# Optical modeling of pixelated digital SiPMs for ARGO

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# The Global Argon Dark Matter Collaboration

ArDM
DarkSide-50
DEAP
MiniCLEAN

The Global Argon Dark Matter Collaboration (2017)

DS-20k
{20 t fid., 100 ton total}

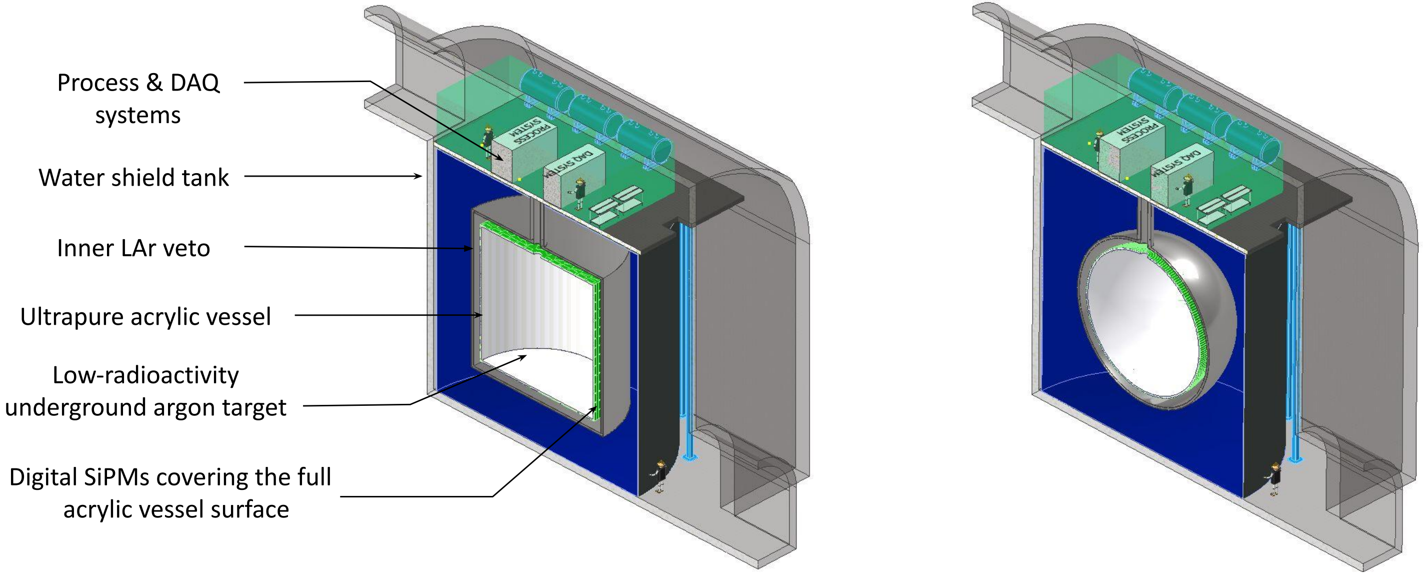
Ops 2028 - 2038, LNGS

**ARGO**
{300 t fid., 400 ton total}

Project early 2030's, SNOLAB

**400 researchers, 100 institutions, 14 countries**

# ARGO conceptual design in SNOLAB Cube Hall

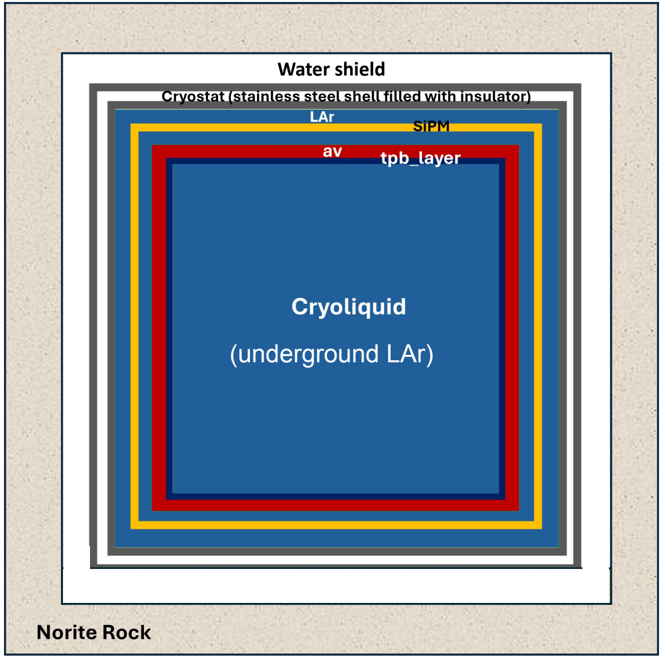



~400 tonnes of underground argon, **300 tonnes fiducial mass**, 3000 tonne-year exposure.

