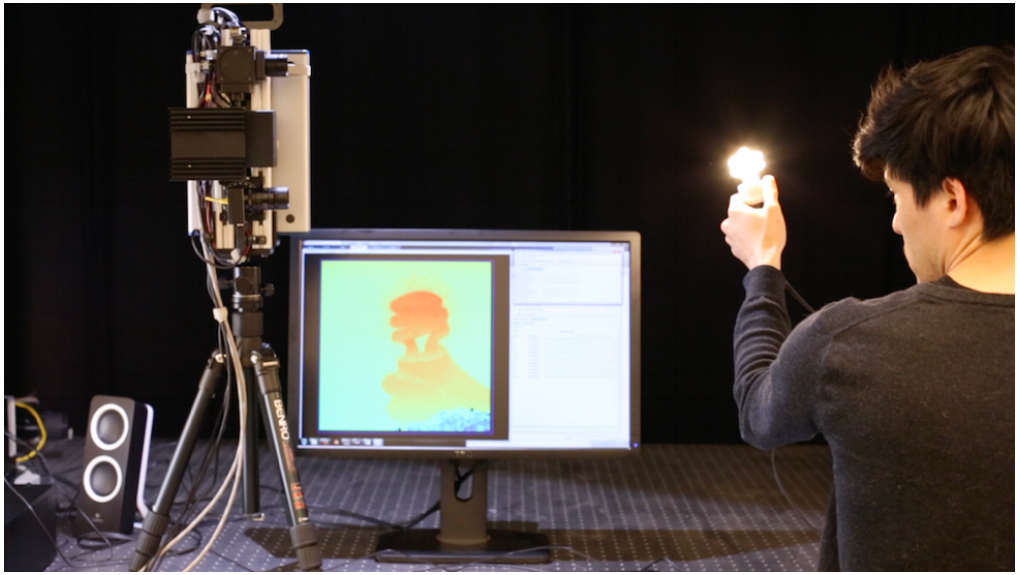
Hardware and Algorithm Co-design with Event Sensors



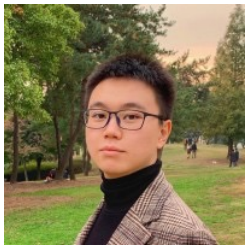
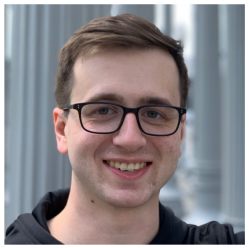
comp photo lab

iVPL

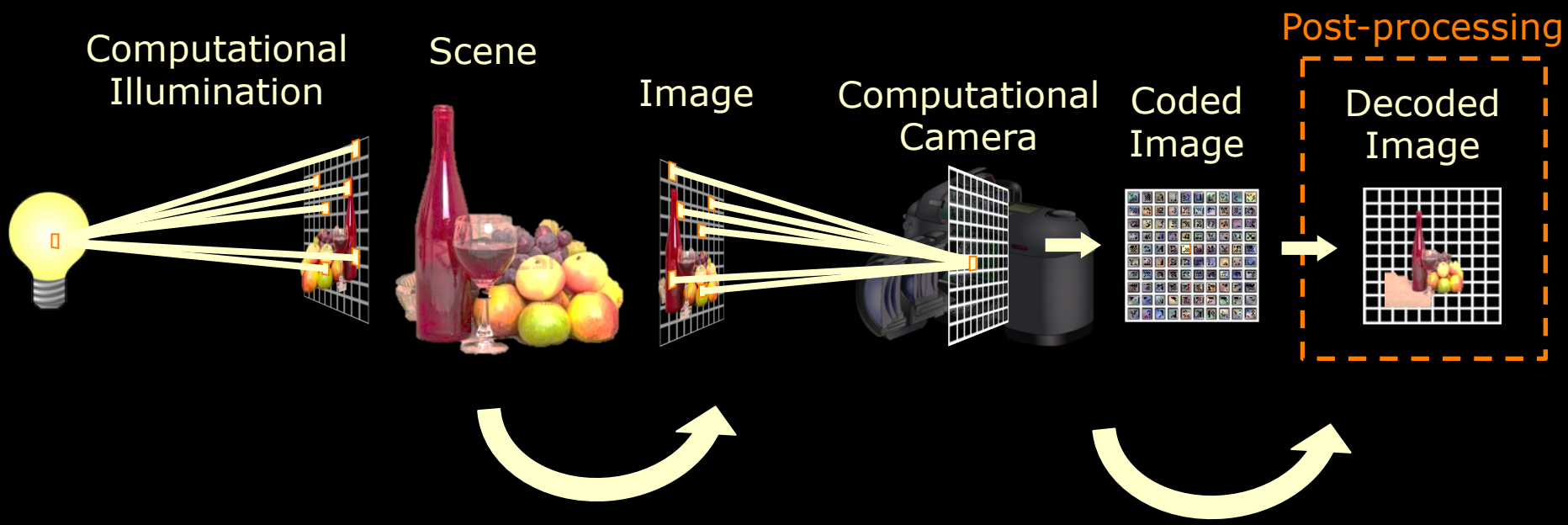
Oliver Cossairt
Associate Professor
ECE/CS Departments
Northwestern University

Aknowledgements

- Nathan Matsuda (NU, FRL)
- Zihao (Winston) Wang (NU, Apple)
- Srutarshi Banerjee (NU)
- Henry Chopp (NU)
- Peng Kang (NU)
- Many others…


