Photon-to-Digital Converters – A 3D Integrated Digital Single-Photon Detector for Large Scale Photodetection Systems

and more…

Serge A. Charlebois[1], Fabrice Retiere[2], Jean-François Pratte[1]
for the GRAMS3D research group

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TRIUMF Science Week, July 2025

3IT Institut interdisciplinaire d'innovation technologique UdS

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TRIUMF

UdS Université de Sherbrooke

Sherbrooke: A team's work

UdS

Université de Sherbrooke

Jean-François Pratte
Serge Charlebois
Artur Turala
Frédéric Nolet
Frédéric Vachon
Gabriel Lessard
Guillaume Théberge-Dupuis
Jeanne Morehead
Jérémy Chenard
Jérôme Deshaies
Keven Deslandes
Nicolas Roy
Philippe Arsenault
Philippe Martel-Dion
Raffaele Aaron Giampaolo
Robin Scarpellini
Samuel Parent
Sean Prentice
Simon Carrier
Tommy Rossignol
Olivier Lepage
Yves-Alexandre Beebe

Collaborators

Fabrice Retiere (TRIUMF)

Lorenzo Fabris (ORNL)

Stéphane Martel (TDSI)

Simon Viel (Carleton)

nEXO Collaboration
nEXO Canada
ARGO Collaboration

Thomas Jennewein
QEYSSAT
QKD Micro-net

Jean-Pierre Veran (NRC)

Steve Maclean (IPlabs)
Pierre Lévesque (IPlabs)

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Oak Ridge National Laboratory

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Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

NSERC CRSNG

Fonds de recherche sur la nature et les technologies
Québec

RESMIQ
Regroupement Stratégique en Microsystèmes du Québec

CMC MICROSYSTEMS

BERKELEY LAB
Lawrence Berkeley National Laboratory

CANADA FIRST RESEARCH EXCELLENCE FUND

APOGÉE CANADA
FONDS D'EXCELLENCE EN RECHERCHE

INSTITUT QUANTIQUE

UNIVERSITÉ DE SHERBROOKE

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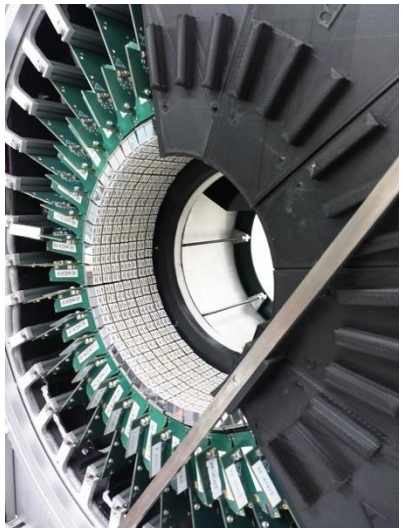
Building Scientific Instruments for…

UDS

- Scintillating crystal-based systems
  - Positron Emission Tomography
  - Computed Tomography
  - Neutron Imaging

} Precise single-photon timing resolution } Visible spectrum

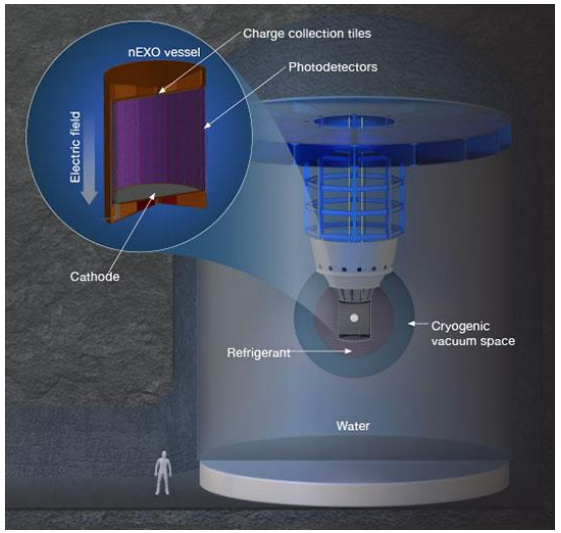


Mid-sized Animal LabPET II

- Noble liquid experiments (Argon and Xenon)
  - Dark matter search
  - Neutrino physics

} Large area detector (~m^2) → Low power } VUV sensitivity

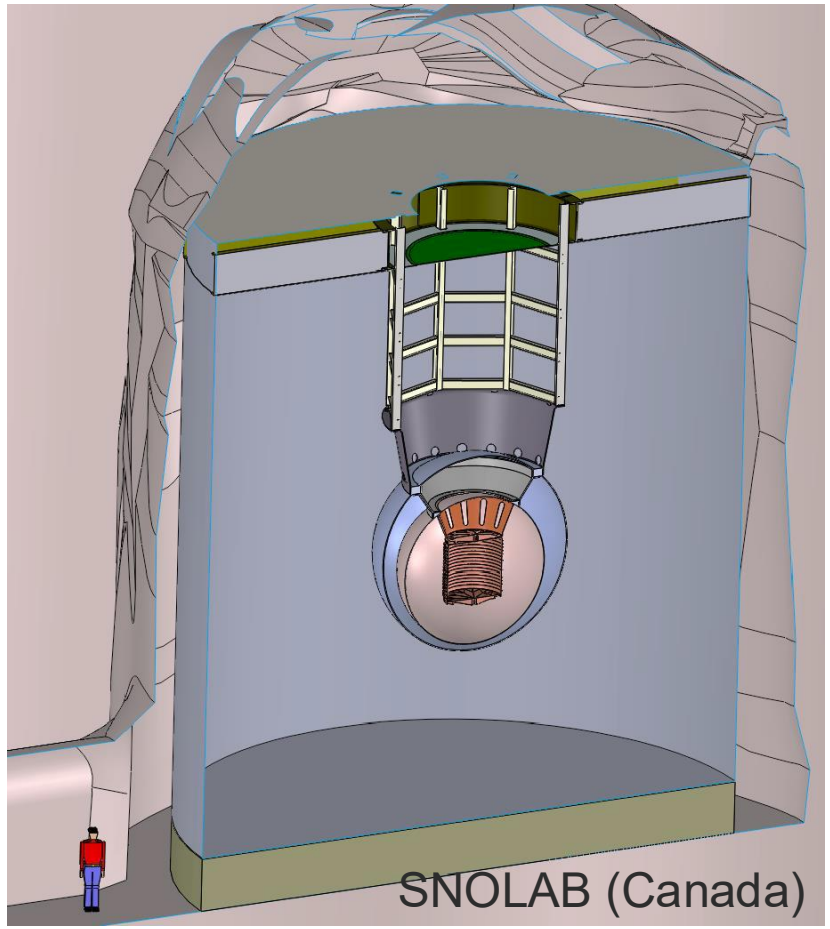
5 to 100s m^2 of detector area!



The nEXO time projection chamber (top left inset) allows measurement of energy and location of double beta decays.
https://nexo.llnl.gov

nEXO – neutrino search

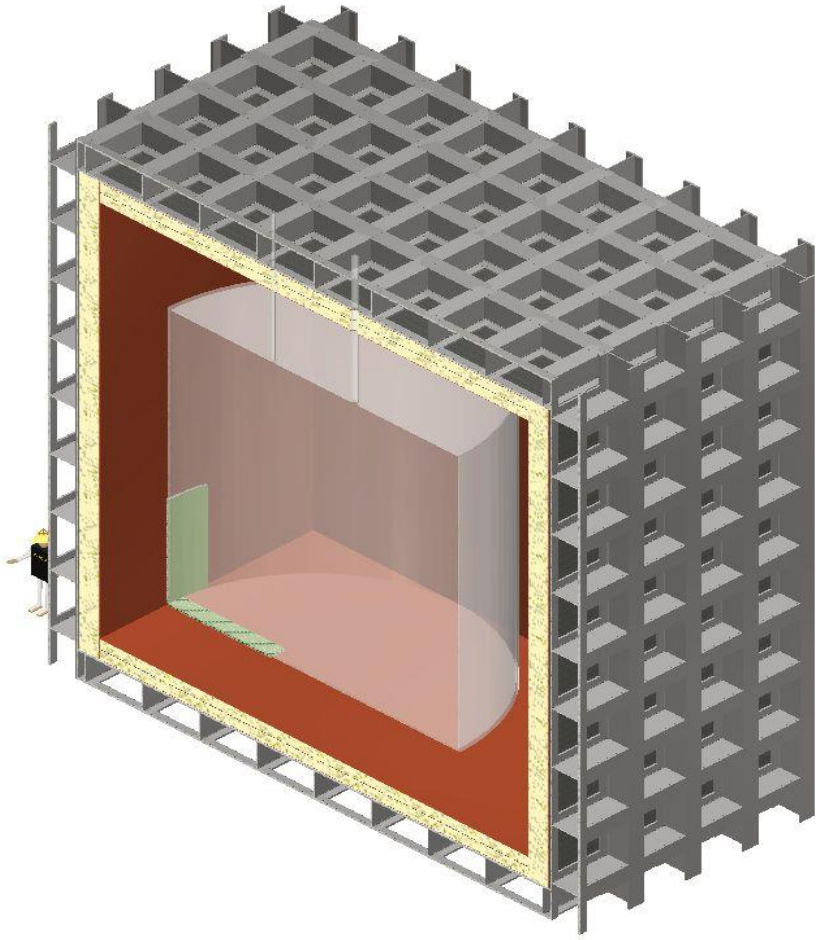
^{136}Xe $0\nu\beta\beta$ decay – xenon as scintillator



5 tonnes of LXe – 4.5 m^2 of photon detectors

ARGO – dark matter search

LAr as interaction media and scintillator

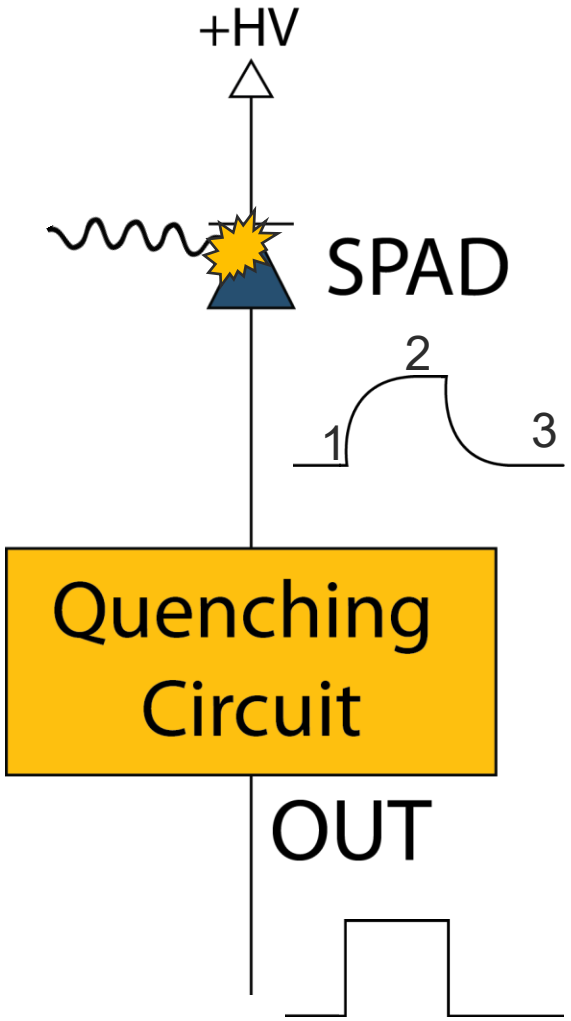


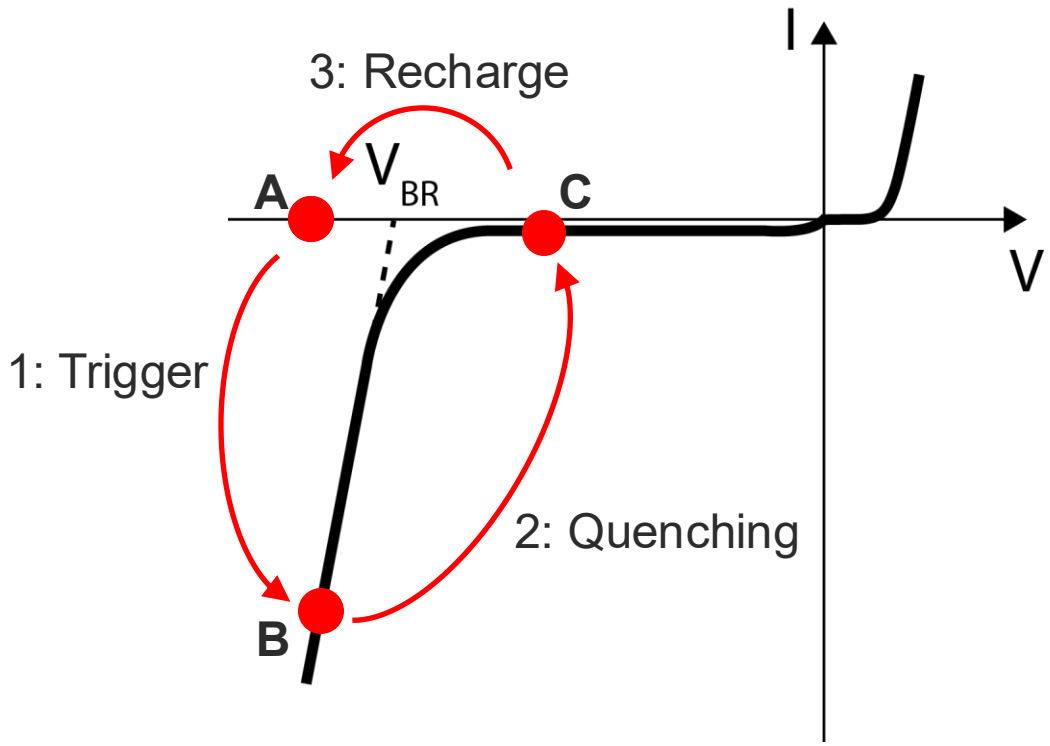
300 tonnes of LAr – 250 m^2 of photon detectors

The Photon-to-Digital Converter Concept

How to turn a single photon into a digital pulse

Single Photon Avalanche Diode Operation Cycle





1. Time precision
2. Sensitivity – gain >10^5 – single photon
3. Low cost

The present trend : SiPM – Silicon PhotoMultiplier

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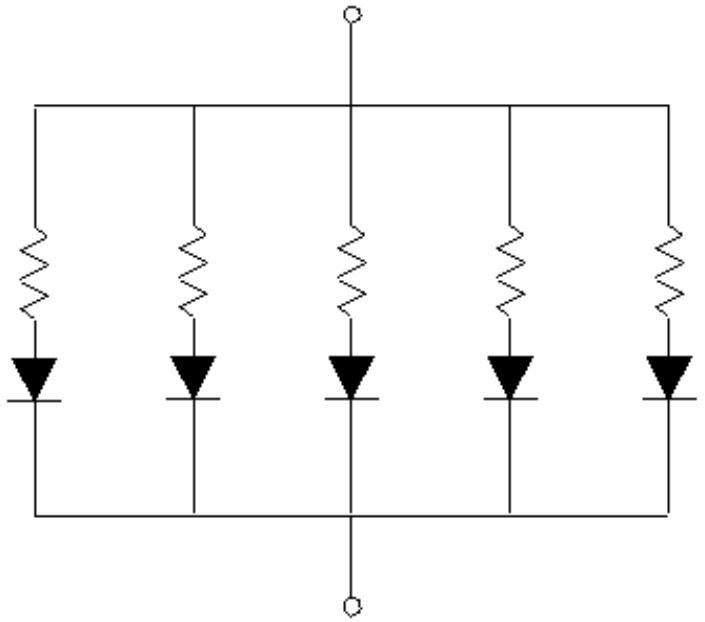
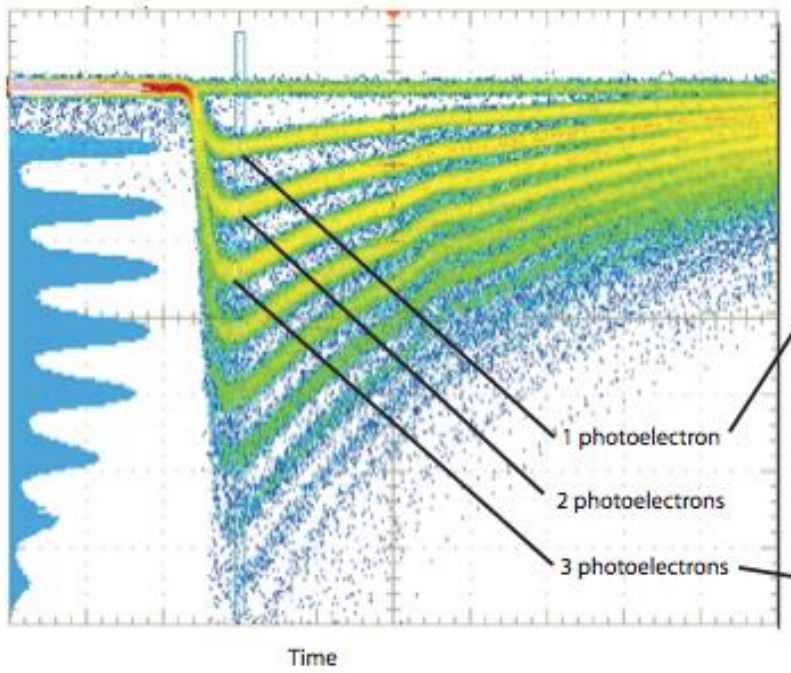
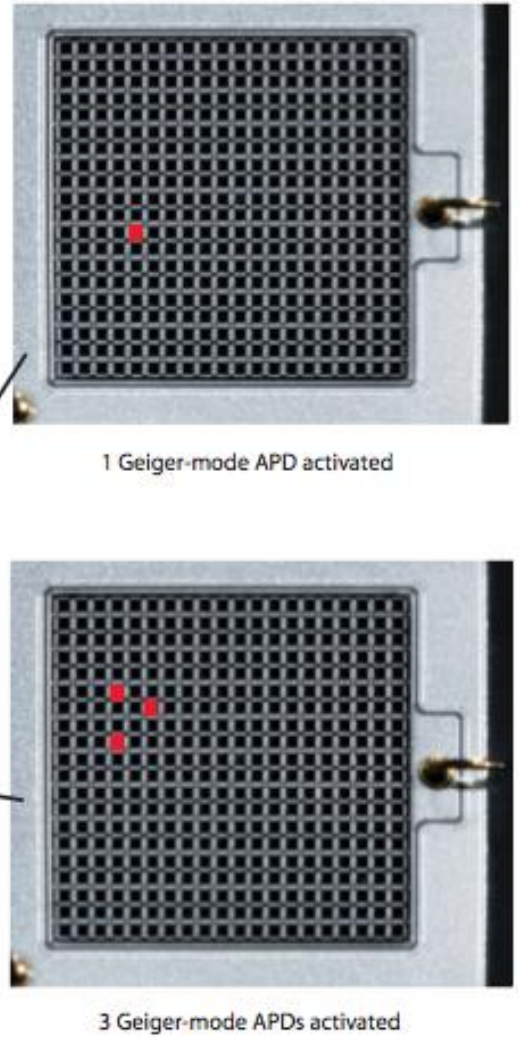
- Array of SPADs in parallel quenched passively



