EPFL aqualab

pi imaging

SPADs for space

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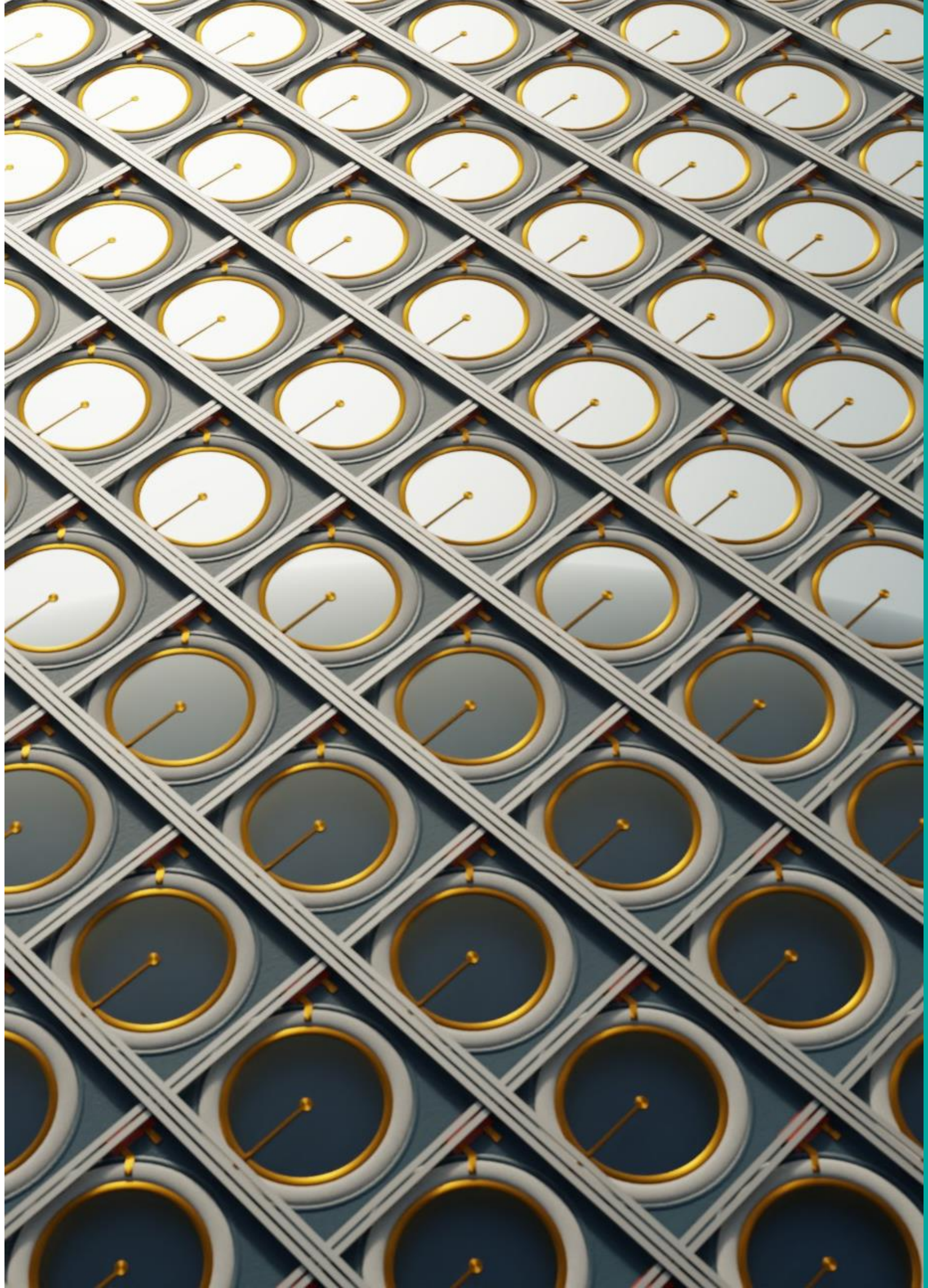
and Edoardo Charbon

SWISS PHOTONICS

04 December 2023

École
polytechnique
fédérale
de Lausanne



Introduction

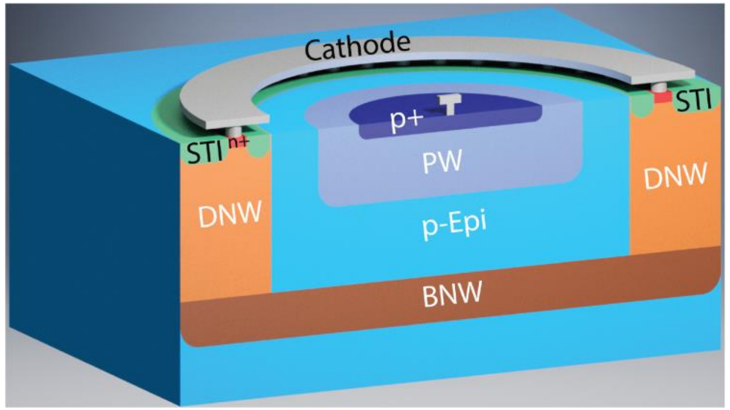
Space environment studies

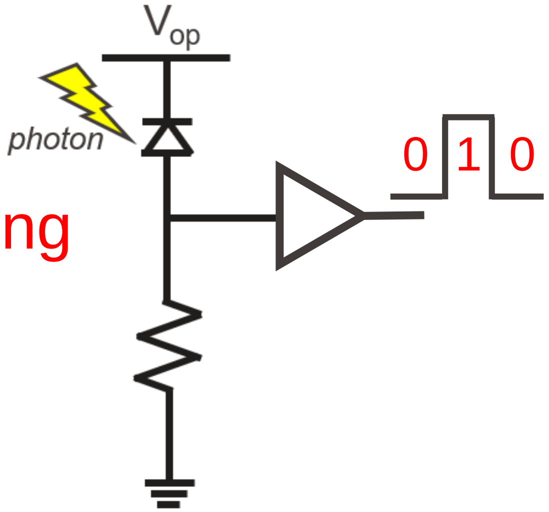
Applications

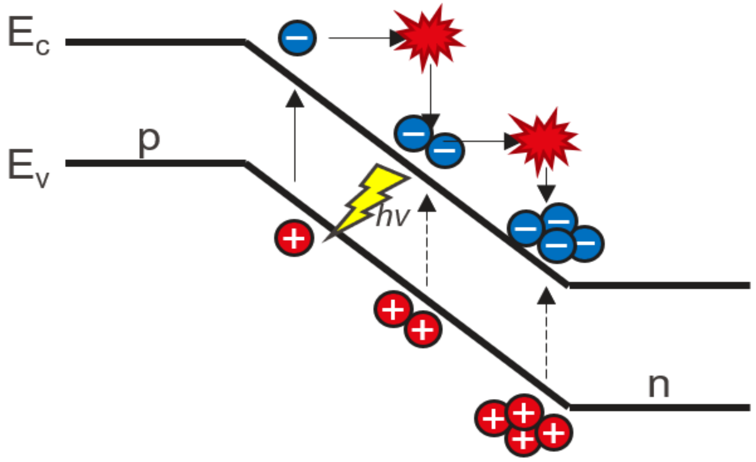
Conclusions

Single-Photon Avalanche Diodes

- Reverse-biased P-N junction operating in Geiger-mode
- High avalanche gain allows single-photon sensitivity and particle detection
- Front-end readout circuits allow digitized photon counting







High E-field multiplication process

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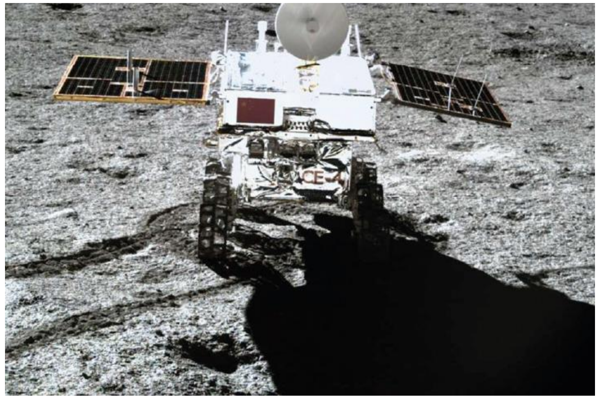
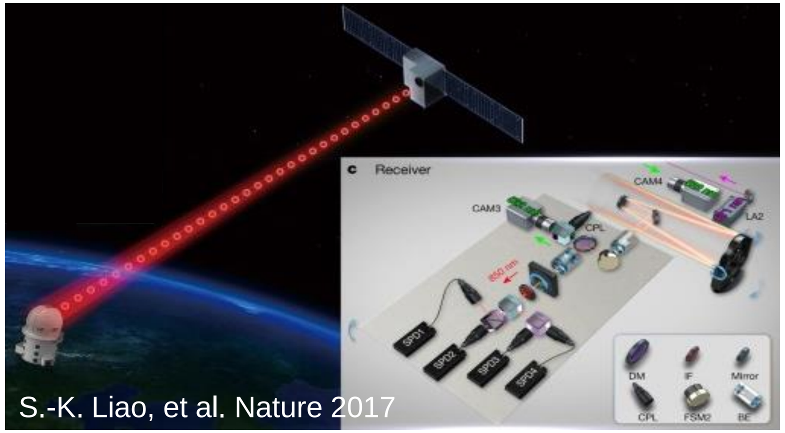
Imaging challenges in space

- Radiation environments
- Temperature fluctuation
- Extreme lighting conditions
  - Low light region
  - Low power resource
  - High contrast scenes



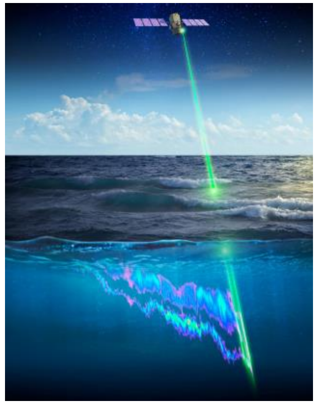
Imaging applications in space

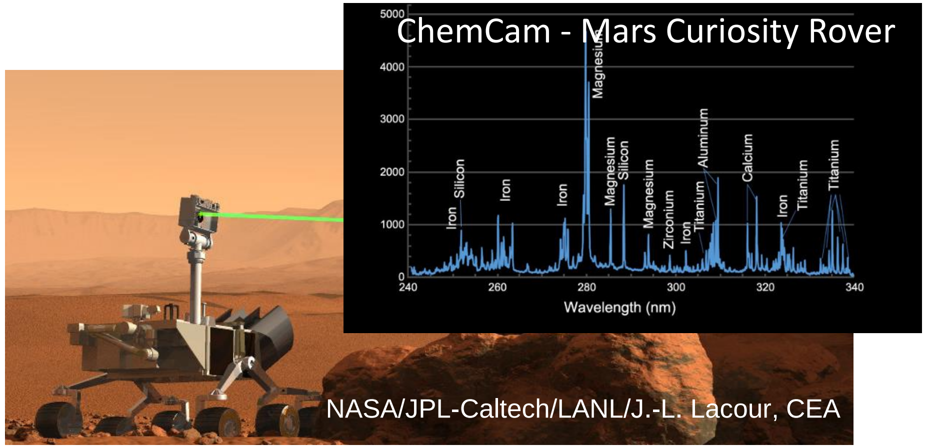
- Space-based surveying:
  2D intensity imaging, HDR (>100dB)



S.-K. Liao, et al. Nature 2017

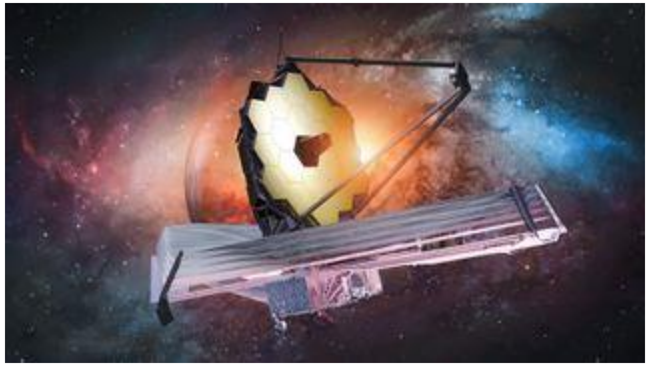
- Applied quantum physics:
  Quantum communication, QRNG, QKD

