Photodetection at cryogenic temperatures

Inés Gil Botella - CIEMAT Madrid

7th International Workshop on new Photon-Detectors

PD 2025 Bologna, Dec 5, 2025

7th international workshop on new Photon-Detectors

PD 2025 **3-5 December 2025**
Bologna, Italy

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Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Plan de Recuperación, Transformación y Resiliencia

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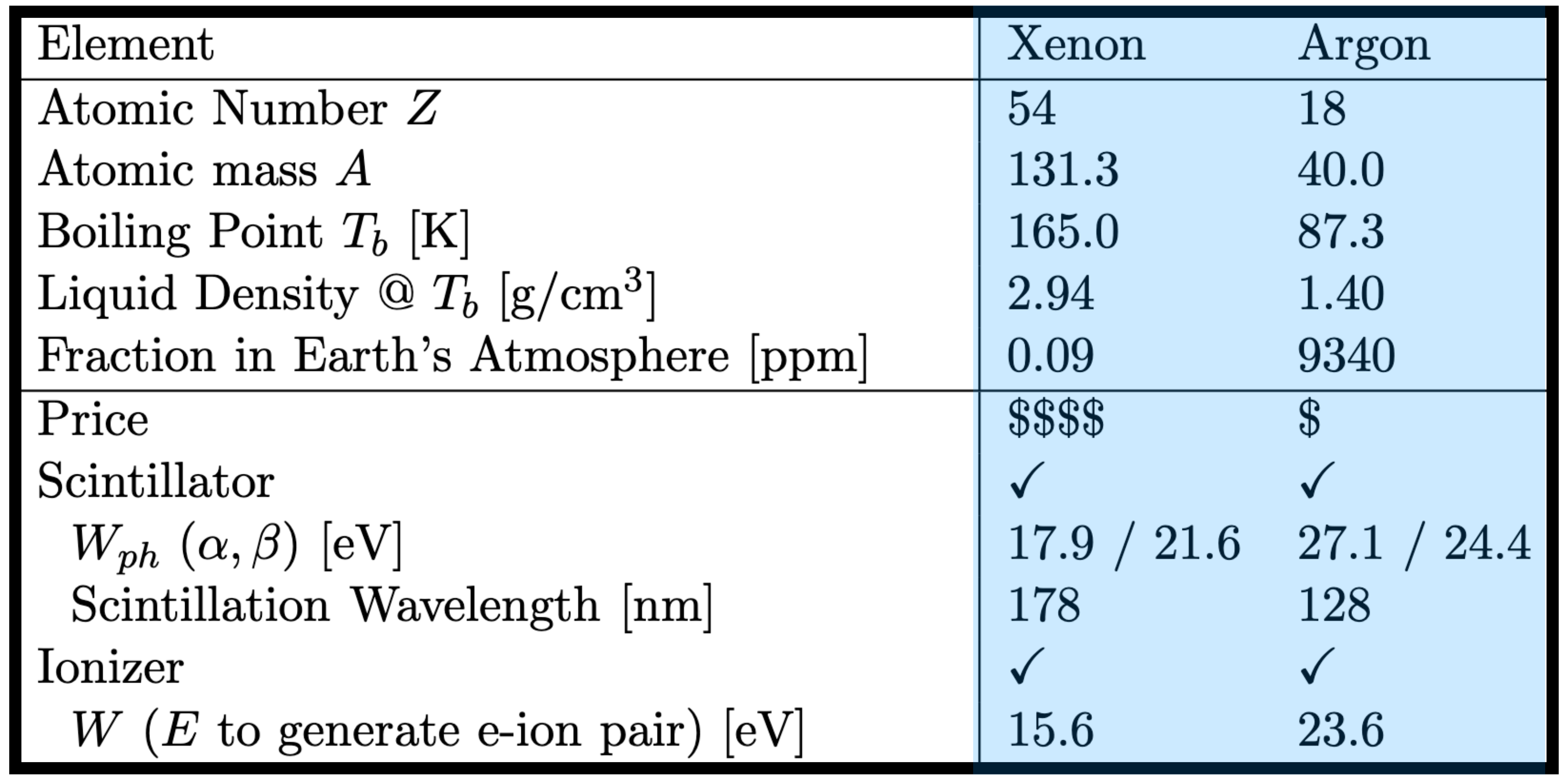
AGENCIA ESTATAL DE INVESTIGACIÓN

Outline

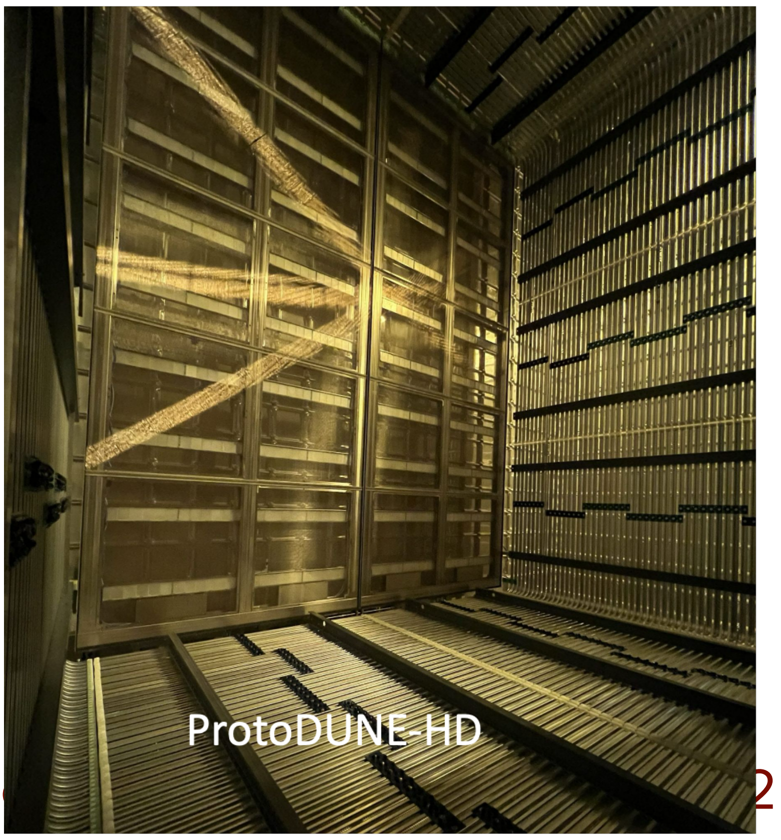
- Photodetection requirements for cryogenics detectors
- Cryogenic photosensor developments
- Photon detection system optimization
- R&D directions and prospects

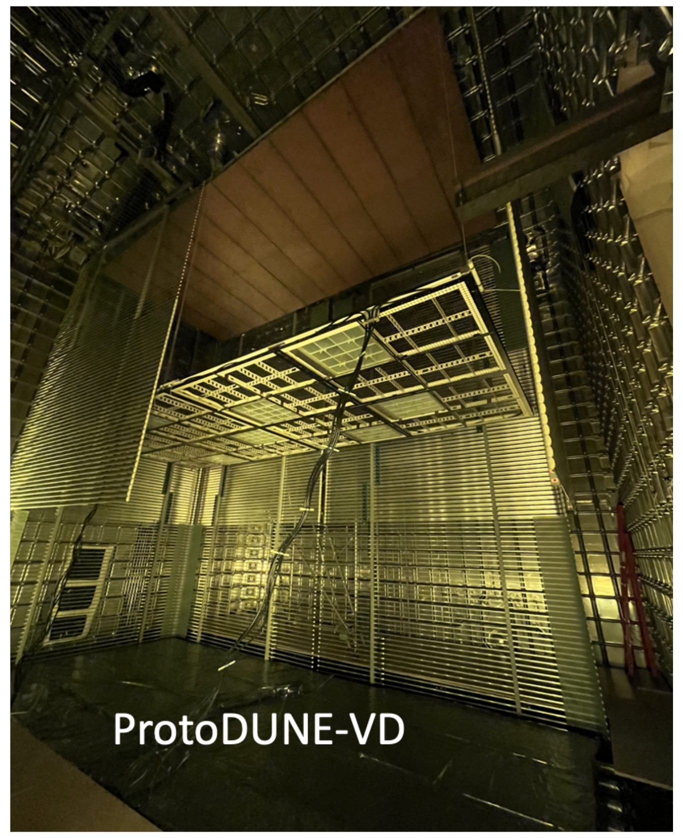
Cryogenic detectors for neutrinos & DM

- Mainly liquid noble gases: LAr/LXe TPCs
  - LXe: XENONnT, LZ, PANDAX-4T, (XLZD), EXO-200 (nEXO)
  - LAr: DEAP-3600, DarkSide-50 (DS-20k), (ARGO), ICARUS, MicroBooNE, SBND, ProtoDUNE (DUNE)



Element	Xenon	Argon
Atomic Number Z	54	18
Atomic mass A	131.3	40.0
Boiling Point T_b [K]	165.0	87.3
Liquid Density @ T_b [g/cm^3]	2.94	1.40
Fraction in Earth's Atmosphere [ppm]	0.09	9340
Price	$$$$	$
Scintillator	✓	✓
W_{ph} (α, β) [eV]	17.9 / 21.6	27.1 / 24.4
Scintillation Wavelength [nm]	178	128
Ionizer	✓	✓
W (E to generate e-ion pair) [eV]	15.6	23.6

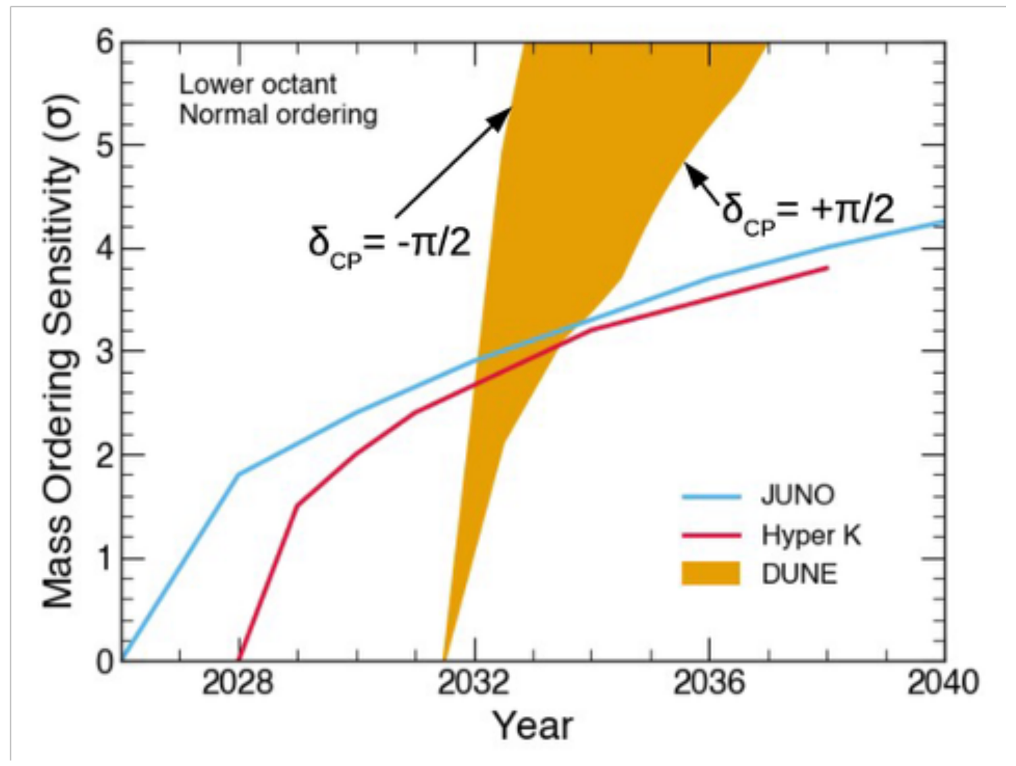


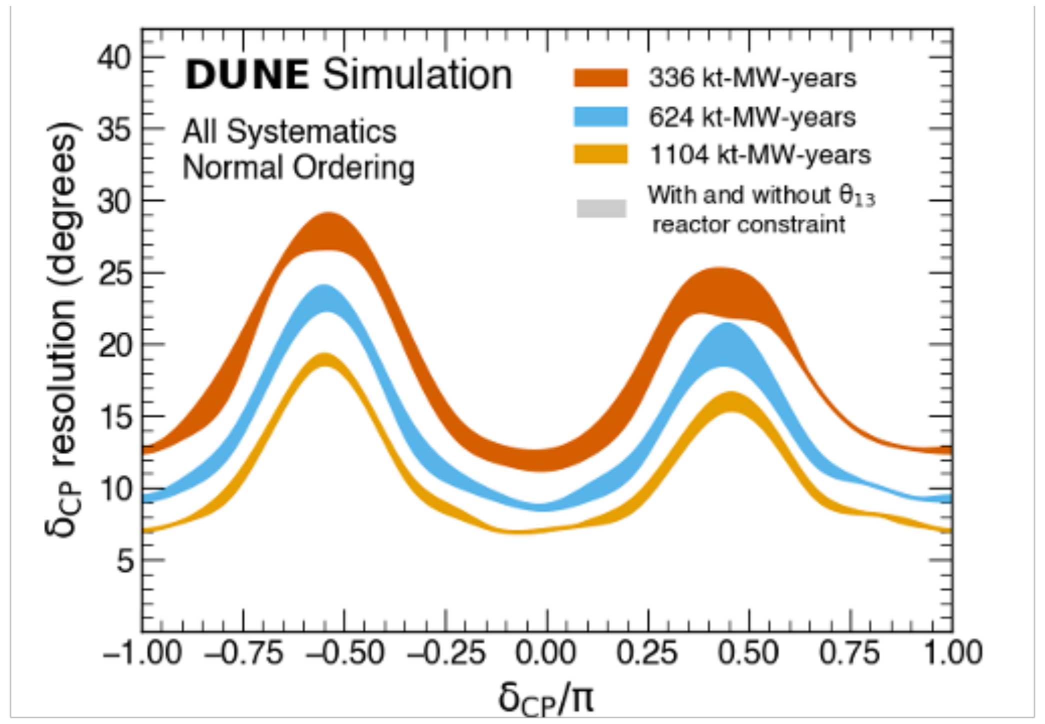


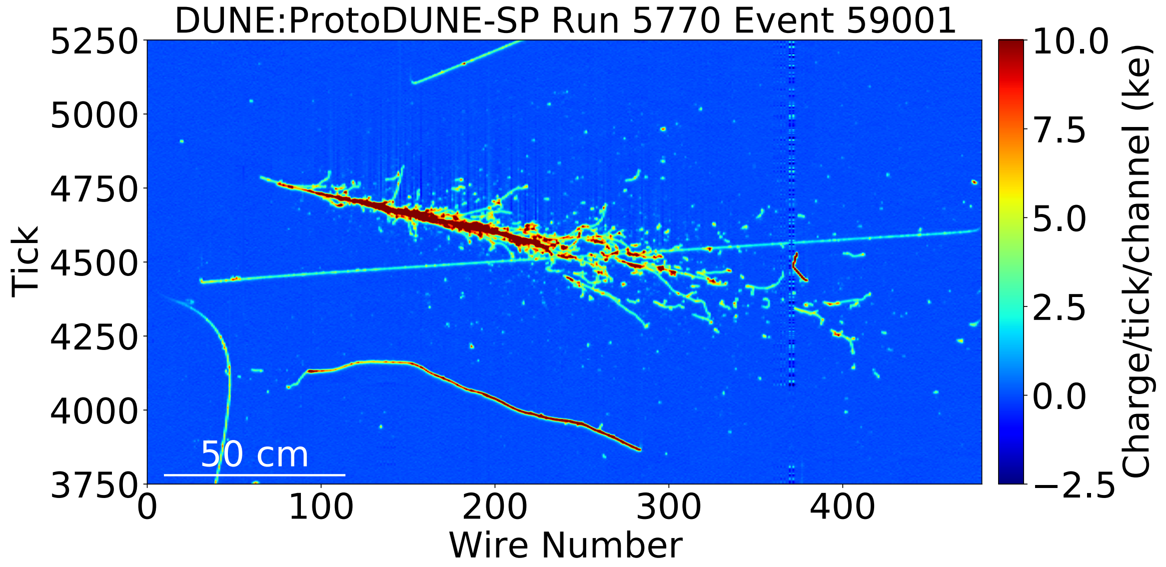
Large noble liquid neutrino detectors

Broad physics program:

- Precise long-baseline neutrino oscillation measurements:
  - Neutrino mass ordering
  - CP violation
  - PMNS unitarity
- Astrophysical neutrinos
  - Supernova and solar neutrino detection
- Beyond Standard Model searches
  - Nucleon decay, HNL, sterile neutrinos, CPT violation, non-standard interactions, dark matter…







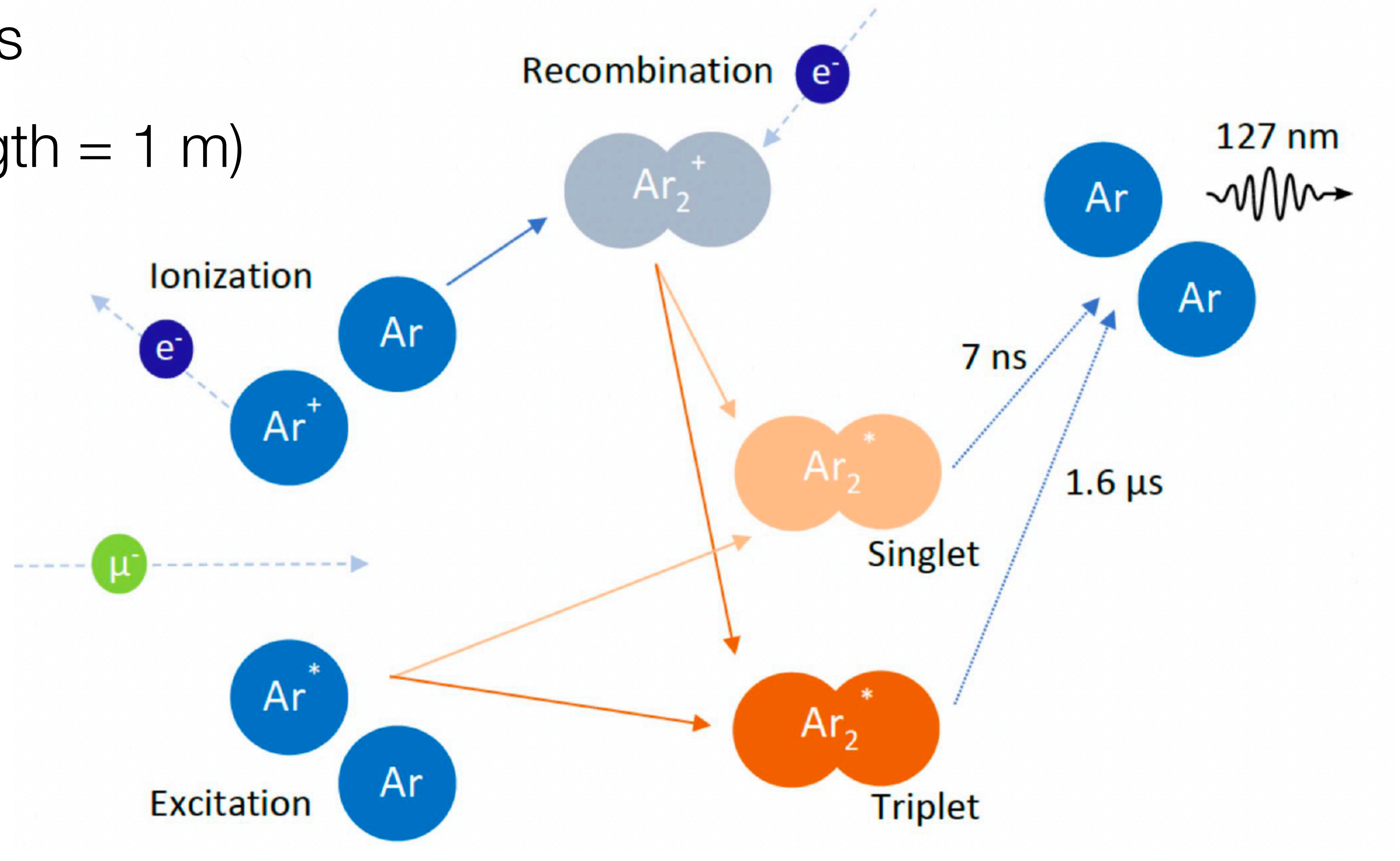
- **Detector requirements**:
  - Large mass detectors
  - Excellent energy resolution
  - Excellent 3D imaging
  - Tracking capabilities
  - Particle identification… over a wide energy range

- Detector **challenges**:
  - Large cryogenic vessels
  - Liquid purification
  - Very high-voltage system
  - Low noise cold electronics
  - VUV scintillation light detection

PDS requirements in LArTPCs for ν detection

- Photodetectors are key systems in LArTPCs with the goals:
  - Provide the drift coordinate of the interaction (t_0) → needed for correct estimation of the energy with the TPC
  - Provide trigger for non-beam events (SNB, solar neutrinos, cosmics, BSM…)
  - But also, PDS could be used to provide calorimetric info and veto cosmics or external backgs
- LAr is an excellent scintillator:
  - ~40,000 photons/MeV @127 nm; fast prompt signal ~6 ns, slow signal ~1.4 us
  - Transparent to its own light (absorption length = 20 m; Rayleigh scattering length = 1 m)
  - Possibility to be doped with Xe $\mathcal{O}$(10 ppm): improve light detection uniformity
- **Challenges**:
  - Be sensitive to **127 nm** (VUV) scintillation photons
  - Work in **cryogenics** environment for **long time**
  - Cover **large detector areas** in **difficult regions** (limited space, HV…)
  - **Match light** with **charge**

Talk by A. Balboni



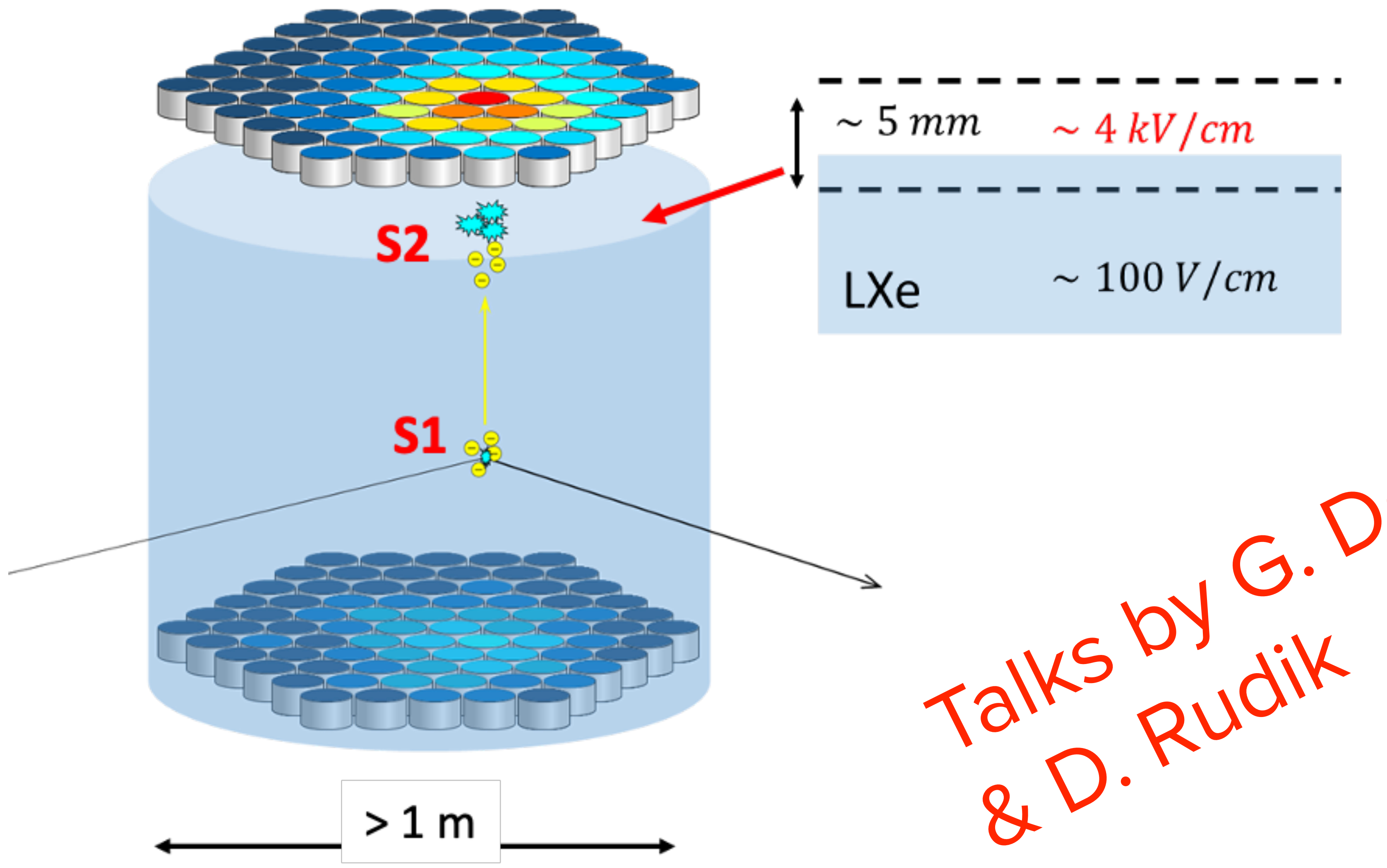
PDS requirements for dark matter (LAr/LXe)

- Dark matter detectors seek for any measurable effects in the target medium caused by the recoil events depositing their energy

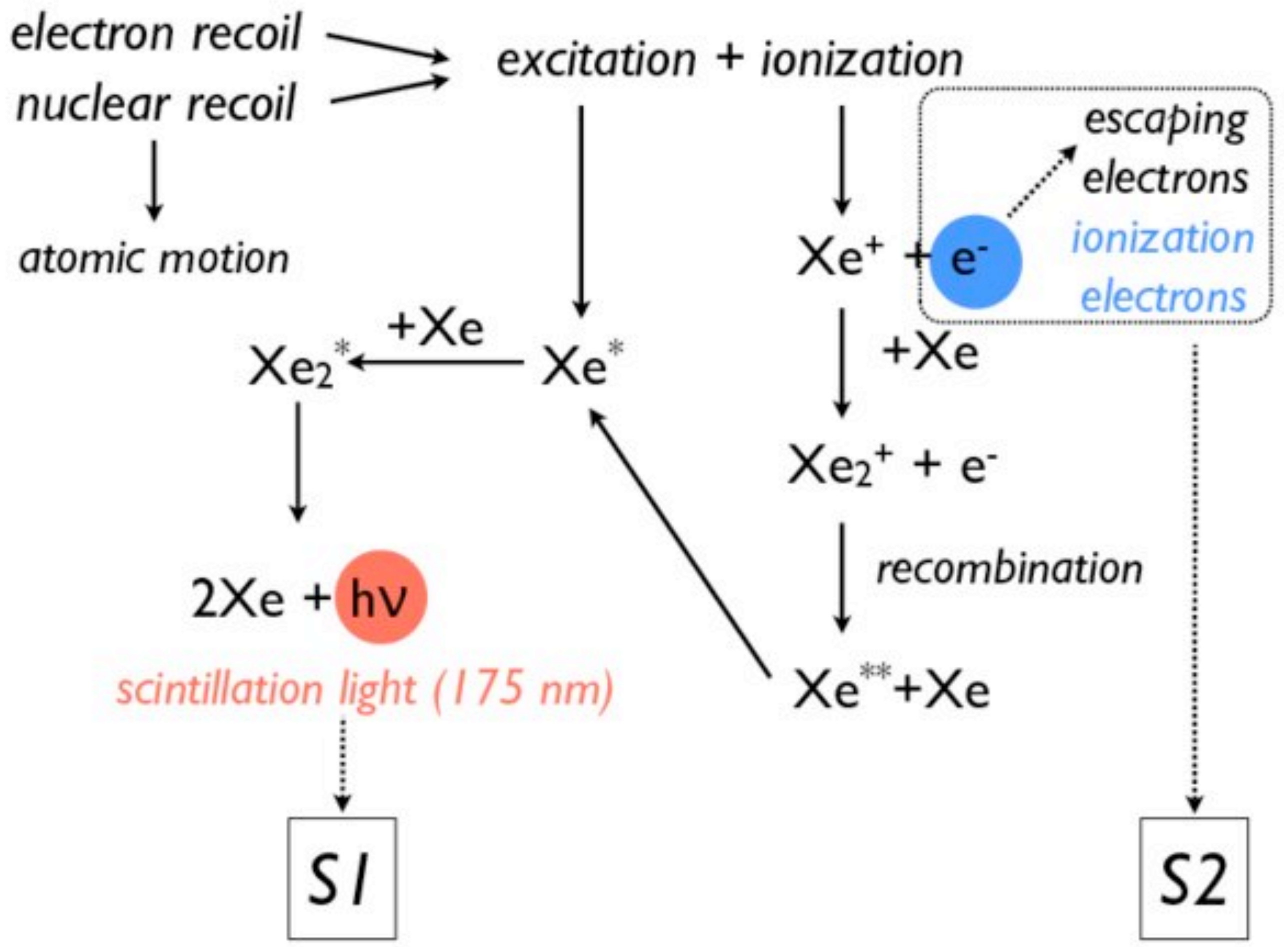
- LAr/LXe DM detectors: only optical measurement!

