SPAD Arrays for Non-Line-of-Sight Imaging

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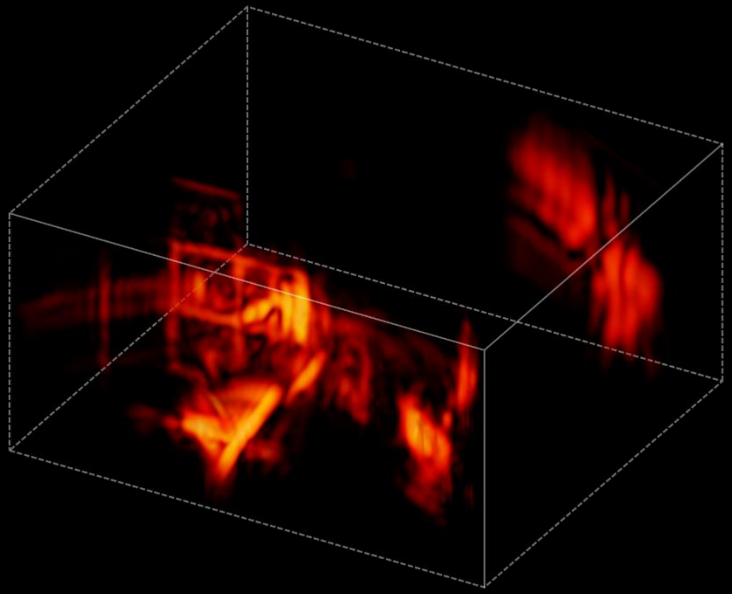

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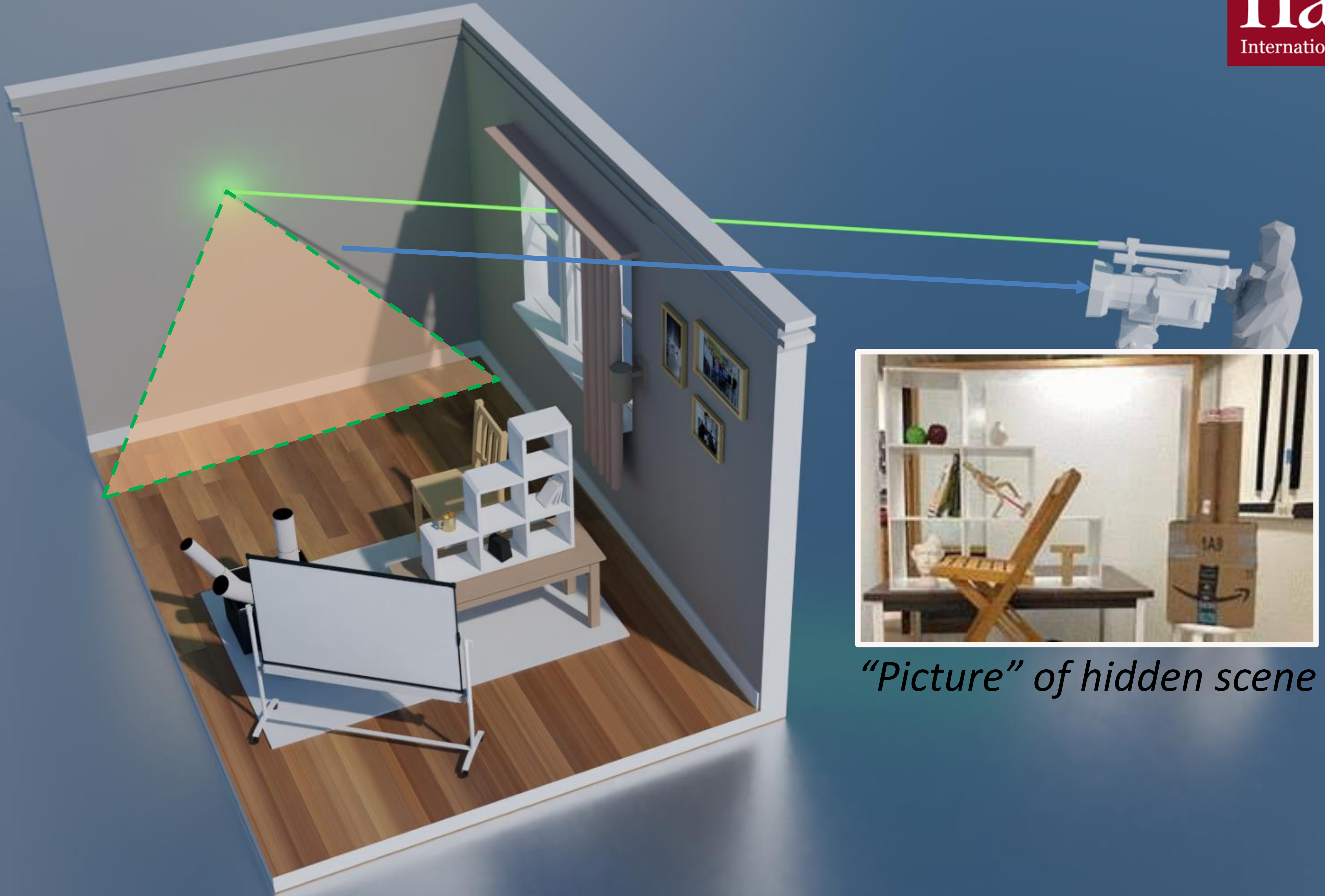
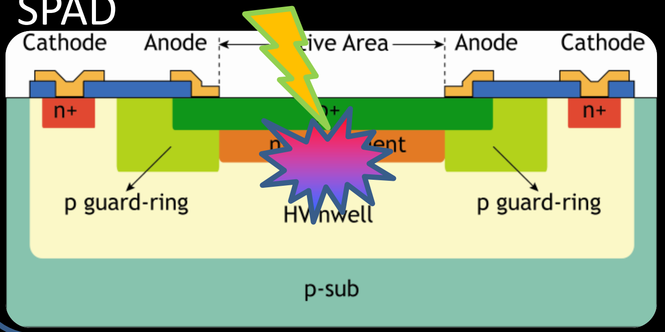
nature
International journal of science

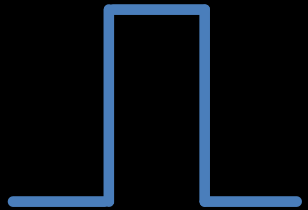


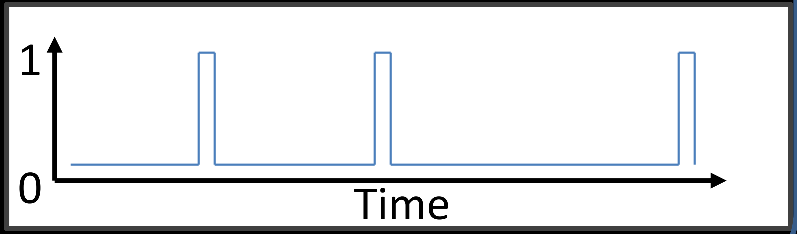
“Picture” of hidden scene

Single Photon Avalanche Diodes (SPAD)