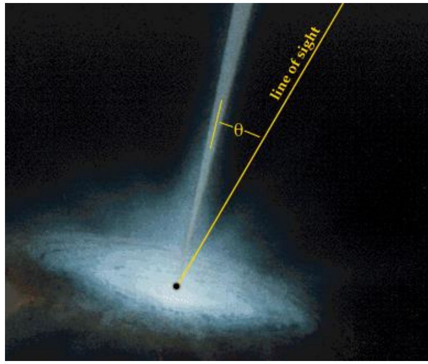




NASA/JPL-Caltech/LANL/J.-L. Lacour, CEA

- 3D imaging / Material science for planetary exploration:
  - LiDAR, Geo-mapping, Raman, LIBS, FLIM





- Astronomy & Astrophysics

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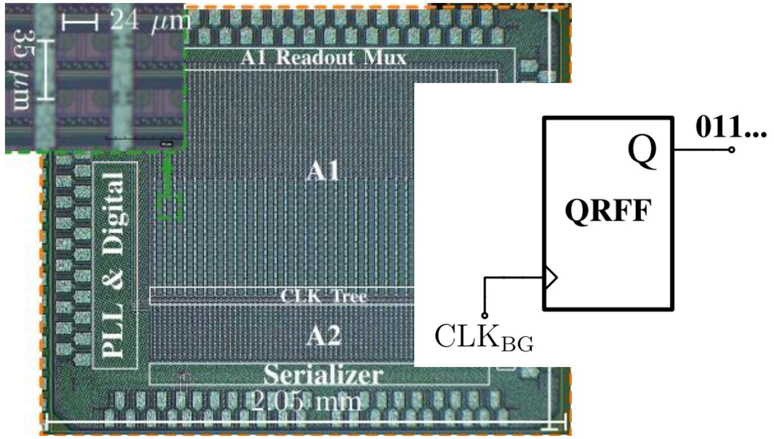
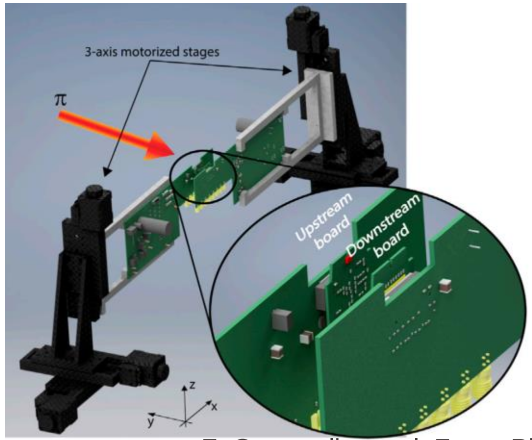
SPAD vs space/radiation applications

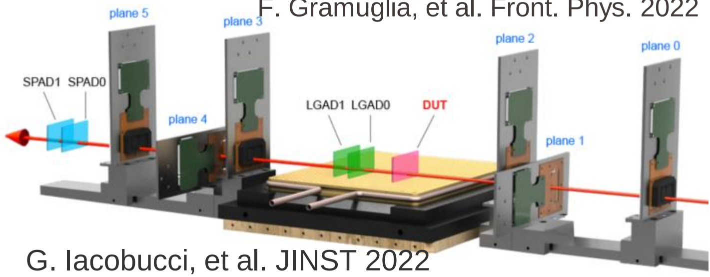
- High speed HDR 2D imaging



- SPAD-based QRNG for Quantum communication



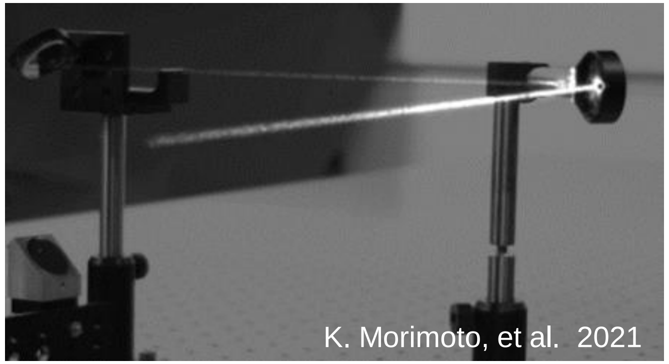
F. Gramuglia, et al. Front. Phys. 2022



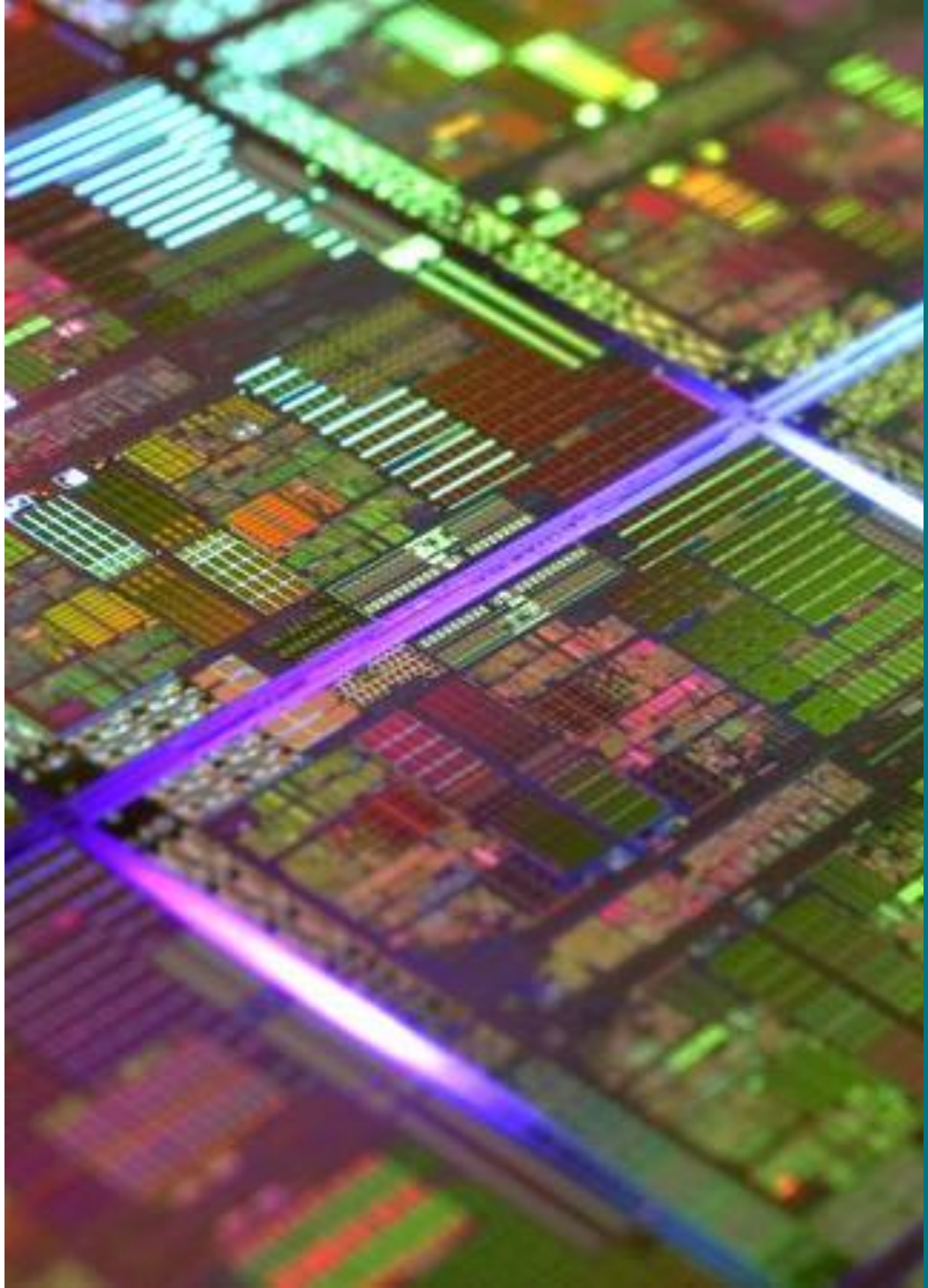
G. Iacobucci, et al. JINST 2022

- High-energy physics: Particle tracking detectors

- 3D imaging and Material science: Object ranging, Raman spectroscopy, FLIM



- 4D Superluminal light-in-flight imaging



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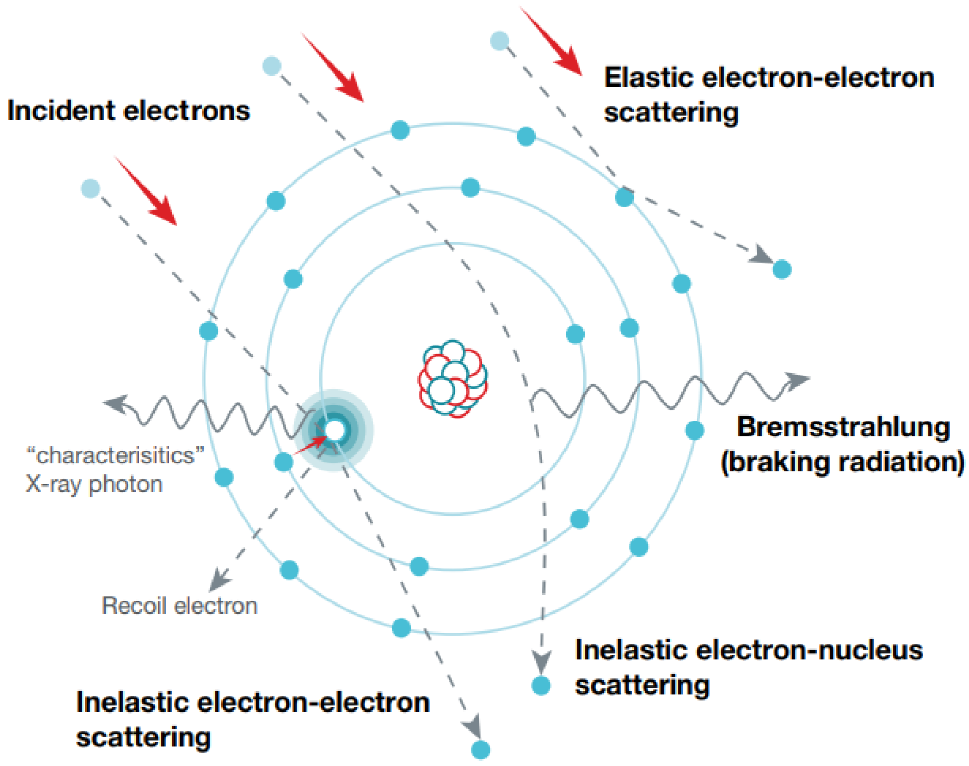
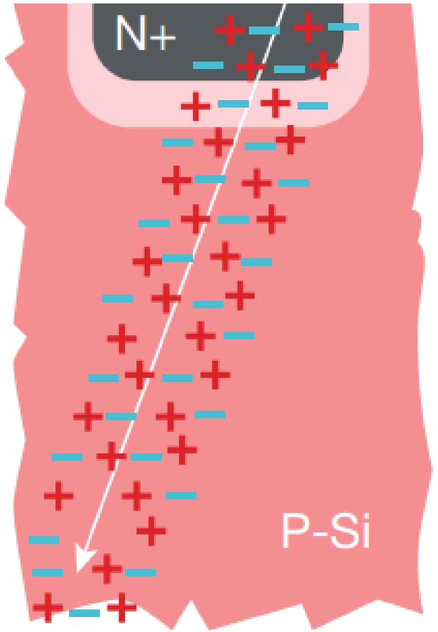
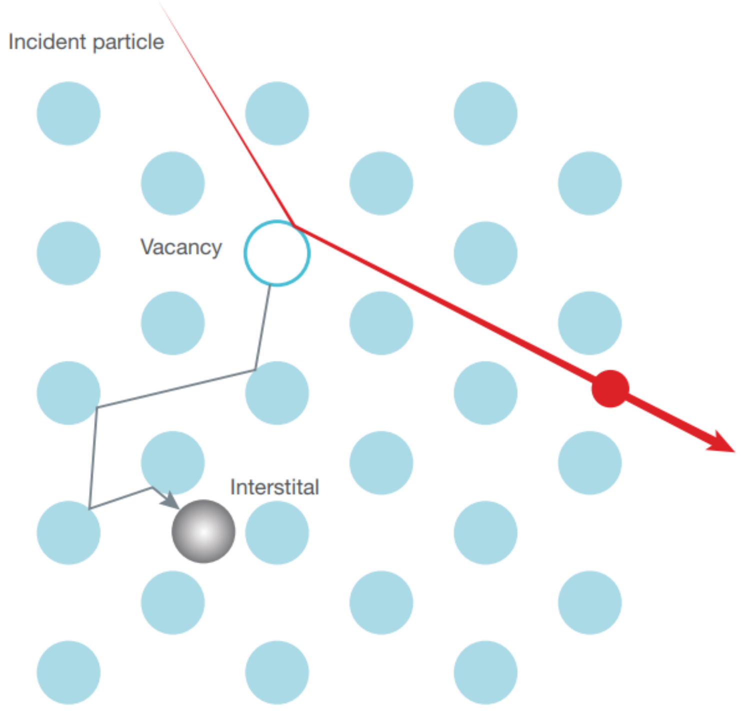
Effect of Radiation on SPAD systems





