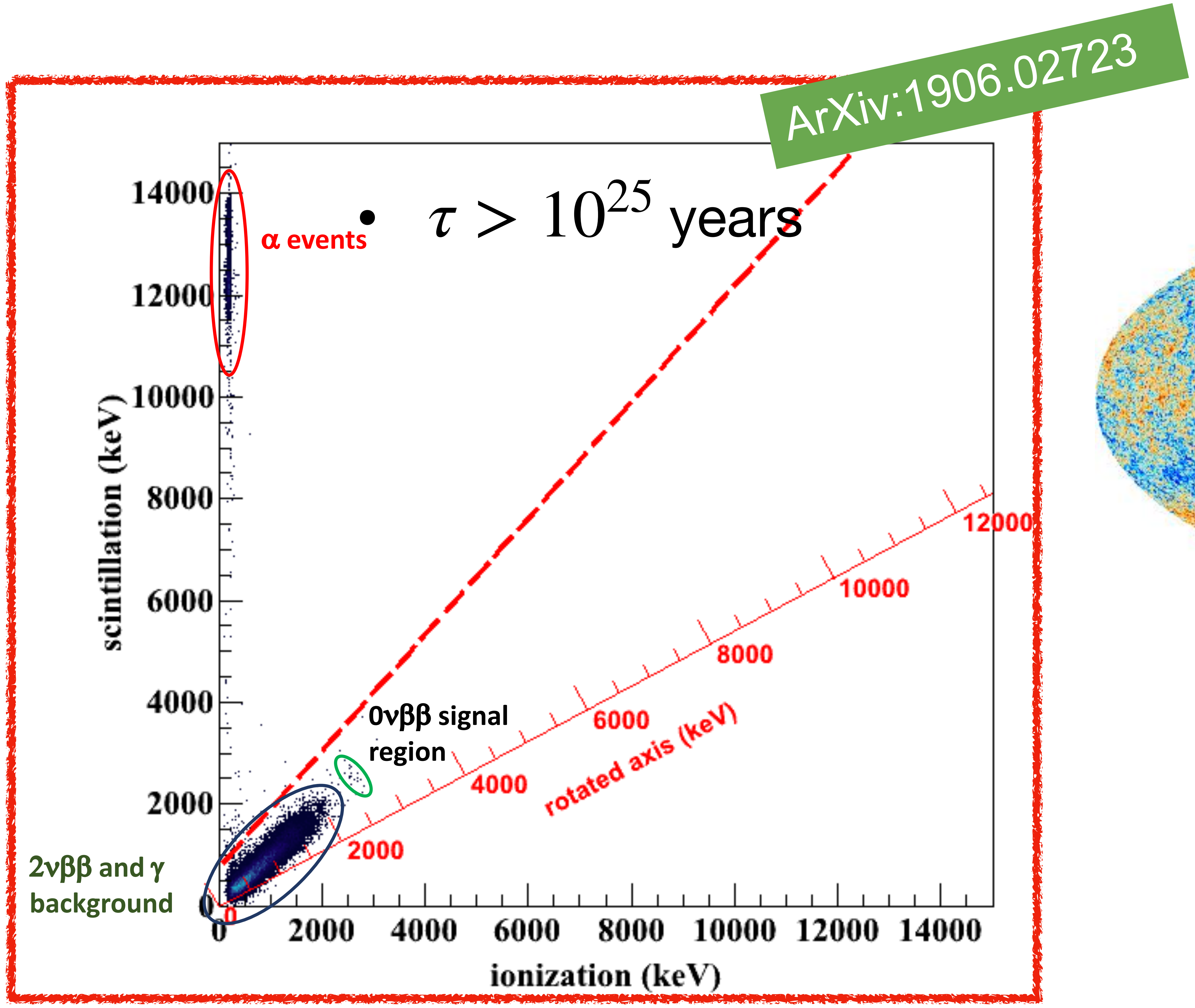
Performance of novel Silicon Photo-Multipliers for the nEXO and Darkside-20k experiments

G. Gallina

Discovery,
accelerated

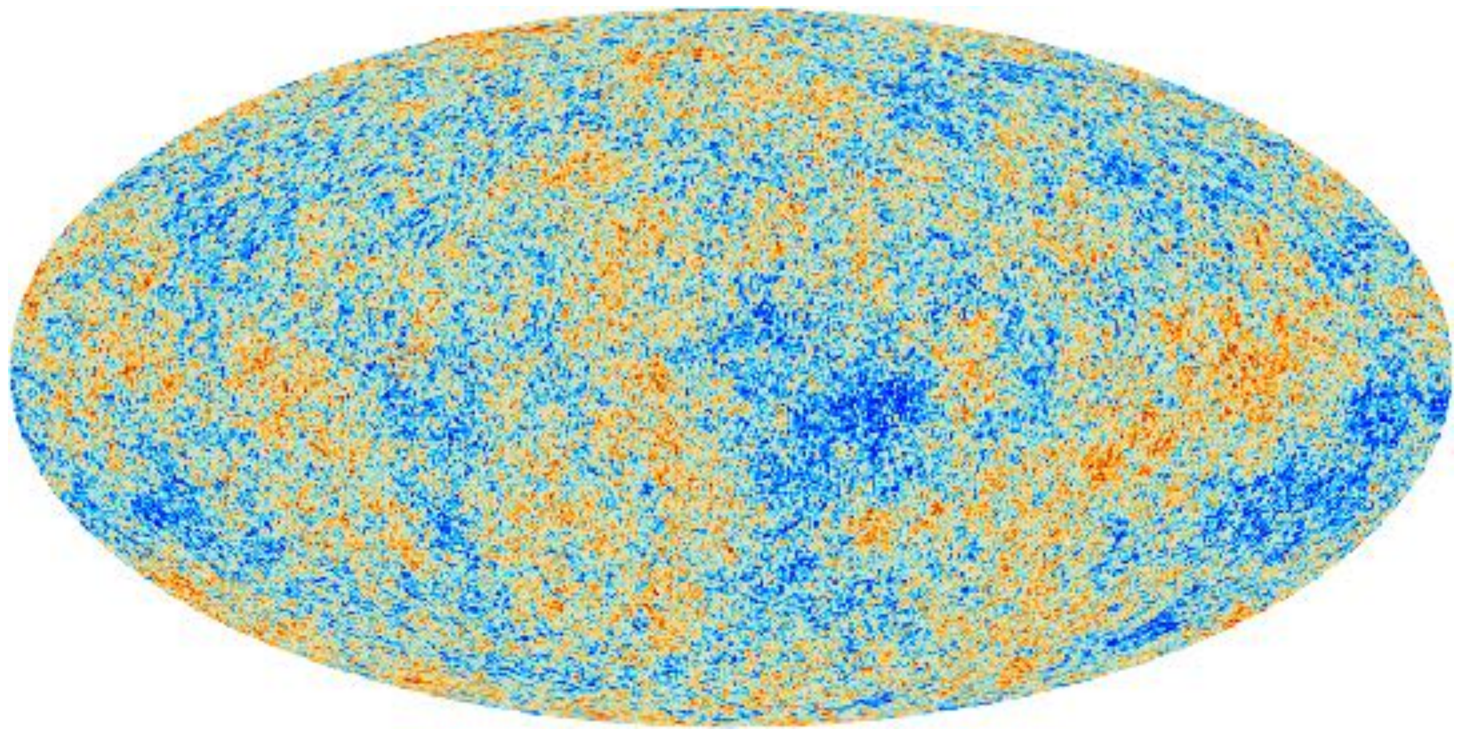
Overview

Signal of new Physics


ArXiv:1906.02723

- $\tau > 10^{25}$ years

Galactic clusters



Thermal anisotropies

Galaxy velocities

Neutrino Physics: $0\nu\beta\beta$ decay

Direct Dark Matter Search

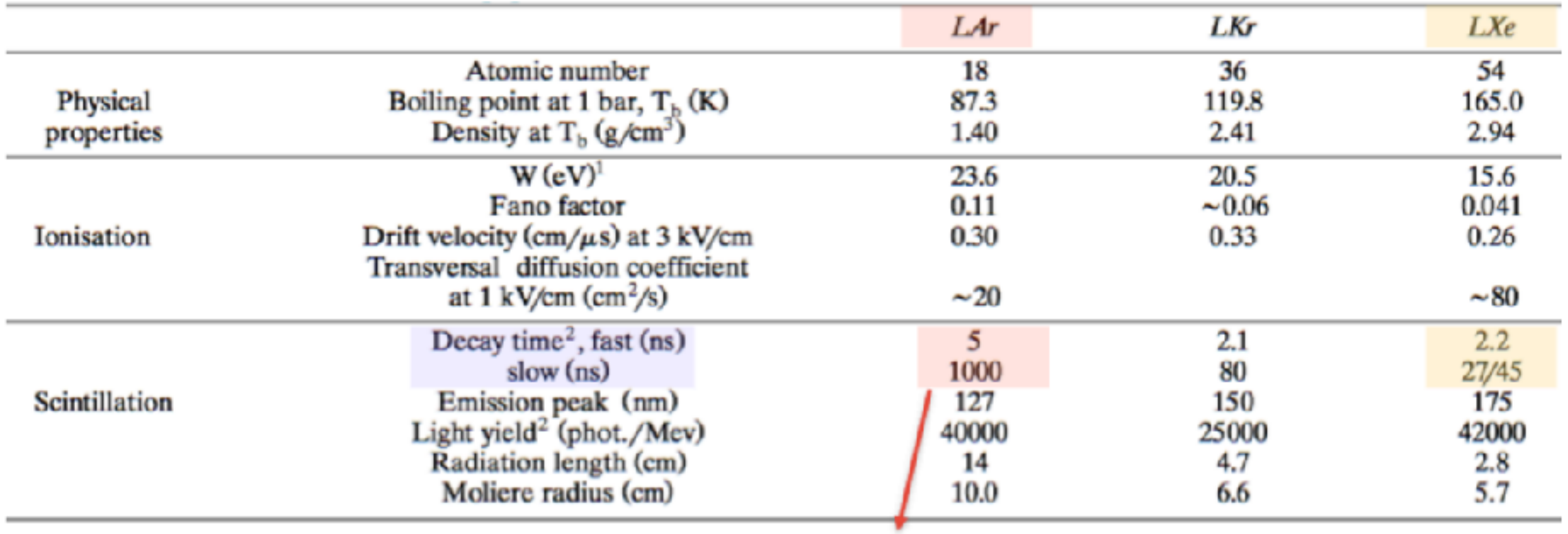
Search with liquified noble elements

- High density ✔
  - Self screening
  - Good scalability
- Easy(-ish) purification, also online ✔
- Scintillation: good light yield ✔
- Ionisation ✔
- ER rejection ✔

→ **Need Light Detectors!**

Excellent detection medium!

and even source !



		LAr	*LKr*	*LXe*
Physical properties	Atomic number	18	36	54
	Boiling point at 1 bar, T_b (K)	87.3	119.8	165.0
	Density at T_b (g/cm^3)	1.40	2.41	2.94
Ionisation	W (eV)[1]	23.6	20.5	15.6
	Fano factor	0.11	~0.06	0.041
	Drift velocity (cm/μs) at 3 kV/cm	0.30	0.33	0.26
	Transversal diffusion coefficient at 1 kV/cm (cm^2/s)	~20		~80
Scintillation	Decay time[2], fast (ns)	5	2.1	2.2
	slow (ns)	1000	80	27/45
	Emission peak (nm)	127	150	175
	Light yield[2] (phot./Mev)	40000	25000	42000
	Radiation length (cm)	14	4.7	2.8
	Moliere radius (cm)	10.0	6.6	5.7

Excellent discrimination power!

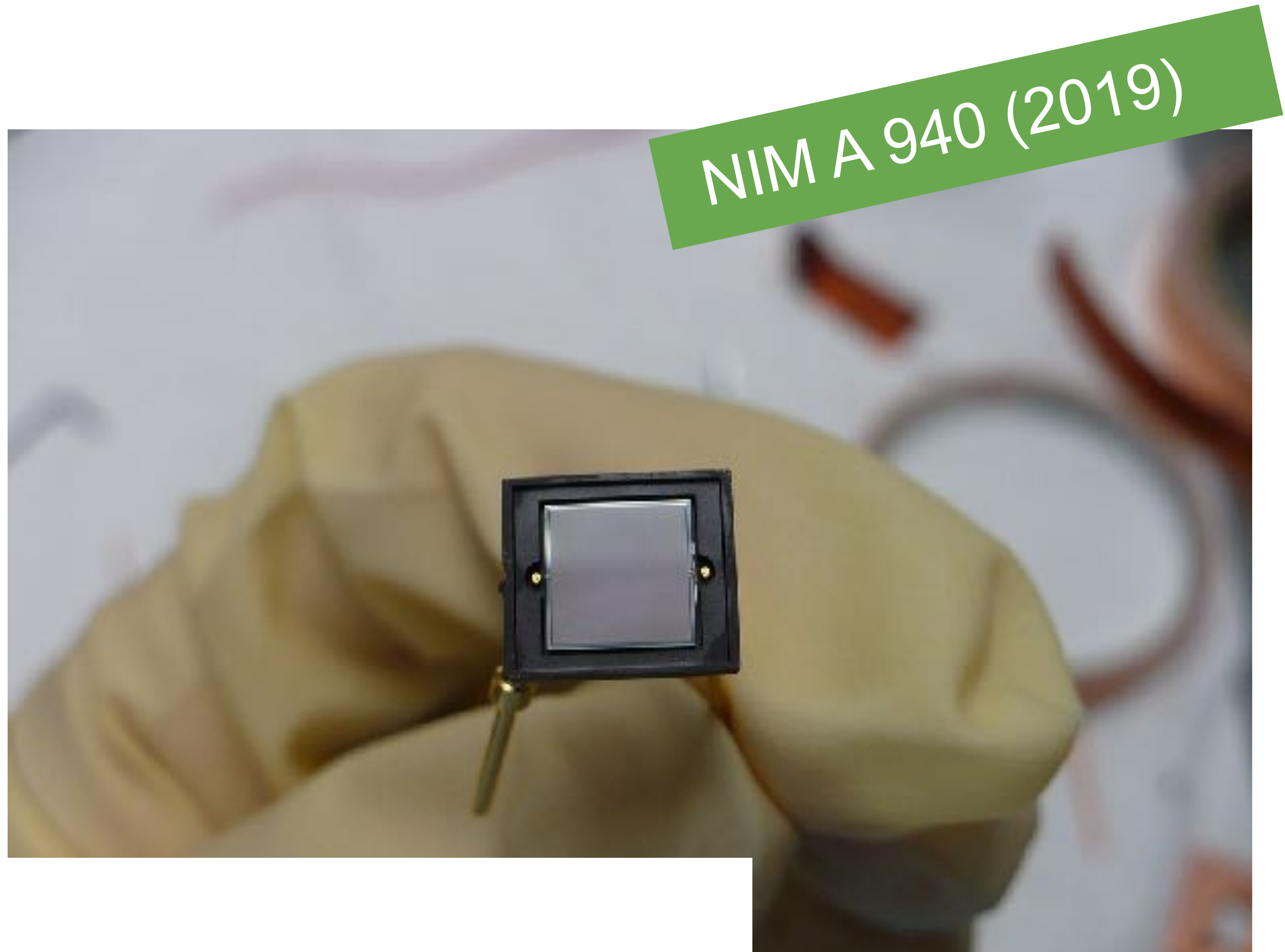
SiPMs technology

Main Characteristics :

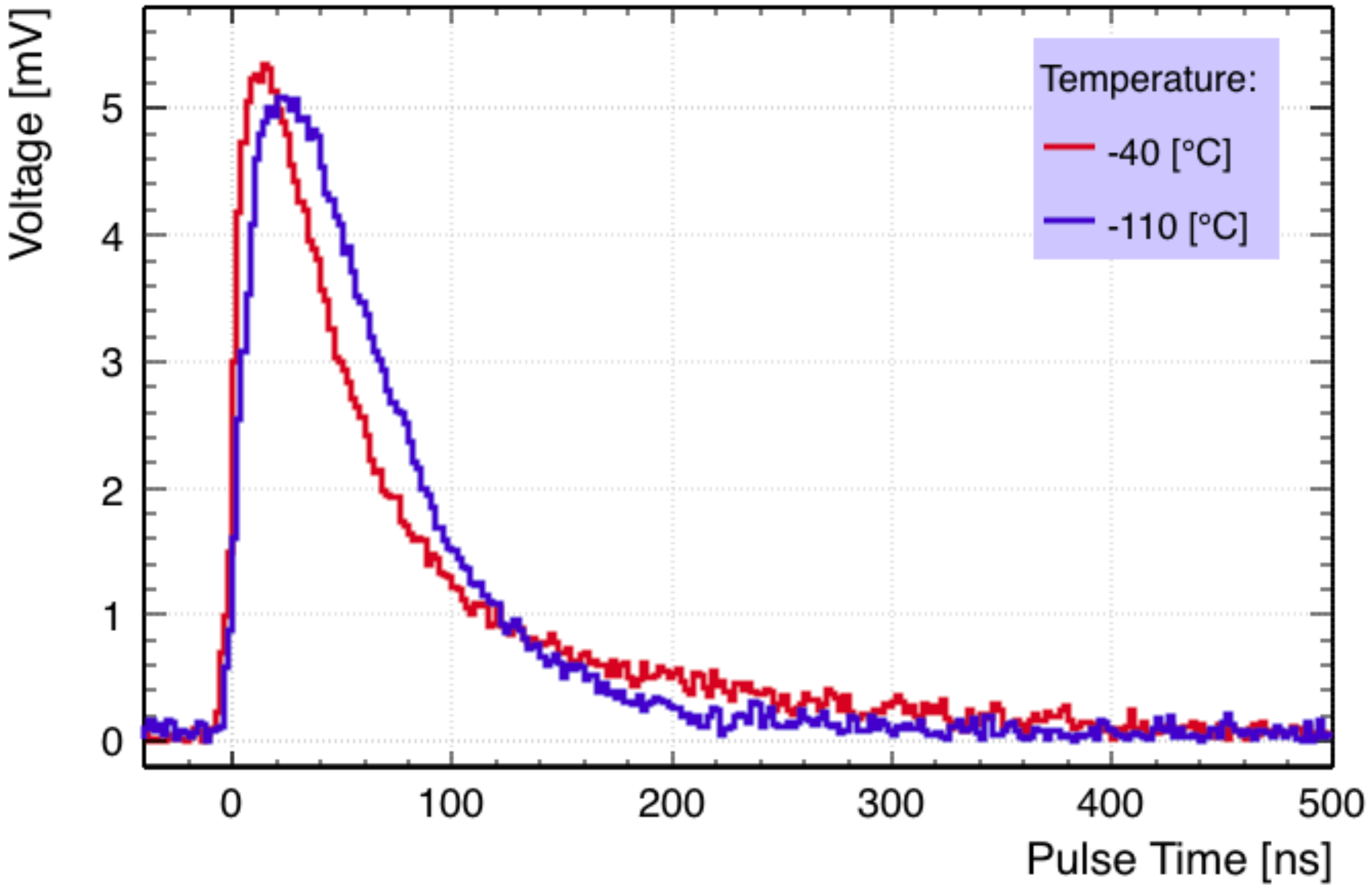
- SPADs connected in parallel operated in reverse bias mode
- Incoming photon triggers charge avalanche
- Single pixel is discharged

Advantages:

- High gain at low bias voltage
- Single photon detection resolution
- High radio purity possible
- Suitable at cryogenic temperature
- **High Photon Detection Efficiency (PDE)**



NIM A 940 (2019)



Noise Sources in SiPMs

Uncorrelated Avalanche Noise

- Dark Count Rate (DCR)

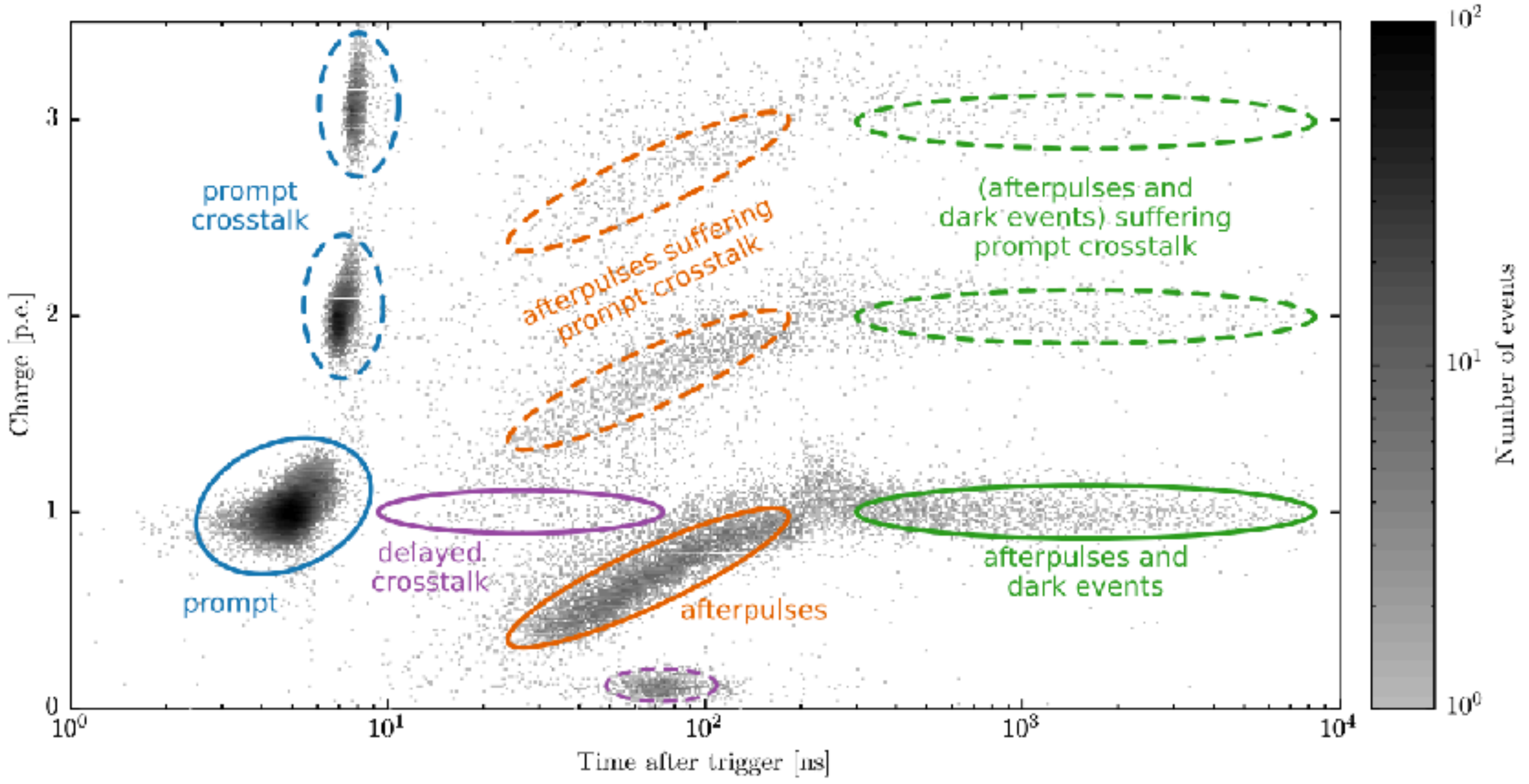
Correlated Avalanche Noise

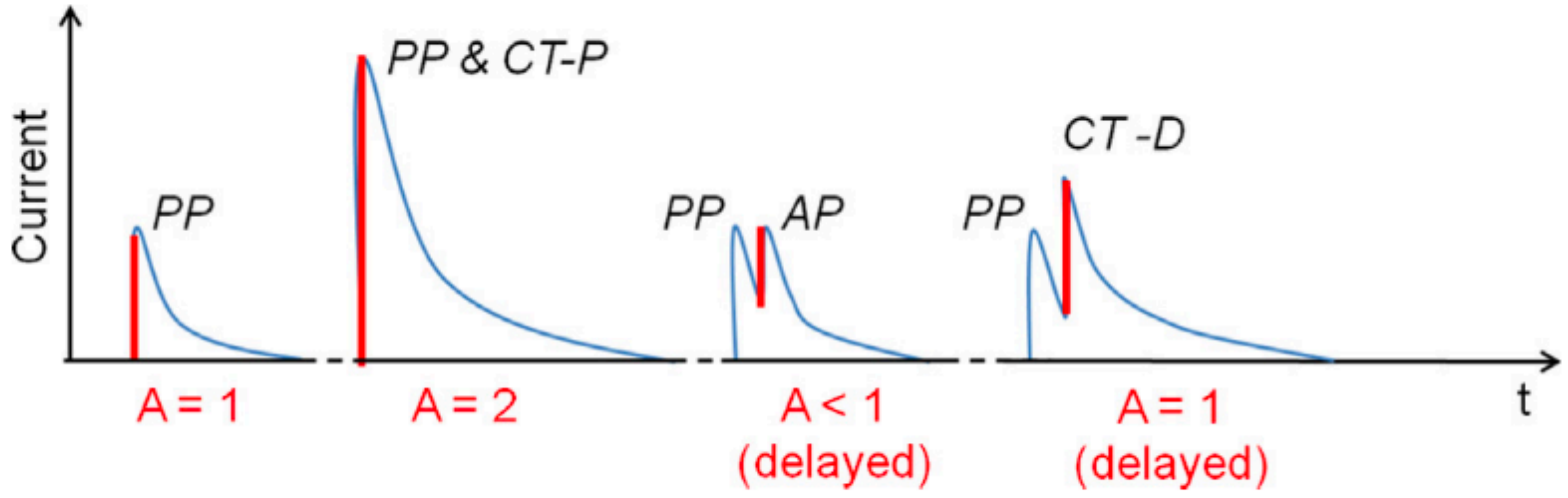
- Afterpulse (AP)
- Internal Cross talk (CT)
- External CT

For Internal Cross Talk an additional discrimination is based on timing :

CT-P : Cross-Talk Prompt (<< 1 ns)
CT-D : Cross-Talk Delayed (> ns)

IEEE Trans.Nucl.Sci. 65 (2018)

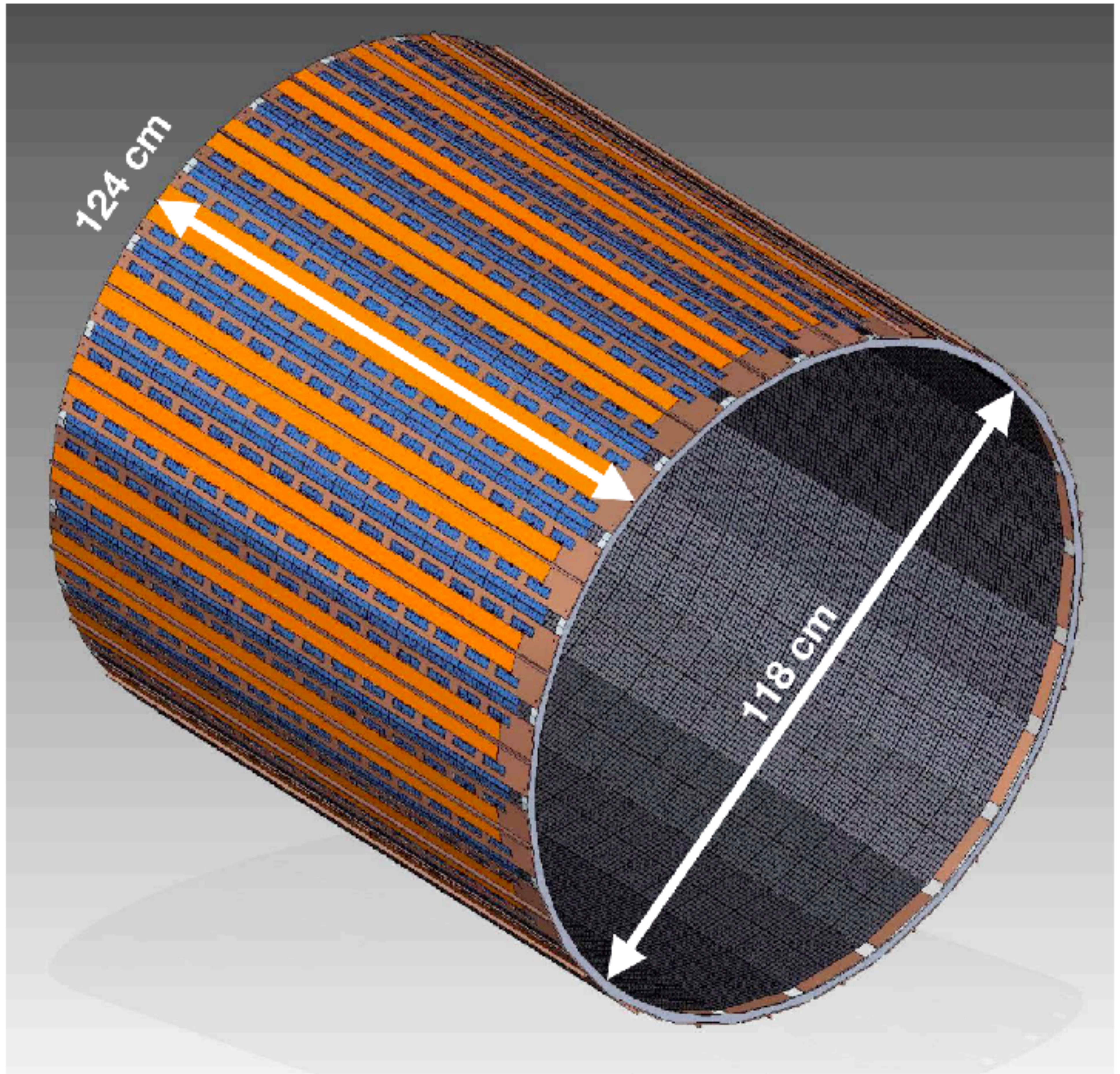




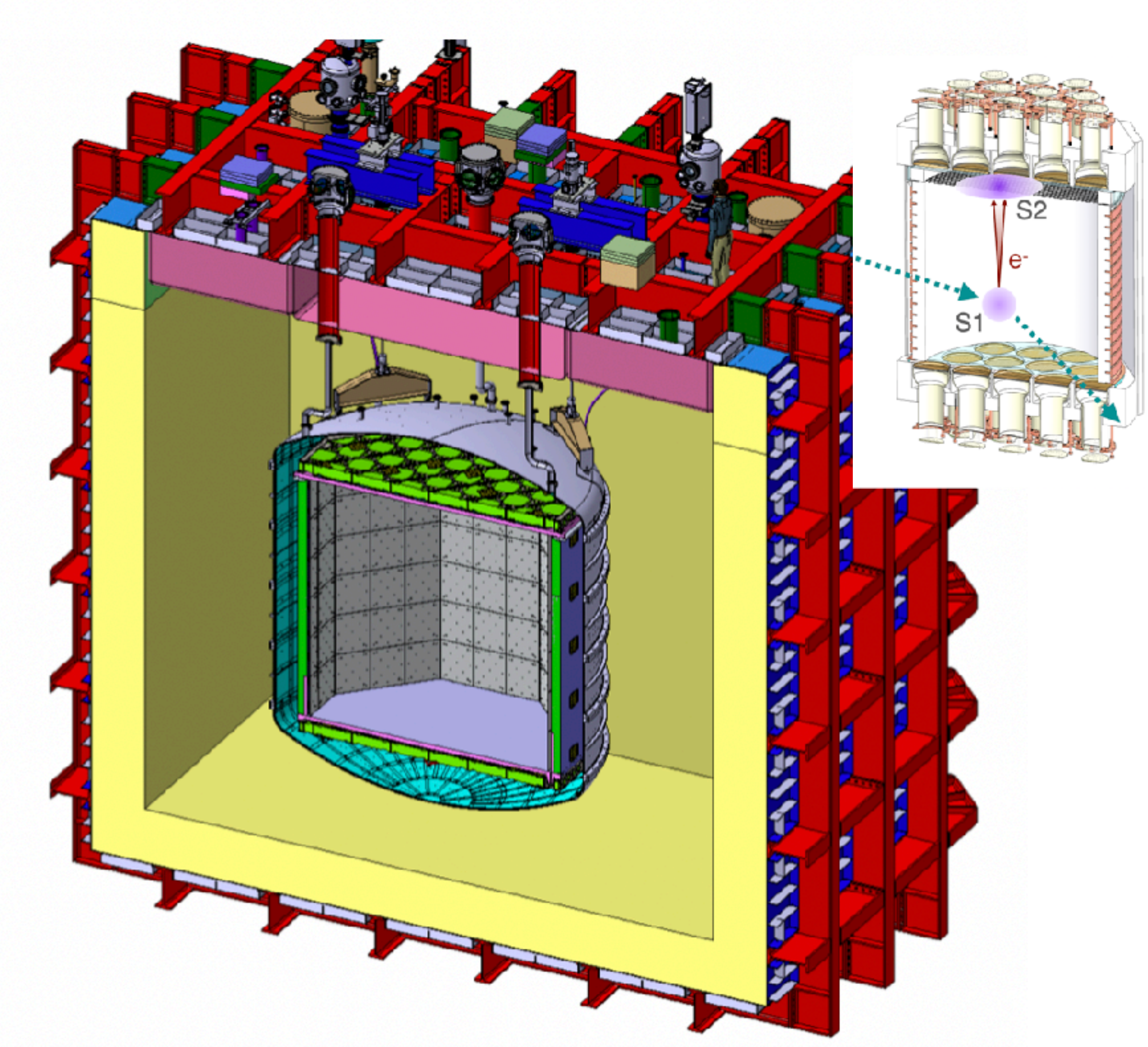
Primary pulses (PP) with different types of correlated pulses such as prompt CT (CT-P), afterpulse (AP) and delayed CT (CT-D).

SiPM are the technology of choice in nEXO and DS-20k!

