TRIUMF

Avalanche diode update
From SiPM to Dark Matter search and beyond

Fabrice Retiere

Instrumentation for Physics discovery and beyond

NSERC CRSNG

CANADA FIRST RESEARCH EXCELLENCE FUND | APOGÉE CANADA FONDS D'EXCELLENCE EN RECHERCHE

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

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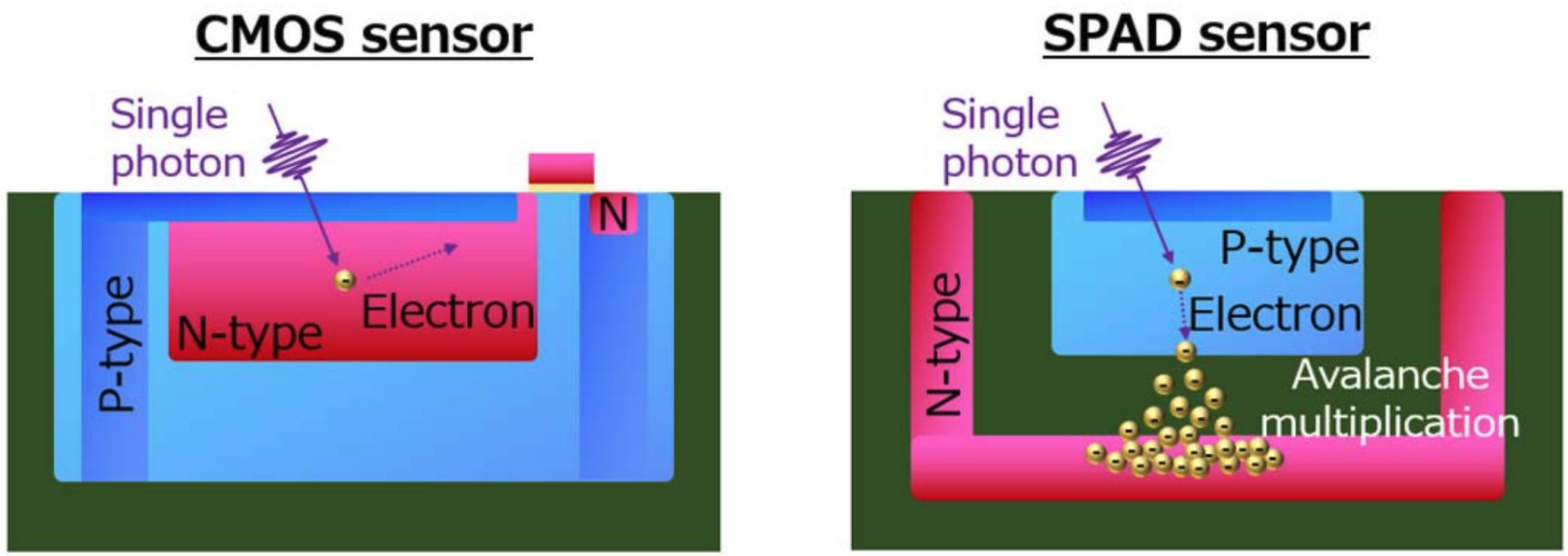
Discovery, accelerated

Single Photon Avalanche Diode

Canon Global

Vision Our Business Newsroom Sustainability About Canon

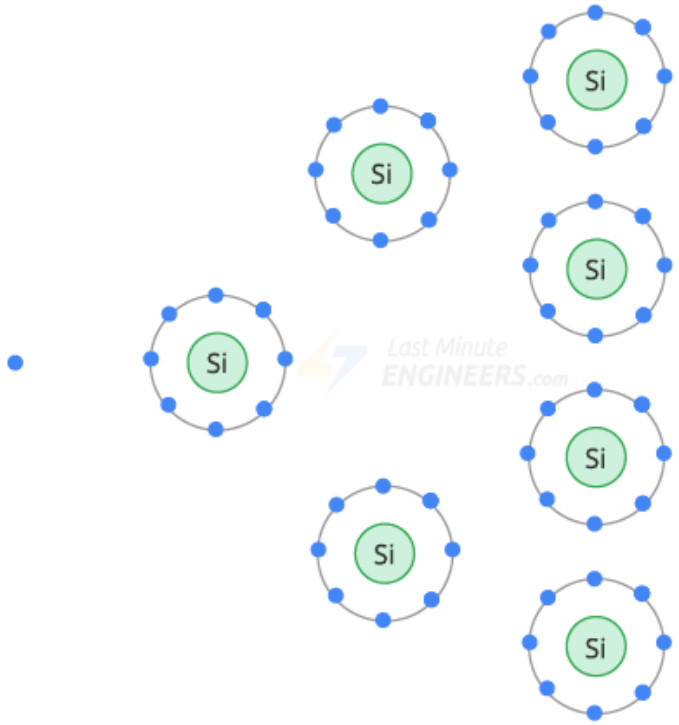


Multiplication gain: approx. 1x

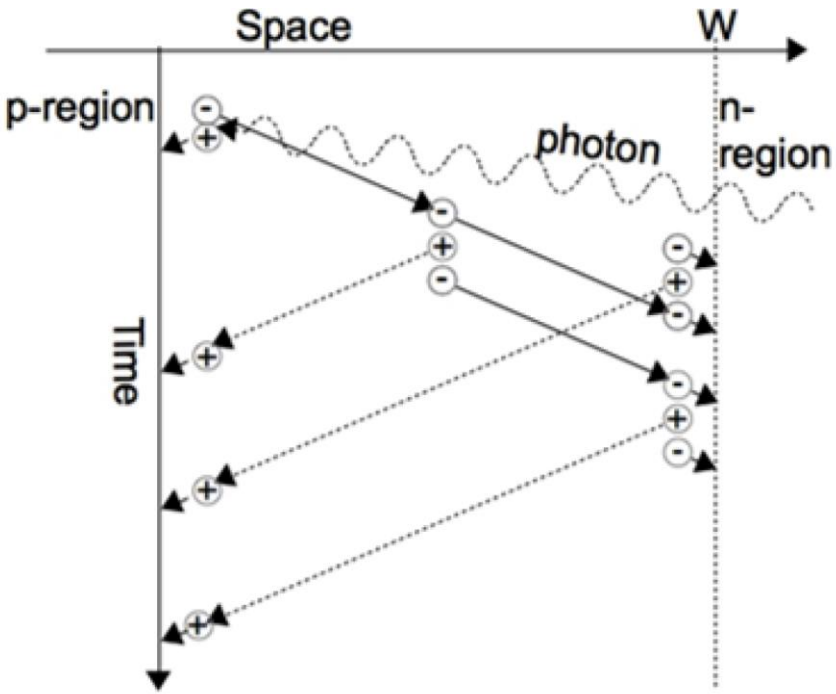
Multiplication gain: approx. 1,000,000x

P-type semiconductor: Intrinsic semiconductor doped with boron (B) or other elements
N-type semiconductor: Intrinsic semiconductor doped with phosphorous (P), arsenic (As) or other elements

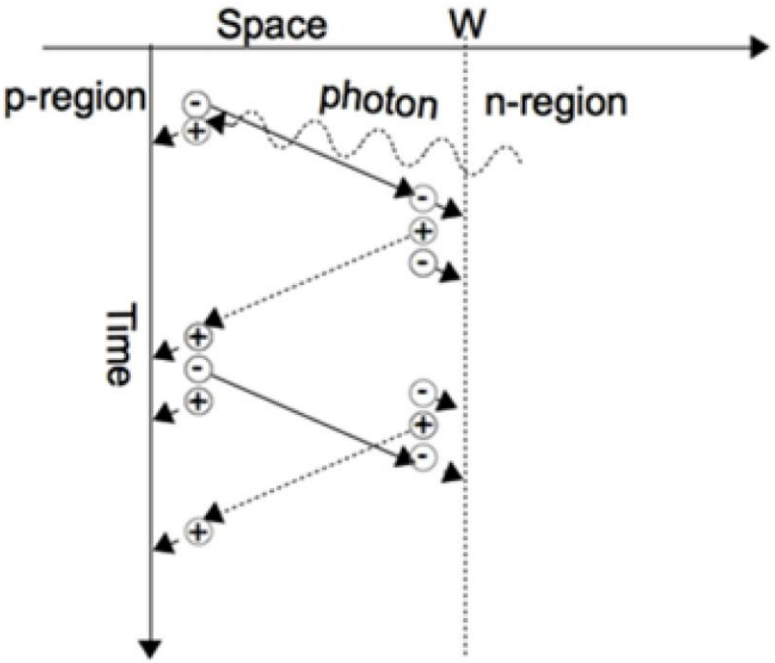
Breaking down



Limited avalanche



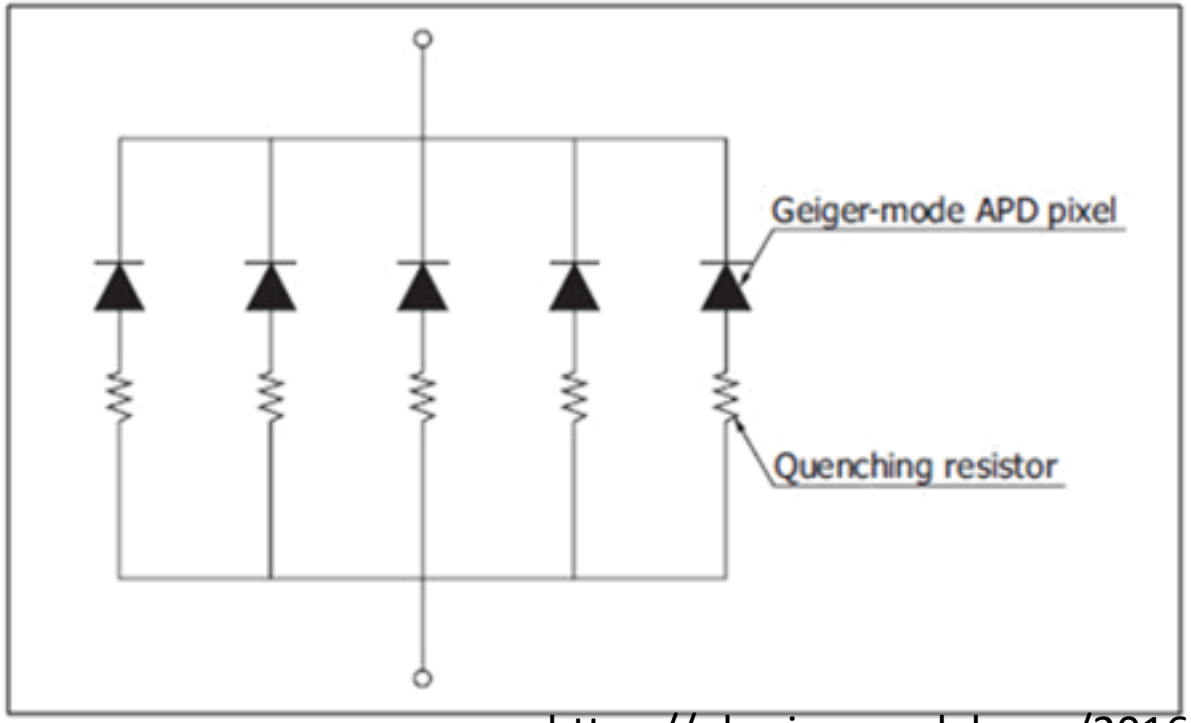
Breakdown

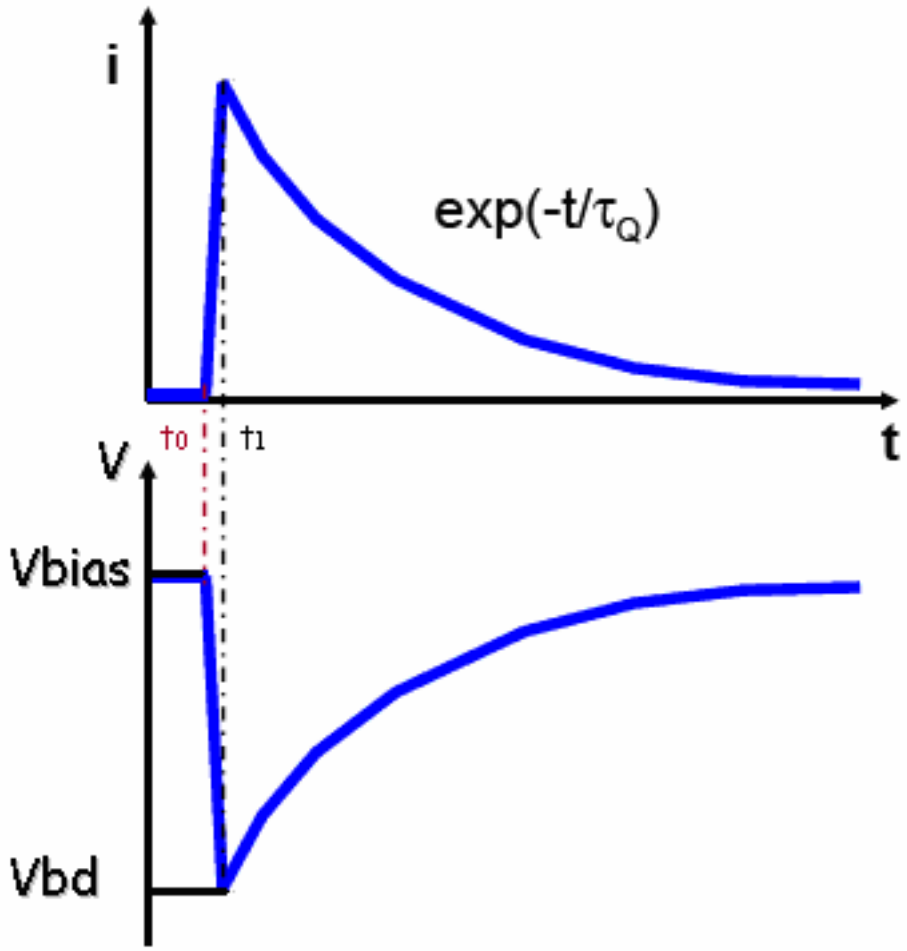


https://www.intechopen.com/chapters/49261

Passive quenching with resistor

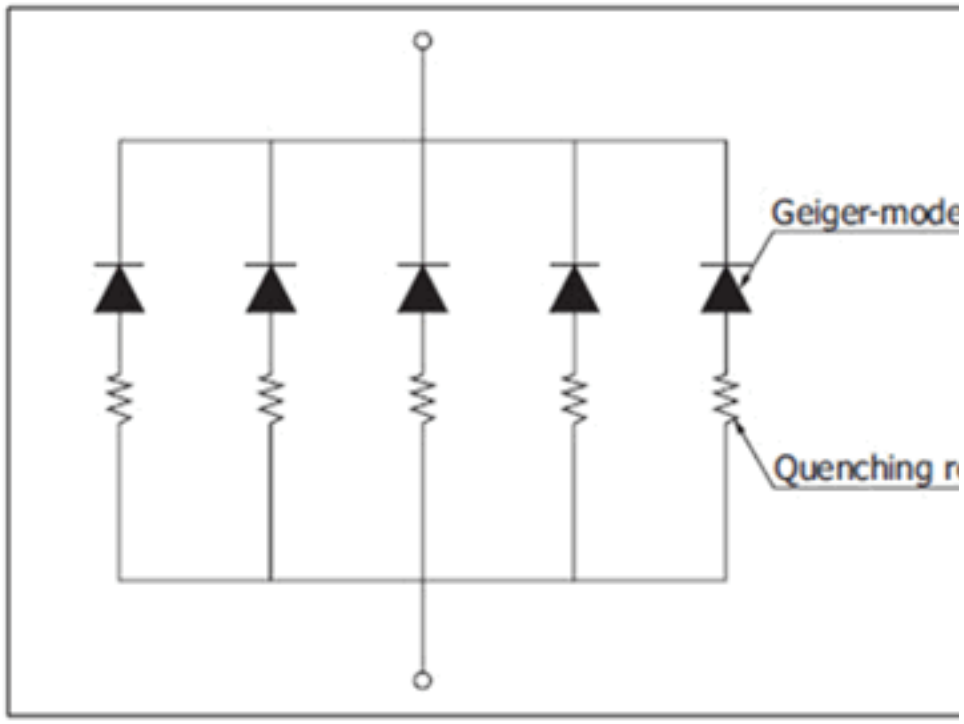
- Quenching resistor for stopping breakdown

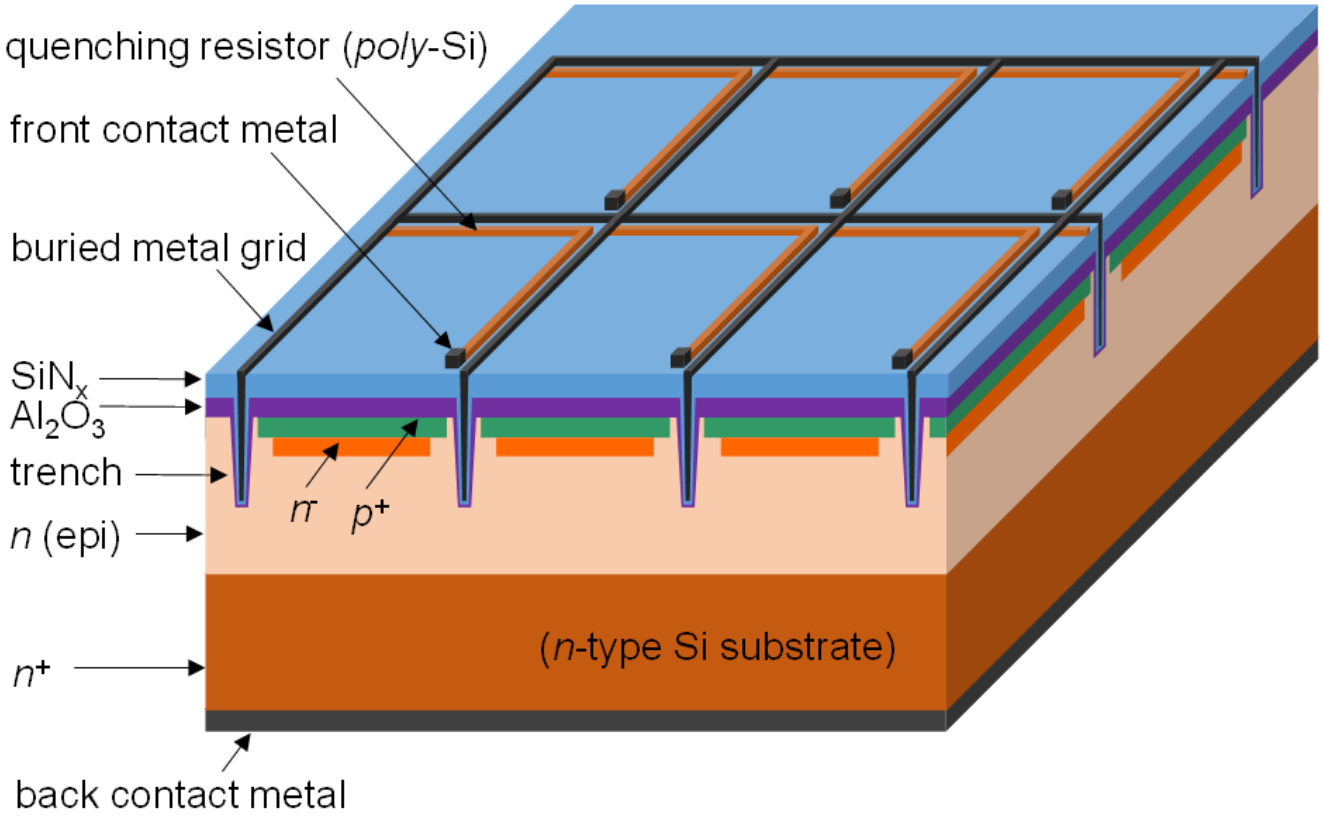




https://physicsopenlab.org/2016/02/16/silicon-photomultiplier-sipm/

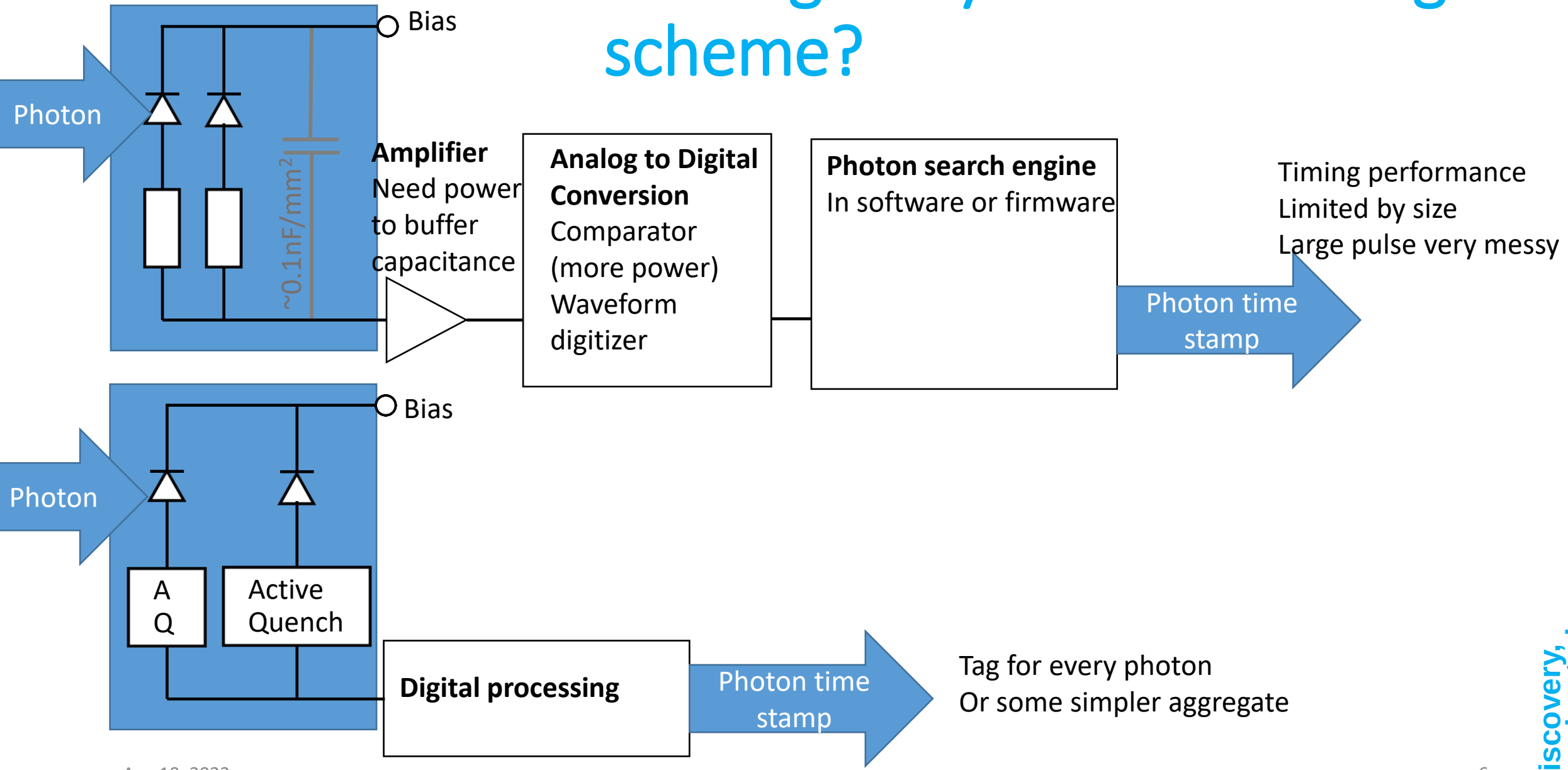
Many SPAD in parallel – aka SiPMs





https://sites.gatech.edu/lanns/research/silicon-photomultipliers/

Moving away from DS analog scheme?



