單光子三維成像

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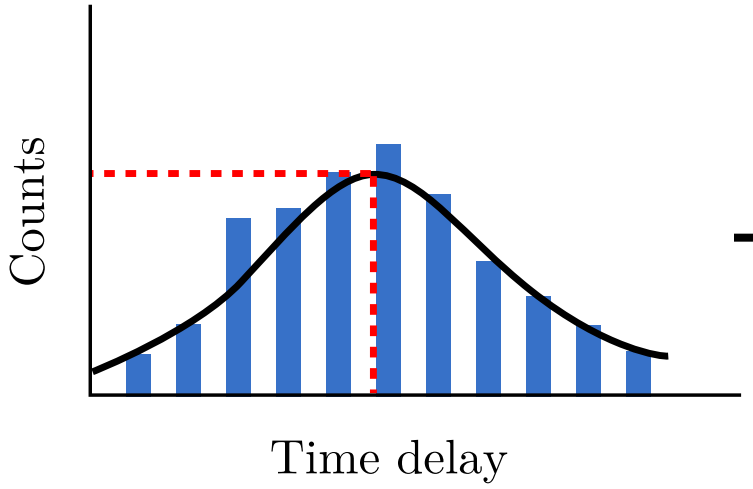
rLe AT MIT

Massachusetts Institute of Technology

Traditional active imaging

Use pulsed, periodic illumination and histogram **tens to hundreds of photons per pixel** of data to obtain accurate depth and reflectivity maps



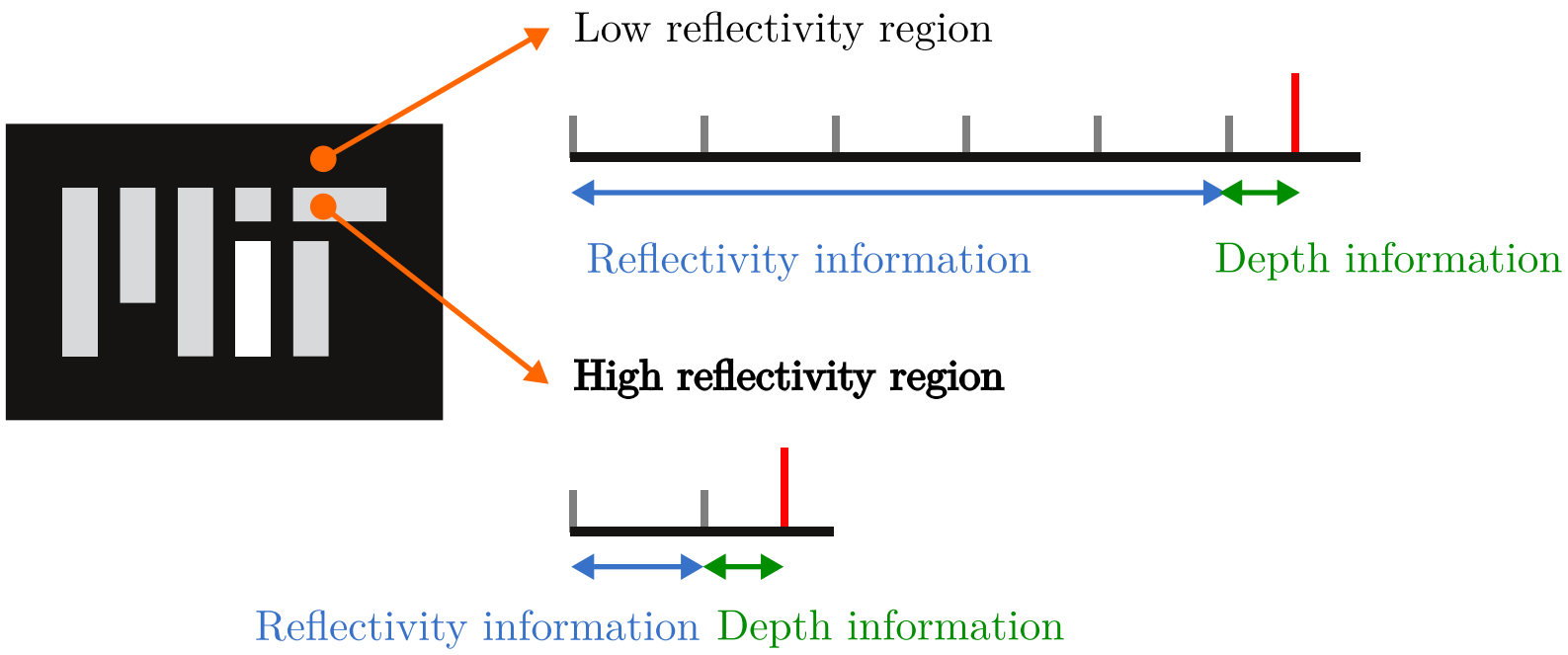
One-pixel histogram

Reflectivity map

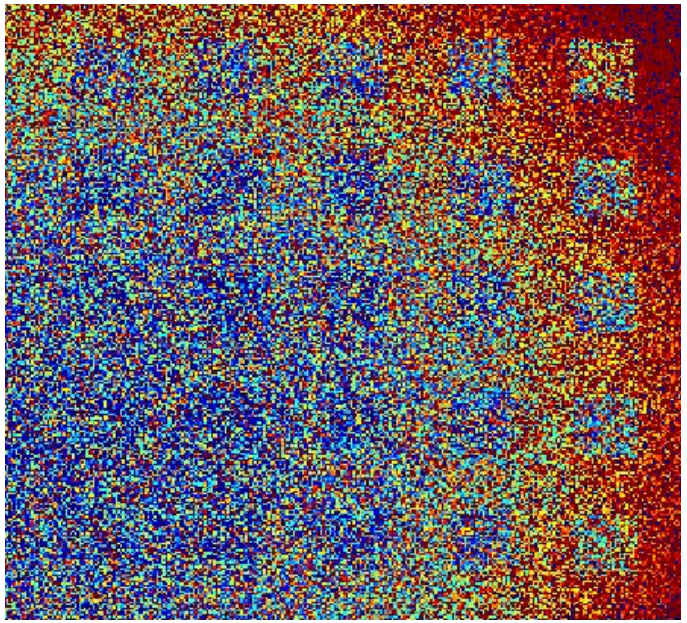
Depth map

First-photon imaging

What if we only used **1 photon per pixel**?



First-photon imaging



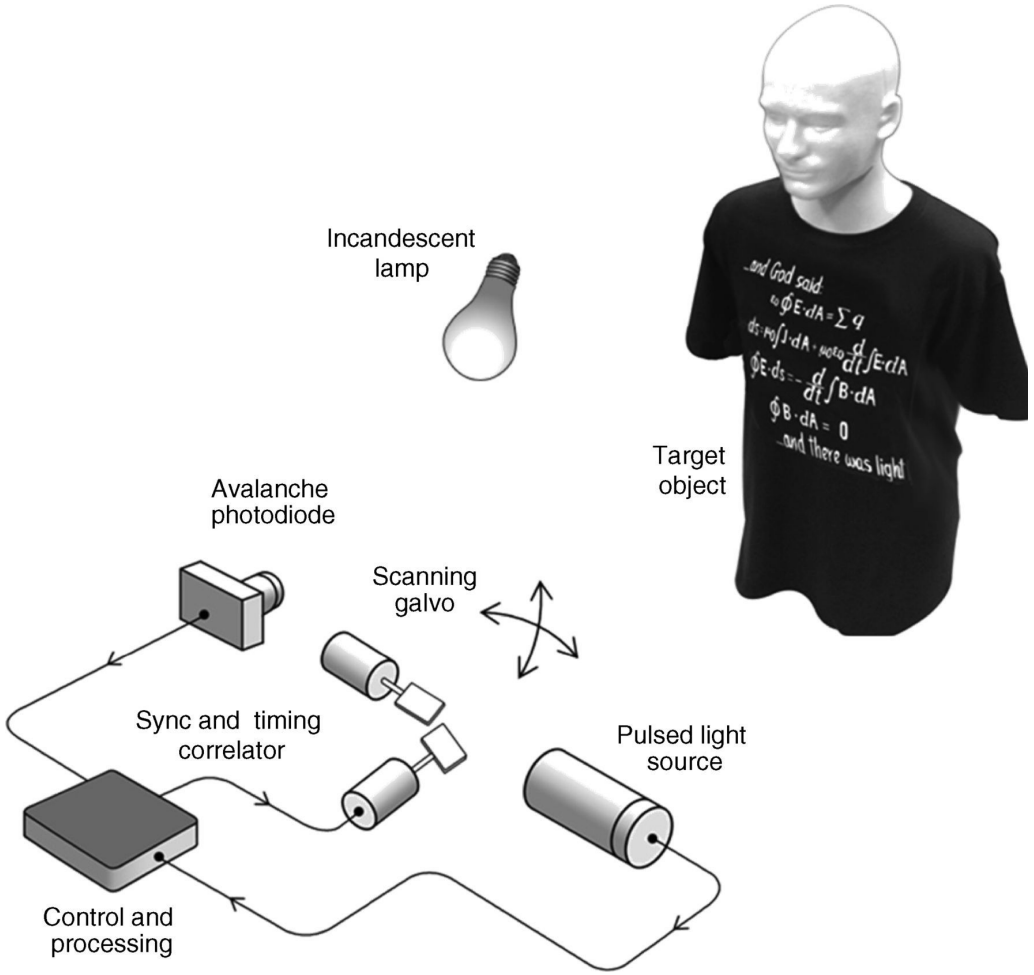
Problem:
Poor-quality images, corrupted by pulse width (depth) and Poisson noise (reflectivity)

Solution:
Use knowledge of single-photon detection statistics

Similar to compressive GI, assume object is realistic and has spatial correlations

Use computational optimization to reconstruct the scene given a small amount of data (1 photon per pixel)

Experimental setup



Illumination:

Laser: 640-nm, 10 MHz repetition rate, 226-ps RMS width

Raster scanning:

2-axis galvo mirror: ±20°, 1000×1000 scan

Detection:

APD: 100×100 μm, 50-ps jitter, 35% efficiency

IF: 2-nm bandwidth, 49% transmission

TDC: 8-ps resolution

Computational reconstruction algorithm

Step 1: Reflectivity reconstruction

Minimize a weighted sum of the log-likelihood given Poisson statistics and a sparsity-promoting term:

$$\{\hat{\alpha}(x,y)\} = \underset{\{\alpha(x,y)\}}{\arg\min}(1-\beta)\left[\sum_x \sum_y \mathcal{L}(\alpha(x,y)|n(x,y))\right] + \beta||\Phi\left(\{\alpha(x,y)\}\right)||_1$$

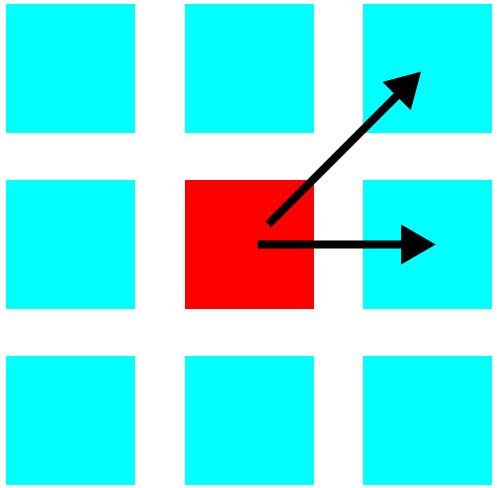
$$\mathcal{L}\left(\alpha(x,y)|n(x,y)\right) = \gamma\left[\alpha(x,y)S + BT_r\right]\left[n(x,y)-1\right] - \log\left[\gamma\alpha(x,y)S + BT_r\right]$$

A. Kirmani, D. Venkatraman, D. Shin, A. Colaco, F. N. C. Wong, J. H. Shapiro, and V. K. Goyal. Science, 343(6166):58–61, 2014.

