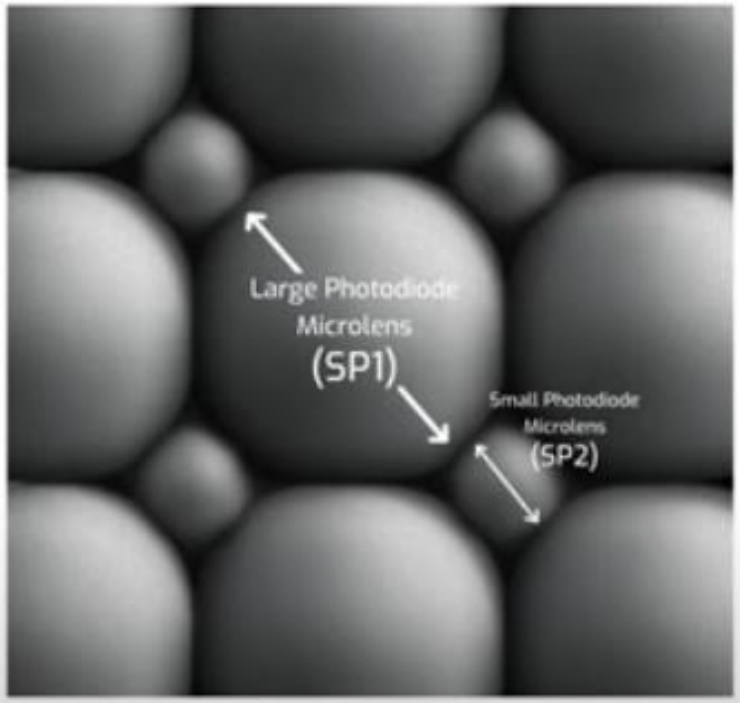
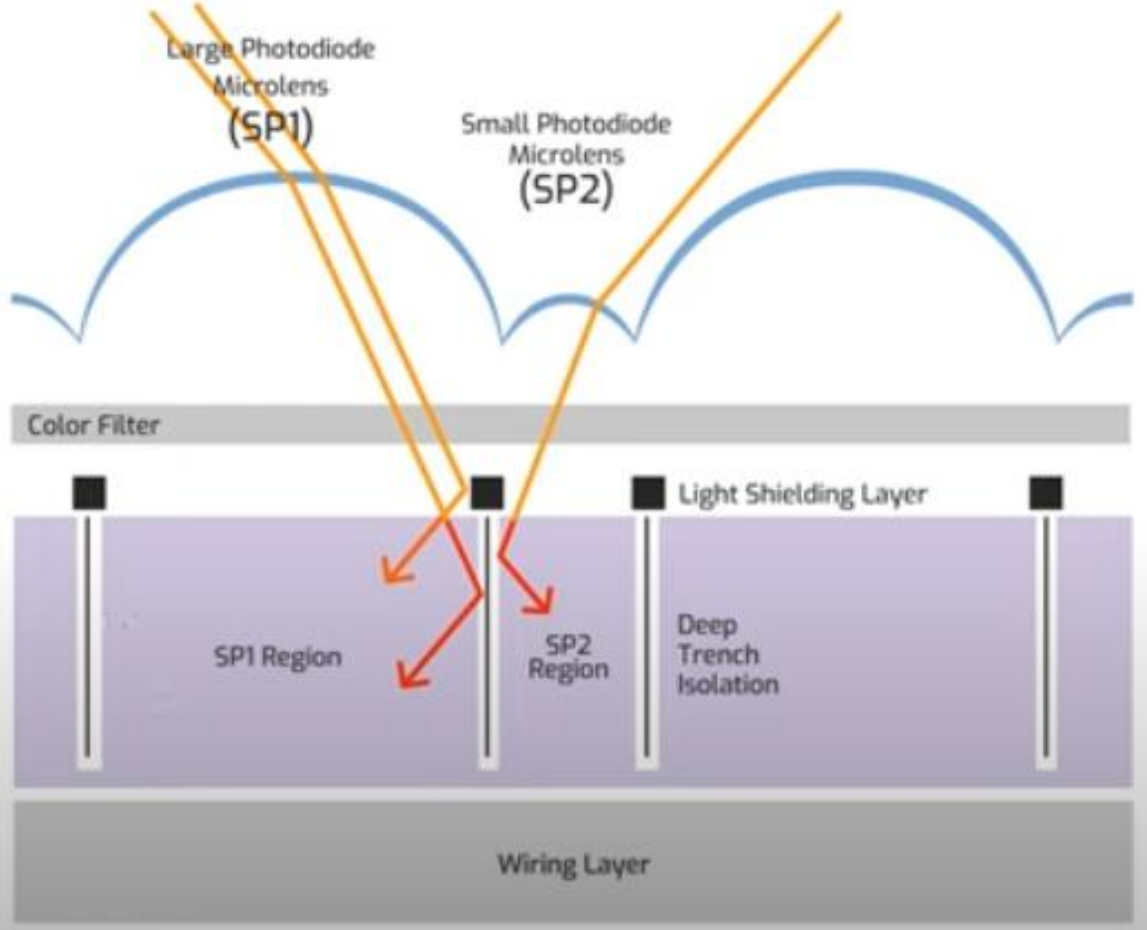
Imaging Sensors for Vision

Matthew O'Toole
Email: motoole2@andrew.cmu.edu

Sony IMX490 Sensor








Sensing polarization

Polarization Photography : Reflections

Reduce Reflections

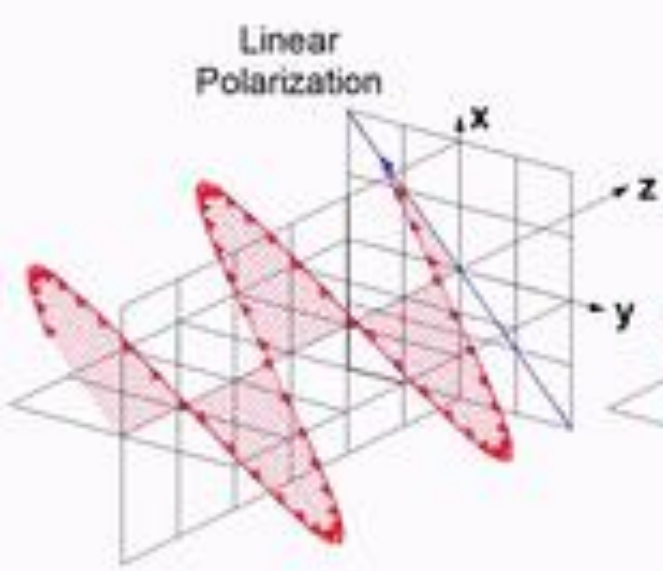
Classification of Polarization

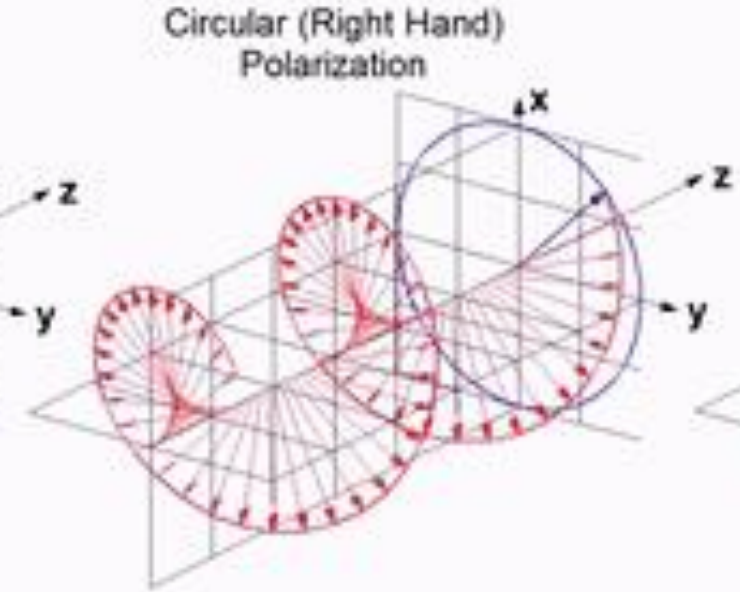
Linear : Two orthogonal plane waves with same phase but possibly different amplitudes.

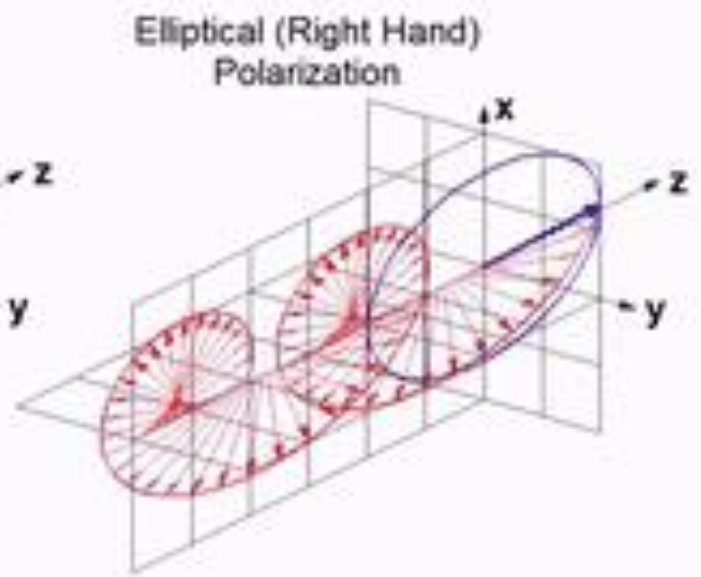
Circular: Two orthogonal plane waves with 90 deg phase shift but same amplitudes.

Elliptical: Possibly any degree phase shift with different amplitudes.

Classification of Polarization



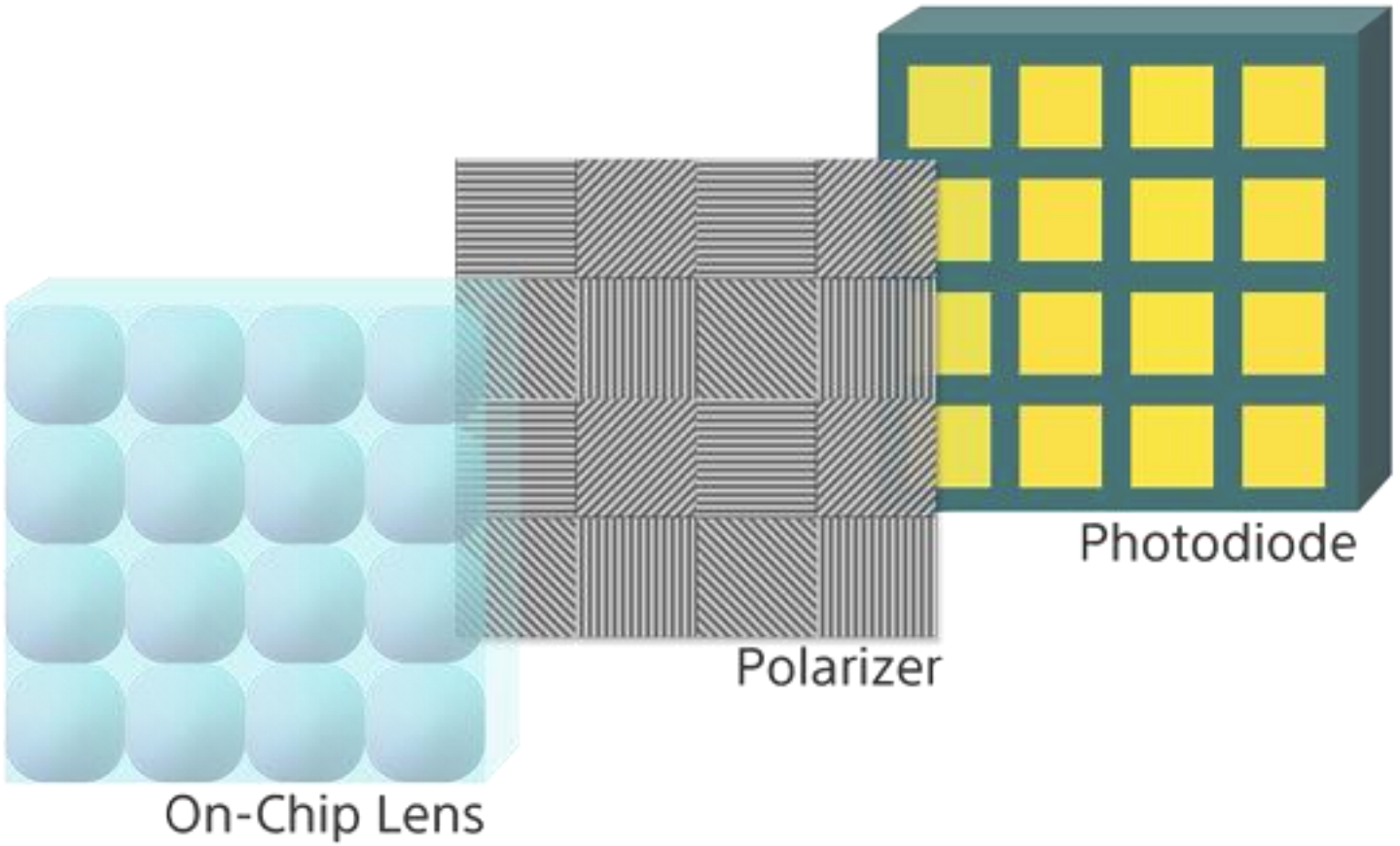




$$\begin{pmatrix} E \\ E \end{pmatrix} \begin{pmatrix} E_{0x}\,e^{i\phi_x} \\ E_{0y}\,e^{i\phi_y} \end{pmatrix} \begin{matrix} +\phi_x) \\ +\phi_y \end{matrix} \begin{pmatrix} E_{0x}\,e^{i\phi_x} \\ E_{0y}\,e^{i\phi_y} \\ 0 \end{pmatrix} e^{i(kz-\omega t)}$$

Jones Vector

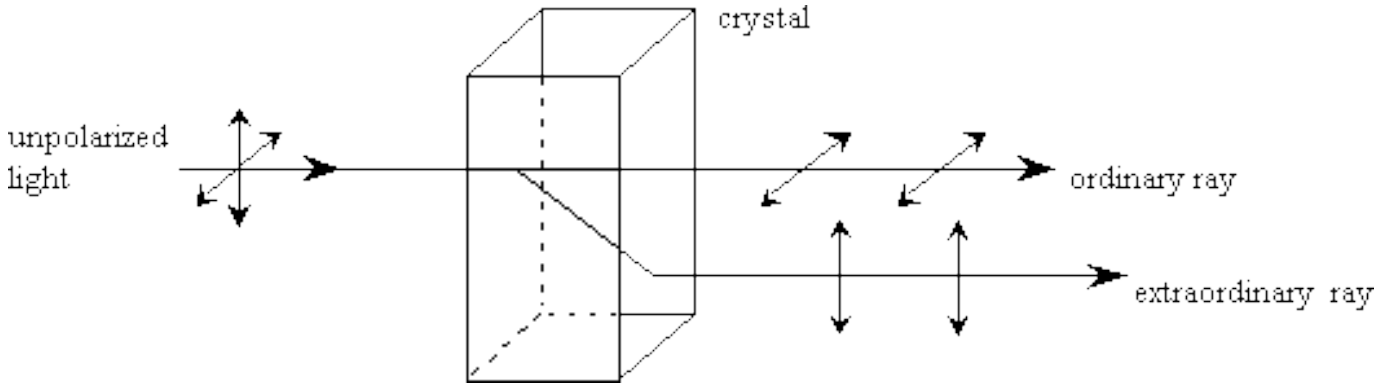
Polarization Image Sensor



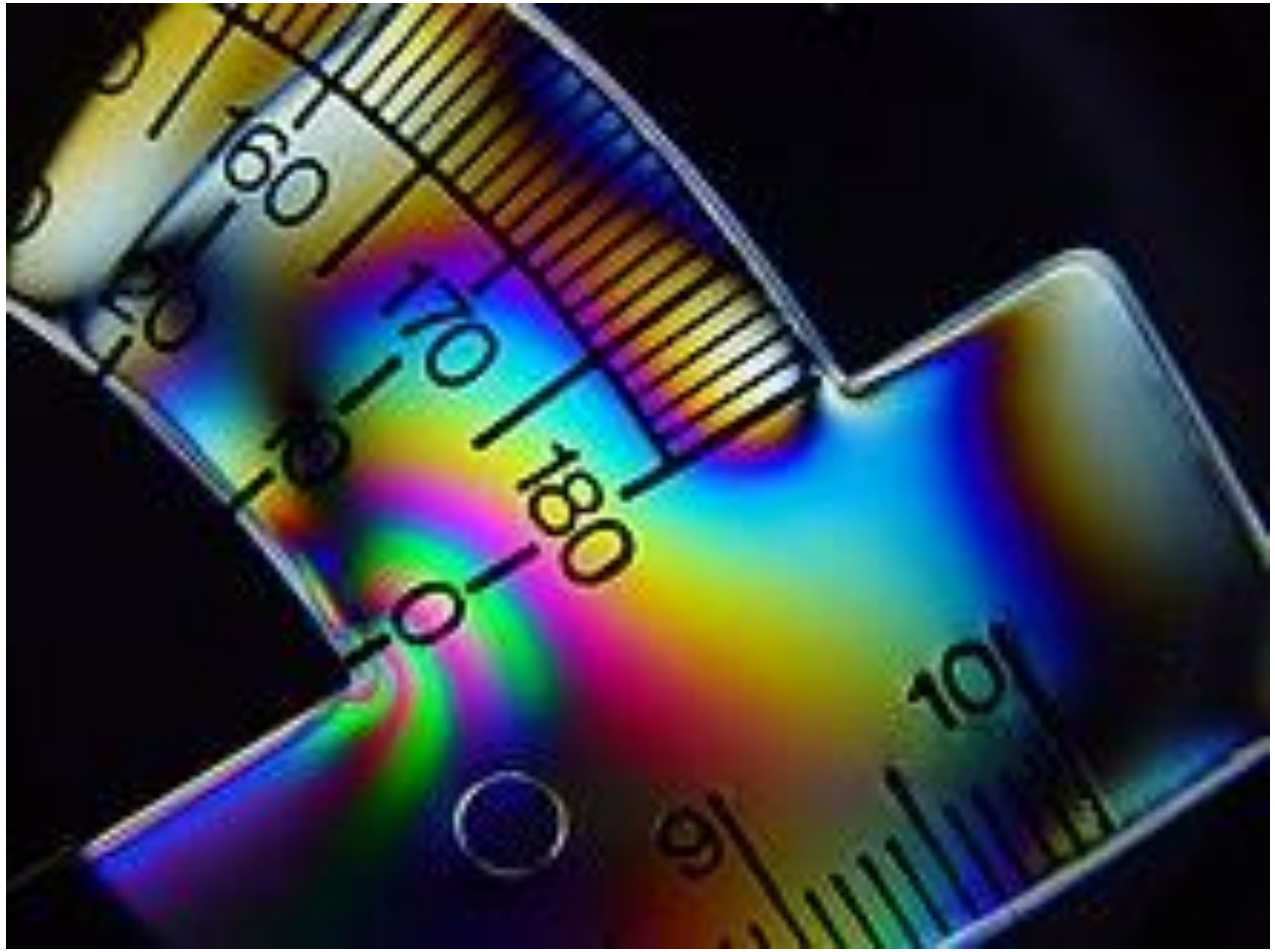
Without polarizer

With polarizer

Birefringence

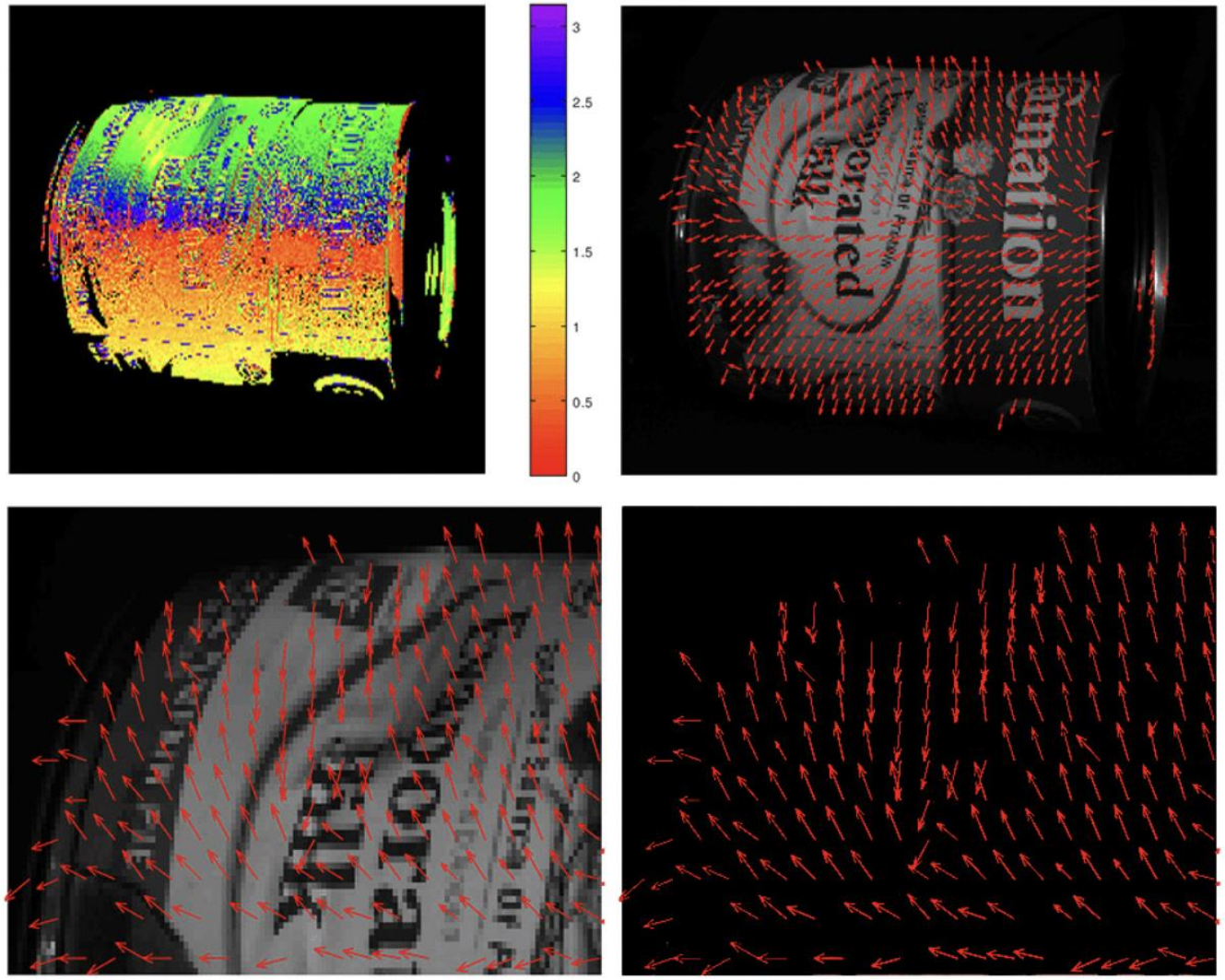


Measuring stress distributions

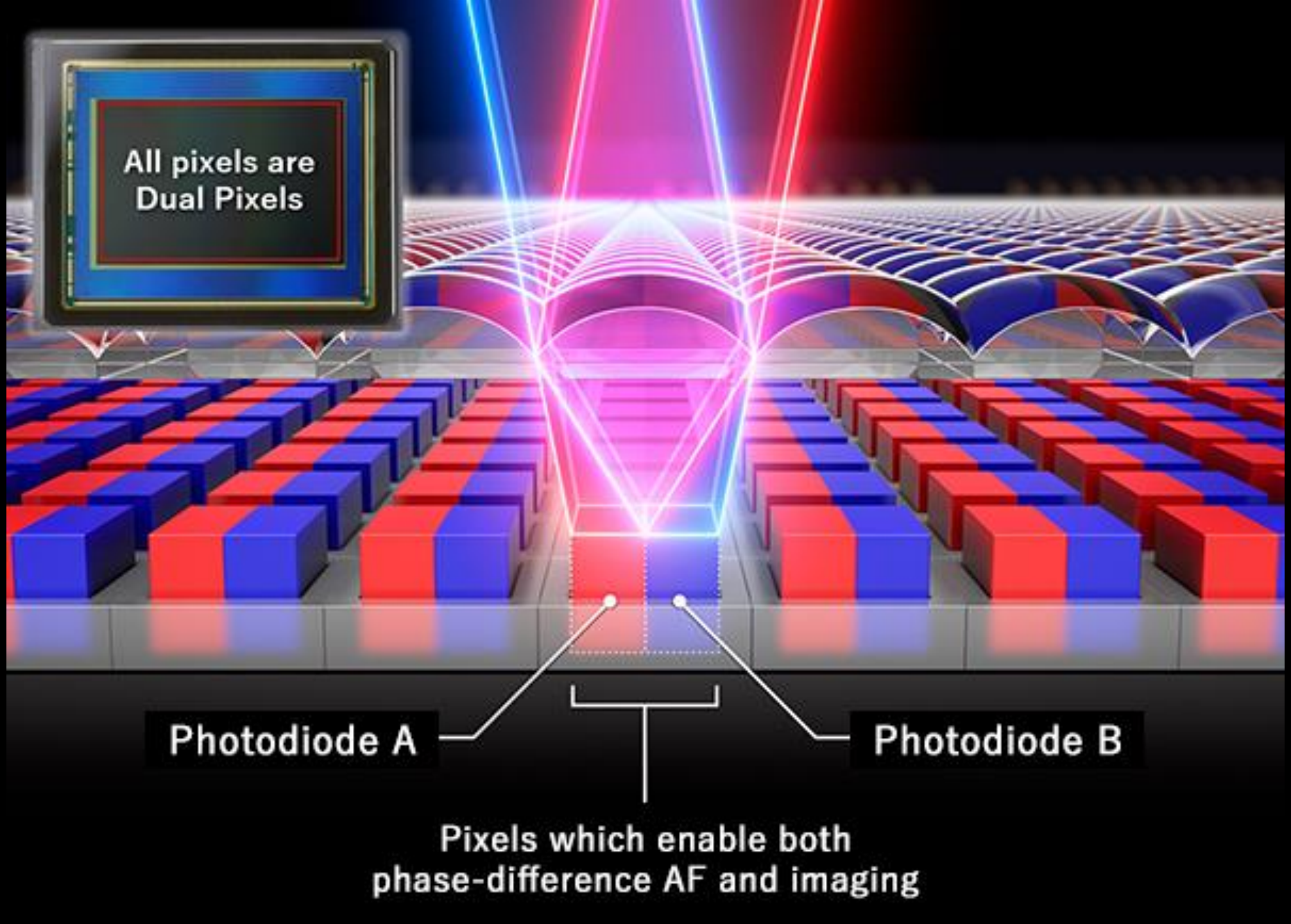


3D Movies

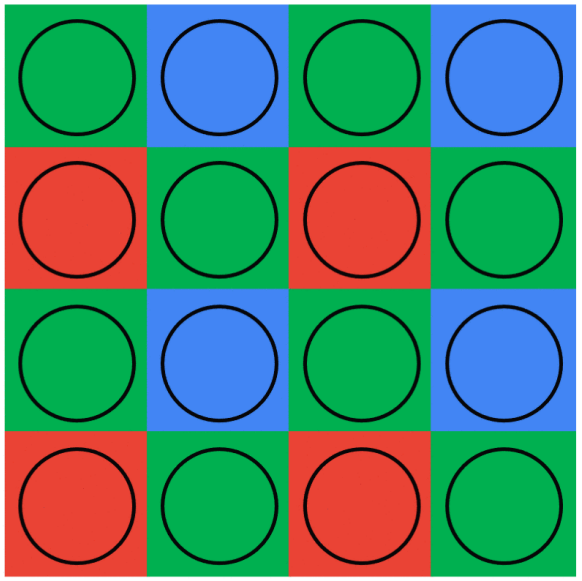
Shape from polarization



Dual pixel sensors

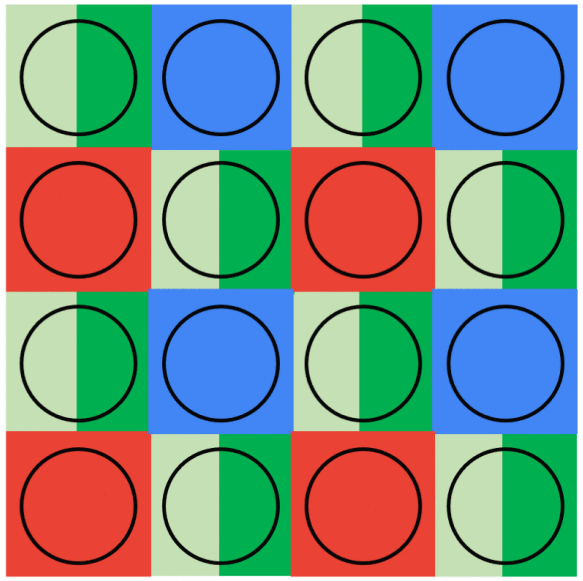

All pixels are
Dual Pixels
Photodiode A
Photodiode B
Pixels which enable both
phase-difference AF and imaging

Dual Pixel (DP) Sensors

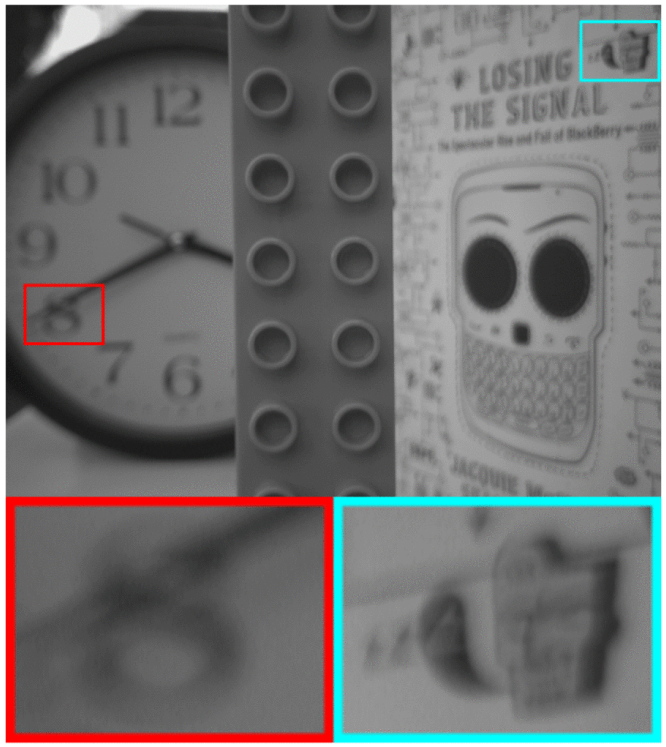


Regular sensor

Left photodiode ⮌ ⮎ Right photodiode



DP sensor

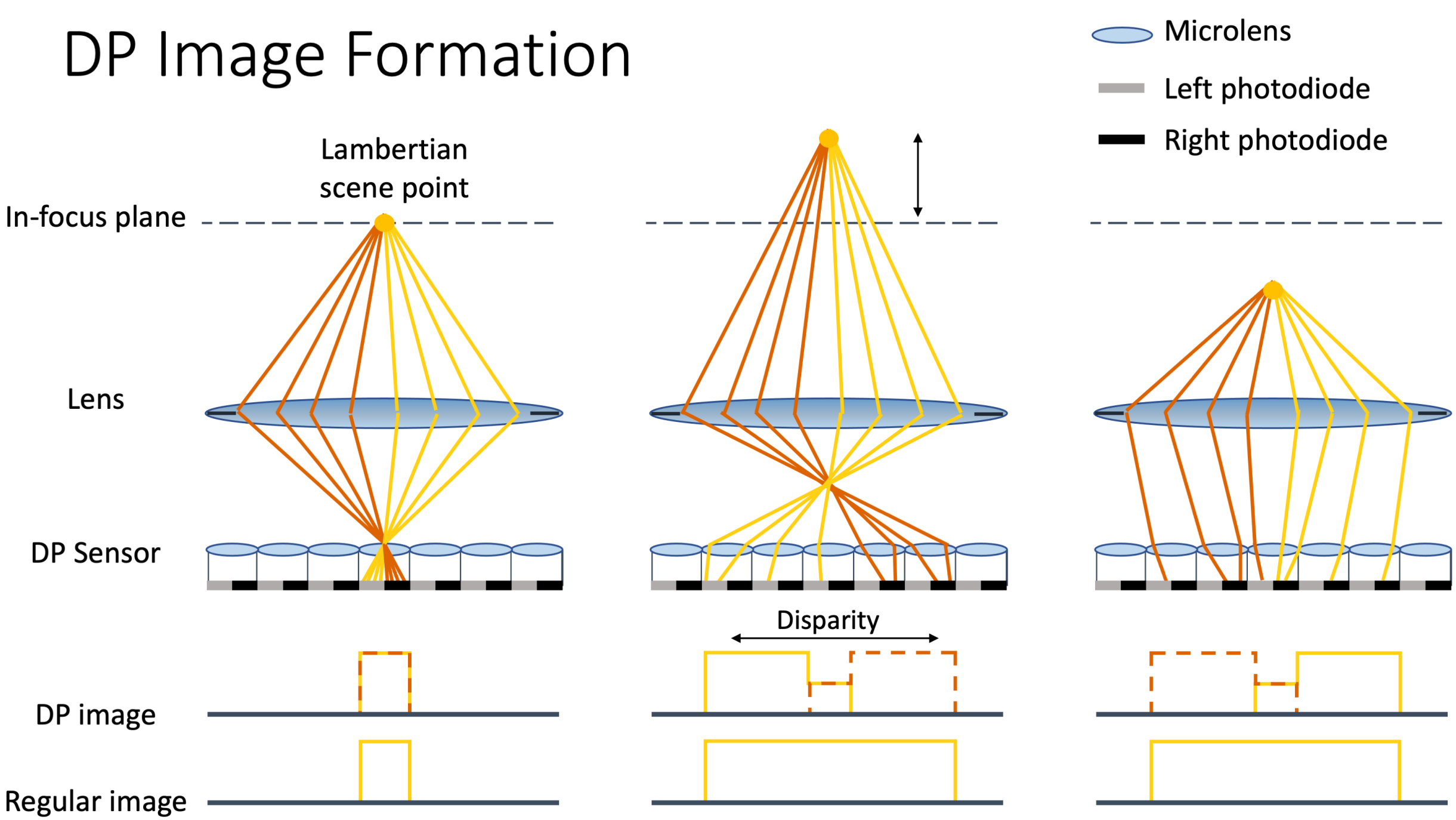


DP image

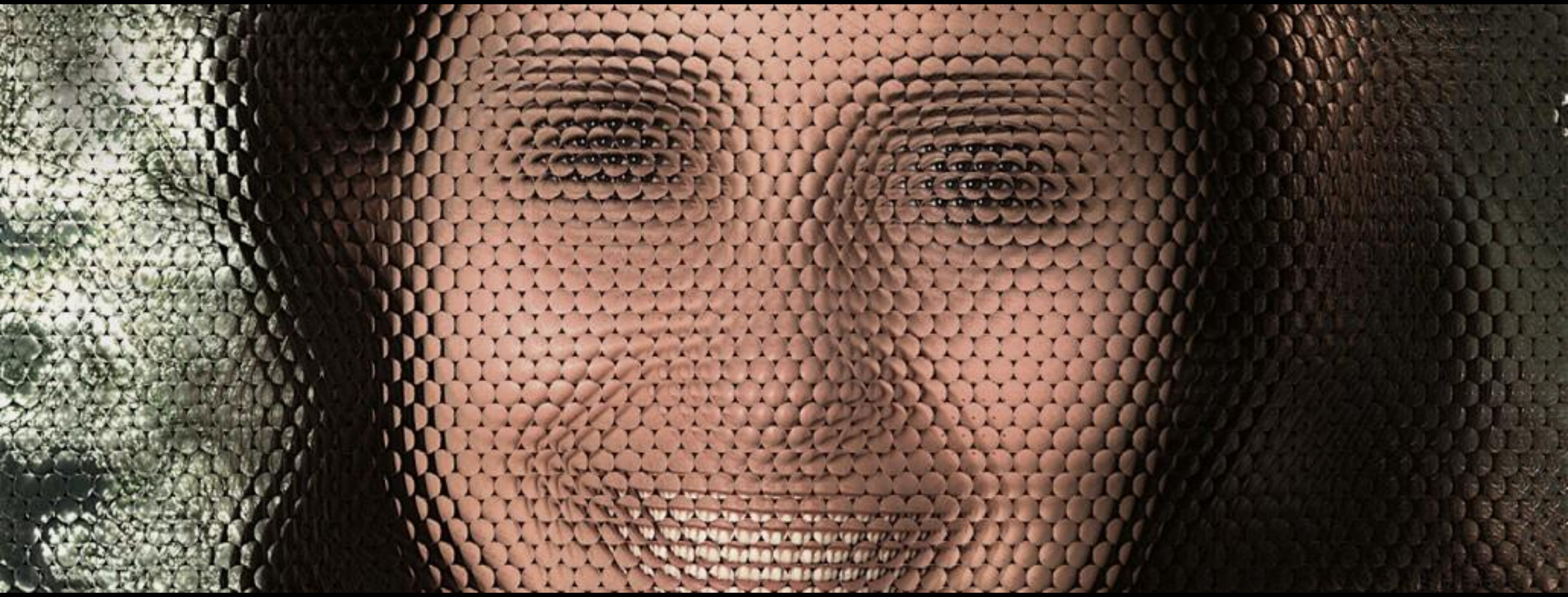
Canon EOS R5

Google Pixel 4

DP Image Formation

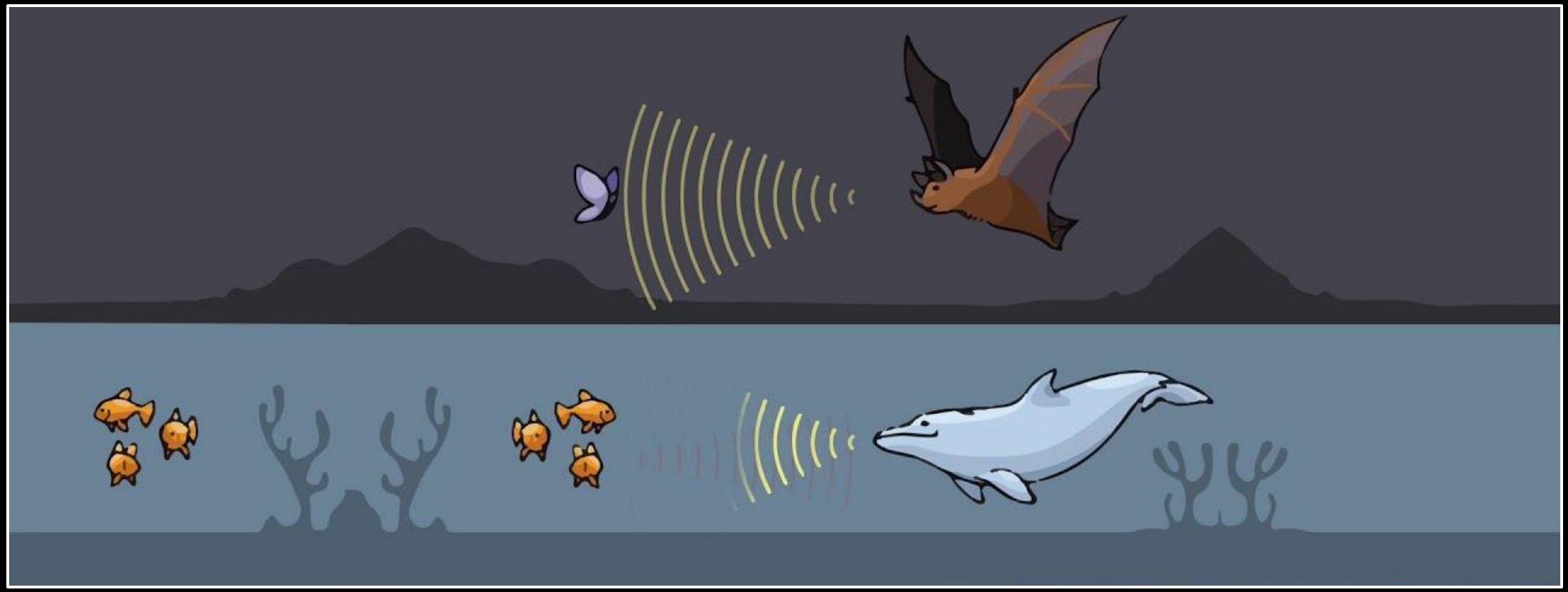


Light field imaging



Time-of-flight sensing

echolocation



speed of sound in air: 343 meters / sec

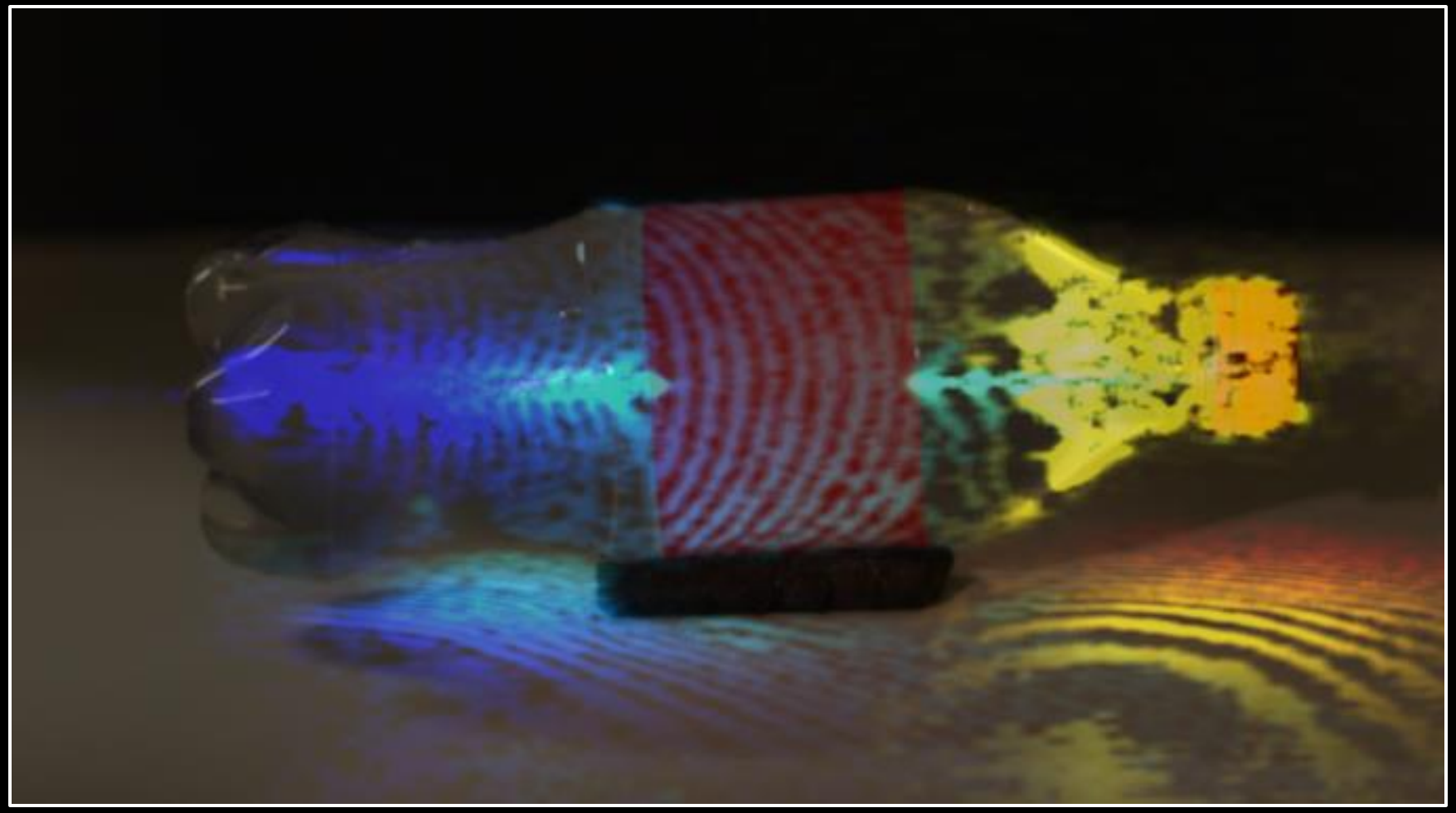
in water: 1480 meters / sec

Light takes 1.255 seconds to travel from the earth to the moon

speed of light in a vacuum: **299,792,458** meters / sec

(Light travels approximation **1 MILLION** times faster than sound!)

transient imaging



speed of light in a vacuum: **299,792,458** meters / sec

(Light travels approximation **1 MILLION** times faster than sound!)

transient imaging (a.k.a. femtophotography)

“Femto-photography: capturing and visualizing the propagation of light”, [Velten et al., 2012]

direct and **indirect** time-of-flight sensors for transient imaging

Velodyne VLS-128

Microsoft Kinect v2

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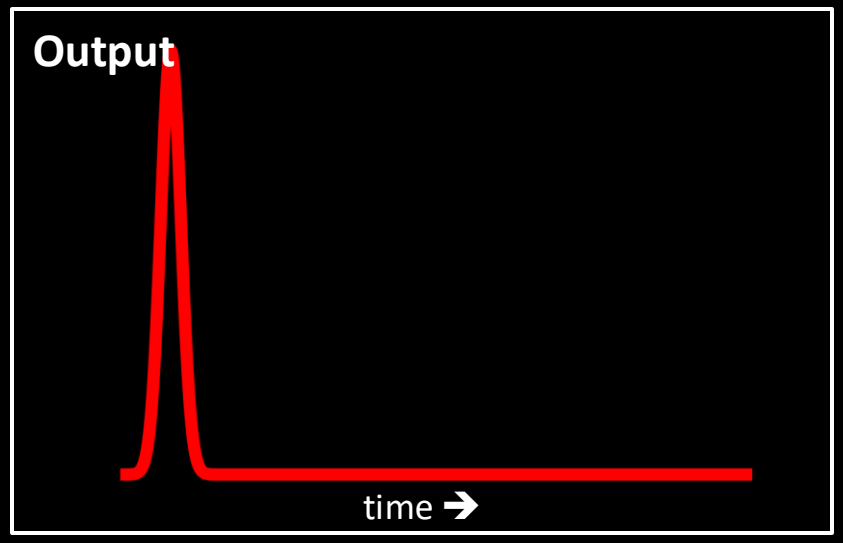
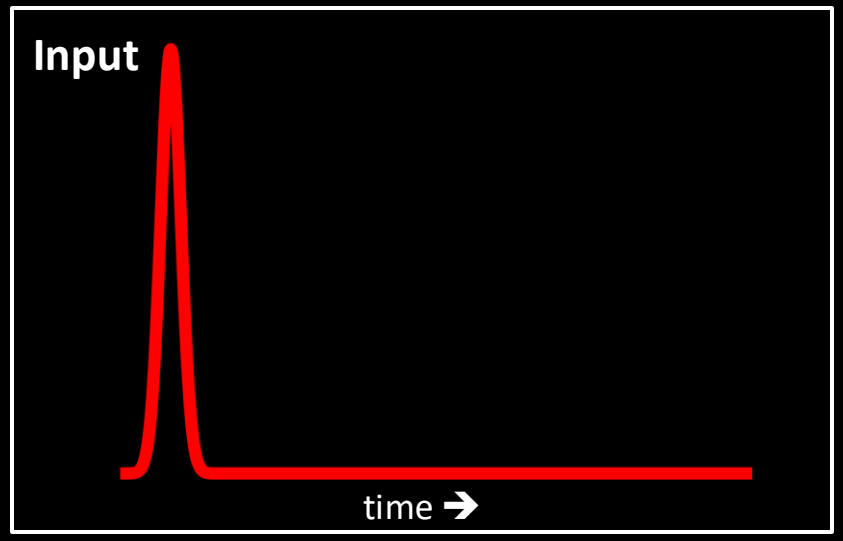
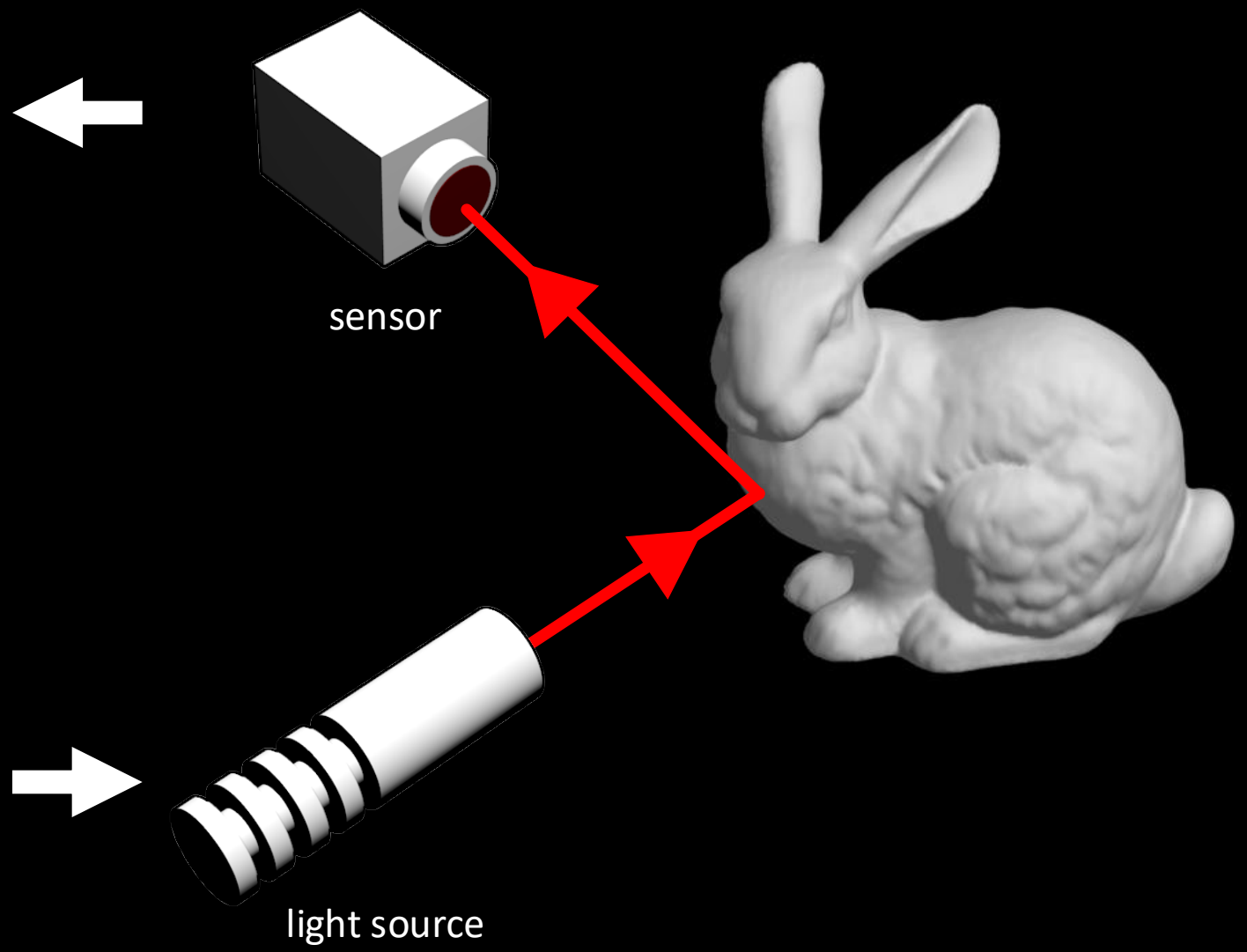
direct and **indirect** time-of-flight sensors for transient imaging