SPAD

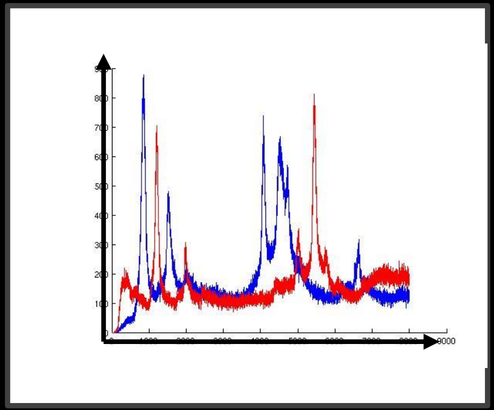




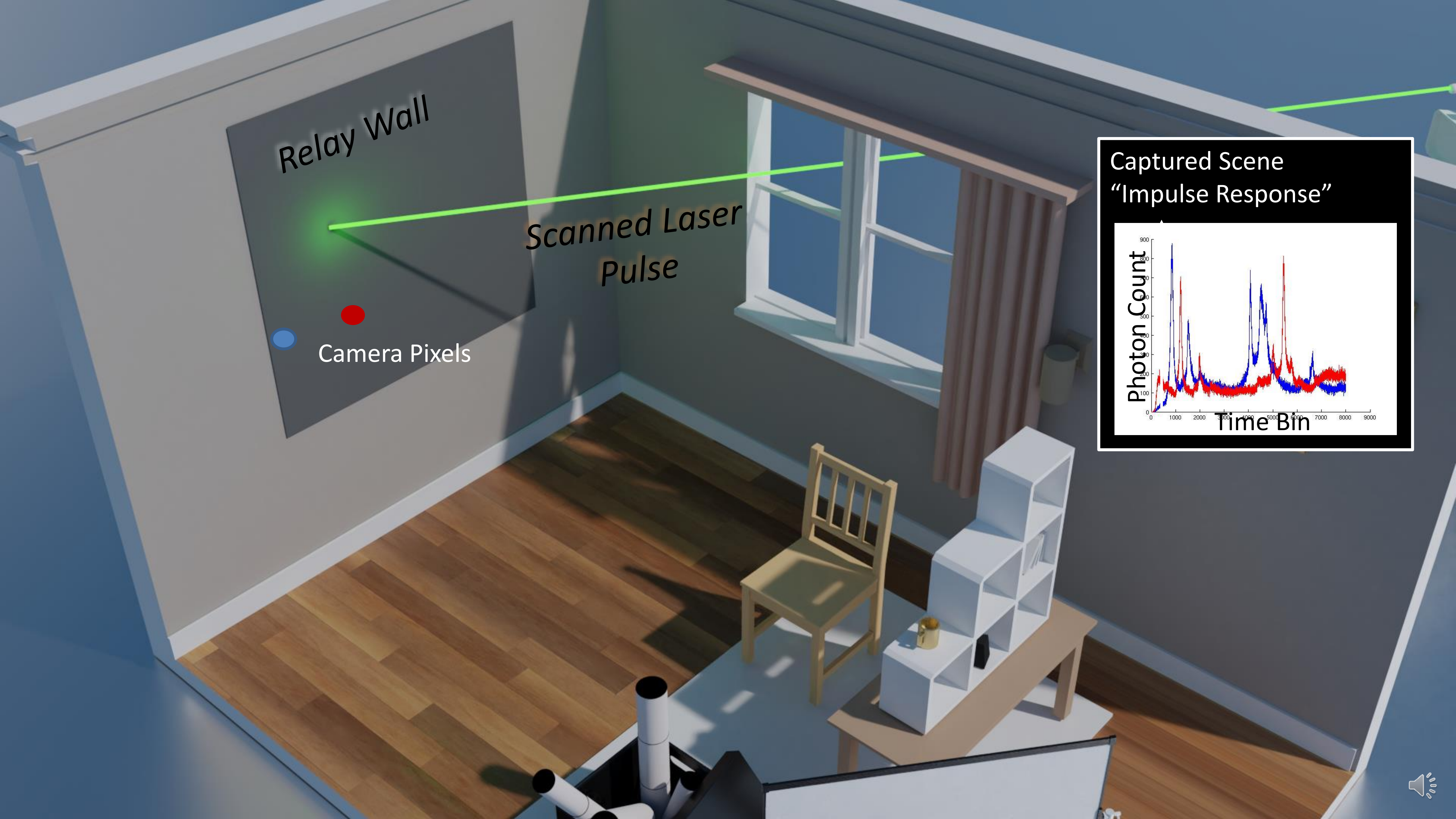


Laser Pulse Train

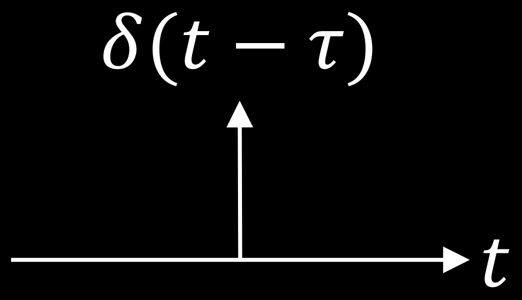
Time Correlated Single Photon Counter (TCSPC)

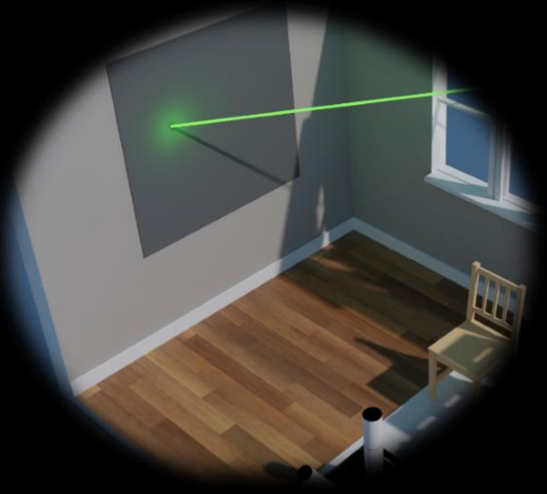


Mauro Buttafava, Alberto Tosi, **Politecnico di Milano, Italy**



Relay Wall
Scanned Laser Pulse
Camera Pixels
Captured Scene
"Impulse Response"
Photon Count
Time Bin


$\delta(t - \tau)$
t



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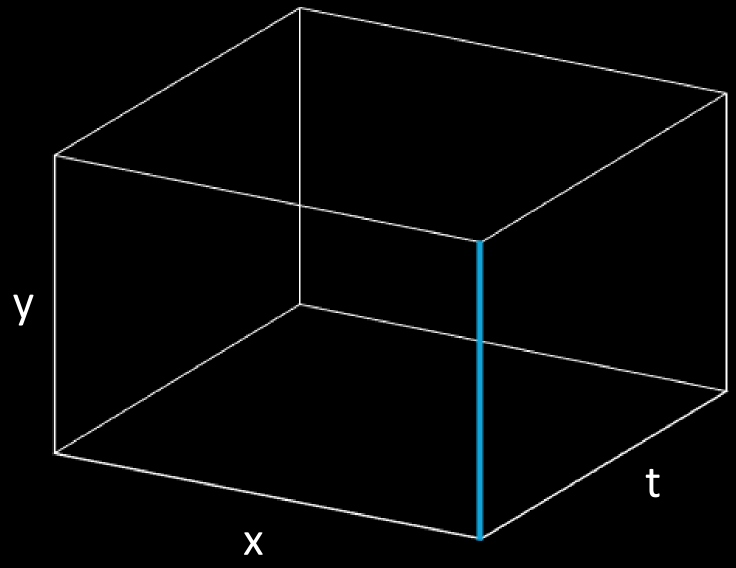
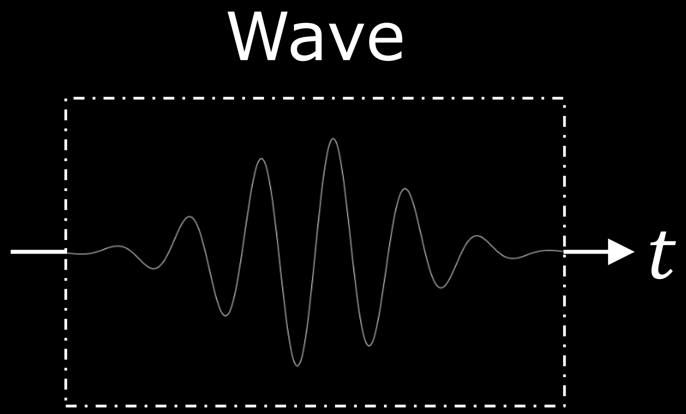
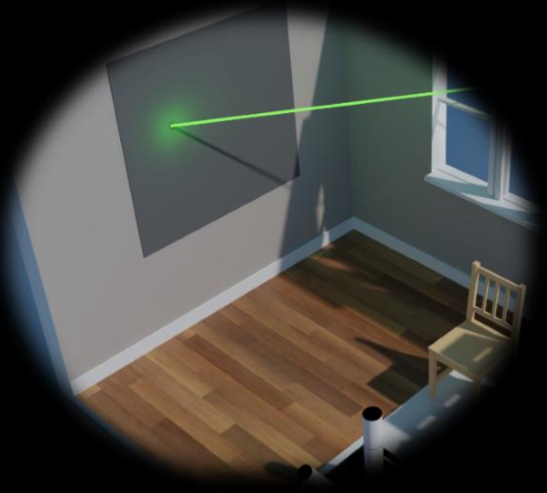