The nEXO and the Darkside-20k experiment



>4.5 m^2 covered with VUV-sensitive SiPMs

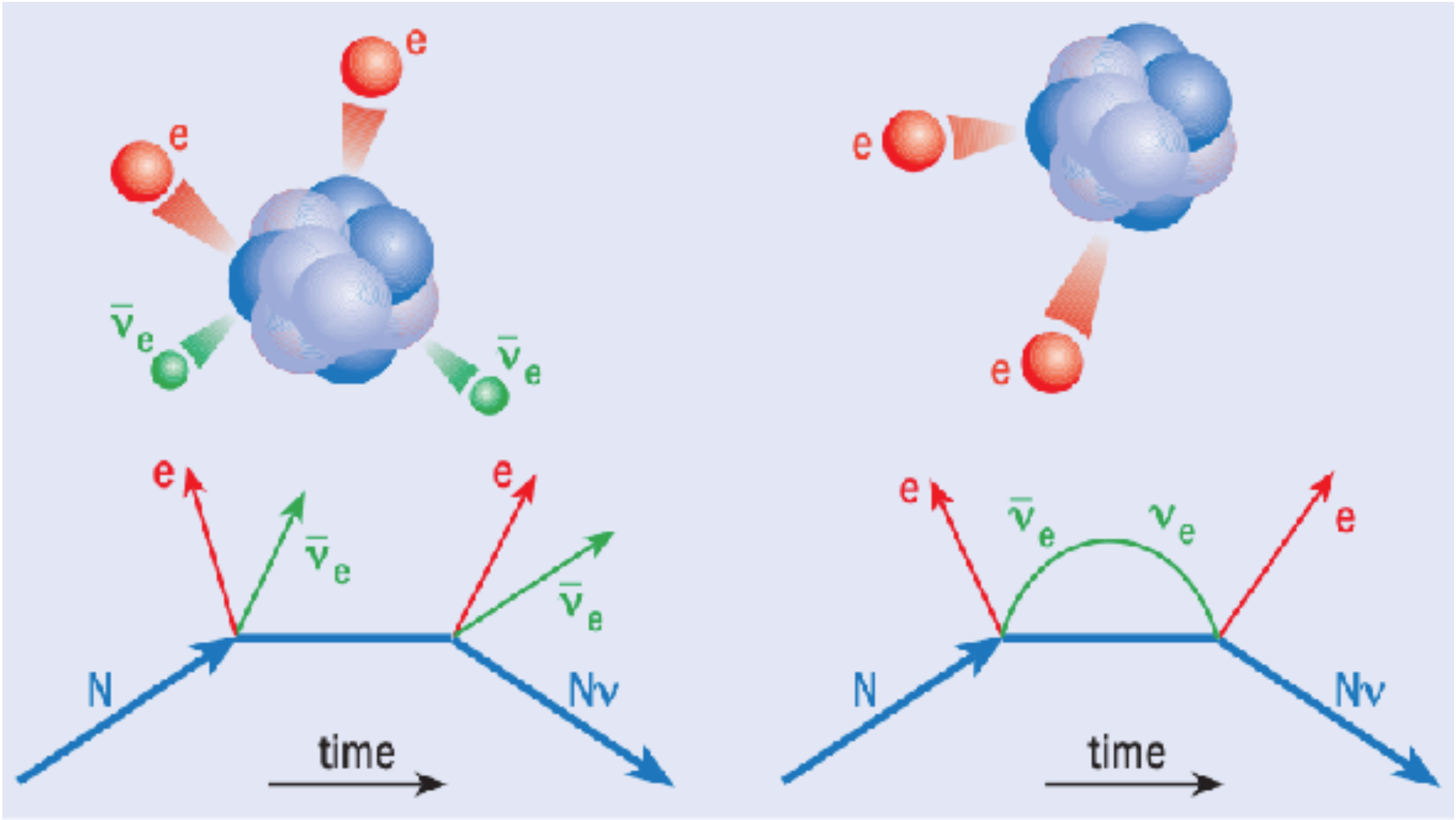


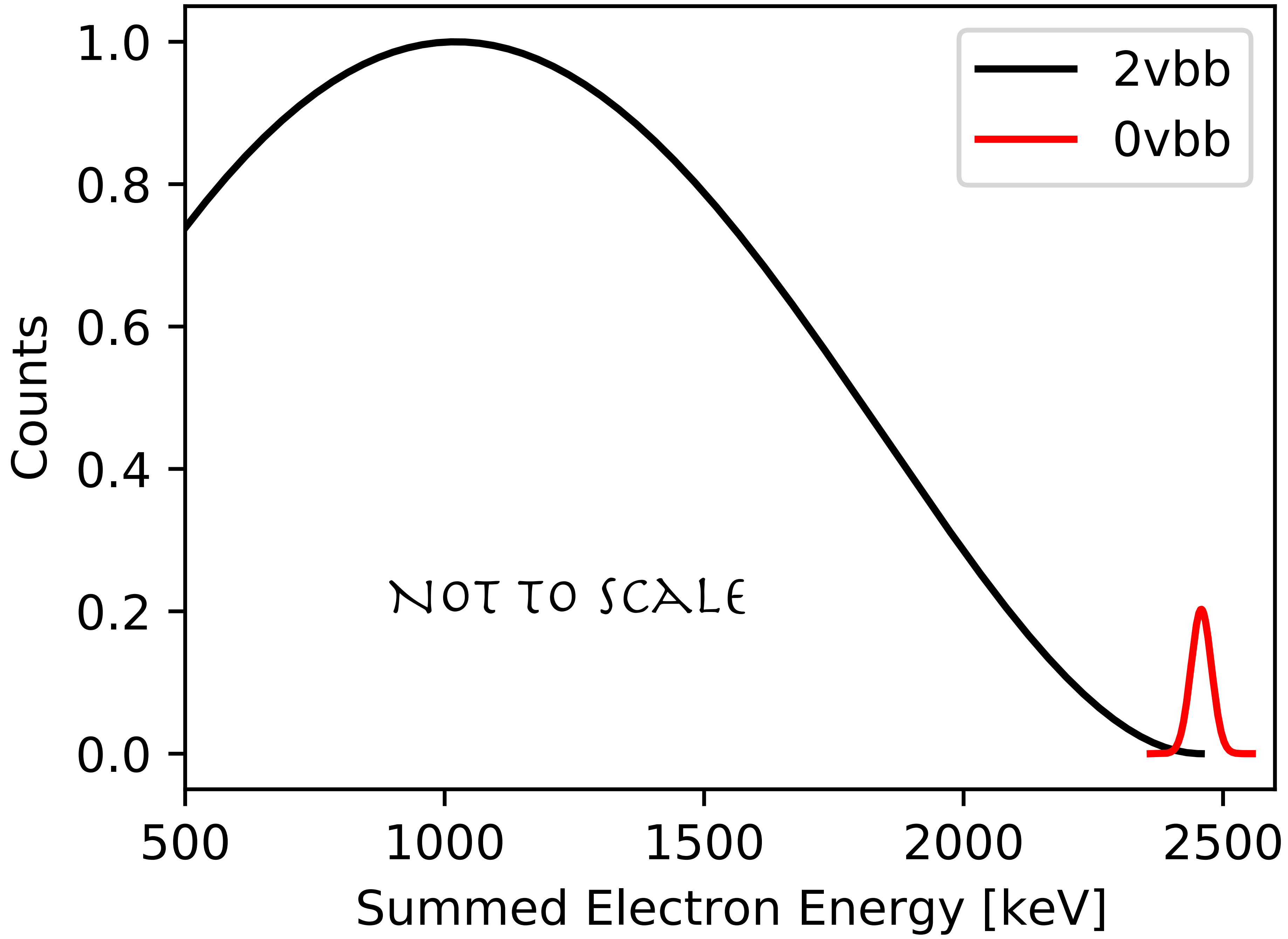
>20 m^2 covered with NUV-sensitive SiPMs

SiPM Technology in nEXO

Motivation for $^{136}\mathrm{Xe}$ Neutrinoless Double Beta Decay

- Finding $0\nu\beta\beta$ always implies new physics
  - Lepton number violation
  - Neutrinos are Majorana fermions ($\nu \equiv \bar{\nu}$)
  - Origin of neutrino masses
  - Insight into absolute neutrino mass scale
  - Possibly linked to matter and anti-matter asymmetry
- Experimental signature is a peak at the Q-value ($2458\,\mathrm{keV}$ for $^{136}\mathrm{Xe}$)





nEXO: Liquid Xenon Detector for $0\nu\beta\beta$

Laurentian University
Université Laurentienne

Carleton University

McGill

Université de Sherbrooke

UMass Amherst

Yale University

Brookhaven National Laboratory

FAU
Friedrich-Alexander Universität Erlangen-Nürnberg

ИТЭФ

Rensselaer

The University of British Columbia

TRIUMF

Pacific Northwest National Laboratory

Skyline College
Achieve

Lawrence Livermore National Laboratory

SLAC National Accelerator Laboratory

Stanford University

Caltech

UC San Diego

Technical University of Munich
TUM

u^b
Universität Bern

ibs Institute for Basic Science

IHEP

IMECAS

Subatech

Drexel University

The University of California · Irvine
Let there be light

Colorado School of Mines

Colorado State University

The University of Alabama
1831

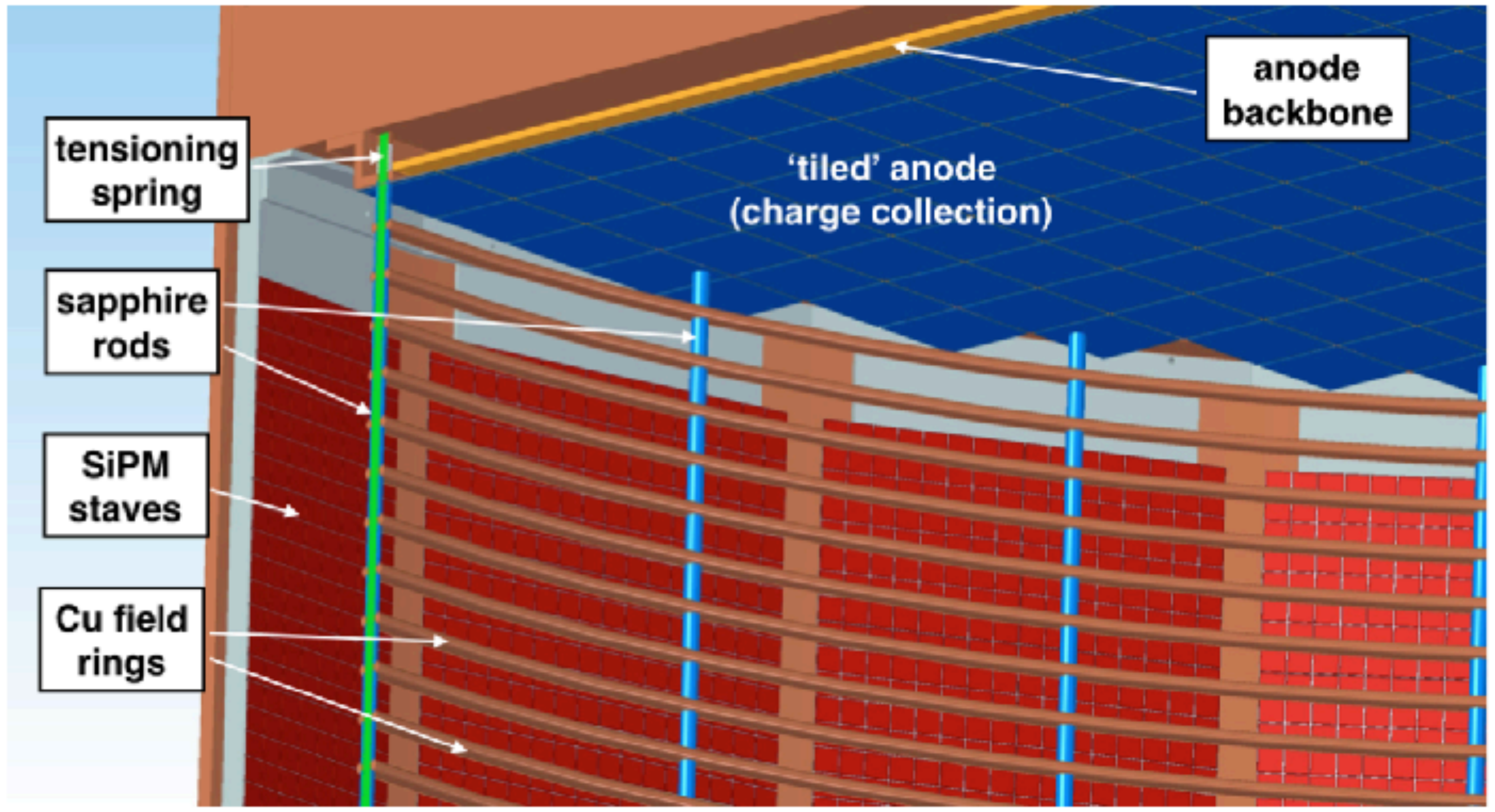
Oak Ridge National Laboratory

University of Kentucky

University of the Western Cape

UNCW
University of North Carolina Wilmington

SiPM technology in nEXO



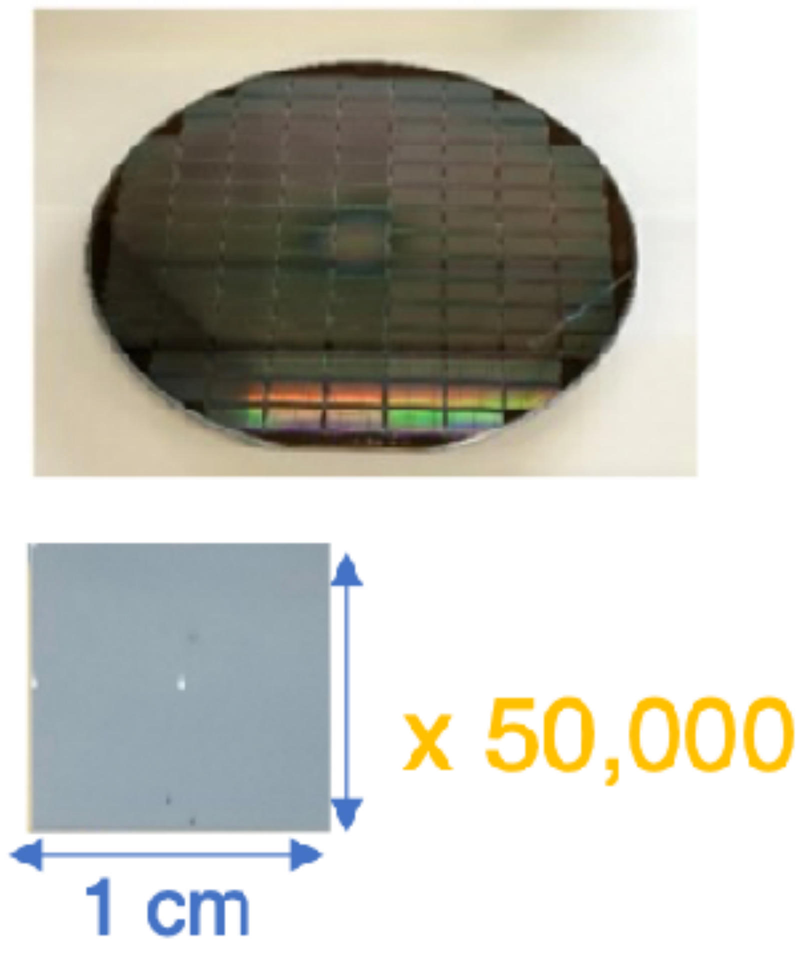
In nEXO we plan to use ~4.5 m^2 covered with VUV-sensitive SiPMs

- 5 t of liquid xenon
- Improved charge (tiles) and light (SiPM) readout
- Projected Sensitivity: $T^{0\nu}_{1/2} \geq 1.35 \times 10^{28}\,\mathrm{yr}$

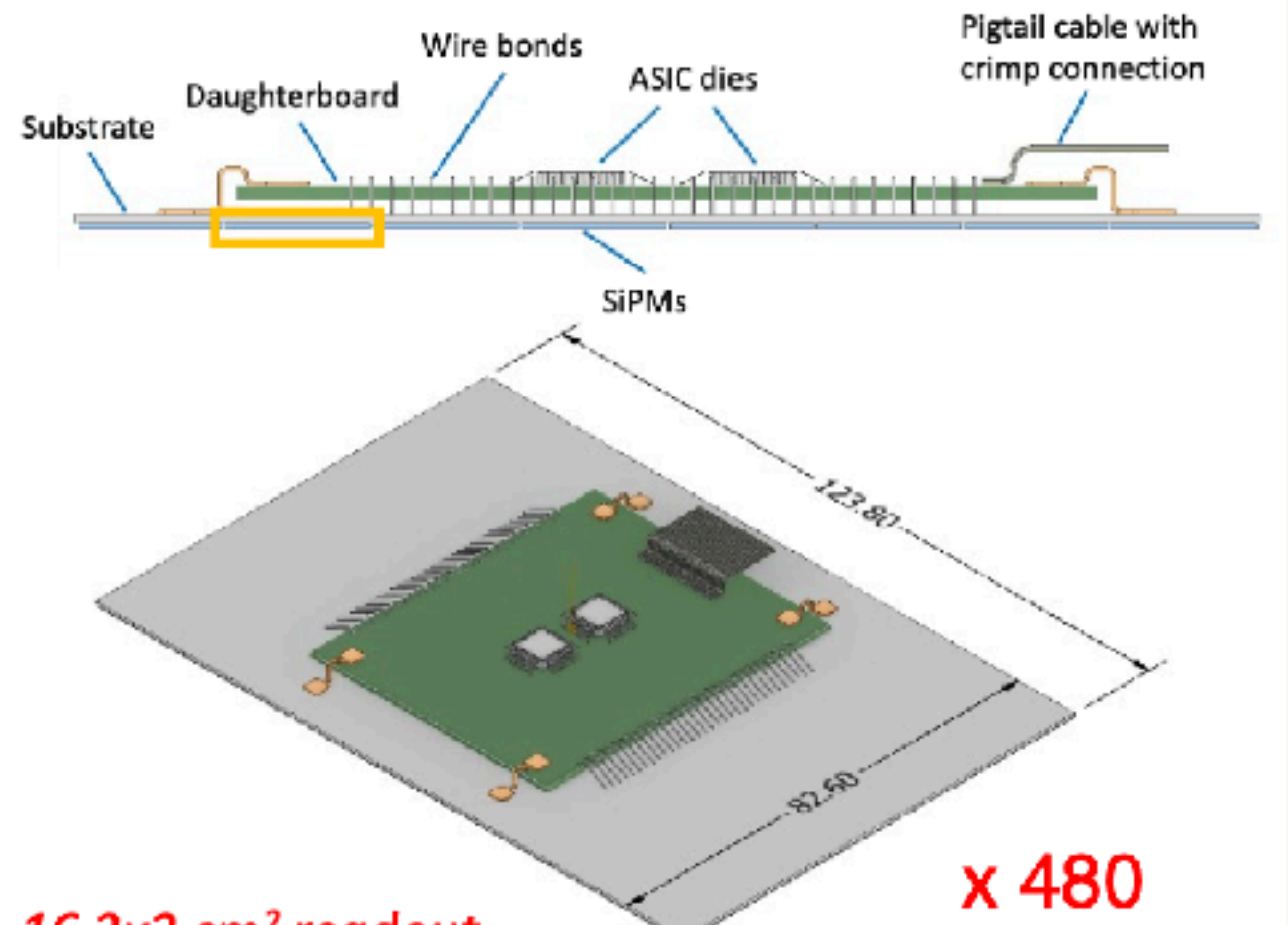
Photon Detector (PD) consists of 4.6m^2 of SiPMs

- ~46,000 1cm x 1cm VUV sensitive SiPMs (grouped into 7680 6cm^2 readout channels)
- Basic integrated element is “tile module” (96 cm^2) with ASIC
- 24 “staves” contain 20 tile modules each

SiPM Devices

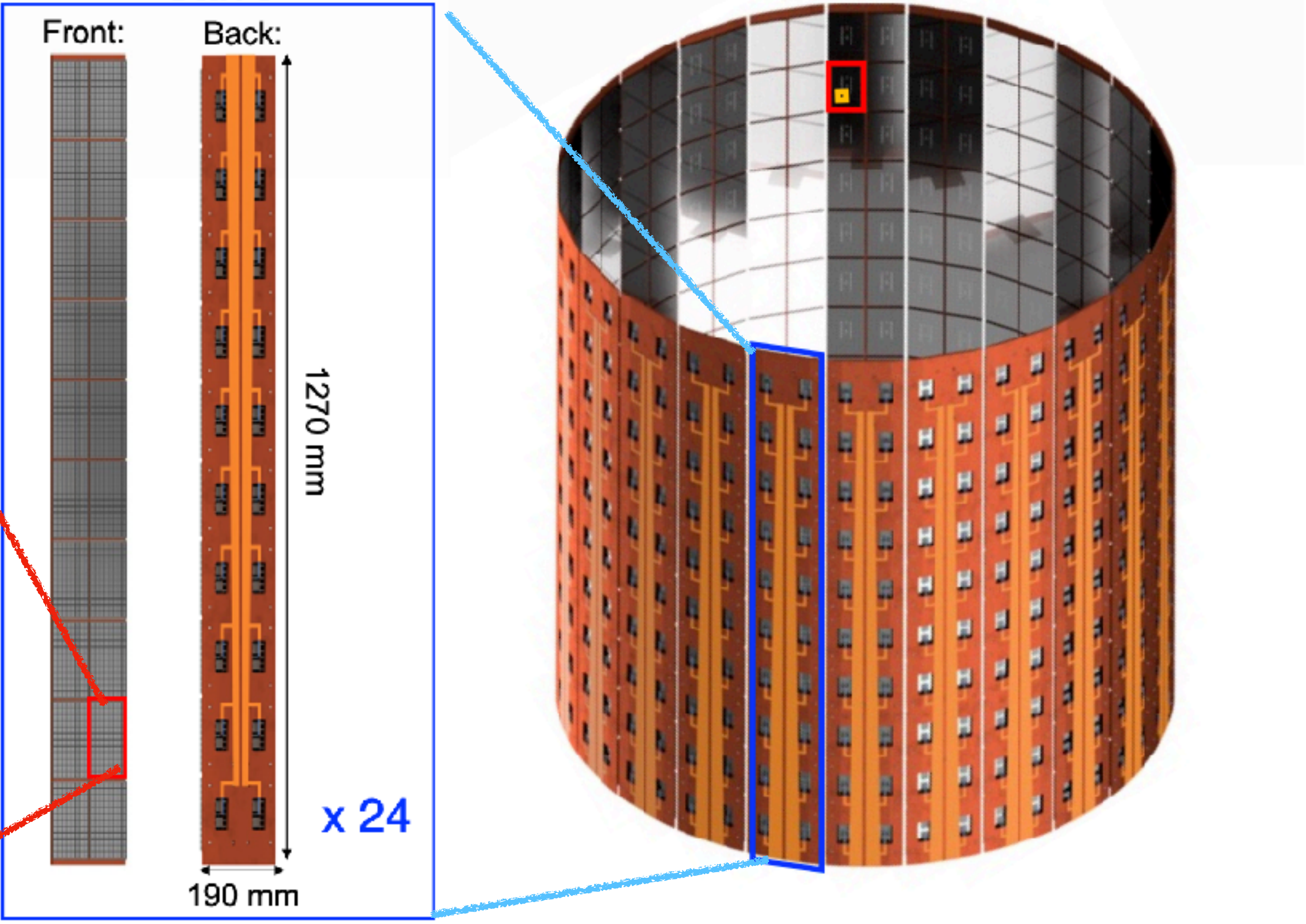


Tile module



16 3x2 cm² readout channels per tile

Stave

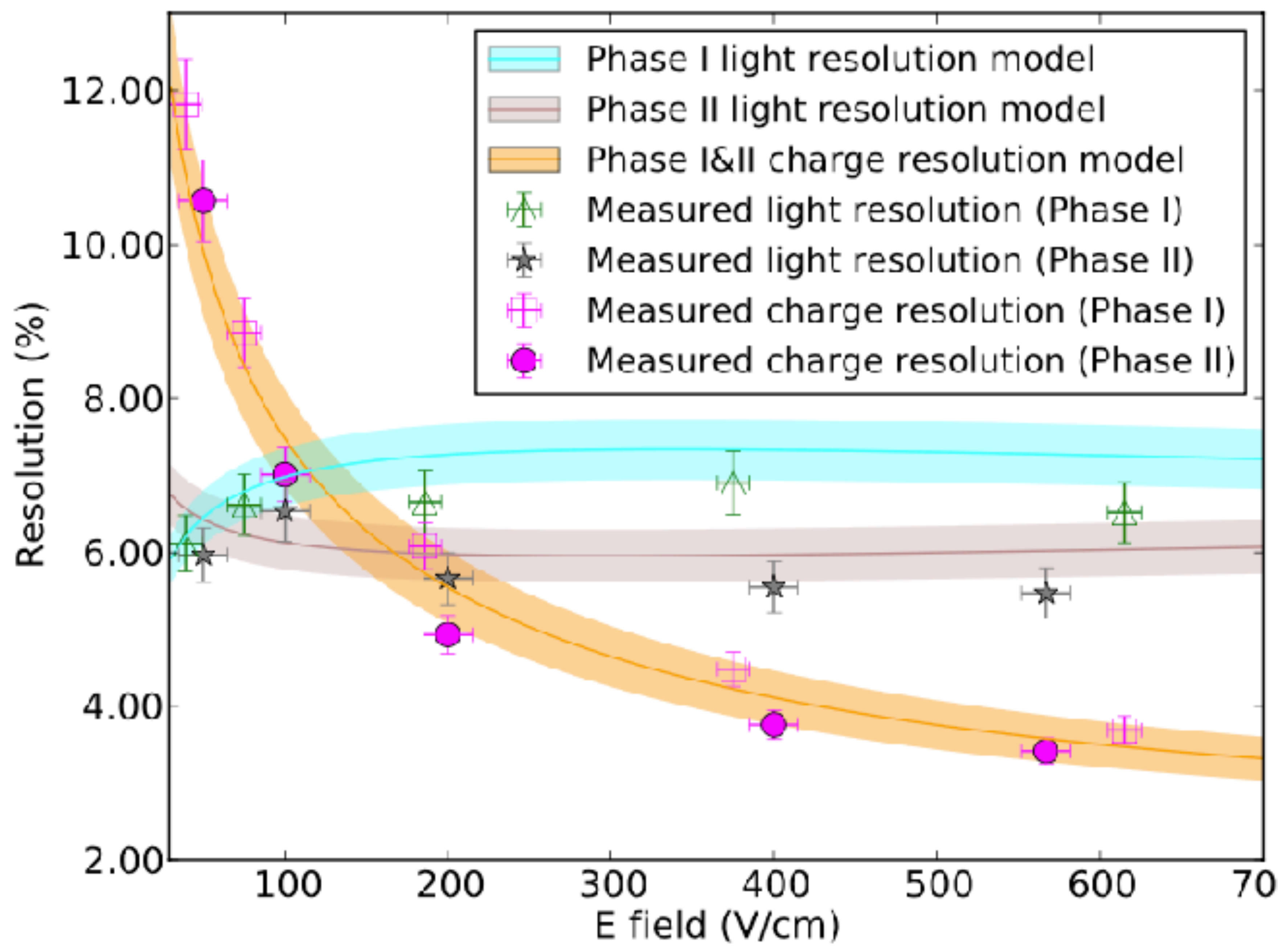


Energy Resolution and photodetector requirements

arXiv: 1908.04128

Rotated energy resolution is dominated by light collection efficiency

- Unlike charge, only <10 % of photons are collected
- Statistical fluctuation in collection drives overall nEXO resolution
- Understanding system level collection efficiency is key to accurately projection nEXO resolution
- Sub-dominat (but not negligible) contribution from fluctuation in correlated avalanches (CA)



Energy resolution measured with EXO-200 APDs at 2615 keV

Collection efficiency

Photon Detection efficiency (PDE)

$$\epsilon_P = \textbf{PTE} \times \textbf{CE} = \textbf{PTE} \times \frac{\textbf{PDE}}{\textbf{1-R}}$$

Photon transport efficiency

Photon collection efficiency

Reflectivity (R)

Correlated avalanches

RMS of CA charge per PE

$$\frac{\sigma_\Lambda}{1+\langle\Lambda\rangle}$$

Mean Charge in CA per primary PE

Uncorrelated avalanches

DCR

nEXO SiPM Requirements at 163 K

$$\mathbf{CAF} \equiv \frac{\sigma_\Lambda}{1 + \langle \Lambda \rangle}$$

Parameters	Value
Photo-detection efficiency (PDE) at 175-178 nm in liquid Xenon	**≥ 15%**
Radio purity: contribution of photo-detectors on the overall background	< 1%
Dark noise rate at -110 °C	**≤ 10 Hz/mm²**
Correlated Avalanches fluctuation (CAF) per pulse in 1μs at -110 C	**≤ 0.4**
Single photo-detector active area	≥ 1cm²
Operational gain	$\geq 1.5 \times 10^6$ **e⁻**
Capacitance per area	< 50 pF/mm²
Equivalent noise charge	< 0.1 PE r.m.s

Three SiPMs analysed in this work: 2 Hamamatsu VUV4 MPPCs and FBK VUVHD3 SiPM

nEXO 6x6 mm^2 SiPMs candidates

Hamamatsu MPPCs

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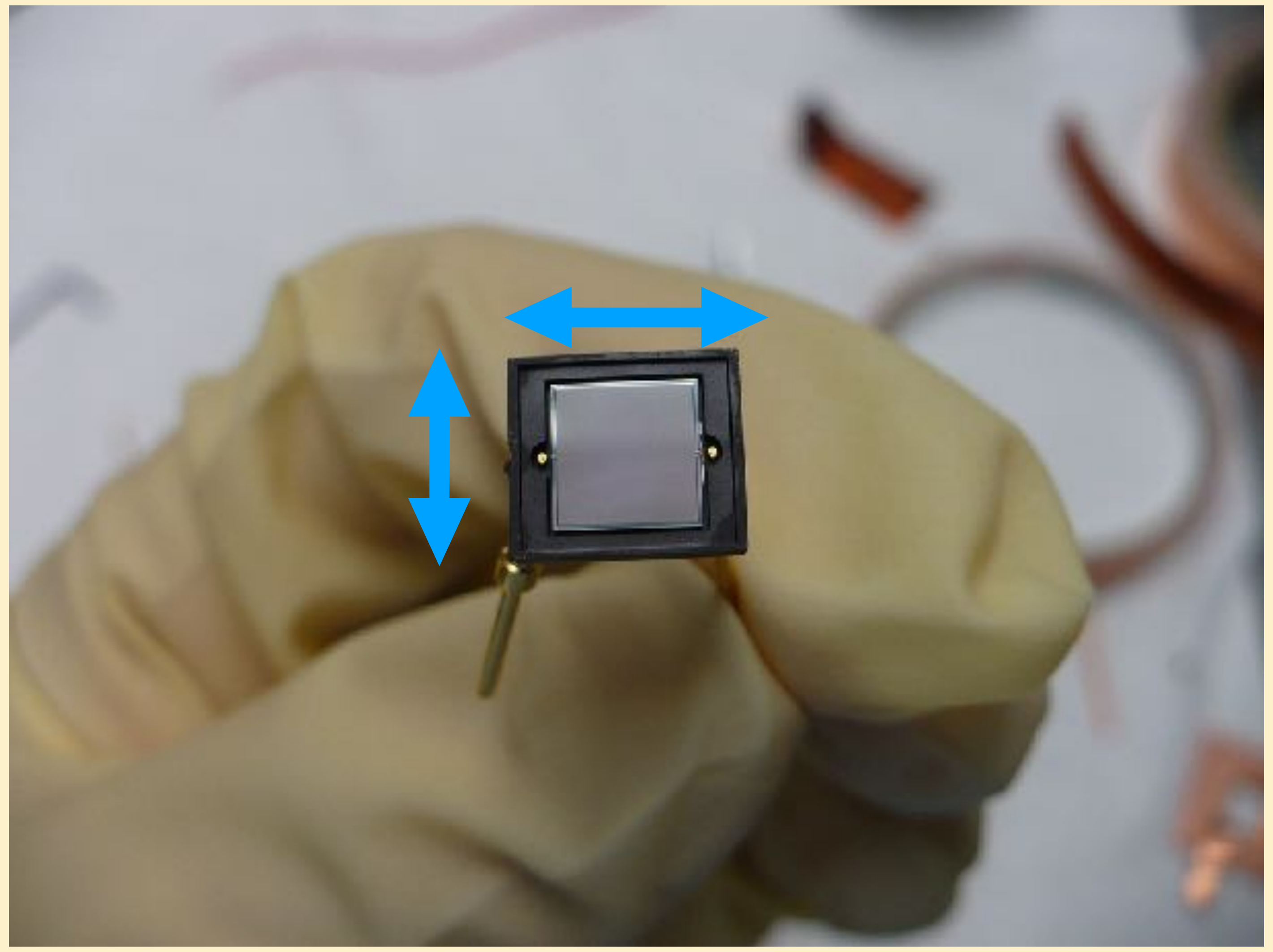

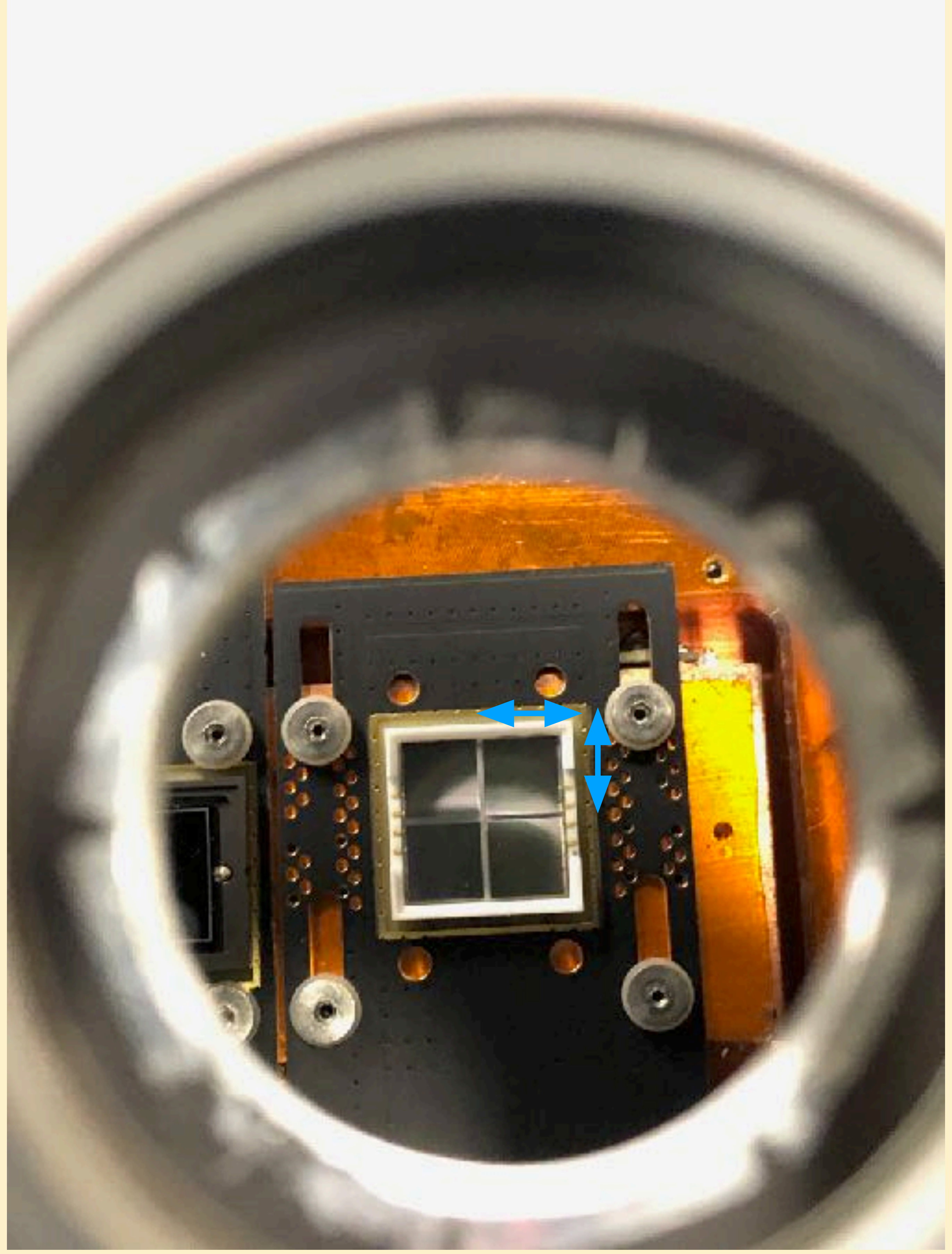

HPK VUV4-50
Single devices
50 um pitch

HPK VUV4-Q-50
Quad devices.
50 um pitch

FBK SiPM

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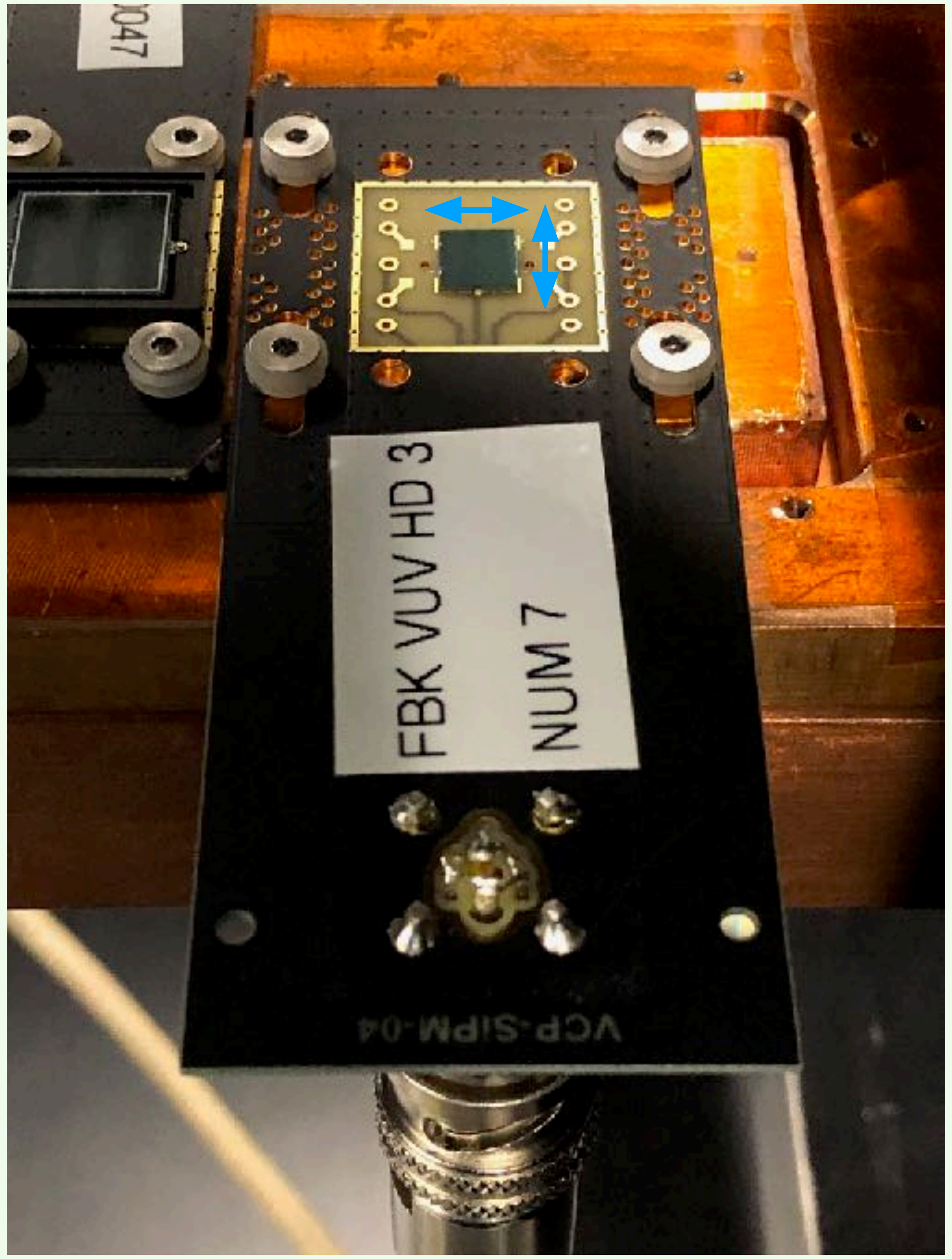


FBK VUVHD3
substitutes
its previous generation
FBK VUVHD1

The nEXO photodetector team

- **This work** is part of a joint effort of the photodetector group where several institutions contributed to data taking and analysis
- It is the end of more that 2 years of data taking/analysis and comparison !

