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Optical modeling of pixelated digital SiPMs for the ARGO dark matter experiment

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ABSTRACT: Silicon photomultipliers (SiPMs) are increasingly being adopted in noble-liquid detectors for rare-event searches owing to their high photon-detection efficiency, low operating voltage, and intrinsic radiopurity. A known drawback of SiPMs is the emission of secondary photons during the avalanche breakdown, which can induce optical crosstalk between microcells and generate correlated noise. To investigate these effects in the context of the ARGO dark matter experiment, we developed a detailed Geant4-based optical model of pixelated digital SiPMs within the RAT simulation framework. The model represents each device as a discretized grid of SPADs with realistic avalanche regions and boundary properties, including an efficiency parameter that emulates the isolation effect of optical trenches. The simulation reproduces measured photon detection efficiencies and internal/external crosstalk yields, and is used to evaluate their impact on detector-level observables such as pulse-shape discrimination and event-position reconstruction. These studies establish performance targets for next-generation digital SiPMs and provide critical input for the ARGOLite prototype program and the design of the full-scale ARGO light-readout system.

KEYWORDS: Dark Matter detectors (WIMPs, axions, etc.); Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Noble liquid detectors (scintillation, ionization, double-phase); Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc)

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1 Introduction

Liquid argon (LAr) has emerged as a leading detection medium for rare-event searches [1] owing to its powerful pulse-shape discrimination capability, scalability to large target masses, and intrinsic radiopurity. Building on the success of the first-generation experiments — ArDM [2], DarkSide-50 [3], miniCLEAN [4], and DEAP [5] — the Global Argon Dark Matter Collaboration (GADMC) was established in 2017 to develop next-generation detectors with multi-tonne active masses. The collaboration is currently constructing DarkSide-20k [6], a 50-tonne (20-tonne fiducial) underground argon detector at LNGS, Italy, scheduled to begin operation in 2028. Its successor, ARGO, will be the flagship project of GADMC, planned for construction at SNOLAB in the next decade. ARGO will feature a 400-tonne underground argon target (300-tonne fiducial) viewed by digital silicon photomultipliers (SiPMs) with a total active area of approximately 250 m². With a projected exposure of 3000 tonne-years, ARGO will achieve unprecedented sensitivity to high-mass WIMPs, probing well into the neutrino-coherent scattering background (the “neutrino fog”) [7].

To meet the stringent optical and noise requirements of such a detector, ARGO will employ pixelated digital SiPMs that combine single-photon sensitivity with fast timing and fine spatial granularity. In these devices, each single-photon avalanche diode (SPAD) integrates local electronics that provide direct digital readout and enable per-SPAD control, reducing electronic noise and allowing the selective disabling of noisy cells. These characteristics make digital SiPMs highly scalable for large-area, low-power cryogenic systems, while also providing precise photon timing for advanced event reconstruction and hit pattern-based background identification.

A key limitation, however, arises from optical crosstalk — secondary photons emitted during SPAD avalanches [8] that can trigger additional avalanches either within the same device (internal crosstalk) or in neighboring SiPMs (external crosstalk). Although internal crosstalk is well studied at the device level, external crosstalk depends strongly on the detector geometry and optical coupling. In a large-scale, highly pixelated detector such as ARGO, correlated noise from crosstalk can impact energy resolution, pulse-shape discrimination, and event reconstruction. To address this, we developed a detailed optical model of pixelated digital SiPMs within a Monte Carlo simulation framework to study detection efficiency and crosstalk behavior at both device and detector scales.

This paper presents an overview of the ARGO detector concept and the motivation for digital SiPM photodetectors, describes the implementation of the geometrical and optical models, discusses the resulting crosstalk characterization, and examines the detector-level implications for light-collection performance and background discrimination.

2 ARGO detector concept and photodetectors

Figure 1 shows two conceptual designs of the ARGO detector within the Cube Hall of the SNOLAB underground facility. The central volume is an acrylic vessel (AV), whose inner surface is coated with tetraphenyl butadiene (TPB) wavelength shifter [10], and contains approximately 400 tonnes of ultrapure underground argon (UAr). Surrounding the AV on the outer side is an array of digital silicon photomultipliers (SiPM) (shown in green), providing a true 4π photodetector coverage. The AV and photodetectors are enclosed in a vacuum-insulated stainless-steel cryostat filled with liquid argon; this buffer region is also instrumented with photodetectors and serves as an active veto for external gammas and neutrons from detector components. The outermost layer is a large water-shield tank that moderates radiogenic neutrons from the cavern walls and acts as a muon veto. Process and data-acquisition (DAQ) systems are housed at the top of the detector. The cylindrical geometry (left panel of figure 1) was used for all detector-level studies of SiPM optical crosstalk.

