

# 3D Time-of-Flight Cameras

From Airborne LiDARs to the Latest iPhone

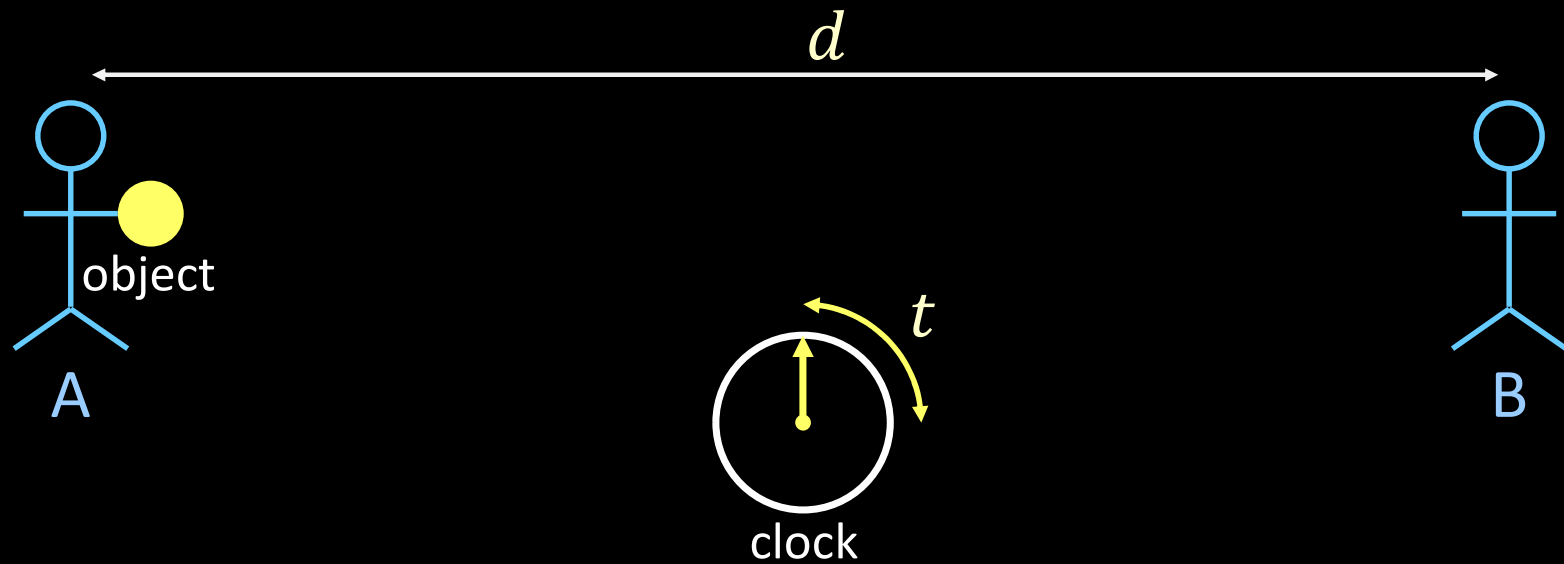
## WISION Lab

Department of Computer Sciences, UW-Madison



Research supported by NSF,  
ONR, DARPA, and WARF

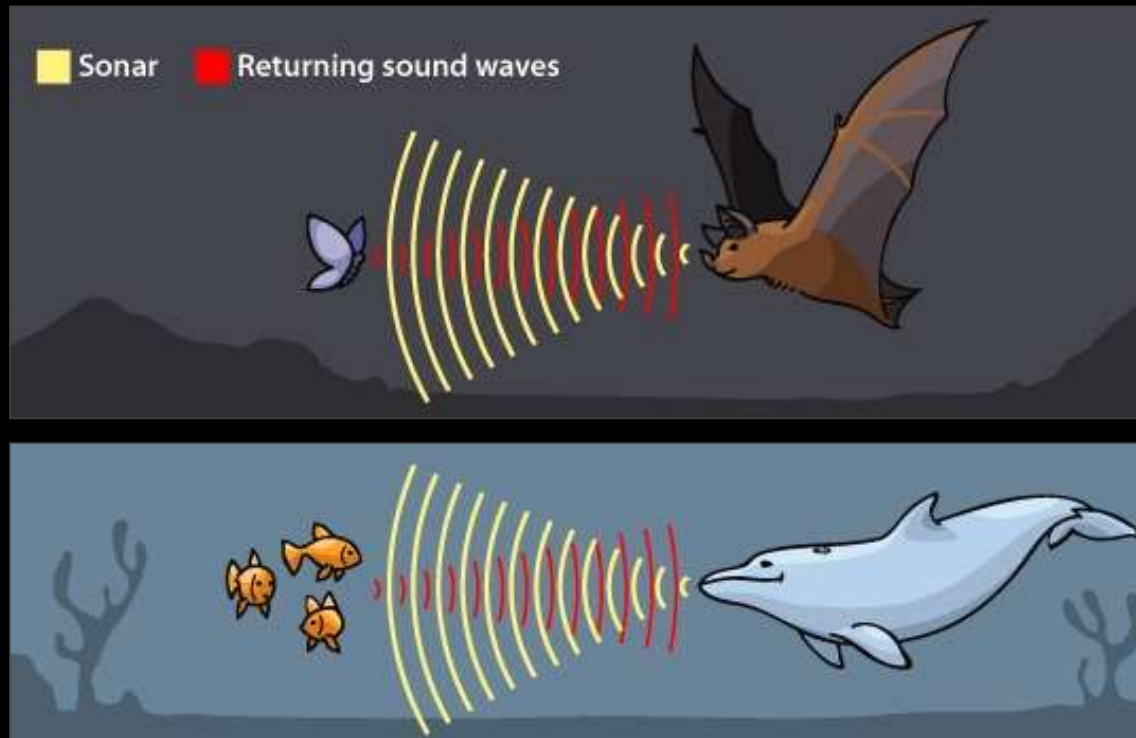
# Time-of-Flight (ToF)



$$d = v \times t$$

distance    velocity    flight time

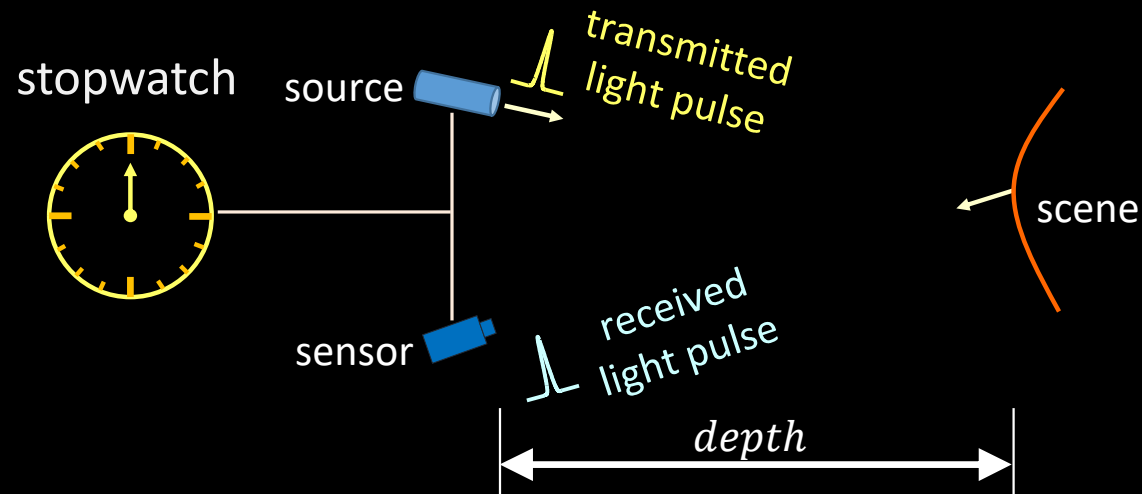
# Time-of-Flight in Nature



Echolocation Using Sound-Wave Time-of-Flight

Image from <http://askbiologist.asu.edu/echolocation>

# Time-of-Flight 3D Cameras



Time-of-flight 3D Camera

$$2 \times \text{depth} = c \times \tau$$

$\uparrow$  speed of light       $\uparrow$  time-of-flight (round trip)

# Time-of-Flight 3D Cameras

## Commercial Devices



Kinect 3D Camera



AR/VR Headsets



Intel LiDAR

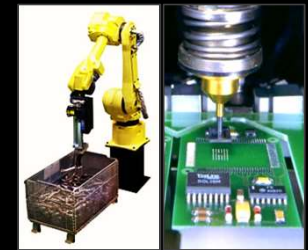


Smartphones

## Applications



autonomous cars



industrial automation



augmented reality



extreme robotics

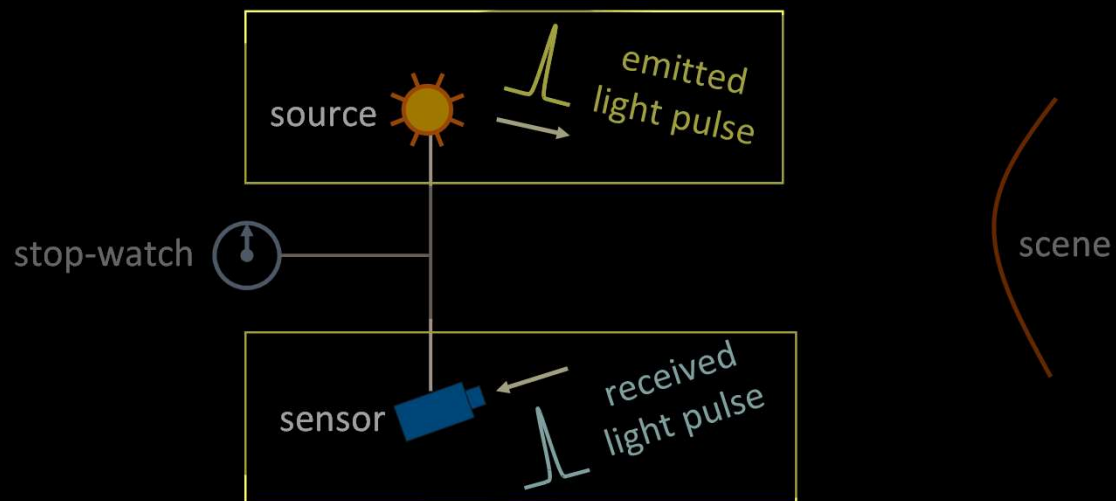
Microsoft Kinect v4, Hololens 2 ([www.microsoft.com](http://www.microsoft.com))

Intel RealSense LiDAR

TOF Sensors <https://wccftech.com/apple-tof-sensor-2019-android-flagships-getting-support/>

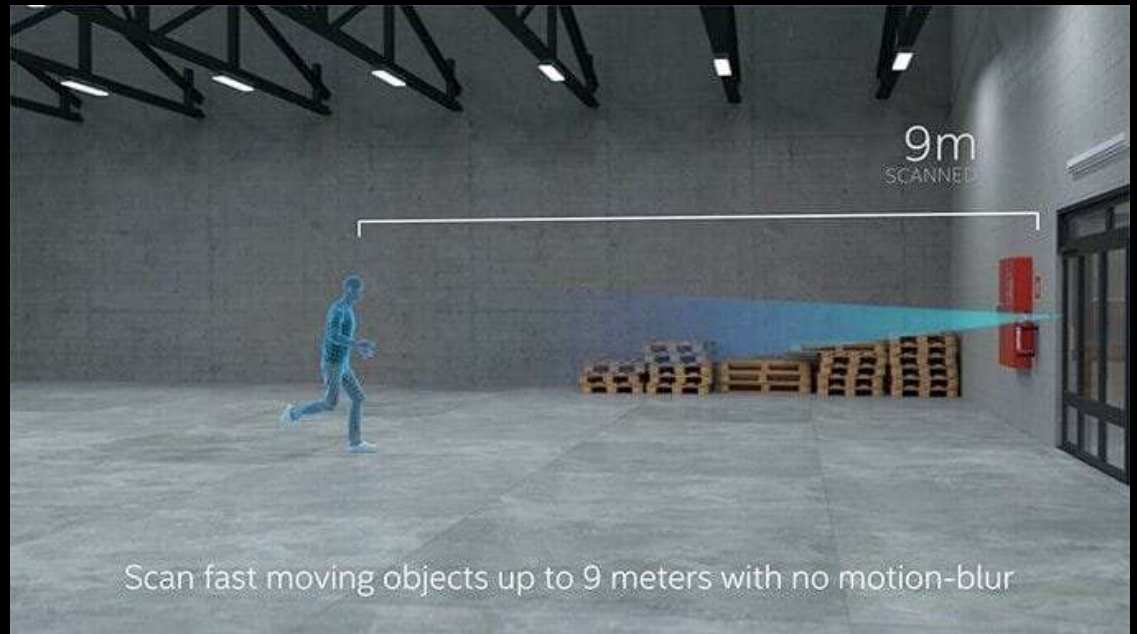
[www.magicleap.com/](http://www.magicleap.com/), <http://www.upi.com/>

# Direct ToF Camera: Requirements



High Speed and Powerful Lasers  
[Short (picosecond) and Powerful (resolvable) Light Pulse]

# Direct ToF Example: Intel RealSense



# Direct ToF Example: Airborne LiDAR

Science

Contents ▾

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RESEARCH ARTICLE

Ancient lowland  
airborne laser scan



Marcello A. Canuto<sup>1,2,†</sup>, Francisco  
+ See all authors and affiliations

Science 28 Sep 2018:  
Vol. 361, Issue 6409, eaau0137  
DOI: 10.1126/science.aau0137



