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

Stimulated Secondary Emission of Single Photon Avalanche Diodes

G. Gallina

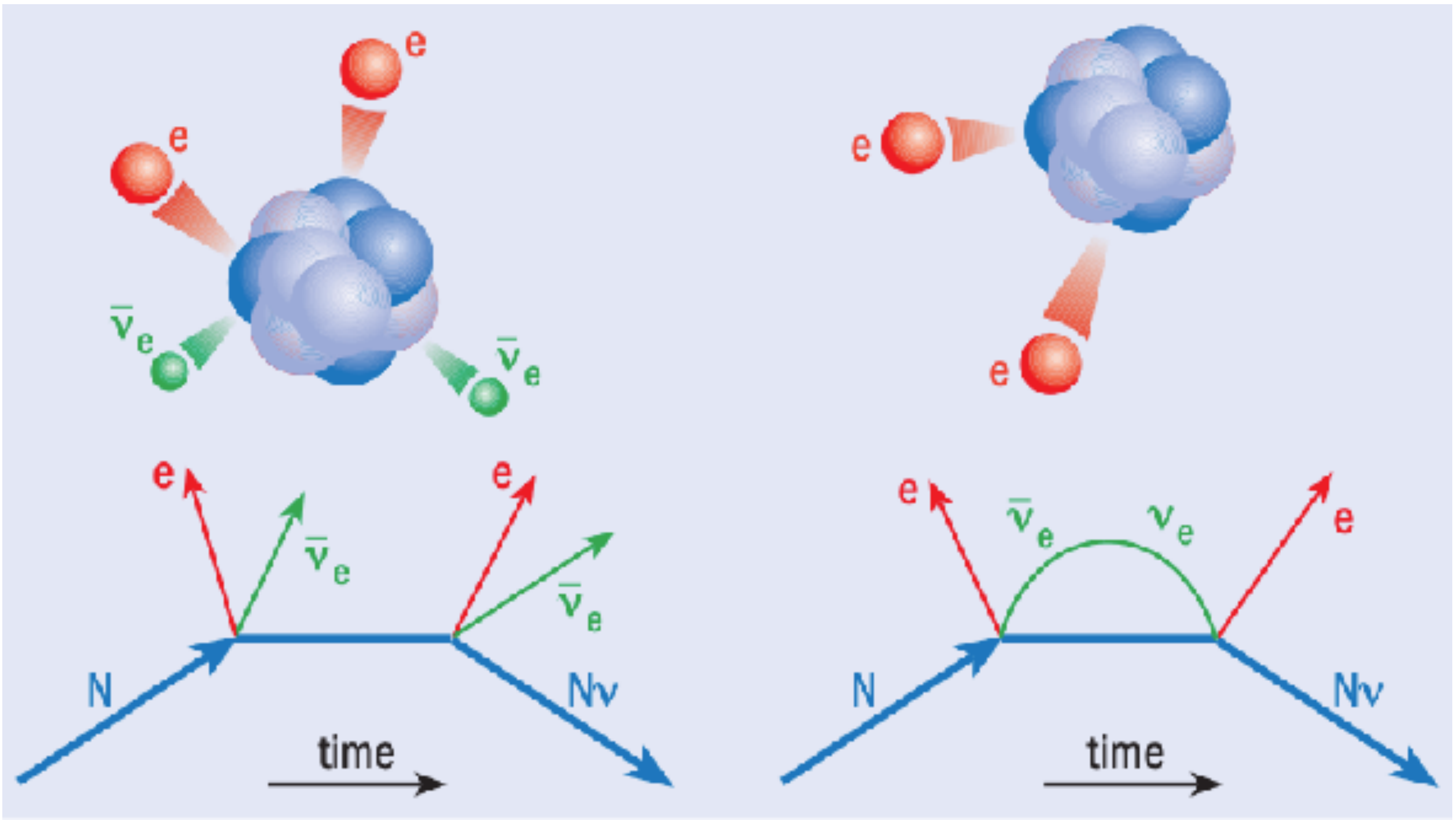
for the nEXO collaboration

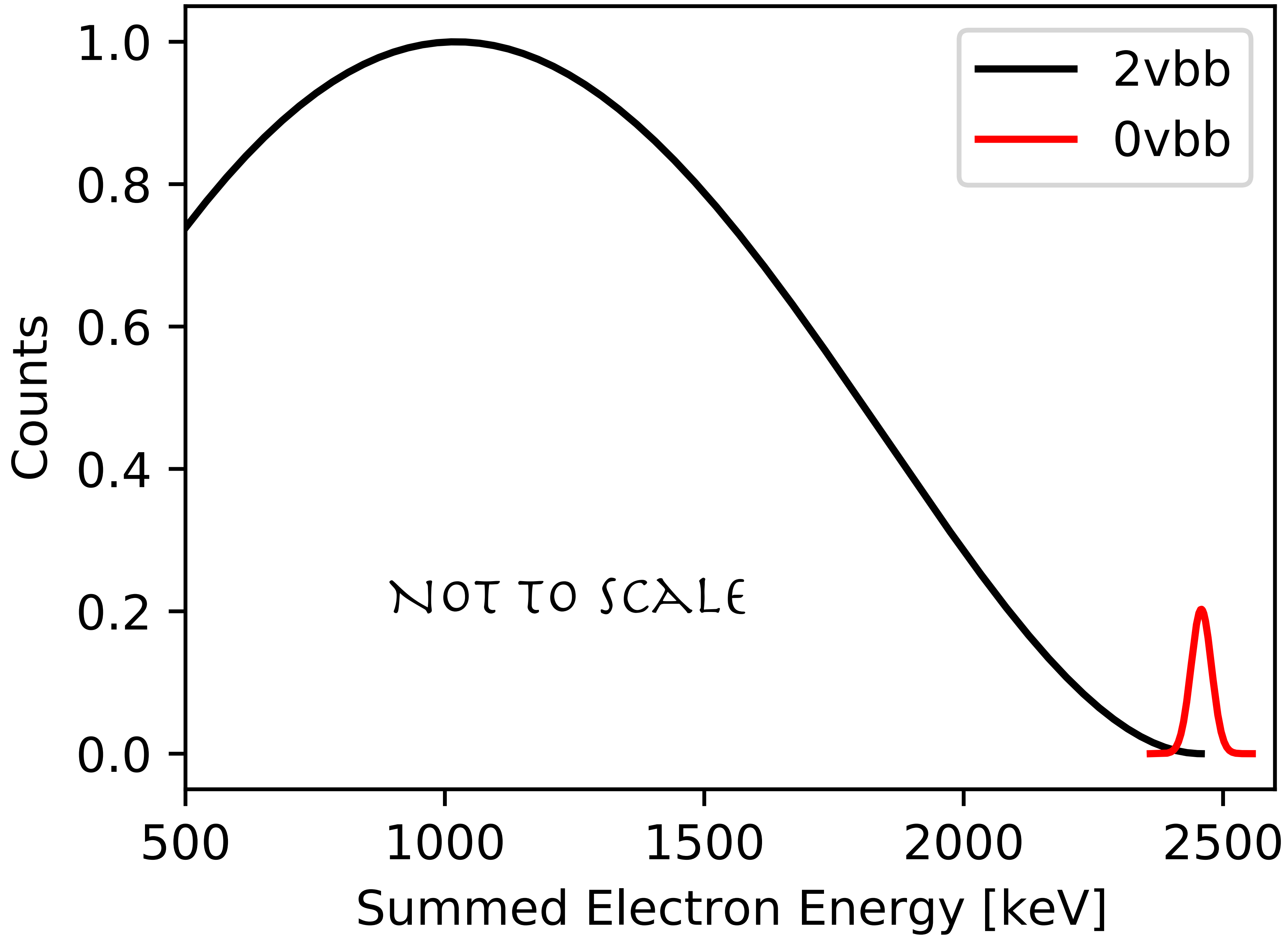
Discovery, accelerated

Overview

Motivation for ^{136}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}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

Technical University of Munich TUM

Universität Bern

Rensselaer

The University of British Columbia

TRIUMF

Pacific Northwest National Laboratory

Skyline College

Lawrence Livermore National Laboratory

SLAC National Accelerator Laboratory

Stanford University

Caltech

UC San Diego

The University of California Irvine

Colorado School of Mines

Colorado State University

The University of Alabama 1831

Oak Ridge National Laboratory

University of Kentucky

University of the Western Cape

Institute for Basic Science

IHEP

IMECAS

Subatech

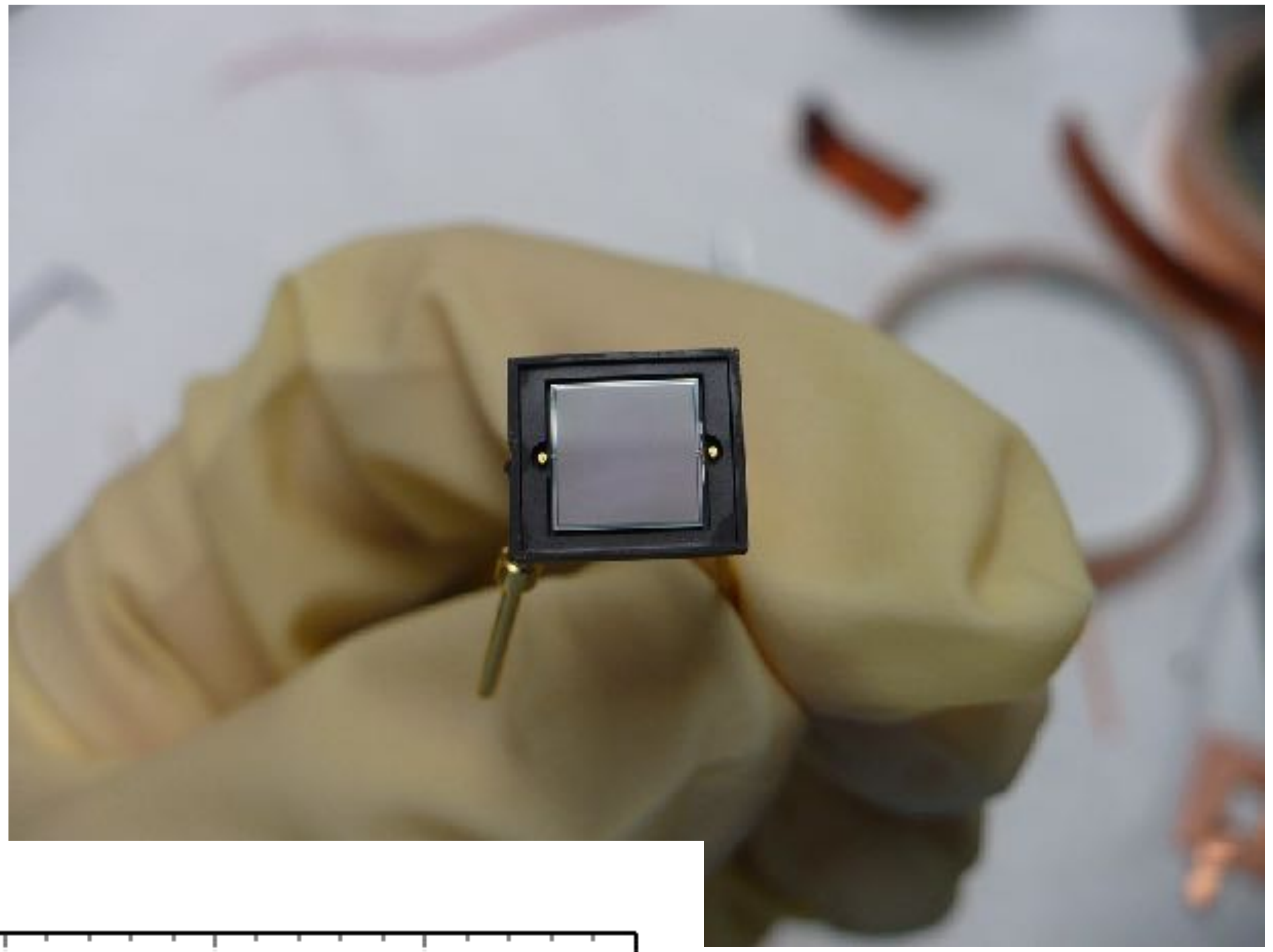
Drexel University

UNCW University of North Carolina Wilmington

SiPM technology in nEXO

NIM A 940 (2019)

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

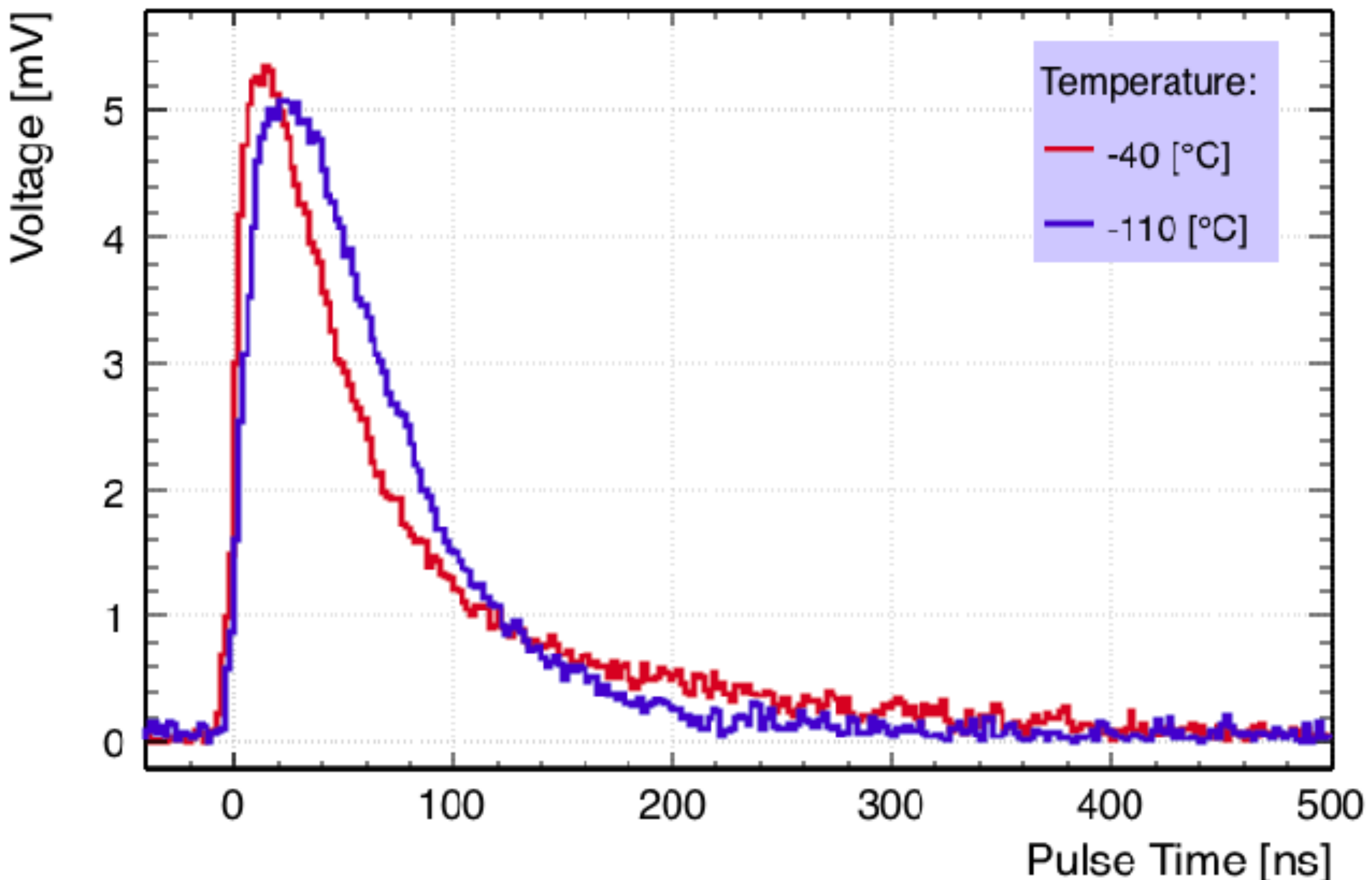


Main Characteristics :

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

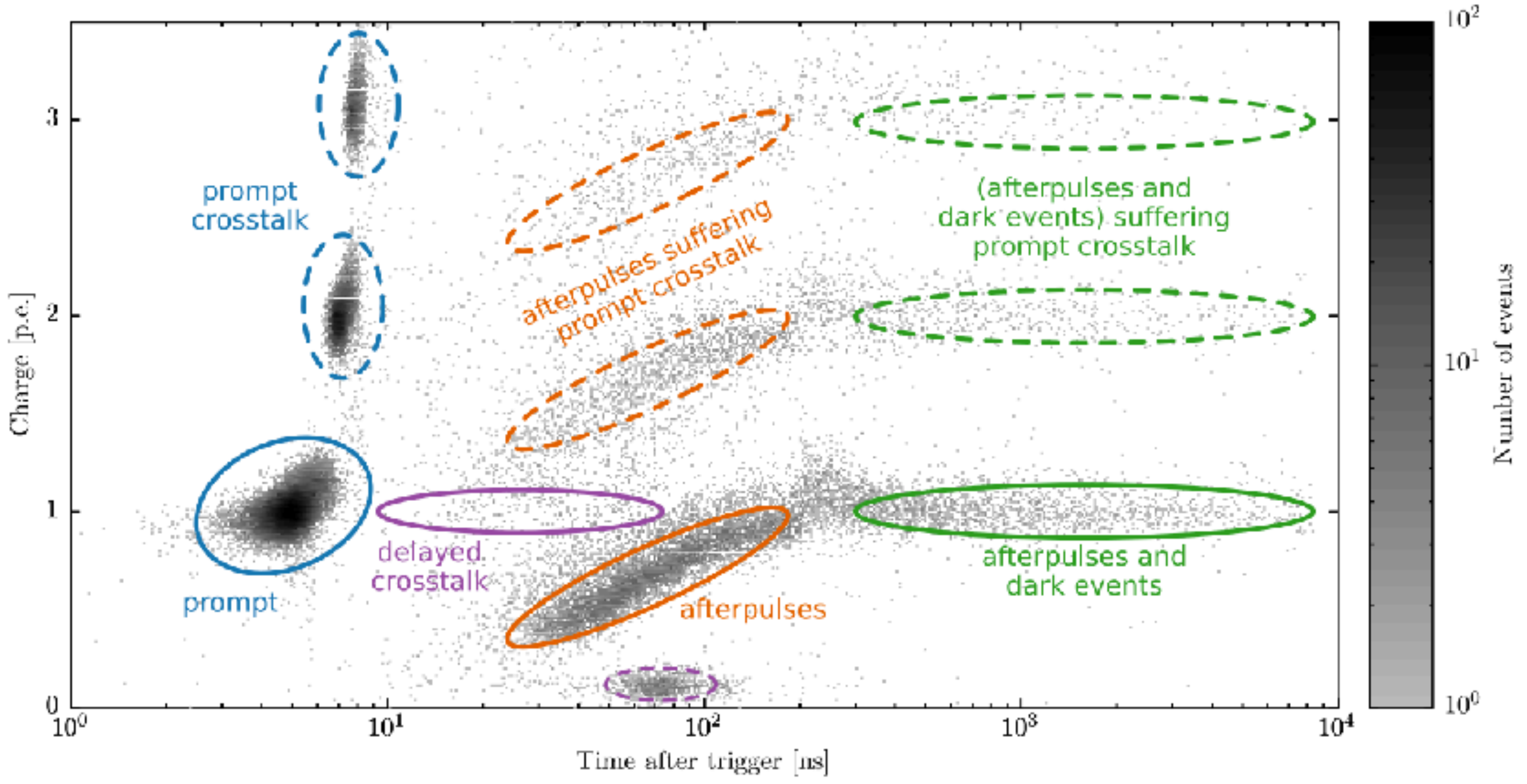
Advantages:

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



Noise Sources in SiPMs

IEEE Trans.Nucl.Sci. 65 (2018)



Uncorrelated Avalanche Noise

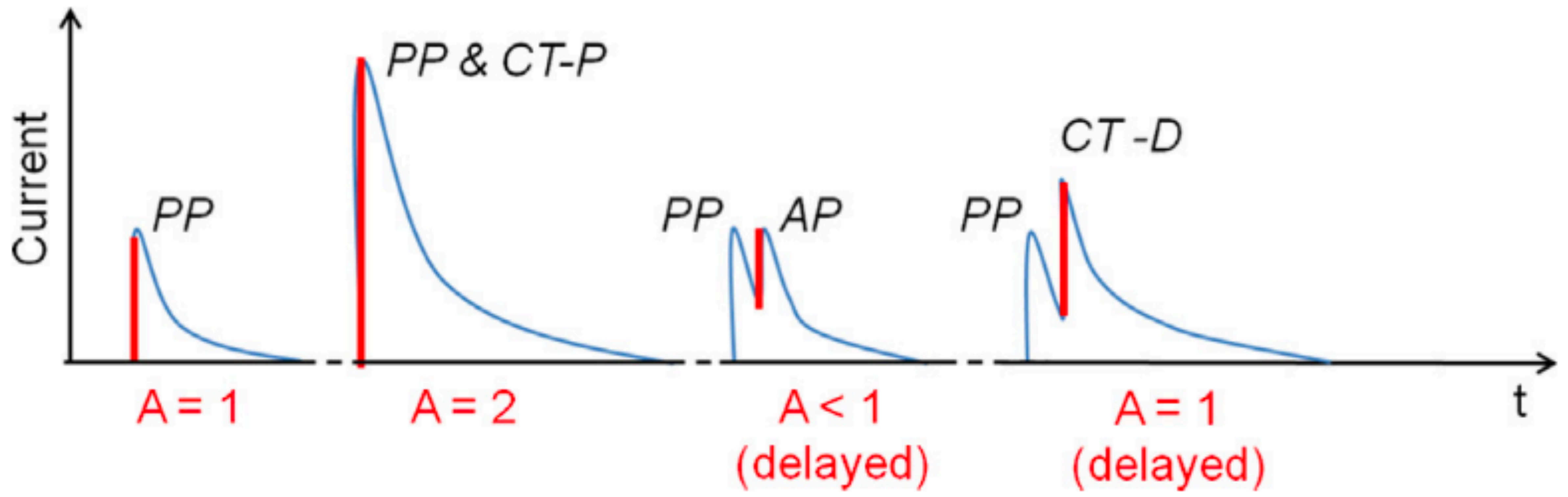
- Dark Count Rate (DCR)

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)

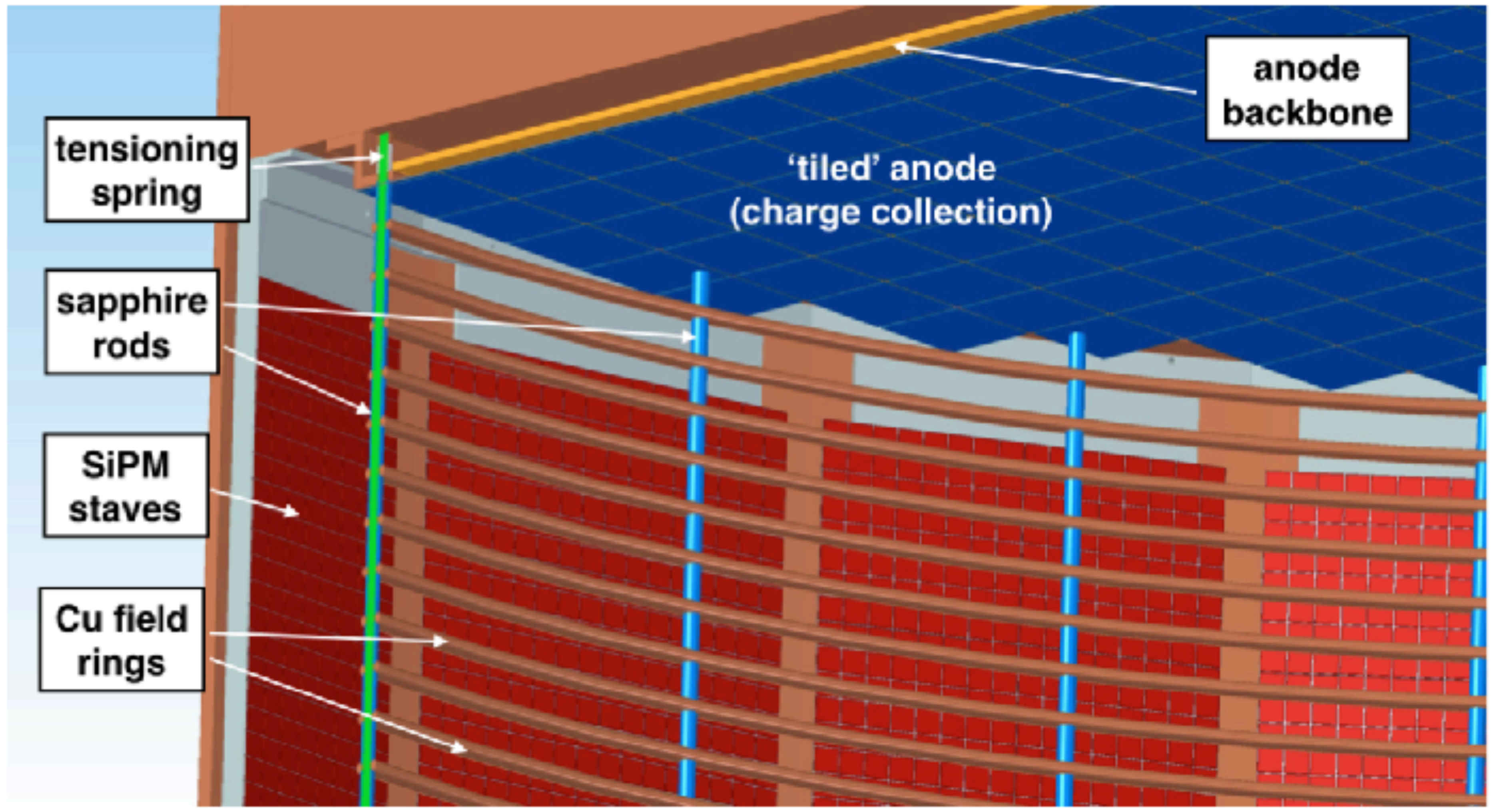


Primary pulses (PP) with different types of correlated pulses such as prompt CT (CT-P), afterpulse (AP) and delayed CT (CT-D).

SiPM technology in nEXO

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

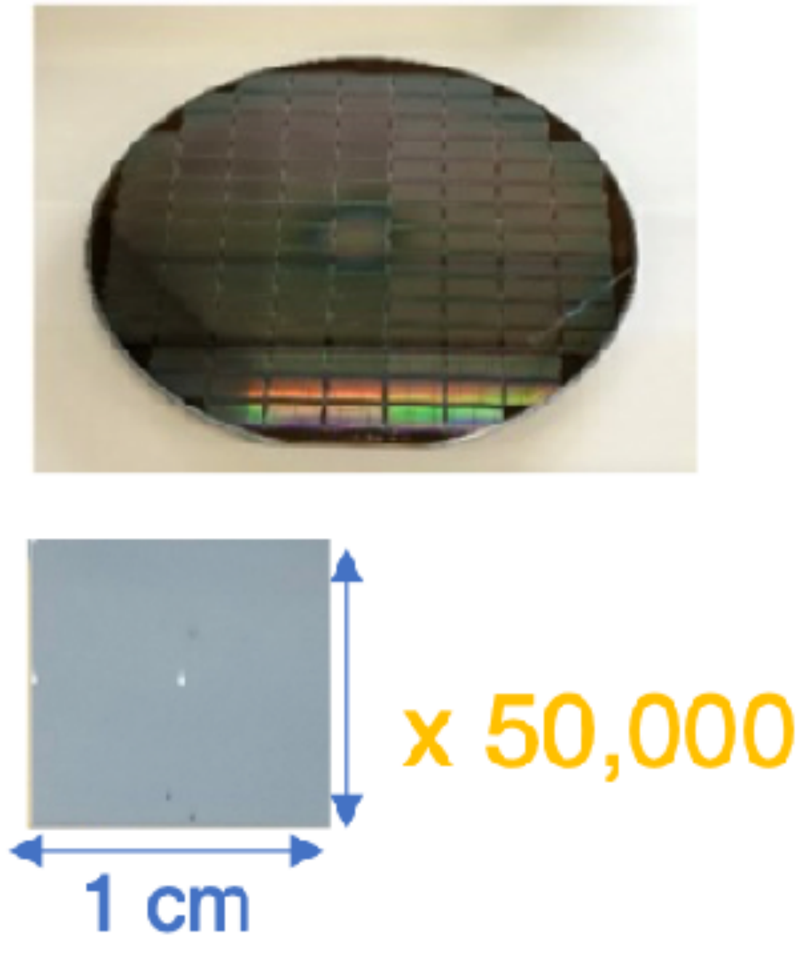
- 5 t of liquid xenon
- Improved charge (tiles) and light (SiPM) readout
- Projected Sensitivity: $T^{0\nu}_{1/2} \geq 1.35 \times 10^{28}\,\mathrm{yr}$



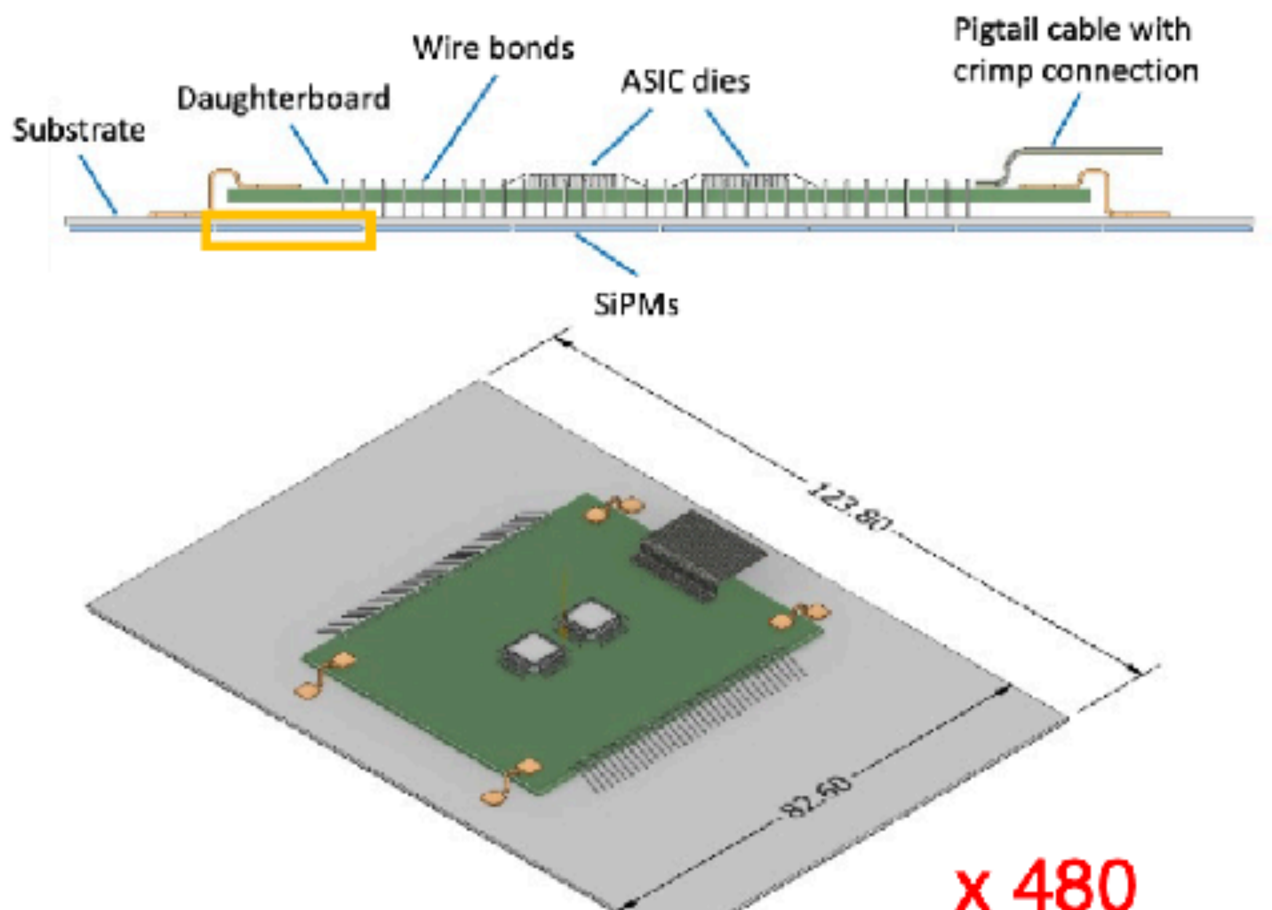
Photon Detector (PD) consists of 4.6m^2 of SiPMs

