LiDAR Fundamentals

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EPFL, Neuchâtel, Switzerland

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SENSE Detector School – Schloss Ringberg

Acknowledgment- Pouyan Keshavarzian, PhD student, AQUA Lab
For his valuable contribution in compilation of the workshop content

Advanced Quantum Architecture Lab (AQUA)

- Where are we from?

EPFL Microcity Neuchâtel

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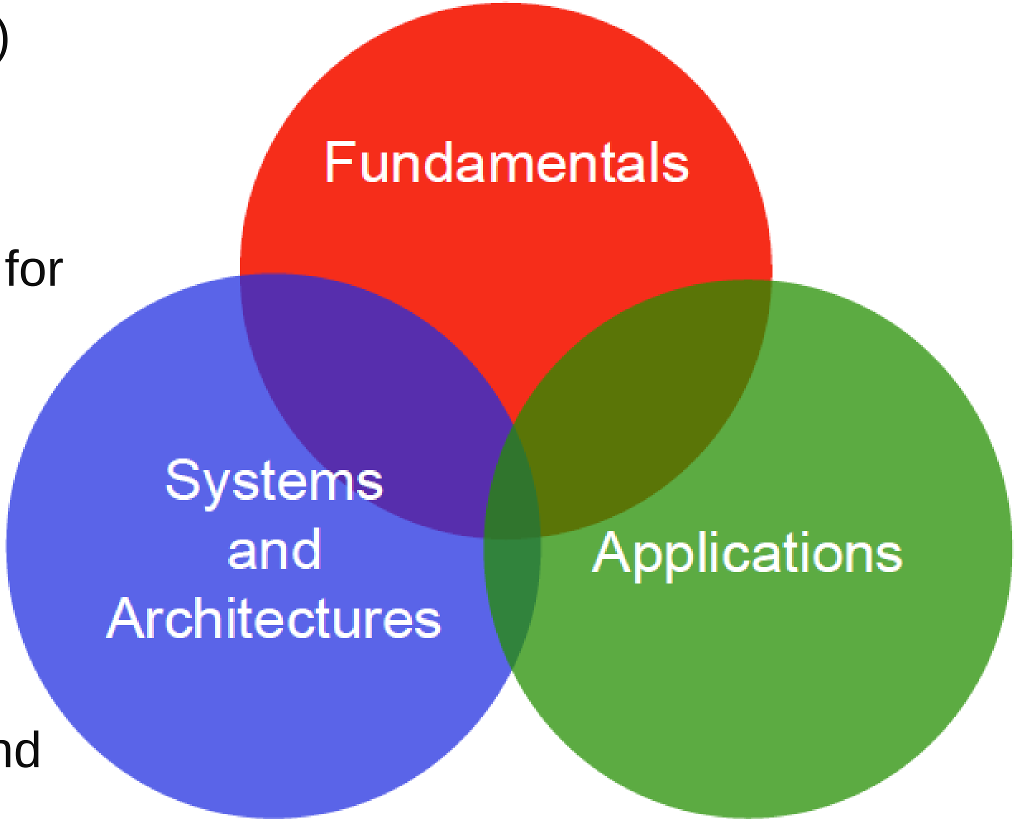
EPFL Neuchâtel

The Canton of Neuchâtel is hosting an important part of EPFL's Microengineering Institute (IMT). It is the biggest academic Institute in Switzerland, with research activities covering topics such as health, microsystems, photovoltaic or watchmaking.

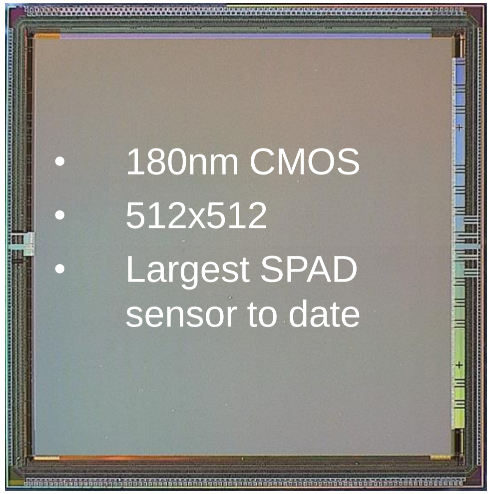
Overview of EPFL-AQUA Activities

- ❑Quantum imaging (single-photon generation and detection)
  - Biosensors (PET, FLIM, FRET, NIRI, NIROT, super-resolution microscopy)
  - Automotive sensors (long distance, high speed telemetry for ADAS and autonomous driving)
  - Time-to-digital converters in ASIC and FPGA
  - Space sensors (guidance and docking in space)
- ❑Ultra-fast imaging (1Gfps camera)
- ❑Quantum random number generators and QKD
- ❑CryoCMOS for quantum computing applications (analog and digital circuits at 4K and below



Recent AQUA designs (EPFL & TU Delft)

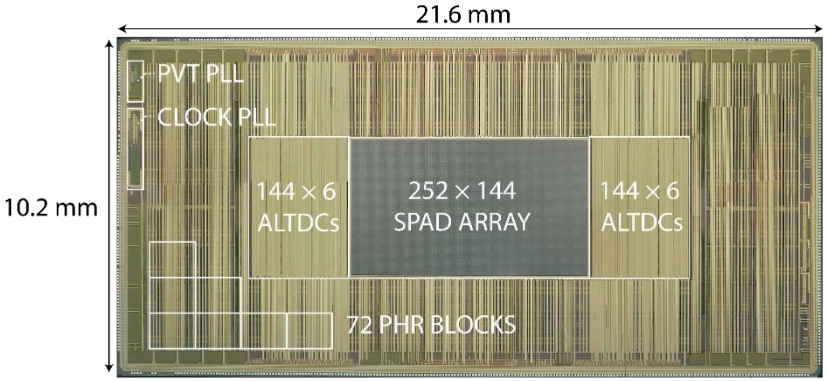
SwissSPAD 2



- 180nm CMOS
- 512x512
- Largest SPAD sensor to date

JSTQE 2019

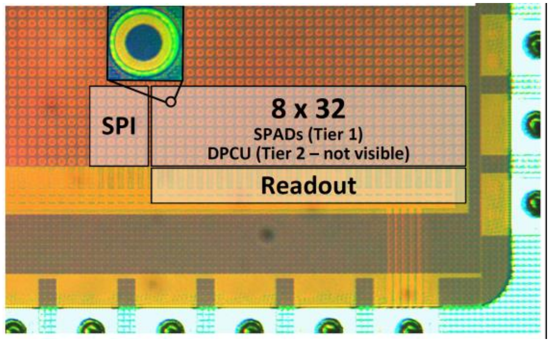
Ocelot



- 180nm CMOS
- 11.2 Gbit/s output data bandwidth

VLSI 2018 / JSSC 2018

Mantis



- 45nm/65nm CMOS 3D stack
- First 3D stacked direct time-of-flight sensor in CMOS

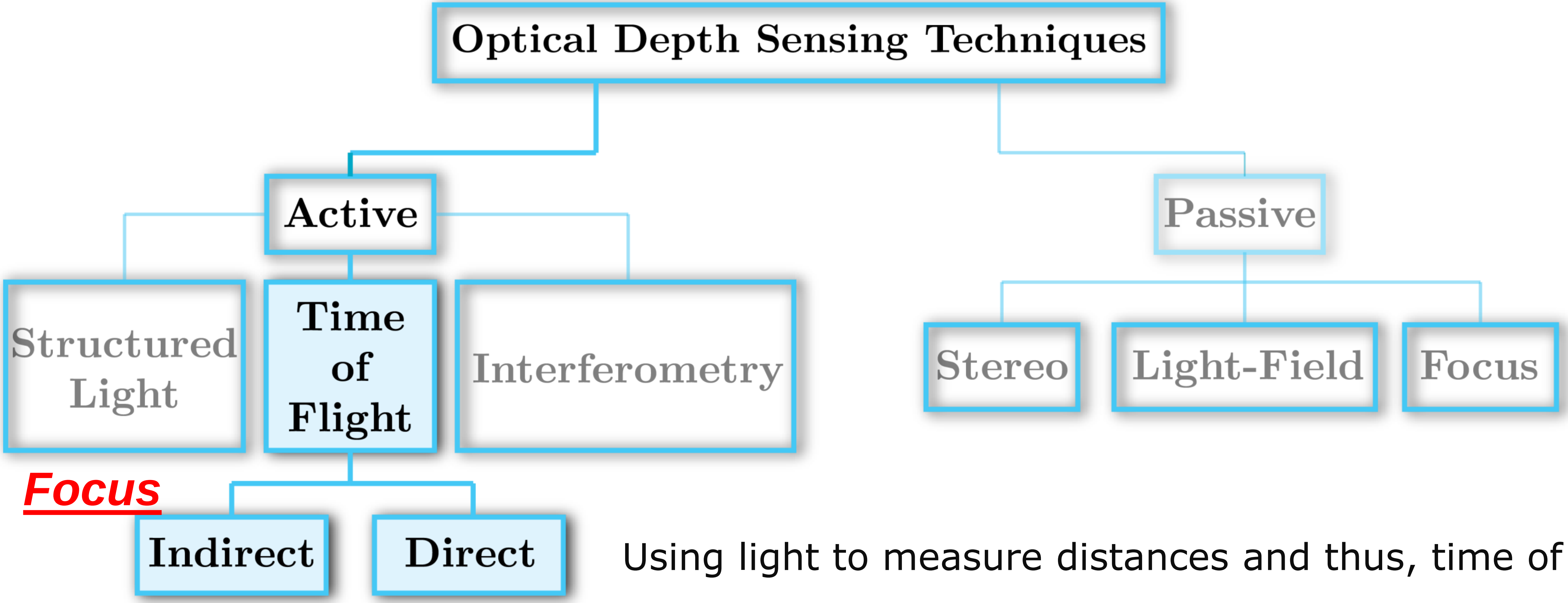
ISSCC 2018

1st International SPAD Workshop

SPADs are “hot”…Les Diablerets, CH, Feb 2018 https://issw.epfl.ch/

Depth Sensing Technologies

Depth Sensing



Using light to measure distances and thus, time of flight (TOF) – LiDAR (Light detection and ranging)

[D. Stoppa et al., SSCS Distinguished lecture 2018]

Time-resolved imaging is all around us

[G. Wetzstein, ISSW 2018]

[Velodyne, 2018]

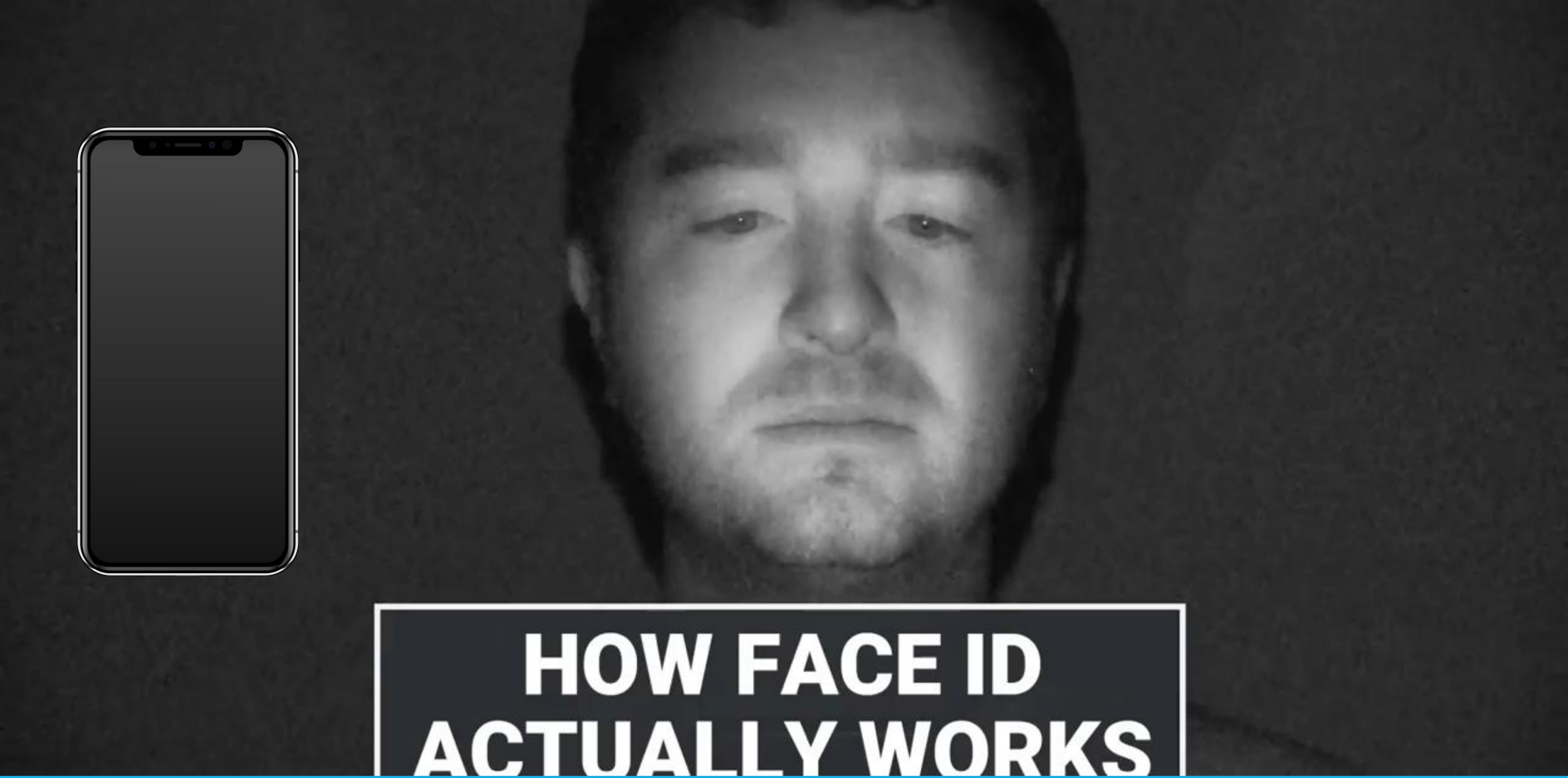
Depth Sensing

[G. Wetzstein, ISSW 2018]

[Velodyne, 2018, https://www.youtube.com/watch?v=KxWrWPpSE8I]

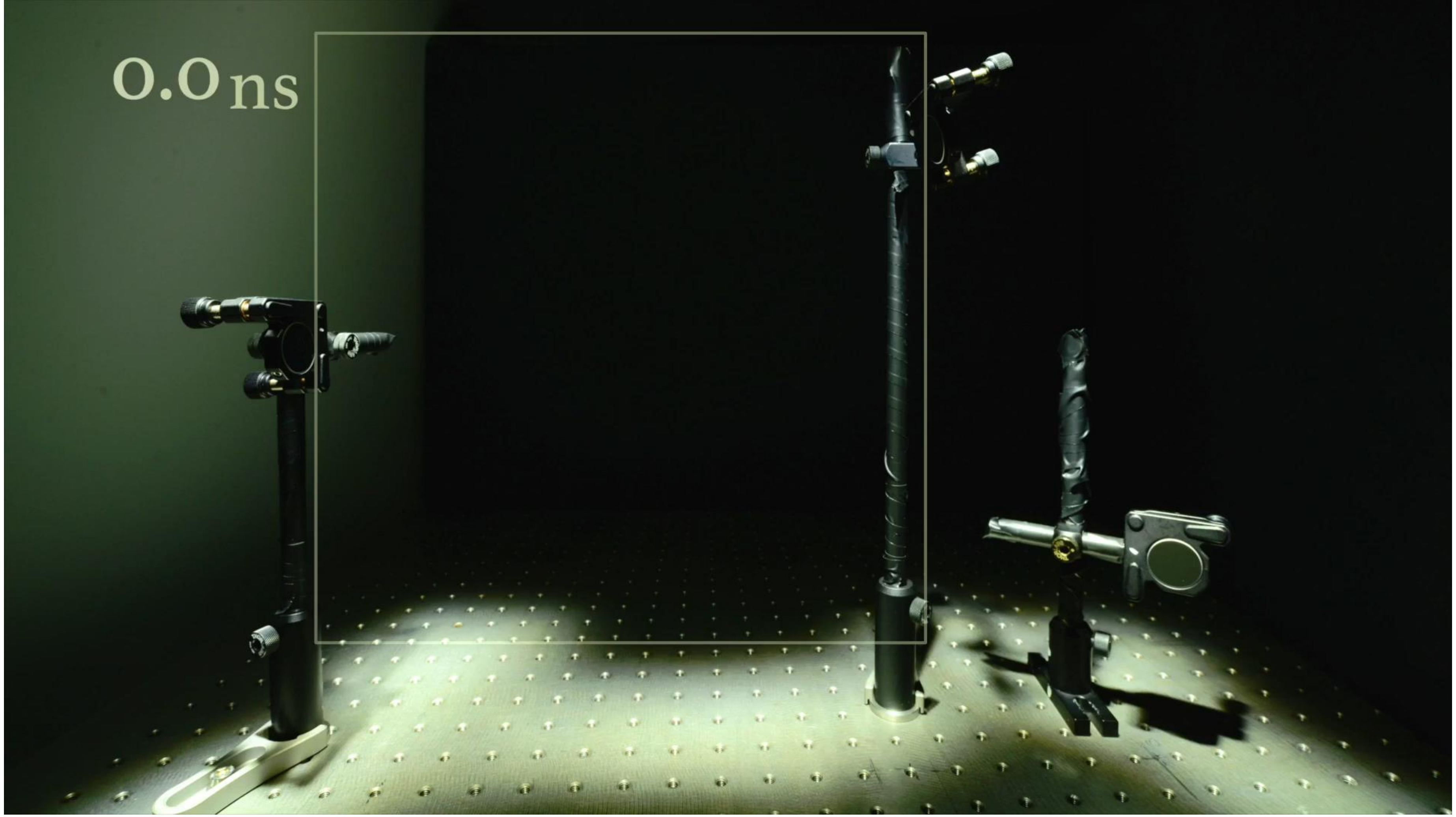
Consumer Smartphones

[G. Wetzstein, ISSW 2018]



[G. Wetzstein, ISSW 2018]

[Tech Insider 2017, https://www.youtube.com/watch?v=g4m6StzUcOw]

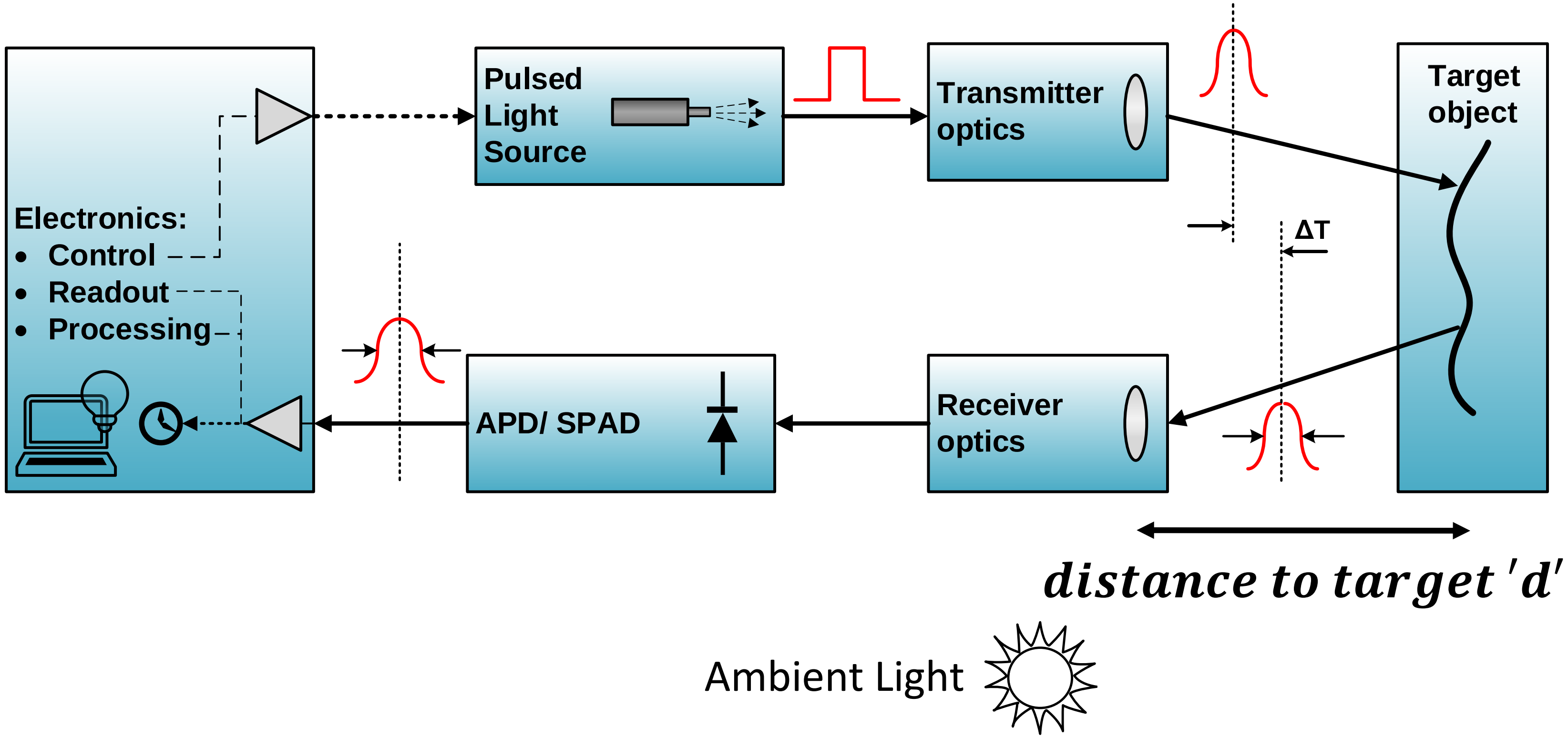


Scientific Applications – Light-In-Flight Imaging

[G. Gariepy et al., Nature Communications 6:6021 doi: 10.1038 2015]

LiDAR Basics & Direct Time-of-Flight (DTOF) Principles, DTOF vs. ITOF

Direct Time-of-Flight



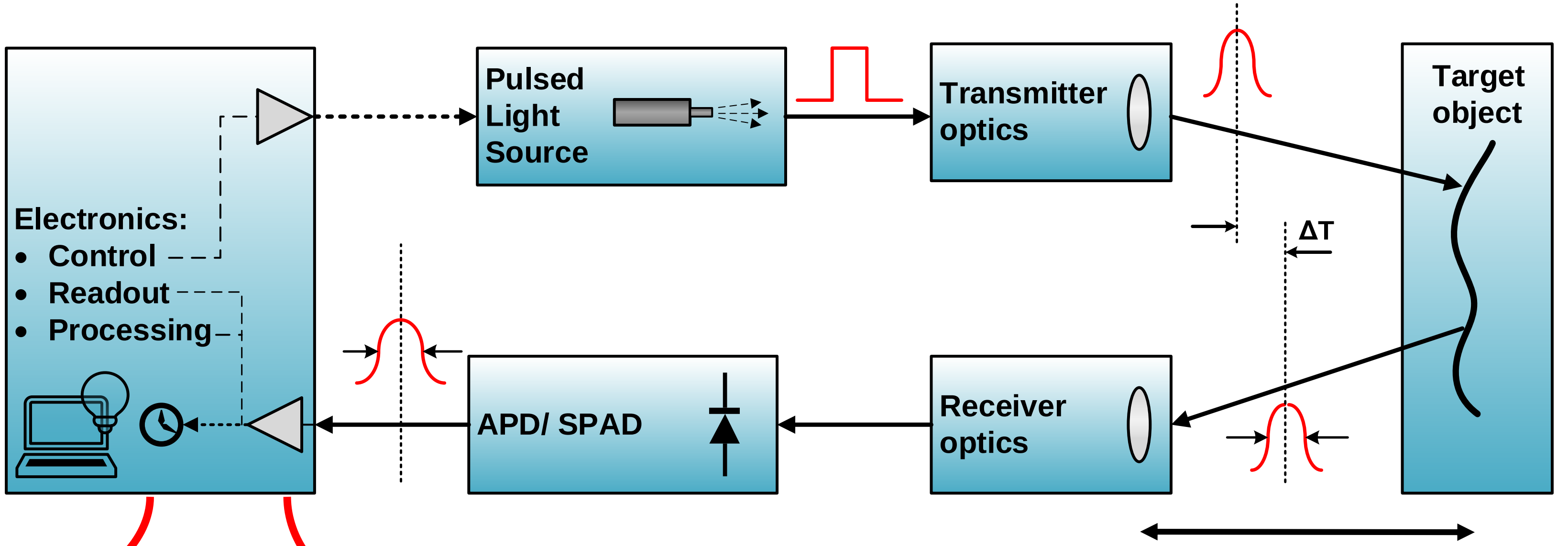
Common applications

- Proximity sensing
- Range-finding
- 3D imaging in scanning or flash mode

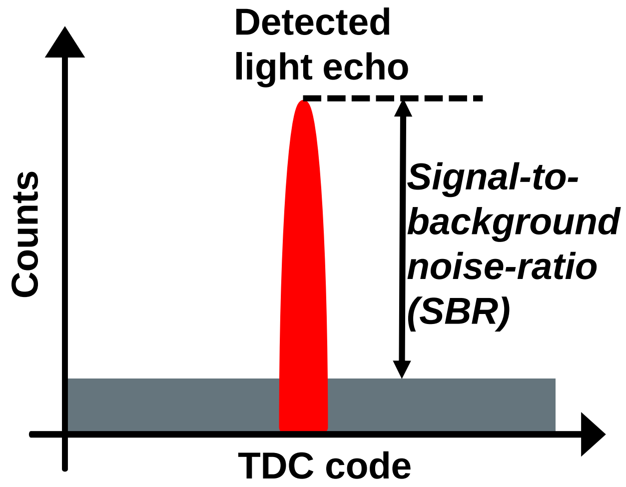
D-TOF system: TOF is 'directly' measured

$$d = \frac{c\Delta T}{2}, \text{ c is speed of light}$$

Direct Time-of-Flight



$$d = \frac{c\Delta T}{2}$$



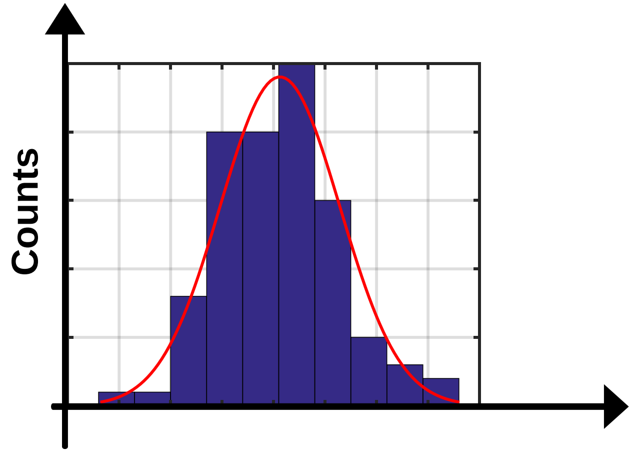
- time-to-amplitude converters (TACs)
- time-to-digital converters (TDCs)

