Optical modeling of pixelated digital SiPMs for ARGO

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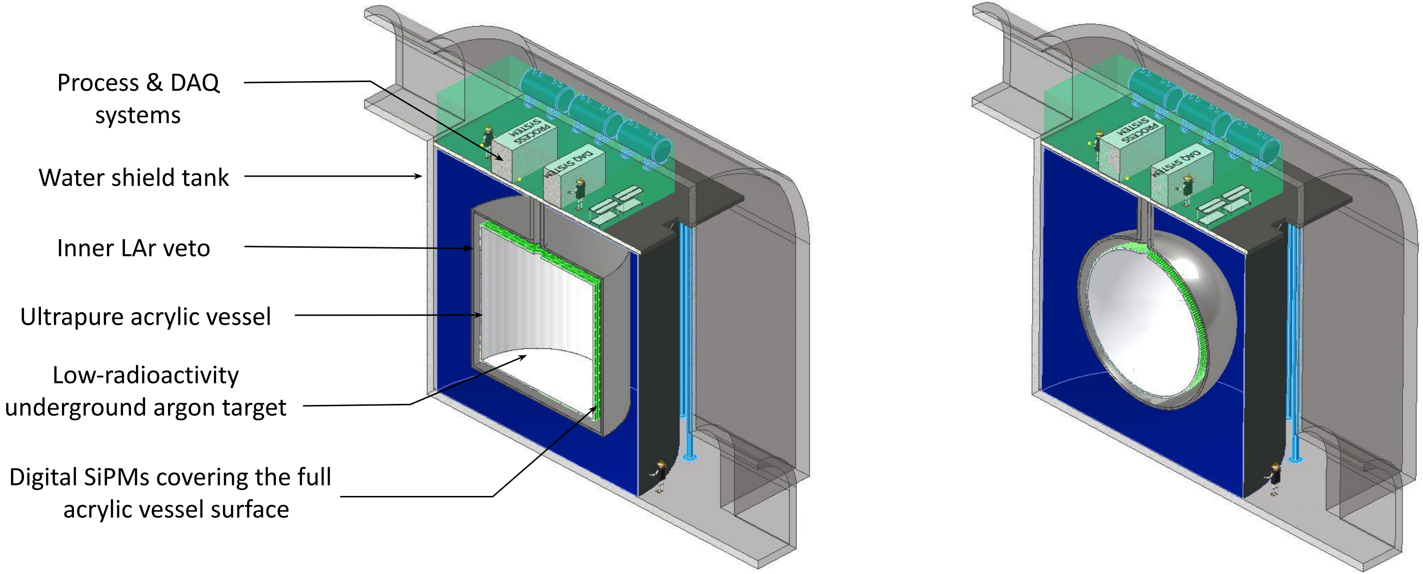
LIDINE 2025: LIght Detection In Noble Elements

Hong Kong, Oct 23, 2025

ARGO conceptual design in SNOLAB Cube Hall

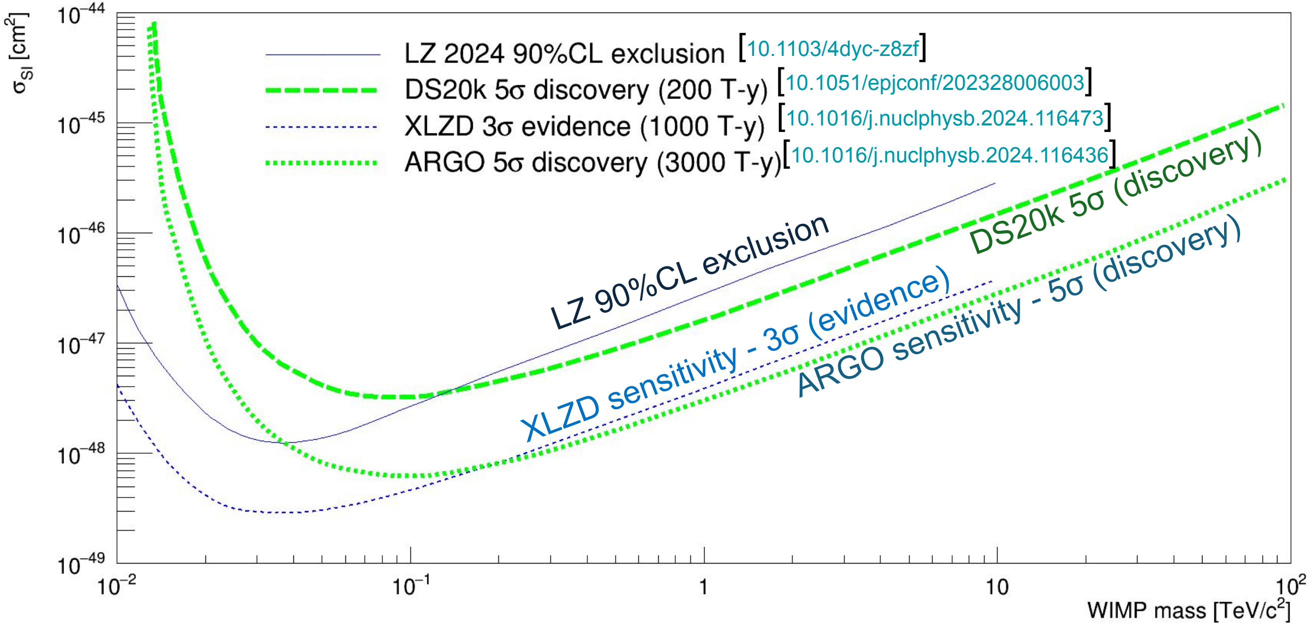


~400 tonnes of underground argon, **300 tonnes fiducial mass**, 3000 tonne-year exposure.

~250 m^2 of pixelated digital silicon photomultiplier (SiPM) readout.

NSERC-funded since 2021. SNOLAB Gateway-1a approval in 2025 for prototyping and concept development.

Sensitivity to WIMP search with ARGO



Complete suppression of ER backgrounds in argon leads to a stronger discovery potential with ARGO.

Broad Neutrino Sensitivity in ARGO

With a large fiducial mass, low-background, high-resolution LAr detector:

- Access to both low- and high-energy solar neutrinos.
- Excellent sensitivity to core-collapse supernova neutrinos.

Solar neutrino flux at Earth [10.1201/9781315195612]

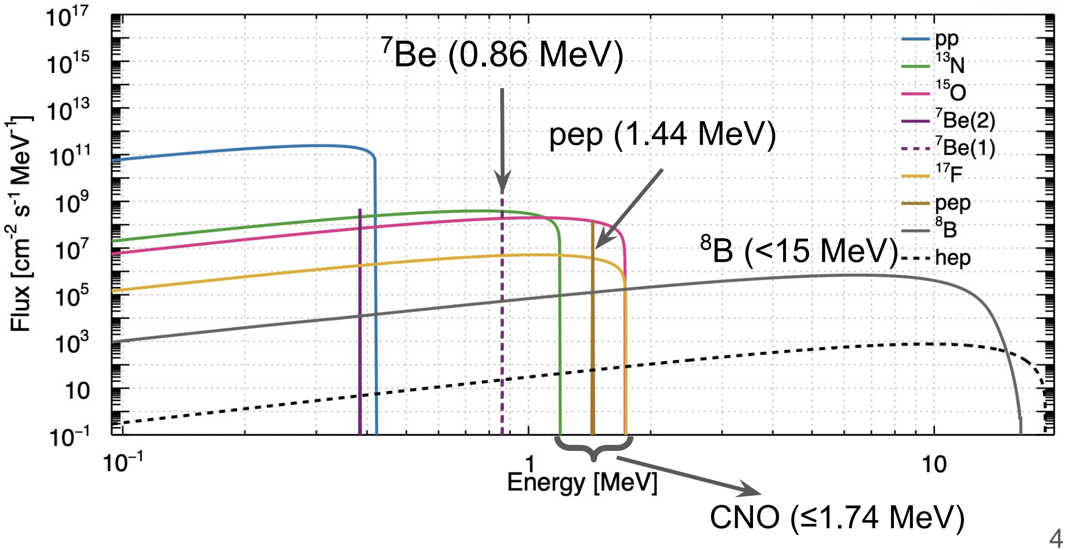
Detection Channels:

CEνNS: atmospheric & supernova neutrinos

Elastic scattering: pep, ^{7}Be, CNO neutrinos

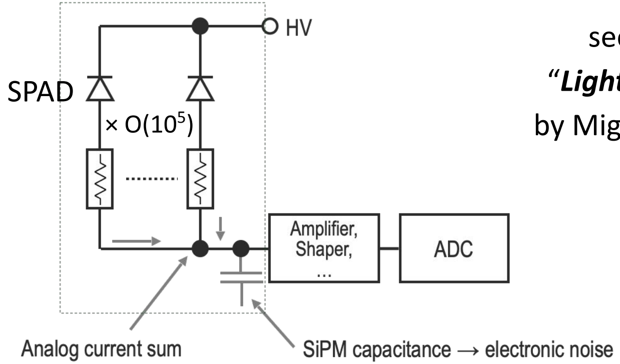
CC absorption: ^{8}B & hep neutrinos on ^{40}Ar

Cross-section being measured by DEAP-3600. Results coming out soon!



