



# GAMES 204



## Computational Imaging

Lecture 18: Temporal Encoding: Time-of-flight Imaging



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点昀技术 (Point Spread Technology)



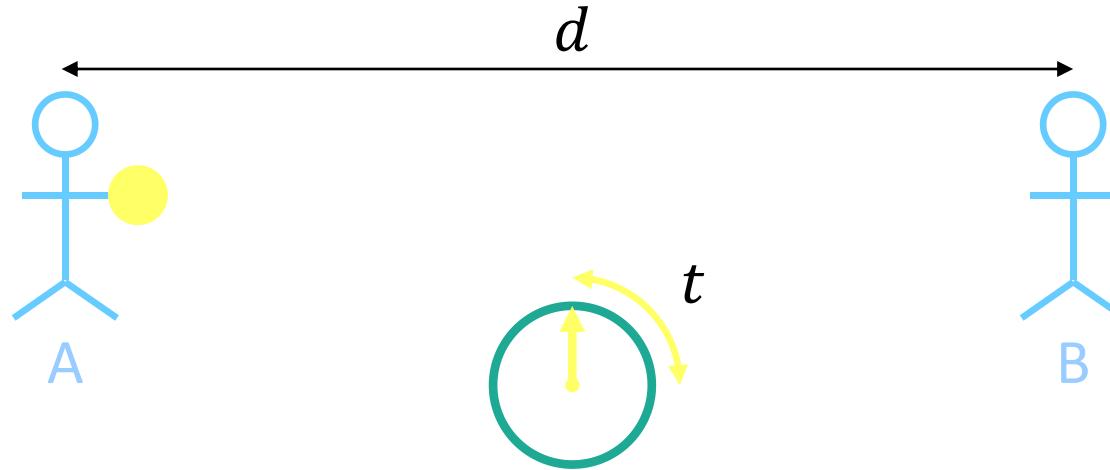
## Today's Topic

- History of the Time-of-flight
- Introduction to Optical Time Resolved Imaging
  - Time-Resolved Image Formation Model
- Direct Time-of-flight Imaging
  - Streak Camera
  - SPAD Array Cameras
  - Single Photon 3D Imaging

# History of the Time-of-flight



# Time-of-flight

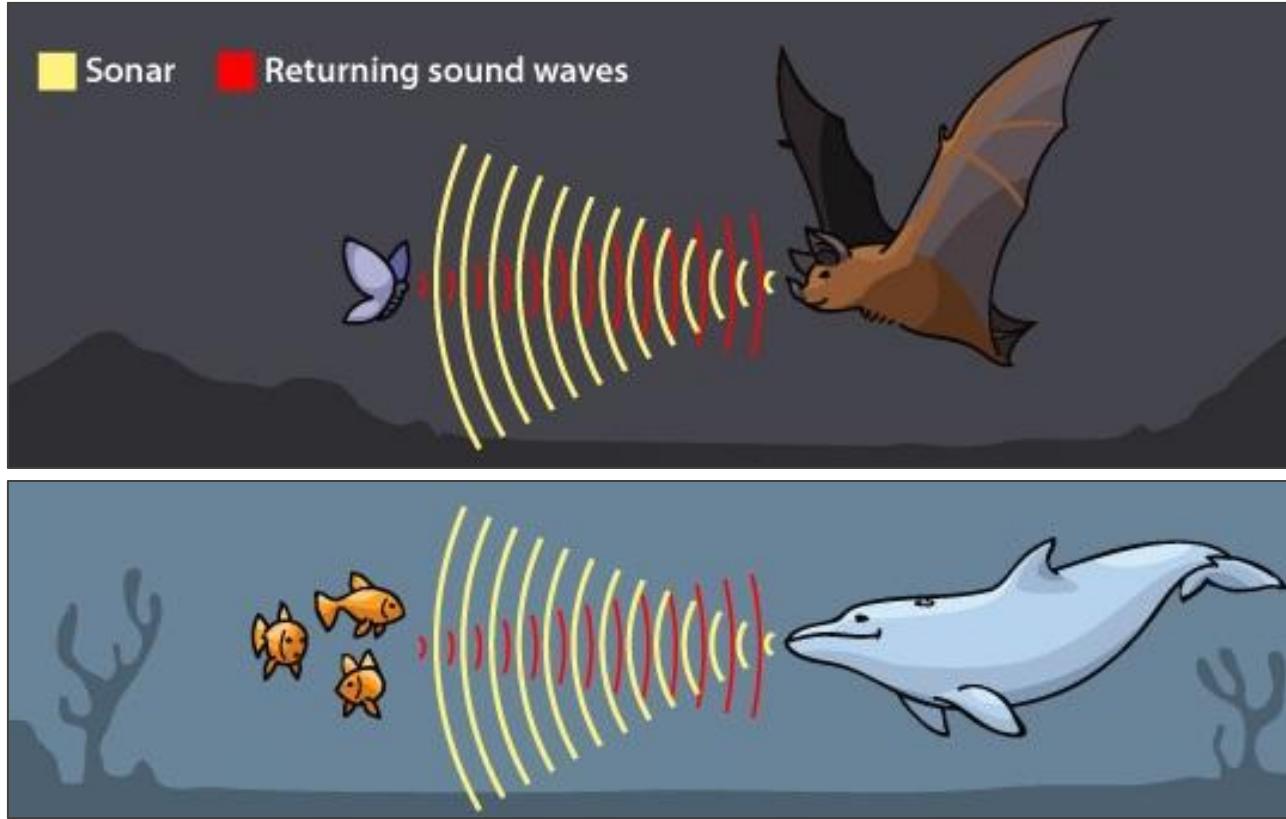


$$d = v \times t$$

distance      velocity      flight time



# Time-of-flight in Nature



## Echolocation Using Sound-Wave Time-of-Flight

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



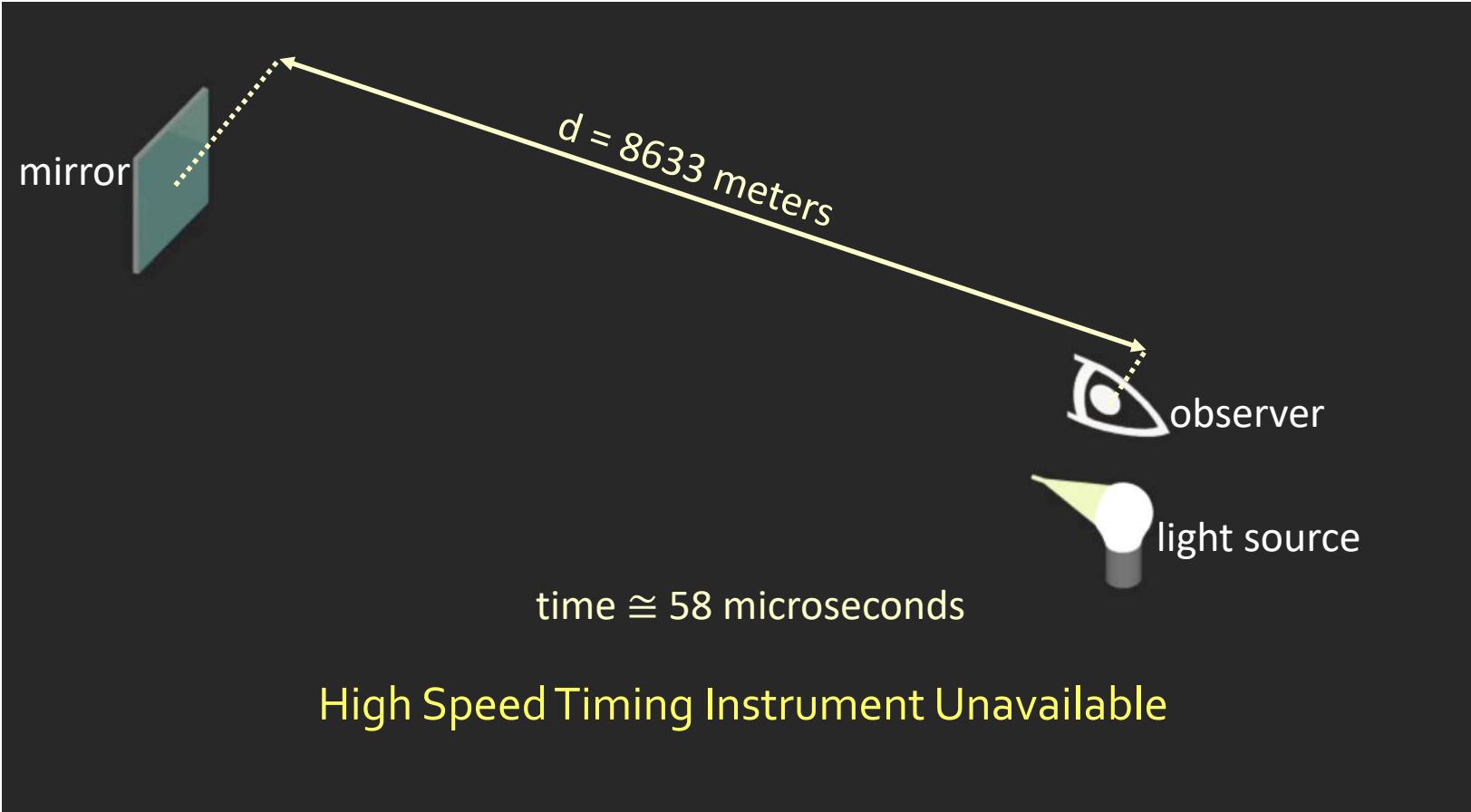
# Galileo's Experiment With Light (1638)



*Galileo's conclusion: "I have not been able to ascertain with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous it is extraordinarily rapid – I should call it momentary"*

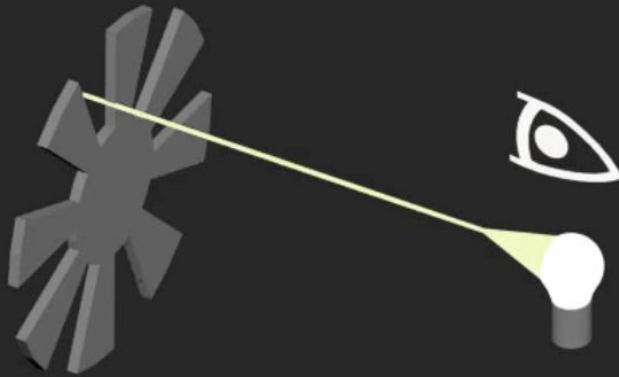


# Fizeau's Experiment (1849)





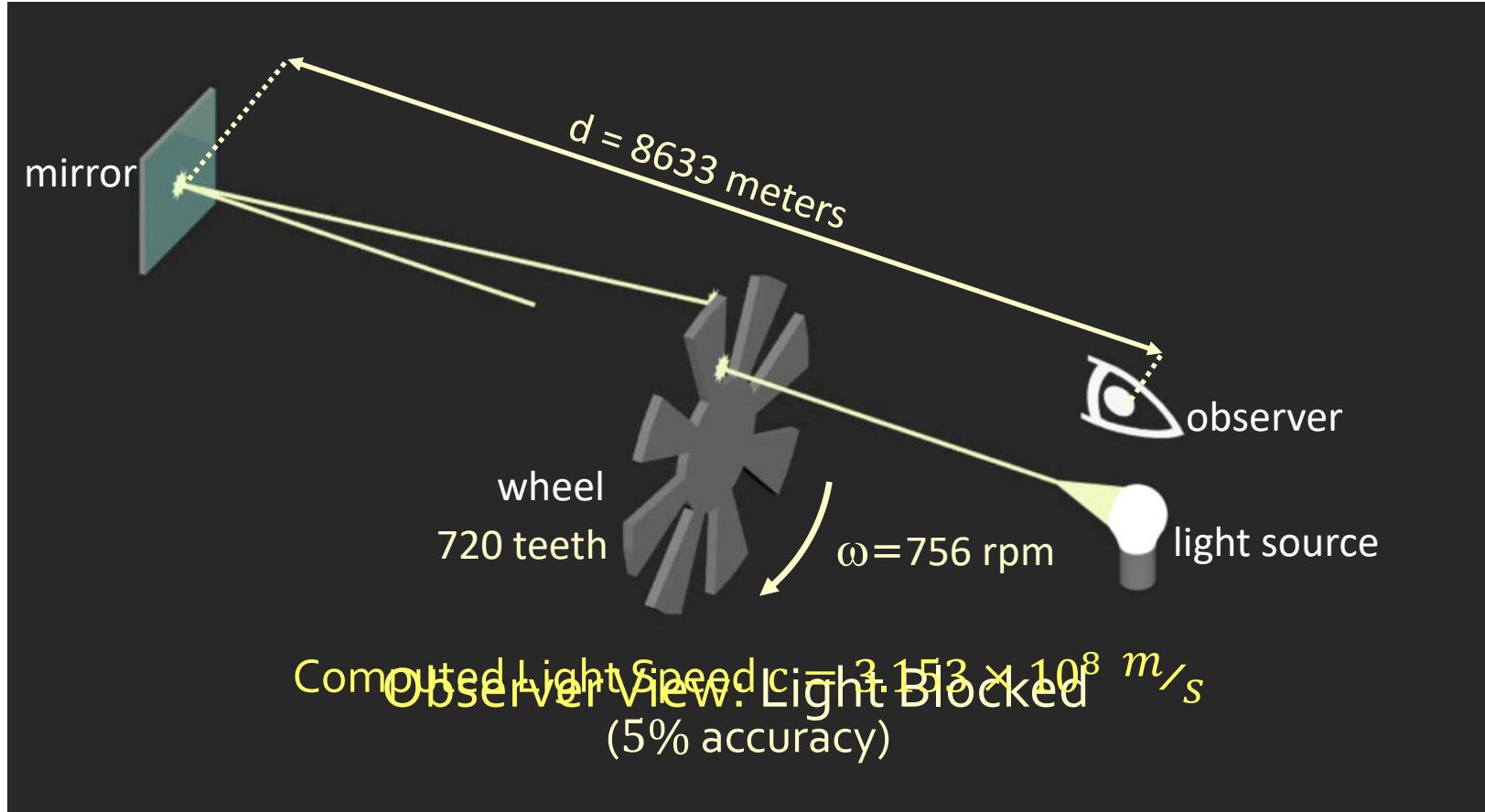
# Fizeau's Experiment (1849)



Observer View: Pulsed Light

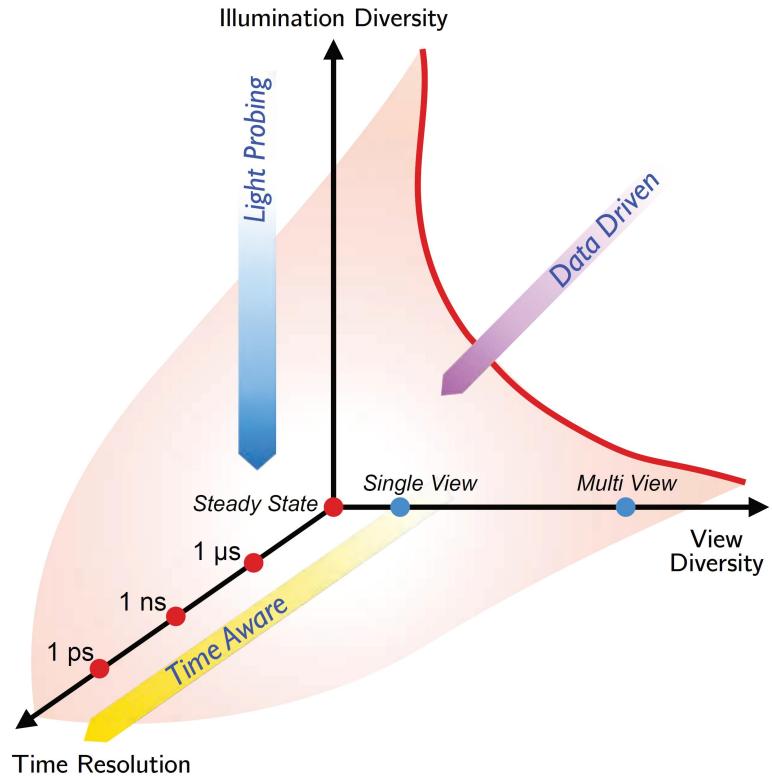


## Fizeau's Experiment: Fast Rotation





# Capturing the High Dimensional Plenoptic Function



plenoptic function

$$P(x, y, z, \theta, \phi, \lambda, t, E_x, E_y)$$

Spatial Position ( $x, y, z$ )

Viewing Direction( $\theta, \phi$ )

