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Photon detection systems

Fabrice Retiere (TRIUMF)

Work done within the TRIUMF astro-particle physics group

Collaboration with U.Sherbrooke (QC, Canada) for the Photon to Digital Converter

With support from TRIUMF Sci Tech dept and NSERC MRS and funding agencies:

NSERC CRSNG

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

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Discovery, accelerated

Outline

- Light production in liquid Xenon
- Light detection with PMT
- Light detection with SiPMs
- Light detection with digital SiPMs

Light production

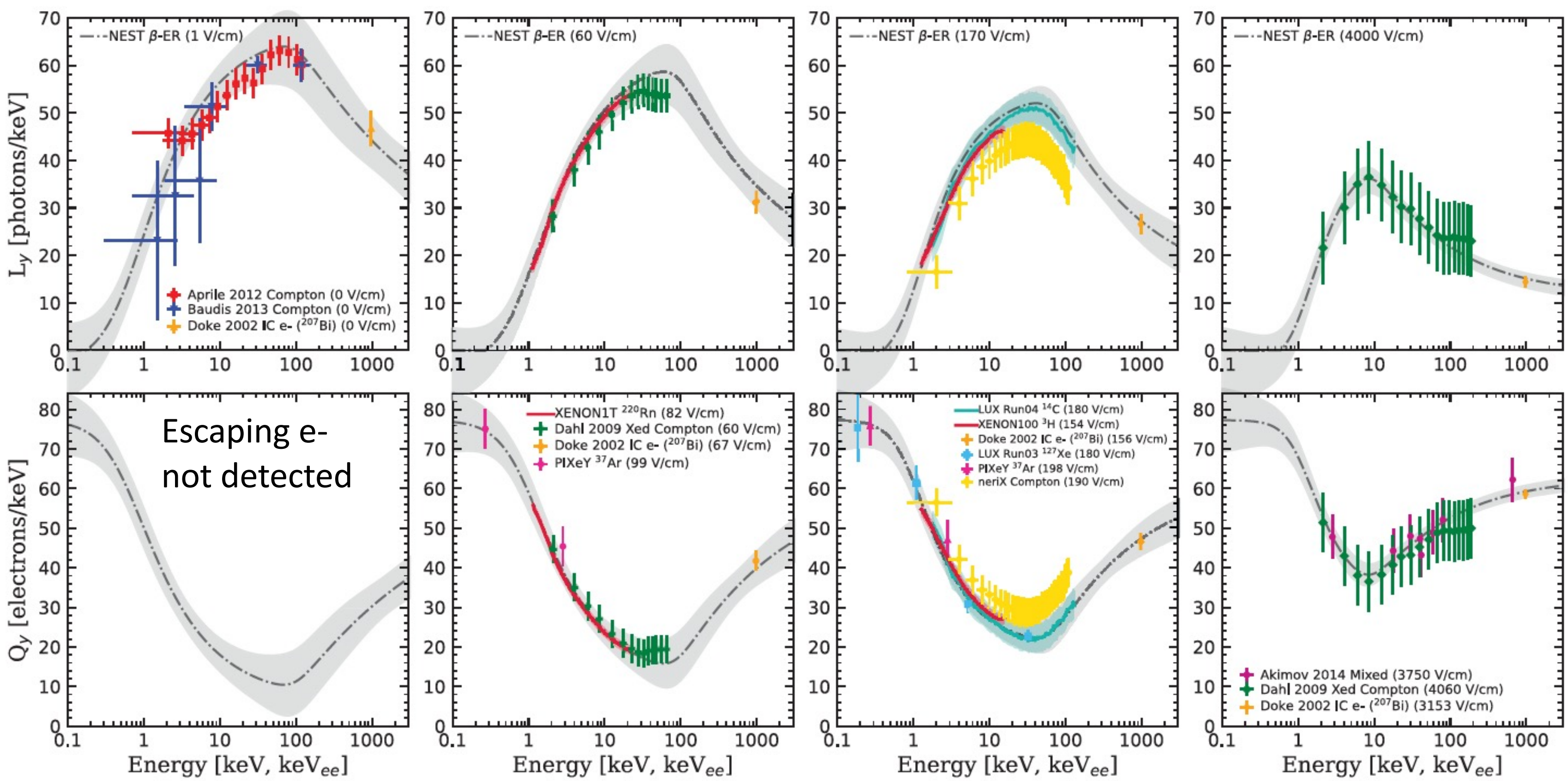
- Scintillation
  - Mean emission wavelength: 174.8 +- 0.14 nm
  - Width (sigma) of the distribution: 4.3 +- 0.1 nm
- Electroluminescence
- Cerenkov

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 795, 21 September 2015, Pages 293-297

High-accuracy measurement of the emission spectrum of liquid xenon in the vacuum ultraviolet region

Keiko Fujii [a], Yuya Endo [a], Yui Torigoe [a], Shogo Nakamura [a], Tomiyoshi Haruyama [b], Katsuyu Kasami [b], Satoshi Mihara [b c], Kiwamu Saito [b c], Shinichi Sasaki [b c], Hiroko Tawara [b]

Scintillation light yield with e-/beta



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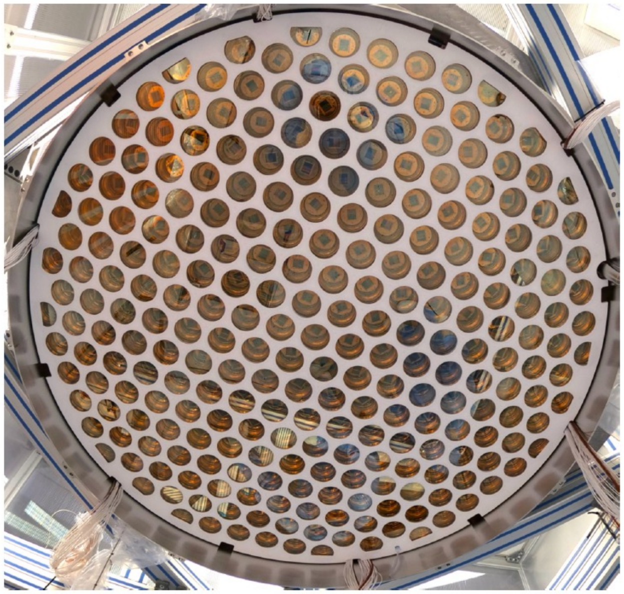
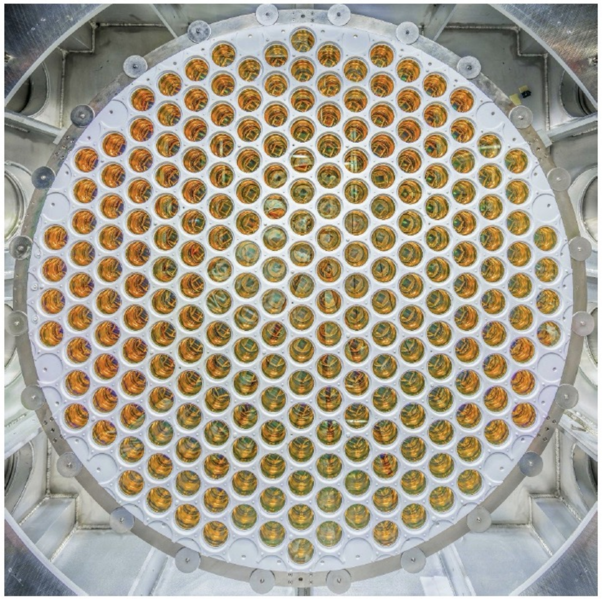
R11410 PMTs

PMT update from Laura Baudis (Zurich)

- Baseline photosensor for XLZD: design book arXiv:2410.17137
- Efforts to reduce their overall activity



XENONnT



LZ

Discovery, accelerated

Nomenclature and further steps

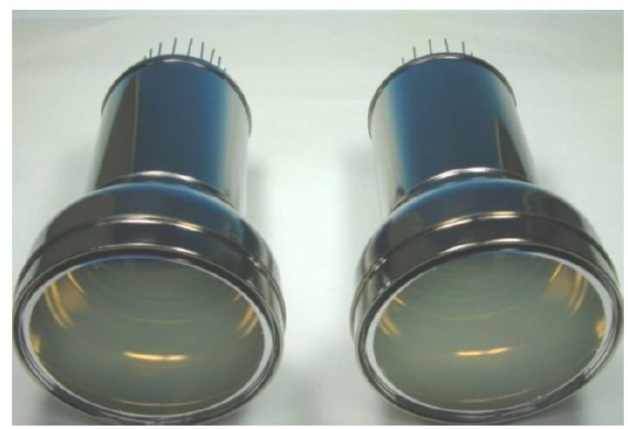
PMT update from Laura Baudis (Zurich)

- PMT with metal stem with glass beads: **new name R17317**
- **Further planned reduction in radioactivity**
    - Photocathode with highly pure K used for XMASS (R13111)
    - Glass beads with low-radioactivity glass used for XMASS (R13111)

Also, we will test all 16 PMTs in GXe and LXe

R11410-21 and R17317

R11410-21 and R17317



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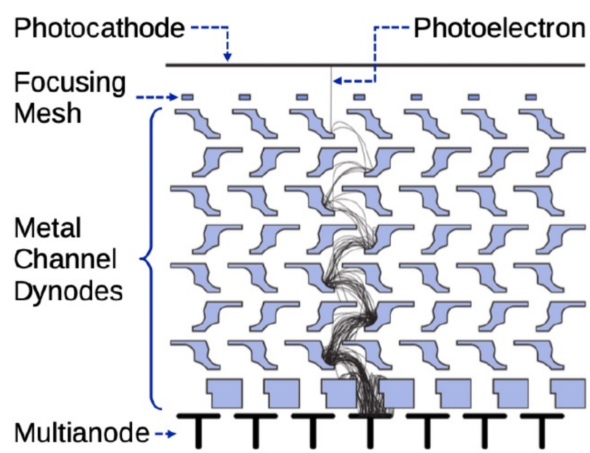
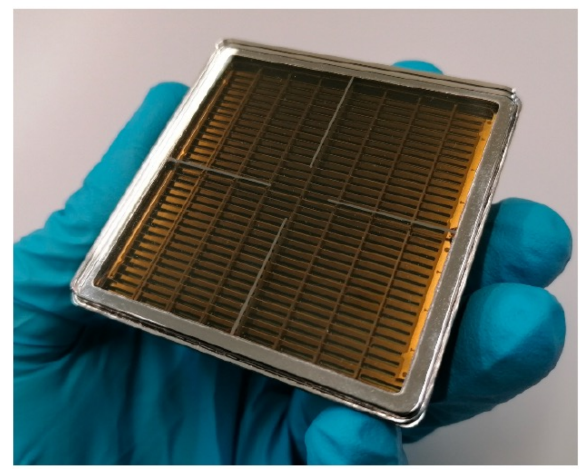
PMT update from Laura Baudis (Zurich)

The 2" square PMT

- **Characterisation in LXe (MarmotX) and in a 2-phase TPC (Xams)**
  - 2506.04844: UZH and Nikhef
  - screening with Gator
- Leakage issue around the pins (Hamamatsu aims to solve within 2025)





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The 2" square PMT

PMT update from Laura Baudis (Zurich)

- Comparison with the 3" unit

	R12699-406-M4	R11410-21
Dimensions (longitudinal / lateral)	14.8 mm / 56 mm [11]	114 mm / 77.5 mm [31]
Packing density	75.0 %	61.8 %
Dynode structure	Metal channel [11]	Box & linear-focused [31]
Number of dynode stages	10 [11]	12 [31]
Quantum efficiency at 175 nm	33 % [11]	32.5 % [31]
Operation voltage (nominal / max.)	1000 V / 1100 V [11]	1500 V / 1750 V [31]
Gain (T_{room})	$(3.3 \pm 0.7) \cdot 10^6$	$(8.4 \pm 2.3) \cdot 10^6$ [15]
SPE resolution (gain $\sim 2 \cdot 10^6$, T_{room})	(37 ± 3) %	(30 ± 3) % [21]
Dark count rate (> 1/4 PE)	(0.4 ± 0.2) Hz/cm^2	(1.4 ± 0.7) Hz/cm^2 [21]
Time response (RT / transit time / TTS)	1.2 / 5.9 / 0.41 ns [11]	5.5 / 46 / 9 ns [31]
Separable afterpulse rate	(1.1 ± 0.2) %/PE	(8.6 ± 2.2) %/PE [21]

2506.04844

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SiPM for lowest radioactivity content

PMT type	Normalized activity [mBq/cm^2]						Ref.
	^{238}U	^{226}Ra	^{228}Th	^{235}U	^{40}K	^{60}Co	
R11410-21	< 0.4	0.016(3)	0.012(3)	0.011(3)	0.37(6)	0.023(3)	this work
R11410-20	< 0.56	< 0.03	0.028(6)	< 0.025	0.37(6)	0.040(6)	this work
R11410-10	< 3.0	< 0.075	< 0.08	< 0.13	0.4(1)	0.11(2)	[20]
R11410-10 (PandaX)	–	< 0.02	< 0.02	0.04(4)	0.5(3)	0.11(1)	[12]
R11410-10 (LUX)	< 0.19	< 0.013	< 0.009	–	< 0.26	0.063(6)	[21]
R11410	1.6(6)	0.19(2)	0.09(2)	0.10(2)	1.6(3)	0.26(2)	[20]
R8778 (LUX)	< 1.4	0.59(4)	0.17(2)	–	4.1(1)	0.160(6)	[21]
R8520	< 0.33	0.029(2)	0.026(2)	0.009(2)	1.8(2)	0.13(1)	[20]

	^{238}U	^{232}Th	^{40}K
Prelim. nEXO requirements for 4m^2	< 0.1 nBq/cm^2	<1 nBq/cm^2	< 10 nBq/cm^2
Bare silicon VUV SiPM (FBK VUV-HD)	0.68 nBq/cm^2	0.12 nBq/cm^2	~3 nBq/cm^2
Packaged SiPM (SensL) [a]	<1.1 mBq/cm^2	<33 μBq/cm^2	<69 μBq/cm^2
Hamamatsu PMT R11410-21 [b]	<0.4 mBq/cm^2	0.016 mBq/cm^2	0.37 mBq/cm^2
Hamamatsu PMT HPK R12699-406-M4[c]	0.02 mBq/cm^2	0.01 mBq/cm^2	1.5 mBq/cm^2