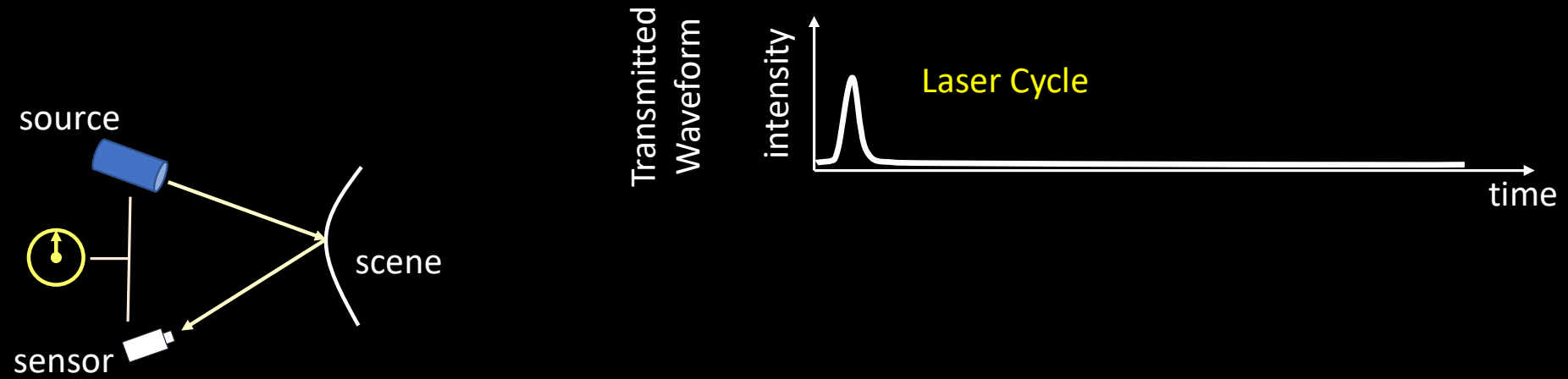
Survey region

Teledyne Optech  
Not eye safe: peak power in megawatts!  
Expensive: >\$100k

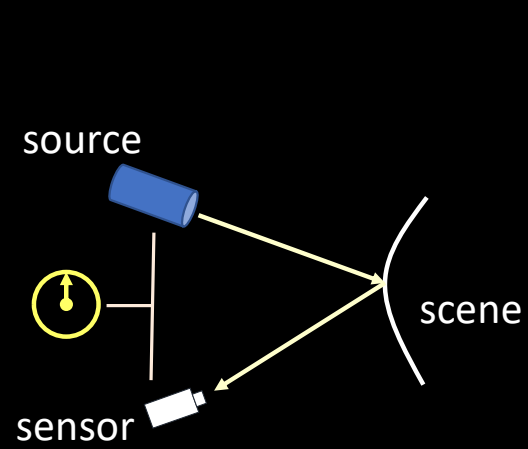




# Conventional Direct ToF Camera (LiDAR)



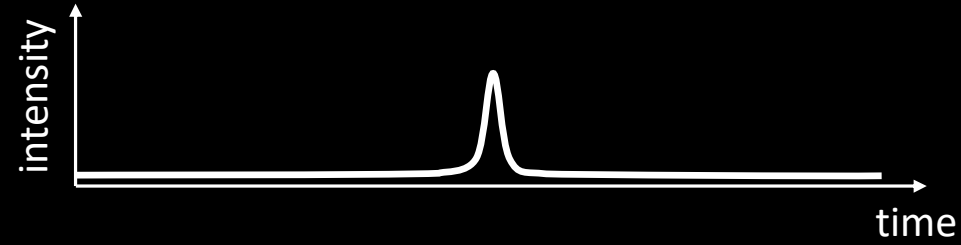
# Conventional LiDAR



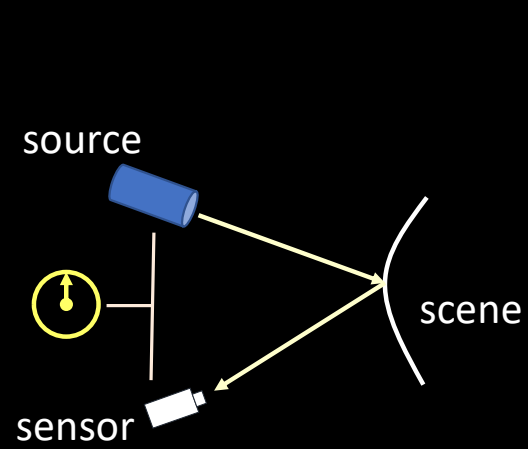
Transmitted  
Waveform



Received  
Waveform



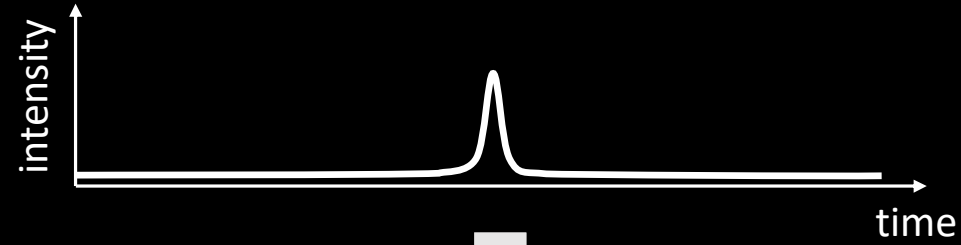
# Conventional LiDAR



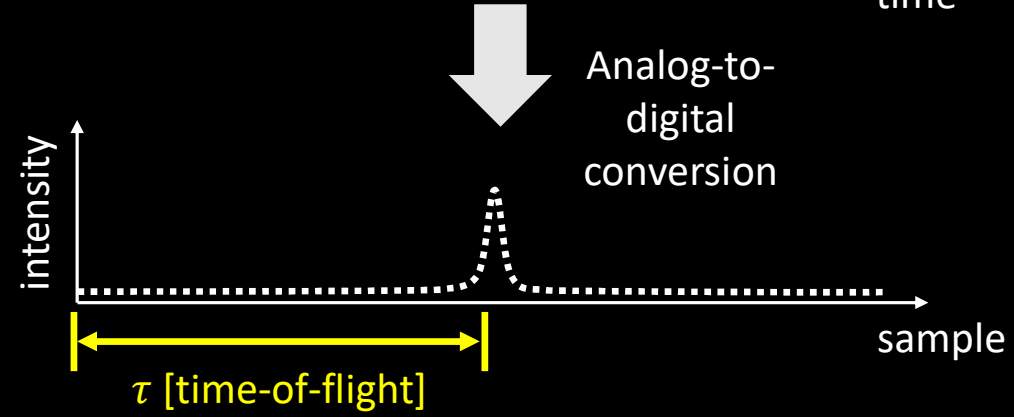
Transmitted  
Waveform



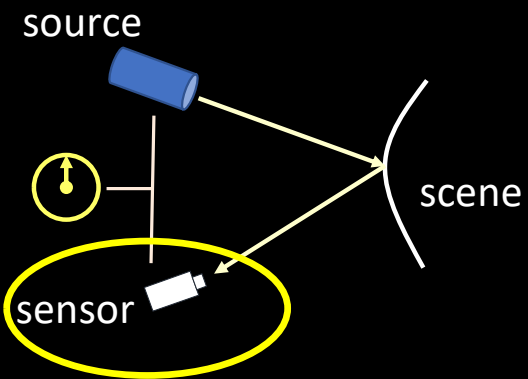
Received  
Waveform



Digitized  
Waveform



# Conventional LiDAR

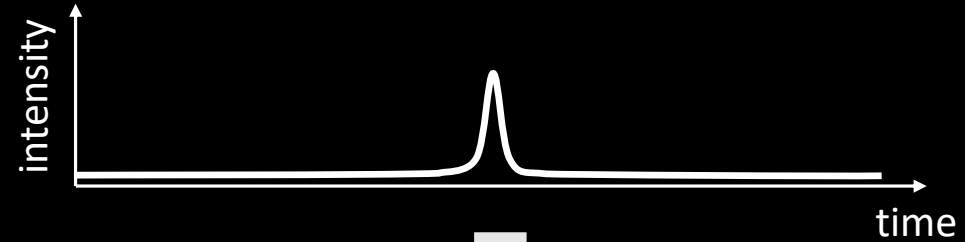


Problems: limited time resolution and limited sensitivity

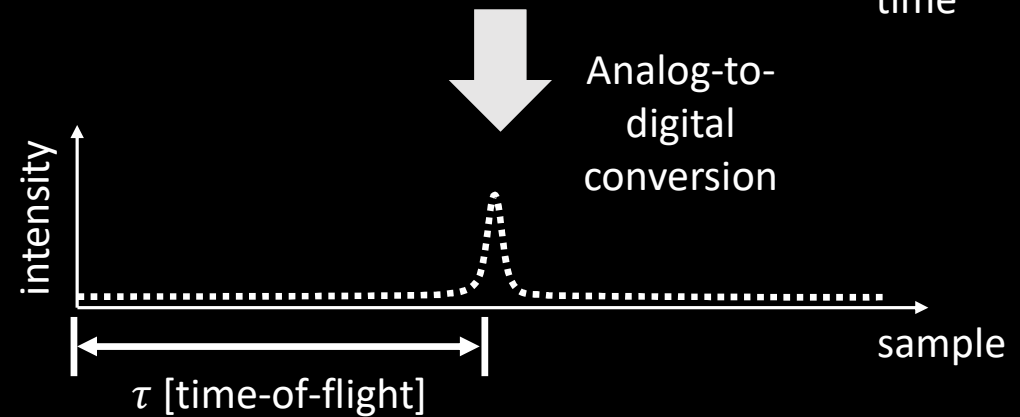
Transmitted Waveform



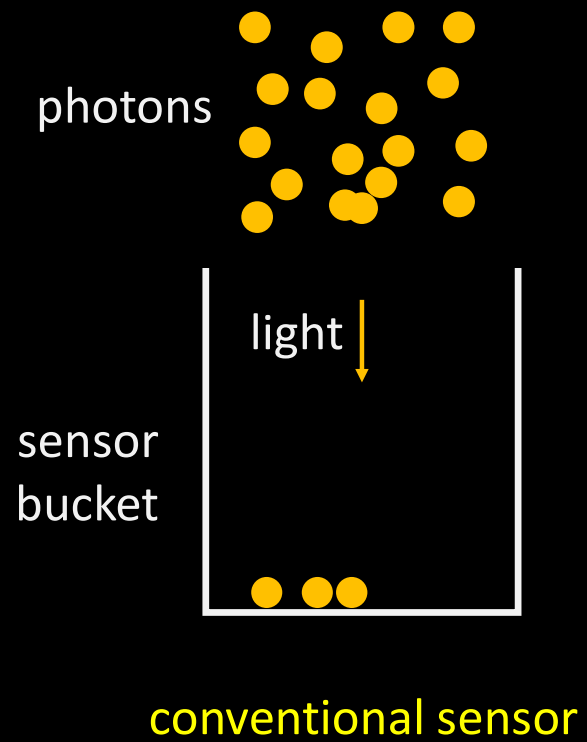
Received Waveform



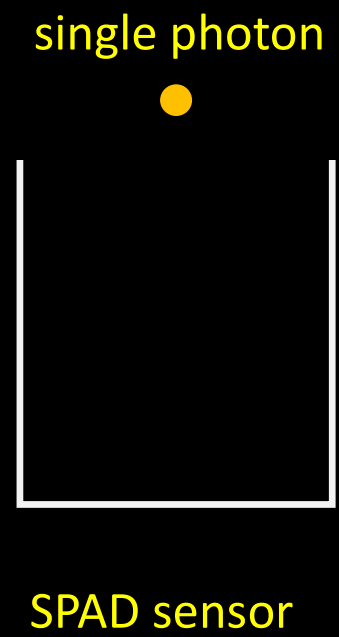
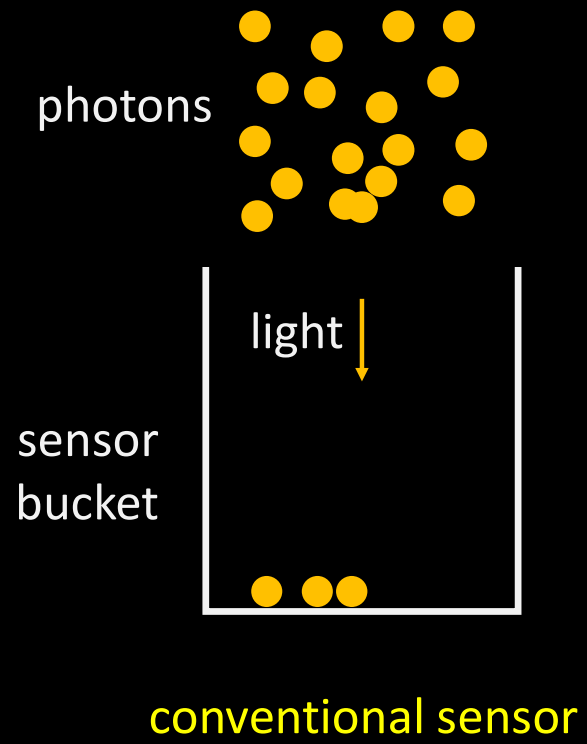
Digitized Waveform



