Light detection with SiPMs for the nEXO experiment

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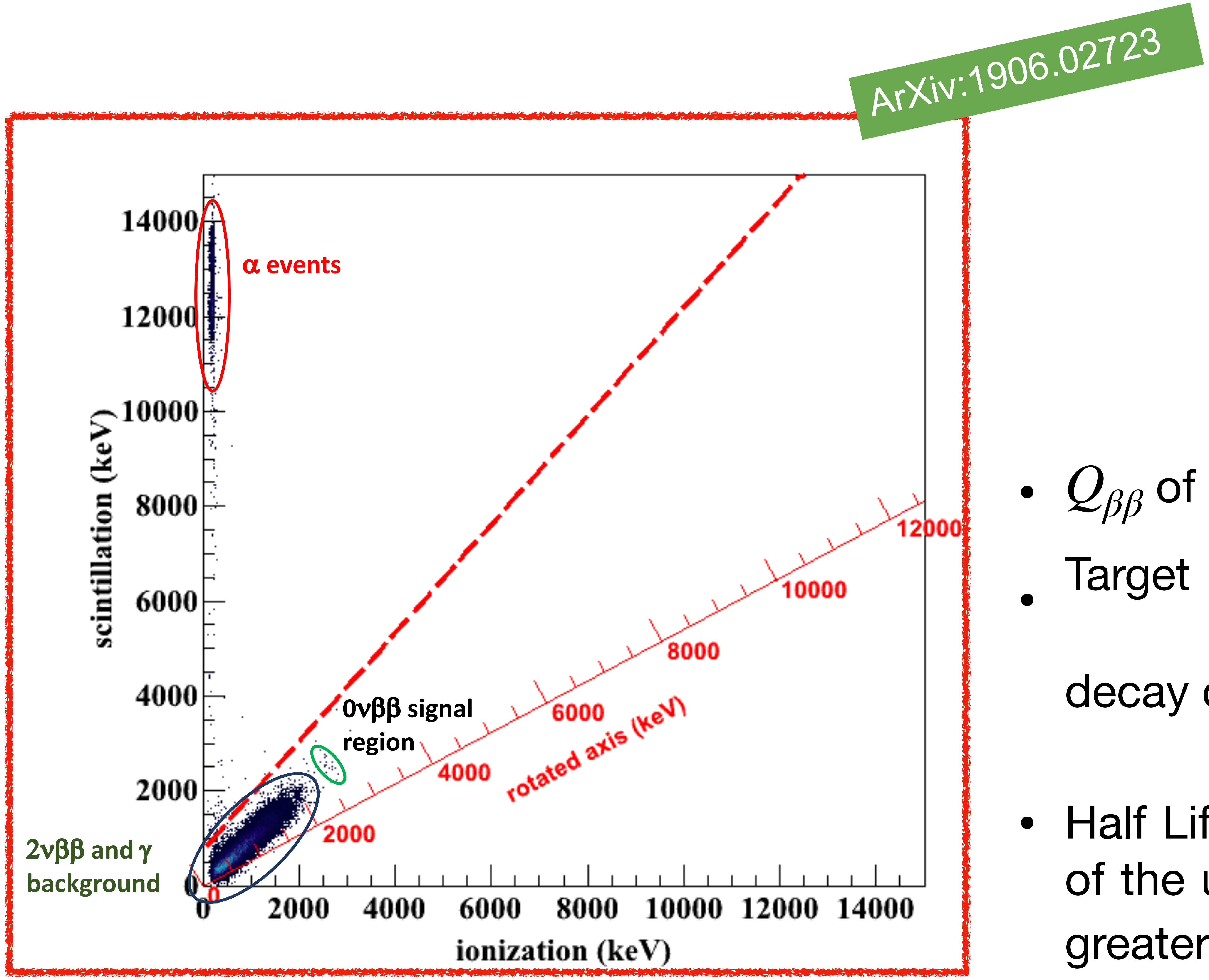
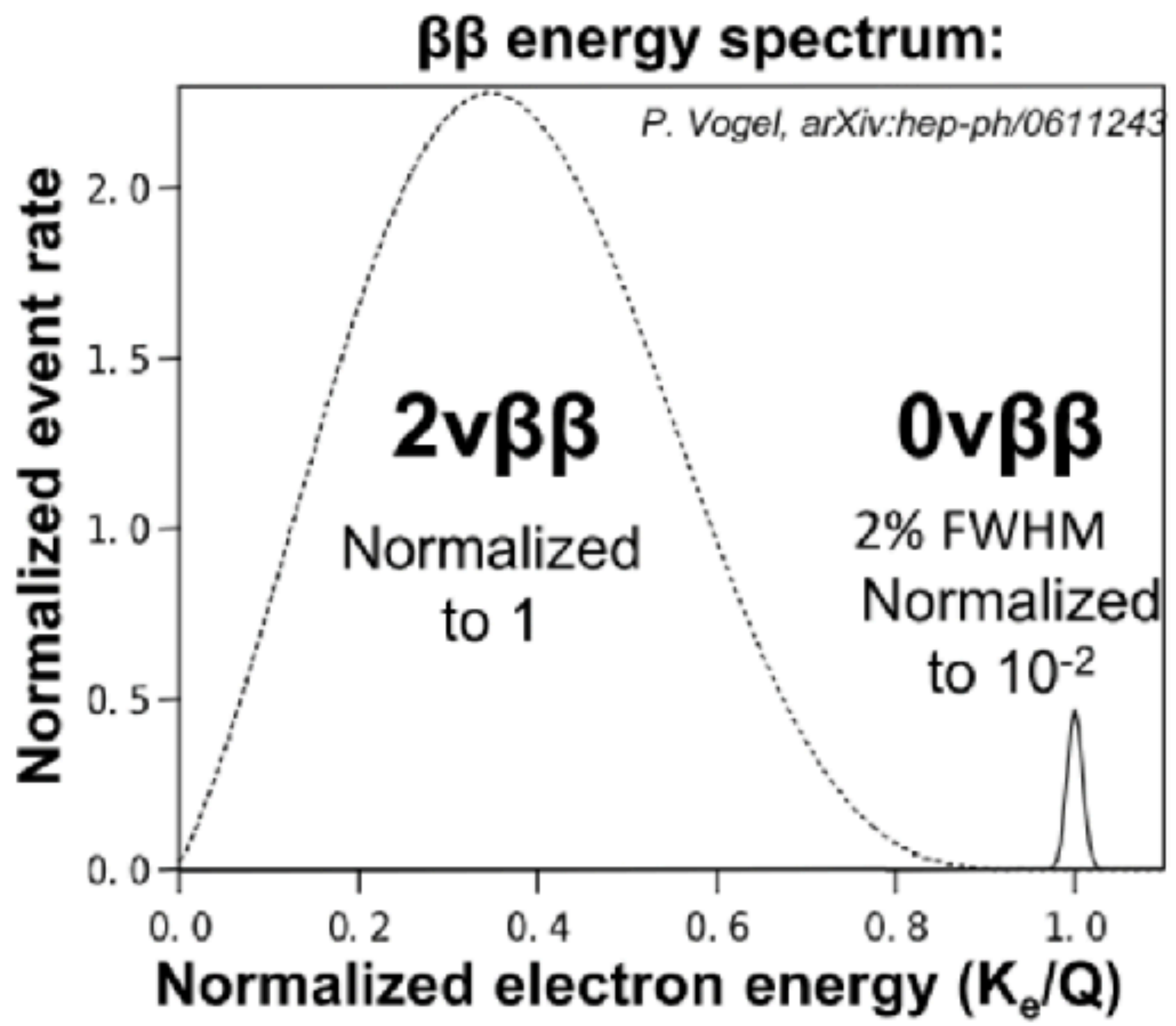
for the nEXO photodetector group

Overview

Search for $0\nu\beta\beta$ Decay





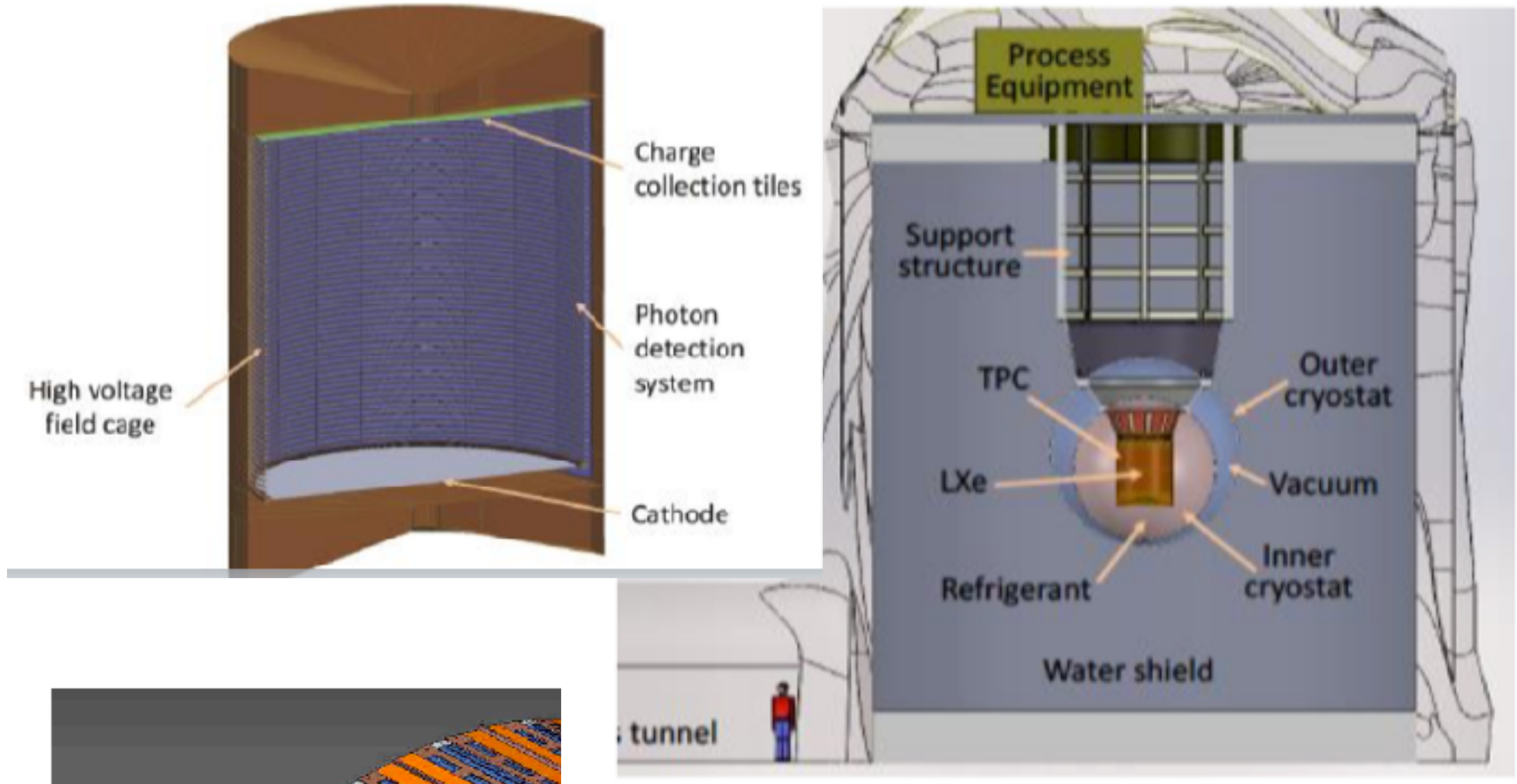
- $Q_{\beta\beta}$ of 2458.07 ± 0.31 keV
- Target energy resolution: $\dfrac{\sigma}{Q_{\beta\beta}}$ of 1 % for the $0\nu\beta\beta$ decay of ^{136}Xe at $Q_{\beta\beta}$
- Half Life is 10^{16} times longer than the estimated age of the universe (Projected half life limit of this decay greater than 10^{25} years)

nEXO Design

nEXO is a proposed ~ 5 tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach $0\nu\beta\beta$ half-life sensitivity of $\sim 10^{28}$ yrs.

