Introduction to Single-Photon Avalanche Diodes

A New Type of Imager for Computer Vision

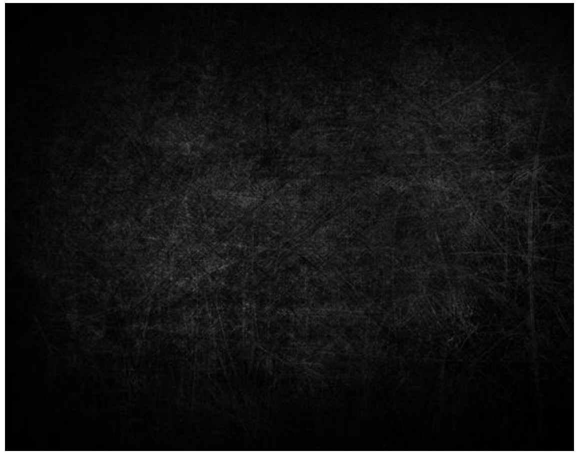
Sebastian Bauer
University of Wisconsin – Madison

Motivation

- Ultimately, computer vision algorithms are limited by the underlying data quality

Blurred motion

Low Light



Poor dynamic range

- Information is lost in the image acquisition process
- Result: loss in speed, quality, or even system failure

Can we do better in terms of image acquisition?

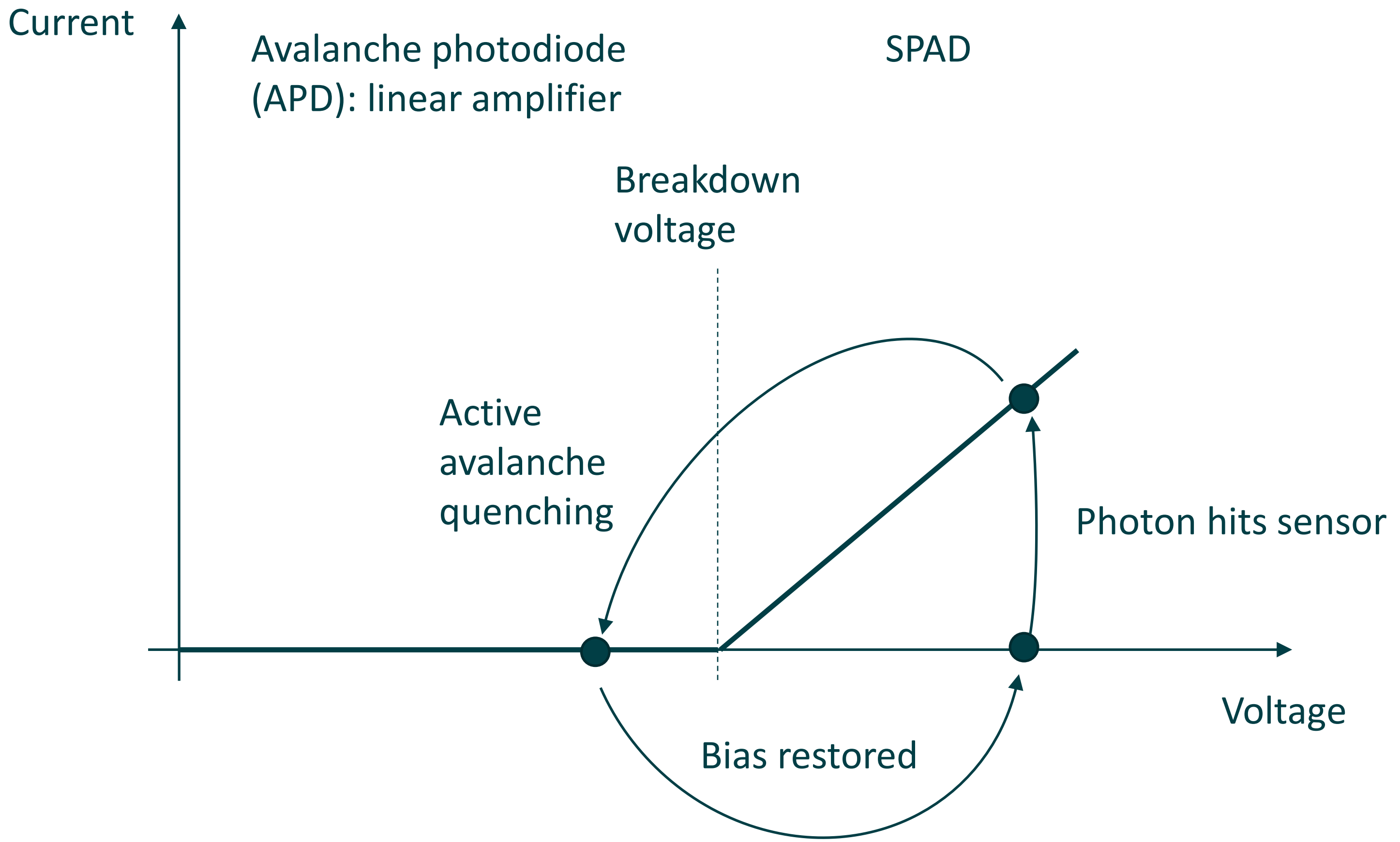
Of course!

- High speed cameras, high dynamic range cameras, single photon sensitive cameras, event cameras, …

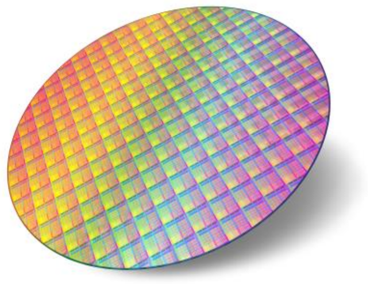
- But #1: all camera types usually only good in what they are designed for
- But #2: high cost

Single-Photon Avalanche Diodes (SPADs)

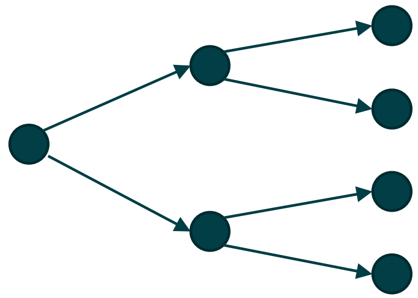
- Semiconductor p-n junction reverse biased above breakdown voltage



Single-Photon Avalanche Diodes (SPADs)



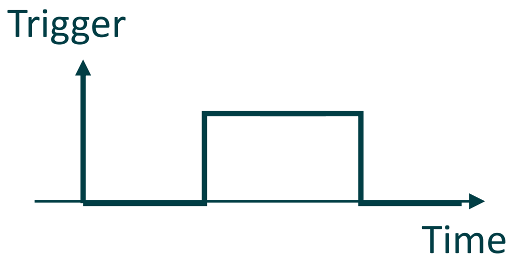
Silicon CMOS



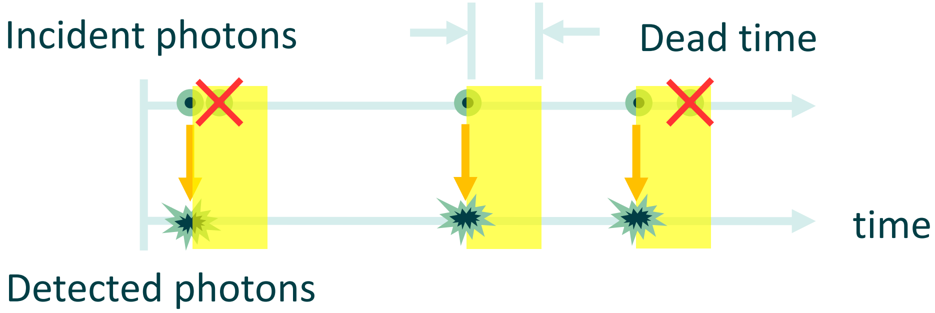
Single photon sensitive: electron avalanche