- Measurement of the two signals is the basis for electron/nuclear recoils discrimination
  - The threshold is determined by S1 (usually 2 or 3 phe are required in coincidence)
  - S2 provides energy and position in (x,y) – typically ~300 ph/e

- In addition to previous challenges, PDS needs low background, low noise photosensors
  - In the case of LXe: sensors sensitive to 175 nm at 165 K



Talks by G. De Rosa & D. Rudik

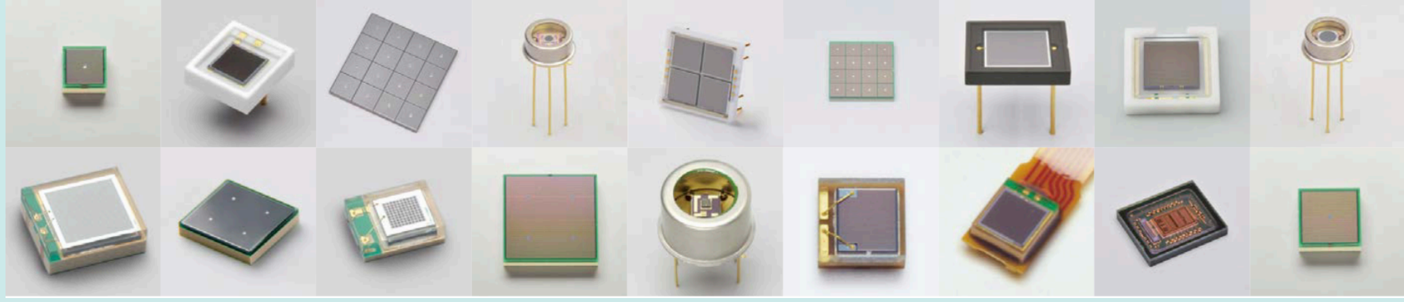


Cryogenic photosensors developments

Cryogenic photomultiplier tubes (active area from ~1 cm to 20” ⌀)

- Many developments in the past by dark matter and neutrino experiments in collaboration with manufacturers
- Used in current LArTPC detectors (ICARUS, SBND) and DM LAr/LXe detectors (XENONnT, LZ, PANDAX-4T)
- Pros:
  - Large active area
  - High gain
  - Mature technology
- Cons:
  - High bias voltage
  - Fragile
  - Sensitive to magnetic field
  - Difficult/expensive scaling-up

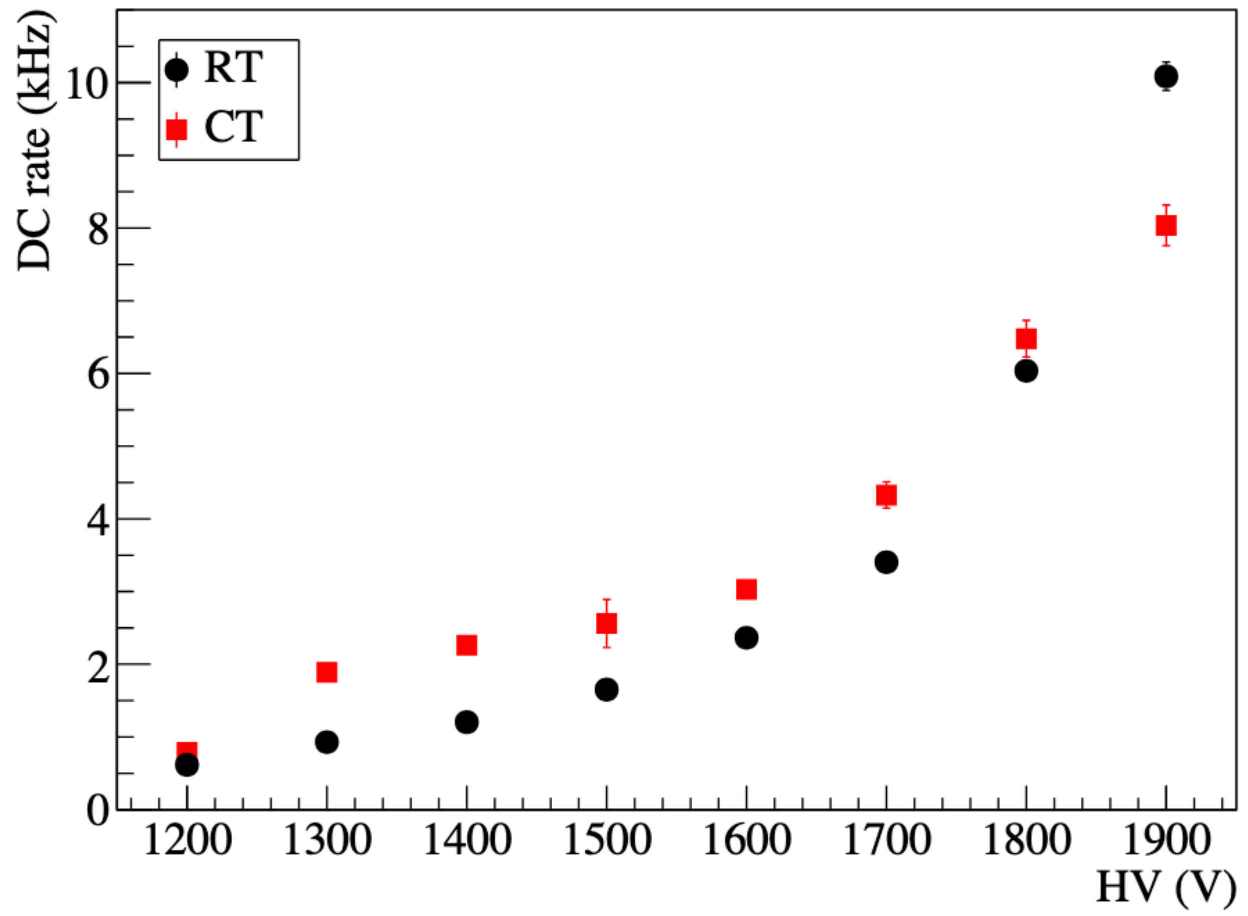
Cryogenic silicon photomultipliers (~1x1 mm^2 - 6x6 mm^2)



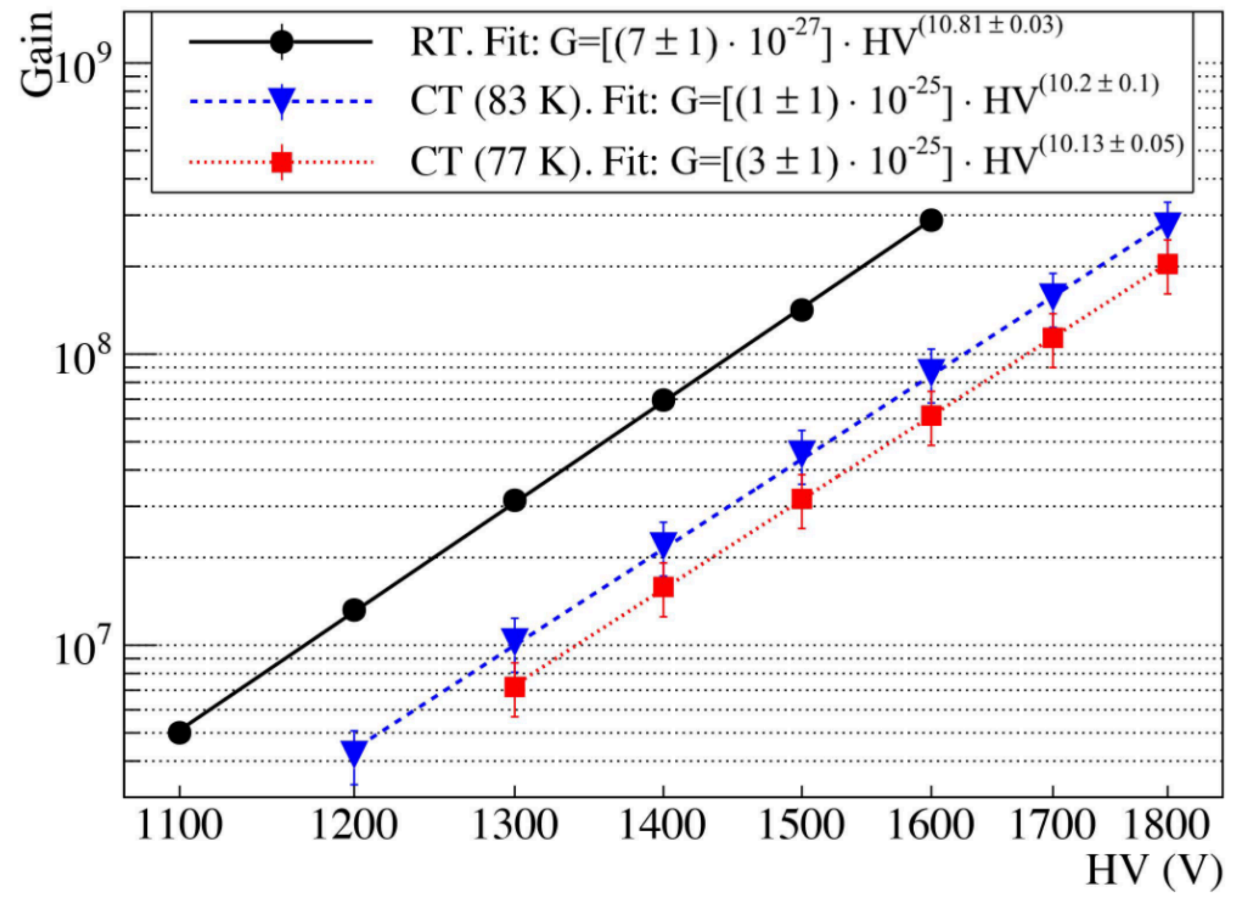
- Pros:
  - Low bias voltage
  - Low dark noise rate
  - High gain and PDE
  - Excellent time resolution
  - Insensitive to magnetic field
  - Compactness
  - Radiopurity
- Cons:
  - Small active area
  - Optical crosstalk and afterpulsing
- Active R&D ongoing to improve performance at cryogenic T and VUV (PDE, correlated noise, fill factor, …)

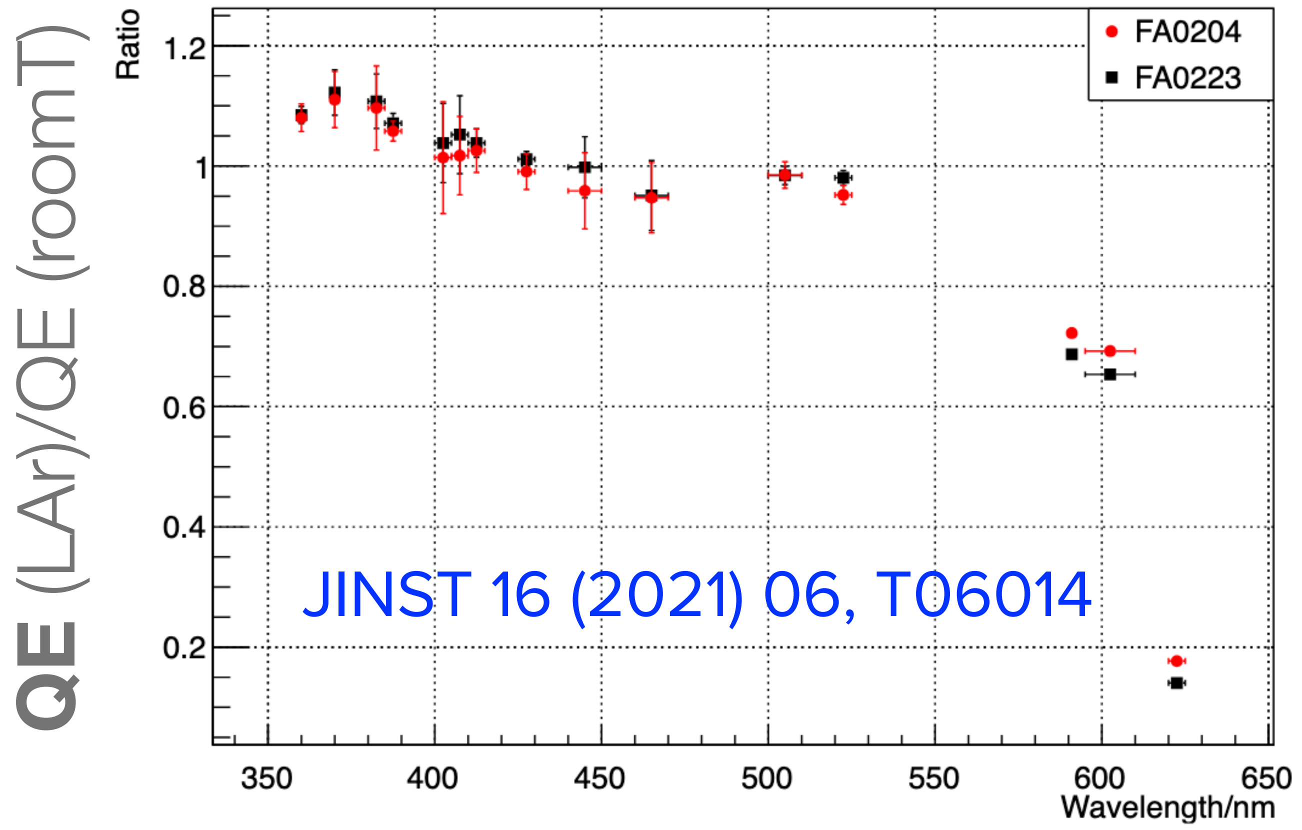
Temperature dependence (PMTs)

- Cryo PMTs (ex: 8” Hamamatsu R5912-20MOD)
  - (Non-thermal) **DCR increases** at cryogenic T
  - **Gain decreases** at cryogenic T
  - **QE** is ~18% and remains within 5% at cryogenic T at 420 nm (small increase ~10% observed at LXe T for smaller PMTs)



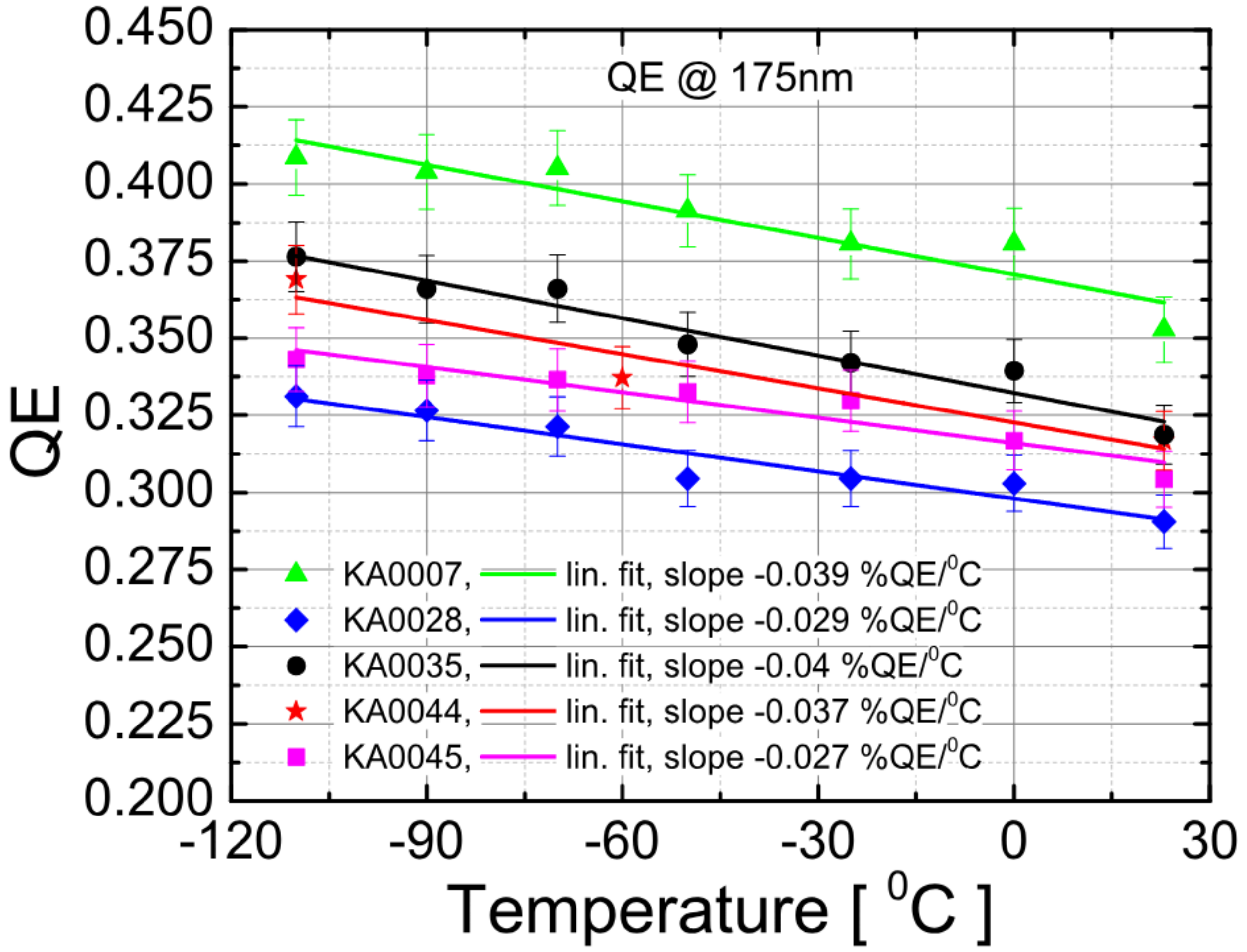
JINST 13 (2018) 10, T10006





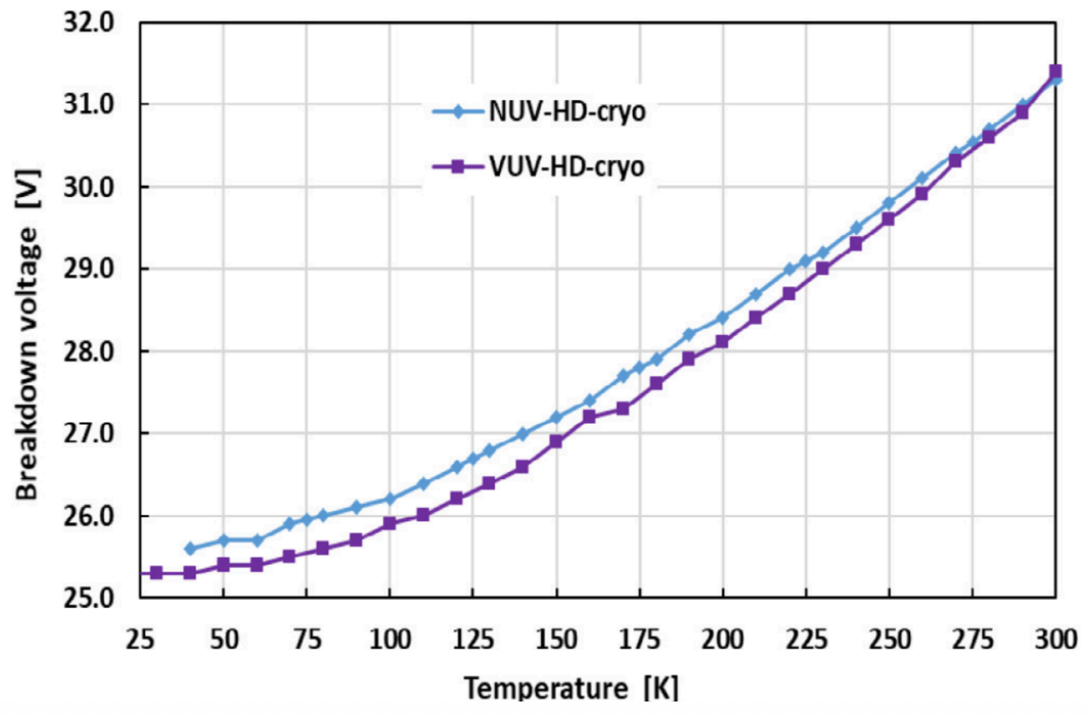
JINST 16 (2021) 06, T06014

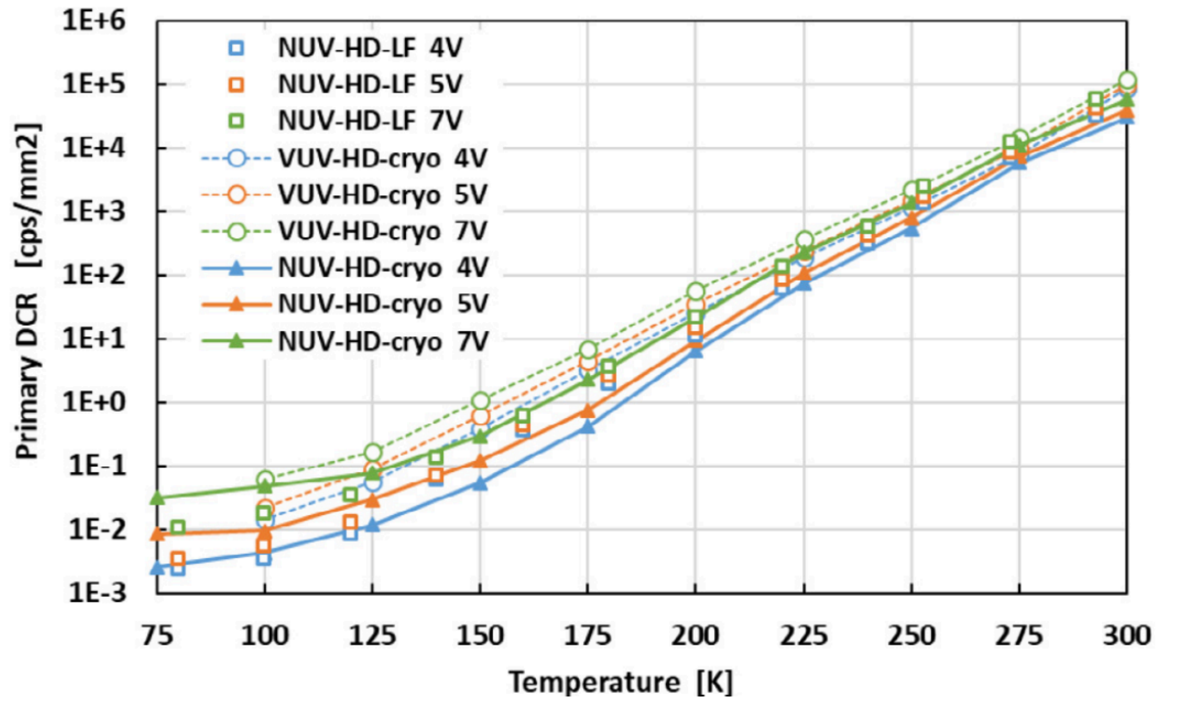
JINST 9 (2014) 11, P11021

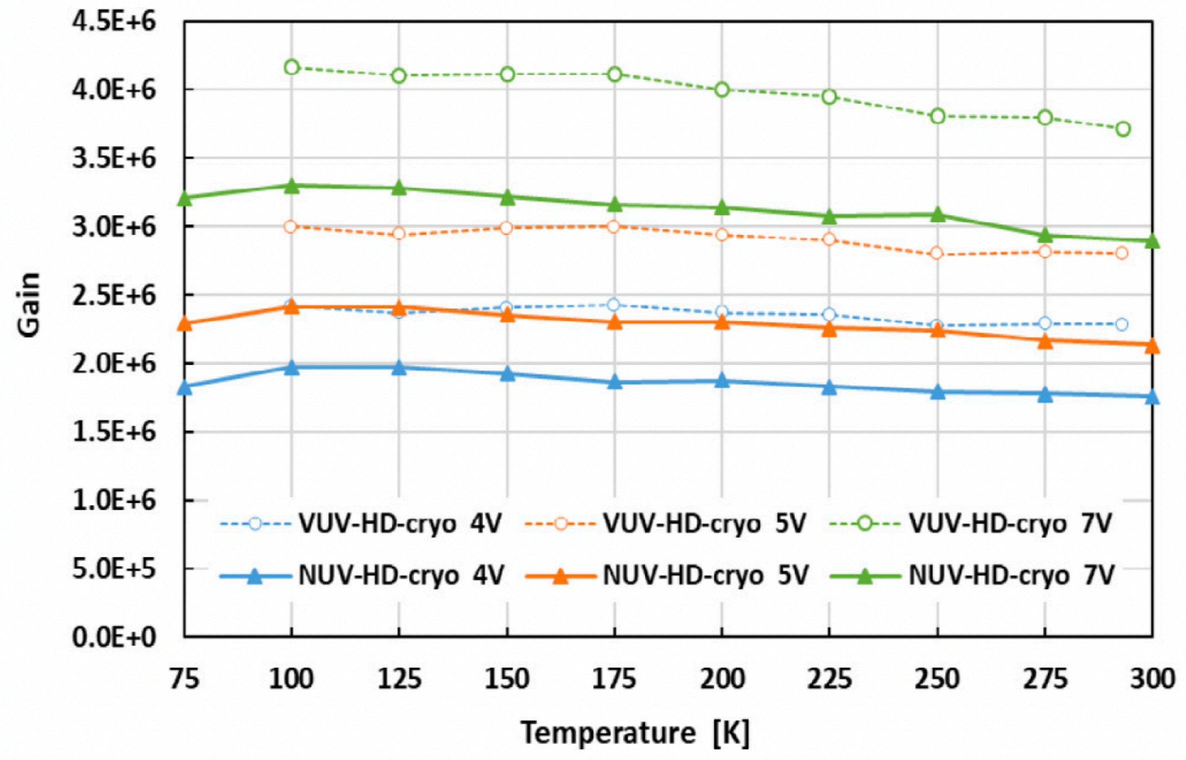


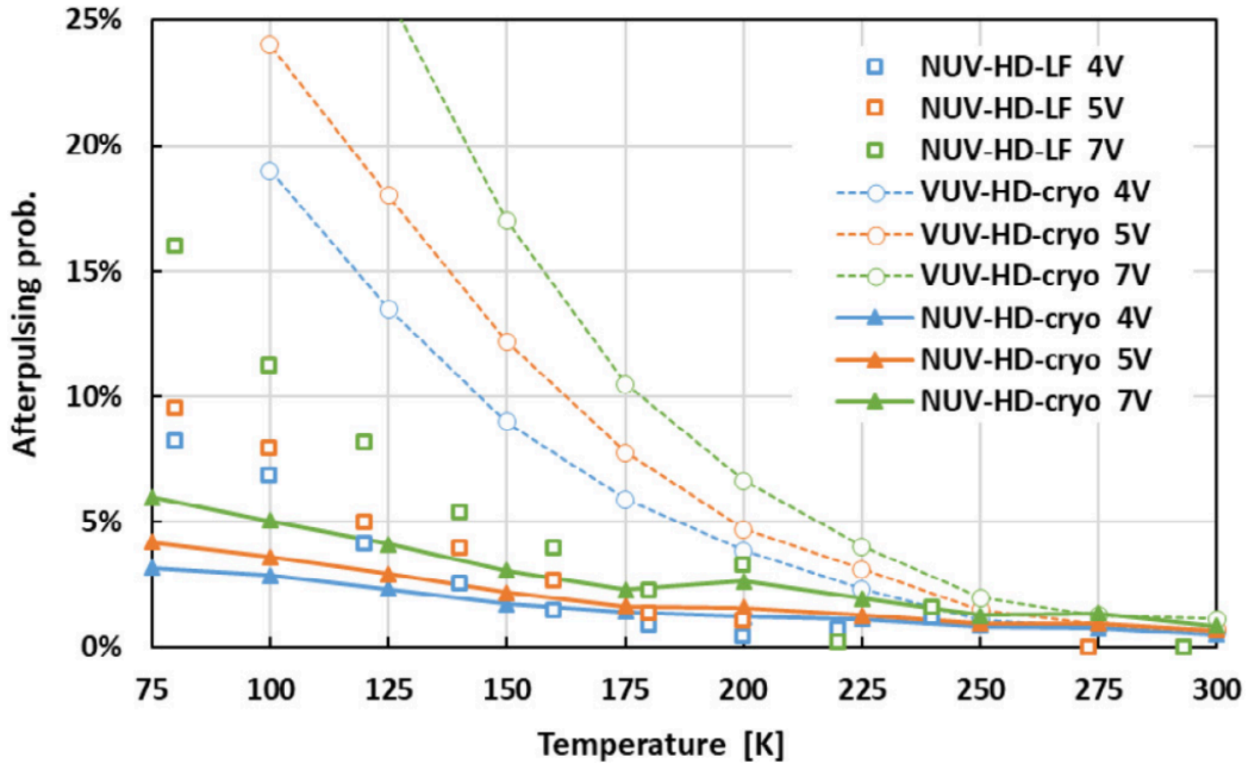
Temperature dependence (SiPMs)

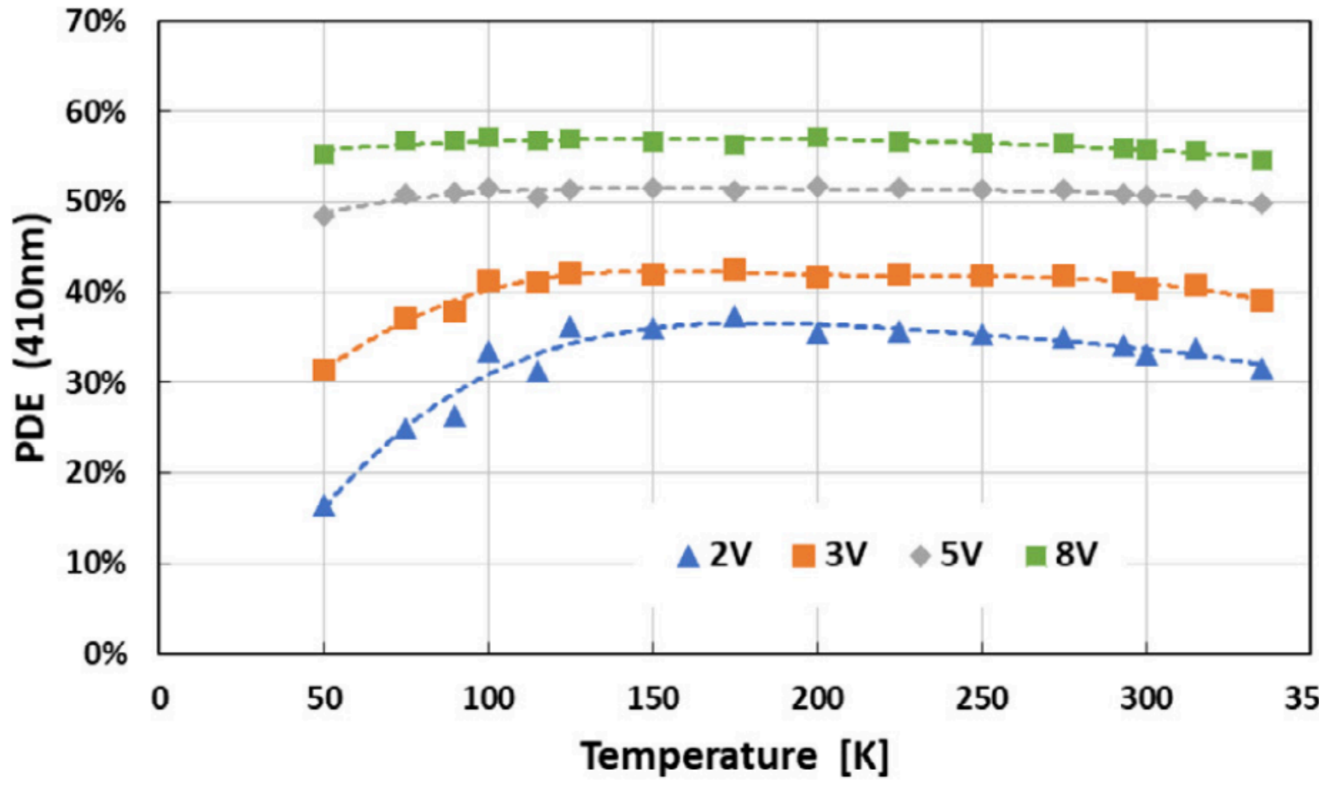
- SiPMs (ex: NUV-HD-cryo & VUV-HD-cryo) NIMA 1046 (2023) 167683
  - **Vbr**, **DCR** **decrease** at cryogenic T
  - Microcell **gain** and the prompt **crosstalk** probability have very little dependence with T
  - **Afterpulsing increases** at cryogenic T
  - **PDE** (in general) **decreases** at cryogenic T but it depends on the wavelength and OV

