Laser-driven secondary photon emission of SiPMs

Kurtis Raymond[1], **Priyanka Kachru**[2], Fabrice Retiere[1], Giacomo Gallina[3]

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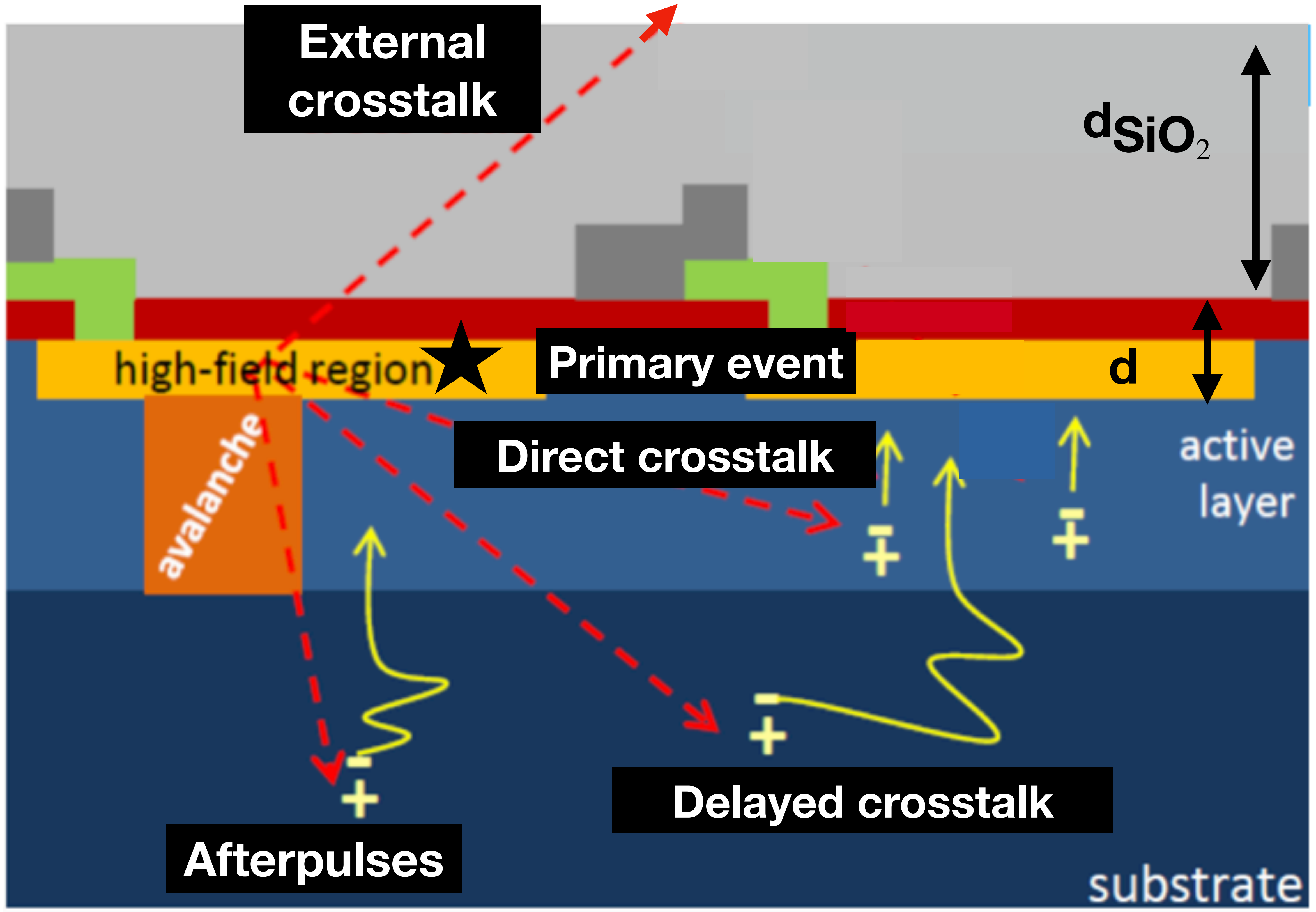
[2]*University of Massachusetts Amherst, USA*
[3]*Princeton University, New Jersey, USA*

TIPP 2023, 4 - 8 September, Cape Town

Photon emission mechanisms in SiPMs



d_{SiO_2} = depth of the SiO_2 coating

d = depth of the depletion region

Primary photon - avalanche of charge carriers in high electric field region

- Causes isotropic photon emission

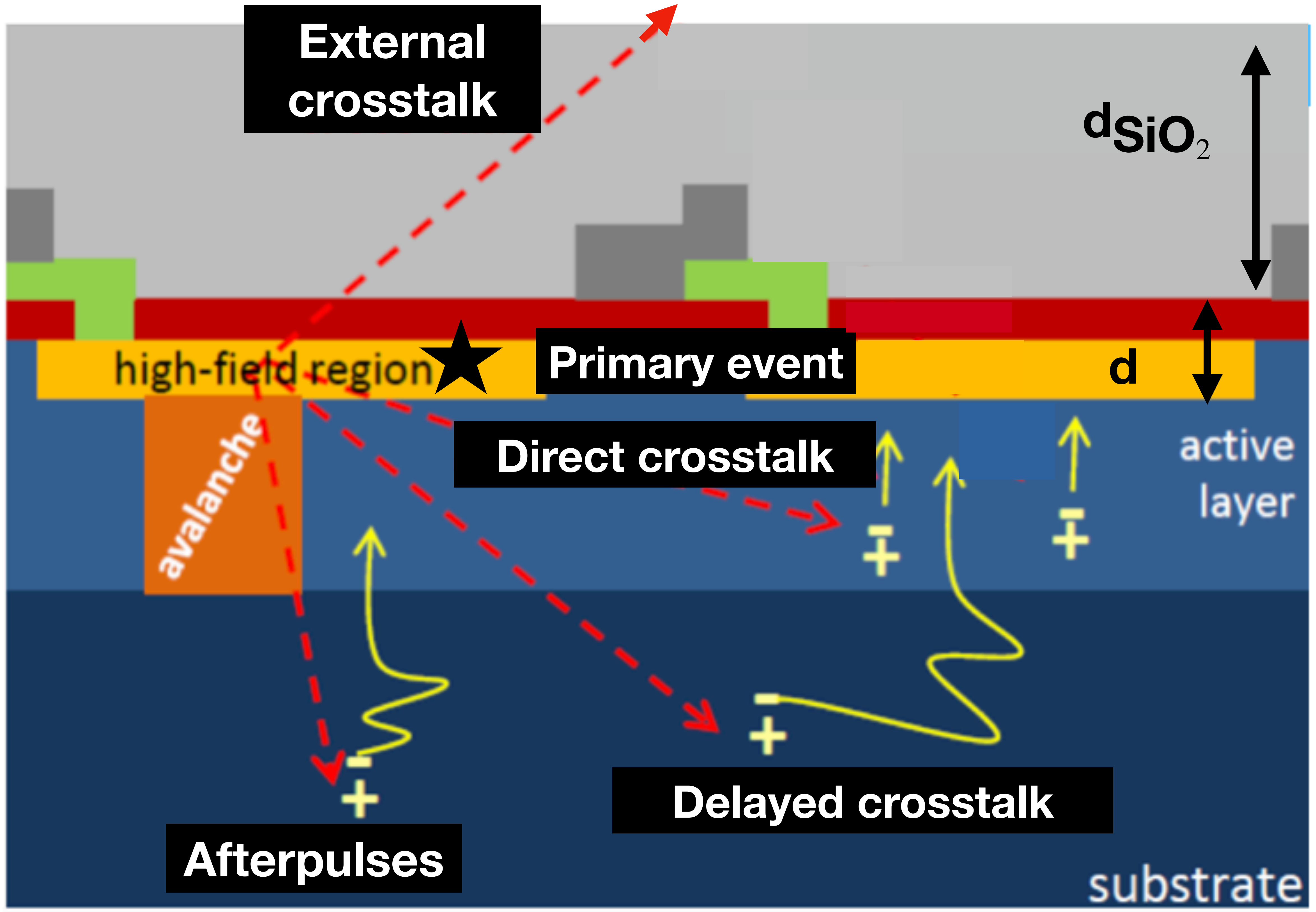
Correlated avalanches cause intrinsic noises

- Direct Crosstalk - neighbouring cells triggered instantaneously
- Delayed Crosstalk - neighbouring cells triggered from delayed release of charge carriers
- Afterpulses - same cell triggered from trapped charge carriers

Correlated avalanches cause extrinsic noise

- External Crosstalk - photon escapes the surface of SiPM

Photon emission mechanisms in SiPMs



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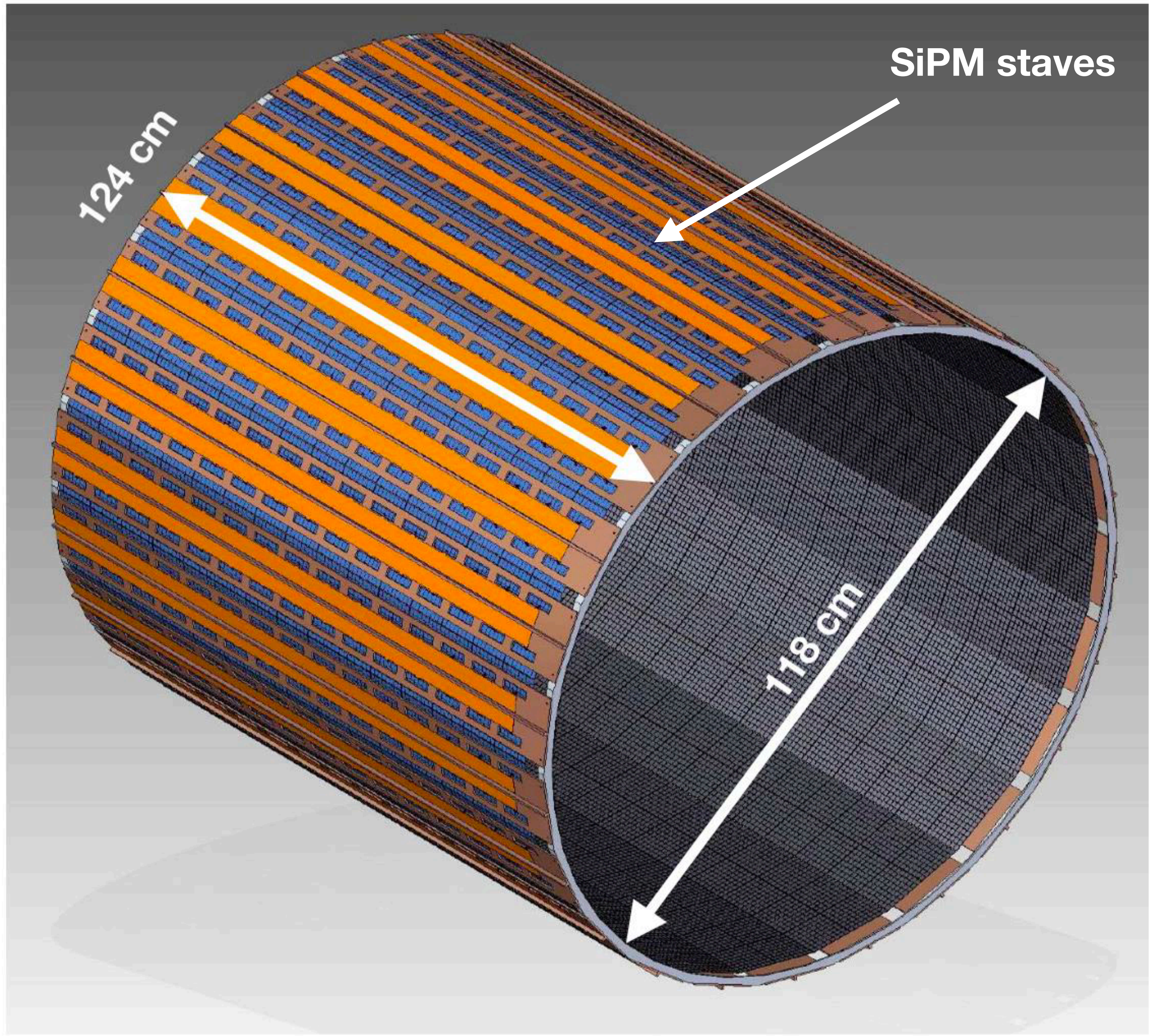
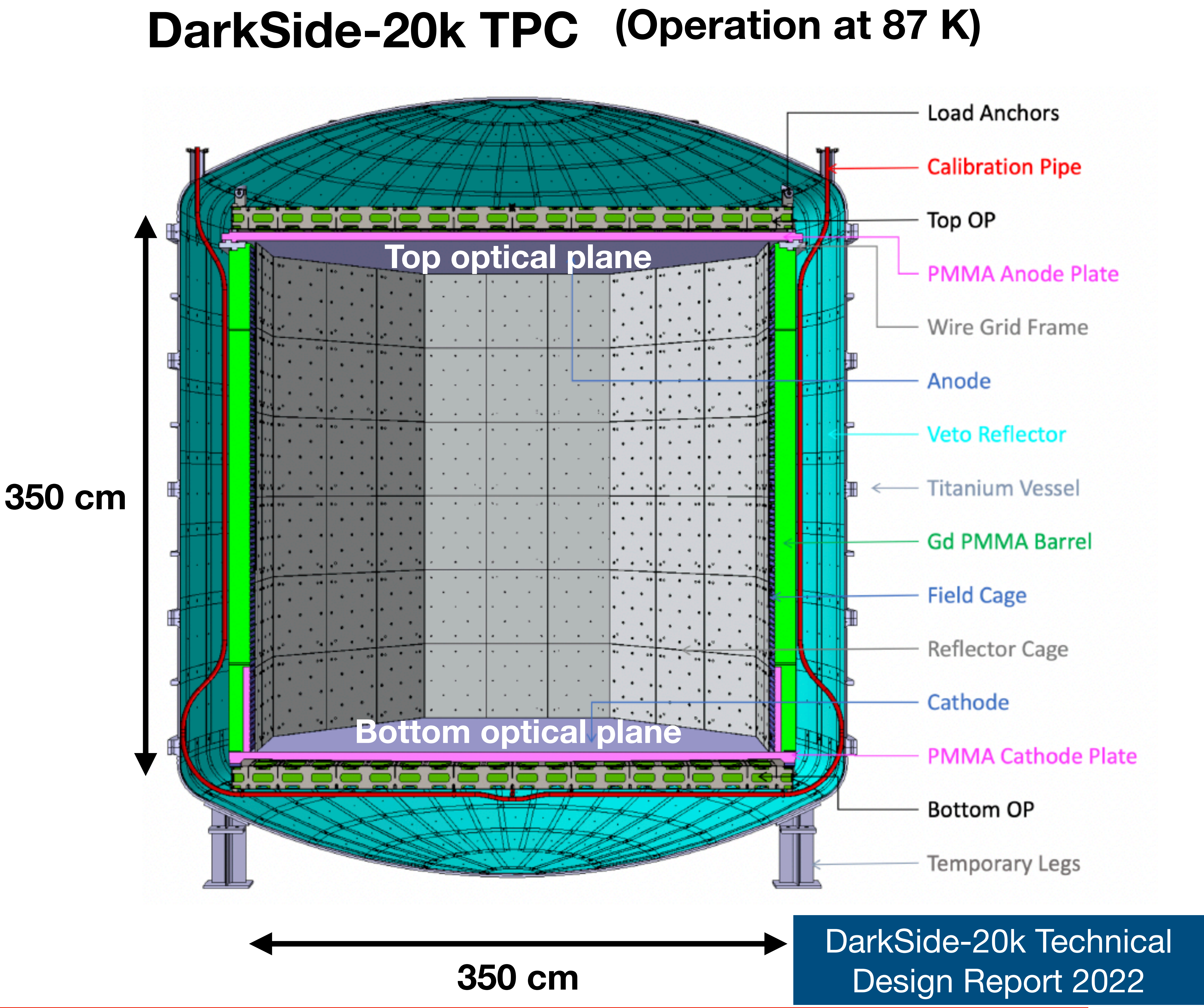
This talk