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

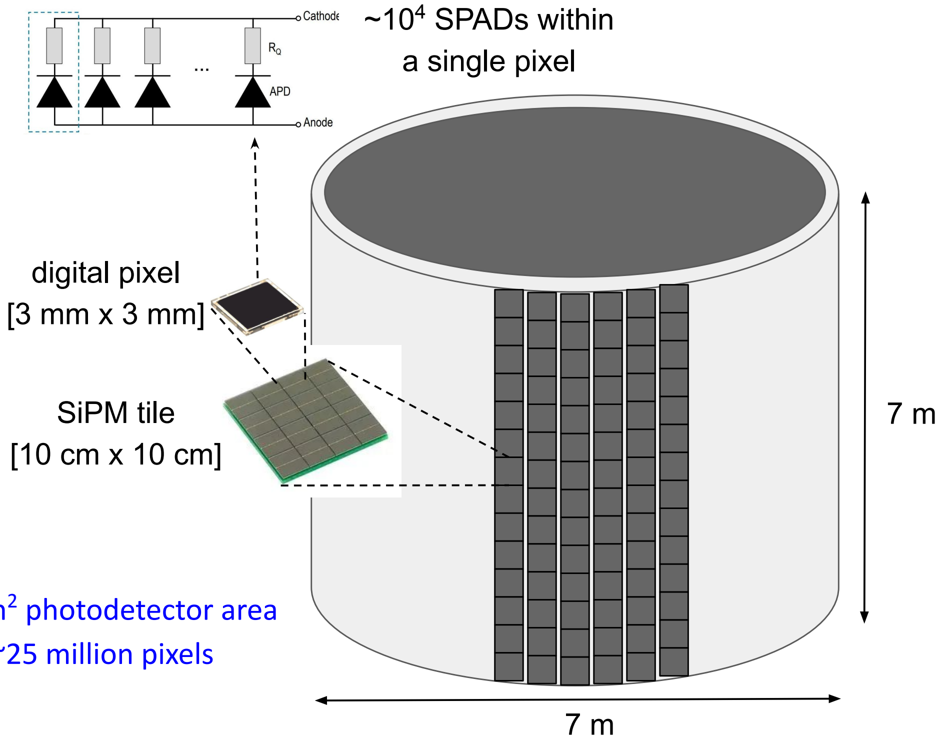
NSERC-funded since 2021. SNOLAB Gateway-1a approval in 2025 for prototyping and concept development.

# ARGO geometry & photodetector arrangement in the MC simulation framework




vertical cross-section of ARGO detector in RAT

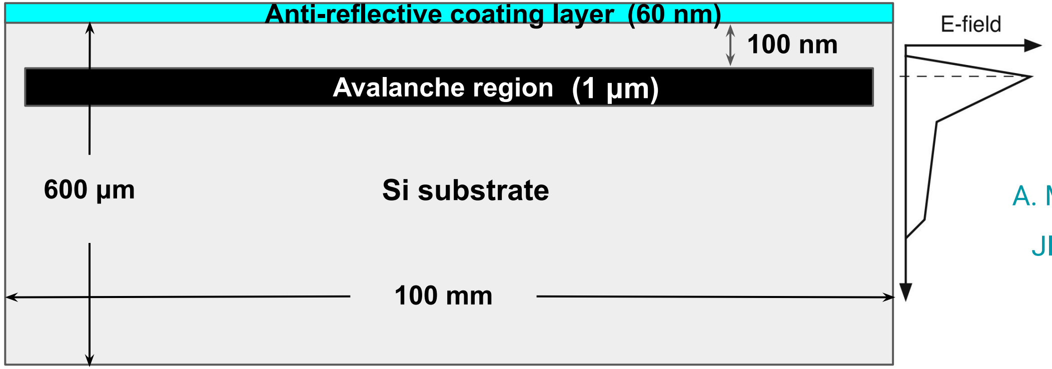
https://rat.readthedocs.io/en/latest/




250 $m^2$ photodetector area
~25 million pixels

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

# A geometrical model for realistic simulation of photon detection in SiPMs



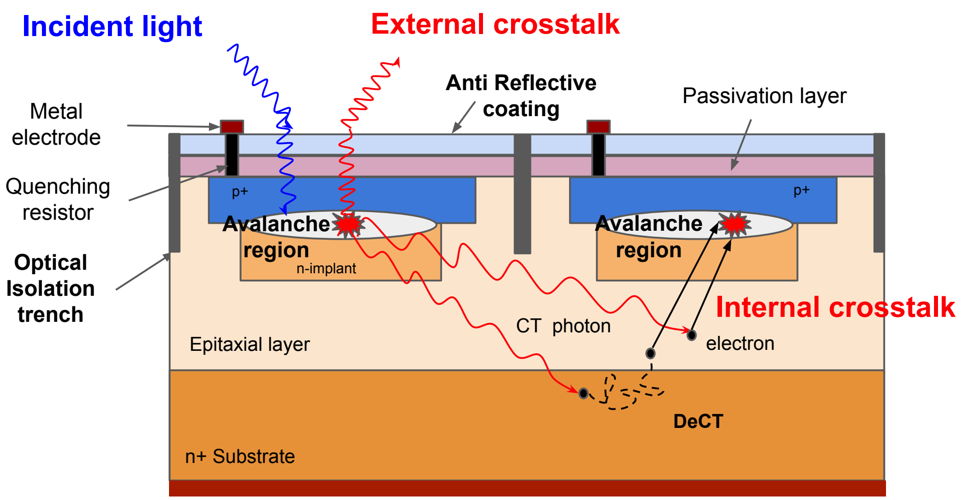

Schematic of a SiPM tile used in the MC

A. Moharana & M. G. Boulay
JINST 21 C04016 (2026)

- SiPM modeled as a virtual grid of SPADs (25 µm pitch) and pixels (3 mm × 3 mm).
- SiPM geometrical fill factor of (70%)
- An efficiency correction factor parametrizes the effect of optical trenches.

