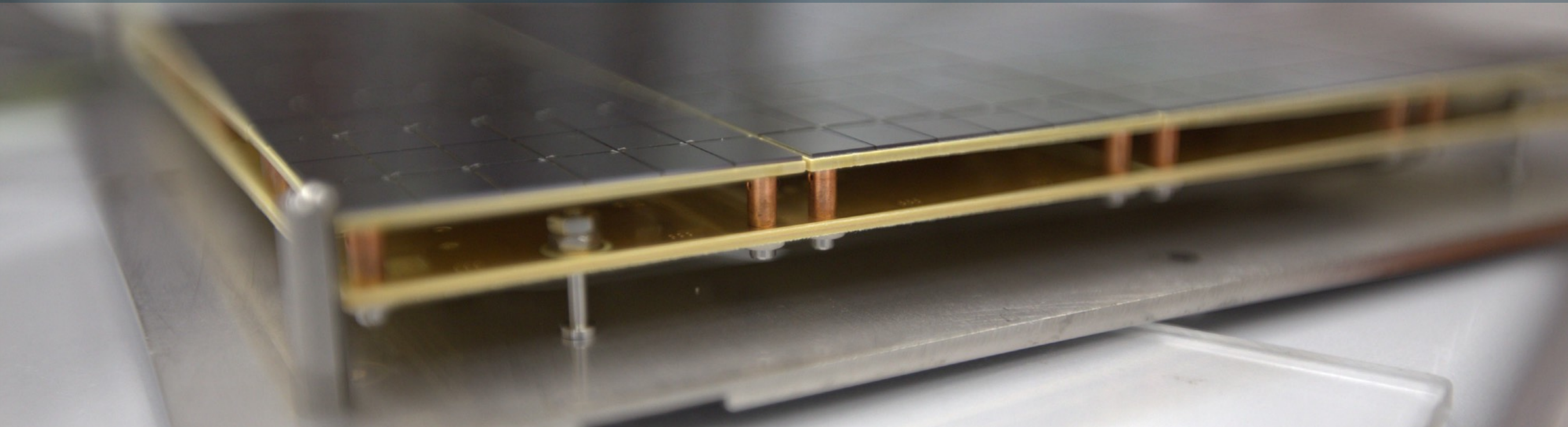
ASPIDES Kick-off Meeting

Dark Matter Detector Applications



G. Fiorillo

University of Naples Federico II, Istituto Nazionale di Fisica Nucleare - Sezione di Napoli

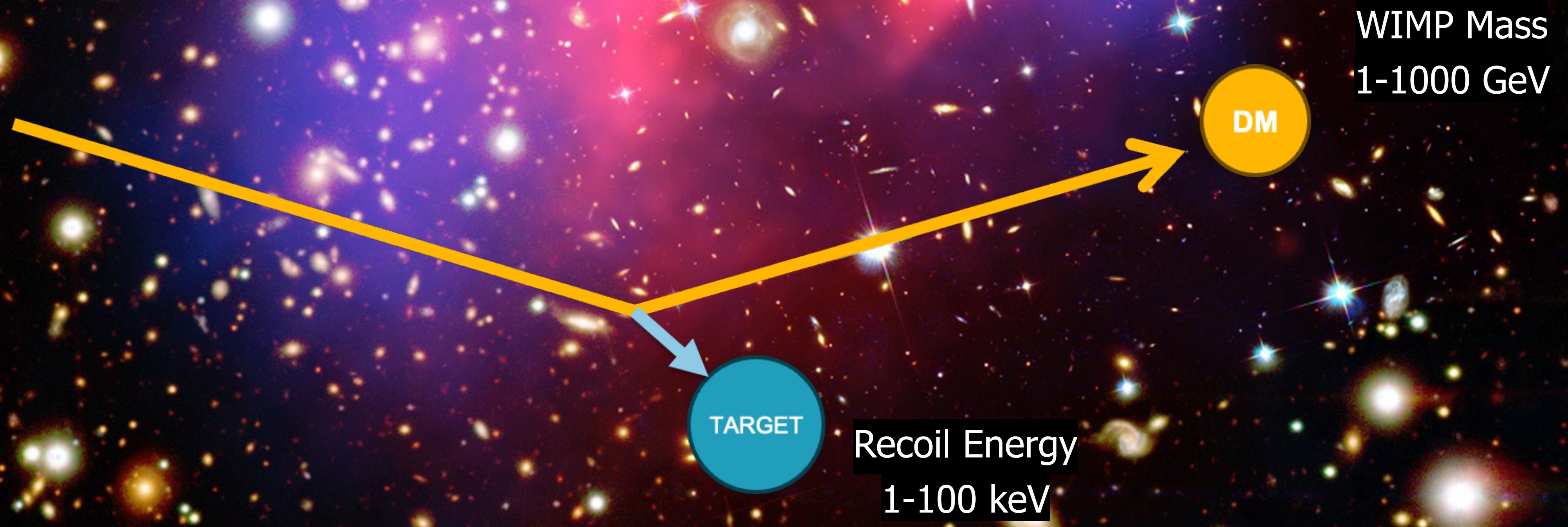
Slides courtesy of Giuseppe Matteucci

Dark Matter: 85% of the matter in the universe

Plausible Candidate: Weakly Interacting Massive Particle

Terrestrial Experiments search for Elastic Scattering on Nuclei

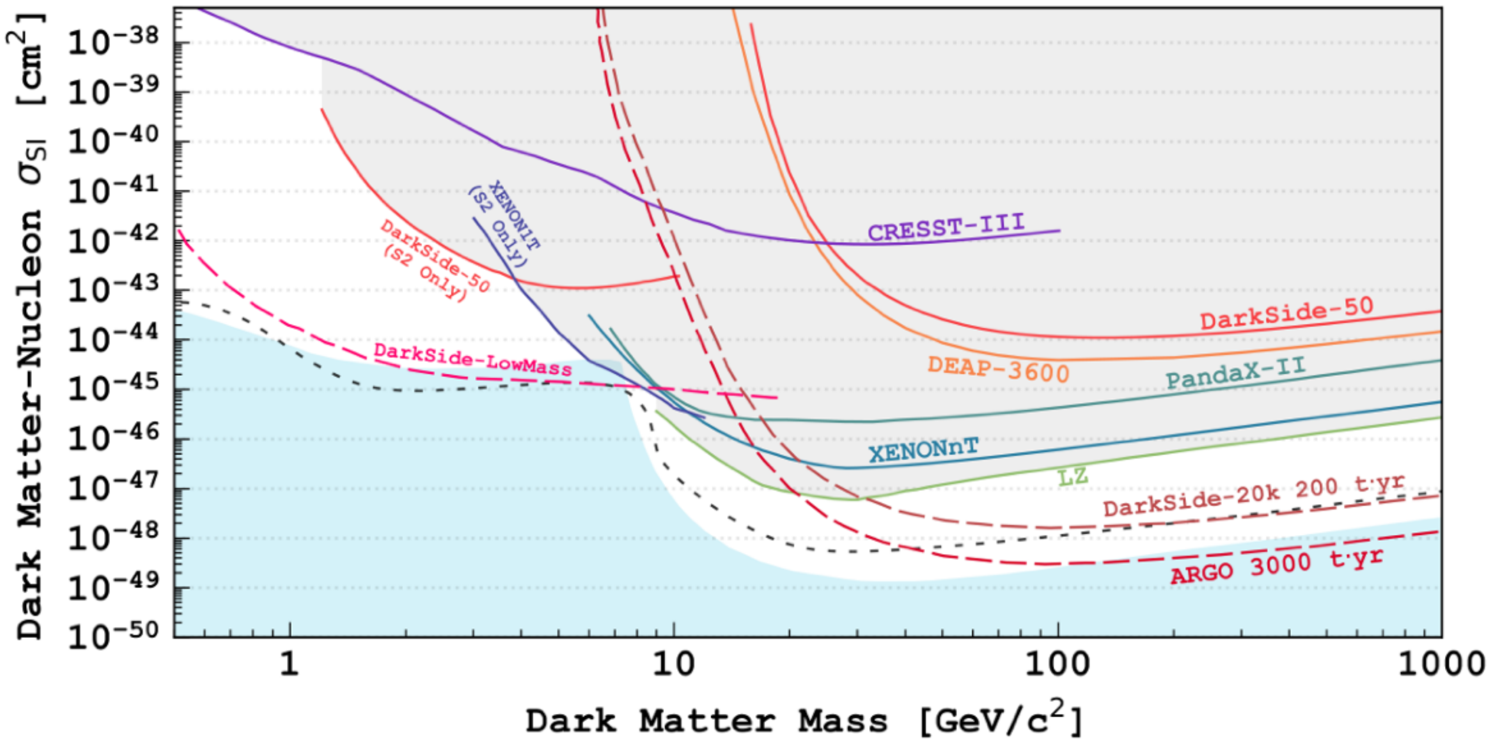
Expected Signal: Ultra-Rare Nuclear Recoils



Direct Detection of Dark Matter

- Requirements:
  - High Exposure
  - Ultra-low background
  - Low Energy Threshold

- Killer Detector Technology: **Noble-Element Two Phase Time Projection Chambers** (XENON, LZ, PandaX, DarkSide)
- Argon and Xenon



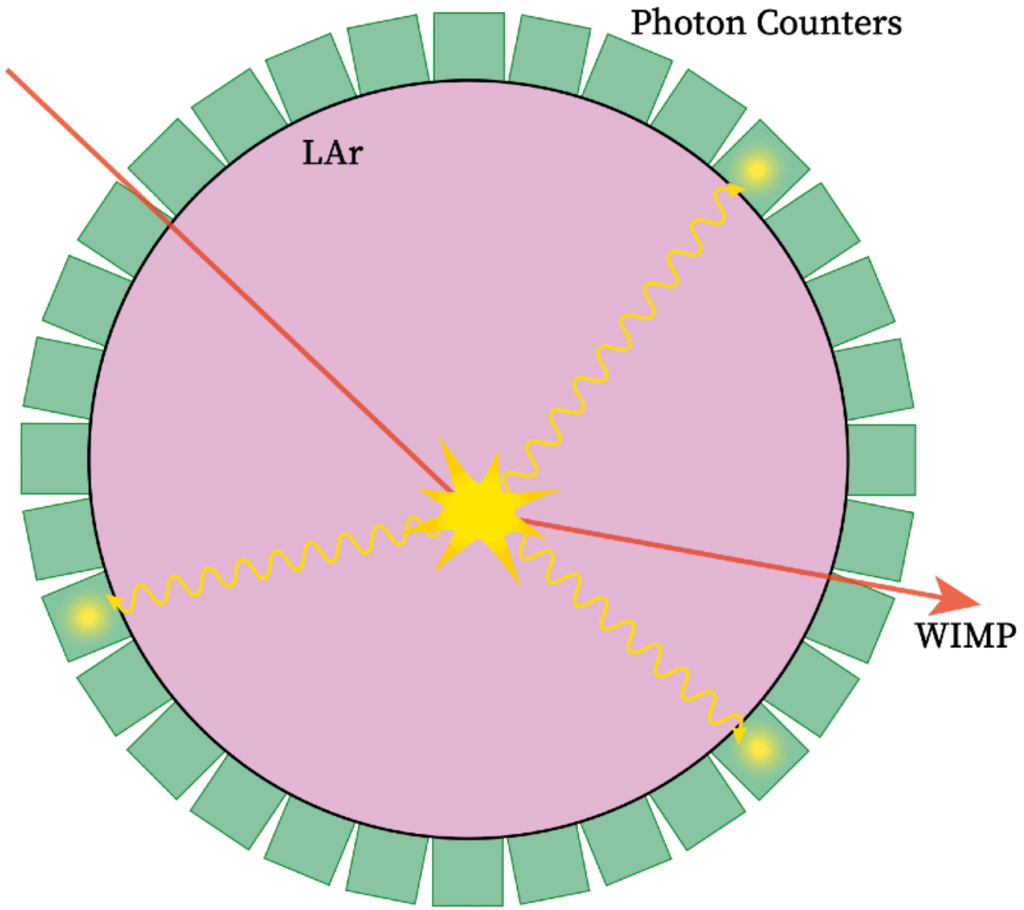
G. Matteucci and G. Fiorillo, "Liquid Argon for Direct Dark Matter Detection", Journal of Advanced Instrumentation in Science, vol. 2024, no. 1, Sep. 2024.

Single Phase Noble Liquid Detector

- Liquid Argon mass instrumented with photosensors
- 4π readout
- Simple design

Cons

- 3D reconstruction not exceptional
- Single detection channel (scintillation), reduced PID capabilities
- No sensitivity to low-mass WIMPs

