Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO

G. Gallina

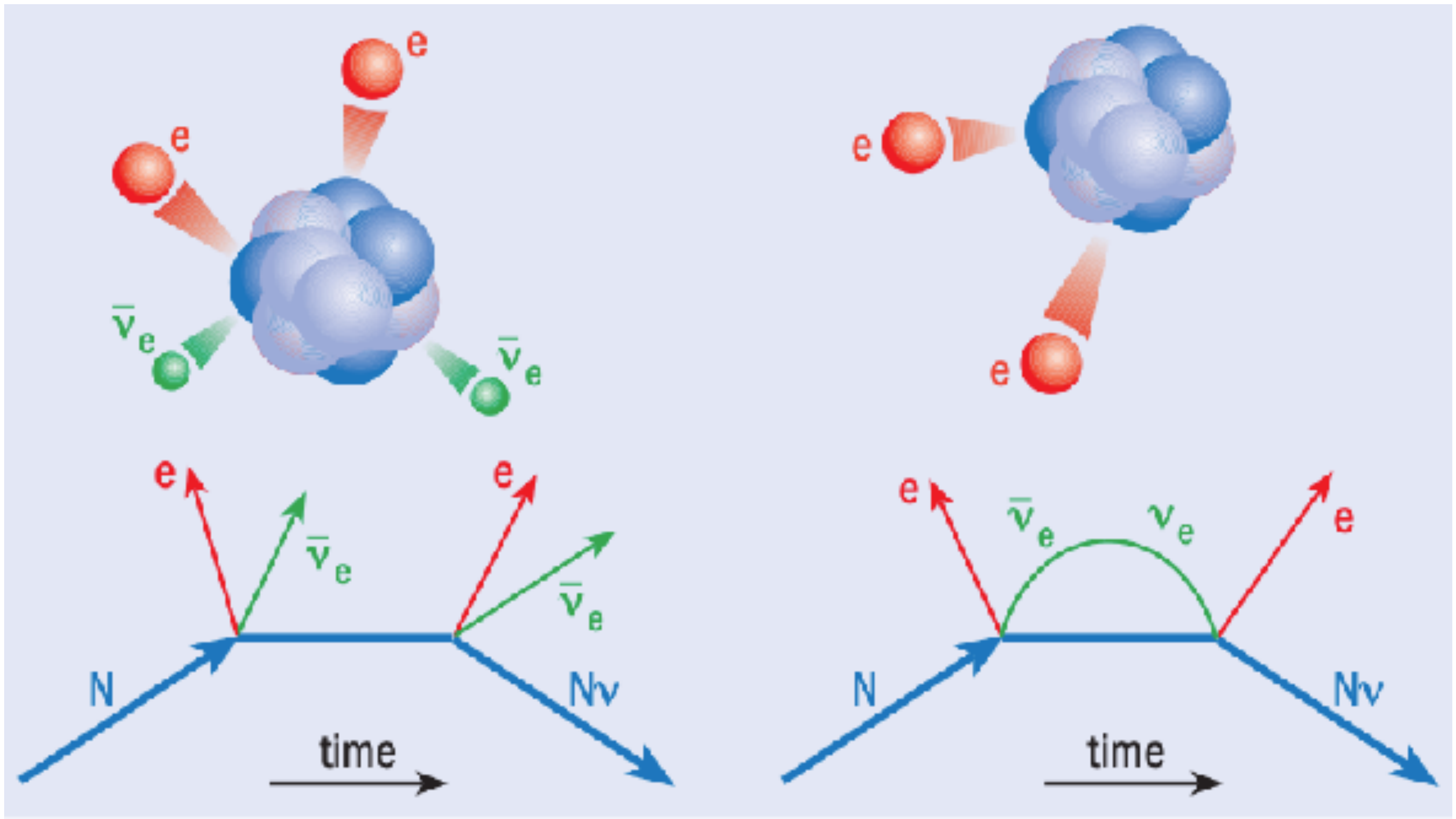
for the nEXO collaboration

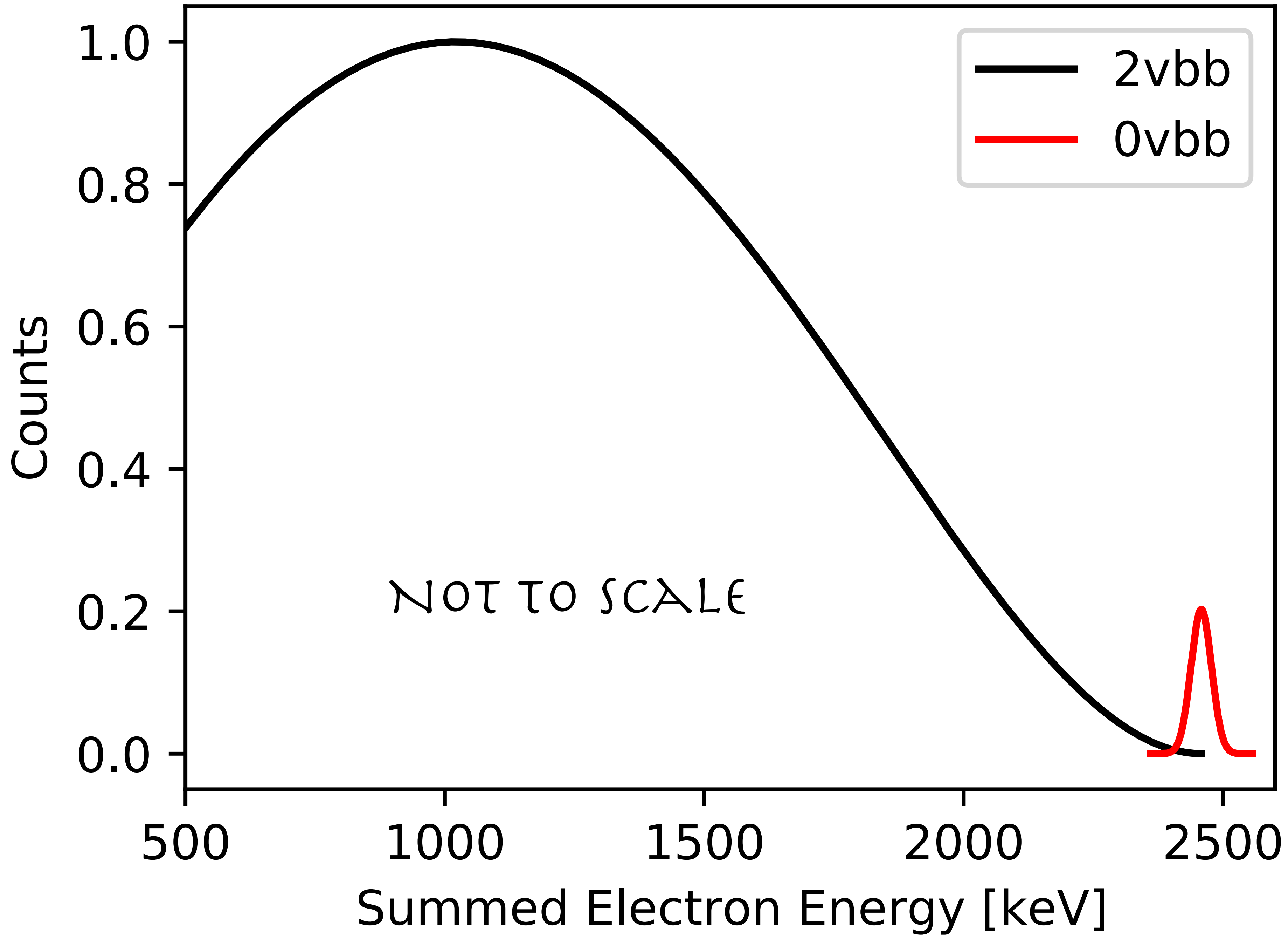
Discovery, accelerated

Overview

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

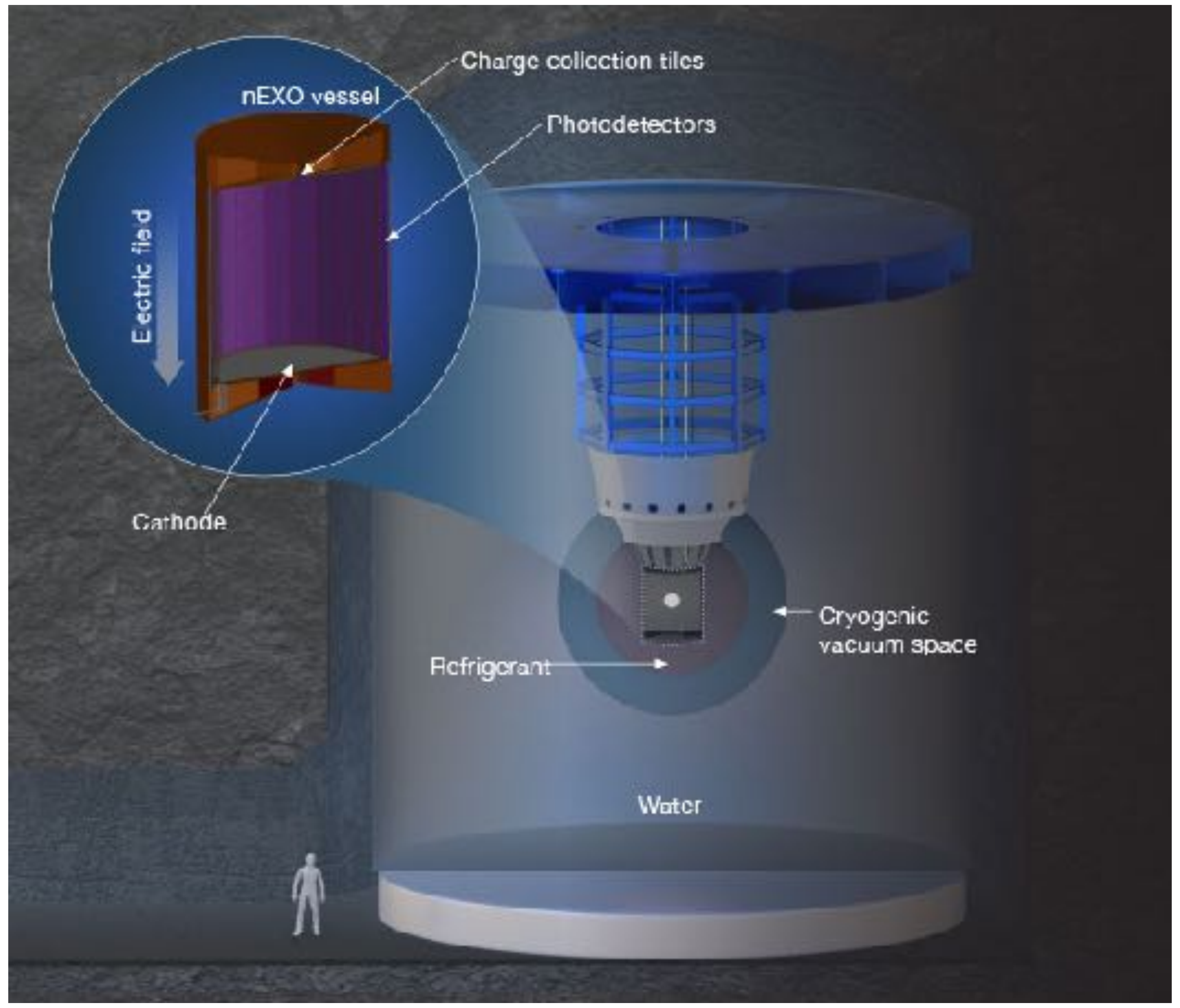
- Finding $0\nu\beta\beta$ always implies new physics
  - Lepton number violation
  - Neutrinos are Majorana fermions ($\nu \equiv \bar{\nu}$)
  - Origin of neutrino masses
  - Insight into absolute neutrino mass scale
  - Possibly linked to matter and anti-matter asymmetry
- Experimental signature is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





SiPM technology in nEXO

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

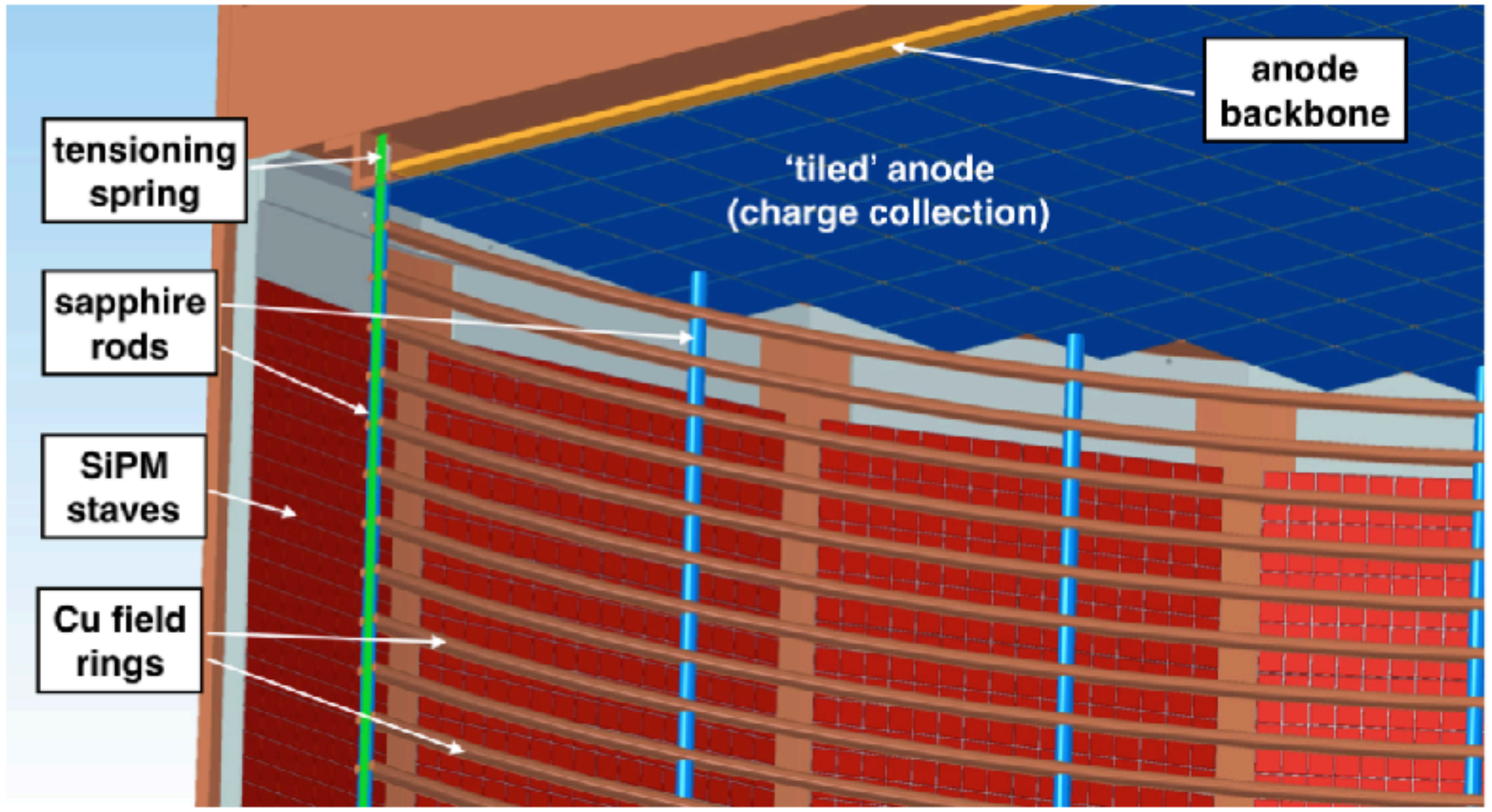


Main Characteristics :