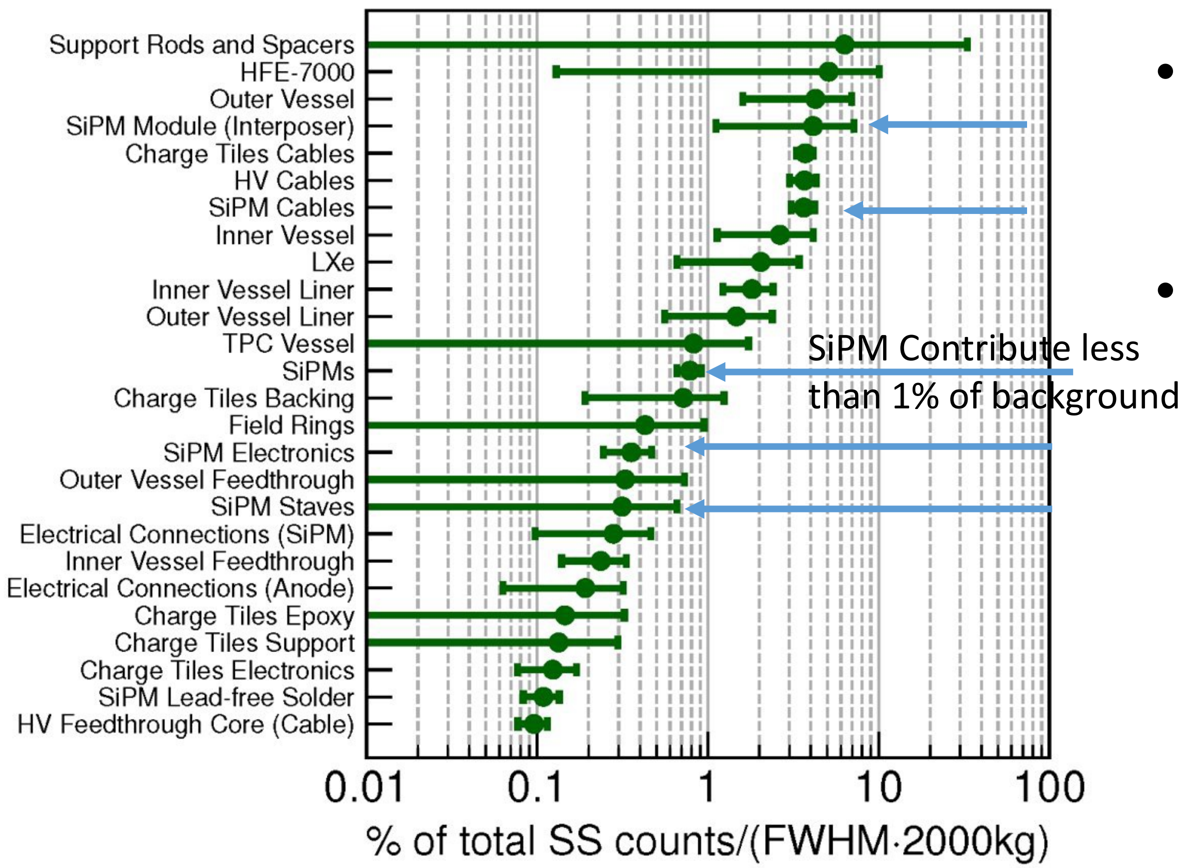
[a] NEXT Ge counting. http://arxiv.org/abs/1411.1433

[b] E. Aprile et al. Material radioassay and selection for the XENON1T dark matter experiment. Eur. Phys. J., C77(12):890, 2017, https://arxiv.org/pdf/1705.01828.pdf

[c] Jiangia Liu’s PANDA-X talk yesterday

Discovery, accelerated

SiPM radiopurity is only part of the problem



- SiPMs are 2 to 3 orders of magnitude lower radioactivity than PMT
- But the system level is challenging. Need low radioactivity
  - Cables → kapton
  - PCB / interposer→ SiO2 or Si
  - Electronics → no package, all Si if possible

Using SiPM? Comparing all performances

Parameters at LXe temperature for cm^2 scale channel size	PMT R11410-21[a]	FBK VUV-HD3 @ 3V [b]	HPK VUV4 MPPC @ 3V [b]
Single channel active area	128 cm^2	25 cm^2 [c]	6 cm^2 [d]
Efficiency at 175nm	34%	24.4 ± 1.4%	20.5 ± 1.1%
Single avalanche charge resolution	25%	5%[c]	5%[d]
Dark noise rate (Hz/cm^2)	1.3 ± 0.4	19 ± 1	35 ± 1
# correlated avalanche in 1 μs	0.02 ± 0.005	0.23 ± 0.06	0.06 ± 0.02
# Photons emitted per avalanche	N/A	1 ± 0.5	1 ± 0.5
Single photon timing resolution, σ	3.9 ± 0.6ns	~10 ns[c]	~100 ns[d]
Radiopurity per active area	**~mBq/cm^2**	Medium [c]	< 10 nBq/cm^2 [d]
Power consumption in LXe	0.75 mW/cm^2	2 mW/cm^2 [c]	2 mW/cm^2 [d]

Compiled at XeSAT 2023

[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 25 cm^2 channel size
[d] nEXO readout scheme for 6 cm^2 channel size (can be applied to FBK)

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Gallina, G., Guan, Y., Retiere, F. et al. *Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO.* Eur. Phys. J. C 82, 1125 (2022), https://arxiv.org/pdf/2209.07765.pdf

But SiPMs distort the energy resolution

$$\frac{\sigma_n}{\langle n\rangle} = \frac{\sqrt{\left(\frac{(1-\varepsilon_p)n_p}{\varepsilon_p} + \frac{n_p}{\varepsilon_p}\cdot\frac{\sigma_\Lambda^2}{(1+\langle\Lambda\rangle)^2} + n_p^2\sigma_{lm}^2\right) + \left(\frac{n_q t}{\tau} + \frac{\sigma_{q,noise}^2}{\varepsilon_q^2}\right)}}{\langle n\rangle}$$

Efficiency contribution

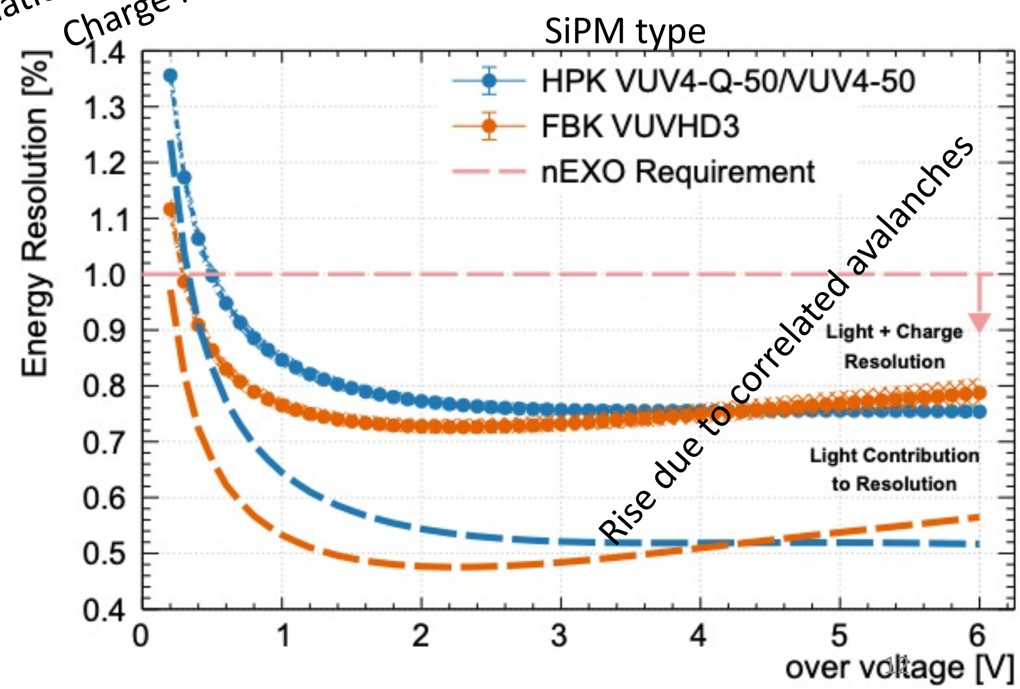
Photo-detector correlated avalanche (excess noise factor)

Light map calibration

Charge attenuation

Charge noise

Calculated for nEXO



Parameter related to photo-detector bias

- Assumptions
  - Negligible intrinsic light+charge fluctuations
  - Photo-detector noise negligible
    - High gain
  - No external cross-talk considered

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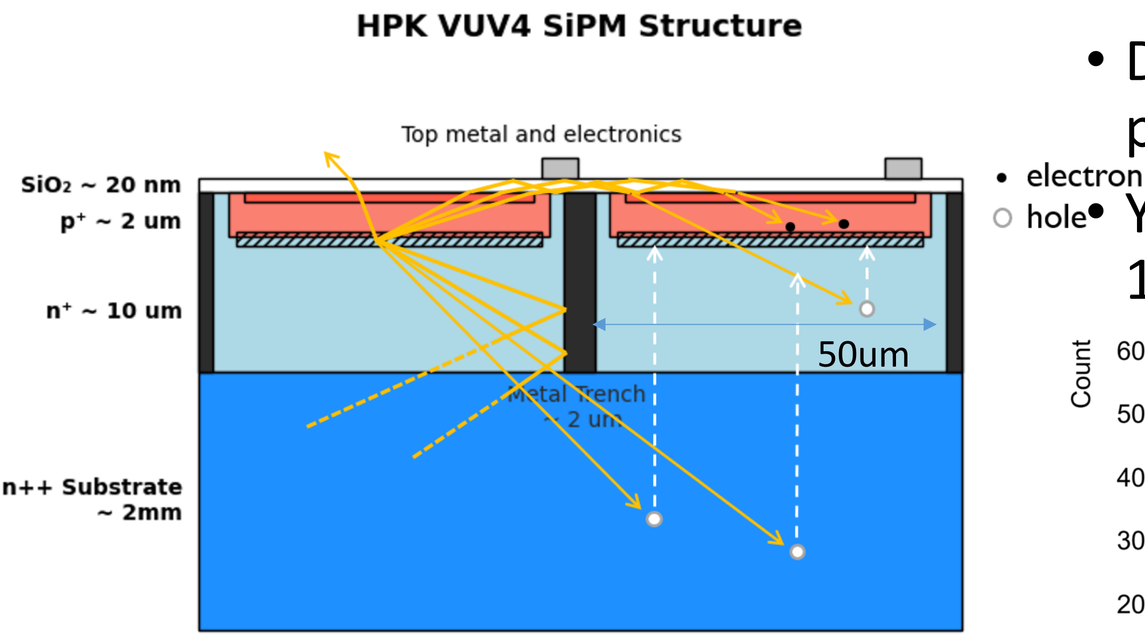
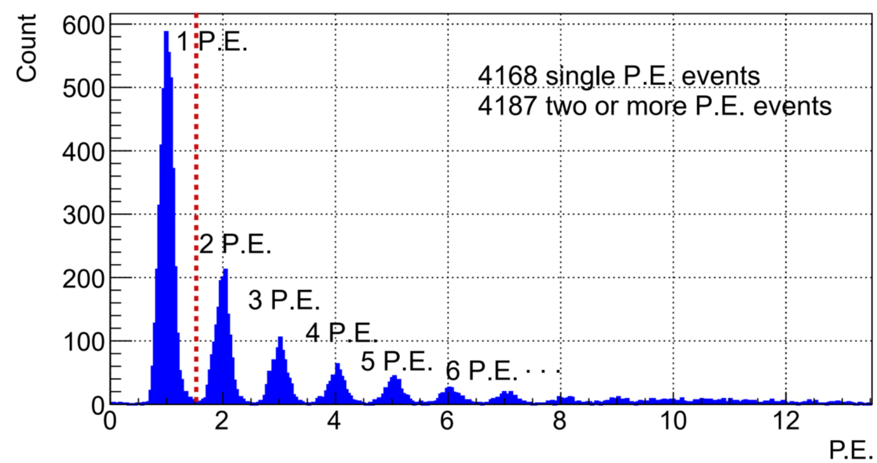
Light emission → internal cross-talk

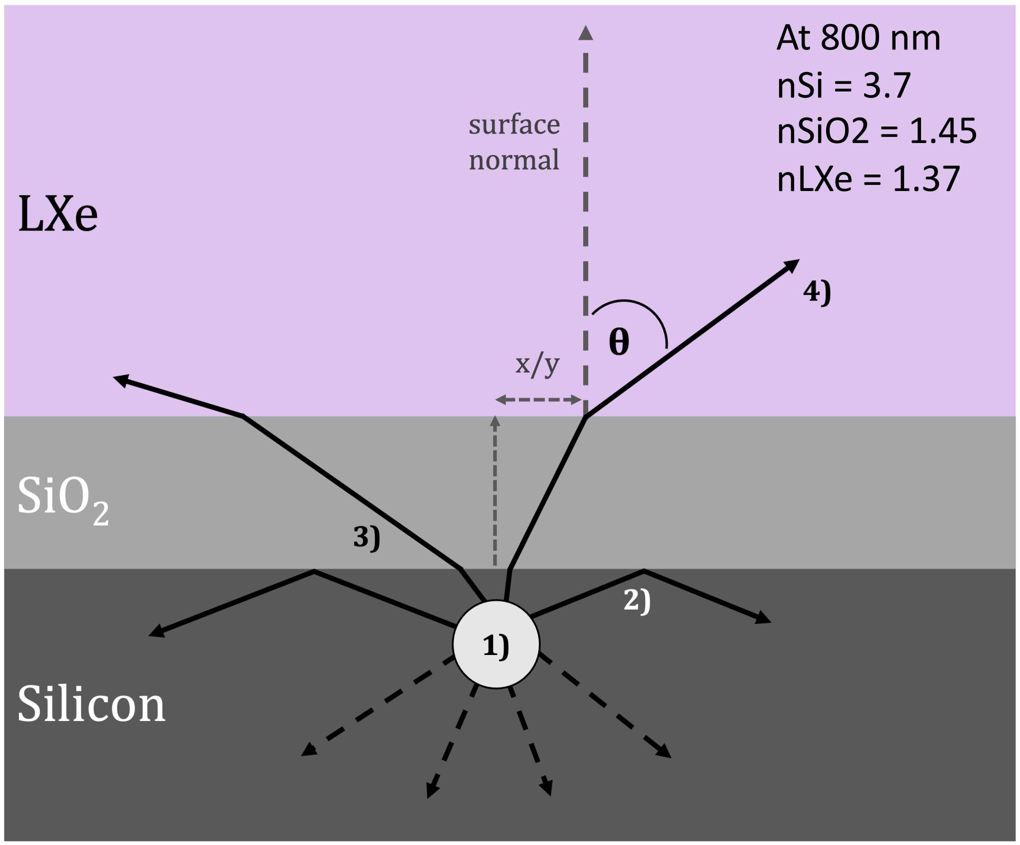


- Dark noise produce only one e-h pair at a time
- Yet, it is common to measure > 1PE prompt = internal cross-talk

