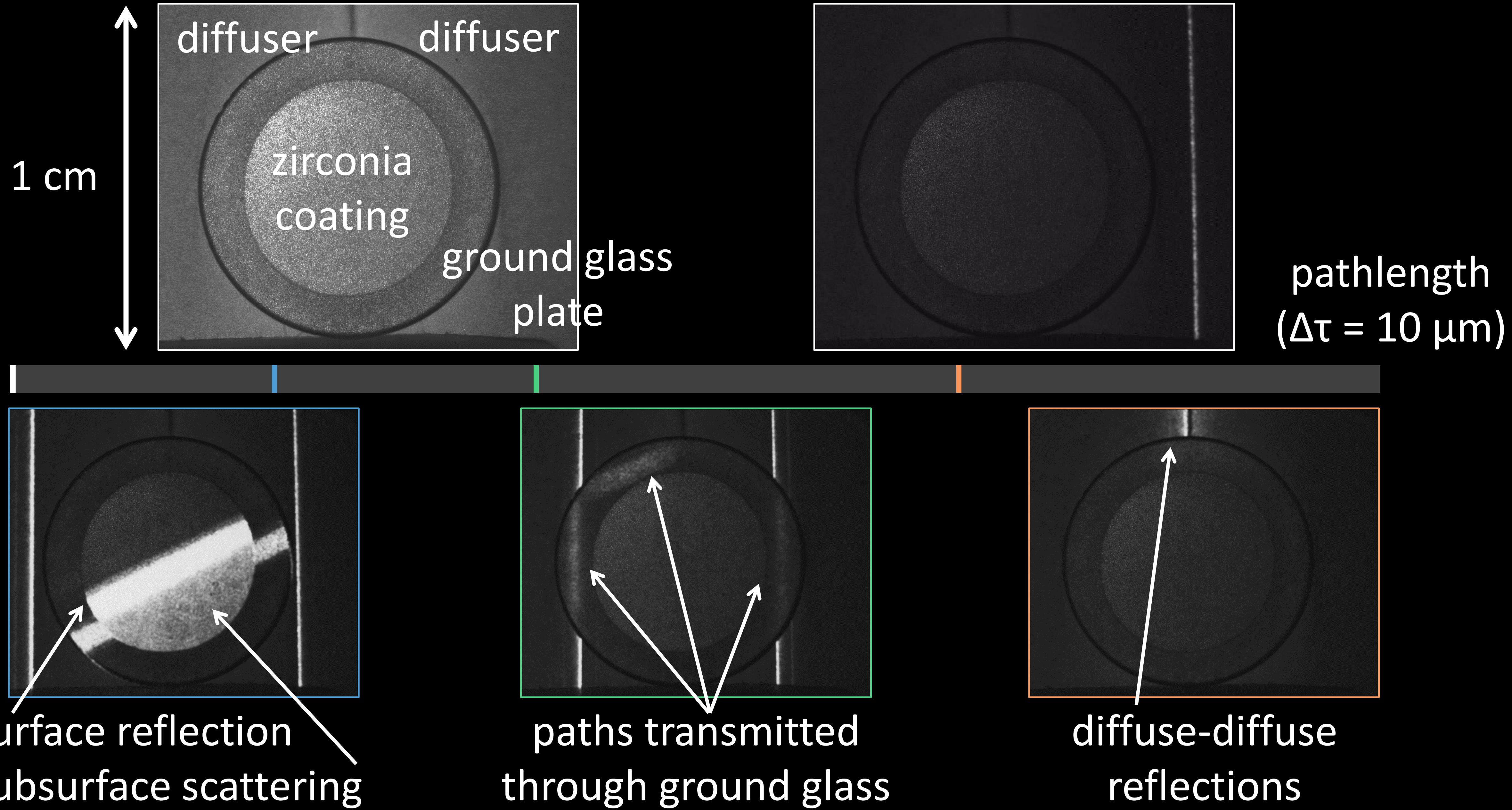
paths through gummy bear

very highly scattered paths

Chess knight and mirror



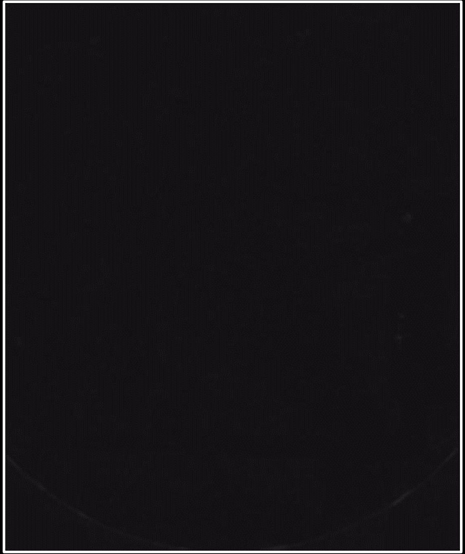
Subsurface scattering



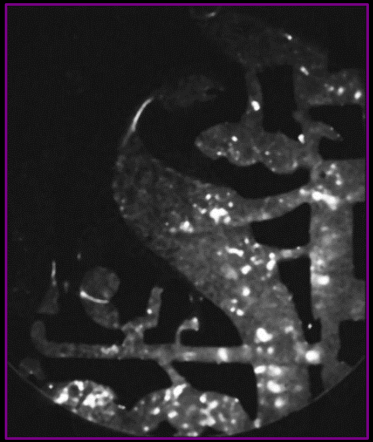
White jade

3 cm