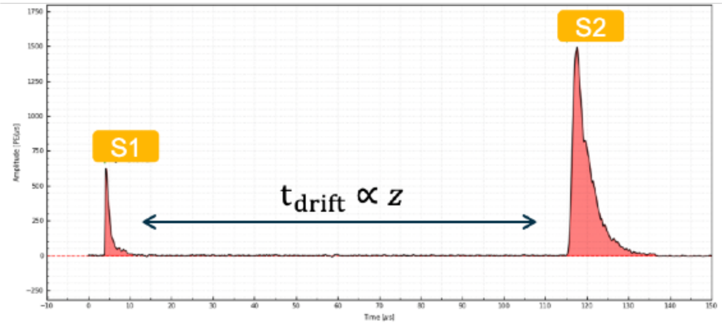


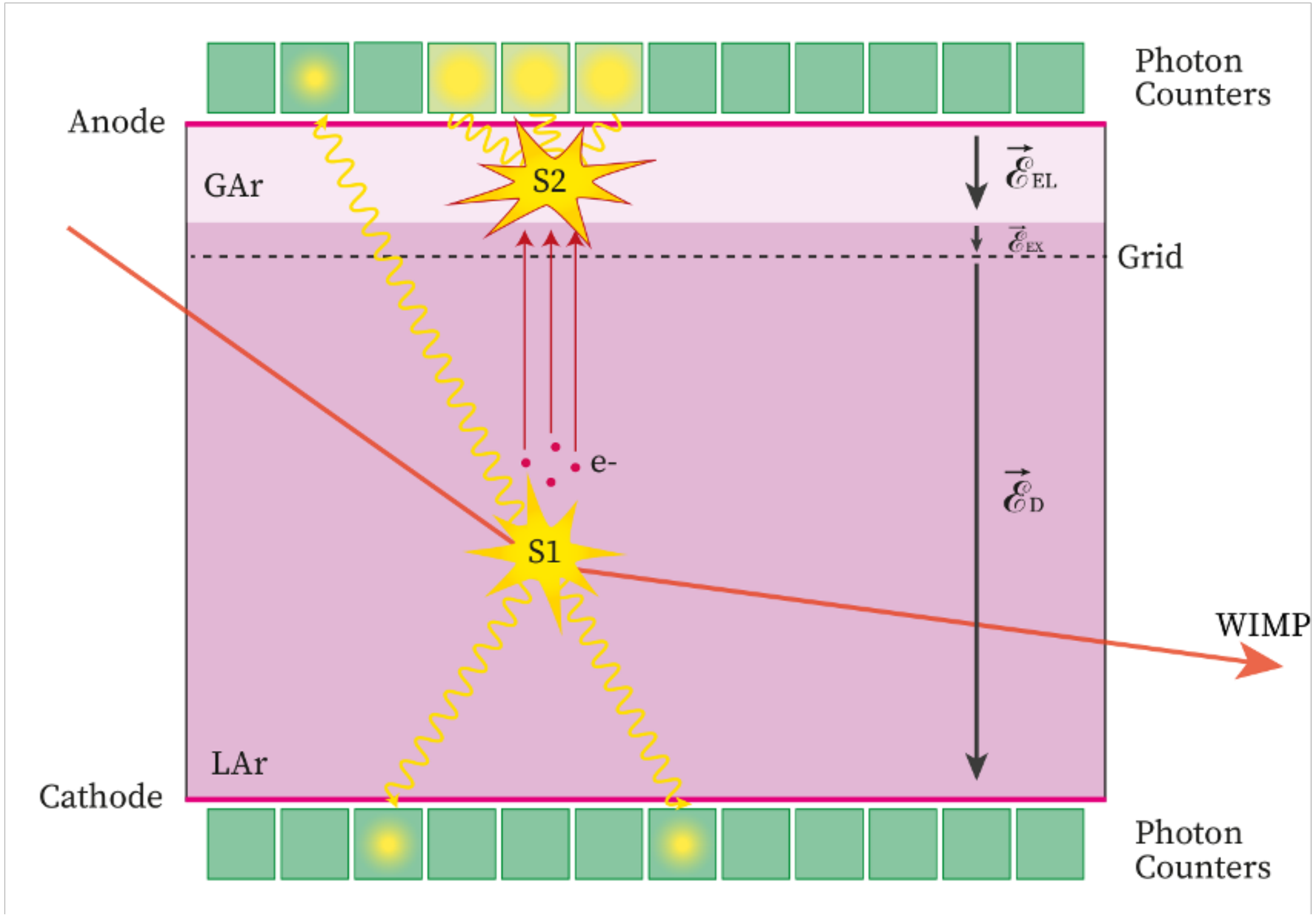
Two Phase Time Projection Chamber

- 3D Reconstruction for Fiducialization
- PID from S2/S1
- Sensitive to low mass WIMPs with "S2-Only Mode"

Cons

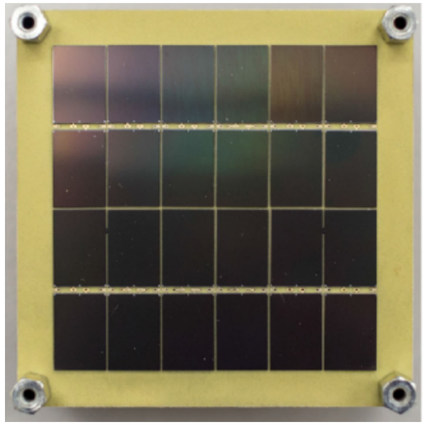
- Gas pocket complicates the design
- Requires HV and transparent electrodes
- Strict geometrical tolerances





State-of-art Photo-Electronics in DM Searches

PMT *transitioning to* **SiPMs**



Why?

1. Compactness
2. Radiopurity → Background Containment
3. Mass Production → Scalability

e.g. Cryogenic Silicon Modular Technology

being pioneered on large scale in DM Searches

by DarkSide-20k, with FBK SiPMs

Developments for the optical readout in DarkSide-20k

In DarkSide-20k

The DarkSide-20k Experiment

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

Outer Veto

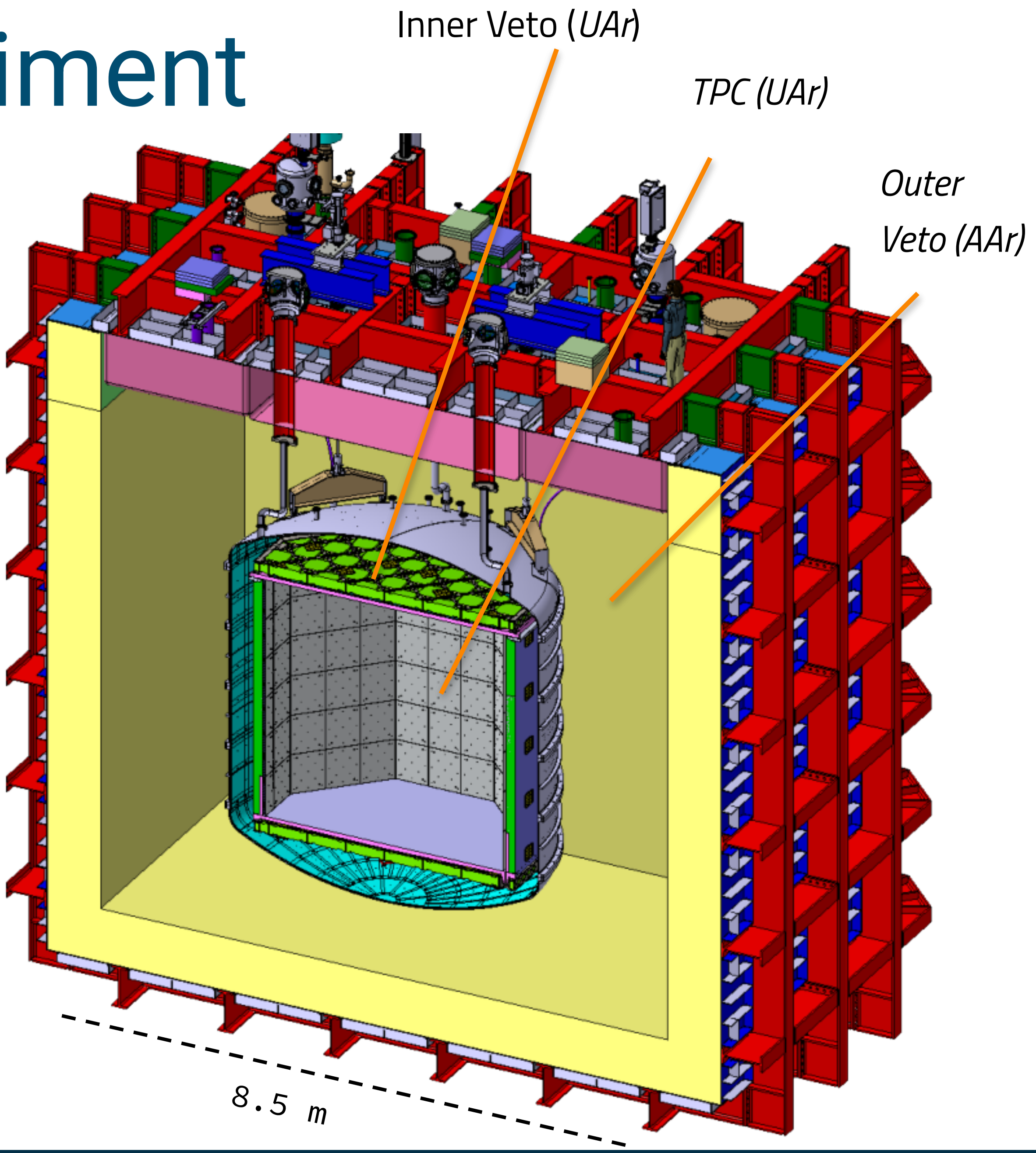
Muon veto
ProtoDUNE-like membrane cryostat 8x8x8 m^3

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

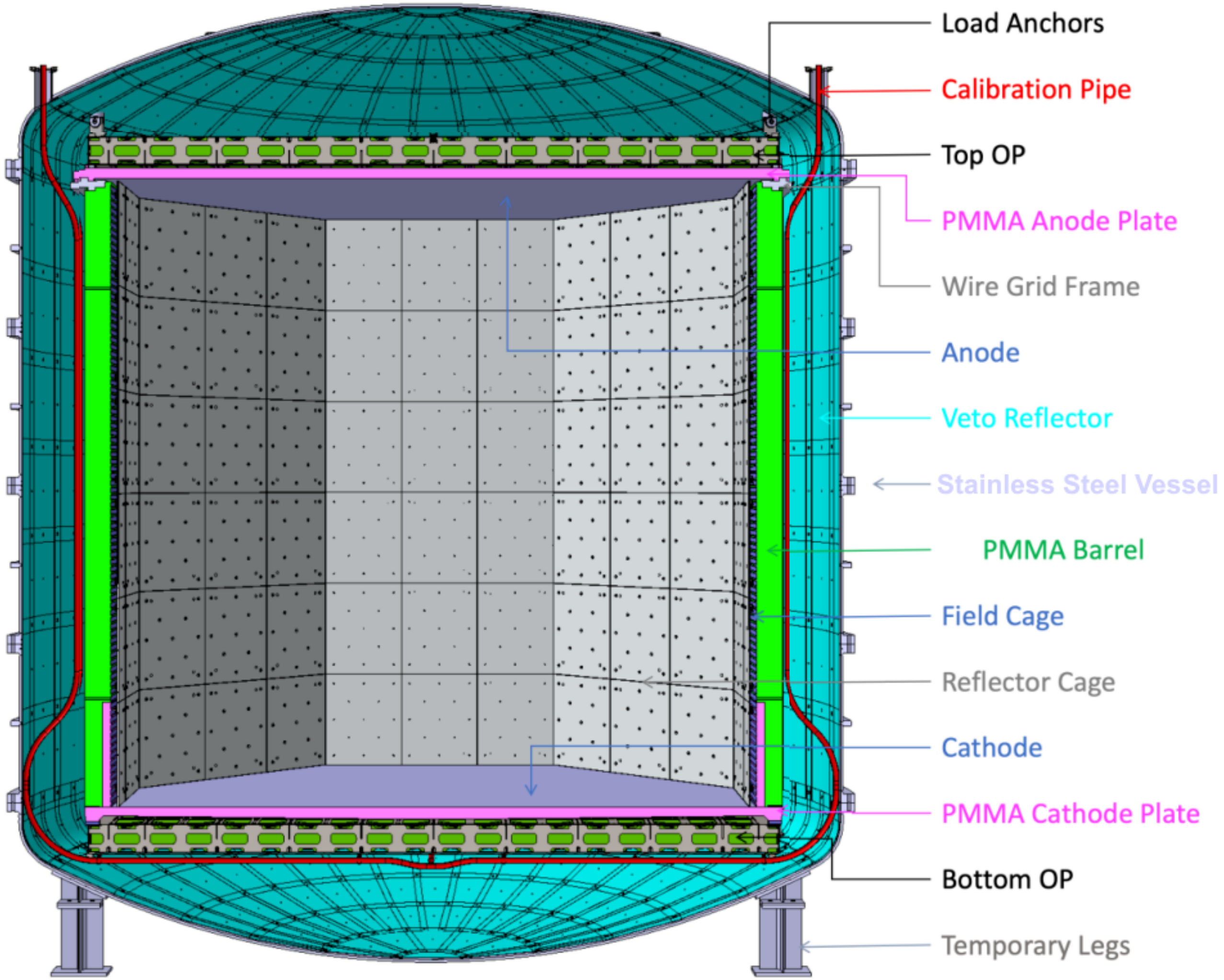
DarkSide-20k TPC:

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

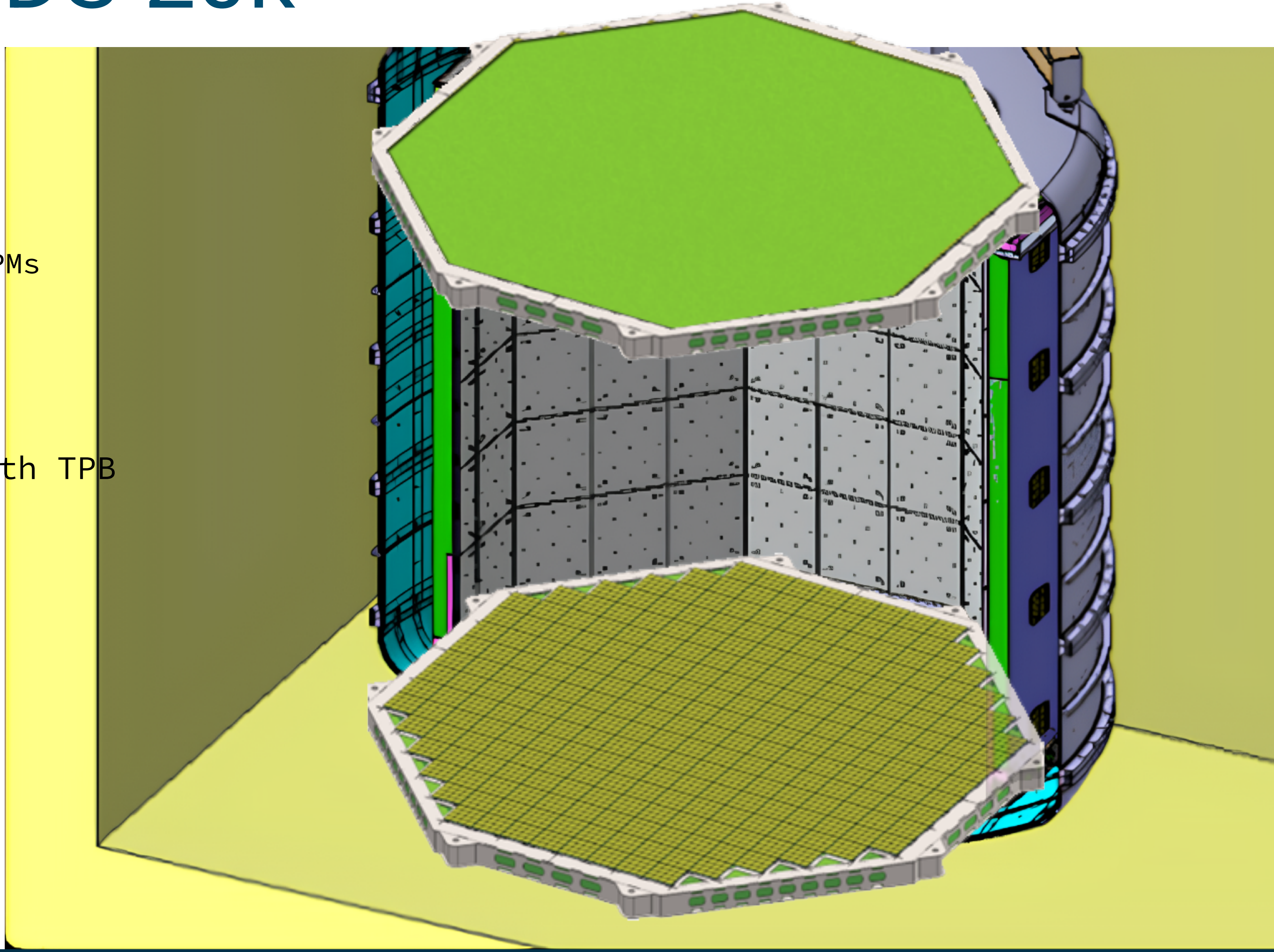
Drift length = 348 cm
Active UAr mass in TPC = 49.7 t (20 t fid.)
Spatial resolution: xy < 5 cm, z ~ 1 mm