Computational reconstruction algorithm

Step 2: Background noise censoring

Background noise makes depth reconstruction non-convex. We eliminate background photons using the ROAD statistic:



1. Calculate differences to nearest 8 pixels

$$(x_1, y_1) - t(x, y)|, \ldots, |t(x_8, y_8) - t(x, y)|$$

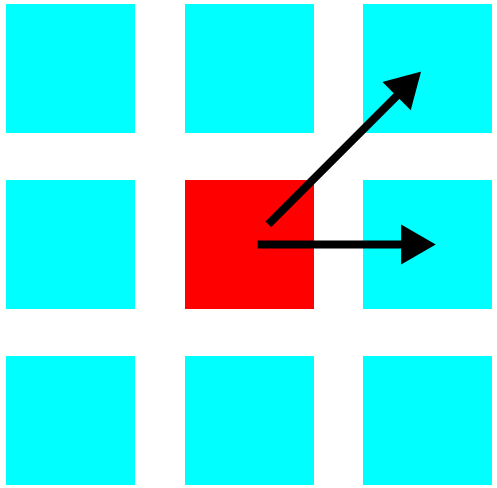
2. Sort in ascending order
3. Define ROAD(x, y) to be the sum of the first 4 values

R. Garnett, T. Huegerich, C. Chui, and W. He. Image Processing, IEEE Transactions on, 14(11):1747–1754, 2005.

Computational reconstruction algorithm

Step 2: Background noise censoring

Background noise makes depth reconstruction non-convex. We eliminate background photons using the ROAD statistic:



4. Binary decision test: If ROAD(x, y) > C, reject pixel and replace with average of neighboring 8 pixels.

$$= 4T_p \frac{BT_r}{\hat{\alpha}(x,y)S + BT_r}$$

D. P. Bertsekas and J. N. Tsitsiklis. Introduction to probability. 2002.

Computational reconstruction algorithm

Step 3: Depth reconstruction

Minimize a weighted sum of the log-likelihood given pulse shape and a sparsity-promoting term:

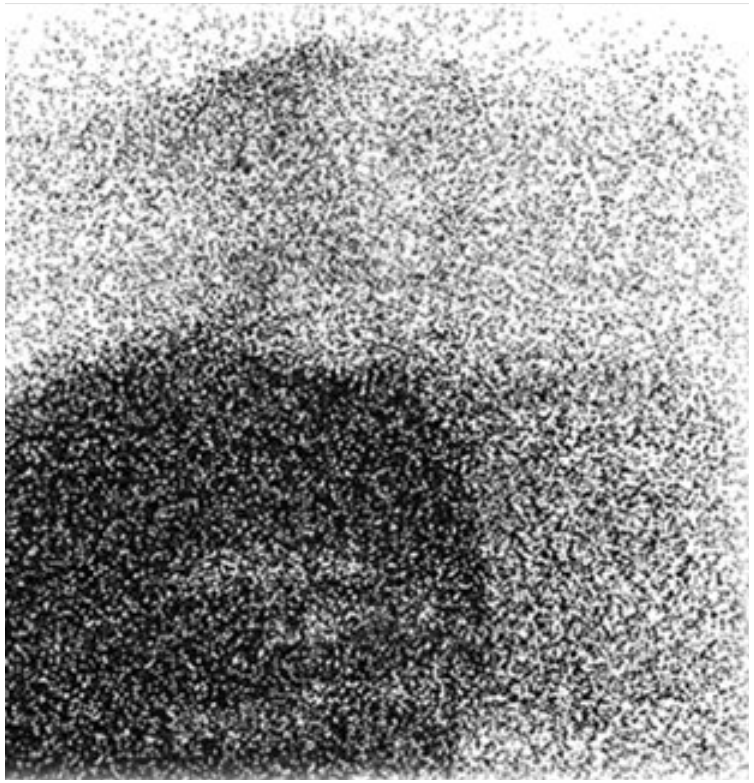
$$\{\hat{Z}(x,y)\} = \underset{\{Z(x,y)\}}{\arg\min}\,(1-\beta)\left[\sum_x \sum_y \mathcal{L}(Z(x,y)|t(x,y))\right] + \beta||\Phi\left(\{Z(x,y)\}\right)||_1$$

$$\mathcal{L}(Z(x,y)|t(x,y)) = -\log\left[s(t(x,y) - \frac{2Z(x,y)}{c})\right]$$

A. Kirmani, D. Venkatraman, D. Shin, A. Colaco, F. N. C. Wong, J. H. Shapiro, and V. K. Goyal. Science, 343(6166):58–61, 2014.

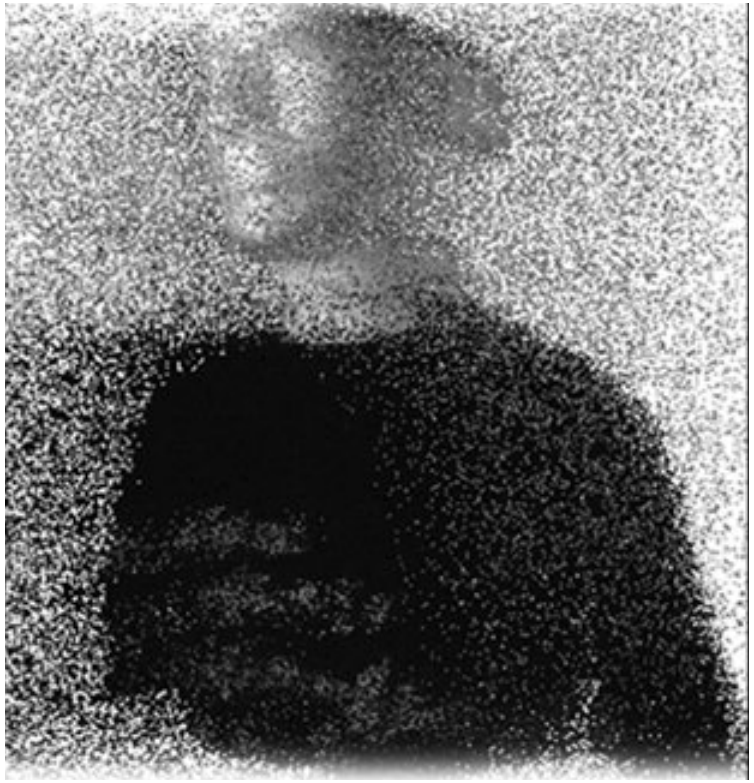
Results

Raw ML estimates



Results

Reflectivity reconstruction



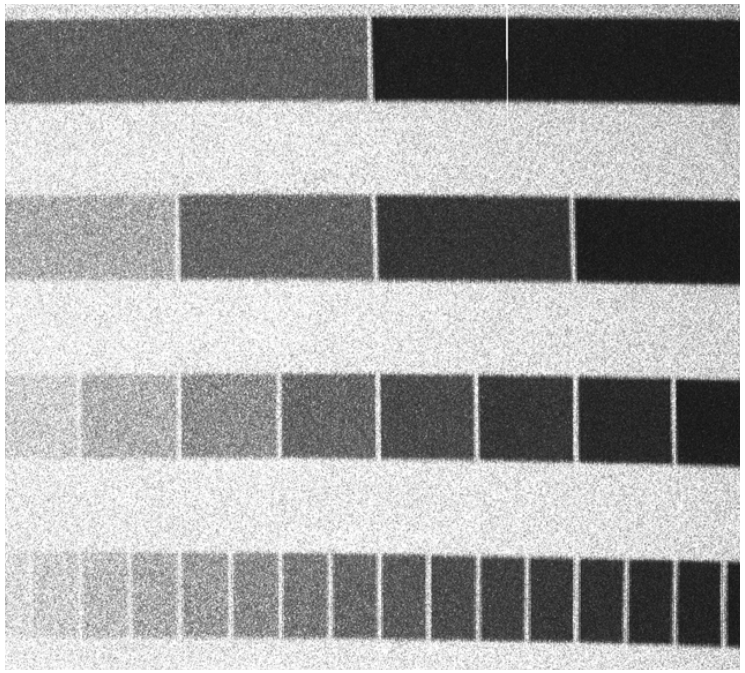
Results

Background noise censoring

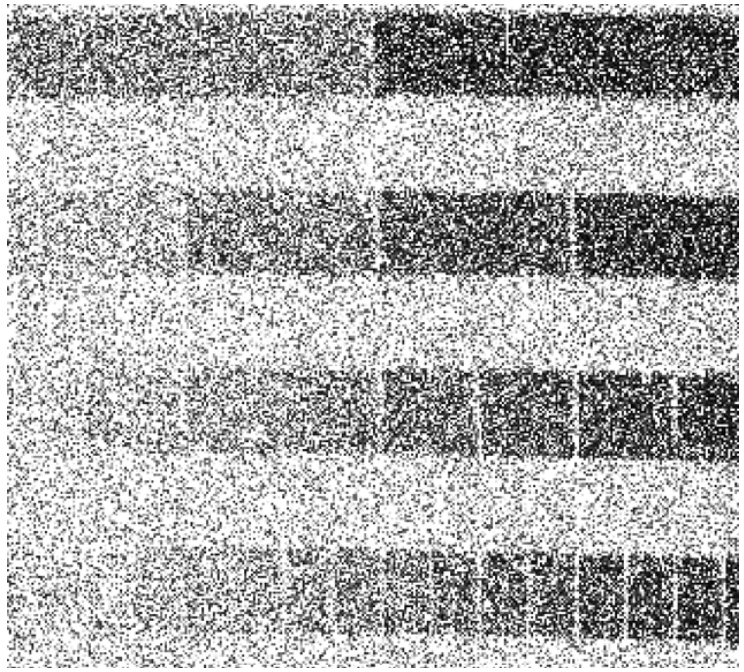
Results

Depth reconstruction

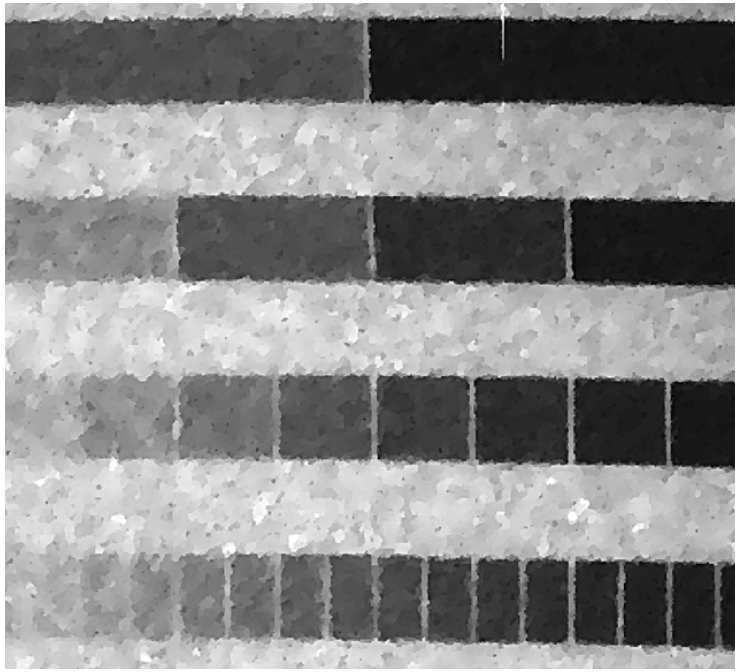
Results: Reflectivity chart



Reference measurement
(~1000 photos/pixel)