- 90% enrichment in ^{136}Xe
- Drift height ~120 cm
- Modular anode tiles on top
- Electric drift field ~ 400 V/cm
- **4.5 m^2 covered with VUV-sensitive SiPMs**
- 600 m^3 water tank as veto and shield

nEXO TPC at SNOLAB



nEXO SiPM staves

SiPM technology

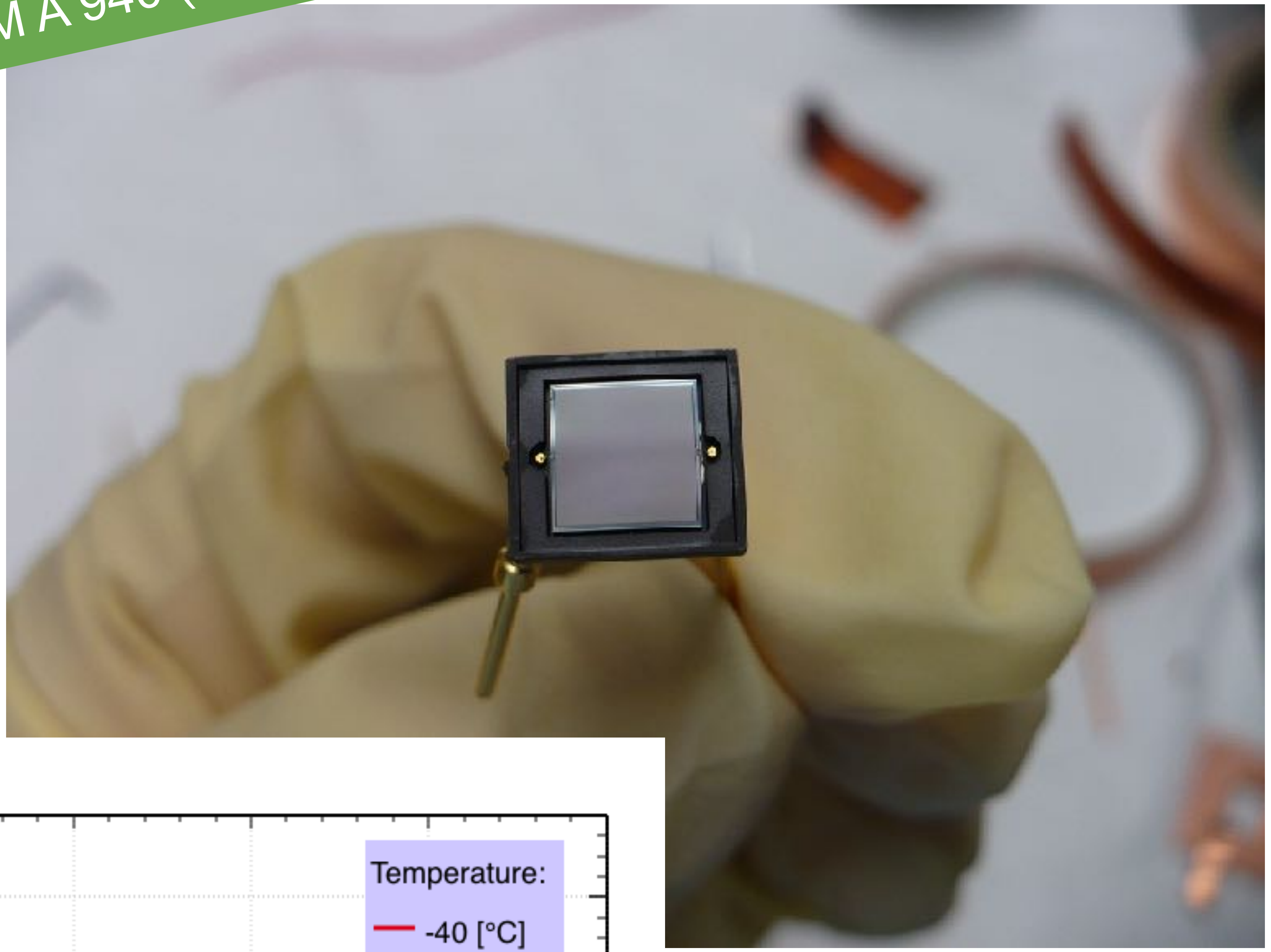
SiPMs technology

Main Characteristics:

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

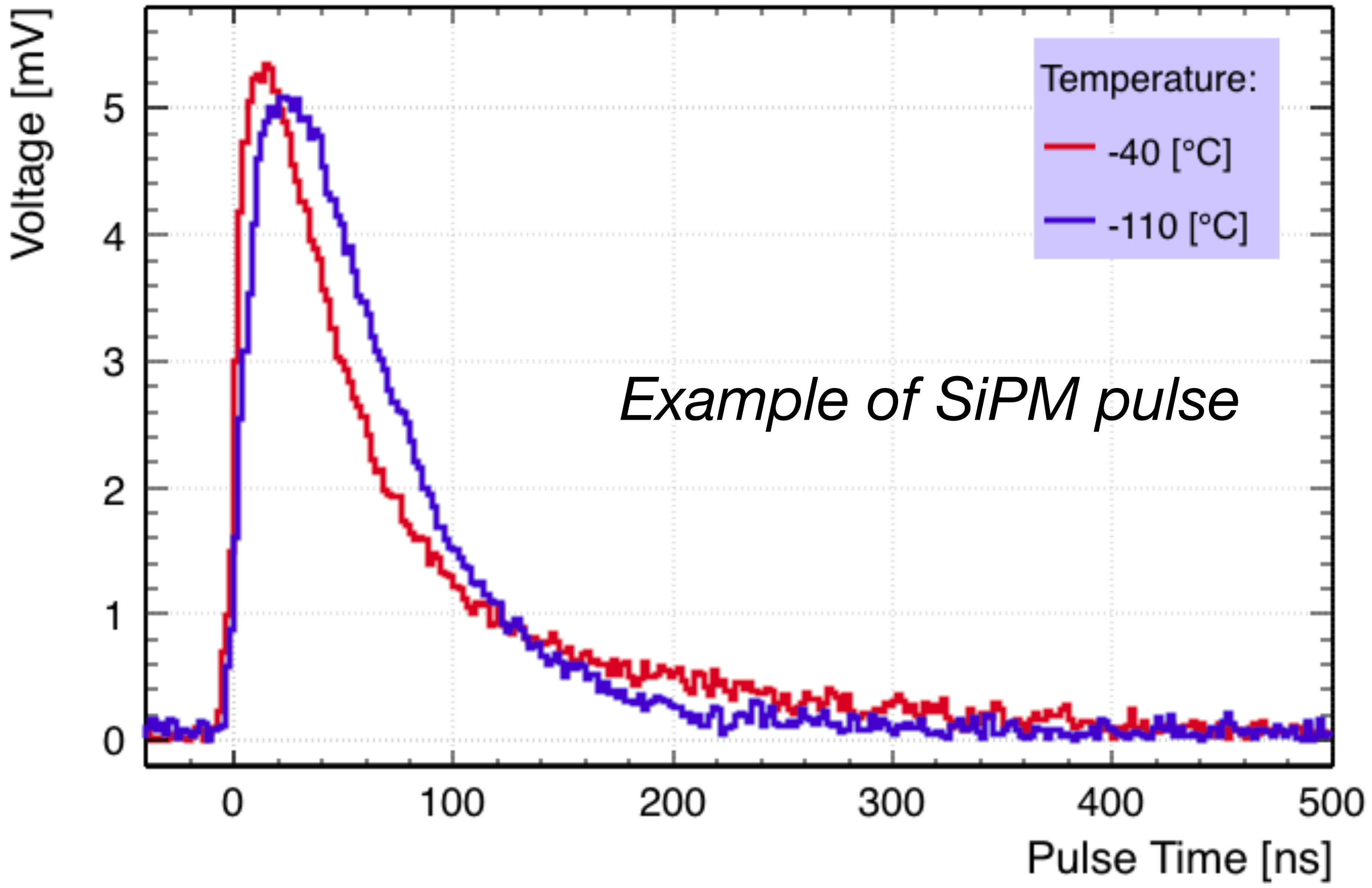
NIM A 940 (2019)

Hamamatsu VUV4 MPPC



Advantages:

- High gain at low bias voltage
- Single photon detection resolution
- High radio purity possible
- Suitable at cryogenic temperature