Correlated avalanches cause extrinsic noise

- External Crosstalk - photon escapes the surface of SiPM

Motivation

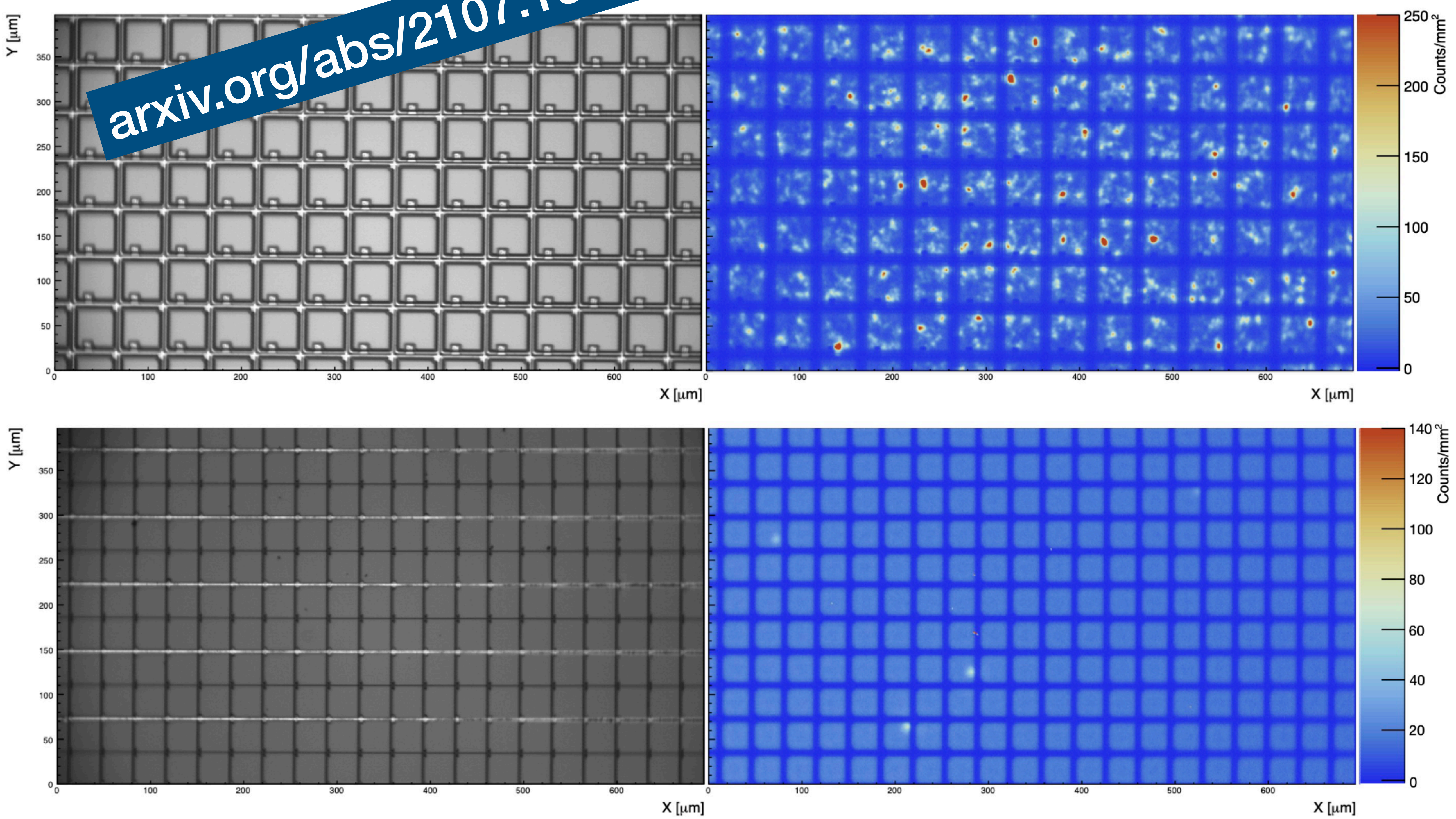


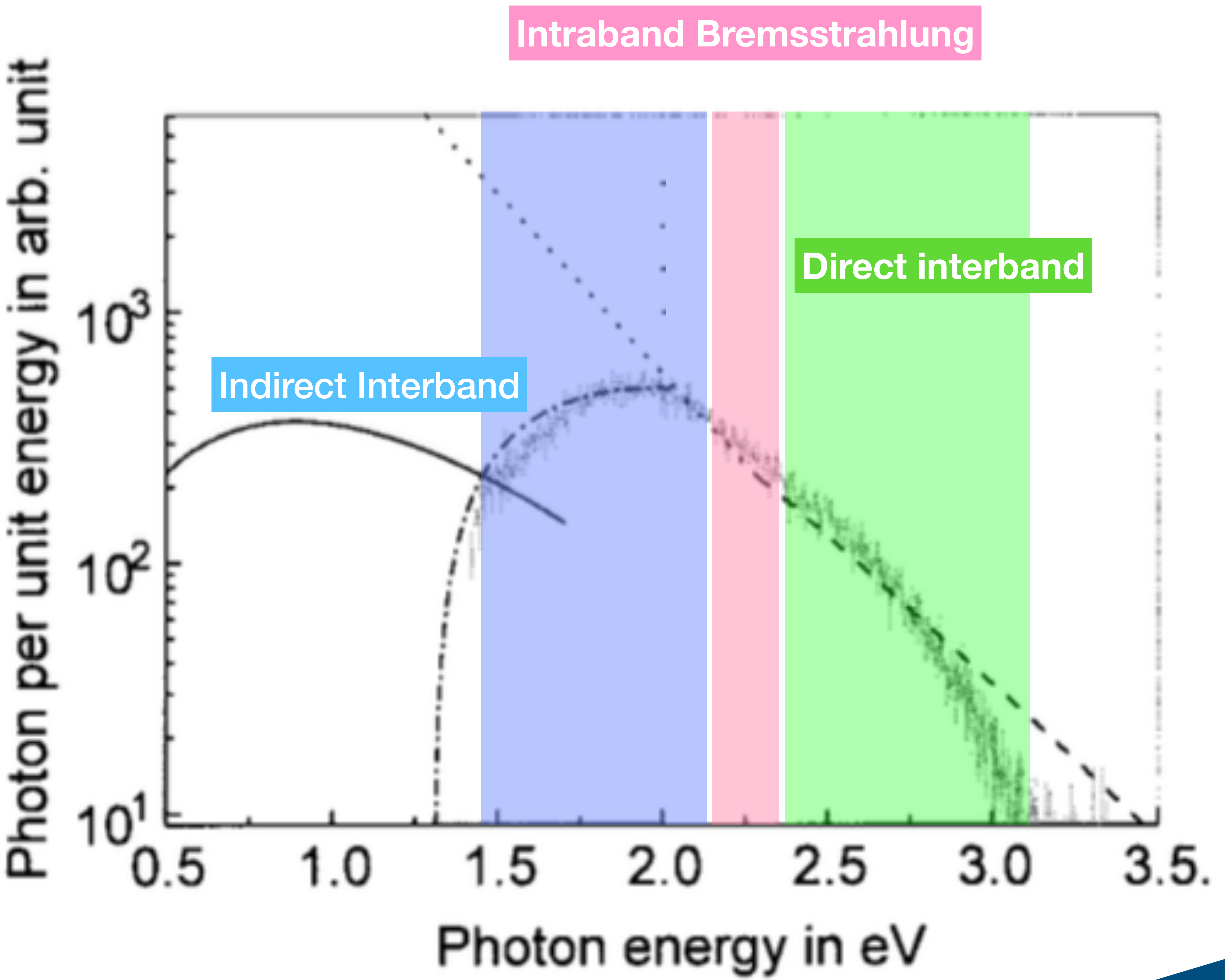


External Crosstalk photons (secondary photon emission) can impact experiments like nEXO and DarkSide-20k. Such photons can be detected by photosensors that face each other - Worse energy resolution

Secondary photon emission

arxiv.org/abs/2107.13753





doi: 10.1109/16.760412

We want to study:

- **properties of source - number of photons emitted per wavelength, dependence on temperature**
- **develop a source emission model - to quantify the impact of these photons on different experiments using angular emission and photon yield outside SiPM**

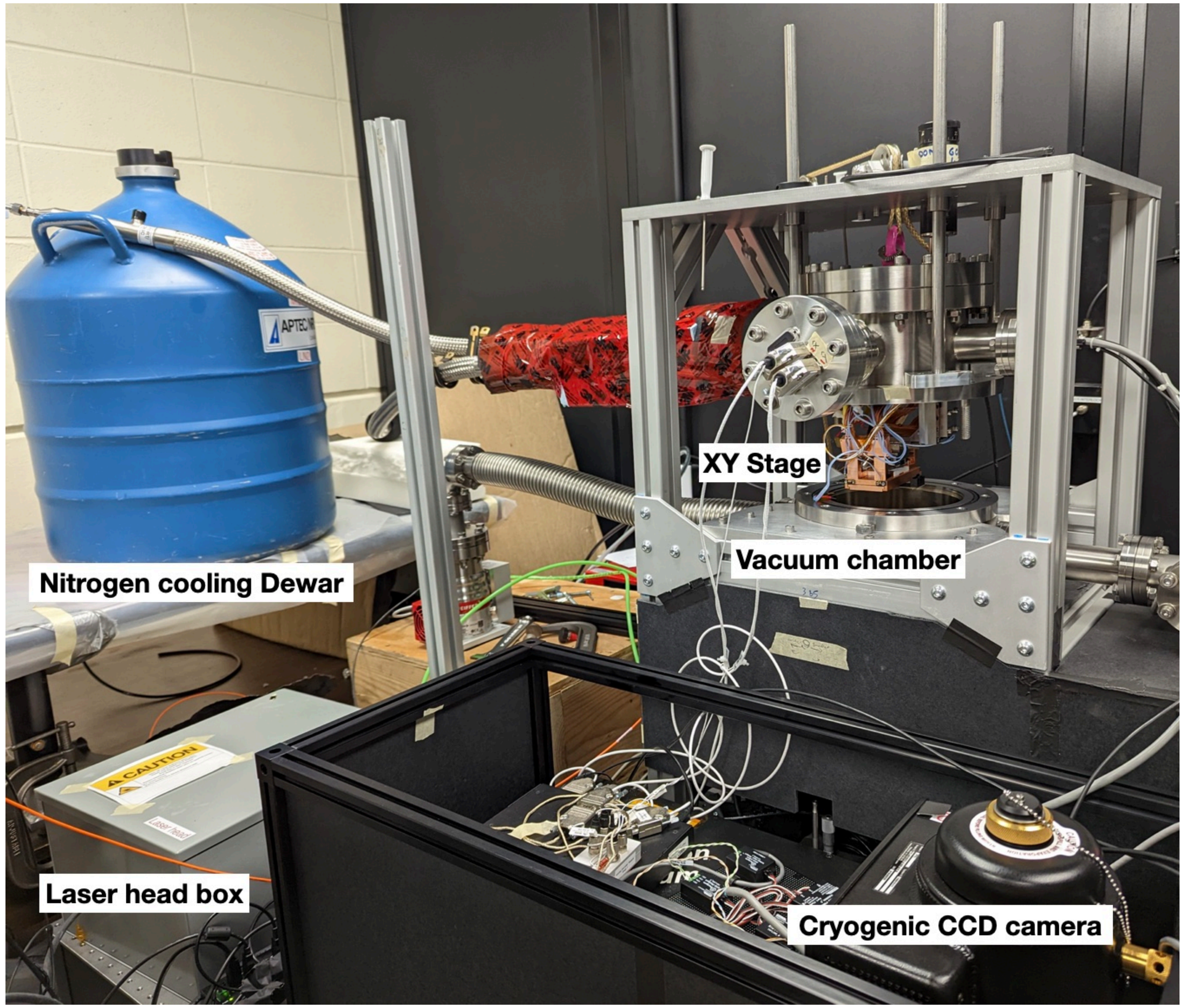
Specifications of DarkSide and nEXO SiPMs

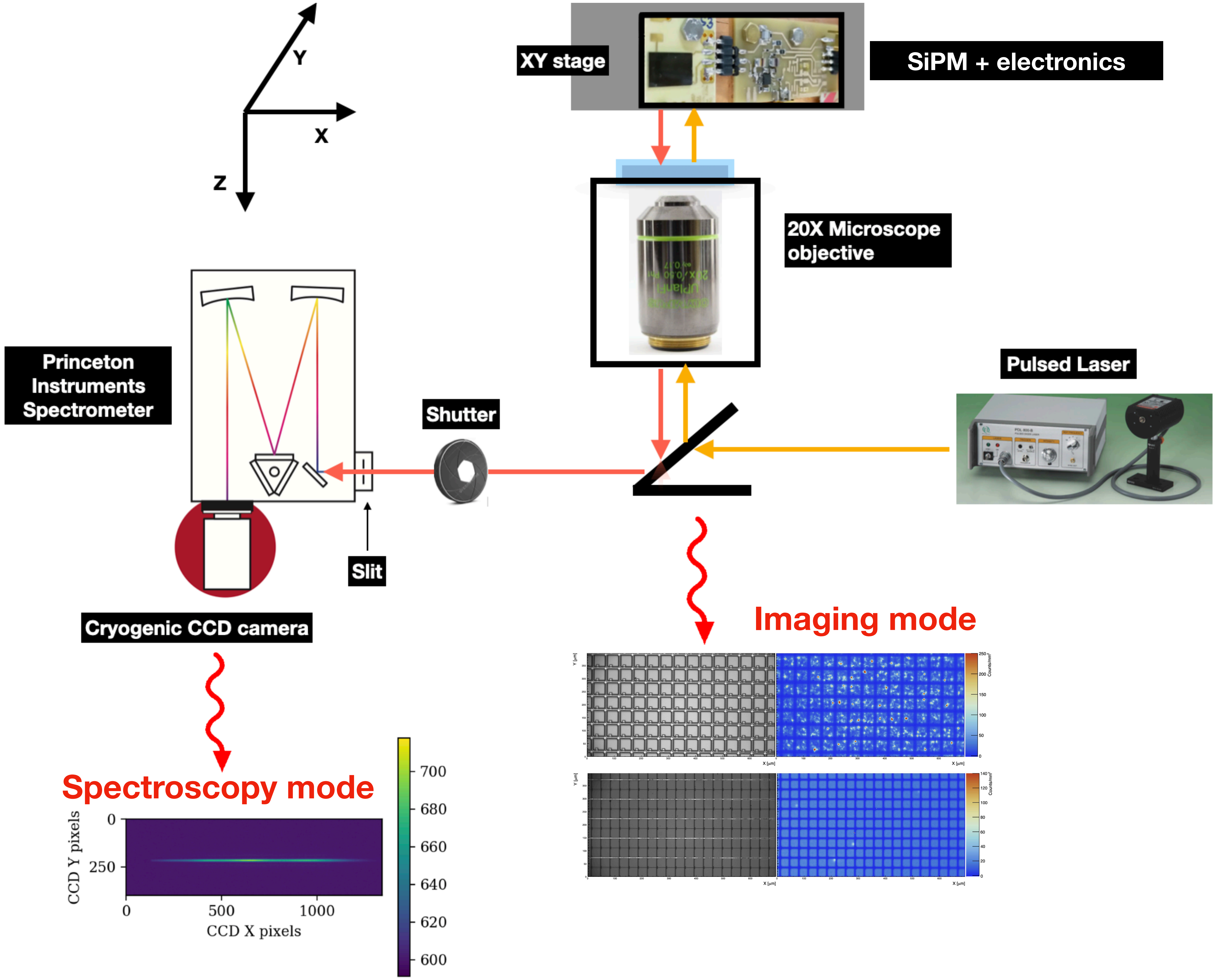
arxiv.org/abs/2107.13753
DarkSide-20k TDR 2022

Experiment	SiPM	Size (mm^2)	Pitch (um^2)
DarkSide-20k	FBK NUV-HD Cryo	11.7×7.9	30×30
nEXO	FBK VUVHD3	5.96×5.56	35×35
	Hamamatsu VUV4	6×6	50×50

Hardware Setup at TRIUMF, Canada

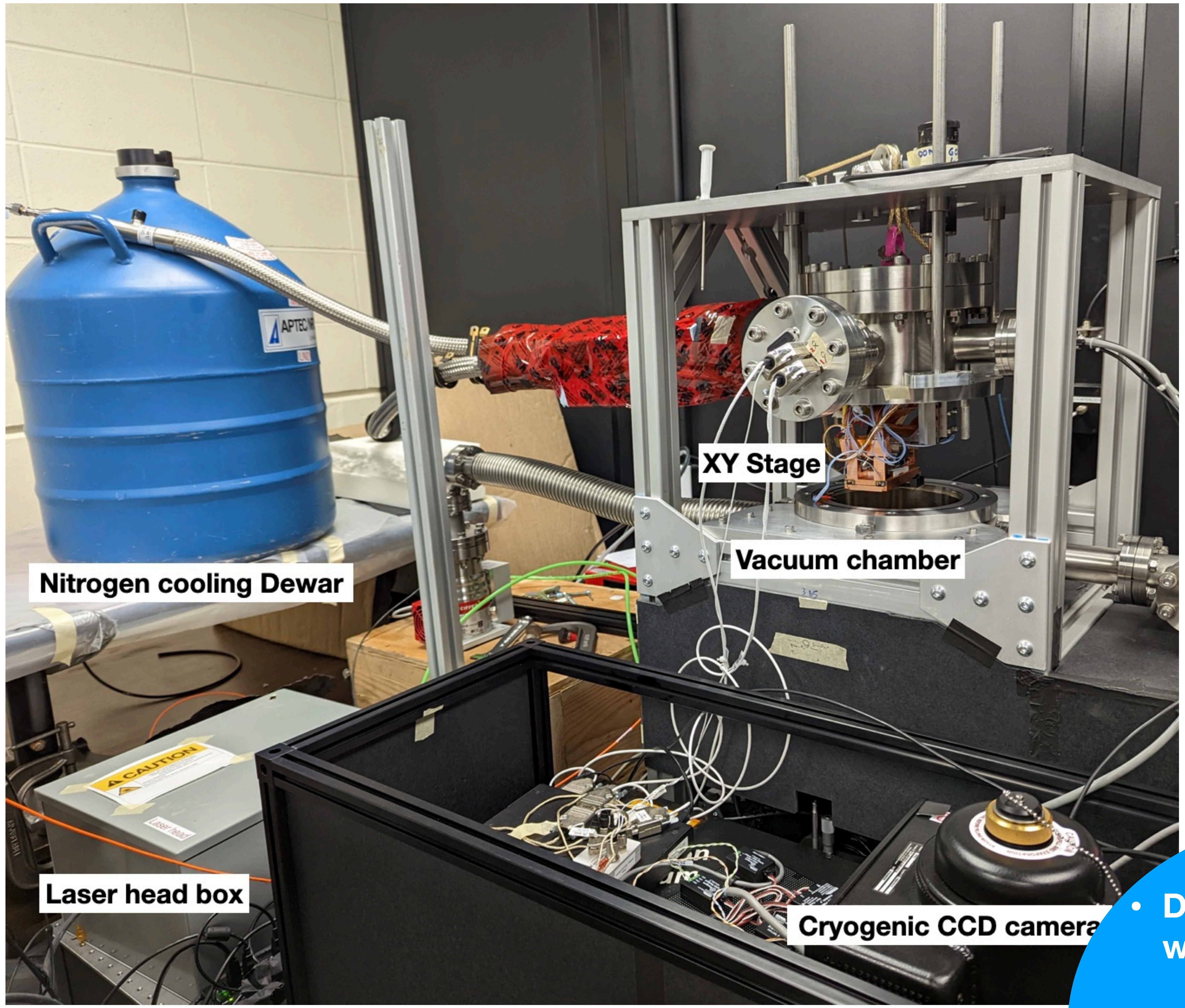
Operations done at cryogenic temperatures 87 K - 290 K

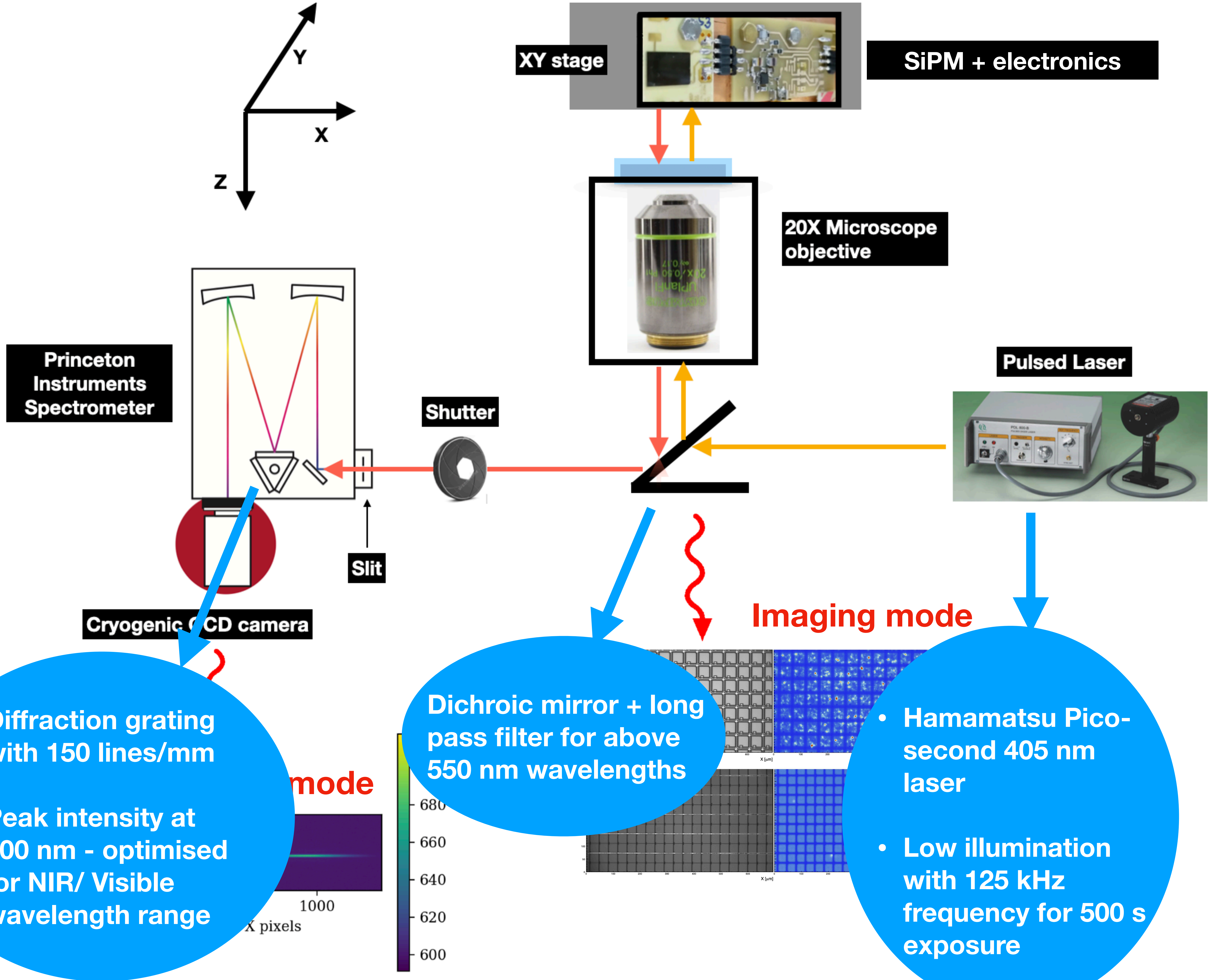




Hardware Setup at TRIUMF, Canada

Operations done at cryogenic temperatures 87 K - 290 K



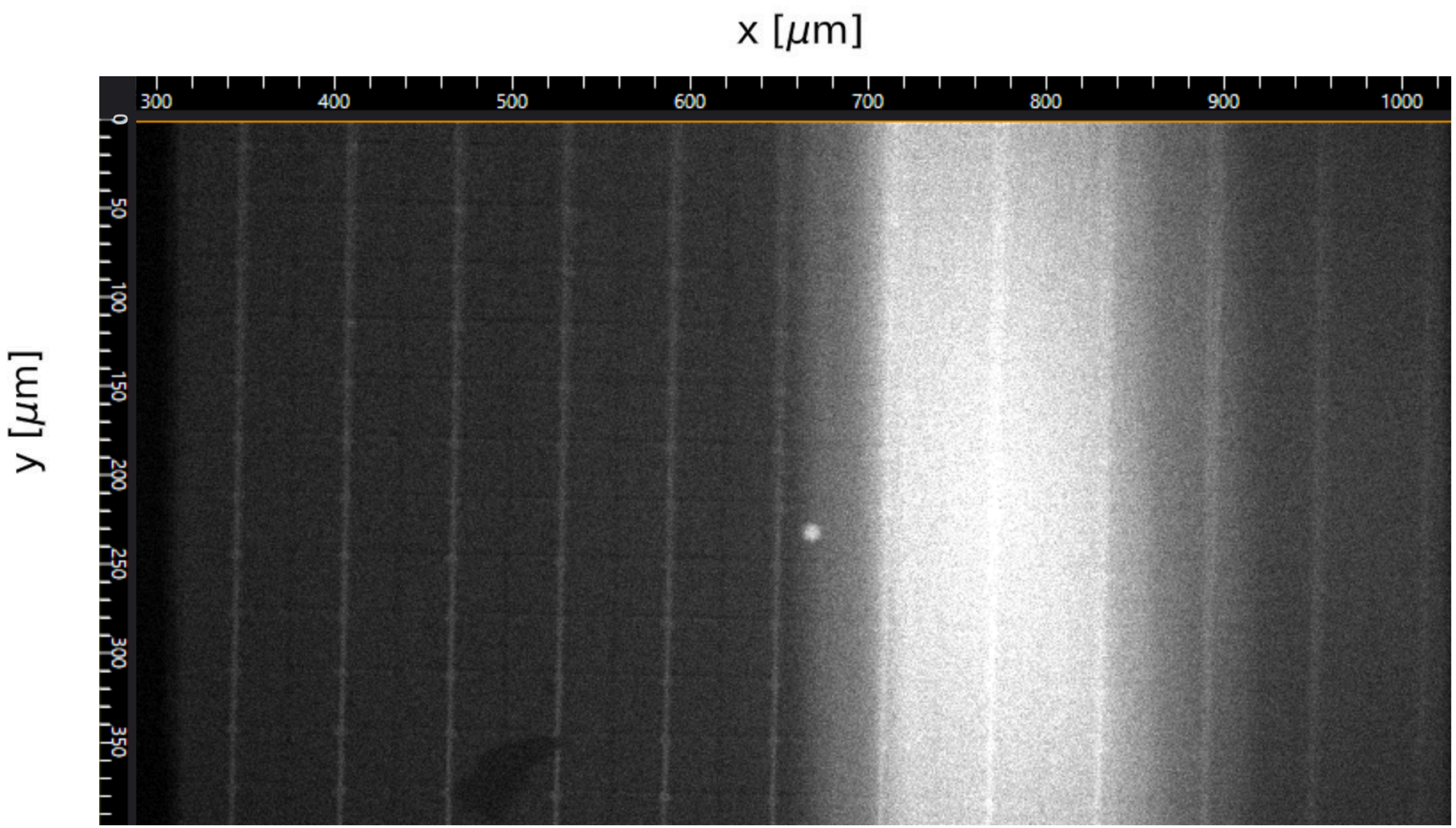


- Diffraction grating with 150 lines/mm
- Peak intensity at 800 nm - optimised for NIR/ Visible wavelength range