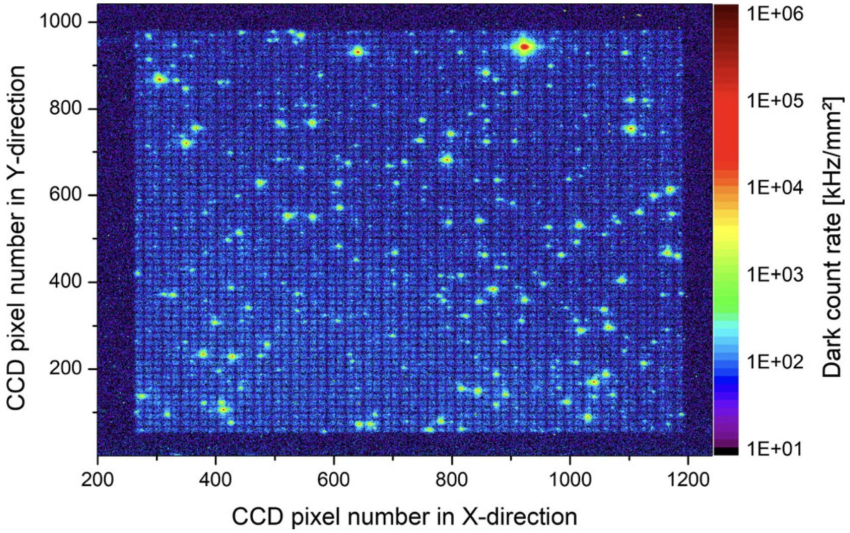
# SiPM noise sources

*Spatially resolved dark count rate of SiPMs,*
Eur. Phys. J. C 78, 971 (2018)




Vertical cross-section of a SiPM

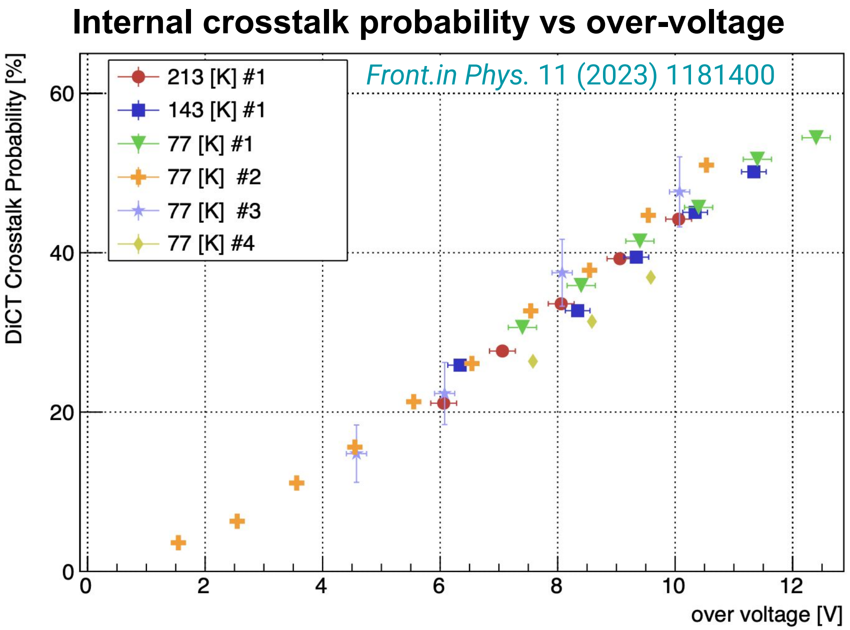
Light emission image of a Ketek PM3350T SiPM recorded with a low-light CCD camera



