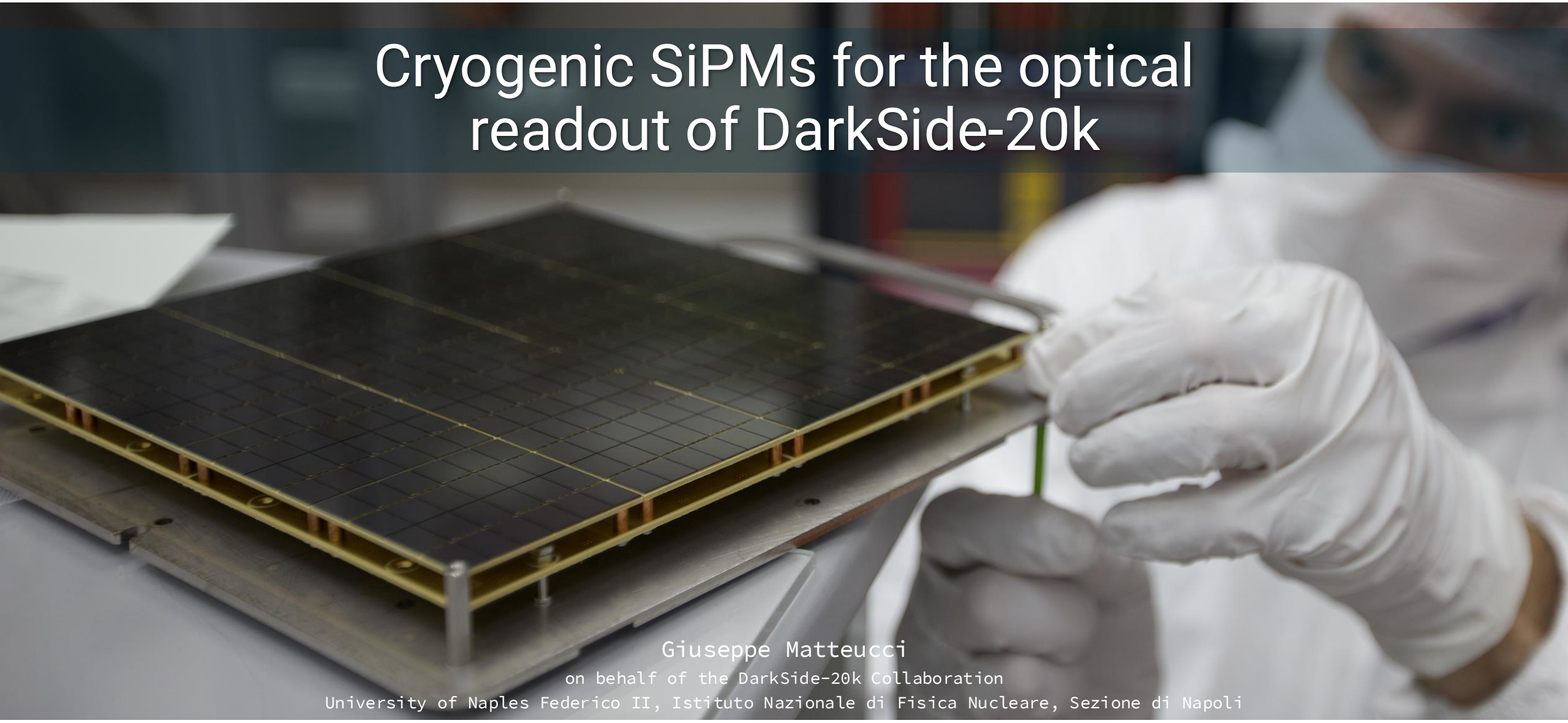
# Cryogenic SiPMs for the optical readout of DarkSide-20k



Giuseppe Matteucci
on behalf of the DarkSide-20k Collaboration
University of Naples Federico II, Istituto Nazionale di Fisica Nucleare, Sezione di Napoli

# The DarkSide-20k Experiment

- In construction at Hall C of LNGS (3800 m w.e.)

**Outer Veto**

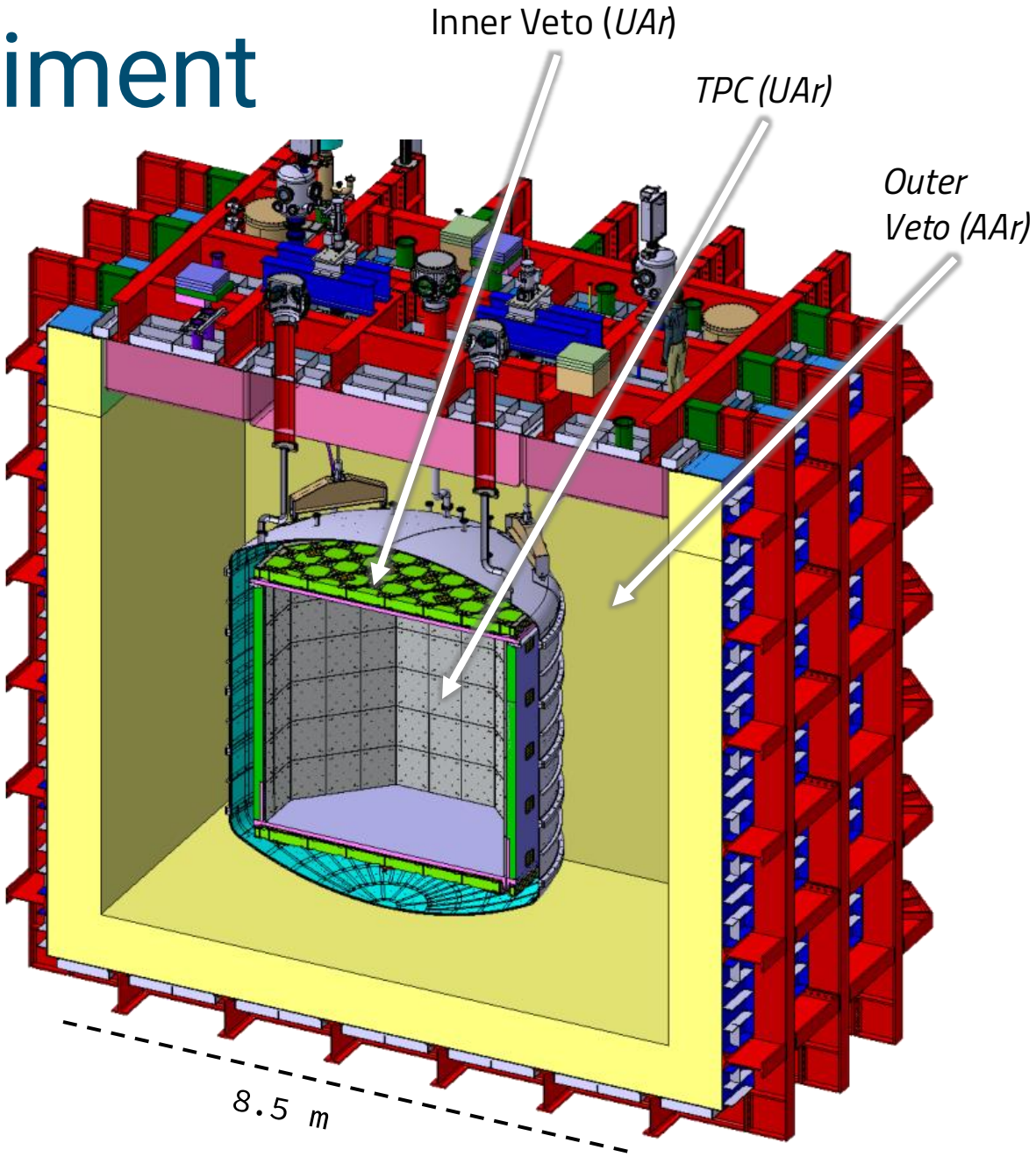
Muon veto
ProtoDUNE-like membrane cryostat 8x8x8 $m^3$

**Inner Detector**

Contained within a stainless steel vessel
100 t of UAr (including TPC UAr )

