ARGO updates & outlook

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ARGO: Key Elements of Conceptual Design

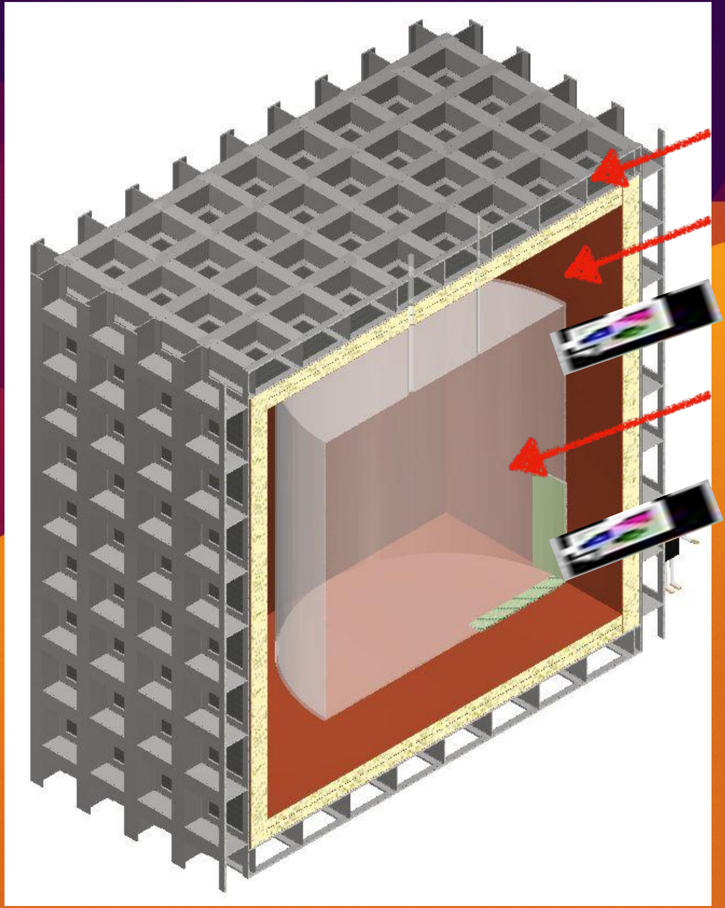
UAr Mass:

- total 400 tonnes
- fiducial 300 tonnes.

SiPMs assemblies arranged as photon-to-digital converters (PDCs).

Data rates:

- operation 5k p.e./(m^2×s)
- calibration 100k p.e./(m^2×s).



Outer cryostat

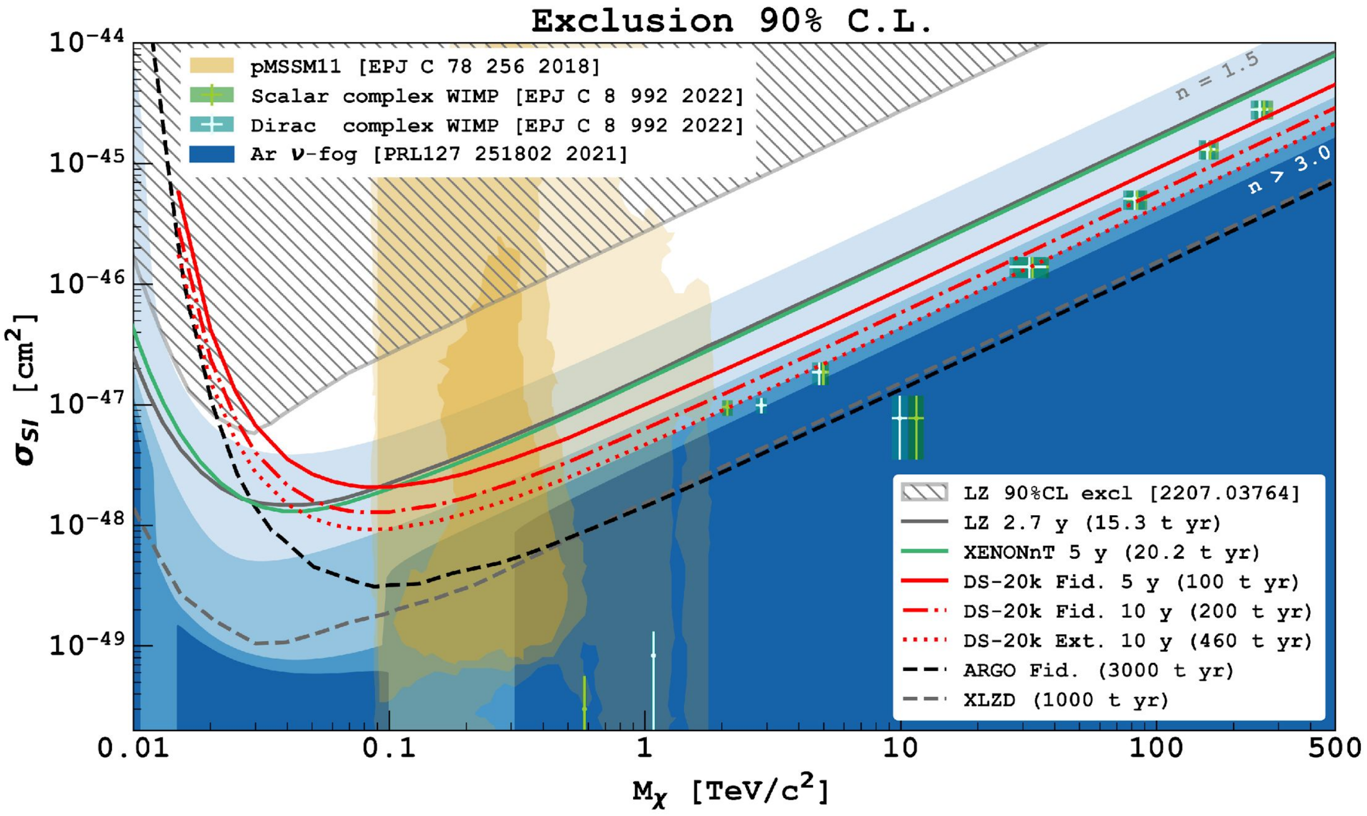
Liquid argon buffer

Ultrapure acrylic vessel (7m diameter and height)

400 tonnes low-radioactivity argon within acrylic vessel

250 m^2 PDCs covering full acrylic vessel surface

ARGO - Projected sensitivity for 10 live years



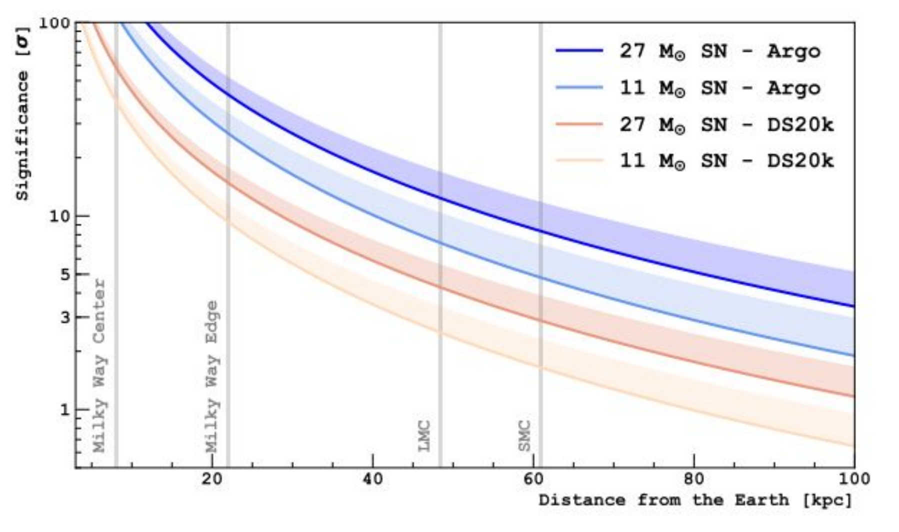
Solar and supernova neutrinos: DS-20k and Argo as neutrino observatories