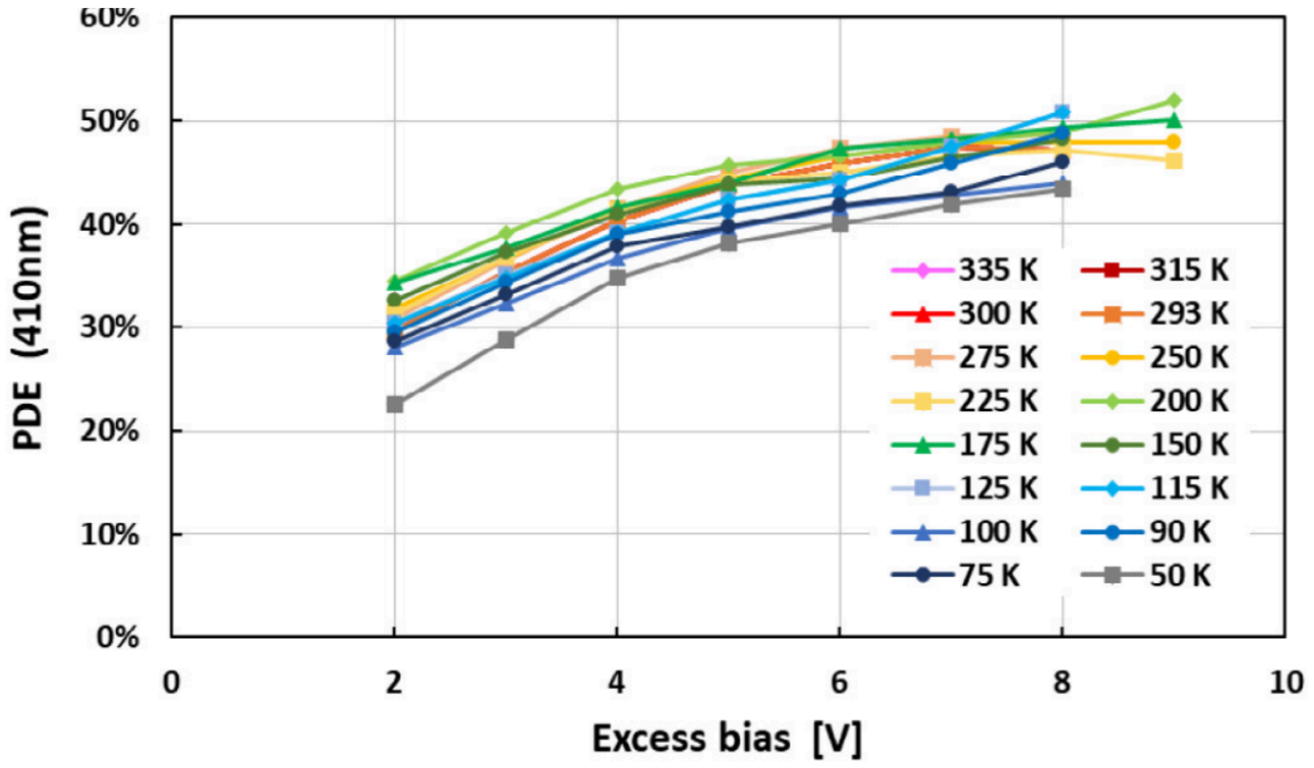








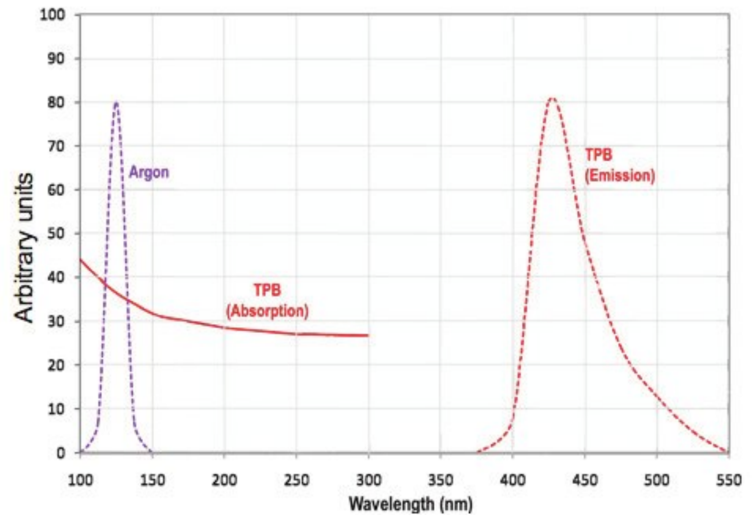


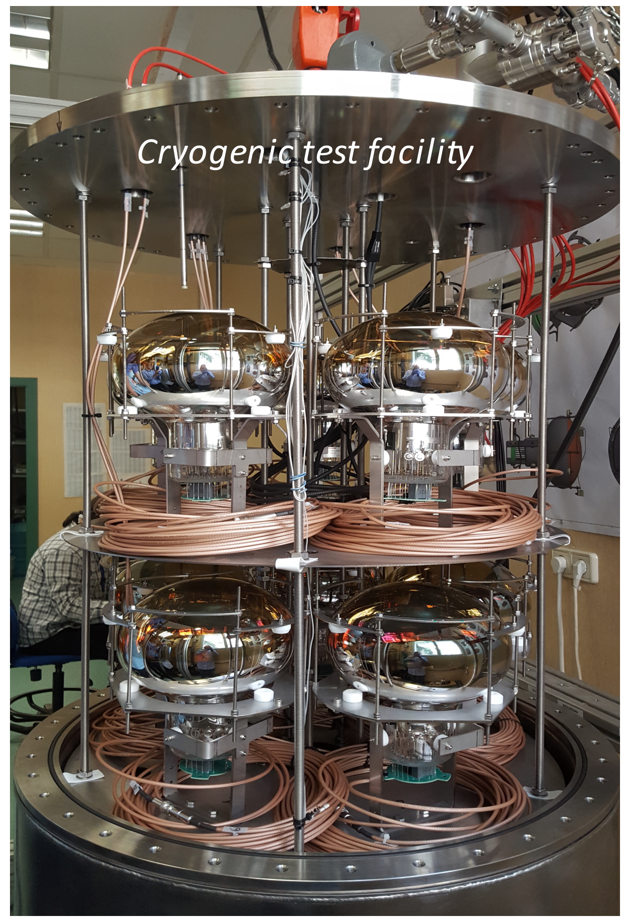


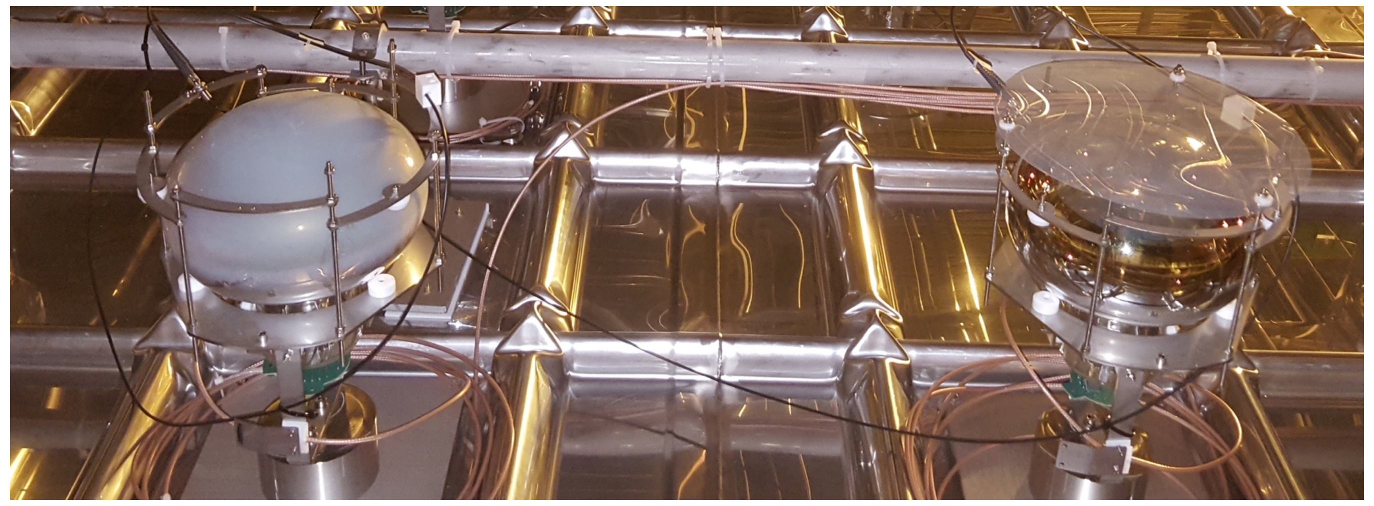
Cryogenic PMTs

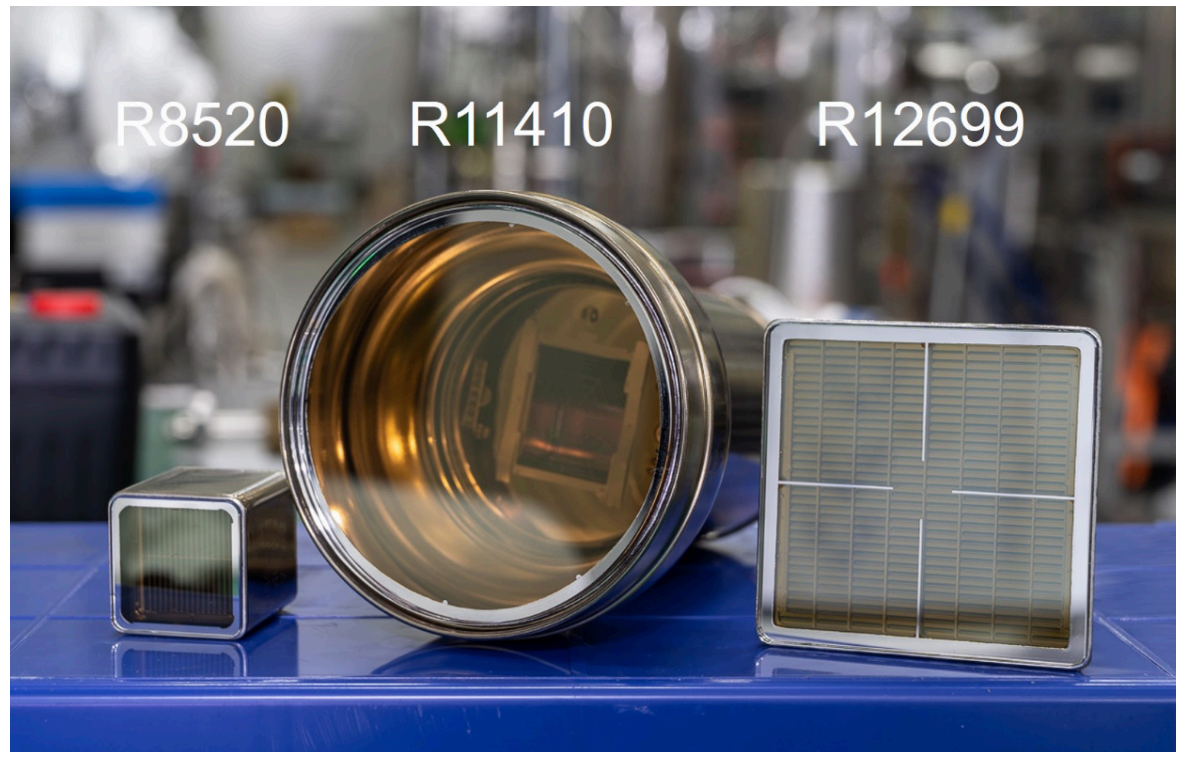
- **8” cryogenic HPK PMTs** (R5912-20MOD) in ProtoDUNE-DP, ICARUS and SBND
  - PMT Quantum efficiency (QE) at 430 nm ~18%
    - QE changes are less than 5% at LAr temperature
  - WLS using TPB (tetraphenyl butadiene) or PEN (polyethylene naphthalate) to shift 127 nm to ~430 nm
  - TPB-coated PMT QE measured at 127 nm (LAr) in ProtoDUNE-DP ~9% *Eur. Phys. J. C* 82 (2022) 7, 618

- **Low-background cryogenic PMTs**
  - XENONnT: 3” R11410-21 *JINST* 16 (2021) 08, P08033
    - Average quantum efficiency (QE) of 34 % measured by Hamamatsu at 25 ºC for 175 nm light (~same QE at 165 K)
  - PANDAX-4T: 3” R11410-23 and new 2” R12699
  - LZ: 3” R11410-20/22 → XLZD: 3” R11410-21/22









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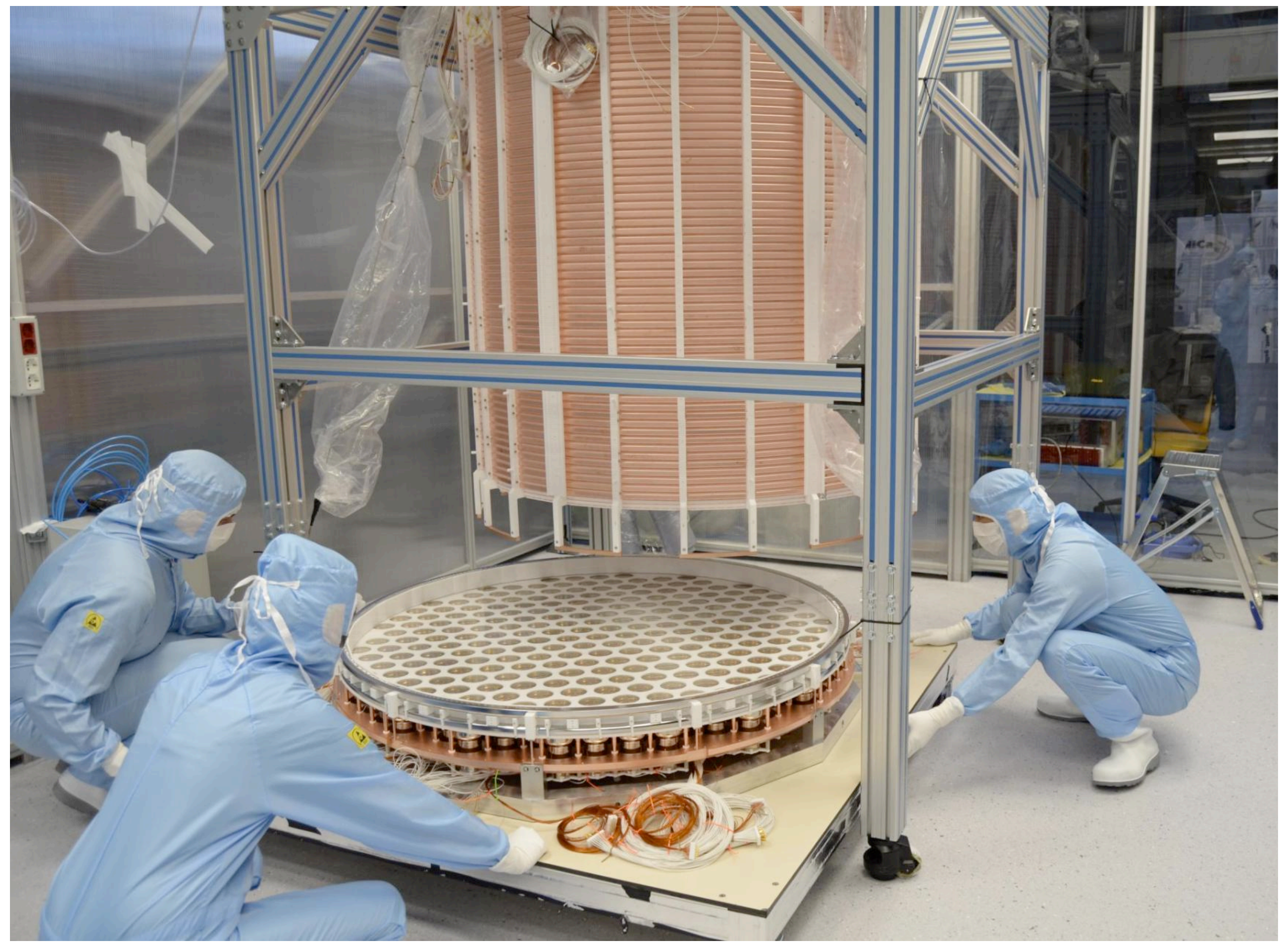
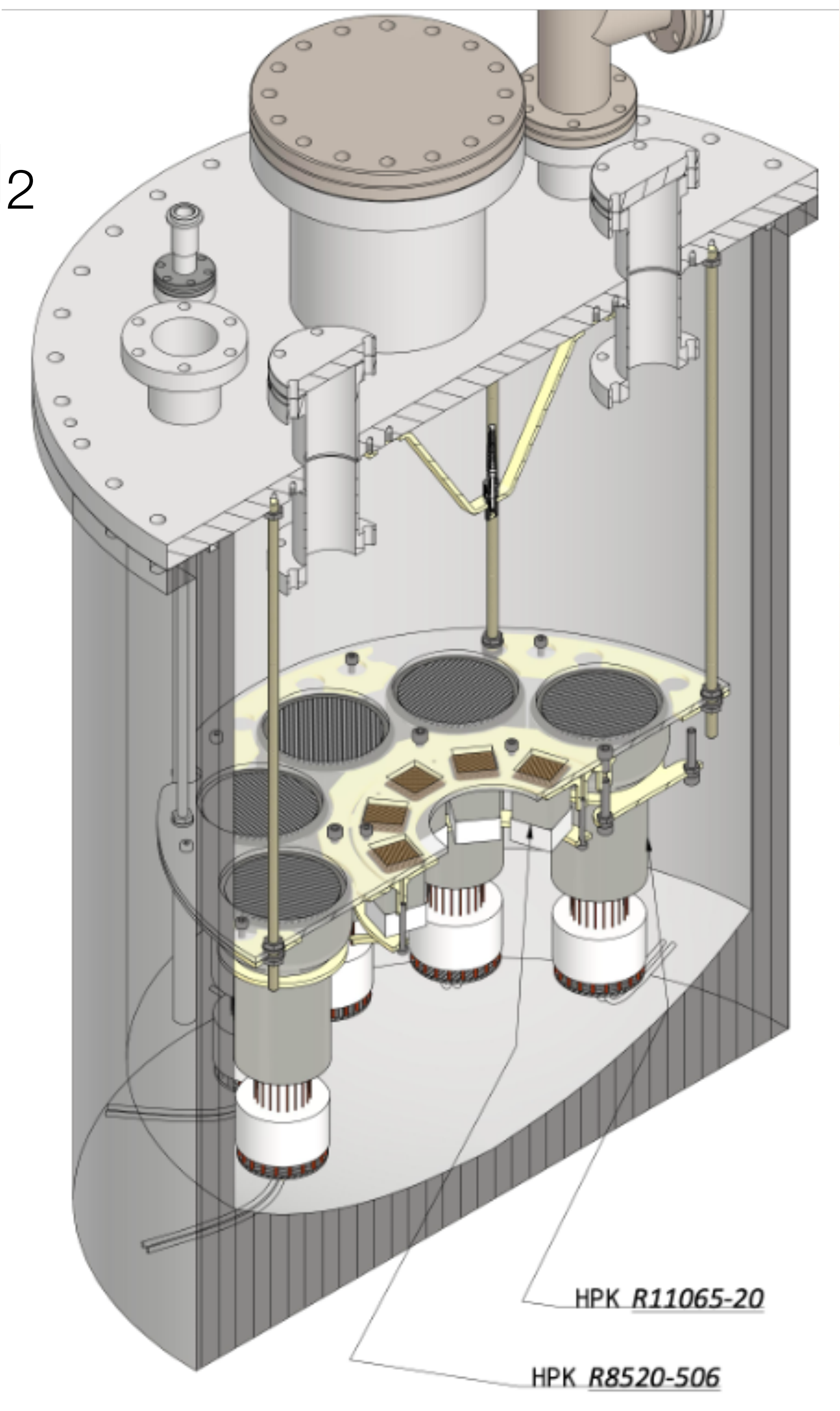
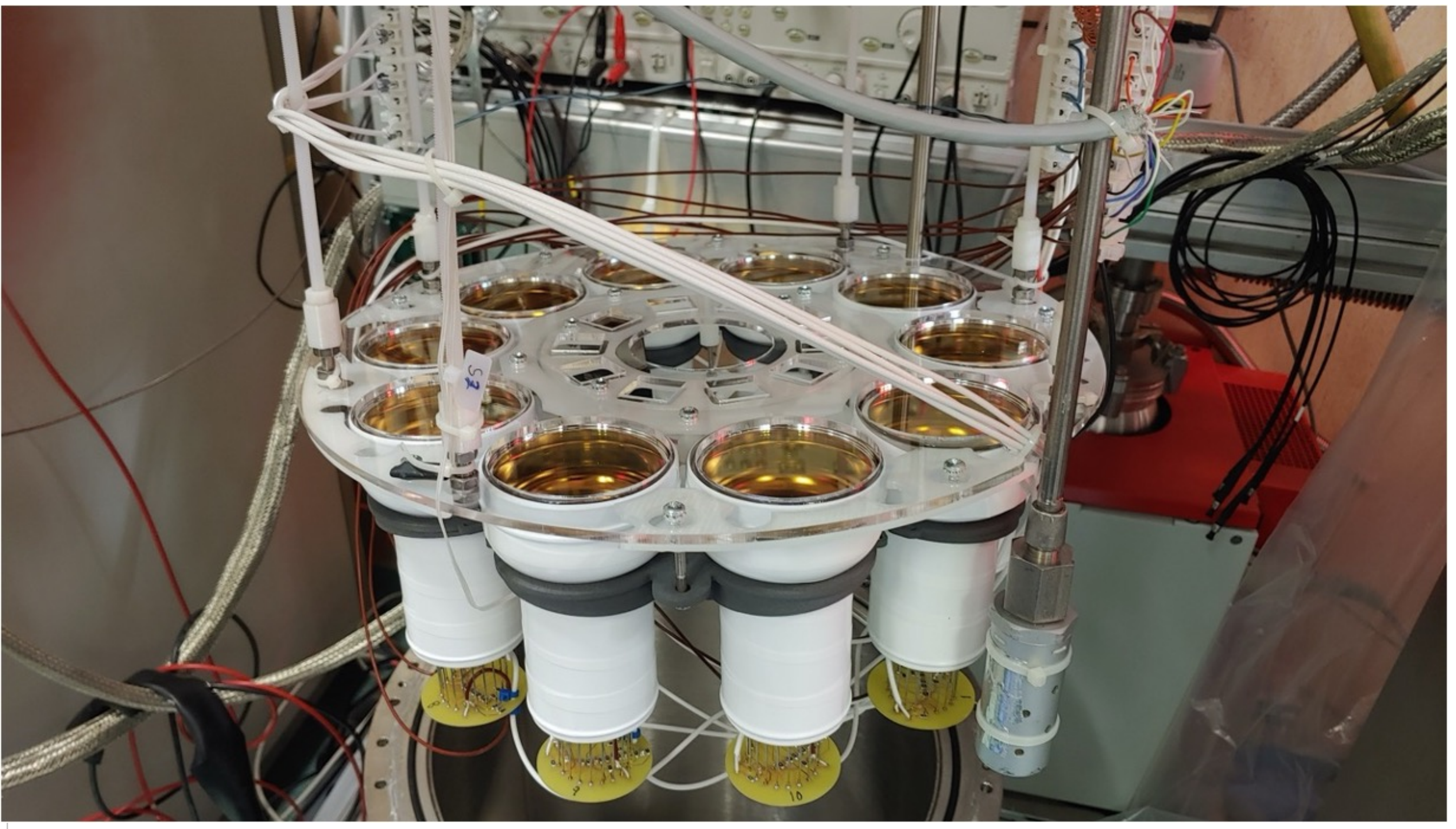
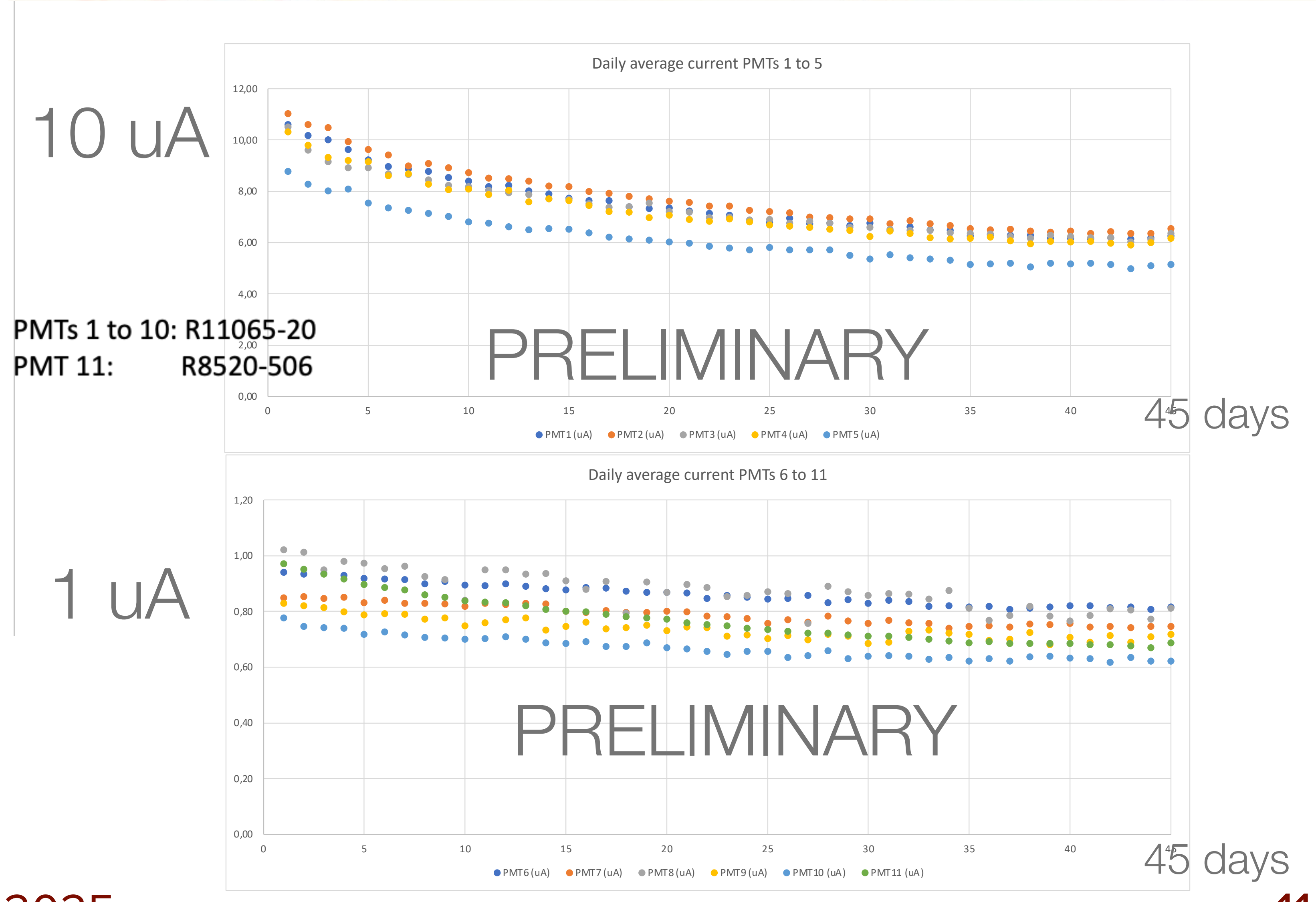


Long-term stability tests at cryogenic T

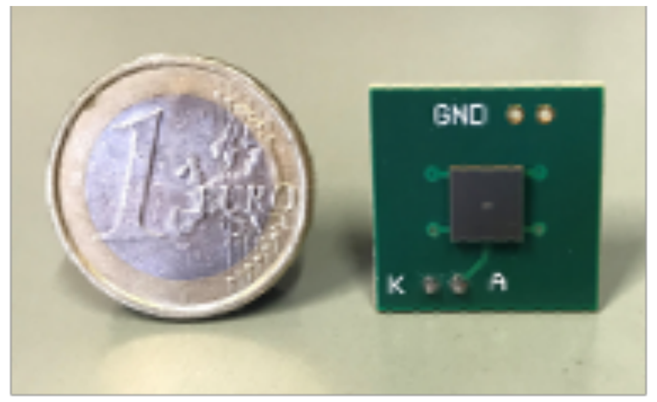
- 3”⌀ **R11065-20** & 1”x1” **R8520-506**
  - 5 PMTs tuned to 10 uA output current in LN_2
  - 6 PMTs tuned to 1 uA output current in LN_2
- **45 days immersed in LN_2** at CIEMAT
- Results:
  - 10.5 uA → 6.5 uA (~60% after 45 days)
  - 1uA → 0.8 uA (~80% after 45 days)
  - Current stable after ~35 days of immersion
- Paper in preparation