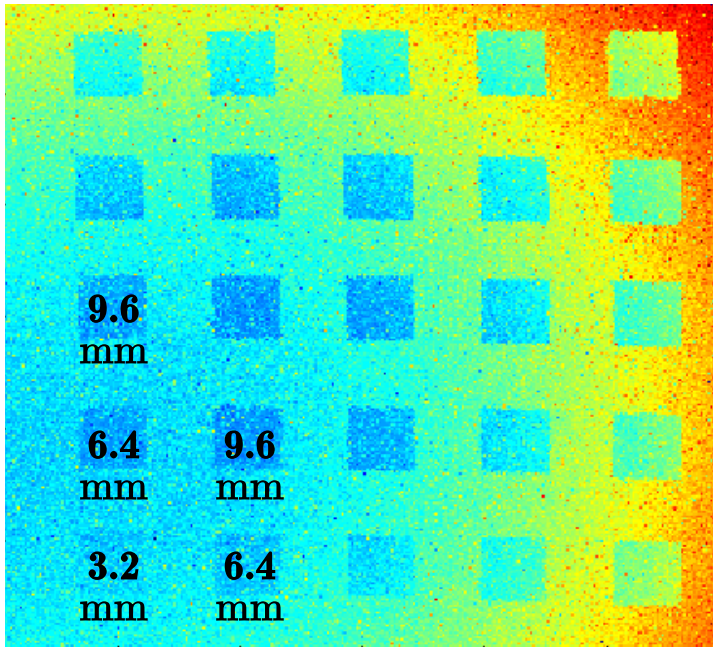


First-photon ML estimate



First-photon, reconstructed

Results: Depth chart



Reference measurement

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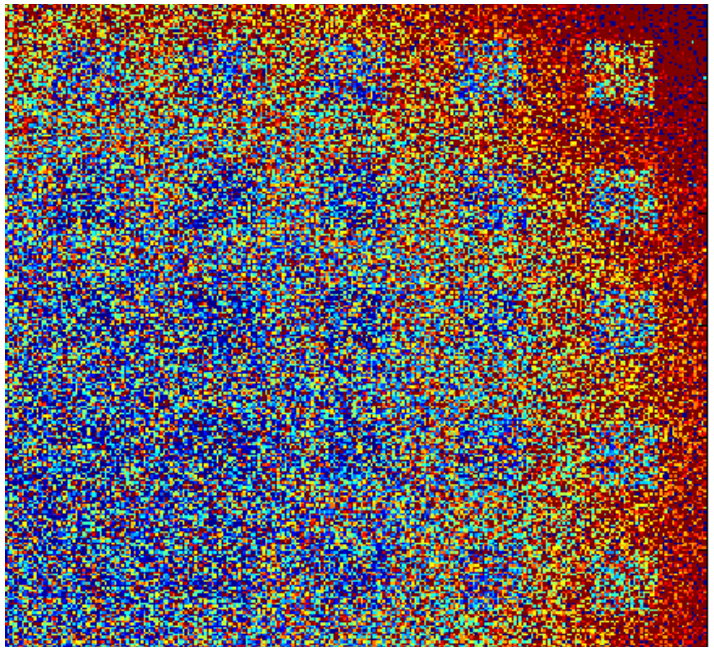
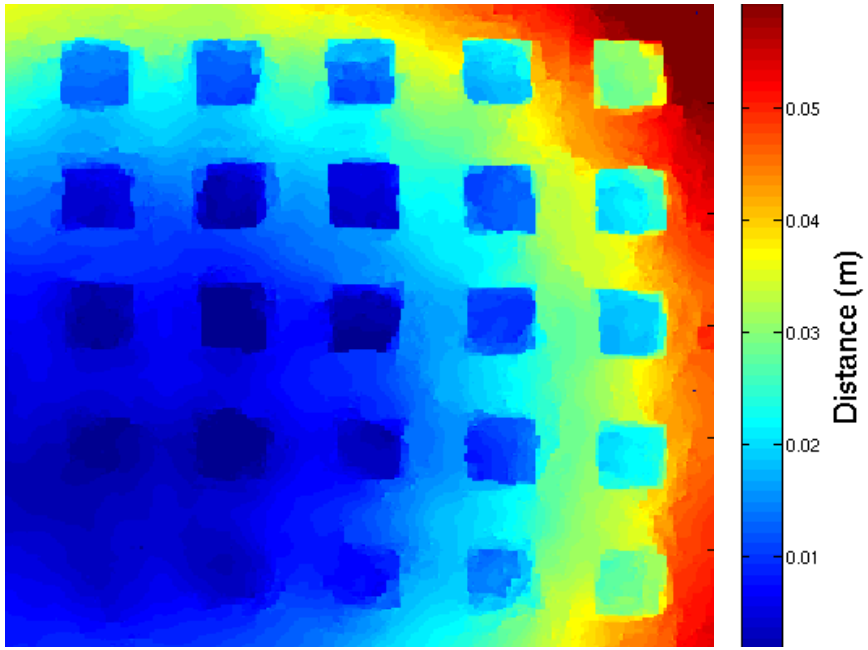


First-photon ML estimate



First-photon, reconstructed

SPAD array imaging

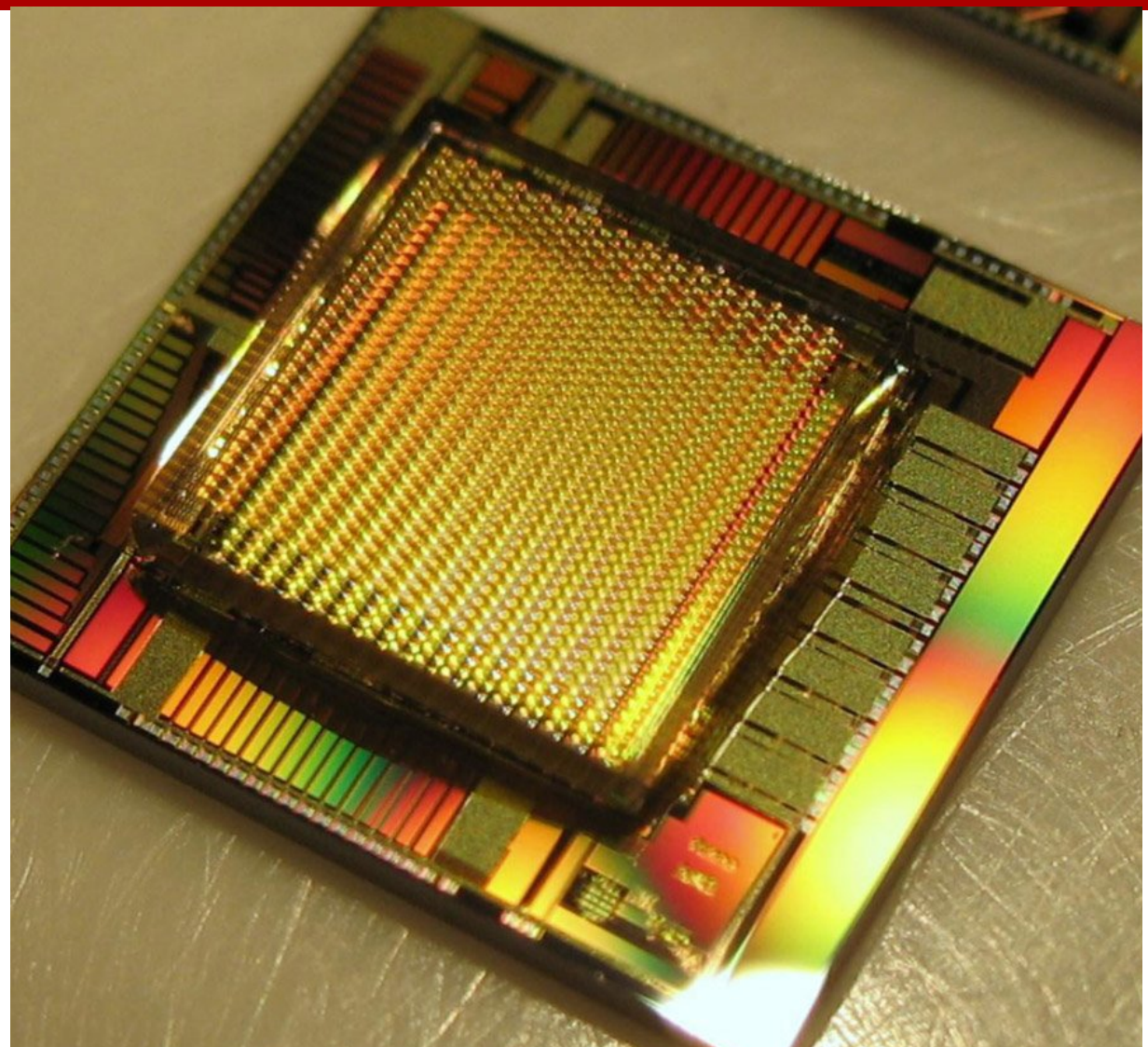
Established research collaboration with Zappa group, Politecnico di Milano