Time-stamping circuits

- Transimpedance amplifier- comparators
- Avalanche quenching circuits

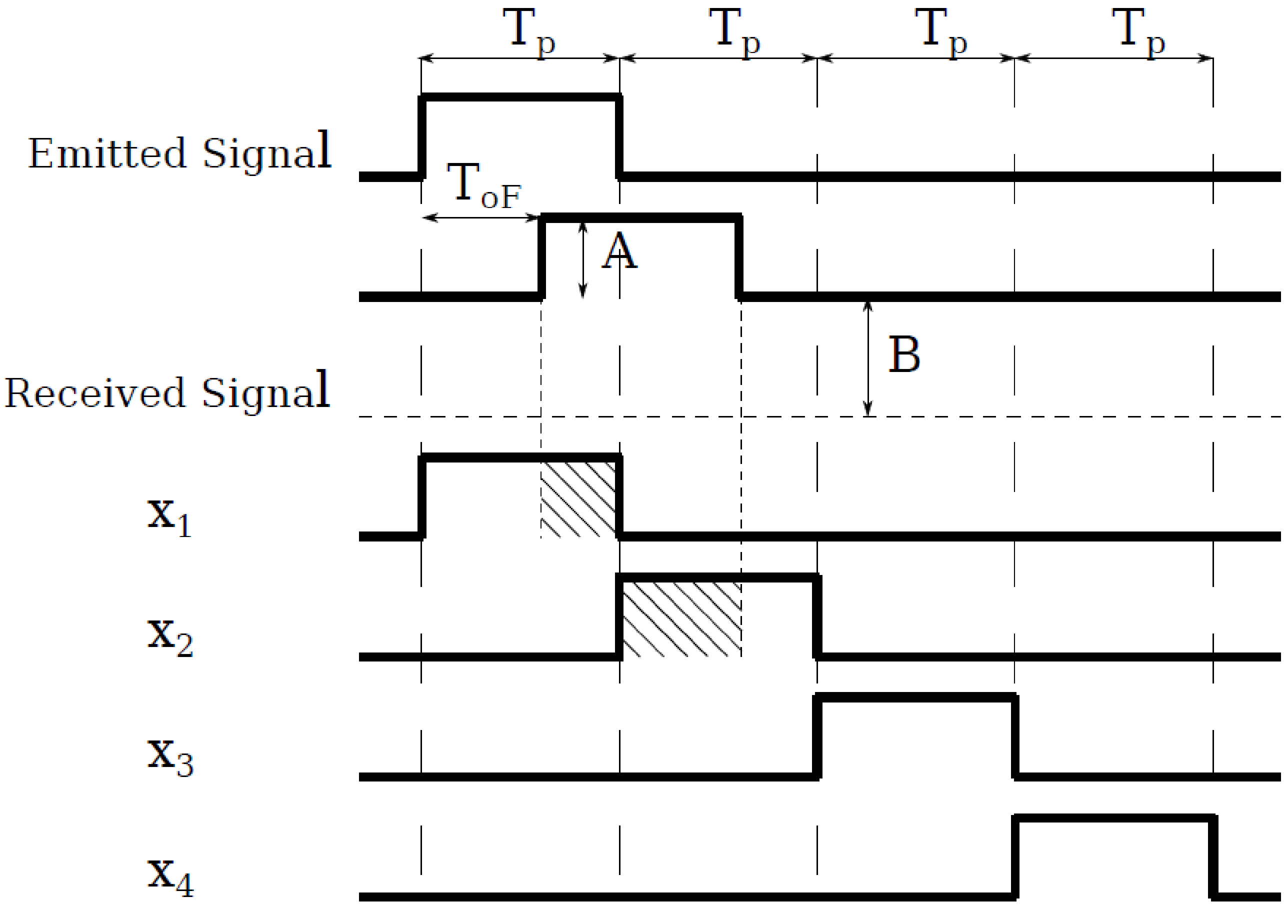
Typical front-end circuits

Histogram of time of arrival of reflected photons from target



Time-correlated single-photon counting (TCSPC)

Indirect Time-of-Flight (Pulsed)



[J. Quinteiro et al., Sensors 2015]

Phase shift determination using 4 windows

- The first measurement interval, X1, is **synchronized with the emitted pulse**
- The second interval, X2, comes right after it.
- The third and fourth measurements are carried out to sense the **background light**

$$x1 = BT_p + A(T_p - T_{oF})$$

$$x2 = BT_p + AT_{oF}$$

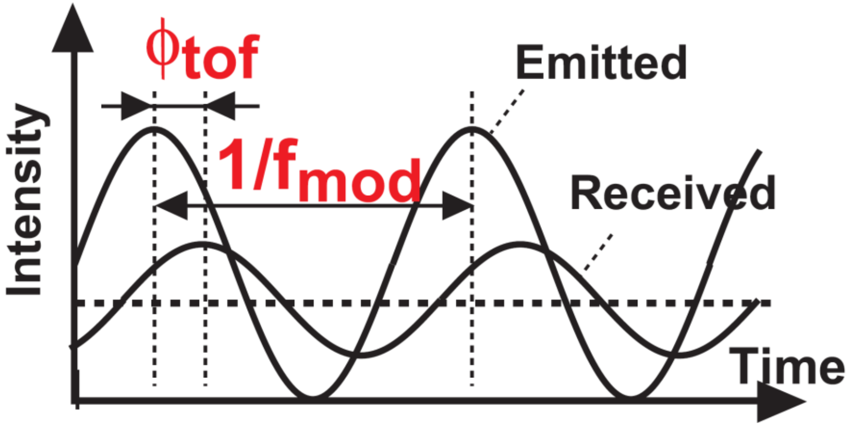
$$x3 = BT_p$$

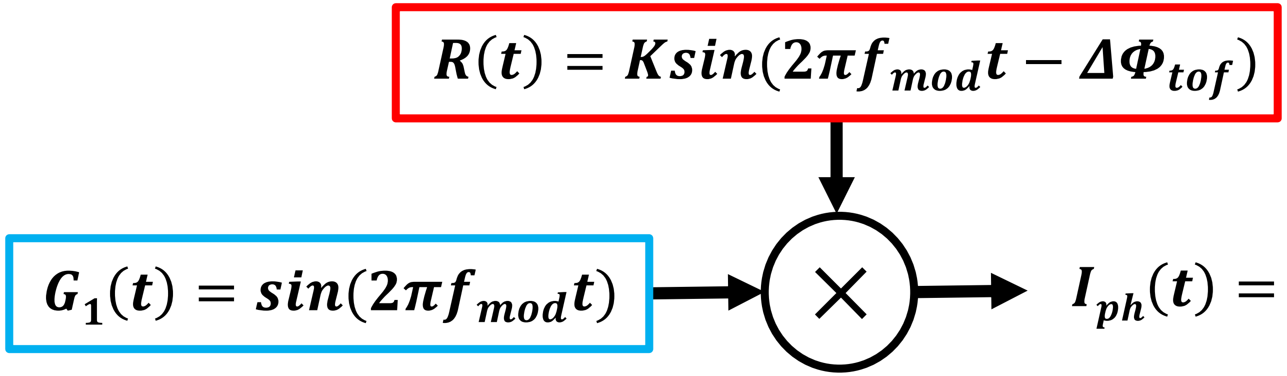
$$x4 = BT_p$$

$$Distance = \frac{c}{2} T_p \frac{x2 - x4}{(x1 - x3) + (x2 - x4)}$$

Indirect TOF (Phase of 1st Harmonic)

- Homodyne detection





Received light echo

$$R(t) = K\sin(2\pi f_{mod}t - \Delta\Phi_{tof})$$

$$G_1(t) = \sin(2\pi f_{mod}t)$$

Electrical Demodulation signal

$$I_{ph}(t) = \frac{K}{2}\left[\underbrace{\cos(\Delta\Phi_{tof})}_{} - \cos(4\pi f_{mod}t - \Delta\Phi_{tof})\right]$$

Low pass filter

DC component

$$\boxed{D = \frac{c\Delta\Phi}{4\pi f_{mod}}}$$

[D. Stoppa et al., SSCS Distinguished lecture 2018]

DTOF vs ITOF (1)

Direct Time-of-Flight (DTOF)

- Measure the direct time-of-flight
- VCSEL output pulse length: 0.2ns - 5ns; the shorter the better (resolution, eye safety)
- **[Used to be]** Limited to a small number of sensor elements
- Ranging from short up to long range (≈ few kilometers) possible; maximum range typically dictated by optical power budget

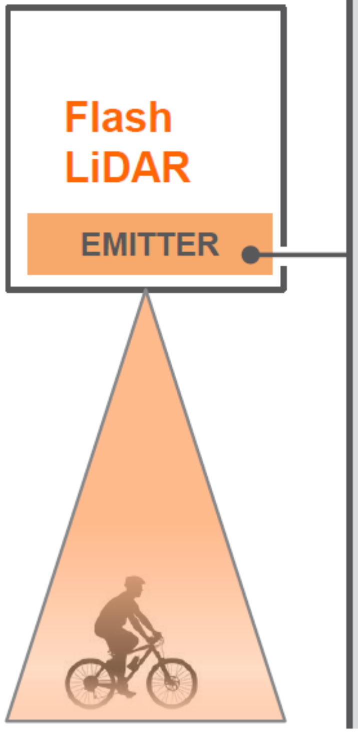
Indirect Time-of-Flight (ITOF)

- Measure the phase shift
- VCSEL output: 20-100MHz modulated sine wave
- Very small pixel, standard CMOS technology, enables high pixel count (QQVGA-VGA)
- Ranging from short up to medium range, typically within 50m; maximum range dictated by modulation frequency

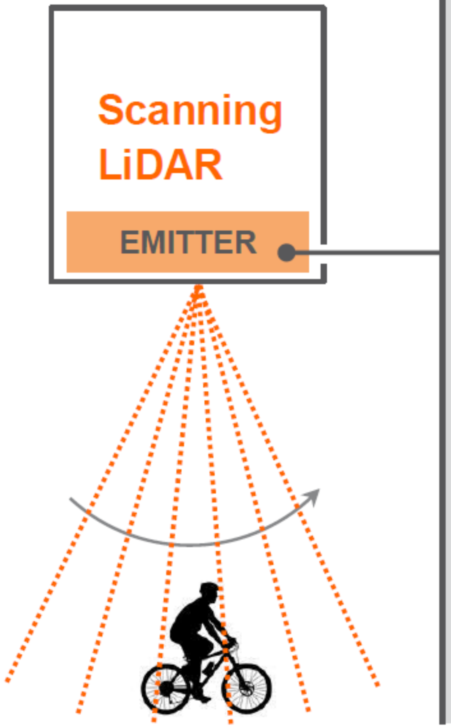
[ams analyst ad investment day report 2017]

Comparison of LiDAR Measurement Techniques: Scanning vs. Flash

Scanning vs. Flash LiDAR



- High to very high power needed to illuminate the whole scene with one laser beam
- In the future, laser bars (edge emitting laser) with high power for longer distances or potential use of VCSEL for SRL



- Highly directional beam with high power needed
- Good thermal performance for high repetition rate
- Today and in future edge emitting lasers operating at 905nm expected to dominate

- The whole FOV is illuminated at once using a wide-angle beam
- No moving parts in the LiDAR module

- Scanning, narrow emitter beam which is being moved across the FOV over time
- Mechanical solution or micro-mirrors used for beam steering

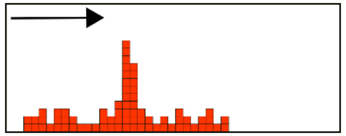
[OSRAM LiDAR Teach-In, 2018]

Detection Devices and Technologies:

Avalanche Photodiodes (APDs & SPADs)

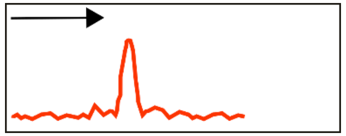
SPAD vs. APD - Principles

Digital

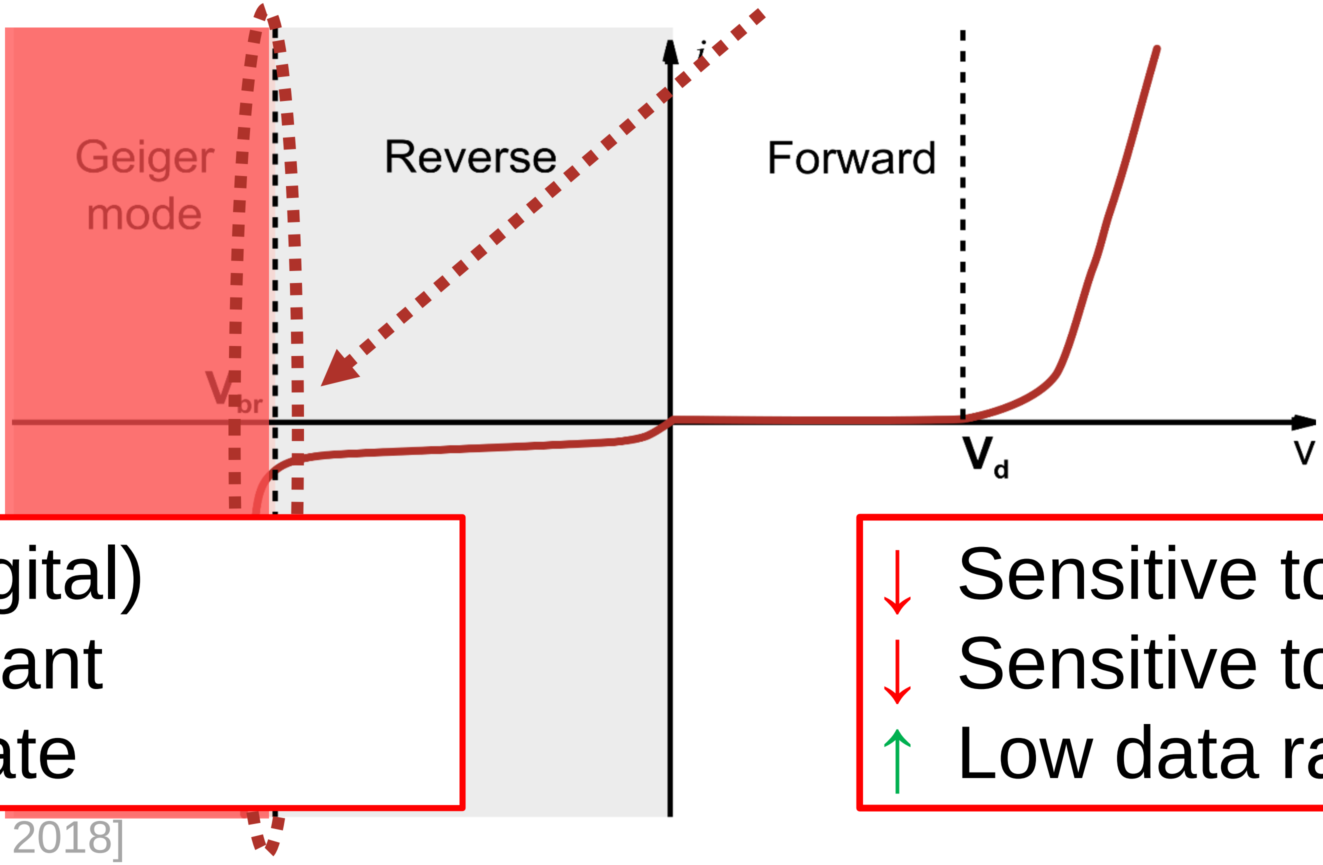


Single Photon Avalanche Diode (SPAD)

Analog



Avalanche Photo-Diode (APD)

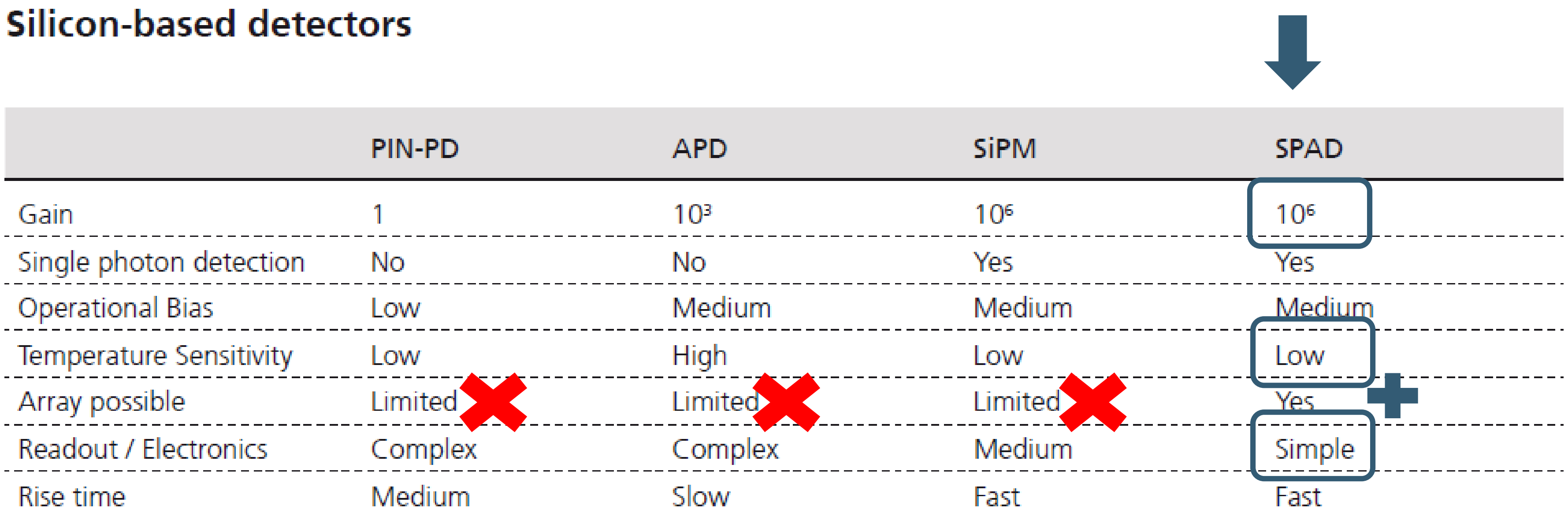


- ↑ Flexible (Digital)
- ↑ Noise resistant
- ↓ High data rate

- ↓ Sensitive to noise
- ↓ Sensitive to temperature
- ↑ Low data rate

[L. Carrara, Fastree3D, ISSW 2018]

Photodiodes in Silicon – Summary



Silicon-based detectors

	PIN-PD	APD	SiPM	SPAD
Gain	1	10^3	10^6	10^6
Single photon detection	No	No	Yes	Yes
Operational Bias	Low	Medium	Medium	Medium
Temperature Sensitivity	Low	High	Low	Low
Array possible	Limited	Limited	Limited	Yes
Readout / Electronics	Complex	Complex	Medium	Simple
Rise time	Medium	Slow	Fast	Fast

Source: forschungsfabrik-mikroelektronik.de

(Forschungsfabrik Mikroelektronik Deutschland: Fraunhofer/Leipniz cooperation concerning Microelectronics in Germany)

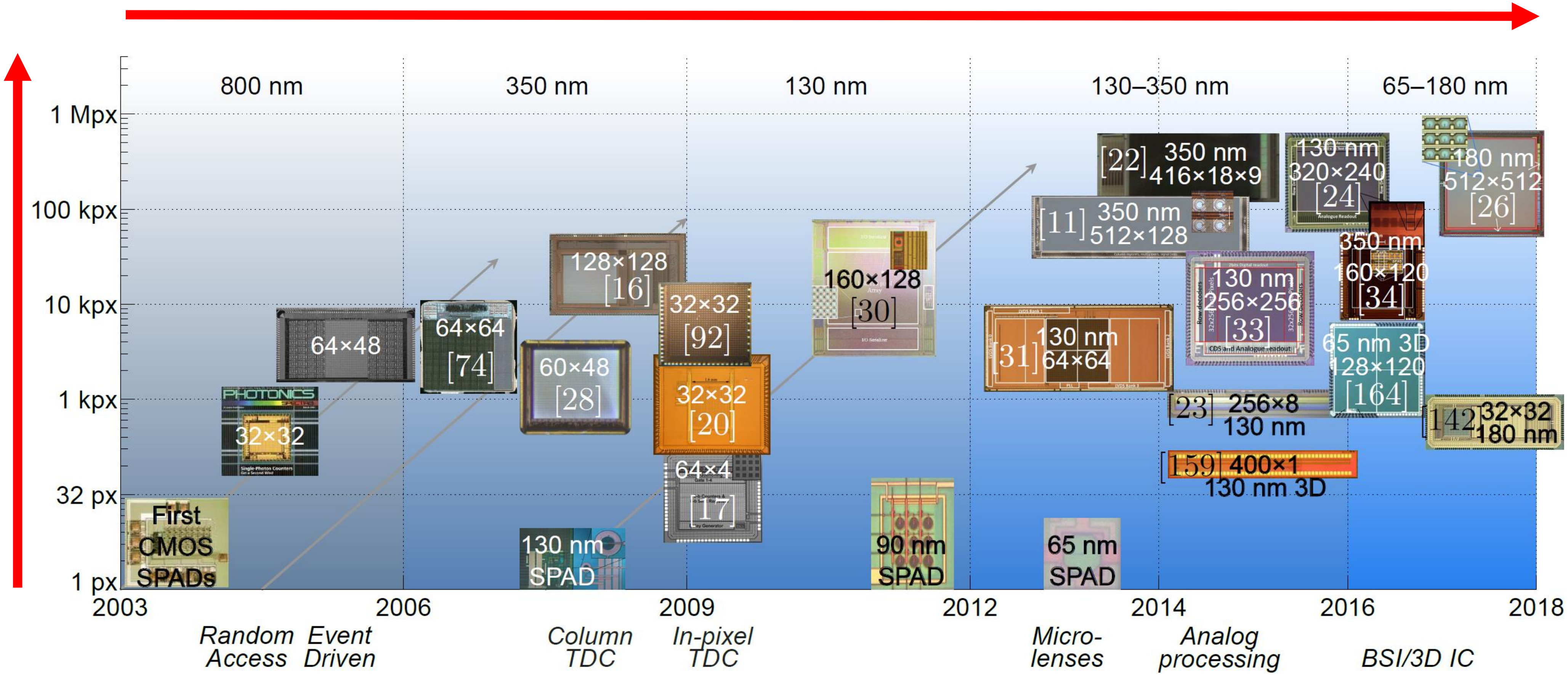
Best choice for Flash LiDAR: SPAD

- Single Photon Avalanche Diodes

[J. Ruskowski, Fraunhofer, SPIE PW 2019]

Trends in SPAD Arrays/Imagers

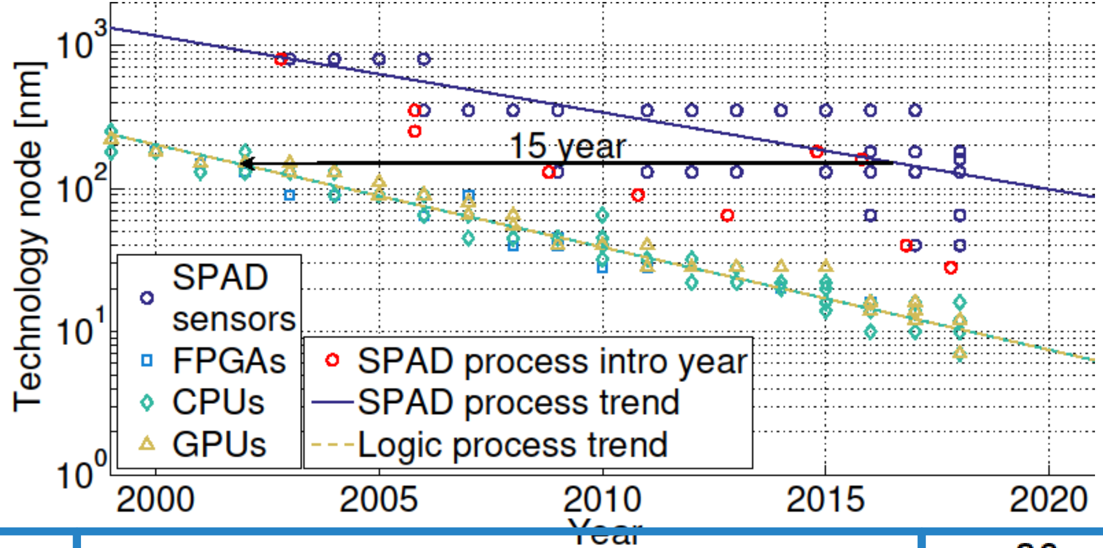
Technology node shrinking



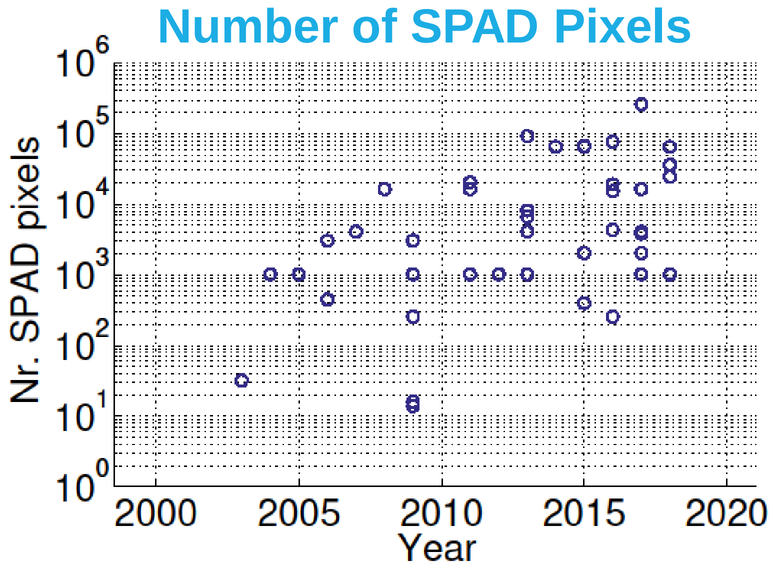
Timeline - monolithic to 3D stacking

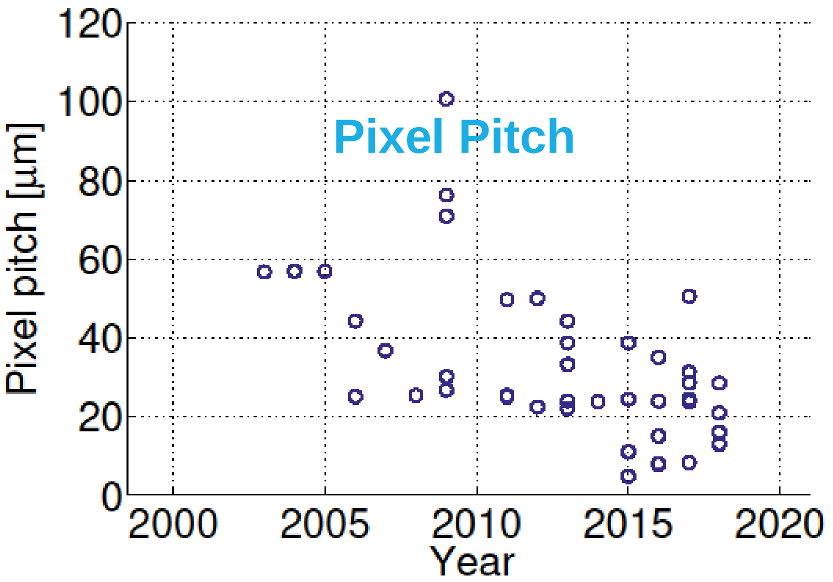
[C. Bruschini et al., EPFL & TU Delft, Light LSA, *accepted for publication*]