**1. Two-phase Ar TPC**
**2. Veto**

- Target background < 0.1 (excluding neutrinos) in 200 t yr



# The two-phase TPC of DS-20k

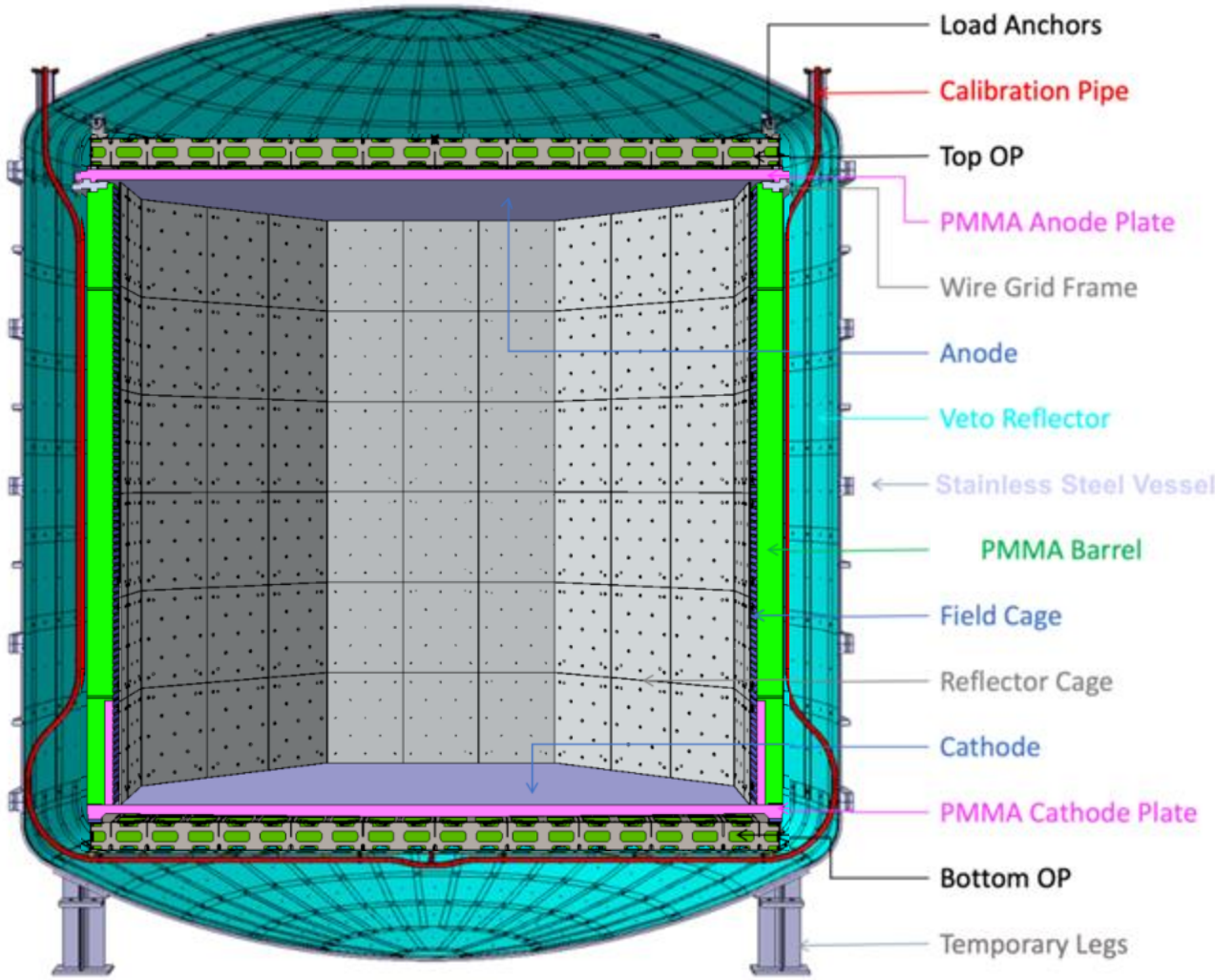
**DarkSide-20k TPC:**

**Walls:**
- PMMA
- ESR Reflector
- TPB wavelenght shifter

**Top and bottom Plates:**
- PMMA
- TPB wavelenght shifter
- Optical planes comprised of SiPM photo-detector units

**Fields:**
- Clevios coating for Anode, Cathode, Field Cage
- Wire grid of stainless steel

**Drift length** = 348 cm
Active UAr mass in TPC = 49.7 t (20 t fid.)
Spatial resolution: xy < 5 cm, z ~ 1 mm



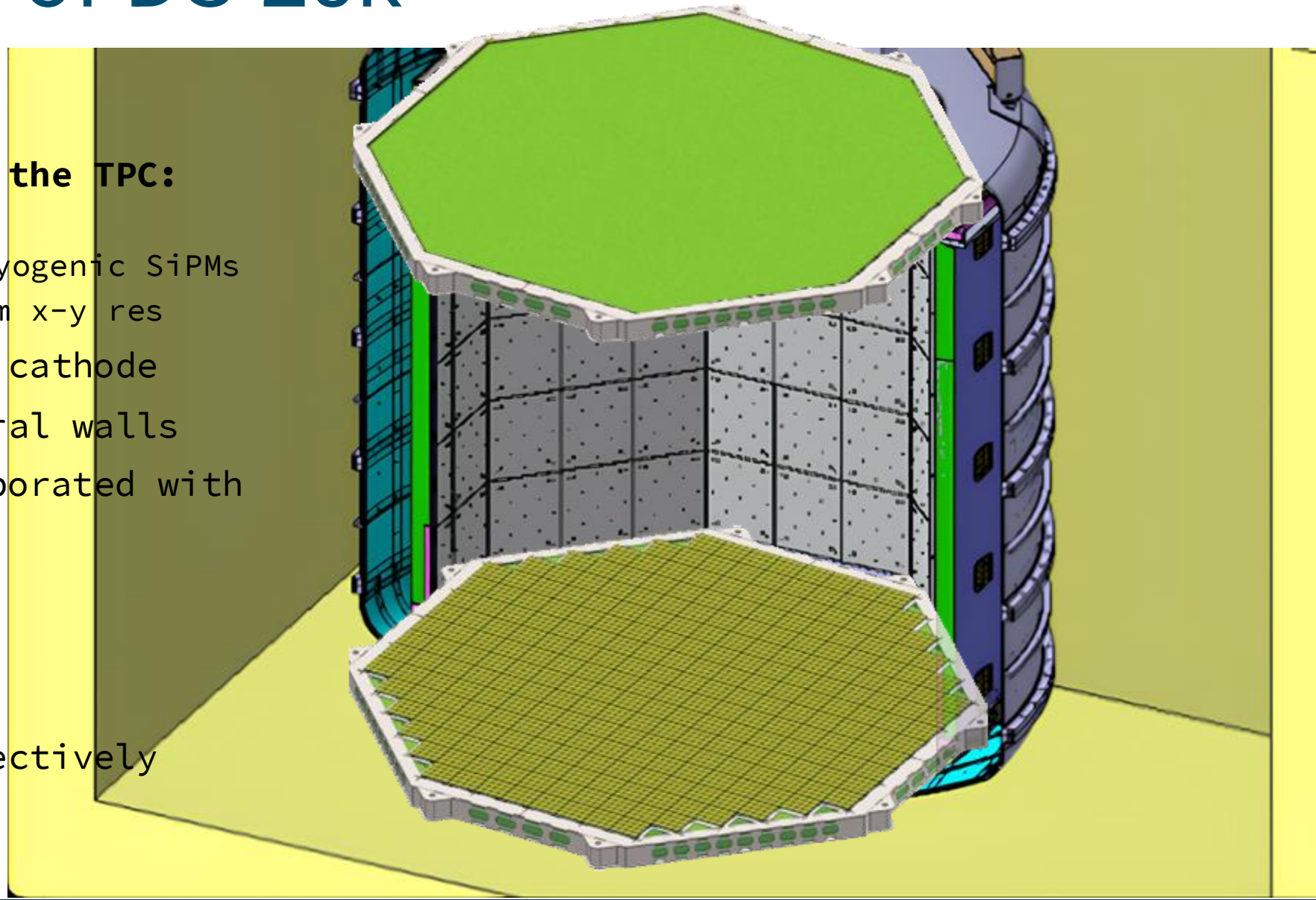
# Light readout of DS-20k

**TPC:**

- **Two optical planes of the TPC:**
  - 21 $m^2$ in total
  - ~100% coverage of cryogenic SiPMs
  - 2112 channels, < 5 cm x-y res
- Transparent anode and cathode
- ESR reflector on lateral walls
- Internal surfaces evaporated with TPB

**Inner and outer veto:**

- Same SiPM technology
- 512+128 channels respectively [~(5+1) $m^2$ ]



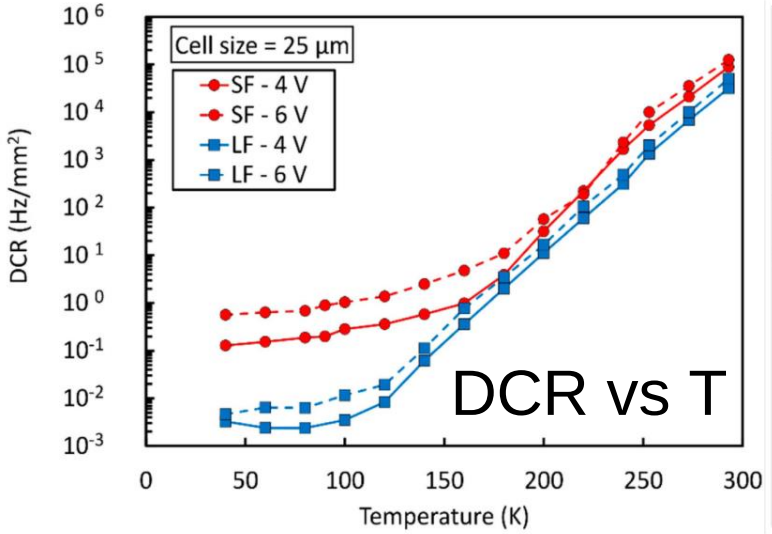
# Cryogenic SiPMs

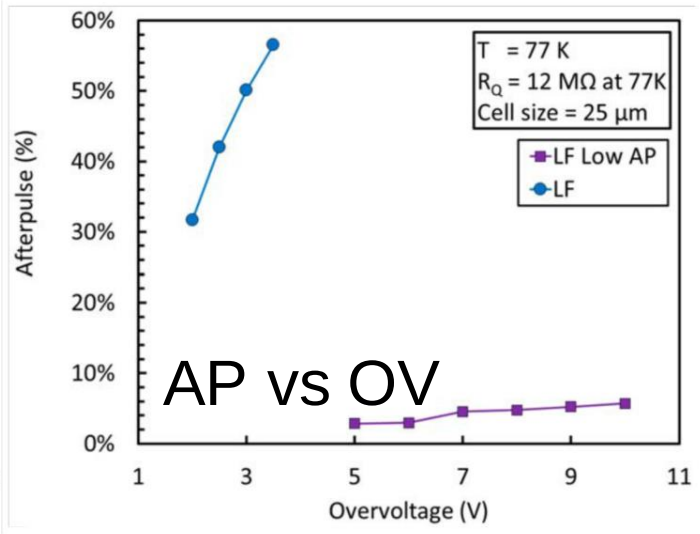
Gola et al. – **2019** Sensors 19(2), 308

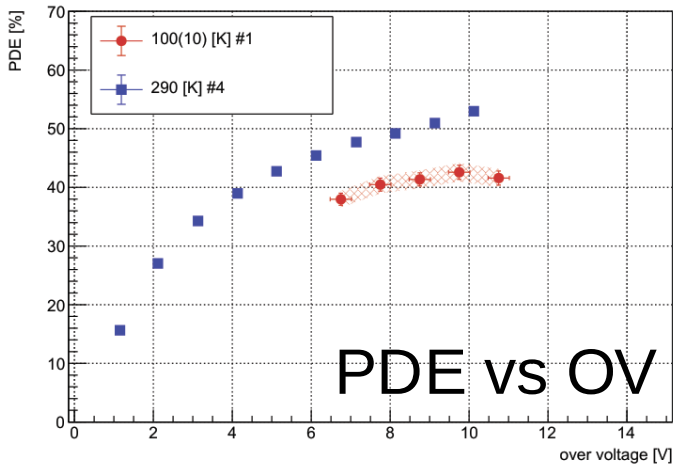
**NUV-SiPMs in Liquid Argon**

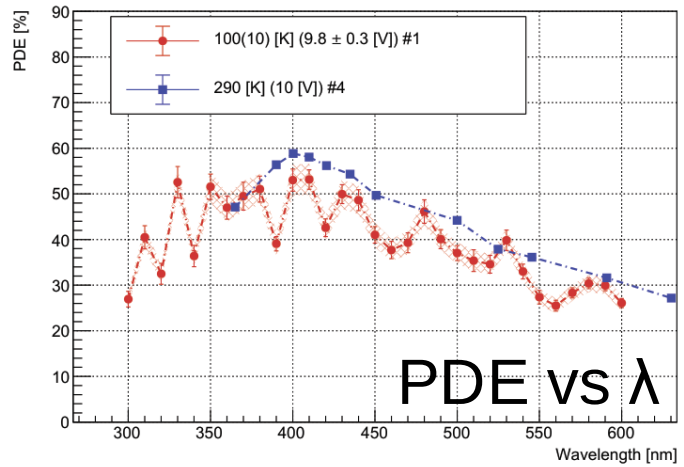
*NUV-HD-CRYO by FBK:*

- Reduced DCR (up to $10^{-6}$ with respect to 300K)
- ~~Increased After Pulsing~~
  → *Low AP Technology*
- ~~Increased Quenching Resistance~~
  → *PolySi resistor with limited temperature dependance*
- Never used in long-exposure experiment → *prototyping and testing*
- *Require wavelength shifter*
- Technology for DS-20k developed by Fondazione Bruno Kessler (FBK)
- Mass production by LFoundry



# SiPM Tile (PDM)

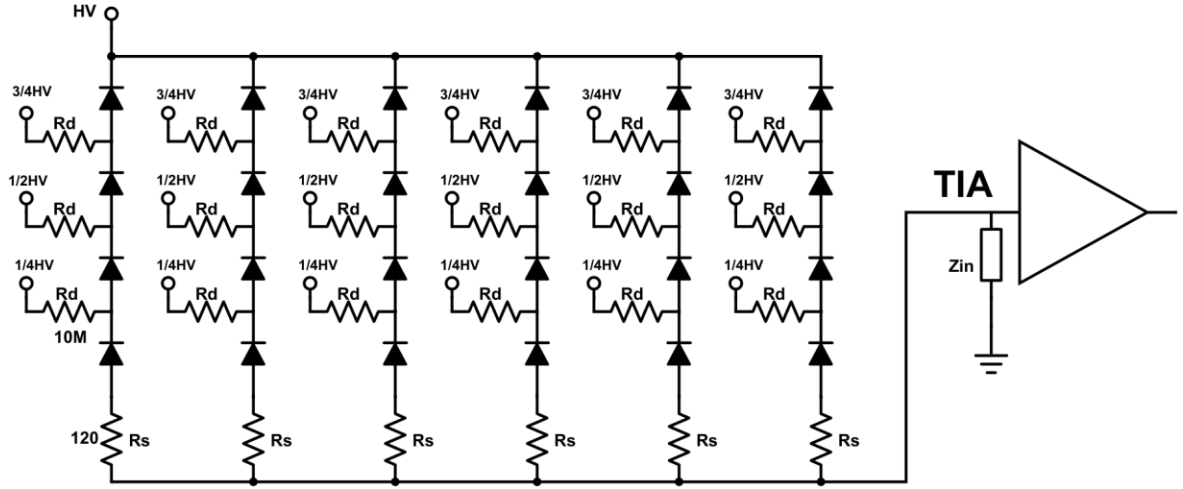
Consiglio et al. – **2022** NCC 45 C 141
Razeto et al. - **2022** JINST 17 P05038
D'Incecco et al. - **2018** IEEE Transactions on Nuclear Science 65 1

**Objective:**

- Large Area SiPM Array
- Low Noise

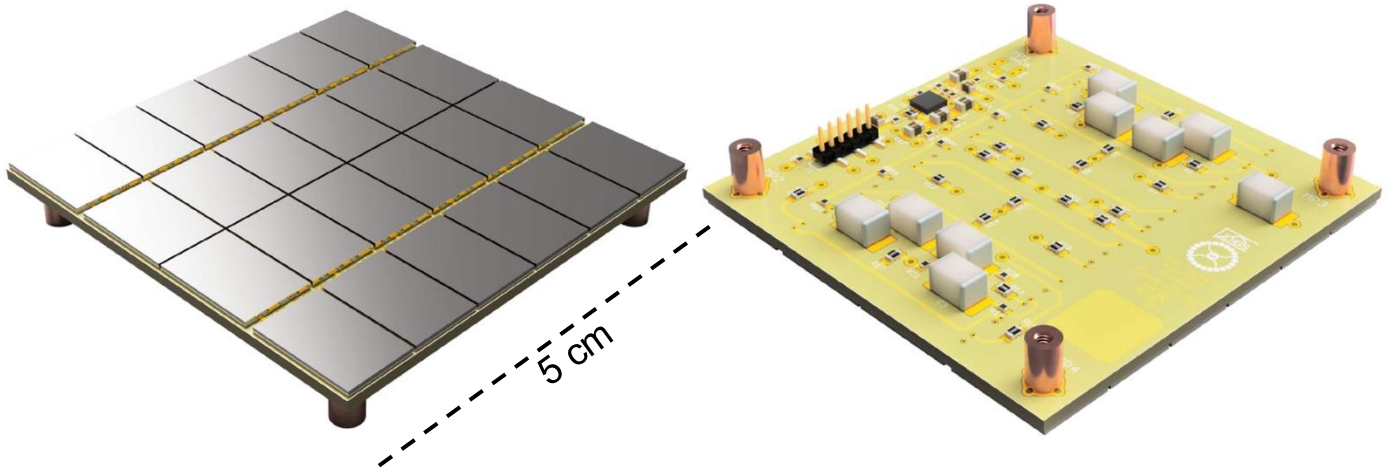
Result of R&D: PDM Tile

- Electronics: Fast Cryogenic Trans Impedence Amplifier (Noise $\propto \sqrt{C_i}$)

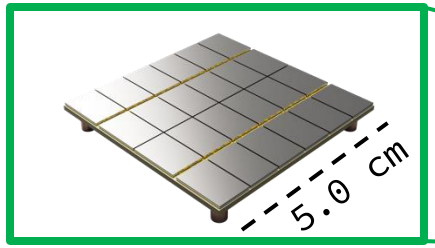



**SiPM Ganging:**

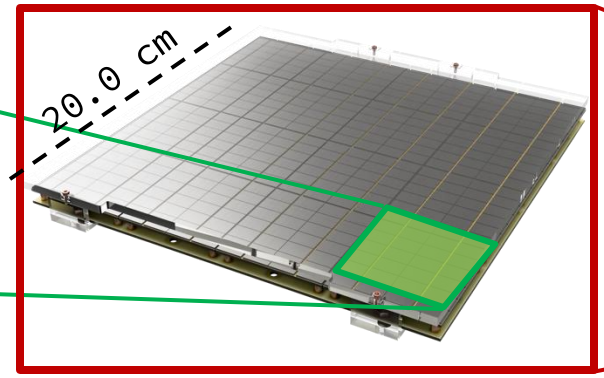
- Many SiPMs in parallel: High Ci
- Many SiPMs in series: Low current
- Compromise: 6p4s configuration
- Precision voltage partitioner to bias the SiPMs