- 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 than PMTs possible
- Suitable at cryogenic temperature



SiPM technology in nEXO

NIM A 940 (2019)

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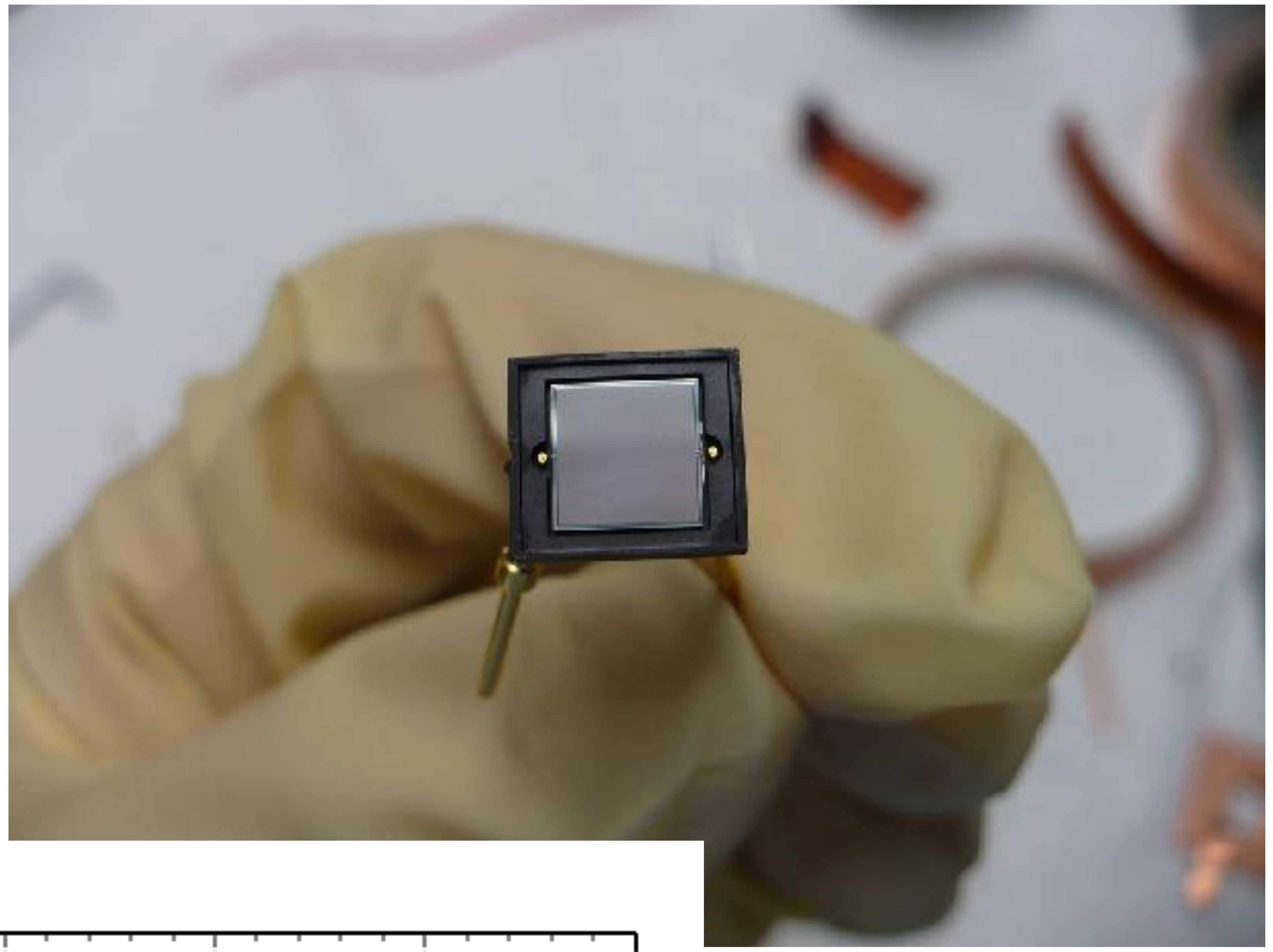

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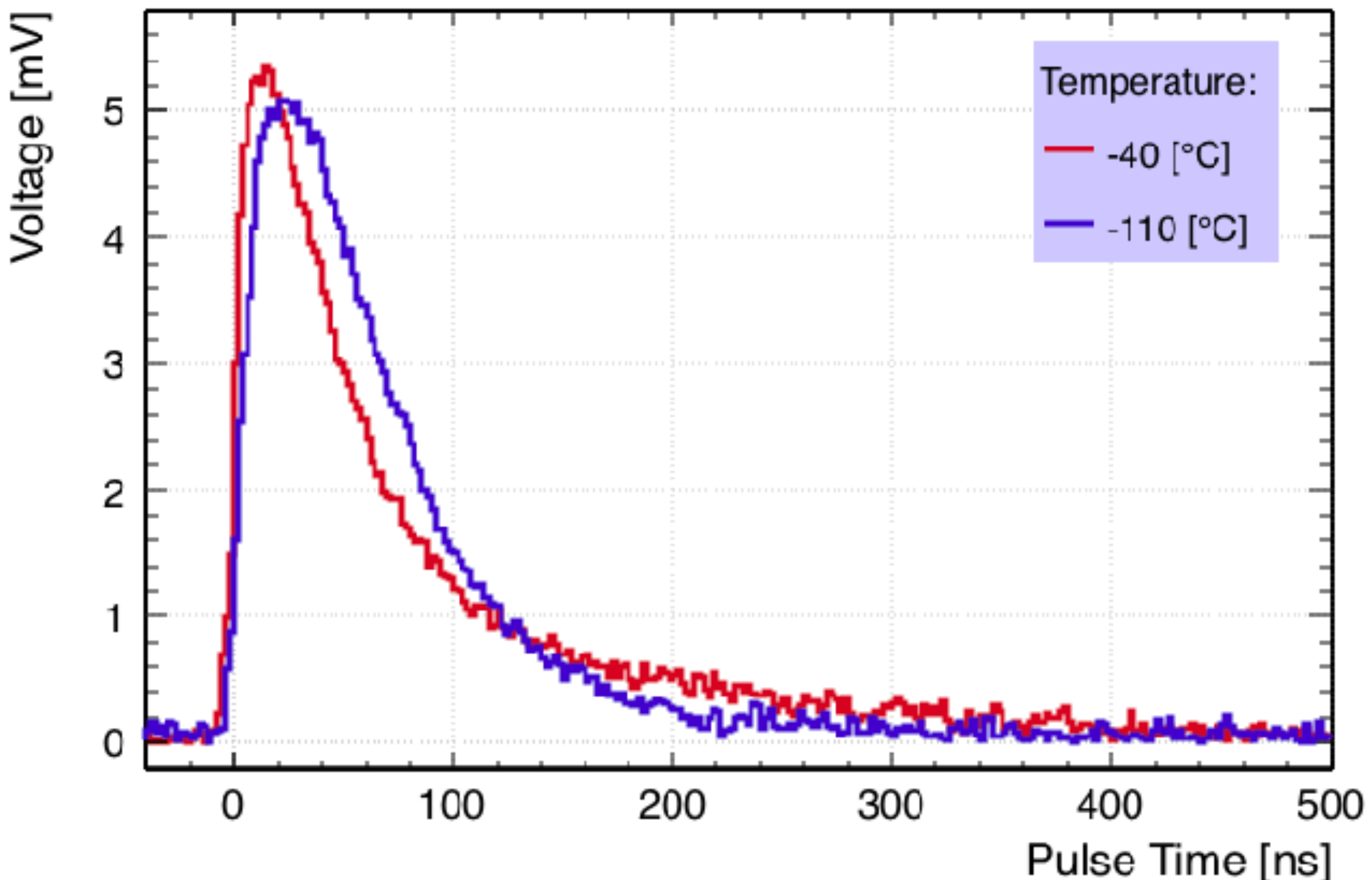


Noise Sources in SiPMs

IEEE Trans.Nucl.Sci. 65 (2018)

Uncorrelated Avalanche Noise

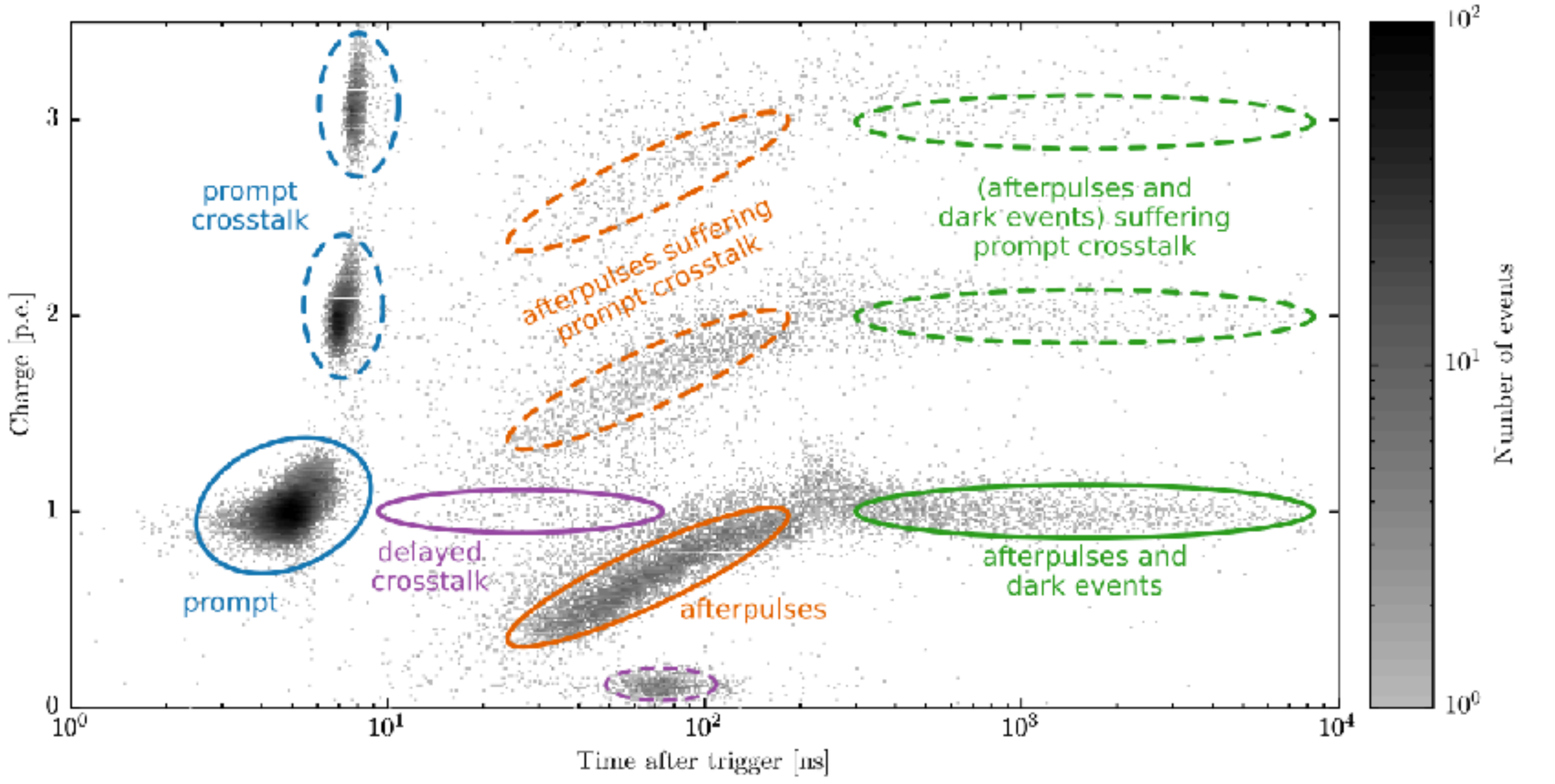
- Dark Count Rate (DCR)

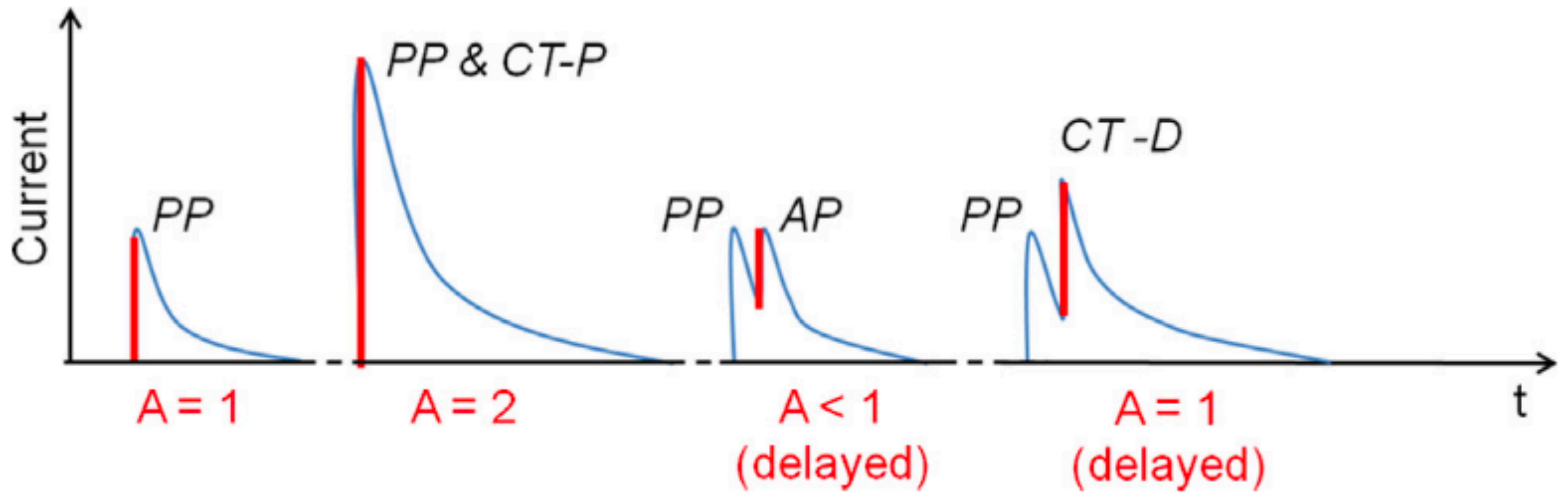
Correlated Avalanche Noise

- 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)