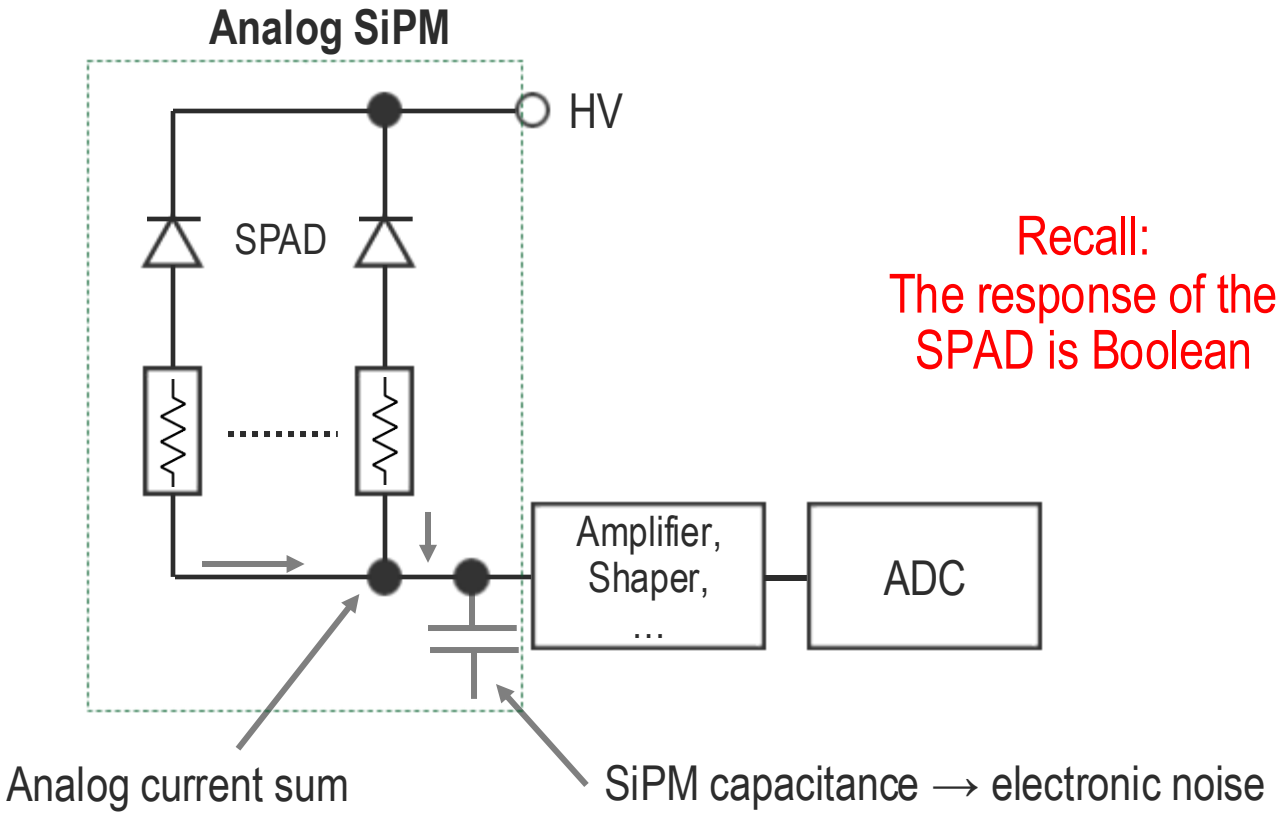


Persistence trace on an oscilloscope

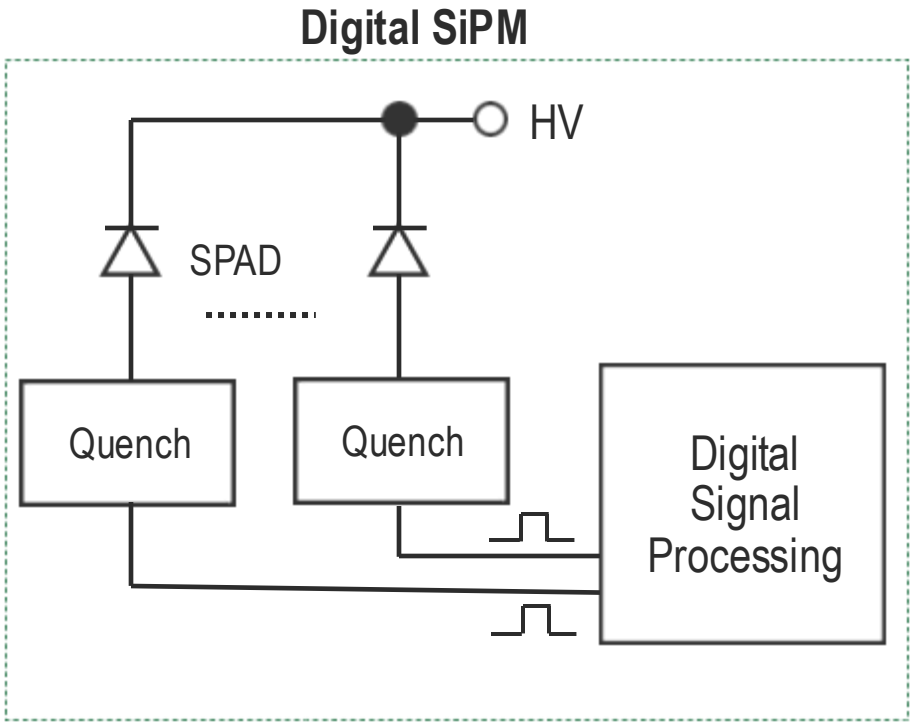


Source: Hamamatsu

SiPM – Silicon Photo Multiplier: an array of SPADs



Recall:
The response of the SPAD is Boolean

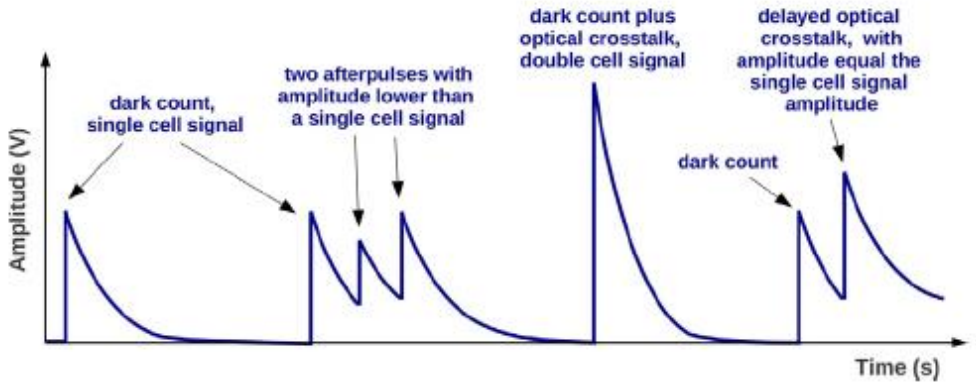


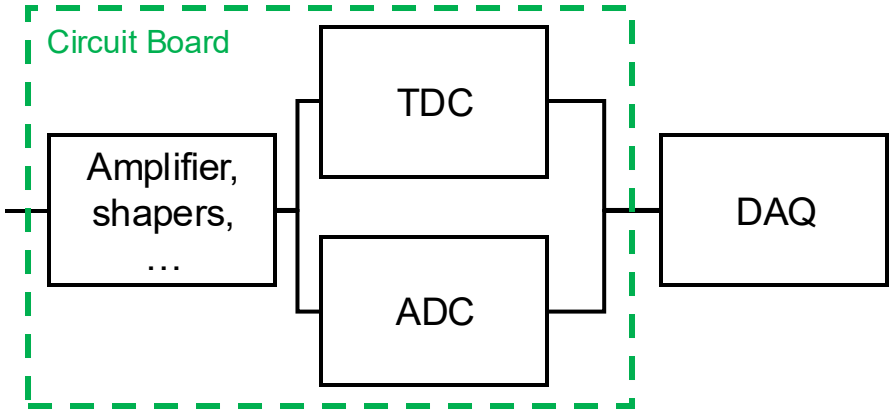
The amplifier transforms charge into voltage and then BACK to digital.

Individual SPAD readout, no D/A+A/D conversion. Everything stays digital.

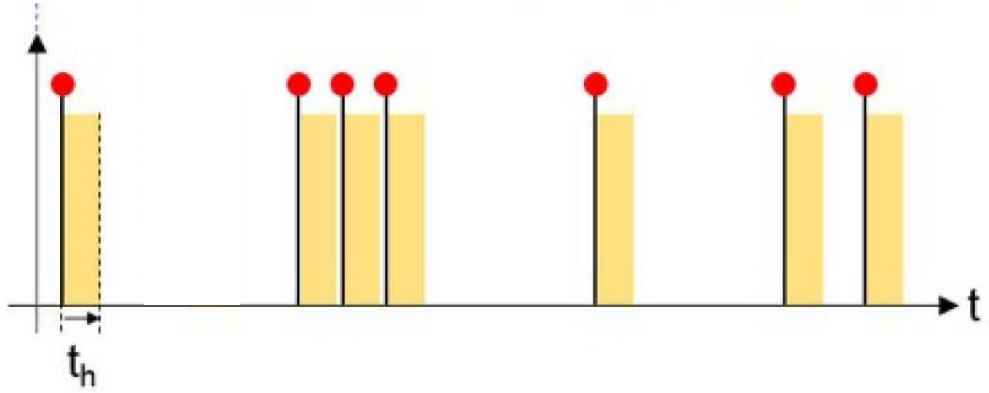
A change of paradigm

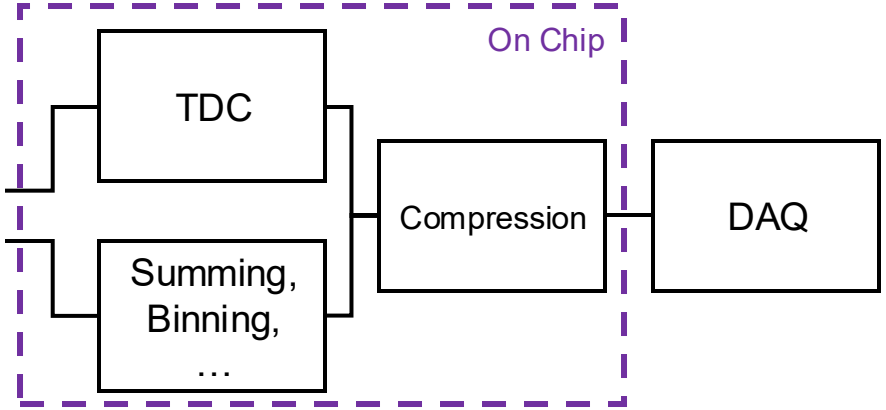
Analog SiPM





Digital SiPM





Are the individual photon pulse shapes really needed?

(with all their complications to analyse)

Acerbi & Gundacker, NIMA 2019

Panel discussion on Wednesday 11h30

Science Technology:

When will digital SiPM move beyond the R&D phase for subatomic physics and other applications?

Nicolas D'Ascenzo
Huazhong University of Science and Technology
China

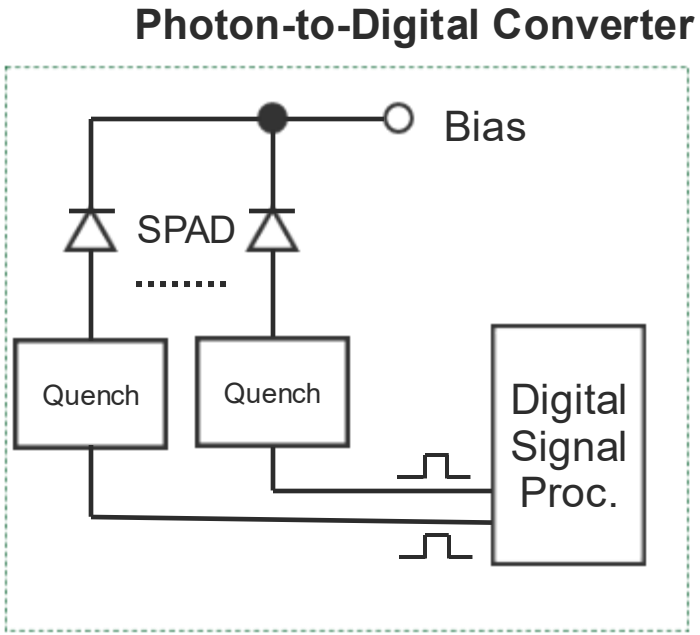
Peter Fischer
Heidelberg University
Germany

Fabrice Retiere
TRIUMF/Simon Fraser U.
Canada

Serge Charlebois
Université de Sherbrooke
Canada

Questions and opinions and welcome!!!

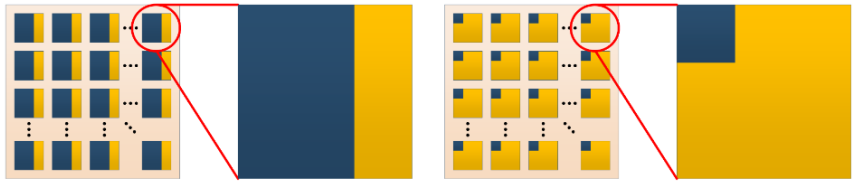
- **Digitally readout array of Single Photon Avalanche Diode (SPAD)**



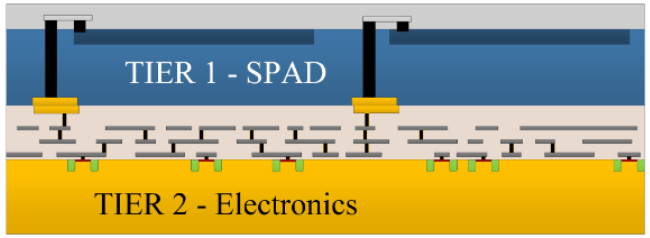
- Direct digital conversion:
  - Single photon resolution on the whole dynamic range
  - Can lower power significantly consumption
- Disabling noisy SPADs: reducing noise
- Programmable hold-off delay: mitigation of afterpulsing
- Embedded signal processing: sum, dark count filters, time-to-digital conversion, etc.

Pratte JF et al. "3D Photon-to-Digital Converter for Radiation Instrumentation: Motivation and Future Works" (2021) Sensors;21(2):598. doi: 10.3390/s21020598

- **SPAD array and CMOS readout vertically stacked (3D) to form a single detector chip**



in 2D: loosing sensitive area



(c)

Development of the SPAD array layer and low power PDC

Thinned TSV-less Frontside Illuminated SPAD Array

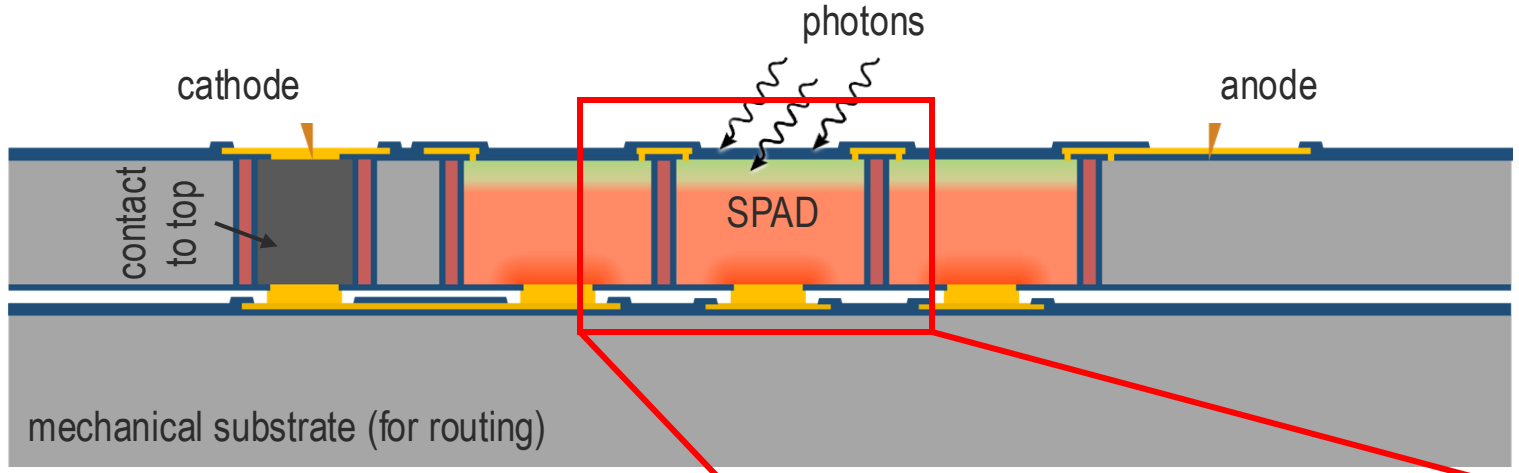
UDS

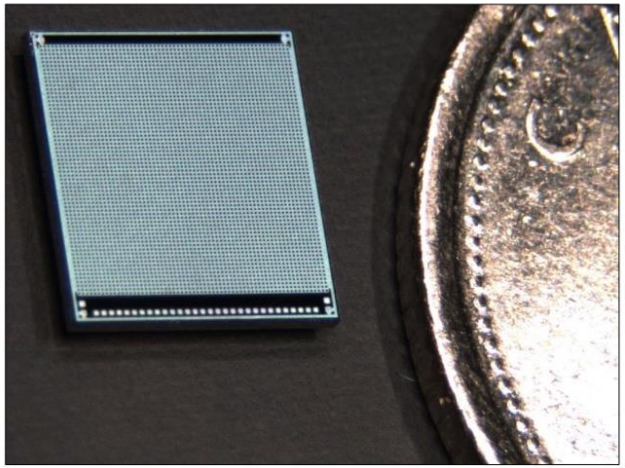
1st fabrication run completed

(Octobre 2024)

Thin SPAD layer + CMOS readout

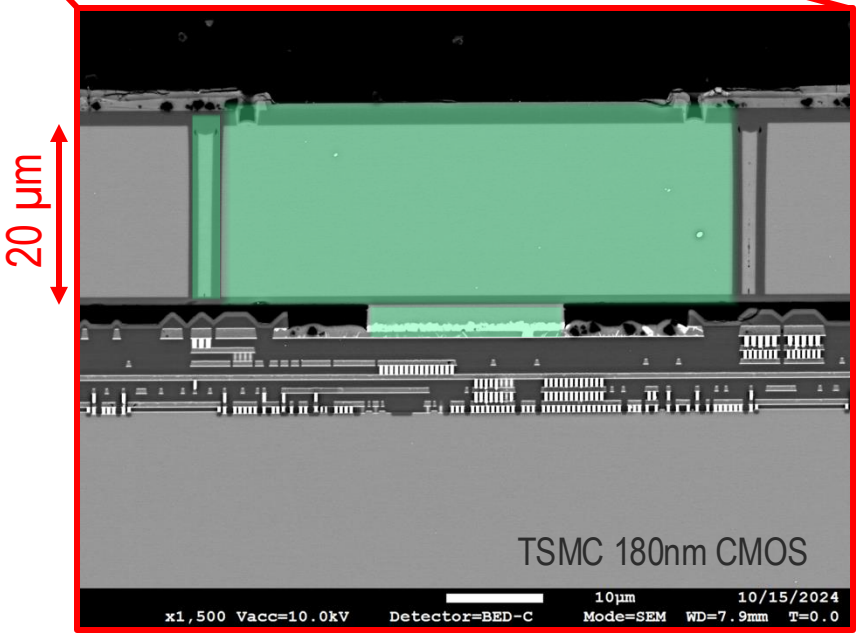
- p⁺n SPAD [1]
- 64 × 64 SPAD Array
- 78 µm pitch
- Al-Ge eutectic bonding
- 5.85 × 5.25 mm² die





3D SPAD array

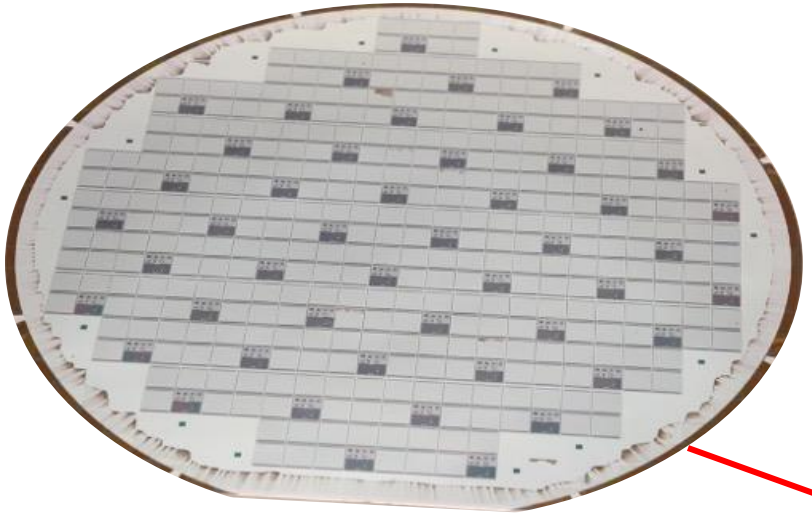
(canadian 10¢ for reference)



SEM cross section image

1. Parent, Samuel, et al. "Single photon avalanche diodes and vertical integration process for a 3D digital SiPM using industrial semiconductor technologies." 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC). IEEE, 2018.