Discovery, accelerated

SPAD nuisances

- Dark noise
  - Thermal. At room temperature ~100kHz/mm^2
- Carrier trap and release => after-pulsing
- Light emission during avalanche
  - Direct cross-talk
  - Delayed cross-talk
  - External cross-talk, aka hit another SiPM

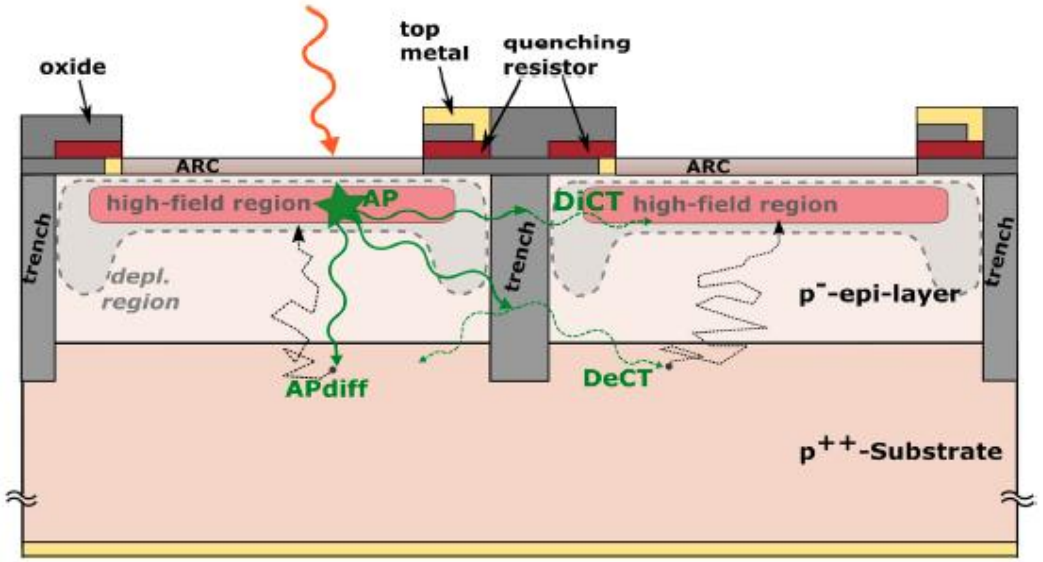
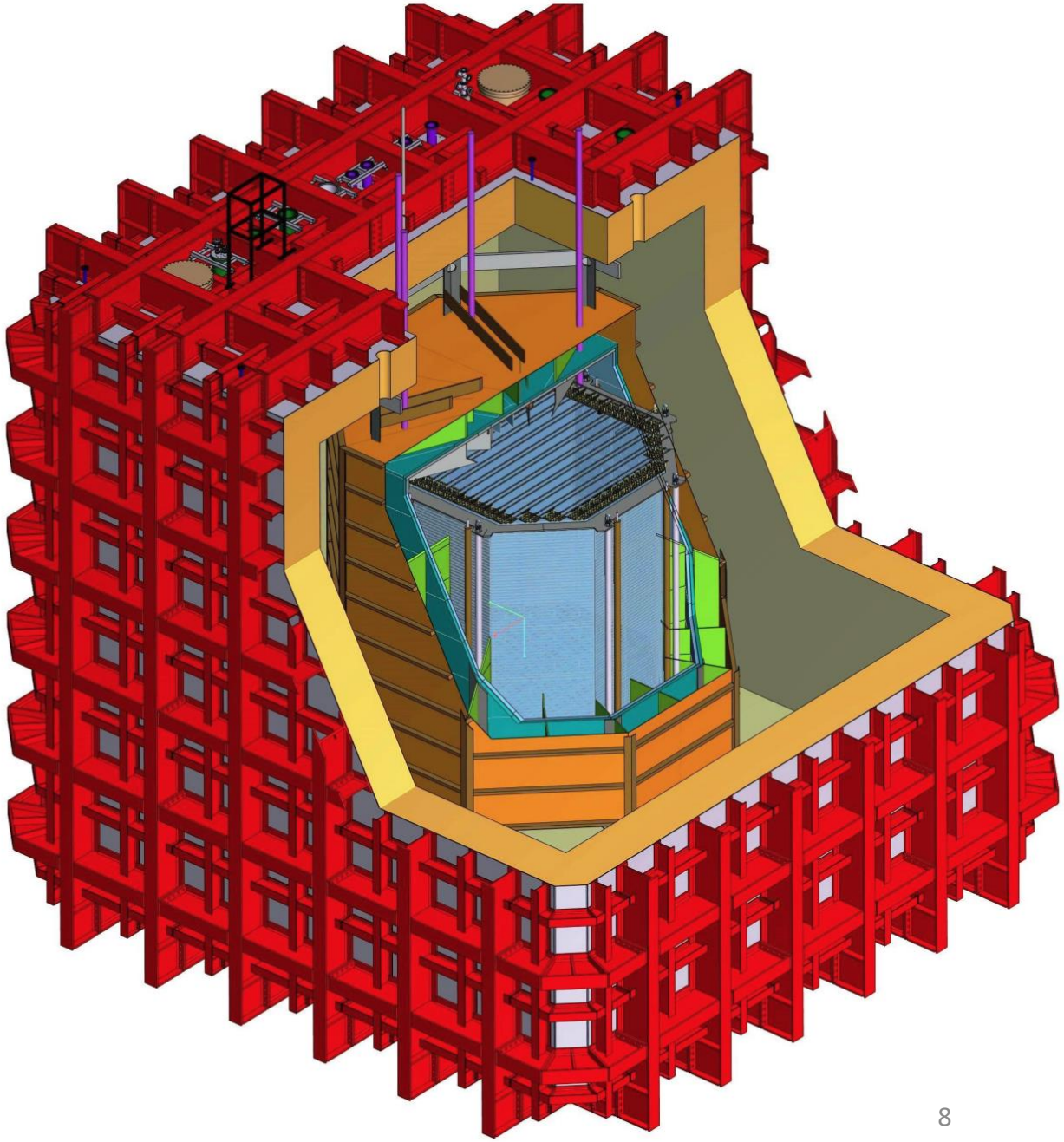


Fig. 1. Schematic representation of the internal structure of FBK Silicon photomultiplier, made in RGB-HD or RGB-UHD technology, with deep trenches between cells (SPADs).

DarkSide-20k

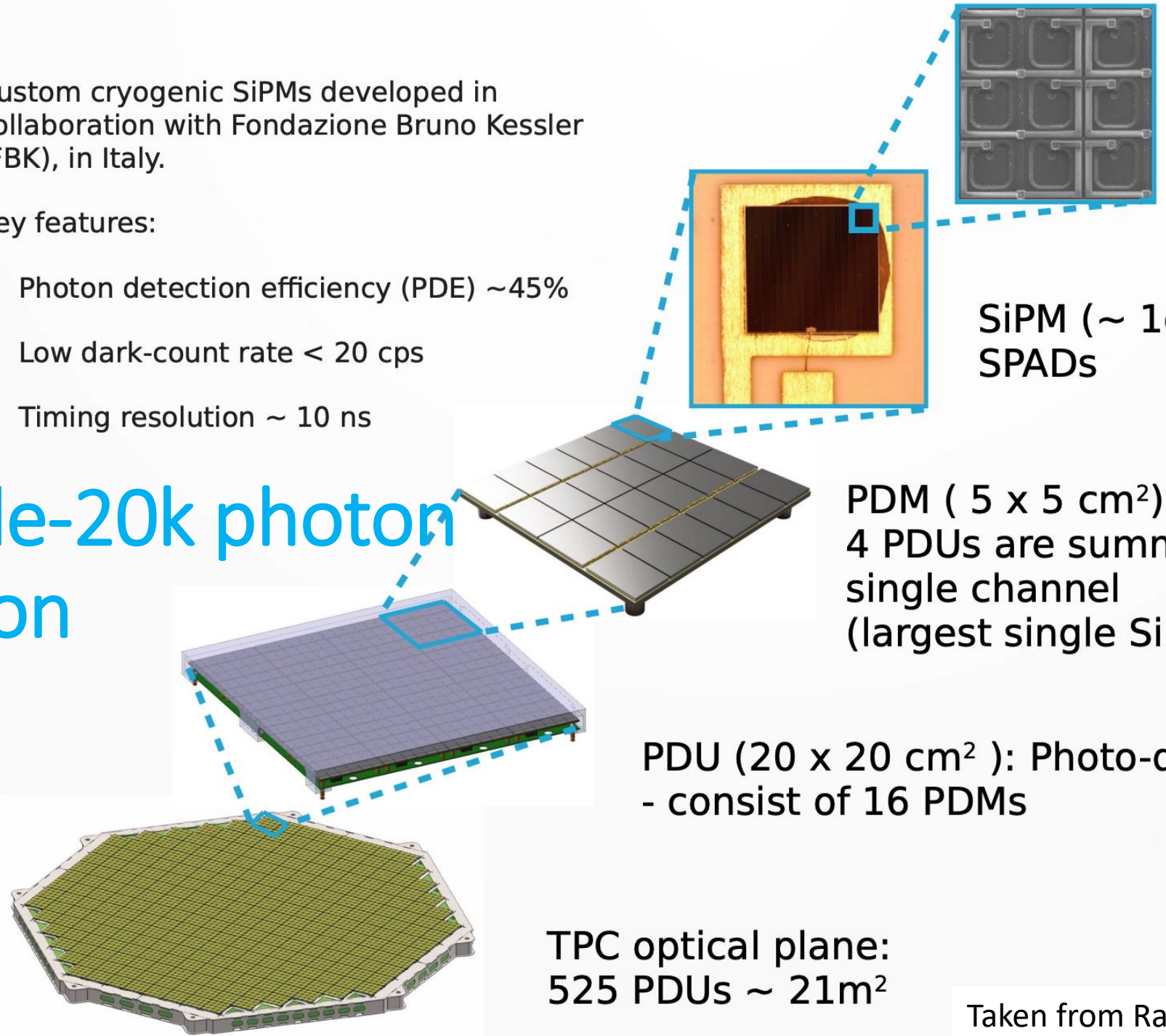
- 30 tons of (depleted) liquid Argon
- Construction on-going
- Start physics running in 2027?



TRIUM

DarkSide-20k photon detection

- Custom cryogenic SiPMs developed in collaboration with Fondazione Bruno Kessler (FBK), in Italy.
- Key features:
  - Photon detection efficiency (PDE) ~45%
  - Low dark-count rate < 20 cps
  - Timing resolution ~ 10 ns



SPAD: Single photon avalanche diode ~25-30 µm²

SiPM (~ 1cm²): 94 900 SPADs

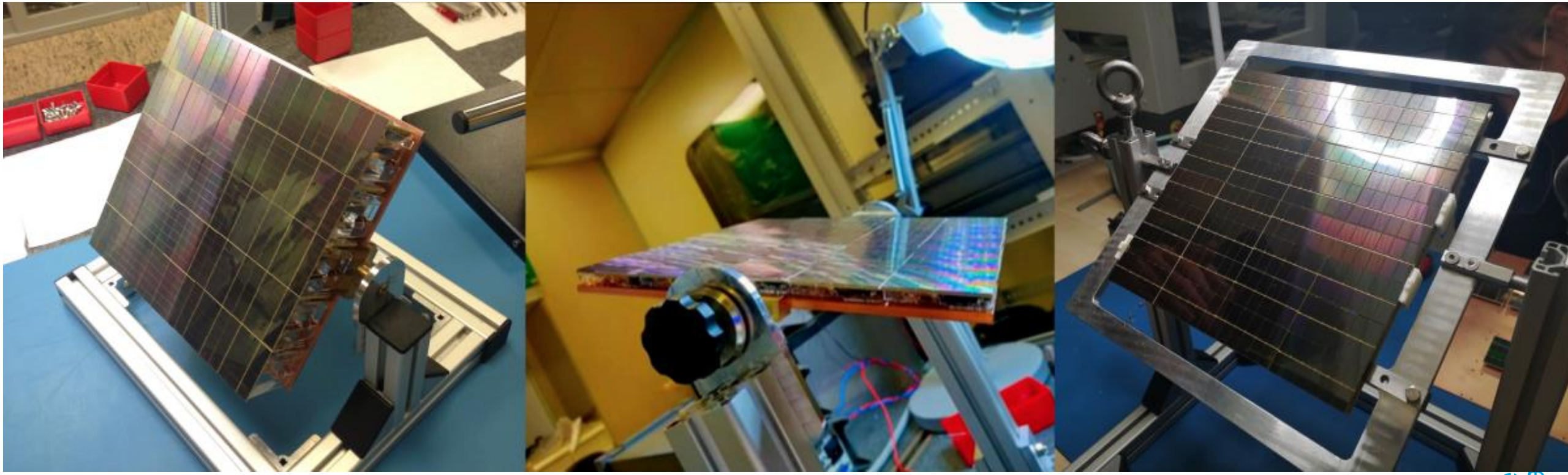
PDM (5 x 5 cm²) : 24 SiPMs
4 PDUs are summed and read as a single channel
(largest single SiPM unit ever!)

PDU (20 x 20 cm²): Photo-detection unit
- consist of 16 PDMs

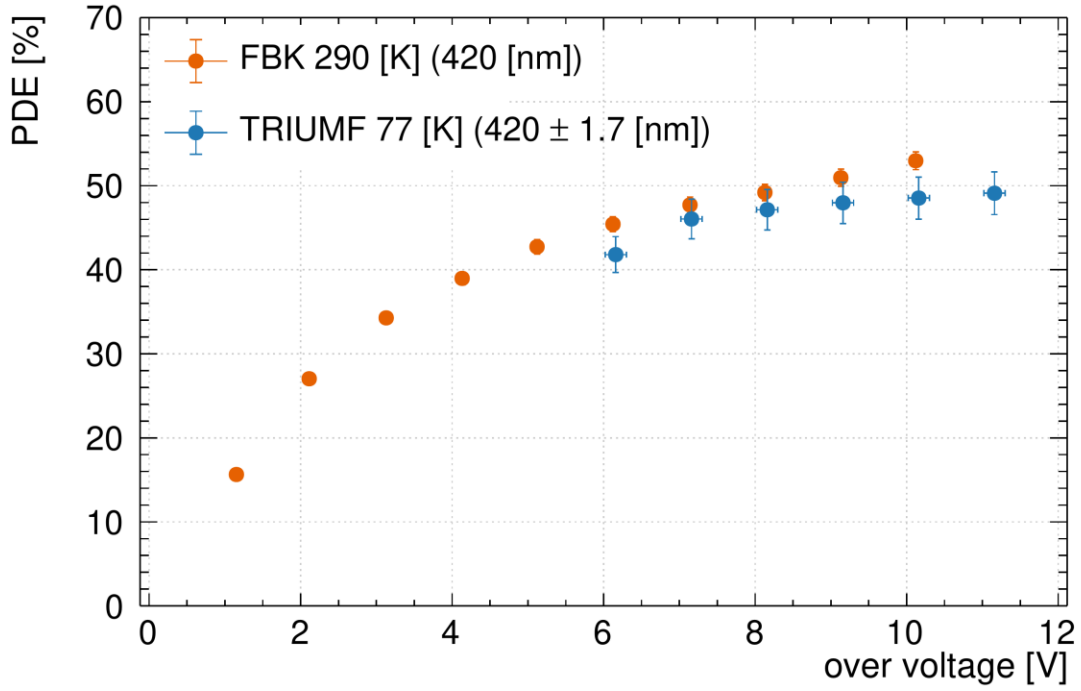
TPC optical plane:
525 PDUs ~ 21m²

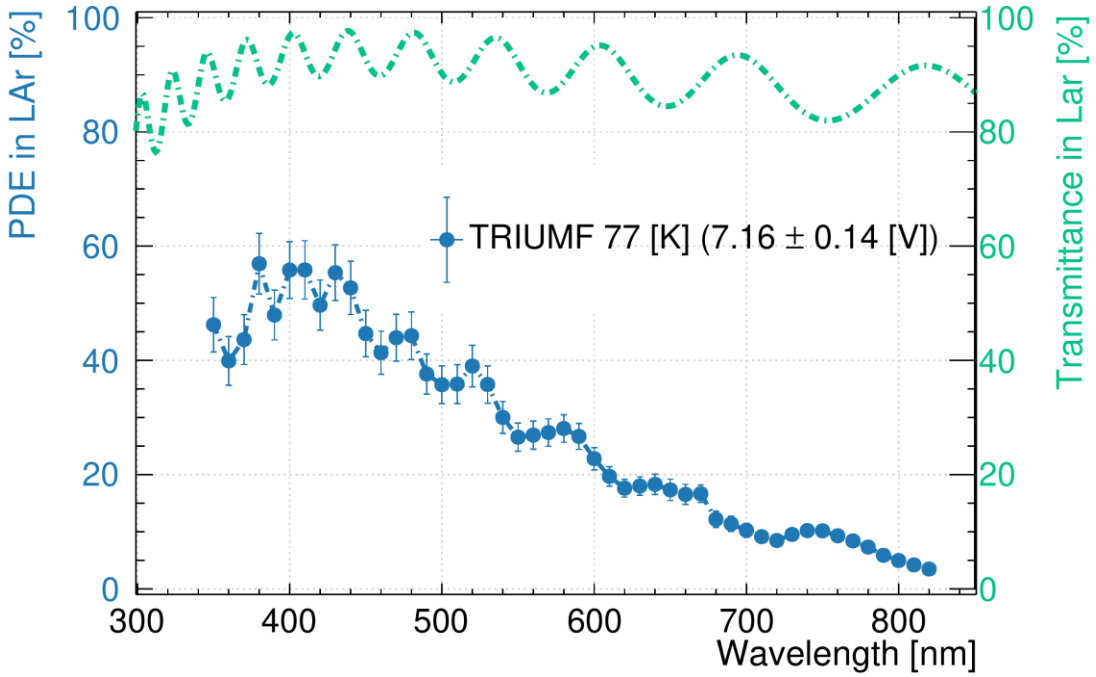
Taken from Rafał Wojaczyński (Astrocent)

Photon Detection Unit



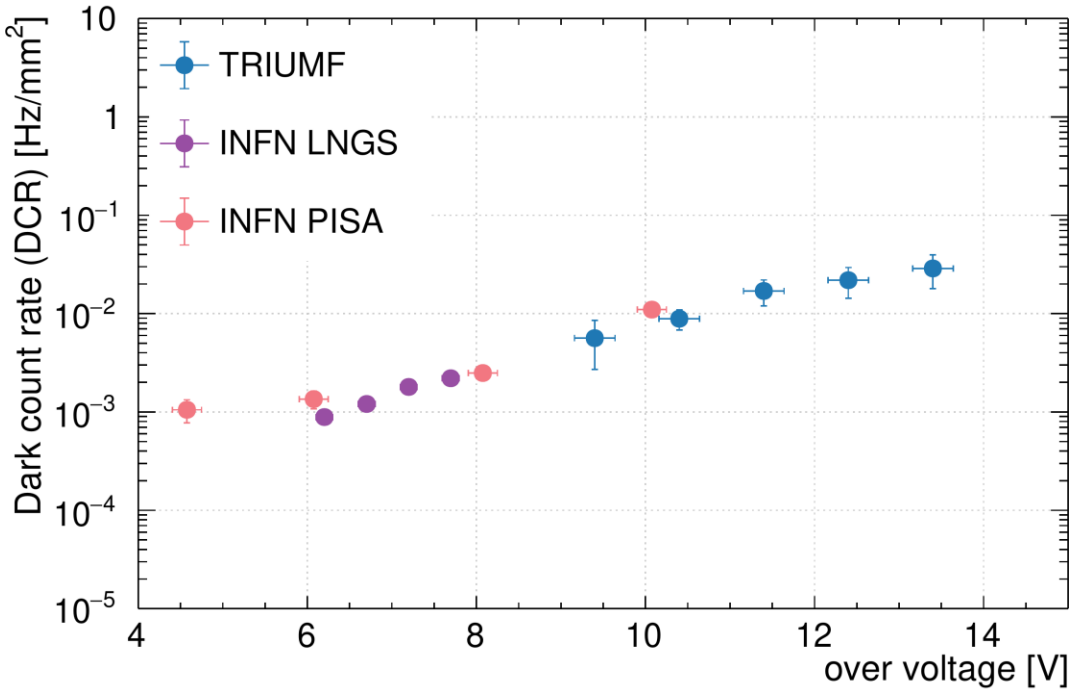
Efficiency requirements are exceeded

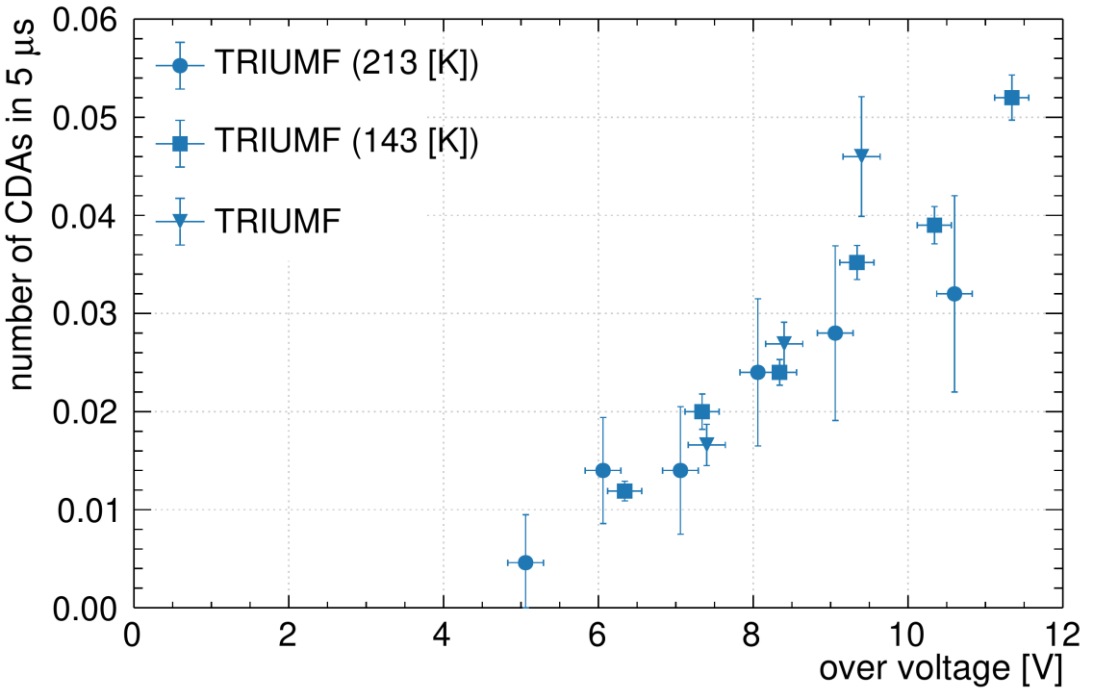


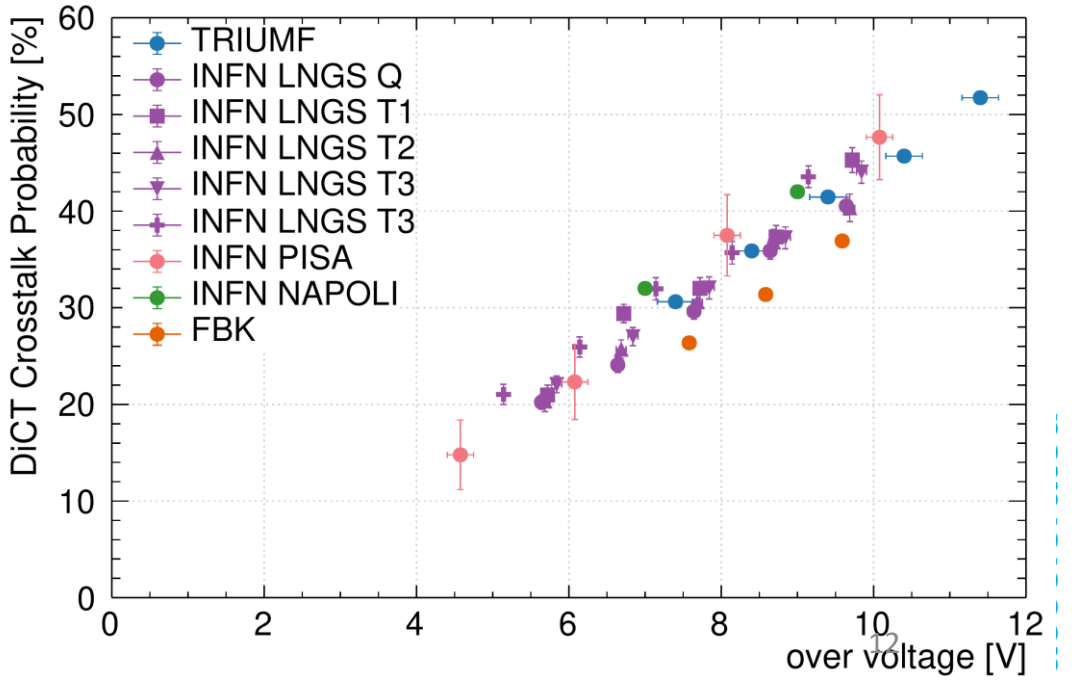


Discovery, accelerated

Nuisances are under-control

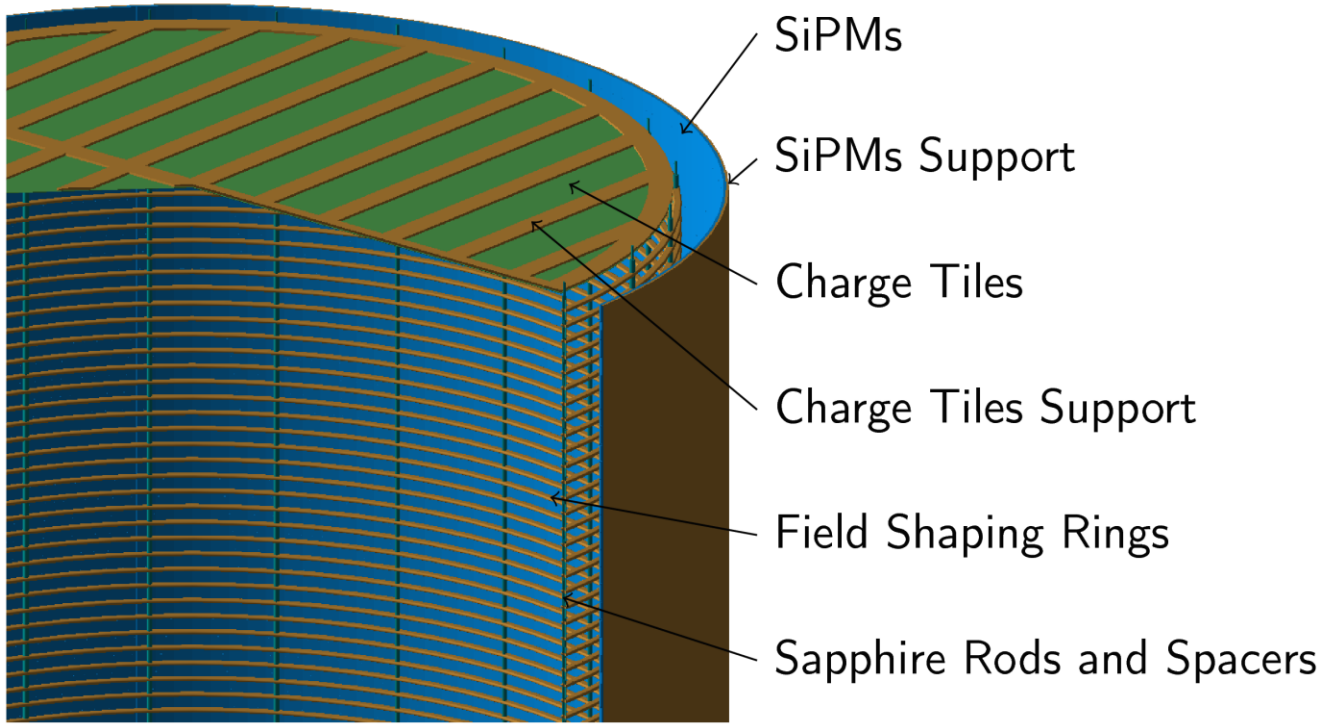






Photon detection in nEXO

- Energy resolution dominated by light
  - Need 3% efficiency of detecting scintillation photons for 1 % energy resolution
  - With negligible noise for light detection
- Need at least 4 m^2 of detection area
- Need reflective electrodes