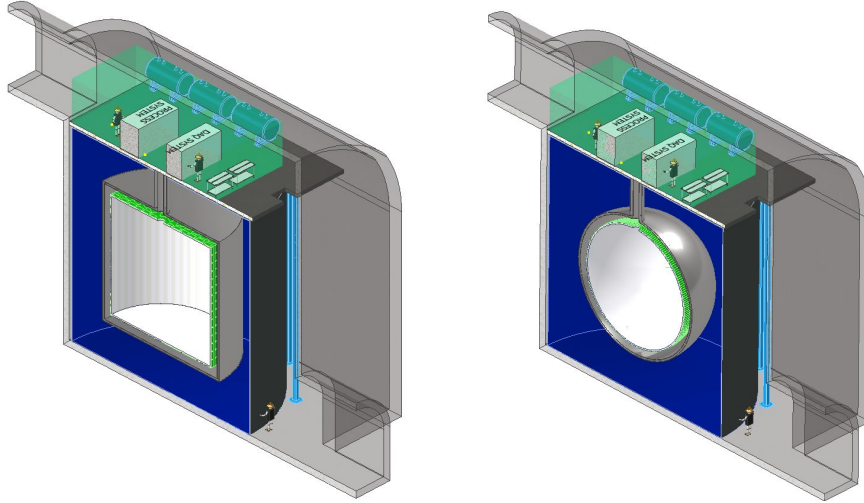


Figure 1. Conceptual designs of the ARGO detector in SNOLAB Cube Hall, with cylindrical (left panel) and spherical (right panel) central acrylic vessels.

3 Geometrical model of SiPMs in Monte Carlo simulation

The Monte Carlo studies were carried out in RAT [11], a Geant4 and ROOT-based Monte Carlo and analysis tool that is also used by SNO+ and DEAP-3600 collaborations. We have a full-scale implementation of the ARGO geometry, which includes the acrylic vessel, TPB wavelength-shifting layer, and surrounding photodetector planes. The individual photodetector units in the simulation are defined as $10\text{ cm} \times 10\text{ cm}$ SiPM tiles positioned and oriented to maximize the overall coverage, corresponding to a total instrumented area of about 250 m^2 . Each SiPM tile is segmented into a

discretized virtual grid of SPADs with a $25\ \mu\text{m}$ pitch and a geometrical fill factor of 70%. The effect of optical trenches between SPADs is modeled using a photon propagation efficiency factor specific to internal crosstalk photons. Figure 2 shows a schematic cross-section of a SiPM tile implemented in the simulation. The model consists of a $600\ \mu\text{m}$ -thick silicon substrate containing a $1\ \mu\text{m}$ -thick avalanche region [12] located $100\ \text{nm}$ beneath the surface. Photons absorbed within this region are recorded as detected hits. A $60\ \text{nm}$ anti-reflective coating (ARC) layer is included on the Si surface, with optical properties derived from spectrophotometric reflectance measurements performed using an integrating-sphere setup. Refractive indices and absorption lengths for silicon, the ARC material, and liquid argon are defined over the wavelength range of $100\text{--}800\ \text{nm}$, enabling realistic photon-transport modeling.

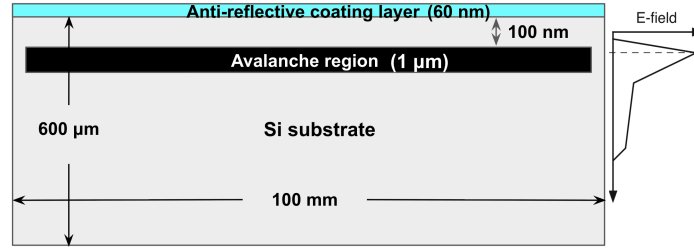


Figure 2. Schematic of a SiPM tile in the MC framework with essential components labeled.

The geometrical model reproduces the photon detection efficiency (PDE) vs. wavelength dependence reported in the manufacturer’s datasheet [13], as shown in figure 3, thereby validating the approach before introducing optical crosstalk processes, described in the following section.