Wavelength  $\lambda$

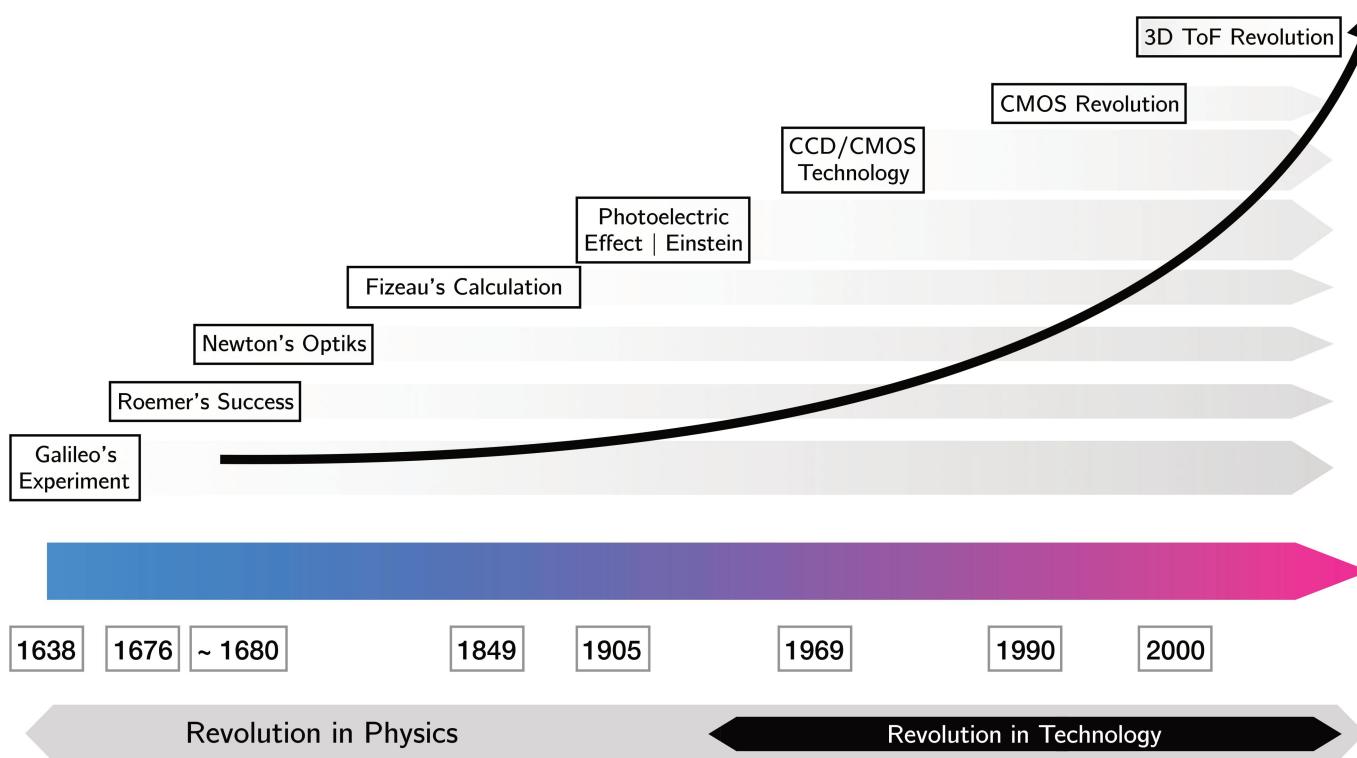
Time  $t$

Polarization ( $E_x, E_y$ )

Different Mechanisms for Creating Diversity in Measurements when Capturing the High Dimensional Plenoptic Function.



# Time-of-flight Revolution



A Brief History of the Time-Resolved Imaging Revolution

# Introduction to Optical Time Resolved Imaging

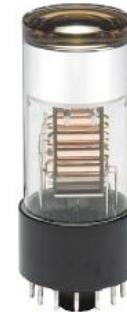
## Available Time-resolved Imaging Hardware



Gated Camera (Phoenix)



SPAD Array (MPD)



Photomultiplier tubes – PMTs  
(Hamamatsu)



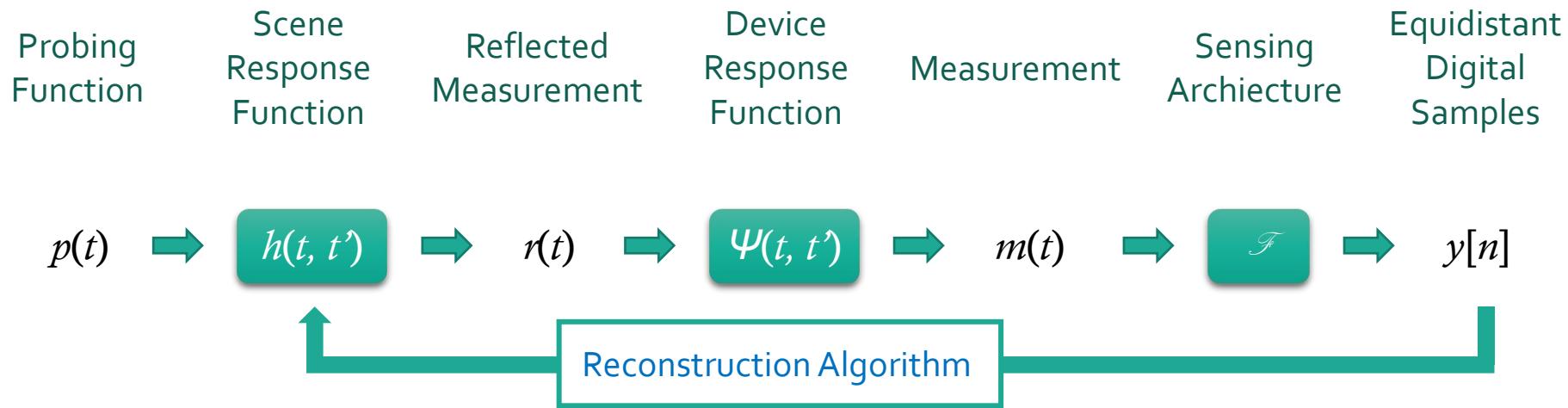
Lock-in Sensors  
(Point Spread Tech. Okulo P1)



Streak Camera (Hamamatsu)



# Time-Resolved Image Formation Model



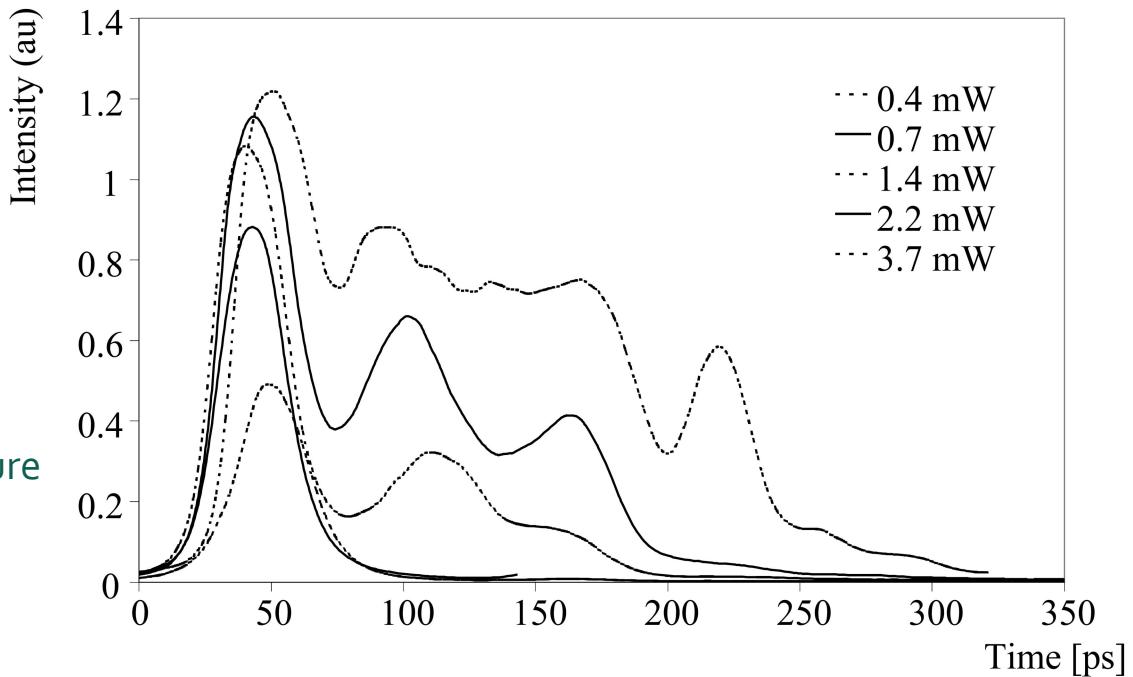
Time-resolved Imaging Pipeline

# Probing Function

- Probing function denoted by  $p(t)$  represents the waveform emitted by the ToF sensor's illumination unit.

Possible probing functions  
(maybe a time-localized pulse)

- B-Spline
- (Multi-)Gaussian
- Exponential-Gaussian mixture
- ...



# Scene Response Function

- Scene Response Function or SRF denoted by  $h(t, t')$  models the transfer function of the scene. This may be a filter, a shift-invariant function, e.g.,

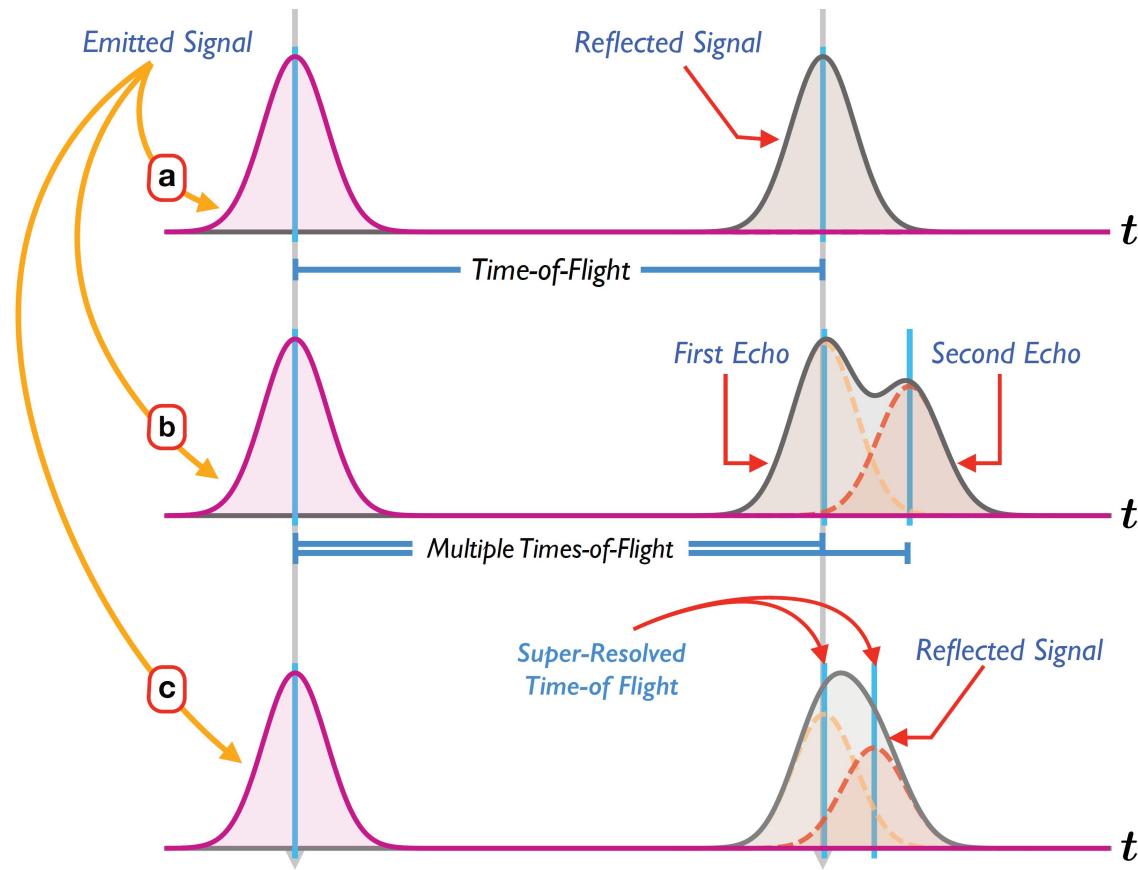
$$h(t, t') = h_{SI}(t, t')$$

Possible probing functions  
(maybe a time-localized pulse)

- B-Spline
- (Multi-)Gaussian
- Exponential-Gaussian mixture
- ...

Temporal profiles of picosecond laser diode pulses

# Time-resolved Information





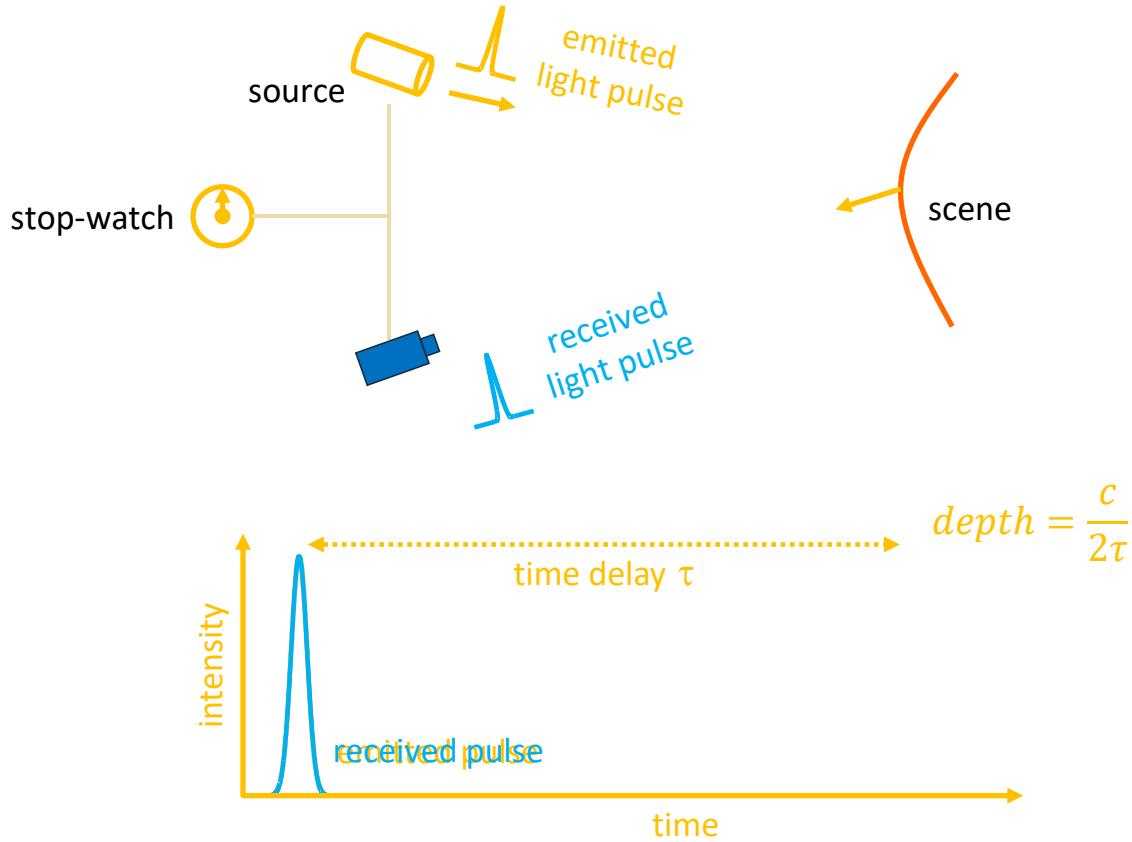
香港中文大學(深圳)  
The Chinese University of Hong Kong, Shenzhen