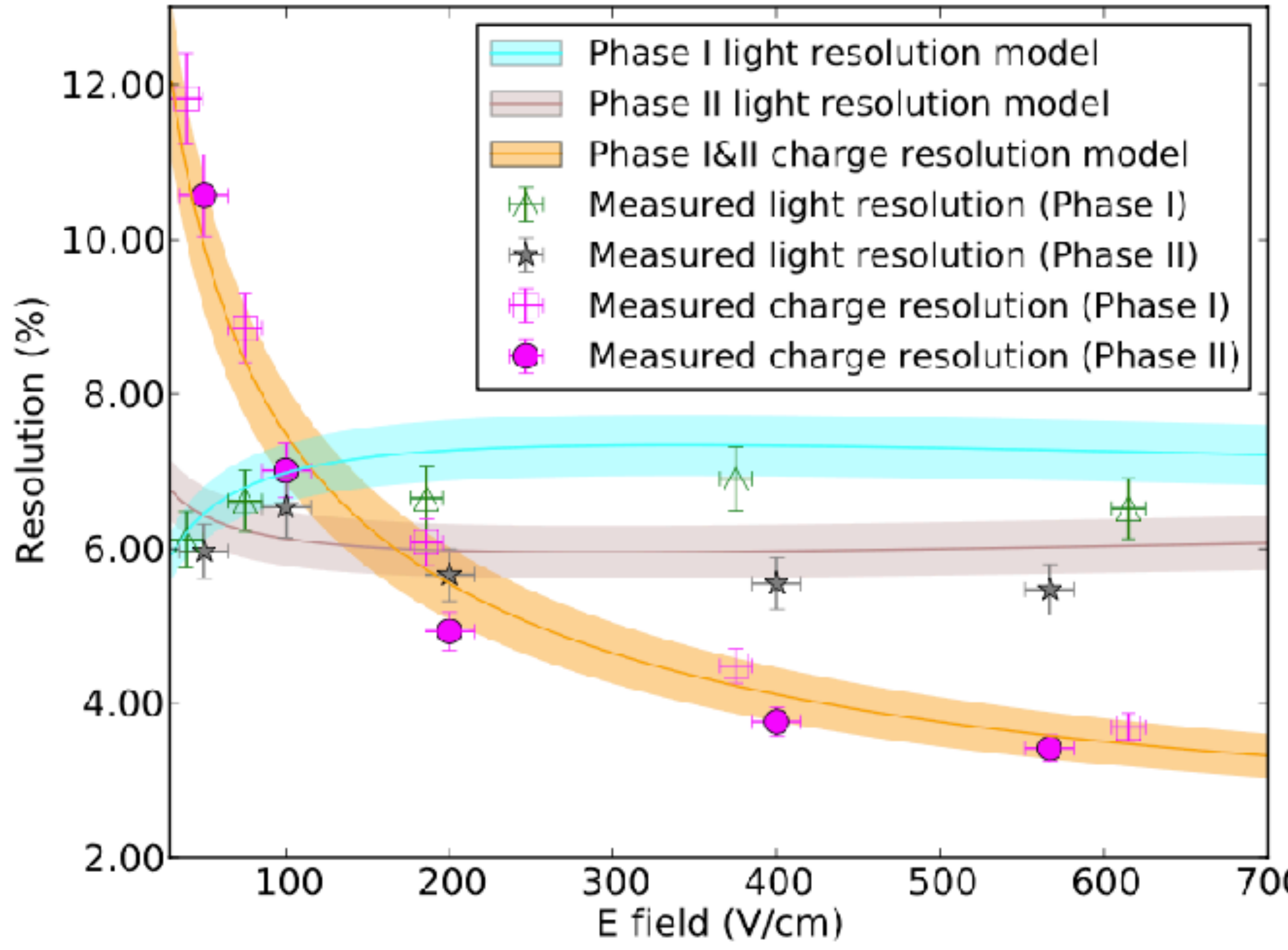
Primary pulses (PP) with different types of correlated pulses such as prompt CT (CT-P), afterpulse (AP) and delayed CT (CT-D).

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

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

Photon transport efficiency

Photon collection efficiency

Photon Detection efficiency (PDE)

Reflectivity (R)

Correlated avalanches

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

RMS of CA charge per PE

Mean Charge in CA per primary PE

Uncorrelated avalanches

DCR

nEXO SiPM Requirements at 163 K

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

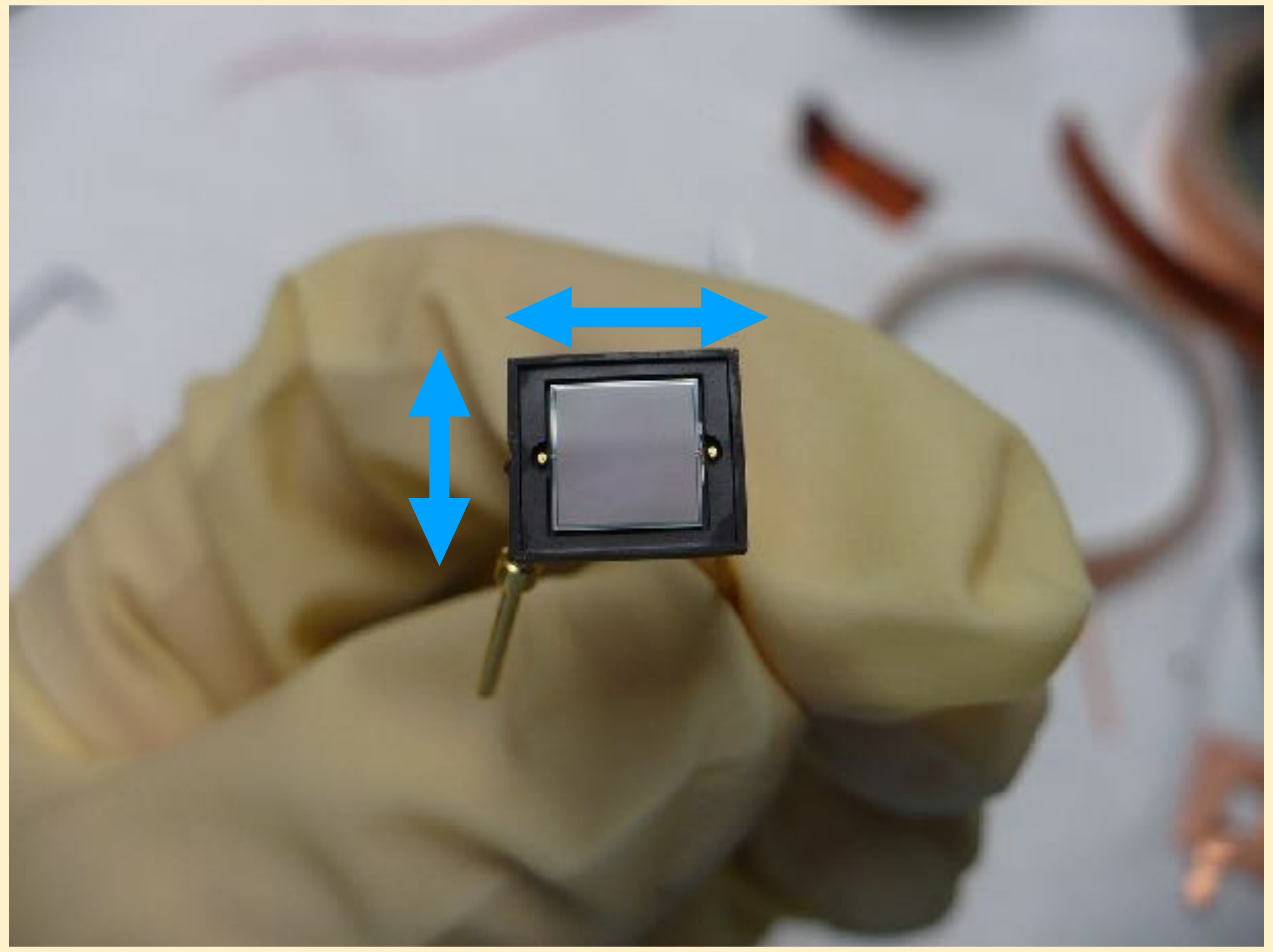
Parameters	Value
Photo-detection efficiency (PDE) at 175-178 nm in liquid Xenon	**≥ 15%**
Radio purity: contribution of photo-detectors on the overall background	< 1%
Dark noise rate at -110 °C	**≤ 10 Hz/mm²**
Correlated Avalanches fluctuation (CAF) per pulse in 1μs at -110 C	**≤ 0.4**
Single photo-detector 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

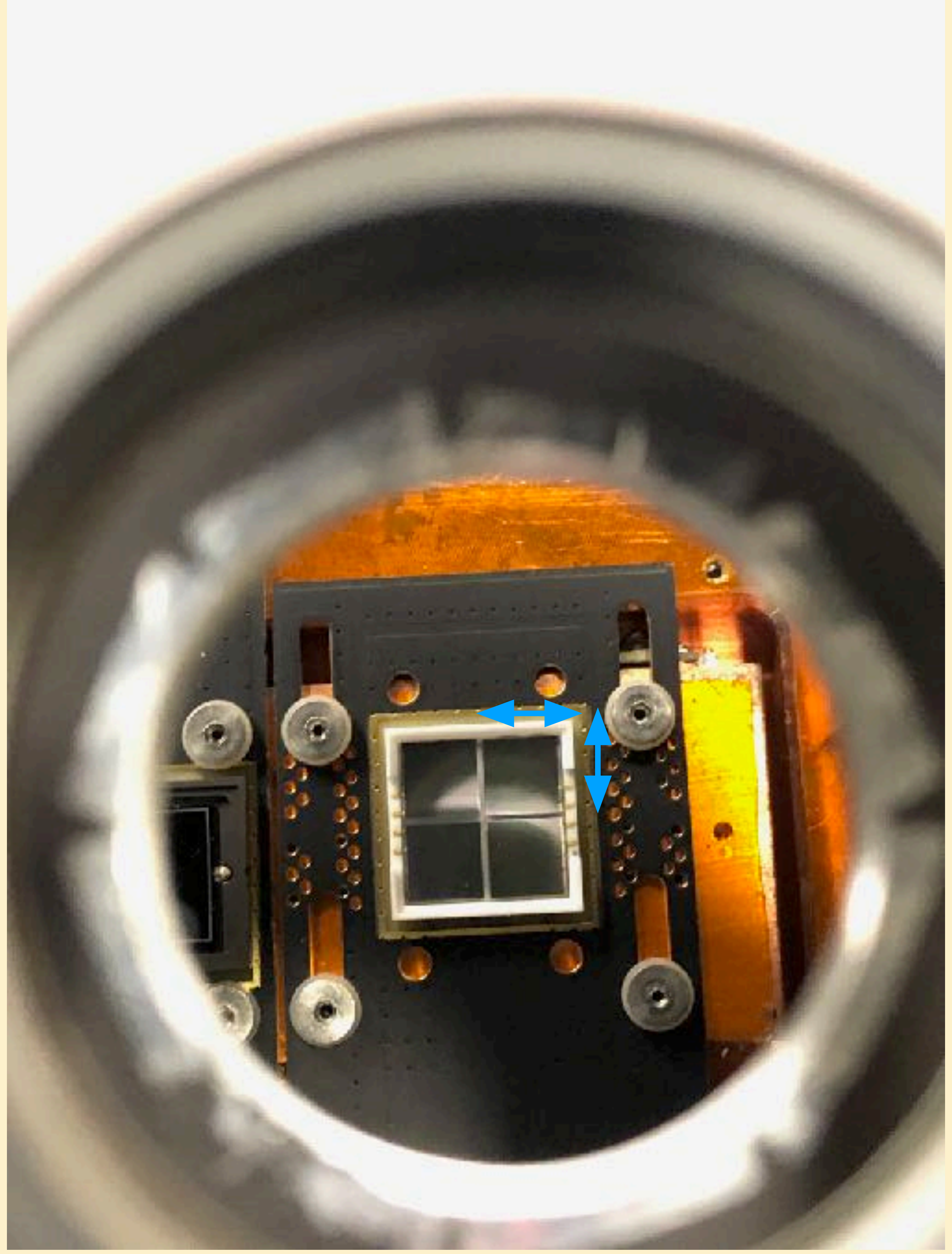
Three SiPMs analysed in this work: 2 Hamamatsu VUV4 MPPCs and FBK VUVHD3 SiPM

nEXO 6x6 mm^2 SiPMs candidates

Hamamatsu MPPCs

NIM A 940 (2019)



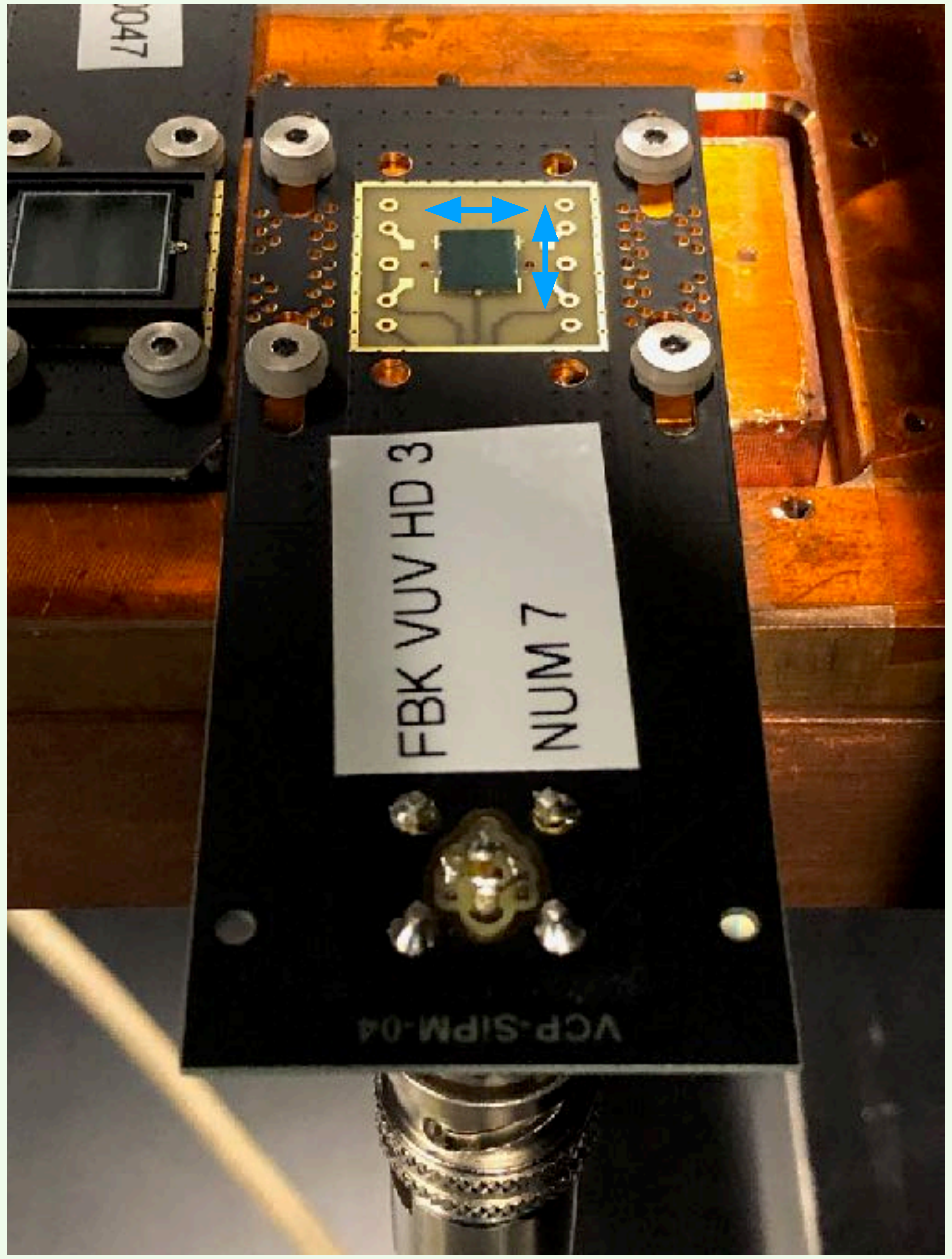


HPK VUV4-50
Single devices
50 um pitch

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

FBK SiPM

IEEE Trans.Nucl.Sci. 65 (2018)



FBK VUVHD3
substitutes
its previous generation
FBK VUVHD1

An international joint effort

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 !