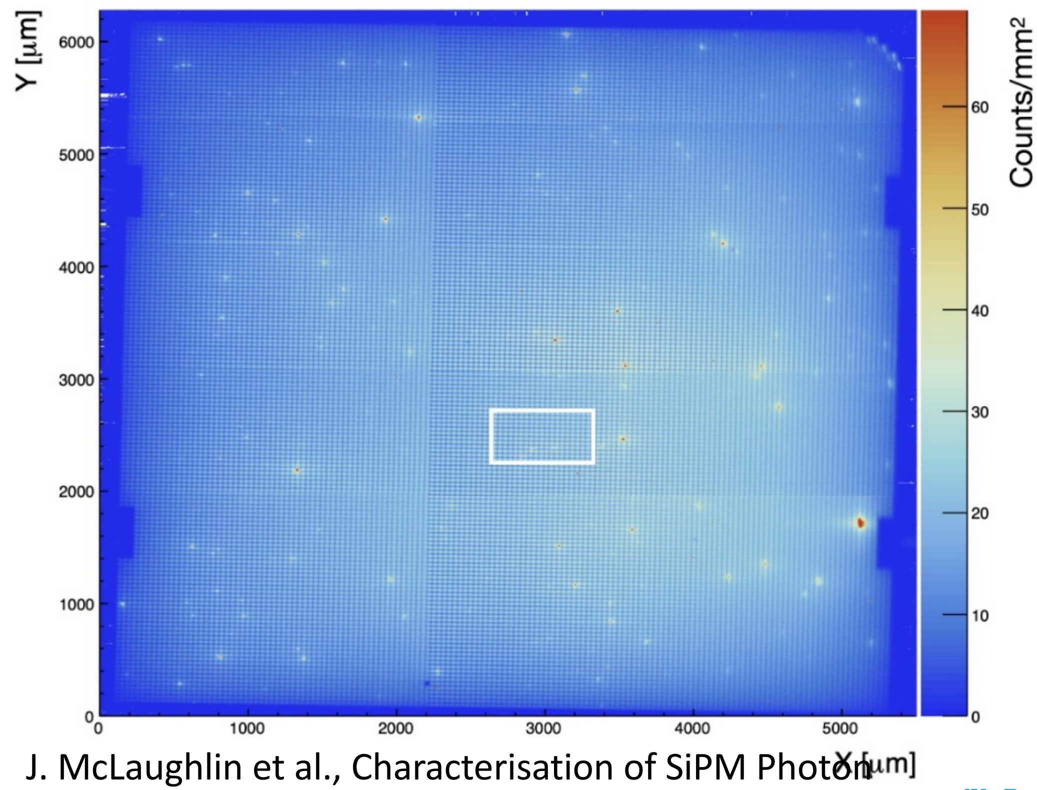


Discovery, accelerated

External cross-talk was a worry because its impact was unknown

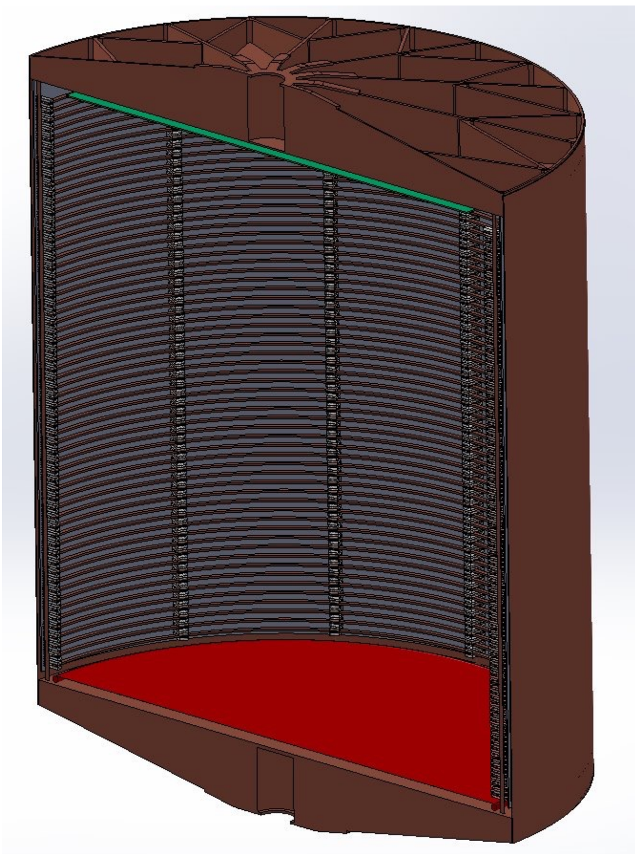


FBK emitting light in the dark

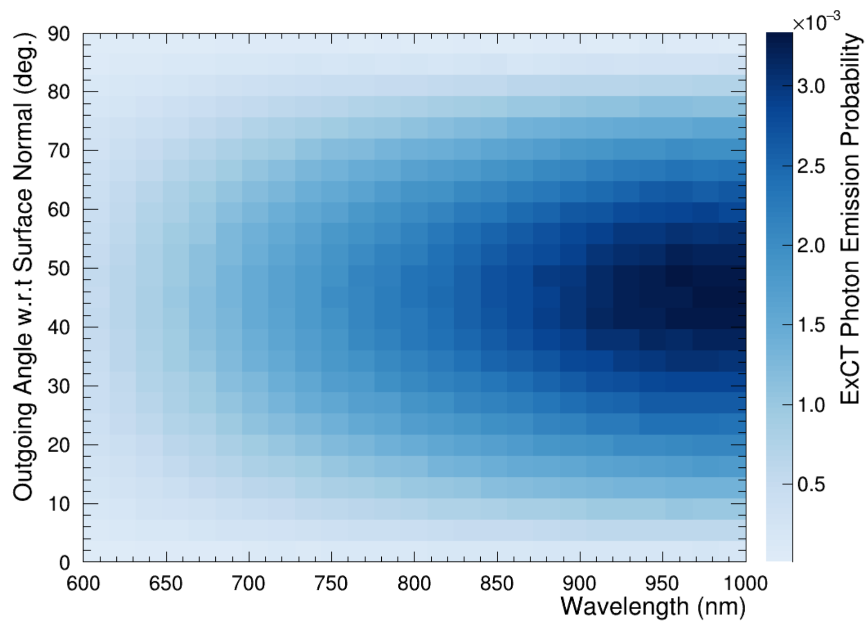


J. McLaughlin et al., Characterisation of SiPM Photon Emission in the Dark, *Sensors* **2021**, *21*(17), 5947

External cross-talk is a worry when SiPM "face" each other



- Well, isotropic emission at source leads to large angle emission



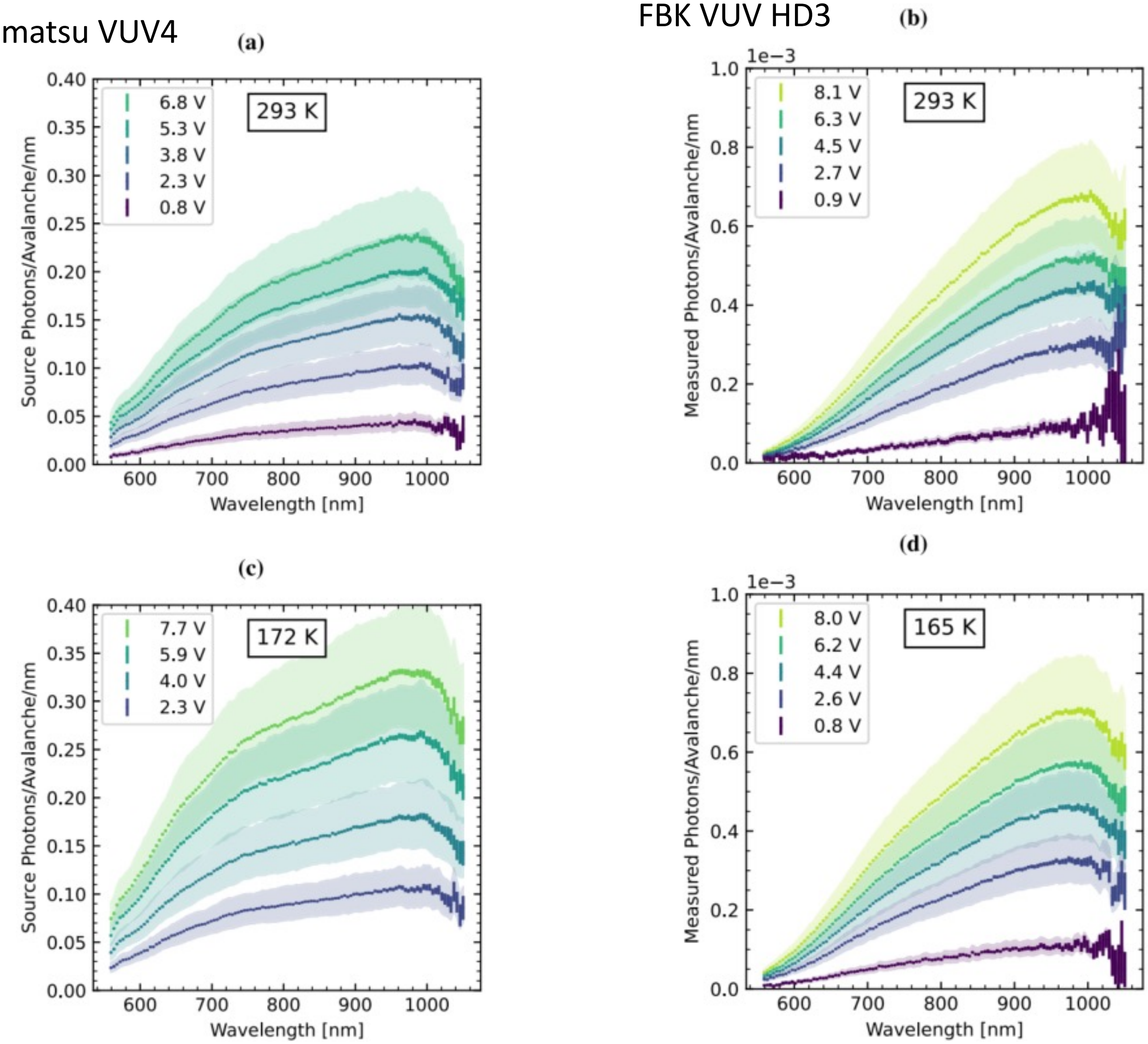
Discovery, accelerated

- Emission in Near Infra-red
- Photons per electron
  - 1.9 ± 0.4 10^{-5} for HPK VUV4
  - 2.6 ± 0.5 10^{-5} for FBK VUV-HD3
  - Same number?

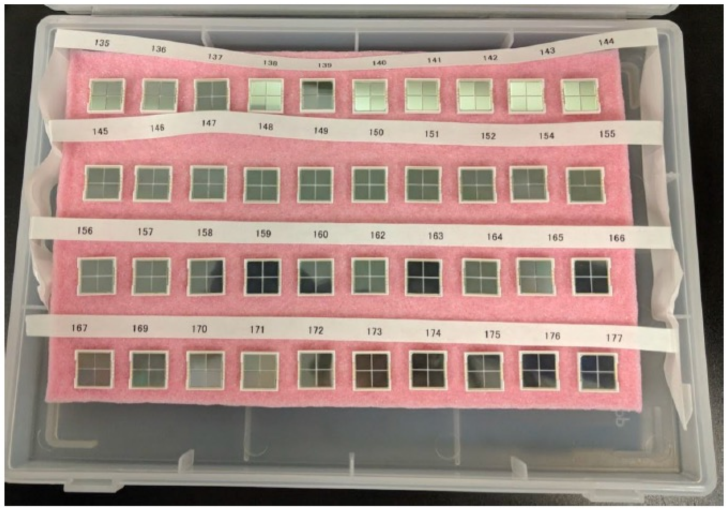
K. Raymond *et al.*, "Stimulated Secondary Emission of Single-Photon Avalanche Diodes," in *IEEE Transactions on Electron Devices*, vol. 71, no. 11, pp. 6871-6879, Nov. 2024