Core-collapse supernova neutrinos

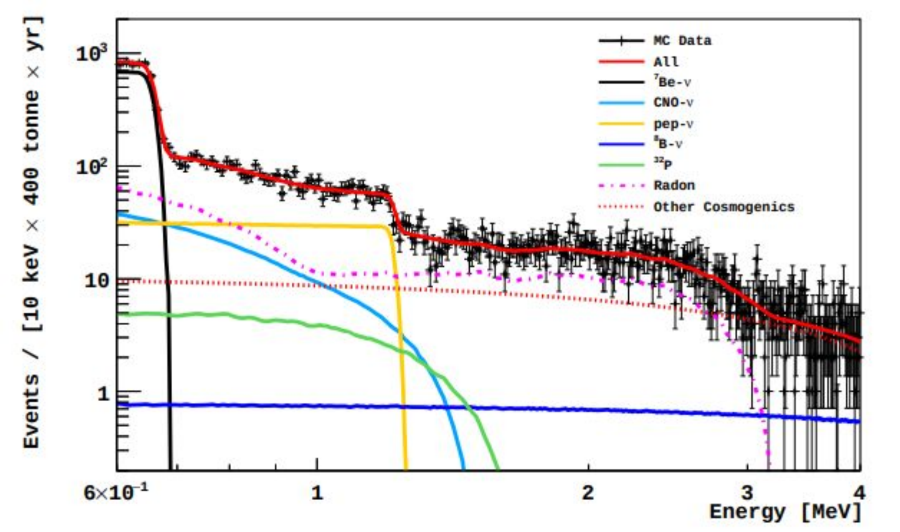
Sensitivity to core-collapse supernova burst neutrinos beyond the Milky Way, with >3σ sensitivity to the neutronization burst

Solar neutrino measurements

High-precision solar neutrino measurements via electron-scattering and other channels; potential to resolve solar metallicity models



DOI: 10.1088/1475-7516/2021/03/043



DOI: 10.1088/1475-7516/2016/08/017

Timeline

ArDM
DarkSide-50
DEAP
MiniCLEAN

}

The Global Argon Dark Matter Collaboration (2017)

}

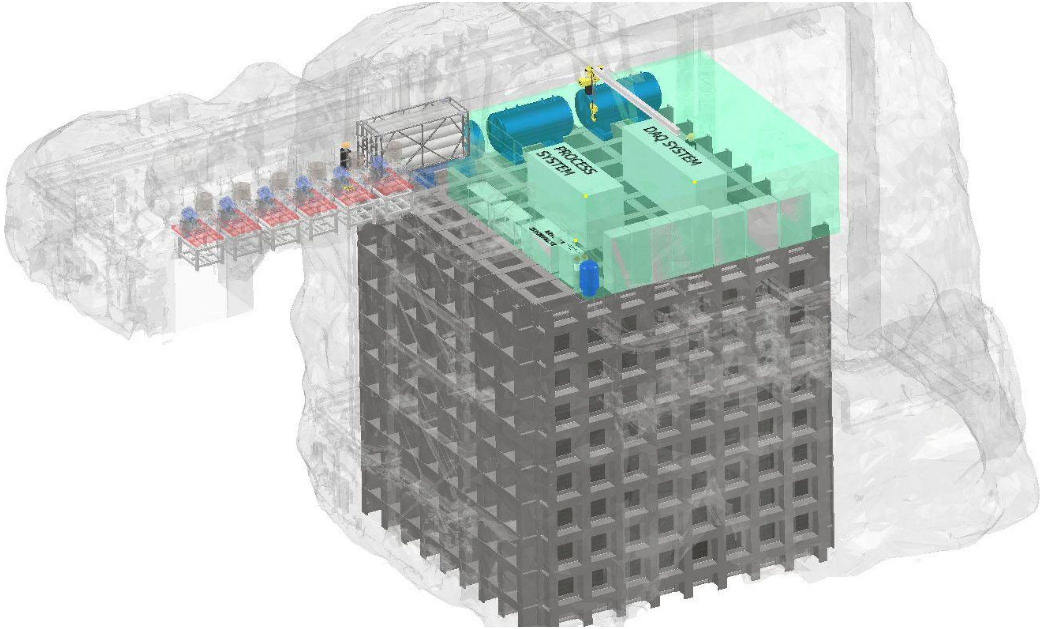
DS-20k
{20 t fid.,
50 t full}
[ops
2027-]

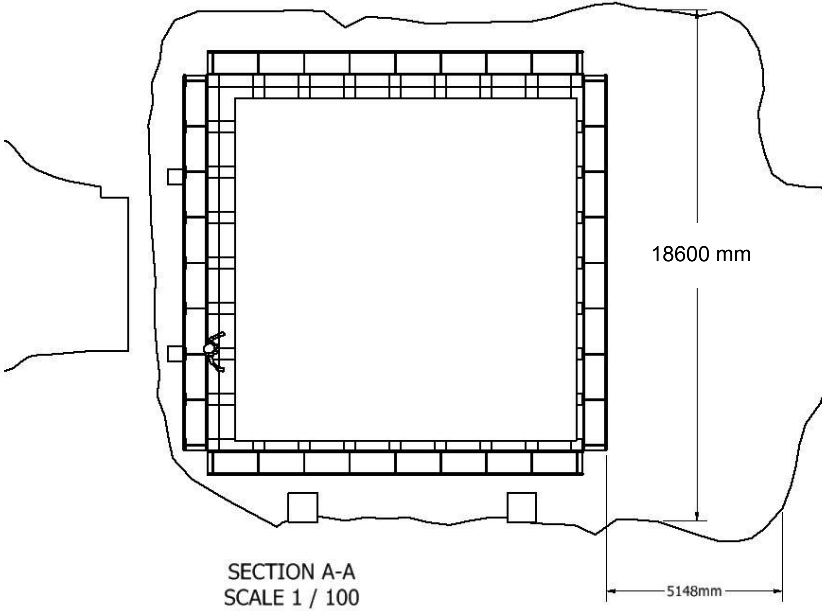
Currently under construction at LNGS, Italy

}

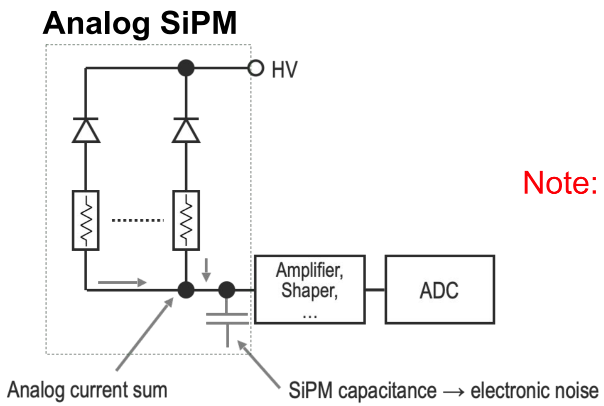
ARGO
{300 t fid.,
400 ton full}
[G3, concept development now, project early 2030's]

ARGO Concept in SNOLAB Cube Hall

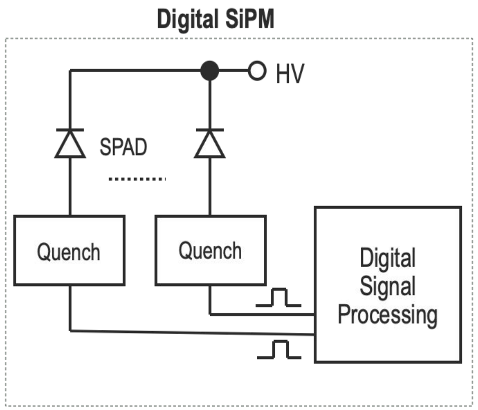




Photodetectors for ARGO - Moving from Analog to Digital SiPMs



Note: The SPAD response is Boolean



Amplifiers transform charge into analog (voltage) signals, which is then converted to digital signals using ADCs.

Individual SPAD readout, no digital-to-analog /analog-to-digital conversion.

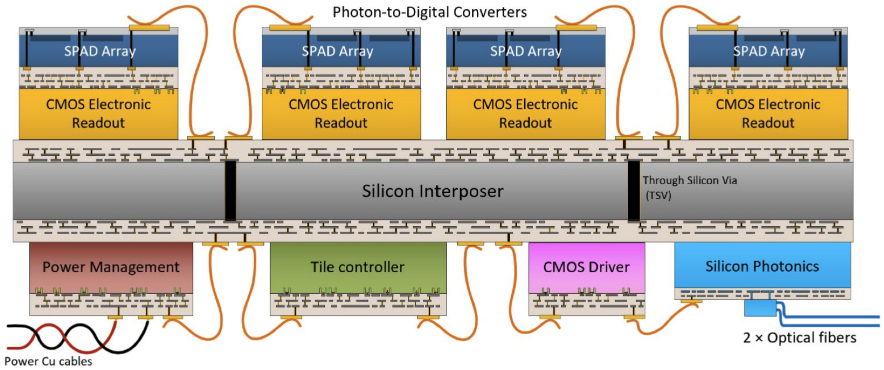
PMT solution used in DEAP can't easily be scaled to ARGO due to both neutron backgrounds and thermal requirements.