# Direct Time-of-flight Imaging



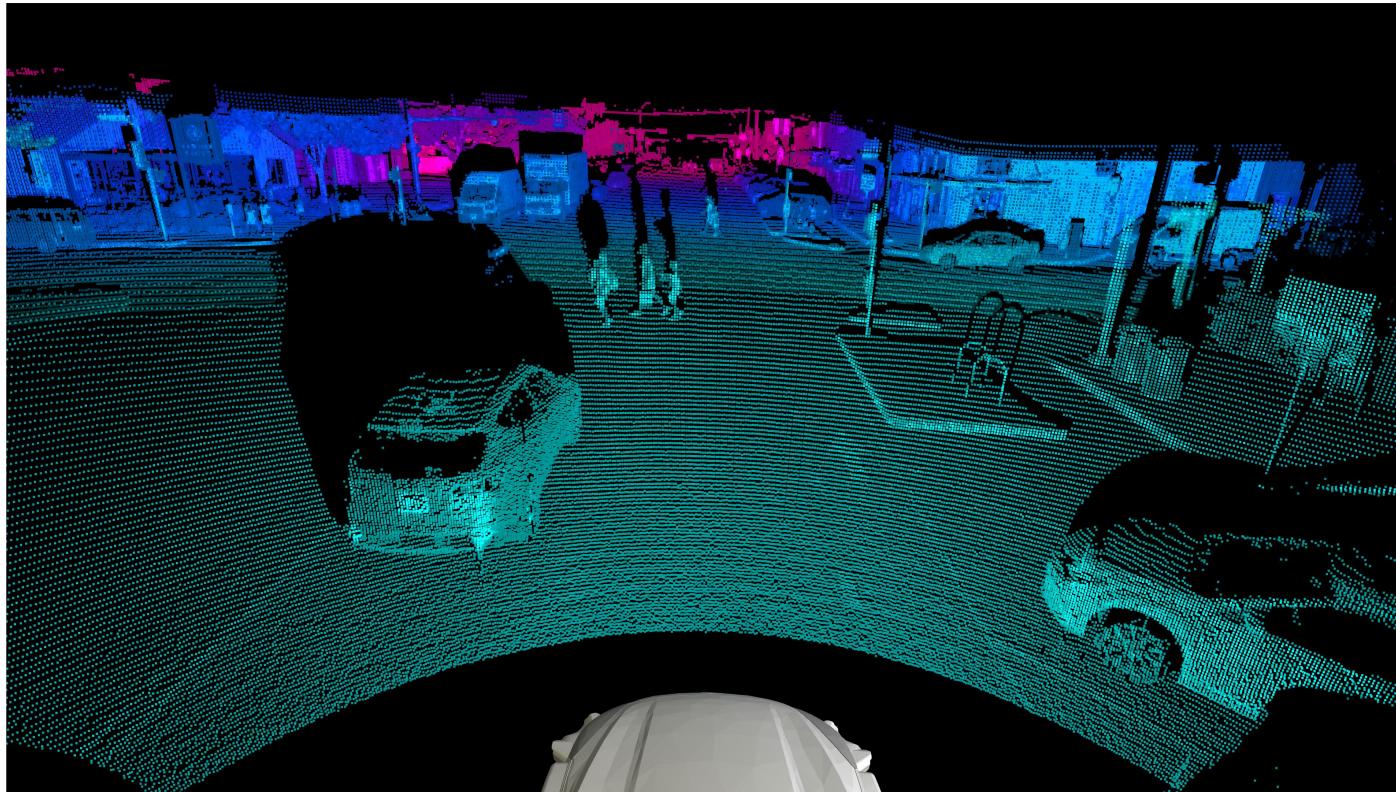
# Direct Time-of-Flight Imaging



[Koechner, 1968]



# Direct Time-of-Flight Imaging: Applications

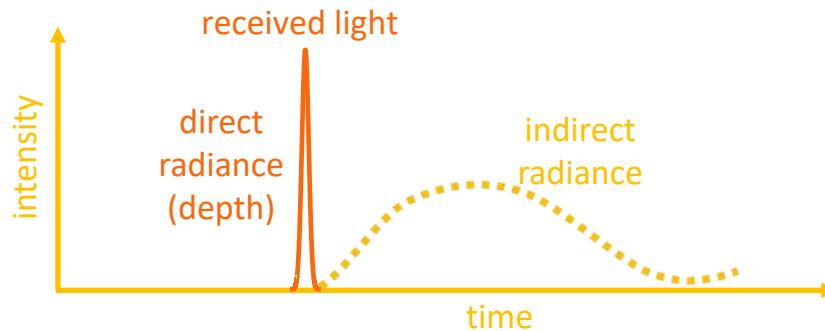
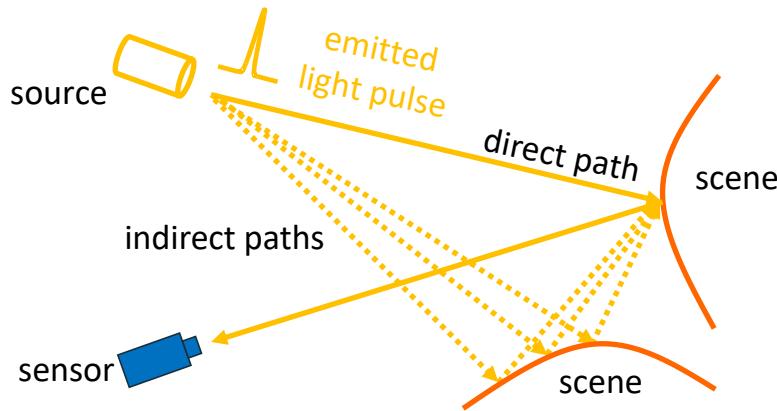


Lidar

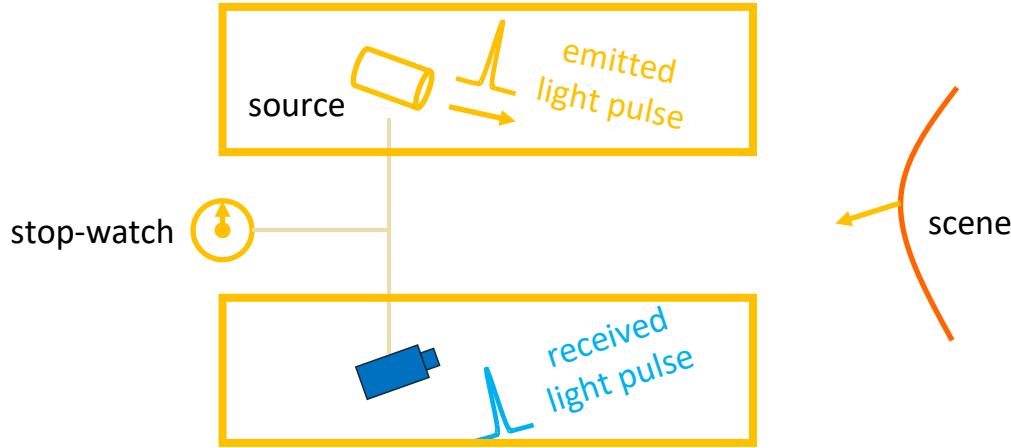
<https://www.argo.ai/company-news/cvpr-2022-how-argo-ai-is-advancing-object-detection-and-perception-for-self-driving-cars/>



# Direct Time-of-Flight Imaging: Indirect Light



# Direct Time-of-Flight Imaging: Requirements



Expensive Lasers

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

High Speed and High Dynamic Range Sensors

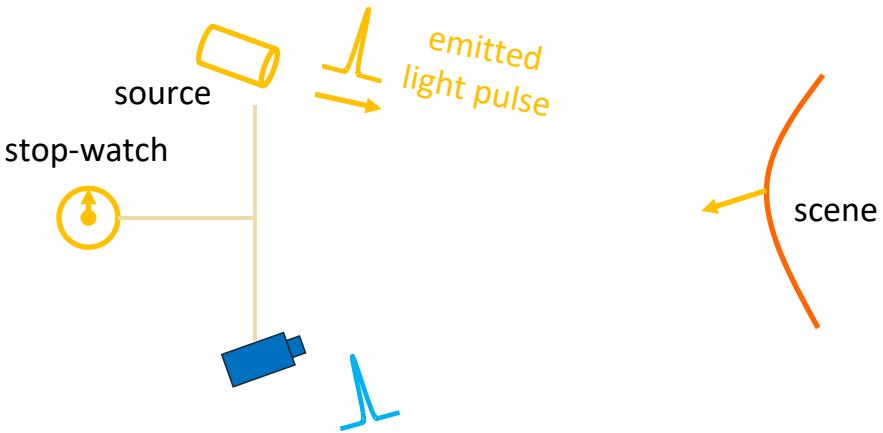
[Picosecond Time Resolution]

Koechner, 1968



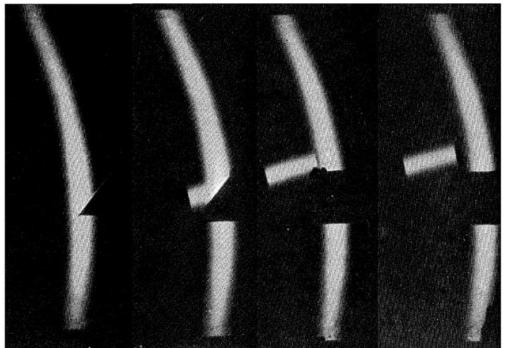
# Transient Imaging

- What is Transient Imaging ?  
a.k.a Light-in-Flight Imaging
  
- Ultrafast imaging of **non-stationary** light distribution in scenes
- Tracking of **wavefronts** of light as they propagate in the scene
- Equivalent to imaging **ultrashort** pulses of light

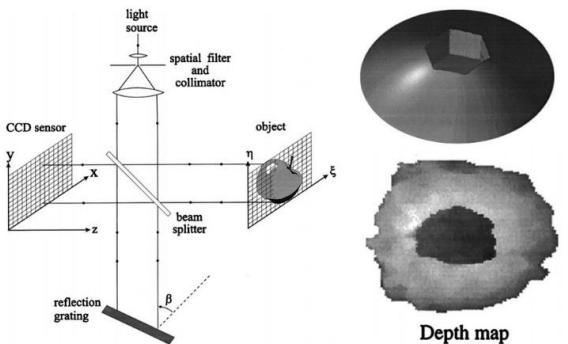




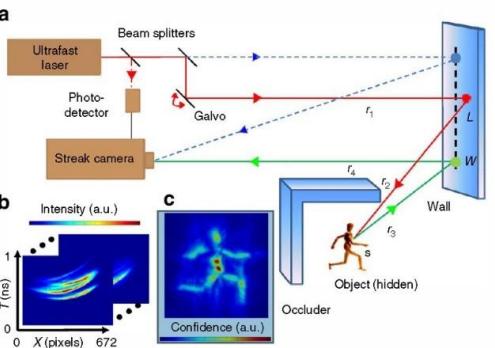
# Transient Imaging



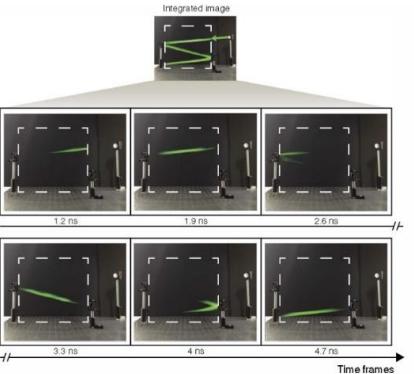
Nils Abramson, et.al. (1978)



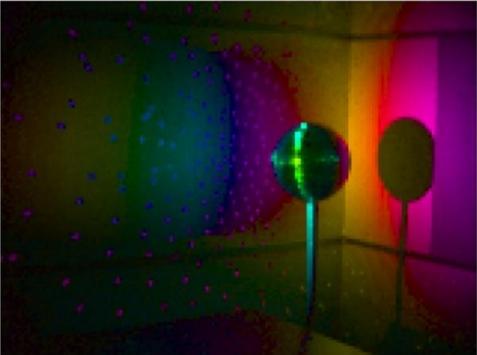
B.Nillson, et.al. (1998)



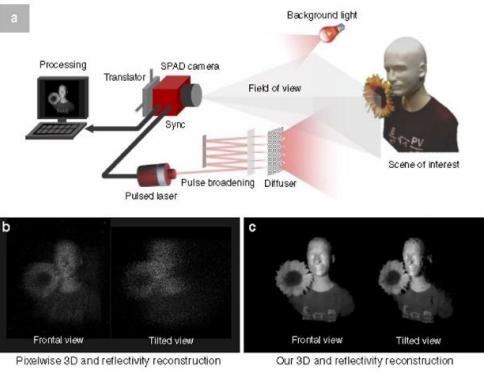
A. Velten, et. al. (2012)



G.Gariepy, et. al. (2015)

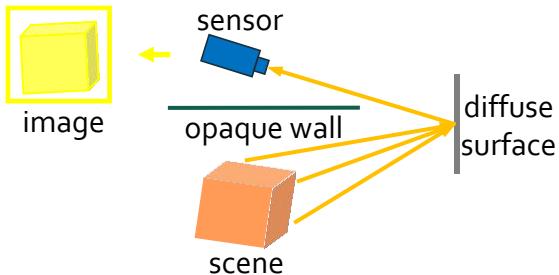


F. Heide, et. al. (2013)



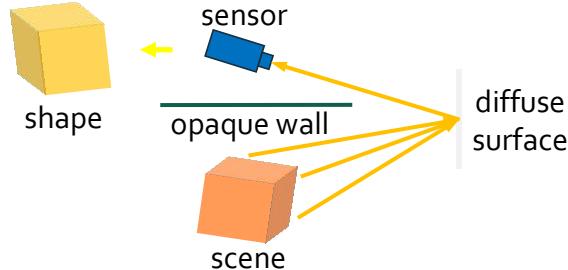
D. Shin, et. al. (2016)

# Direct Time-of-Flight Imaging: Applications



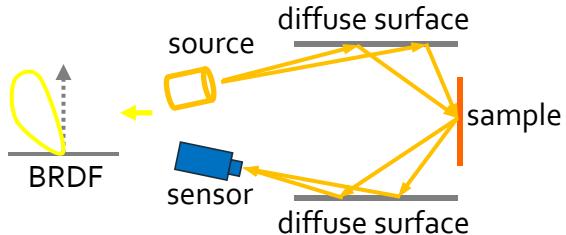
Imaging around the corner

[Kirmani *et. al.*, 2009]



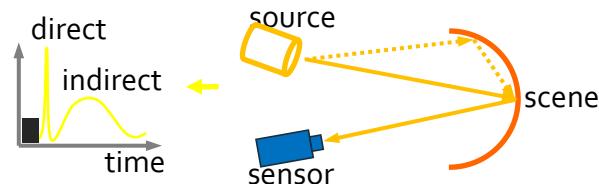
3D around the corner

[Velten *et. al.*, 2012]



BRDF estimation

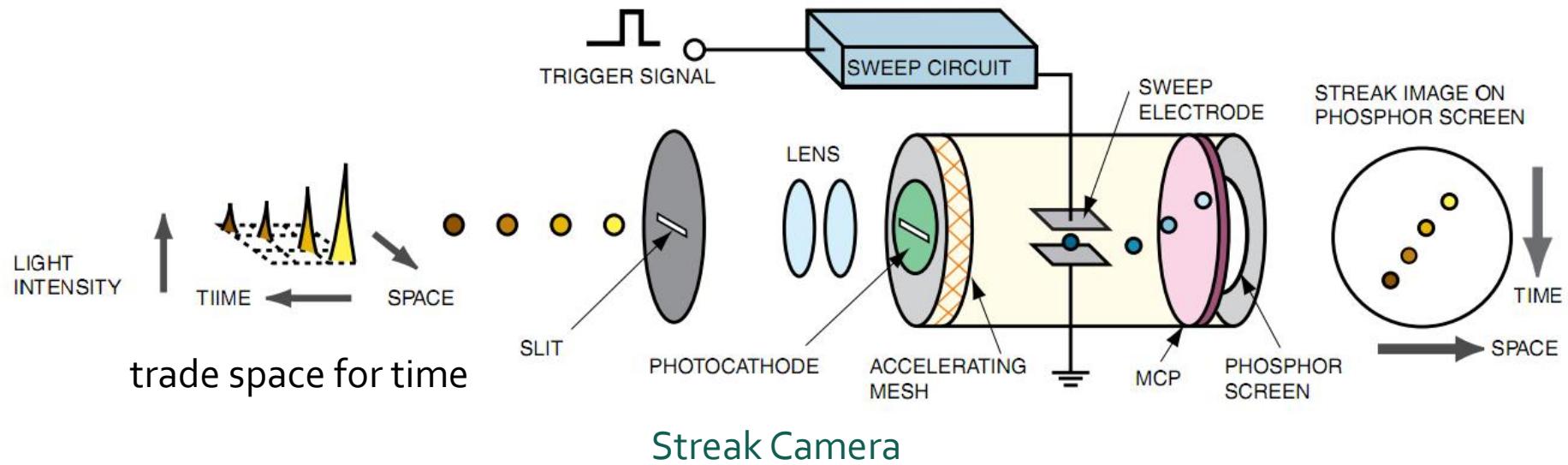
[Naik *et. al.*, 2011]



Light Transport Analysis

[Wu *et. al.*, 2012]