Example of SiPM pulse

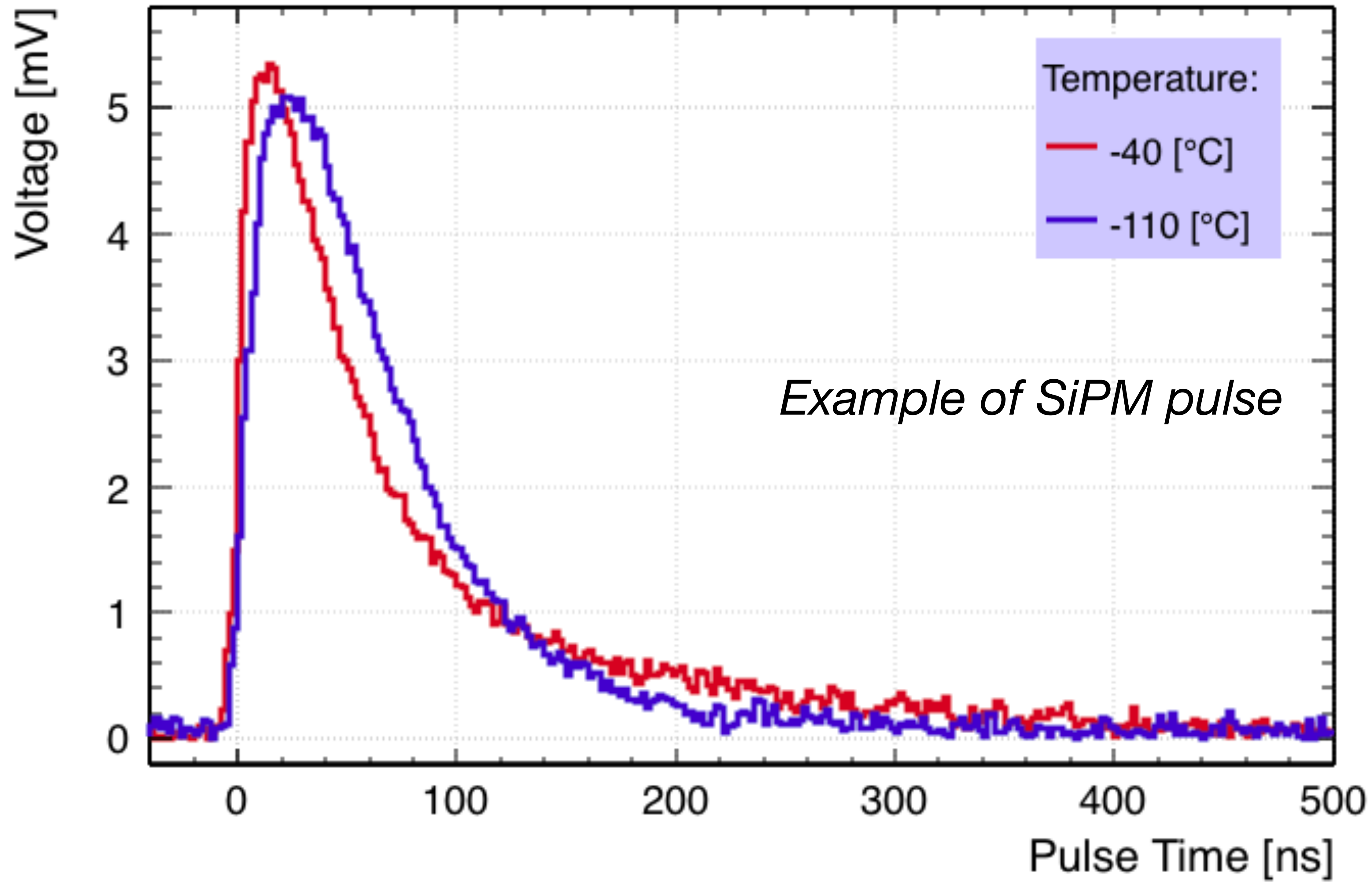
Noise Sources in SiPMs

Uncorrelated Avalanche Noise

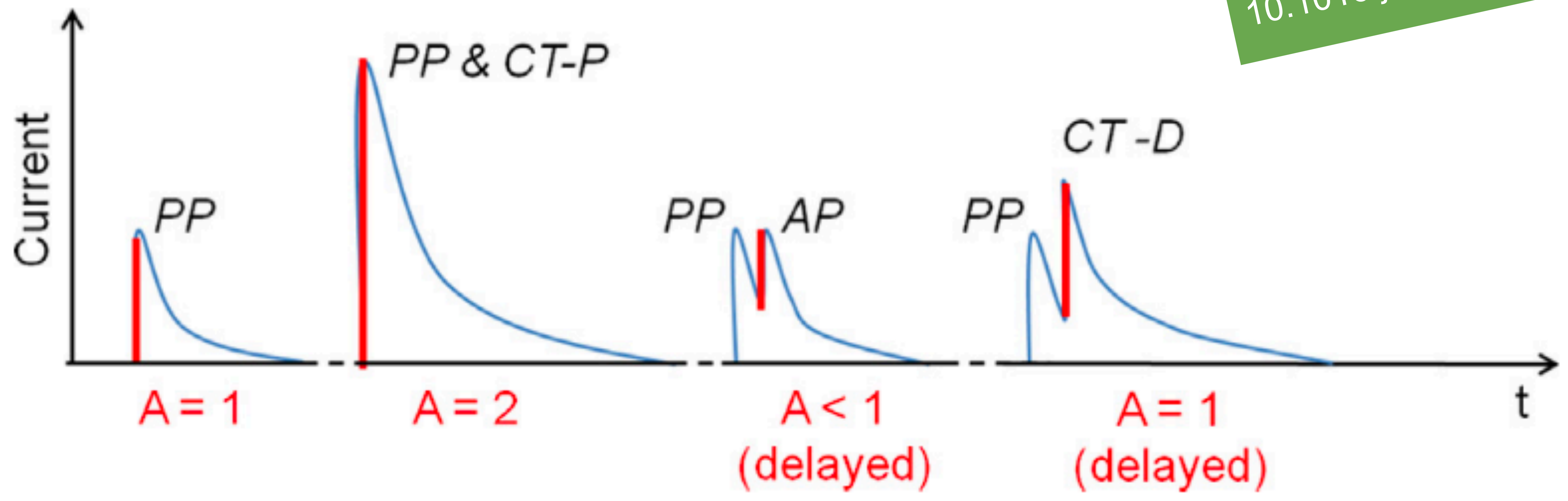
- Dark Noise (DN)

Correlated Avalanche Noise

- extra charge realised per avalanche
  - Afterpulse (AP)
  - Cross talk (CT)



10.1016/j.nima.2014.04.045



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

nEXO SiPM Requirements

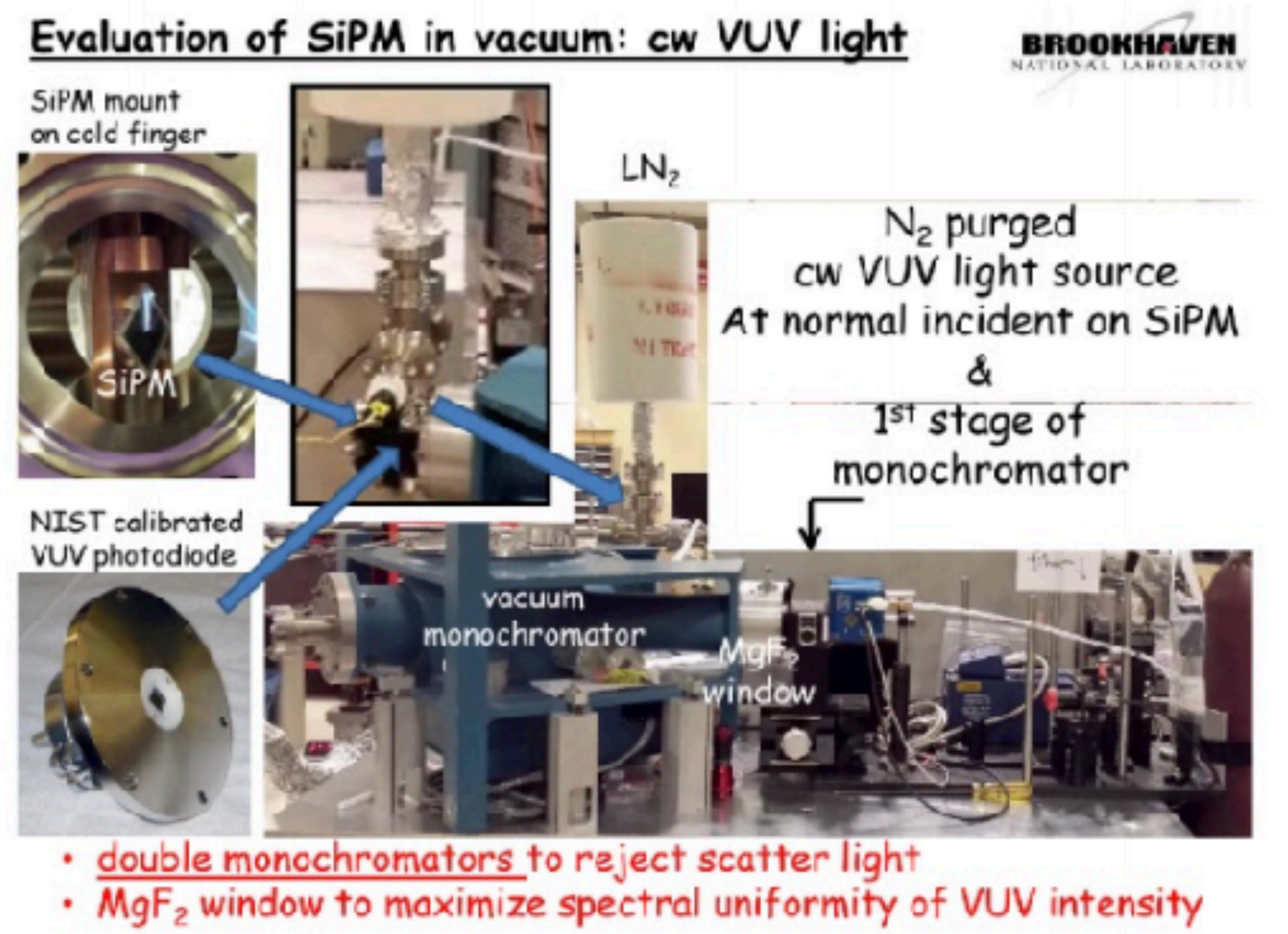
Parameters	Value
Photo-detection efficiency (PDE) at 175-178 nm in liquid Xenon (PDE)	**≥ 15%**
Radio purity: contribution of photo-detectors on the overall background	< 1%
Dark noise rate at -110 °C	**≤ 50 Hz/mm^2**
Relative Fluctuation of the mean number of Correlated Avalanches (CA) at -110°C within 1μs	**≤ 0.4**
Single photo-detector active area	≥ 1cm^2
Capacitance per area	< 50 pF/mm^2
Equivalent noise charge	< 0.1 PE r.m.s

Three SiPMs considered for nEXO: Hamamatsu VUV4 MPPC and FBK VUVHD1/VUVHD3 SiPM

nEXO Test Setups

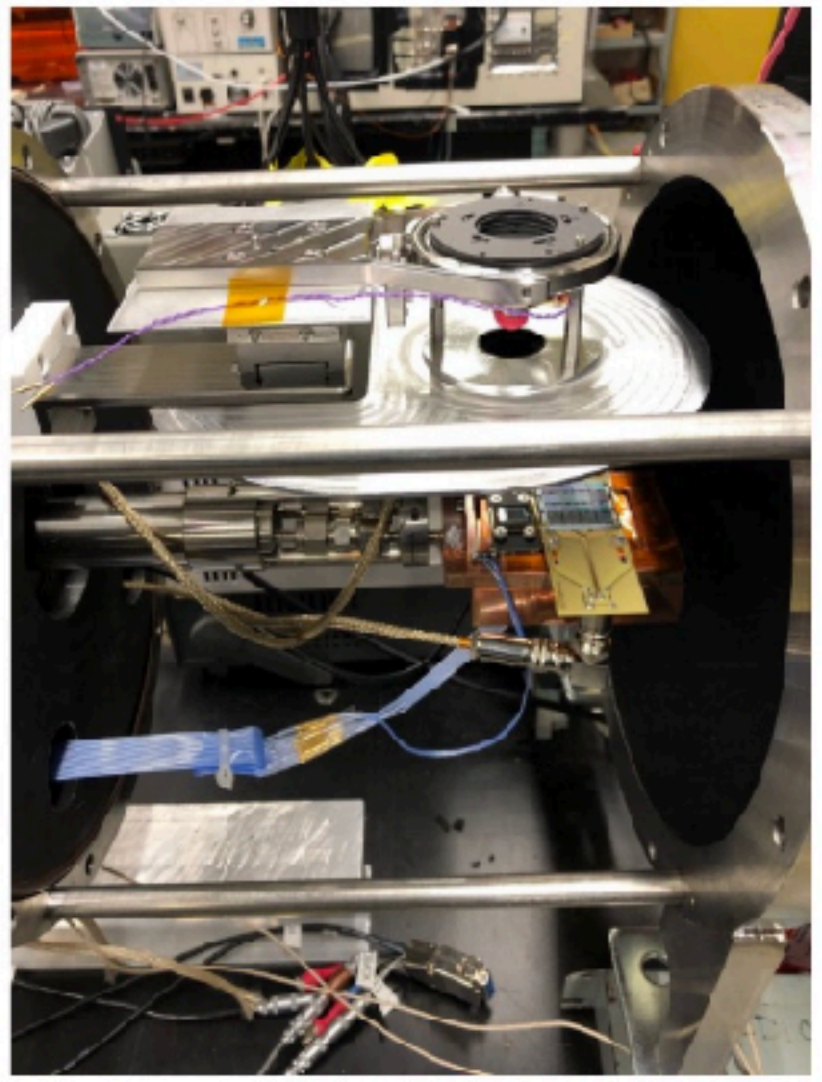
- Several setups and test facilities currently testing prototype devices:

BNL:



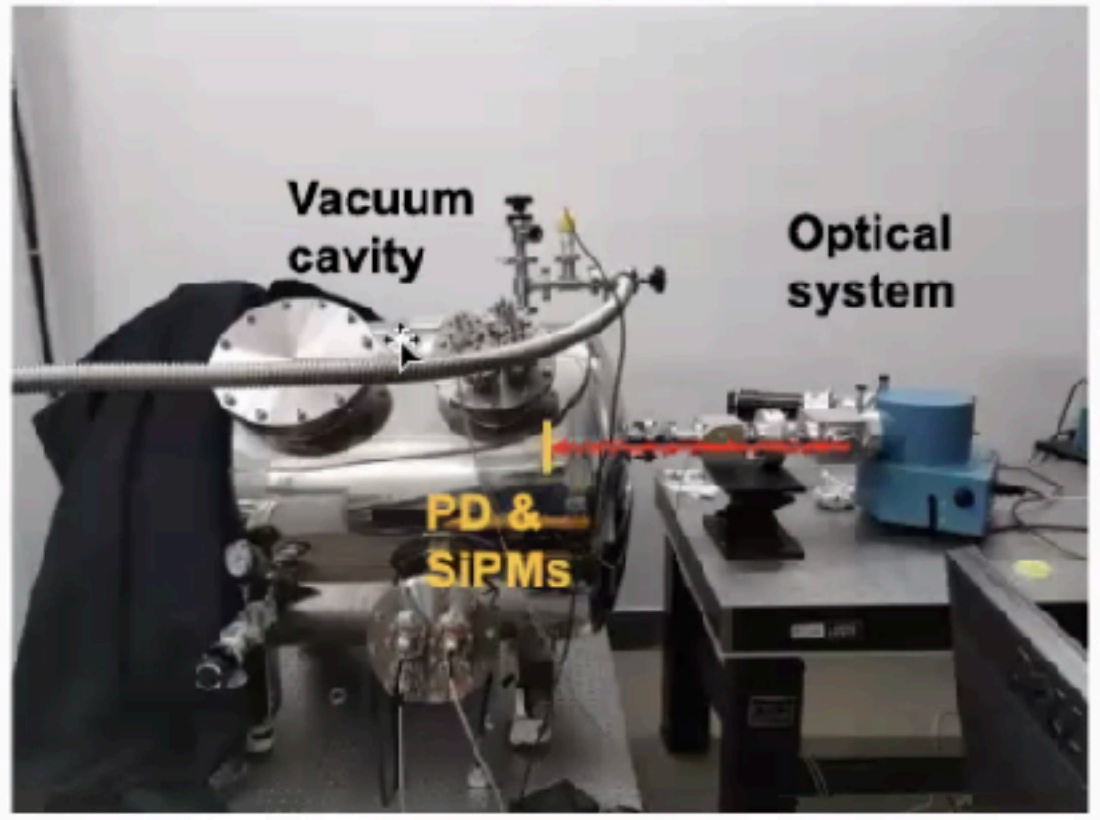
- Testing in vacuum at LXe temps
- CW VUV light source (with monochrometer)
- Upgrades to record temperature and eliminate dead time in scope acquisition

TRIUMF:



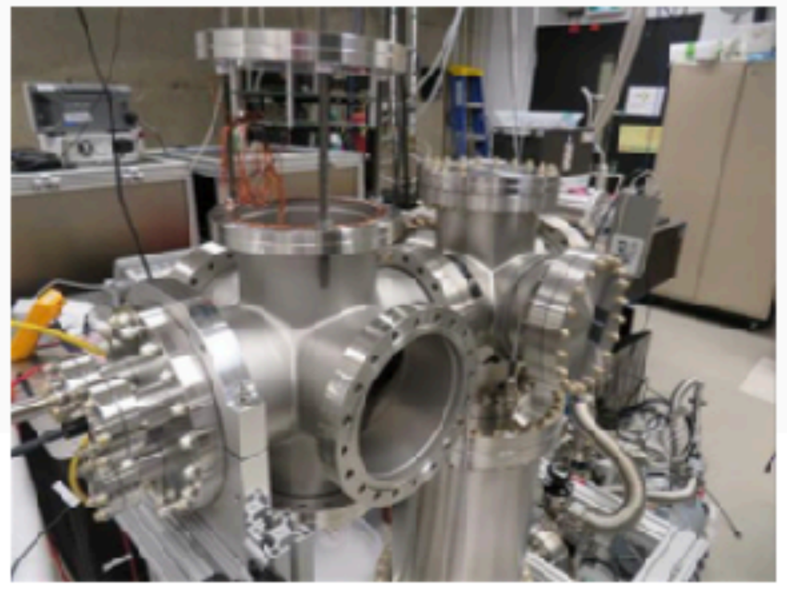
- Testing in vacuum at LXe temps
- CW VUV light source (with monochrometer)
- Improvements in pumping/baking to eliminate residual water films

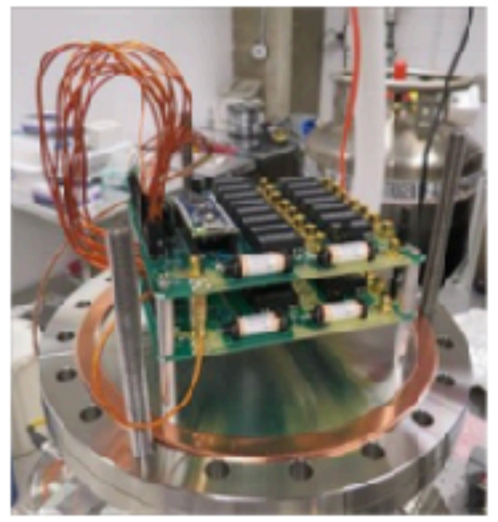
IHEP:



- Testing in vacuum at room temp to -50 C
- CW VUV light source (with monochrometer)
- Back online and measurements of new devices (HD3, VUV4) in progress

McGill:



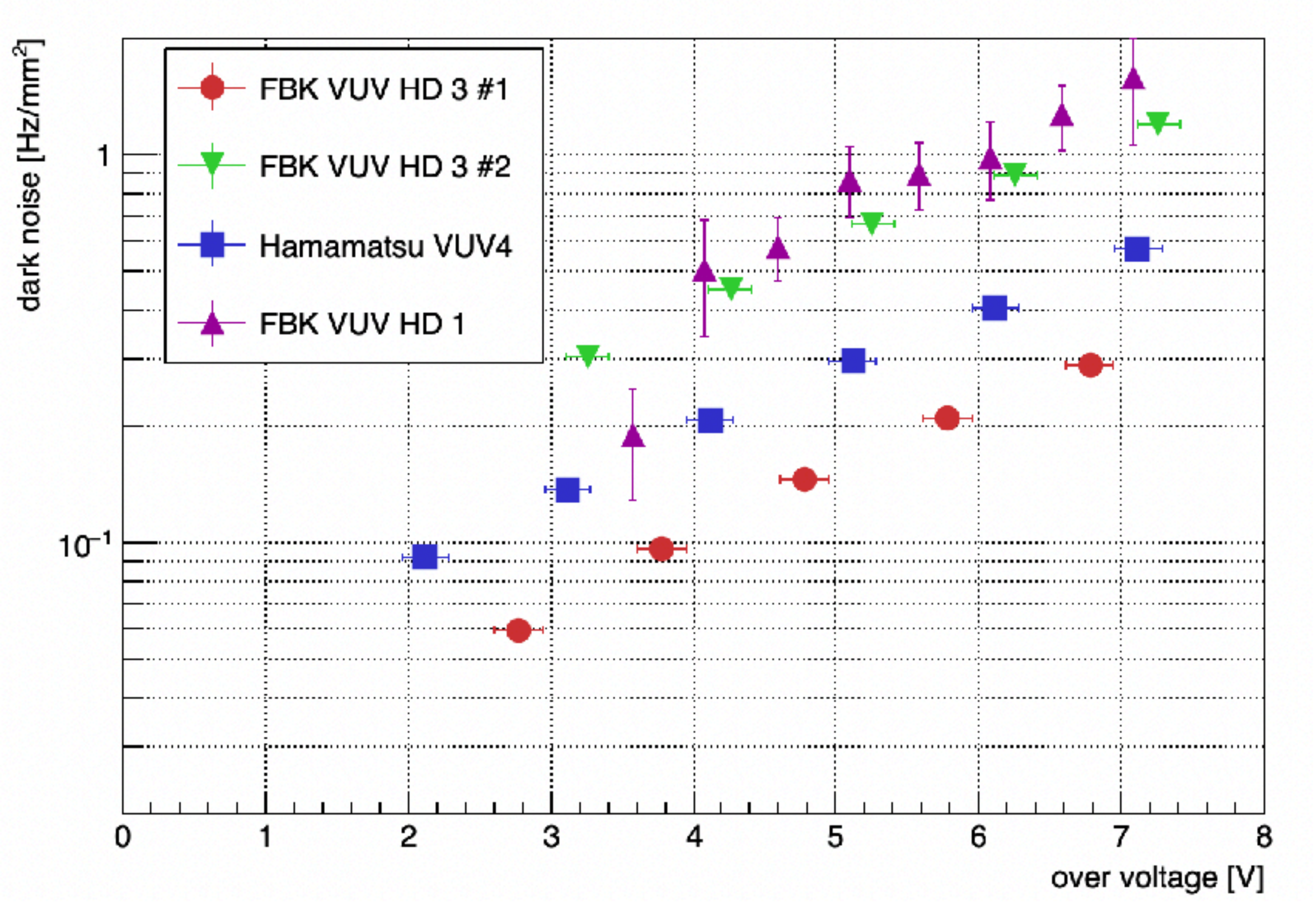


- Testing in vacuum at LXe temp
- Several different light sources, including scanning laser
- Multiplexer able to acquire IV curves for many devices

+ UMass, Stanford, UofA setups used for previous measurements

Dark Noise Rate at 163 [K]