Dichroic mirror + long pass filter for above 550 nm wavelengths

- Hamamatsu Pico-second 405 nm laser
- Low illumination with 125 kHz frequency for 500 s exposure

Image of laser stimulated SPAD



FBK NUV-HD Cryo SPAD array, 30 x 30 um^2 pitch

- After localising the laser spot onto a SPAD, we put the slit on
- This makes sure the emission observed through spectrometer comes strictly from the vertical slice containing illuminated SPAD

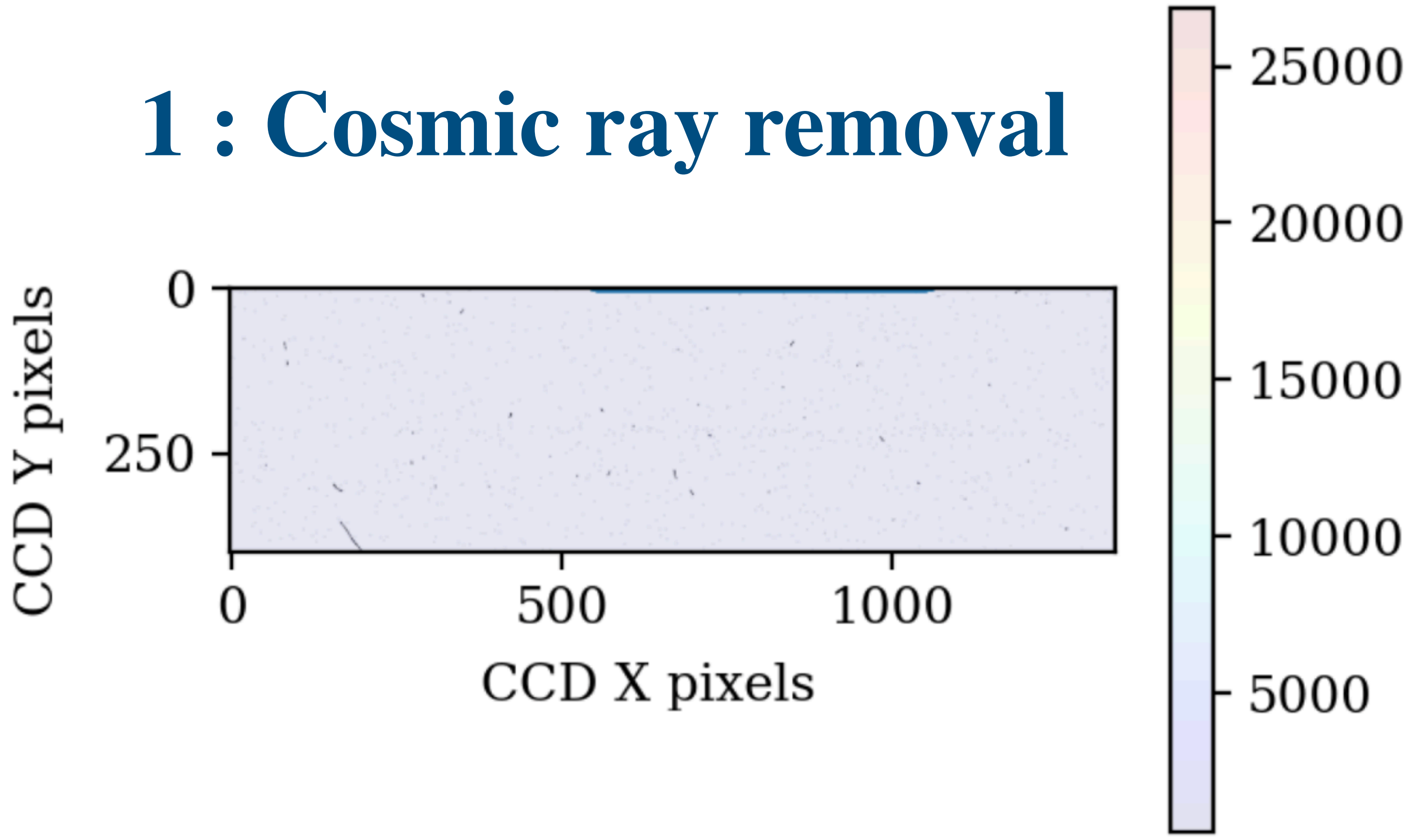
Photon emission spectra from FBK NUV-HD Cryo SiPMs

Spectroscopic study on DarkSide-20k SiPMs

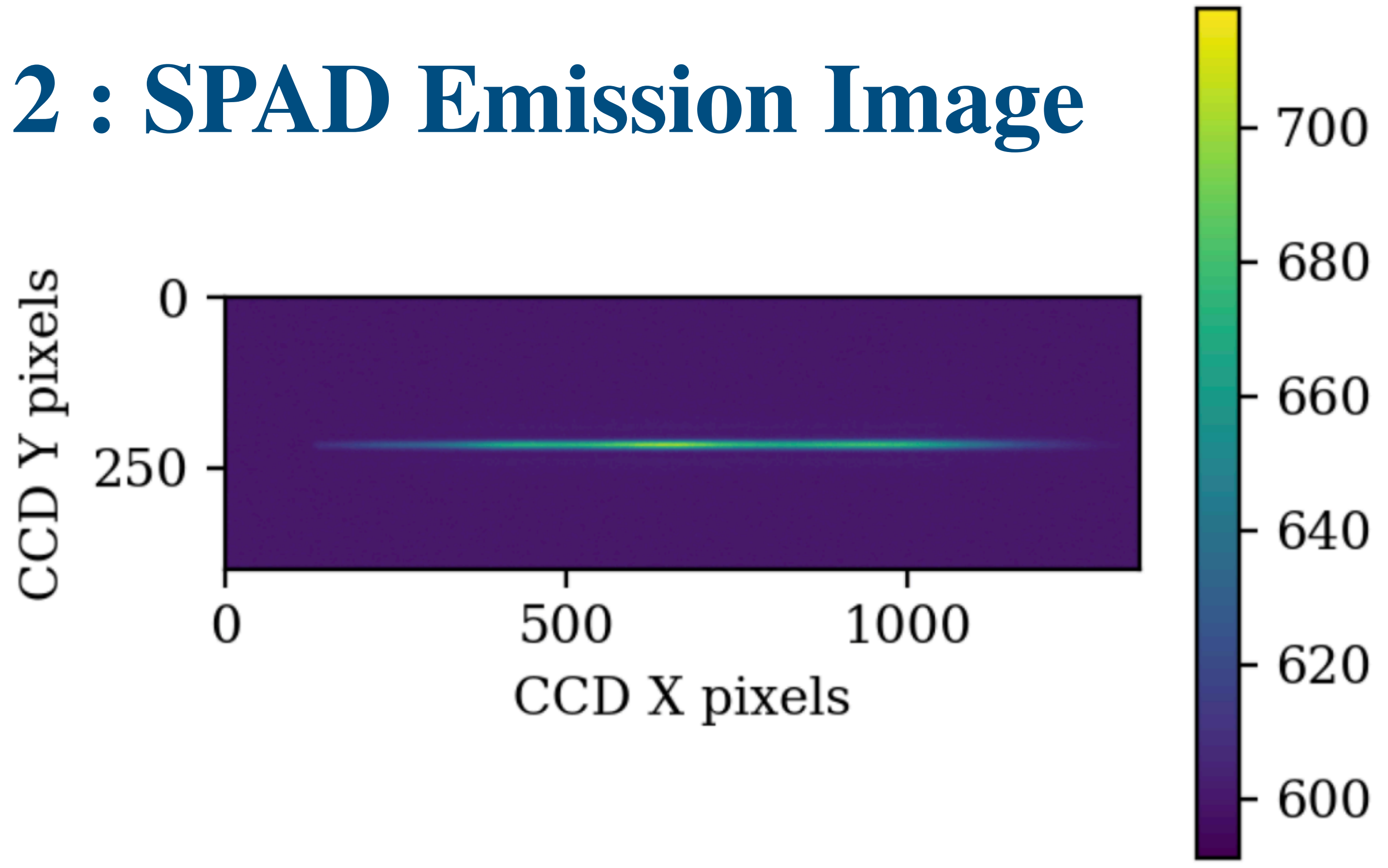
Priyanka Kachru, Kurtis Raymond, Fabrice Retiere, Giacomo Gallina

Spectral Analysis Work flow

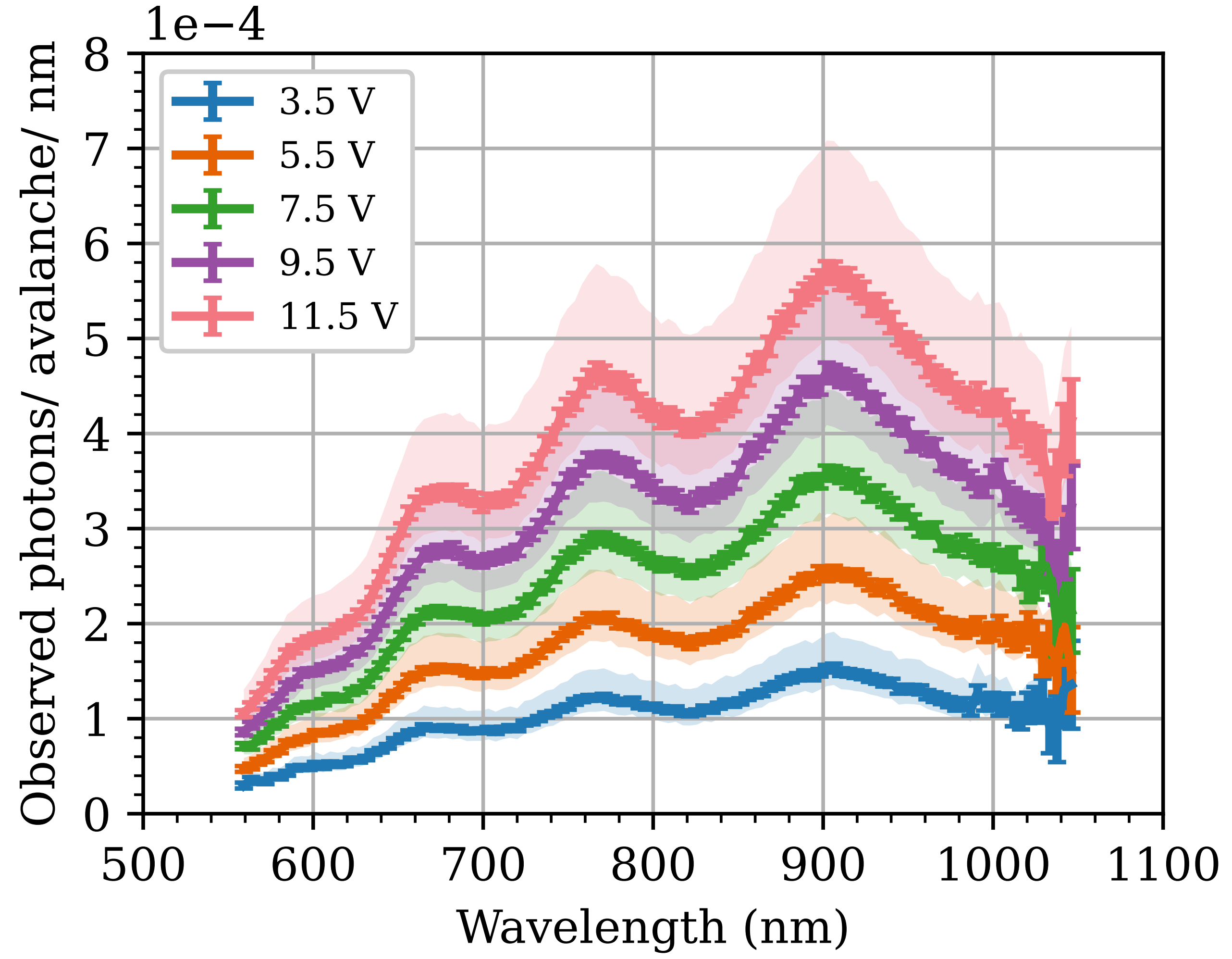
1 : Cosmic ray removal



2 : SPAD Emission Image



3 : Observed number of photons



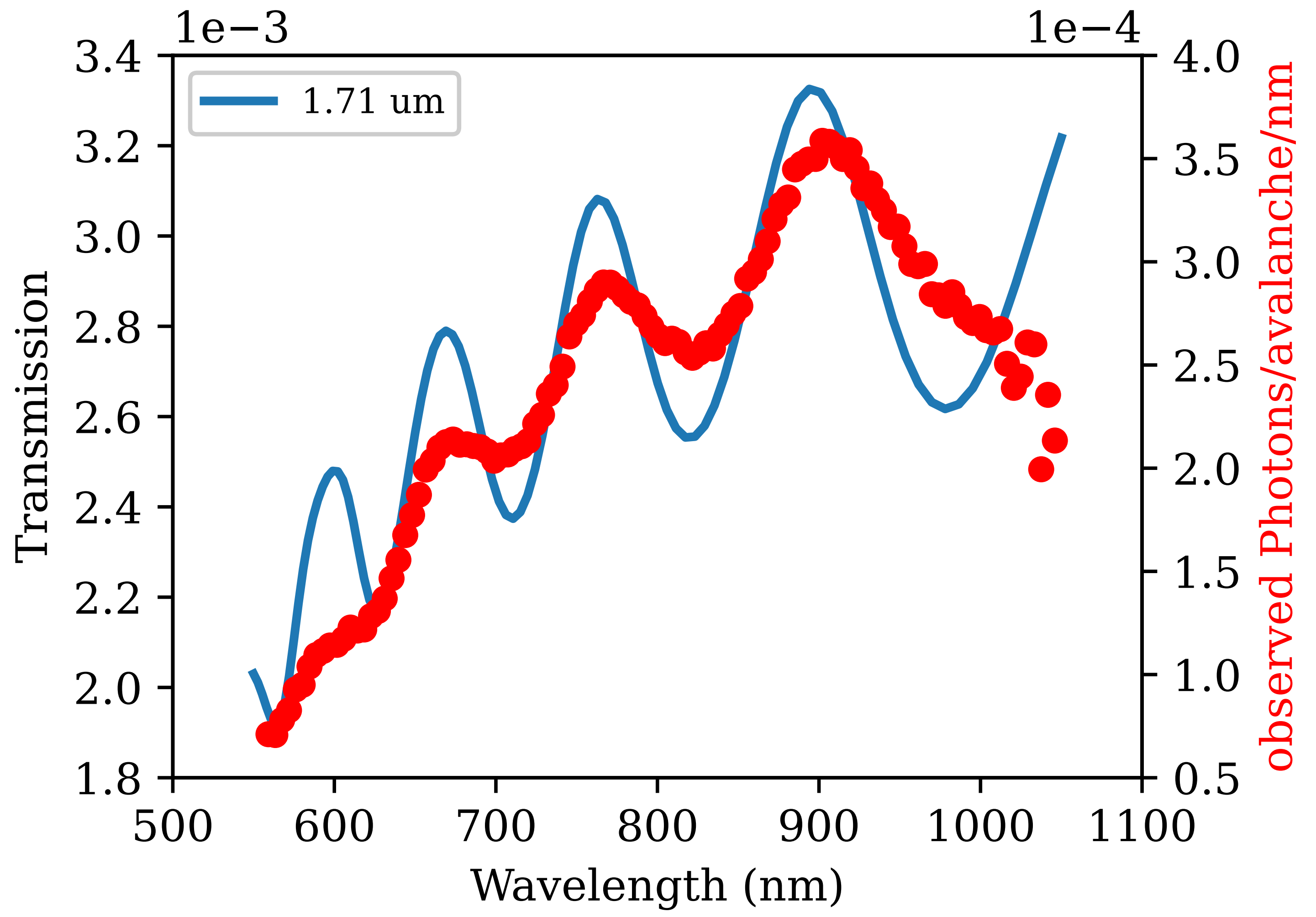
Source correction factor depends on :