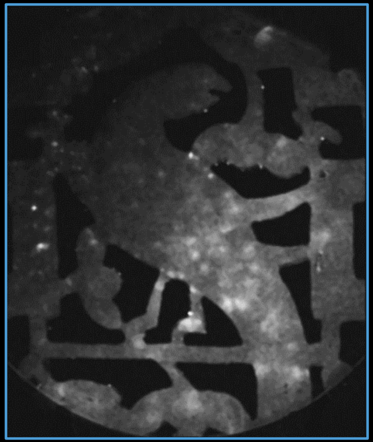
exquisite white jade



time (10^{-15} seconds)



specular reflections



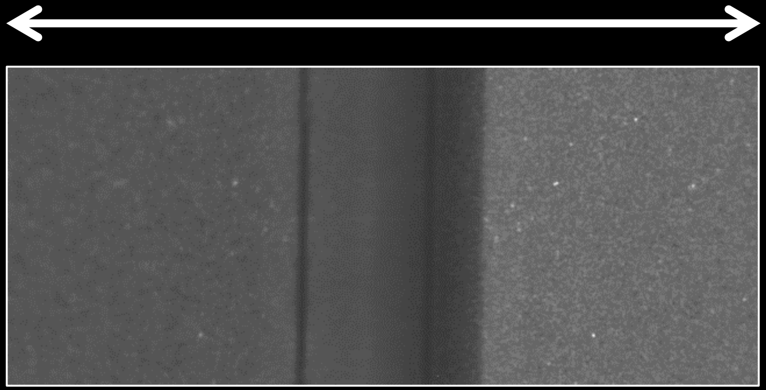
low-order scattering

mid-order scattering

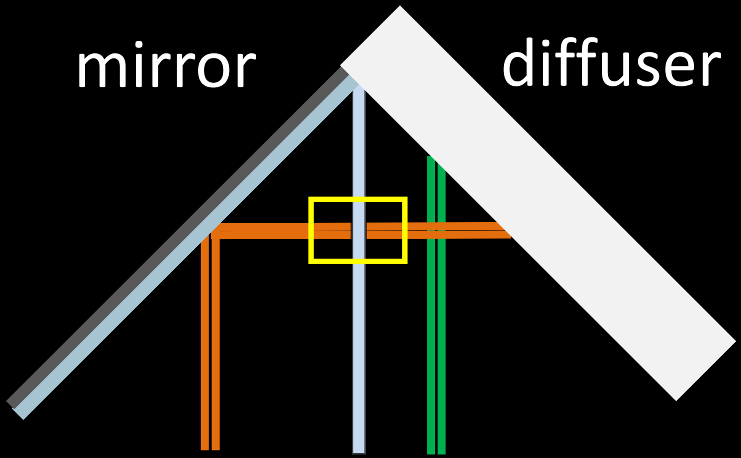
high-order scattering [TOG 2015]