Extrapolated from time distribution between pulses



<u>nEXO Requirement is outside this plot</u>

nEXO Requirement: DN < 50 Hz/mm^2

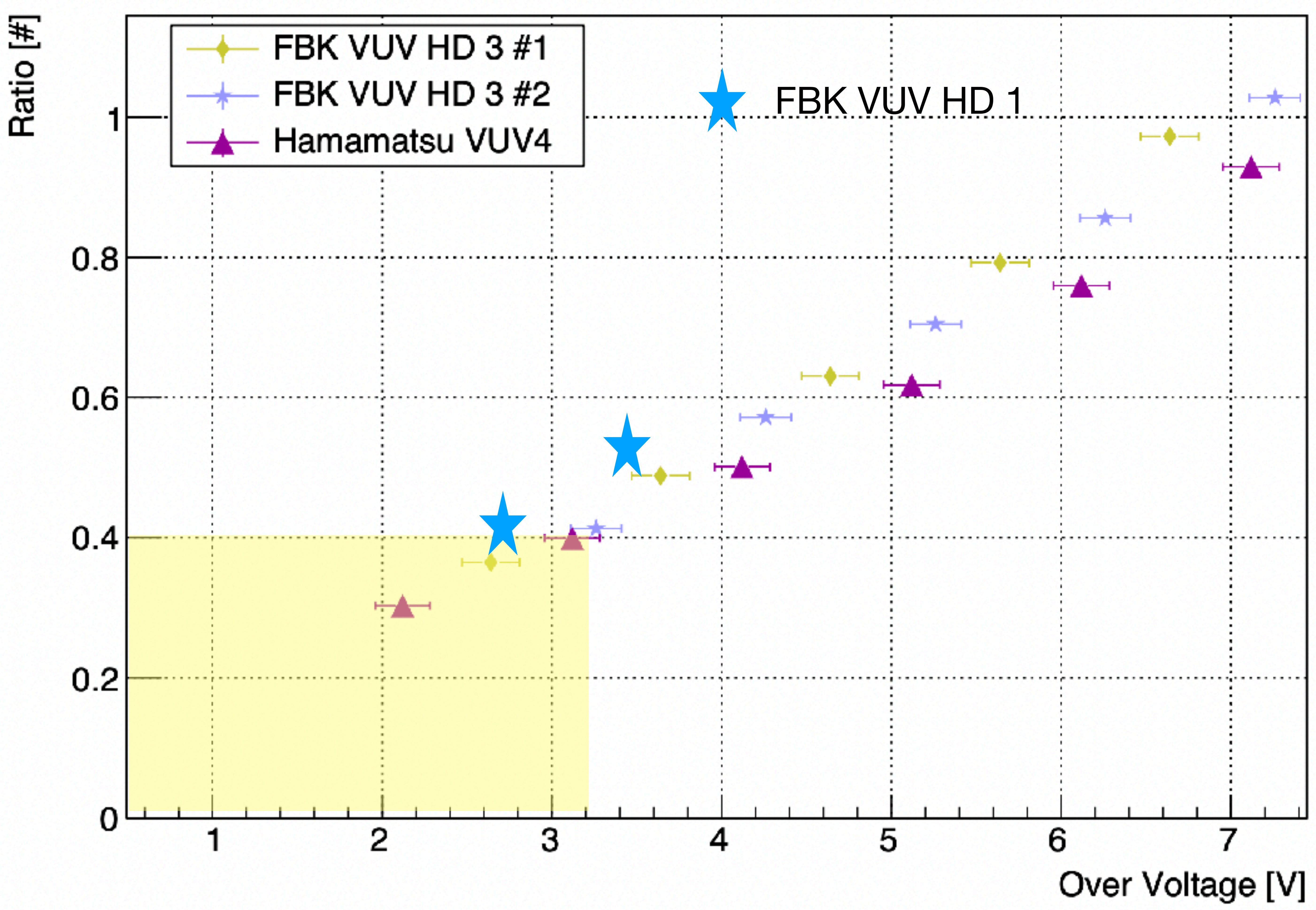
All the devices tested have a Dark Noise Rate that is well below the nEXO spec. at 163 [K]

Correlated Avalanche Noise (CA) in 1 us at 163 [K]

Mean Number of CA: $\langle\Lambda\rangle$ + STD Number of CA: σ_Λ →

nEXO Requirement: Ratio < 0.4

with Ratio $\equiv \dfrac{\sigma_\Lambda}{1+\langle\Lambda\rangle}$

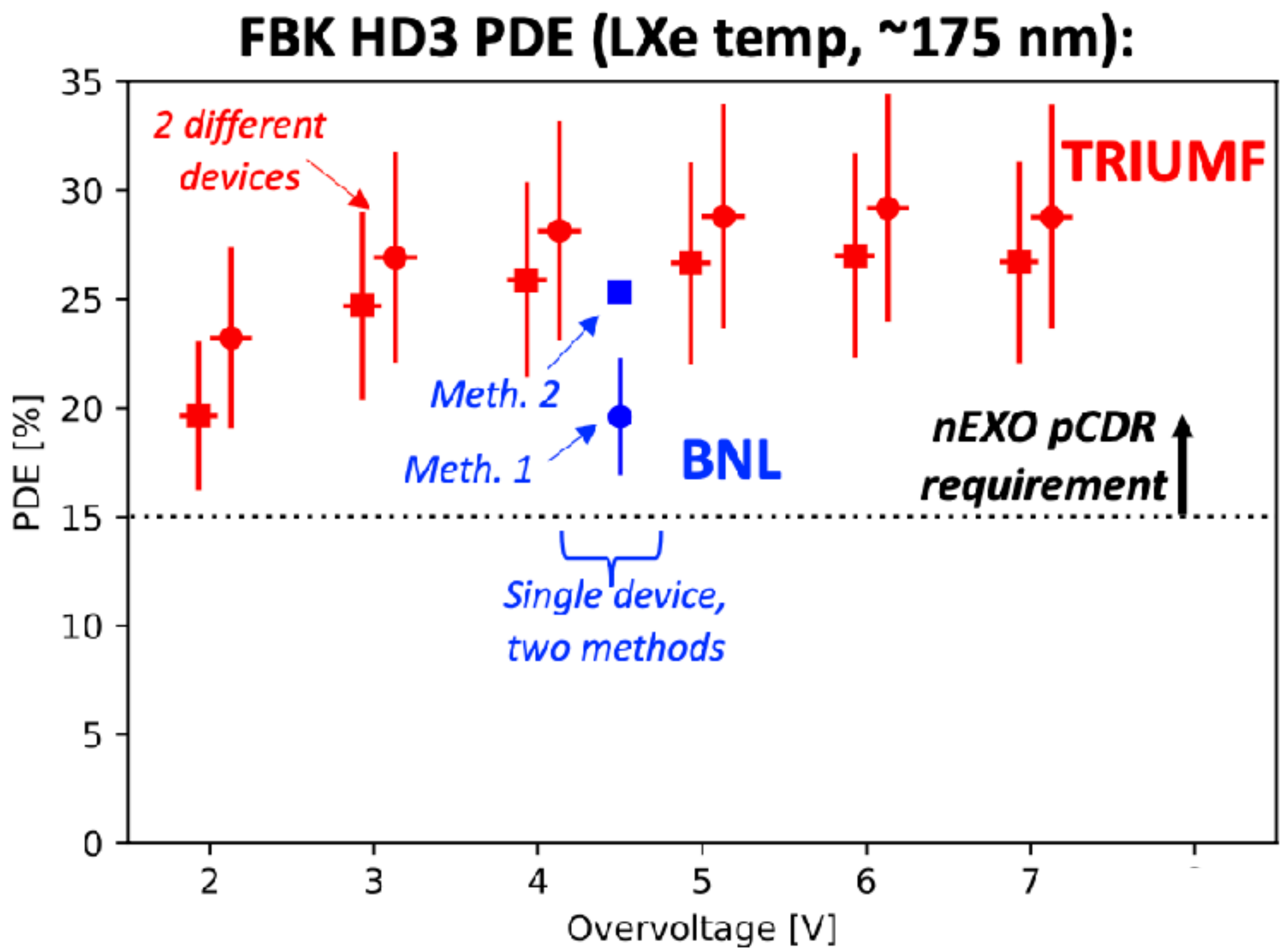


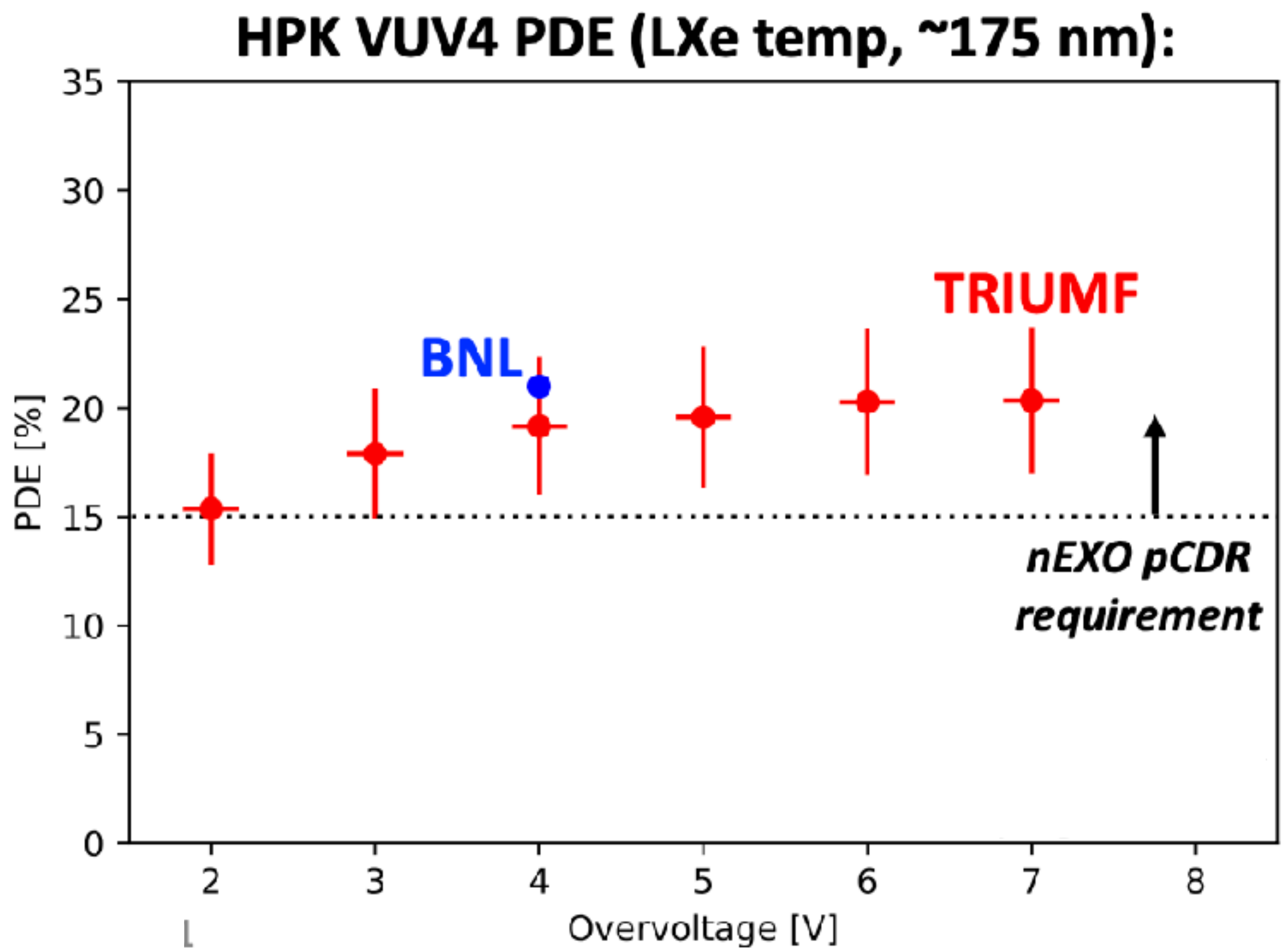
Great Improvement of new FBK devices if compared with previous generation

- VUV4 can be operated up to 3.5 V.
- FBK VUV HD 1 can be operated up to 2.5 V.
- FBK HD 3 has 1 OV improvement compared to previous generation.