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]

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

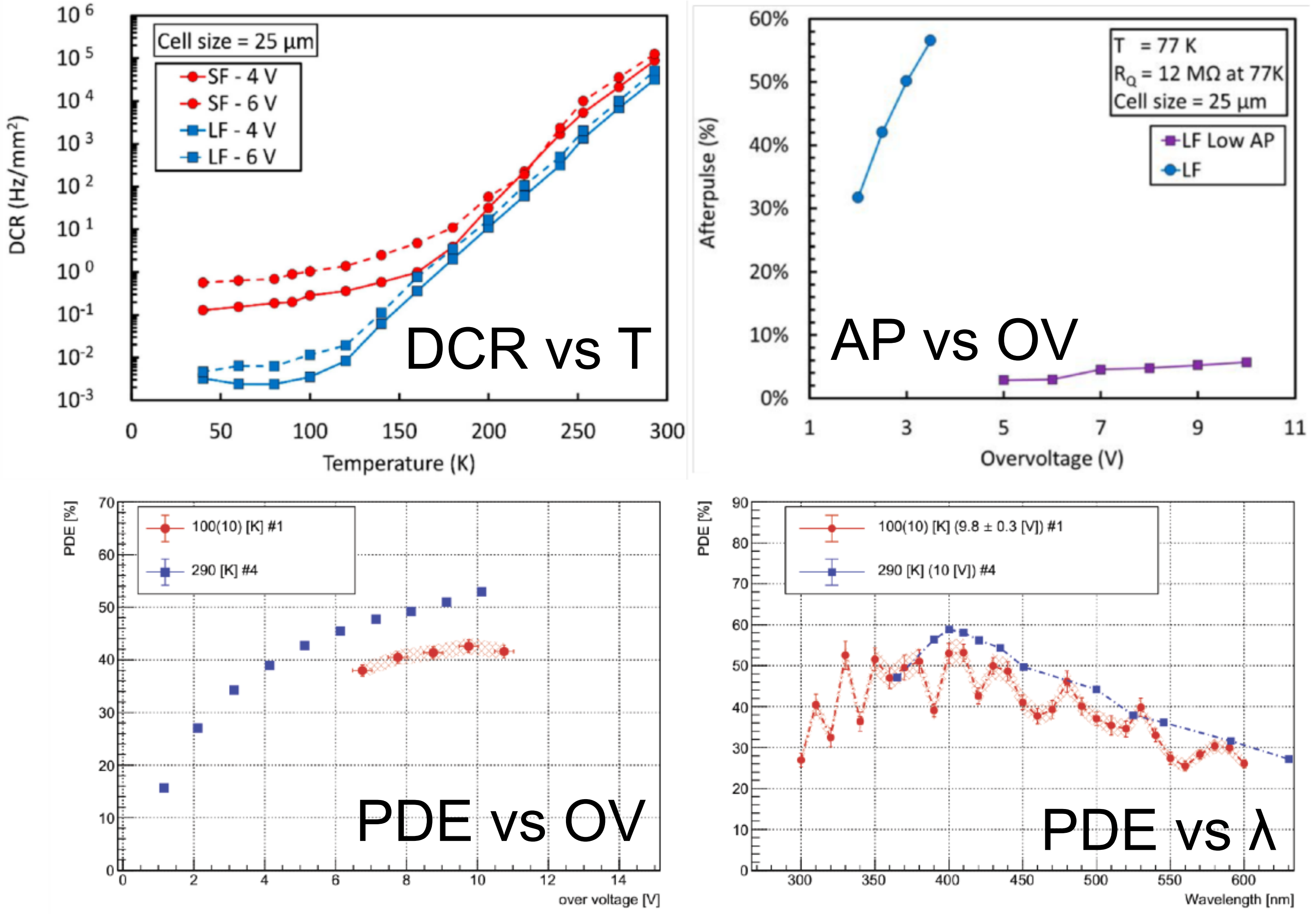
Cryogenic SiPMs

NUV-SiPMs in Liquid Argon

NUV-HD-CRYO by FBK:

- Reduced DCR (up to 10^{-6} with respect to 300K)
- *Specific design modifications to contain AP*
- PolySi resistor with limited temperature dependance
- Technology for DS-20k developed by Fondazione Bruno Kessler (FBK), mass production by LFoundry

- **Problem to solve: large surface single photon detector to reduce no. of analog readouts**



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:

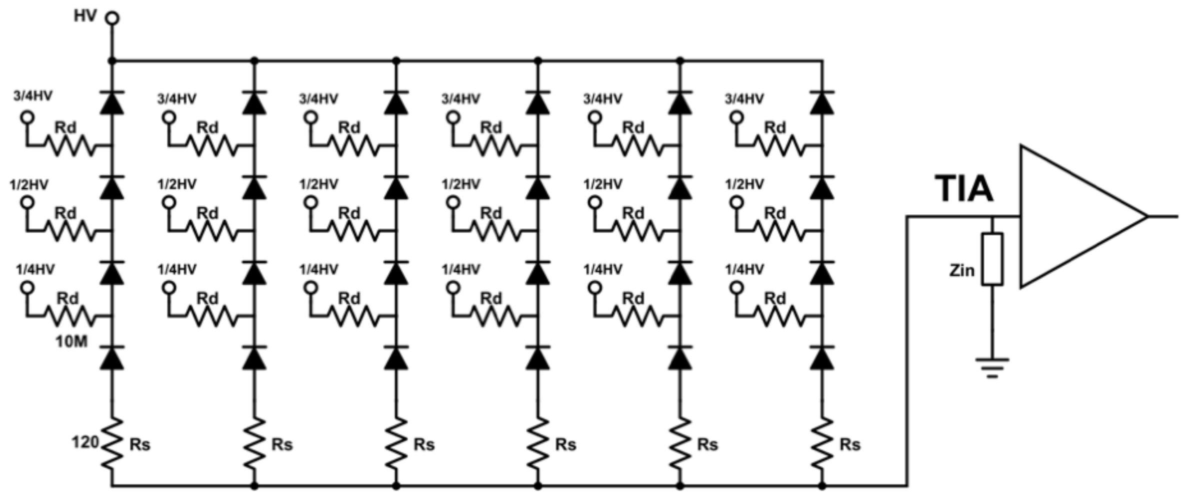
- Large Area SiPM Array
- Low Noise

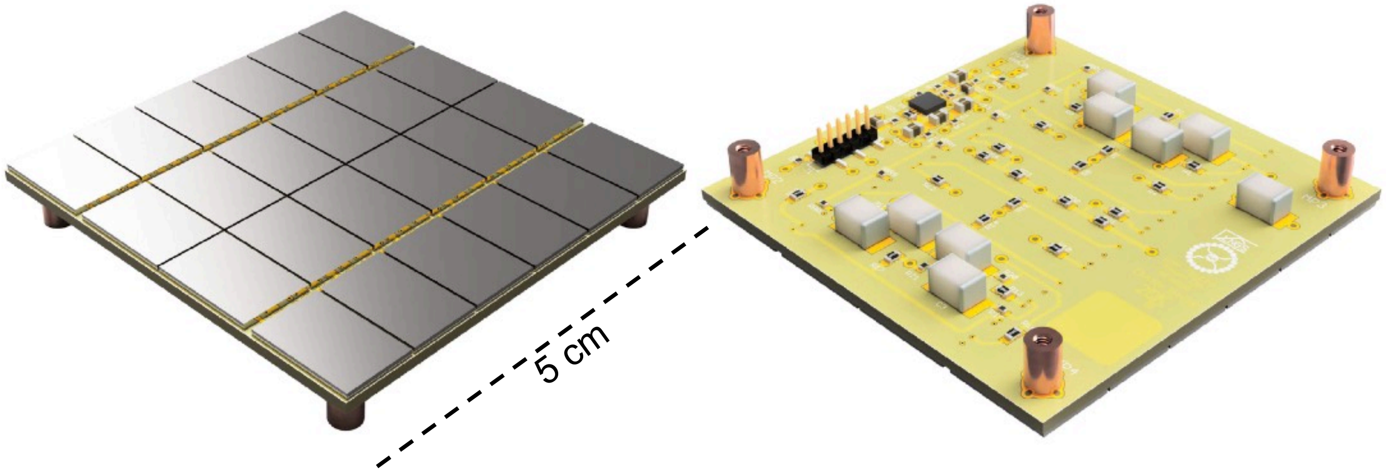
Result of R&D: PDM Tile

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

SiPM Ganging:

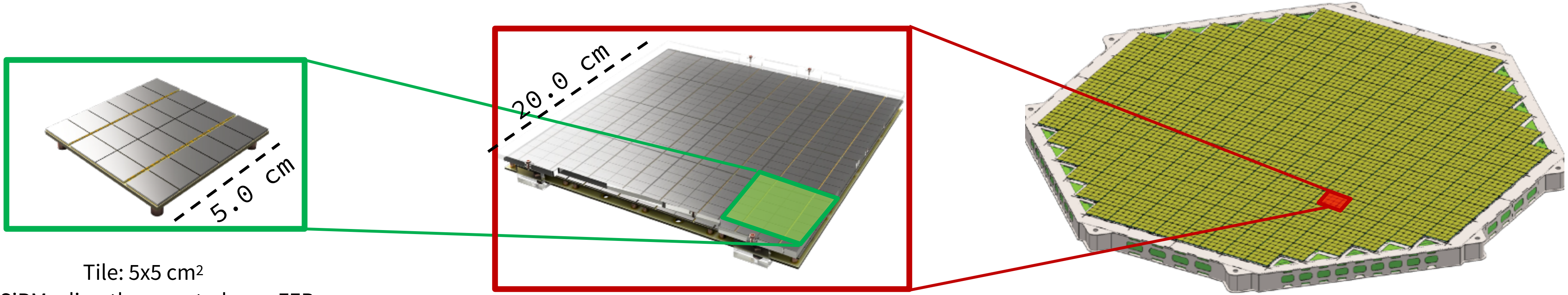
- Many SiPMs in parallel: High Ci
- Many SiPMs in series: Low current
- Compromise: 6p4s configuration
- Precision voltage partitioner to bias the SiPMs





The PDU

Consiglio - **2020** JINST 15 C05063

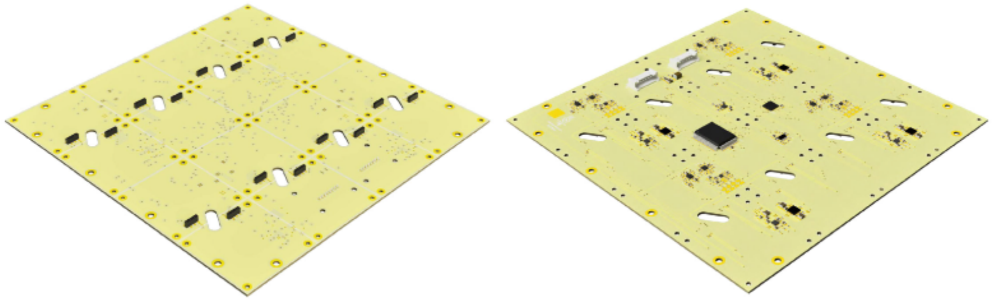


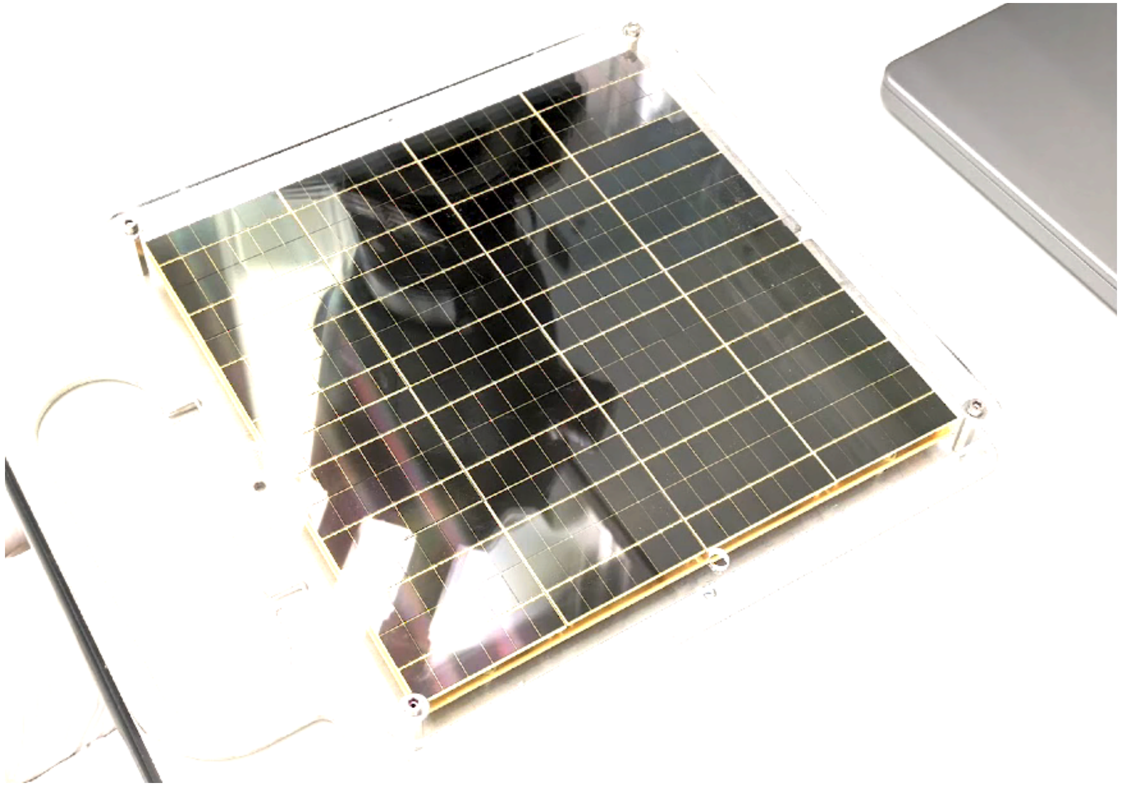
Tile: 5x5 cm^2
24 SiPMs directly mounted on a FEB
SiPM: NUV-HD-CRYO developed by FBK and produced by LFoundry

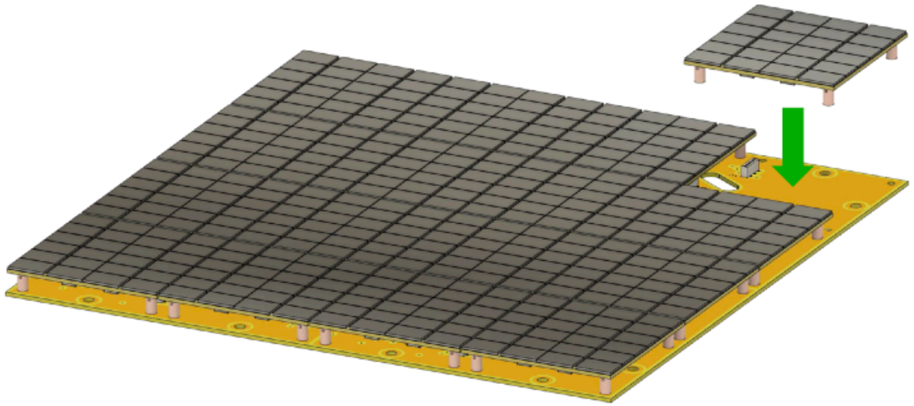
PDU: 20x20 cm^2
16 Tiles Assembled on a Motherboard
4 readout Channel