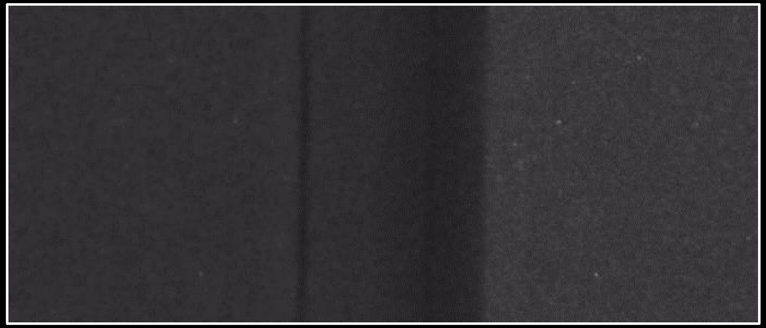
Dispersion

1 cm

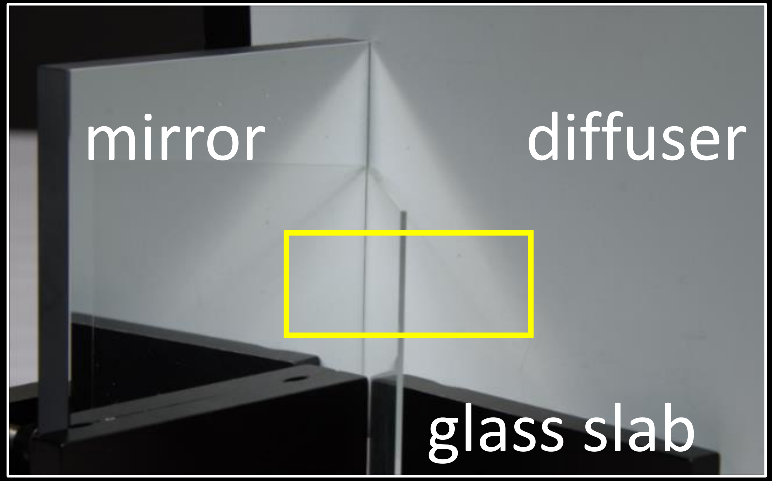


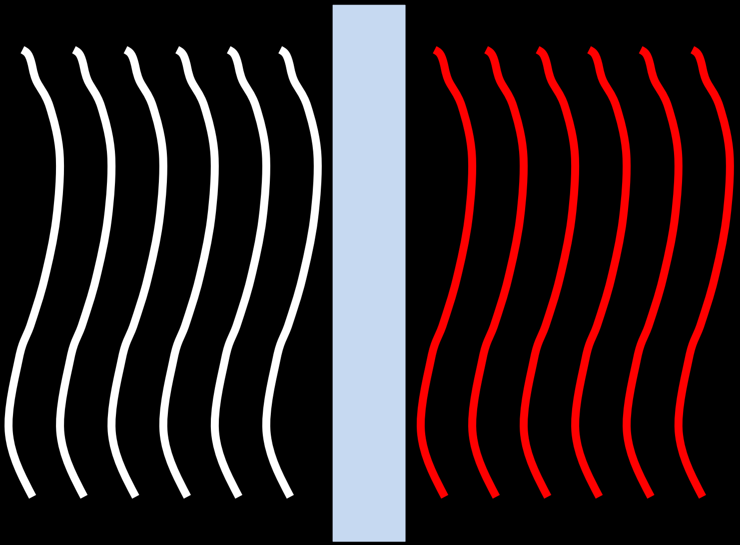