Velodyne VLS-128

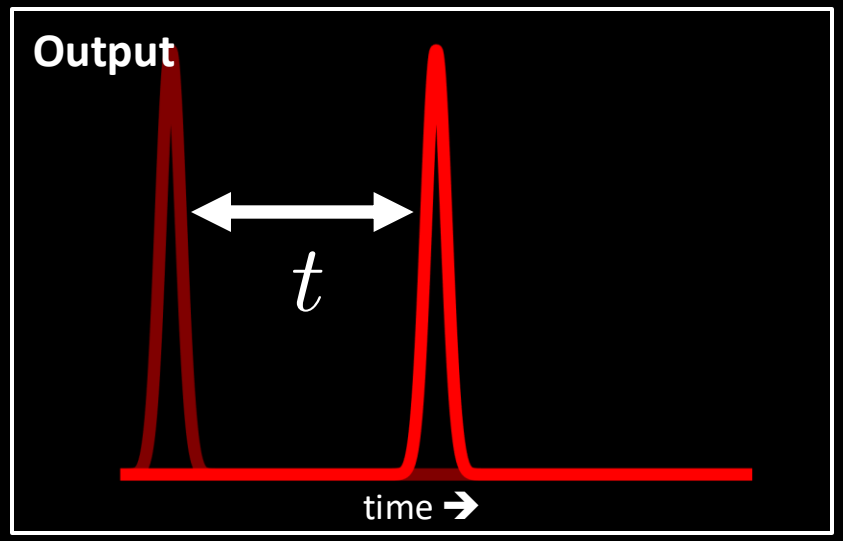
direct time-of-flight principle

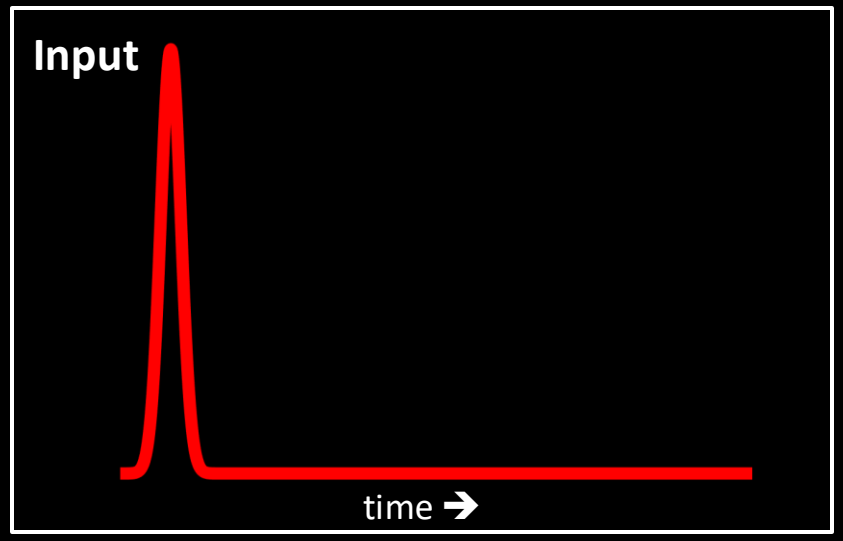


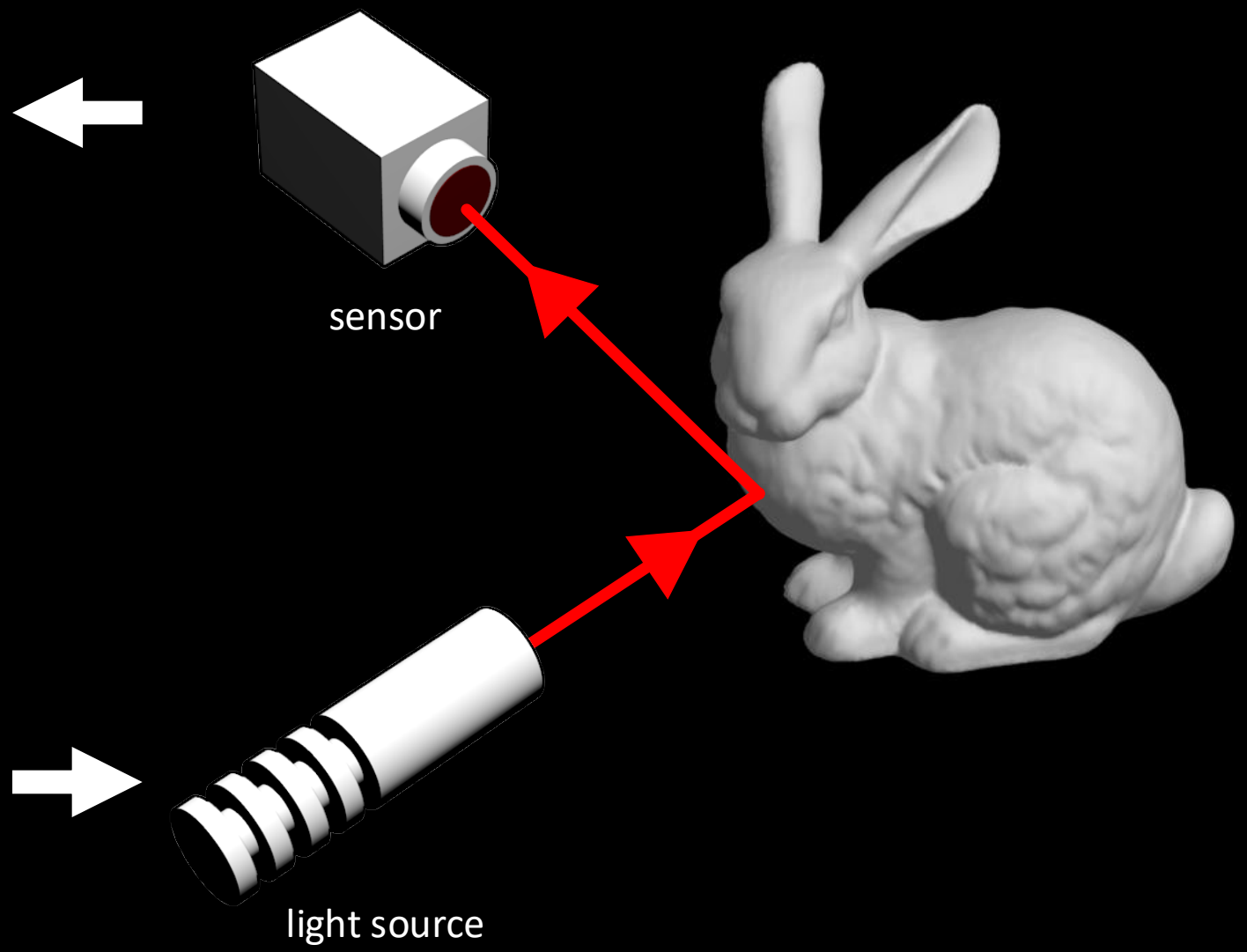




direct time-of-flight principle







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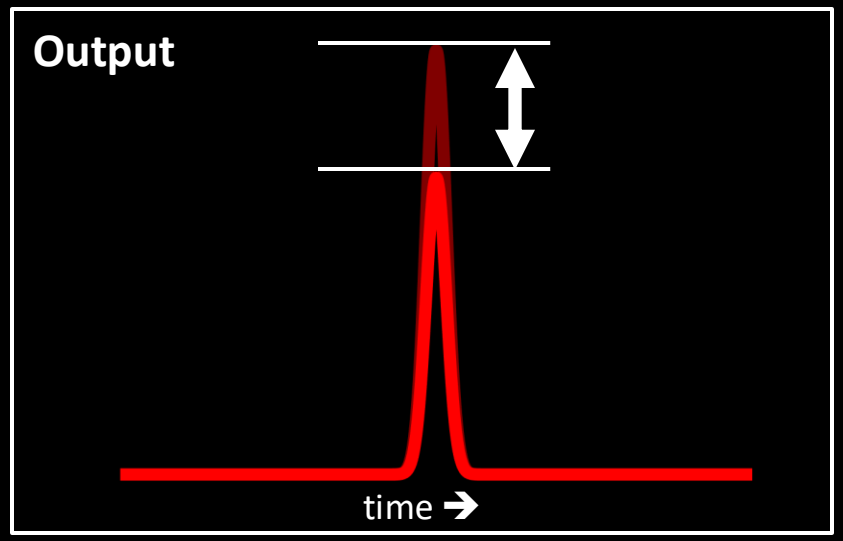

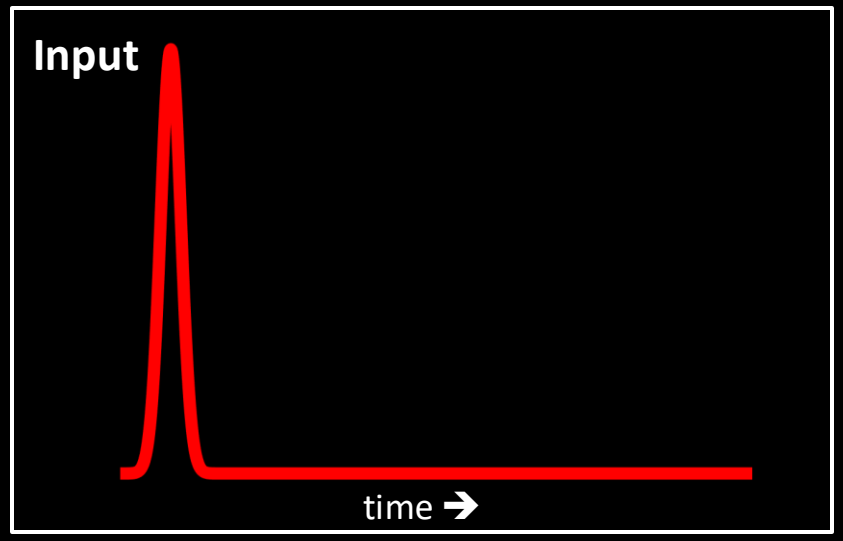

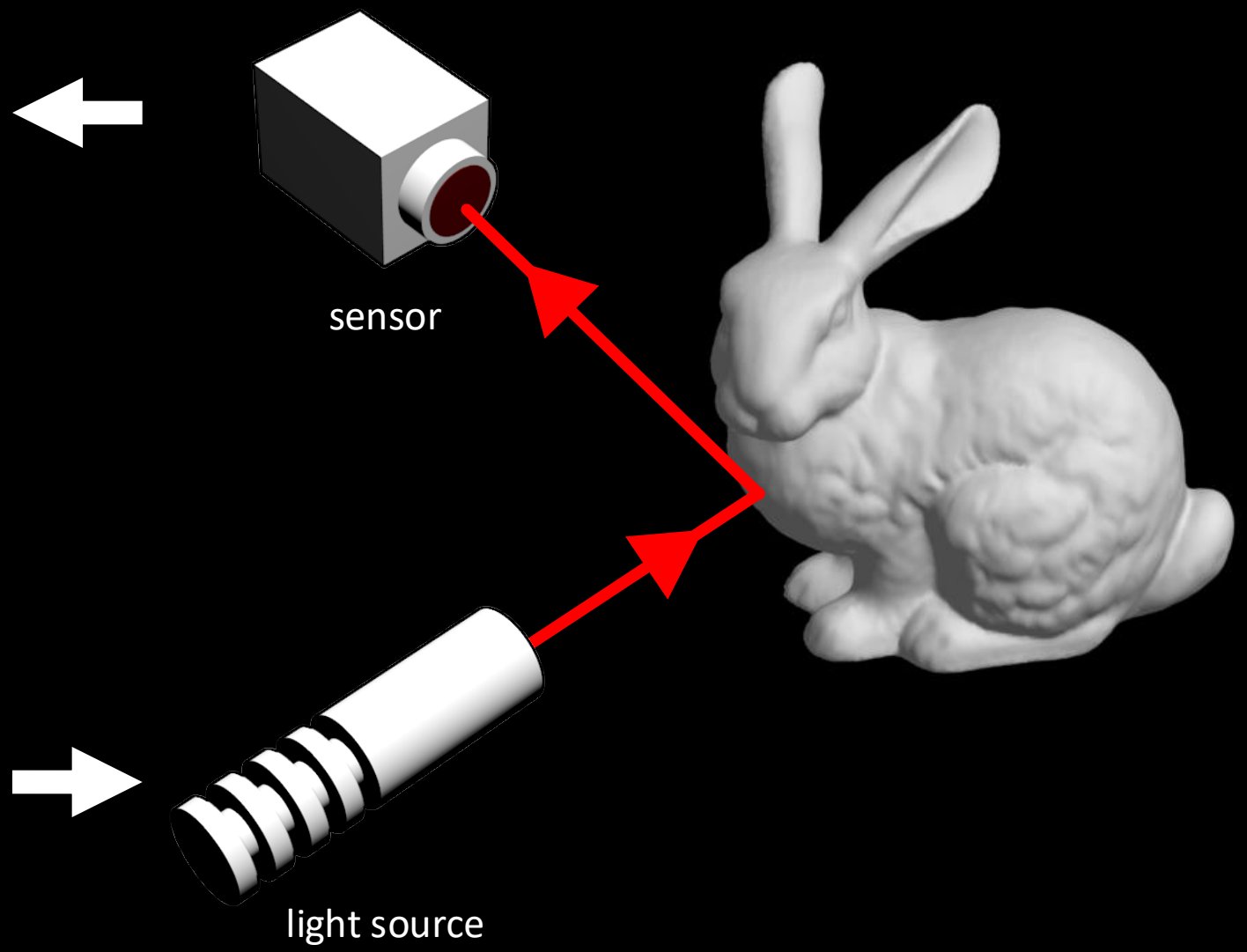

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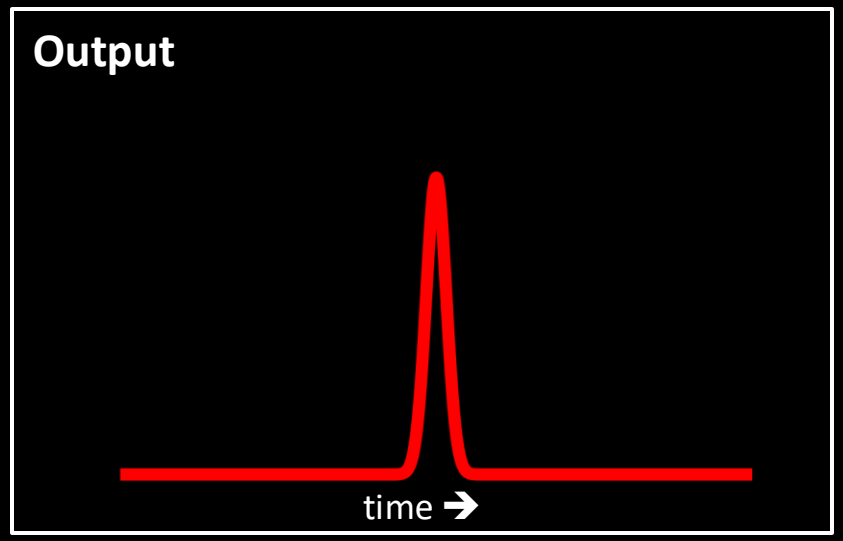

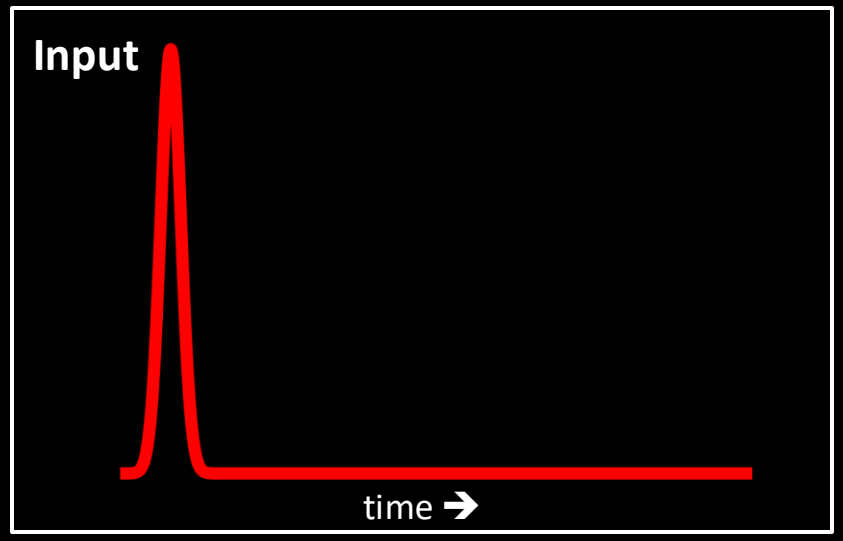

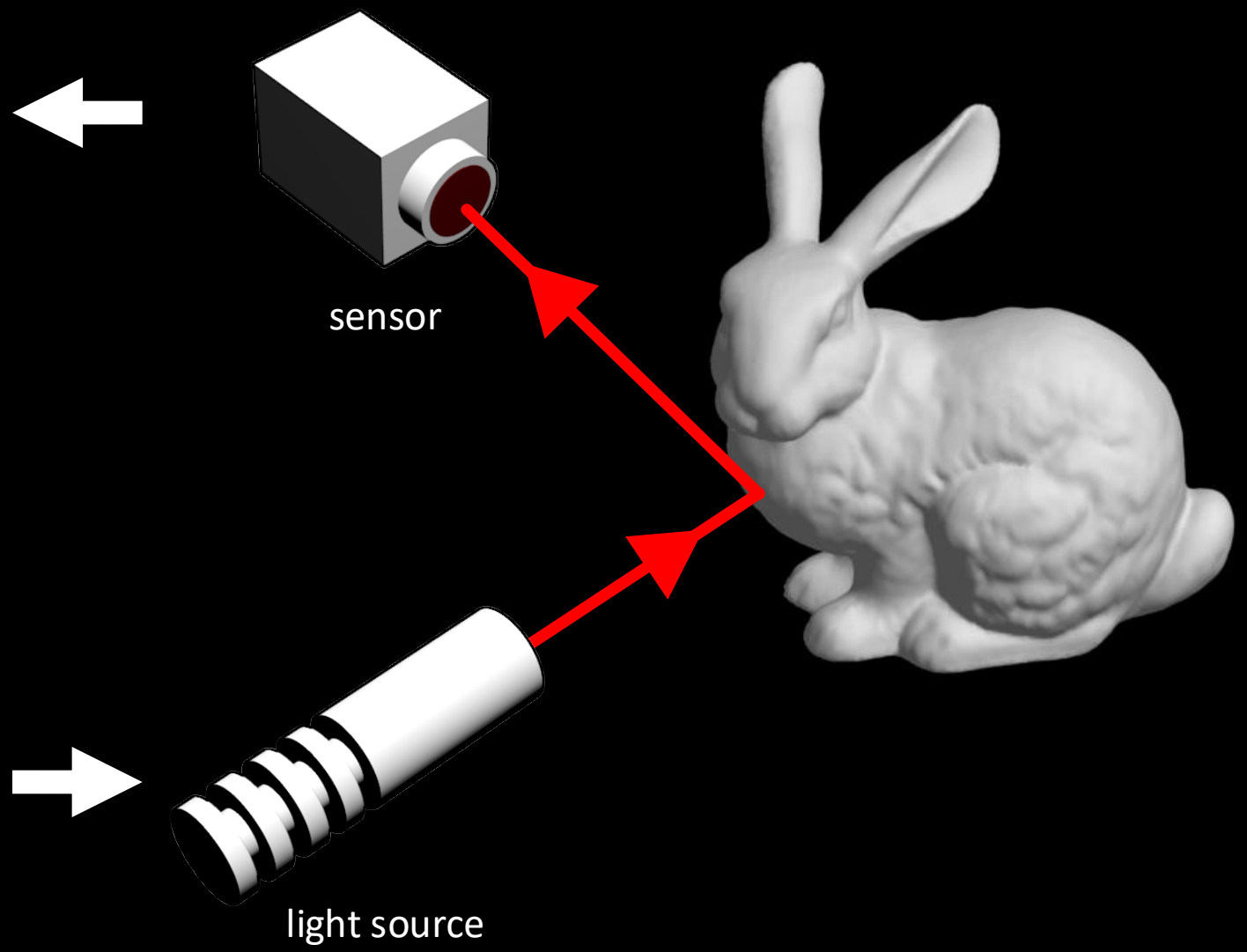

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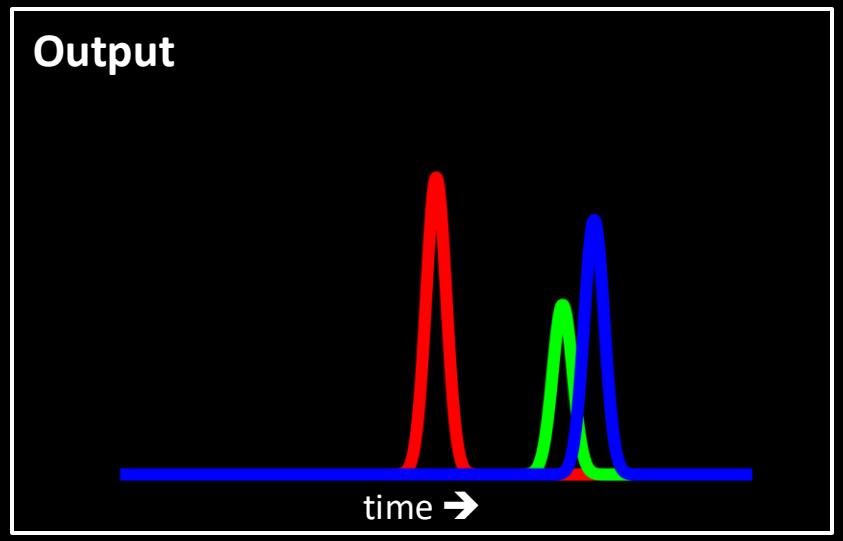

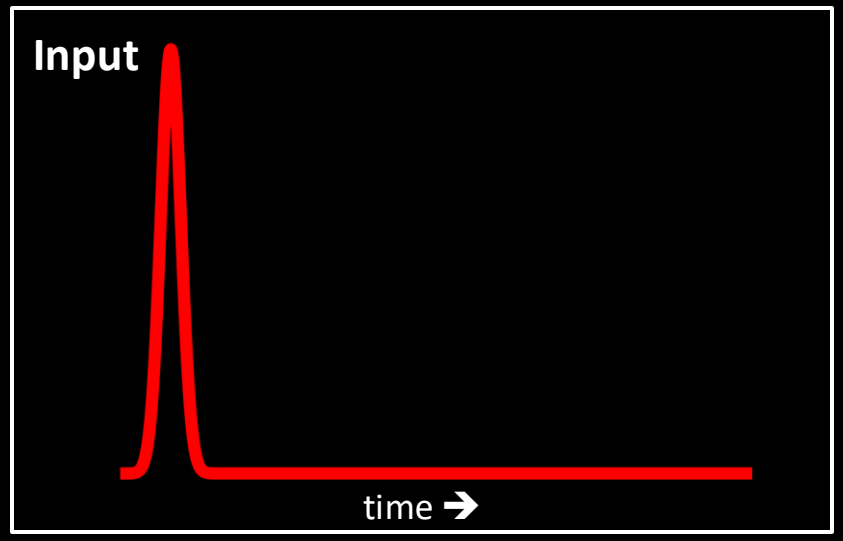

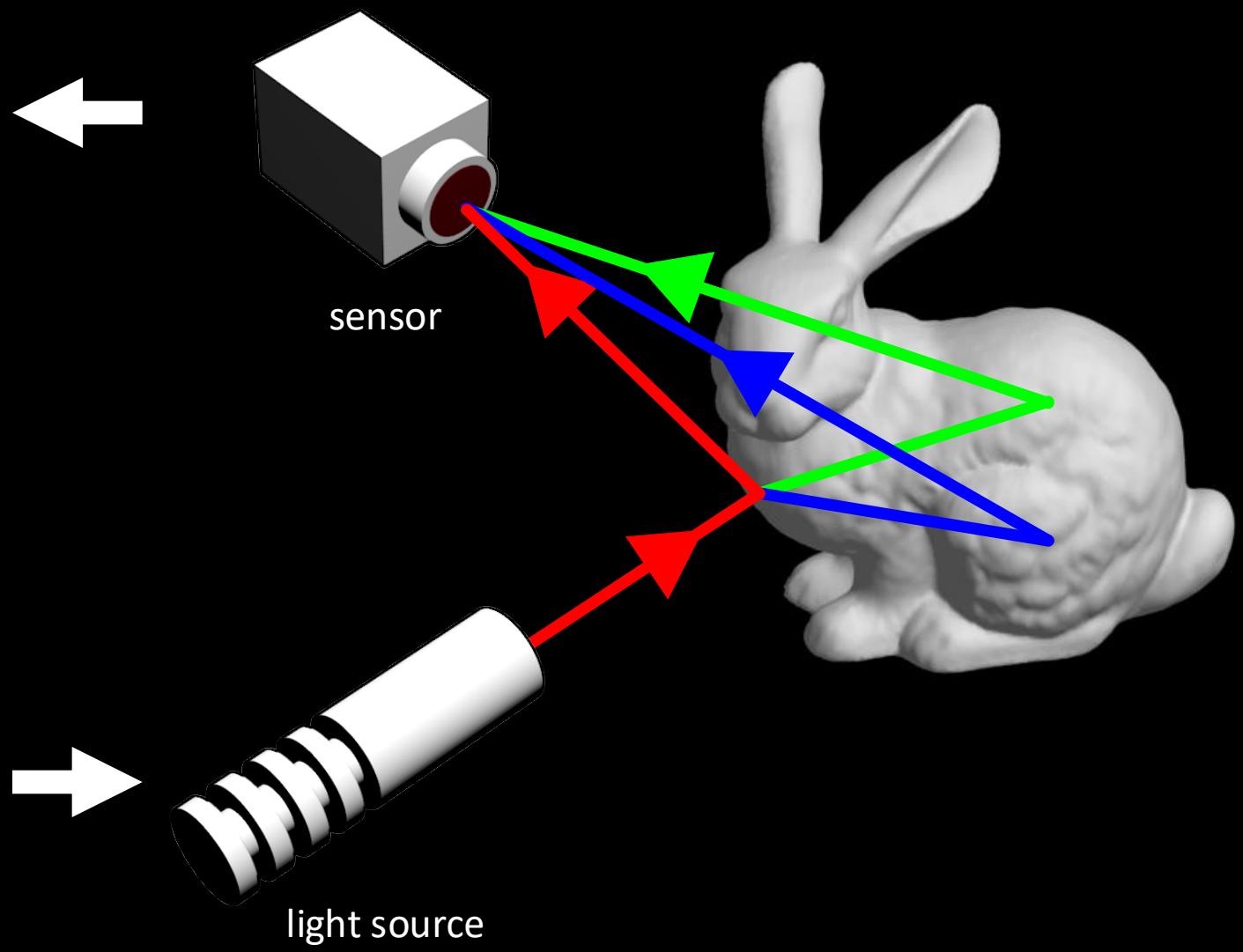

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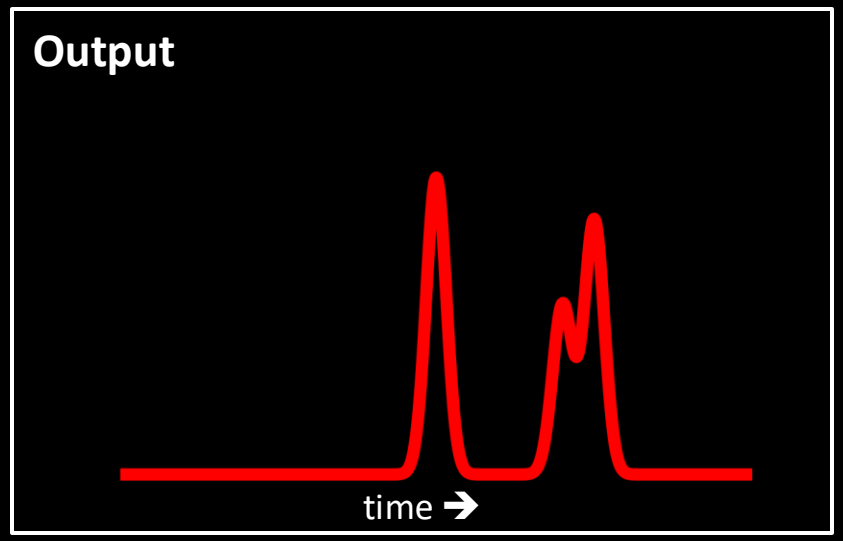

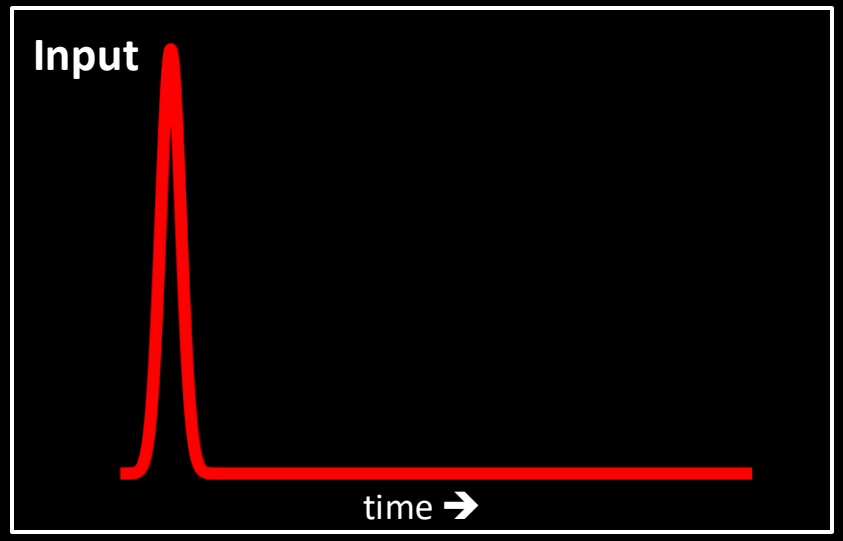

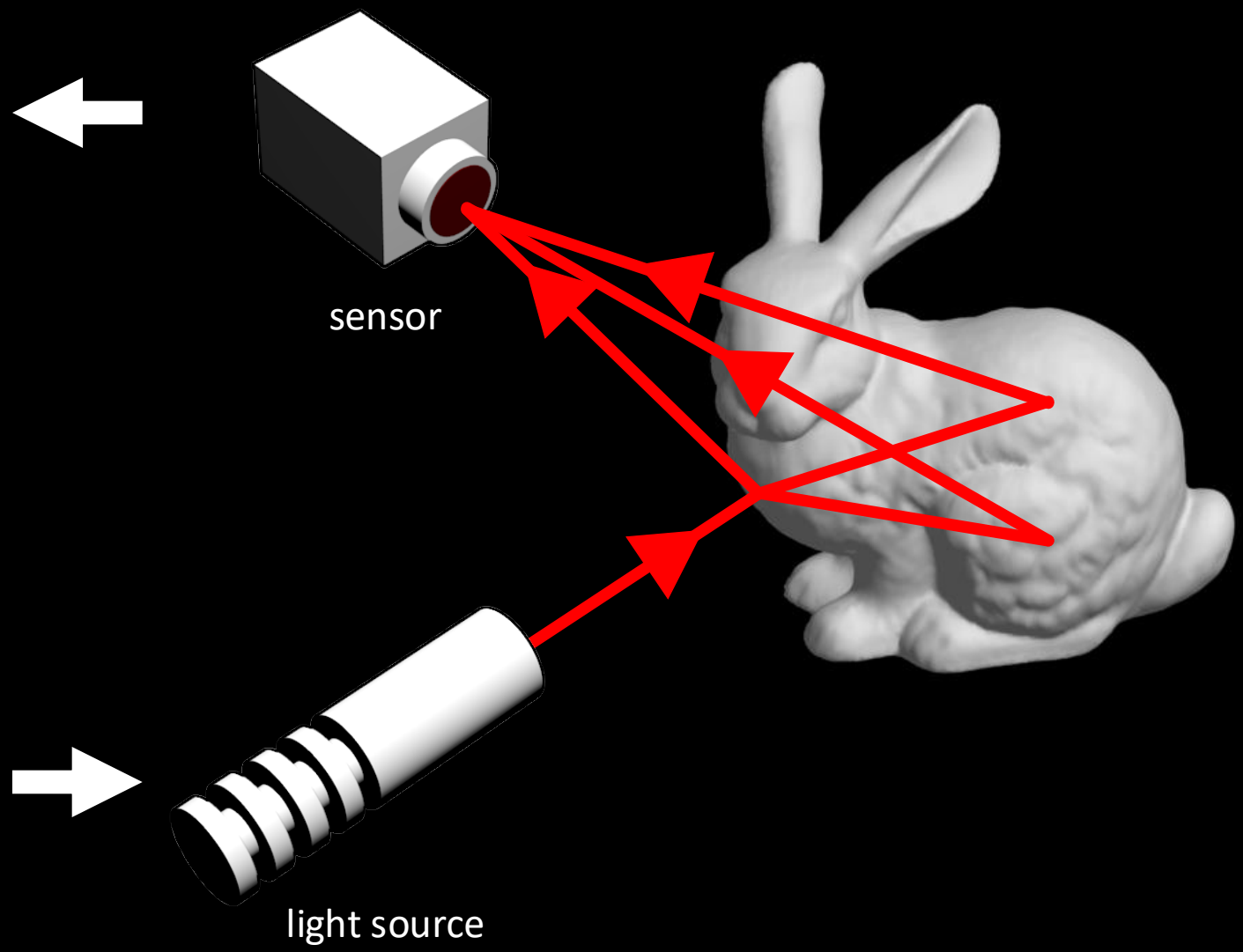

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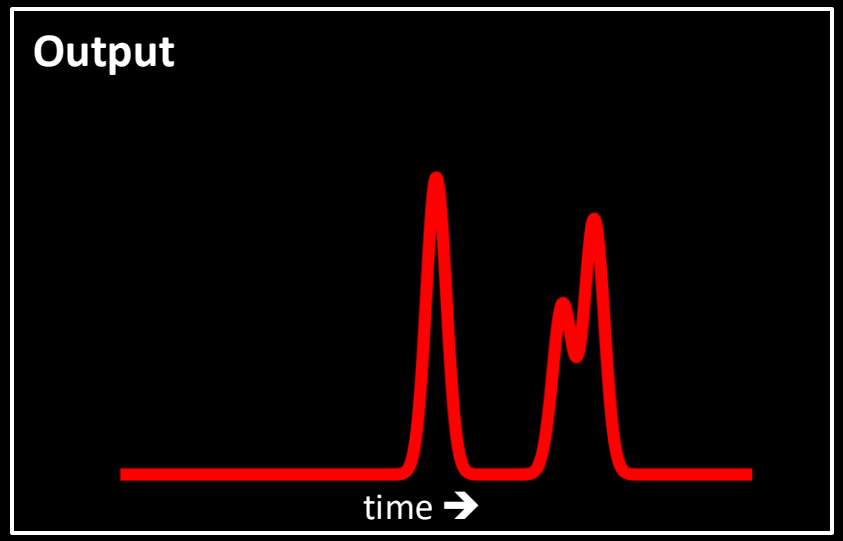


transient measurement

direct and **indirect** time-of-flight sensors for transient imaging

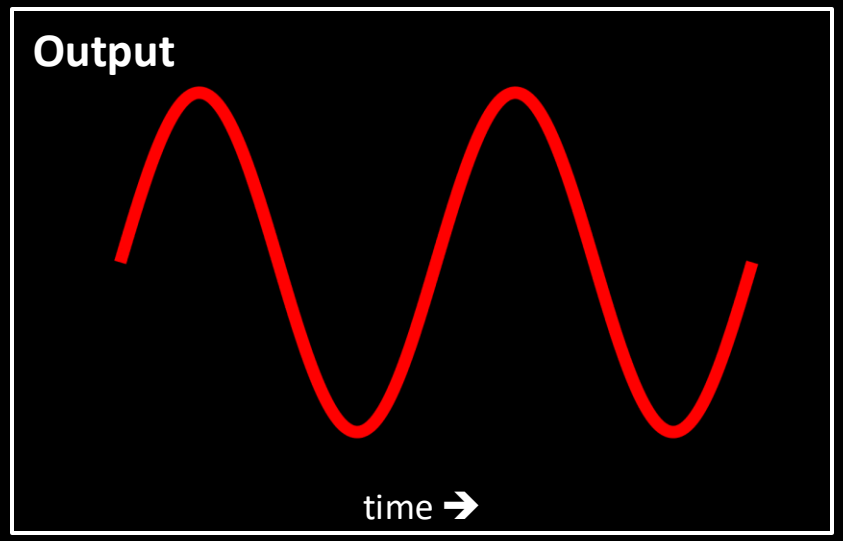
Velodyne VLS-128

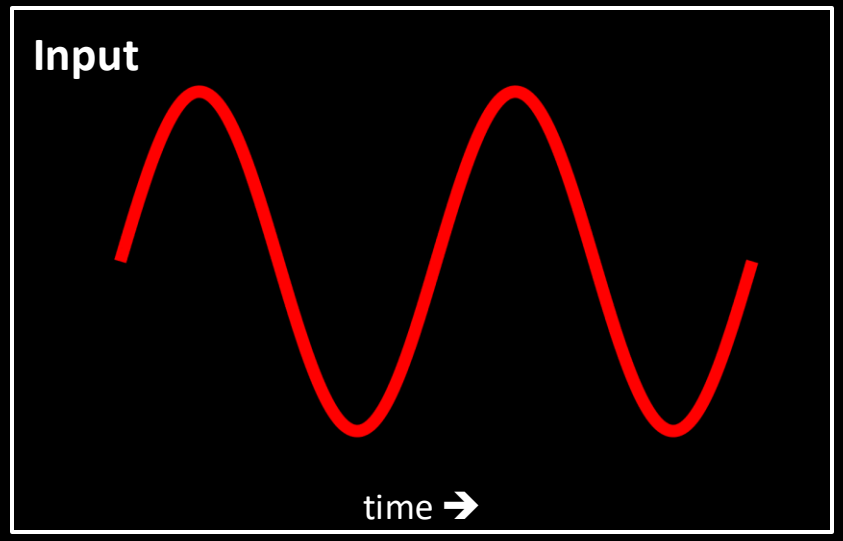
Microsoft Kinect v2

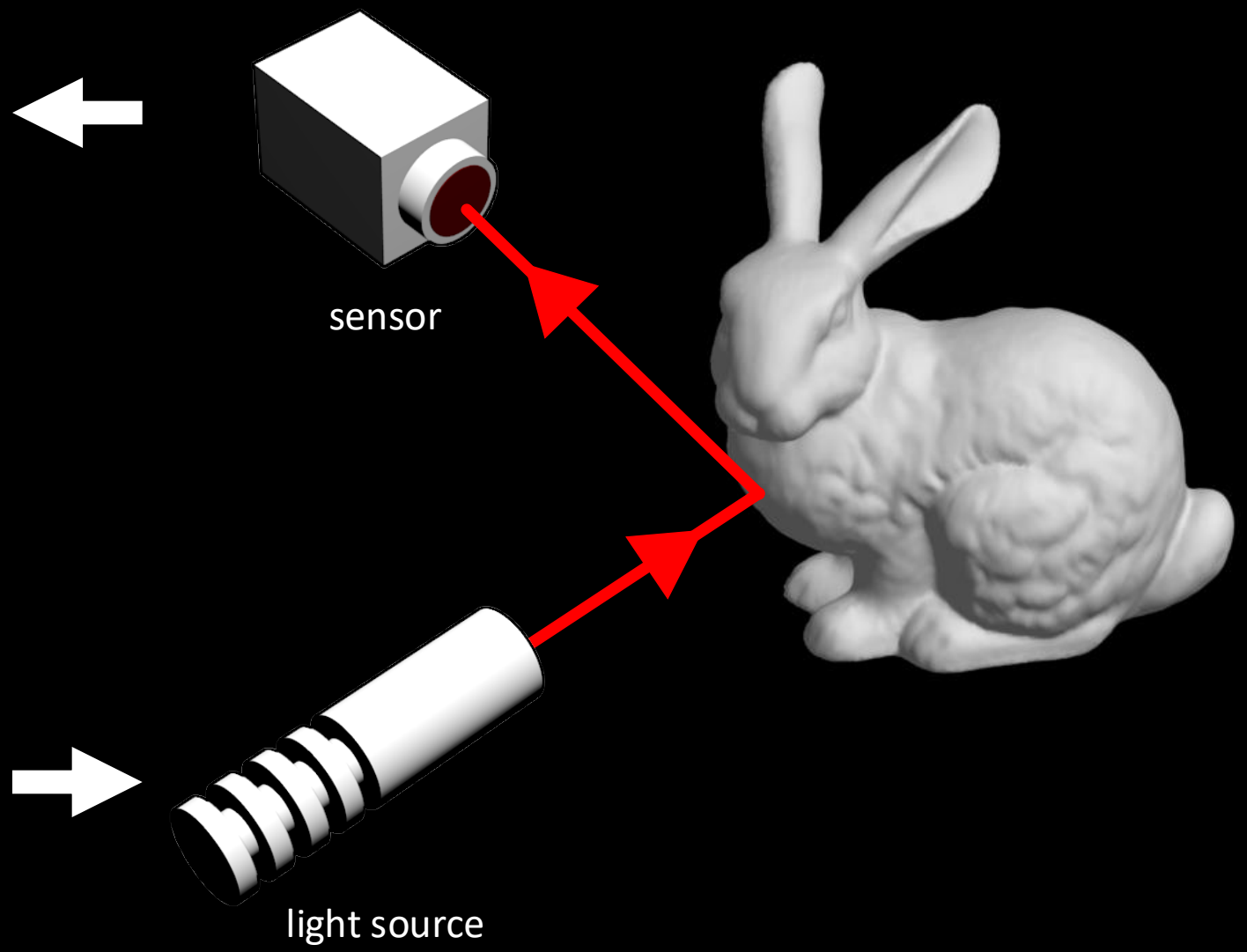
direct and **indirect** time-of-flight sensors for transient imaging