Hamamatsu VUV4

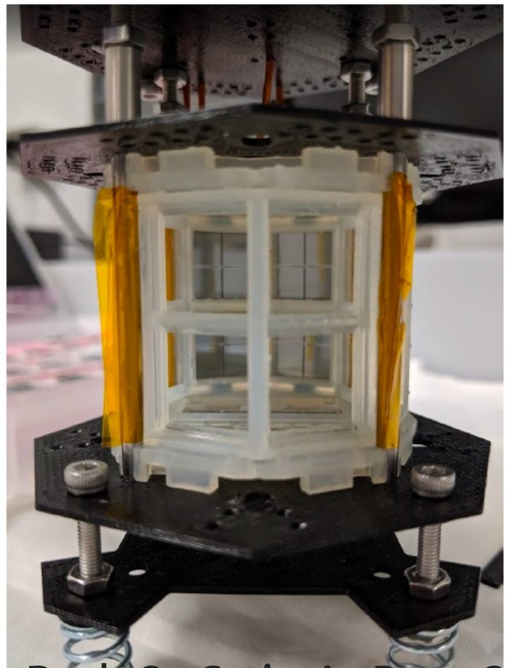
FBK VUV HD3

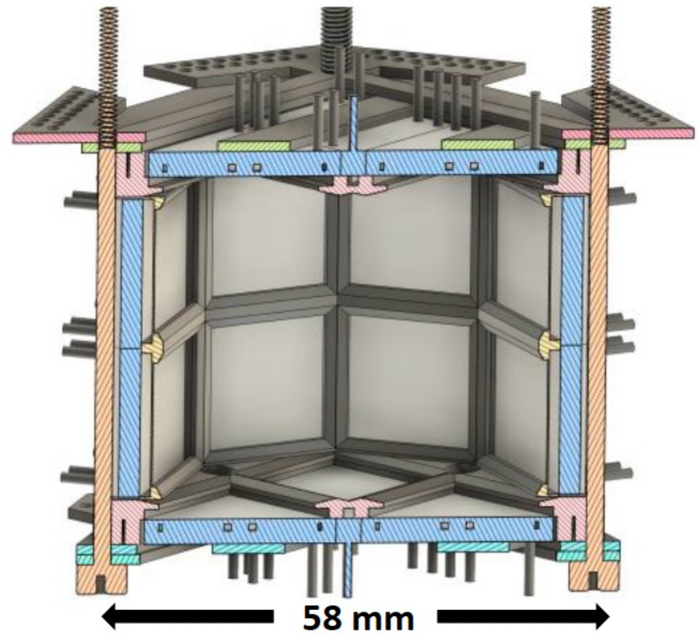


Light emission → external cross-talk
Probing the photons that escape with LoLX



(From LolX group pictures)



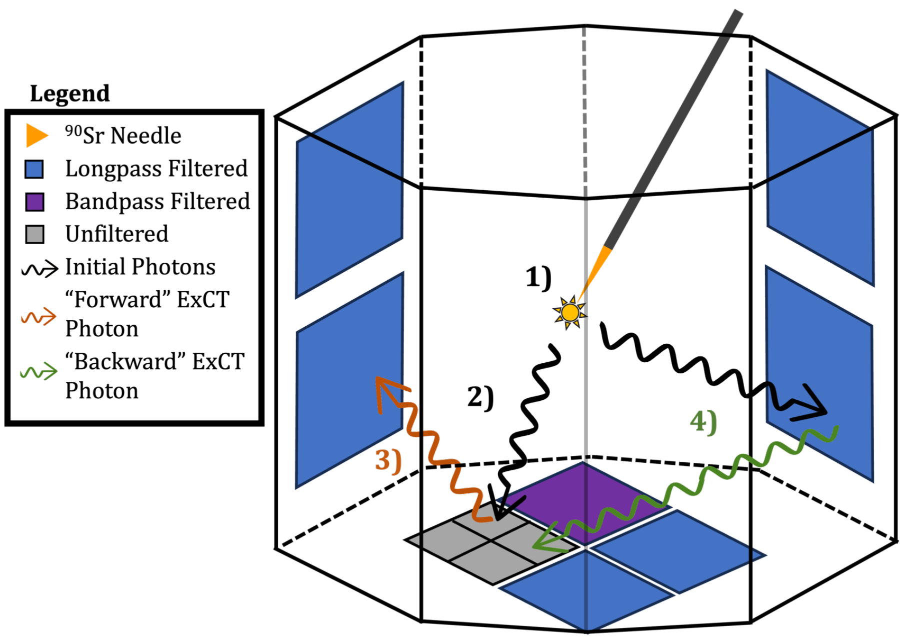


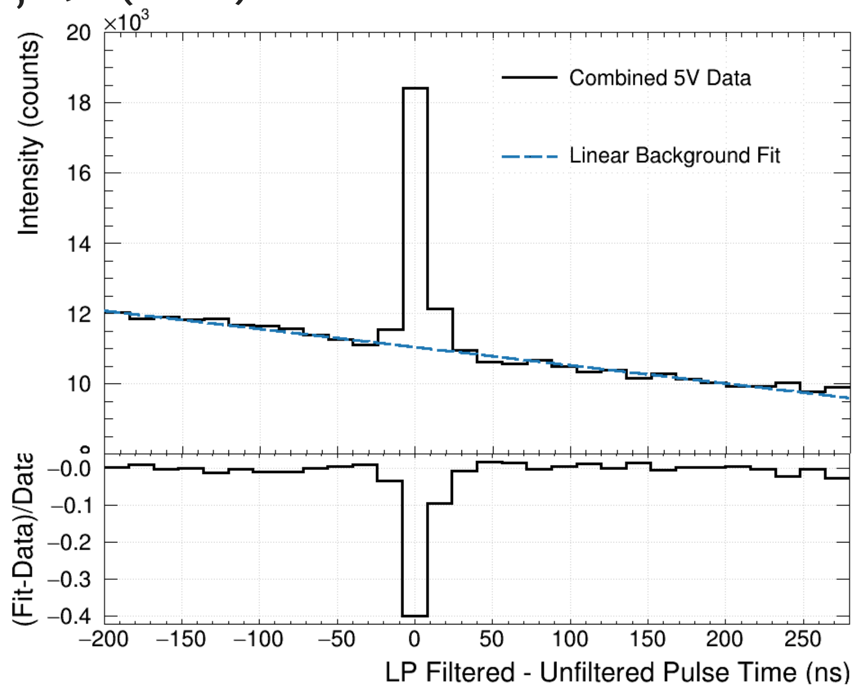
Gallacher, D., de St. Croix, A., Bron, S. *et al.* Characterization of external cross-talk from silicon photomultipliers in a liquid xenon detector. *Eur. Phys. J. C* **85**, 692 (2025)

Light emission → external cross-talk

Use photons straggling after main scintillation event

Gallacher, D., de St. Croix, A., Bron, S. *et al*. Characterization of external cross-talk from silicon photomultipliers in a liquid xenon detector. *Eur. Phys. J. C* **85**, 692 (2025)





LoLX external cross-talk result

Overvoltage	Observable $P_{corr,B}$ (%)	ExCT probability (P_{Forw}) (%)	Emission within Si (γ/Av.)	Emission into LXe, N_{Xe} (γ/Av.)
4 V	3.9 ± 0.2 (stat.) $^{+0.5}_{-0.3}$ (sys.)	$2.1^{+1.2}_{-1.3}$	20^{+11}_{-9}	$0.5^{+0.3}_{-0.2}$
5 V	5.2 ± 0.2 (stat.) $^{+0.6}_{-0.4}$ (sys.)	2.6 ± 1.4	25^{+12}_{-9}	$0.6^{+0.3}_{-0.2}$

Probability that one avalanche by a SiPM triggers one or more avalanche in any neighbors

- MIEL predicts 1.55 ∓ 0.62 photon emitted in liquid Xenon
- Acceptance about 50%
- Efficiency about 10%

Expected about 5%

Simulate

- Photon prod. using in Si isotropic assumption and spectrum from MIEL data
- Transport photons outside Si and within Lxe
- Use measured data for efficiency

Number in tension with MIEL predicted yield

Gallacher, D., de St. Croix, A., Bron, S. *et al.* Characterization of external cross-talk from silicon photomultipliers in a liquid xenon detector. *Eur. Phys. J. C* **85**, 692 (2025)

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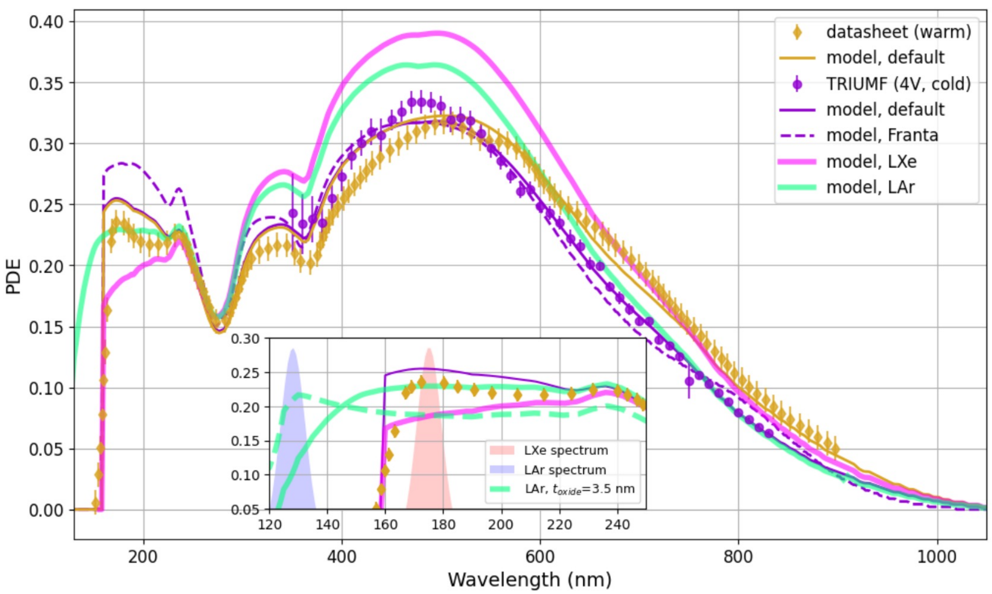
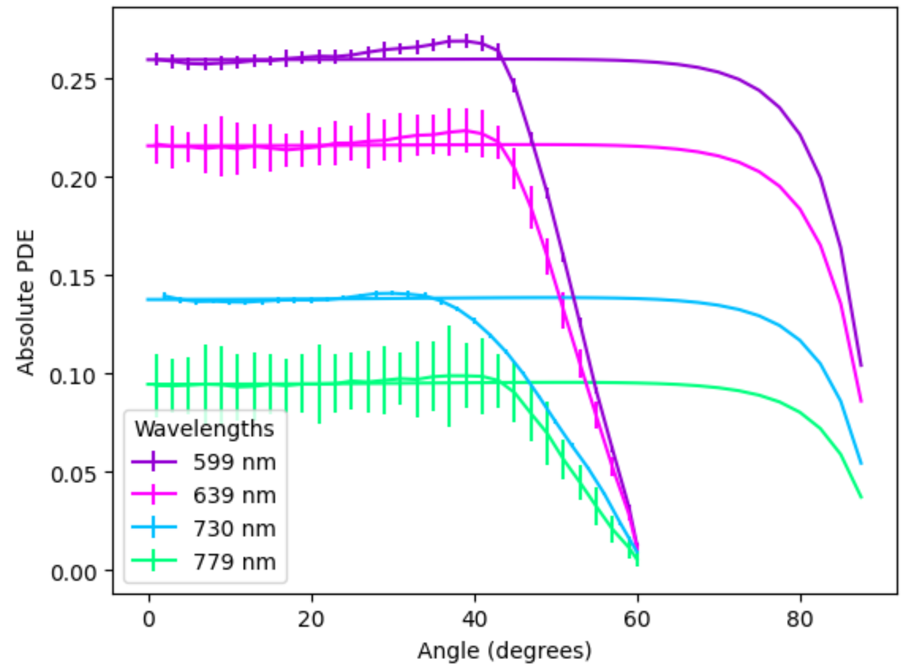
And to interpret cross-talk we had to look at near infra-red efficiency