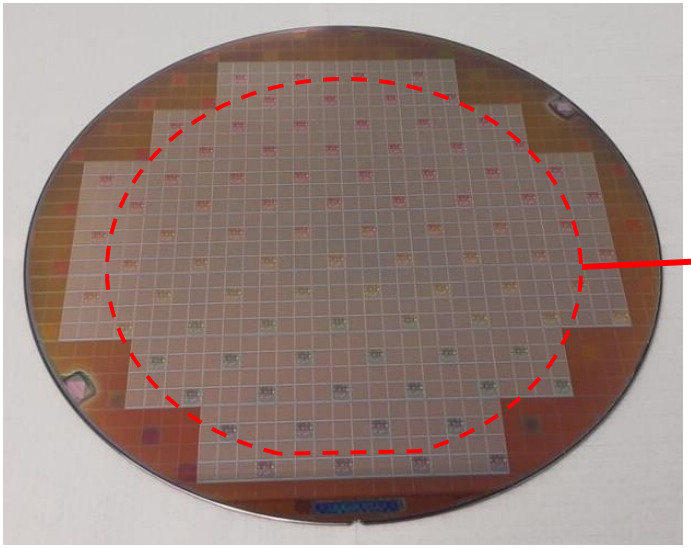
SPAD wafer bonding to CMOS wafer – Assembling the PDC



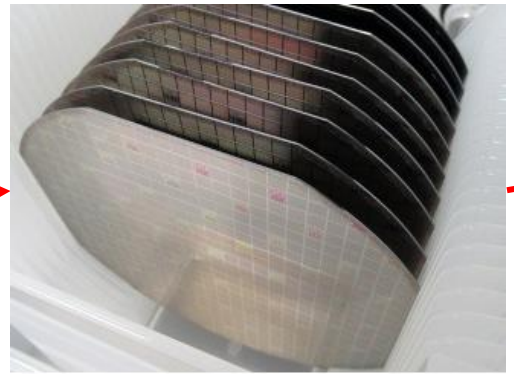
150 mm SPAD wafer

Wafer level bonding

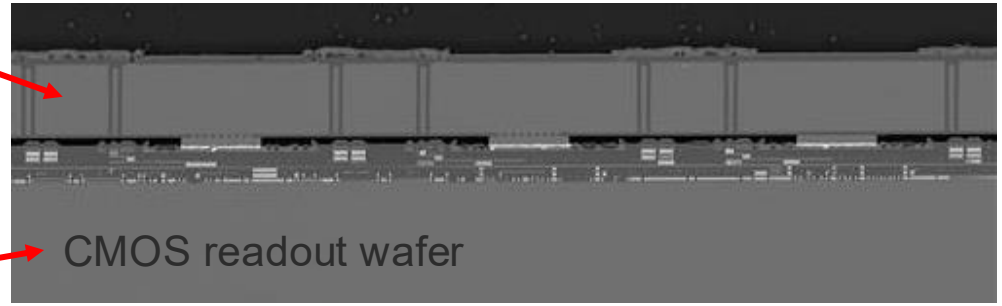
- Al-Ge eutectic: CMOS aluminum pad to SPAD Ge
- Resizing 200 mm to 150 mm (while matching patterns)



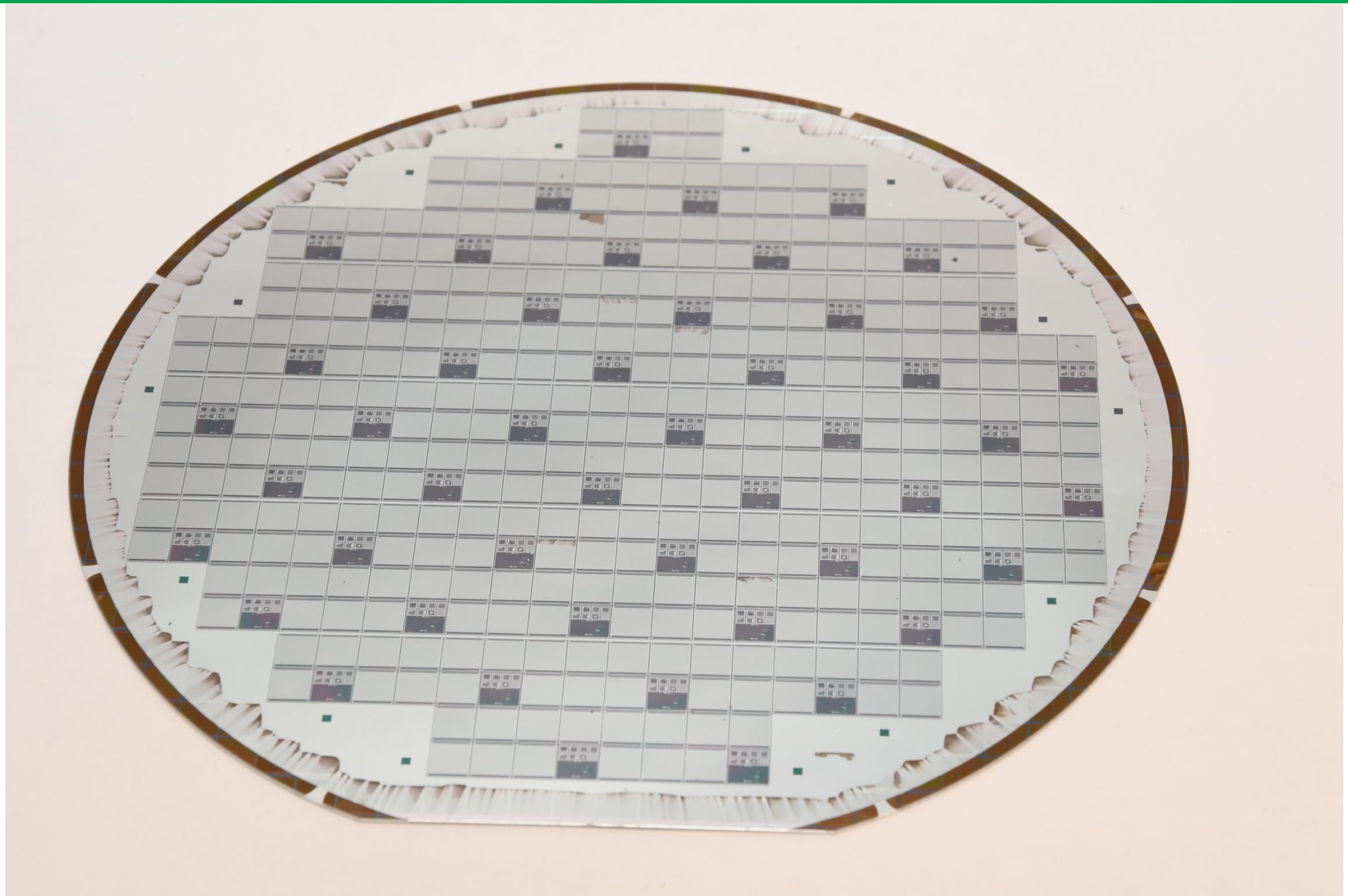
200 mm TSMC 180 nm CMOS wafer



Resized to 150 mm



CMOS readout wafer



Fabricated by Teledyne DALSA

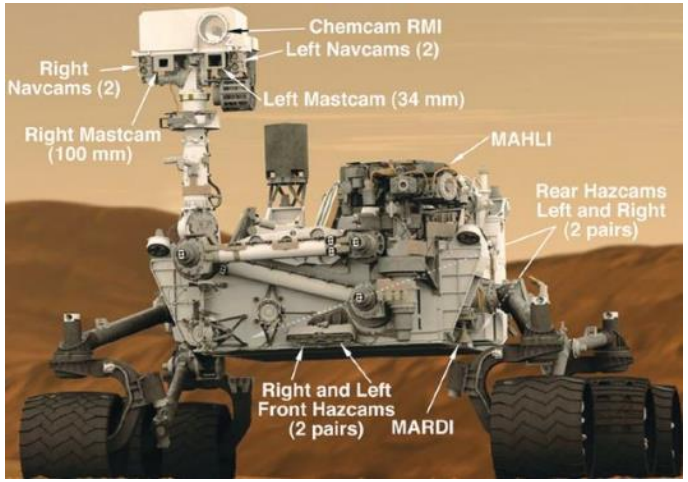
UDS

High-end CCD process line
--> excellent for SPAD R&D

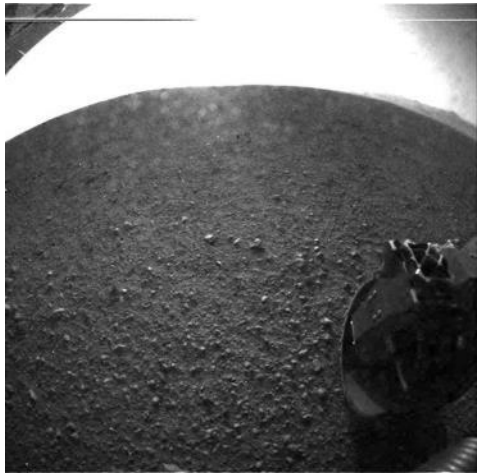
- 150 mm process line
- low contaminant / gold free clean rooms

World top 5 MEMS Foundry
--> excellent for wafer level integration

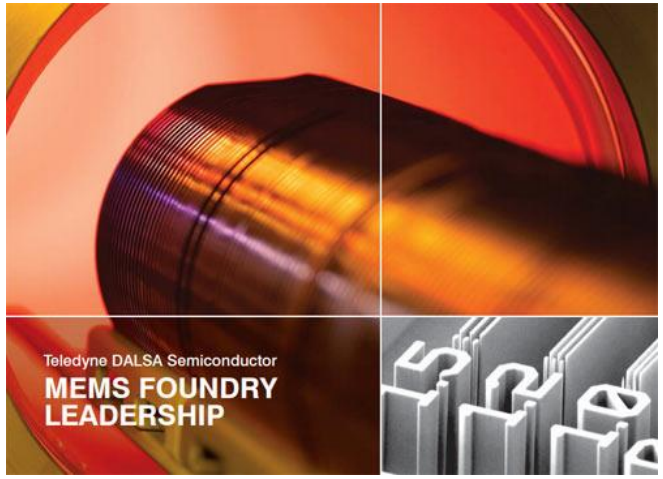
- 150 mm and 200 mm process line
- Wafer thinning, deep etching, bonding, ...



The Eyes of the Mars Curiosity Rover. Tech Briefs (2012)



Life on Mars: Rover landing gives boost to Canadian tech sector. The Globe and Mail (2012)



Courtesy of Teledyne DALSA

MEMS Foundry Rankings (2017 sales in US$M)	
STMicroelectronics	174
Teledyne DALSA	60
Silex Microsystems	50
TSMC	47
X-Fab	42

Status of the MEMS Industry 2018 Market and technology Report Yole Development (2018)

TELEDYNE DALSA
Everywhereyoulook™

Teledyne DALSA Semiconductor (est. 1980)
~ 500 employees located at Bromont near Montreal, Canada

PDC designed for low power use in noble liquid experiments

Photon-to-Digital Converter: Architecture

UDS

Flag output

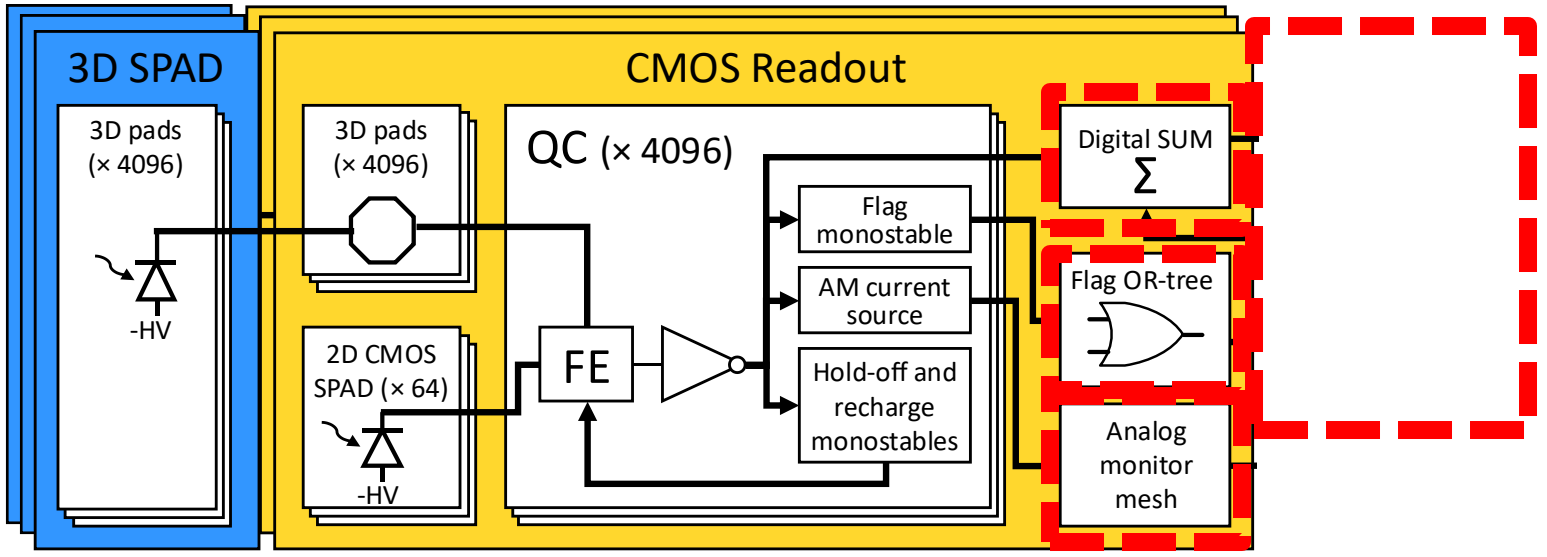
- Pulsed output (adjustable from few ns to tens of ns).
- From an OR-tree.
- Timing jitter better than 100 ps RMS.

Digital Sum

- Digital count of triggered SPADs inside a bin (dynamic range of 4096 photons).
- Adjustable bin width from 10 ns up to µs.
- Internal FIFO of 128 bins.

Analog Monitor

- Current proportional to triggered SPADs.

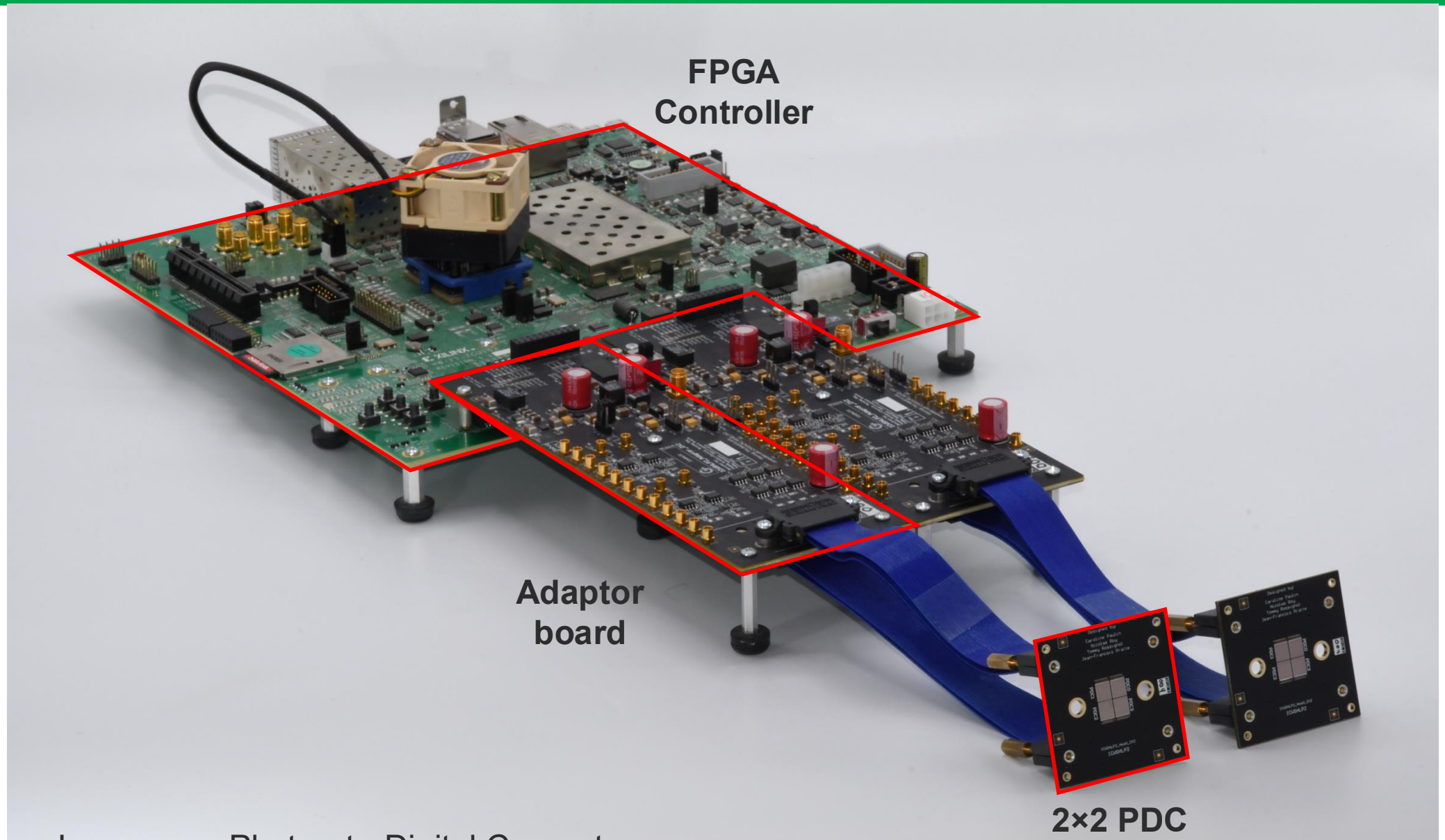


Controller (1 for 64 PDCs)

- Start PDC acquisition, based on the number of flag received to discriminate dark count.
- Bank of TDCs for timing measurements on flags.
- Receives data from PDCs and includes post-processing.
- Communicate with an external computer.

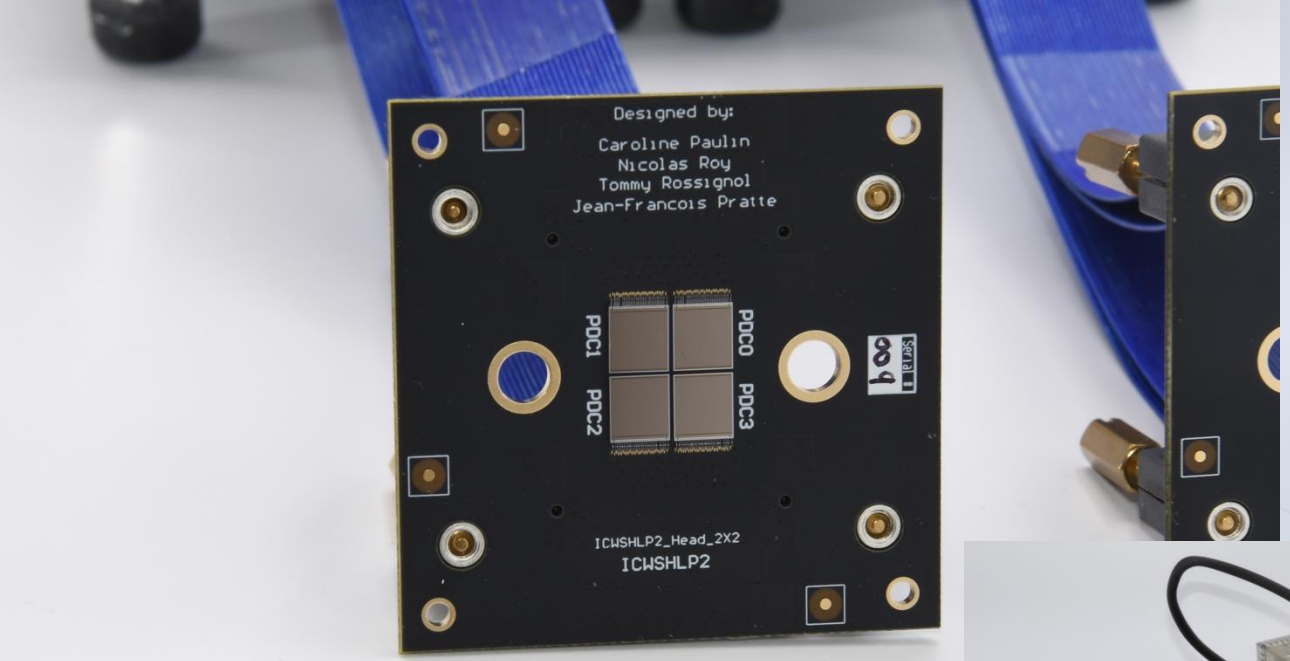
PDC technology dissemination:

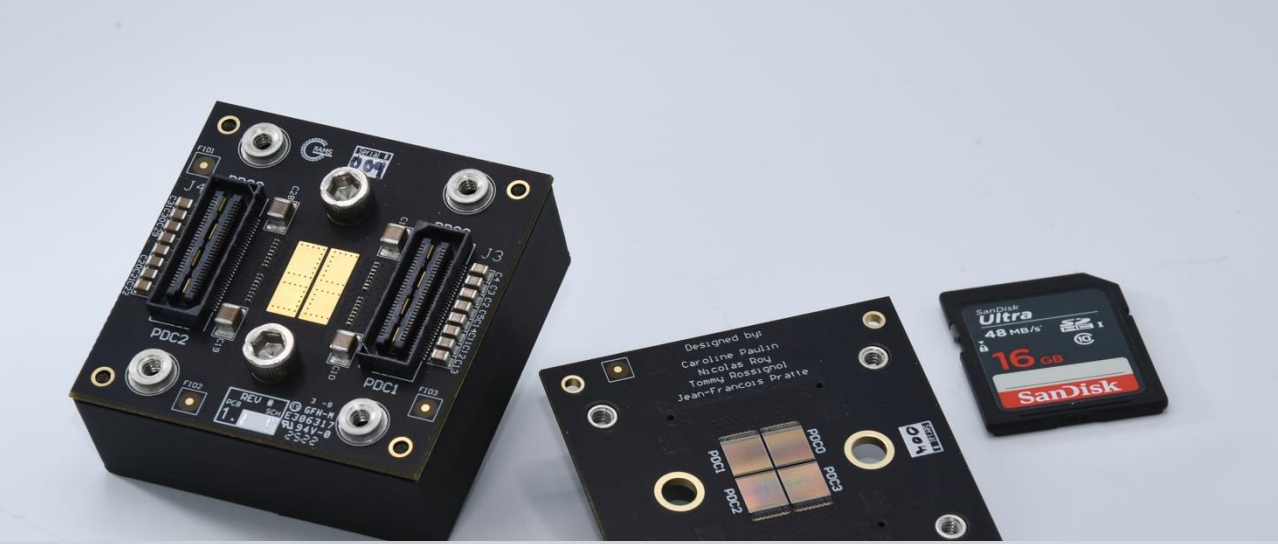
Sharing a test platform
to allow collaborators
to explore the technology