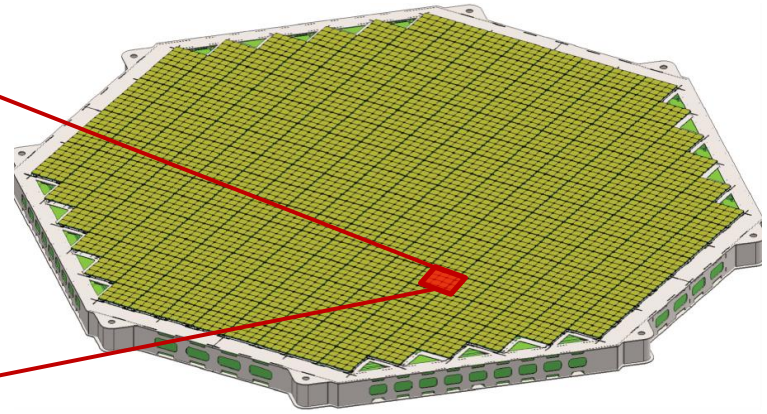
# The PDU




Tile: 5x5 cm$^2$
24 SiPMs directly mounted on a FEB
SiPM: NUV-HD-CRYO developed by FBK and produced by LFoundry

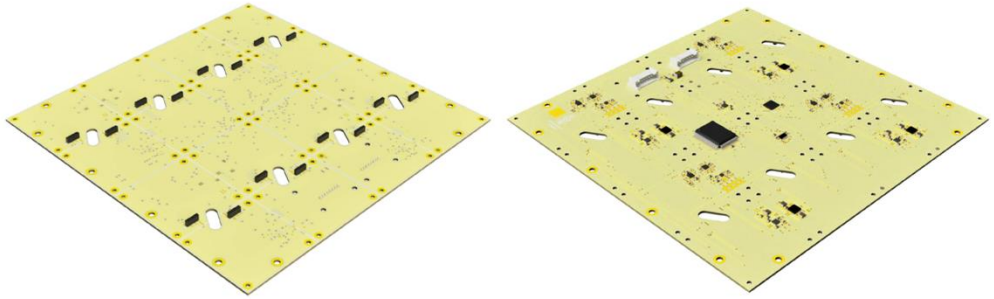


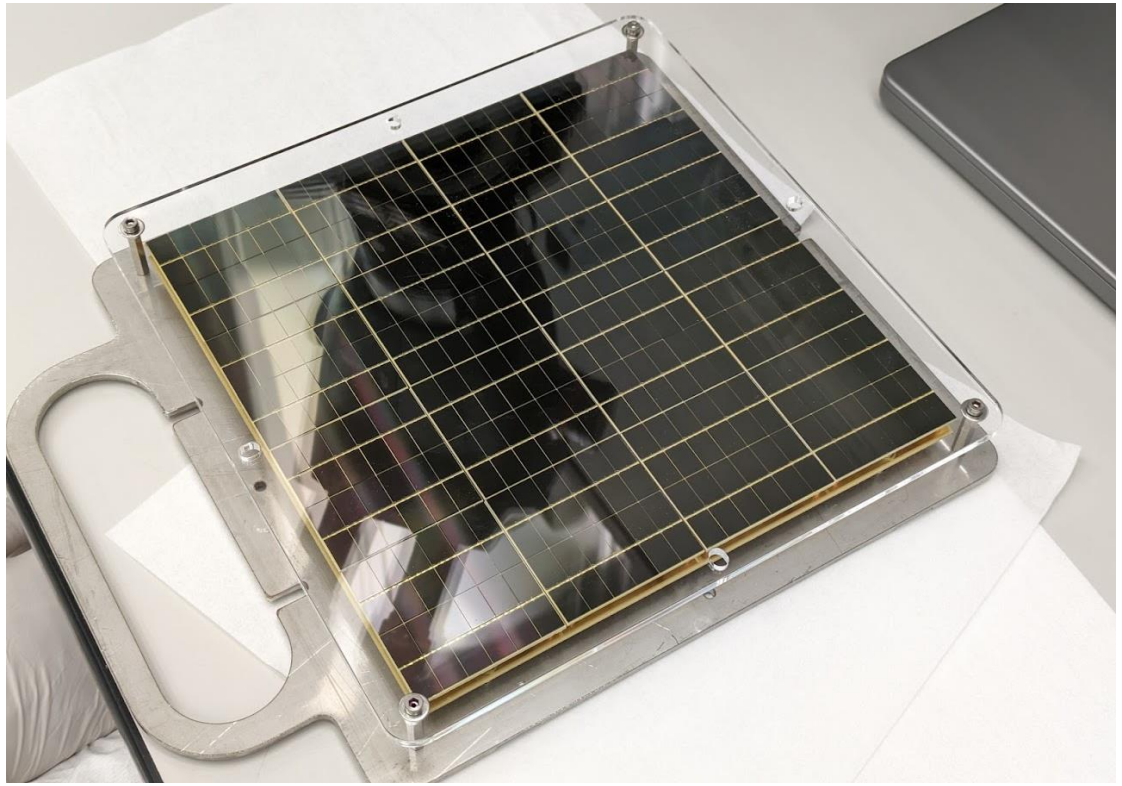

**PDU: 20x20 cm$^2$**
**16 Tiles Assembled on a Motherboard**
**4 readout Channel**

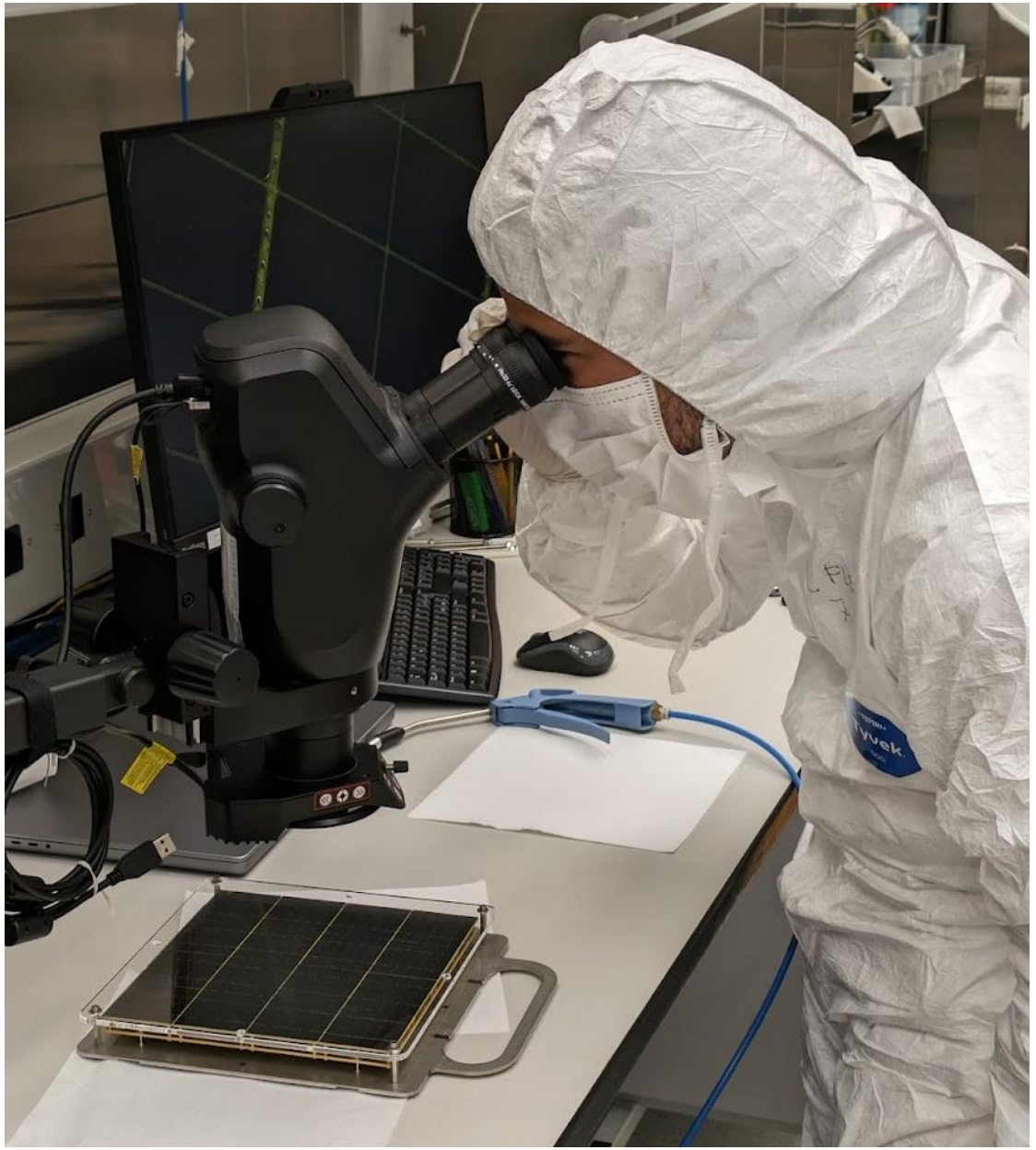


Optical planes: ~2x10 m$^2$
Total PDUs used (TPC): 528
Readout Channels: 2112

- A Motherboard which houses 16 Tiles →
  → Active adders sum tiles in groups of 4
  → Differential transmitter → 4 Readout CHs
- A power Magement Unit allows for remote switching of HV and LV for **each tile independently**
- ~1.8 W consumption in LN





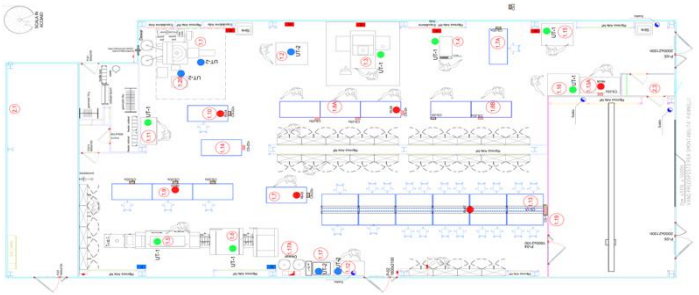


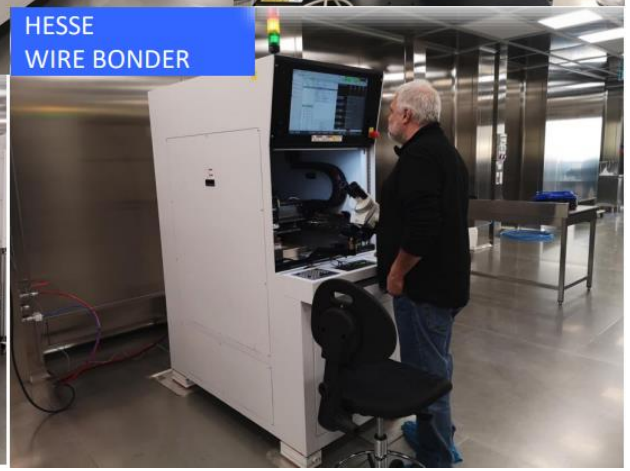
# NOA Production Facility

Presentation by L. Consiglio at TAUP23

## Nuova Officina Assergi

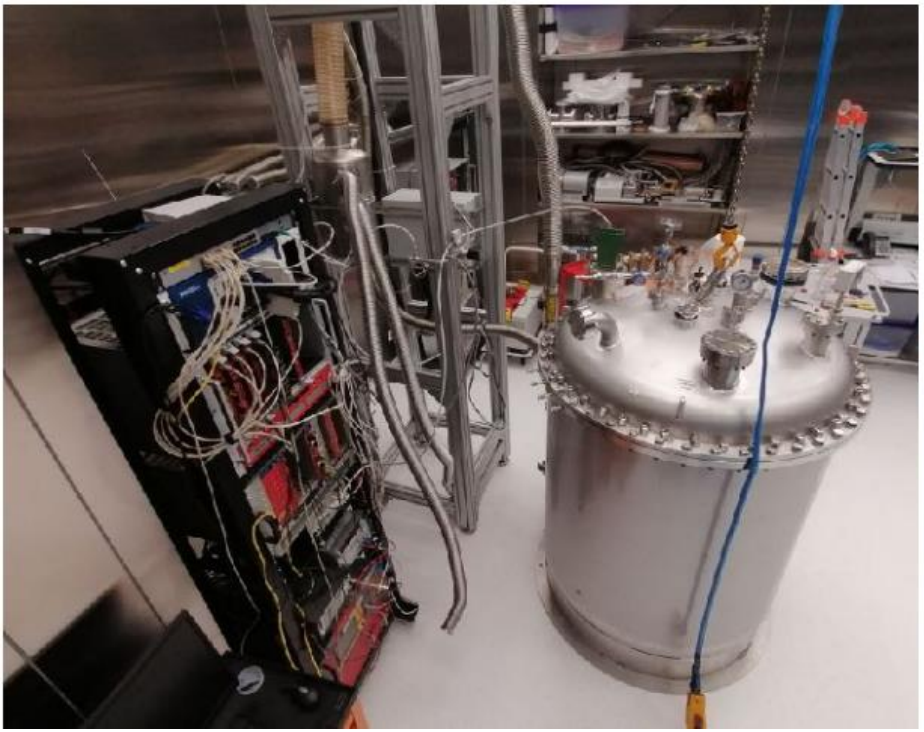
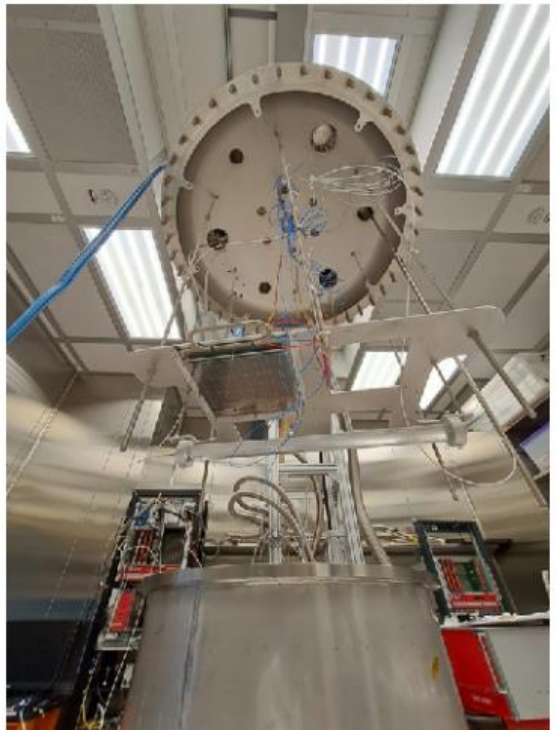
- ISO6 Clean Room
- 420 $m^2$
- Continuous Rn Monitoring
- CR3 Equipped with:
  Cryoprobe, Dicer
  Chip Bonder, Wire Bonder
  Microscopes, Packaging Tools
- PDU Production