Microsoft Kinect v2

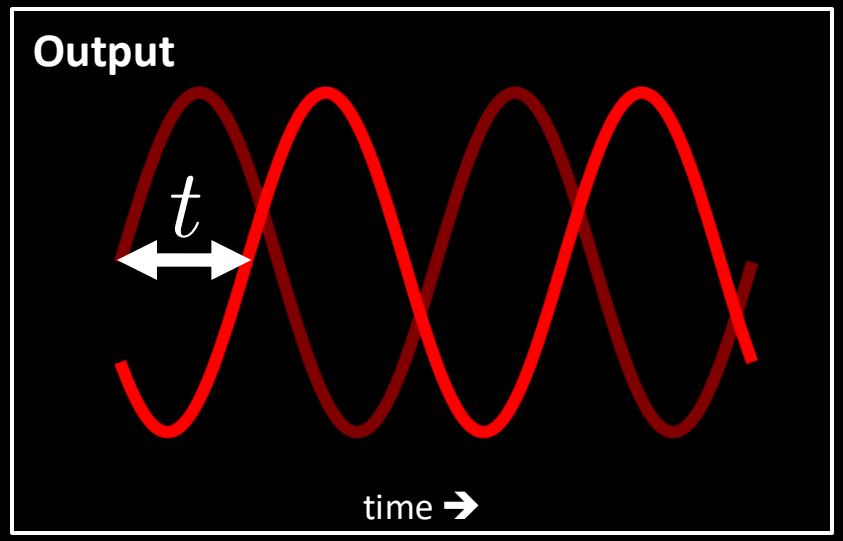
indirect time-of-flight principle

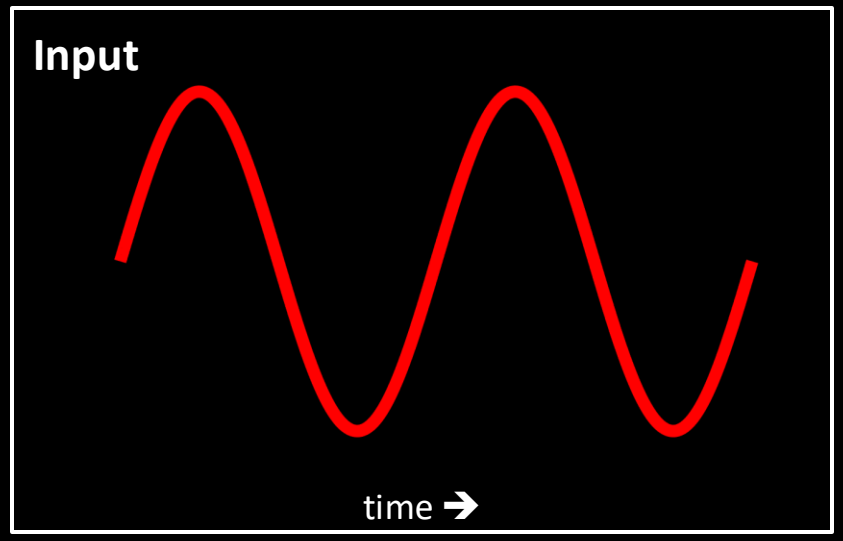


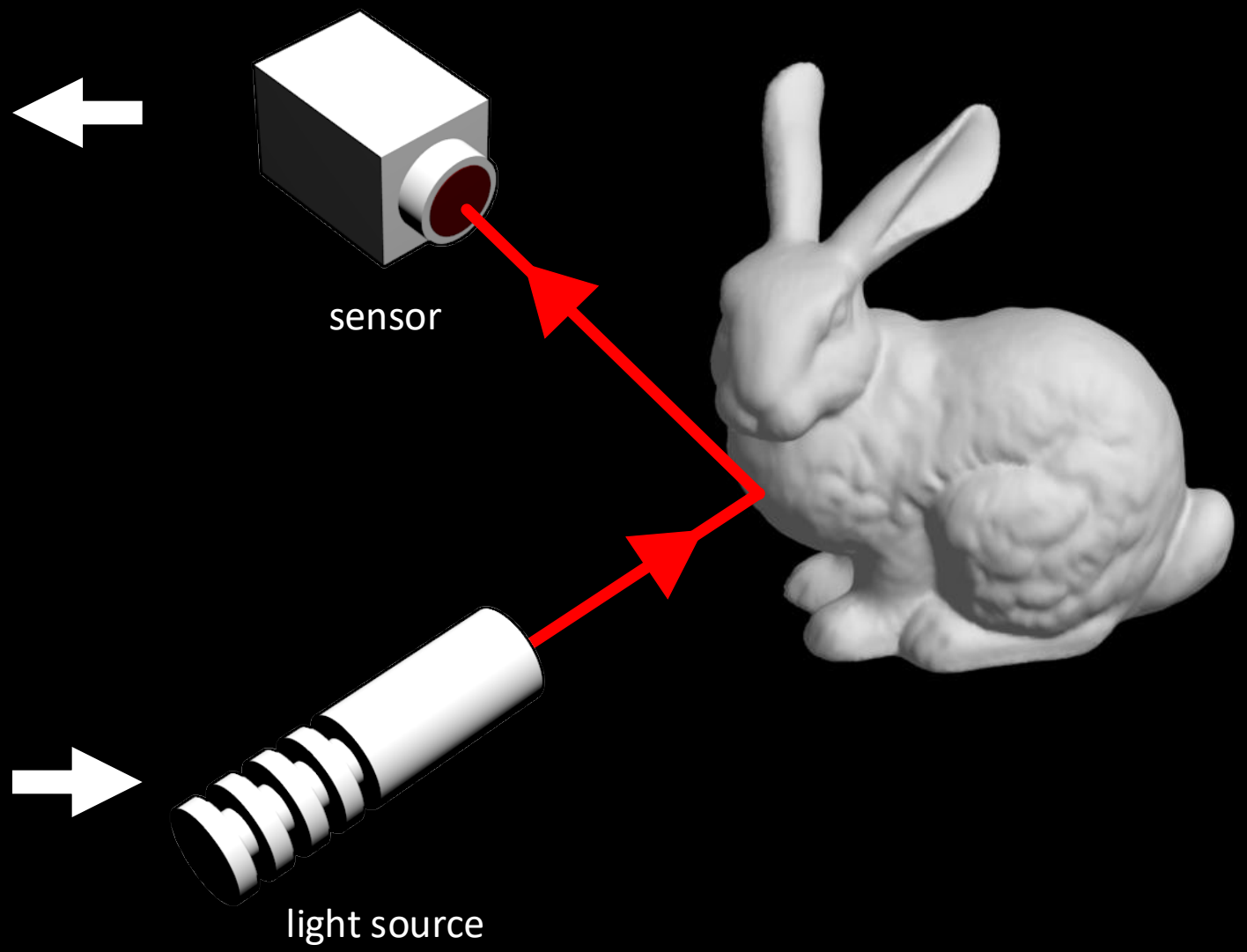




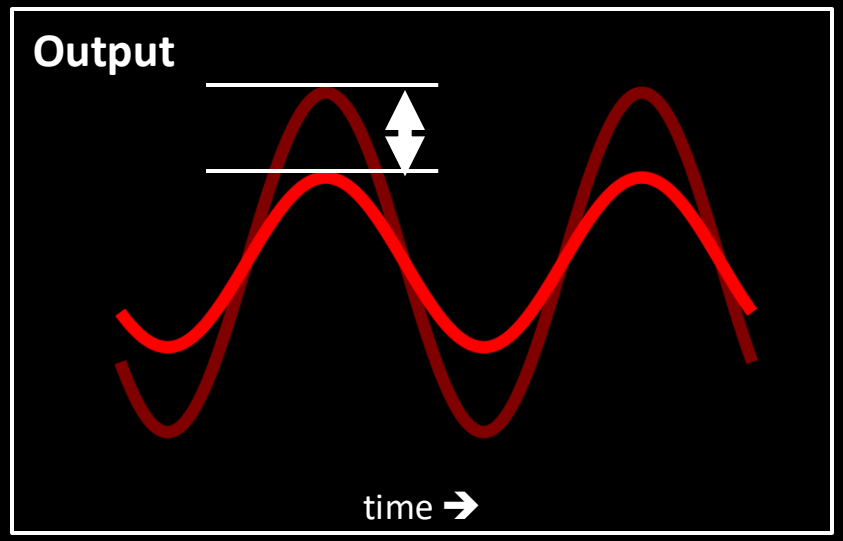
indirect time-of-flight principle

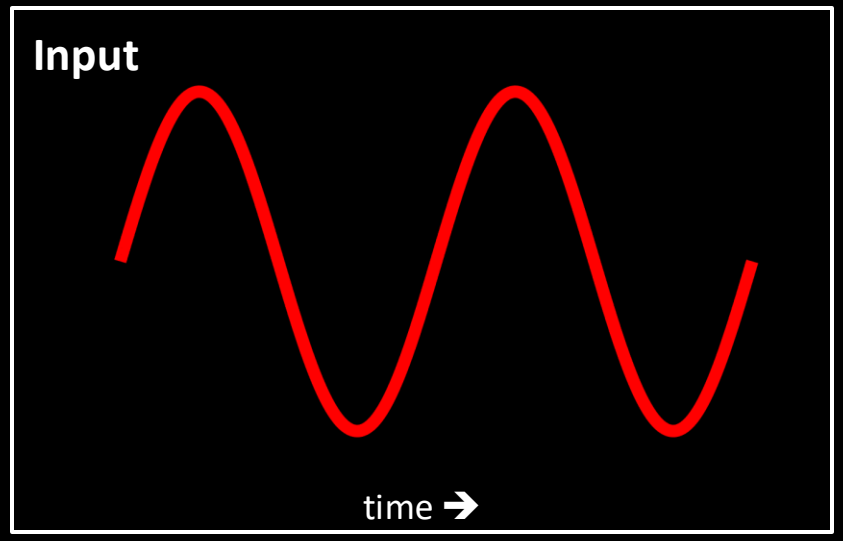


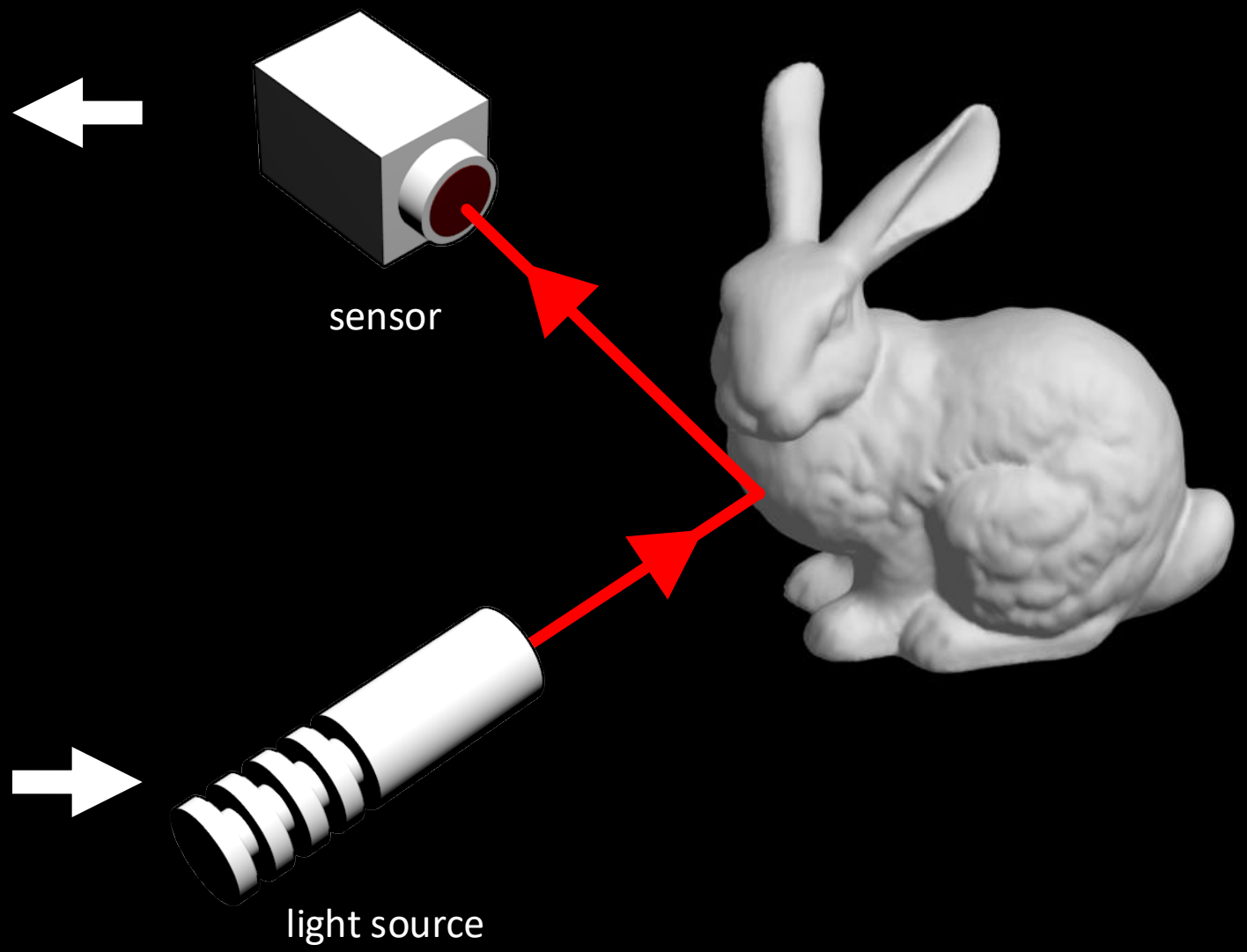




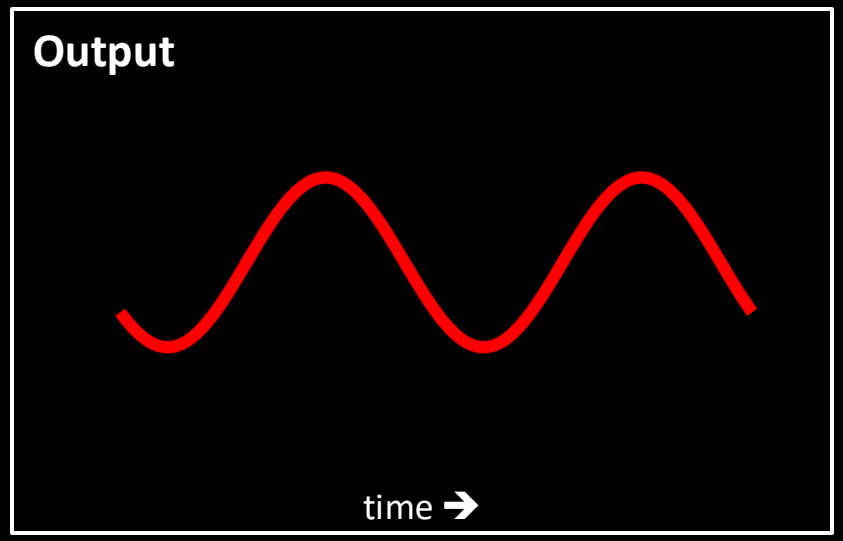
indirect time-of-flight principle

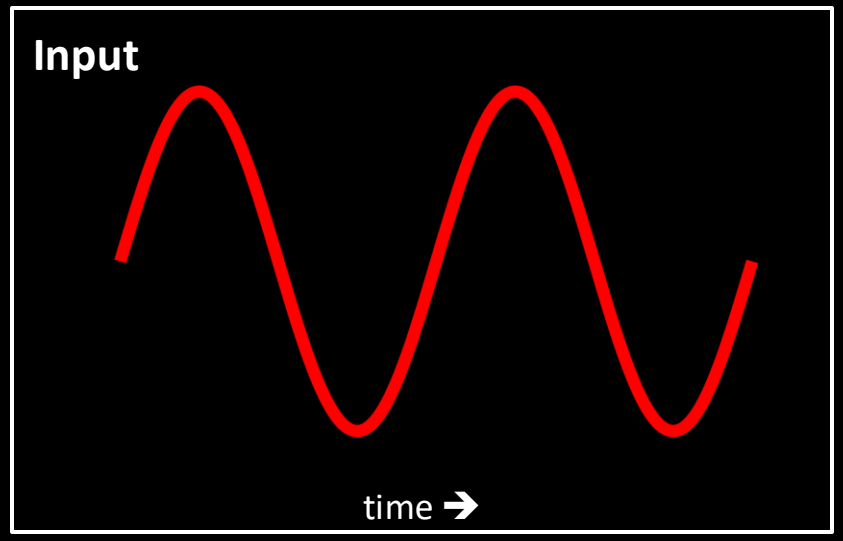


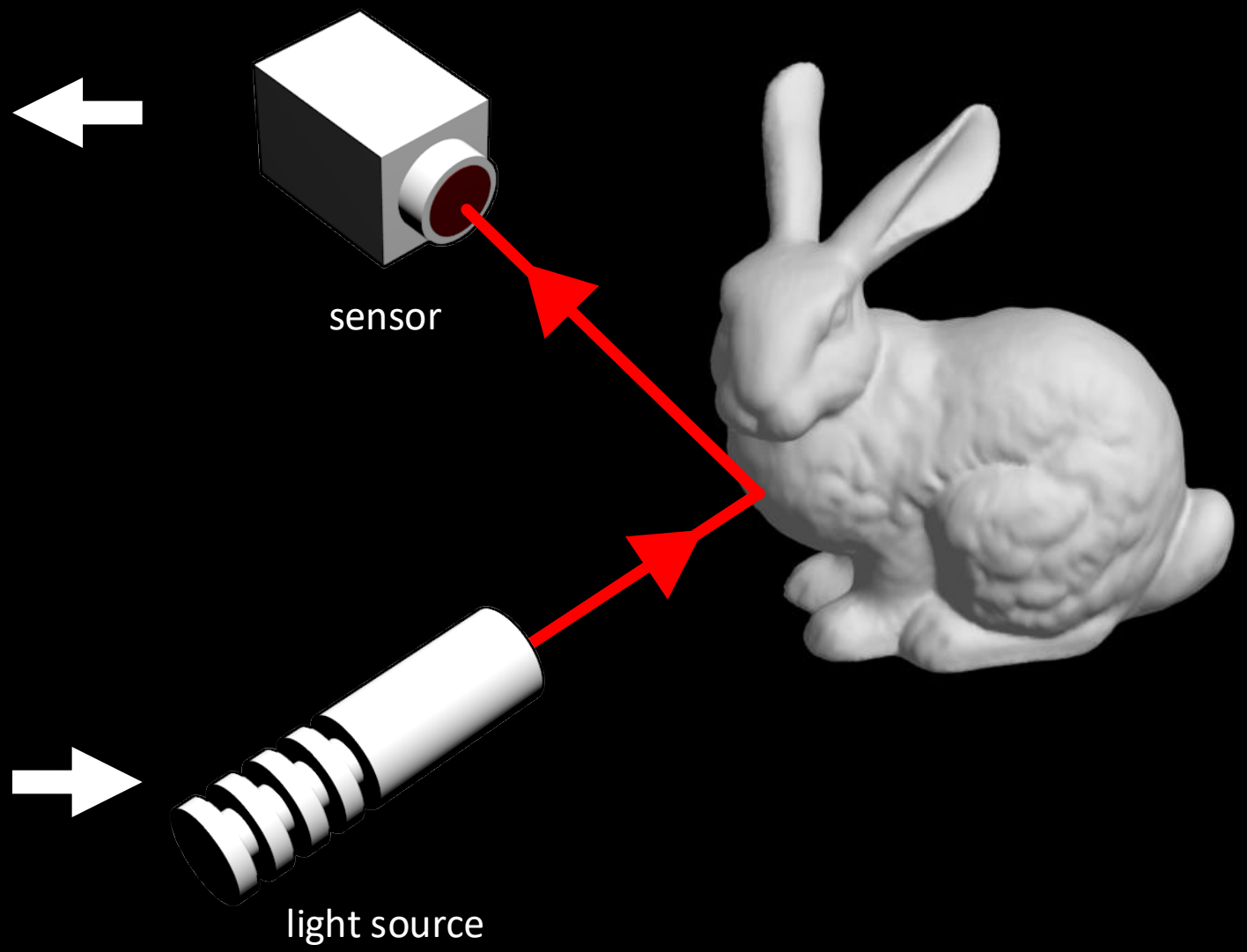




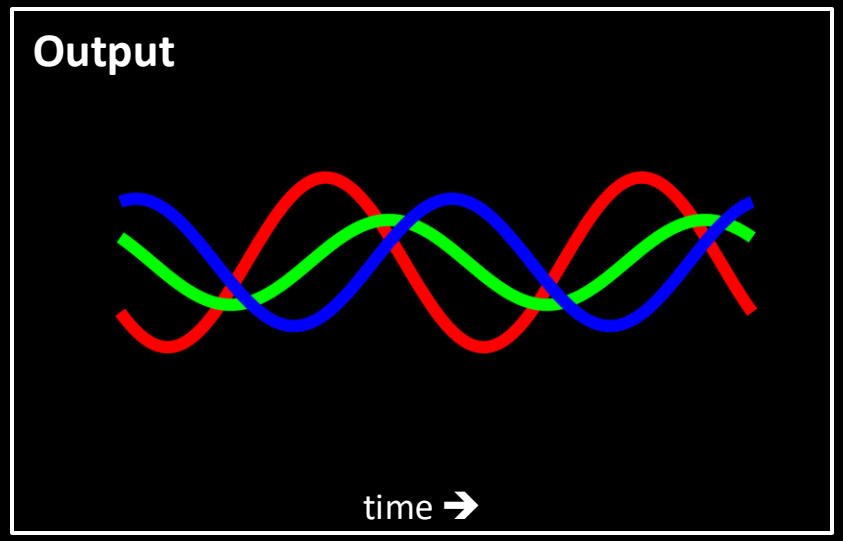
indirect time-of-flight principle

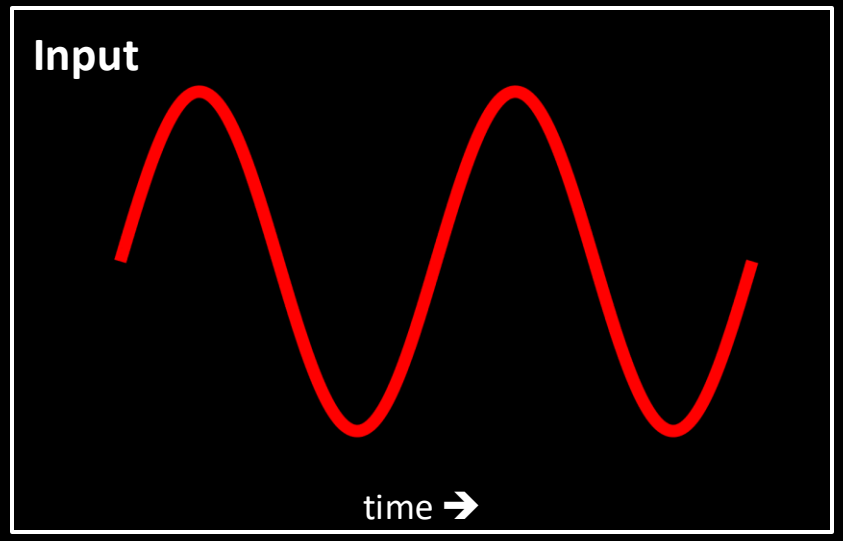


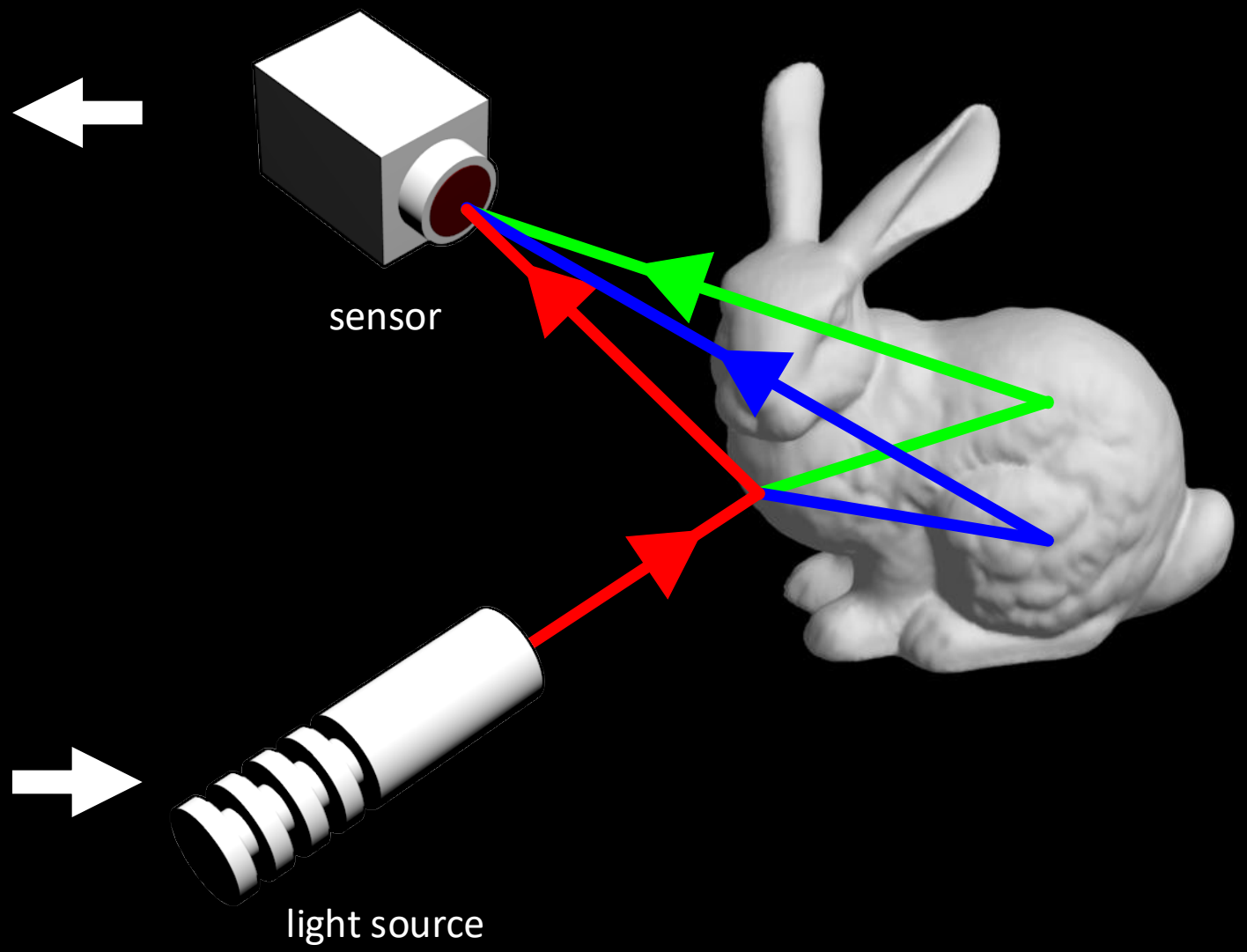




indirect time-of-flight principle







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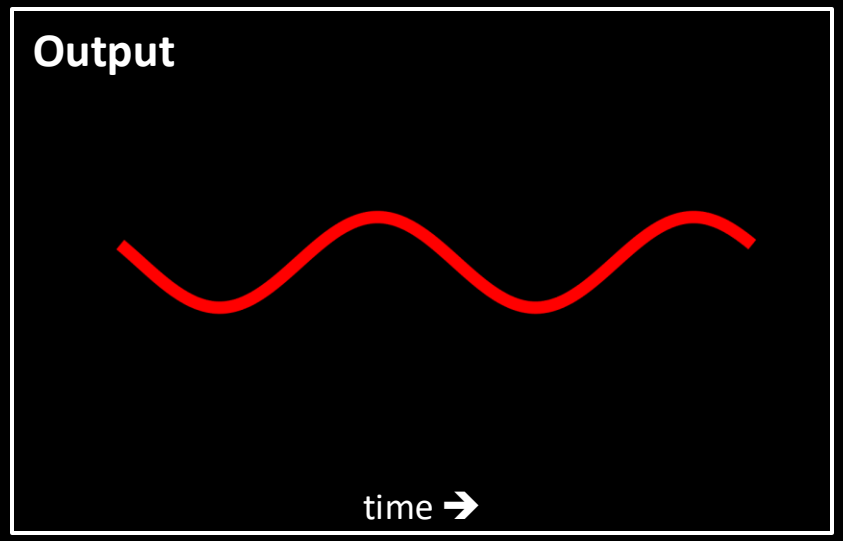

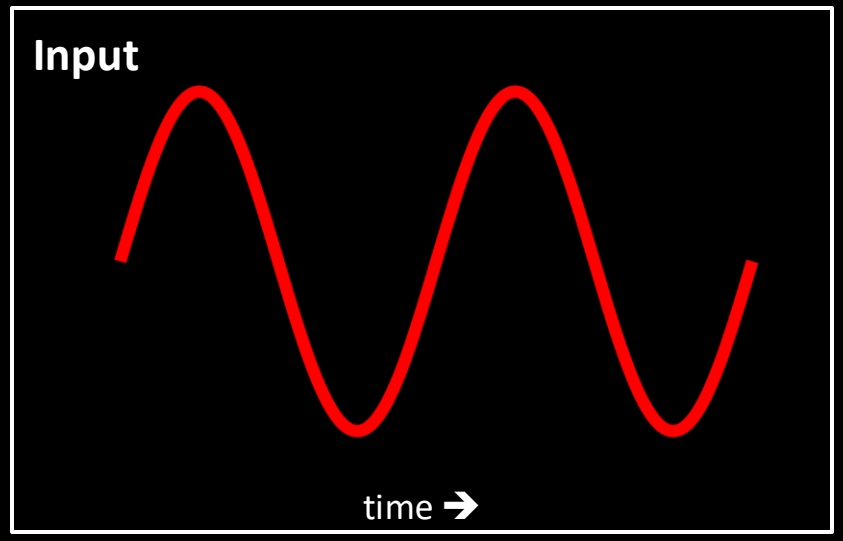

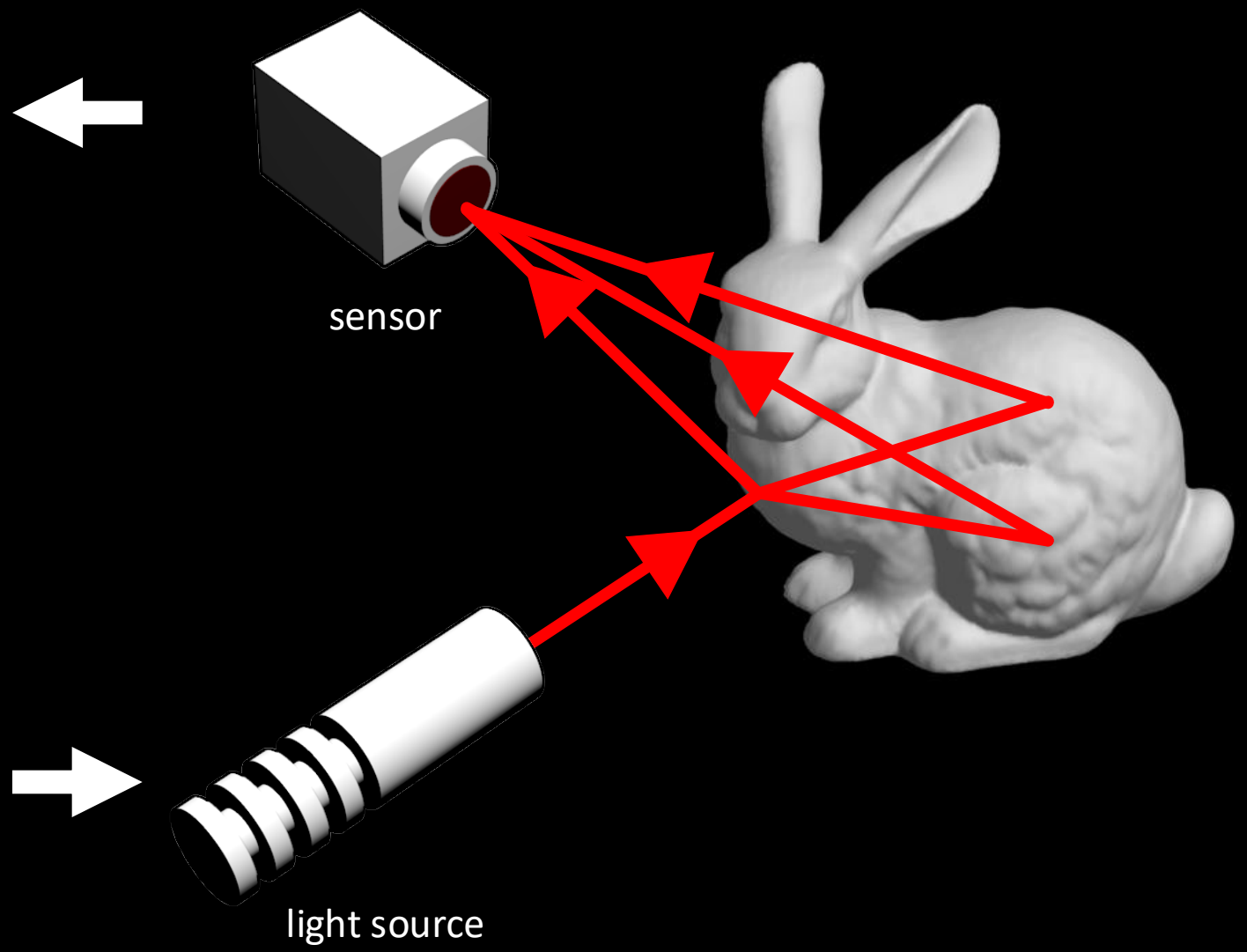

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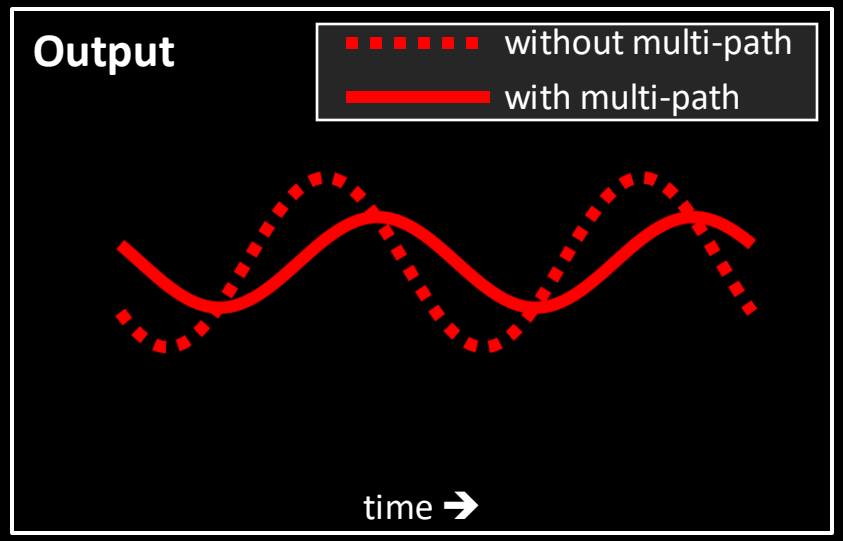
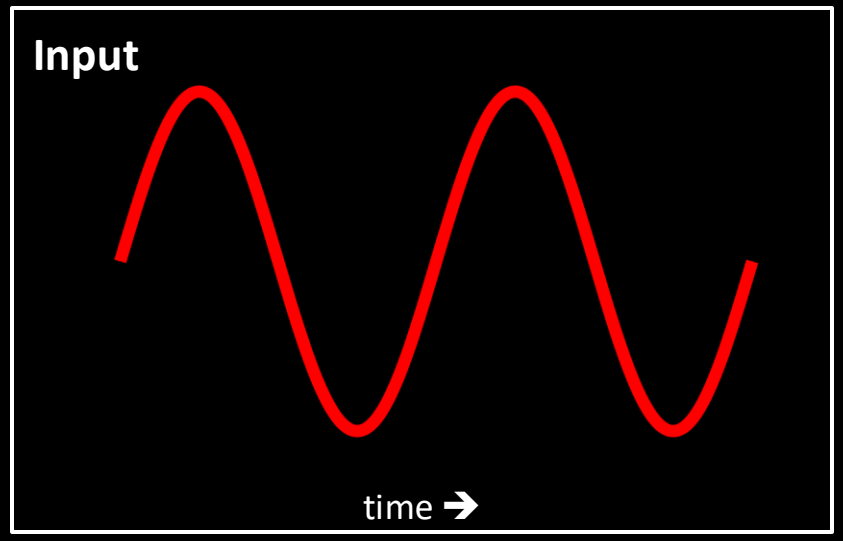
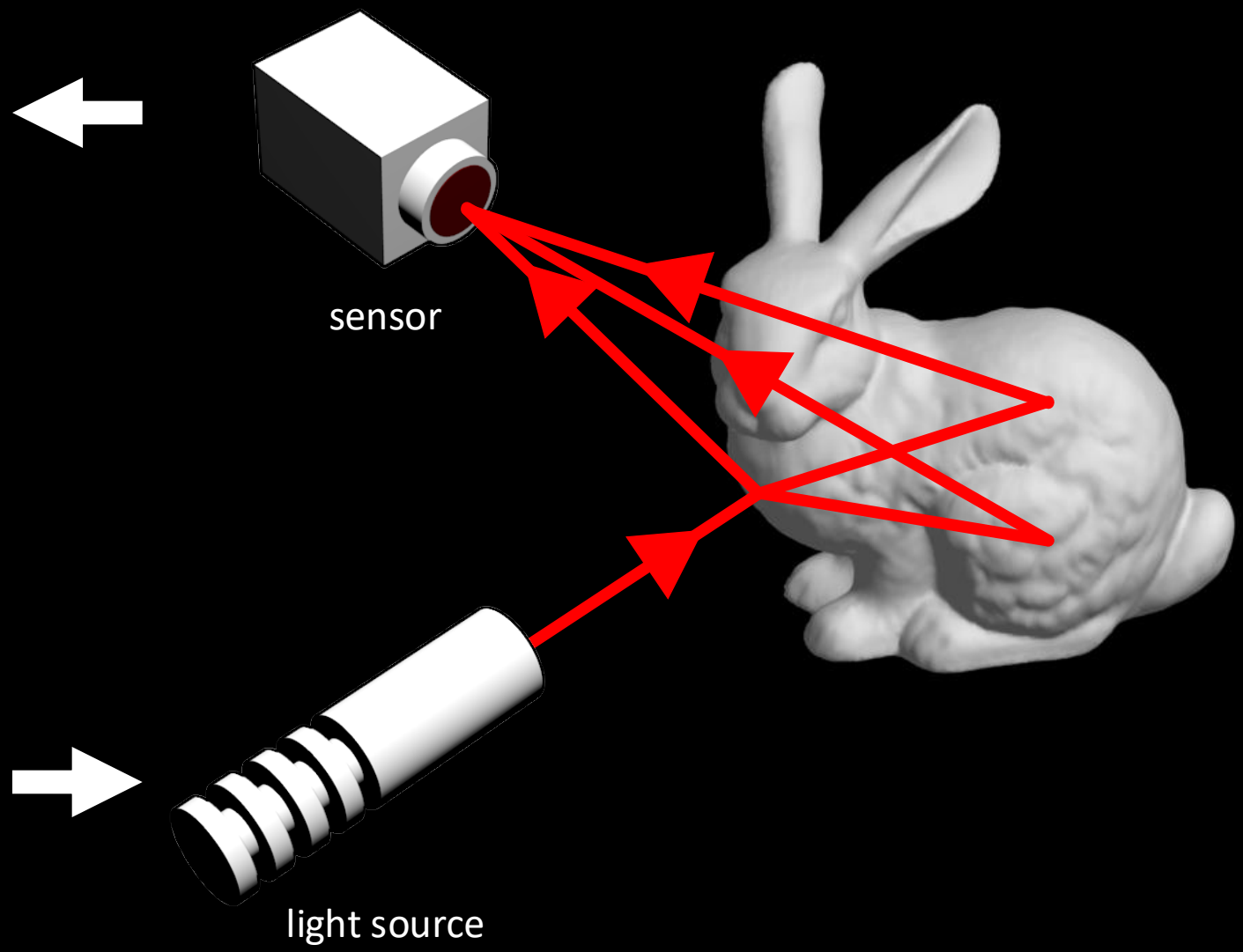
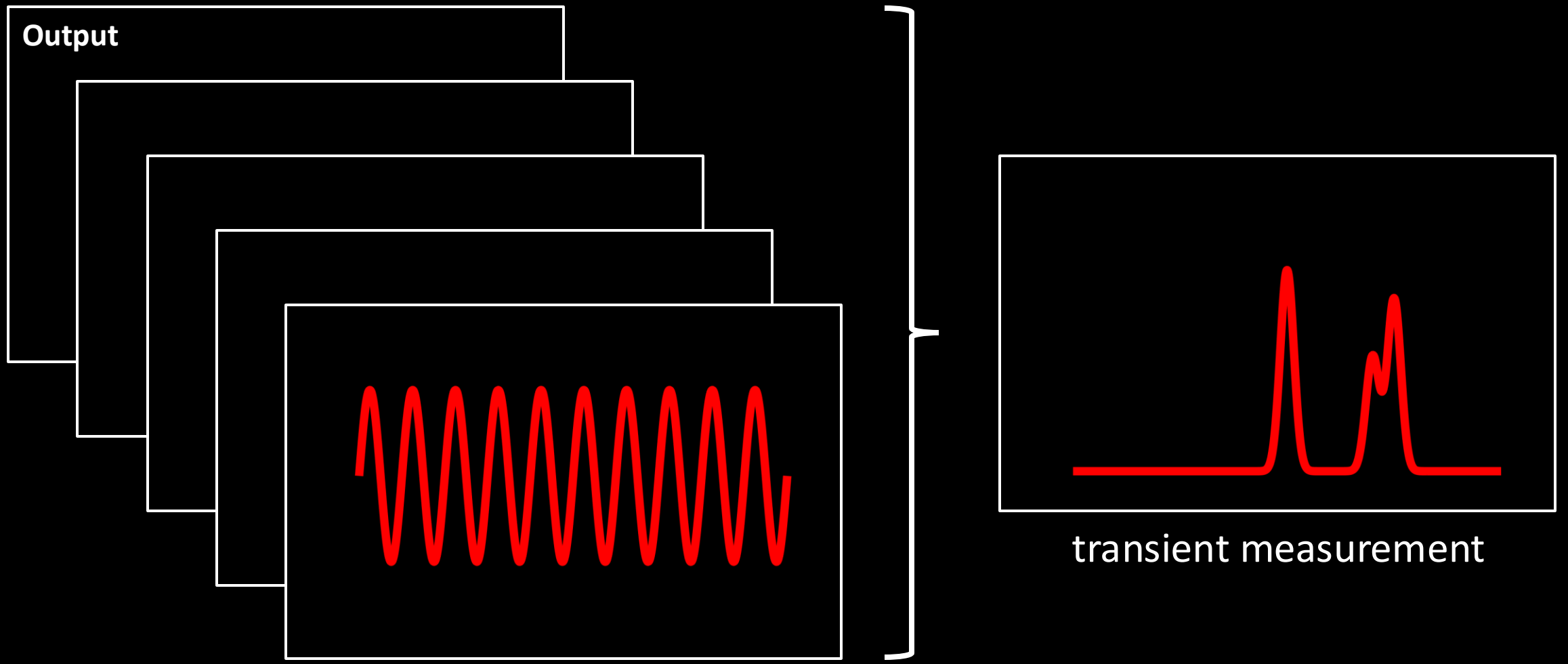






indirect time-of-flight principle



"Low-budget Transient Imaging using Photonic Mixer Devices" [Heide et al., 2013]

transient sensing technologies

optical coherence tomography	streak camera	single-photon avalanche diodes	time-of-flight cameras	avalanche photodiode	
1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	100 picosecond (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)	**temporal resolution**
quadrillion fps	trillion fps	10 billion fps	billion fps	100 million fps	**frame rate**
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)	**distance travelled**

Slide by Ioannis Gkioulekas

transient sensing technologies

optical coherence tomography	streak camera	single-photon avalanche diodes	time-of-flight cameras	avalanche photodiode	
	(direct)	(direct)		(direct)	
1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	100 picosecond (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)	**temporal resolution**
quadrillion fps	trillion fps	10 billion fps	billion fps	100 million fps	**frame rate**
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)	**distance travelled**

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transient sensing technologies

optical coherence tomography	streak camera				
	(direct)				
1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)				temporal resolution
quadrillion fps	trillion fps				frame rate
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)	distance travelled

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transient sensing technologies

optical coherence tomography	streak camera	**single-photon avalanche diodes**	time-of-flight cameras	avalanche photodiode	
		(direct)		(direct)	
		100 picosecond (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)	**temporal resolution**
		10 billion fps	billion fps	100 million fps	**frame rate**
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)	**distance travelled**

Micro Photon Devices

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transient sensing technologies

optical coherence tomography	streak camera	single-photon avalanche diodes	time-of-flight cameras	avalanche photodiode	
	(direct)			(direct)	
1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	1		10 nanoseconds (10^{-8} secs)	**temporal resolution**
quadrillion fps	trillion fps			100 million fps	**frame rate**
1 micron (10^{-6} meters)	1 millimeter (10^{-3} meters)	(10^{-1} meters)	(10^{0} meters)	10 meters (10^{1} meters)	**distance travelled**

Velodyne VLS-128

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transient sensing technologies

optical coherence tomography	**streak camera**	**single-photon avalanche diodes**	**time-of-flight cameras**	**avalanche photodiode**	
(indirect)	(direct)	(direct)	(indirect)	(direct)	
1 femtosecond (10^{-15} secs)	1 picosecond (10^{-12} secs)	100 picosecond (10^{-10} secs)	1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)	**temporal resolution**
quadrillion fps	trillion fps	10 billion fps	billion fps	100 million fps	**frame rate**
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)	**distance travelled**

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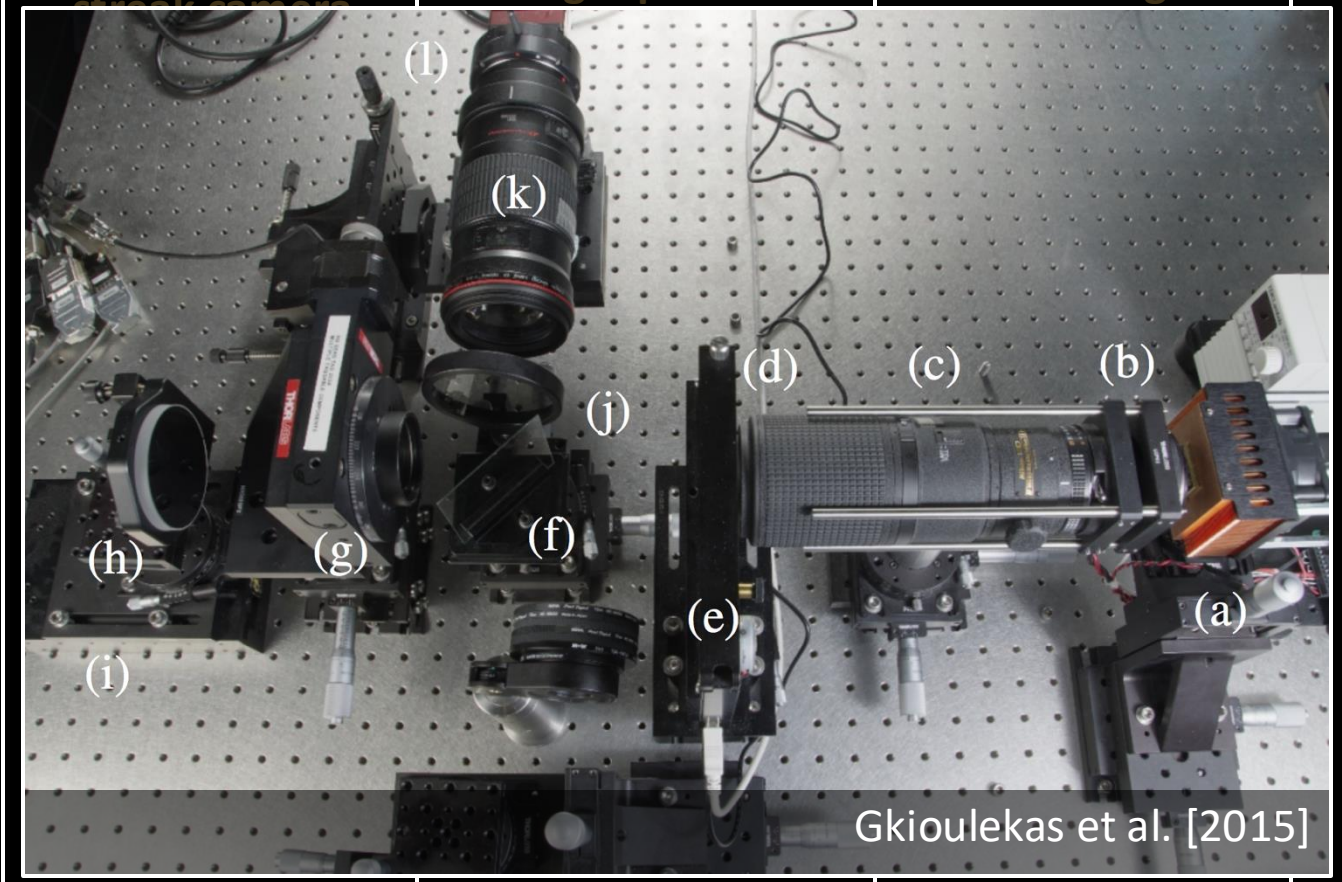
transient sensing technologies

optical coherence tomography	streak camera	single-photon	time-of-flight	avalanche photodiode	
(indirect)				(direct)	
1 femtosecond (10^{-15} secs)				10 nanoseconds (10^{-8} secs)	**temporal resolution**
quadrillion fps				100 million fps	**frame rate**
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)	**distance travelled**



Gkioulekas et al. [2015]

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transient sensing technologies

optical coherence tomography	streak camera	single-photon avalanche diodes	time-of-flight cameras	avalanche photodiode	
(indirect)	(direct)	(direct)	(indirect)	(direct)	
 Heide et al. [2013]			1 nanosecond (10^{-9} secs)	10 nanoseconds (10^{-8} secs)	**temporal resolution**
			billion fps	100 million fps	**frame rate**
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)	**distance travelled**

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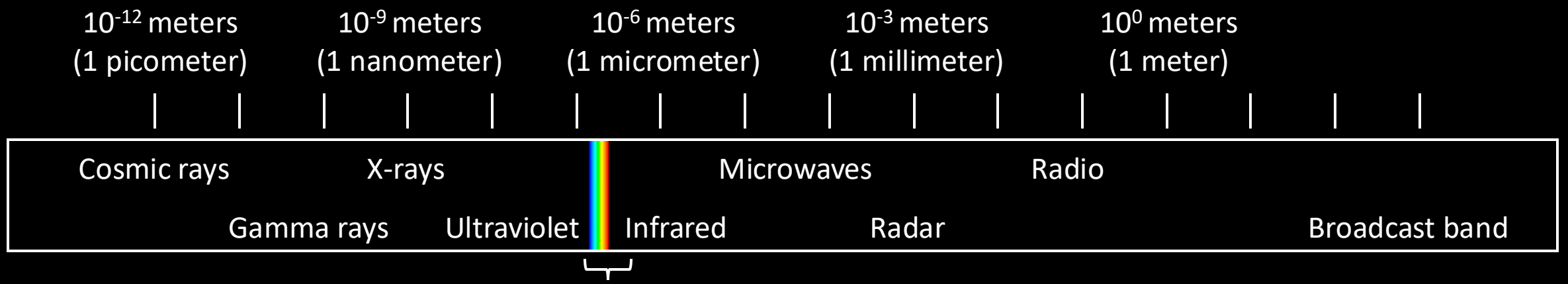
spectrum of transient sensing technologies



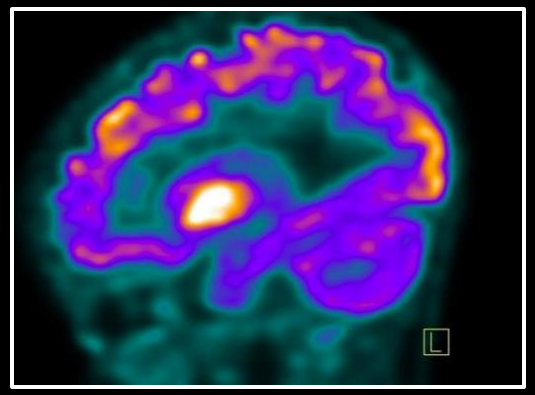
- **optical coherence tomography**
- **streak camera**
- **single-photon avalanche diodes**
- **time-of-flight cameras**
- **avalanche photodiode**

spectrum of transient sensing technologies

10^{-12} meters (1 picometer) | 10^{-9} meters (1 nanometer) | 10^{-6} meters (1 micrometer) | 10^{-3} meters (1 millimeter) | 10^{0} meters (1 meter)

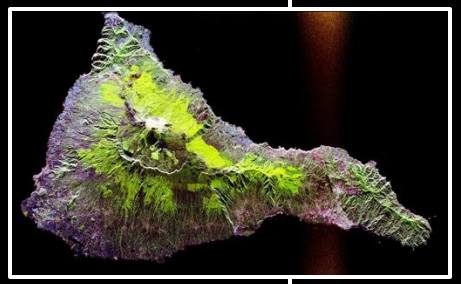
Cosmic rays | X-rays | Microwaves | Radio

Gamma rays | Ultraviolet | Infrared | Radar | Broadcast band

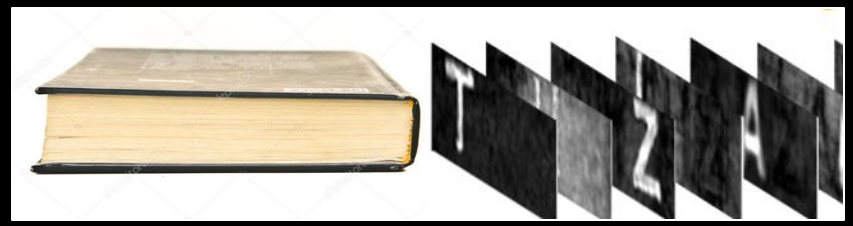


Positron Emission Tomography (PET) Scan

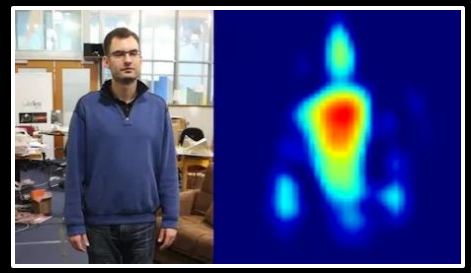
- optical coherence tomography
- streak camera
- single-photon avalanche diodes
- time-of-flight cameras
- avalanche photodiode



Synthetic Aperture Radar (SAR)



Terahertz Time-gated Imaging [Redo-Sanchez et al., 2015]

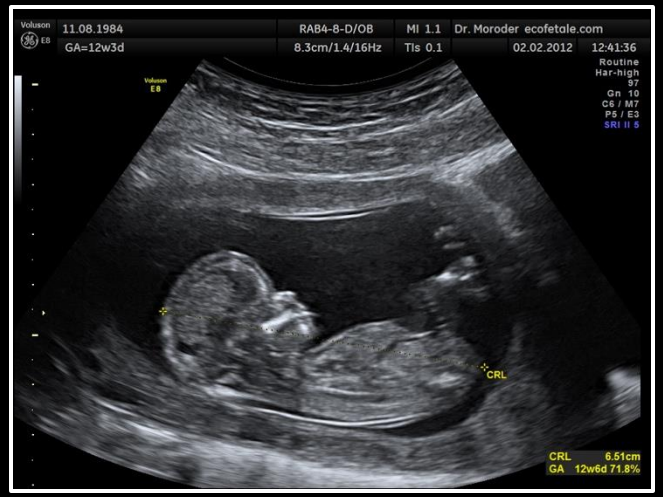


Seeing through Walls [Adib et al., 2015]

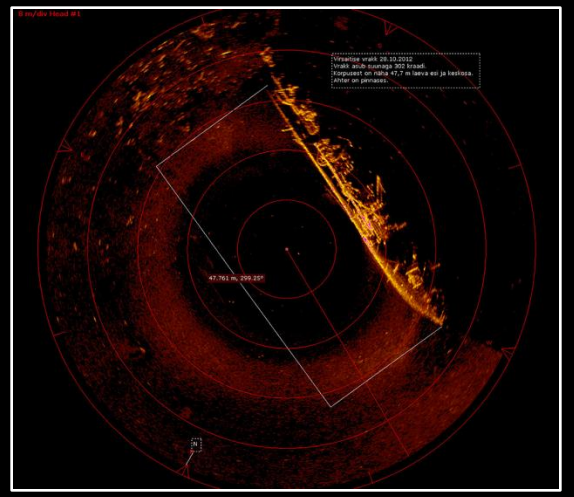
spectrum of transient sensing technologies

10^{-12} meters (1 picometer) | 10^{-9} meters (1 nanometer) | 10^{-6} meters (1 micrometer) | 10^{-3} meters (1 millimeter) | 10^{0} meters (1 meter)

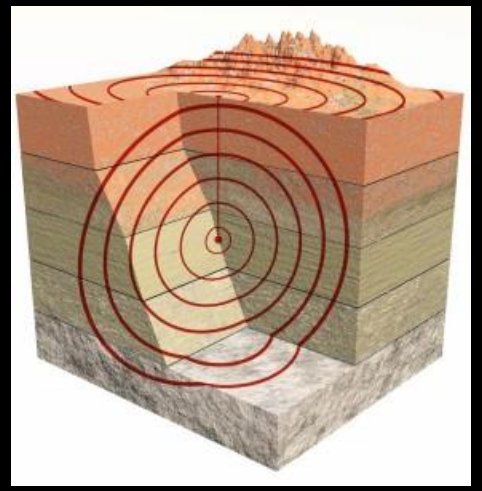
mechanical waves (e.g., acoustic, seismic)



Ultrasound Imaging



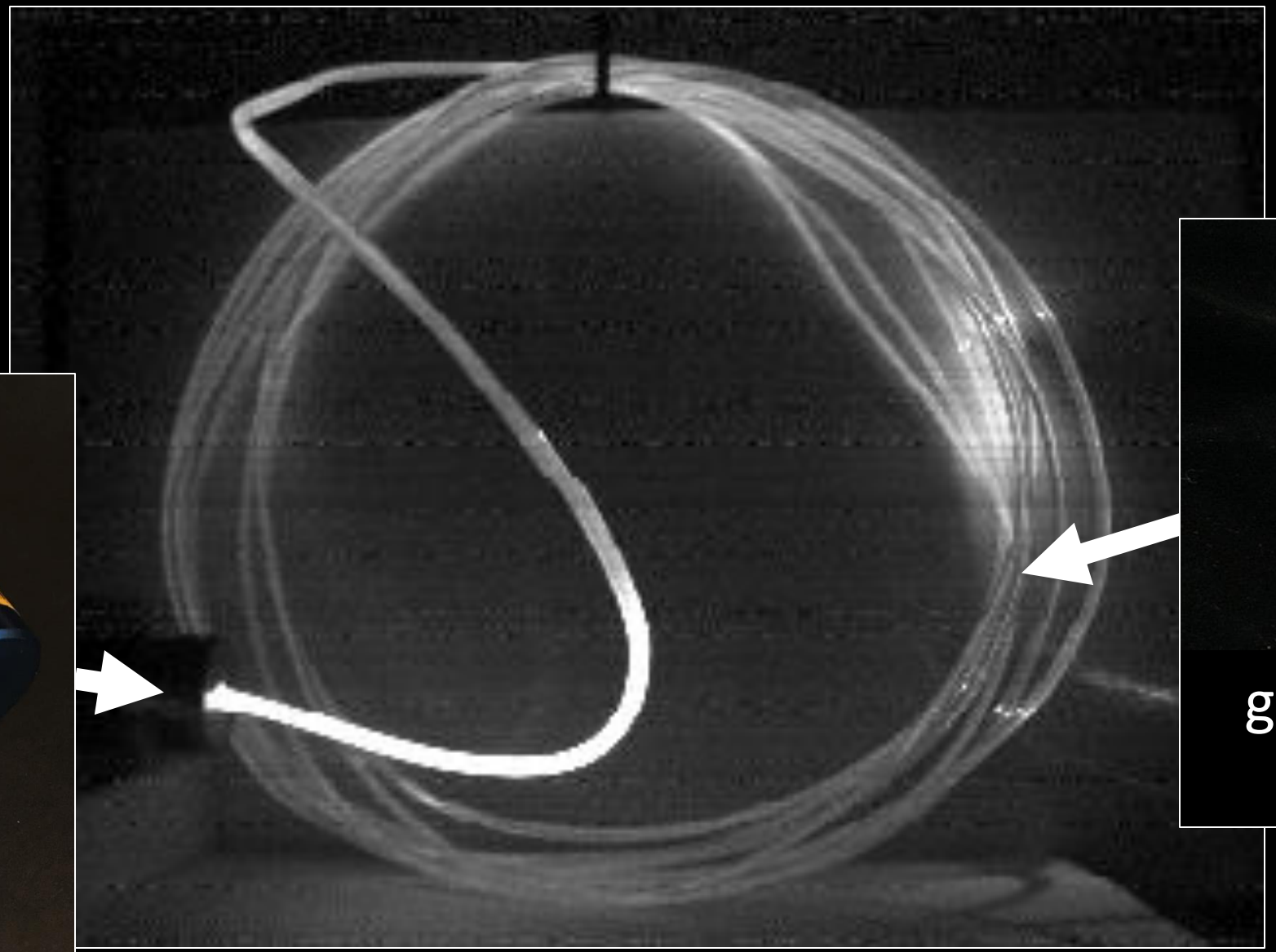
SONAR
(Sound Navigation and Ranging)

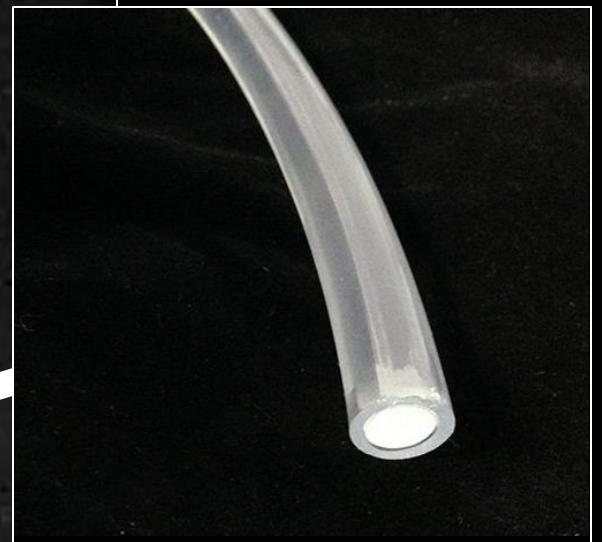


Seismic Imaging

Single-Photon Avalanche Diodes (SPADs)