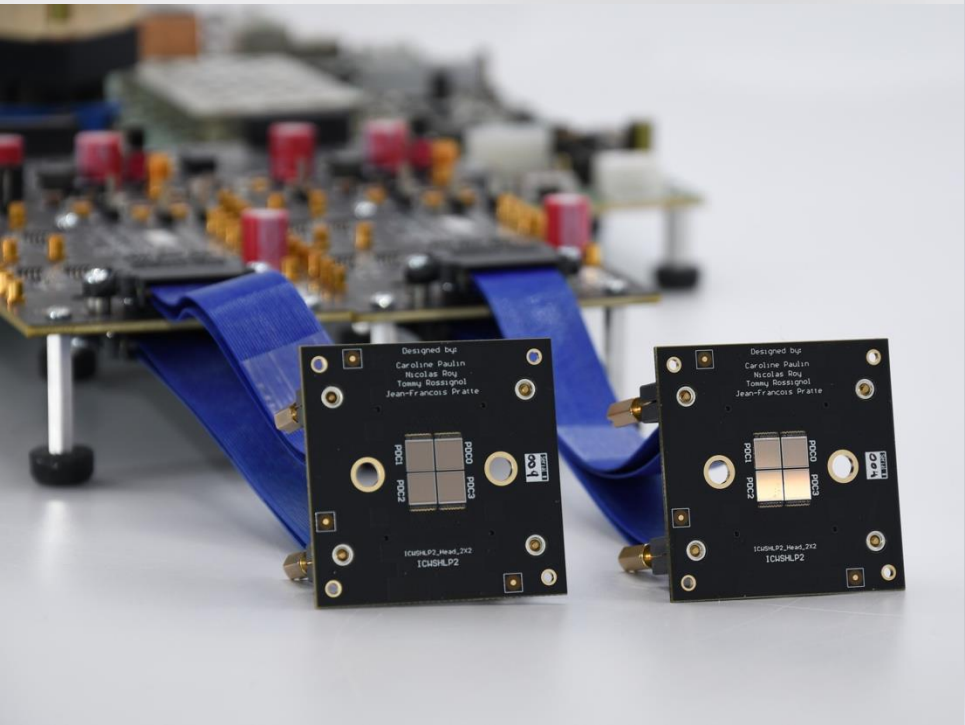


Low power Photon-to-Digital Converter

For details, see T. Rossignol et al., J. Inst., vol. 19, no. 09, p. P09017, Sep. 2024
https://doi.org/10.1088/1748-0221/19/09/P09017


Designed by:
Caroline Paulin
Nicolas Roy
Tommy Rossignol
Jean-Francois Pratte
PDC1
PDC0
PDC2
PDC3
ICWSHLP2_Head_2X2
ICWSHLP2


PDC2
PDC1
Designed by:
Caroline Paulin
Nicolas Roy
Tommy Rossignol
Jean-Francois Pratte
SanDisk Ultra
48 MB/s
16 GB
SanDisk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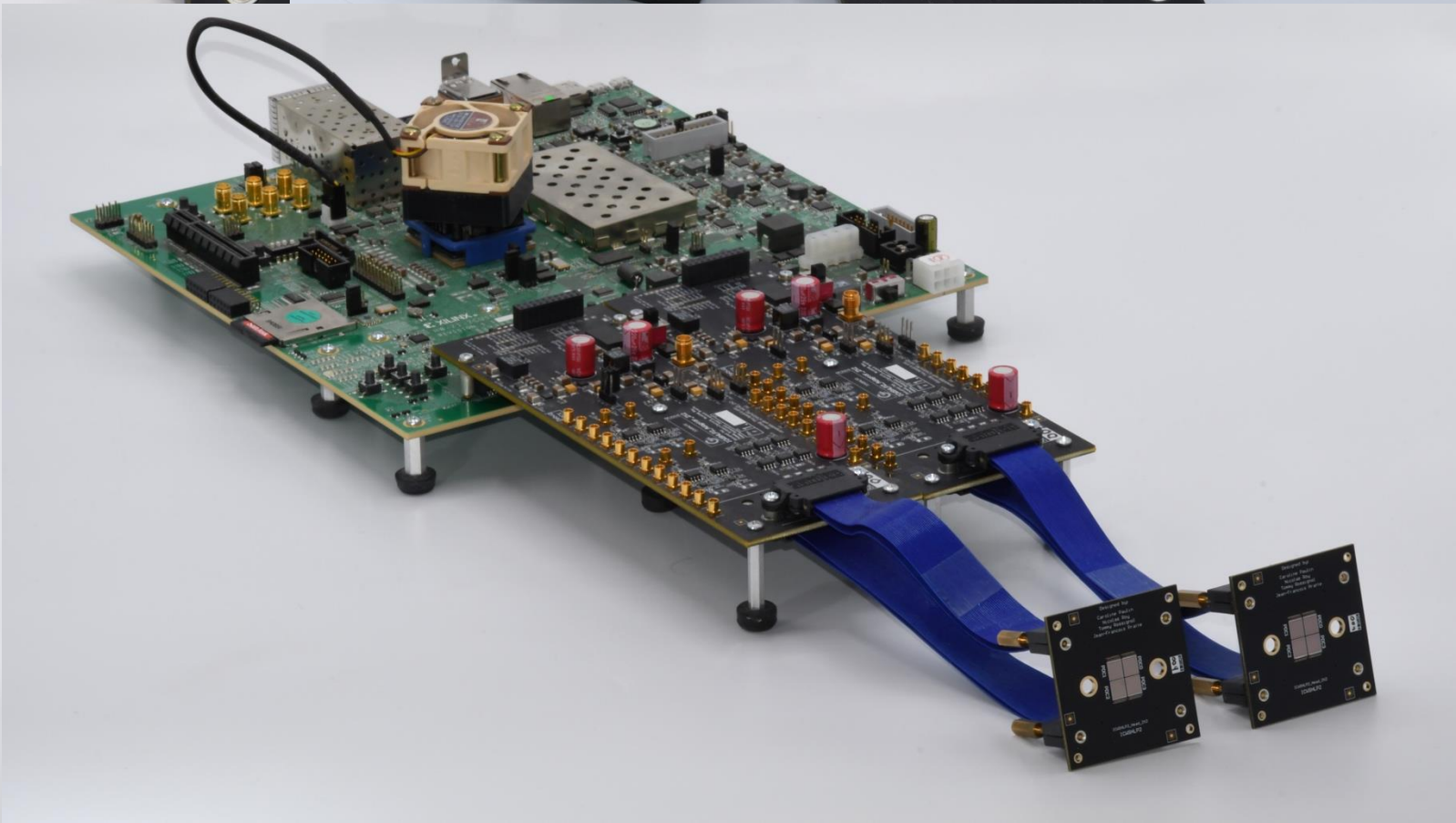
Nicolas Roy
Tommy Rossignol
Jean-Francois Pratte
ICWSHLP2_Head_2X2
ICWSHLP2

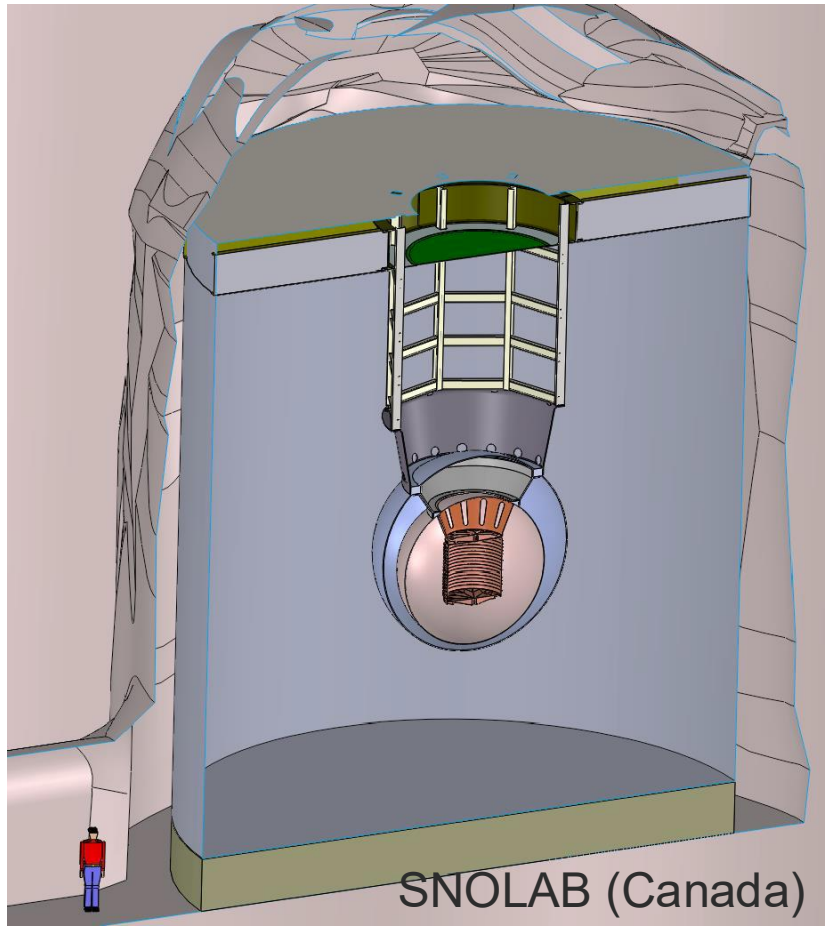


Our global research program:

Photon Detection Modules

nEXO – neutrino search

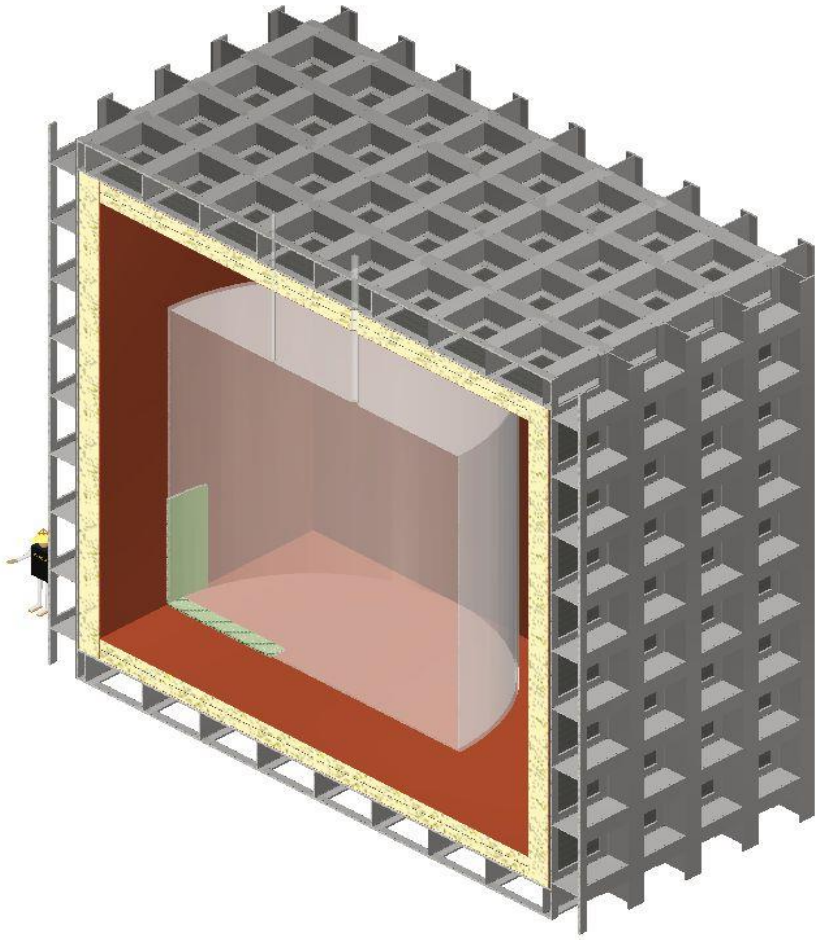
^{136}Xe $0\nu\beta\beta$ decay – xenon as scintillator



5 tonnes of LXe – 4.5 m^2 of photon detectors

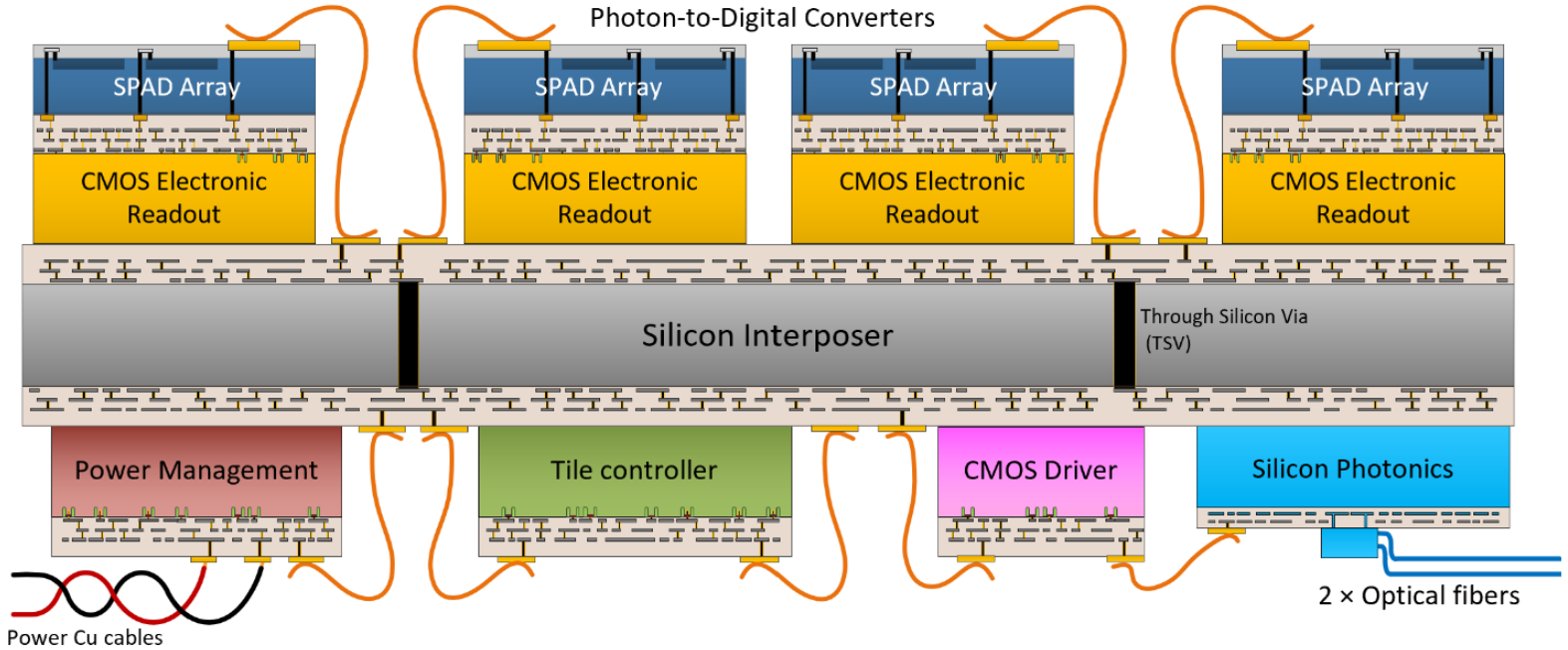
ARGO – dark matter search

LAr as interaction media and scintillator



300 tonnes of LAr – 250 m^2 of photon detectors

Our global ambition

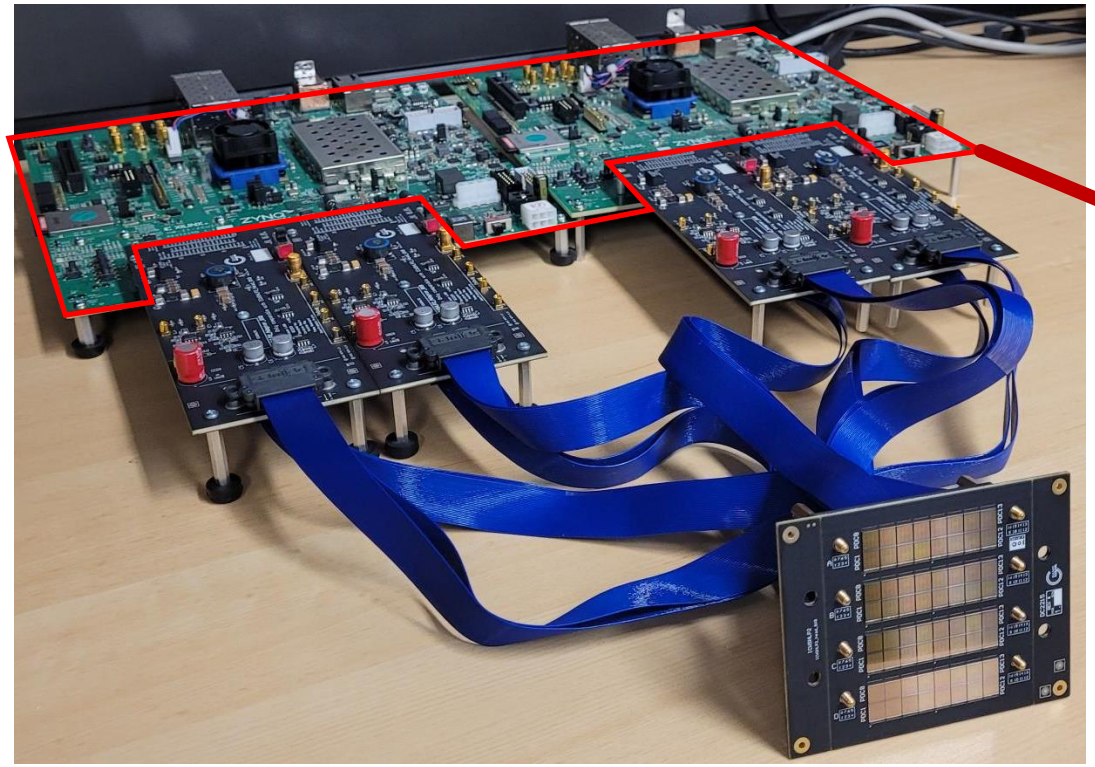


- Demonstrated small tile prototypes
- Silicon interposer for low background large scale integration
- Optical (digital) communication
- Embedded time-to-digital conversion

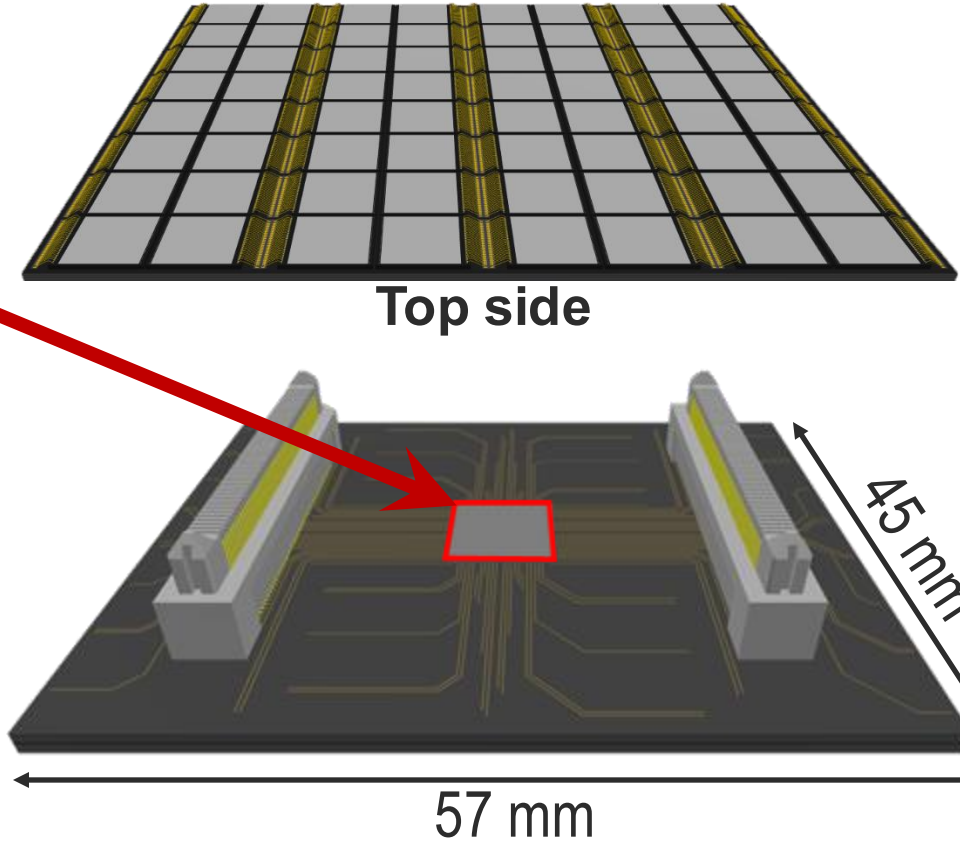
Next Step: FPGA board to a Tile controller