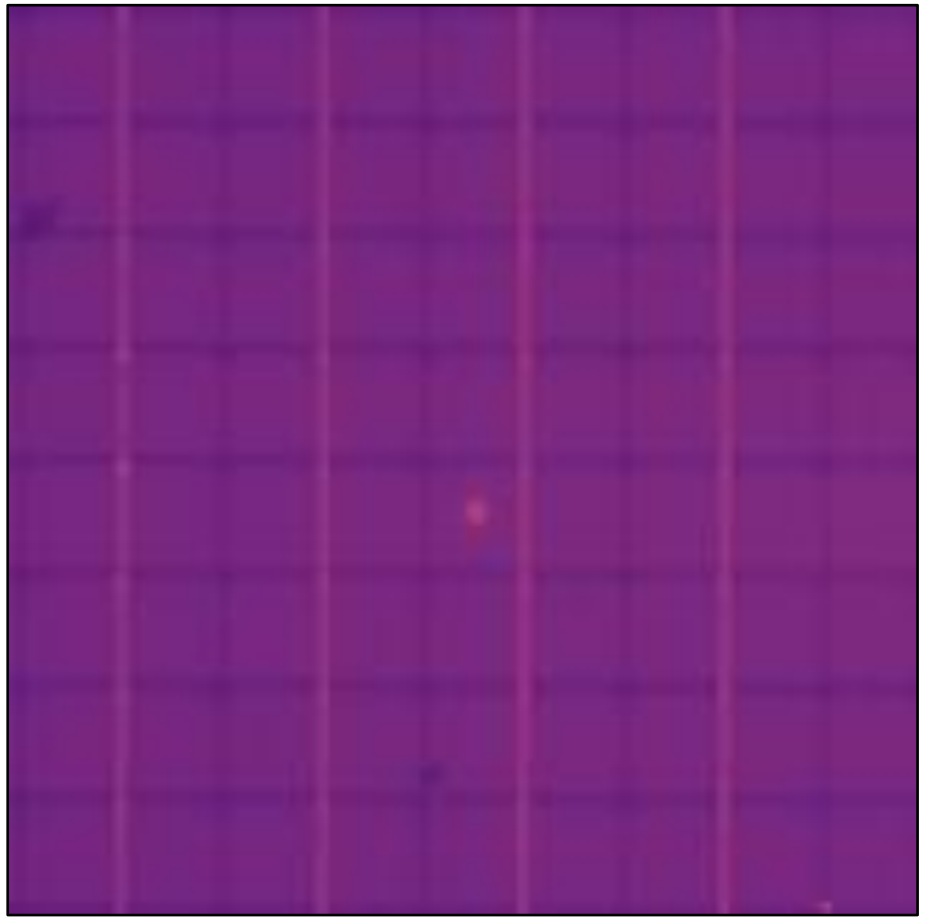


Technical detour: SPAD light emission

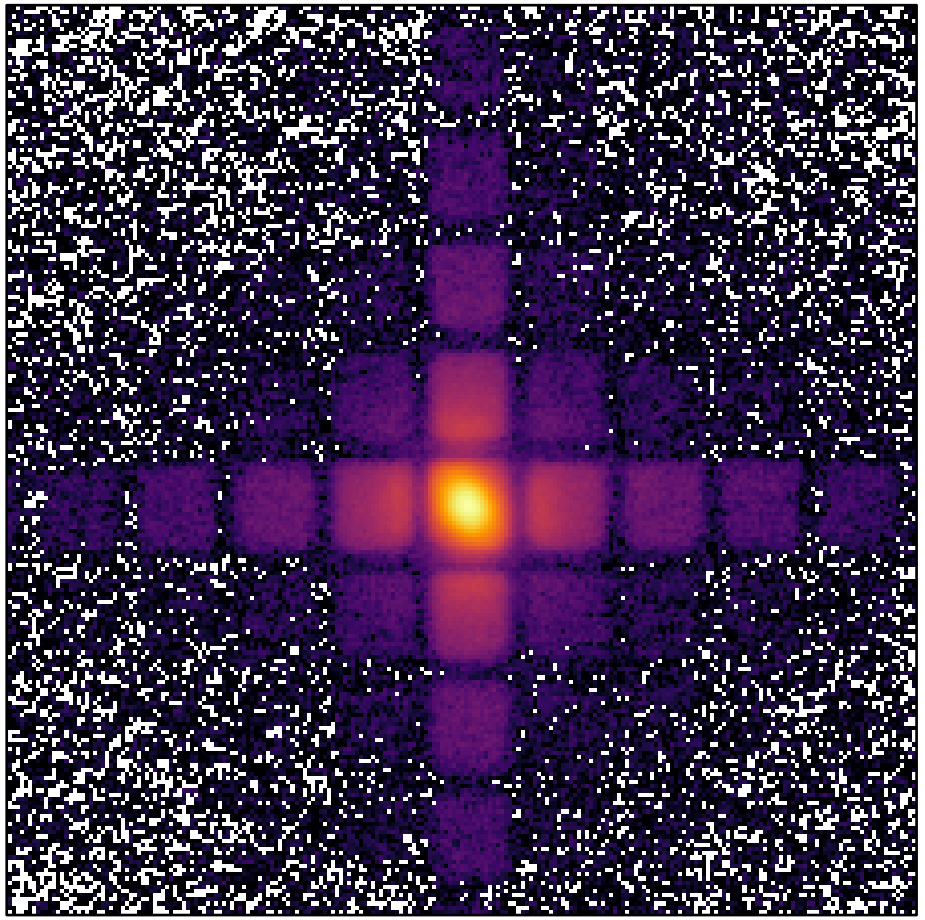
Imaging re-emitted light

FBK VUV-HD3

Reflected light

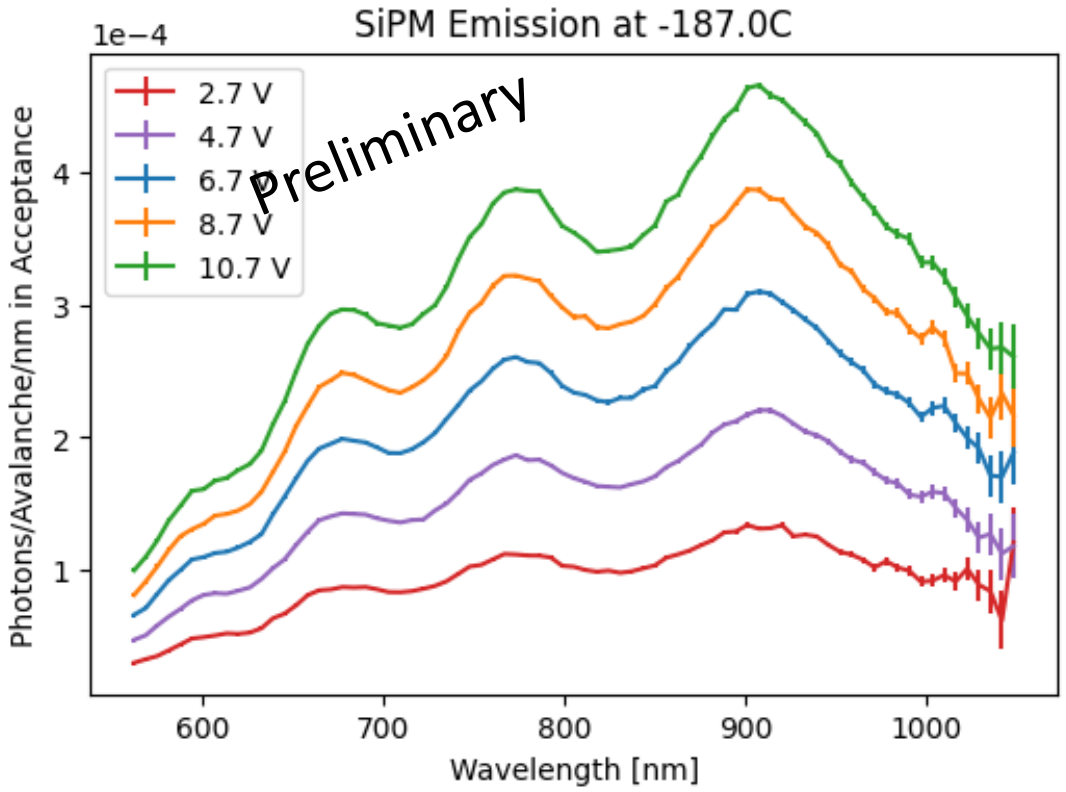


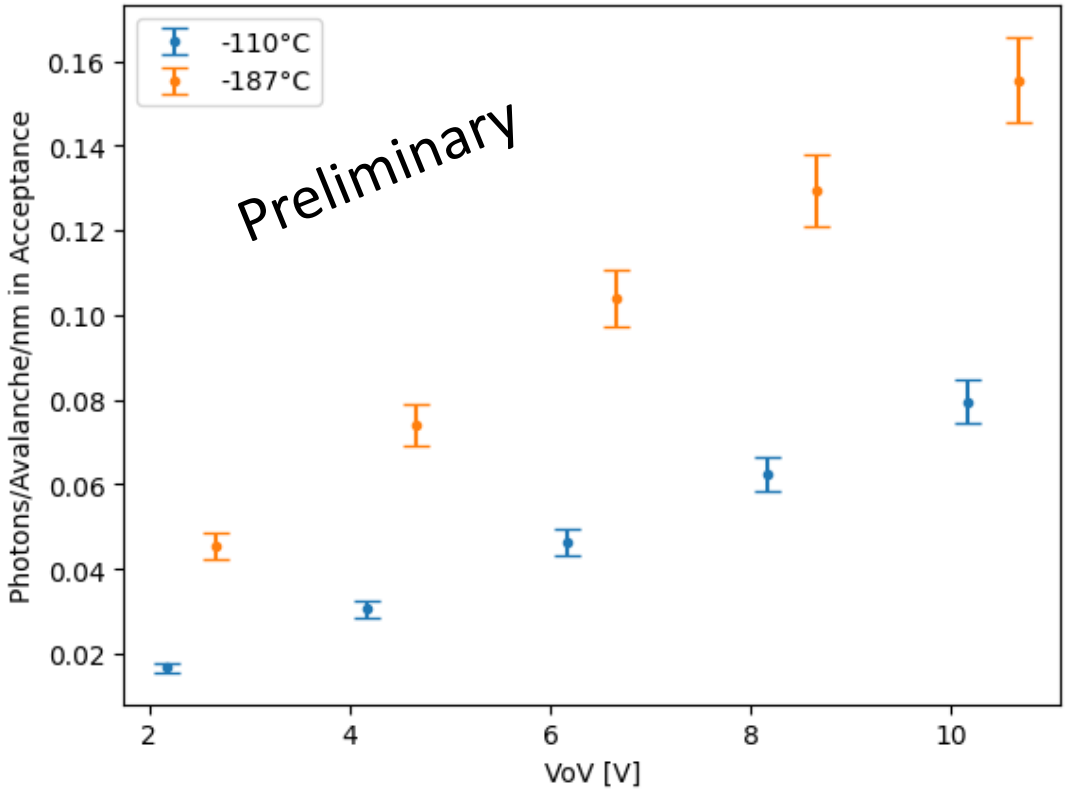
Re-emitted light



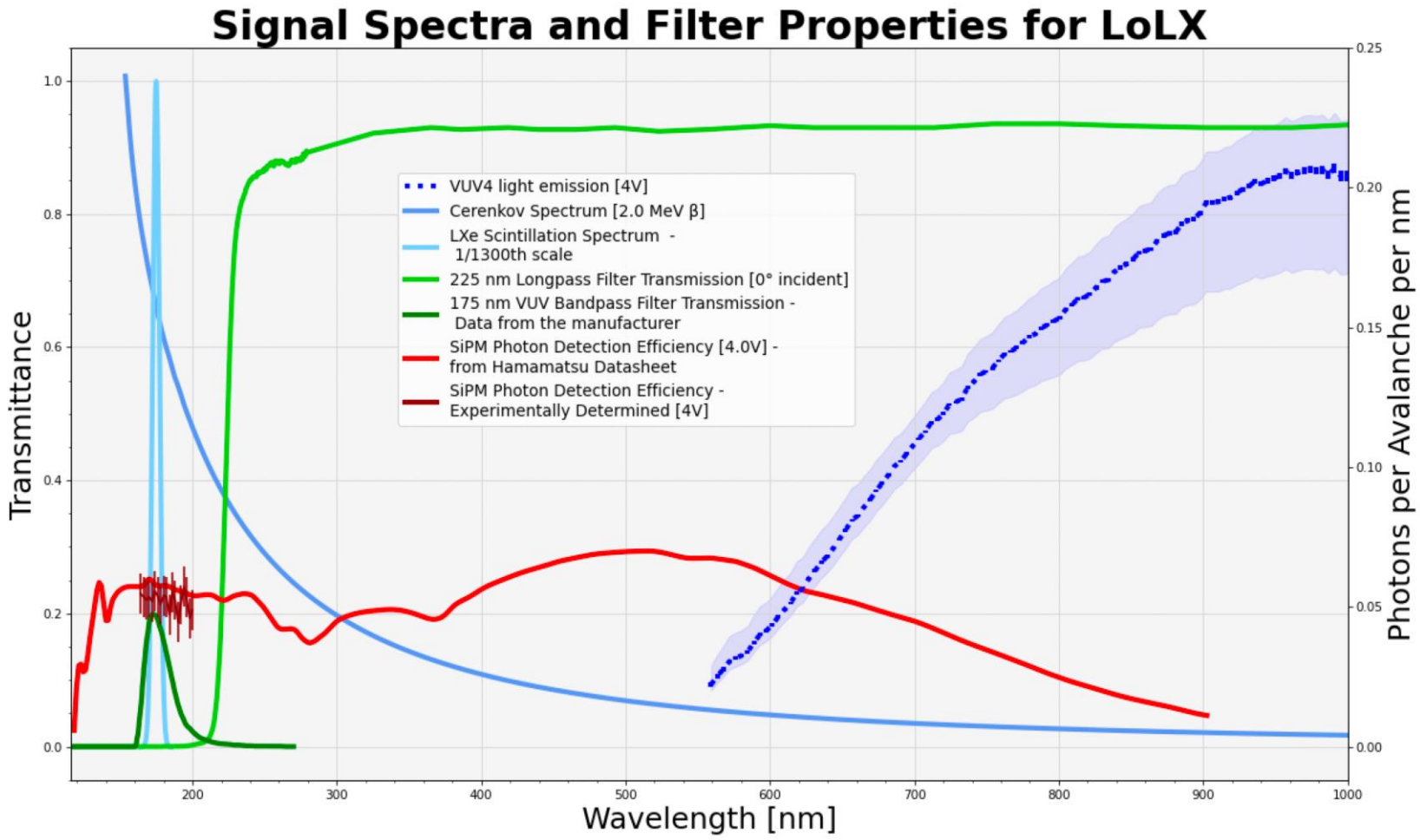
Spectra

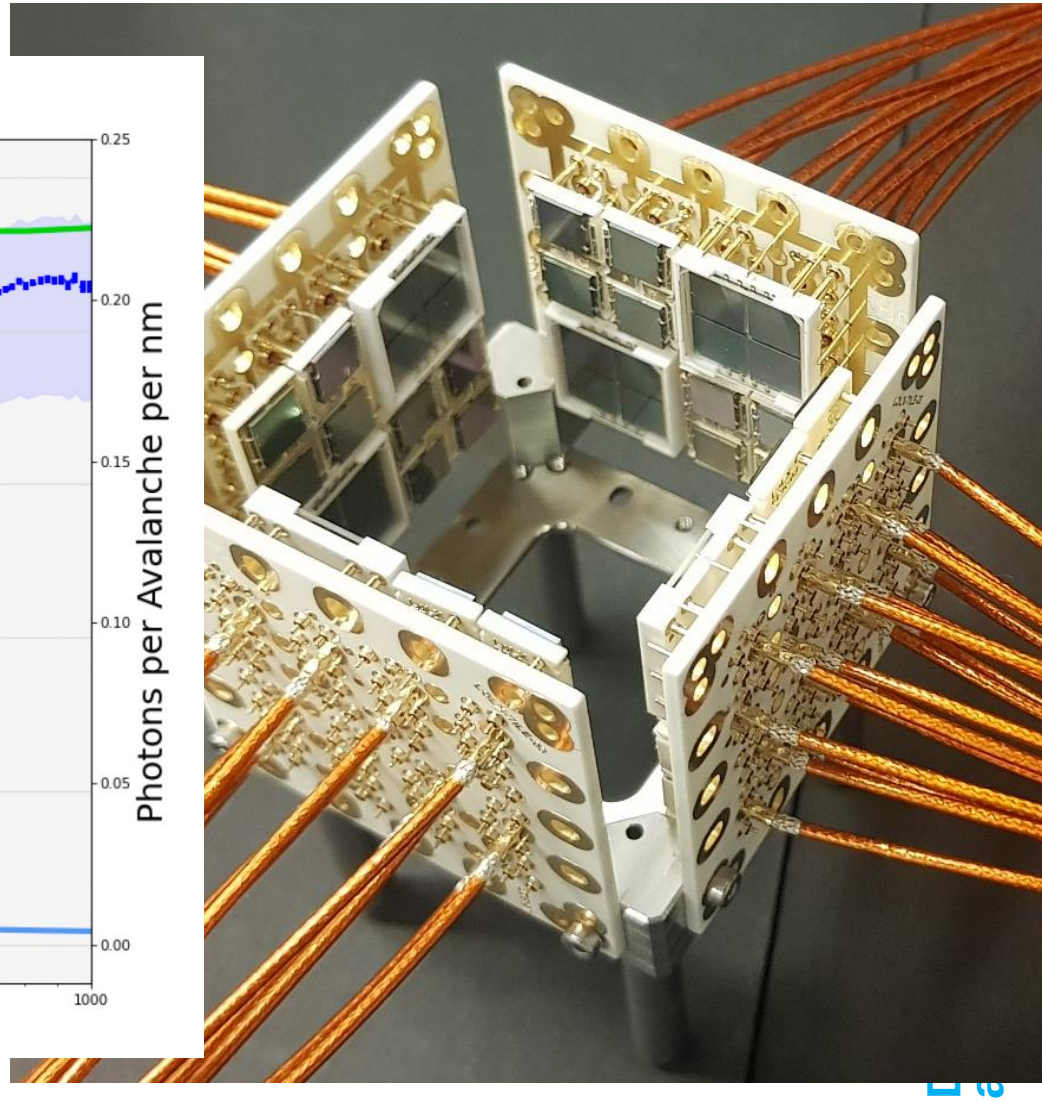
Acceptance:
Objective NA=0.45, i.e. $\theta < 26.7°$
Simulation shows that acceptance is about 10% of total



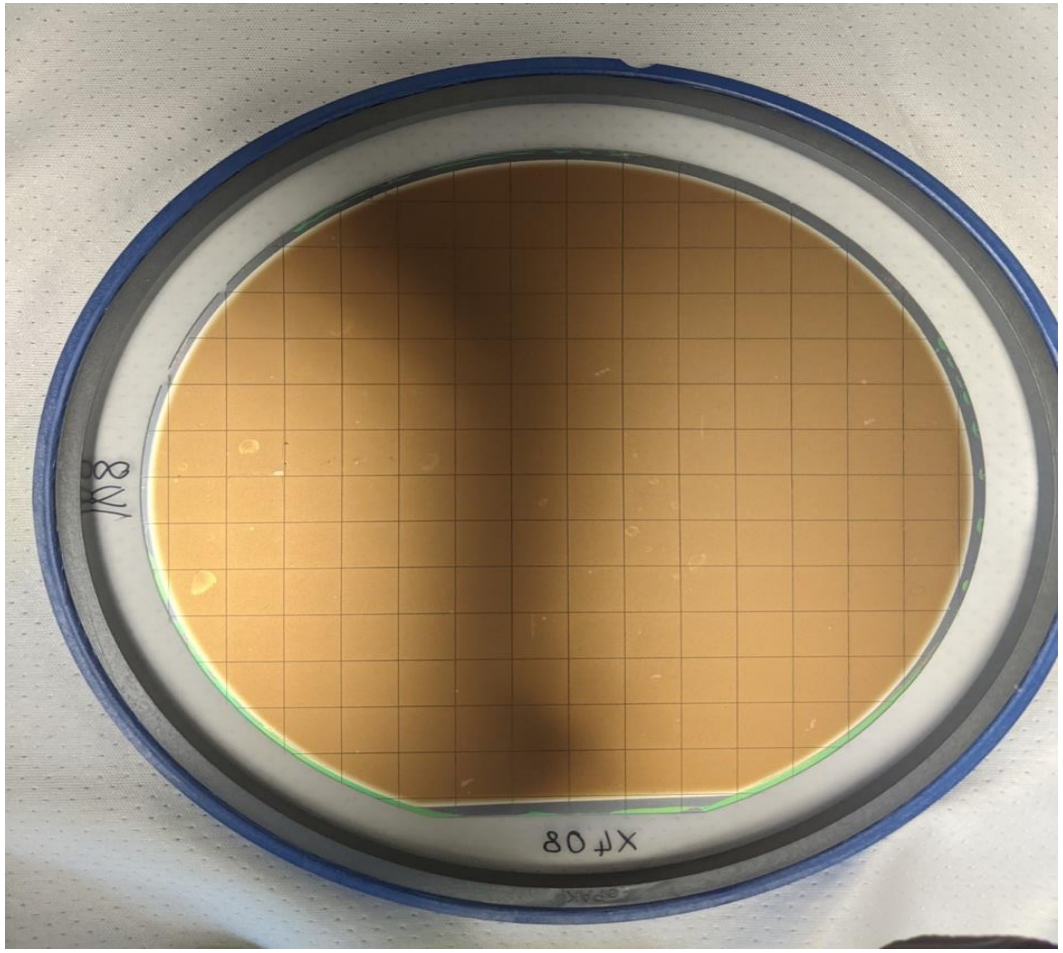


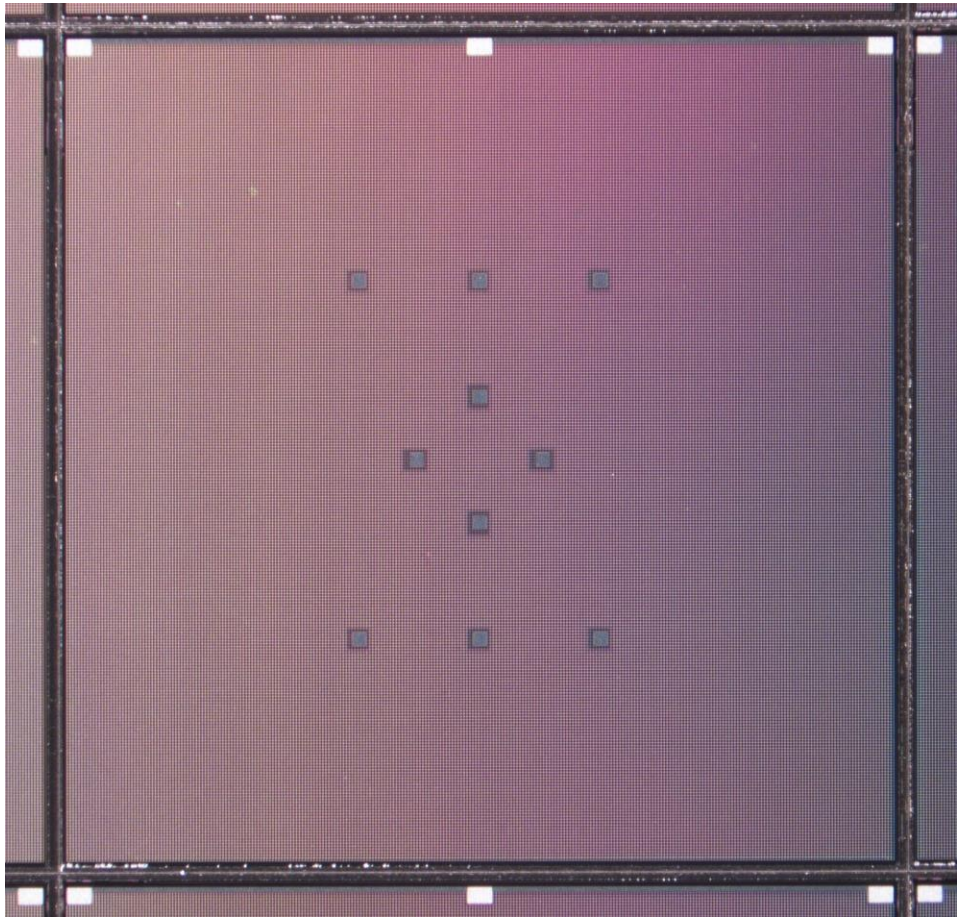
All processes in Lxe probed by the light only liquid Xenon experiment