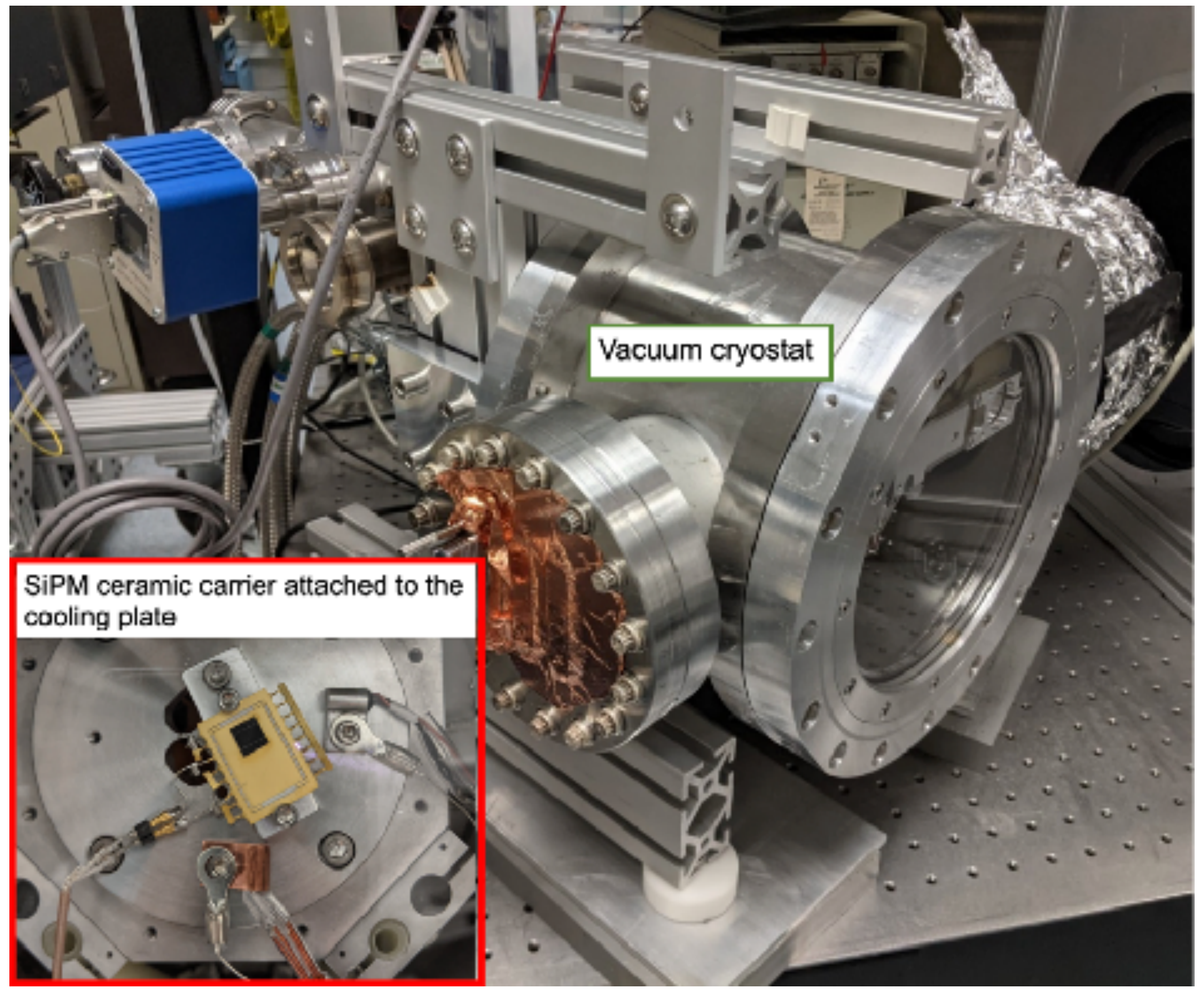
TRIUMF	IHEP	YALE
G. Gallina, F. Retiere, P. Margetak, N. Massacret, M. Mahtab et al.	G. Cao, Y. Guan et al.	A. Jamil, A. Bhat, D. Moore

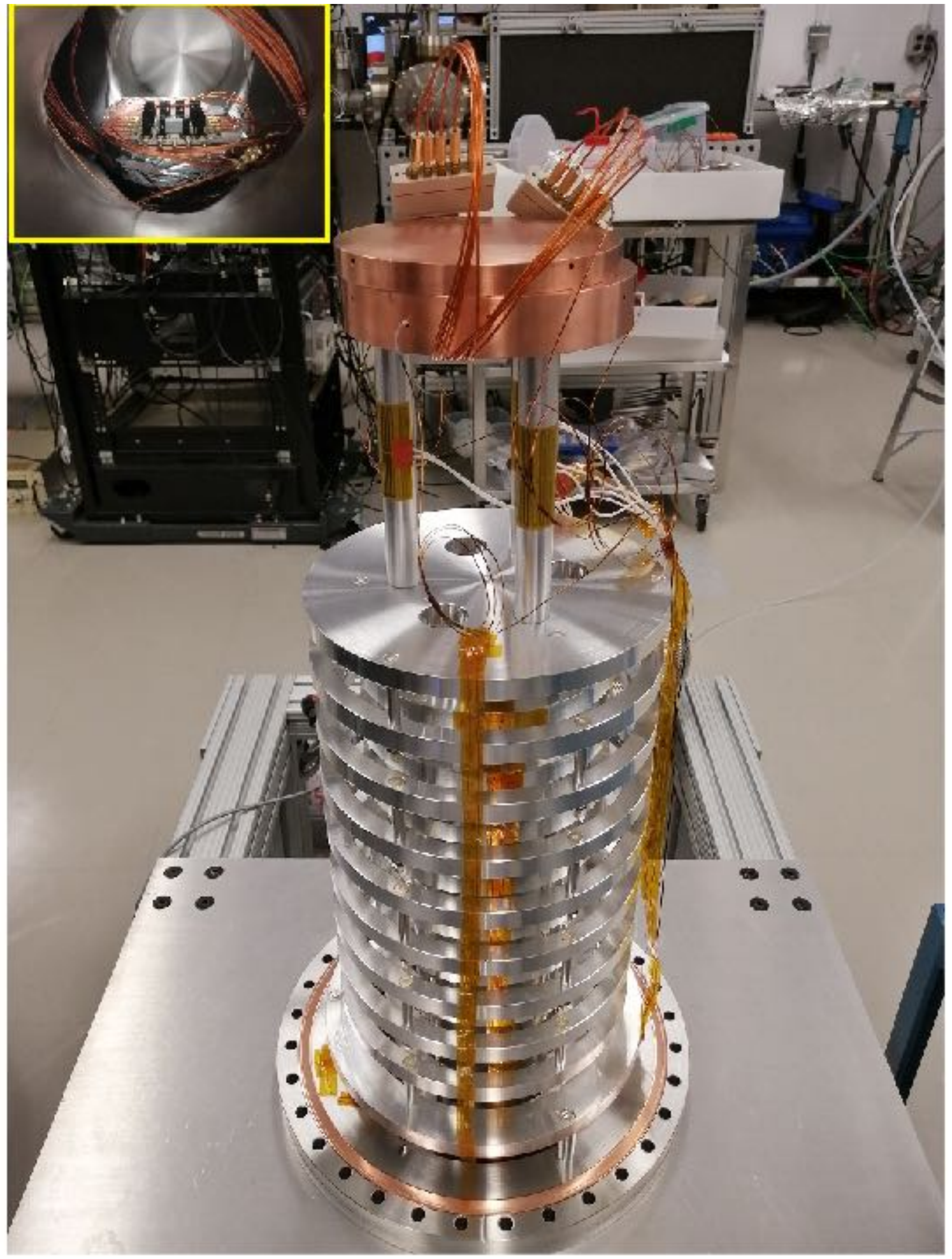
BNL/Drexel	UMass	McGill
A. Bolotnikov, I. Kotov, A. Kumar et al.	A. Pocar, W. Gillis, Reed C. et al.	L. Darroch, T. Brunner et al.