1. Depth of avalanche region

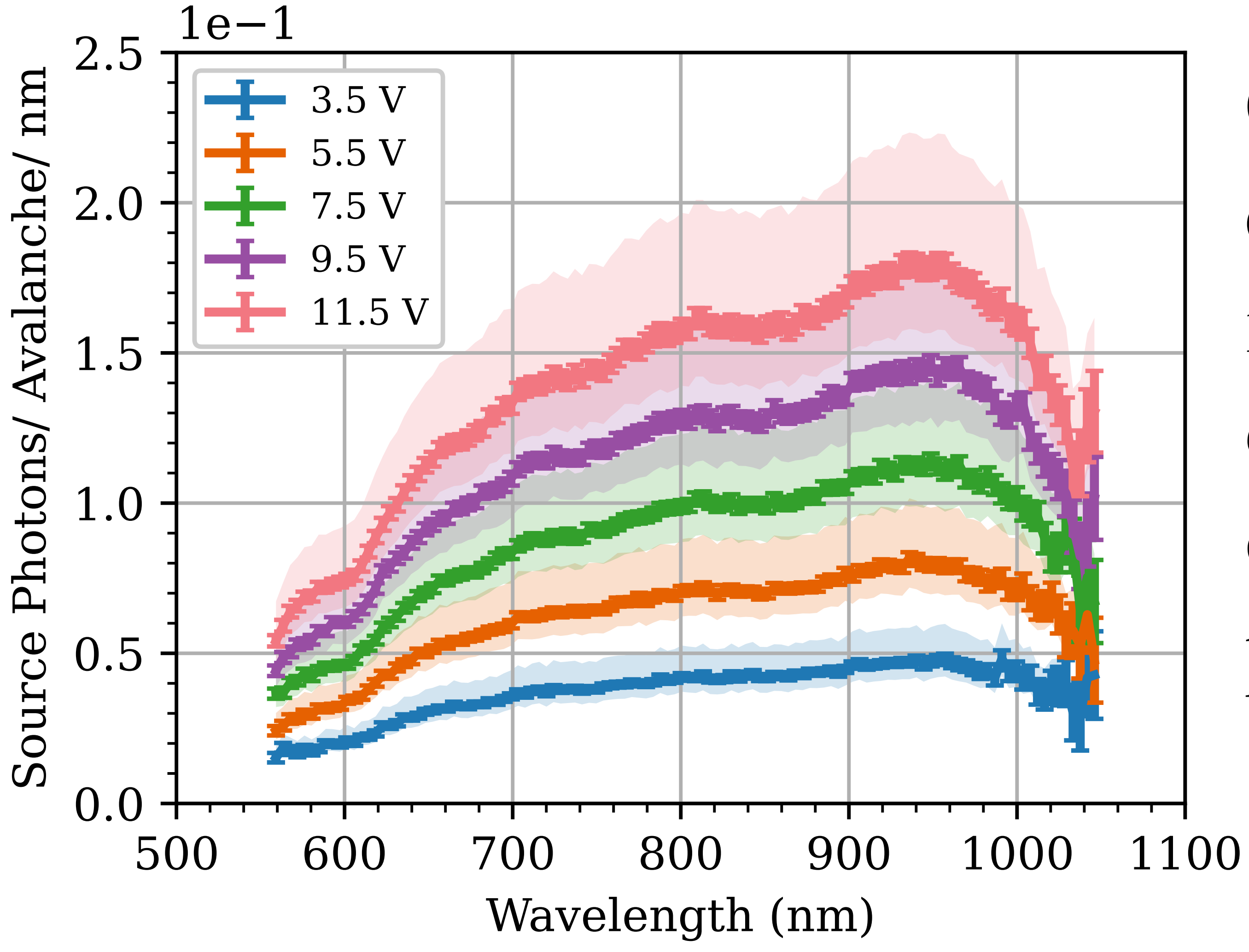
2. Limited microscope aperture

3. Optical losses

4 : Source correction factor

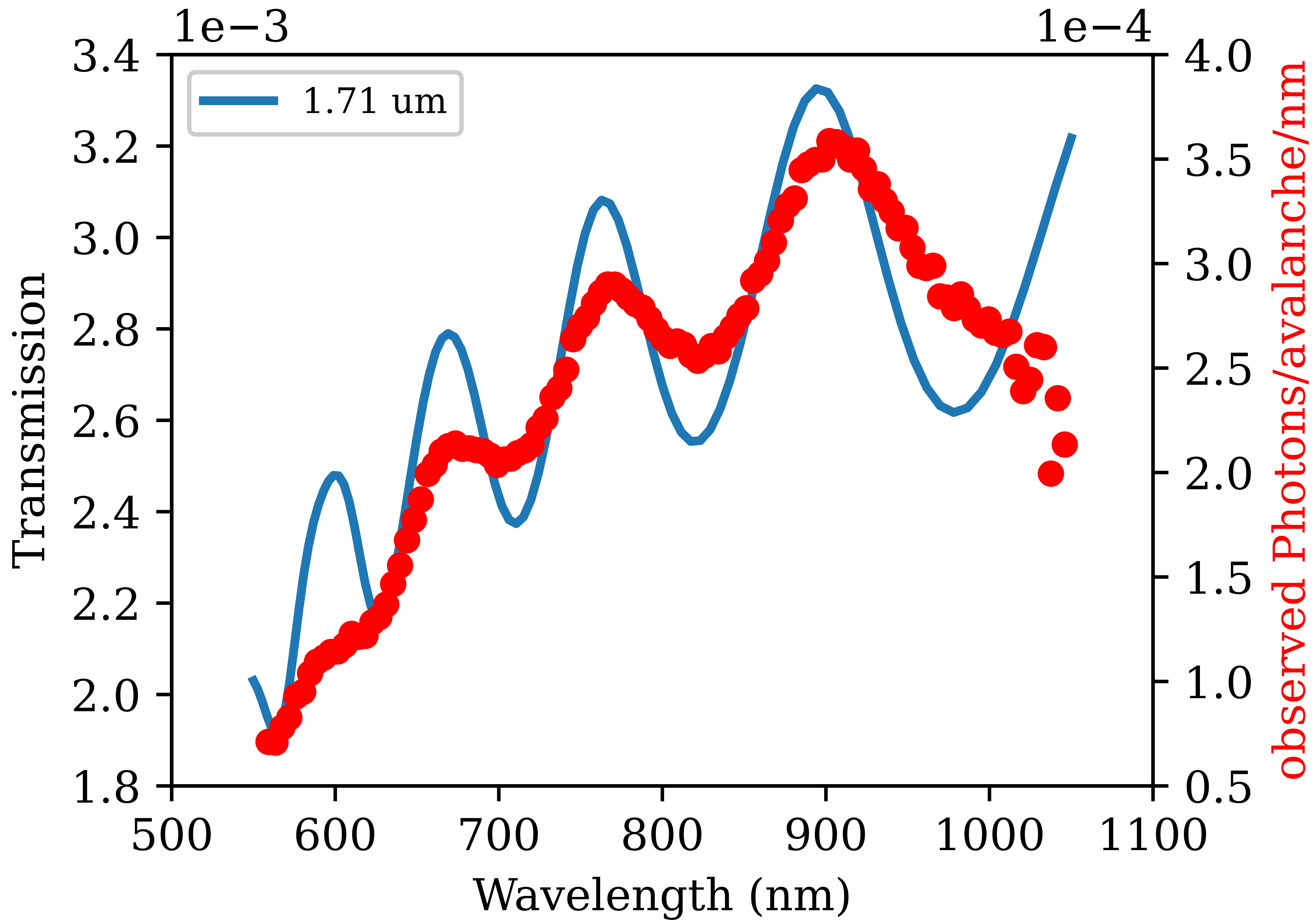


5 : Source number of photons



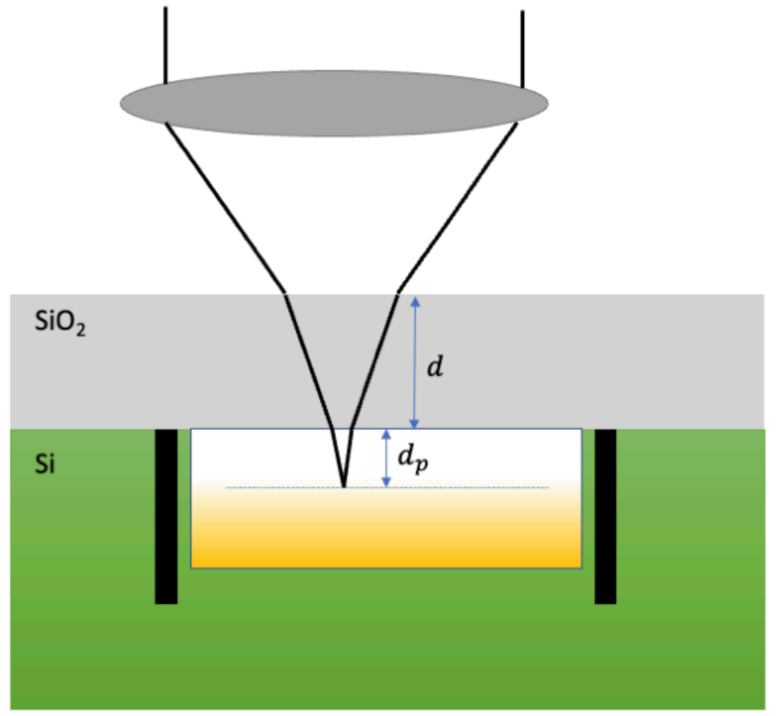
Correction factor eliminates the interference pattern due to the SiO_2 coating on the SiPM to produce number of source photons

Source correction factor (FBK NUV-HD Cryo SiPM)



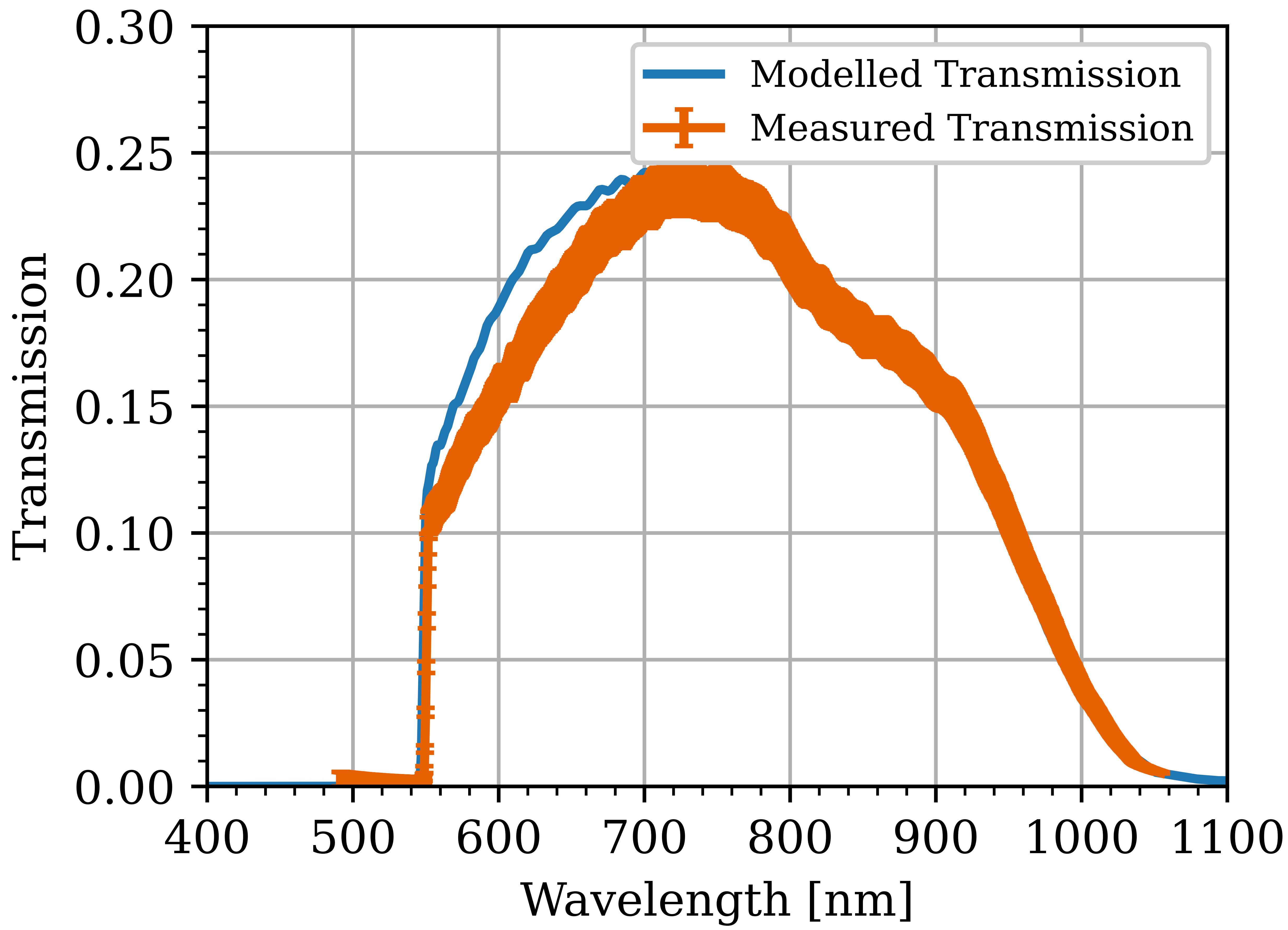
Source correction factor was calculated :

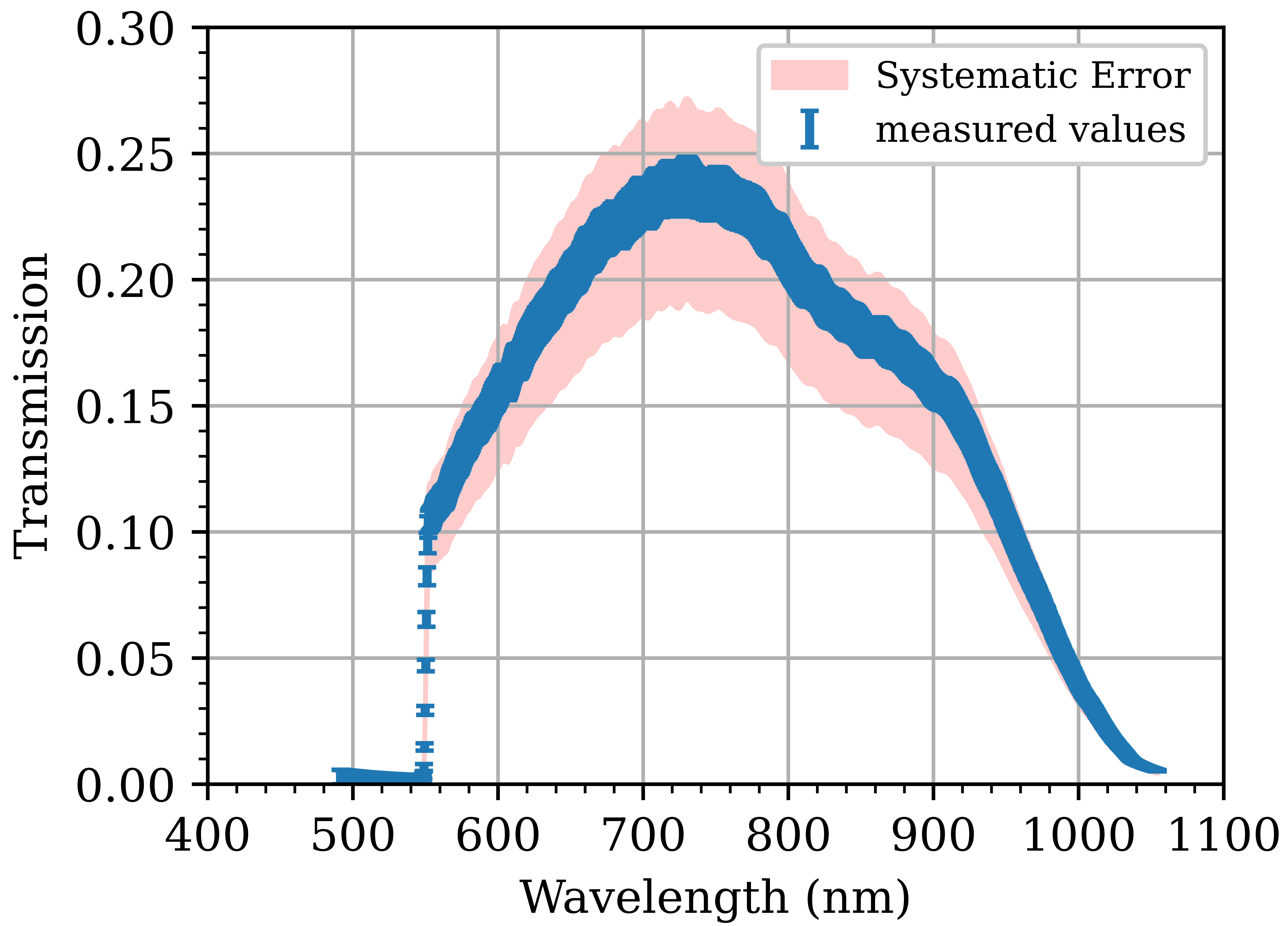
- **Using transmission through Si - SiO_2 interface at the top of SiPM through 0.45 NA (Numerical Aperture) of microscope objective**
- **Thickness of SiO_2 layer was estimated by matching the oscillation peaks**
- **The estimated thickness (d_{SiO_2}) was 1.71 um simulated in Lumerical**



Ansys Lumerical FDTD simulation

Intensity calibration of the setup



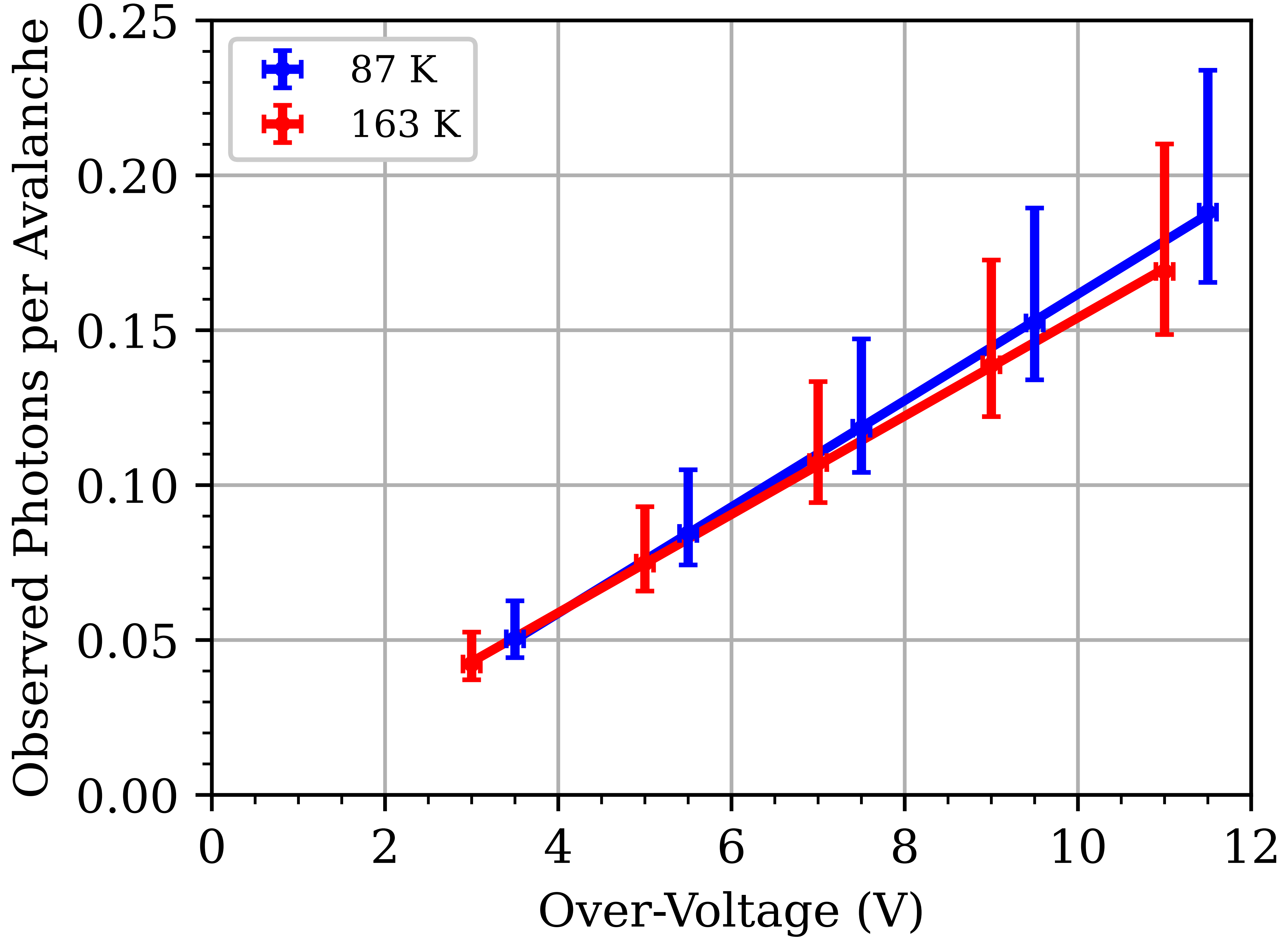


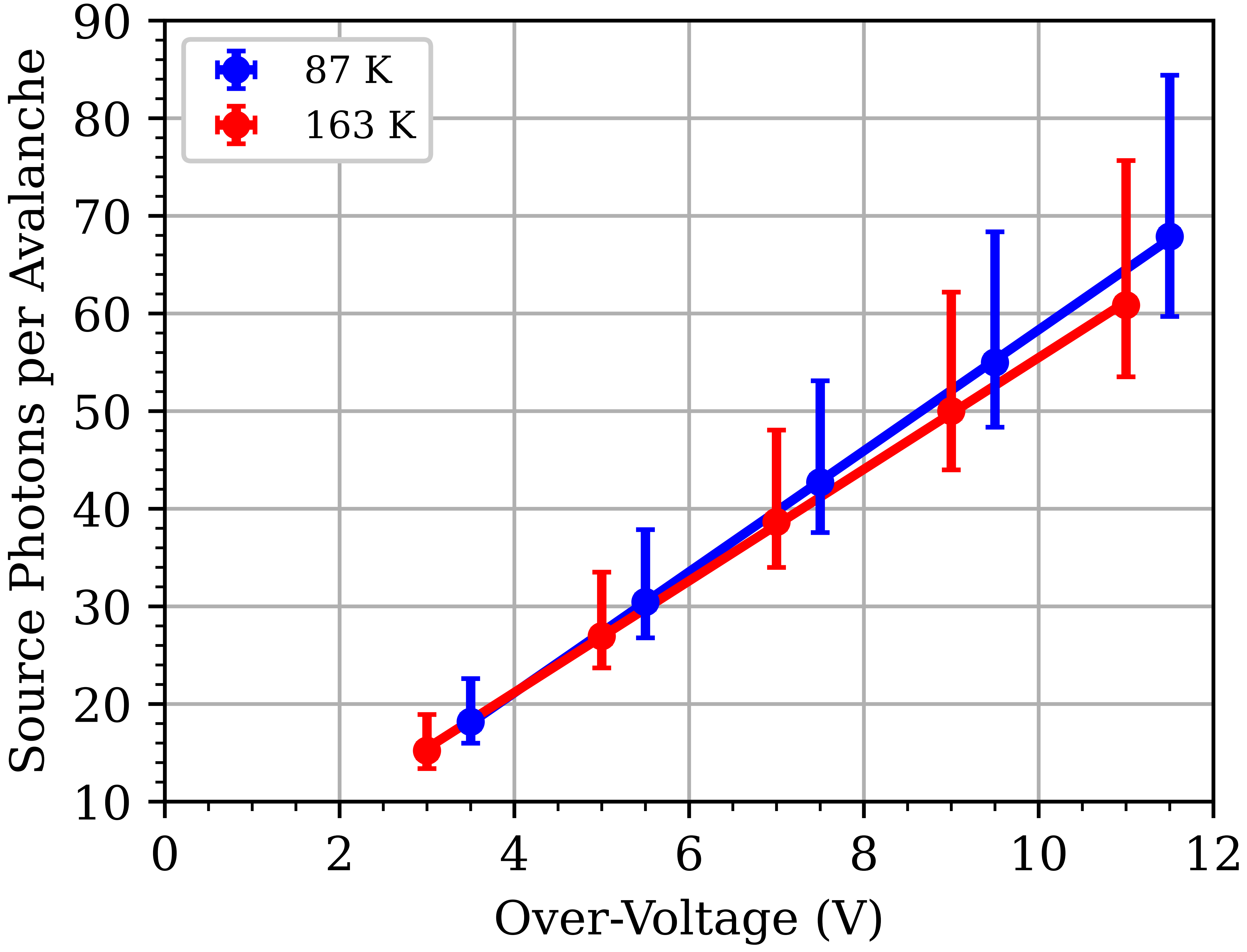
The measured transmission curve results from calibrated Tungsten halogen source in the setup
The modelled transmission curve results from individual transmission curves of optical components