Digital solution can be scaled to several hundred m^2 and maintain low noise levels needed for pulse-shape discrimination in argon.

Excellent time resolution (<1ns-scale) and spatial resolution (currently targeting ~3 mm) allows advanced vertex reconstruction and event ID for background rejection.

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

U. Sherbrooke

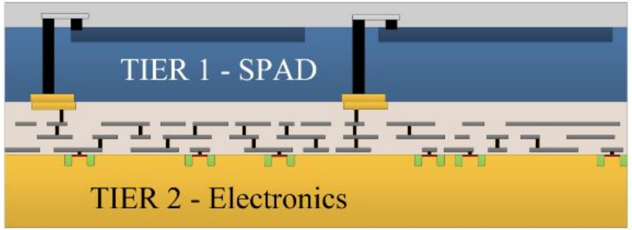


Schematic of a full 3D integrated photon detection module

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

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

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



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

Data acquisition for ARGO will be a challenge:

- Huge area of photodetectors
- Immense number of channels
- Complex cryogenic environment

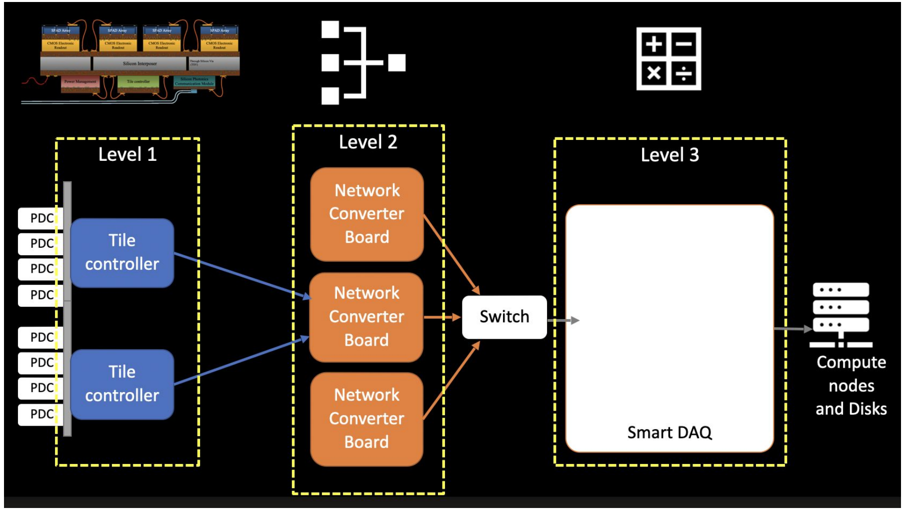
Noise estimate :

- Dark count rate : 0.1 cps/mm^2
- PDC surface : 250 m^2
- Total noise rate : 25 Mcps (dominant event rate)

Multi-level architecture with multi-level real time analysis:

- low-level preprocessing and neural networking to filter (real-time smart veto) and reduce data before sending it to subsequent stages of the data acquisition architecture.

- Novel Machine Learning on distributed FPGA for high level analysis on more complex signals, and for monitoring DAQ performance.

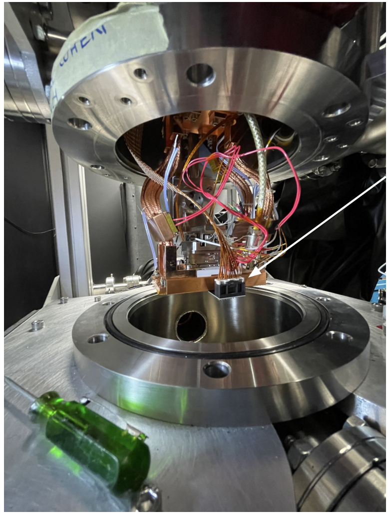


Data acquisition architecture using smart triggering
[courtesy of Audrey Corbeil Therrien, U. Sherbrooke]

Study of SiPM dark count rate (DCR) mechanisms @ TRIUMH

Goals:

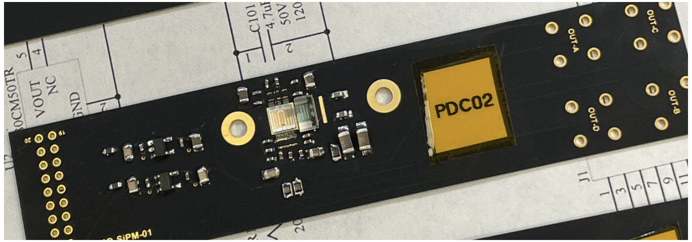
- Study the dark count rate in SiPMs
- Compare data with analytical estimations to better understand the underlying physics of dark noise production.
- Facilitate the reduction of dark noise for development of future devices.