Extreme time resolution (30 … 50 ps)

Low dark count rate

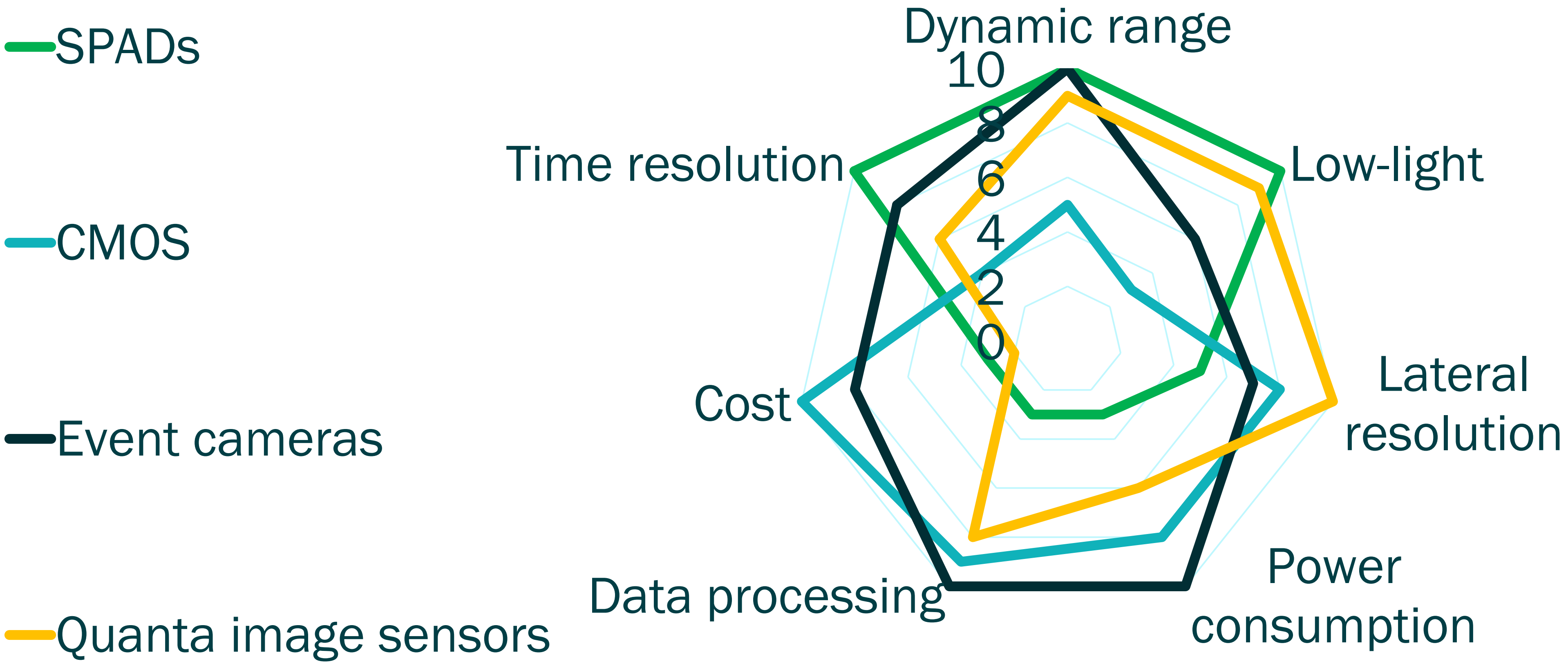


Some models: gateable



1…100 ns dead time

SPADs and other Novel Sensors

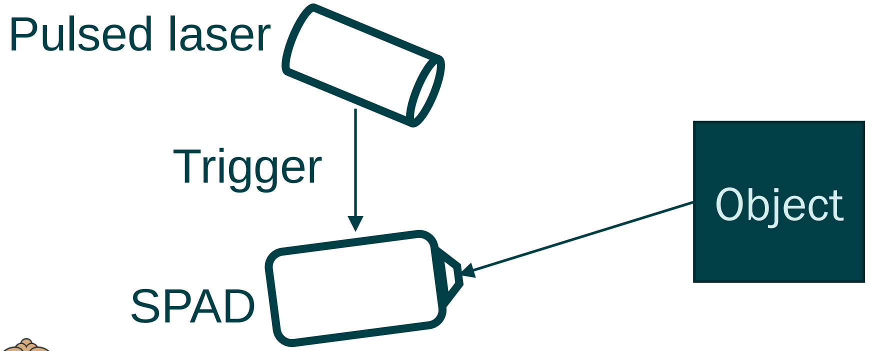


Note: this comparison is to be understood quantitatively. Even within each sensor type, there are different models with different parameters. Most importantly, SPADs, event cameras and quanta image sensors still are rather young technology, so there's still a lot of research going on, and the numbers are volatile

Single-Photon Avalanche Diodes (SPADs)

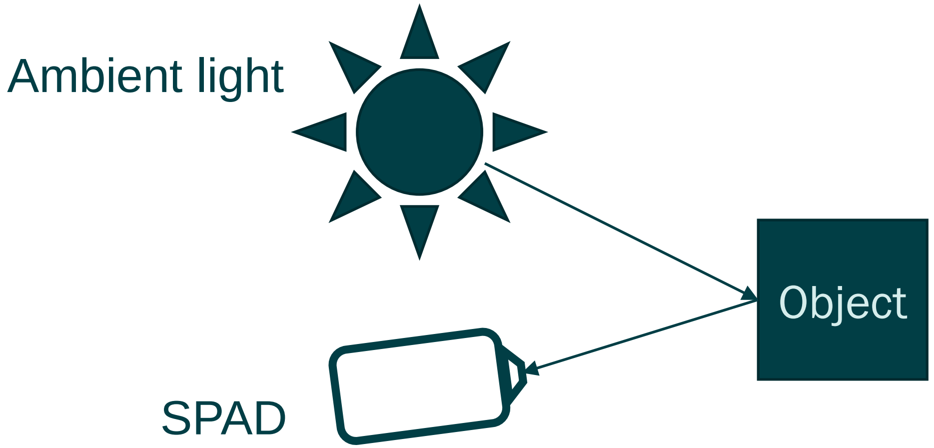
Active imaging with laser illumination

- Fluorescence lifetime imaging
- 3D imaging (LiDAR)
- Seeing around corners
- Seeing through fog