# PDU Test Facility in Napoli

Balmforth et al. - **2023** JINST 18 C03024

- ~800 L double wall **cryostat** with domed flange
- ~100 ps pulsed **laser for calibration**
- Readout of up to 16 PDUs (64 CHs) with CAEN VX2740 ADC

- Custom support structure with room for 16 PDUs inside the cryostat
- Custom illumination system with PMMA rods as diffusers
- High end local servers for DAQ and Acquisition with O(1 PB) storage

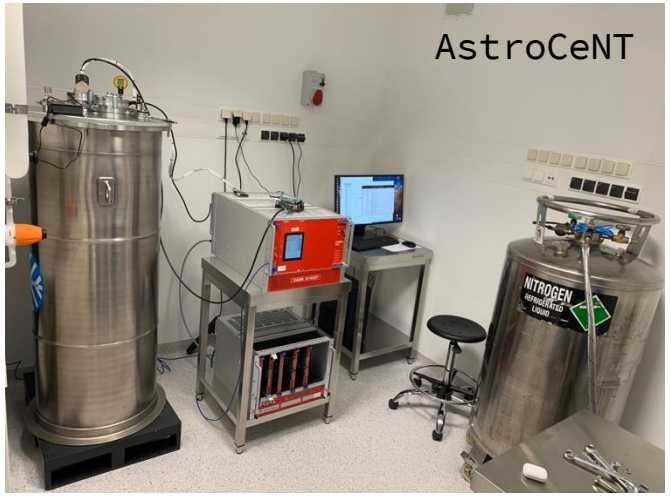
- MIDAS DAQ Framework
- Fully automated cold box, remotely controllable with fast FILL and DRAIN
- Two external 3000L each reservoirs
- Already testing pre-production

# Veto PDU Facilities

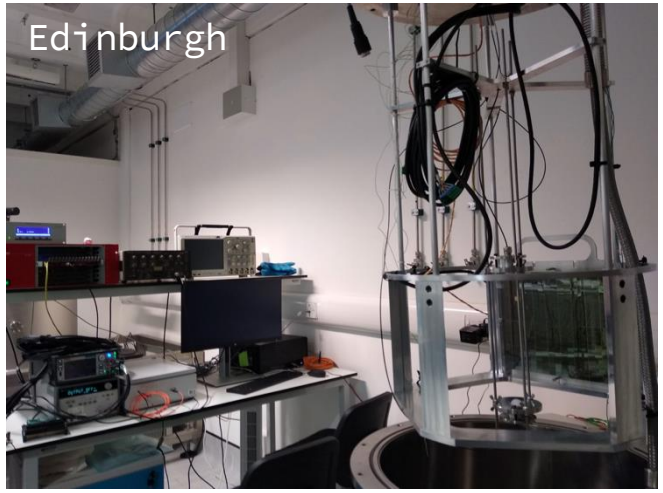
Production in Birmingham, STFC interconnect, Manchester, Liverpool → Testing Facilities

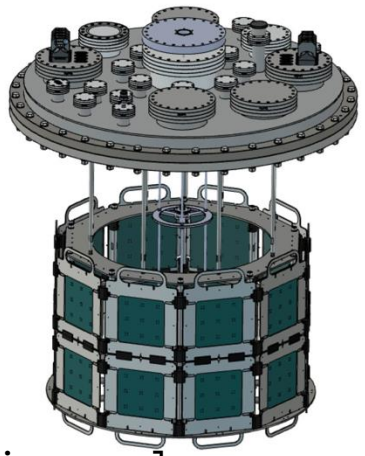
Lancaster

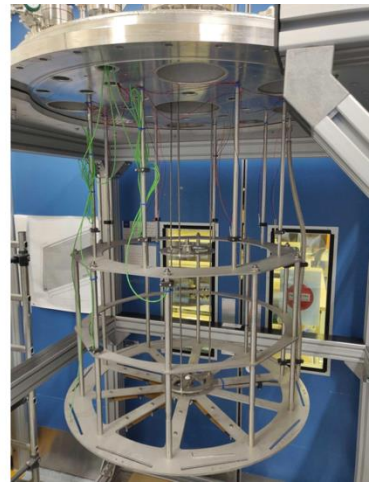
Birmingham



AstroCeNT

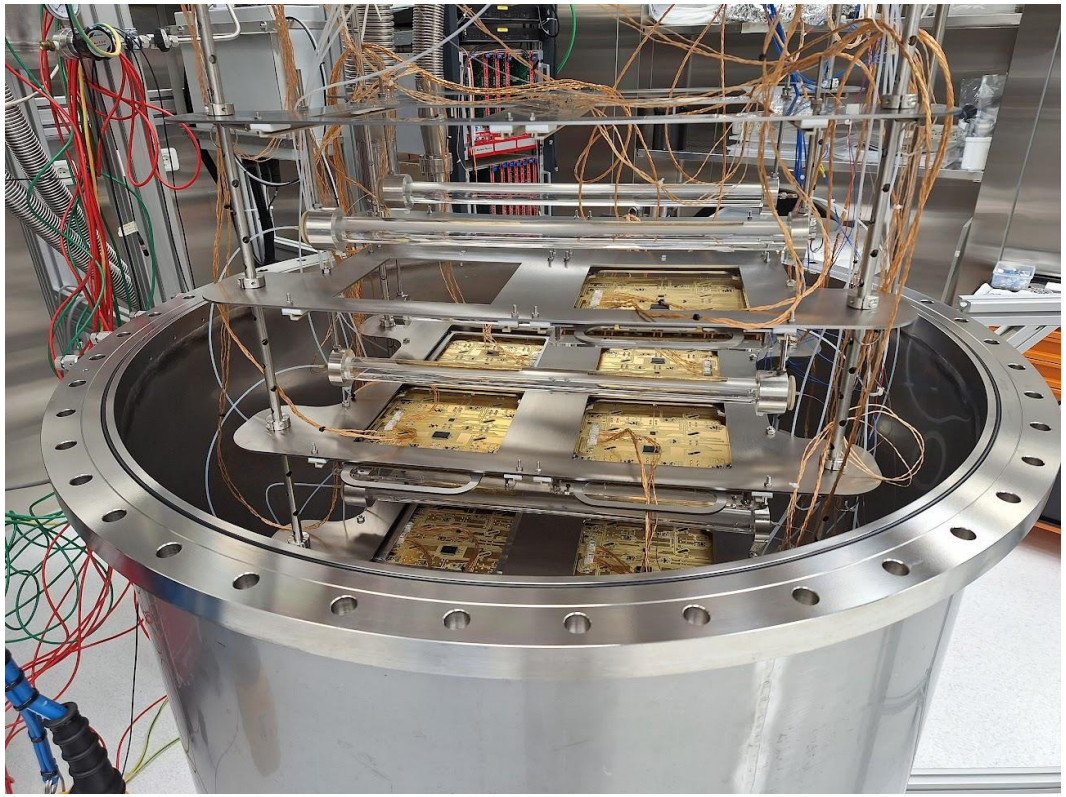

Edinburgh


Liverpool

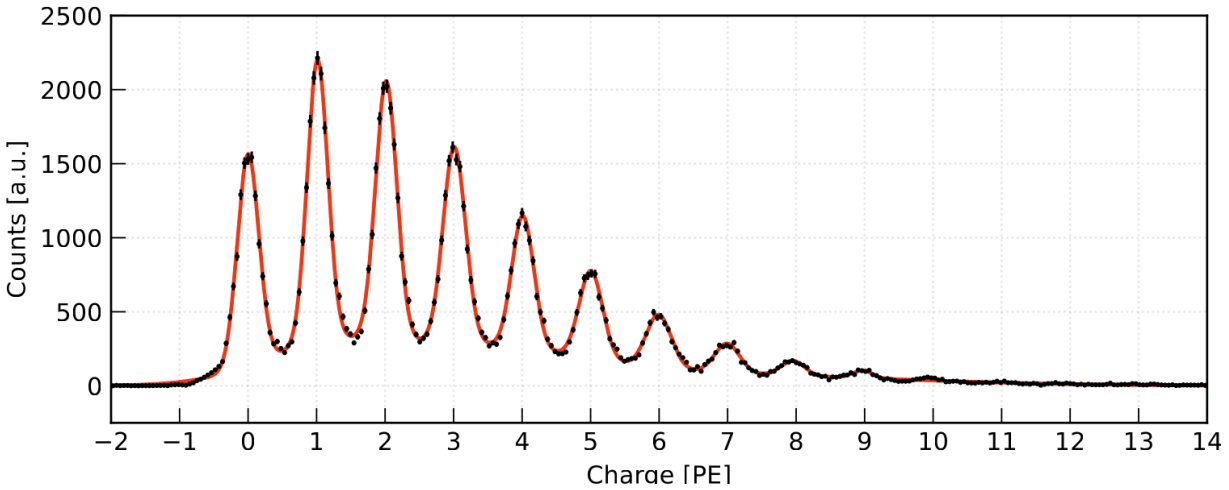


# PDU: Laser Calibration and SPE

S. Vinogradov et al. 2009 IEEE NSS/MIC **2009** 1496-1500



Performance Study in LN2
- Varying overvoltage
- Long term testing



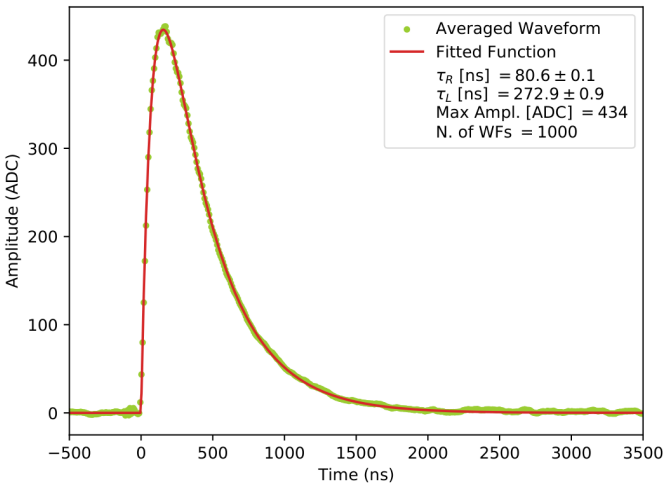

**At 7 V o.v. 77 K**

**Single PE response (SPE)**
SPE = 6.76 mV·µs

**Waveform Template**
*For matched filter*

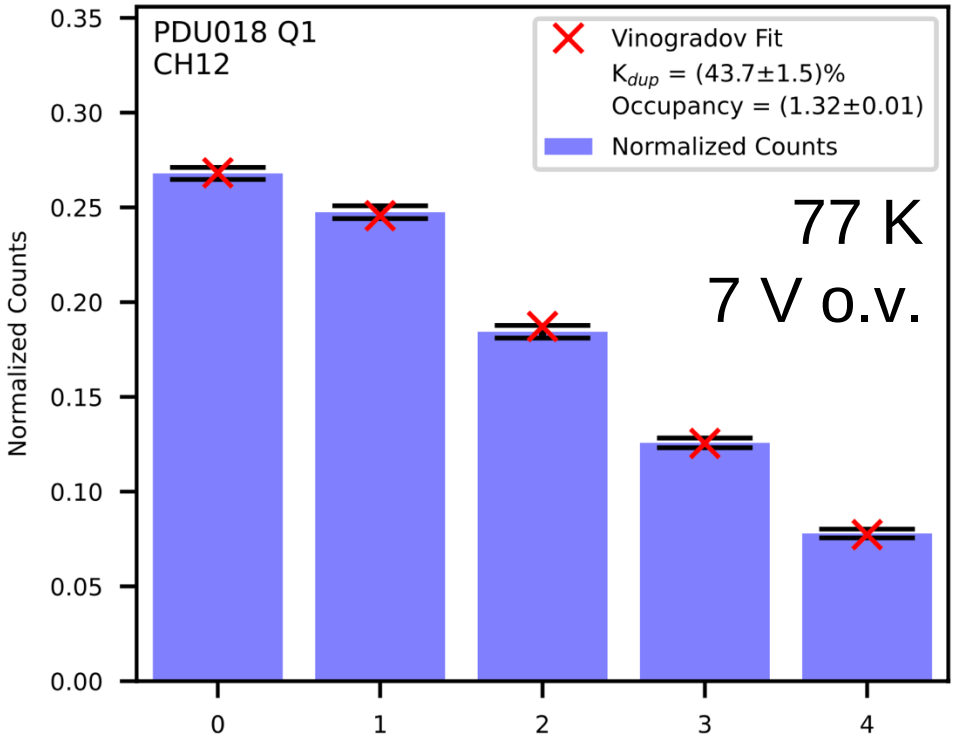
$$V(t) = A\left(e^{-\frac{t-t_0}{\tau_L+\tau_R}} - e^{-\frac{t-t_0}{\tau_R}}\right)\Theta(t-t_0)$$