- Need broadband
- Need angular dependence



A. de St. Croix et al., https://arxiv.org/abs/2508.16005
Trying to get this paper published



Discovery, accelerated

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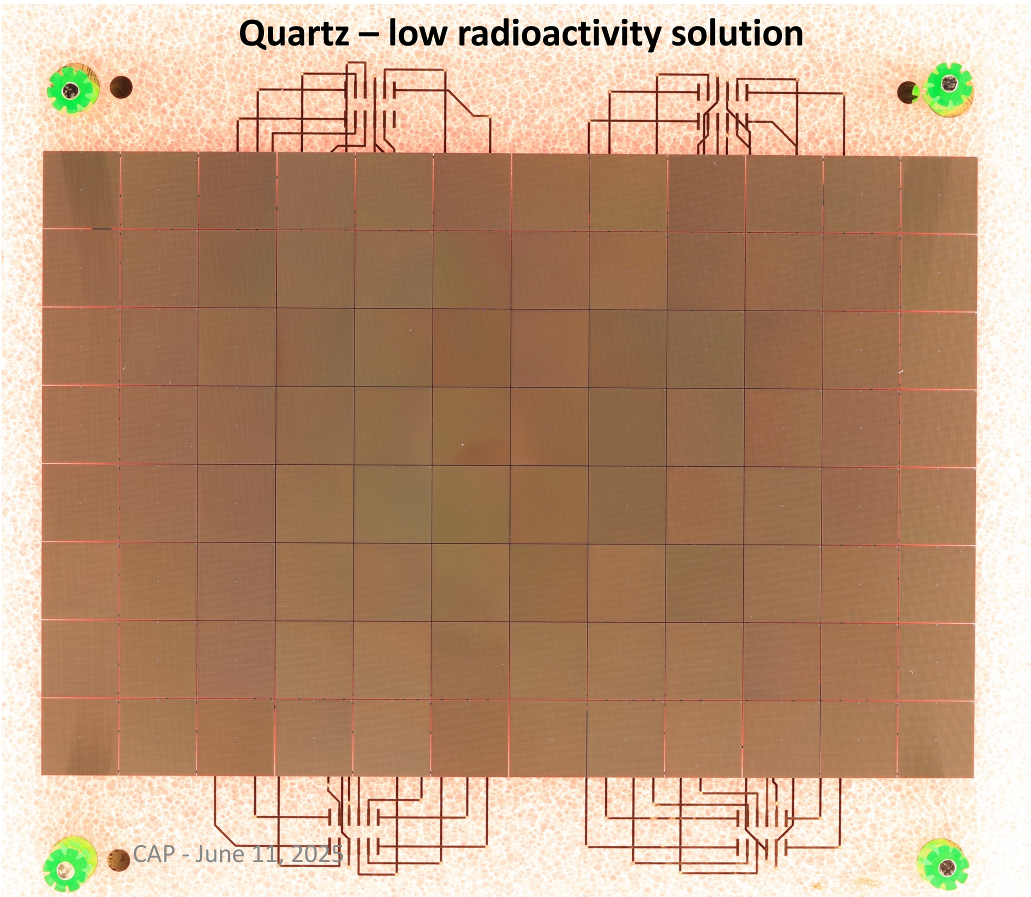
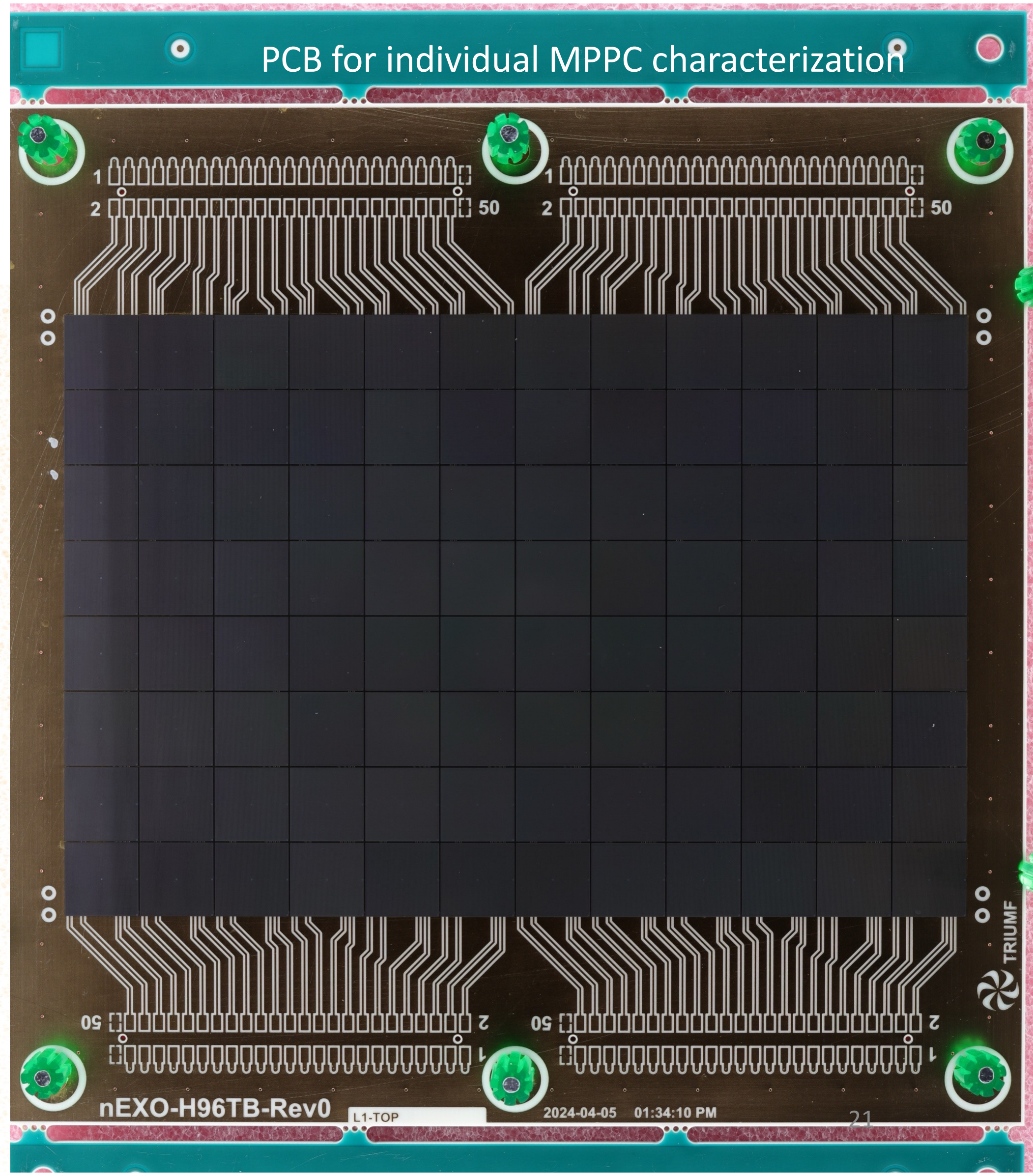
nEXO tiles – 12x8 1cm^2 Hamamatsu MPPC



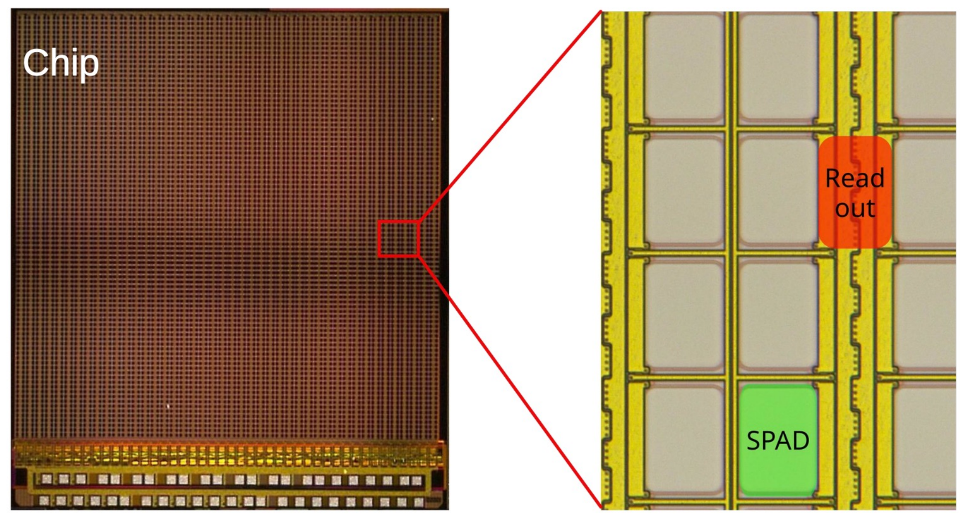


The next frontier: digital SiPM

- Pros
  - “no” power dissipation when idling
  - Tailor performances to needs. E.g. dynamic range, timing, imaging,…
  - Less complex at system level
- Cons
  - In 2D, some efficiency loss
  - More complex at chip level
  - Mass production not demonstrated

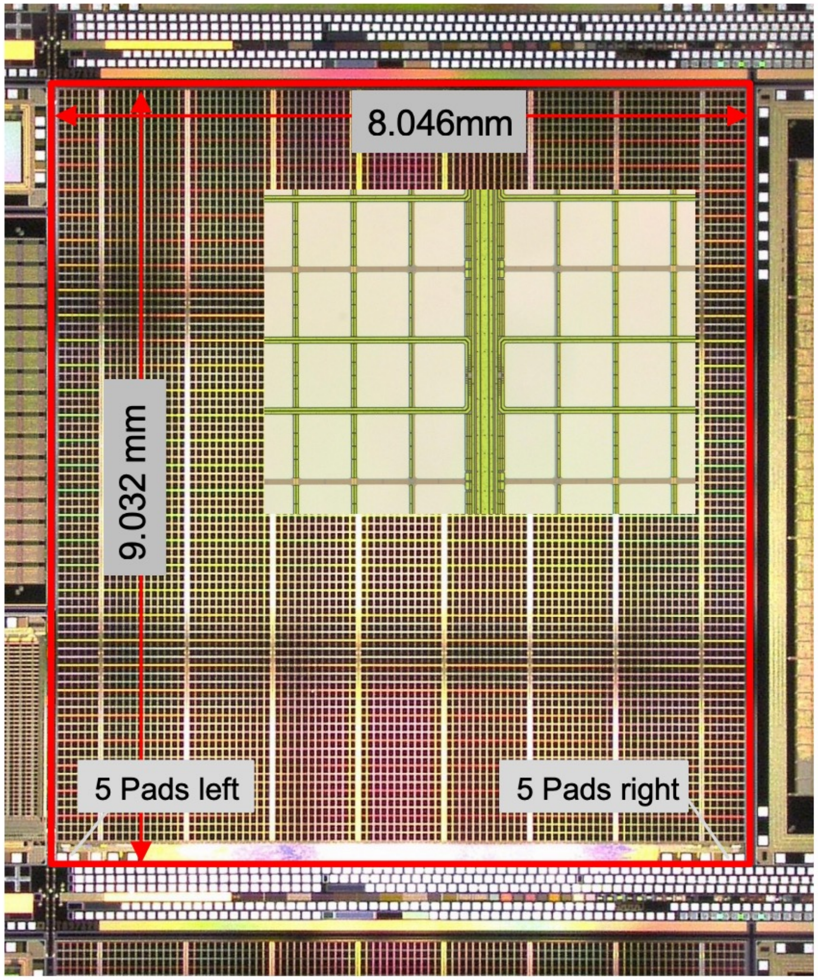
Digital SiPMs for DARWIN

Michael Keller, Peter Fischer, Robert Zimmermann, Michael Ritzert – University of Heidelberg
DARWIN Collaboration Meeting 2023 at University of Heidelberg



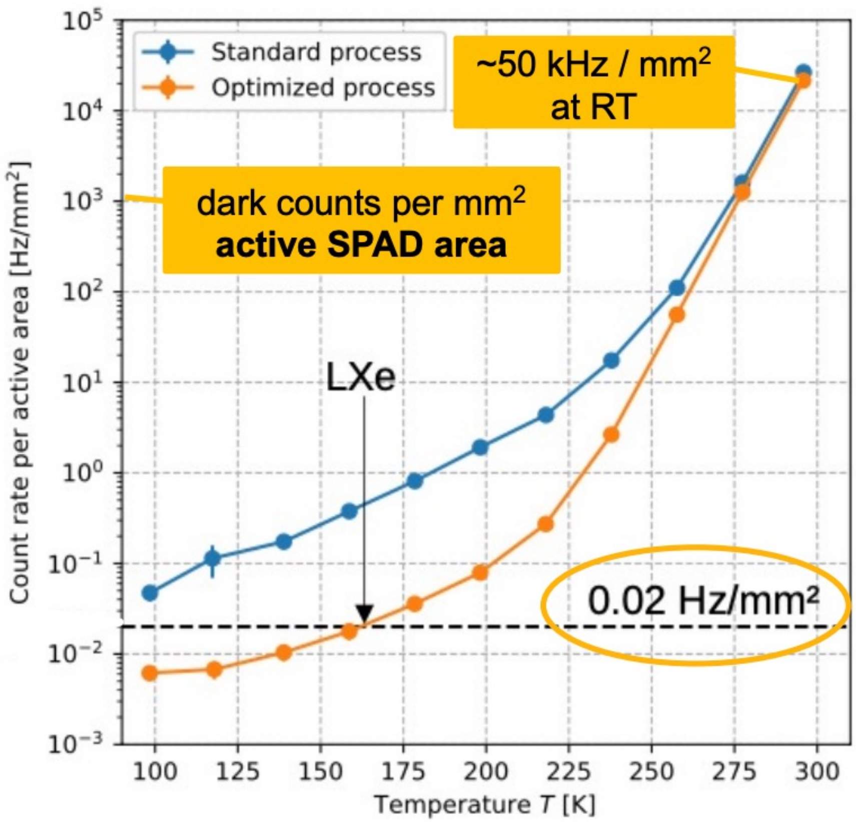
'DARWIN' Chip

- Chip size: ~8 × 9 mm²
- 32 × 30 pixels of 240 × 290 µm²
  - One pixel contains 9 SPADs which can be masked individually (if noisy)
- SPAD active area fill factor ~72% (including periphery, before pixel masking)
- Only 7 chip signal:
  - 4 logic: Clk / Command / SerIn, SerOut
  - 3 supplies: GND, VDD, HV (pads duplicated)
- Manufactured at Fraunhofer IMS, Duisburg
  - 350nm CMOS Process, 4 metal layers
- P. F. et al, JINST 20, 2025
  - DOI 10.1088/1748-0221/20/06/C06008 (O.A.)