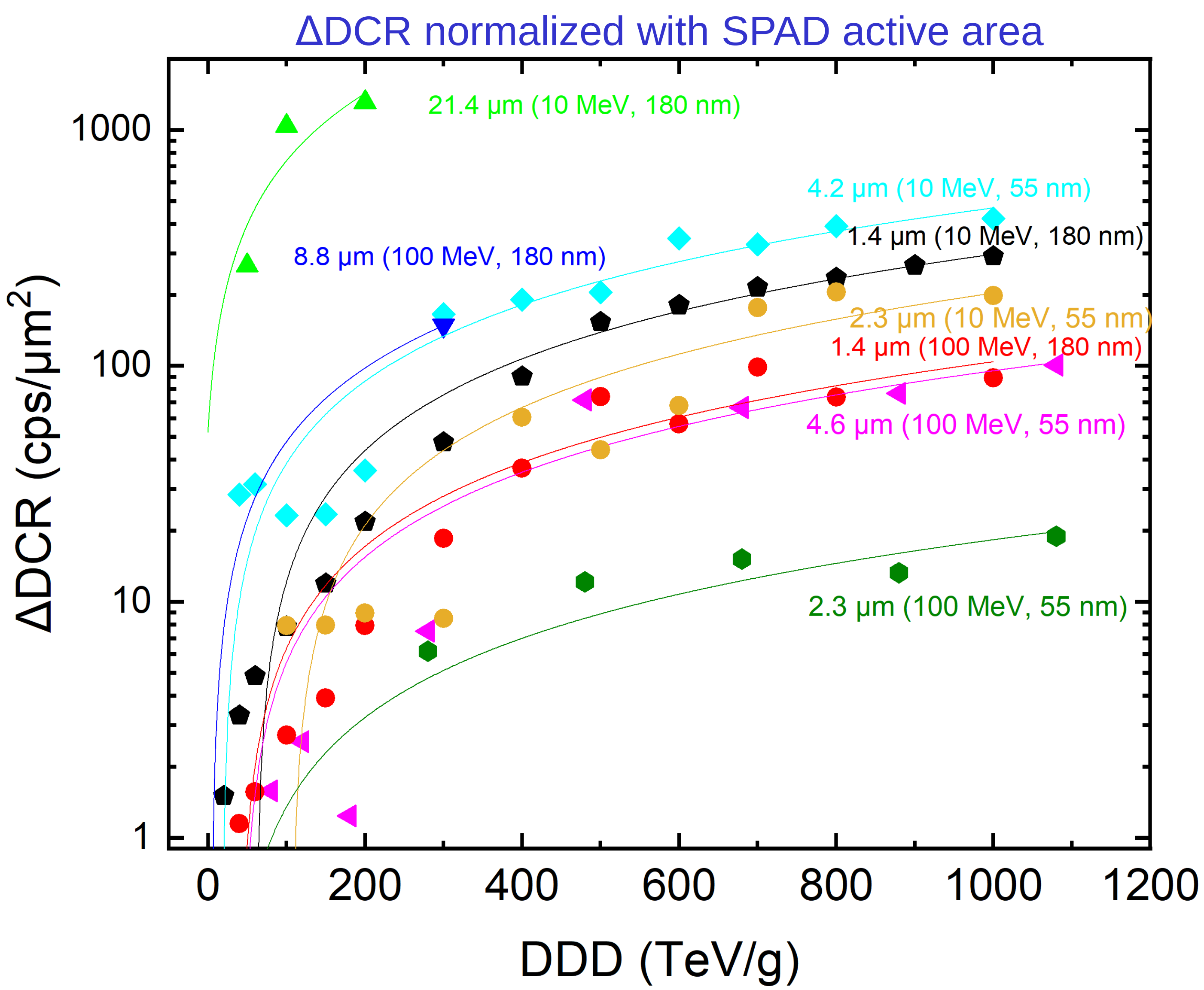


Ionizing damage | **Single-event effect** | **Non-ionizing damage**

Radiation Handbook for Electronics, Texas Instrument

Radiation effect on SPADs: noise

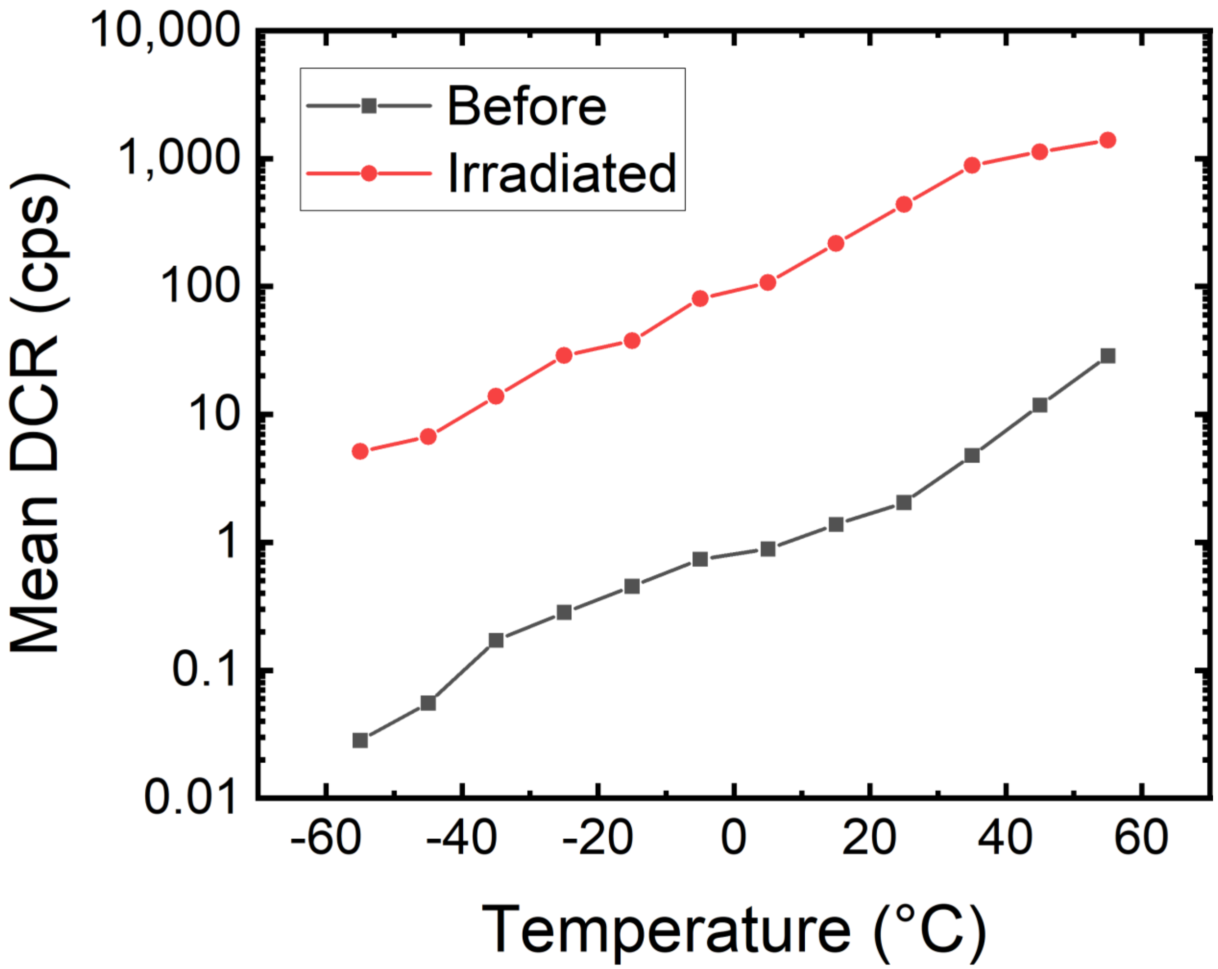
DCR: dark count rate



- Bigger SPAD → Larger ΔDCR
- Lower energy protons → Larger ΔDCR despite same DDD
- Slow ΔDCR increase at low fluence: lower damage probability