Computational Imaging: Hardware Software Co-design



Coded Image | Coding Function | Noise

$$y = A(x) + n$$

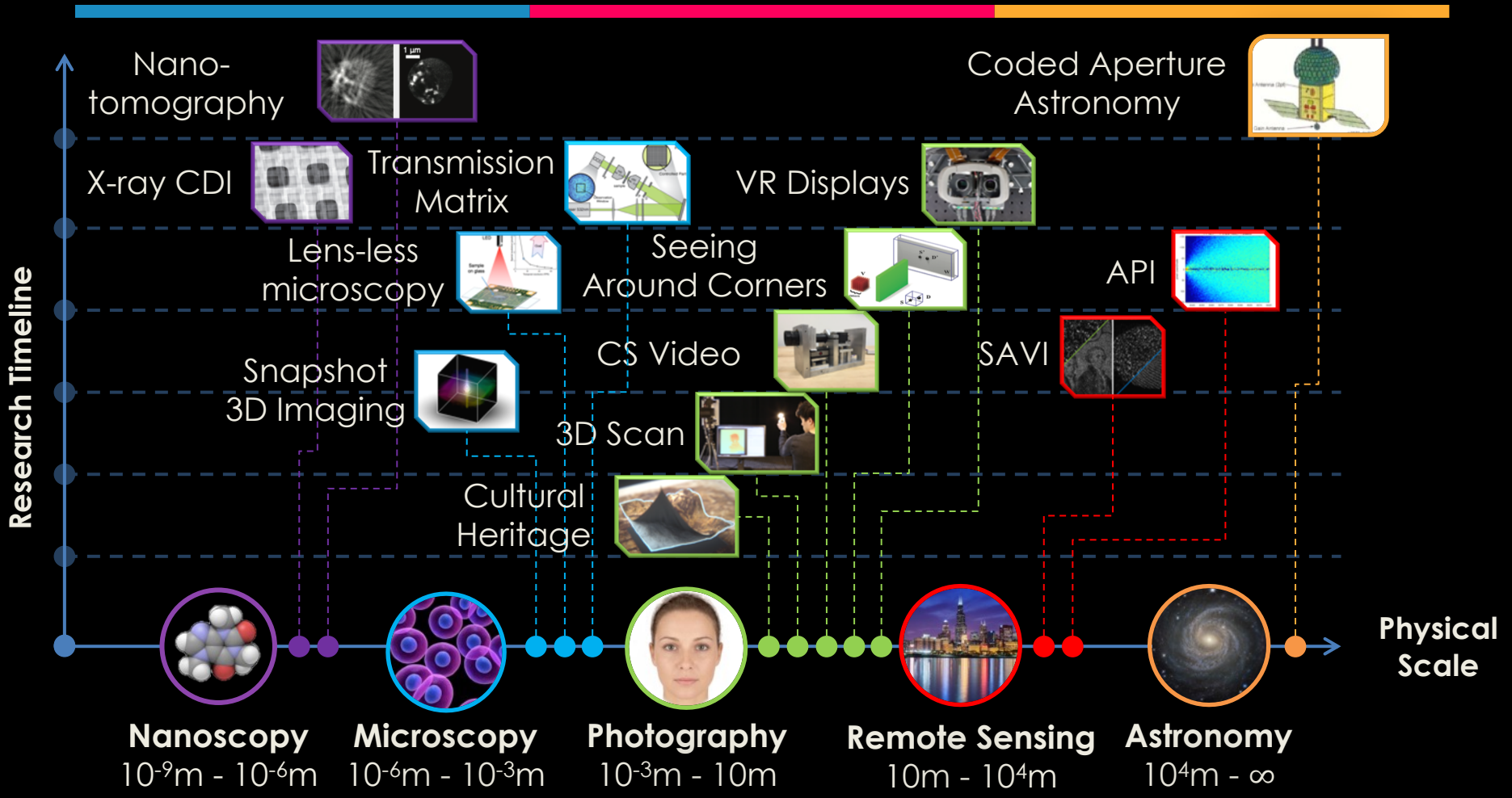
Optical Coding Equation

Decoded Image | Coded Image

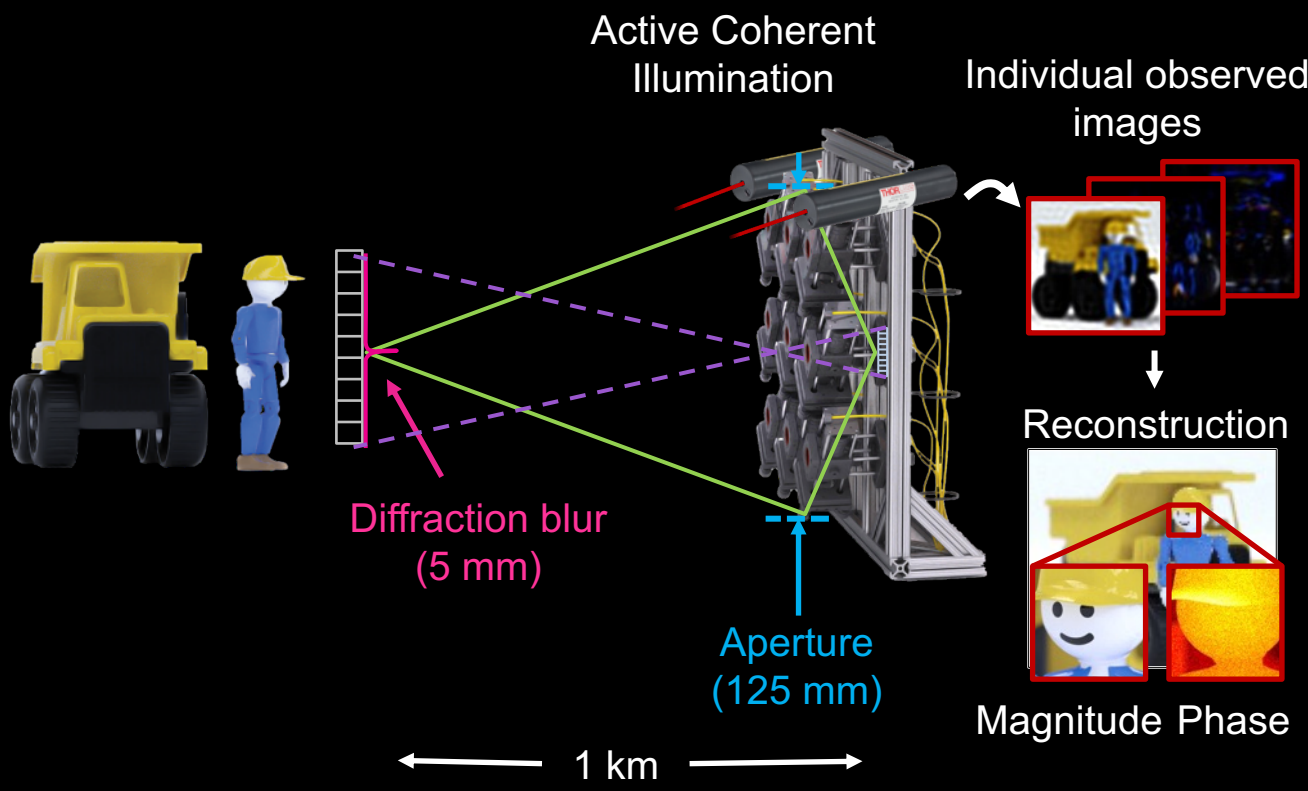
$$\hat{x} = A^{-1}(y)$$

Decoding Equation

At Northwestern: CI Across Scale

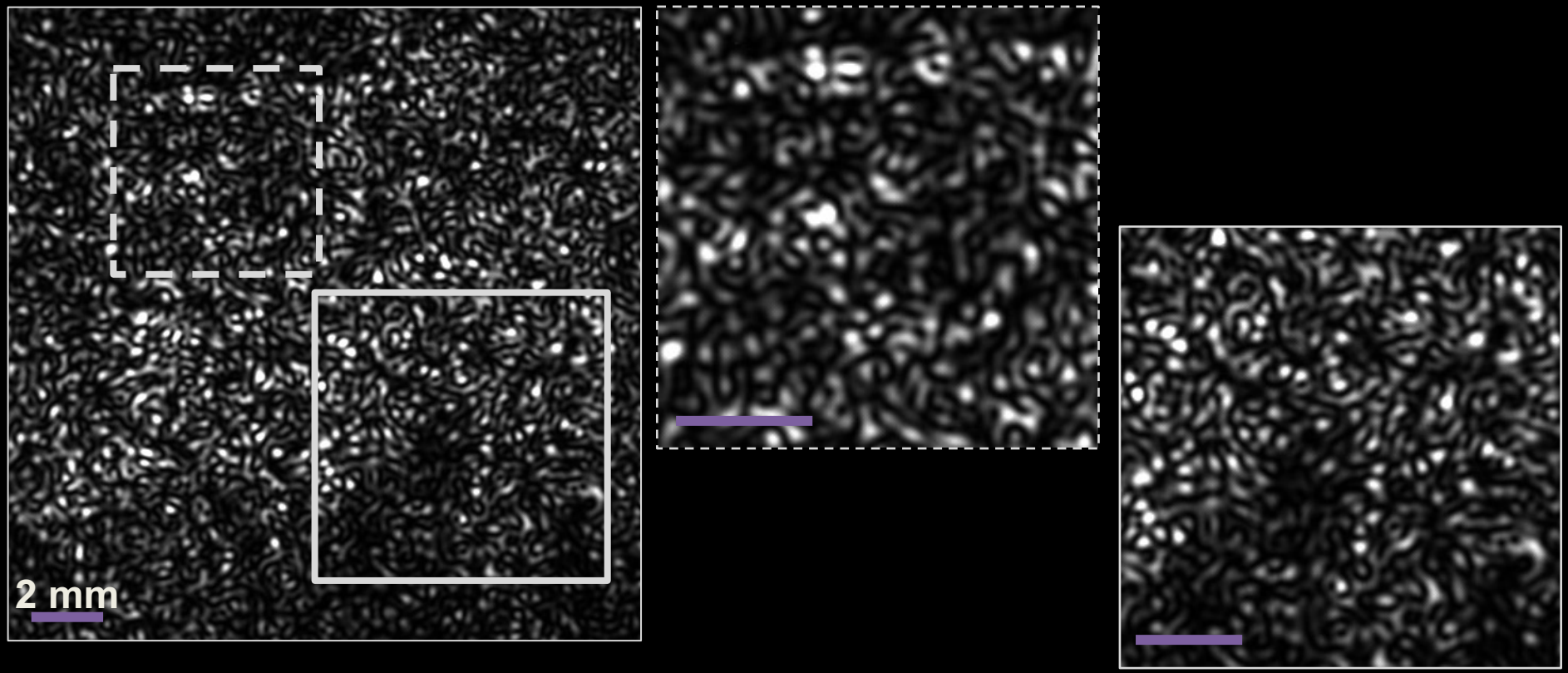


Remote Fourier Ptychography Imaging

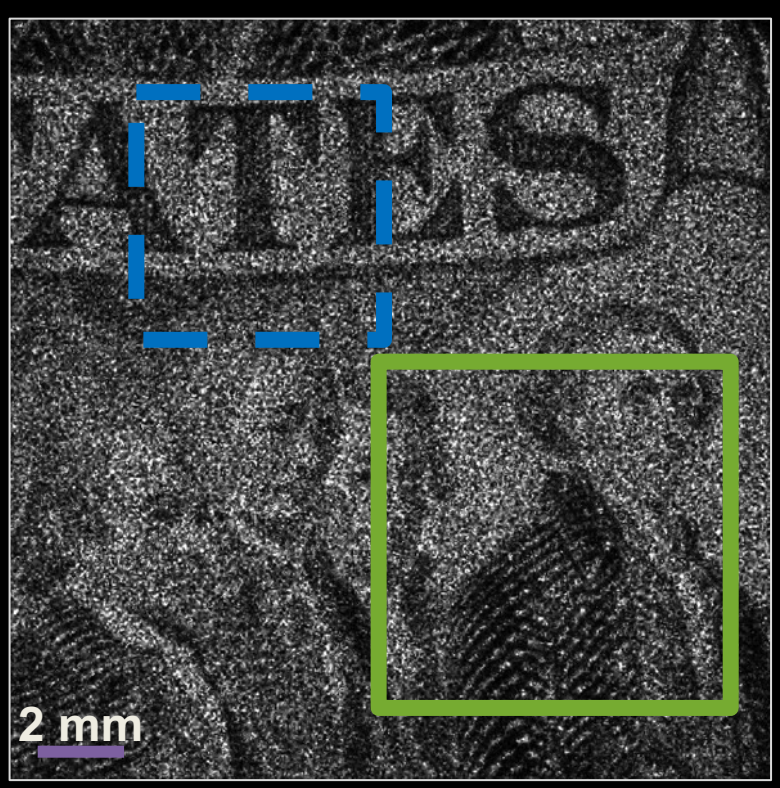


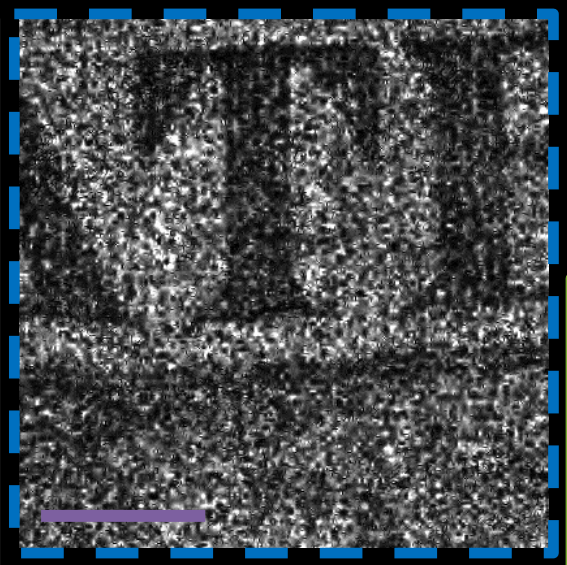
Holloway et al.,
Science Advances, 2019

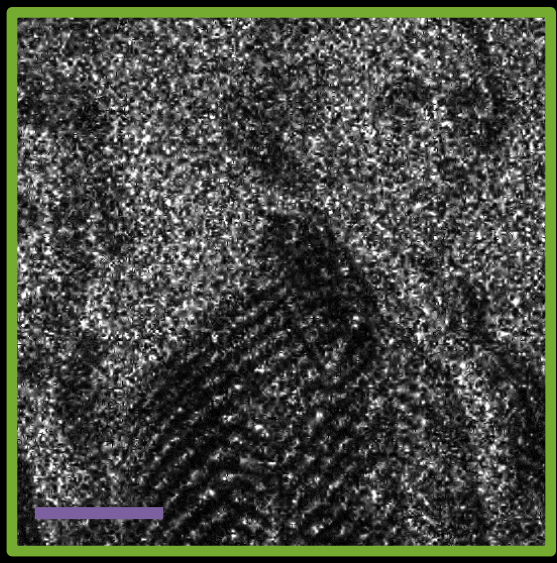
Diffuse Everyday Objects – Mystery Object #1