Dark count rate is coming down

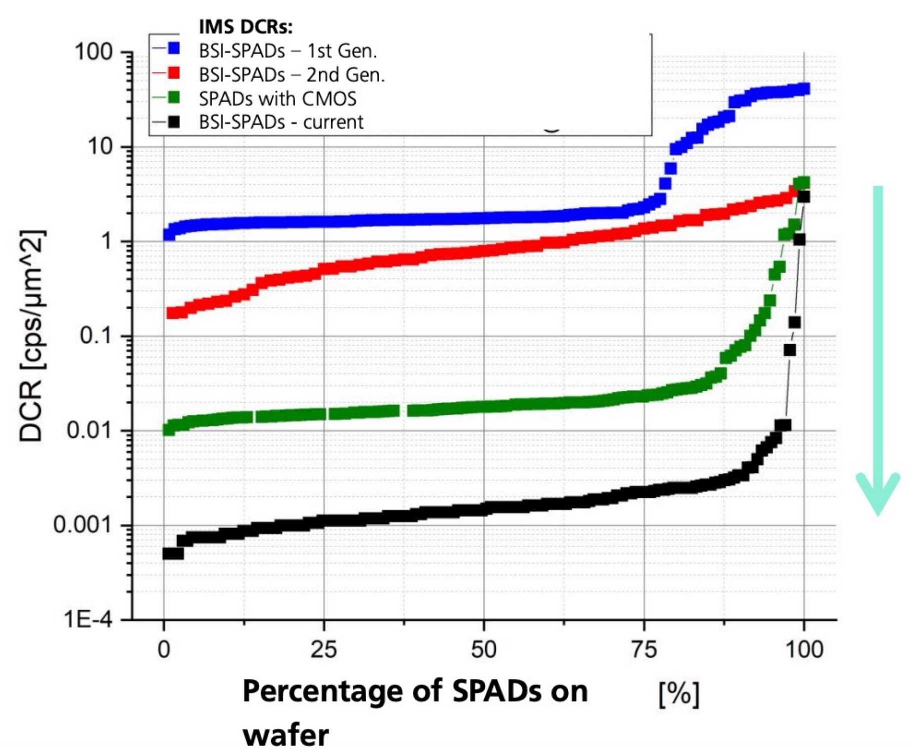
DARWIN chip



Latest Fraunhofer production at room temperature

Can reduce DCR by another order of magnitude by masking

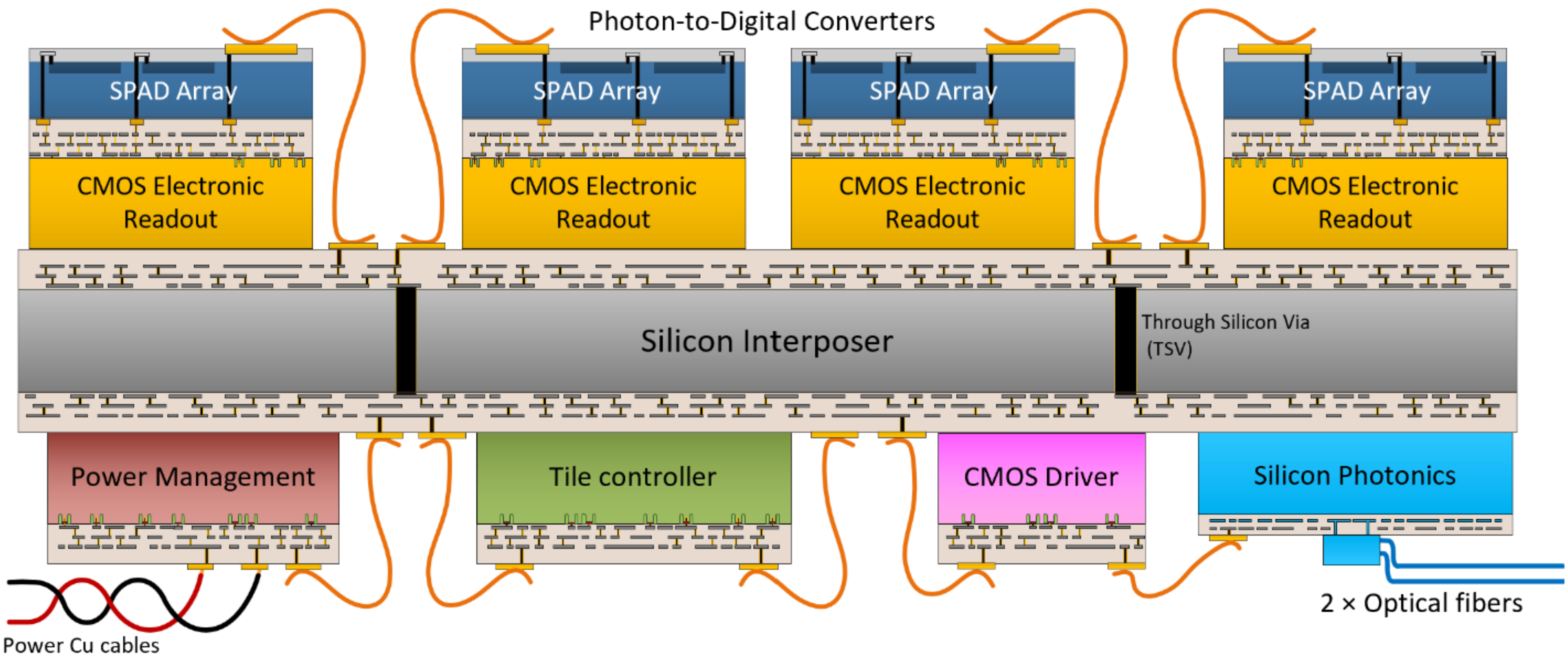
Cost 20% PDE



However production issue

- Fraunhofer no longer offer the production line
- We are working on validating the X-FAB (Germany) SPAD line
  - Chip expected by mid-2026
- So, meanwhile in Canada, the photon to digital converter option is making major progress

Photon to Digital Converter – complete system



All silicon – ultra-low radioactivity solution

The **Photon-to-Digital Converter** – a thinned Frontside Illuminated SPAD Array

UDS

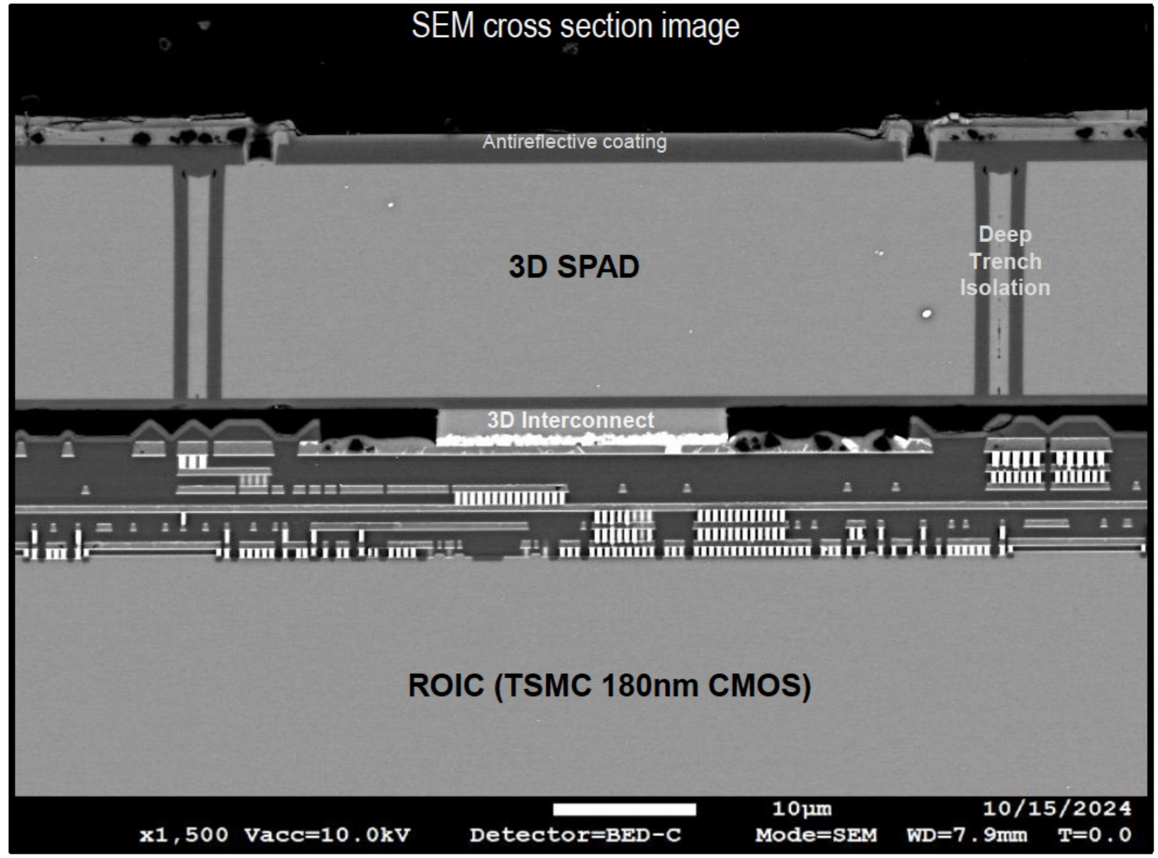
2nd run of improved devices delivered on April 2025

- p^+n SPAD [1]
- **64 × 64 SPAD Array**
- **78 µm pitch** (FF = 26.2%)
- 5.85 × 5.25 mm^2 die
- Peek photon detection probability (PDP) :

  60% @ 420 nm → PDE = 15.8%

  >10% @ 400-800 nm
- **Low power CMOS optimisation** dedicated to high energy physics applications

20 µm



J.-F. PRATTE, S. Parent, S. CHARLEBOIS, and H. DAUTET, "Opto-electrical insulated frontside illuminated 3d digital silicon photomultiplier," US20240113147A1, Apr. 04, 2024 https://patents.google.com/patent/US20240113147A1/en?oq=18%2f526%2c681

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.

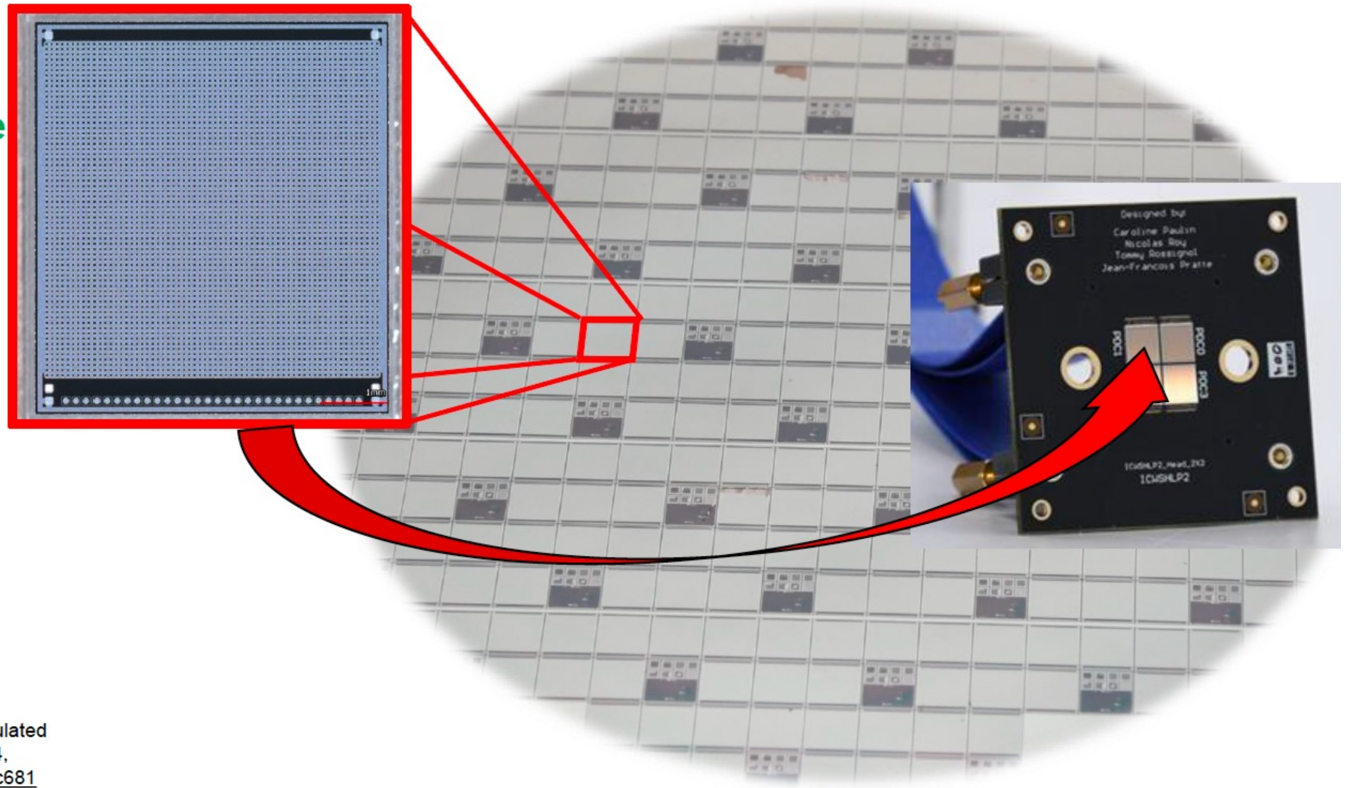
Catherine.Pepin@USherbrooke.ca

The **Photon-to-Digital Converter** – a thinned Frontside Illuminated SPAD Array

UDS

Photon-to-Digital Converter on Head:

- 2 × 2 array of PDCs
- Individual internal quenching circuit:
  → can **enable one SPAD at the time**
  → **programmable** holdoff, recharge
- Shared readout tree:
  → **shared output** (don't know the address of the firing pixel)

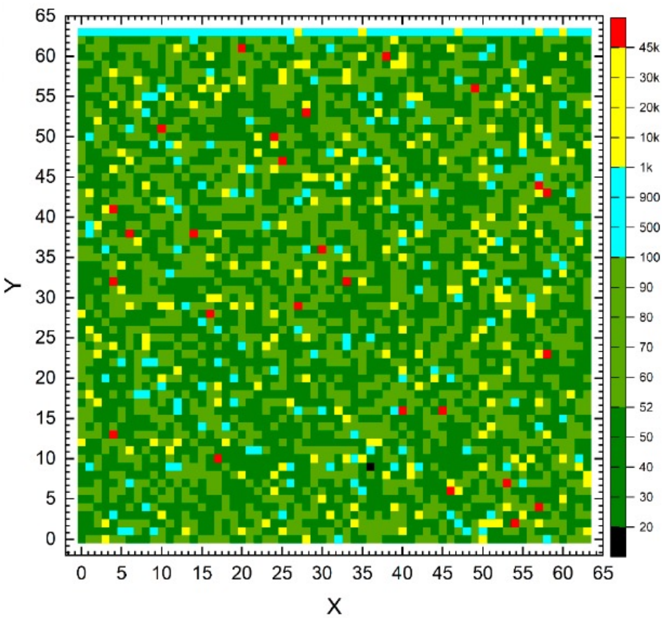


J.-F. PRATTE, S. Parent, S. CHARLEBOIS, and H. DAUTET, "Opto-electrical insulated frontside illuminated 3d digital silicon photomultiplier," US20240113147A1, Apr. 04, 2024 https://patents.google.com/patent/US20240113147A1/en?oq=18%2f526%2c681

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.