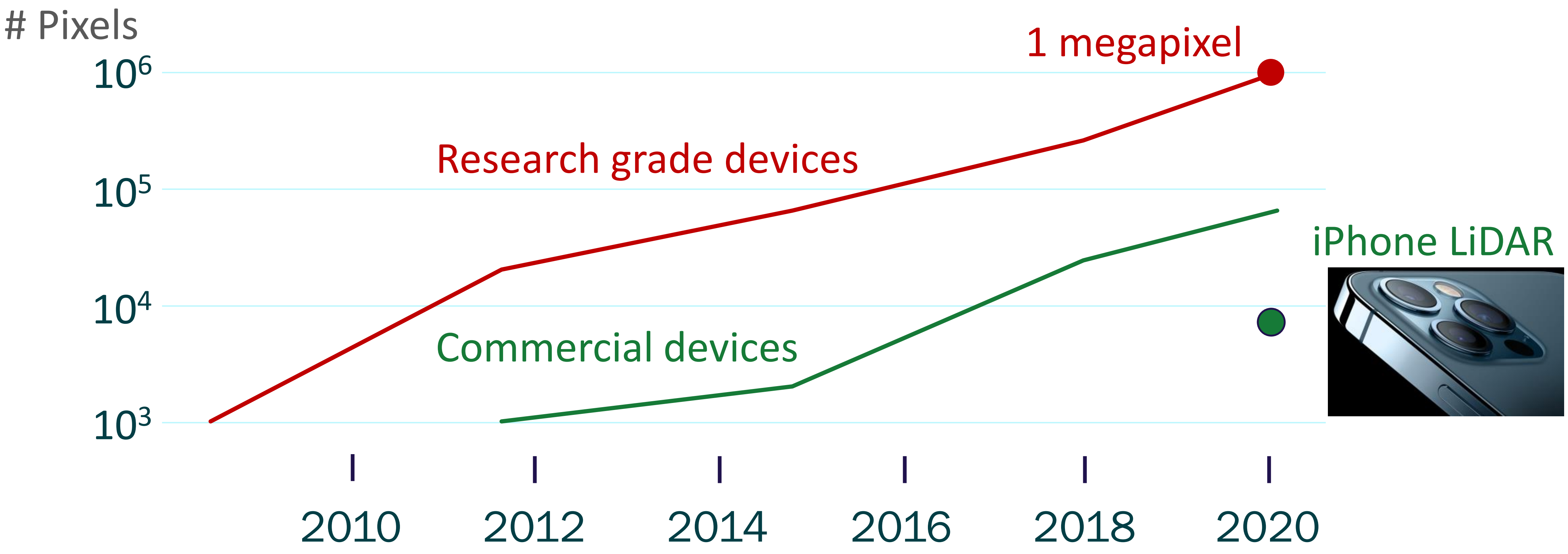


Passive imaging

- Extreme dynamic range
- Imaging of moving objects with minimal blur



SPAD Evolution



Data source: https://imagesensors.org/Past%20Workshops/2020%20ISSW/KazuhiroMorimoto.pdf

SPAD LiDAR

- Automotive LiDAR: SPADs are major cost reduction factor: digital or solid-state LiDAR without moving parts
- Apple: convincing AR user experience not achievable with cameras alone

https://www.ifixit.com/News/45482/how-lidar-works-and-why-its-in-the-iphone-12-pro

Challenges

- High resolution sensors not yet available
- Sensor data rate
- Data processing effort
- Power consumption
- Cost
- Color imaging not yet available

Challenges

- Array sensors: readout electronics eat a lot of space → 3D stacking

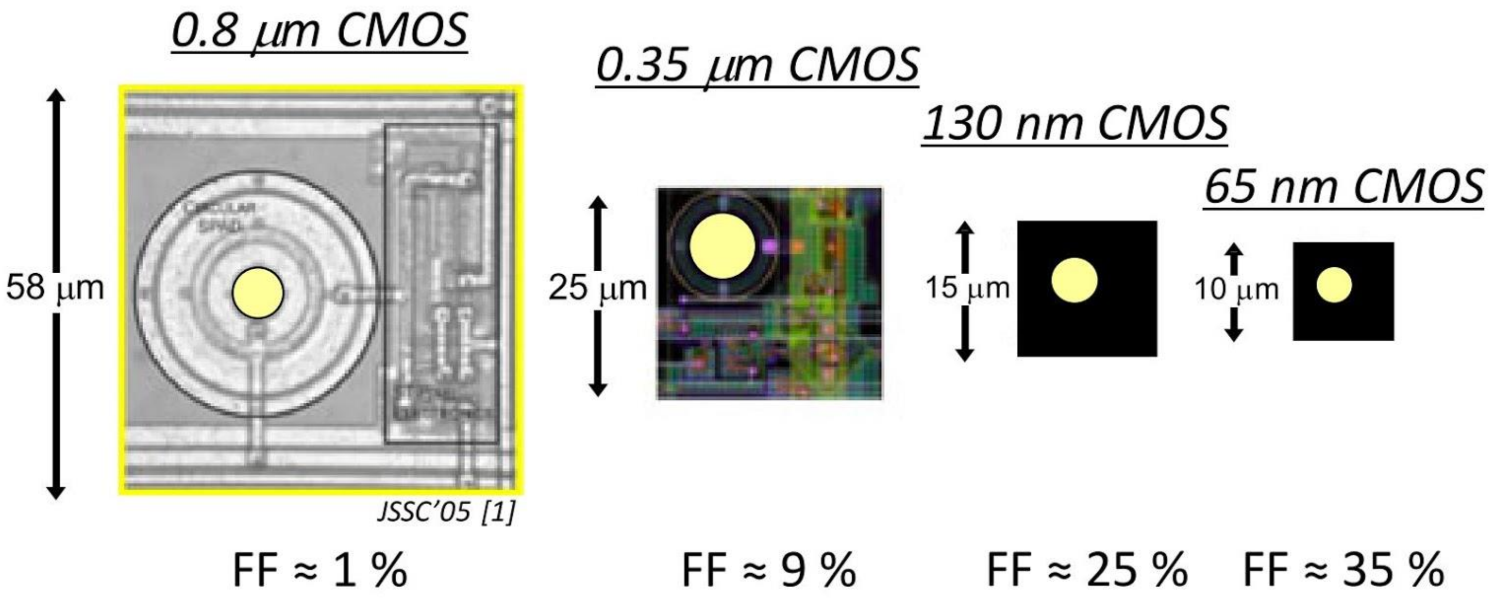


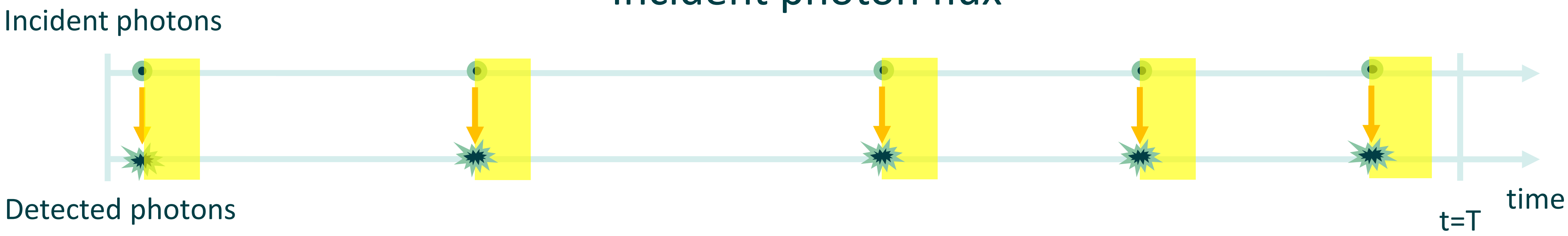
Fig. 1. Examples of SPAD's fill factor increases according to the technology node shrinking. The yellow circles represent the SPADs' active areas.