y
x
t


Wave
t



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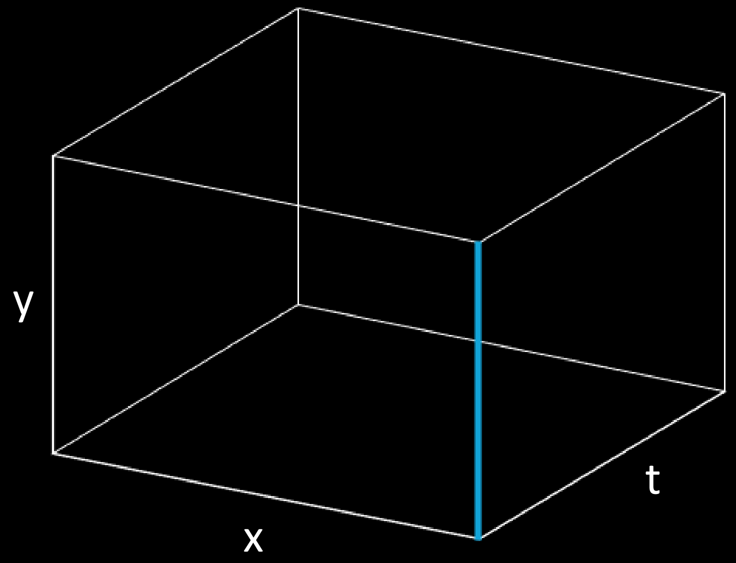
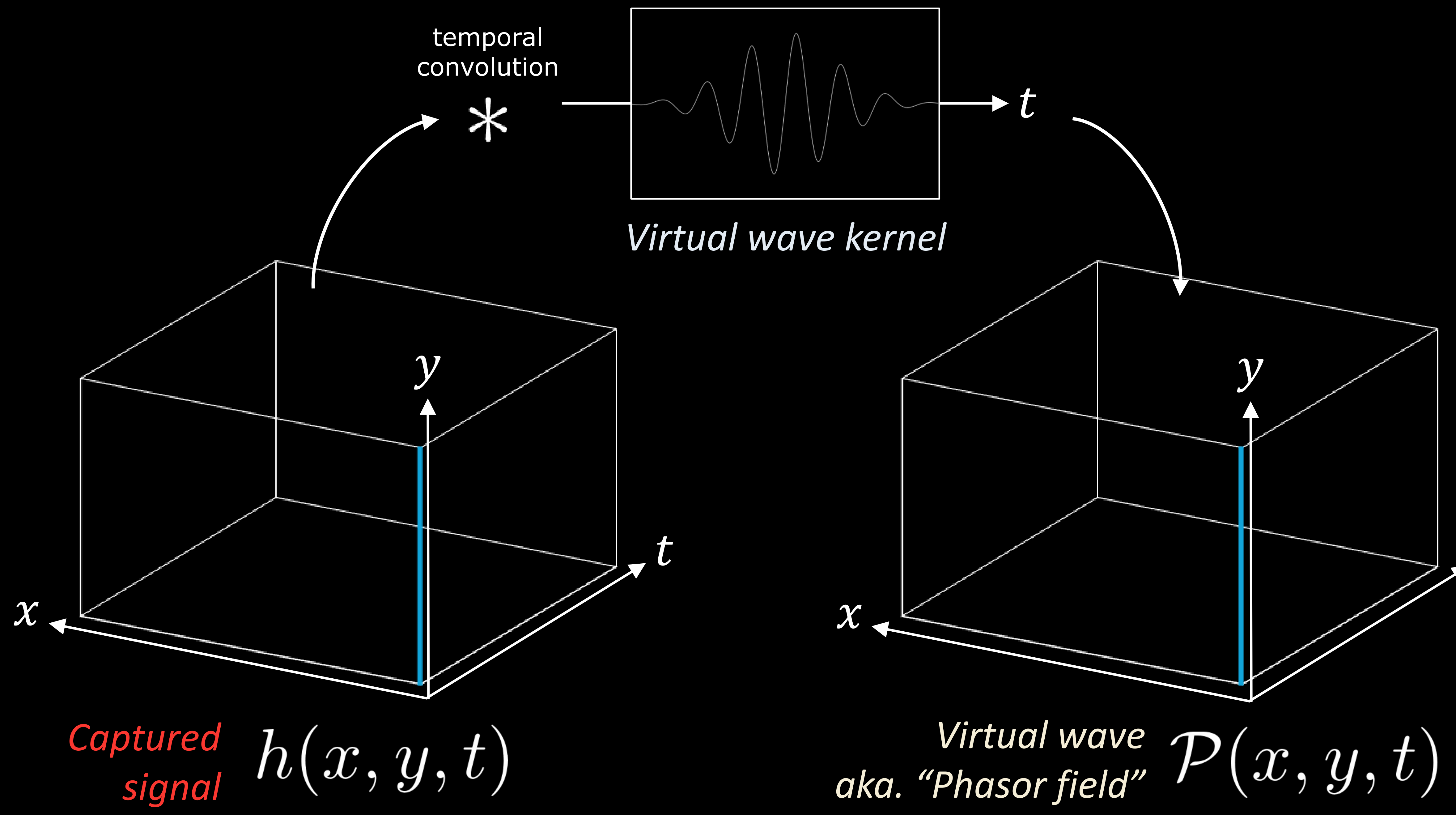