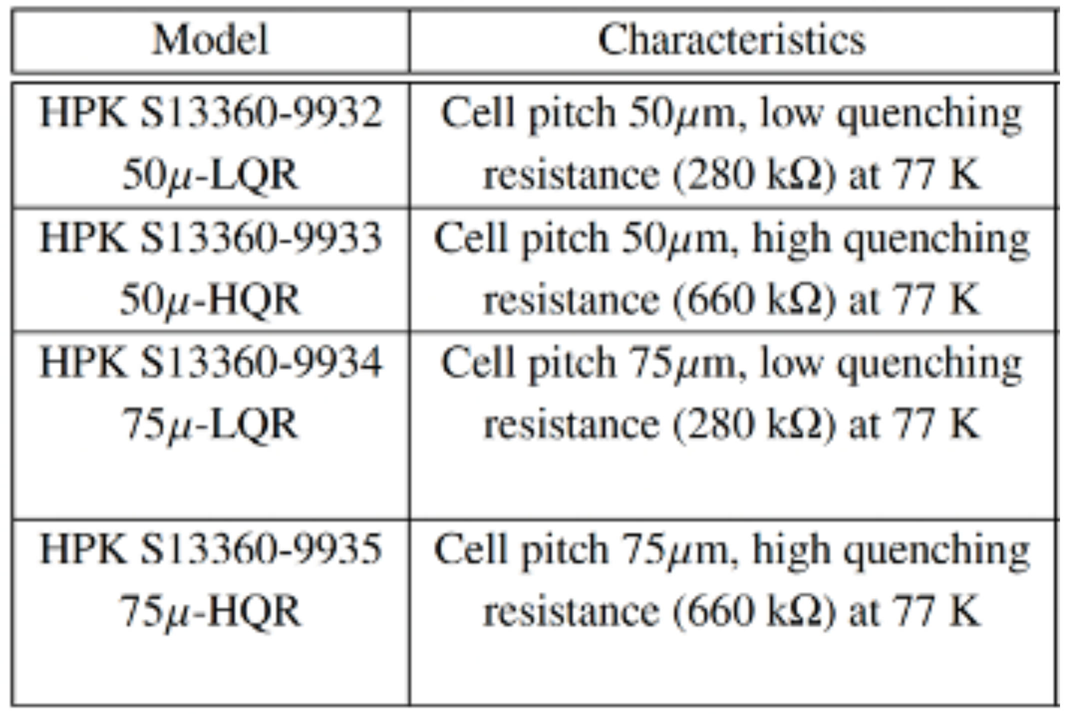


HPK cryo SiPMs

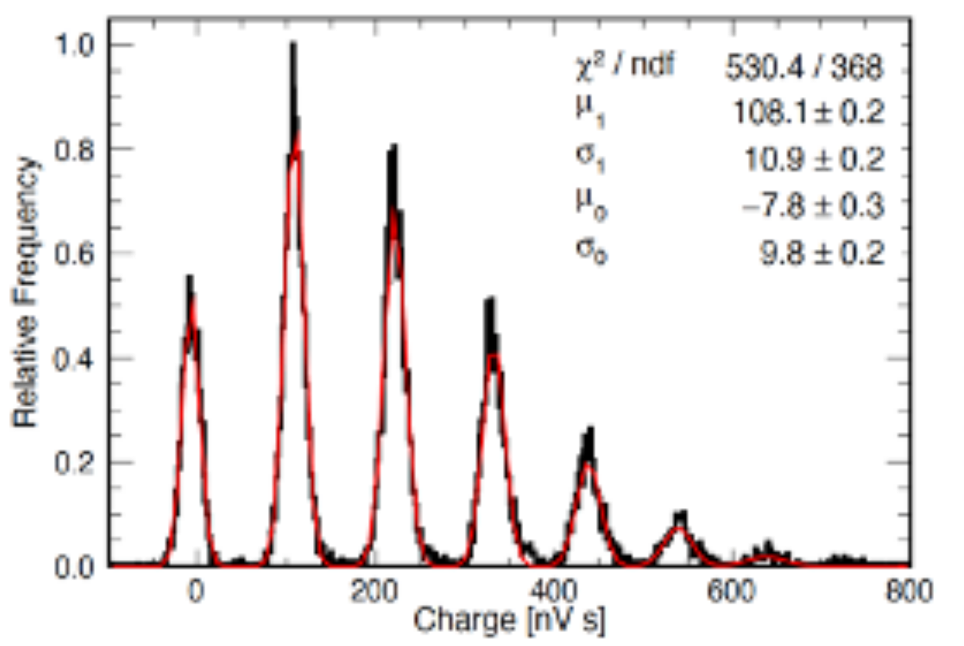


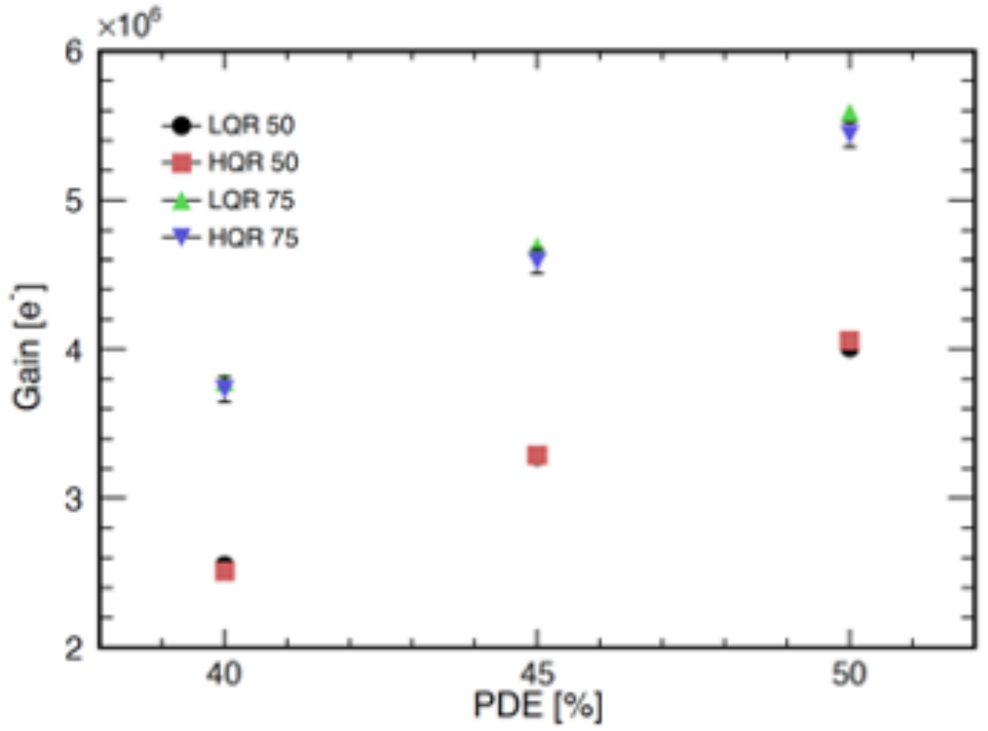
JINST 19 (2024) 01, T01007

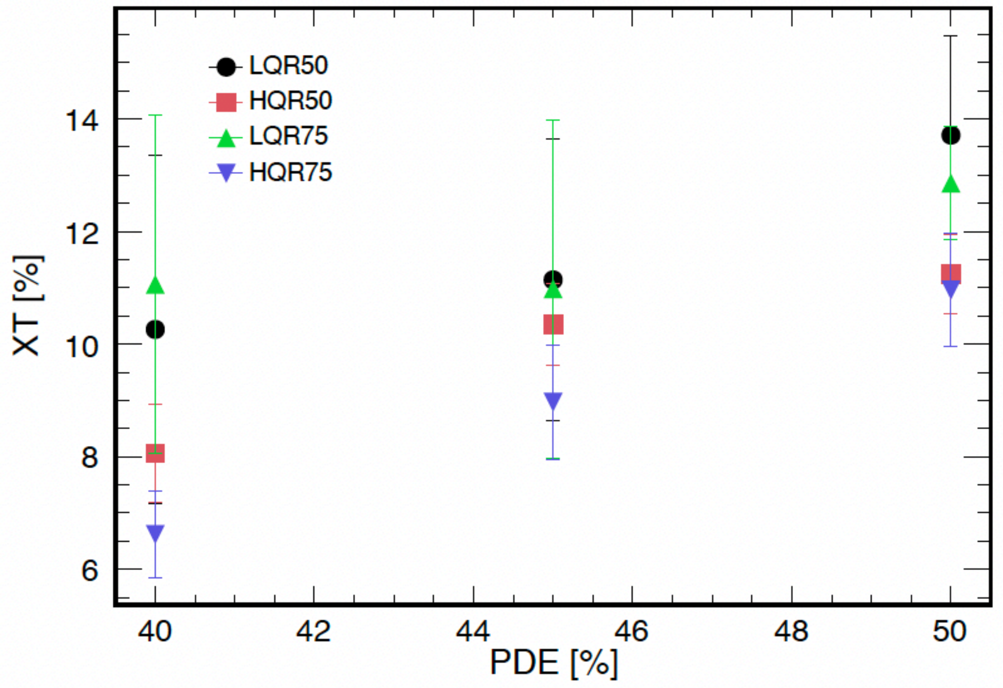
- High-efficient low-noise cryogenic SiPM development in collaboration with HPK and FBK:
  - New cryogenic sensors fulfilling the DUNE requirements
  - 4 HPK types tested (6x6 mm^2)
- **Characterization and cryo reliability tests** of standalone SiPMs and groups of 6 sensors per PCB (ganging mode):
  - At room T and after 20 thermal cycles in LN$_2$ (77 K)
  - IV-curves, gain, S/N, DCR, cross-talk, afterpulses
  - Individual and ganged tests
- 150,000 HPK SiPMs tested at CACTUS sites (Bologna, Milano Bicocca, Ferrara, Granada, Prague)



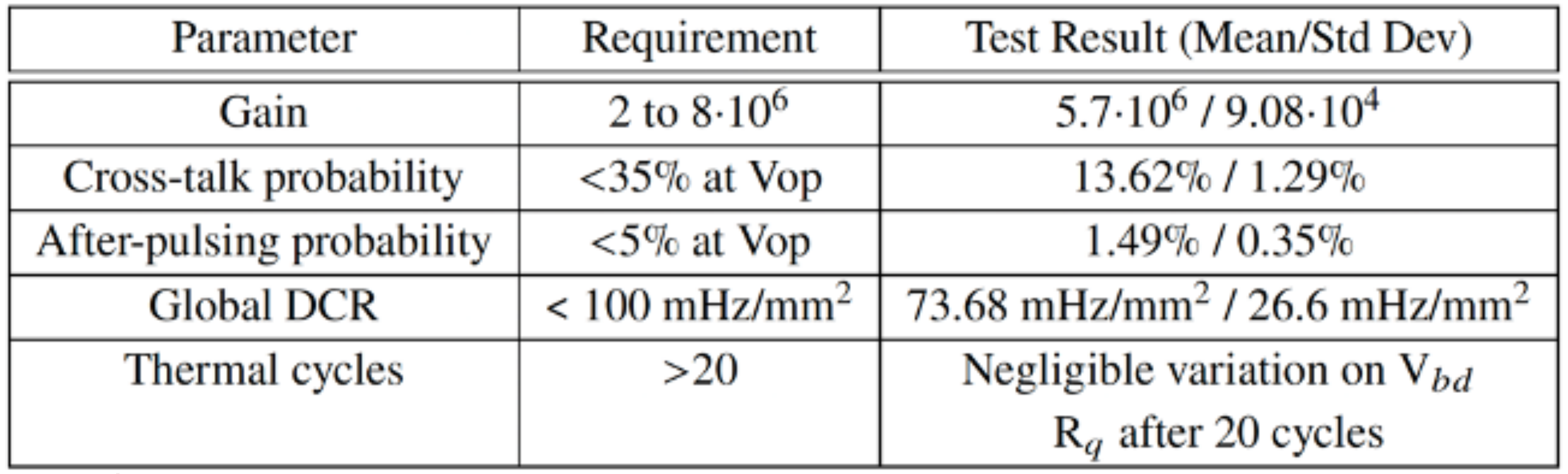
Model	Characteristics
HPK S13360-9932 50μ-LQR	Cell pitch 50μm, low quenching resistance (280 kΩ) at 77 K
HPK S13360-9933 50μ-HQR	Cell pitch 50μm, high quenching resistance (660 kΩ) at 77 K
HPK S13360-9934 75μ-LQR	Cell pitch 75μm, low quenching resistance (280 kΩ) at 77 K
HPK S13360-9935 75μ-HQR	Cell pitch 75μm, high quenching resistance (660 kΩ) at 77 K





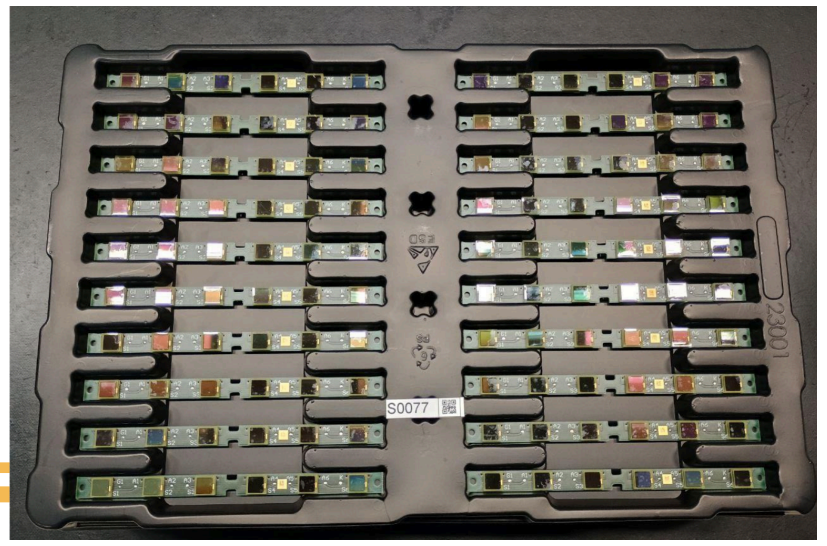


HPK HRQ 75µm selected for DUNE

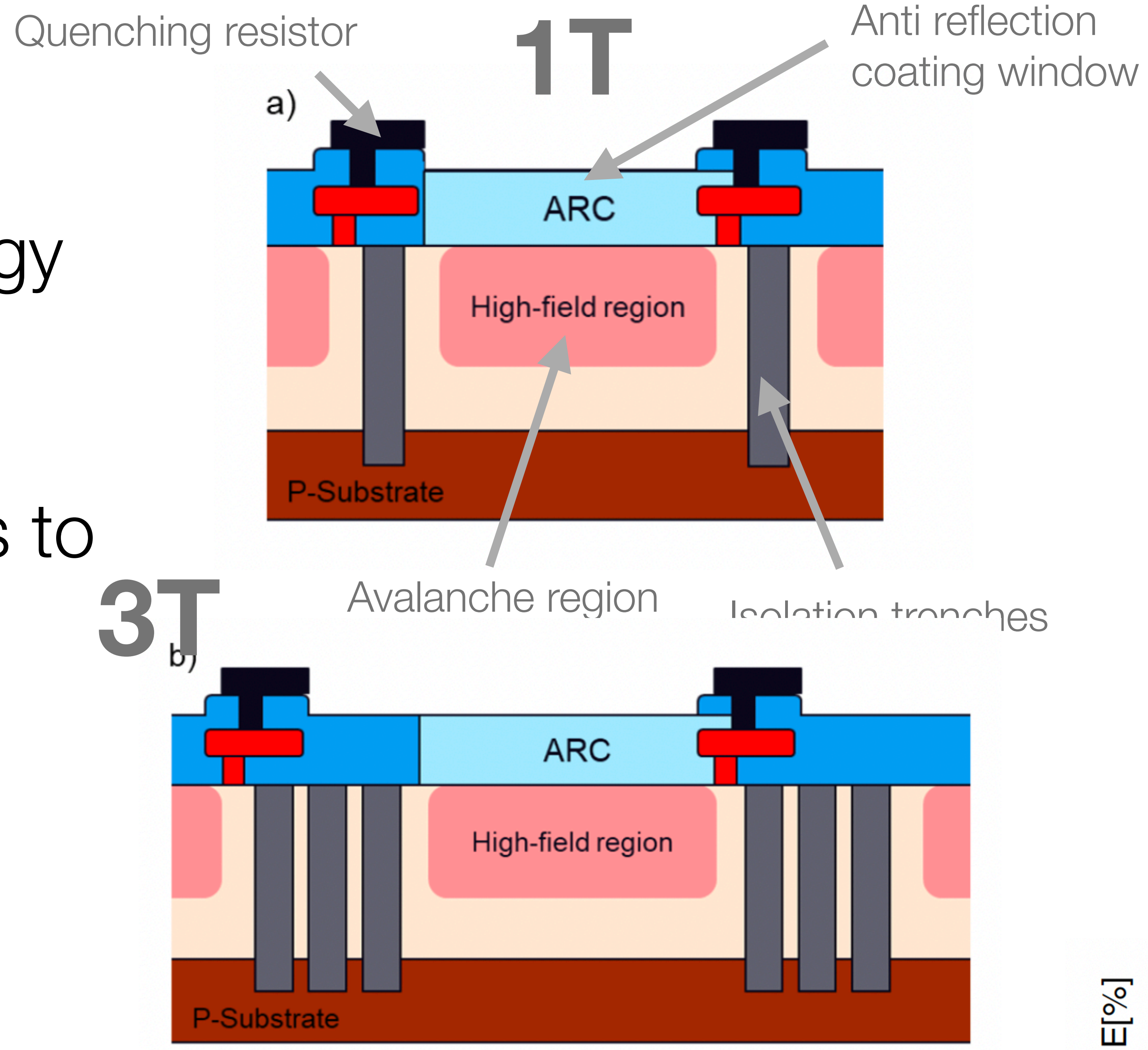


Parameter	Requirement	Test Result (Mean/Std Dev)
Gain	2 to 8·10^6	5.7·10^6 / 9.08·10^4
Cross-talk probability	<35% at Vop	13.62% / 1.29%
After-pulsing probability	<5% at Vop	1.49% / 0.35%
Global DCR	< 100 mHz/mm^2	73.68 mHz/mm^2 / 26.6 mHz/mm^2
Thermal cycles	>20	Negligible variation on V_{bd} R_q after 20 cycles

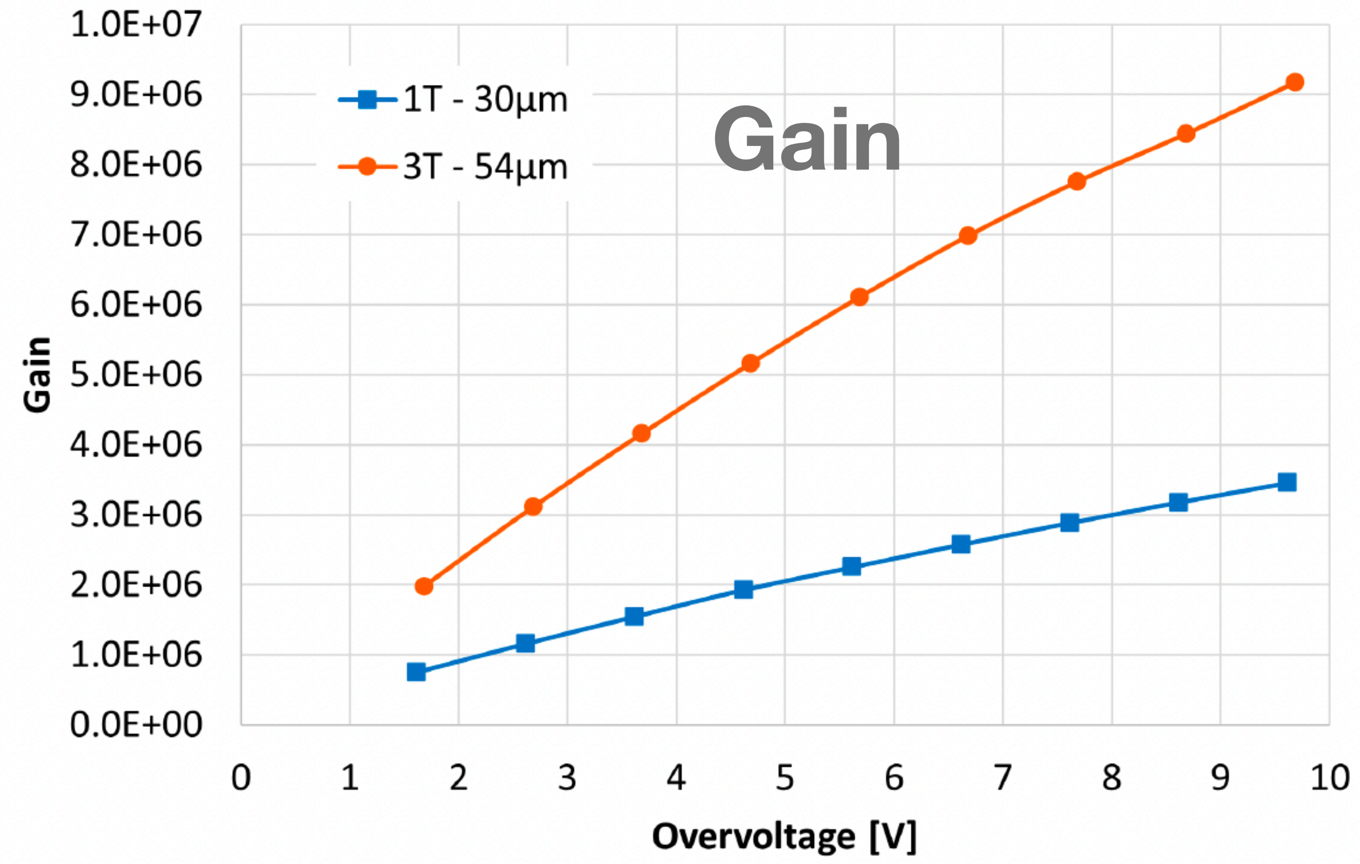
FBK NUV-HD Cryo Triple Trench

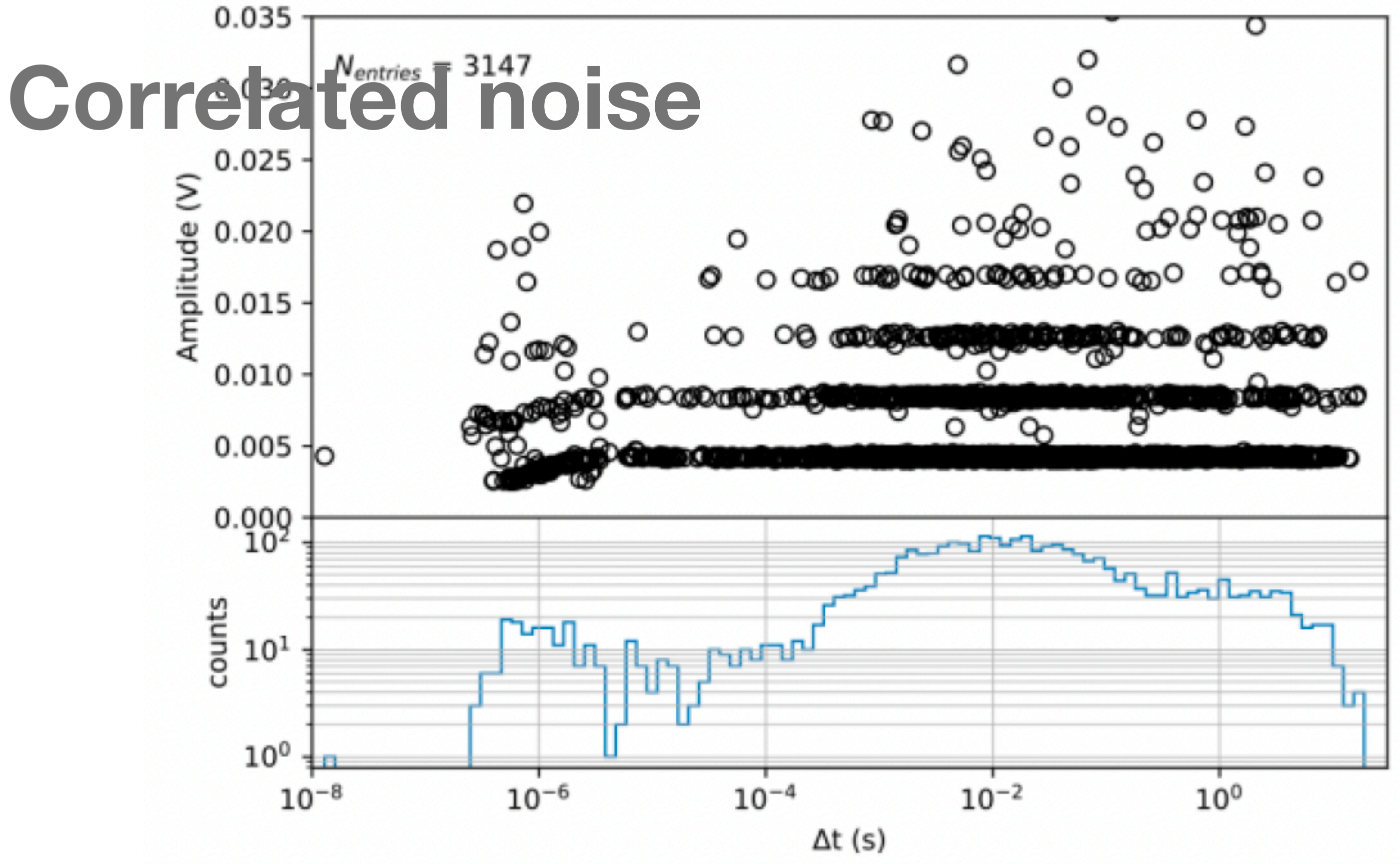


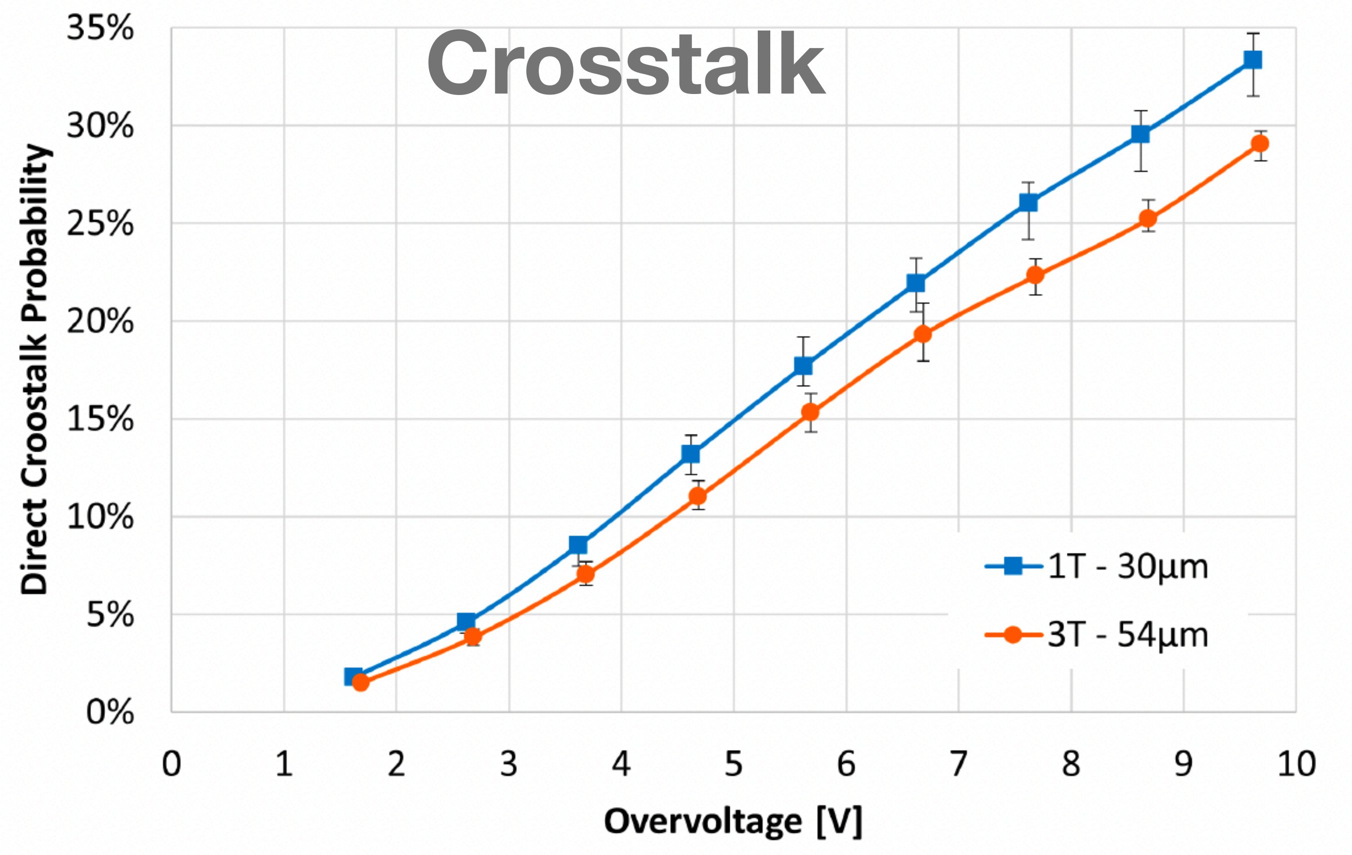
- Customization for DUNE experiment
- Based on the NUV-HD Cryo technology
- 54 um cell pitch and 6x6 mm^2 area
- 3 isolating trenches (3T) between cells to decrease crosstalk probability
- PDE = 50% at 420 nm at OV7
- 150,000 FBK SiPMs being tested at CACTUS sites