- ~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

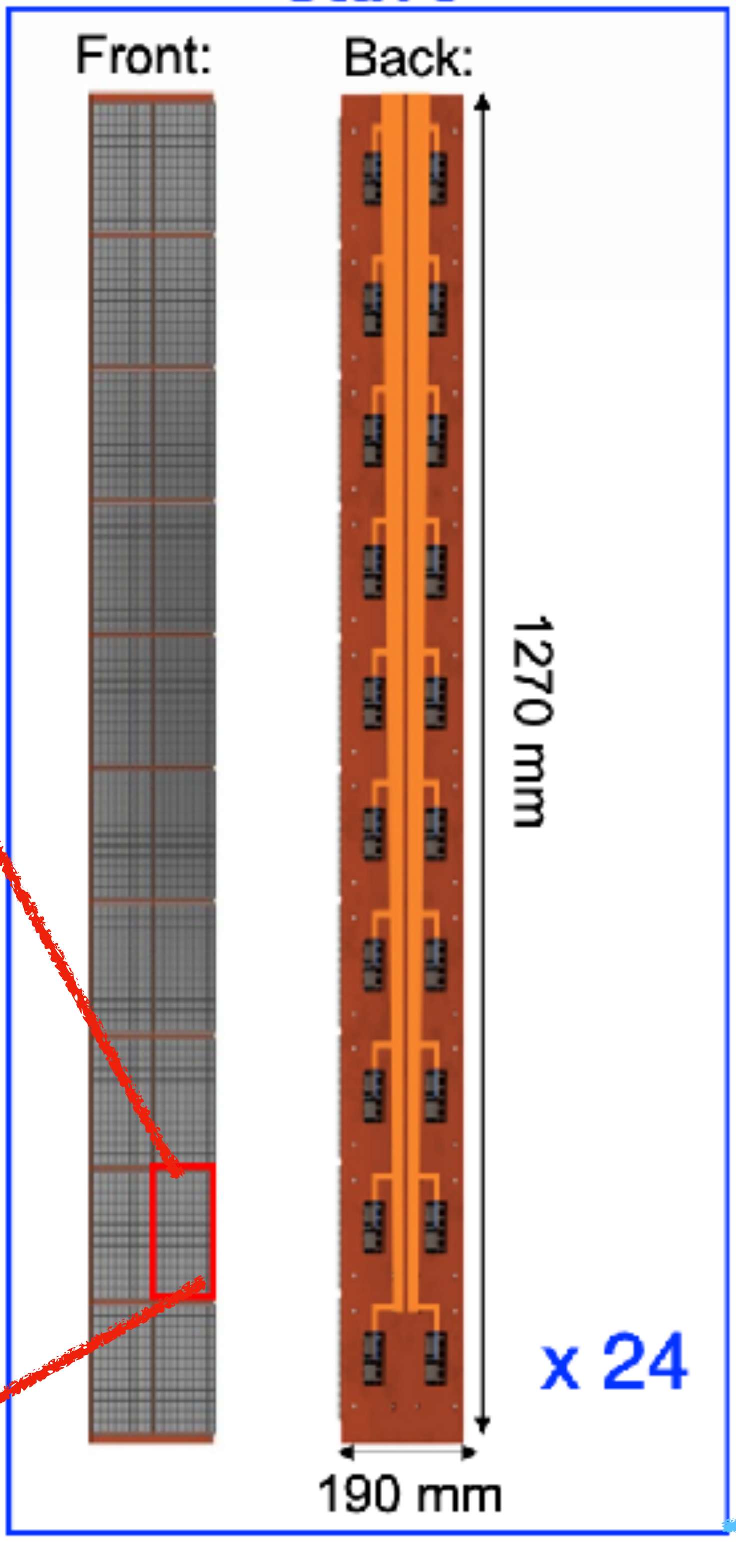


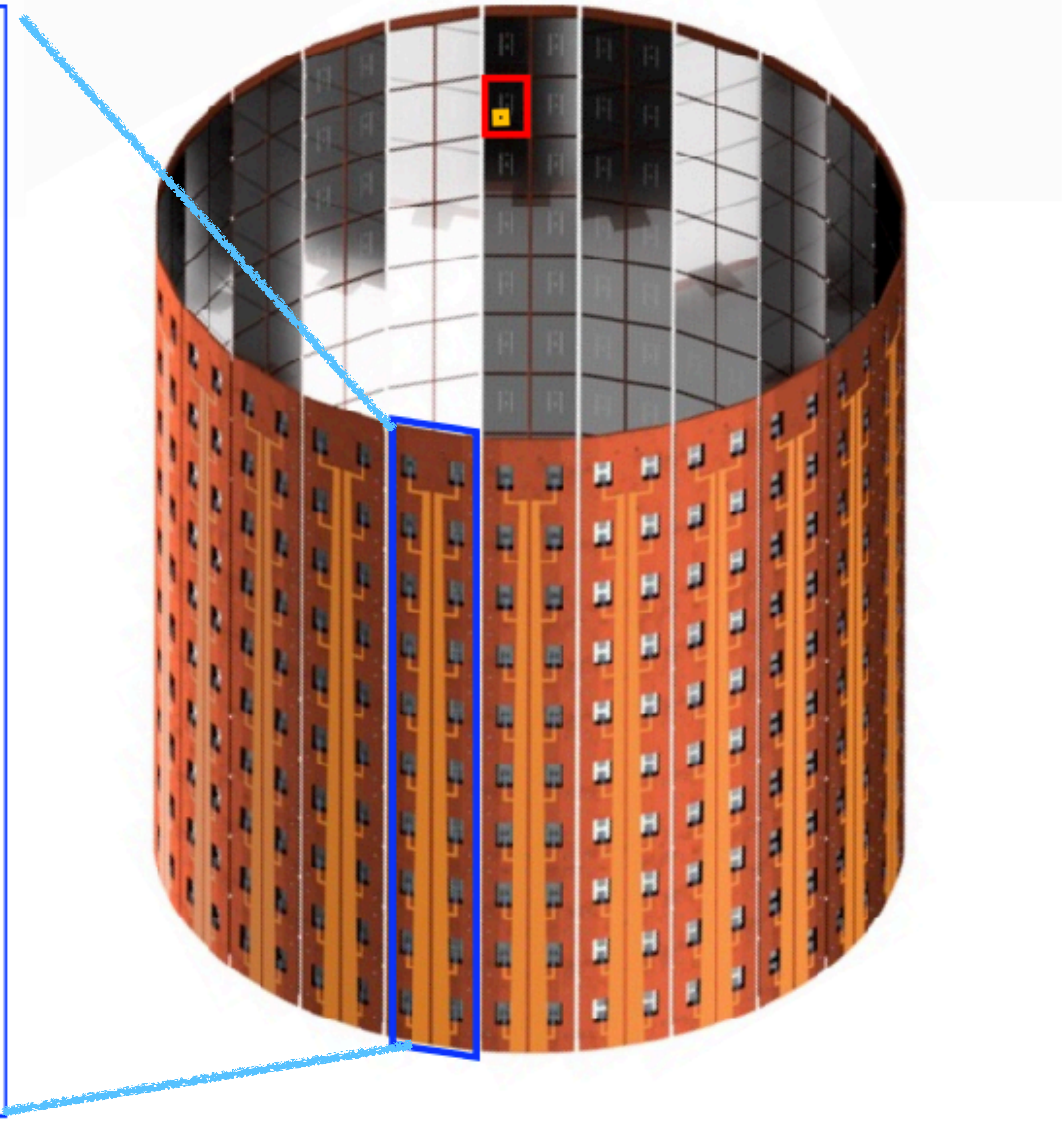
Tile module



16 3x2 cm^2 readout channels per tile

Stave



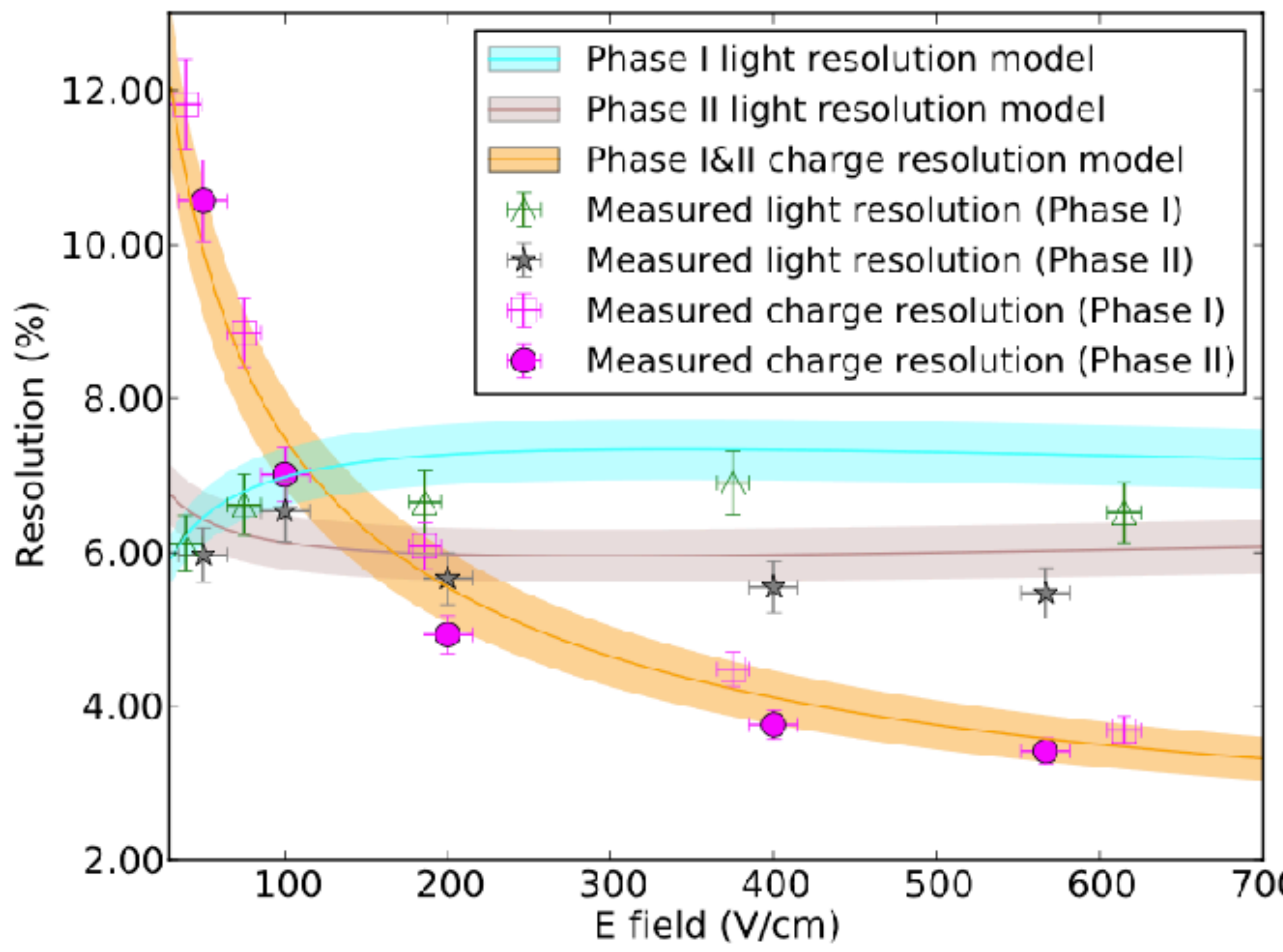


Energy Resolution and photodetector requirements

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

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

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

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

See my Seminar for more details

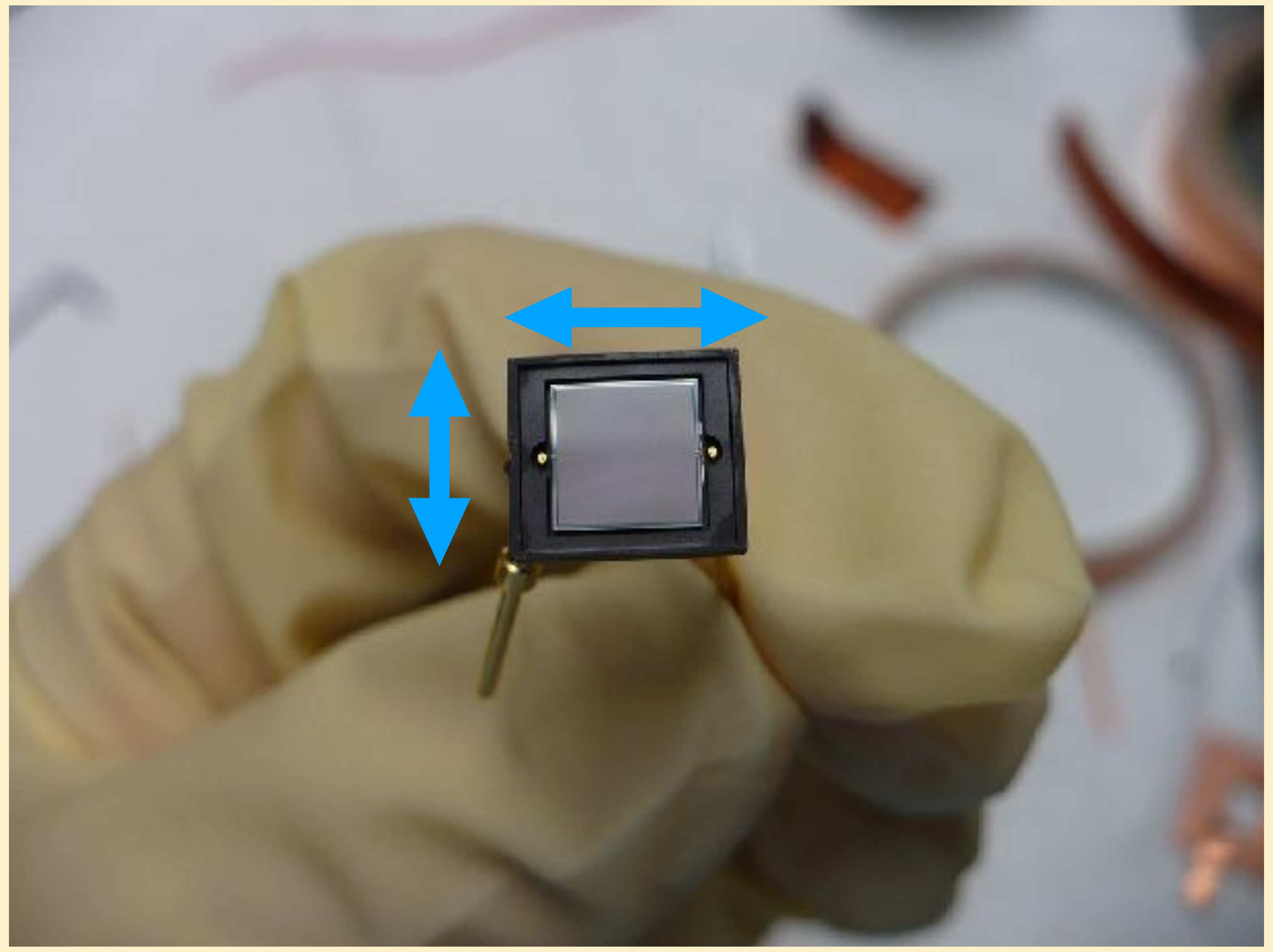
Parameters	Value
Photo-detection efficiency (PDE) at 175-178 nm in liquid Xenon	**≥ 15%**
Radio purity: contribution of photo-detectors on the overall background	< 1%
Dark noise rate at -110 °C	≤ 10 Hz/mm^2
Correlated Avalanches fluctuation (CAF) per pulse in 1µs at -110 C	≤ 0.4
Single photo-detector active area	≥ 1cm^2
Operational gain	$\geq 1.5 \times 10^6$ **e$^-$**
Capacitance per area	< 50 pF/mm^2
Equivalent noise charge	< 0.1 PE r.m.s

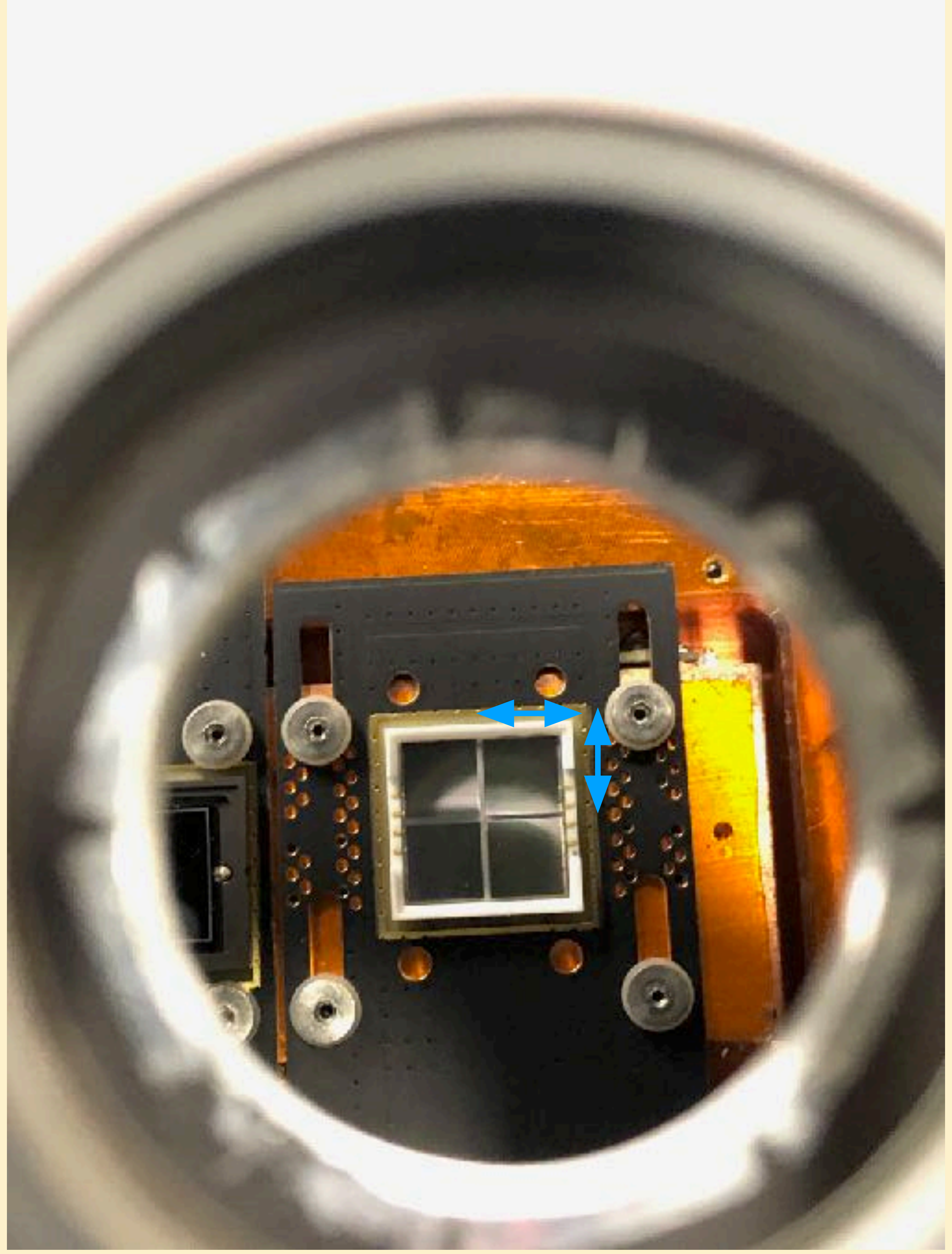
Three SiPMs analysed in this work: 2 Hamamatsu VUV4 MPPCs and FBK VUVHD3 SiPM

nEXO 6x6 mm^2 SiPMs candidates

Hamamatsu MPPCs

NIM A 940 (2019)



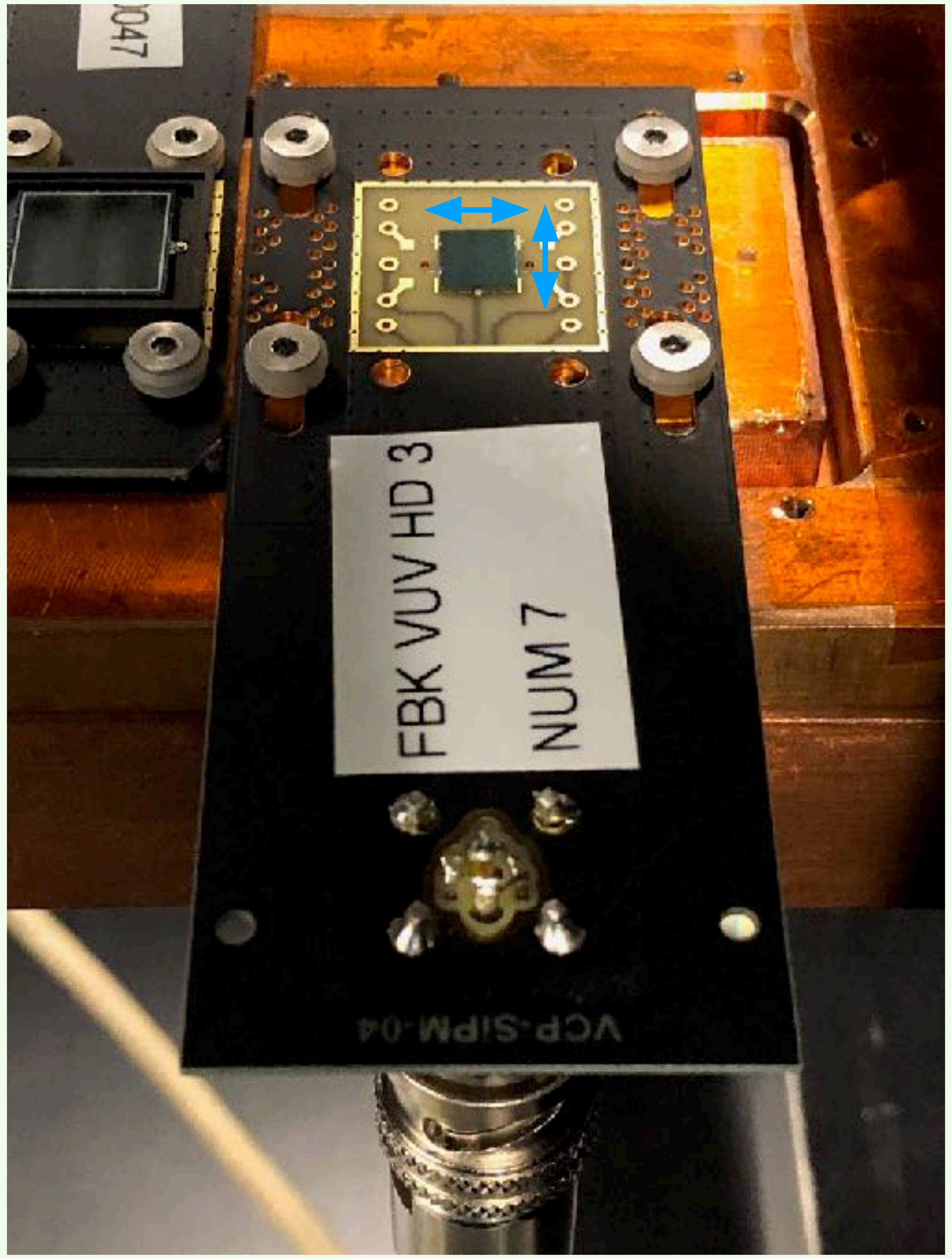


HPK VUV4-50
Single devices
50 um pitch

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

IEEE Trans.Nucl.Sci. 65 (2018)

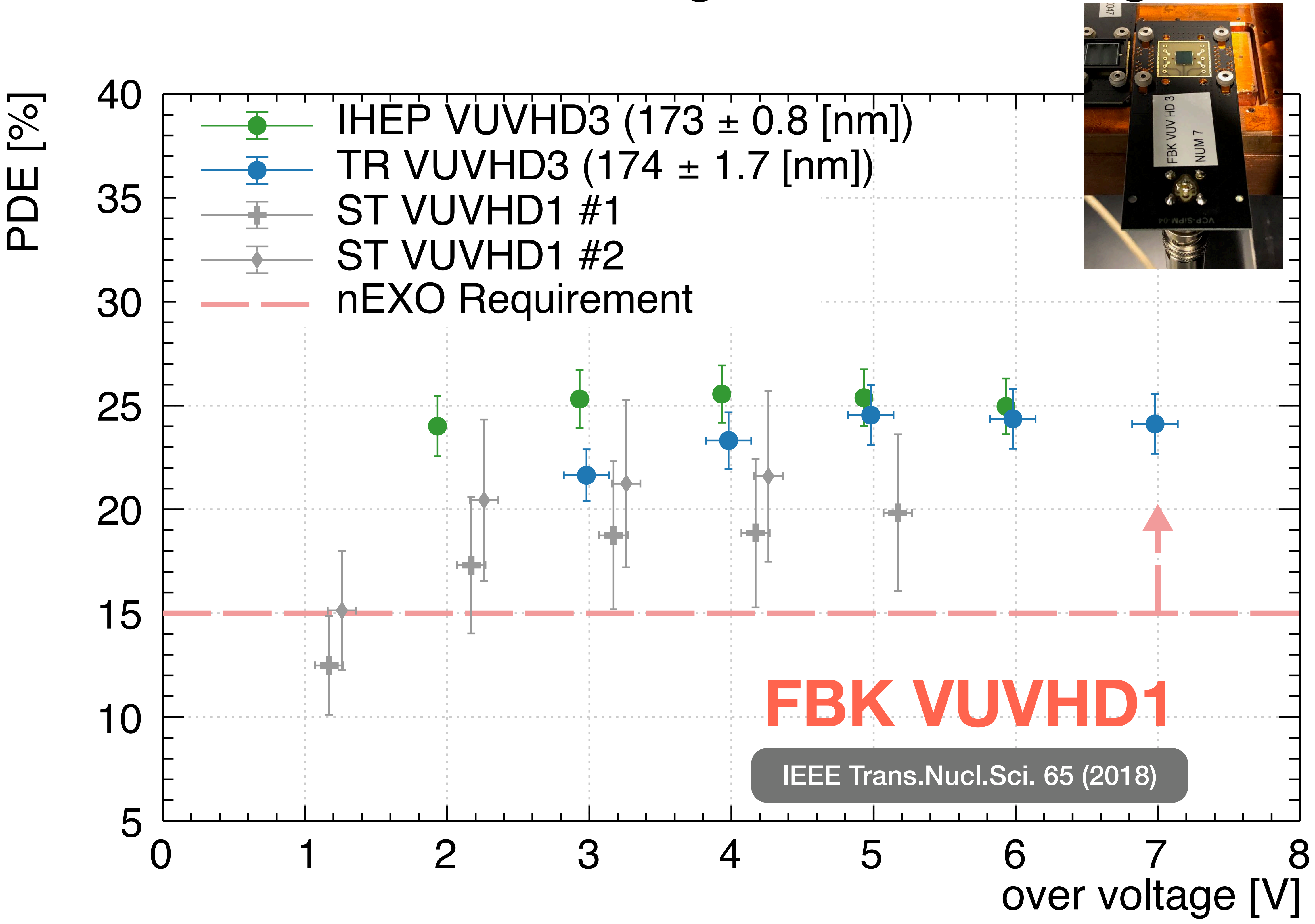
FBK SiPM

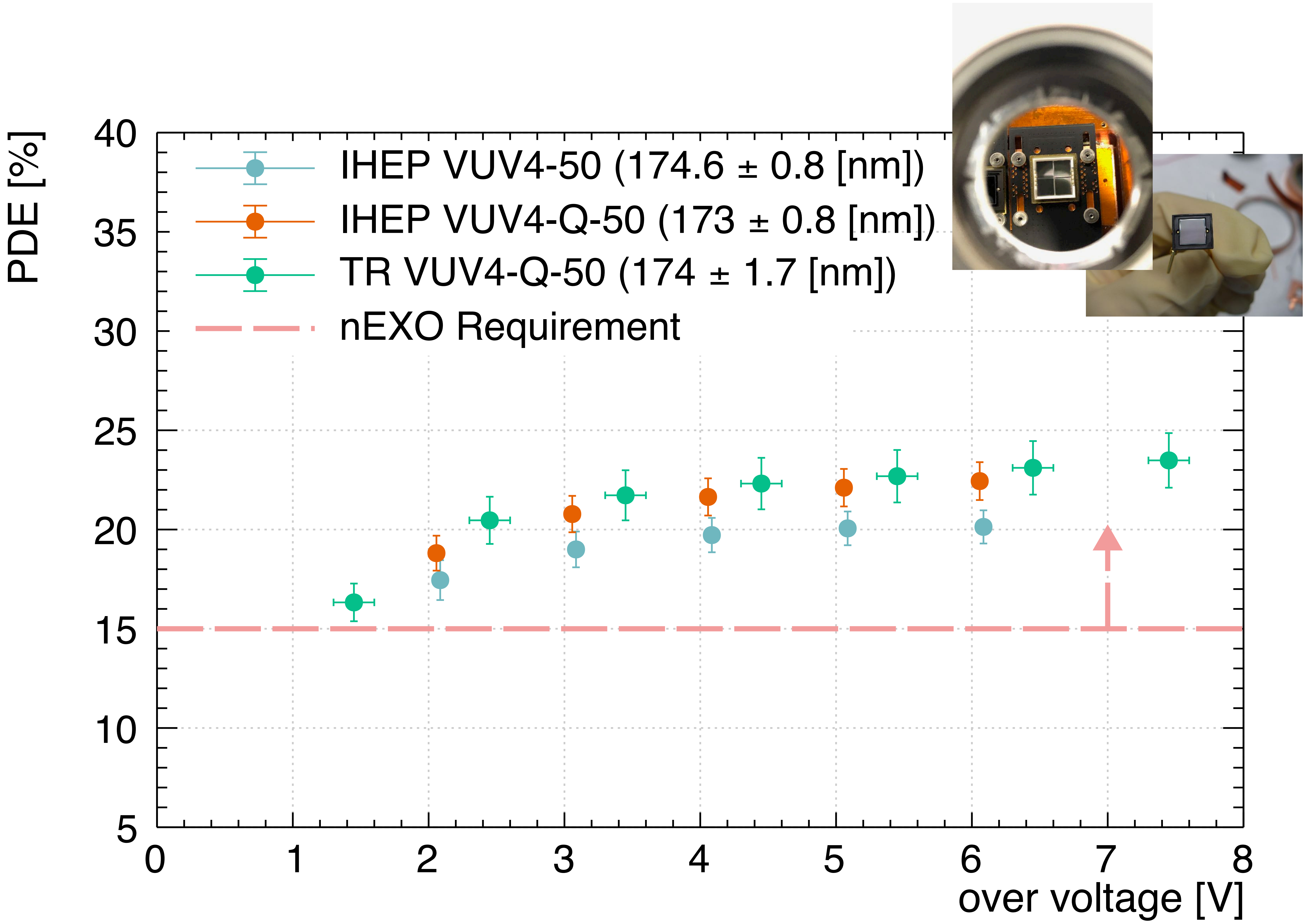


FBK VUVHD3
substitutes
its previous generation
FBK VUVHD1

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

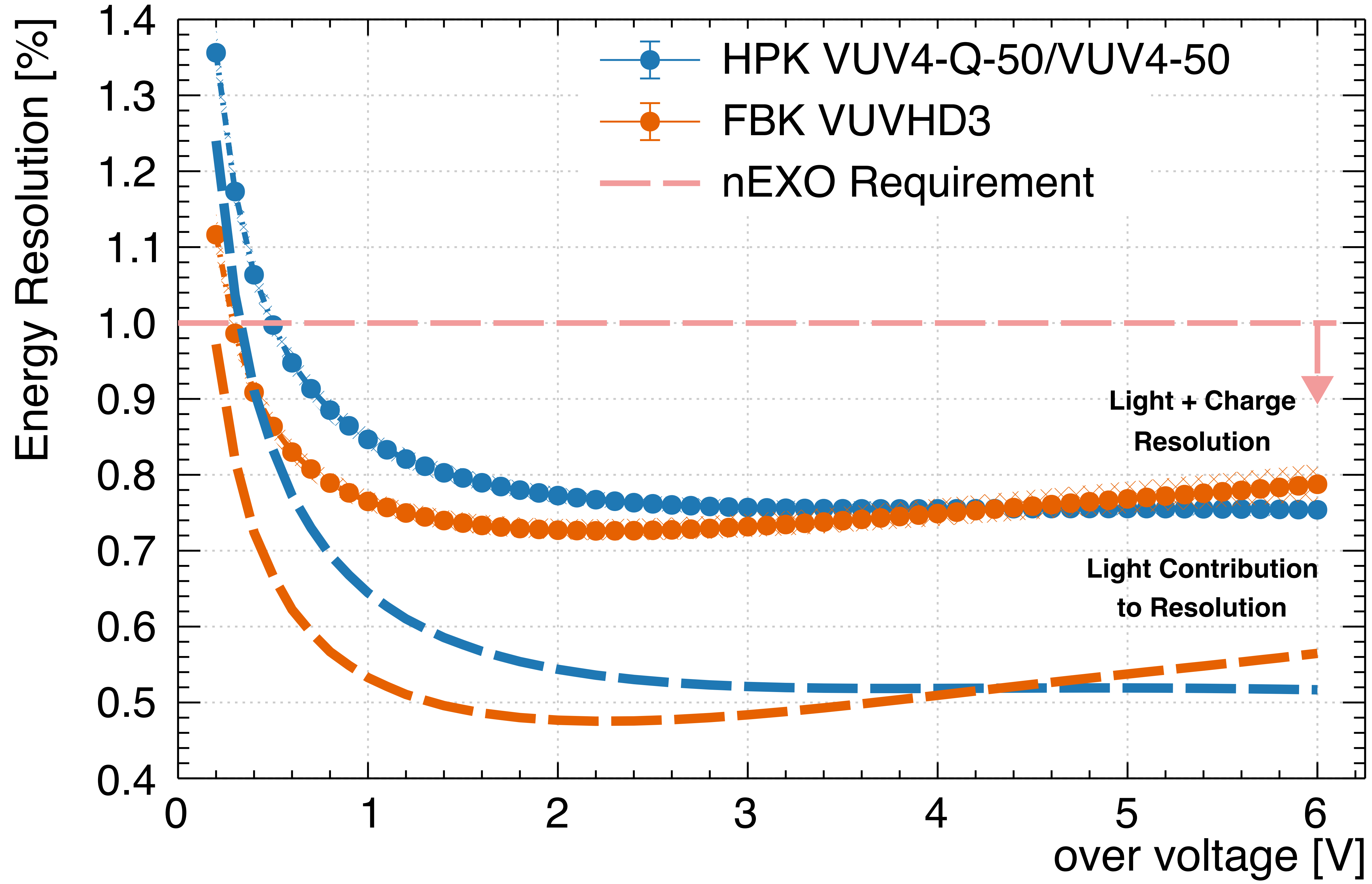
Requirement met from 1.5 V of OV !

nEXO Energy Resolution at ($2458\,\mathrm{keV}$ 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

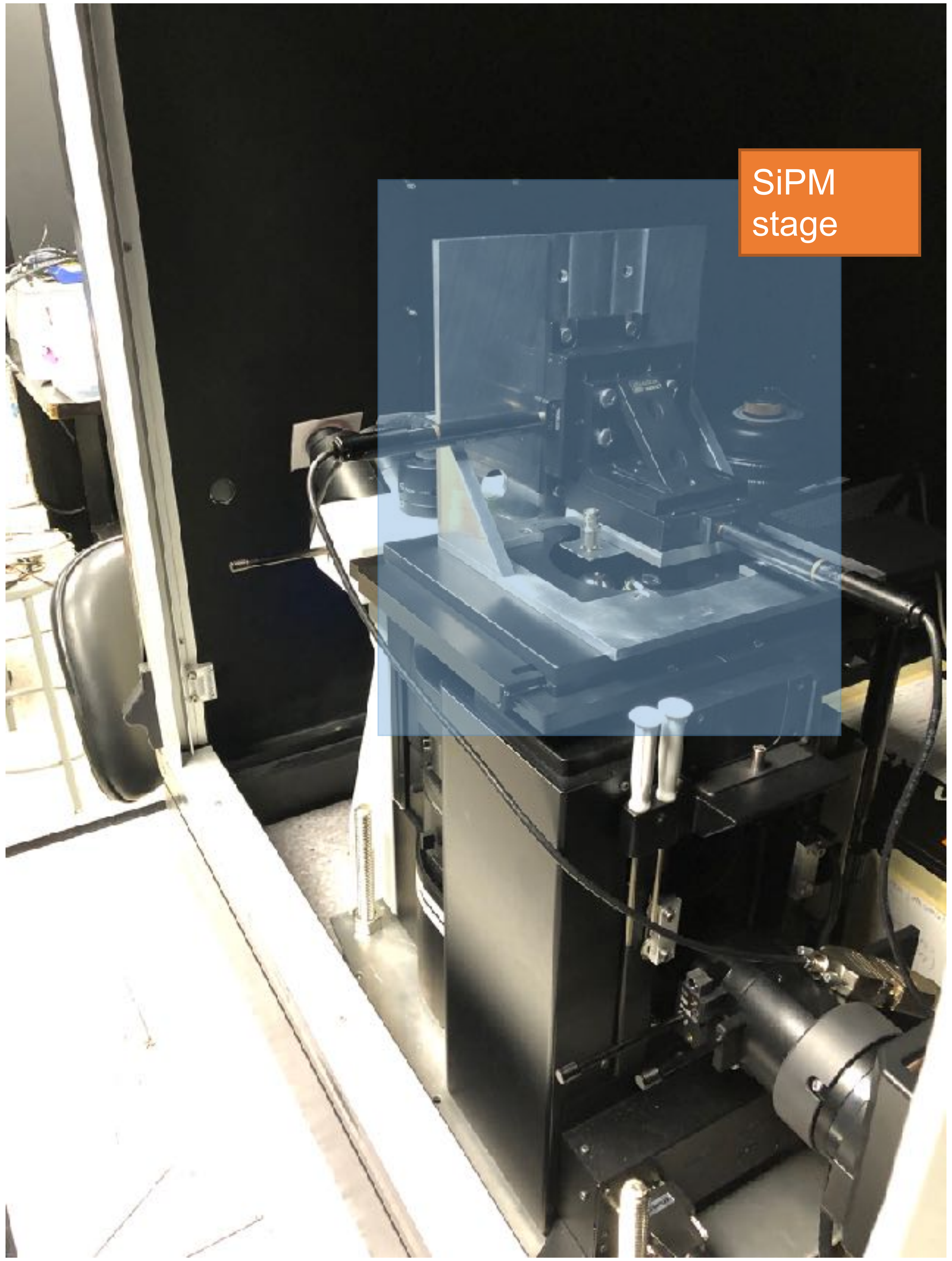
PDE drives the minimum.