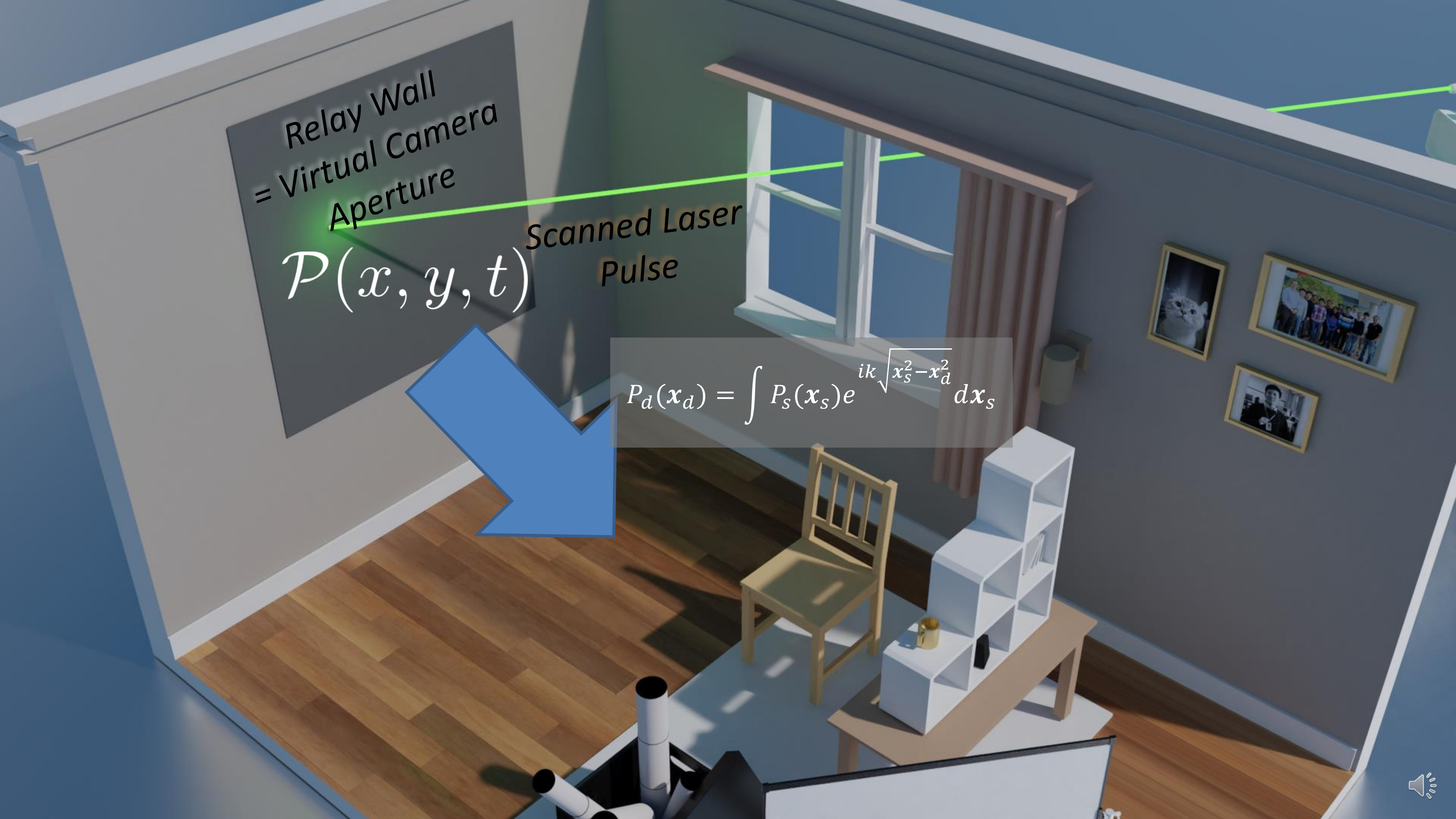
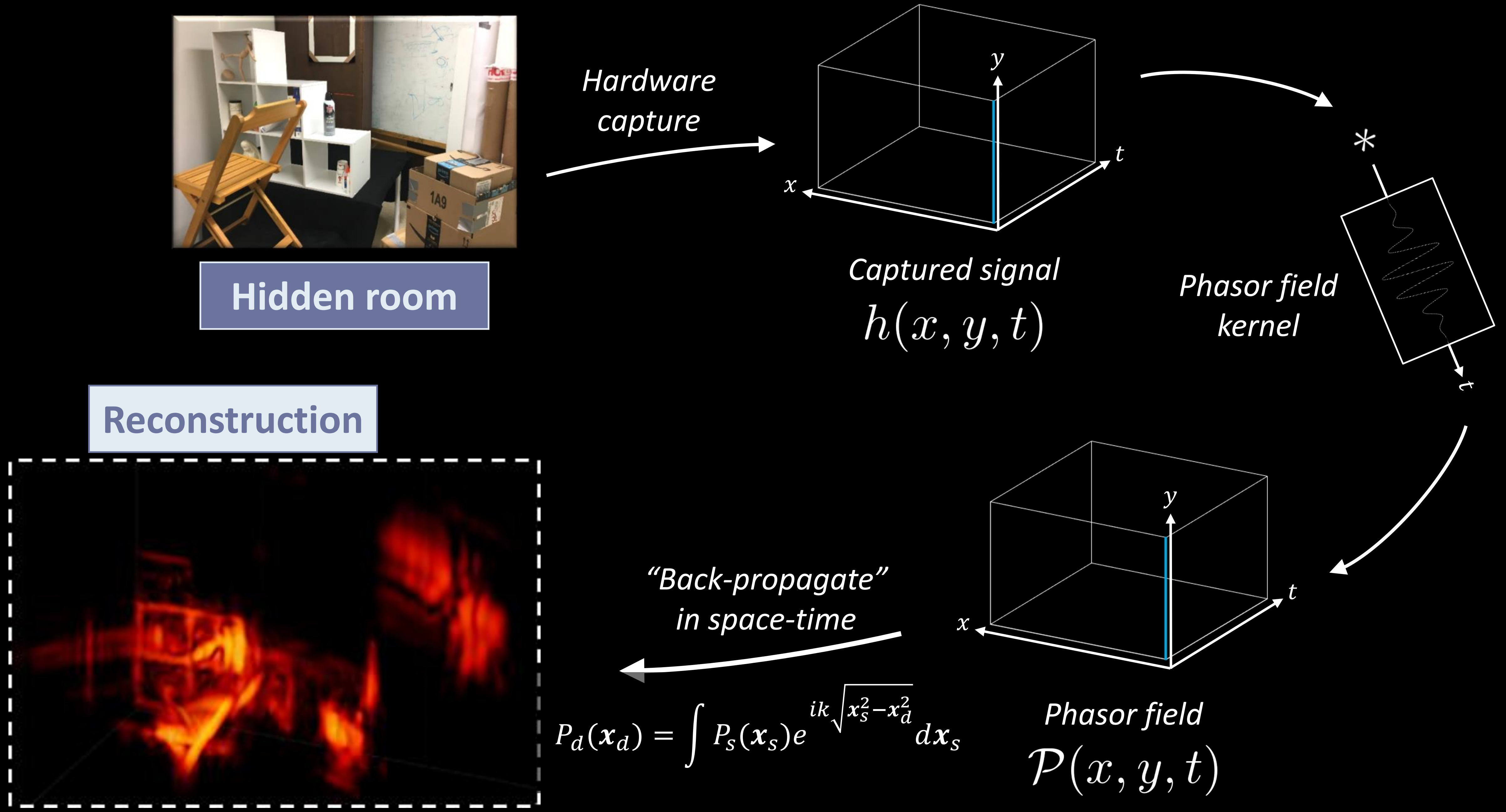
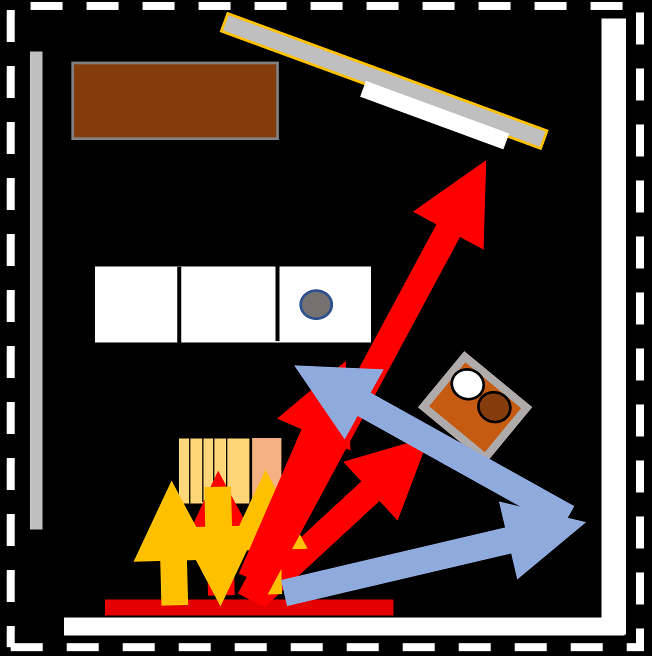