# Capturing Ultrafast Signals: Streak Camera



Streak Camera

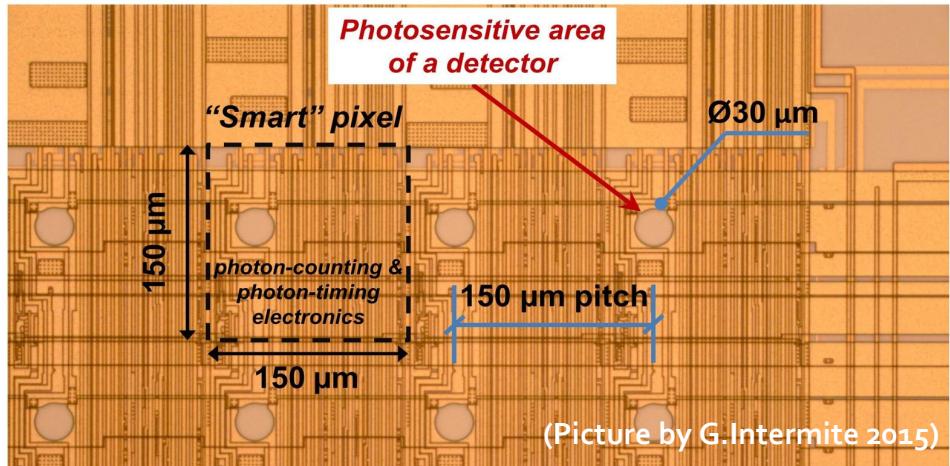
- Picosecond time resolution
- 1D: 1x672 pixels
- Result as 2D image ("Streak Photo")



# Capturing Ultrafast Signals: SPAD and TCSPC



Single-Photon Avalanche Diodes  
(SPADs) array Camera

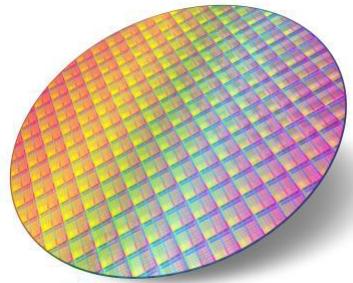


Smart SPAD Pixel

- Single photon level sensitivity
- Pico-second level time resolution



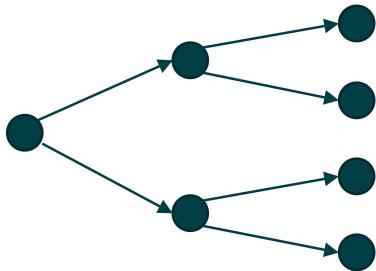
# Single-Photon Avalanche Diodes (SPADs)



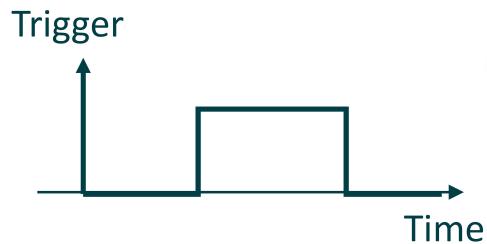
Silicon CMOS



Low dark count rate



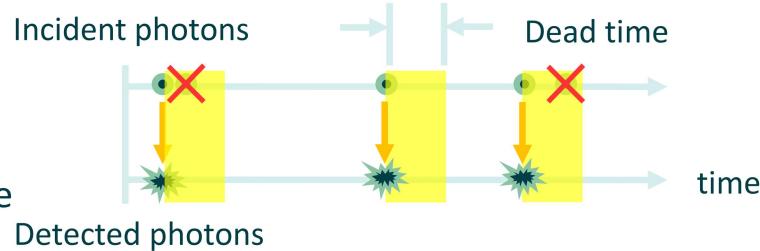
Single photon sensitive:  
electron avalanche



Some models: gateable



Extreme time resolution  
(5 ... 50 ps)



1...100 ns dead time



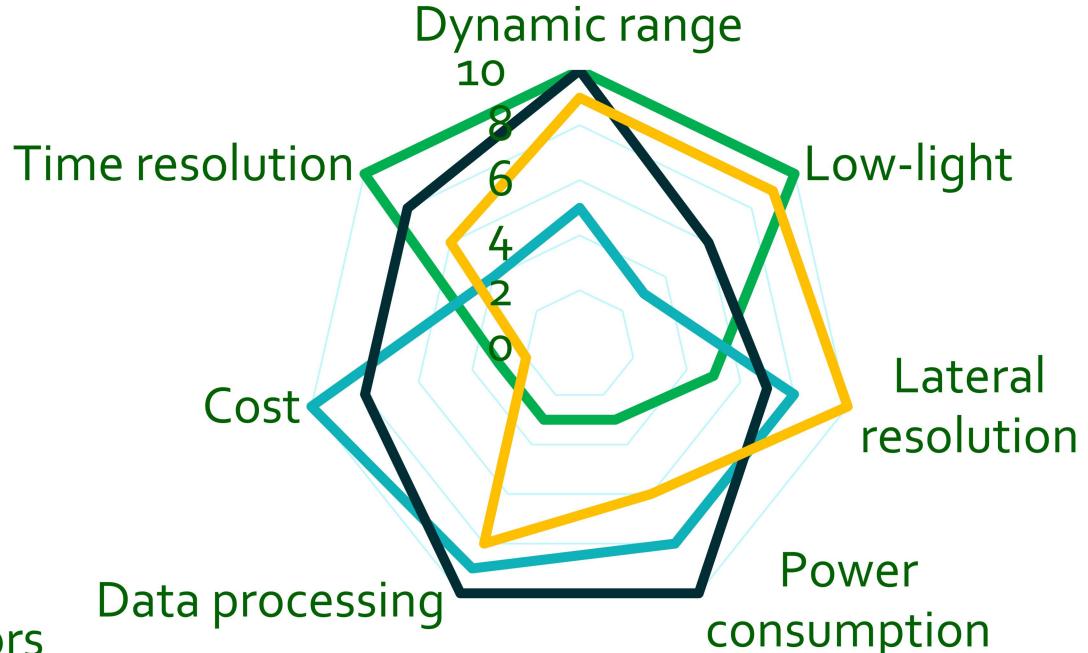
# SPADs and other Novel Sensors

— SPADs

— CMOS

— Event cameras

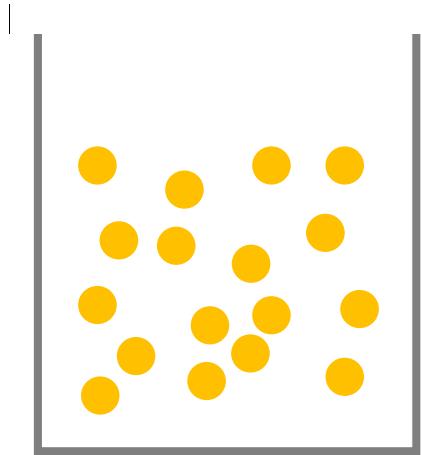
— Quanta image sensors





# Single-Photon Avalanche Diodes (SPADs)

~100-1000 photons



conventional camera pixel

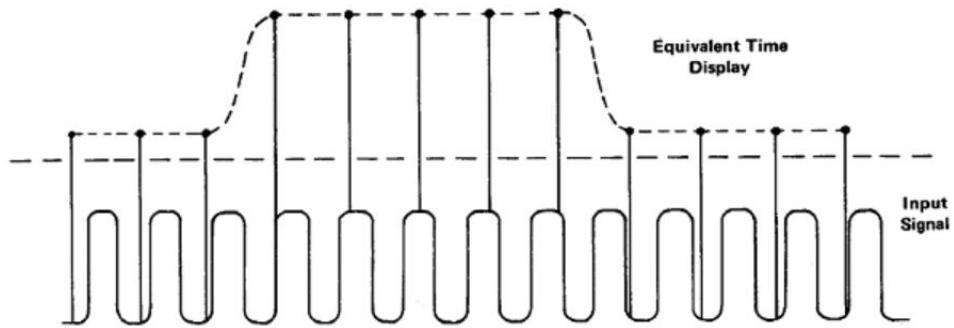
single photon



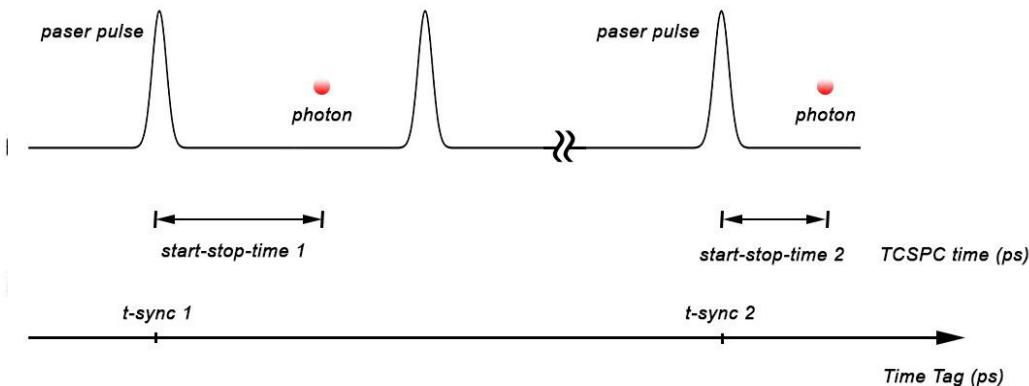
single-photon camera pixel



# Capturing Ultrafast Signals: SPAD and TCSPC



trade time for time

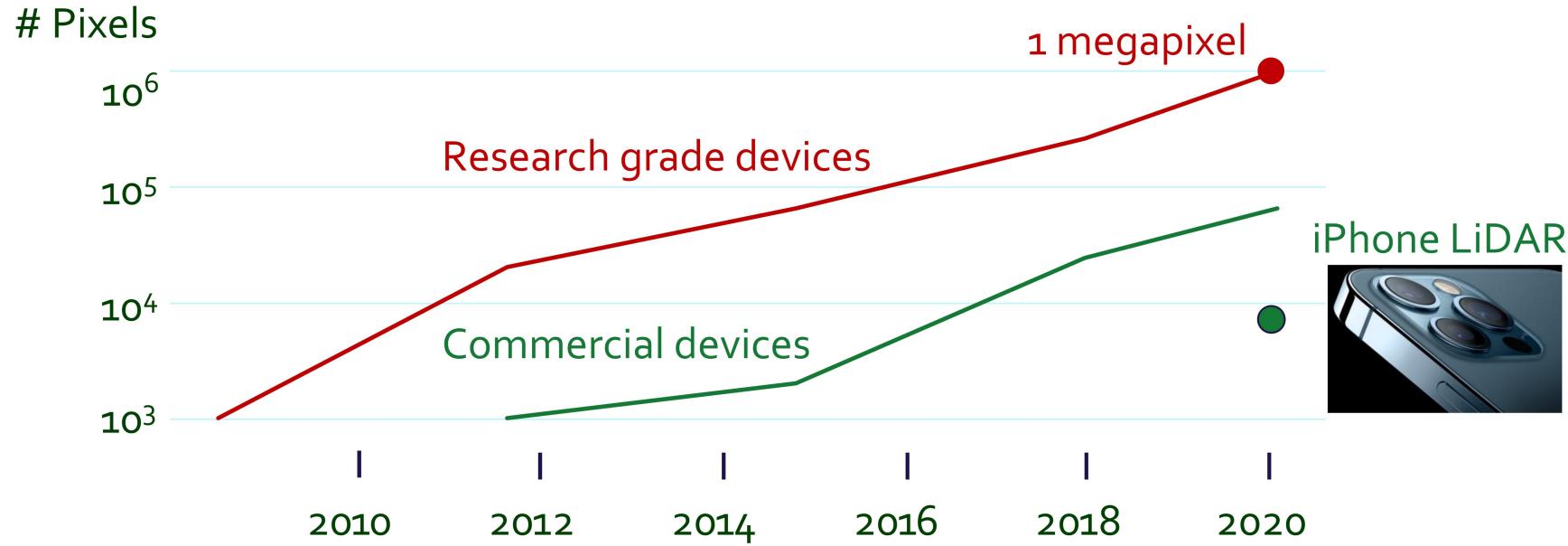


In oscilloscopes, sometimes we need ultra-high time resolution:  
**Equivalent time sampling**

Similar idea:  
**Time Corelated Single Photon Counting (TCSPC)**

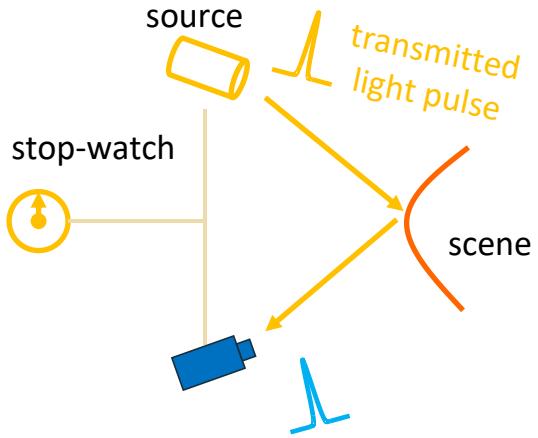


# SPAD Array Evolution



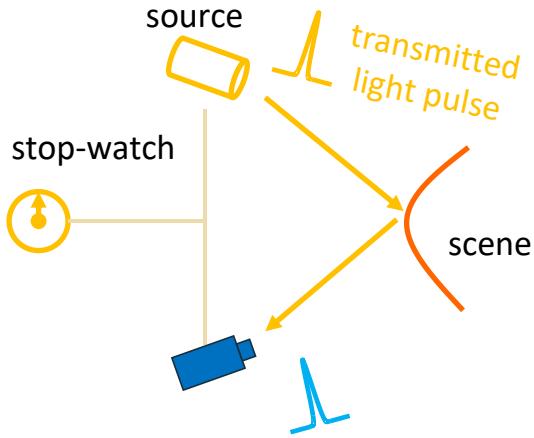


# Single-Photon 3D Camera

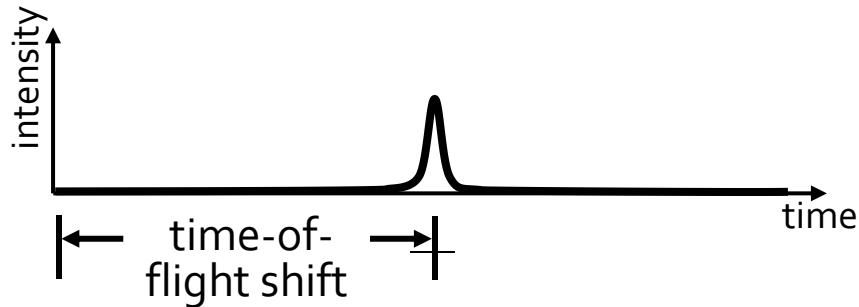




# Single-Photon 3D Camera

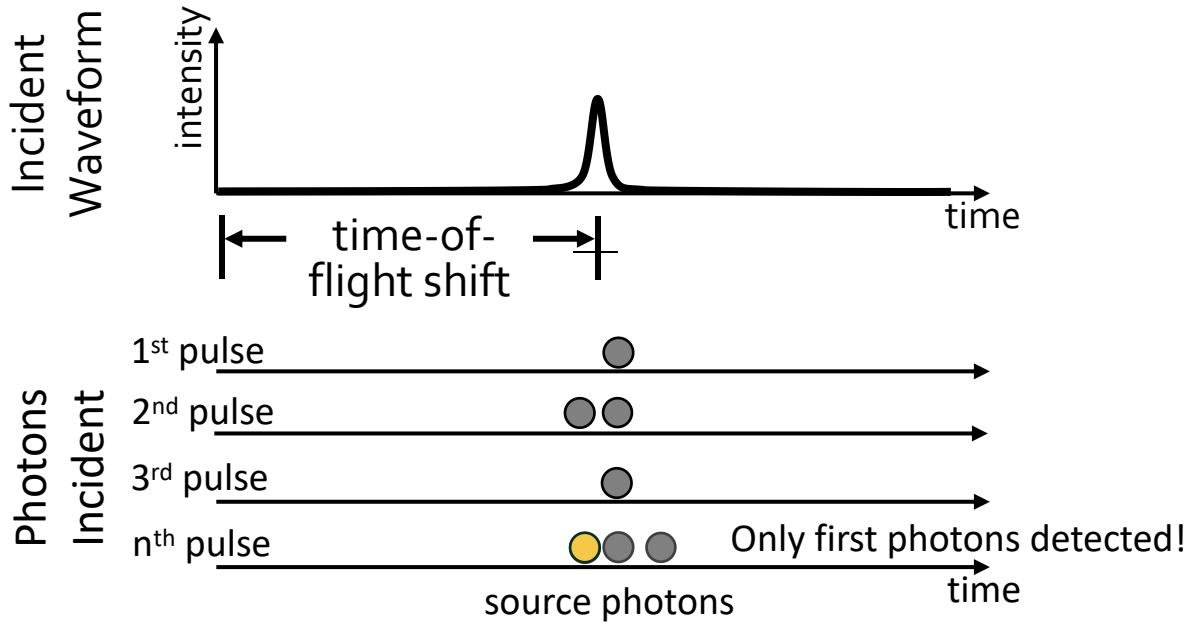
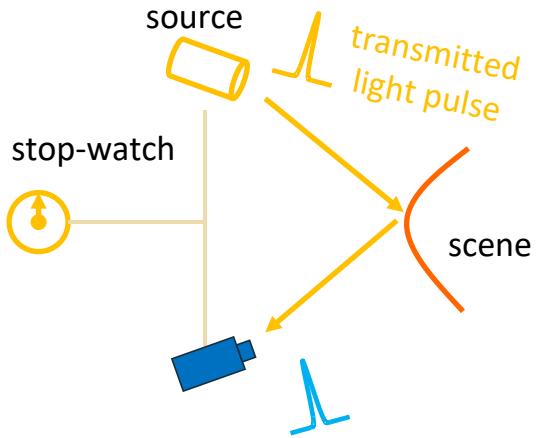