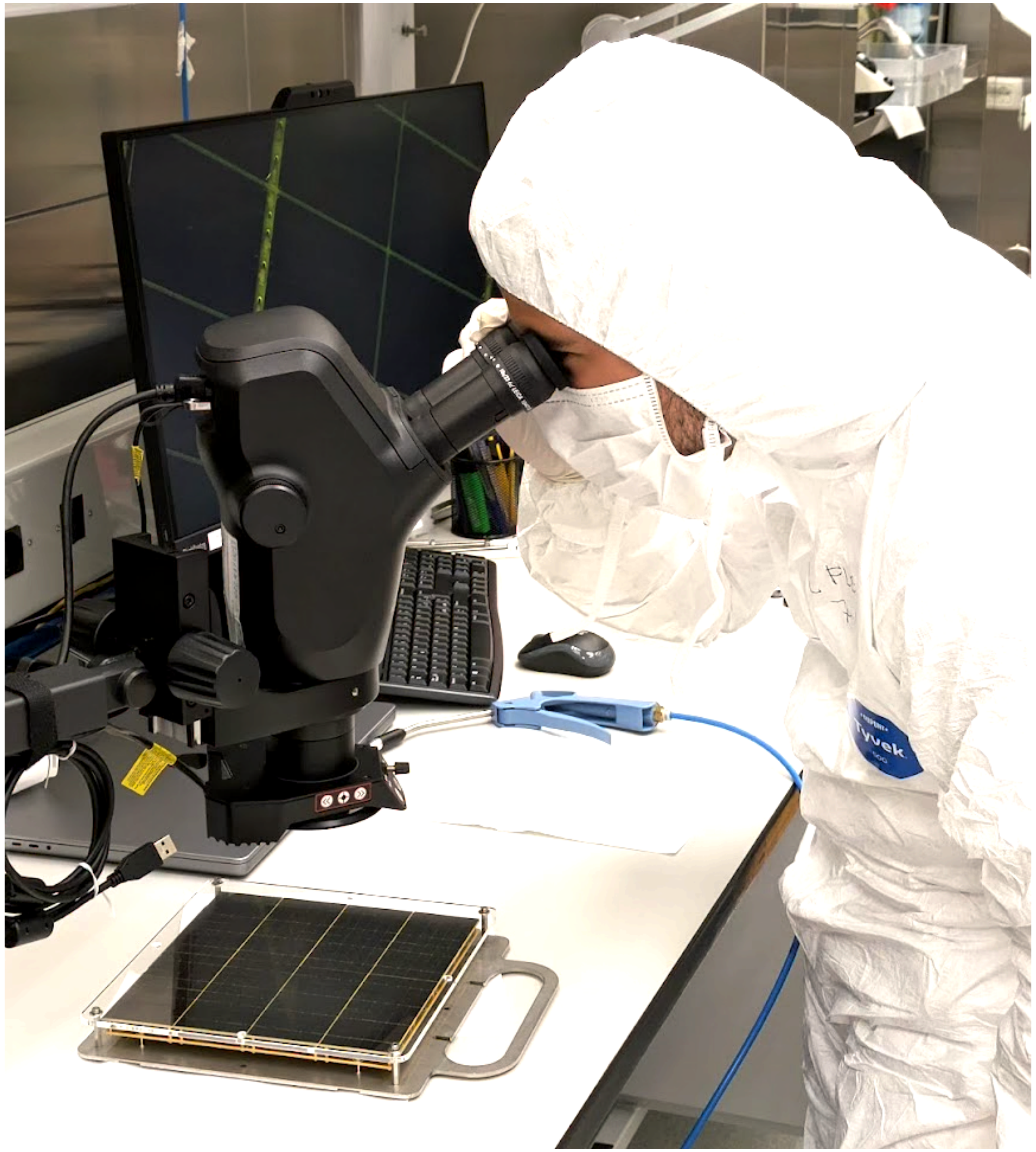
Optical planes: ~2x10 m^2
Total PDUs used (TPC): 528
Readout Channels: 2112

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







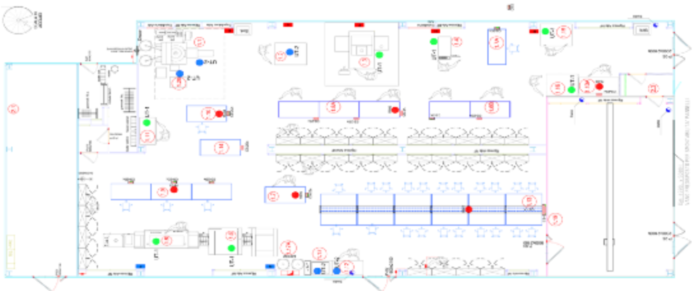

Tyvek

NOA Production Facility

Presentation by L. Consiglio at TAUP23

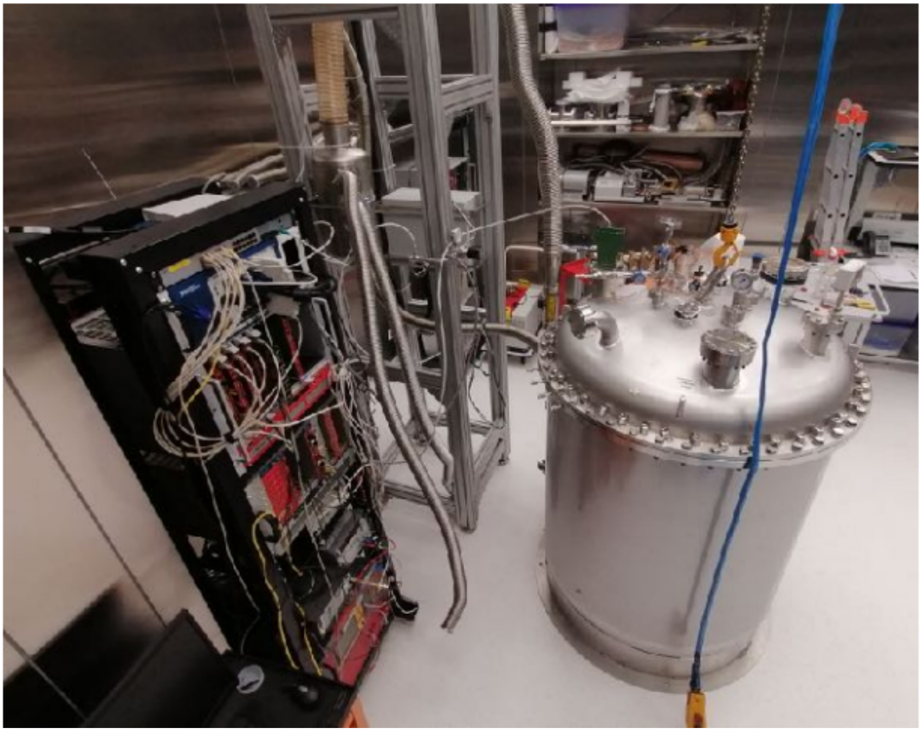
Nuova Officina Assergi

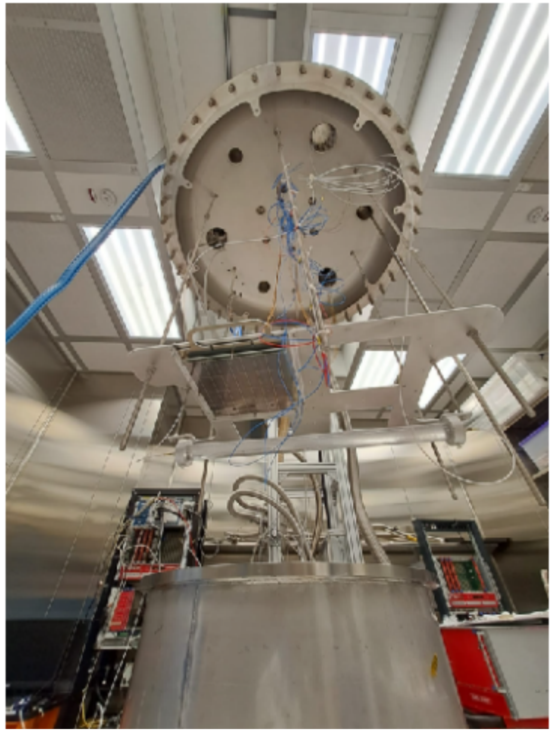
- ISO6 Clean Room
- 420 m²
- Continuous Rn Monitoring
- CR3 Equipped with:
  Cryoprobe, Dicer
  Chip Bonder, Wire Bonder
  Microscopes, Packaging Tools
- PDU Production



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

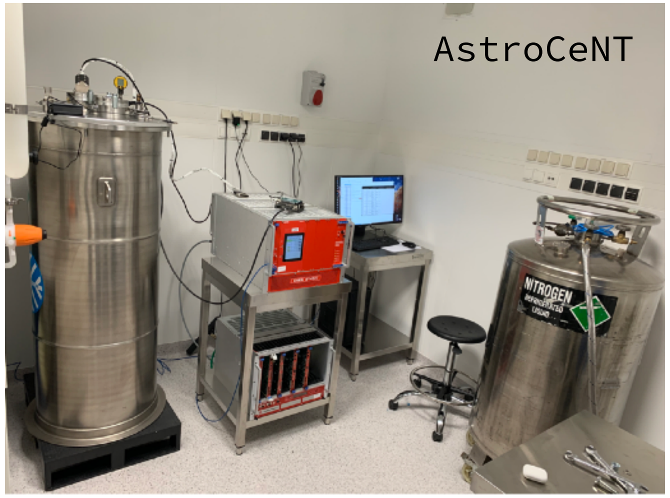
- MIDAS DAQ Framework
- Fully automated cold box, remotely controllable with fast FILL and DRAIN
- Two external 3000L each reservoirs
- Already testing pre-production

Veto PDU Facilities

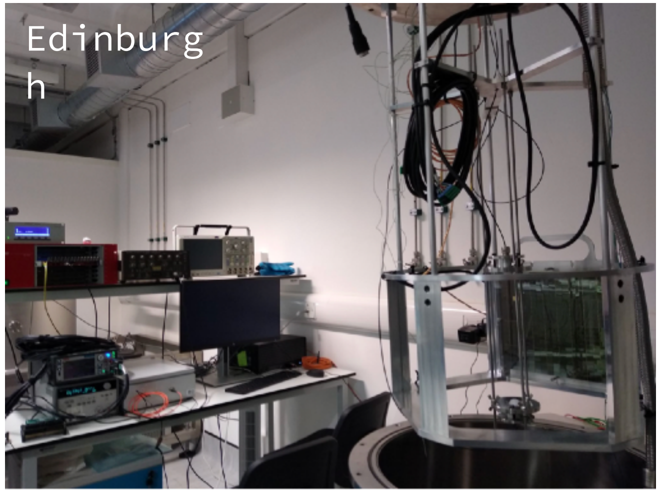
Production in Birmingham, STFC interconnect, Manchester, Liverpool → Testing Facilities