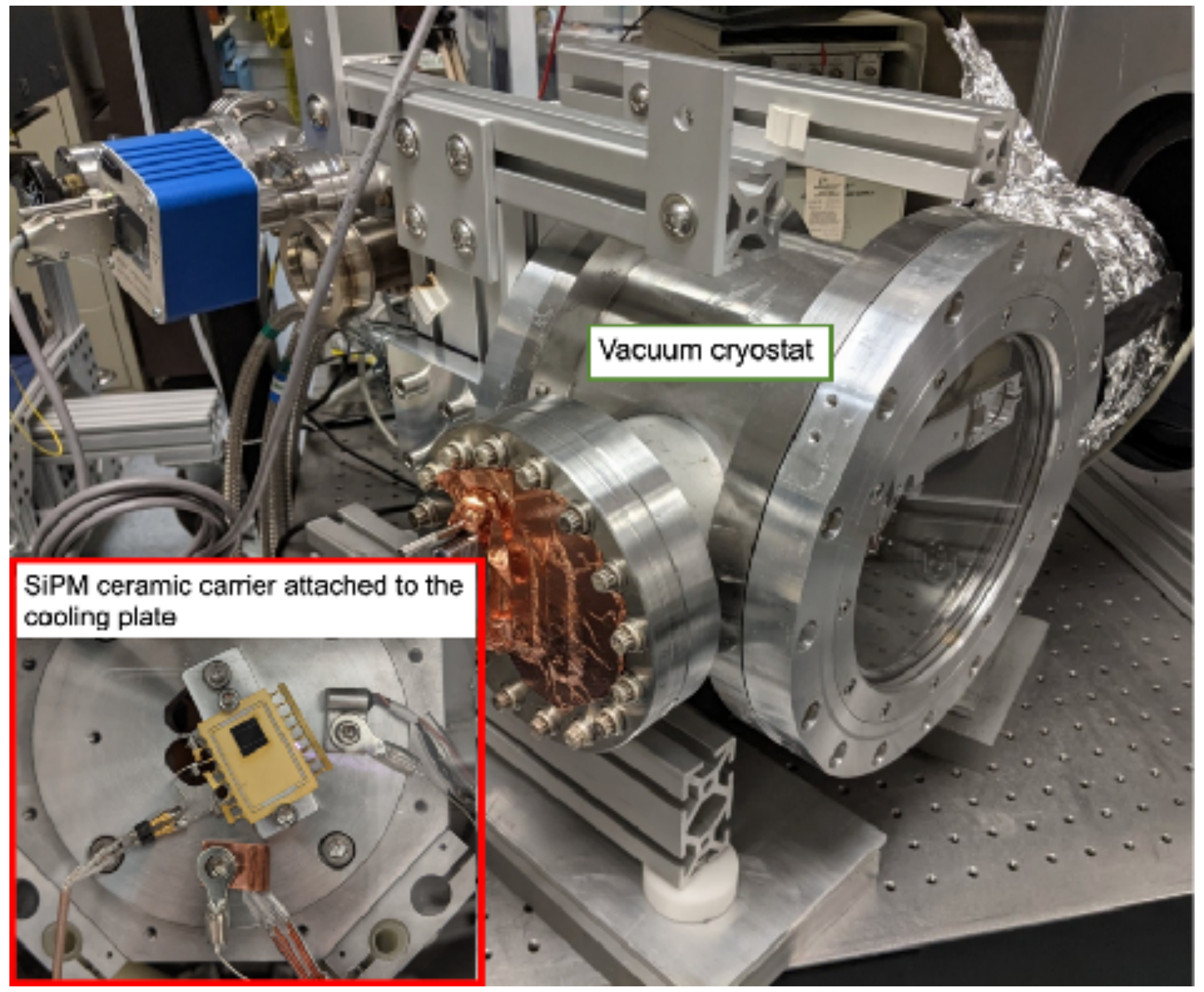
TRIUMF	IHEP	YALE
G. Gallina, F. Retiere, P. Margetak, N. Massacret, M. Mahtab et al.	G. Cao, Y. Guan et al.	A. Jamil, A. Bhat, D. Moore

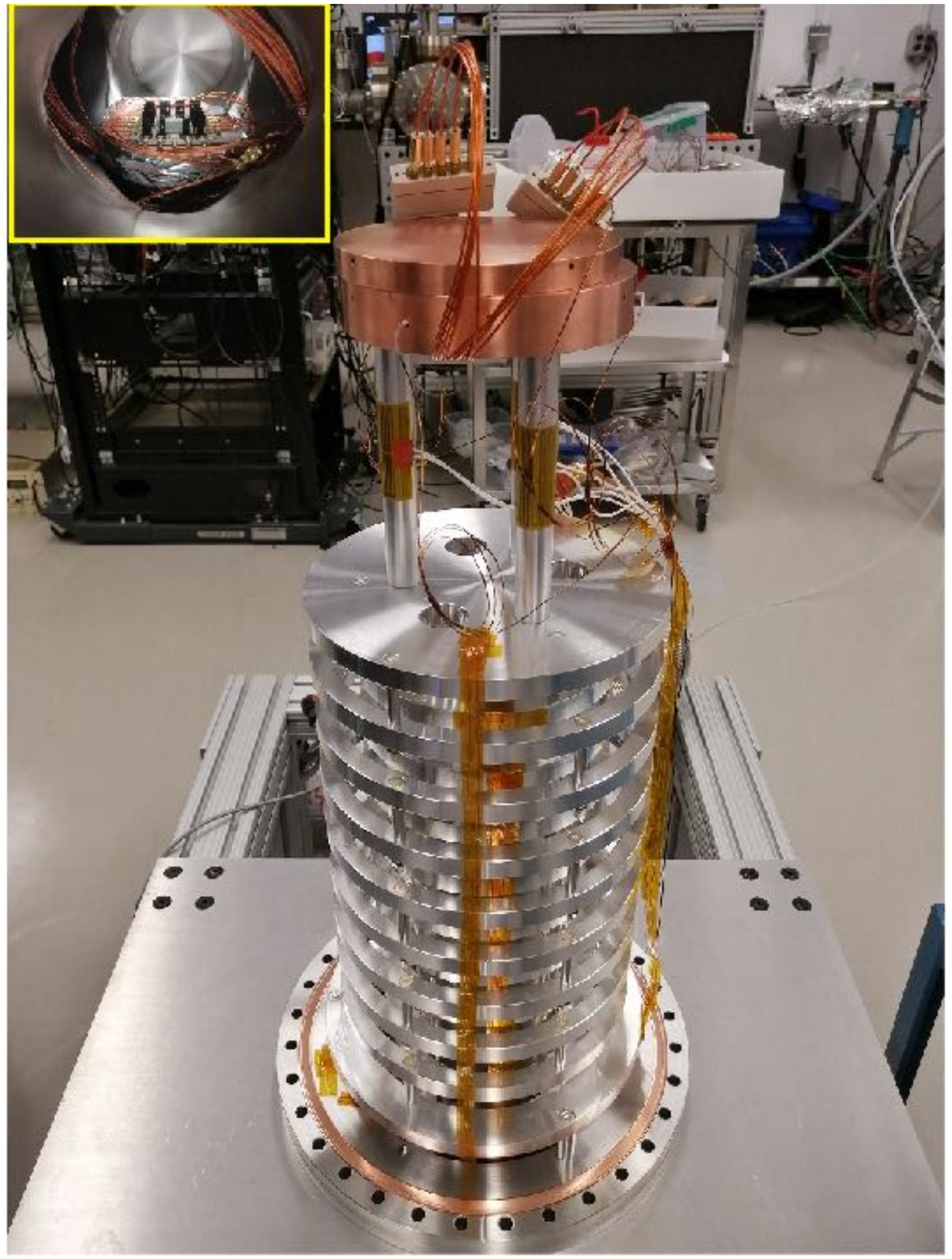
BNL/Drexel	UMass	McGill
A. Bolotnikov, I. Kotov, A. Kumar et al.	A. Pocar, W. Gillis, Reed C. et al.	L. Darroch, T. Brunner et al.

New measurements in EPJC ! arXiv:2209.07765

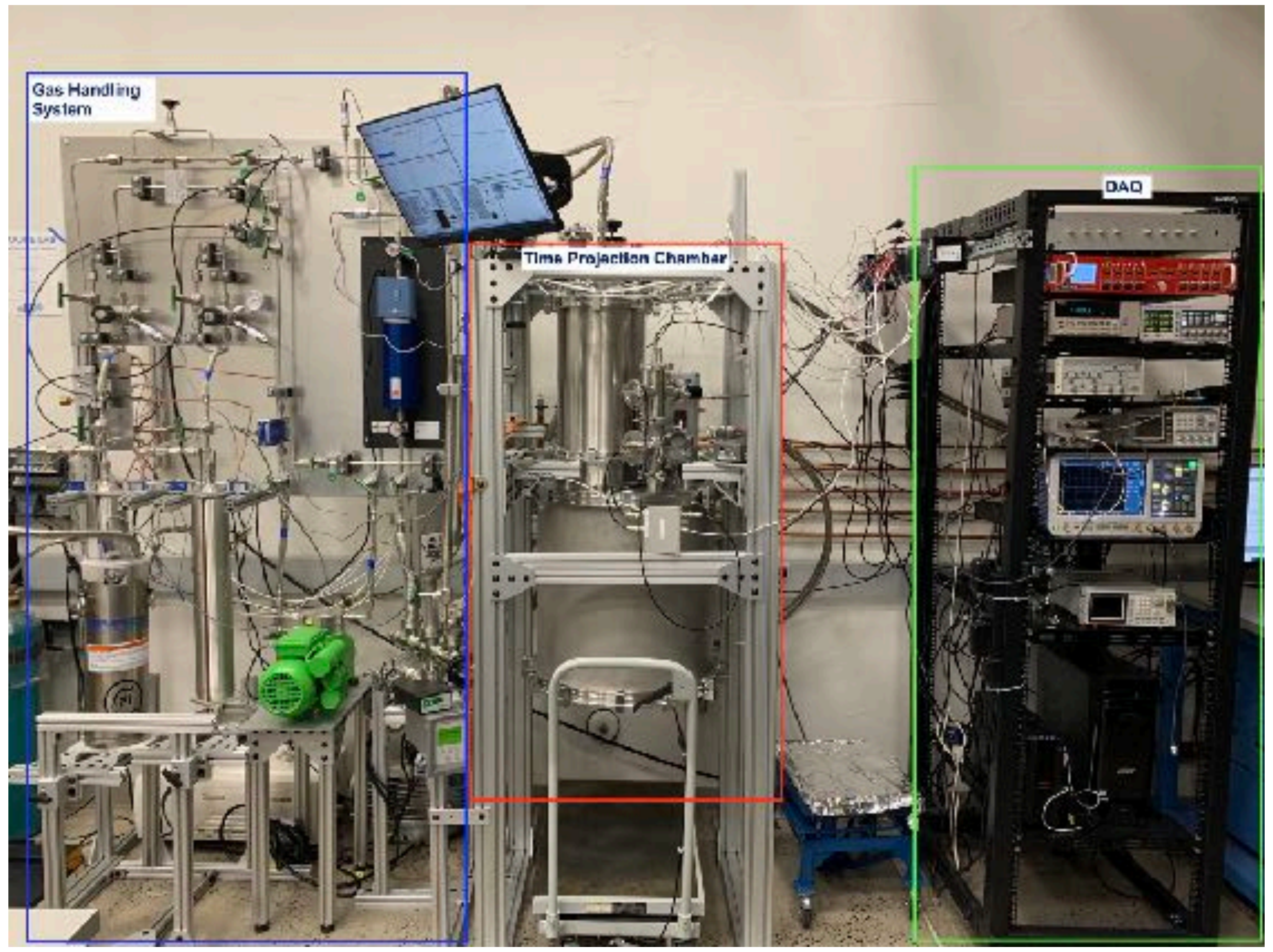
nEXO Testing setups: Dark measurements

BNL Setup

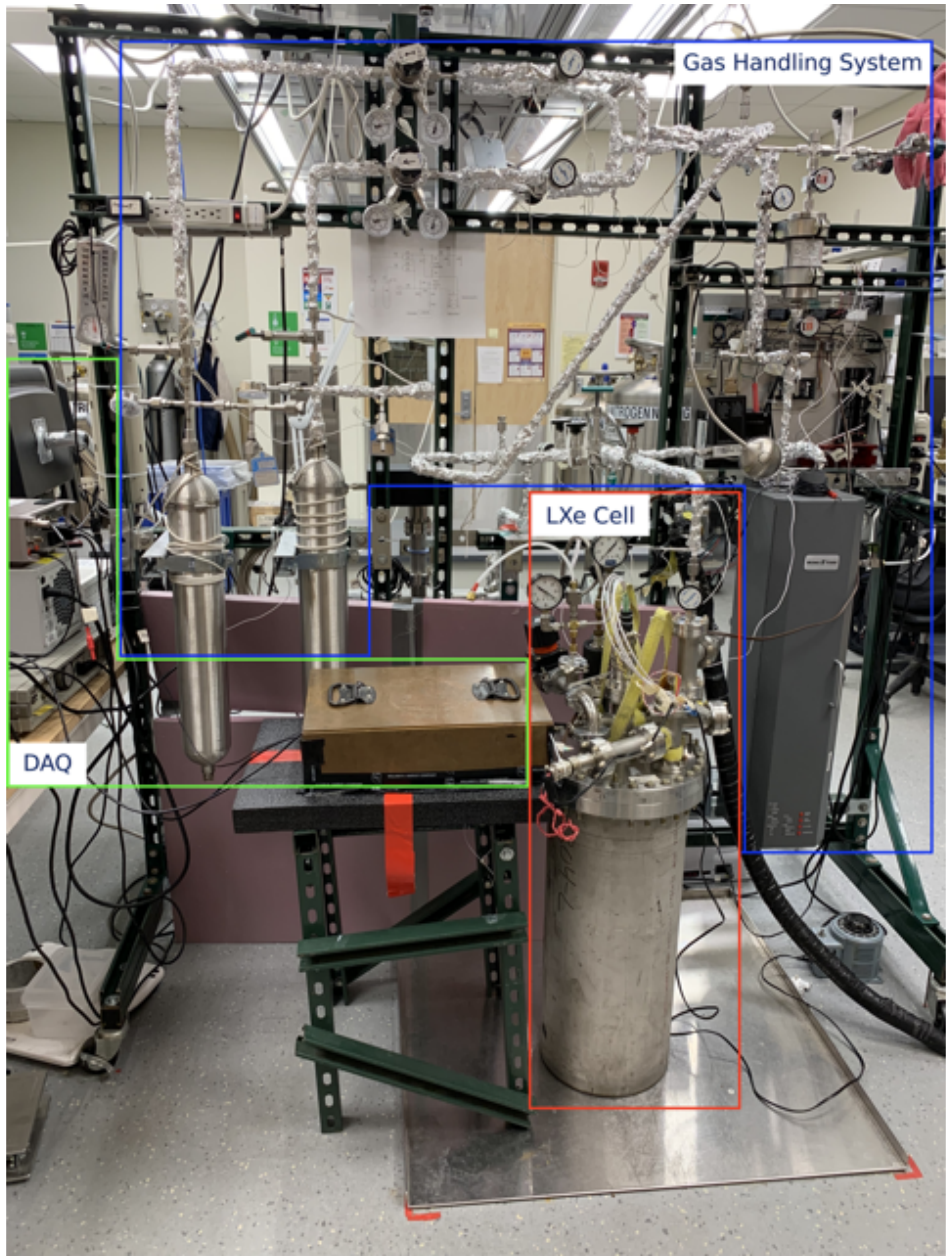




McGill Setup

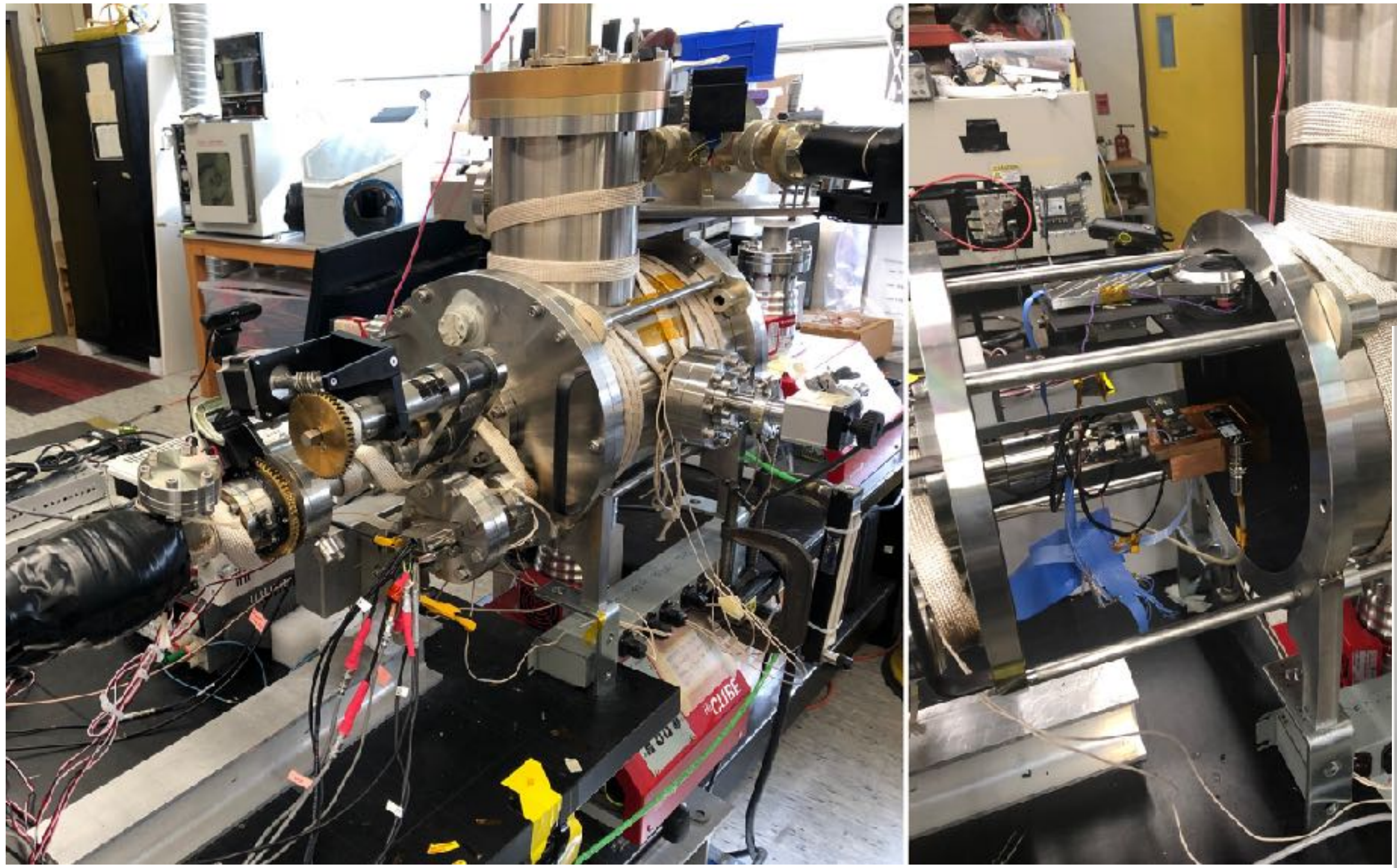


Yale LXe Setup



UMass LXe Setup

nEXO Testing setups: Dark and PDE measurements



TRIUMF Setup

IHEP Setup

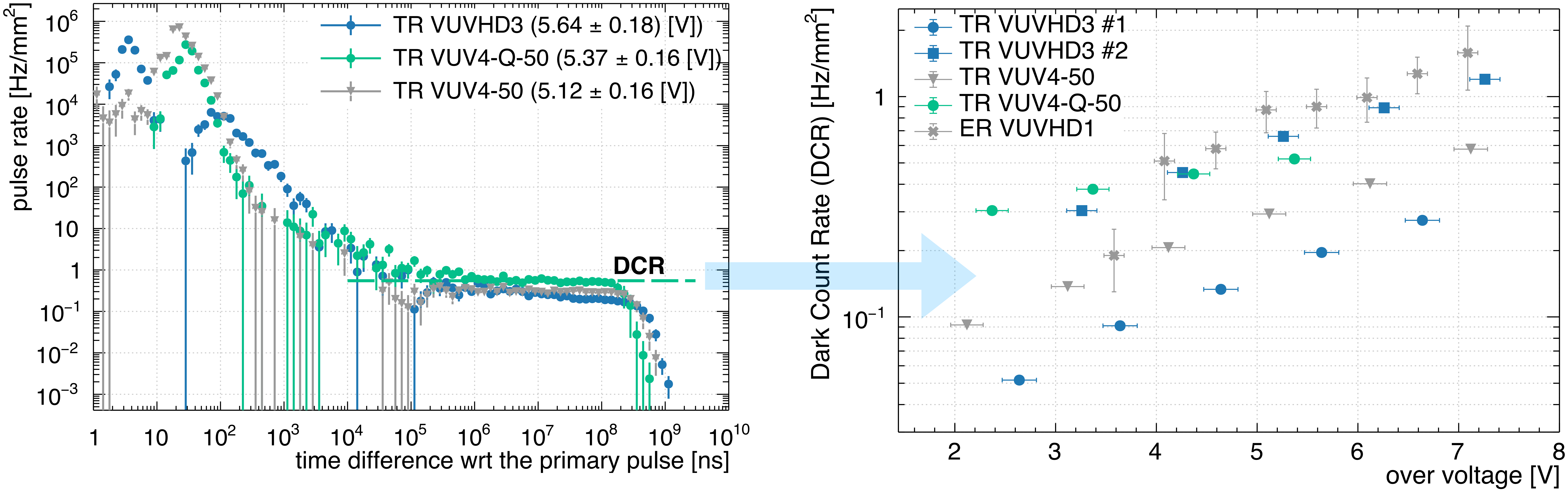
Grey points !

NIM A 940 (2019)

IEEE Trans.Nucl.Sci. 65 (2018)

Dark Count Rate (DCR)

Computed using time differences between pulses as shown in 10.1016/j.nima.2017.08.035



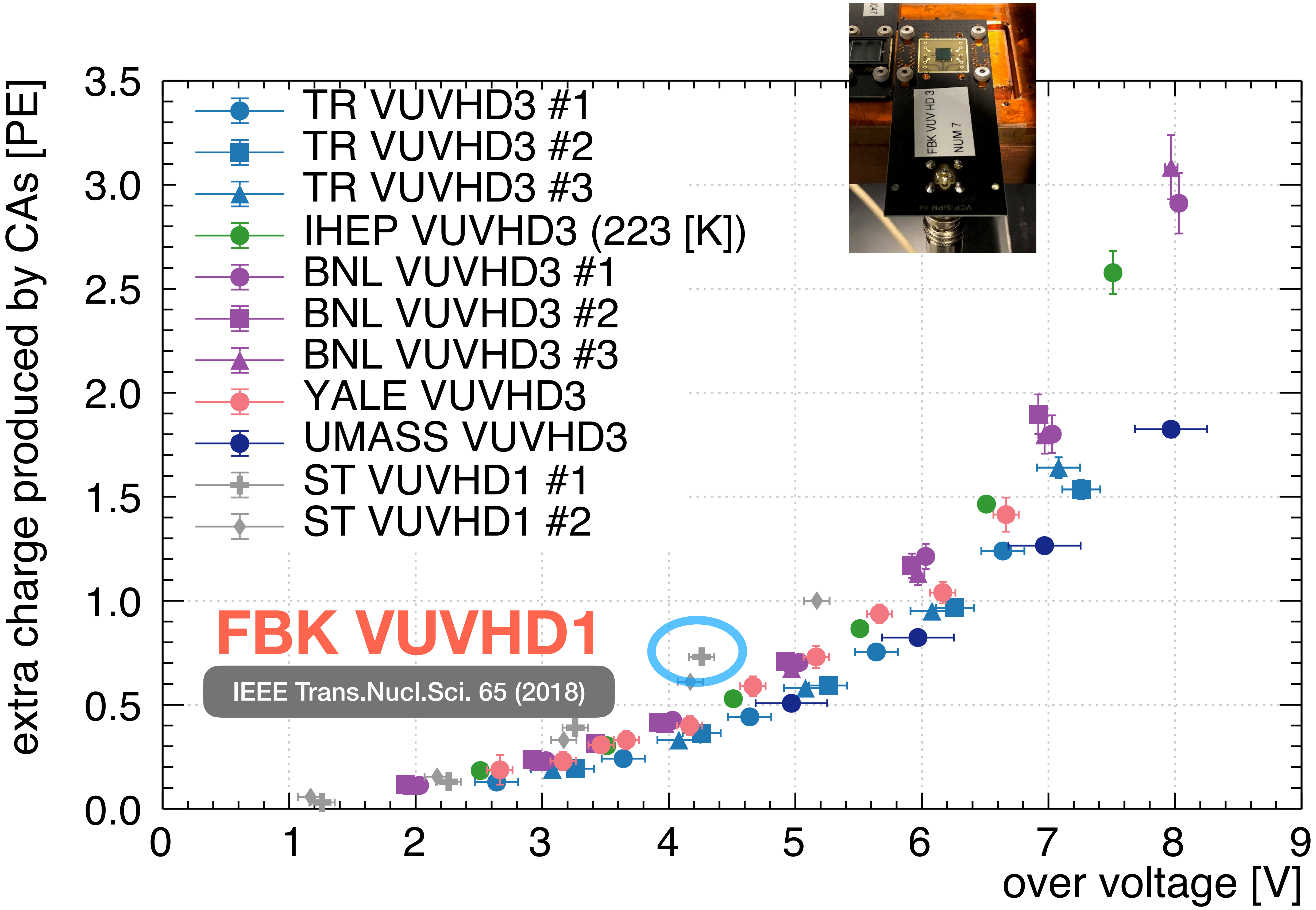
Requirement at 163 [K]: DCR < 10 Hz/mm^2

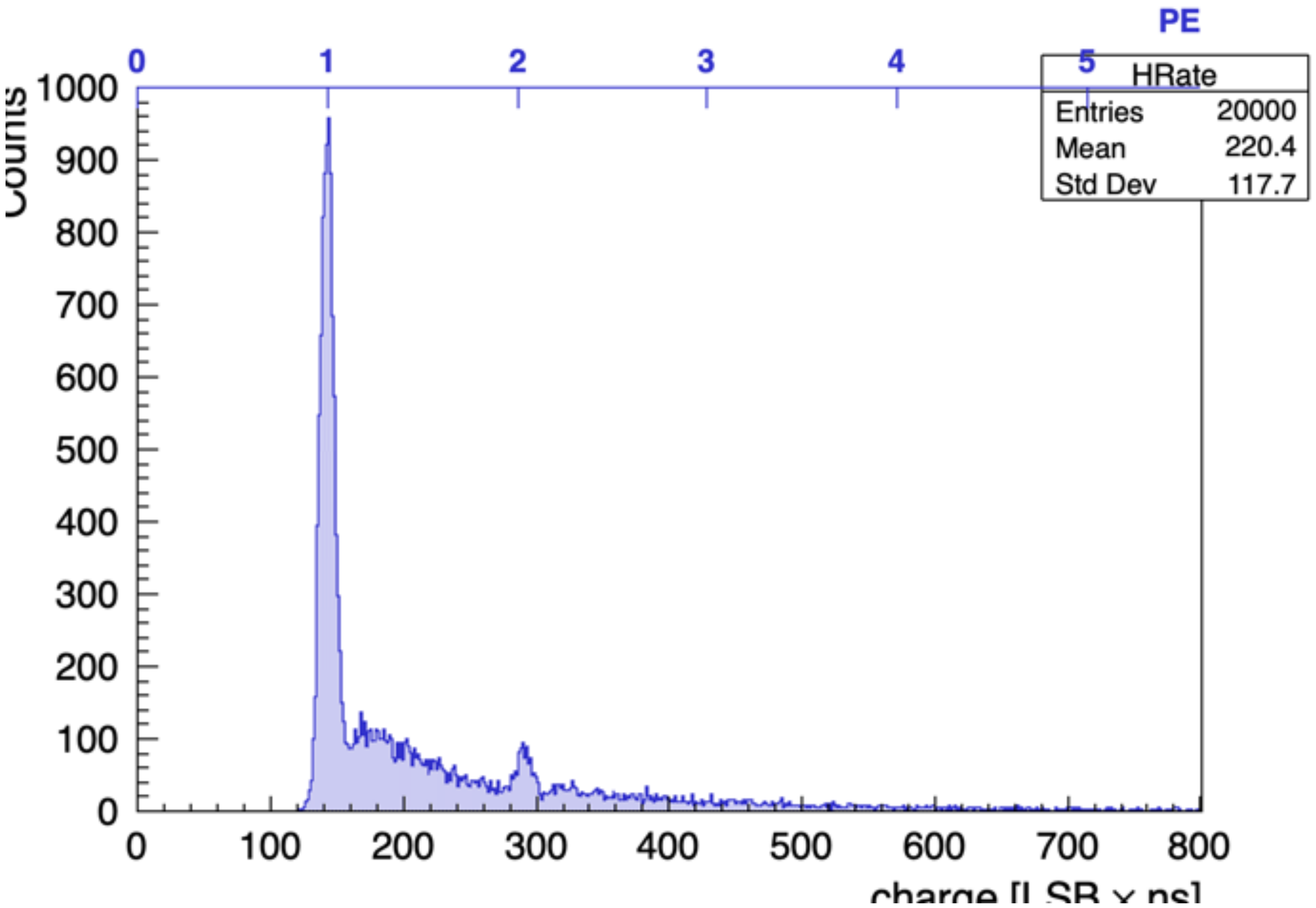
- **Requirement met in the entire range of OV studied!**

Correlated Avalanches FBK VUVHD3

$$\mathbf{CAF} \equiv \frac{\sigma_\Lambda}{1 + \langle \Lambda \rangle}$$

- Defined as the ratio between the RMS (σ_Λ) and the mean $\langle \Lambda \rangle$ extra charge procured by correlated avalanches (CA) per pulse