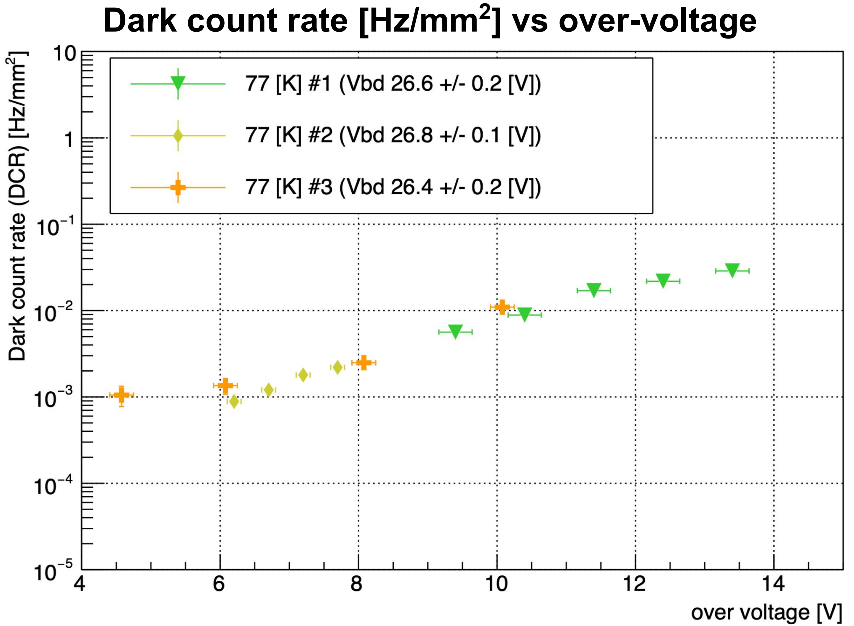

**Optical crosstalk:** photons generated in SPAD avalanches that trigger secondary avalanches in other SPADs.

**Dark Counts:** secondary avalanches triggered by charge carriers generated in the avalanche region through thermal excitation/tunneling mechanisms.

# SiPM noise measurements



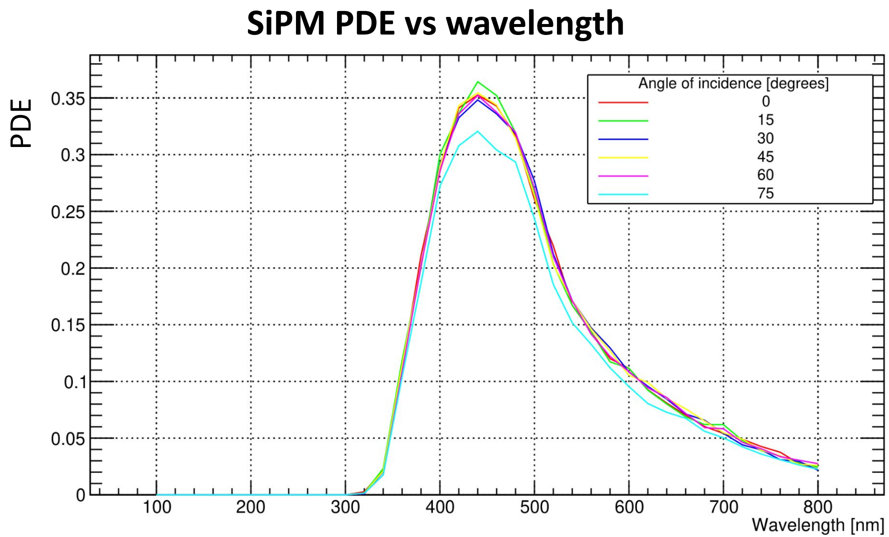

~30% iCT at 7 V over-voltage

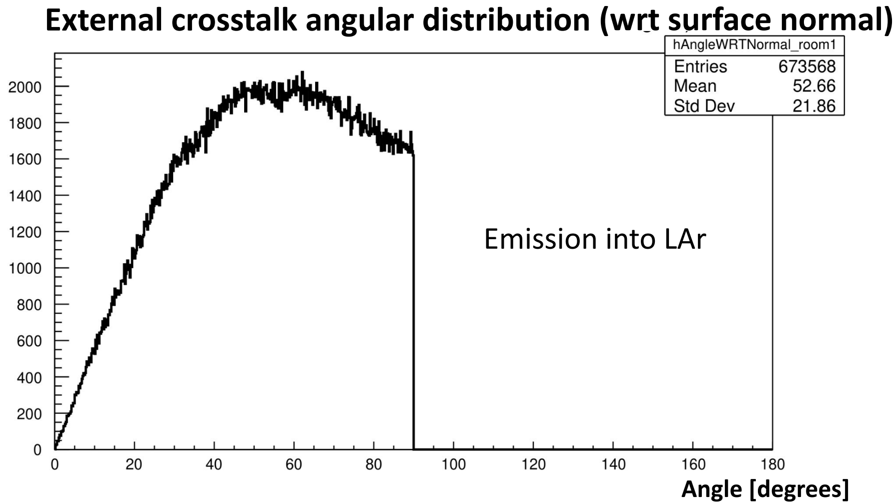


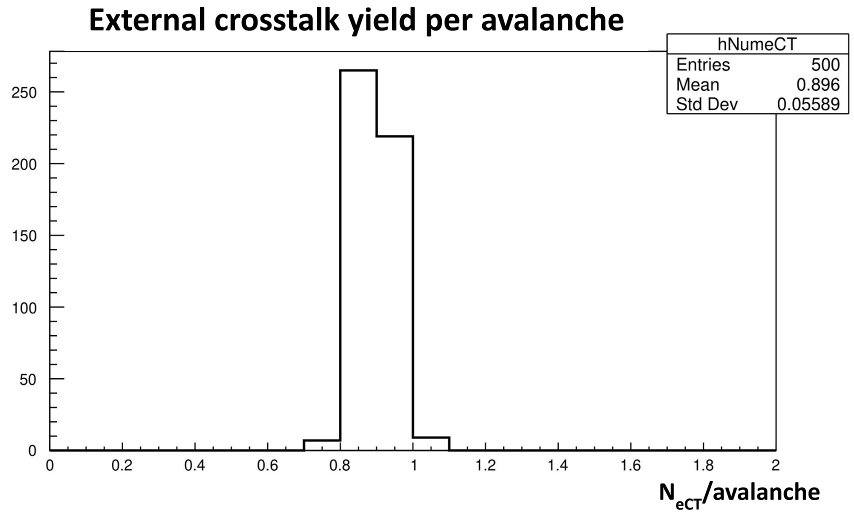

~10 mHz/mm$^2$ at 7 V over-voltage

External crosstalk probability measured to be ~8% using small-scale LAr prototypes equipped with SiPM tiles.