http://image-sensors-world.blogspot.com/2018/11/3d-stacked-spad-array.html

Extreme Dynamic Range

Extreme Dynamic Range

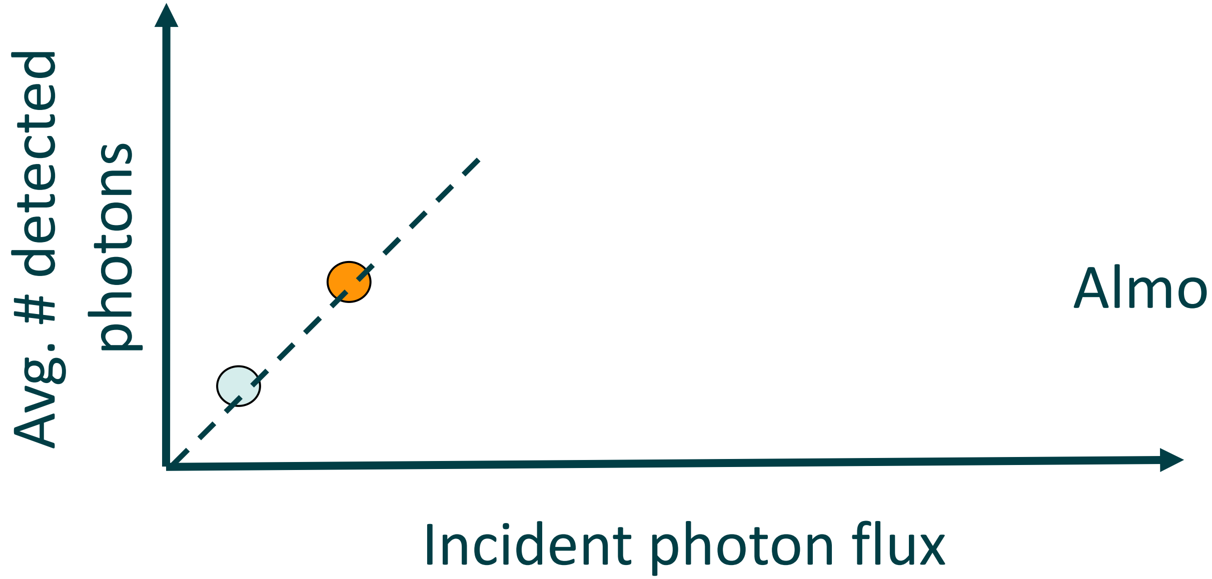
- Low flux



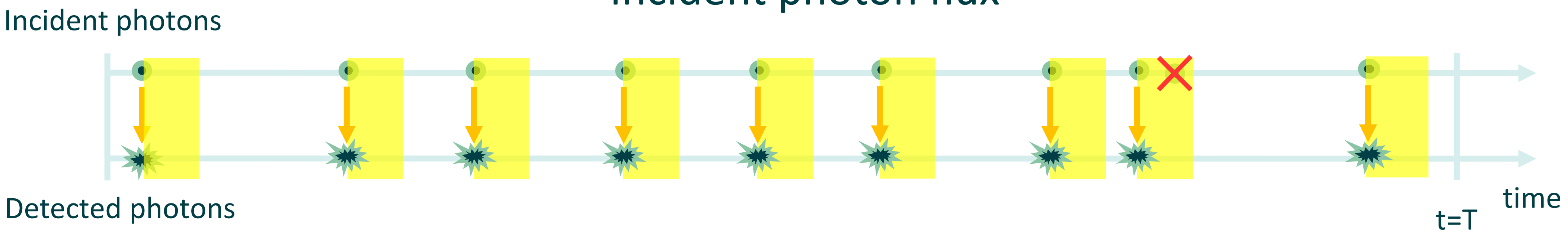
Ingle, Atul, Andreas Velten, and Mohit Gupta. "High flux passive imaging with single-photon sensors." *Proceedings CVPR*. 2019.

Extreme Dynamic Range

- Low flux



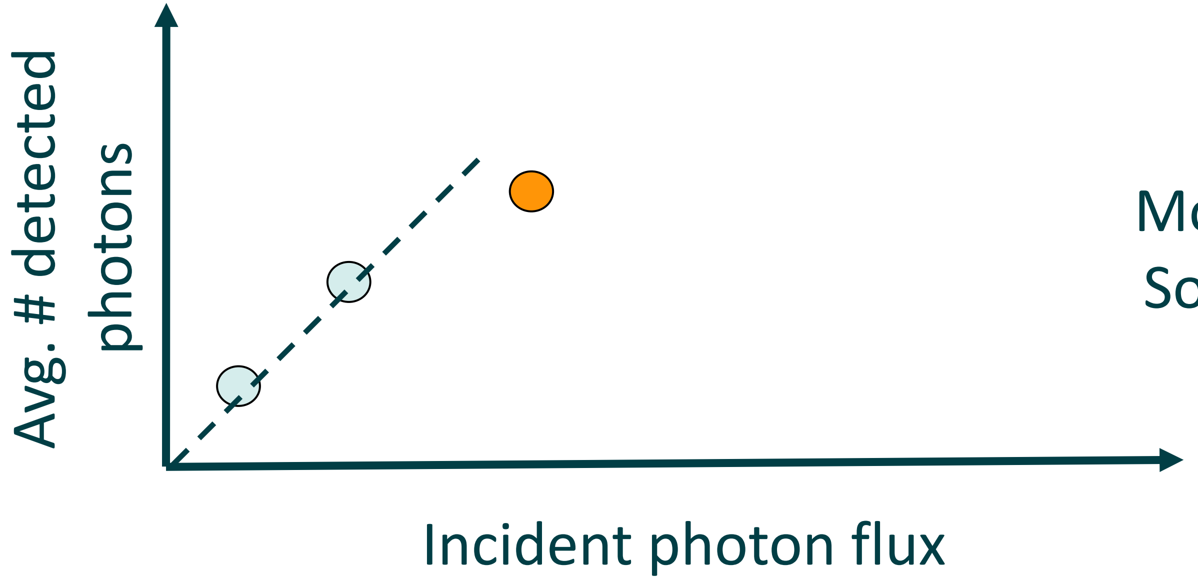
Low photon flux:
Almost all photons counted



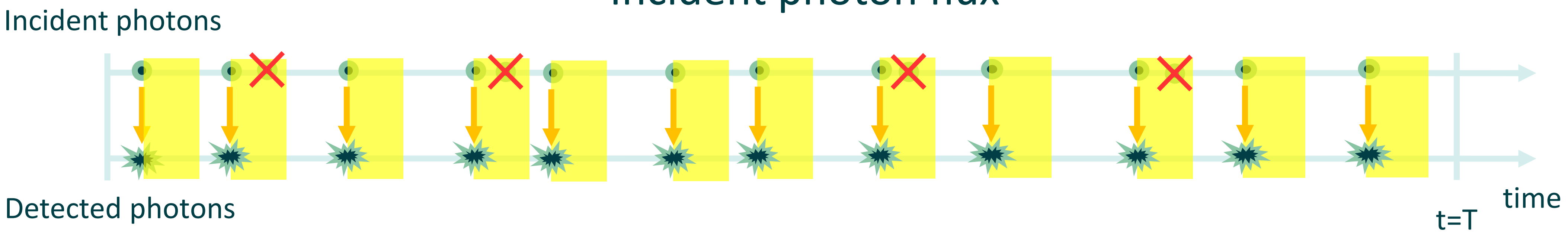
Ingle, Atul, Andreas Velten, and Mohit Gupta. "High flux passive imaging with single-photon sensors." *Proceedings CVPR*. 2019.