Lancaster

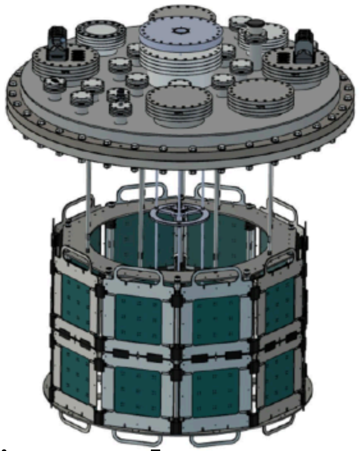
Birmingham

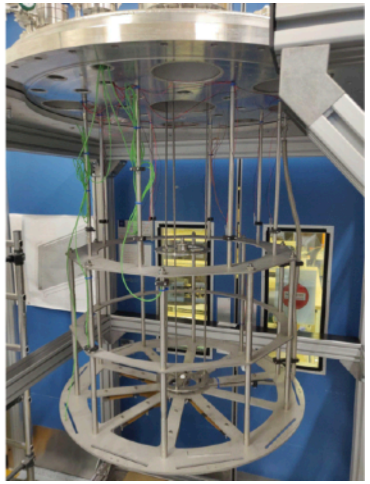


AstroCeNT



Edinburgh

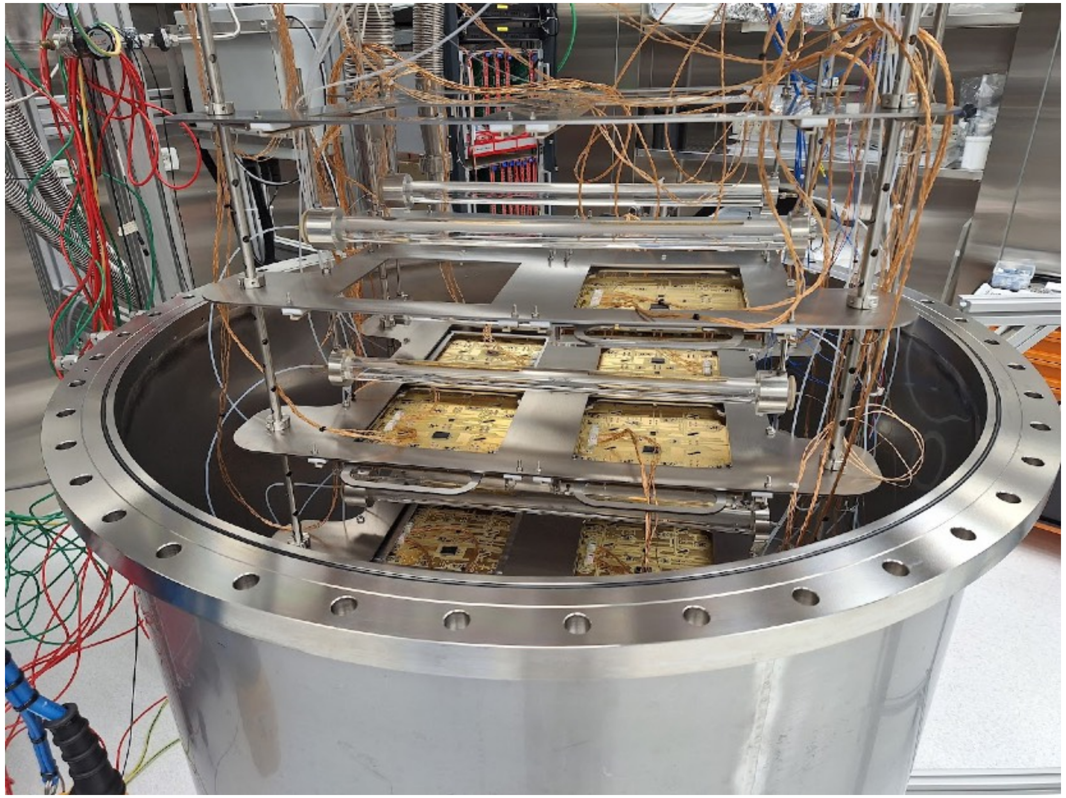




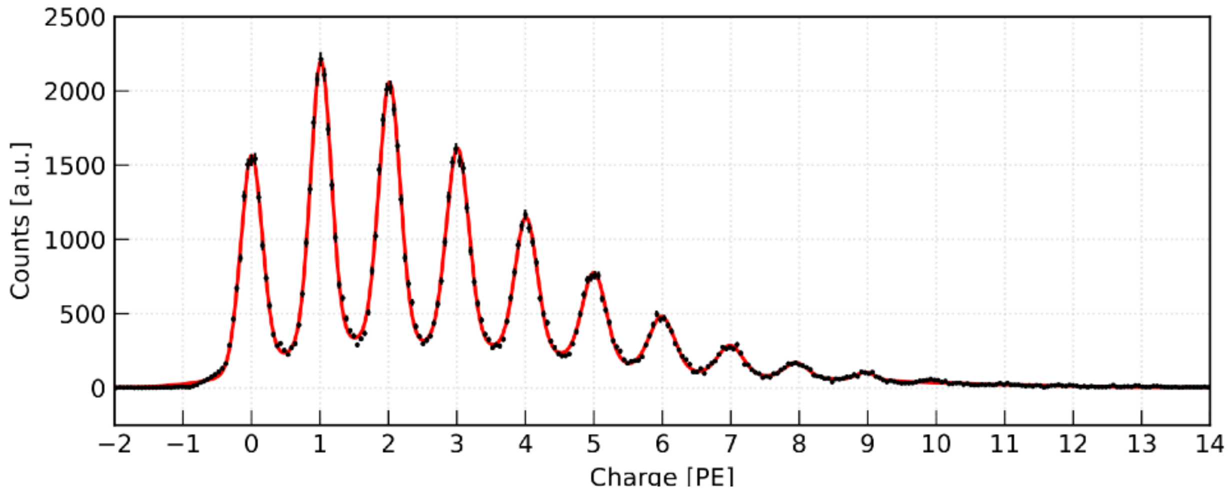
Liverpool

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



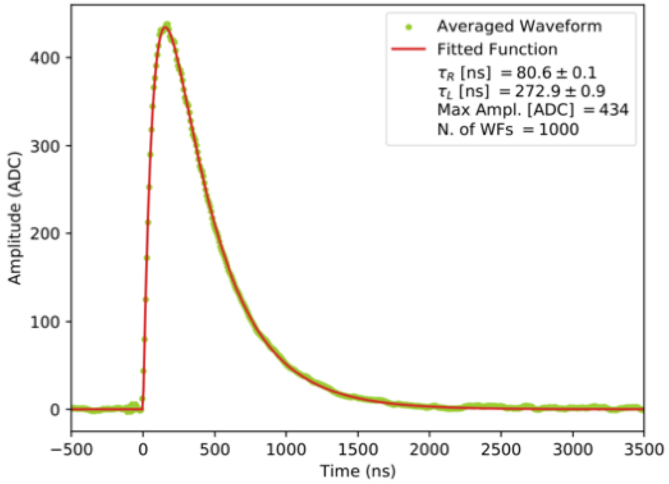
At 7 V o.v. 77 K

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

Waveform Template
For matched filter

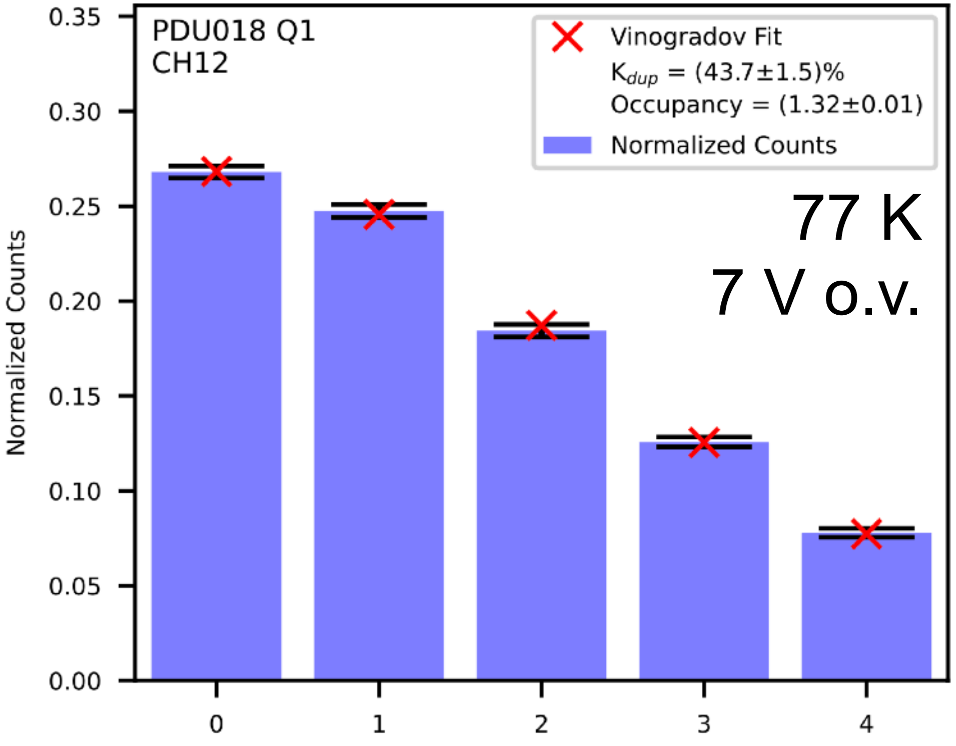
$$V(t) = A\left(e^{-\frac{t-t_0}{\tau_L+\tau_R}} - e^{-\frac{t-t_0}{\tau_R}}\right)\Theta(t-t_0)$$

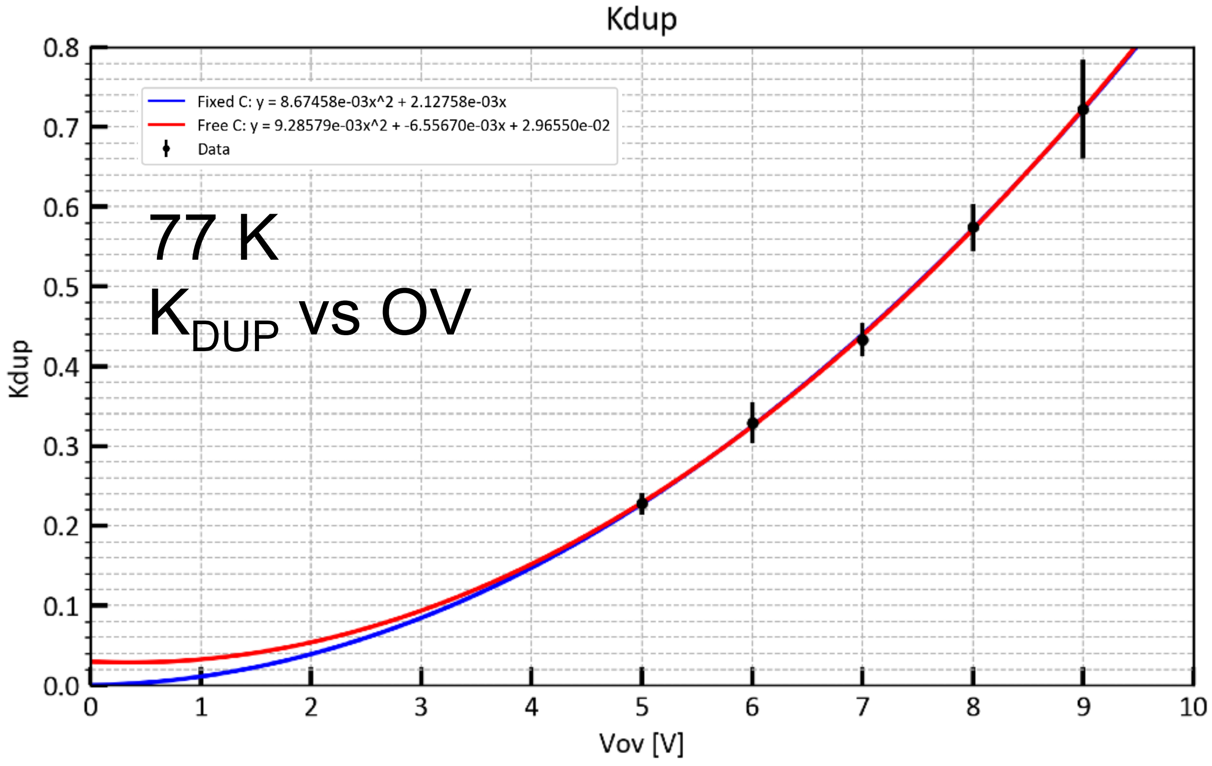
1 PE Ampl. = 12.5 mV
Fall time = 350 ns



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)

$$N_{hits} = N_{true}(1+K_{DUP})$$

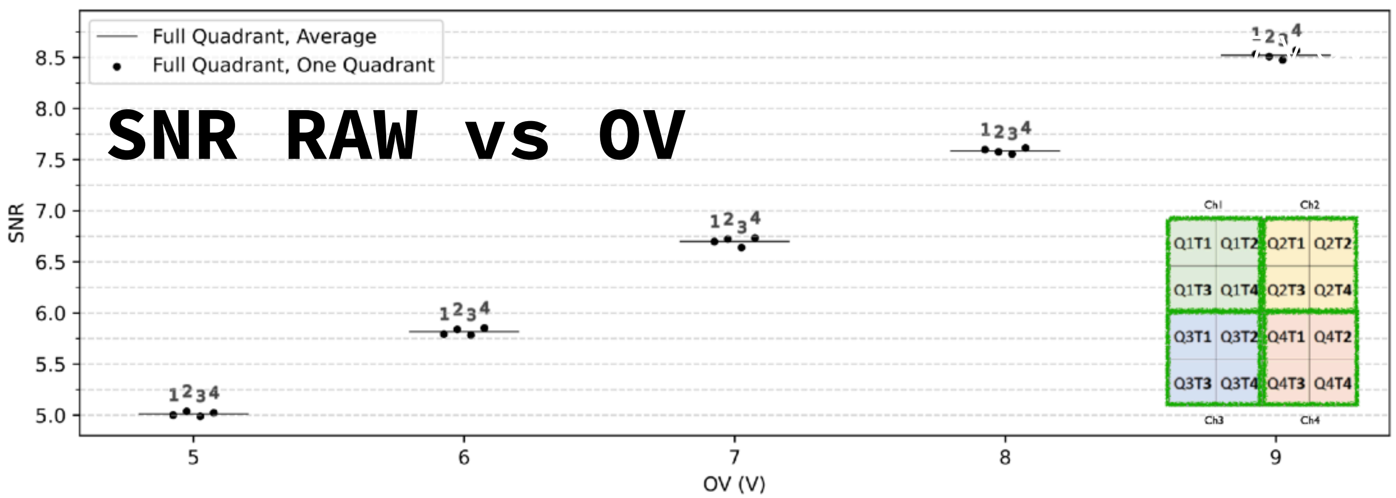
K_{DUP} = ~45% @ 7 V o.v.