4 Optical crosstalk modeling and results

Optical crosstalk in silicon photomultipliers occurs when secondary photons, generated during a SPAD avalanche, trigger additional avalanches in neighbouring microcells. In the simulation, for each photon detection within the avalanche region defined in the geometrical model, a random number of crosstalk photons is sampled from a Gaussian distribution with a mean of 60, consistent with recent measurements on HPK VUV4 and FBK VUV-HD3 devices [14]. The emission spectrum follows the measured infrared distribution [15], and photon directions are sampled isotropically within the high-field region. Photon transport through the silicon substrate, the anti-reflective coating (ARC), and the surrounding liquid-argon medium was found to be sufficiently well described by standard Fresnel processes in Geant4; hence, optical interference effects in the ARC were not explicitly added to the optical model. An empirical attenuation parameter ϵ was introduced to model the effective absorption of internal crosstalk (iCT) photons due to optical trenches between SPADs. The survival probability of an iCT photon is parameterized as $P = \exp(-d/\epsilon)$, where d is the photon propagation distance within the Si bulk. This probability is used as an acceptance criterion during photon tracking based on a uniform random number in $(0,1)$. Figure 4 illustrates the dependence of iCT probability on ϵ . A value of $\epsilon = 0.0036$ reproduces an iCT probability of approximately 30% in the simulation, consistent with laboratory measurements [16].

The simulation yields a mean external-crosstalk yield per avalanche of $\langle N_{\text{eCT}} \rangle \approx 0.9$, in agreement with measurements based on the direct observation of secondary-photon emission in SPADs [14]. This corresponds to the escape of approximately one photon per avalanche, which leads to a $\sim 9\%$ contribution

to detected signals in the detector-level simulation, consistent with laboratory measurements [16]. The angular distribution of external-crosstalk photons emitted into LAr, shown in figure 5, peaks at large emission angles relative to the SiPM surface normal. This is consistent with total-internal-reflection behaviour at the SiO_2 –LAr interface due to significant differences in the refractive indices of SiO_2 (~ 1.45) and LAr (~ 1.23) at crosstalk emission wavelengths.

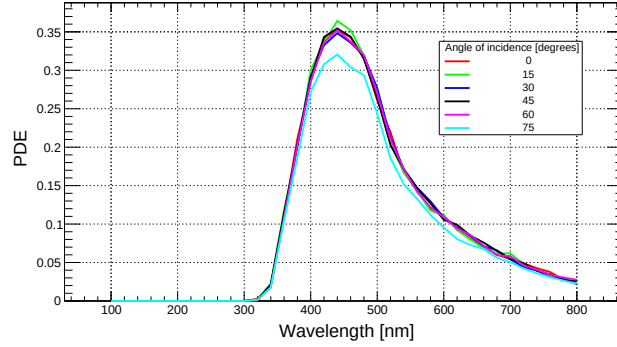


Figure 3. Simulated photon detection efficiency (PDE) of the SiPM as a function of wavelength. The PDE curves for different angles of incidence are also shown.

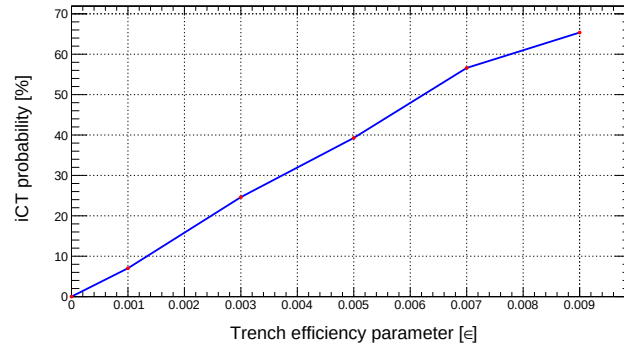


Figure 4. Simulated internal crosstalk probability as a function of the efficiency parameter introduced in the simulation to model the effective optical absorption by trenches between SPADs.