cropped frame



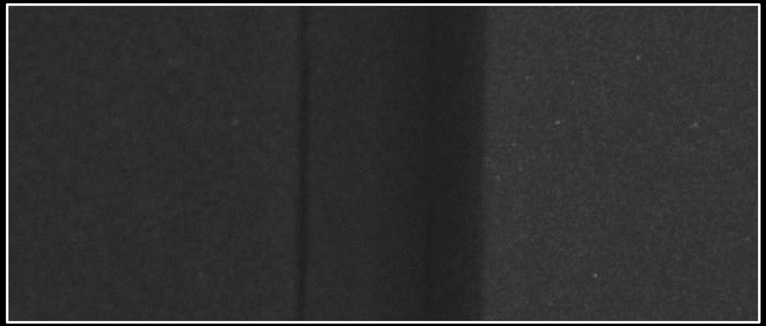


$\Delta t \sim ns$



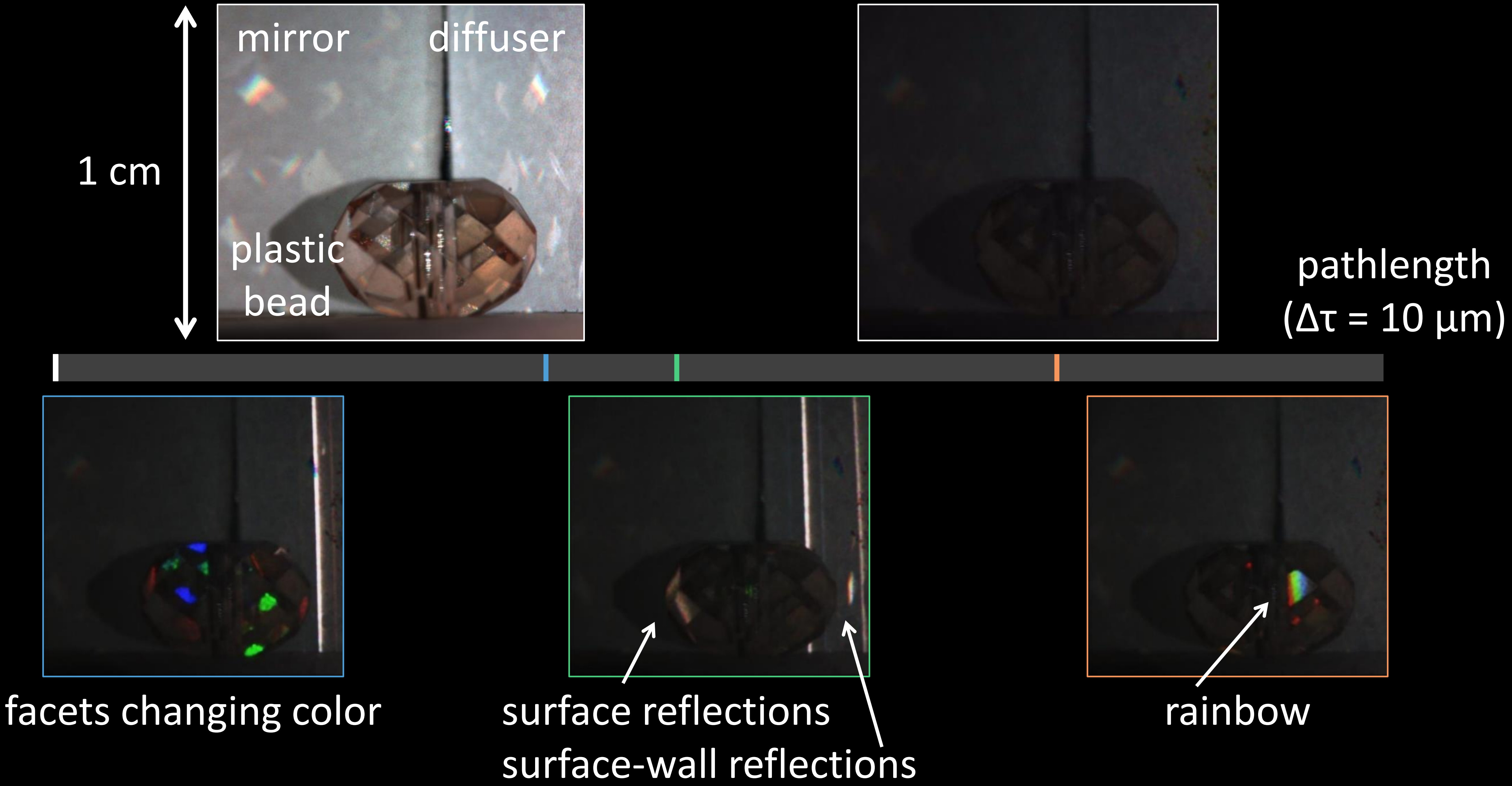


refractive index η(wavelength)