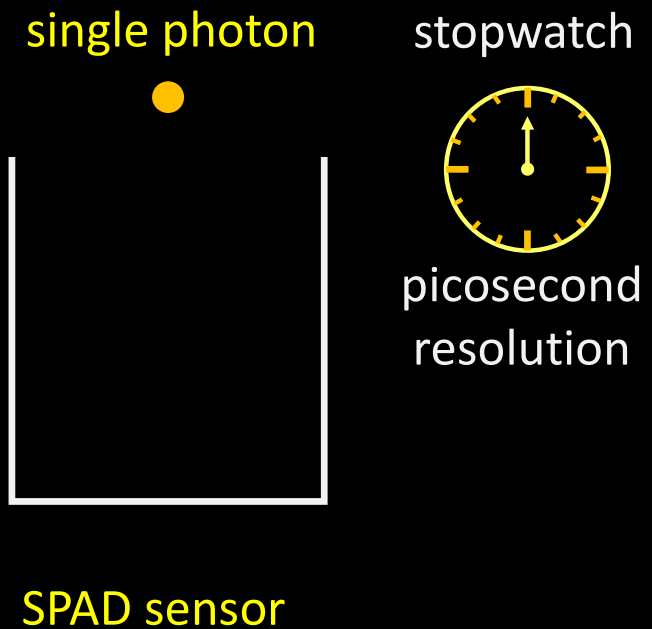
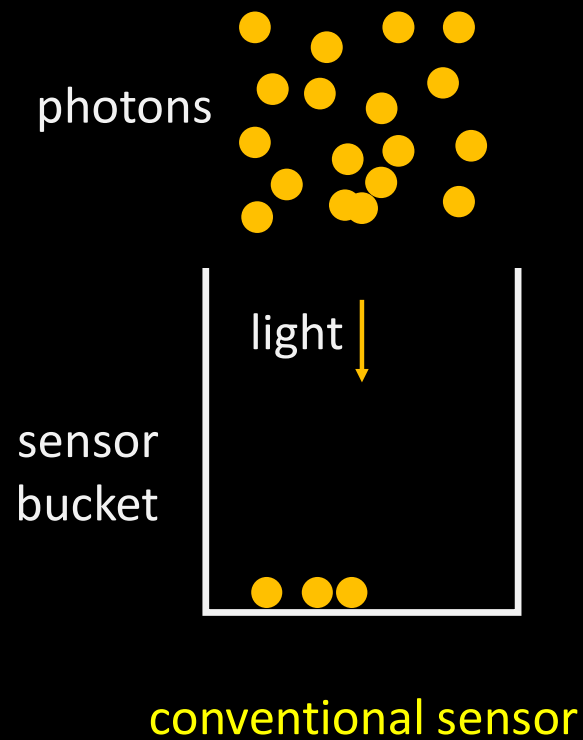
# Conventional Light Sensor



# Single-Photon Avalanche Diode (SPAD) Sensor



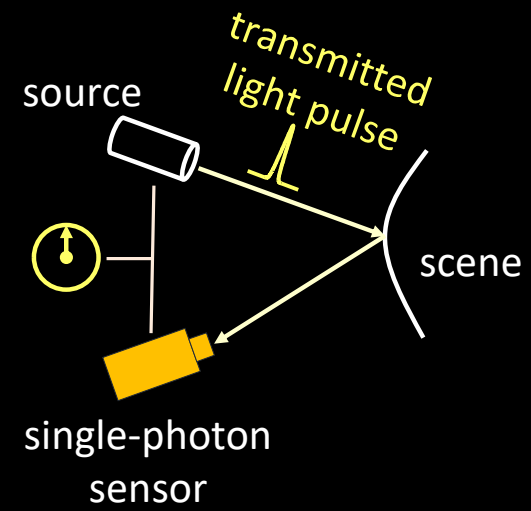
# Single-Photon Avalanche Diode (SPAD) Sensor



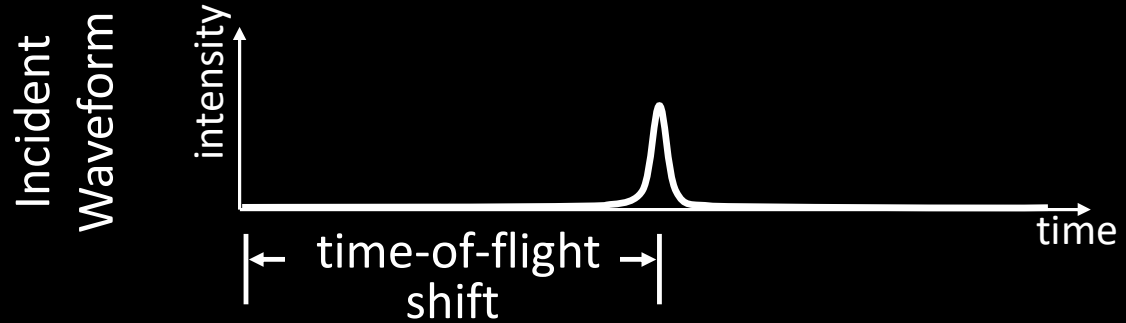
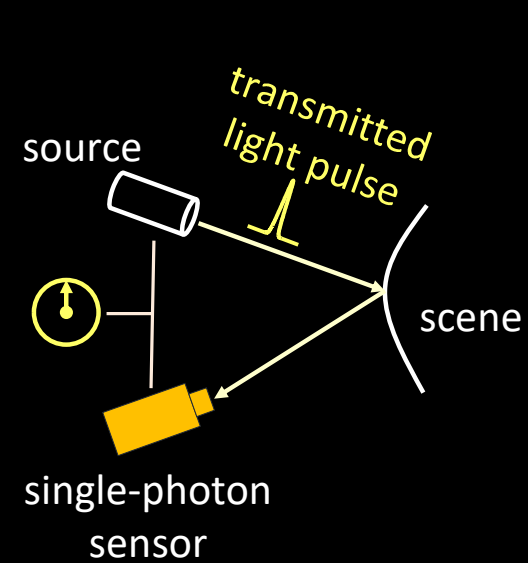
Can we build a 3D time-of-flight camera with  
single-photon sensors?



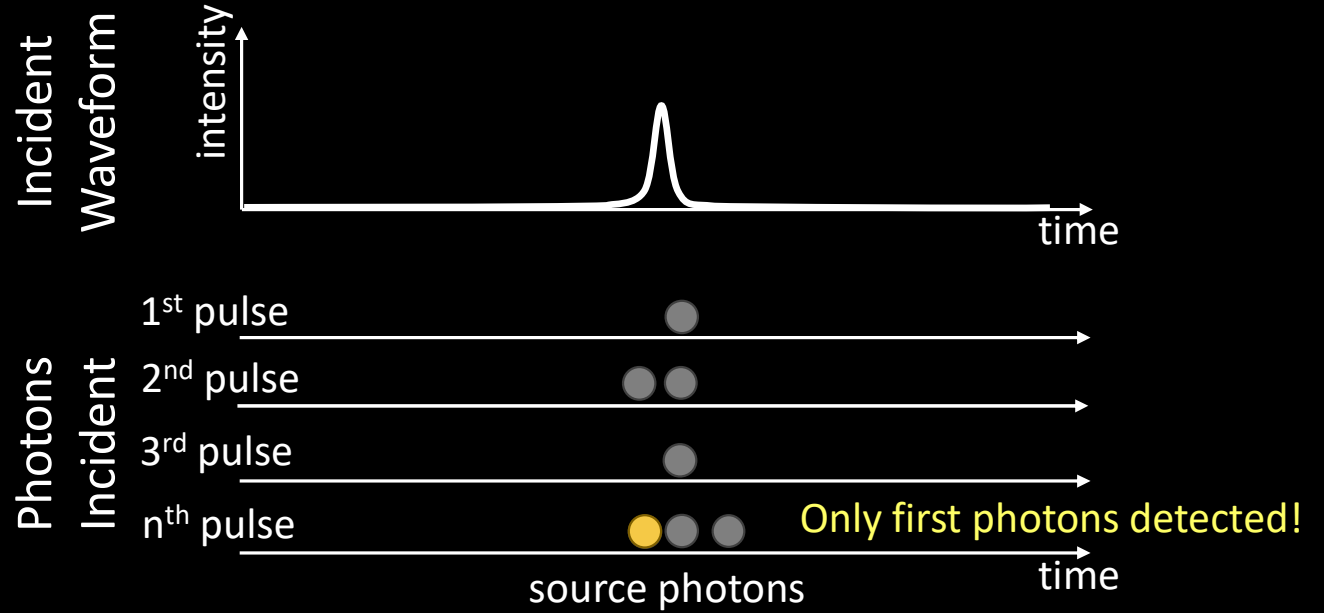
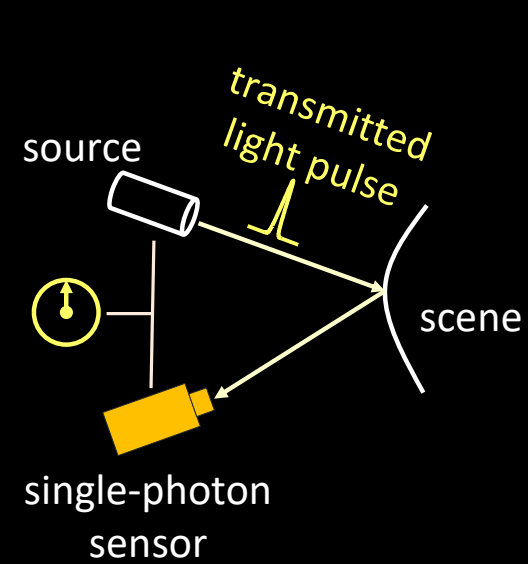
# Single-Photon 3D Camera



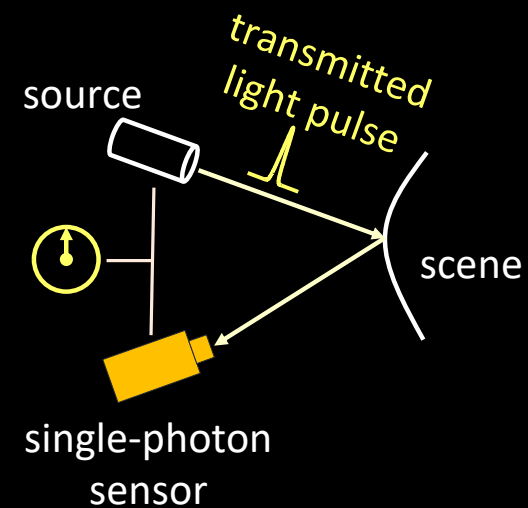
# Single-Photon 3D Camera



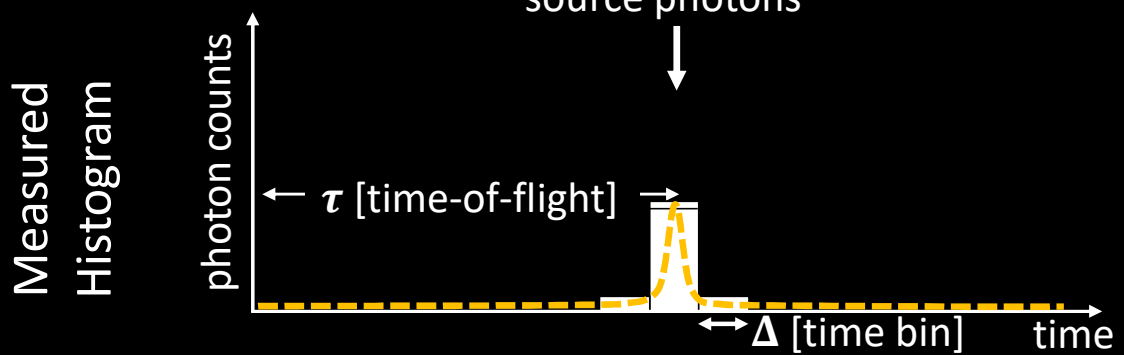
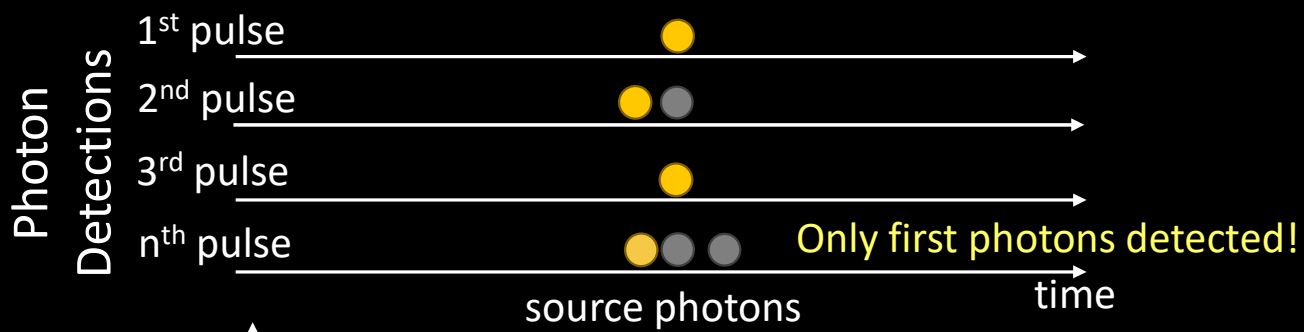
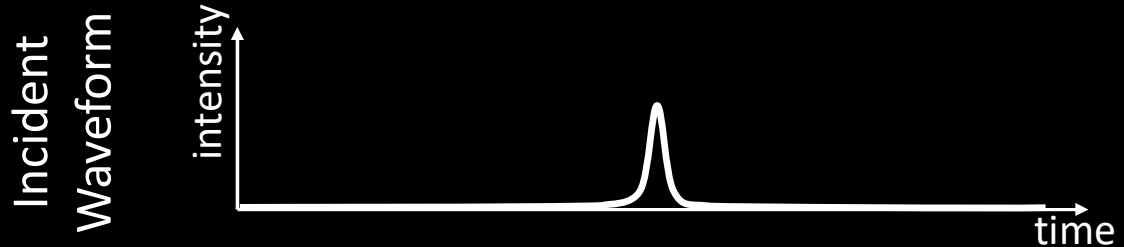
# Single-Photon 3D Camera