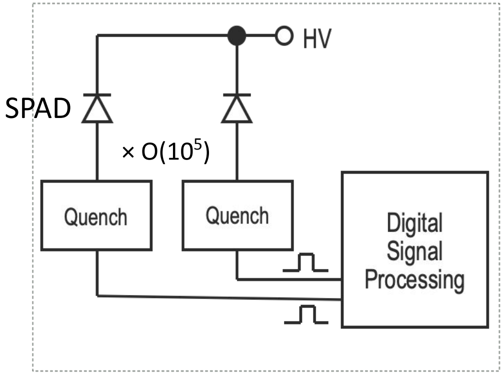
Photodetectors for ARGO: Digital SiPMs

Analog SiPM



see, yesterday's talk
"***Light Detection in DRD2***"
by Miguel Angel Garcia Peris

Digital SiPM



Analog sum of SPAD currents → electronic noise

conversion to digital using external ADCs.

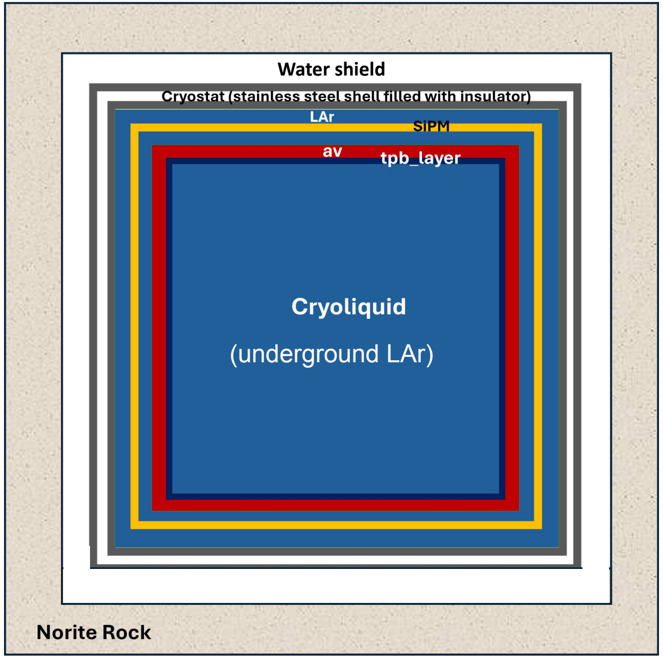
embedded electronics → direct digital output

SPAD level control → selectively disable noisy SPADs

Programmable hold-off delay → afterpulse mitigation

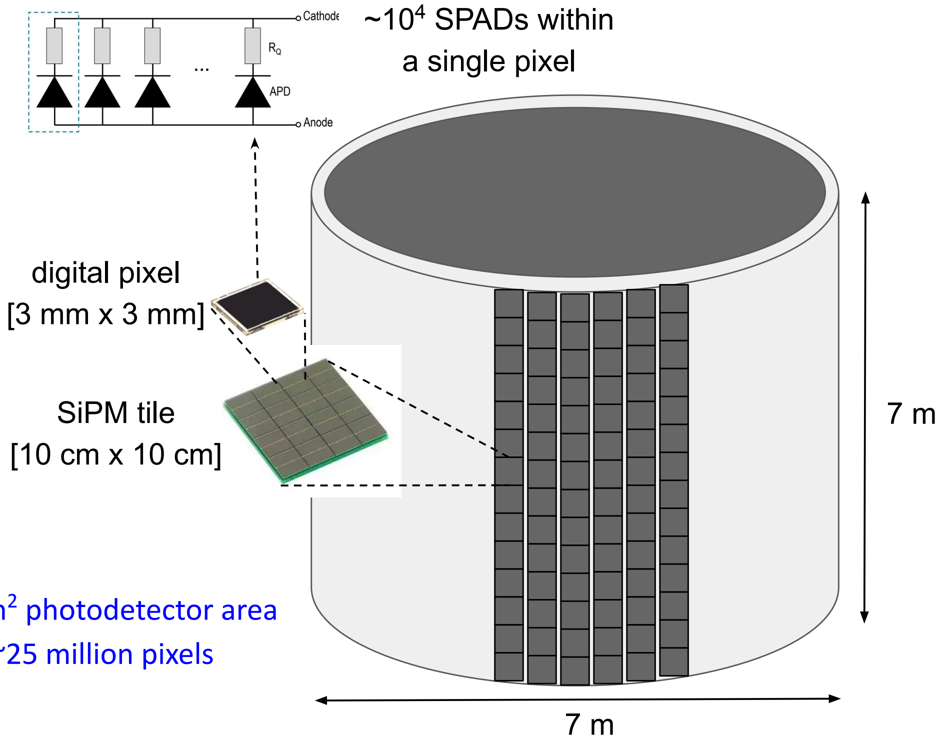
- scalability to 100s of square meters, while maintaining low noise levels.
- Excellent timing (~1 ns-scale) & spatial resolution → advanced vertex reconstruction & event ID.

ARGO geometry & photodetector arrangement in the RAT simulation framework



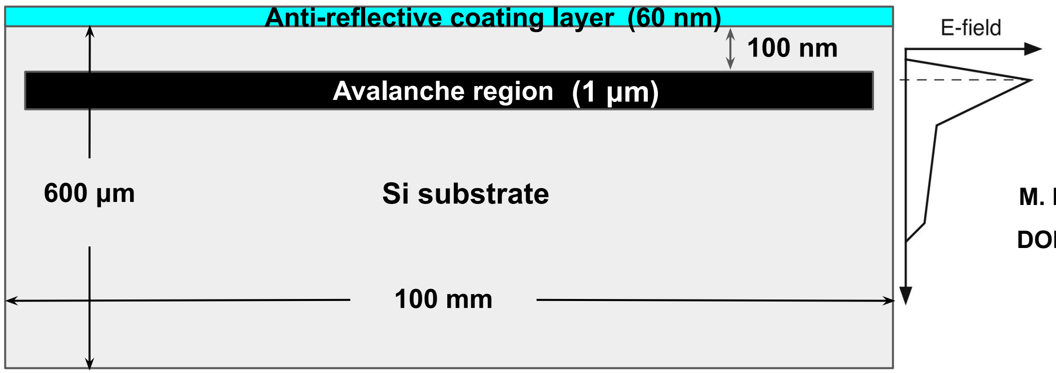
vertical cross-section of ARGO detector in RAT

https://rat.readthedocs.io/en/latest/



SiPM tile arrangement on the outer side of acrylic vessel, providing a 4π photodetector coverage.