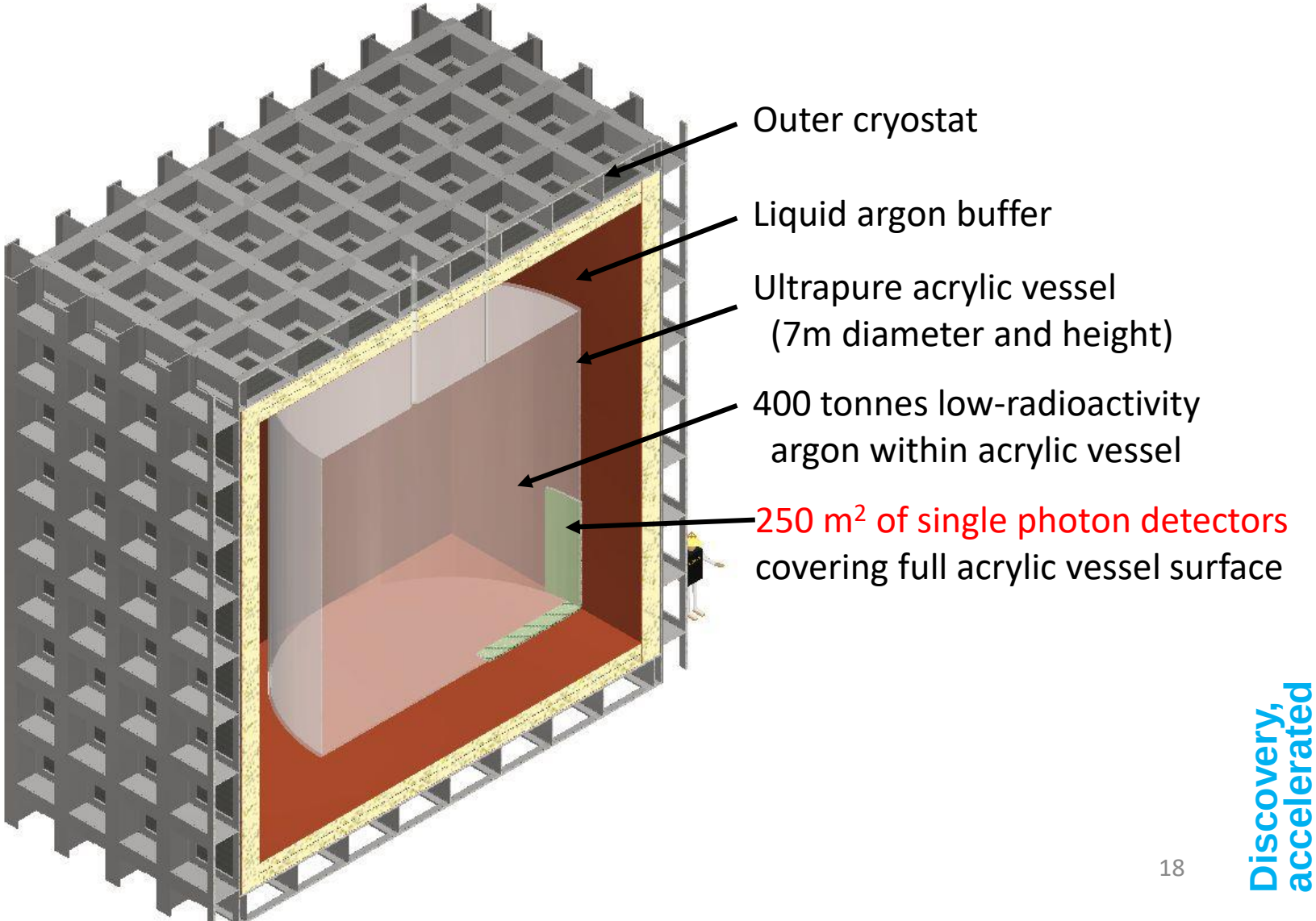
New FBK production for nEXO and SBC 1x1cm2 but most SiPMs don't work…





ARGO beyond DarkSide-20k

- 300 tons of LAr
- R&D ongoing
- Key challenge is light readout over huge area
- Foreseen at SNOLAB in the 2030s era



ARGO photon detection requirements

	DarkSide-20k	ARGO minimum	ARGO desirable
Surface Area	40 m^2	250 m^2	250 m^2
Efficiency at 420 nm	>40%	>50%	>60%
Efficiency at 128 nm	0	0	>20%
Dark noise rate at 86K	< 1kHz/m^2	< 1kHz/m^2	< 0.1kHz/m^2
Correlated prompt avalanche (cross-talk)	<50%	<50%	<10%
Correlated delayed avalanche (after pulsing)	<5%	<5%	<1%
External cross-talk	Unknown	<50%	<10%
Single Photon Timing resolution	20ns	1ns	0.1ns
Granularity	25cm^2	1 m^2	10 cm^2
Radioactive content	Very low	Very low	Ultra low

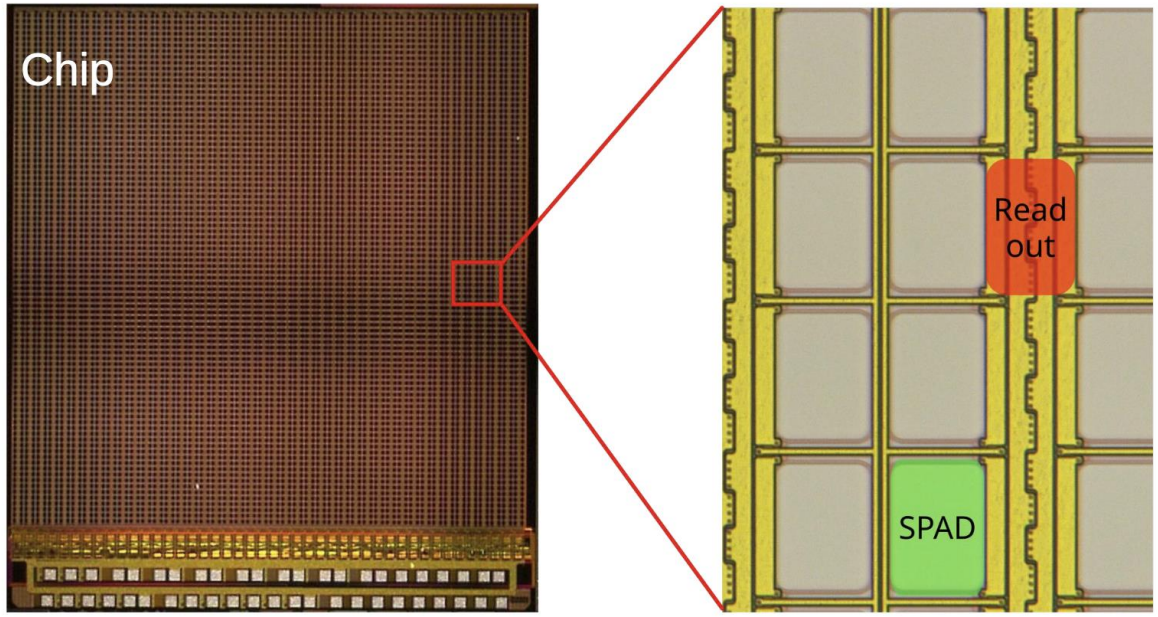
The future is digital!
2D SPAD @ Heidelberg

- 2D SPAD array designed by Heidelberg built by Fraunhofer IMS
- The good
  - Single chip doing everything
  - Dark noise rate of 0.02 Hz/mm^2
- The bad
  - Some loss of active area
  - No VUV sensitivity… yet

Digital SiPMs for DARWIN

Michael Keller, Peter Fischer, Robert Zimmermann, Michael Ritzert – University of Heidelberg

DARWIN Collaboration Meeting 2023 at University of Heidelberg

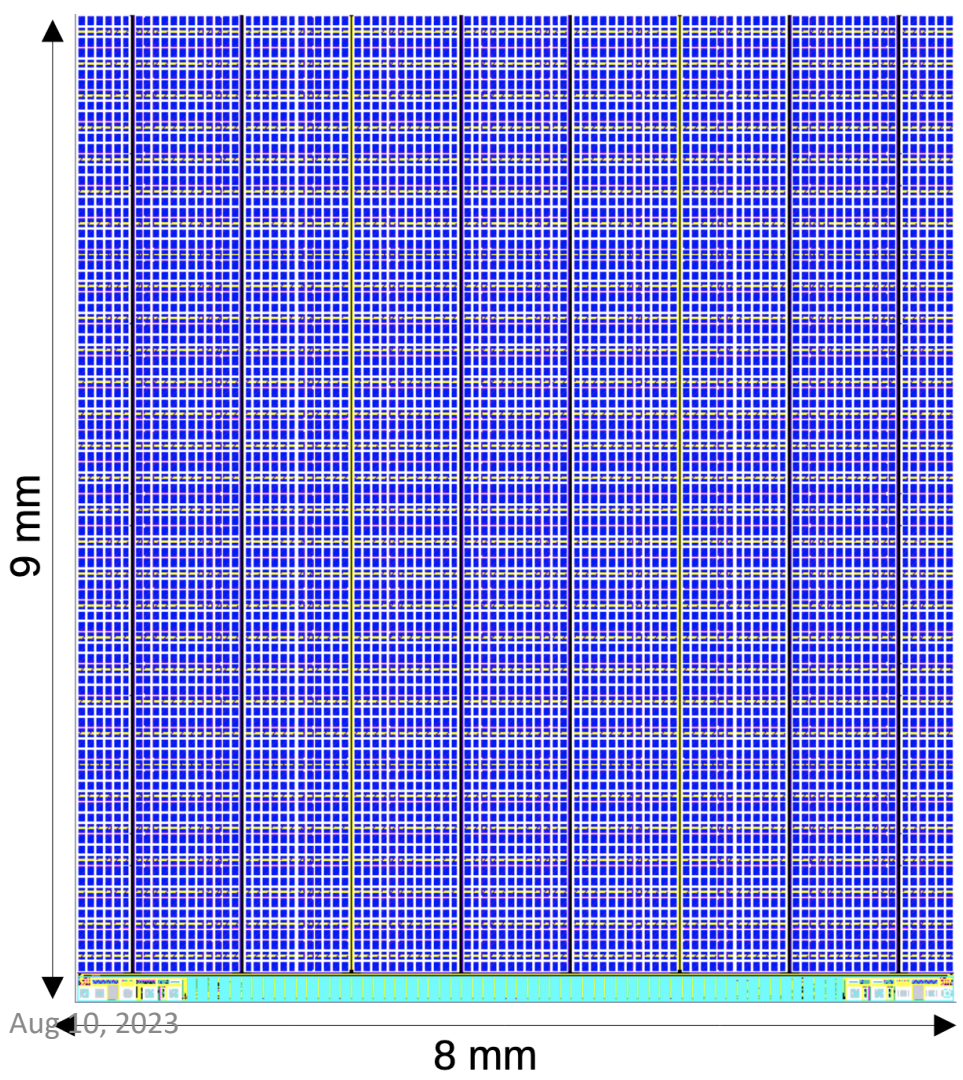


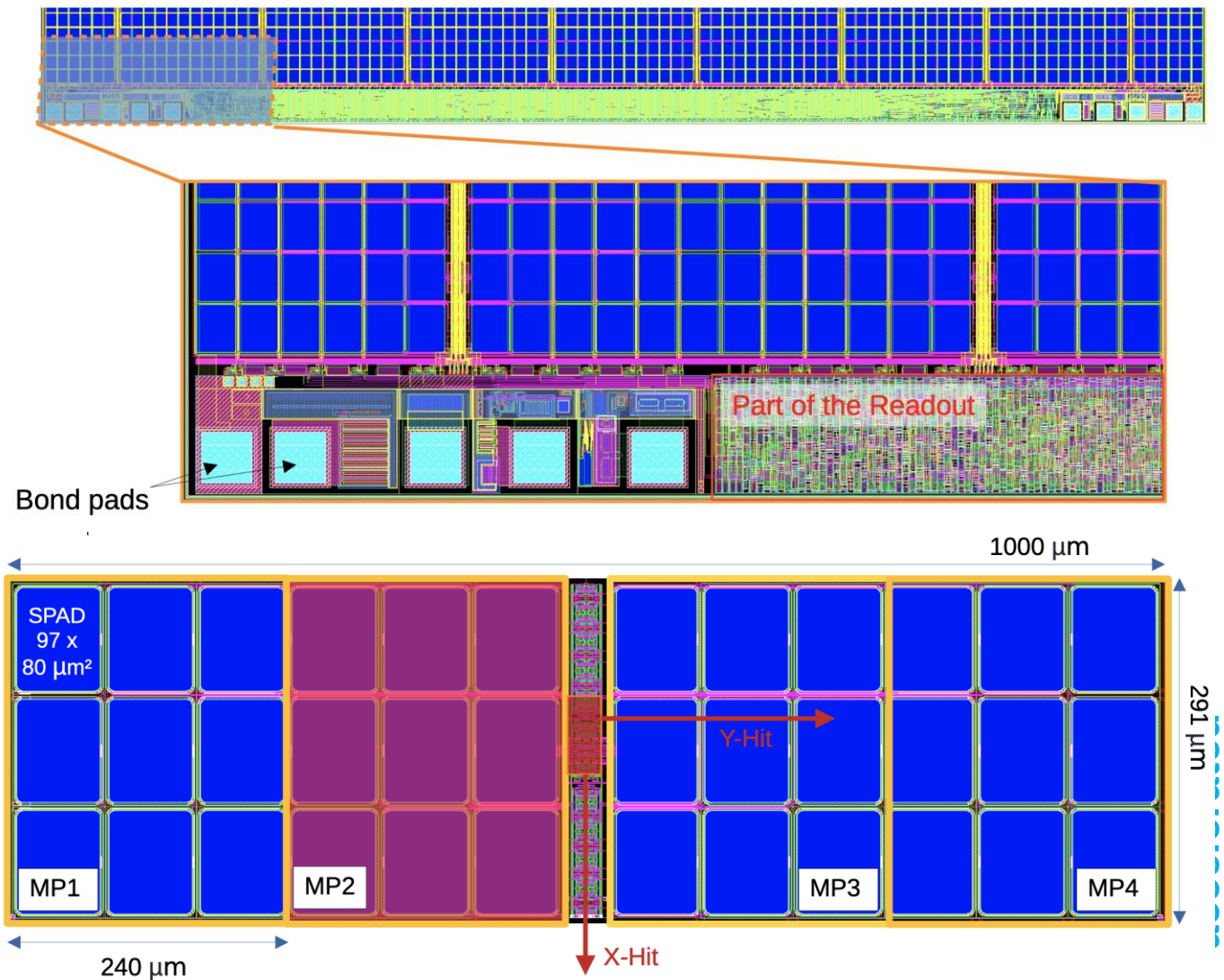
2D SPAD array for DARWIN

Digital SiPMs for DARWIN

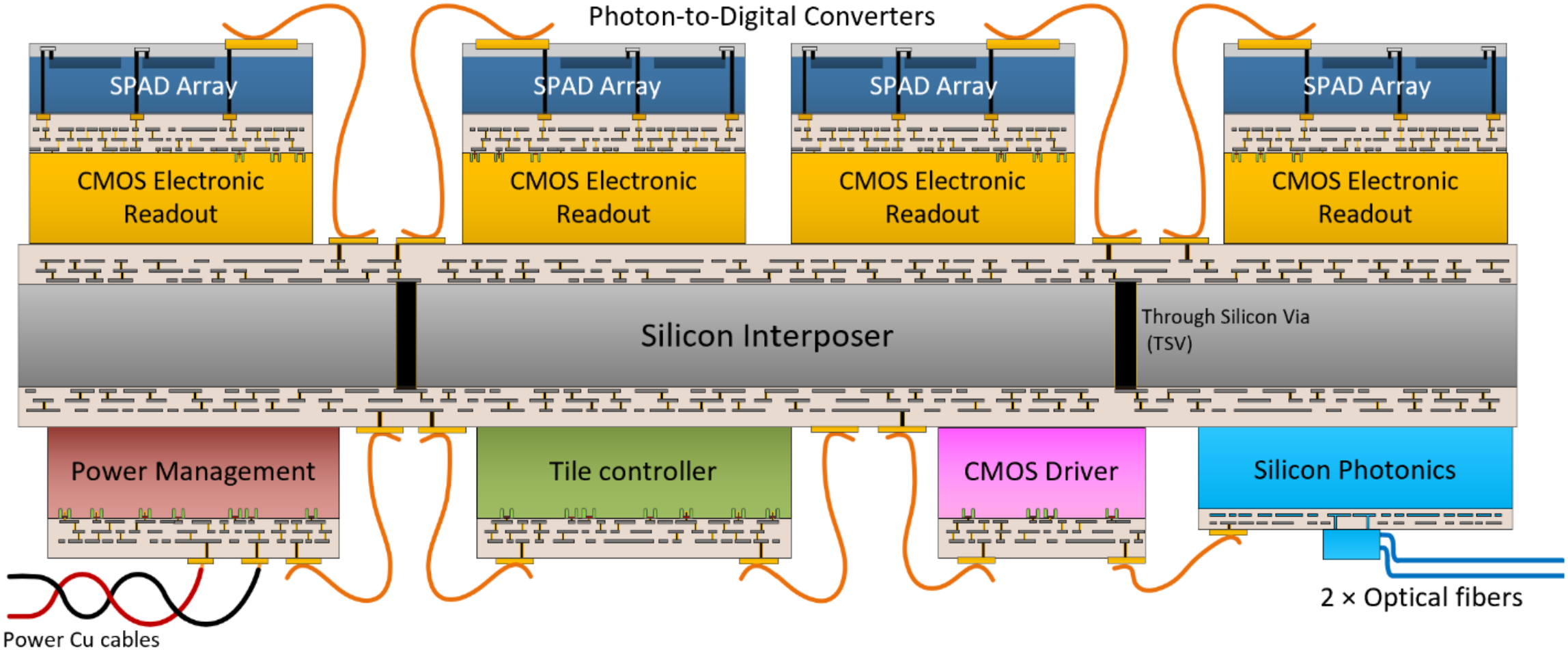
Michael Keller, Peter Fischer, Robert Zimmermann, Michael Ritzert – University of Heidelberg

DARWIN Collaboration Meeting 2023 at University of Heidelberg



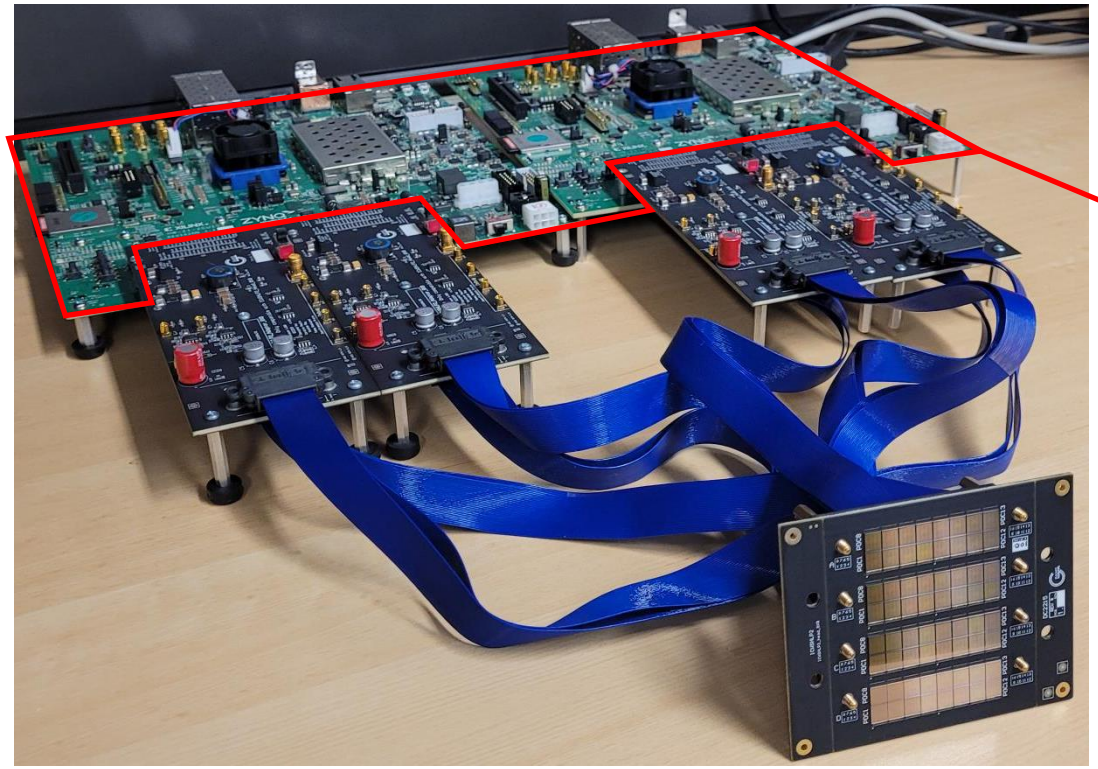


Photon to Digital Converter – Canadian tech.