Diffuse Everyday Objects – Mystery Object #1

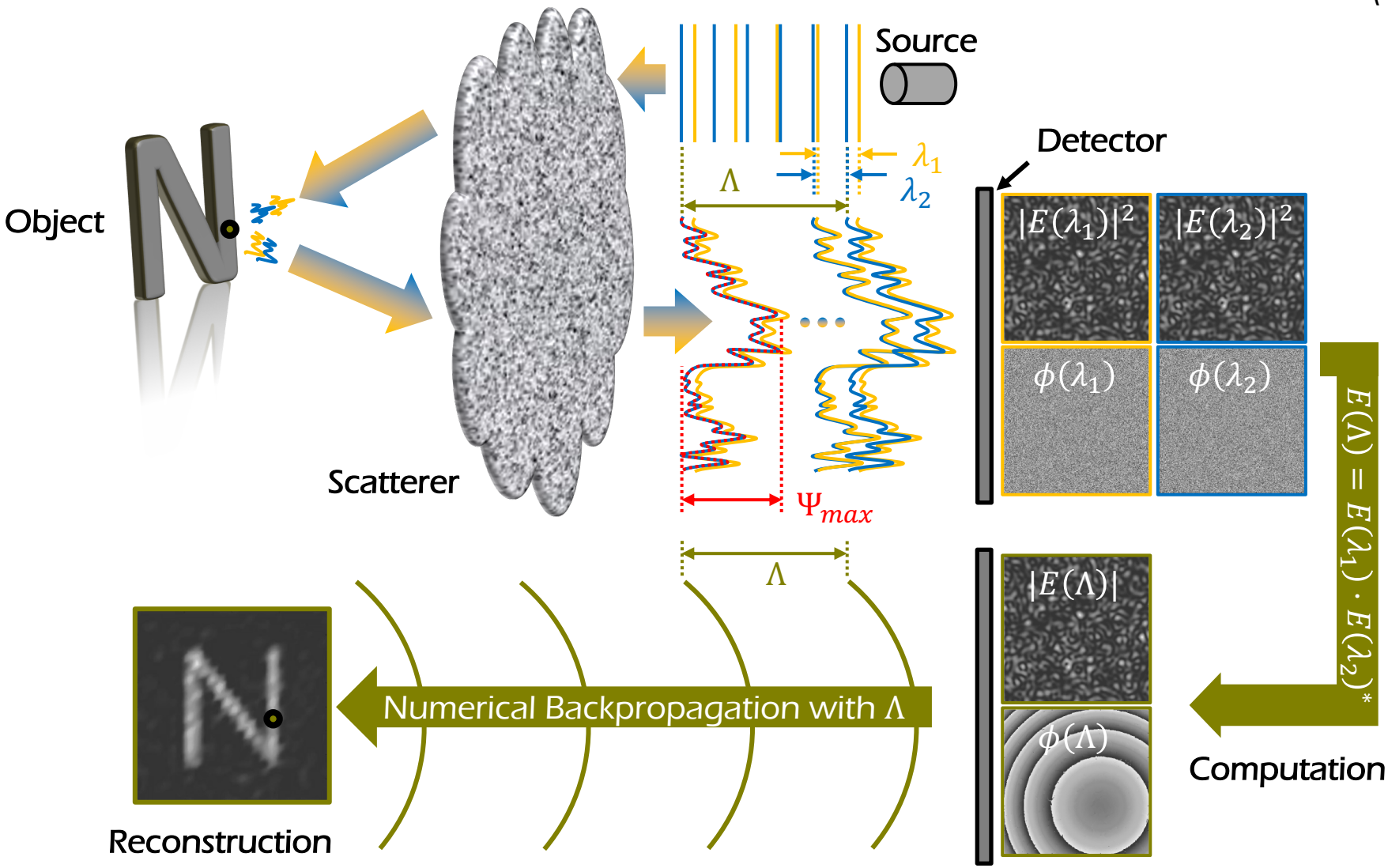




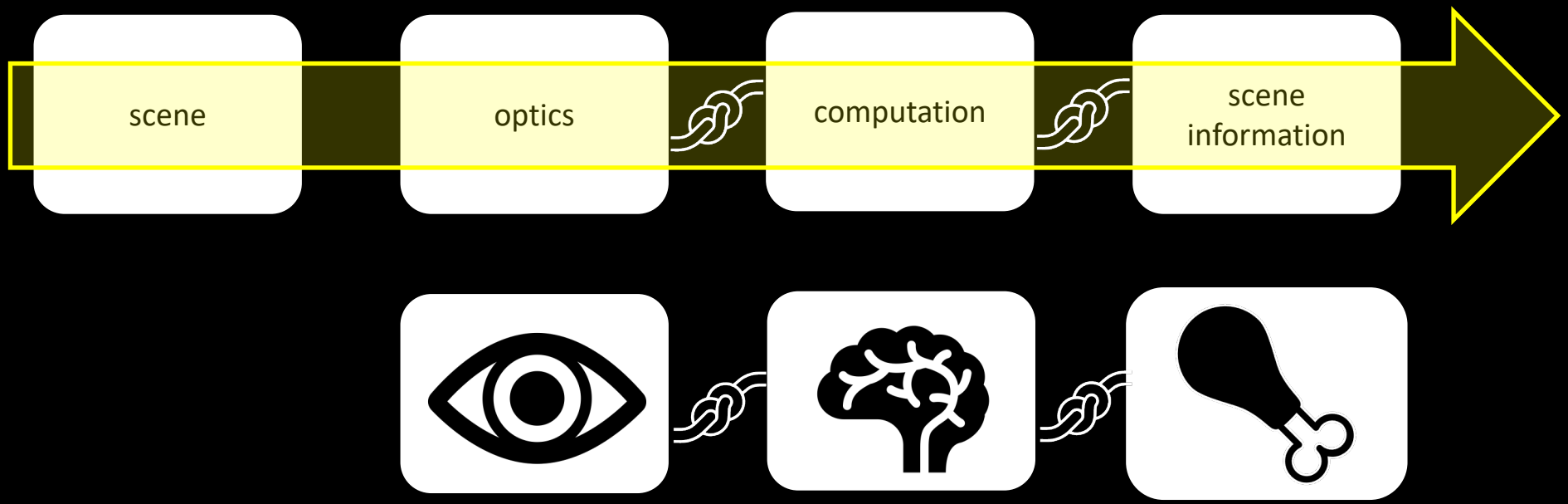


Synthetic Wavelength Holography

Willomitzer et al.,
ArXiv preprint:
1912.11438 (2019)



Bio-Inspired Computational Imaging?

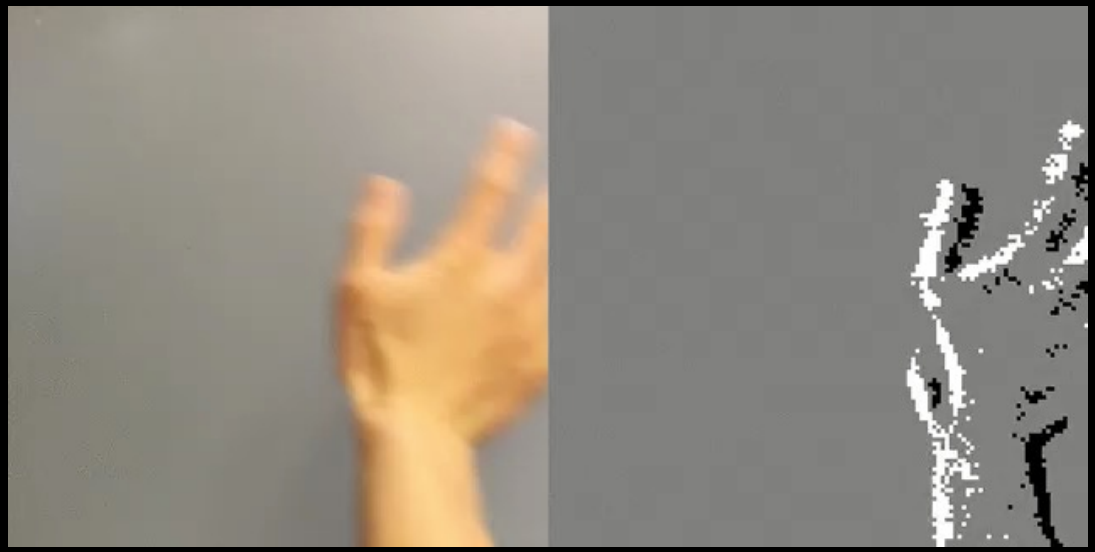


Biological image sensing and visual processing are intricately linked

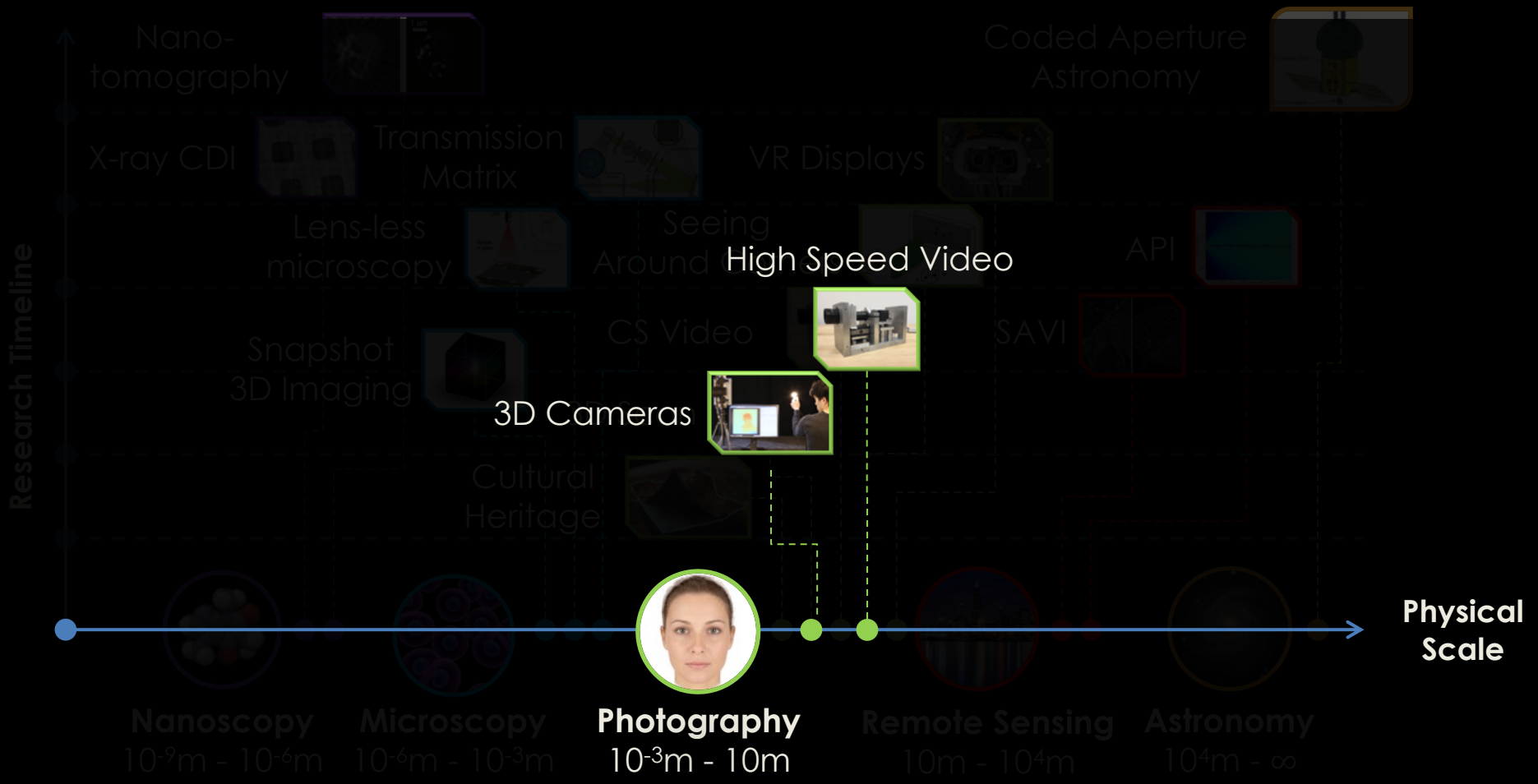
Slide credit: Emma Alexander

Intensity vs. Event Cameras

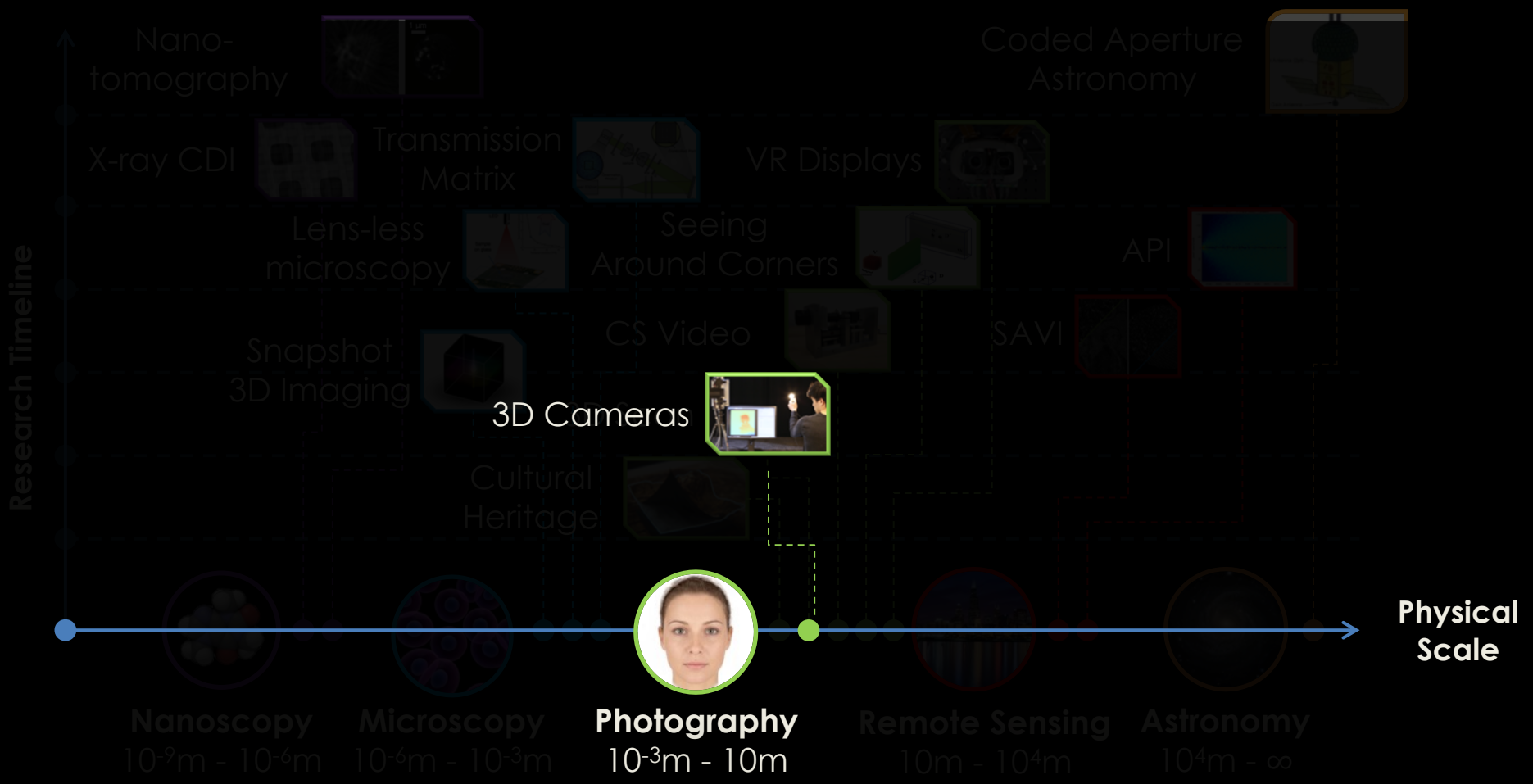
- Same bandwidth for Video and motion contrast
- Video frames are dense, temporal resolution is low
- Event streams are sparse in space and time