y
x
t


temporal
convolution
*
t
Virtual wave kernel
y
t
x
y
t
x
Captured
signal
$h(x, y, t)$
Virtual wave
aka. “Phasor field”
$\mathcal{P}(x, y, t)$


Relay Wall
= Virtual Camera
Aperture
$\mathcal{P}(x, y, t)$
Scanned Laser
Pulse
$P_d(\boldsymbol{x}_d) = \int P_s(\boldsymbol{x}_s) e^{ik\sqrt{\boldsymbol{x}_s^2 - \boldsymbol{x}_d^2}} d\boldsymbol{x}_s$


Hidden room
Hardware capture
y
t
x
Captured signal
$h(x, y, t)$
*
Phasor field kernel
t
y
t
x
Phasor field
$\mathcal{P}(x, y, t)$
"Back-propagate" in space-time
$P_d(\boldsymbol{x}_d) = \int P_s(\boldsymbol{x}_s) e^{ik\sqrt{\boldsymbol{x}_s^2 - \boldsymbol{x}_d^2}} d\boldsymbol{x}_s$
Reconstruction

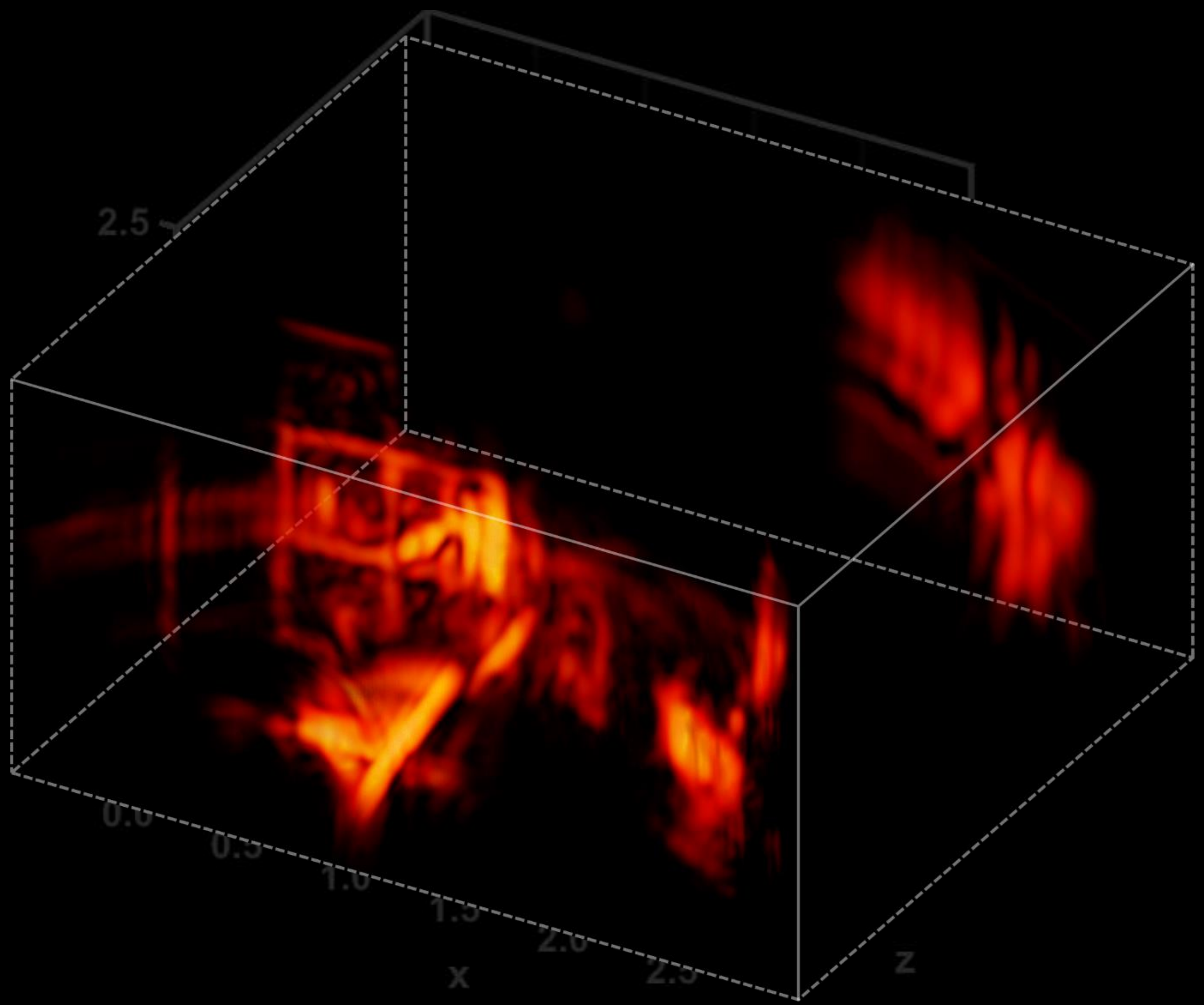
Virtual Wave Reconstruction



3rd Bounce

5th Bounce

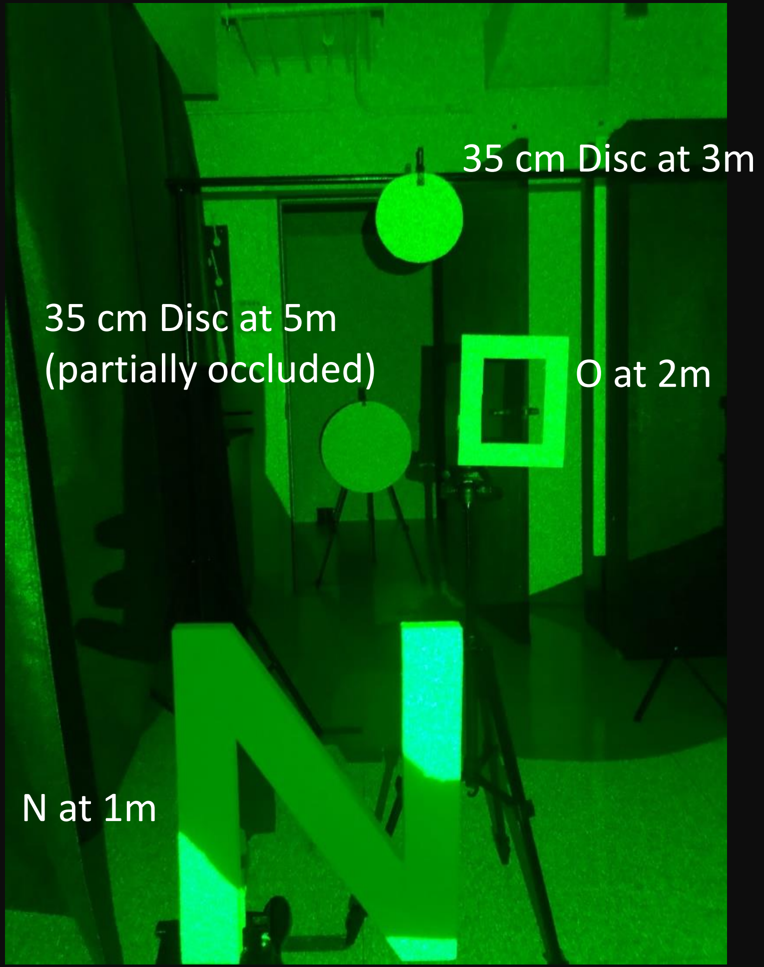
4th Bounce

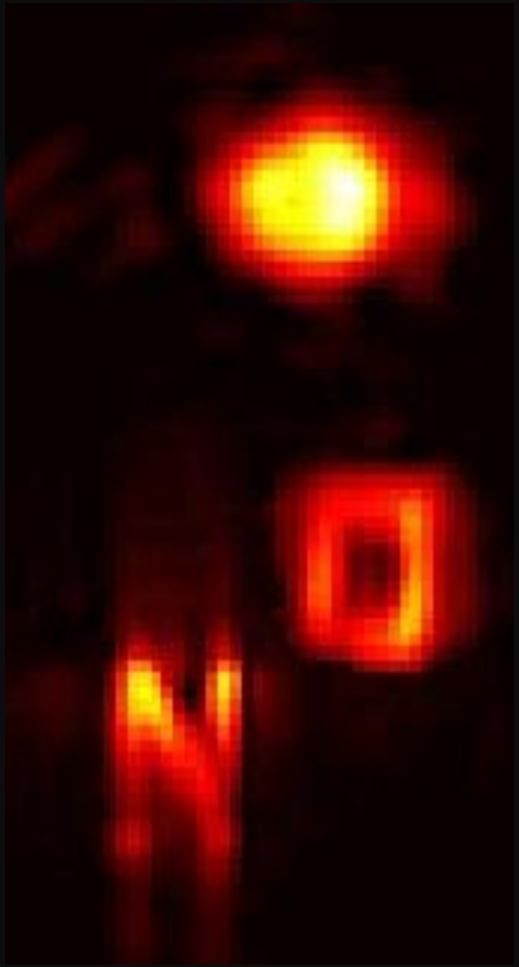


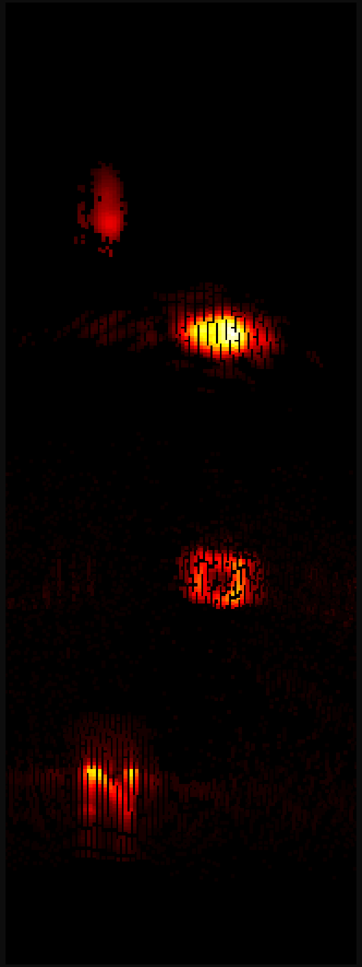
Virtual Wave Optics for Non-Line-of-Sight Imaging

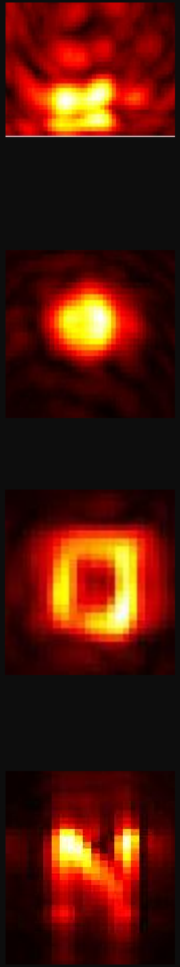
Xiaochun Liu, et. al., Arxiv, https://arxiv.org/abs/1810.07535 (**2018**)