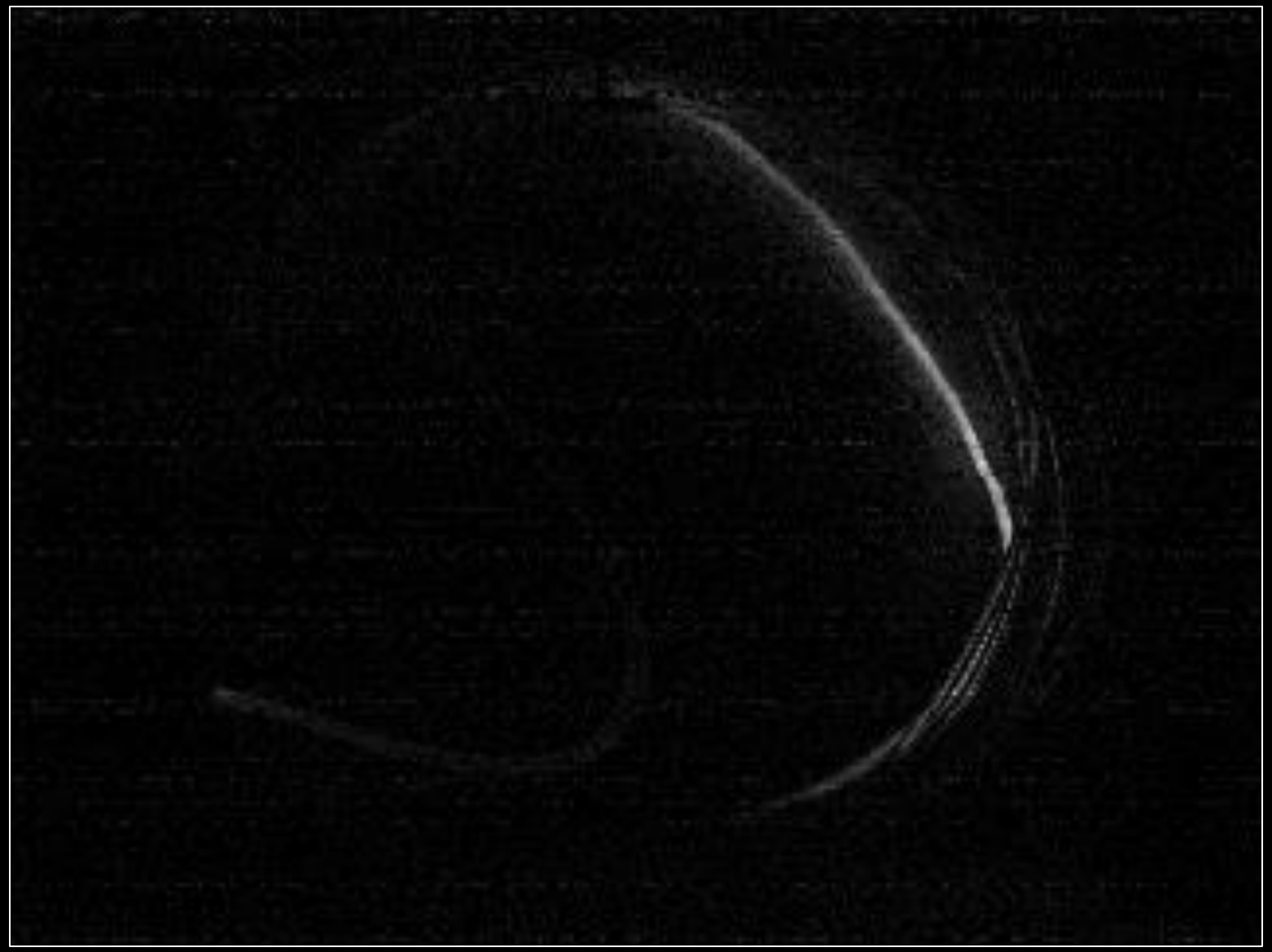
picosecond laser





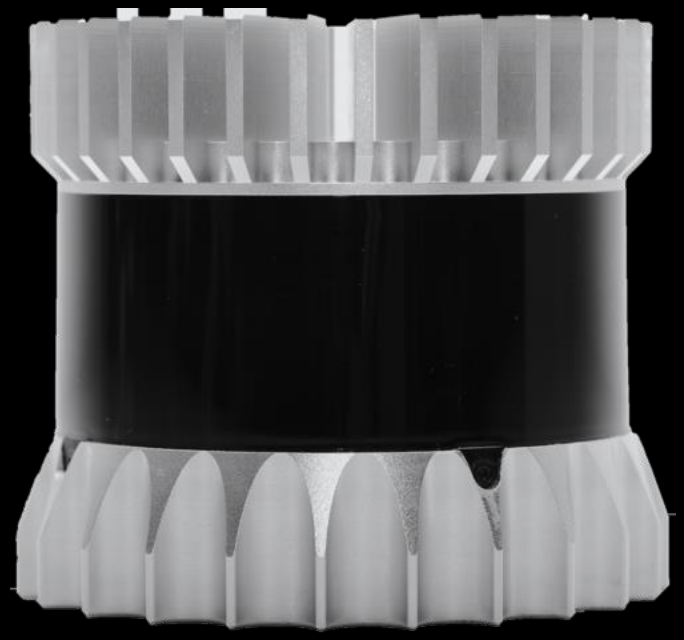
glowing fiber optic cable

regular image

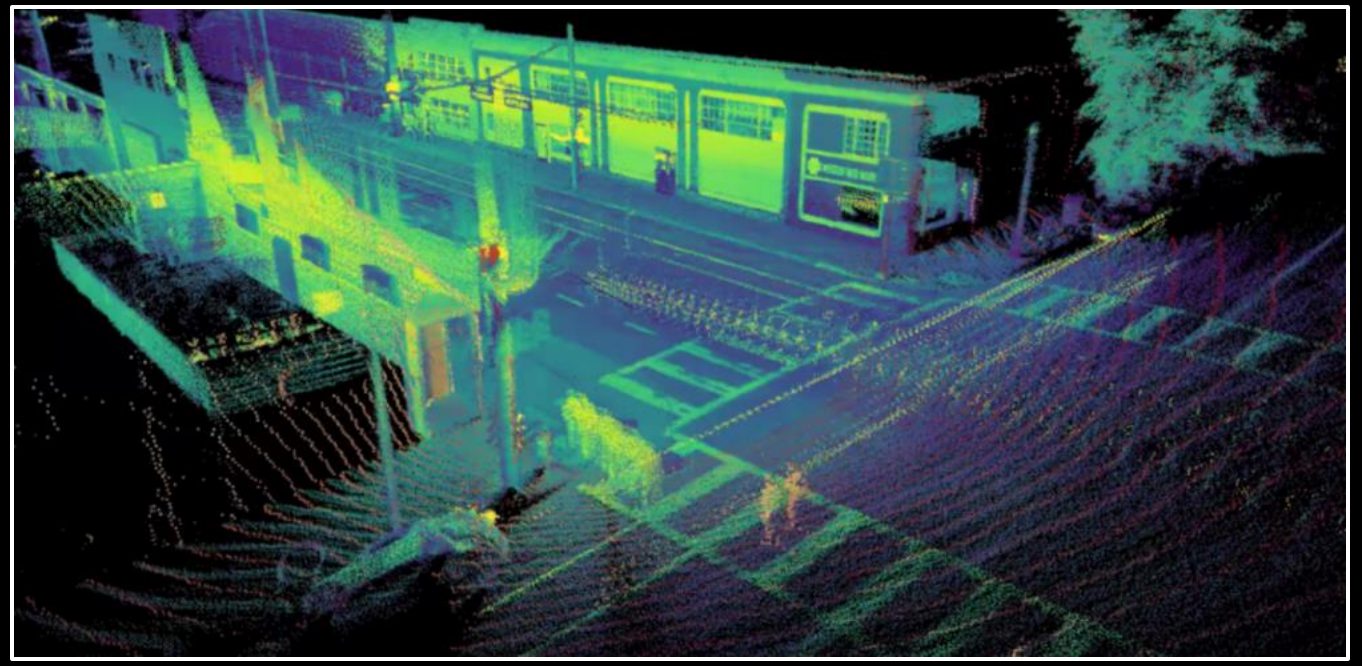


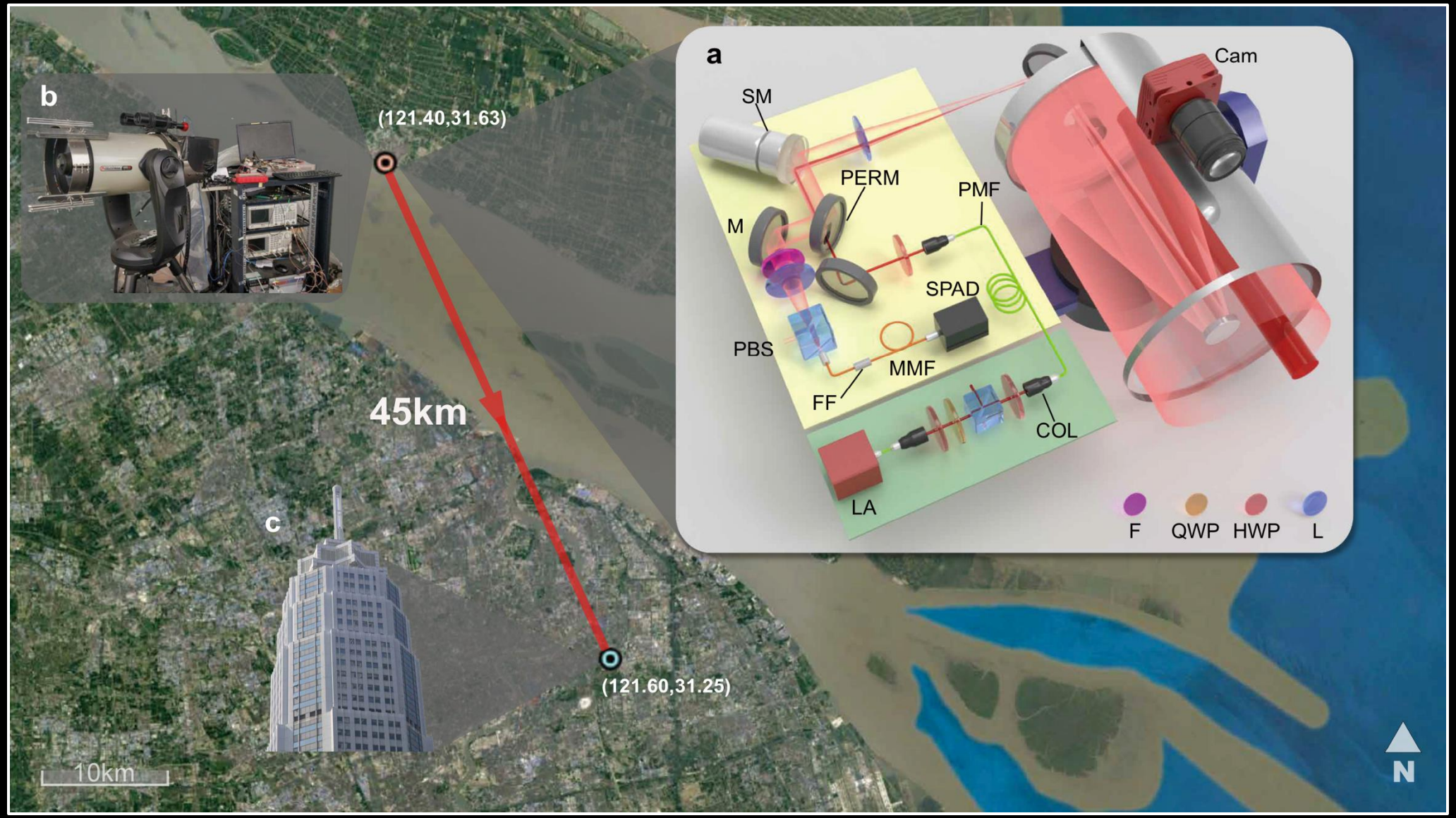
transient image

single-photon LIDARs



Ouster OS1-64

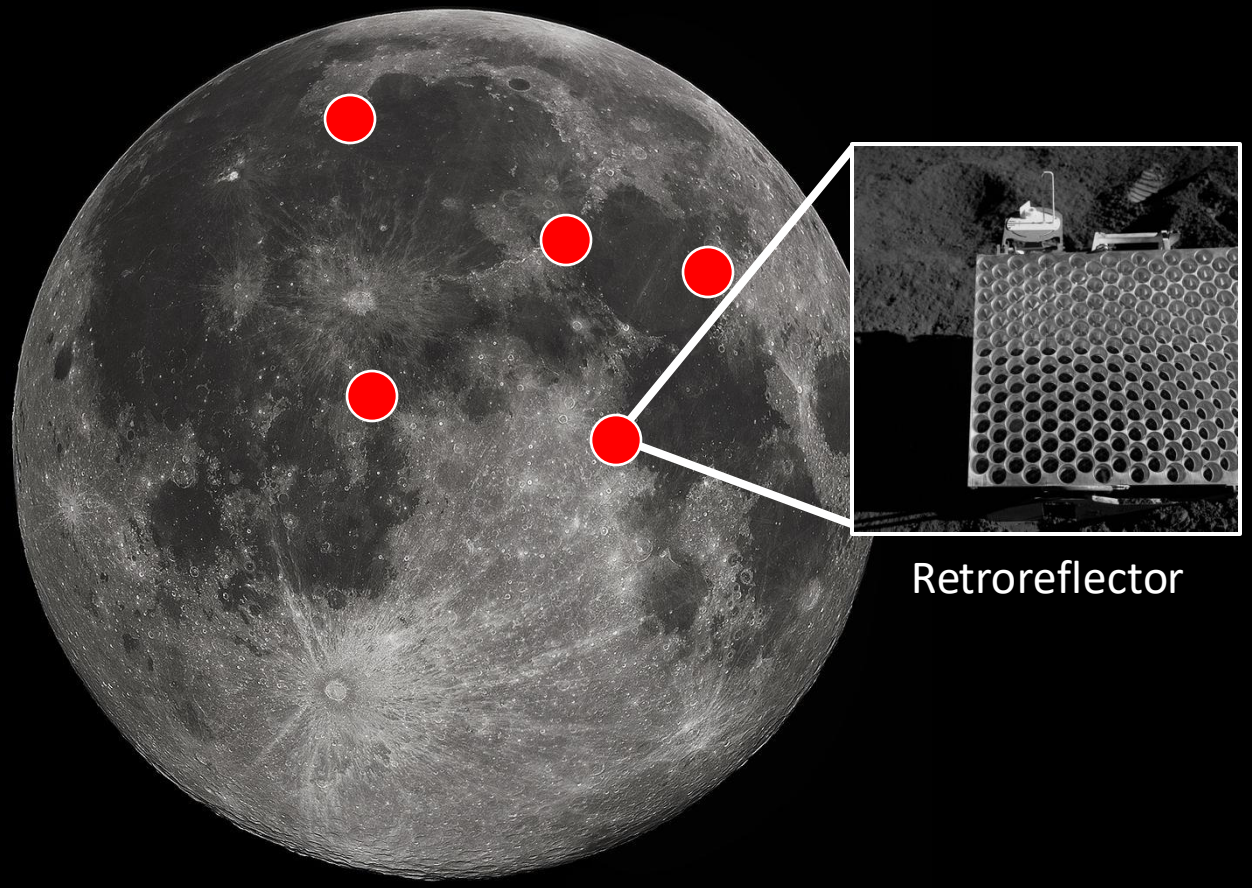




"Single-Photon Computational 3D Imaging at 45 km" [Li et al., 2019]

lunar & satellite laser ranging

International Laser Ranging Service (ILRS)

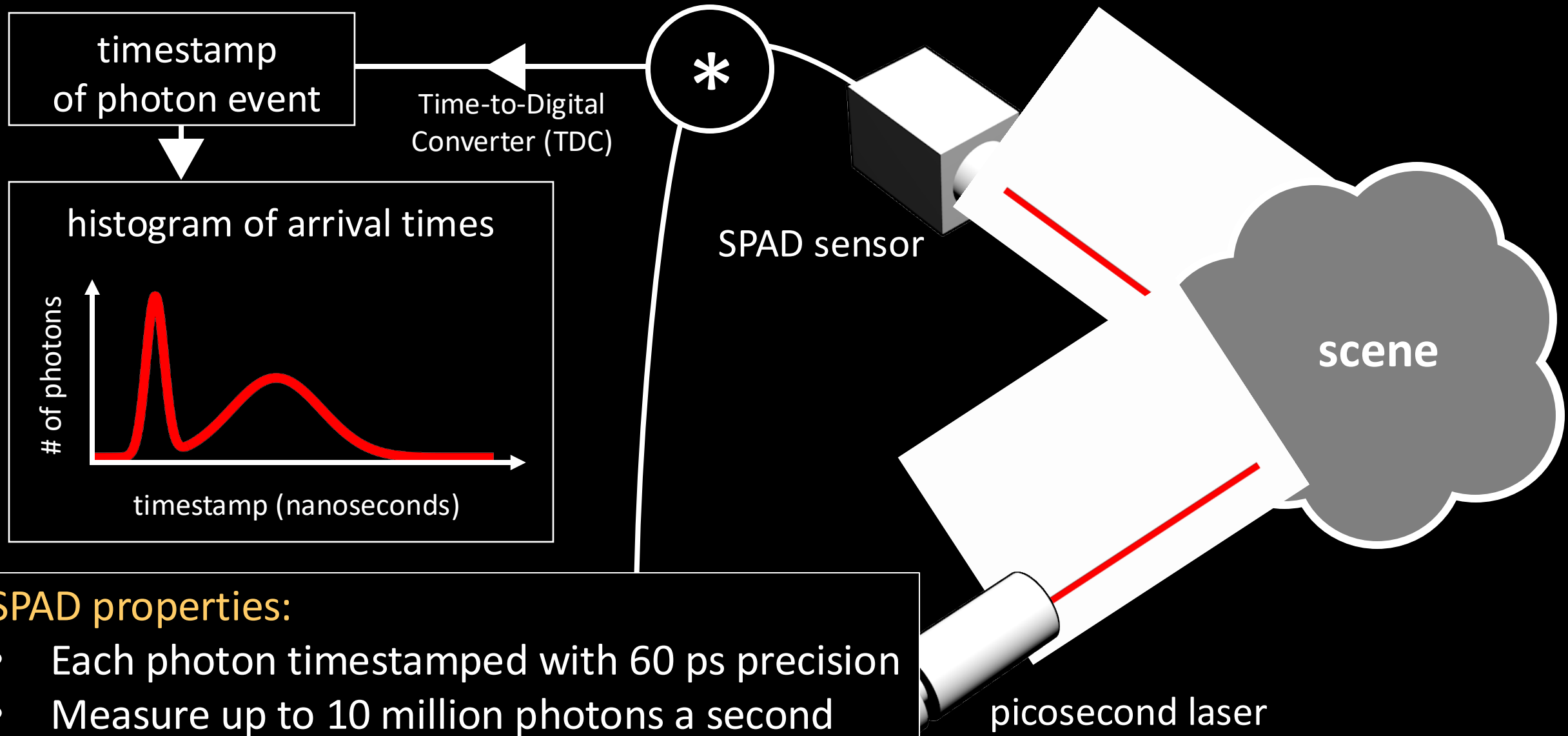


Retroreflector

Lunar Laser Ranging (LLR)

● - Location of Lunar Retroreflector

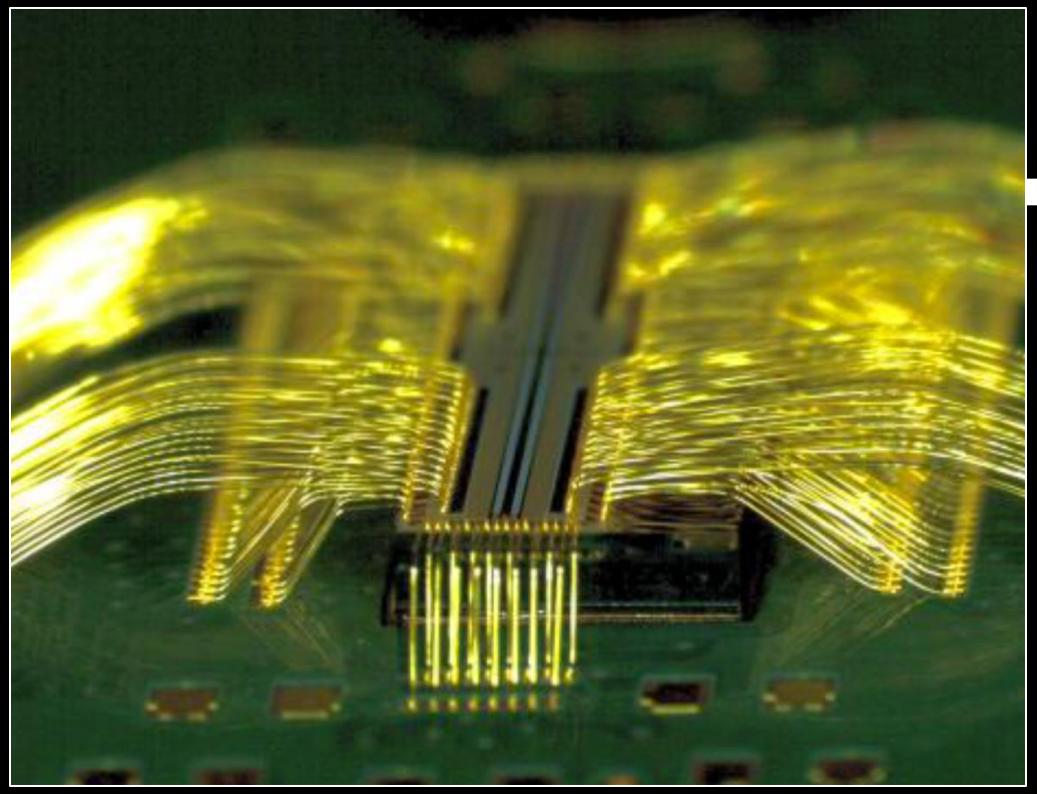
single-photon avalanche diode (SPAD)



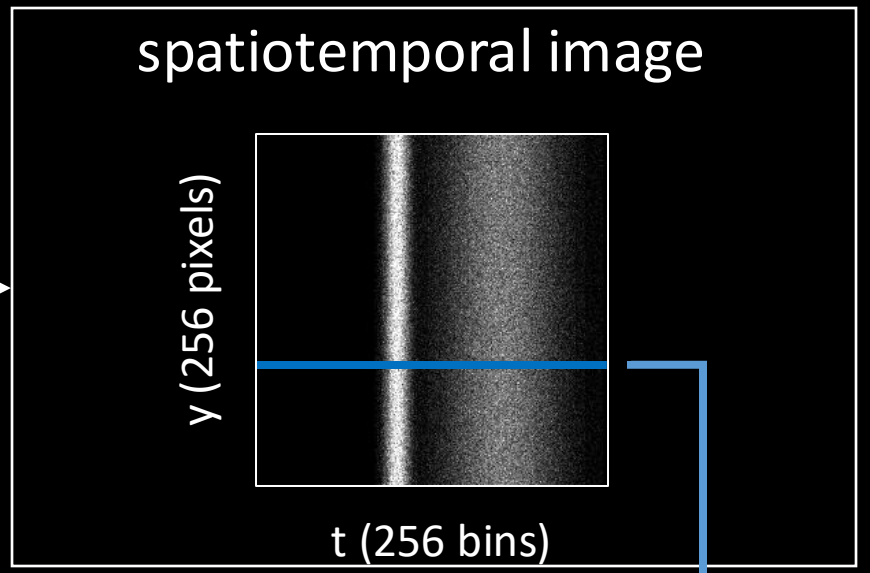
SPAD properties:

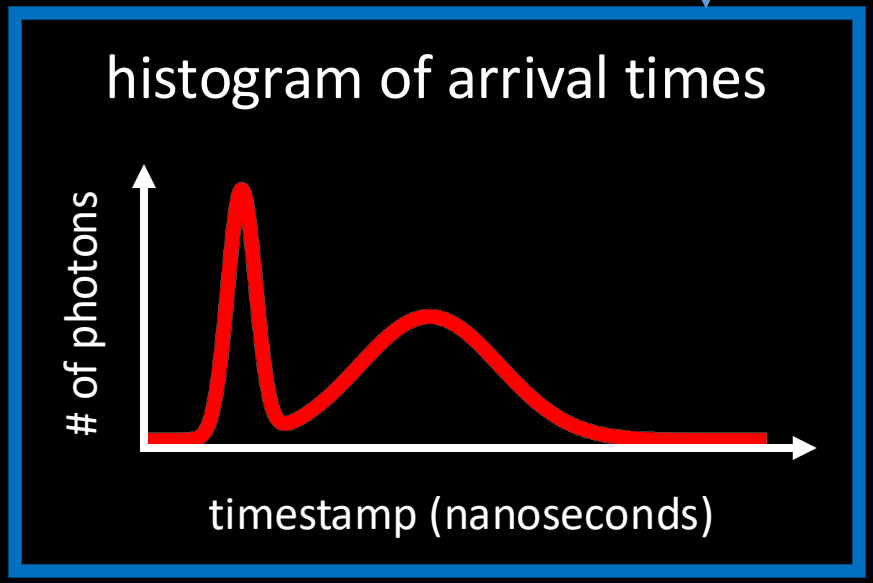
- Each photon timestamped with 60 ps precision
- Measure up to 10 million photons a second
- No electronic read noise

linear array of SPADs

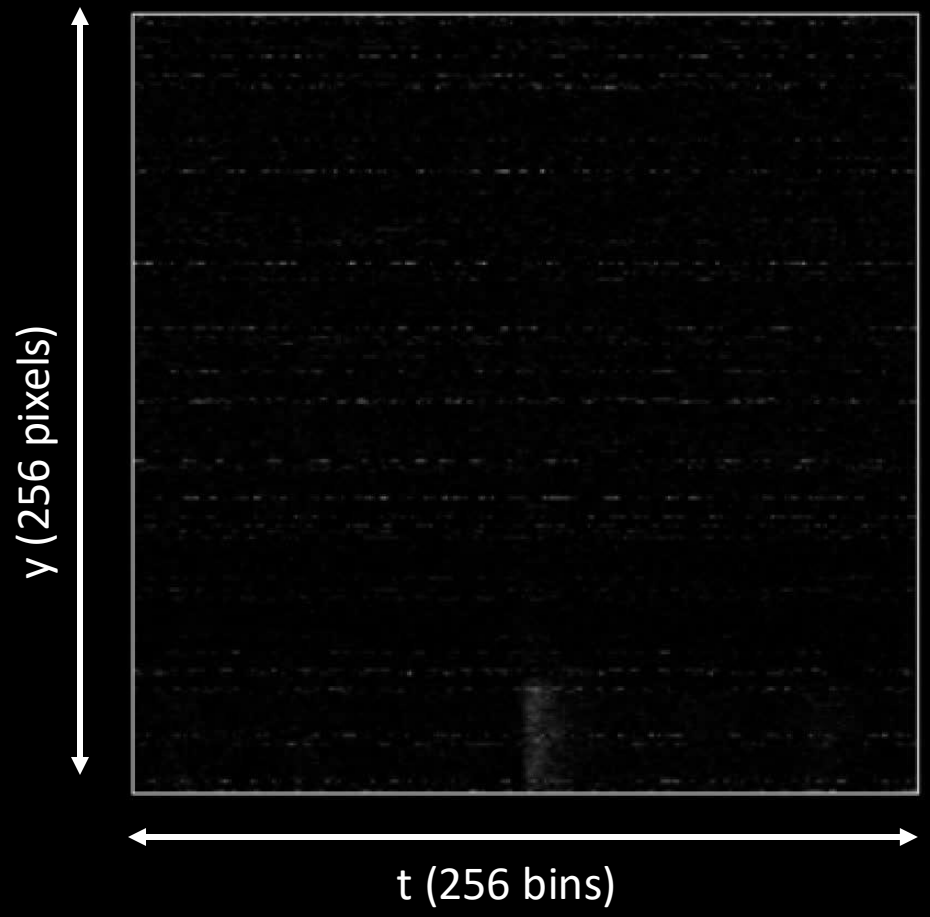


LinoSPAD from FastTree 3D

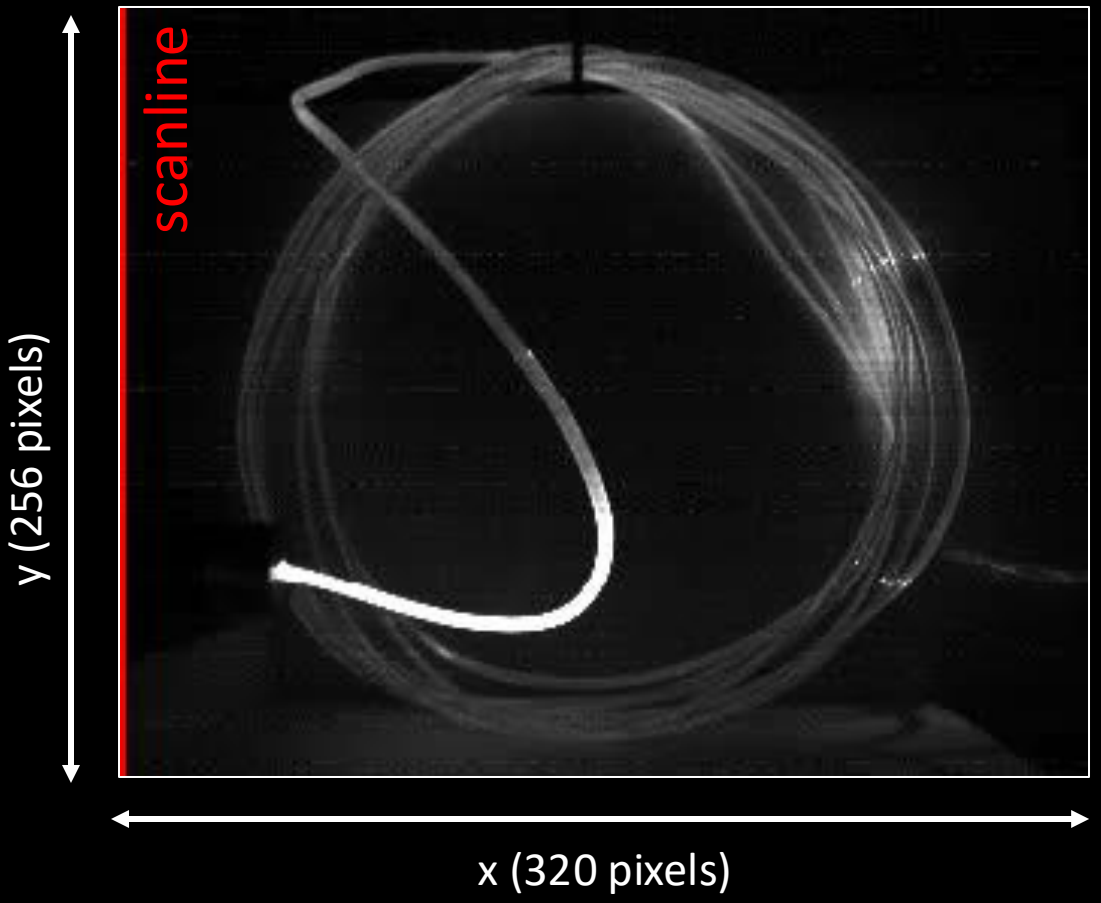




scanning procedure

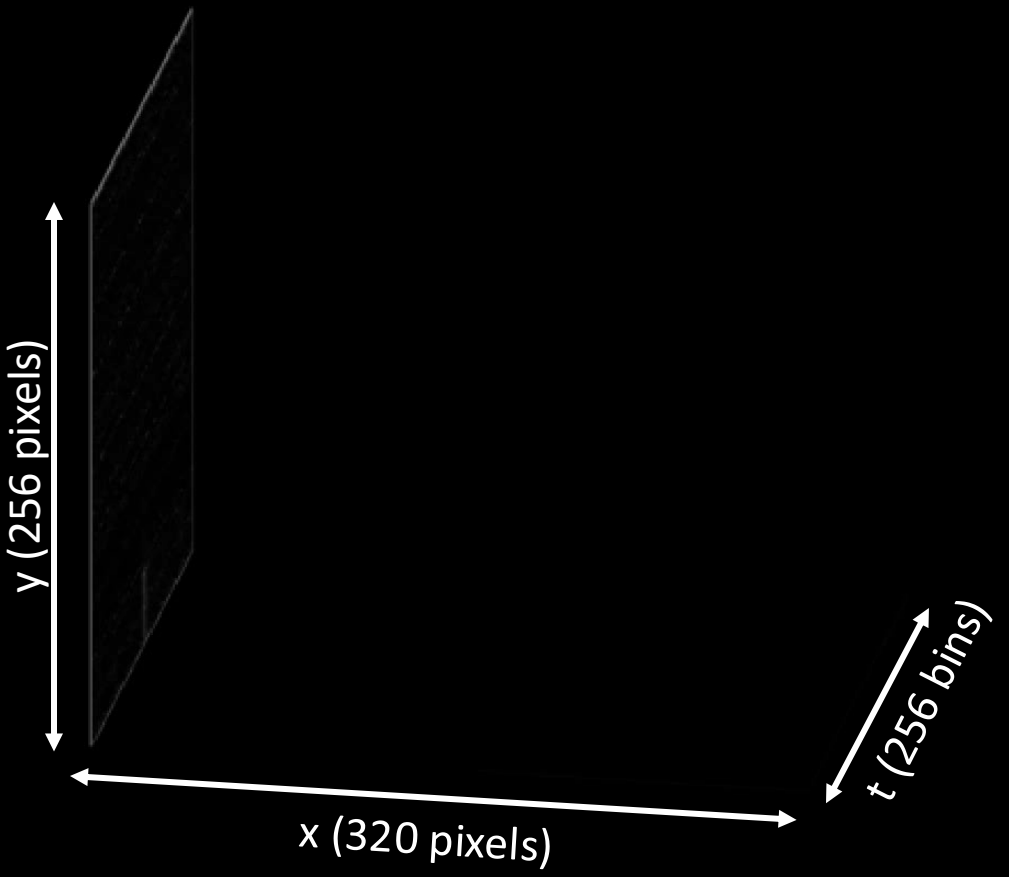


SPAD output

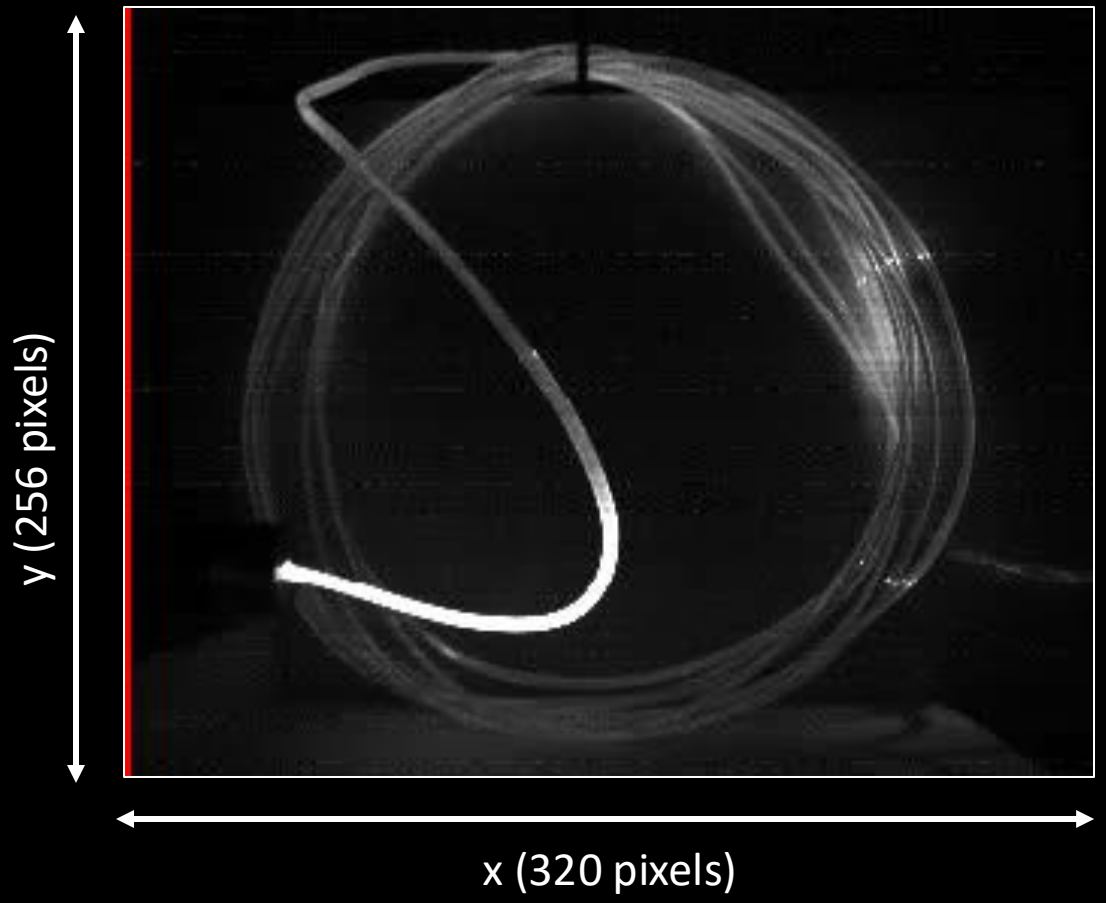


regular image

scanning procedure

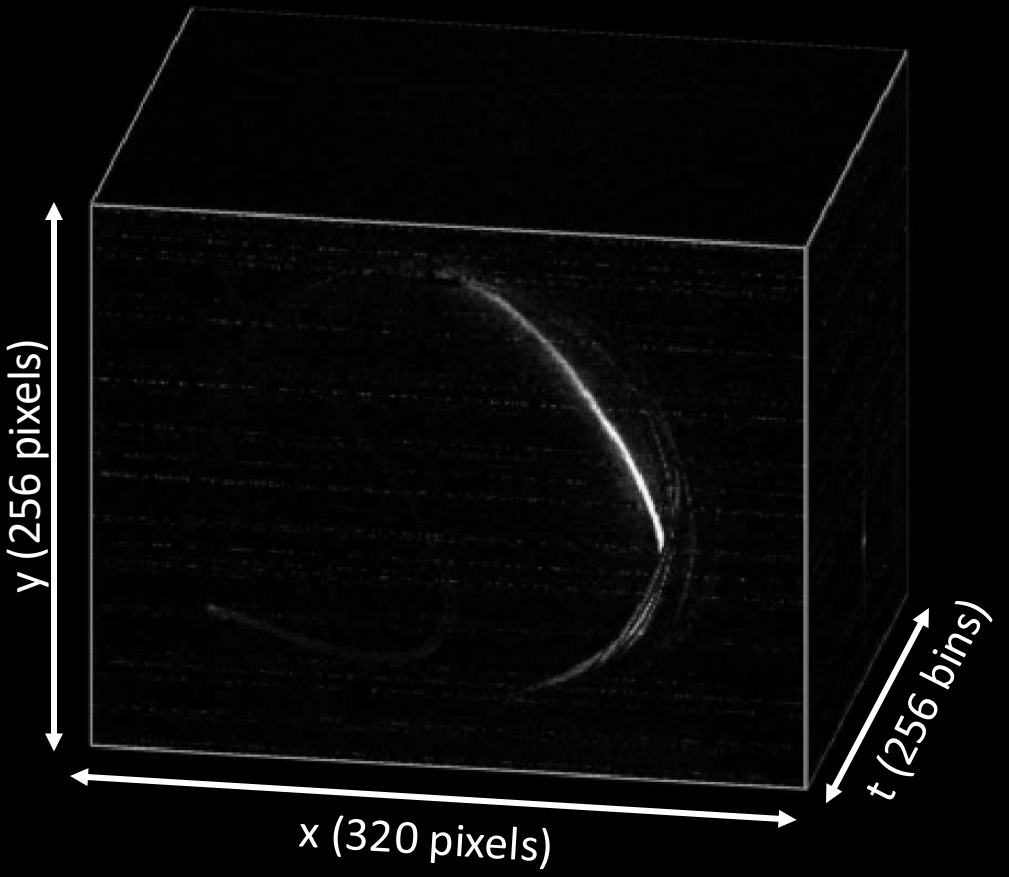


transient image

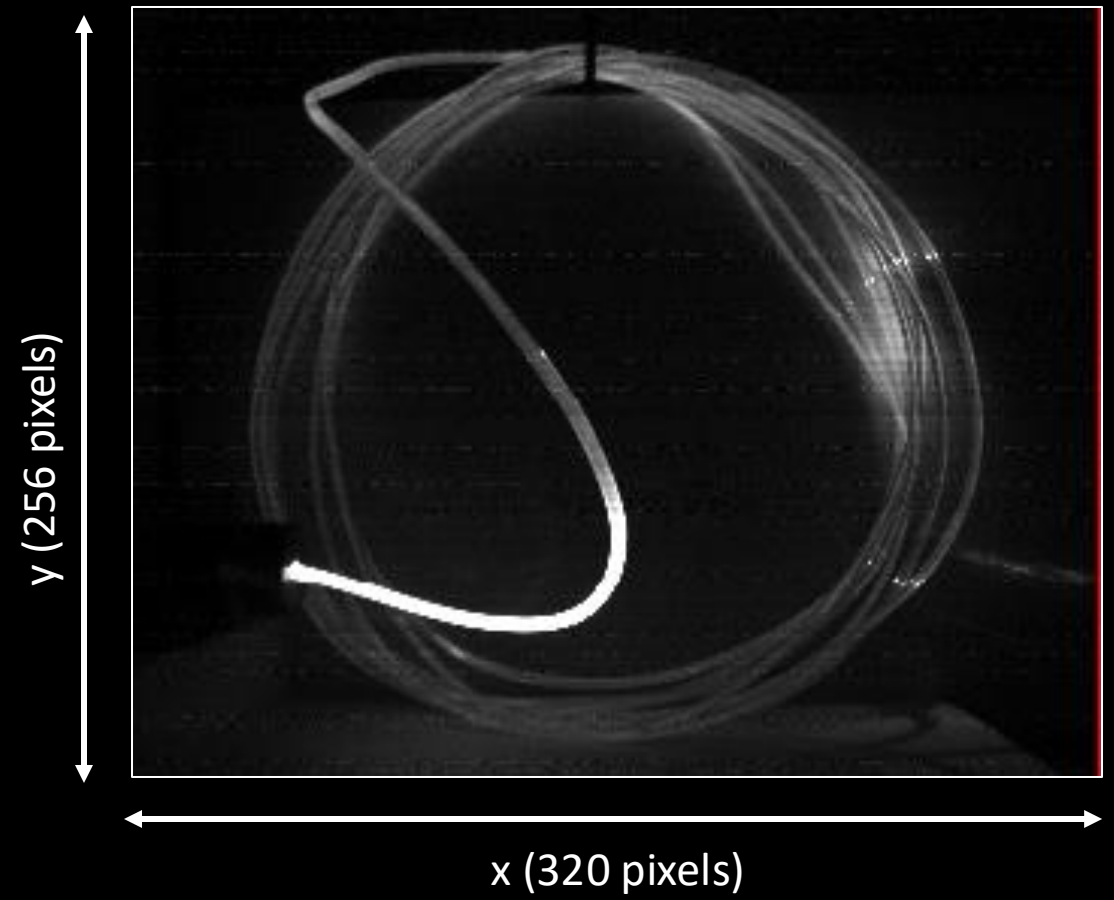


regular image

scanning procedure



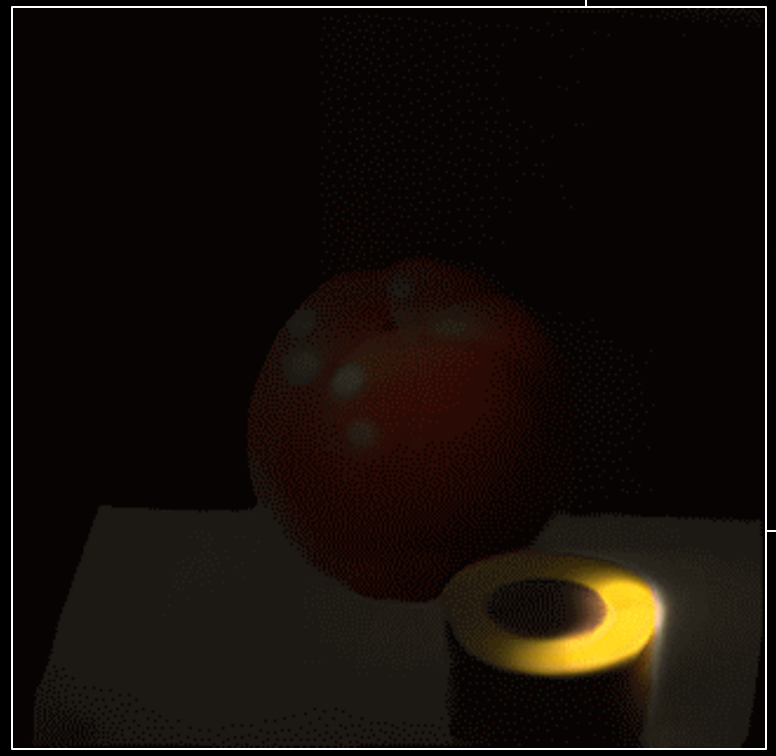
transient image

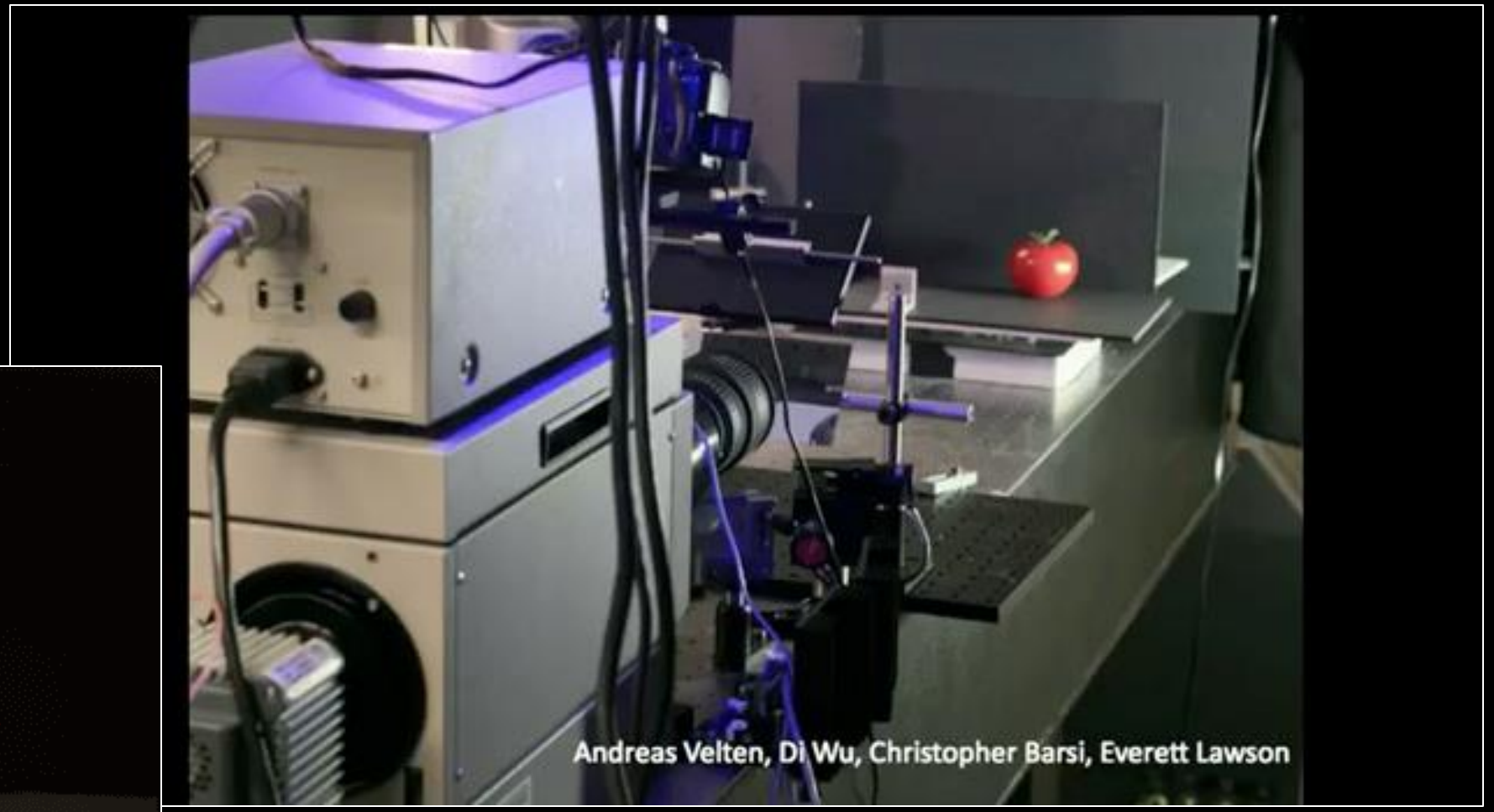


regular image

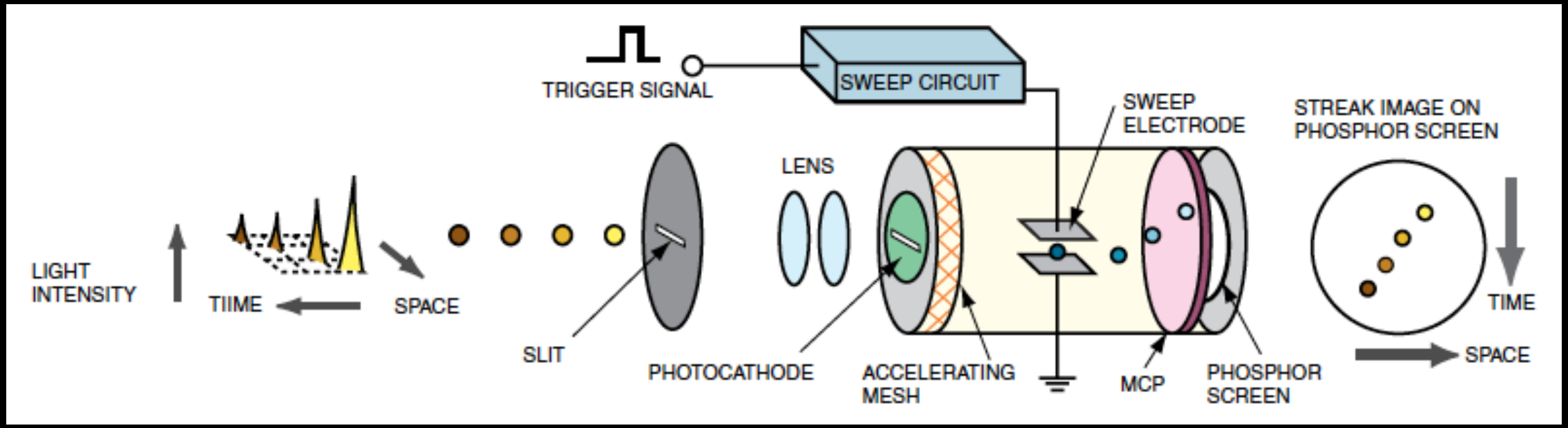
Streak Cameras

streak cameras

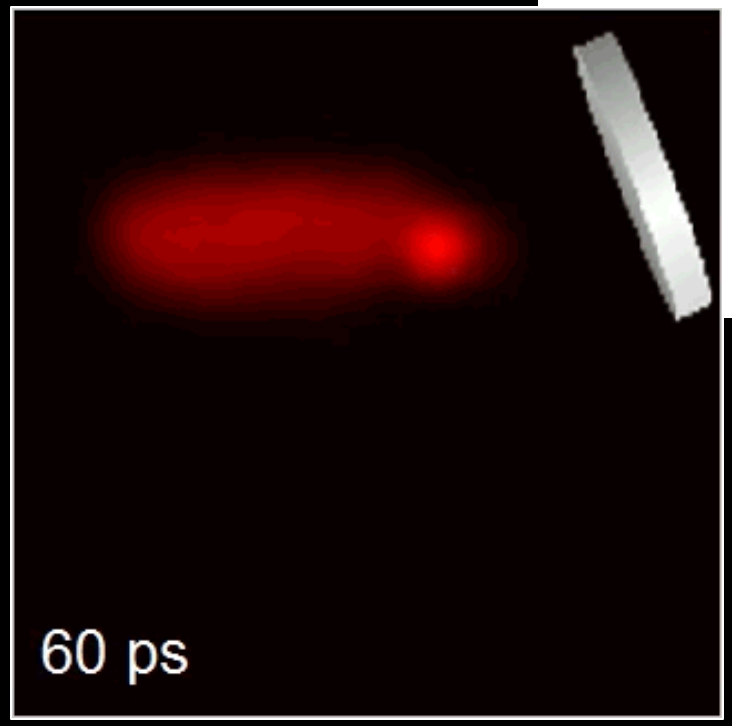


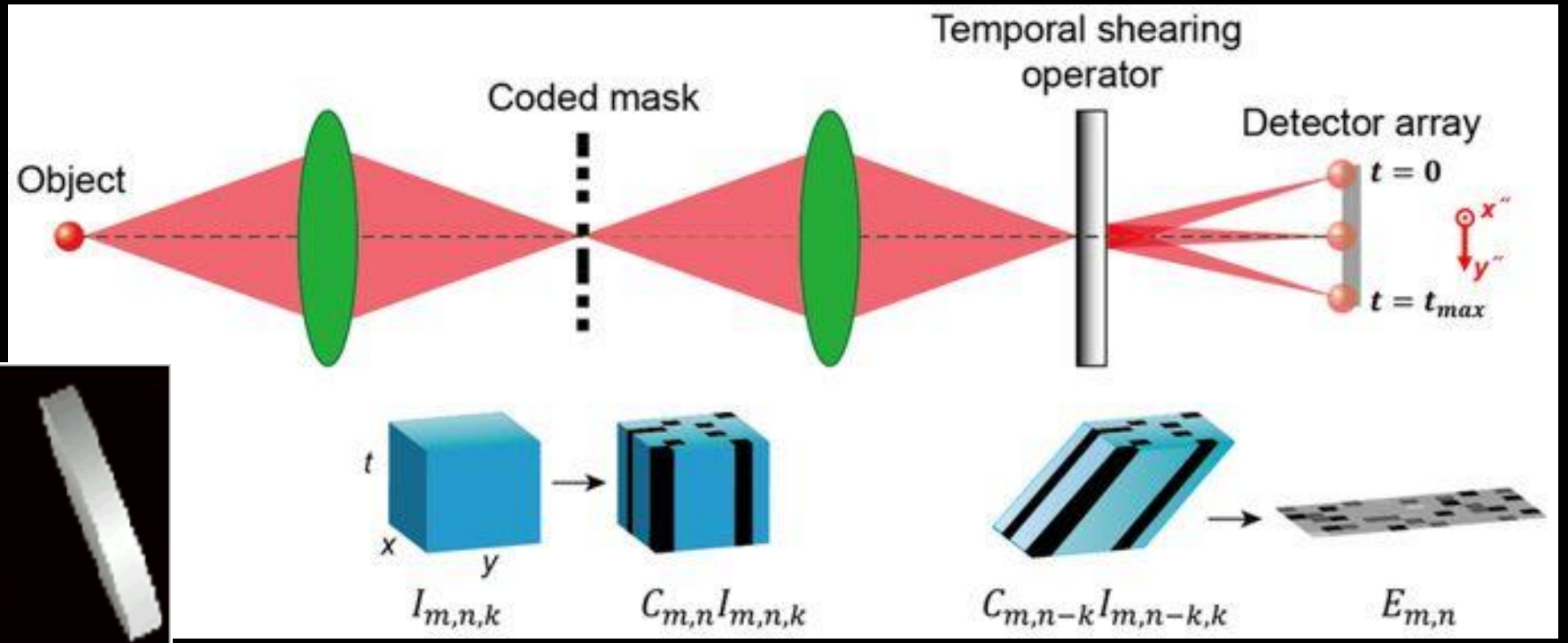


streak cameras



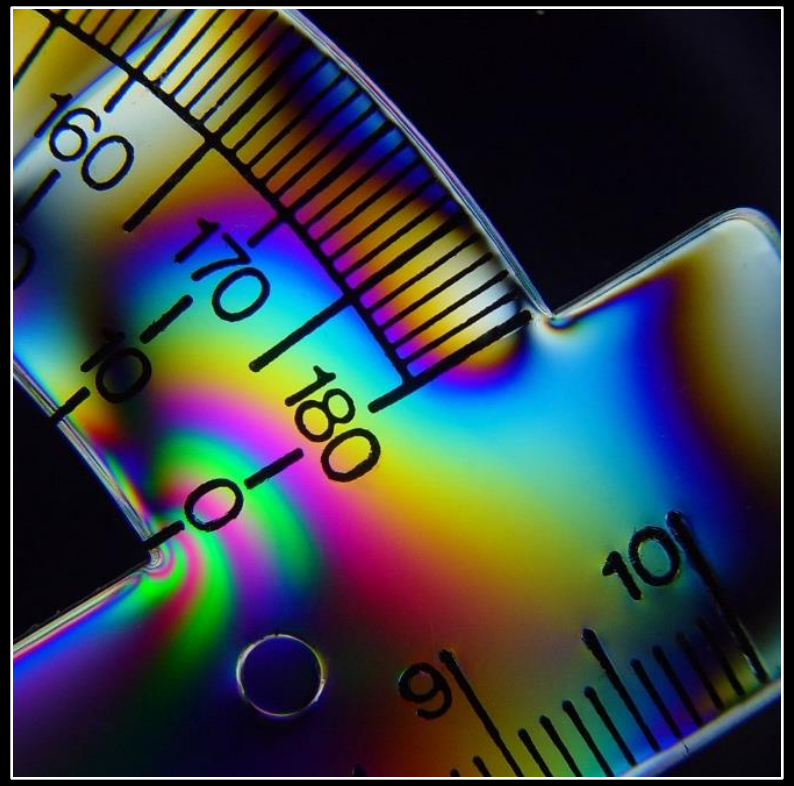
streak cameras – compressed ultrafast photography