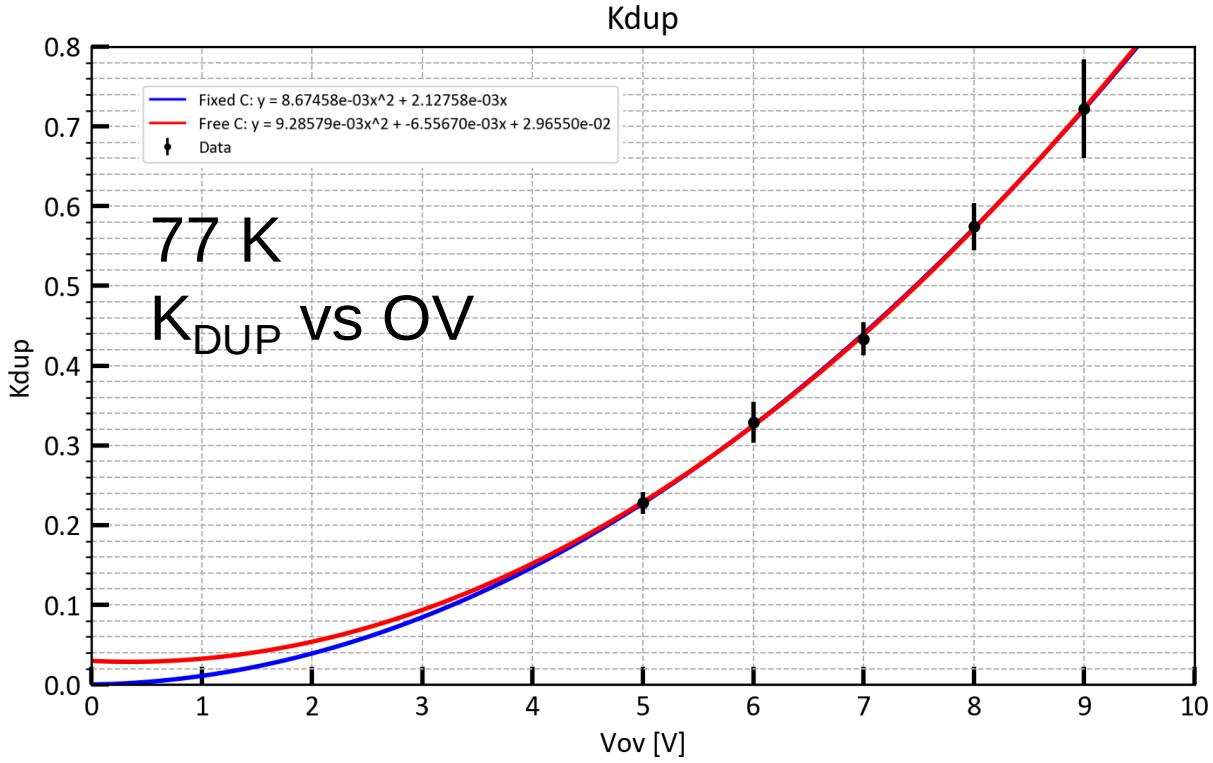
*1 PE Ampl. = 12.5 mV*
*Fall time = 350 ns*



# PDU: Correlated Pulses

S. Vinogradov et al. 2009 IEEE NSS/MIC
**2009** 1496-1500




**(one method for) Quantifying and monitoring Additional Correlated Pulses**

$K_{DUP}$ = Average number of correlated additional hits with respect to true photon hits
*In a compound poissonian regime (Vinogradov model)*

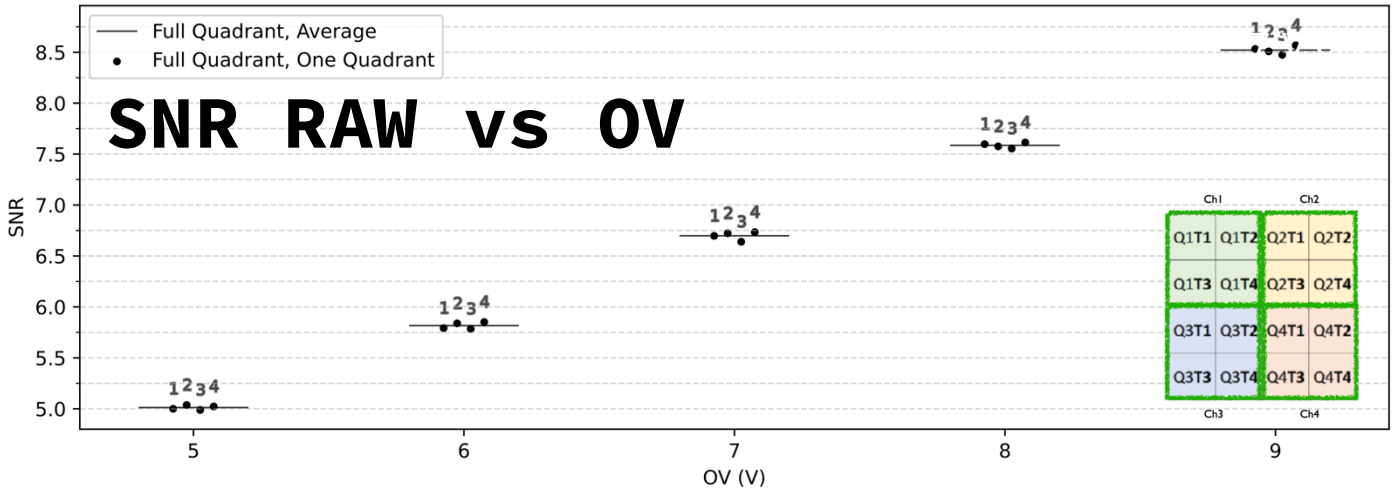
$$N_{hits} = N_{true}(1+K_{DUP})$$
$$K_{DUP} = \sim 45\% \text{ @ } 7 \text{ V o.v.}$$

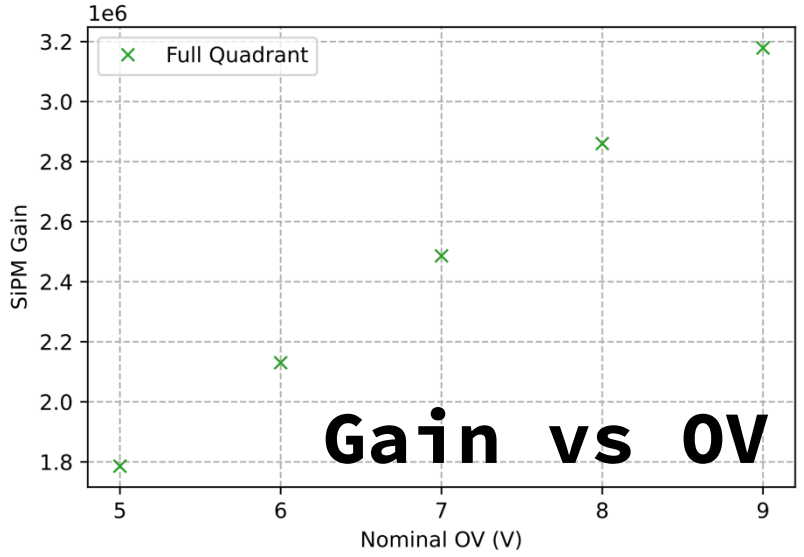
# PDU: SNR, resolution, gain

*Definitions*
*SNR = 1 PE Ampl. / Noise*
*Resolution = 1 PE Sigma / 1 PE Charge*
*GAIN = 1 PE Charge / e*

**RES (RAW) = 13%**
**SNR (RAW) = 7**
**SNR (Matched Filter) = 14**
**Gain = 2.5e6**

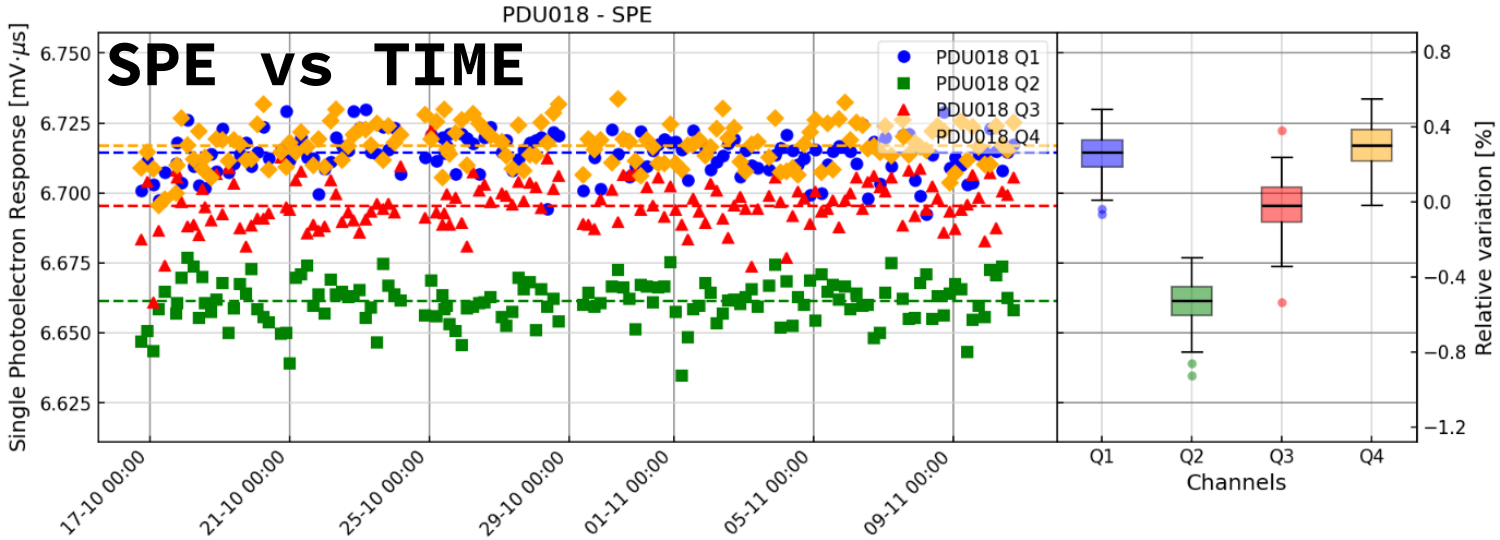
**@ 7 V o.v. and 77 K**

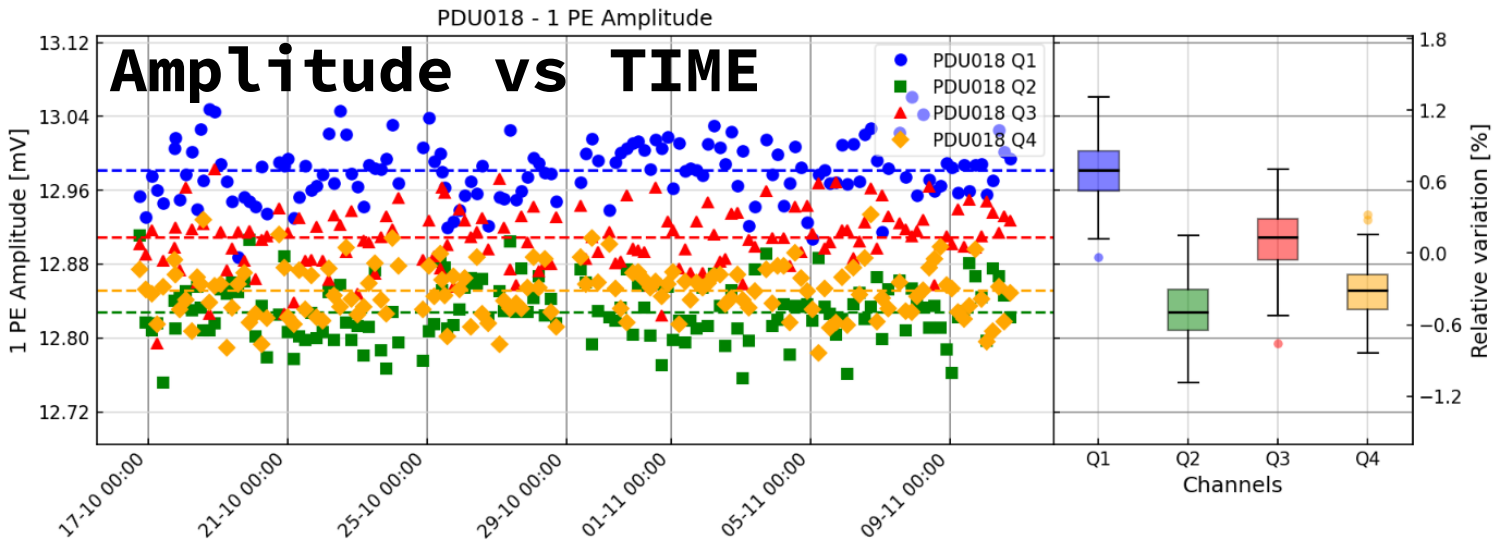


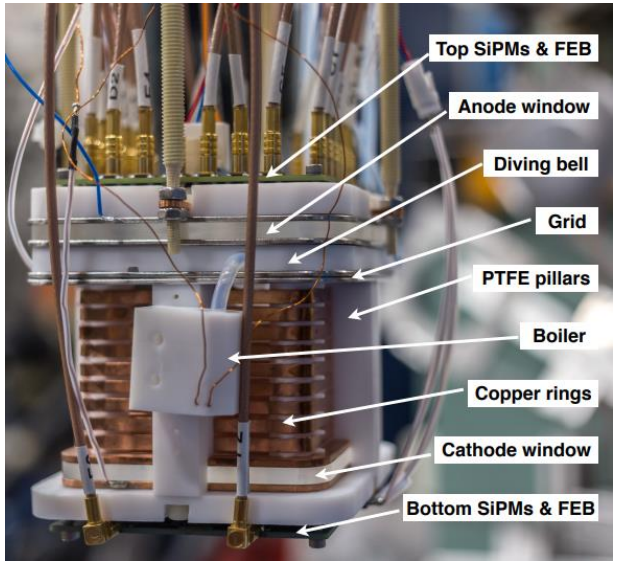
# PDU: Stability

- All parameters stable on the order of months (O(1%))
- First prototypes
- SPE Stability < 0.5%
- Amplitude stability ~0.5%