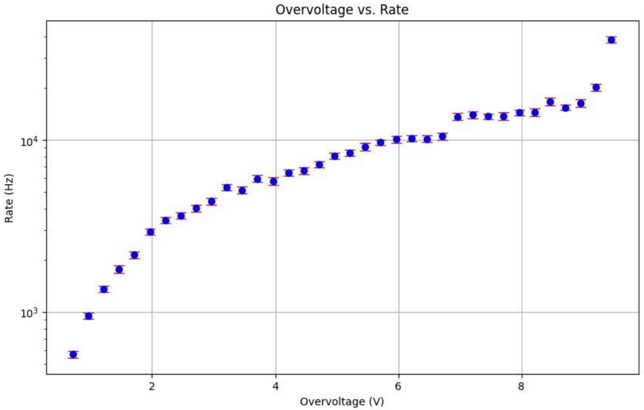


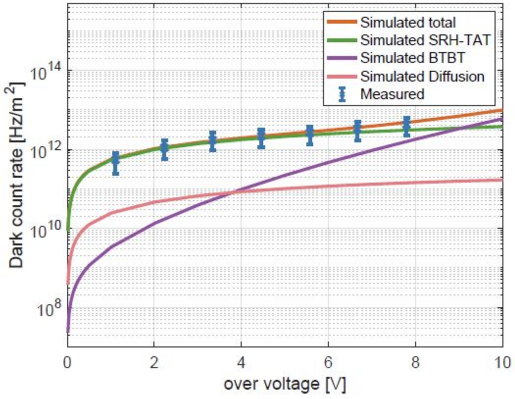
MIEL Test Chamber

Temperature Controlled Stage:
Room to LAr temperature

PDC Board

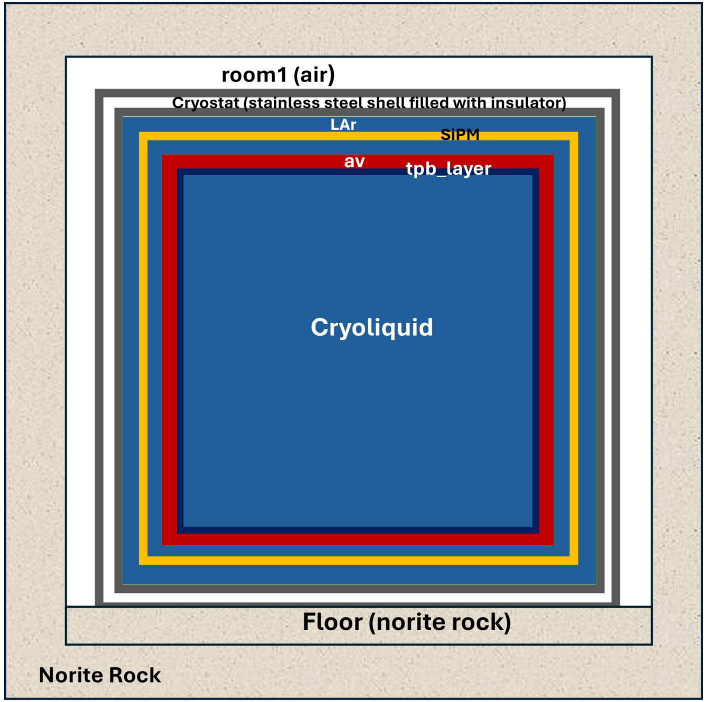




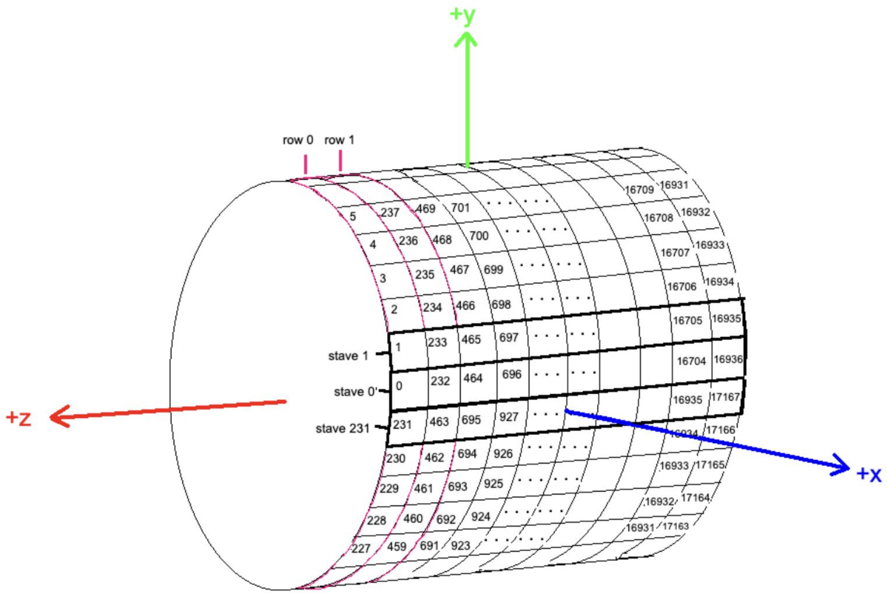


Monte Carlo simulation efforts for ARGO

ARGO detector geometry for MC simulations

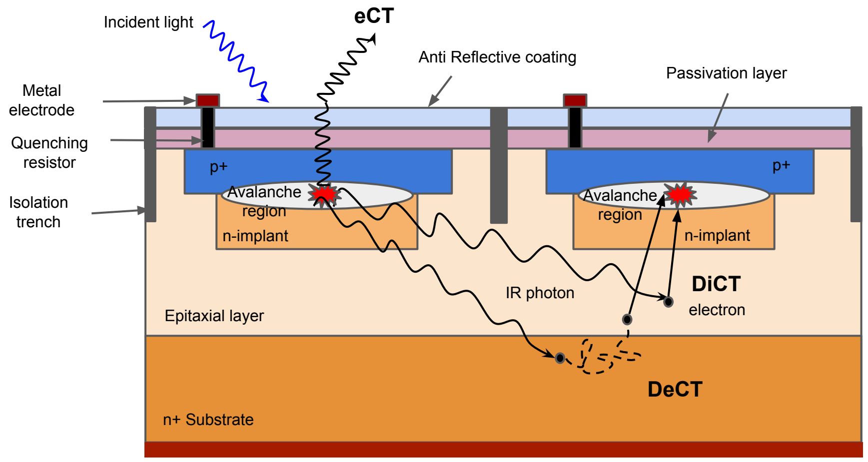


2D cross-section of ARGO detector in MC simulation



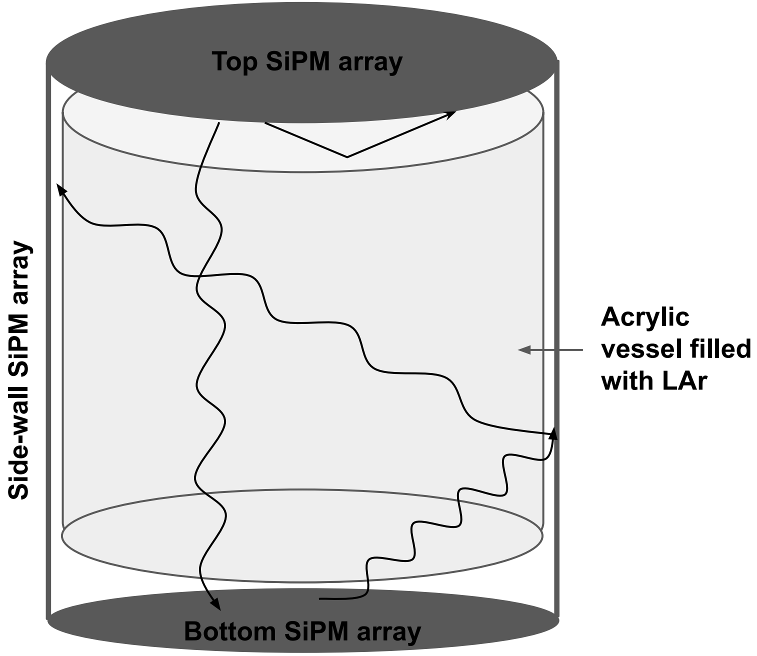
Schematic of SiPM photosensor units (10 cm ✕ 10 cm) placed on the outer side of acrylic vessel, with ~4pi photodetector coverage

SiPM optical crosstalk (oCT) in ARGO detector



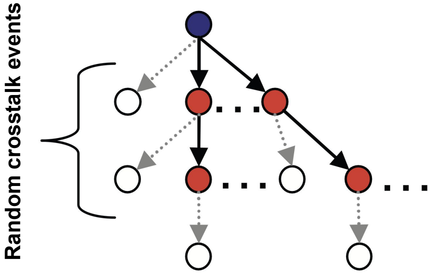
Optical crosstalk can affect the position and energy reconstruction of events, distort hit pattern IDs, thus limiting the background rejection and PSD capabilities of the detector.

In a detector like ARGO, the impact of eCT can be significant due to presence of very large number of SiPMs, and high light collection efficiency.



Schematic showing eCT photons traversing entire detector volume

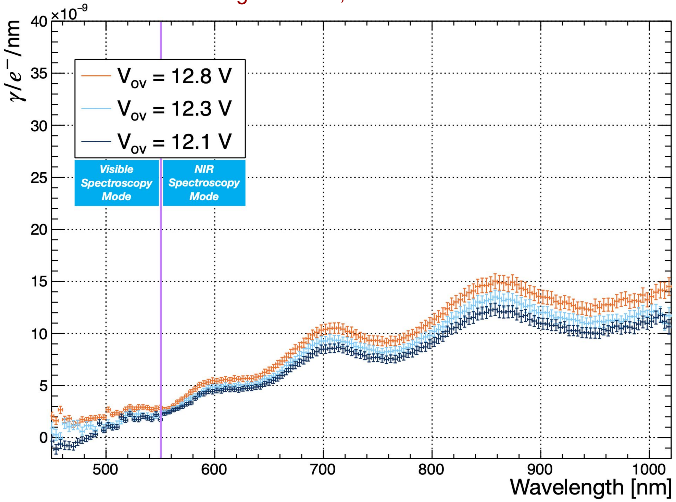
Model for SiPM optical crosstalk (oCT) simulation in ARGO



Schematic of the crosstalk process model

S.Vinogradov, DOI: 10.1016/j.nima.2011.11.086

J. McLaughlin et. al., DOI: 10.3390/s21175947



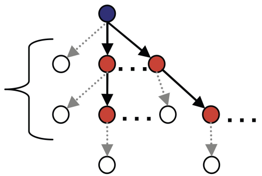
Measured differential light emission spectrum from avalanches in FBK VUV-HD3 SiPMs

Each preceding event produces a Poisson distributed (**with a provided input mean**) random number of succeeding events, and then again, until extinction, representing a branching Poisson process.

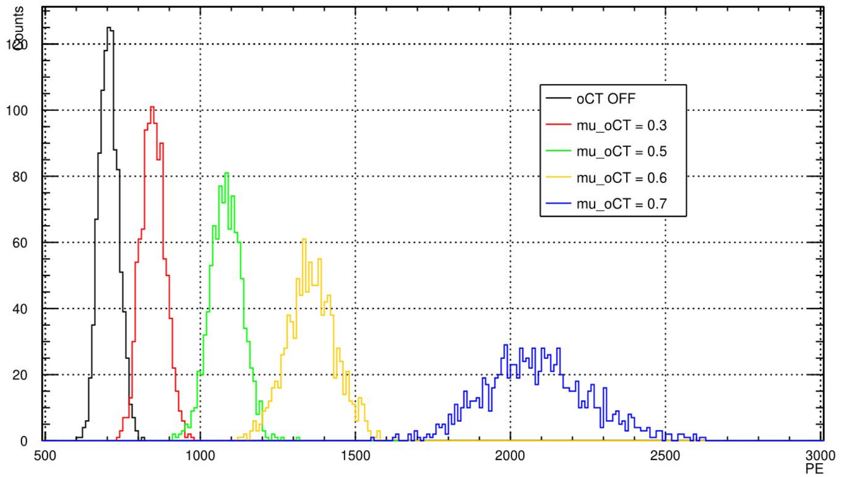
The wavelengths of secondary photons is chosen from the input emission spectrum, with their number proportional to the emission intensity at the specific wavelength.