Extreme Dynamic Range

- Moderate flux



Moderate photon flux:
Some photons missed

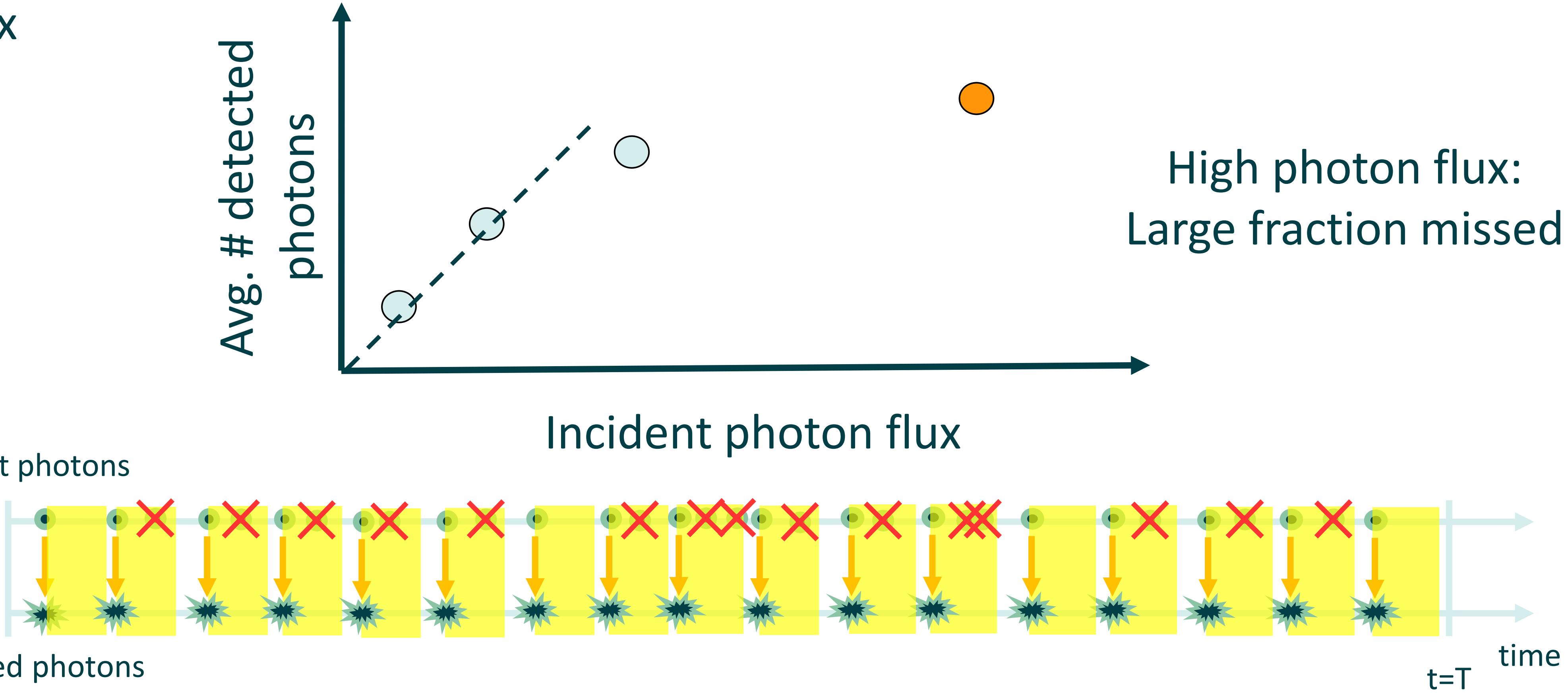


Ingle, Atul, Andreas Velten, and Mohit Gupta. "High flux passive imaging with single-photon sensors." *Proceedings CVPR*. 2019.

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

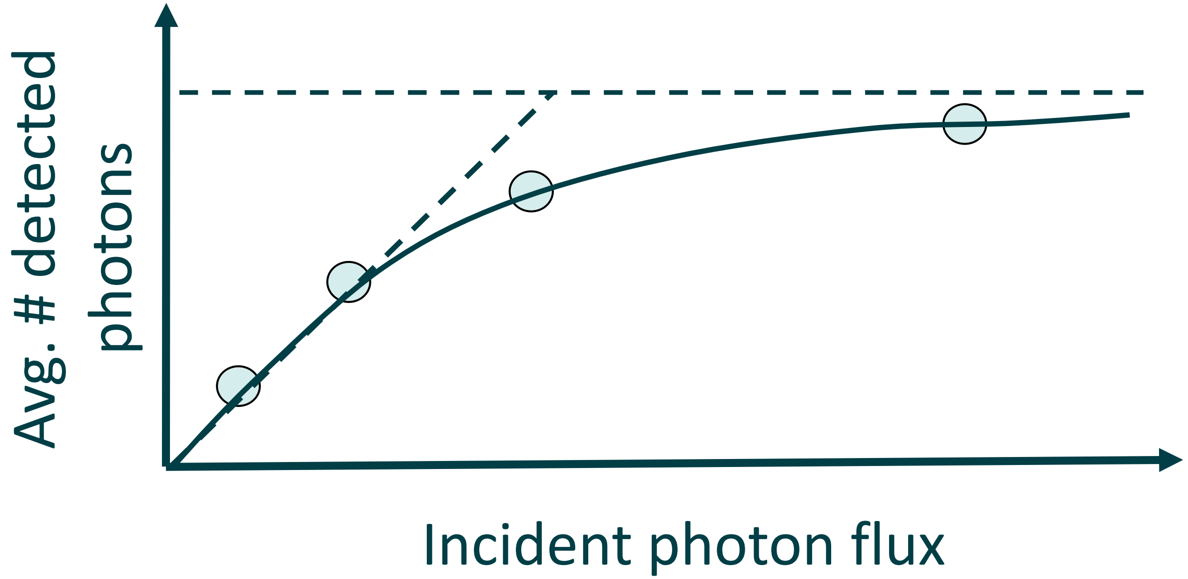
Extreme Dynamic Range

- High flux



Ingle, Atul, Andreas Velten, and Mohit Gupta. "High flux passive imaging with single-photon sensors." *Proceedings CVPR*. 2019.

Extreme Dynamic Range

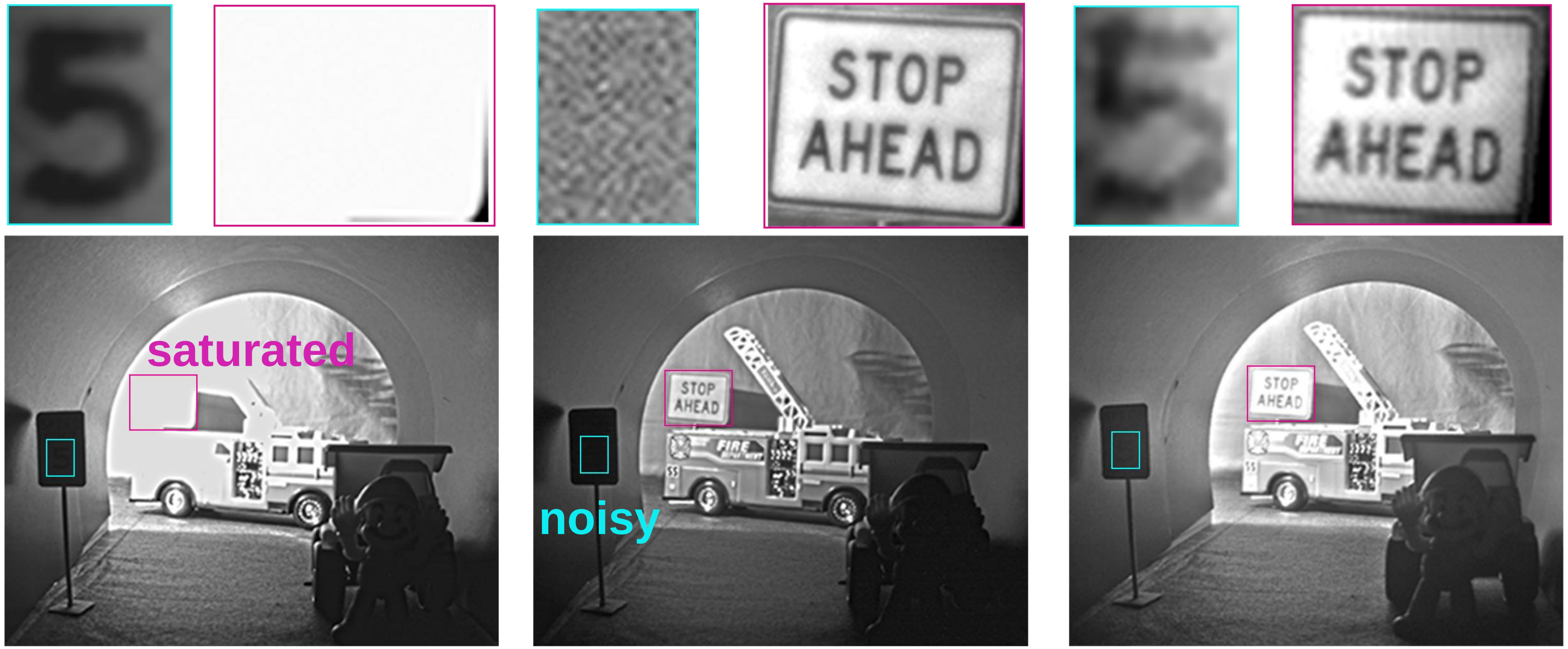


No saturation, invertible

Ingle, Atul, Andreas Velten, and Mohit Gupta. "High flux passive imaging with single-photon sensors." *Proceedings CVPR*. 2019.