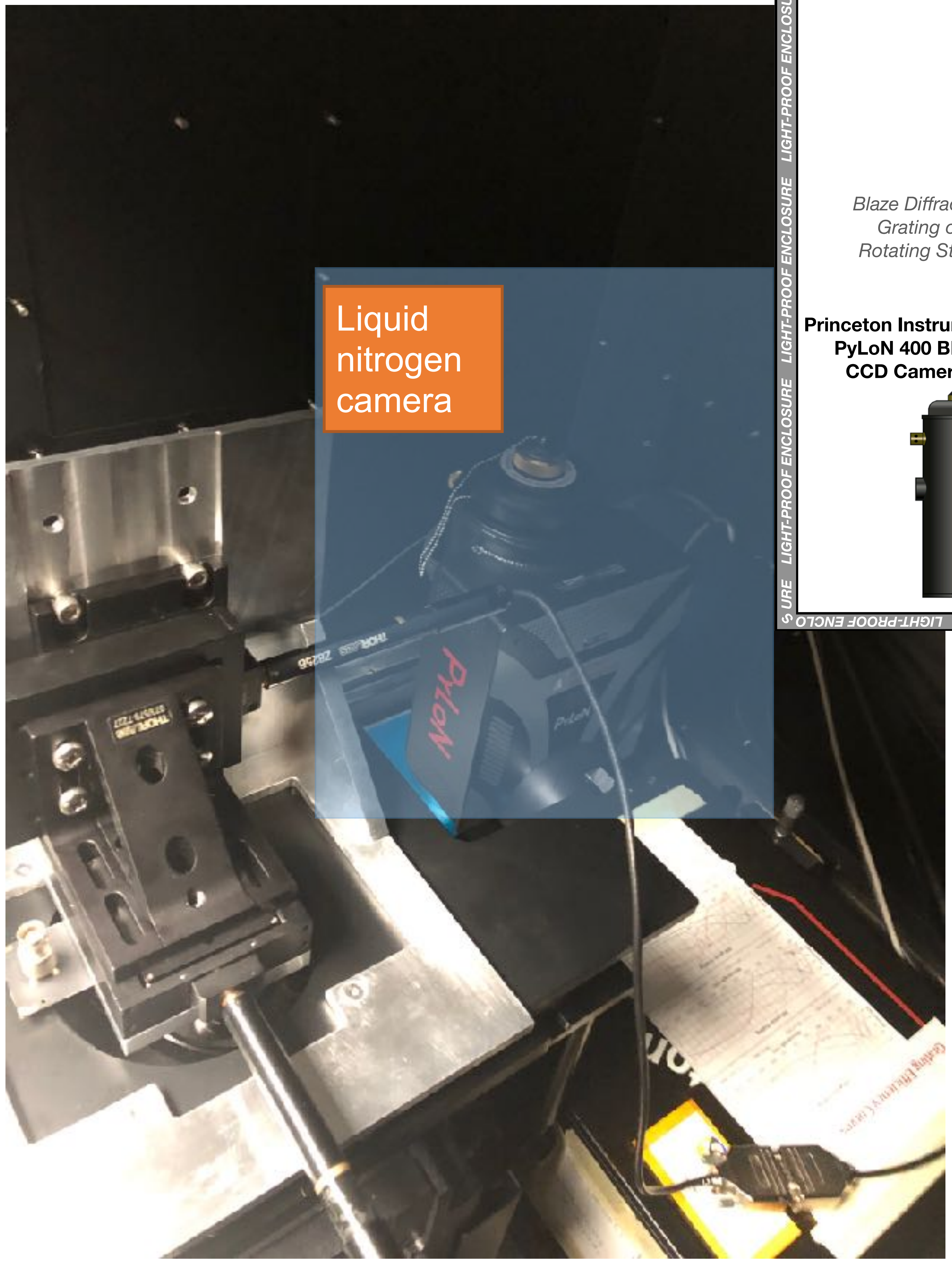
eCT is not yet accounted . **This talk**

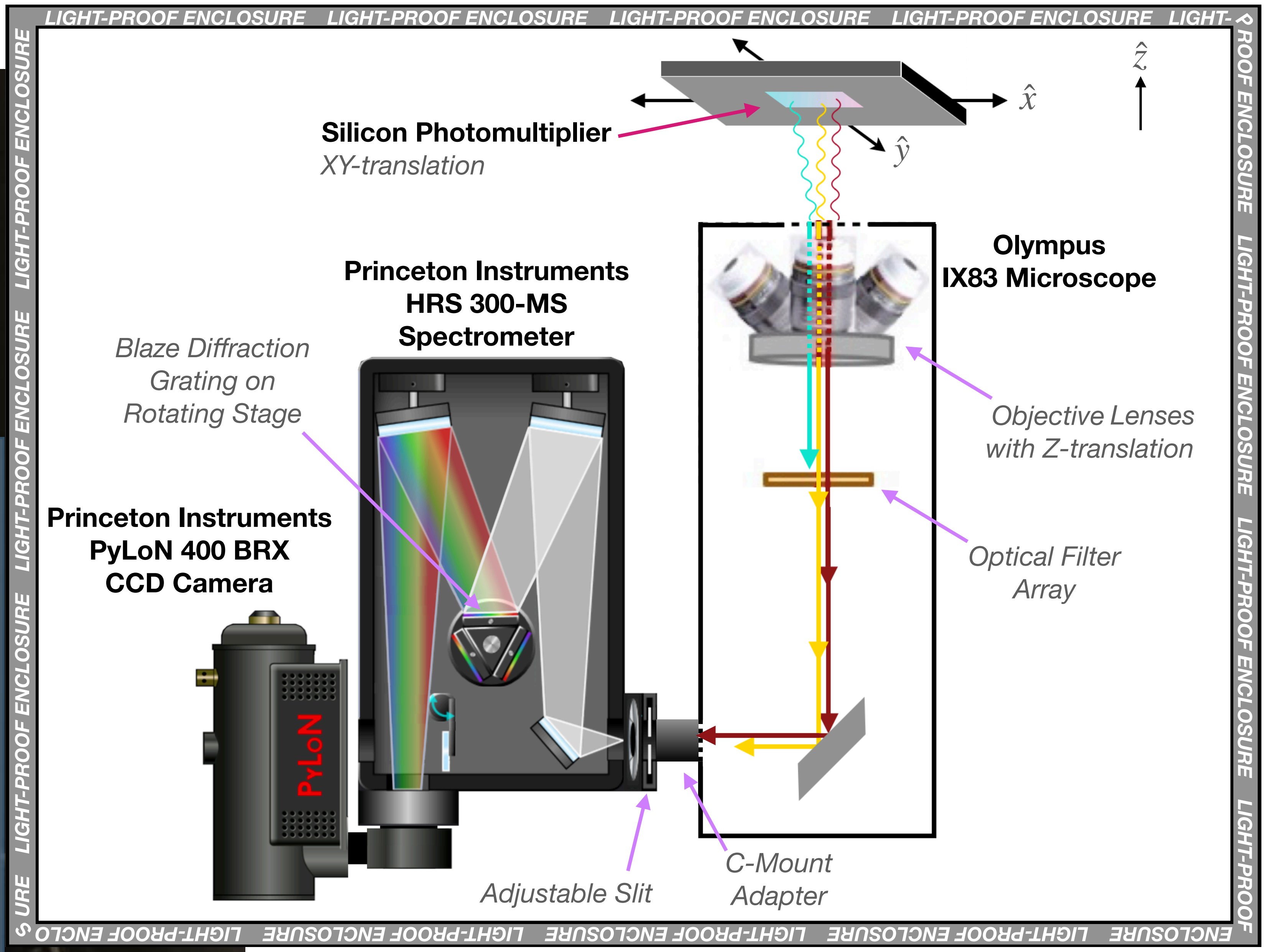
External Crosstalk

Optical Cross talk measurements at TRIUMF

PHASE 1





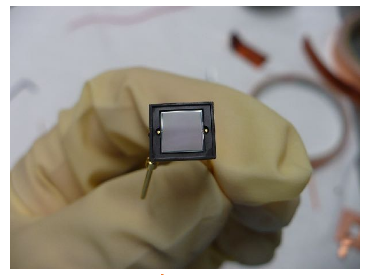


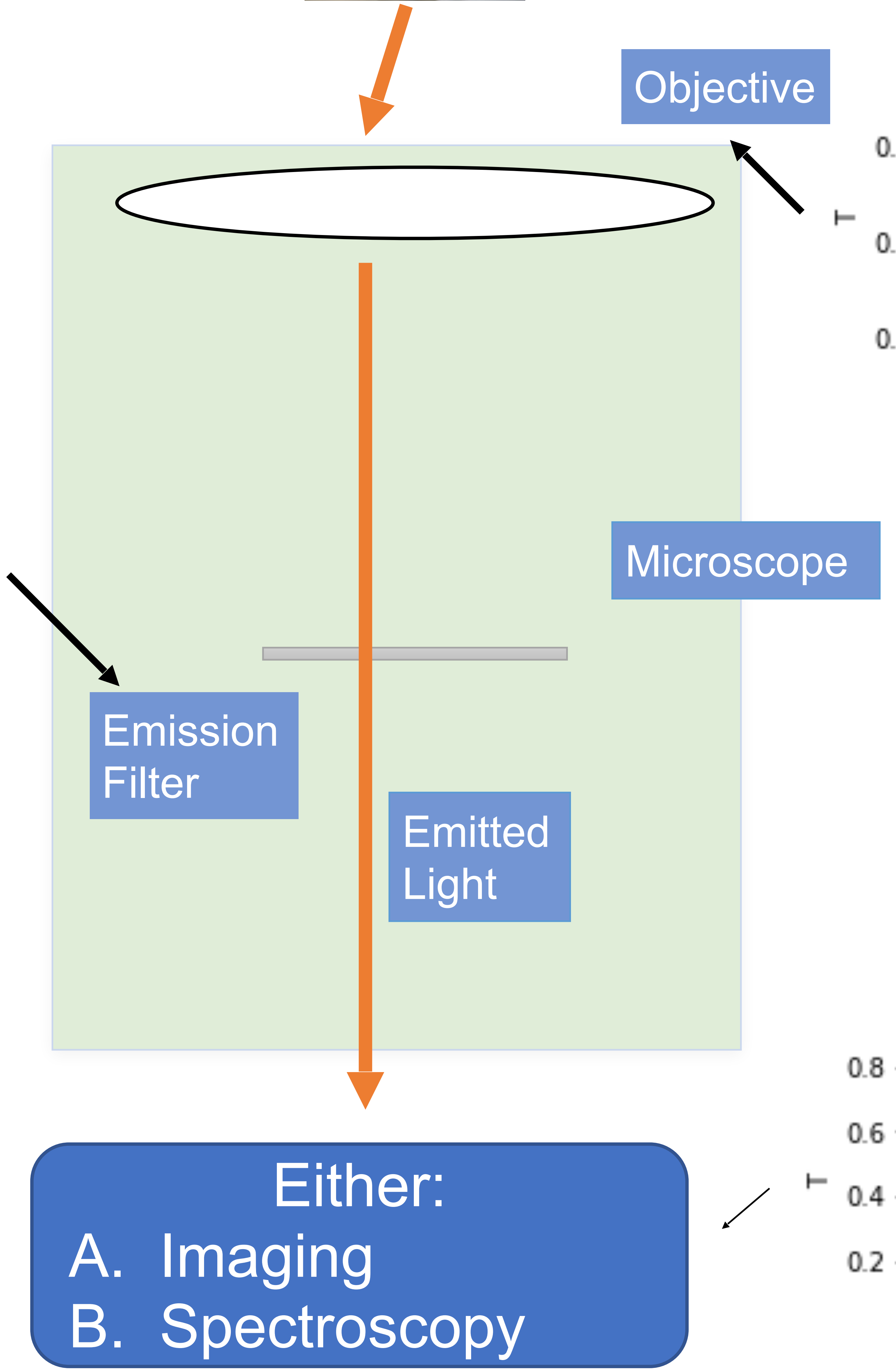
- Room temperature measurements
- Emission of light limited from dark noise driven avalanches
- Limited at high over voltages

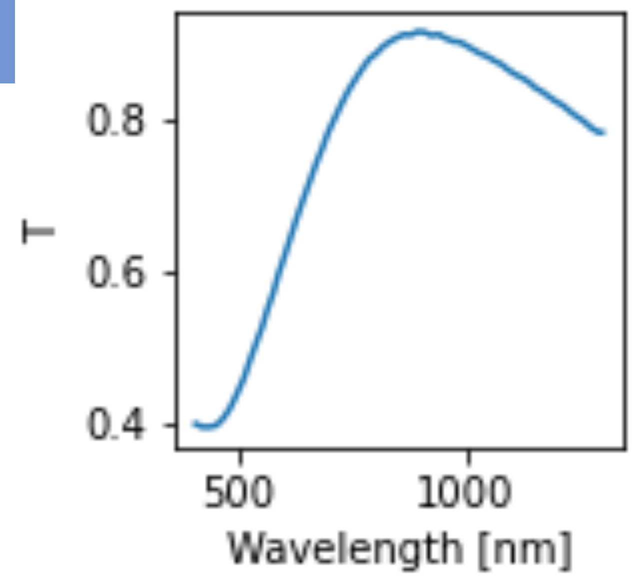
Two SIPMs studied: Hamamatsu VUV4 MPPC and FBK VUVHD3 SiPM

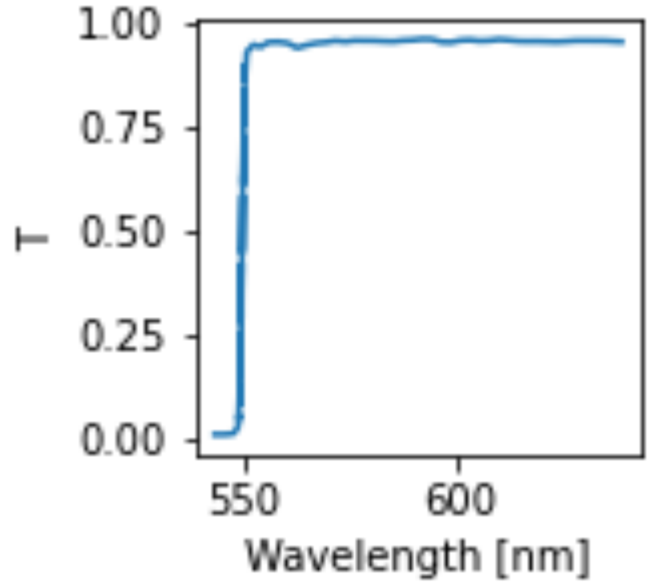
TRIUMF setup in a nutshell

10.3390/s21175947



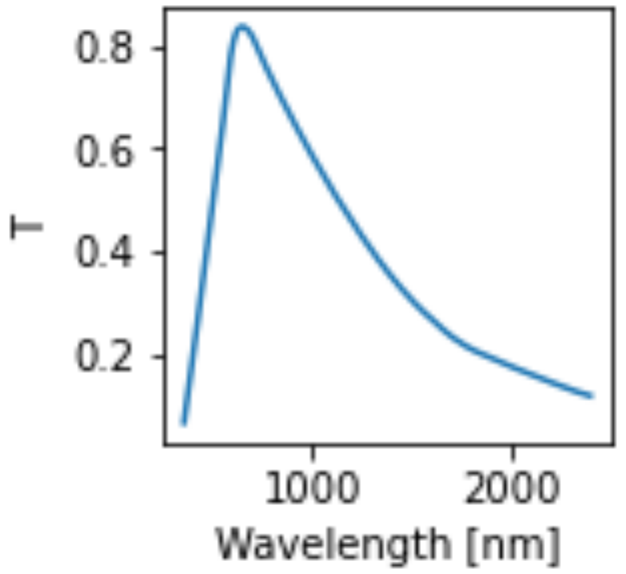






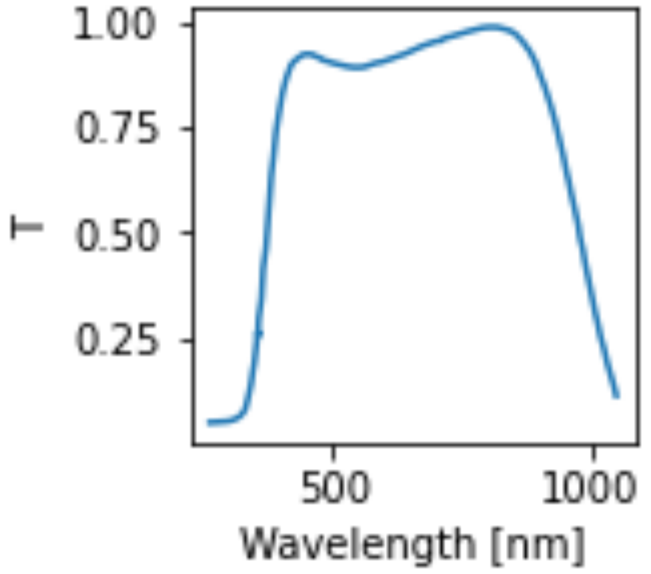
2nd order cut

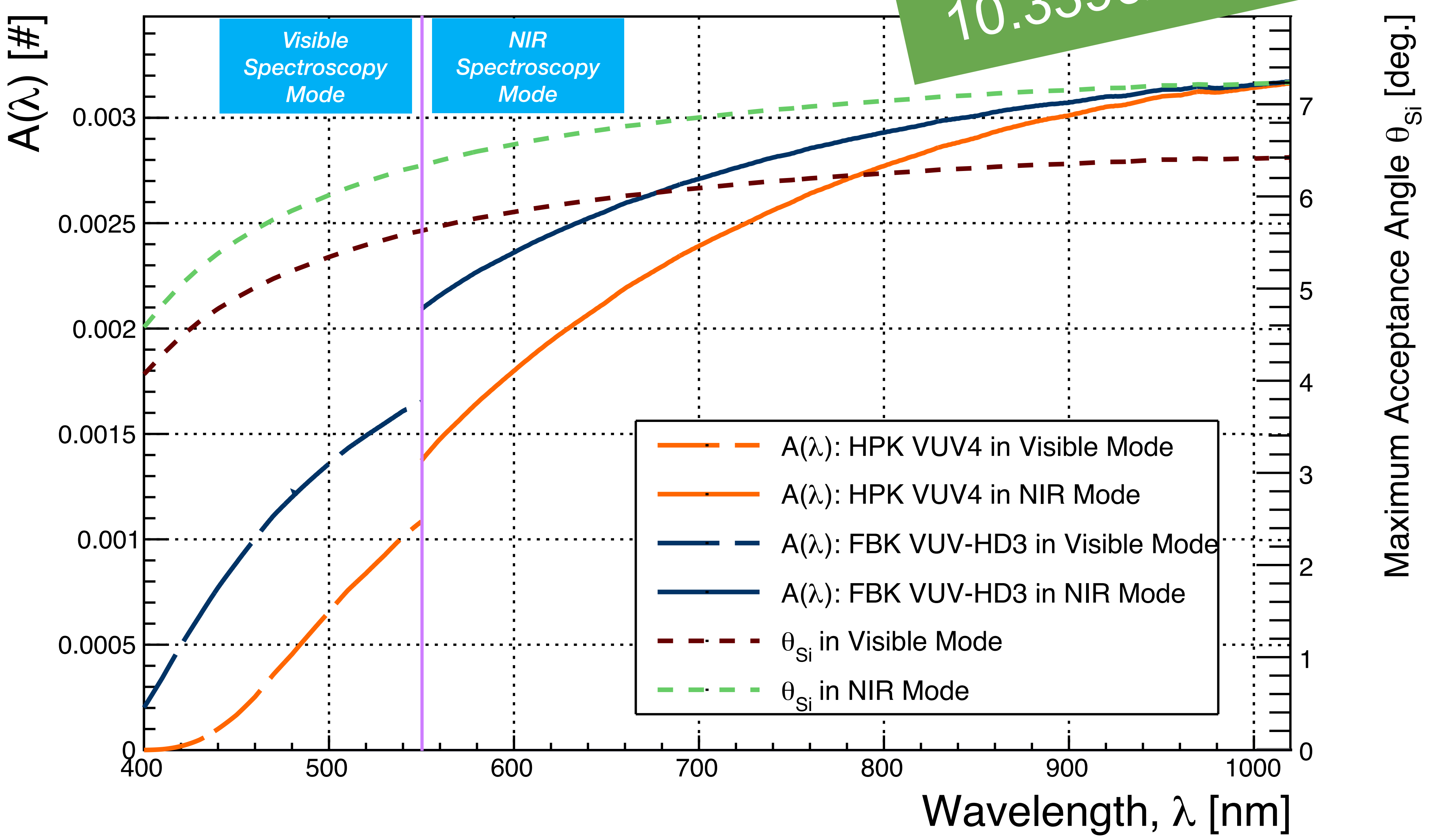
Diffraction Grating

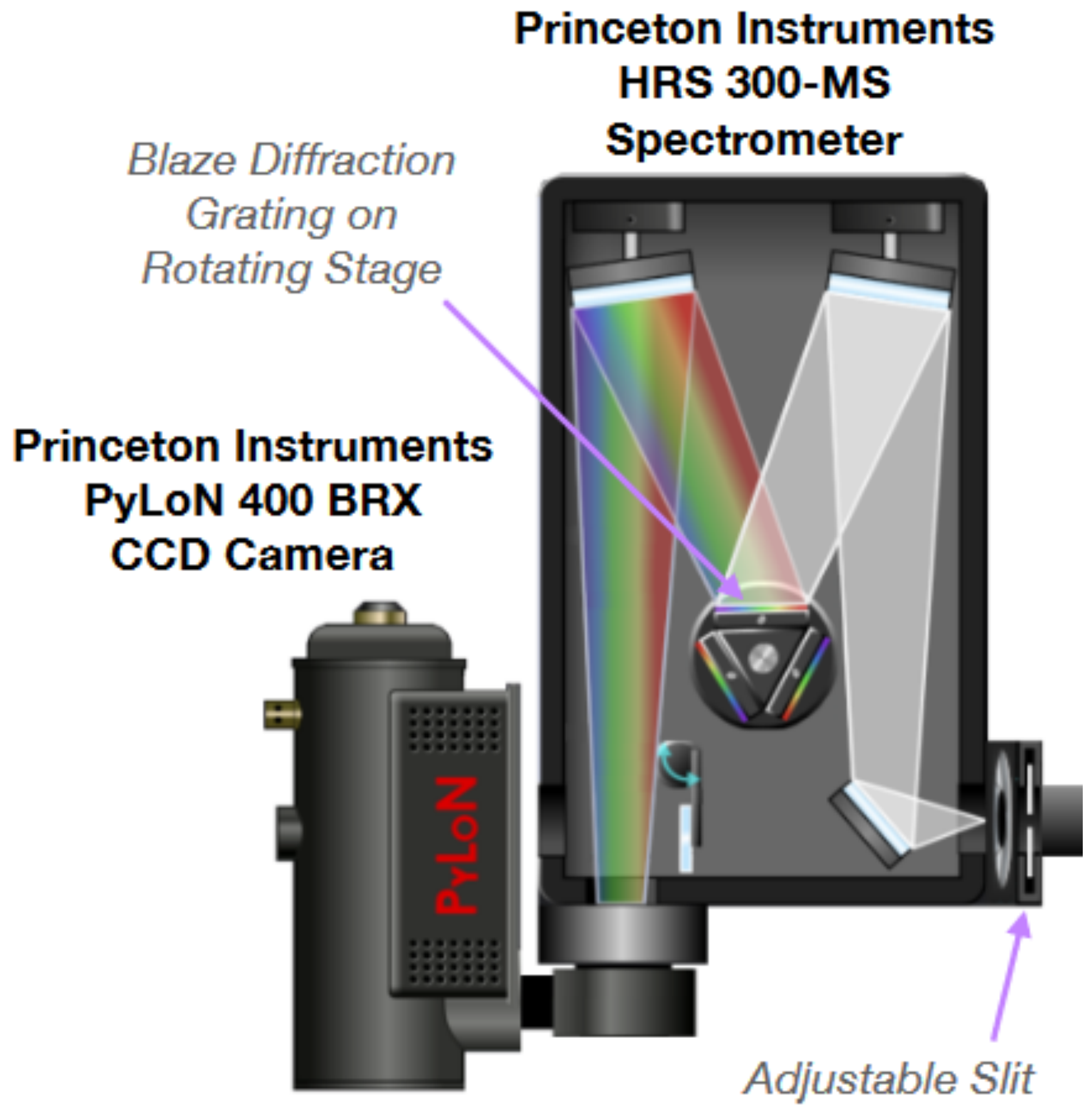


+

Cryogenic Camera

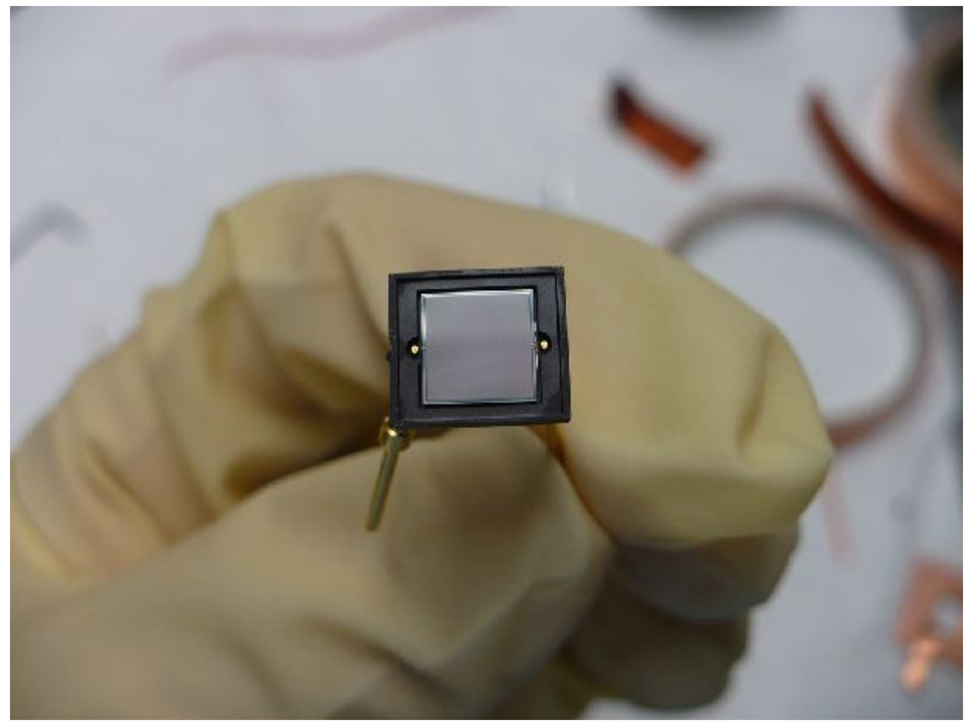


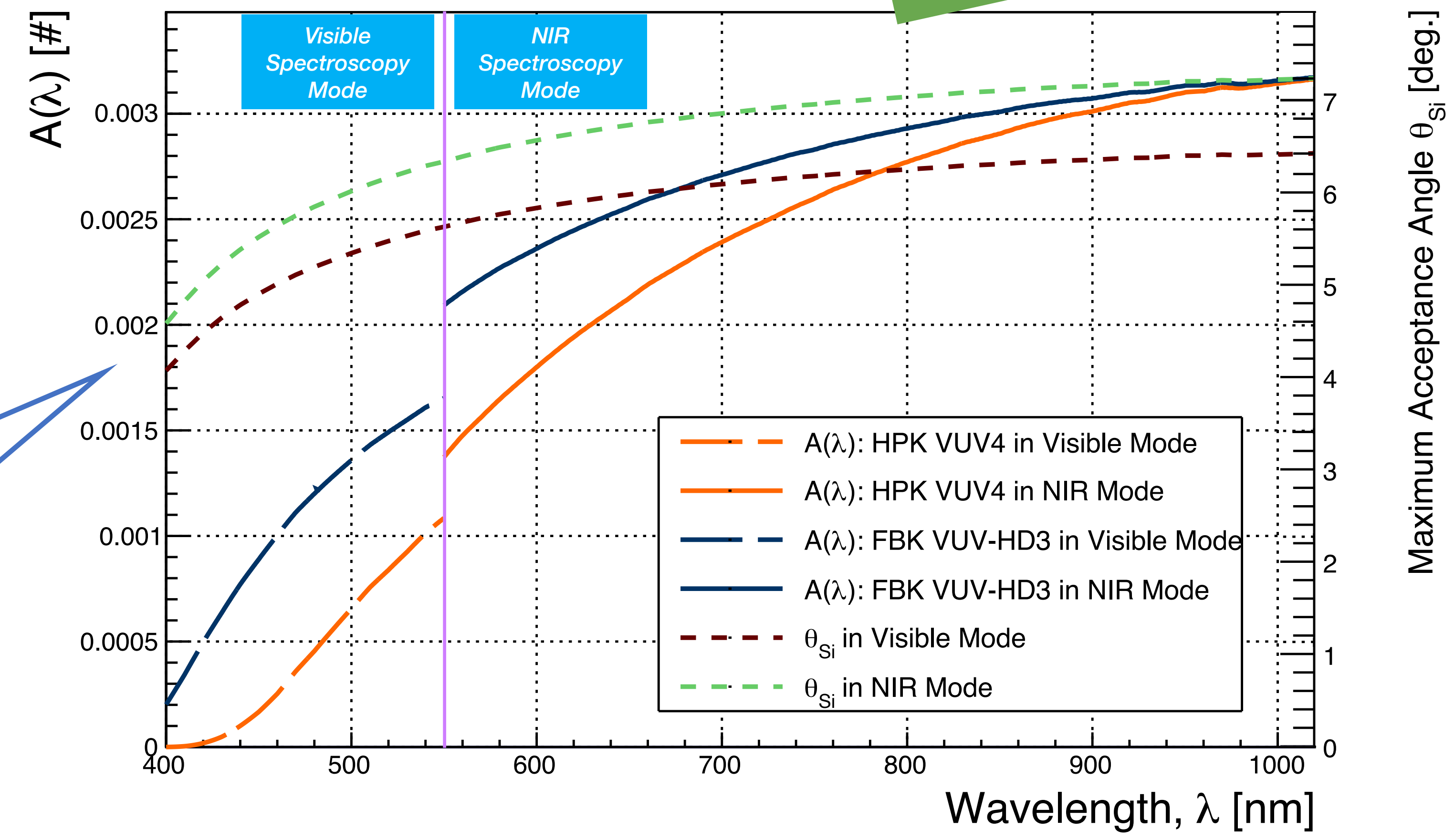


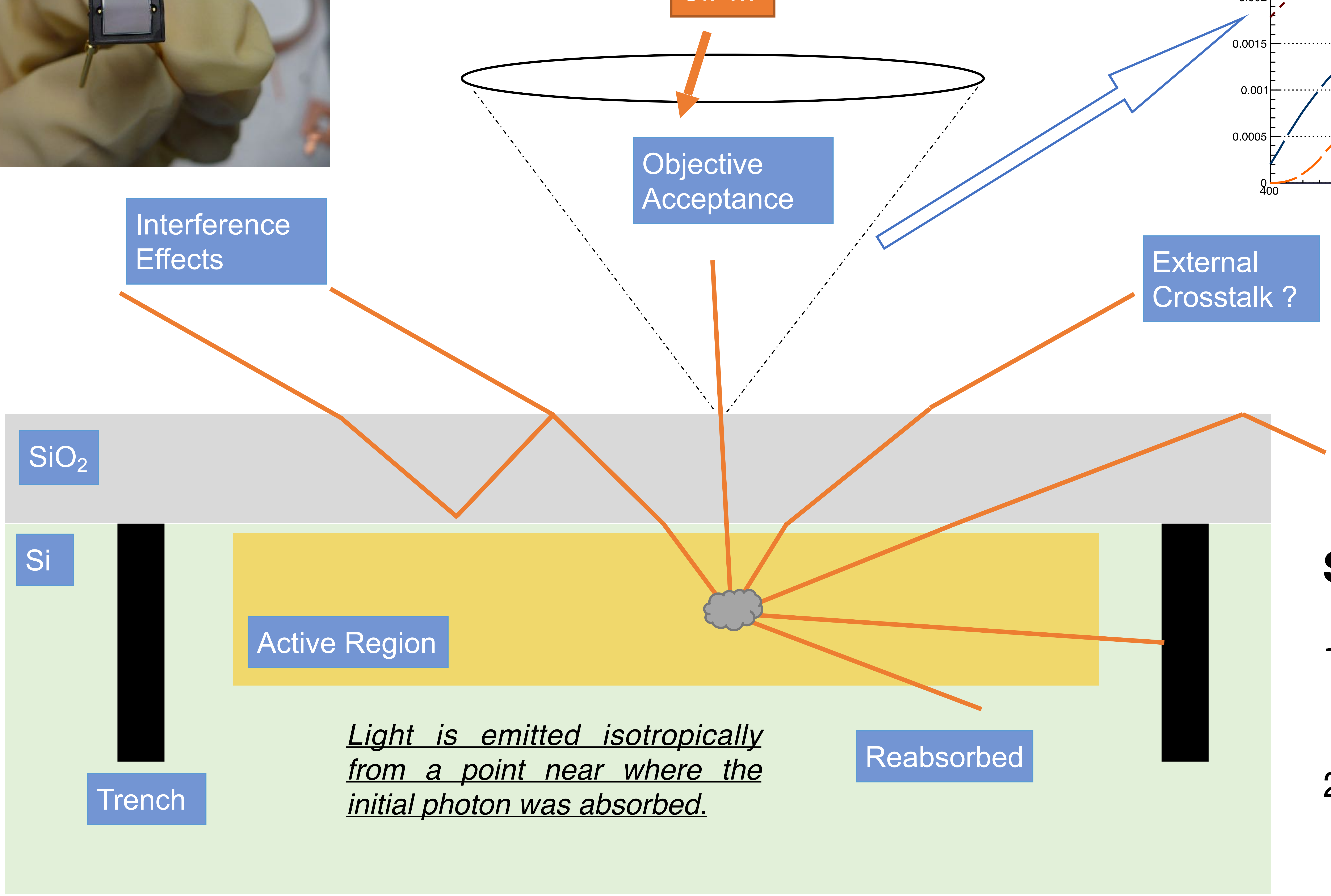


SiPM structure and light emission

10.3390/s21175947





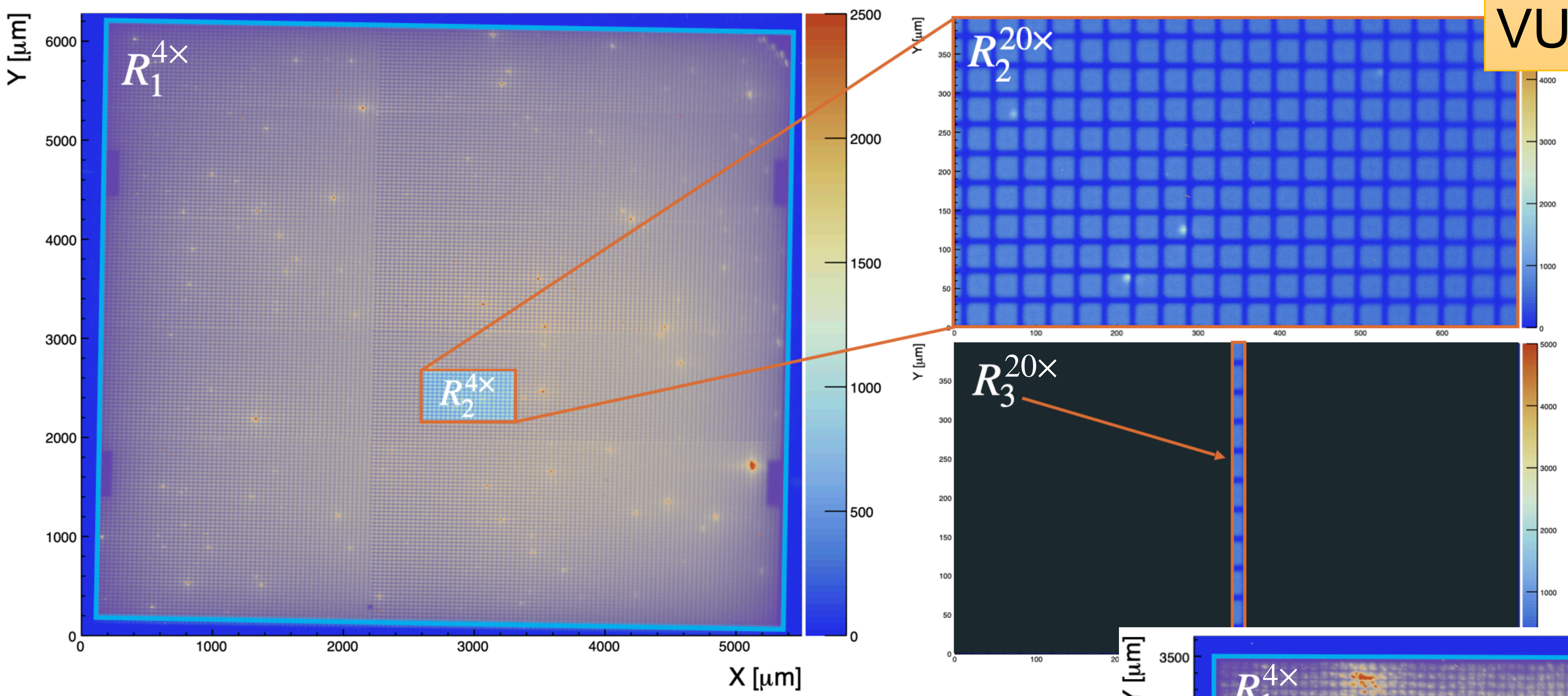


Some considerations:

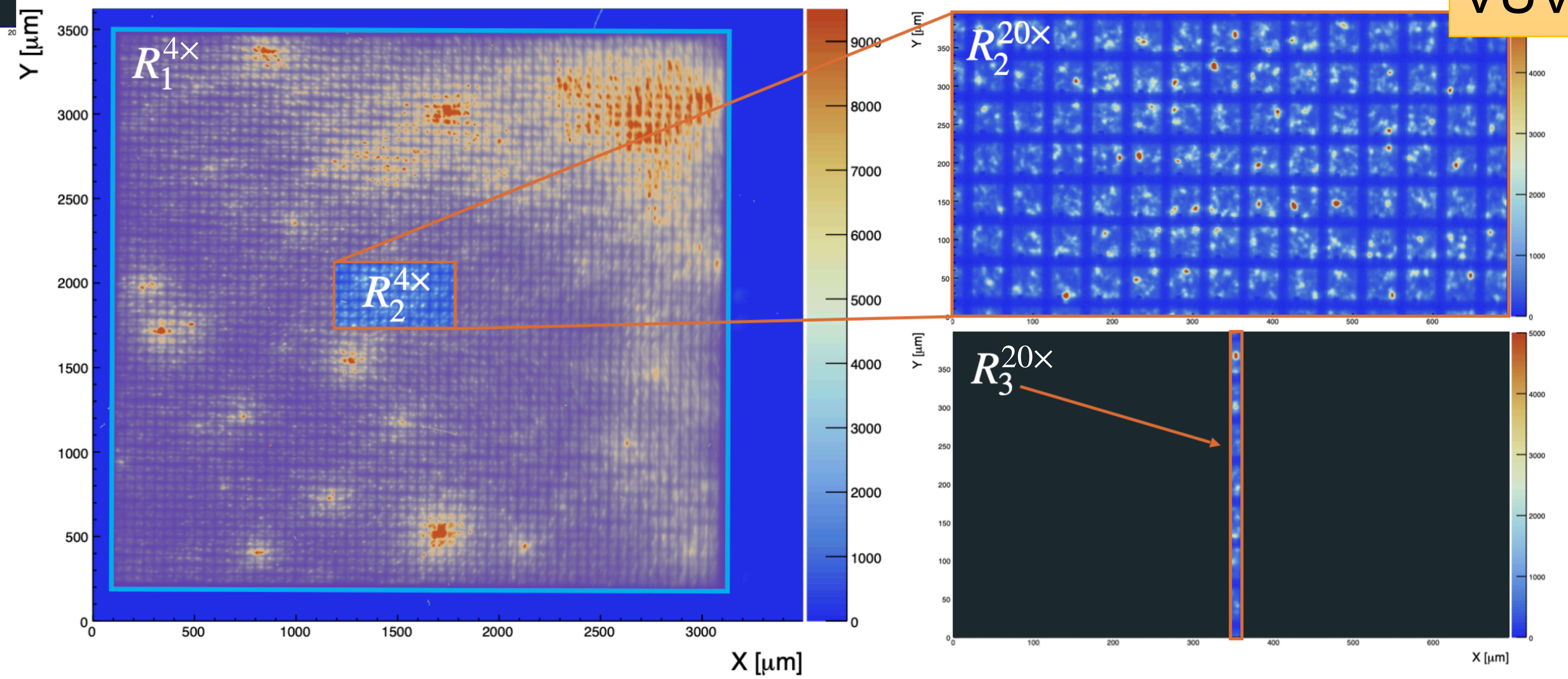
1) Objective Acceptance is really small due to limited NA
2) Isotropic emission is spoiled by SiPM top structure

External CT driven by Dark Avalanches: Imaging mode

10.3390/s21175947



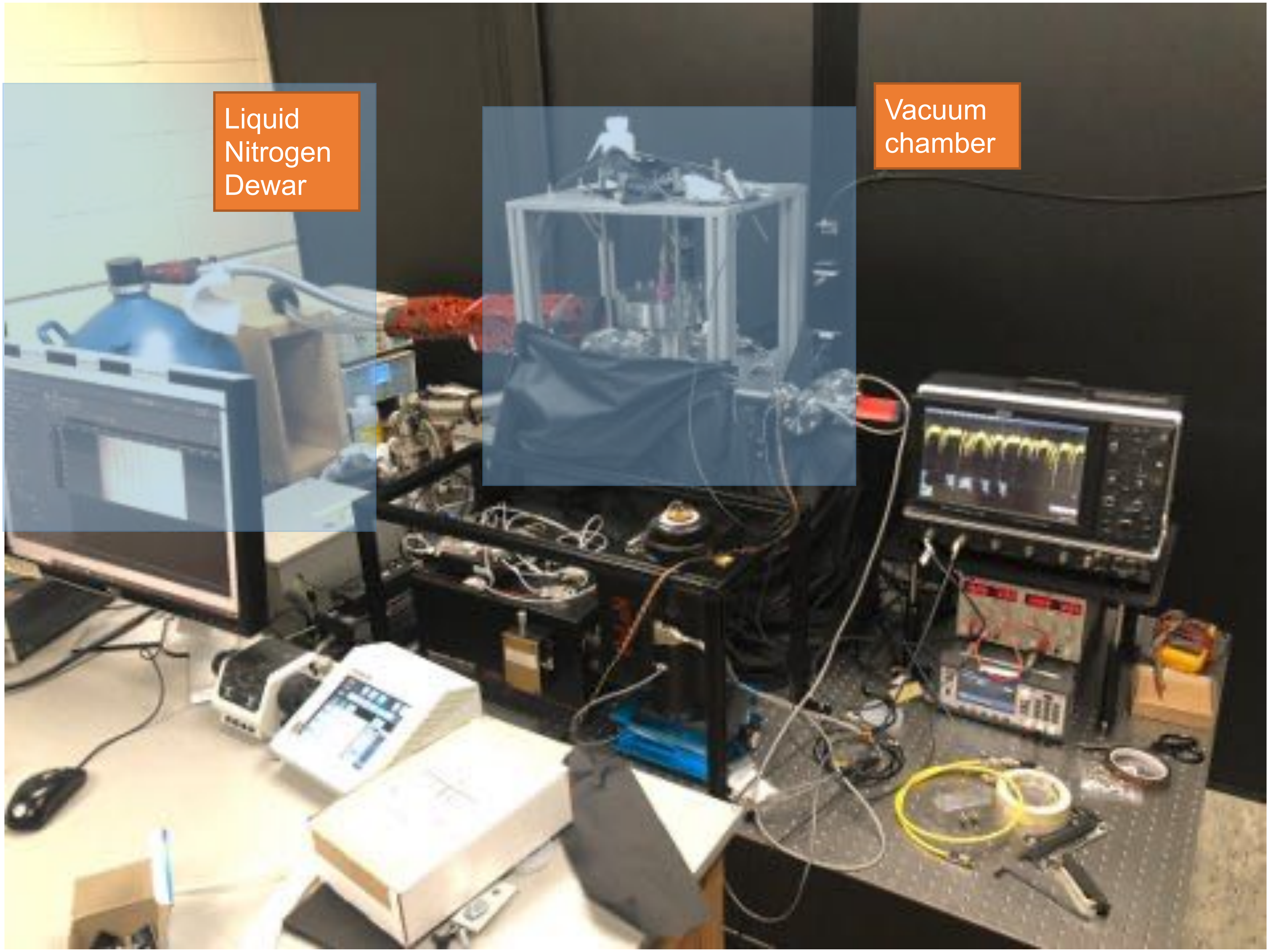
FBK Light Emission is extremely uniform

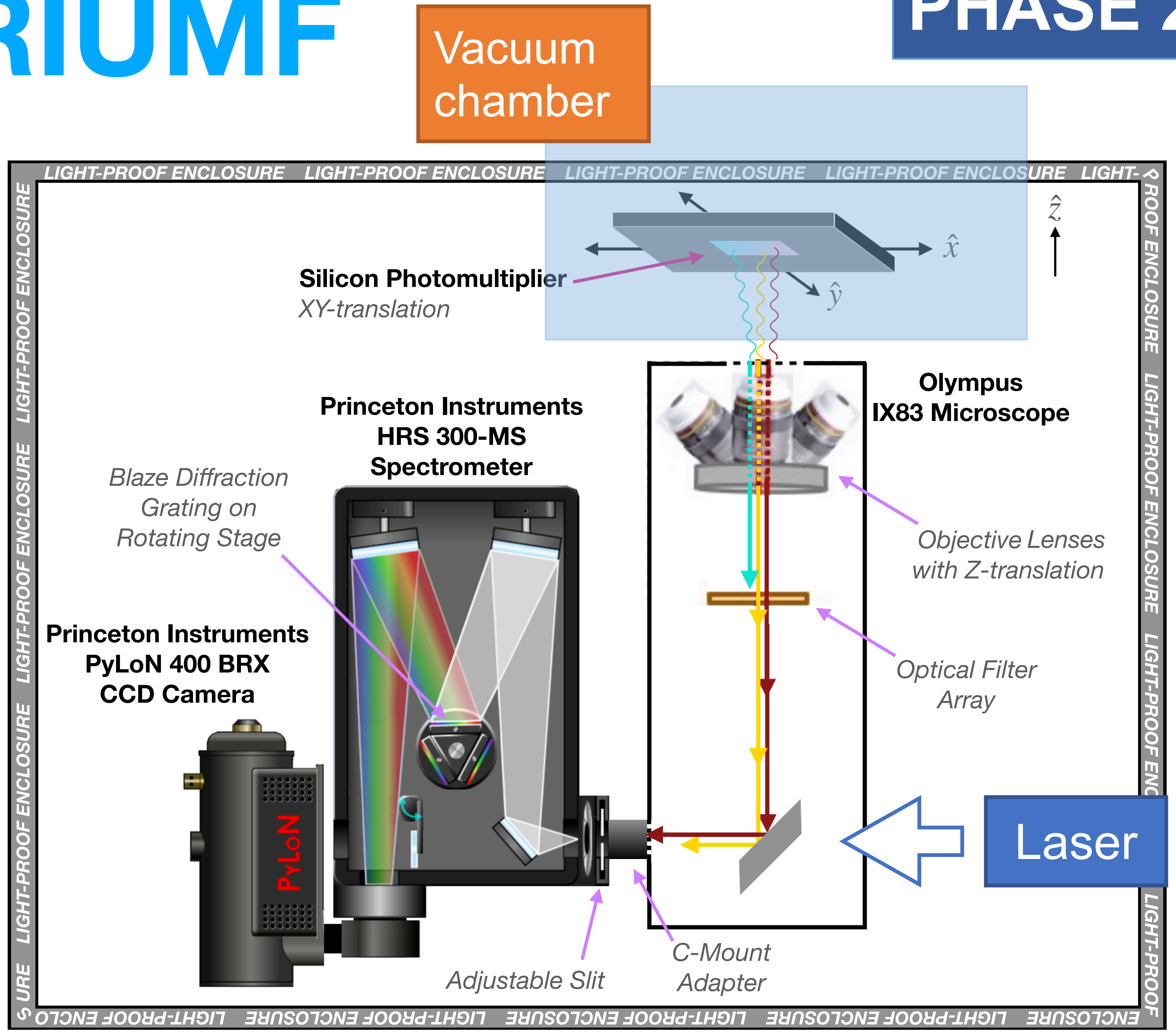


HPK light emission present not-uniform distribution

Optical Cross talk measurements at TRIUMF

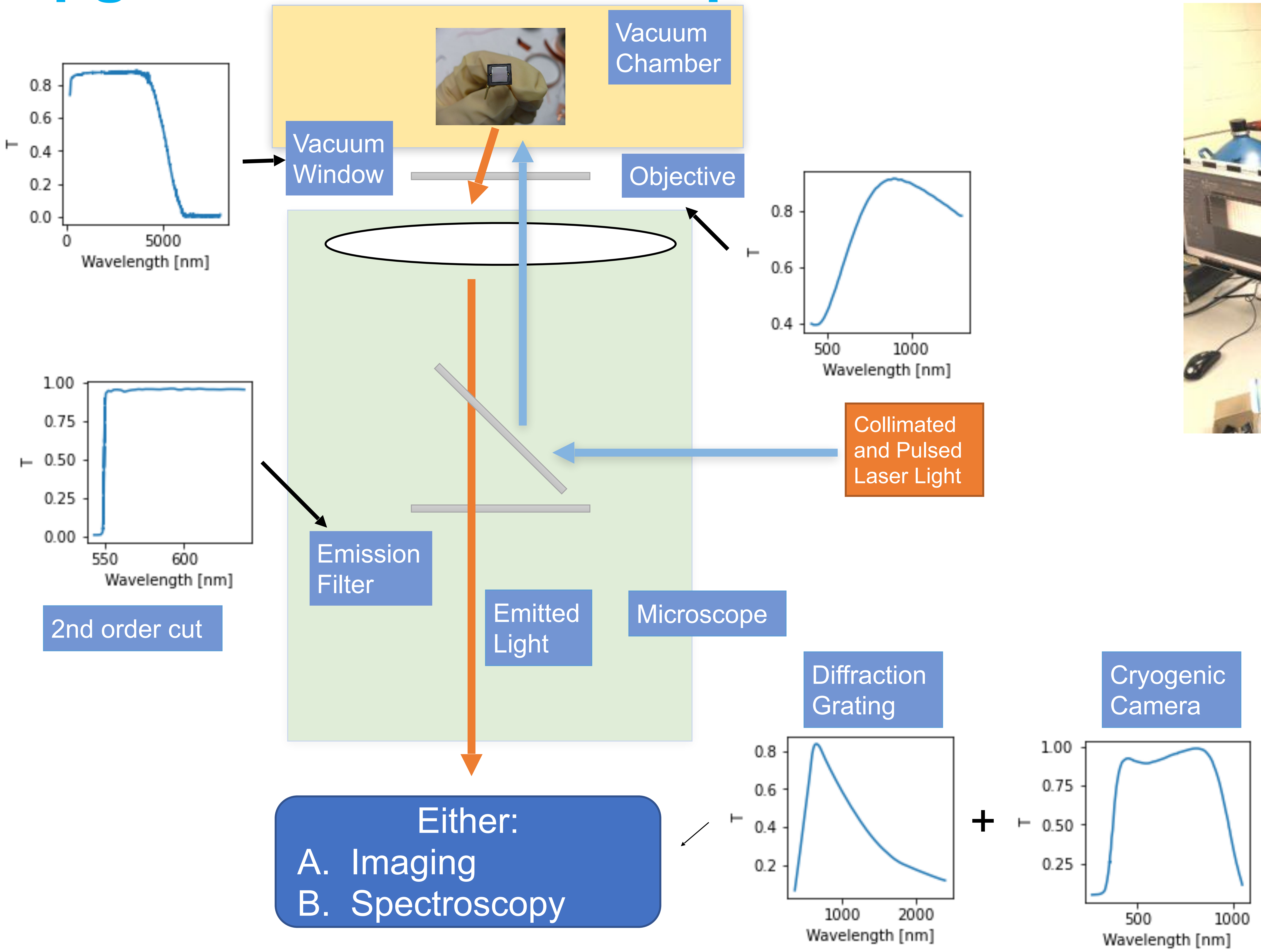
PHASE 2

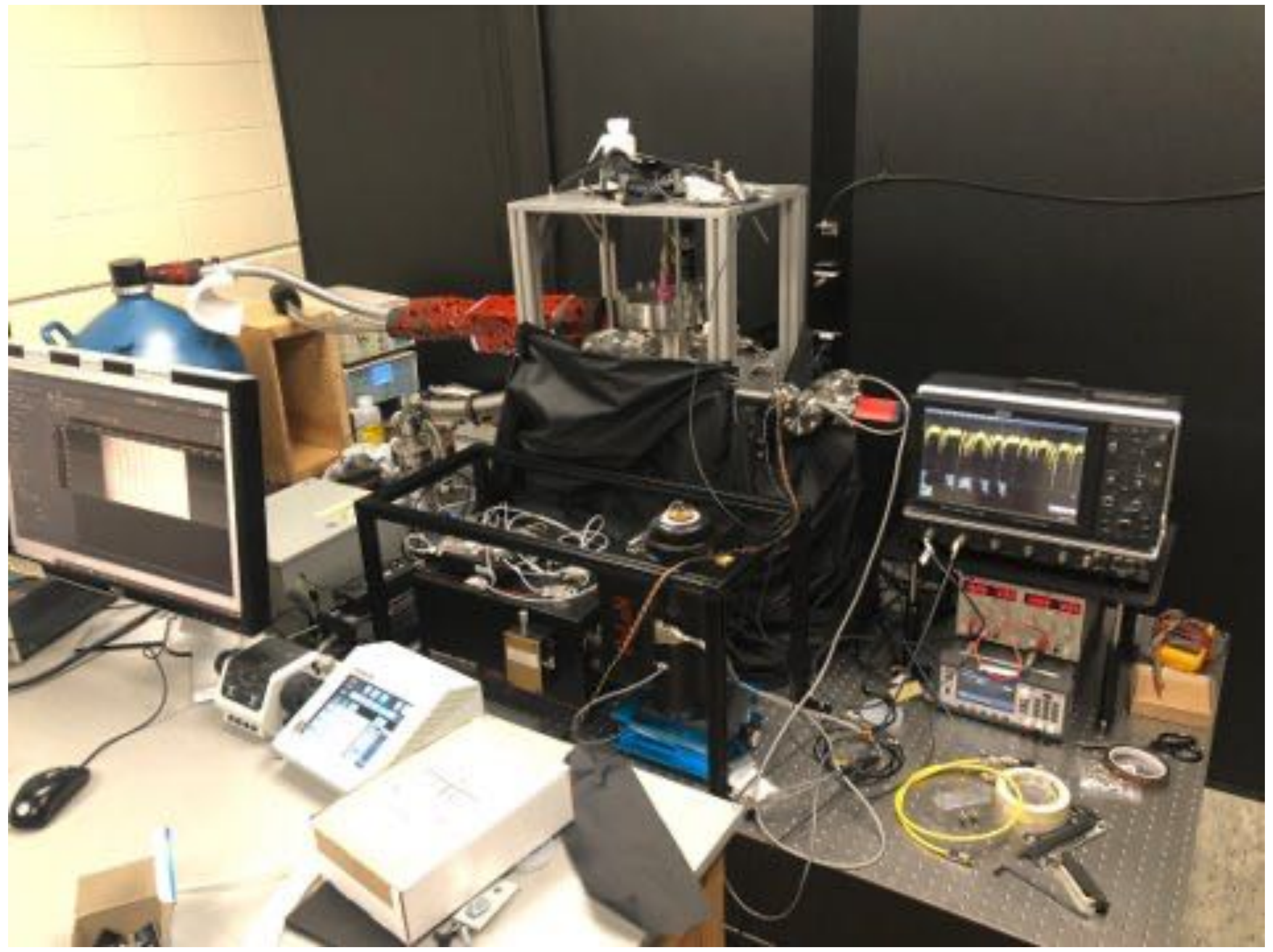


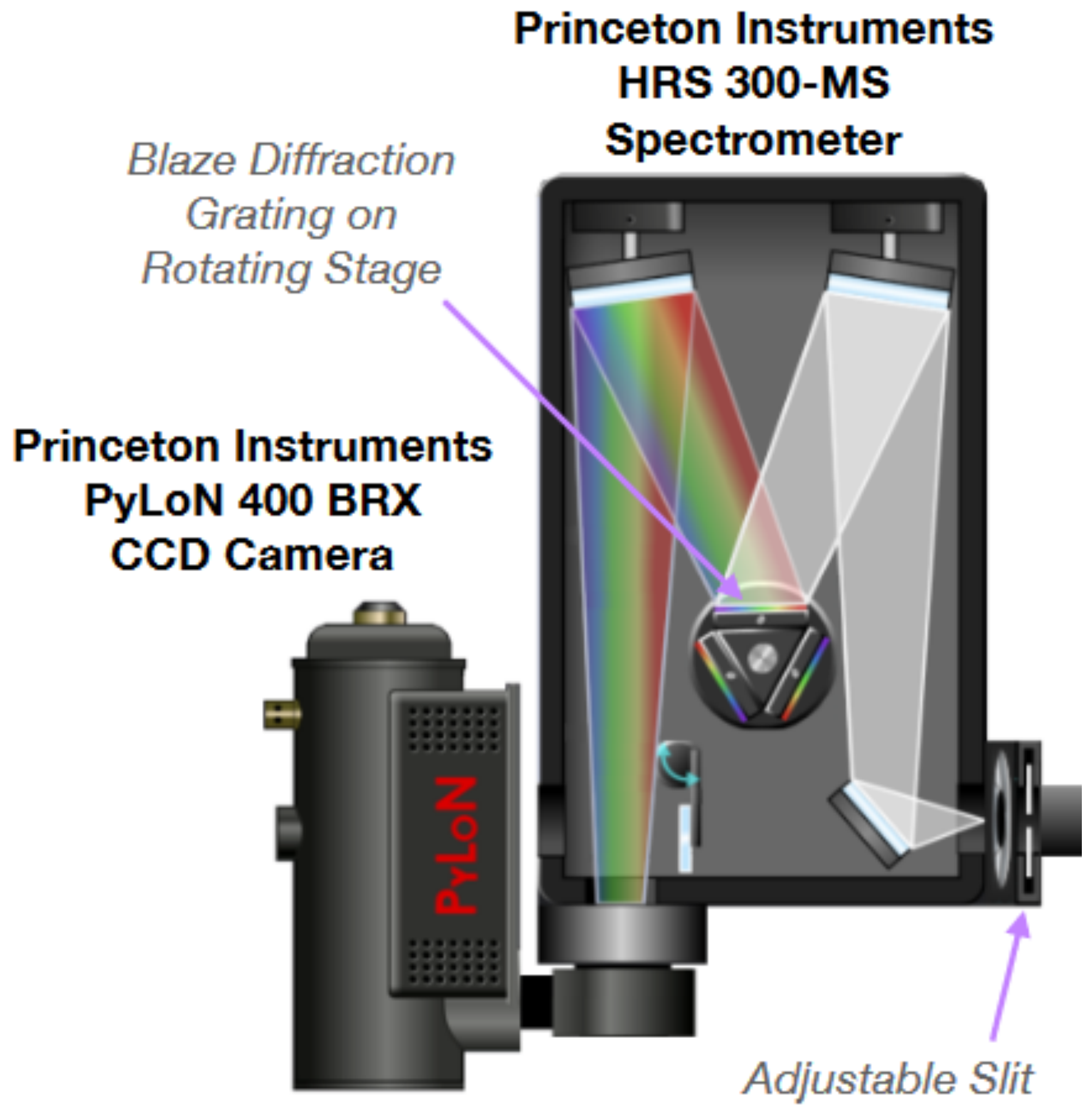


- Cryogenic measurements.
- Vacuum chamber at the top of the microscope with a window
- Laser injection to probe low over voltages

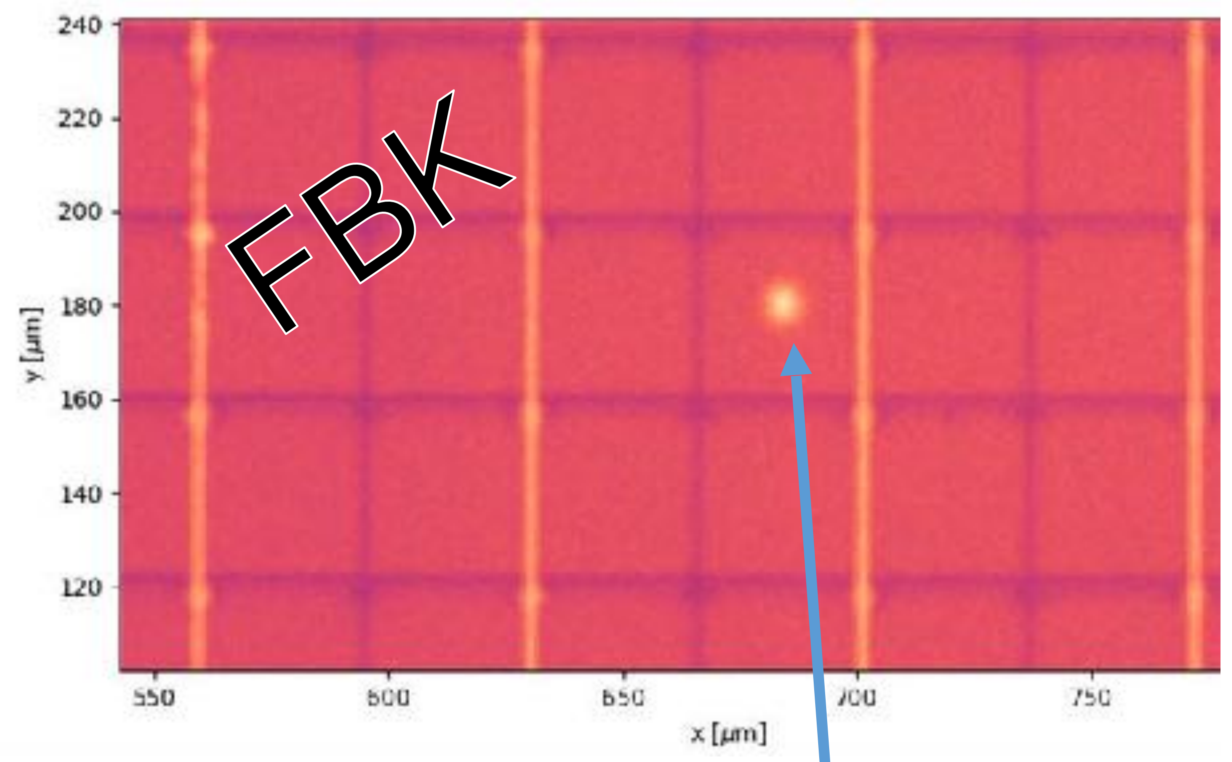
Upgraded TRIUMF setup



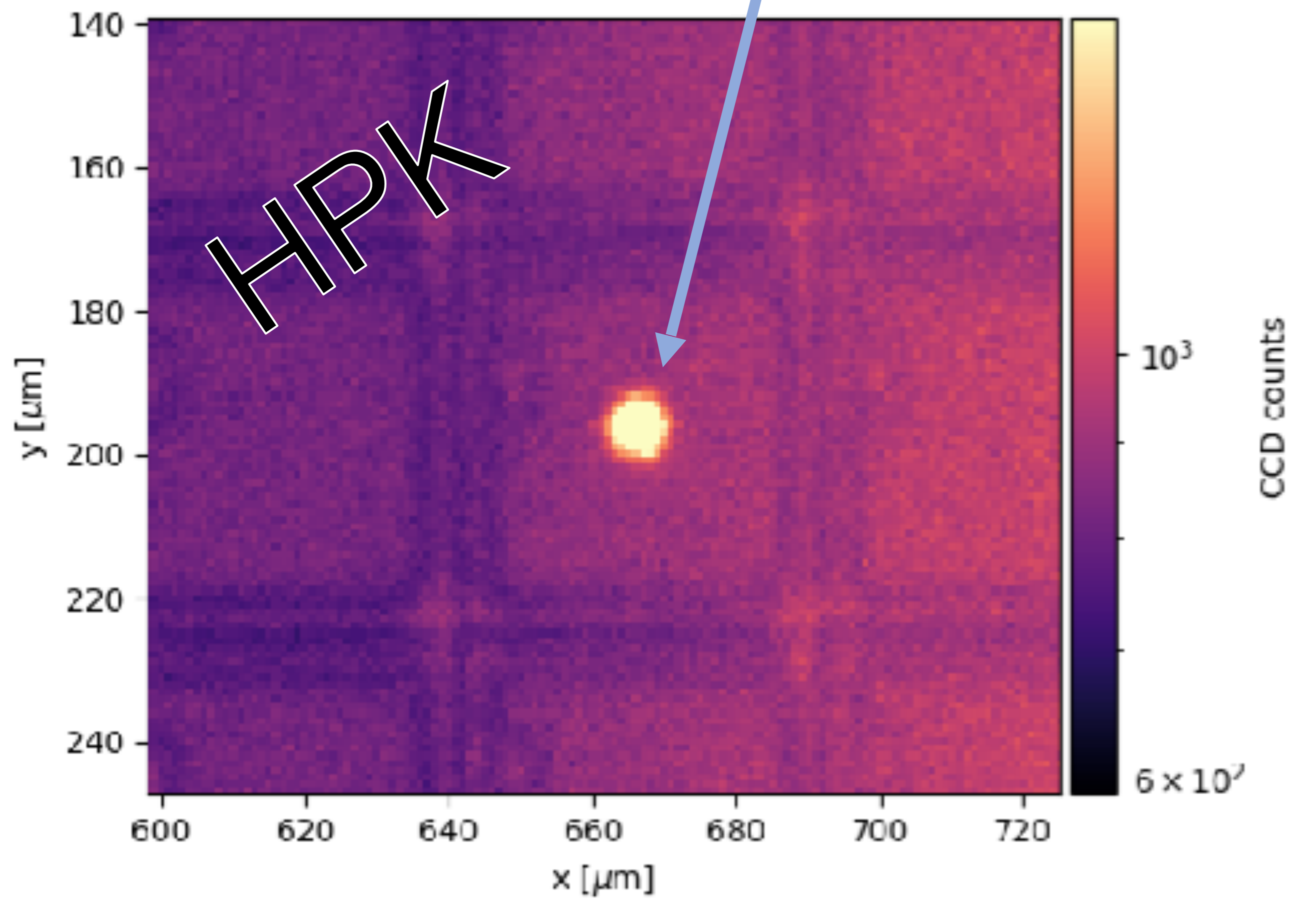




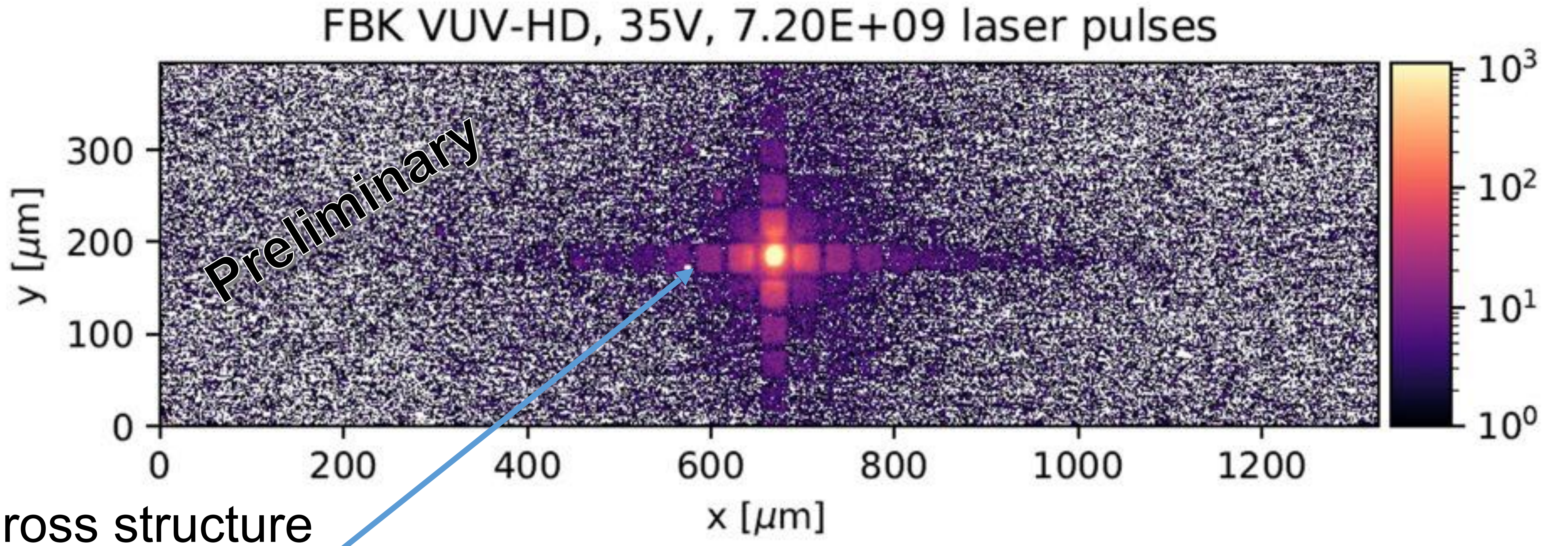
External Crosstalk measurements Laser Driven



Laser Spot

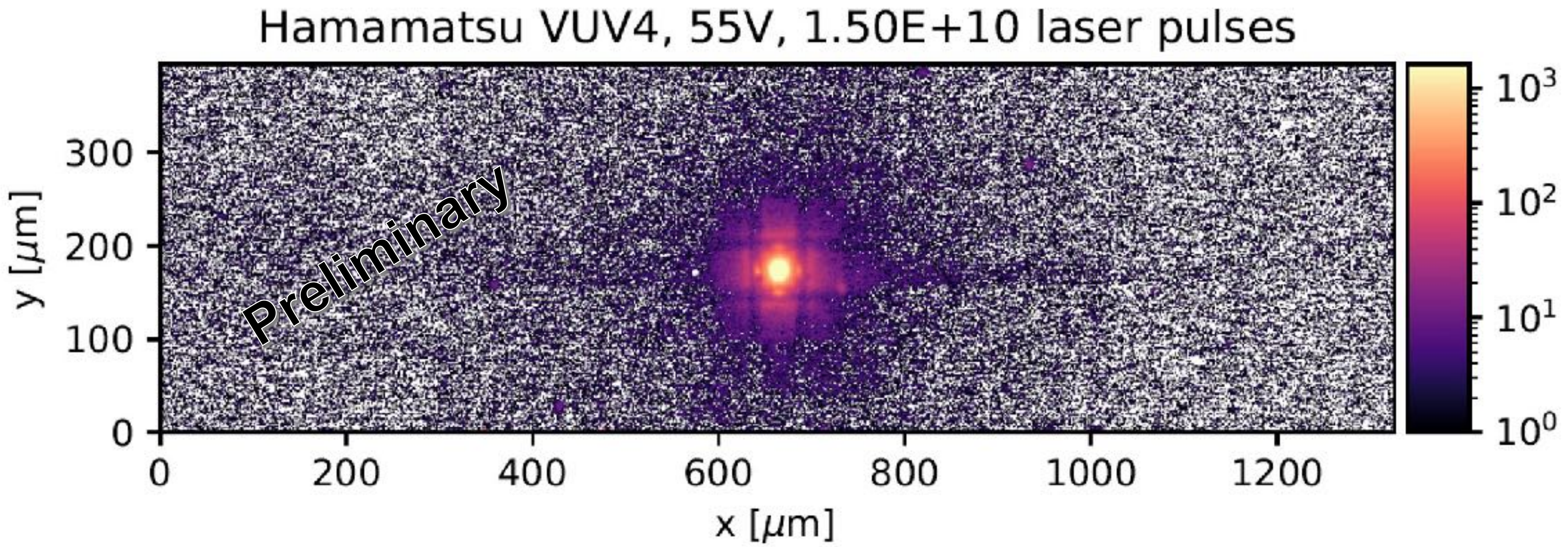


Emission Map (A)