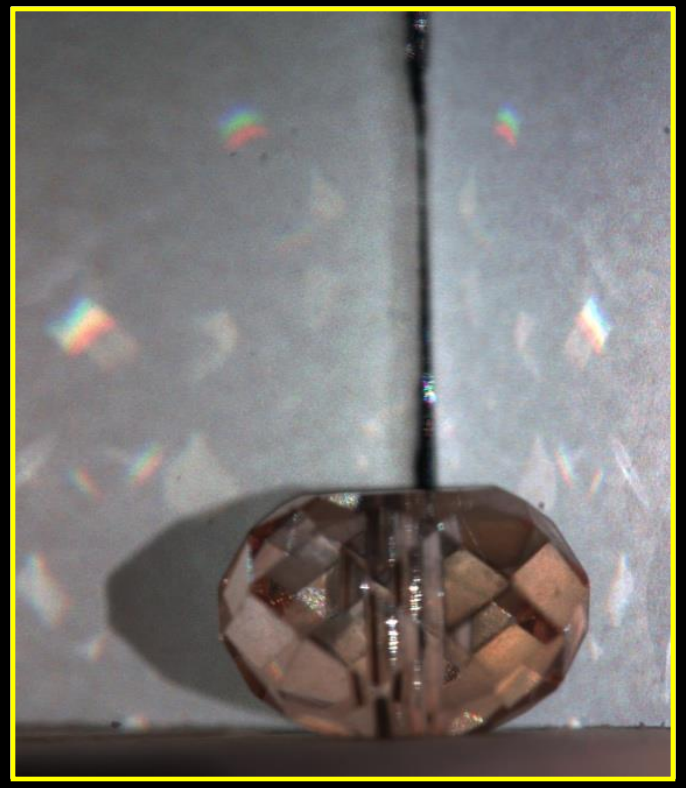


Interferometric Cameras

Material properties



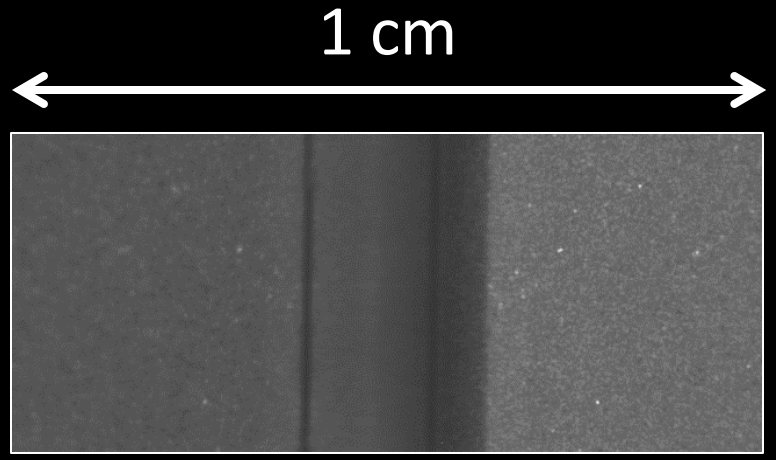
birefringence



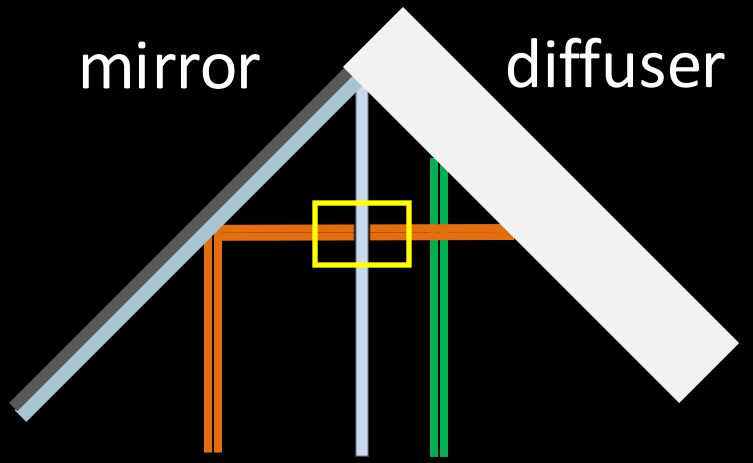
dispersion

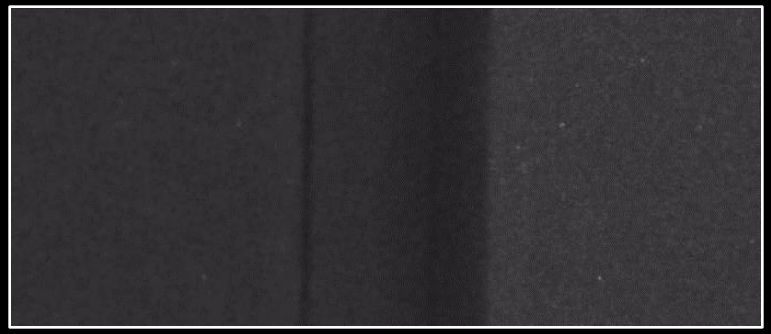
scattering

Dispersion

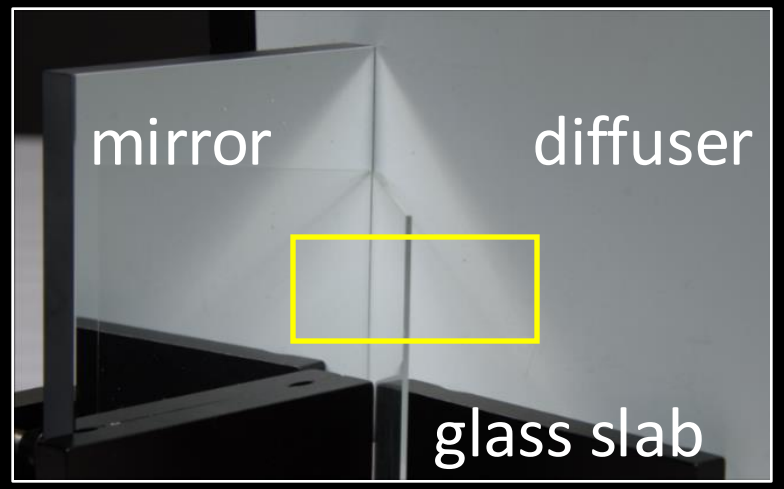


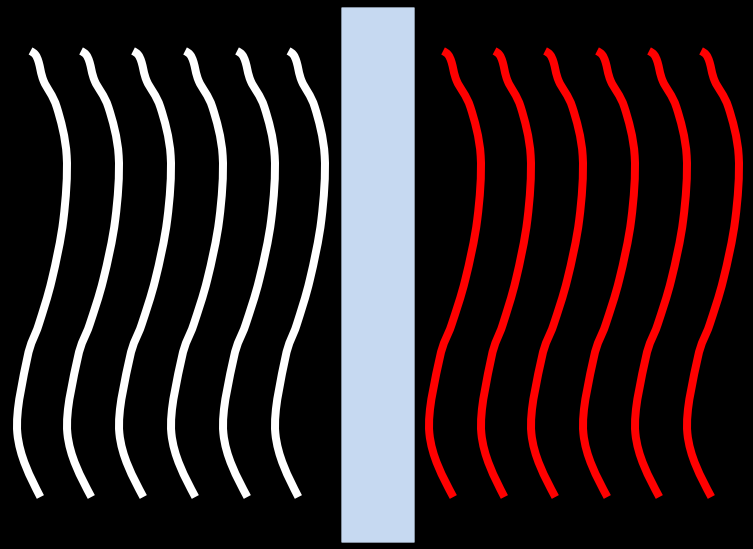
cropped frame

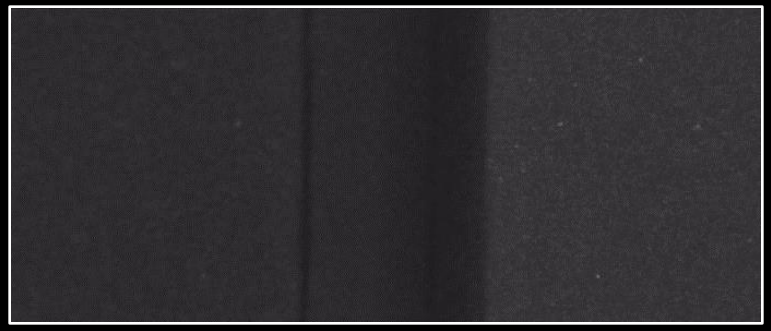




Δt ~ ns



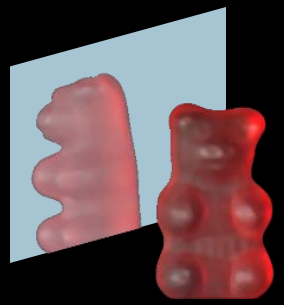




Δt ~ 10^{-3} ns

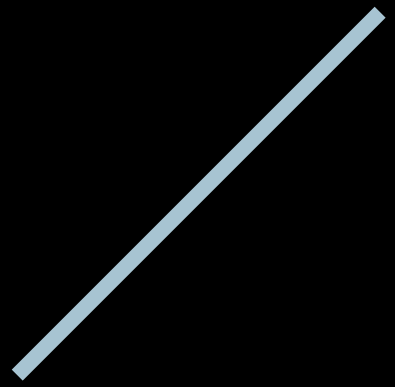
refractive index η(wavelength)

Transient imaging example



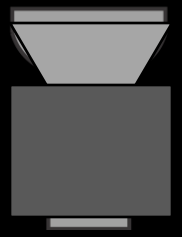
scene

light source



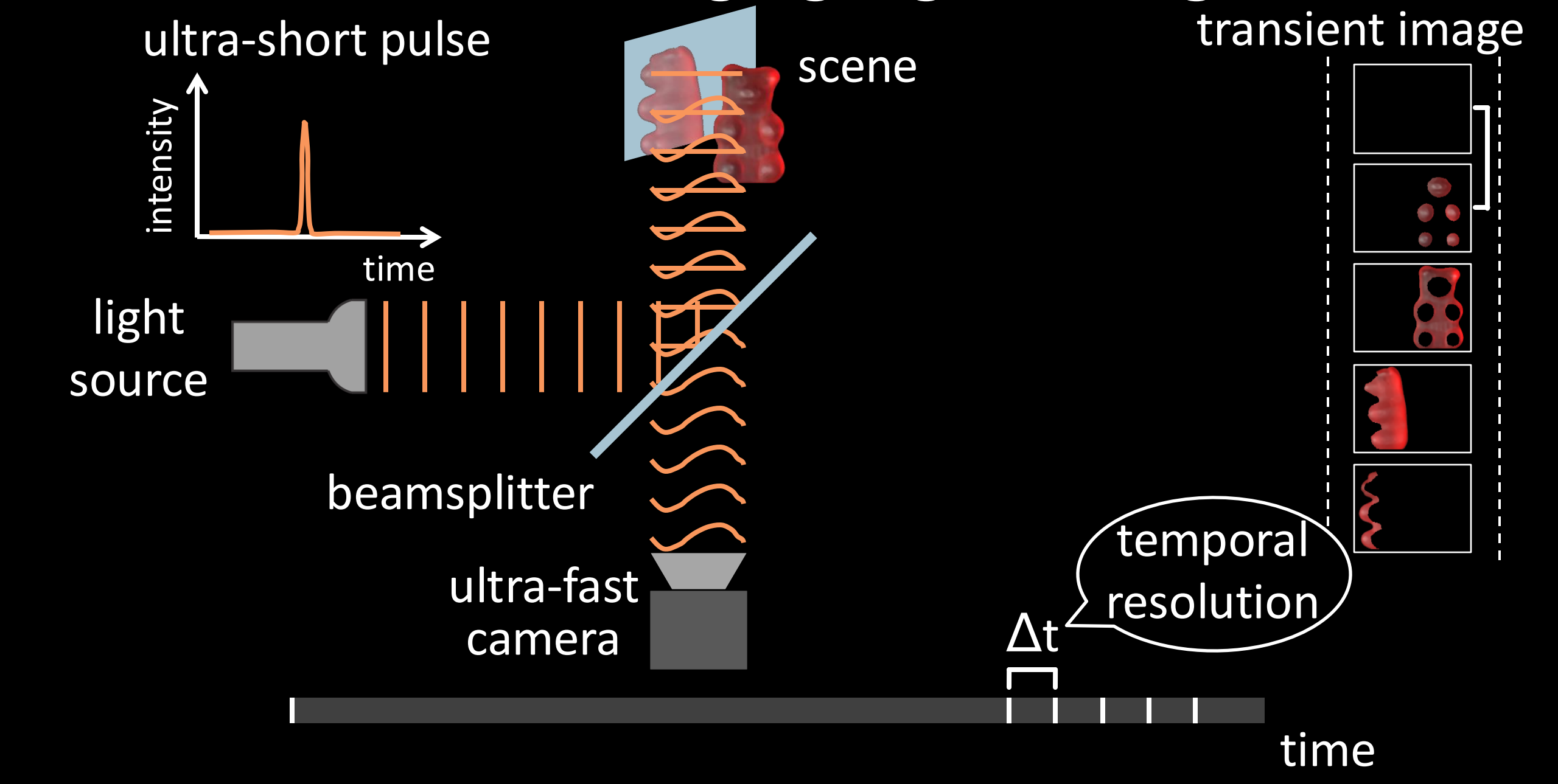
beamsplitter

camera

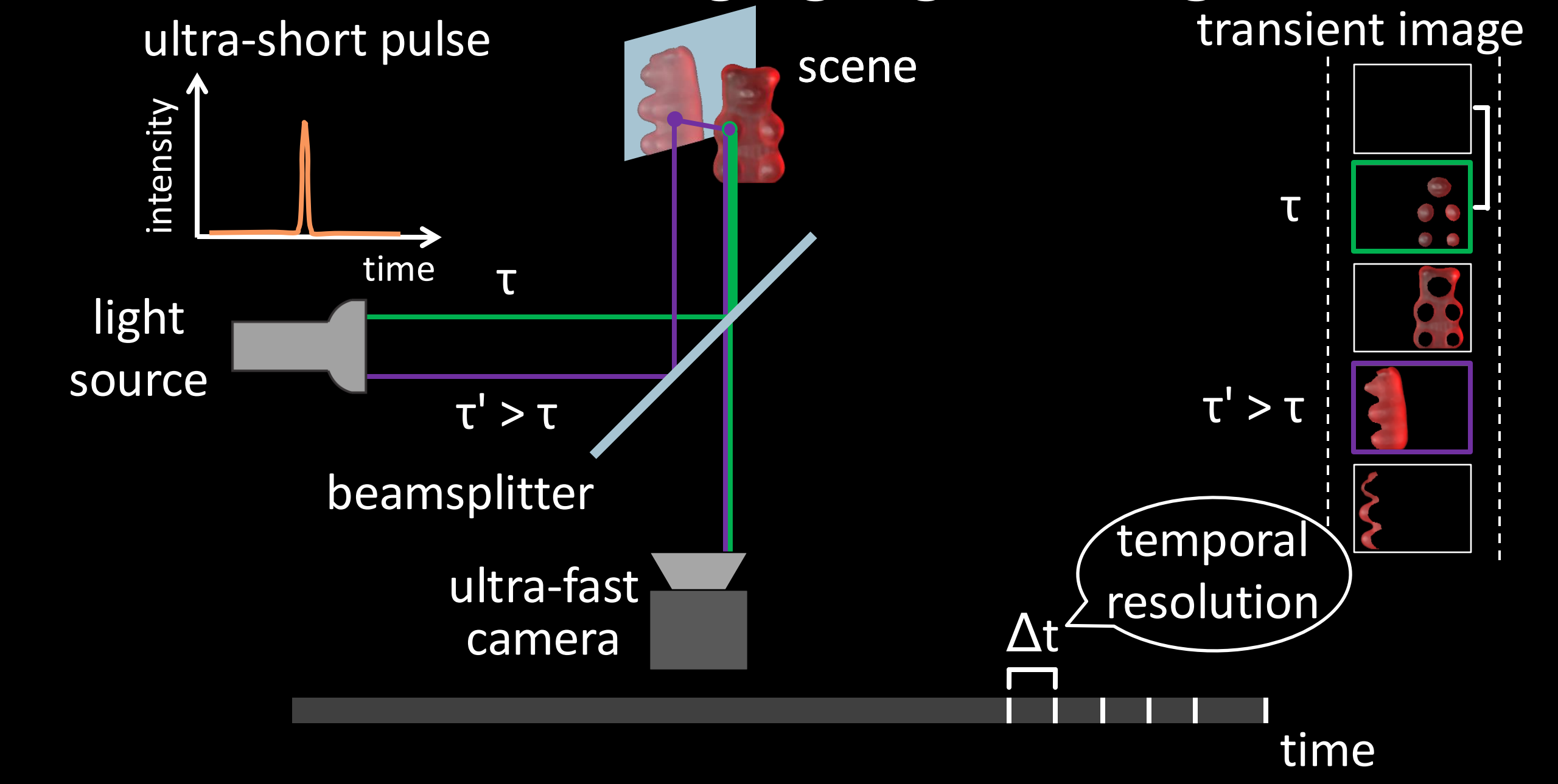


light source

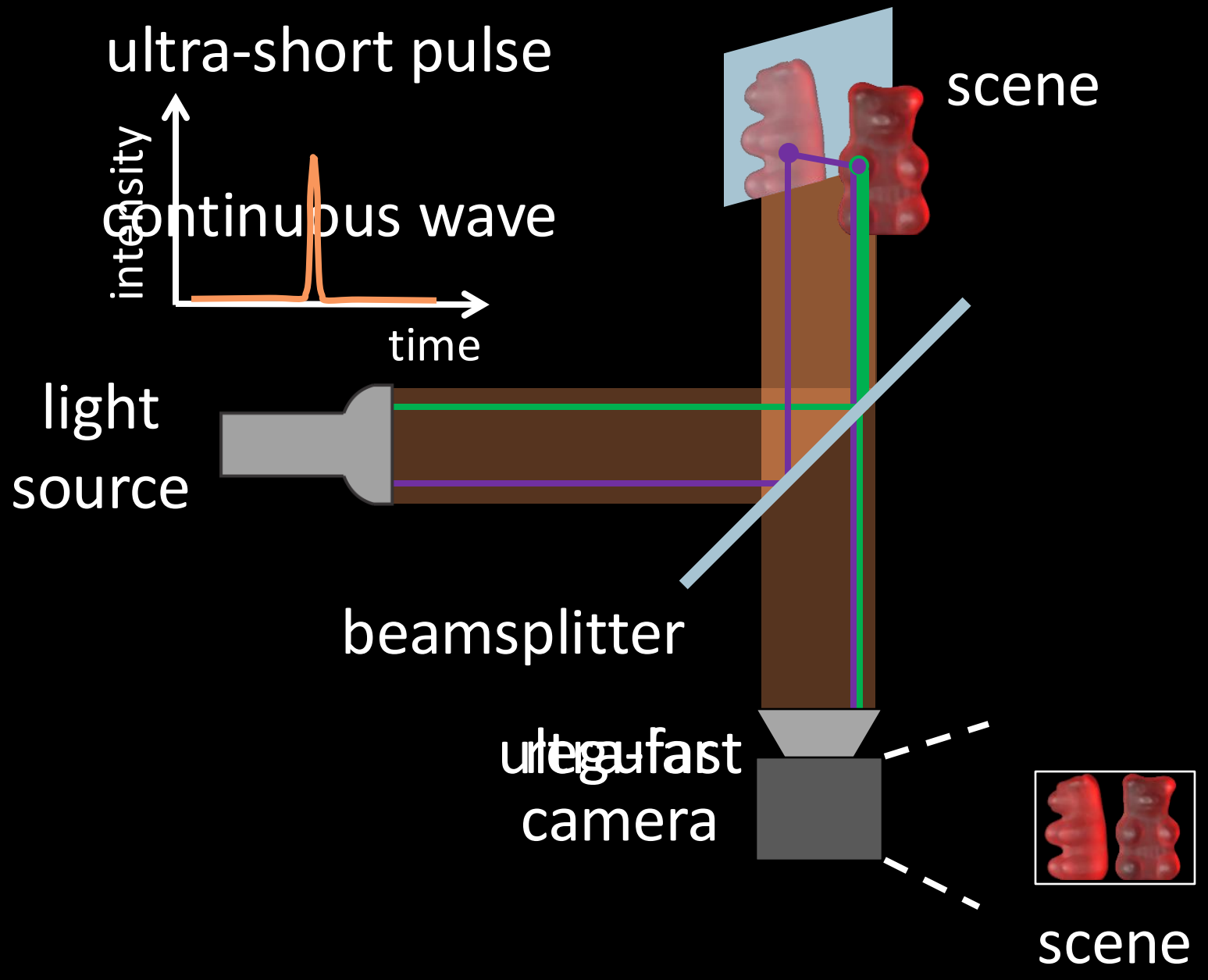
Transient imaging: light-in-flight



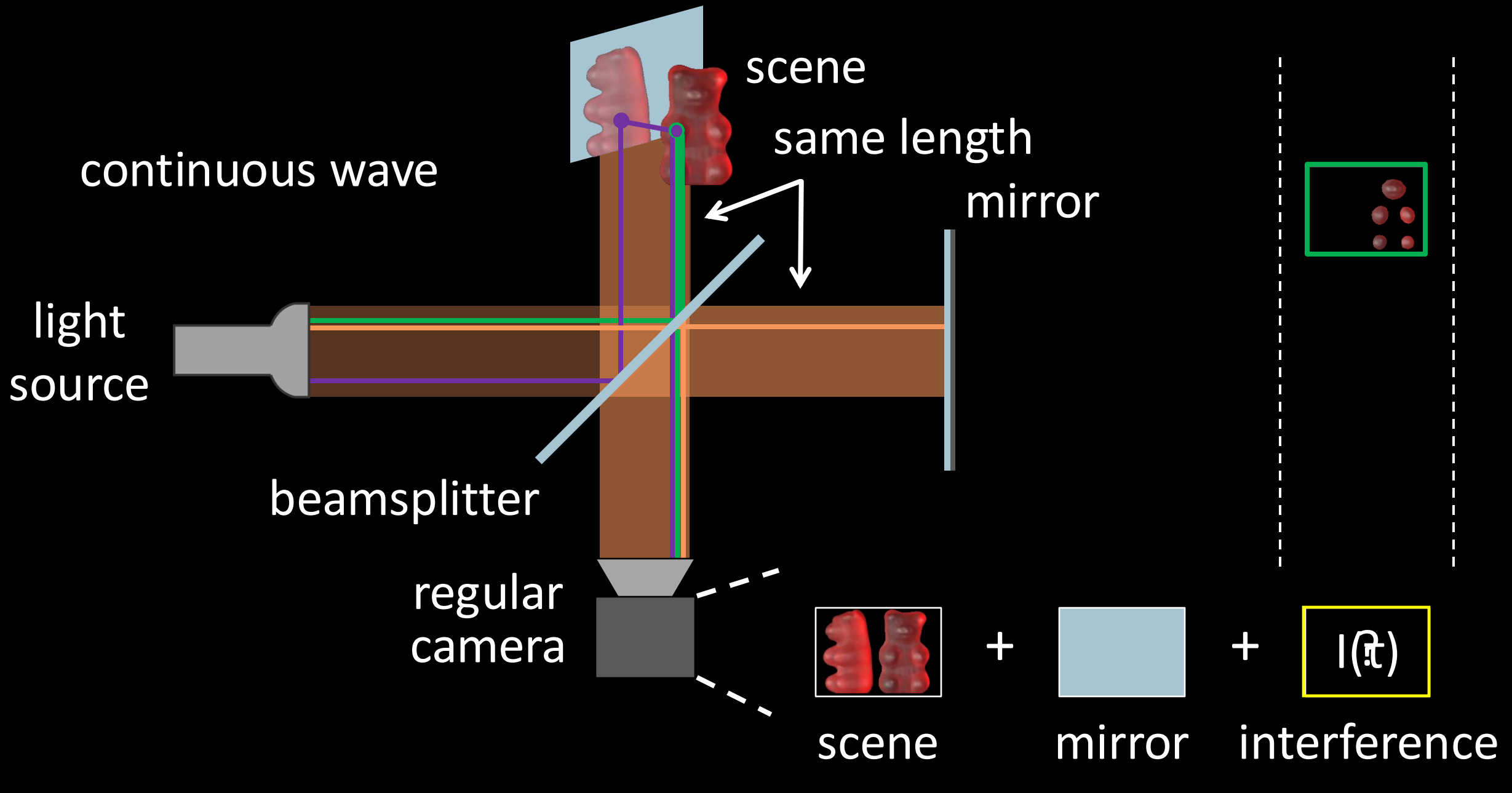
Transient imaging: light-in-flight



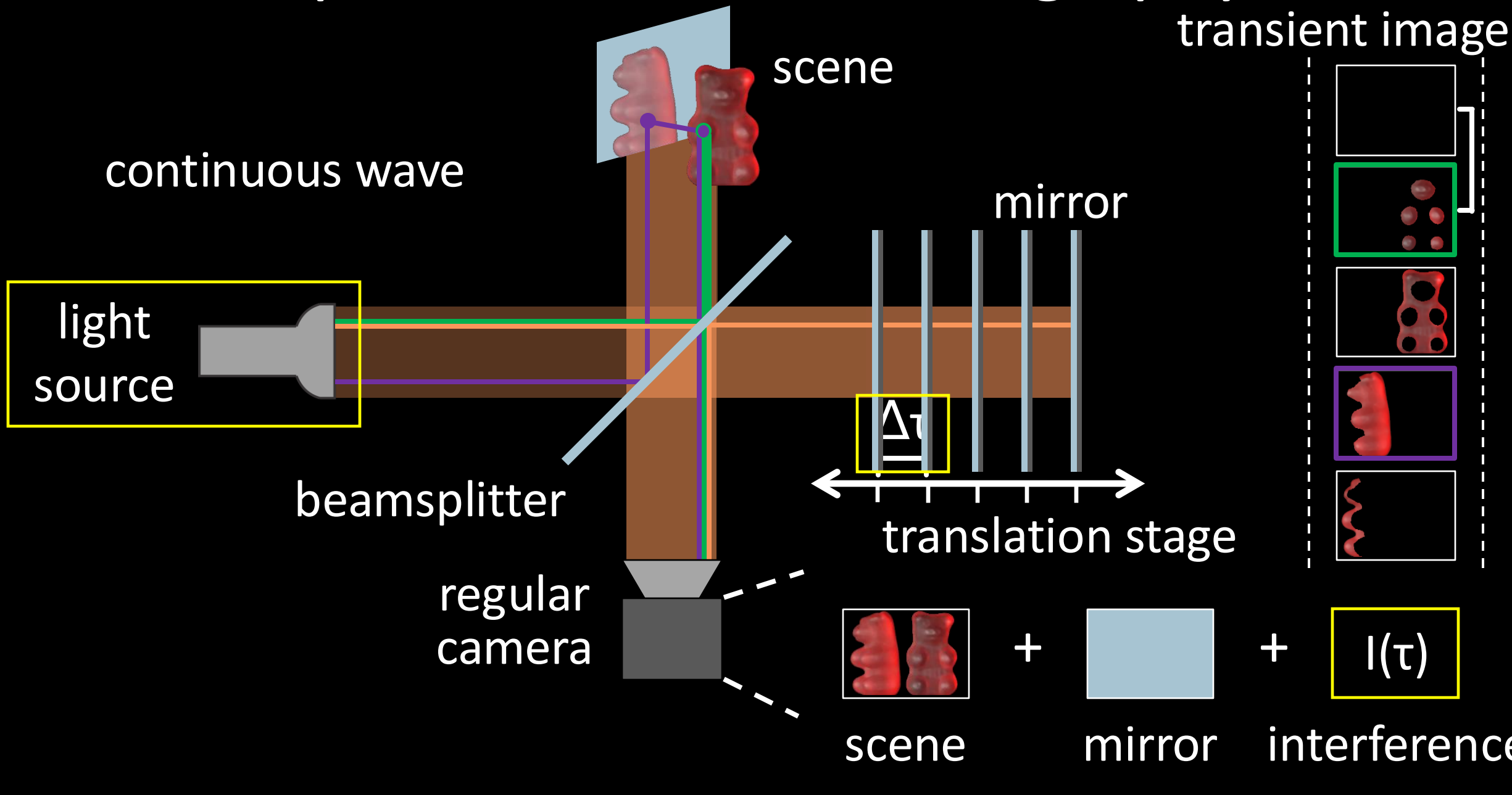
Michelson interferometer



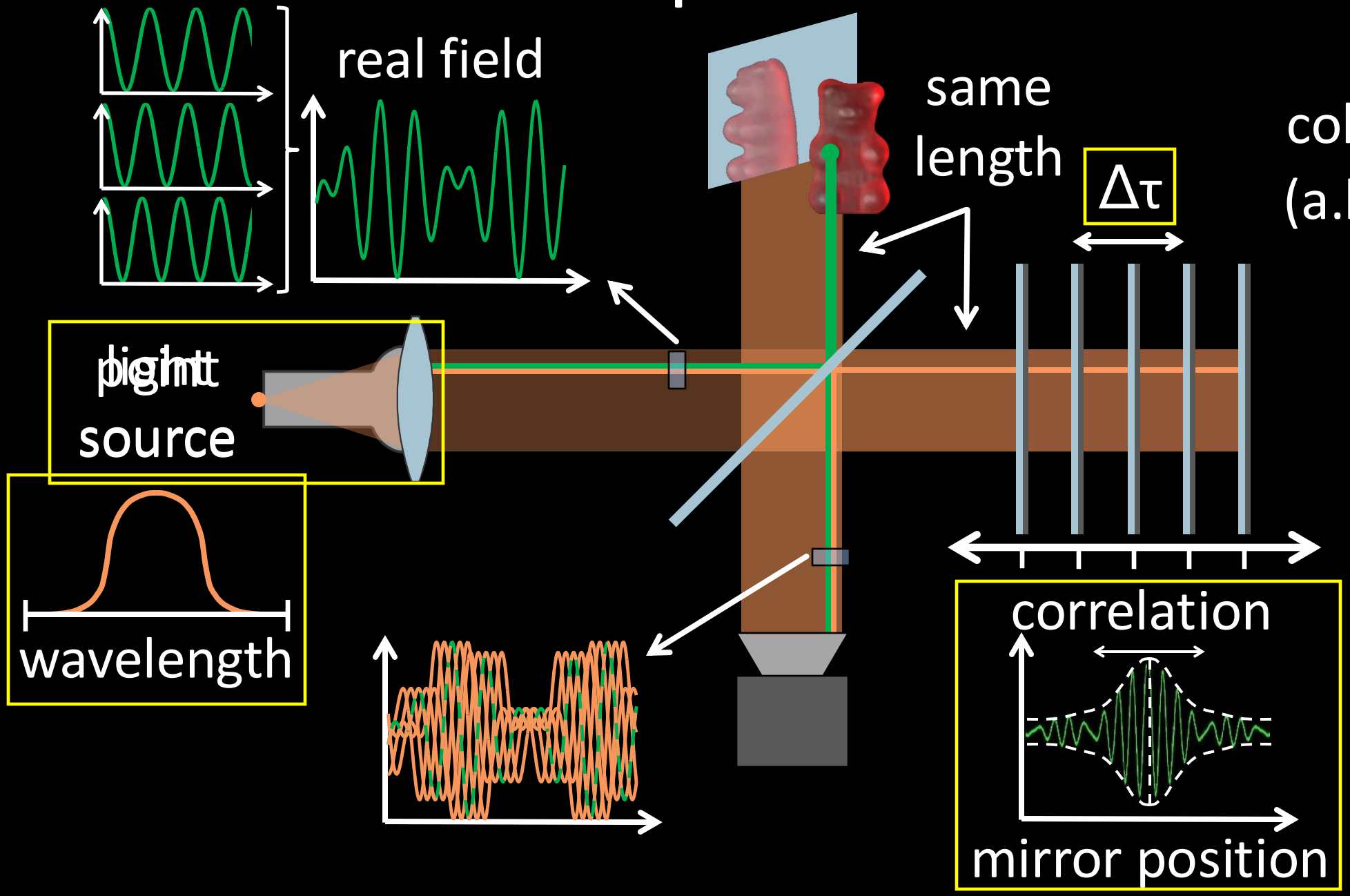
Michelson interferometer



Optical coherence tomography



Temporal coherence



temporal coherence length (a.k.a. pathlength resolution)

= I(τ)

interference

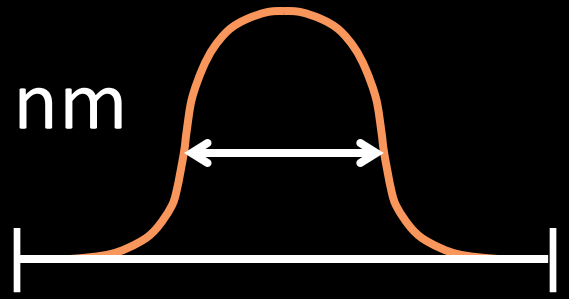
Temporal coherence length

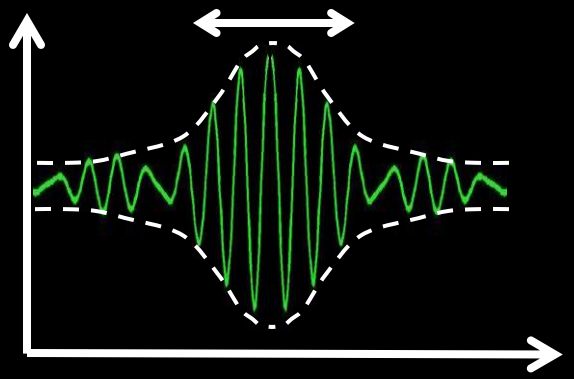
bandwidth

correlation

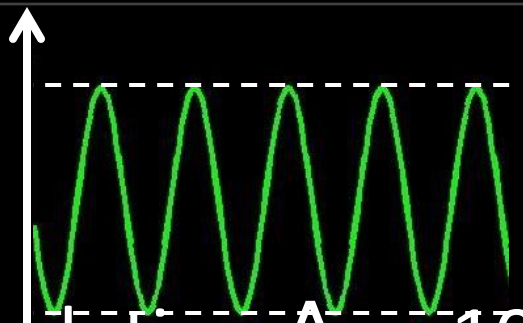
broadband

25 nm





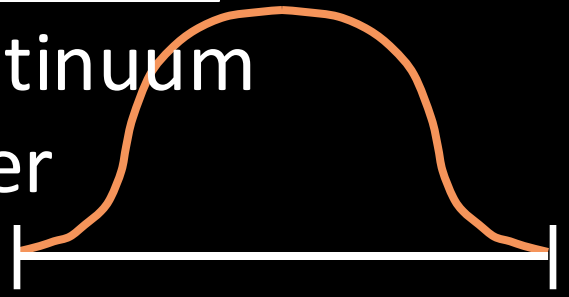
monochromatic

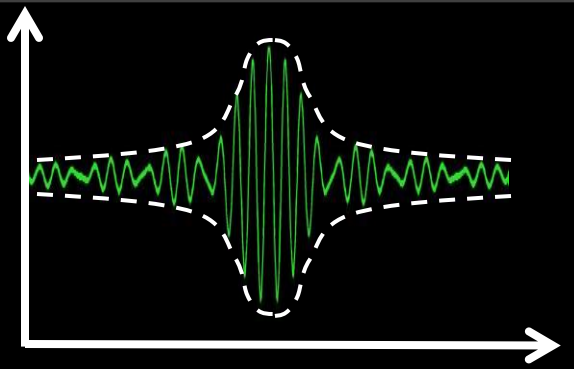


pathlength resolution $\Delta t \sim 10\,\mu m$

very broadband superluminescent diode

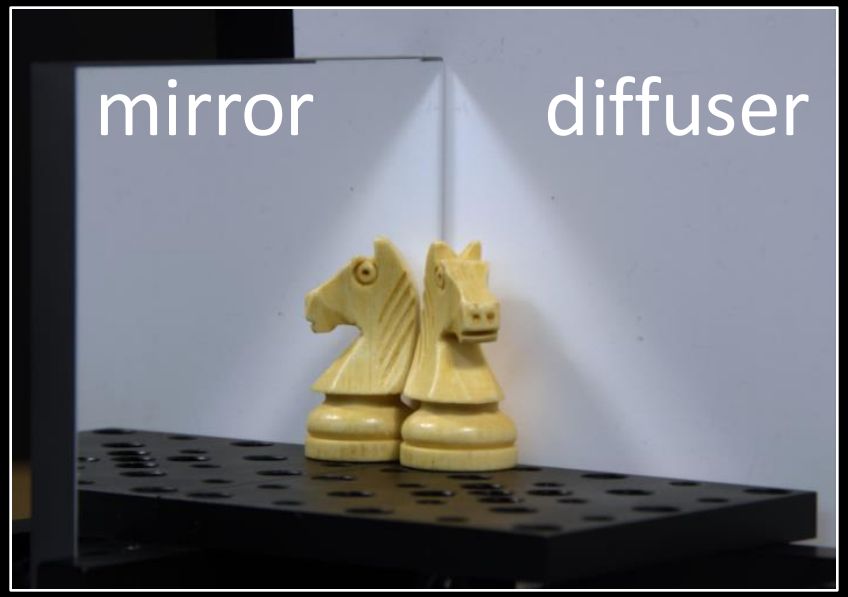
supercontinuum laser

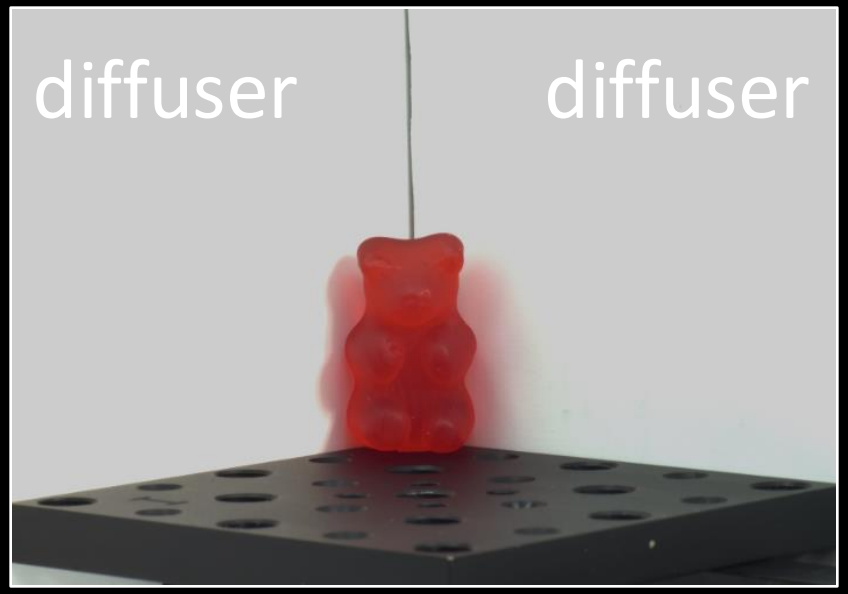




Some transient images

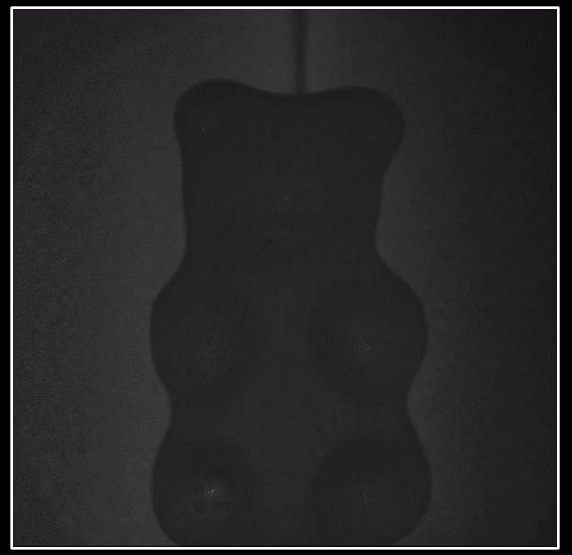
centimeter-sized objects





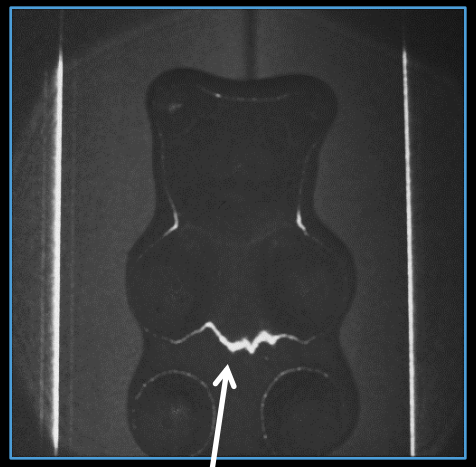
Gummy bear and diffuse corner

2 cm



pathlength
($\Delta\tau$ = 10 µm)

dark frame



surface reflections

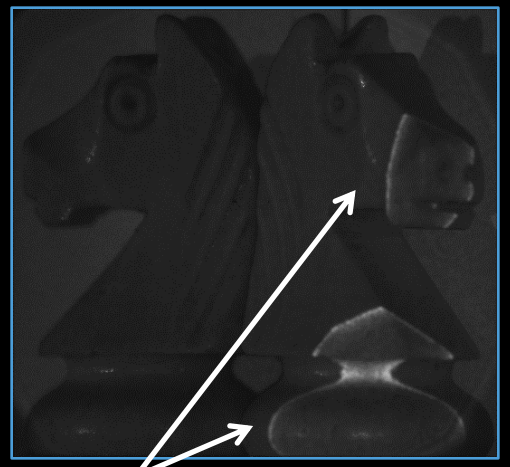
paths through gummy bear

very highly scattered paths

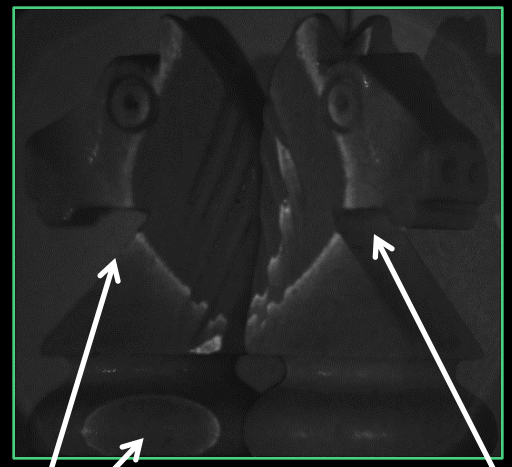
Chess knight and mirror

3 cm

pathlength
($\Delta\tau$ = 10 µm)

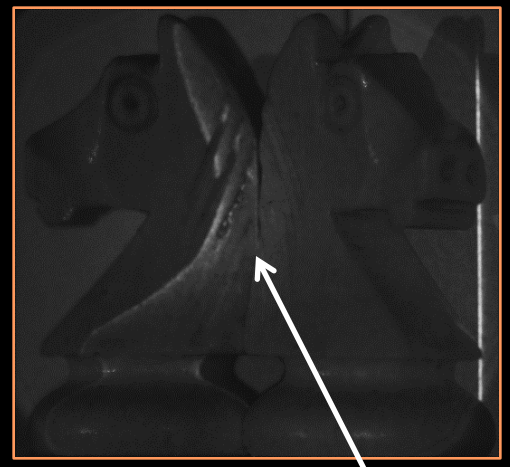


surface reflection



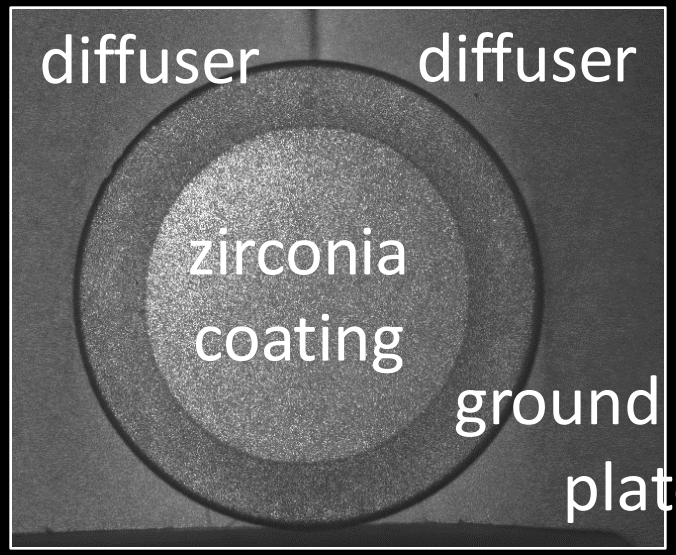
mirror-object

object-mirror

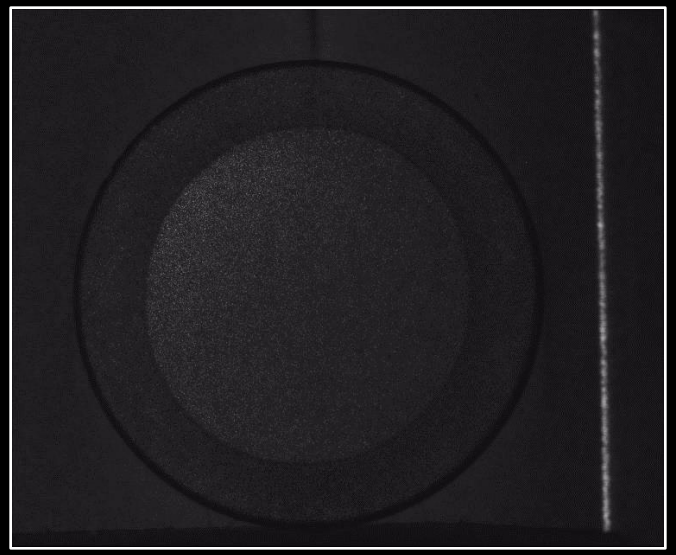


mirror-object-mirror

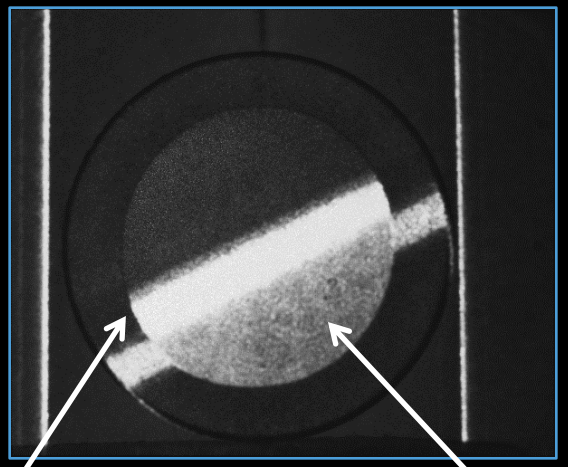
Subsurface scattering



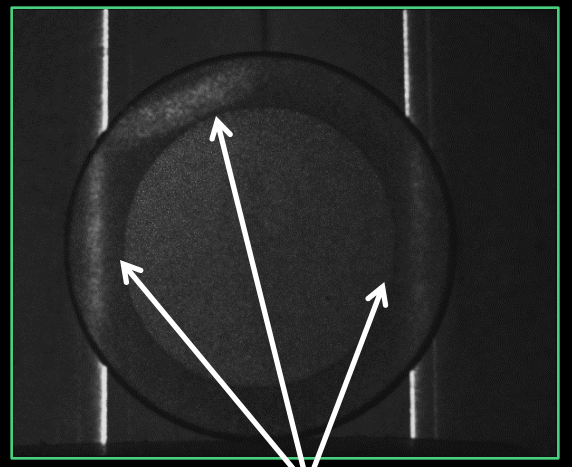
1 cm



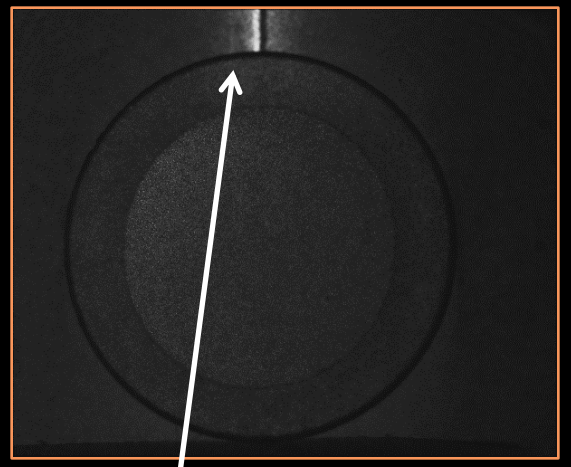
pathlength
($\Delta\tau$ = 10 µm)



surface reflection
subsurface scattering

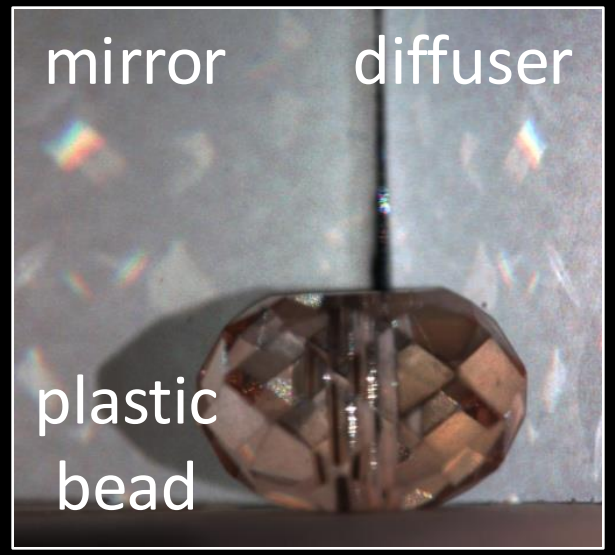


paths transmitted
through ground glass



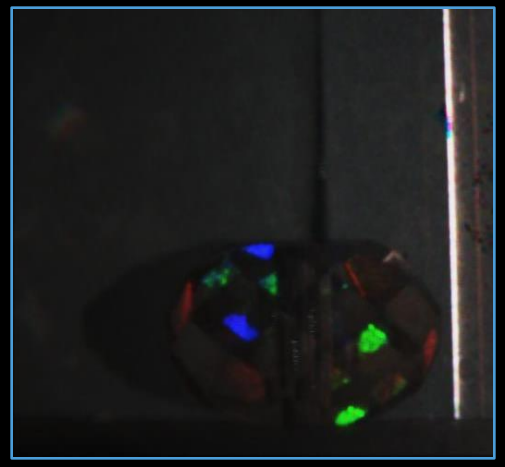
diffuse-diffuse
reflections

Dispersion



1 cm

pathlength
($\Delta\tau$ = 10 µm)