- **FBK VUVHD3** is improved compare to **FBK VUVHD1.**

Correlated Avalanches FBK VUVHD3

$$\textbf{CAF} \equiv \frac{\sigma_\Lambda}{1 + \langle \Lambda \rangle}$$

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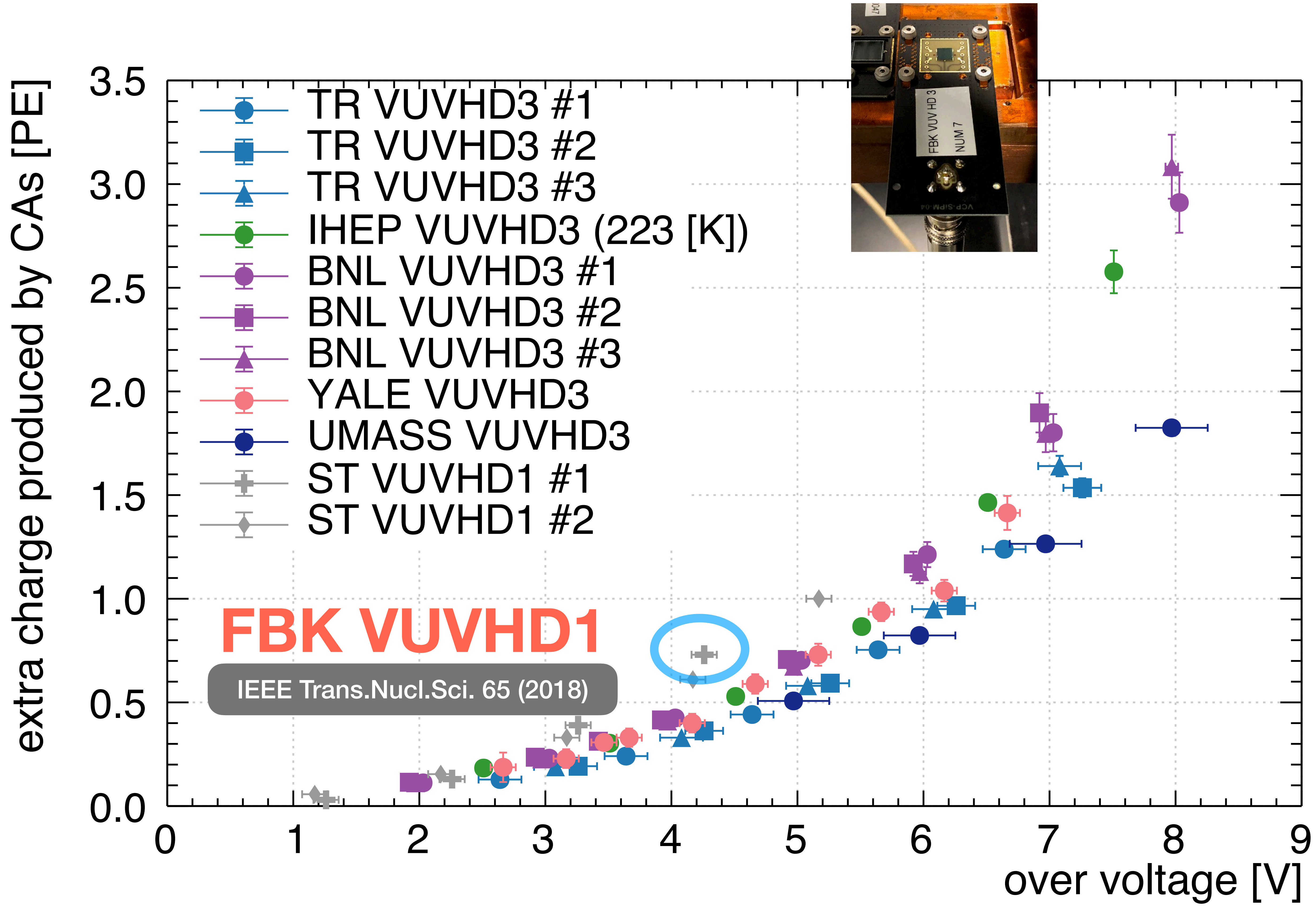
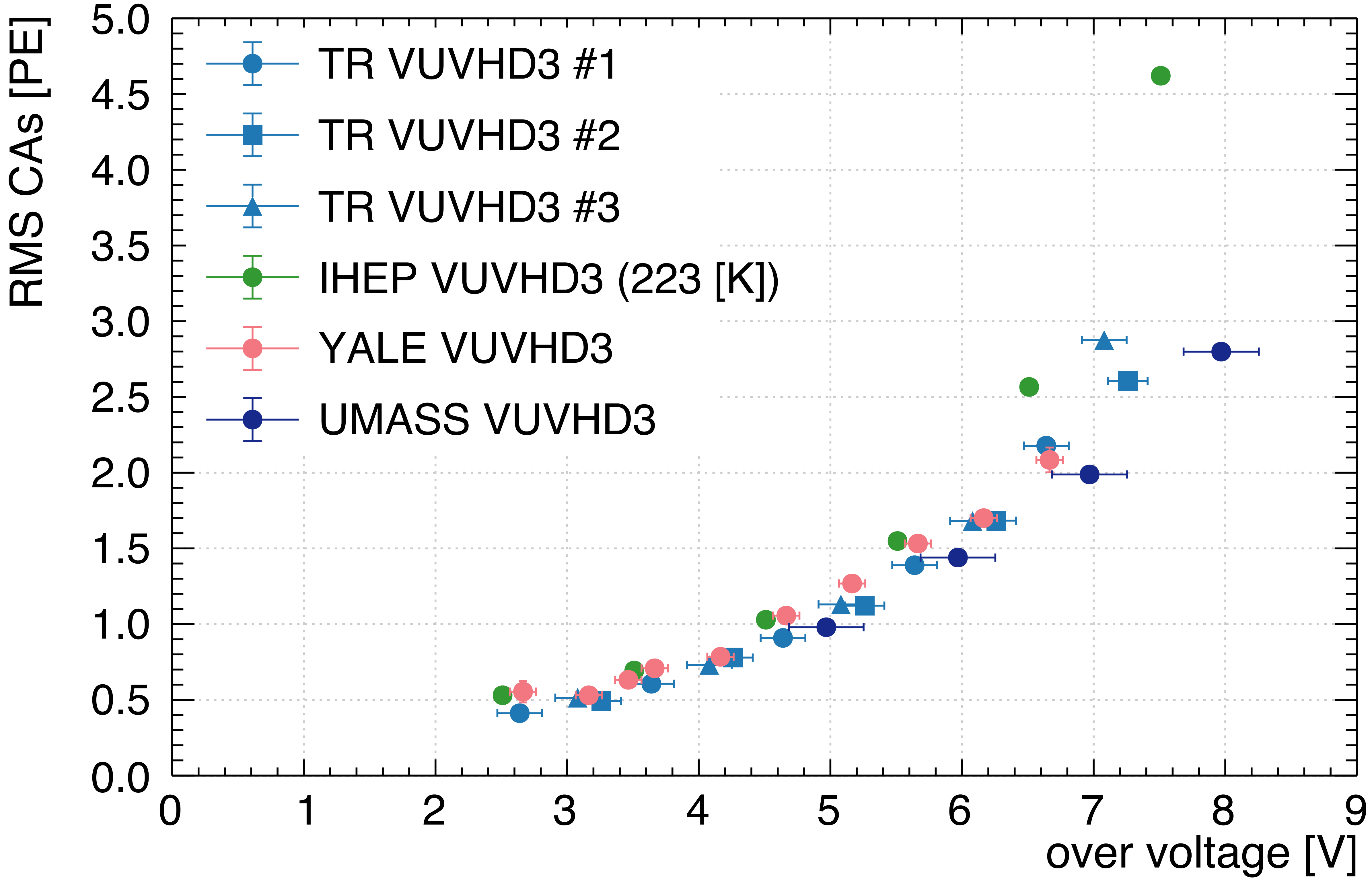


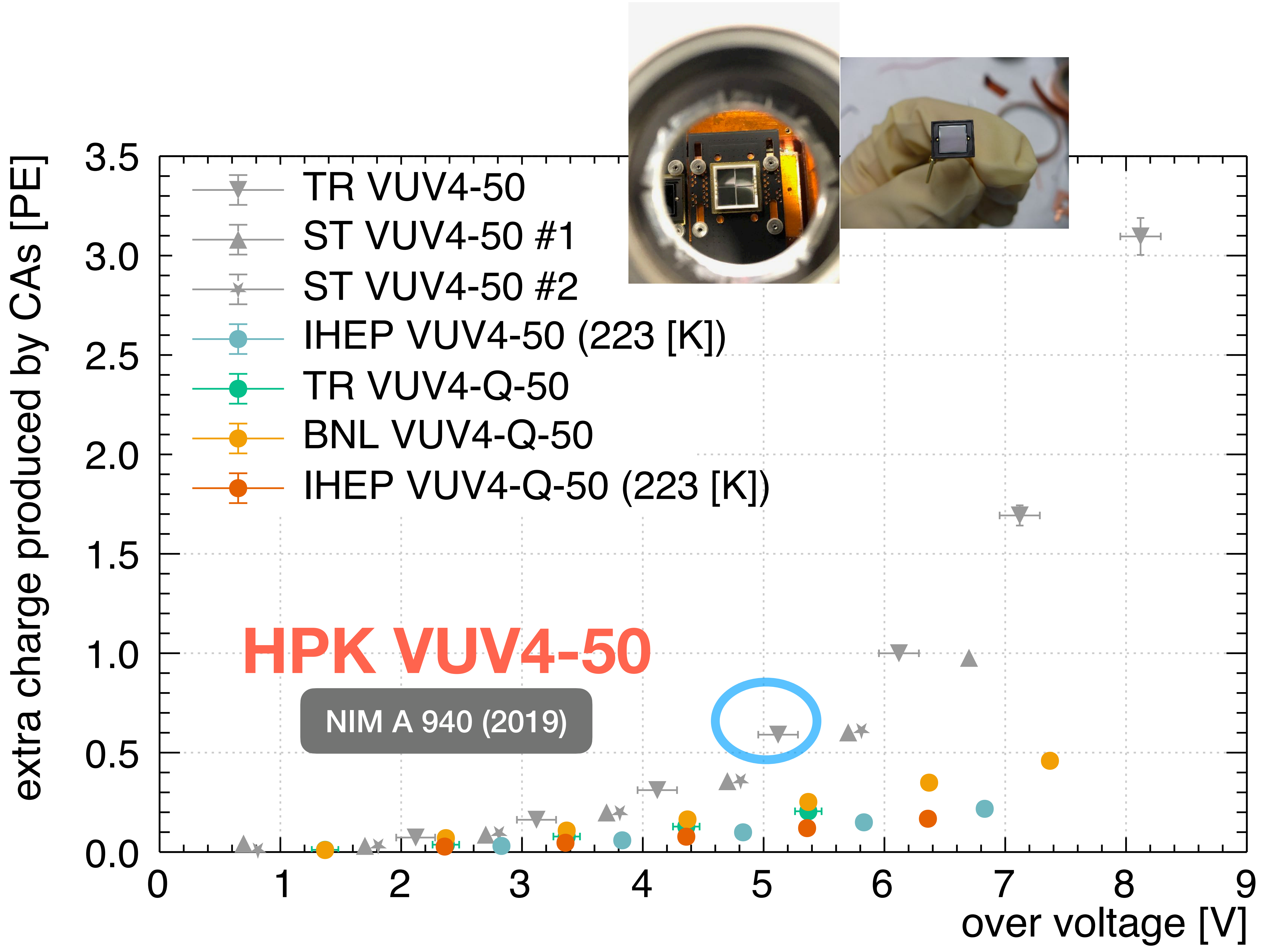


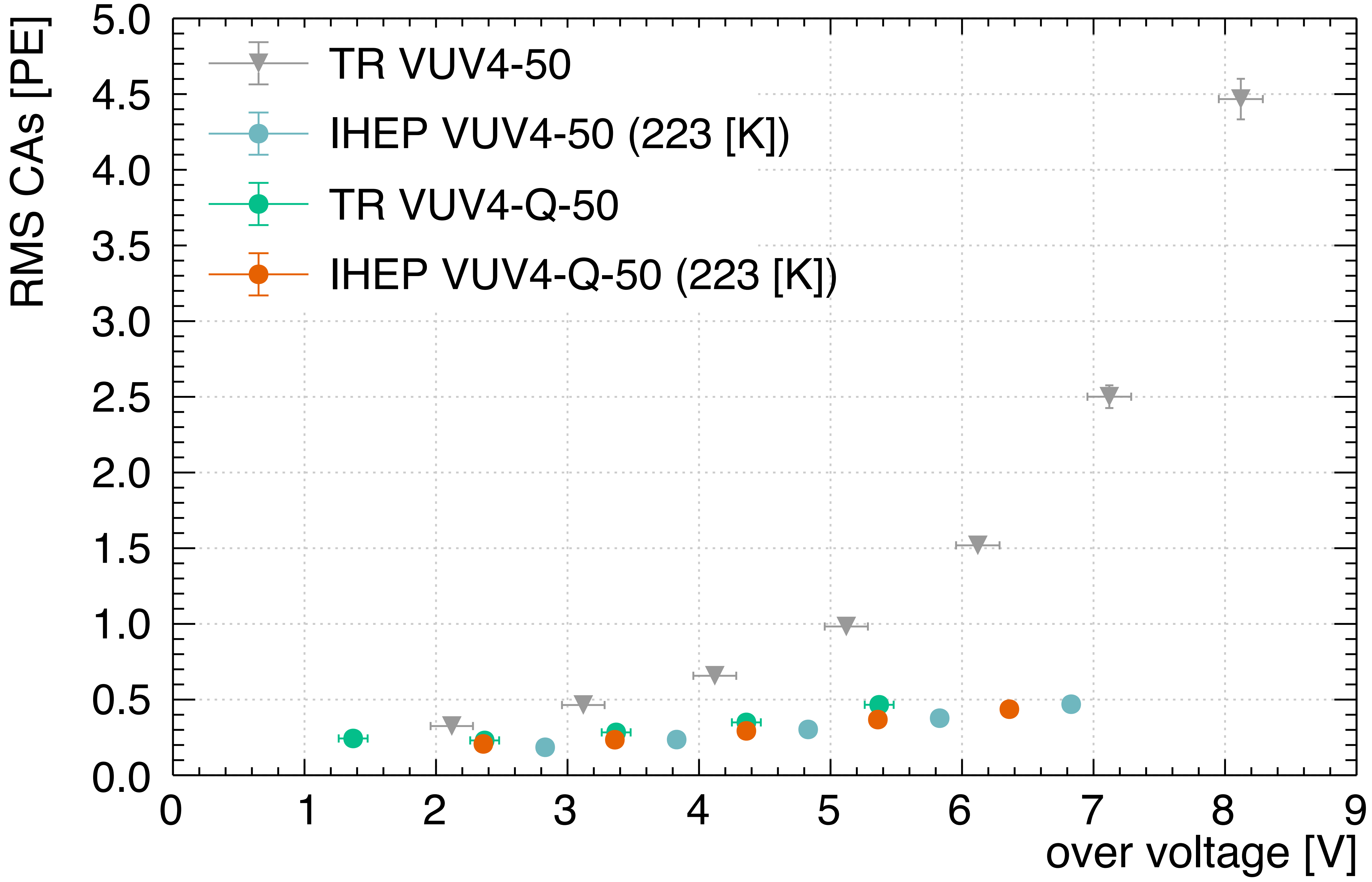
- **FBK VUVHD3** is improved compare to **FBK VUVHD1.**

Correlated Avalanches HPK VUV4 MPPCs

$$\textbf{CAF} \equiv \frac{\sigma_\Lambda}{1+\langle\Lambda\rangle}$$

- Defined as the ratio between the RMS (σ_Λ) and the mean $\langle\Lambda\rangle$ extra charge procured by correlated avalanches (CA) per pulse





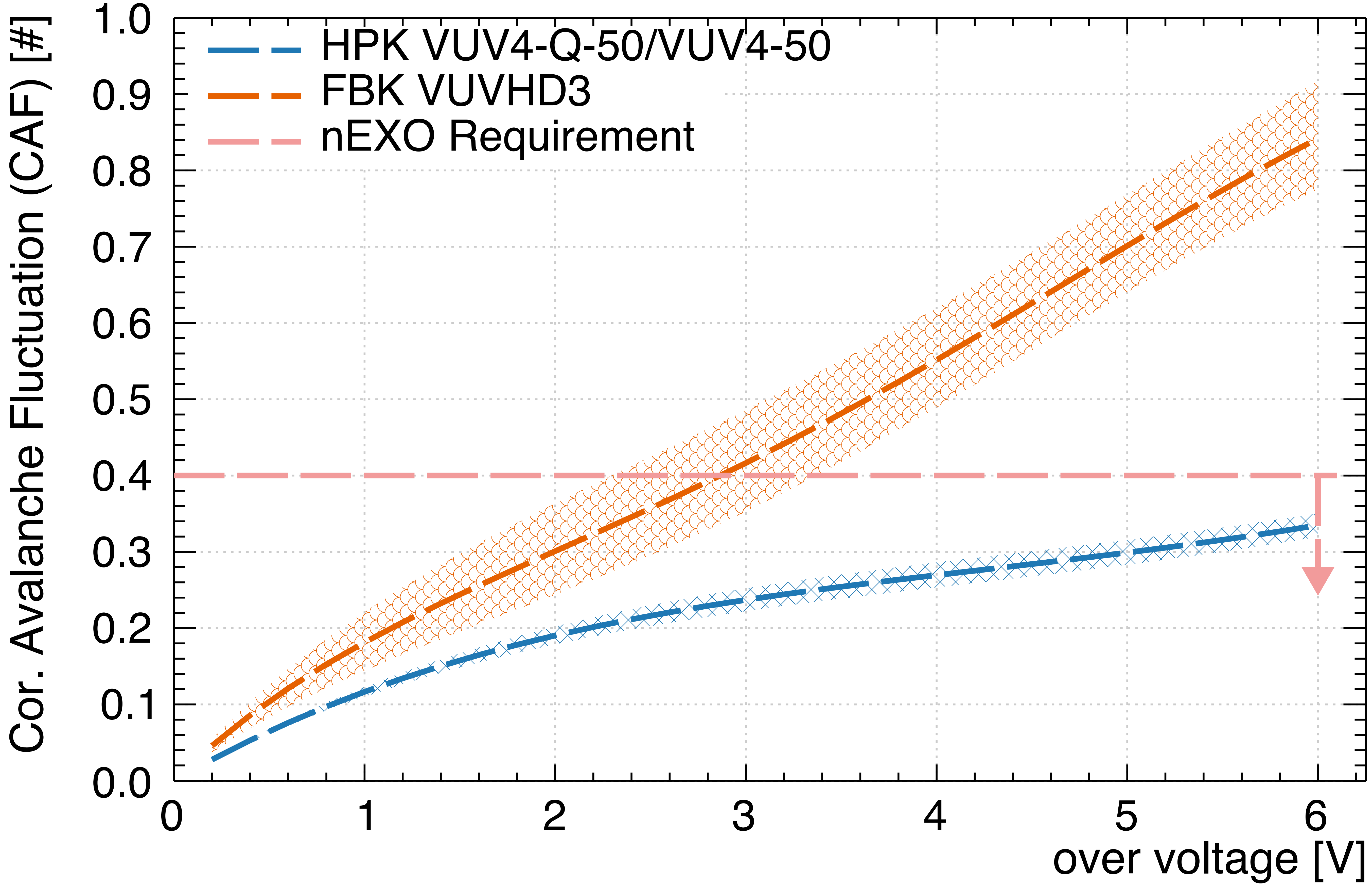
- **HPK VUV4** has almost **no correlated avalanches (CA) and it is significantly better than the HPK VUV4-50 tested previously**

Correlated Avalanche Fluctuation (CAF)

- Defined as the ratio between the RMS (σ_Λ) and the mean $\langle\Lambda\rangle$ extra charge procured by correlated avalanches (CA) per pulse

$$\textbf{CAF} \equiv \frac{\sigma_\Lambda}{1+\langle\Lambda\rangle} < 0.4$$

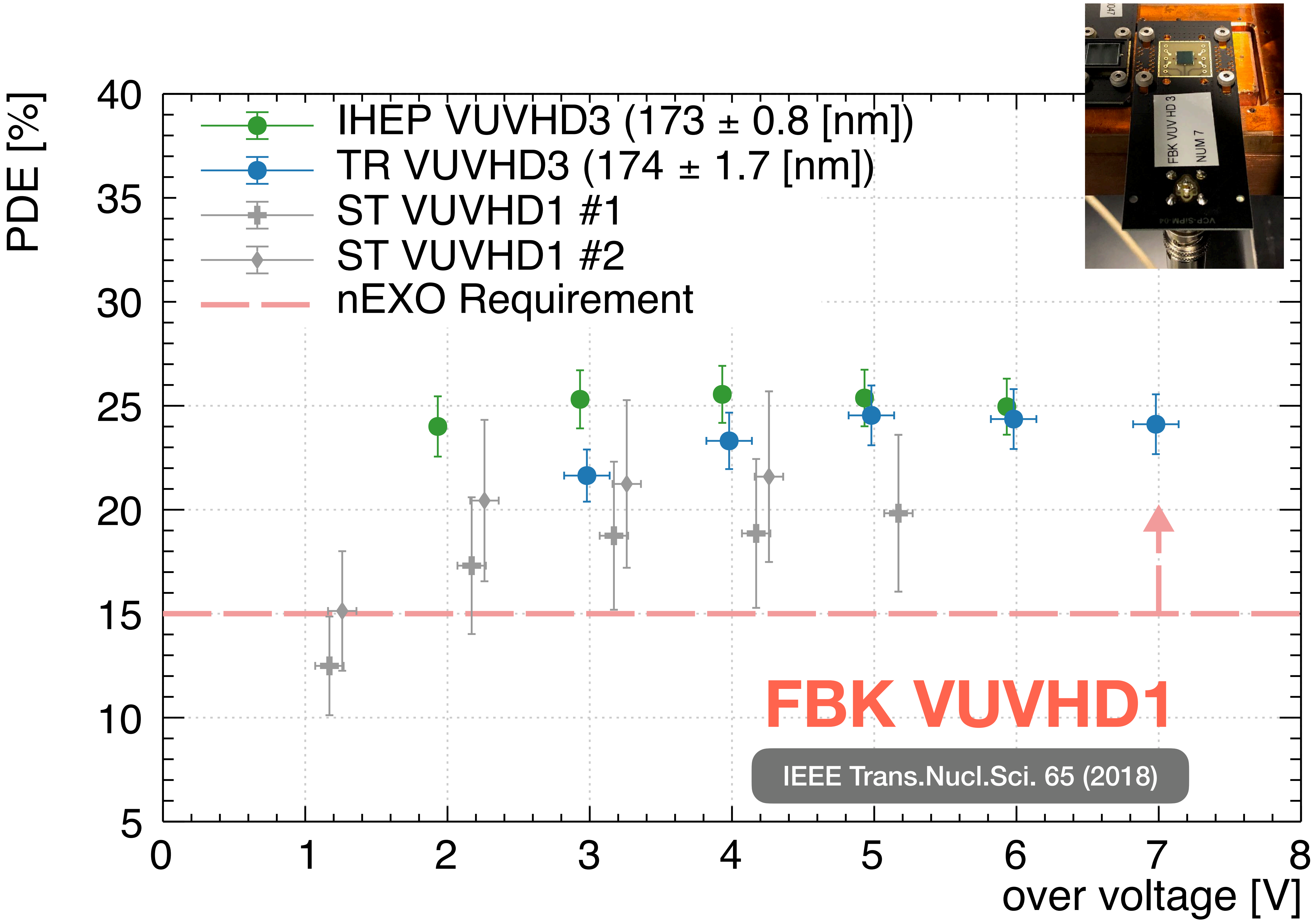
- The error bars **account for the spread** between different measurements
- HPK MPPCs **satisfies the requirement** in the entire range of OV studied
- FBK VUVHD3 **satisfies the requirement up to 3/3.5 V** of OV

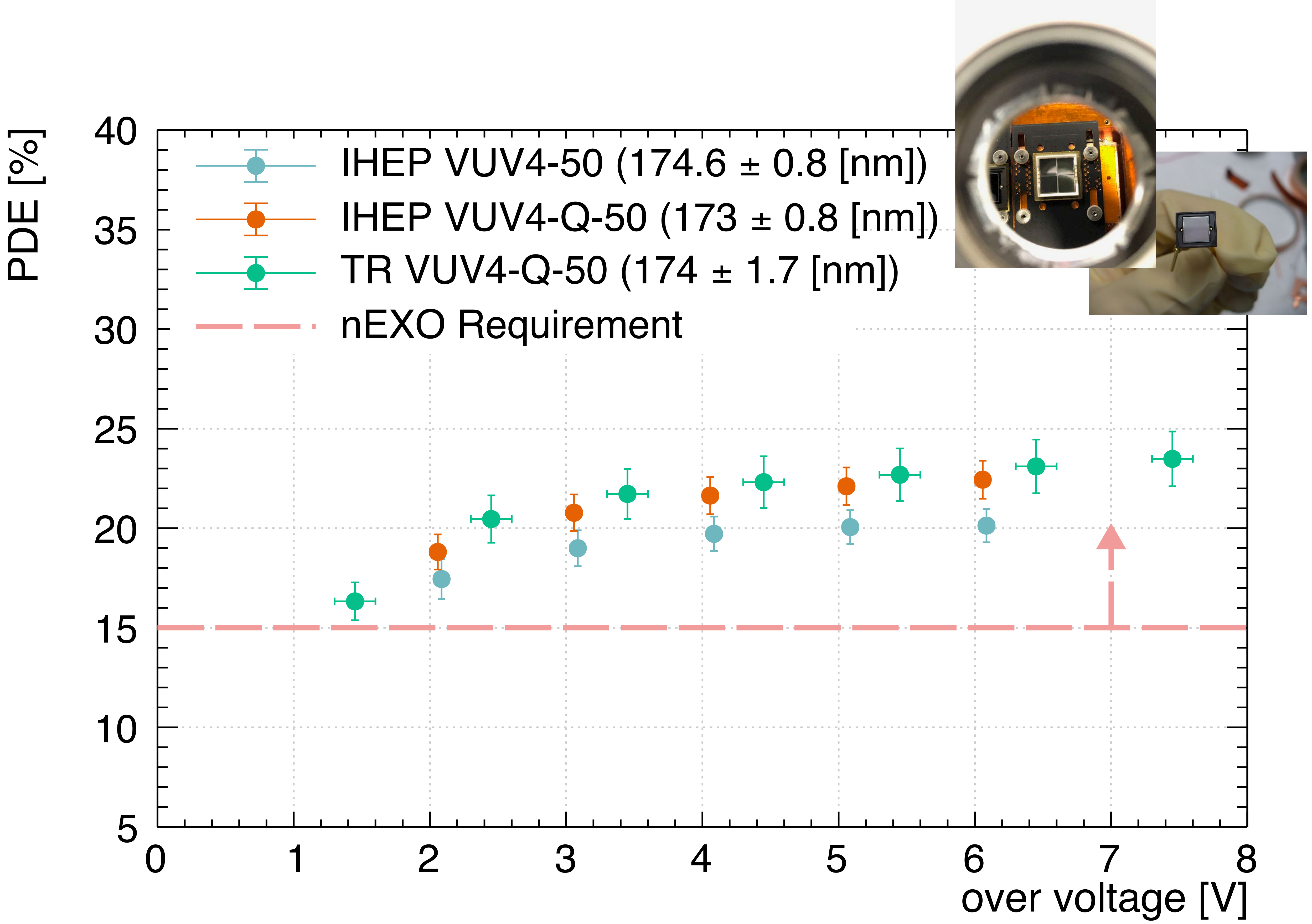


Requirement at 163 [K]: CAF < 0.4

Photon Detection Efficiency (PDE) at 174 nm at 163 K

- PDE has been measured by TRIUMF and IHEP at 163 K and 233 K, respectively as a function of over voltage and wavelength



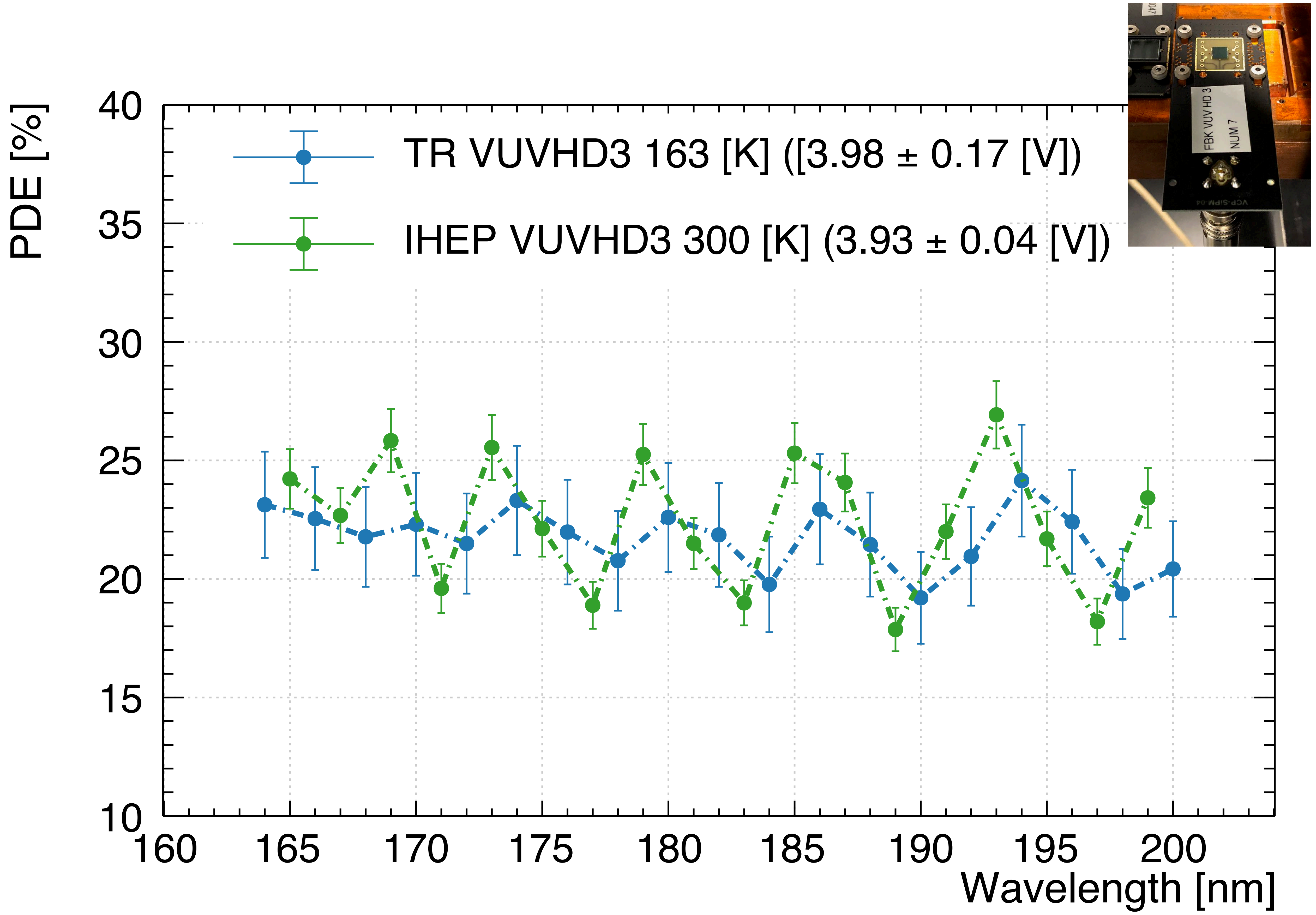


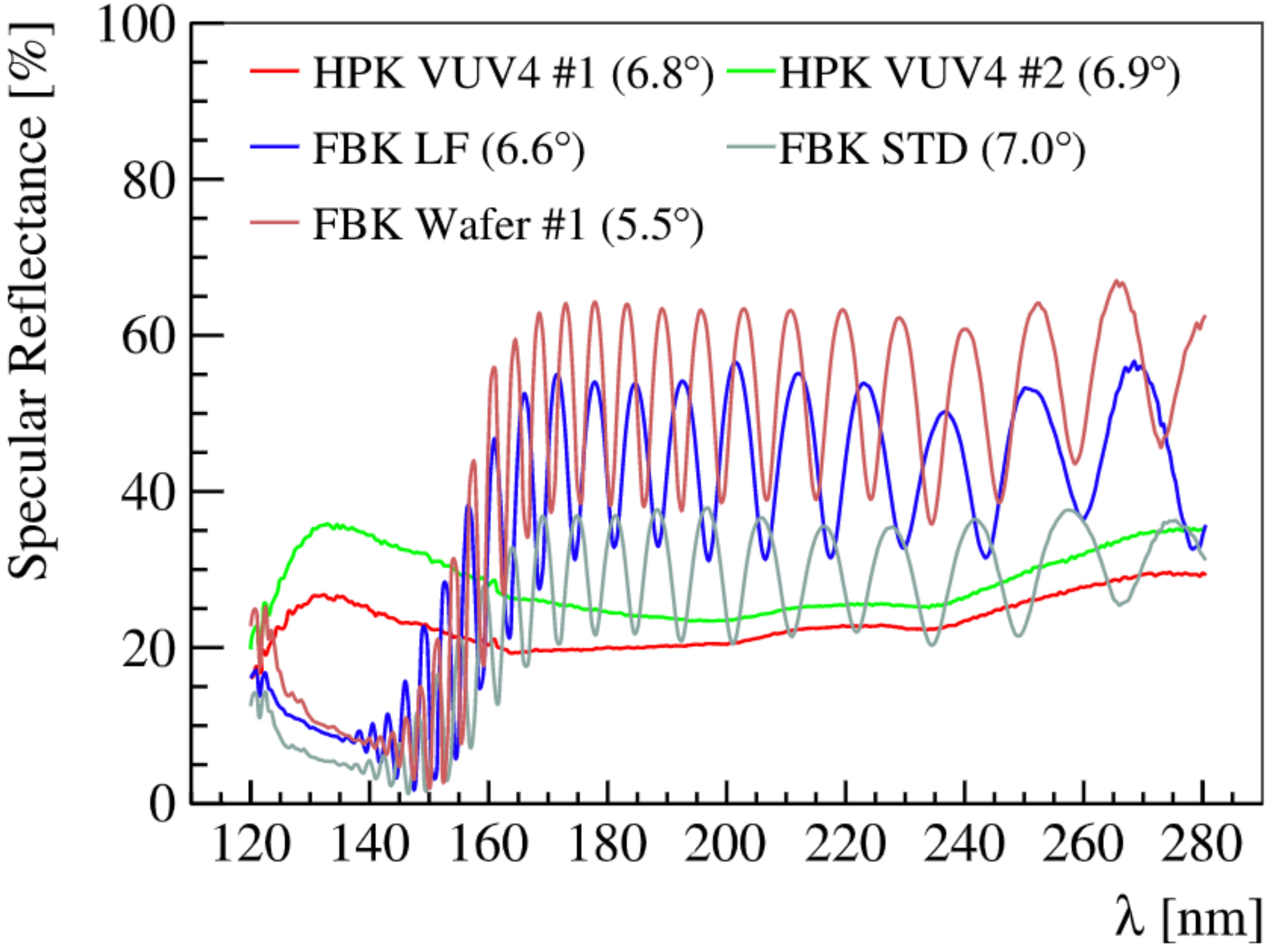
Requirement > 15% at ~ 175 nm

Requirement met from 1.5 V of OV !