The secondary photons are emitted instantaneously from the same location where the parent photon was detected.

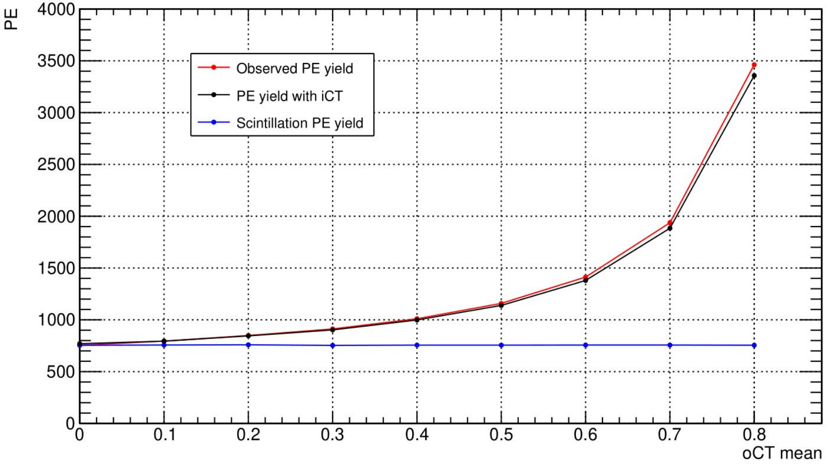
Photoelectron yield & energy resolution vs oCT mean



PE yield of 50 keV electrons vs input oCT mean



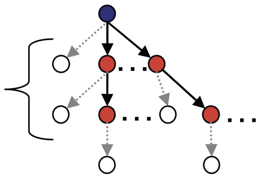
Contribution of iCT and eCT to the PE yield



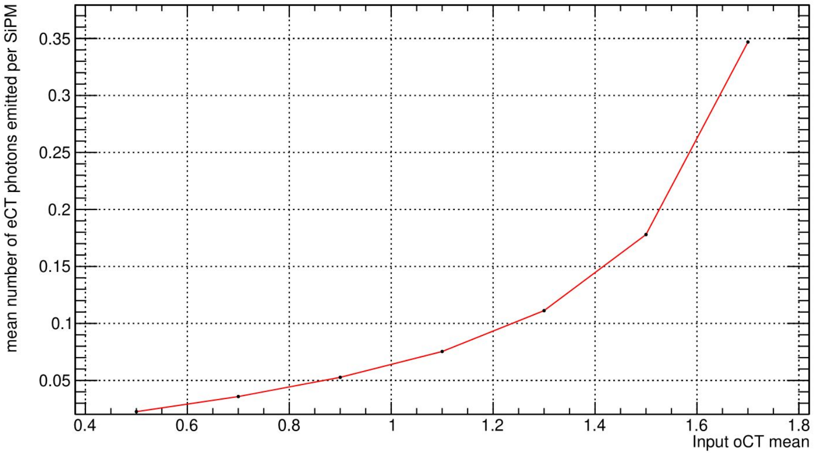
- The energy resolution of the detector becomes worse with increasing optical crosstalk levels, which can limit the pulse-shape discrimination (PSD) capabilities in ARGO.
- The end goal is to estimate quantitatively the performance of PSD for different levels of optical crosstalk.

MC Run: 50 keV electrons emitted isotropically from the center of the acrylic vessel.

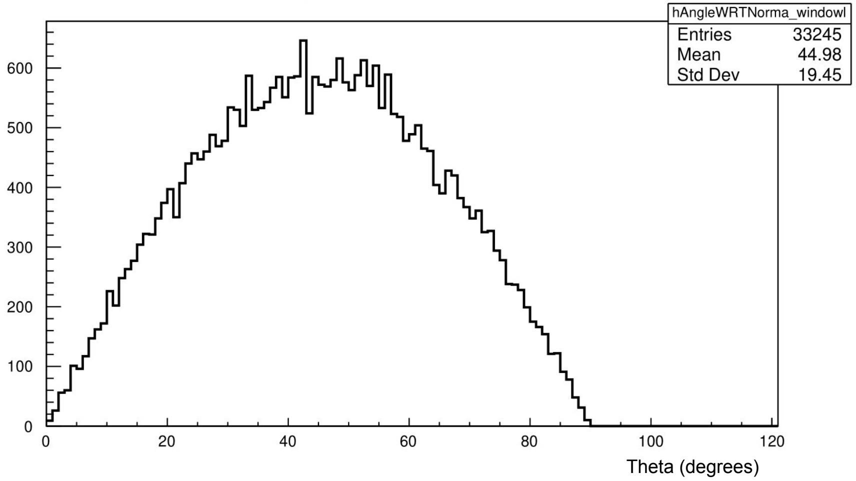
external CT photon yield vs oCT mean



Mean number of eCT photons per SiPM vs oCT mean



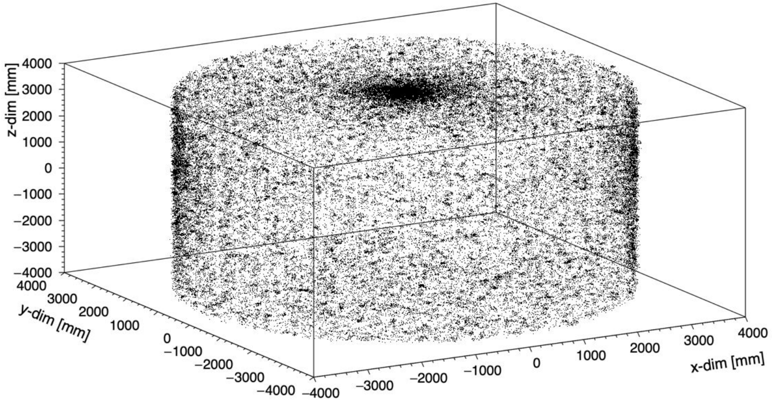
Angular distribution of emitted eCT photons

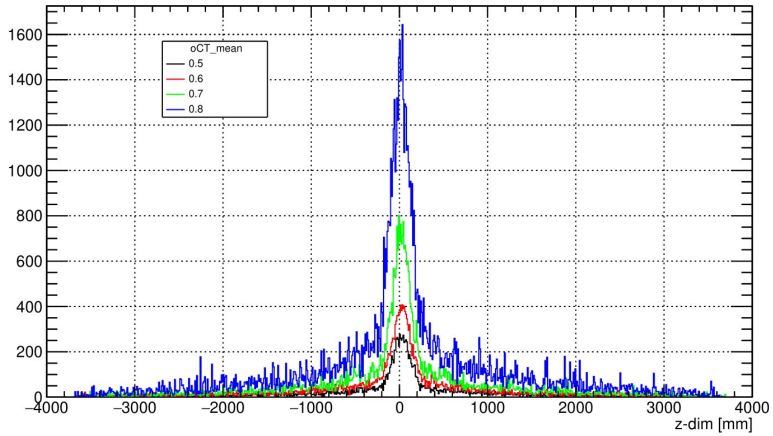


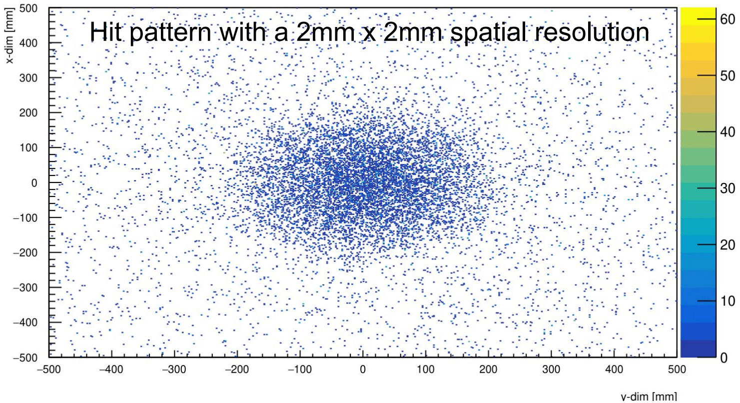
- Estimating the eCT photon yield per avalanche, tuning the input oCT value so that the eCT yield agrees with recent measurements, such as those performed at TRIUMH.
- Estimating the angular distribution of eCT photons by propagating them from within a 3 μm layer defined within the SiPM volume and located 30 nm below the SiPM surface.