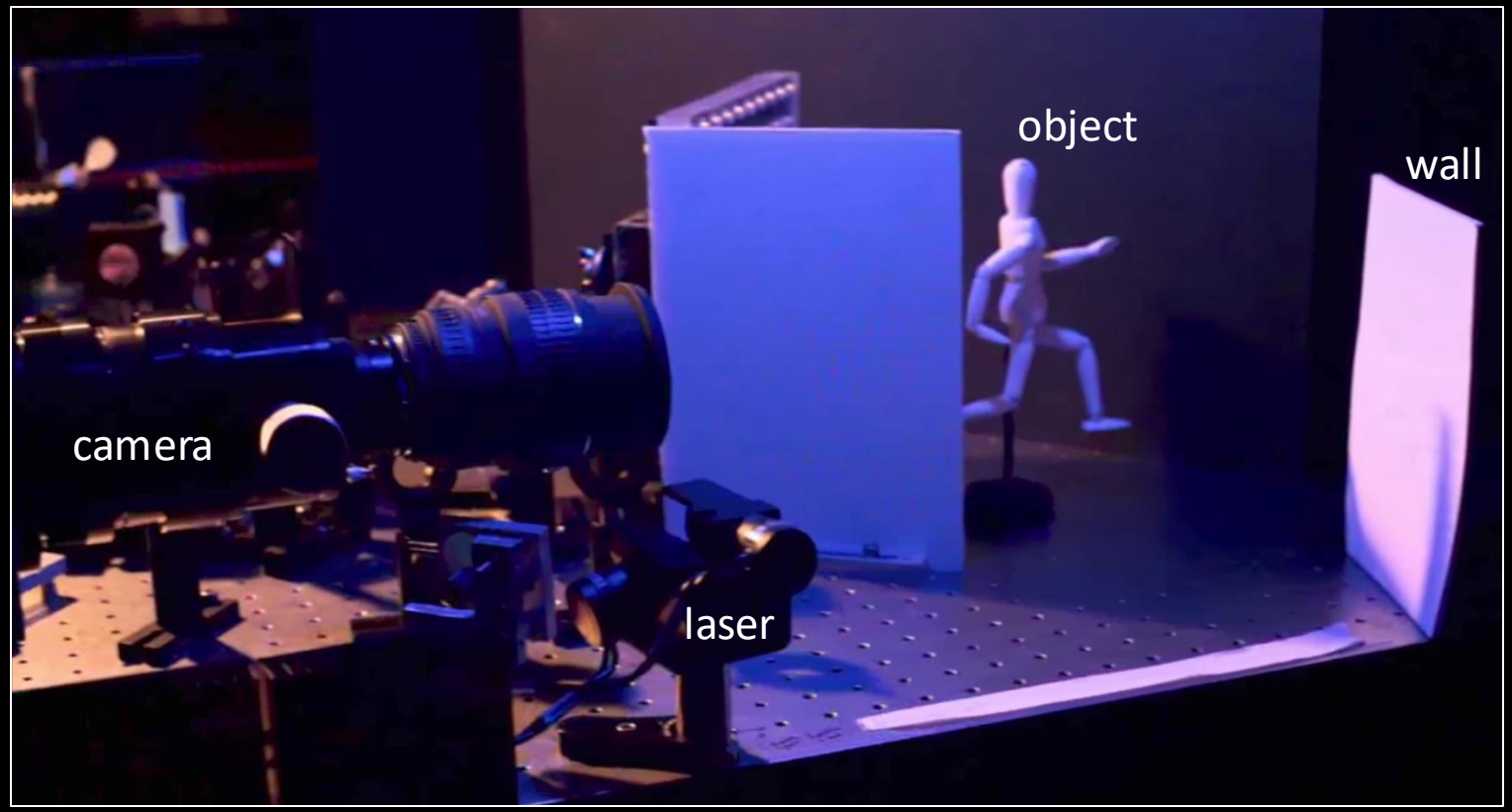


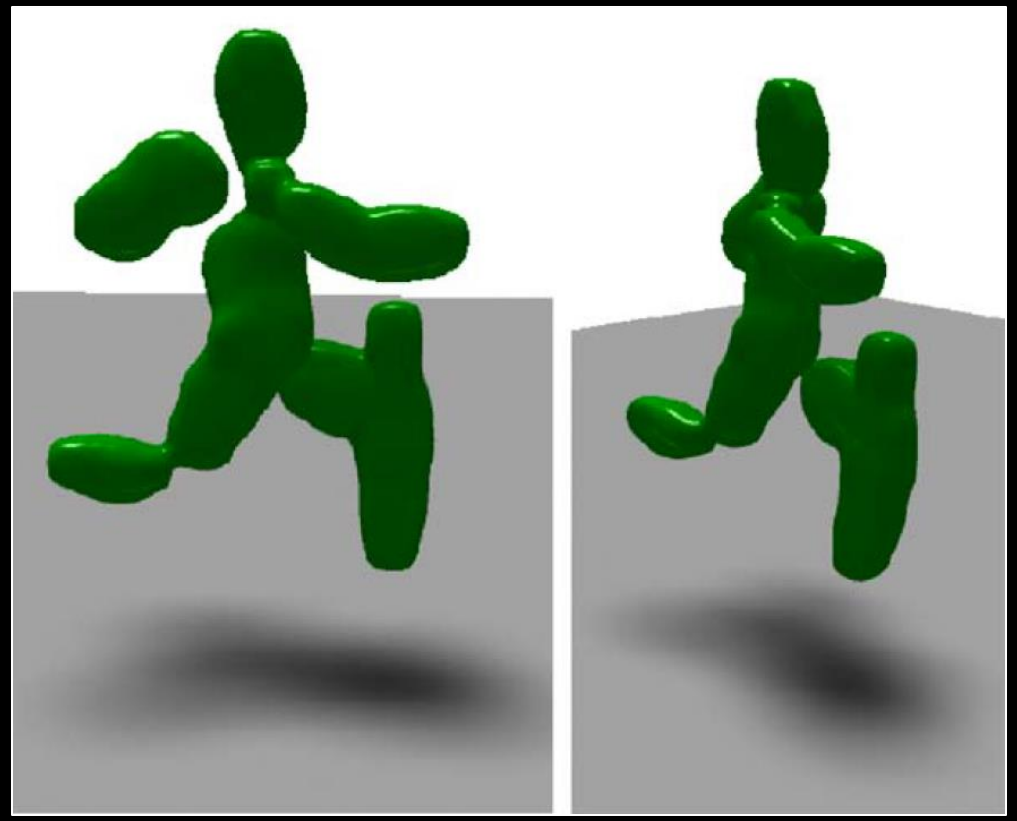
facets changing color

surface reflections
surface-wall reflections

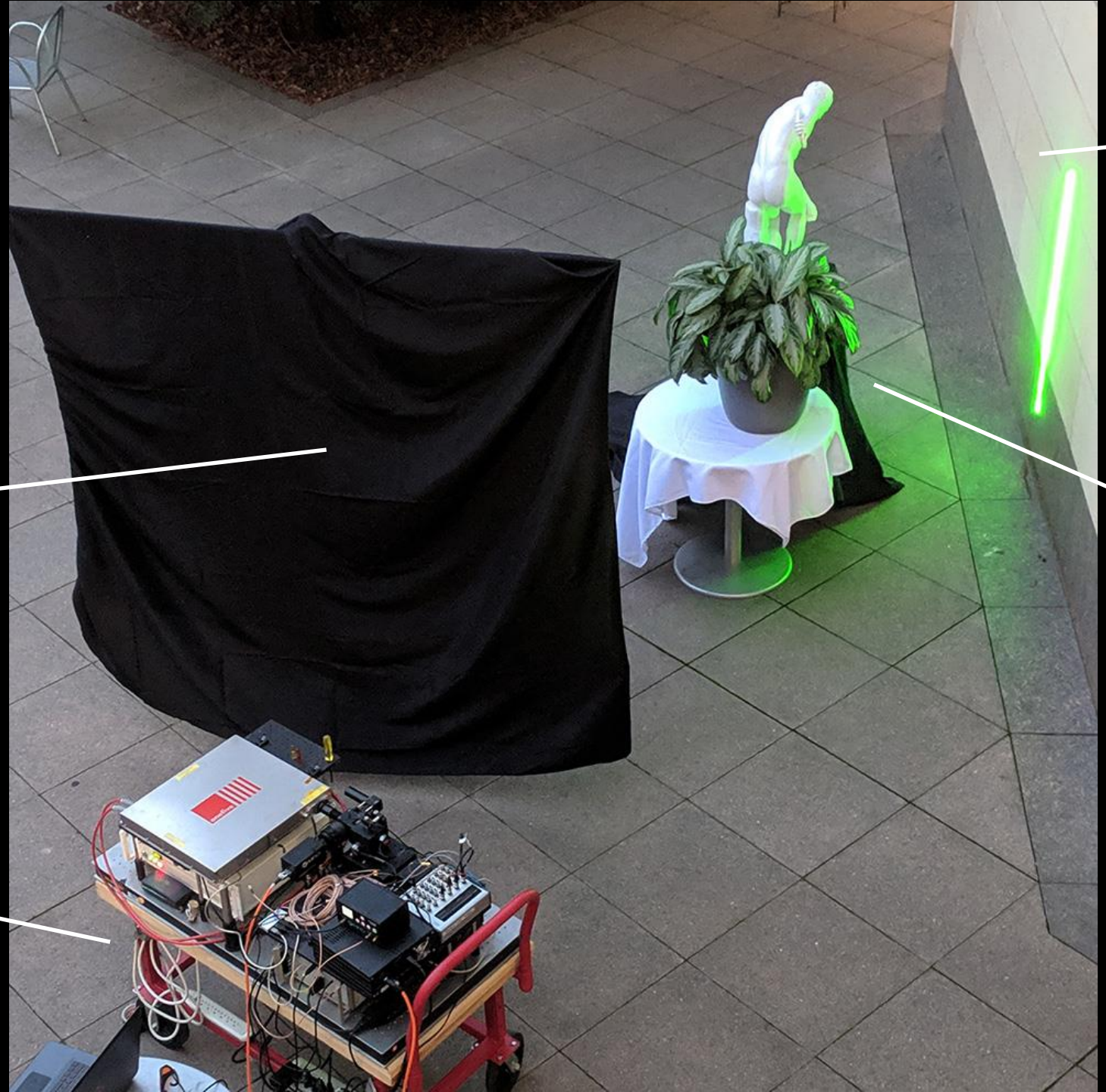
rainbow

Non-line-of-sight Imaging





Velten et al., Nature Communications 2012

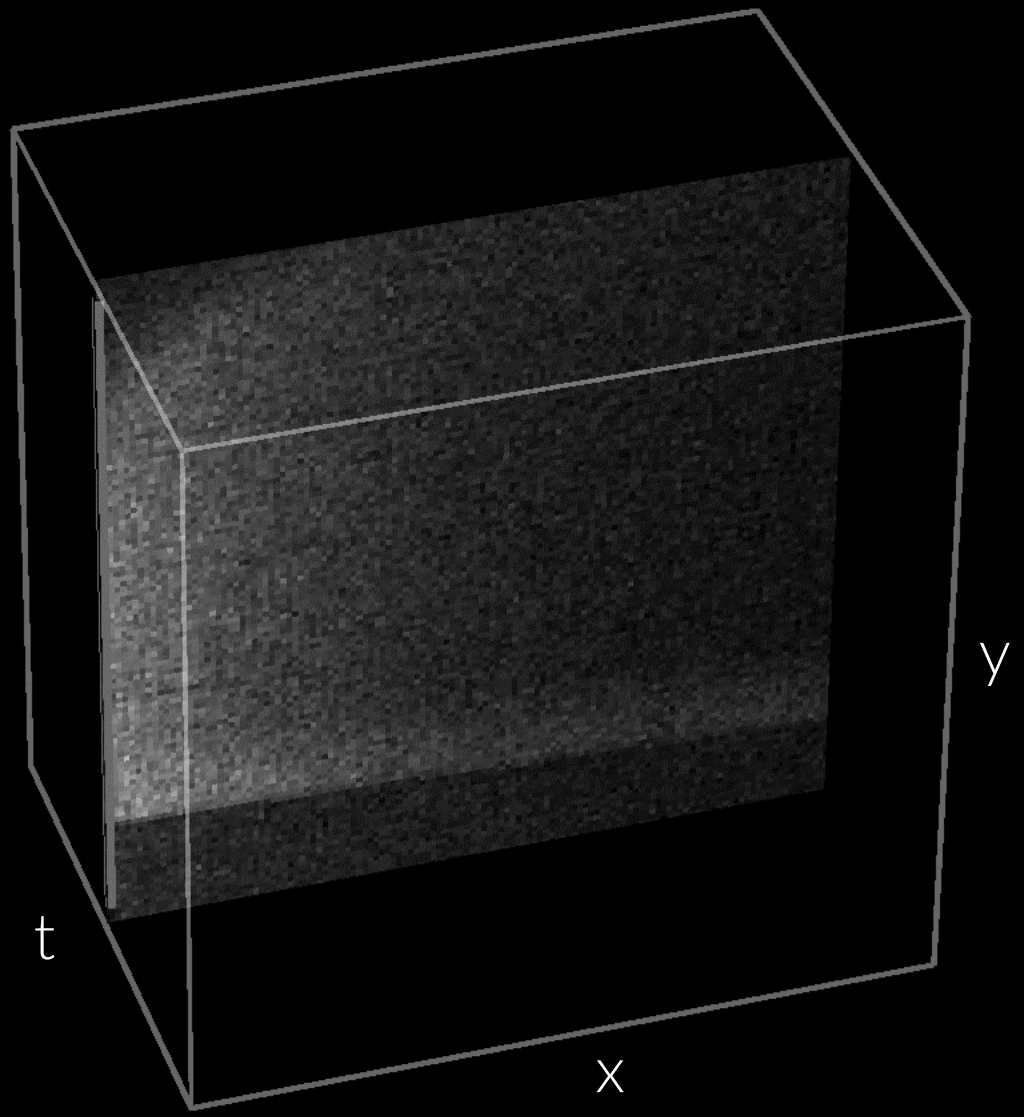

wall
occluder
hidden scene
NLOS imaging system


scanning mirrors
laser
detector
PICOSECOND
DELAYER
INPUT
MPD
NIM OUT
TTL OUT


resolution: 128 x 128
area: 2 m × 2 m

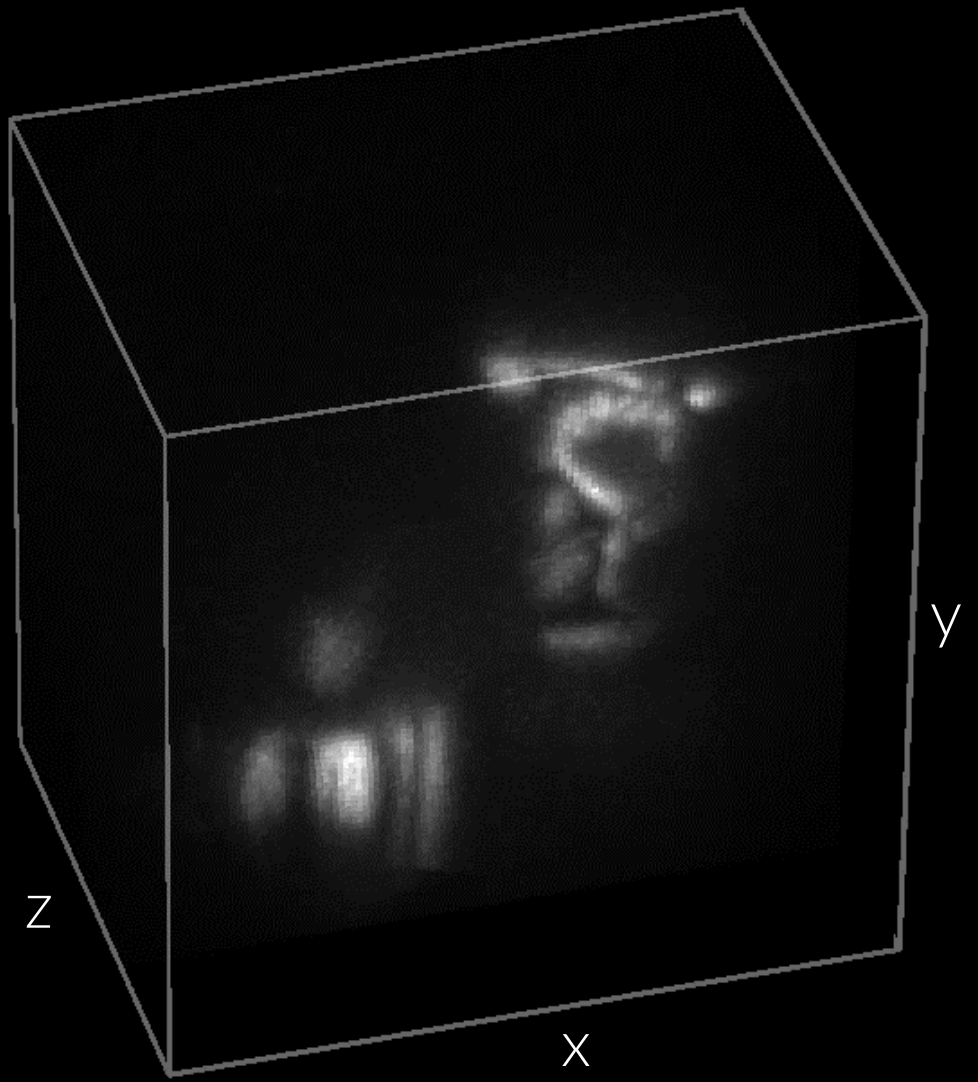
scene photo

measurements

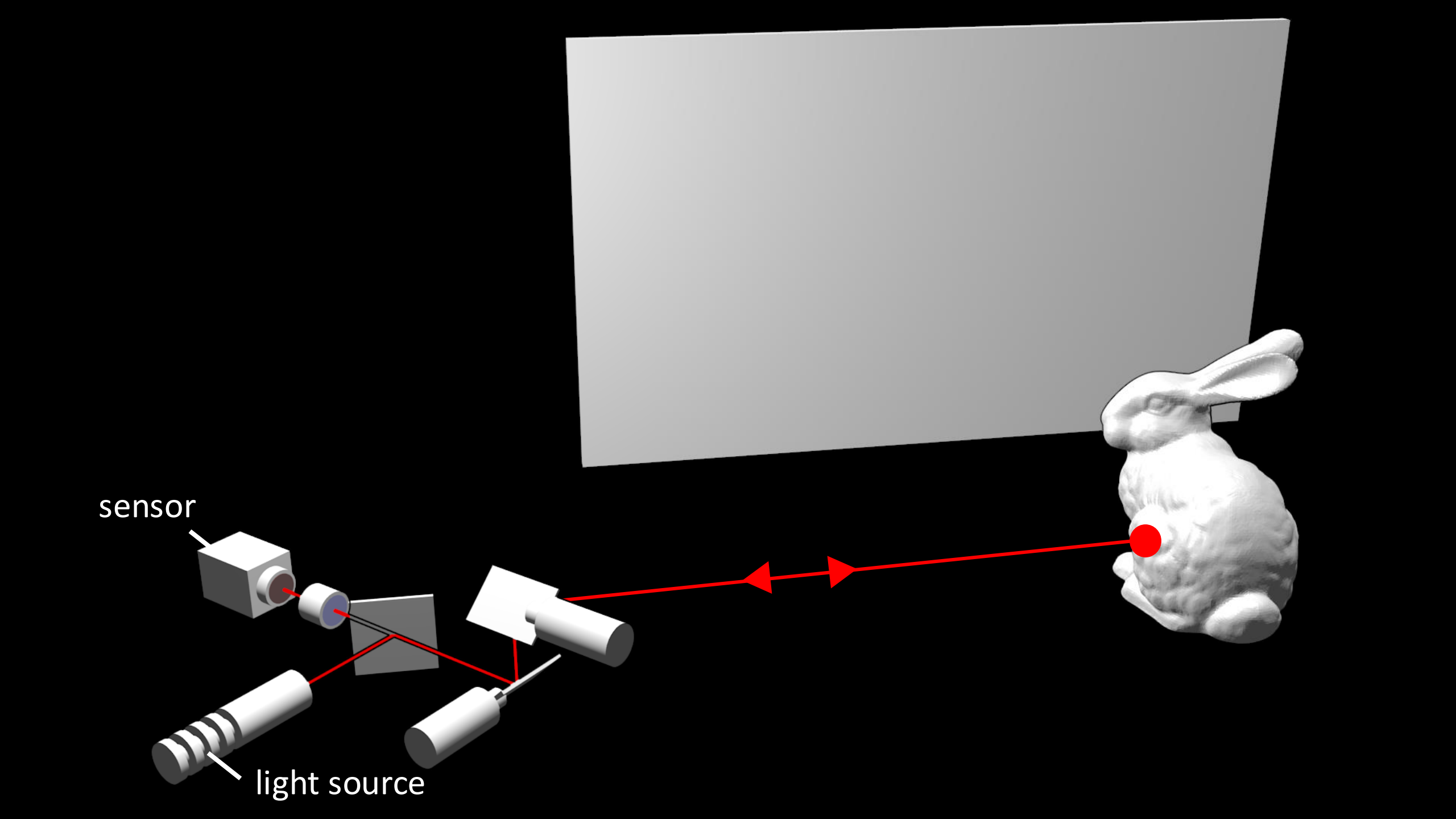


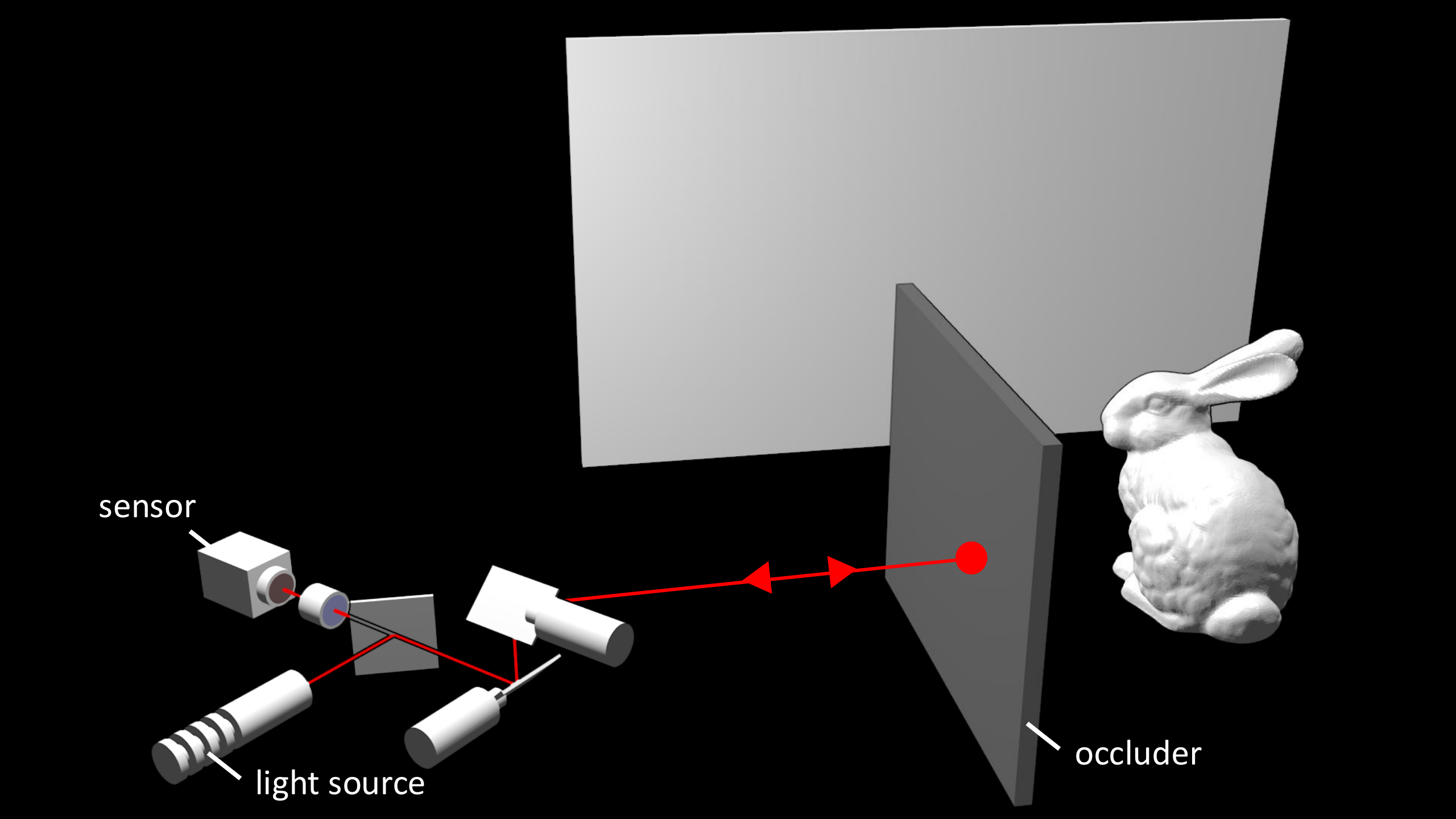
scene photo

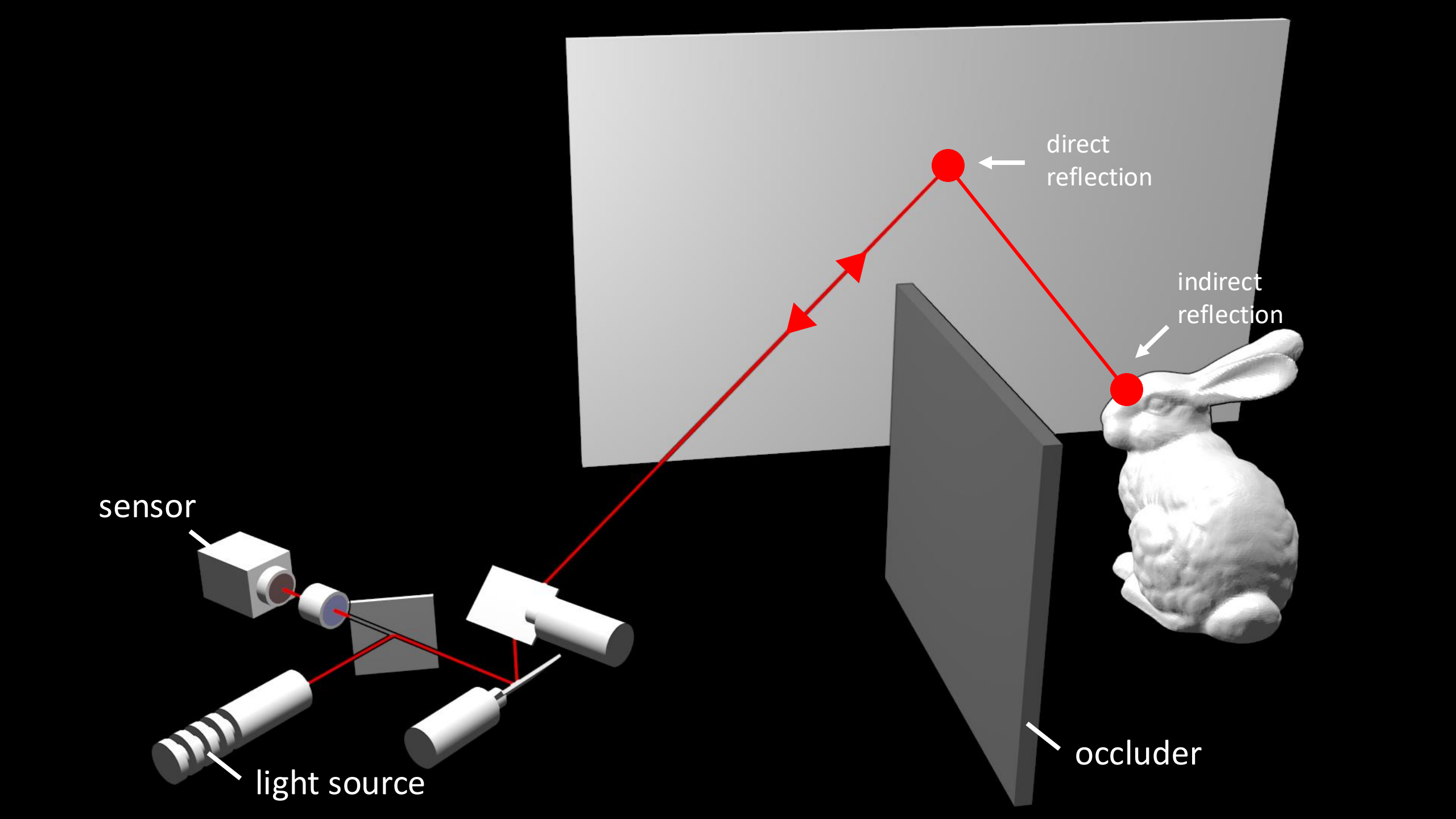
reconstruction



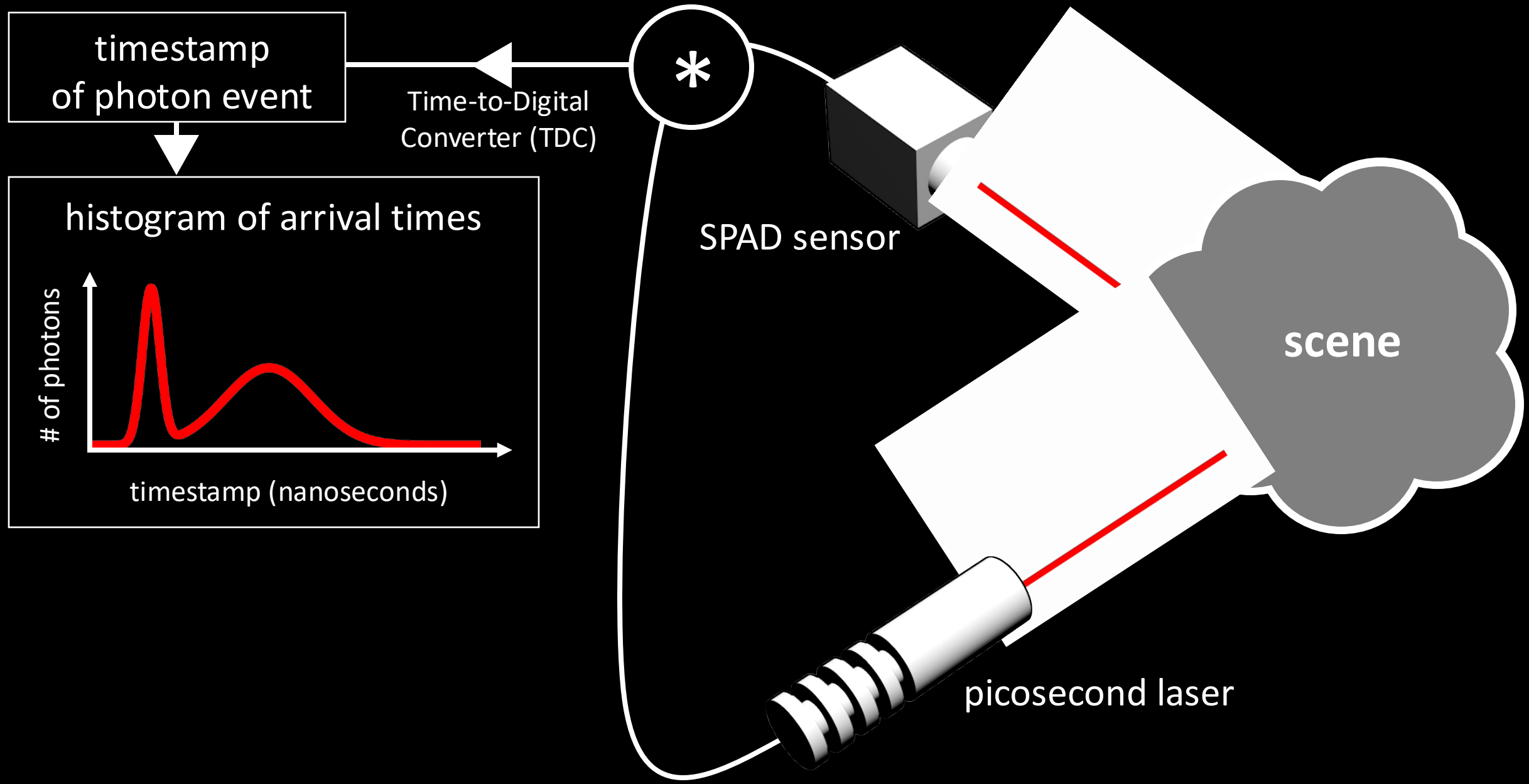
Dimensions: 2 m x 2 m x 1.5 m

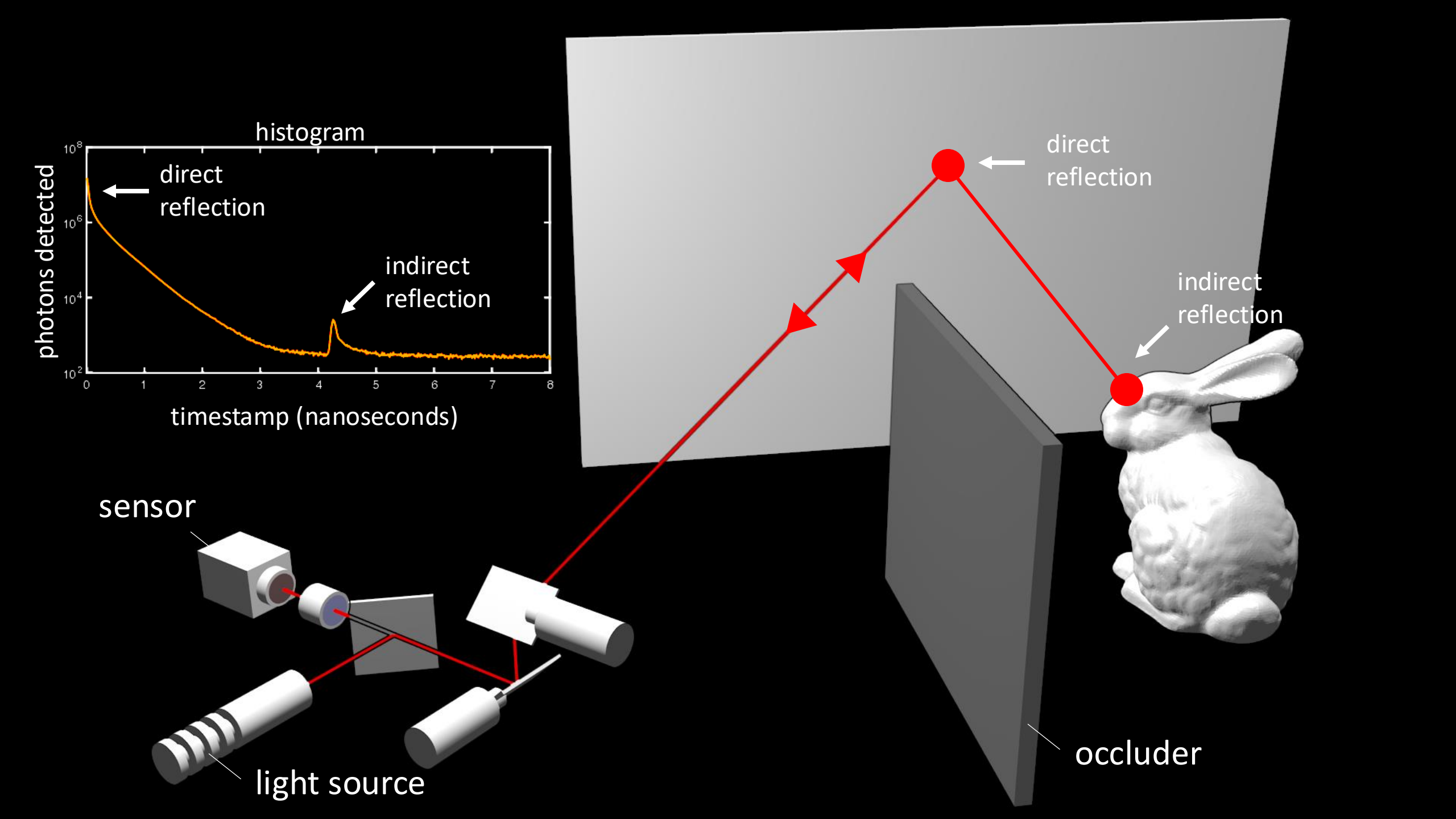

sensor
light source

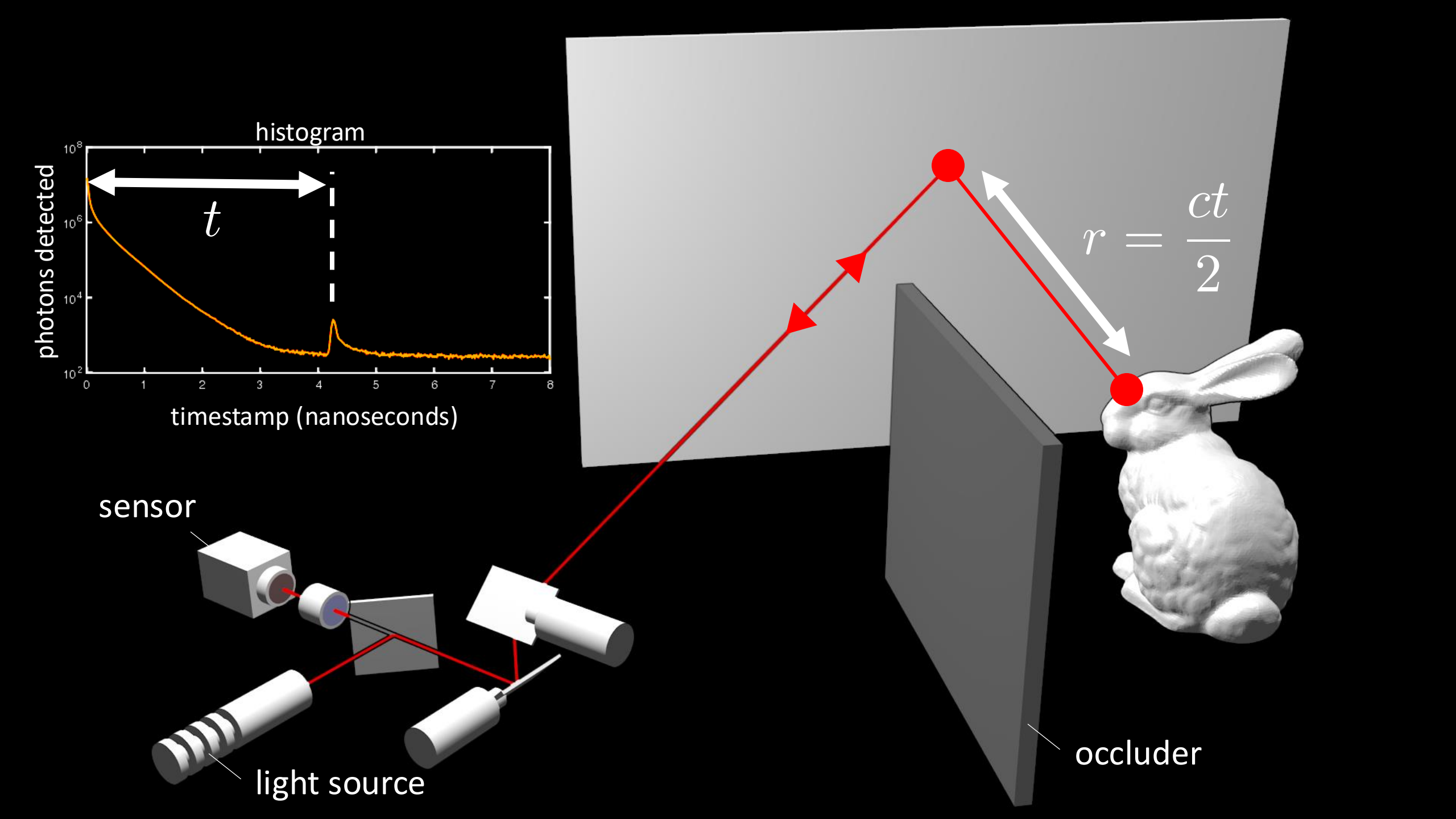

sensor
light source
occluder


direct
reflection
indirect
reflection
sensor
light source
occluder

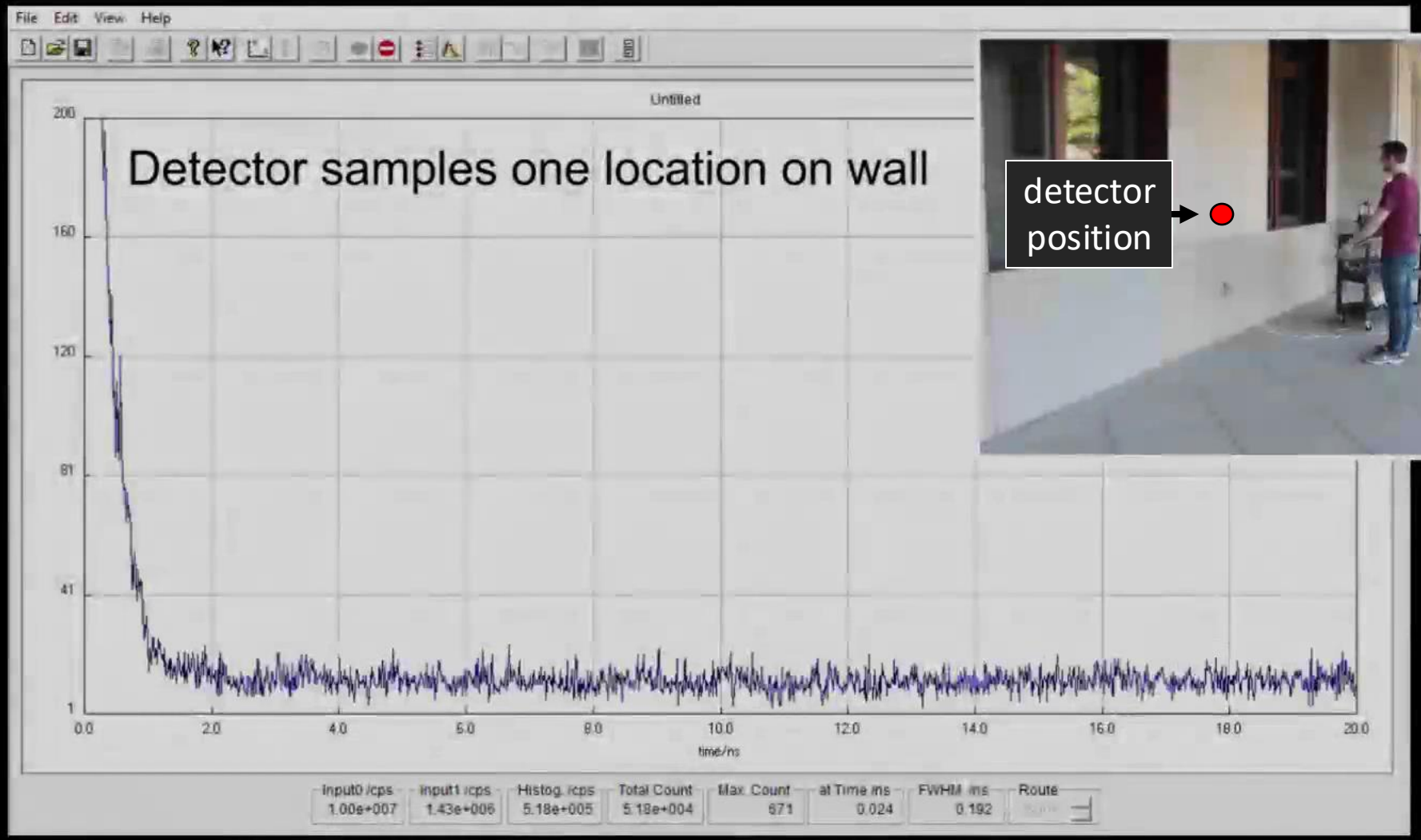
single photon avalanche diodes (SPADS)



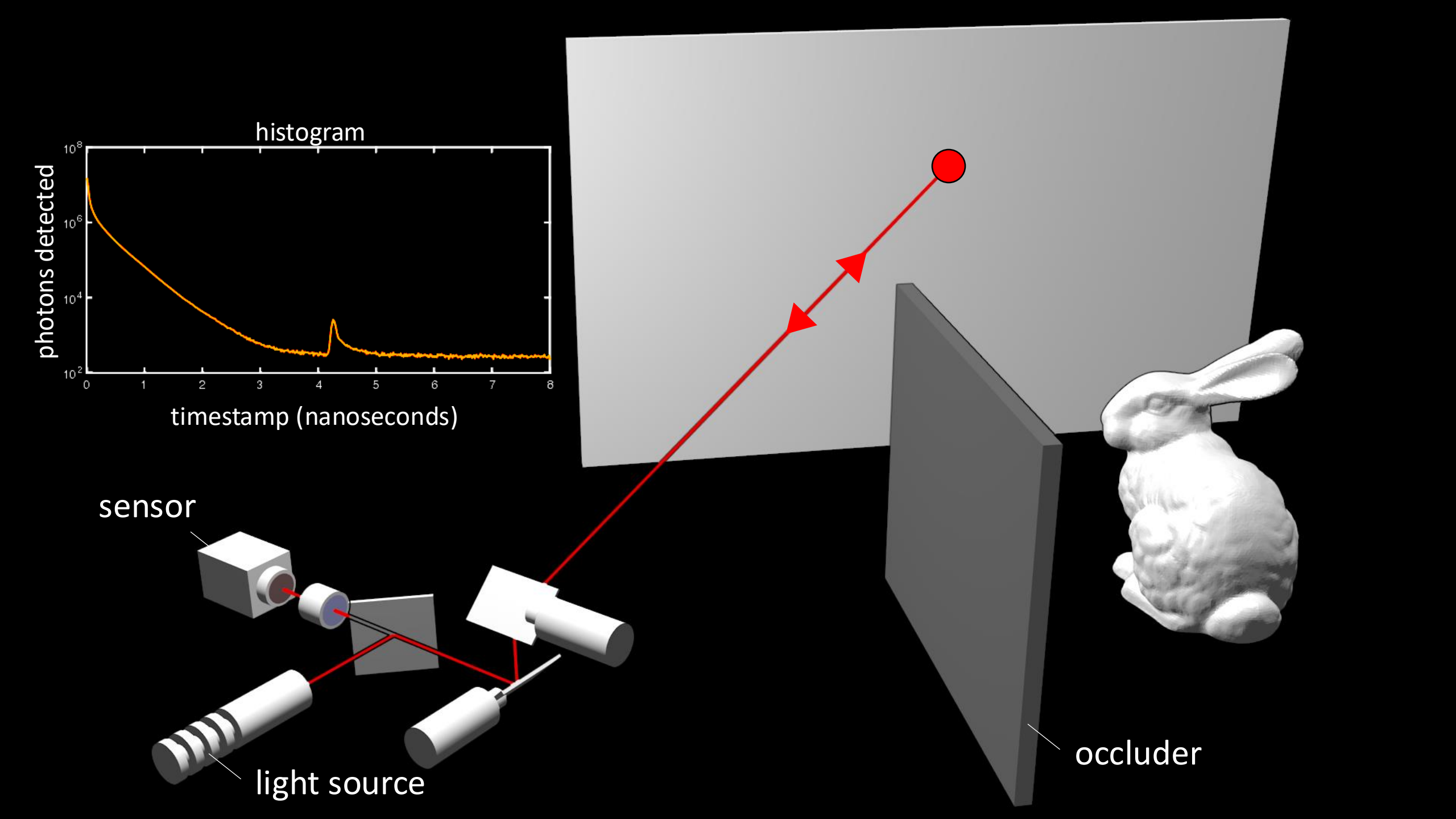

histogram
direct reflection
indirect reflection
photons detected
timestamp (nanoseconds)
direct reflection
indirect reflection
sensor
light source
occluder

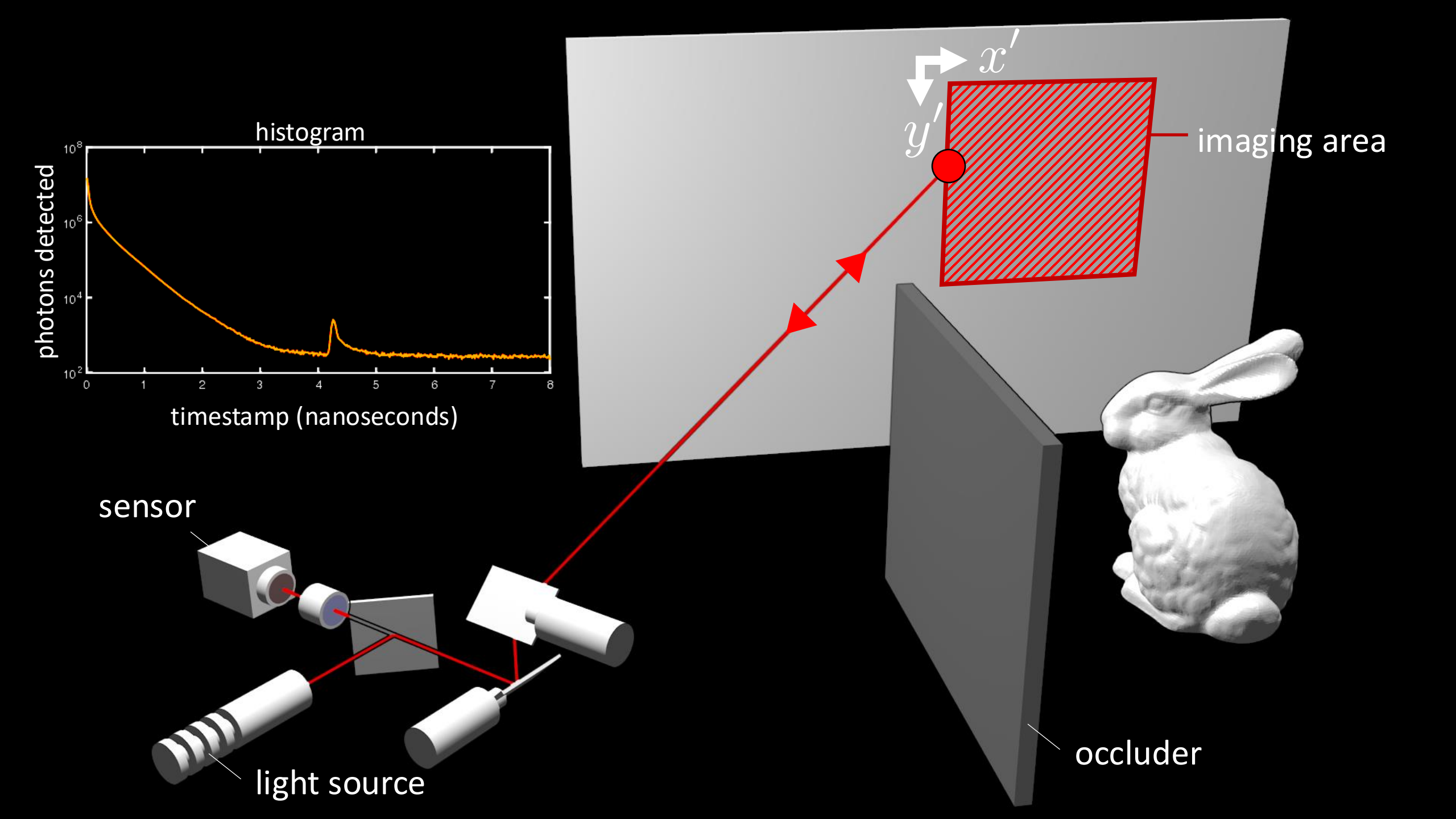

histogram
photons detected
10^8
10^6
10^4
10^2
0
1
2
3
4
5
6
7
8
timestamp (nanoseconds)
t
$r = \frac{ct}{2}$
sensor
light source
occluder

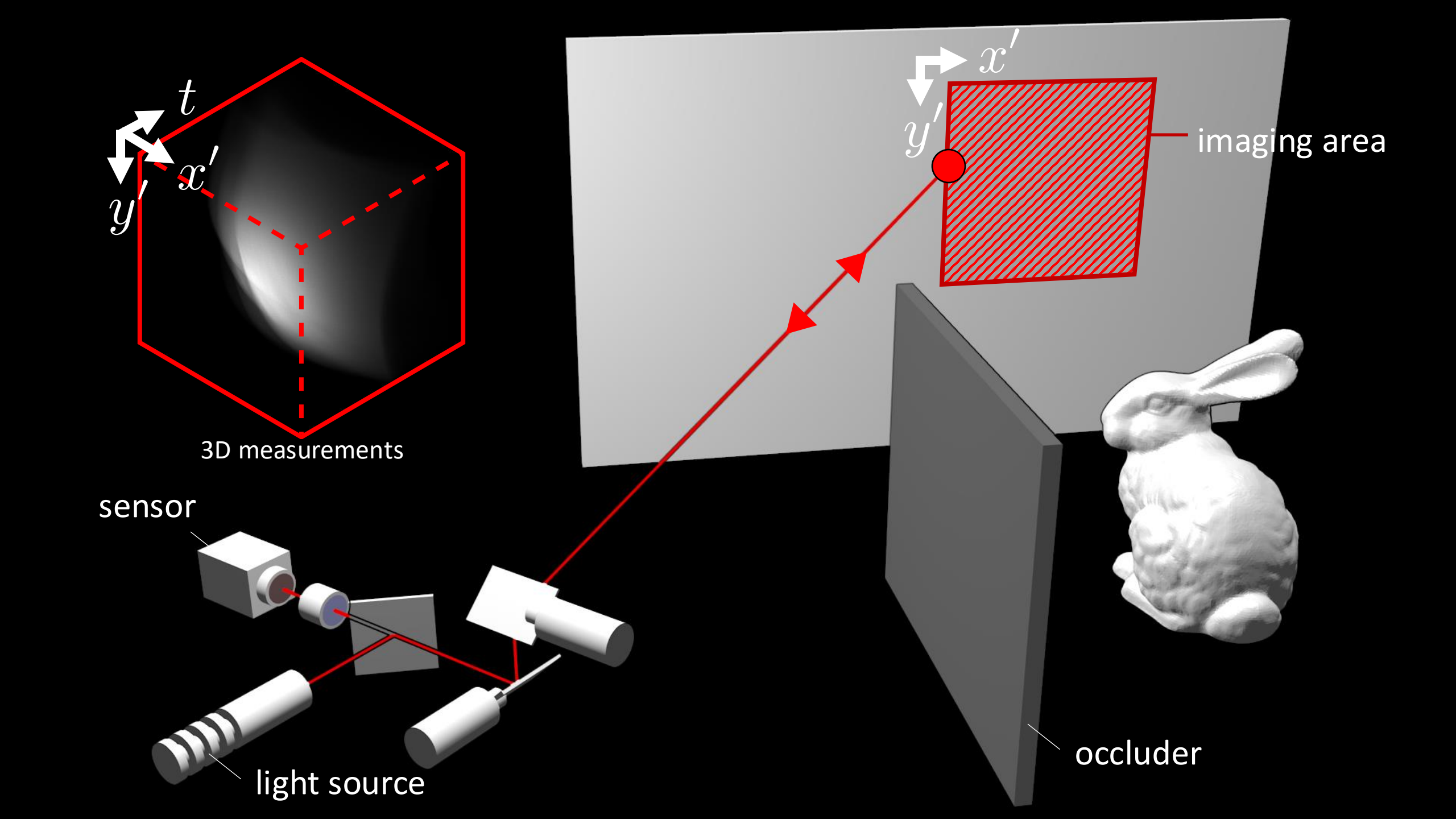
RAW histogram (10 FPS)

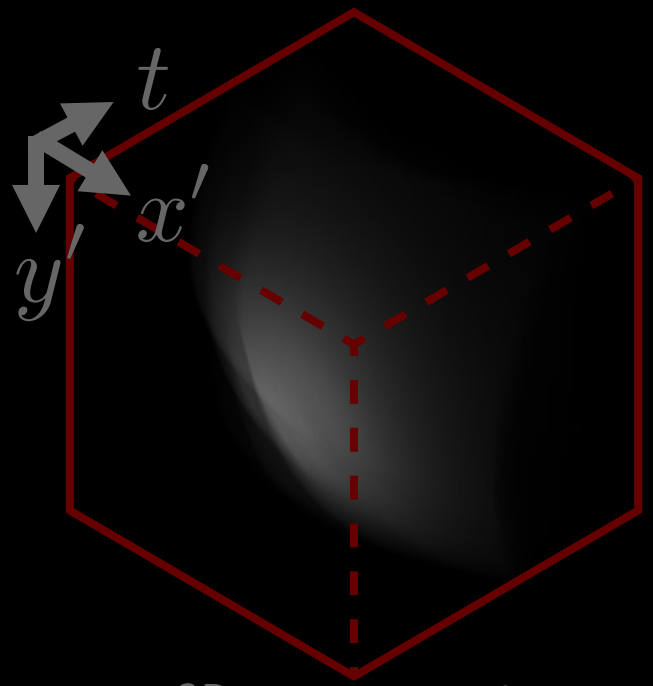


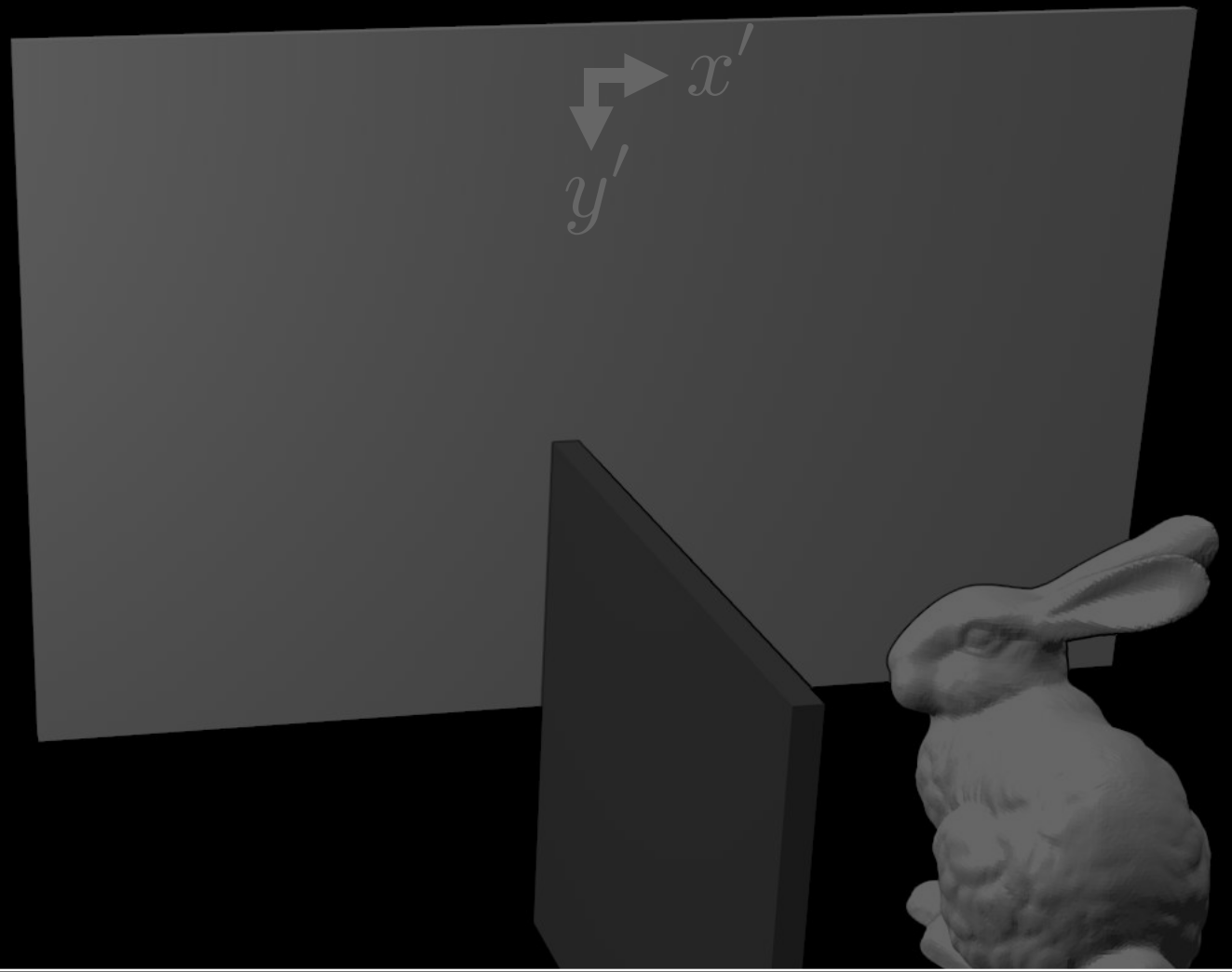
object


histogram
photons detected
timestamp (nanoseconds)
sensor
light source
occluder


histogram
photons detected
10^8
10^6
10^4
10^2
0
1
2
3
4
5
6
7
8
timestamp (nanoseconds)
x'
y'
imaging area
sensor
light source
occluder