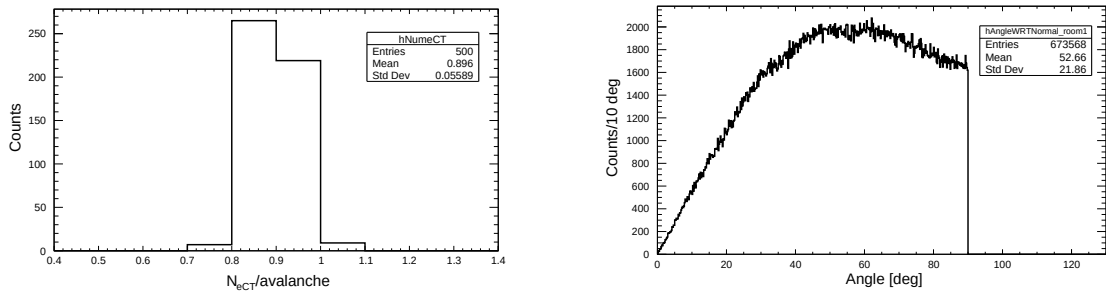


Figure 5. Left: simulated mean external crosstalk yield per avalanche. Right: angular distribution of external crosstalk photons emitted into liquid argon, peaking at large emission angles relative to the SiPM surface normal.

5 Detector-level implications

The validated SiPM optical model was incorporated into the full ARGO Monte Carlo framework to study how correlated noise from optical crosstalk influences key detector observables, including pulse-shape discrimination, photon-hit clustering, and event reconstruction.

5.1 Pulse-shape discrimination (PSD)

The ability to distinguish electron-recoil (ER) and nuclear-recoil (NR) events in liquid argon relies on their distinct scintillation time profiles. The discrimination parameter,

$$F_{\text{prompt}} = \frac{\int_0^{t_{\text{prompt}}} S(t) \cdot dt}{\int_0^{t_{\text{total}}} S(t) \cdot dt}, \quad (5.1)$$

defined as the ratio of the prompt to total integrated signal, provides powerful background rejection. The DEAP-3600 experiment has demonstrated an ER rejection factor of approximately 10^9 using this technique [9]. To evaluate PSD performance in ARGO, we generated ER and NR Monte Carlo samples with energy deposits between 5–35 keV_{ee} in the fiducial volume and fitted the ER F_{prompt} distribution using the empirical PSD function, $PSD(f)$, developed by DEAP-3600. The ER leakage probability at a given F_{prompt} value, f , is estimated as

$$P_{\text{leak}}(f) = \frac{\int_f^1 PSD(f) \cdot df}{\int_0^1 PSD(f) \cdot df} \quad (5.2)$$

The resulting curves for the lowest PE bin of the ROI (figure 6) show that the ER leakage probability at 50% NR acceptance (NRA) is approximately an order of magnitude higher in the presence of optical crosstalk (oCT). This behavior is consistent with physical expectations, as oCT introduces additional Poisson fluctuations in the detected photon counts, thereby broadening the F_{prompt} distributions for both ER and NR events. The effect is most pronounced at low energies, where photon statistics are limited, leading to degraded PSD performance. Our simulation further indicates that iCT is the dominant contributor to this degradation. These results constrain the achievable energy threshold for ARGO under current crosstalk conditions and establish quantitative limits on acceptable SiPM crosstalk levels required to meet the experiment’s background-rejection goals.

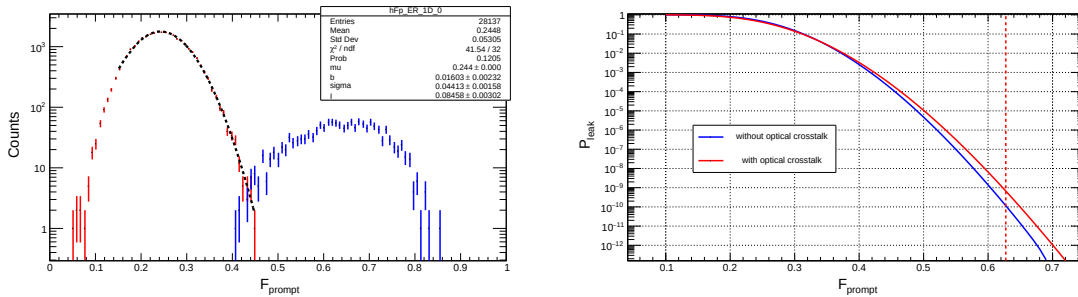


Figure 6. Left: ER (red) and NR (blue) F_{prompt} distributions for the lowest PE bin of the ROI, with the empirical PSD function fit (black line) to the ER data. Right: ER leakage probability with (red) and without (blue) optical crosstalk as a function of F_{prompt} ; the dashed vertical line corresponds to 50% NR acceptance.