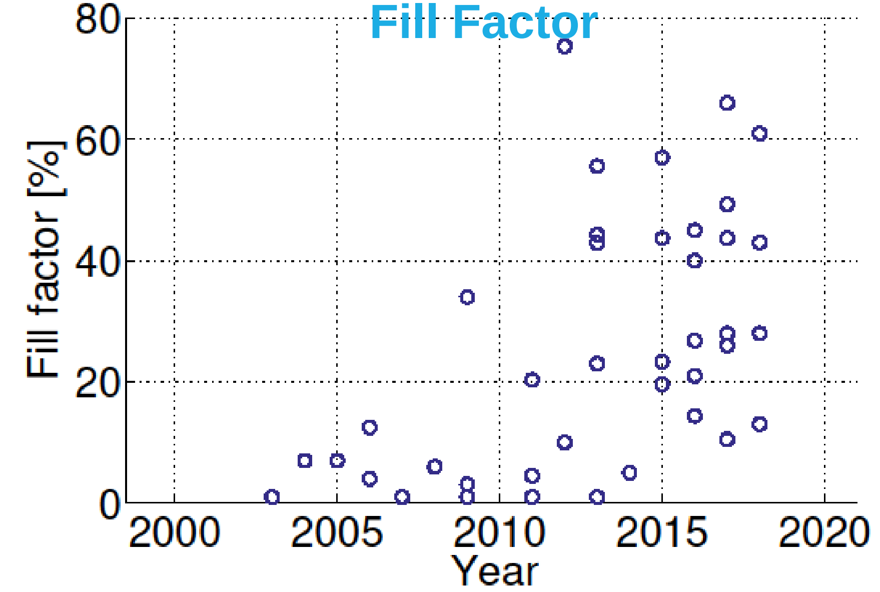
Trends in SPADs



Process node


Number of SPAD Pixels

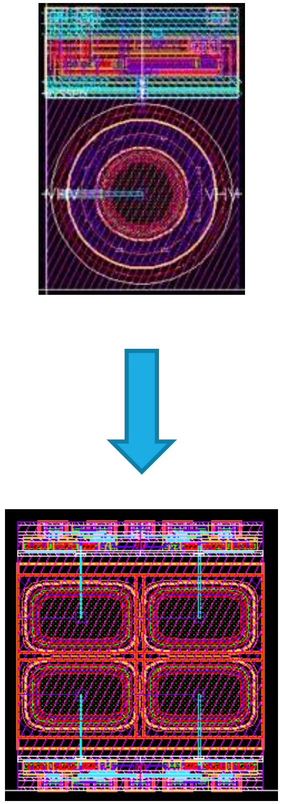

Pixel Pitch


Fill Factor

[C. Bruschini et al., EPFL & TU Delft, *to be published*]

Industrialised SPADs – STMicroelectronics 130nm

Pixel only containing passive quenching circuit



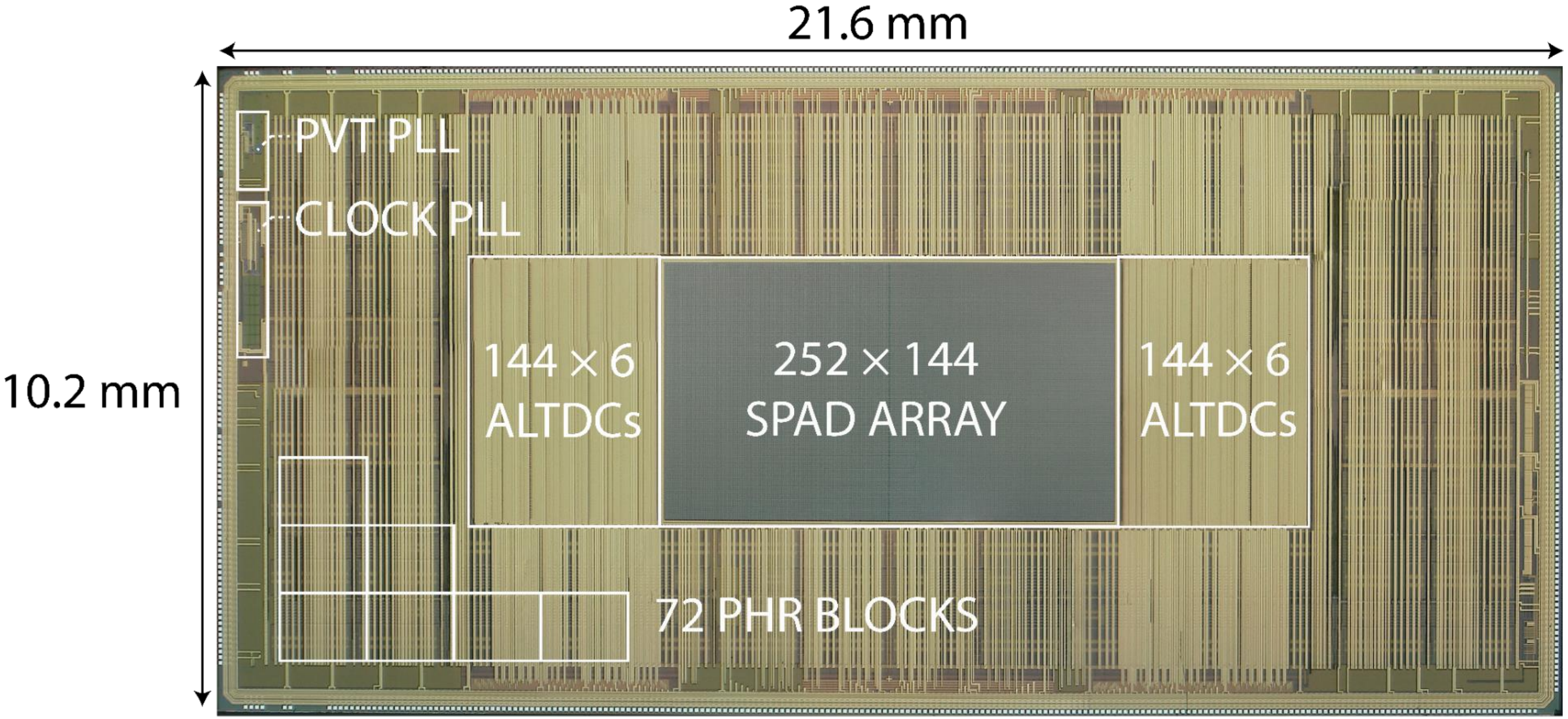
Metric	**IMG175SPAD Value (@ 60°C)** [SPIE Photon Counting Conference]
VHV0	13.8V
DCR Median	~1k cps
PDP	3.1% (850nm)
Fill Factor	6% → 21.6%
Pulse Width	25ns
Max Count Rate	37Mcps
Jitter	120ps FWHM, 870ps FW1%M
Current per Pulse	0.08pA
After-Pulsing	<0.1%
Cross-Talk	<0.01% (isolated SPAD)

[Source: S. Pellegrini, STMicroelectronics ISSW 2018]

Sensor Architectures, Monolithic vs. 3D-Stacked Approaches

- ❑ **Monolithic Technology**
  - SPAD-based architectures
    - TCPSC & binary/gated sensors
  - Hybrid & multi-digital SiPM architectures
- ❑ 3D-Stacked
  - CIS (CMOS Image Sensors)
  - SPAD-based architectures & devices
  - SPAD-based TOF examples

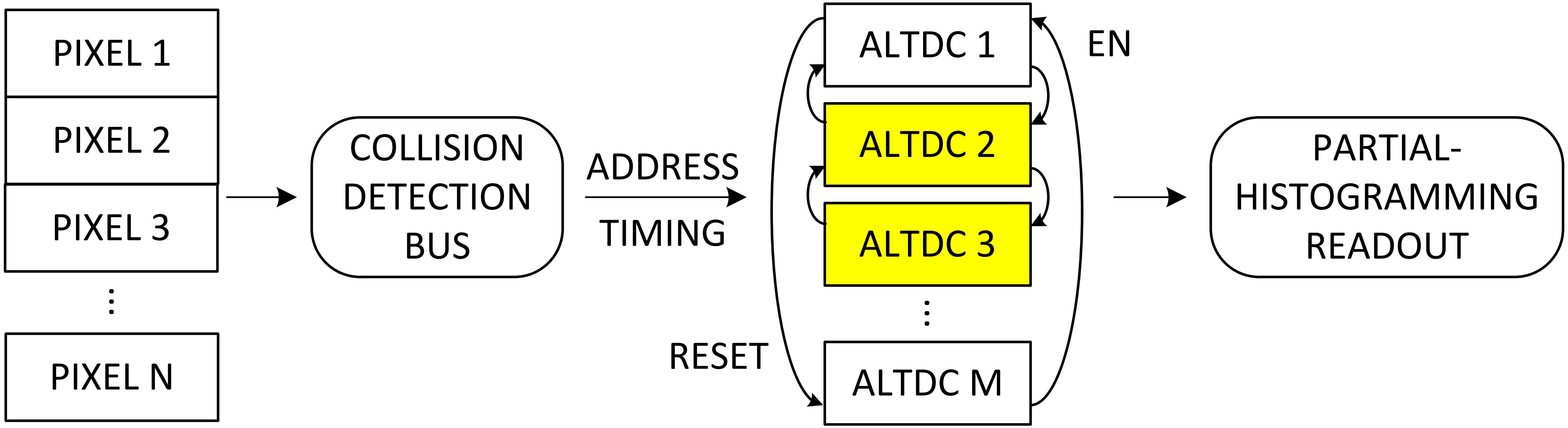
TCSPC Monolithic SPAD Array: Ocelot (252x144)



- 180nm CMOS technology
- Partial histogramming readout (PHR) for data compression
- 28% fill factor (28.5µm pitch)

[S. Lindner et al., IISW 2017, Sym. VLSI 2018]

Ocelot TCSPC Architecture



PIXEL 1

PIXEL 2

PIXEL 3

⋮

PIXEL N

COLLISION DETECTION BUS

ADDRESS

TIMING

ALTDC 1

ALTDC 2

ALTDC 3

⋮

ALTDC M

EN

RESET

PARTIAL-HISTOGRAMMING READOUT

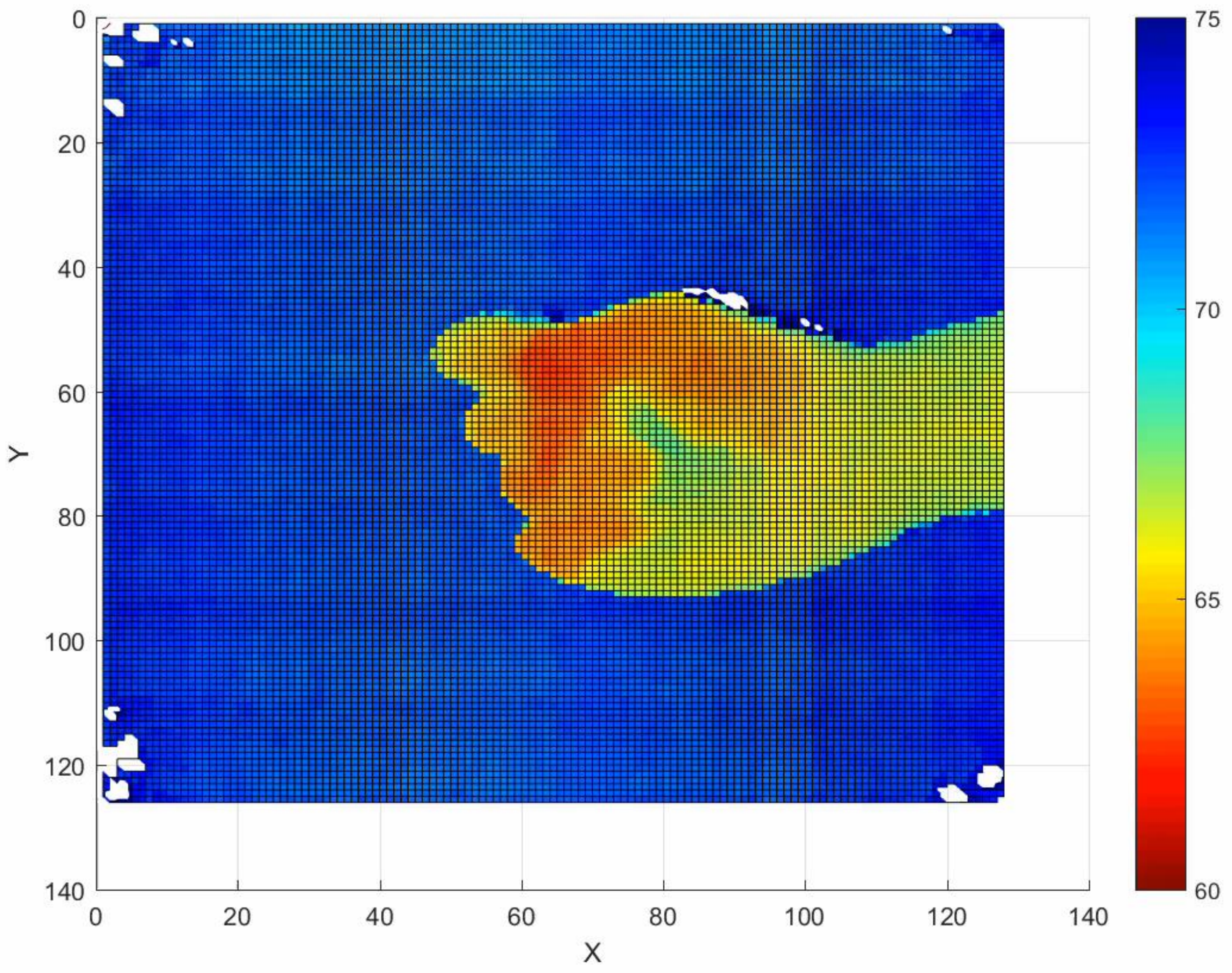
[S. Lindner et al., EPFL & TU Delft, IISW 2017, Sym. VLSI 2018]

2 mW laser

637 nm

126 × 128

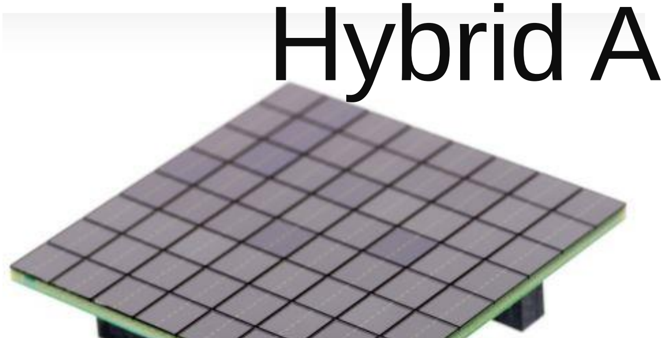
30 fps



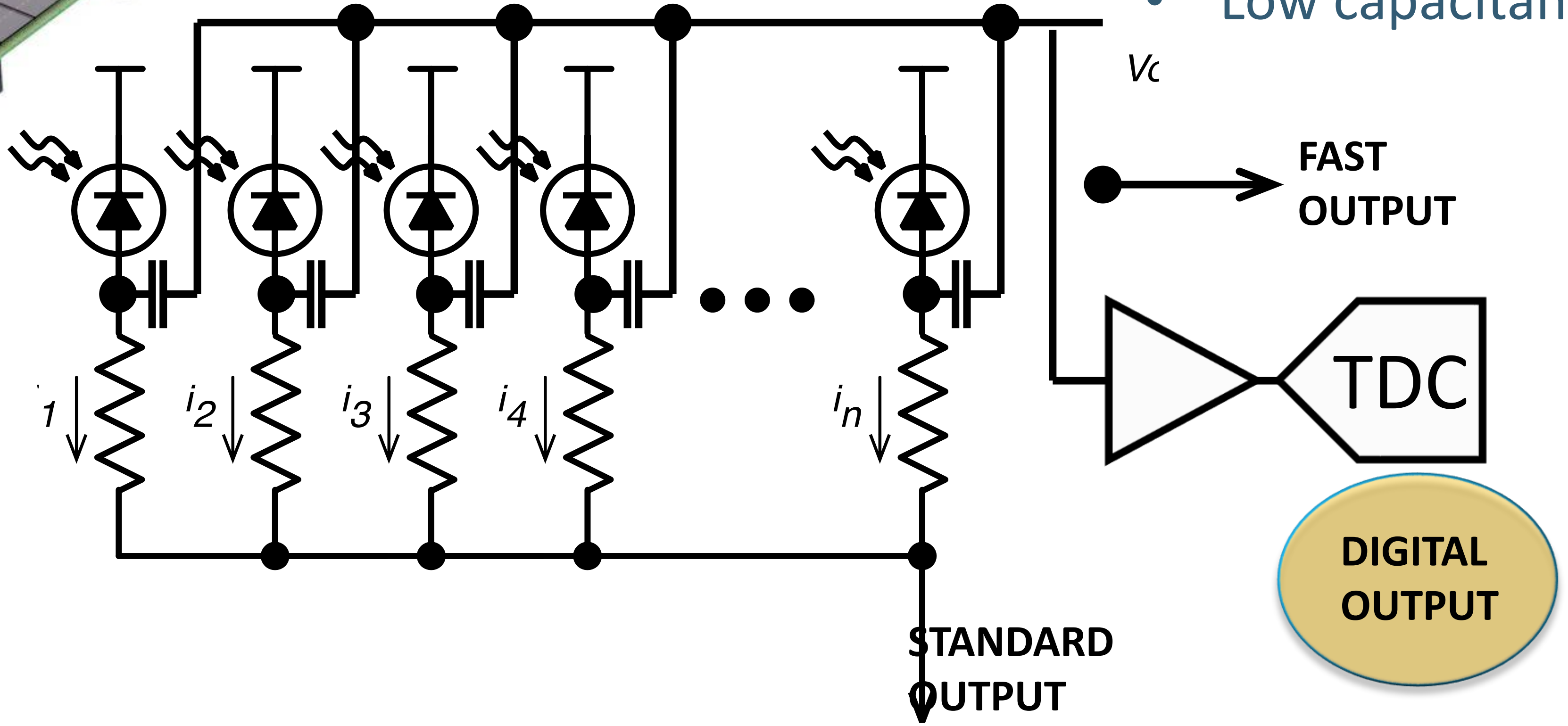
Flash Video Demo

[S. Lindner et al, EPFL & TU Delft, IISW 2017, Sym. VLSI 2018]

Hybrid Architectures: Digital Analog SiPM



- Ultra-fast output
- Low capacitance



[A. Muntean et al., EPFL, IEEE NSS-MIC 2018]

Sensor Architectures, Monolithic vs. 3D-Stacked Approaches

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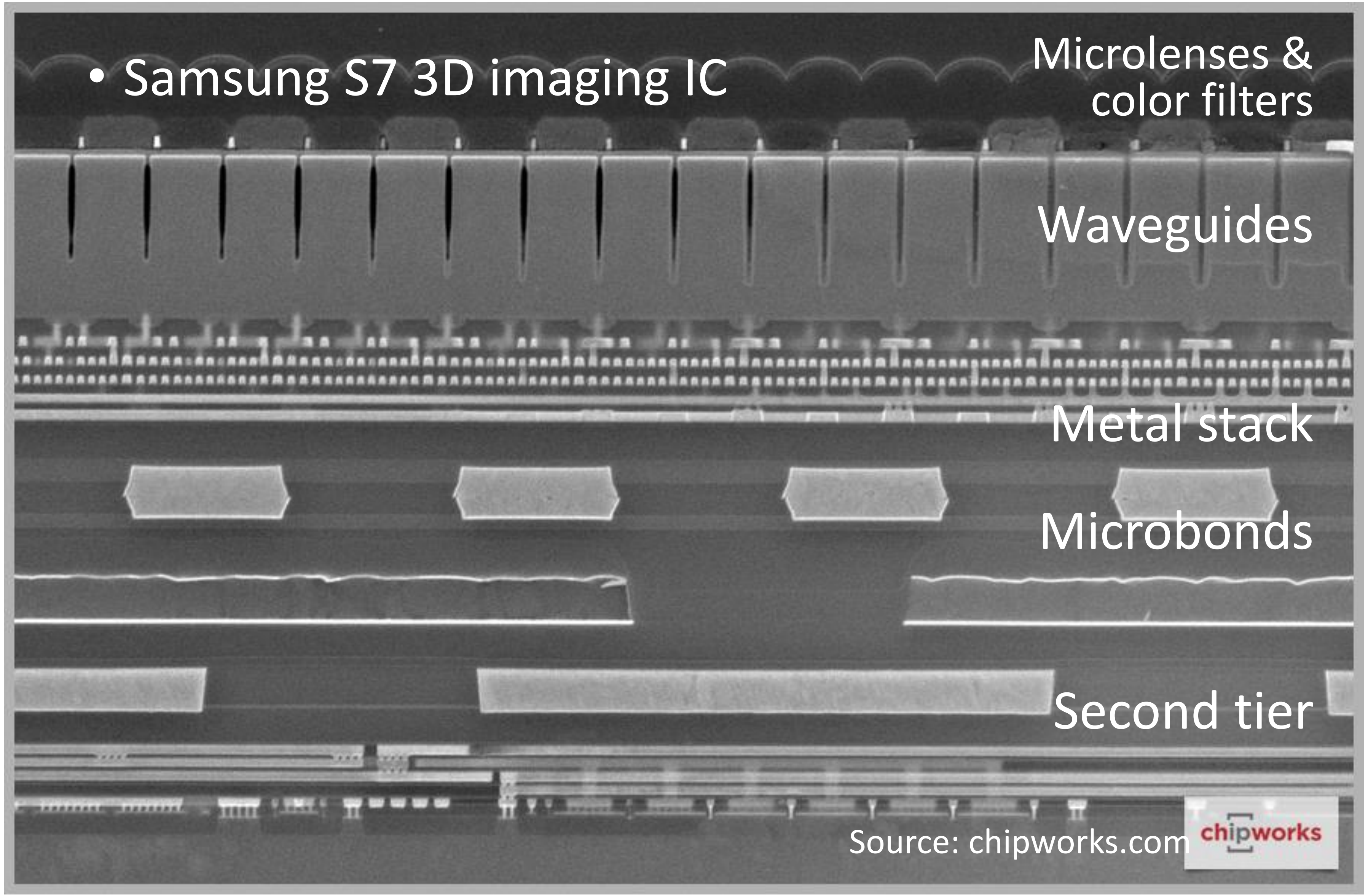
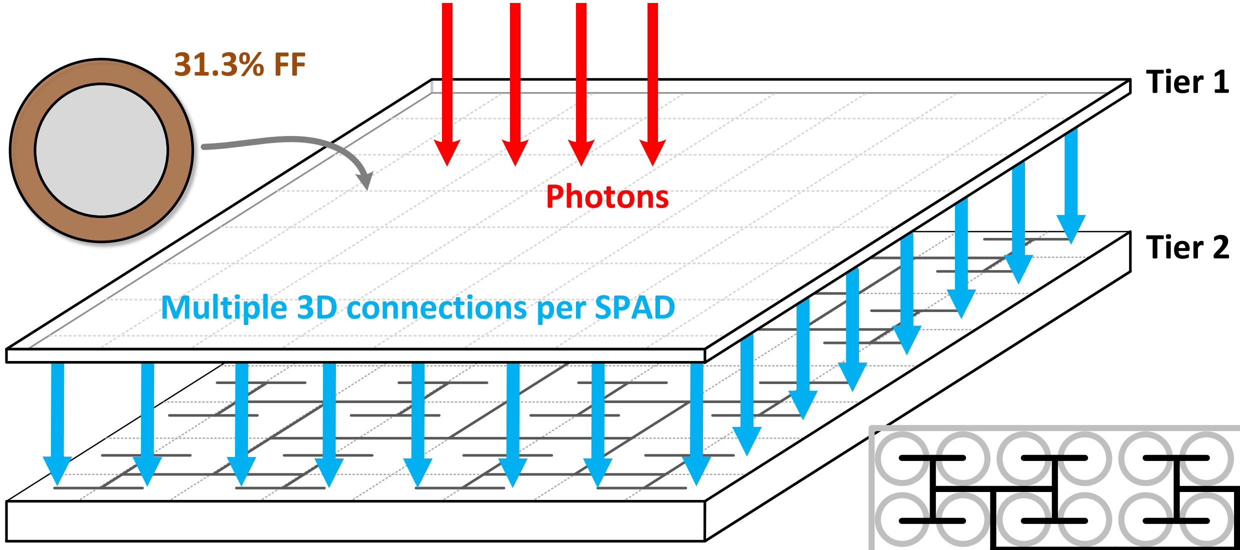
Conventional (CMOS) 3D BSI Imager

