Cryogenic Silicon-based photosensors: the Photon Detection Units for dark matter detection in DarkSide-20k

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on Behalf of the DarkSide Collaboration

TIPP 2023
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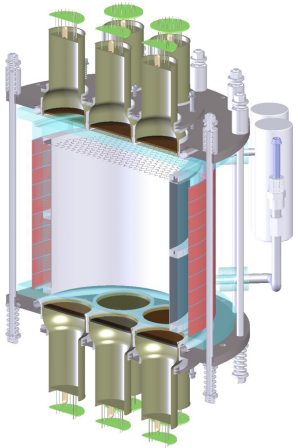
CTICC CAPE TOWN SOUTH AFRICA

Overview

- DarkSide program and DarkSide-20k detector concept
- Cryogenic SiPM development and measured performances
- Photon Detection Unit (PDU)
- PDU Test Facility in Naples
- PDU characterization

DarkSide program

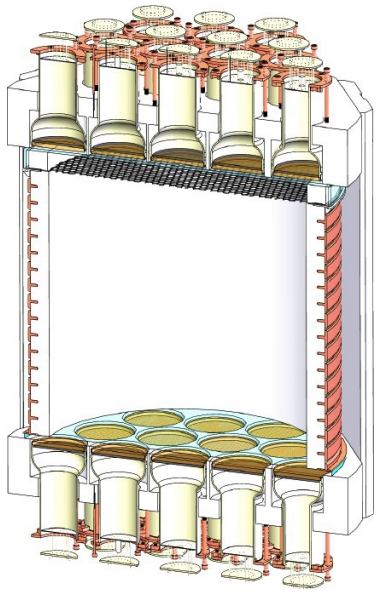
2012



DarkSide-10

- First prototype
- LY > 9PE/keV

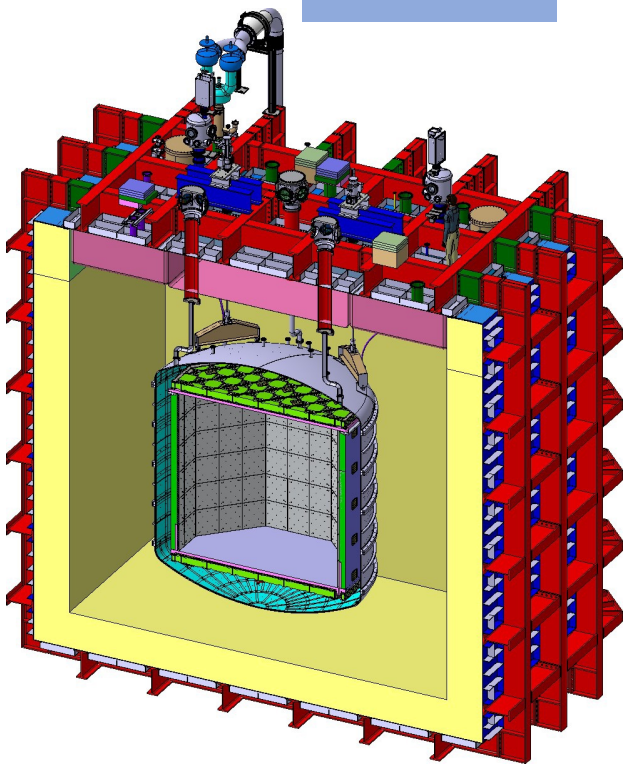
2013-2018



DarkSide-50

- Science detector
- First background-free results with UAr
- Best limits for low mass WIMP search

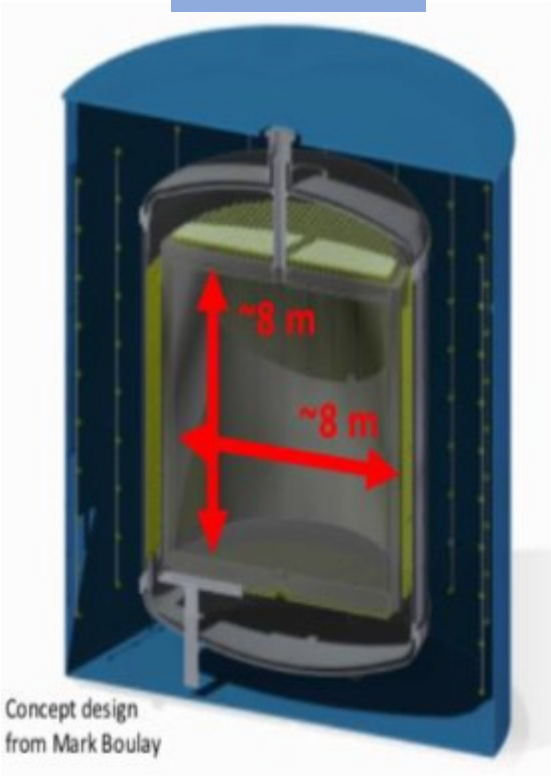
2026-2036



DarkSide-20k @LNGS

- Novel photosensor technologies
- Large scale use of UAr
- Nominal exposure: 200 t×y