Event-based Computational Imaging



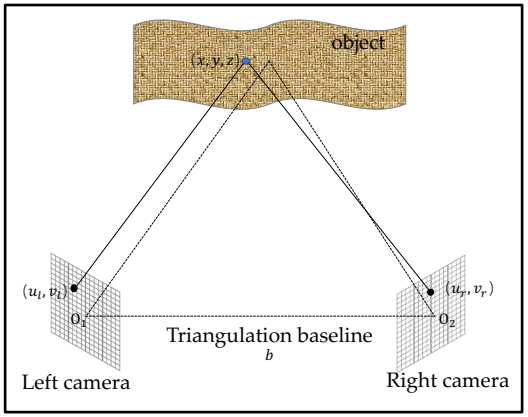
Event-based Computational Imaging



Review – Current off-the-shelf 3D sensors

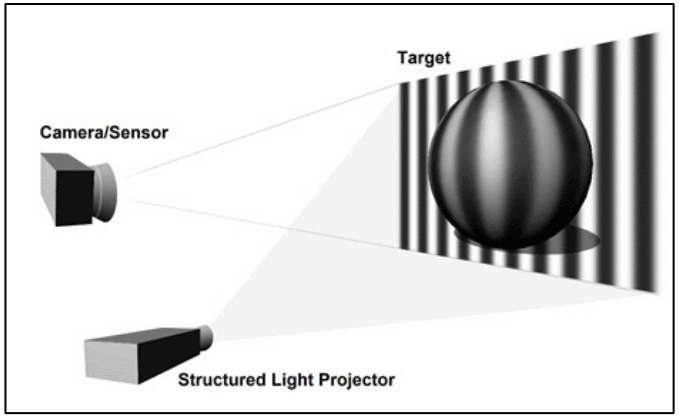
Triangulation based 3D sensors

Stereo



[S. T. Barnard et al., 1982]

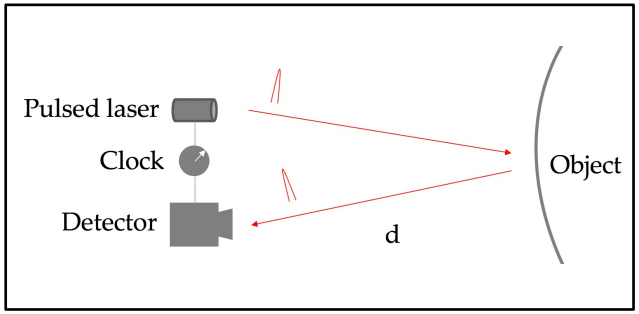
Structured light



[J. L. Posdamer et al., 1982]

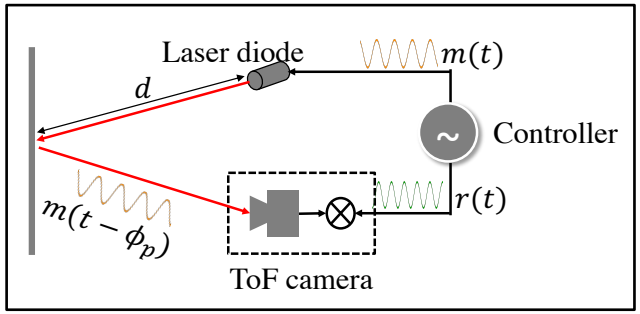
Time-of-flight based 3D sensors

Pulsed LIDAR



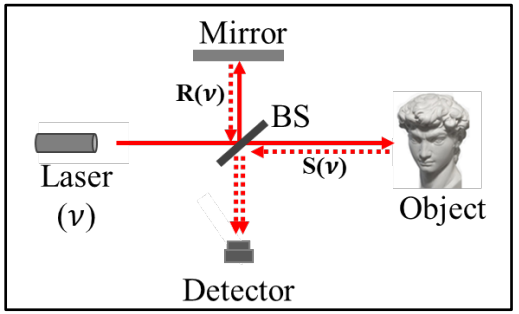
[P. A. Davis, 1969]

Time of flight camera



Schwarte et al., 1997

Optical interferometry

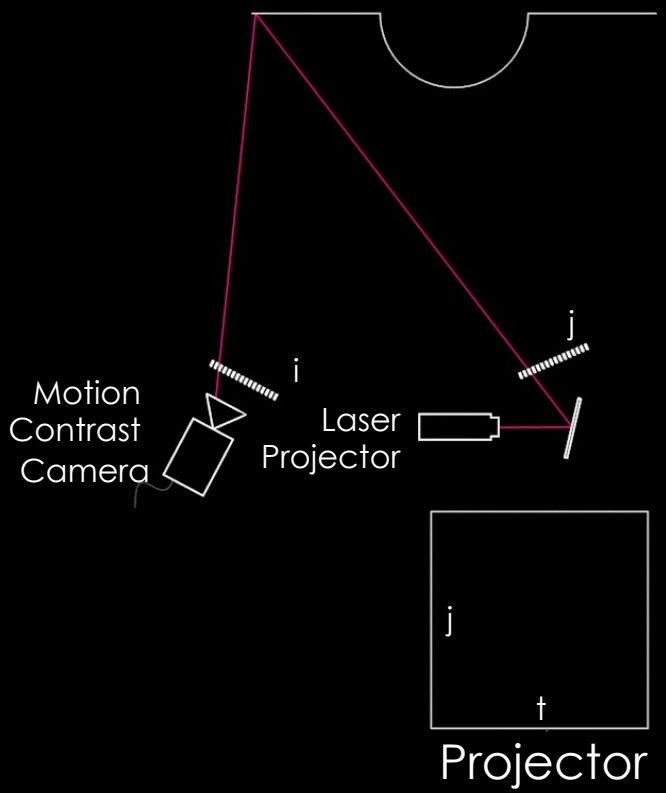


[A. Michelson et al., 1887]