The relative error between the measured and modelled curves gives the systematic uncertainty

Photons spectra into 0.45 NA (FBK NUV-HD Cryo SiPM)

Integrated over wavelength





Out of source photons generated isotropically, only 0.4 % are detected through the microscope acceptance whereas 99.6% are lost

Photon emission spectra from FBK VUVHD3 and HPK VUV4 SiPMs

Spectroscopic study on potential nEXO SiPMs

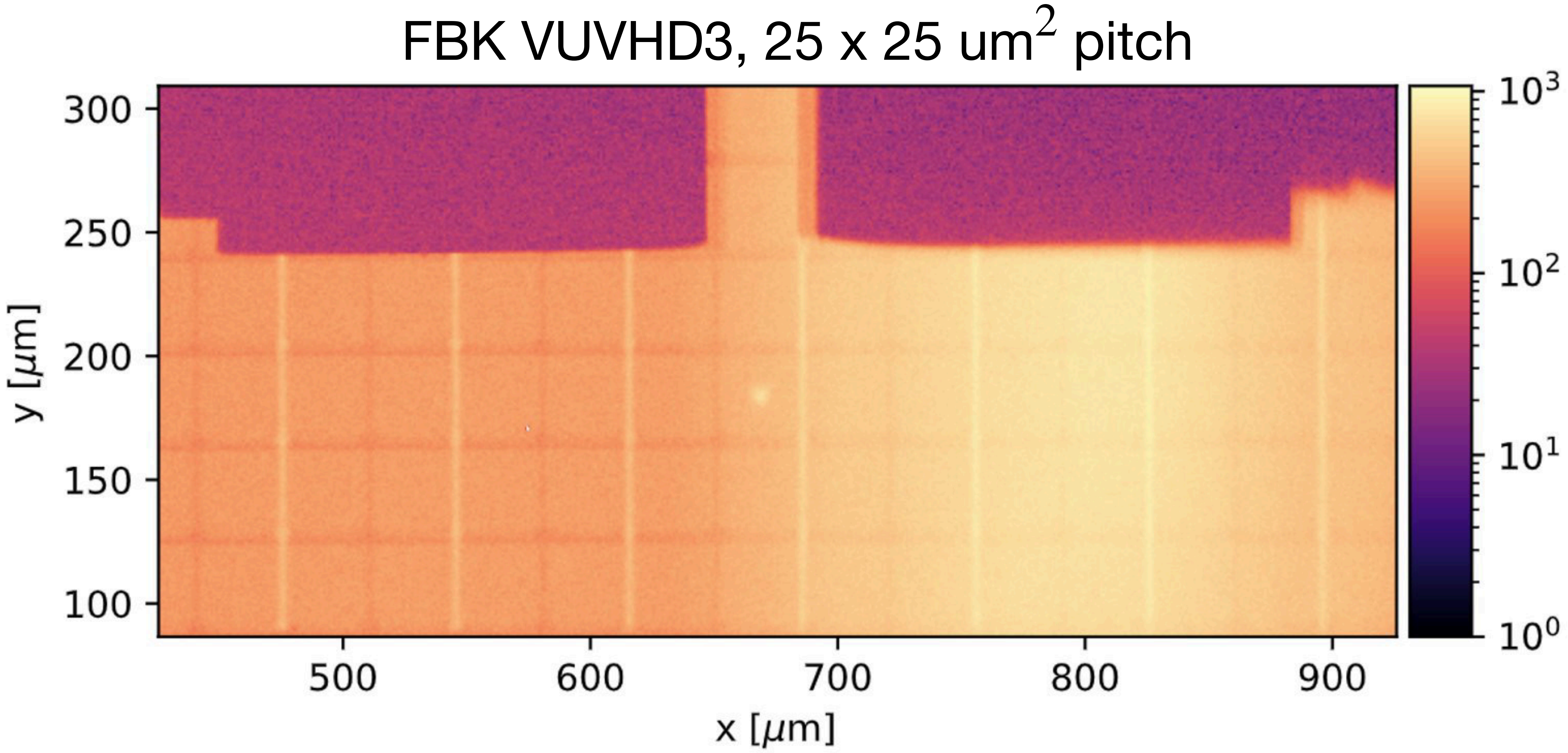
Kurtis Raymond[1], Fabrice Retiere[1], Mahsa Mahtab[1], Duncan McCarthy[1]

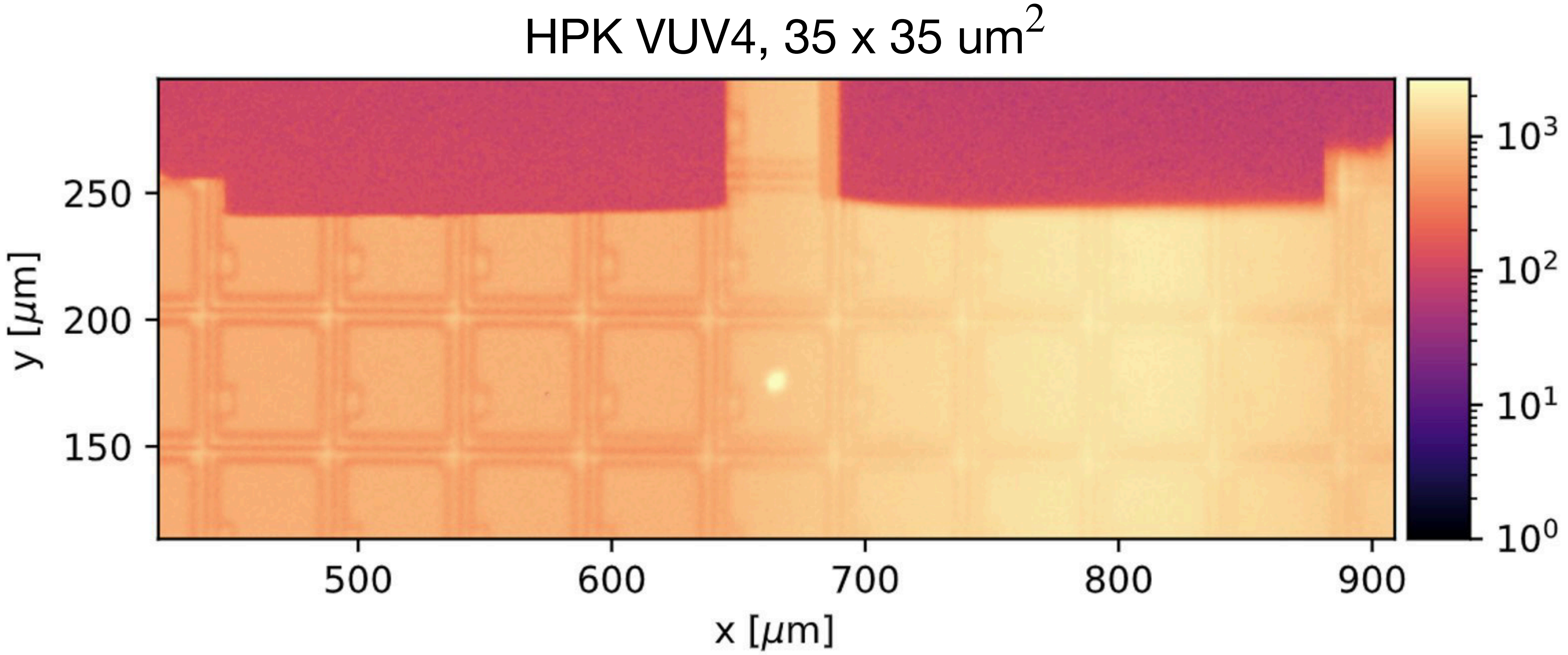
[1]TRIUMF Vancouver (BC), Canada

<u>Characterisation scope of nEXO SiPMs</u>

- HPK VUV4 Hamamatsu devices are older than the FBK VUVHD3 SiPMs
- HPK VUV4 have much lower direct crosstalk compared to FBK devices (arxiv.org/abs/2107.13753)
- nEXO SiPM characterisation is same as DarkSide SiPM, **EXCEPT :**
    1. An additional step of **calculating the absolute photon yield emitted outside SiPM in the air has been achieved**
    2. An effort to measure the **photon emission in a realistic nEXO-like detector** - **L**ight **o**nly **L**iquid **X**enon (LoLX) experiment (doi.org/10.1016/j.nima.2022.167876)