Borrowed prototype of a 32×32 pixel SPAD array with 6-bit TDC at each pixel

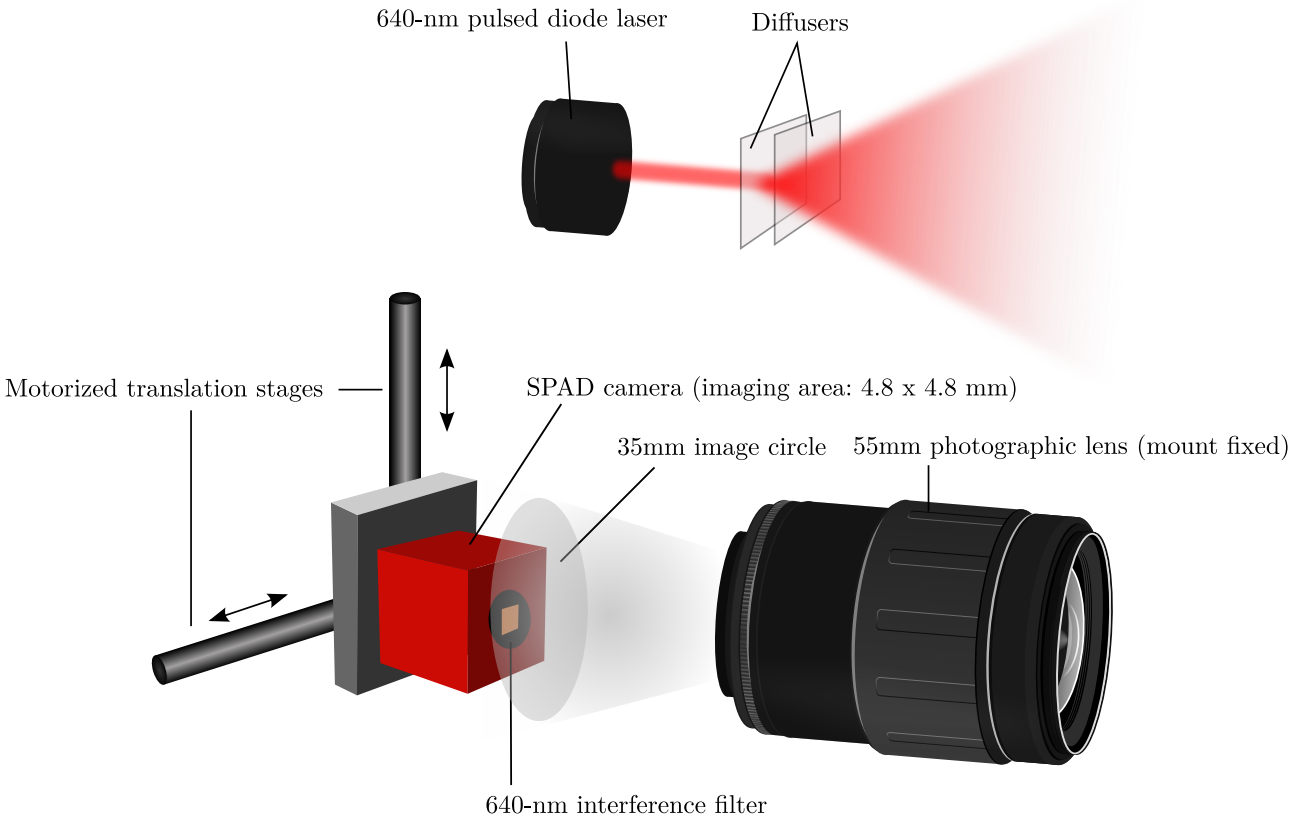
Counting mode:
6-bit resolution (0-63 photon arrivals)

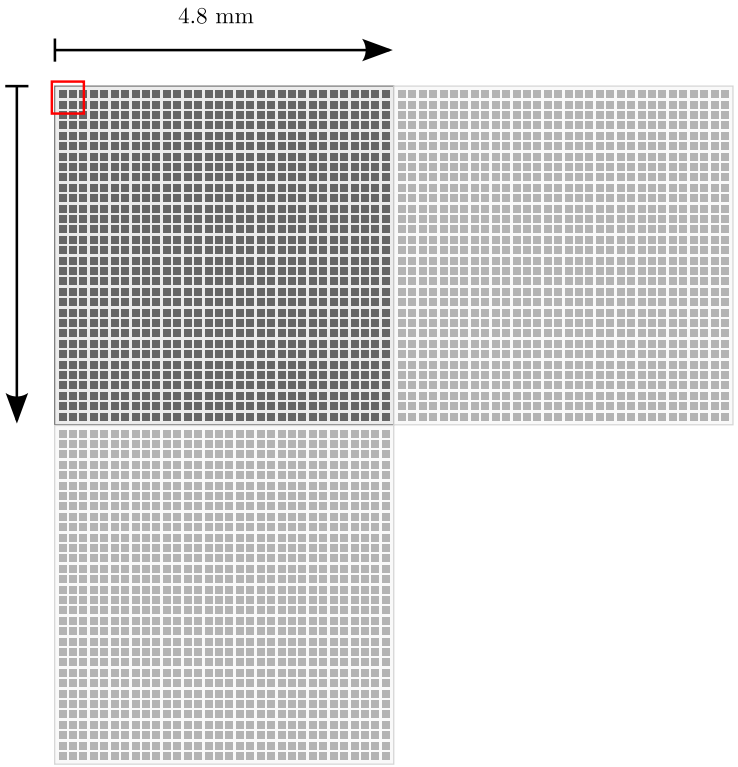
Timing mode:
10-bit, 1024 bins, each 389.9 ps

F. Villa et al. Photonics Journal, IEEE, 4(3):795–804, June 2012.

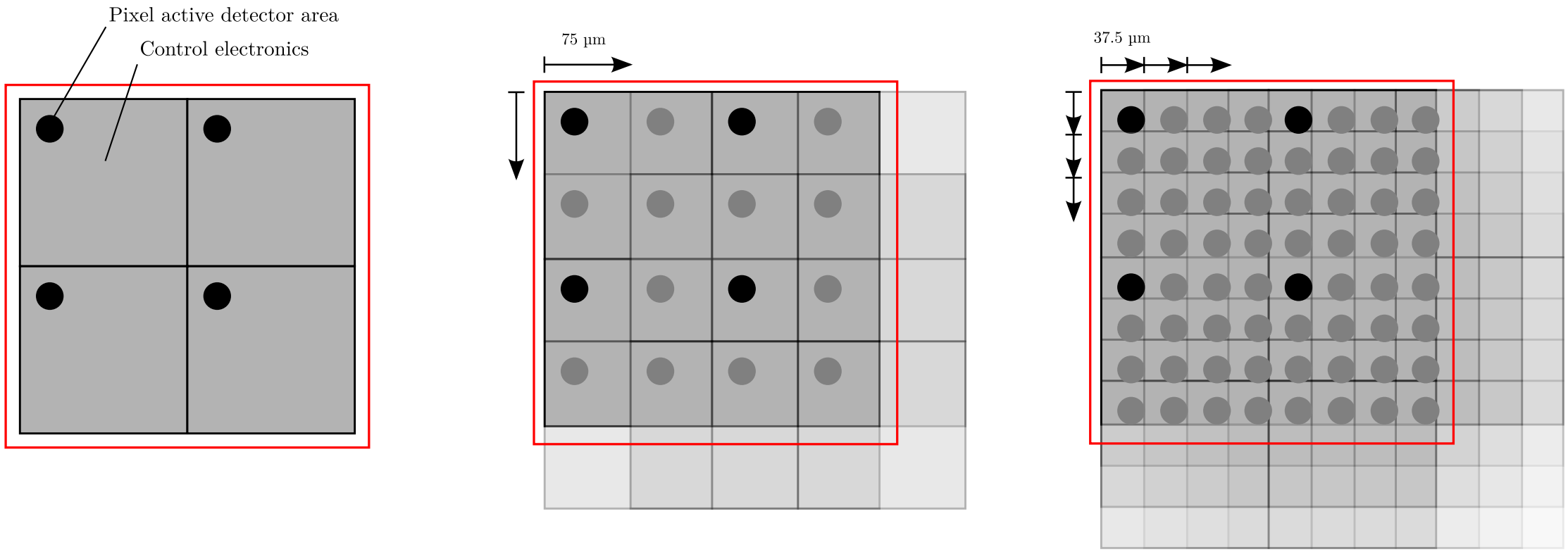


SPAD array imaging





Subpixel scanning for higher resolution



Computational reconstruction algorithm

Step 1: Reflectivity reconstruction

Instead of time until first arrival, we now use the number of photon detection events in a fixed dwell period.

$$\mathcal{L}\left(\alpha(x,y)|n(x,y)\right) = \gamma\left[\alpha(x,y)S + BT_r\right]\left[n(x,y) - 1\right] - \log\left[\gamma\alpha(x,y)S + BT_r\right]$$

$$\downarrow$$

$$\mathcal{L}\left(\alpha(x,y)|k(x,y)\right) = \gamma\left[\alpha(x,y)S + BT_r\right]\left[N - k(x,y)\right] - k(x,y)\log\left[1 - \exp\left[-\gamma\alpha(x,y)S + BT_r\right]\right]$$

D. Shin, A. Kirmani, V. K. Goyal, and J. H. Shapiro. arXiv/stat, 2014

Computational reconstruction algorithm

Step 2: Background noise censoring

1. Compute $t_{ROM}(x,\ y)$ = median value of all detections in neighboring 8 pixels

2. Define a set of indices of detections to keep as valid, rejecting the others.

$$\mathcal{J}(x,y) = \left\{ \ell : |t_\ell(x,y) - t_{ROM}(x,y)| < 2T_p \left(\frac{BT_r}{\gamma\alpha(x,y)S + BT_r} \right), 0 \leq \ell < k(x,y) \right\}$$

D. Shin, A. Kirmani, V. K. Goyal, and J. H. Shapiro. arXiv/stat, 2014

Computational reconstruction algorithm

Step 3: Depth reconstruction

Instead of using only first arrival, we make use of all valid data.