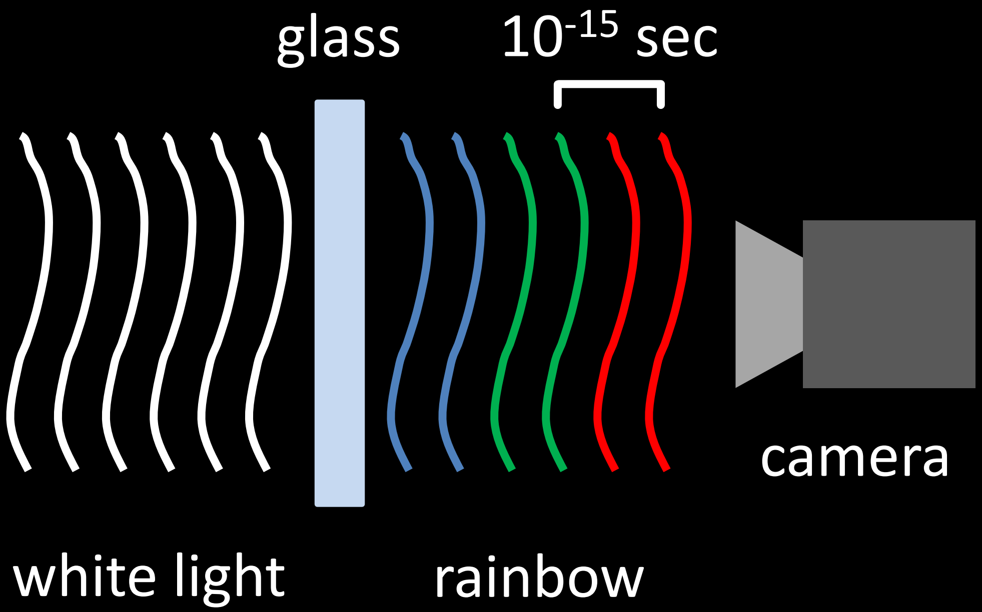
$\boxed{\Delta t \sim 10^{-3}\ ns}$

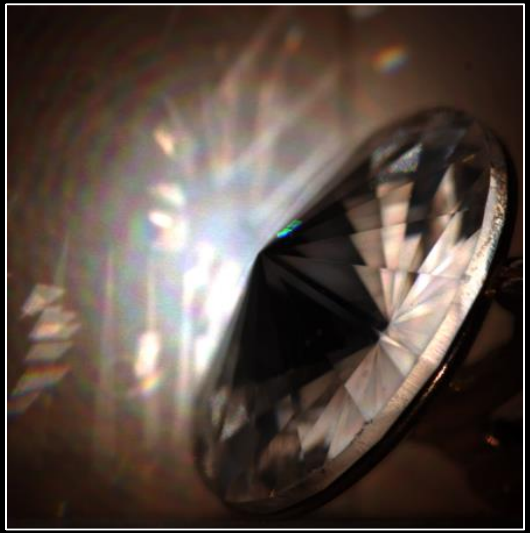
Dispersion



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

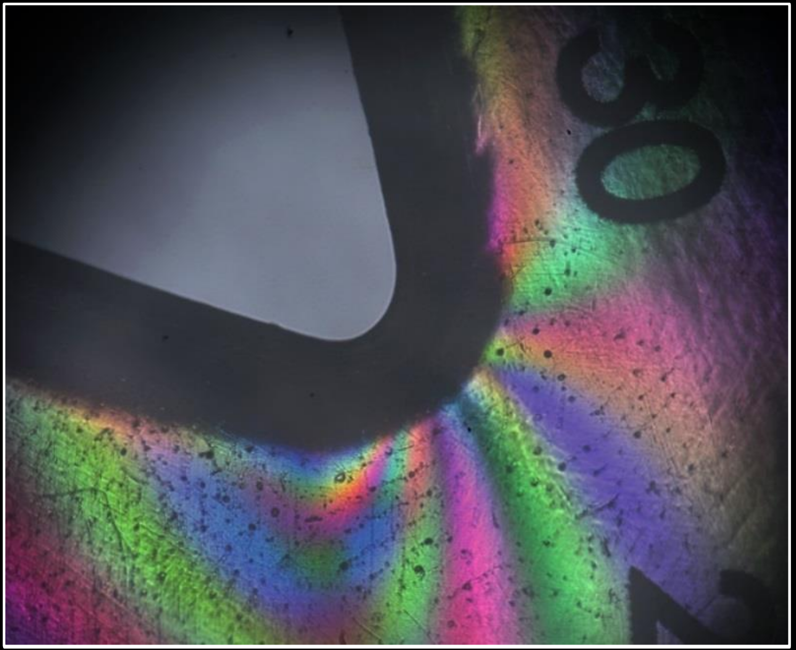
Visualizing dispersion




what a regular camera sees