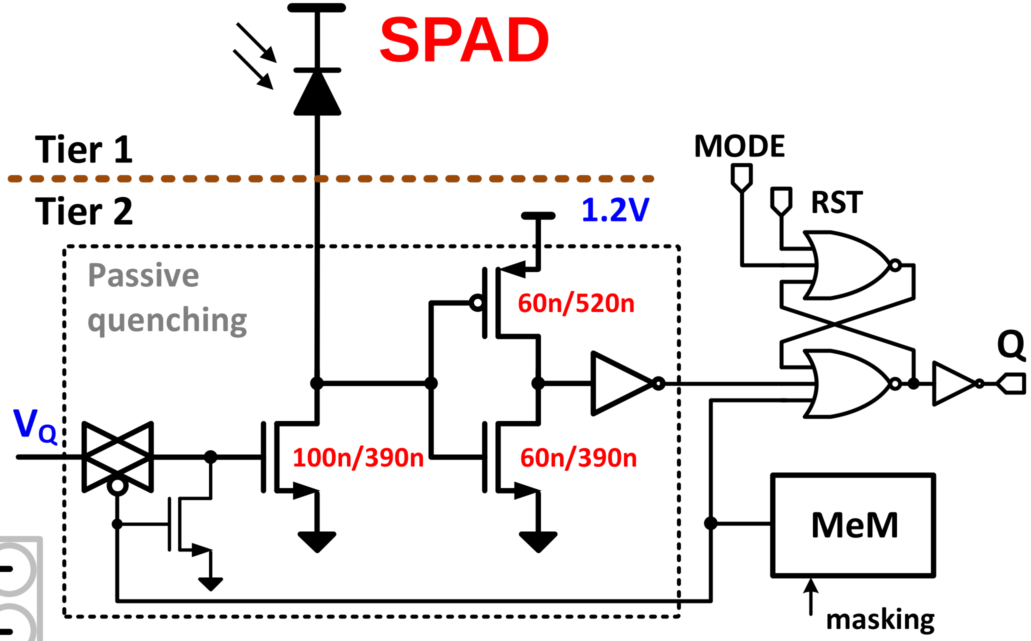


- Samsung S7 3D imaging IC

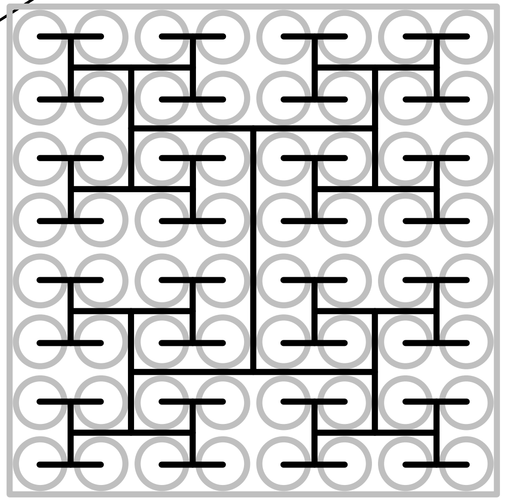
Source: chipworks.com

3D BSI SPADs: Stacking and Modularity





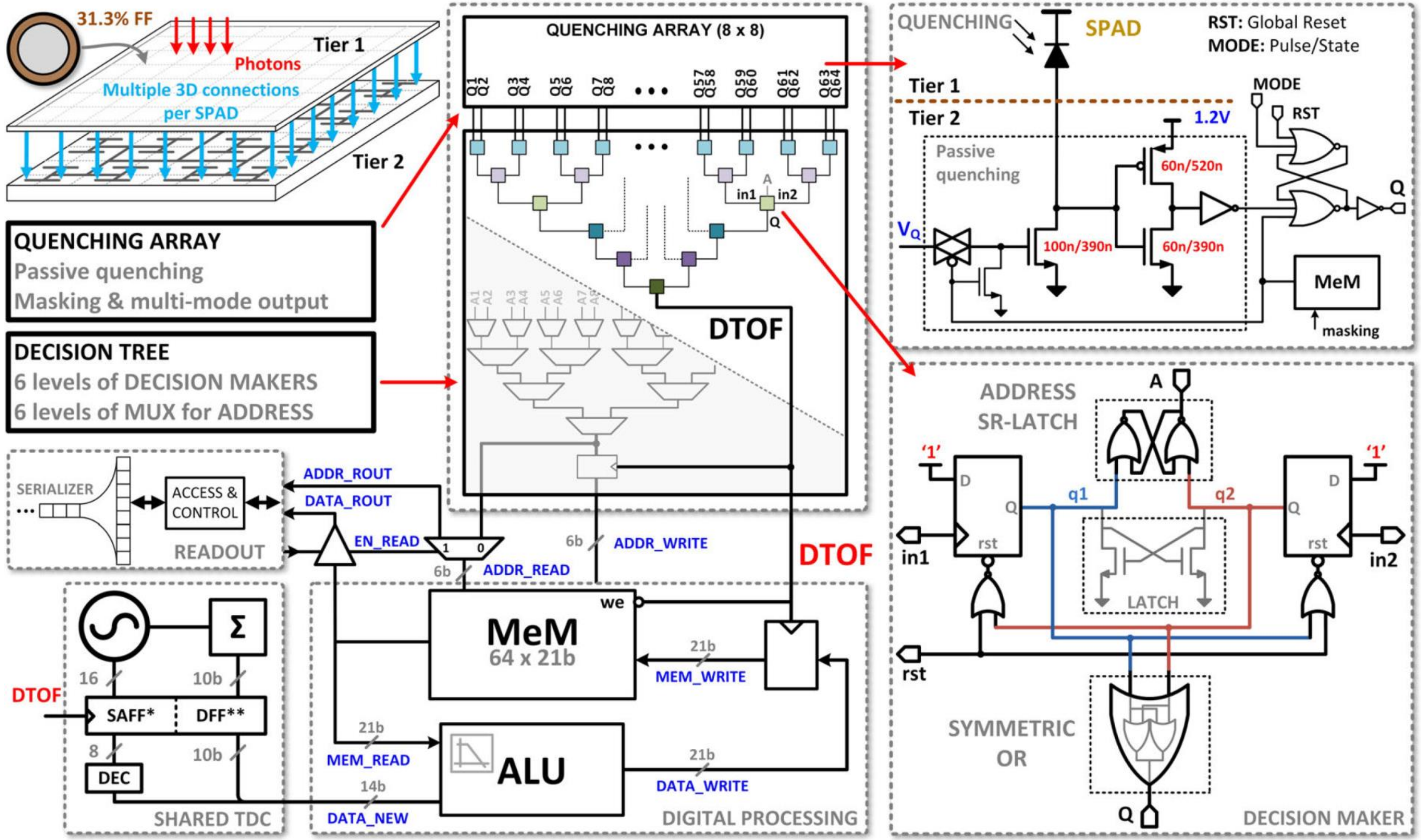
SUBGROUP
8 x 8 SPADs



- **Passive quenching**
- **Electrical & optical mask**
- **Pulse/State output modes**
- **External Reset**

[A. Ximenes/P. Padmanabhan, TU Delft & EPFL, ISSCC 2018, “**A 256×256 45/65nm 3D-Stacked SPAD-based…**”

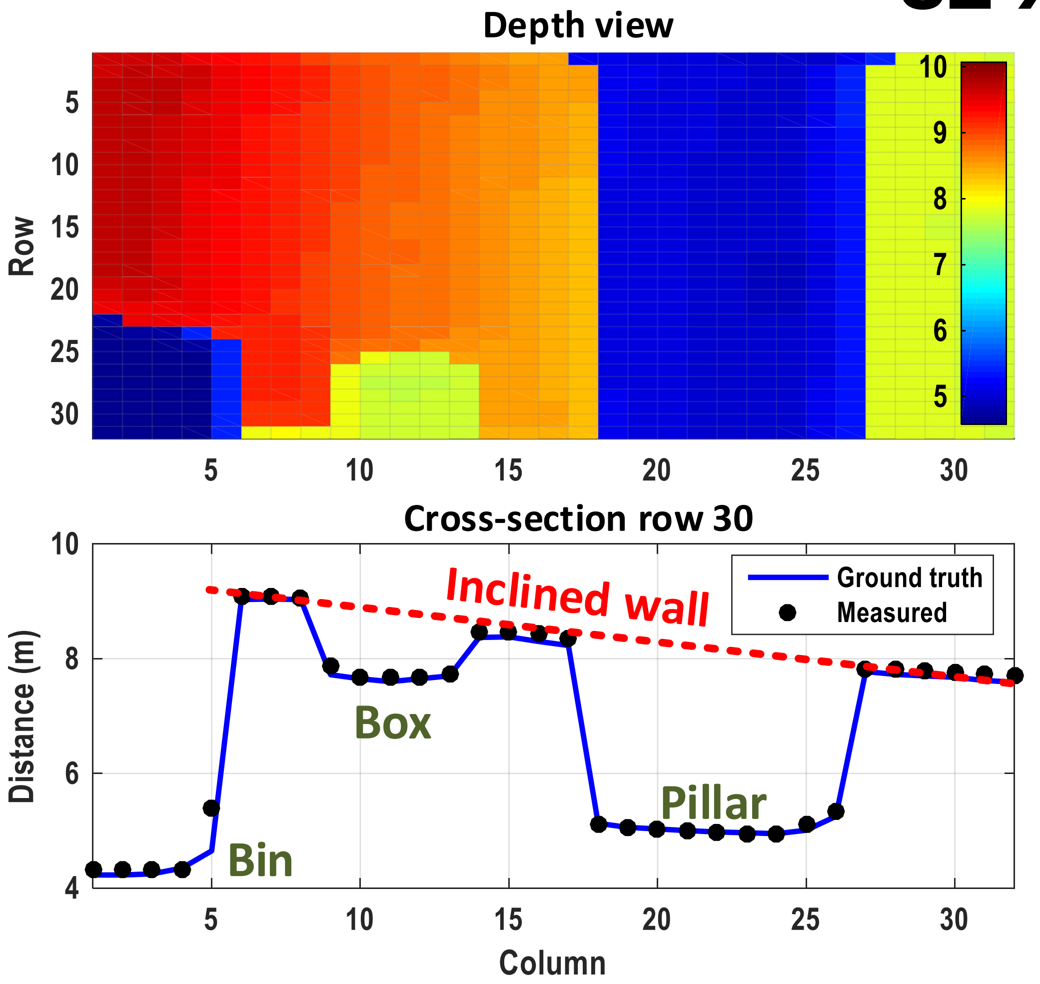
Bottom Tier Architecture Example

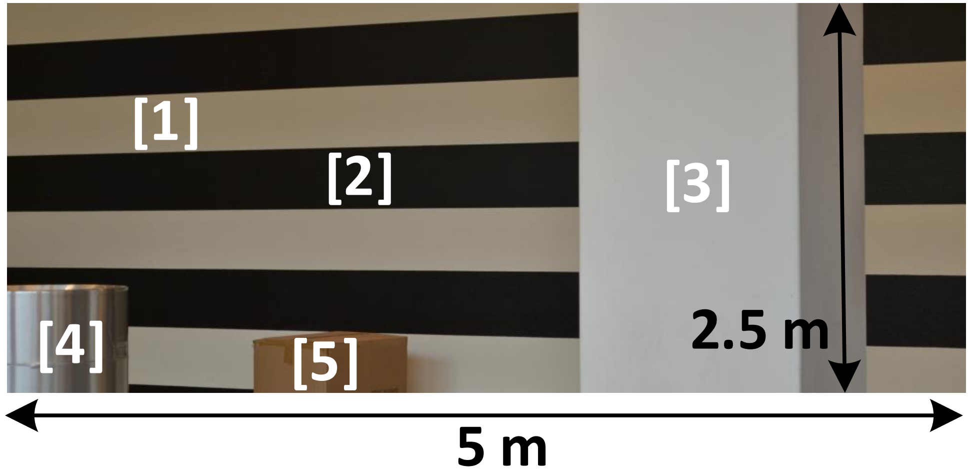


[A. Ximenes/P. Padmanabhan, TU Delft & EPFL, ISSCC 2018, “**A 256×256 45/65nm 3D-Stacked SPAD-based…**”

Scanner System

32 x 32



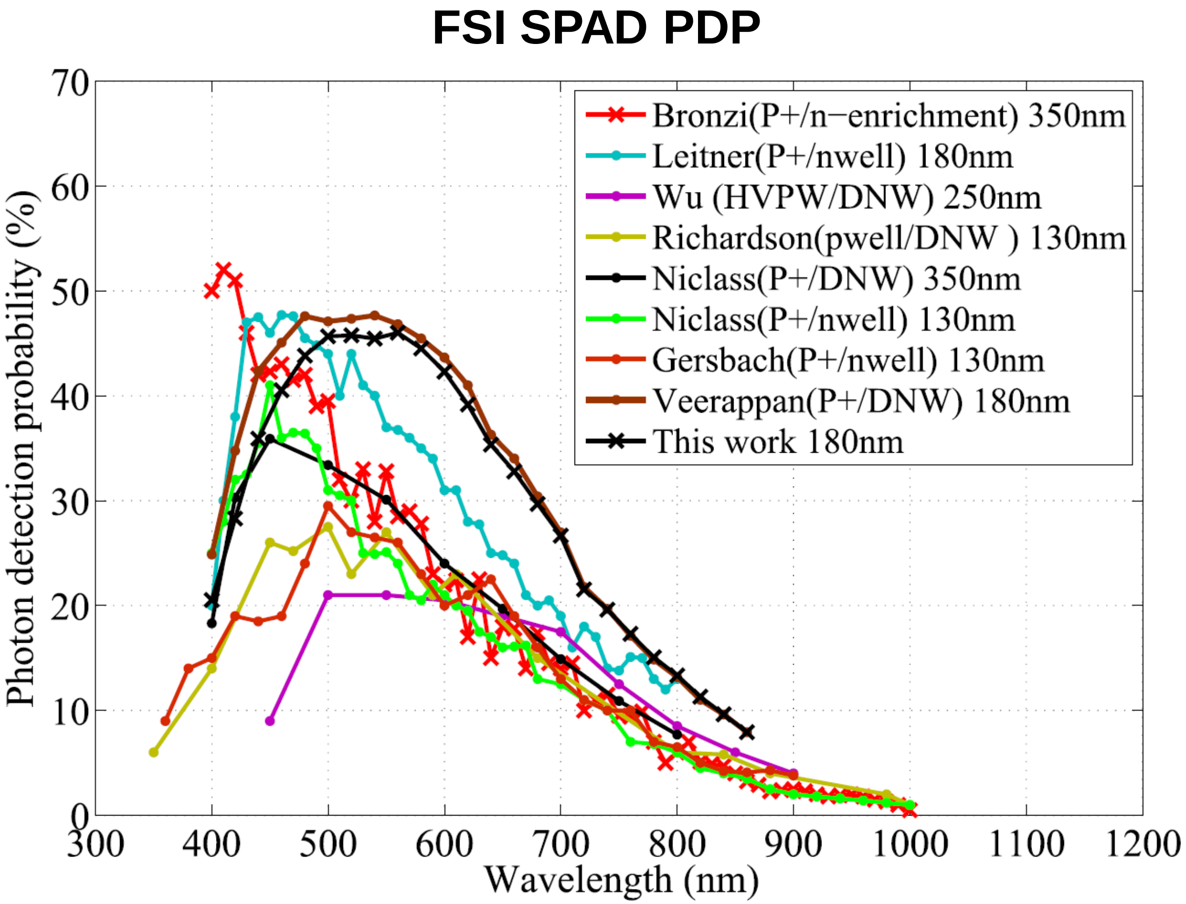


Different target reflectivities

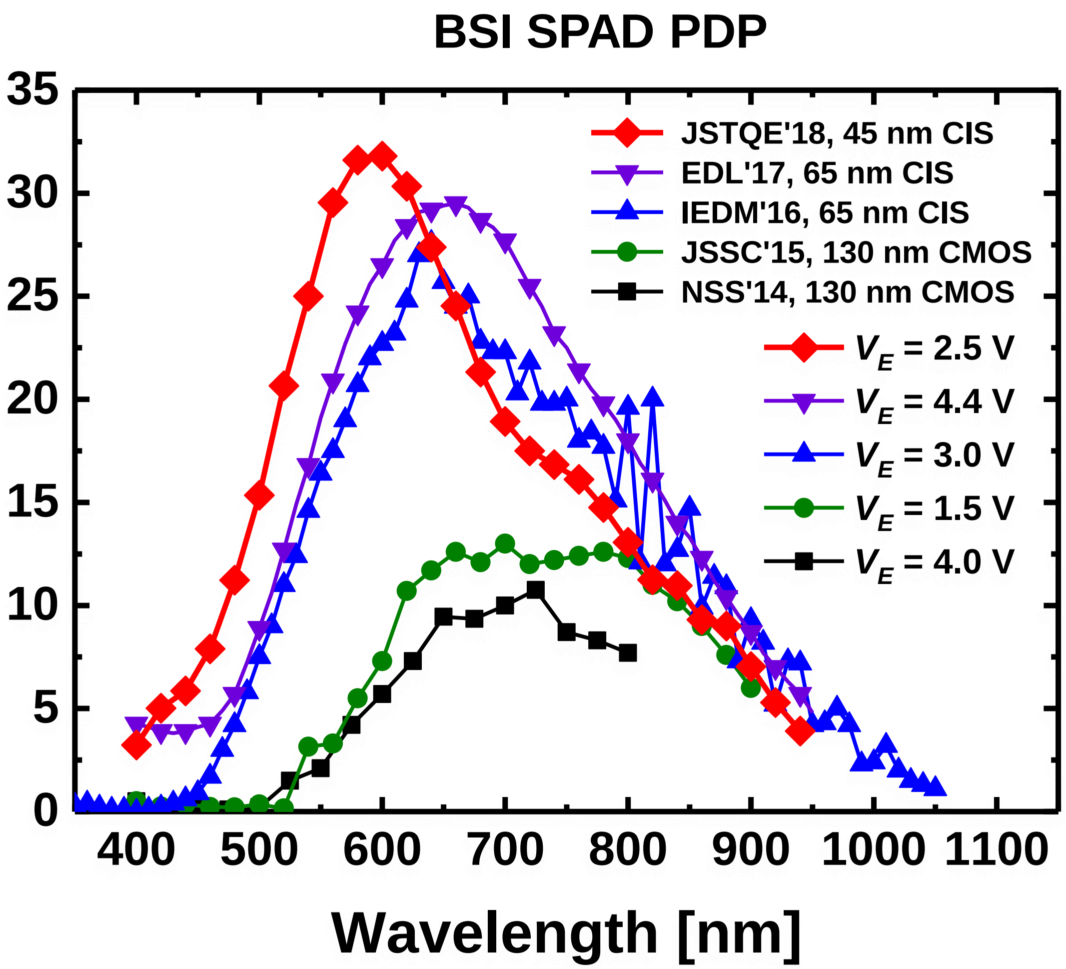
[1] – White wall – 50%
[2] – Black wall – 8%
[3] – White pillar – 60%
[4] – Aluminum bin – 54%
[5] – Cardboard box – 21%

[A. Ximenes/P. Padmanabhan, TU Delft & EPFL, ISSCC 2018, “**A 256×256 45/65nm 3D-Stacked SPAD-based…**”

FSI & BSI 3D SPAD – PDP Comparison



C. Veerappan & E. Charbon, TED(63) 2016



M.-J. Lee *et al.*, Jpn. J. Appl. Phys 2018

ToF Consumer Application Examples

SPAD-SiPM Technology in Products

forimtech
fiber optic radiation imaging tech

BOSCH

LG

GE Healthcare

Miniature 3D Depth Camera

VL53L5, Compact Integrated Module

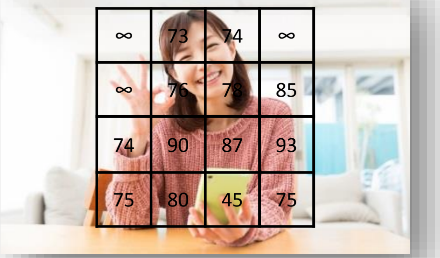
- Class 1 certified 940nm invisible VCSEL
- 61° diagonal, square FoV

Ranging Capabilities

- Up-to 64 (8x8) ranging zones
- Up-to 4m ranging per zone

Human Presence detection

- Instant Windows Hello® sign-in
- Power saving
- Security & Privacy Control



Camera Assist

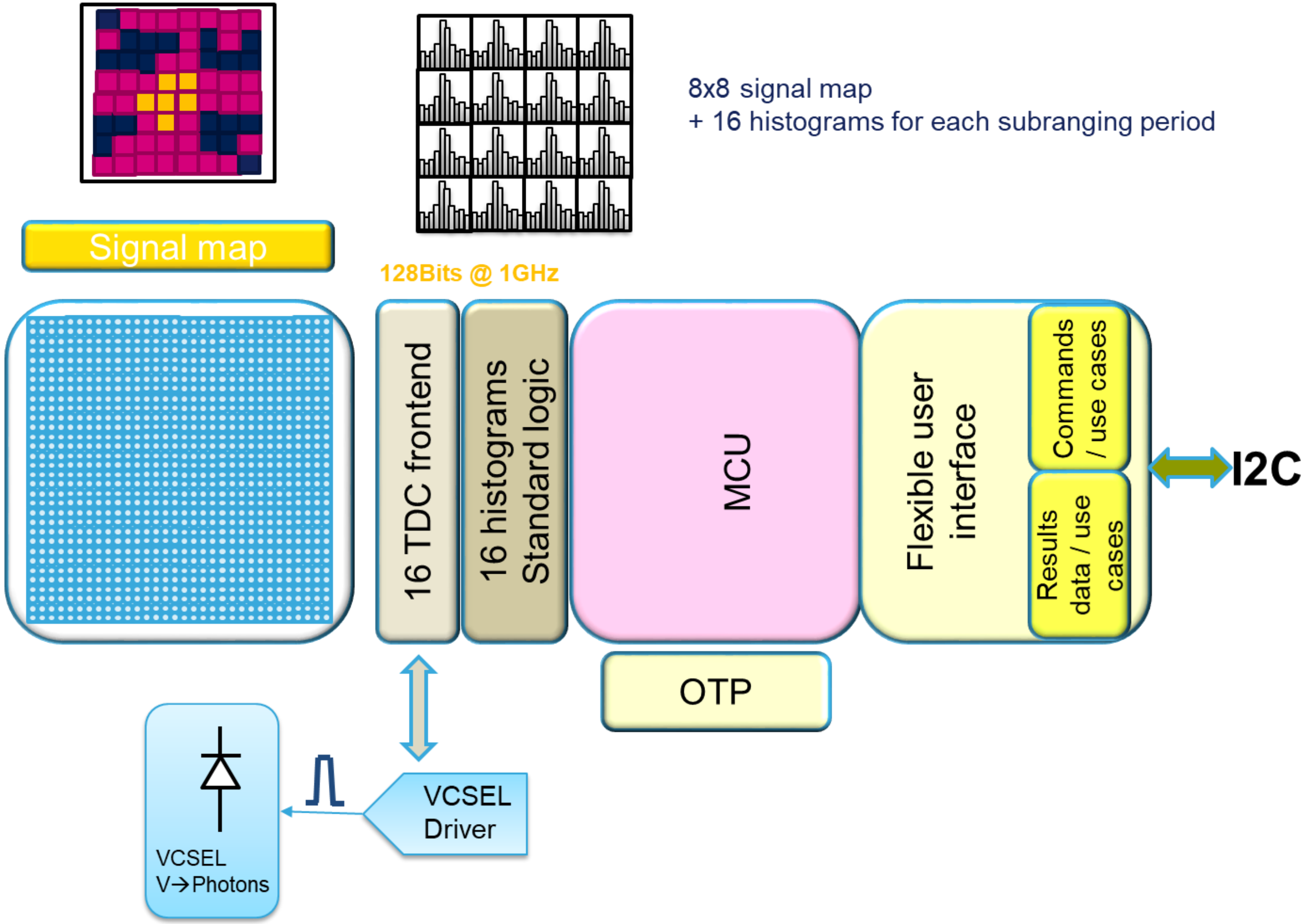
- Laser Autofocus
- Multi ROI touch-to-focus
- Scene understanding

Augmented Reality

- 3D Depth Map
- Gaming & Object tracking
- Depth Extraction Assistance

[Mellot/Rae, STMicroelecrtonics, IISW 2018]

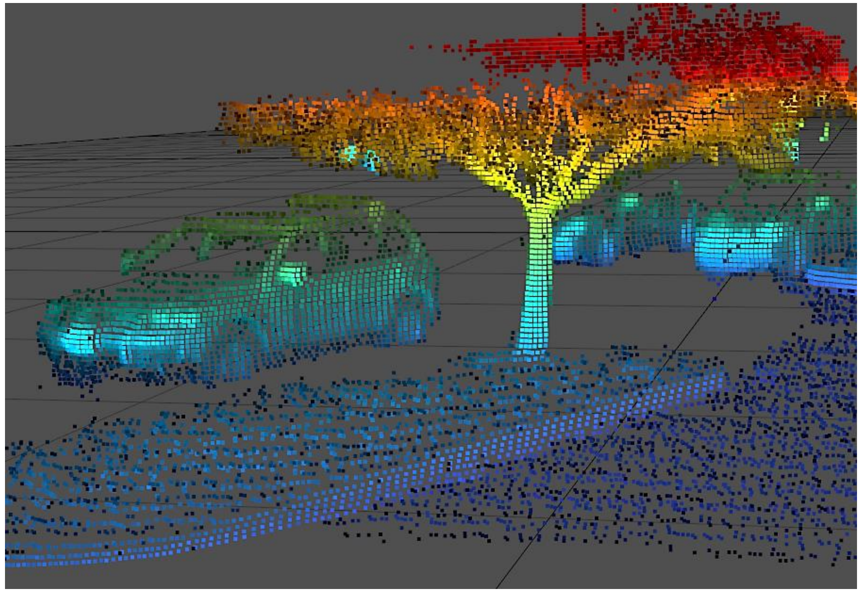
Miniature 3D Depth Camera: Device Overview



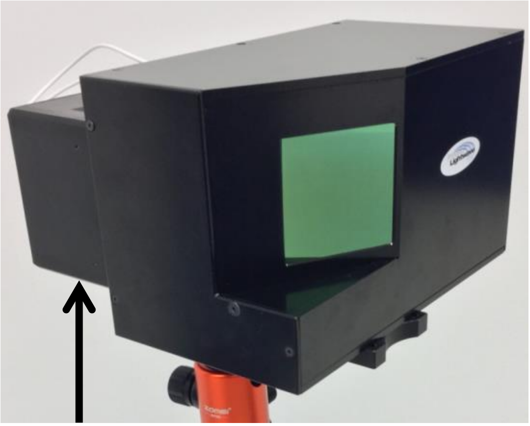
8x8 signal map
+ 16 histograms for each subranging period

[Mellot/Rae, STMicroelecrtonics, IISW 2018]