$$\mathcal{L}(Z(x,y)|t(x,y)) = -\log\left[s(t(x,y) - \frac{2Z(x,y)}{c})\right]$$

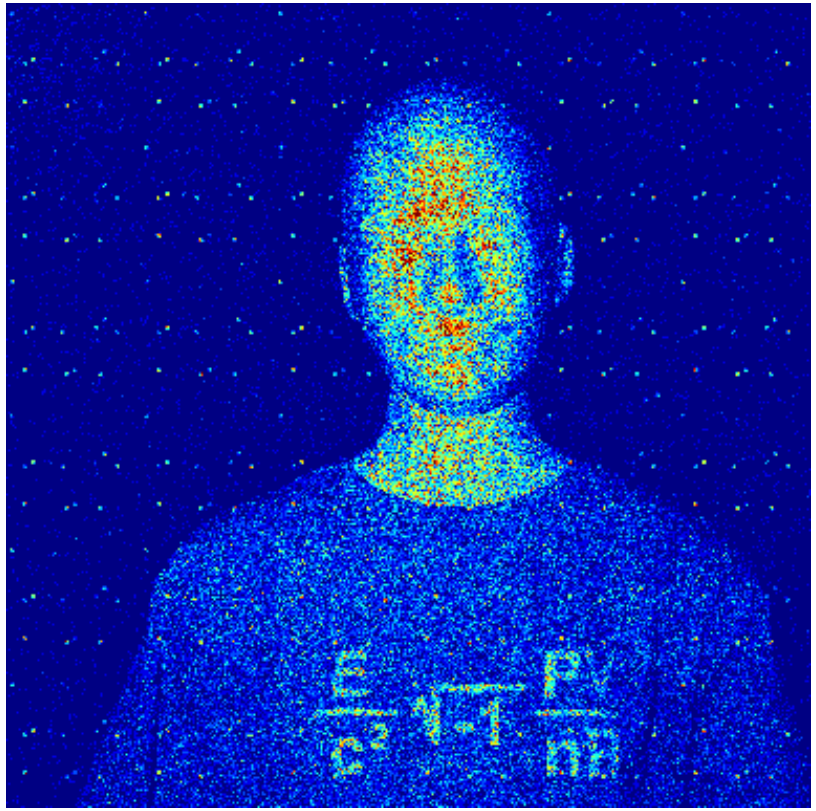
$$\downarrow$$

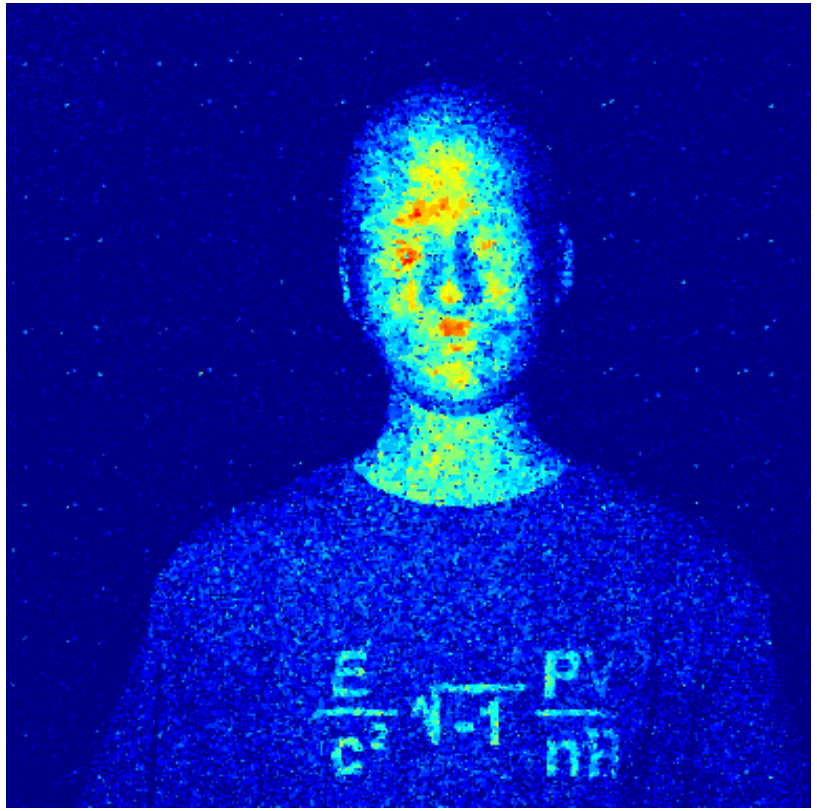
$$(Z(x,y)|\,\{t_\ell(x,y)|\ell \in U(x,y)\}) = -\sum_{\ell \in U(x,y)} \log\left[s(t_\ell(x,y) - \frac{2Z(x,y)}{c})\right]$$

Dongeek Shin, Ahmed Kirmani, Vivek K. Goyal, and Jeffrey H. Shapiro. arXiv/stat, 2014

Results: Reflectivity

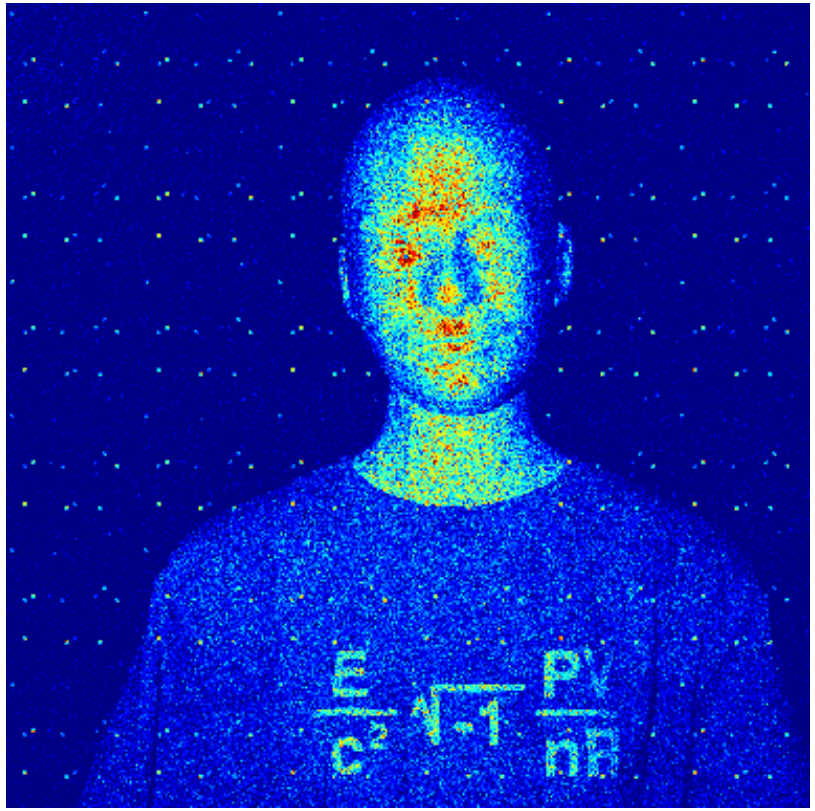
25 frames

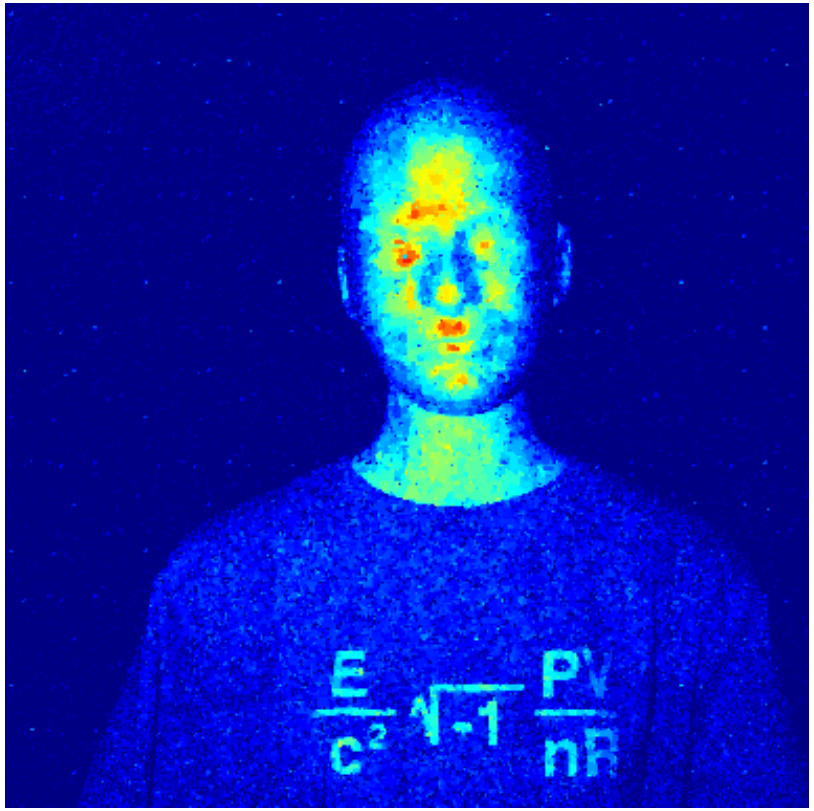




Results: Reflectivity

50 frames





Results: Reflectivity

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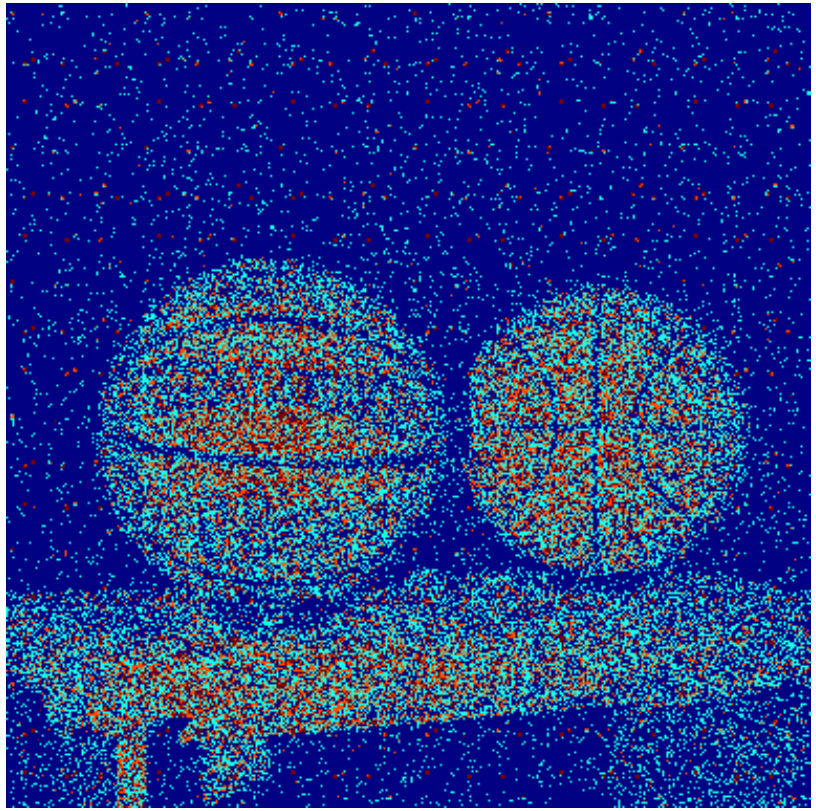