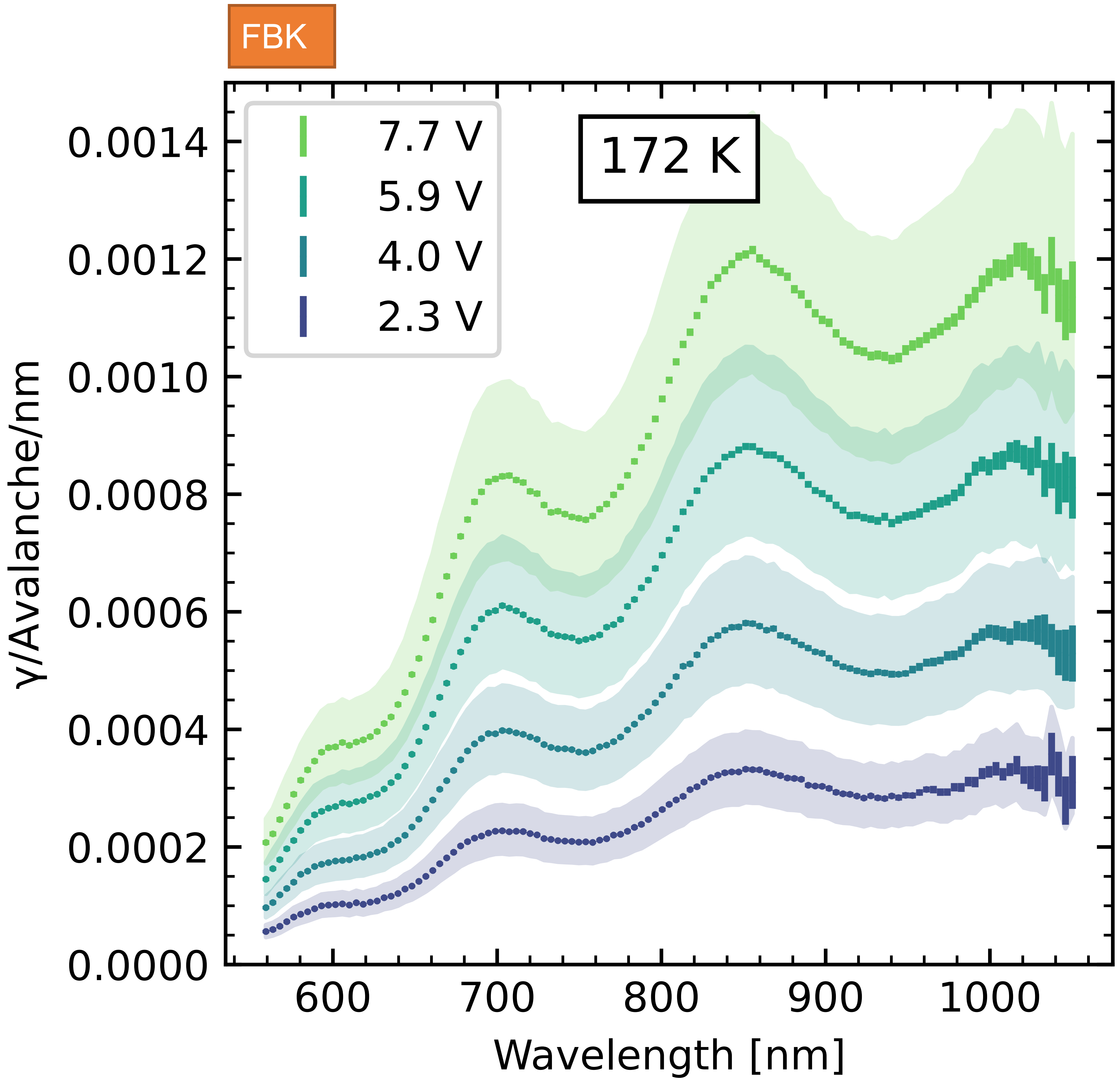
Cross structure

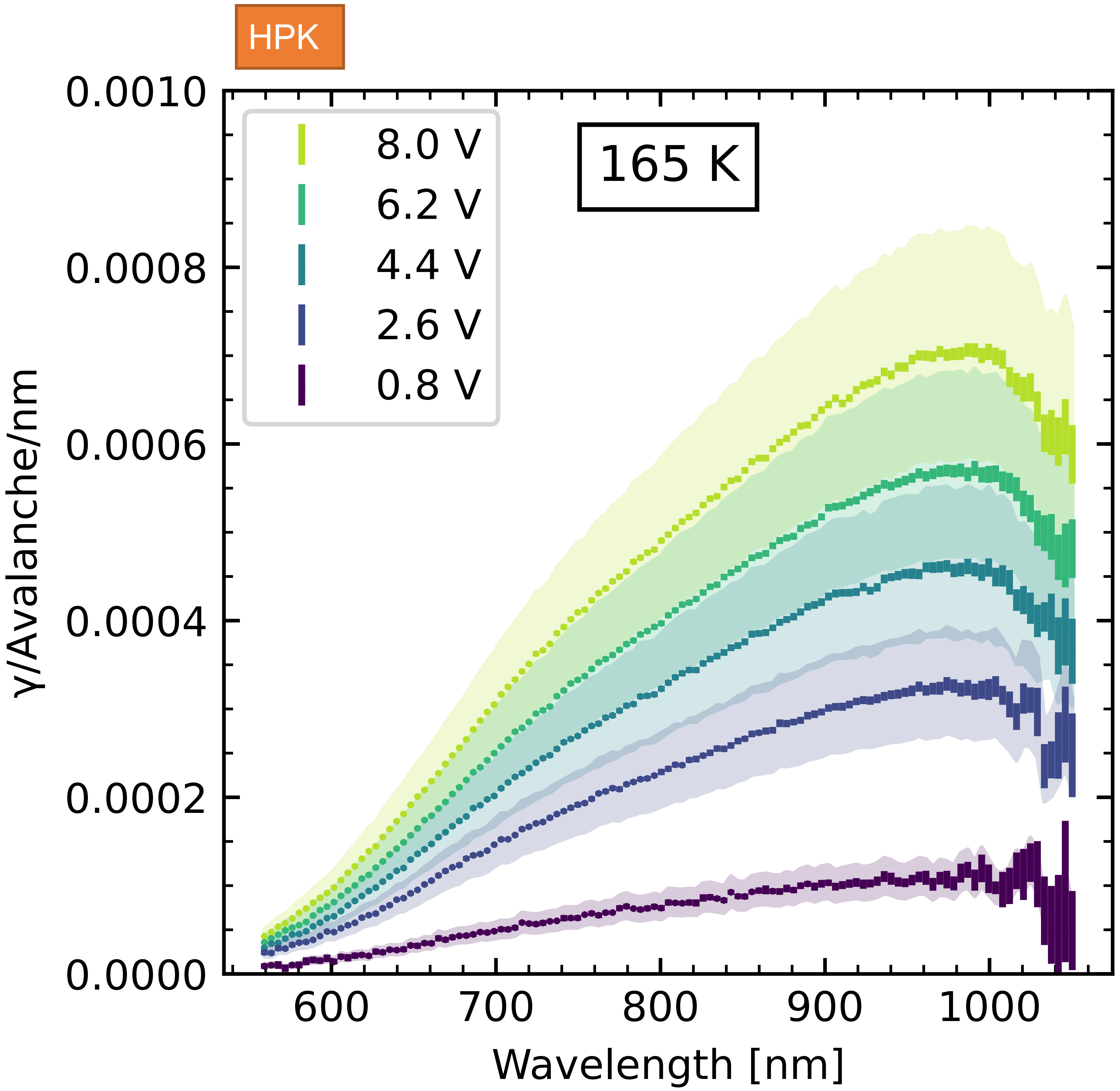
*images include prompt and delayed cross-talk



External CT driven by Laser Avalanches: Spectroscopy mode

Preliminary



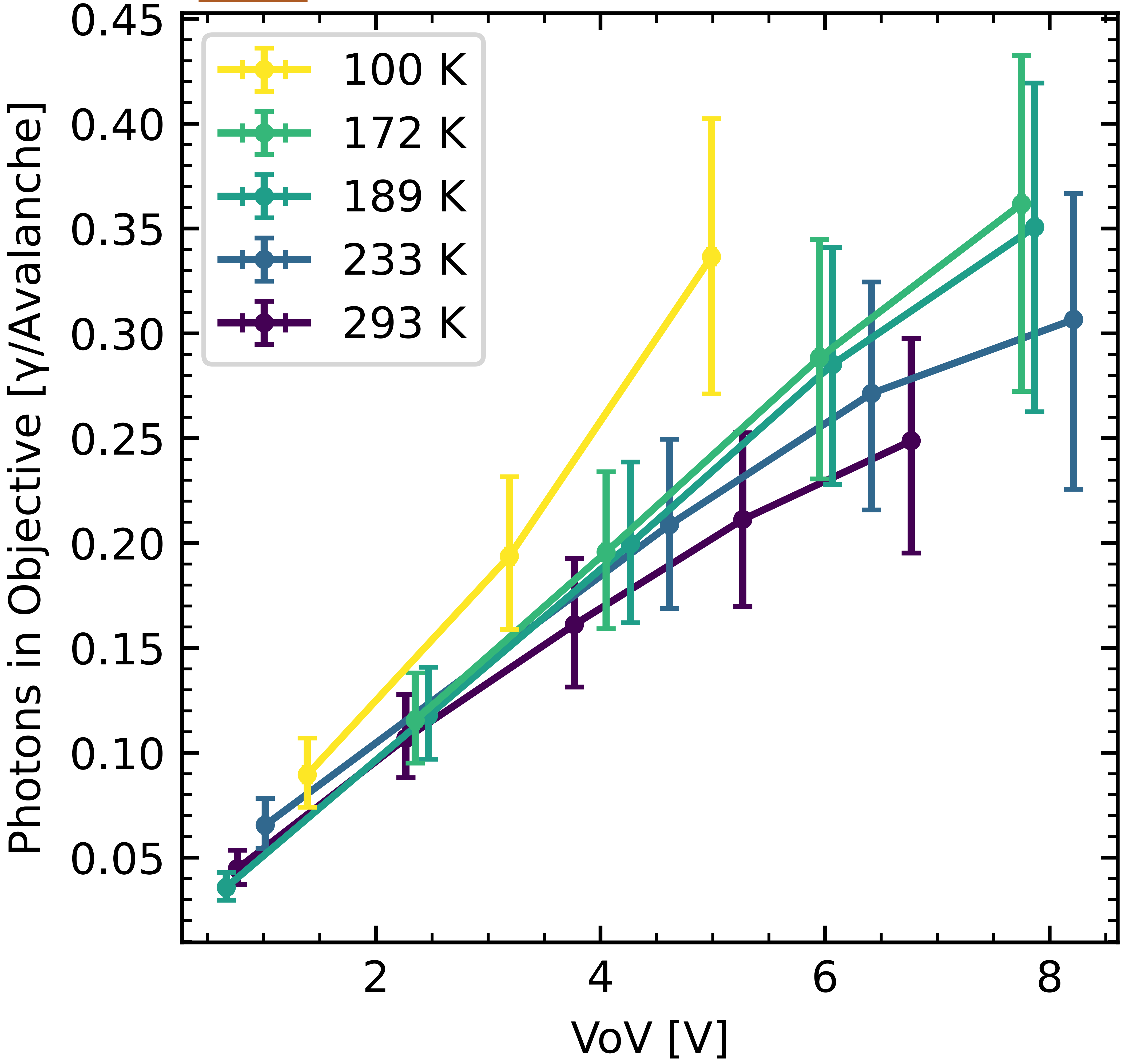


- Interference patter compatible with PDE measurements

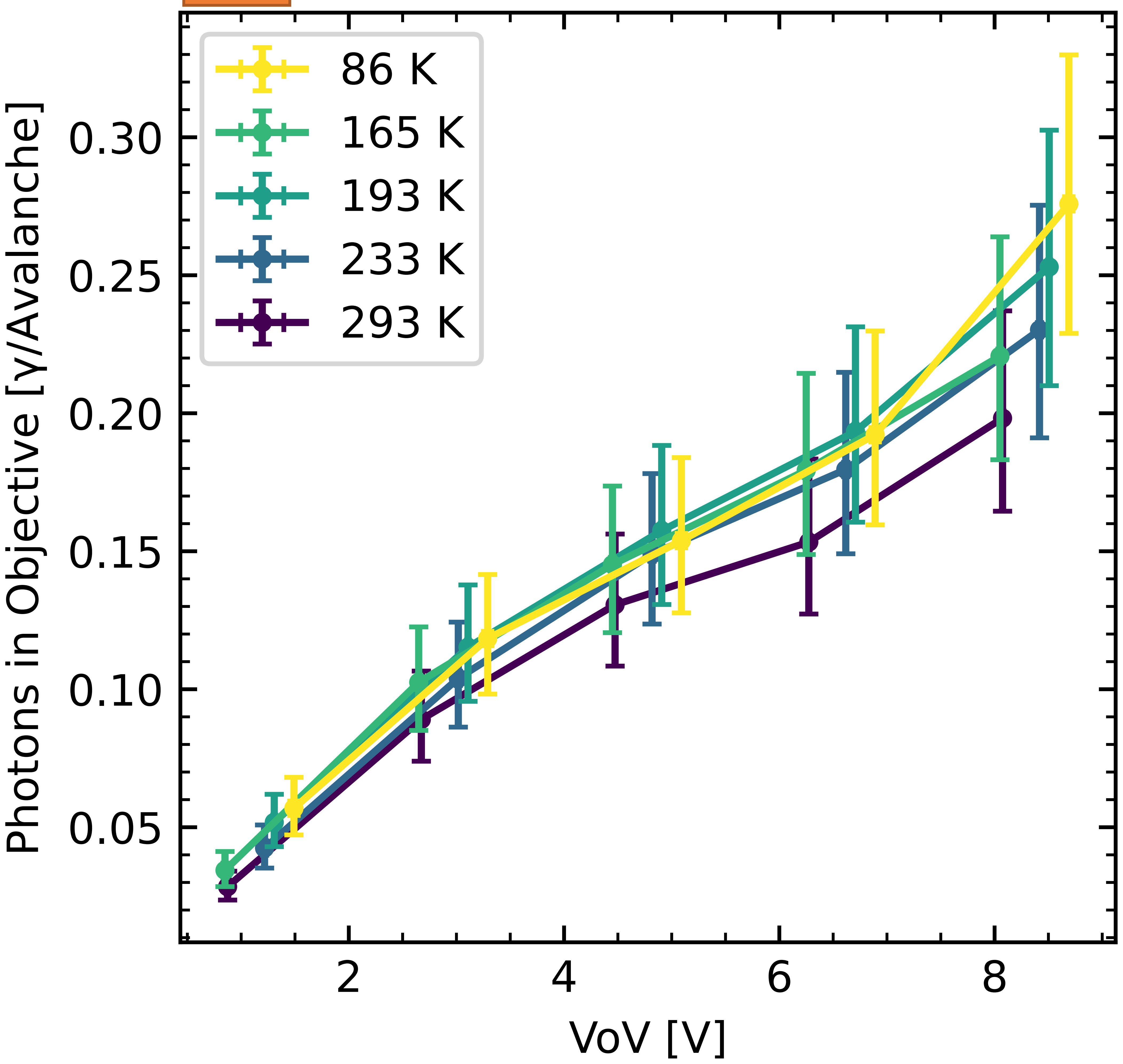
External CT driven by Laser Avalanches: Spectroscopy mode (Integral)

Preliminary

FBK

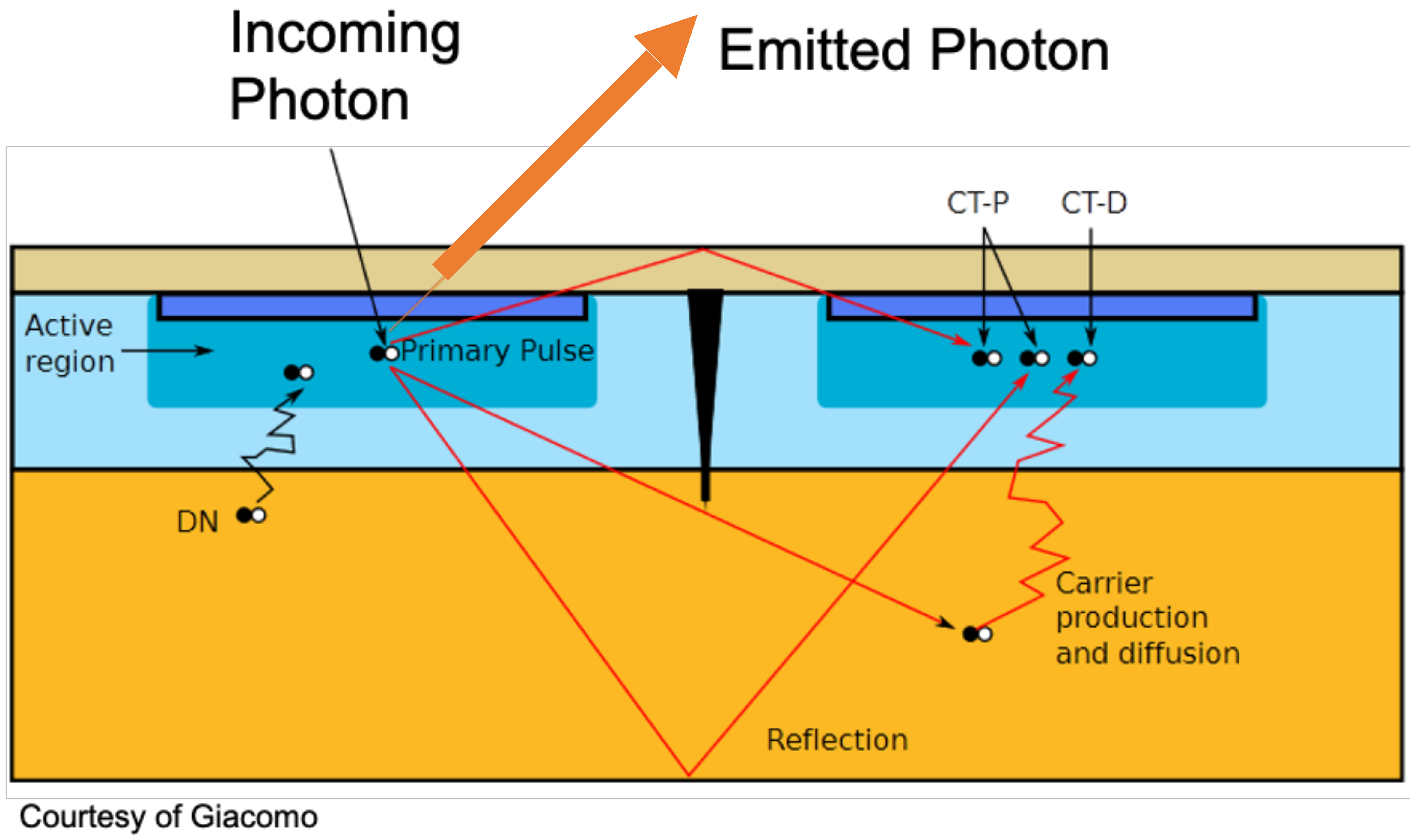


HPK

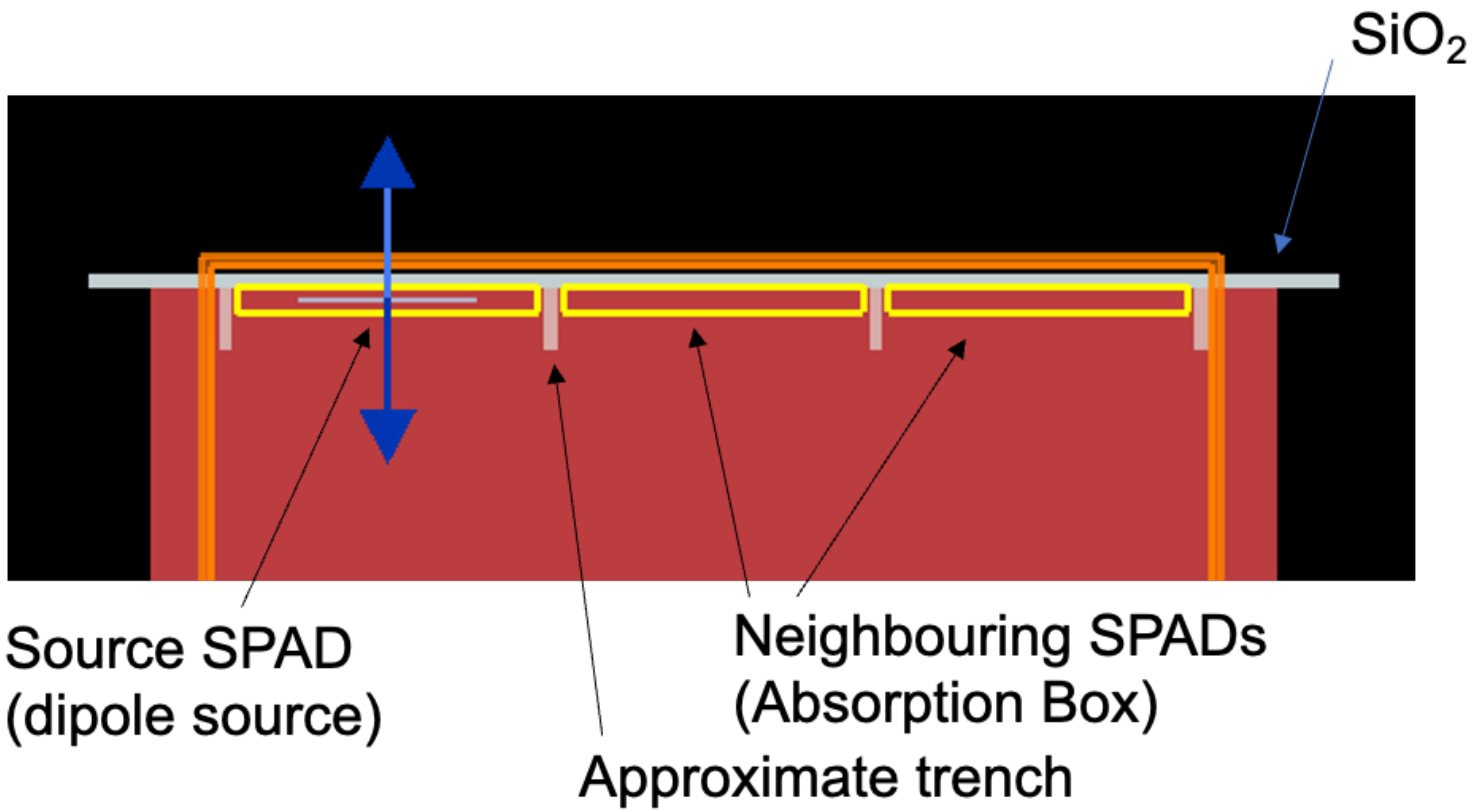


Very little ! Yes, but this is only what it gets in the NA of the objective ….

Extraction of the photon source term



Ansys Lumerical FDTD

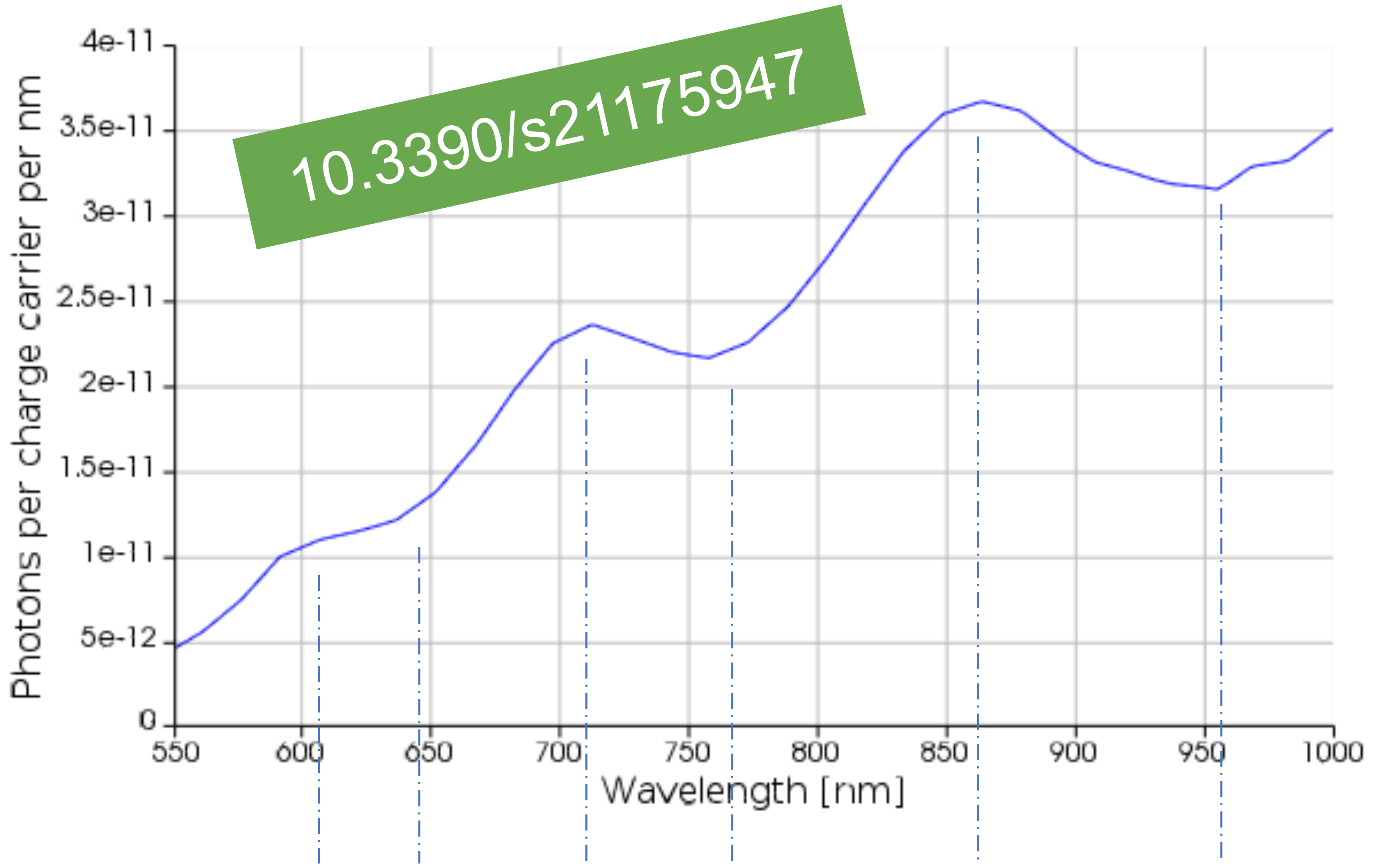


•Photons are produced as a result of the avalanche process

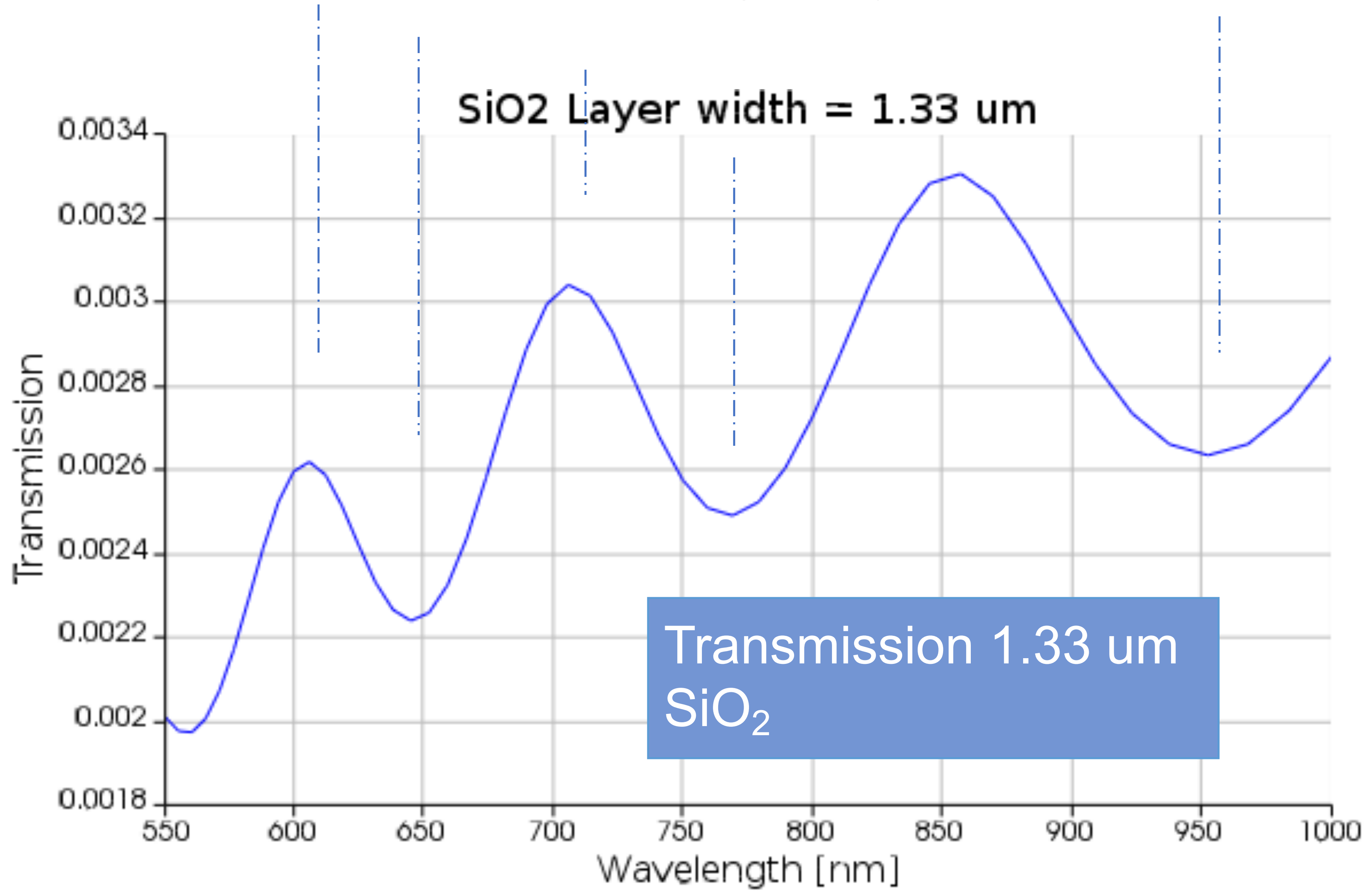
- Attempt at simulating the cross-talk effects using an isotropic source located in the avalanche region

Extraction of the photon source term

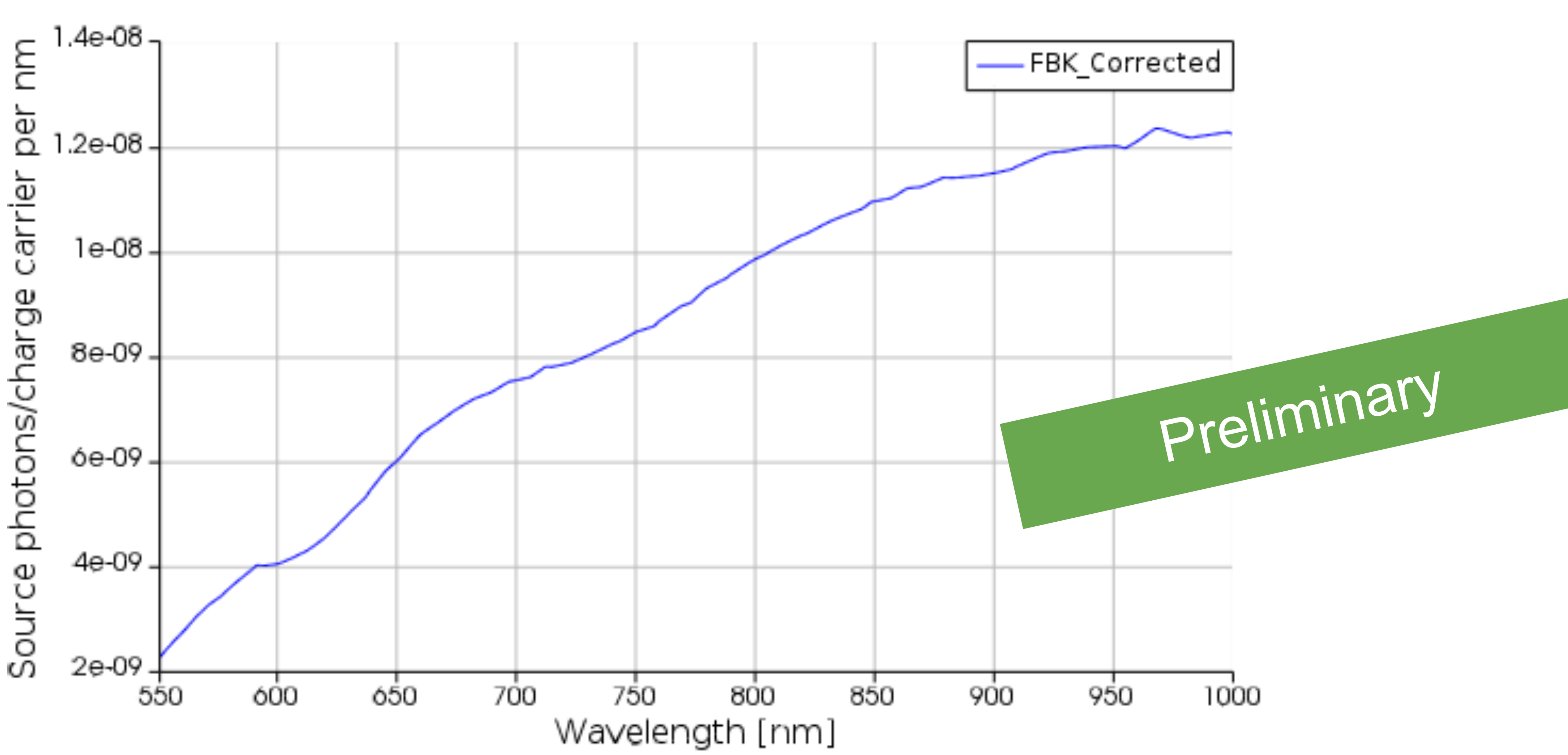
Published FBK Measured Emission Spectrum



Simulated transmission using Ansys Lumerical FDTD



Extracted Photon Production Spectrum at Source



- **Slight miss-alignment** between interference peaks leads to small oscillation.
- The source spectrum is **not expected to have any oscillations**

Extraction of the photon source term

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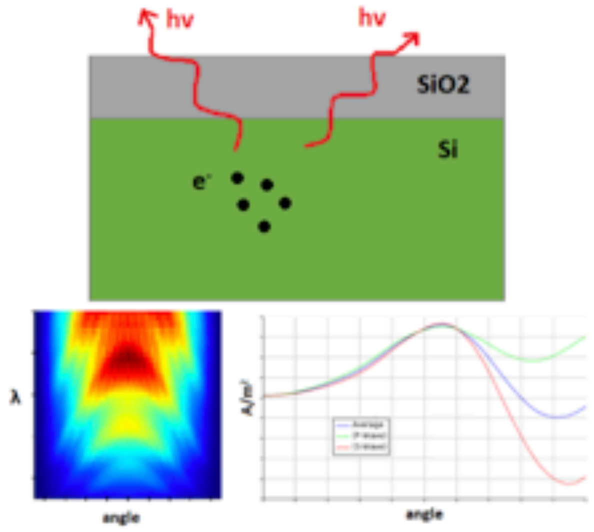
In this article

SPAD Secondary Emission and Absorption

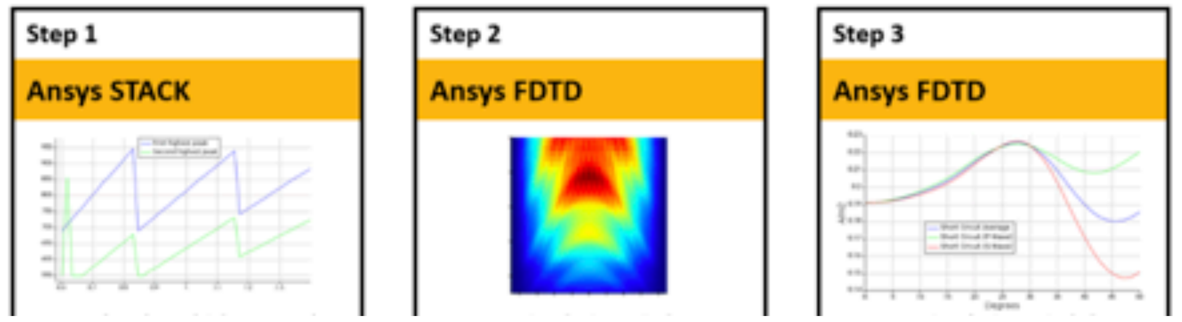
FDTD | STACK | Photonic Integrated Circuits - Active

Secondary photons are emitted during the avalanche process of a single photon avalanche detector (SPAD) and they contribute to the internal and external cross-talk. In this example, we demonstrate how to calculate the transmission function between the secondary light source location inside SPAD and the measuring microscope objective. This transmission is a correction factor that, when combined with the measurements of the far-field secondary emission spectrum, allows us to calculate the secondary photon production spectrum at the source inside SPAD. We then demonstrate how to scale the far-field simulated power to include the correct source photon production spectrum. In the end, we demonstrate how to perform an external light absorption simulation in the same SPAD.