MC Run: 50 keV electrons emitted isotropically from the center of the acrylic vessel.

Hit distribution of crosstalk photons & readout granularity







Hit pattern studies:

- Generating scintillation events at a single location near a SiPM, and looking at the spatial distribution of crosstalk hits. Useful for event ID based on characteristic hit patterns.
- Study the density hit pattern of clustered points near the event. Useful for optimizing the readout granularity of digital SiPMs.

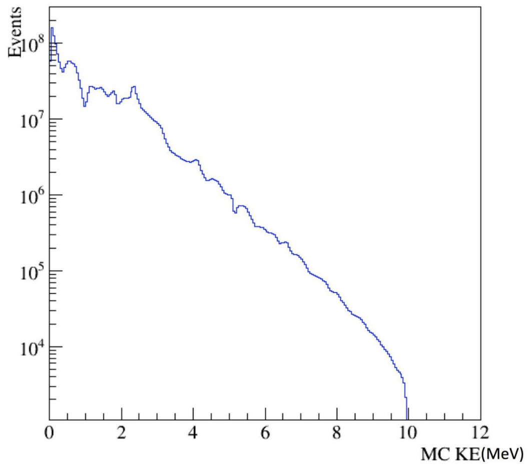
MC Run: 50 keV electrons emitted along the +z axis from a point ~16 cm below the top photodetector plane

Neutron background simulation for ARGO

Target: <1 neutron event in the WIMP ROI (15 keV_{ee} - 35 keV_{ee}) over the full 3000 ton yr fiducial volume exposure.

Work in progress:

- ➔ Generating rock neutrons and propagating them through detector materials to check how many neutrons leak into the WIMP ROI in the current configuration.
- ➔ Simulate radiogenic neutrons from SiPM photodetector units for the full volume exposure over 10 years.
- ➔ Testing various shielding configurations, such as increasing the acrylic vessel thickness, adding a water tank shielding outside the cryostat, adding a high density polyethylene shielding etc.



Energy spectrum of (α, n) neutrons propagated through ~1m of SNOLAB norite rock

Goal: Update current geometry with the optimized shielding option, and set an upper limit on the neutron background budget of detector components.

Prototyping Facility / New CFI request

Testbed for future 4π digital SiPM systems and first demonstration of large area digital SiPMs and prototyping of a (2m x 2m) DS-style TPC.

- Fast timing and pixelation allows demonstration of position reconstruction and hit pattern ID of background events. New SiPMs will be optimized for low optical crosstalk.
- designed with calibration ports for low-background assay, in particular measurement of surface alpha contamination at the level of **10 microBq/m^2** (currently not possible anywhere else but required for DM and other experiments).
- Will design in the possibility of assay of ^{42}Ar in underground argon (and by default assay of ^{39}Ar in UAr).
- Will design for low gamma background, so that in the event a low-mass WIMP signal is seen in other experiments, we could reconfigure for a low-mass WIMP argon search for confirmation.
- 2025 CFI IF proposal / 2027-2030 prototyping at SNOLAB and Carleton + continued ARGO development.

The ultimate deliverable is a final concept for ARGO that has been prototyped and risk-mitigated ready to move forward (around 2031).

Summary and conclusion

- **Third-gen direct dark matter detector:** ARGO features excellent sensitivity to high mass (>50 GeV/c^2) WIMPs extending deep into the Ar neutrino fog, with complete suppression of electron recoils and other instrumental backgrounds.
- **No extrapolation needed:** thanks to planned use of underground argon suppressed in ^{39}Ar, the required background rejection has been already demonstrated in the DEAP-3600 run (with atmospheric argon).
- **Great potential for complementary physics goals:** Solar and Supernova Neutrinos
- Funded in Canada for the development of ARGO concept. MC simulation efforts are underway.
- **Work in progress:** Submitting both a formal LOI to SNOLAB this round and funding request in 2025 in Canada for
  - developing siting requirements and engineering for ARGO and
  - developing a prototyping facility for ARGO, including digital SiPMs, that will replace DEAP-3600 around 2027 for operation 2027-2030.
- Approximate timeline is prototyping + design in place by 2030 to move ahead with ARGO project implementation.
- SNOLAB is the collaboration's preferred option.

The Global Argon Dark Matter Collaboration

With many thanks for support to:

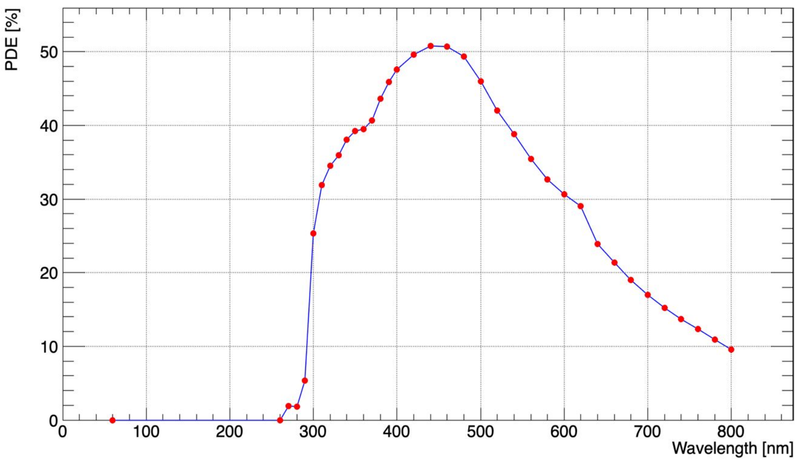
- CFI and NSERC (Canada)
- IN2P3 (France)
- INFN (Italy)
- STFC (UK)
- NSF and DOE (U.S.)
- Poland and Spain Ministries for Science and Education

Thank you!

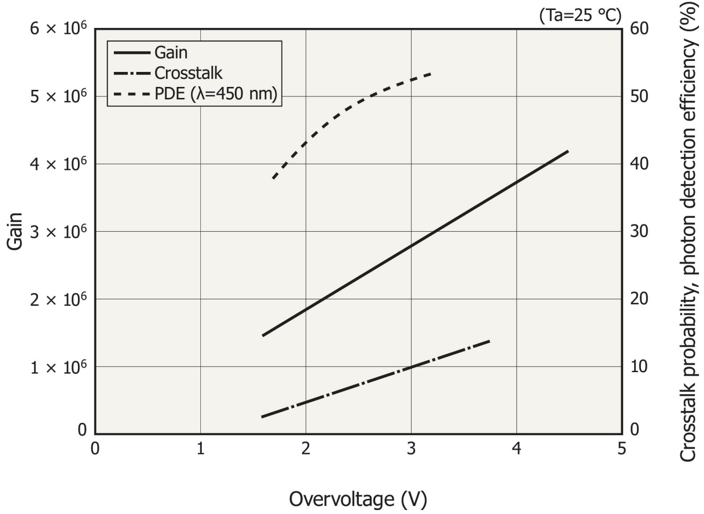
Extra slides

Input parameters for SiPM optical crosstalk simulation in ARGO

PDE vs wavelength @ 25 ℃, and 2.7 VoV



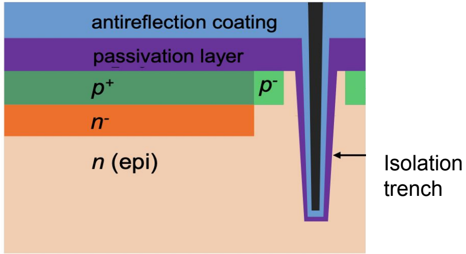
PDE vs overvoltage @ 25 ℃, and 450 nm

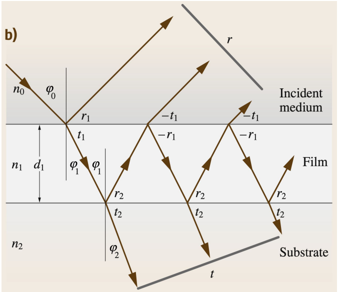


Hamamatsu H-S14161-3050HS-08 MPPC

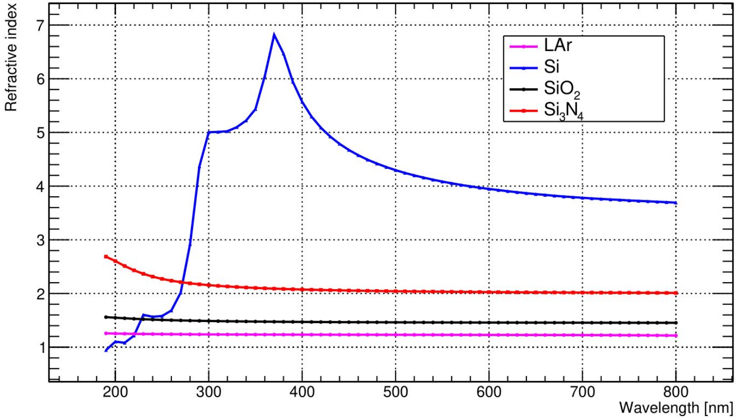
https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf