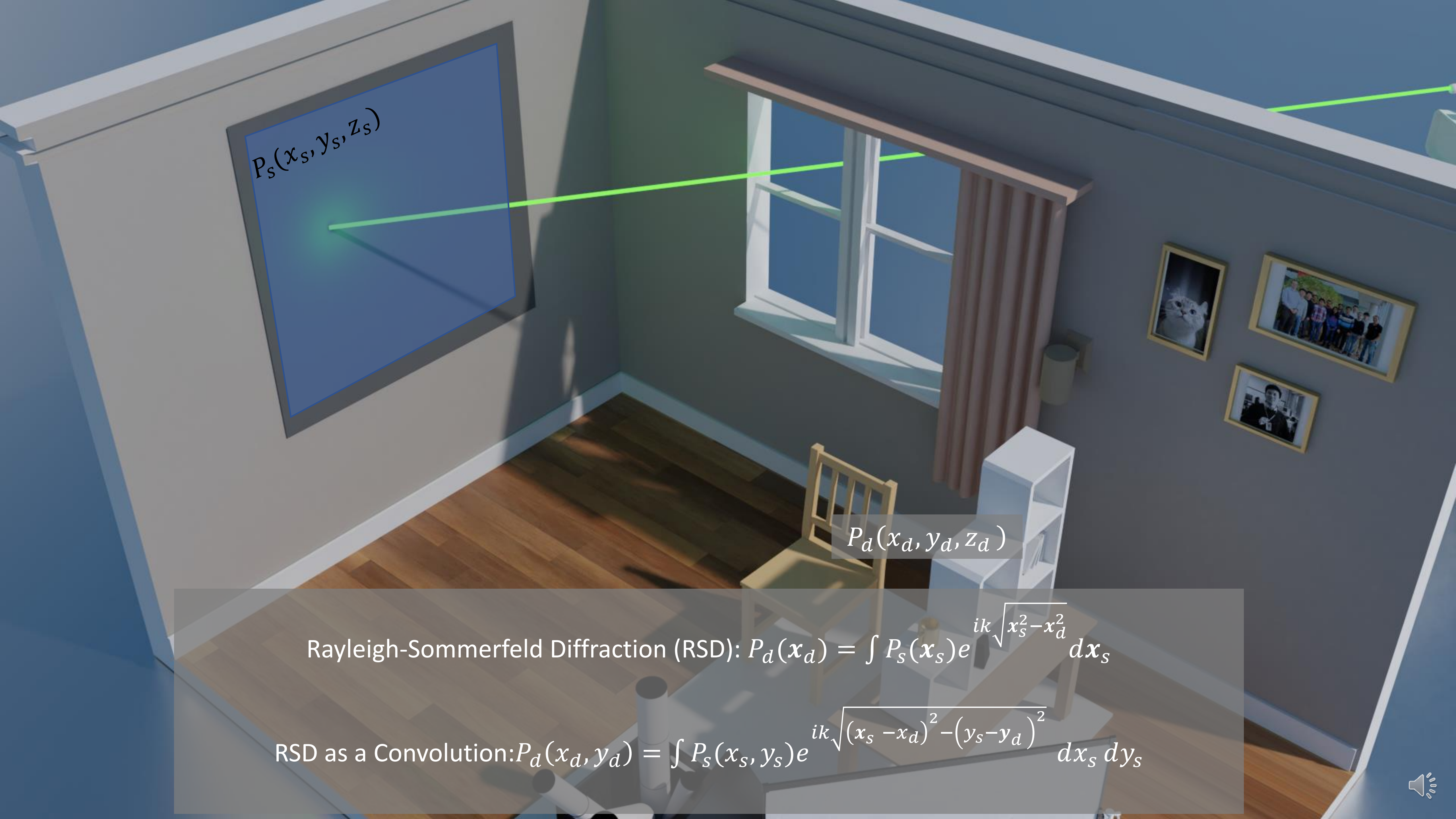
Phasor Field Reconstruction Results









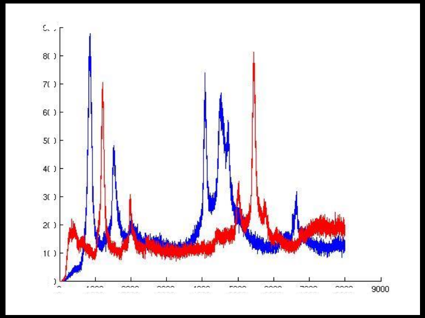


Rayleigh-Sommerfeld Diffraction (RSD): $P_d(\boldsymbol{x}_d) = \int P_s(\boldsymbol{x}_s) e^{ik\sqrt{x_s^2 - x_d^2}} d\boldsymbol{x}_s$

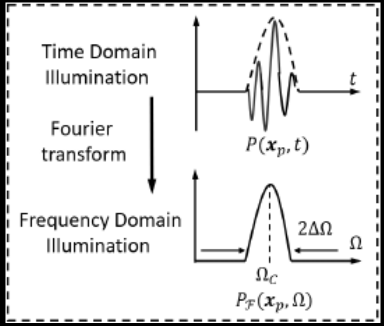
RSD as a Convolution: $P_d(x_d, y_d) = \int P_s(x_s, y_s) e^{ik\sqrt{(\boldsymbol{x}_s - x_d)^2 - (y_s - \boldsymbol{y}_d)^2}} dx_s \, dy_s$

Convolution Based Phasor Field Reconstruction Algorithm - Explanation

Time FFT of
Captured Data ($t \rightarrow \Omega$):
$H_F(x, y, \Omega)$



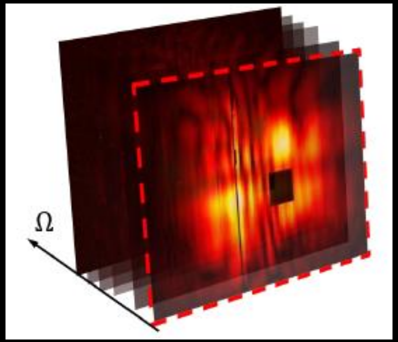
Multiply



Time FFT of
Virtual Illumination P-Field ($t \rightarrow \Omega$):
$P_F(x_p, y_p, \Omega)$

$$\iint_{-\infty}^{+\infty} \mathcal{P}_{\mathcal{F}}(x_c, y_c, 0, \Omega) \underbrace{\frac{\alpha(x_v, y_v, z_v) e^{-j\frac{\Omega}{c}\sqrt{(x_c-x_v)^2+(y_c-y_v)^2+z_v^2}}}{\sqrt{(x_c-x_v)^2+(y_c-y_v)^2+z_v^2}}}_{\text{RSD diffraction kernel}} dx_c\, dy_c$$

Fourier Domain
P-Field wave front
at Relay Wall:
$P_F(x_c, y_c, \Omega)$

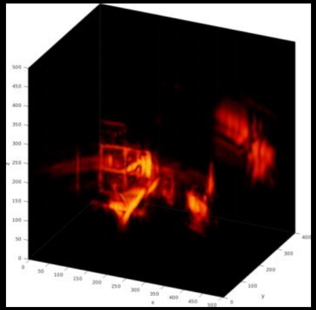


Convolve in x,y

$U(x, y, z, \Omega)$

RSD Kernel
(computed on the fly,
pre-compute for additional
speedup)

iFFT in Time ($\Omega \rightarrow t$)



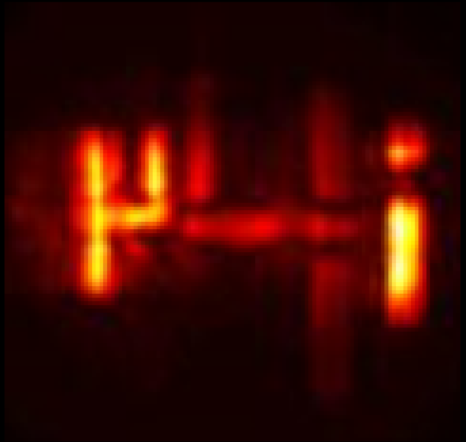
Reconstruction
(computed z-slice by z-slice)

Phasor Field Diffraction Based Reconstruction for Fast Non-Line-of-Sight Imaging Systems, X. Liu, S. Bauer, and A. Velten, Nature Communications, 2020

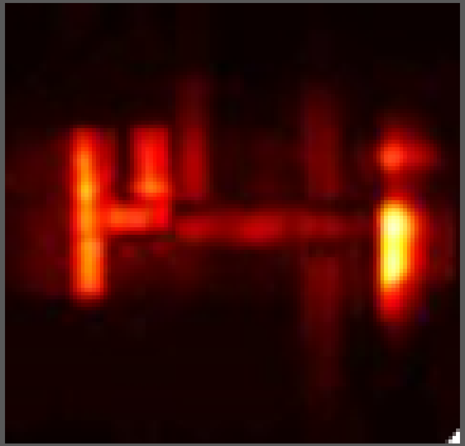
Convolution Based Phasor Field Reconstruction Algorithm - Results

Phasor Field (Nature 2019)

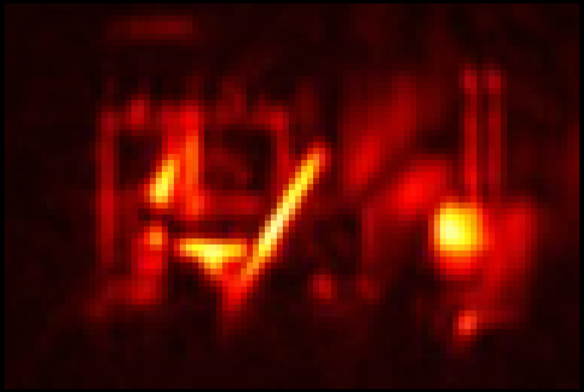
Fast Phasor Field



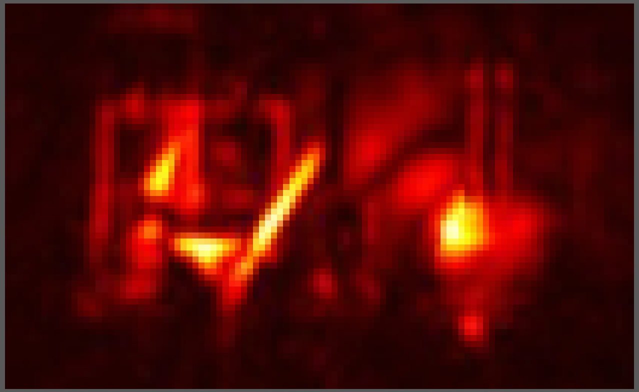
1300s (single thread)
C++ code called from Matlab



2.8s (Matlab Script)