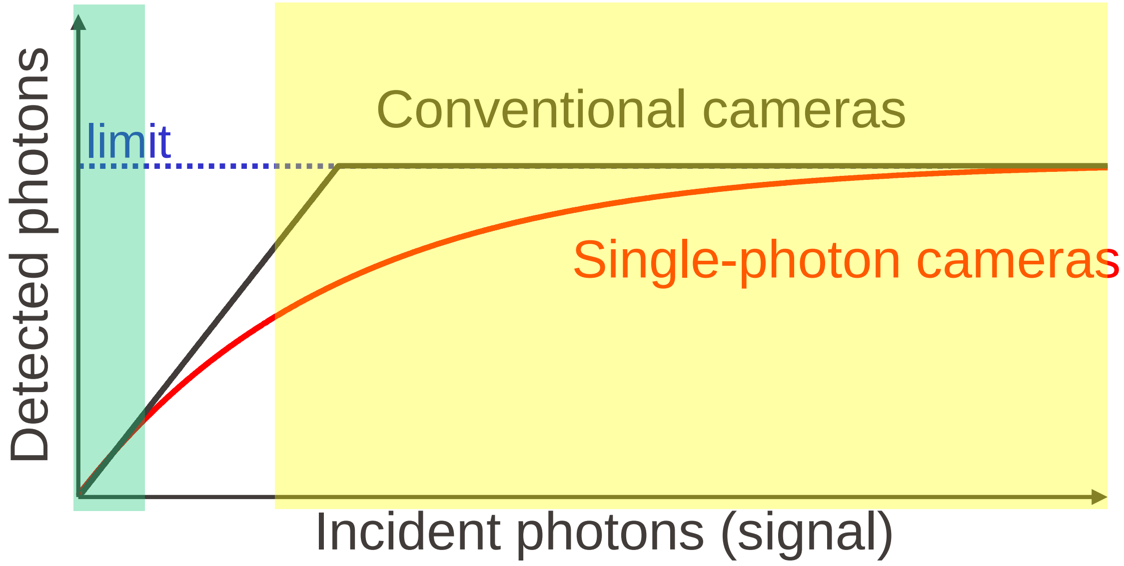
M.-L. Wu, E. Charbon, et al. 2022

SPAD noise vs Temperature



M.-L. Wu, E. Charbon, et al. 2022

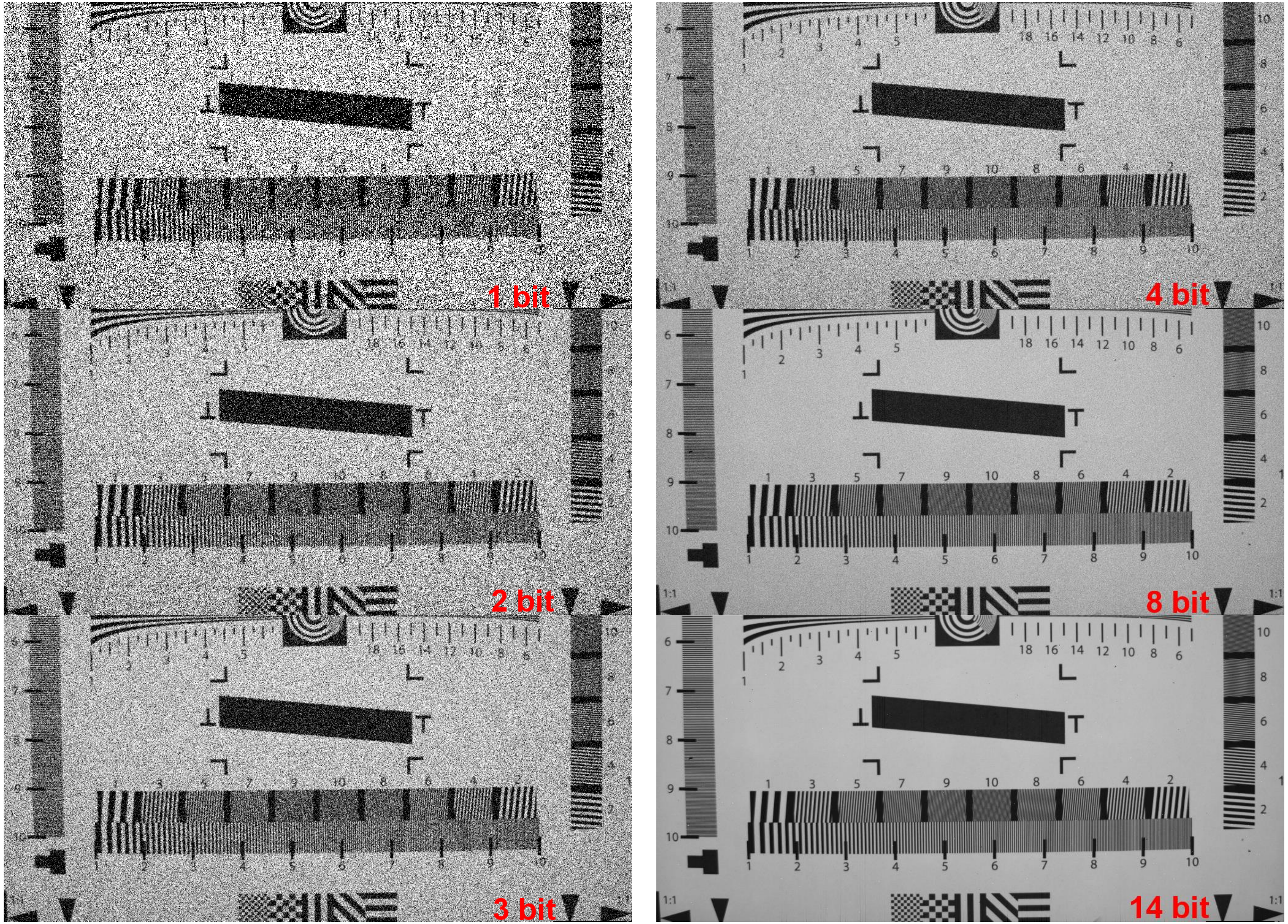
Light vs SPAD: SNR & Dynamic range



High dynamic range!

	Conventional cameras	**Single-photon cameras**
limit	full well capacity	number of binary frames
response	linear	nonlinear
saturation	hard saturation	soft saturation
high signal	noninvertible after reaching full well	invertible (Poisson statistic)
low signal	limit by readout and excess noise	no readout and excess noise

Accumulating binary images…



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Dynamic range vs DCR

clock-driven single-photon camera

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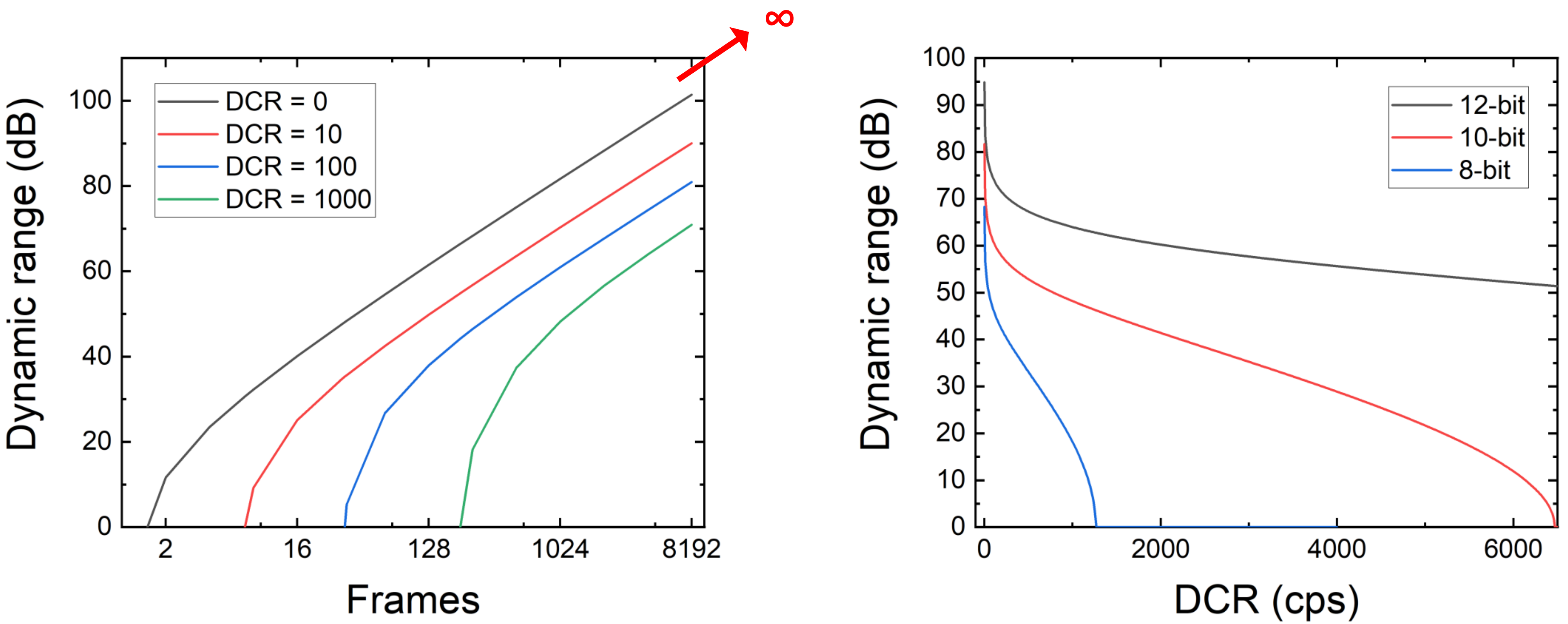
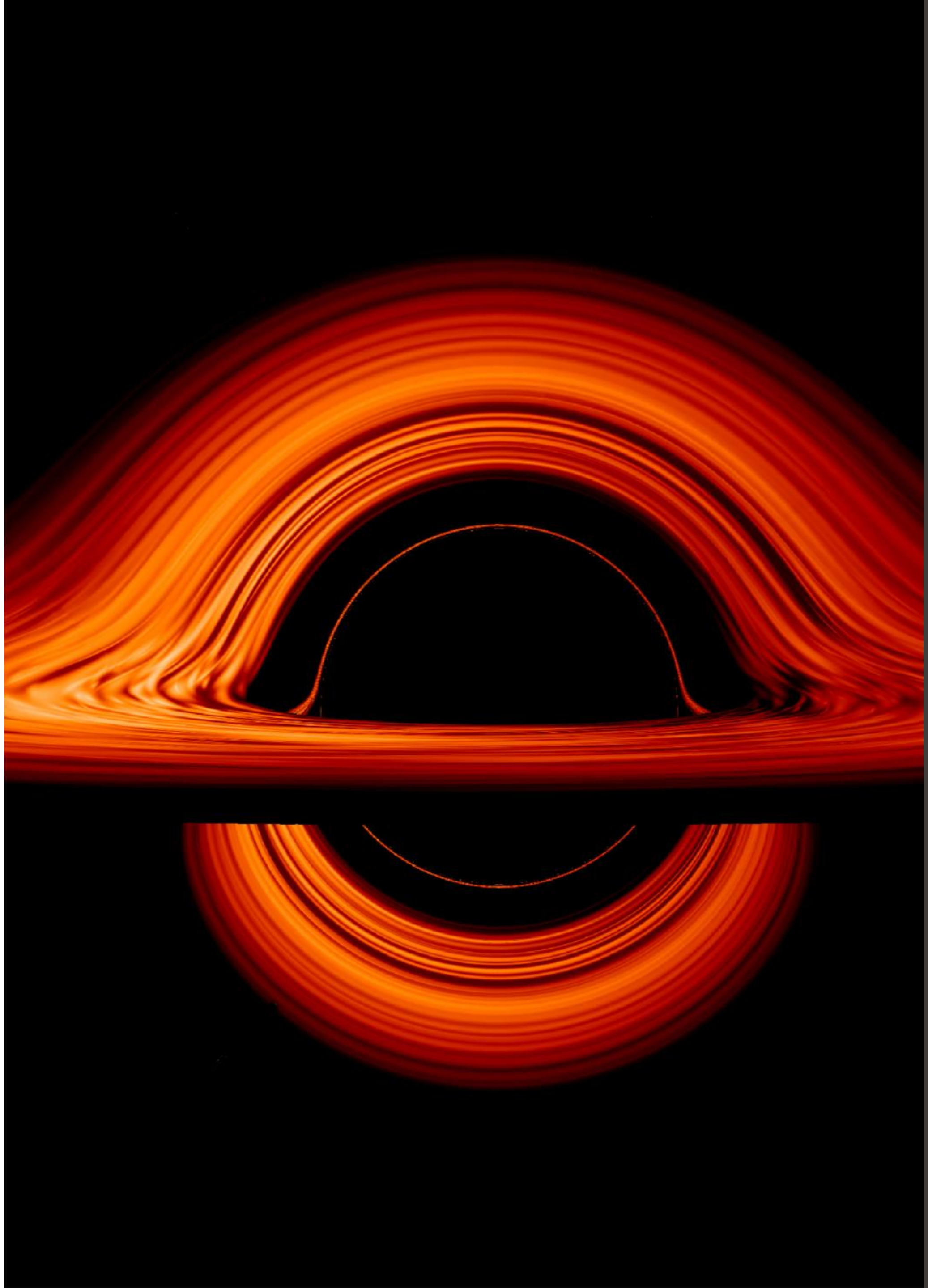


Higher frame rate/bit depth, lower noise → Higher dynamic range
dynamic range ~125 dB at 100,000 fps,1 sec exposure