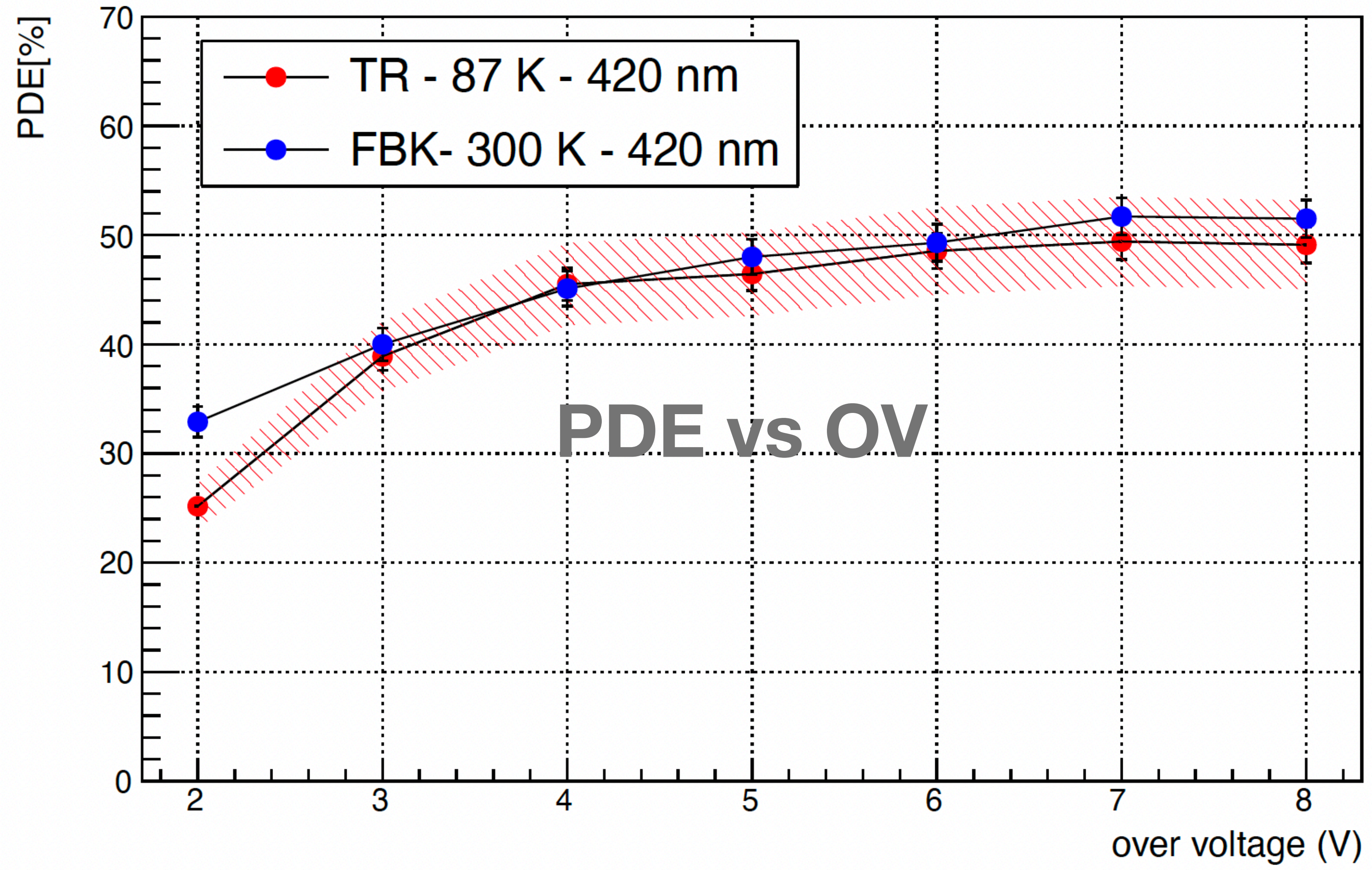


arXiv:2511.9095



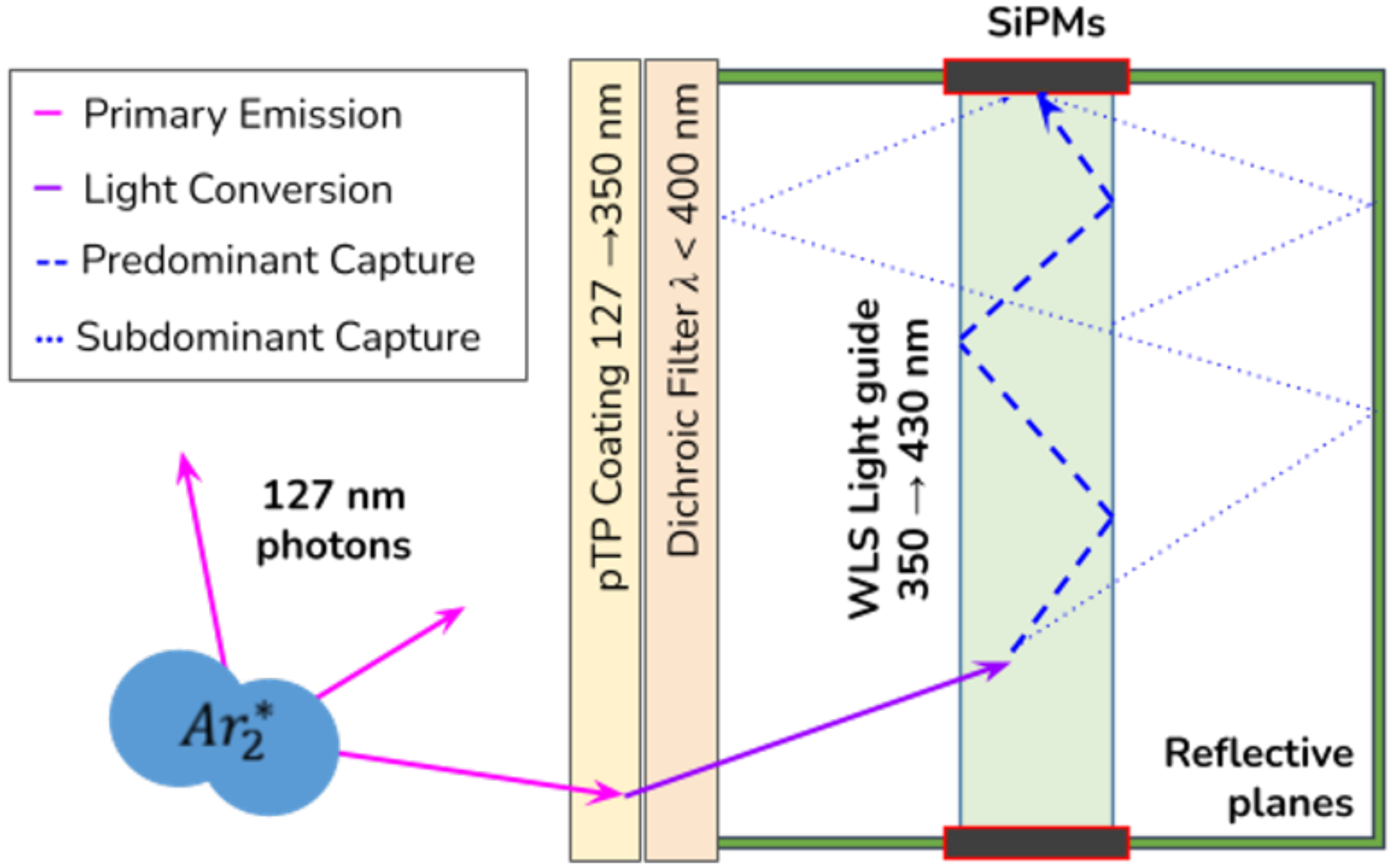




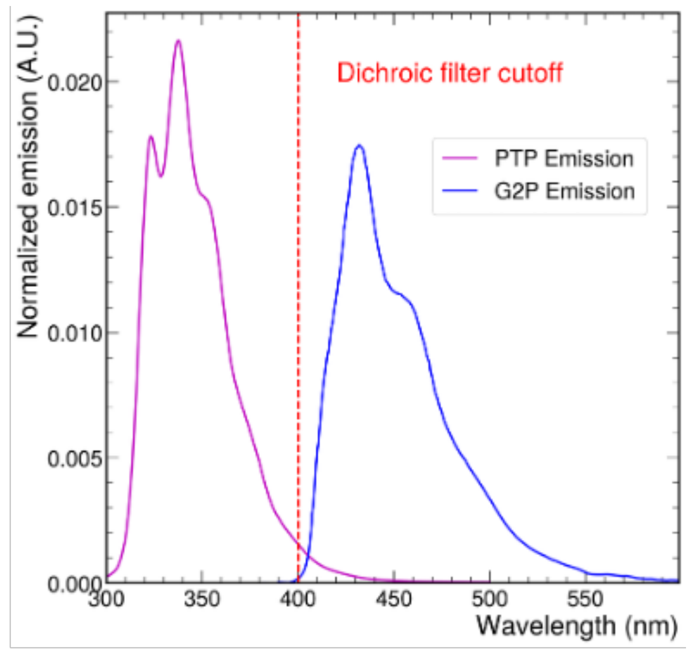


Shifting VUV to visible light

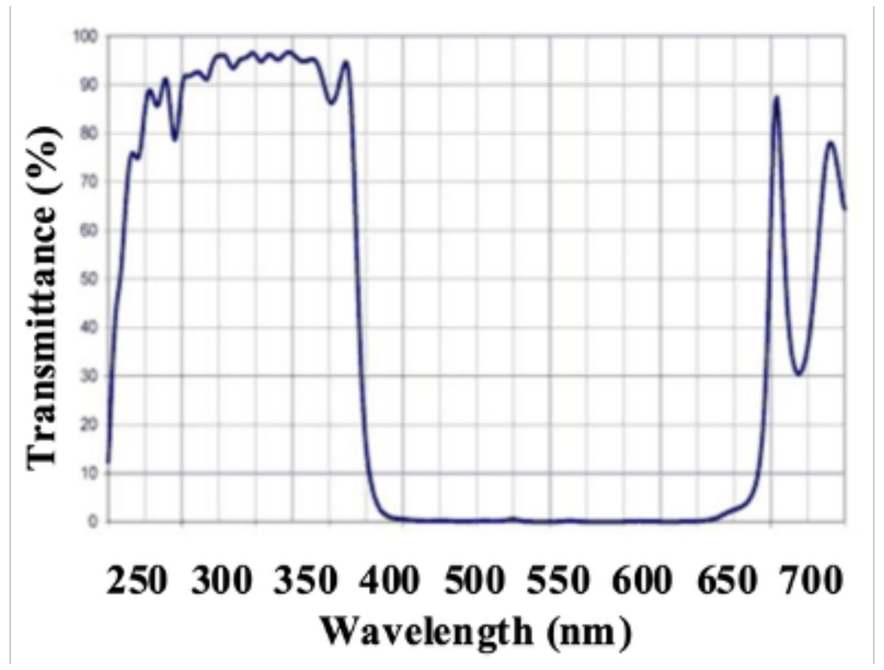
- **X-ARAPUCA** concept (VUV light trap)
  - Initially proposed by E. Segreto and A. Machado (Campinas)
  - Allows to shift VUV light to visible light covering large areas
  - First light conversion by the pTP → transmission through DF → second conversion by the WLS light guide towards SiPMs → DF blocks photons inside XA → photon detection by SiPM
  - XA Photon Detection Efficiency quite low ~**2%**



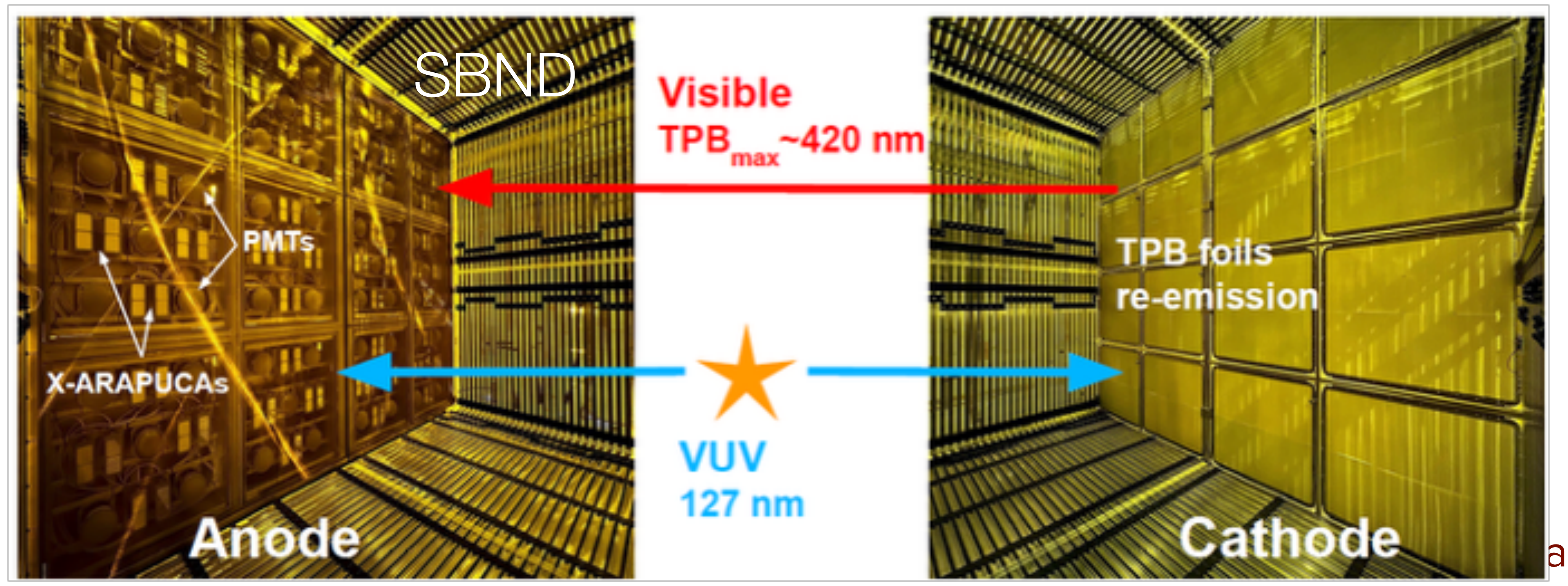
pTP & WLS emission



Ideal DF transmittance

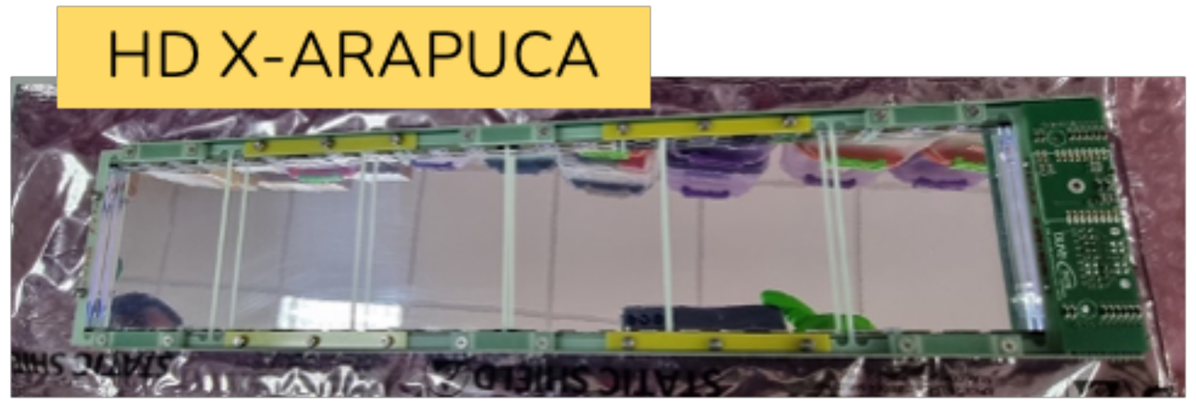


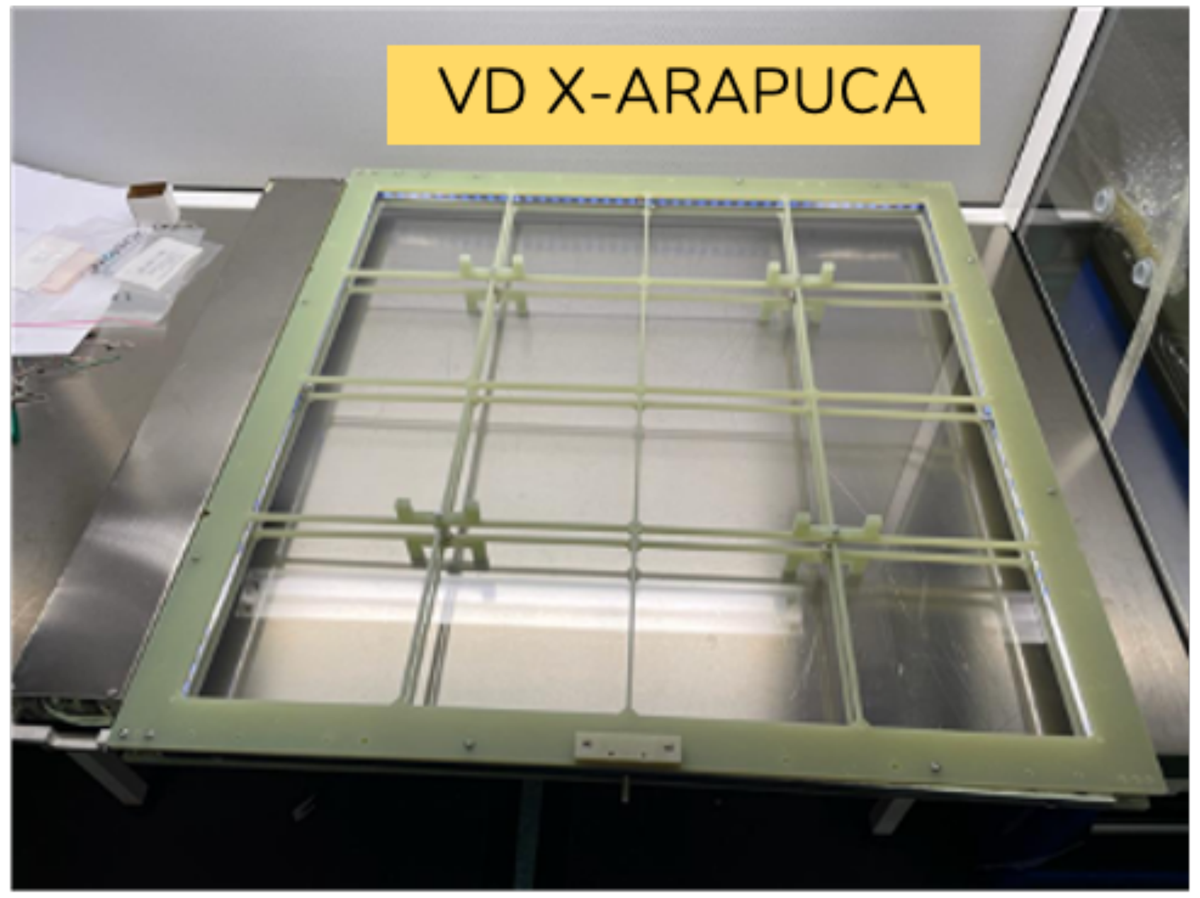
- **Reflective foils**
  - TPB-coated PTFE reflectors to shift 127 nm to visible light



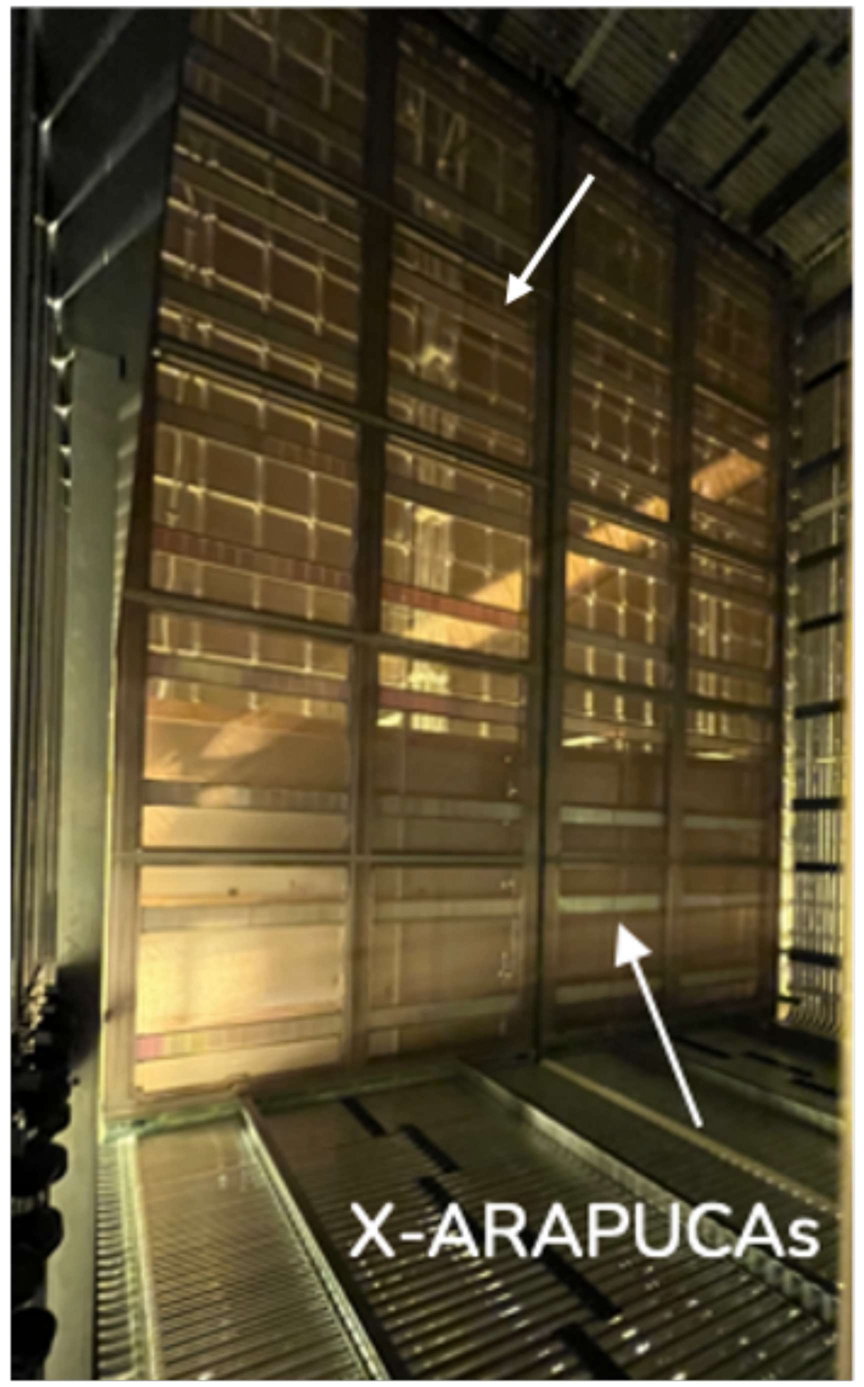
X-ARAPUCAs in DUNE and SBND

- DUNE HD X-ARAPUCAs (10x50 cm^2): 48 SiPMs/module - 6000 modules in DUNE FD (tested in ProtoDUNE-HD)
- DUNE VD X-ARAPUCAs (60x60 cm^2): 160 SiPMs/module - 672 modules in DUNE FD (tested in ProtoDUNE-VD)
- SBND X-ARAPUCAs (10x24 cm^2): 4-8 SiPMs/module - 192 modules (visible and VUV sensitive) – in use

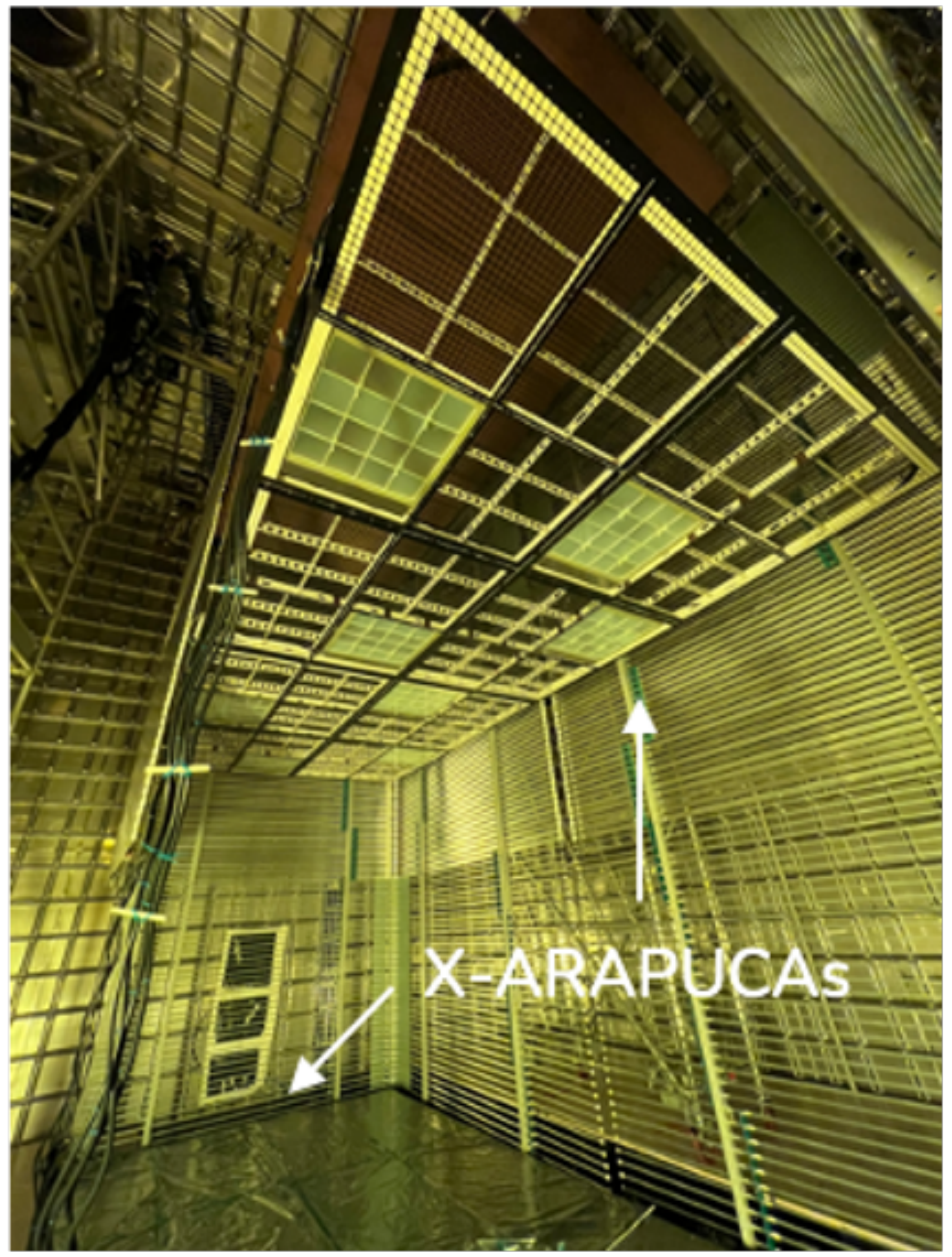




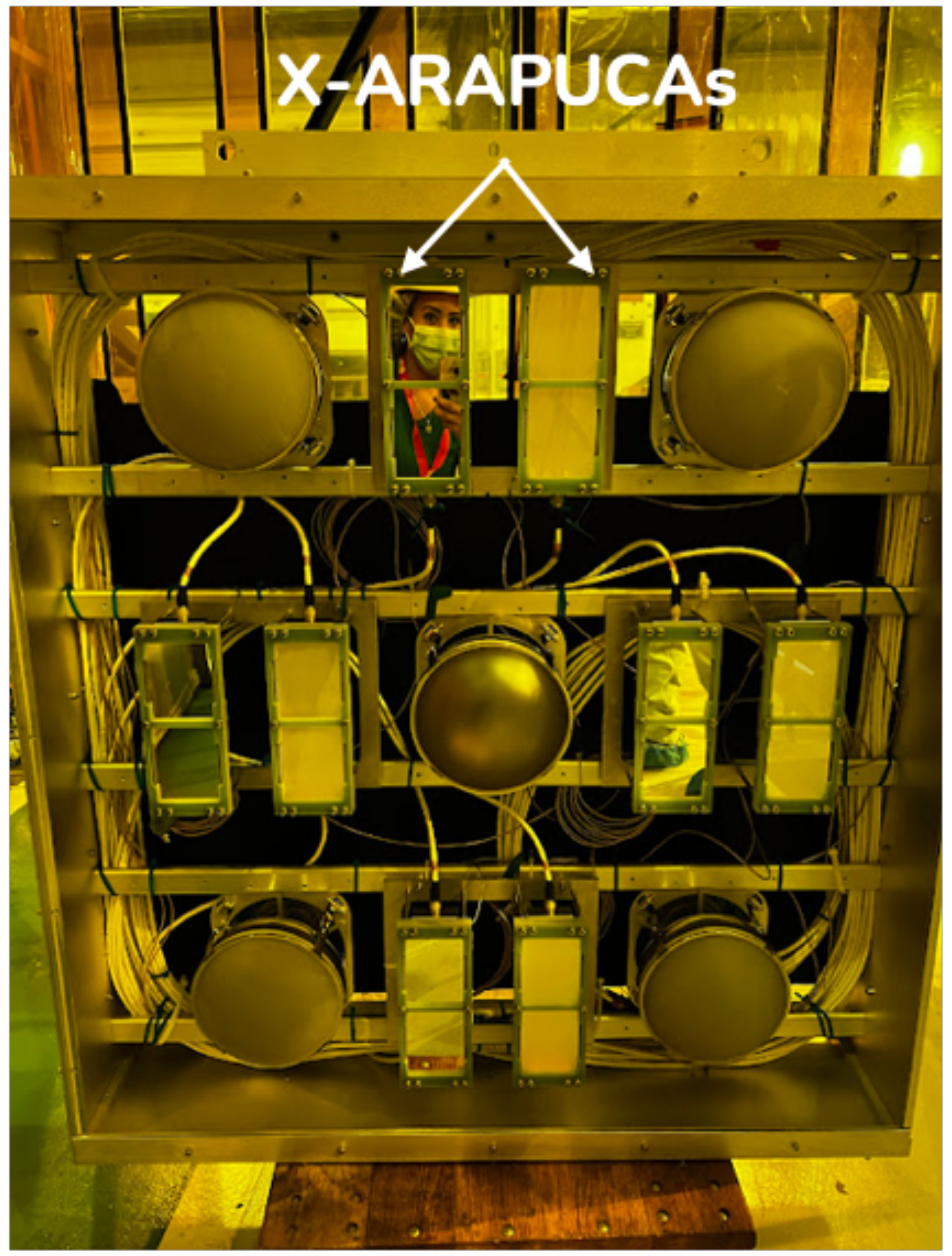
ProtoDUNE-HD



ProtoDUNE-VD

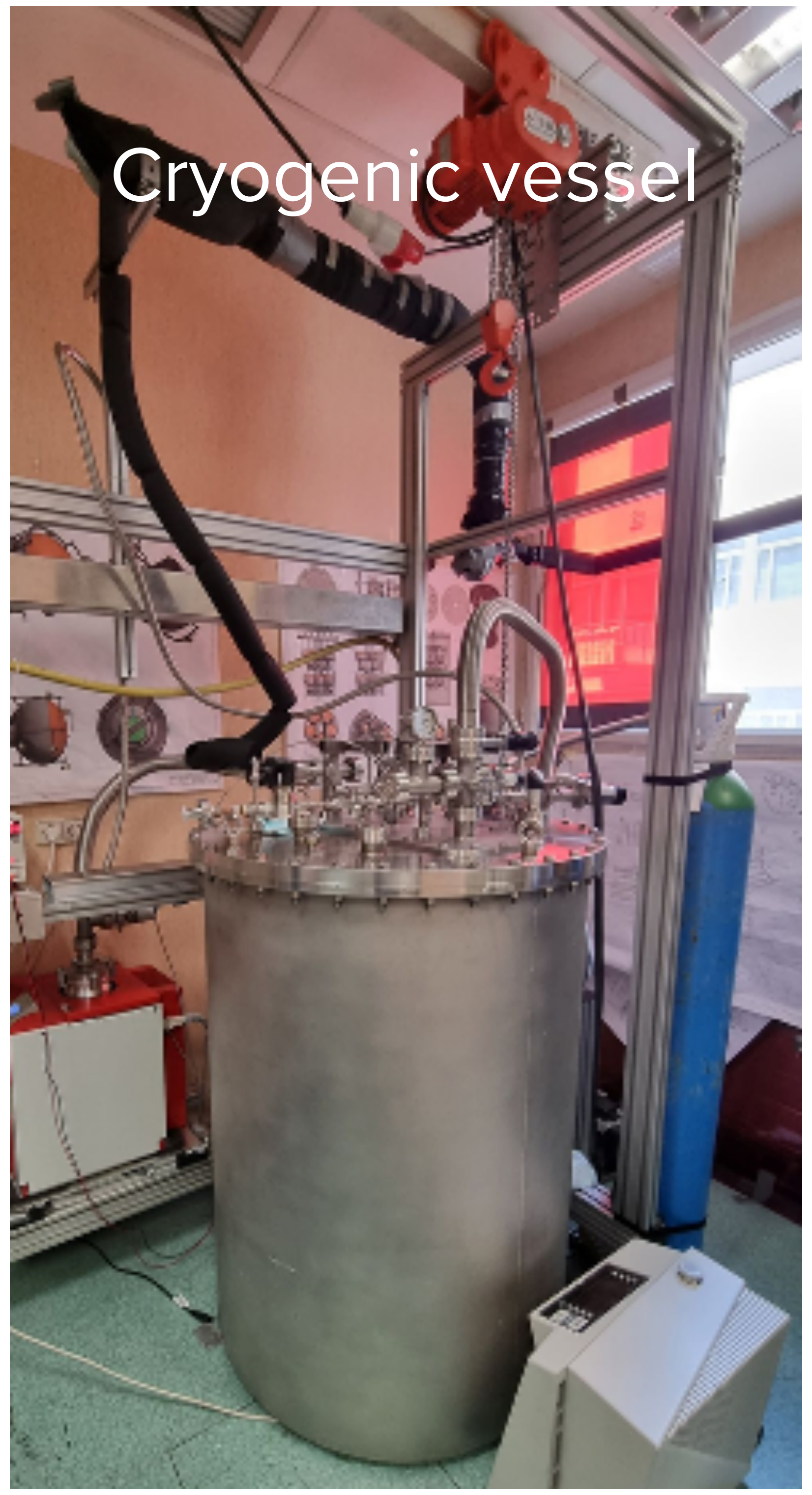


SBND



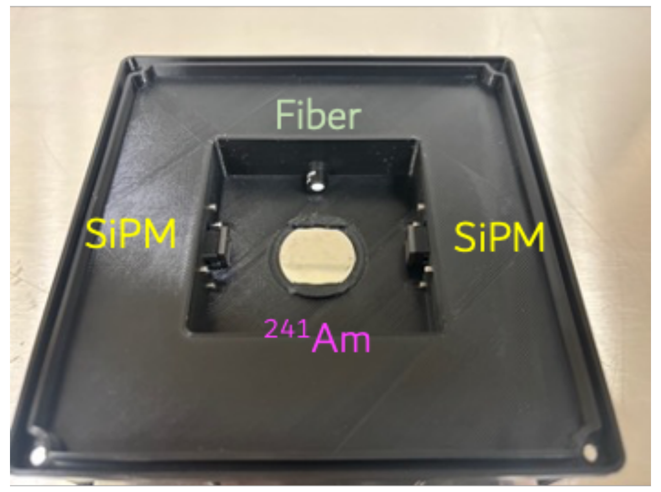
Photon Detection Efficiency measurement

- X-ARAPUCA optimization focused on increasing PDE:
  - Better coupling WLS plate-SiPMs
  - more efficient WLS plate
  - optimized dichroic filter cutoff for LAr light
  - replacement of filter by pTP-coated glass substrates
  - improved reflective surfaces
- Dedicated cryogenic facilities developed to characterize the PDS performance
  - ^{241}Am alpha source + 2 VUV reference SiPMs in a calibration black box