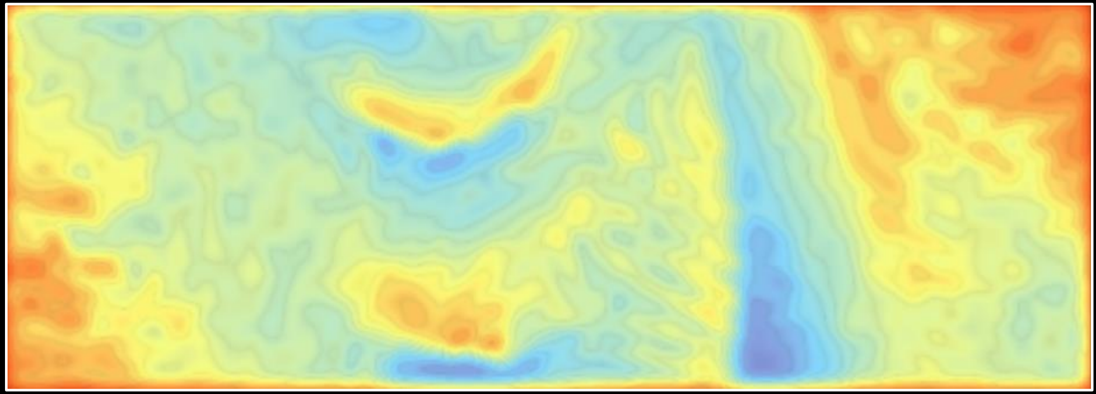

what our camera sees

Visualizing photoelasticity



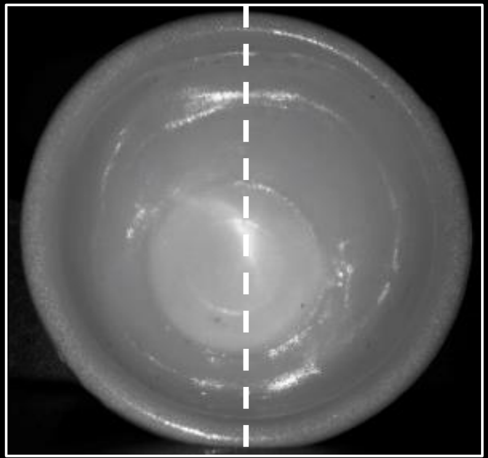
detail under polarized light
scene

low resolution $\Delta\tau$ = 1 mm

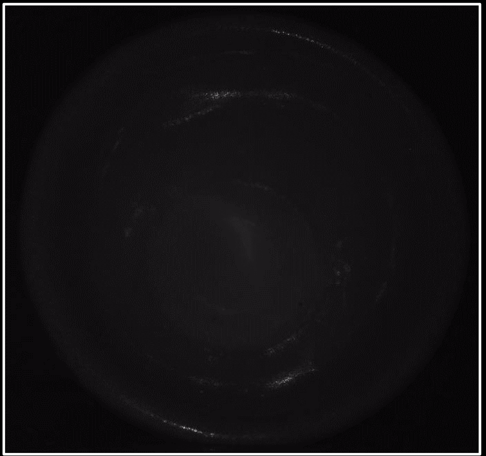


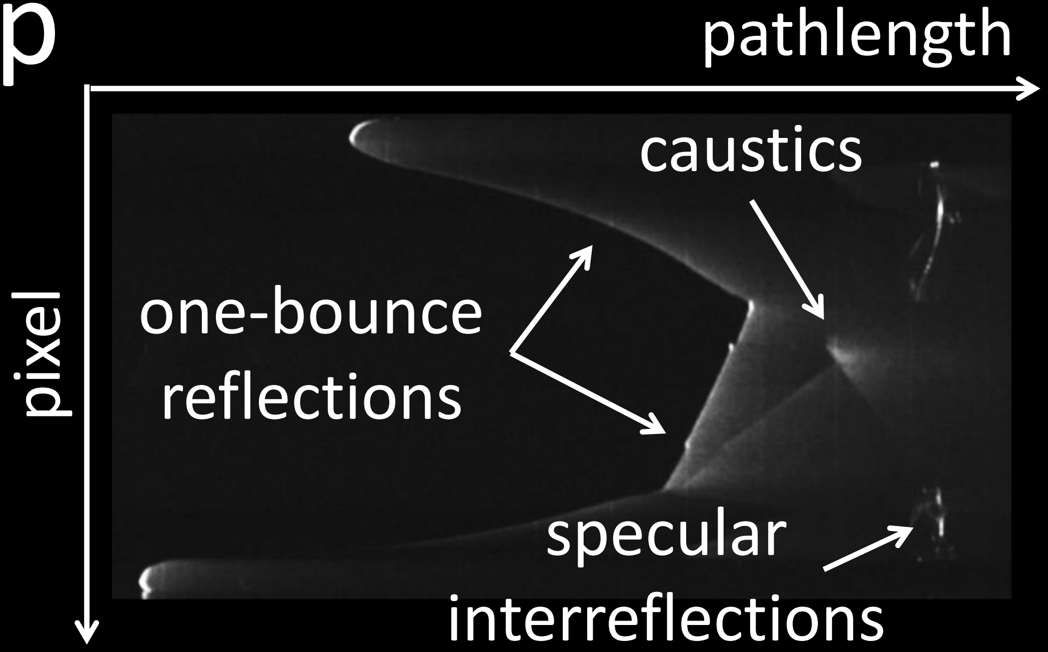