2030s-…

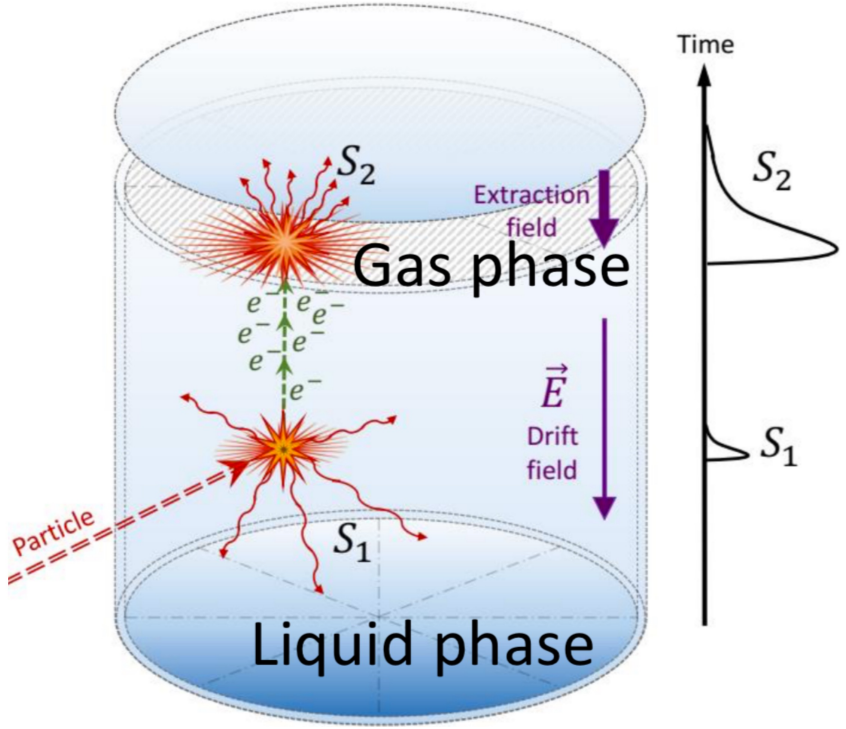


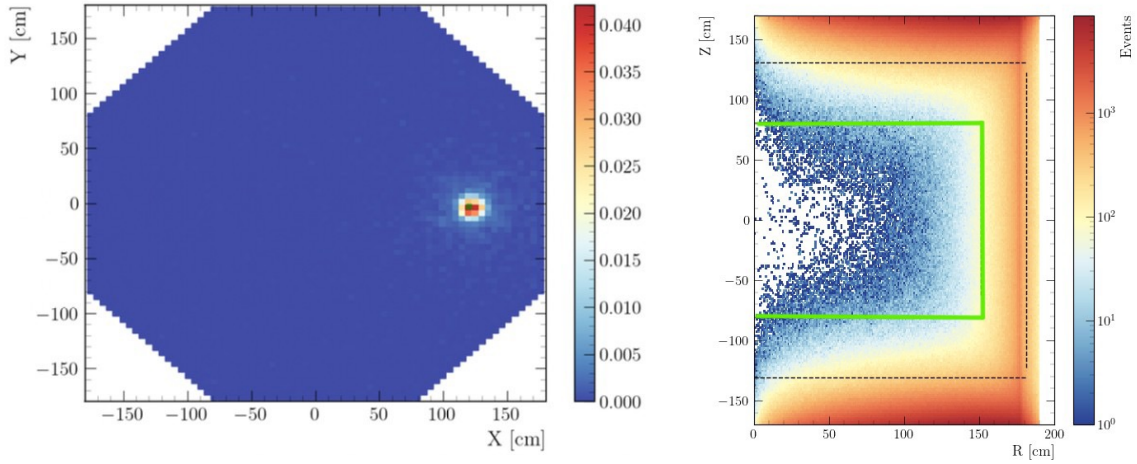
Argo@SNOLAB

- Ultimate LAr DM detector
- Nominal exposure: 3000 t×y

TPC dual phase

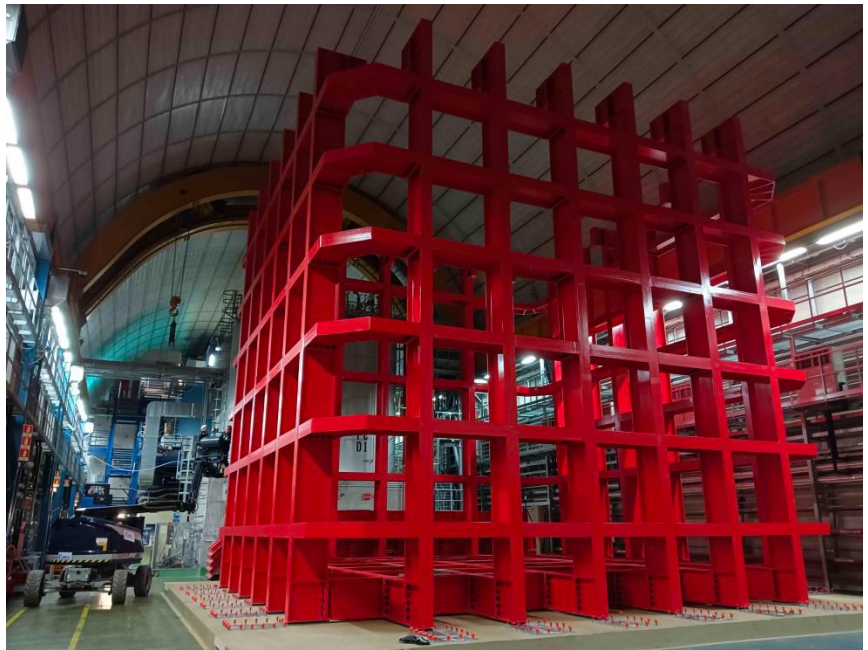
- Readout: two planes (top and bottom) of arrays of cryogenic solid state photosensors
- Incoming particle produces a flash of scintillation VUV light called S1
- Ionization created electrons drift to the anode plane, passing from the liquid to the gas phase
- Drift in gas phase produces large flash of VUV light (electroluminescence), called S2
- The scintillation in gas phase is proportional to extracted ionization charge
- Event 3D vertex reconstruction
  - XY determined by localizing S2 with the top photosensor array
  - Z is reconstructed via the arrival time difference between S1 and S2
  - 3D fiducialization is possible for background suppression
  - Multiple scattering rejection

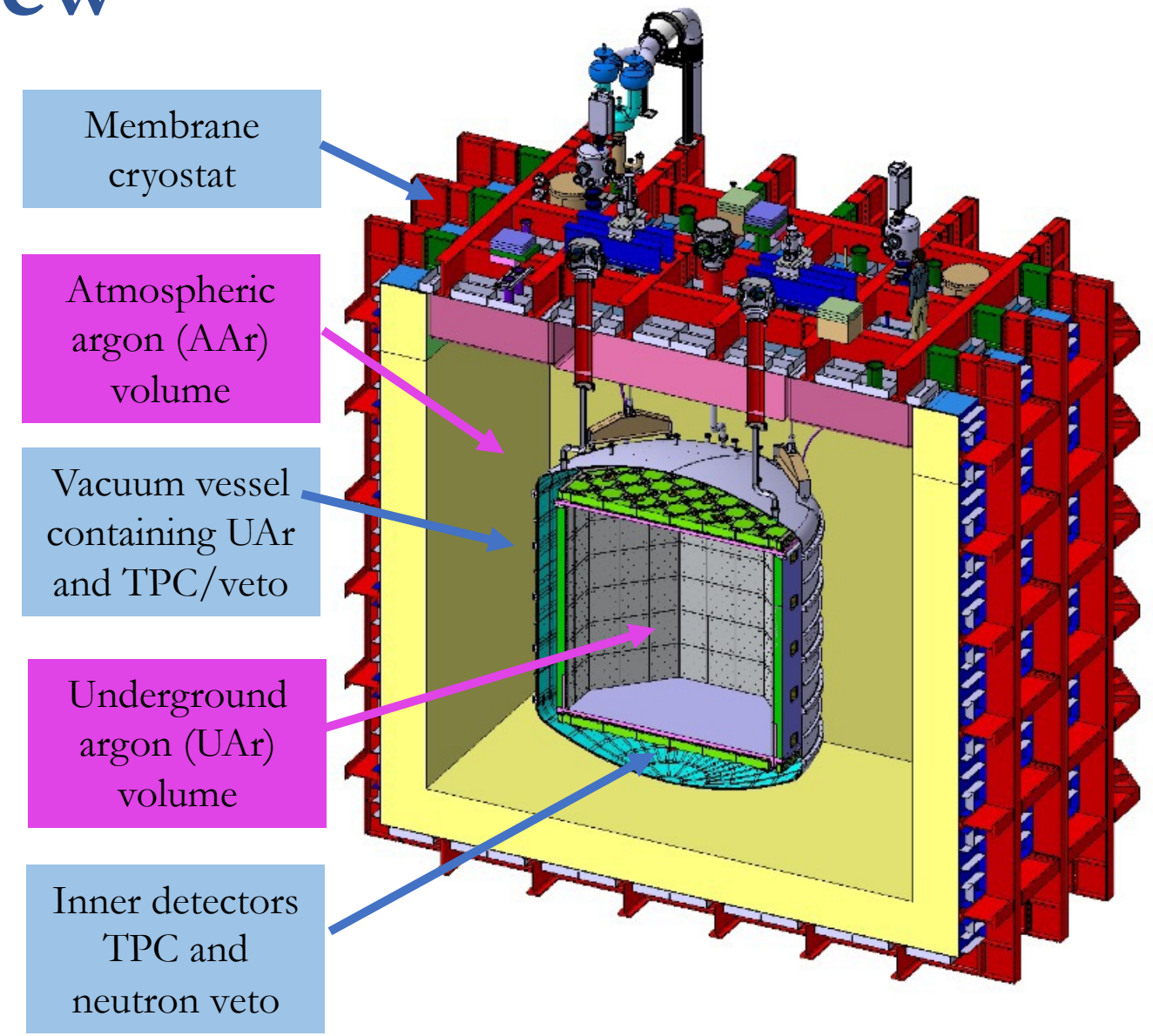




Darkside-20k overview

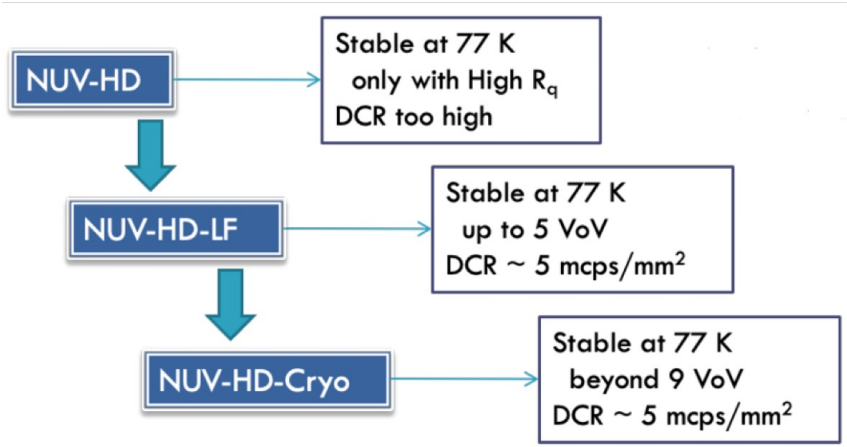
- Vessel housed within an atmospheric argon (AAr) volume maintained by a instrumented muon veto cryostate (8x8x8 m^3)
- Stainless Steel vessel separating AAr from UAr
- WIMP detector fiducial volume of ≈ 20 tonnes (≈ 50 tonnes total) of underground argon (UAr), depleted in ^{39}Ar. (Details in R. Santorelli talk yesterday)
- Active neutron veto integrated into the TPC structure via gadolinium-loaded acrylic
- Silicon photomultilier (SiPM) based photo detection (total area ≈ 26 m^2)





DarkSide-20k SiPM design and requirements

Development of new SiPMs, suitable for production of large area SiPM working in LAr temperature, in collaboration with Foundation Bruno Kessler (FBK) started in 2014.