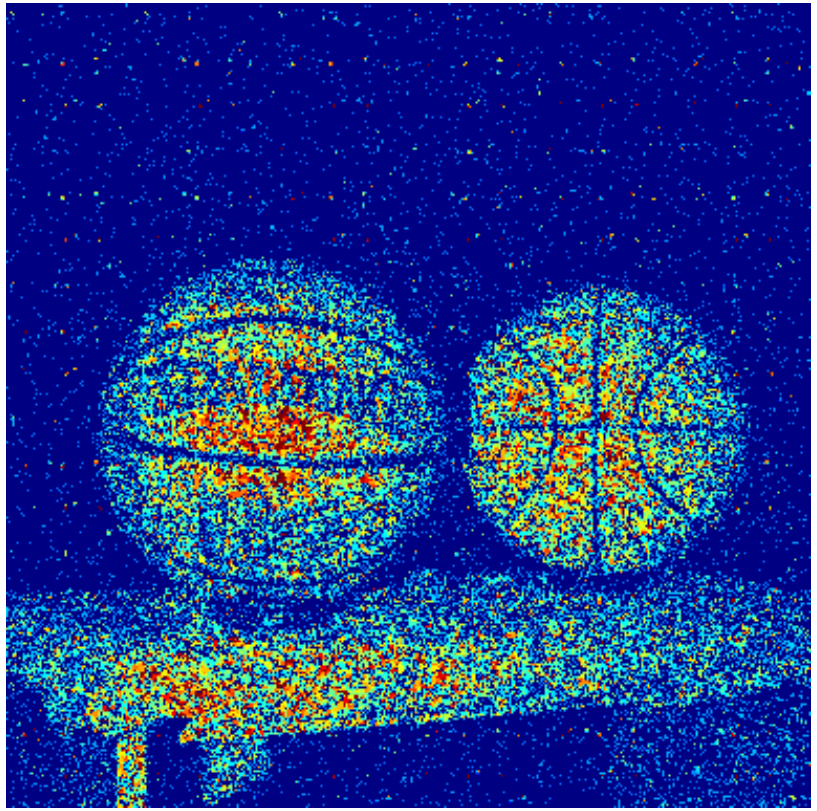

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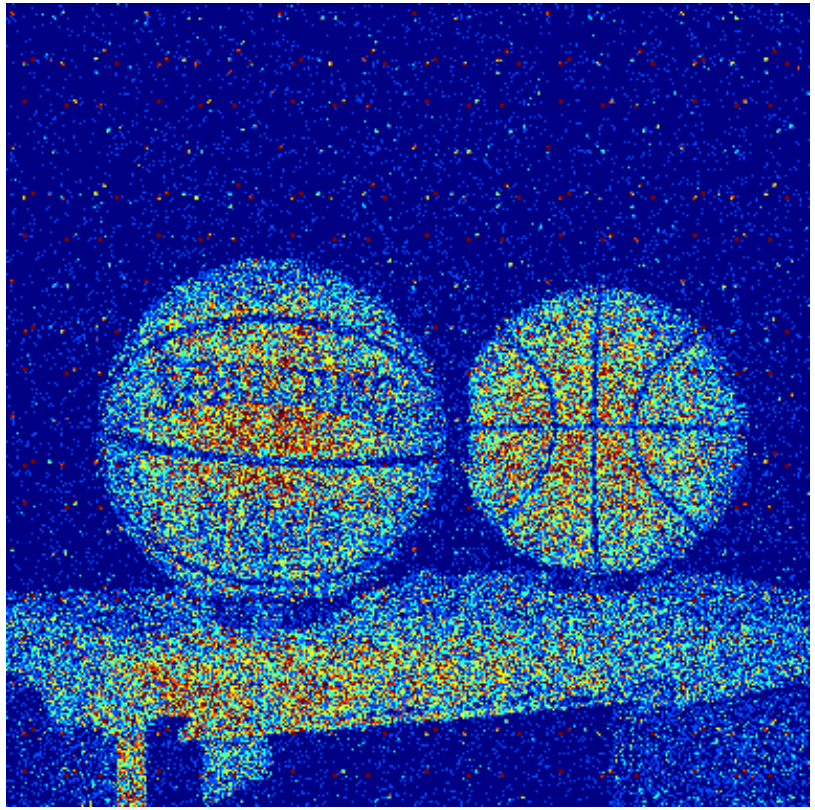

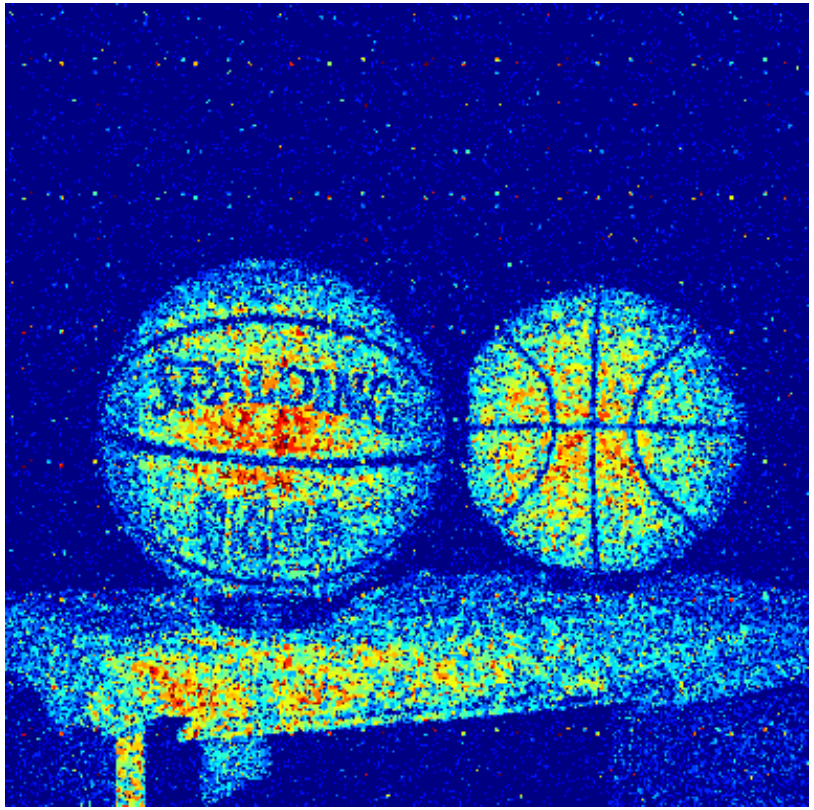

Results: Reflectivity

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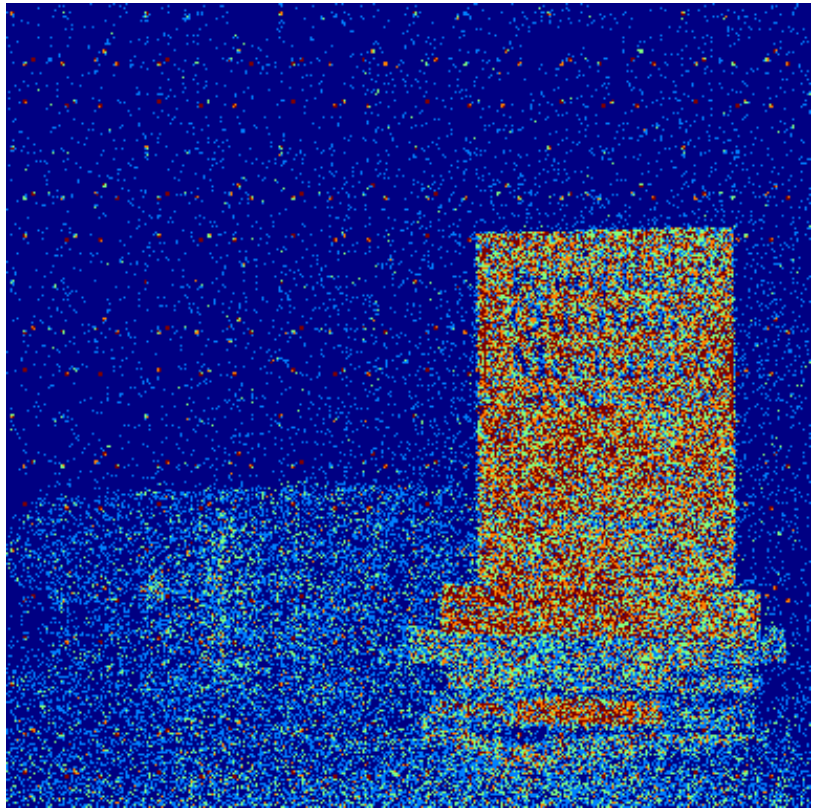