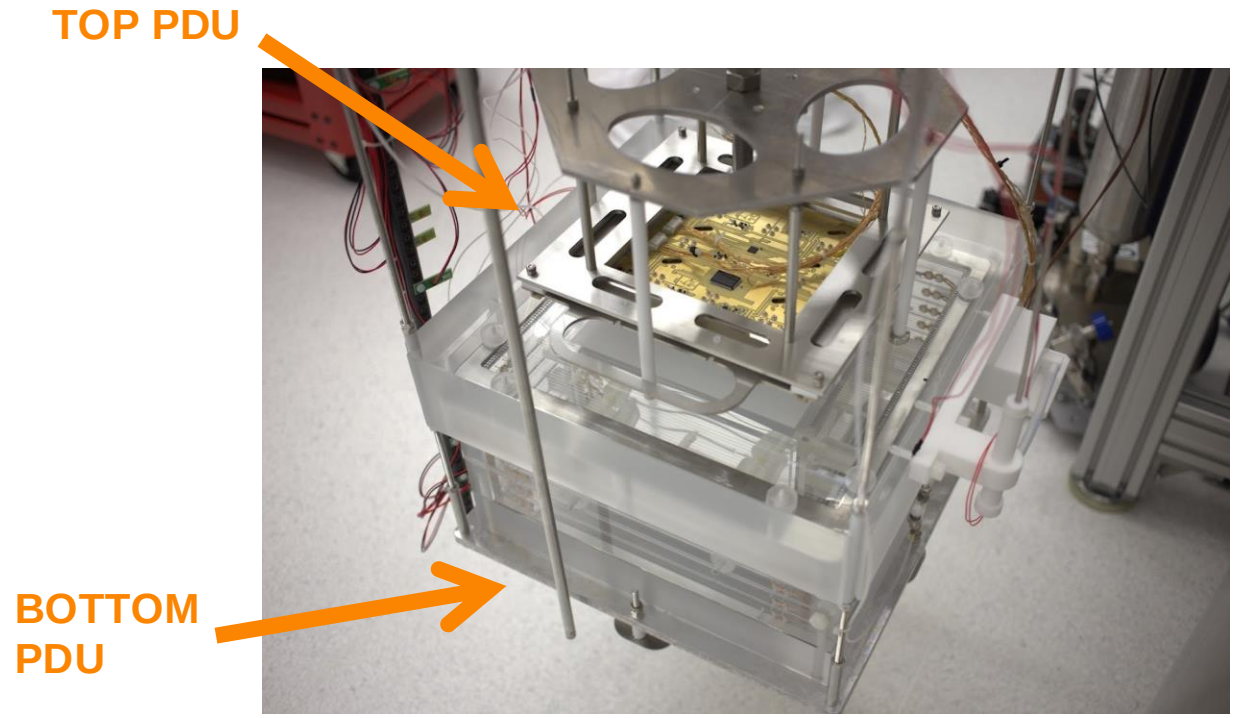



# In Liquid Argon…

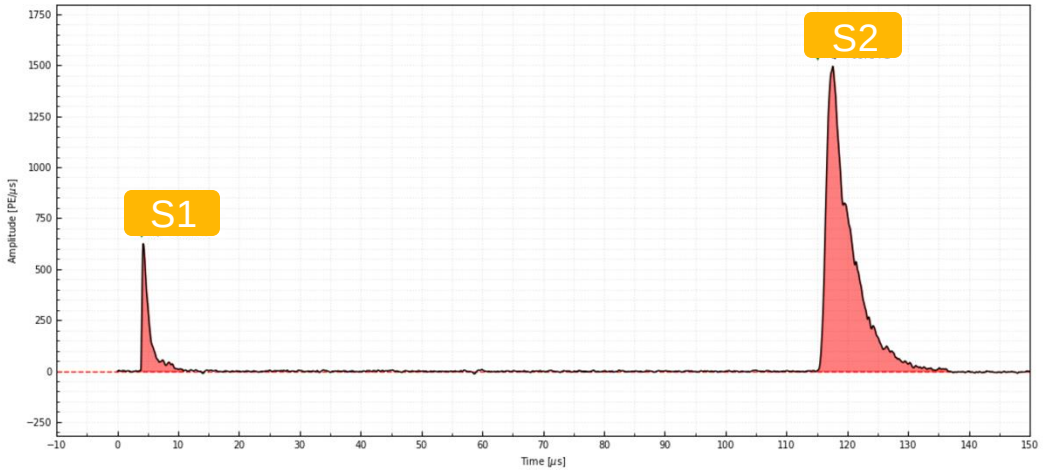



**ReD – Recoil Directionality**
*Contraints on directional sensitivity for NR in LArTPCs*
2 Phase LArTPC
~6 months LN calibration
> 1 y in cryogenic environment

Agnes. P et al. Eur. Phys. J. C 81, 1014 (2021)
DarkSide-20k Collaboration Eur. Phys. J. C 84, 24 (2024)



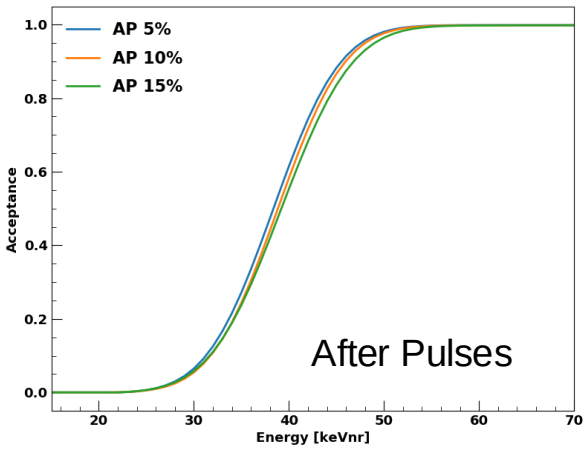

DarkSide Proto-0 – DS-20k Prototype with PDUs

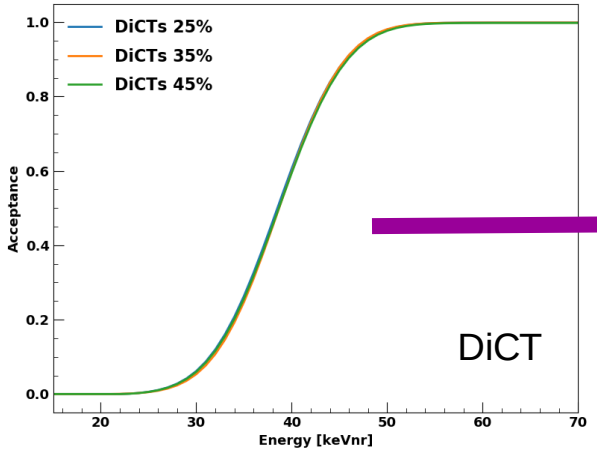


# PDU: impact on sensitivity



- Impact of PDU performance on PSD → effect on sensitivity
- DiCT influence on sensitivity can be reduced with a **hit-based reconstruction** for S1 (instead of charge integration)




| Parameter | Value | Sensitivity at 100 GeV/$c^2$ [cm$^2$] |
|---|---|---|
| PDE | 40% at 6 VoV ($C_e$=0.200) | 2.06e-48 |
| PDE | 42% at 7 VoV ($C_e$=0.210) | 2.00e-48 |
| PDE | 45% at 9 VoV ($C_e$=0.225) | 1.94e-48 |
| DCR | $2\times10^{-5}$ ns$^{-1}$ at 6 VoV | 2.00e-48 |
| DCR | $4\times10^{-5}$ ns$^{-1}$ | 2.01e-48 |
| DCR | $6\times10^{-5}$ ns$^{-1}$ | 2.01e-48 |
| DiCT | 25% at 6 VoV | 2.00e-48 |
| DiCT | 35% at 8 VoV | 2.02e-48 |
| DiCT | 45% NA | 2.01e-48 |
| AP | 5% at 6 VoV | 2.00e-48 |
| AP | 10% at 9 VoV | 2.02e-48 |
| AP | 15% NA | 2.05e-48 |

- Non-negligeable impact on sensitivity:
  - **PDE, After Pulsing**
- Negligible impact:
  - Dark Count Rate (DCR), Direct Cross Talk (DiCT)

***Hit based S1 Reconstruction***

The Analysis ROI for WIMPs has S1 ~ 500 PE

This result in occupancy for a single channel << 1 PE in 1 us time - we do not lose information.

# Conclusions

- DarkSide-20k for WIMP direct search:
  - two-phase argon TPC with 20 t fiducial volume
  - Underground-extracted radiopure argon

- Photo-Electronics of DS-20k:
  - Developement with an Assembly of Cryogenic SiPMs
  - PDU: Photon Detection Unit (20x20cm$^2$, 384 SiPMs + FEB → 4 Channels)
  - 2112 read-out channels in the TPC
  - Excellent SNR (7 raw, 14 with matched filter)
  - 12.5 mV amplitude and 13% (raw) resolution for single photon
  - DCR, AP and CT within specification for DS-20k physics goal

Acknowledgments: Dr. Yury Suvorov, Dr. Dmitrii Rudik (INFN Napoli) for picture and plots in slides 10, 13, 19, 20