Specs for SiPM & Electronics:

- Single SiPM size ~cm^2.
- PDE (420 nm) >40%.
- Dark Count Rate (77K) <0.1 Hz/mm^2.
- S/N (87K) >8.
- Time resolution <30ns.
- Gain >10^6.
- Dynamic Range >50.
- Compact & radiopure

Three technological steps based on different doping profiles.

- Near UltraViolet High Density SPADs
- NUV-HD-LF
- NUV-HD-Cryo.

Selected technology: NUV-HD-Cryo, most suitable for DarkSide needs.

Measurements provided by FBK

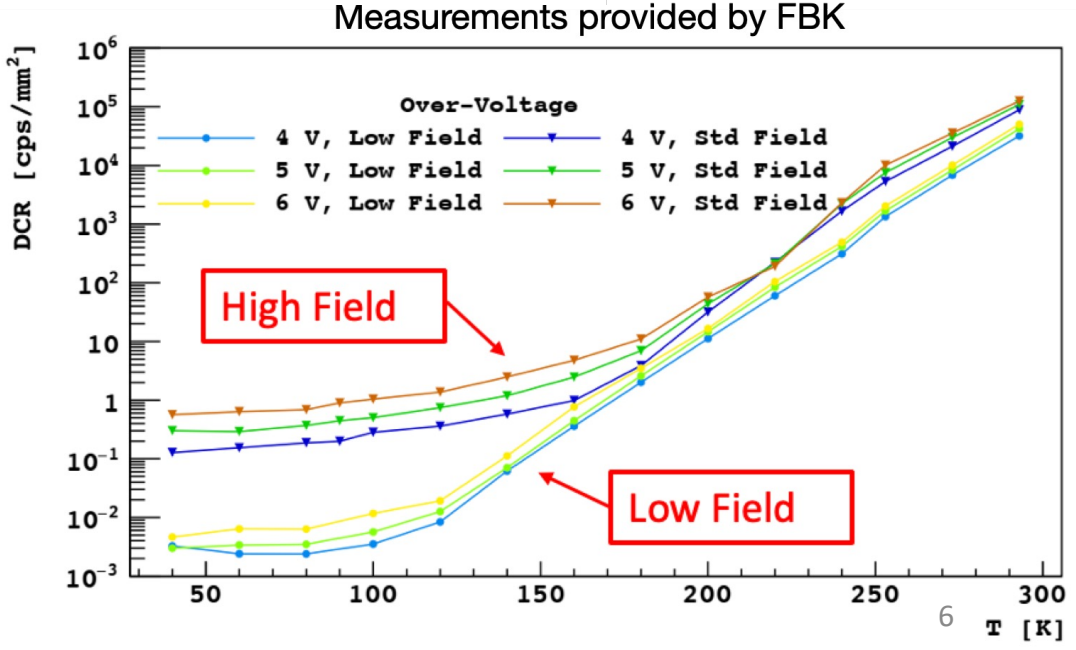
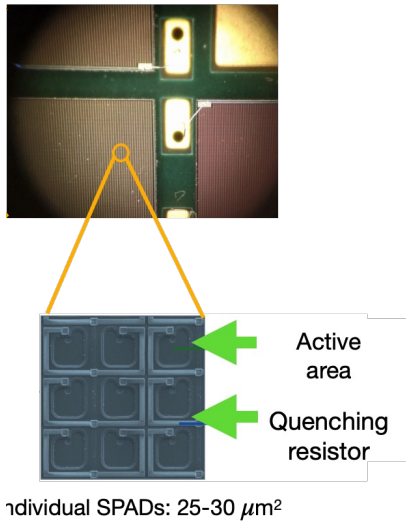