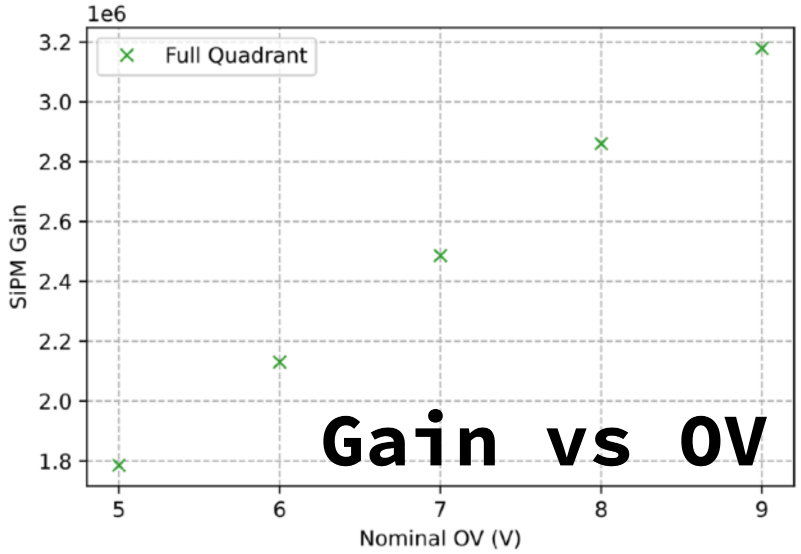
PDU: SNR, resolution, gain

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

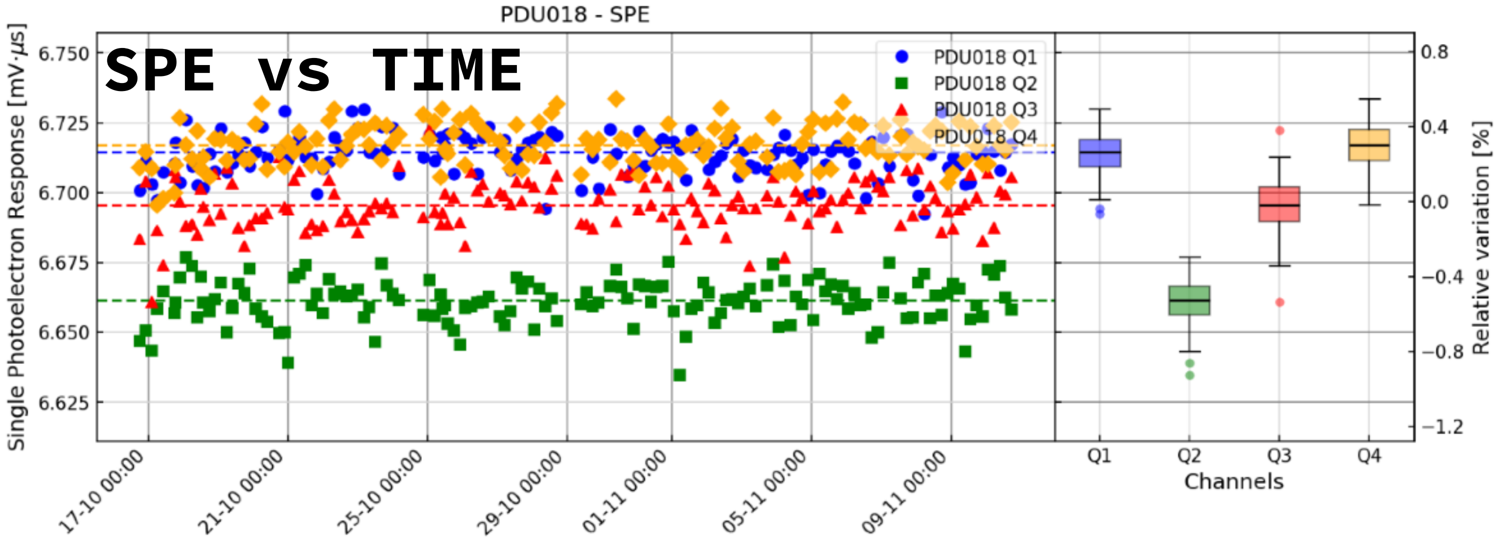
@ 7 V o.v. and 77 K

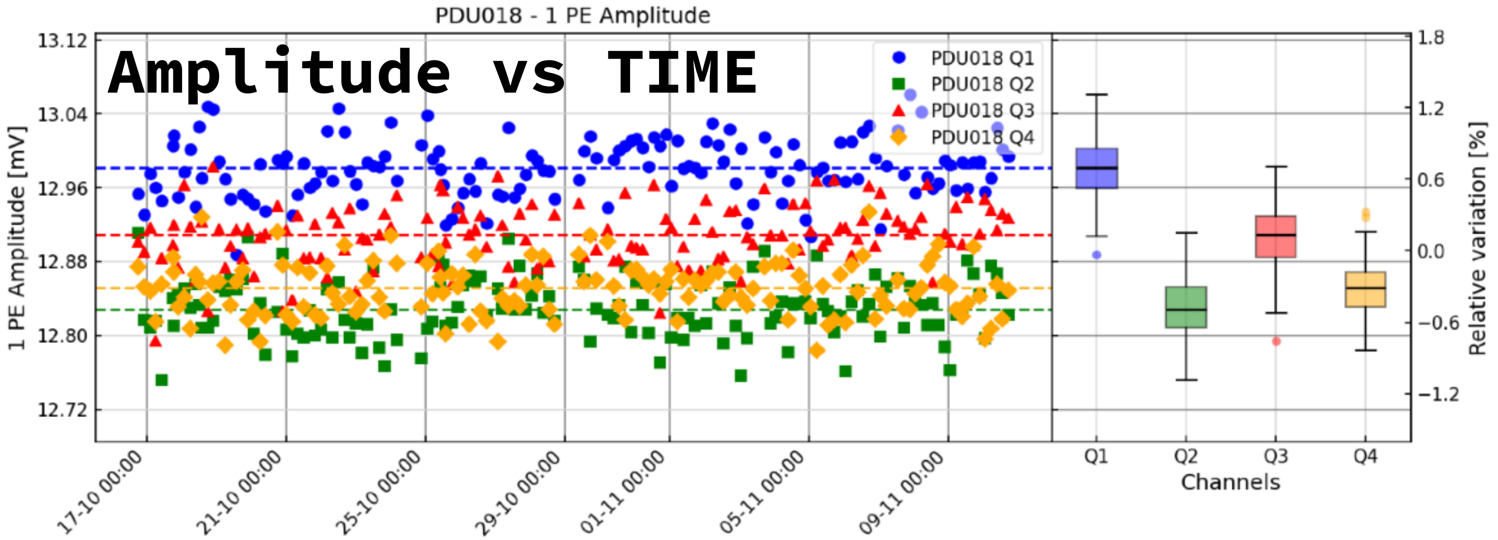




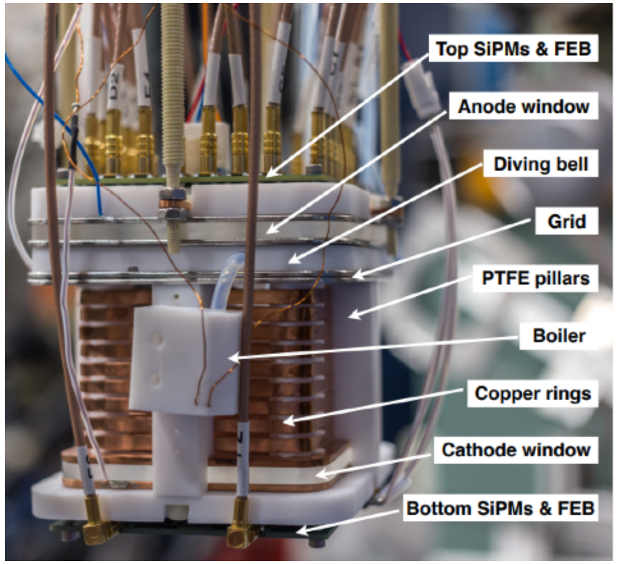
PDU: Stability

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



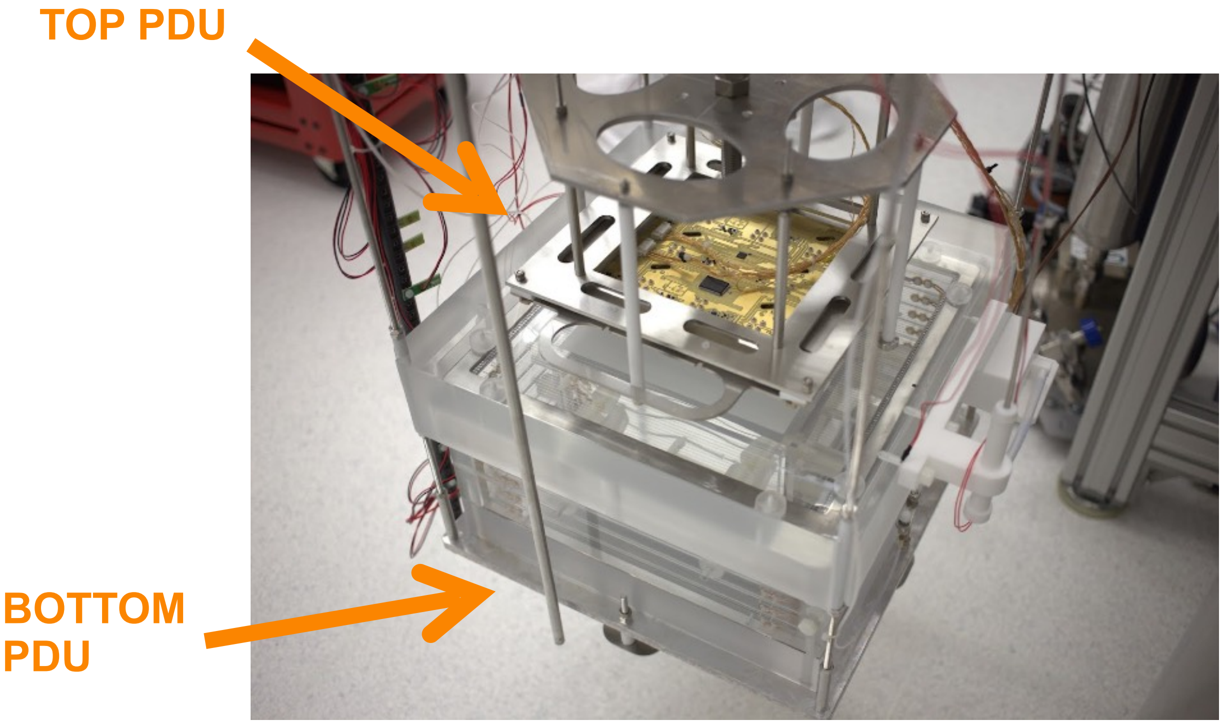


In Liquid Argon…

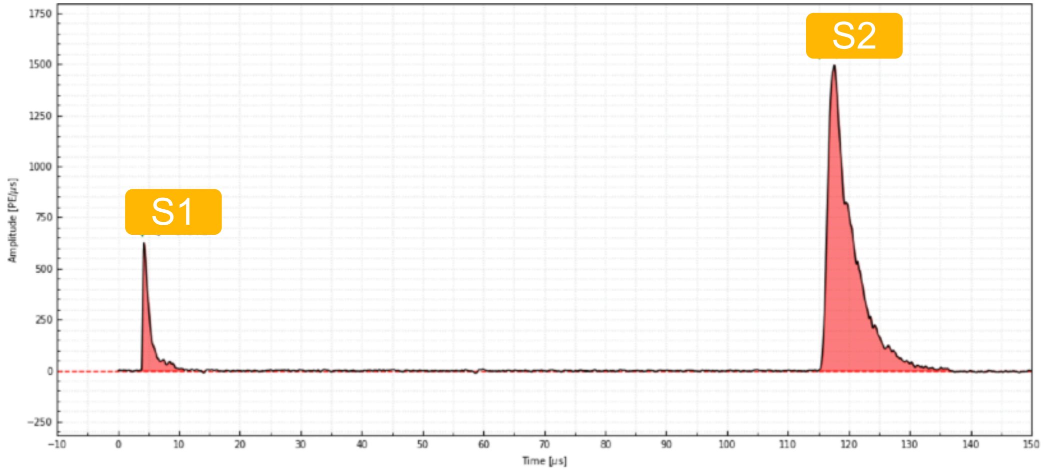


ReD – Recoil Directionality
Contraints on directional sensitivity for NR in LArTPCs
2 Phase LArTPC
~6 months LN calibration
> 1 y in cryogenic environment

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



Next-generation SiPMs for dark matter searches

In DarkSide-20k

Next-Generation Photon Detectors

Analog photon detectors	
Large area *(Few readout channels)*	***Small Area*** *(Many readout channels)*
Lower Signal-to-Noise 👎	Higher Signal-to-Noise 👍
Less Cables → Less Material → Lower Background 👍	More Cables → More Material → Increased Background 👎
Lower Data Throughput 👍	Higher Data Throughput 👎
Lower Spatial Resolution 👎	Higher spatial resolution 👍

- Problem worsens with increased area
- Data Throughput mitigated with Zero Suppression
- **Best solution: go digital**

Experiment	Type	Photodetector	Area (m^2)
nEXO	LXe	FBK, Hamamatsu, 3DdSiPM	5
DARWIN	LXe	SiPM is one option	8
TAO	LSci	FBK	10
DarkSide-20k	LAr	FBK NUV-HD triple dopant	30
ARGO	LAr	SiPM is baseline option	200
DUNE	LAr	Light guide or trap + SiPM	10-1000

Optical area of future experiments with noble liquids

Furthermore…

↓ DARK NOISE by turning off hot pixels

↓ CORR. NOISE by silencing cell

These affect sensitivity of DM experiments

SiPM Requirements for DM Searches

Requirements	Dark matter
SiPM Unit area (mm^2)	10x10
Micro-cell pitch (μm)	25-30
PDE (%)	> 45
DCR (kHz)	< 0.1 Hz/mm^2 (at LN)
AP (%)	Total Correlated Noise Probability (Xtalk + AP) < 60 %
Xtalk (%)	
Trigger	self
Output data: light intensity	
Output data: time	ToA and TOT
Time resolution (ps)	
Module size and form factor	

From ASPIDES Proposal

Parameter	7 V of OV	9 V of OV
Internal Cross Talk probability at 77 K	$<$ 33 %	$<$ 50 %
Dark noise rate at 77 K	$<$ 0.01 Hz/mm^2	$<$ 0.1 Hz/mm^2
Afterpulse probability at 77 K [within 5μs]	-	$<$ 10 %
PDE at 420 nm at 77 K	-	>40 %
Breakdown Voltage at 77 K (SPE charge)	26.8 ± 0.2 V	
Breakdown Voltage at 77 K (SPE amplitude)	27.5 ± 0.2 V	
Single Cell Capacitance (from SPE charge)	62.5 ± 2.5 fF	

TABLE 43. Summary of the SiPM Requirements for the Darkside-20k SiPMs. SPE stands for Single Photon Electron.

Depends on Detector Technology

For TPCs,

σ_t < 10 ns

is acceptable (required for pulse shape discrimination)

For Single Phase Scintill. Detectors, good time resolution can improve fiducialization

σ_t ~ O(200 ps)

Constraints

A. Low Radioactivity

B. Low Power: avoid bubbling and minimize required cooling power

C. Light Collection Efficiency: maximize active surface, keep low encumbrance

D. PDE: preserve FF & increase QE in NUV-VUV

backup

DCR of DarkSide-20k SiPMs

DCR_{SiPM} = 2 x 10^{-3} Hz/mm^2 in LN (7 Vov)

DCR_{Tile} = 5 Hz in LN (7 Vov)

$DCR_{Quad.}$ = 20 Hz in LN (7 Vov)

Parameter	7 V of OV	9 V of OV
Internal Cross Talk probability at 77 K	< 33 %	< 50 %
Dark noise rate at 77 K	< 0.01 Hz/mm^2	< 0.1 Hz/mm^2
Afterpulse probability at 77 K [within 5μs]	-	< 10 %
PDE at 420 nm at 77 K	-	>40 %
Breakdown Voltage at 77 K (SPE charge)	26.8 ± 0.2 V	
Breakdown Voltage at 77 K (SPE amplitude)	27.5 ± 0.2 V	
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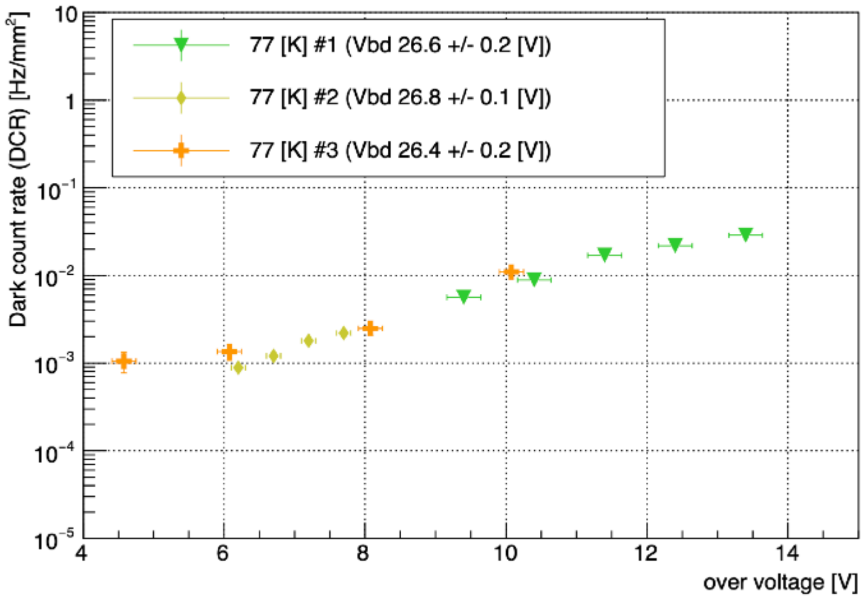
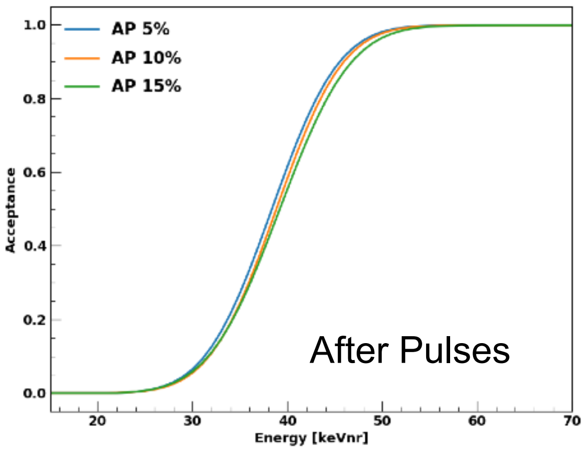
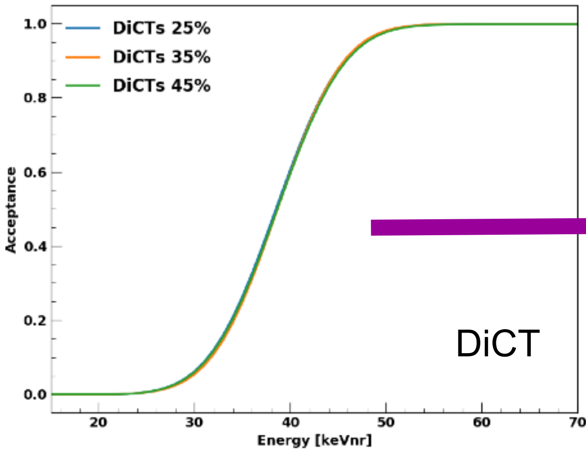


Dark Noise (DN) rate normalized by the SiPM photon sensitive area as a function of the applied over voltage. TRIUMF data is labeled as #1 while LNGS, INFN PISA and FBK data are labeled as #2, #3, and #4 respectively, when available. From DarkSide-20k TDR (Fig. 14)

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	2×10^{-5} ns^{-1} at 6 VoV	2.00e-48
DCR	4×10^{-5} ns^{-1}	2.01e-48
DCR	6×10^{-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.