Overview

Understand the simulation workflow and key results



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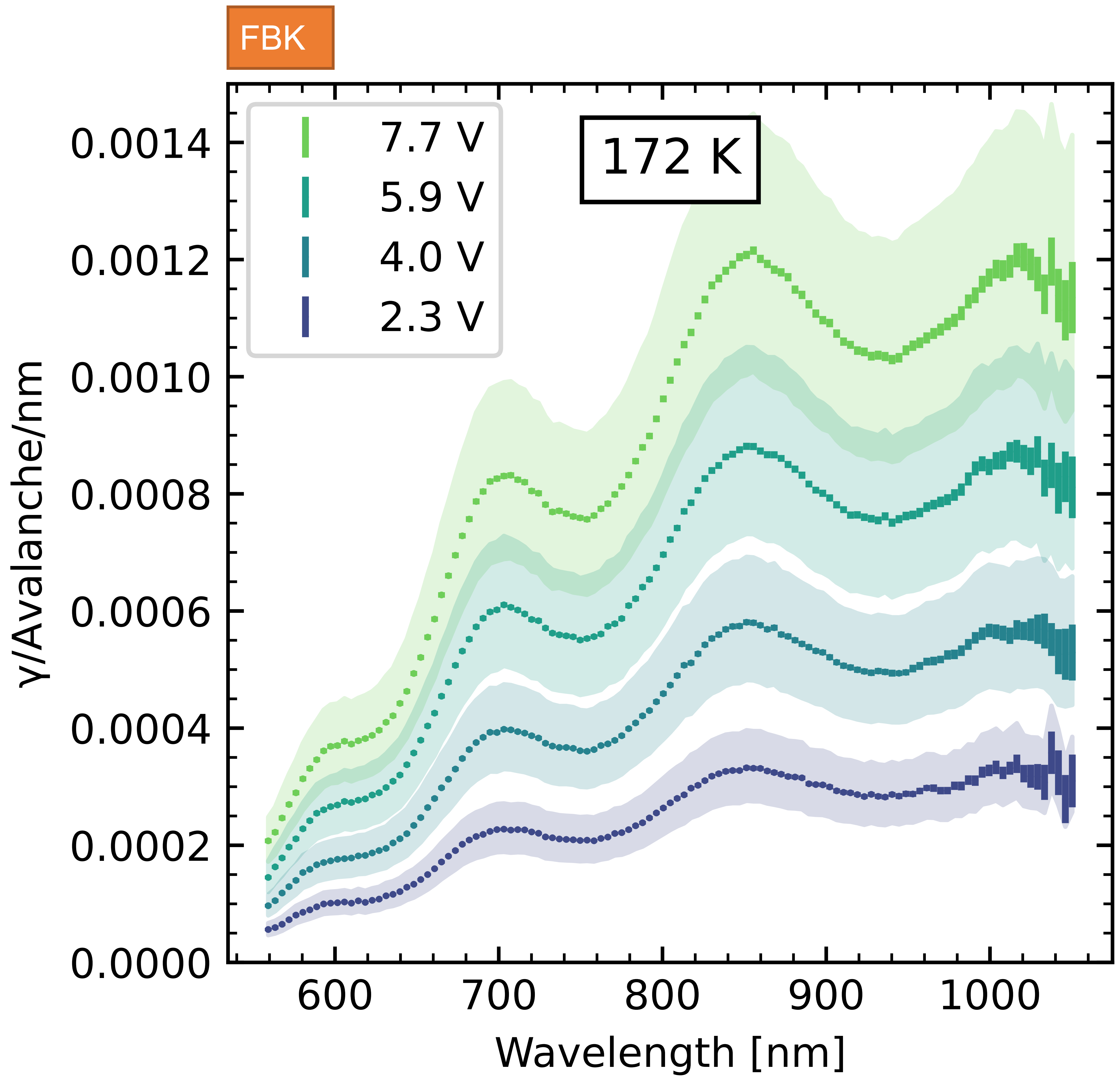
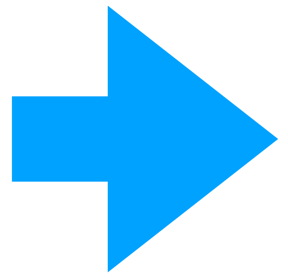
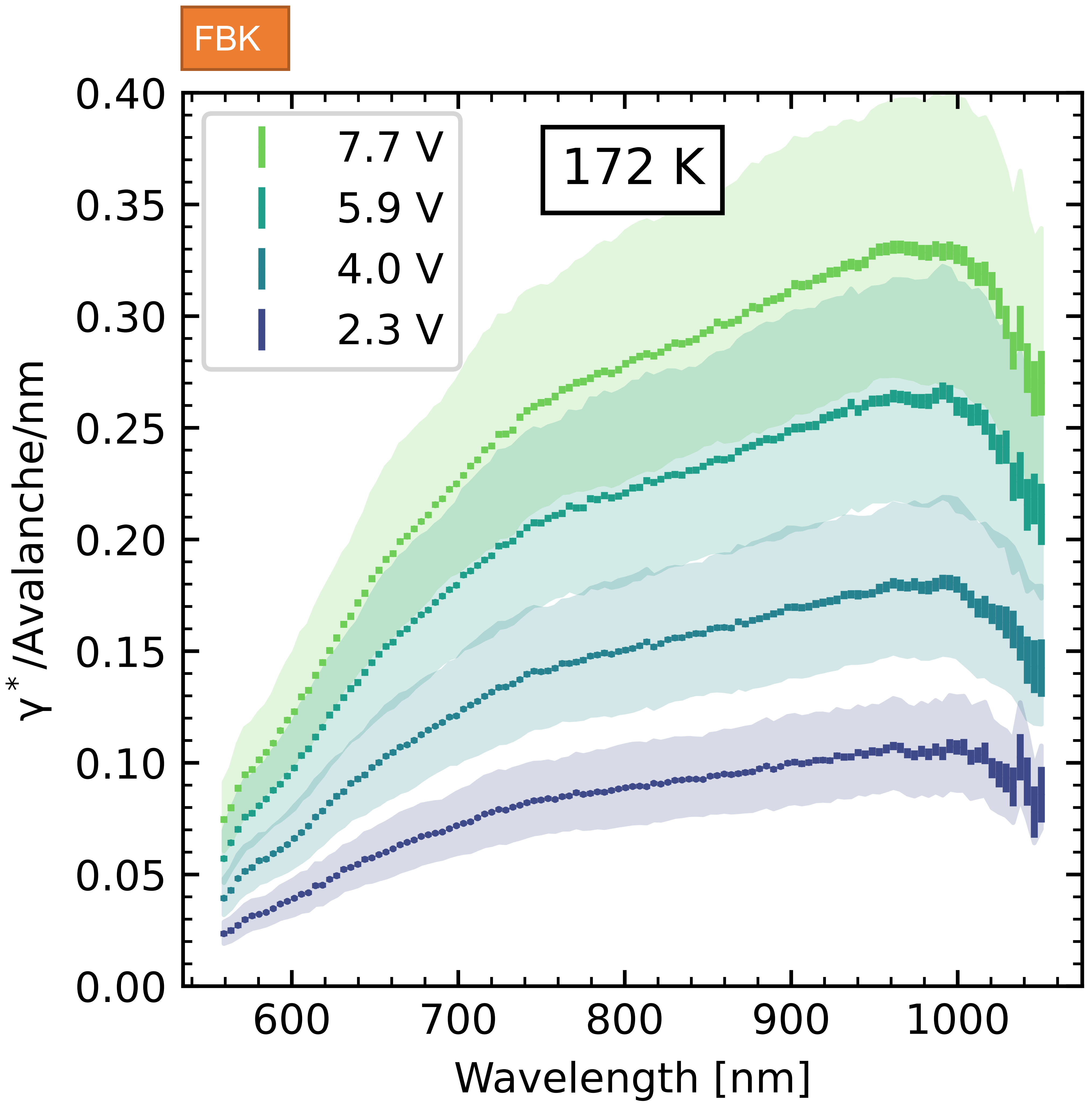
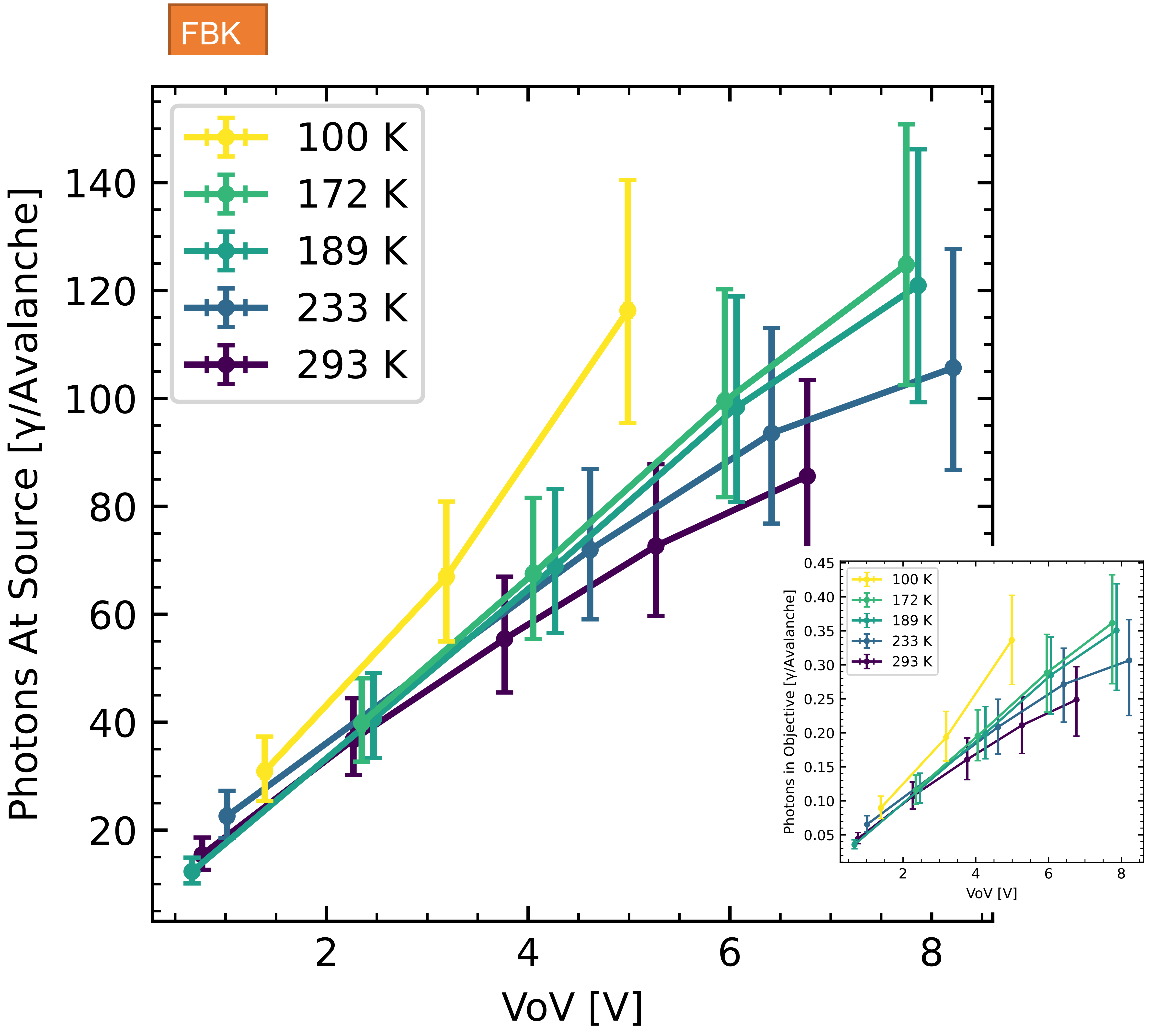
Extraction of the photon source term

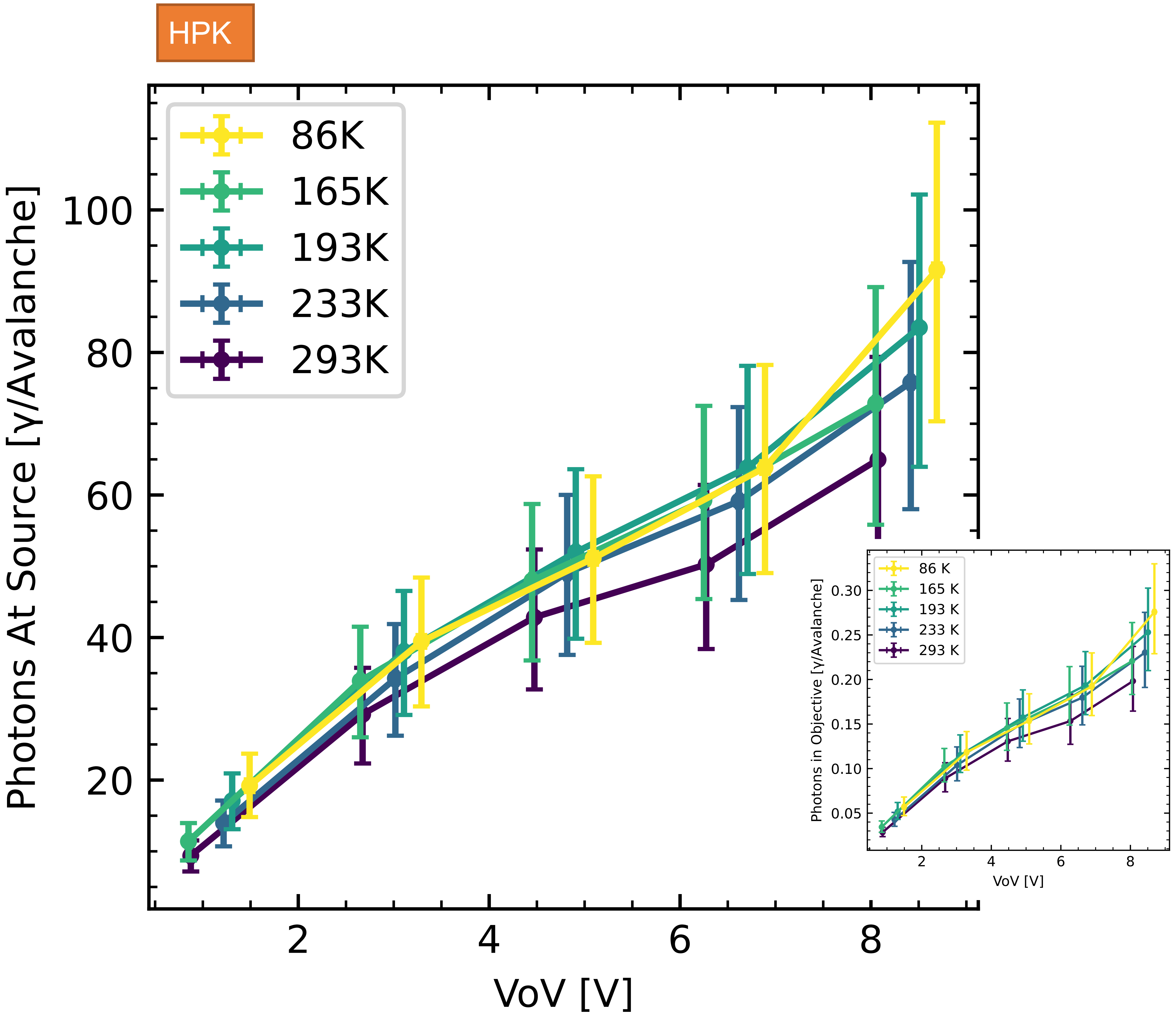






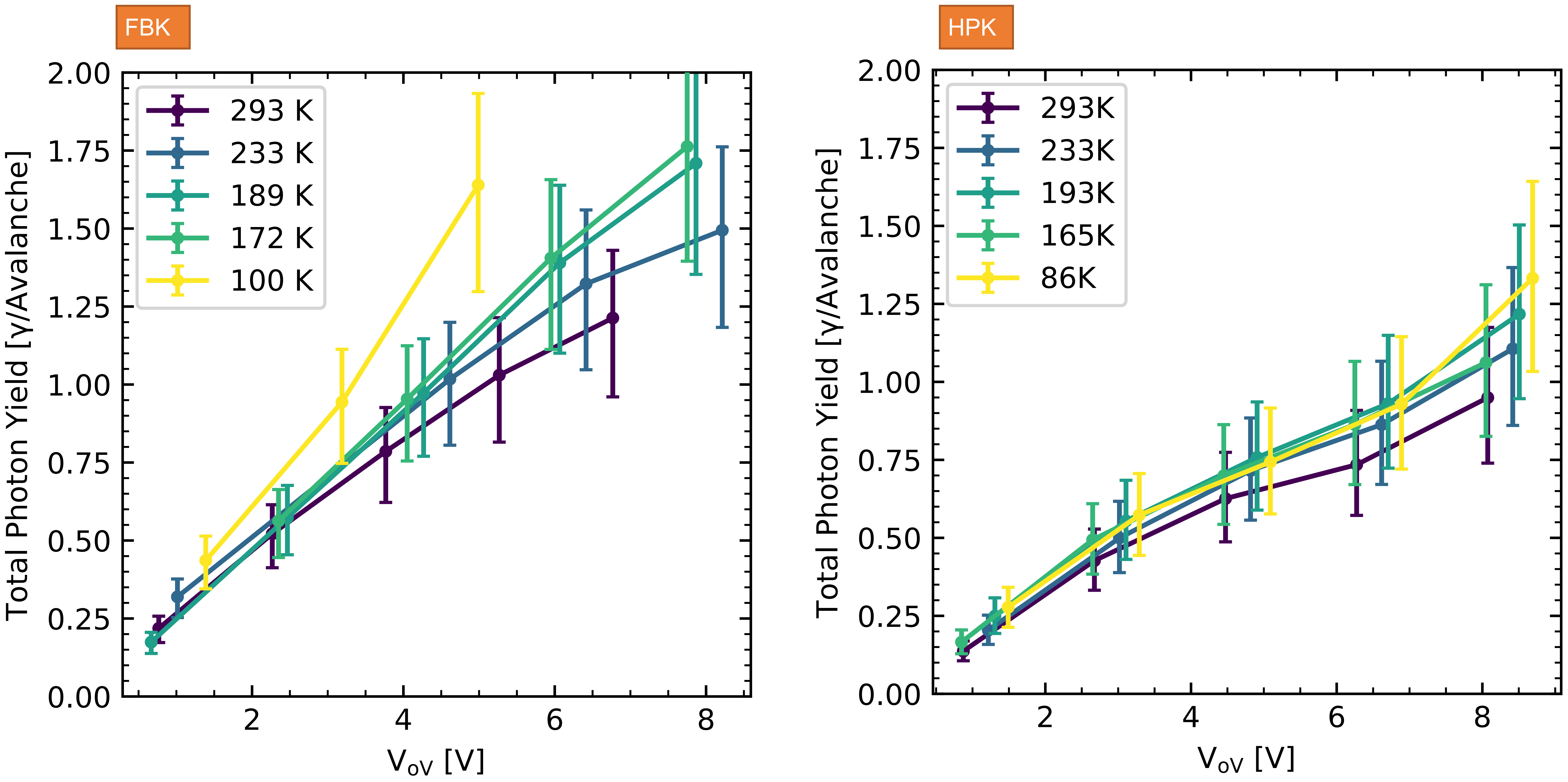
Light Produced/Source in the silicon (Integral)





More that 100 photons produced x avalanche, depending from Vov ! But again this is **in the silicon.**

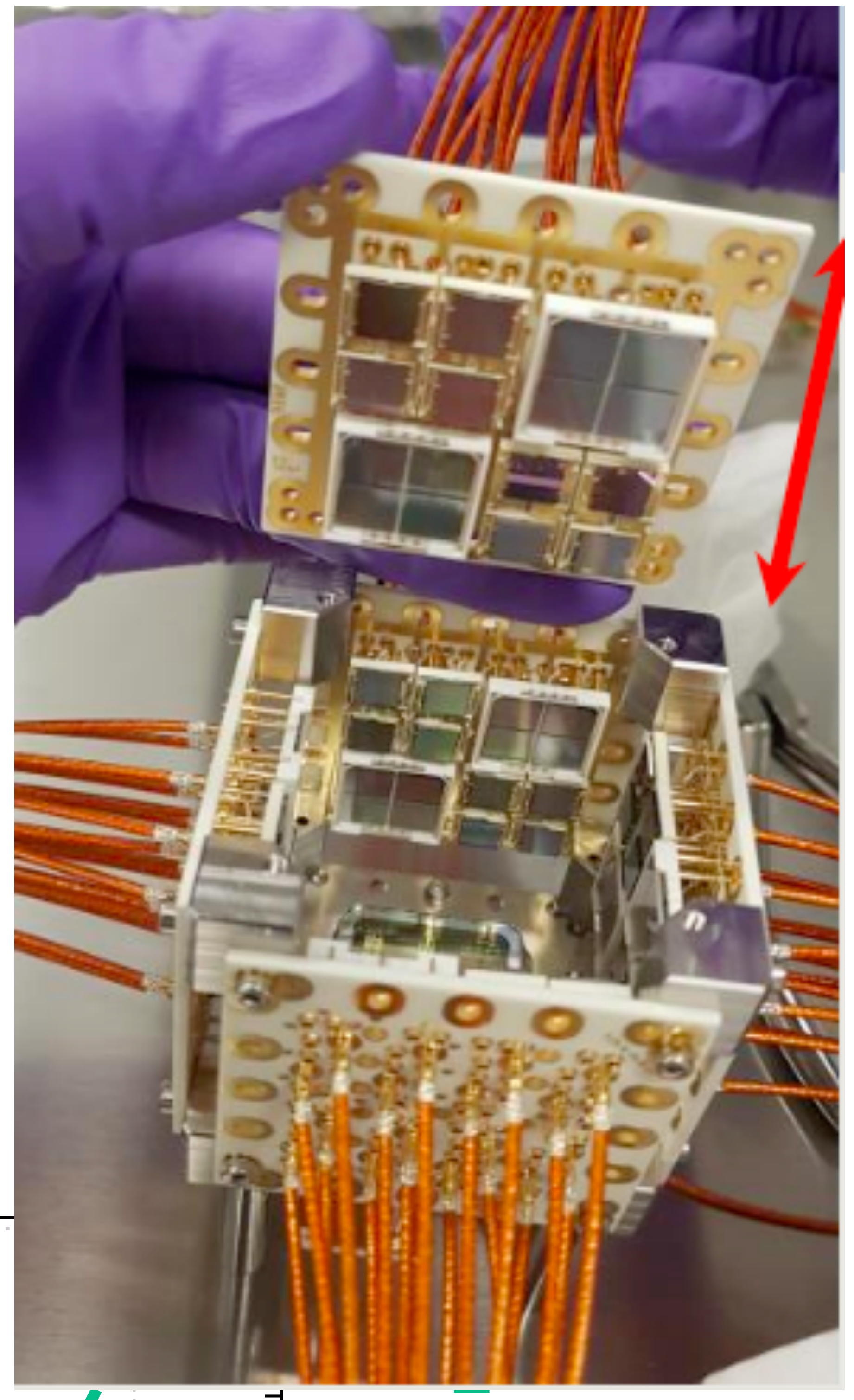
External CT driven by Laser Avalanches in Air



On average 1/2 photons per pulse are emitted in Air, depending from Vov, what about LXe and LAr ?

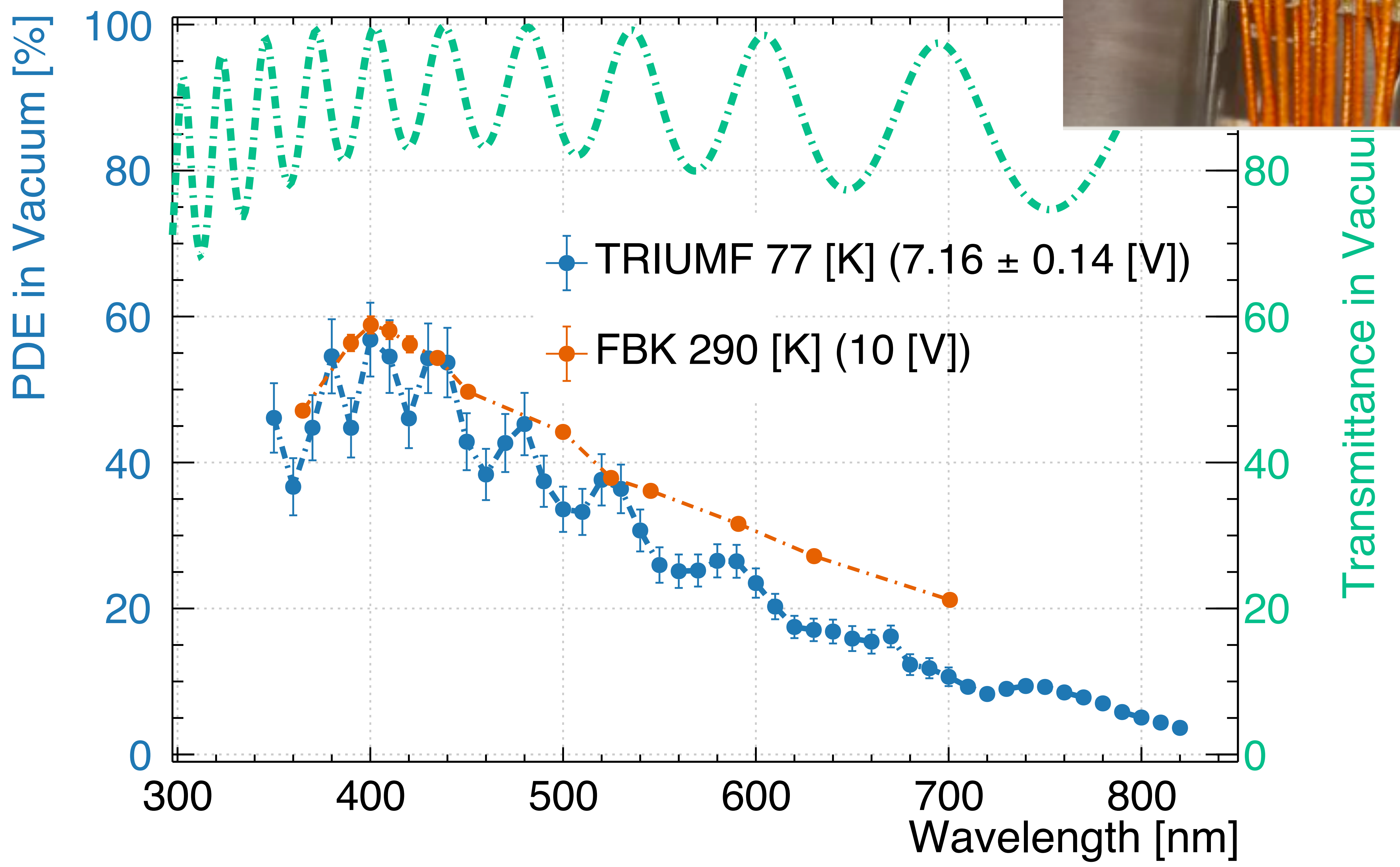
External CT driven by Laser Avalanches (LXe/LAr) at 4Vov

Device	Source Photon (at 293°K) per Avalanche	Source Photon (at 293°K) per e^-	Photon Yield/Avalanche Air	Photon Yield/Avalanche LXe
HPK VUV4	37 ± 7	$(1.5 \pm 0.3)\times10^{-5}$	0.6 ± 0.2	1.2 ± 0.4
FBK VUV-HD3	56 ± 7	$(2.4 \pm 0.3)\times10^{-5}$	0.8 ± 0.2	1.8 ± 0.4



Strategy that follows

- Measure Photon Yield in MIEL
- Measure PDE in the infrared (see DS-20k SiPMs as an example)~10%
- Use LolX to validate in situ (LXe) results



Conclusions

Conclusions

- Presented a complete set of measurements on eCT that can be used in simulation.
- A publication is in progress with these new results.
- Need more time to understand the impact on energy resolution.
- Minimum is preserved but it may degrade energy resolution at higher Vov

LOGO GENERIC COLORIZED JOURNAL, VOL. XX, NO. XX, XXXX 2023 1

Stimulated Secondary Emission of Single Photon Avalanche Diodes

Kurtis Raymond, *Student Member, IEEE*, Fabrice Retière, *Member, IEEE*, Andrea Capra, Harry Lewis, Duncan McCarthy, Austin de St Croix, Giacomo Gallina, Joe McLaughlin, Juliette Martin, Nicolas Massacret, Paolo Agnes, Ryan Underwood, *Member, IEEE*, Seraphim Koulosousas, Peter Margetak

***Abstract*—Large-area next-generation physics experiments rely on using Silicon Photo-Multipliers (SiPM) devices to detect single photons. SiPMs are a 2-dimentional array of Single Photon Avalanche Diodes (SPADs), achieving gains in excess of 10^6. Secondary photons are also produced during this avalanche process. The internal cross-talk process is the production of spurious avalanches when these photons travel to neighbouring SPADs within the same device. The external process is when the photons the SiPM and produce an avalanche in a neighbouring SiPM. This latter process is potentially a major issues for experiment non-optically isolated SiPMs, as one thermal avalanches can potentially yield to multiple channels firing at the same time. The scope of this paper is the detailed characterization of the light escaping the SiPM. SiPMs from Hamamatsu (HPK) VUV4 and Fondazione Bruno Kessler (FBK) HD3 devices were characterized at a range of voltages and temperatures from 293°K to 86°K. Accounting for the photon transport processes from emission to detection in the MIEL system, yields 47±9 and 56±7 photons produced per avalanche for HPK VUV4 and FBK VUV-HD3 respectively, with no significant temperature dependence within the measurement uncertainties. The number of photons produced per electron is relatively constant between 1 and 2 10^{-5}. This paper then includes a prediction of the wavelength and angular distribution of the photons emitted in air/vacuum, liquid Argon and liquid Xenon that can be used to predict the performance of future large experiments.**

***Index Terms*—silicon photomultipliers (SiPM), SiPM Cross-talk, SiPM Emission, silicon photo-multiplier (SiPM)**

I. Introduction

Silicon Photomultipliers (SiPMs) have emerged as a compelling solution for detecting single photons in applications ranging from particle physics to medical imaging and beyond [1]. They have sub-nanosecond timing resolution in addition to being compact and insensitive to magnetic fields [2]. In this paper, we focus on the characterization of SiPMs developed by Fondazione Bruno Kessler (FBK) and Hamamatsu Photonics (HPK) for use in liquid Xenon in the context of the nEXO experiment [3]. The most relevant features are their sensitivity in the vacuum ultraviolet range (higher than 15% efficiency at 175 nm for $\geq$ 2V over-voltage) and very low dark noise rate (less than 1 Hz/mm^2 at 3V over-voltage) at liquid Xenon temperature (about 168K) [4].

A SiPM is an array of single photon avalanche diodes (SPADs), that are electrically isolated from each other and operated above the device-dependent breakdown voltage, V_{br}. Incident photons on the device surface will produce a charge 'avalanche,' corresponding to a single SPAD's full discharge. The charge of an avalanche is given by the product of the diode capacitance, C_d, and the over-voltage $V_{OV} = V - V_{br}$, where V is the device operating voltage. Photon counting is achieved in SiPMs by counting the number of avalanches. However, the avalanche process produces further secondary photons, resulting in internal and external cross-talk noise mechanisms.

More generally, with internal cross-talk, we refer to secondary photons that trigger avalanches in neighbouring SPADs of the same SiPM without escaping from the SiPM itself. This includes secondary photons that escape from the surface of one SPAD and reflect back into the SiPM at the surface coating interface and trigger avalanches in neighbouring SPADs [5]. This process has been extensively studied in literature with both measurements [6] and simulation [7]. For the two devices of interest in this work, internal cross-talk was found to be more than 20% for the FBK SiPM but less than 5% for the HPK Multi-Pixel Photon Counter at $3V_{ov}$ [4].

External cross-talk labels the process that lead to avalanches in separate SiPMs. This process can be problematic for large surface area, SiPM-based detectors such as nEXOsince each SiPM can trigger other SiPMs in their vicinity, thus contributing to the detector background. For this reason, it is important to study the SiPM secondary photon emission to quantify the systematic effects hindering the overall detector performance.

This paper's scope is the characterization of light production in SiPM avalanche by recording the position and wavelength of the photons that escape the SiPMs. This work is to help develop models of photon production in SPADs and to predict the impact of external cross-talk on future experiment when embedded within simulations, modelling photon transport and detection efficiency. This work builds upon earlier studies by our group [8] characterizing the light produced by thermal avalanches. However, the measurements were performed operating the SiPMs at very high over-voltage in order to gather enough light. SiPMs are not used under such conditions in normal operation. This new paper used a focused laser beam to overcome the lack of photon counts at low over-voltages by forcing avalanches within a specific SPAD, therefore increasing the avalanche rate within the field of view by several orders of magnitude. This strategy enables reducing systematic errors, facilitating comparison with earlier work [9]–[12] (albeit with different devices), and eventual comparison with theoretical models [13]–[15].

II. Experimental setup and technique

A. Apparatus: the Microscope for the Injection and Emission of Light

This paper relies on a setup, called the Microscope for the Injection and Emission of Light (MIEL), which is capable of characterizing stimulated emission from single SPADs. MIEL is a confocal microscope including a cryogenic stage as shown in Figure 1. It is built around an Olympus IX-83 inverted microscope. A vacuum chamber is affixed above the microscope with a broadband anti-reflective coated sapphire window separating the vacuum space from the air space within the microscope. Inside the vacuum chamber is a Micronix sub-micron cryogenic x-y-positioning stage is coupled

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Thanks!