# Single-Photon 3D Camera



3D imaging in dark



# Single-Photon 3D Camera: Sunlight

Extreme darkness

Bright daylight

High dynamic range



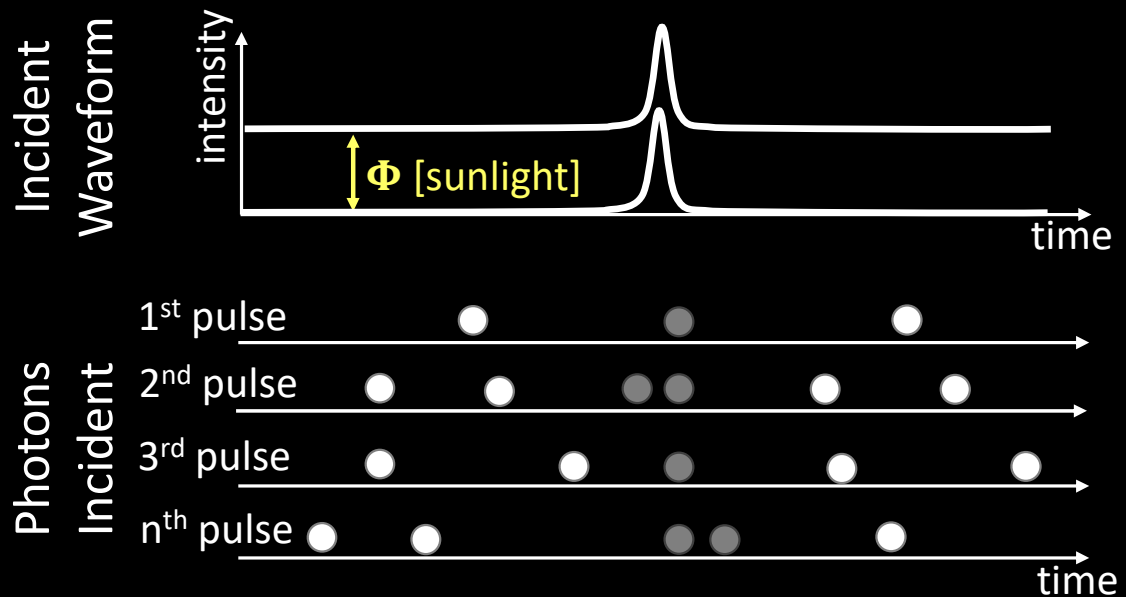
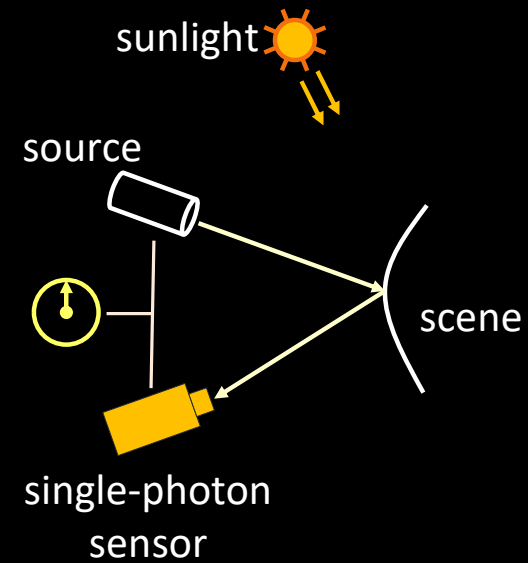
✓

?

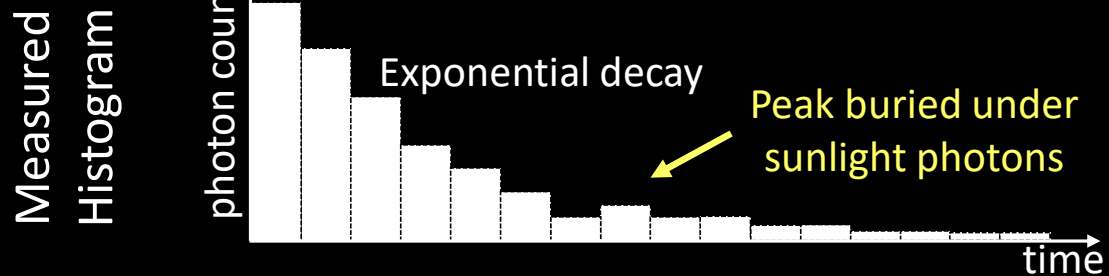
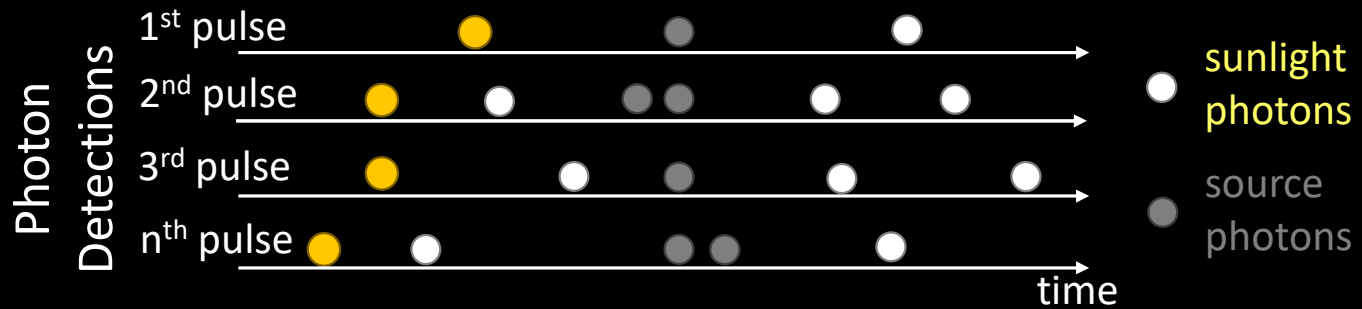
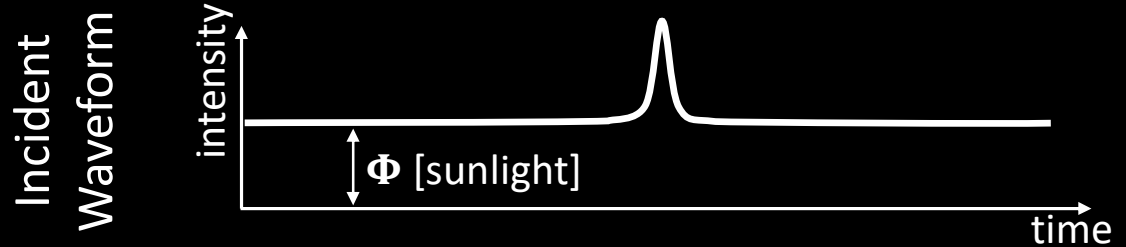
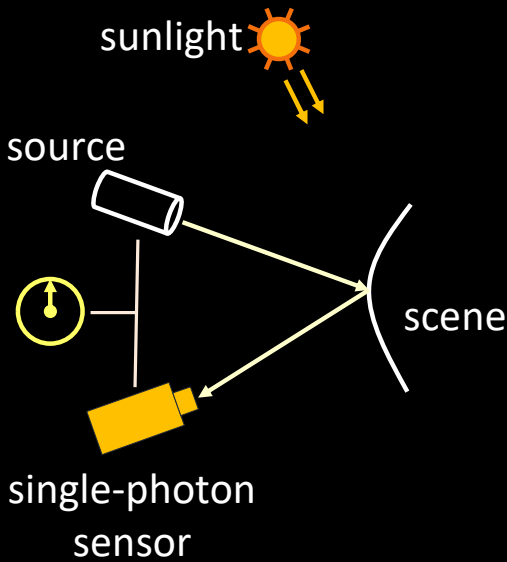
?

Need to operate under a wide range of illumination conditions

# Single-Photon 3D Camera: Sunlight

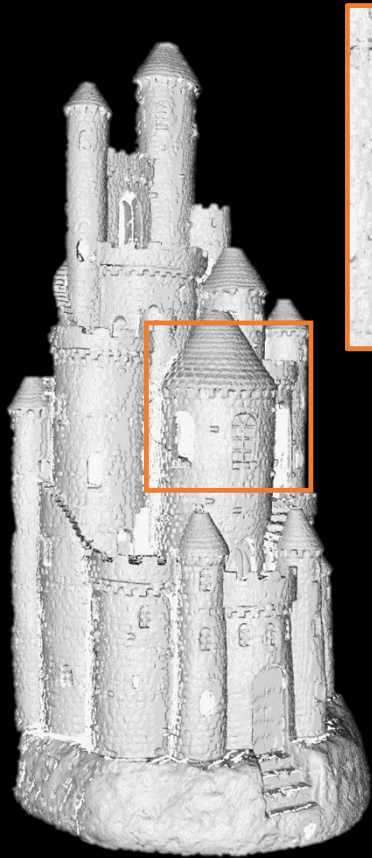


# Single-Photon 3D Camera: Sunlight

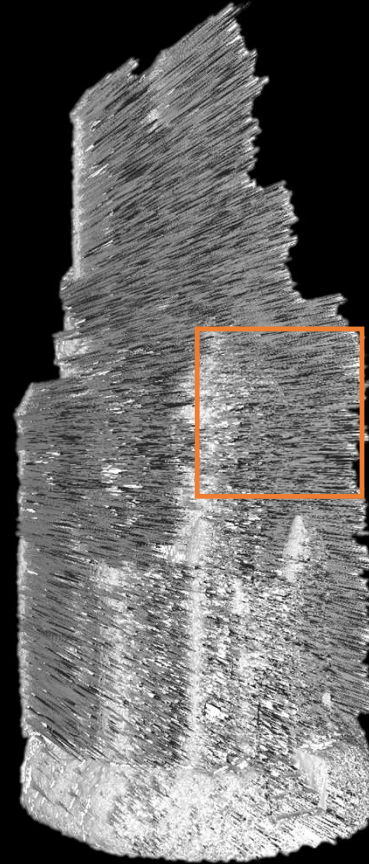


Peak difficult to locate due to distortion

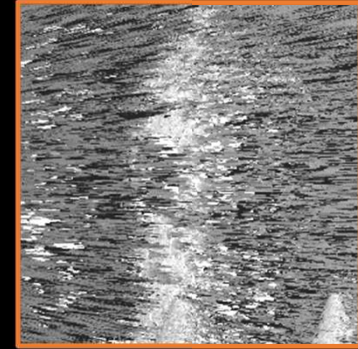
# Single-Photon 3D Camera: Simulated Result



No Sunlight



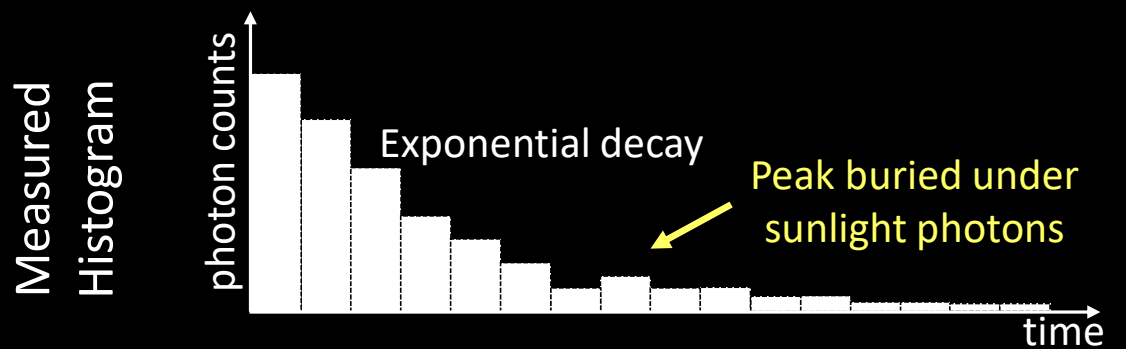
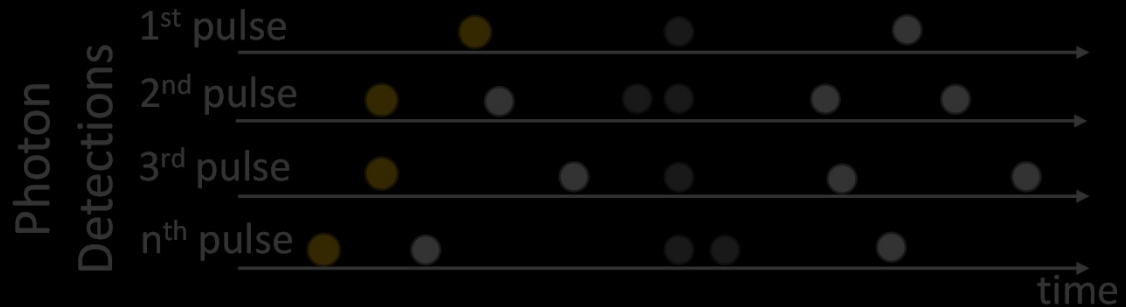
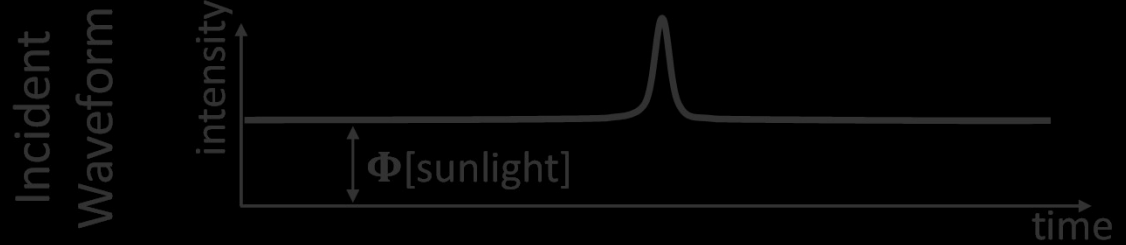
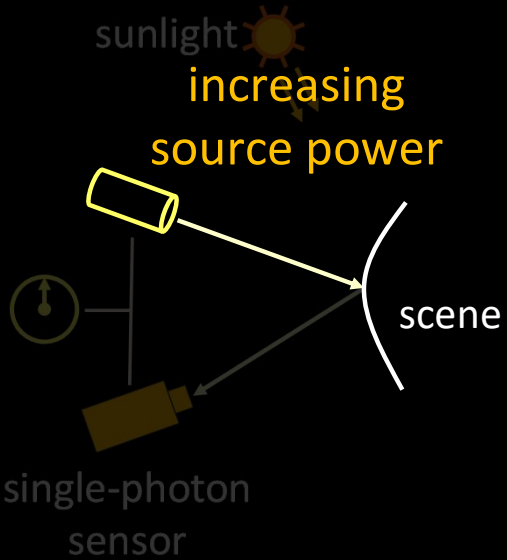
With Sunlight (2000 lux)