high resolution $\Delta\tau$ = 10 µm

Toy cup

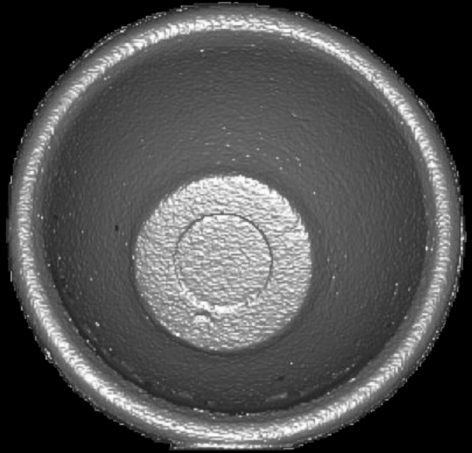


full transient

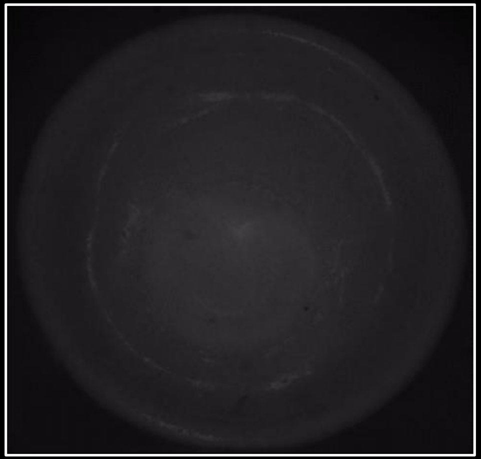


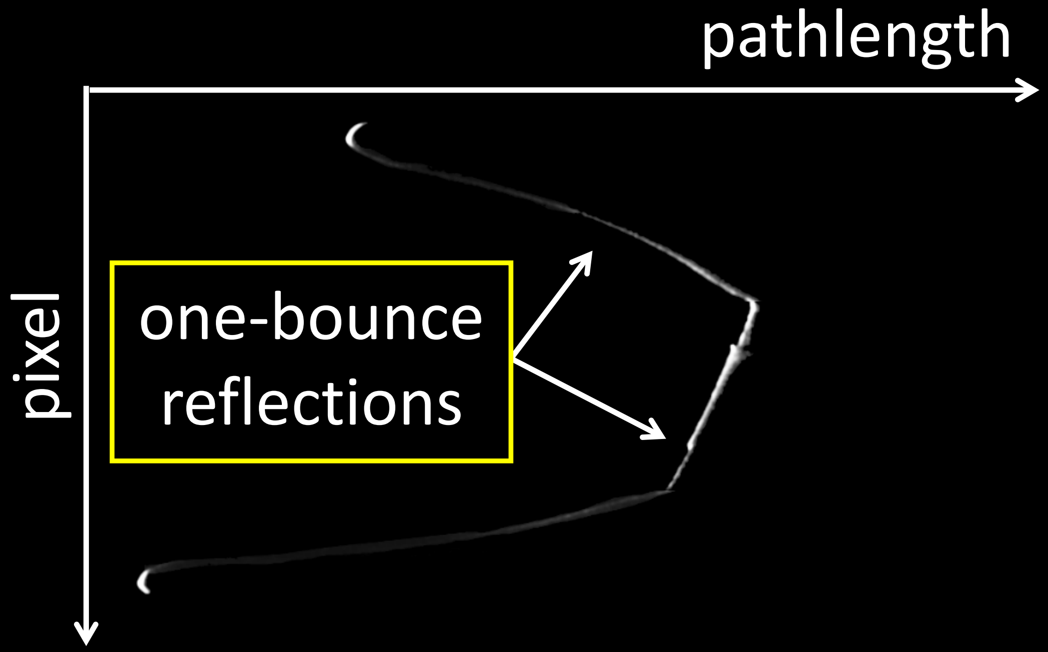


measured depth



direct-only transient



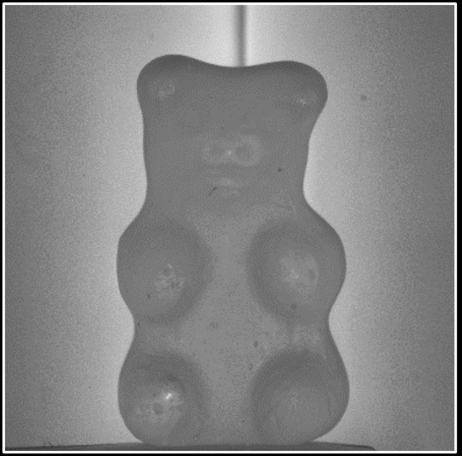


Depth scanning