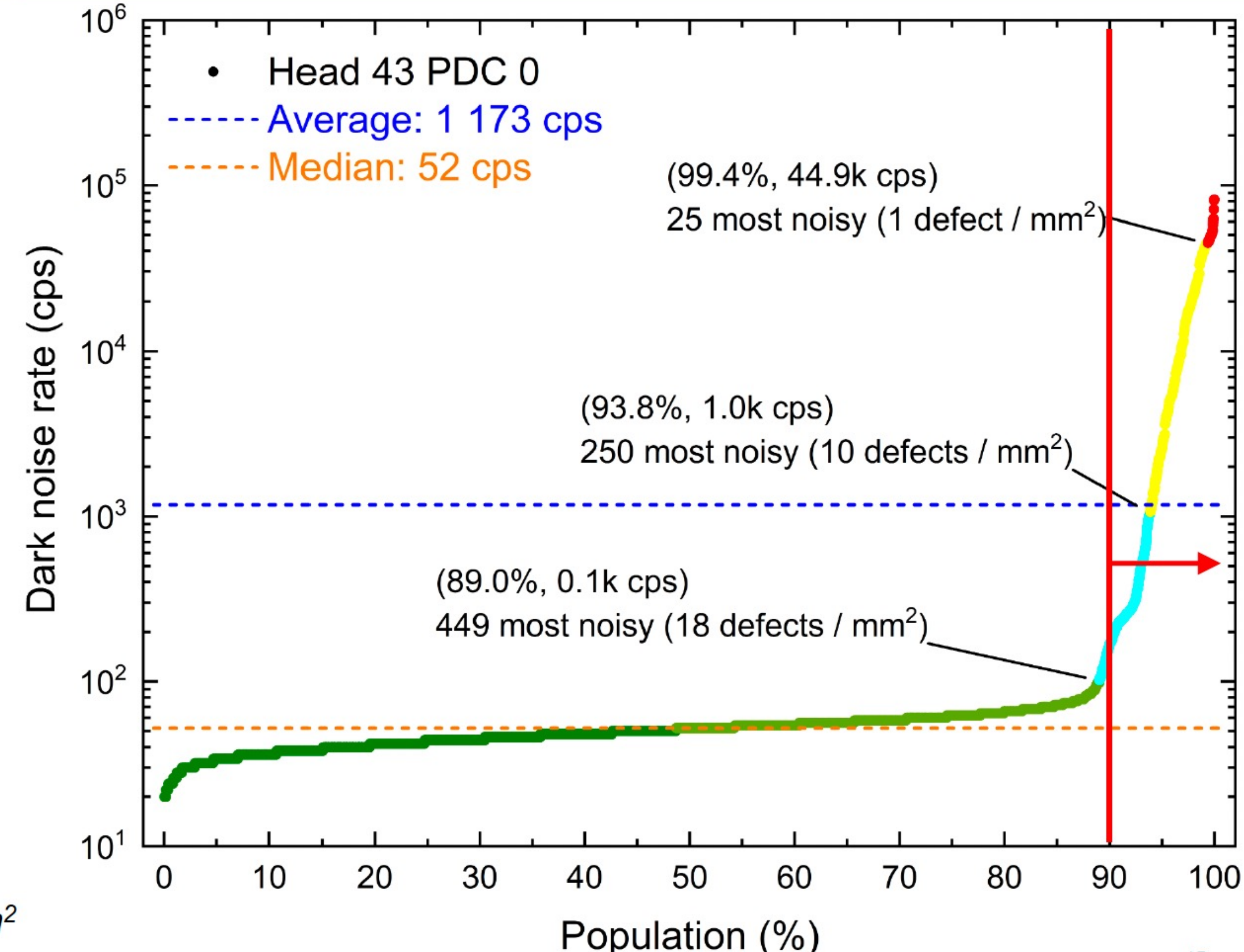
Photon-to-Digital Converter (PDC) | Dark Count Rate (DCR)

Disabling 10% of SPADs
cuts 96% of DCR



Ø SPADs: 40 µm
100 cps → 0.03 cps/µm²

PDC



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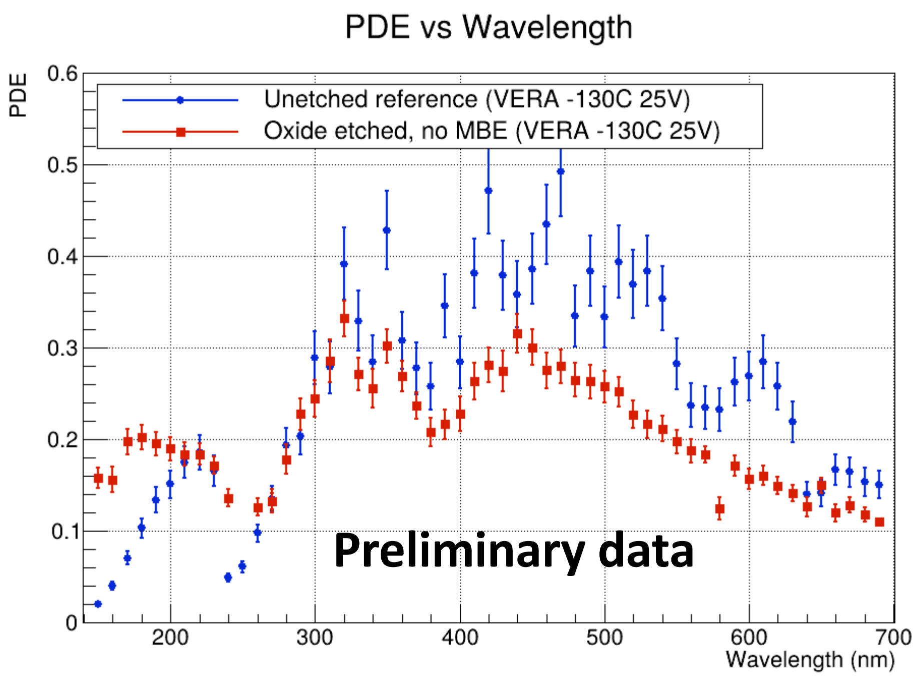
PDC for use in Xenon in large quantity



- Validation of the readout scheme at Manchester
- Detailed characterization at TRIUMF
  - With precursors of 3D PDC
- Facility at Teledyne-DALSA (Bromont about 1h drive from here) to be upgraded in 2026

TRIUMF

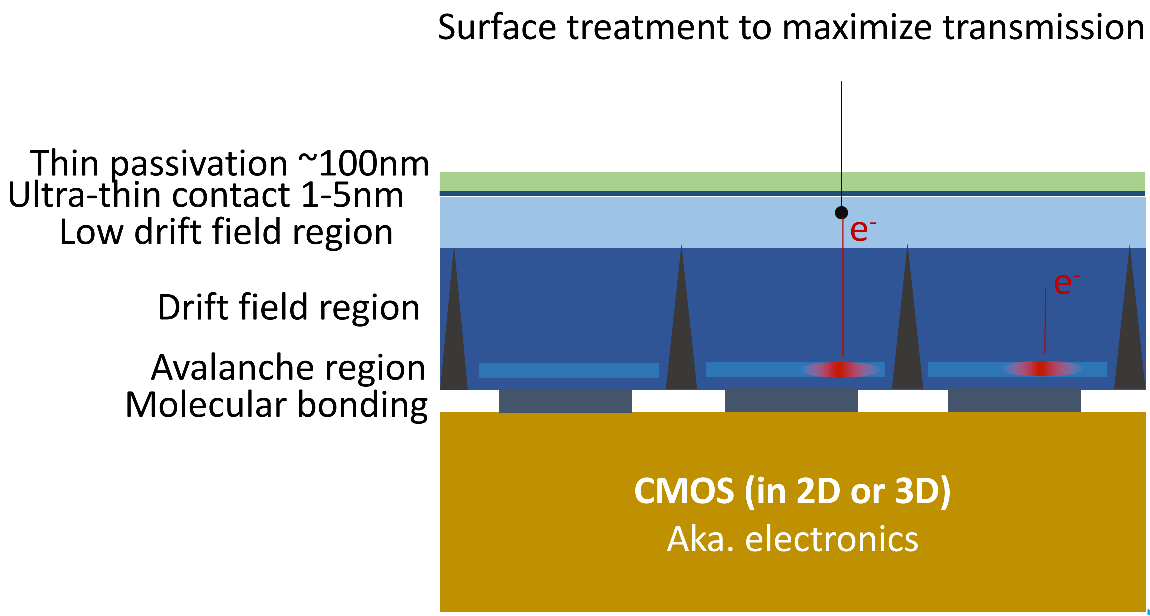
Summary table

Parameter	HPK R11410-21	HPK R12699-406-M4	HPK VUV4	Composite dSiPM
Type	Cylindrical PMT	Square PMT	Square SiPM	Square SiPM
Dimension	$\pi/4 \times 77.5^2 \times 118$ mm^3	56x56x14.8 mm^3	10x10x0.5 mm^3	0.8x0.9x0.5mm^3 [1]
Packing density	61.8%	75%	90%	90%
PDE at 175nm	32.5%	33%	20-25%	20% [2]
Dark count rate	1.4 ± 0.7 Hz/cm^2	0.4 ± 0.2 Hz/cm^2	50 Hz/cm^2	~1 Hz/cm^2 [3]
After-pulsing	8.6 ± 2.2%	1.1 ± 0.2%	10%	0 using holdoff
Light cross-talk	0	0	0.5%(int.)/2.5%(ext)	?
Th Content	16,000 nBq/cm2	10,000 nBq/cm2	0.6 nBq/cm2	?

[1] Peter Fischer's DARWIN chip, Fraunhofer
[2] Sherbrooke's low power PDC, DALSA
[3] Fraunhofer 3D digital SiPM with 20% bad pixel masking

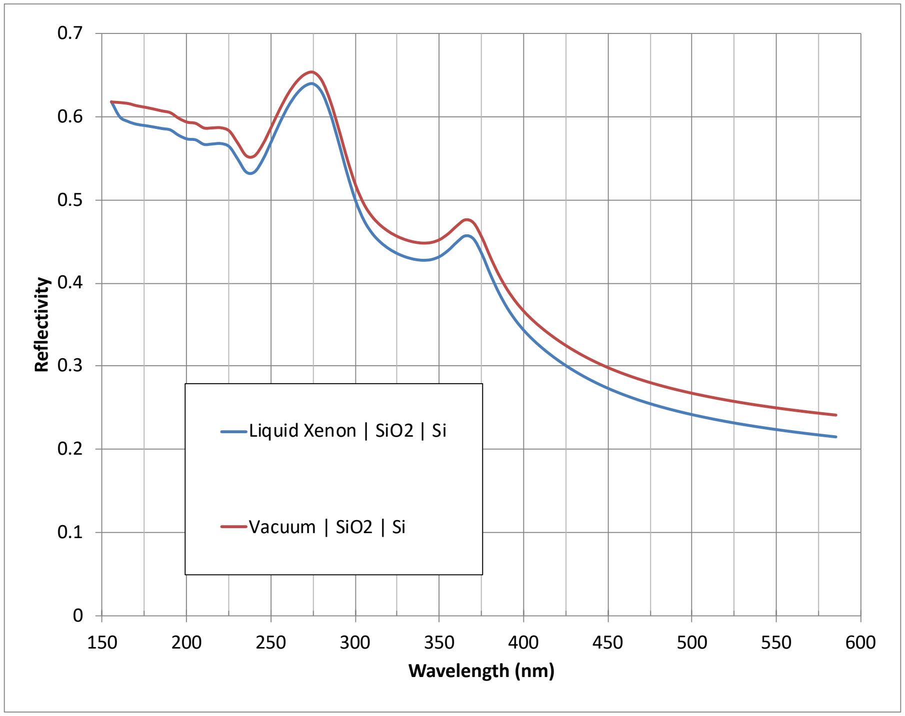
Way forward. The ultimate detector

- SPAD
  - Get to 50% efficiency using Back-side illuminated with VUV surface treatment
  - Use small SPADs
    - Low gain eliminates cross-talk
    - High dynamic range for counting
- Readout
  - Many bits for counting
  - Compromise timing to 10ns if needed
    - Tag first and may be ”last” photon per chip
- Get to production scale
  - Teledyne-DALSA 8” line



In Canada?
Or build an intermediate 2D SPAD step?

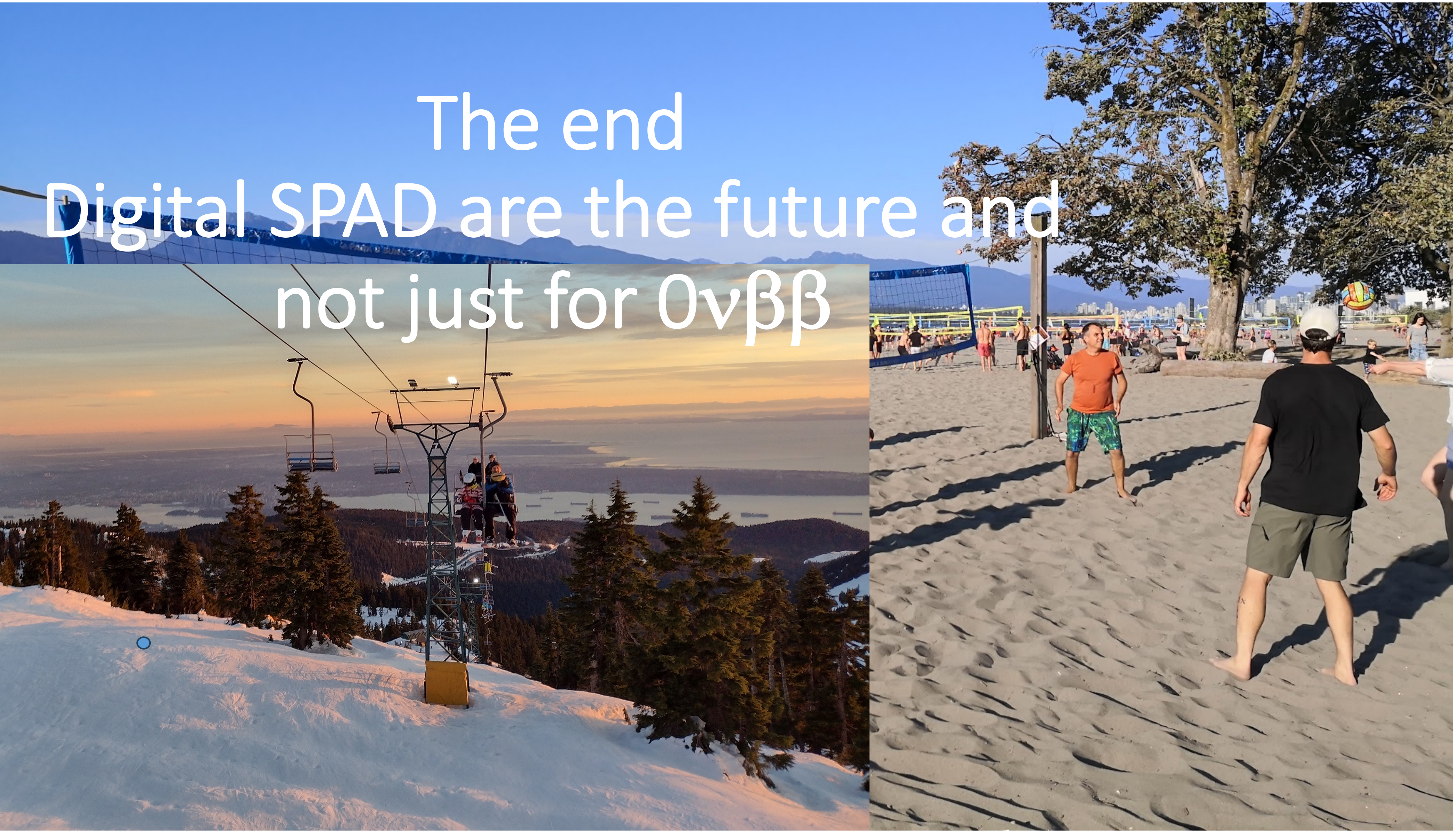
Way forward – enhancing efficiency for silicon detectors