Large depth errors

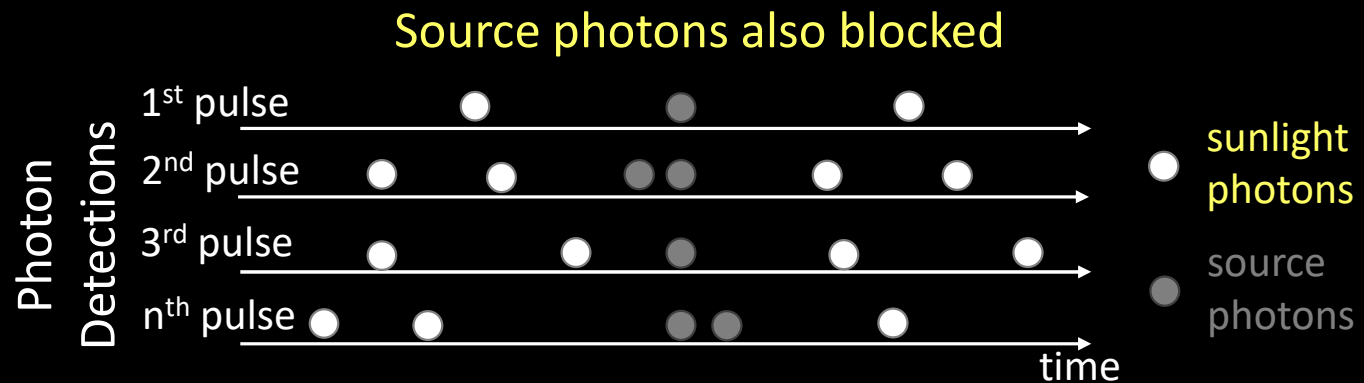
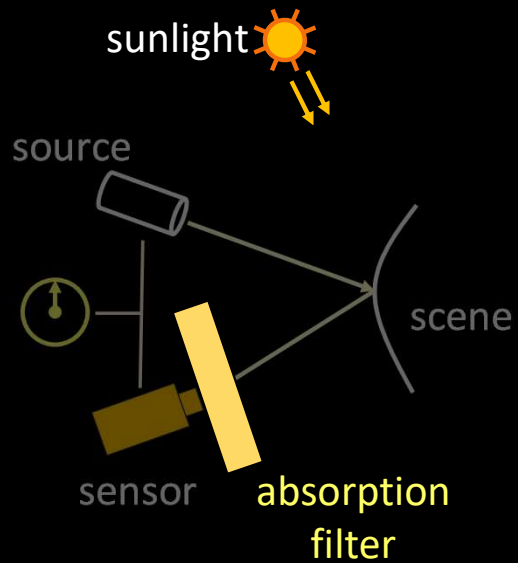