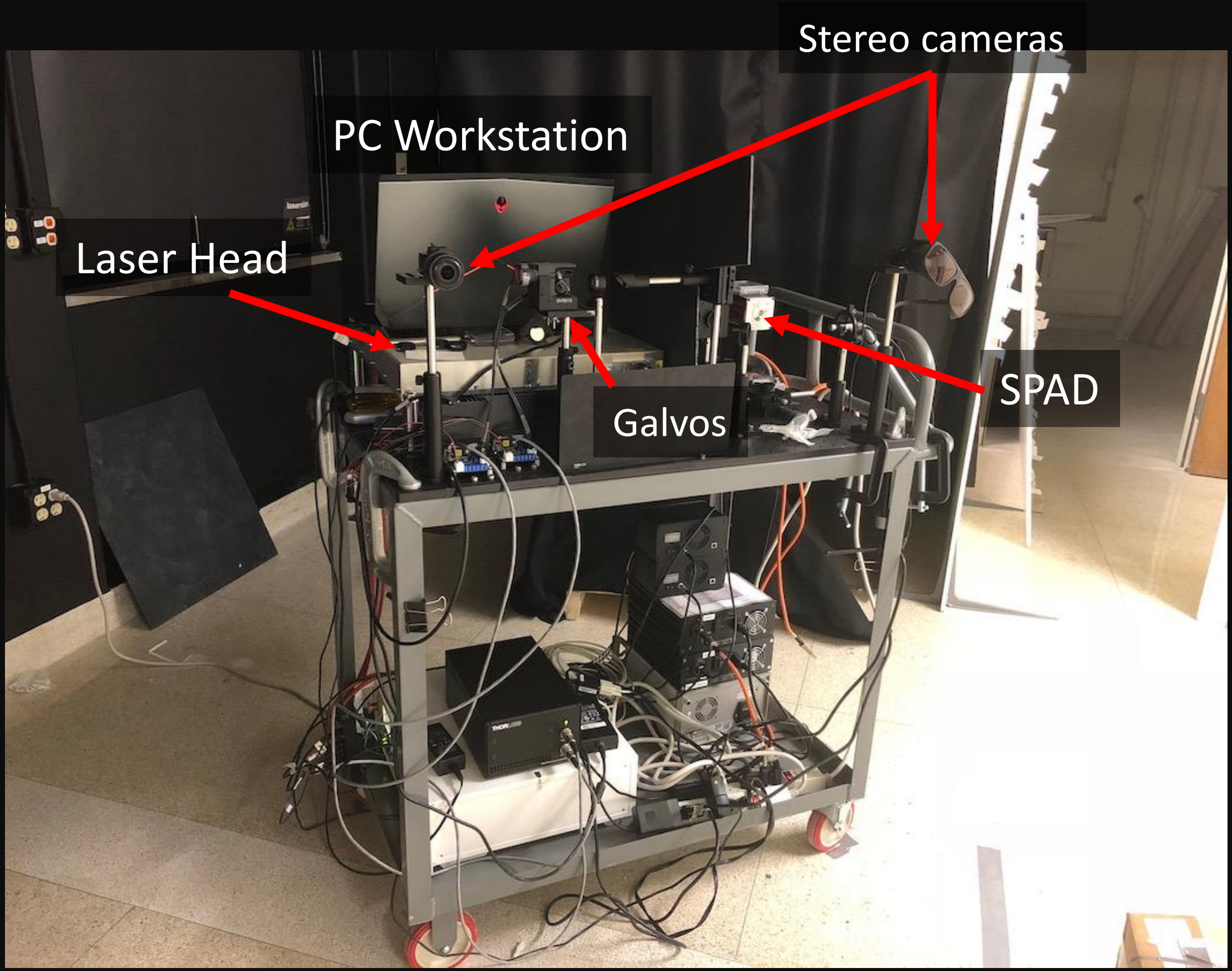
8000s (single thread)
C++ code called from Matlab

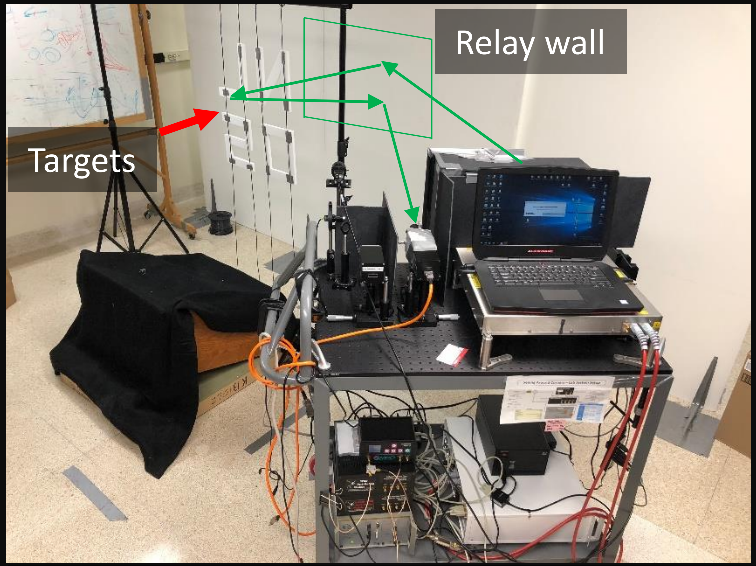


25s (Matlab Script)

6s, ~20 MB (C++, on laptop)
0.2s, 5 GB (C++, using pre-computed kernels)
0.06s, CUDA on Quadro P5000 GPU

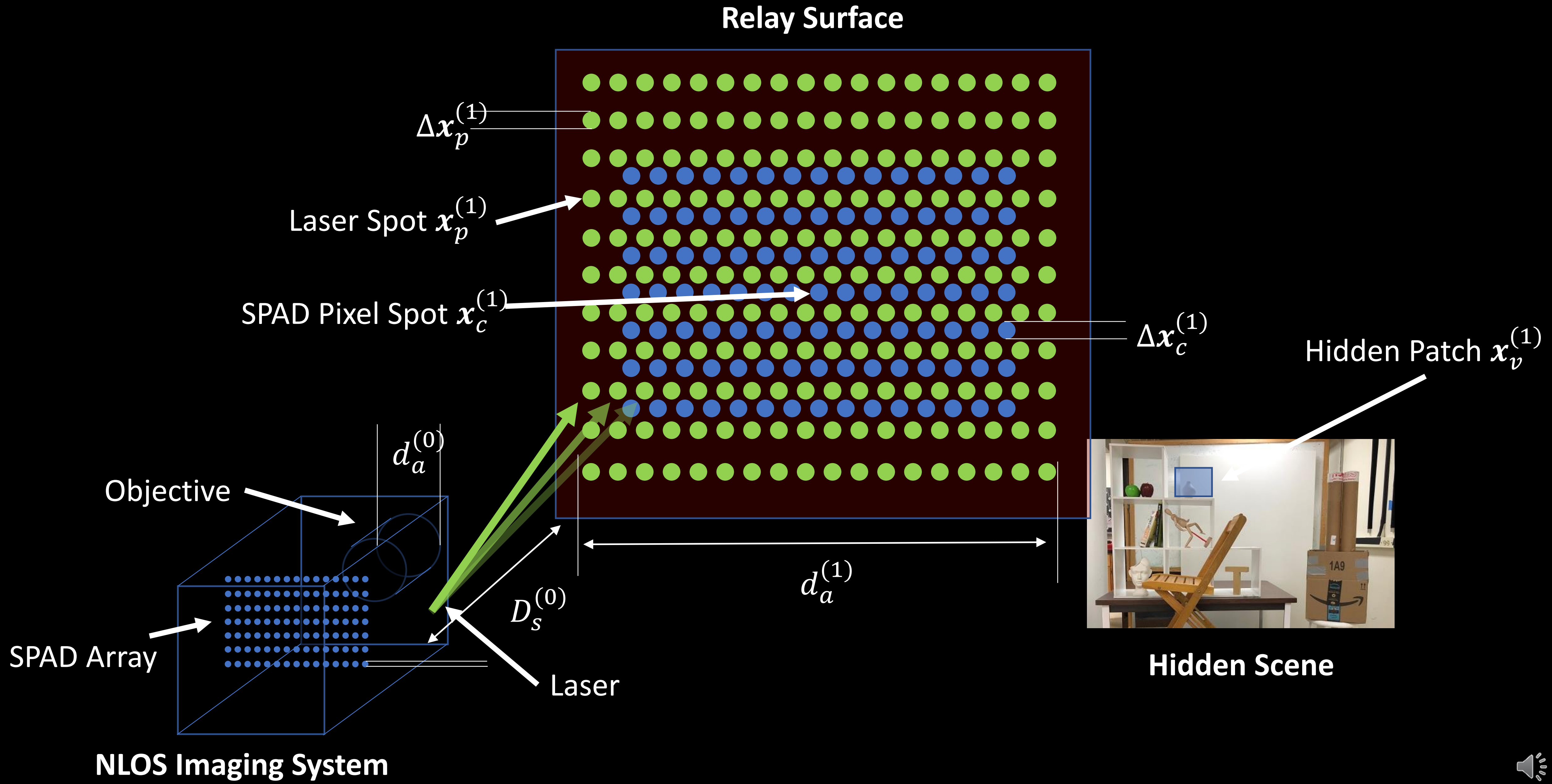
Seeing Around Corners Setup





Note: Occluder wall was removed to show the imaging system and the scenario together

SPAD Arrays for NLOS Imaging



Problems with Prior LiDAR SPAD Arrays

- Low time resolution
- No Gate
- Small pixels optimal at large (>100m) stand-off distances ..
- Low repetition rate

Fast-gated SPAD array

16x1 SPAD array module

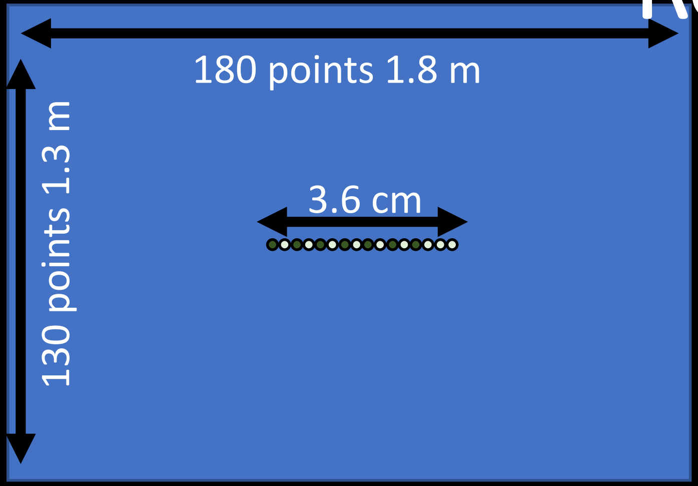
Linear 16 x 1 SPAD array coupled to fast-gating ASIC (M1)