5.2 Surface-background rejection

The fine segmentation of pixelated digital SiPMs enables the analysis of photon hit patterns for event identification. Simulations of α -decays from the inner surface of the acrylic vessel exhibit distinctive clustering of detected photons on the SiPM plane (figure 7, left), providing a spatial signature for surface backgrounds. The simulation results indicate that crosstalk does not significantly affect photon hit-clustering patterns of surface events. A complementary reconstruction algorithm based on photon time-of-flight further localizes these events outside the fiducial volume, as shown in figure 7 (right). The impact of optical crosstalk on the position reconstruction performance is under investigation and will be reported in future work.

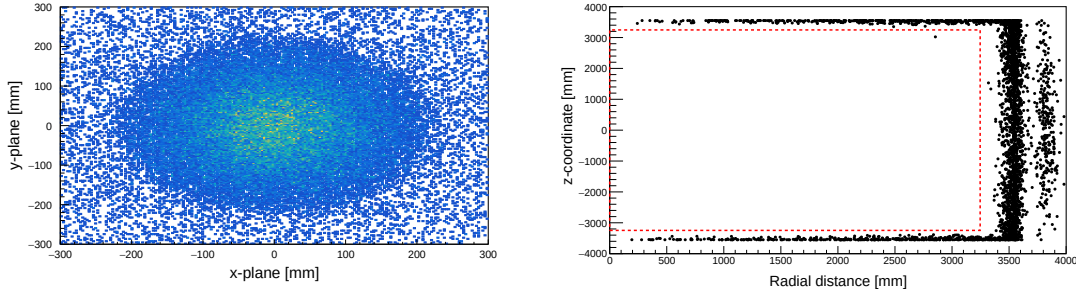


Figure 7. Left: photon-hits with a $3\text{ mm} \times 3\text{ mm}$ readout granularity, mapped onto a $60\text{ cm} \times 60\text{ cm}$ SiPM plane behind simulated surface alpha events. Right: performance of the event reconstruction algorithm based on photon time-of-flight, showing reconstructed positions of surface events relative to the fiducial volume boundary represented by the dotted red box.

Combining these spatial and temporal reconstruction techniques yields a projected surface-event rejection at around 10^{-7} , demonstrating the potential of pixelated digital photodetectors for achieving robust background suppression in large-scale liquid-argon detectors.

6 Ongoing developments

The optical modeling studies presented here will be benchmarked in a small prototype detector planned at SNOLAB in the near future. Following the decommissioning of DEAP-3600 in 2027, its cryogenic, purification, and shielding systems will be repurposed for ARGOLite, a single-phase LAr detector designed as a technology demonstrator for ARGO. The prototype will host a 2 m^2 array of pixelated digital SiPMs coupled to an AI-based DAQ system. It will serve as a testbed for detector-level characterization of SiPM correlated noise, PSD, and surface event rejection performance.

For photodetectors, two complementary technologies are being pursued within the collaboration: (1) 3D photon-to-digital converters (PDCs) [17] developed at the University of Sherbrooke in Canada, in which each SPAD is vertically stacked onto a CMOS readout, achieving per-SPAD digitization; and (2) the ATARI system [18] under development by FBK and INFN-LNGS in Italy, which couples $3\text{ mm} \times 3\text{ mm}$ SiPM pixels to dedicated readout ASICs through a passive interposer (a 2.5D architecture). Both approaches aim to deliver low-noise, low-power photodetectors with fast photon timing, suitable for the $\sim 250\text{ m}^2$ light-collection system of ARGO. Sample wafers from both programs are being fabricated to assess yield, timing resolution, and dark count rate. These results will guide the selection of the most suitable technology for integration into ARGOLite.

Parallel efforts are underway at the University of Sherbrooke to develop a smart DAQ system [19] that can efficiently manage the high channel count expected in ARGO. This multi-level system combines real-time neural-network-based preprocessing for noise and dark count filtering with distributed FPGA-level algorithms for higher-order feature extraction and trigger decisions.