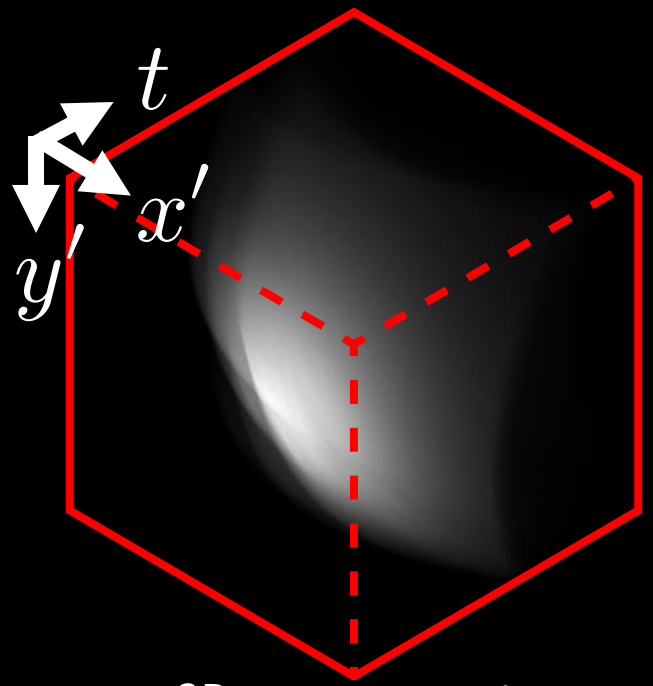

t
x'
y'
3D measurements
x'
y'
imaging area
sensor
light source
occluder



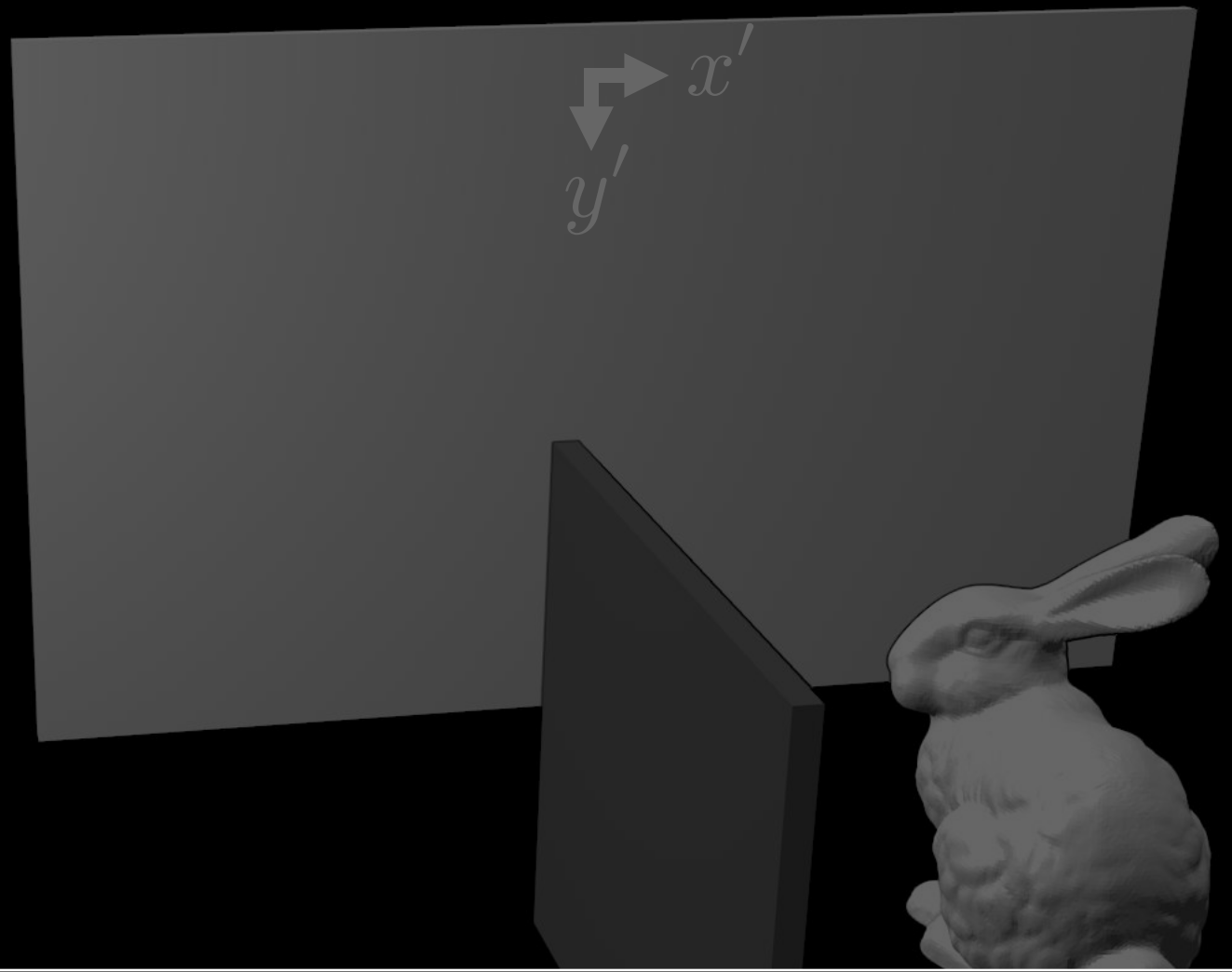


$$\tau(x', y', t) = \iiint_{\Omega} \frac{1}{r_l^2 r^2} \delta\left(r_l + r - tc\right) \cdot \rho(x, y, z)\, dx\, dy\, dz$$

3D measurements — radiometric term — geometric term — hidden 3D volume



3D measurements



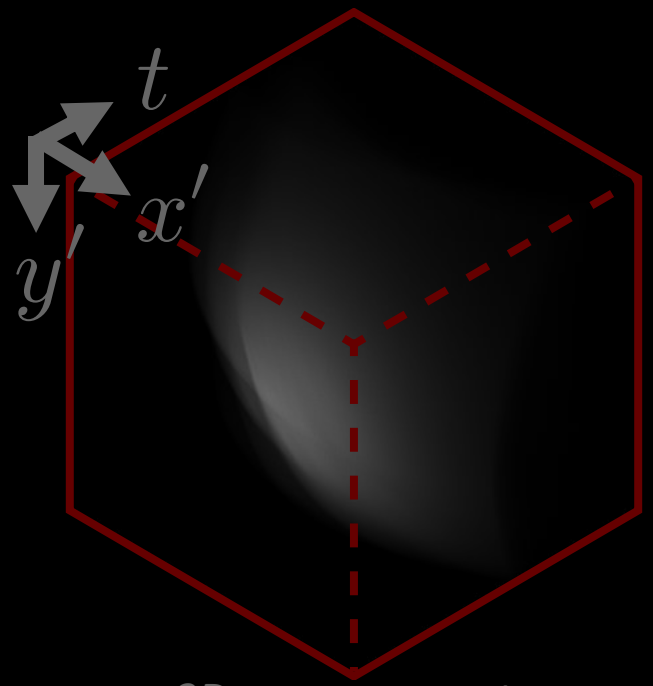
$$\tau(x', y', t) = \iiint_{\Omega} \frac{1}{r_l^2 r^2} \delta\left(r_l + r - tc\right) \cdot \rho(x, y, z)\, dx\, dy\, dz$$

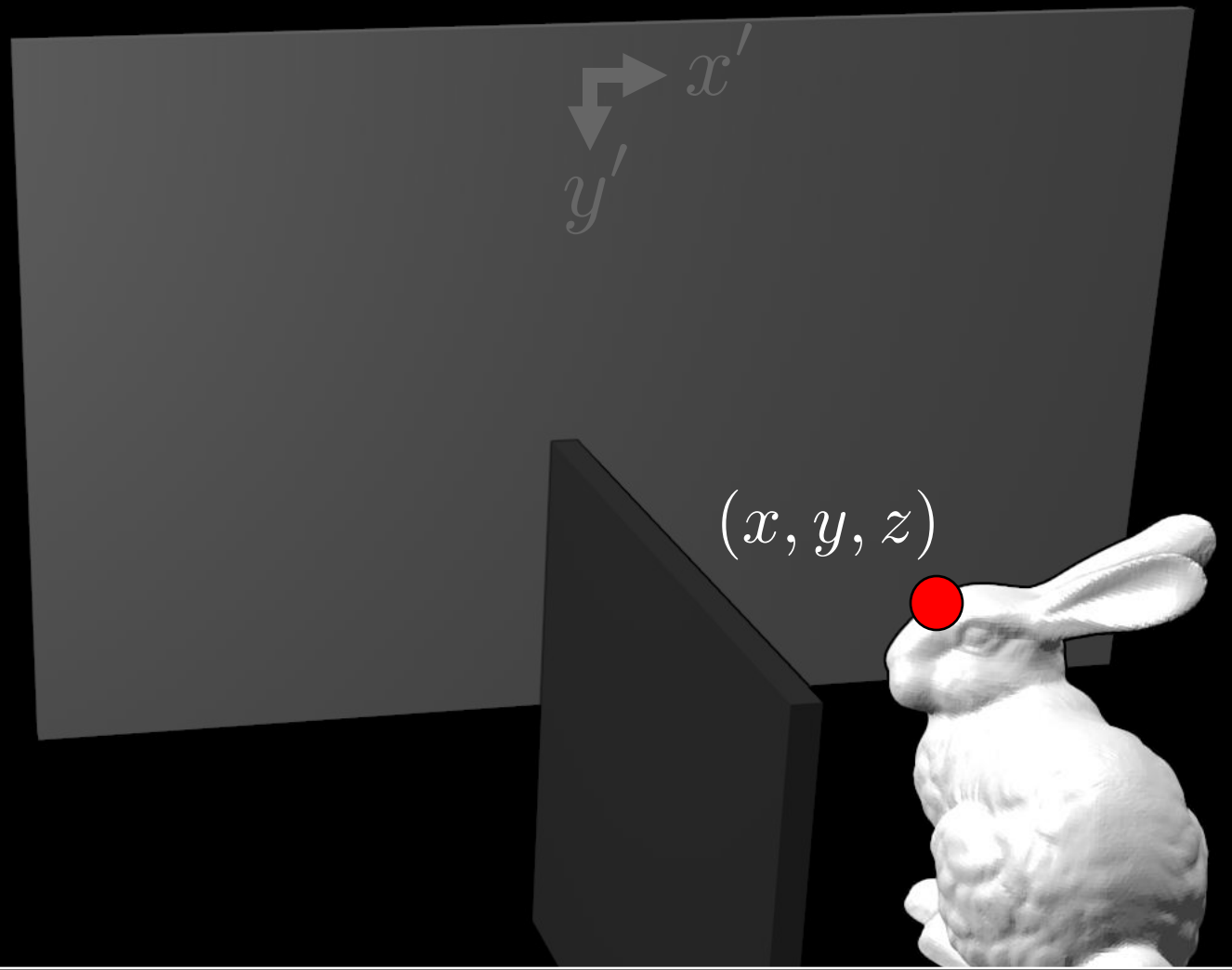
3D measurements

radiometric term

geometric term

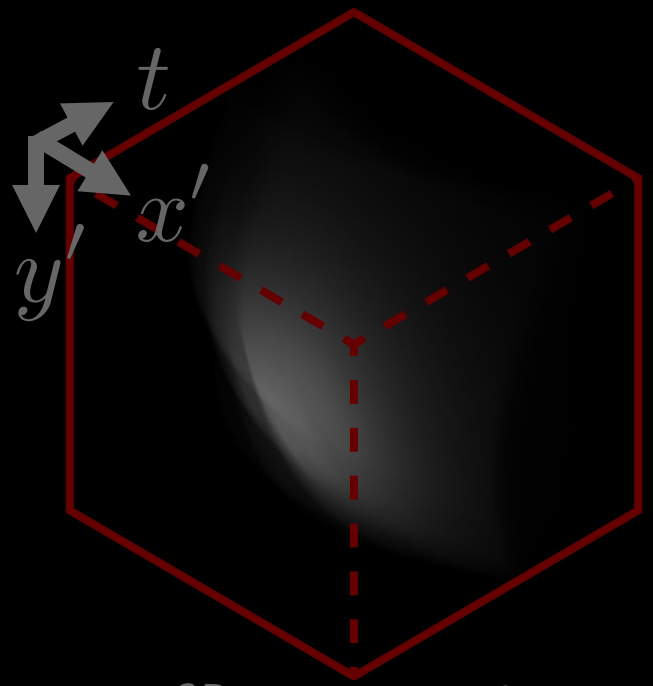
hidden 3D volume

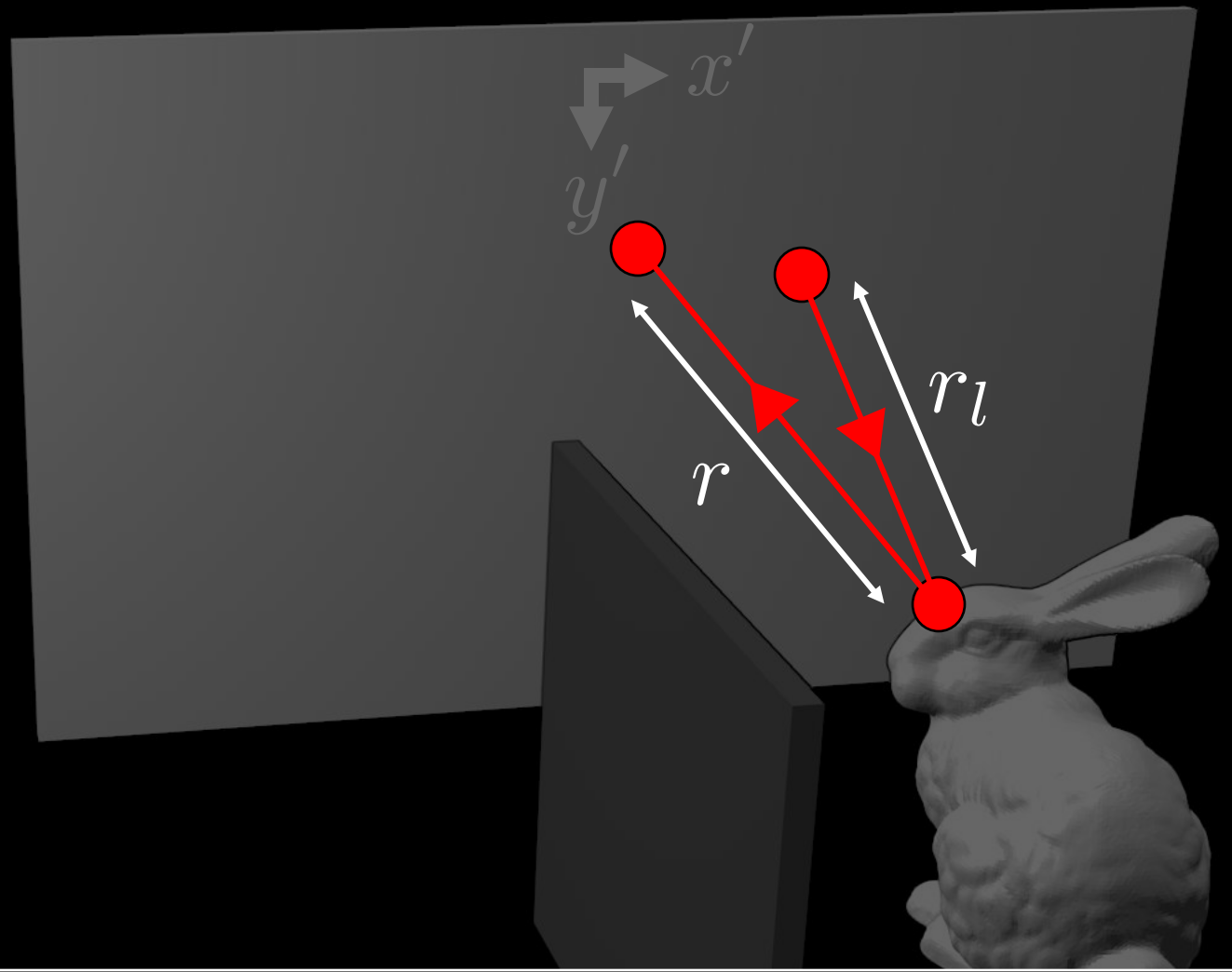




$$\tau(x', y', t) = \iiint_{\Omega} \underbrace{\frac{1}{r_l^2 r^2}}_{\text{radiometric term}} \underbrace{\delta\left(r_l + r - tc\right)}_{\text{geometric term}} \cdot \underbrace{\rho(x, y, z)}_{\text{hidden 3D volume}} \, dx \, dy \, dz$$

3D measurements





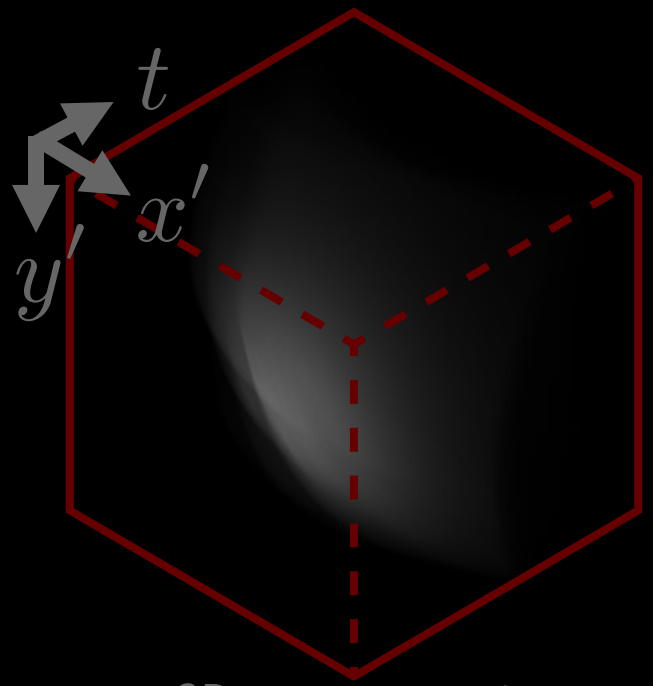
$$\tau(x', y', t) = \iiint_{\Omega} \frac{1}{r_l^2 r^2} \delta\left(r_l + r - tc\right) \cdot \rho(x, y, z)\, dx\, dy\, dz$$

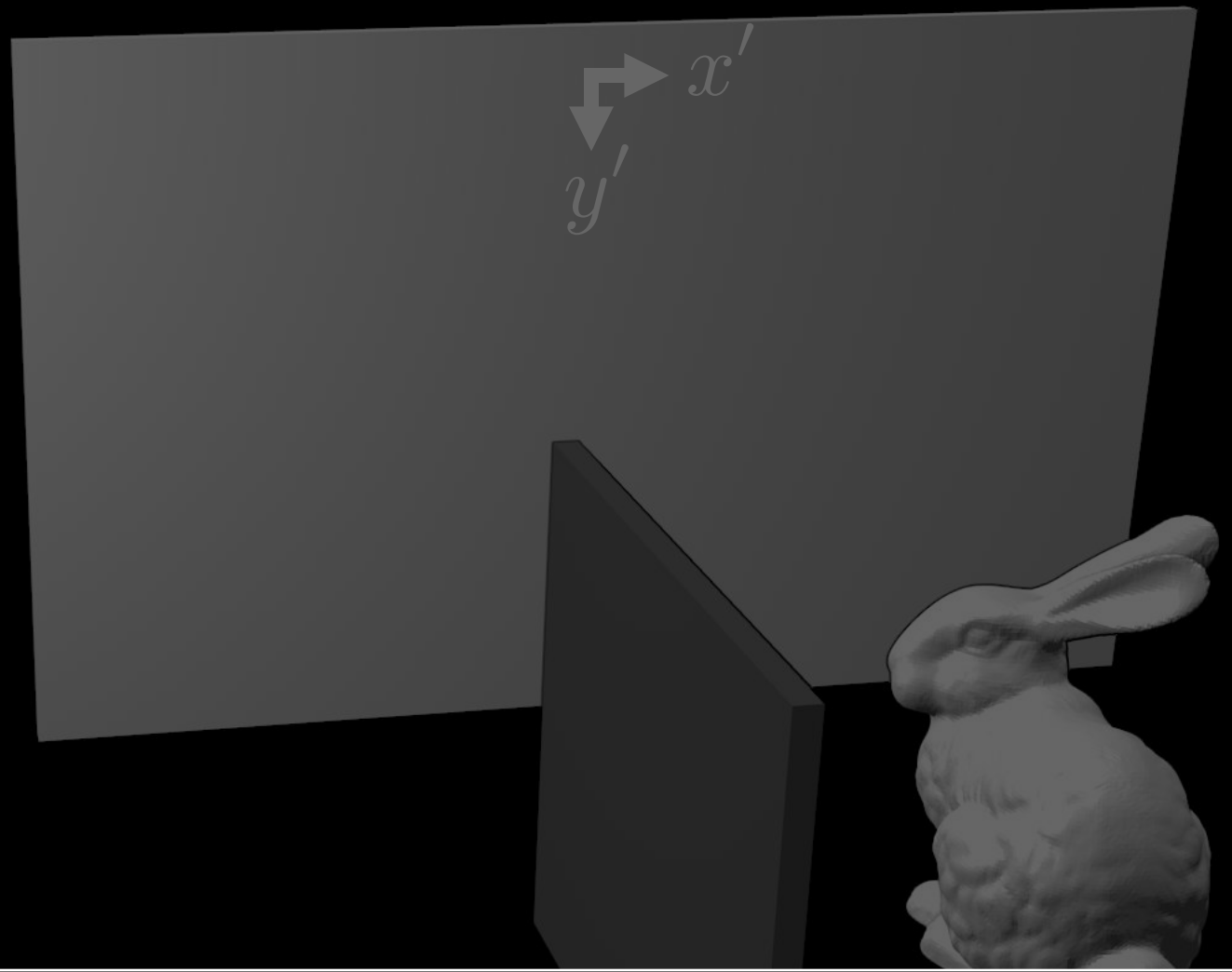
3D measurements

radiometric term

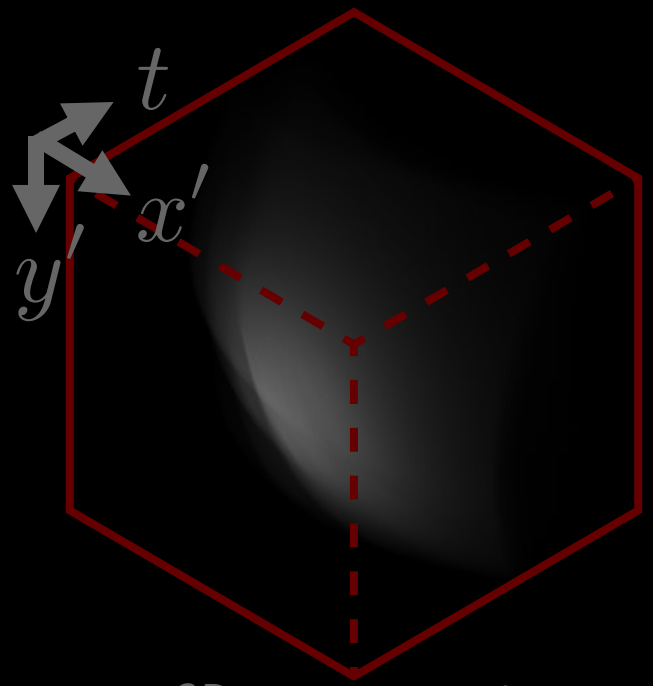
geometric term

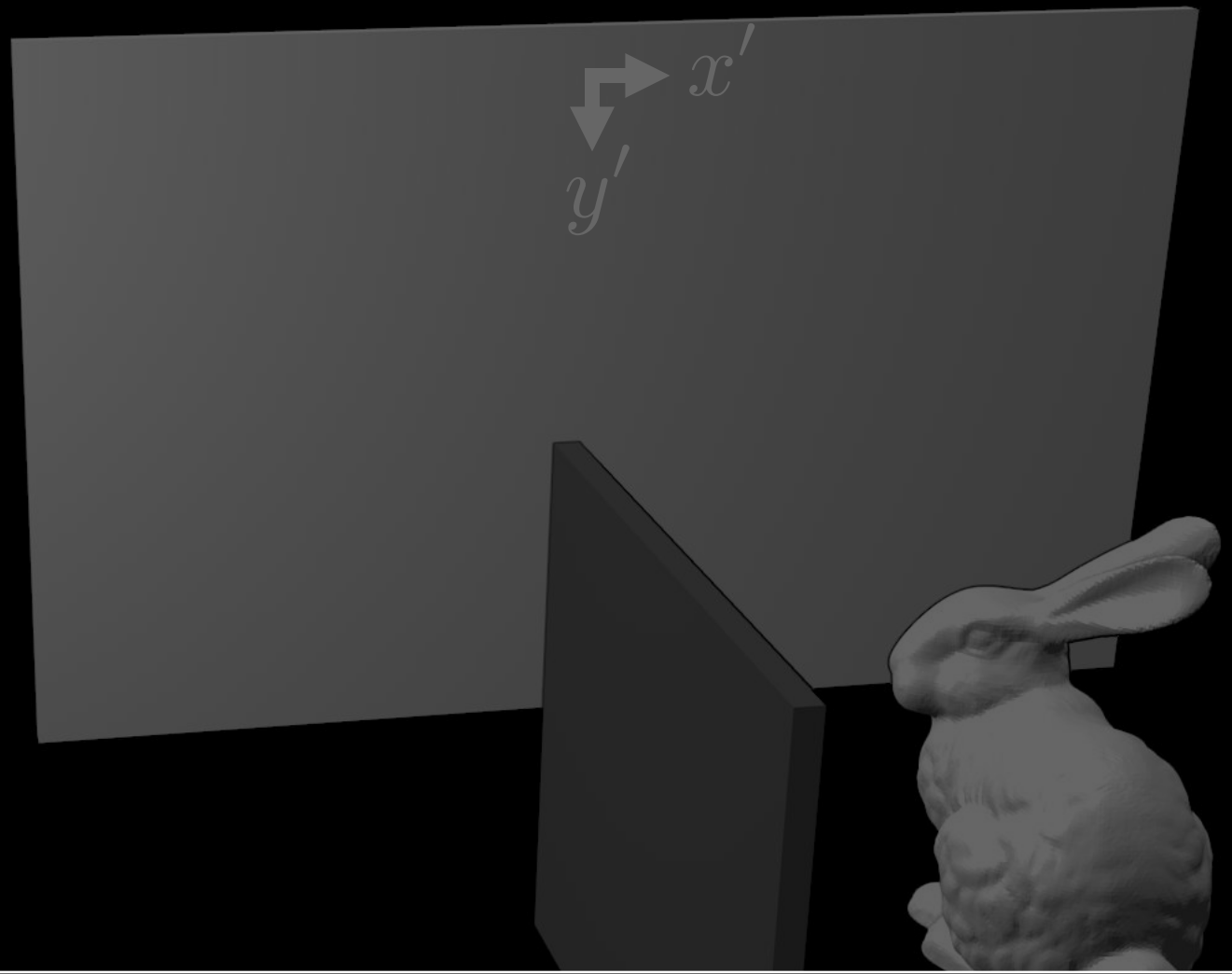
hidden 3D volume





$$\tau(x', y', t) = \iiint_{\Omega} \frac{1}{r_l^2 r^2} \delta\left(r_l + r - tc\right) \cdot \rho(x, y, z)\, dx\, dy\, dz$$





$$\underbrace{\tau(x', y', t)}_{\tau} = \underbrace{\iiint_{\Omega} \underbrace{\frac{1}{r_l^2 r^2} \delta\left(r_l + r - tc\right)}_{\mathbf{A}} \cdot \underbrace{\rho(x, y, z)}_{\rho}\, dx\, dy\, dz}_{\times}$$

NLOS image formation mode:

$$\tau = \mathbf{A}\rho$$

measurements $n^3 \times 1$ — transport matrix $n^3 \times n^3$ — unknown volume $n^3 \times 1$

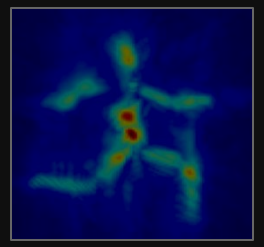
PROBLEM: $\mathbf{A}$ extremely large in practice (e.g., for n = 100, $\mathbf{A}$ has 1 trillion elements)

Backpropagation [Velten 12, Buttafava 15]

Flops: $O(n^5)$

Memory: $O(n^3)$

Runtime: Approx. 10 min.



Iterative Inversion [Gupta 12, Heide 13]

Flops: $O(n^5)$ per iter.

Memory: $O(n^5)$

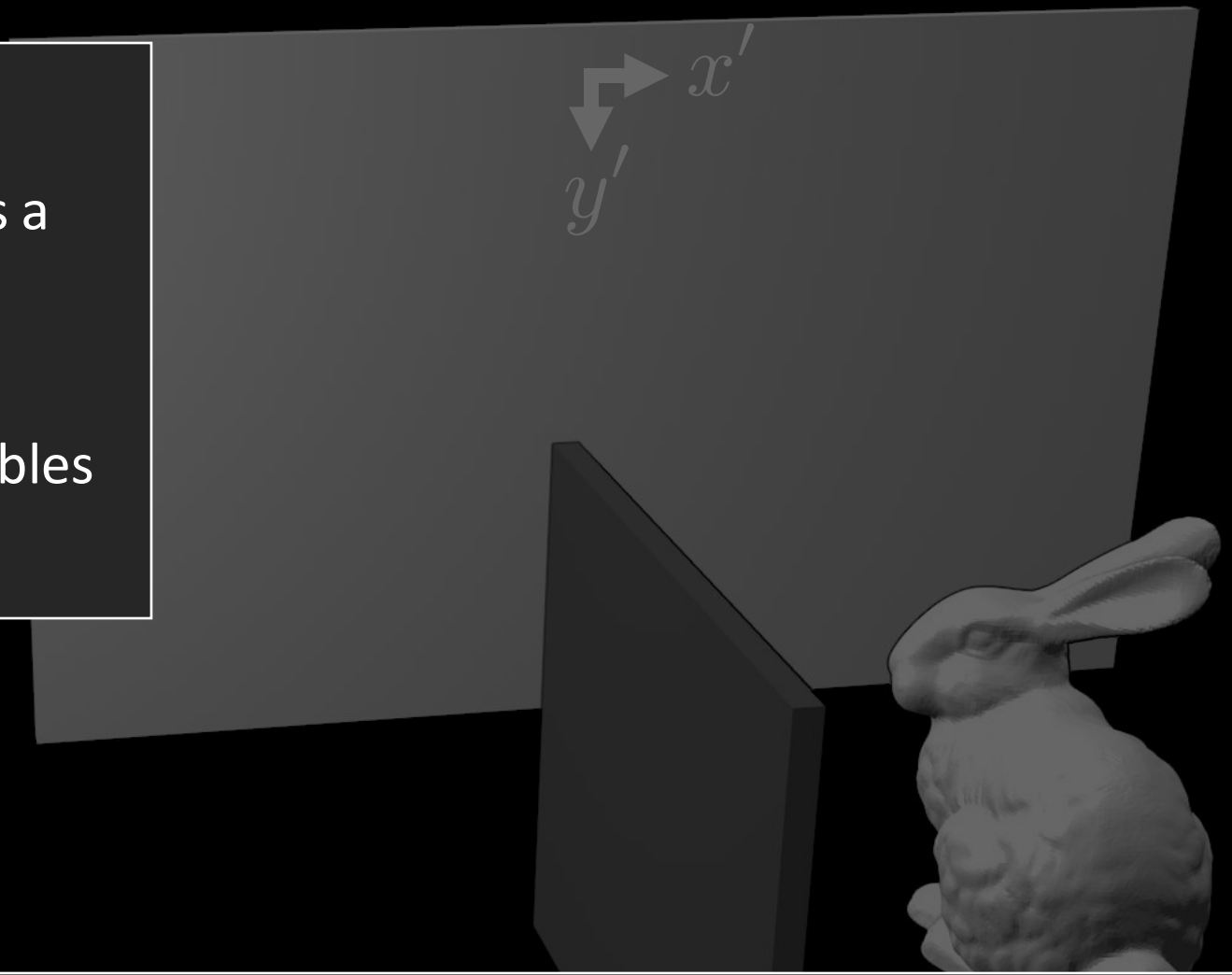
Runtime: > 1 hour

Our approach

express image formation model as a 3D convolution, by:

1. confocalizing measurements
2. performing a change of variables (set $z = \sqrt{u}\,,\ t = 2\sqrt{v}/c$)

3D measurements



$$\tau(x', y', t) = \iiint_{\Omega} \frac{1}{r_l^2 r^2} \delta\left(r_l + r - tc\right) \cdot \rho(x, y, z)\ dx\ dy\ dz$$

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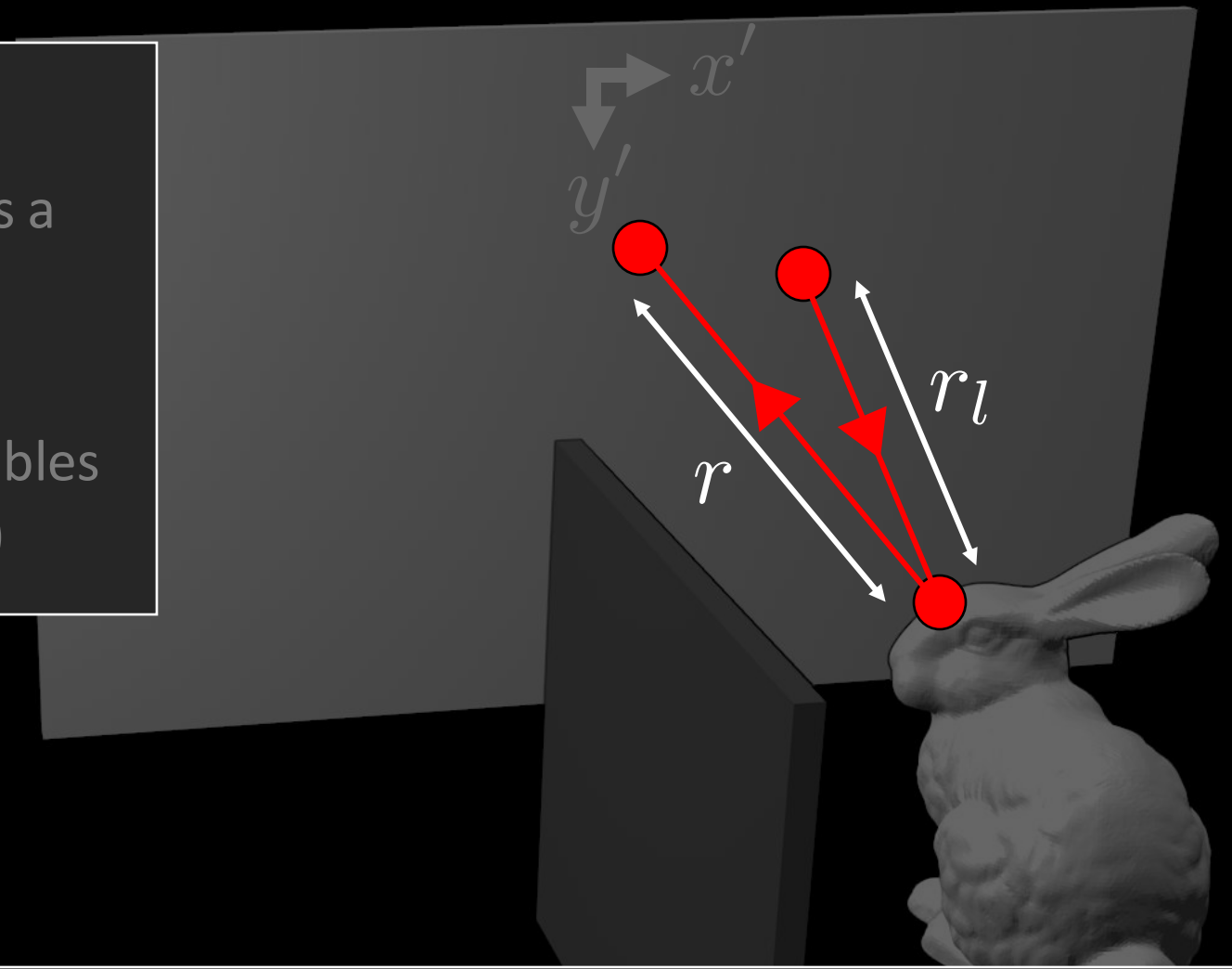

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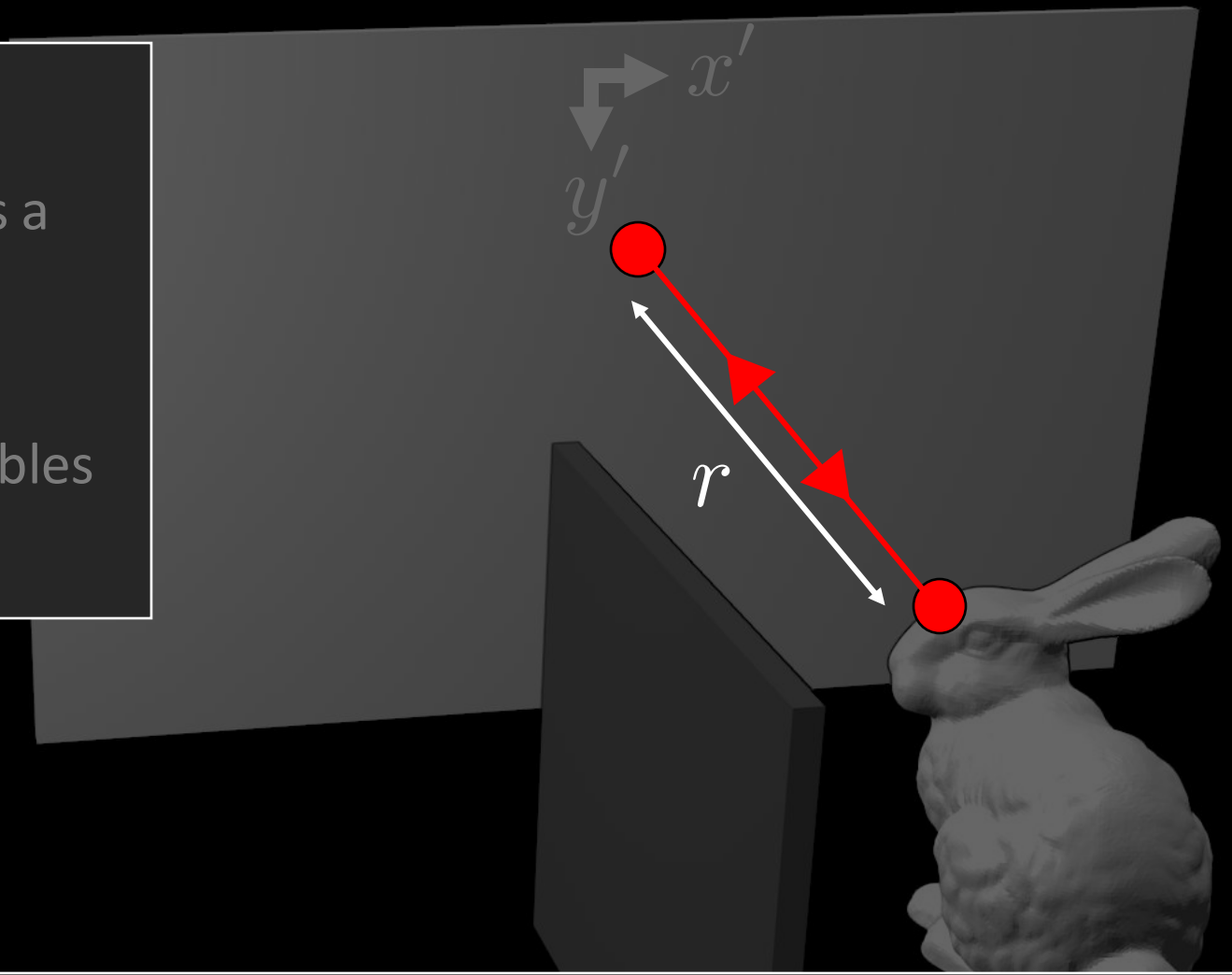

$$\tau(x', y', t) = \iiint_{\Omega} \frac{1}{r^4} \delta\left(2r - tc\right) \cdot \rho(x, y, z)\ dx\ dy\ dz$$

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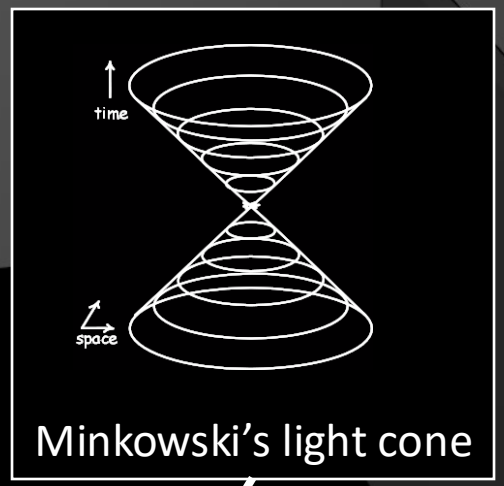
3D measurements



Minkowski's light cone

$$\tau(x', y', t) = \iiint_{\Omega} \frac{1}{r^4} \delta\left(2r - tc\right) \cdot \rho(x, y, z)\ dx\ dy\ dz$$

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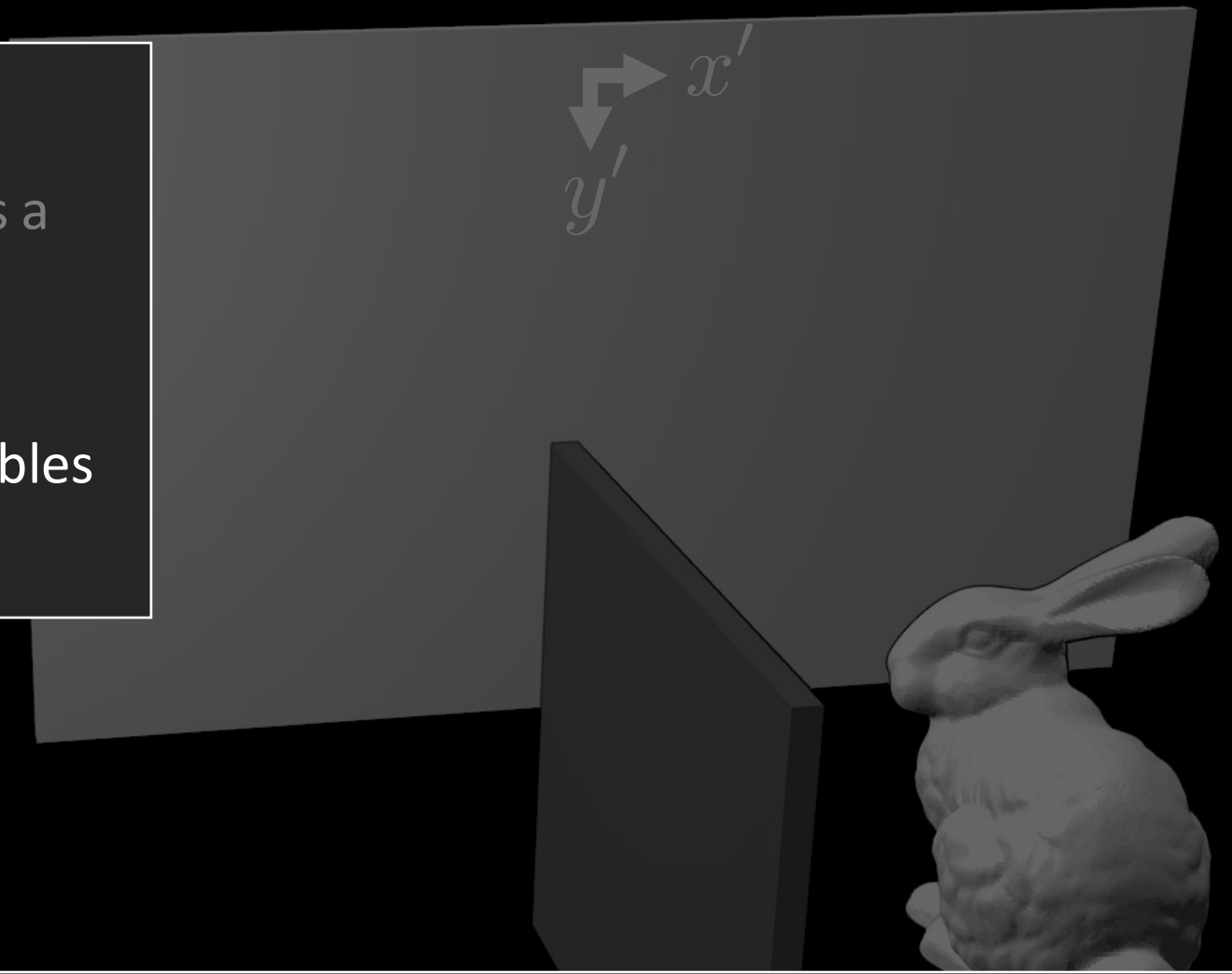
3D measurements



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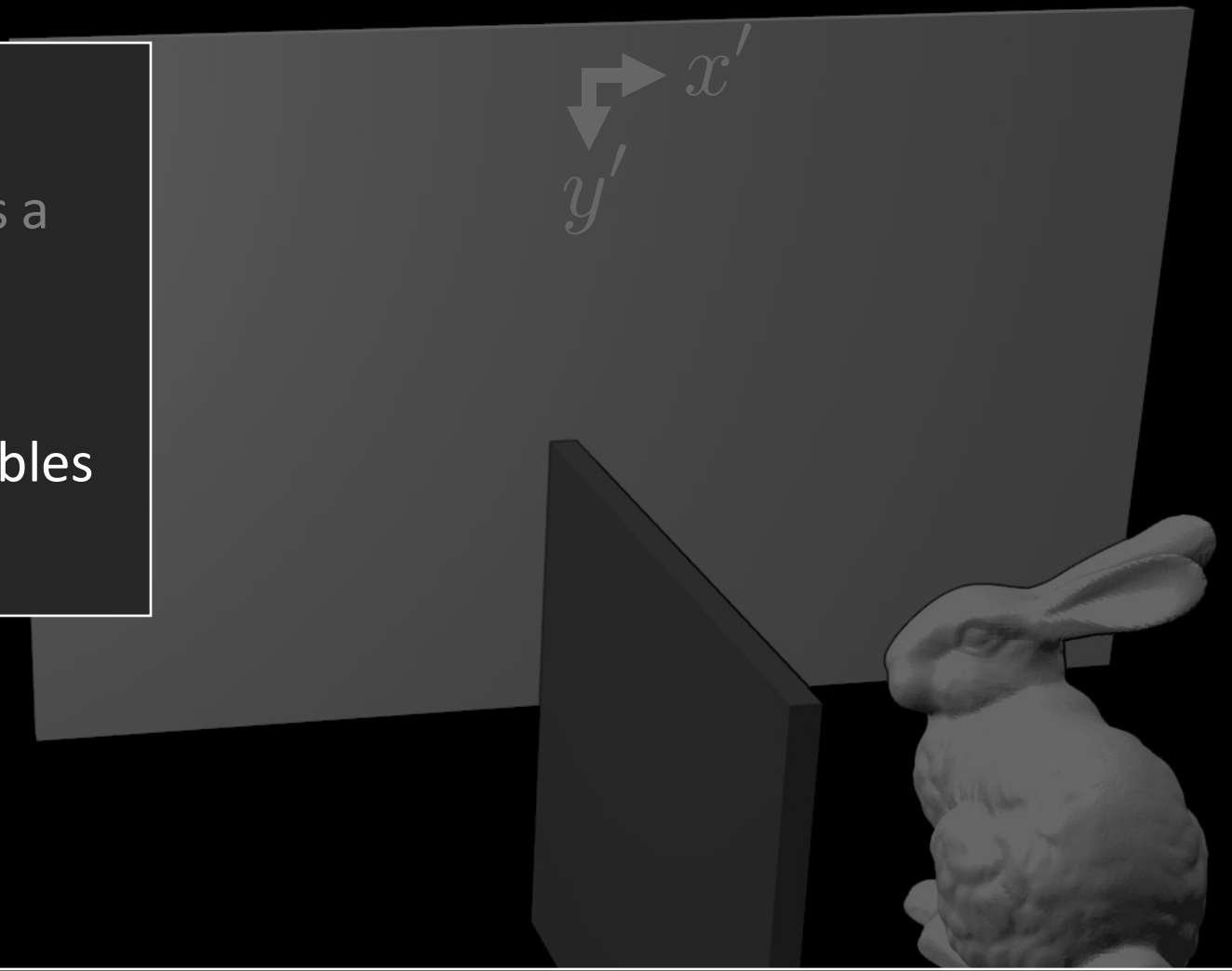

$$v^{3/2}\tau(x', y', \frac{2}{c}\sqrt{v}) = \iiint_{\Omega} \frac{1}{2\sqrt{u}}\delta\left((x'-x)^2 + (y'-y)^2 + u - v\right) \cdot \rho(x, y, \sqrt{u})dxdydu$$

Our approach

express image formation model as a 3D convolution, by:

1. confocalizing measurements
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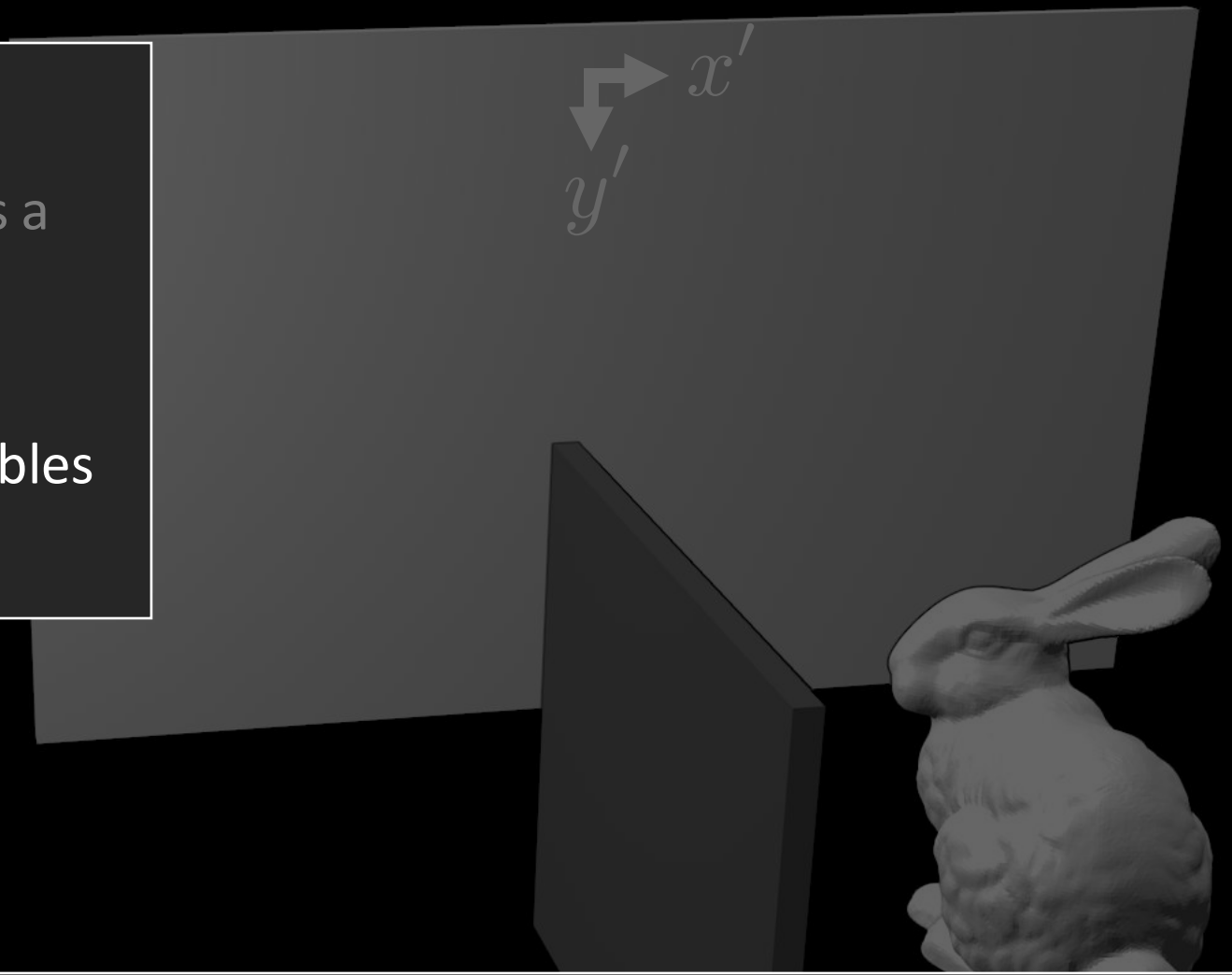
3D measurements



$$\underbrace{v^{3/2}\tau(x', y', \frac{2}{c}\sqrt{v})}_{\tau} = \underbrace{\iiint_{\Omega} \frac{1}{2\sqrt{u}}\delta\left((x'-x)^2 + (y'-y)^2 + u - v\right)}_{\mathbf{a}} * \underbrace{\cdot\, \rho(x, y, \sqrt{u})}_{\rho} dx dy du$$

NLOS image formation mode:

$$\tau = \mathbf{A}\rho$$

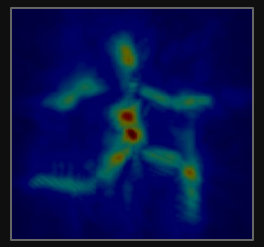
measurements $n^3 \times 1$ | transport matrix $n^3 \times n^3$ | unknown volume $n^3 \times 1$

Backpropagation [Velten 12, Buttafava 15]

Flops: $O(n^5)$

Memory: $O(n^3)$

Runtime: Approx. 10 min.



Iterative Inversion [Gupta 12, Heide 13]

Flops: $O(n^5)$ per iter.

Memory: $O(n^5)$

Runtime: > 1 hour

Confocal NLOS image formation mode:

$$\tau = \mathbf{a} * \rho$$

measurements $n \times n \times n$ | blur kernel $n \times n \times n$ | unknown volume $n \times n \times n$

NLOS image formation mode:

$$\tau = \mathbf{A}\rho$$

measurements $n^3 \times 1$ — transport matrix $n^3 \times n^3$ — unknown volume $n^3 \times 1$

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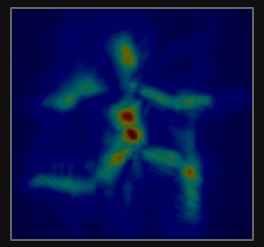

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Flops: $O(n^5)$ per iter.