UDS

FPGA-based Controller

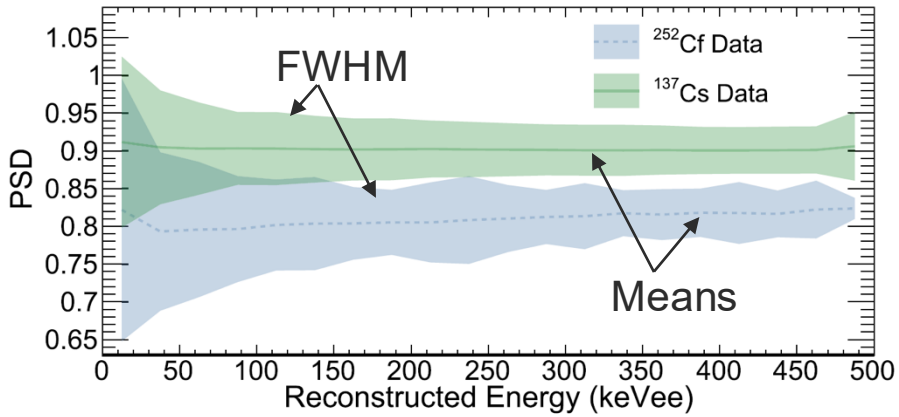


ASIC-based Controller



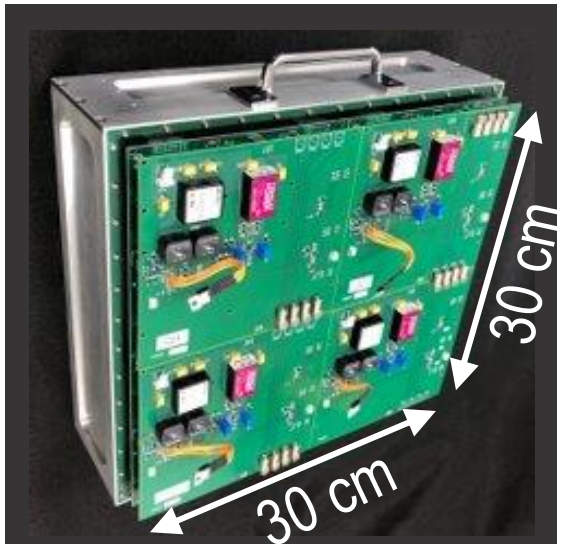
Supported by OAK RIDGE National Laboratory

Associate particule neutron imaging – Supported by ORNL

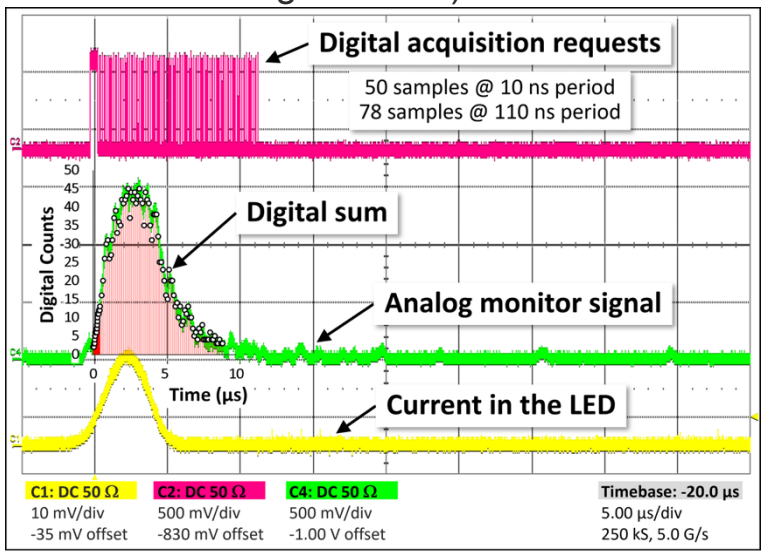


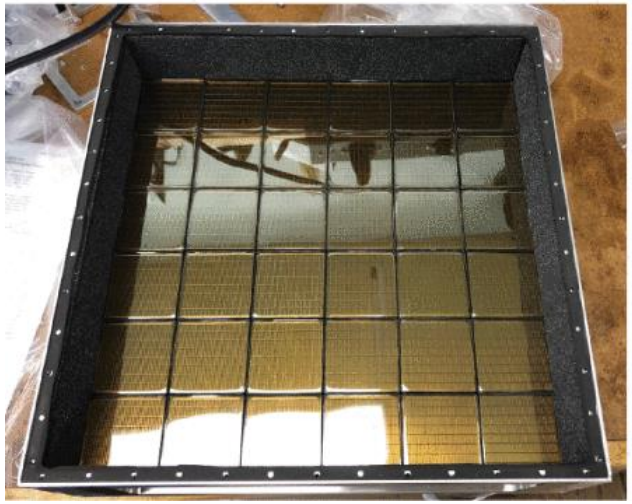
PSD parameter as a function of energy. [1]

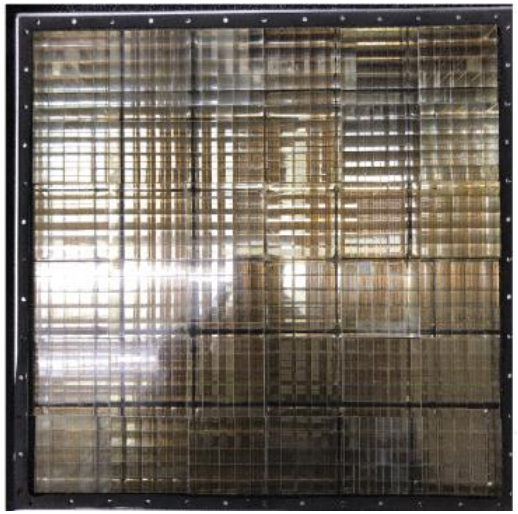
Goal:
next generation of portable neutron detector panel



Capability of the PDC to measure PSD
(here simulated LED light source)







ORNL Portable Pixelated Fast-Neutron Imaging Panel [1]
Left: Multi-Anode PMT | Right: Pixelated scintillators

[1] M. R. Heath *et al.*, "Development of a Portable Pixelated Fast-Neutron Imaging Panel" 10.1109/TNS.2021.3136344.

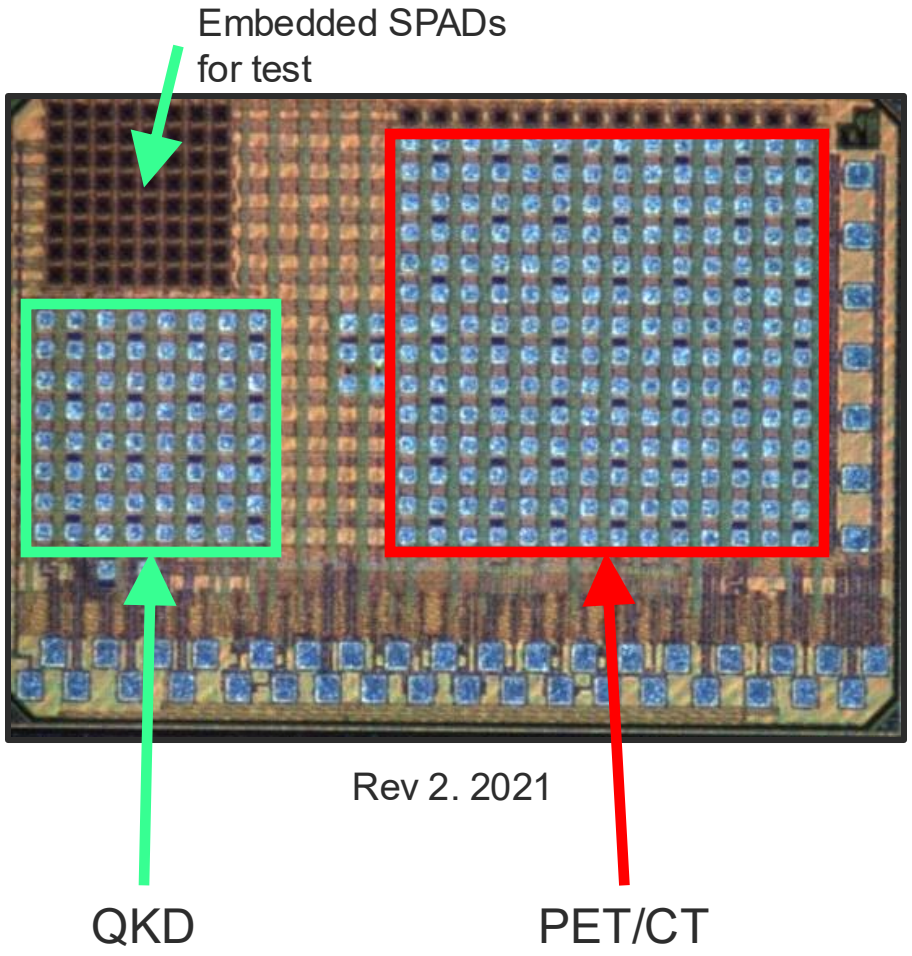
Photo-to-Digital Converteur designed for precise timing applications

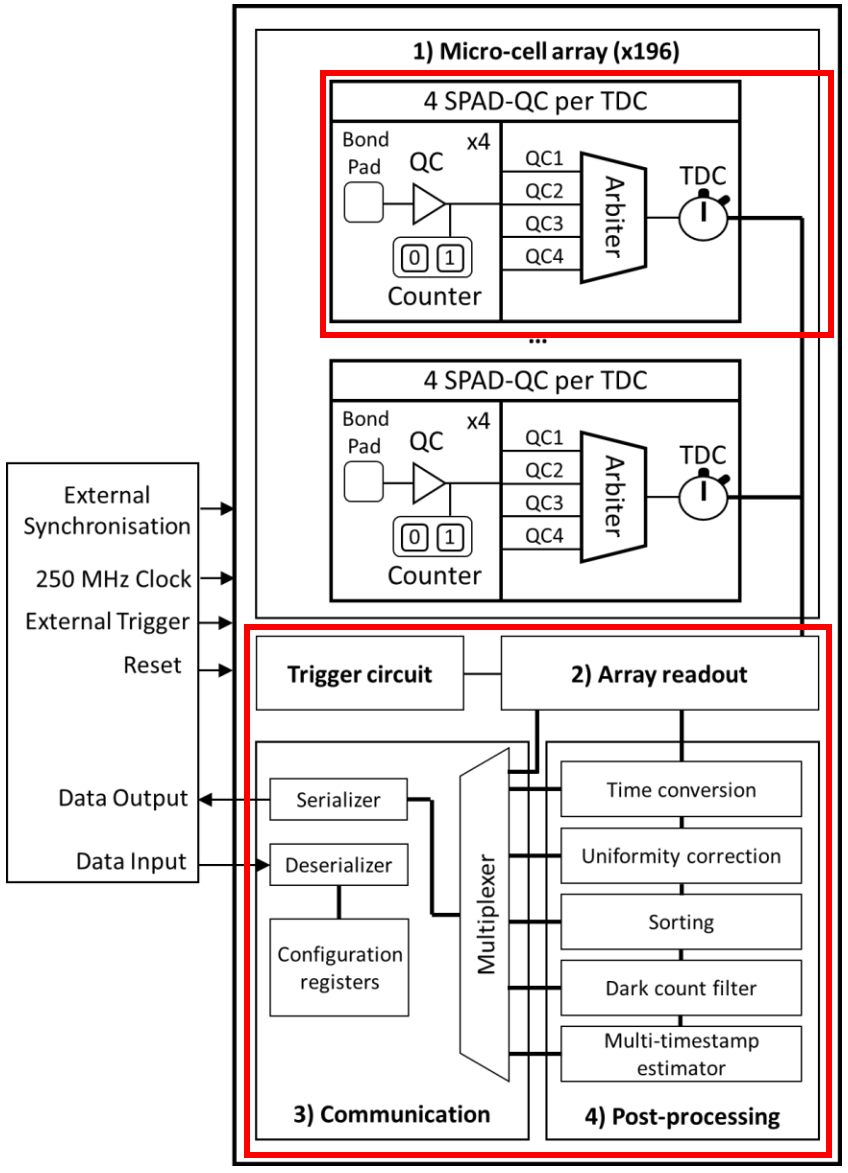
Quantum key distribution,
Wavefront sensing,
Medical imaging ToF-PET, ToF-CT,
...

Overview of the Second 65nm ASIC: PET + CT + QKD

UDS

- TSMC 65 nm CMOS
- 16 × 16 pixels in 1.1 × 1.1 mm²





1 Sub-20 ps TDC for 4 SPADs

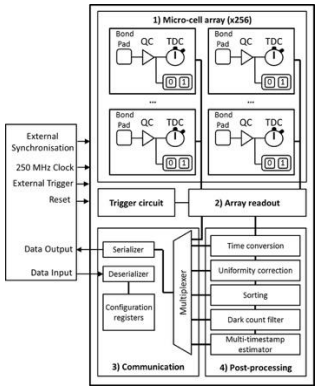
Advanced digital signal processing:

- Time windowing
- TDC code to time conversion
- Uniformity correction
- Timestamp sorting
- Dark count filtering
- BLUE

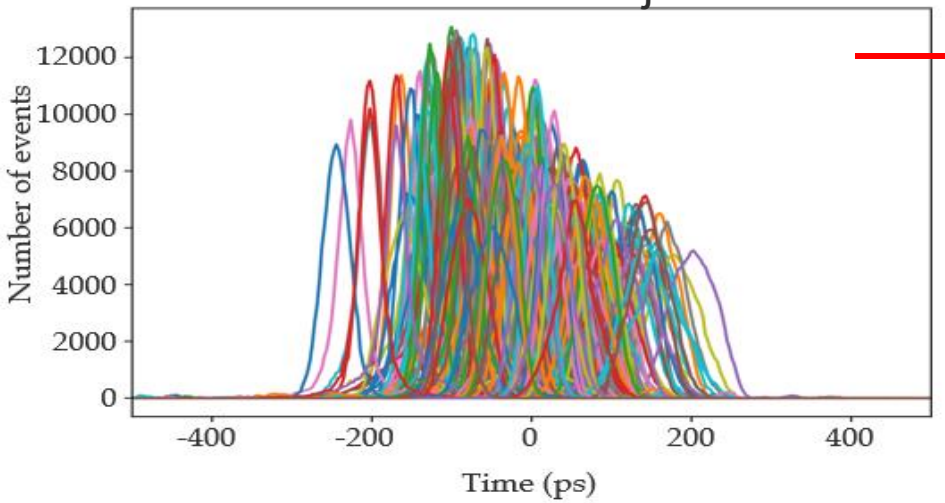
And for QKD

- Time categorization

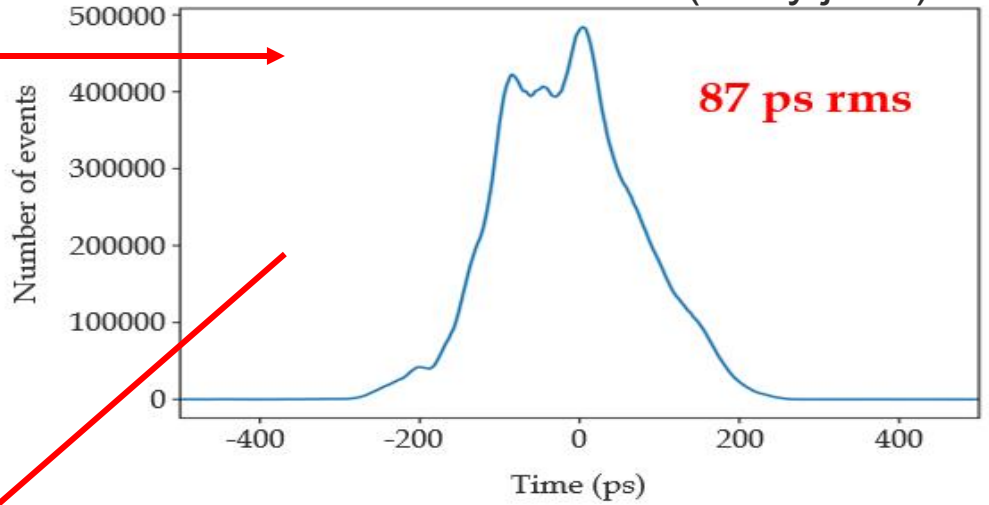
Embedded Digital Signal Processing Example: Uniformity Correction

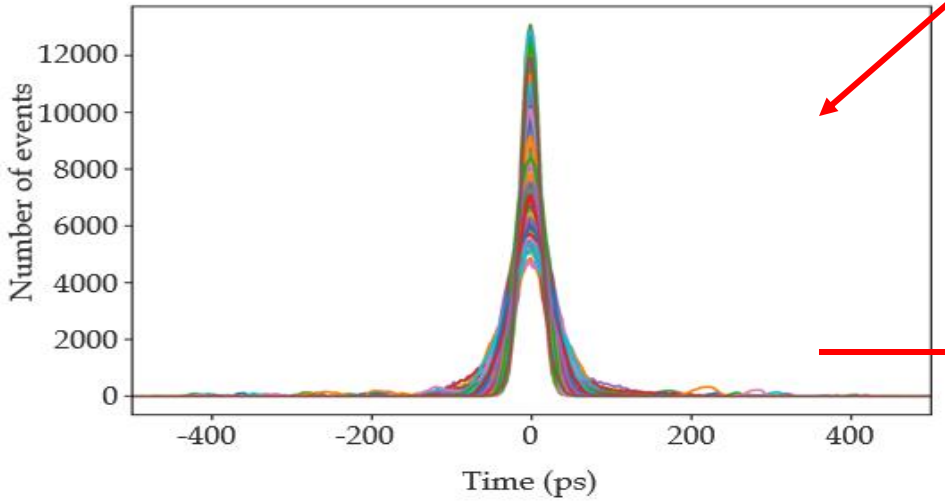


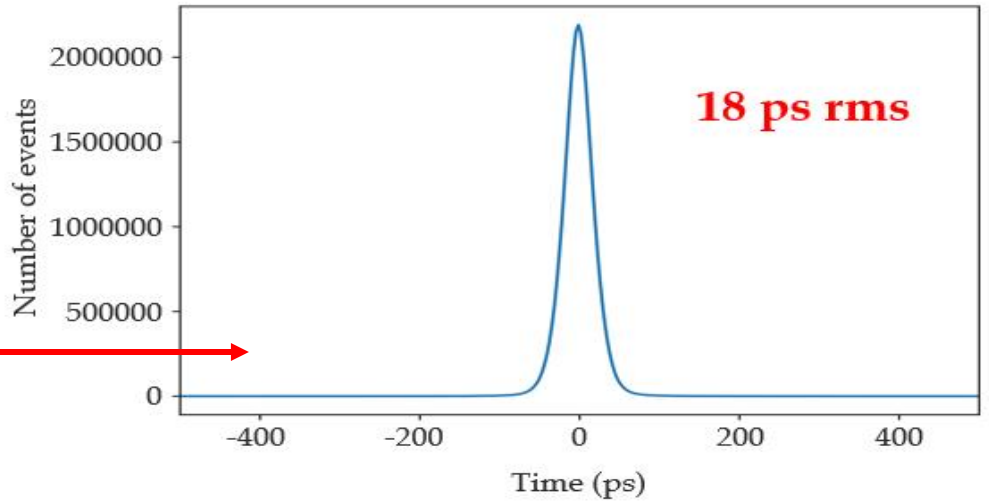
256 channels jitter



Sum of all channels (array jitter)







ToF Computed Tomography

Using time-of-flight to exclude noise from scattering X-ray photons

ToF Scatter Rejection Principle

How do that?