Extreme Dynamic Range

Conventional sensor		SPAD
Long exposure	Short exposure	Single exposure



+2 orders of magnitude dynamic range compared to conventional CMOS cameras

Ingle, Atul, Andreas Velten, and Mohit Gupta. "High flux passive imaging with single-photon sensors." *Proceedings CVPR*. 2019.

Extreme Dynamic Range

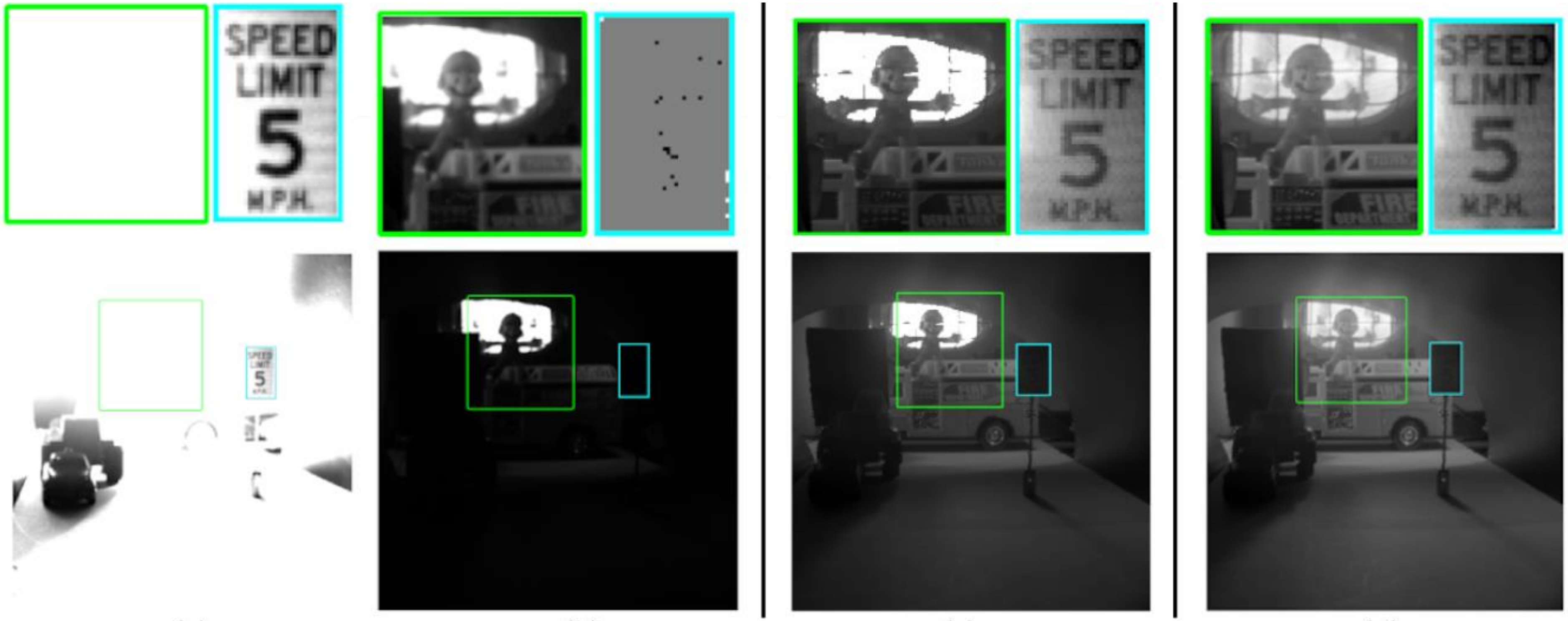
- Experiments done by point-scanning with single-pixel SPAD
- Quantization of counts limits dynamic range
- Further improvement: incorporating timing information between photons

- Additional 2 orders of magnitude dynamic range (~7 in total)
- Point-scanning with adapted single-pixel SPAD for stable dead time

Ingle, A., Seets, T., Buttafava, M., Gupta, S., Tosi, A., Gupta, M., & Velten, A. (2021). Passive Inter-Photon Imaging. *arXiv preprint arXiv:2104.00059*

Extreme Dynamic Range

Conventional sensor		SPAD, counting	SPAD, timing
T=5 ms	T=0.005 ms	T=5 ms	T=5 ms



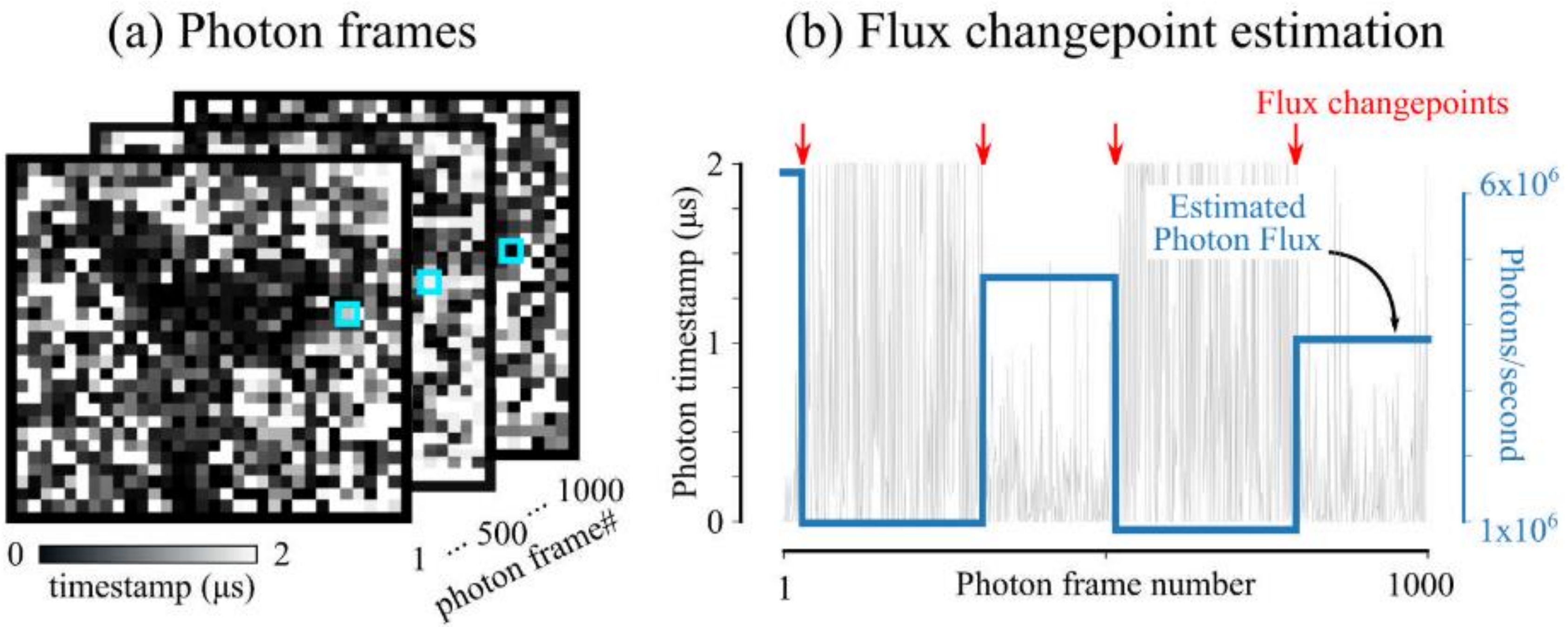
(a) (b) (c) (d)