New measurements in EPJC ! arXiv:2209.07765

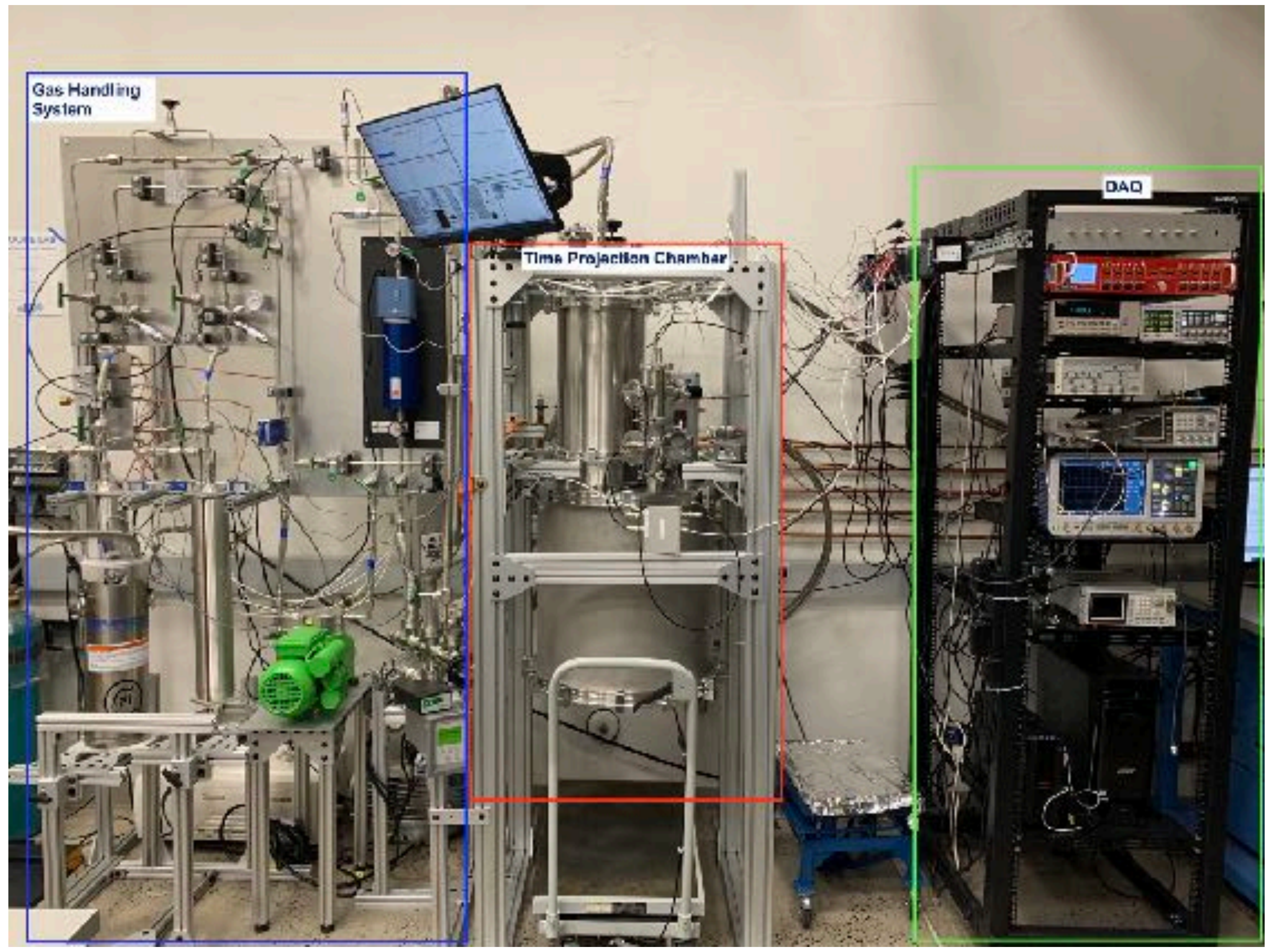
nEXO Testing setups: Dark measurements

BNL Setup

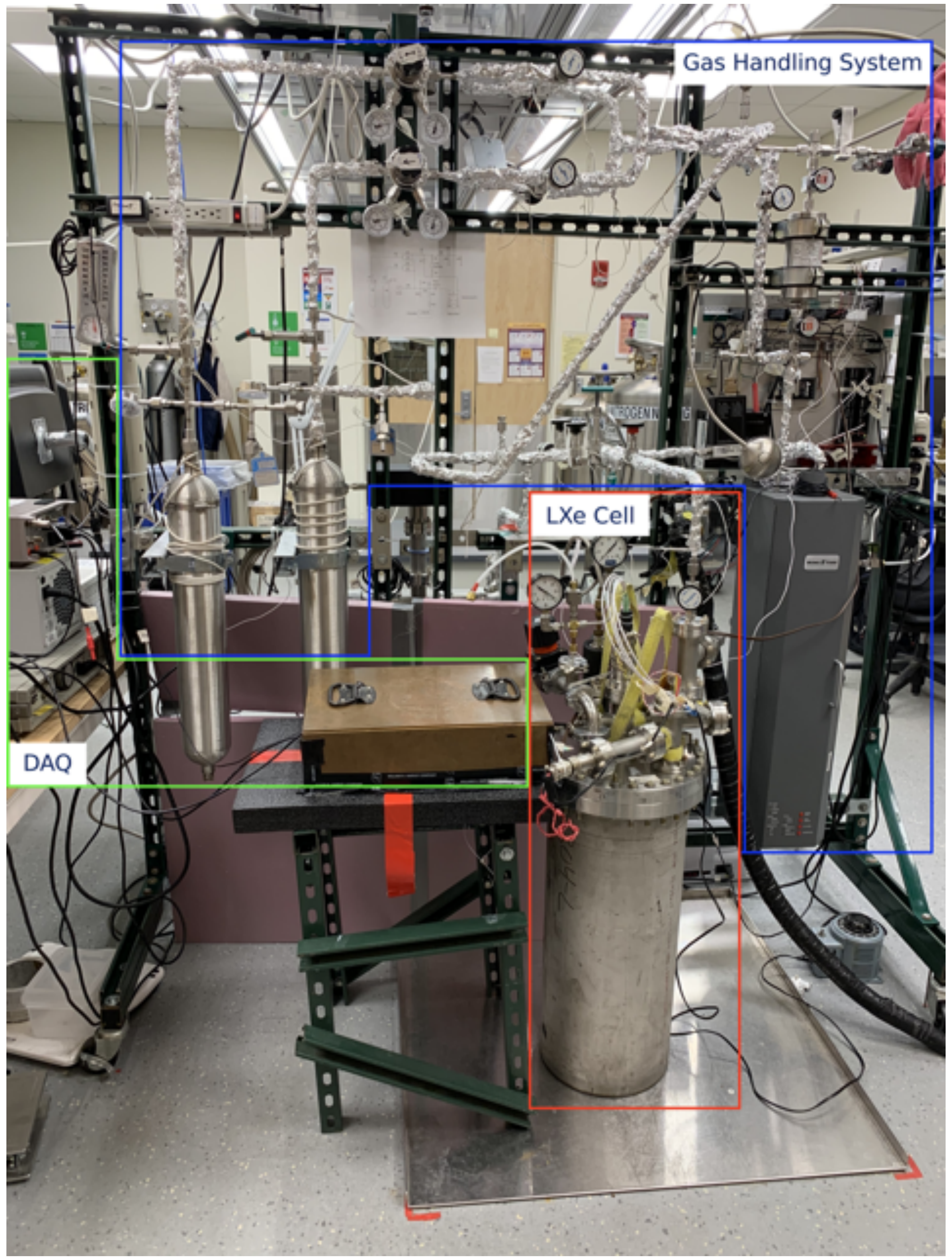




McGill Setup

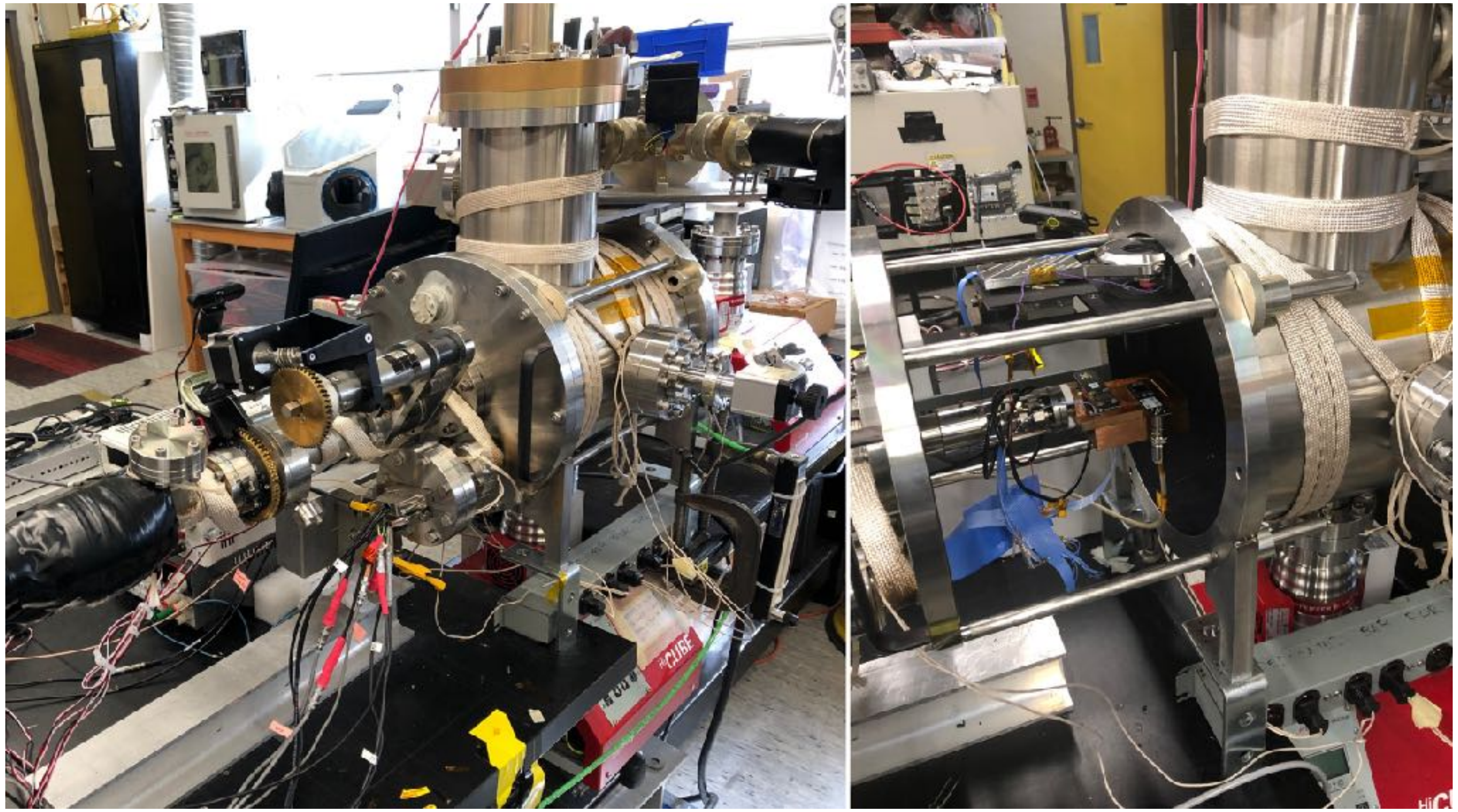


Yale LXe Setup

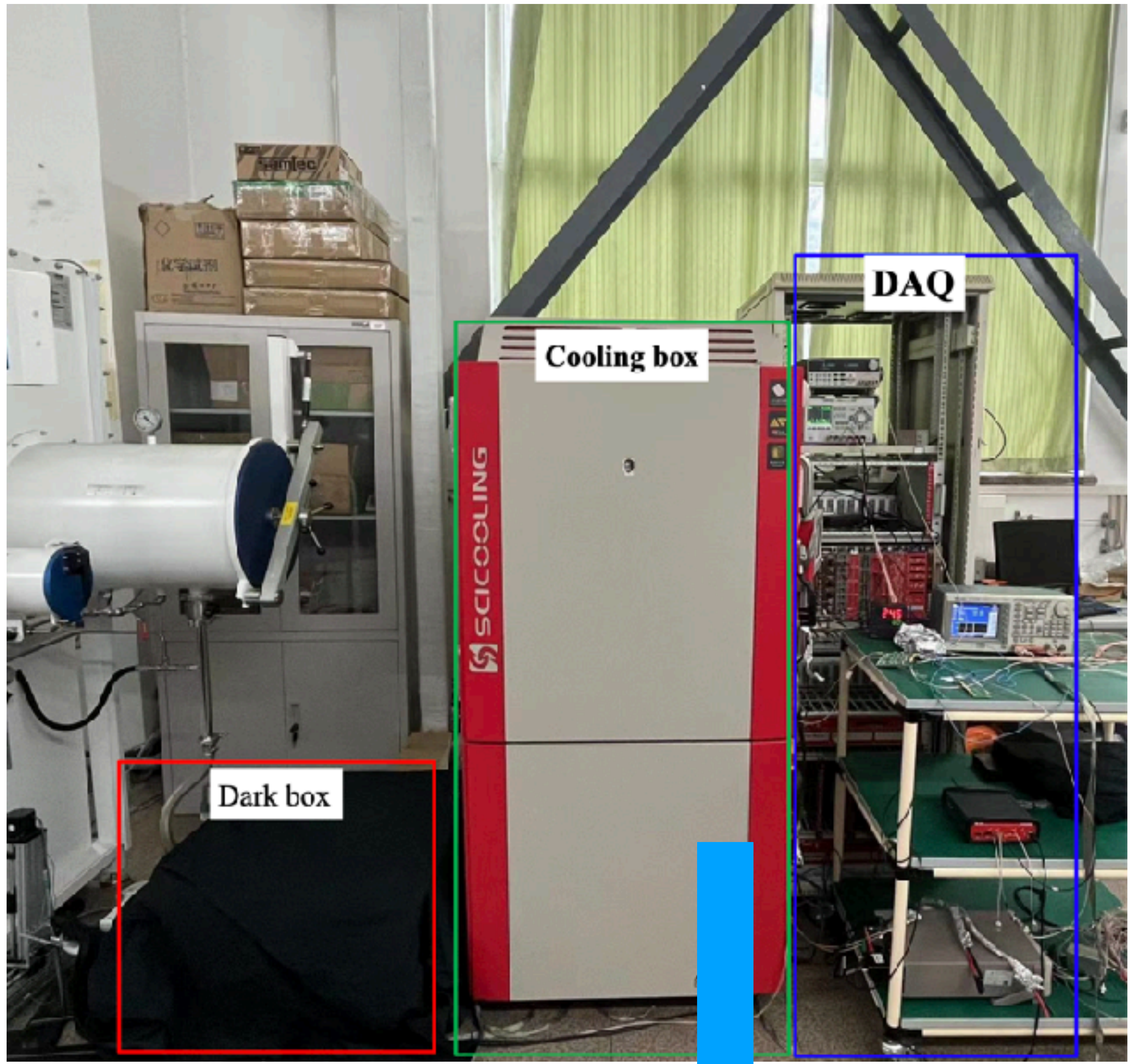


UMass LXe Setup

nEXO Testing setups: Dark and PDE measurements



TRIUMF Setup



IHEP Setup

- Both setups are equipped with vacuum monochromators.
- IHEP PDE measurements are done at 233 K, TRIUMF ones at 163 K

Dark Count Rate (DCR)

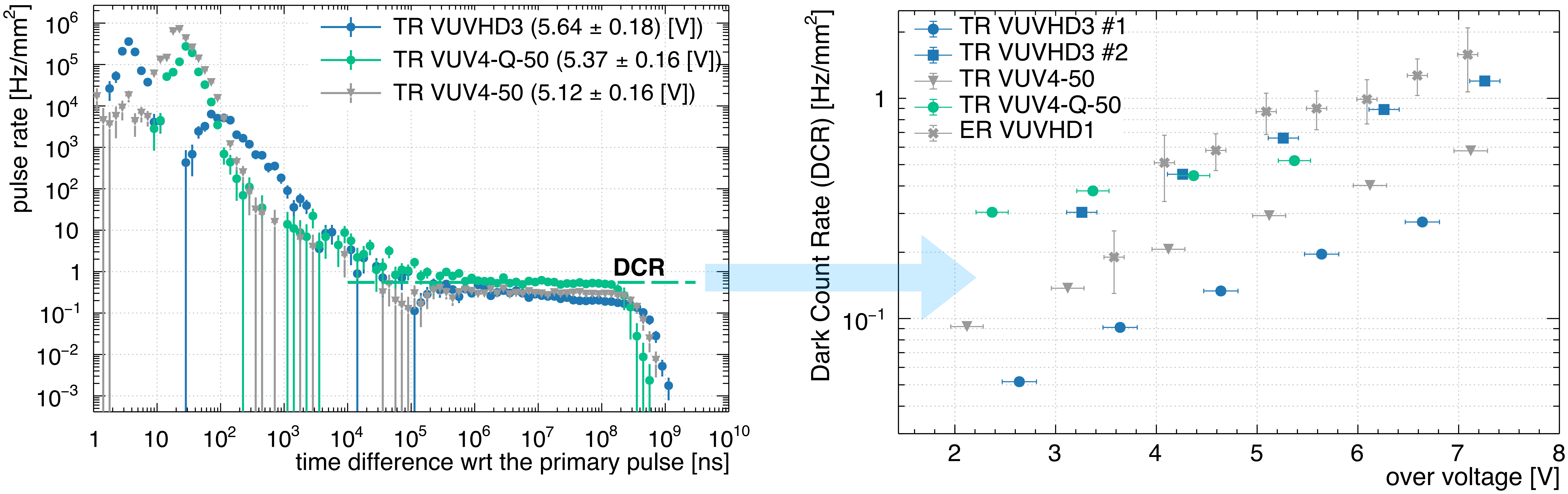
Dark Count Rate (DCR)

Grey points !