# Single-Photon 3D Camera: Sunlight



**Histogram distortion persists even for high source powers**

# Dealing with Sunlight: Current Wisdom

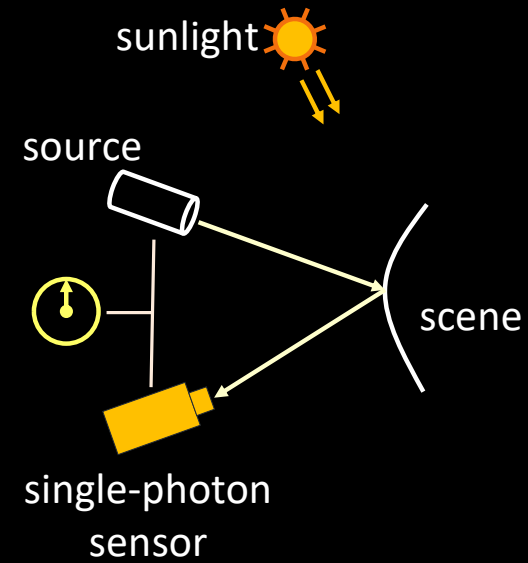


Sunlight photons blocked

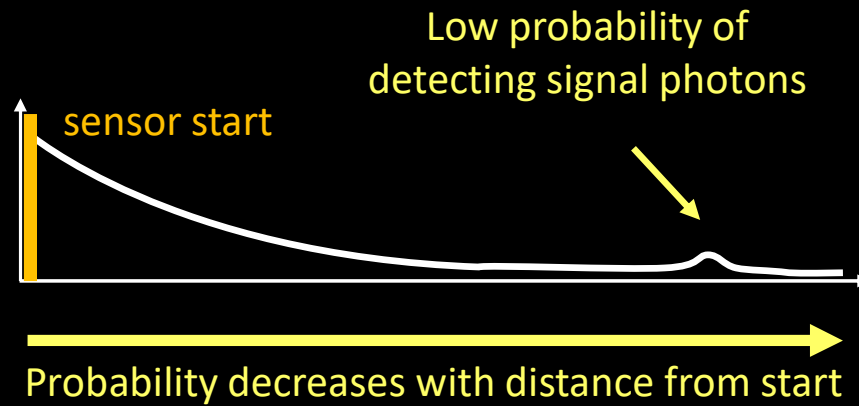


Peak difficult to locate due to low SNR

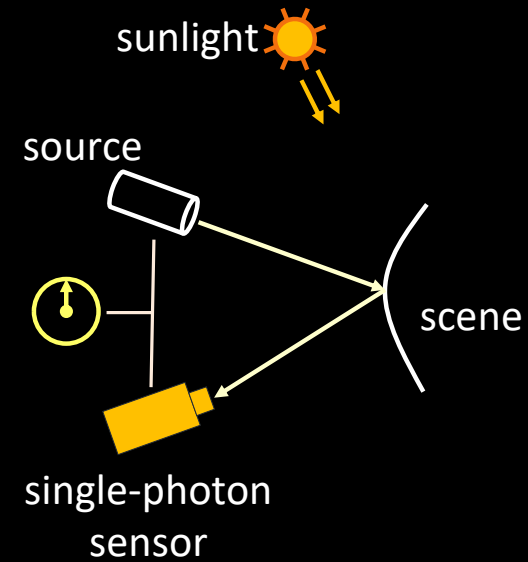
# Histogram Distortion: Key Observation



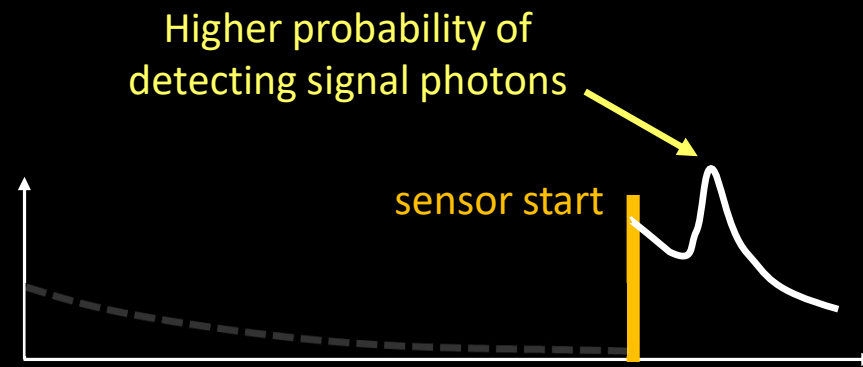
Photon Detection  
Probability



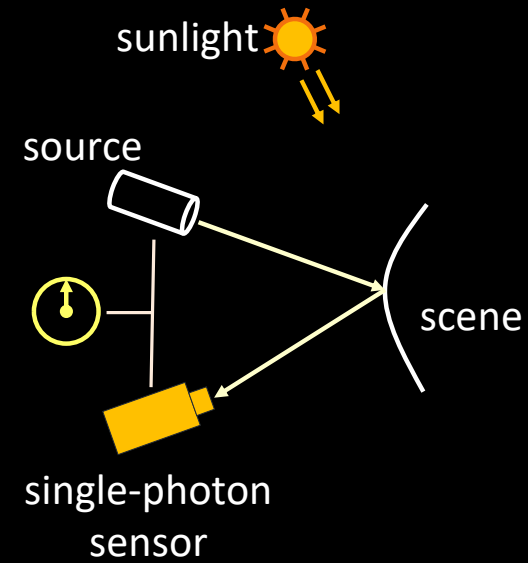
# Histogram Distortion: Key Observation



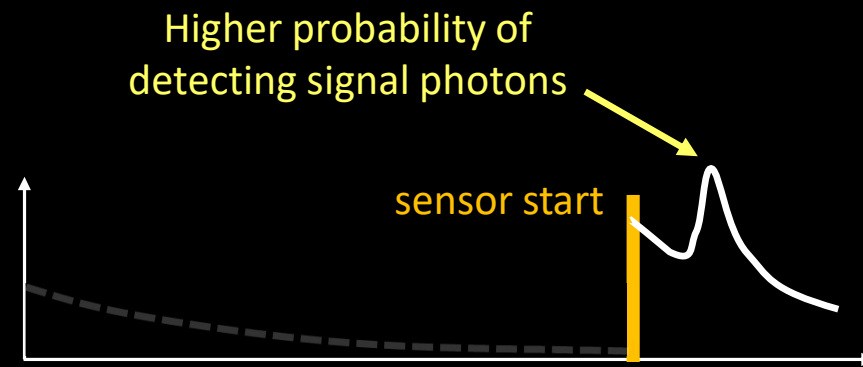
Photon Detection  
Probability



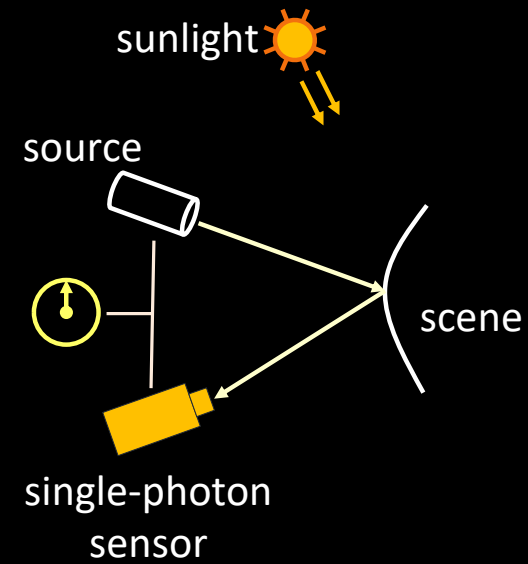
# Histogram Distortion: Key Observation



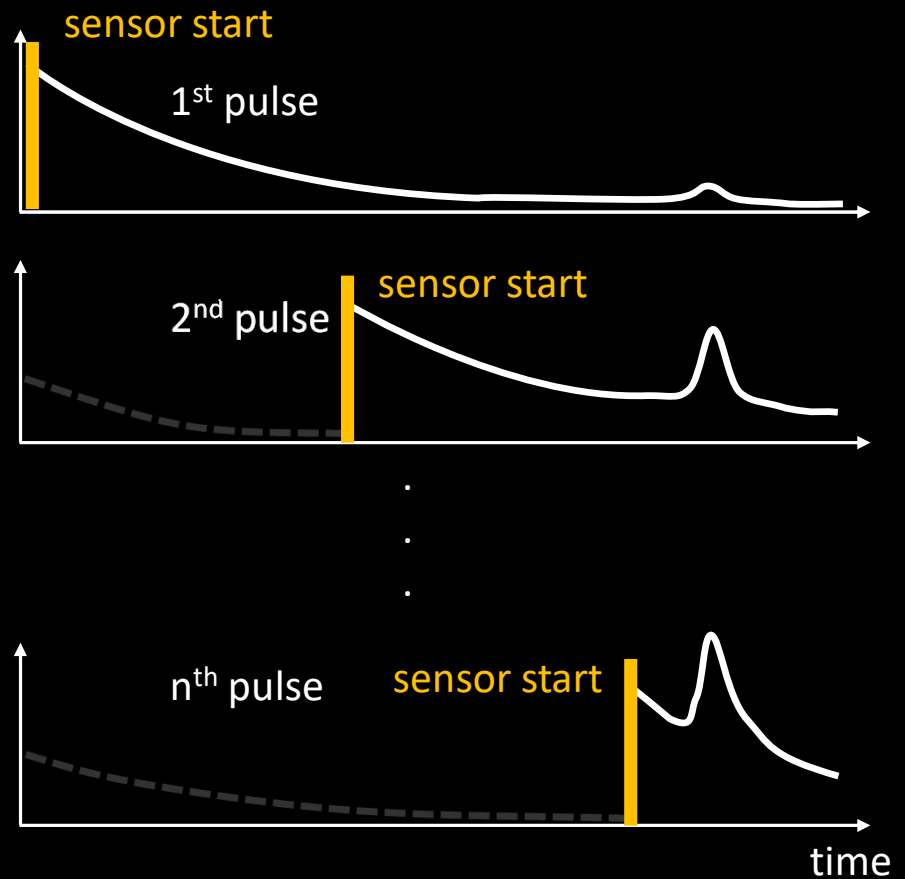
Photon Detection  
Probability



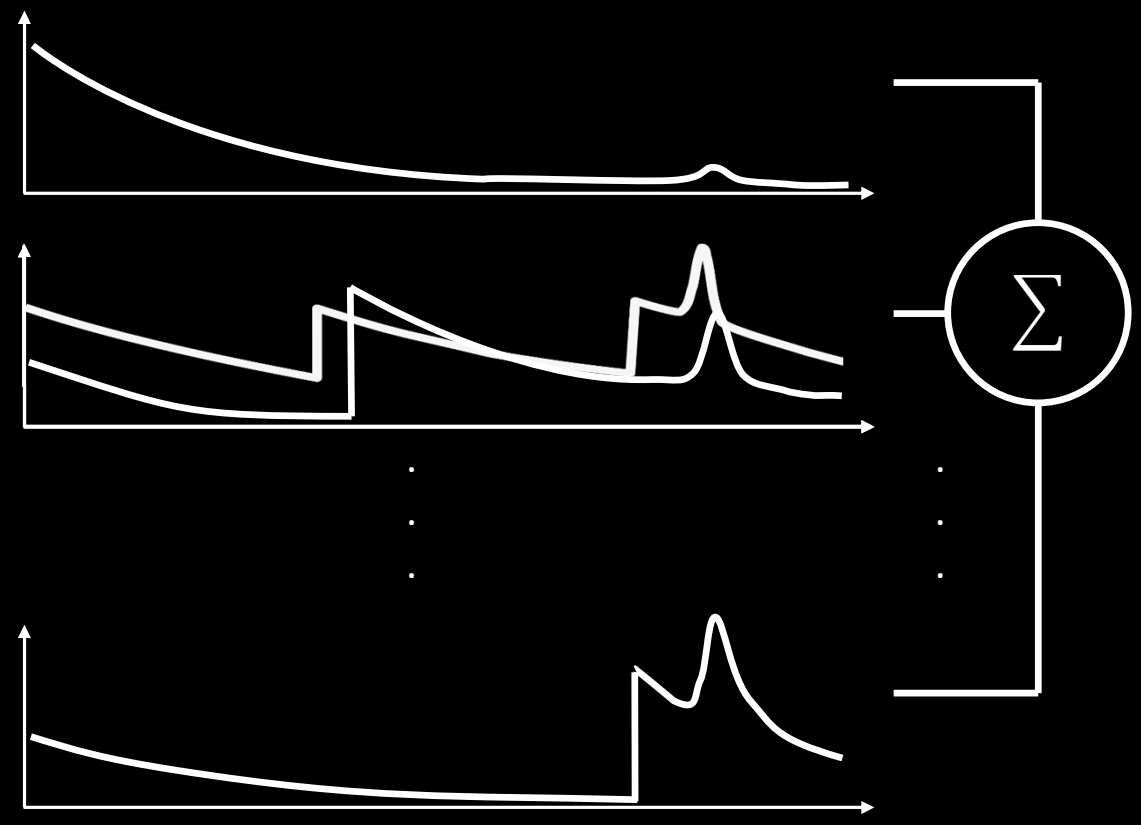
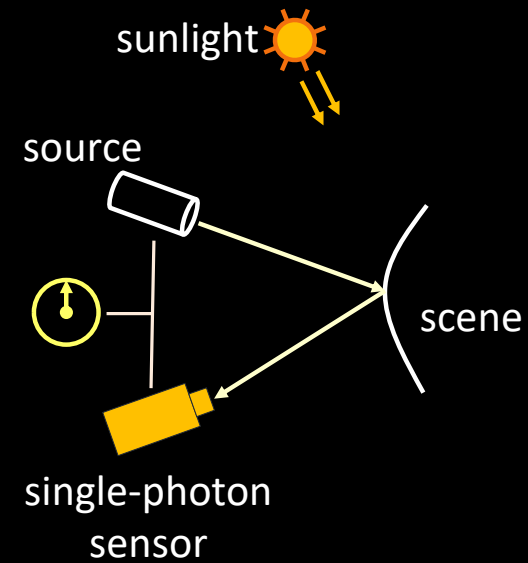
# Main Idea: Asynchronous Operation



Photon Detection  
Probability



# Asynchronous Operation [proposed]

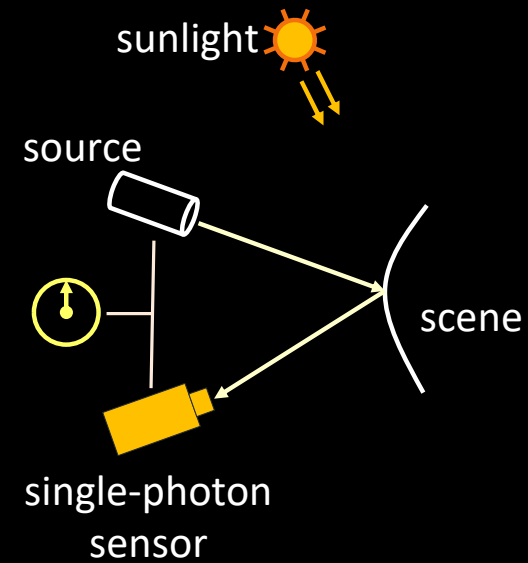


Expected histogram shape

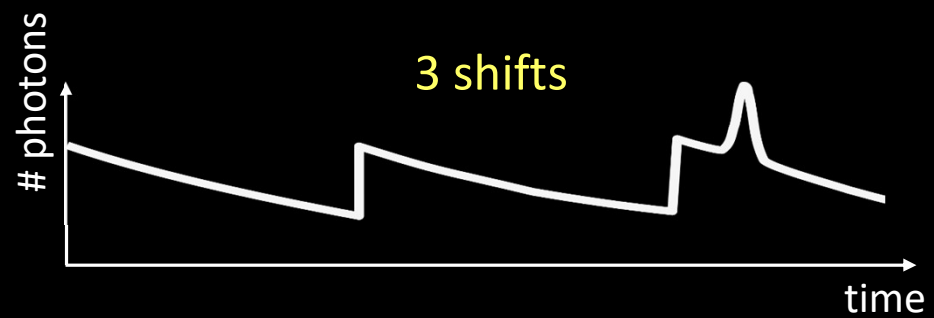
$\propto$

Sum of probabilities over all cycles

# Asynchronous Operation [proposed]

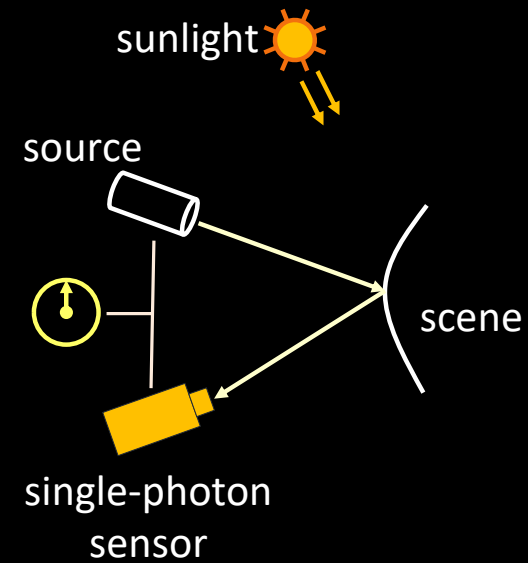


Expected  
Histogram

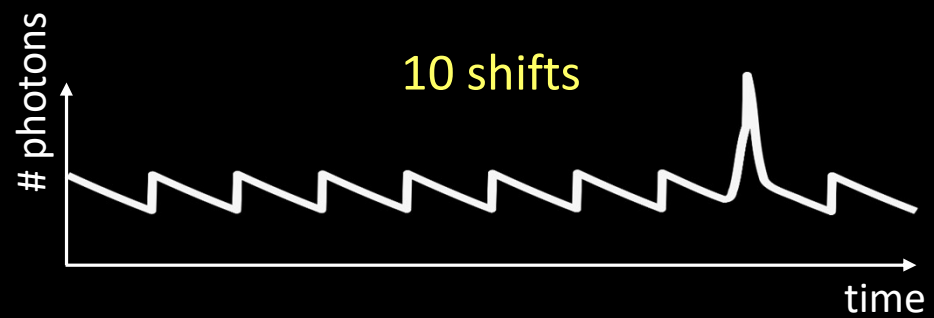




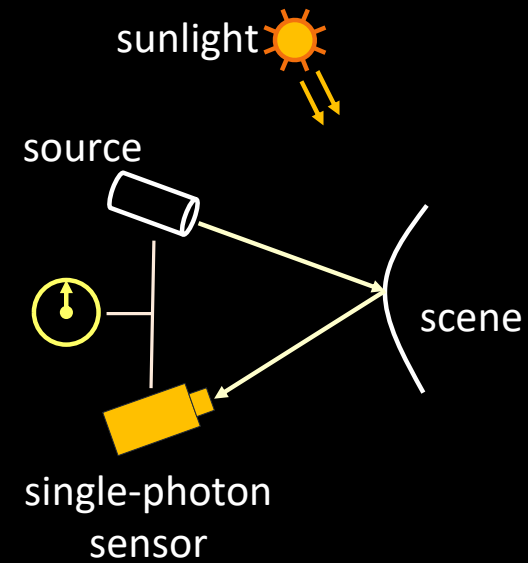
# Asynchronous Operation [proposed]



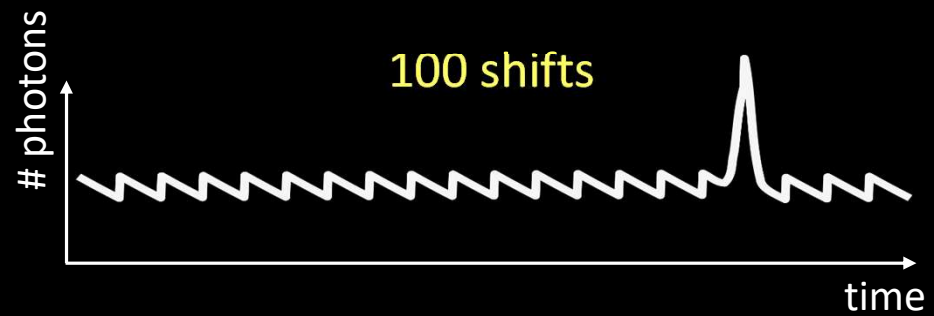
Expected  
Histogram



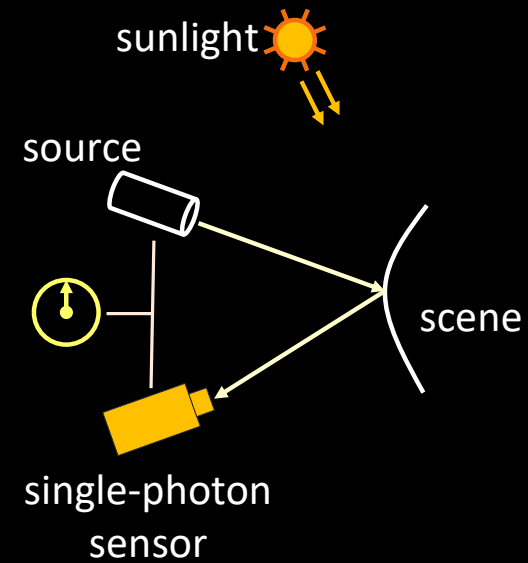
# Asynchronous Operation [proposed]



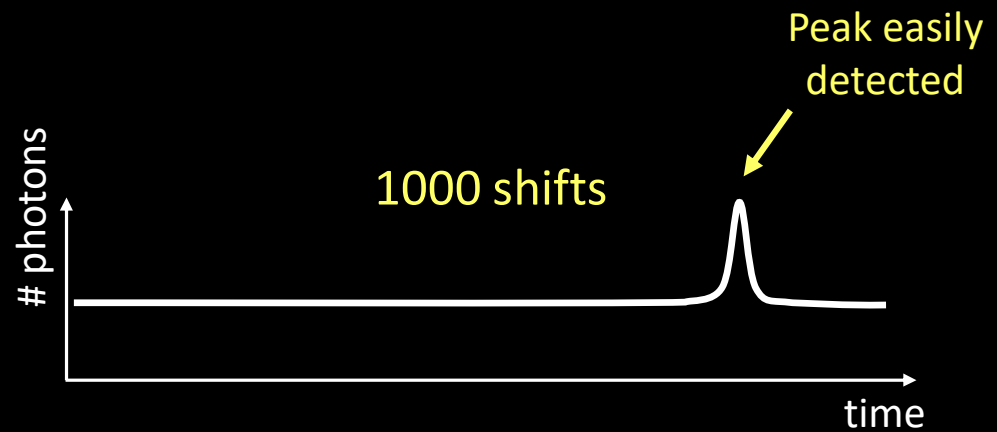
Expected  
Histogram



# Asynchronous Operation [proposed]

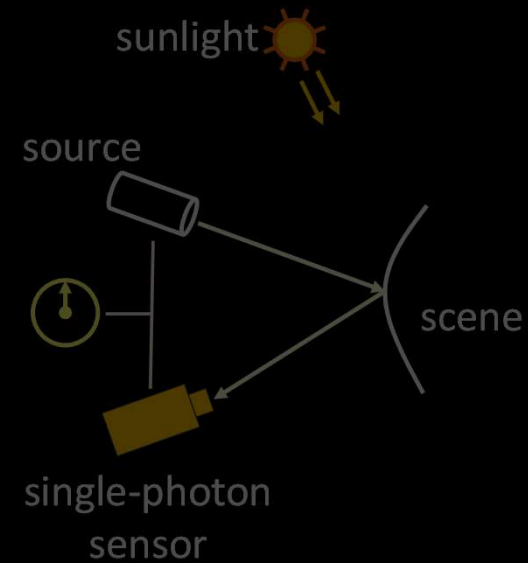


Expected  
Histogram

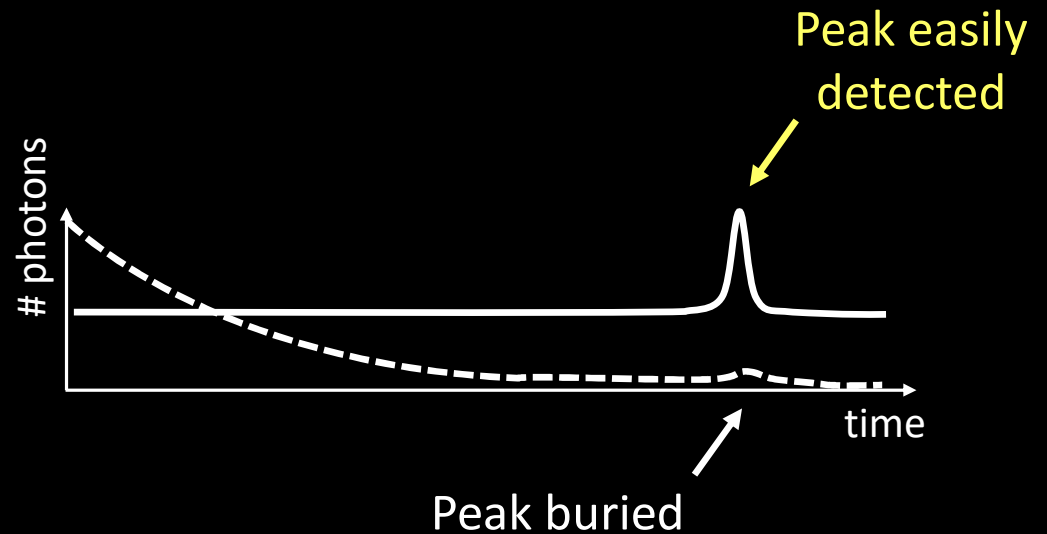


Expected histogram resembles true waveform shape.