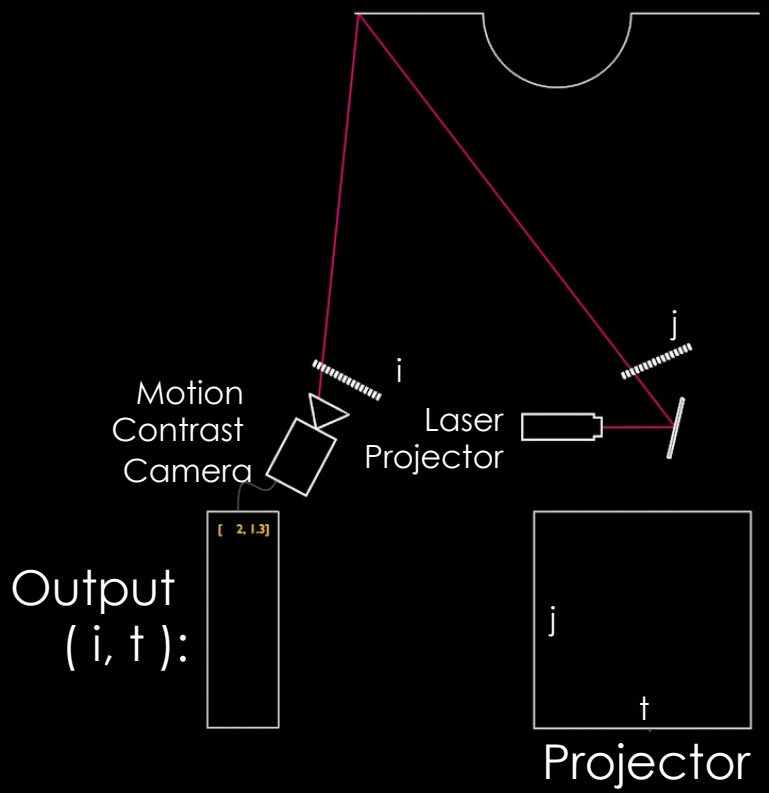
MC3D Principle

Matsuda et al.,
ICCP, 2016

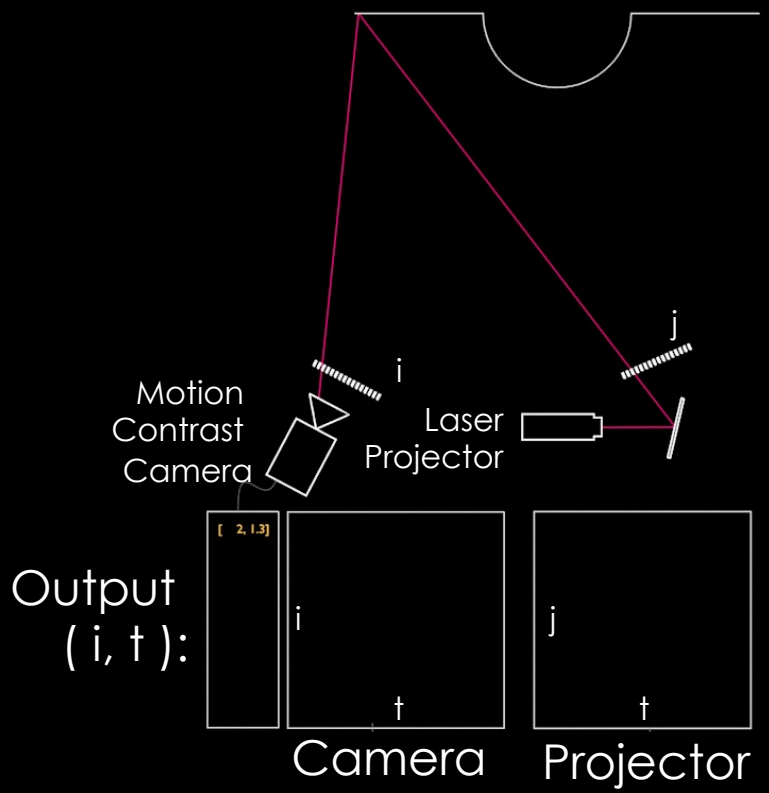
MC3D Principle



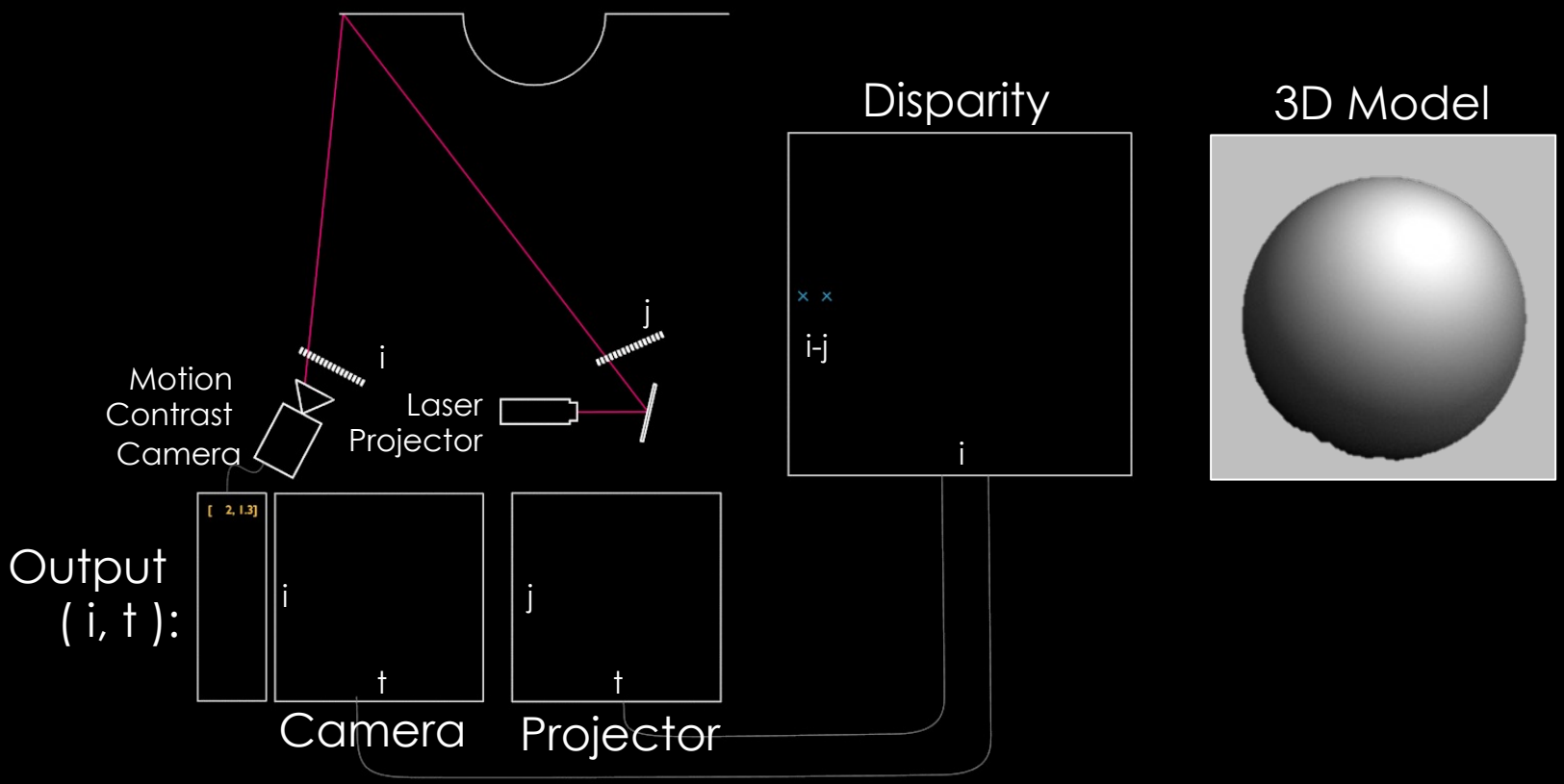
MC3D Principle



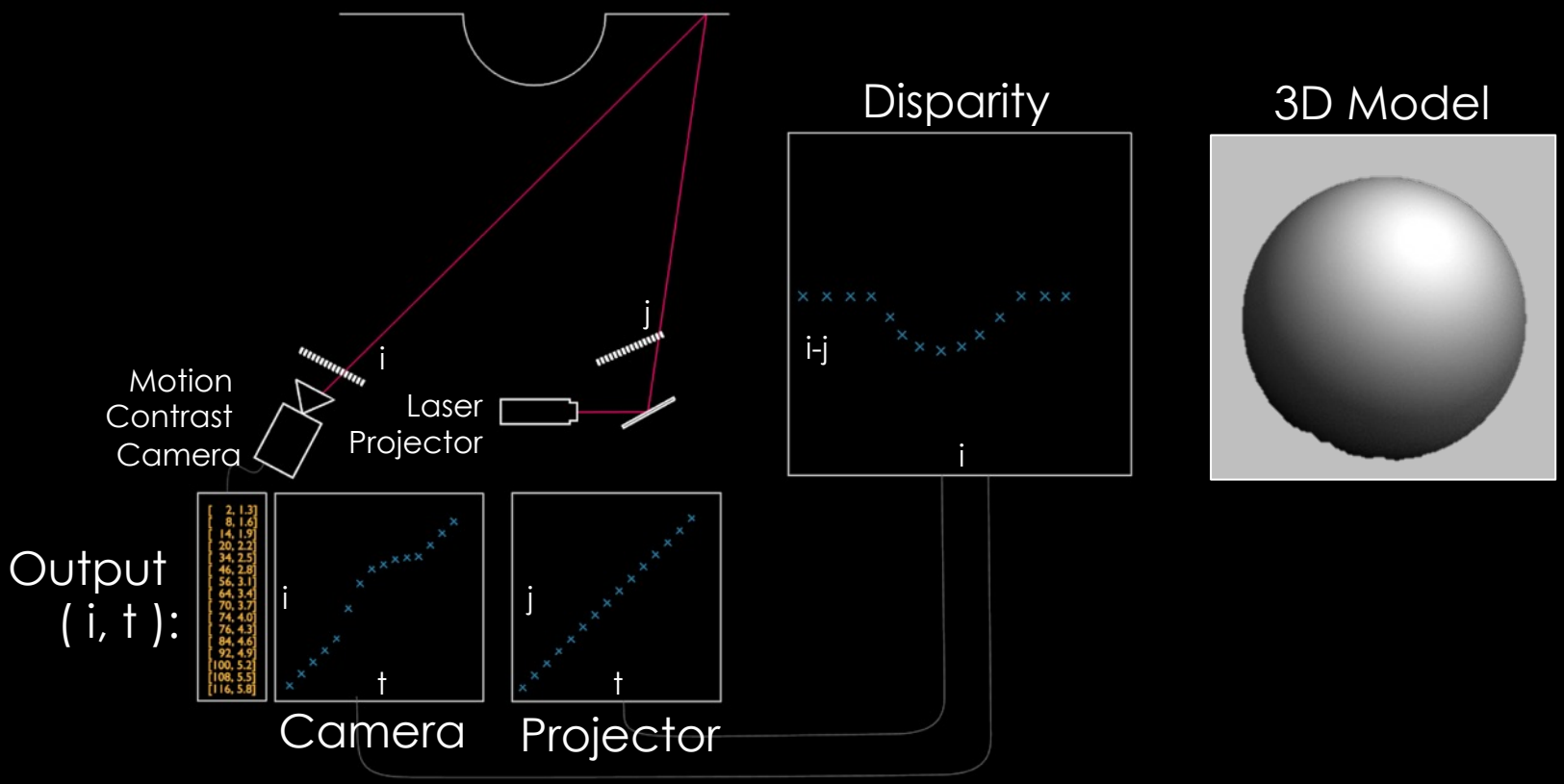
MC3D Principle



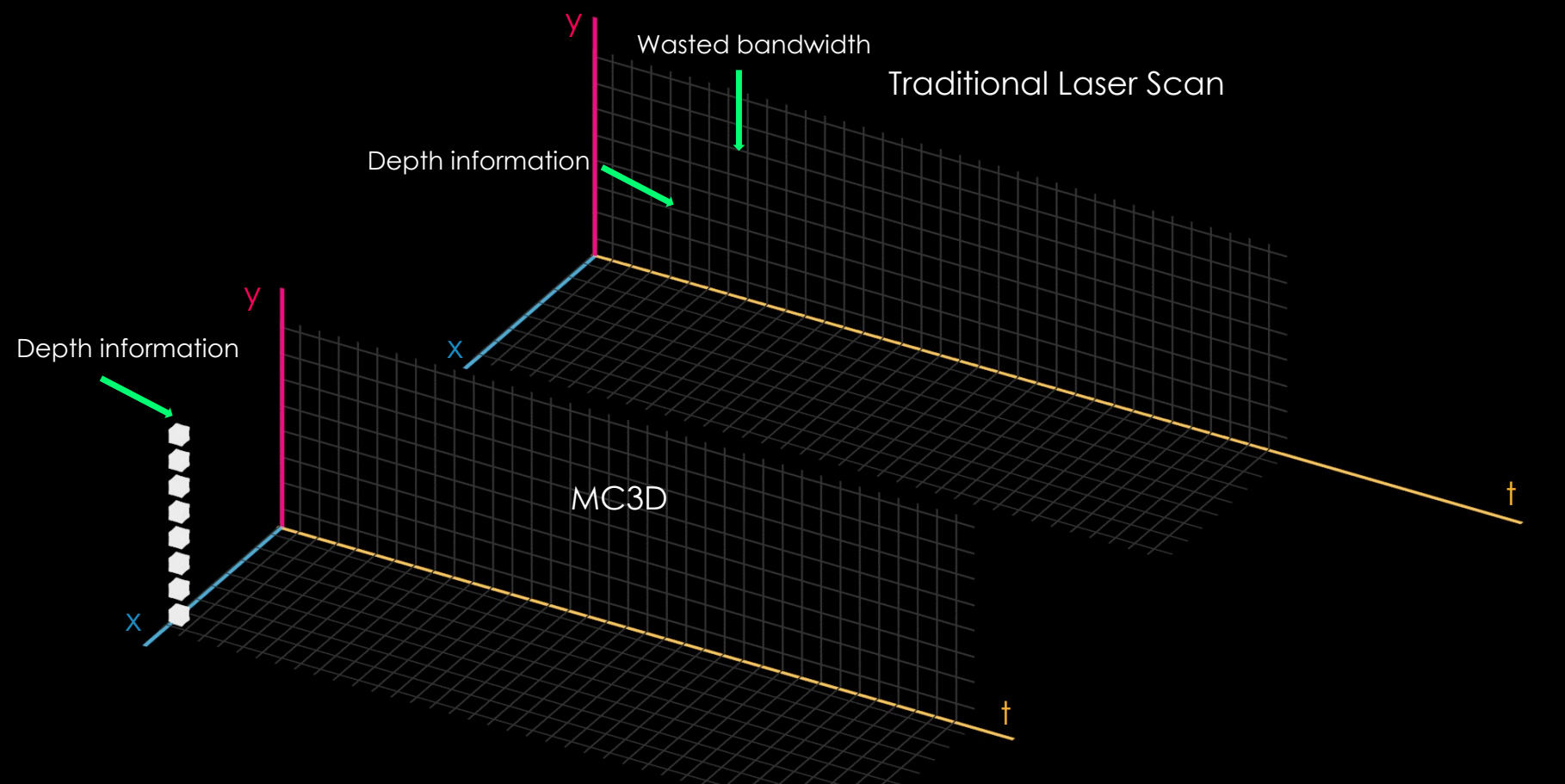
MC3D Principle



MC3D Principle



MC3D Advantage: Bandwidth

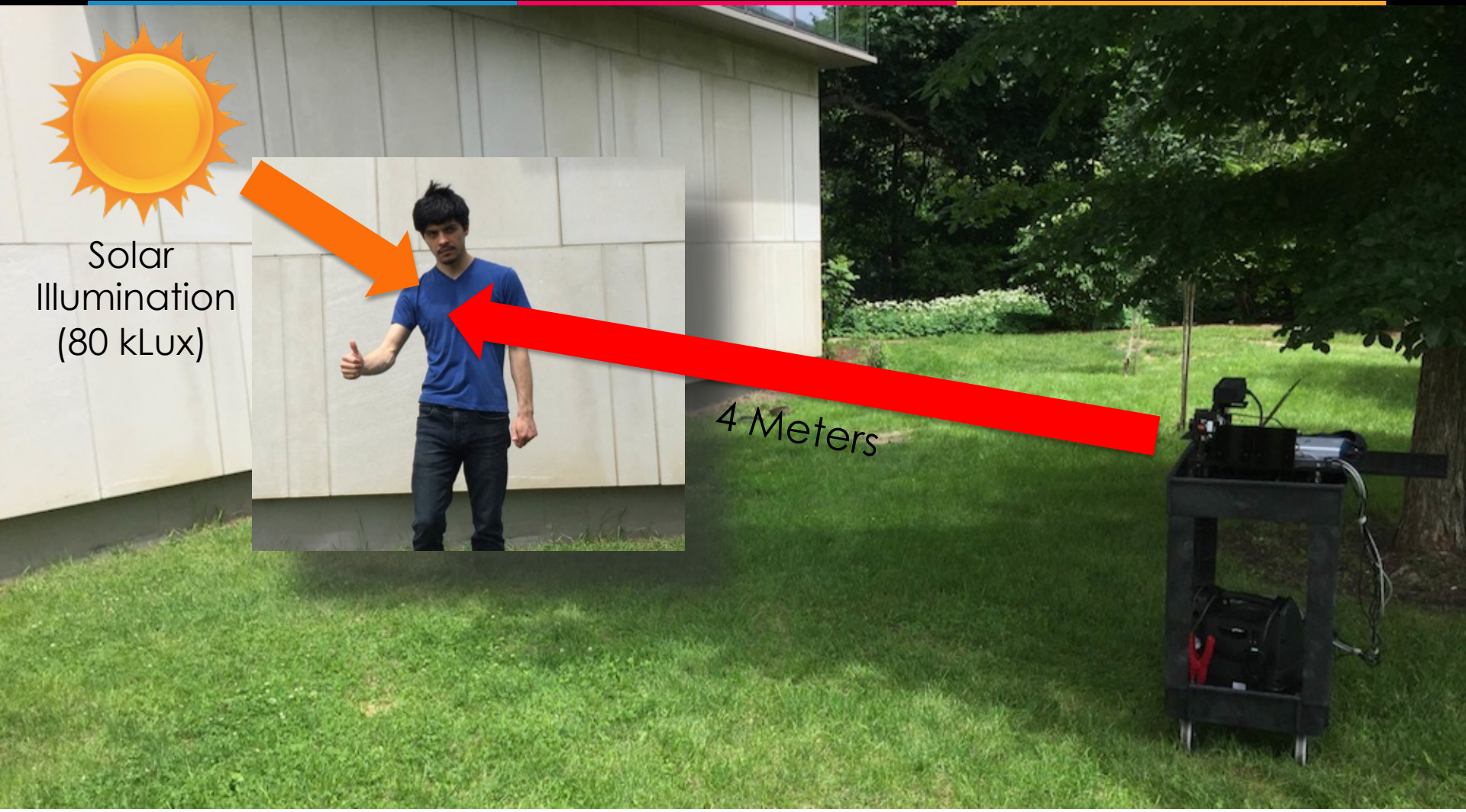


- Requires only one measurement per pixel

Results: Ambient Illumination

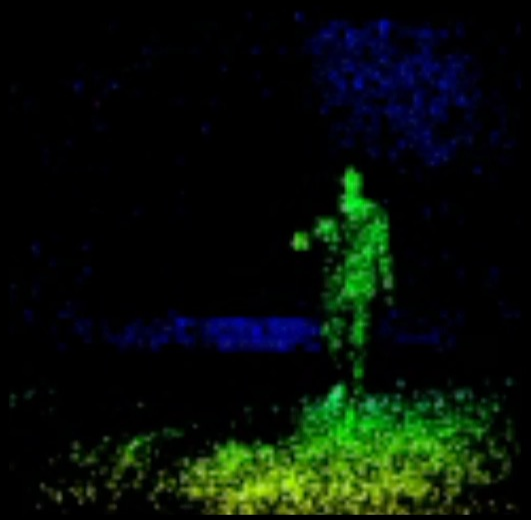
- Second Generation MC3D works with 50,000lux

Live Outdoor 3D Scanning

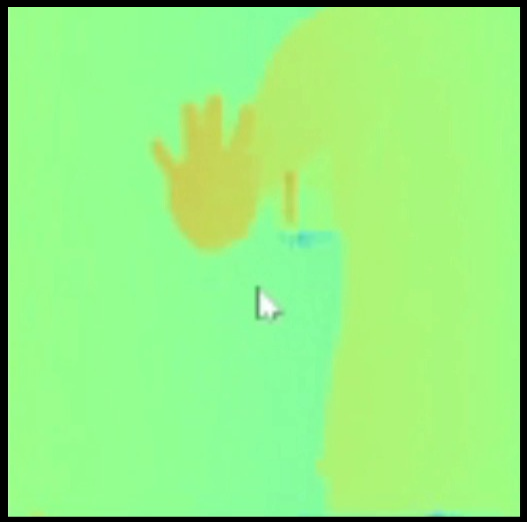


Live Outdoor 3D Scanning

Kinect2



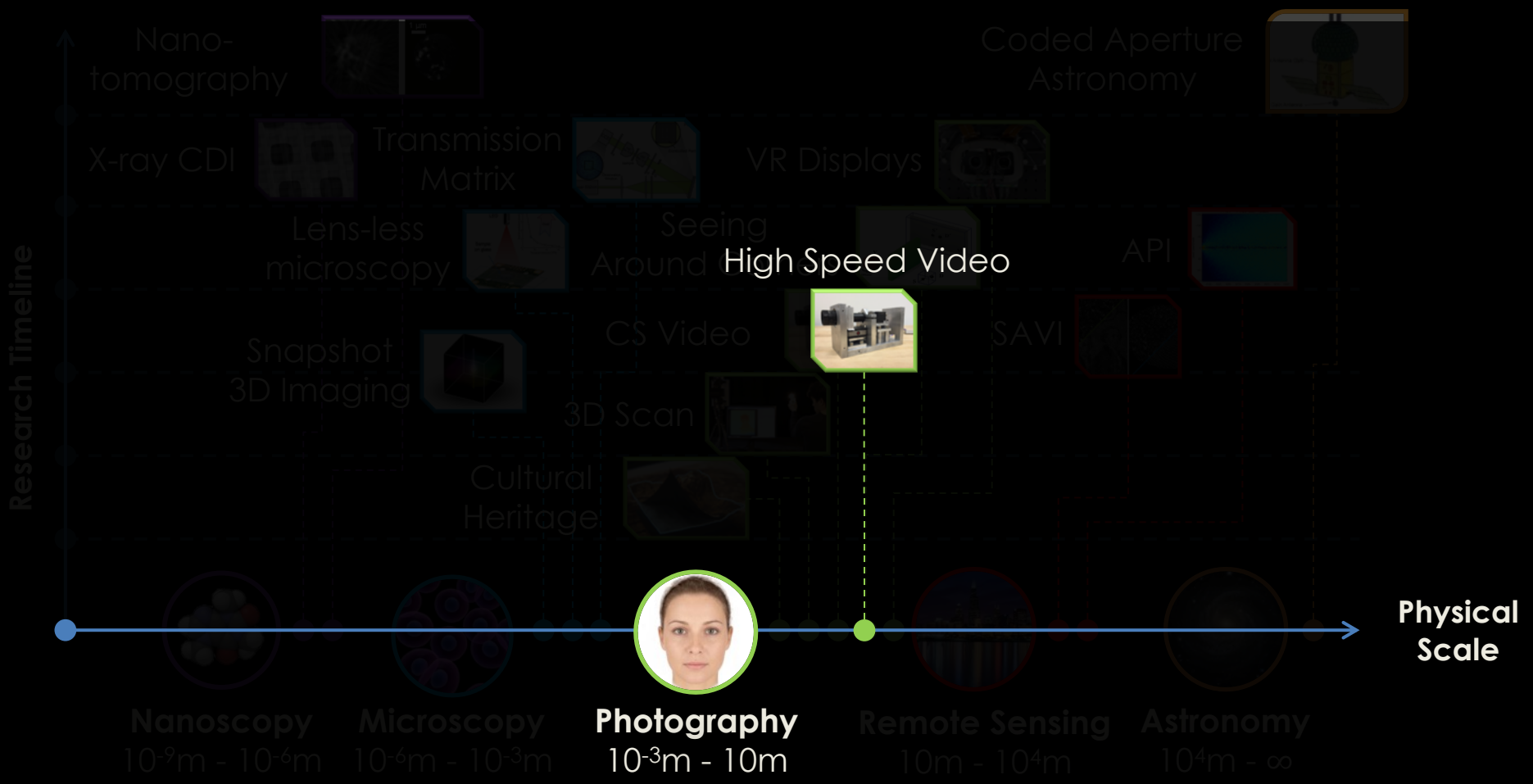
MC3D (Zoom Lens)



IR Image

- MC3D works with 80,000 lux at 4m stand-off distance

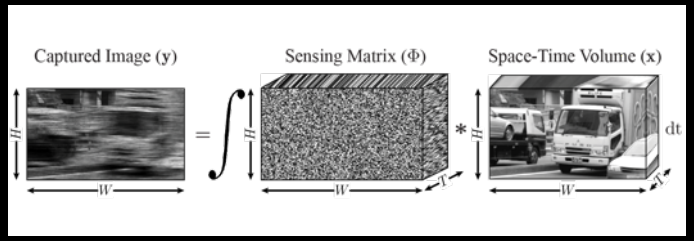
Event-based Computational Imaging