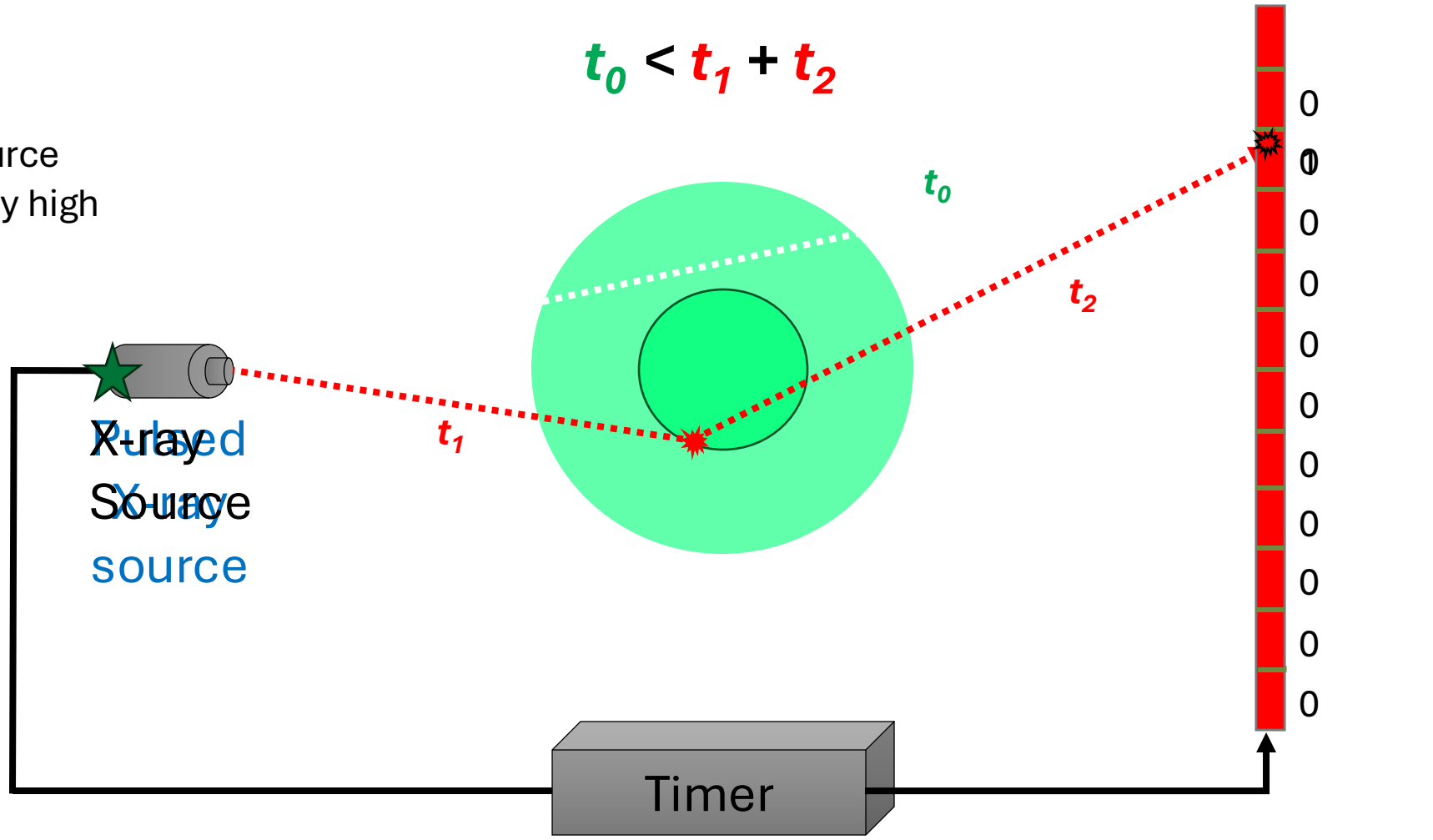
To do this we need:

- Synchronized pulsed X-ray source
- Time-resolved detectors of very high precision (~10-200 ps FWHM)

Threshold for rejection:

t_{th} ~10-500 ps FWHM

$$t_1 + t_2 > t_0 + t_{th}$$



Quantum Key Distribution

Exploiting in timestamp processing

Time-stamp classification (Not single photon yet…)

UDS

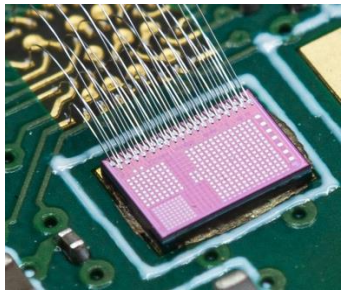
Raw time stamp data

Each photon is timestamped in the chip

- ~20ps resolution and precision
- Timestamps are transmitted to the computer

The histogram shows 3 modes to the distribution corresponding to the projection of the 4 states of the qubit onto the time base (center bin holds 2 states)

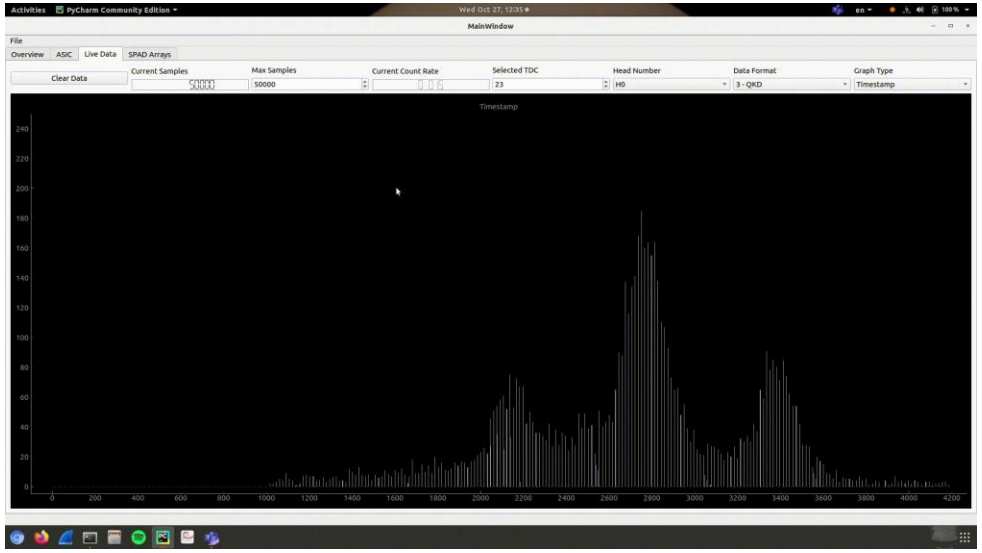
Classified time-bins

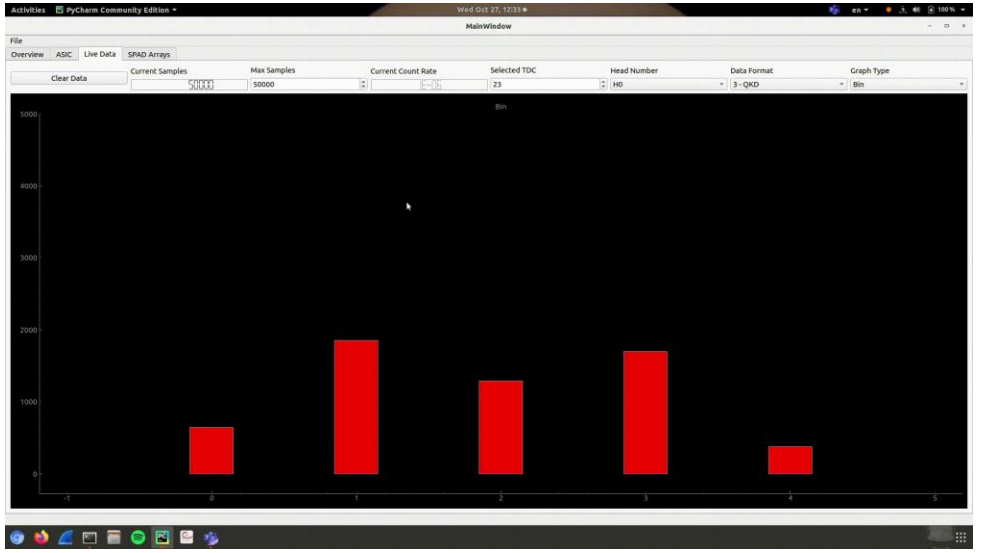


Timestamps are classified inside the chip into 5 bins

- Two bins for out-of-range values
- Programmable bins

This provides effective data compression, limiting the relevant information to only 2-3 bits for each qubit



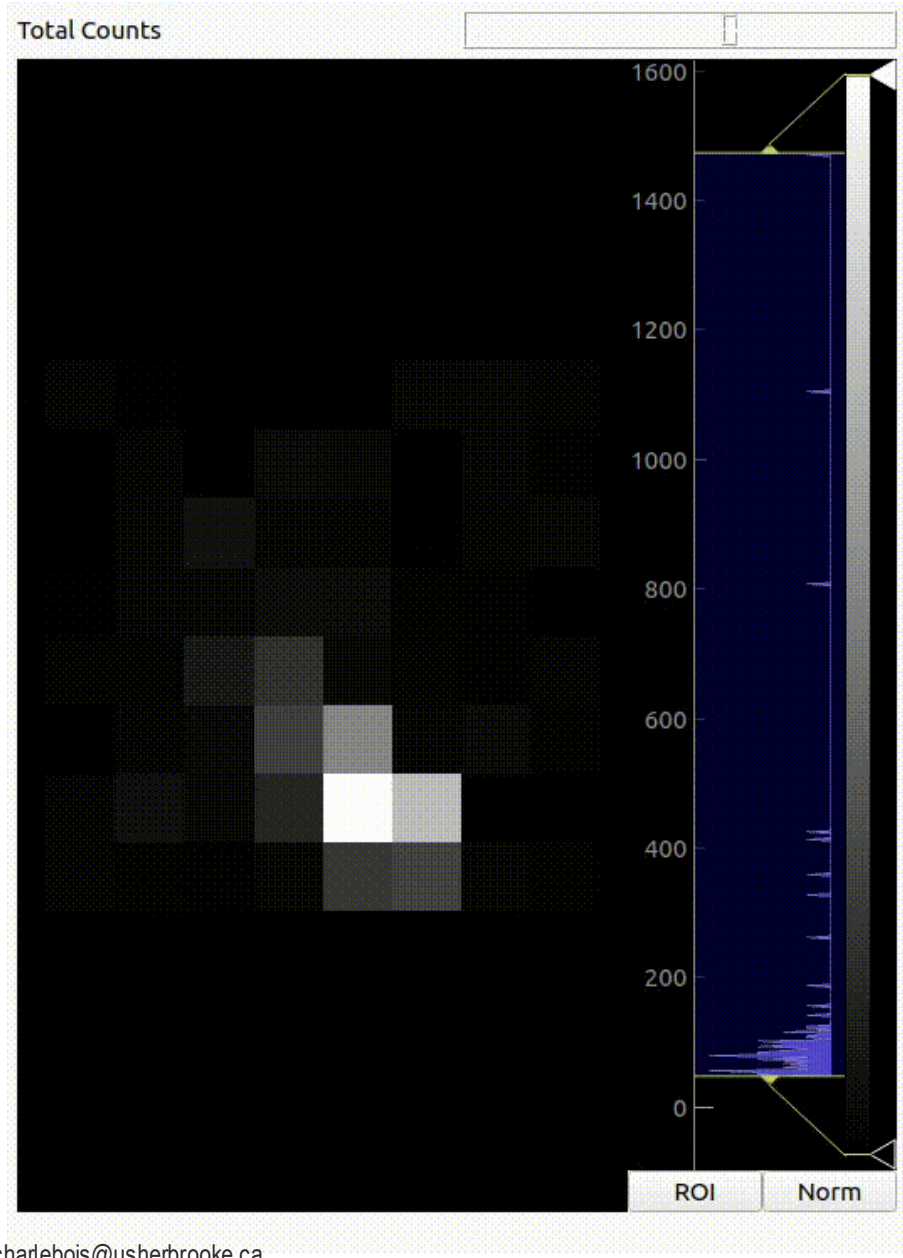


The two graphs show different measurements.
Time variations are due to slow tuning of polarizer/interferometer for the purpose of this demonstration.

- Applied in an array we get
  - The timestamps or time bins

AND

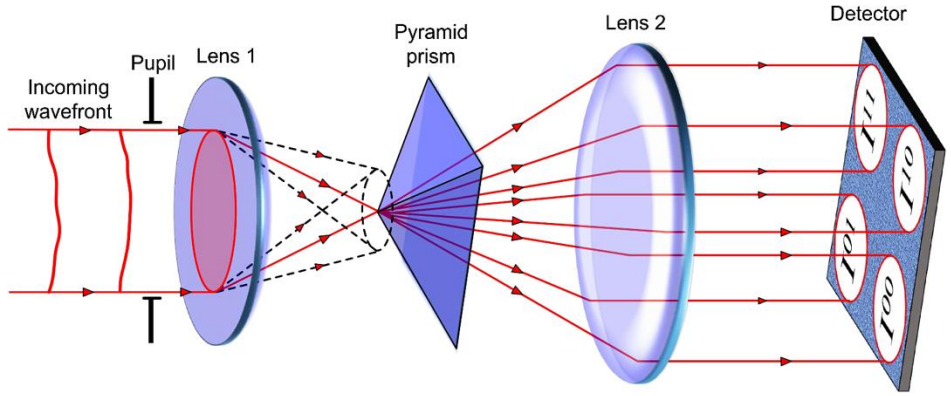
  - Photon location on the array



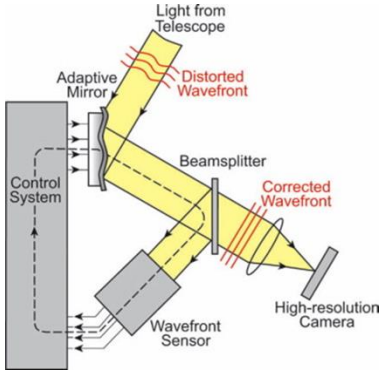
Rapid Wavefront Sensing

For exoplanet search

Pyramidal Wavefront Sensing for AO

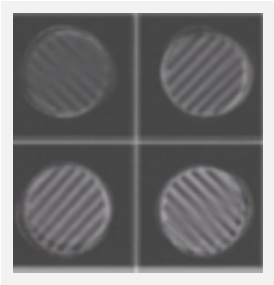


Shatokhina et al. 2020 10.1117/1.JATIS.6.1.010901



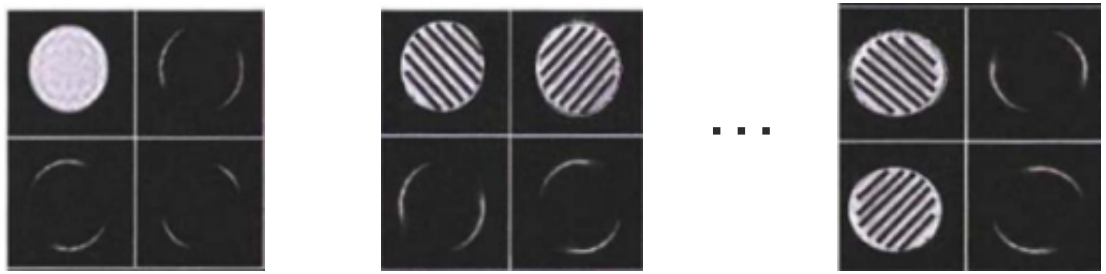
Conventional Pyramid WaveFront Sensing (PWFS)

- Integrates photons over a modulation cycle



Time-resolved PWFS

- Separates a modulation cycle into 48 frames
- Because each frame captures one diffraction pattern
  - Increases signal to noise ratio

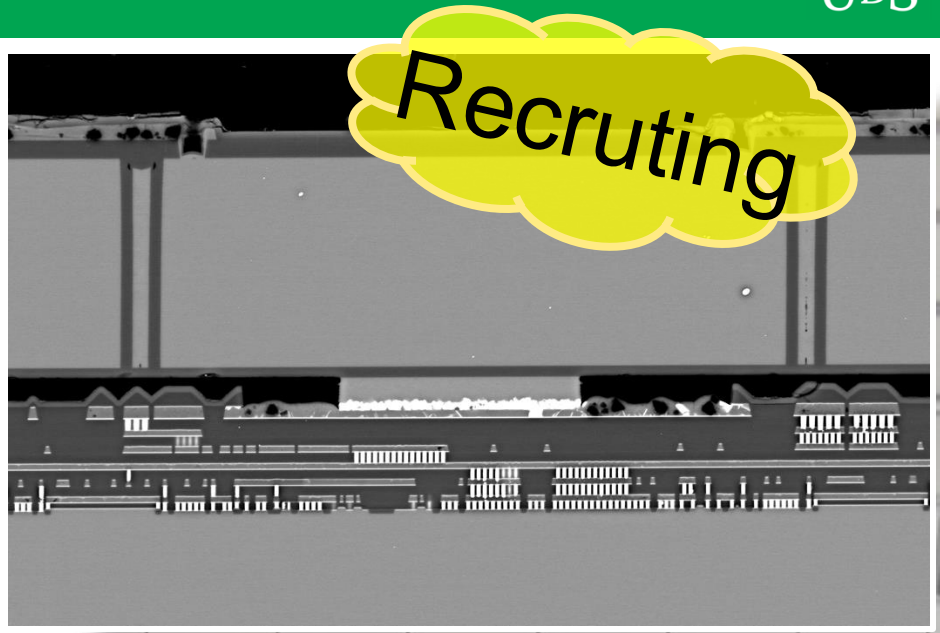


Conclusion

Conclusion

UDS

- **3D Photon-to-Digital Converters in fabrication**
  - PDC fabrication runs planned every 4-6 months
    - Increasing the manufacturability,
    - Tuning/exploring performance improvements
  - PDC now being assembled on test boards (instead using probing station)



- **Dissemination of test platforms to collaborators**
  - Training on CMOS-only boards
  - PDC boards should be available Fall 2025

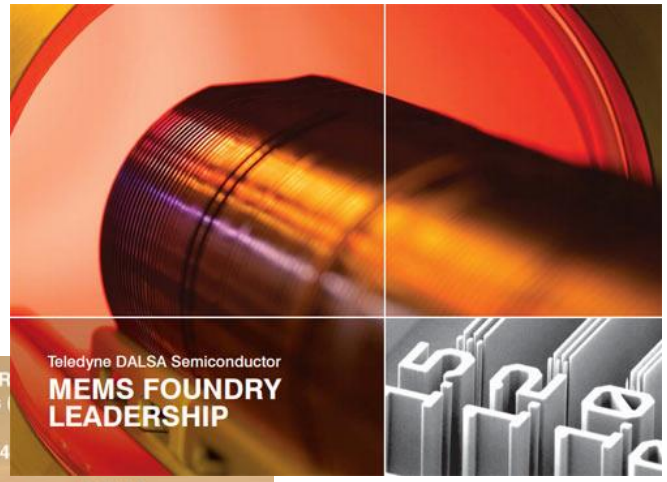
MI supported

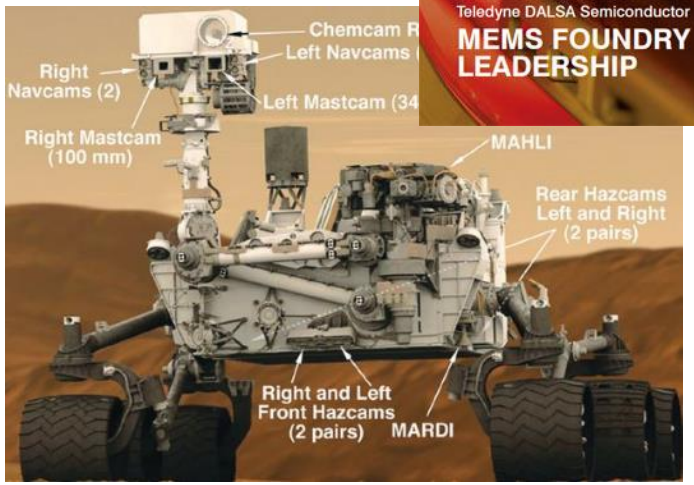
- **High performance Photon-to-Digital Converter**
  - Small array demonstrated: quenching σ<5 ps, TDC σ<10 ps
  - Completing design/validation of 5×5 mm^2 array → 2026
    - Readout prototyping → 2026
  - Wafer level 3D assembly with SPADs → 2027

A perfect synergy

UDS

TELEDYNE DALSA
Everywhereyoulook™





L'UdeS fait partie des 10 plus grandes universités de recherche au Canada

On PDC development

- T. Rossignol et al., “A 3D photon-to-digital converter readout for low-power and large-area applications,” J. Inst., vol. 19, no. 09, p. P09017, Sep. 2024, doi: 10.1088/1748-0221/19/09/P09017.
- S. Parent et al., “Wafer-Level Characterization and Monitoring Platform for Single-Photon Avalanche Diodes,” IEEE J. Electron Devices Soc., vol. 12, pp. 127–137, 2024, doi: 10.1109/JEDS.2024.3359088.
- J.-F. Pratte et al., “Fast neutron radiography-based on single-photon digital photosensor: concept and demonstration,” in Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XXV, N. J. Cherepy, M. Fiederle, and R. B. James, Eds., San Diego, United States: SPIE, Oct. 2023, p. 12. doi: 10.1117/12.2682610.
- F. Nolet et al., “Quenching Circuit Discriminator Architecture Impact on a Sub-10 ps FWHM Single-Photon Timing Resolution SPAD,” Instruments, vol. 7, no. 2, p. 16, Apr. 2023, doi: 10.3390/instruments7020016.
- S. Carrier et al., “Towards a Multi-Pixel Photon-to-Digital Converter for Time-Bin Quantum Key Distribution,” Sensors, vol. 23, no. 7, p. 3376, Mar. 2023, doi: 10.3390/s23073376.
- Rossignol, T. “Conception d’un circuit de lecture d’une matrice de photodiodes à avalanche monophotonique pour les détecteurs de physique des particules dans les gaz nobles liquéfiés”. Dissertation, Université de Sherbrooke, 2020.