Automotive LiDAR System Emulation



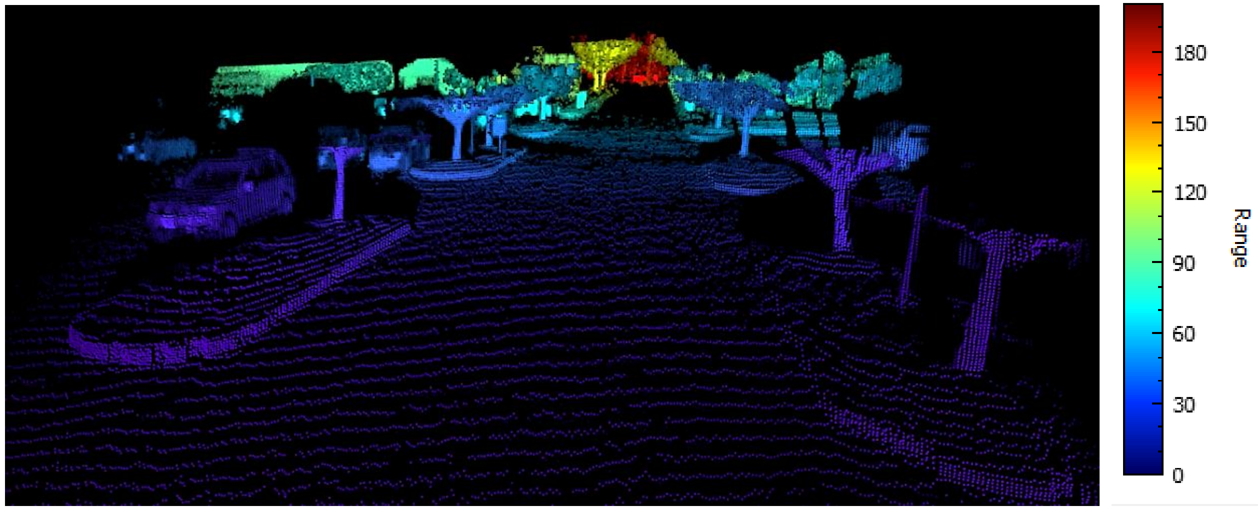
Color-coded for height



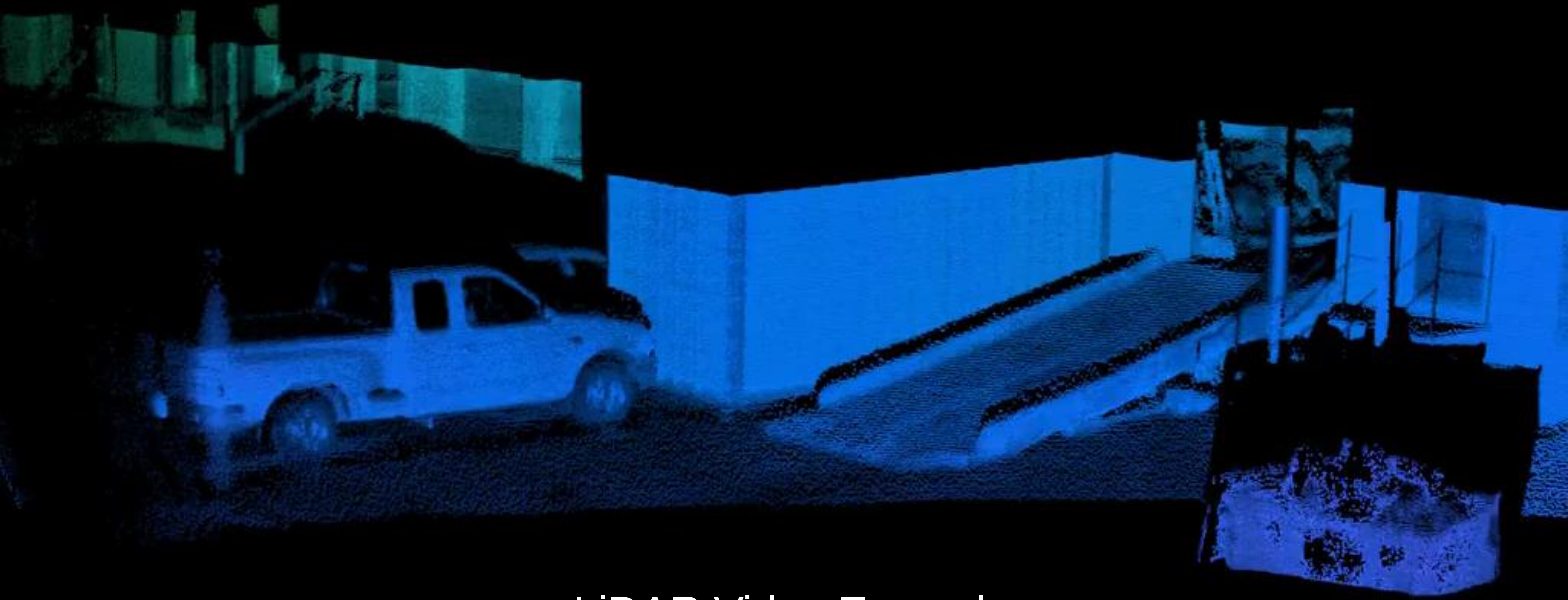
GmAPD 128 x 32 camera

512 x 64 demo 3D point cloud format
Scaling to 2048 x 512 equivalent

Color-coded for distance



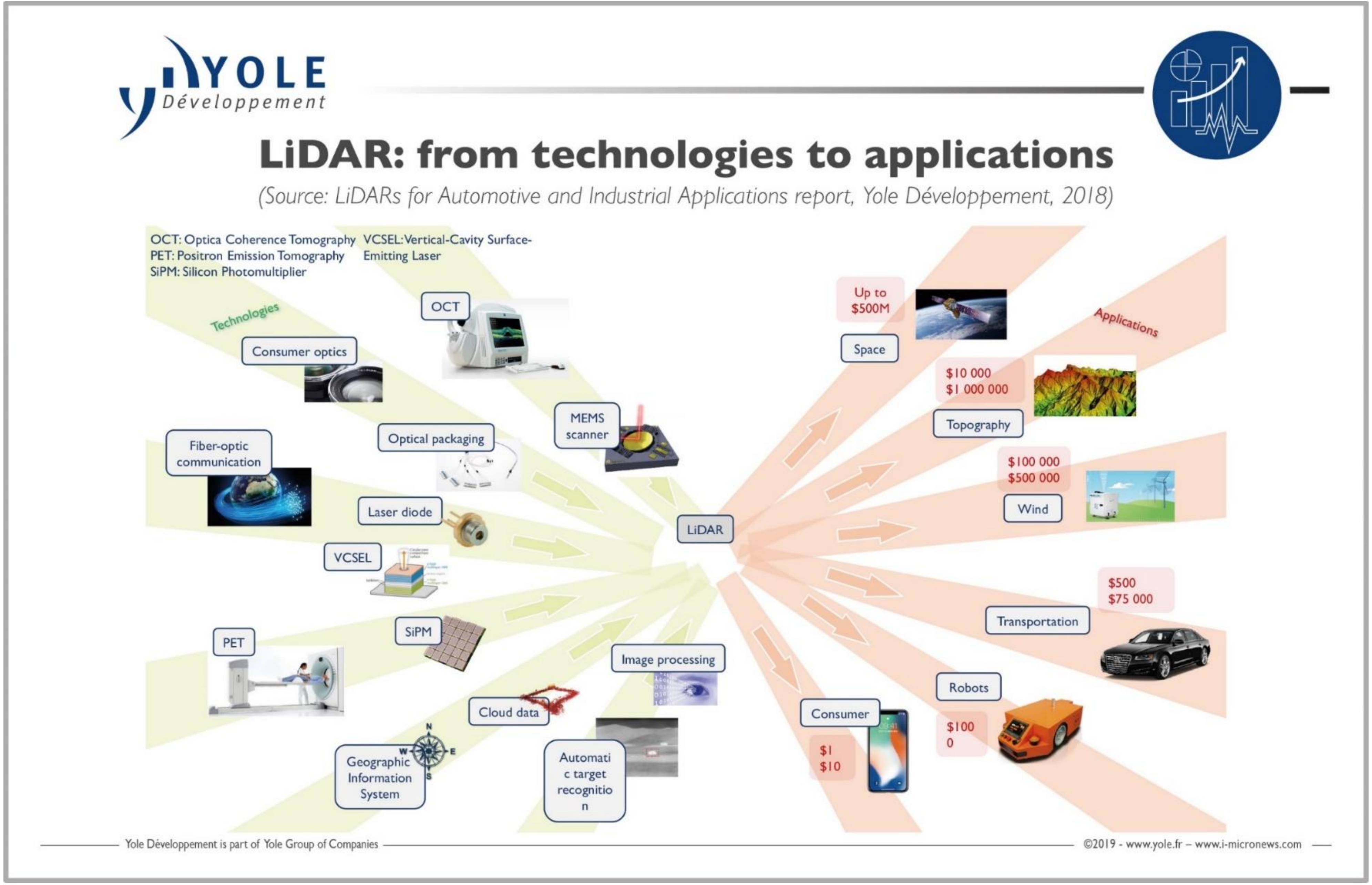
[M. Itzler, Argo AI, IISW 2018]



LiDAR Video Example

[M. Itzler, Argo AI, ISSW 2018]

LiDAR Market Perspectives



LiDAR: from technologies to applications

(Source: LiDARs for Automotive and Industrial Applications report, Yole Développement, 2018)

OCT: Optica Coherence Tomography
PET: Positron Emission Tomography
SiPM: Silicon Photomultiplier
VCSEL: Vertical-Cavity Surface-Emitting Laser

Yole Développement is part of Yole Group of Companies

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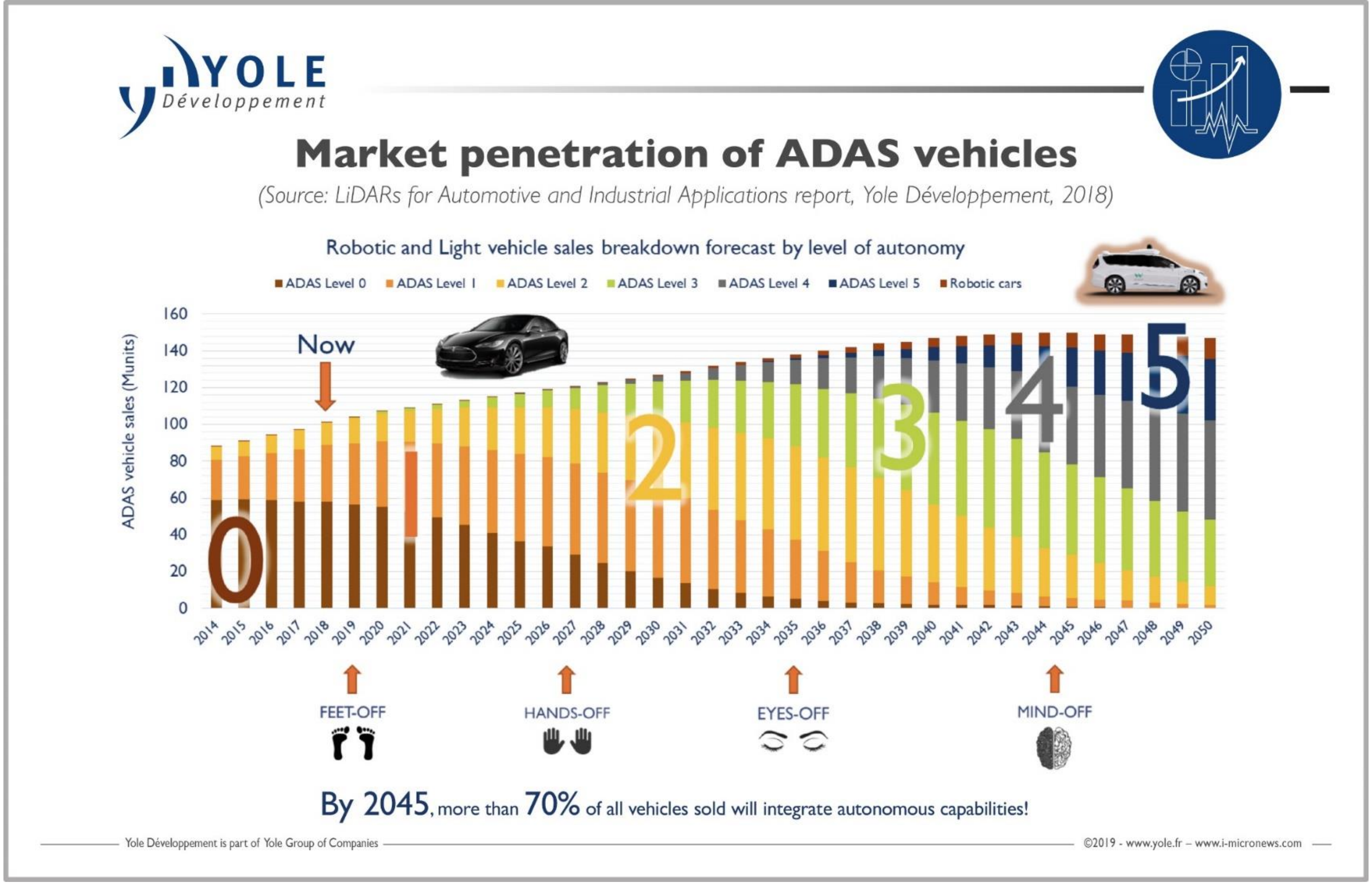
[Yole, 2018]



YOLE Développement

Market penetration of ADAS vehicles

(Source: LiDARs for Automotive and Industrial Applications report, Yole Développement, 2018)

By 2045, more than 70% of all vehicles sold will integrate autonomous capabilities!

Yole Développement is part of Yole Group of Companies

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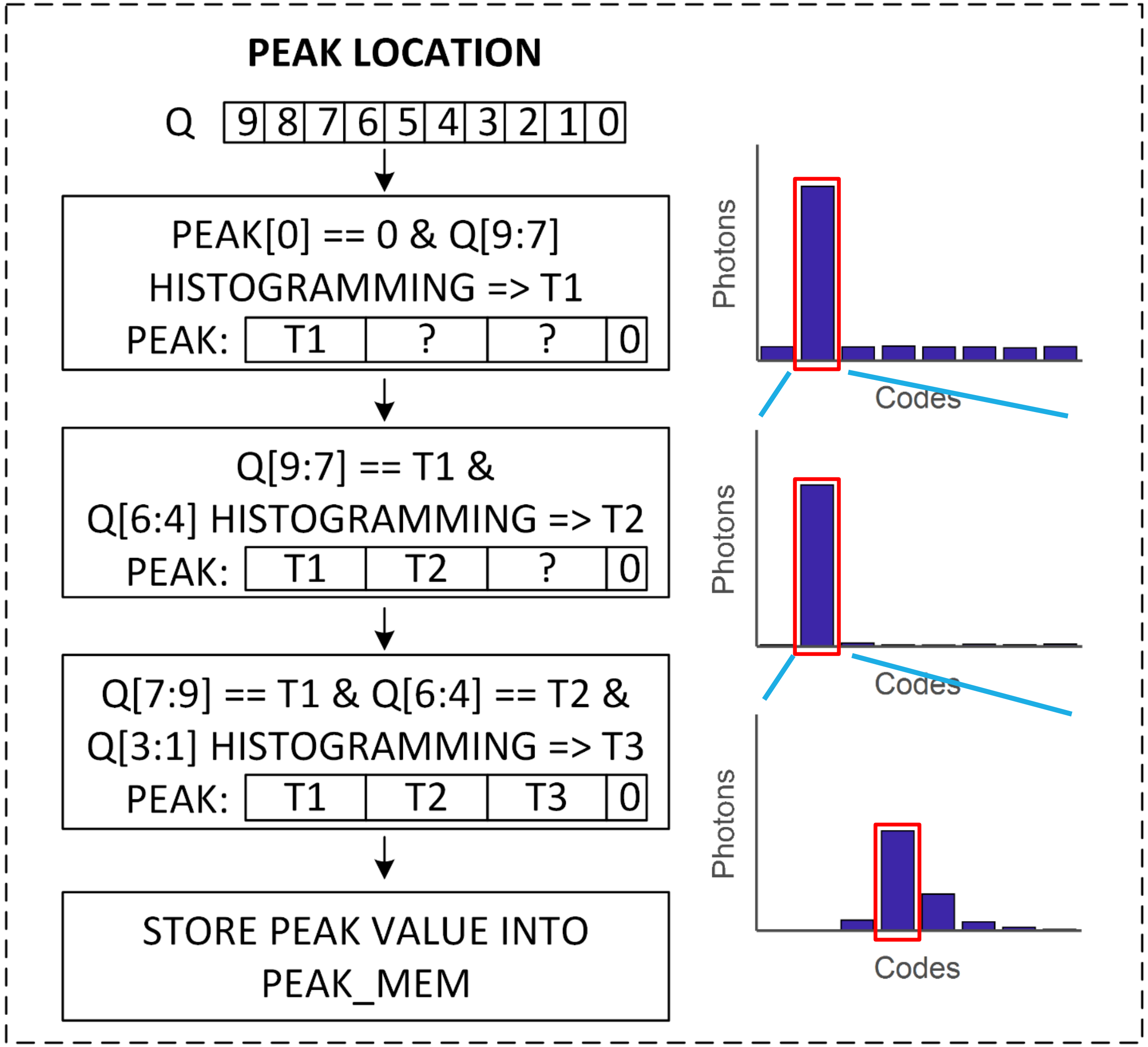
[Yole, 2018]

Sensor and System-Level Challenges

Data Rate Issue -> On-chip (partial) Histogramming

S. Lindner et al., IISW 2017, Sym. VLSI 2018,
DOI: 10.1109/VLSIC.2018.8502386



PEAK LOCATION

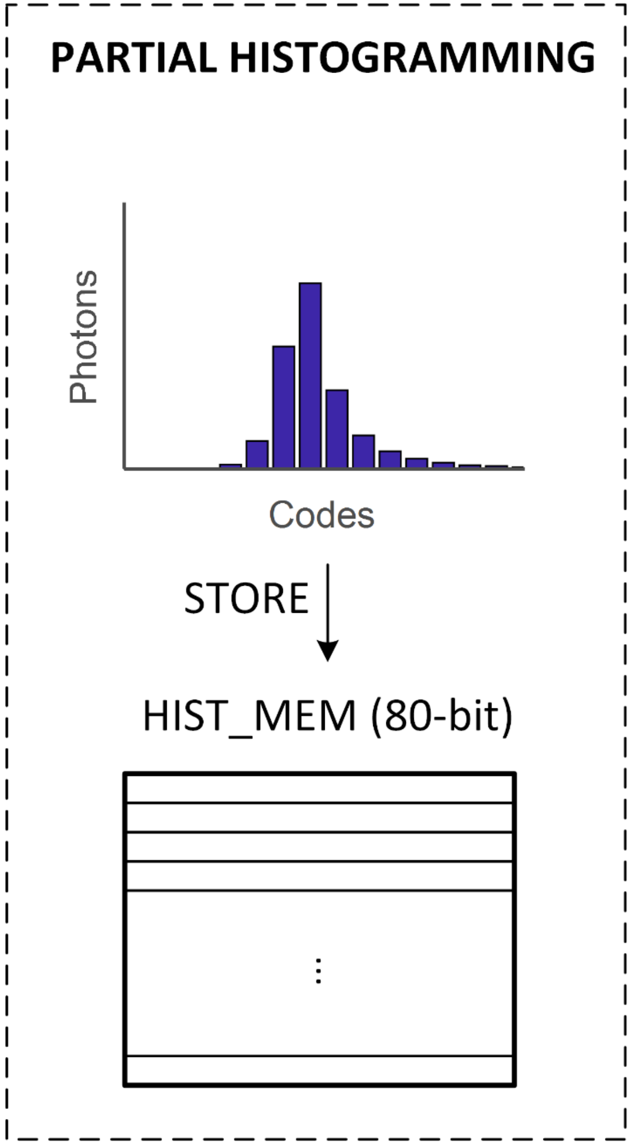
Q | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0

PEAK[0] == 0 & Q[9:7]
HISTOGRAMMING => T1
PEAK: | T1 | ? | ? | 0

Q[9:7] == T1 &
Q[6:4] HISTOGRAMMING => T2
PEAK: | T1 | T2 | ? | 0

Q[7:9] == T1 & Q[6:4] == T2 &
Q[3:1] HISTOGRAMMING => T3
PEAK: | T1 | T2 | T3 | 0

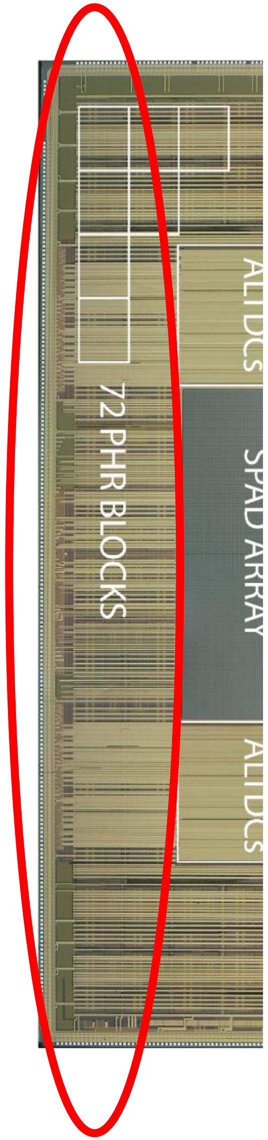
STORE PEAK VALUE INTO
PEAK_MEM



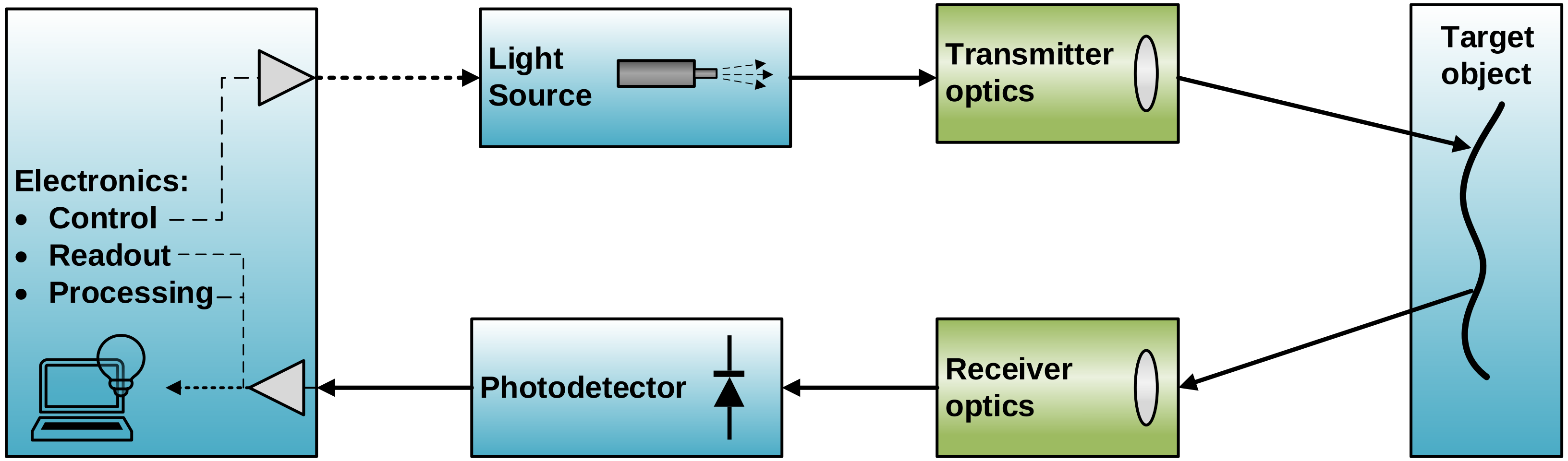
PARTIAL HISTOGRAMMING

STORE

HIST_MEM (80-bit)

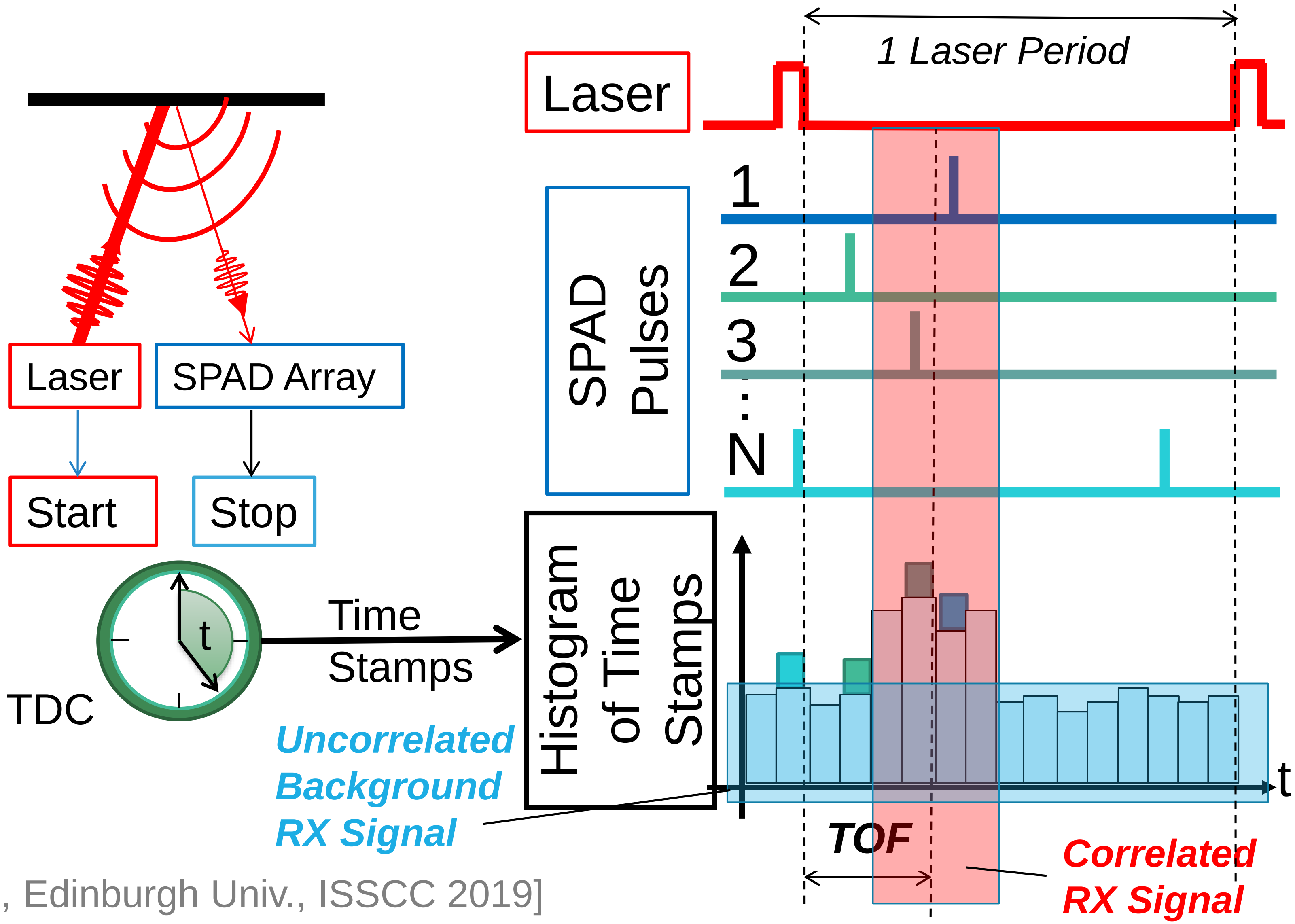


Background Light Issues -> Optical Components



- Optical filters – band-pass filters typically centered around illumination wavelength, filter ambient light
  - *NB: Take into account application requirements such as temperature drifts*
- Optical lenses and collimators
- Diffusers, attenuators to adjust the received illumination power