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

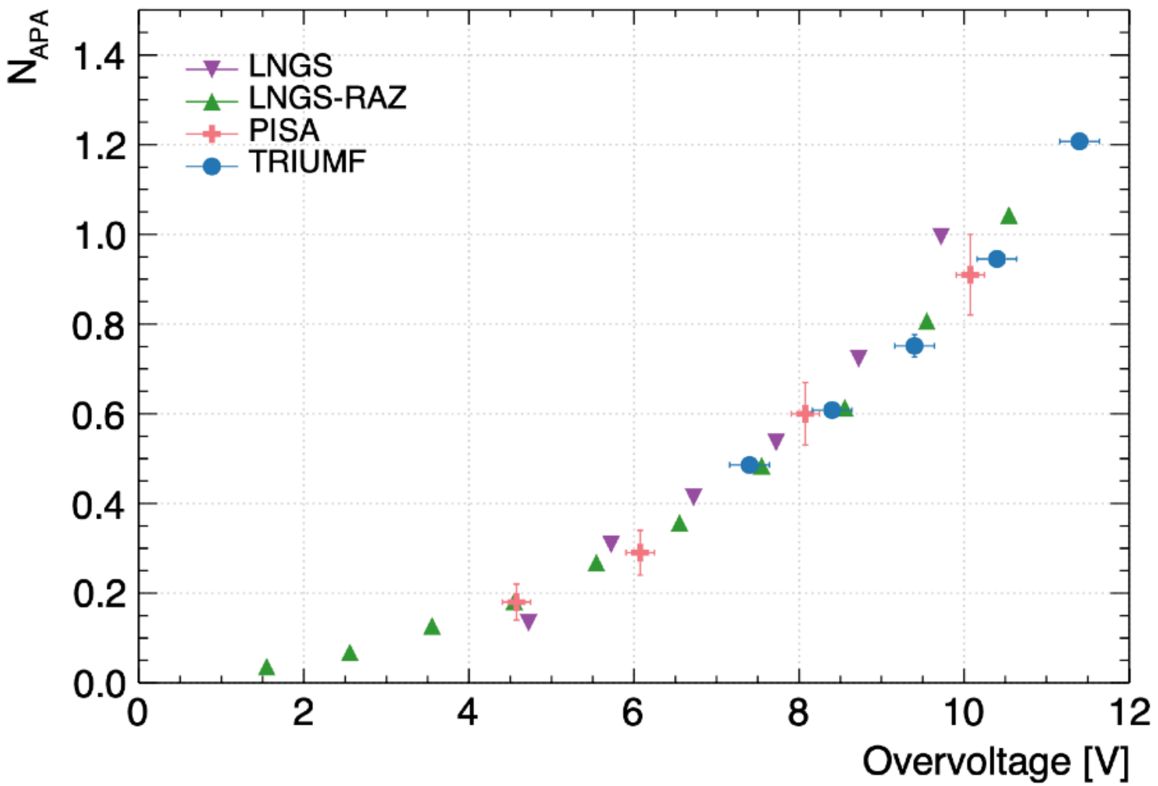
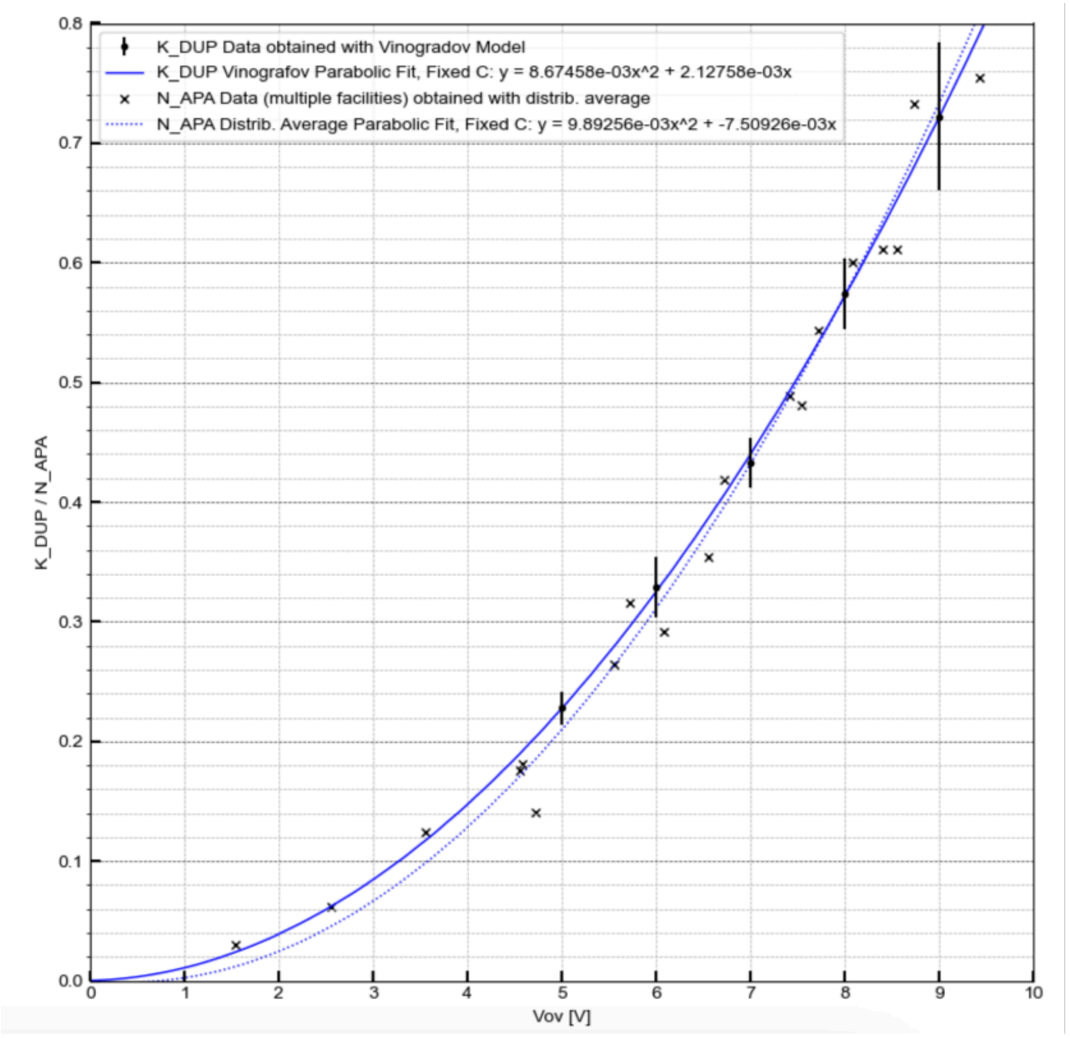
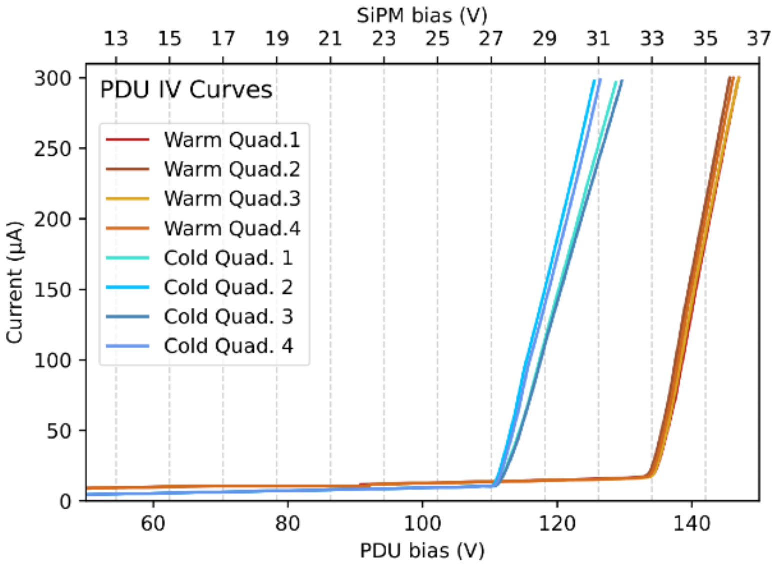


Fig. 17 Number of Additional Prompt Avalanches (APAs) measured at 77 K as a function of the over voltage.

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



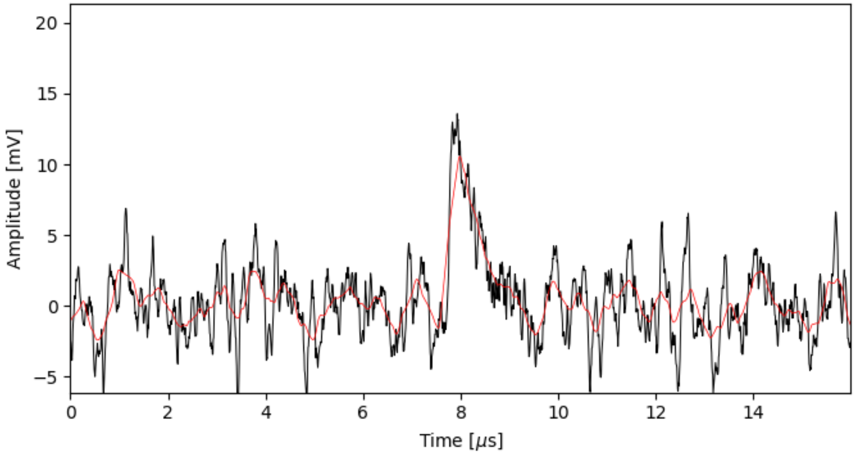
PDU: Breakdown voltage and signal shape



IV Curves

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

V_{BD} (77 K) = 27 V



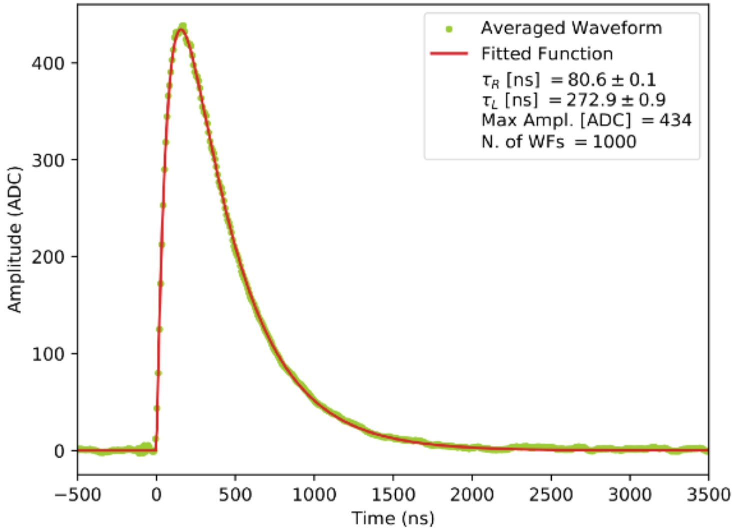
Typical waveform

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

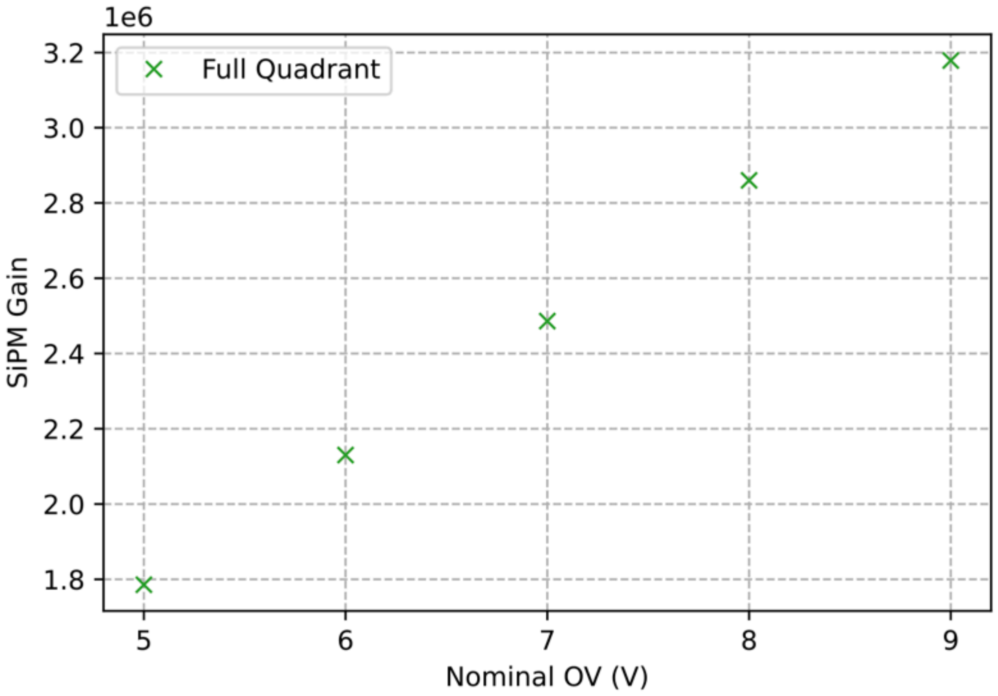
To be used in matched filter

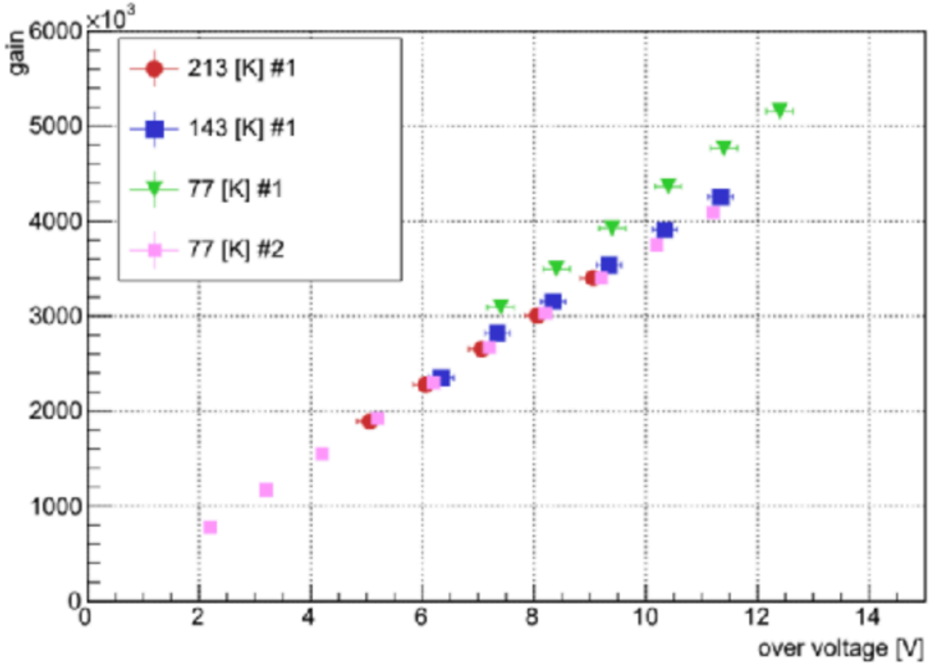
$$V(t) = A\left(e^{-\frac{t-t_0}{\tau_L+\tau_R}} - e^{-\frac{t-t_0}{\tau_R}}\right)\Theta(t-t_0)$$