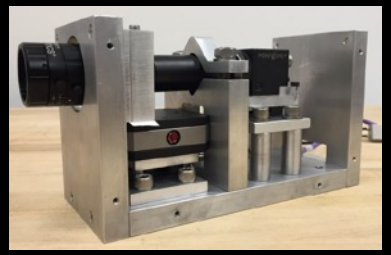
Previous Research: High Speed Imaging

Compressed Sensing Video

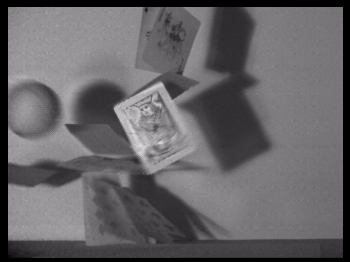
Measurement Model:

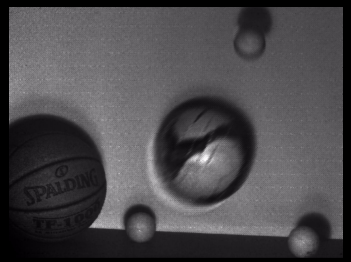


CS Video Camera:



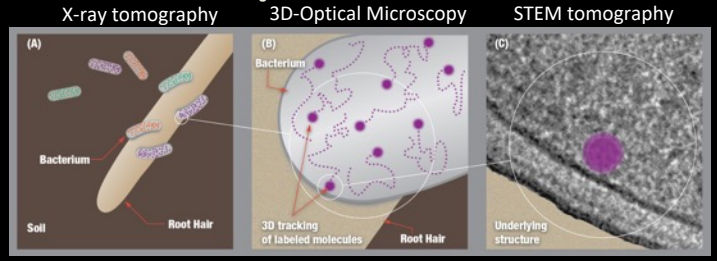
Snapshot Video Reconstructions:



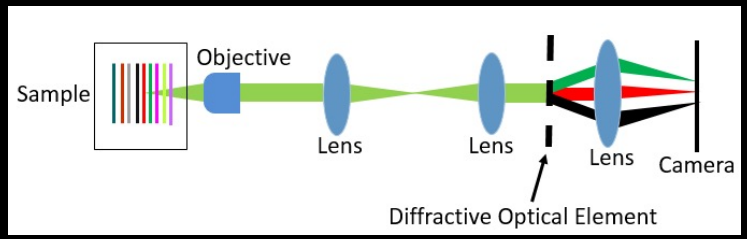


Snapshot 3D Microscopy

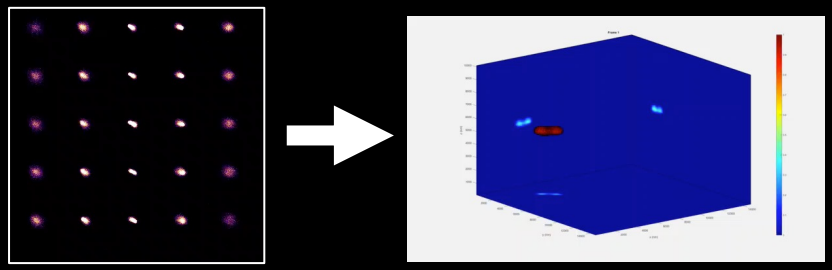
Small Worlds DOE Project :



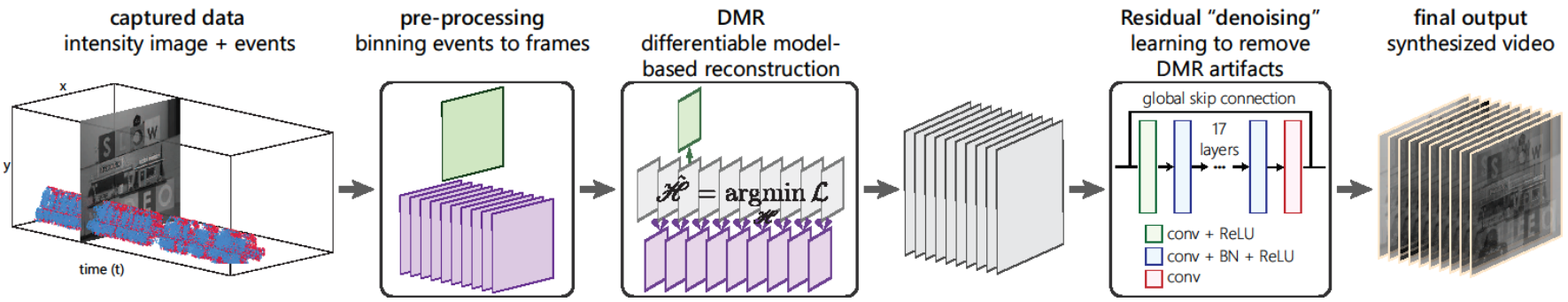
MultiFocal Microscopy (MFM):



Snapshot 3D Reconstructions:

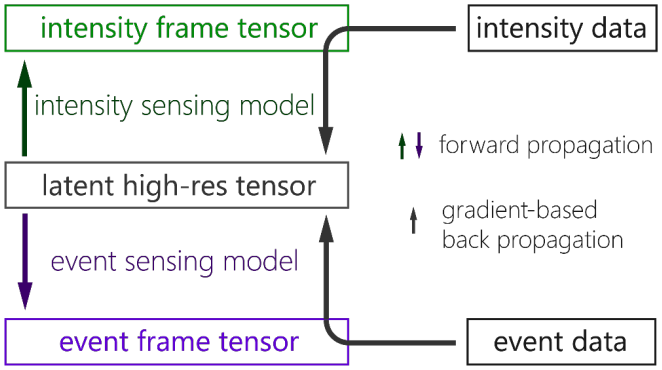


Event-driven video frame synthesis



1. Differentiable model-based reconstruction (DMR)
3-in-1 solver: frame interpolation, extrapolation, and motion deblur

2. Residual learning for further improvement:
Residual nets are easy to train



Wang, Zihao W., et al. "Event-driven video frame synthesis." *CVPR Workshop,* 2019.