Ingle, A., Seets, T., Buttafava, M., Gupta, S., Tosi, A., Gupta, M., & Velten, A. (2021). Passive Inter-Photon Imaging. *arXiv preprint arXiv:2104.00059*

Minimal Blur Imaging

Minimal Blur Imaging

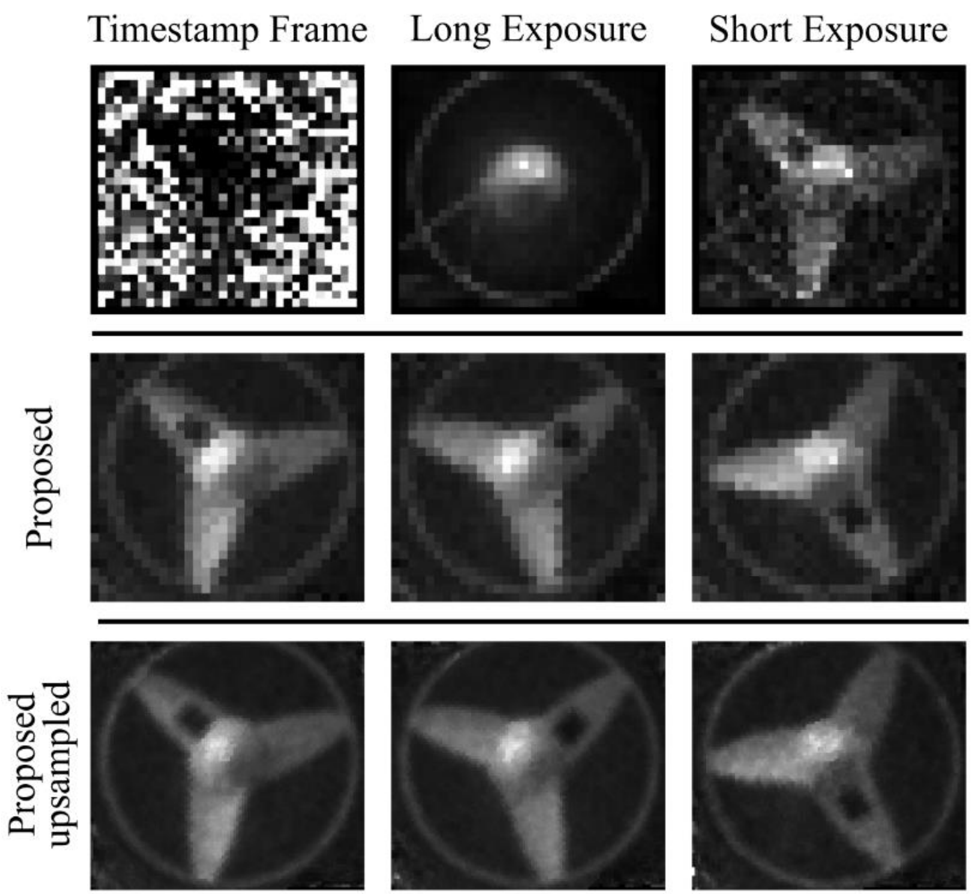
- In each time frame, at most one photon arrival time stamp

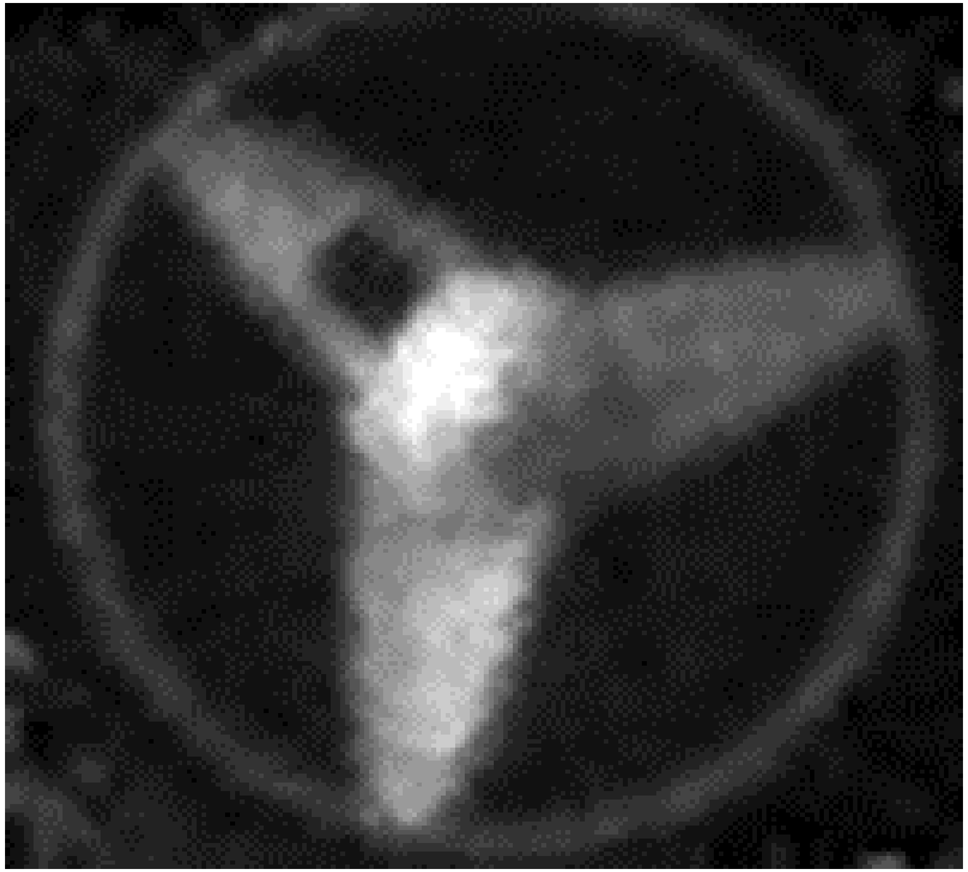


- These experiments: 32 x 32 pixels InGaAs SPAD array, 2 μs frame duration

Seets, T., Ingle, A., Laurenzis, M., & Velten, A. (2021). Motion Adaptive Deblurring with Single-Photon Cameras. *Proceedings IEEE/CVF WACV* (pp. 1945-1954)