*(part of) The DarkSide-20k Collaboration at LNGS*

# backup

A different method (less model dependant) to study additional correlated pulses

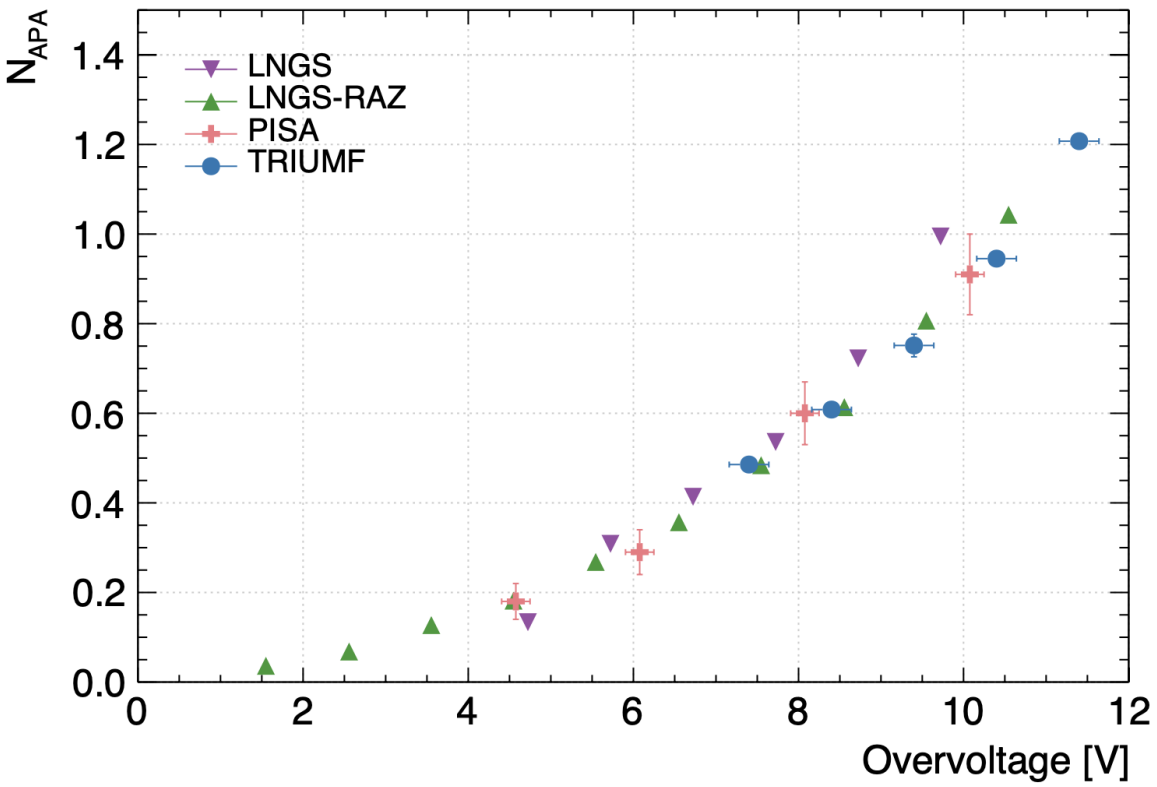
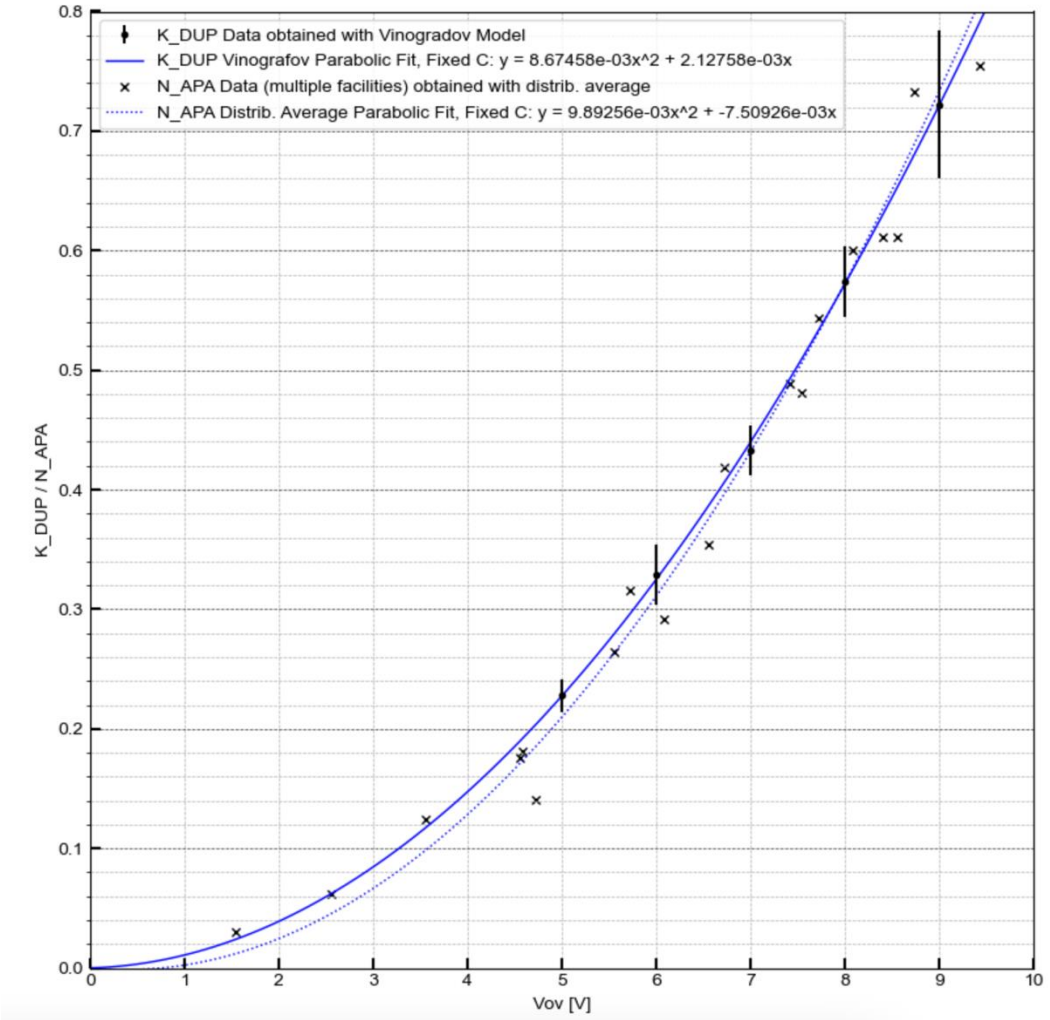
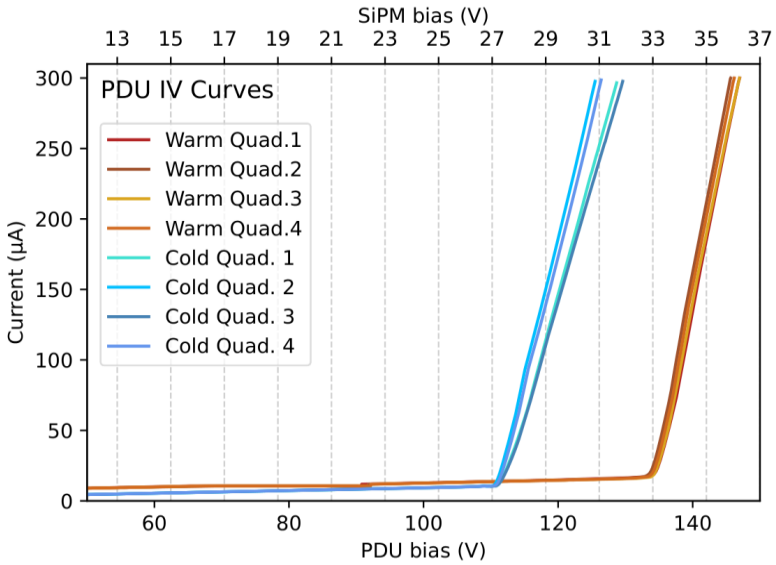



**Fig. 17** Number of Additional Prompt Avalanches (APAs) measured at 77 K as a function of the over voltage.

$$N_{APA} = \frac{\langle Q_h \rangle}{\mu_P} - 1$$



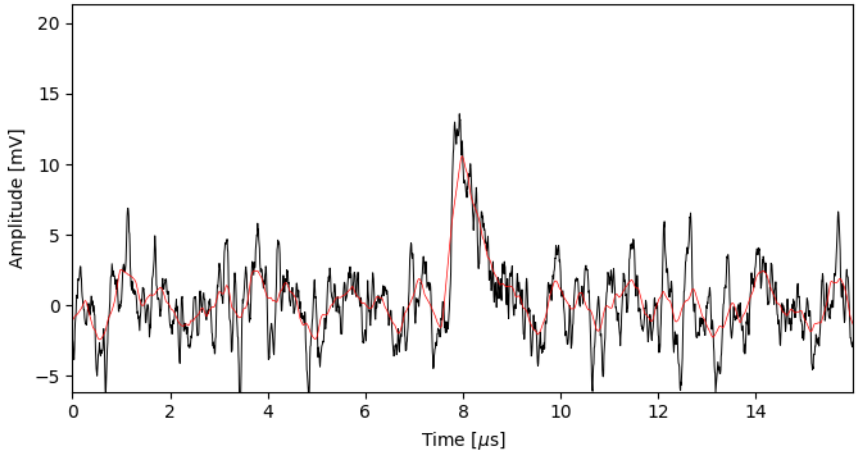
# PDU: Breakdown voltage and signal shape




**IV Curves**

*SiPM bias is different than PDU bias as the voltage is partitioned on four SiPMs*

$V_{BD}$ (77 K) = 27 V



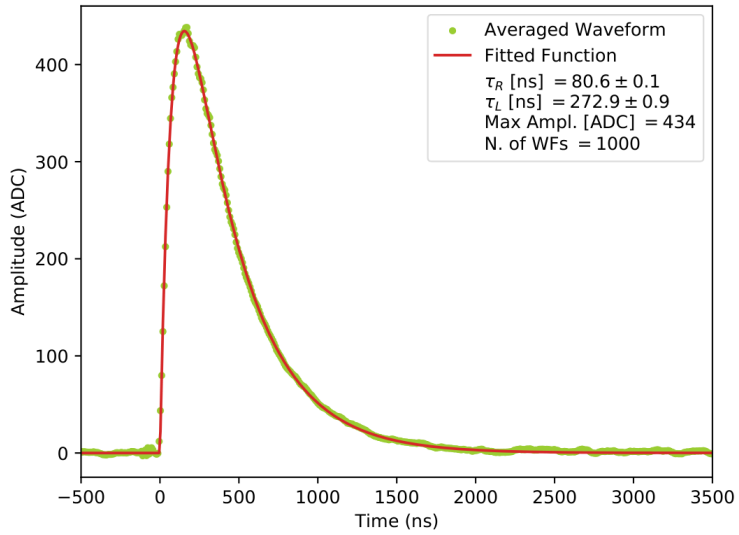

**Typical waveform**

*Acquired with CAEN VX2740*

***Black:*** *Unfiltered single PE waveform*

**Red:** 50 Sample MA Filter

Obtained with external triggering in correspondance with fast pulsed laser




**Waveform Template**

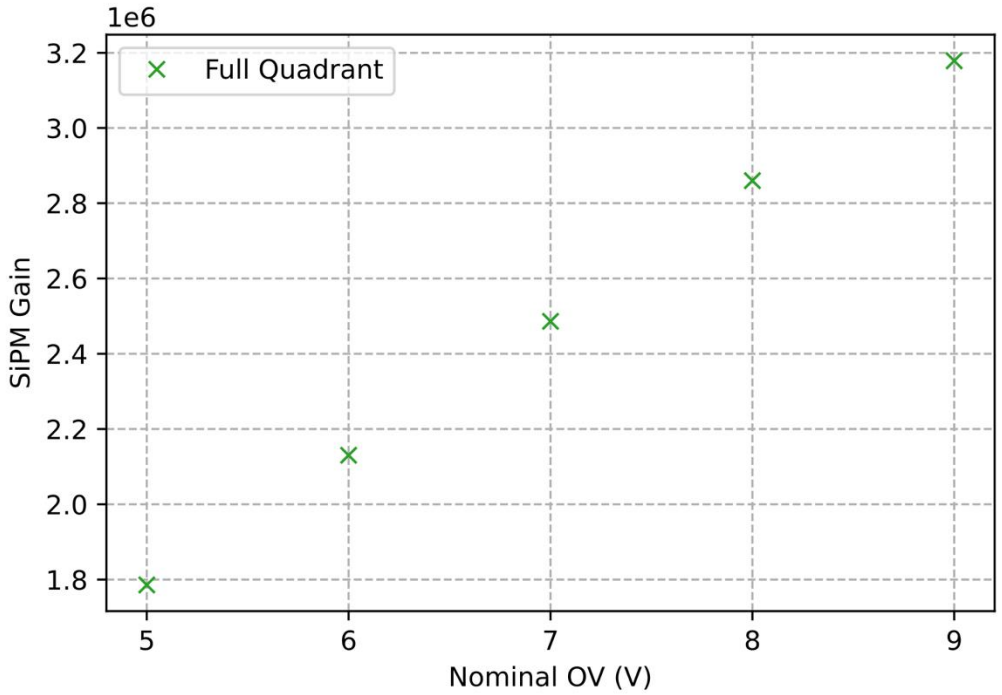
*To be used in matched filter*

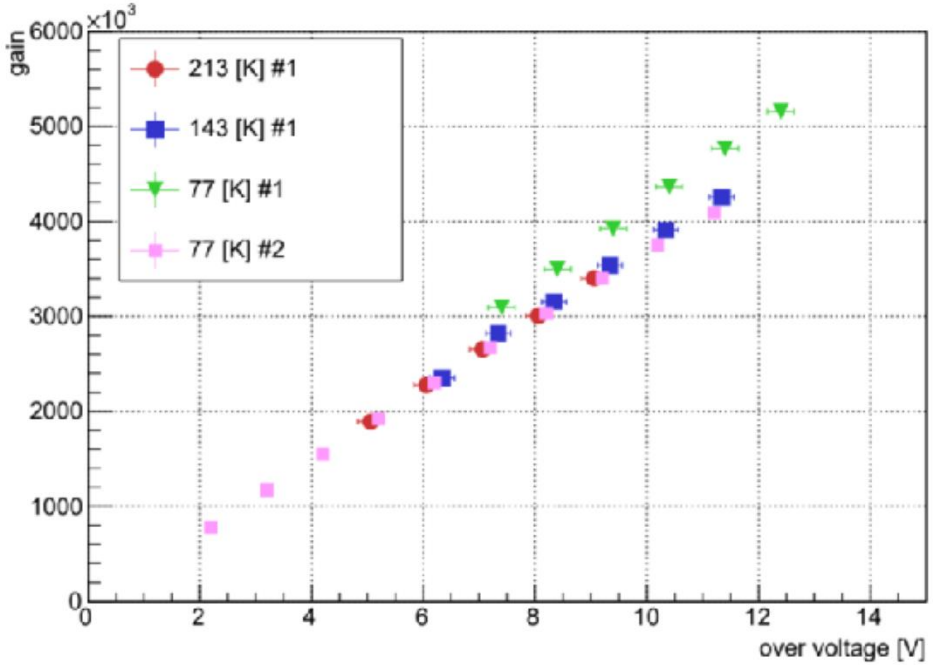
$$V(t) = A\left(e^{-\frac{t-t_0}{\tau_L+\tau_R}} - e^{-\frac{t-t_0}{\tau_R}}\right)\Theta(t-t_0)$$

*1 PE Ampl. = 13 mV*

*Descent time = 350 ns*

# PDU: Gain




**Gain**

*Charge of a single hit in units of elementary charge*

*Left*: Measurement from PDU
*Right*: Measurement from Single SiPM

G = 2.5e6 @ 7 V O.V.

# Correlated Avalanches in SiPMs

F. Nagy et al. **2014** NIMA 759 44-49
McLaughlin et al. **2021** Sensors, 21(17), 5947

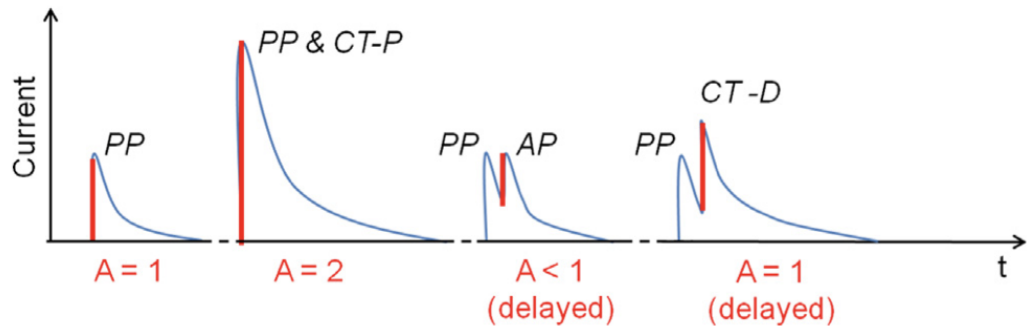



**Fig. 7.** Primary pulses (PP) with different types of correlated pulses such as prompt CT (CT-P), afterpulse (AP) and delayed CT (CT-D).