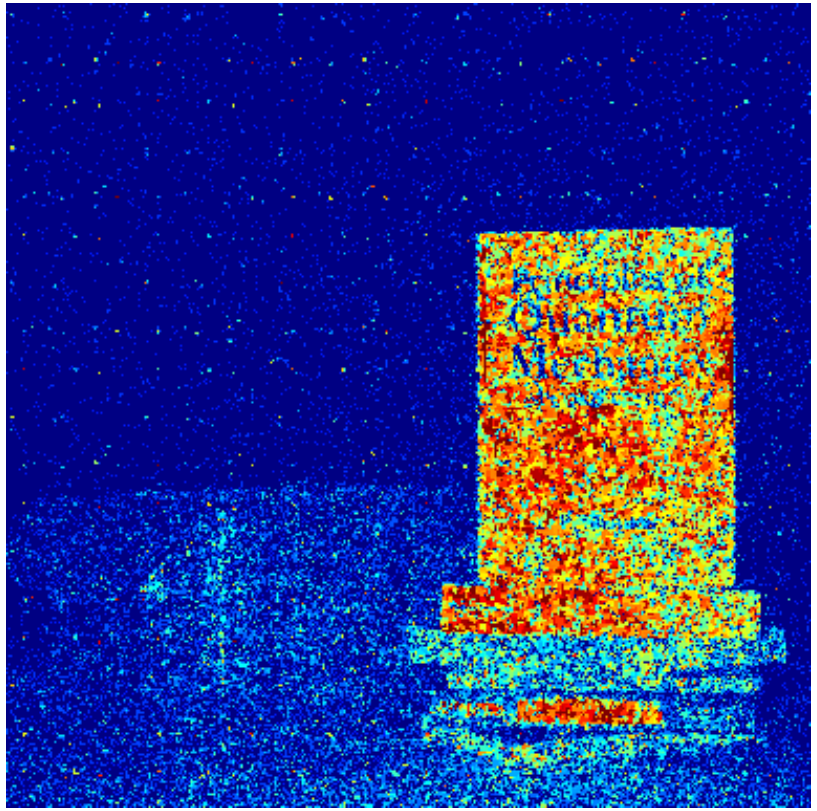

Results: Reflectivity

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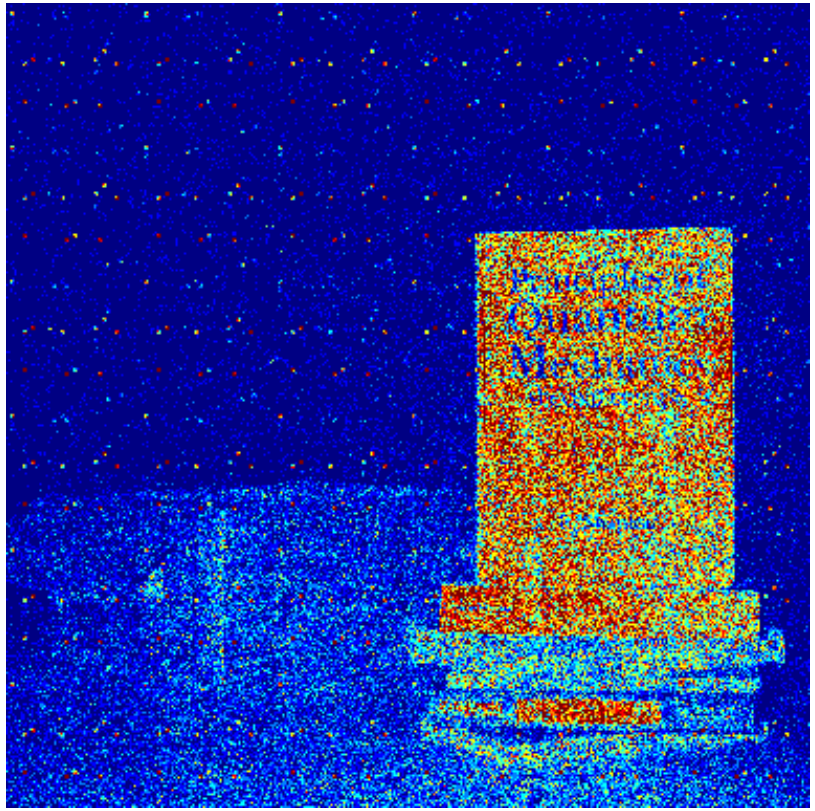
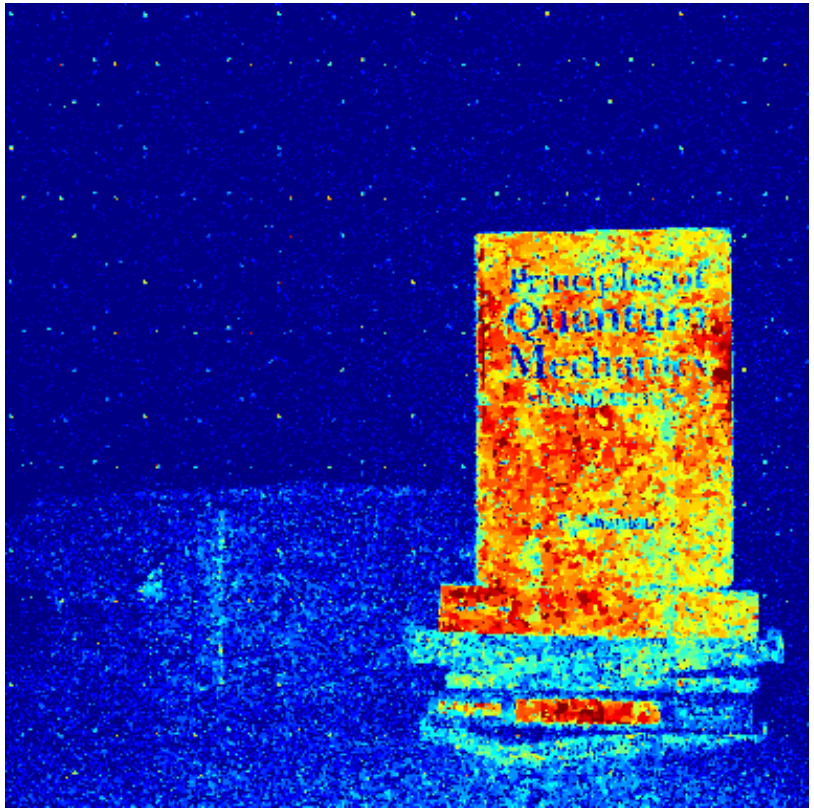




Results: Reflectivity

Results not as striking as first-photon imaging

» Fixed-dwell time severly impacts dynamic range

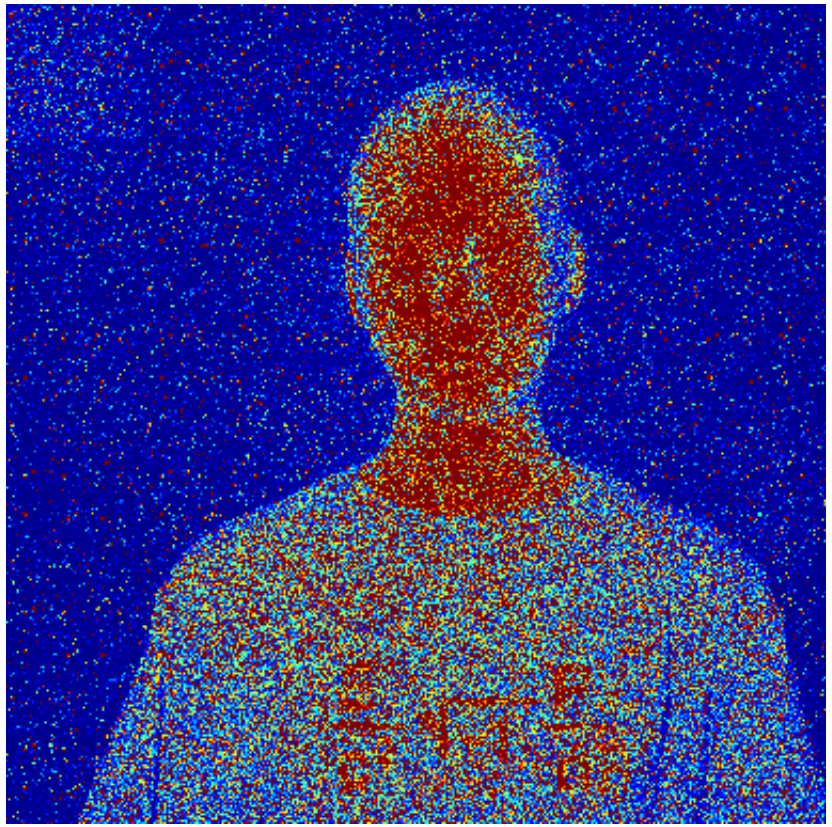
» Many pixels with no detection events

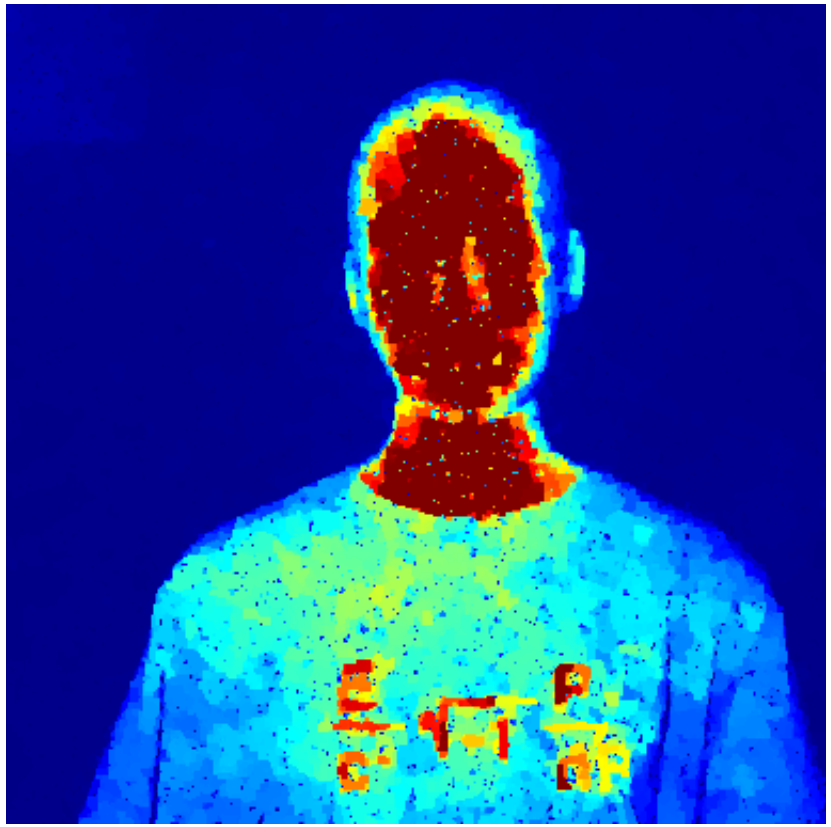
» Need global long dwell times to get any detections in dark regions