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

coin | gnocchi | soap carving | gummy bear and diffusers



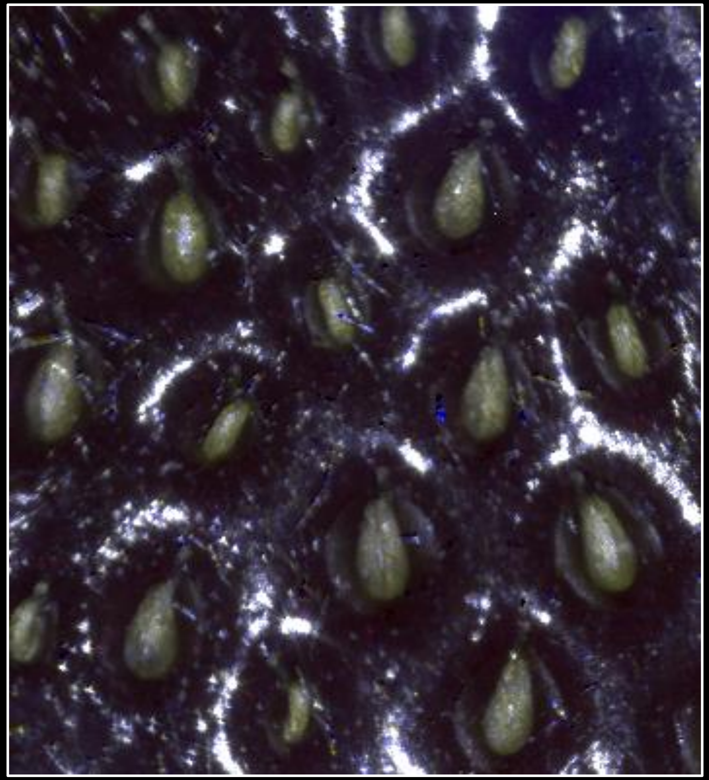


2.5 cm | 1 cm | 1.5 cm | 3 cm

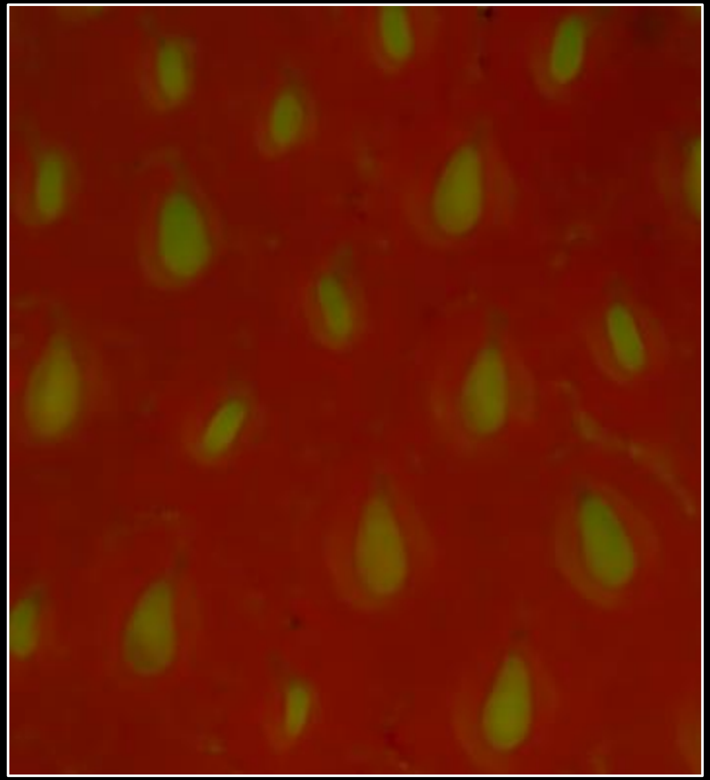


Direct-global separation

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.