Incident Waveform



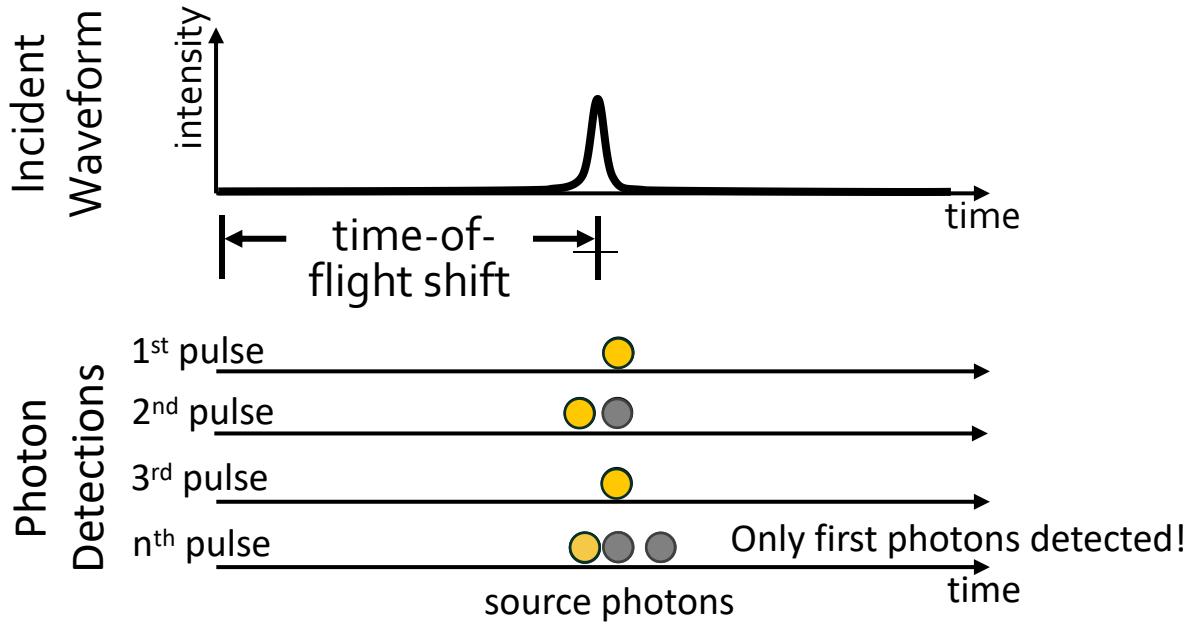
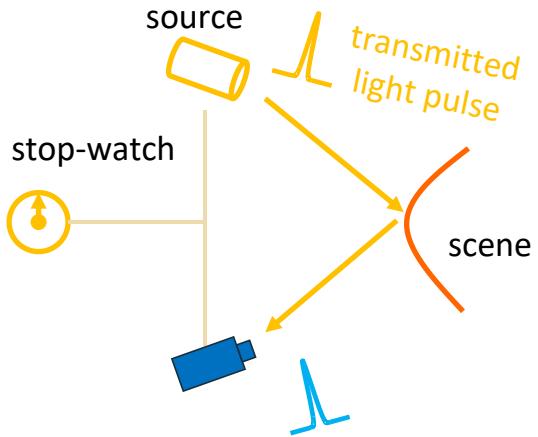


# Single-Photon 3D Camera



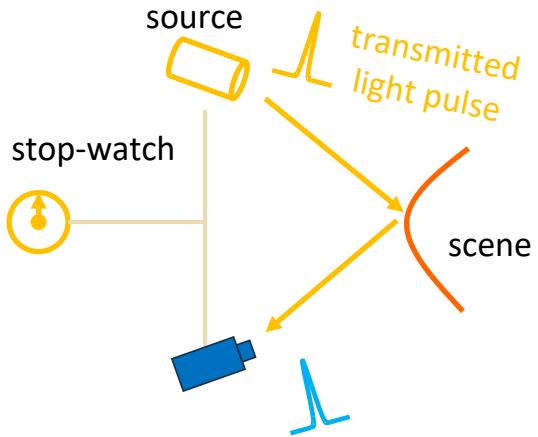


# Single-Photon 3D Camera

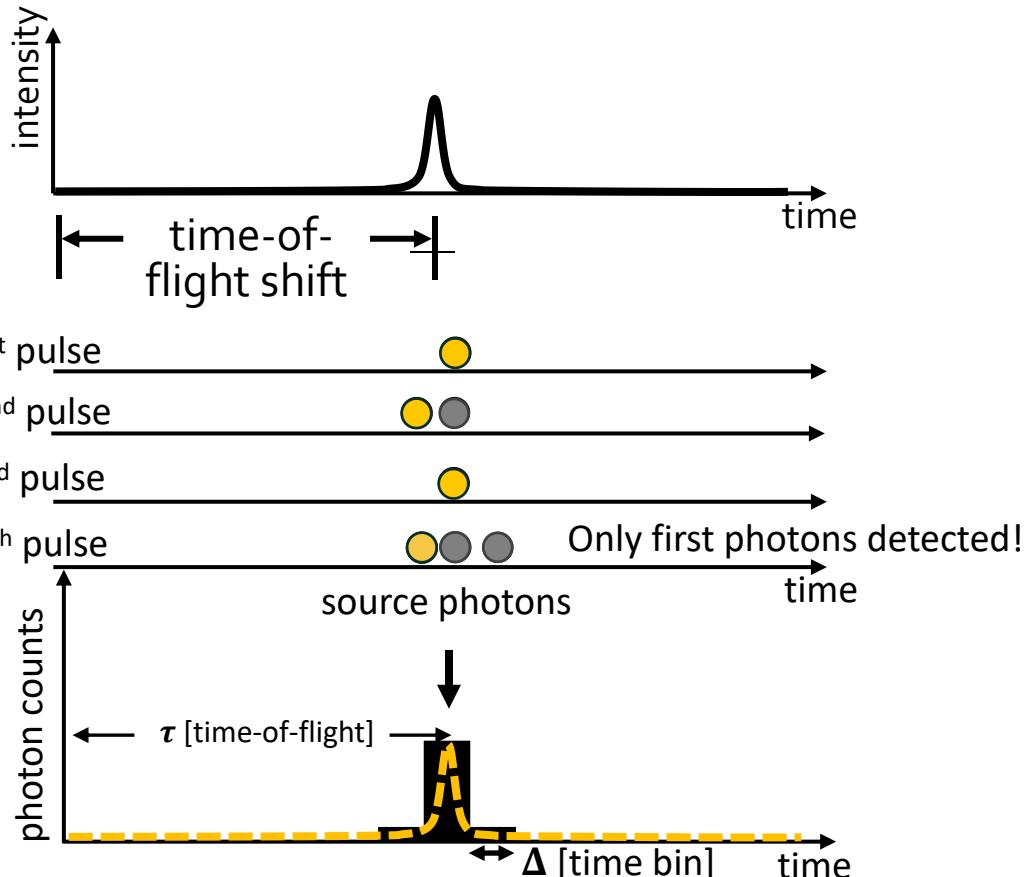




# Single-Photon 3D Camera



Measured Histogram  
Photon Detections





# Single-Photon 3D Camera: Bright Light

Extreme darkness



Bright daylight



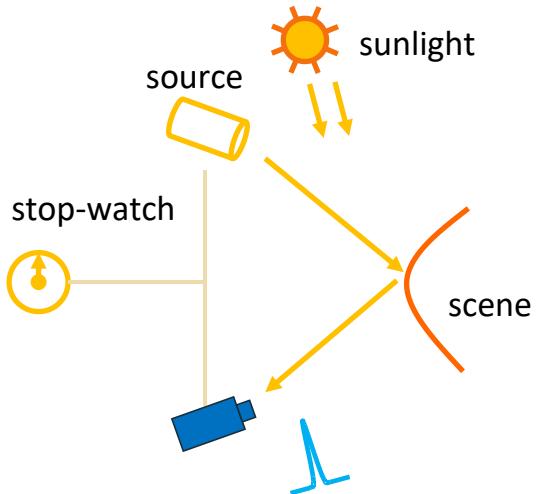
High dynamic range



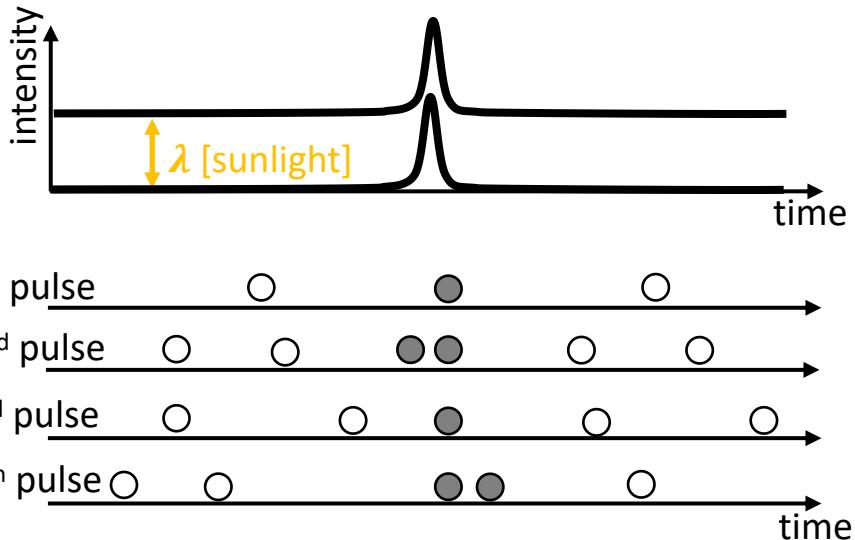
Need to operate under a wide range of illumination conditions



# Single-Photon 3D Camera: Sunlight

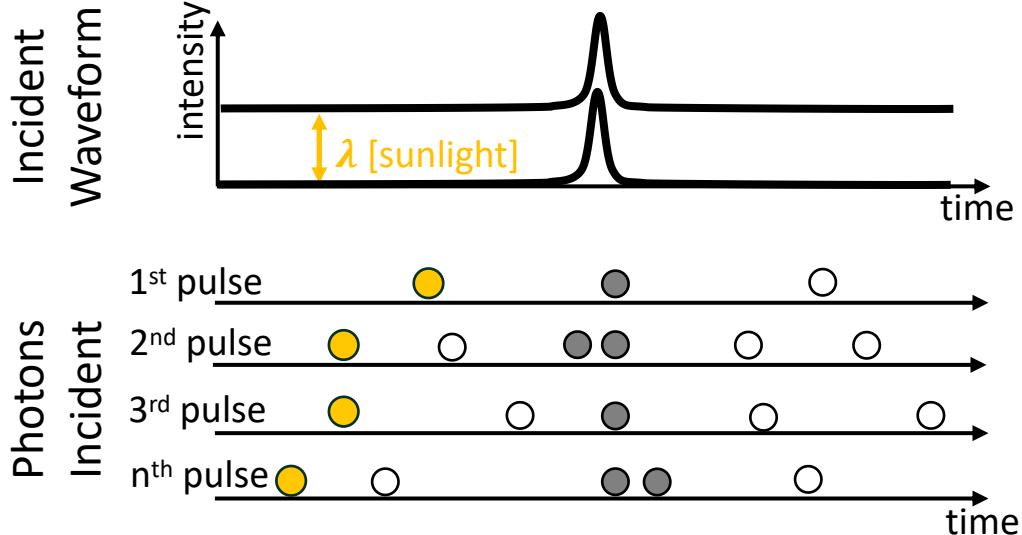
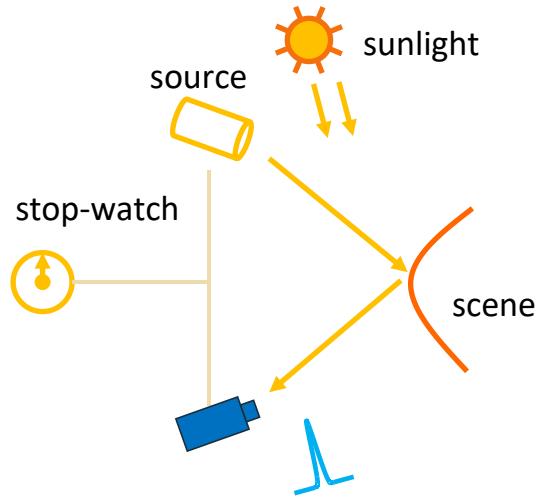