On ToF CT

- D. Gaudreault, J. Rossignol, Y. Bérube-Lauzière, and R. Fontaine (2021), IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 5, no. 3, pp. 343–349
- J. Rossignol, G. Bélanger, D. Gaudreault, A. C. Therrien, Y. Bérubé-Lauziére, et R. Fontaine, « Time-of-flight scatter rejection in x-ray radiography », Phys. Med. Biol., vol. 69, no 5, p. 055027, mars 2024, doi: 10.1088/1361-6560/ad1f85.
- J. Rossignol, G. Bélanger, M. Fromont, A. C Therrien, R. Fontaine, et Y. Bérubé-Lauzière, « Scatter estimation and correction using time-of-flight and deconvolution in x-ray medical imaging », Phys. Med. Biol., vol. 69, no 17, p. 175017, sept. 2024, doi: 10.1088/1361-6560/ad700e.
- G. Belanger, J.Rossignol, , Y. Berube-Lauziere, and R. Fontaine (2024), To be published

On ToF PET

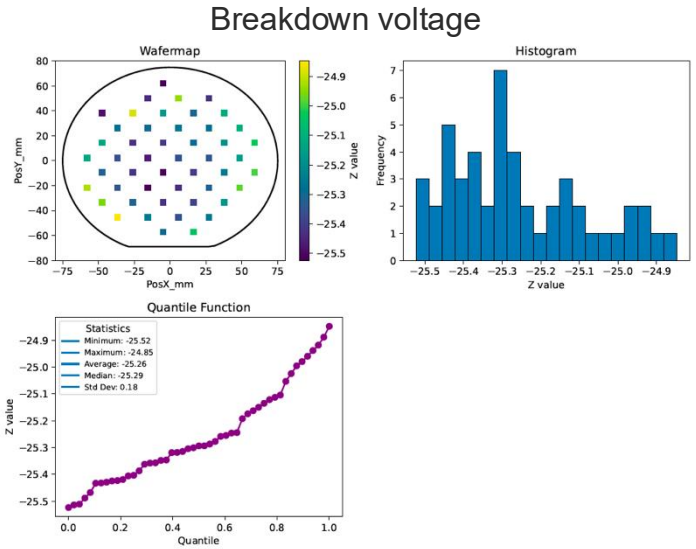
- Pratte, J.-F., et al. "3D Photon-to-Digital Converter for Radiation Instrumentation: Motivation and Future Works" (2021) Sensors;21(2):598. doi: 10.3390/s21020598
- Parent, S., et al. "Single photon avalanche diodes and vertical integration process for a 3D digital SiPM using industrial semiconductor technologies." 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC). IEEE, 2018.
- Parent, S., et al. “Characterization and Monitoring Platform for Single-Photon Avalanche Diodes in the Development of a Photon-to-Digital Converter Technology.”, 2022 IEEE International Conference on Microelectronic Test Structures Proceedings (ICMTS). IEEE, 2022.
- Parent, S., “Design of a Vertically Integrated Single-Photon Avalanche Diodes, Manufactured at Wafer level, for a Photon-to-Digital Converter Technology”, PhD Thesis (to be published), 2022.
- Nolet, F. et al., “Quenching Circuit and SPAD Integrated in CMOS 65 nm with 7.8 ps FWHM Single Photon Timing Resolution”, Instruments 2018, 2, 19.
- Nolet, F. et al., “Digital SiPM channel integrated in CMOS 65 nm with 17.5 ps FWHM single photon timing resolution”, Nuclear Instruments and Methods in Physics Research Section A, 912, 29-32, 2018.
- Nolet, F. et al., “A 256 Pixelated SPAD readout ASIC with in-Pixel TDC and embedded digital signal processing for uniformity and skew correction”, Nuclear Instruments and Methods in Physics Research Section A, 949, 162891, 2020.
- Lemaire, W. et al., “Embedded time of arrival estimation for digital silicon photomultipliers with in-pixel TDCs”, Nuclear Instruments and Methods in Physics Research Section A, 959, 163538, 2020.
- Roy, N., et al. “Low Power and Small Area, 6.9 ps RMS Time-to-Digital Converter for 3-D Digital SiPM”, IEEE Transactions on Radiation and Plasma Medical Sciences, 1(6) 2017.
- Therrien, A. C., et al. “Energy discrimination for positron emission thomography using the time information of the first detected photons”, Journal of Instrumentation, 13, 2018.
- Loignon-Houle, F., et al., “DOI estimation through signal arrival time distribution: a theoretical description including proof of concept measurements”, Physics in Medicine and Biology, 66(9), pp. 095015, 2021.

Extras

First PDC Characterization Results

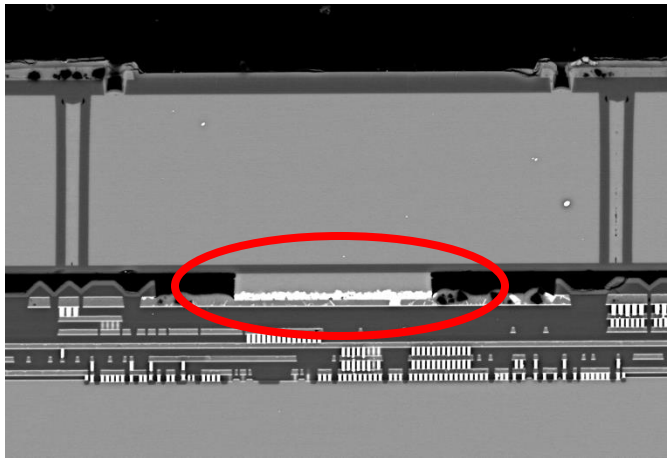
Completion of the first 3 wafers of PDC

- 1st run: Delivered on Oct. 13th 2024 (3 wafers)
- 2nd run: Delivered on April 29th 2025 (2 wafers)



Process control monitor results:

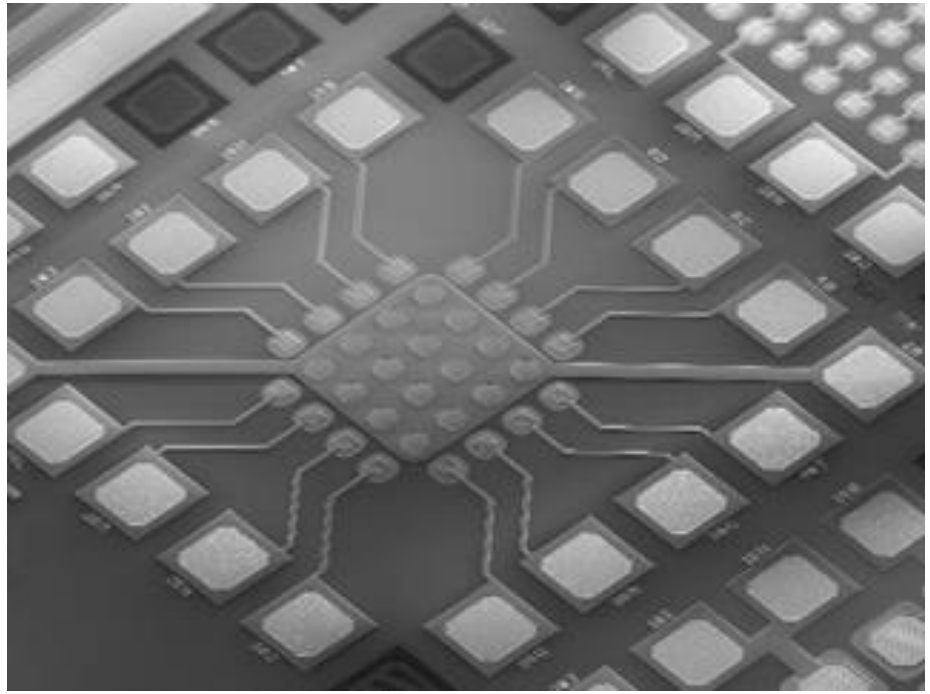
- Standard foundry process monitoring structures
  - All in specs on all wafers (~30 types of tests)
- SPAD performances: comparable to our previous SPAD runs
  - Breakdown voltage on specifications: 25.26V ± 0.18Vσ (@ 1µA bias)
  - DCR ~ 50-60 cps/SPAD @ 20-25% V_{ex} @ RT → ~0.03 cps/µm^2
  - Afterpulsing ~1.3%
- SPAD-to-Quench connection yield > 99.8%
  - Only 30 defective structures out of 980 (47040 contacts)



SPADs with external quenching

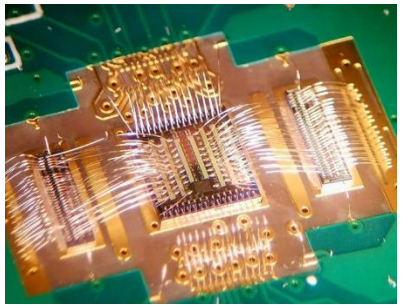
UDS

- Testing individual SPADs of a small array
  - SPADs with trenches, nominally identical to those in PDCs
  - Anode routed to top surface (resistive vias)



- Crosstalk – ongoing
  - Enabling one or two SPADs and comparing count rate
  - Preliminary: ~10%
  - To come: study through time delay distributions

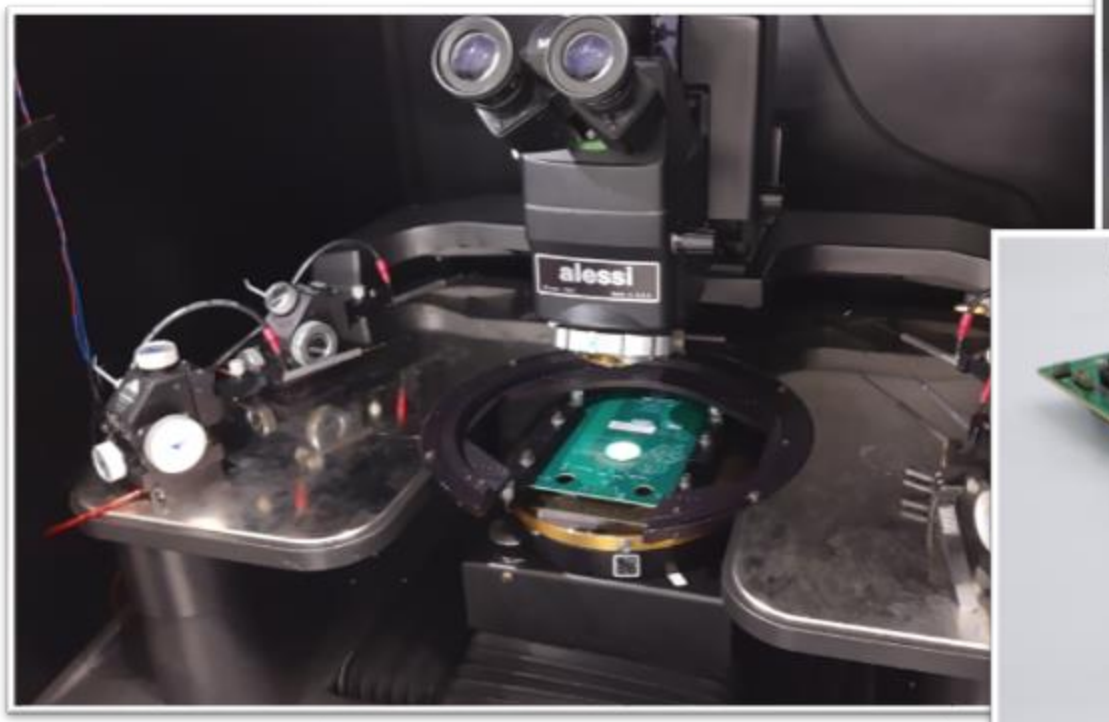
- SPTR measurement – ongoing
  - External quenching slows response and increases SPTR
  - Preliminary: 70 to 150 ps (wavelength dependant), comparable to 2023 results
  - To come: measurements on the PDC itself with local quenching

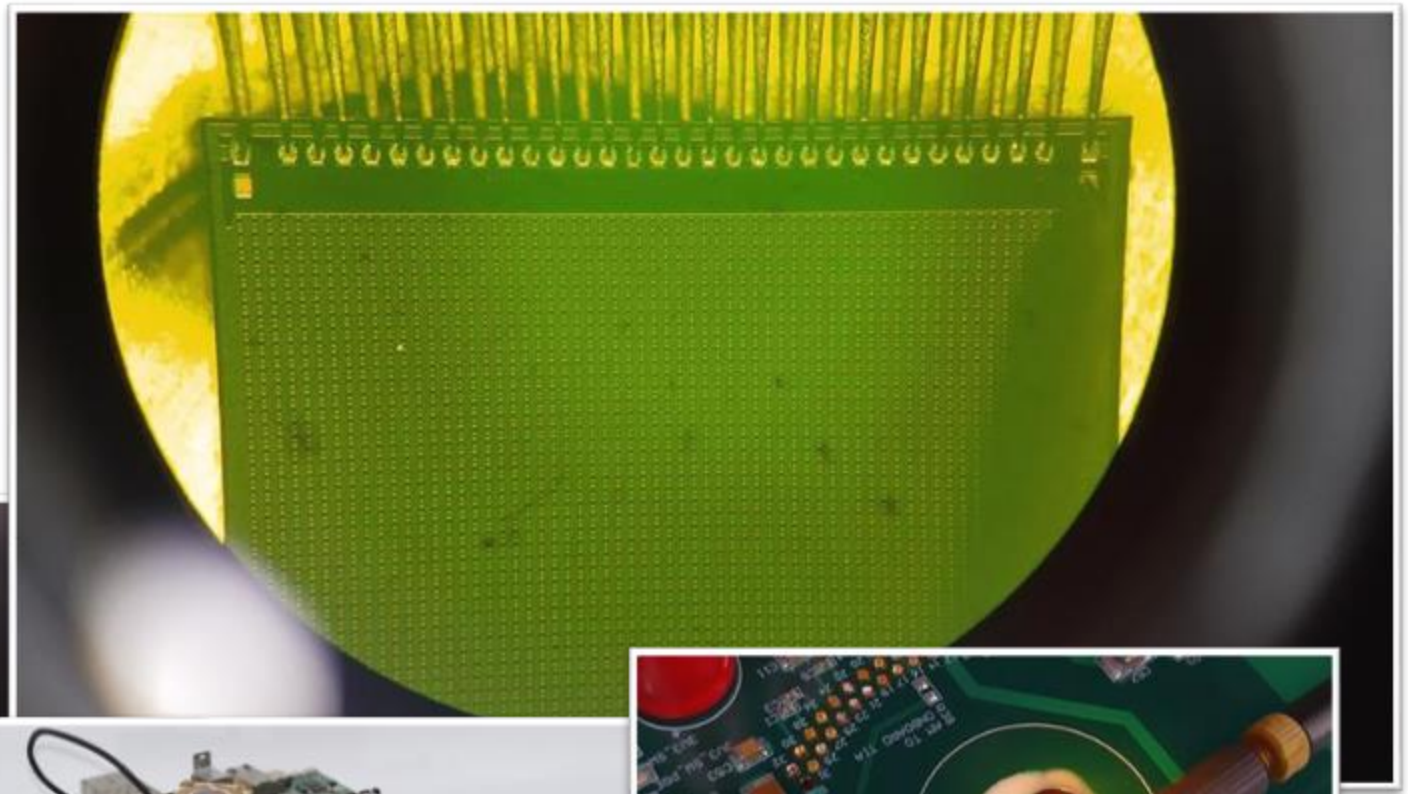


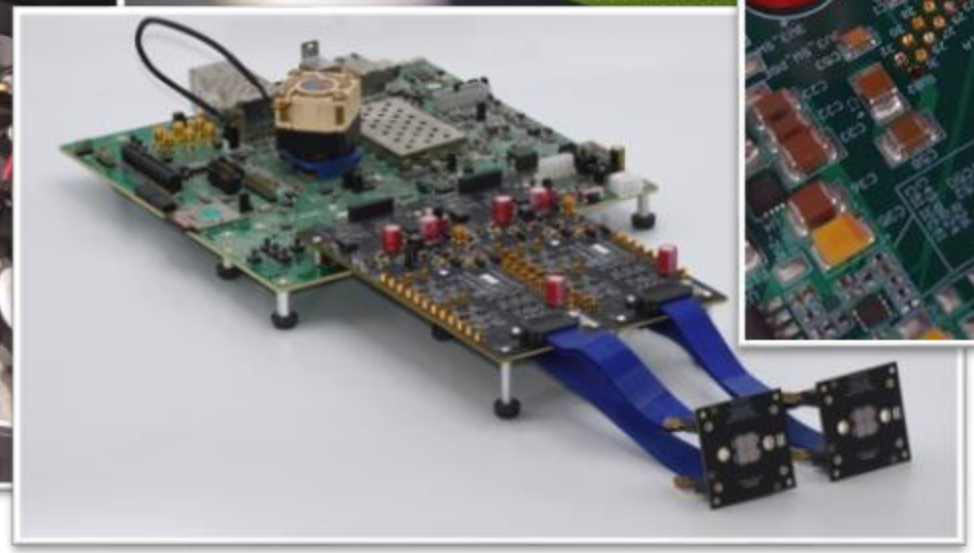
PDC Characterization

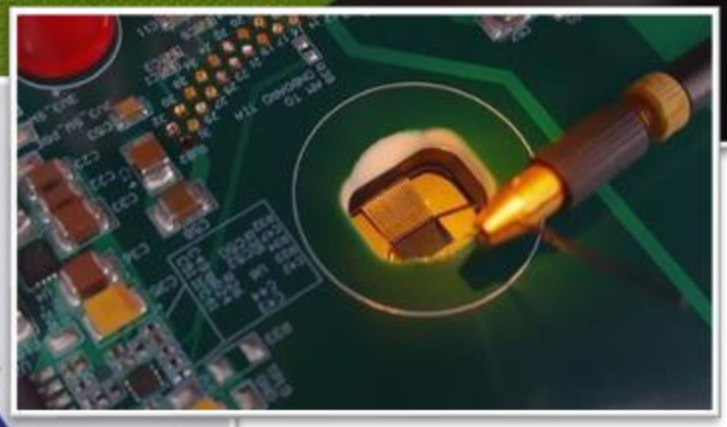
UDS

- Active testing of PDC performed with FPGA controller board*
- Flat cable connecting a probe card
- Ethernet connection to DAQ computer



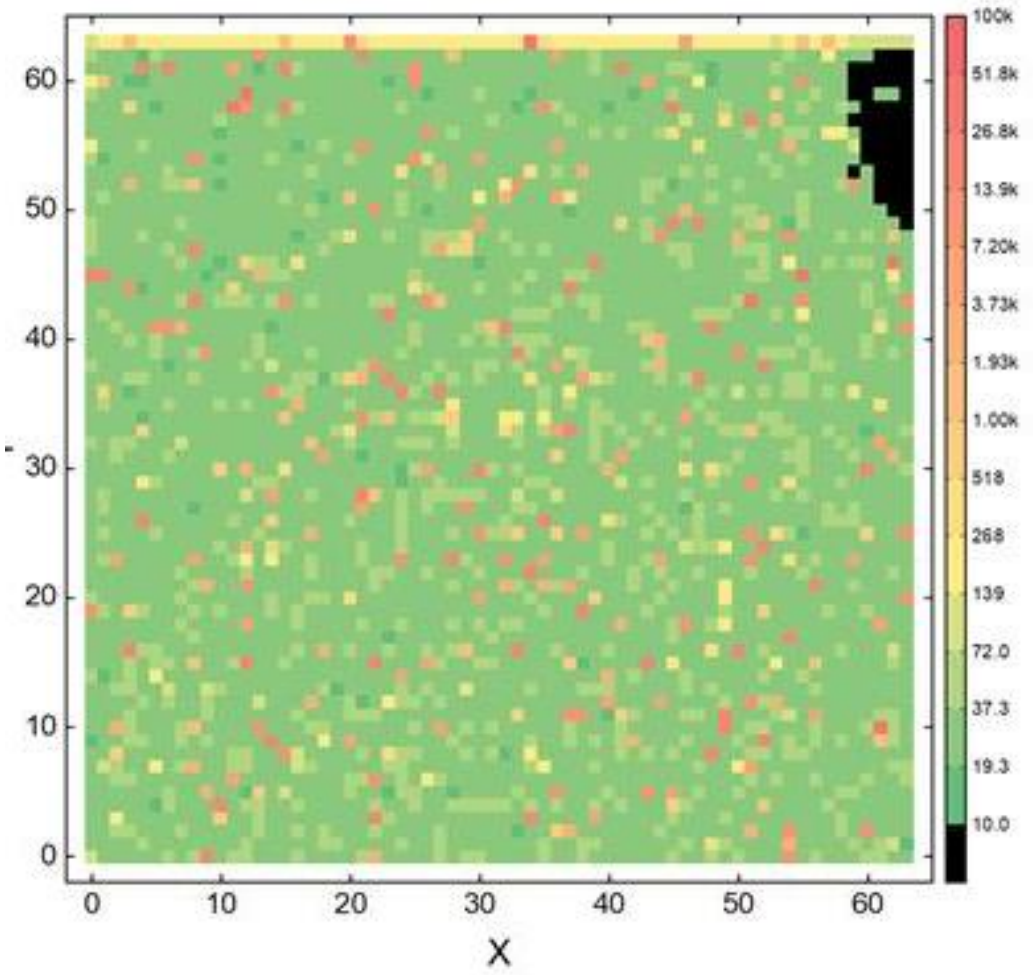






- Scan of all 4096 SPADs of the PDC
  - Activate a single SPAD
    - Therefore no crosstalk contribution in this measurement
  - Count “events” over one second → TCR
    - In this map: using flag output and counter in FPGA
    - Also possible: use the numeric sum (to come)

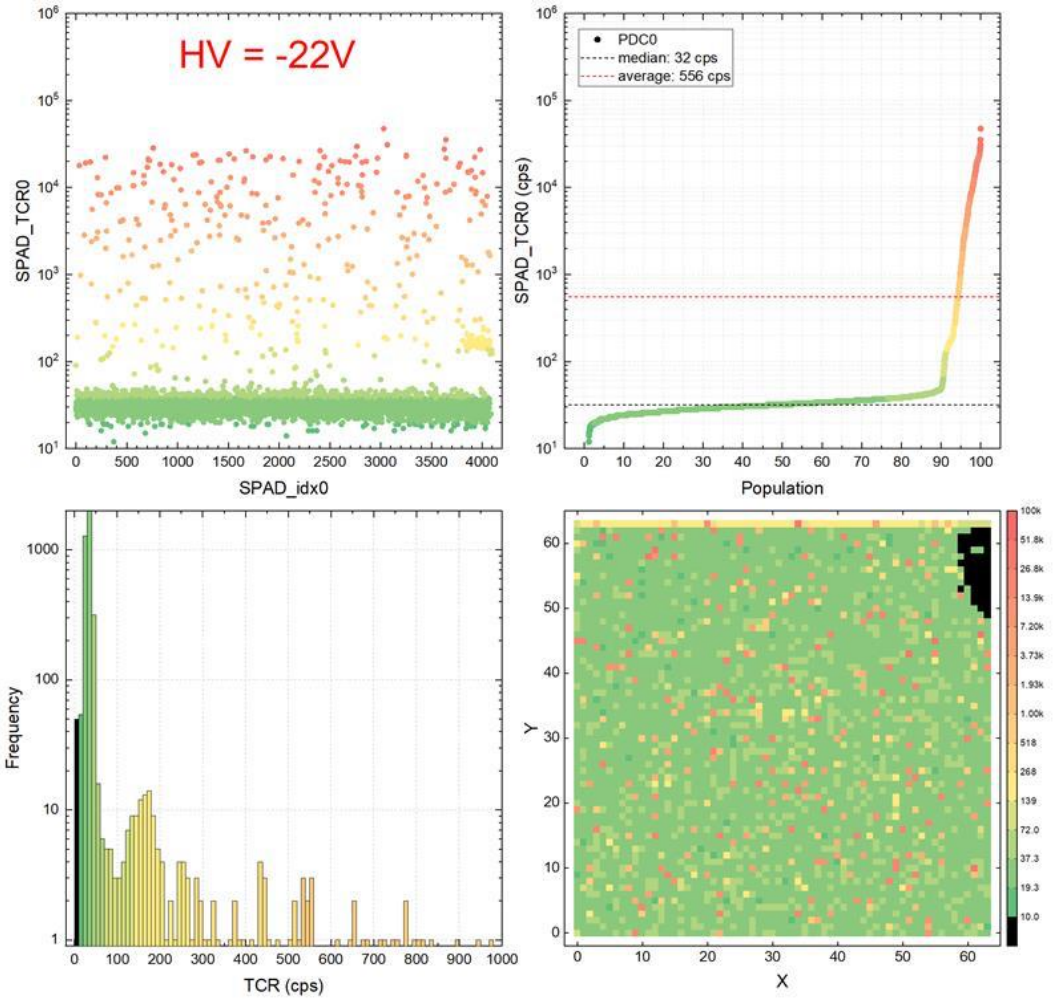
Map of total count rate (DCR+AP) per SPAD (4096)