Minimal Blur Imaging

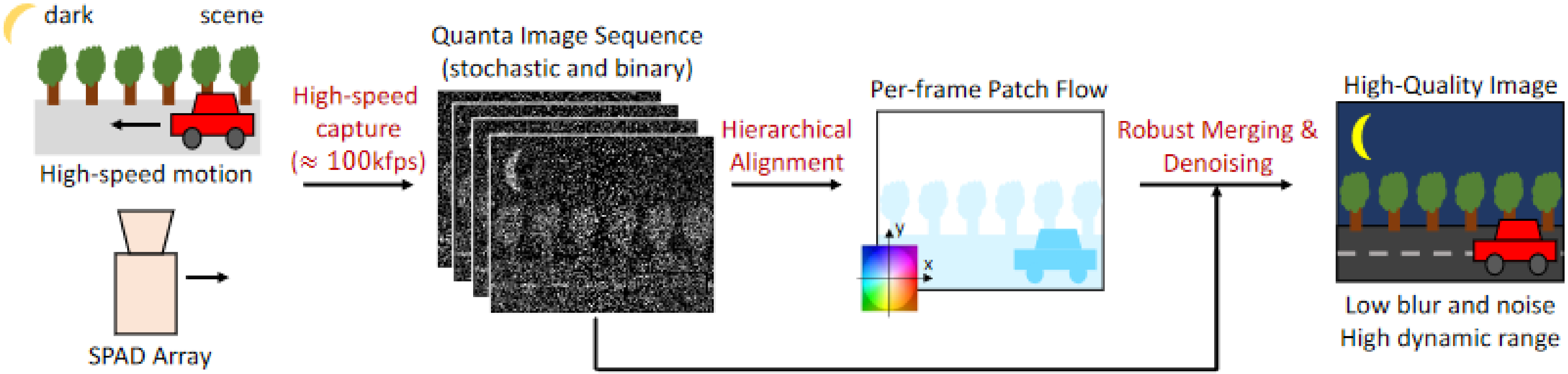




Seets, T., Ingle, A., Laurenzis, M., & Velten, A. (2021). Motion Adaptive Deblurring with Single-Photon Cameras. *Proceedings IEEE/CVF WACV* (pp. 1945-1954)

Quanta Burst Photography

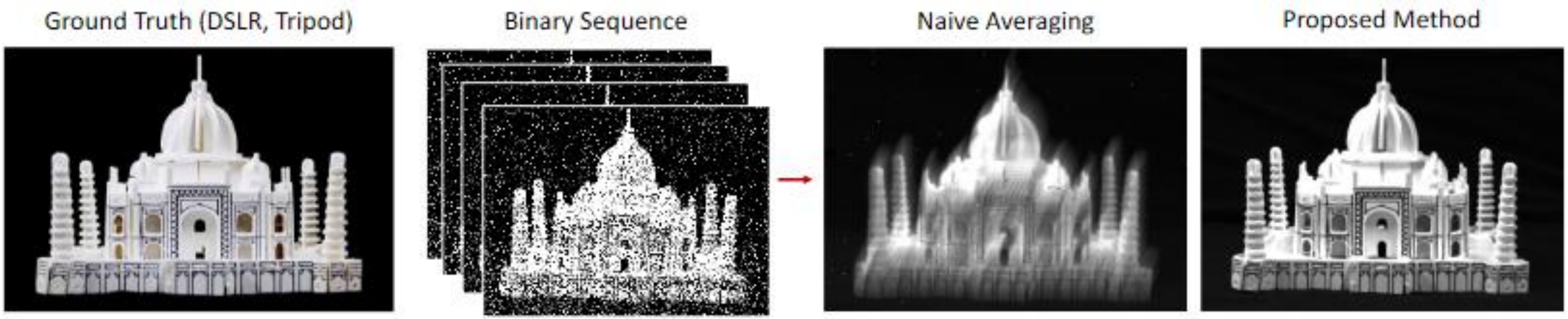
- Similar approach. This time: 512 x 256 pixels Si array, ~100 kHz frame rate



Ma, S., Gupta, S., Ulku, A. C., Bruschini, C., Charbon, E., & Gupta, M. (2020). Quanta burst photography. *ACM Transactions on Graphics (TOG)*, *39*(4), 79-1.

Quanta Burst Photography

- Similar approach. This time: 512 x 256 pixels Si array, ~100 kHz frame rate



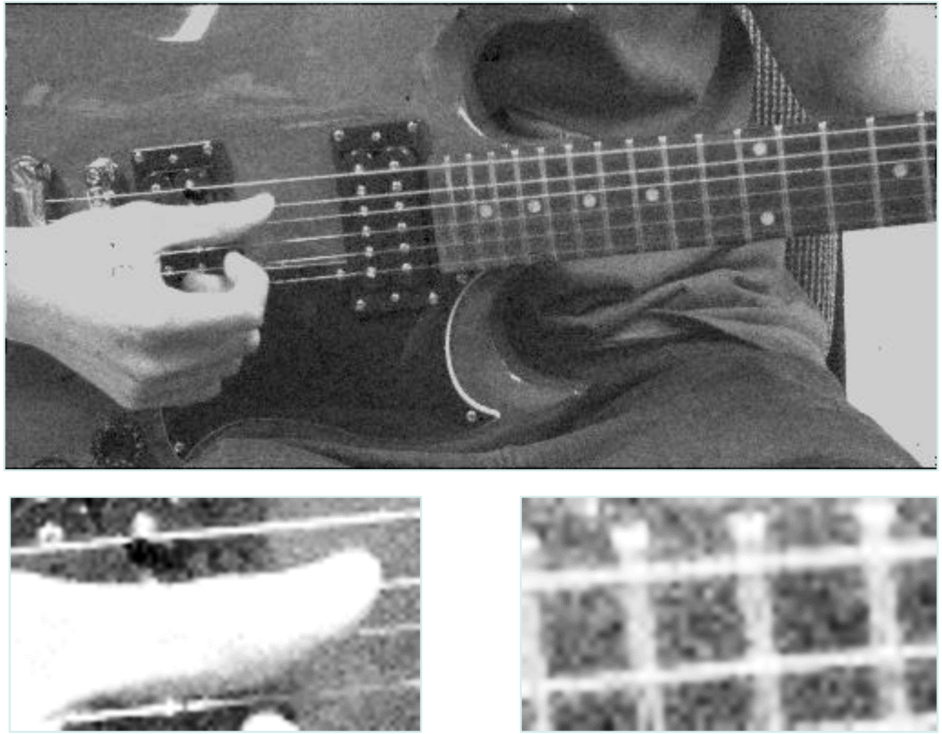
Ma, S., Gupta, S., Ulku, A. C., Bruschini, C., Charbon, E., & Gupta, M. (2020). Quanta burst photography. *ACM Transactions on Graphics (TOG)*, *39*(4), 79-1.

Quanta Burst Photography

- Non-rigid scene motion

Naive Averaging (Long Sequence)

Naive Averaging (Short Sequence)



Ma, S., Gupta, S., Ulku, A. C., Bruschini, C., Charbon, E., & Gupta, M. (2020). Quanta burst photography. *ACM Transactions on Graphics (TOG)*, *39*(4), 79-1.

Quanta Burst Photography

- Non-rigid scene motion: Align & merge video reconstruction

Ma, S., Gupta, S., Ulku, A. C., Bruschini, C., Charbon, E., & Gupta, M. (2020). Quanta burst photography. *ACM Transactions on Graphics (TOG)*, *39*(4), 79-1.

Summary

- SPADs are highly versatile sensors
- Single-photon capability and high time resolution allow for almost motion-blur free imaging in dark environments
- With active illumination: LiDAR and seeing around corners
- Plethora of future applications possible: industrial inspection cameras, automotive vision, night vision,…

- Different methods need different SPAD parameters/capabilities
- Power consumption and data processing effort are most critical problems
- High-resolution arrays not yet commercially available

Resources

More than happy to discuss, shoot me an email: sbauer8@wisc.edu

SPAD operating principle: http://www.everyphotoncounts.com/spad.php

Apple LiDAR: https://www.apple.com/augmented-reality/, https://ouster.com/blog/why-apple-chose-digital-lidar/, https://www.ifixit.com/News/45482/how-lidar-works-and-why-its-in-the-iphone-12-pro

UW-Madison WISION lab https://wisionlab.cs.wisc.edu/

UW-Madison Computational Optics Group https://biostat.wisc.edu/~compoptics/

EPFL Aqua Lab (SPAD hardware) https://www.epfl.ch/labs/aqua/

PoLiMi SPADlab (hardware) http://www.everyphotoncounts.com/