» Traditional averaging begins to work well for longer dwell times

Results: Reflectivity

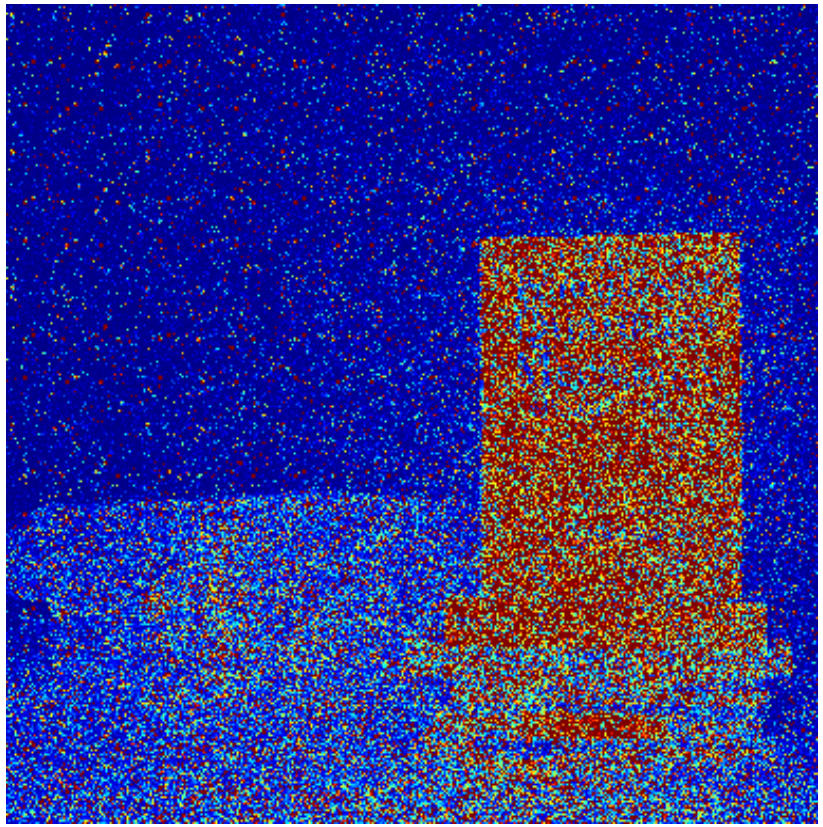
Simulated FPI

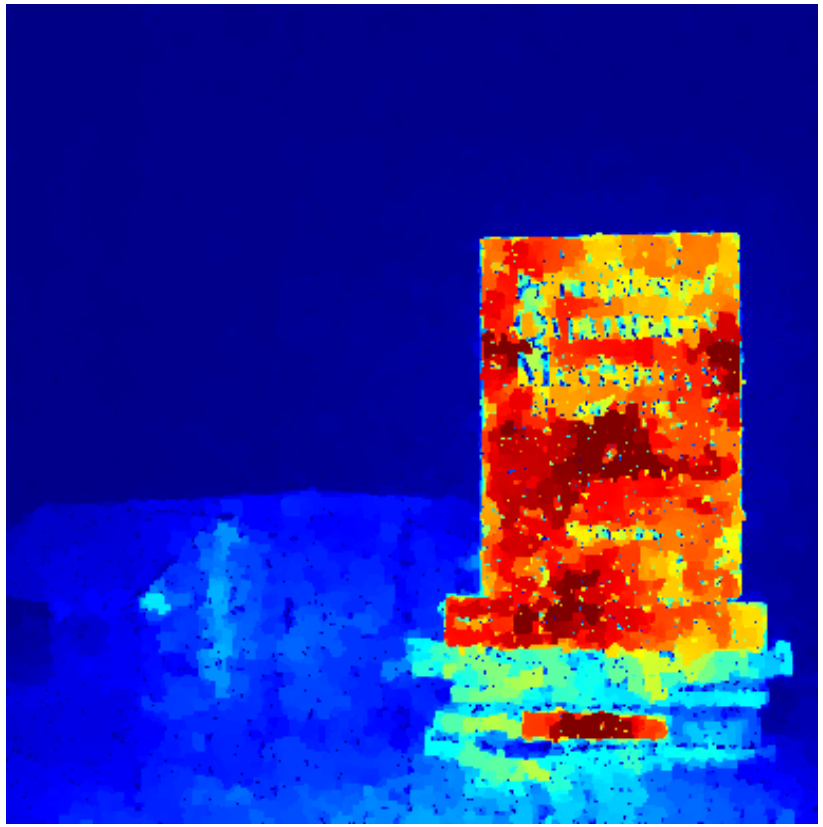




Results: Reflectivity

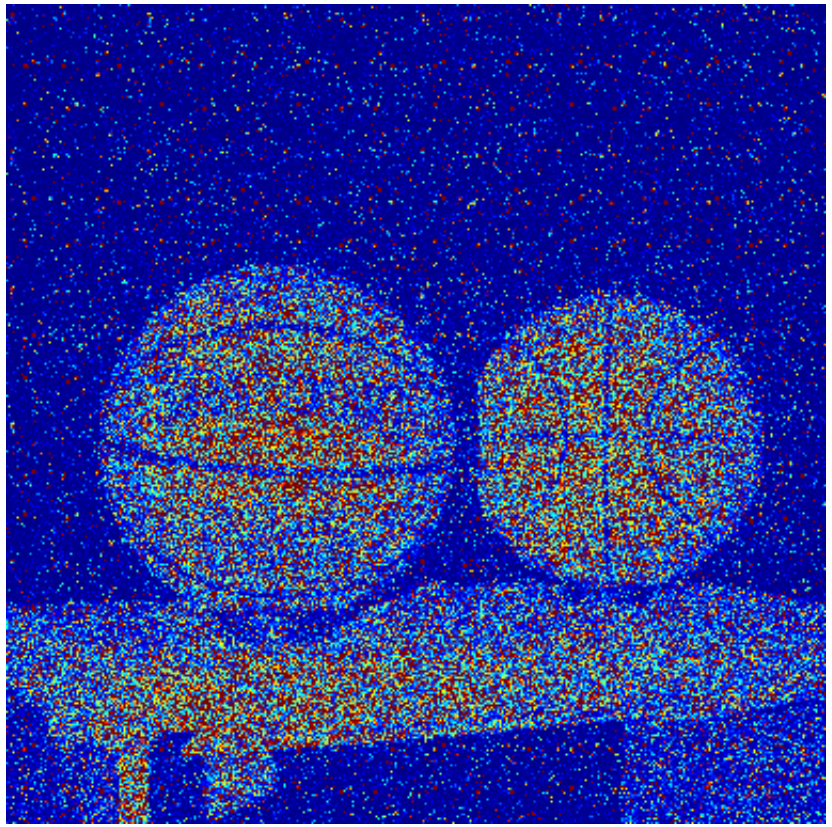
Simulated FPI





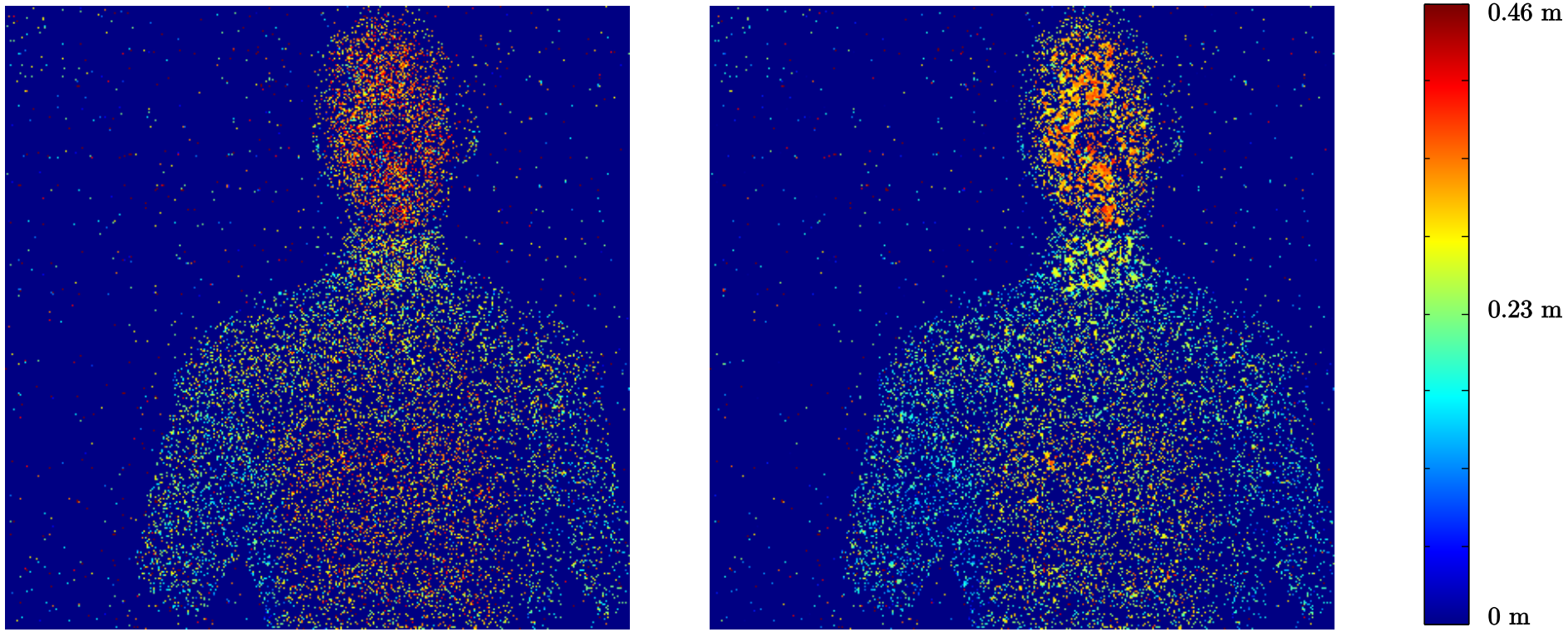
Results: Reflectivity

Simulated FPI



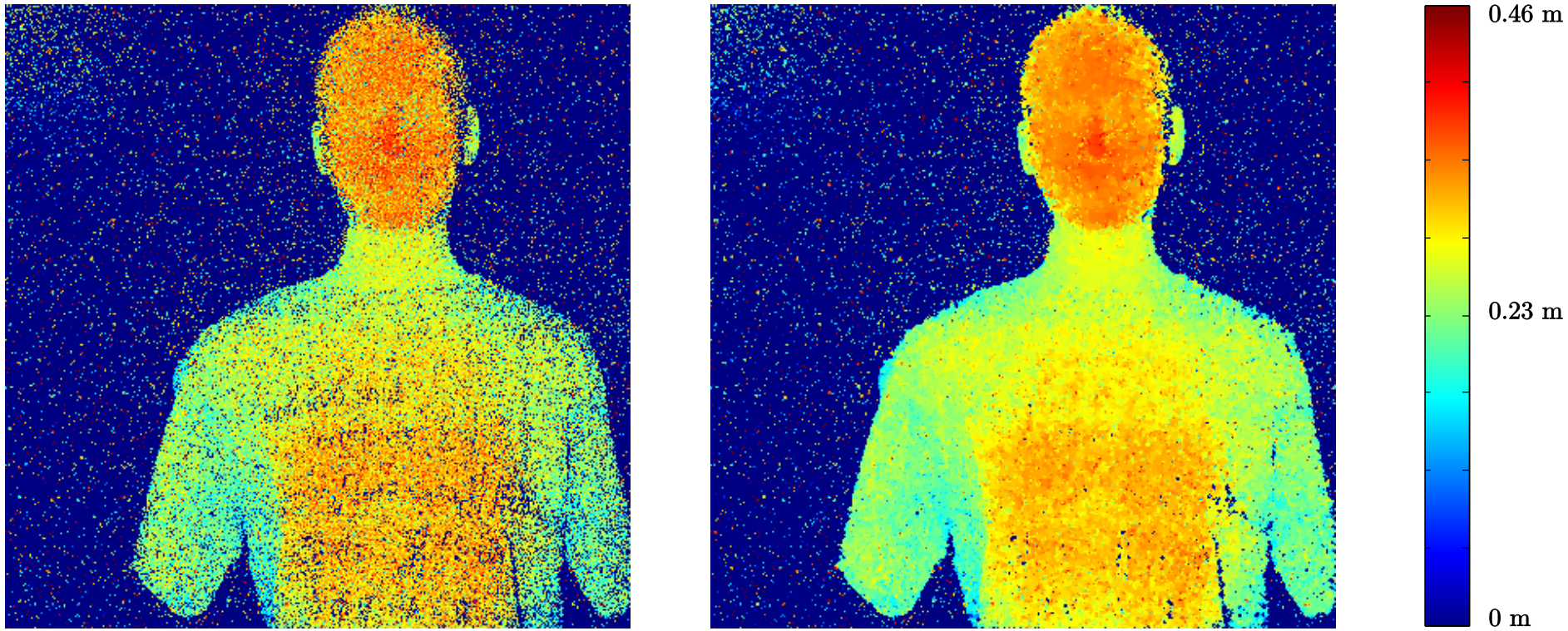
Results: Depth

25 frames



Results: Depth

400 frames



Results: Depth

Mismatch of laser pulse, object features, and time bin size

» FPI: time bin (8 ps) < features (~50 ps) < pulse width (226 ps)

» SPAD: time bin (389.9 ps) > pulse width (226 ps) > features (~50 ps)

Future experiments:

» Change illumination to 1-2 ns pulse width

» Change object to large, several-meter sized objects

» SPAD arrays with improved time resolution

Single-photon imaging conclusions

First-photon imaging

» Established collaboration with STIR group at MIT

» Used techniques similar to compressed sensing to acquire high-quality depth and reflectivity images using 1 photon per pixel

» Factor-of-100 speedup from traditional active imagers

» Factor-of-10 sub-pulse depth resolution

» 3-4 bit intensity resolution

Single-photon imaging conclusions

SPAD array imaging

» Established collaboration with Zappa group at PdM

» Adapted FPI algorithm to fixed dwell time case

» Acquired and processed initial set of data

» Reflectivity shows improvements but dynamic range limited

» Depth images need larger objects and/or a longer pulse to show improvements using algorithm

Acknowledgements

Advisors / Thesis committee

Franco N. C. Wong, Jeffrey H. Shapiro, Vivek K. Goyal

Collaborators

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Group members

Zheshen Zhang, Sara Mouradian, Murphy Niu, Valentina Schettini, Maria Tengner, Raúl García-Patrón, Veronika Stelmakh, Tian Zhong, Taehyun Kim, Onur Kuzucu, Saikat Guha, Nicholas Hardy, Baris Erkmen

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