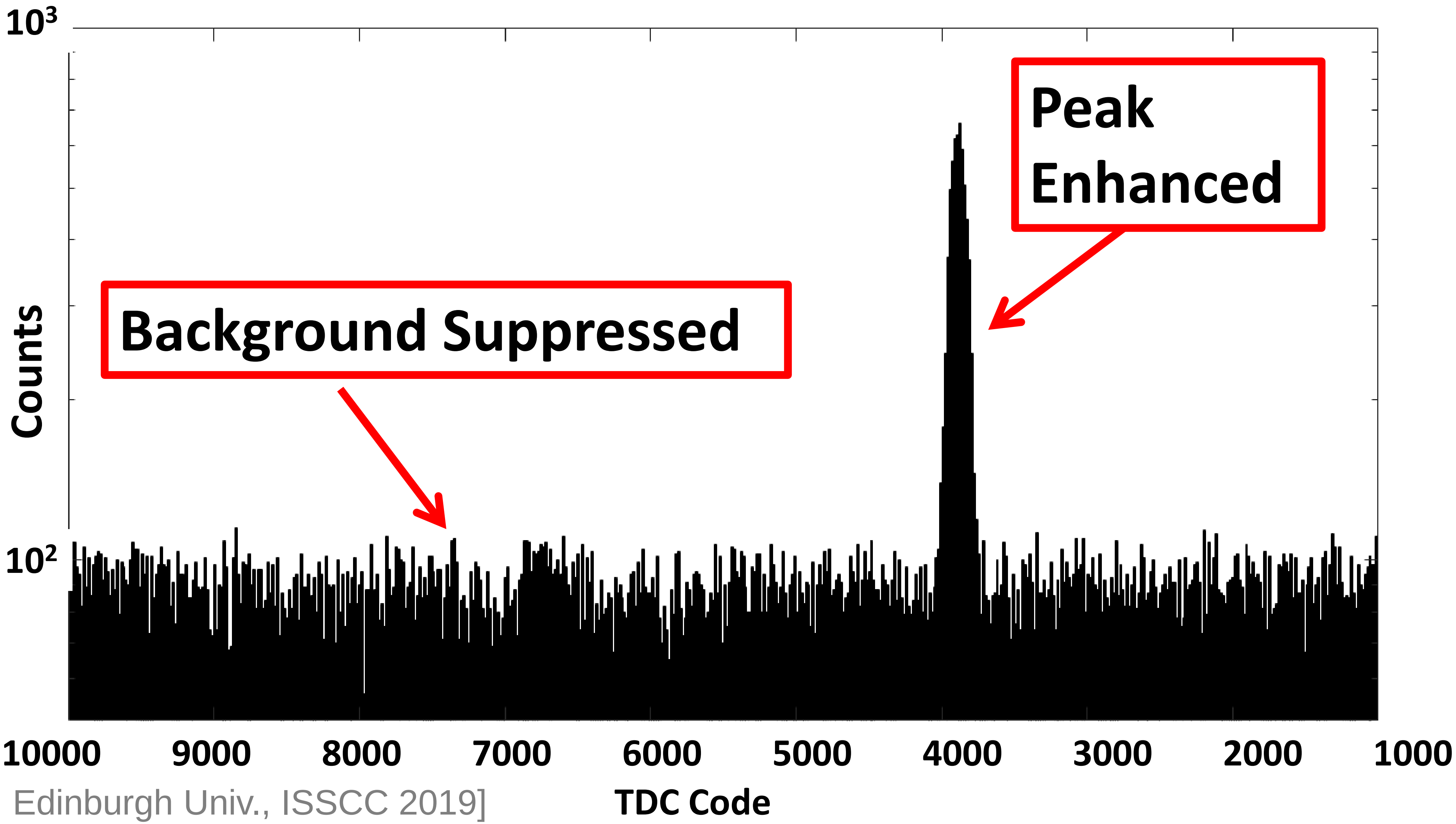
Background Light Issue -> Coincidence Detection



[R. Henderson, Edinburgh Univ., ISSCC 2019]

[Dutton, AACD 2018]

Result: Multiphoton Trigger Histogram



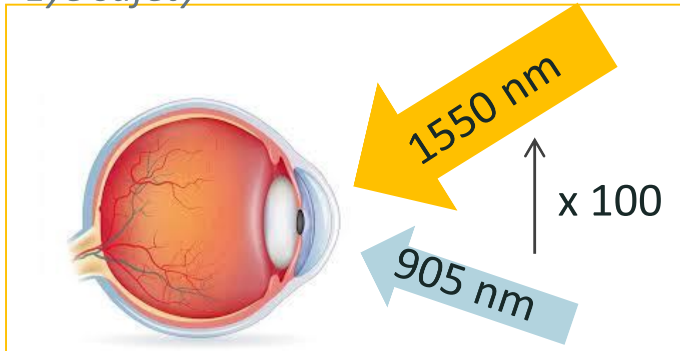
[R. Henderson, Edinburgh Univ., ISSCC 2019]

Background Light Issue -> Spectral Range

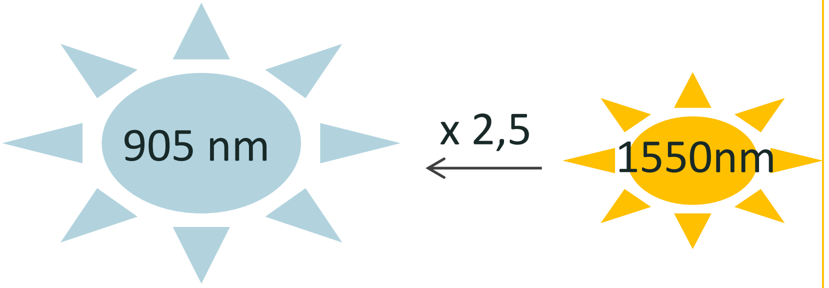
Laser wavelength

1550 nm (InGaAs) - 905 nm (Silicon)

Eye safety



Solar spectrum

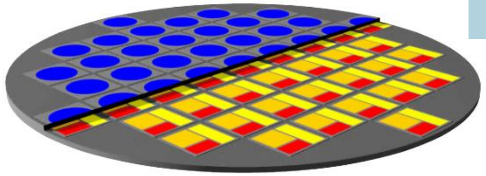


Device noise

InGaAs (1550 nm):
high noise even under cooling

Si (905nm):
factor of 10^5 lower noise

Production cost



Si (905 nm) ✓

InGaAs (1550 nm): Wafer-to-Wafer bonding not possible; only costly Chip-to-Wafer devices

[J. Ruskowski, Fraunhofer IMS, SPIE PW 2019]

Scattering/Absorption (e.g. Turbid Water) -> TCSPC

- TCSPC provides high sensitivity and precise temporal resolution
  - Provide high spatial and depth resolution imaging

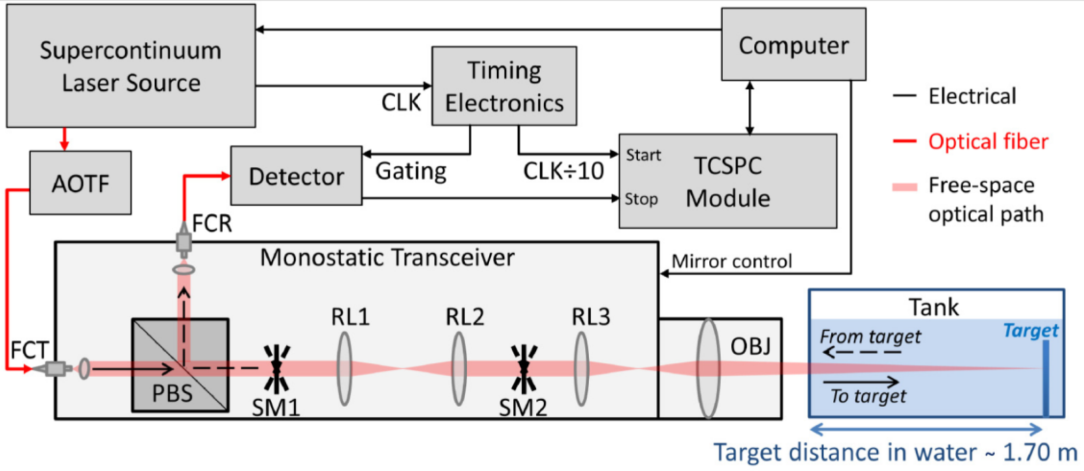


Fig. 3. Schematic of the single-photon depth imaging system, which comprises a pulsed supercontinuum laser source and a monostatic scanning transceiver unit fiber-coupled to an individual Si-SPAD detector. A time-gated configuration was used, with the single-photon detector being gated on for a 6 ns temporal window in correspondence with the return signal from the target. The optical components shown in the transceiver unit include a fiber collimation package for the transmitting channel (FCT) and the receiving channel (FCR). A polarizing beam splitter (PBS) was used to separate the transmit and receive channel. Three relay lenses (RL1, RL2, RL3) were used in conjunction with the two galvanometer mirrors (SM1, SM2) to perform the scanning in the vertical and horizontal directions. A camera objective lens (OBJ) was used to focus the transmitted laser light onto the target surface and collect the scattered return signal.

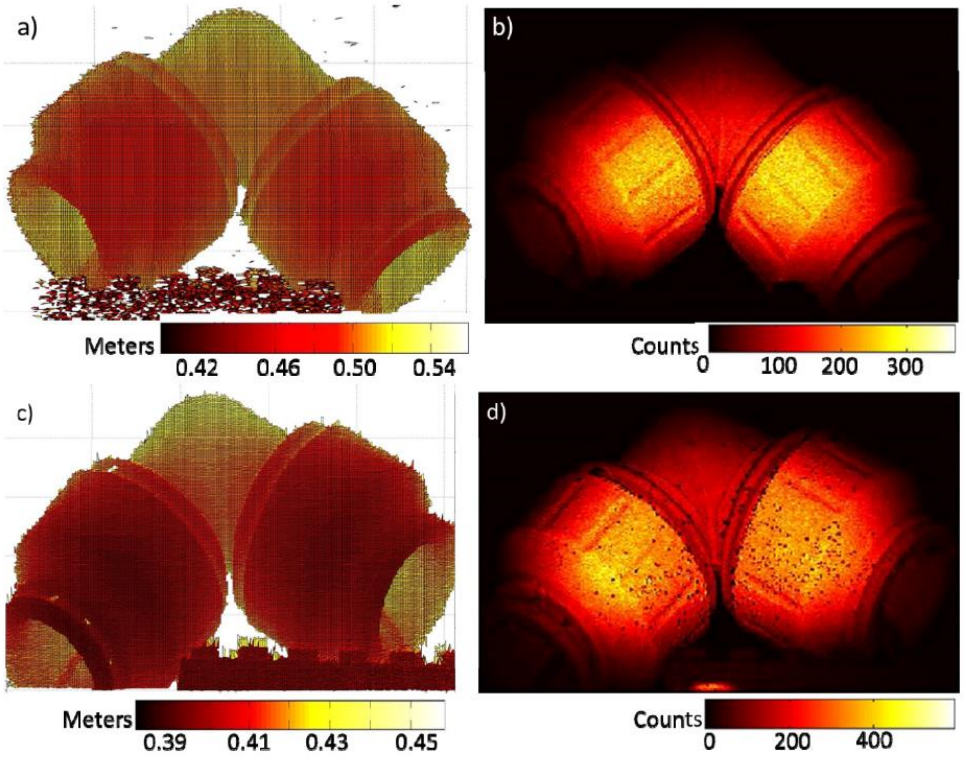


Fig. 6. (a) Representation of a 256 × 256 pixel depth scan of the plastic pipe acquired in clear water at $\lambda = 525$ nm, and a stand-off distance of 1.7 meters, corresponding to 0.2 attenuation lengths between transceiver and target. Each pixel had an acquisition time of 30 ms and an average optical power 8.7 nW was used. (b) The same target displayed with the number of photons returned per pixel, i.e. the intensity map. (c) A 256 × 256 pixel depth scan made in water with 0.01% of Maalox at $\lambda = 690$ nm, and a stand-off distance of 1.7 meters, corresponding to 1.2 attenuation lengths between transceiver and target. A per-pixel acquisition time of 50 ms and an average optical power 121 µW was used. (d) The same target displayed with the number of photons returned per pixel. The depth and the number of photons are displayed in the color scales shown in the insets.

[A. Maccarone et al. OSA 2015, DOI:10.1364/OE.23.033911]

Summary/1

- ❑ LiDAR is a special case of time-resolved imaging, also known as depth sensor
  - LiDAR applicability spans from close range (≈50cm) for consumer to long range (hundreds of kilometers) for space-based applications

- ❑ Many active optical depth sensors exist, we focused on time-of-flight (TOF)
  - TOF can be measured using both direct and indirect methods
  - Indirect TOF (ITOF) provides high accuracy for small ranges; problem with multi-target condition
  - Direct TOF (DTOF) enables discrimination of multiple echoes easily

- ❑ Steady growth is expected in the depth sensing market for the foreseeable future
  - High-volume applications in mobile/consumer areas including automotive, point-of-care and internet-of-things (IoT)
  - Unique and shared challenges for different applications

Summary/2

- ❑ Flash vs. Scanning
  - Flash LiDAR promising due to its simplicity and no moving parts
  - Scanning LiDAR more practical for imaging beyond ≈50m
- ❑ Single-photon detectors booming due to high photo-sensitivity and timing resolution
  - Customized process developments
  - Optimized detector technology made available
- ❑ SPAD-based sensors: have received a **great amount of attention by scientific & industrial communities** for a wide variety of applications
  - *Important performance improvements in all metrics (pixel size, photon detection probability, dark count rate, fill factor, etc.)*
  - **Trend towards 3D-stacked CMOS SPAD sensors is apparent**
  - *Strong impact on* ***next-generation LiDAR & other time-resolved applications***
- ❑ Possible extension to **other materials (InGaAs/InP)/wavelengths** & **processing paradigms** (neural networks, reconfigurable imagers)

Summary/3

- ☐ Consumer proximity sensors have reached maturity but 3D technologies may still change trends
- ☐ LiDAR is in full bloom with developing standards and sensors that follow wavelength requirements

- ☐ Main Challenges:
  - The main challenges are to move data out of the sensor fast enough and how to reduce these data in size thereby performing filtering (e.g. histogramming)
  - The other challenge is to increase sensitivity through 3D integration and/or microlenses
  - The final challenge is to parallelize light detection through redundancy, i.e. MD-SiPMs

Acknowledgments

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- **Mark Itzler,** ARGO AI
- **Sara Pellegrini & Bruce Rae,** ST Microelectronics
- **Jennifer Ruskowski,** Fraunhofer IMS
- **Lucio Carrara,** Fastree3D

- **Jiuxuan Zhao,** EPFL
- **Augusto Ximenes, TU Delft**
- **Ivan Michel Antolovic,** EPFL
- **Scott Lindner,** EPFL
- **Harald Homulle,** TU Delft
- **Andrada Muntean,** EPFL
- **Kazuhiro Morimoto,** EPFL
- **AQUA Lab members**

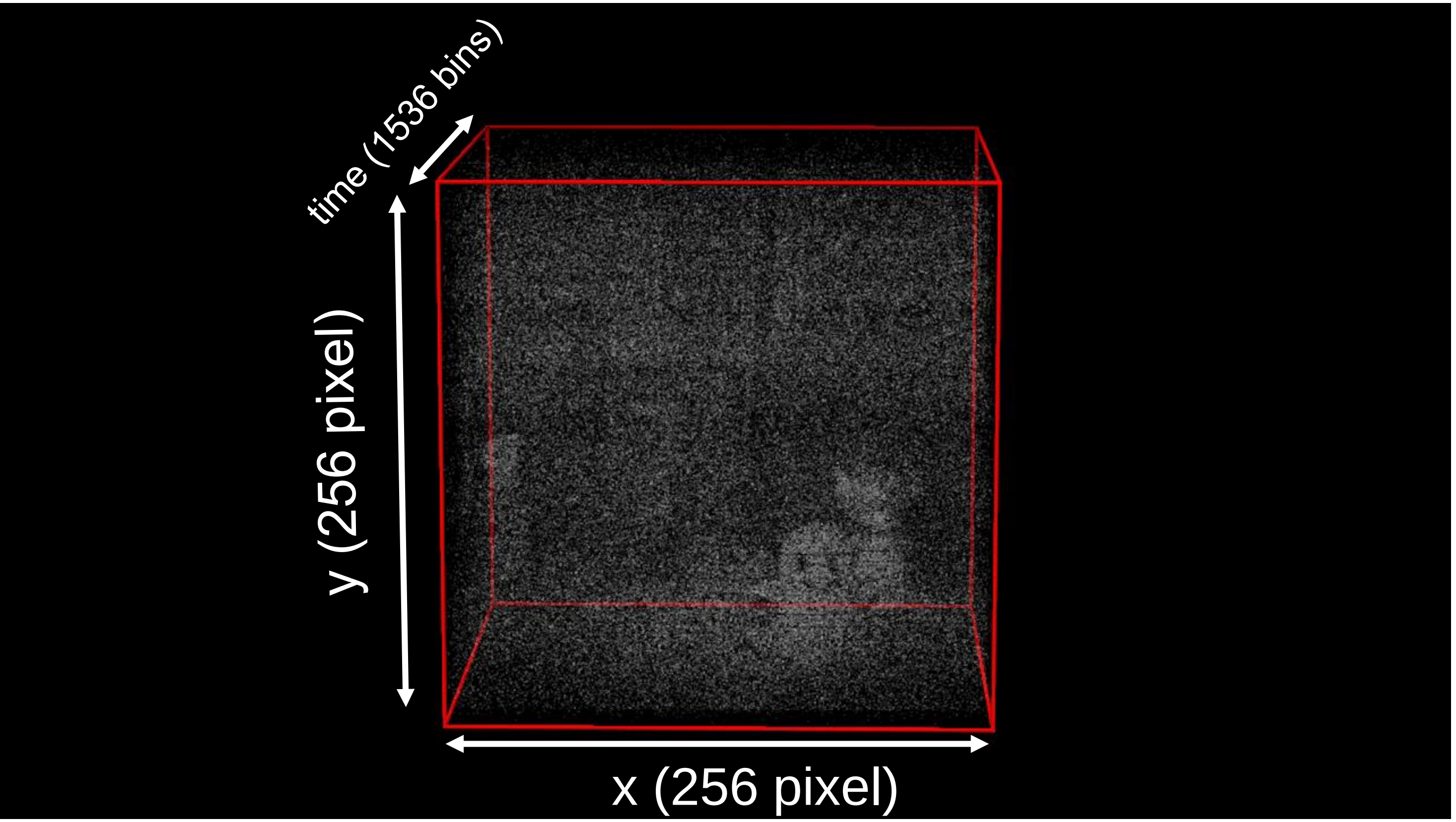
Robert Henderson
Edinburgh University

…and many other contributors

Bonus – Future Perspectives:

Non-Line-of-Sight, Deep Learning and Few-Photon Imaging

Transient Imaging Measurements

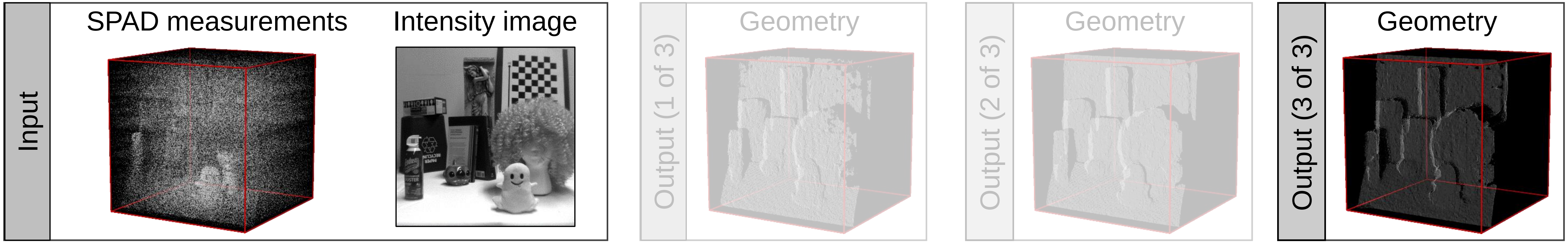


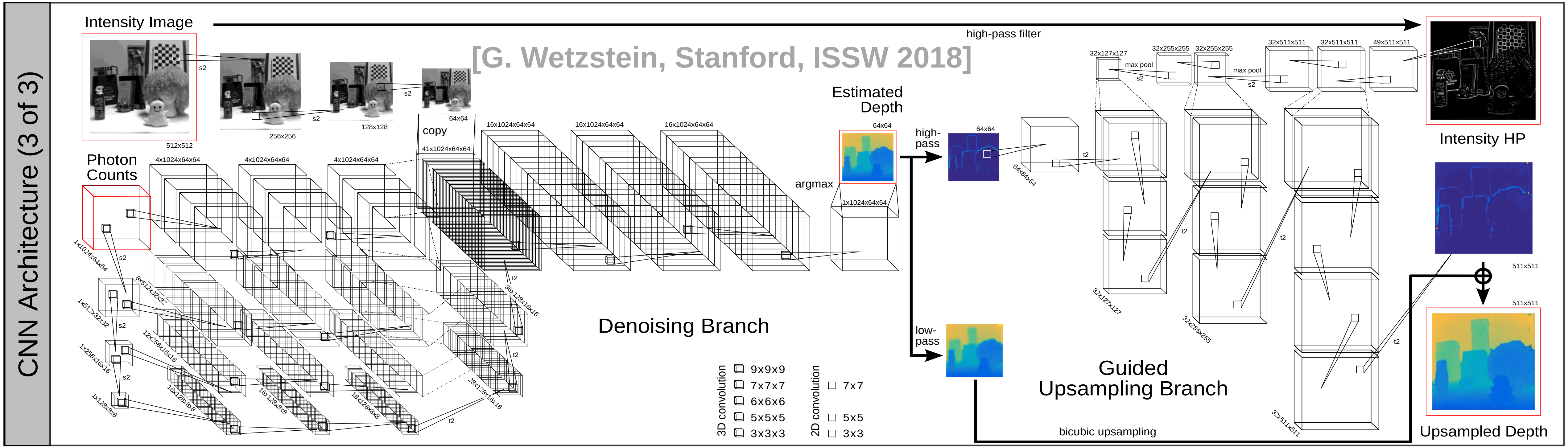
SPAD measurements
(256 x 256 x 1536)

Intensity image
(1024 x 1024)

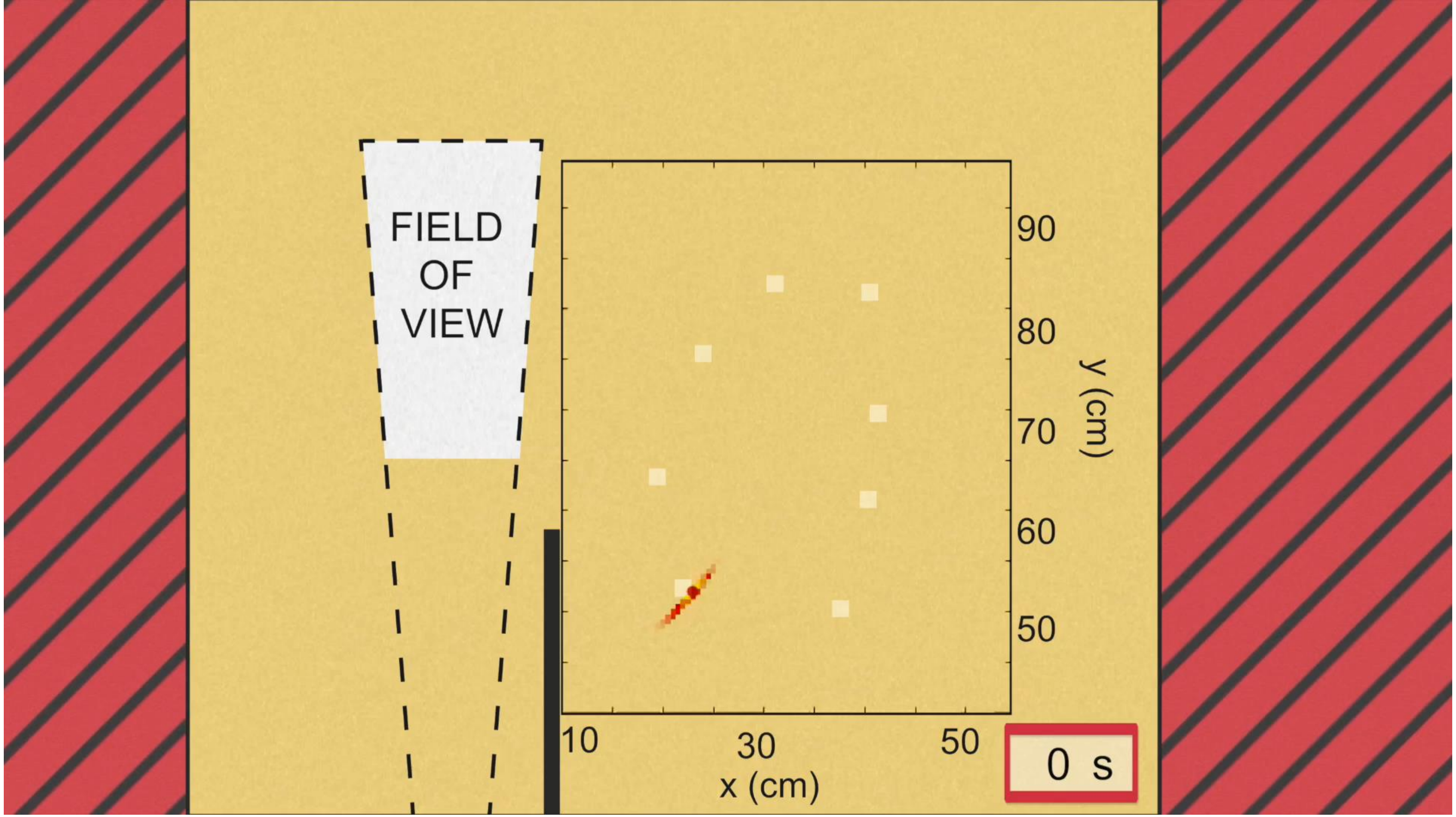
[Lindell et al., SIGGRAPH 2018]