Image of laser stimulated SPAD

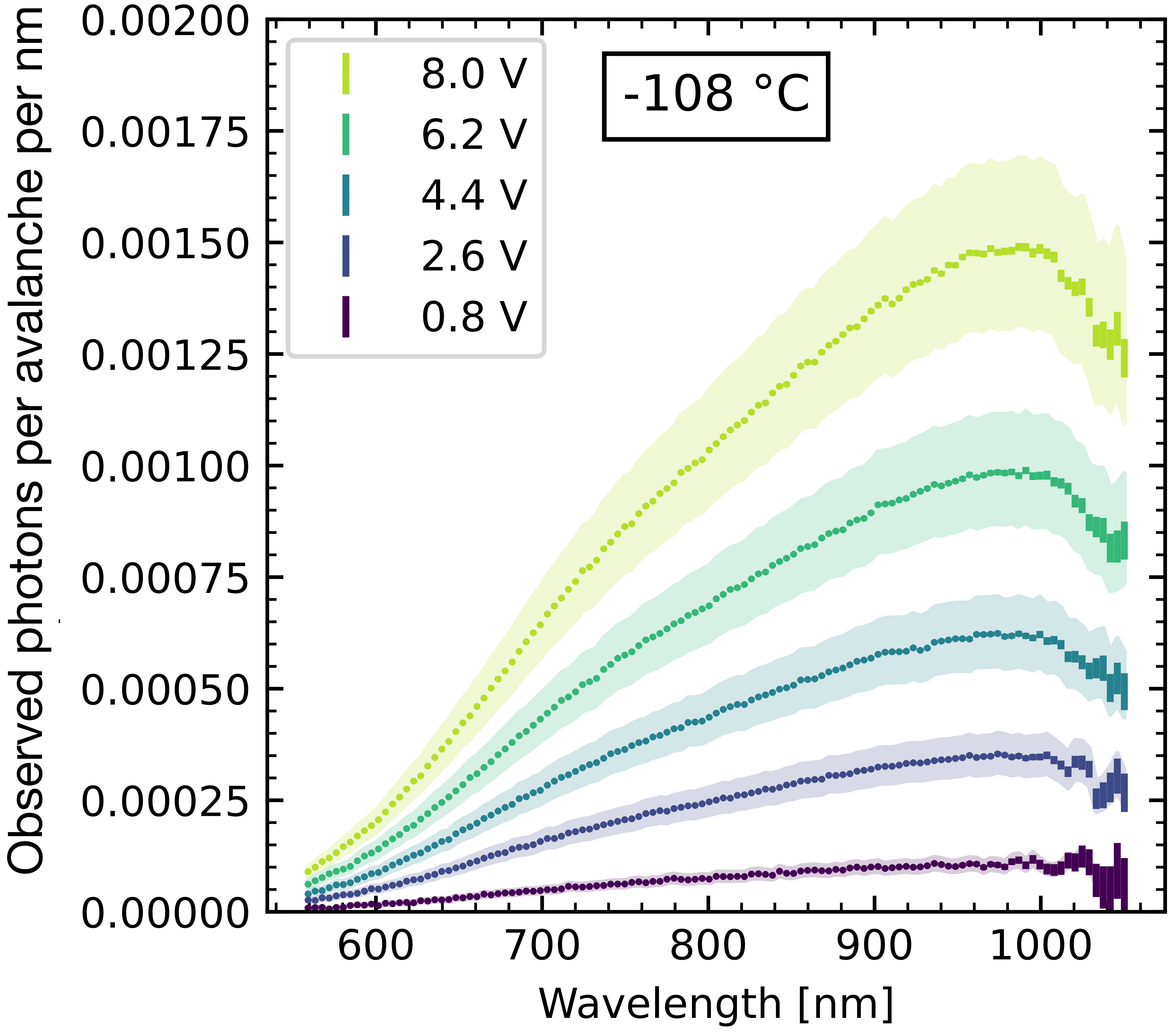




Observed Photons spectra into 0.45 NA

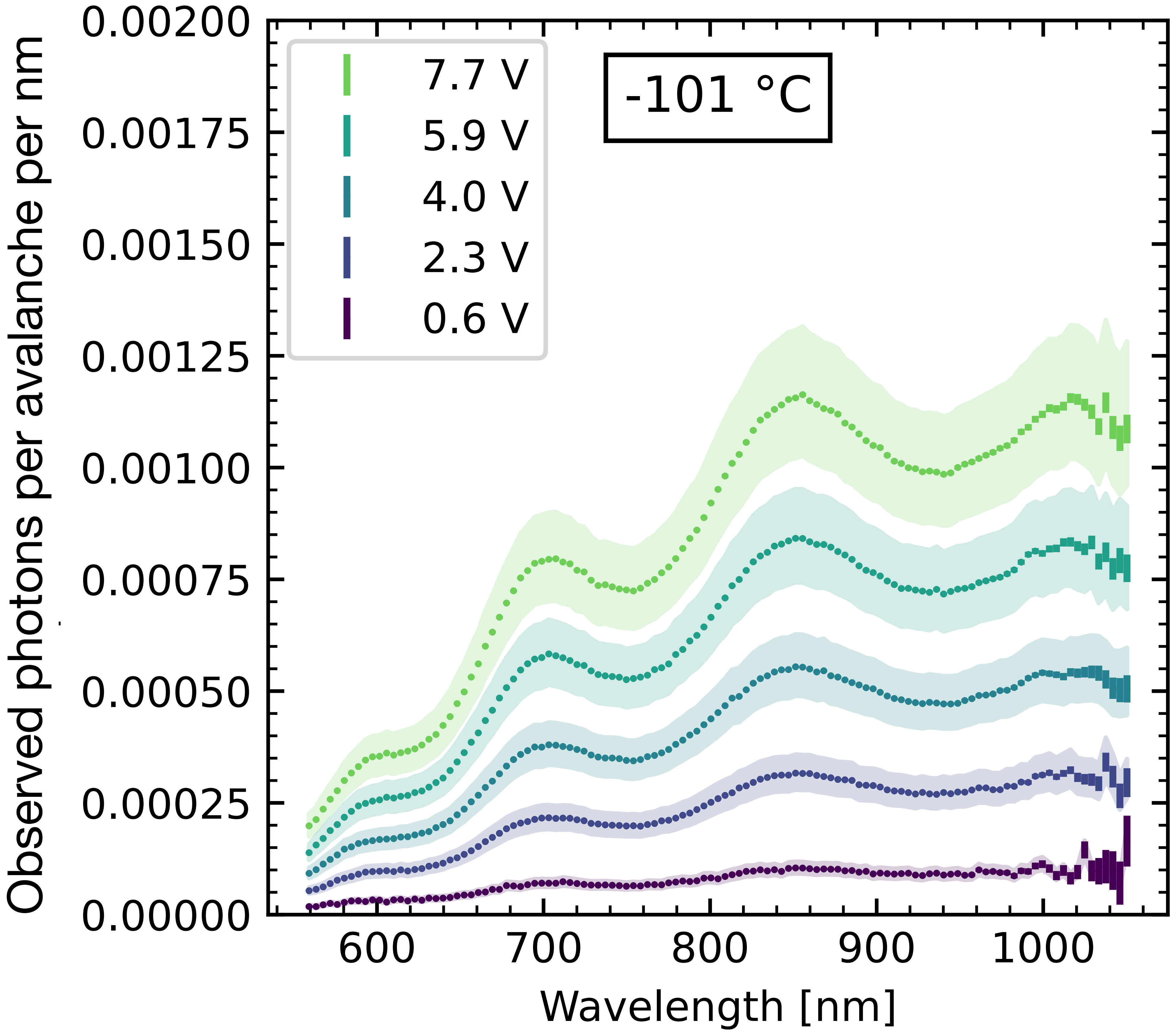
HPK VUV4

165 K



FBK VUVHD3

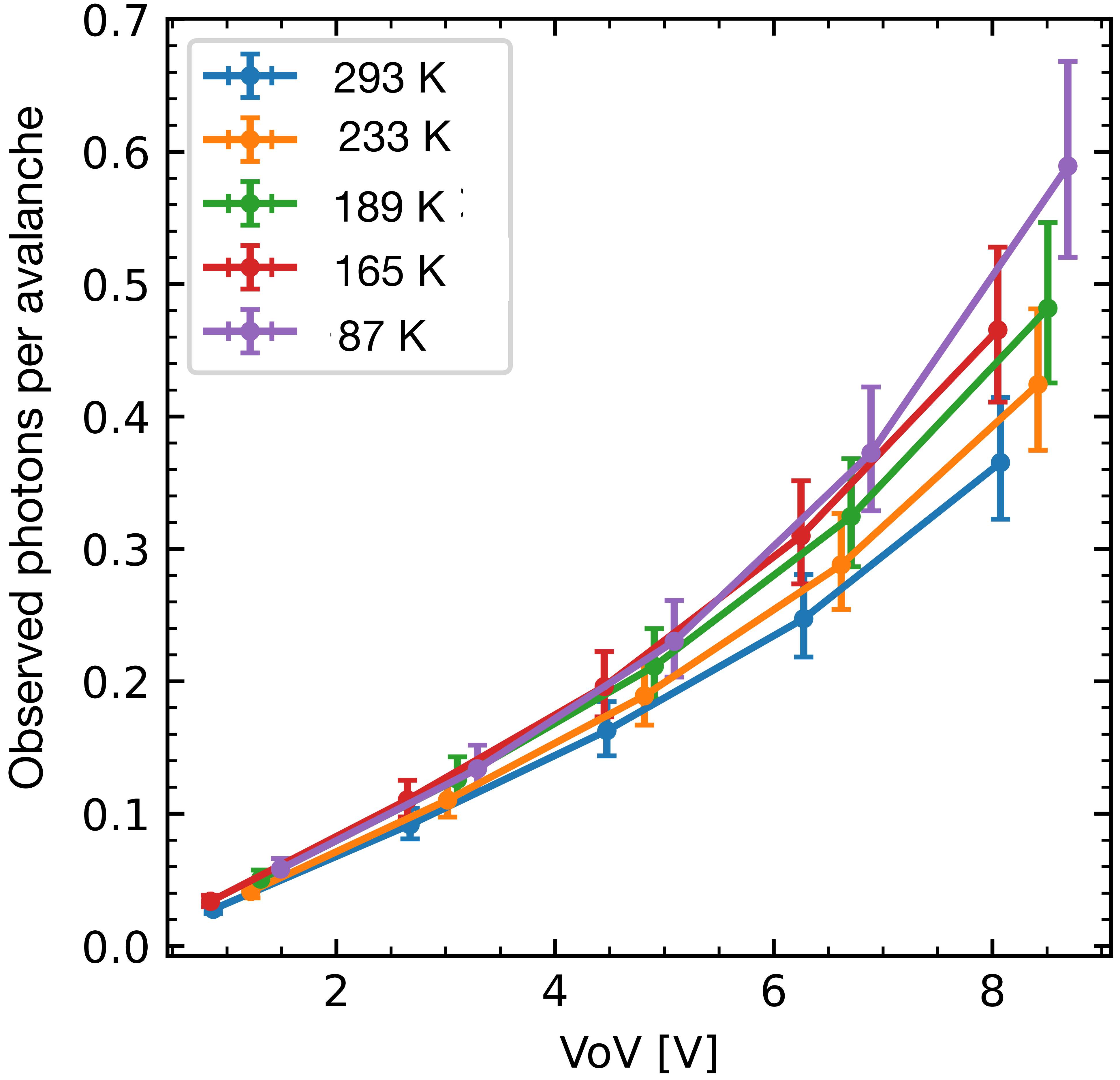
172 K



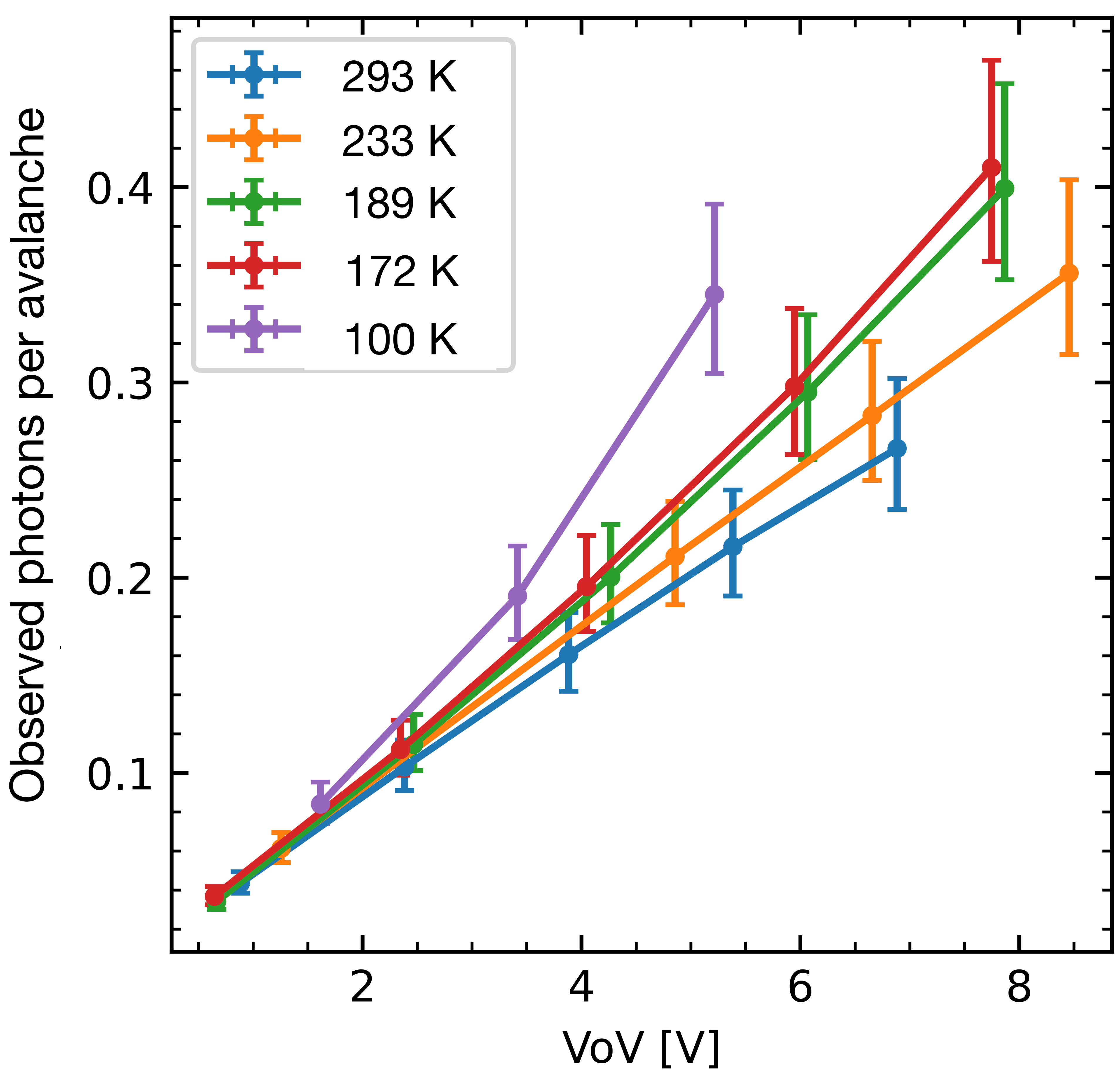
Observed Photons spectra into 0.45 NA

Integrated over wavelength

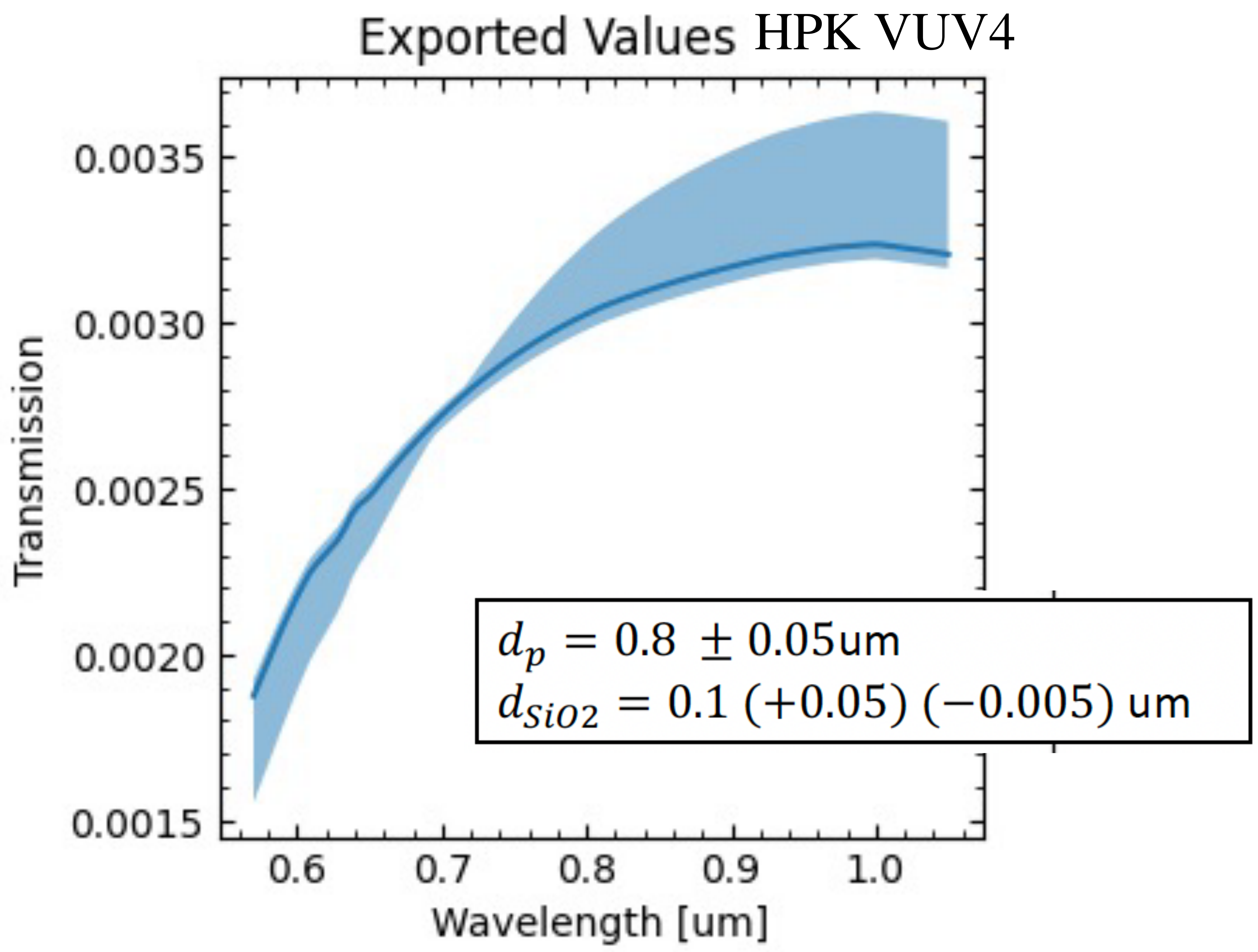
HPK VUV4

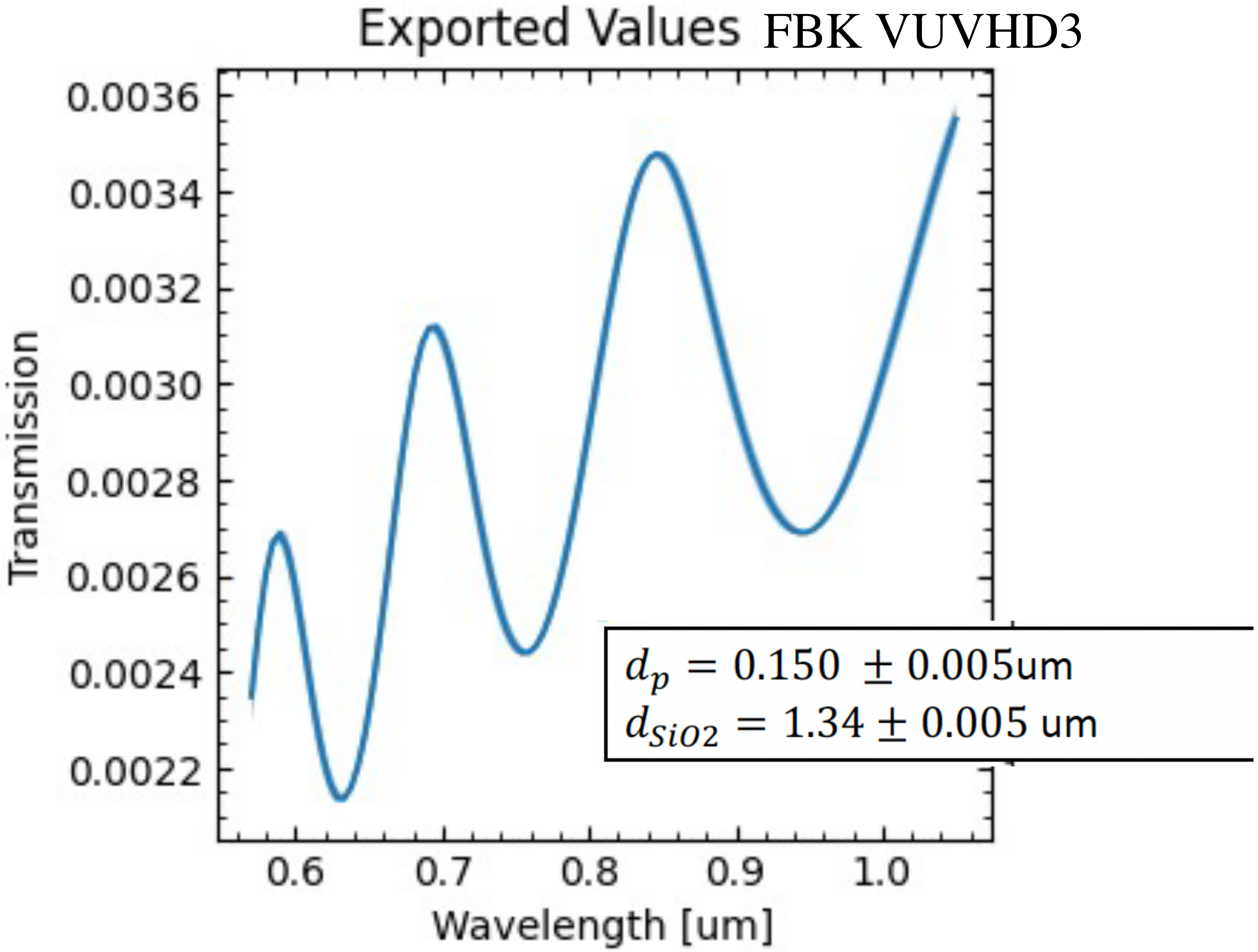


FBK VUVHD3



Source Correction factors





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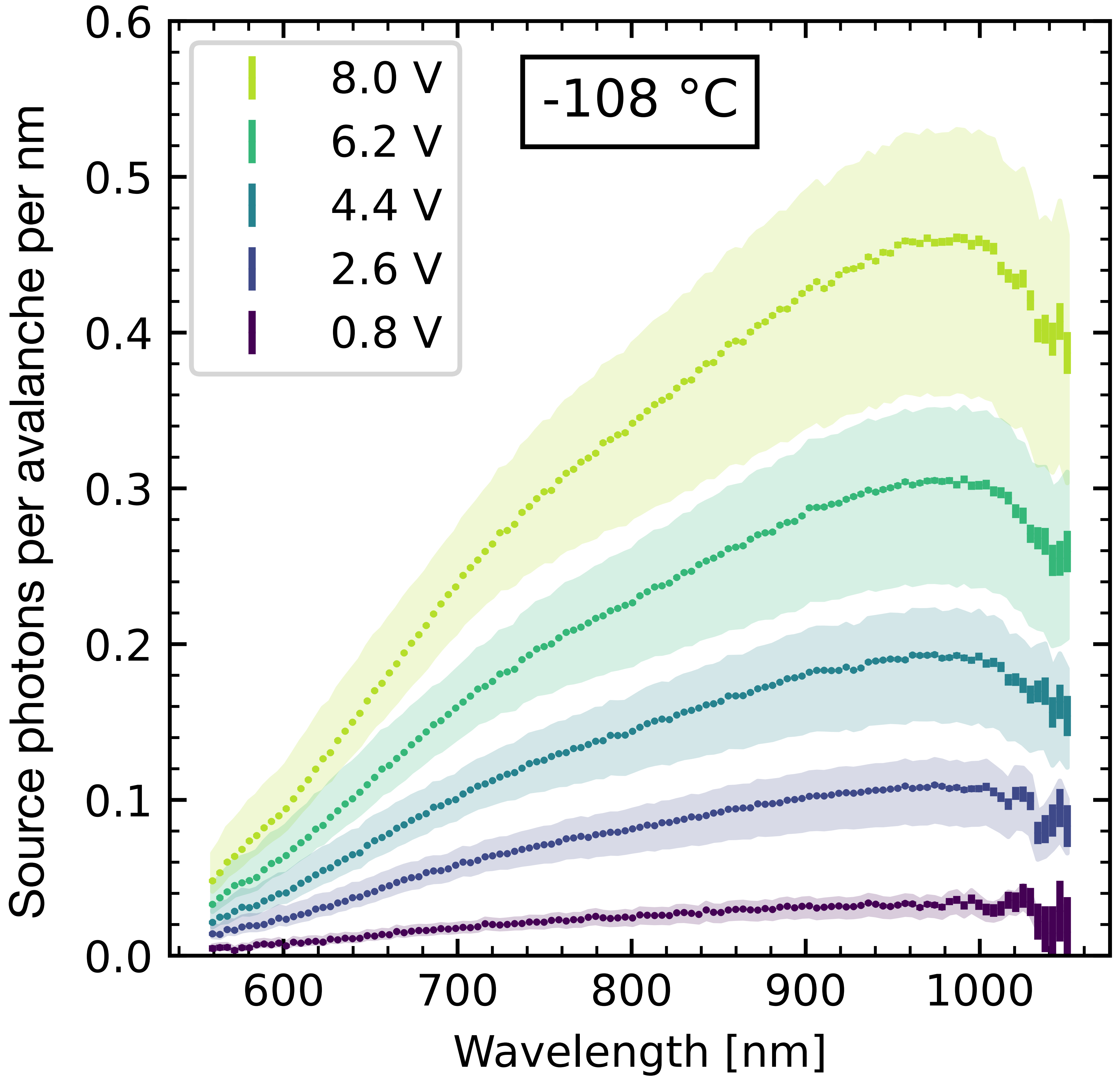
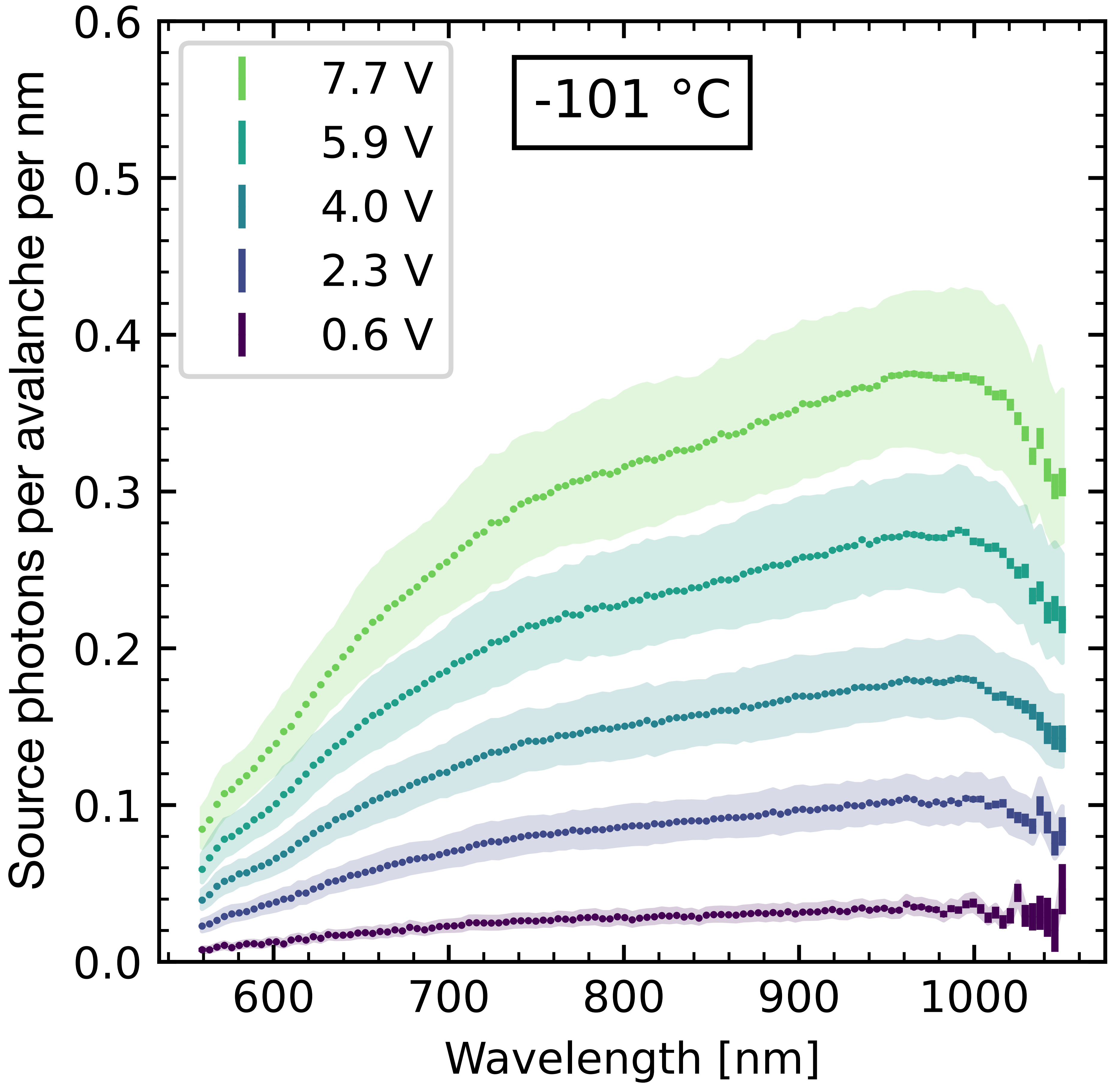