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HDR & High speed 2D imaging

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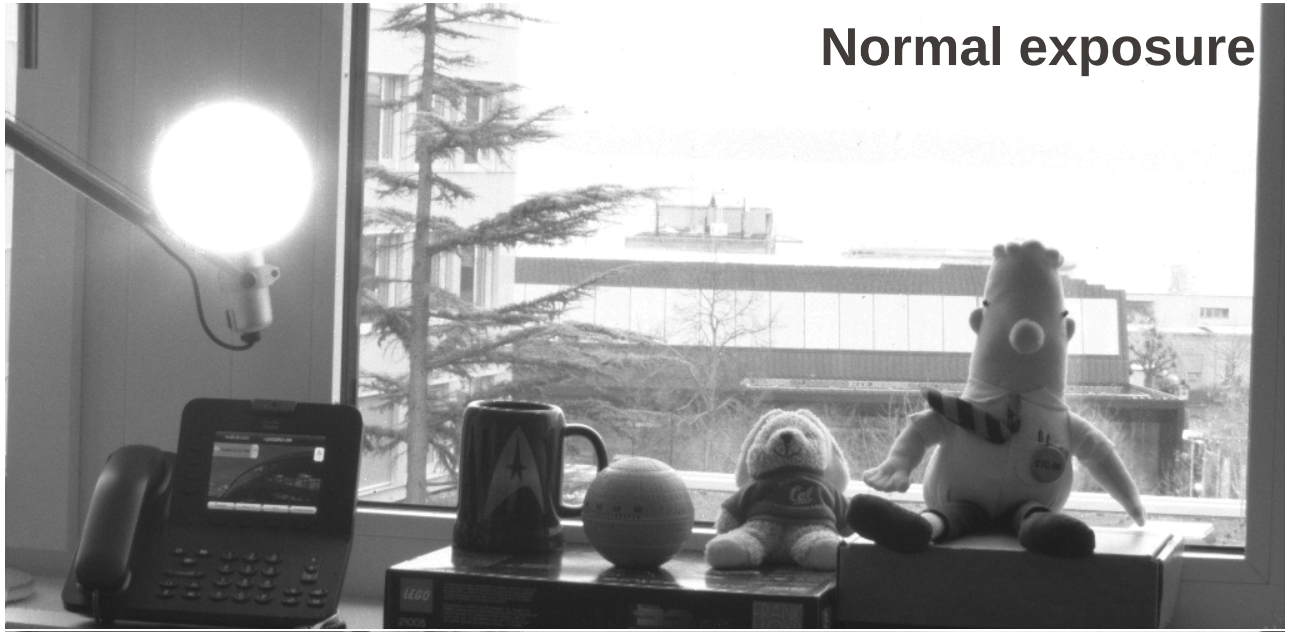

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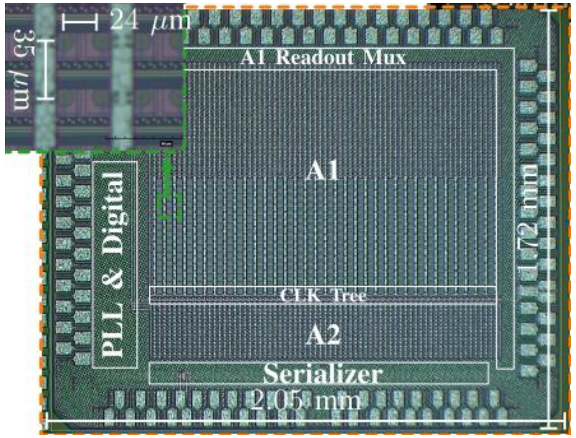
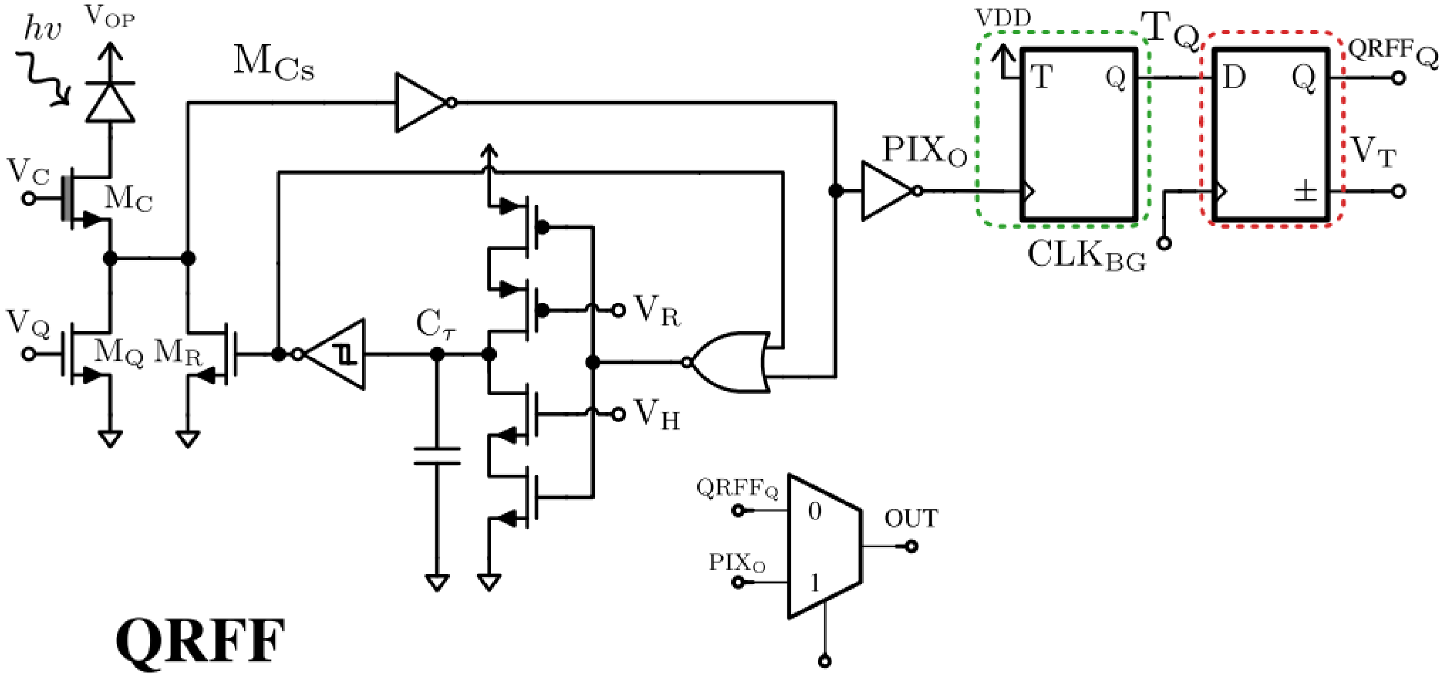
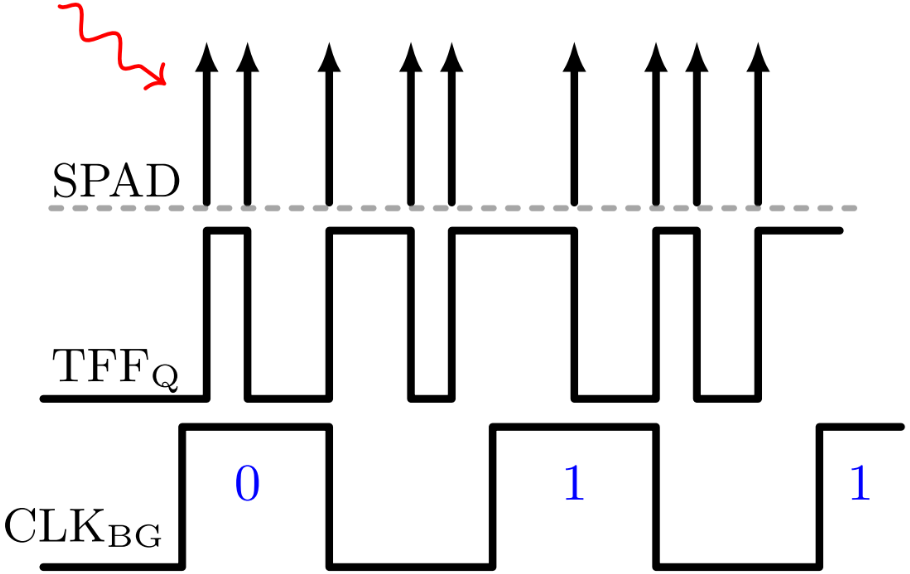
Quantum communication: Quantum random number generation

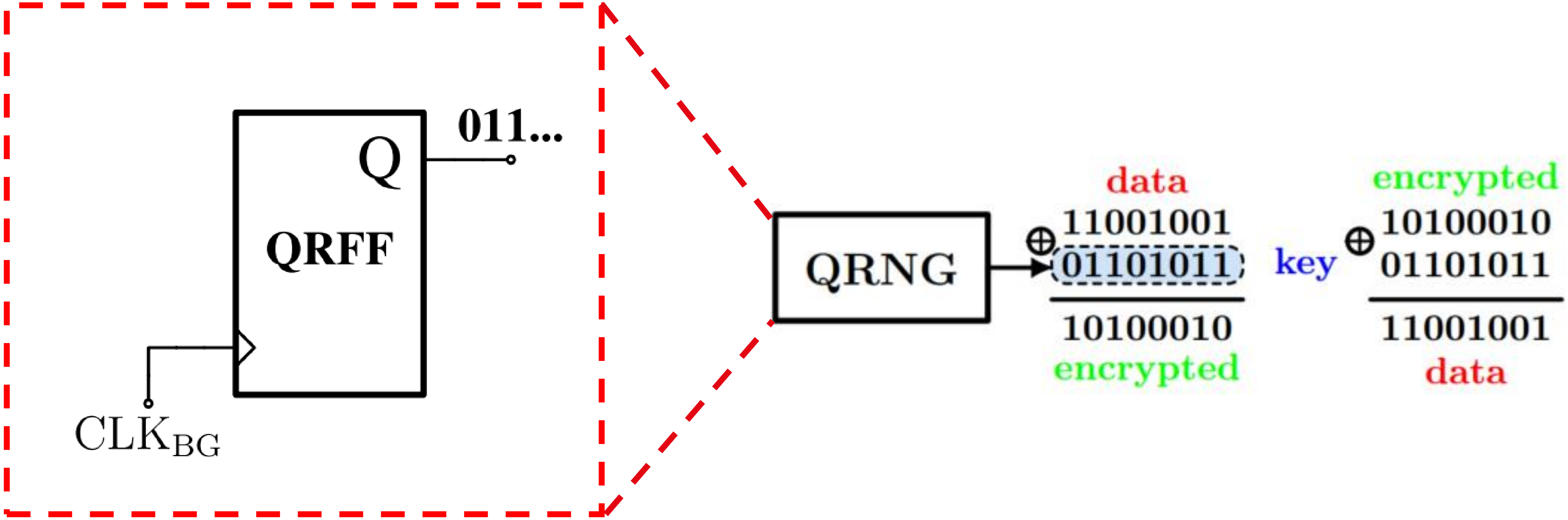






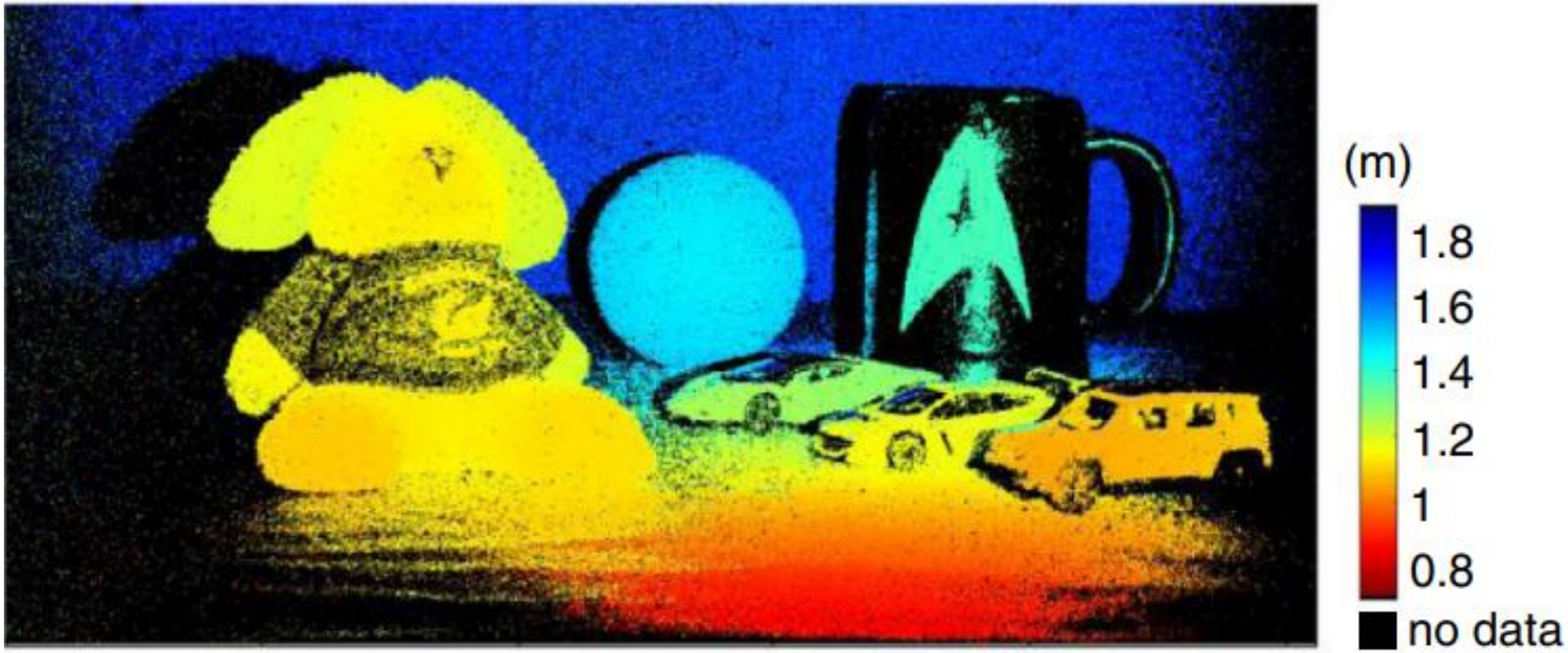
A 3.3-Gb/s SPAD-Based Quantum Random Number Generator
P. Keshavarzian, E. Charbon, et al. 2023