Cryogenic vessel


Immersion in LAr

Calibration box




3 calib boxes on XA-VD

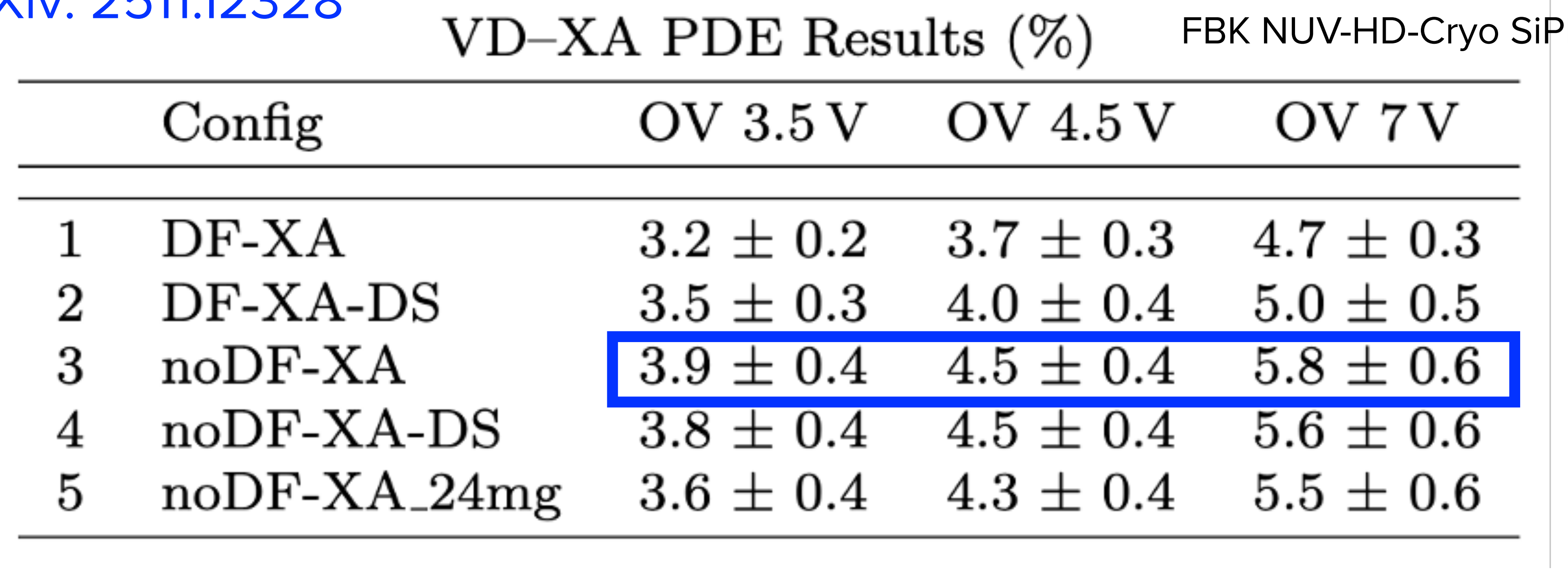
Optimized XA-HD & XA-VD PDE

- XA-VD: **PDE ~4-6%** (22% PDE increase by removing the dichroic filters (noDF) due to the non-ideal DF transmittance)

arXiv: 2511.12328

XA-DS: double-sided XA

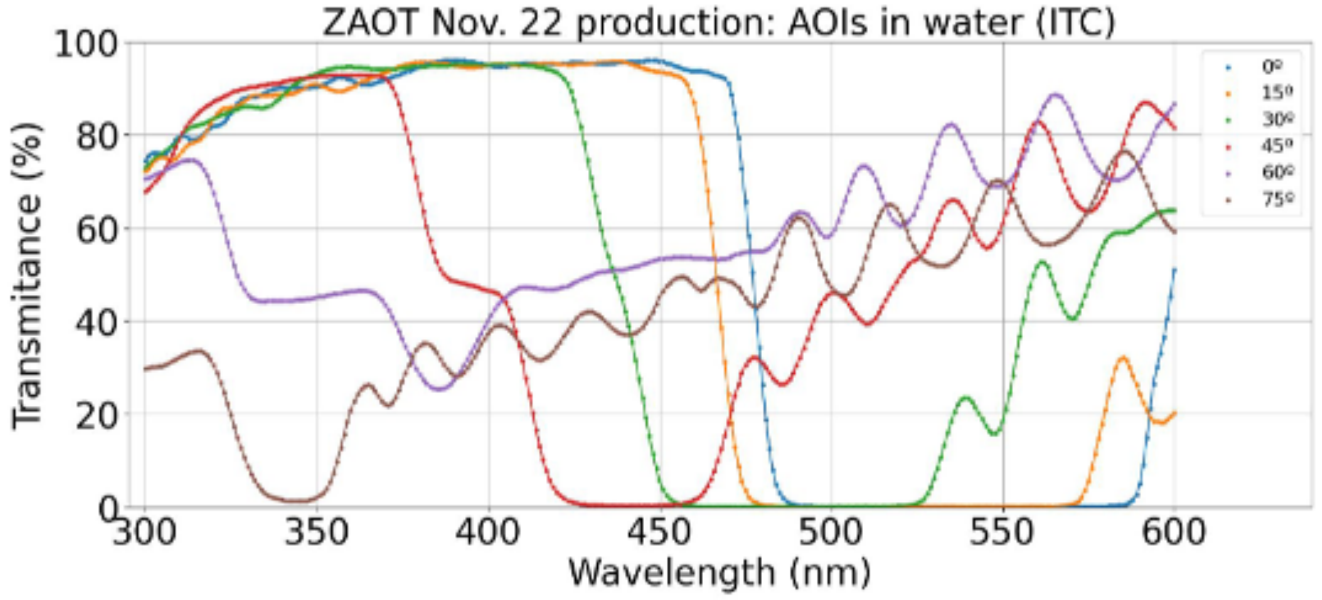
FBK NUV-HD-Cryo SiPM



VD–XA PDE Results (%)

	Config	OV 3.5 V	OV 4.5 V	OV 7 V
1	DF-XA	3.2 ± 0.2	3.7 ± 0.3	4.7 ± 0.3
2	DF-XA-DS	3.5 ± 0.3	4.0 ± 0.4	5.0 ± 0.5
3	noDF-XA	3.9 ± 0.4	4.5 ± 0.4	5.8 ± 0.6
4	noDF-XA-DS	3.8 ± 0.4	4.5 ± 0.4	5.6 ± 0.6
5	noDF-XA_24mg	3.6 ± 0.4	4.3 ± 0.4	5.5 ± 0.6

Transmission curves (TC) measured for ZAOT Nov. 22 production in water

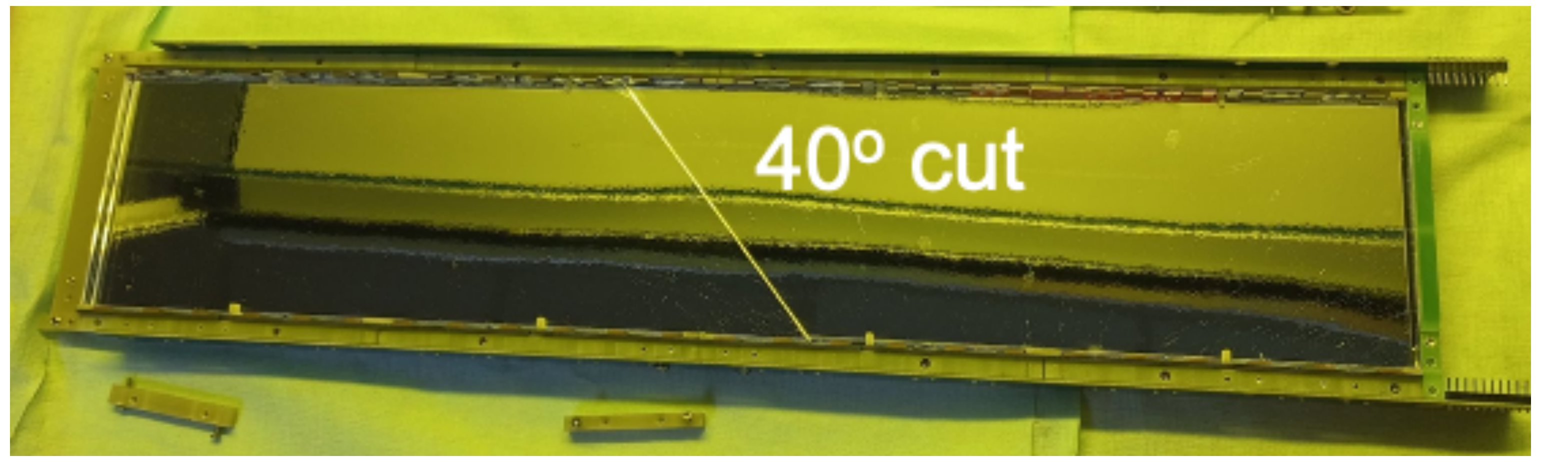


- XA-HD: **PDE ~ 4%** (~80% PDE increase by removing DF and adding a cut on the WLS bar)

HPK SiPMs

OV	Relative PDE noDF/DF	Relative PDE cut/no_cut
2 V	1.36 ± 0.02	1.33 ± 0.01
2.5 V	1.38 ± 0.02	1.32 ± 0.01
3 V	1.40 ± 0.02	1.31 ± 0.01

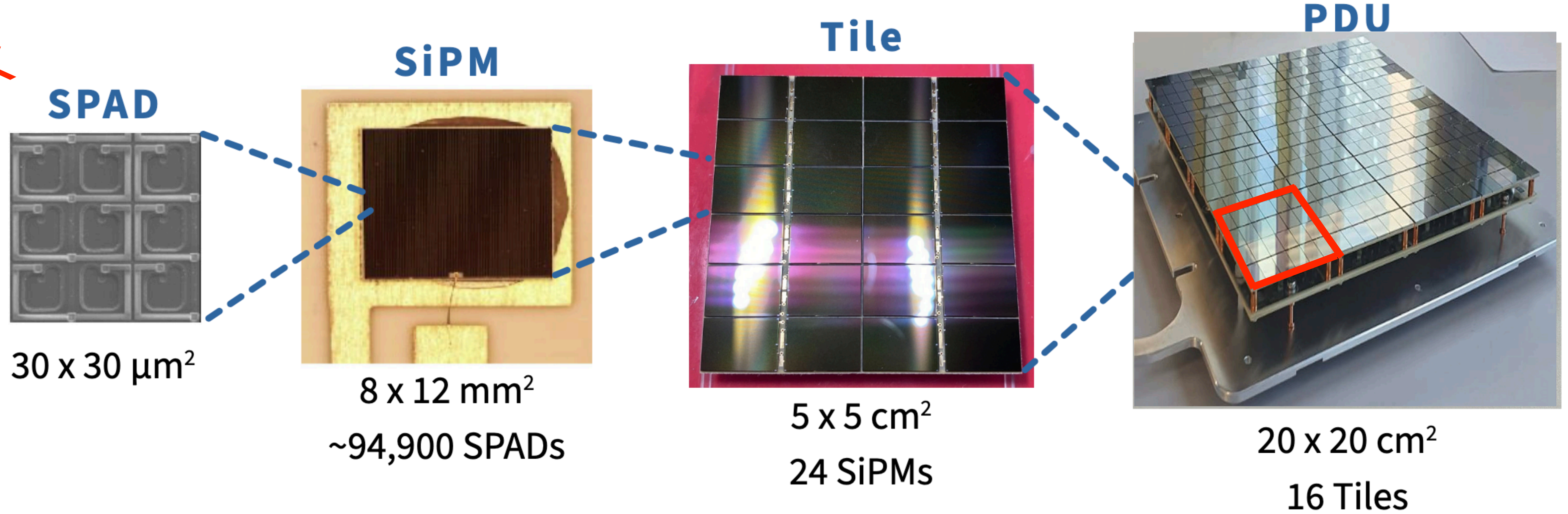
Paper in preparation



SiPM arrays for DM detection & 0νββ

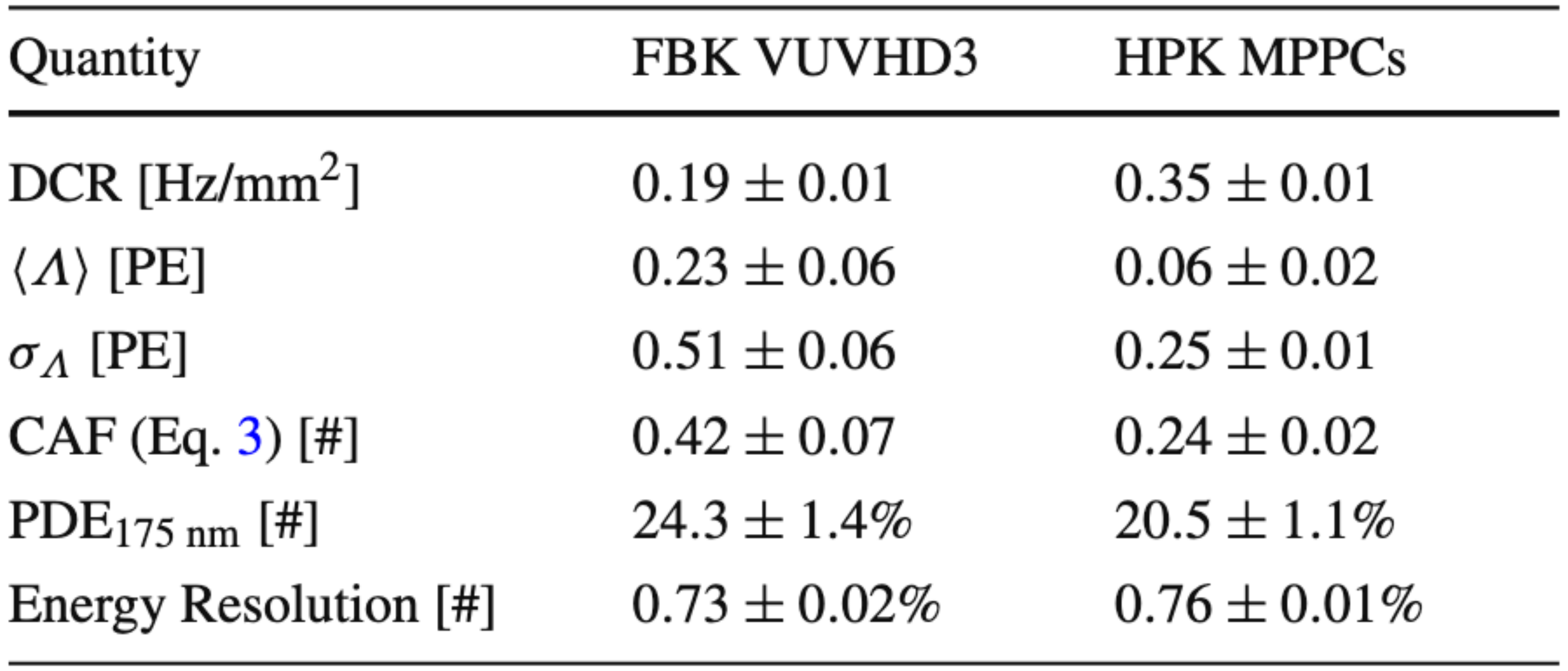
Talk by D. Rudik

- **DarkSide-20k**: SiPM arrays for DM detection
  - SiPMs: 11.8 mm × 7.9 mm near-UV sensitive, high-density Cryo NUV-HD SiPMs developed by FBK
    - PDE > 40% at 410 nm & DCR <1 Hz/cm^2 at 77 K
- **nEXO**: VUV SiPM measurements at 163 K at different setups
  - new FBK VUVHD3 sensitive to 175 nm vs HPK VUV4 MPPCs (S13370-6050CN & S13371-6050CQ)



Optical Plane = 264 PDUs

Eur. Phys. J. C (2022) **82**: 1125   at 163 K & OV3

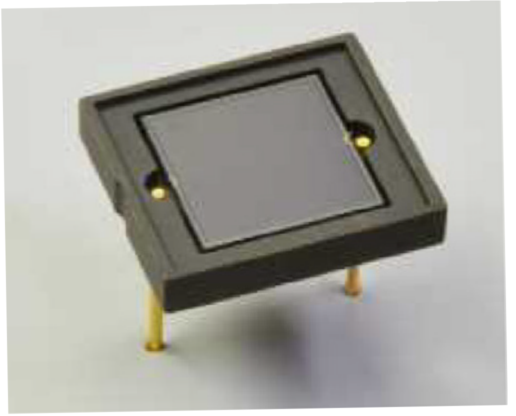


Quantity	FBK VUVHD3	HPK MPPCs
DCR [Hz/mm^2]	0.19 ± 0.01	0.35 ± 0.01
$\langle\Lambda\rangle$ [PE]	0.23 ± 0.06	0.06 ± 0.02
σ_Λ [PE]	0.51 ± 0.06	0.25 ± 0.01
CAF (Eq. 3) [#]	0.42 ± 0.07	0.24 ± 0.02
PDE$_{175\ \mathrm{nm}}$ [#]	$24.3 \pm 1.4\%$	$20.5 \pm 1.1\%$
Energy Resolution [#]	$0.73 \pm 0.02\%$	$0.76 \pm 0.01\%$

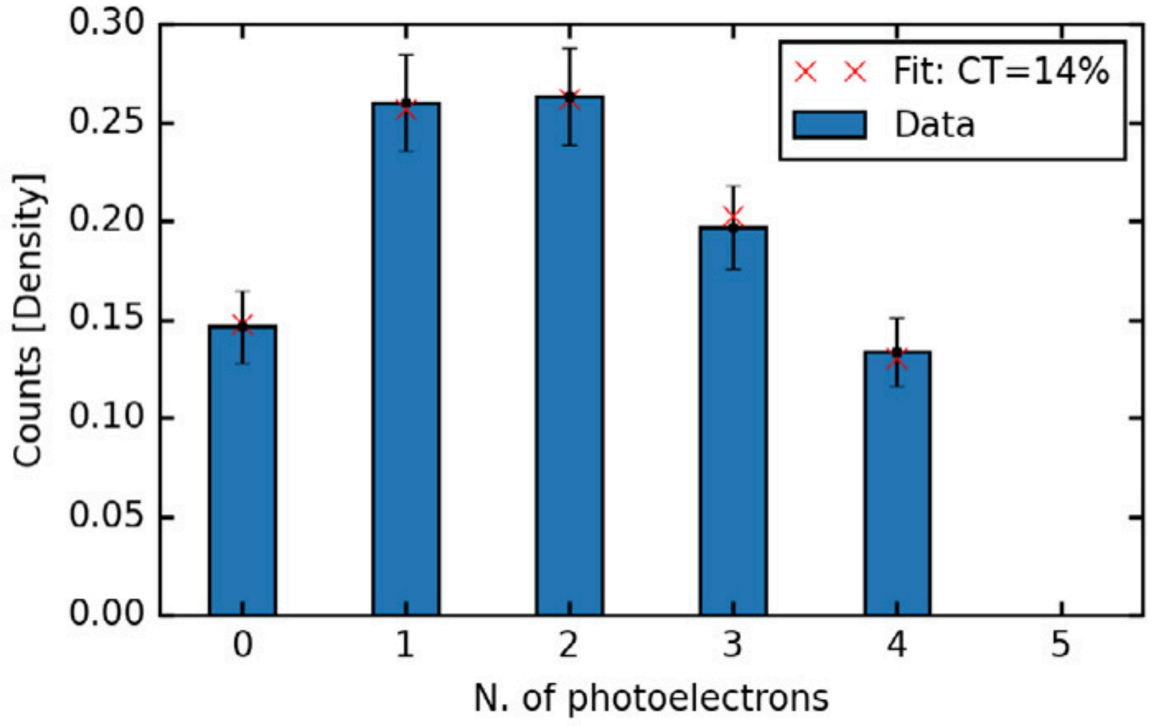
HPK VUV4 cryo SiPMs

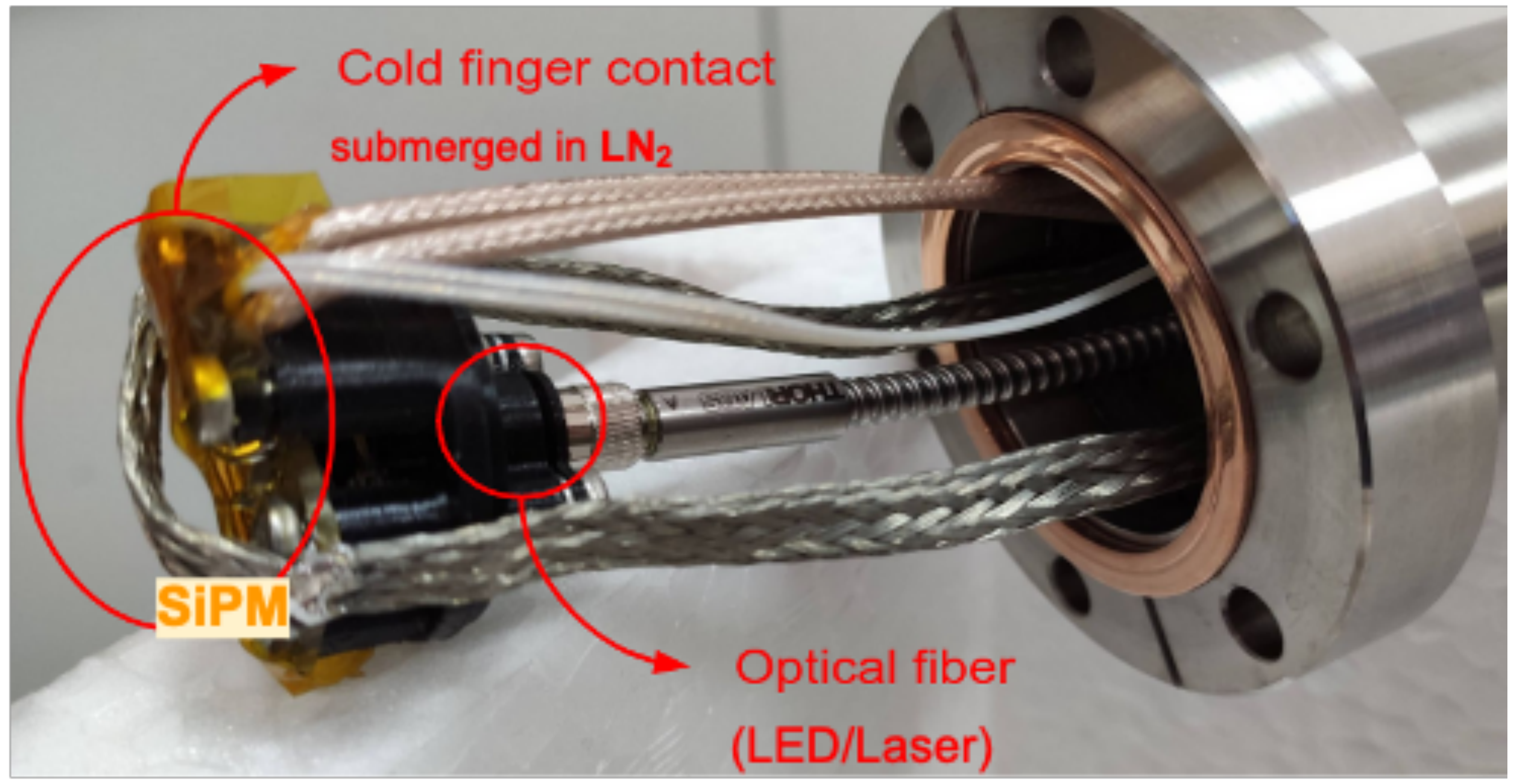
NIMA 1064 (2024) 169347

- S13370–6075CN (6x6 mm^2)
- Sensitive to **127 nm**
- PDE measurement vs wavelength at different temperatures at CIEMAT



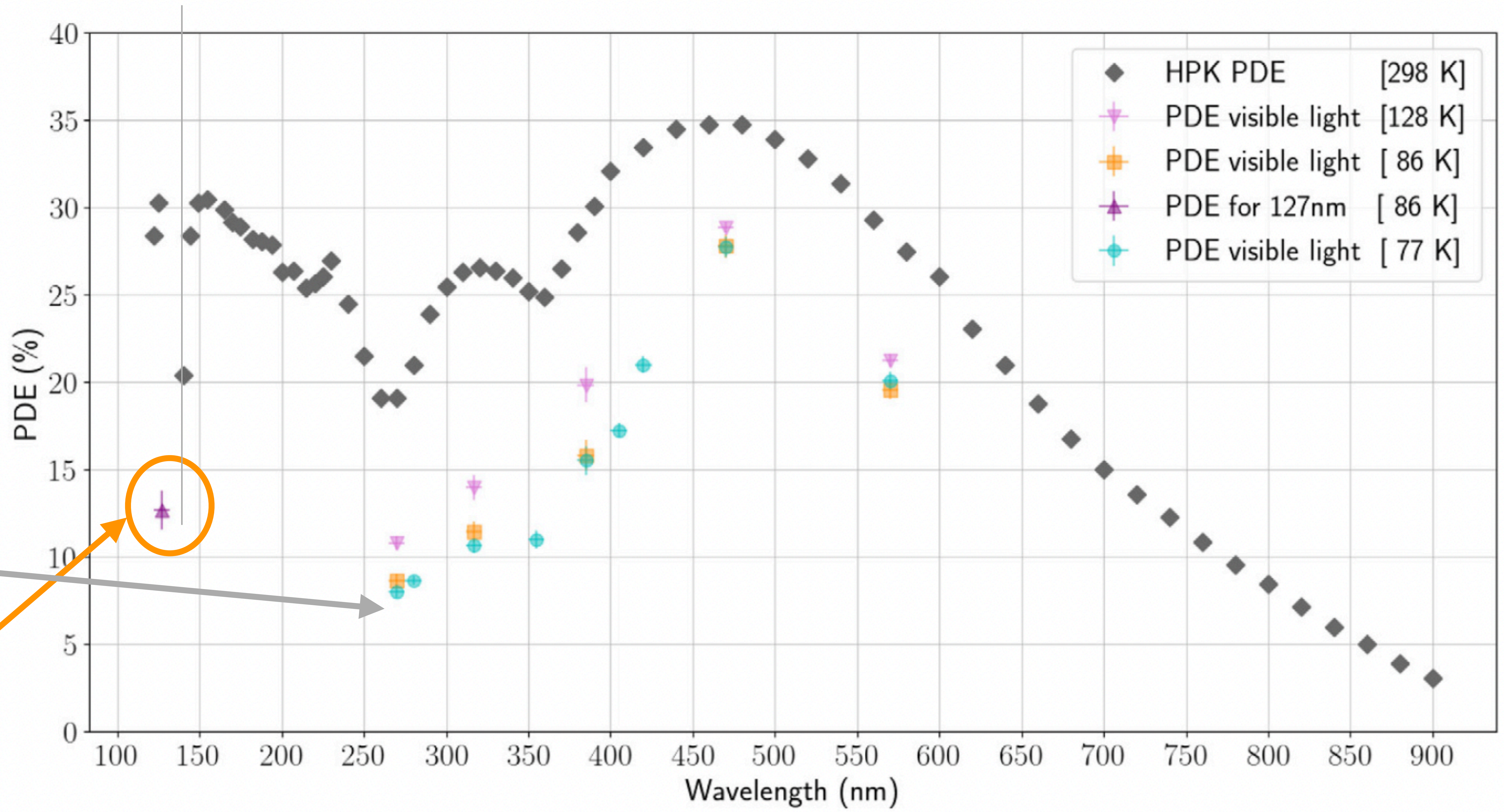
Parameter	Value
Effective photosensitive area	(6×6) mm^2
Size	(10×9) mm^2
Pixel pitch	75 µm
Terminal capacitance	1.28 nF
Fill factor	70%
Crosstalk probability	5%
Gain	$5.8 \cdot 10^6$
Dark counts (typ.)	0.11 MHz
Breakdown voltage	(55 ± 0.2) V
Breakdown voltage [86.15 K]	(42 ± 0.2) V





$$PDE_{CT} = \frac{PE_{CT}}{PE_{RT}} PDE_{RT}$$

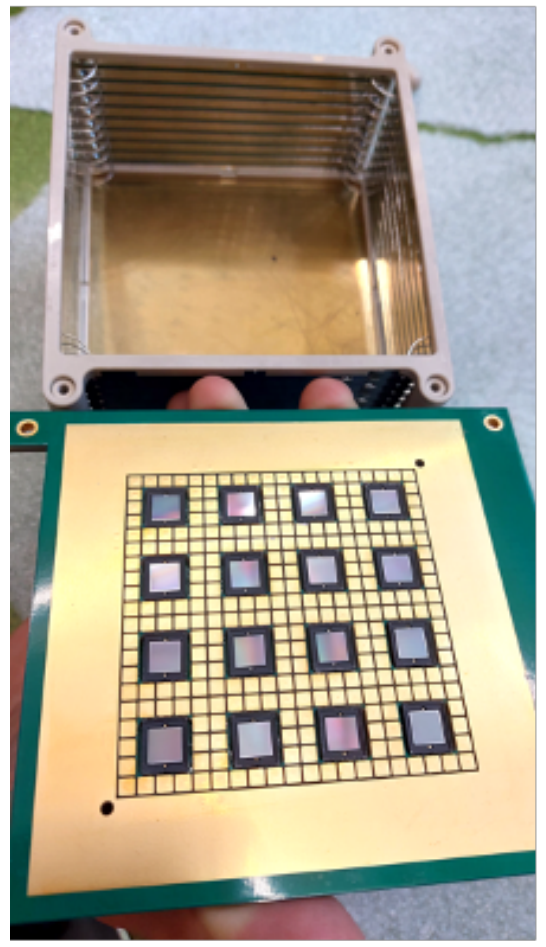
- ❋ Strong decrease of PDE wrt room T
- **PDE at 127 nm at 86 K** with ^{241}Am source
  - ❋ **~12% at OV4**



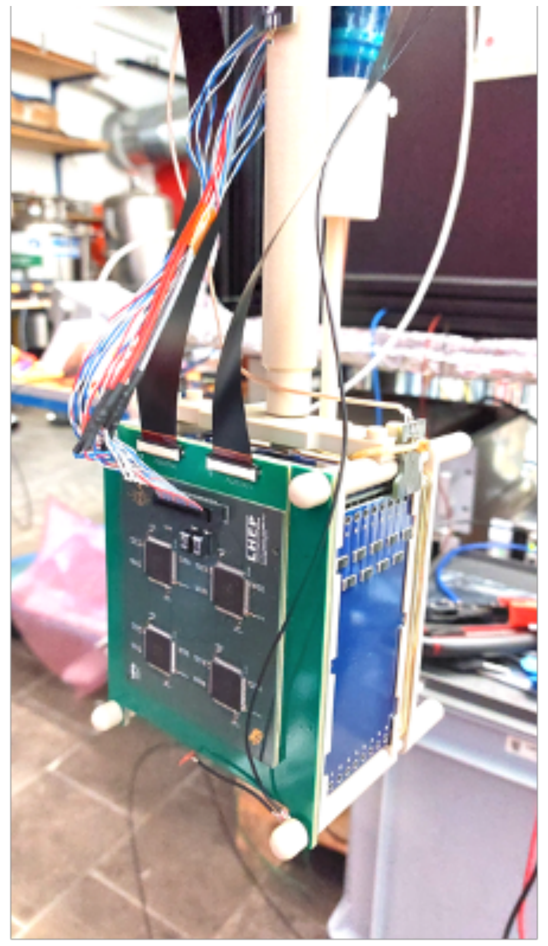
SoLAr project: pixels + light readout

- **Pixelated charge readout** (enhanced event reconstruction) **with HPK VUV4 SiPMs integrated in the anode** (Q+L calorimetry and enhanced E resolution ~7%) with background suppression (passive shielding, PSD, …)
- Physics goal: enhance the detection of low-energy neutrino signals (in particular solar νs)
- **Prototype v1** (LAr TPC 12x11 cm^2 x 5 cm drift): cosmics test run at Bern in **Oct 2022**
  - First demonstration of combined light and charge readout on the same anode plane
- SoLAr_v1 prototype demonstrator published: JINST 19 (2024) 11, P11010