Photon Detection Efficiency (PDE) Wavelength Dependence

- LXe scintillation spectrum is a gaussian with a mean of 174.8 nm and a STD of 4.33 nm

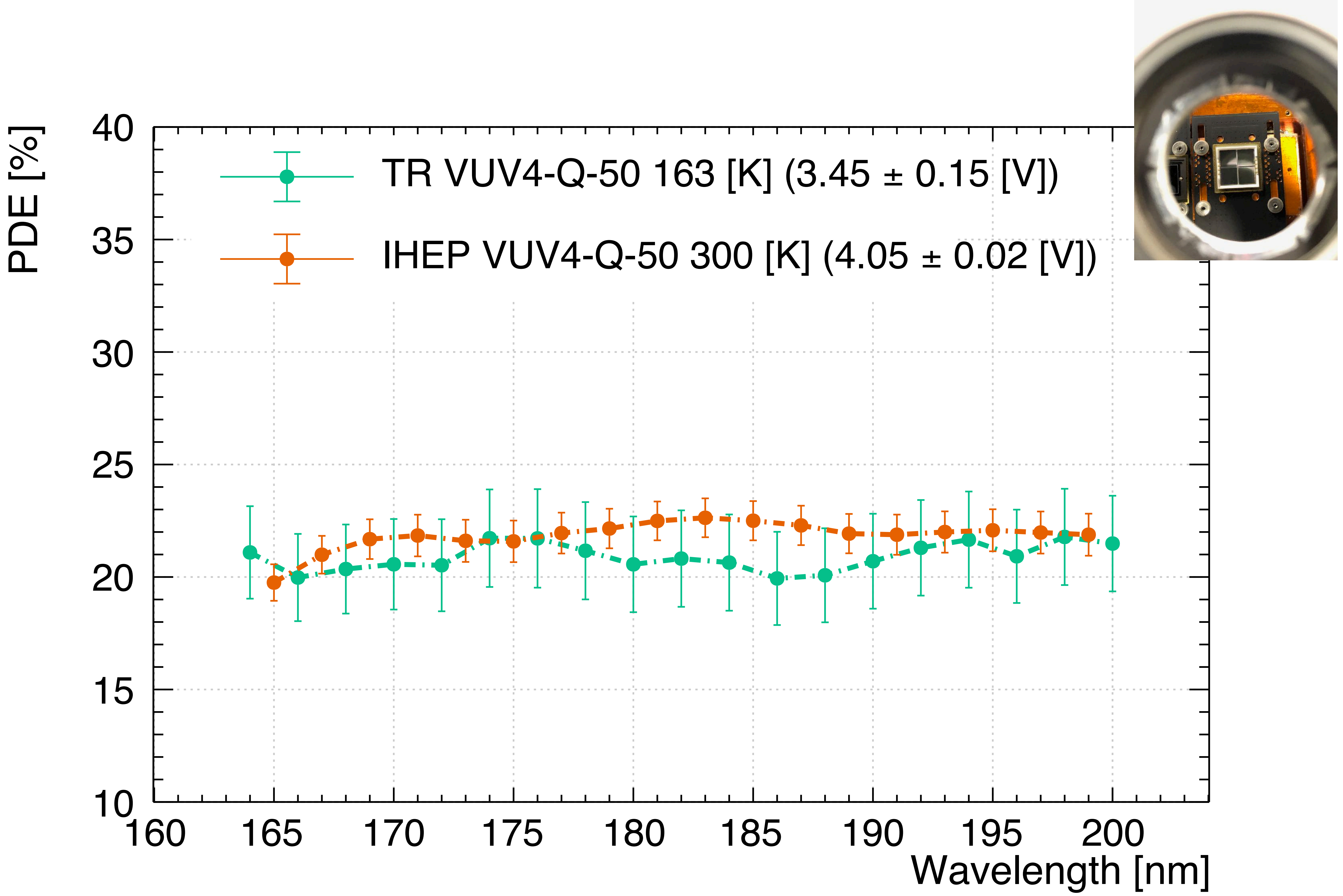


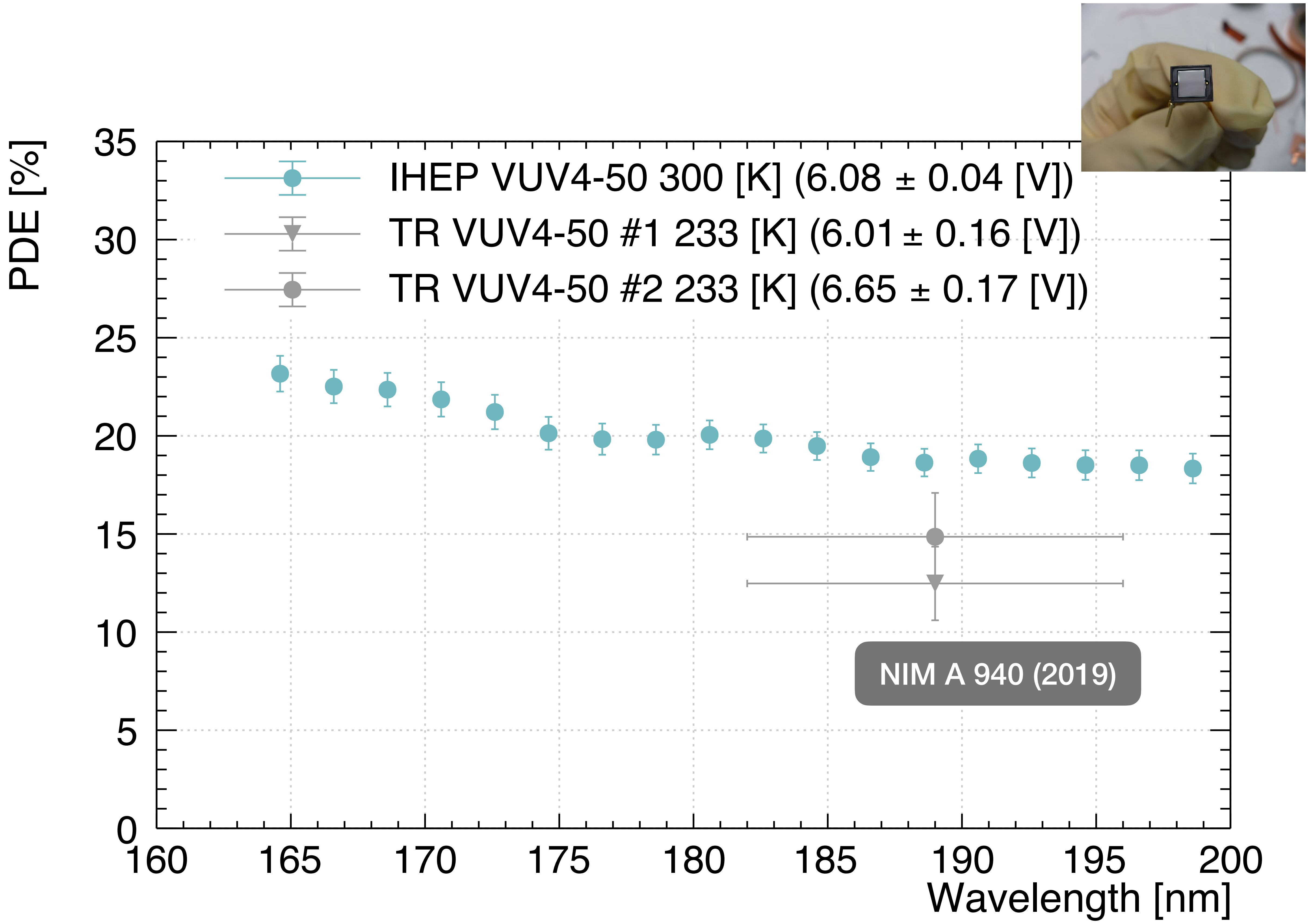


- FBK thin film interference in the SiO2 top layer. Compatible with specular reflectivity measurements done at IHEP and published in 10.1109/TNS.2020.3035172

Photon Detection Efficiency (PDE) Wavelength Dependence

- LXe scintillation spectrum is a gaussian with a mean of 174.8 nm and a STD of 4.33 nm





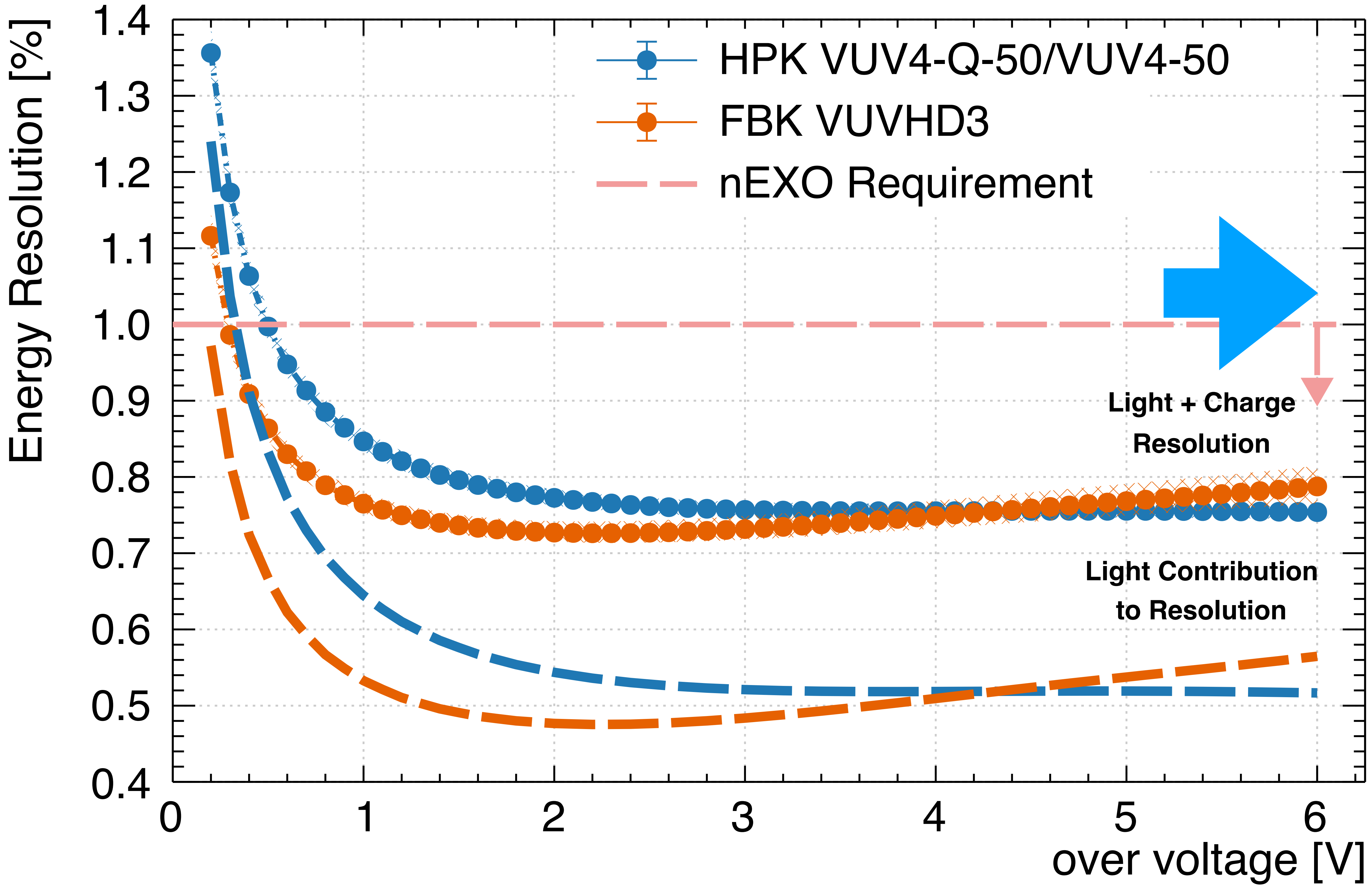
- HPK MPPCs Quad devices have an efficiency higher of the corresponding single package 50um pitch device

nEXO Energy Resolution at $(2458\,\mathrm{keV}$ for $^{136}\mathrm{Xe})$

arXiv:2209.07765

$$\frac{\sigma_n}{\langle n \rangle} = \frac{\sqrt{\left(\frac{(1-\epsilon_p)n_p}{\epsilon_p} + \frac{n_p}{\epsilon_p}\cdot\frac{\sigma_\Lambda^2}{(1+\langle\Lambda\rangle)^2} + n_p^2\sigma_{lm}^2\right) + \left(\frac{n_q t}{\tau} + \frac{\sigma_{q,noise}^2}{\epsilon_q^2}\right)}}{\langle n \rangle}$$

nEXO Requirement: $\frac{\sigma_n}{\langle n \rangle} \leq 1\,\%$



Fluctuation due to number of photons detected (PDE)

Fluctuation Due to Correlate Avalanche Noise (CA/RMS)

Residual Calibration Uncertainty

Fluctuation due to the number of charges detected

Fluctuation due to electronic noise in charge channel

PDE drives the minimum. **Need to better understand SiPM PDE**

eCT is not yet accounted . **See talk on Thursday**

Understanding SiPM PDE

SiPM Photon-Detection Efficiency

The Photo-Detection-Efficiency (PDE) is defined as the probability for a photon (of a given wavelength) to be detected and produce a measurable signal in the SiPM.

Usually PDE is defined as

$$\boxed{\mathrm{PDE} = \mathrm{FF} \cdot \mathrm{QE}(\lambda) \cdot T_p(V, \lambda)}$$

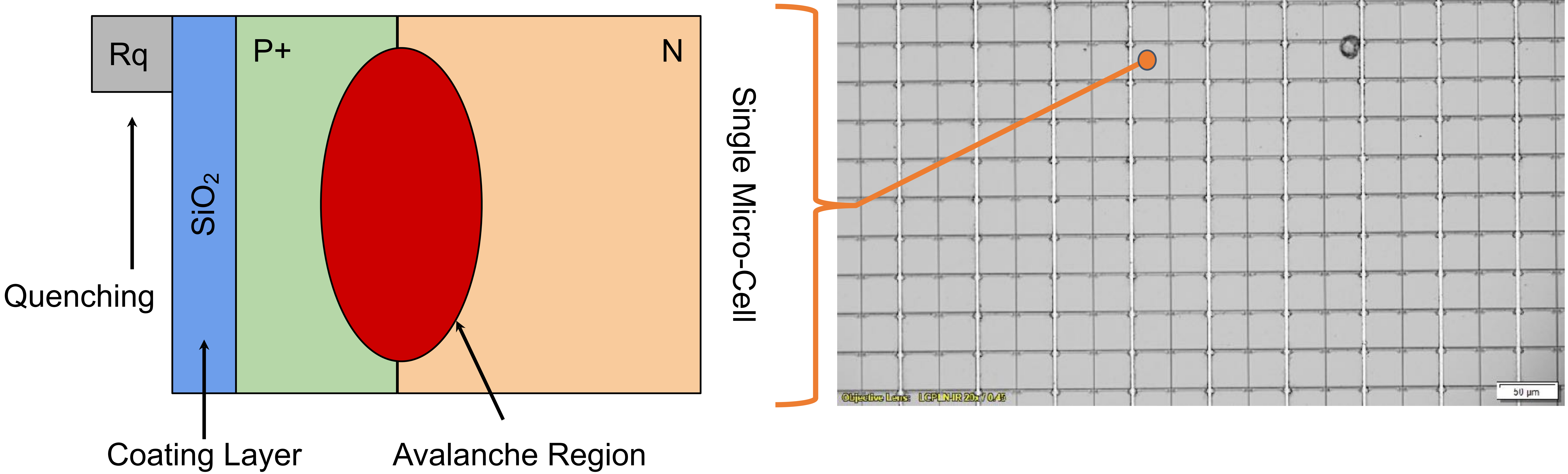
Fill-Factor Quantum Efficiency Avalanche-Triggering-Probability

1) lack of formal separation between the different processes that define the total PDE.
2) lack of an analytical expression

How Do SiPMs work ?

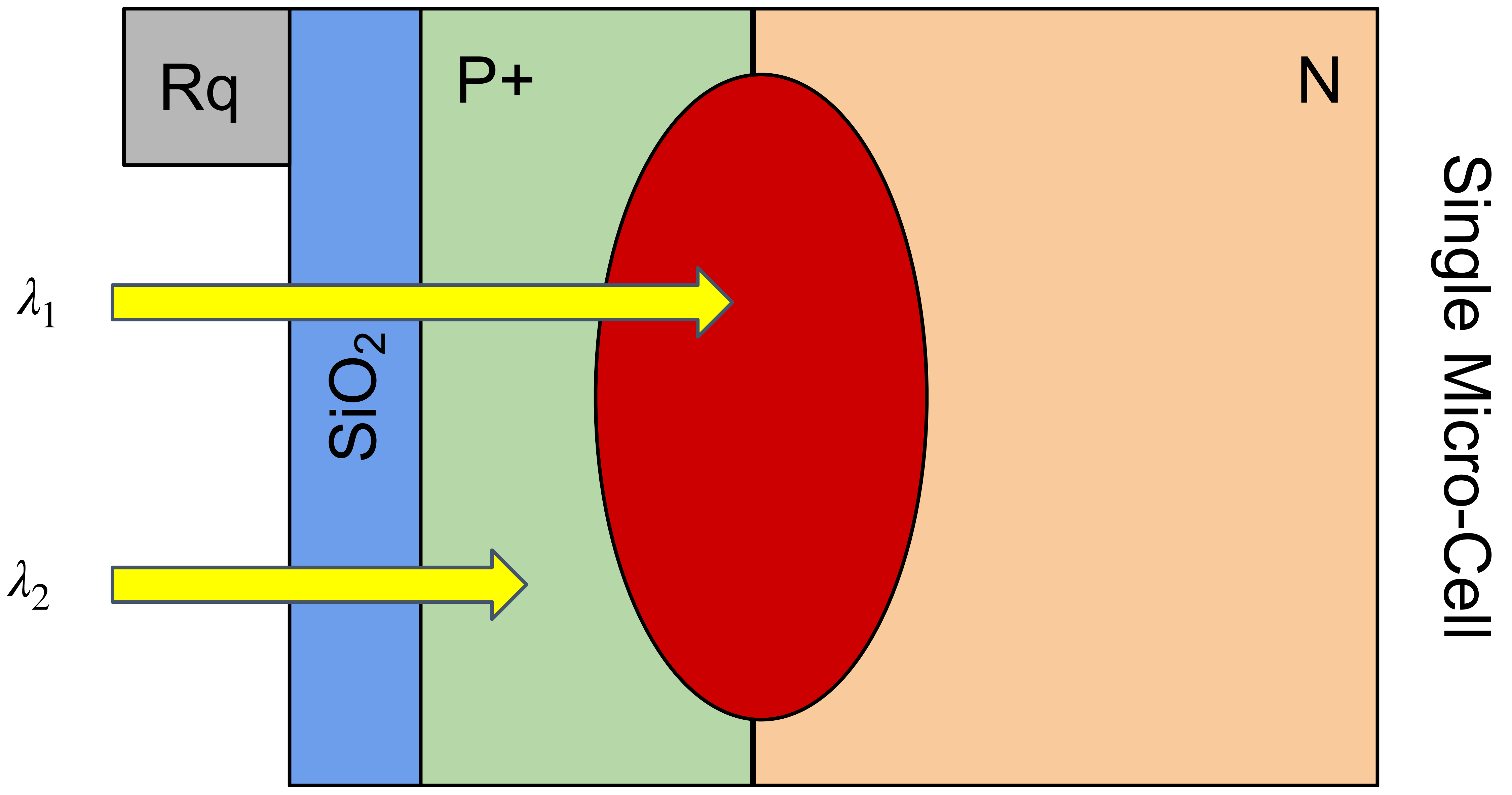
iEEE TED 66.10 (2019)

p-n junctions micro-cells operated in Geiger-mode, with an added quenching resistor. Each SiPM is composed by multiple micro-cells.



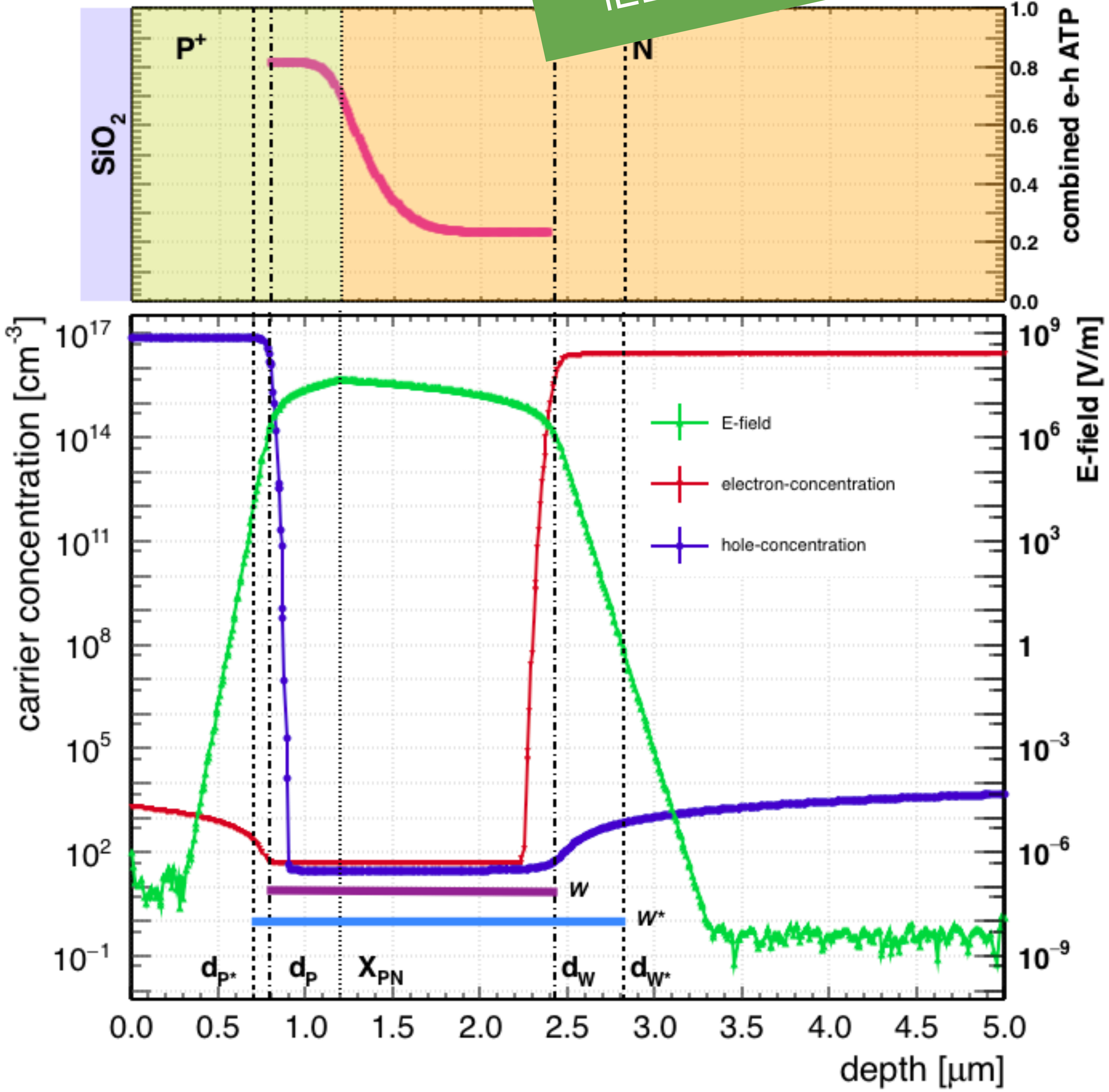
How Do SiPMs work ?

An incoming photon enters the junction and it is absorbed (wavelength dependent process : λ).



$\lambda_1 > \lambda_2$

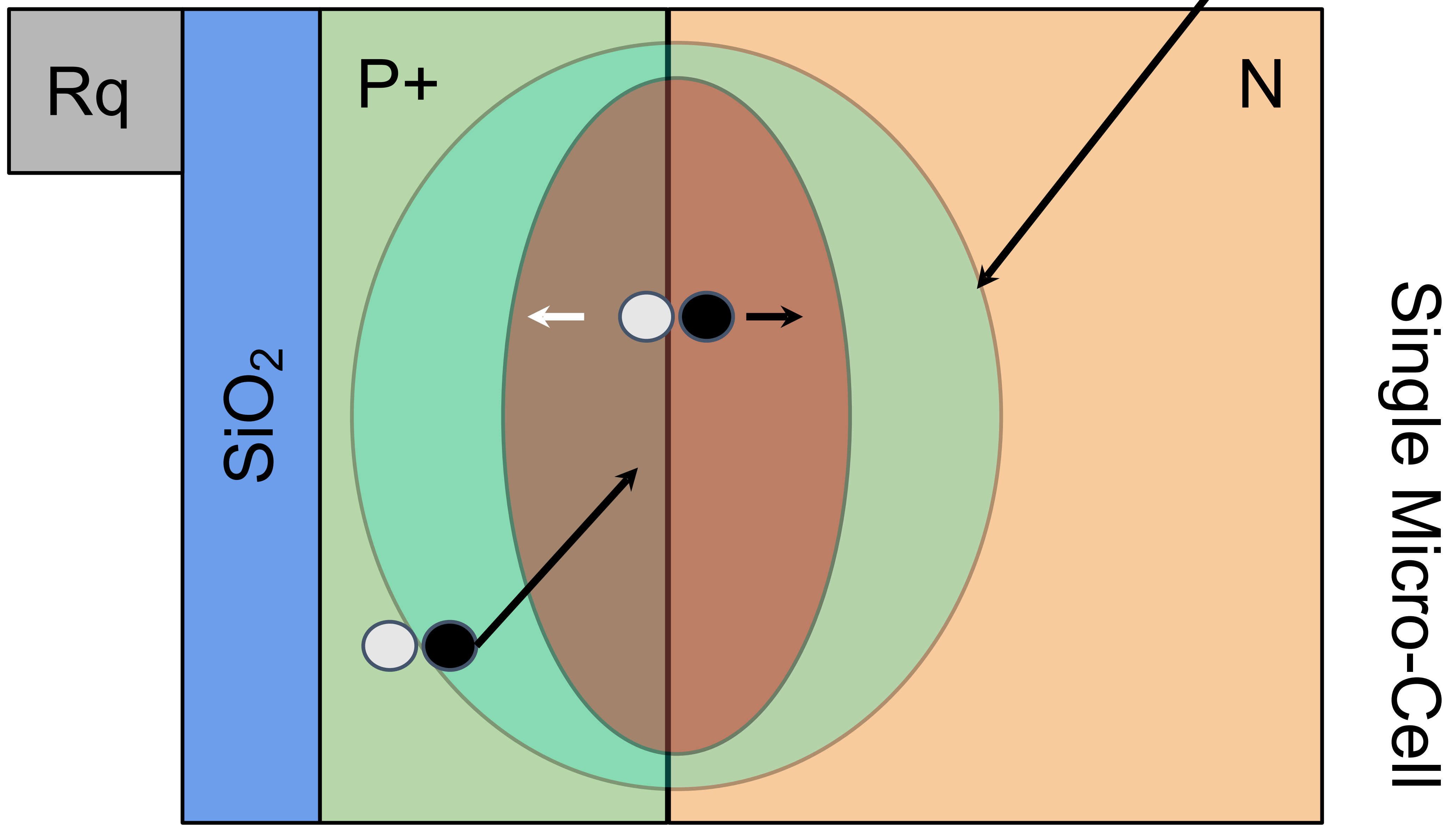
iEEE TED 66.10 (2019)



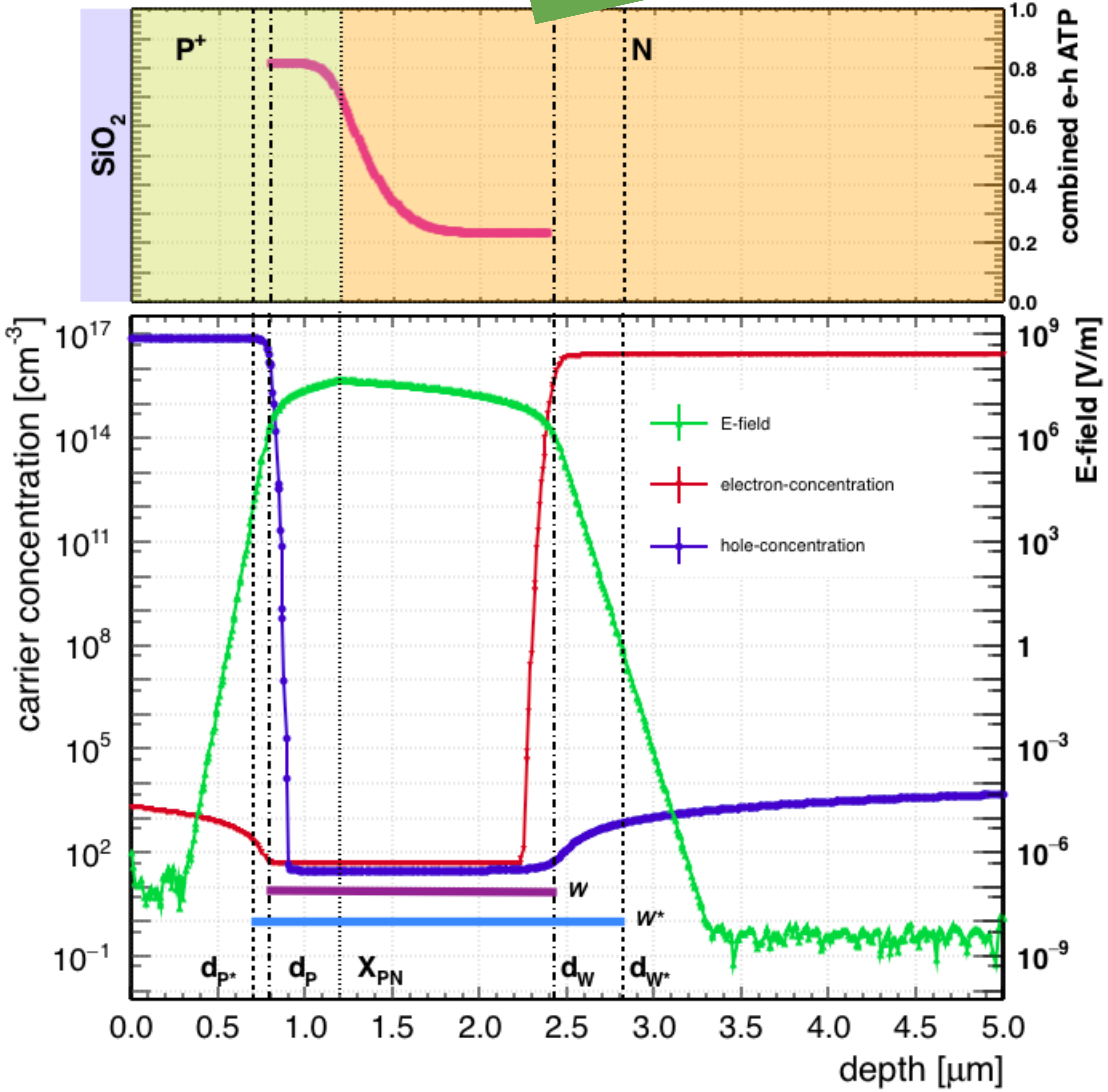
How Do SiPMs work ?

The internal field of the junction brings the generated carrier (e/h) to the avalanche region.

Effective photon collection region



iEEE TED 66.10 (2019)

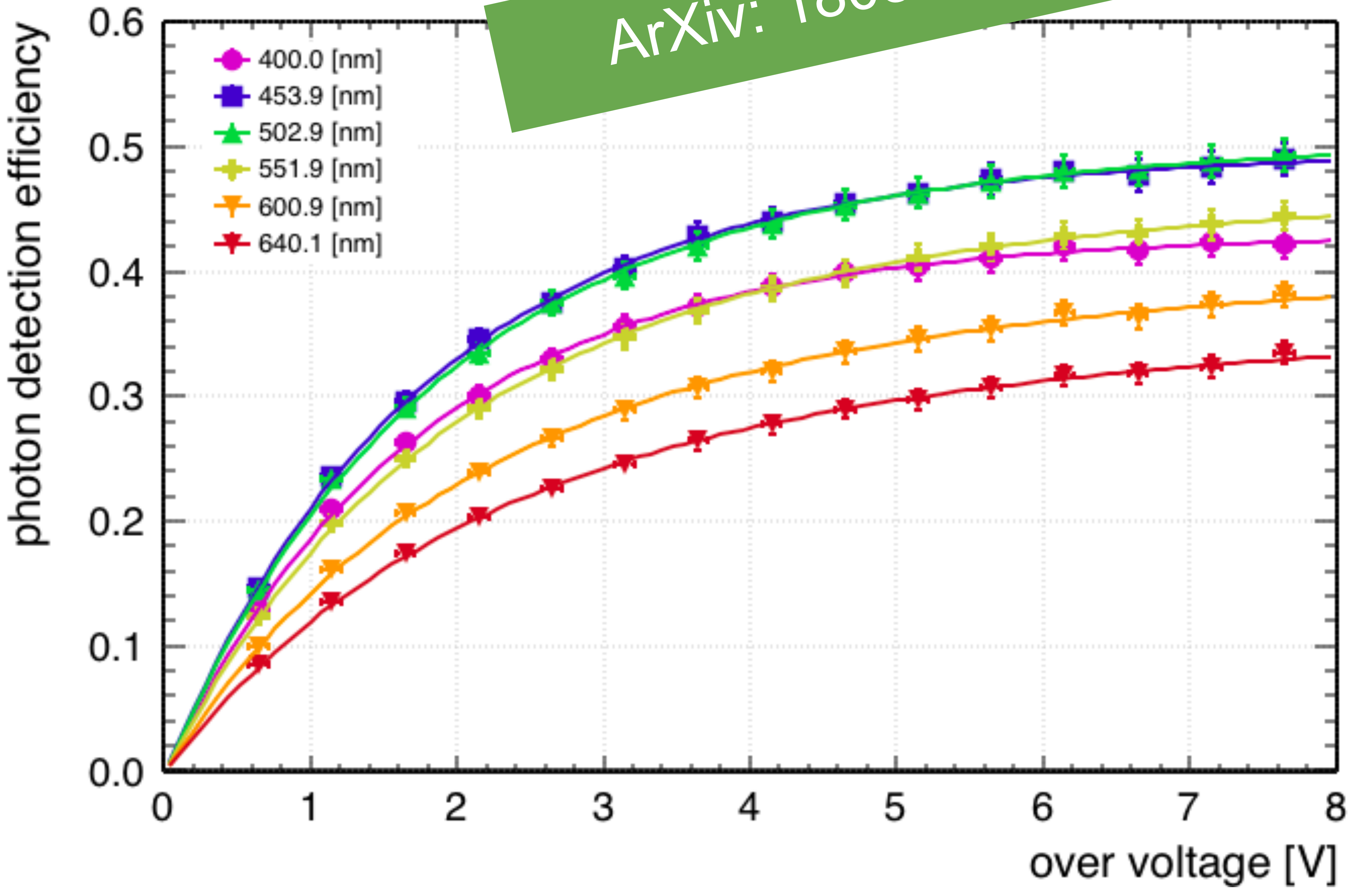


1) The e-h pair can be created or not in the depleted region.

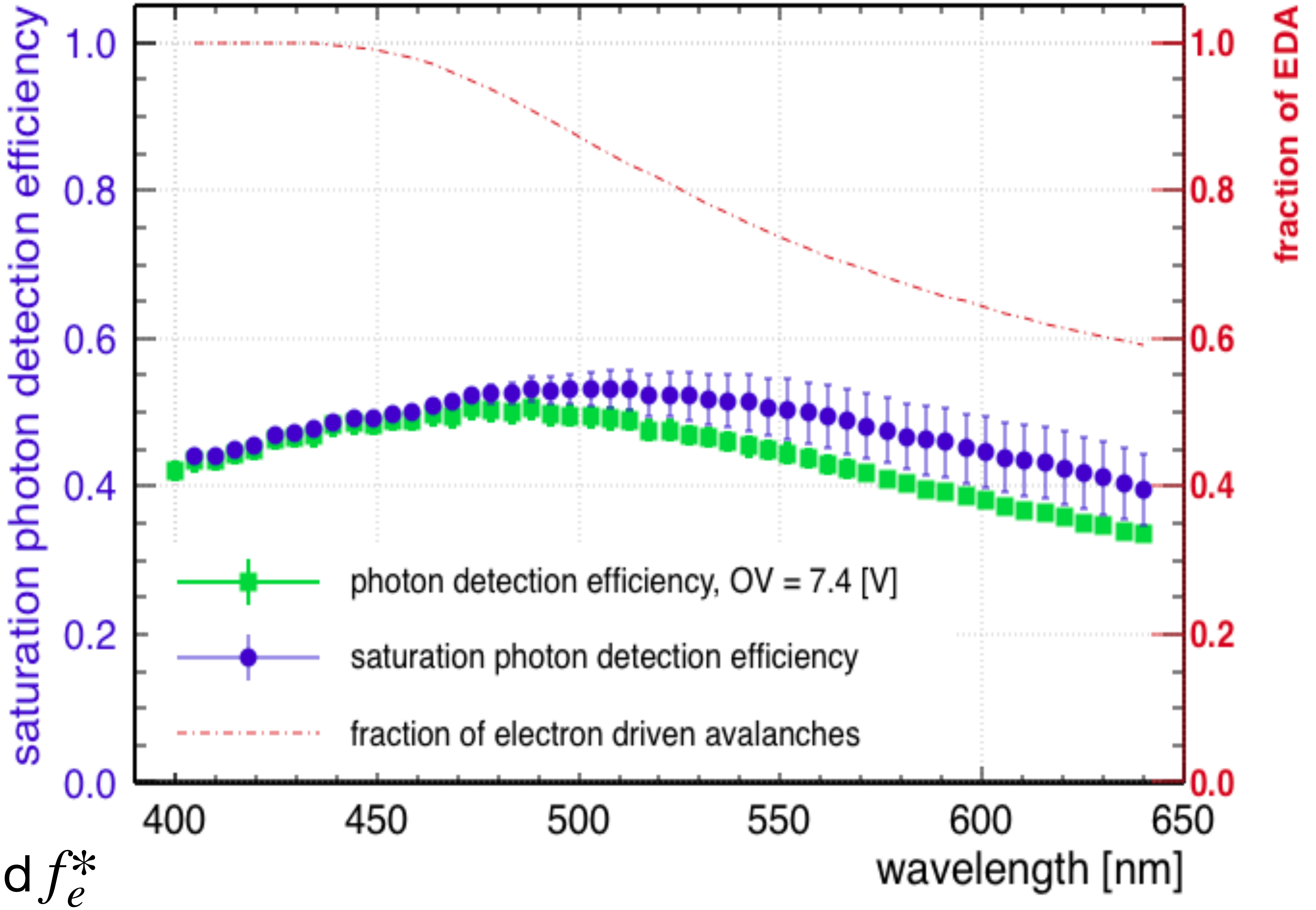
2) Absorption and avalanche triggering probabilities are correlated since the latter probability depends where the photon is absorbed

Avalanche Triggering Probability

iEEE TED 66.10 (2019)



ArXiv: 1808.05775



PDE data were fitted with

$$\mathbf{PDE}_{\lambda} = \mathbf{PDE}_{\mathbf{MAX}} \cdot \left(\mathbf{P}_{e}(d_P) \cdot f_e^* + \mathbf{P}_{h}(d_W) \cdot (1 - f_e^*) \right)$$

and used to extrapolate: $P_e(d_P)$, $P_h(d_W)$ and f_e^*

EDA: Electron Drive Avalanches == f_e^*

This model is useful to infer SiPM's internal characteristics without knowing the exact internal structure and ..much more!