FBK VUV HD 3 has triple-doping technology to suppress After Pulse.

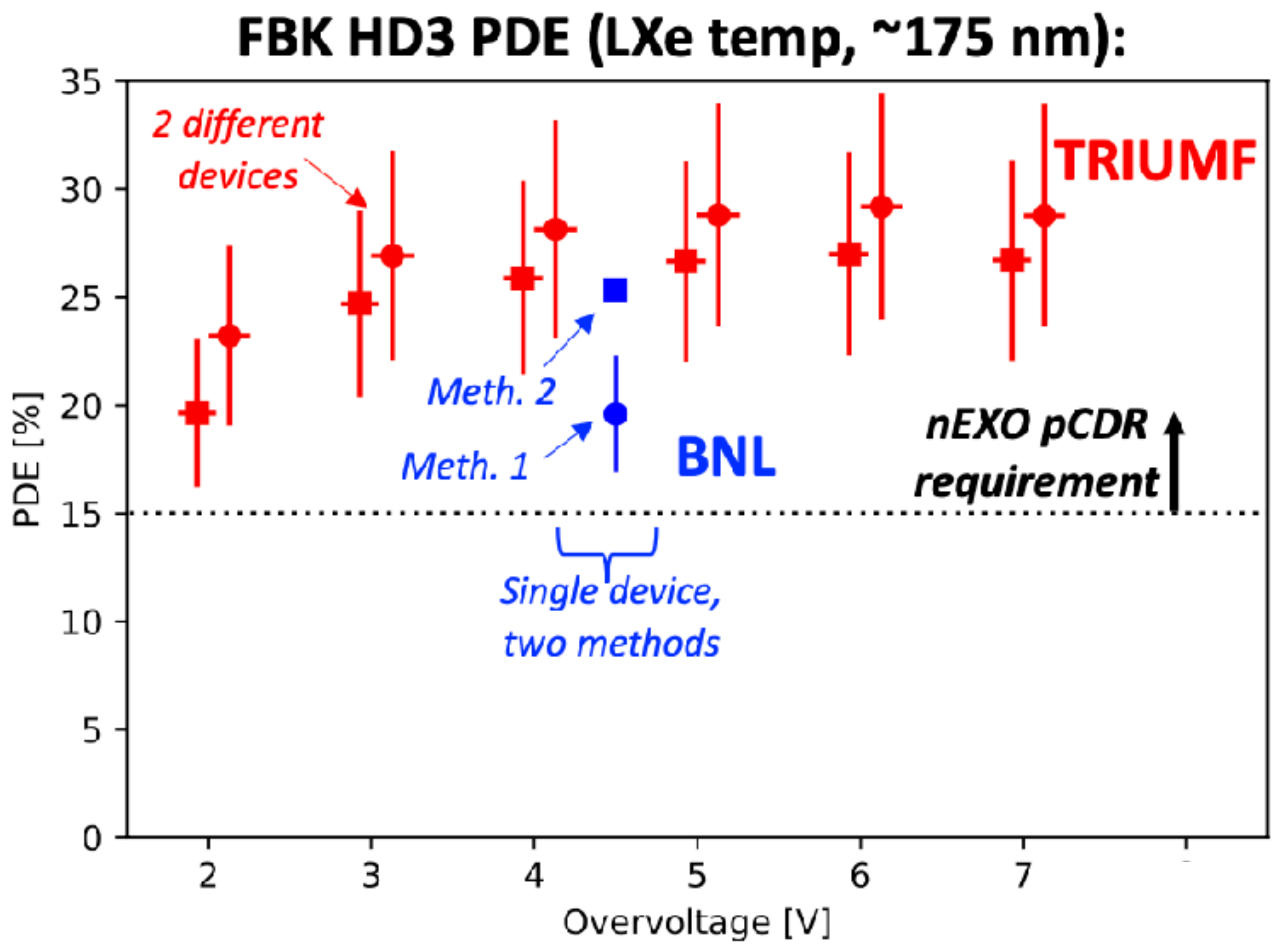
Photon detection efficiency (PDE)

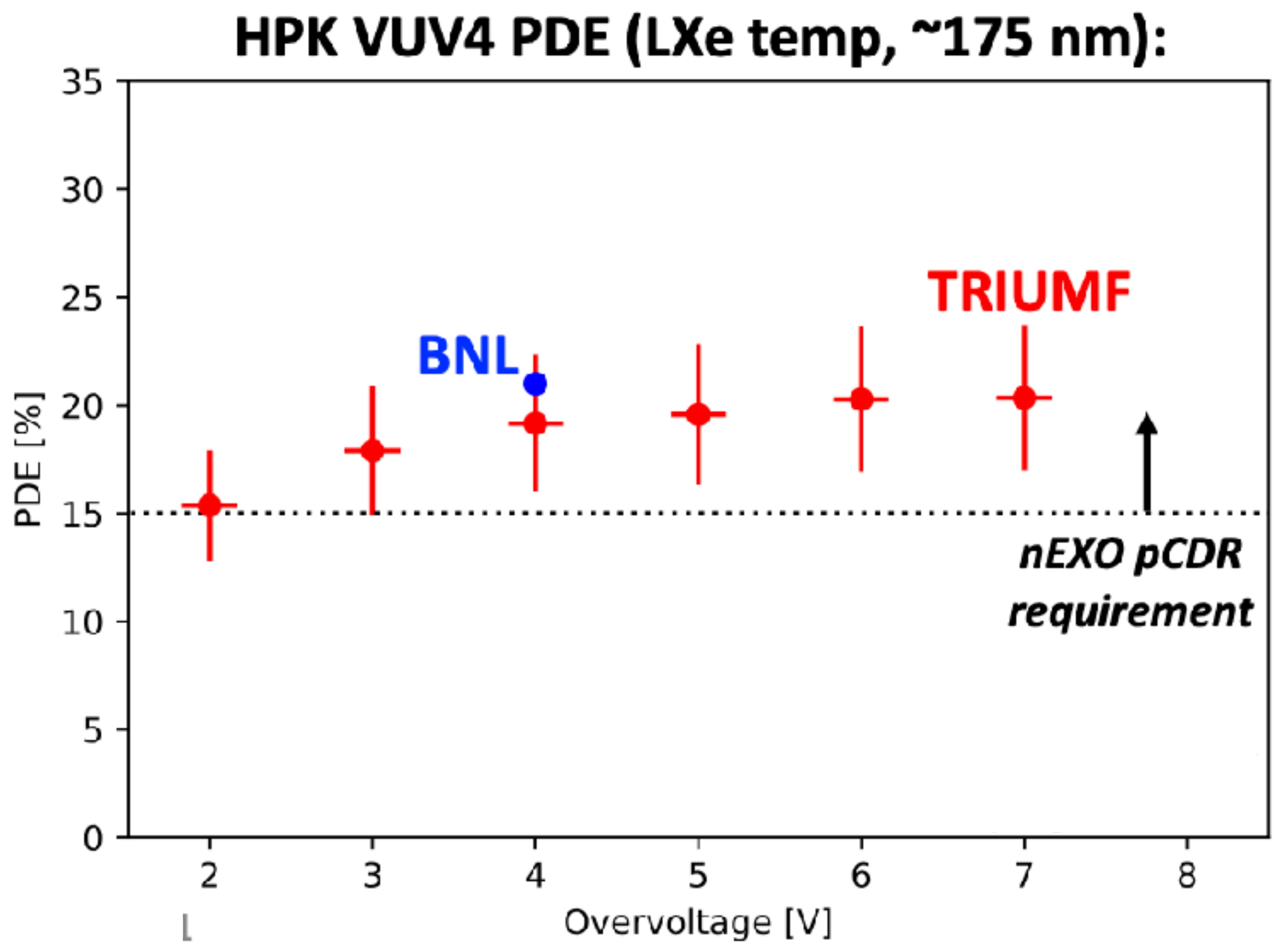




- PDE is within nEXO Spec.
- Hamamatsu VUV4 SiPM seems showing a correlation between VUV exposure and PDE loss even for extremely small light fluxes (e.g. MEG 2).
- This last aspect is under investigation.

Photon detection efficiency (PDE)





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Why these measurements are important ?

nEXO Energy Resolution

n = number of quanta produced by the original $0\nu\beta\beta$ energy deposition

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

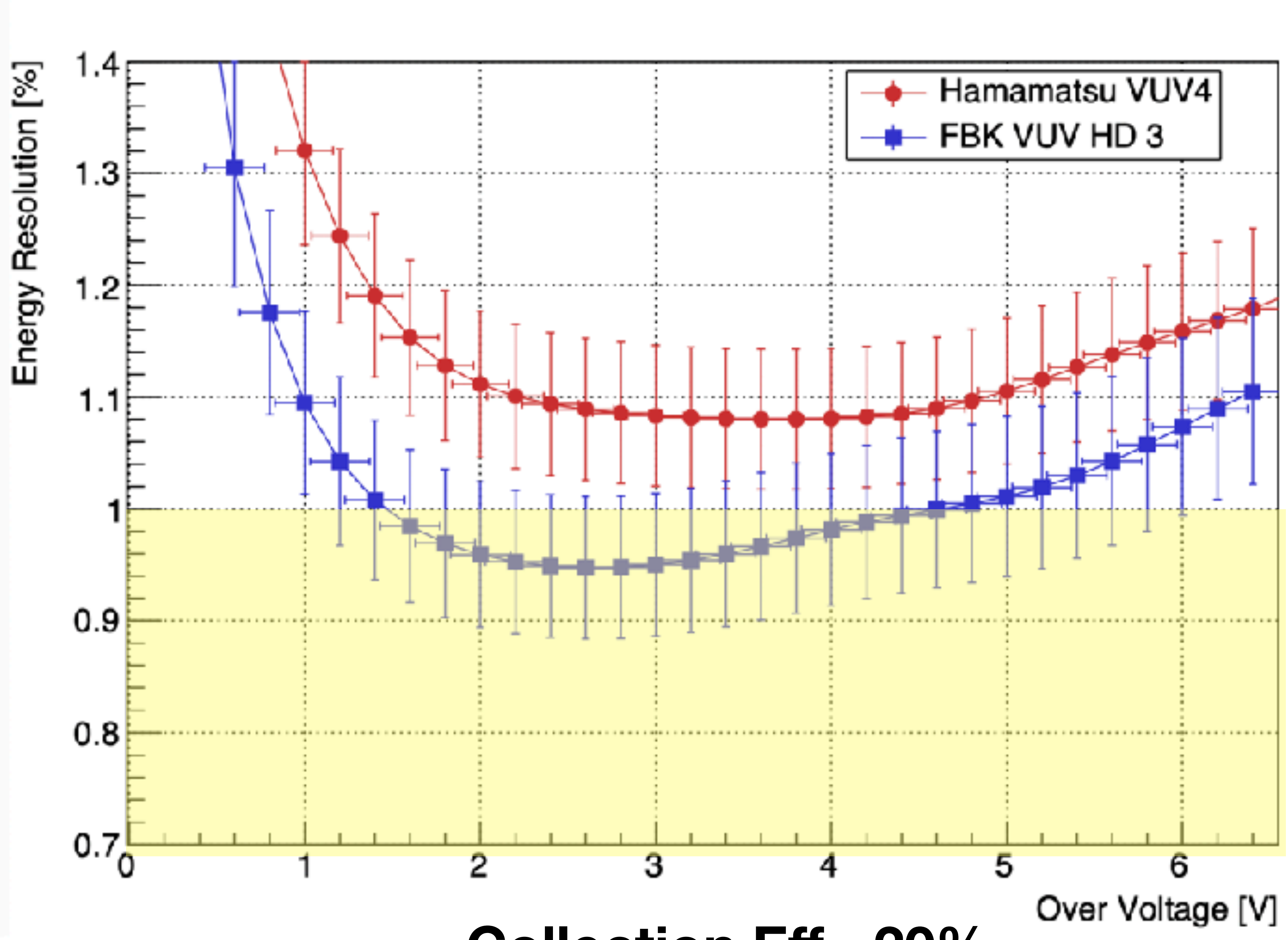
$$\frac{\sigma_n}{\langle n\rangle} = \frac{\sqrt{\left(\frac{(1-\varepsilon_p)n_p}{\varepsilon_p} + \frac{\varepsilon_p n_p \sigma_\Lambda^2}{(\varepsilon_p(1+\langle\Lambda\rangle))^2}\right) + \left(\frac{(1-\varepsilon_q)n_q}{\varepsilon_q} + \frac{\sigma_{q,noise}^2}{\varepsilon_q^2}\right)}}{\langle n\rangle}$$