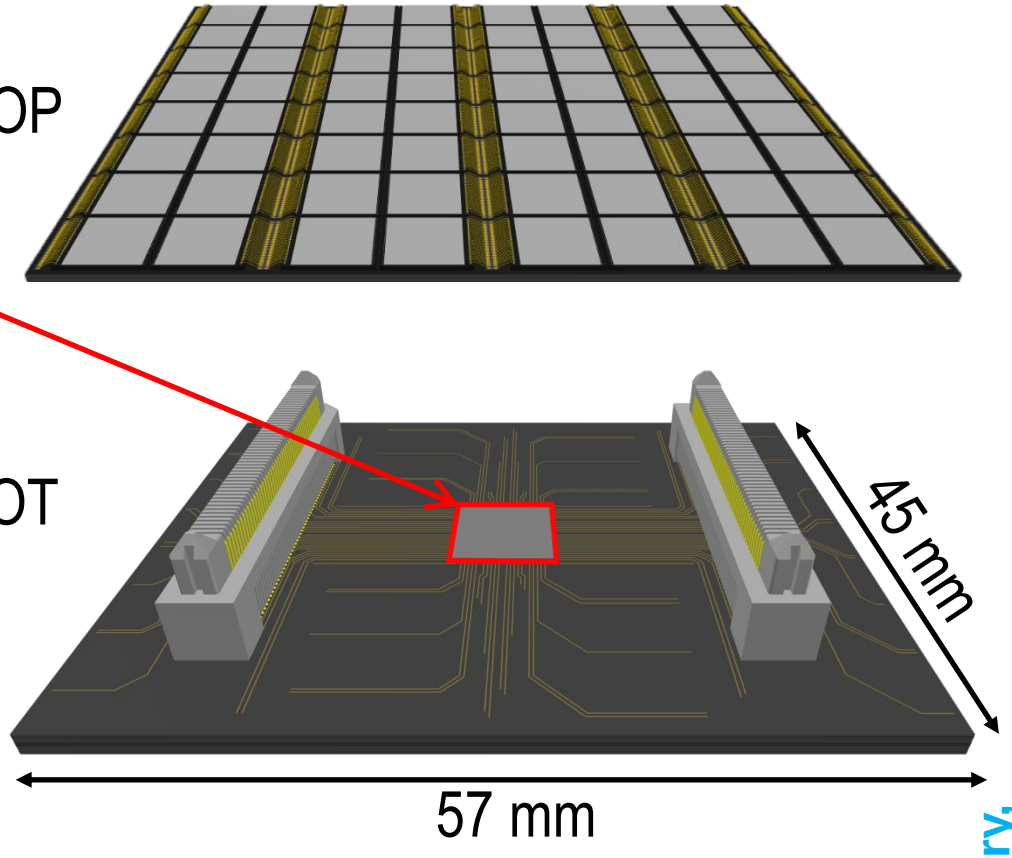


Current development state

FPGA-based Controller

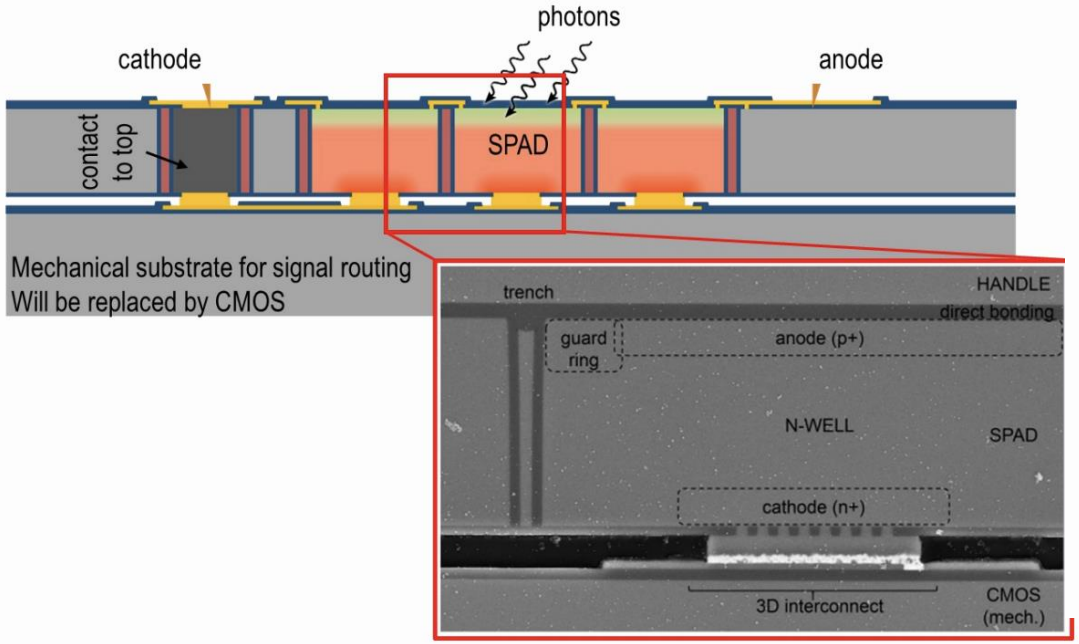


ASIC-based Controller

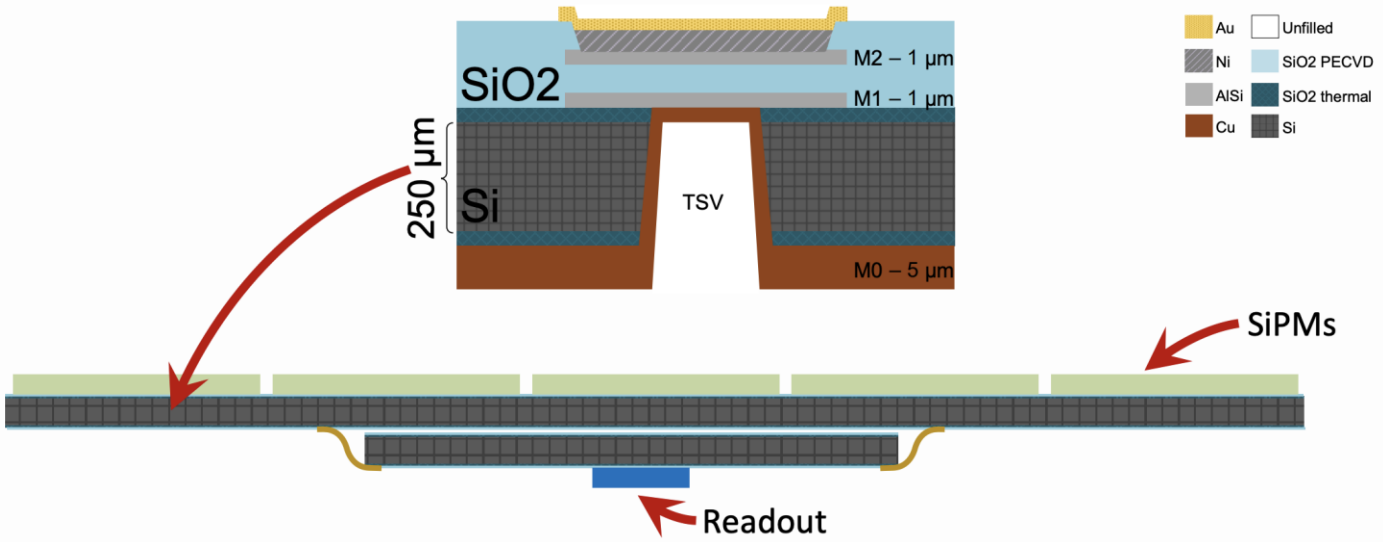


Prototyping progress by Sherbrooke's group

PDC 3D integration



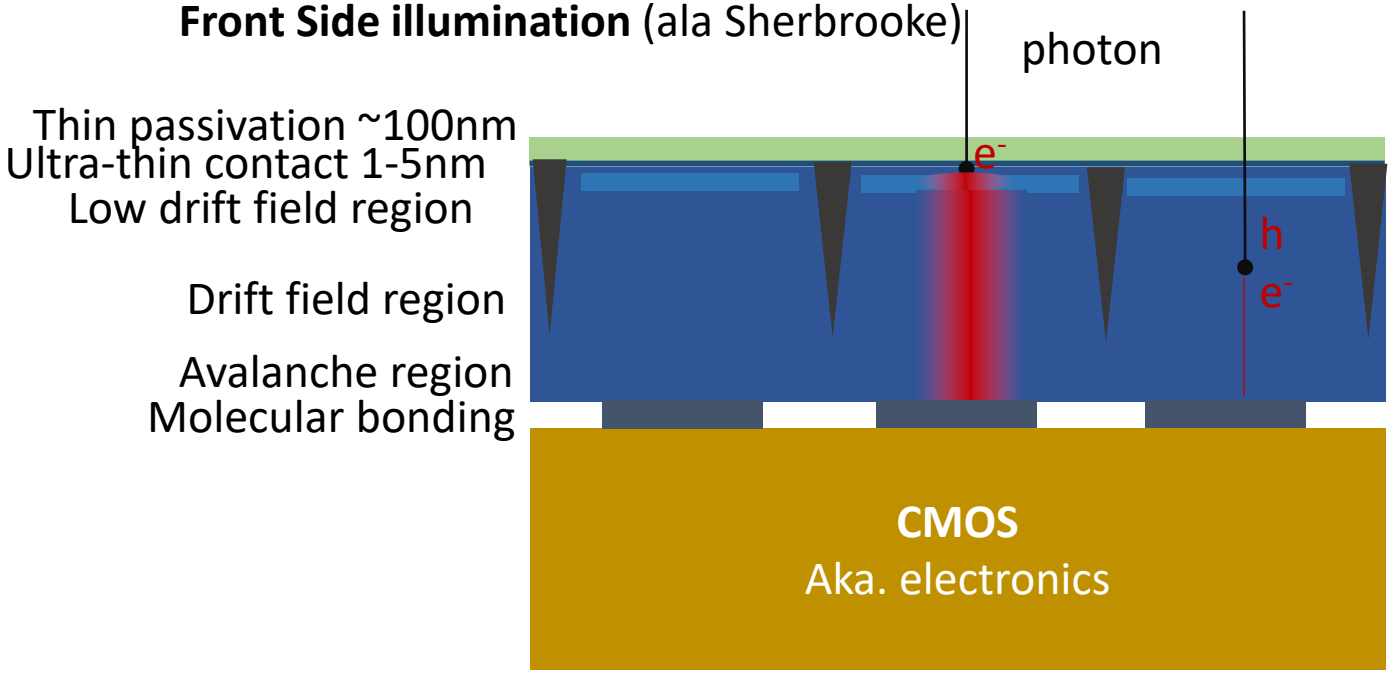
Silicon interposer



PDC ++?

- Front side: best for <500nm wavelength
  - Electron produced in high field region for optimum timing
  - Drawbacks: Efficiency, higher manufacturing complexity
- Back side illuminated: versatile
  - Adjust thickness for desired thickness
  - CMOS/CCD BSI sensors are now common

Front Side illumination (ala Sherbrooke)



Back side illumination

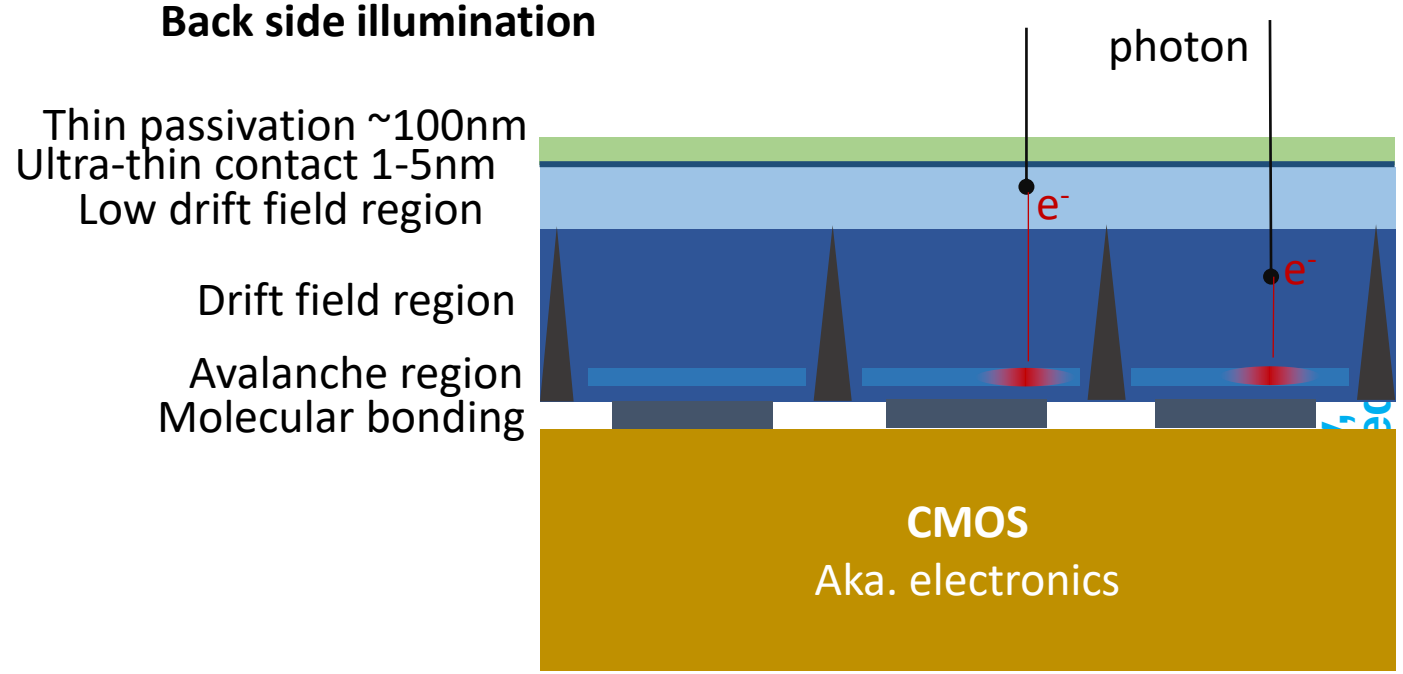


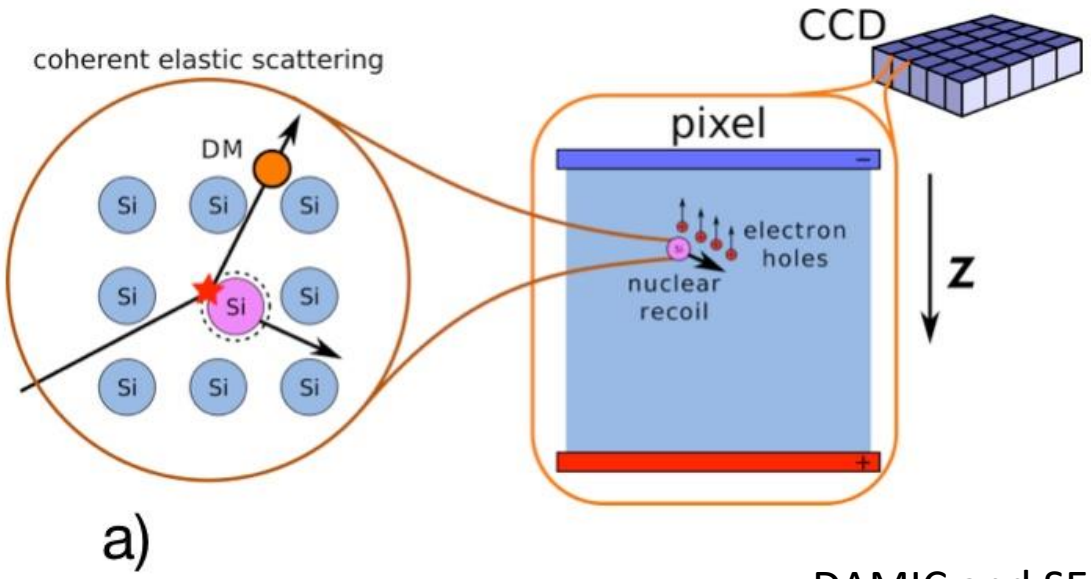
Photo-detector performance comparison

Issue to scale up to 1cm^2. Impacting SBC and nEXO

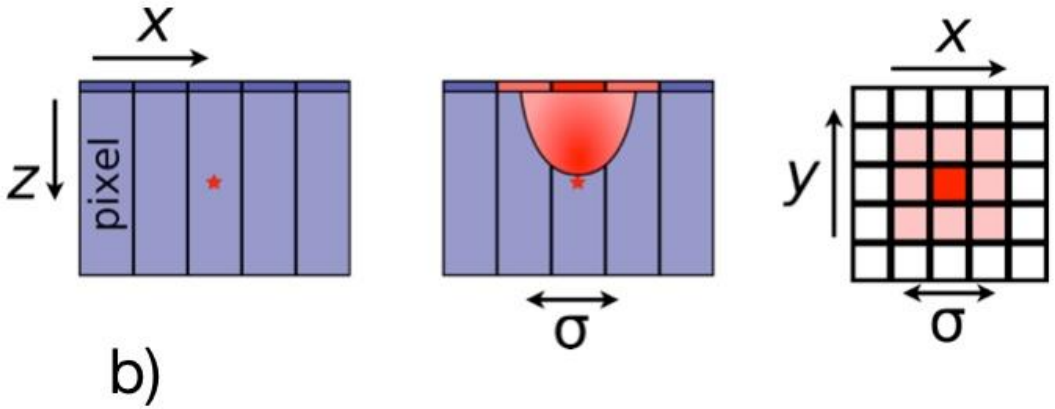
Parameters at LXe temperature for cm^2 scale channel size	Hamamatsu PMT[a]	FBK family [b]	Hamamatsu family[b]	Heidelberg 2D SPAD array	Sherbrooke 3D SPAD array
Efficiency at 128nm (LAr)	0%	%	10%	0	0
Efficiency at 175nm (Lxe)	34%	24.4±1.4%→?	20.5±1.1%→?	0→25%→?	0→25%→?
Efficiency at 420nm	35%	60%	50%	50%	15%→?
Single avalanche charge resolution	25%	5%[c]	5%[d]	N/A	N/A
Dark noise rate (Hz/cm^2) in LXe	0.23 ± 0.07	19 ± 1	35 ± 1	2	1000
# correlated avalanche in 1 μs	0.02 ± 0.005	0.23 ± 0.06	0.06 ± 0.02	AP=0, XT=?	AP=0, XT=?
# Photons emitted per avalanche	N/A	1 ± 0.5	1 ± 0.5	?	?
Single photon timing resolution	3.9 ± 0.6ns	~10 ns[c]	~100 ns[d]	100ps	100ps
Radiopurity per active area	**~mBq/cm^2**	Medium [c]	< 10 nBq/cm^2 [d]	~nBq/cm^2	~nBq/cm^2
Power consumption in LXe	0.13 mW/cm^2	2 mW/cm^2 [c]	2 mW/cm^2 [d]	< 1mW/cm^2	< 1mW/cm^2

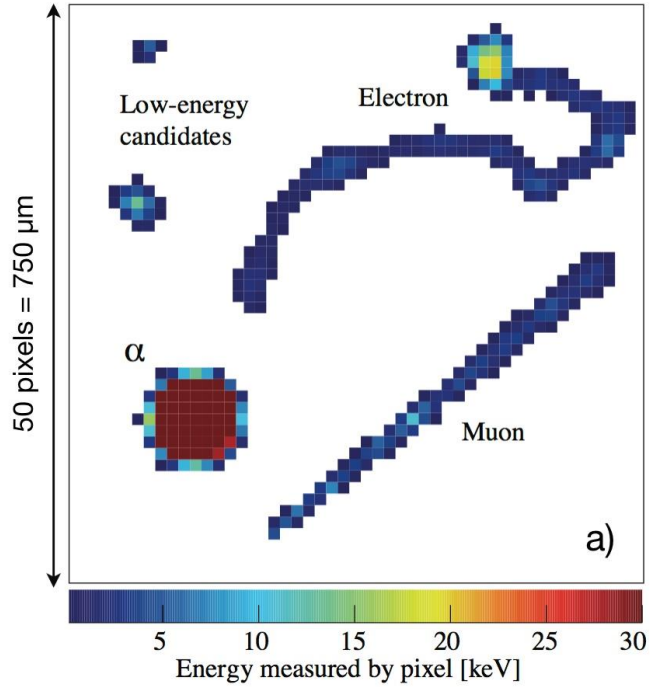
[a] Massaged from P. Barrow et al., https://arxiv.org/pdf/1609.01654.pdf
[b] G.Gallina et al., https://arxiv.org/pdf/2209.07765.pdf
[c] DarkSide-20k readout scheme for 25cm^2 channel size
[d] nEXO readout scheme for 6cm^2 channel size (can be applied to FBK)

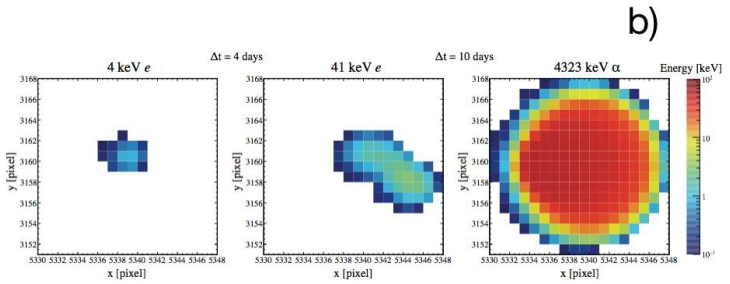
Dark matter search with CCD detour…



DAMIC and SENSEI experiments



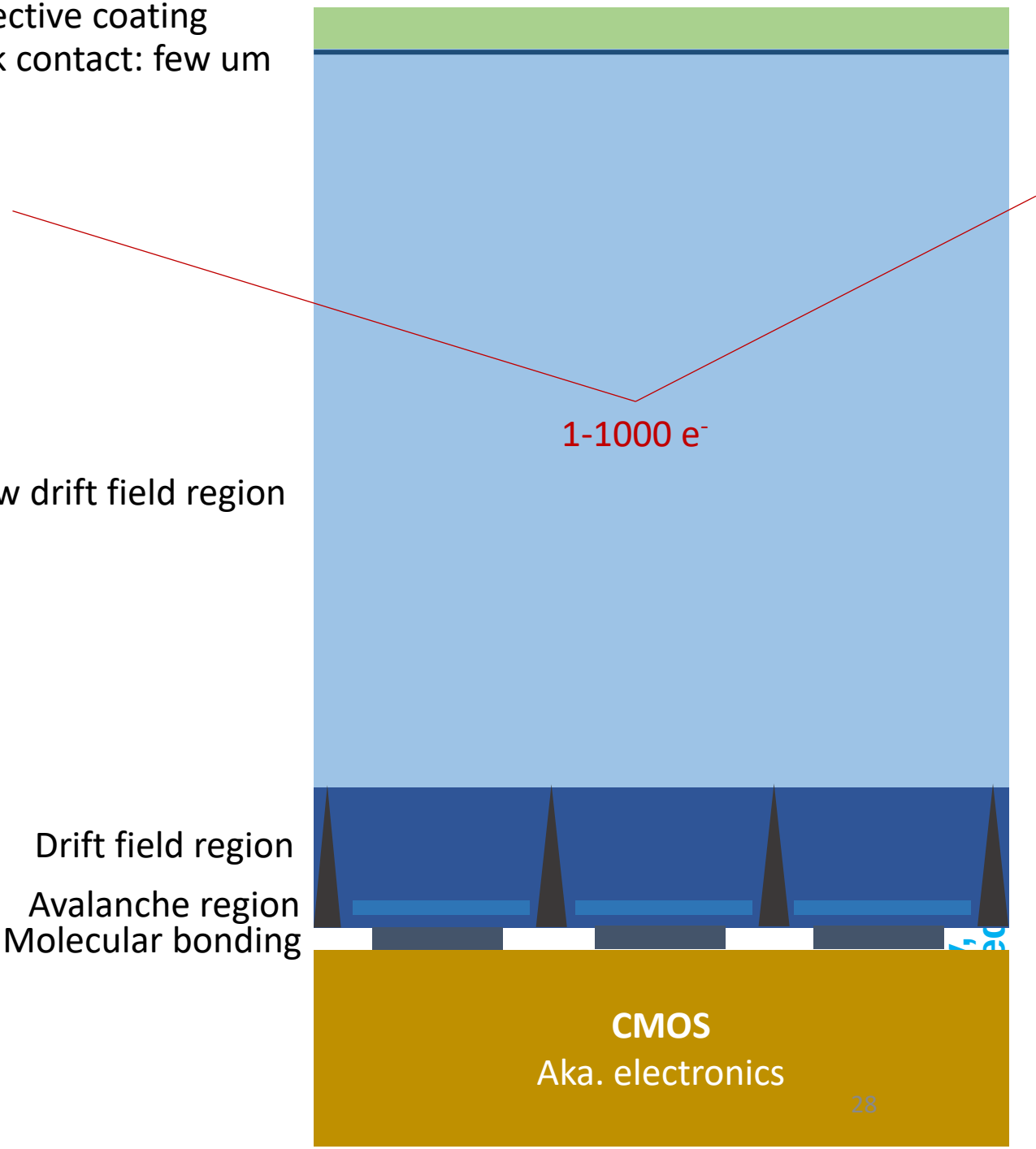




Discovery, accelerated

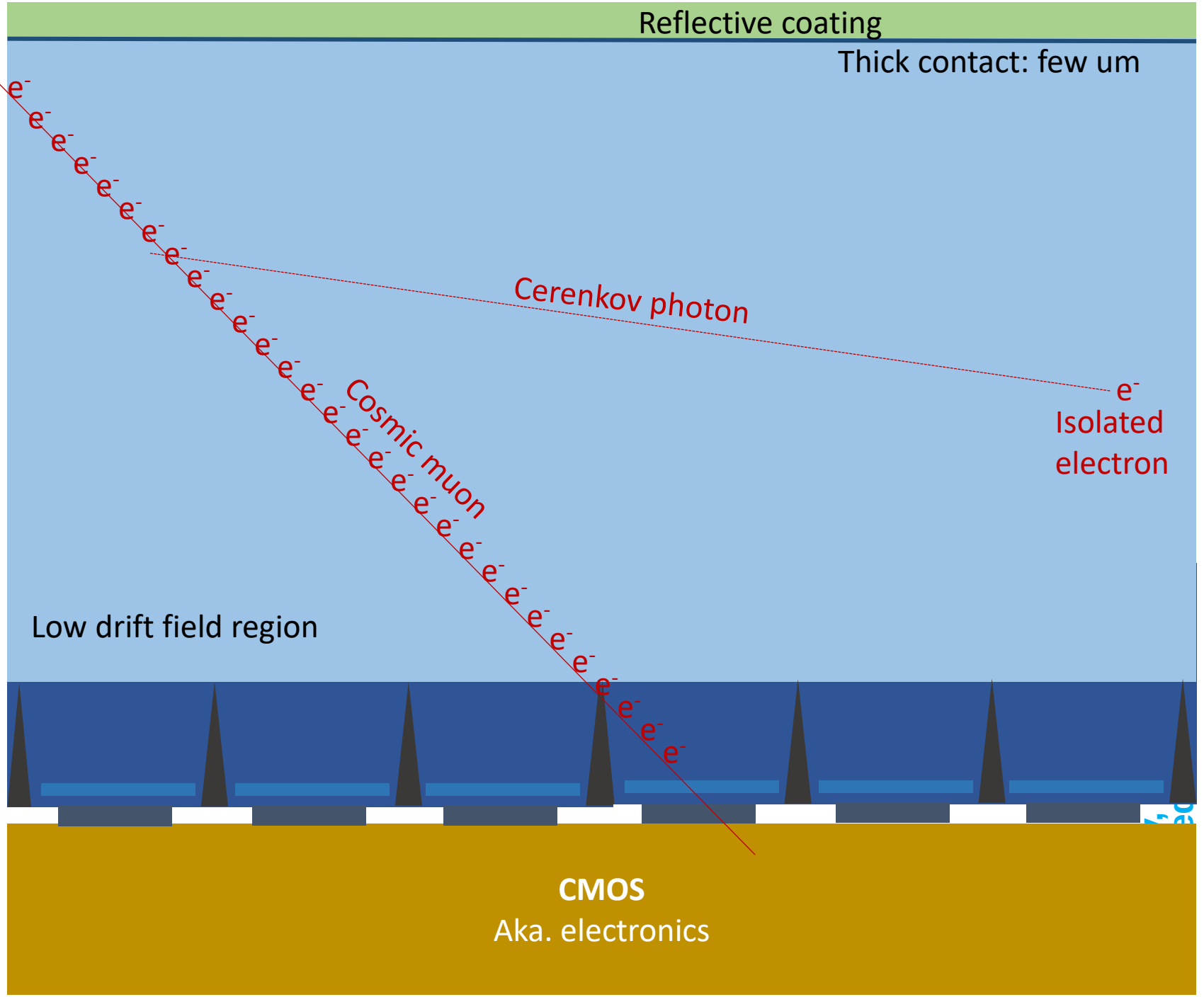
Direct DM search with avalanche diode

- Block external photons
- Using timing coincidence to reject background
  - May operate at shallow depth