Quantum communication:
Quantum random number generation



Modelling and design of CMOS SPAD sensors for quantum random number generation
P. Keshavarzian

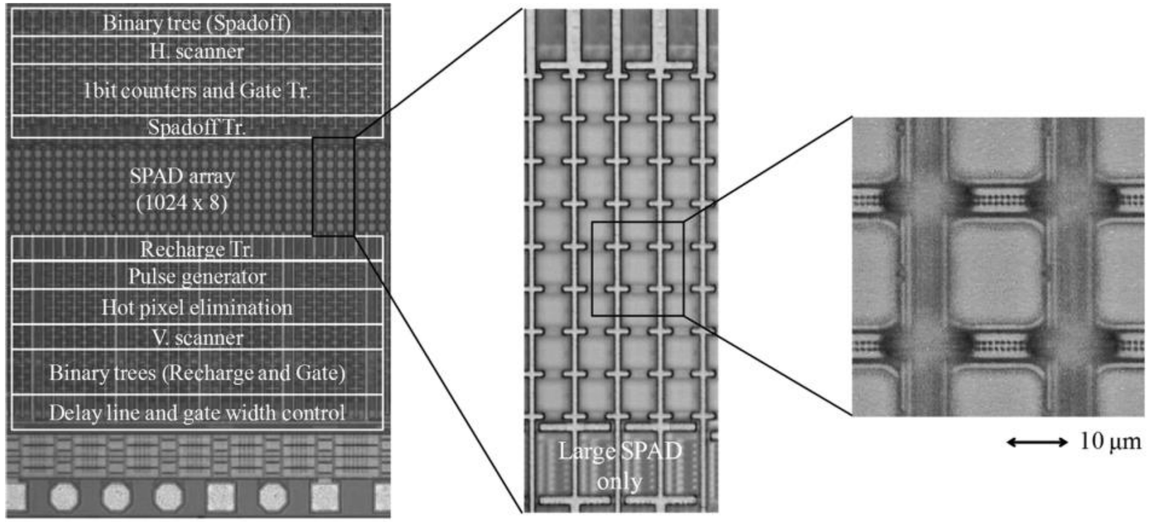
3D imaging object ranging

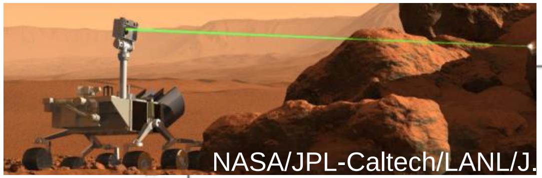


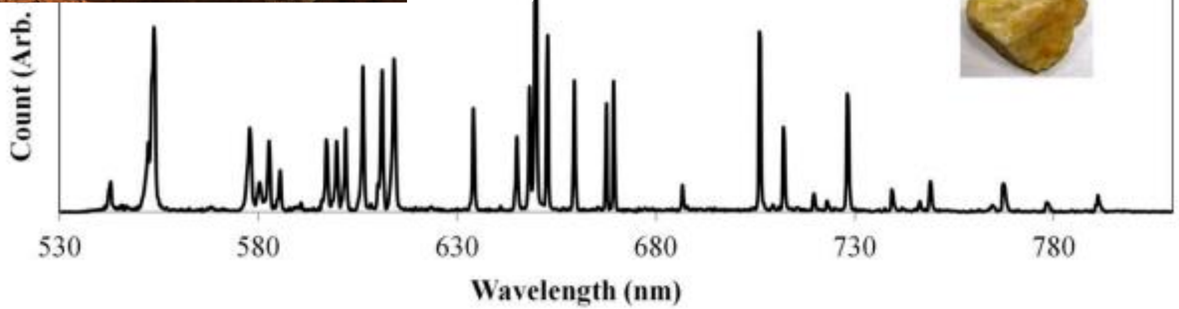
Megapixel time-gated SPAD image sensor for 2D and 3D imaging applications

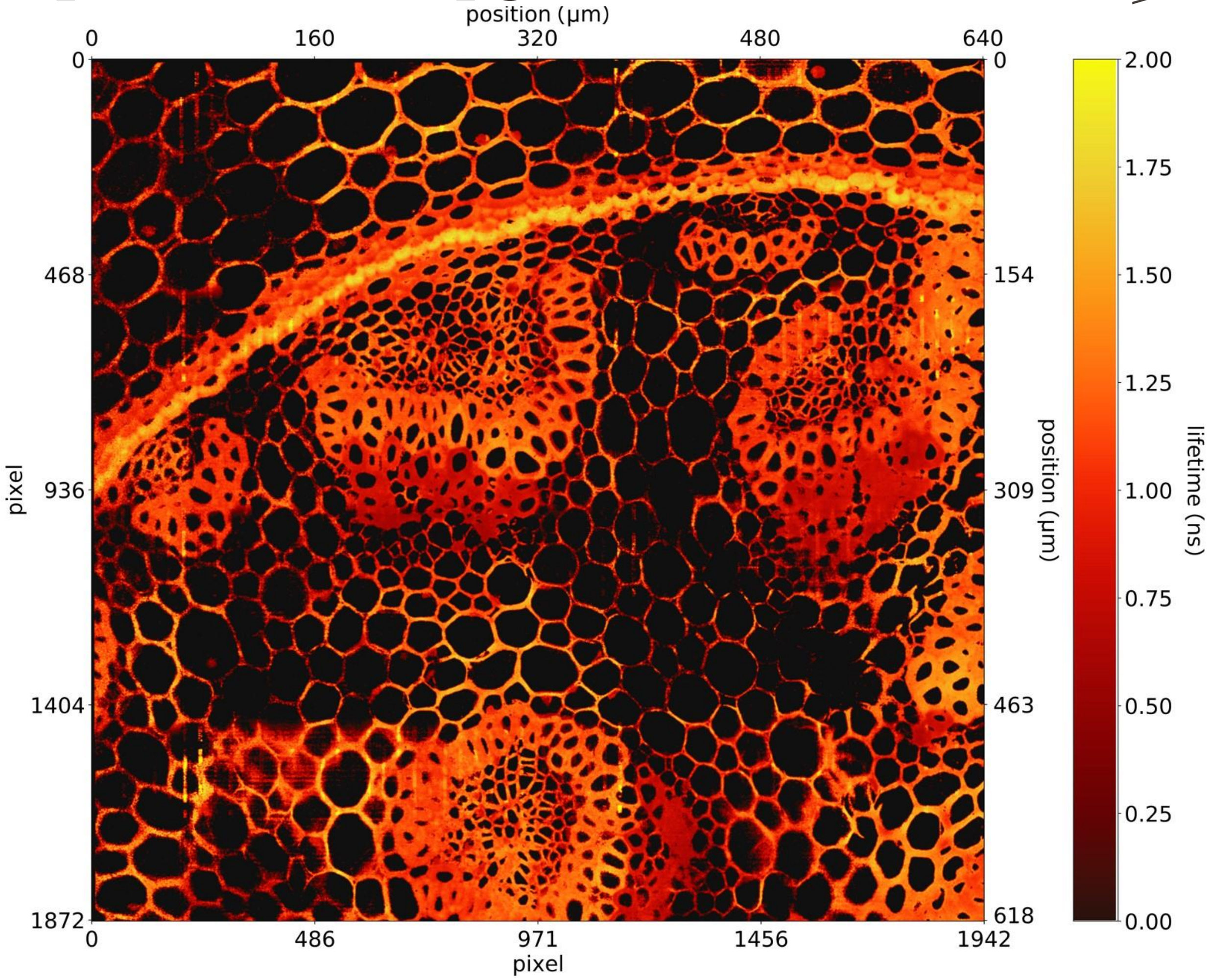
K. Morimoto, E. Charbon et al.

Material science: Raman spectroscopy, LIBS, FLIM









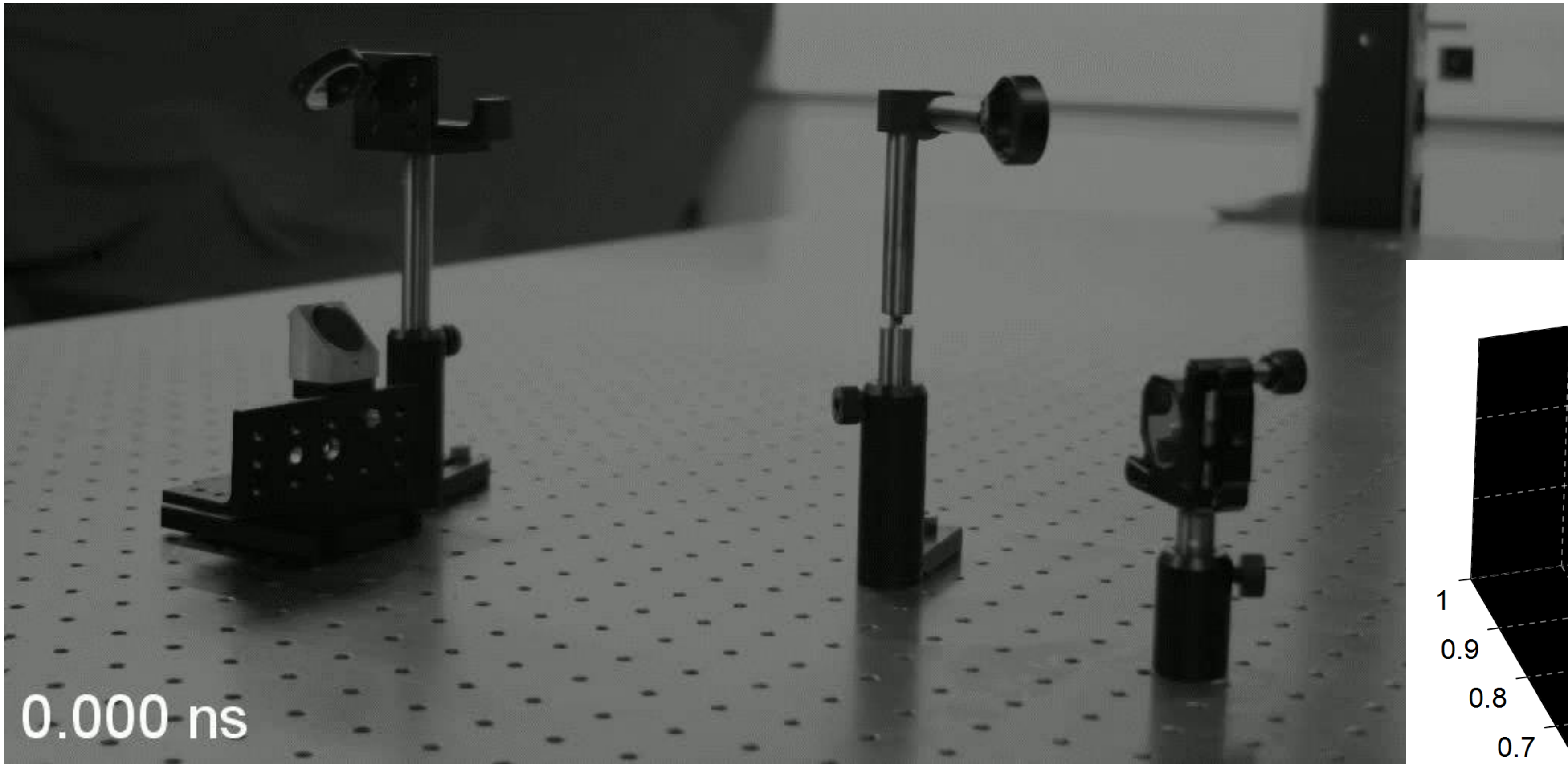
A 1024x8, 700-ps Time-Gated SPAD Line Sensor for Planetary Surface Exploration With Laser Raman Spectroscopy and LIBS