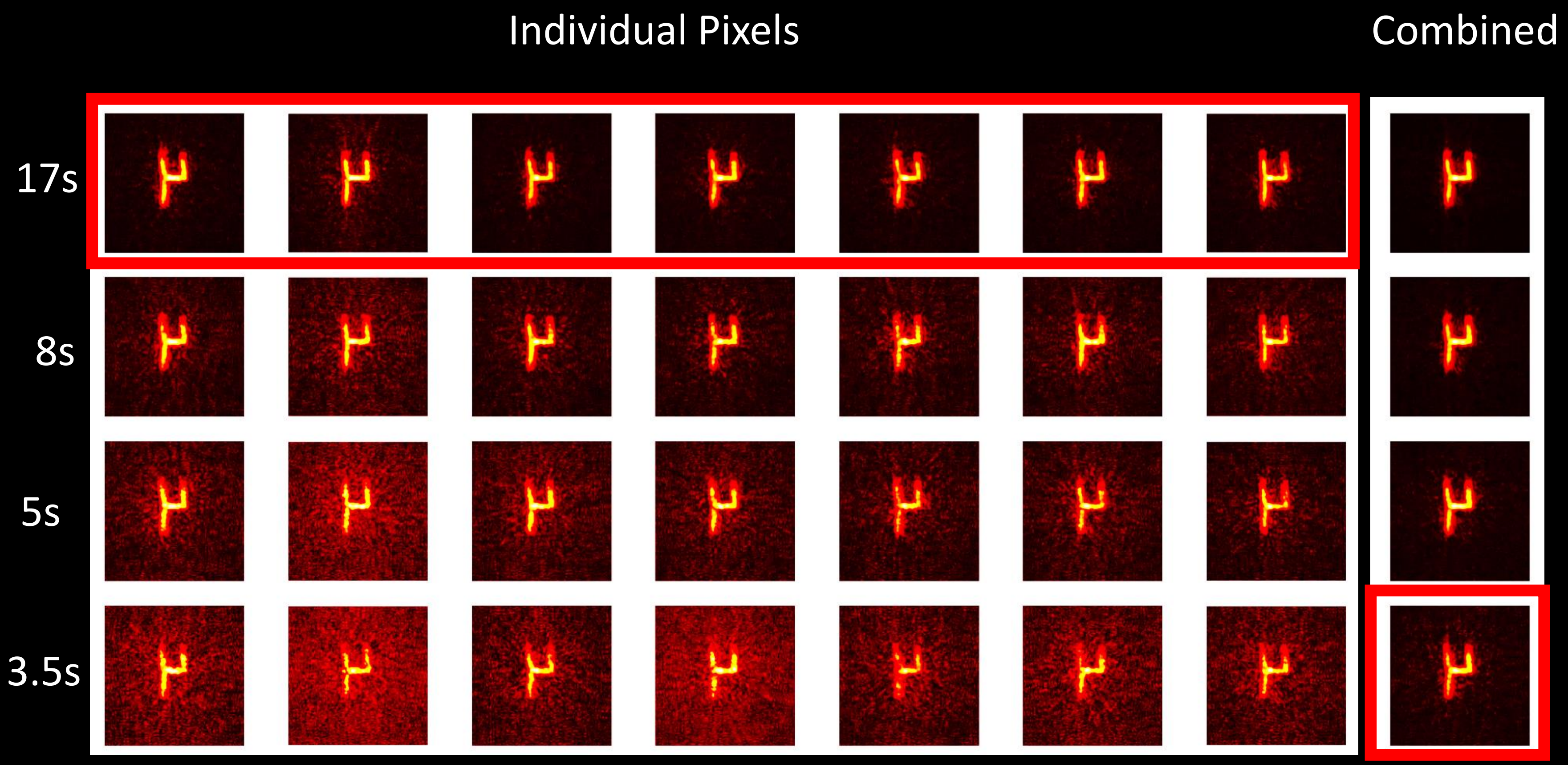
Built By The group of Alberto Tosi, Politechnico di Milano

- **50 micron pixels**
- **75% fill factor**
- **75 ps time resolution**
- **Independent free running pixels**
- **100 ns dead time**
- **Fast gated**

Renna, M.; Nam, J.H.; Buttafava, M.; Villa, F.; Velten, A.; Tosi, A. Fast-Gated 16 × 1 SPAD Array for Non-Line-of-Sight Imaging Applications. *Instruments* **2020**, *4*, 14.

Reconstructions With Array





Images have increased contrast to show noise

SPAD Arrays for Non-Line-of-Sight Imaging

Martin Laurenzis, **French-German Resarch Institute, St. Louis , France**

Mohit Gupta, **CS, UW Madison**

Mauro Buttafava, Alberto Tosi, **Politecnico di Milano, Italy**

Karl Mitchell, James Ashley, Stephen Dawson, Nitin Arora, Andrew Shapiro, **NASA Jet Propulsion Lab, Pasadena, CA**

Jeffrey Nosanov, **Nosanov Consulting, LLC**

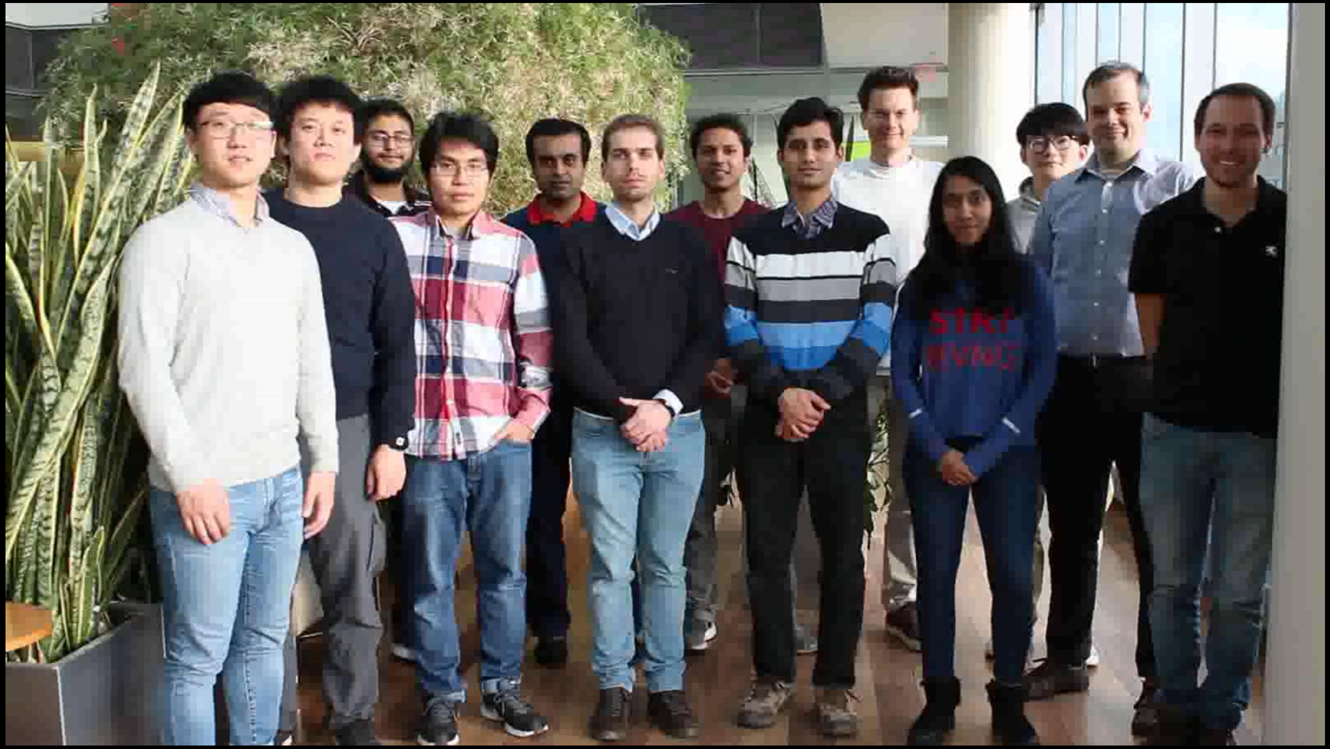
Ibon Gulien, Belen Masia, Adrian Jarabo, Diego Gutierrez, **Universidad de Zaragoza, Spain**

Kevin Eliceiri, **LOCI, UW Madison**

Di Wu, Everett Lawson, Andy Bardagjy, Otkrist Gupta, Rohit Pandharkar, Nikhil Naik, Christopher Barsi, Amy Fritz, Ramesh Raskar, **MIT Media Lab, Cambridge, MA**

Thomas Willwacher, **Harvard University**

Ashok Veeraraghavan, **Rice University**



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