A geometrical SiPM model for realistic simulation of photon detection in SPADs

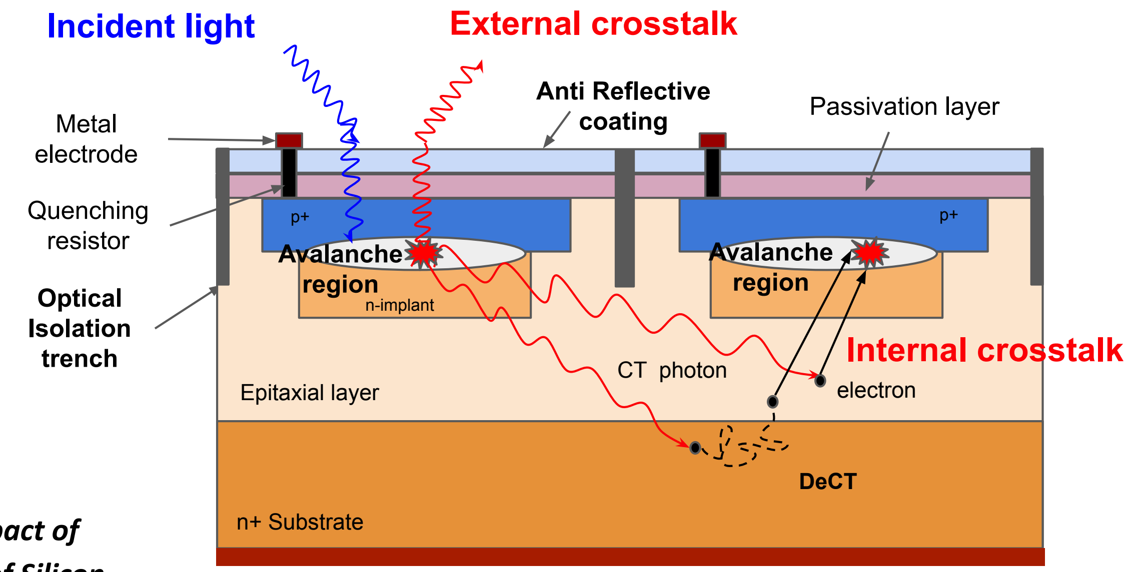


M. L. Knoetig et. al., *IEEE* 2014,
DOI: 10.1109/TNS.2014.2322957

Schematic of a SiPM tile used in the MC

- SiPM modeled as a discretized virtual grid of SPADs (25 µm pitch).
- SiPM geometrical fill factor of (70%)
- An efficiency correction factor parametrizes the effect of optical trenches.

Optical crosstalk: photons generated in SPAD avalanche that trigger secondary avalanches in other SPADs



Vertical cross-section of a SiPM

see, yesterday's talk "***The impact of secondary photon emission of Silicon photomultipliers (SiPM) to noble liquid detectors***" by Lei Wang

Measurements of optical CT yield in SPAD avalanches

Number of crosstalk photons generated in an avalanche

External CT photon yield per avalanche

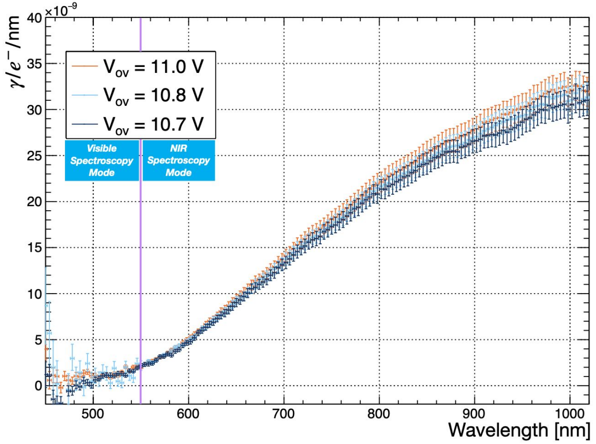
4 V_{oV}

Device	Source Photon per		Photon Yield/Avalanche		
	Avalanche	e^-	Air	LAr	LXe
HPK VUV4	47 ± 9	$(1.0 \pm 0.2)\times 10^{-5}$	0.50 ± 0.08	0.8 ± 0.1	1.1 ± 0.2
FBK VUV-HD3	56 ± 7	$(1.2 \pm 0.2)\times 10^{-5}$	0.76 ± 0.11	1.8 ± 0.2	1.7 ± 0.2

K. Raymond et. al., *IEEE* 2023, DOI: 10.1109/NSSMICRTSD49126.2023.10338577

Also see, yesterday's talk by Lei Wang.

Differential emission spectrum of crosstalk photons in HPK VUV4 SiPMs

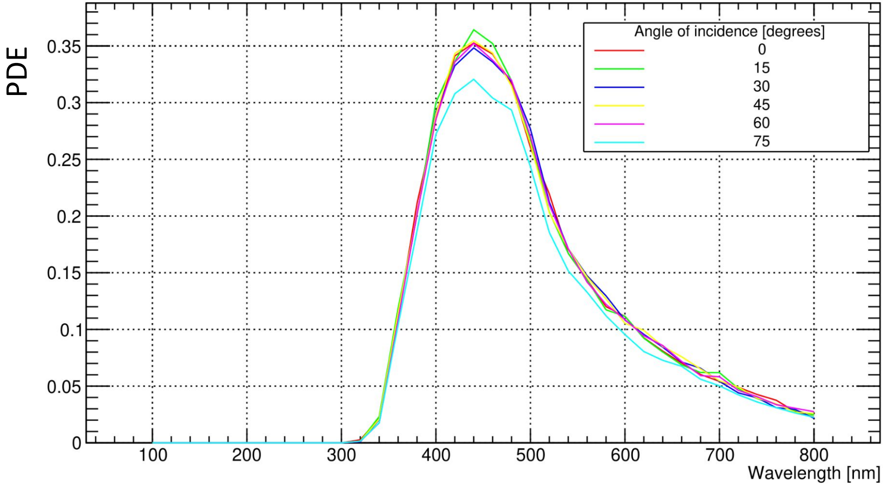


J. McLaughlin et. al., *Sensors* 2021, DOI: 10.3390/s21175947

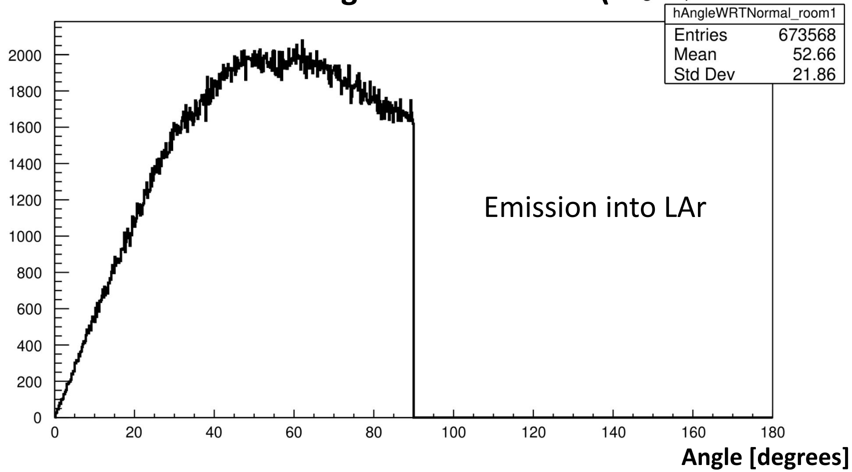
- **(50 - 60) optical crosstalk photons generated** in a SPAD avalanche.
- Per avalanche, **(1 - 2) CT photons escape the SiPM bulk** → potential external crosstalk.
- Infrared emission wavelength of CT photons; low detection efficiency.

Key results from MC simulation

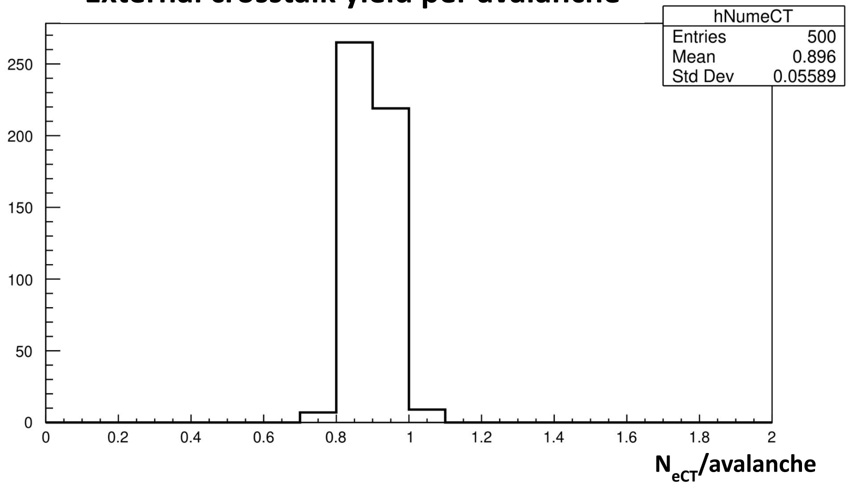
SiPM PDE vs wavelength



External crosstalk angular distribution (wrt surface normal)



External crosstalk yield per avalanche



Impact of optical crosstalk on key detector observables

- How does crosstalk affect the energy threshold?
- Does it distort photon hit clustering patterns?
- What is its impact on event position reconstruction?