Fluctuation due to number of photons detected

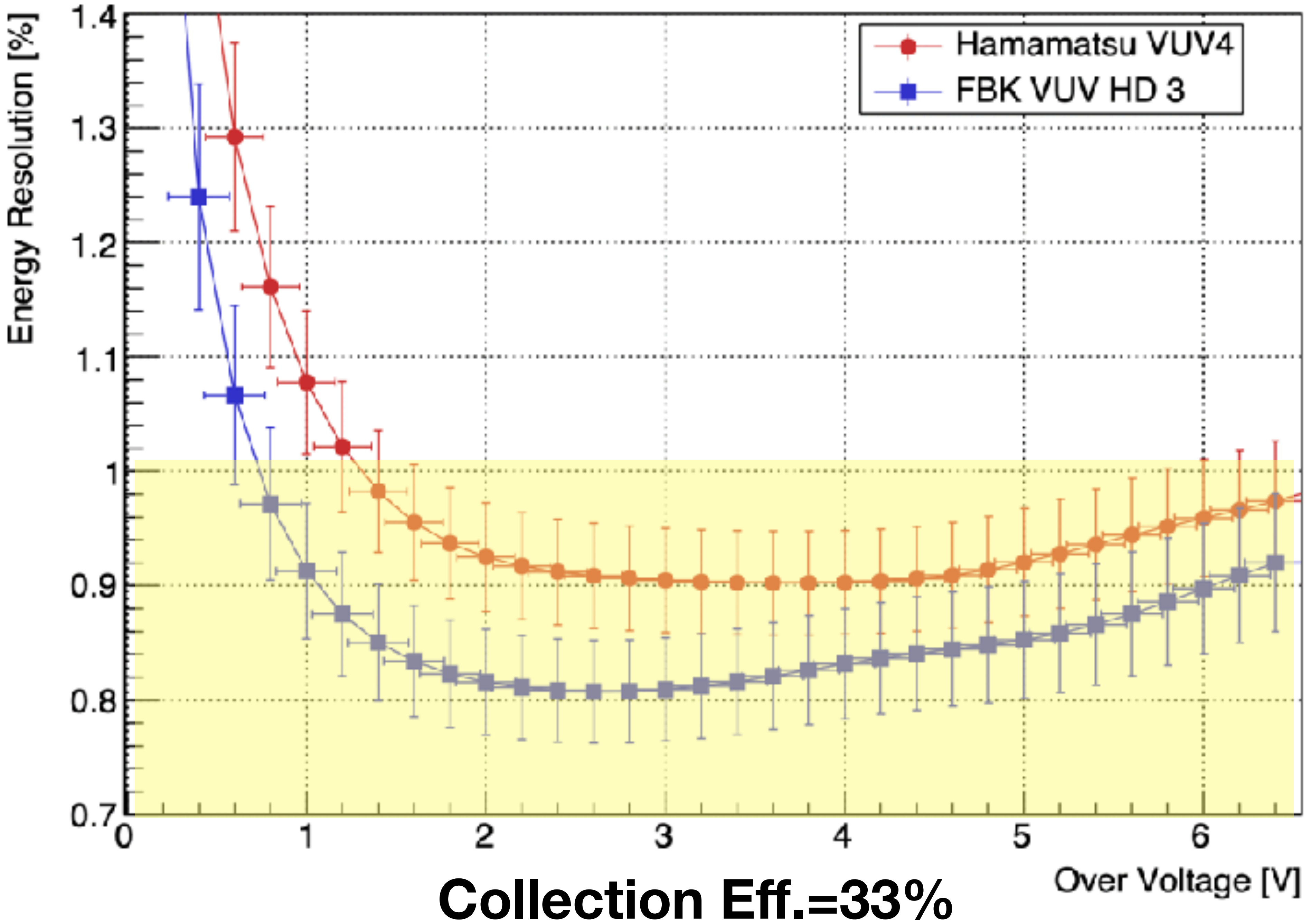
Fluctuation Due to Correlate Avalanche Noise

Fluctuation due to number of charges detected

Fluctuation due to electronics in charge channel



Collection Eff.=20%



Collection Eff.=33%

Summary

Summary

Requirement:	Hamamatsu VUV4		FBK HD3	
	BNL	TRIUMF	BNL	TRIUMF
PDE (>15%):	21%	$19 \pm 3\%$	20%	$27 \pm 5\%$
CA (<0.2* at >3V OV):	0.15@3V		0. 42@4V	0.17@3V
Dark counts (<50 Hz/mm²):	0.8 Hz/mm²@4V	0.2 Hz/mm²@4V		0.2 Hz/mm²@4V

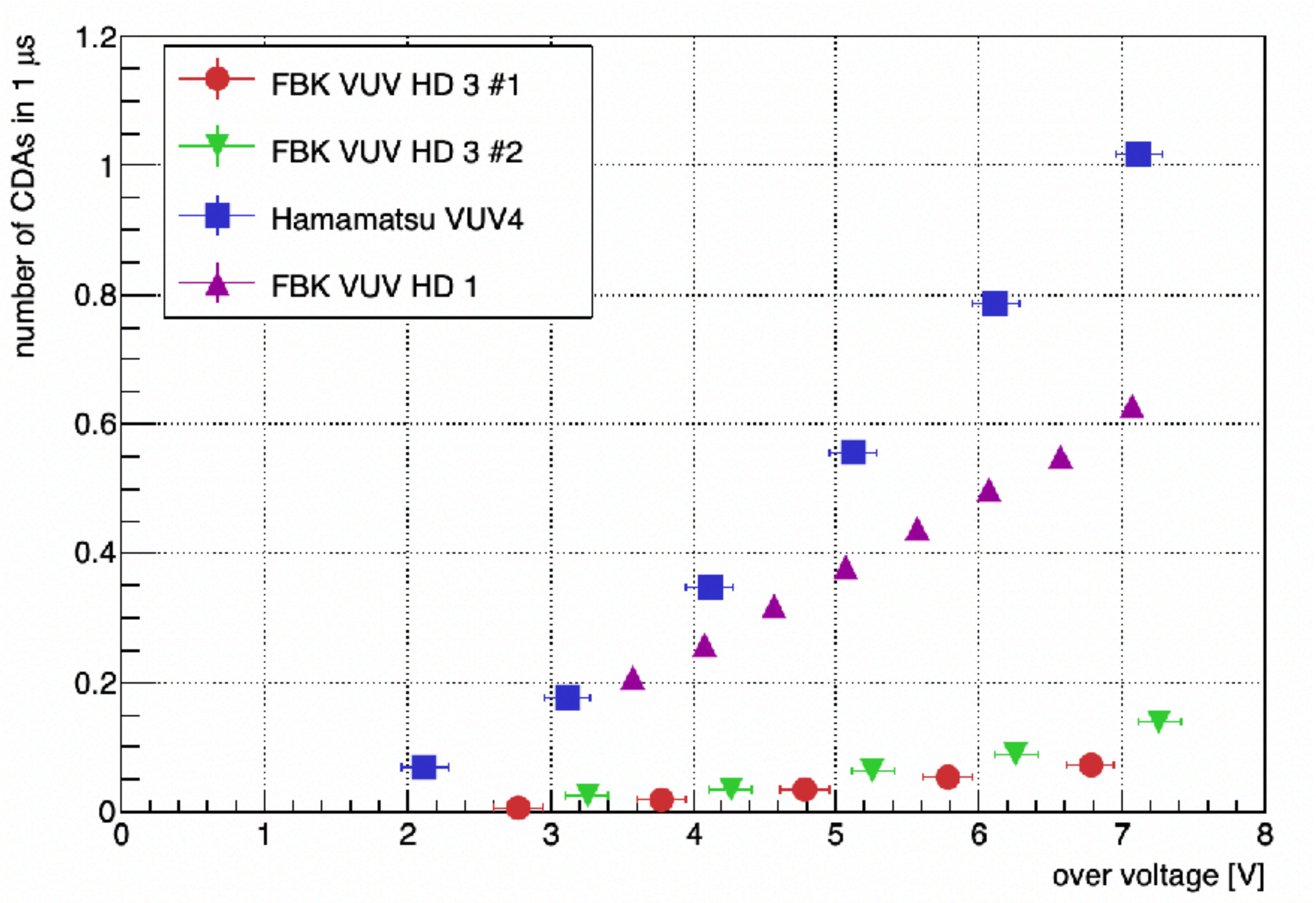
Next steps :

- Understand CA in detail, publish paper with consistent results from all groups showing devices meeting specs (target summer 2021)
- Test upcoming prototypes (HPK and FBK 1cm^2 devices, eventually with TSVs)
- Understand device uniformity and performance over time, including in LXe