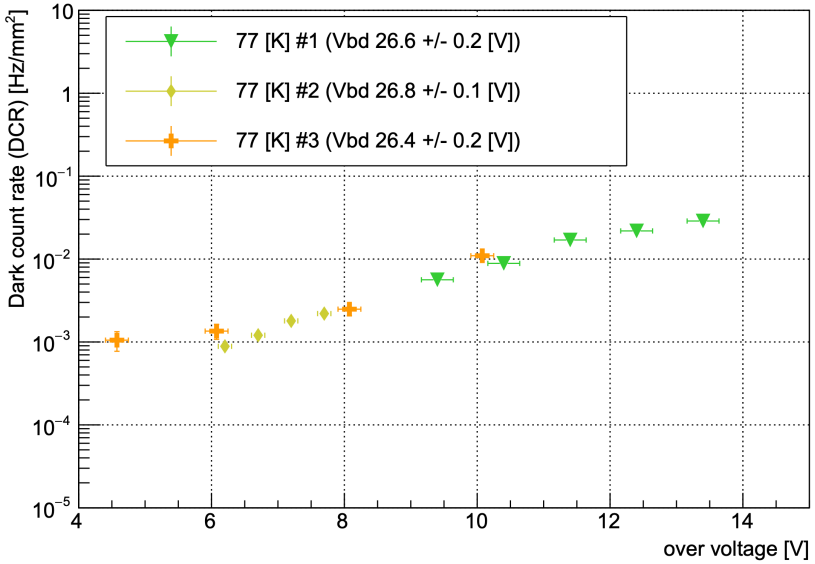
Figure of merit for DarkSide-20k SiPMs

Single SiPM: 12 x 8 mm²

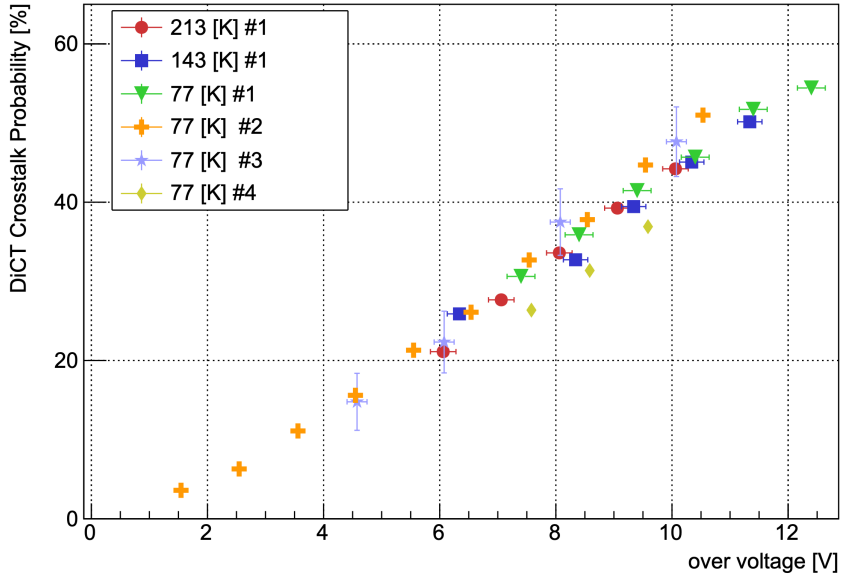


ndividual SPADs: 25-30 μm^2

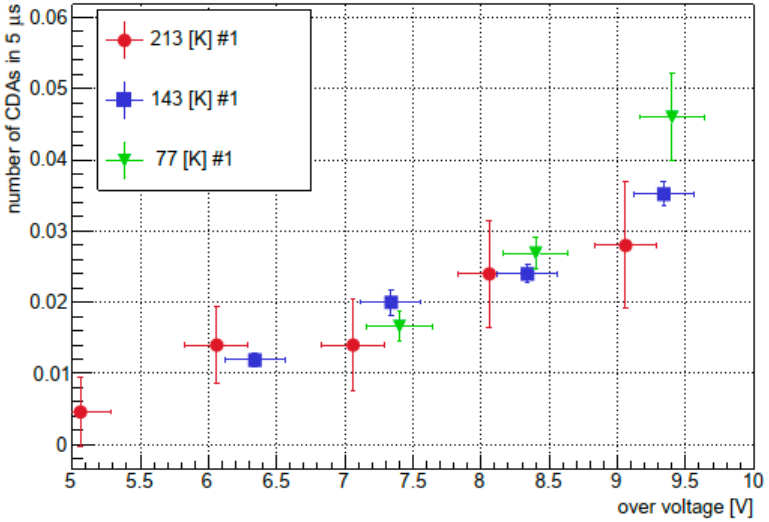
Dark Count Rate



Direct Cross Talk

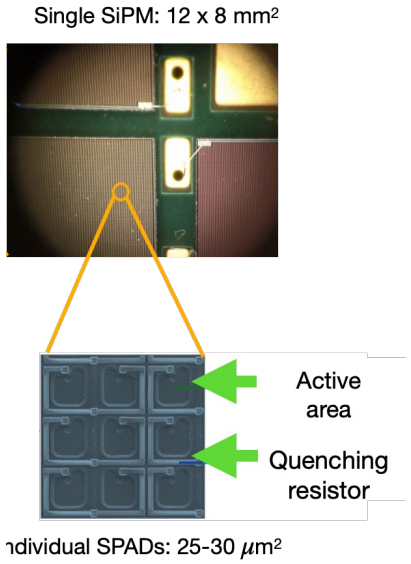


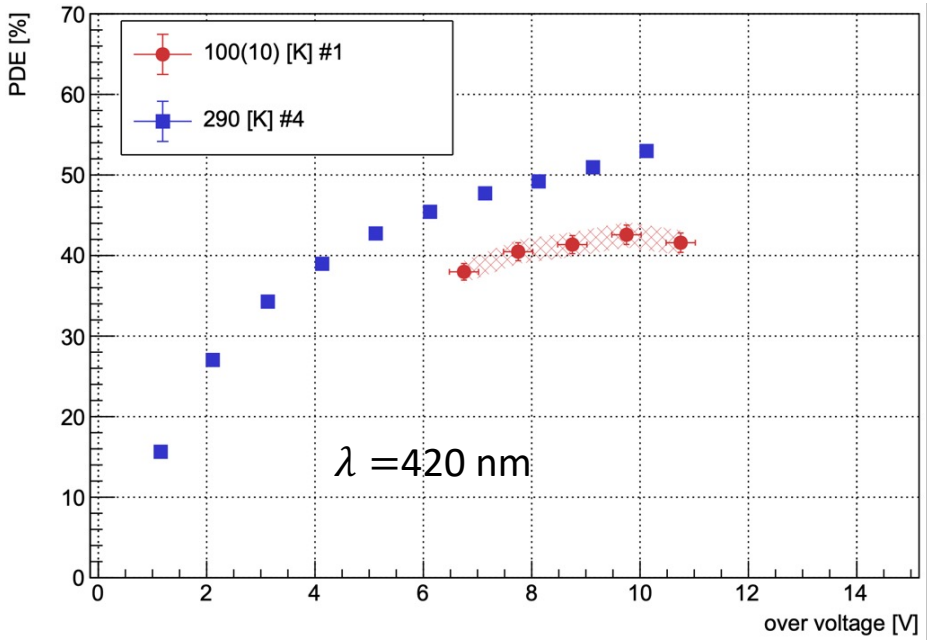
Afterpulse in 5 us

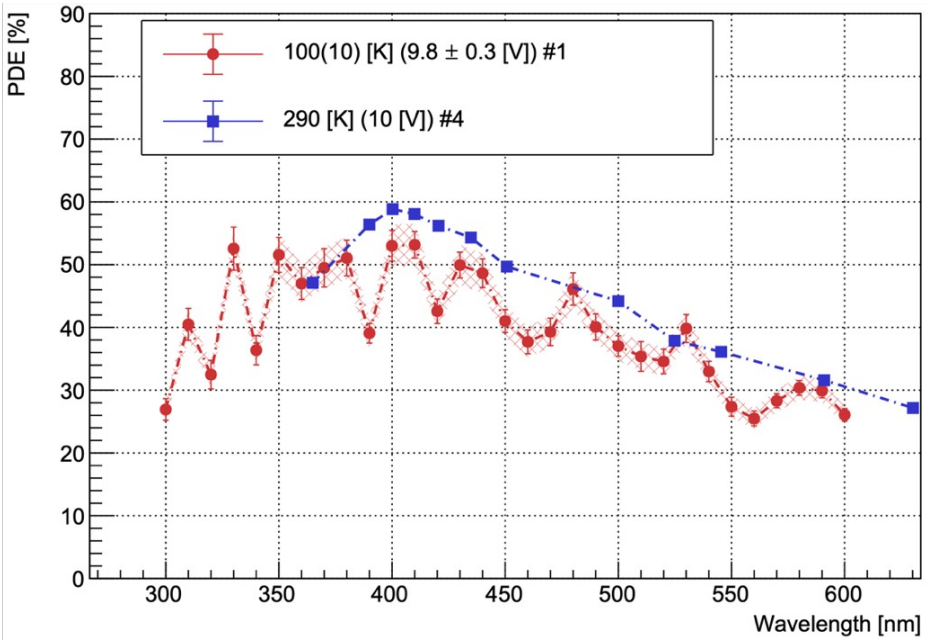


The 24 rectangular SiPMs (12x8 mm2) assembled in one 5x5 cm2 tile. Coupled with Front End Board (**Photo Detecting Module**)

Photon Detection Efficiency for DarkSide-20k SiPMs





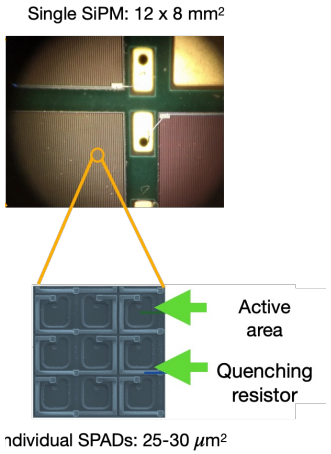


Measured at TRIUMF with a dedicated system to determine the PDE at cryogenic temperatures