PDC Characterization

UDS

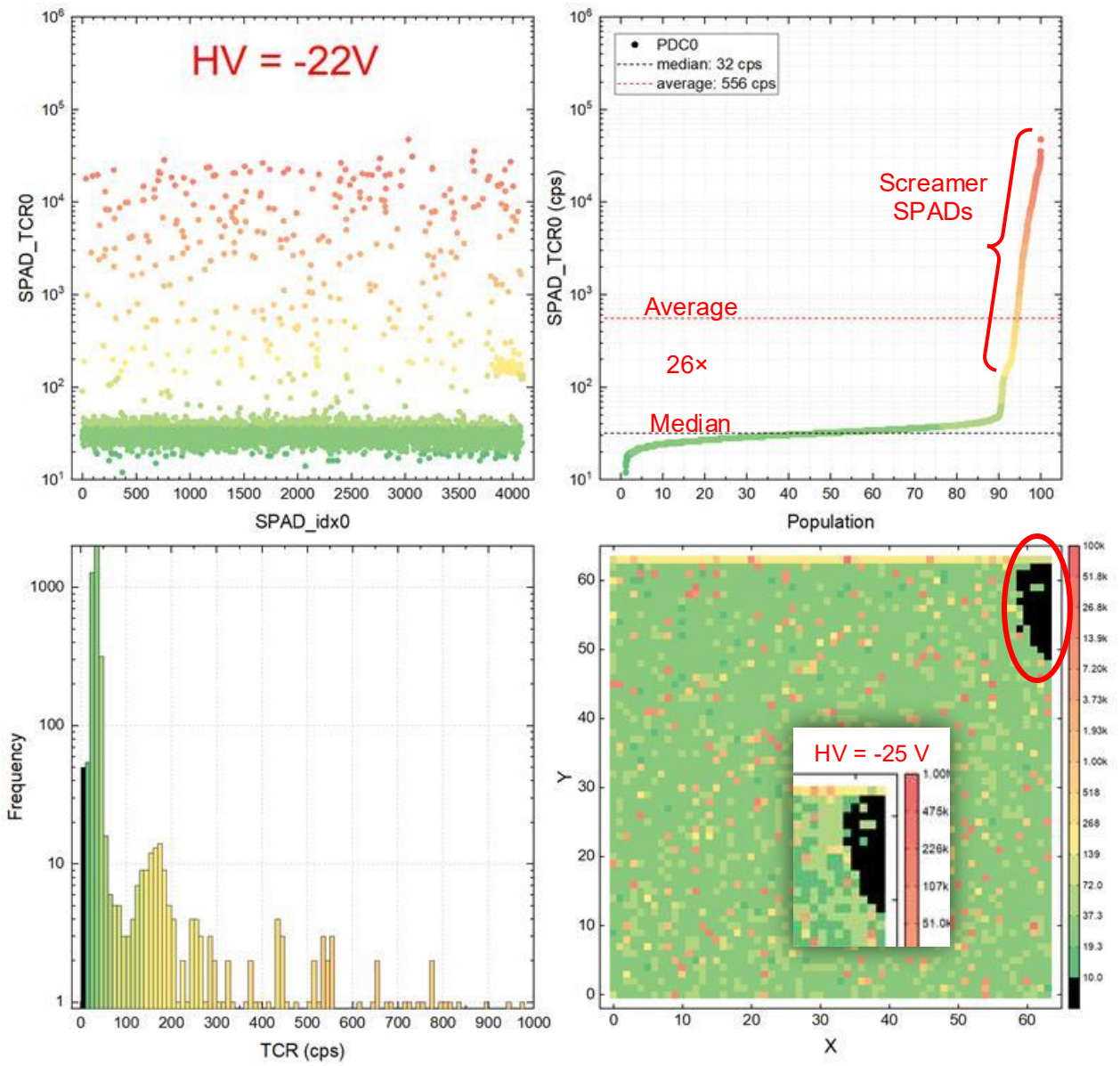
- Scan of all 4096 SPADs of the PDC
  - Activate a single SPAD
    - Therefore no crosstalk contribution in this measurement
  - Count “events” over one second → TCR
    - In this map: using flag output and counter in FPGA
    - Also possible: use the numeric sum (to come)
- Upper left: SPAD index mapping
- Upper right: Population ordered by TCR
  - Allow identifying the ”screamer” sub-population and its impact on overall TCR
- Bottom left: TCR histogram



Four ways to look at the data to get a PDC’s “unique” fingerprint

PDC Characterization – Observations on PDC08

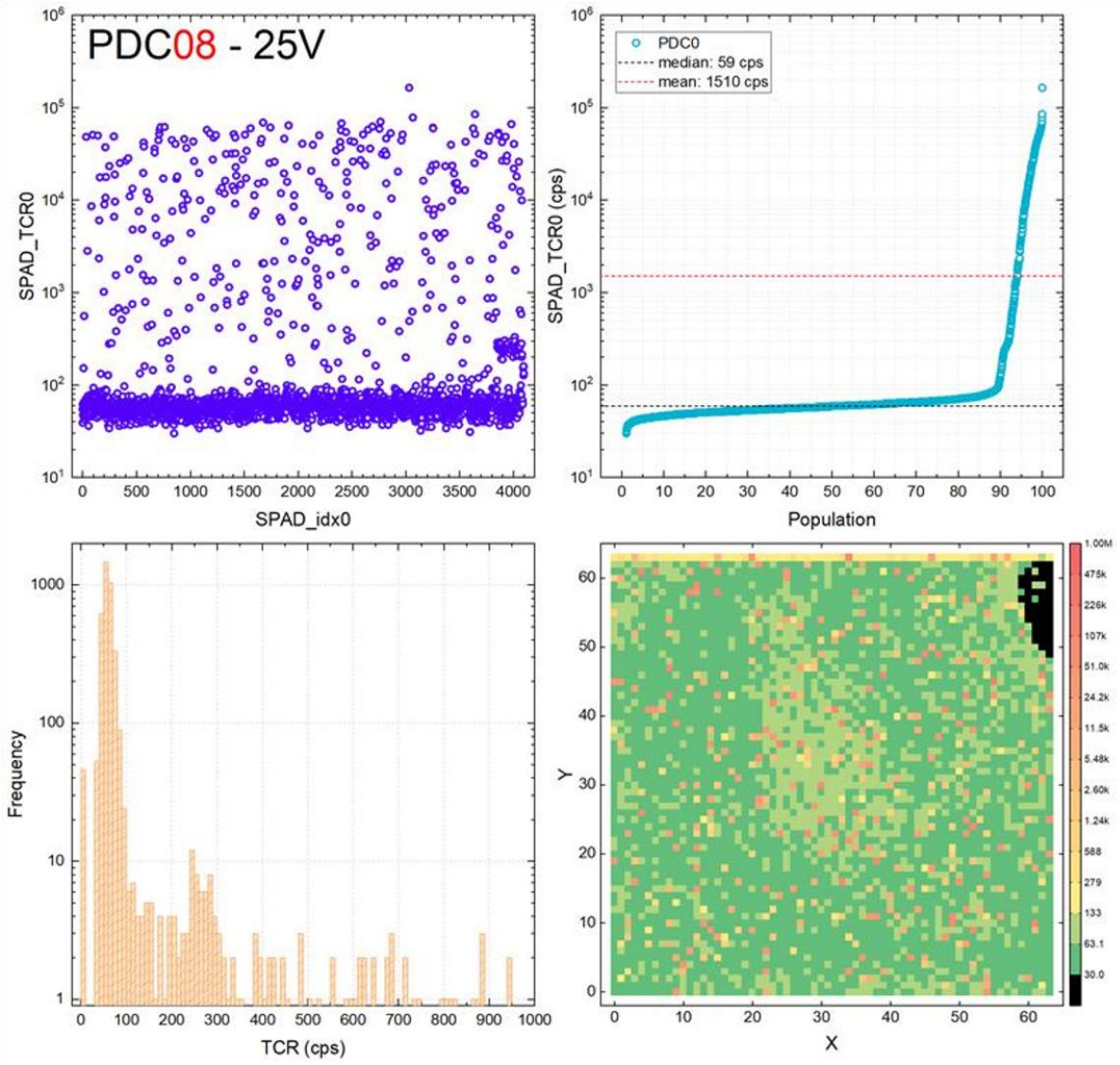
- 4096 SPADs in a 64 × 64 array
- 46 SPADs not responding (at -22 V bias)
  - 4 of these SPADs respond at -25 V bias
  - Under investigation
- Average TCR is dominated by screamers
  - 5% to 7% of population (depends on definition)
  - Median TCR is 26× lower than average TCR
  - Typical from literature, also expected in SiPMs



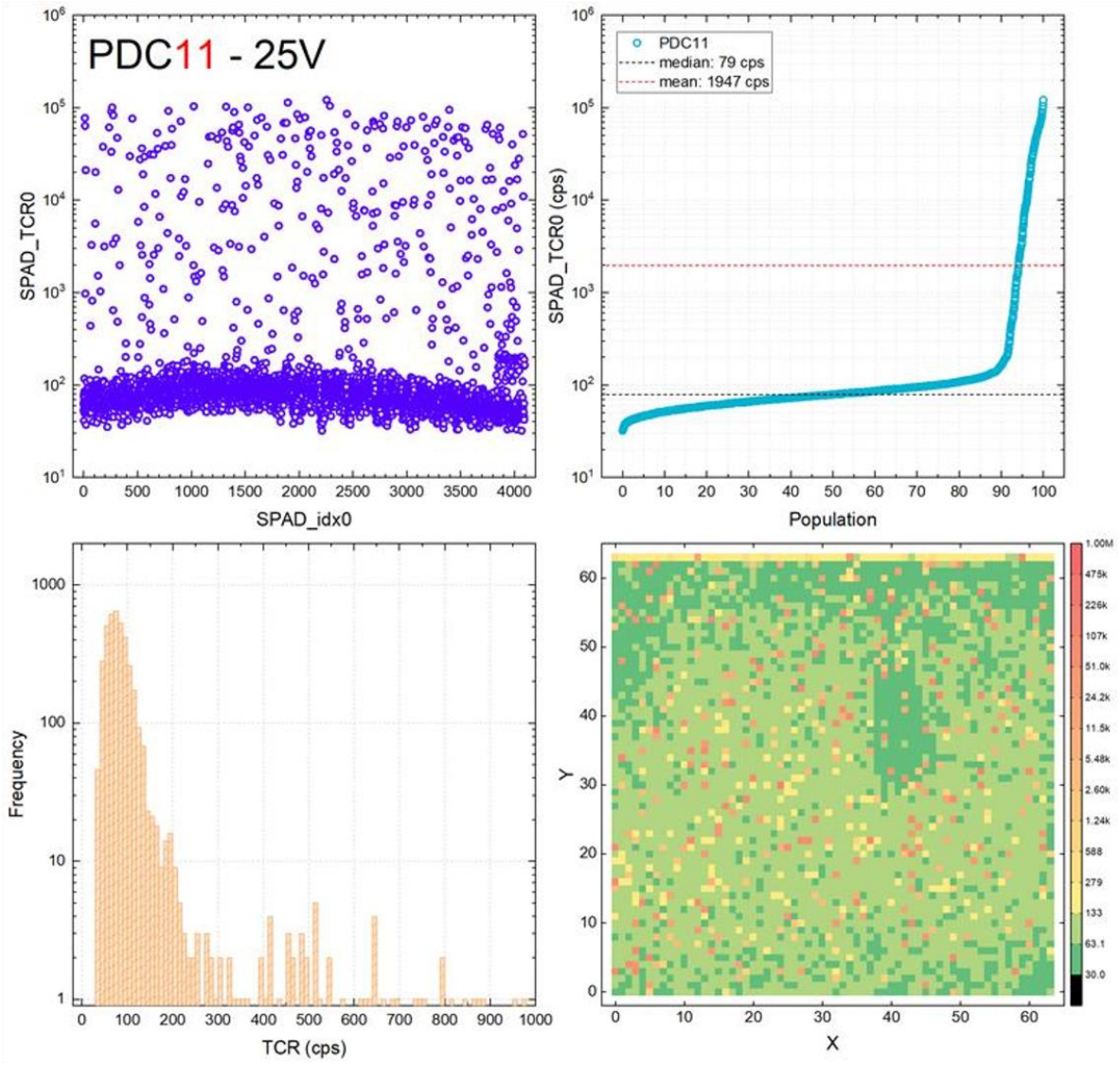
PDC Characterization – Observations on PDC08 and PDC11

UDS

PDC08



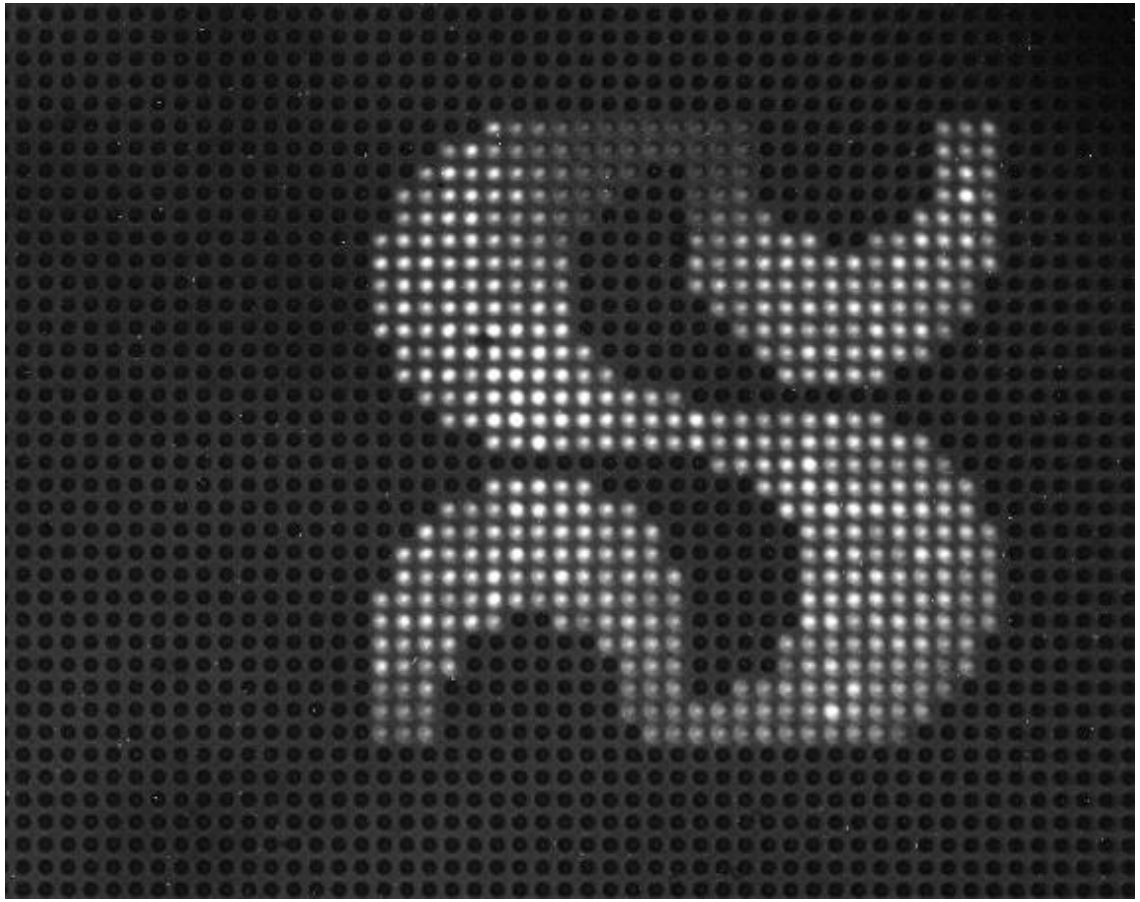
PDC11



PDC Characterization – Light emission

UDS

- During avalanche, SPADs emit light
  - Source of cross-talk both internal and external
- Demonstration of the capability of single SPAD activation/deactivation
  - SPADs forming a motif were activated
  - Long exposure of a sensitive camera reveals electroluminescence of the activated SPADs (here deliberately saturated to the show!)
  - Deactivated SPADs show no emission
- We will investigate the use of light emission to rapidly characterize PDC DCR



Light emission – PDC11 – 2 min exposure 24.5 V

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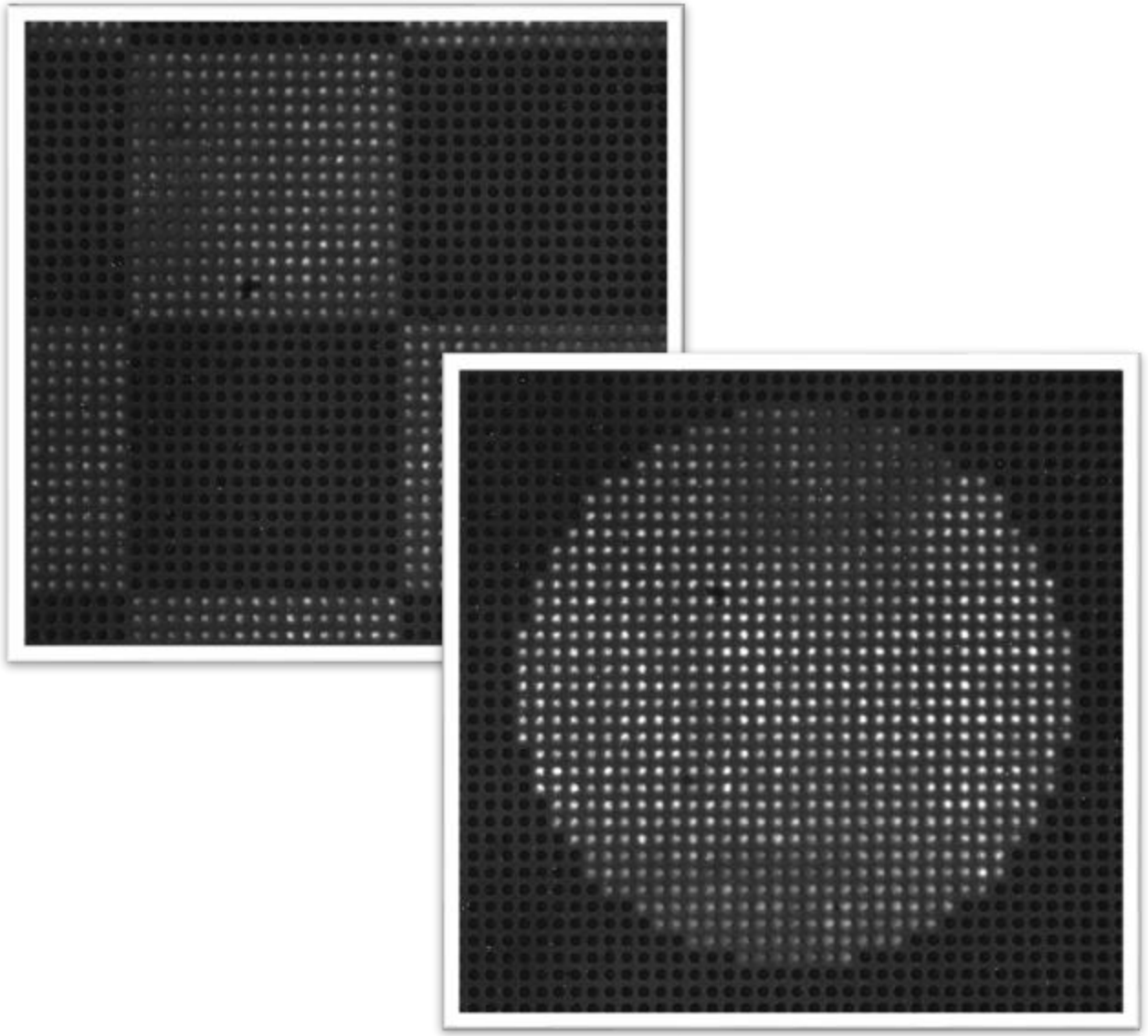

Light emission – PDC11 – 2 min exposure 24.5 V