Rejecting ER backgrounds through pulse-shape discrimination

Exploit the different lifetimes of LAr excimer states.

Singlet (6 ns) vs. triplet (1600 ns) → strong ER background rejection.

PSD parameter, $$f_p = \frac{\int_0^{t_p} S(t)\,dt}{\int_0^{t_{tot}} S(t)\,dt} \in (0, 1)$$

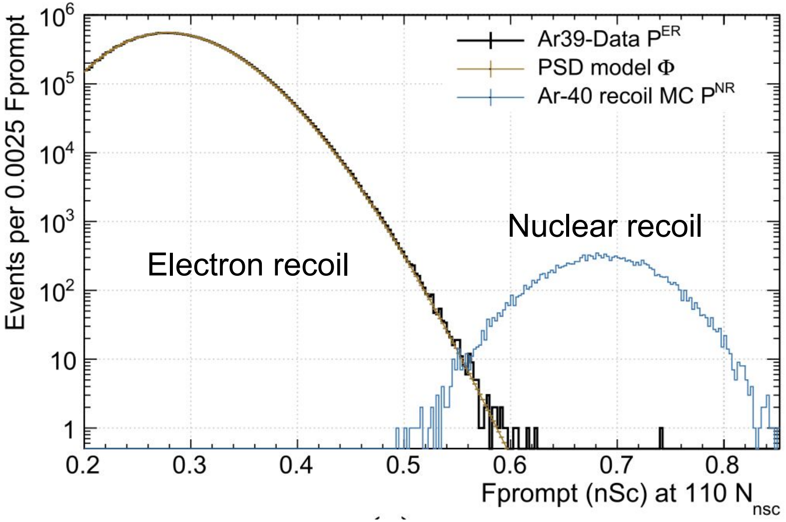
Using PSD, **ER background rejection at ~10^{-9} demonstrated by DEAP-3600**.

In ARGO,

➢ SiPM photodetectors (optical crosstalk noise)

➢ Increased Rayleigh scattering (much larger size)

Eur. Phys. J. C 81, 823 (2021)



F_p distribution in the lowest PE bin of the ROI

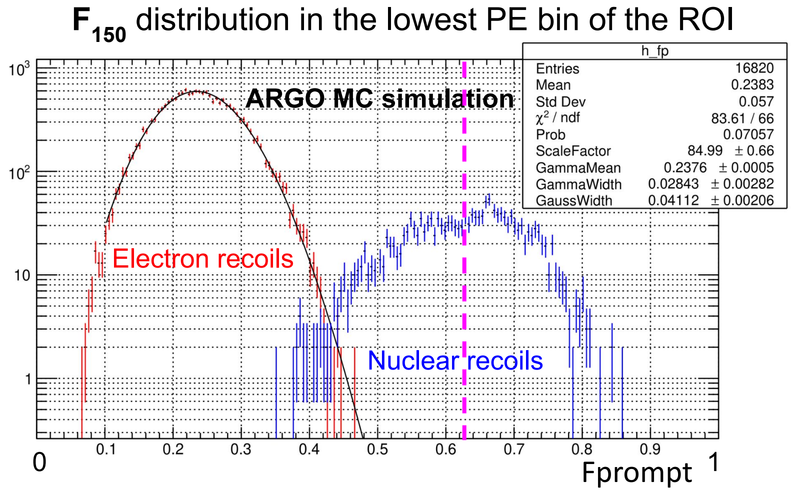
Pulse-shape discrimination with SiPMs

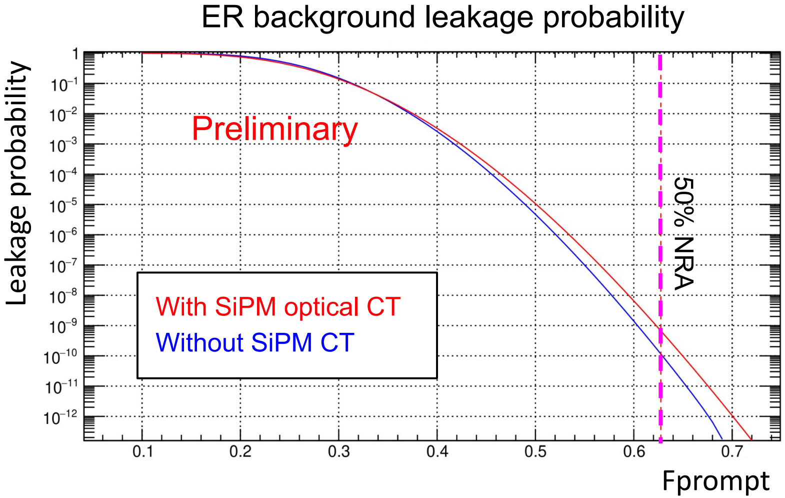
Target: < 0.05 ER events in the ROI in 10 live-years.

Leakage probability *PL(f)* at f_p value corresponding to 50% NRA → probability for an ER event to occur in the $[\mathbf{f_p}, 1]$ range.

$$PL(f) = \frac{\int_f^1 PSD(f)df}{\int_0^1 PSD(f)df}$$

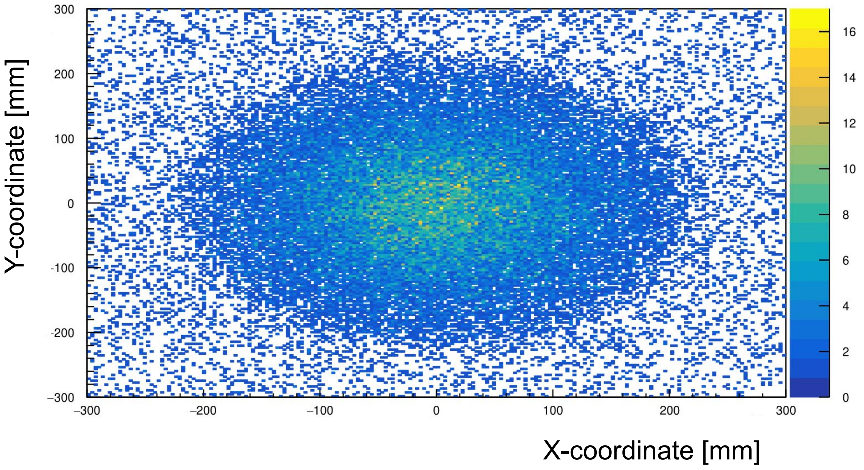
- evaluating detector performance with current SiPM specifications.
- determining constraints on SiPM devices to reach targeted performance.