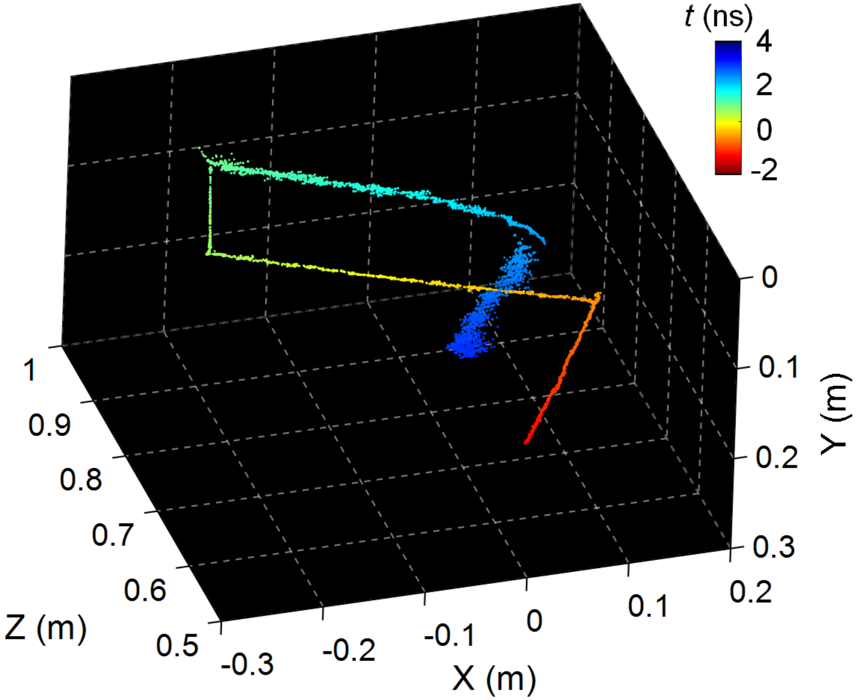
Y. Maruyama, E. Charbon et al.

Fluorescence lifetime imaging with a megapixel SPAD camera and neural network lifetime estimation

V. Zickus, M.-L. Wu, E. Charbon et al.

4D light in flight imaging with SPAD camera

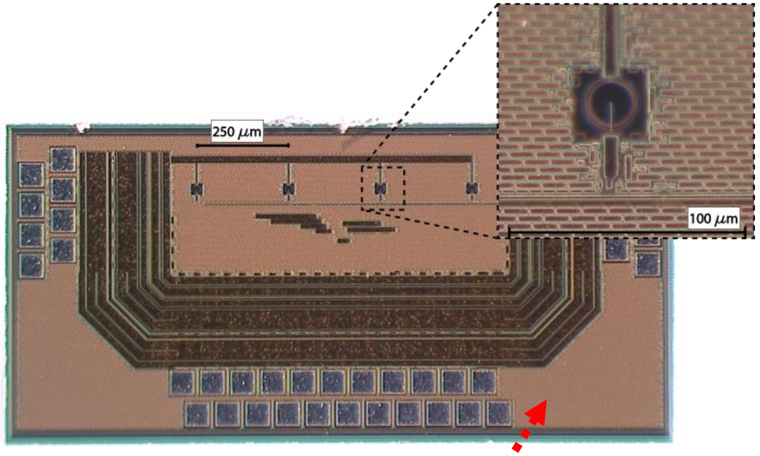


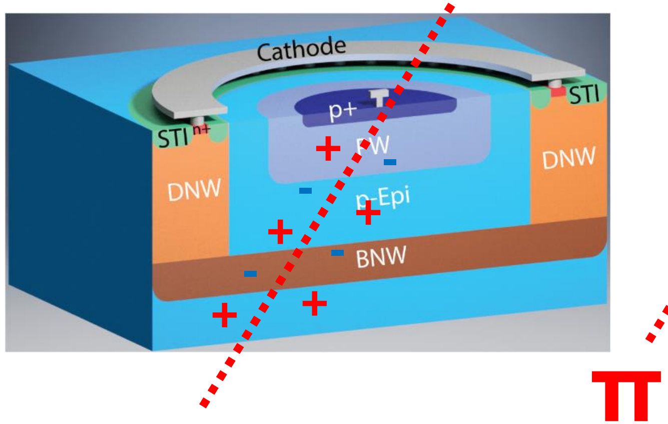


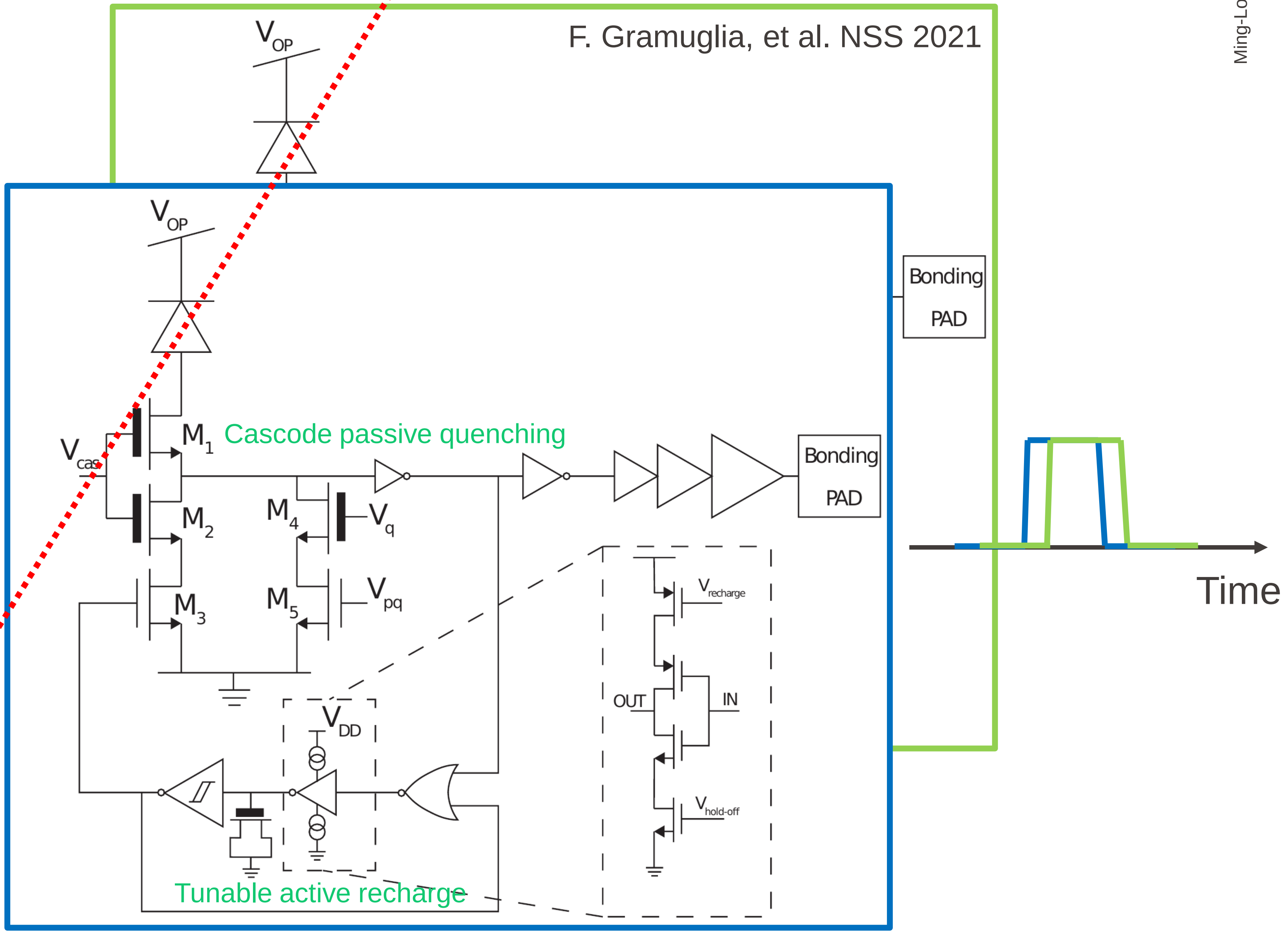
Superluminal motion-assisted four-dimensional light-in-flight imaging
K. Morimoto, M.-L. Wu, A. Ardelean & E. Charbon

Radiation / MIP coincidence detection

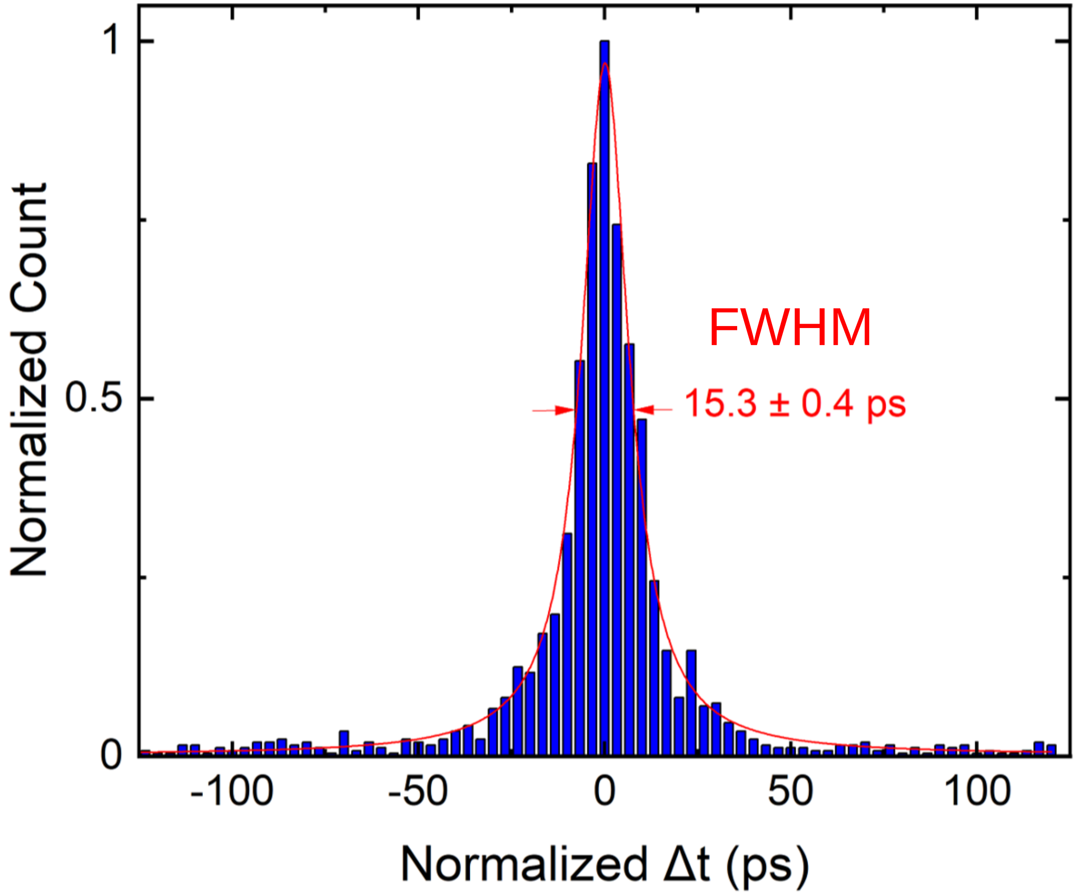
180 nm SPAD pixels
with sub-10 ps timing precision