NIM A 940 (2019)

IEEE Trans.Nucl.Sci. 65 (2018)

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



Requirement at 163 [K]: DCR < 10 Hz/mm²

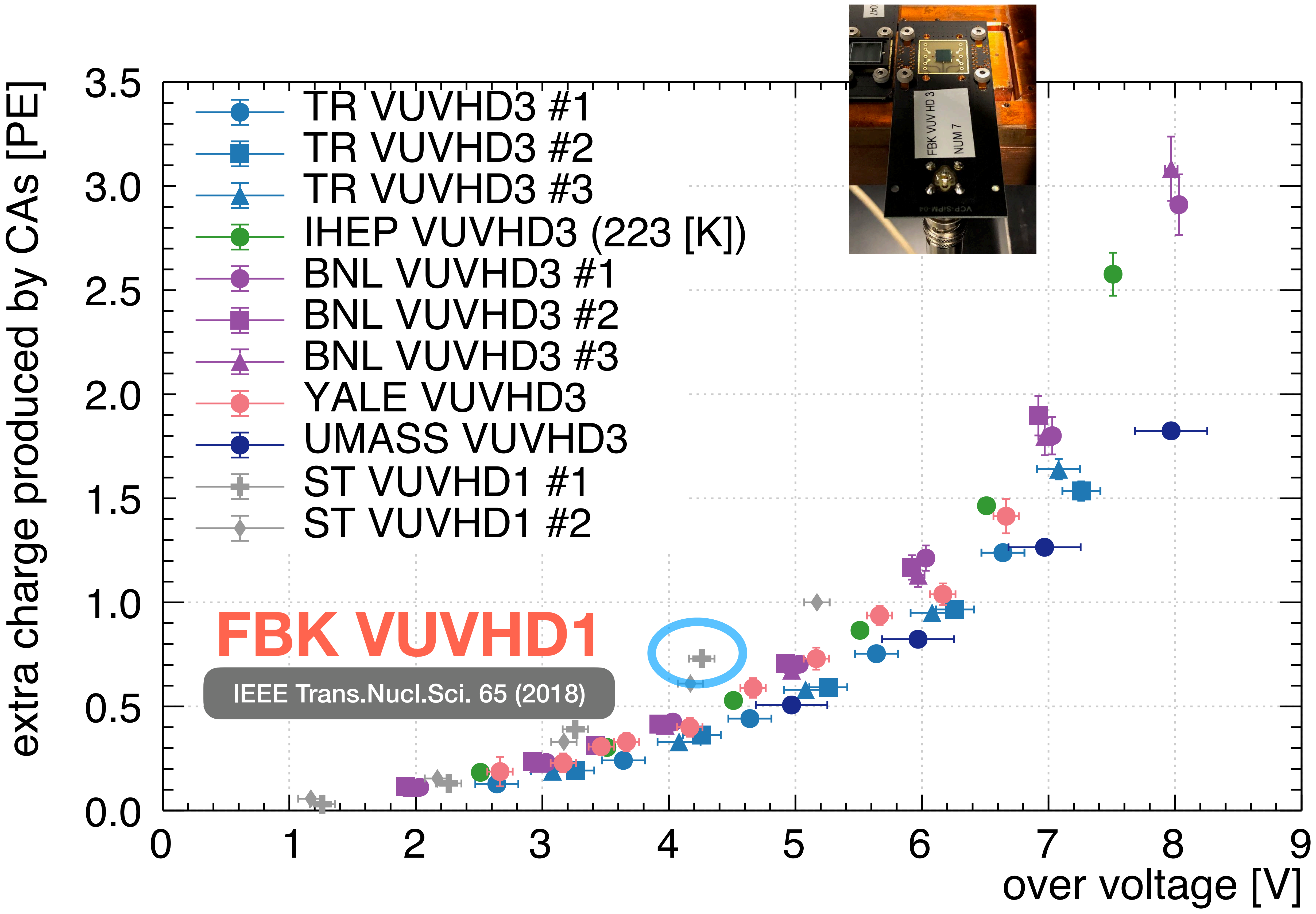
- **Requirement met in the entire range of OV studied!**

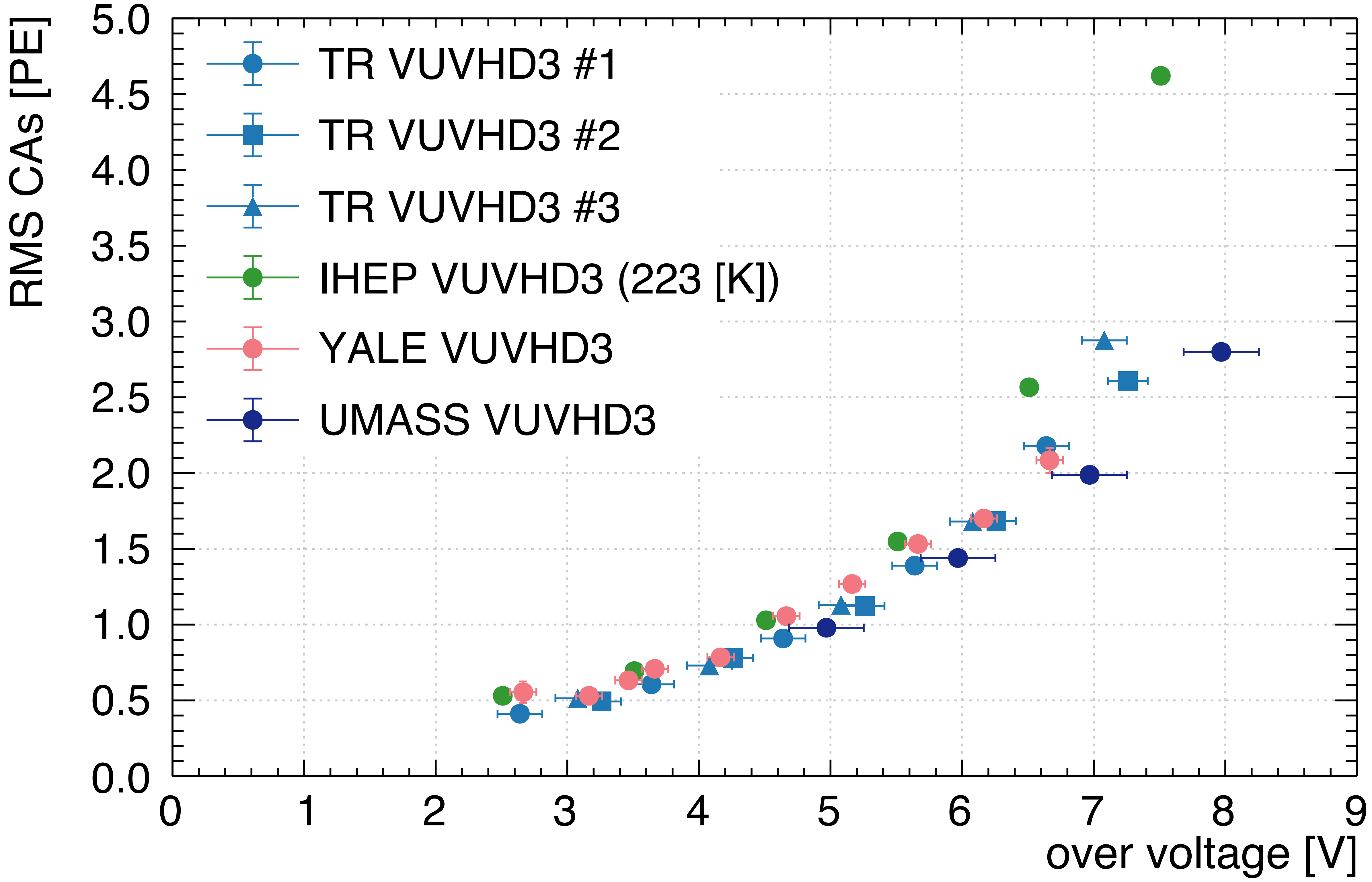
Correlated Avalanches

Correlated Avalanches FBK VUVHD3

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

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



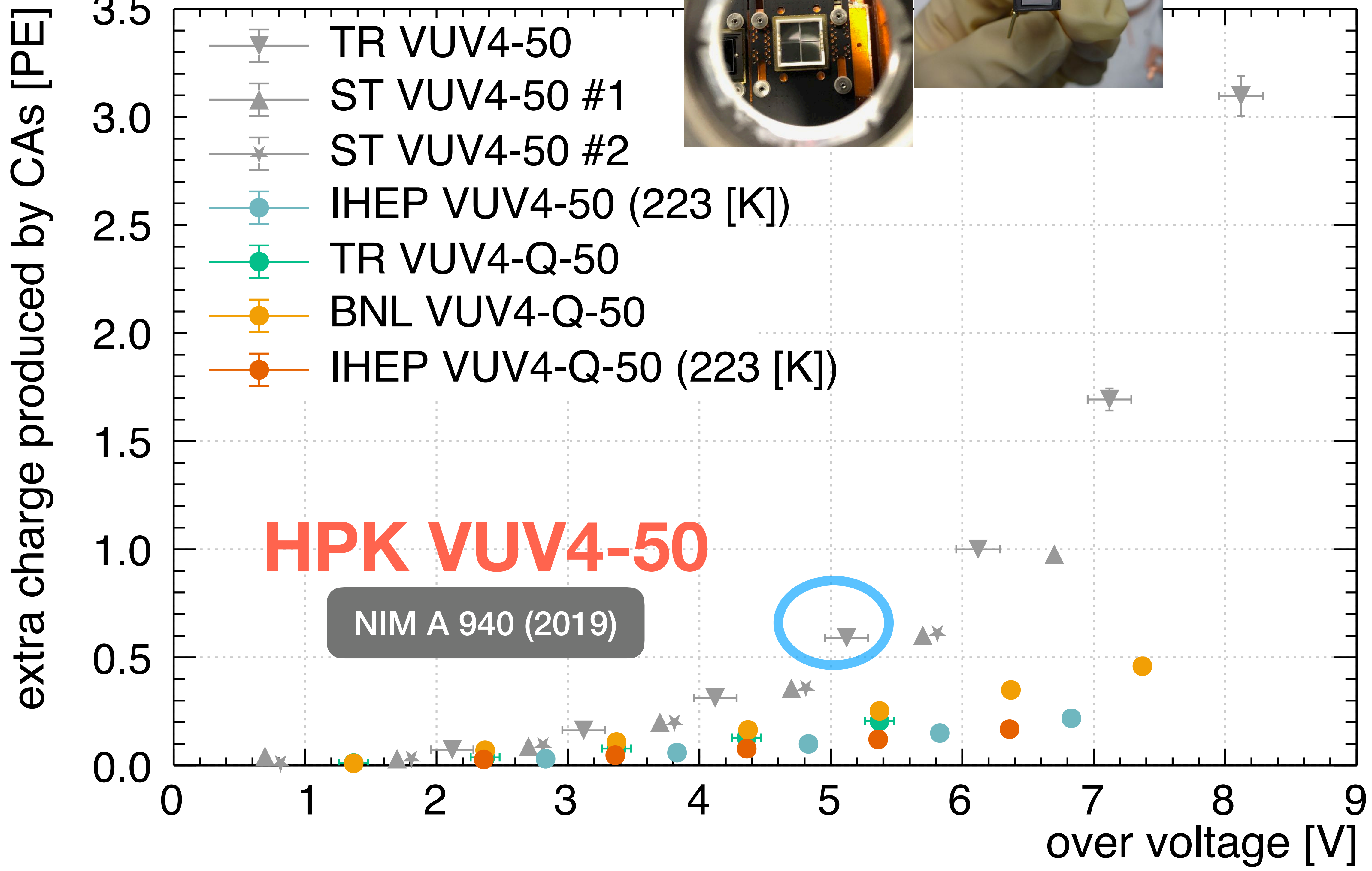


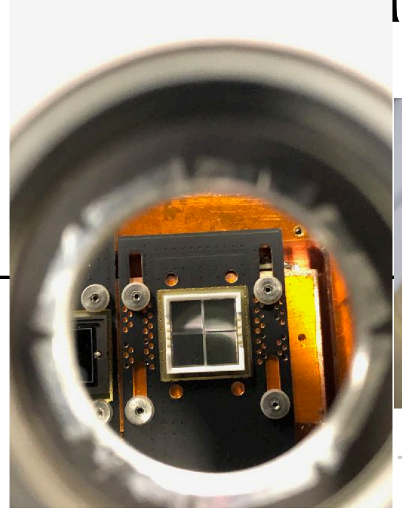
- **FBK VUVHD3** is improved compare to **FBK VUVHD1.**

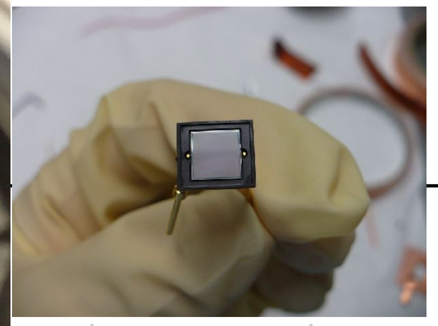
Correlated Avalanches HPK VUV4 MPPCs

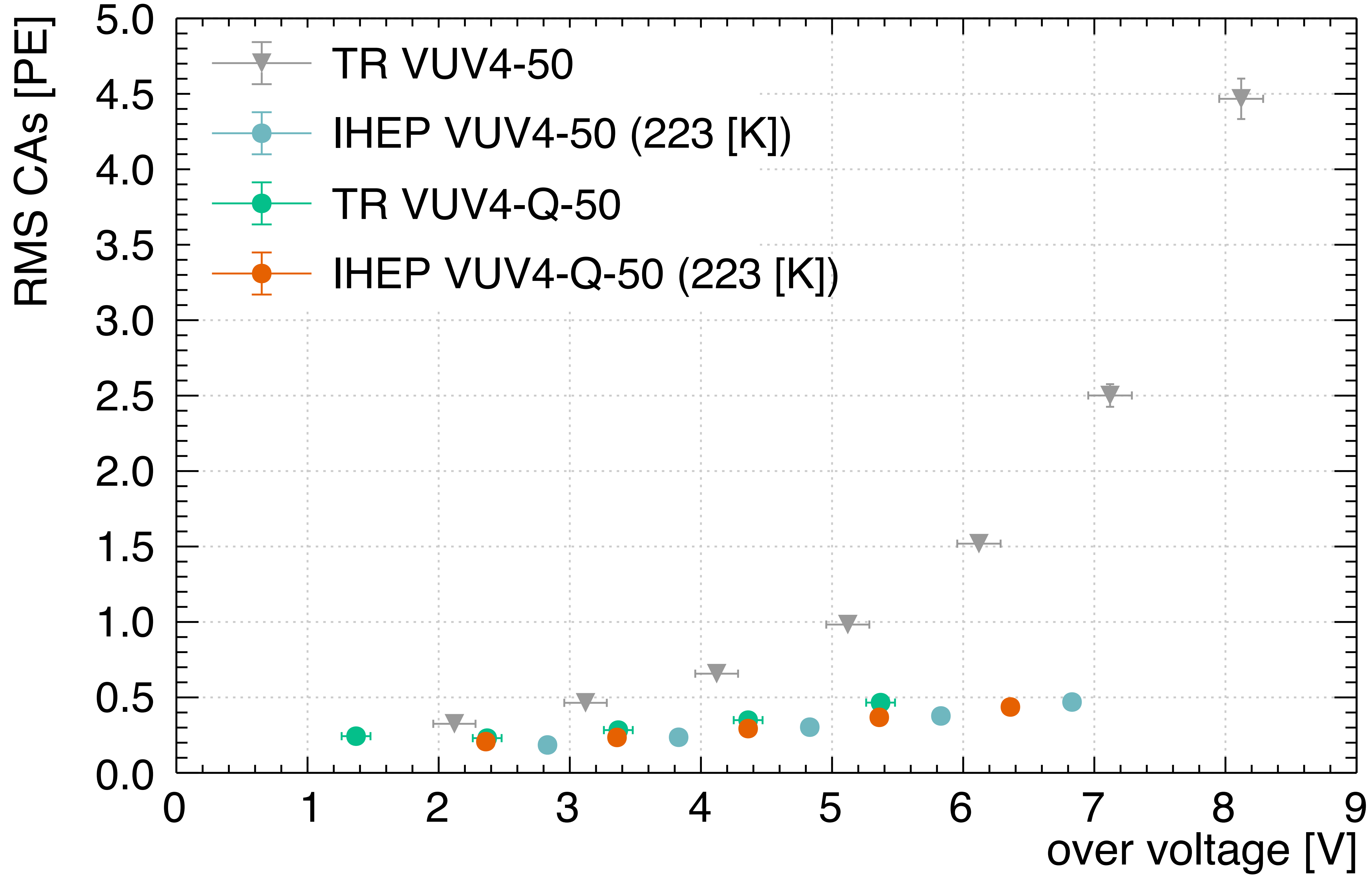
- Defined as the ratio between the RMS (σ_Λ) and the mean $\langle\Lambda\rangle$ extra charge procured by correlated avalanches (CA) per pulse