# Key results from MC simulation



# Studying the impact of SiPM noise contributions on energy threshold

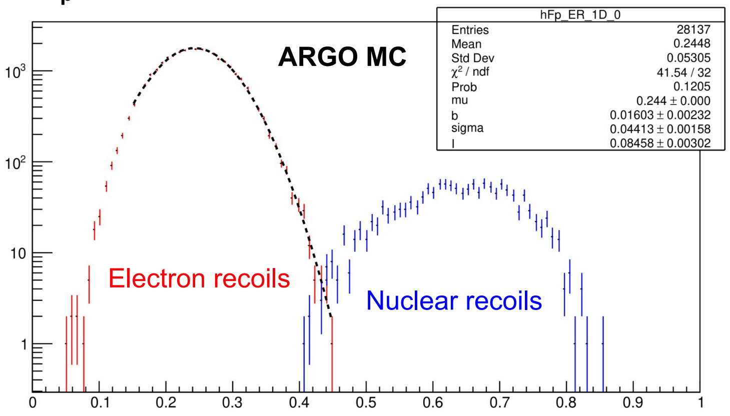
Strong ER background rejection through **pulse-shape discrimination** (PSD), as demonstrated by DEAP-3600 [*Eur. Phys. J. C* 81, 823 (2021)]

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

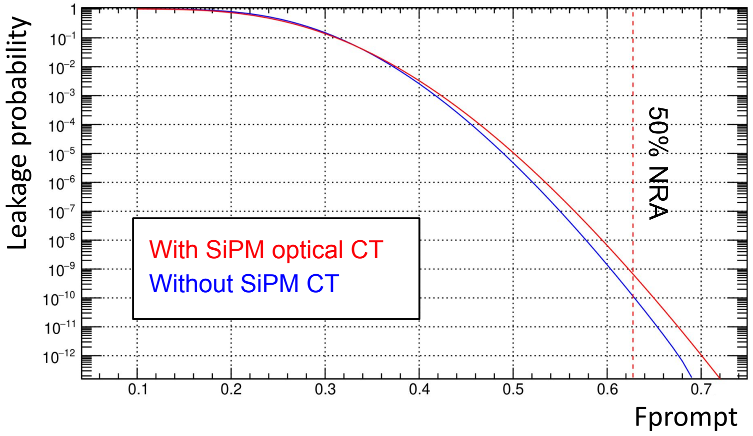
**Leakage probability *PL(f)*** at an $\mathrm{f_p}$ value → probability for an ER event to occur in the [$\mathbf{f_p}$, 1] range.

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

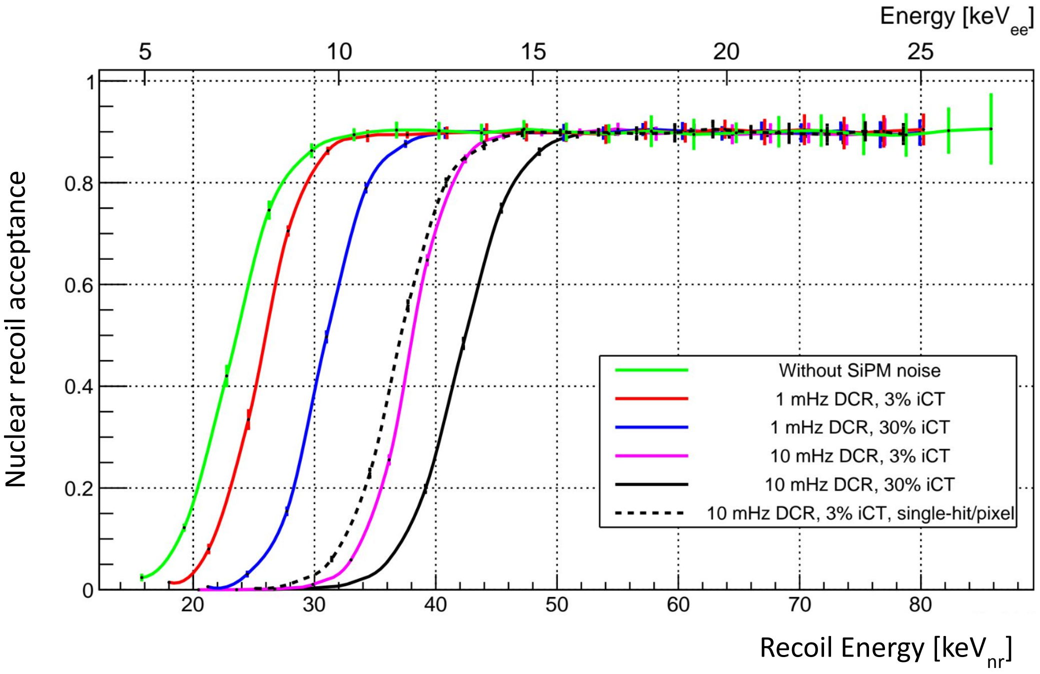
$\mathbf{f_p}$ distribution in the lowest PE bin of the ROI