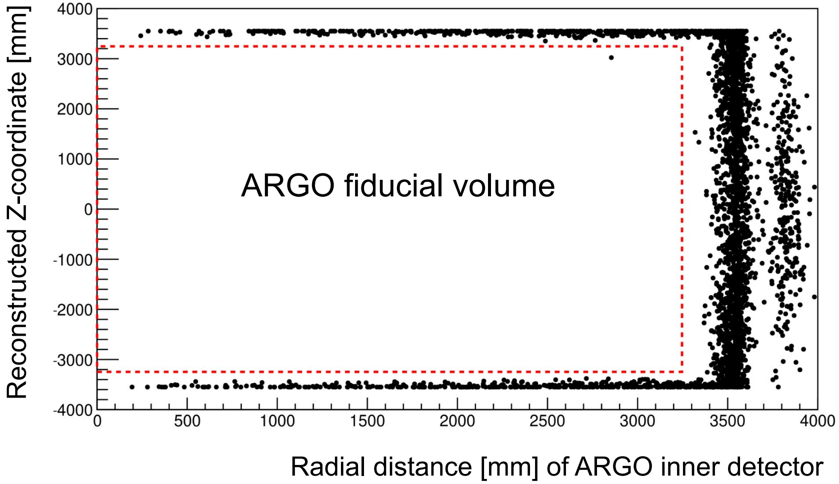


Position reconstruction and event ID with pixelated photodetectors

Photon hit clustering for surface events, with a 3mm x 3mm pixelated readout



Surface alpha event reconstruction based on photon time-of-flight

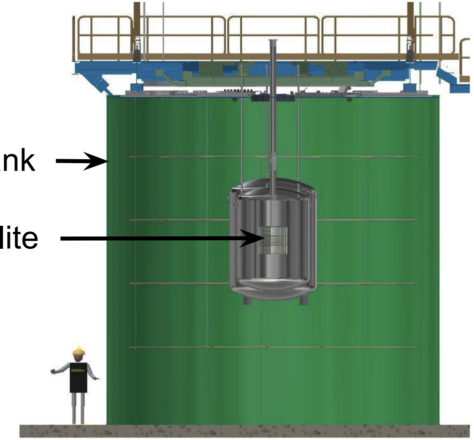


Event ID based on characteristic hit patterns – a powerful tool for background rejection.

Time/charge–based position reconstruction algorithms for external & surface backgrounds.

Target of demonstrating a combined surface alpha rejection at 10^{-7} or better.

ARGOlite: A single-phase Ar prototype in DEAP-3600 shield tank at SNOLAB



Re-use DEAP systems: cryogenics, purification, shield tank.

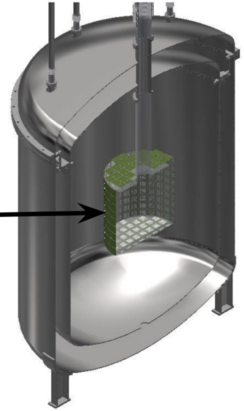
Pixelated digital photodetectors (2 m^2 array) and AI-based DAQ.

Targets:

- demonstrate ER/NR PSD at 10^{-9} with pixelated digital SiPMs.
- demonstrate surface alpha rejection (combined) at 10^{-7} or better.
- qualify the full optical chain for ARGO design.

New capabilities for materials assays:

- surface alpha assay at 10 μBq/m^2 and ^{42}Ar (^{39}Ar) in Ar.
- direct material neutron rates, high sensitivity.



Photon-to-digital converters (U. Sherbrooke & TRIUMF, Canada; LNGS, U. L'Aquila, FBK, Italy

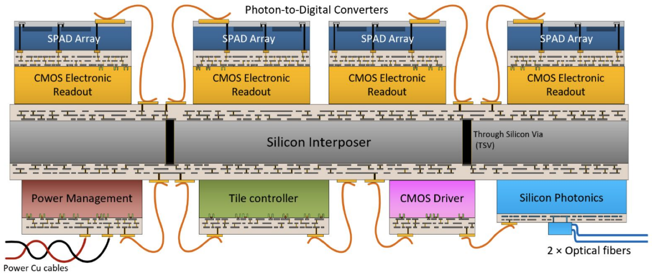
Two technologies for pixelated digital SiPMs for ARGO:

1) **Sherbrooke PDCs:** fully digital system in which each SPAD is stacked onto a CMOS readout.

2) **ATARI system FBK/LNGS:** hybrid system with pixels of 3 mm pitch connected to a readout ASIC on the opposite side of a passive interposer.

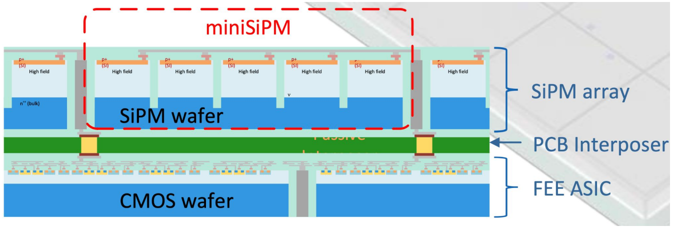
Currently fabricating some sample wafers to evaluate yield and performance, to decide on the 2m^2 array for ARGOlite.

Pratte JF et al. doi: 10.3390/s21020598



3D integrated photon detection module

A. Gola et. al., DRD4 – WG1



2.5D integrated photon detection module

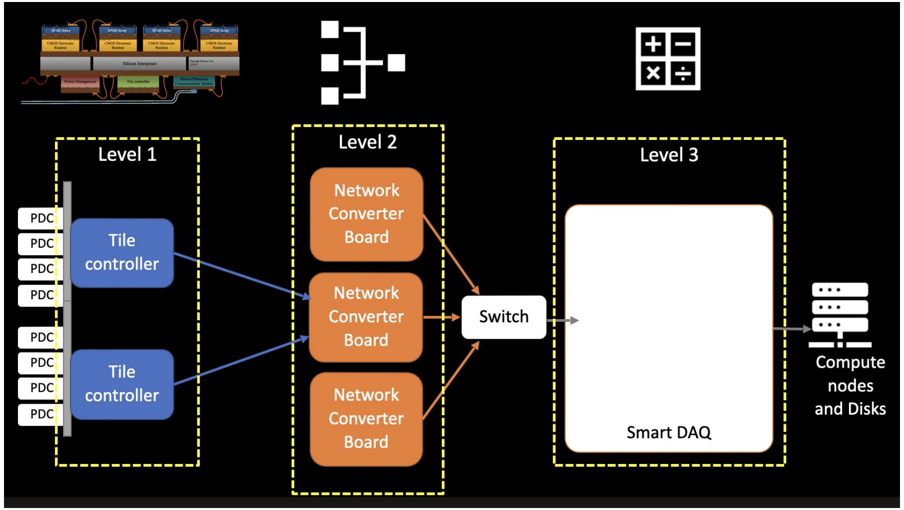
Smart DAQ system with edge computing for ARGO (U. Sherbrooke)

Data acquisition challenges:

- Large photodetector coverage → 250 m² total active area.
- Extremely high channel count.
- Operation in a complex cryogenic environment.

Multi-level DAQ architecture:

- Low-level pre-processing with neural network–based real-time filtering to reduce data volume.
- High-level analysis with distributed FPGA-based ML algorithms for complex signals and DAQ performance monitoring.



Data acquisition architecture using smart triggering

Conclusions

- ARGO is a **300-ton UAr fid. mass DM detecto**r planned at SNOLAB. Flagship project of GADMC.
- Photodetectors for ARGO: **pixelated digital SiPMs with fast photon timing** → excellent position reconstruction & event ID based on characteristic hit patterns.
- Developed a **detailed geometrical model of SiPMs, including optical crosstalk:**
  - Reproduces SiPM PDE vs. wavelength, provides internal & external CT yields, and external crosstalk angular distribution.
- Developing a **prototyping facility** for ARGO, **including digital SiPMs**, that will replace DEAP-3600 in 2027, for operation from **2028 – 2030**.
- Approximate timeline is **prototyping + design in place by 2031** to move ahead with ARGO project implementation.