CNN for Depth from Single-Photon





[G. Wetzstein, Stanford, ISSW 2018]

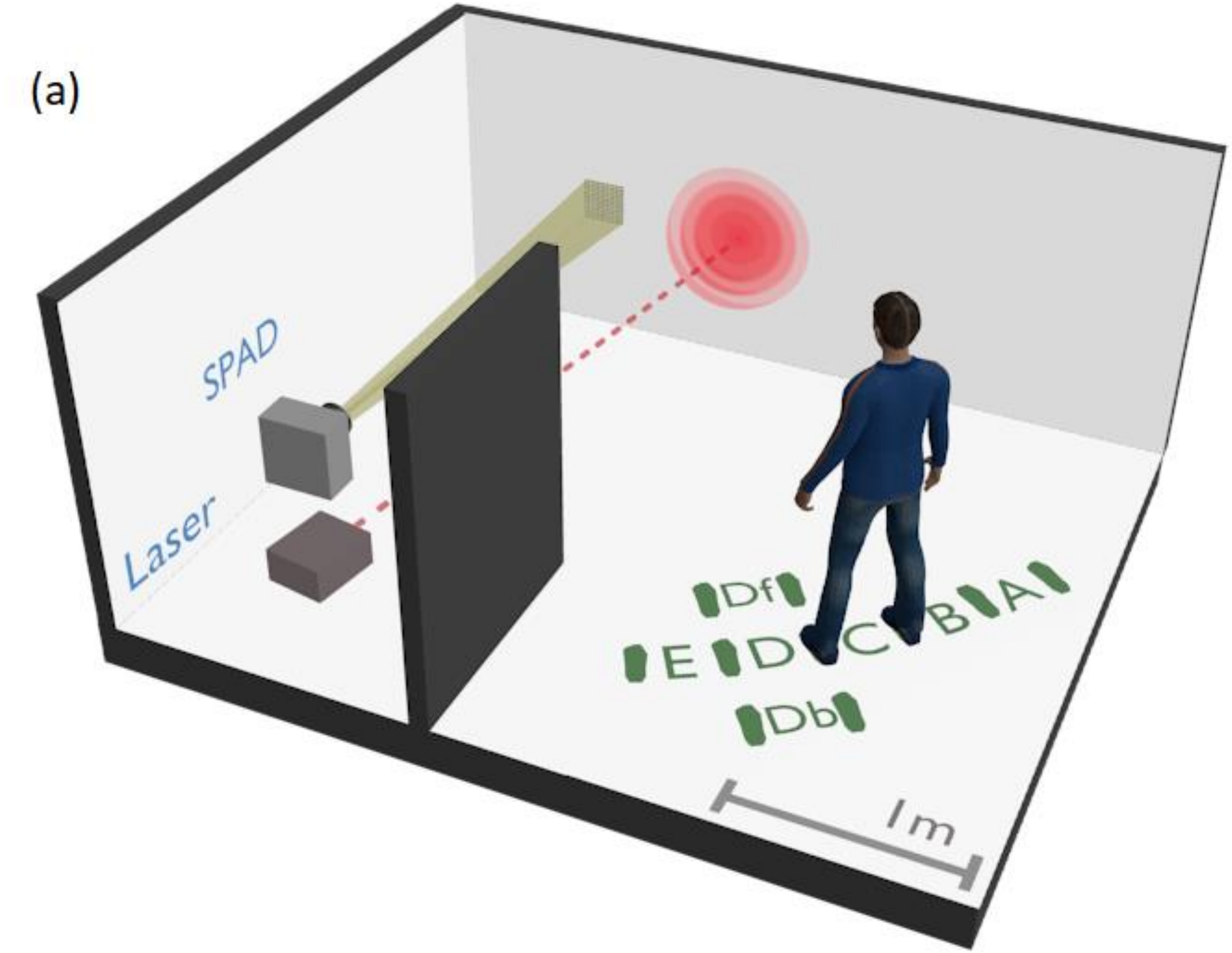


Nature Photonics **10**, 23–26 (2016) | doi:10.1038/nphoton.2015.234

Tracking Moving Objects in Real Time

[D. Faccio, Glasgow Univ., ISSW 2018]

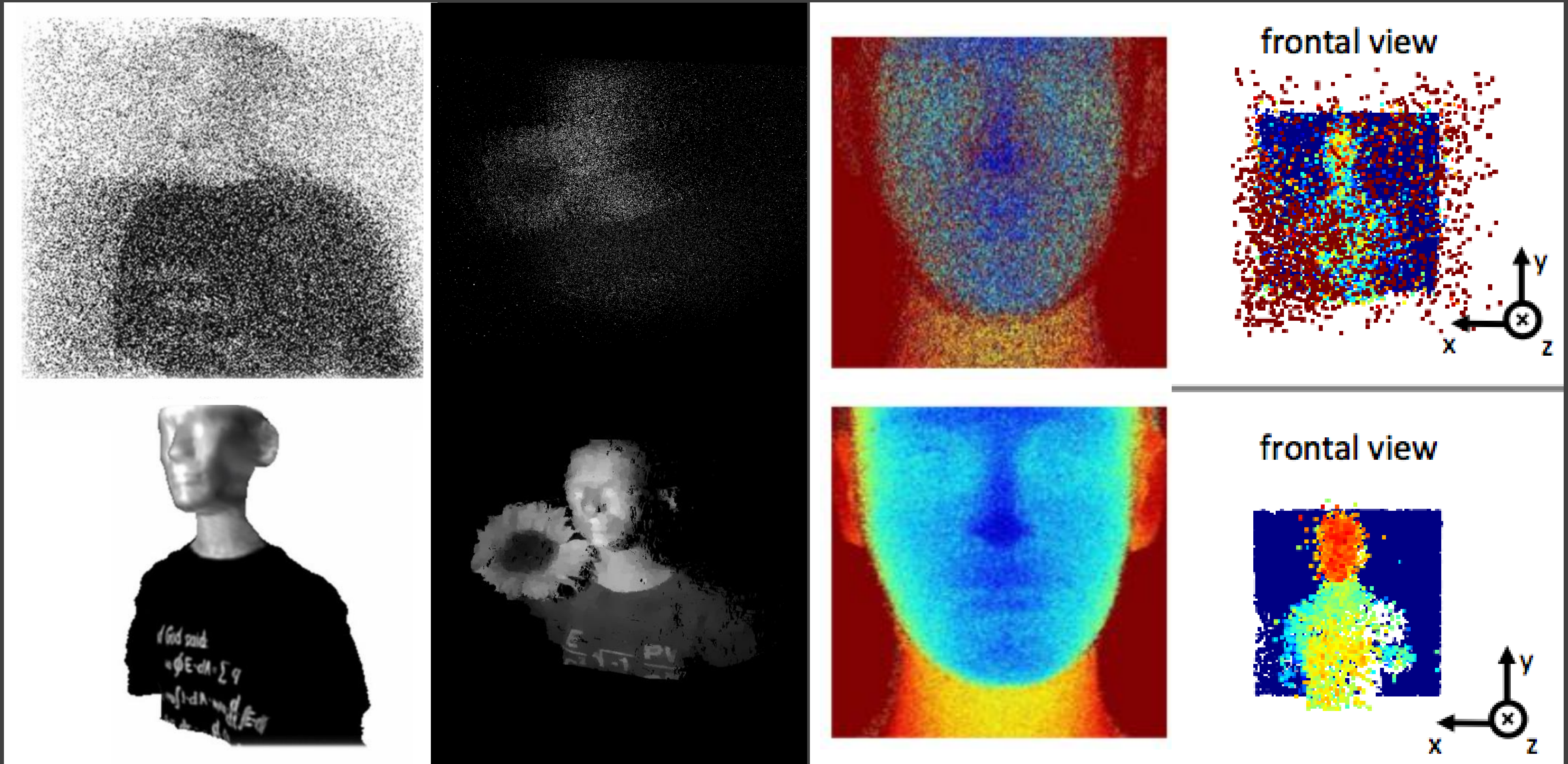
(Combination with) Deep Learning



[D. Faccio, Glasgow Univ., ISSW 2018]

Reflectivity and depth from a few photons per pixel (ppp)

first-photon imaging	SPAD array	unsmoothed	19 scene ppp
0.5 signal ppp	1 signal ppp	13.5 signal ppp	20 scatter ppp
0.5 ambient ppp	1 ambient ppp	1.5 ambient ppp	6 ambient ppp
Science (2014)	Nat. Commun. (2016)	IEEE SPL (2015)	Opt. Expr. (2016)



[V. Goyal, Boston Univ., 2019]

Summary/4

- Since the creation of SPADs in CMOS, single-photon detection is possible reliably and in great numbers
- New imaging modalities have become possible in (and outside) the computational imaging community
  - An example is NLOS imaging
- Time-resolved NLOS imaging has become practical and robust
- Deep-learning techniques applied to TOF imaging and single-photon imaging have become a trend in the community

Acknowledgments

Gordon Wetzstein
Stanford University

Vivek Goyal
Boston University

Daniele Faccio
Univ. Glasgow

Appendix

DTOF vs ITOF (2)

Direct Time-of-Flight (DTOF)

- Ranging from short up to long range (≈ few kilometers) possible; maximum range typically dictated by optical power budget

- Background resilience is dictated by:
  - Detector active area
  - Detector dead time
  - Detector temporal compression
  - Multi-photon threshold
  - TDC + histogram latency

Indirect Time-of-Flight (ITOF)

- Ranging from short up to medium range, typically within 50m; maximum range dictated by modulation frequency

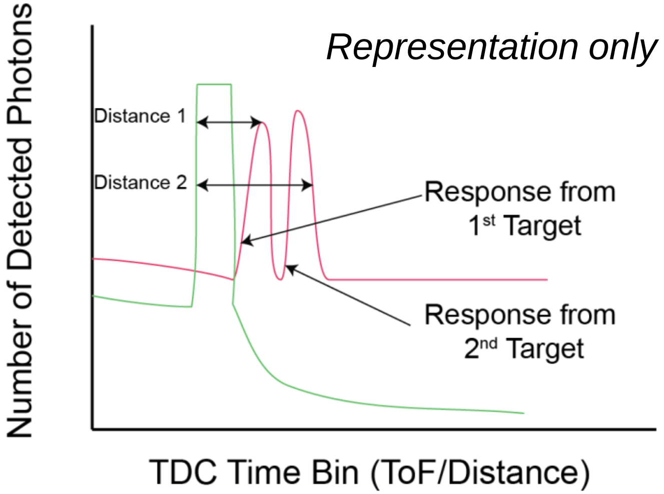
- Background resilience limited by:
  - Full-well capacity (of the floating diffusions)
  - Common-mode compensation
  - Shot noise

[D. Stoppa et al., SSCS Distinguished lecture 2018]

DTOF vs ITOF (3)

Direct Time-of-Flight (DTOF)

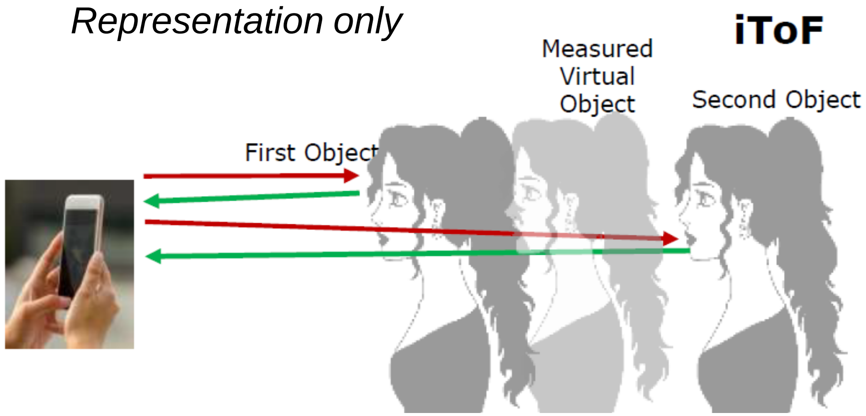
- Multiple echoes can be identified in the histogram up to the point where two light pulses overlaps
- Resolution between two targets is set mainly by laser pulse width
- Cover glass can be easily detected and removed completely



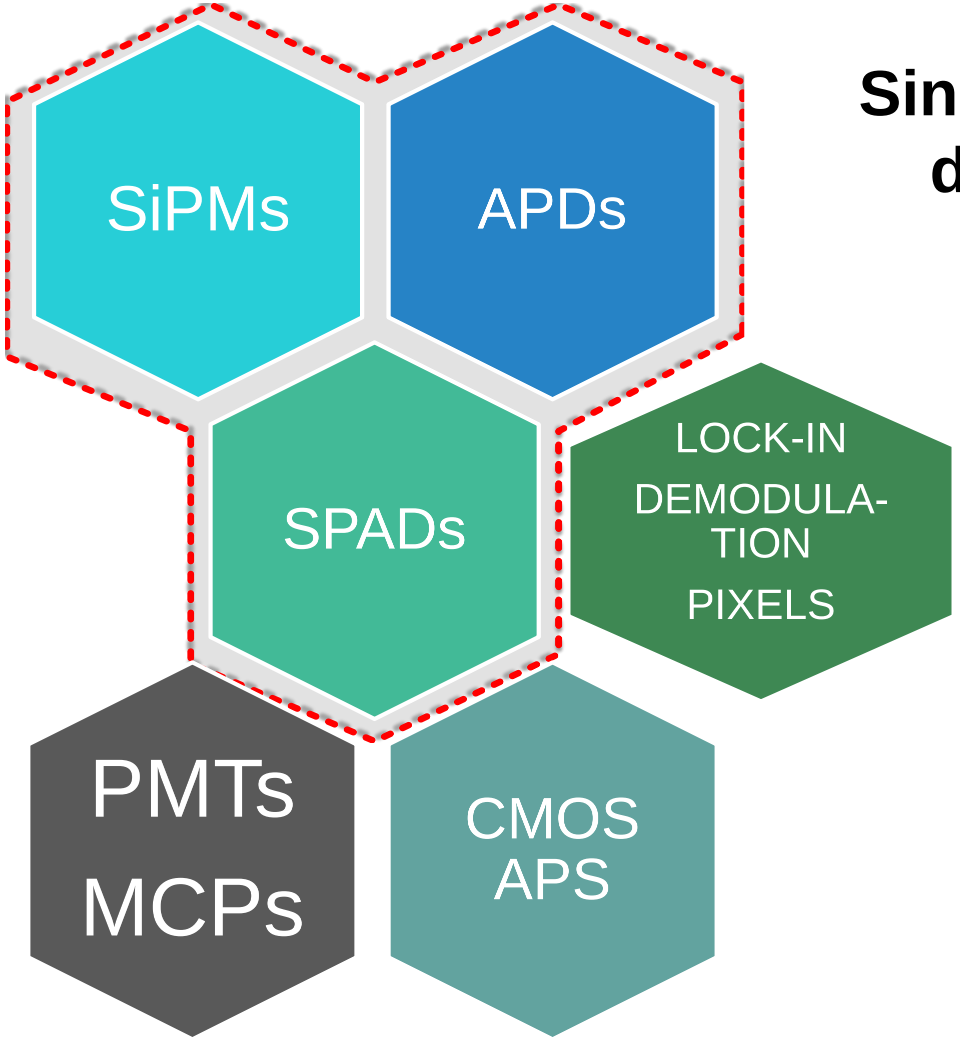
[D. Stoppa et al., SSCS Distinguished lecture 2018]

Indirect Time-of-Flight (ITOF)

- ITOF measure an average distance between them, weighted by the target reflectivity (out of control)
- Compensation of cover glass echo is possible through calibration but second order effects are difficult to cancel



Photodetectors



Single-photon detectors

Conventional detectors

SiPMs

APDs

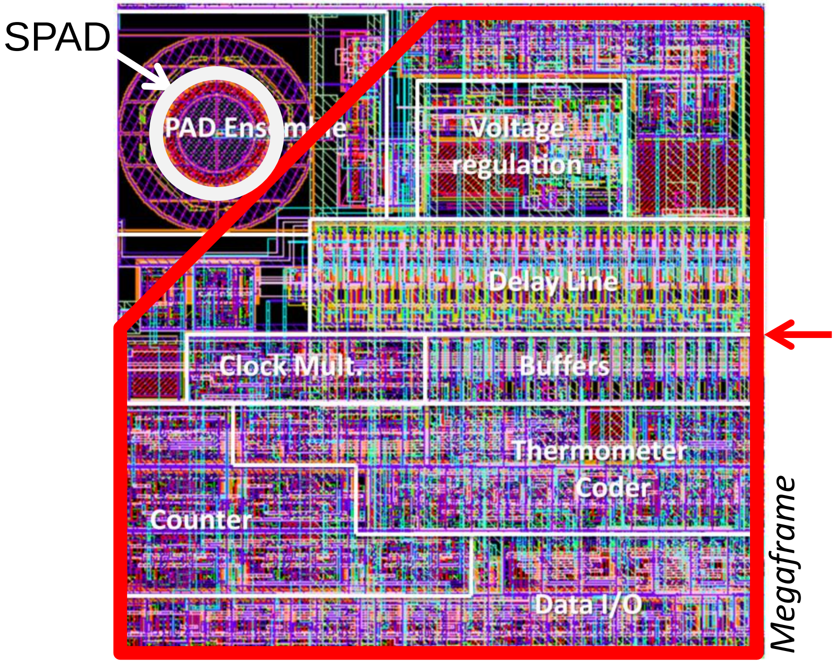
SPADs

LOCK-IN DEMODULATION PIXELS

PMTs MCPs

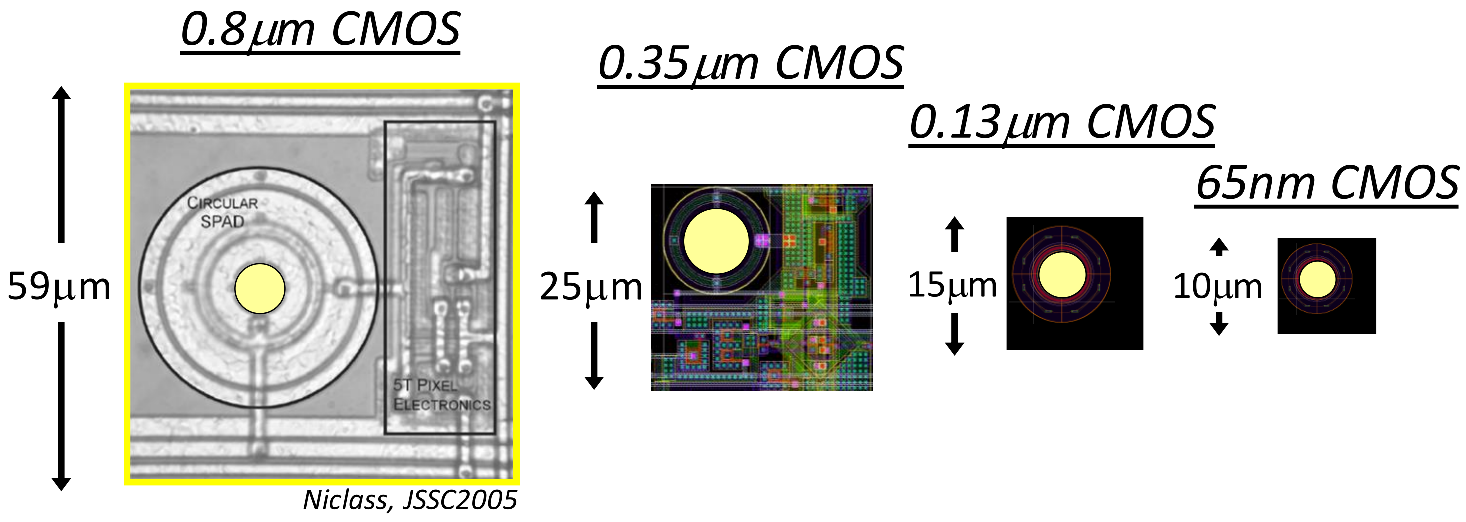
CMOS APS

Trends in SPADs



Monolithic Integration of a SPAD and electronic circuits in standard CMOS technology

***Limitation**: low fill factor (FF)*



Niclass, JSSC2005

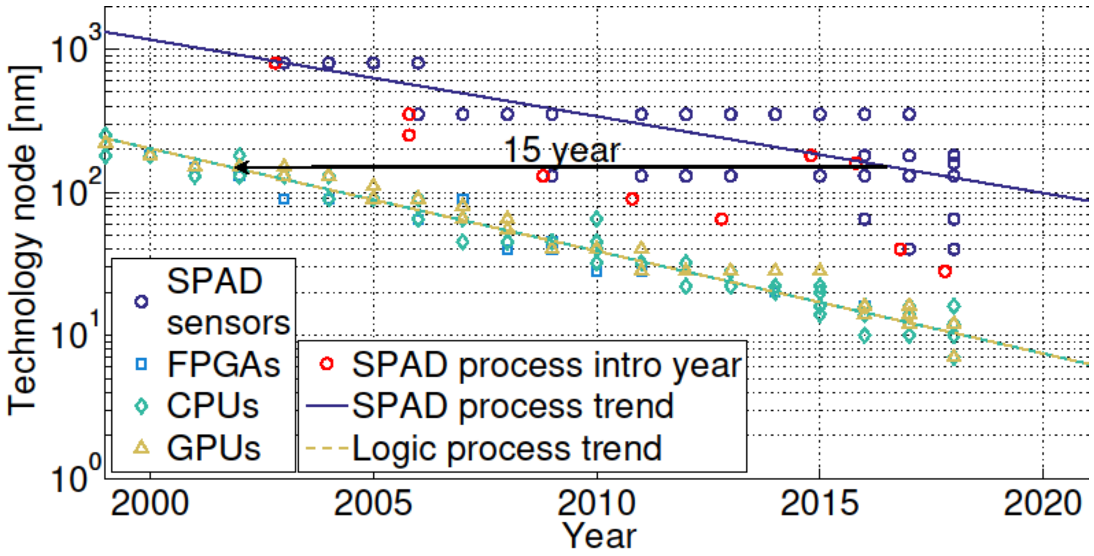
FF = 1 % FF = 9 % FF = 25 % FF = 35 %

- **Higher fill factor, higher resolution**
- **Lower power consumption, more cost-effective**

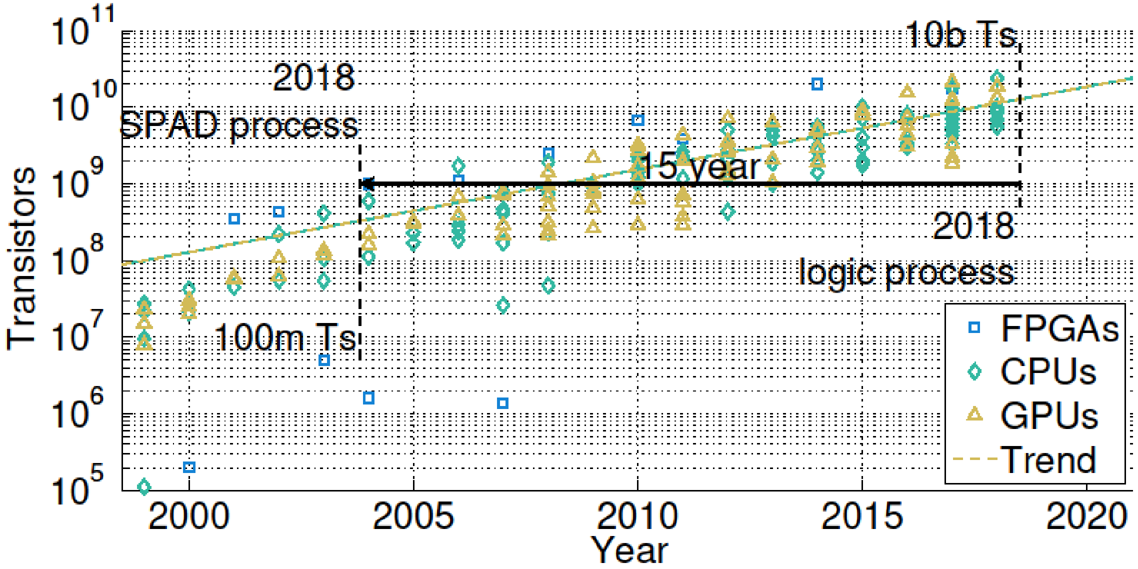
- **Higher doping concentration ➔ narrow depletion**
  ➔ **higher dark count rate (DCR)** (higher tunneling)
  ➔ **lower photon detection probability (PDP)**

[M.-J. Lee, EPFL, IEDM 2017]