ER background leakage probability

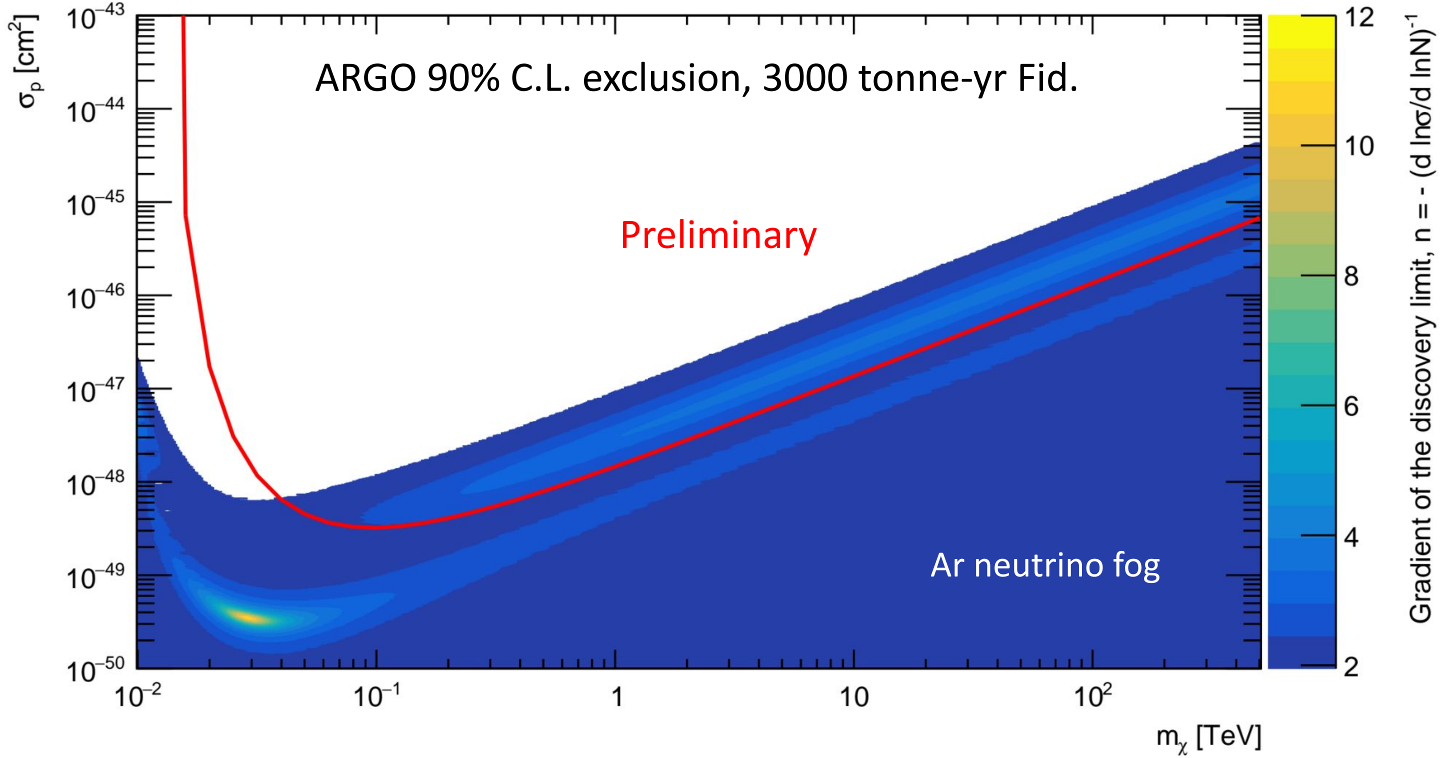


# Energy threshold curves for different SiPM noise scenarios



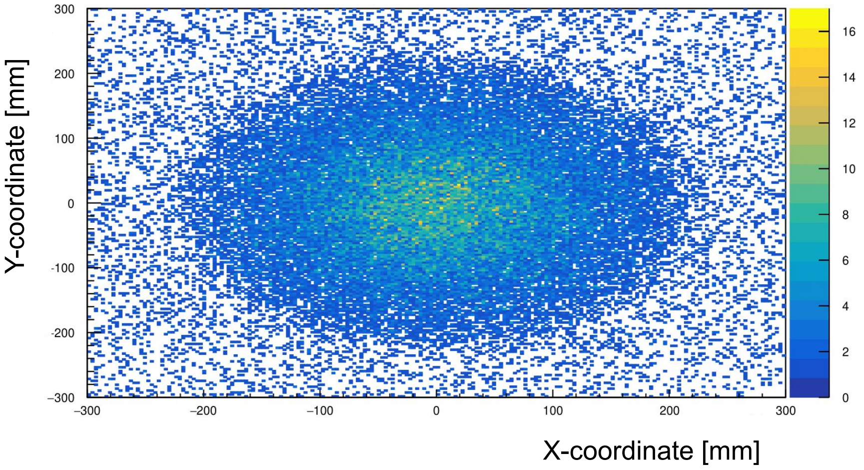

- Nuclear recoil acceptance curves generated **considering an ER leakage < 0.05 events** in 10 live-years.
- Impact of internal CT can be reduced by accepting single hit per pixel (dimensions: 3 mm × 3 mm).