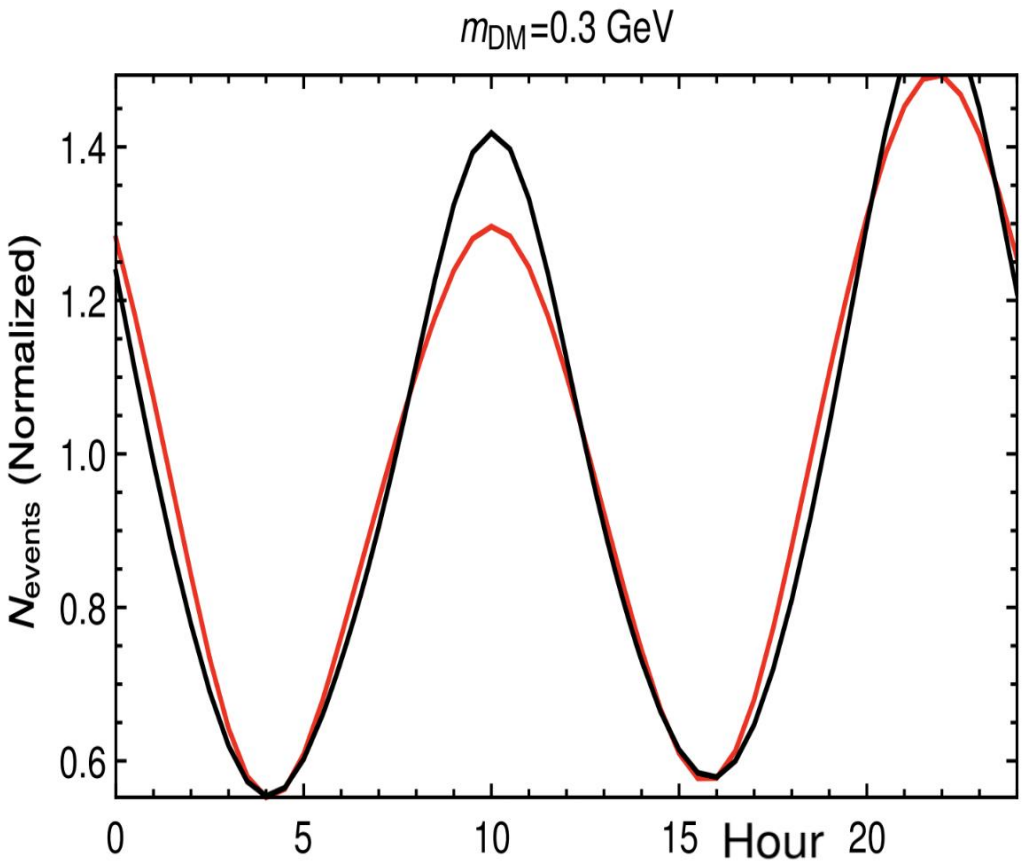


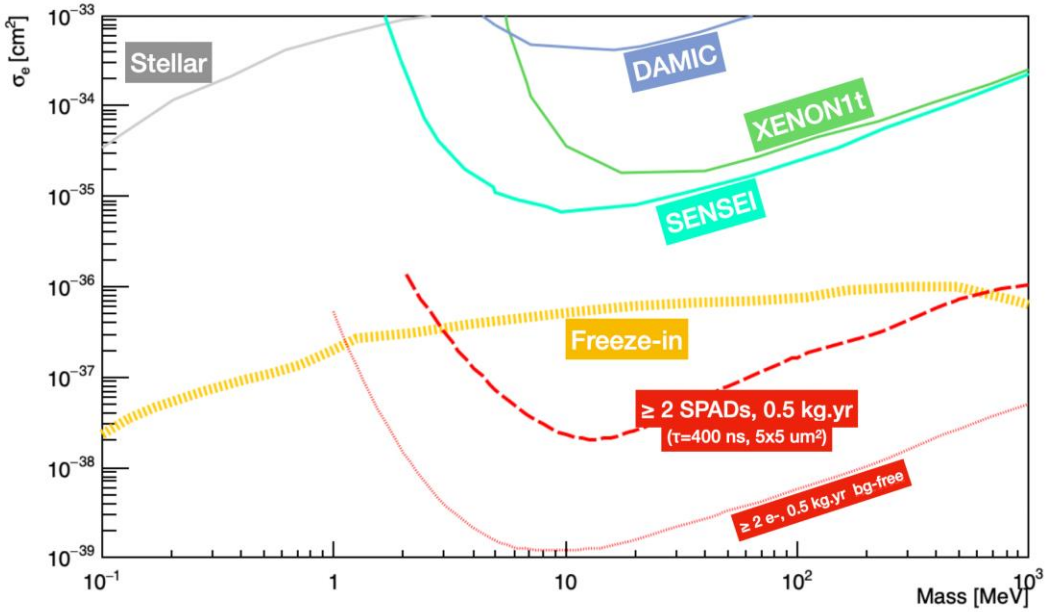
Adding timing

- CCD readout once every ~12h
- Avalanche diode coincidence: ns possible
- Remove correlated background



Performances expectations



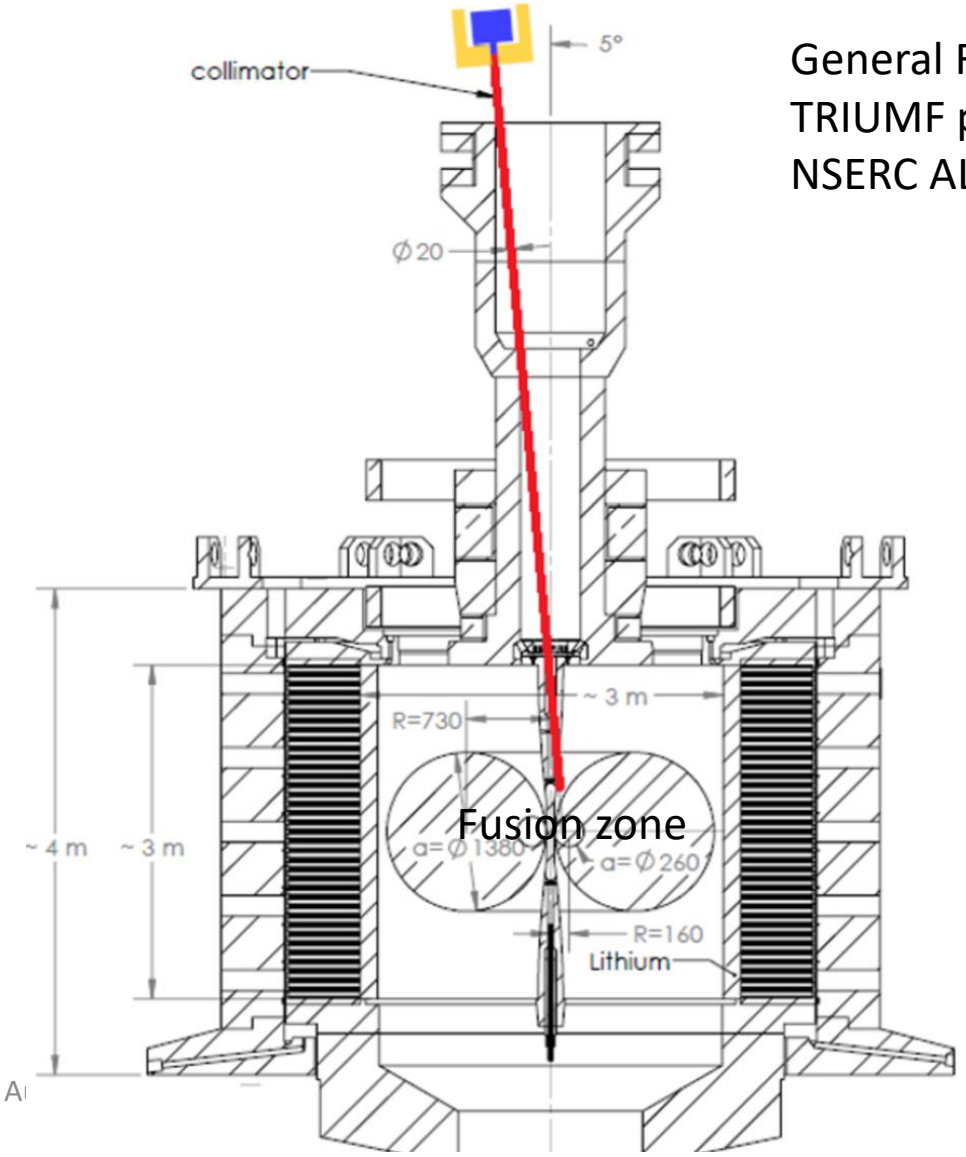


Work done by GSSI (Agnes) and RHUL (Monroe)'s group

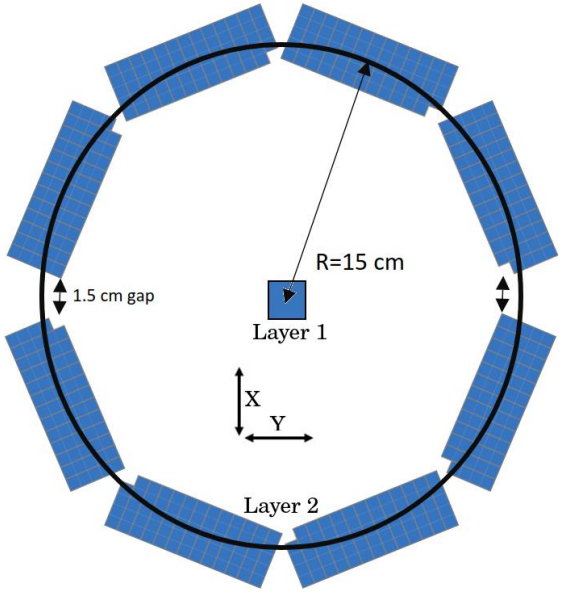
Beyond Dark Matter search

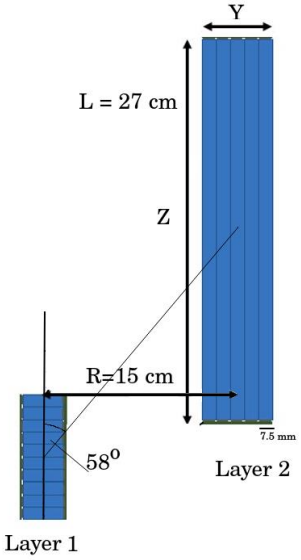
Aug 10, 2023

Supporting General Fusion



General Fusion is a company headquarter in Richmond BC
TRIUMF proposed a concept for neutron spectrometry
NSERC ALLIANCE grant being written

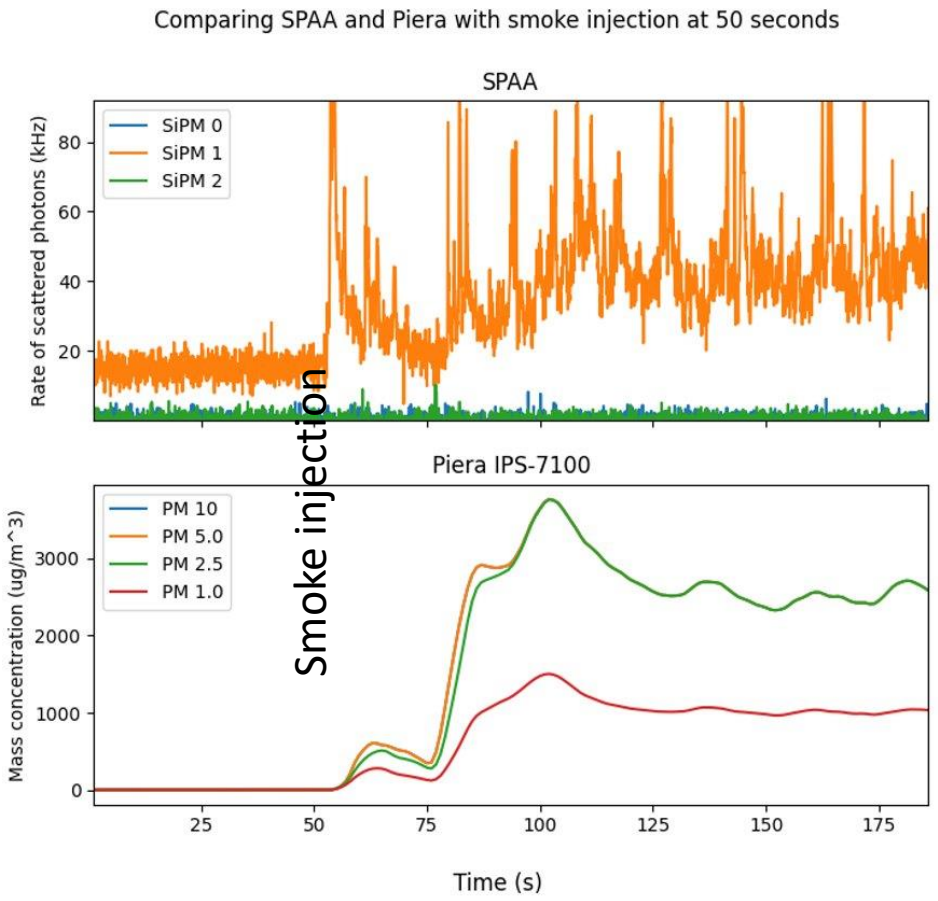




Neutrons

Discovery, accelerated

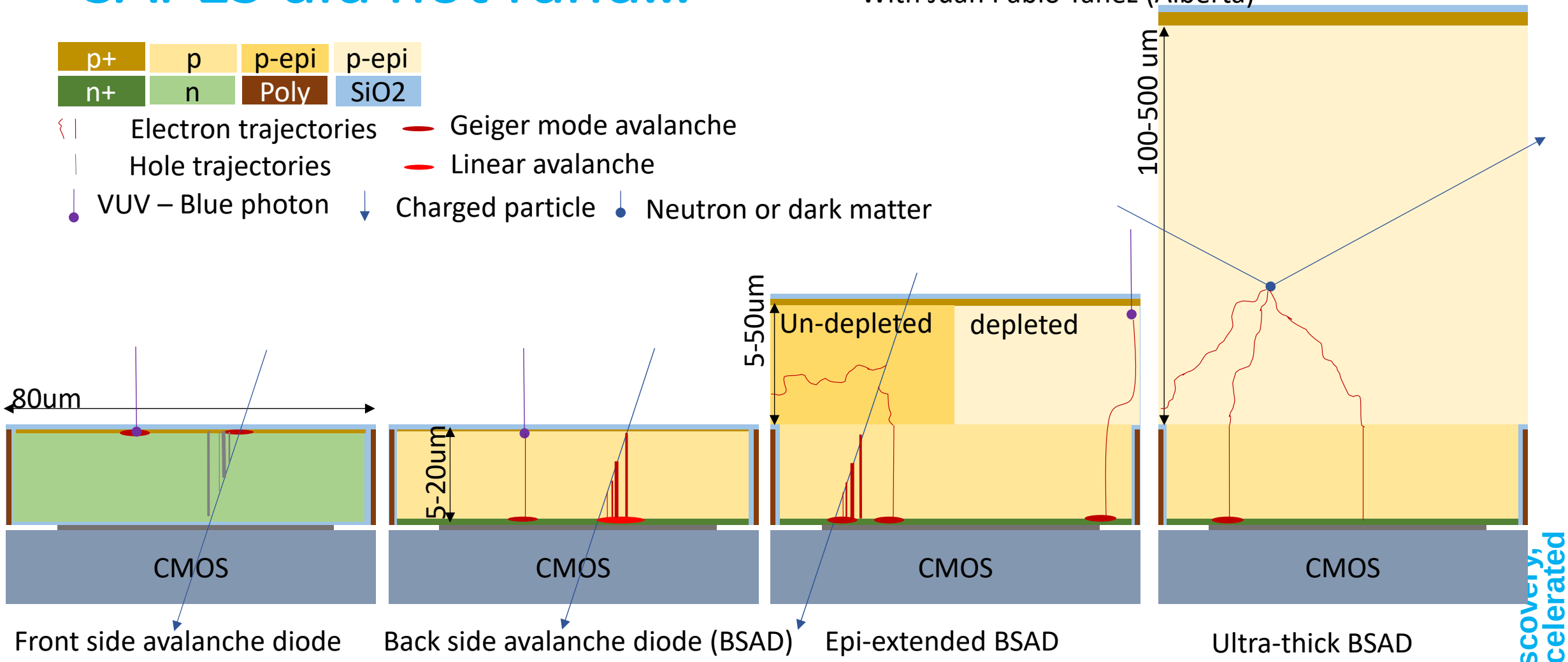
Working using SiPM to detect smoke



- Demonstrated over the summer 2022
- Photon counting is compelling
- New design coming. Easier to build

“Outlook” – the 3D integrated revolution that SAPES did not fund…

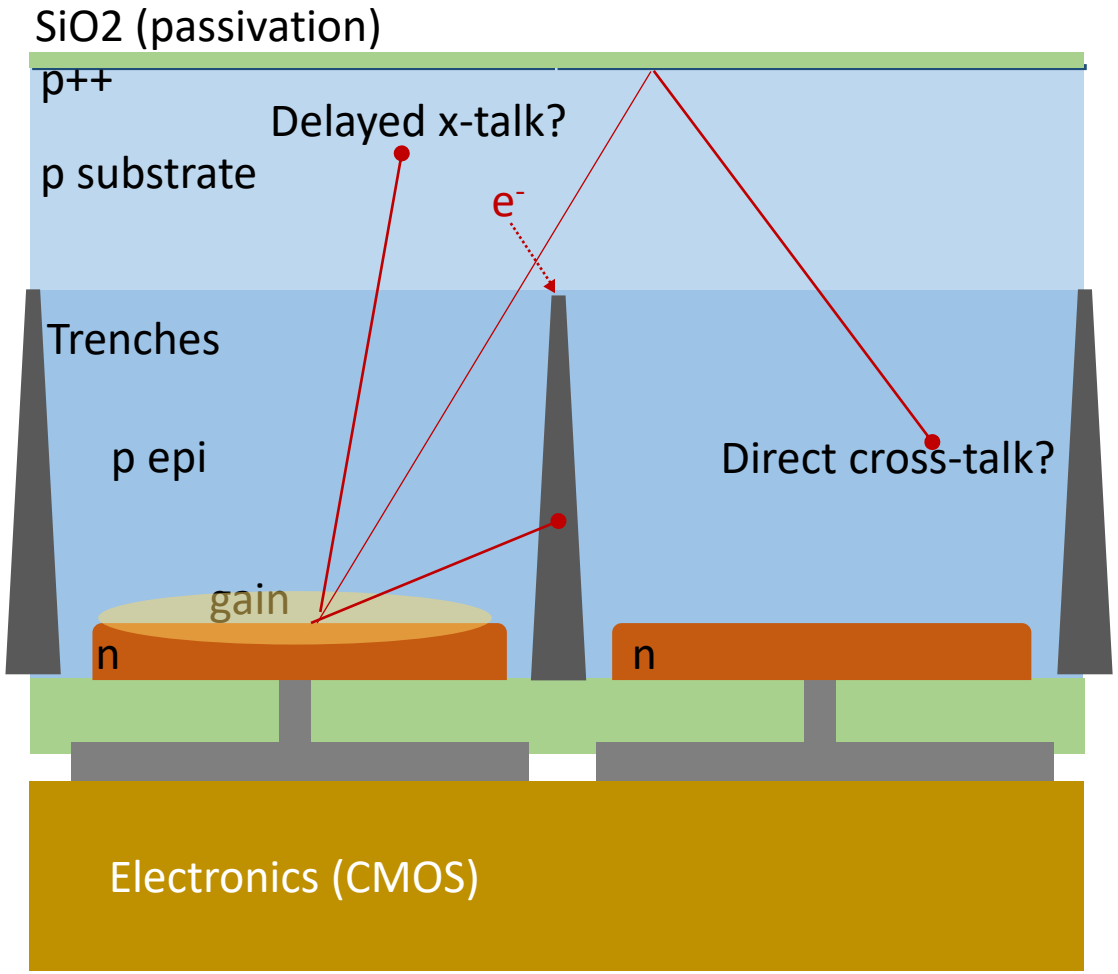
+ Digital Hybrid Photodetector
With Juan Pablo Yanez (Alberta)



Discovery, accelerated

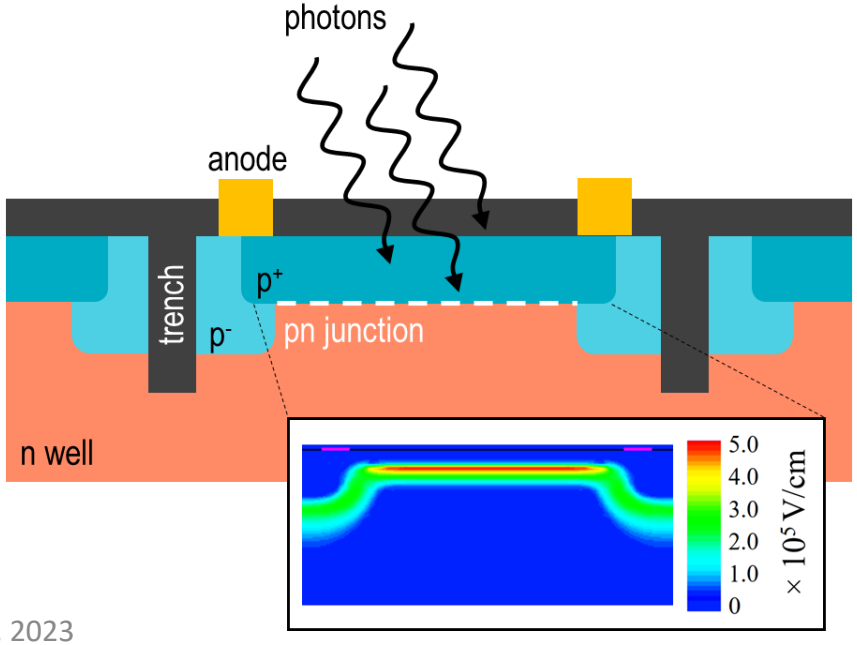
The end

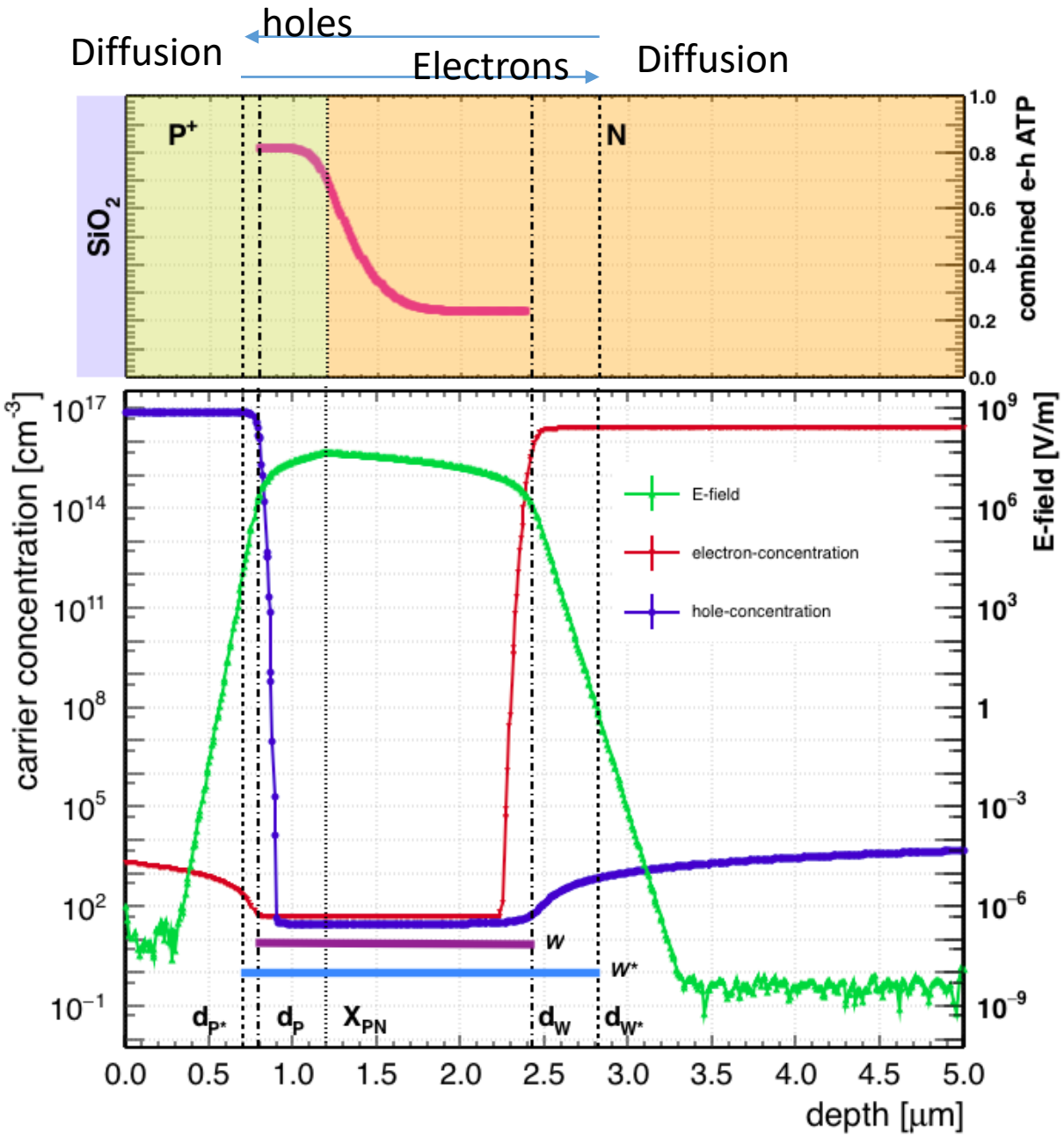
Back-side conceptual issue: light emission?