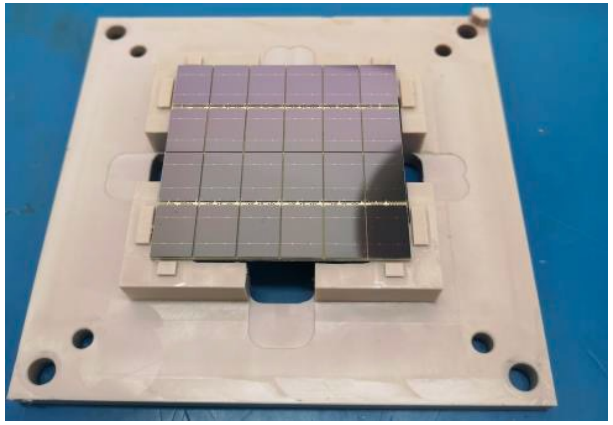
Photon Detection Unit

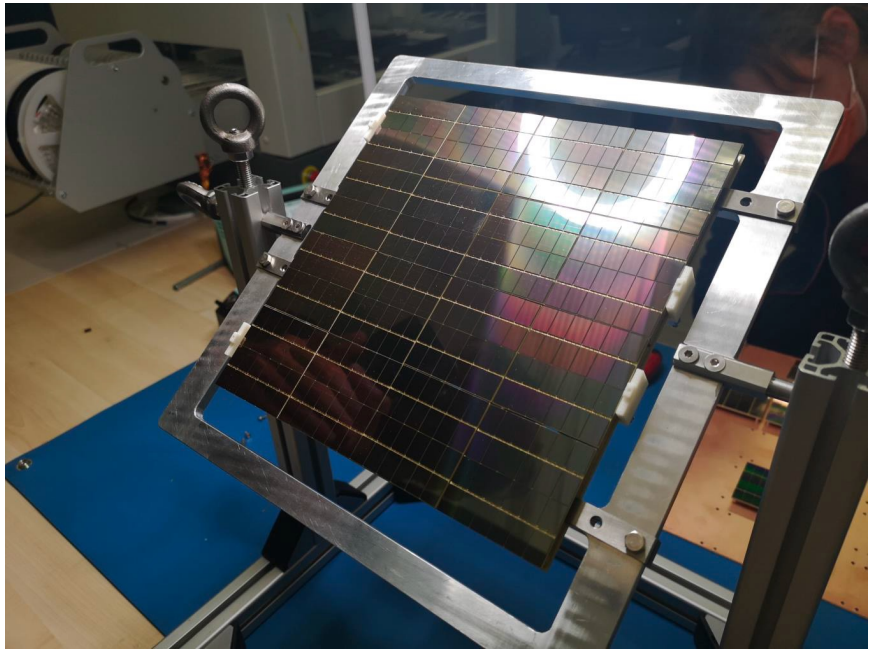
PDU: 20 x 20 cm²

Single SiPM



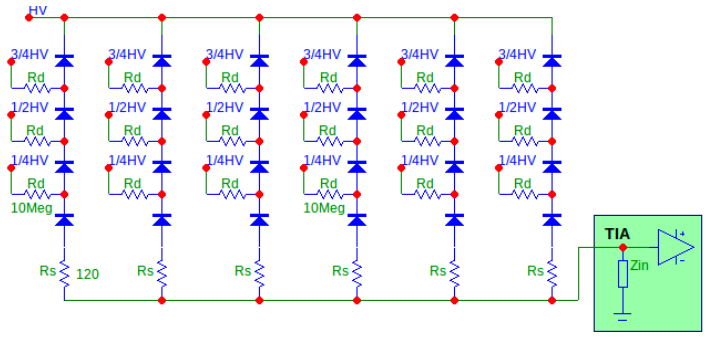
PDM: 5 x 5 cm²

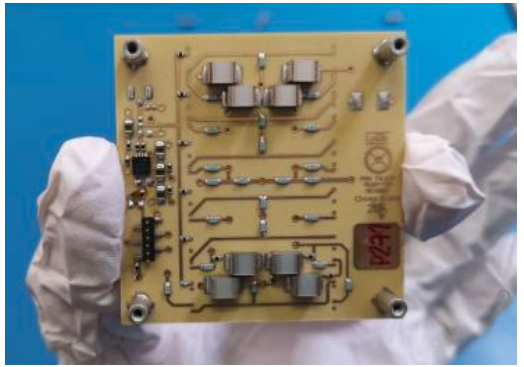




PDU: 16 PDMs size 20x20 cm². with an overall weight of ~ 0.4 kg.
No single PDM readout. Four PDMs (1 Quadrant) are summed in one channel (100 cm²).
PDU has 4 output channels

Cryogenic front end electronics:
Series/Parallel ganging **4s 6p**
PDM+front-end integrated in a unique PCB

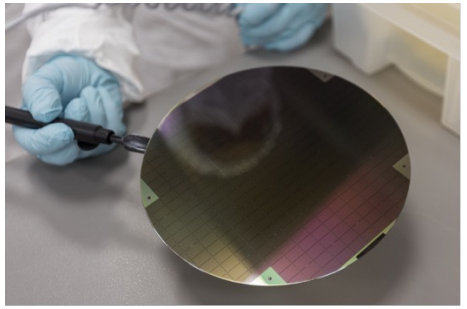
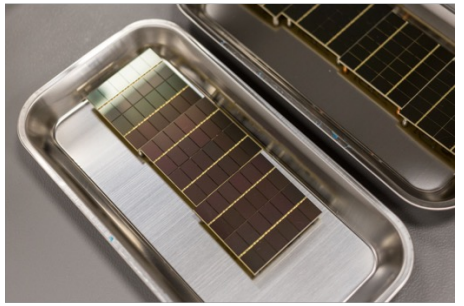
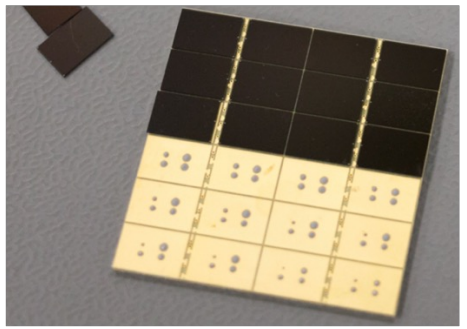




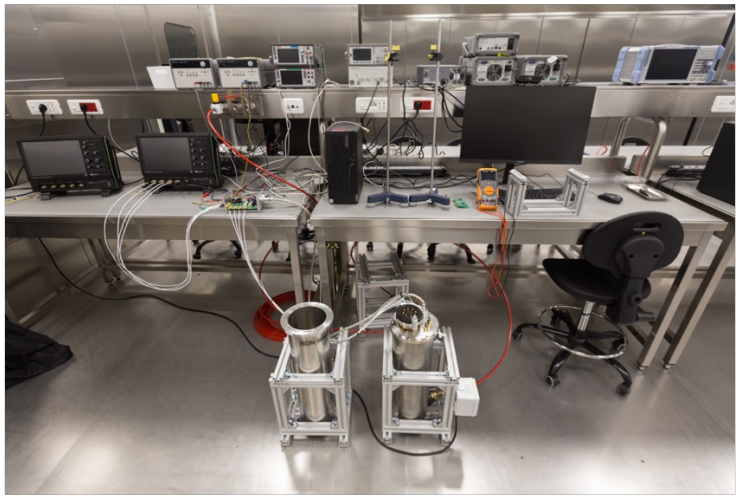
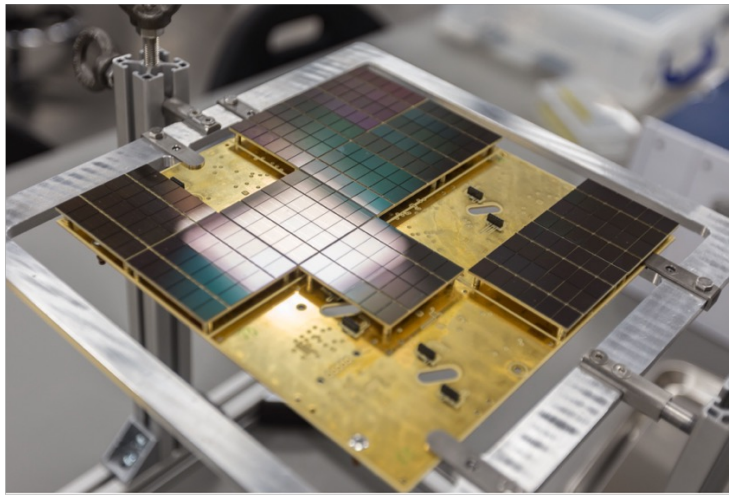
DarkSide-20k NOA

Nuova Officina Assergi (NOA) dedicate ISO6 Clean Room (420 m^2) at Laboratori Nazionali del Gran Sasso (LNGS), Italy.

- **1400 raw wafer, produced by LFoundry**. Tests in cryo-probe machine are ongoing. 15% done, to be completed in Q3 of 2024.
- **Dicing** of the wafer to cut the it in 268 single SiPMs (12x8 mm^2).
- Fully Automated **Flip-chip bonder** to assemble PCB with 24 individual SiPMs.
- **Wire-bonder** to make an electrical connection of individual SiPMs.
- Test measurements of IV and SPE (@LN) for all tiles in two identical dedicated setups (8 tiles a batch).
- Assembly of the **528 PDUs** (from Feb 2024, ~60-70 weeks) and shipping to Naples PDU test Facility (PTF) for full test in Liquid Nitrogen

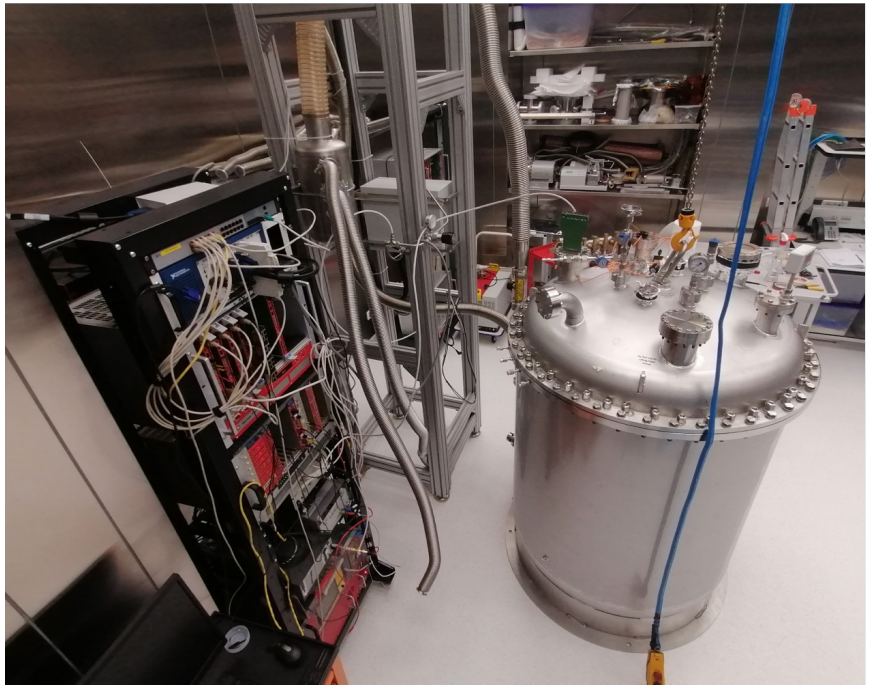
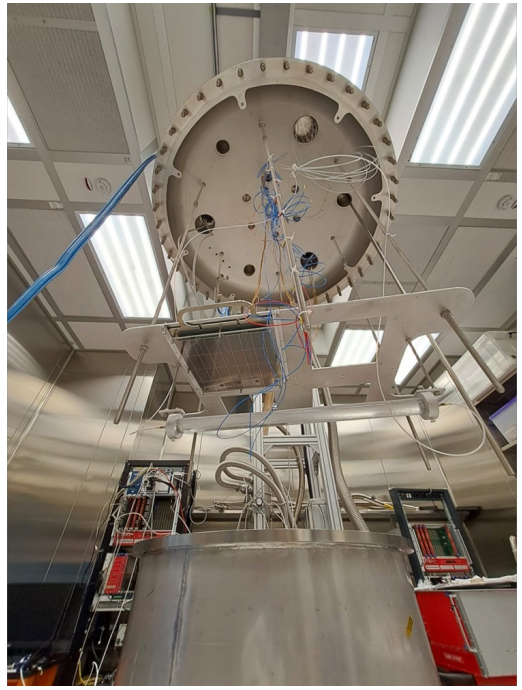