Dark Noise Rate (WIP)

The total SiPM Dark Noise Rate is due to several processes

$$R_{dn}(V,T) = R^I_{diff} + R^I_{bbt} + R^I_{trap}$$

Diffusion

$$R^I_{\textbf{diff}} \equiv \left(R_{\textbf{n-diff}}(d_P)P_e(d_P) + R_{\textbf{p-diff}}(d_W)P_h(d_W) \right)$$

Band to Band tunneling

$$R^I_{bbt} \equiv \int_{d_P}^{d_W} R^V_{bbt}(x)P_e(x)\ dx$$

Shockley-Read-Hall Recombination

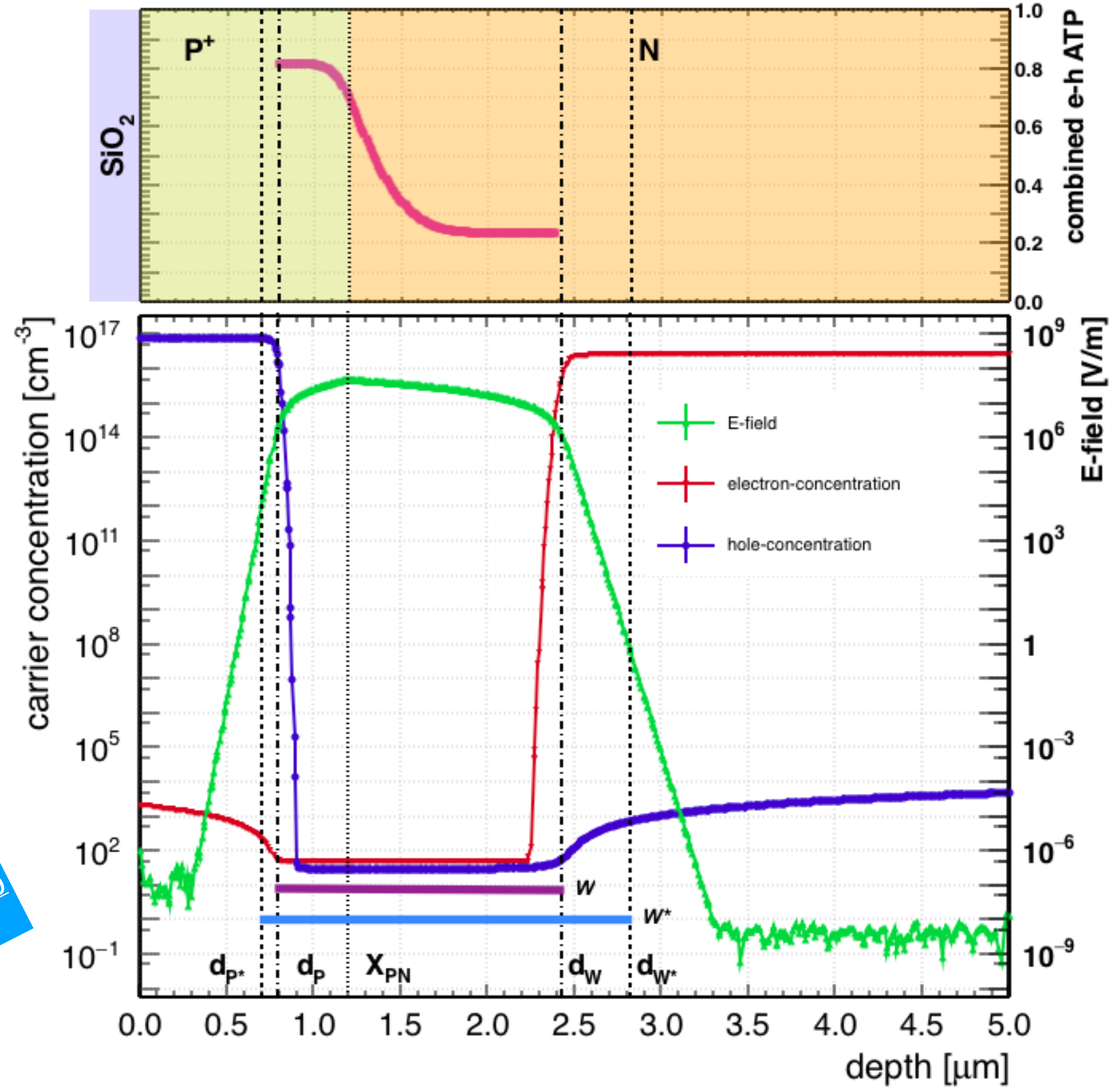
$$R^I_{trap} \equiv \int_{d_P}^{d_W} R^V_{trap}(x)P_P(x)\ dx$$

Several parameterisation are available for

$$R_{\textbf{n-diff}}(d_P), R_{\textbf{p-diff}}(d_W), R^V_{trap}(x), R^V_{bbt}(x)$$

DOI: 10.1016/0038-1101(89)90146-9
DOI: 10.1109/16.155882

$$\mathbf{P}_{\mathbf{P}}(x,V) \equiv \left(\mathbf{P}_e(x,V) + \mathbf{P}_h(x,V) - \mathbf{P}_e(x,V)\cdot \mathbf{P}_h(x,V) \right)$$

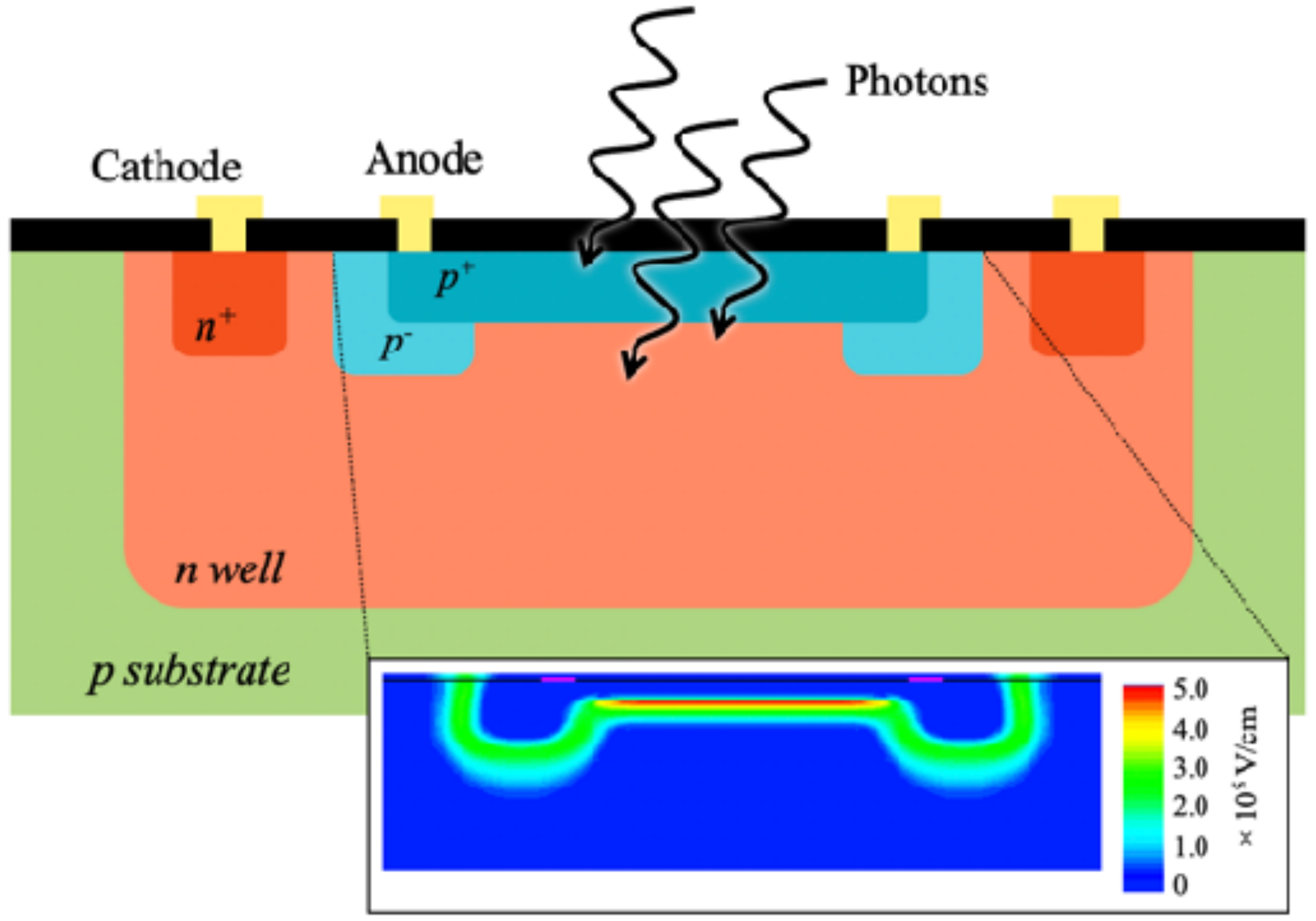


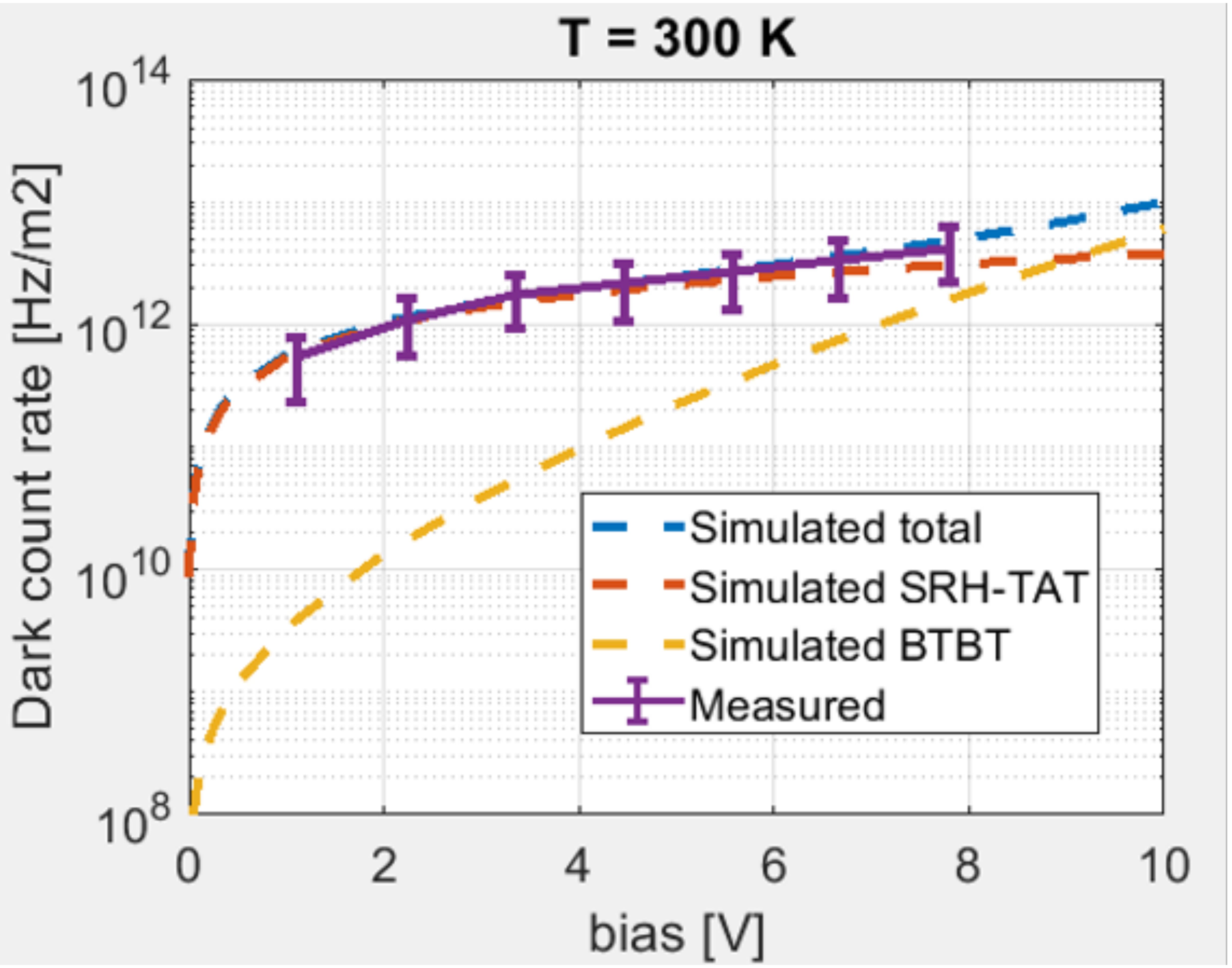
Dark Noise Rate: overvoltage dependence

$$R_{dn}(V,T) = R^I_{diff} + R^I_{bbt} + R^I_{trap}$$

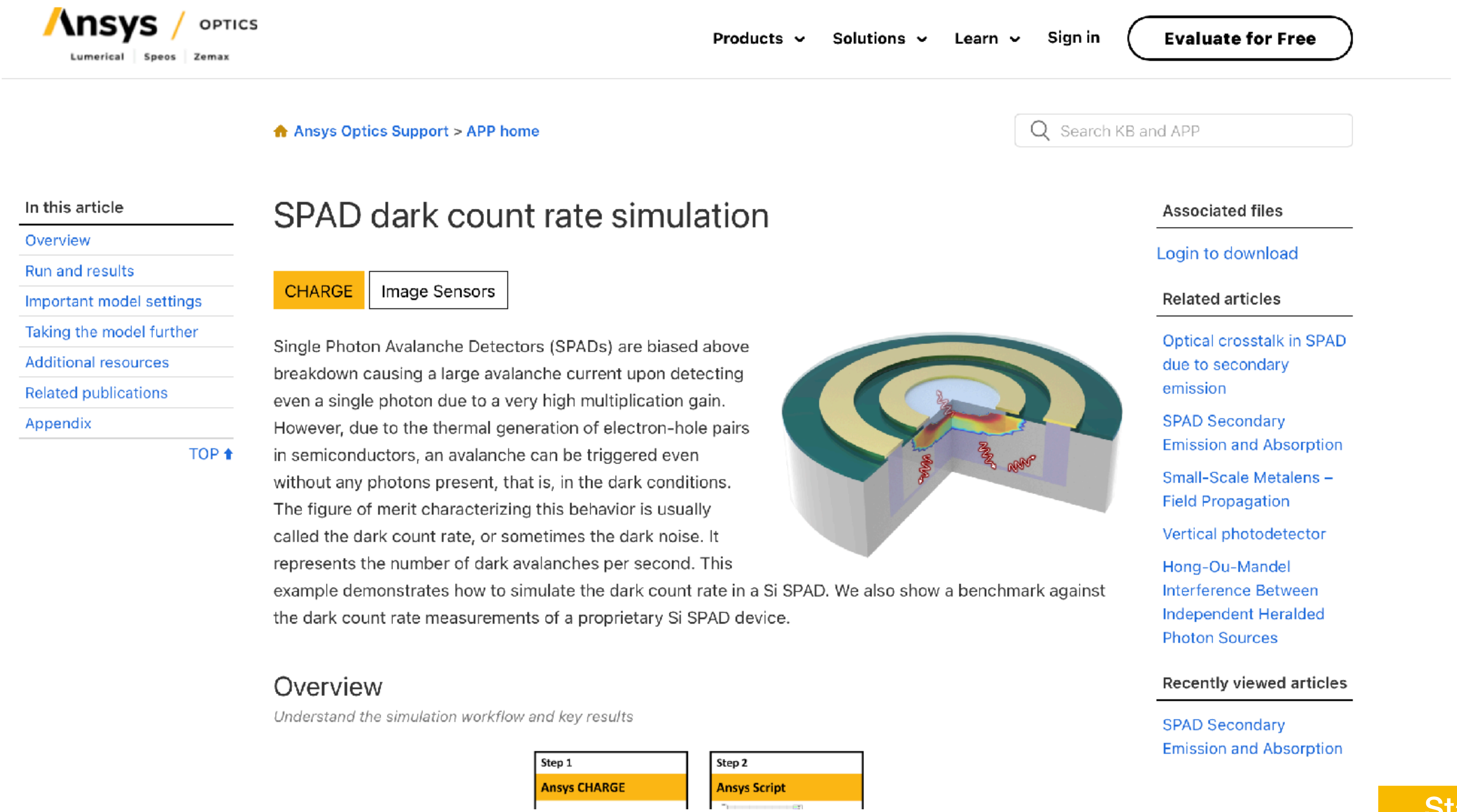
Ansys Lumerical CHARGE:

- Simulate electric field on a finite element mesh given the doping profile
- Simulate thermal generation processes
- Calculate avalanche triggering probability
- **Calculate DN rate**





Dark Noise Rate (ANSYS)



SPAD dark count rate simulation

Single Photon Avalanche Detectors (SPADs) are biased above breakdown causing a large avalanche current upon detecting even a single photon due to a very high multiplication gain. However, due to the thermal generation of electron-hole pairs in semiconductors, an avalanche can be triggered even without any photons present, that is, in the dark conditions. The figure of merit characterizing this behavior is usually called the dark count rate, or sometimes the dark noise. It represents the number of dark avalanches per second. This example demonstrates how to simulate the dark count rate in a Si SPAD. We also show a benchmark against the dark count rate measurements of a proprietary Si SPAD device.

Overview

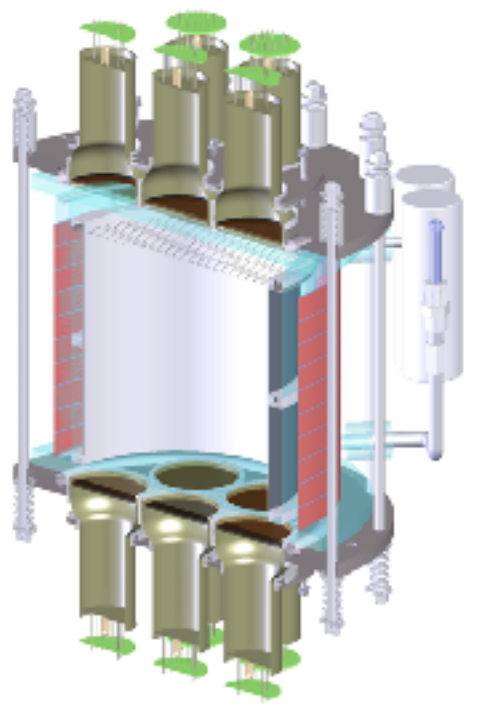
Understand the simulation workflow and key results

Stay tuned..

SiPM Technology in Darkside

A multi-stage approach

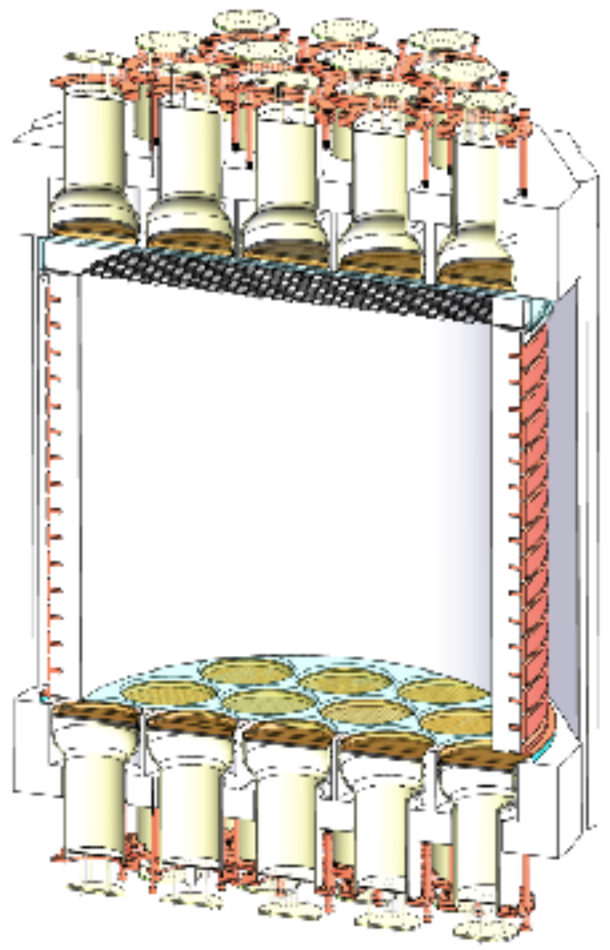
2012



DarkSide-10

- First prototype
- Helped to refine TPC design
- Demonstrated a light yield >9PE/keV$_{ee}$

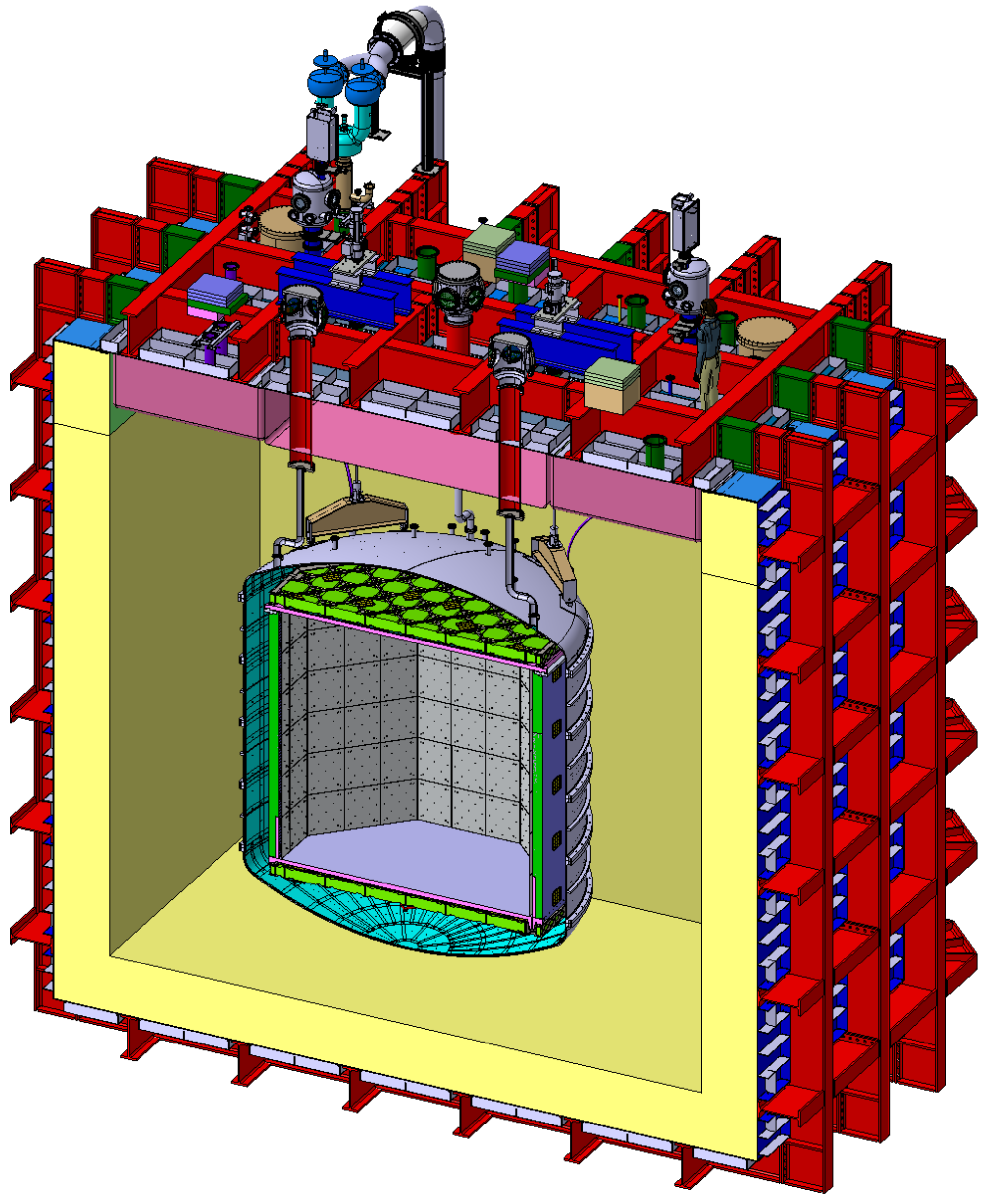
2013 - 2018



DarkSide-50

- Science detector
- Demonstrated the use of UAr
- First background-free results
- Best limits for low mass WIMP searches

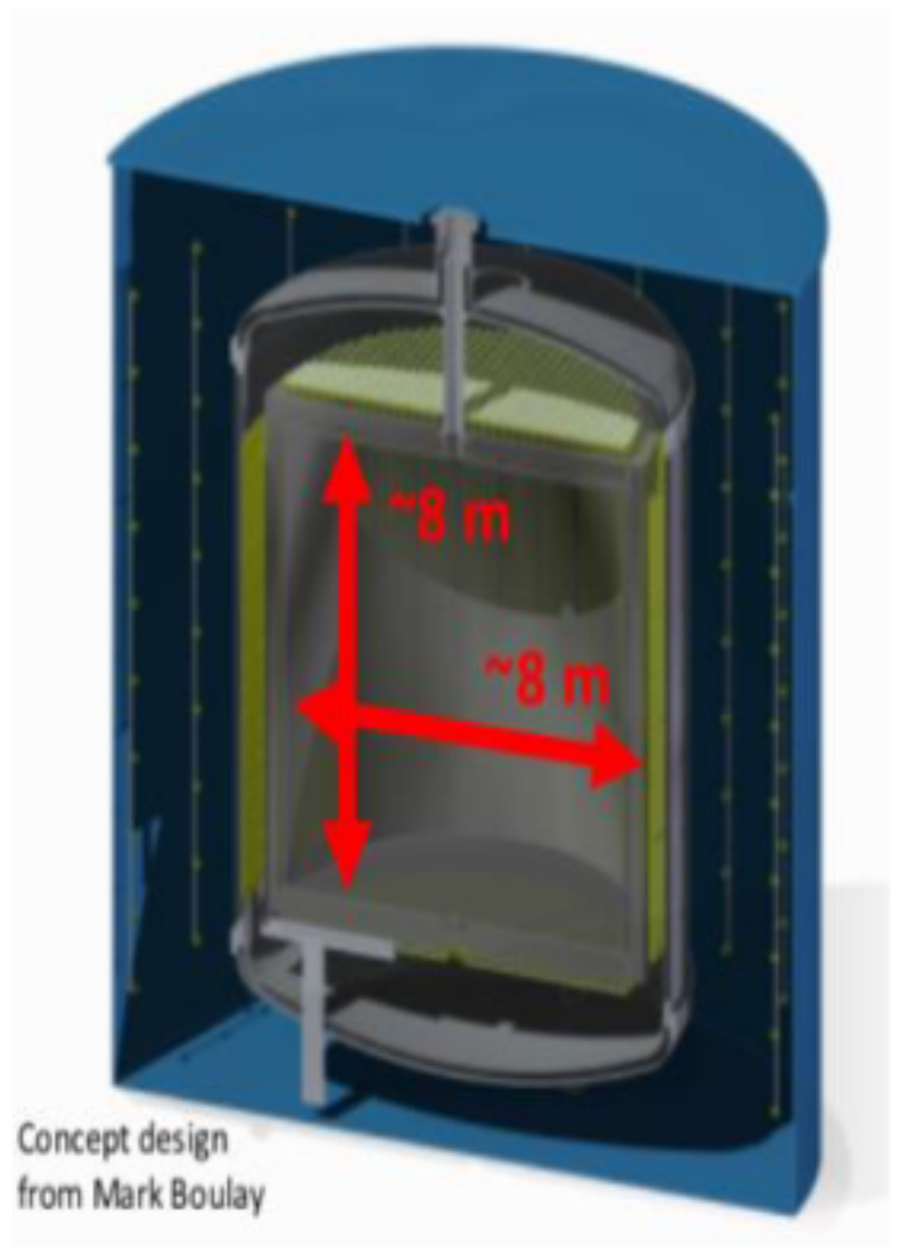
2025 - 2035



DarkSide-20k @ LNGS

- Novel technologies
- First peek into the neutrino fog
- Nominal exposure: 200 t y

2030s - ...



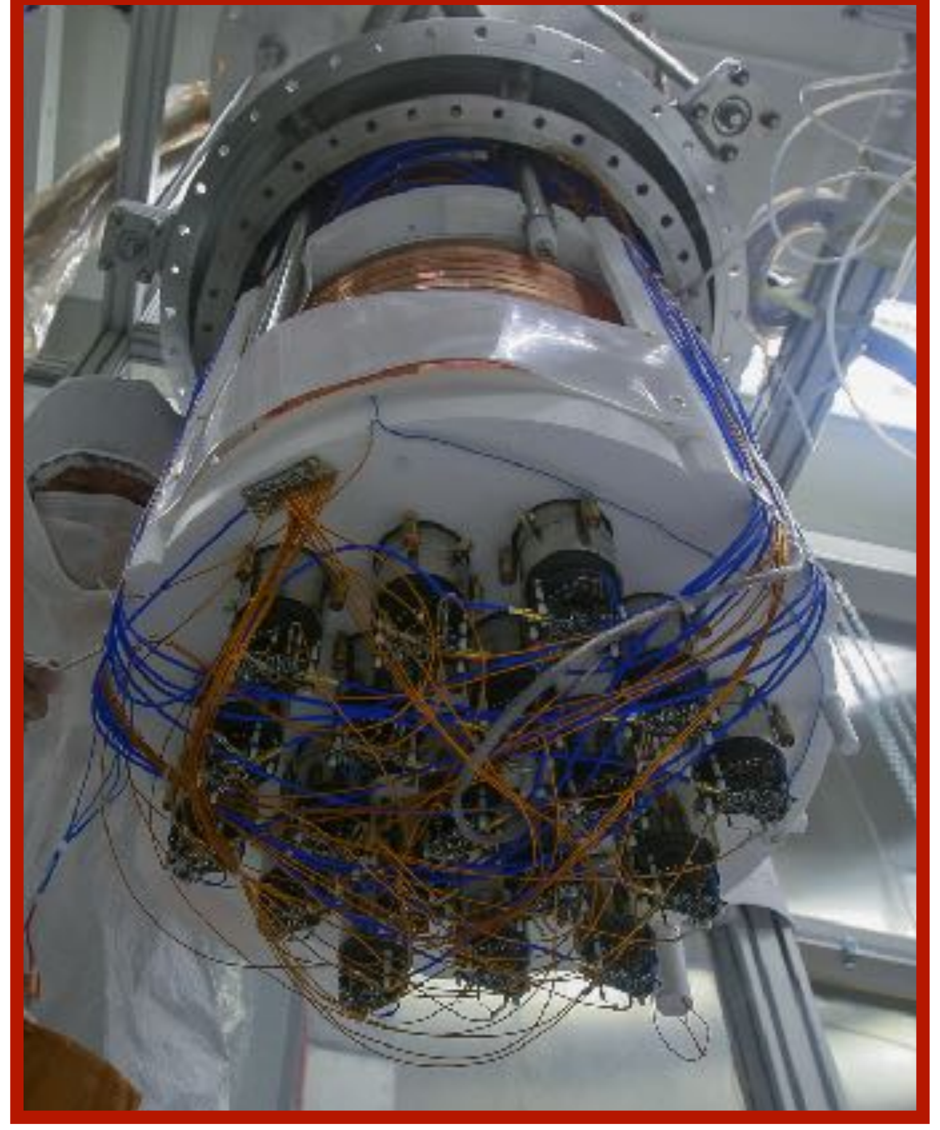
Concept design from Mark Boulay

Argo @ SNOLAB

- Ultimate LAr DM detector
- Push well into the neutrino fog
- Nominal exposure: 3000 t y

The GADMC

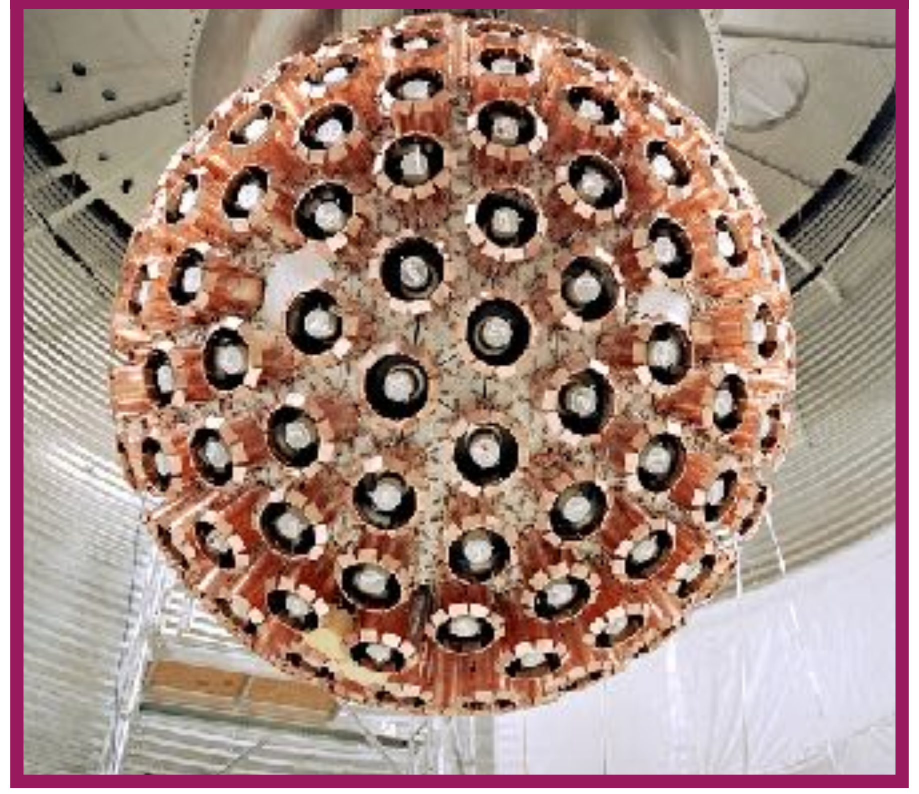
DarkSide-50 @ LNGS



ArDM @ Canfranc

MiniClean @ Snolab

DEAP @ Snolab



>400 scientists, >100 institutions distributed across 13 countries

DarkSide-20k overview

Nested detectors structure

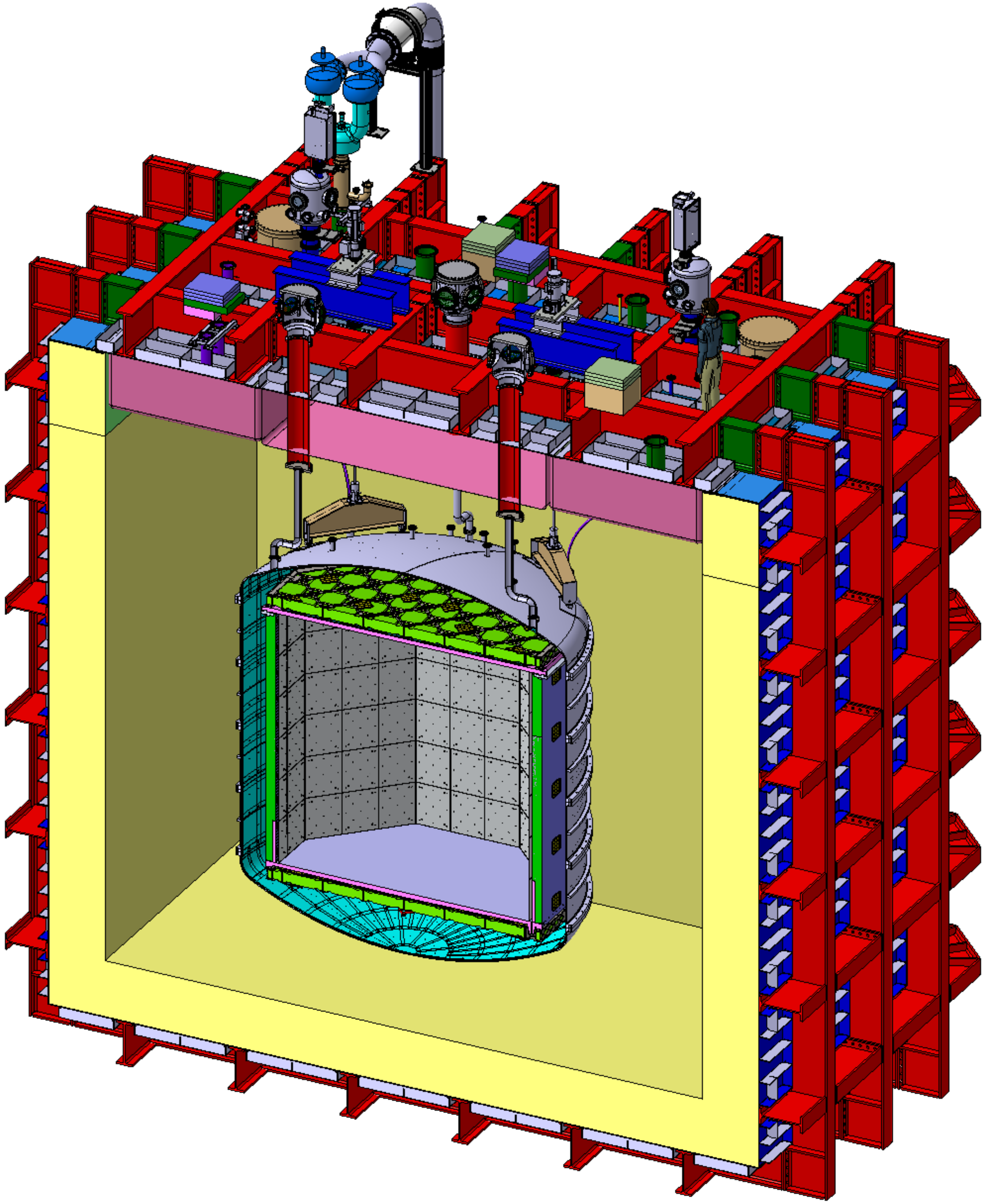
- ProtoDUNE-like cryostat (8x8x8m^3) - Muon veto
- Ti vessel separating AAr from underground UAr.
- Neutrons and γ veto
- WIMP detector: dual-phase TPC hosting 50t of LAr
- Fiducial mass: 20 tonnes