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







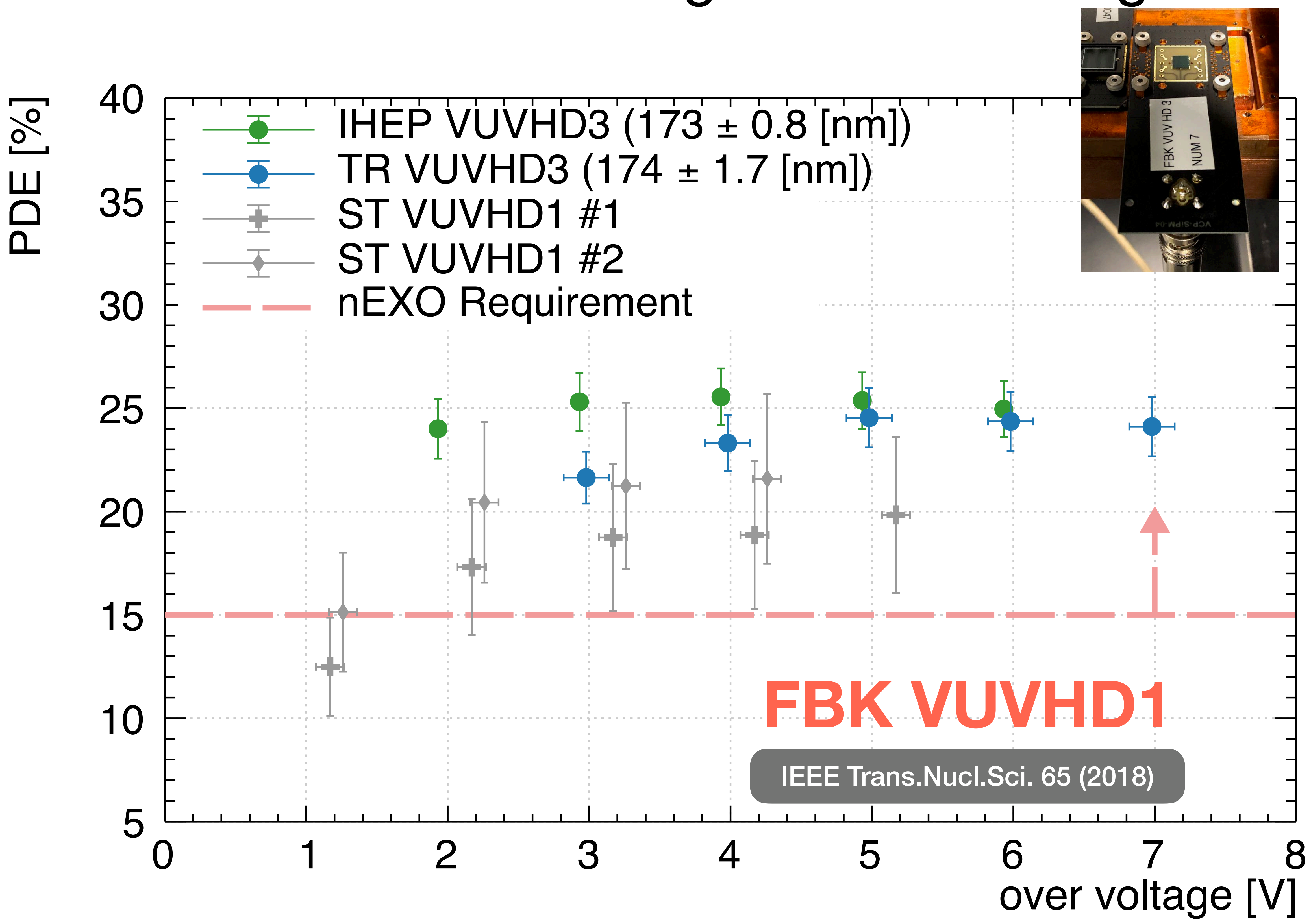


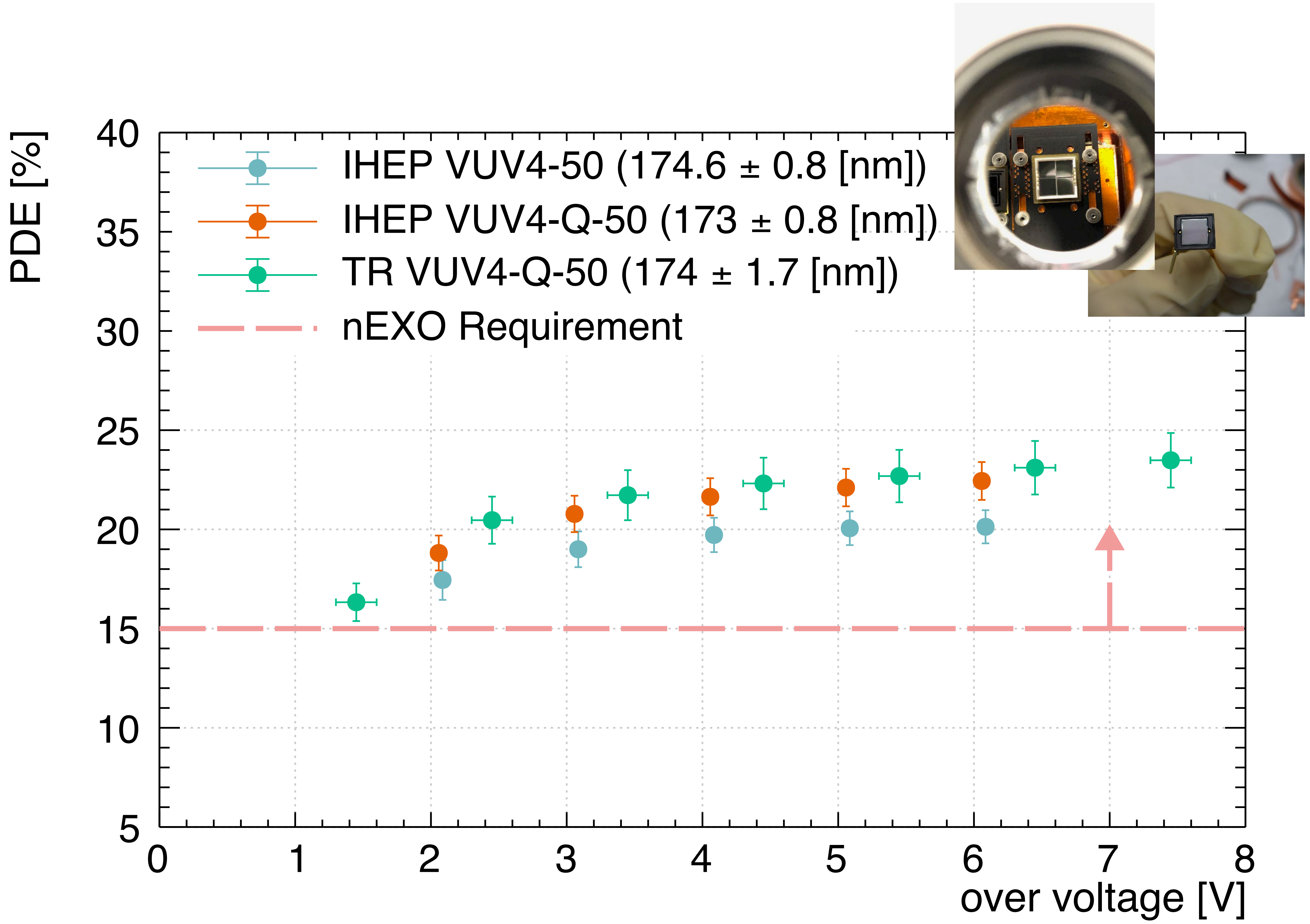
- **HPK VUV4** has almost **no correlated avalanches (CA) and it is significantly better than the HPK VUV4-50 tested previously**

Photon Detection Efficiency (PDE)

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



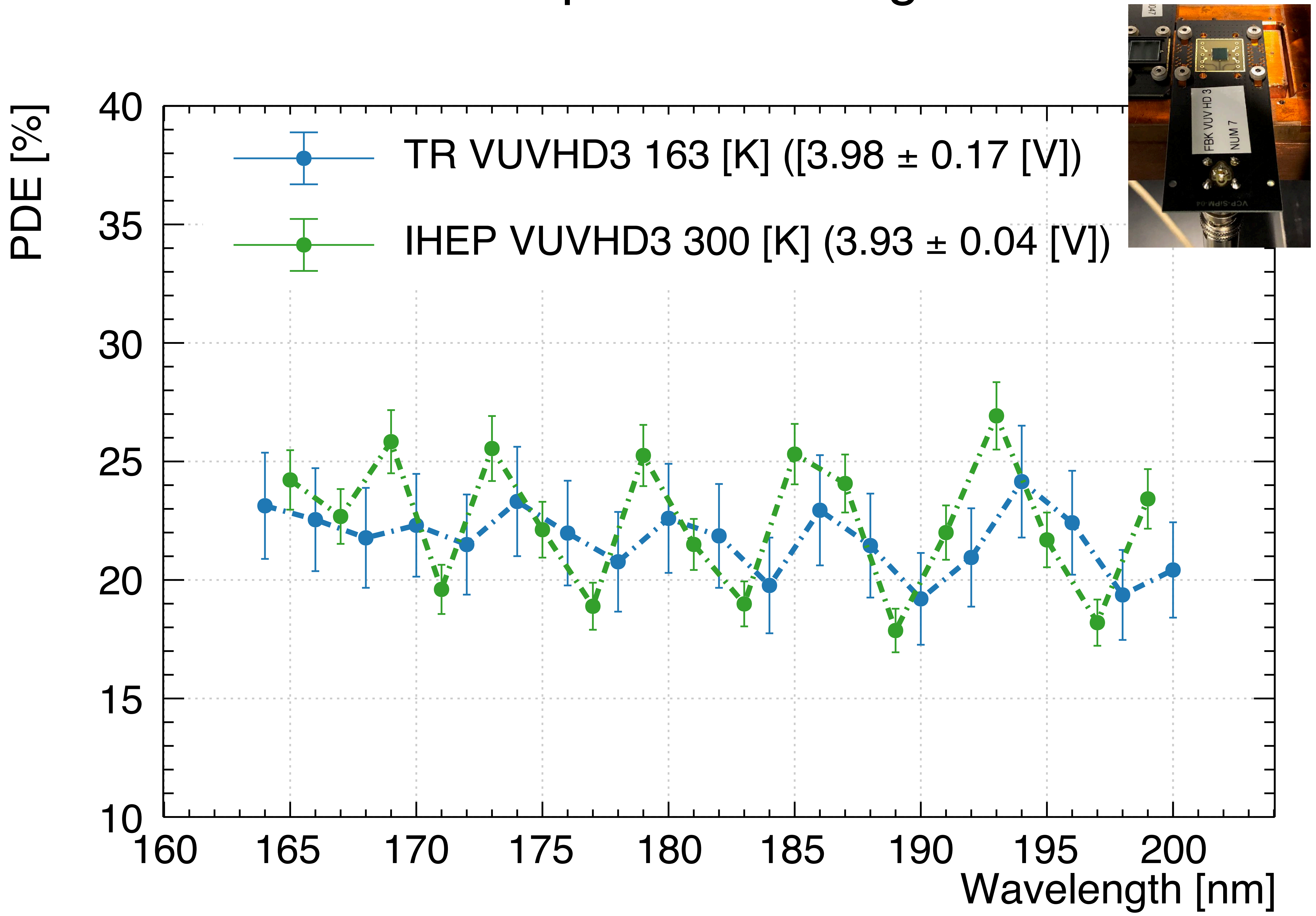


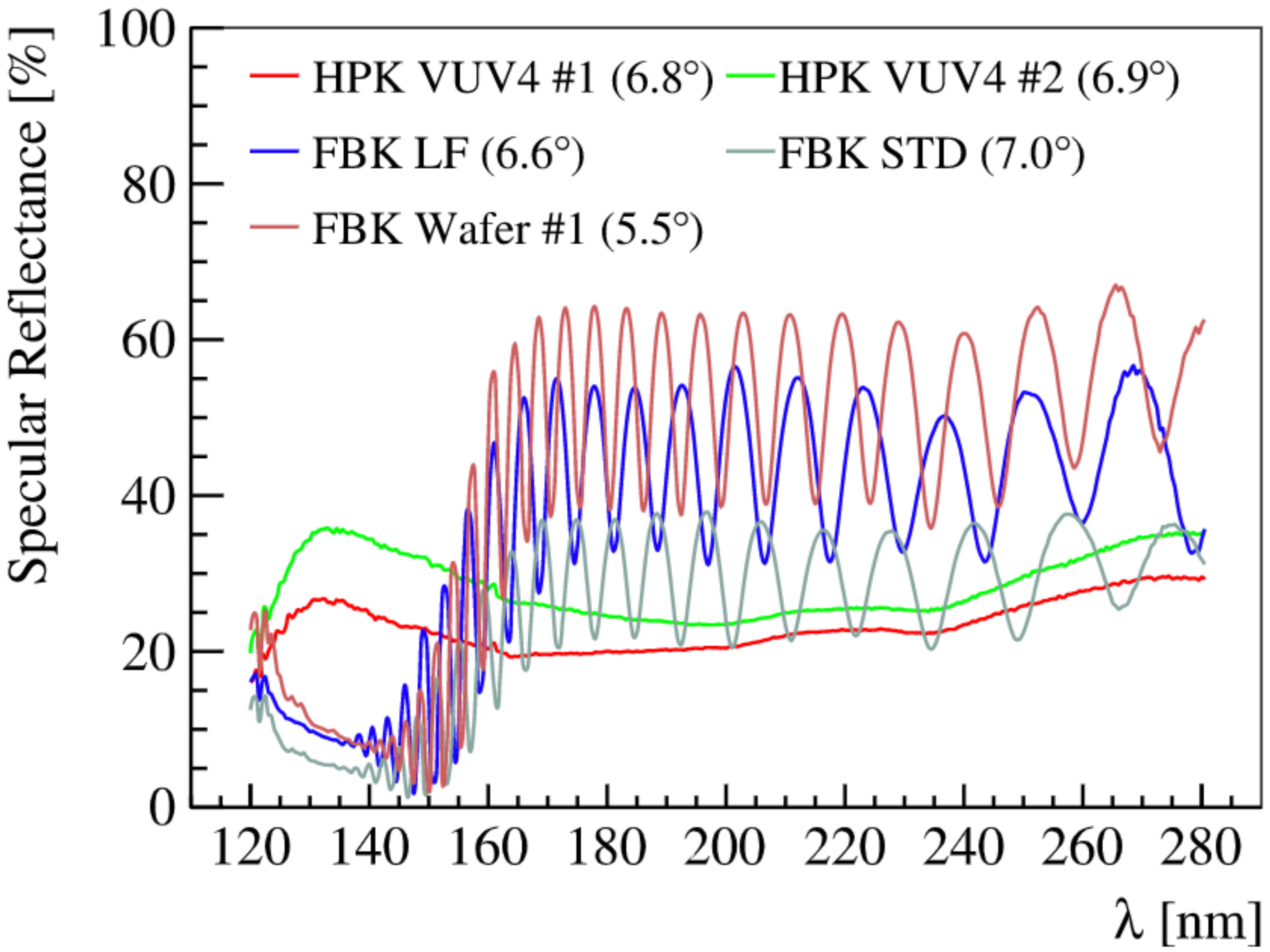
Requirement > 15% at ~ 175 nm

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 SiO_2 top layer. Compatible with specular reflectivity measurements done at IHEP and published in 10.1109/TNS.2020.3035172