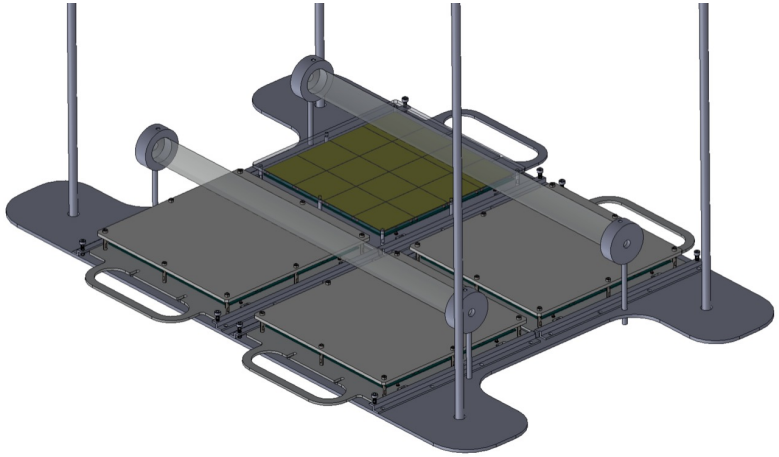
Naples PDU Test Facility

The Naples PDU Test facility (PTF) is composed of ~800L double wall cryostat with domed top flange, coupled with custom cryogenic system. Vacuum insulated inlet and outlet lines for LN and cold vent. Custom Cold Box. External LN storage plant with 3000L tanks.

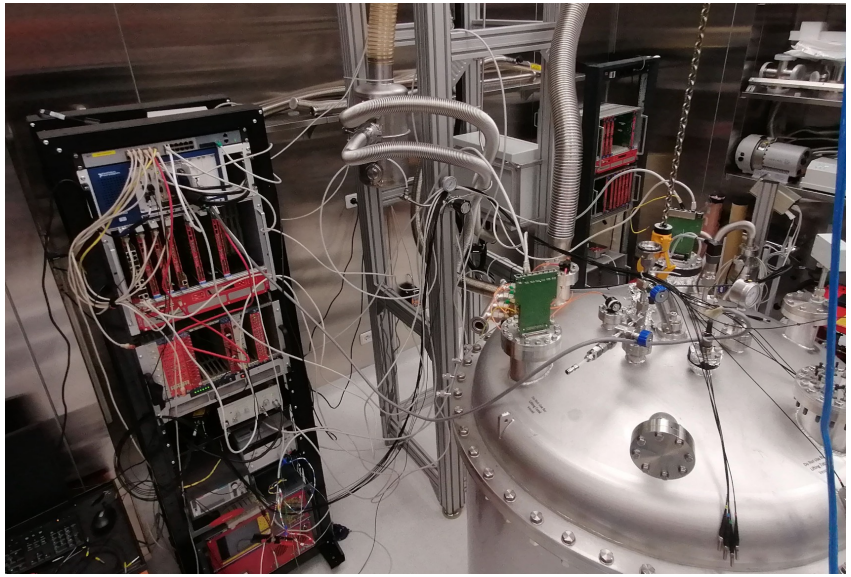




ISO6 50m^2 clean room for PDU handling and LN characterization.
Fully automated process of FILL, DRAIN and constant level maintenance over the period of testing (evaporation rate of 0.2 cm/h).

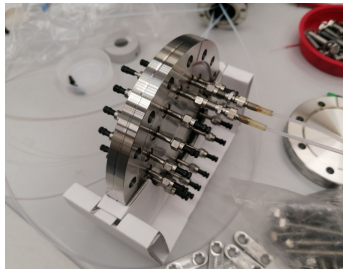
Naples PDU Test Facility



Mechanical structure composed of four floors to host 4 PDUs each (16 in total). Full integration with light distribution system.



Electronic rack with Caen mainframe for the Power Supplies board, VME crate for VX2740 ADCs, NIM crate with trigger logic formation unit and laser unit



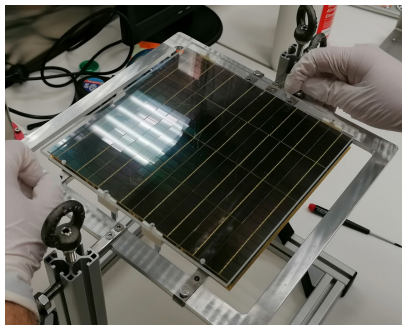
Optical feedthrough

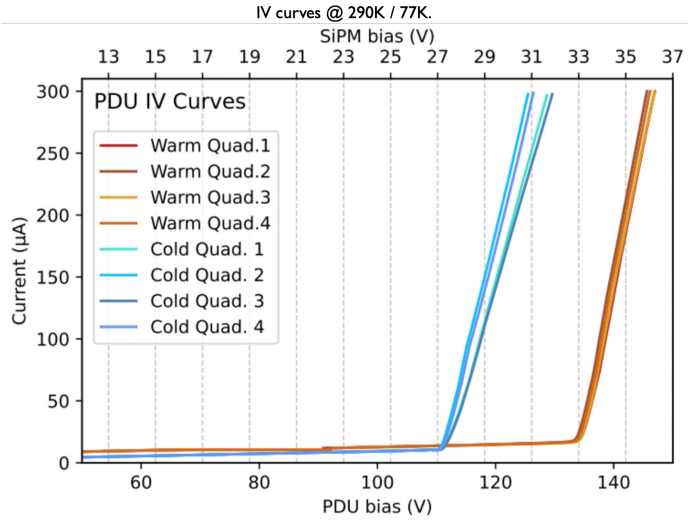
1st PDU Test Results

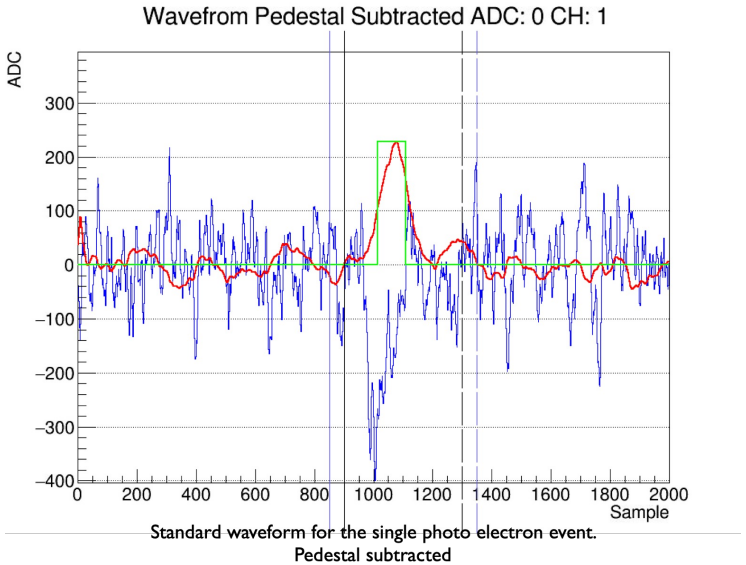
May - June of 2022: first intense LN testing campaign of fully populated PDU prototype (4 weeks).