# Asynchronous Operation [proposed]

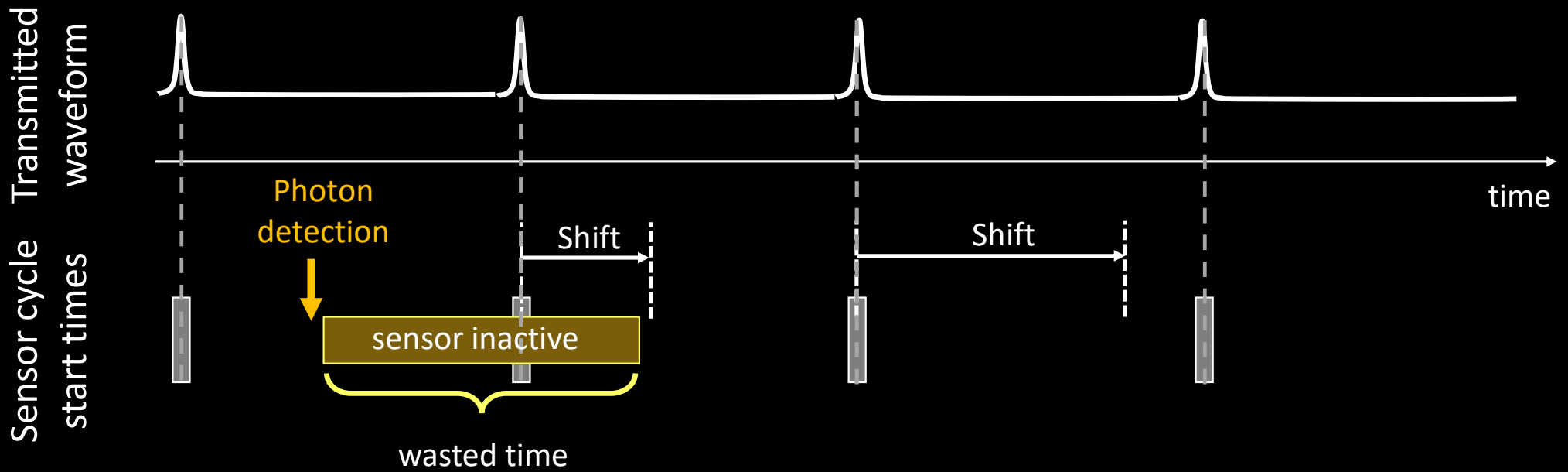


Expected Histogram



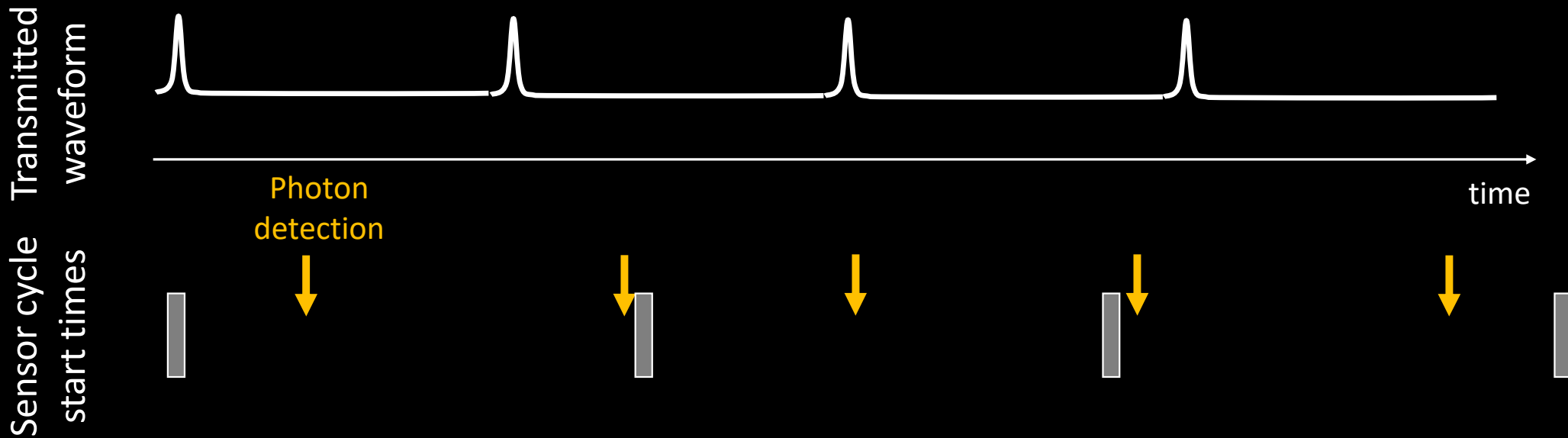
—— Asynchronous [proposed]  
----- Conventional acquisition

# Achieving Asynchrony in Practice



Conventional acquisition  
[synchronized sensors]

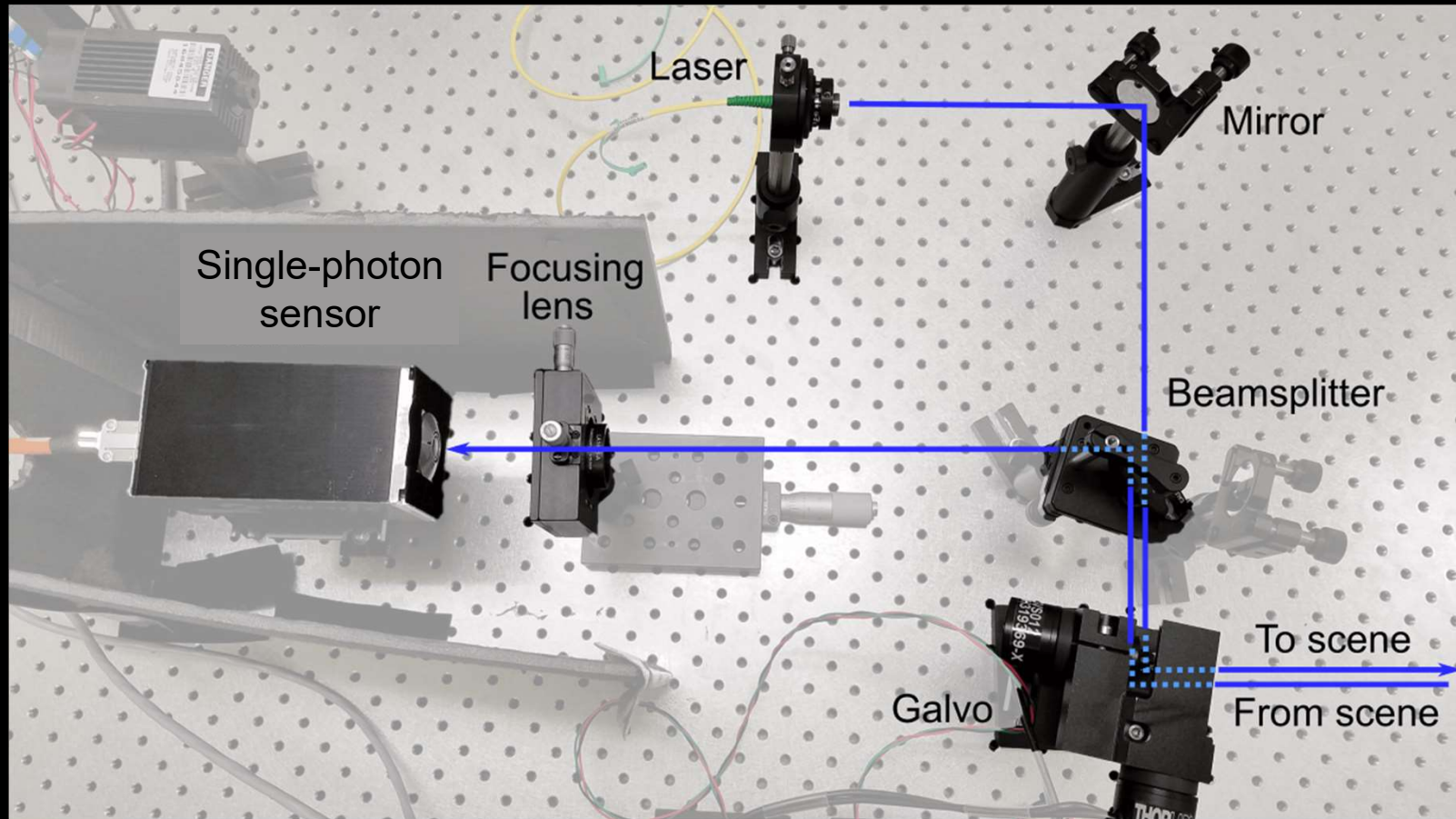
# Achieving Asynchrony in Practice



Photon-driven asynchronous acquisition.

Easy to implement. Does not require major hardware changes.

# Hardware Prototype



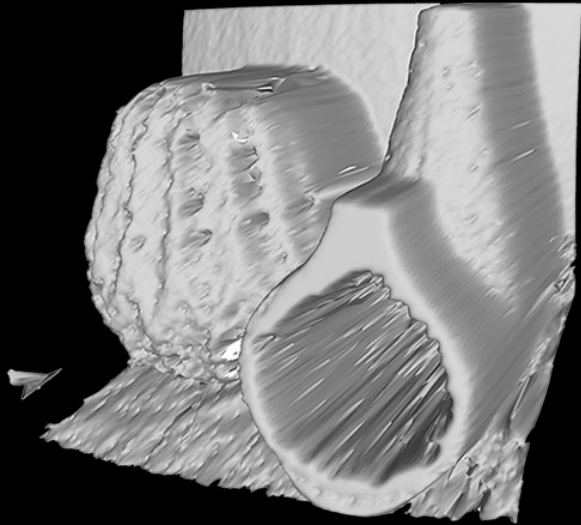
# Experiment Result 1





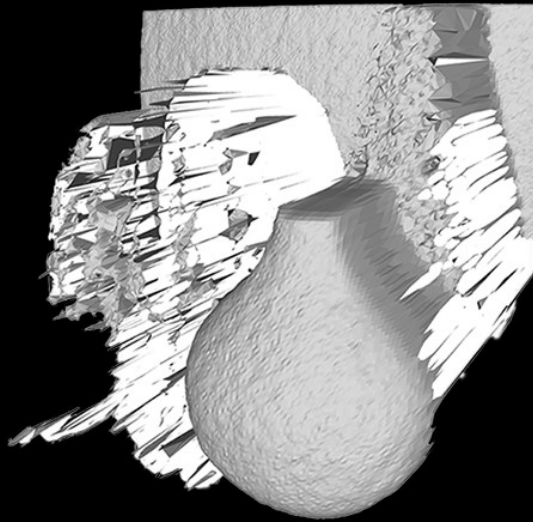
# Experimental Result 1

Conventional Acquisition  
(high exposure)

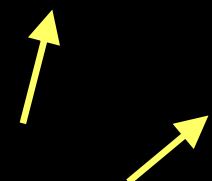


RMSE=4.5 cm

Conventional Acquisition  
(low exposure)