Incident Waveform  
Photons Incident

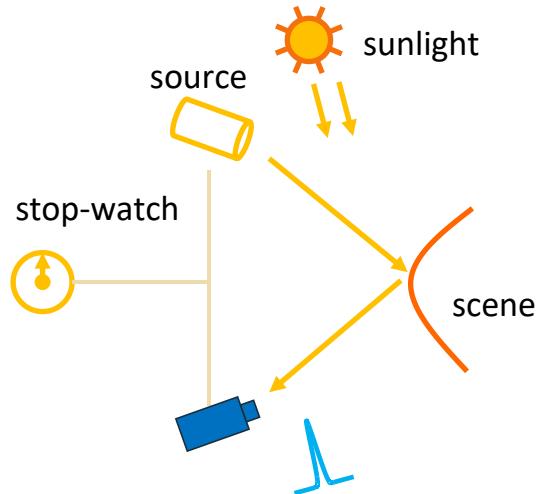




# Single-Photon 3D Camera: Sunlight

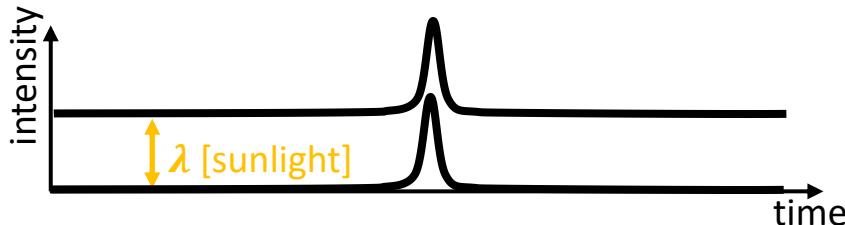


# Single-Photon 3D Camera: Sunlight

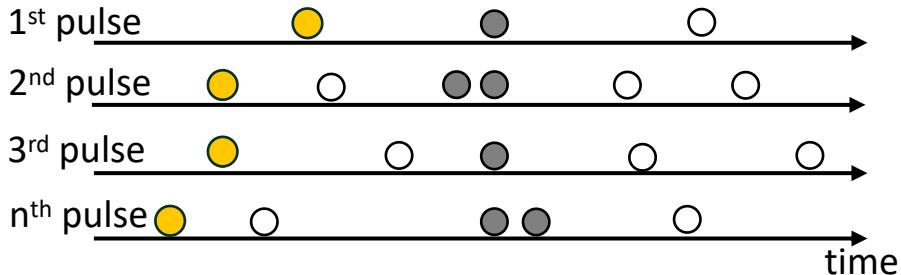


Peak difficult to locate  
due to distortion

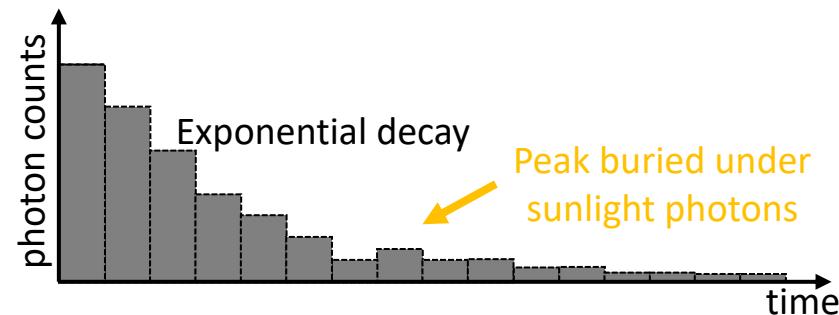
Incident Waveform



Photons Incident

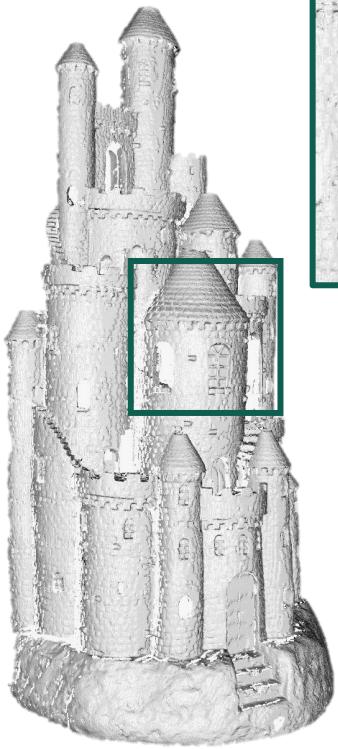


Measured Histogram

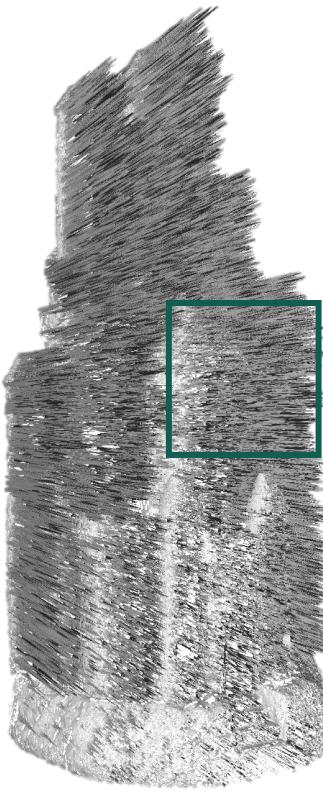




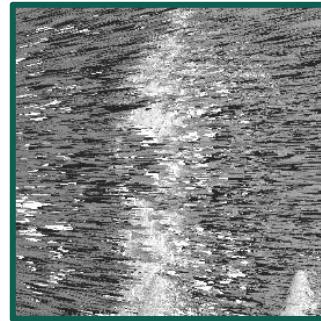
# Single-Photon 3D Camera: Simulation



No Sunlight

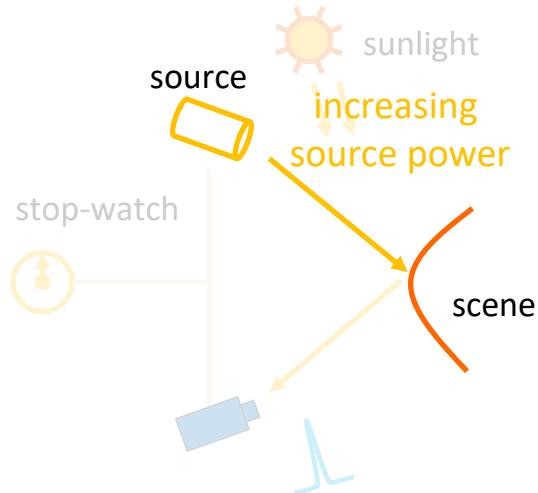


With Sunlight (2000 lux)



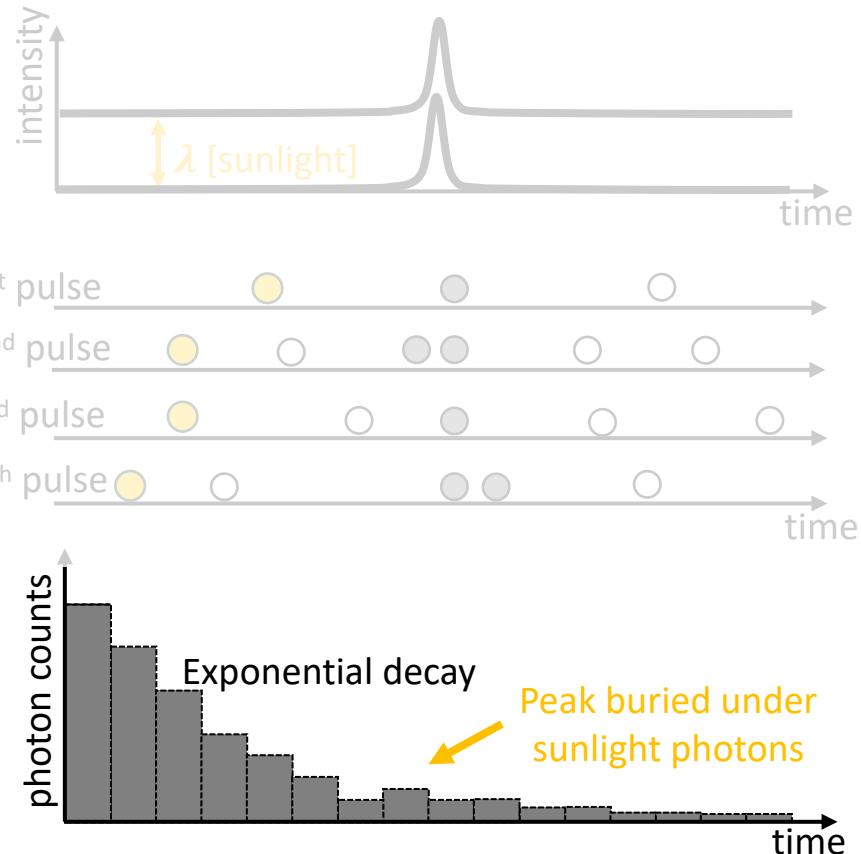
Large depth errors

# Single-Photon 3D Camera: Sunlight



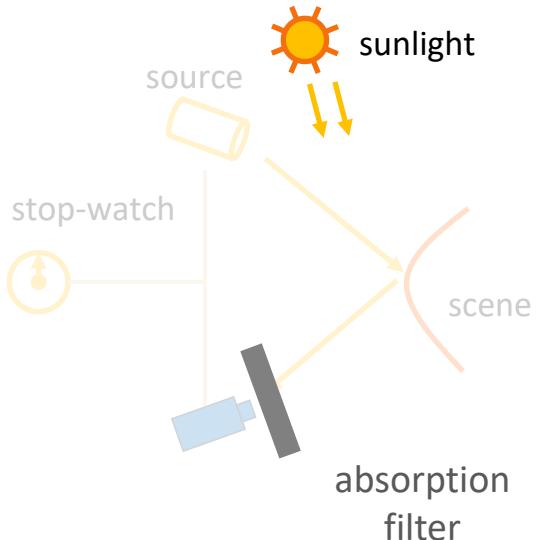
Histogram distortion  
persists even for high  
source powers

Incident Waveform  
Photons Incident  
Measured Histogram

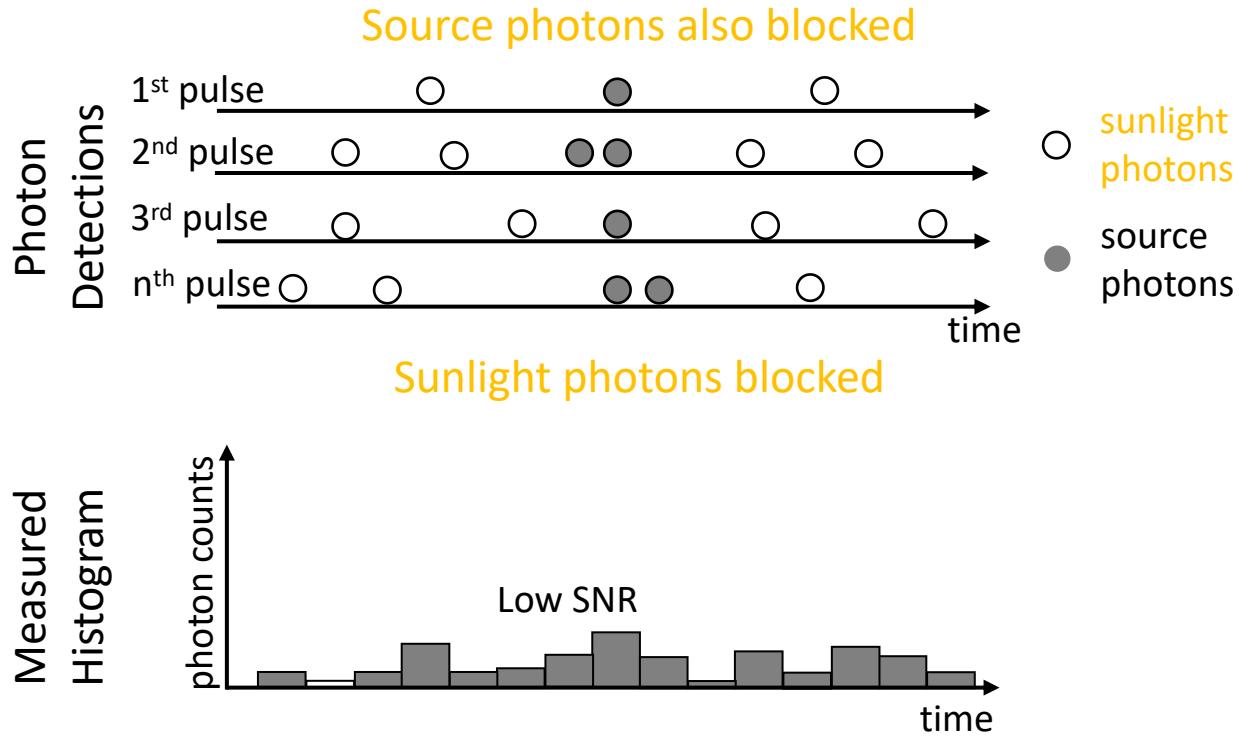




# Dealing with Sunlight: Current Wisdom



Histogram distortion  
persists even for high  
source powers

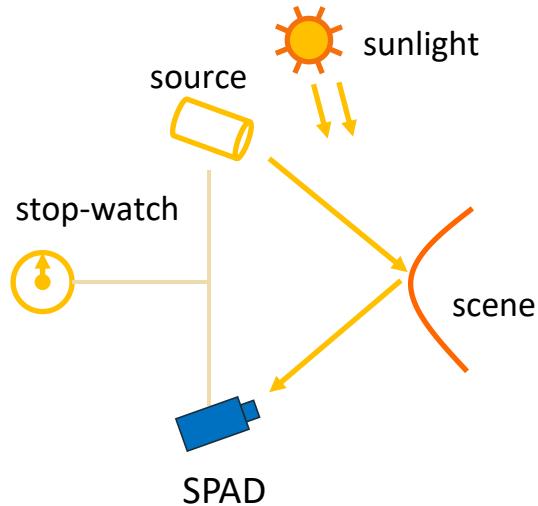




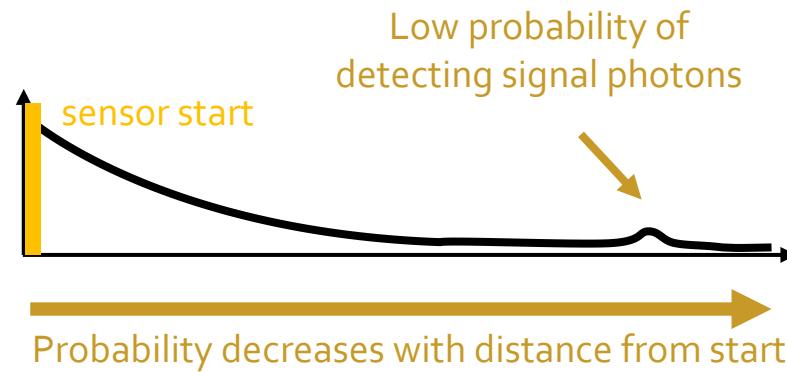
# Asynchronous Single-Photon 3D Imaging



# Histogram Distortion: Key Observation

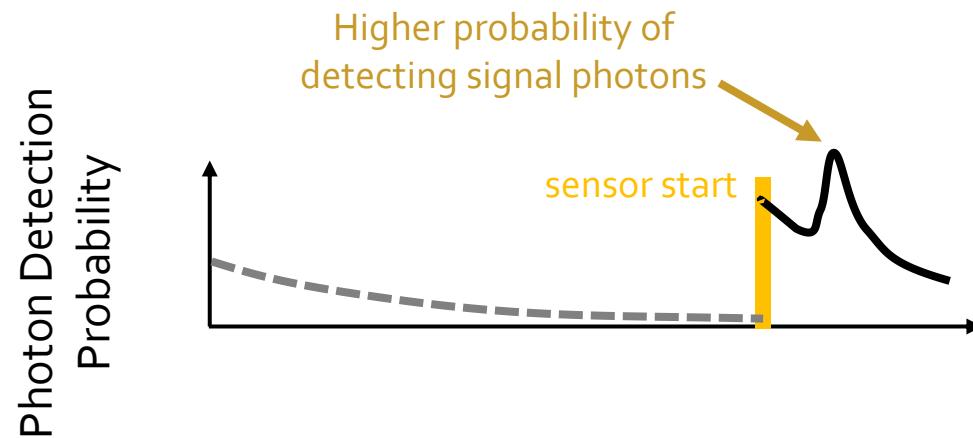
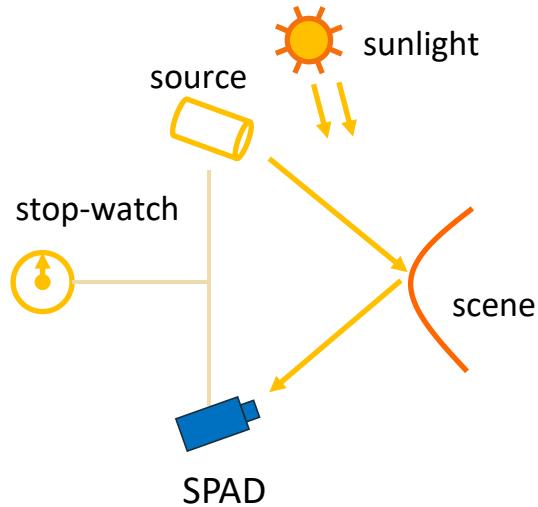


Photon Detection Probability



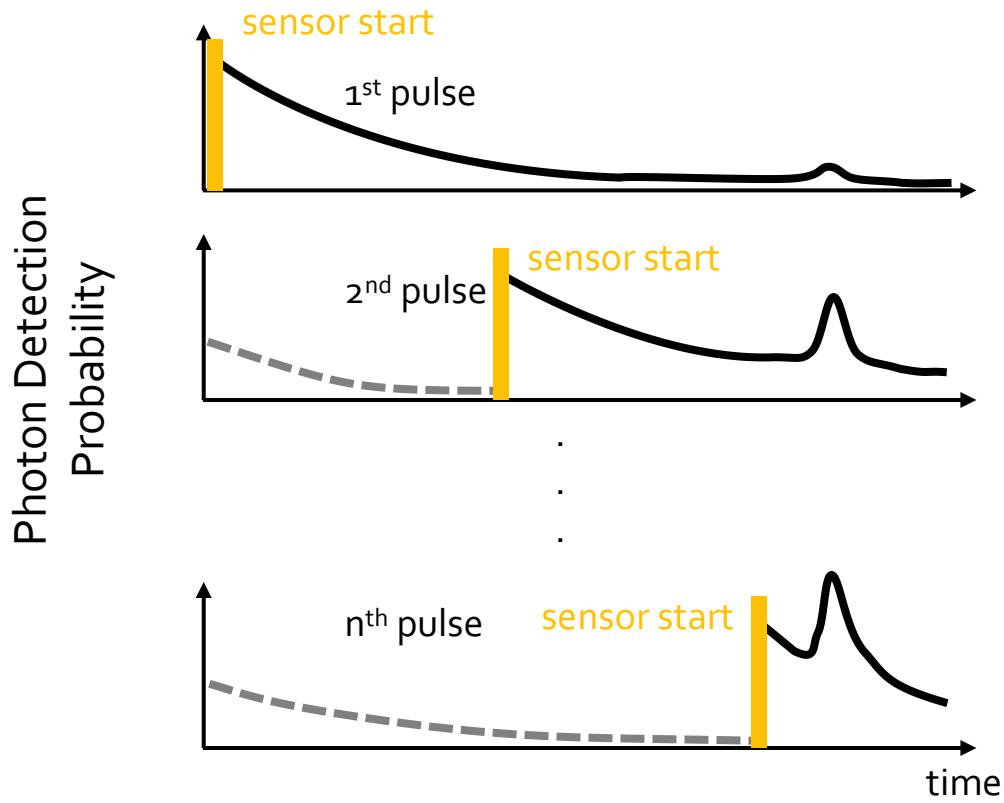
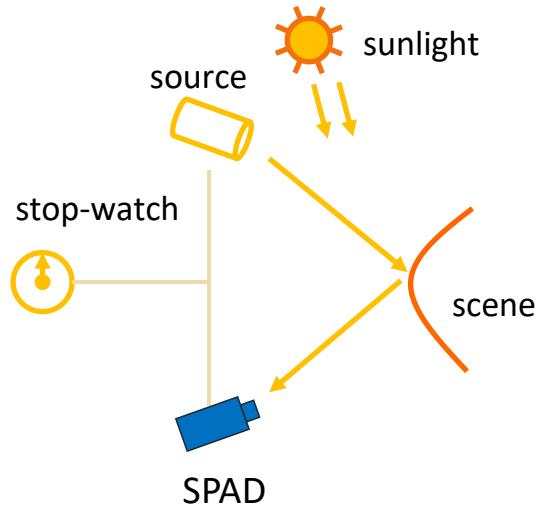