Results for event-driven video frame synthesis

Interpolation using APS-only

Interpolation using APS + DVS

SepConv [CVPR'17]

Ground truth

Ours (DMR + Refinement)

Guided Event Filtering

Imaging device

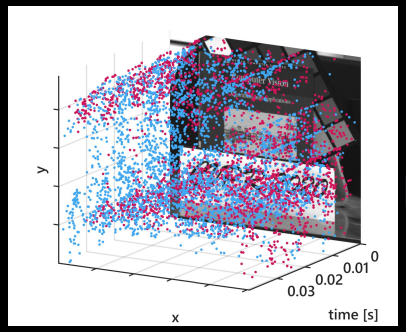


Image and events

Guided Event Filtering

Filtered event frame

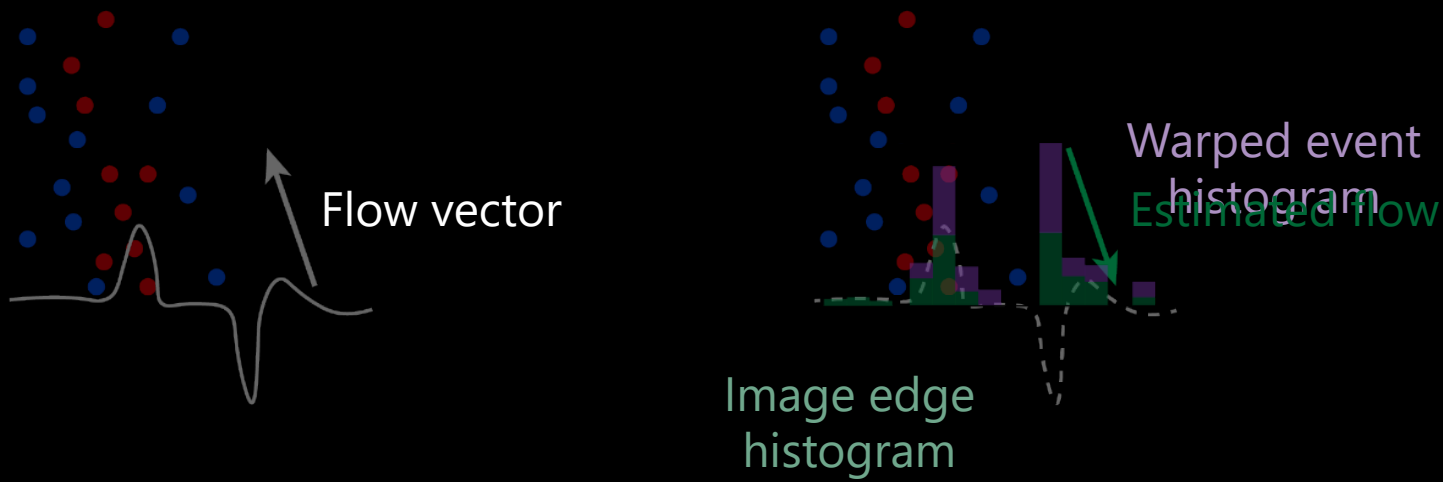
Applications

Wang, Zihao W., et al. "Joint filtering of intensity images and neuromorphic events for high-resolution noise-robust imaging." *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*. 2020.

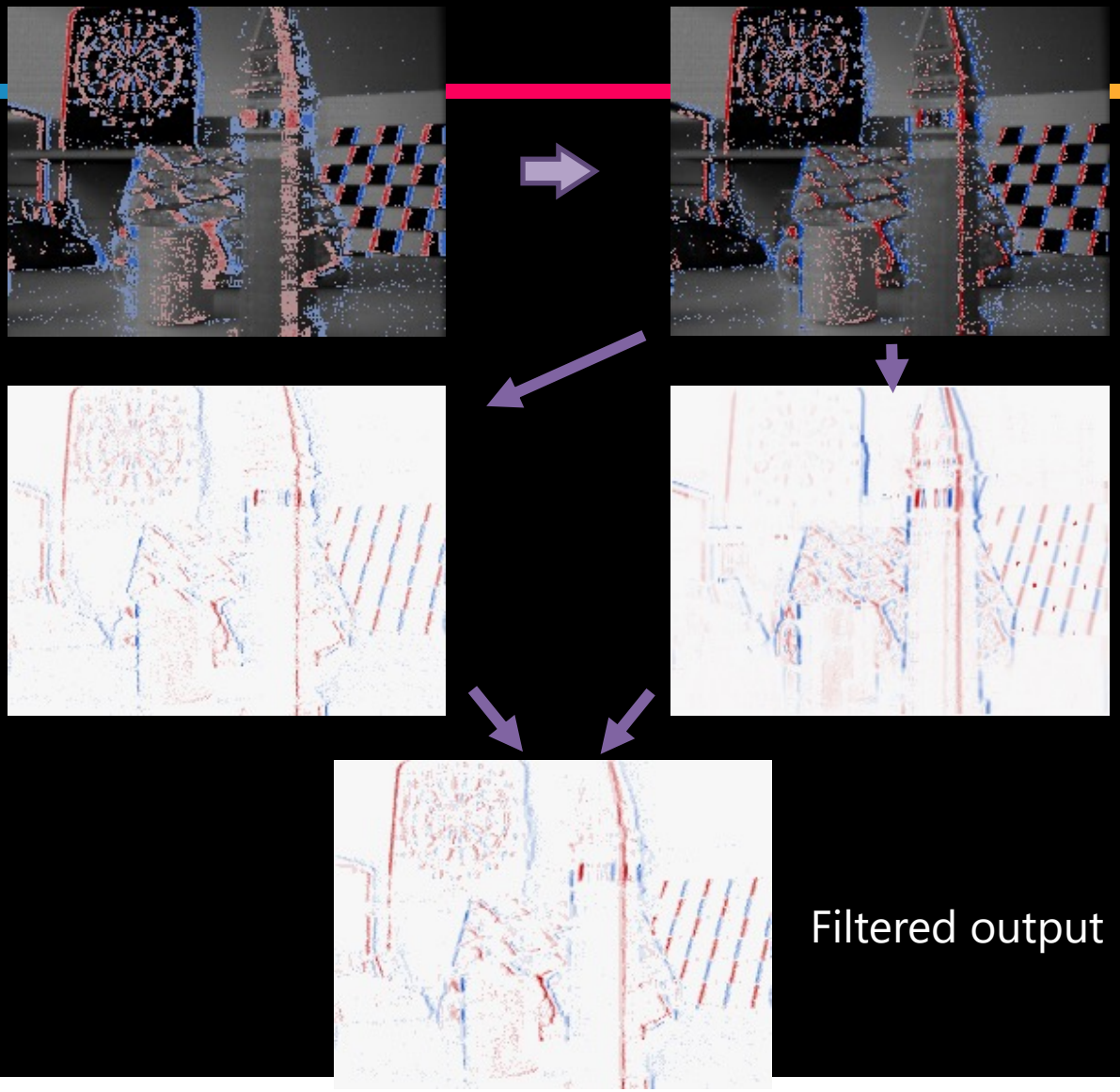
Wang, Zihao W., et. al., "Guided Event Filtering: Synergy between Intensity Images and Neuromorphic Events for High Performance Imaging", *submitted to IEEE Trans. of Imag. Proc.*