Trends in SPADs



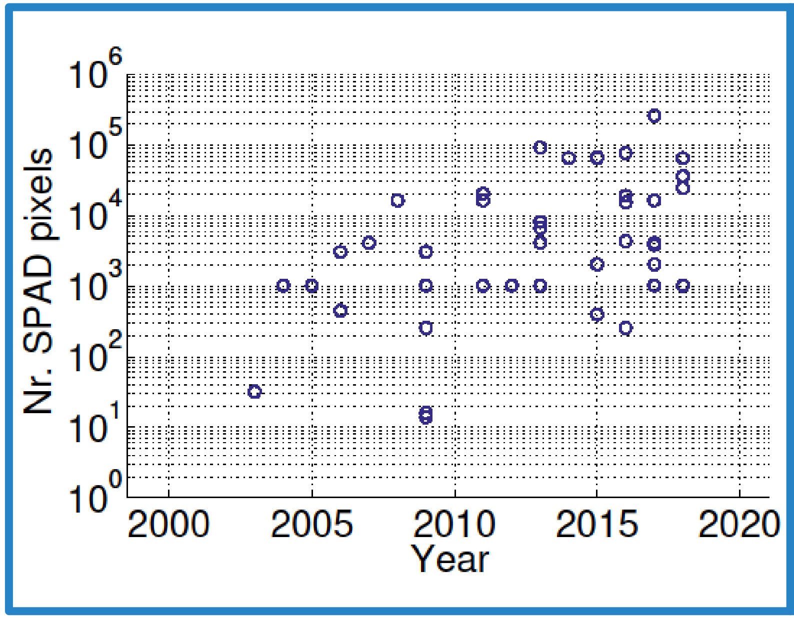
Process node

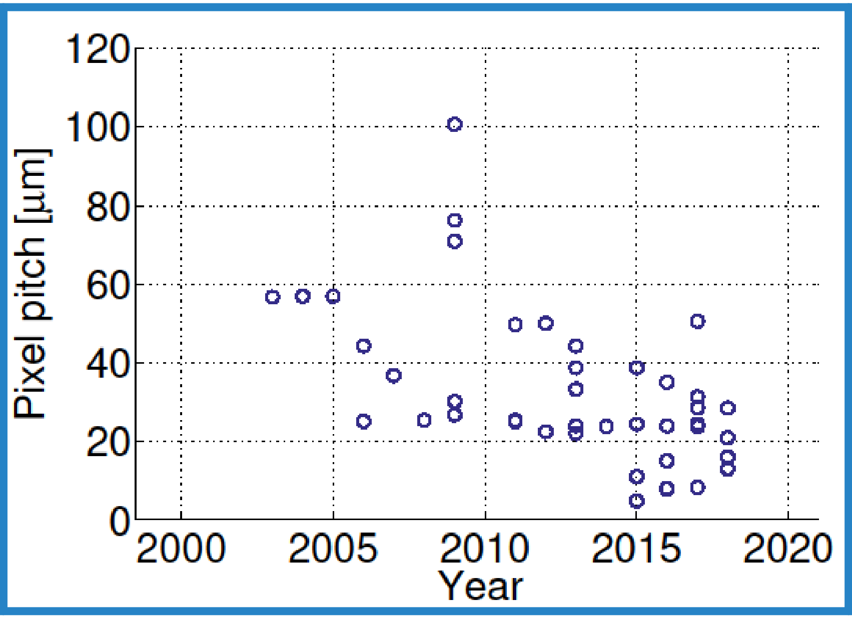


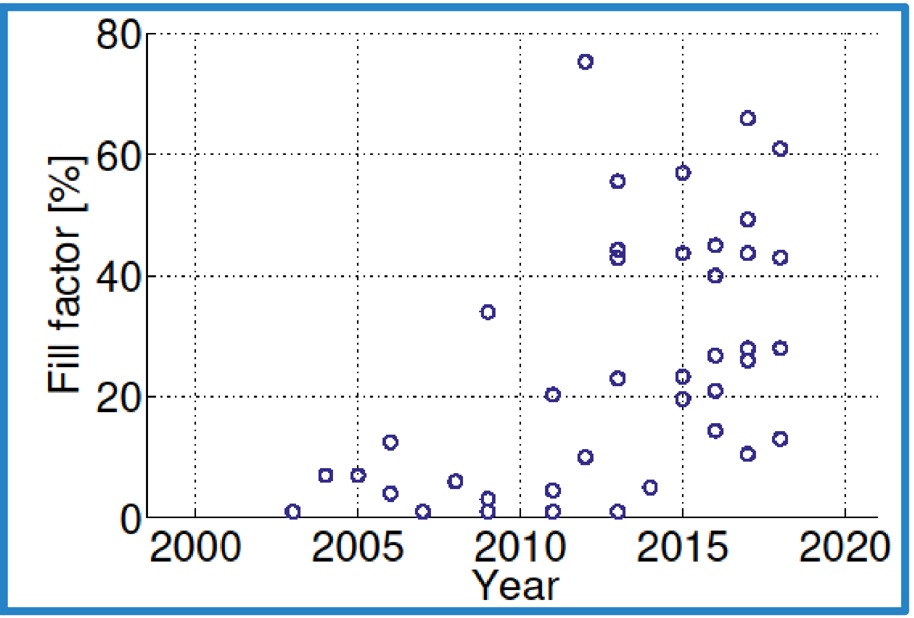
Number of transistors

[C. Bruschini et al., EPFL & TU Delft, *to be published*]

Trends in SPADs







Number of SPAD Pixels

Pixel Pitch

Fill Factor

[C. Bruschini et al., EPFL & TU Delft, *to be published*]

ST Performance Summary Table

Metric	**IMG175SPAD Value (@ 60°C)** **[SPIE Photon Counting Conference]**	**40nm SPAD (@60°C)**
VHV0	13.8V	15.5V
DCR Median	~1k cps	700 cps
PDP	3.1% (850nm)	5% (850nm)
SPAD Fill Factor	6%	>70%
Max Count Rate	37Mcps	150Mcps
Jitter	120ps FWHM, 870ps FW1%M	140ps FWHM, 1.3ns FW1%M
Current per Pulse	0.08pA	0.06pA
After-Pulsing	<0.1%	<0.1%
Cross-Talk	<0.01% (isolated SPAD)	<2% (Shared well)
Digital gate density		80% higher than 130nm CMOS
Power consumption		85% lower than 130nm CMOS

[Source: S. Pellegrini, STMicroelectronics ISSW 2018]

Noteworthy Stacked CIS Chips

- Commercialized stacked CIS chips

Chip Vendor	Year	Stacked CIS Foundry/Gen.	Stacked ISP Foundry/Gen.
Sony	2013	Sony 90 nm	Sony 65 nm
Sony	2014	Sony 90 nm	TSMC 40 nm
Sony	2016	Sony 90 nm	TSMC 28 nm
OmniVision	2015	XMC 65 nm	XMC 65 nm
OmniVision	2016	TSMC 65 nm	TSMC 65 nm
Samsung	2015	Samsung 65 nm	Samsung 65 nm
Samsung	2016	Samsung 65 nm	Samsung 28 nm HKMG
Sony	2017	90 nm CIS 30 nm DRAM 40 nm ISP	

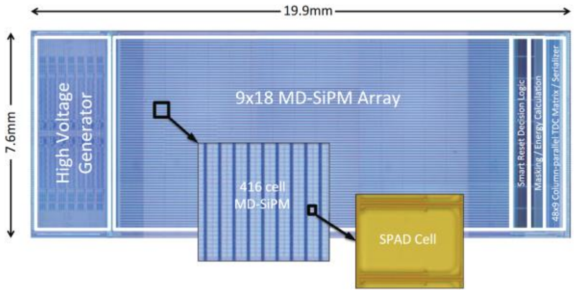
Optimized process for photodiodes + advanced process for data processing

- https://www.techinsights.com/about-techinsights/overview/blog/survey-of-enabling-technologies-in-successful-consumer-digital-imaging-products-part-2/

SPADs: From 2D to 3D

[1]

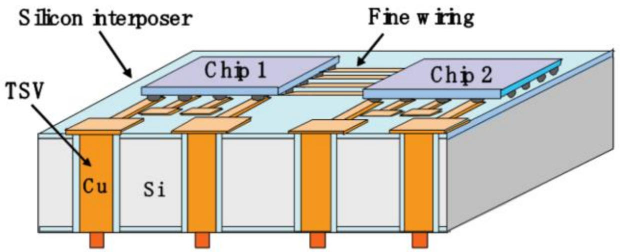
2D Integration



- Consolidated design flow
- Low fill factor, especially for digital
- Same technology for sensor and logic
- Limited amount of processing at pixel level

[2]

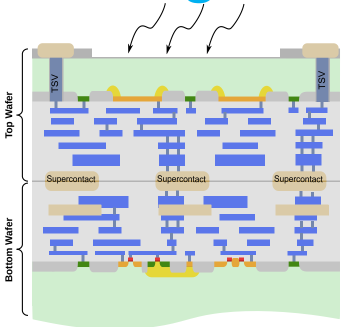
2.5D Integration



- Bare dies are integrated side by side
- Finer pitch than packages or boards
- Improved thermal options w.r.to full 3D stacking
- Heterogeneous Integration of multiple IC platforms

[3]

3D Integration

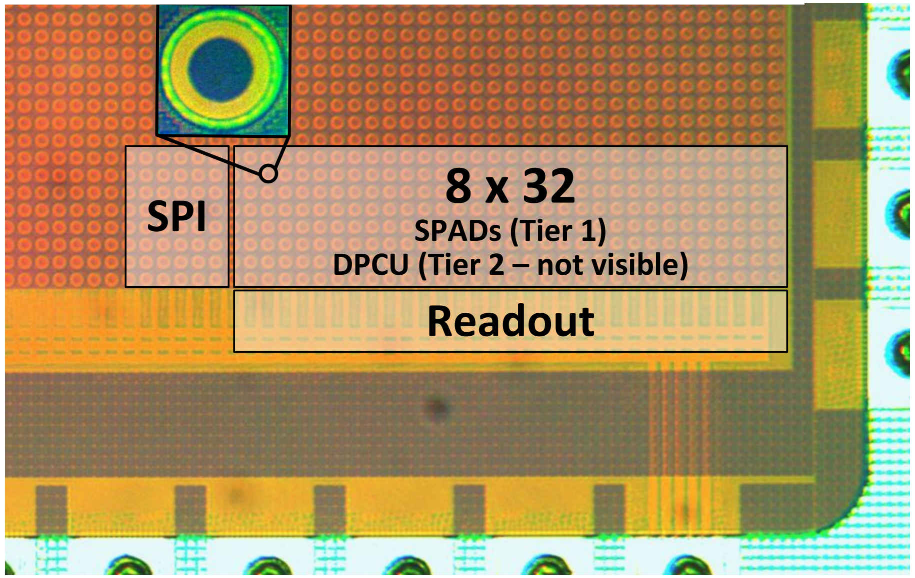


- Top tier: Technology optimized for SPAD (e.g. low DCR and high PDP)
- Bottom tier: state-of-the-art (more advanced) technology node
- Huge increase of processing capability on chip (per pixel)

[Slide: F. Gramuglia, EPFL, 2018; 1. A. Carimatto, et al., ISSCC 2015; 2. V. Sundaram, IEDM 2017; 3. M.-J. Lee, et al., IEDM 2017]

Summary

- First 3D-stacked DTOF sensor
- DPCU digitally synthesized
- Longest single-point measurement in cmos
- Proposed laser signature



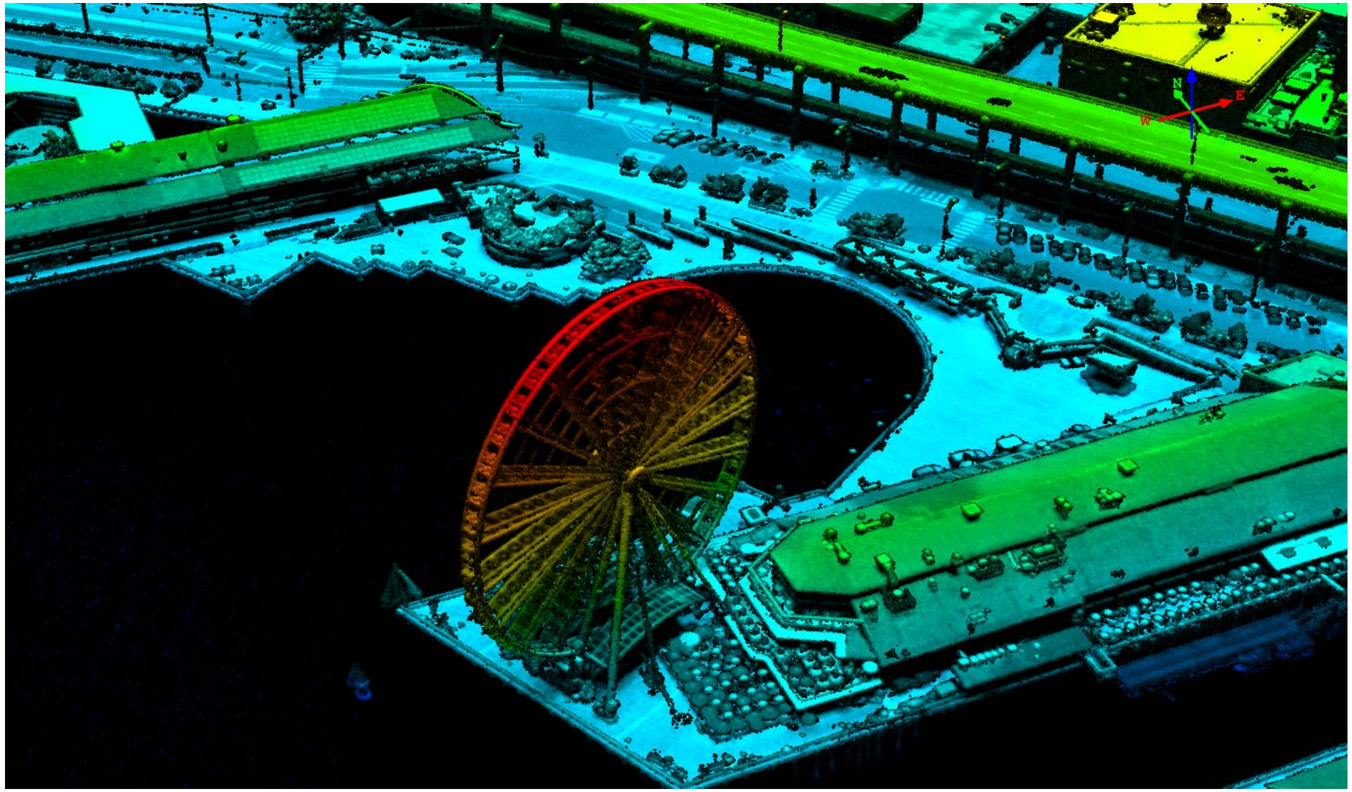
Parameter	**Performance**
Technology	45/65nm CMOS
Pixel pitch	19.8µm
Pixel fill factor	31.3/50.6%
SPAD median DCR	55.4 cps/µm^2 @ 2.5V
TDC resolution	60 – 320ps
TDC power	0.5 – 0.1mW
TDC area	**550µm^2**
Distance range	**150 – 430m**
Precision (σ)	0.15 – 0.47m
(Repeatability)	**0.1 – 0.11%**
Accuracy	0.07 – 0.8m
(Non-linearity)	**0.3 – 0.4%**

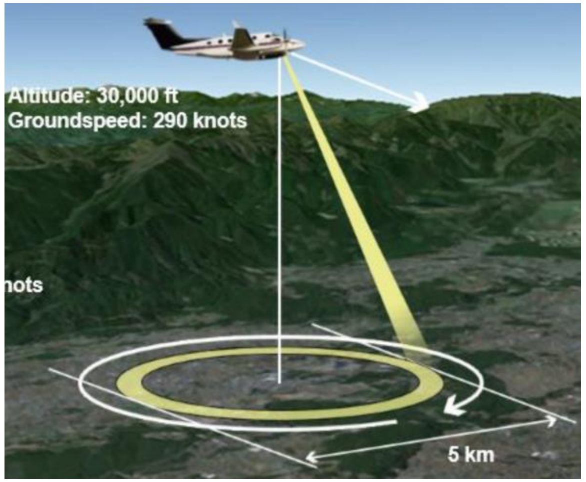
[A. Ximenes/P. Padmanabhan, TU Delft & EPFL, ISSCC 2018, “**A 256×256 45/65nm 3D-Stacked SPAD-bassed…**”

Geiger-Mode 3D LiDAR Mapping

GmAPD-based commercial mapping systems by Harris Corp.

- based on PLI 128 x 32 GmAPD cameras
- enables 10X faster data collection than other LIDAR technologies





aerial photo: Seattle ferris wheel

[M. Itzler, Argo AI, IISW 2018]

imagery courtesy of HARRIS

Automotive LiDAR – Design Considerations

Autonomous vehicles: most exciting short-range LiDAR application

Market size, societal impact

Safety imperative for sensors with complementary modalities

Wide consensus that driverless car sensor suite will have:

LiDAR ***Cameras*** ***RADAR***

LiDAR

- ✓ *Good Low-light Performance*
- ✓ *Good Weather Performance*
- ✓ *True 3D, High Resolution*
- ✗ *Little Ability To Read Signs*

Cameras

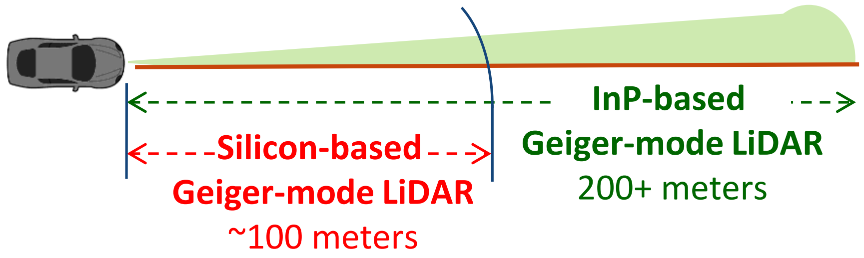
- ✗ *Poor Low-light Performance*
- ✗ *Worst Weather Performance*
- ✗ *Inferred 3D, Not True 3D*
- ✓ *Reads Signs / Sees Colors*

RADAR

- ✓ *Good Low-light Performance*
- ✓ *Best Weather Performance*
- ✗ *True 3D, Low Resolution*
- ✗ *Cannot Read Signs*

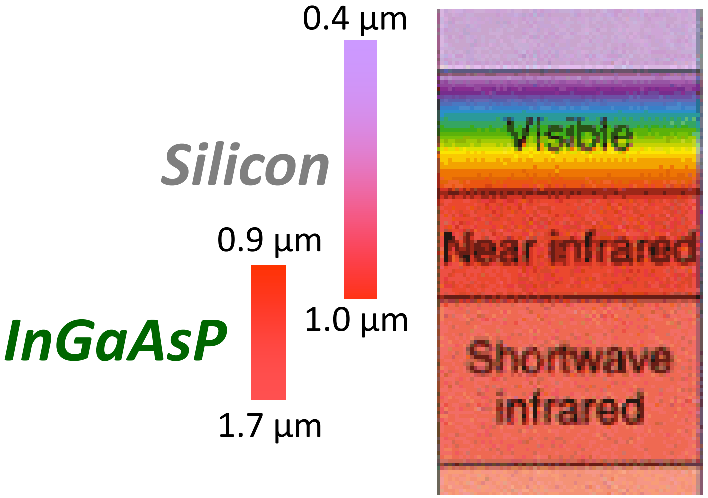
[M. Itzler, Argo AI, ISSW 2018]

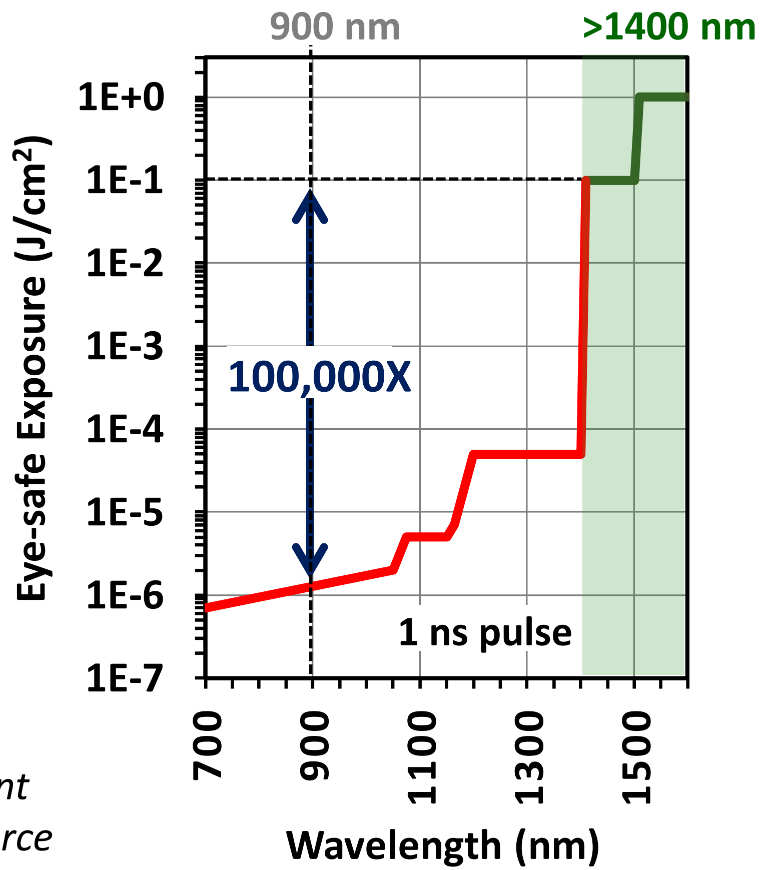
Wavelength Selection for Automotive LiDAR



InP-based
Geiger-mode LiDAR
200+ meters

Silicon-based
Geiger-mode LiDAR
~100 meters





Point
source
1 ns pulse

Greater eye safety for >1400 nm LiDAR: longer range detection

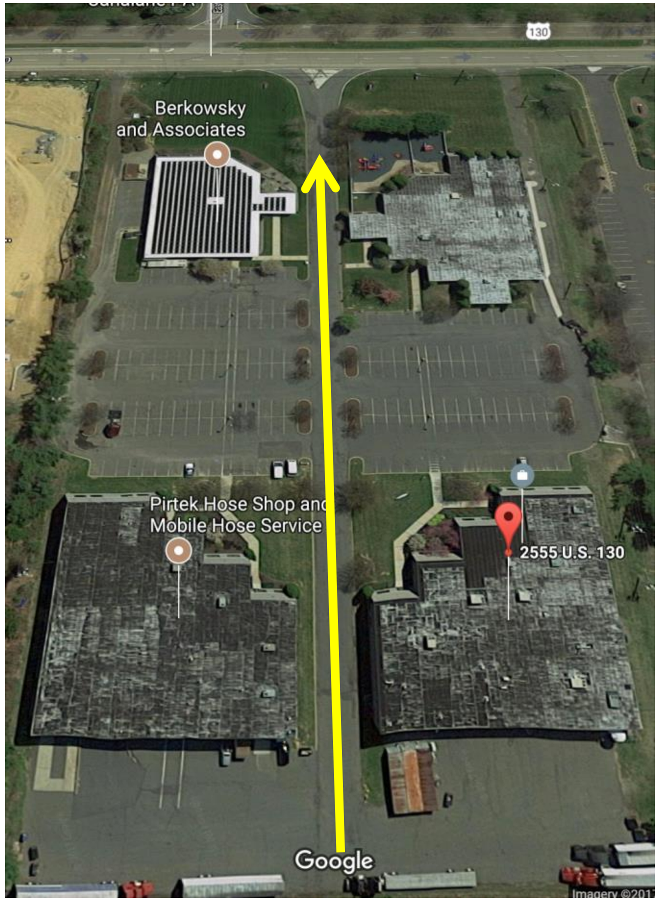
Eye-safety constraints 900 nm LiDAR to <100 m for low reflectance objects

[M. Itzler, Argo AI, ISSW 2018]

3D Driving Video Imagery with Demonstrator

Imagery taken with demonstrator mounted to car roof

Google maps view of 300 m driveway through office park



[M. Itzler, Argo AI, IISW 2018]

Application Challenges

Automotive / Outdoor

- Immunity to background light
- Scanning vs. flash systems
- Eye-safe illumination source
- Adverse weather conditions
- Hidden-object detection
- Low cost

Biomedical

Common issues

- Crosstalk in detectors
- Dynamic range issues
- Close-in time-of-flight

- Dark count rate (DCR)
- Scattering
- Sensitivity

Consumer

- Immunity to background light
- Cover glass issue
- Eye-safe illumination source
- Low cost
- Miniaturization

Main Challenges

- ☐ Sensitivity
- ☐ Data Rate
- ☐ Background Light Suppression
- ☐ Interference Suppression
- ☐ Wide Range of Operating Conditions/High Dynamic Range
- ☐ Non-Uniformities in Imagers
- ☐ Optical Interface & (Cross-)Coupling, Cross-Talk Reduction
- ☐ Illuminator (Speed, Power Control, Eye Safety)
- ☐ Scattering and Absorption
- ☐ Improving Timing Statistics

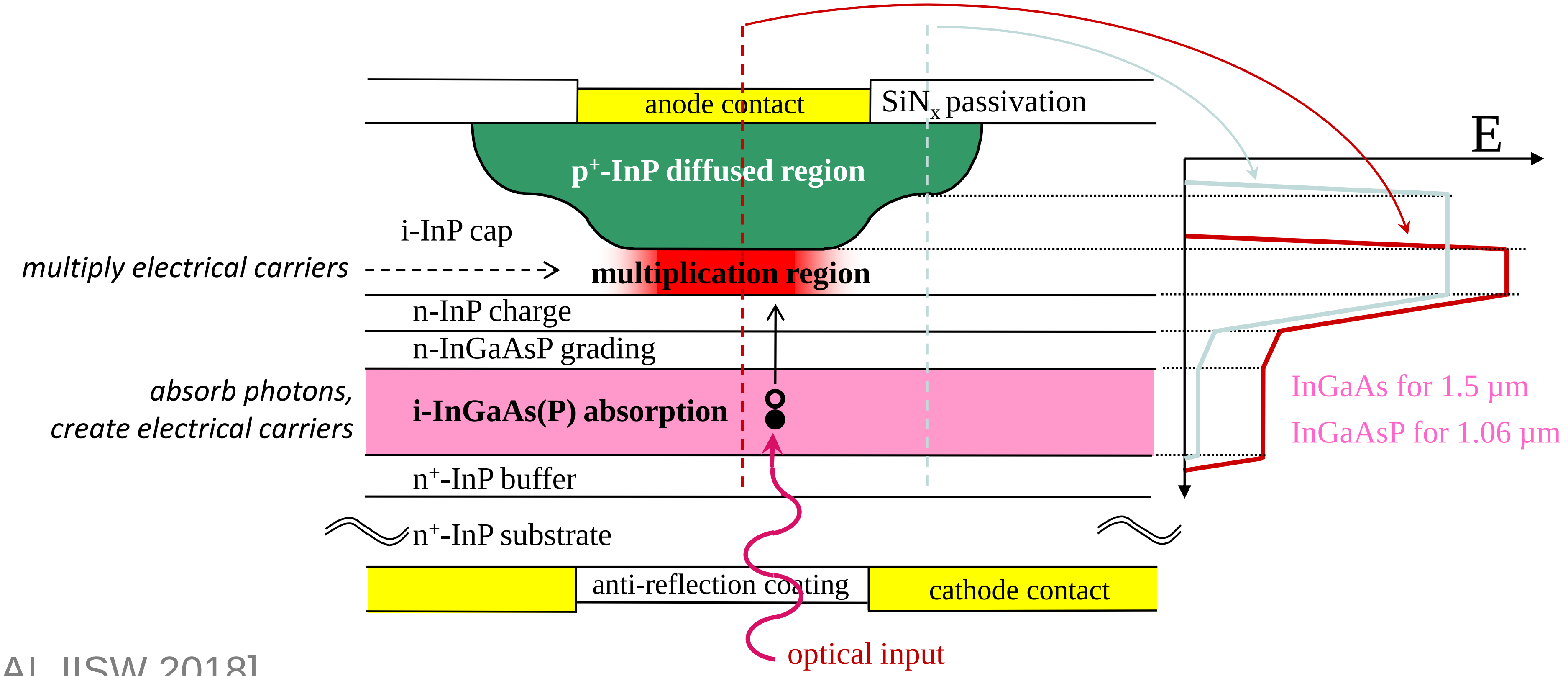
Background Light Issue -> SWIR detection

Two key device regions:

Multiplication region: Create additional carriers by avalanche gain

Absorption region: Absorb photon to create electrical carrier

InGaAs(P) APD design



[M. Itzler, Argo AI, IISW 2018]