# Sensitivity to WIMP search with ARGO

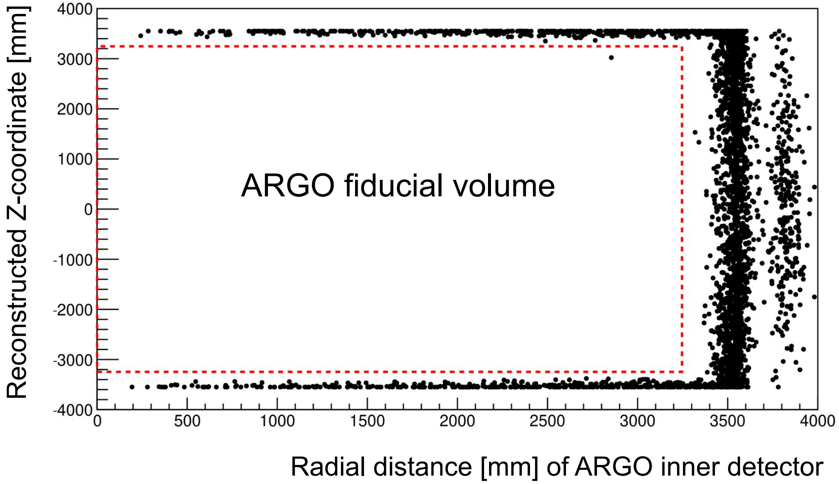


# Position reconstruction and event ID with pixelated photodetectors

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.

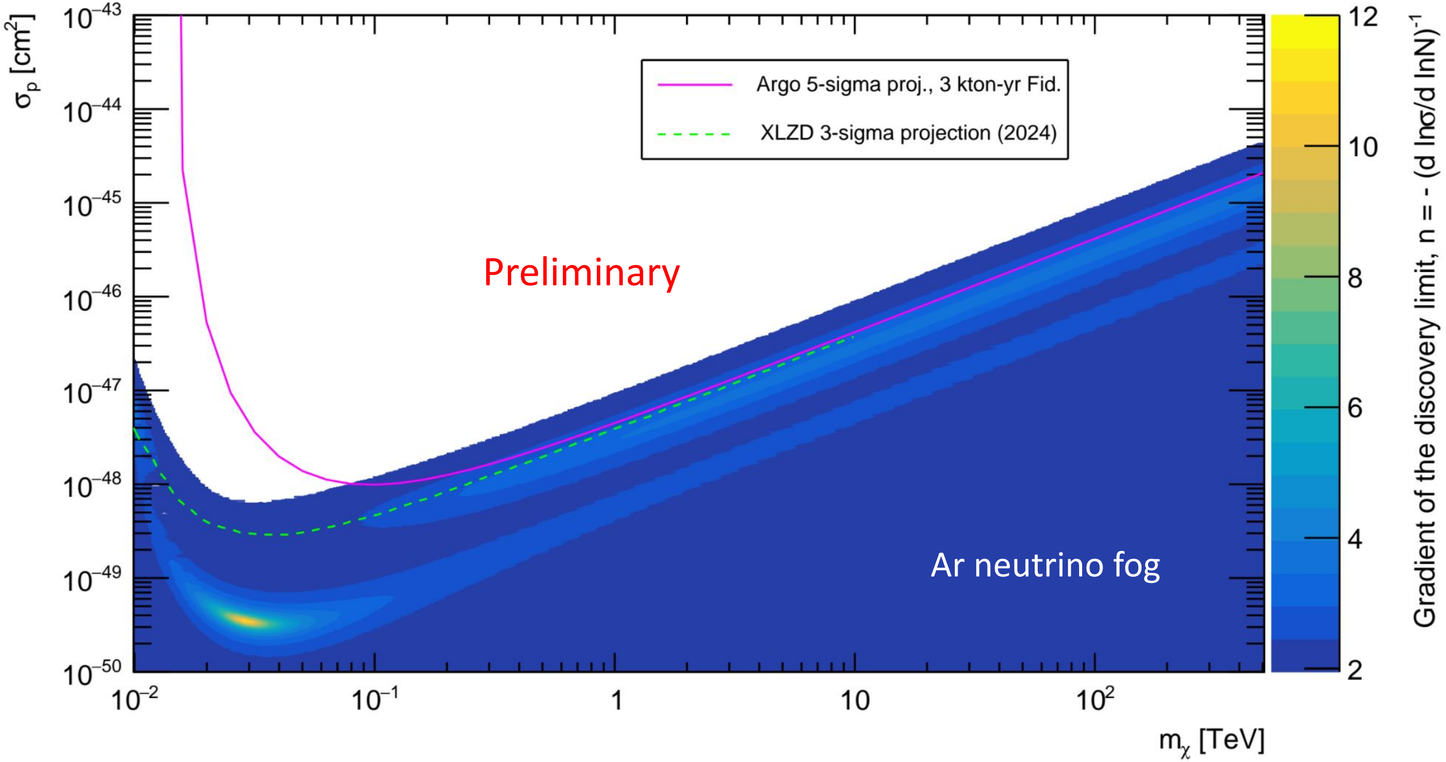
**Target: A combined surface alpha rejection at $10^{-5}$ or better.**