FBK VUVHD3

172 K



Source Photons spectra into 0.45 NA

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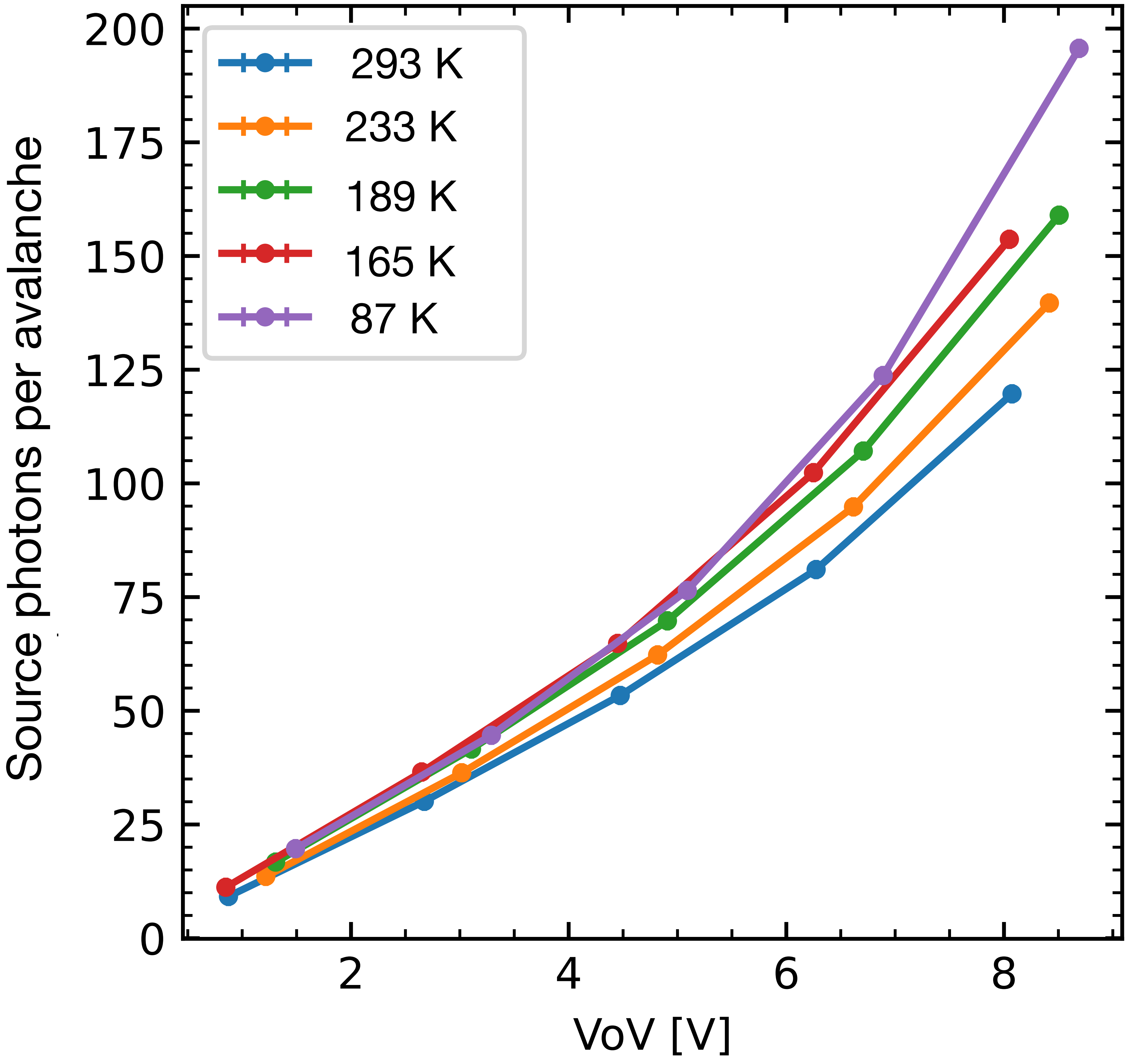
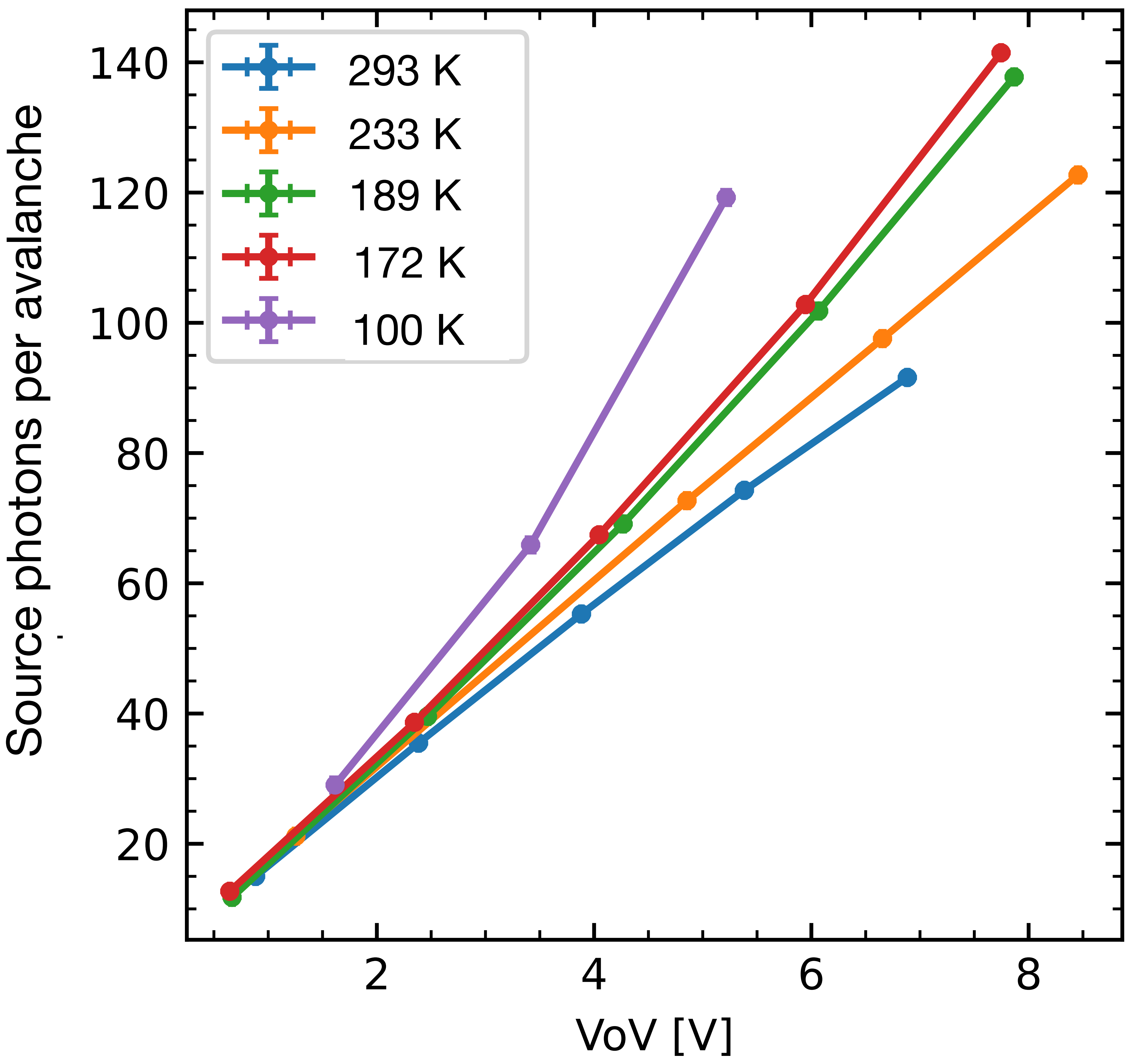
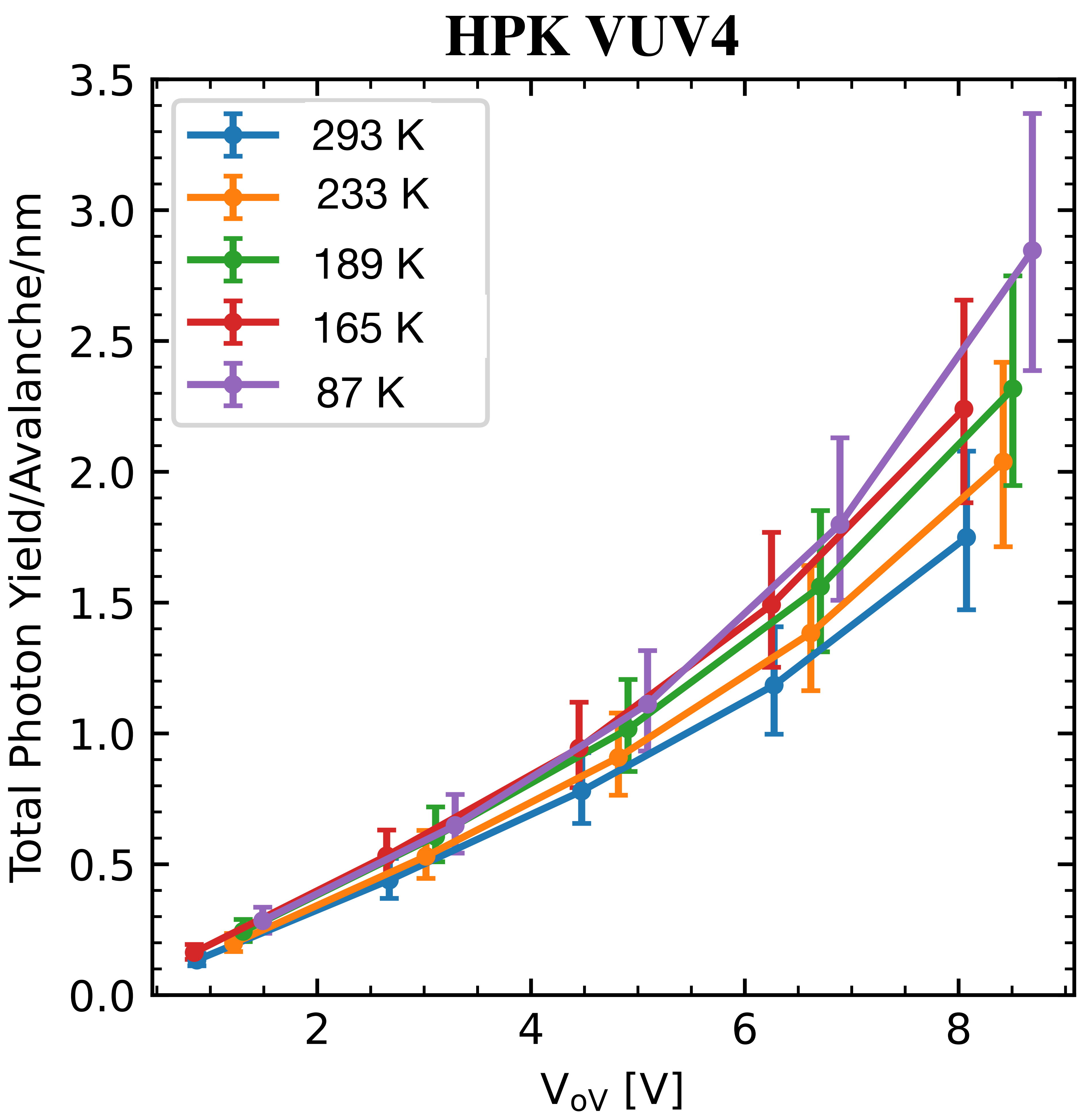
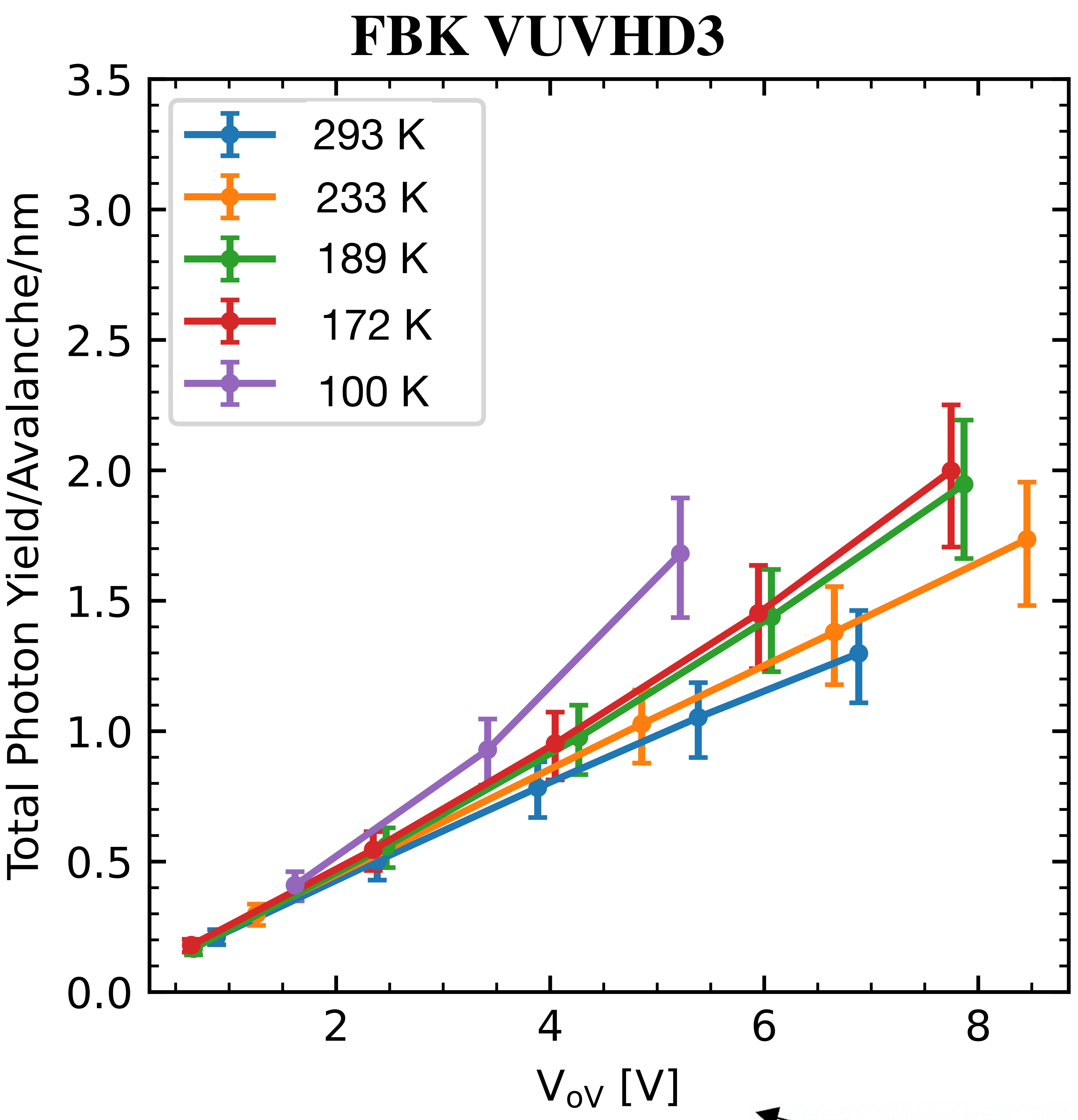


FBK VUVHD3

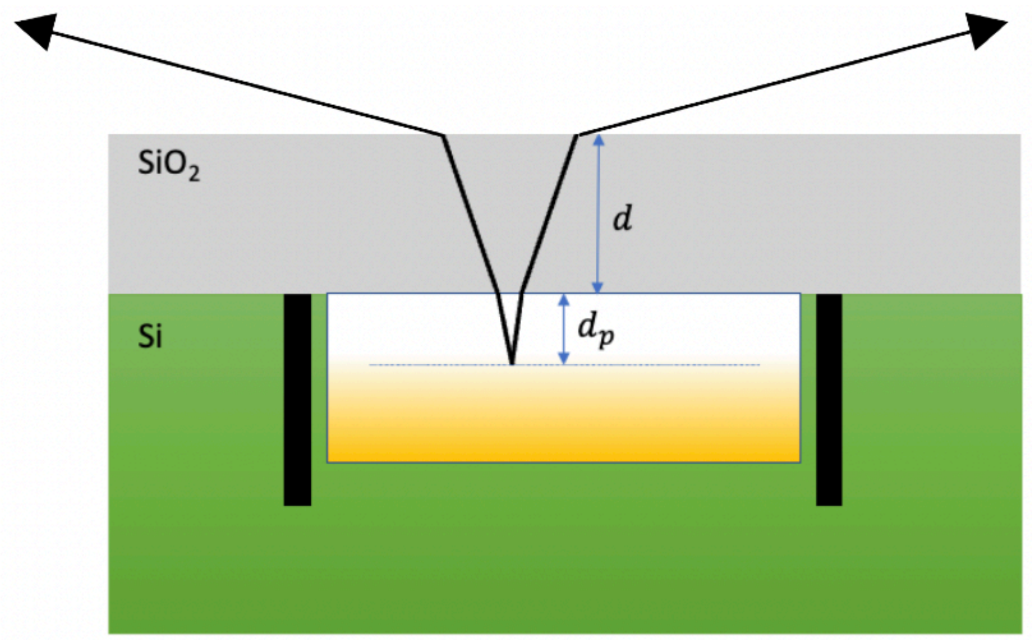


Absolute Photon Yield emission of SiPM in the air





$$\text{Total Yield} = \frac{\text{Observed Photons per avalanche (0.45 NA)}}{\text{Transmission 0.45 NA}} \cdot \text{Transmission } 1 \text{ NA}$$



Summary and Conclusion

1. Laser driven secondary photon emission of SiPMs is calculated at nominal experimental operating over-voltages : 2 - 10 V

2. Future experiments like DarkSide-20k and nEXO will use SiPMs as photodetectors and might have to quantify this noise phenomenon to understand the impact on detector's performance

3. Microscopic Spectroscopy was conducted on FBK NUV HD-Cryo, FBK VUVHD3, and HPK VUV4 SiPMs

4. They were studied at various cryogenic temperatures for determining the temperature dependence of the phenomenon

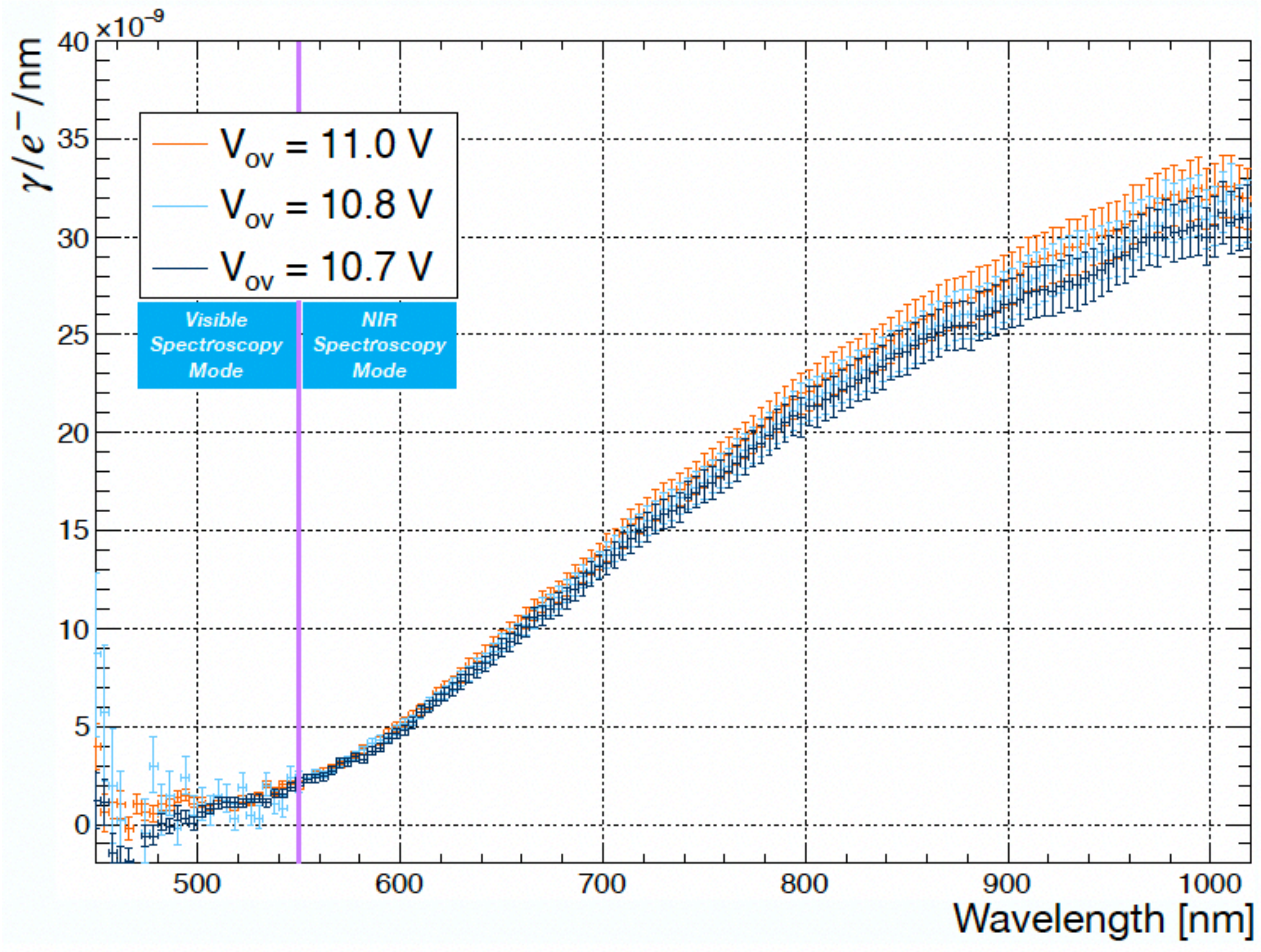
6. **In the future,** we want to characterise the impact on tonne scale detectors