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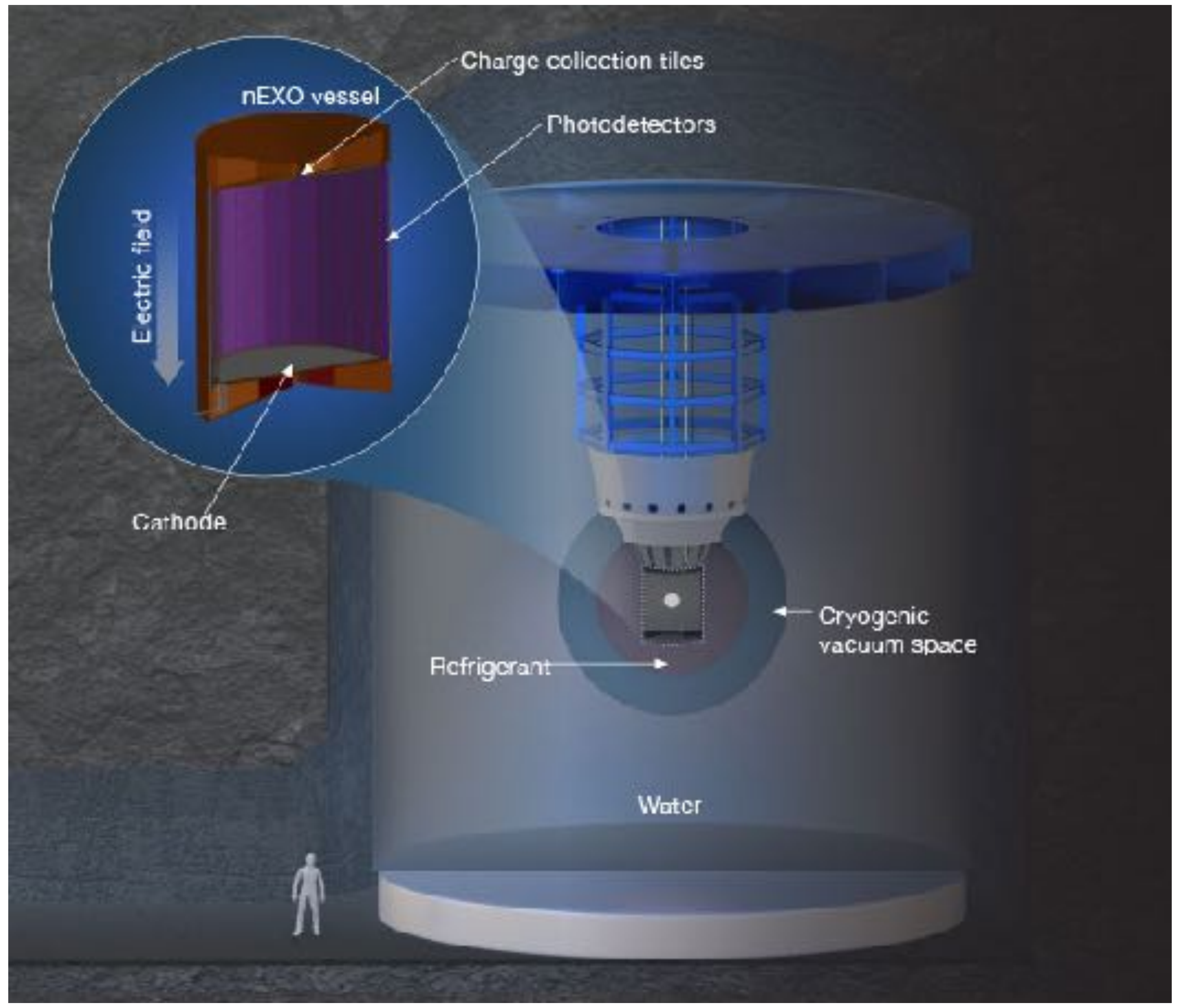
Discovery, accelerated

Backup

SiPM technology in nEXO

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

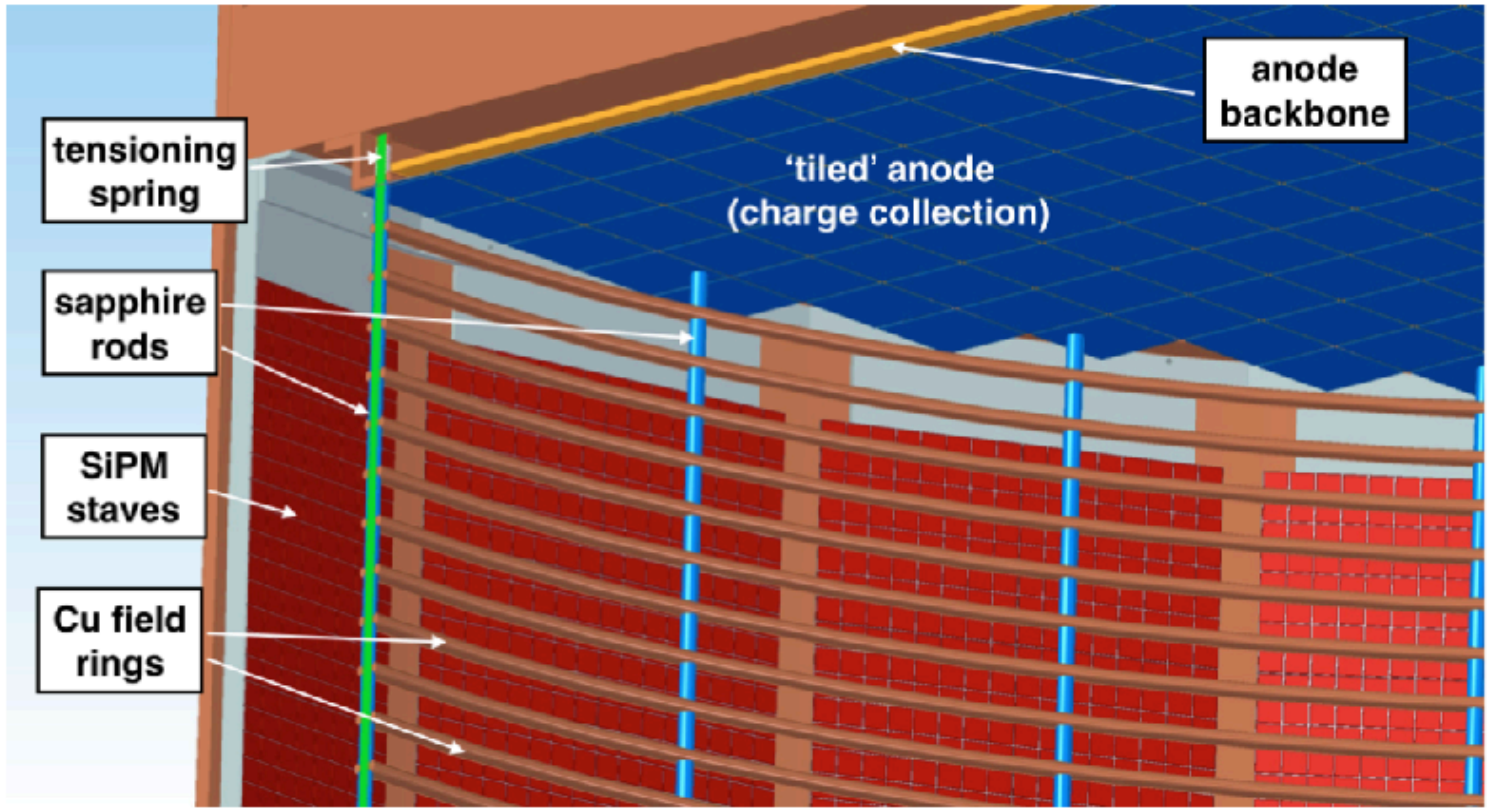


Main Characteristics :

- 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



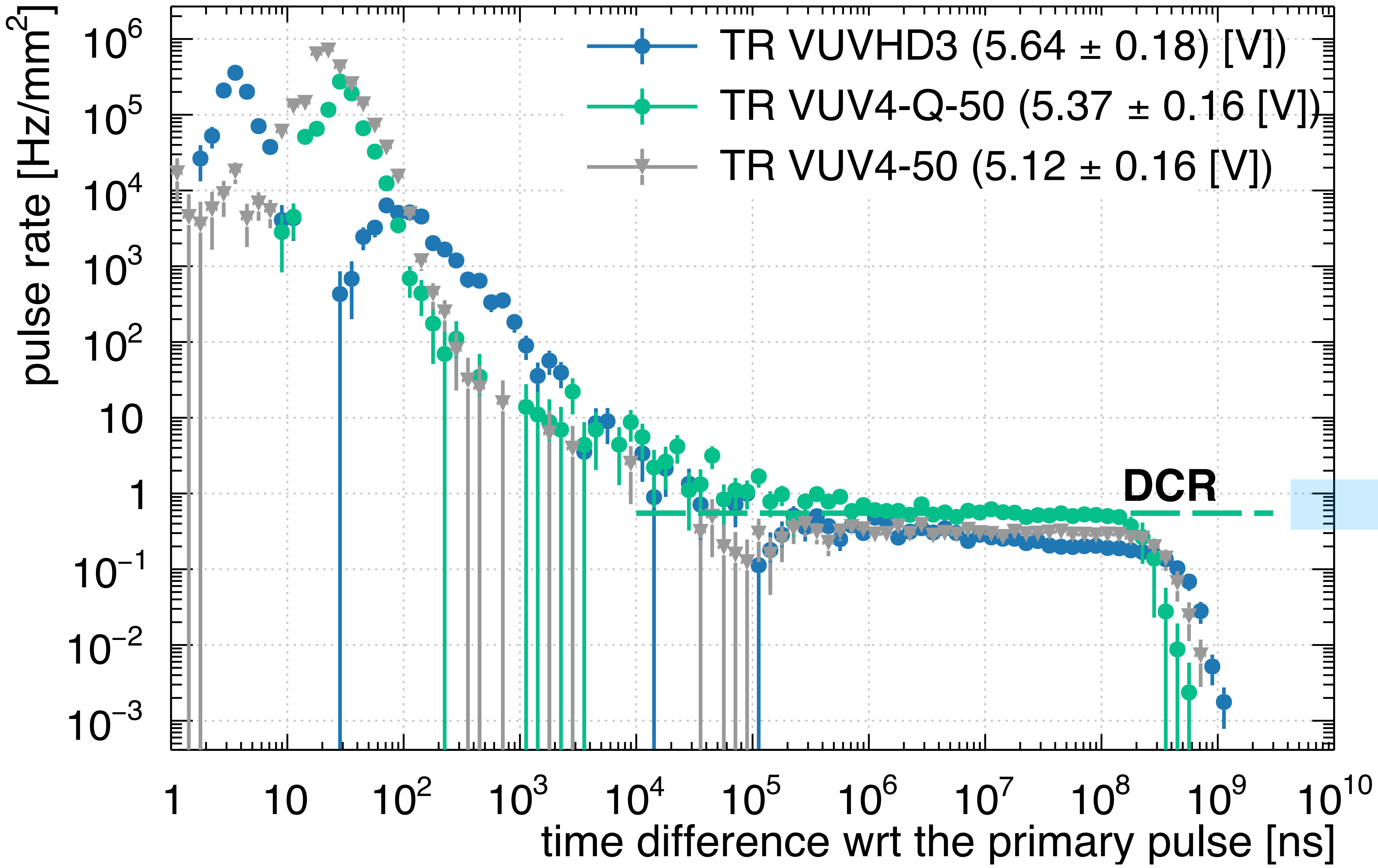
Dark Count Rate (DCR)

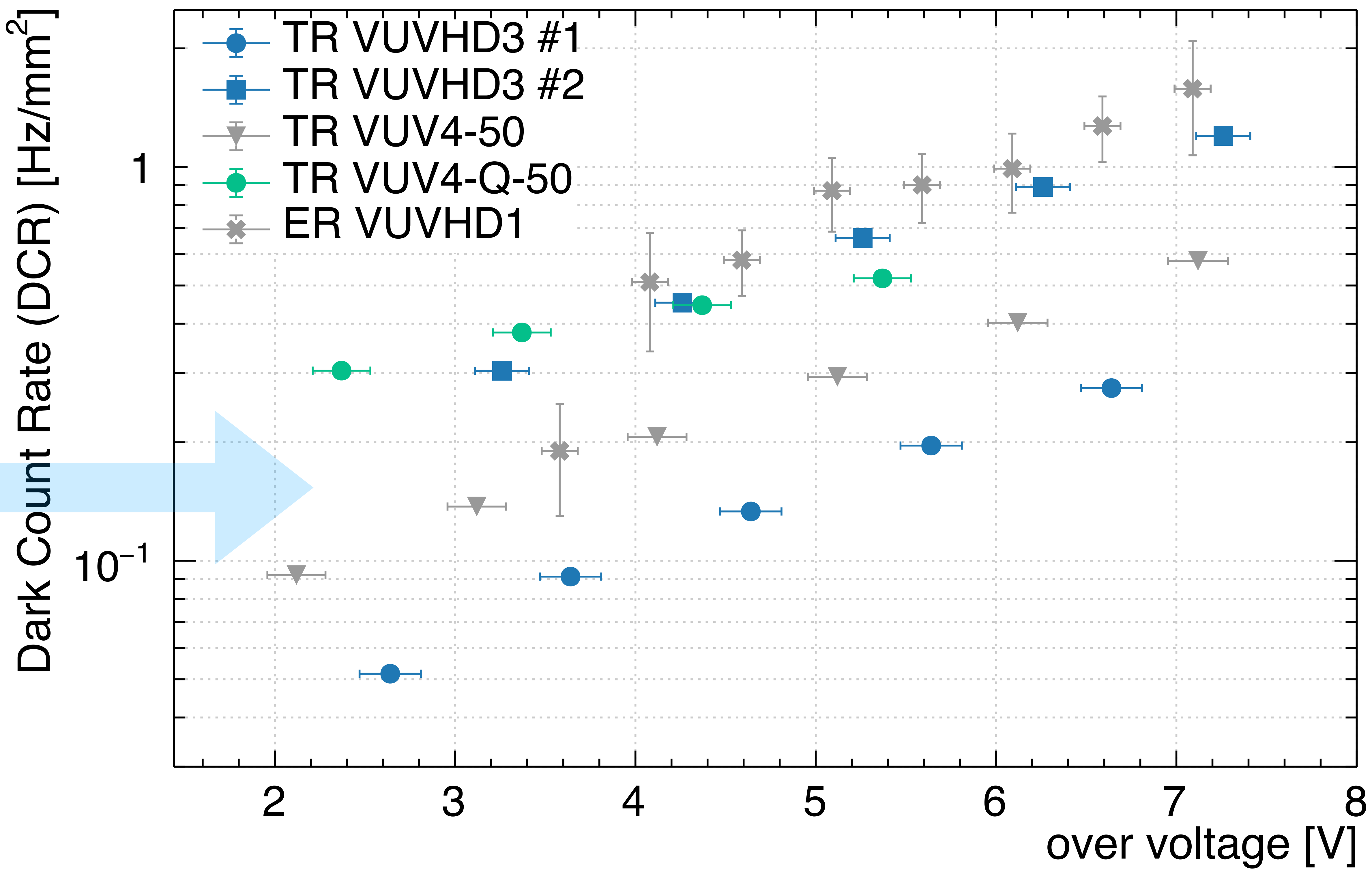
Grey points !

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





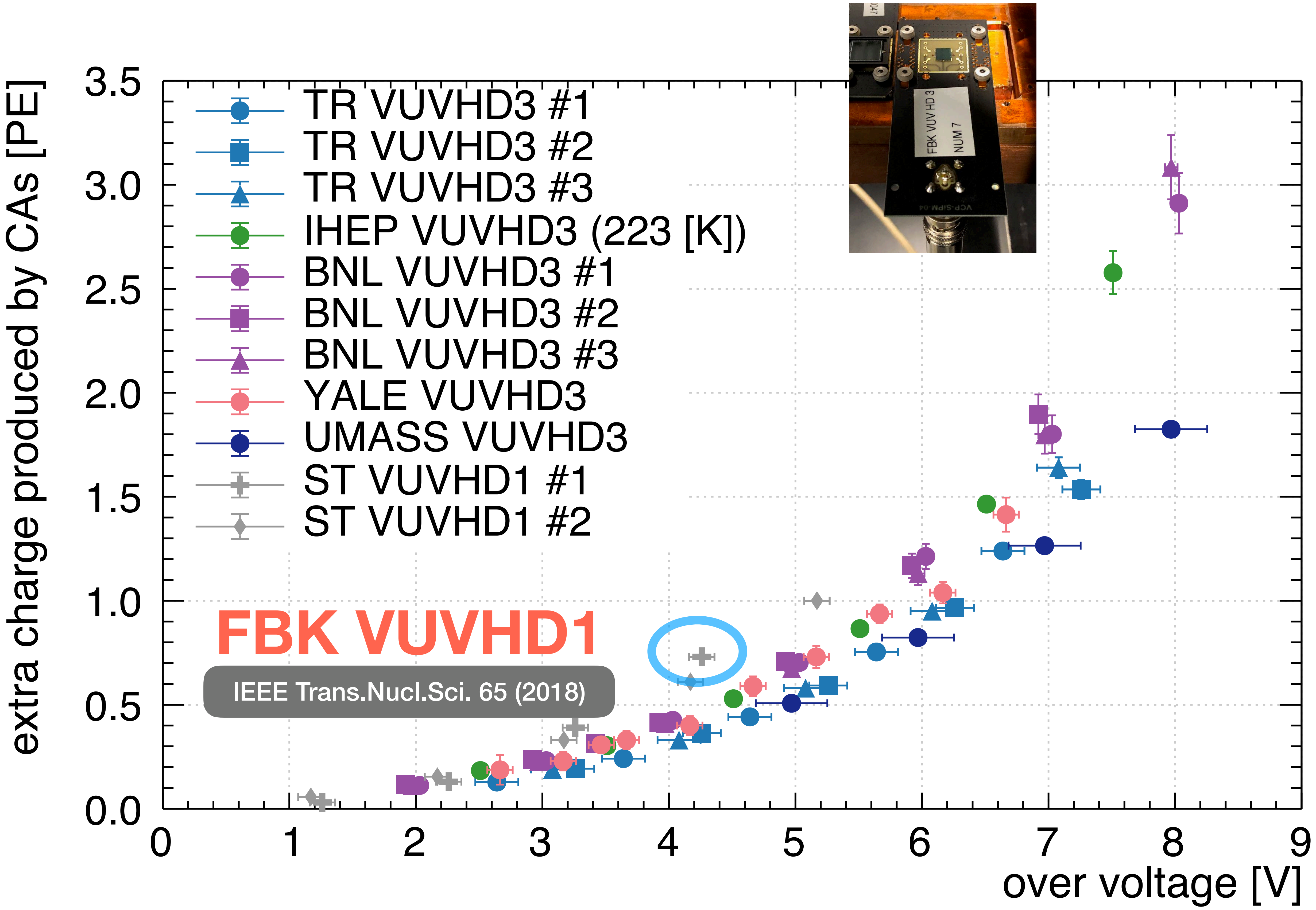
Requirement at 163 [K]: DCR < 10 Hz/mm^2

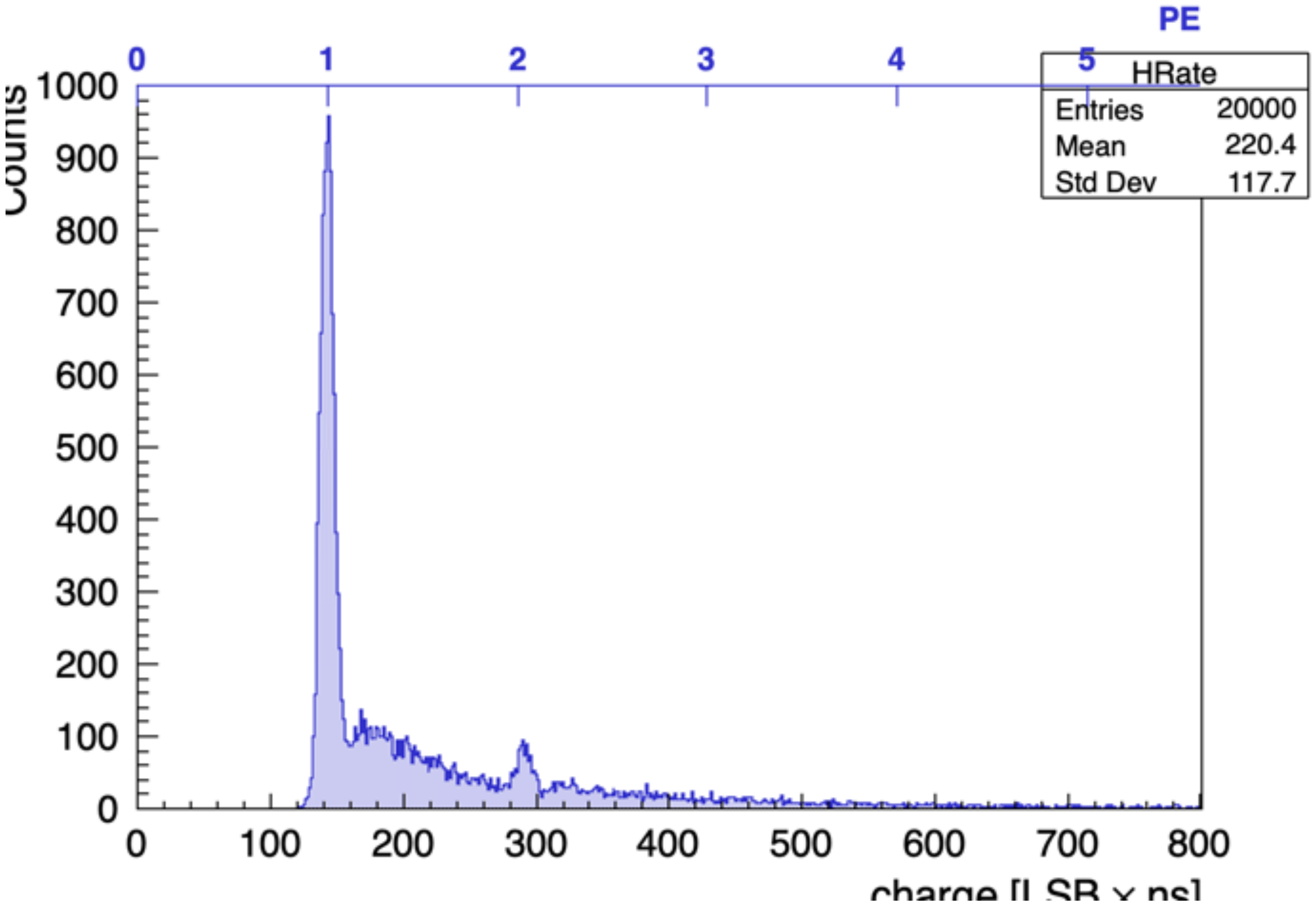
- **Requirement met in the entire range of OV studied!**

Correlated Avalanches FBK VUVHD3

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

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



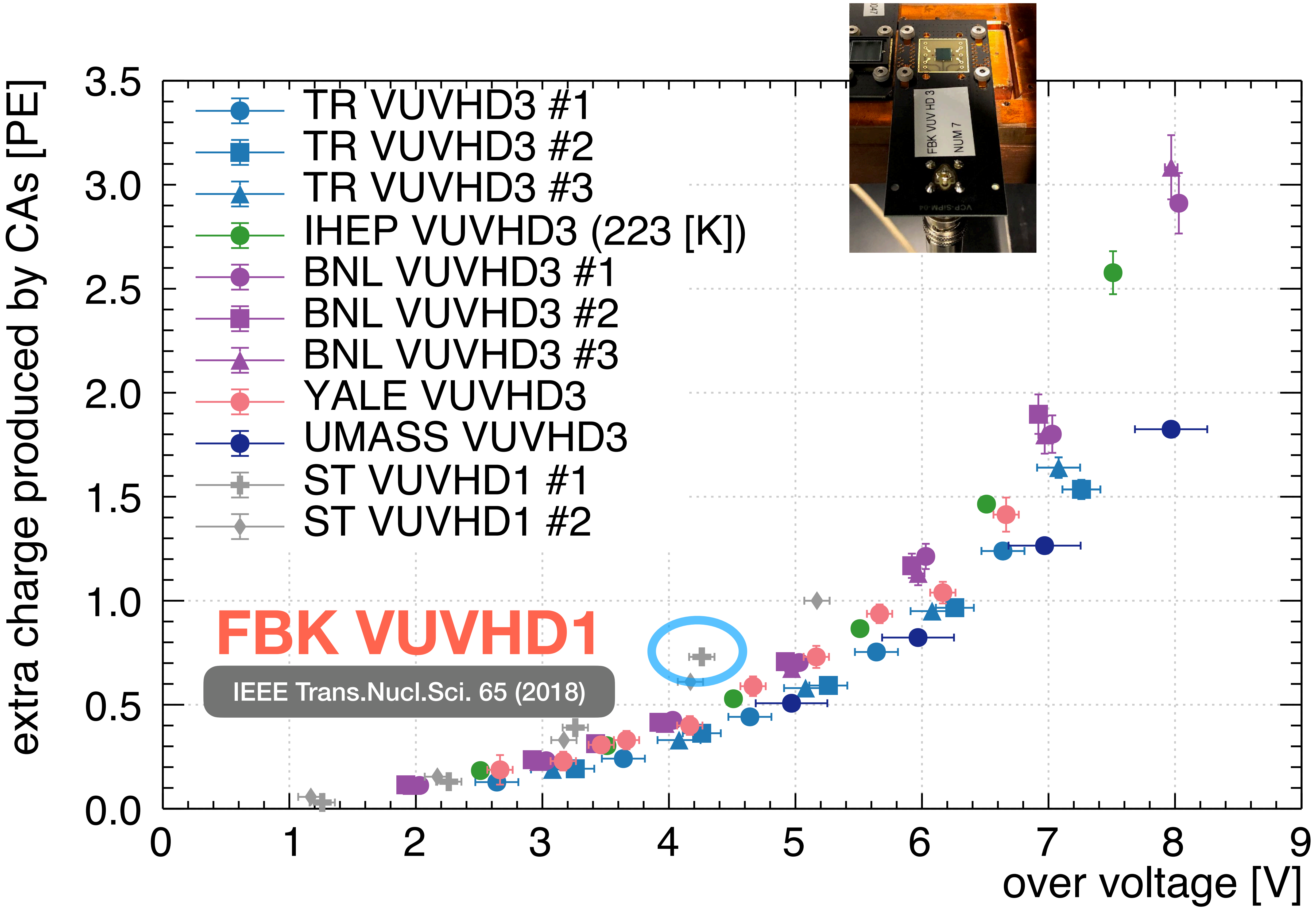


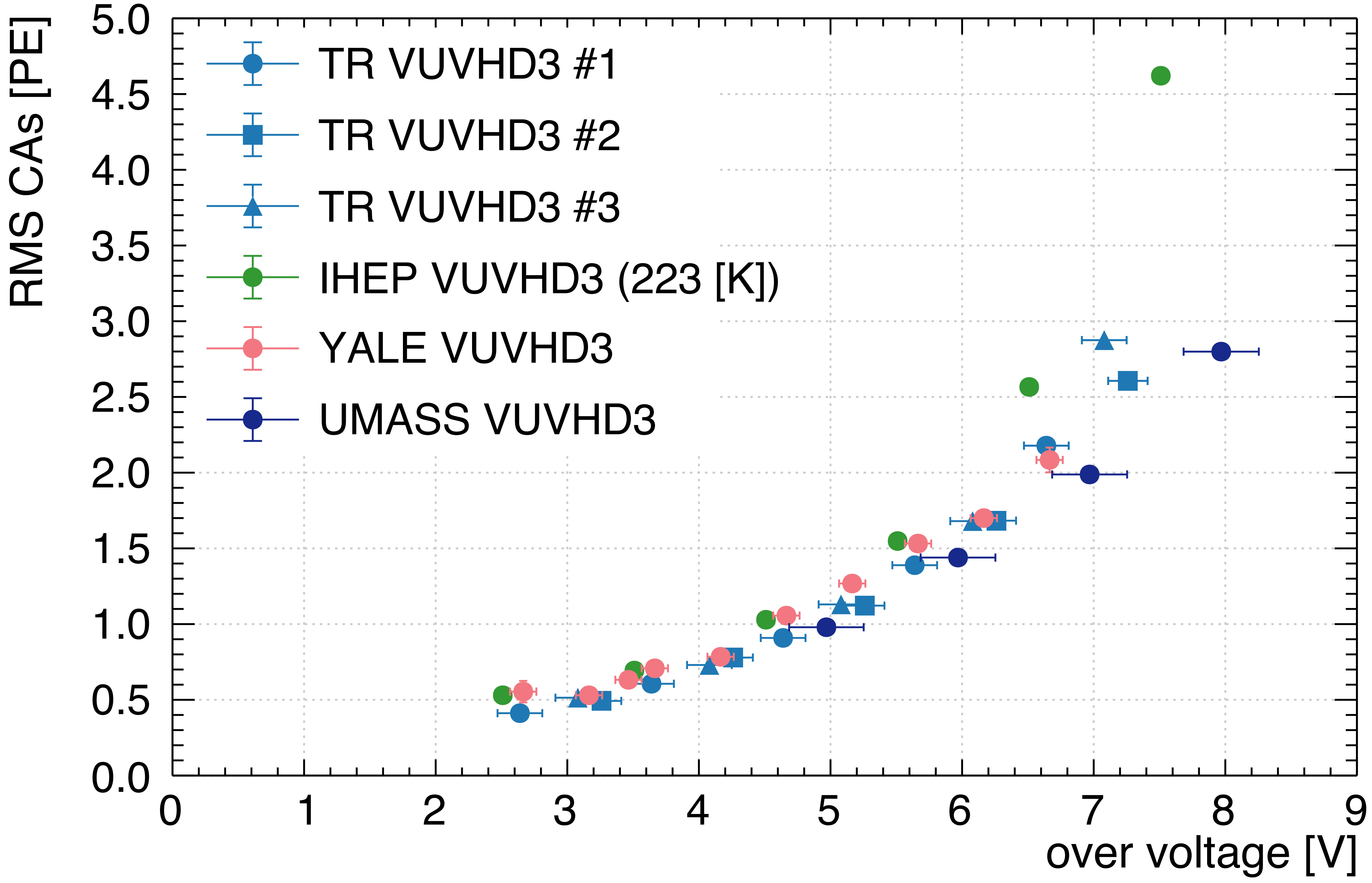
- **FBK VUVHD3** is improved compare to **FBK VUVHD1.**

Correlated Avalanches FBK VUVHD3

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

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



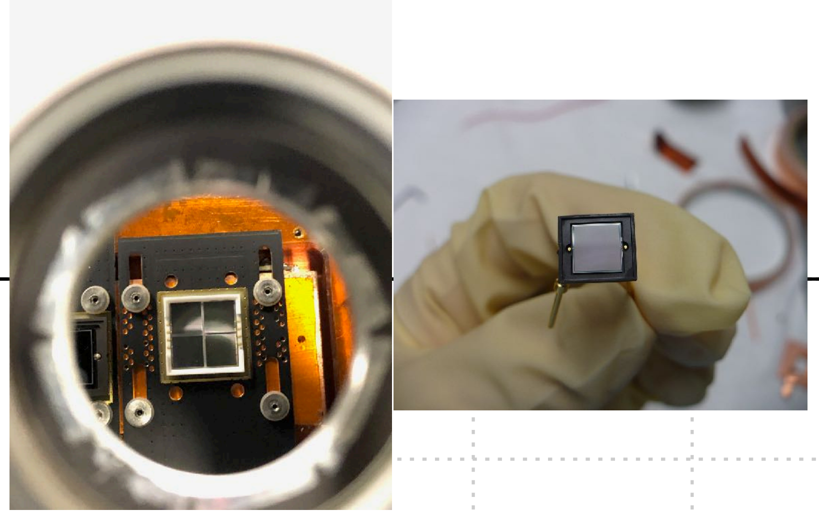


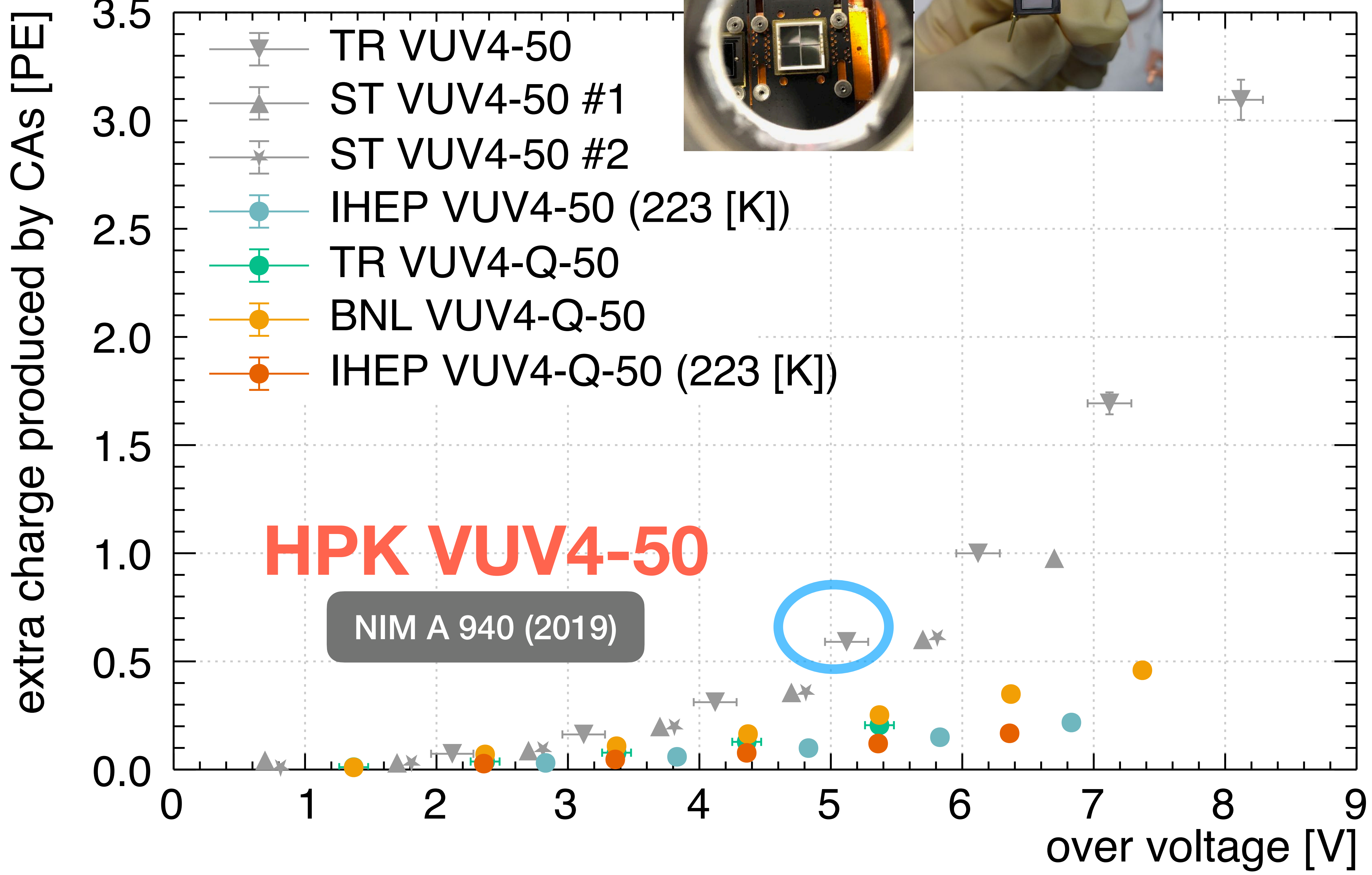
- **FBK VUVHD3** is improved compare to **FBK VUVHD1.**