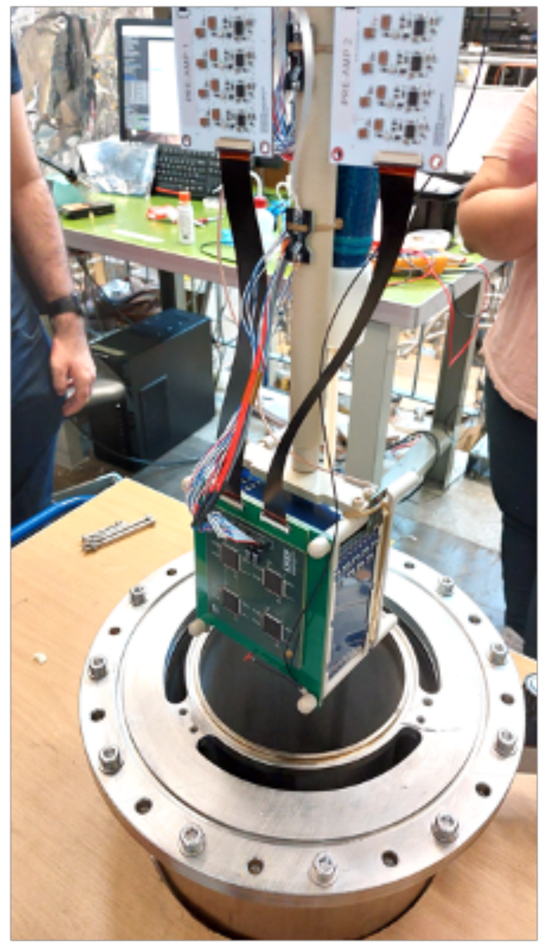
- Charge pixel pads: 3mm
- Pixel pitch: 3.5mm
- SiPM sensitive area: 6mm x 6mm
- SiPM pitch: 17.5mm
- Readout area: 70mm x 70mm



Inside the TPC

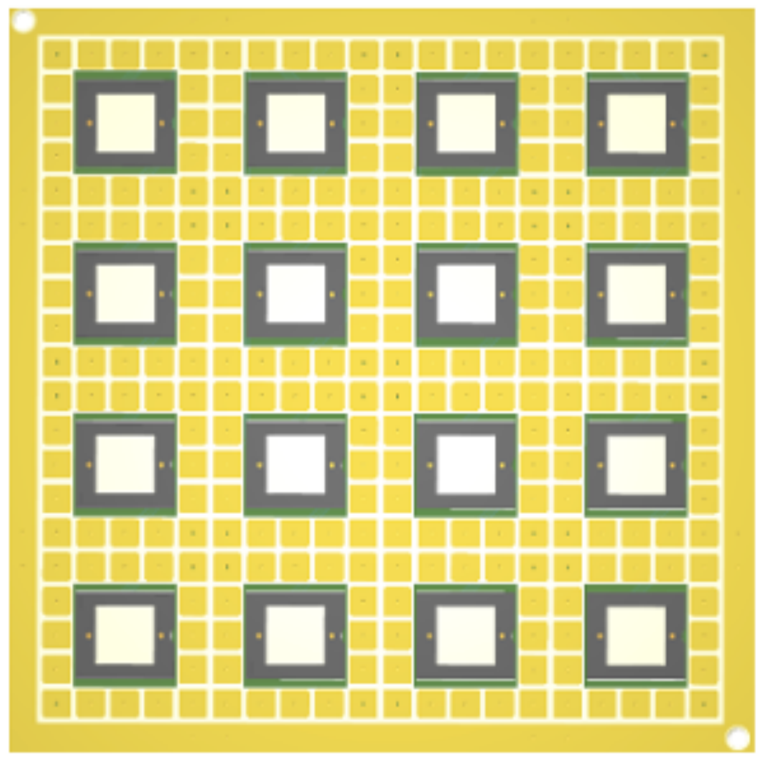


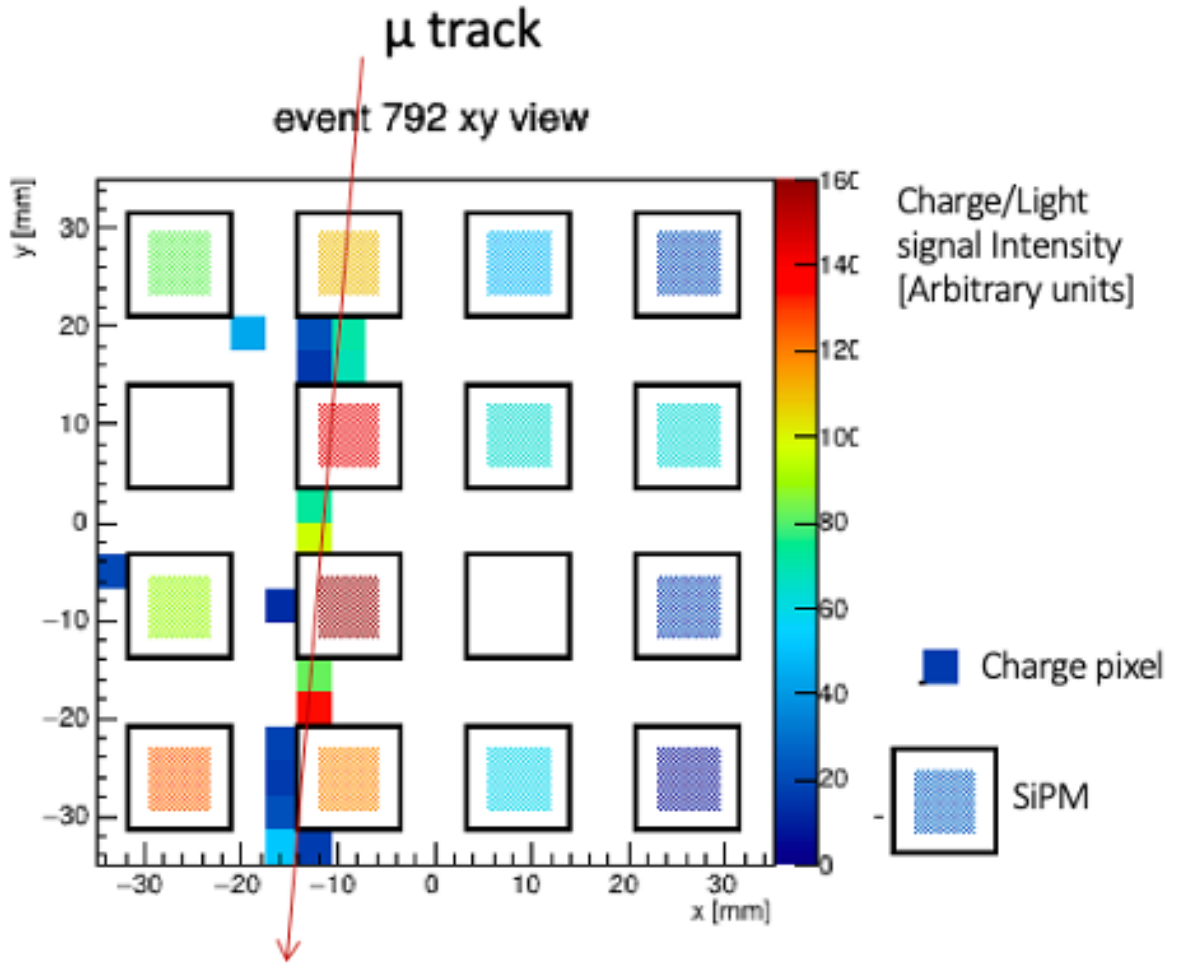
SoLAr-v1 TPC



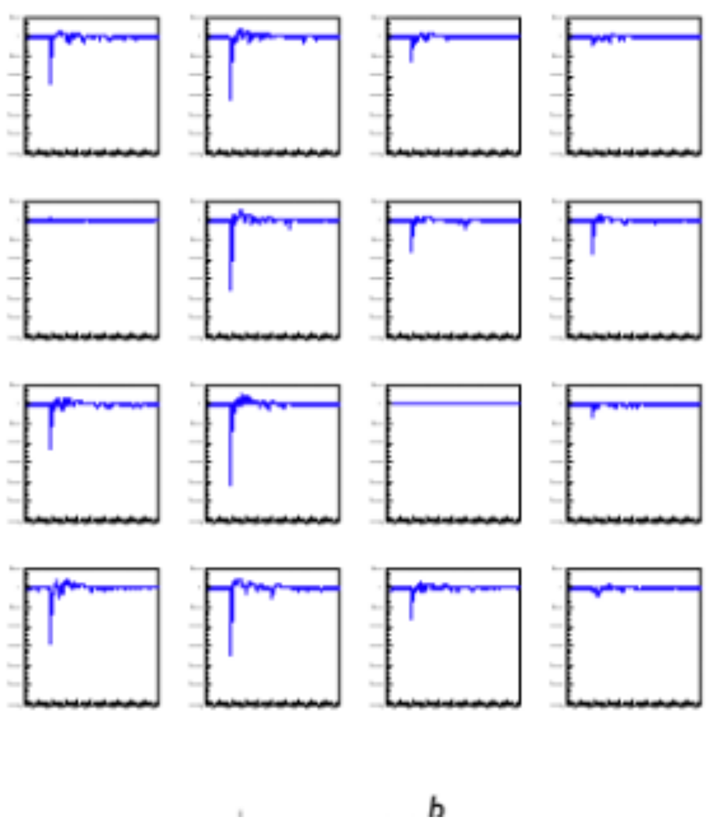
Insertion into cryostat

Anode plane visual guide



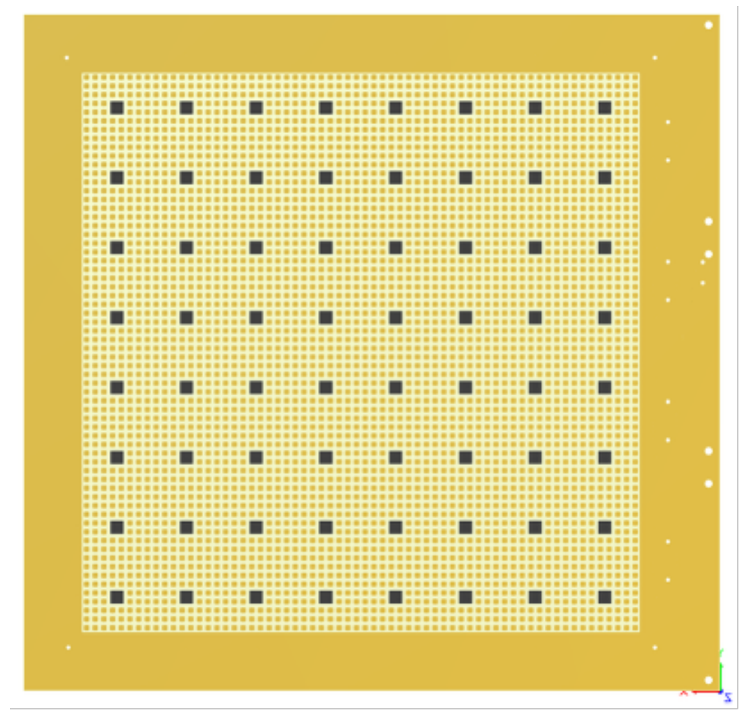


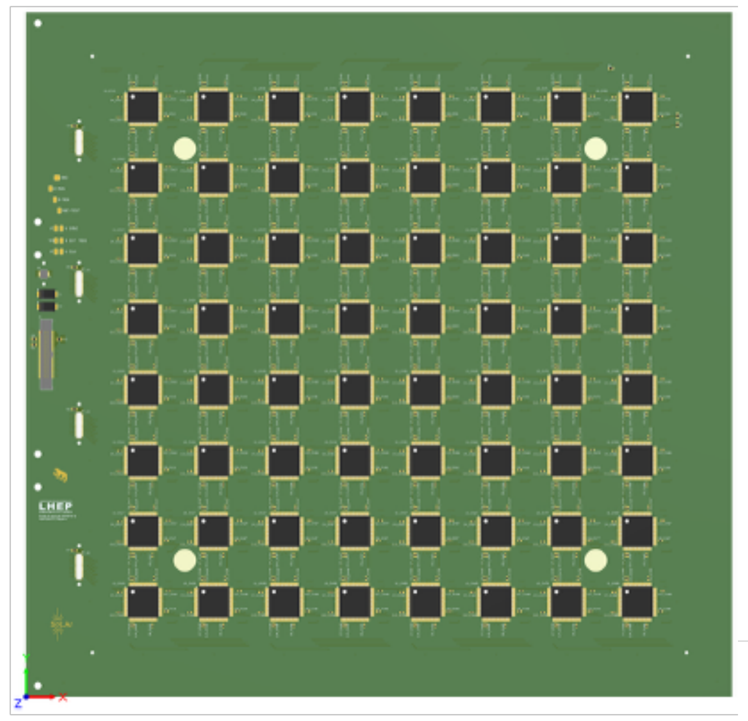
SiPM waveforms

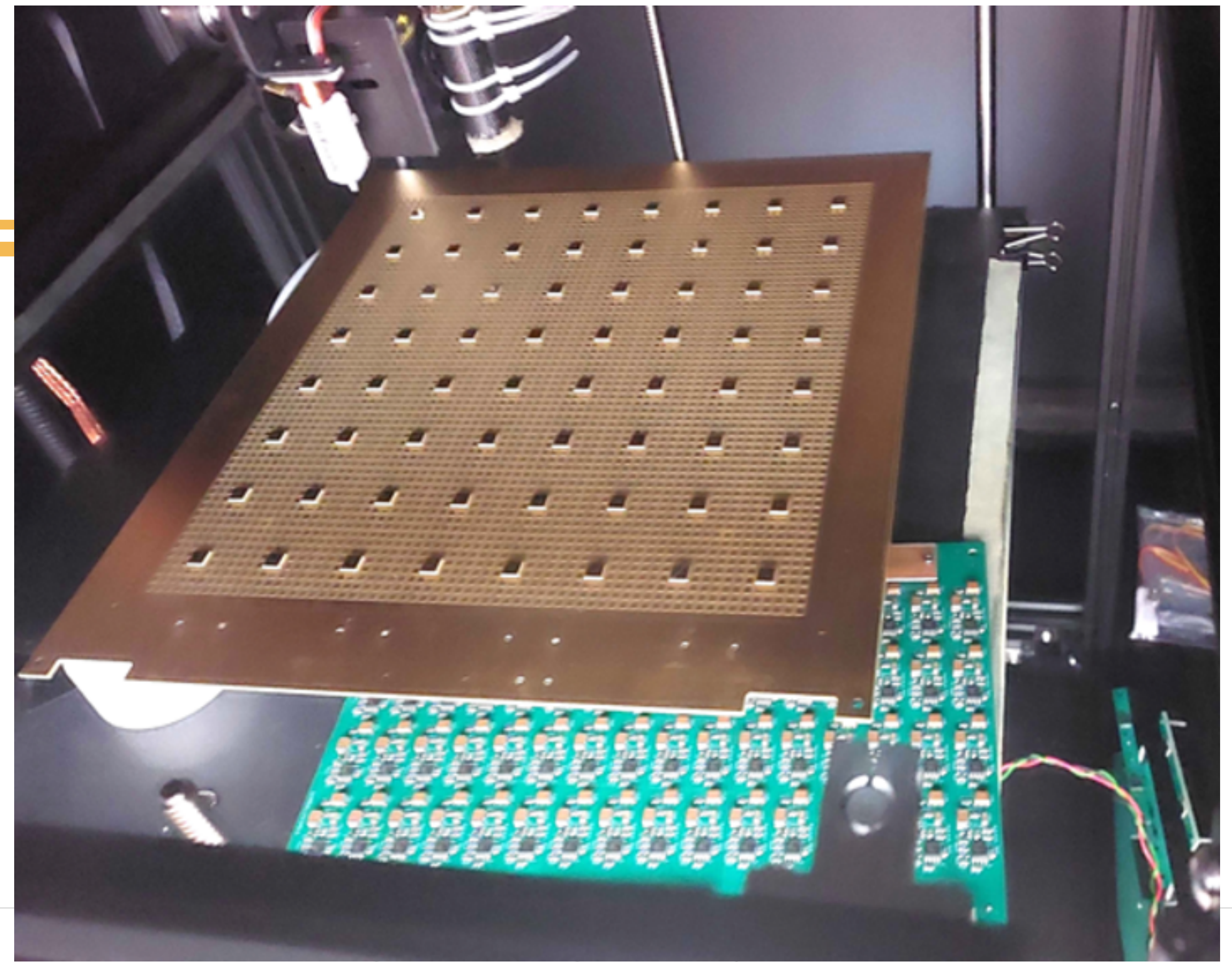


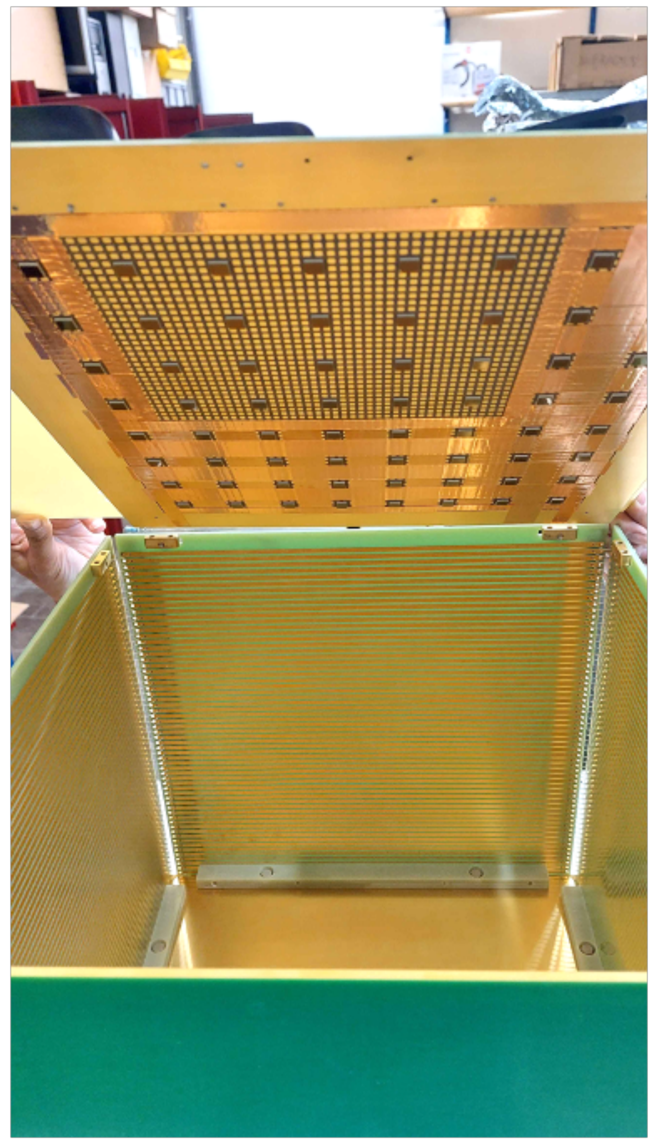
SoLAr prototype v2

- New LArTPC prototype
  - 8-layer PCB, dimensions 31cm x 32 cm
  - Divided into 8x8 regions: 1 region = 60 pixels+1 SiPM; pixel pitch: 4mm
- 64 LArPix (60 routed channels)
- 64 Hamamatsu VUV SiPMs
  - SMD type, 6 mm x 6 mm
  - SiPM pitch: 32 mm
- Cosmics test run at Bern in July 2023 at nominal HV 15 kV and special Cobalt-60 source run
- Anode tile was populated with 64 VUV SiPMs and 20 LArPix v2b chips
- Publication under review

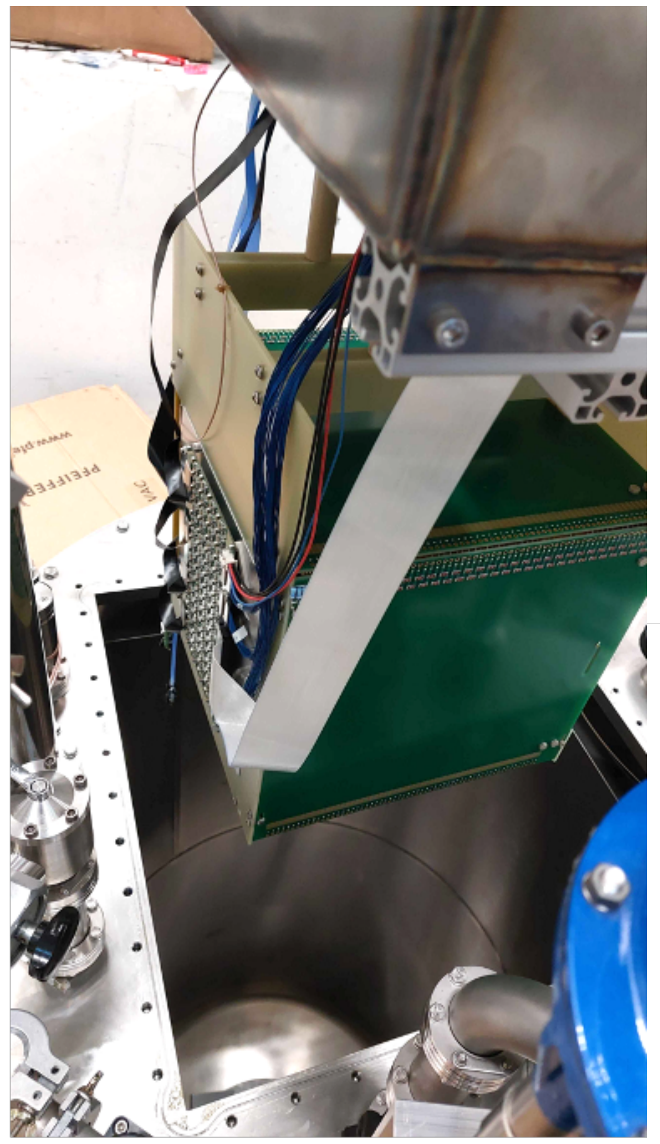




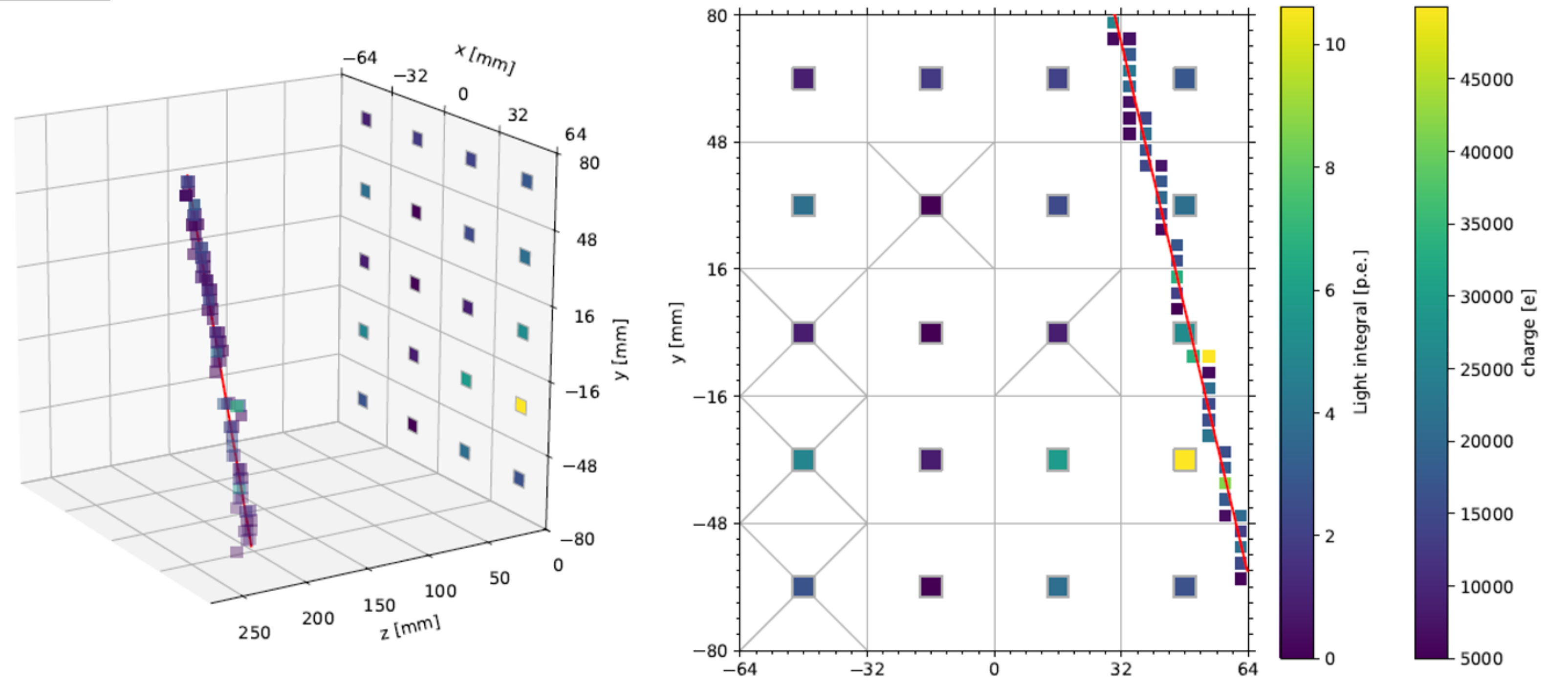


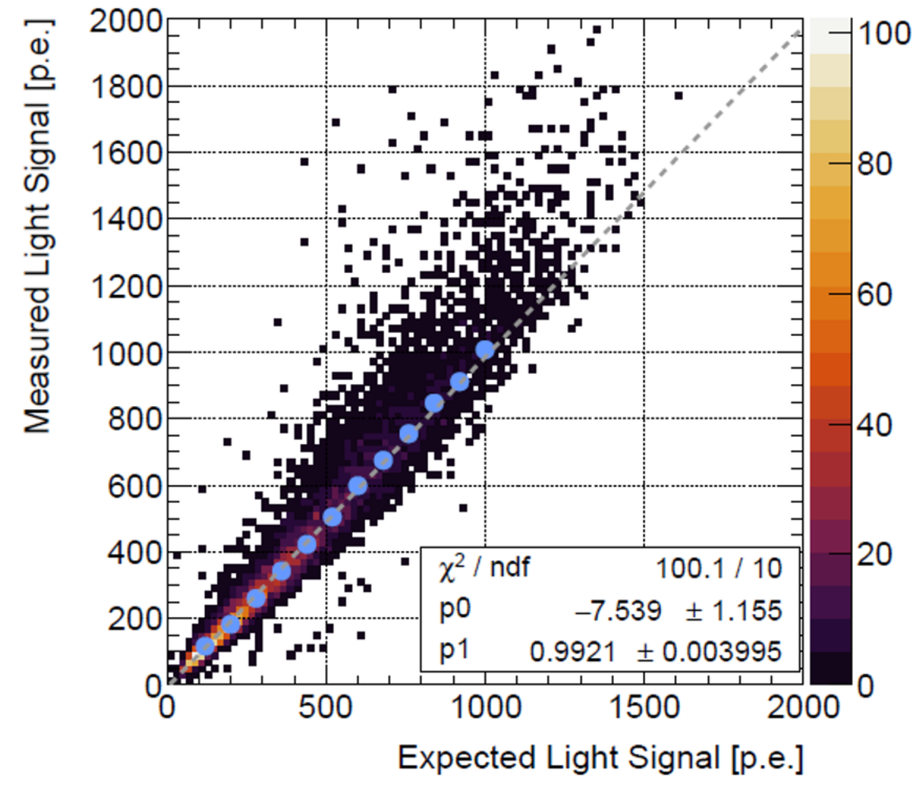


Inner view of the TPC



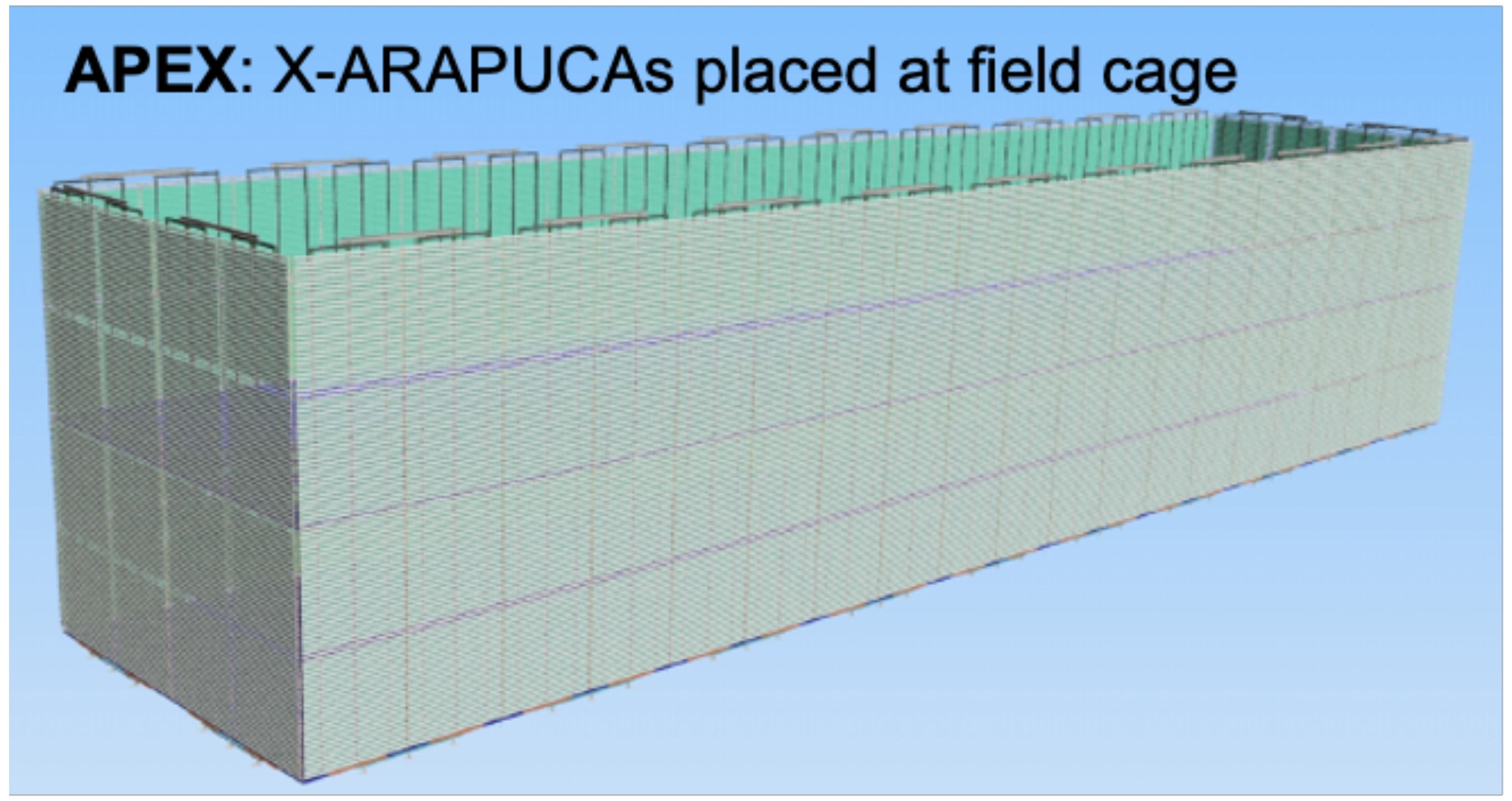
Insertion into cryostat





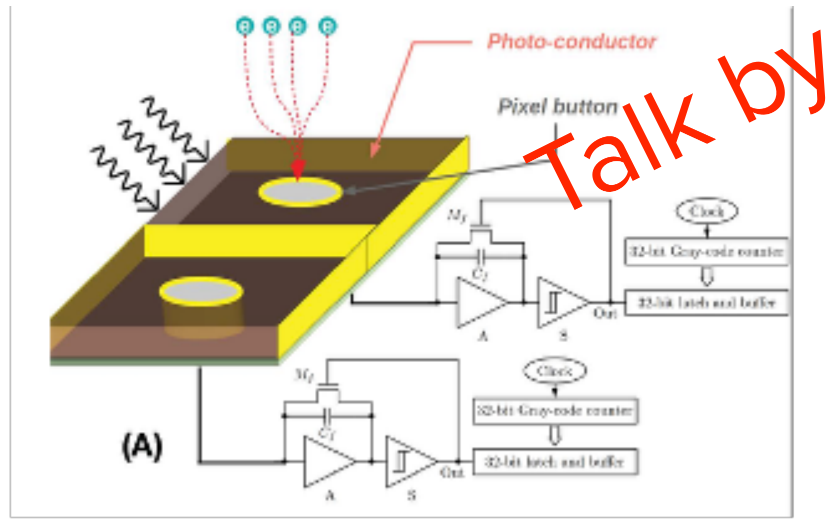
ProtoDUNE-III @CERN Neutrino Platform

- "DUNE Phase II: scientific opportunities, detector concepts, technological solutions", [JINST 19 (2024) 12, P12005]
- Several new photon detection systems are being explored for next DUNE FD modules (tests at large scale foreseen at CERN)
  - SoLAr, APEX, ARIADNE, PoWER, Q-Pix-LILAr