Full characterisation in terms of:

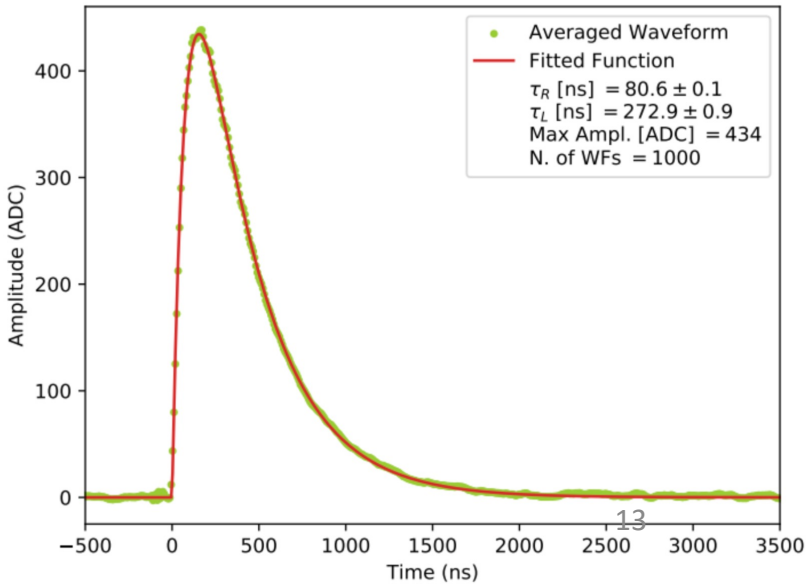
- breakdown voltage
- pulse shape of single photoelectron
- response of single photoelectron,
- gain, amplitude and charge spectra
- signal-to-noise ratio (on quadrant bases, 4 tiles summed)
- Stability of the PDU parameters in time, on a ~ month scale.







Standard waveform for the single photo electron event.
Pedestal subtracted

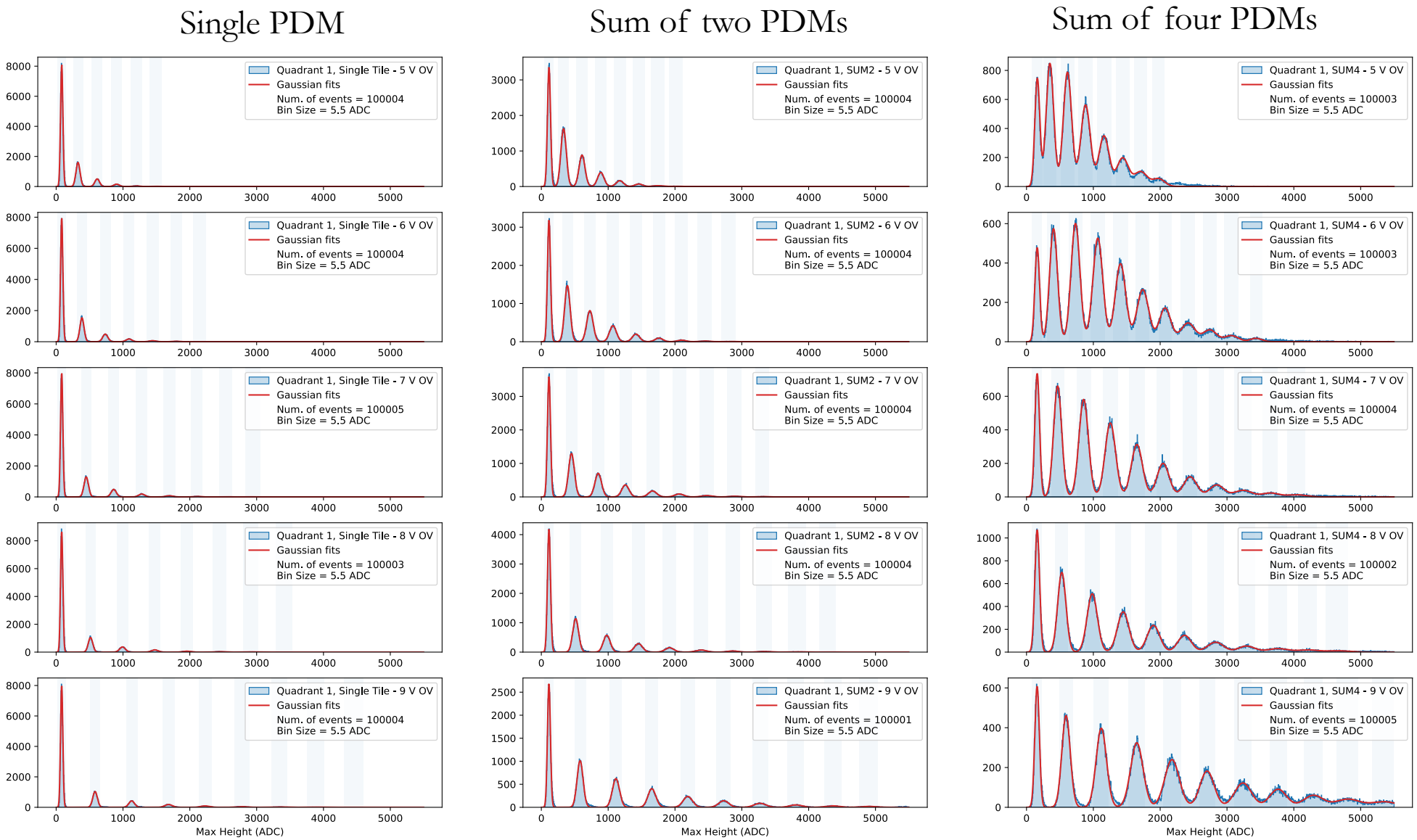


Single Photo-electron Response

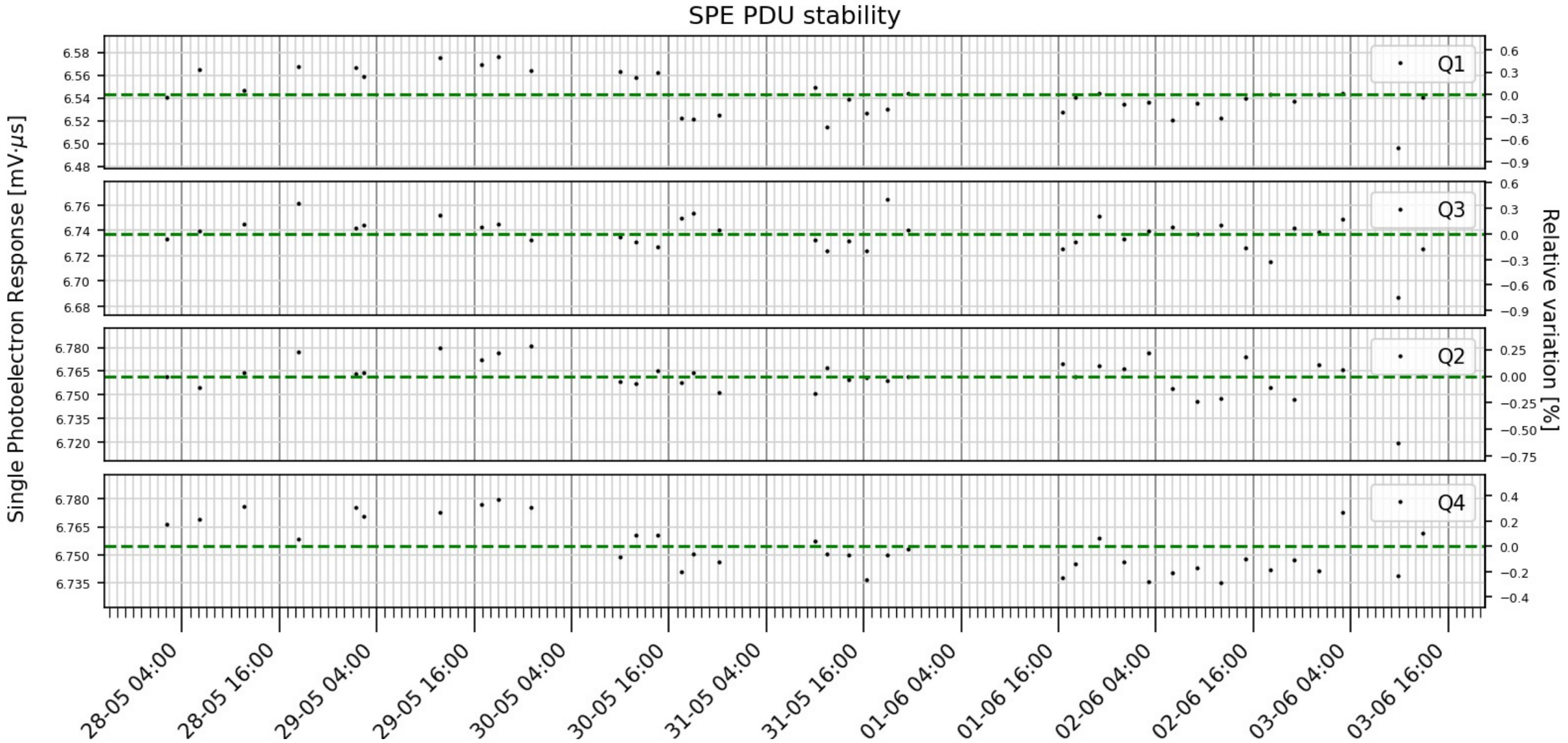
The SPE response for sum of: 1 PDM, 2 PDMs or 4 PDMs

Different values of OV: 5V – 9V

Resolution single PE: σ_{PE} / A_{PE} : ~13 %.