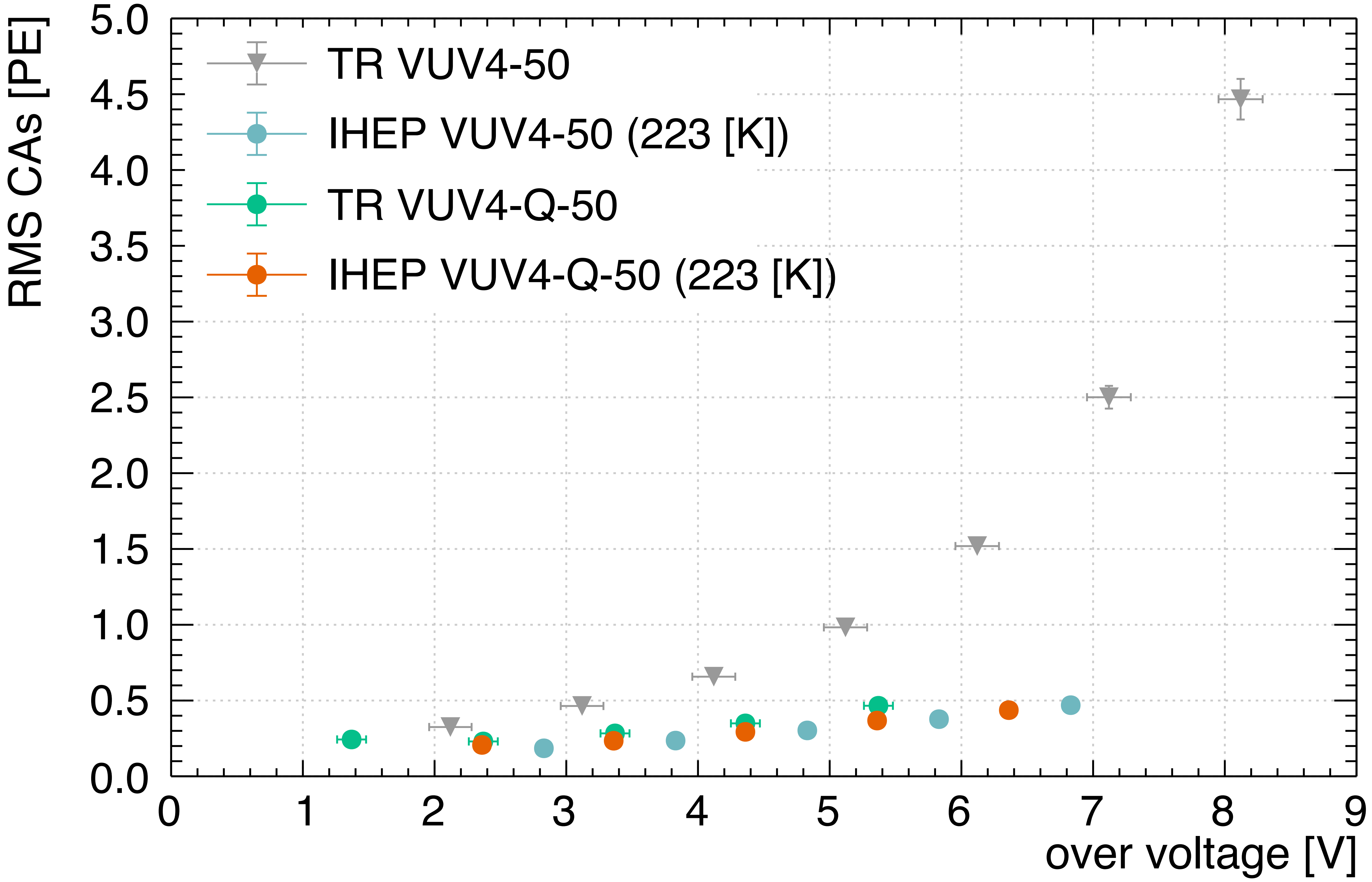
Correlated Avalanches HPK VUV4 MPPCs

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

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







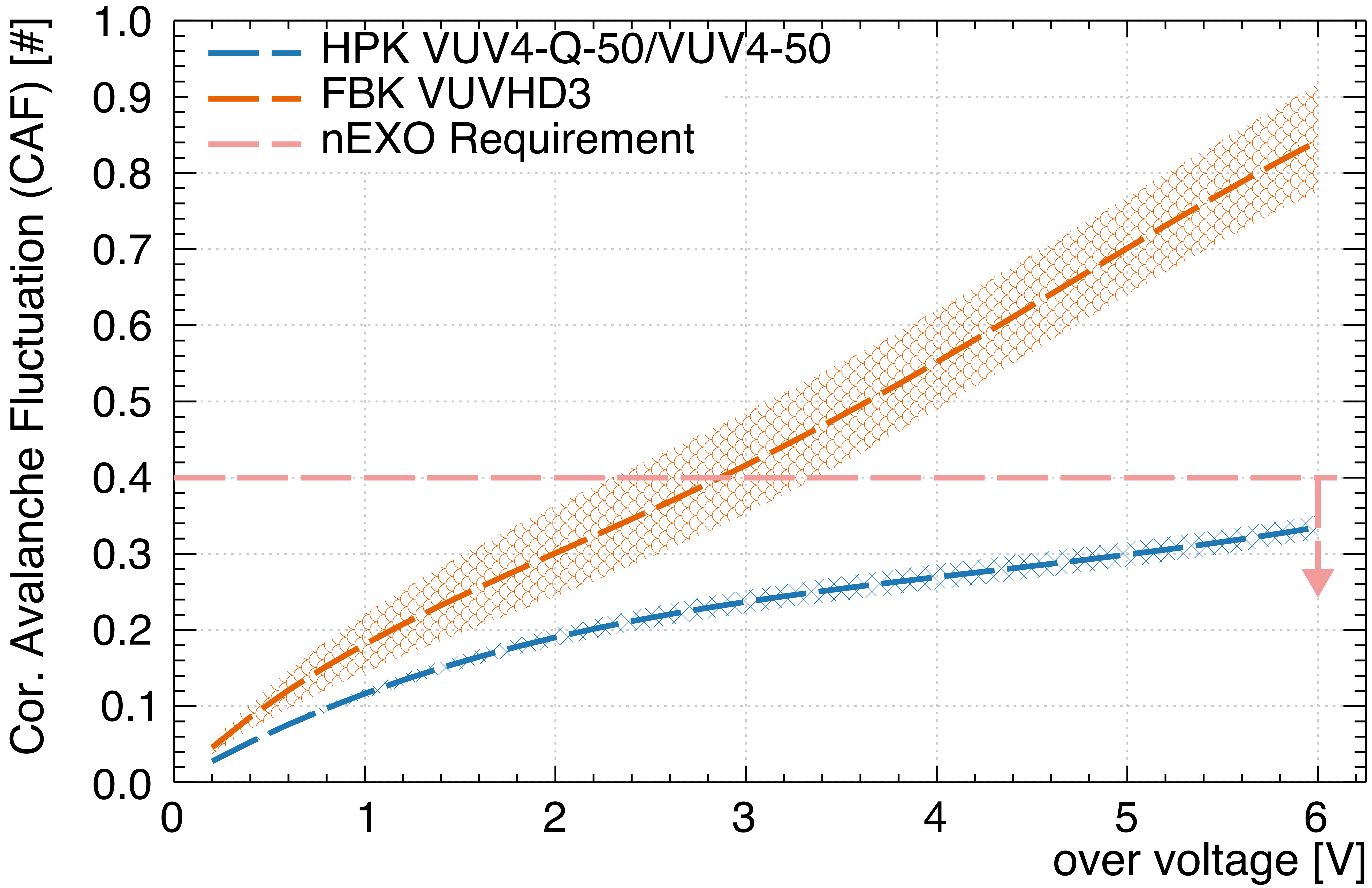
- **HPK VUV4** has almost **no correlated avalanches (CA) and it is significantly better than the HPK VUV4-50 tested previously**

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

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

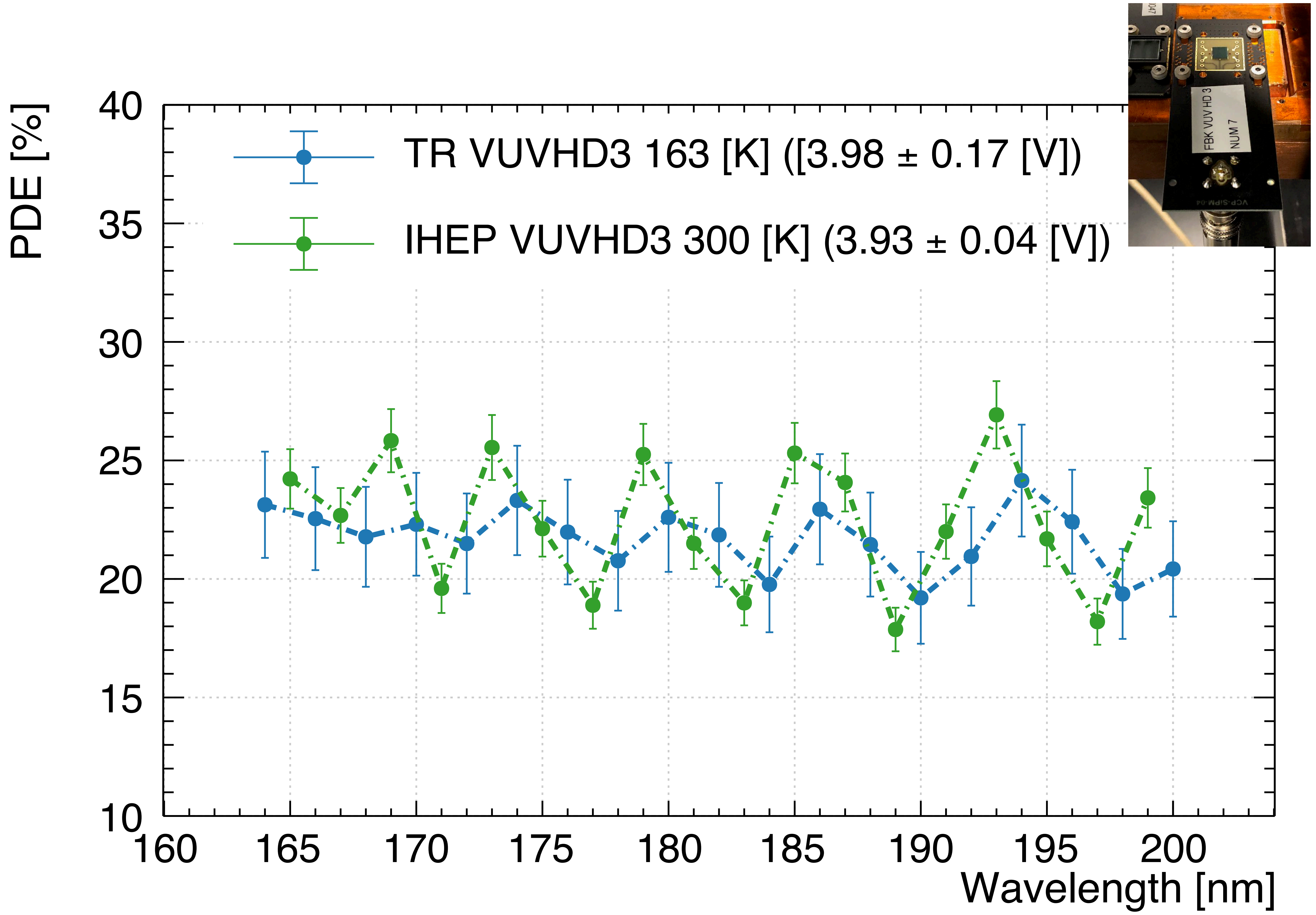
- The error bars **account for the spread** between different measurements
- HPK MPPCs **satisfies the requirement** in the entire range of OV studied
- FBK VUVHD3 **satisfies the requirement up to 3/3.5 V** of OV

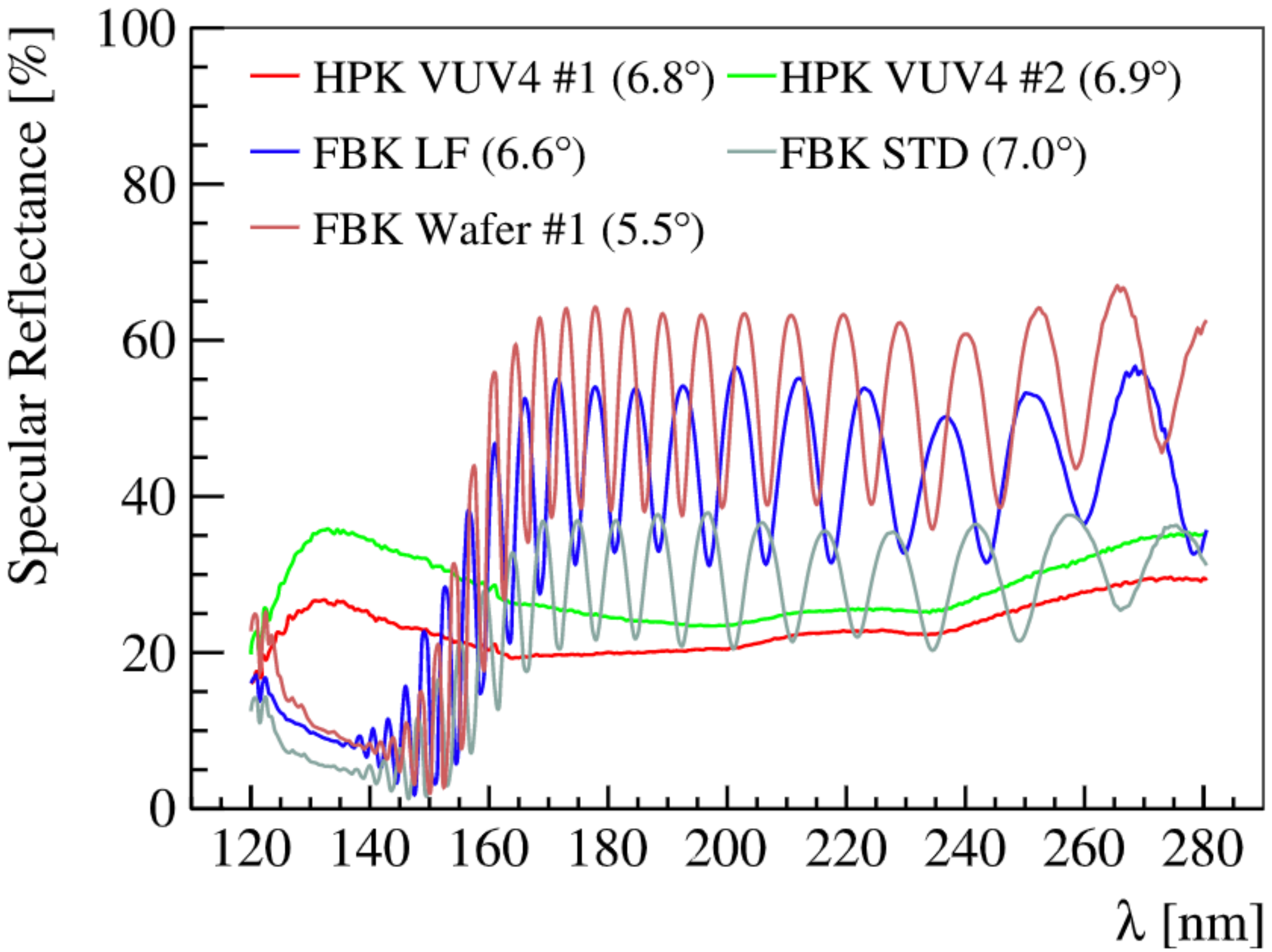


Requirement at 163 [K]: CAF < 0.4

Photon Detection Efficiency (PDE) Wavelength Dependence

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

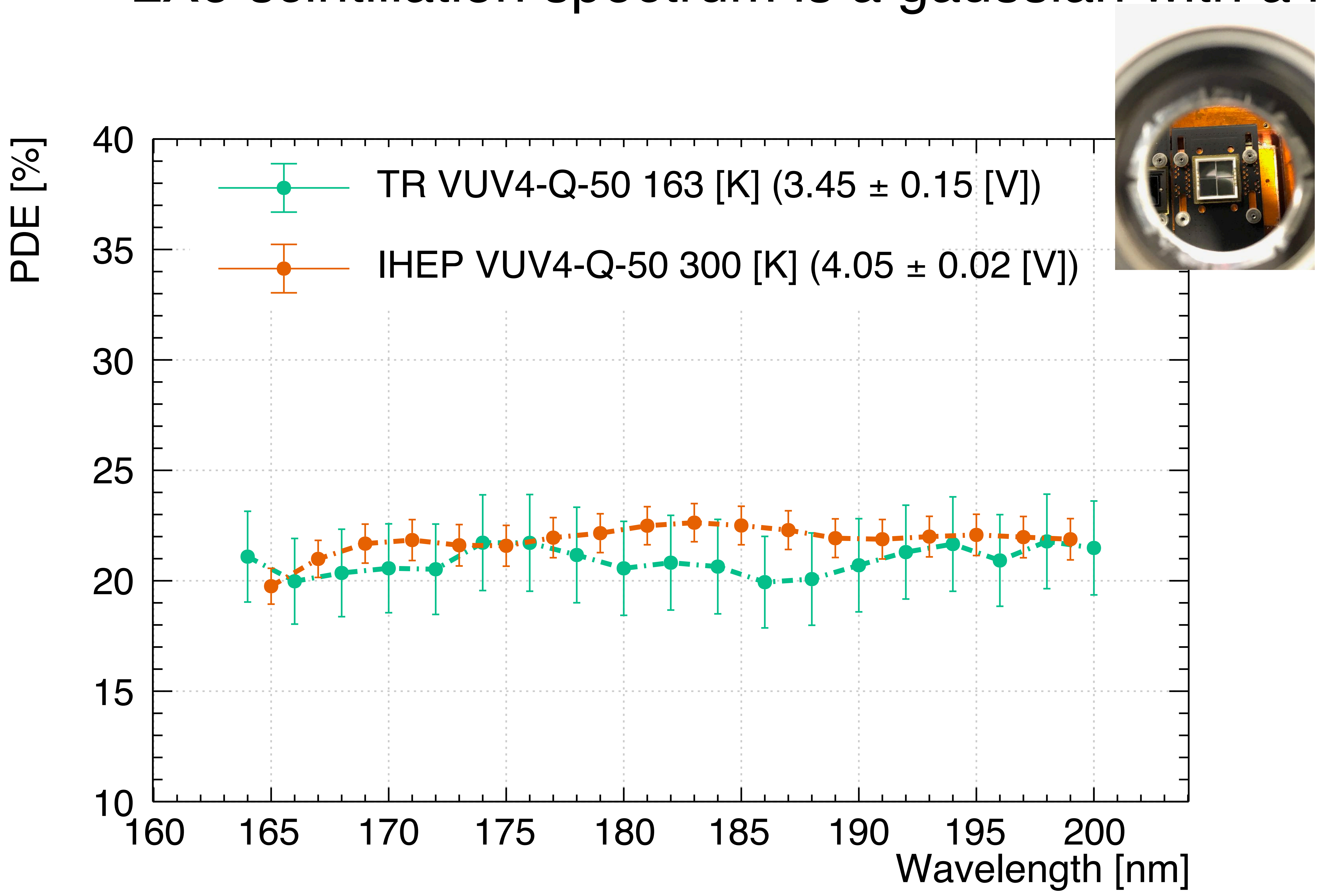


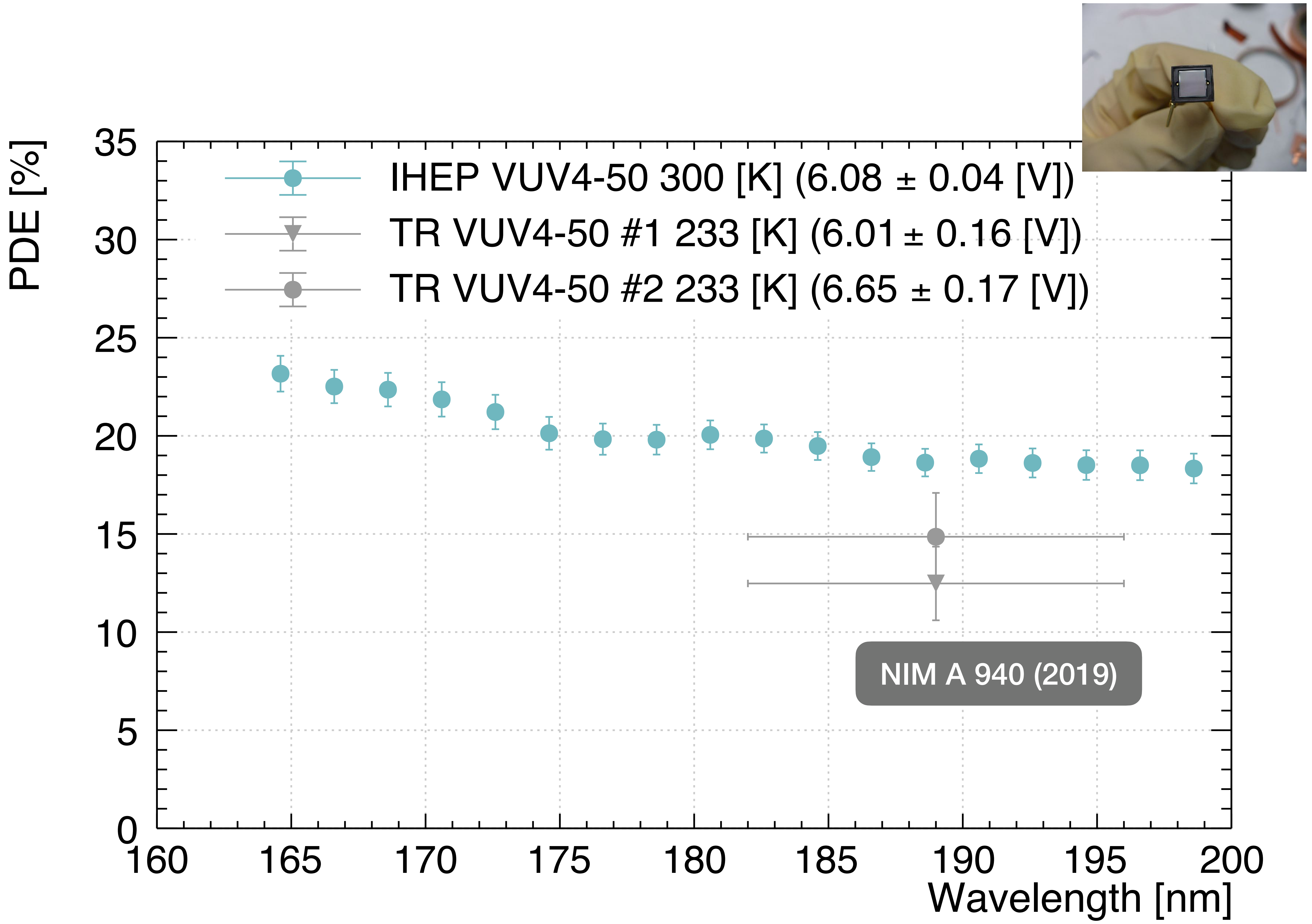


- FBK thin film interference in the SiO2 top layer. Compatible with specular reflectivity measurements done at IHEP and published in 10.1109/TNS.2020.3035172

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

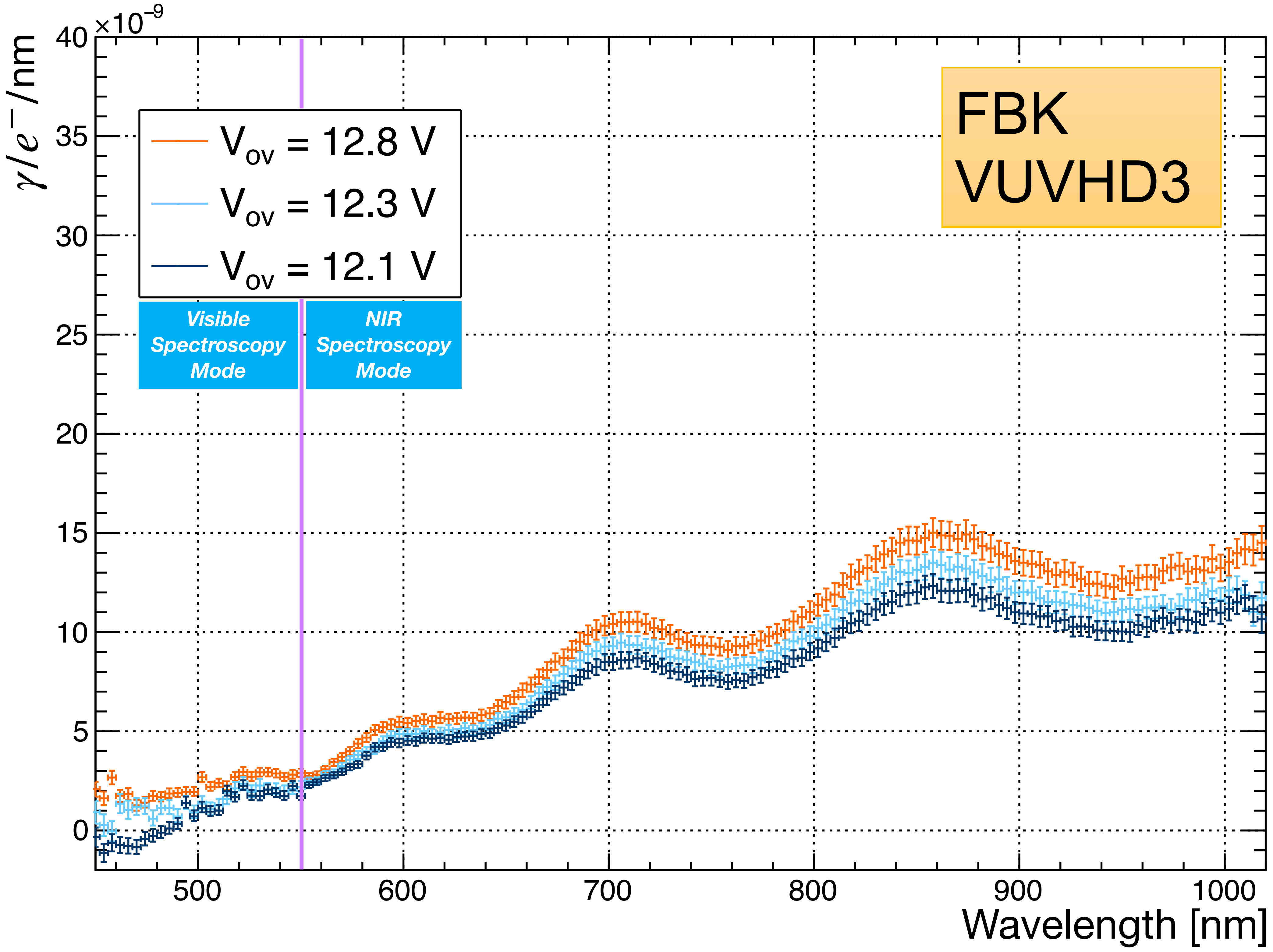


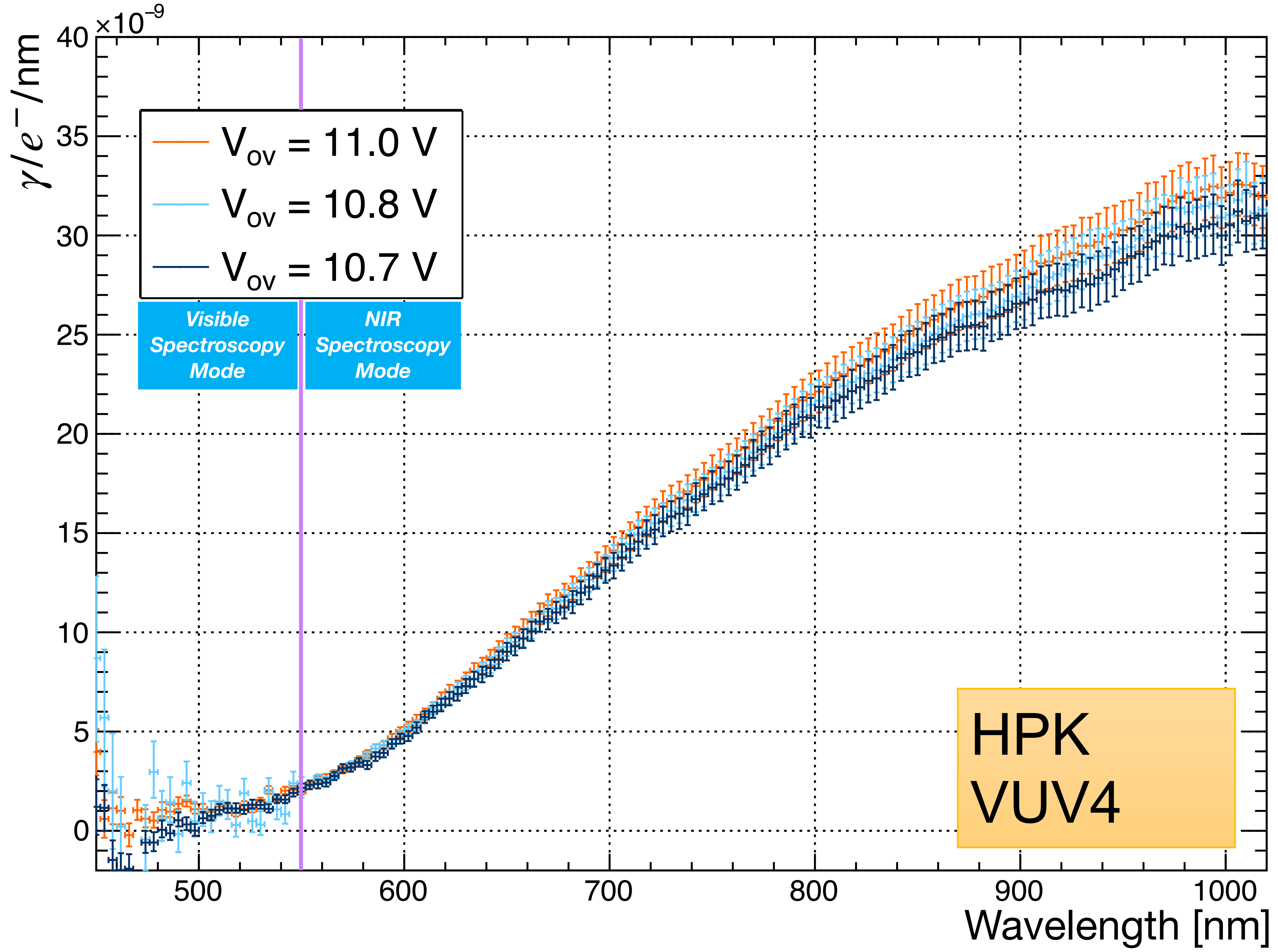


- HPK MPPCs Quad devices have an efficiency higher of the corresponding single package 50um pitch device

External CT driven by Dark Avalanches: Spectroscopy mode

10.3390/s21175947





10.1109/TNS.2020.3035172

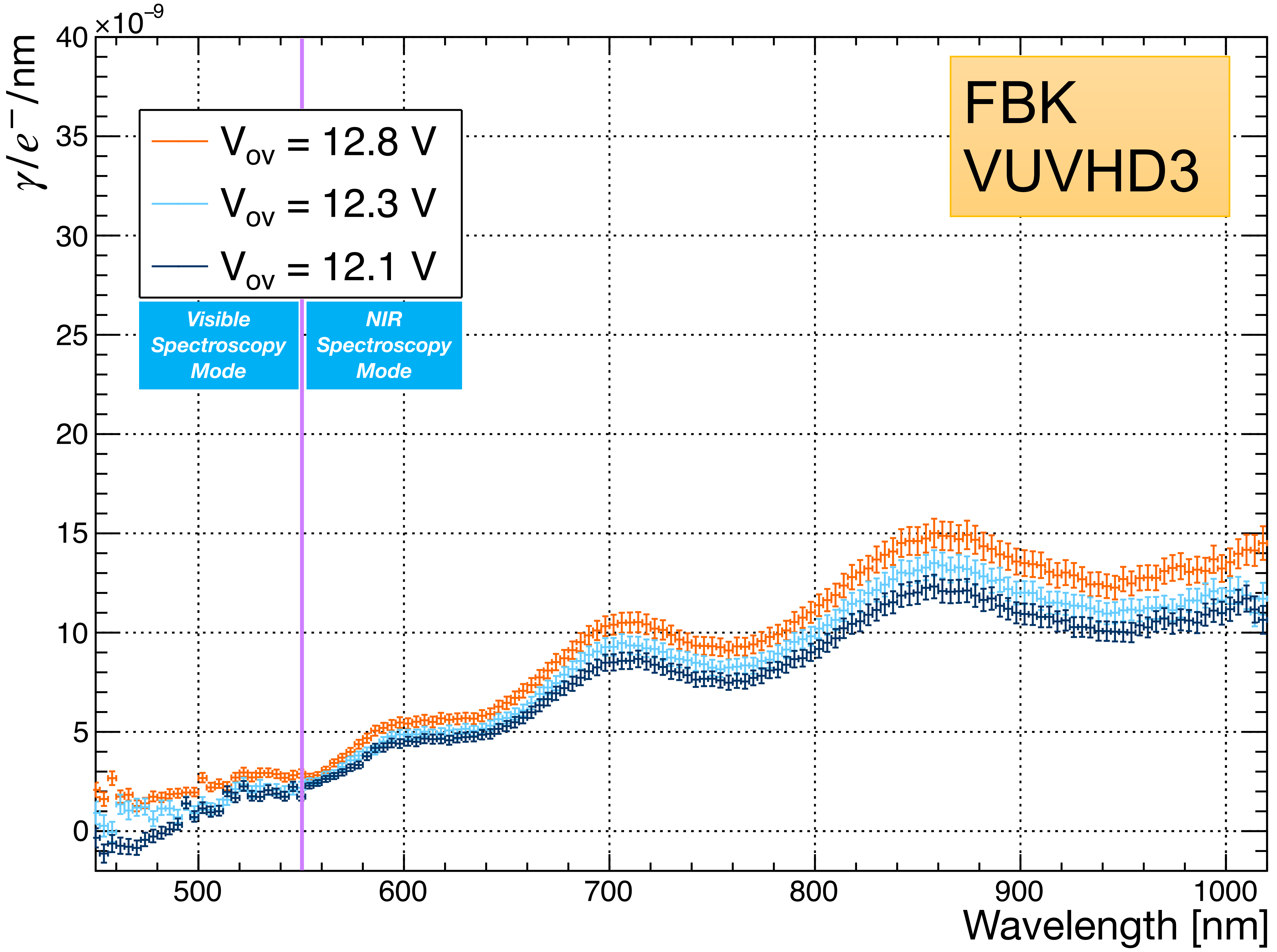
FBK VUV-HD3		HPK VUV4	
V_{ov} [V]	Photon Yield [γ/e^-]	V_{ov} [V]	Photon Yield [γ/e^-]
12.1±1.0	$(4.04 \pm 0.02) \times 10^{-6}$	10.7±1.0	$(8.71 \pm 0.04) \times 10^{-6}$
12.4±1.0	$(4.45 \pm 0.02) \times 10^{-6}$	10.8±1.0	$(8.98 \pm 0.06) \times 10^{-6}$
12.8±1.0	$(5.10 \pm 0.02) \times 10^{-6}$	11.0±1.0	$(9.24 \pm 0.05) \times 10^{-6}$
Photon Yield in [26] (500–1117 nm): $1.2 \times 10^{-5}\ \gamma/e^-$			
Photon Yield in [17] [0.5-4.5] mA (413–1087 nm): $2.9 \times 10^{-5}\ \gamma/e^-$			

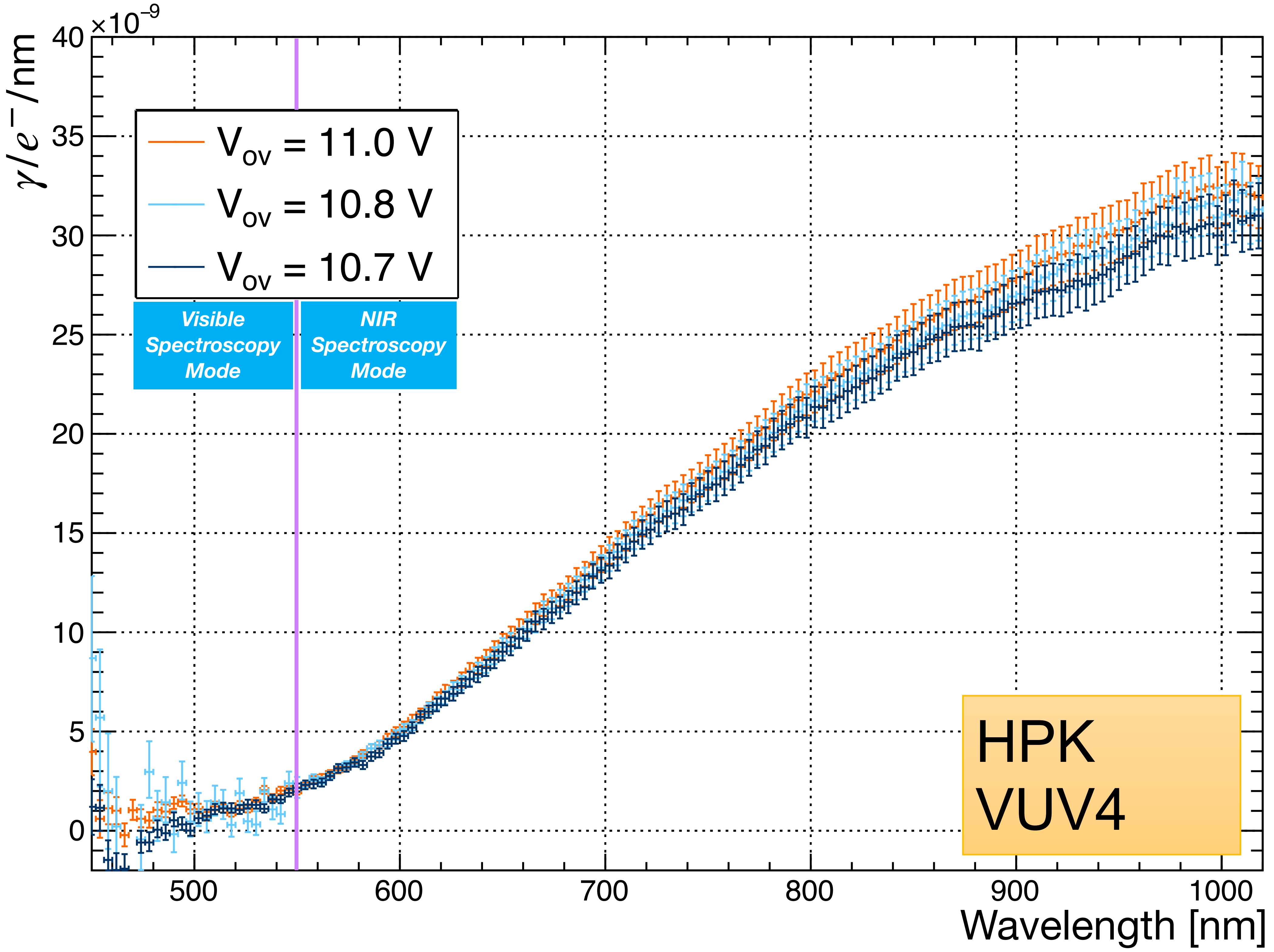
- FBK produces **less** light than HPK
- FBK light emission shows **interference pattern**. Compatible with reflectivity measurements done done in the context of nEXO

Simulation studies

10.3390/s21175947

In the previous paper **interference** was not accounted. We **corrected** for the objective **NA**.
Now we are interested to see the **photon angular distribution. We need a careful simulation**





Measurements → Extraction of the sources term → Predict Angular distribution