Triggering an avalanche

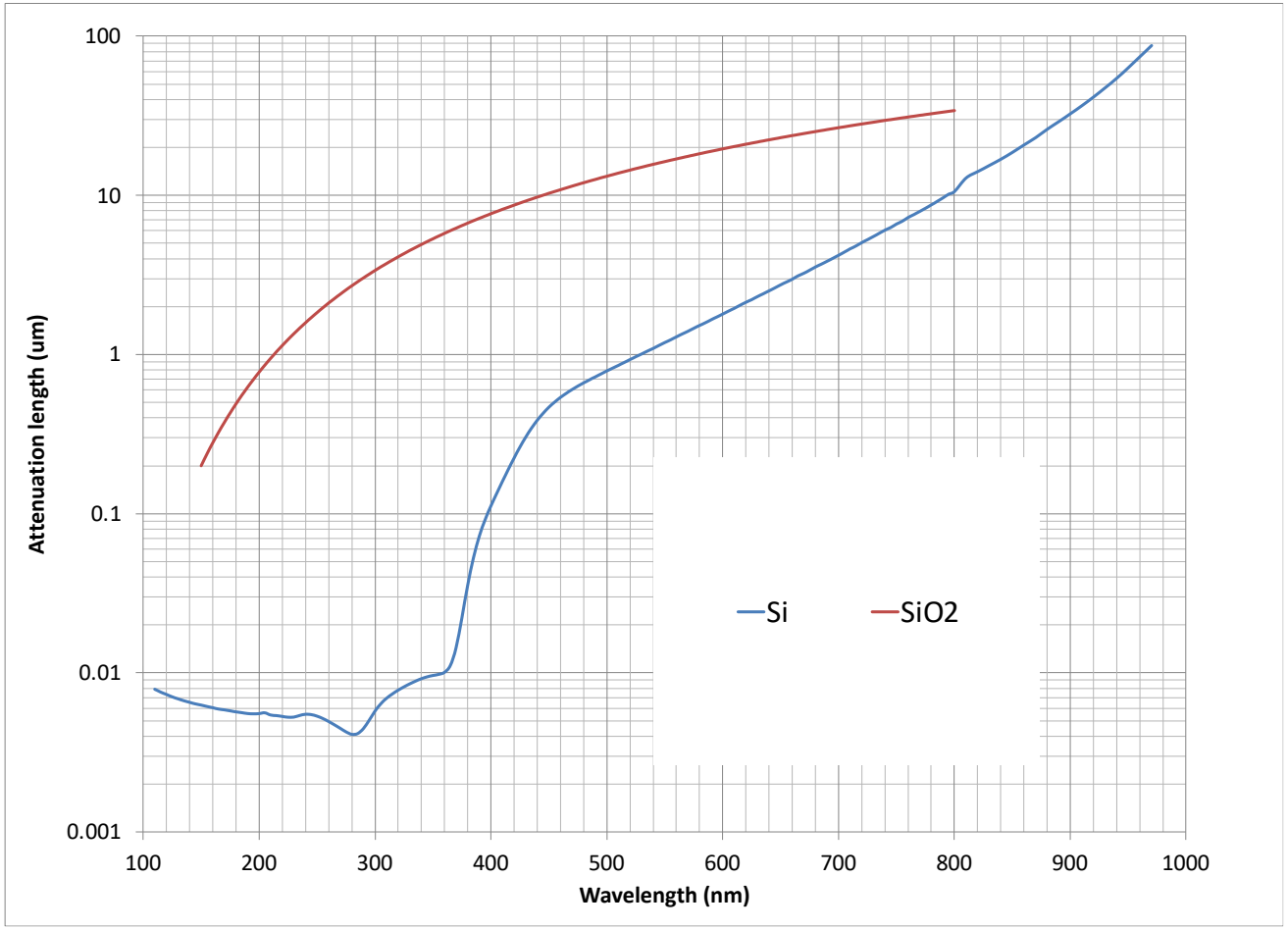
- Easier for electrons to start an avalanche than for holes
- Only a limited region of silicon is active

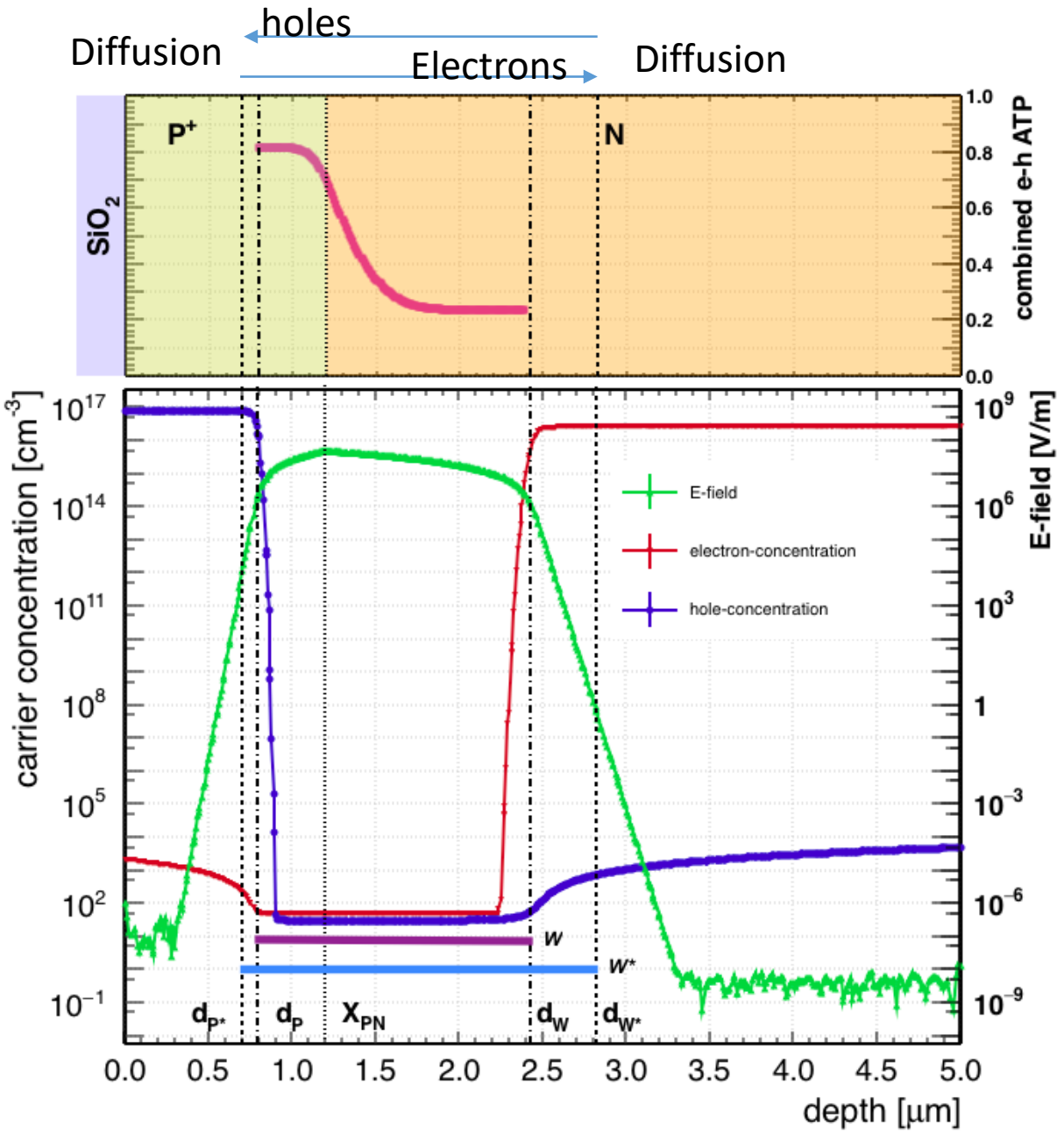




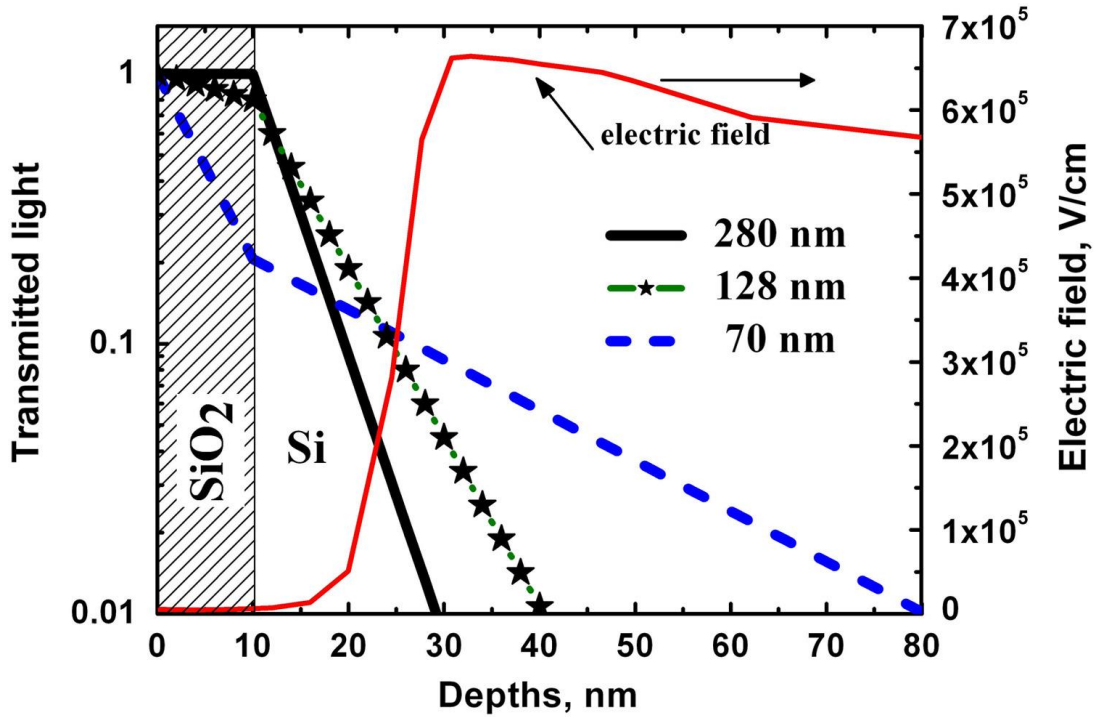
TRIUMF

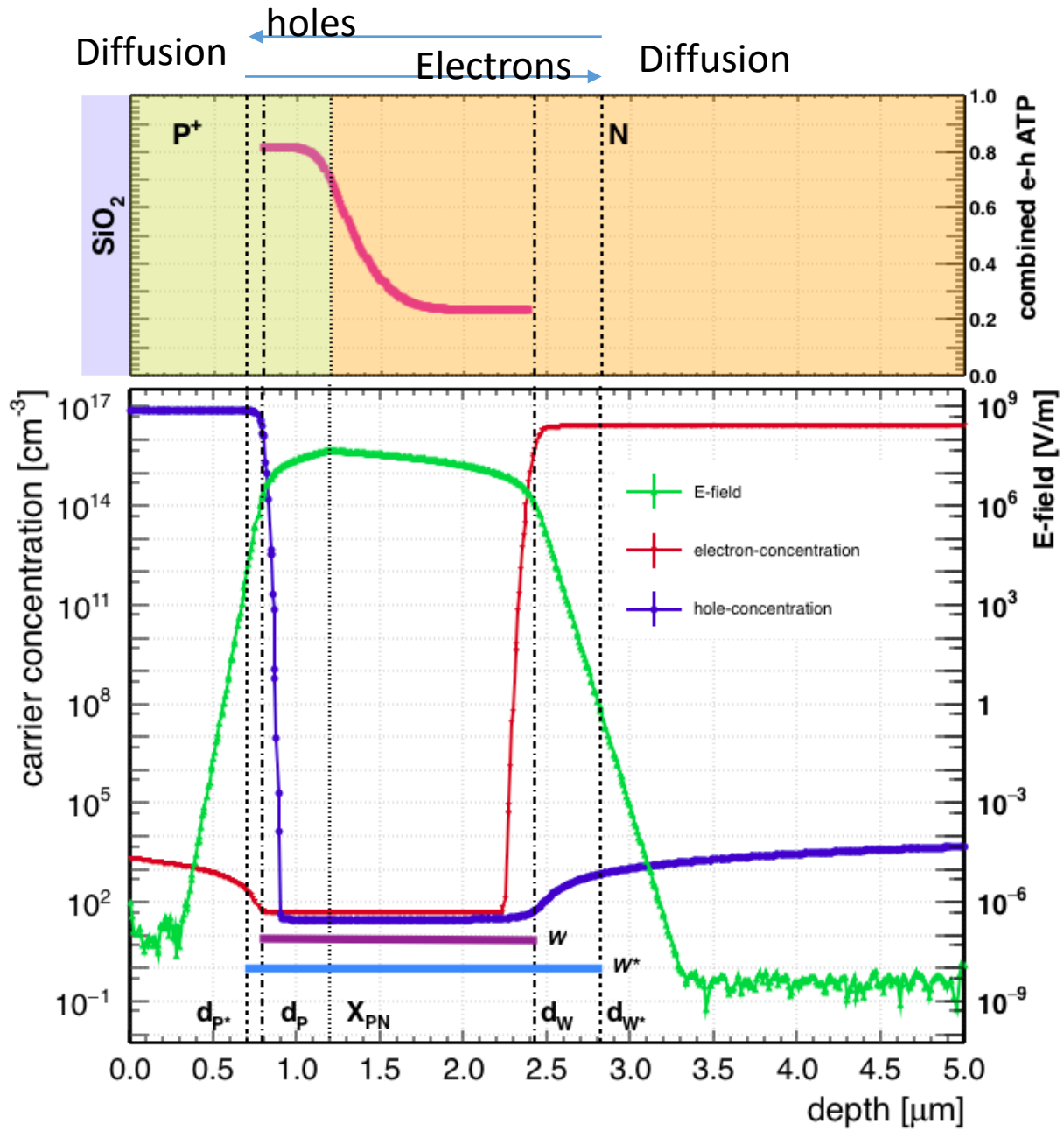
Detecting photons



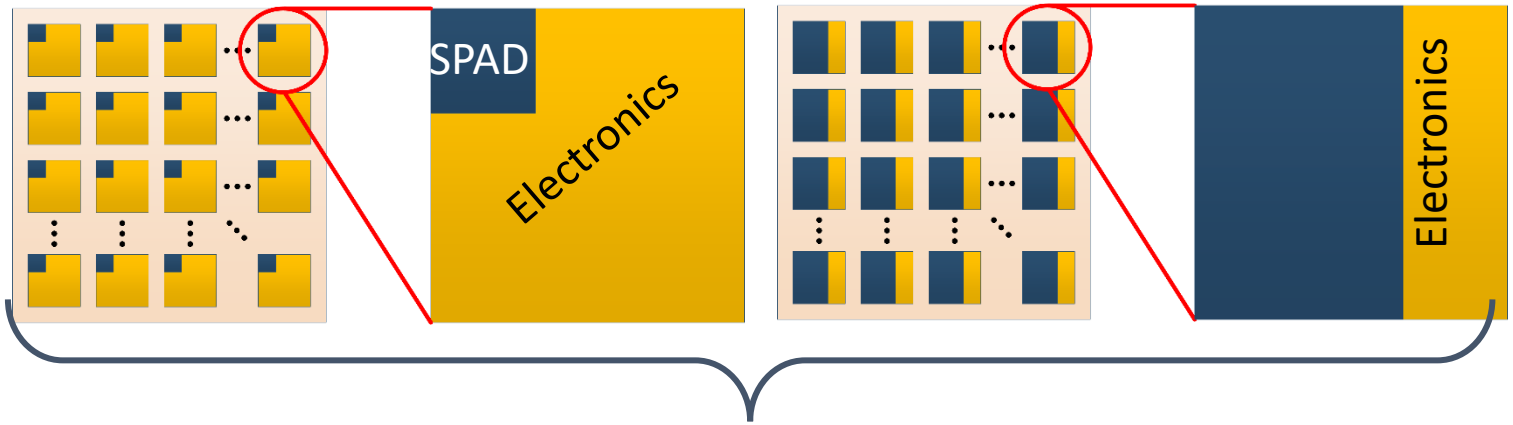


VUV focus

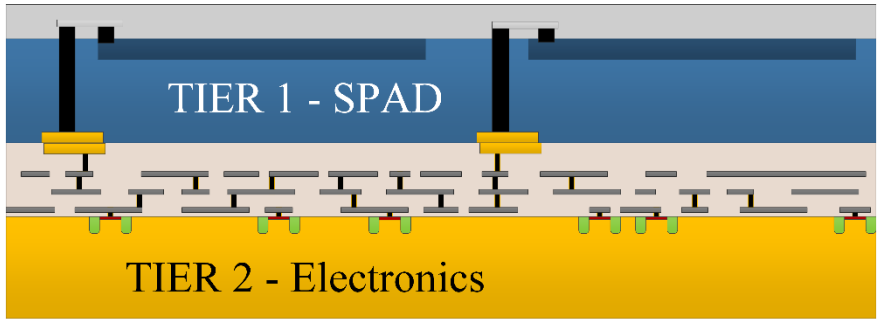

Transmitted light
Electric field, V/cm
Depths, nm
electric field
280 nm
128 nm
70 nm
SiO2
Si
1
0.1
0.01
0
10
20
30
40
50
60
70
80
7x10^5
6x10^5
5x10^5
4x10^5
3x10^5
2x10^5
1x10^5
0


Diffusion
holes
Electrons
Diffusion
P+
N
SiO2
combined e-h ATP
carrier concentration [cm-3]
E-field [V/m]
E-field
electron-concentration
hole-concentration
W
W*
dP*
dP
XPN
dW
dW*
depth [µm]

3D vs 2D digital option

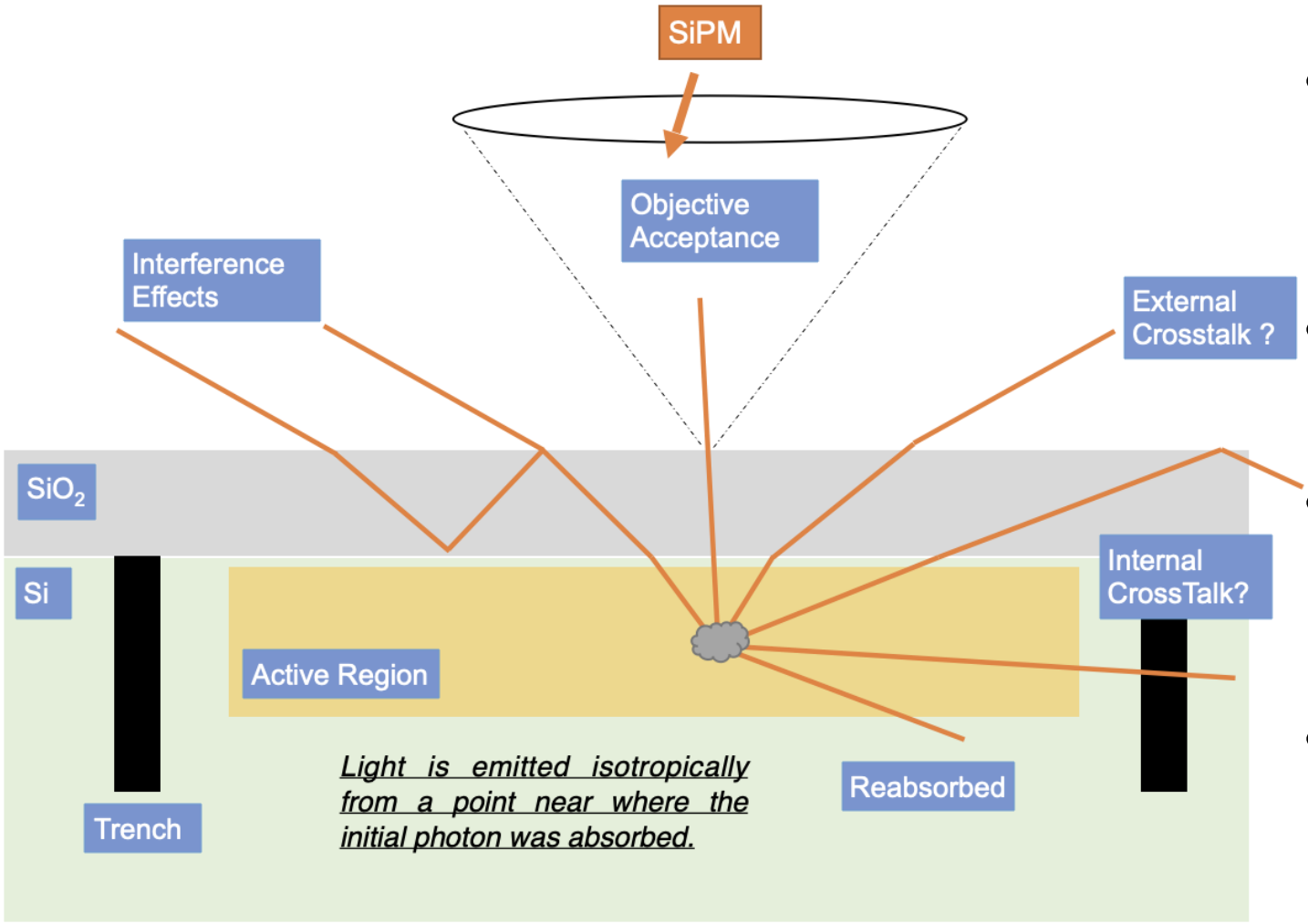


2D - trade-off between photon detection and electronics performances



3D vertical integration – Complexity

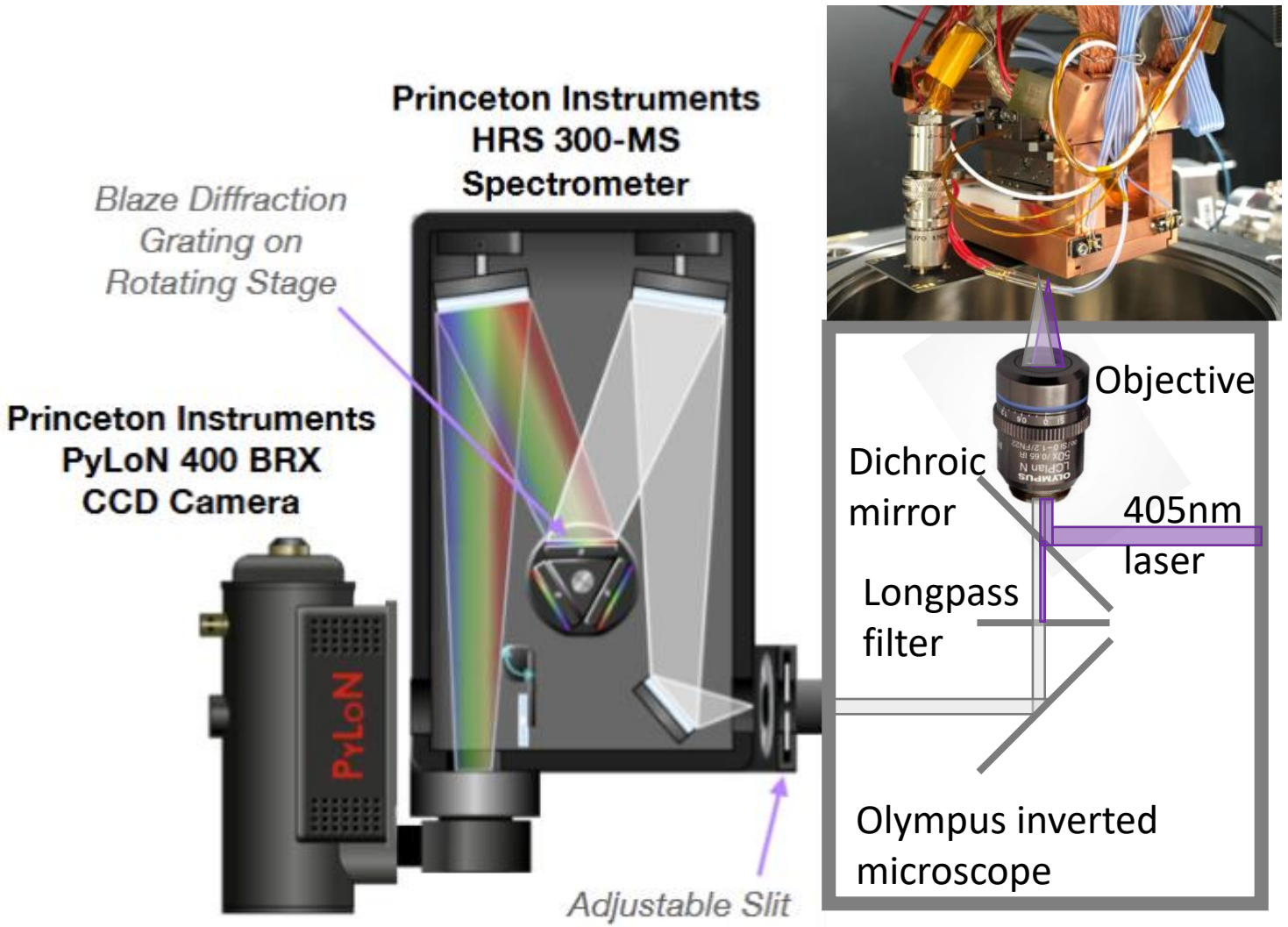
Or are they? What about light emission into the detector?



- Light emission assumptions:
  - At p-n junction – maximum field
  - Isotropic
- External cross-talk
  - Photon escaping the SiPM surface
- Internal cross-talk
  - Photons being absorbed in a neighboring SPAD
- We measure photons escaping with objective acceptance

Technical dtour: SPAD light emission

Microscope for the Injection and Emission of Light



- Cryogenic stage: 80-290K
- Laser injection at 405nm
- Record SiPM signal with waveform digitizer
  - Assess the probability that the laser trigger an avalanche

Can we, particle physicists, help mitigate the impact of climate change?