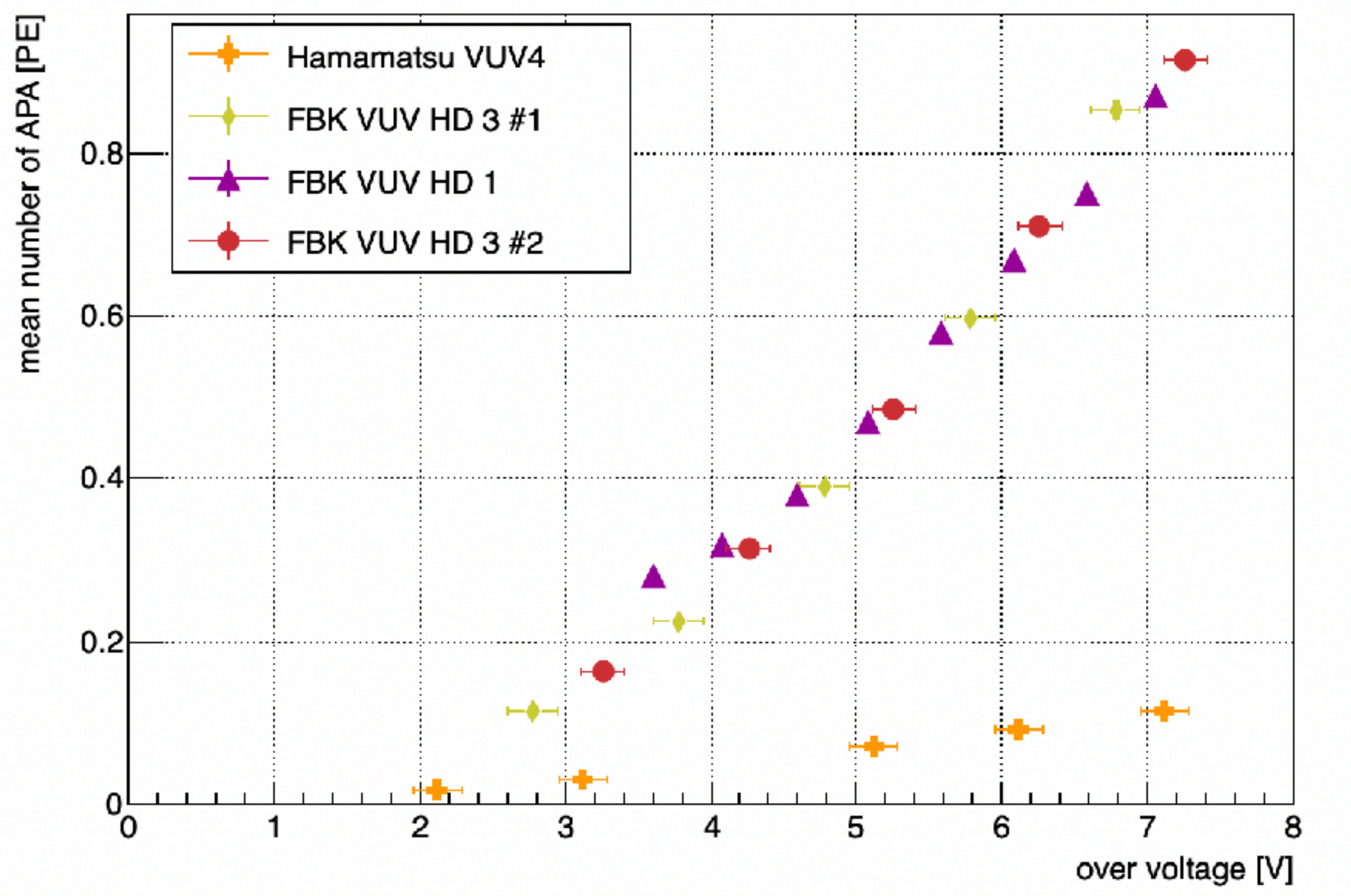
Backup

Correlated Delayed Avalanche Noise and Additional Prompt Avalanches 163 [K]

Triple Doping technology suppresses After Pulse

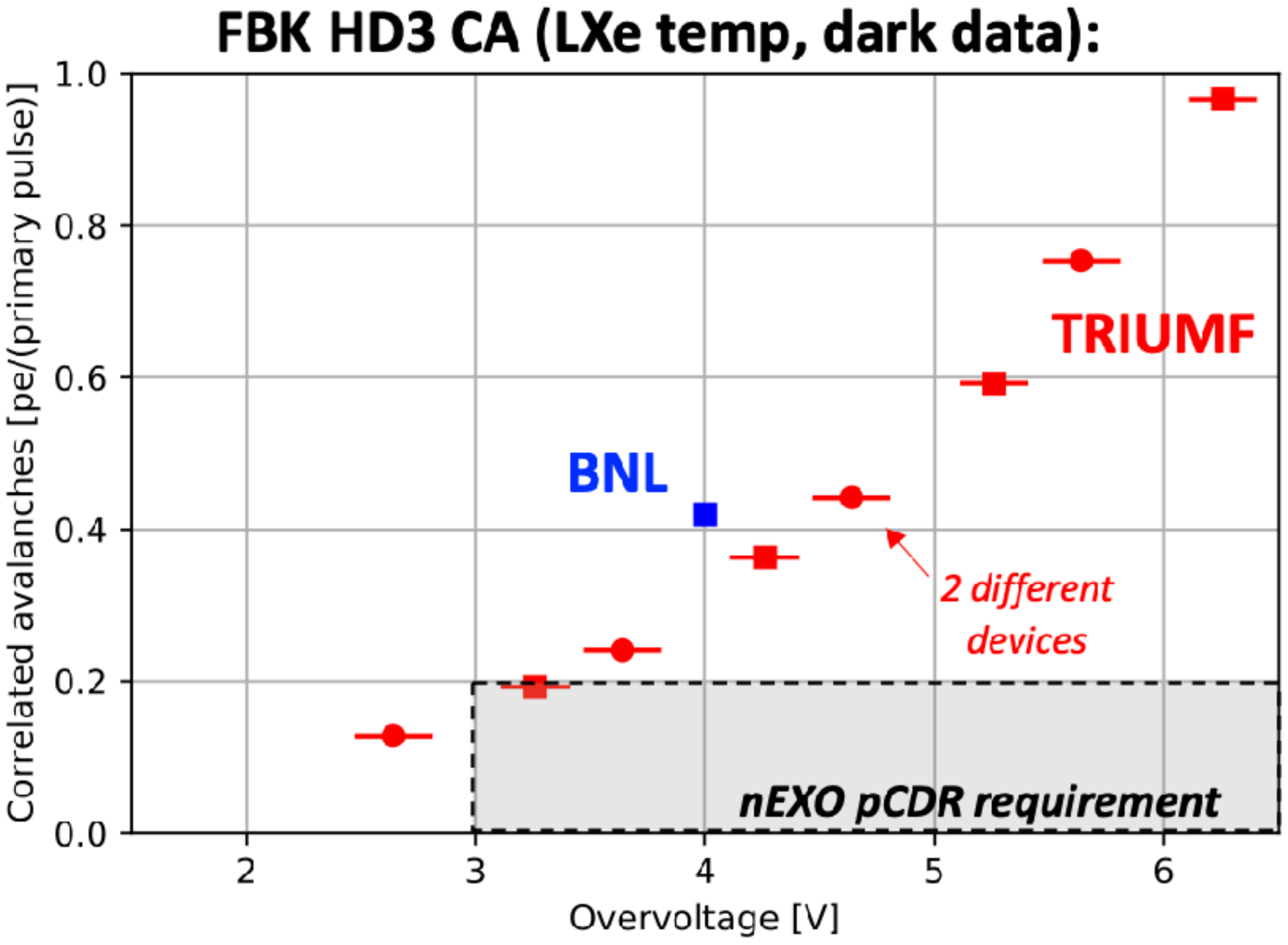


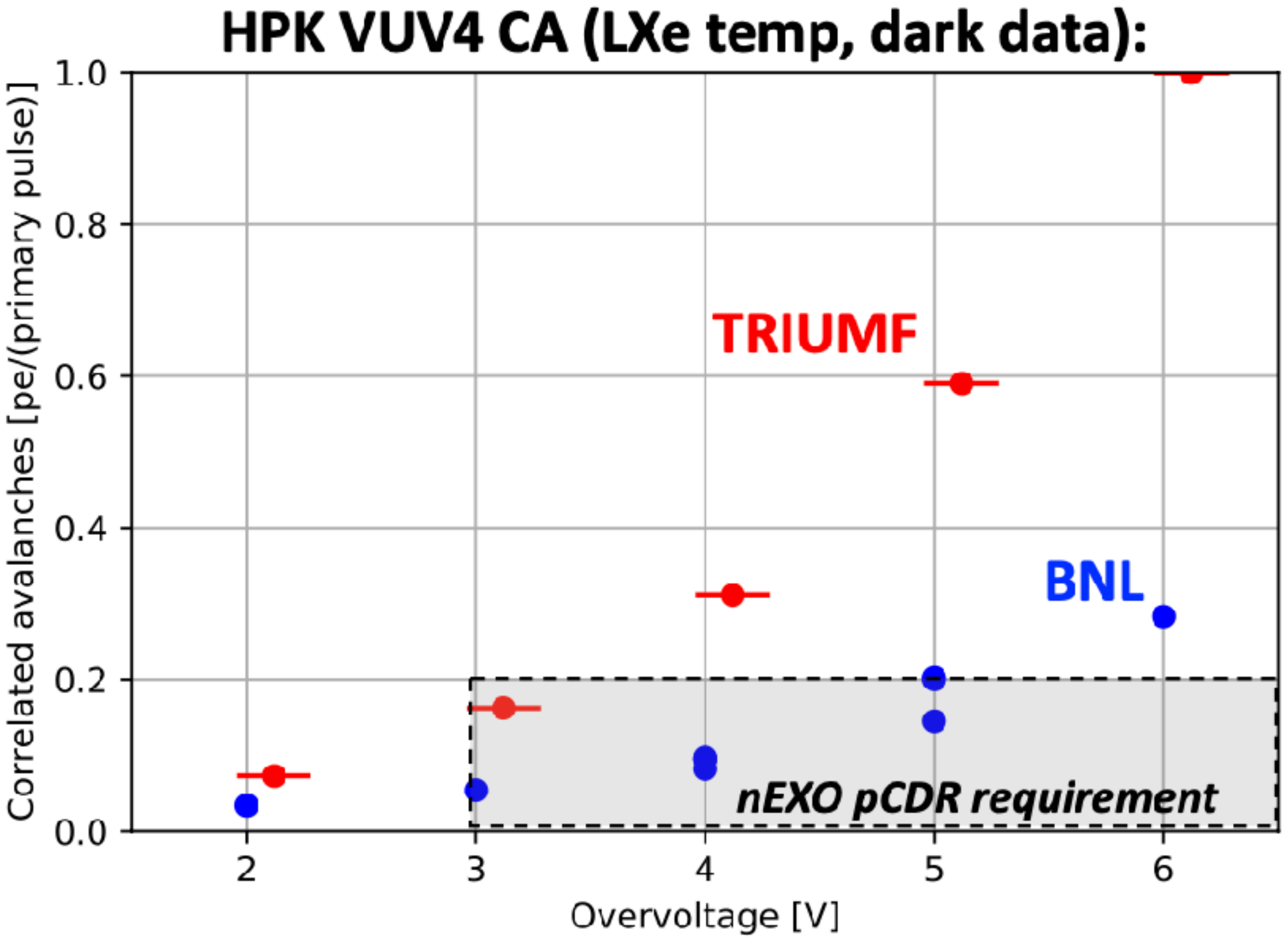
CDA= Correlate Delayed Avalanches i.e. *Afterpulse*
After Pulse is strongly suppressed



APA=Additional Prompt Avalanches i.e. *Direct Crosstalk*
Cross Talk is the same of the previous generation

Correlated Avalanche Noise (CA) in 1 us at 163 [K]





Some disagreement between BNL and TRIUMF measurements of CA (HD3 higher, VUV4 lower)

- Device to device variations? Measurement techniques?