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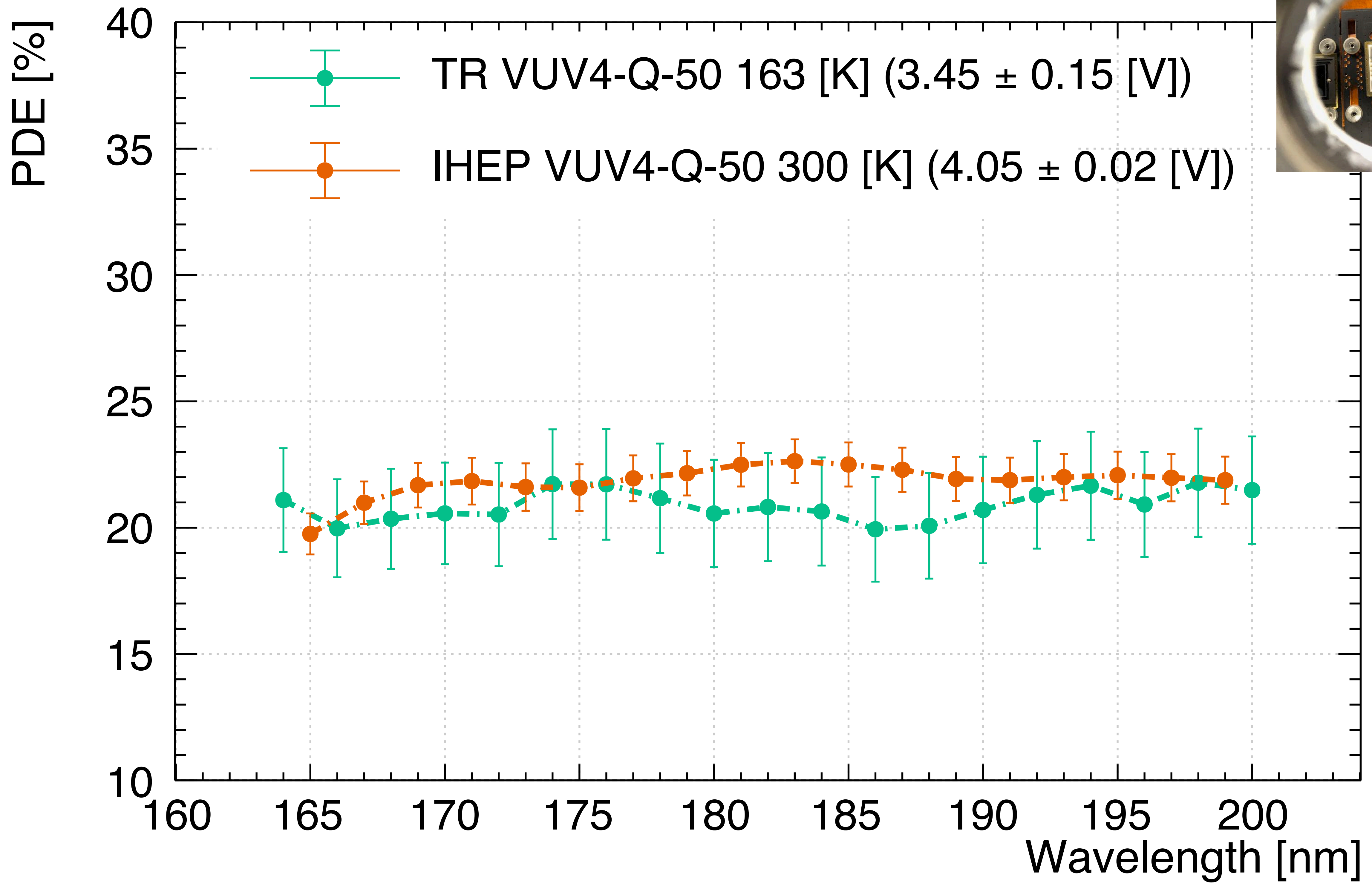
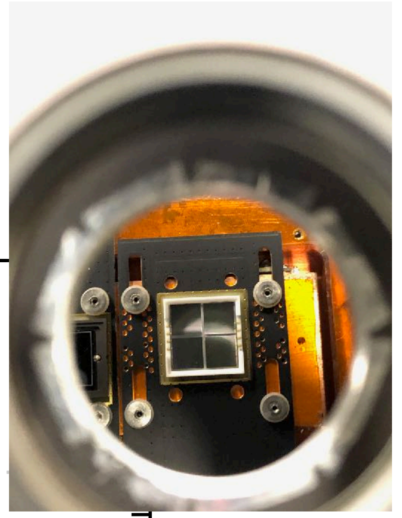
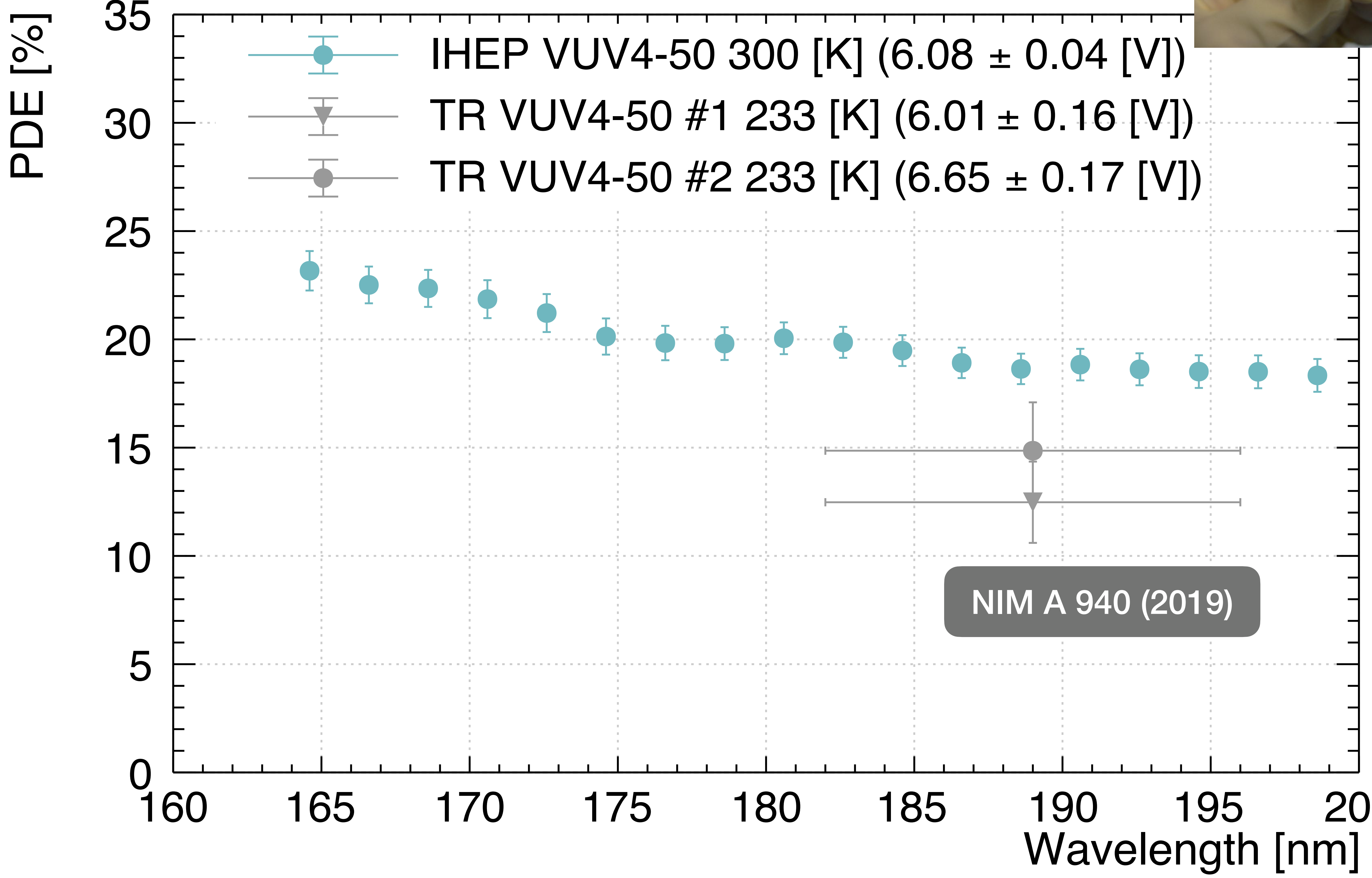
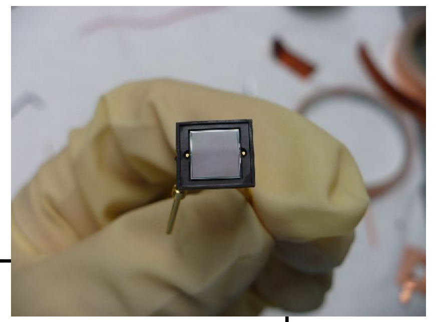








- HPK MPPCs Quad devices have an efficiency higher of the corresponding single package 50um pitch device

Estimation of the nEXO Energy Resolution

nEXO Energy Resolution at ($2458\,\text{keV}$ for ^{136}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: $\frac{\sigma_n}{\langle n\rangle} \leq 1\,\%$

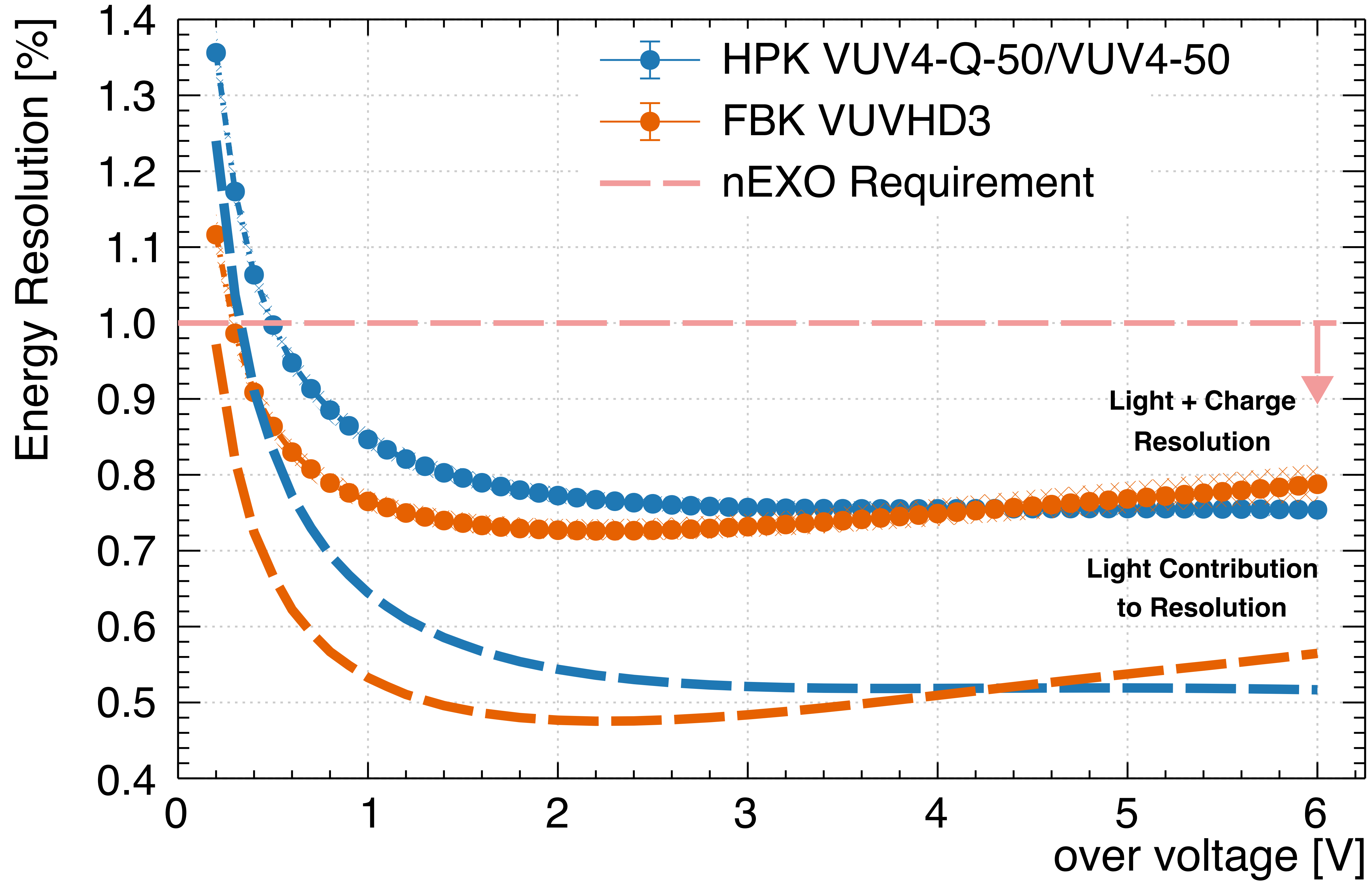
Fluctuation due to number of photons detected (PDE)

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



- eCT is not yet accounted. It may produce a slightly steeper rise.
- Not expected to impact the minimum

Conclusions

Conclusions

- Presented a **complete set of measurements with good agreement between several inst. !**
- The three photosensors tested look to be **excellent candidates for nEXO to reach sub-percent energy resolution**
- **Significantly more information** is now available (PDE wavelength dependence etc ..) compared to what was previously known.
- 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 ..**)

Thanks !


Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

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arXiv:2209.07765