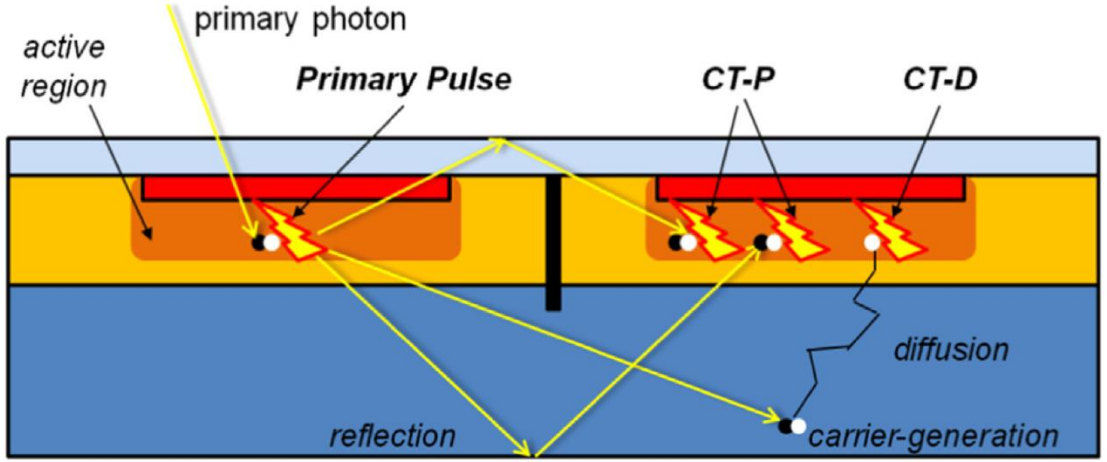
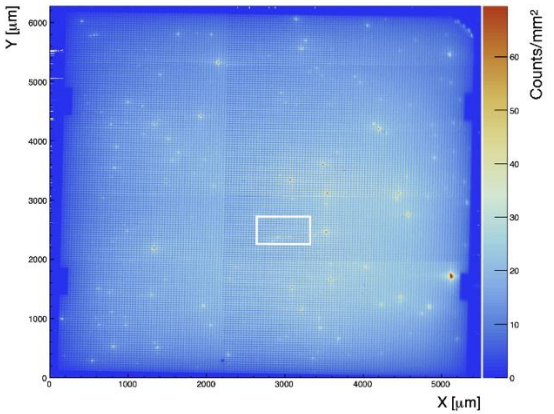



**Fig. 2.** Two different types of crosstalk: prompt (CT-P) and delayed (CT-D).

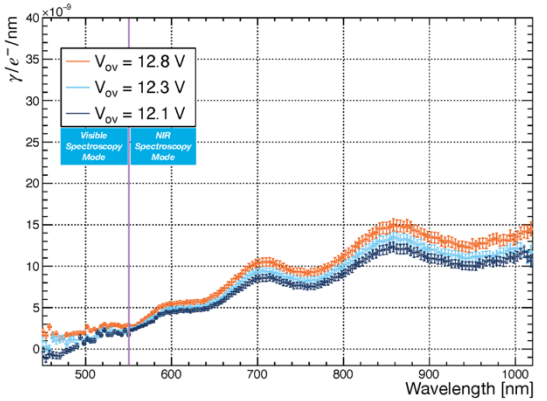
Correlated avalanches:

- After Pulsing (AP)
- Direct Cross Talk (DiCT)
- Delayed Cross Talk (DeCT)
- External Cross Talk (exCT)

## Origin of external Cross-Talk




(b) FBK VUV-HD3




(b) FBK VUV-HD3

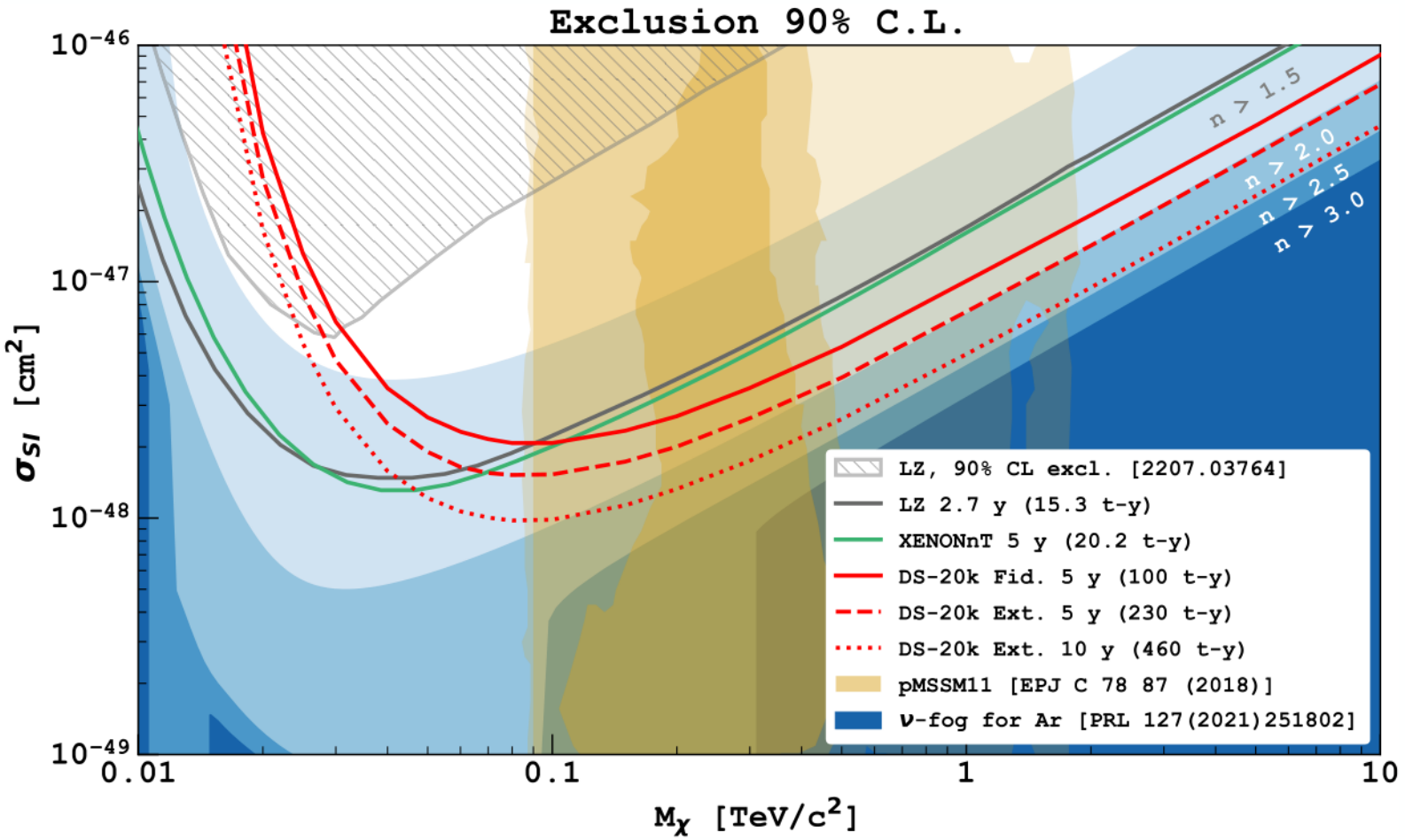
# DarkSide-20k Sensitivity Projections

Upper limits for a 100 GeV/$c^2$ WIMP (90% C.L.) at 100 t.y:

$\sigma_{100t.y}$ = 2.0 x $10^{-48}$ $cm^2$

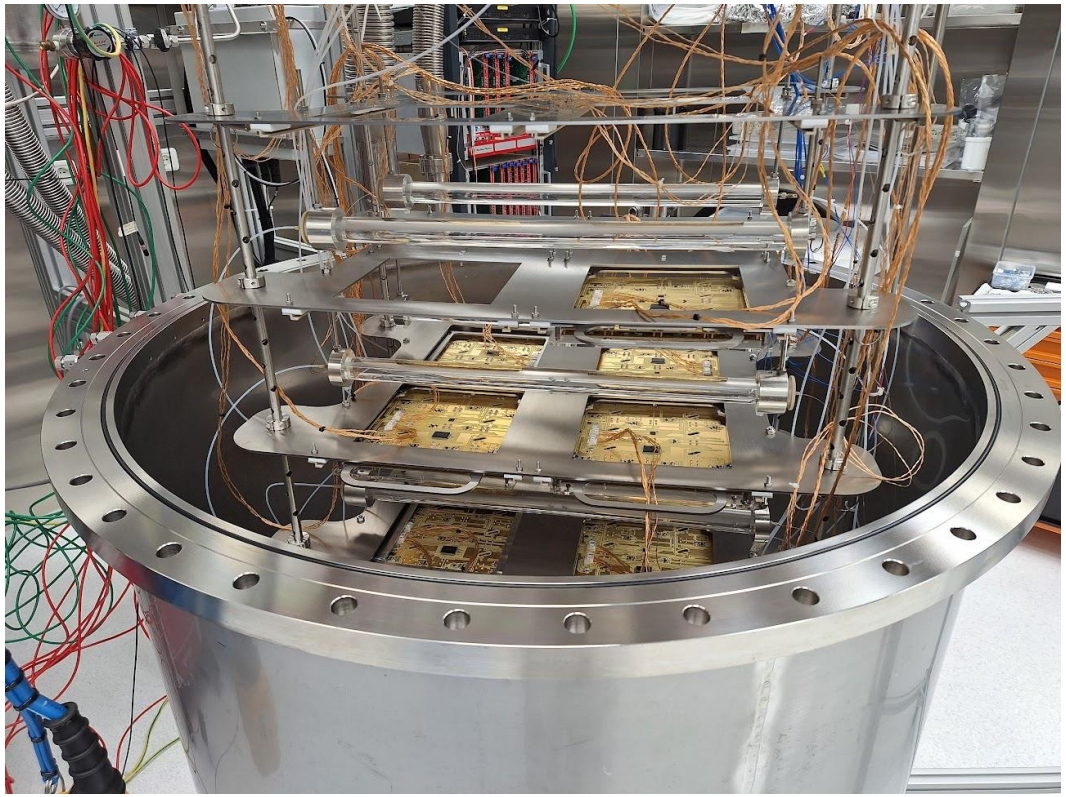
First measurement of the neutrino “fog” for n > 1.5

~3 neutrinos in 200 ton.y

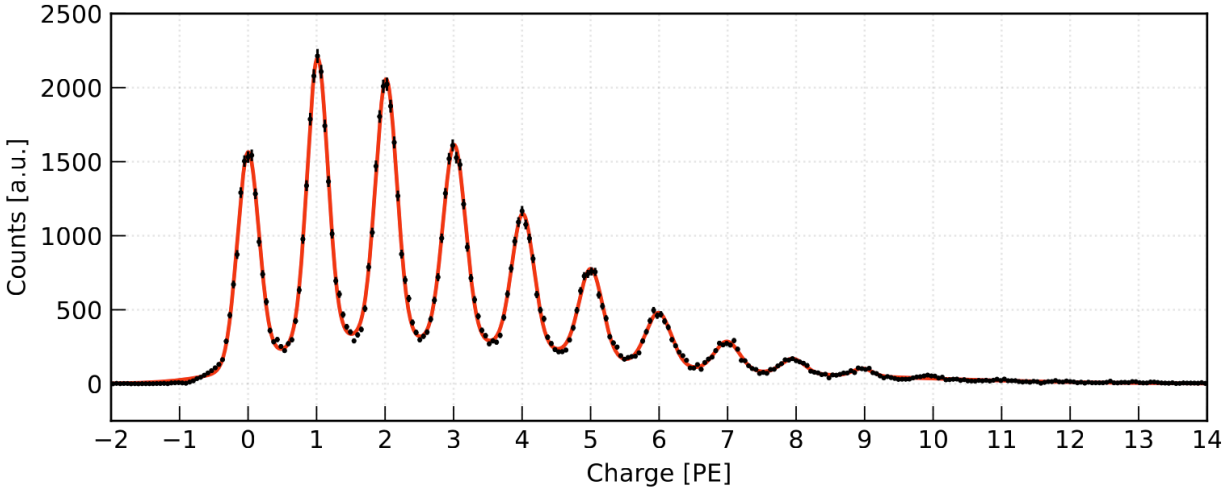


# PDU: Laser Calibration and SPE

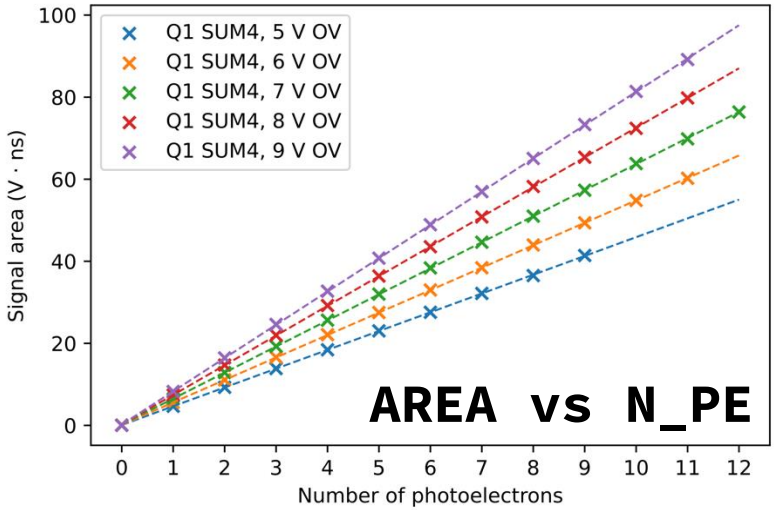
S. Vinogradov et al. 2009 IEEE NSS/MIC **2009** 1496-1500



Performance Study in LN2
- Varying overvoltage
- Long term testing




**Single PhotoElectron response (SPE)**

*Slope of signal integral of N hits vs number of hits*

SPE = 6.76 mV·µs
@ 7 V o.v.