- Defeating reflections requires an "exotic" solution
  - Graphene (UK groups)
  - Al2O3 pillar called black silicon is very promising but fragile
  - Growing pillars in silicon?
  - Embedding wavelength shifter material (Manchester)

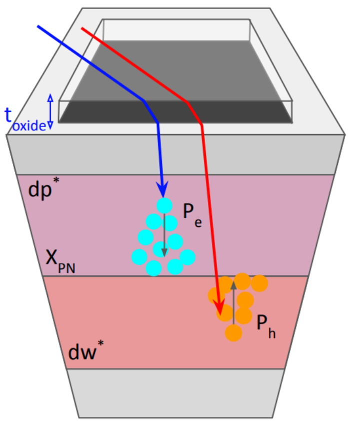
Test all this in a low mass DM + $0\nu\beta\beta$ demonstrator

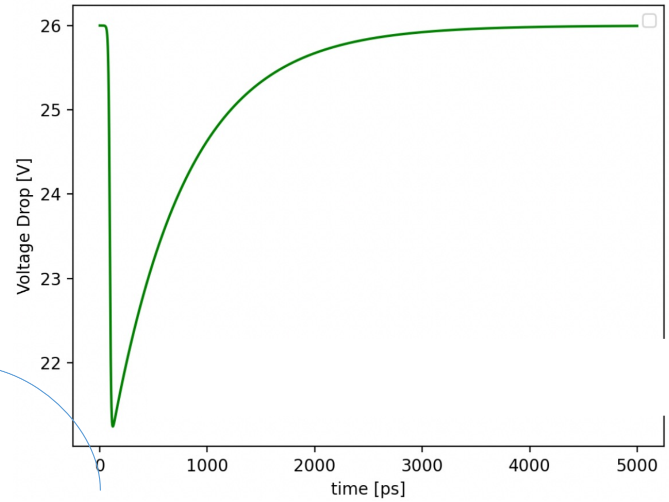
- Build a LAr or/and LXe double phase TPC
  - Plan for low mass DM with LAr in Canada could hold 3,500 kg of Lxe
  - Using ultra-low background digital SiPMs tailored for the application
- Deliverables
  - Low mass DM. Demonstrate the single/few e- threshold with LAr and Lxe
  - Demonstrate radiopurity at system level. Use detector itself to gauge background level and validate ICMPS extrapolations
  - Demonstrate ability to handle dynamic range from 1 photons to >1,000 per channel
  - Demonstrate energy resolution. 0.5% FWHM at 2.45 MeV should be achievable


The end
Digital SPAD are the future and
not just for 0νββ

SiPM, Silicon photomultiplier

An array of Single Photon Avalanche Diodes (SPAD)



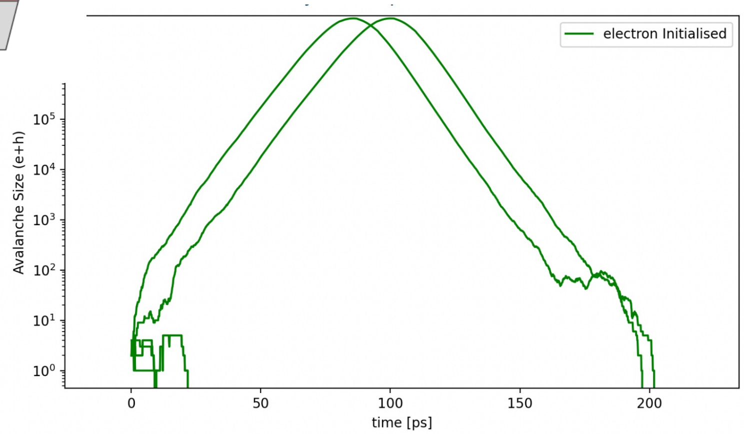


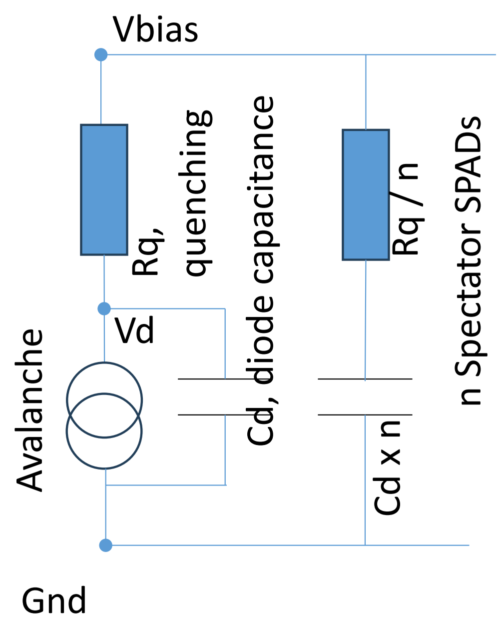
Cd recharges

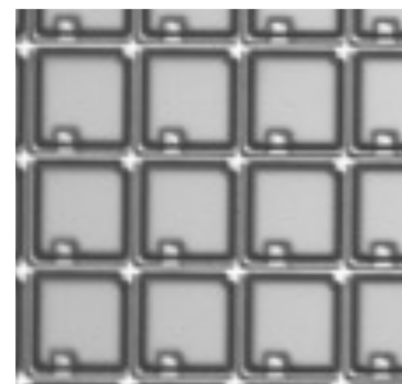
Seed carrier

Vd drops
Cd empties

Avalanche

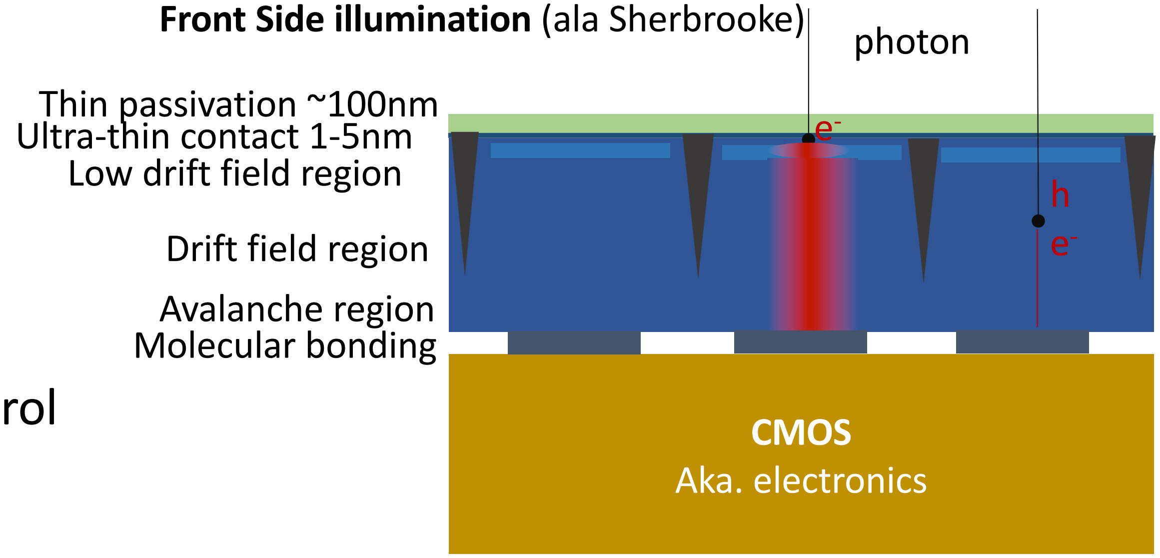


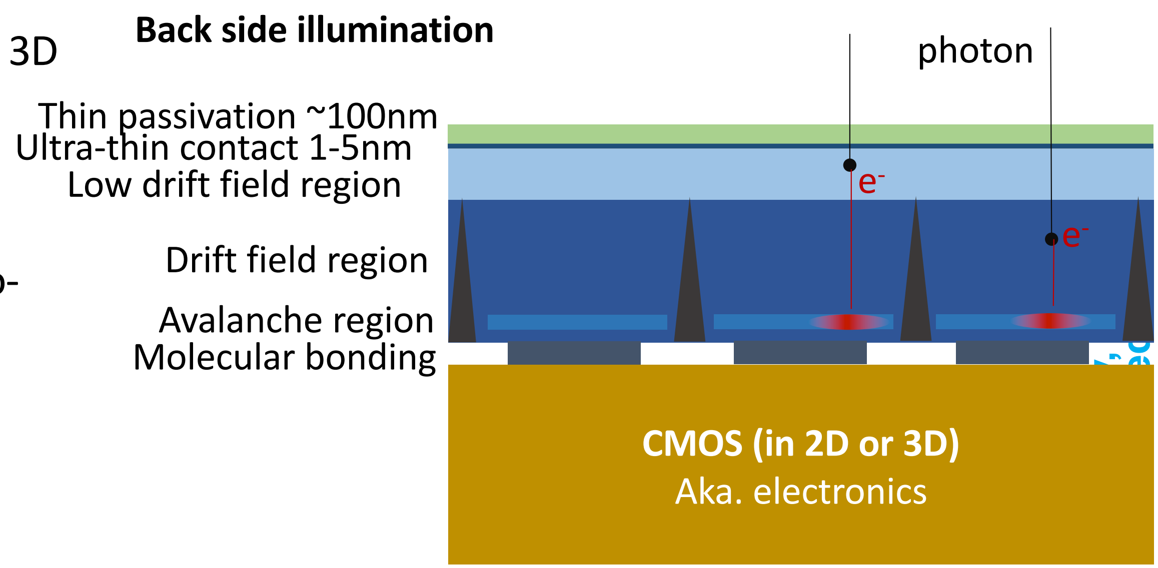




PDC detour

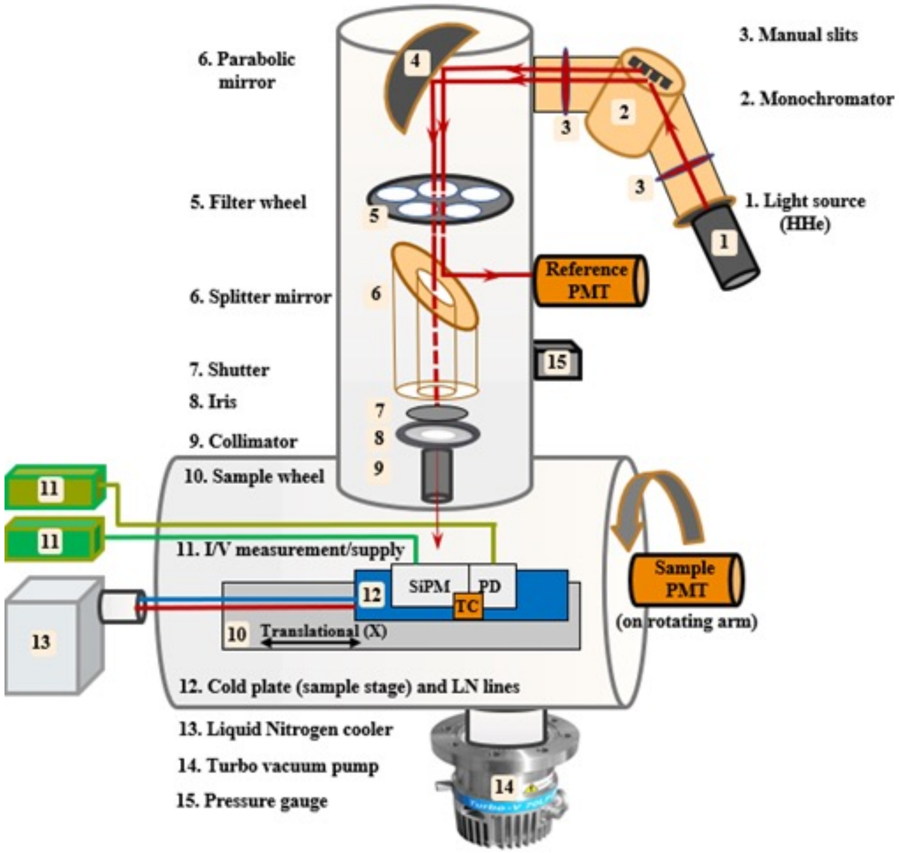
- Versatility
  - Visible to IR via thickness control
  - Deep UV through Back-side surface processing
    - Unconventional Anti-reflective coating: black silicon, graphene, 3D structures
  - Non-photon detection
    - Minimum ionizing
    - keV scale electron (hybrid photo-detector)
    - Dark matter





TRIUMF

Asset: Vacuum Ultra-Violet Efficiency reflectivity and Absorption setup (VERA)



For example: inferring the number of electrons produced per VUV photon