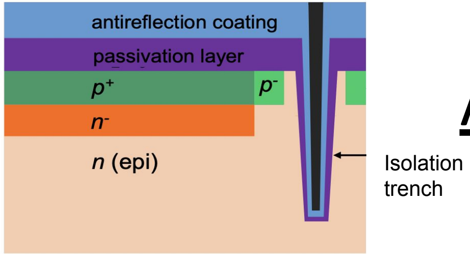
The Global Argon Dark Matter Collaboration

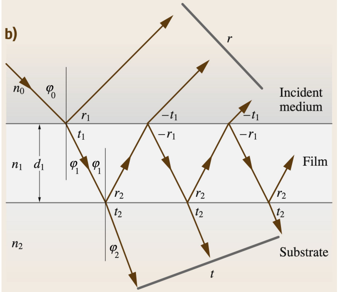
With many thanks for support to:

- CFI and NSERC (Canada)
- IN2P3 (France)
- INFN (Italy)
- STFC (UK)
- NSF and DOE (U.S.)
- Poland and Spain Ministries for Science and Education

Backup slides

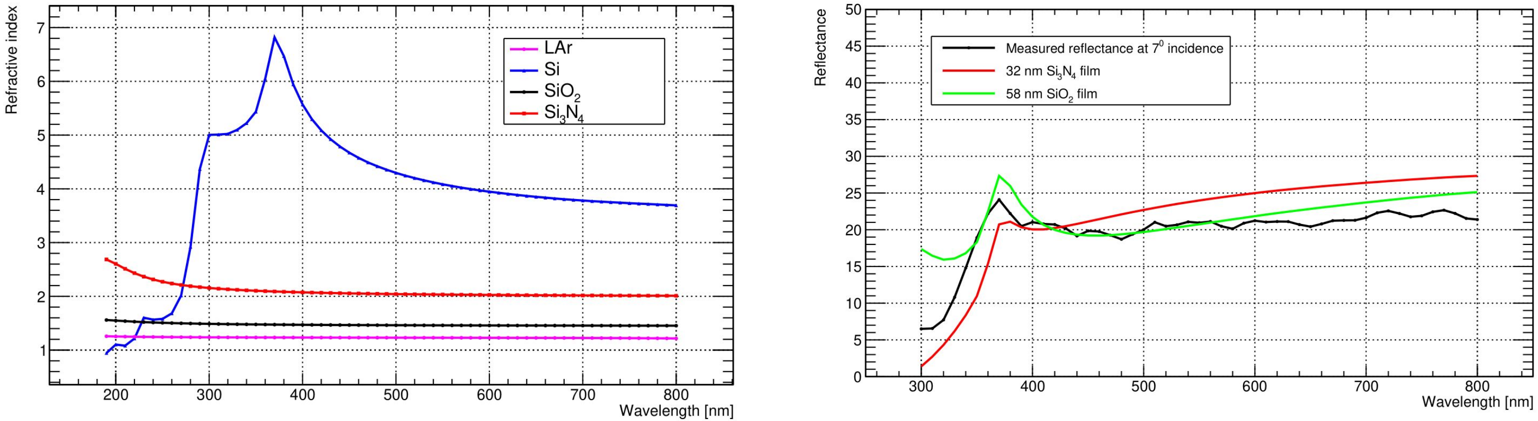
Anti-reflection coating in SiPMs





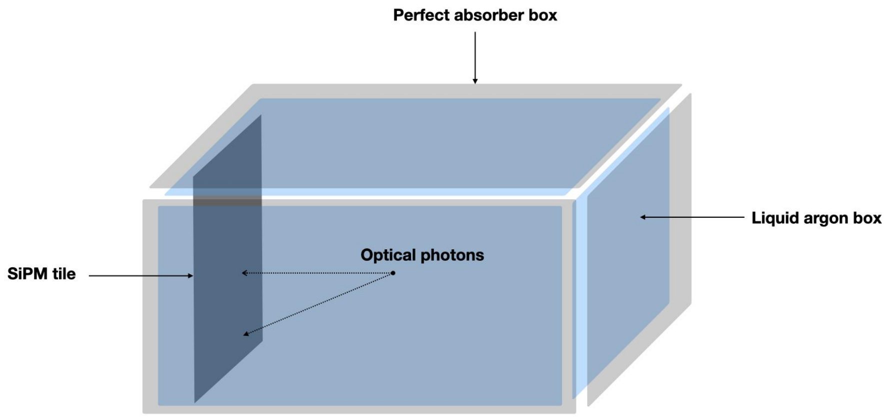
Refractive index vs wavelength

SiPM reflectance vs wavelength

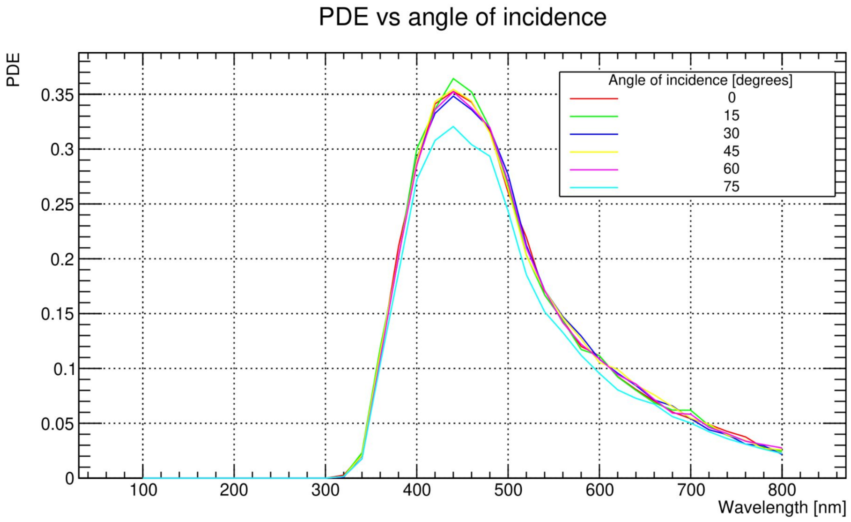


- Anti-reflective coating: reduce photon loss due to surface reflections (large difference in the RI of LAr and Si)
- SiPM reflectance measured with a spectrophotometer equipped with an integrating sphere.
- Considering a non-absorbing single film deposited on a substrate, estimate film thickness that best matches the measured reflectance.

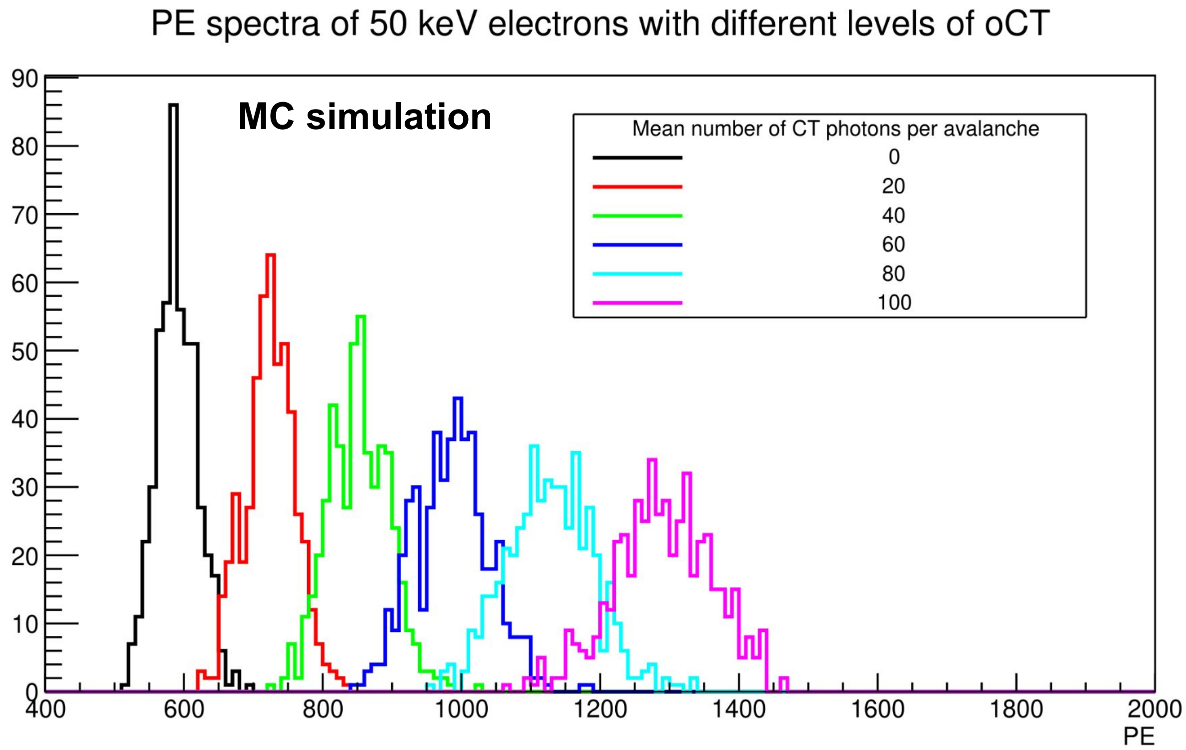
Photon detection efficiency as an emergent property of the geometrical MC model