# Histogram Distortion: Key Observation



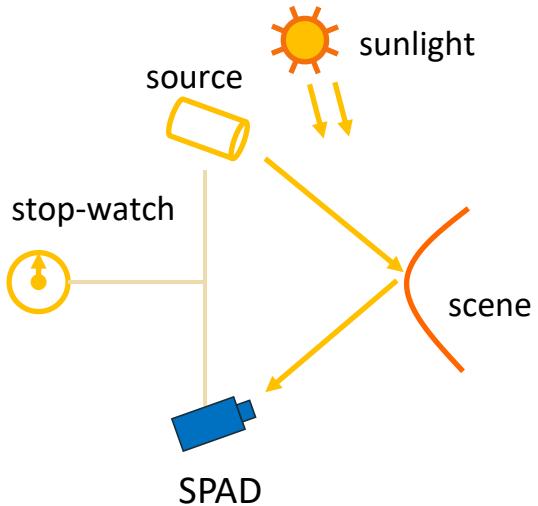


# Asynchronous Operation





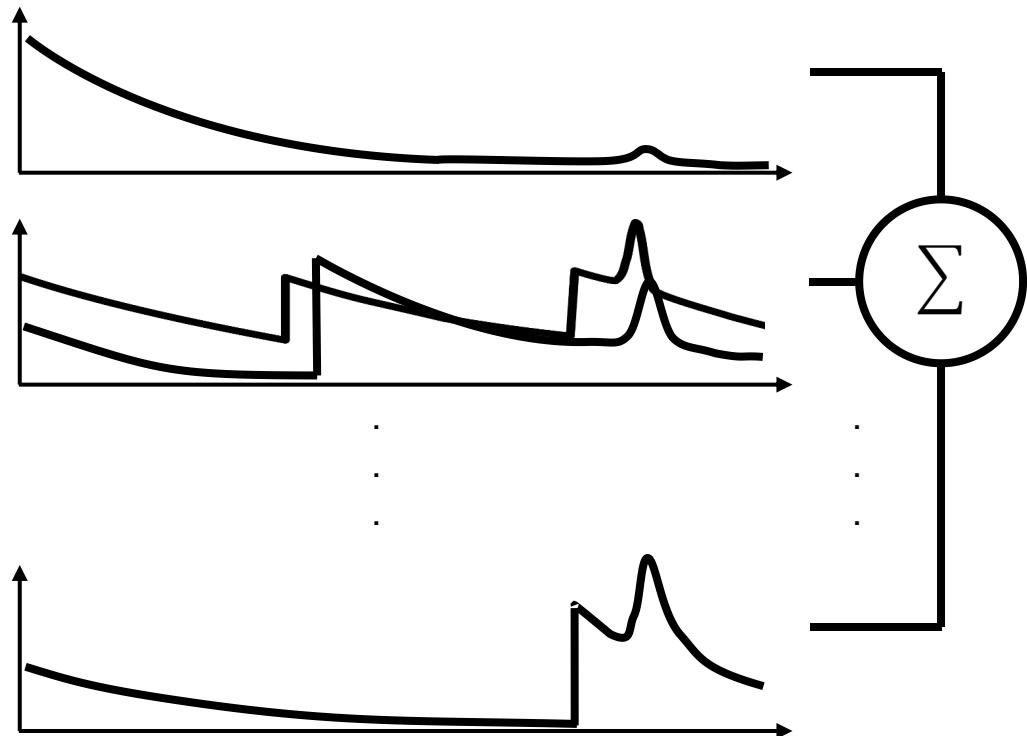
# Asynchronous Operation



Expected histogram shape

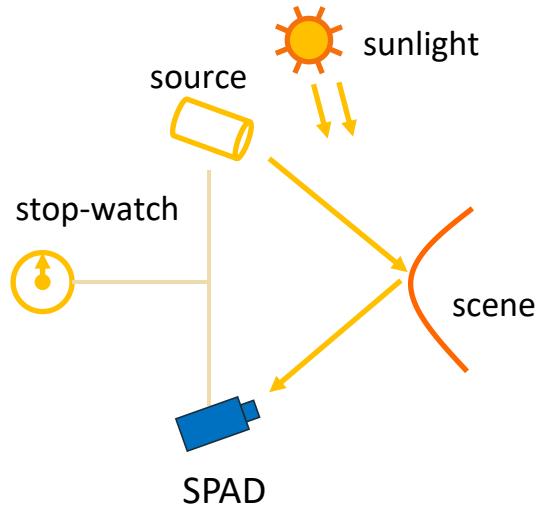
$$\propto$$

Sum of probabilities over all cycles

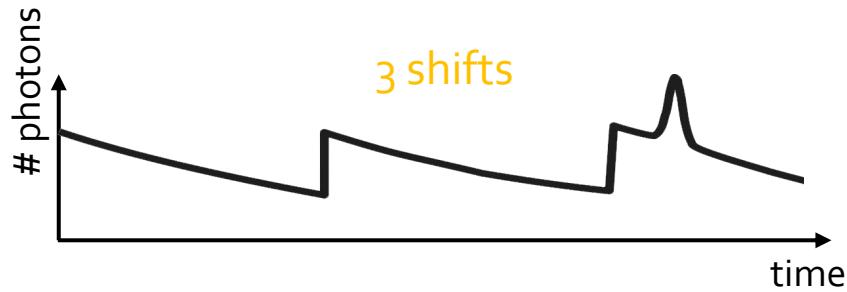




# Asynchronous Operation

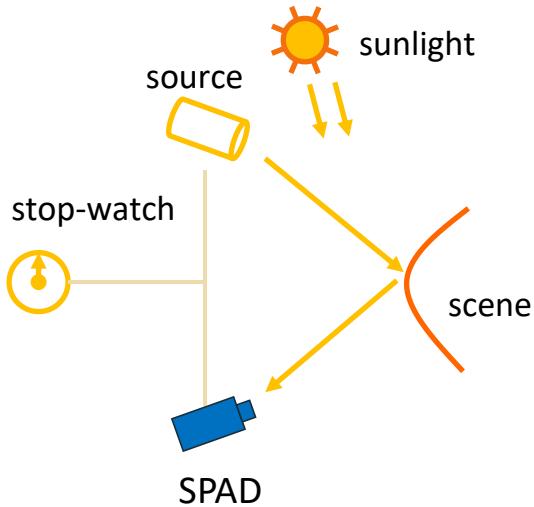


Expected  
Histogram

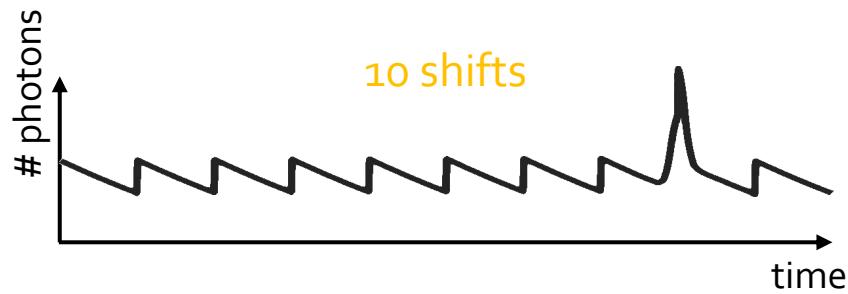




# Asynchronous Operation

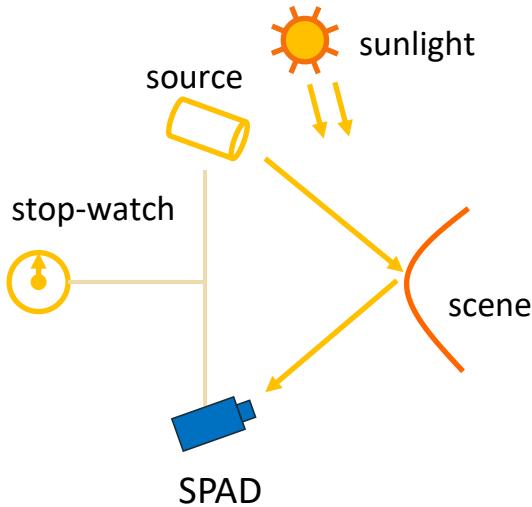


Expected  
Histogram

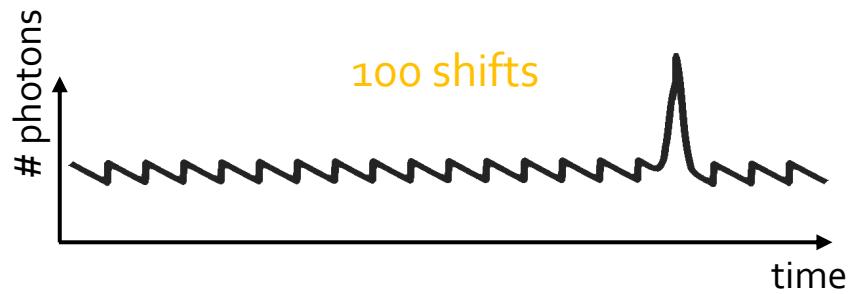




# Asynchronous Operation

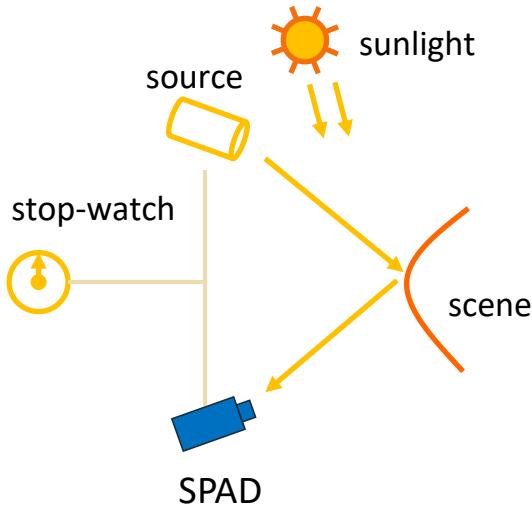


Expected  
Histogram

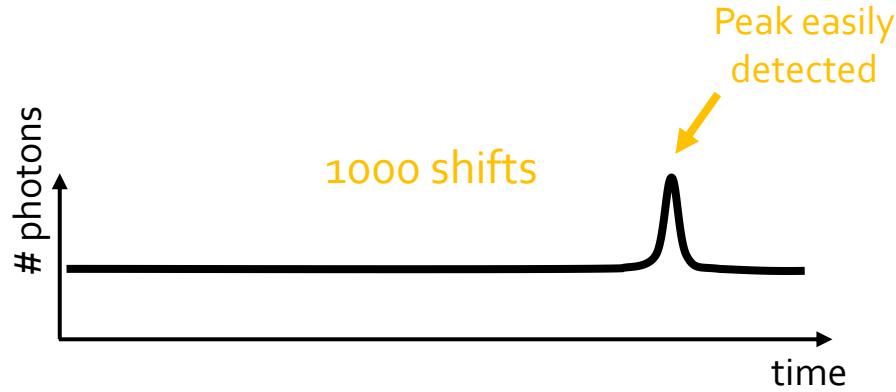




## Asynchronous Operation



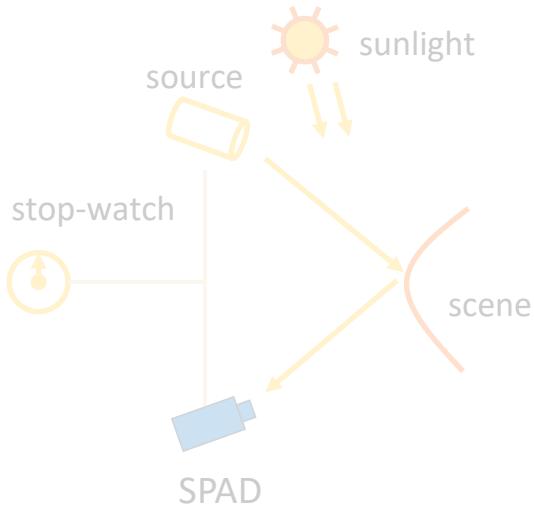
Expected Histogram



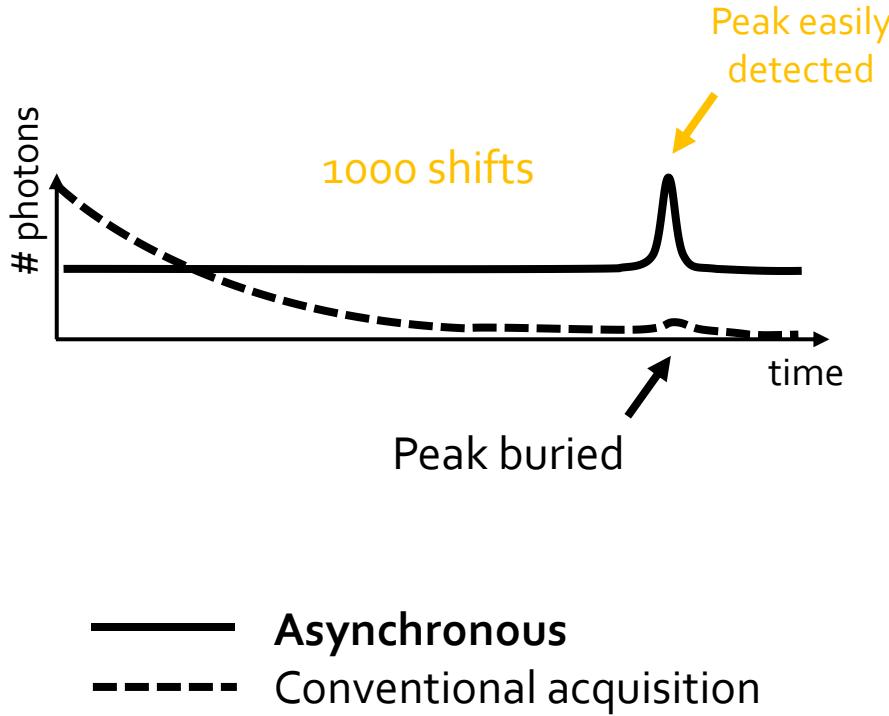
Expected histogram resembles true waveform shape.