Motion Compensation

Joint contrast maximization

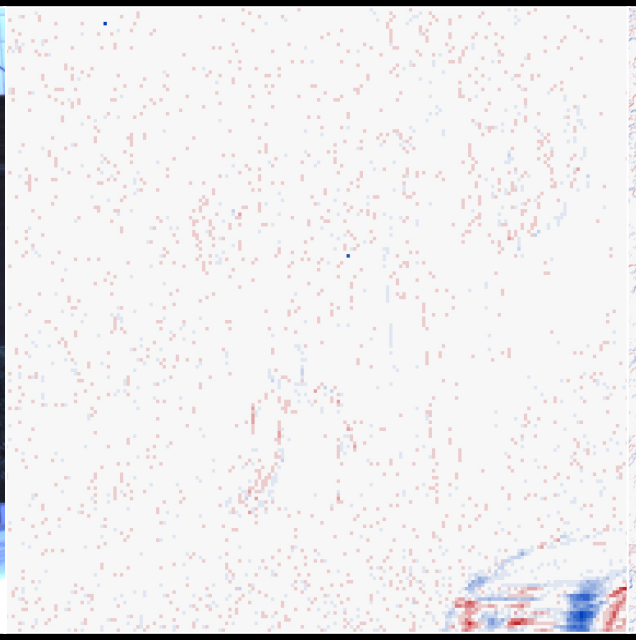


Joint Filtering

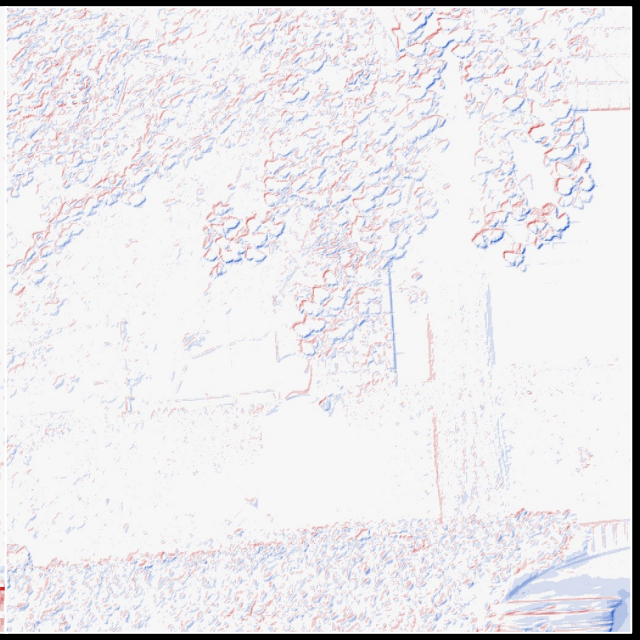


GEF Results

RGB video

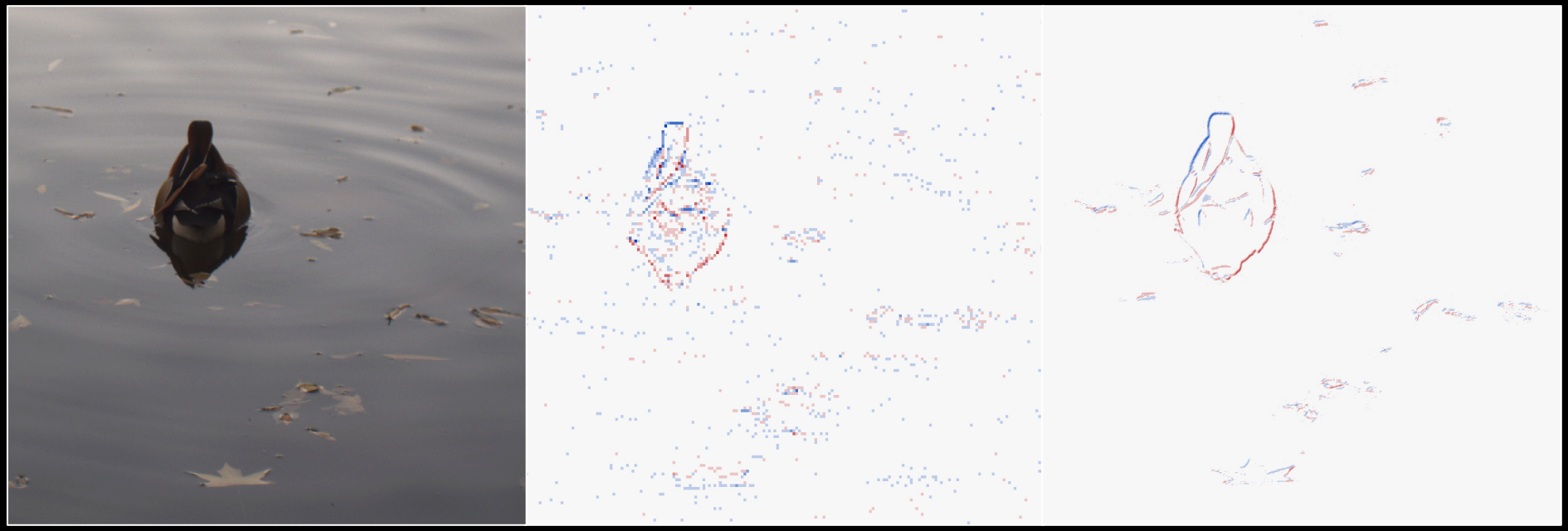


Event video



Filtered result (8x)

GEF Results

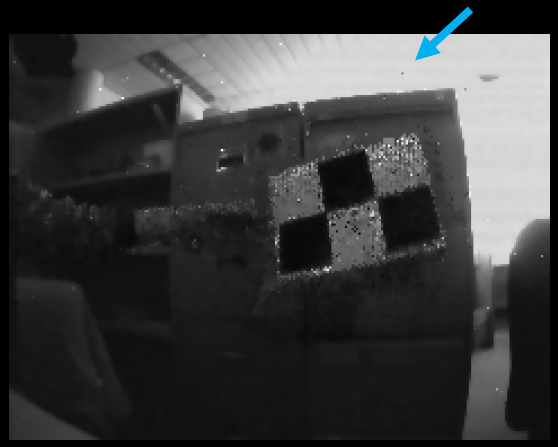


RGB video | Event video | Filtered result (8x)

GEF: Motion Deblurring

Blurry image

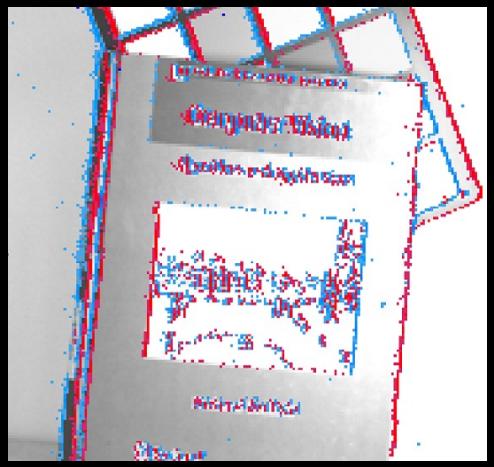
w/o GEF



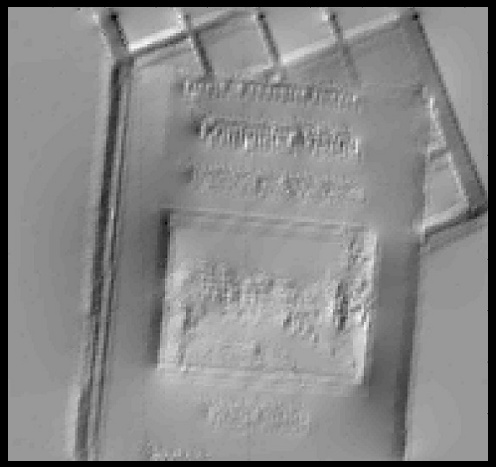
w/ GEF

L. Pan, et al. Bringing a blurry frame alive at high frame-rate with an event camera.. CVPR 2019

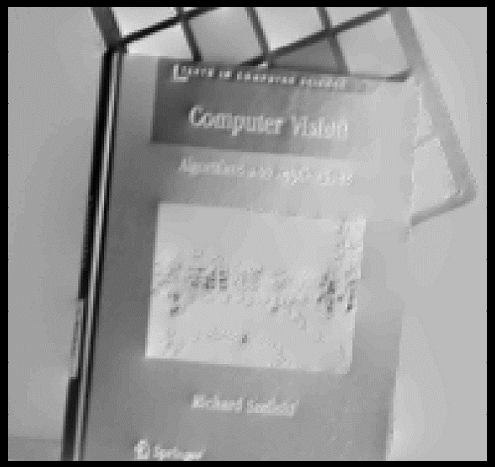
GEF: HDR Imaging



LDR image + events



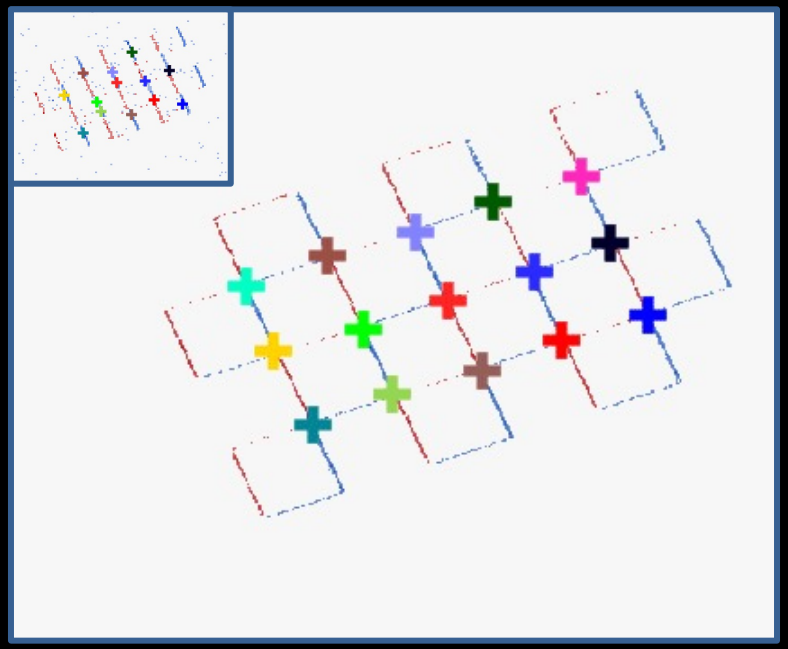
w/o GEF



w/ GEF

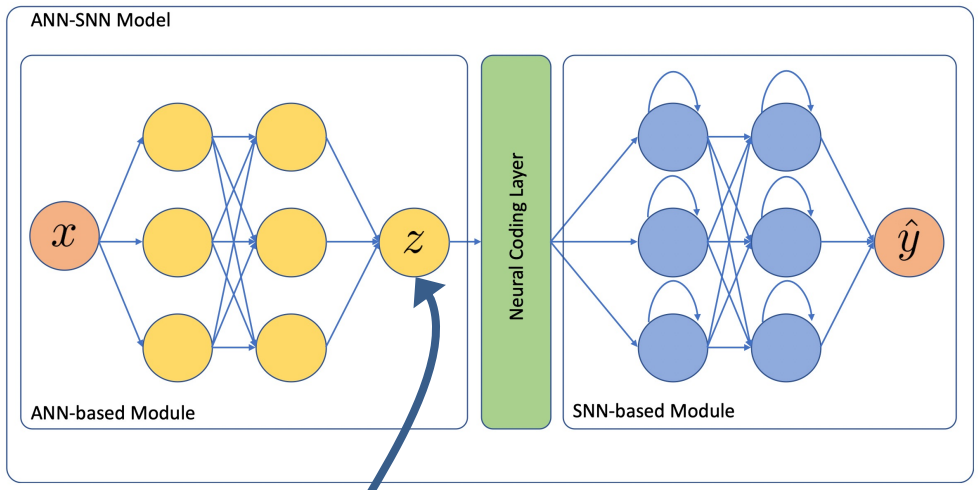
GEF: Corner detection & tracking

w/o GEF

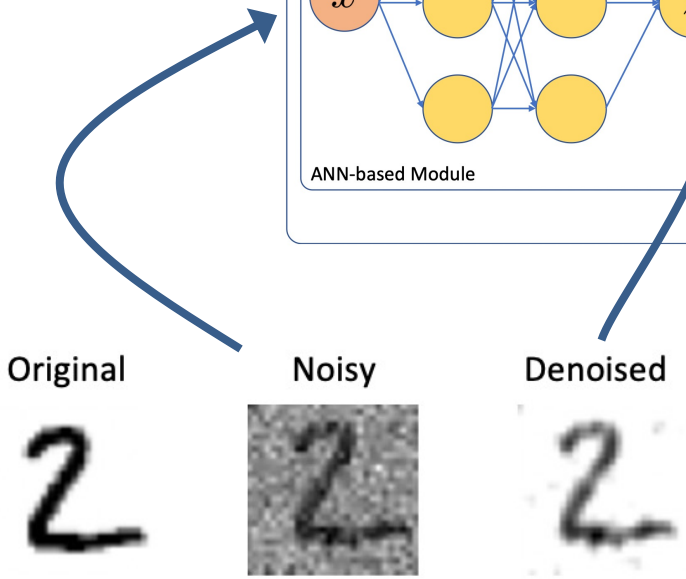


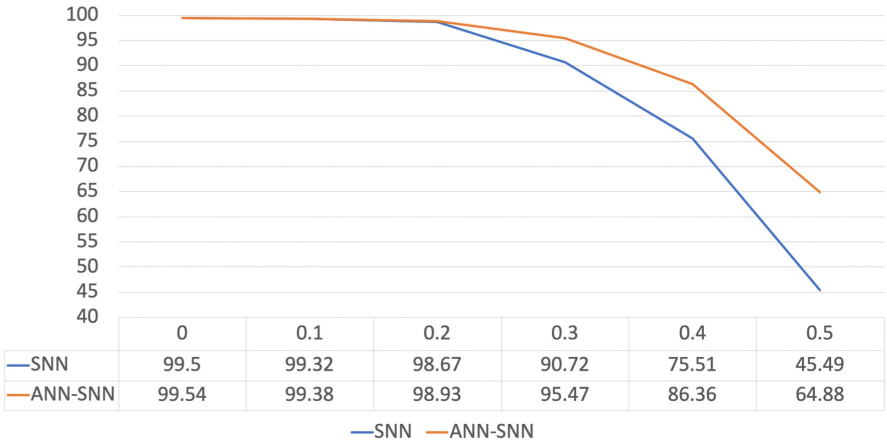
w/ GEF (4x)

Future Directions: Spiking and Hybrid NN Models



MNIST Classification





	0	0.1	0.2	0.3	0.4	0.5
SNN	99.5	99.32	98.67	90.72	75.51	45.49
ANN-SNN	99.54	99.38	98.93	95.47	86.36	64.88

Increasing Noise

Kang, Peng, et al., "Human Vision Like Robust Object Recognition," *accepted to IEEE ICIP 2021.*

Conclusions

- Computational imaging (CI) leverages joint hardware software design
- Many applications in 3D and high-speed camera design
- Bio-inspired CI offers can maximize task-specific performance with low-power and high bandwidth
- CI with SNNs could enable better end-to-end HW+SW performance with lower power