- Early forest fire detection

BOSCH

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The Dryad early forest-fire detection system

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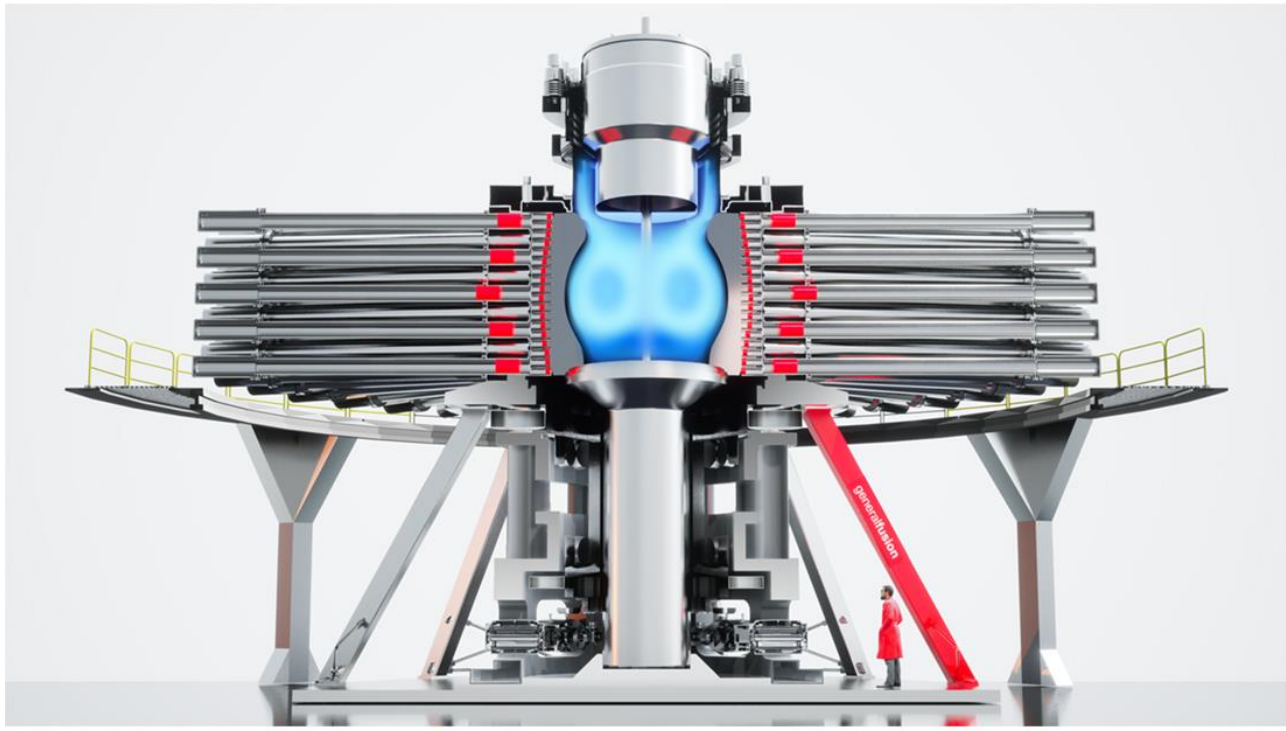
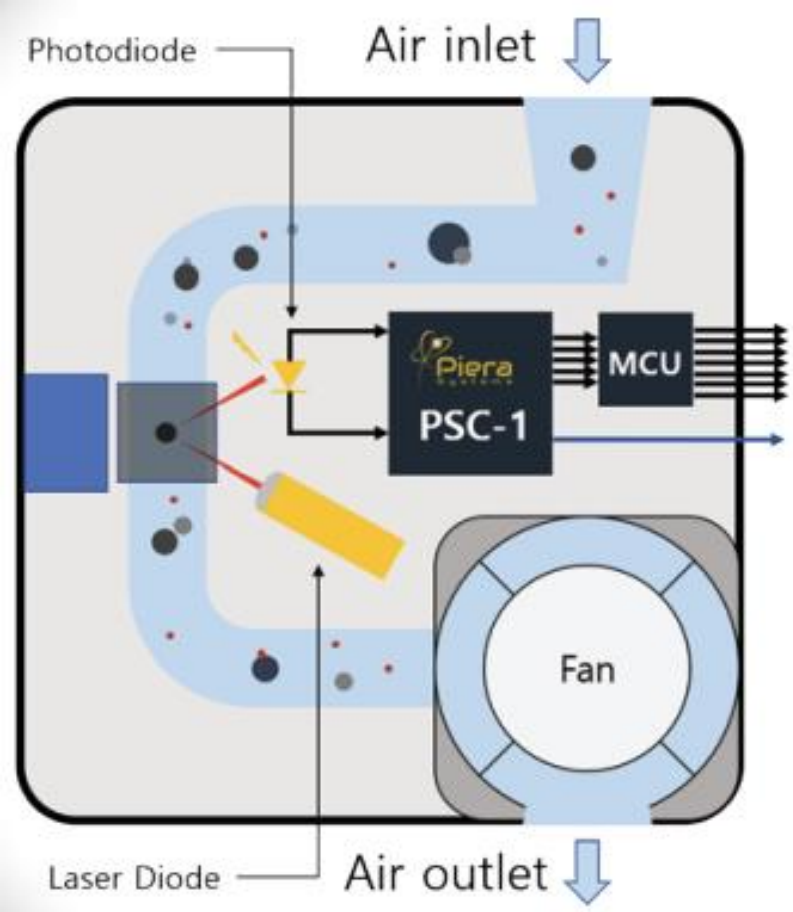
Preventing wildfires with a small sensor

How artificial intelligence can help fight climate change

- Supporting emergence of clean energy sources



Characterizing smoke by detecting particulate scattering

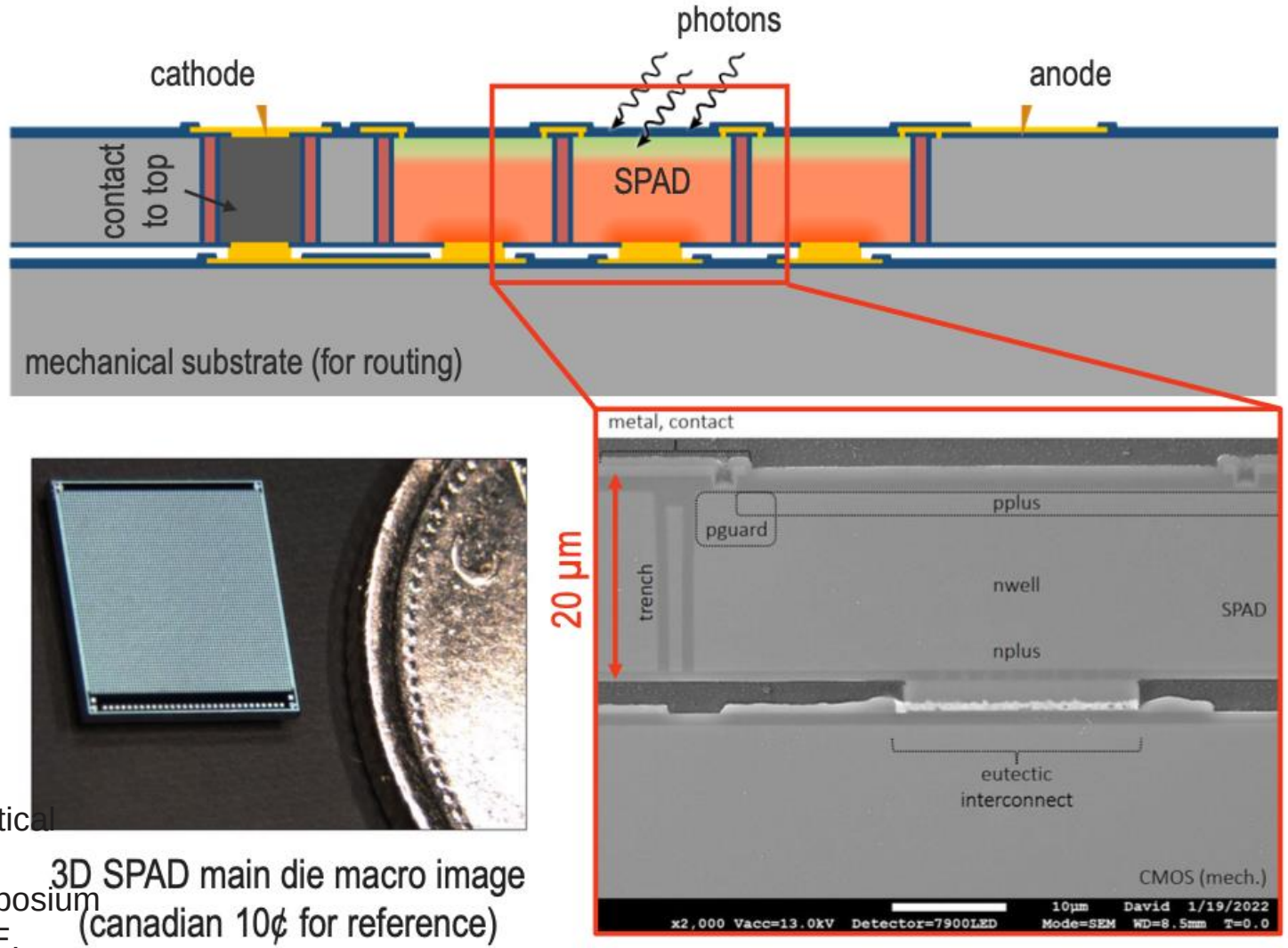


Based on a single photo-diode
Low noise electronics in an ASIC + AI

Designed primarily in Mississauga, ON
80$/unit

Core Single Photon Detection technology

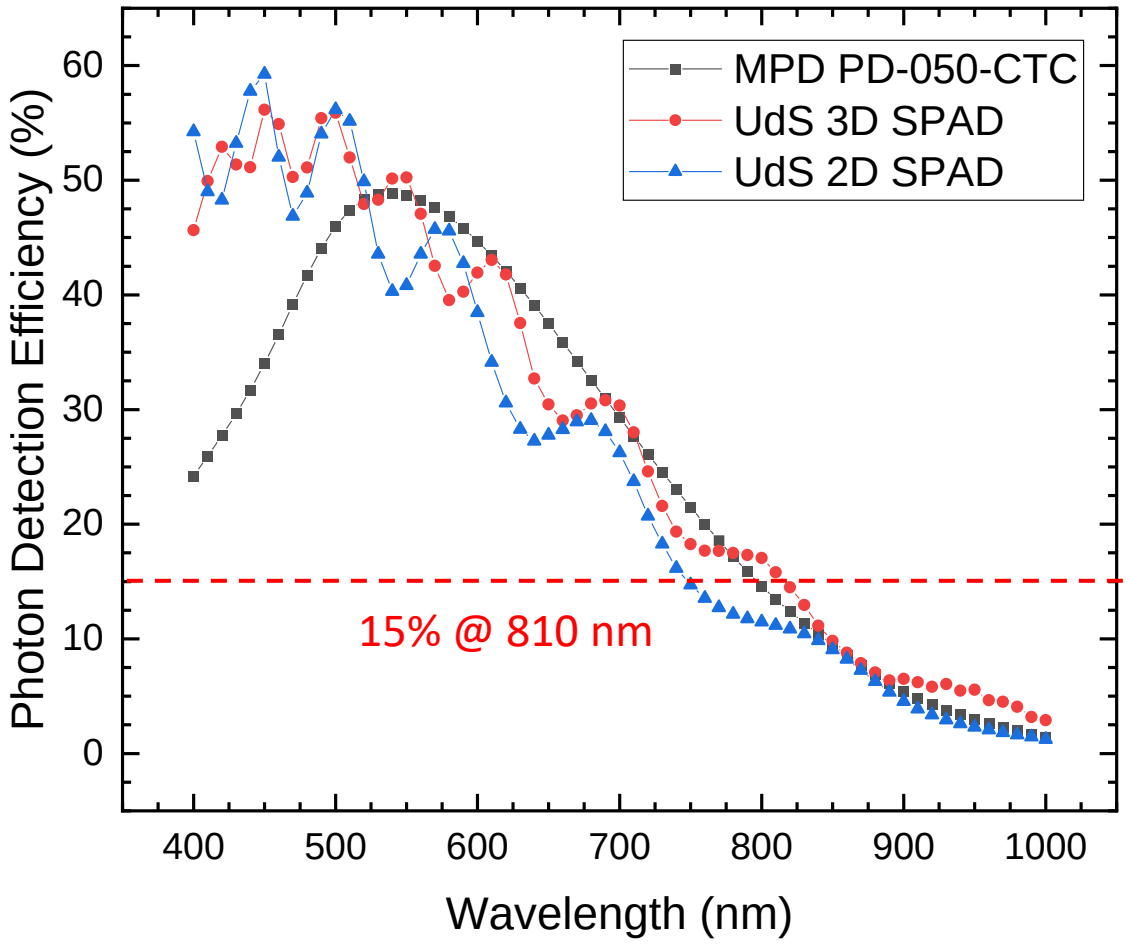
- PDC developed for Astro-particle physics
- “Front-side” illuminated single photon detector
- Designed at U.Sherbrooke (QC, Canada)
- Built at Teledyne-DALSA (QC, Canada)



3D SPAD main die macro image
(canadian 10¢ for reference)

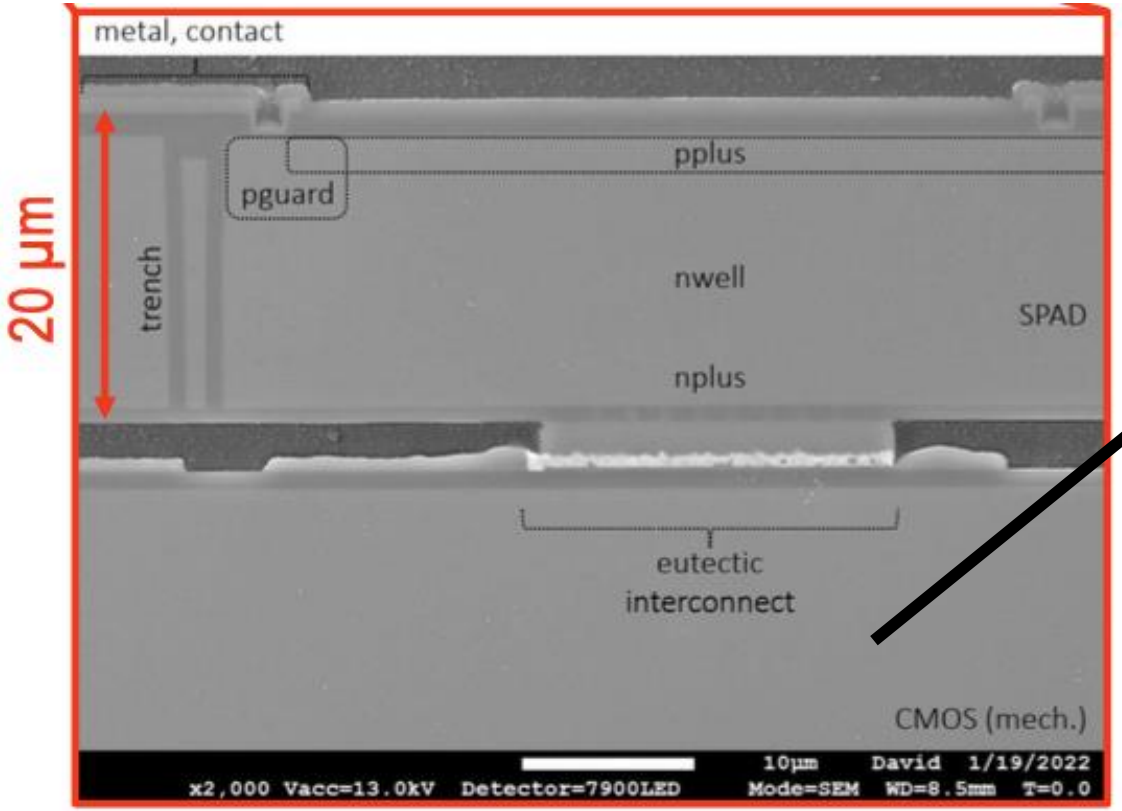
Parent, Samuel, et al. "Single photon avalanche diodes and vertical integration process for a 3D digital SiPM using industrial semiconductor technologies." 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC). IEEE,

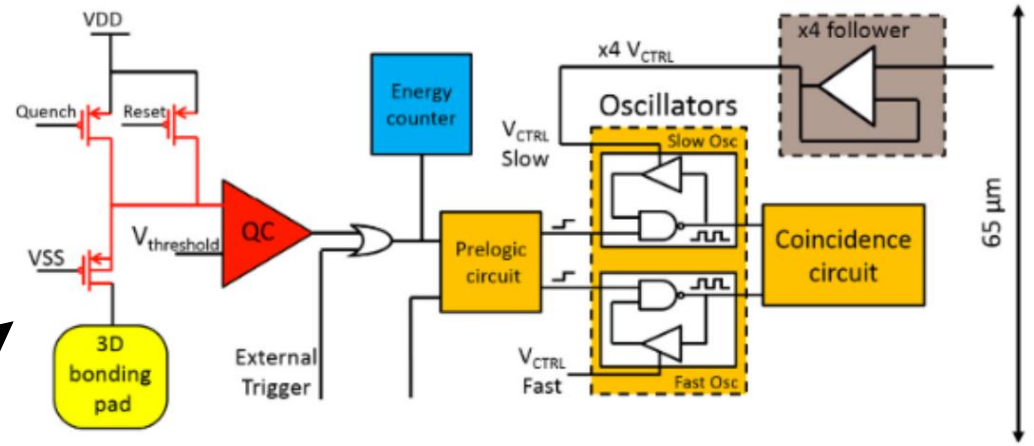
(single SPAD) Photo-detection efficiency in 2022



*all measurements done at 20°C, V_{ov} = 25%, t_{ho} = 545 ns, typical.

TDC integrated in each Single Photon Avalanche Diode (SPAD)





Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 949, 1 January 2020, 162891

A 256 Pixelated SPAD readout ASIC with in-Pixel TDC and embedded digital signal processing for uniformity and skew correction ☆

Frédéric Nolet, William Lemaire, Frédérik Dubois, Nicolas Roy, Simon Carrier, Arnaud Samson, Serge A. Charlebois, Réjean Fontaine, Jean-Francois Pratte

Interdisciplinary Institute for Technological Innovation and Department of Electrical and Computer Engineering, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada

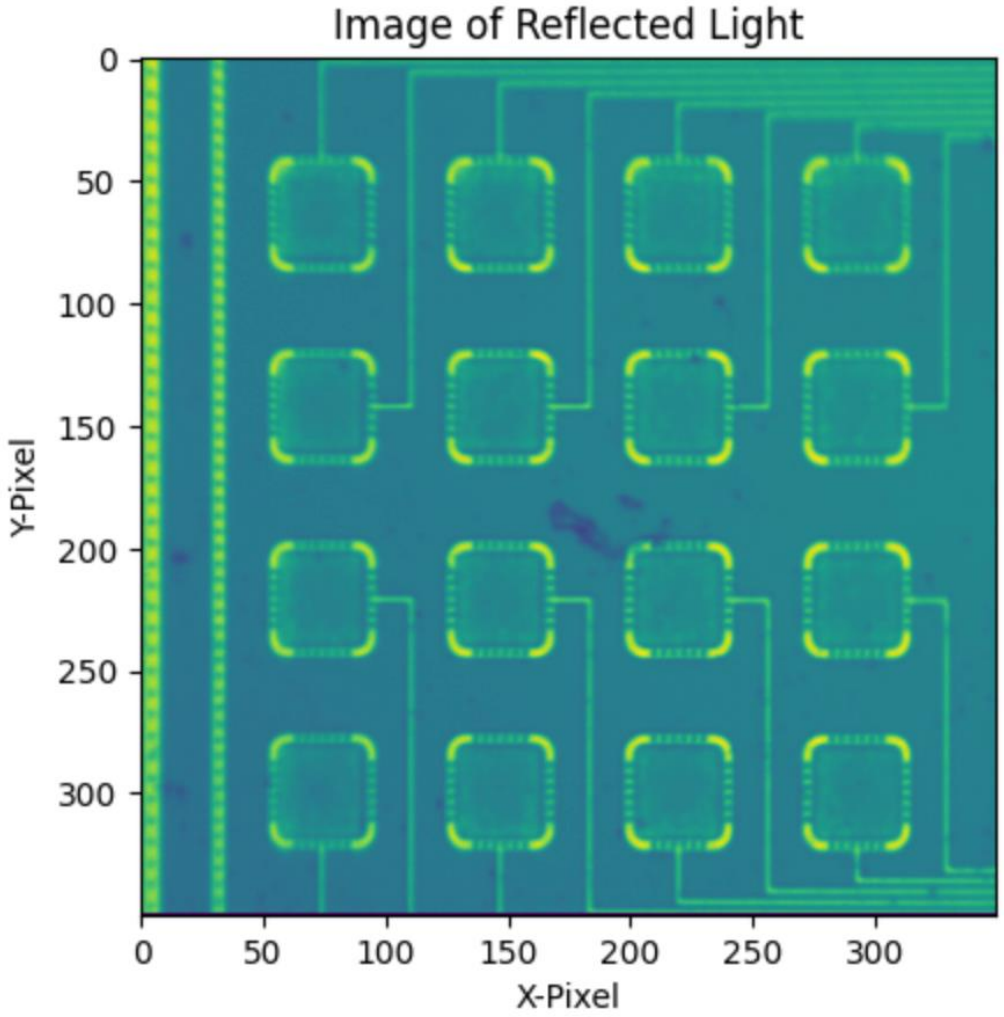
Received 28 June 2019, Revised 24 September 2019, Accepted 29 September 2019, Available online 1 October 2019, Version of Record 4 October 2019.

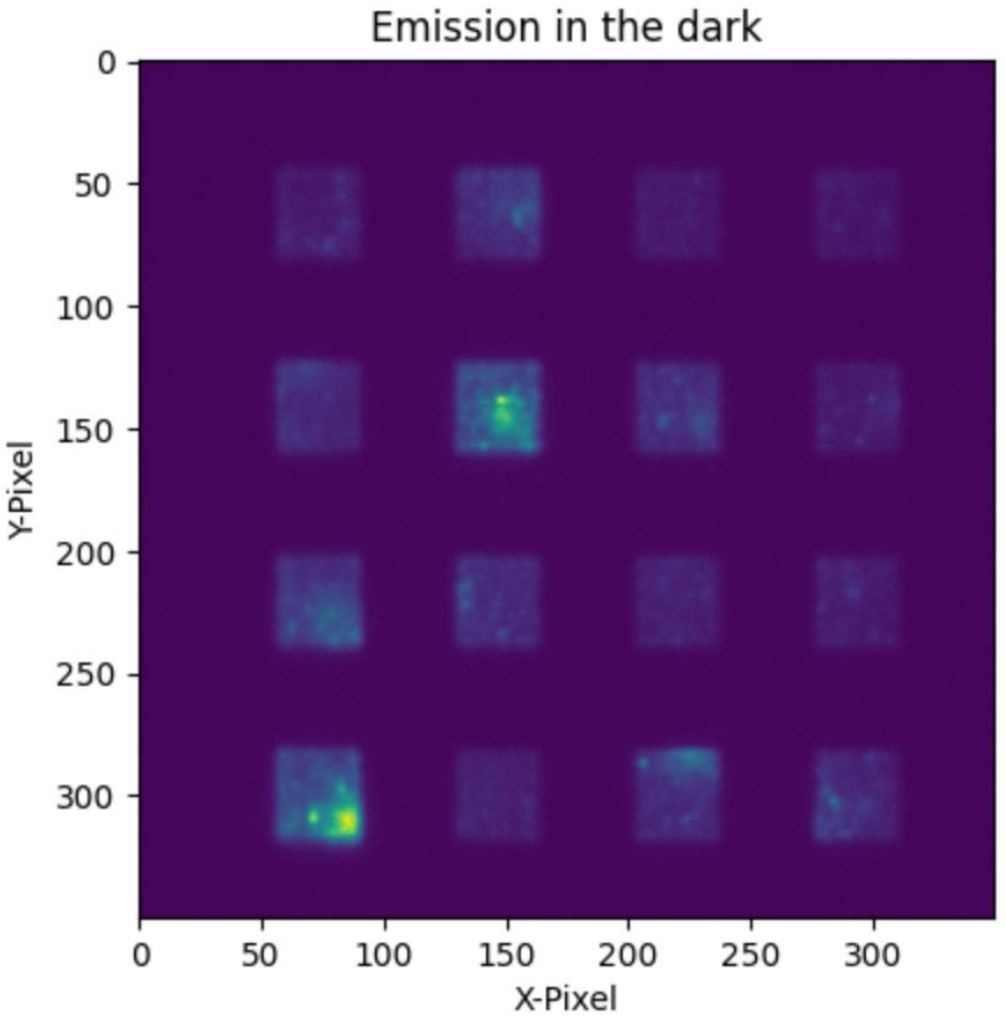
Discovery, accelerated

Technical detour: SPAD light emission

Photon to digital converter in the dark

Sherbrooke's 2D SPAD





keV e- for Digital Hybrid Photo-Detector

- Beat down dark noise by firing multiple SPADs Diffusion layer
  - Photocathode thermal noise at room temperature ~1Hz/mm^2
  - SPAD thermal noise at room temperature ~100kHz/mm^2