Standalone MC geometry for SiPM PDE studies



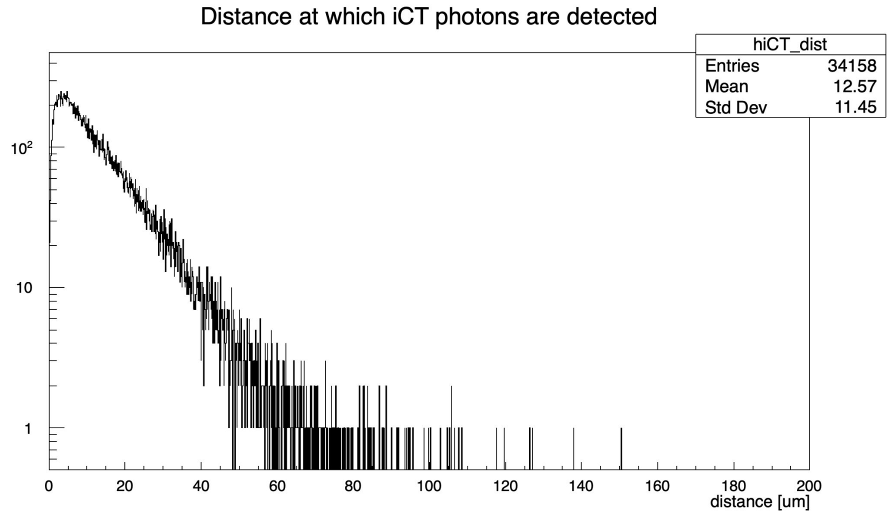
- Shoot optical photons of a given wavelength at the SiPM; check how many photons are detected.
- Photon wavelength: (100 - 800 nm); Angle of incidence: (0 - 75 degree)

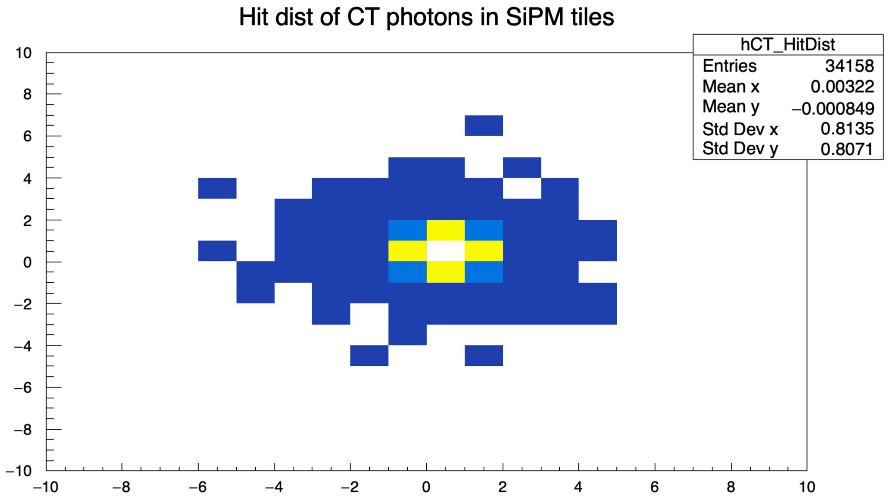


Photoelectron spectra of simulated 50 keV e-s (uniformly distributed within the LAr volume) for different mean number of crosstalk photons per avalanche.

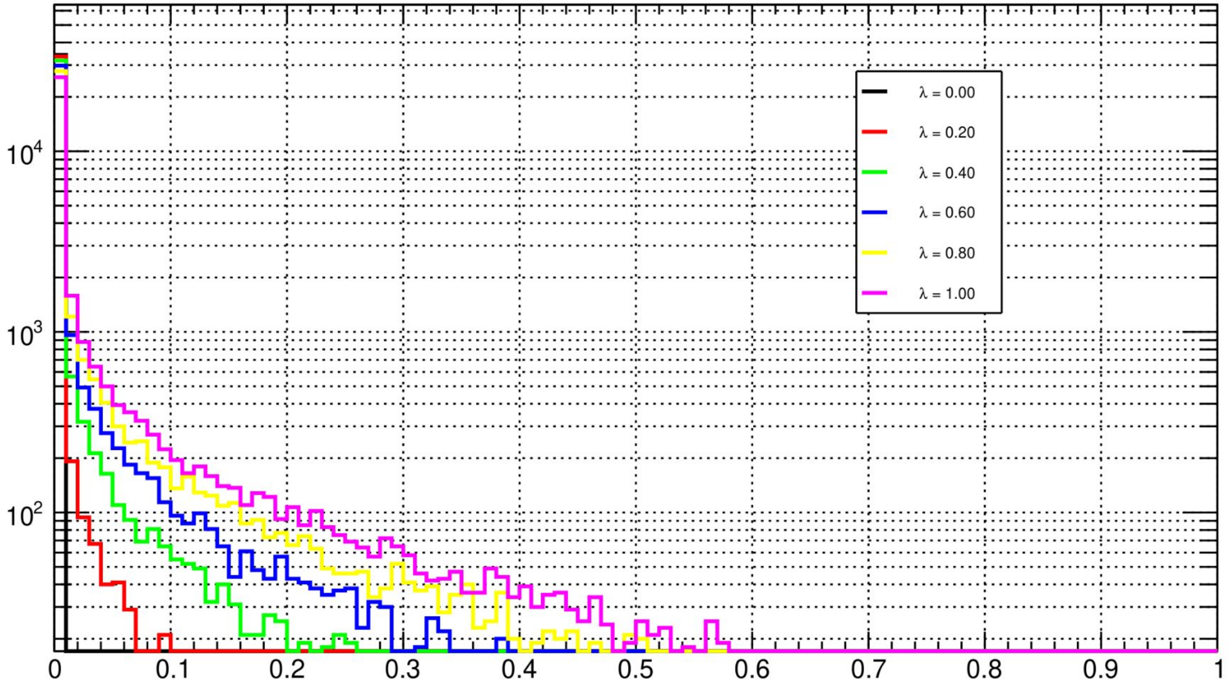
With increasing oCT, the PE yield is amplified, along with the worsening of the energy resolution.

Internal crosstalk propagation



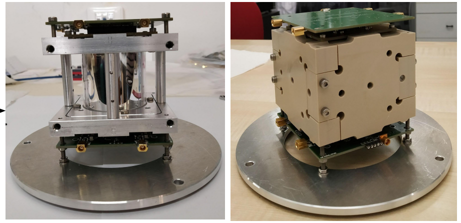


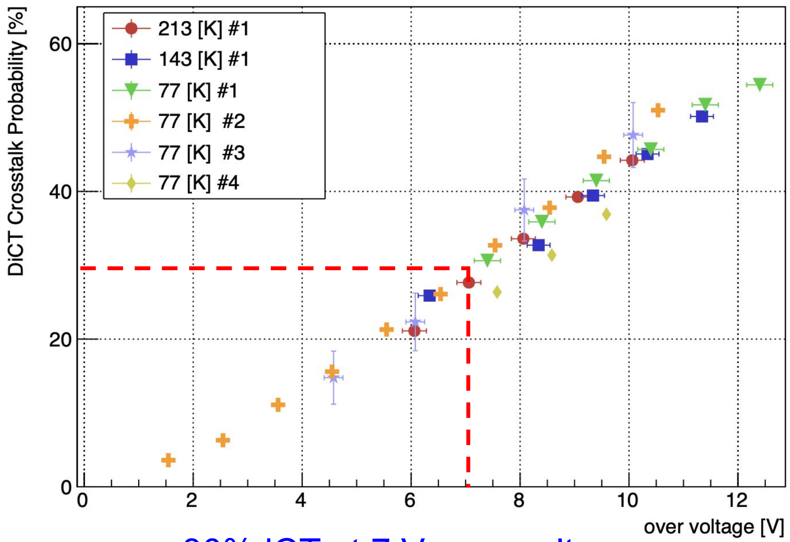
Efficiency factor P = exp[-iCT_dist / λ]