Antireflective coating in SiPMs

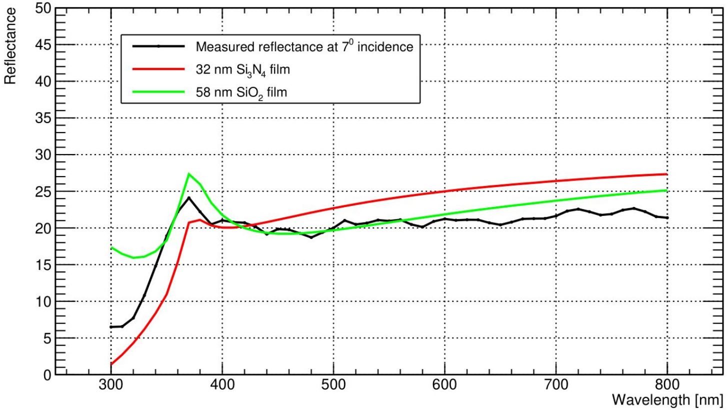




Refractive index vs wavelength



SiPM reflectance vs wavelength



The antireflection coating layer is used to reduce photon losses due to surface reflections, as there is a significant difference in the refractive index between the incident medium and silicon.

The SiPM reflectance was measured with a spectrophotometer equipped with an integrating sphere.Considering the case of a non-absorbing single film deposited on a substrate, the film thickness that best matches the measured reflectance was estimated.

Event Reconstruction For ARGO

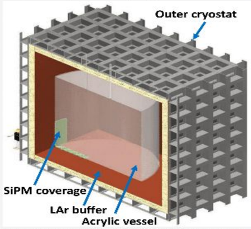
Badamsambuu Jigmeddorj* ***behalf of ARGO collaboration***
****Laurentian University, Sudbury, ON***

INTRODUCTION

ARGO is a liquid-argon scintillation detector aimed to directly observe elastic scattering of galactic WIMPs in the target. It is proposed to be deployed at SNOLAB, known for its low-background environment conducive to sensitive experiments. ARGO is designed as a single-phase detector housing 400 tonnes of low-radioactivity liquid argon within a cylindrical acrylic vessel measuring seven meters in height and diameter.

The primary objective of this study is to understand the requirements for efficient photon sensing, particularly in rejecting surface events such as alpha particles. This entails determining the optimal photon detectors needed and their required properties for effective operation.

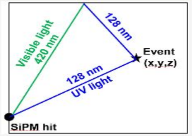
Conceptual design of the ARGO



We developed time- and charge-based reconstruction algorithms to predict the origin coordinates of events within the ARGO detector, focusing specifically on surface events. These algorithms demonstrate a strong relationship between predicted and true coordinates.

Due to the large size of the detector, the contribution of Rayleigh scattering events is significant, posing a challenge for event reconstruction, especially for the time-based method. To mitigate this bias, we focused on the prompt part of the signal, as it provides the most reconstruction power.

TIME FITTER



Event diagram in ARGO

Time-of-flight corrected SiPM residual time

$$t_{res} = t_{hit} - t_{fit} - \frac{|\overrightarrow{r_{fit}} - \overrightarrow{r_{hit}}|}{V_g}$$

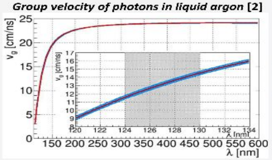
V_g - group velocity of UV photons

$$PDF_t = \mathrm{F}(r_{fit}, t_{fit}, r_{hit}, t_{hit}) \qquad LL_t = \sum_i Log(PDF_t^i)$$

$\{t_{fit}, r_{fit}\}$ defined maximizing the likelihood function.

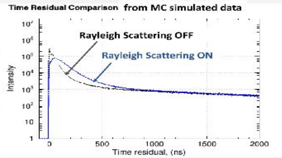
We used effective group velocity of visible light in liquid argon to avoid negative residual time distribution.

Group velocity of photons in liquid argon [2]

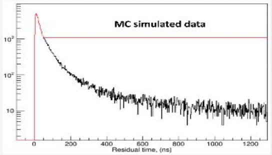


The presence of Rayleigh scattered light causes the residual time distribution to widen after the prompt light peak and become thicker in the later part. To address this issue, we flattened the distribution after the 75 ns mark to prevent likelihood misbehaving.

Rayleigh Scattering effect



Time distribution flattened beyond 75 ns



CHARGE FITTER

The charge-based method relies on the pattern of charges measured by the Silicon Photo-Multipliers (SiPM) positioned across the surface of the liquid argon vessel in the ARGO detector. The X and Y coordinates are determined by maximizing a likelihood function constructed using a probability distribution defined as a function of X and Y coordinates from Monte Carlo simulated events, while the Z coordinate is inferred from the measured charge distribution along the Z axis.

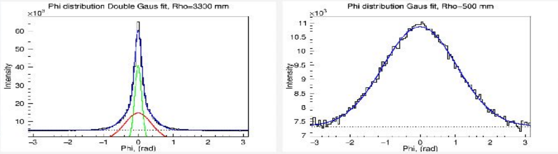
Probability distribution function for charge-based method

$$PDF_c = \mathrm{F}(\varphi_{fit}, \rho_{fit}, \varphi_{hit}, \rho_{hit}) \qquad LL_c = \sum_i Log(PDF_c^i)$$

$\{\varphi_{fit}, \rho_{fit}\}$ defined maximizing the likelihood function.

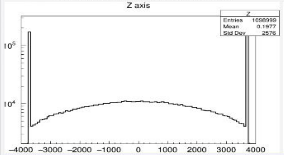
The probability of detecting photons by a SiPM is a highly non-linear function of the event's coordinates and changes rapidly as the interaction point comes closer to the PMT. We used double Gaussian functions for fitting Phi distribution.

Phi distributions of events created at a different positions

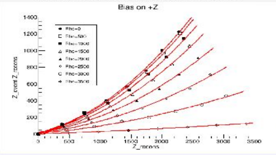


The Z coordinate was determined by identifying the location where the amount of charge dropped to half in the charge distribution along the Z axis. Initial simulations showed bias on Z-reconstruction and we corrected as shown below.

Charge distribution along Z axis



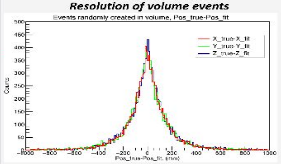
Bias distribution for Z reconstruction



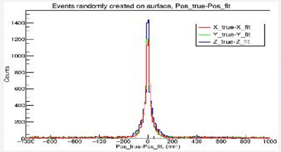
RECONSTRUCTION RESOLUTION (CHARGE FITTER)

We reconstructed Monte Carlo (MC) simulated surface and volume events using the algorithm based on charge fitting. The following figures display resolution of 10000 reconstructed events created by MC simulations of 100 keV alphas within the entire volume (left) and on the surface (right) of the ARGO detector.

Resolution of volume events



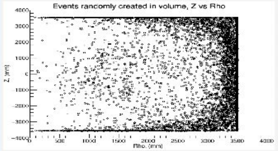
Resolution of surface events



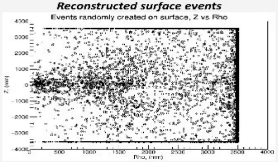
RECONSTRUCTED EVENTS (TIME FITTER)

The following figures display 10000 reconstructed events created by MC simulations of 100 keV alphas within the entire volume (left) and on the surface (right) of the ARGO detector.