Radiation detection with SPAD: Timing performance



Detectors	Resolution$_{best}$ (ps)	Time walk	Efficiency	
PicoAD	σ = 17.3	yes	>99%	G. Iacobucci et al. 2022
UFSD	σ = 16[a]	yes	>99%	N. Cartiglia et al. 2017
TIMESPOT	σ = 11.5	yes	~99%	A. Lampis et al. 2023
This work	FWHM = 15.3	no	>99%	M.-L. Wu et al. 2023

(σ ~ 6.5)

QUASAR:
Resolving accretion disks with quantum optics

- HBT Intensity interferometry

- SNR $\propto A_T * \sqrt{N_\lambda} / \sqrt{\tau_{detector}}$

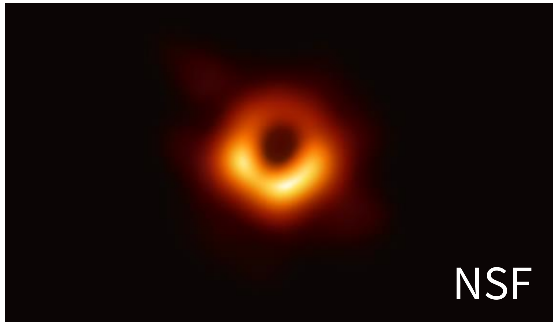
  A_T : telescope area

  N_λ: number of spectral channel

  $\tau_{detector}$: detector timing resolution

- Extremely Large Telescope (2027) x 10 ps SPTR SPAD

  → sub μparcsec resolution



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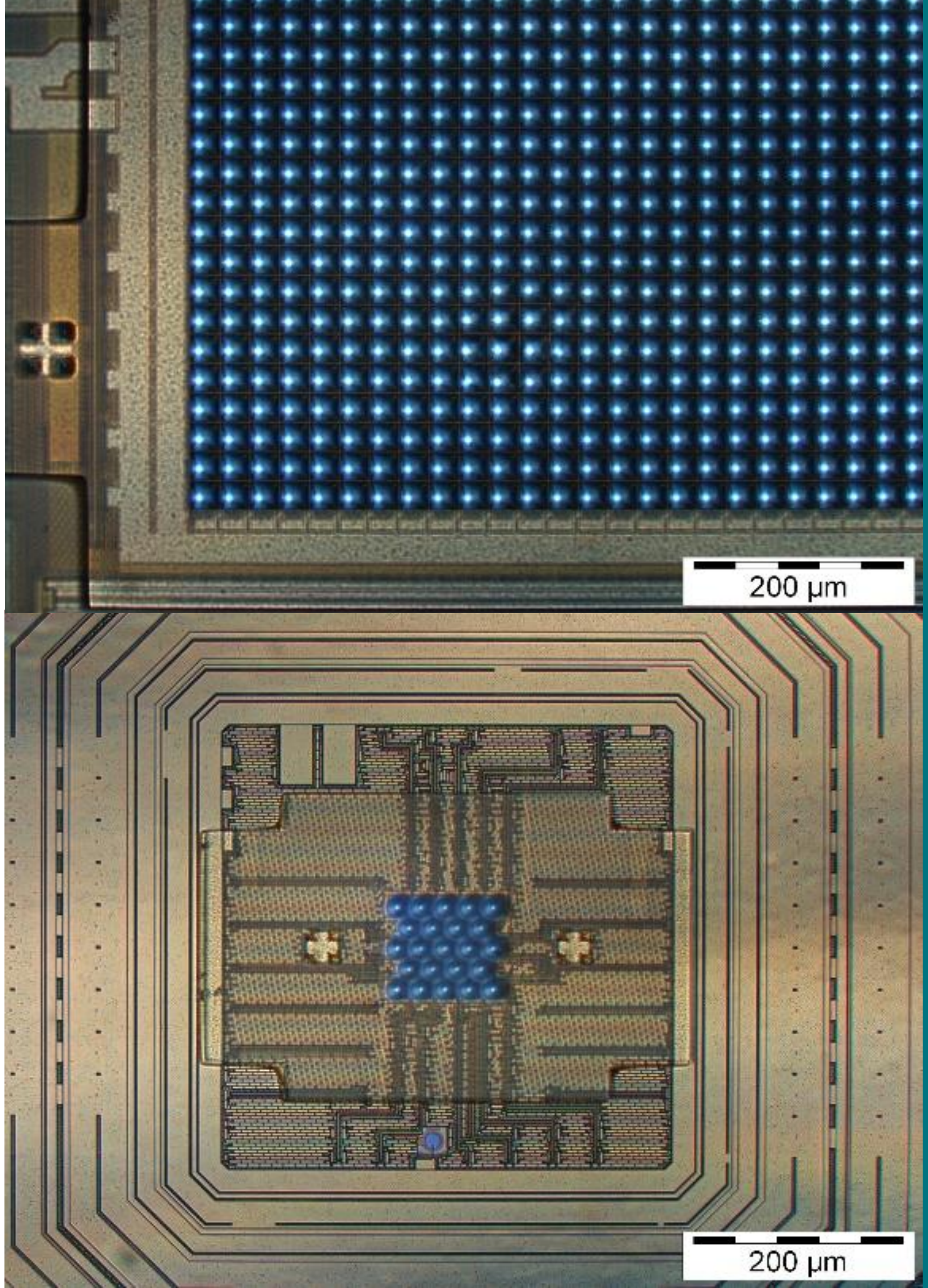
200 µm
200 µm

Summary & Conclusions

- Performance of SPAD-based systems in space environments has been studied:
  - Tolerant to high radiation environments
  - Lower DCR at low temperatures
  - More capable of capturing high dynamic range scenes than conventional cameras

- Demonstrated multiple low-light, high-speed, precise timing applications:
  - HDR 2D intensity imaging up to 100,000 fps
  - QRNG for quantum communication
  - 3D object ranging
  - Material science characterizations (LIBS, Raman, FLIM…)
  - 4D imaging for fast phenomenon tracking
  - Radiation / particle detection with sub 10 ps timing

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Moore's Law for SPADs

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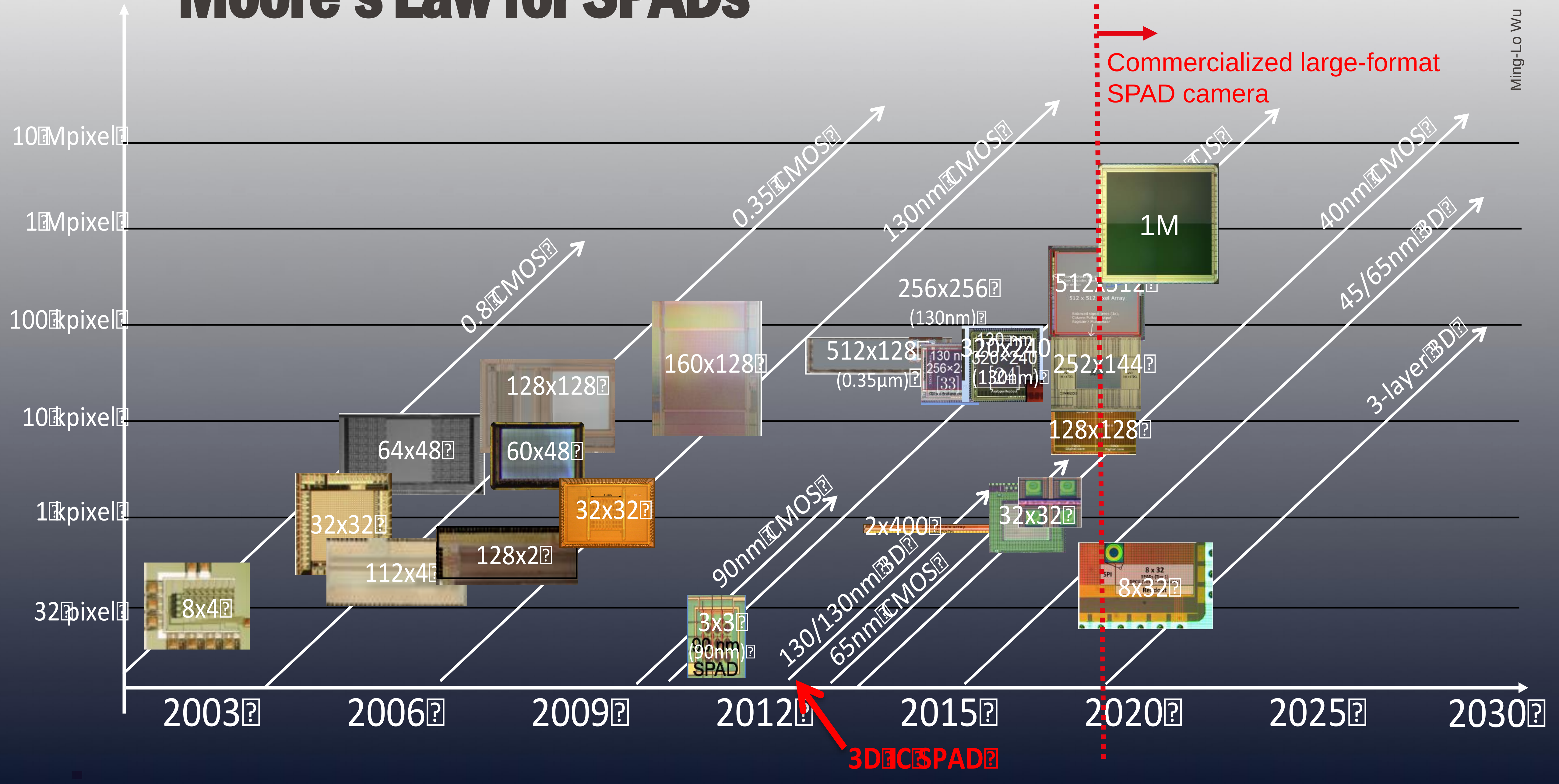
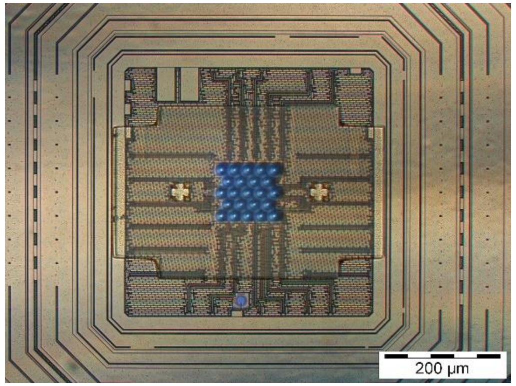
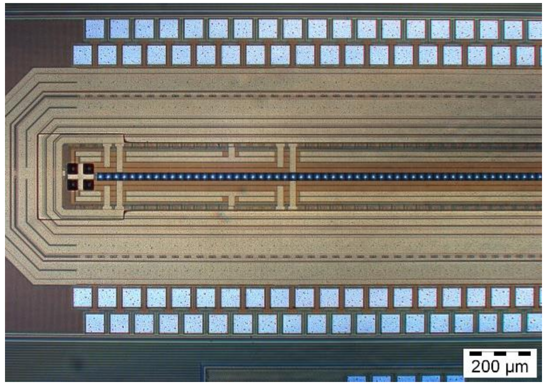
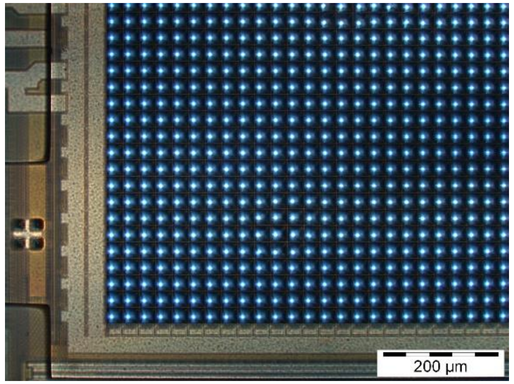


SPAD-based systems







Point	Linear array	2D array
Point detection/scanning Photon counting Time tagging	Linear detection/scanning Spectral application Photon counting Time tagging/gating	Widefield detection Imaging application Photon counting Time gating

SPADs for space...space for SPADs?

Thank you!

pi imaging