# Asynchronous Operation

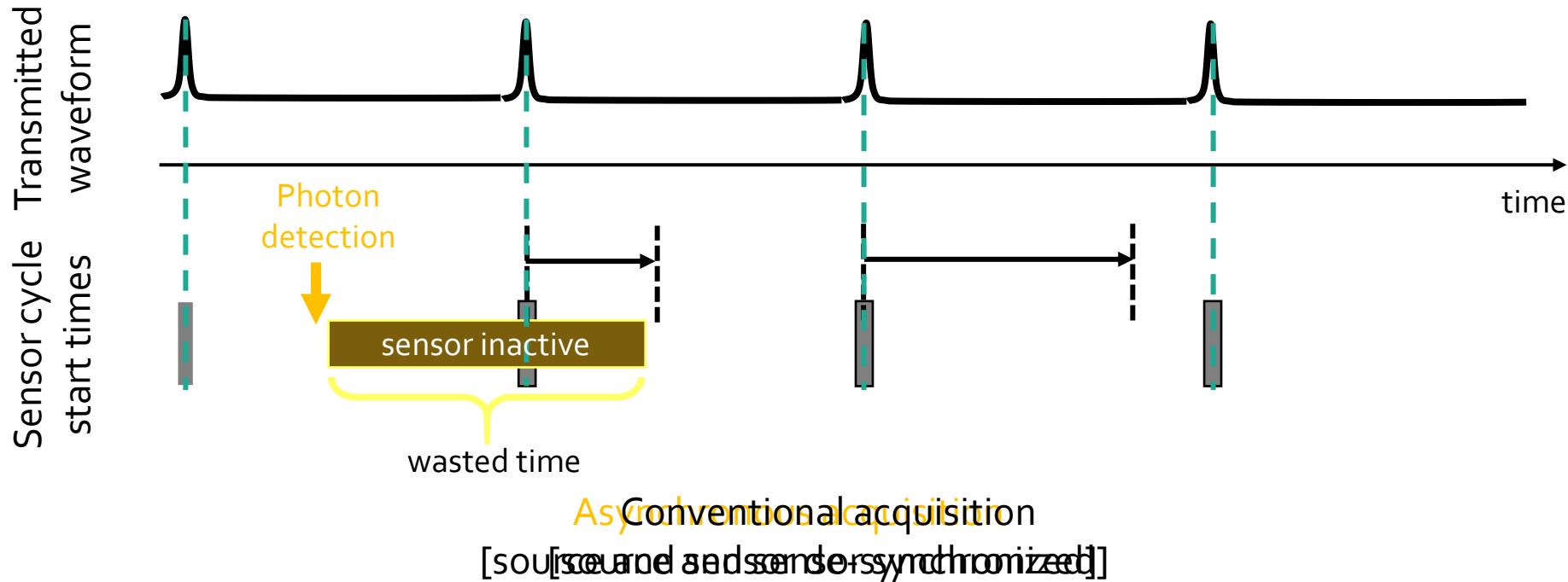


Expected Histogram



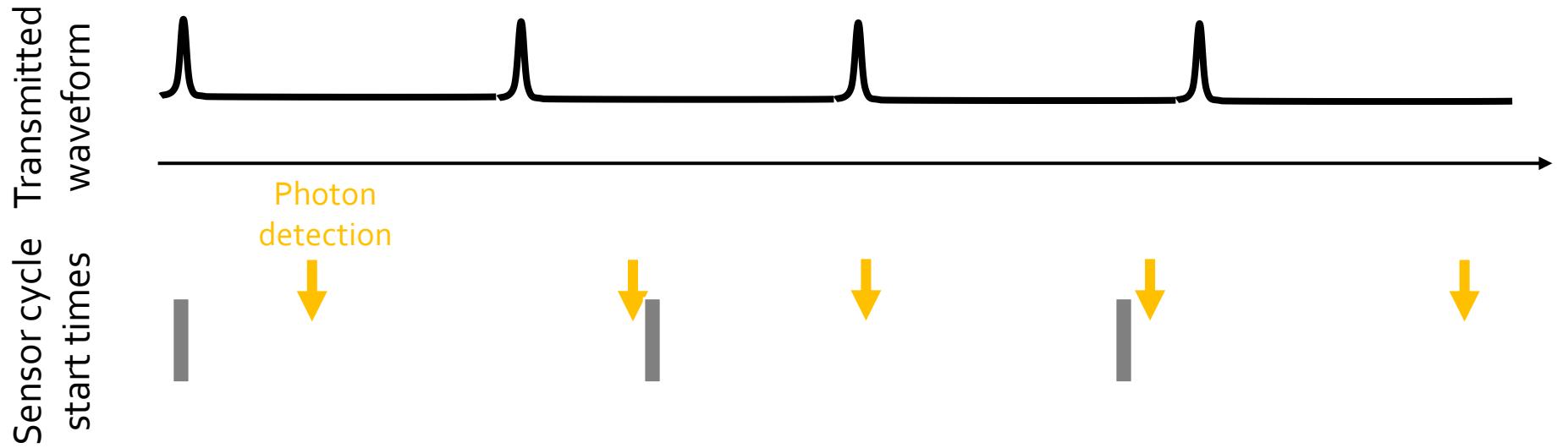


# Achieving Asynchrony in Practice





# Achieving Asynchrony in Practice

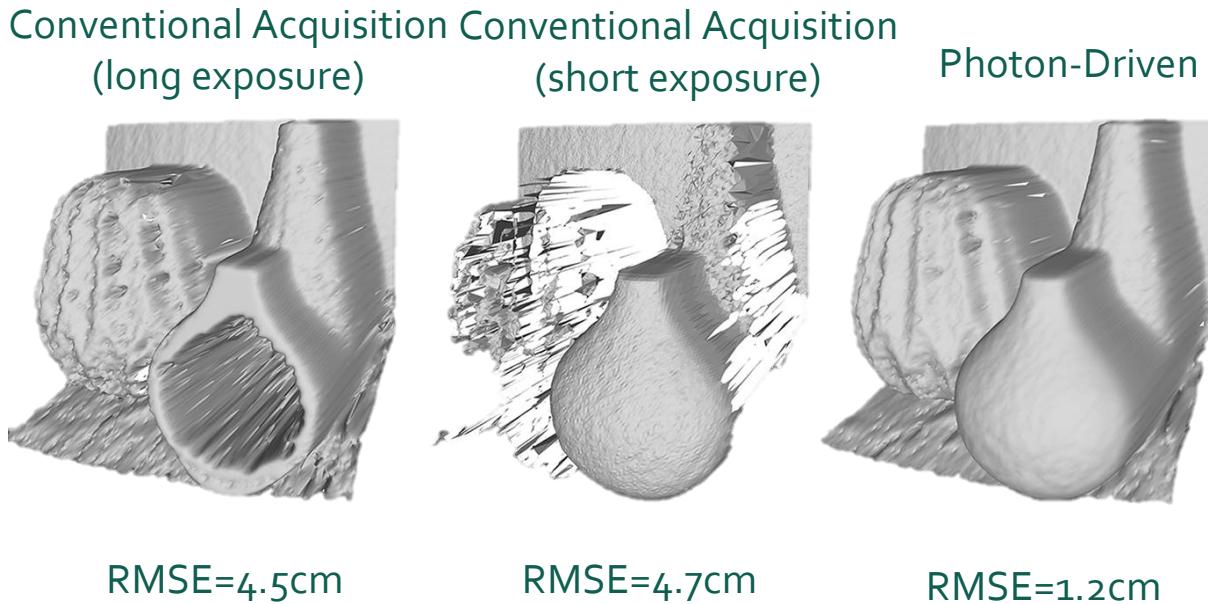


Photon-driven asynchronous acquisition

Easy to implement. Does not require major hardware changes.

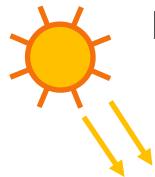


# Experiments





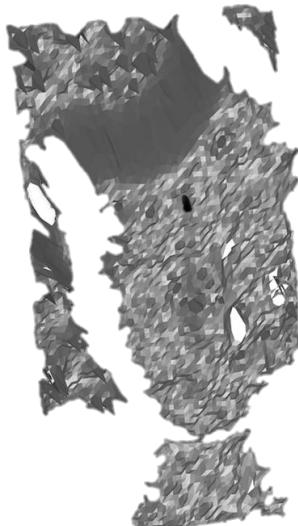
# Experiments



Bright sunlight  
 $>20,000$  lux

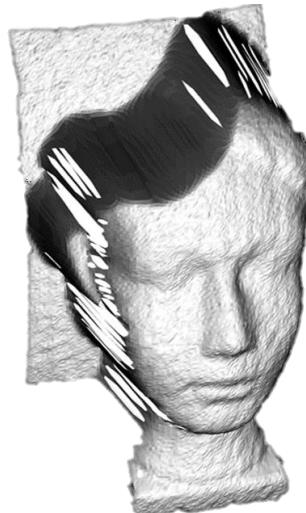


Conventional Acquisition



RMSE=5.6cm

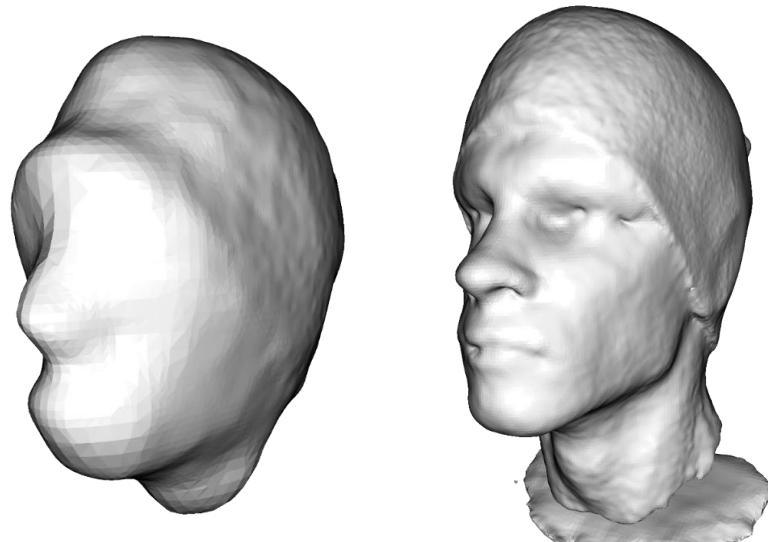
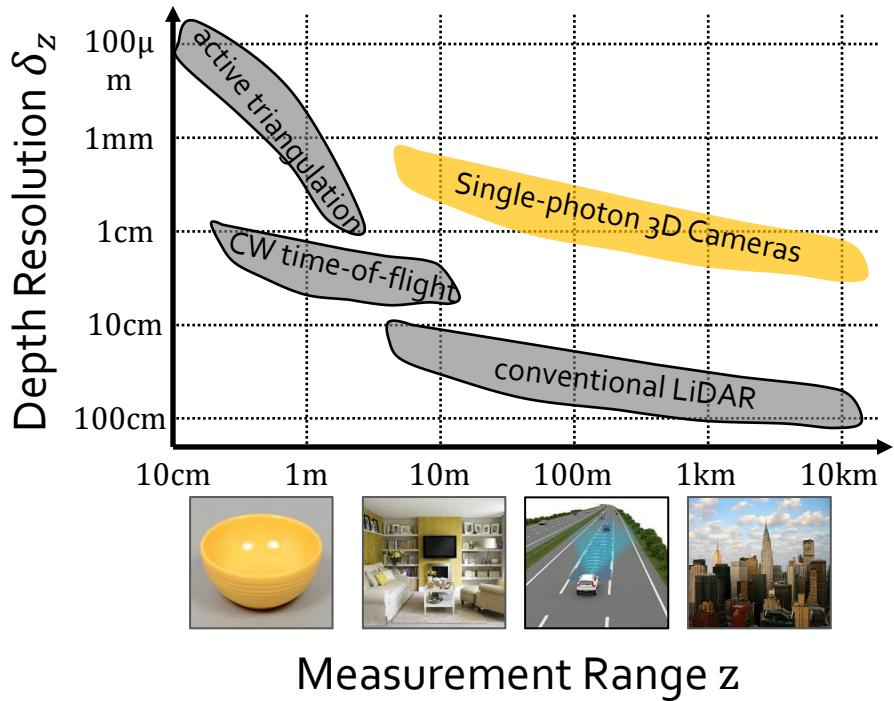
Asynchronous Acquisition



RMSE=0.65cm



# Long-Range High-Resolution 3D Cameras



Depth Resolution  
 $\sim 1 \text{ cm at } 100 \text{ m}$

Depth Resolution  
 $\sim 1 \text{ mm at } 100 \text{ m}$



# Single-Photon Cameras: Active Imaging

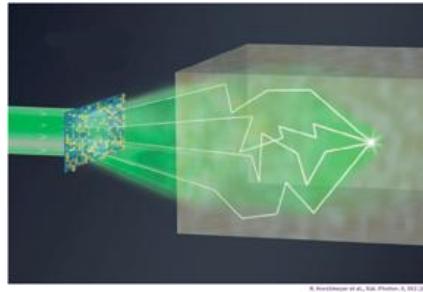
3D Imaging



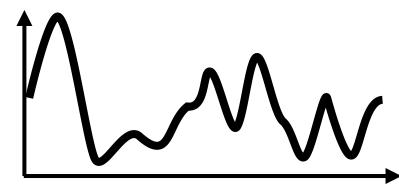
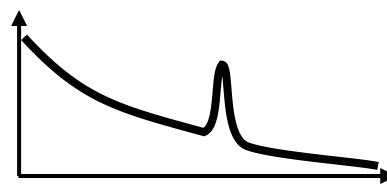
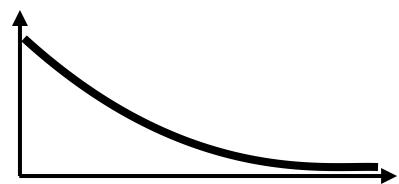
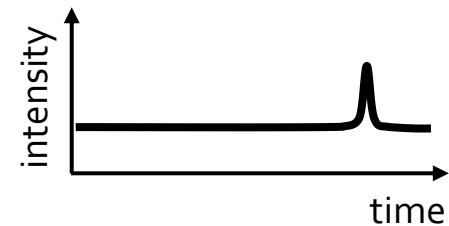
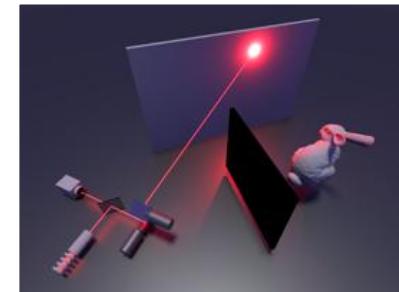
Fluorescence Microscopy



Scattering media



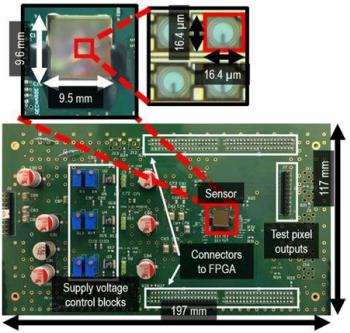
NLOS Imaging



# Single-Photon Cameras



MPD



SwissSPAD2 EPFL



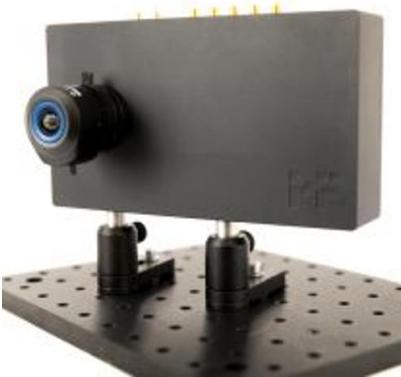
Ouster LiDAR



Voxtel, Inc.



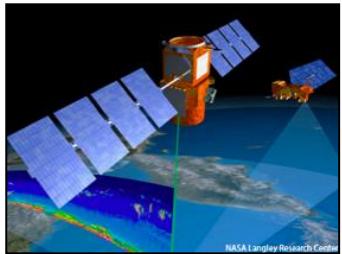
Gigajot



PhotonForce



# Single-Photon Cameras



Long range



Low power



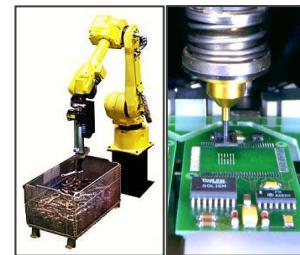
High  
dynamic  
range



Extreme



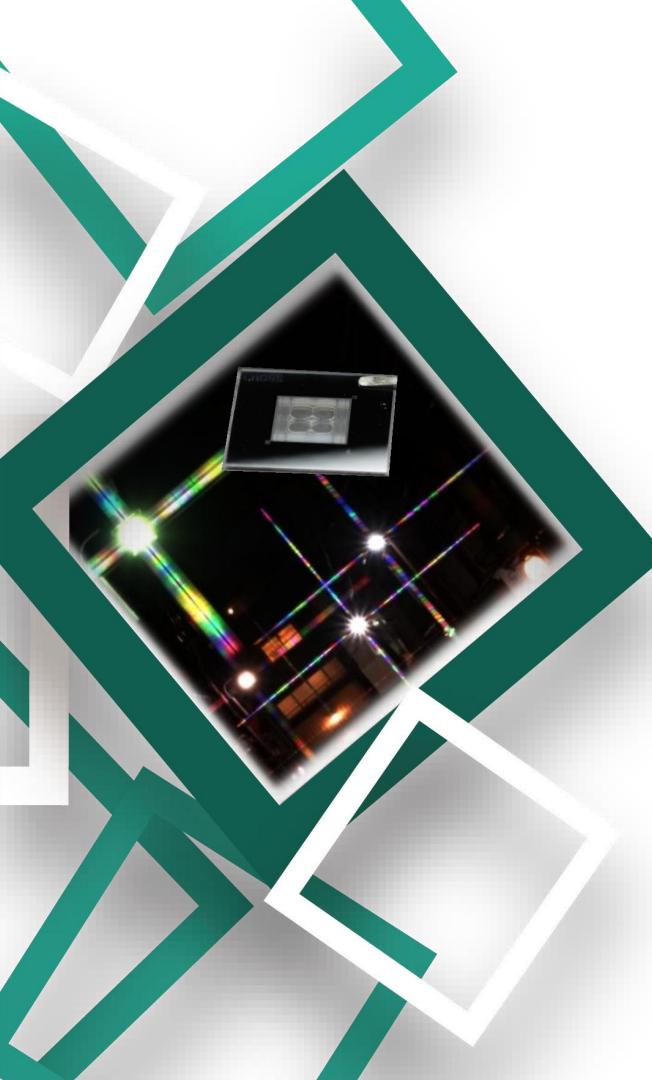
High depth  
resolution





## Today's Topic

- History of the Time-of-flight
- Introduction to Optical Time Resolved Imaging
  - Time-Resolved Image Formation Model
- Direct Time-of-flight Imaging
  - Streak Camera
  - SPAD Array Cameras
  - Single Photon 3D Imaging



GAMES 204



Thank You!



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点昀技术（Point Spread Technology）