# 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 dark noise & optical crosstalk:**
    - Reproduces SiPM PDE vs. wavelength, gives a random distribution of dark noise hits, provides internal & external CT yields, and external crosstalk angular distribution.
- Excellent sensitivity for precise solar neutrino measurements through multiple detection channels.
- Working on the ARGO design and sensitivity paper.

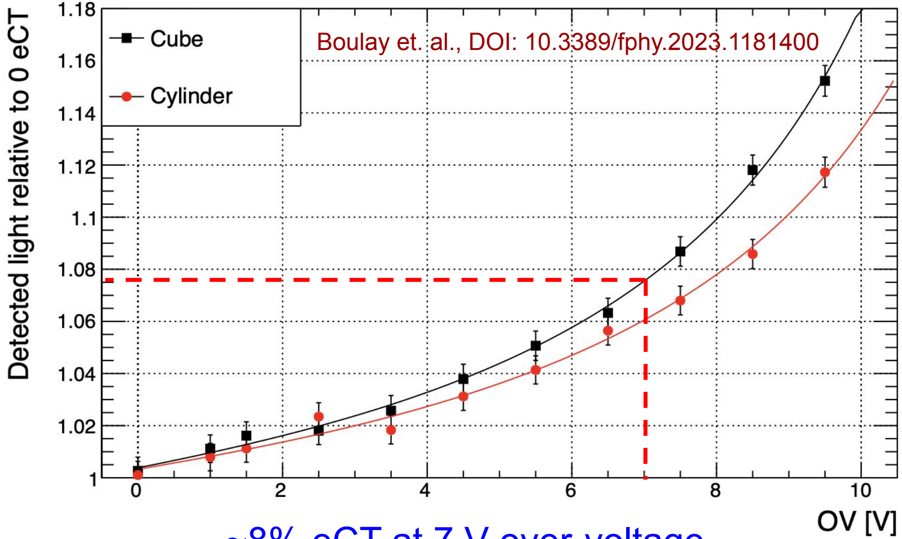
# Backup slides

# Sensitivity to WIMP search with ARGO

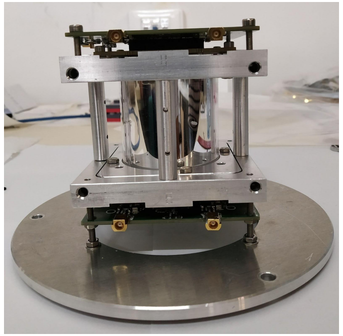


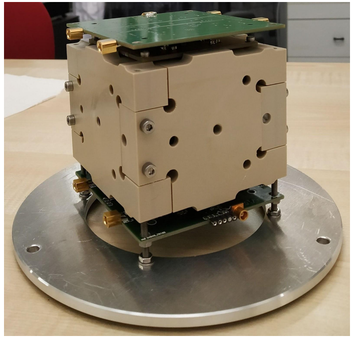
# Measurements of SiPM external crosstalk

**Photoelectron gain due to eCT vs over-voltage**



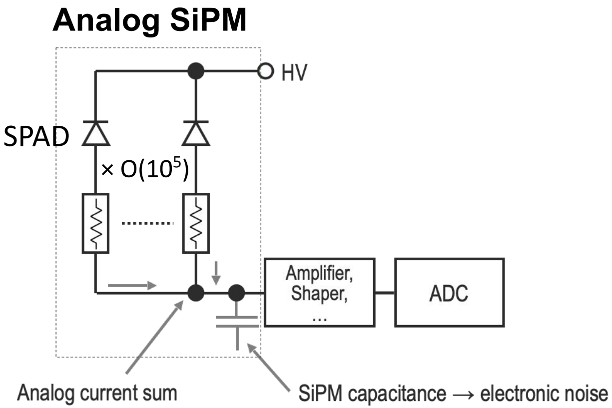

~8% eCT at 7 V over-voltage

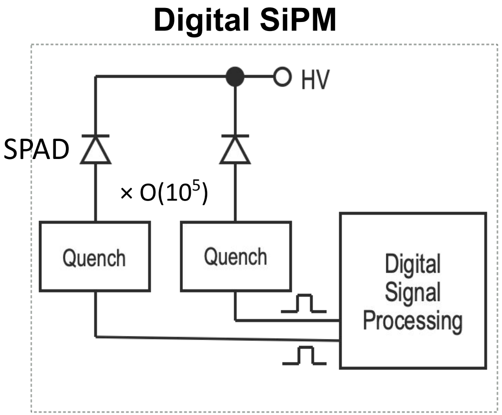




Small-scale liquid argon prototype detectors equipped with SiPM tiles used for making precise measurements of external crosstalk

# Photodetectors for ARGO: Digital SiPMs




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.