7 Conclusions

In this work, we presented a detailed optical model of pixelated digital SiPMs that has been integrated into the ARGO simulation framework. The model reproduces measured PDE and external CT yields, providing a predictive tool to quantify the impact of SiPM correlated noise on pulse-shape discrimination and event-position reconstruction in ARGO. These studies define performance targets for future SiPM devices and inform the design of the ARGO photodetector and DAQ systems. The ARGOLite prototype program at SNOLAB will experimentally validate these results and establish the technological basis for the full-scale ARGO detector, aimed at background-free multi-tonne LAr dark-matter searches.

Acknowledgments

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References

- [1] A.B. McDonald, *Dark matter detection with liquid argon*, *Nucl. Phys. B* **1003** (2024) 116436.
- [2] ARDM collaboration, *Commissioning of the ArDM experiment at the Canfranc underground laboratory: first steps towards a tonne-scale liquid argon time projection chamber for Dark Matter searches*, *JCAP* **03** (2017) 003 [[arXiv:1612.06375](#)].
- [3] DARKSIDE collaboration, *DarkSide-50 532-day Dark Matter Search with Low-Radioactivity Argon*, *Phys. Rev. D* **98** (2018) 102006 [[arXiv:1802.07198](#)].
- [4] K. Rielage, *Status and prospects of the MiniCLEAN dark matter experiment*, *AIP Conf. Proc.* **1441** (2012) 518.
- [5] DEAP collaboration, *Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB*, *Phys. Rev. D* **100** (2019) 022004 [[arXiv:1902.04048](#)].
- [6] DARKSIDE collaboration, *Direct Detection of Dark Matter with DarkSide-20k*, *EPJ Web Conf.* **280** (2023) 06003.
- [7] A.J. Anderson et al., *Coherent Neutrino Scattering in Dark Matter Detectors*, *Phys. Rev. D* **84** (2011) 013008 [[arXiv:1103.4894](#)].
- [8] R. Newman, *Visible light from a silicon $p - n$ junction*, *Phys. Rev.* **100** (1955) 700.
- [9] DEAP collaboration, *Pulse-shape discrimination against low-energy Ar-39 beta decays in liquid argon with 4.5 tonne-years of DEAP-3600 data*, *Eur. Phys. J. C* **81** (2021) 823 [[arXiv:2103.12202](#)].

- [10] R. Francini et al., *VUV-Vis optical characterization of Tetraphenyl-butadiene films on glass and specular reflector substrates from room to liquid Argon temperature*, 2013 *JINST* **8** P09006 [[arXiv:1304.6117](#)].
- [11] RAT (is an Analysis Tool) User's Guide, *RAT-PAC: Geant4-based simulation and analysis toolkit*, <https://rat.readthedocs.io/en/latest/>.
- [12] M.L. Knoetig, J. Hose and R. Mirzoyan, *SiPM Avalanche Size and Crosstalk Measurements with Light Emission Microscopy*, *IEEE Trans. Nucl. Sci.* **61** (2014) 1488.
- [13] Hamamatsu S14161-3050HS-08 MPPC array, https://www.hamamatsu.com/eu/en/product/optical-sensors/mppc/mppc_array/S14161-3050HS-08.html.
- [14] K. Raymond et al., *Laser induced SiPM Luminescence*, in the proceedings of the 2023 *IEEE Nuclear Science Symposium, Medical Imaging Conference and International Symposium on Room-Temperature Semiconductor Detectors (NSS MIC RTSD)*, Vancouver, BC, Canada (2023) [[DOI:10.1109/nssmicrtsd49126.2023.10338577](#)].
- [15] J.B. McLaughlin et al., *Characterisation of SiPM Photon Emission in the Dark*, *Sensors* **21** (2021) 5947 [[arXiv:2107.13753](#)].
- [16] M.G. Boulay et al., *SiPM cross-talk in liquid argon detectors*, *Front. in Phys.* **11** (2023) 1181400 [[arXiv:2201.01632](#)].
- [17] J.-F. Pratte et al., *3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works*, *Sensors* **21** (2021) 598.
- [18] A. Gola, *DRD4 — WG1 Update*, presentation at the 3rd *DRD4 Collaboration Meeting*, CERN, 9 April 2025 [<https://indico.cern.ch/event/1473071/contributions/6447976>].
- [19] M. Rahimifar, *Real-time Data Compression Using FPGA-Based Edge Machine Learning for Instrumentation*, Ph.D. Thesis, University de Sherbrooke, Canada (2024).