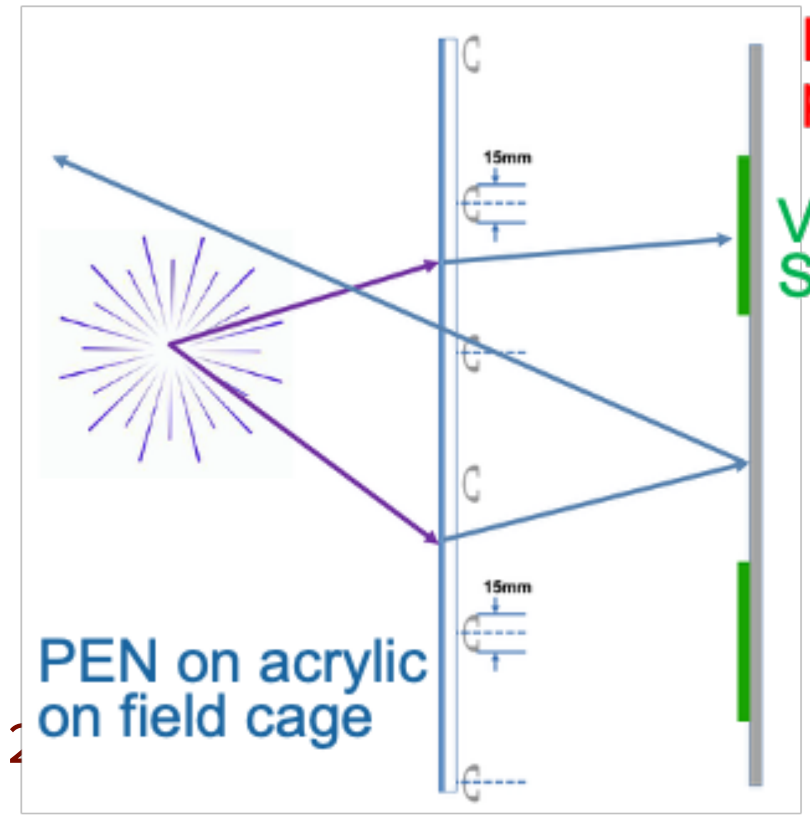
APEX: X-ARAPUCAs placed at field cage

ARIADNE: Dual-phase optical charge (S2 produced in THGEMs) readout with fast cameras (TimePix3)



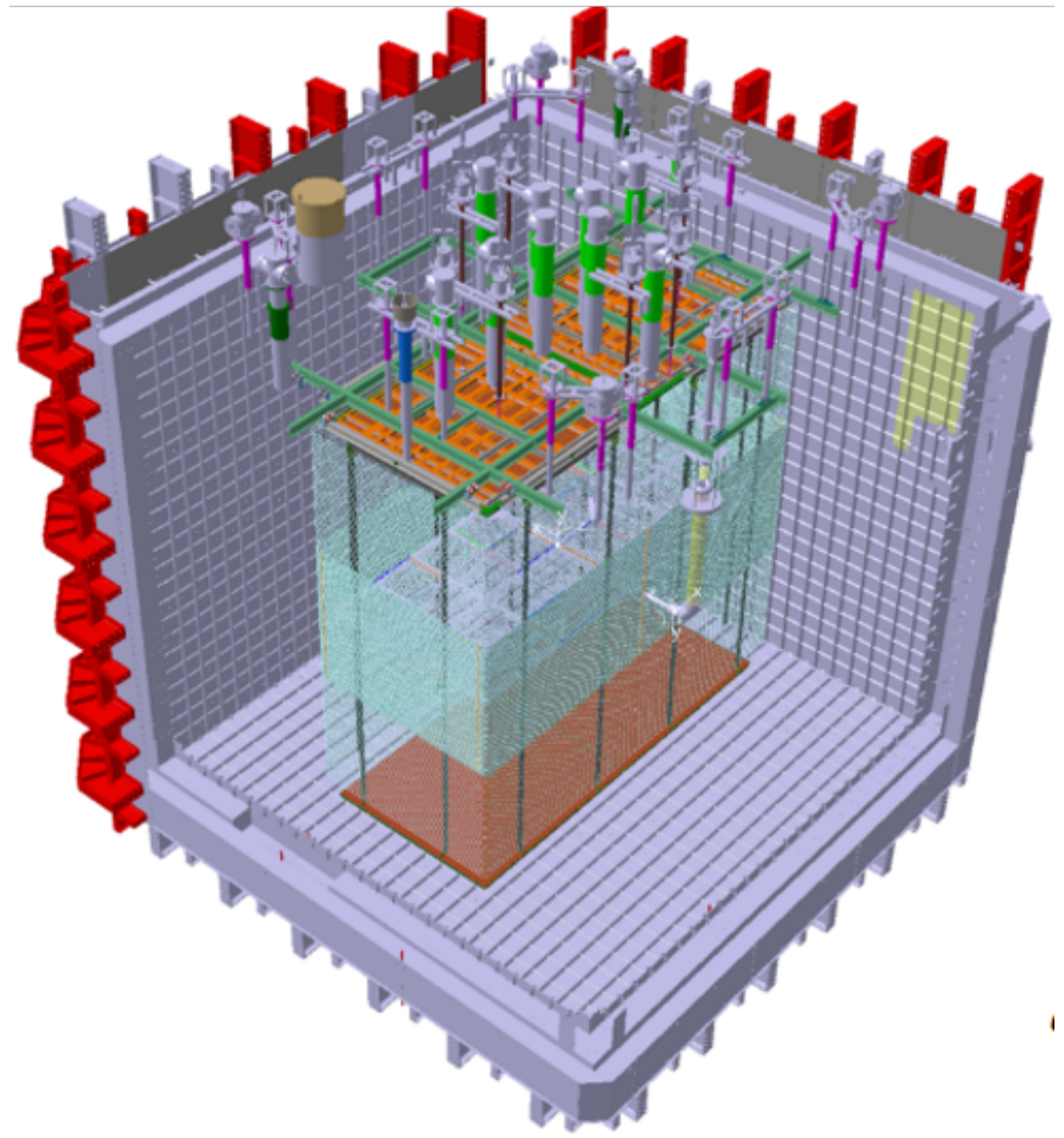
Talk by E. Gramellini

Q-Pix-LILAr: coating a charge readout pixel with a type of photo-conductive material



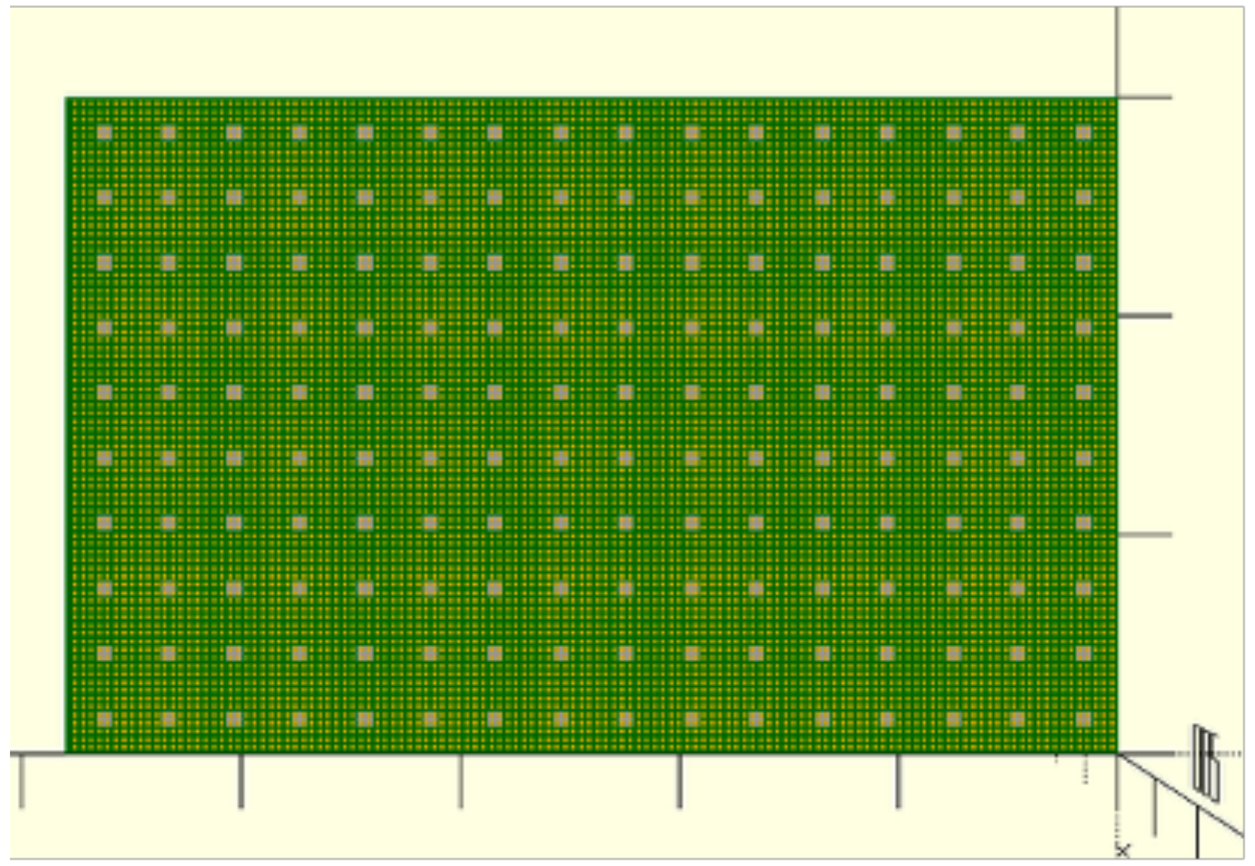
PoWER: PEN + reflectors + SiPMs

SoLAr in ProtoDUNE-III

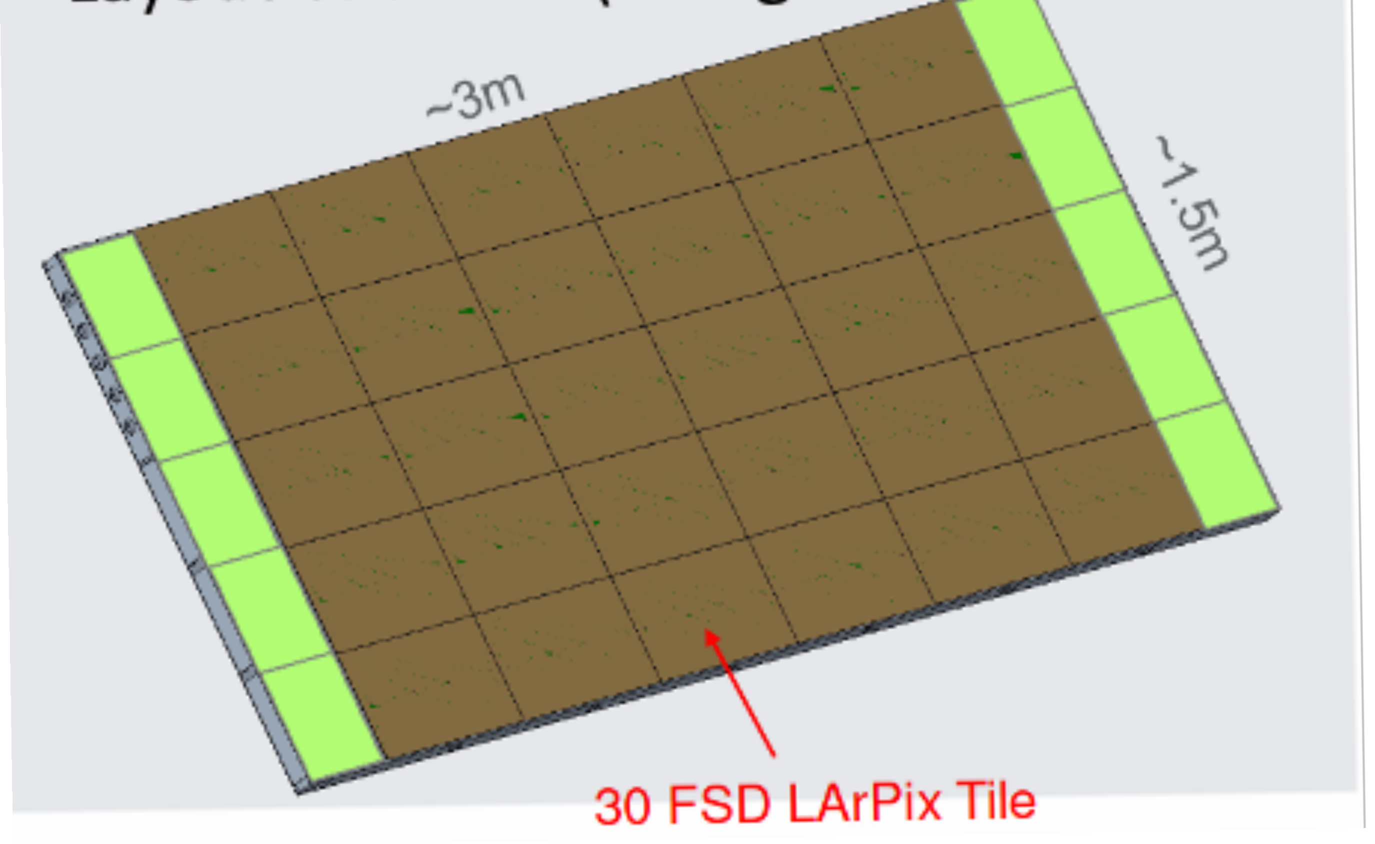


- Replace a few of LArPix tiles with SoLAr tiles in the planned pixelated CRP
- It can be fully integrated through the same data acquisition chain
- Larger SoLAr tiles to match the LArPix tiles proposed for pixelated CRP - Dimensions: 30 cm x 48 cm (160 LArPix, 160 SiPMs)
- Charge readout: LArPix; possibility to use LightPix for SiPM readout

SoLAr tile



Layout of a CRU (charge readout unit)



LightPix: scalable digital readout for cryo SiPMs

- **Adapt existing LArPix ASIC** to provide scalable readout for many (e.g. >106) Silicon Photomultipliers
- Reuse demonstrated LArPix system architecture: Very-low-power (~100 μW/channel), cryo-compatible (87 K), highly-scalable at O($0.10)/channel system cost
- TDC with ns precision
- Unique channel for every SiPM (no analog ganging) → Highly granular detector

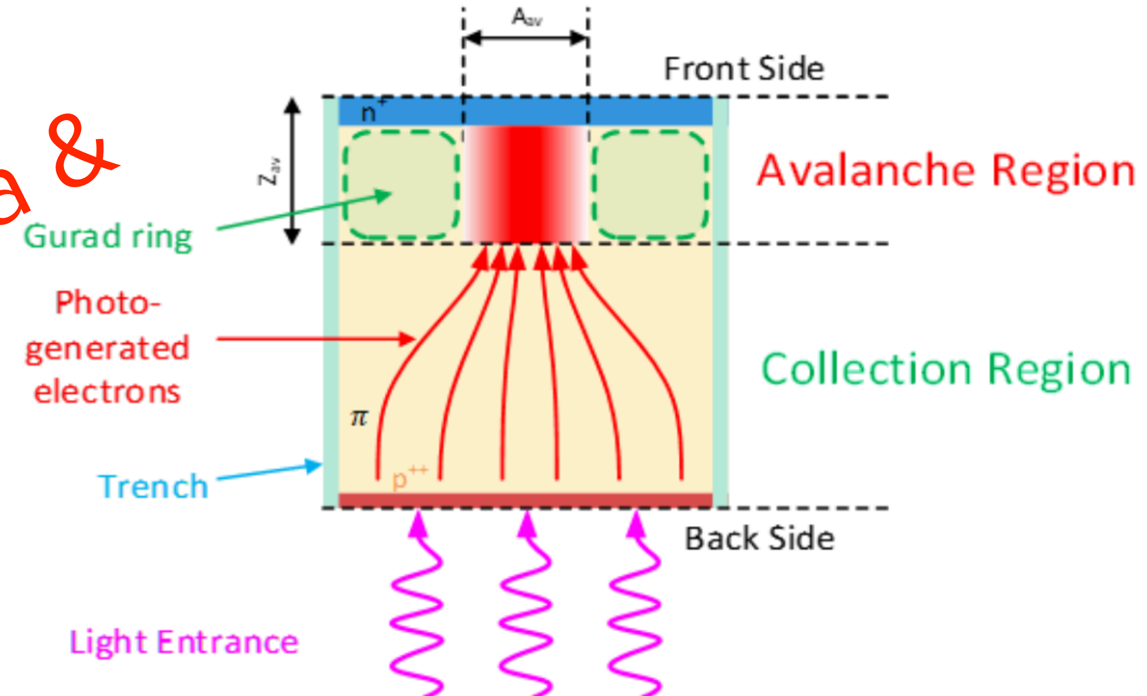
R&D on cryogenic VUV photodetectors

- R&D on new photon detector systems at cryogenic temperature (DRD2)
  - Photosensor PDE and photon collection improvement

next page

- Cryogenic back-side illuminated SiPMs (DRD4)
  - R&D with FBK NUV-BSI SiPMs

Talks by A. Gola & P. Katchru



New BSI-SiPM structure

- Improving timing capabilities (~100 ps) of VUV-sensitive cryogenic photon detectors
  - Interesting for some projects as nuSCOPE, DUNE low E, …

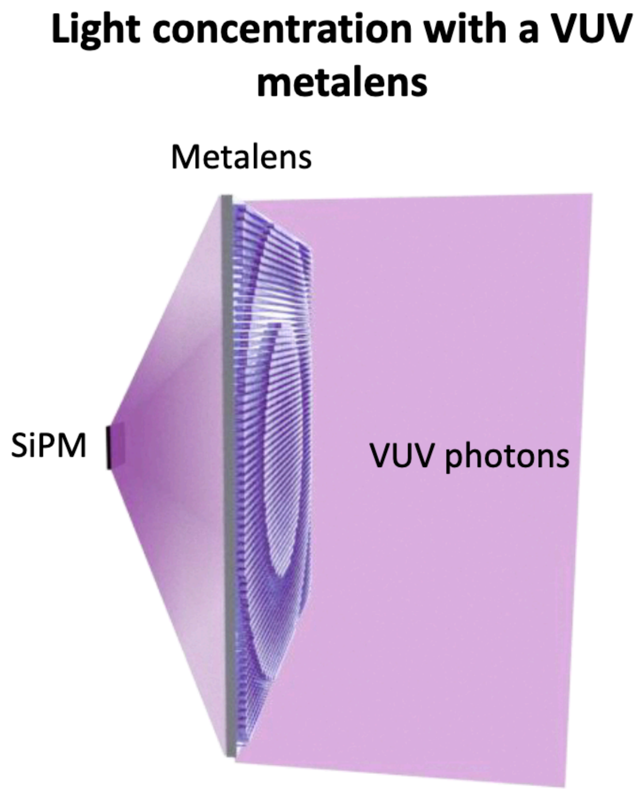
R&D on VUV light detection

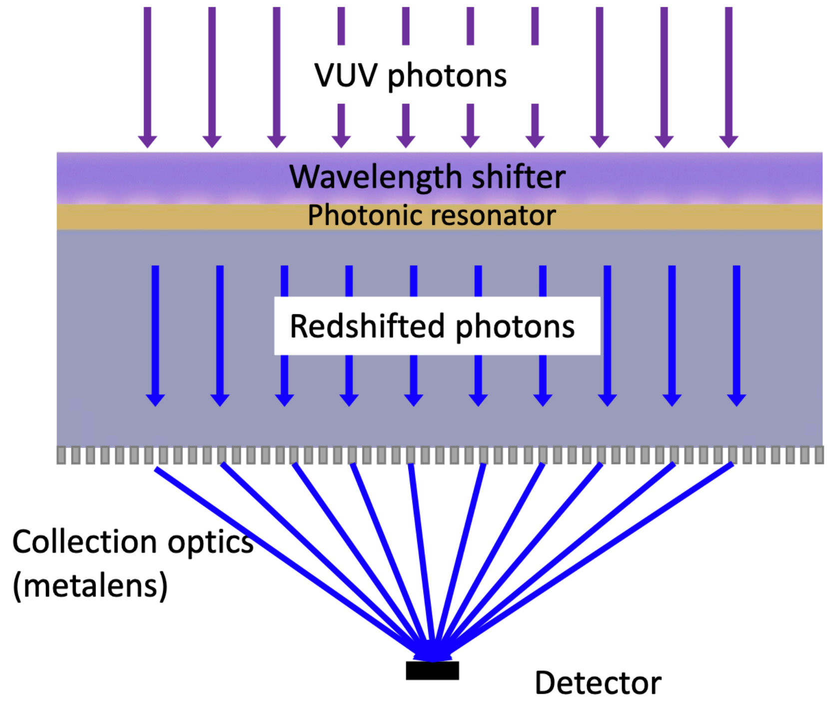
Goal: increase **photon detection efficiency** and **photon collection** capabilities

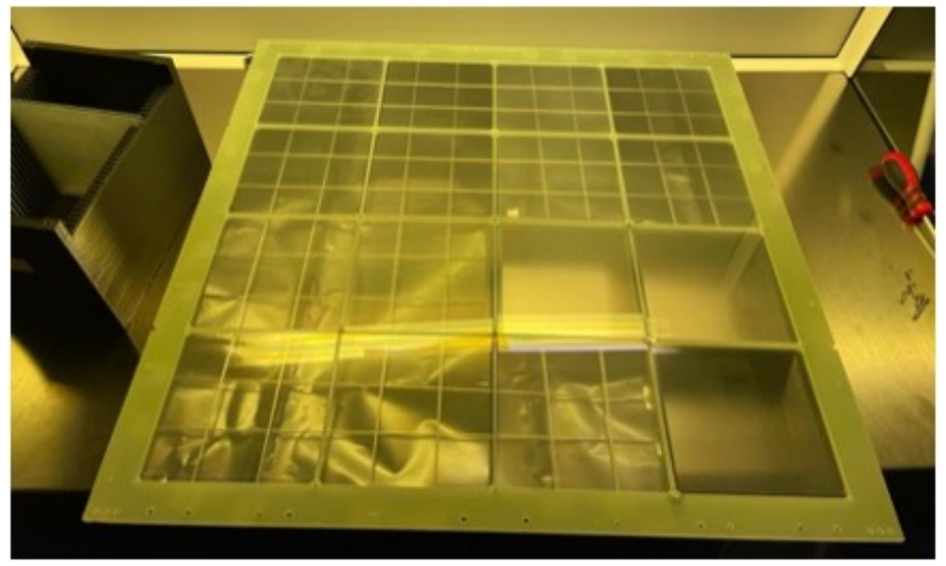
- Large area **WLS** and **reflectors**: new materials, characterization facilities
- Organic **photosensors** & **digital cryogenic SiPMs** (CMOS SPADs, BSI SPADs)

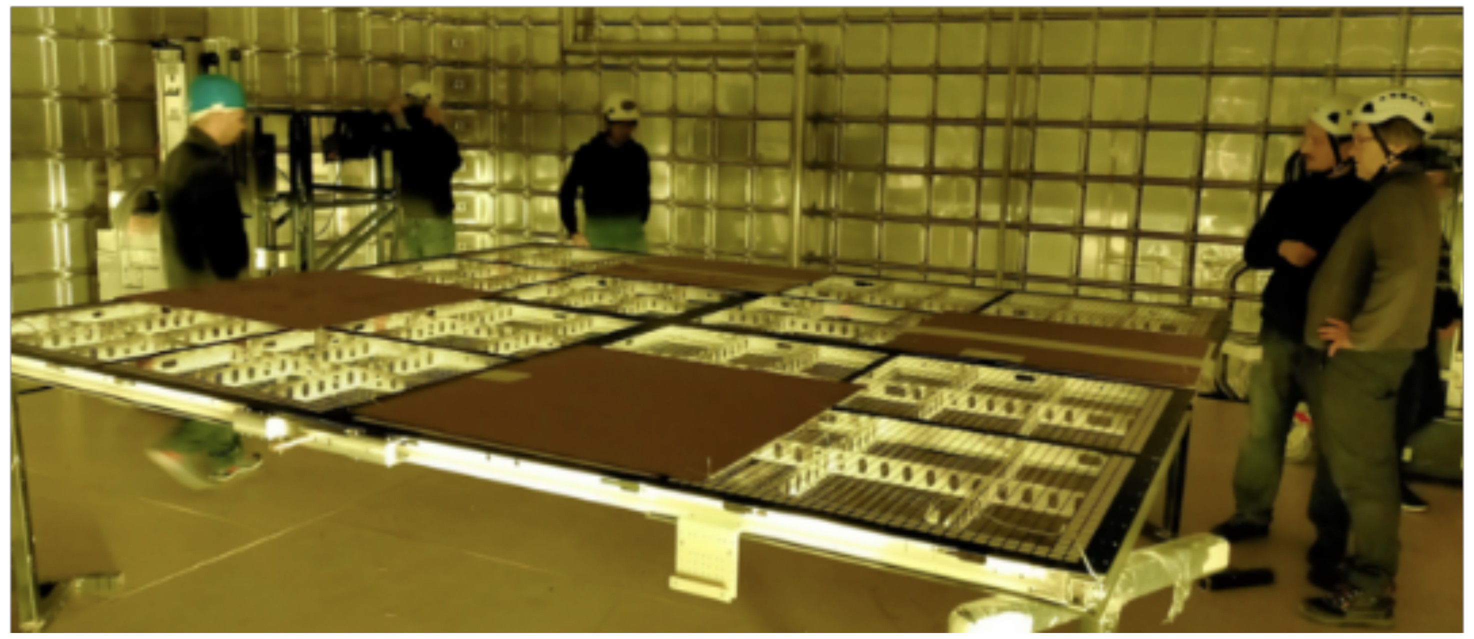
Talk by P. Fisher

- Photodetectors in **HV** environment:
  - Instrument field cage and cathode to increase photocoverage in TPCs using Power-over-Fiber and Signal-over-Fiber transmission technologies
- Development of dedicated **cryogenic facilities** for VUV sensor characterization and optimization









Summary

- Cryogenic photon detectors continue to be developed for neutrino and dark matter detection (in collaboration with manufacturers).
- VUV cryogenic photodetectors (down to 127 nm and down to 86 K) present many challenges in photon collection, detection, and cryogenic electronics.
- The problem of scalability/photocoverage (from a few m^2 to 100-1000 m^2) and #channels vs cost remain significant.
- New ideas including digital SiPMs, BSI SiPMs, and new materials are being developed. Applications for VUV and cryogenics are worth pursuing.
- An R&D program on new cryogenic photodetection is ongoing at the CERN DRD2 (and DRD4) collaboration.

Grazie Bologna!

ines.gil@ciemat.es

7th international workshop on new Photon-Detectors

PD 2025 **3-5 December 2025**
Bologna, Italy

Related publications

1. F. Acerbi et al., “Cryogenic characterization of FBK NUV-HD-Cryo 3T SiPM sensors for the DUNE photon detection system”, arXiv:2511.9095
2. G. Botogoske et al., “Laboratory Measurement of the X-ARAPUCA's Absolute Photon Detection Efficiency for the Deep Underground Neutrino Experiment's Vertical Drift Far Detector”, arXiv: 2511.12328
3. R. Alvarez et al., “Measurement of the photon detection efficiency of Hamamatsu VUV4 SiPMs at cryogenic temperature”, NIMA 1064 (2024) 169347
4. M. Andreotti et al., “Cryogenic characterization of Hamamatsu HWB MPPCs for the DUNE photon detection system”, *JINST* 19 (2024) 01, T01007
5. R. Alvarez et al., “Measurement of the absolute efficiency of the X-ARAPUCA photon detector for the DUNE Far Detector 1”, *Eur. Phys. J. C* 84 (2024) 10, 1004
6. N. Anfimov et al., “First demonstration of a combined light and charge pixel readout on the anode plane of a LArTPC”, *JINST* 19 (2024) 11, P11010
7. E. Calvo et al., “Validation of electrodeposited 241Am alpha-particle sources for use in liquified gas detectors at cryogenic temperatures”, Appl. Radiat. Isot. 200 (2023) 110913
8. A. Abed Abud et al., “Scintillation light detection in the 6-m drift-length ProtoDUNE Dual Phase liquid argon TPC”, *Eur. Phys. J. C* 82 (2022) 7, 618
9. B. Aimard et al., “Study of scintillation light collection, production and propagation in a 4 tonne dual-phase LArTPC”, *JINST* 16 (2021) 03, P03007
10. D. Belver et al., “Cryogenic R5912-20Mod Photomultiplier Tube Characterization for the ProtoDUNE Dual Phase Detector", *JINST* 13 (2018) 10, T10006