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Confocal NLOS image formation mode:

$$\tau = \mathbf{a} * \rho$$

measurements $n \times n \times n$ — blur kernel $n \times n \times n$ — unknown volume $n \times n \times n$

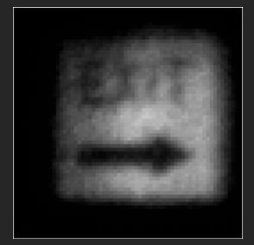
3D Deconvolution (with Light Cone Transform)

[O'Toole et al. 2018]

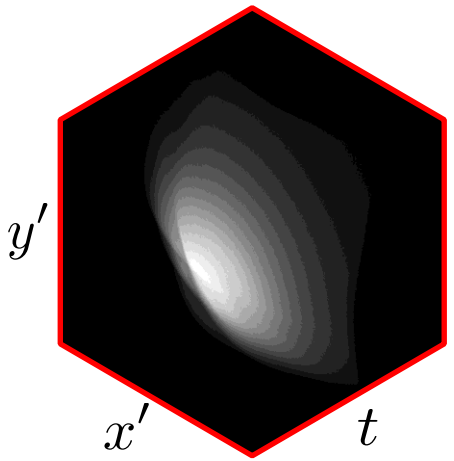
Flops: $O(n^3 \log(n))$

Memory: $O(n^3)$

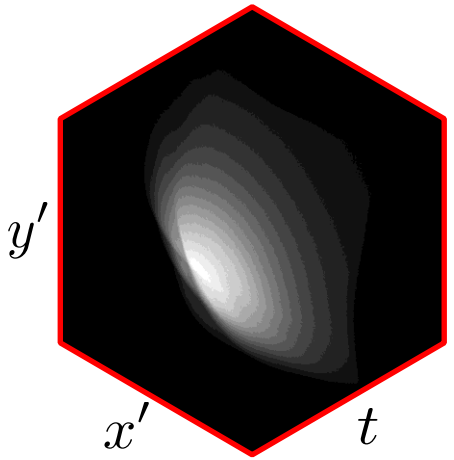
Runtime: 1/30 second



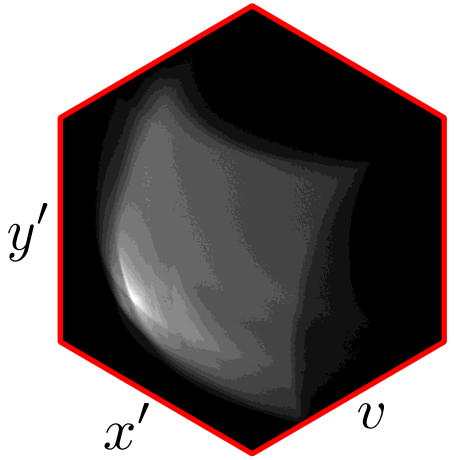
measurements

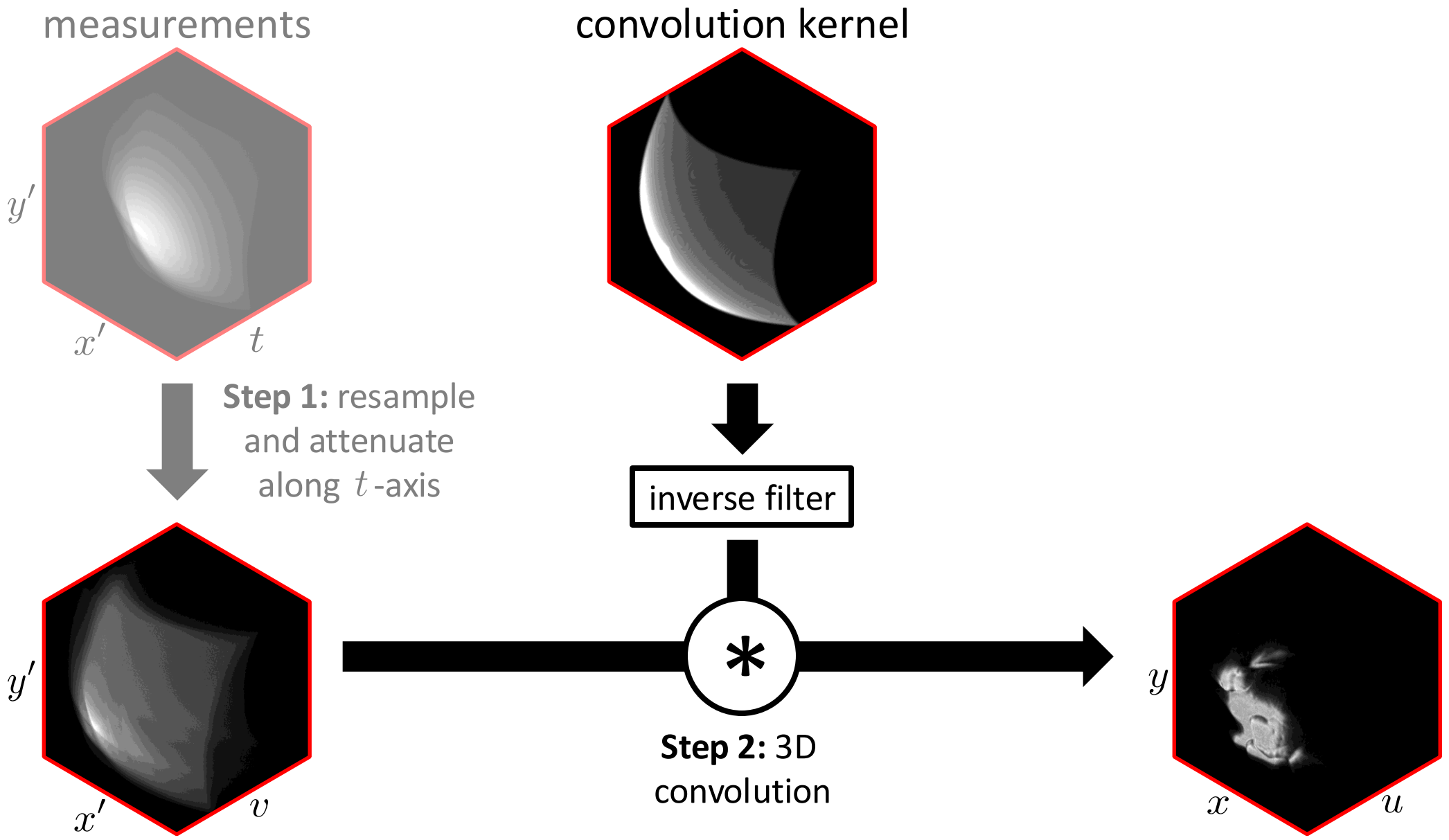


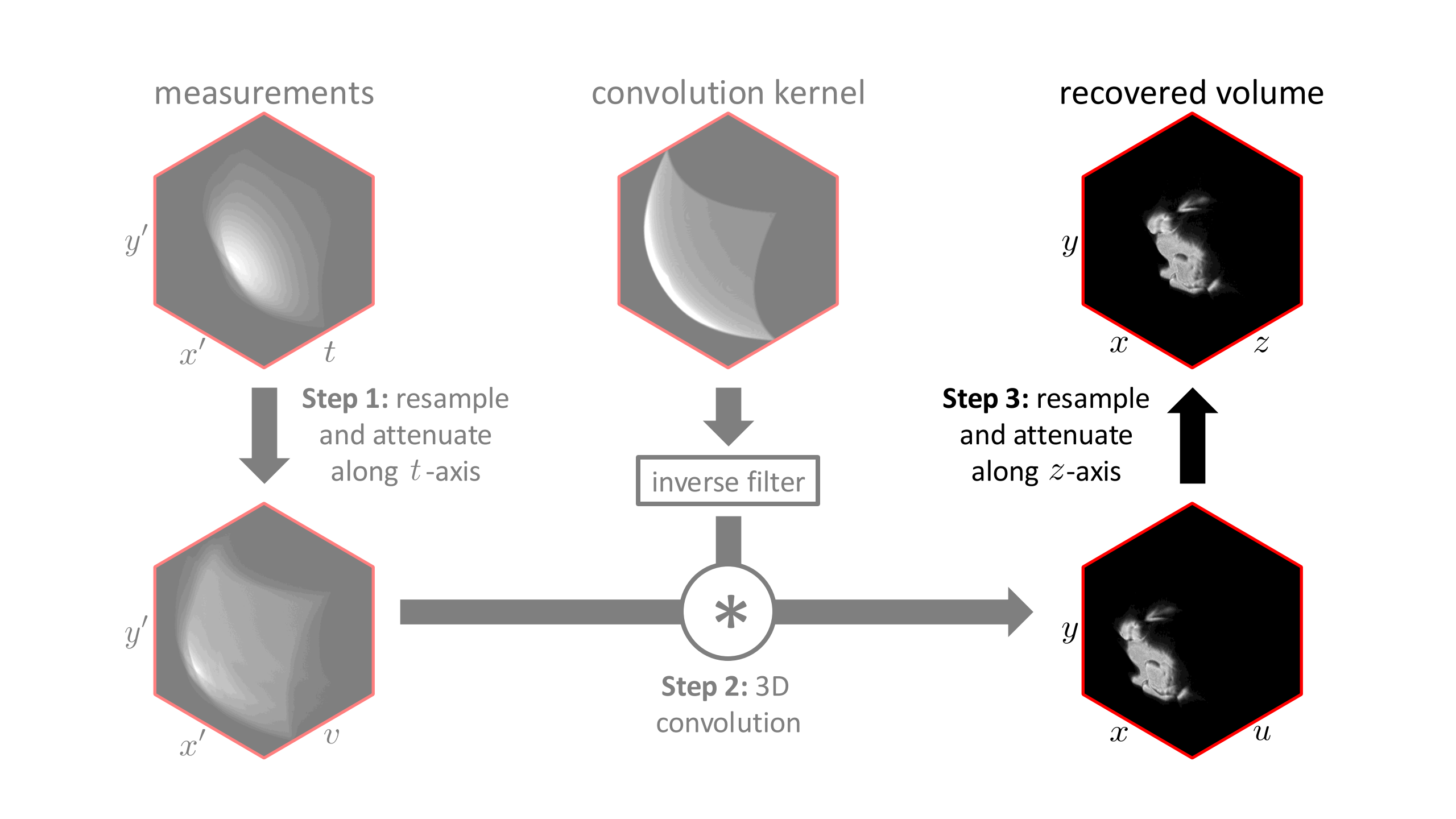
measurements

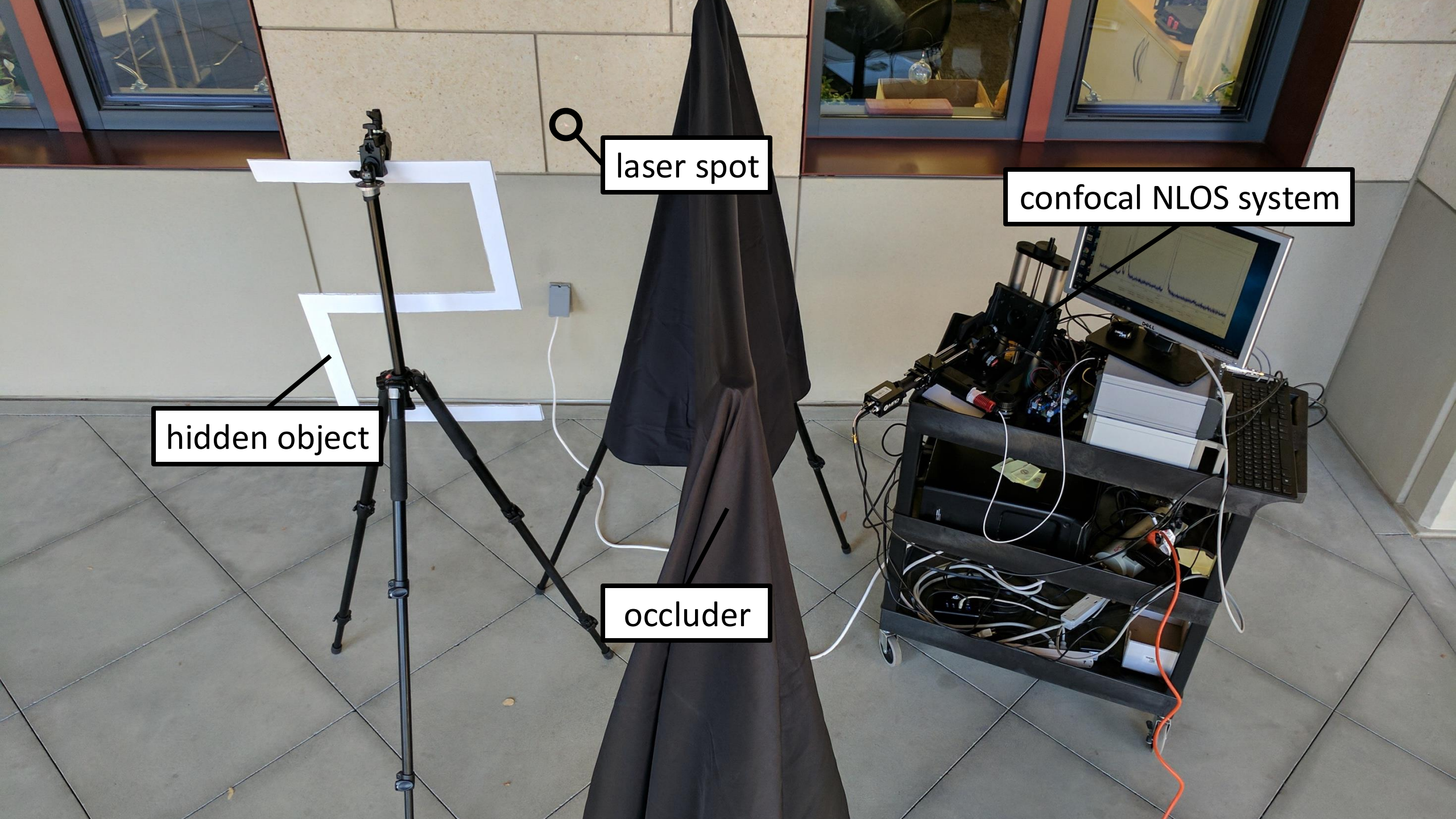


Step 1: resample and attenuate along t-axis

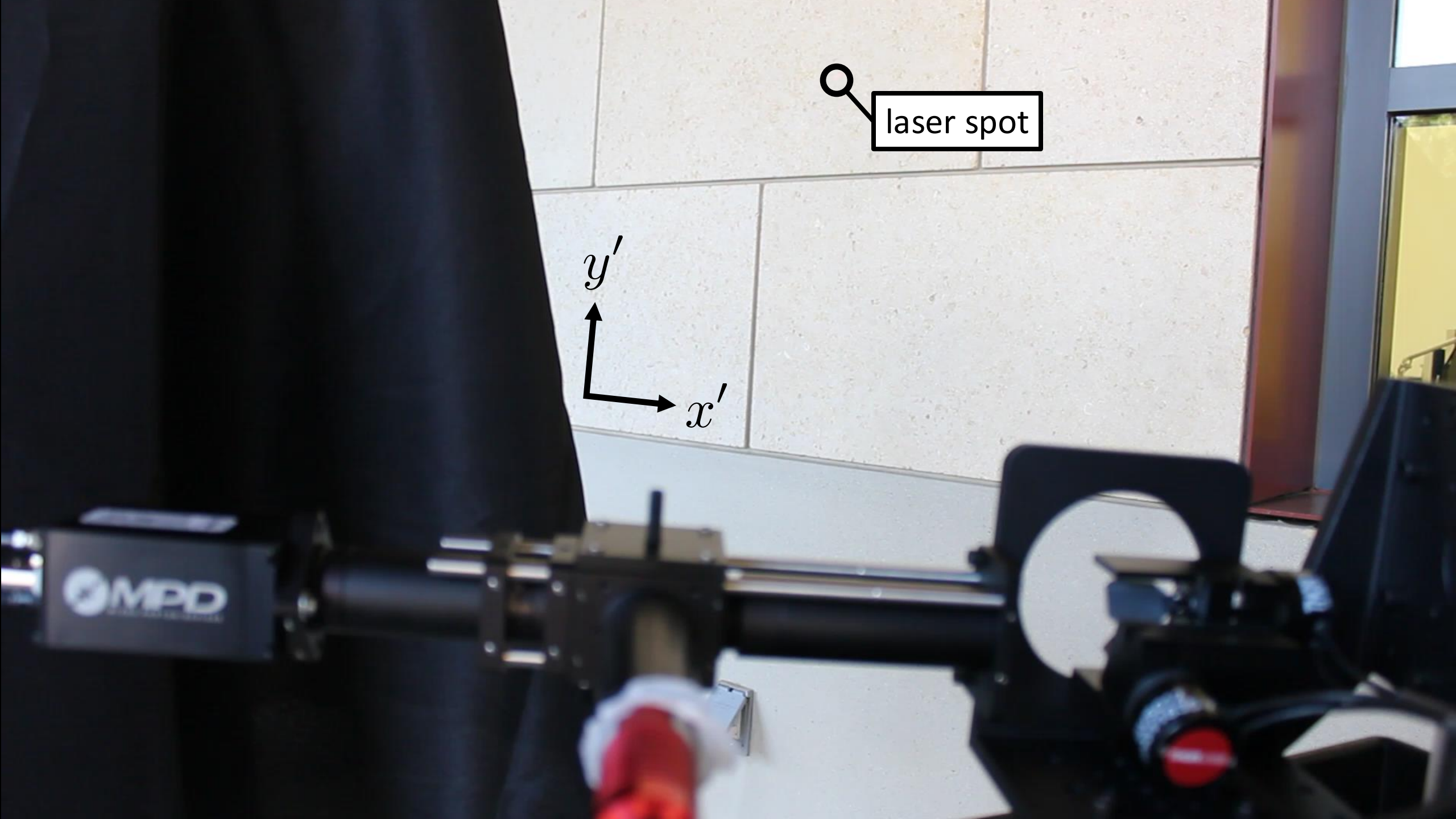



measurements
convolution kernel
y'
x'
t
Step 1: resample and attenuate along t-axis
inverse filter
y'
x'
v
*
Step 2: 3D convolution
y
x
u

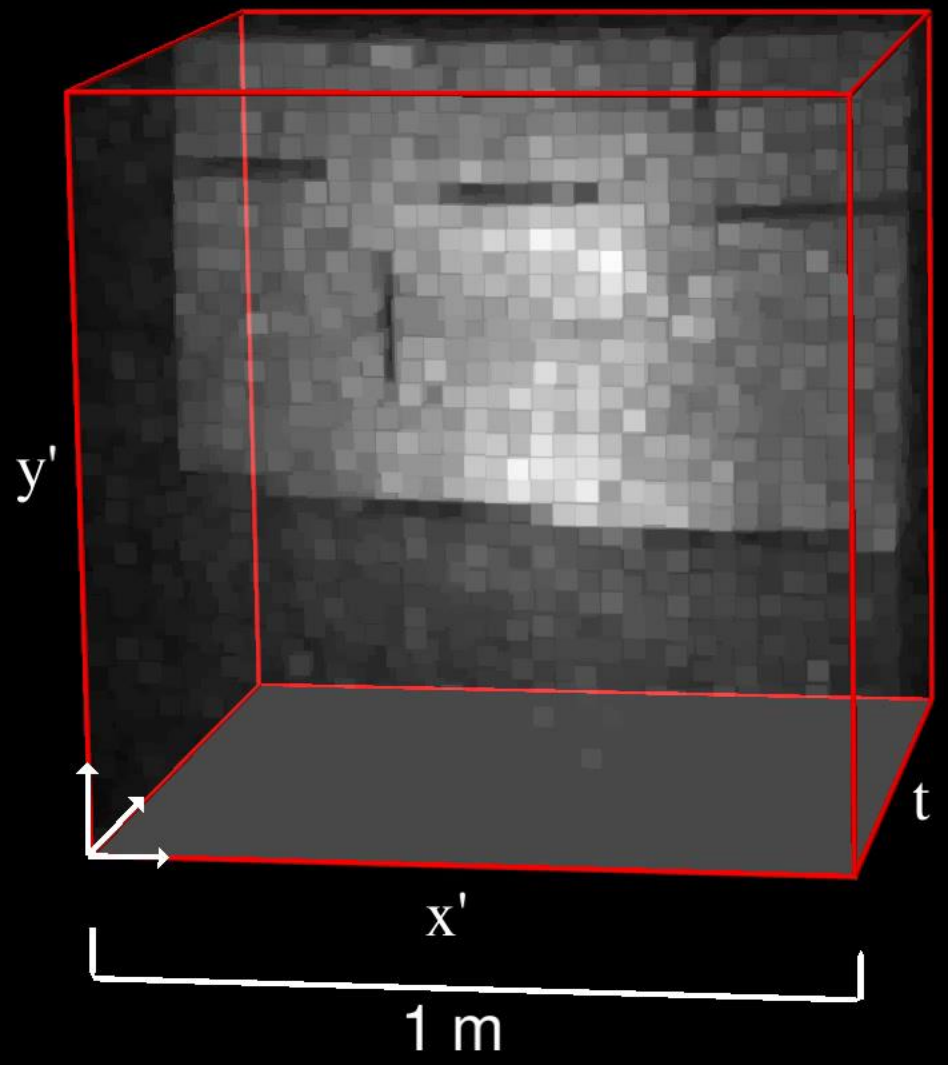

measurements
convolution kernel
recovered volume
y'
x'
t
Step 1: resample and attenuate along t-axis
inverse filter
y
x
z
Step 3: resample and attenuate along z-axis
y'
x'
v
*
Step 2: 3D convolution
y
x
u


laser spot
confocal NLOS system
hidden object
occluder


1.25 meters

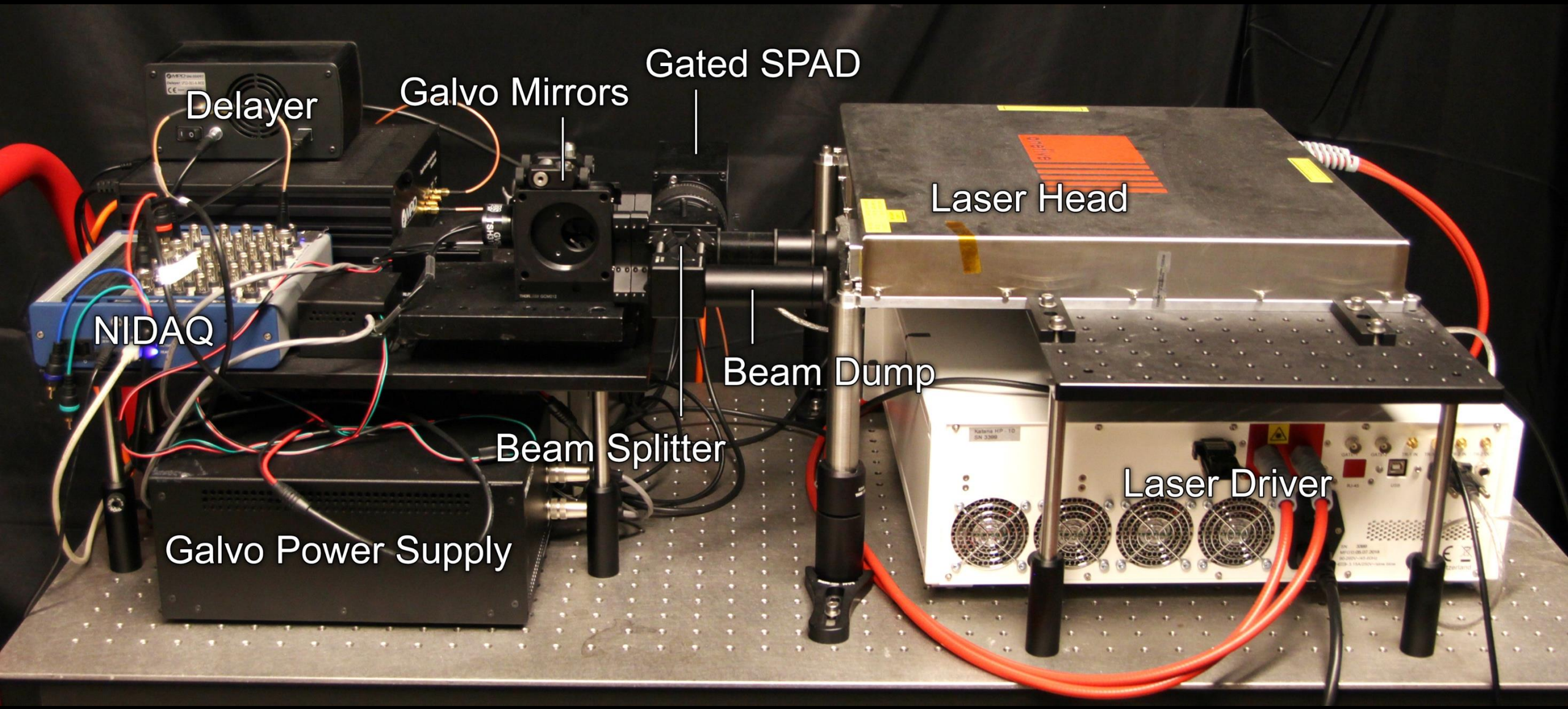

laser spot
y'
x'
MPD

measurements

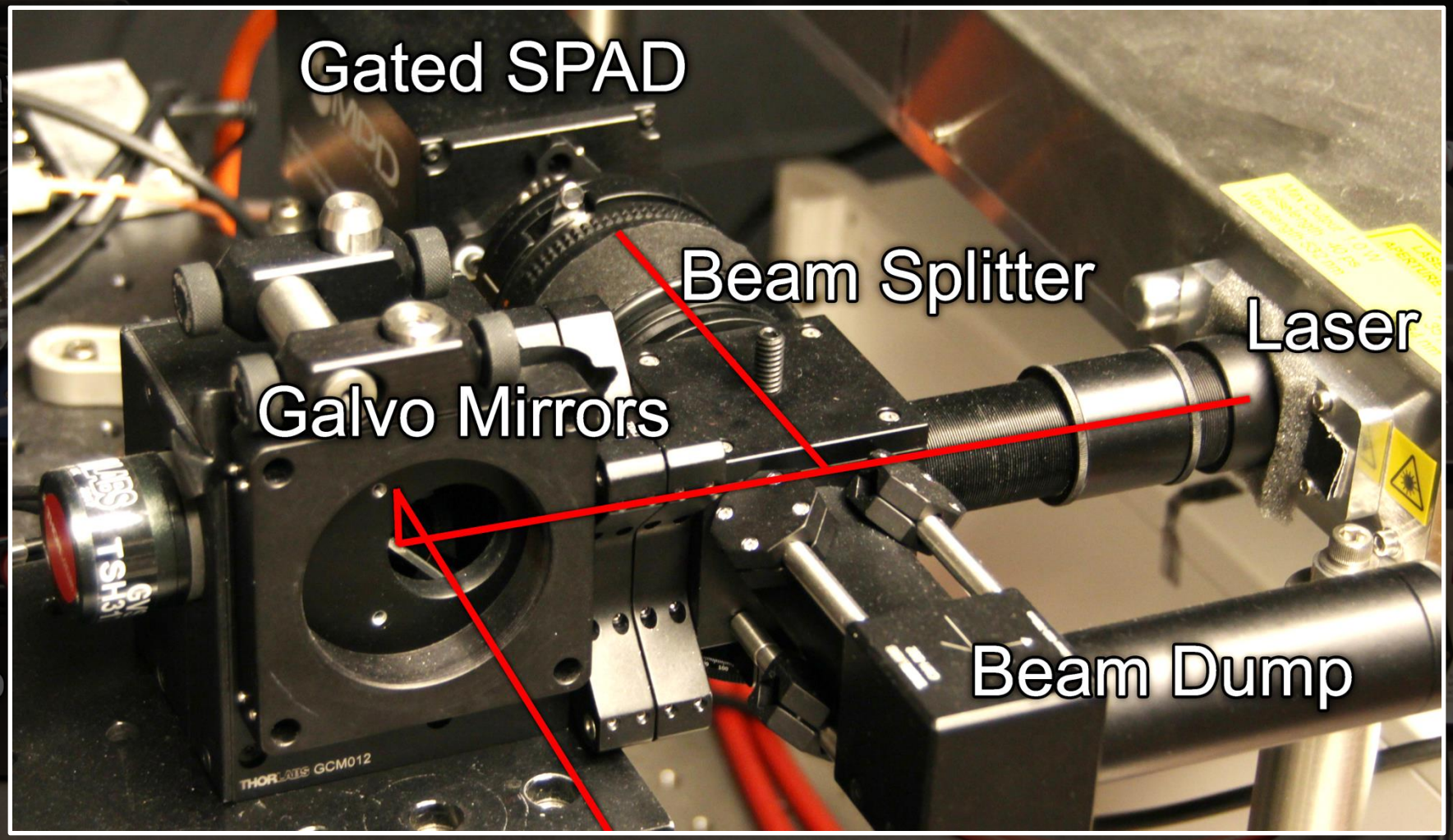


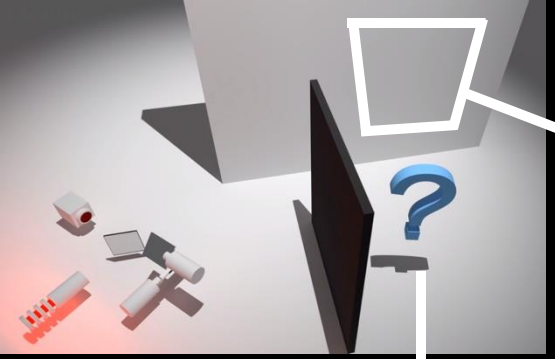
Maximum Intensity Projection

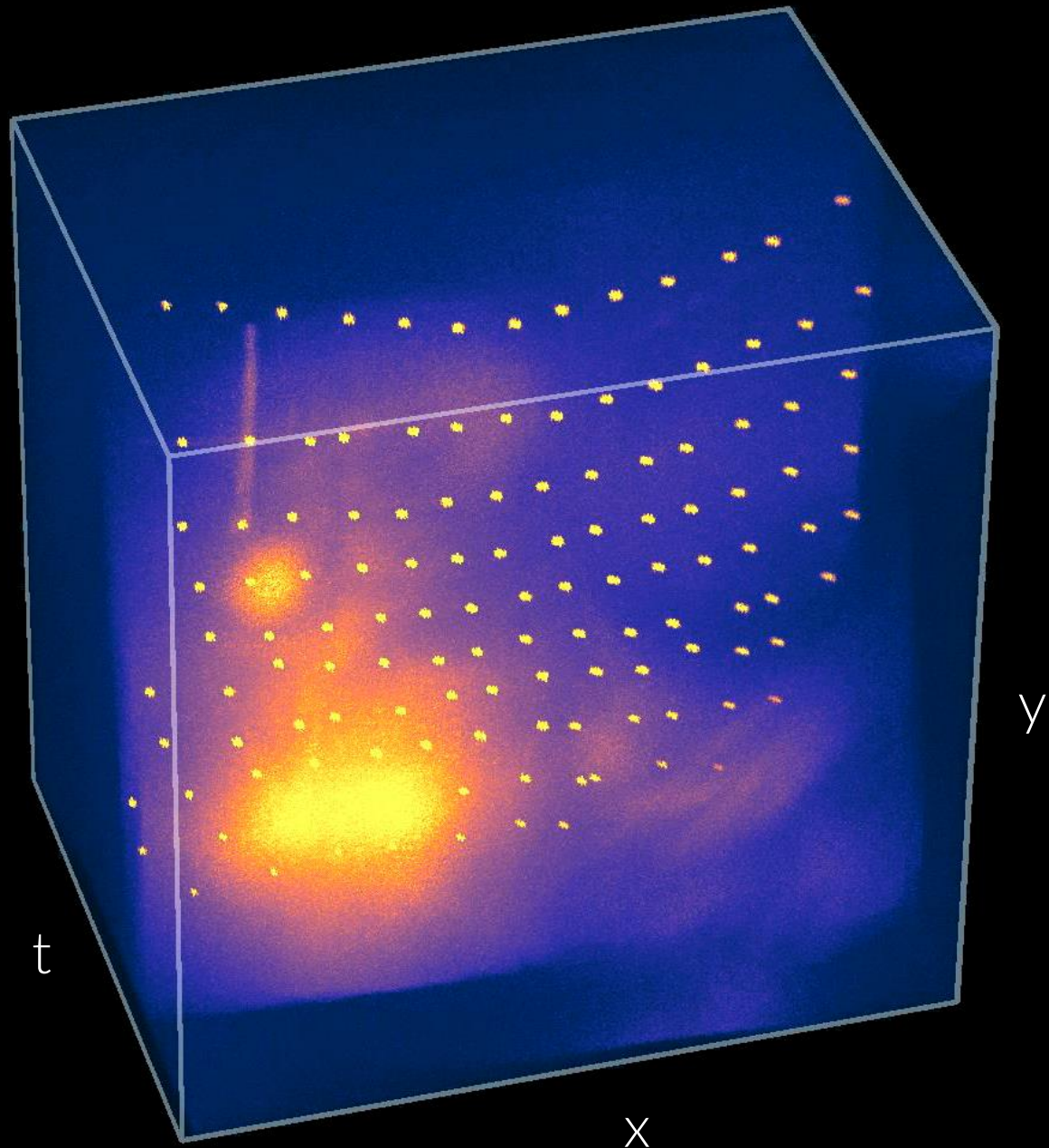
hardware prototype



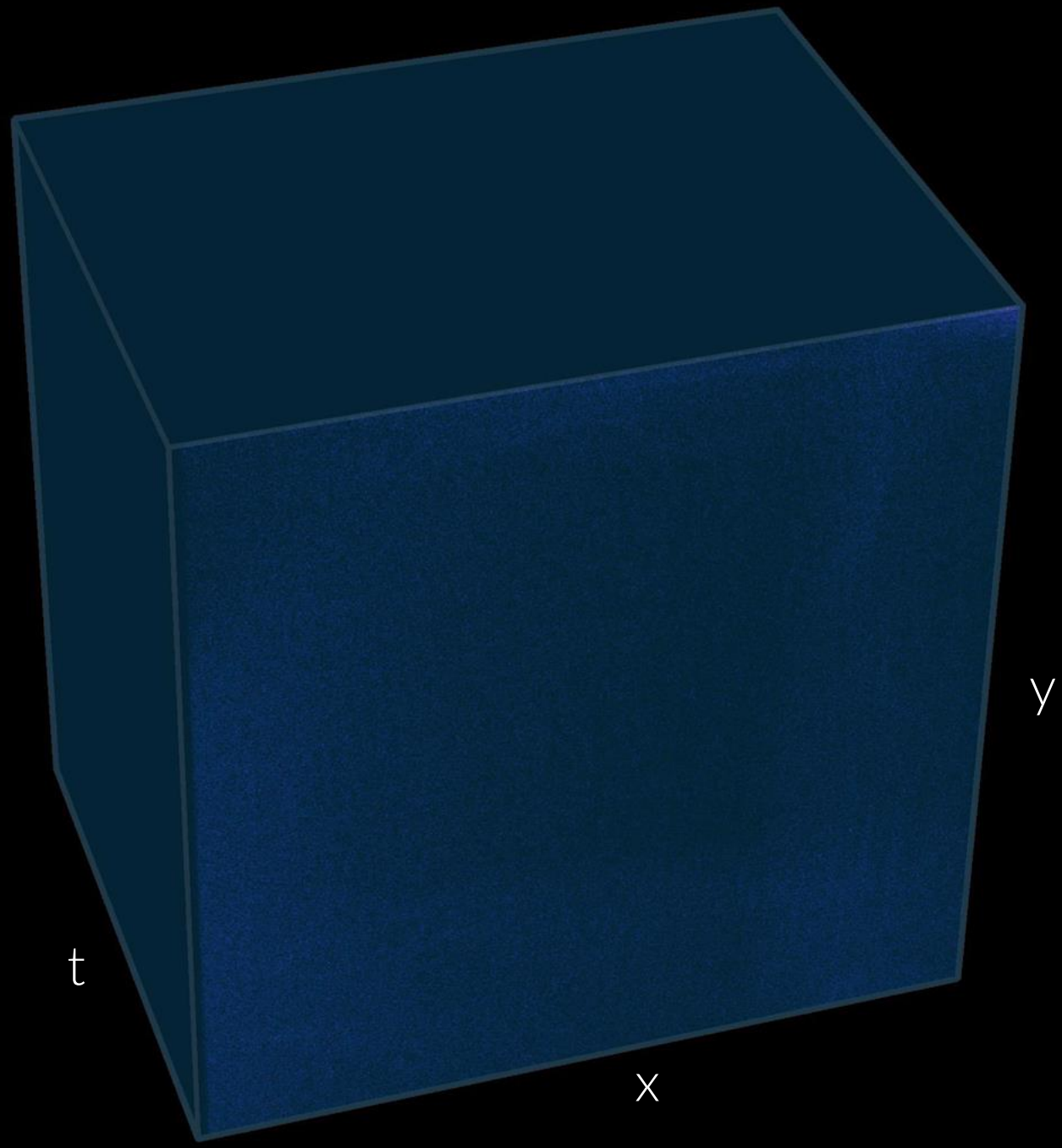
hardware prototype

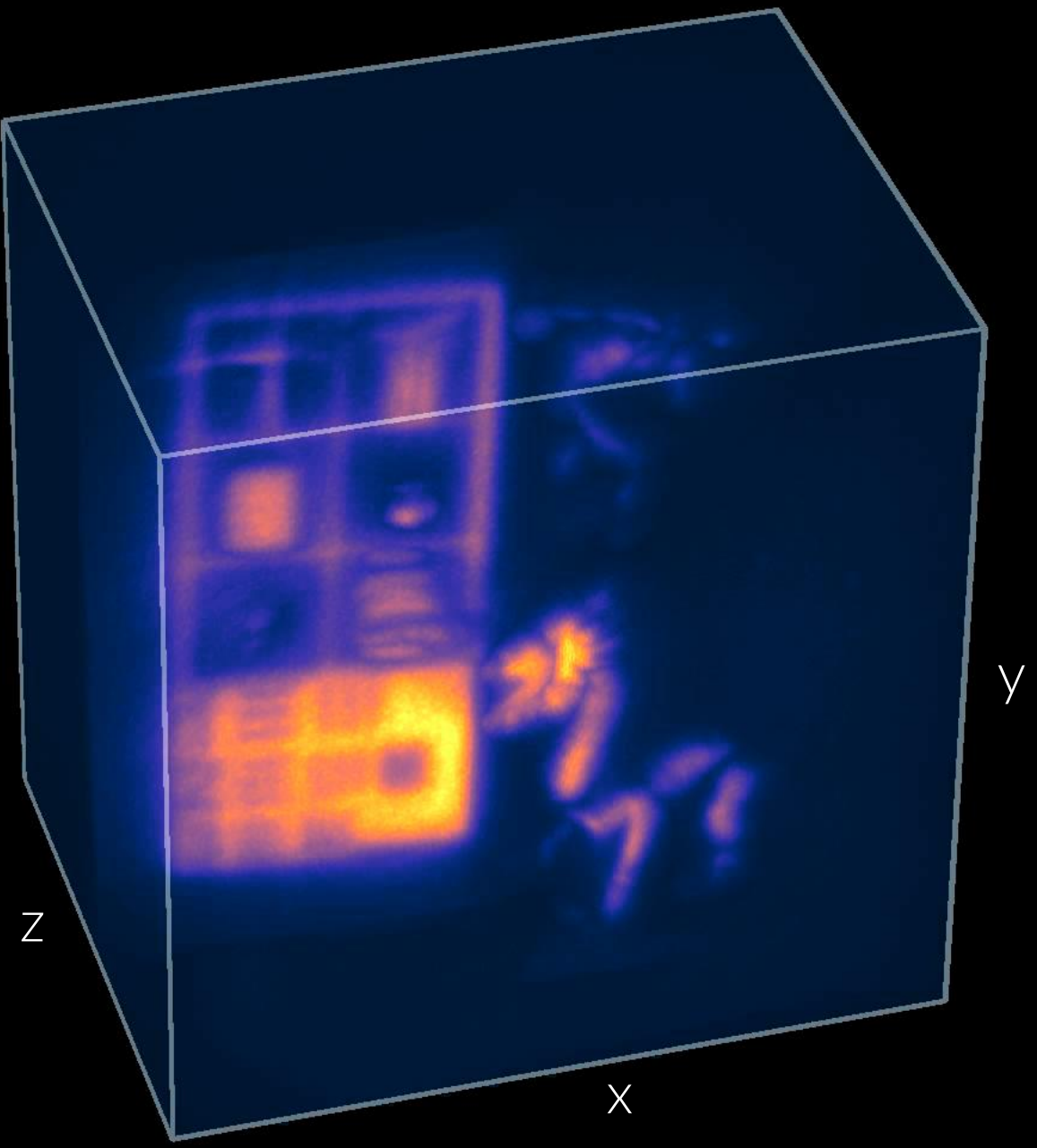






Captured Measurements

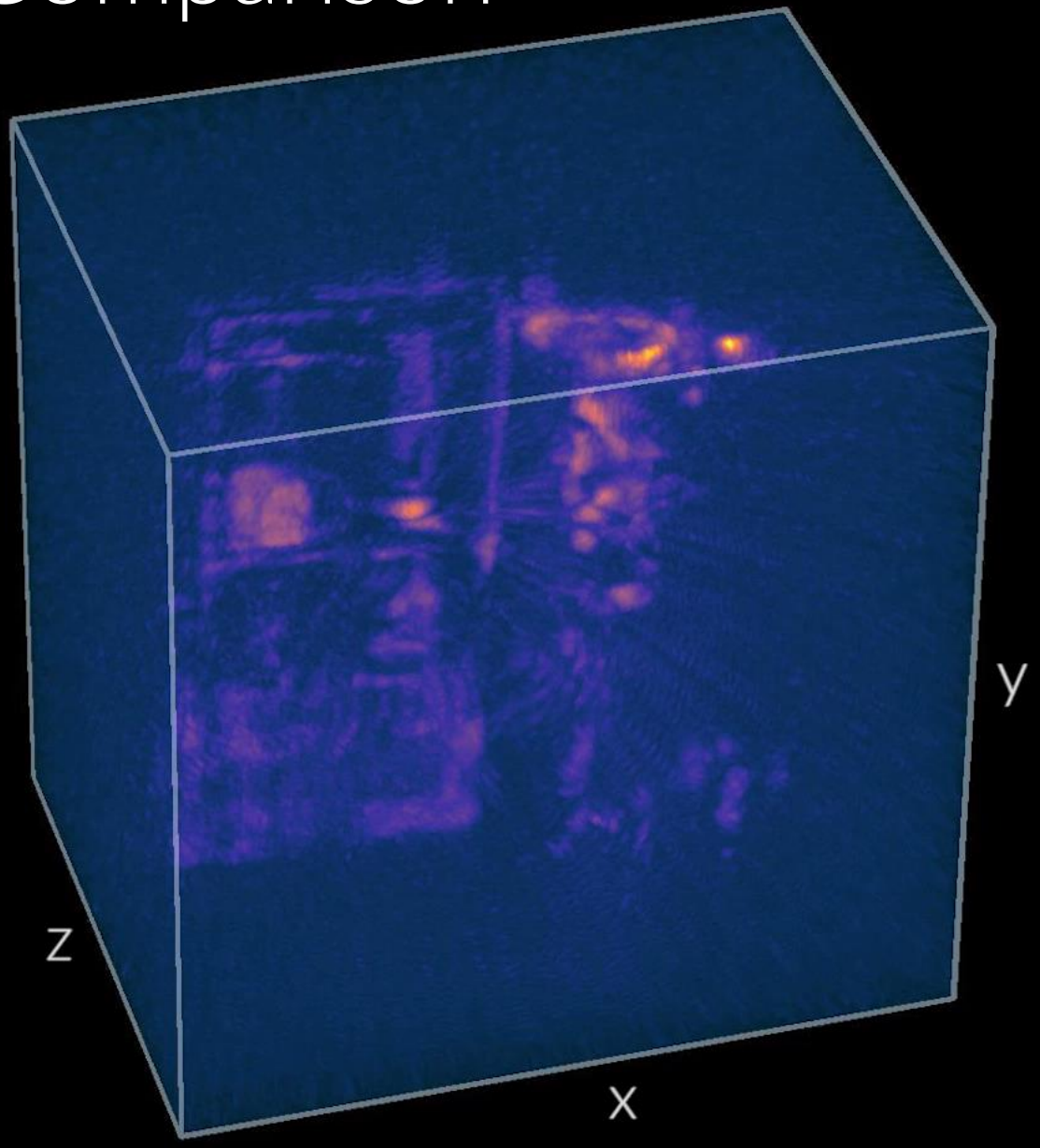

y
t
x



Dimensions: 2 x 2 m
Exposure: 180 min
Time Resolution: 32 ps

Reconstruction Comparison

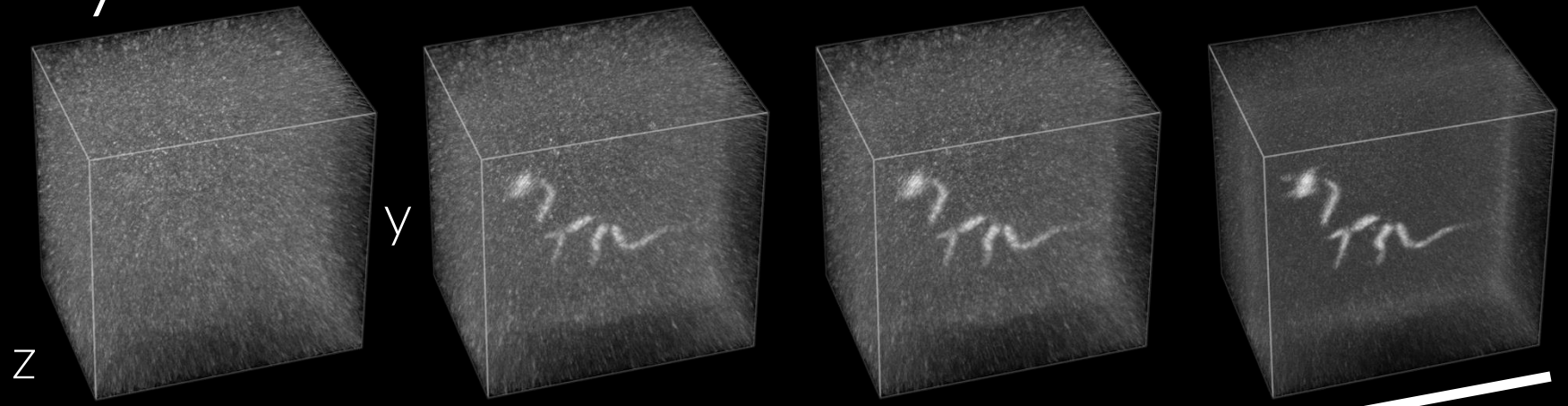
dimensions: 2 m x 2 m x 1.5 m



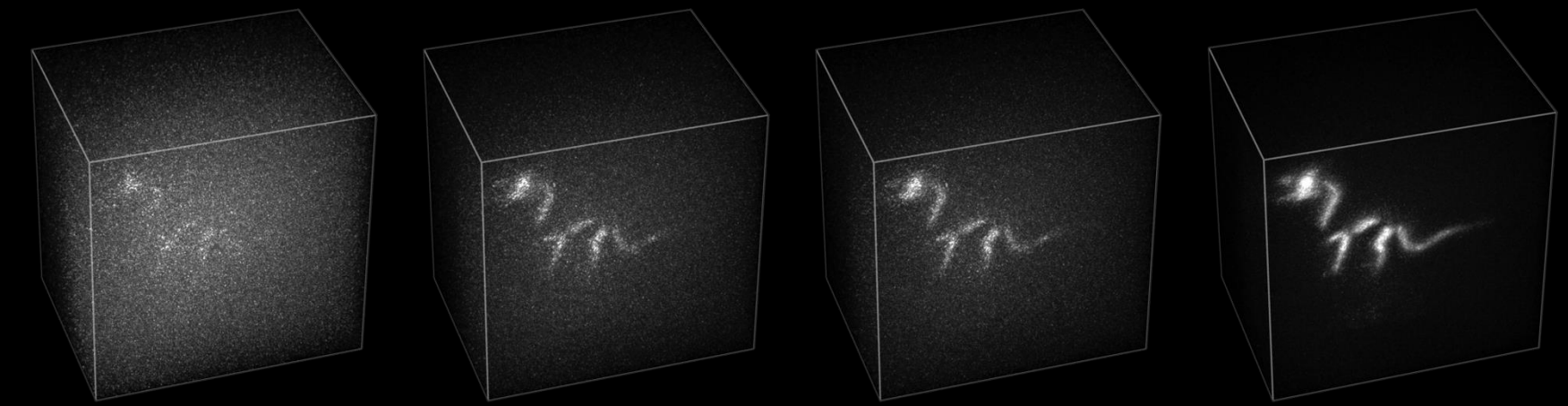
Filtered Backprojection

noise sensitivity

LCT

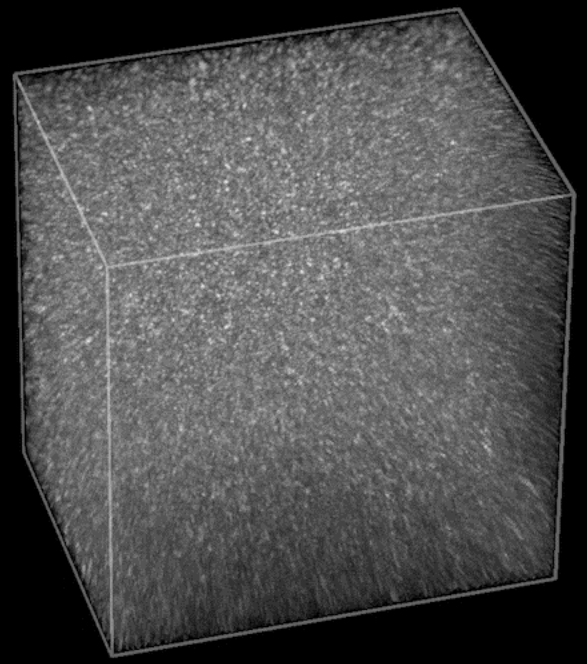


f-k Migration

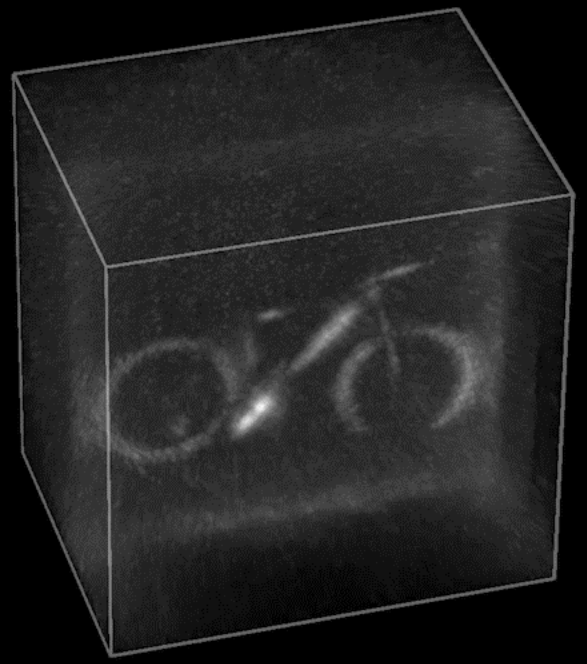


15 sec 1 min 2 min 15 min

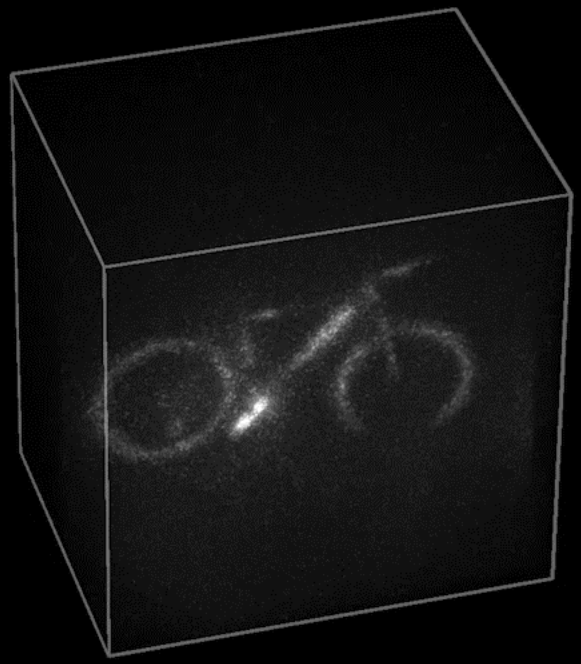
noise comparison



Filtered Backprojection



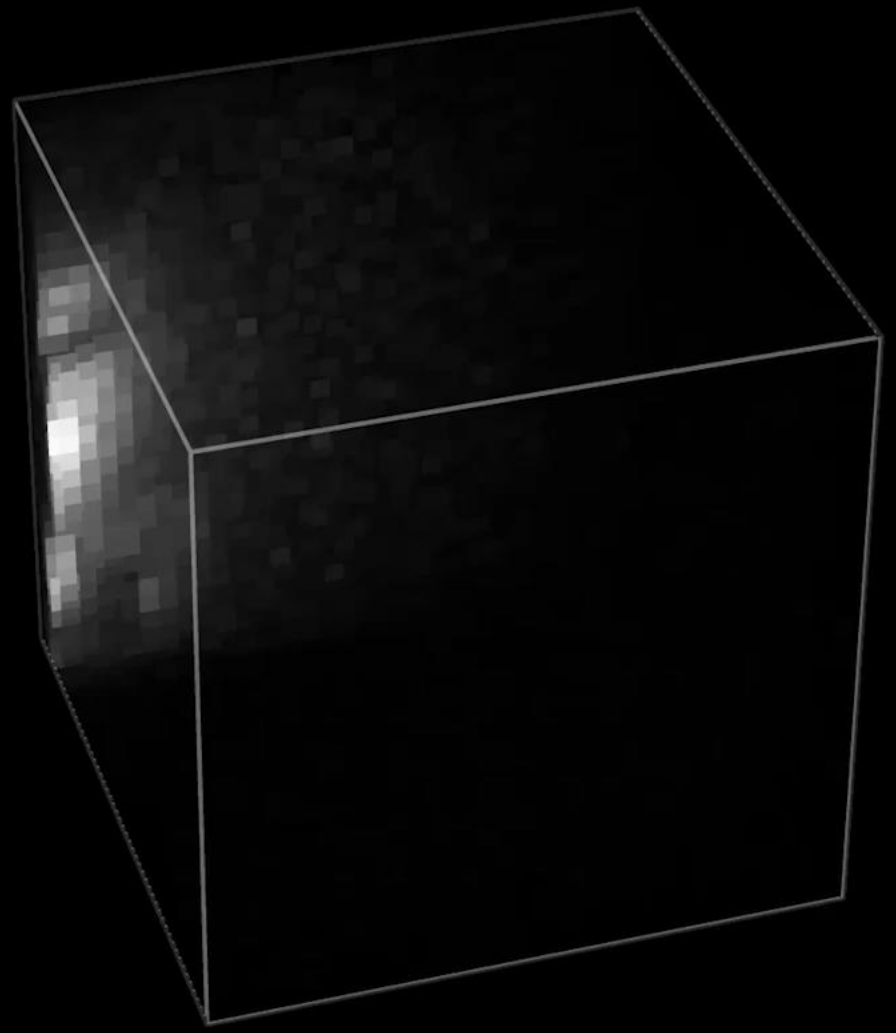
LCT



f-k Migration

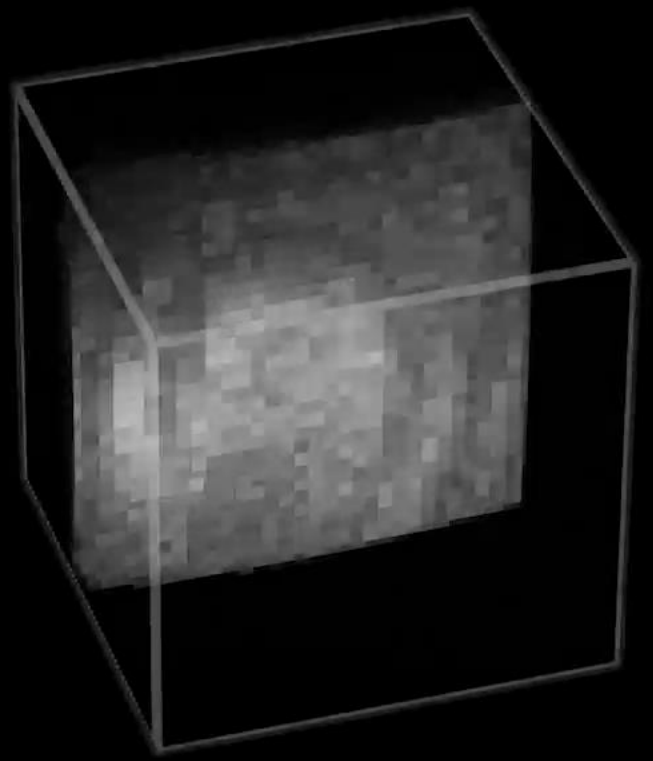
10 min. exposure

real-time scanning



Framerate: 4 Hz
Resolution: 32 x 32
Dimensions: 2 m x 2 m x 2 m

Transient Image (Input)



3D Human Pose (Output)

(Reference Only)
Person Hidden by Wall