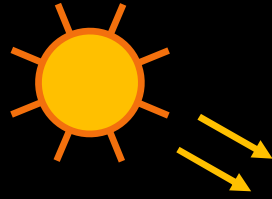
4.7 cm



Photon-driven acquisition: Both dark and bright points recovered accurately

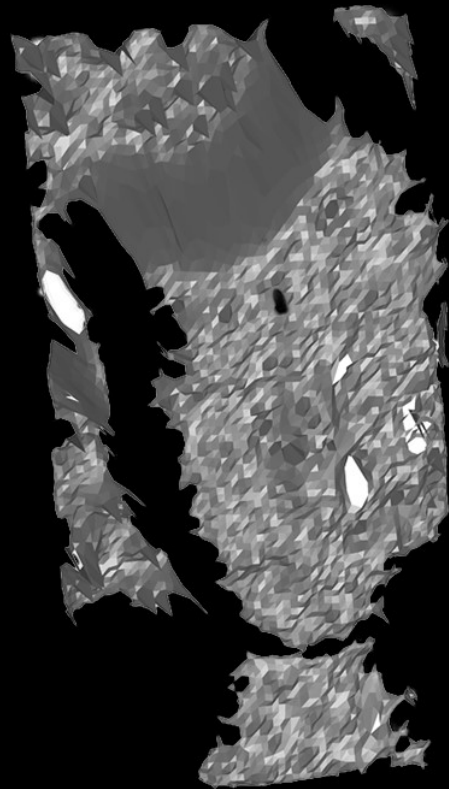
## Experimental Result 2

bright sunlight  
>20,000 lux



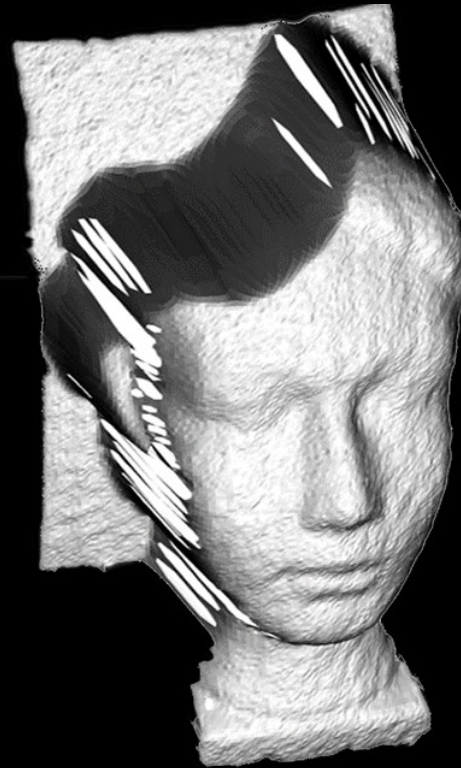
## Experimental Result 2

Conventional Acquisition



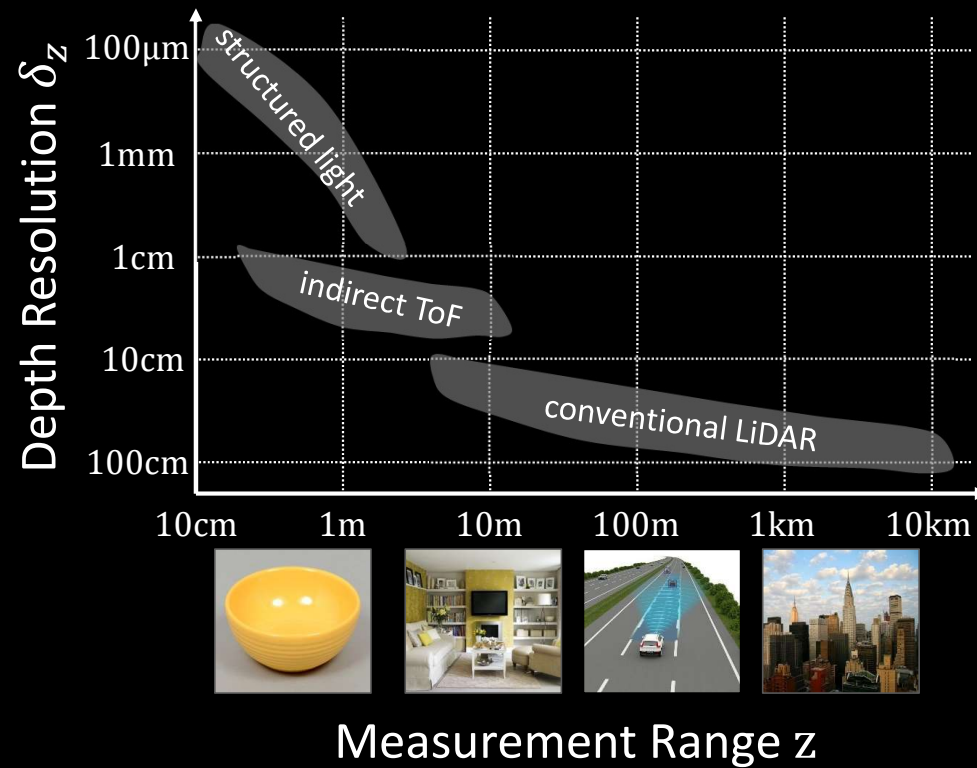
RMSE=5.6 cm

Asynchronous Acquisition  
[proposed]

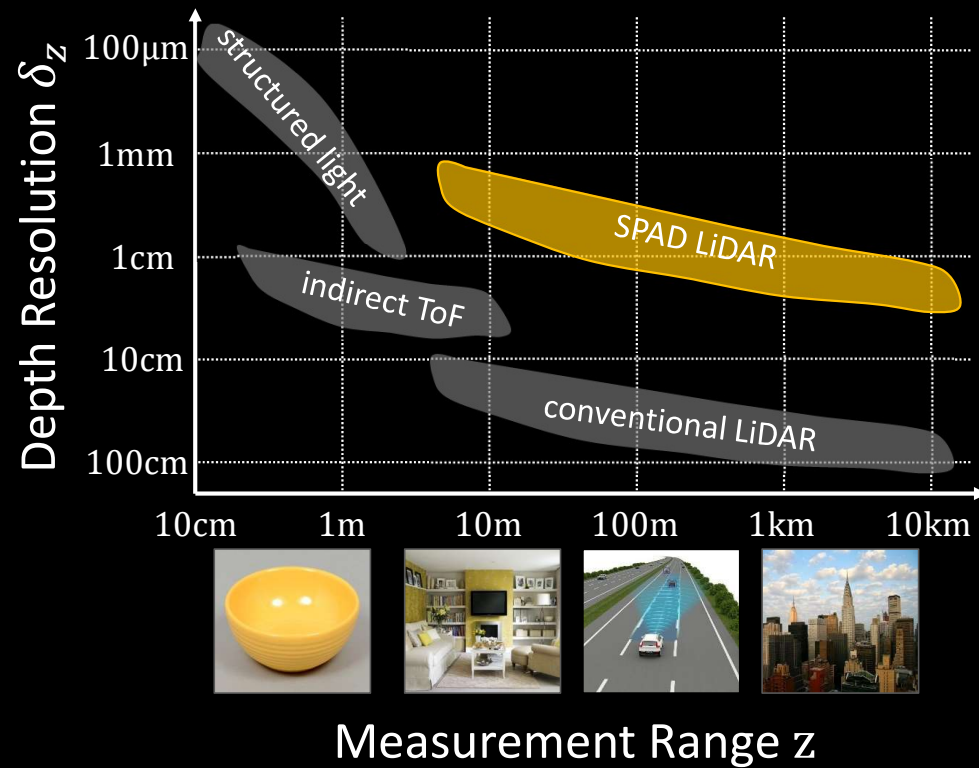


0.65 cm

# Towards Long-Range High-Resolution 3D Cameras



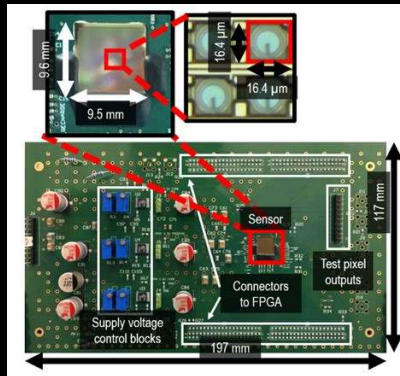
# Towards Long-Range High-Resolution 3D Cameras



# Single-Photon Cameras



MPD



SwissSPAD2 EPFL



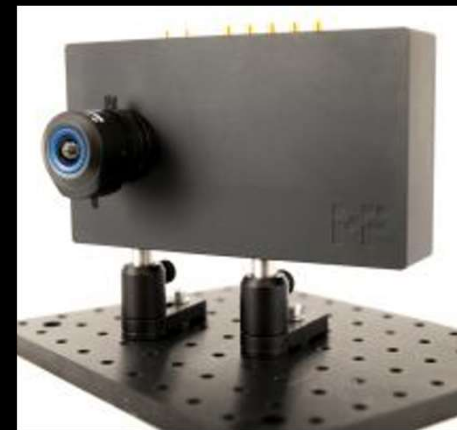
Ouster LiDAR



Voxtel, Inc.



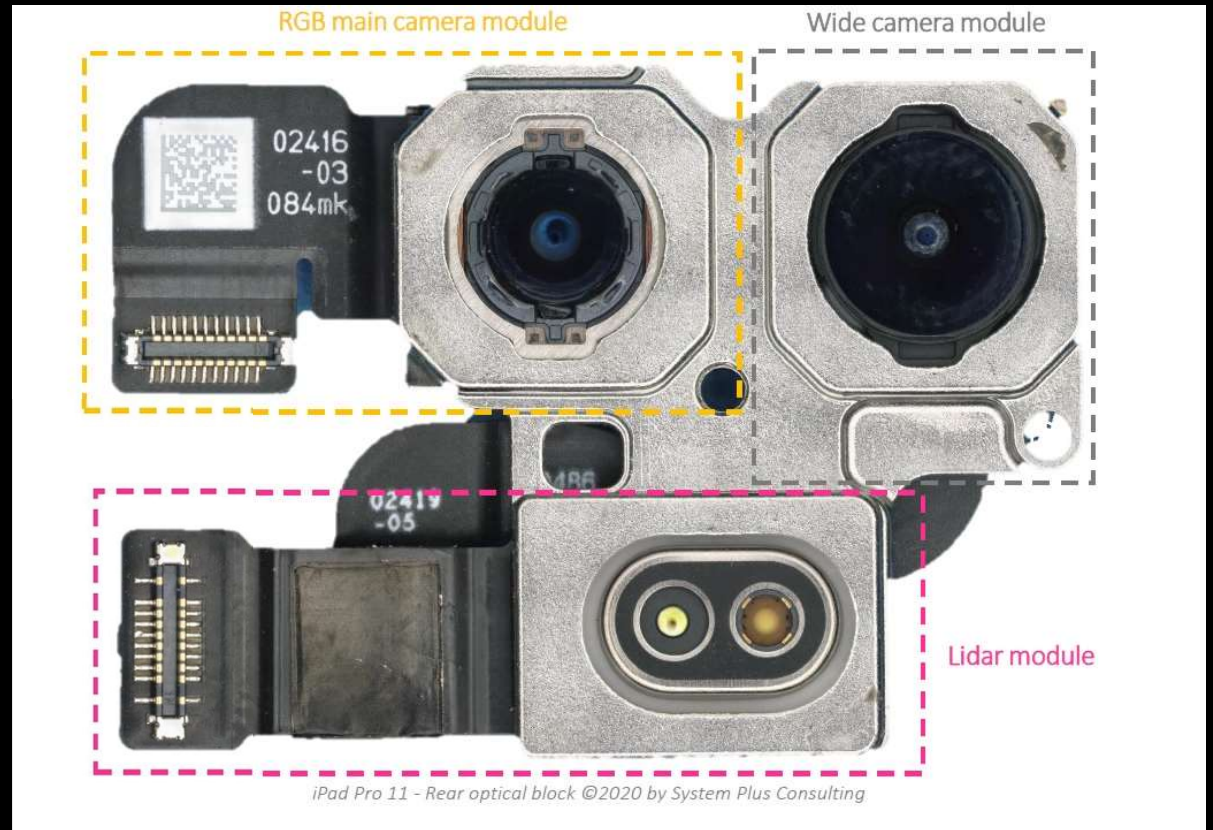
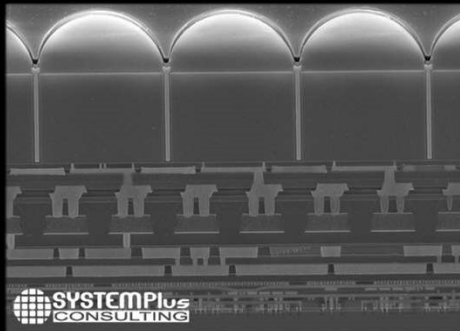
Gigajot



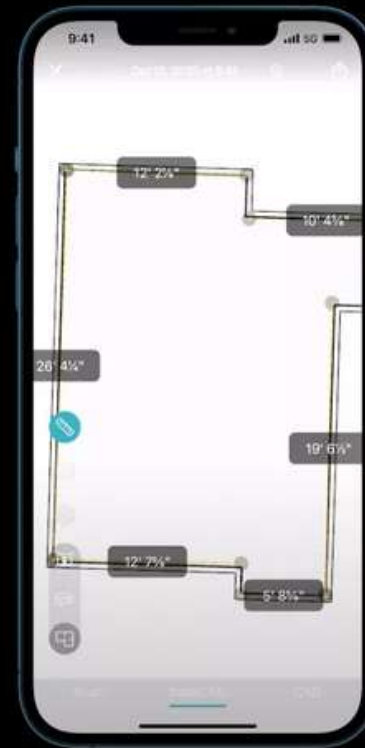
PhotonForce

# Latest iPhone 12/iPad Pro

LiDAR Scanner



# Latest iPhone 12/iPad Pro



Snapchat

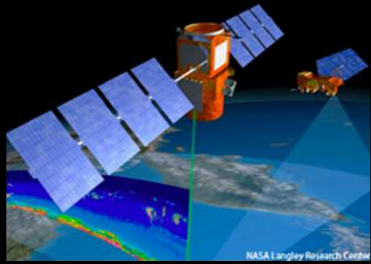


# Latest iPhone 12/iPad Pro



Occipital

# Single-Photon Cameras

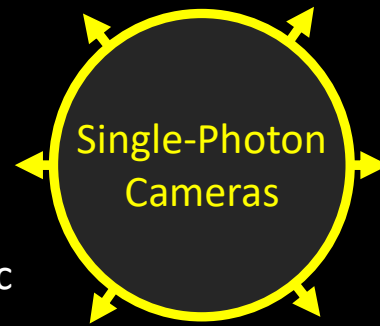


Long range

Low power

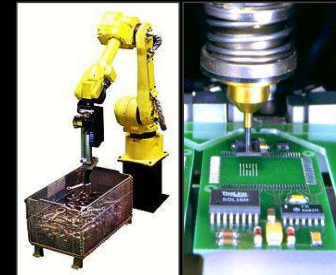


High dynamic range



Extreme sensitivity

High depth resolution



[www.SinglePhoton3DImaging.com](http://www.SinglePhoton3DImaging.com)