Multiple detection channels for bkg supression:

- Neutron after cuts: < 0.1 in 10 y
- β and γ after cuts: < 0.1 in 10 y

Position reconstruction resolution:

- 1 cm in XY
- 1 mm in Z

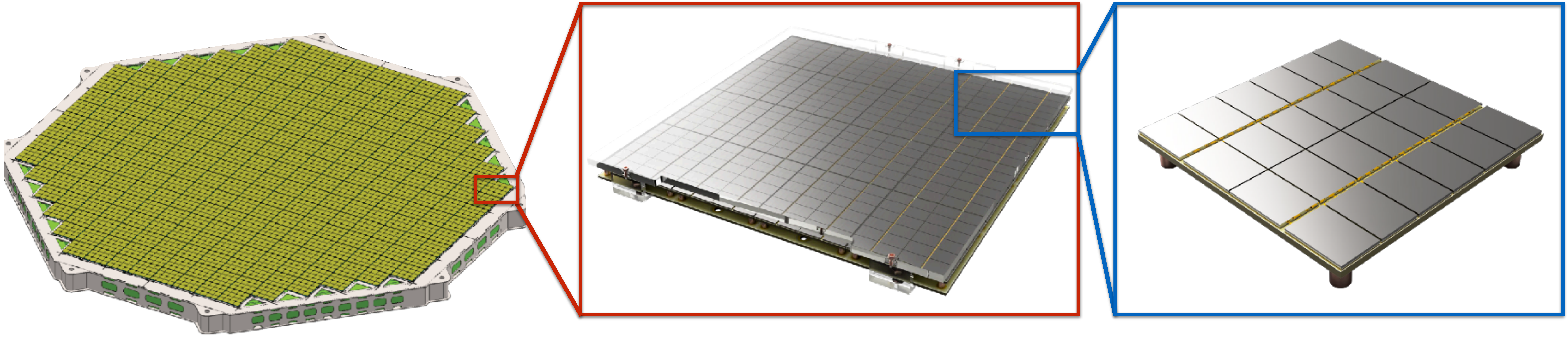


Photodetector System

TPC optical plane

Photo-Detection Unit

Tile



TPC planes area: ~21m^2

Organized in 525 PDUs

100% coverage of TPC top and bottom

16 tiles arranged in 4 readout channels

SiPM bias distribution

cryogenic pre-amplifiers bias

Signal transmission

Channels switch-on/off

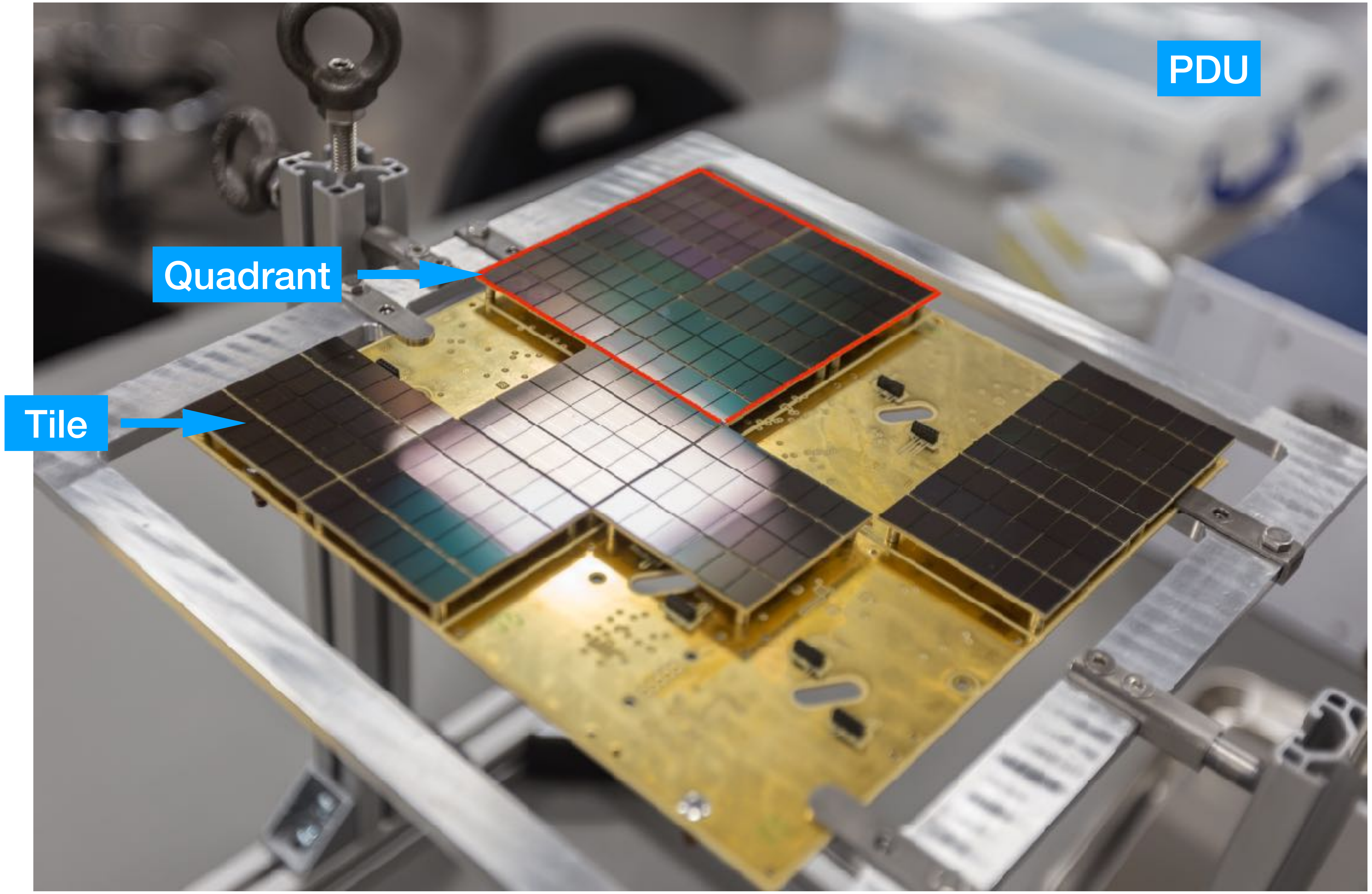
Photosensor

Array of 24 SiPMs

Signal pre-amplification

The Darkside-20k PDU

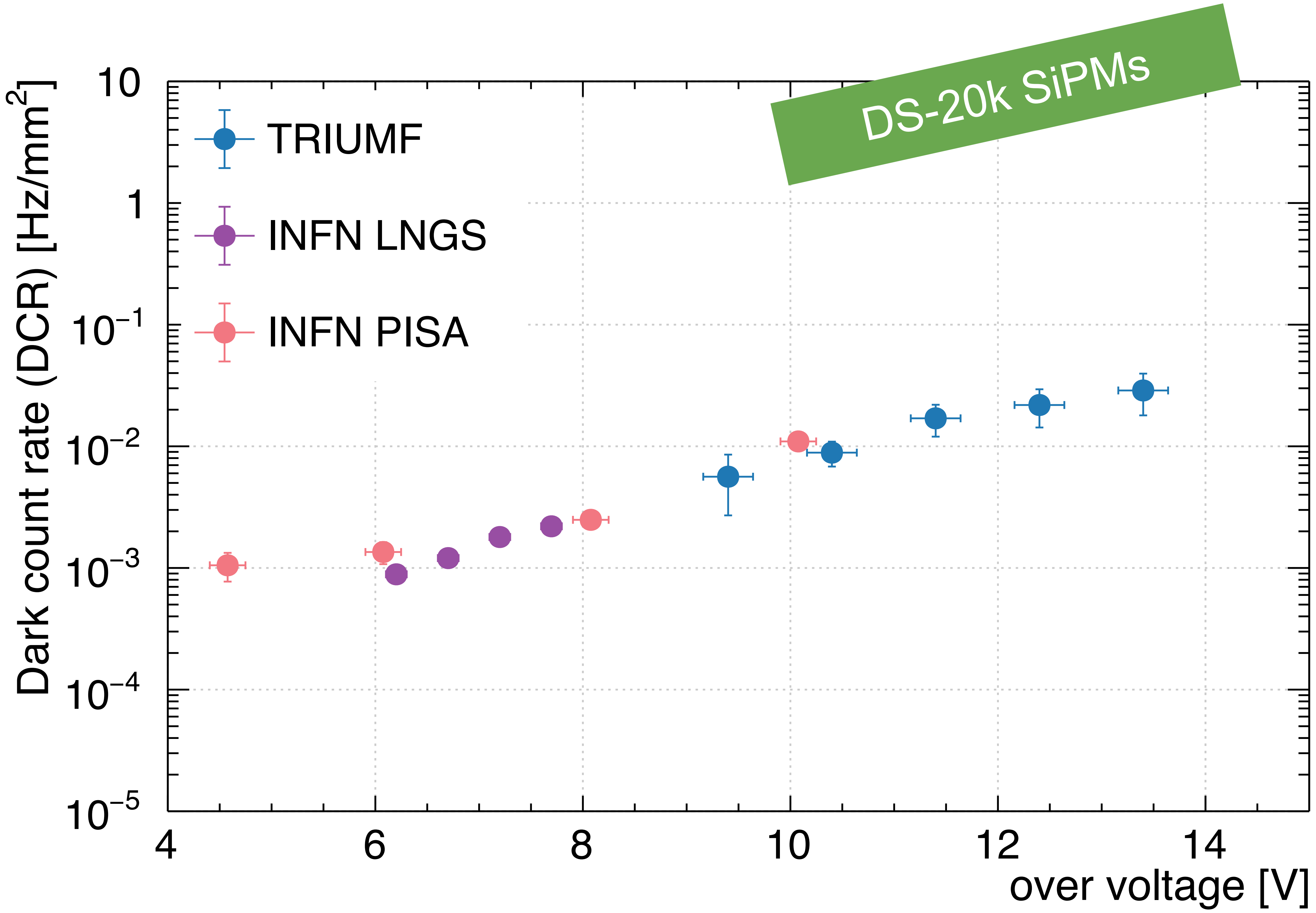
- 24 FBK NUV-HD-Cryo SiPMs are aggregated in objects called tiles
- Tile have 4s6p topology
- SiPMs are read by a low noise transimpedance amplifier (TIA) or by a custom designed ASIC
- Tiles, in groups of four, are further aggregated in quadrants each of them read as 1 analog readout channel

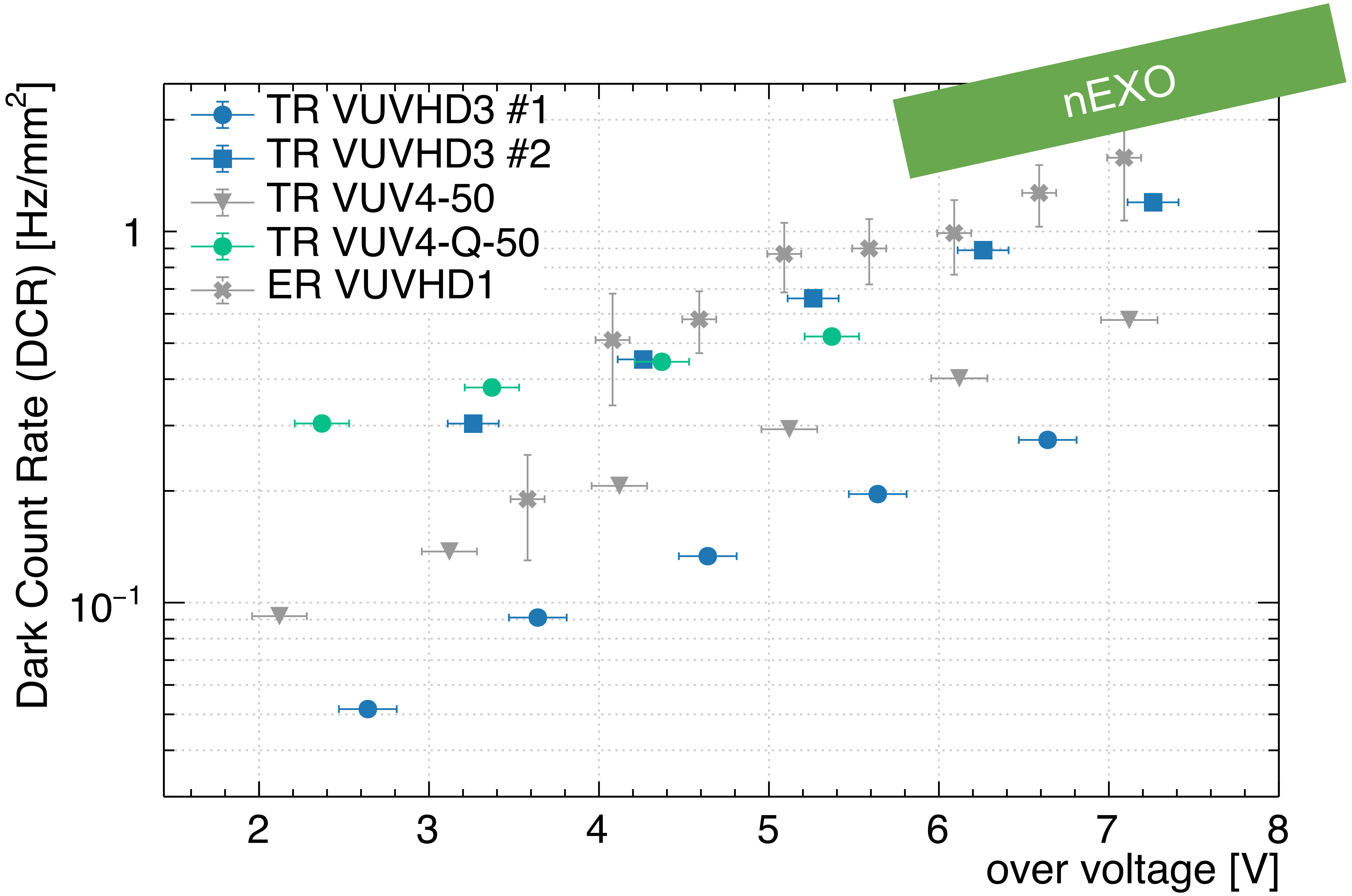


Dark Count Rate (DCR)

Computed using time differences between pulses as shown in 10.1016/j.nima.2017.08.035

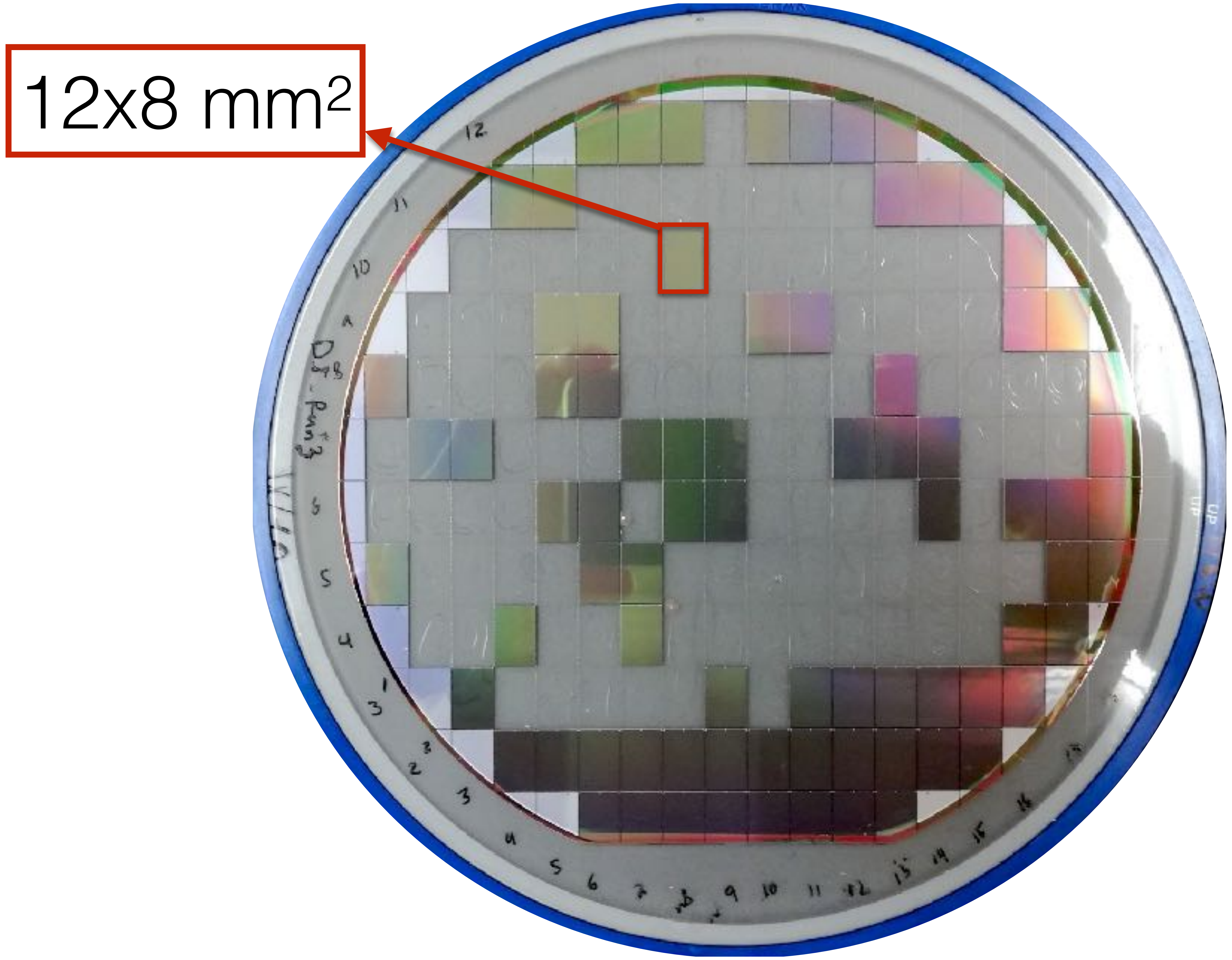
Roughly one order of magnitude lower than LXe temperature



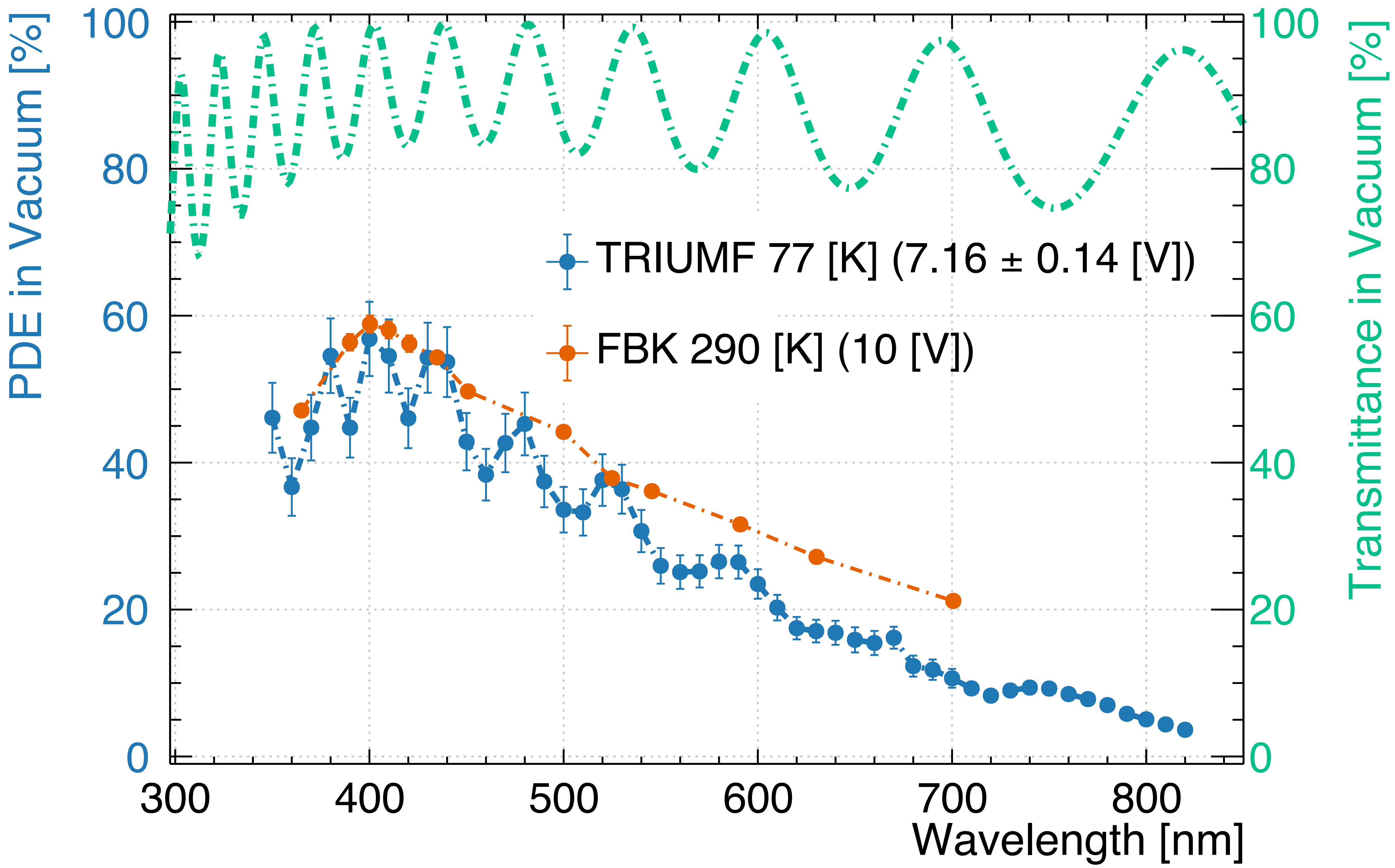


One/two order of magnitude lower DCR at 77 K

SiPMs development



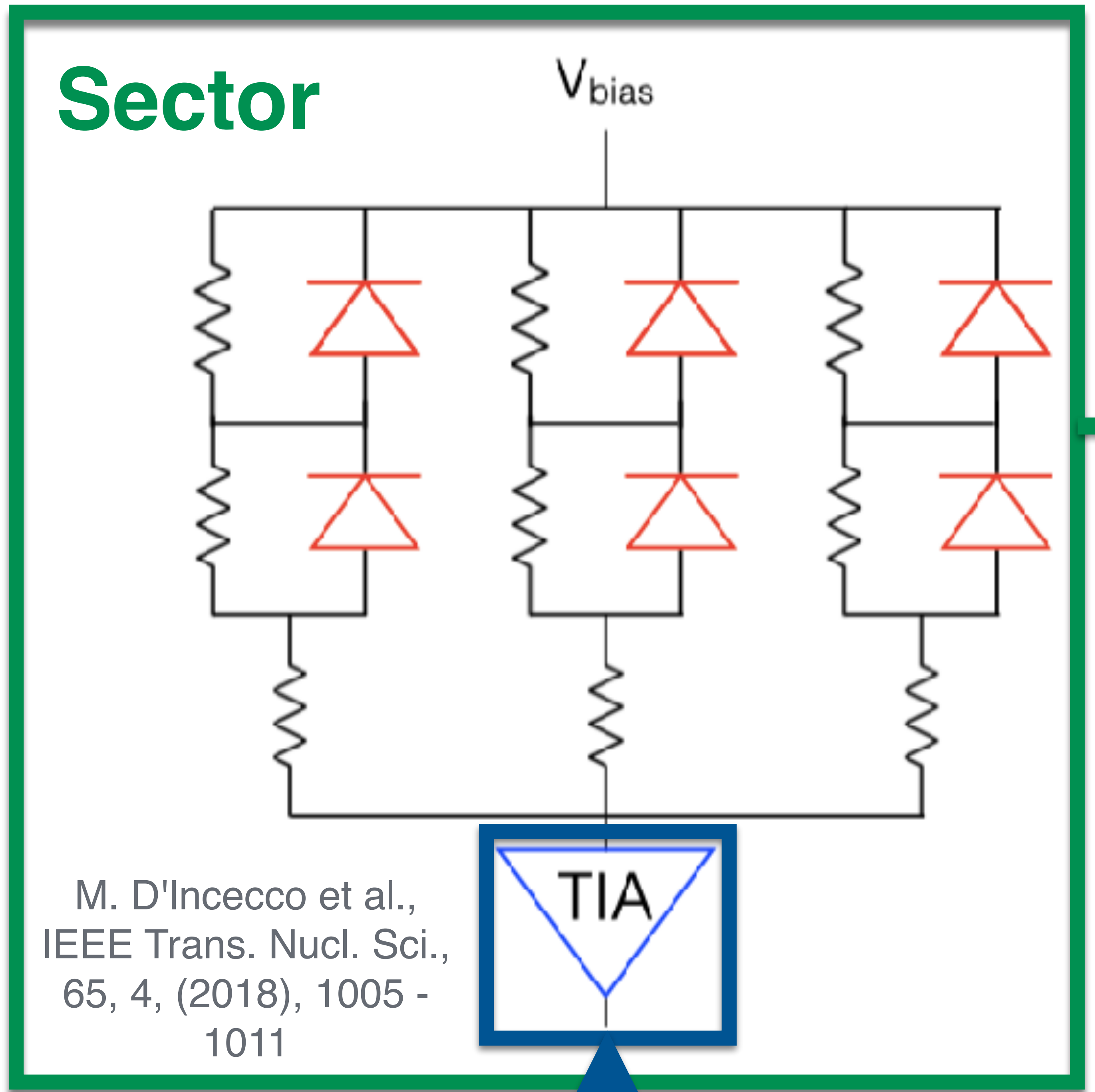
- NUV vs RGB choice
- Cell pitch and fill factor (FF) optimization
- **E** field profile ⇒ DCR+CN reduction



$$PDE = QE \times P_{01} \times FF$$

PDE ~50% in LAr

Readout electronics design

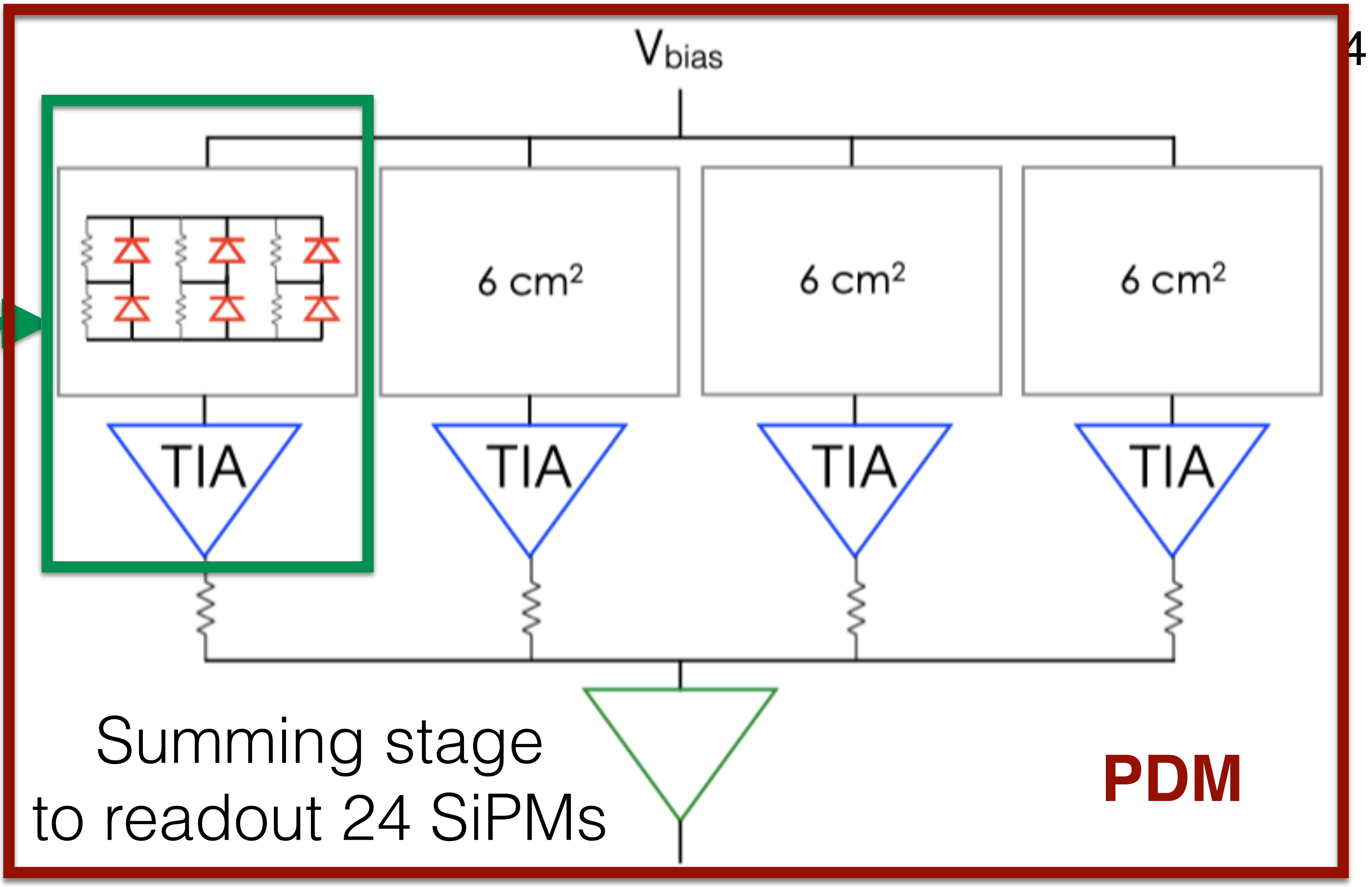


M. D'Incecco et al., IEEE Trans. Nucl. Sci., 65, 4, (2018), 1005 - 1011

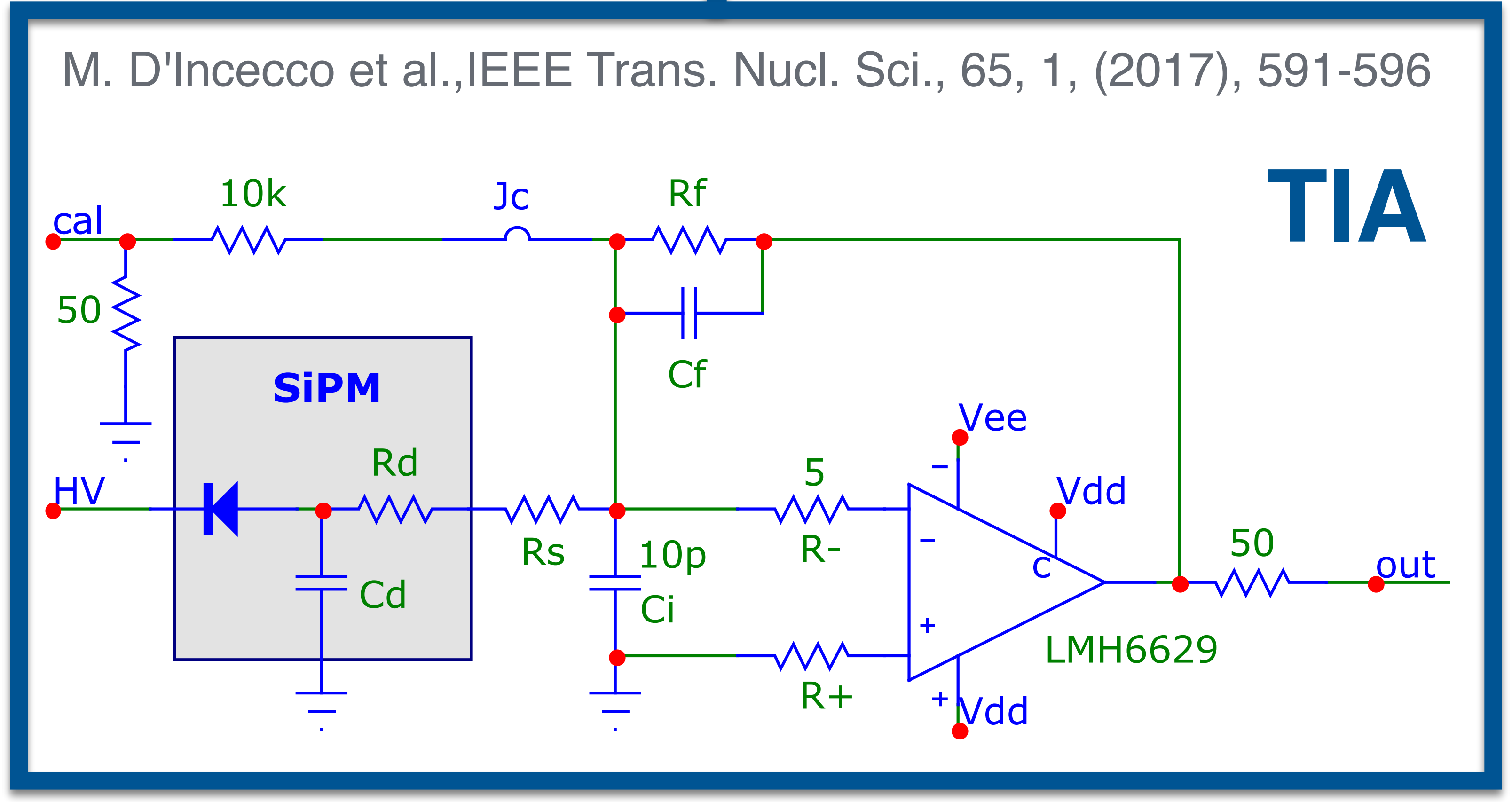
Mixed series/parallel configuration

Reduce C_{in}@TIA

Preserve BW



Summing stage to readout 24 SiPMs



M. D'Incecco et al.,IEEE Trans. Nucl. Sci., 65, 1, (2017), 591-596

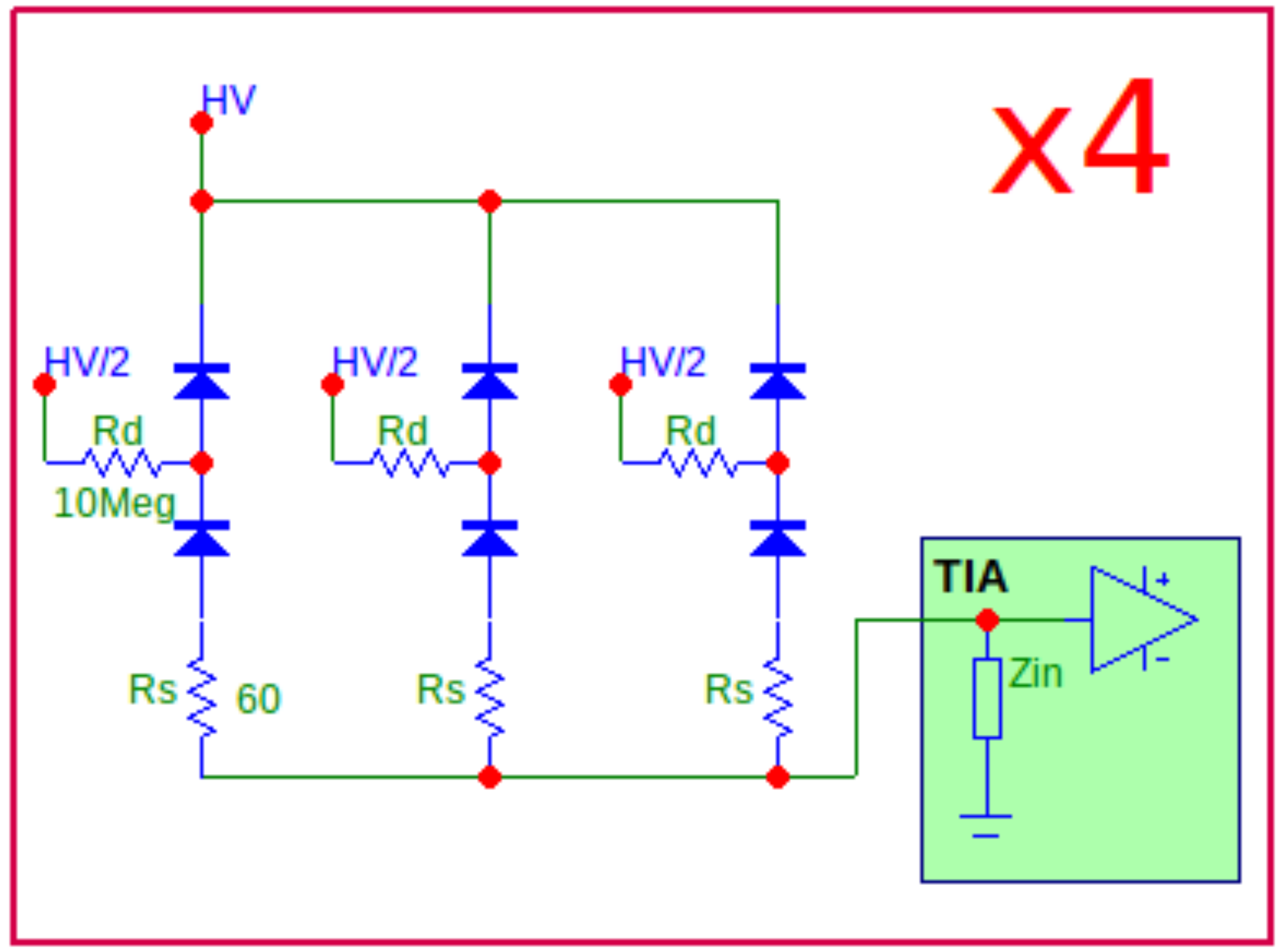
SiPM = current generators + huge output capacitance (~50pF/mm²)