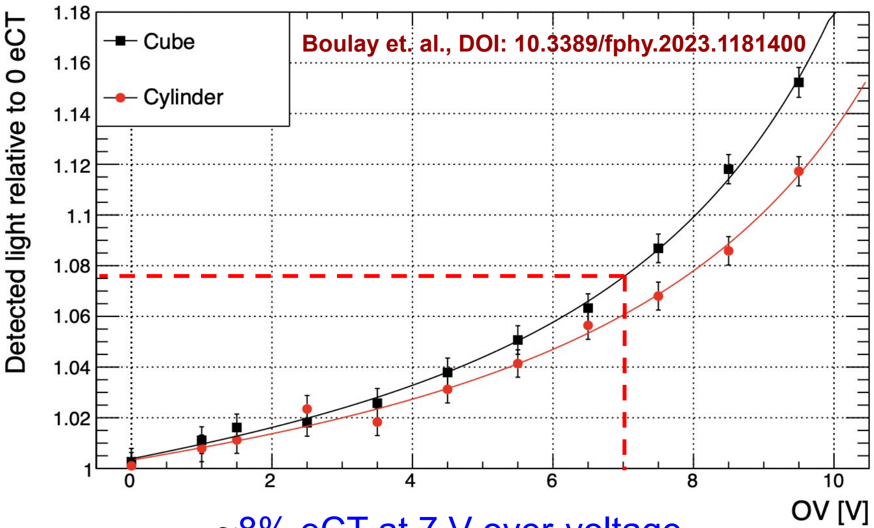
Quantifying the size of this correlated noise (crosstalk detection)

Precise measurements of external CT made with small-scale prototype LAr detectors equipped with SiPM tiles.



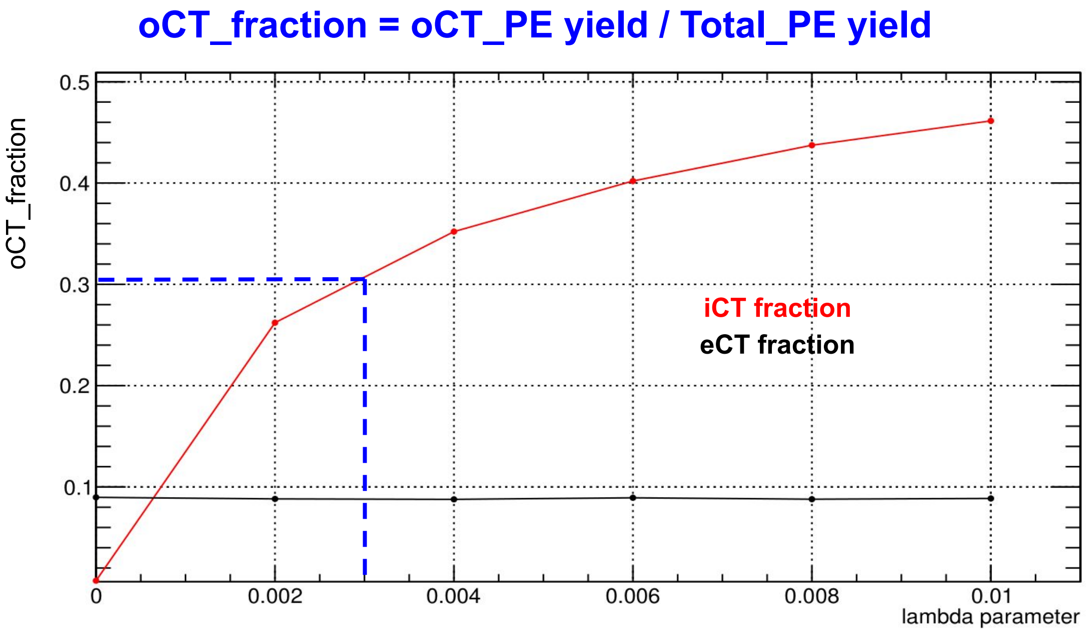


~30% iCT at 7 V over-voltage



~8% eCT at 7 V over-voltage

Optical crosstalk fraction vs trench efficiency



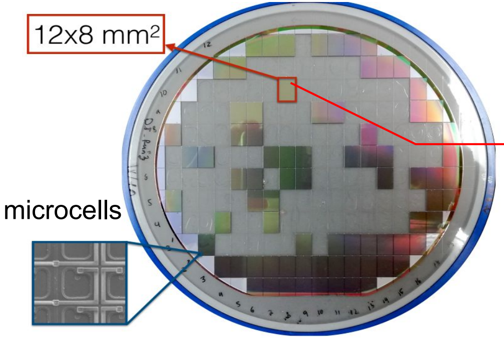
SPAD size = 25 microns,

Fill factor = 70%,

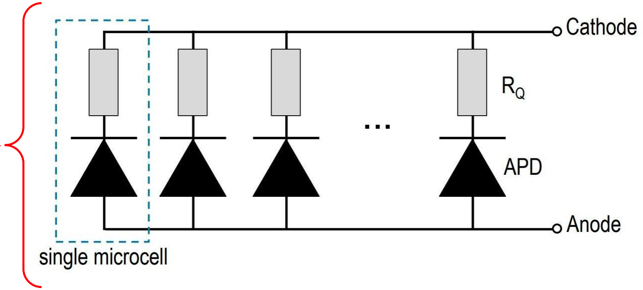
MeanNumXtalkPhotons = 60

For a lambda value of ~0.003, the iCT fraction is roughly 30%, and the eCT fraction is around 9%; similar to the measurement results shown previously,

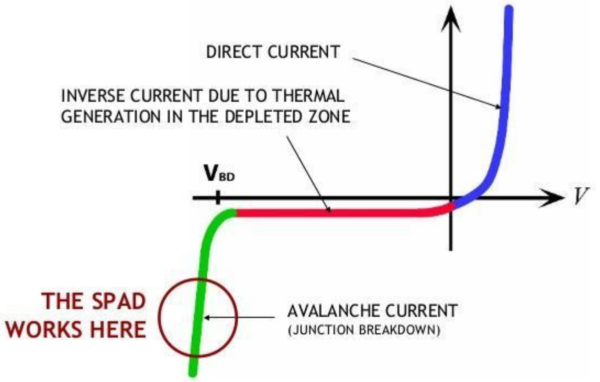
SiPMs: A dense array of SPADs operated in Geiger mode that trigger avalanche upon photon absorption



Single SiPM devices



Array of microcells (SPAD + quenching resistor)



Geiger mode operation

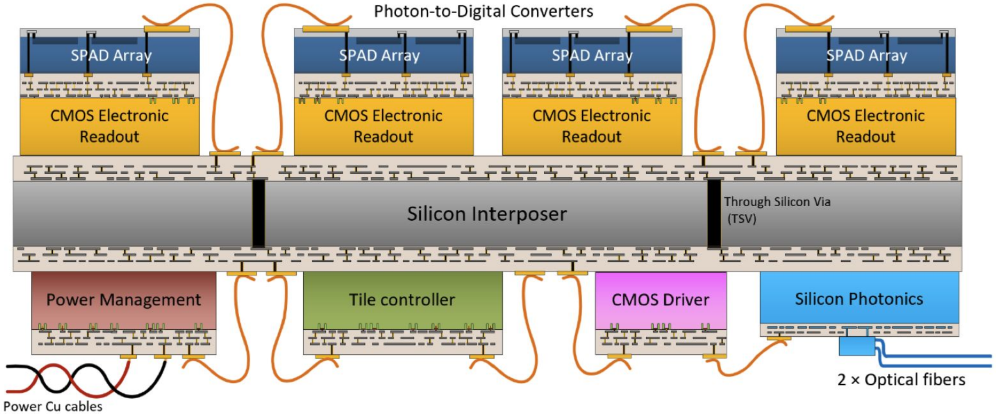
- Photon absorption in SPAD high-field region triggers an avalanche, quenched via a resistor.
- SPAD recharges ($\tau \approx$ few 100 ns) and becomes ready for the next photon.
- Summed microcell photocurrents provide a measure of the incident photon flux.

3D Photon-to-Digital Converters (U. Sherbrooke)

Fully digital system with SPAD level control:

- Single-photon resolution with fast timing, across the full dynamic range.
- Noisy SPADs can be selectively disabled, reducing overall noise.
- Programmable hold-off delay for afterpulsing mitigation.

U. Sherbrooke *Pratte JF et al. doi: 10.3390/s21020598*



Full 3D integrated photon detection module