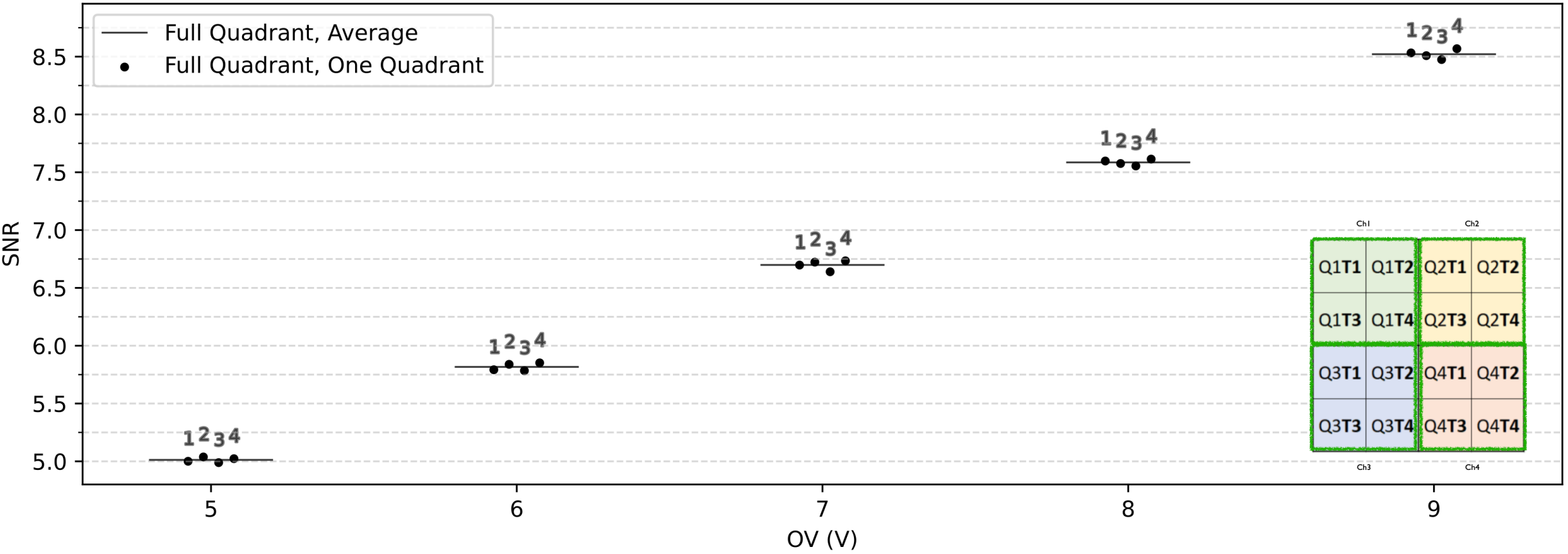
SPE stability



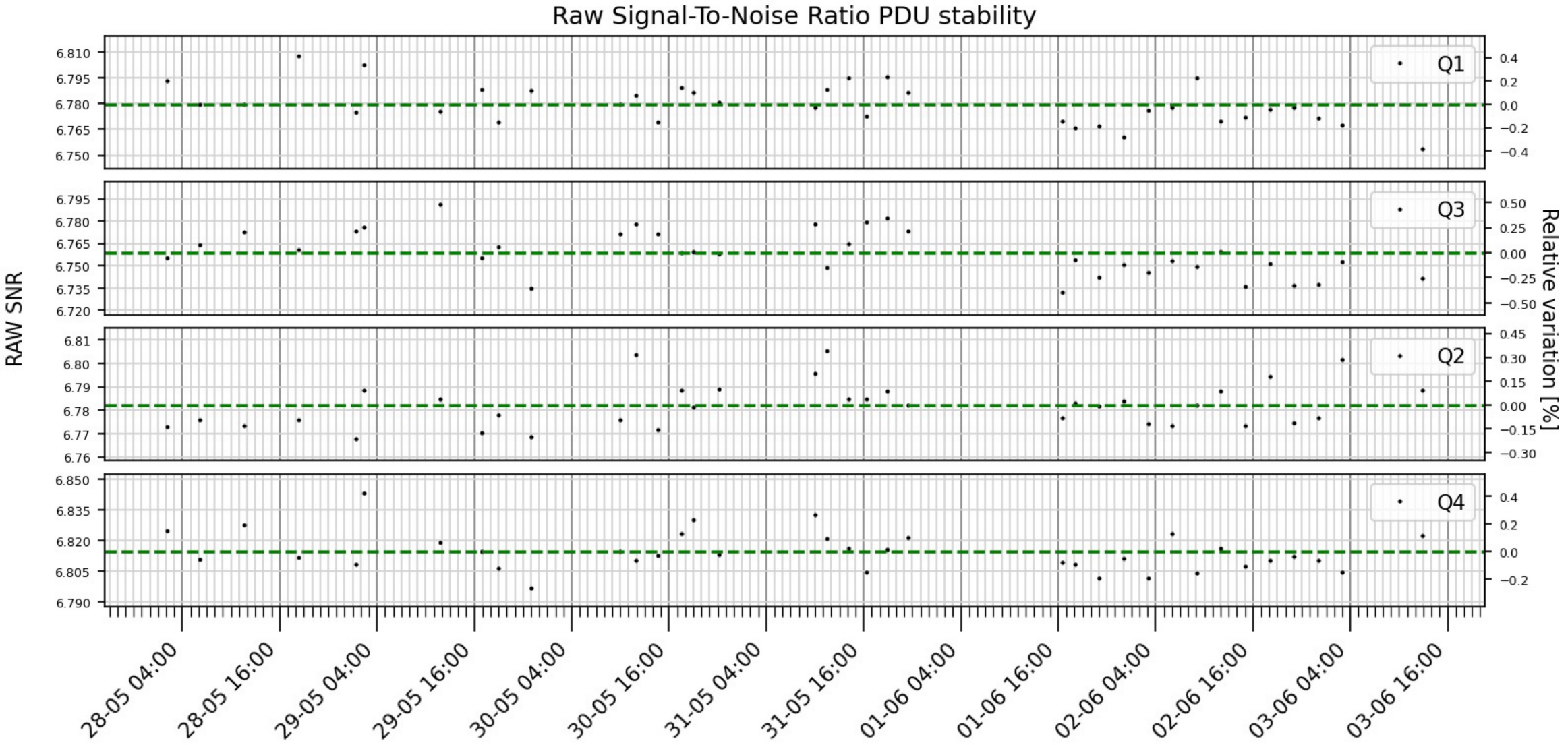
Signal to Noise Ratio

Raw SNR for all quadrants, in range from 5 (@5V VOV) to 8.5 (@9V VOV).

Raw SNR: A_{1PE} / RMS_{BL}



SNR stability



Conclusions

- DarkSide-20k experiment for direct WIMP search will use cryogenic SiPM-based optical readout
- NOA has produced the first PDU prototype, a pre-production of 10 PDU will be performed by the end of year. **Production of PDUs will start in 2024.**
- The PDU Test Facility in Naples is ready to start testing and qualifying the PDUs
- Test results of the first prototype showed excellent performance meeting the DarkSide-20k requirements

Back-up slides

DS-20k Experimental Project Summary Timeline