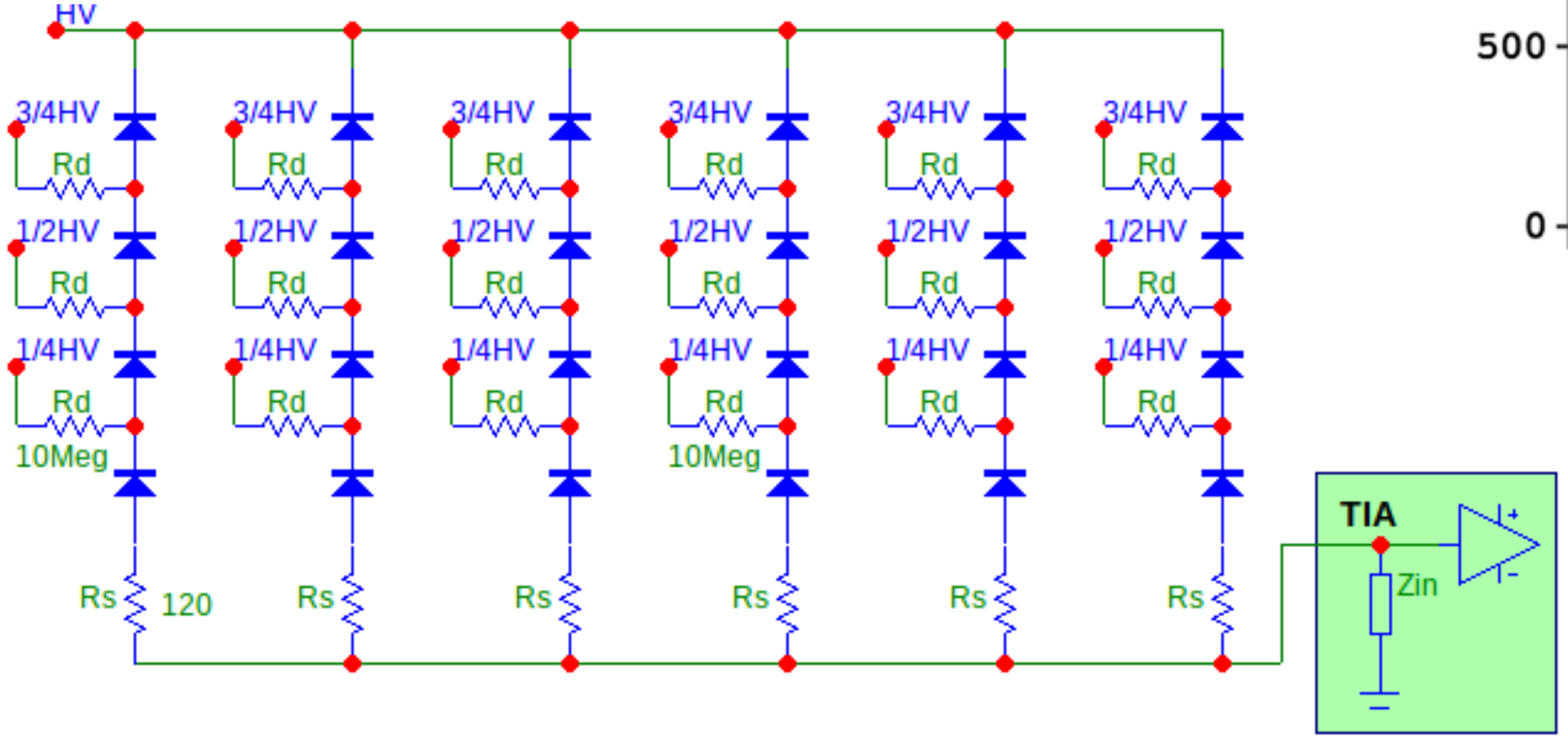
Transimpedance amplifier (TIA) High Bandwidth and Low Noise

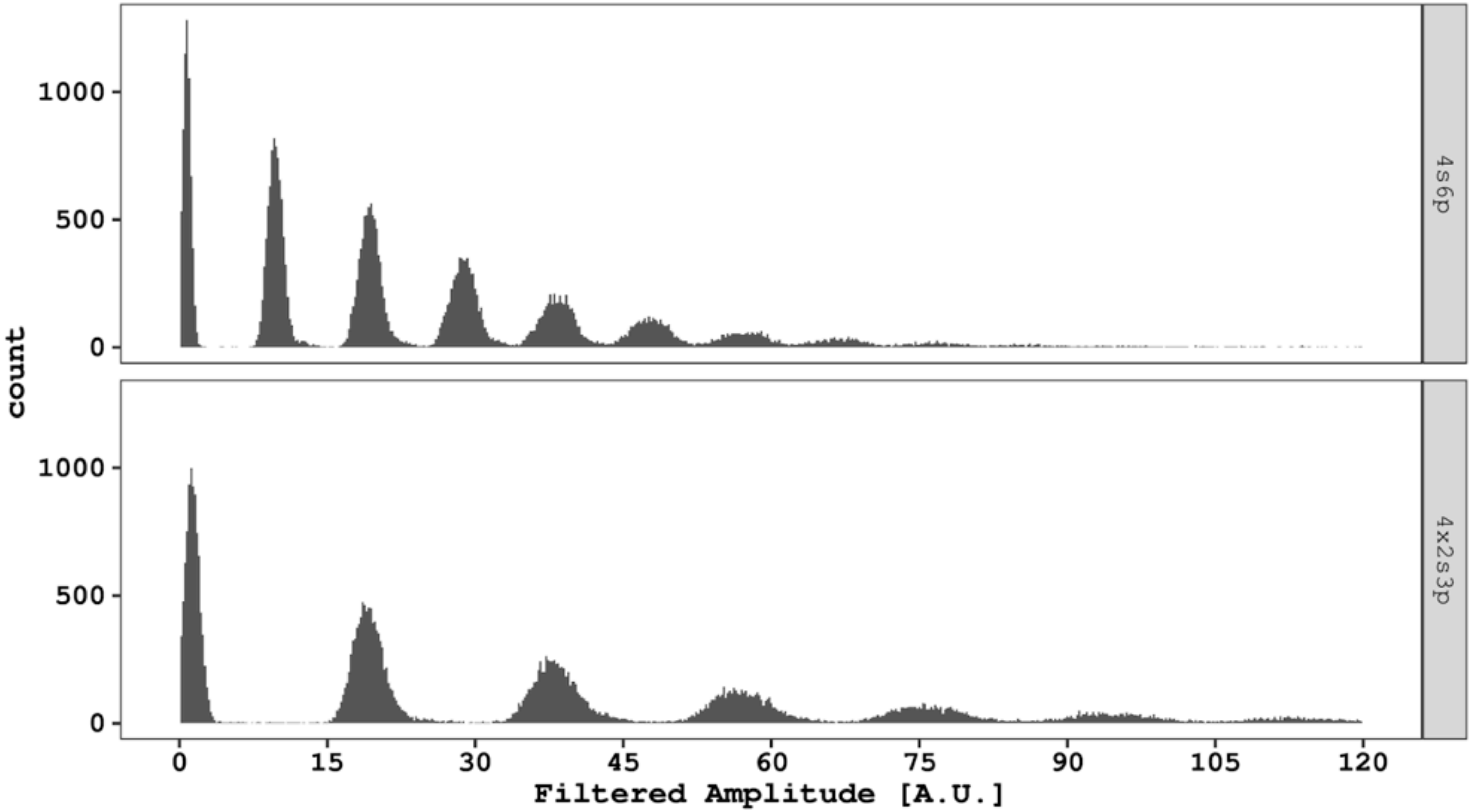
SNR is reduced wrt a single SiPM, but still very high

Power dissipation is < 250mW per PDM

… and upgrades







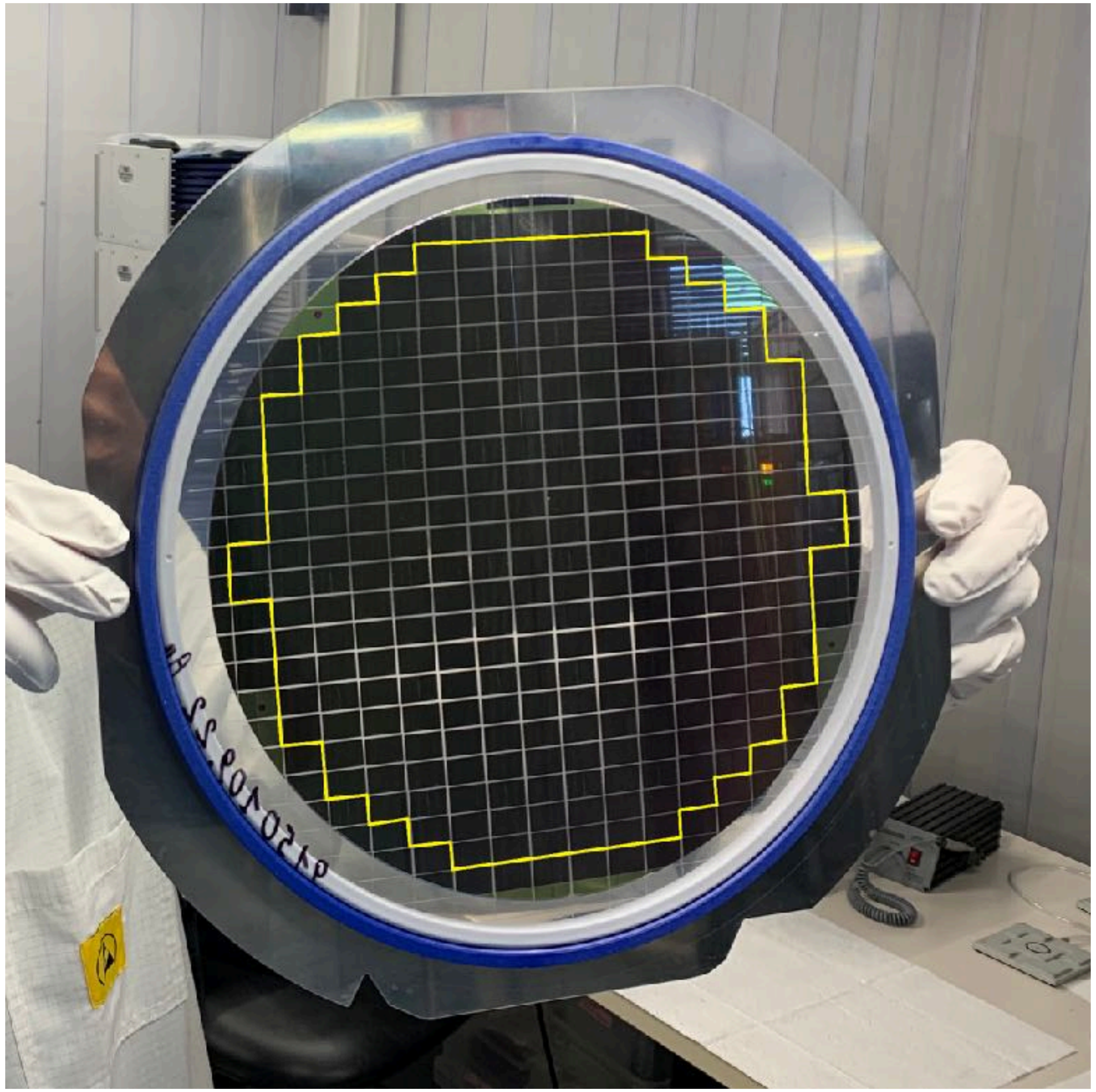
Switch from 4 sectors ($6cm^2$) to 1 single $24cm^2$ unit

Power dissipation < 50mW per tile

See talk on Thursday

Wafers

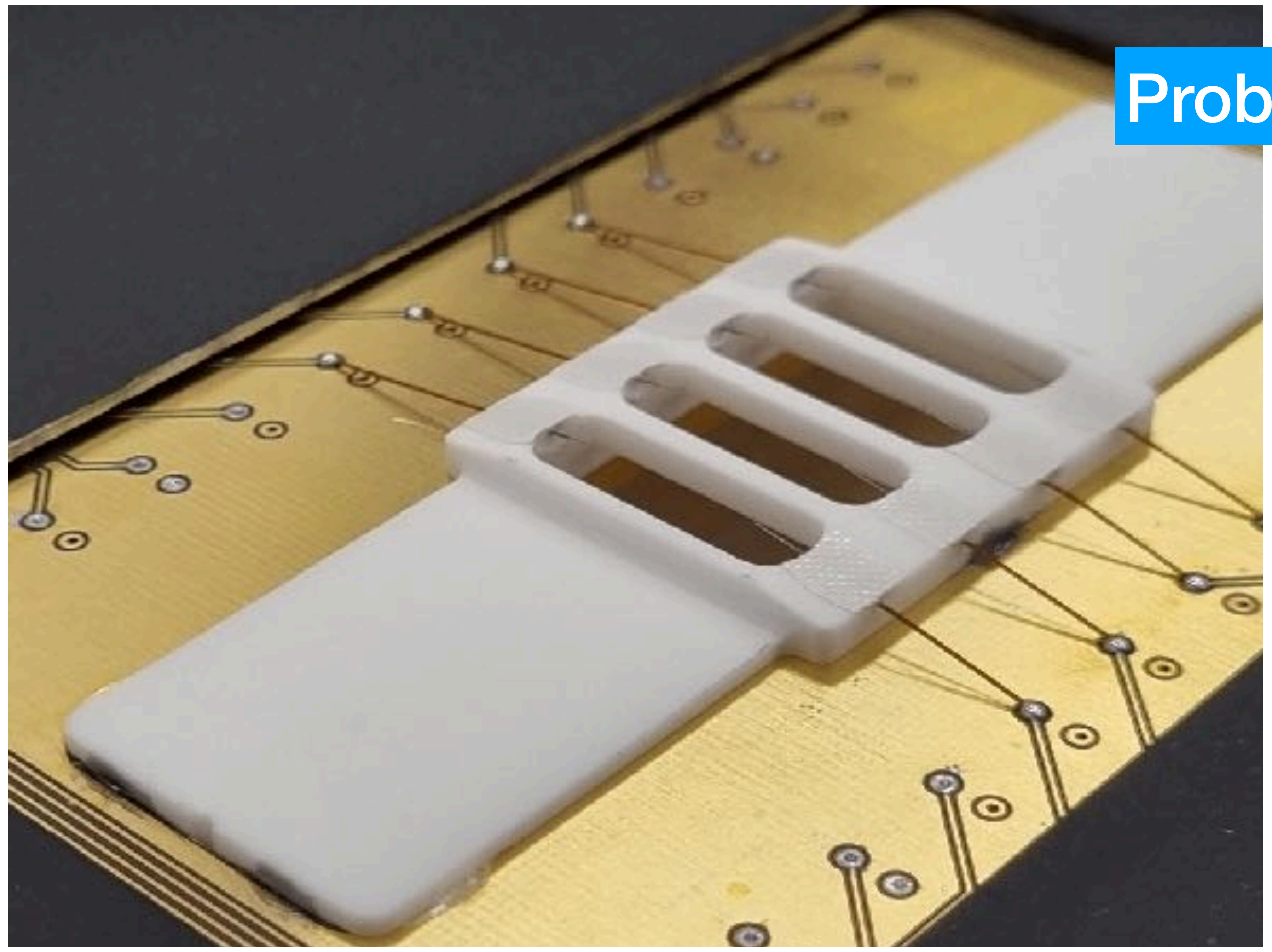
- Wafers are produced by LFoundry (1400 in total) s.r.l. (Avezzano, AQ, Italy).
- 268 potentially working dice x wafer (264 testable).
- Wafer are produced by LFoundry in Lots (~25 wafers), 57 in total.
- Each of the ~25 wafers in a Lot travels together through the foundry process steps.
- The largest variation in the wafer performance is expected when comparing different lots.



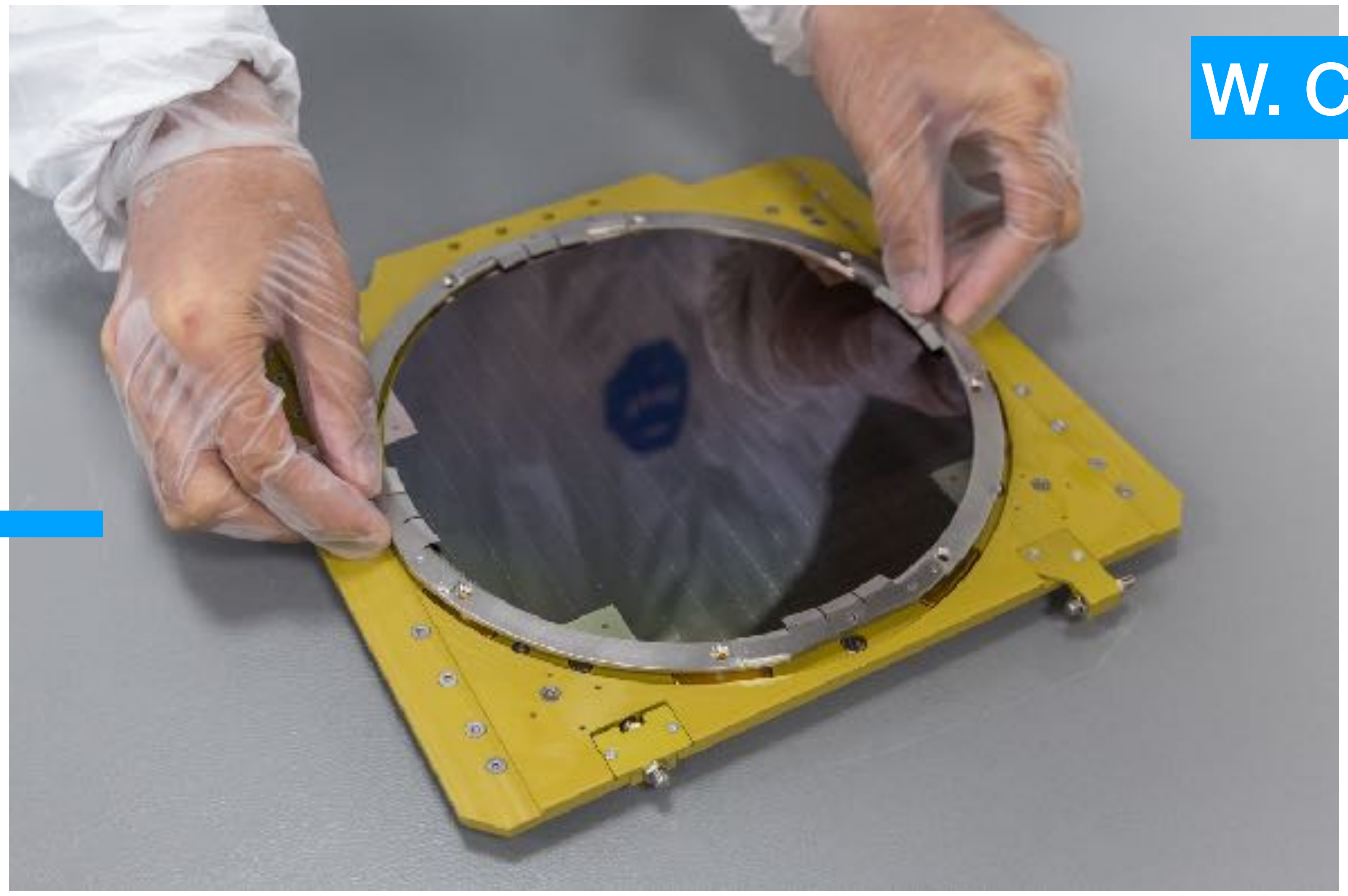
Hardware Setup

See talk on Thursday

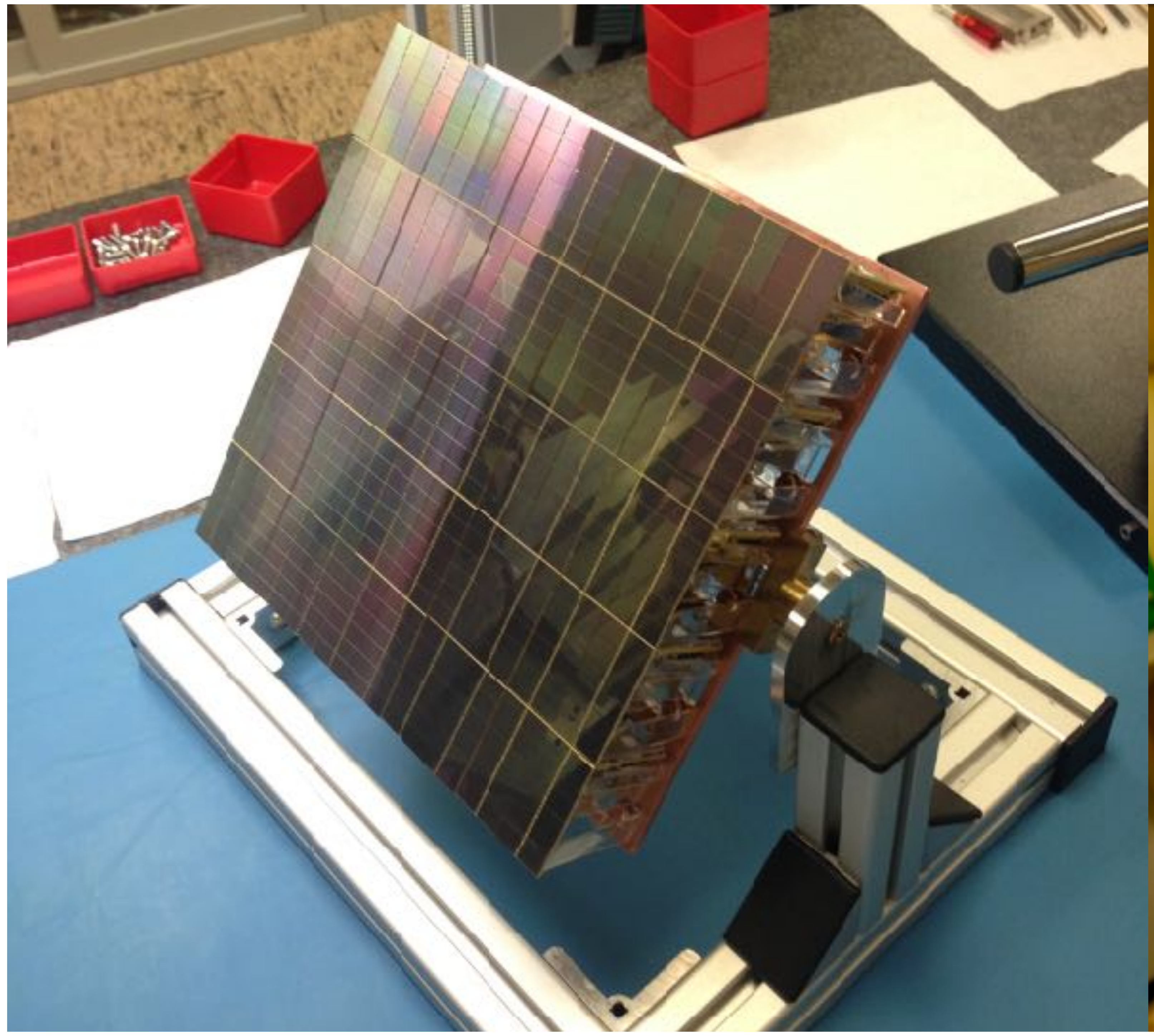
- Wafer are tested with a PAC-200 cryoprobe with a needle-based probecard (common cathode)


Probecard

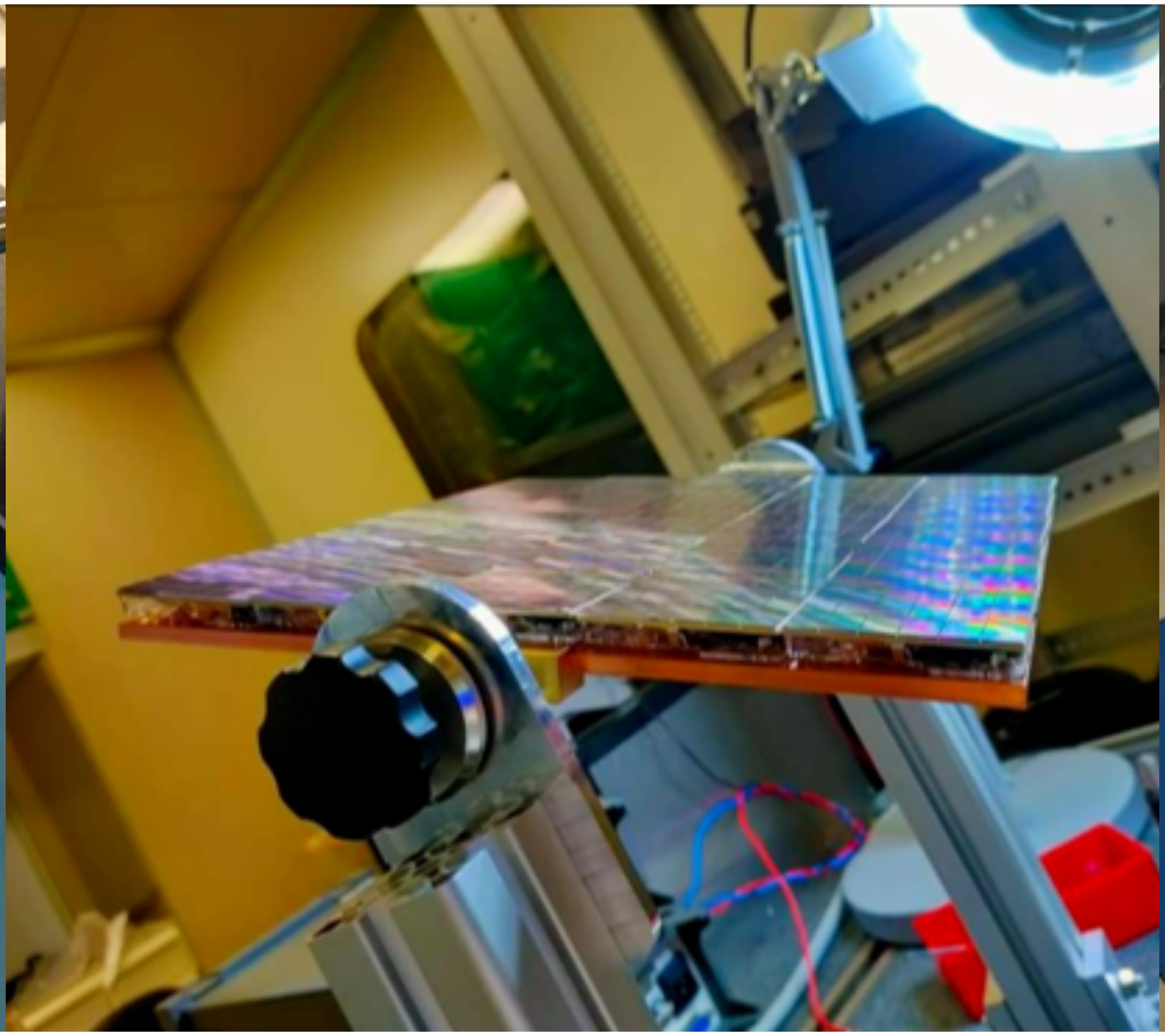

To be updated


W. Carrier

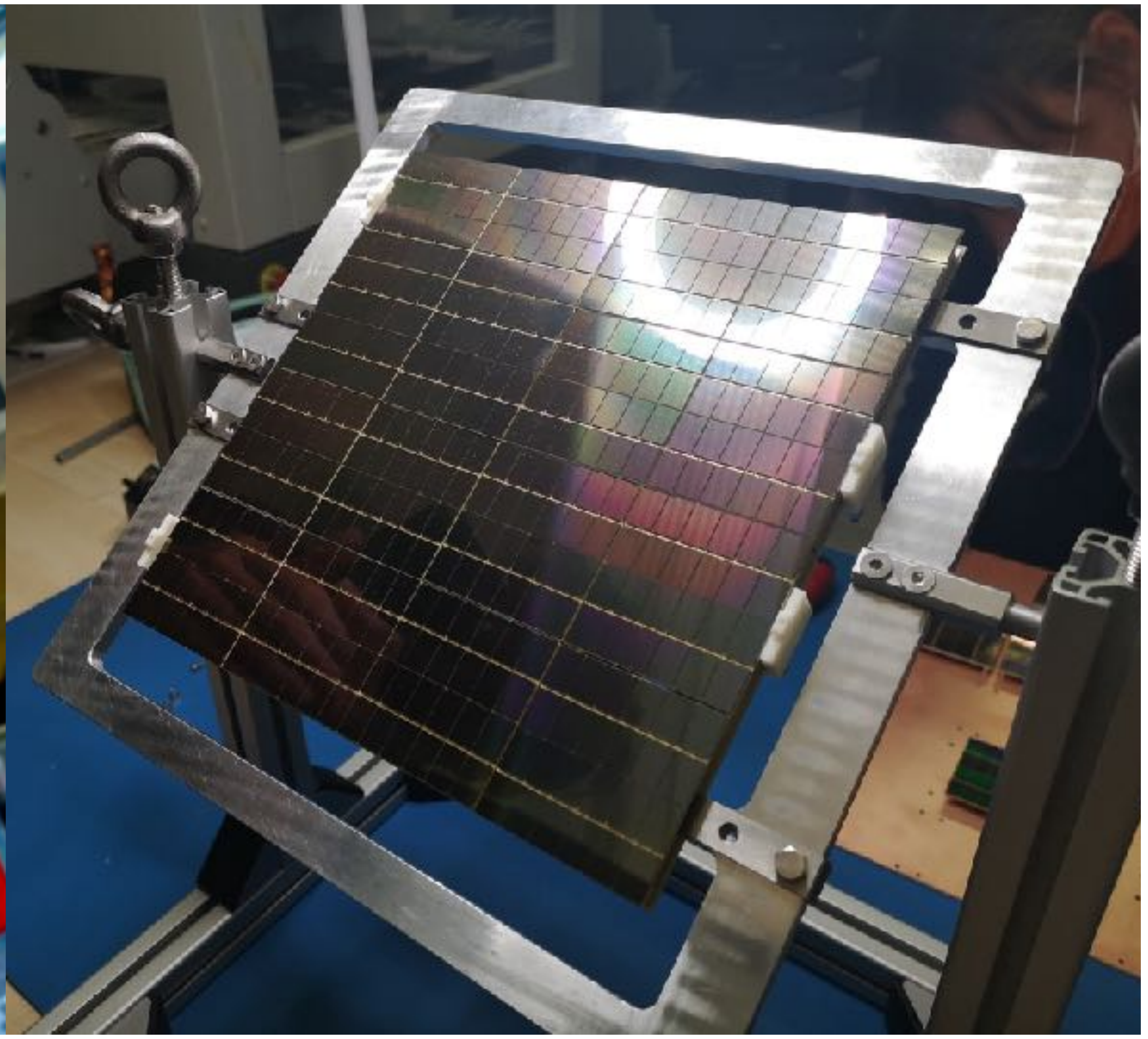
Status of photo-detection systems



First PDU prototype with 25 channels



PDU with 25 channels, less material



Final PDU: 16 tiles grouped
in 4 or 8 readout channels

- Several prototypes of Photo-Detection Units (PDU) have been produced and tested in LN and LAr.
- All the requirements on gain, SiPM noises, SNR and timing resolution are met or exceeded.
- Mass production soon to start in a dedicated facility (NOA).

Conclusions

Conclusions

- Exiting time are in front of us for photon detection for nEXO and DS-20k !
- **Significantly more information** is now available compared to what was previously known especially for PDE at cryogenic temperature !
- More measurements are available than what was shown today (i.e. **gain and Vbd** as a function of **bias voltage and temperature**, respectively, **CDA, APA etc ..**), see reference in the talk.
- Full production for DS-20k is ongoing and hopefully for nEXO we will start in the next years!
- One Darkside paper is coming soon!

Thanks!

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Discovery,
accelerated