Reconstructed volume events



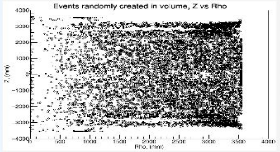
Reconstructed surface events



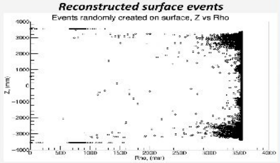
The time fitter needs some improvement due to observed misconstructions. Specifically, there are fewer events reconstructed in the middle of the detector compared to the surface, despite the events being uniformly created throughout the volume. Additionally, there are extra events reconstructed at the center while the events being created on the surface, indicating inaccuracies in the time fit.

RECONSTRUCTED EVENTS (CHARGE FITTER)

Reconstructed volume events



Reconstructed surface events



The charge fitter demonstrates reasonable reconstruction accuracy for events uniformly distributed within the volume, as opposed to the time fitter. However, there is a small area where no events are reconstructed. The charge fitter's performance is less optimal in reconstructing surface events compared to the time fitter. Specifically, fewer events are reconstructed at the top and bottom of the detector compared to the barrel surface, despite the uniform creation of events across the surface.

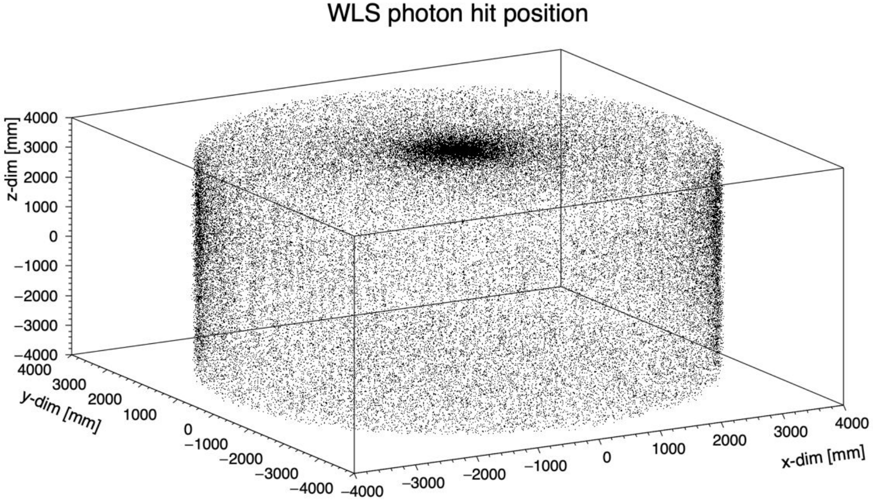
SUMMARY AND FURTHER WORK

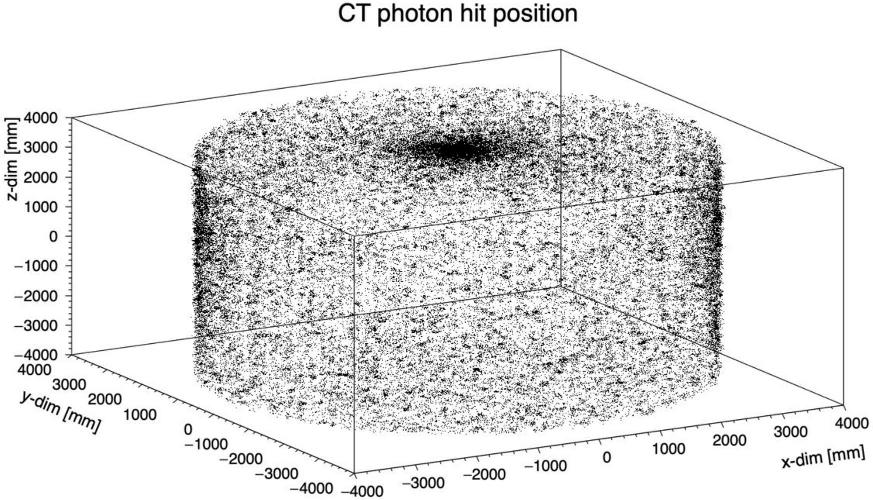
Through MC simulations and utilizing time and charge fitting algorithms, we have successfully reconstructed both surface and volume events in the ARGO detector. This work significantly contributes to ongoing efforts aimed at understanding the critical requirements for photon sensing and surface event rejection within the detector, which are crucial for detecting WIMPs. While our results demonstrate successful reconstructions, we have also observed some misconstructions with both the time and charge fitters. Moving forward, our focus will be on enhancing the accuracy of the reconstruction algorithms, particularly for surface events. We plan to incorporate machine learning techniques to further refine our reconstruction capabilities and to cross-check different algorithms, ensuring robustness in the reconstruction process. Additionally, our MC simulations will include more detailed modeling of Silicon Photomultiplier (SiPM) effects, such as external cross-talk.

REFERENCES

1. S. Cebrián, Review on dark matter searches, J. Phys. Conf. Ser. 2502 (2023) 012004.
2. LIDINE proceedings (2023), arXiv:2312.07712

Hit distribution of crosstalk photons

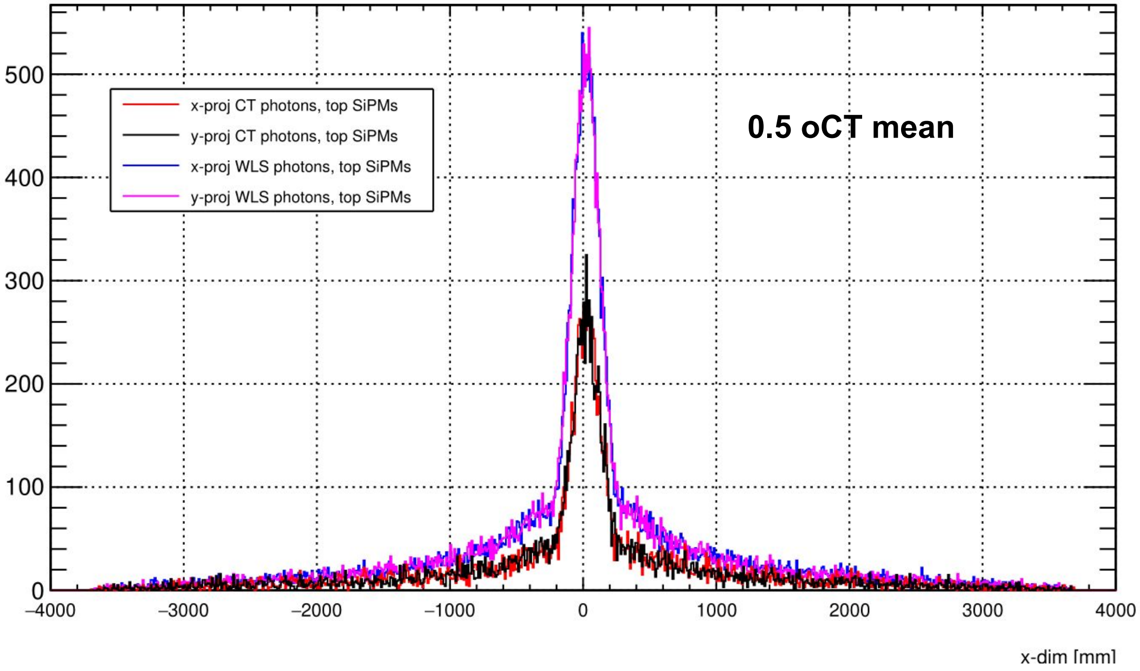




0.8 oCT mean

MC Run: 50 keV electrons emitted along the +z axis from a point (25.0, 25.0, 3540.0), just below the top TPB layer

Hit distribution of WLS and CT photons in the top SiPM array



For 50 keV electrons generated ~16 cm below the top SiPM array, and directed upwards

The Sun shines by the energy produced in a thermonuclear reaction chain built up on the fusion of four protons to produce one ^{4}He nucleus. The chain has three major links:

ppI - the fundamental proton–proton fusion leading to the production of ^{3}He;
ppII - the production of ^{7}Be via the reaction $^{3}He + ^{4}He$;
ppIII - the production of ^{8}B via $^{7}Be + p$

each step terminating with the production and accumulation of ^{4}He. Each of these links produces electron neutrinos. The ^{7}Be from the ppII link decays by electron capture with a ≃90% branch yielding mono-energetic 0.862 MeV neutrinos. The ^{7}Be contribute a substantial (≃10%) fraction of the solar flux, whereas only 10^{-4} of the total flux arises from ppIII.

The prediction of the ^{7}Be neutrino flux depends both on the solar model and on the cross section of the ^{3}He-^{7}Be reaction, therefore a measurement of the ^{7}Be neutrino flux is an important and timely test of the Standard Solar Model.