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

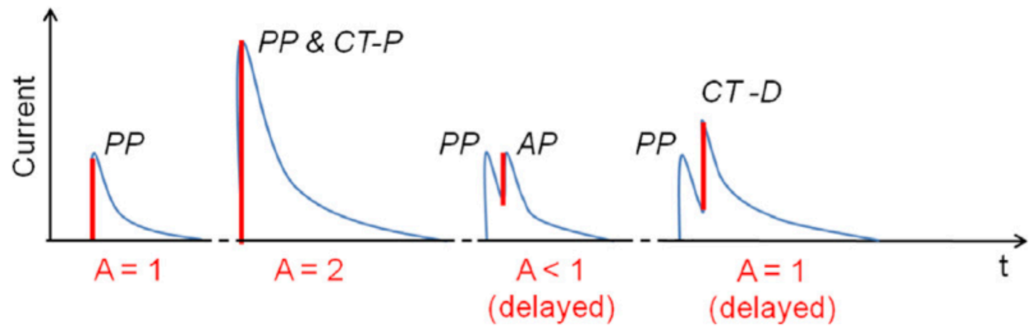


Fig. 7. Primary pulses (PP) with different types of correlated pulses such as prompt CT (CT-P), afterpulse (AP) and delayed CT (CT-D).

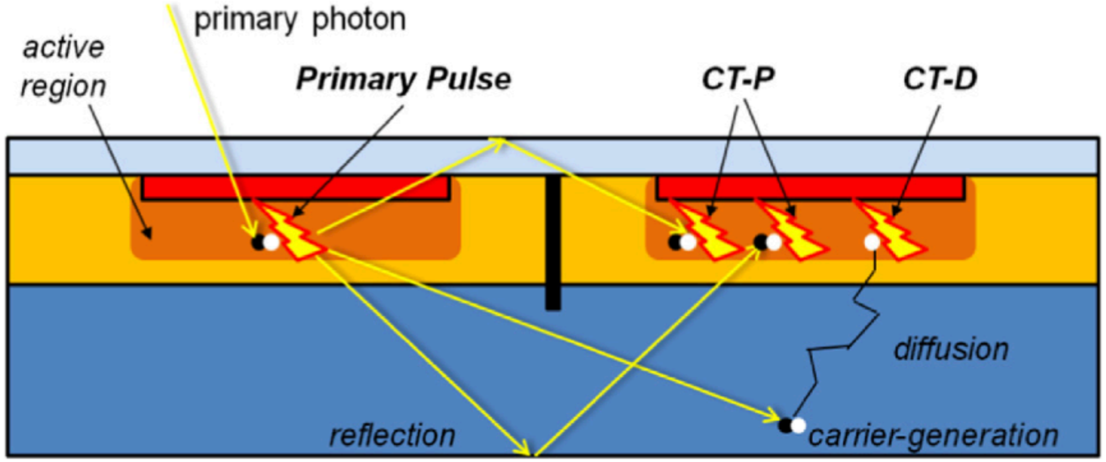
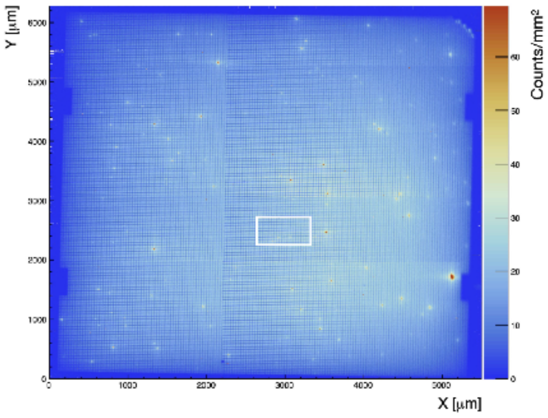


Fig. 2. Two different types of crosstalk: prompt (CT-P) and delayed (CT-D).

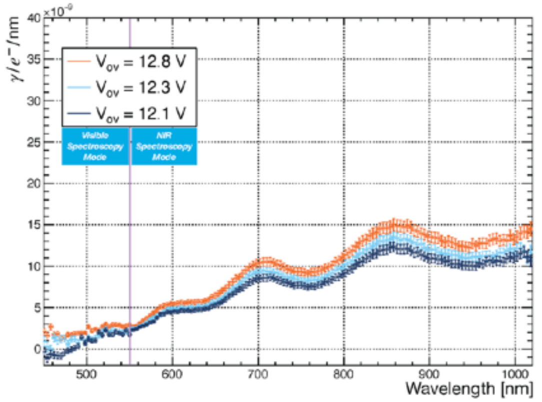
Correlated avalanches:

- 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

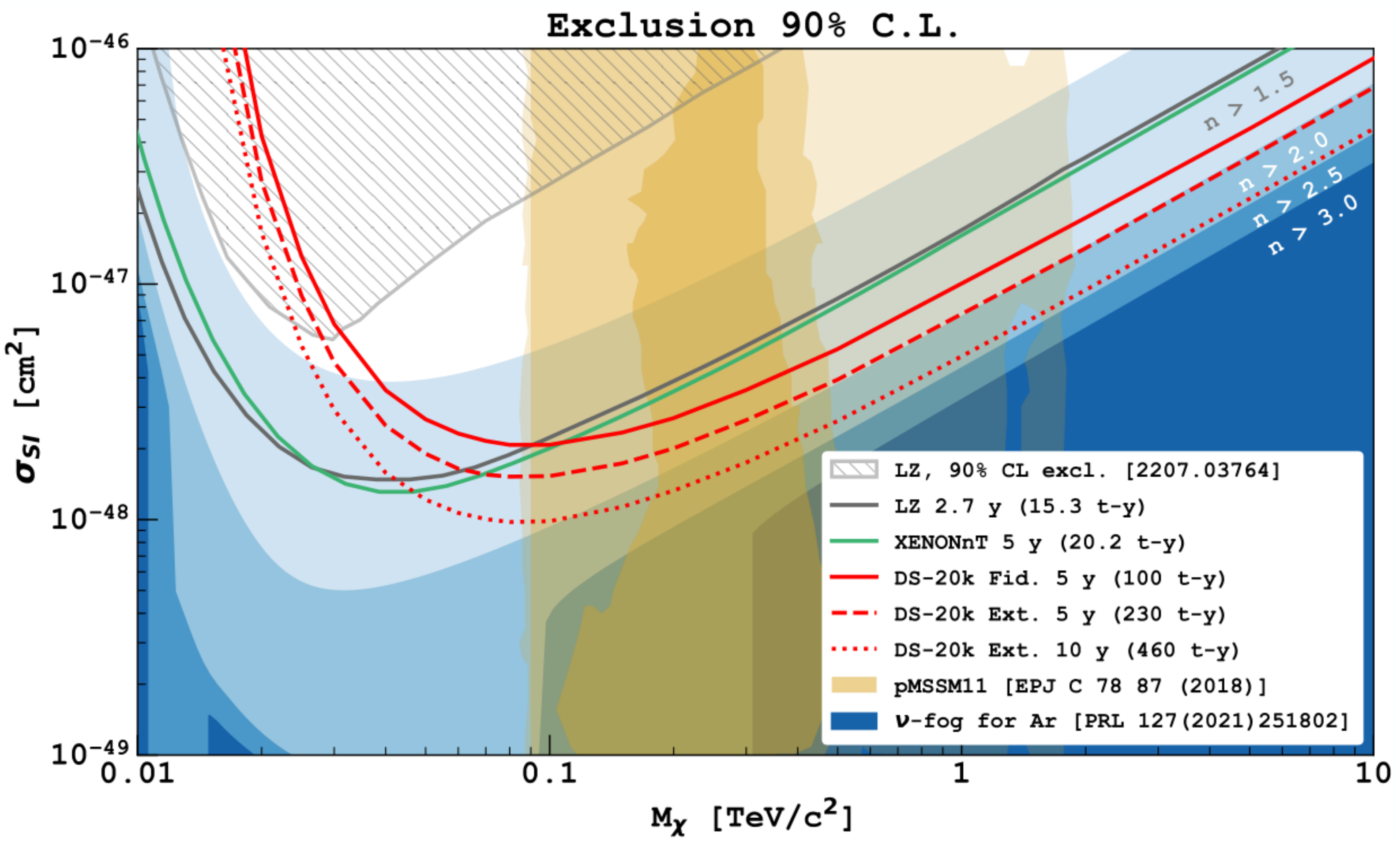
DarkSide-20k Sensitivity Projections

Upper limits for a 100 GeV/c² WIMP (90% C.L.) at 100 t.y:

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

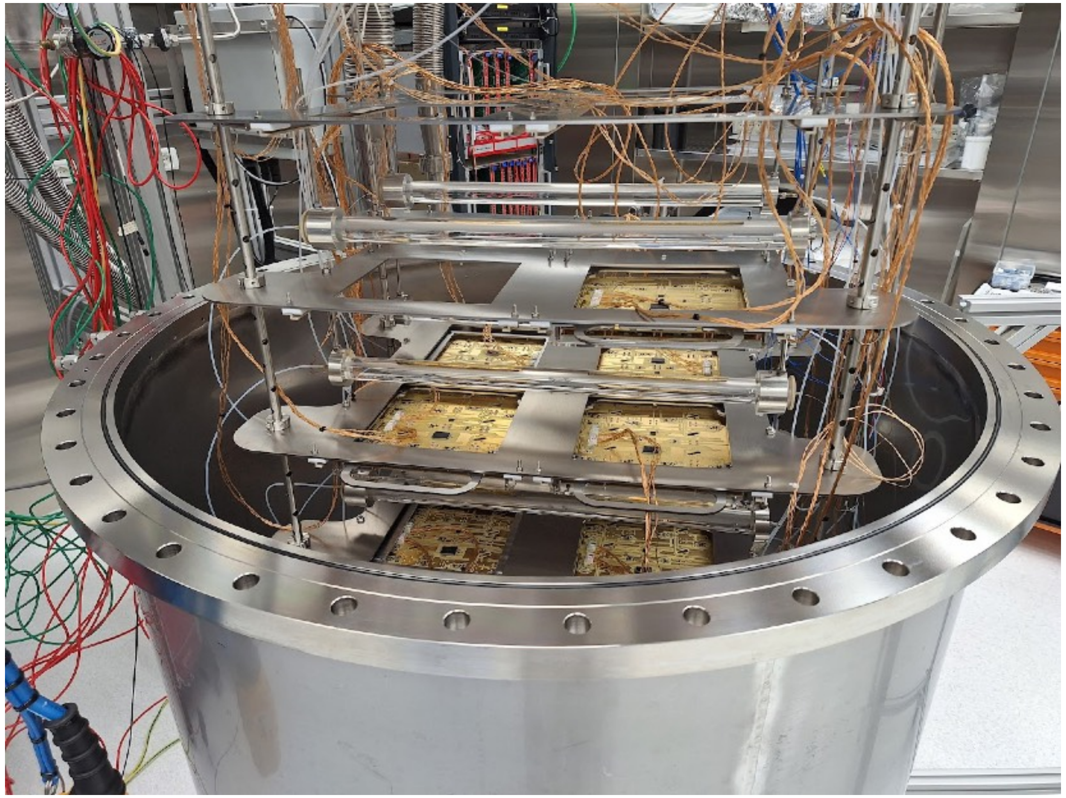
First measurement of the neutrino "fog" for n > 1.5

~3 neutrinos in 200 ton.y

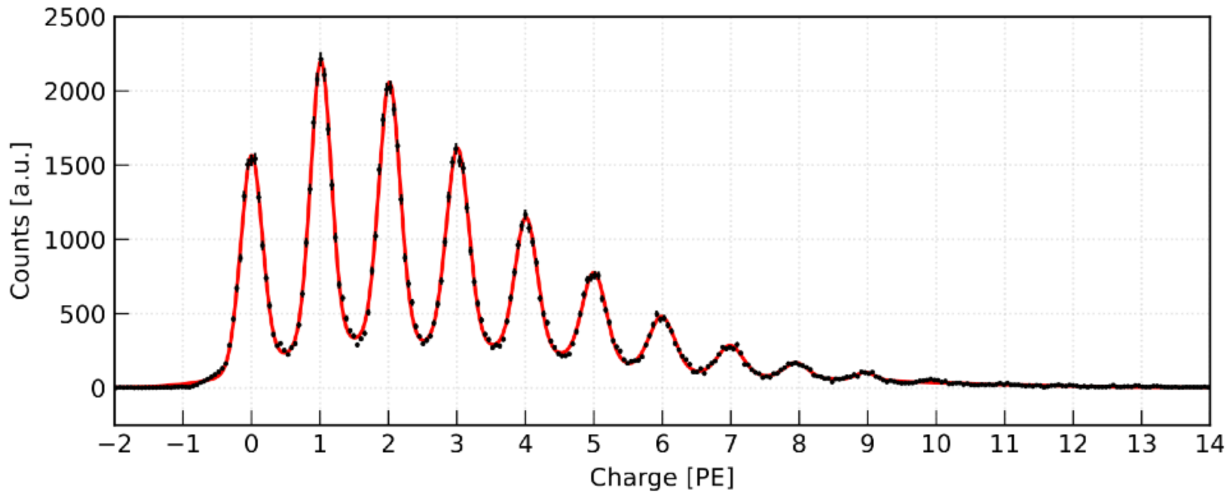


PDU: Laser Calibration and SPE

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.