BACKUP

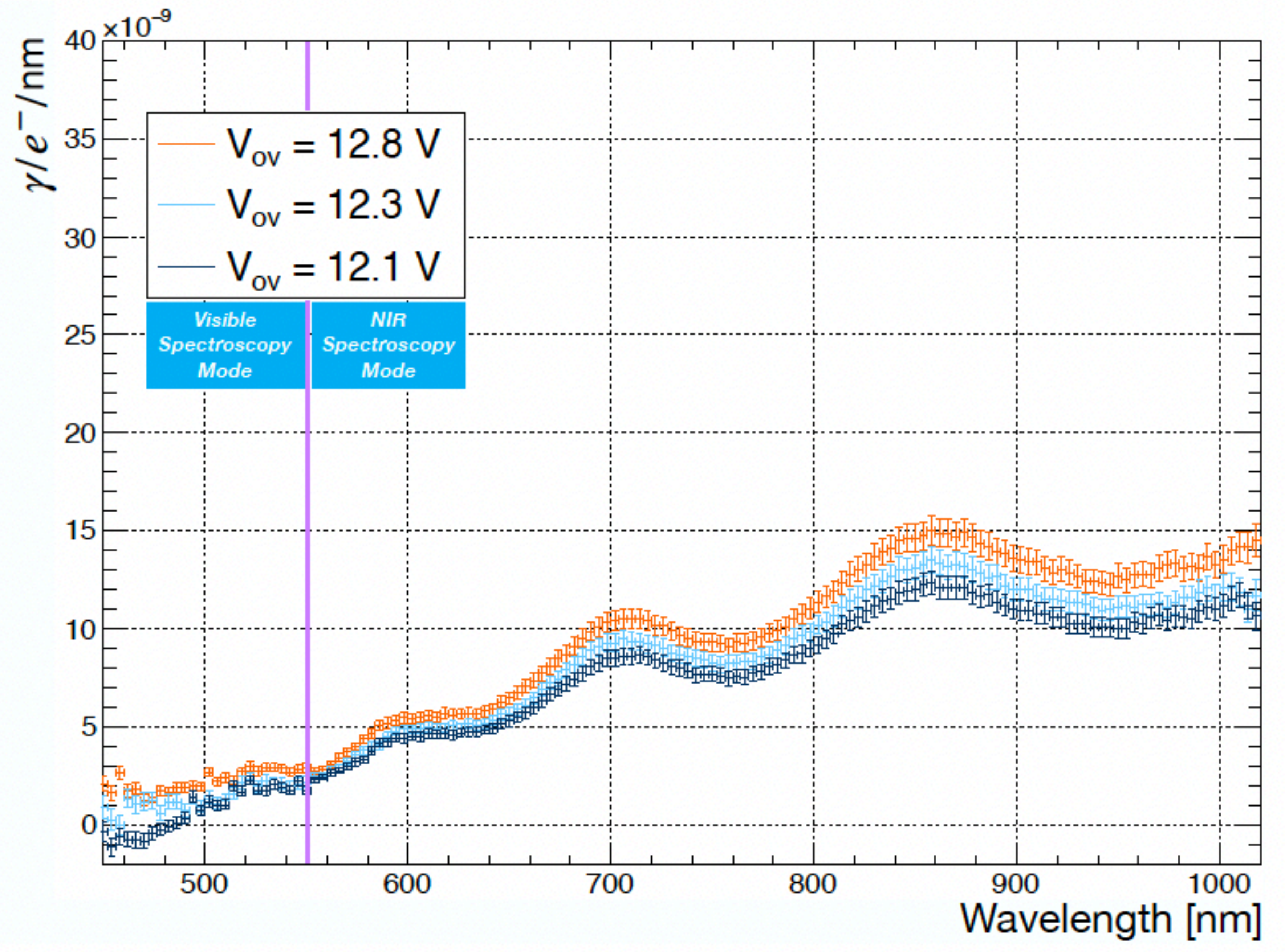
arxiv.org/abs/2107.13753

SiPM photon emission in dark

HPK VUV4



FBK VUVHD3



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	$(9.24 \pm 0.05) \times 10^{-6}$

- Long camera exposures of ~ 8 hours
- Operated at relatively high over-voltages (> 10 V) to obtain good statistics for spectroscopy
- Measurements done at room temperature (300 K)

Spectral Analysis Work flow

Emission spectra

(Camera gain, detection efficien
of the setup, components of the
microscope objective)

↓

Cosmic ray correction

(Removal of the spurious cosm
ray events)

↓

Calculate number of observed photons

↓

(**Correction factor** for the microscope aperture + optical losses + depth of avalanche location)

Calculate number of source photons

Calculation of Observed Number of Photons

$$N_{\mathrm{av}}(\lambda) = \frac{N_{\mathrm{ADU}}^{\mathrm{SPAD}}(\lambda)\,\eta_{\mathrm{ADU}}^{\gamma}}{\mu_{\text{av-exp}}}\left(\frac{1}{\varepsilon(\lambda)}\right)$$

N_{av} = number of emitted photons per avalanche
N_{ADU}^{SPAD} = raw ADU units
η_{ADU}^{γ} = calibration gain of the camera ($0.7\ \gamma/ADU$)
$\epsilon(\lambda)$ = detection transmission efficiency of the optical setup

$$\mu_{\text{av-exp}} = P_{trig}^{av} \times f \times \Delta t$$

$\mu_{\text{av-exp}}$ = total number of avalanches per laser pulse
P_{trig}^{av} = probability of SPAD firing
f = frequency of laser trigger
Δt = laser exposure time

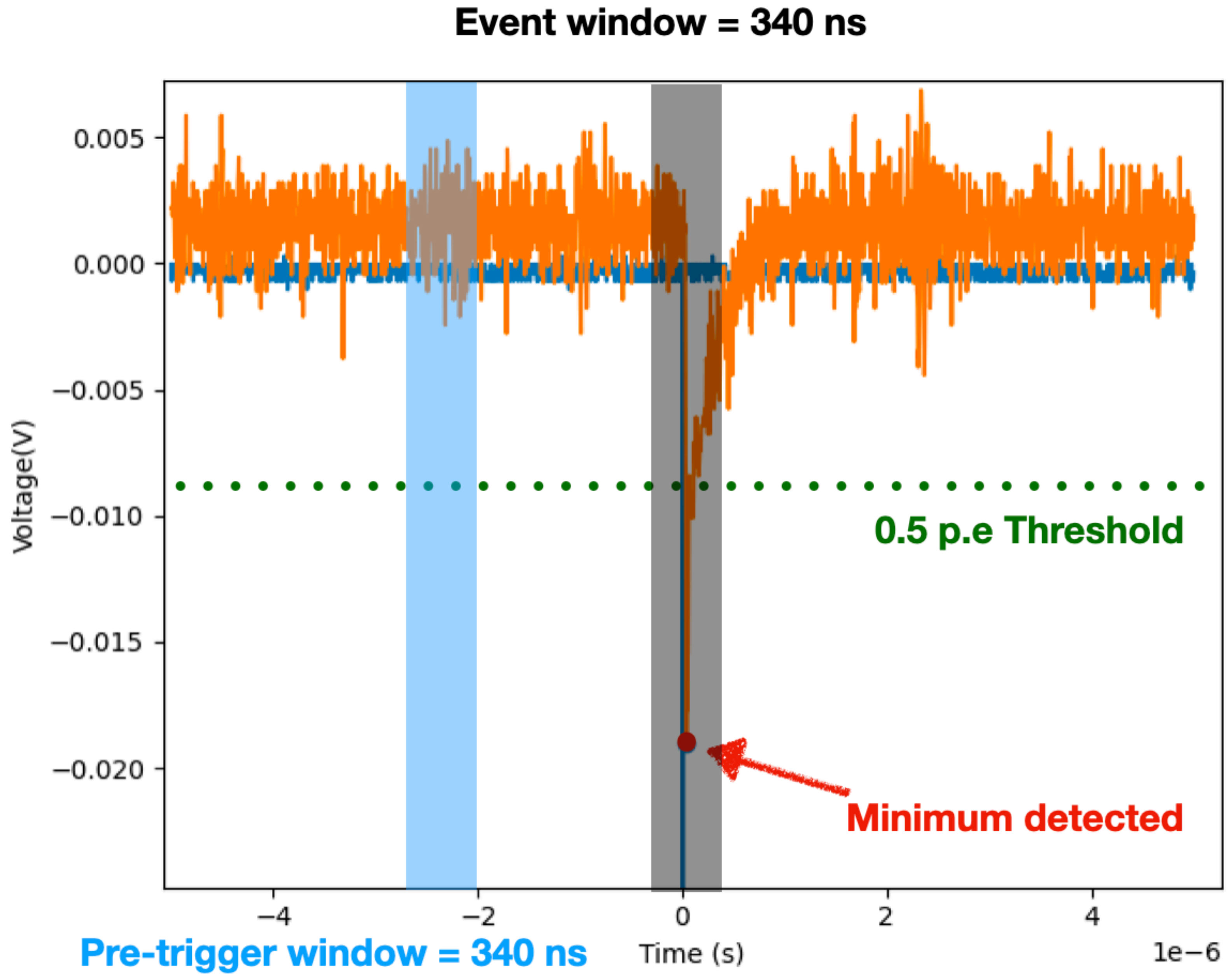
$$P_{trig}^{av} = 1 - \frac{N_0}{N_{tot}}$$

N_0 = number of 0 PE pulses in the trigger window
N_{tot} = total number of events in the trigger window

$$\mu_{\mathrm{DCR}} = -\ln\left(\frac{N_{\text{0-dark}}}{N_{\mathrm{tot}}}\right)$$

μ_{DCR} = mean number of Dark counts
$N_{\text{0-dark}}$ = number of 0 PE pulses in pre-trigger window
N_{tot} = total number of events in the pre-trigger window

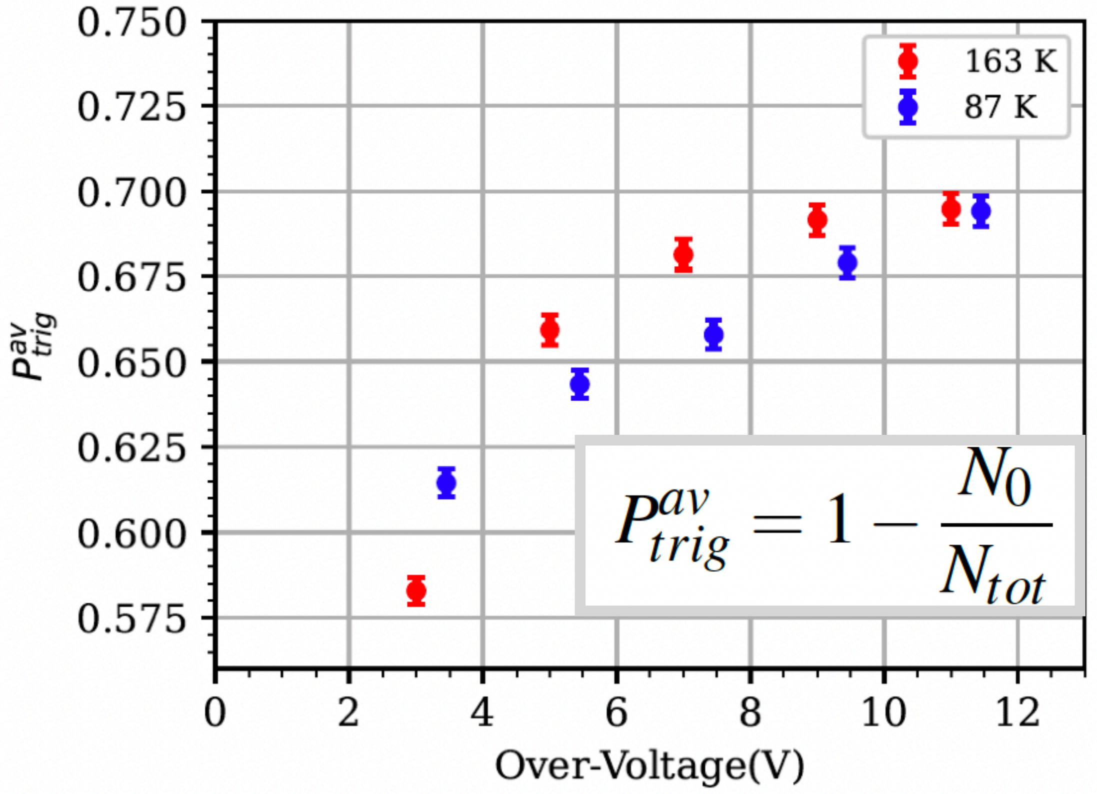
Laser triggered avalanche and DCR

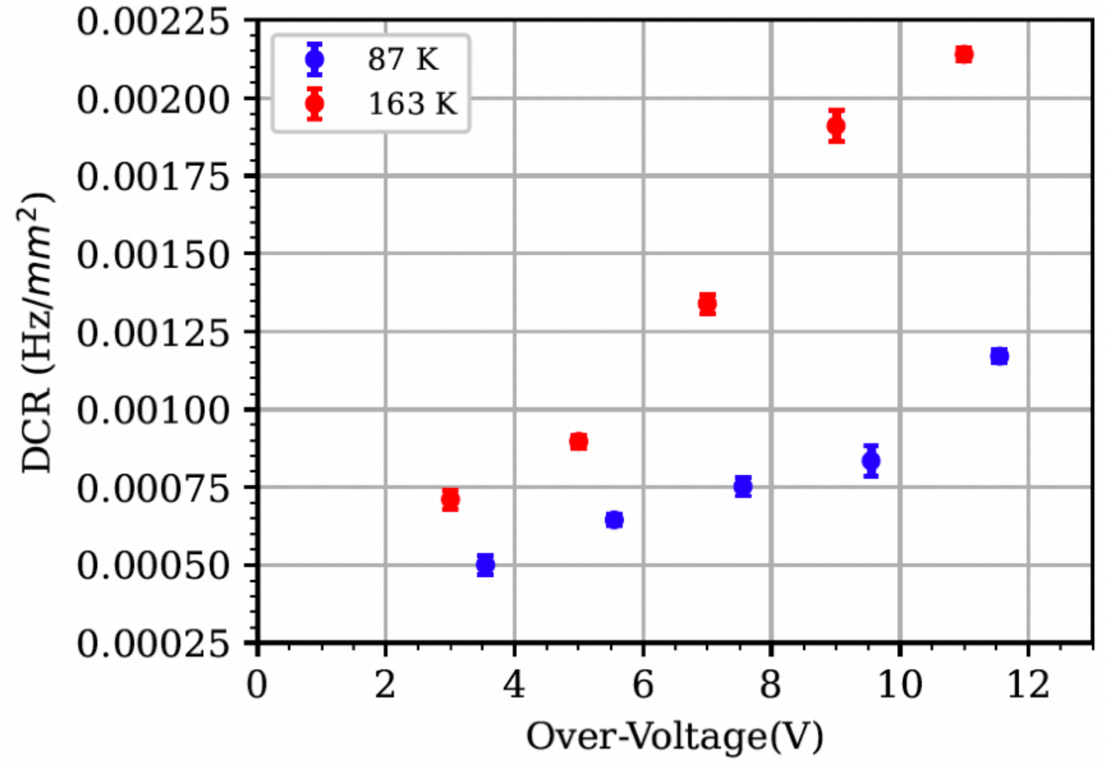


$$\mu_{\text{av-exp}} = P^{av}_{trig} \times f \times \Delta t$$

125 kHz   500 s

$$\mu_{\text{DCR}} = -\ln\left(\frac{N_{\text{0-dark}}}{N_{\text{tot}}}\right)$$





Calculation of Observed/Source Number of Photons

$$N_\gamma^*(\lambda) = \frac{N_{\text{av}}(\lambda)}{\Delta\lambda}$$

N_γ^* = observed number of photons per avalanche per nm

$\Delta\lambda$ = wavelength resolution (1.7 nm)

$$N_{\text{av}}^S(\lambda) = \frac{N_{\text{av}}(\lambda)}{A(\lambda)}$$

$N_{av}^S(\lambda)$ = number of source photons per avalanche

$A(\lambda)$ = correction factor - finite numerical aperture of microscope, reflection and absorption losses due to SiPM surface coating and depth of avalanche region

$$N_\gamma^{S*}(\lambda) = \frac{N_{\text{av}}^S(\lambda)}{\Delta\lambda}$$

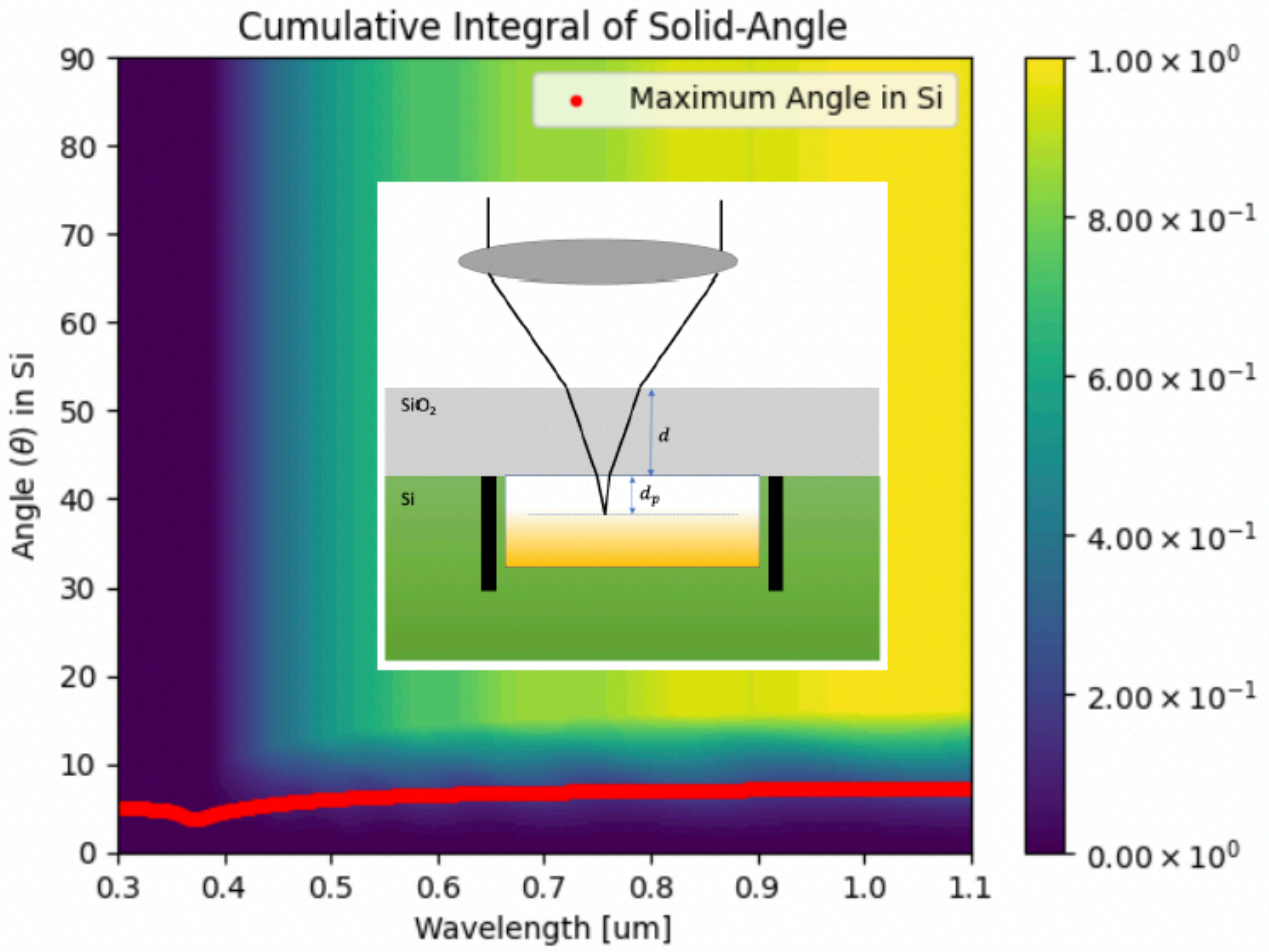
N_γ^{S*} = number of source photons per avalanche per nm

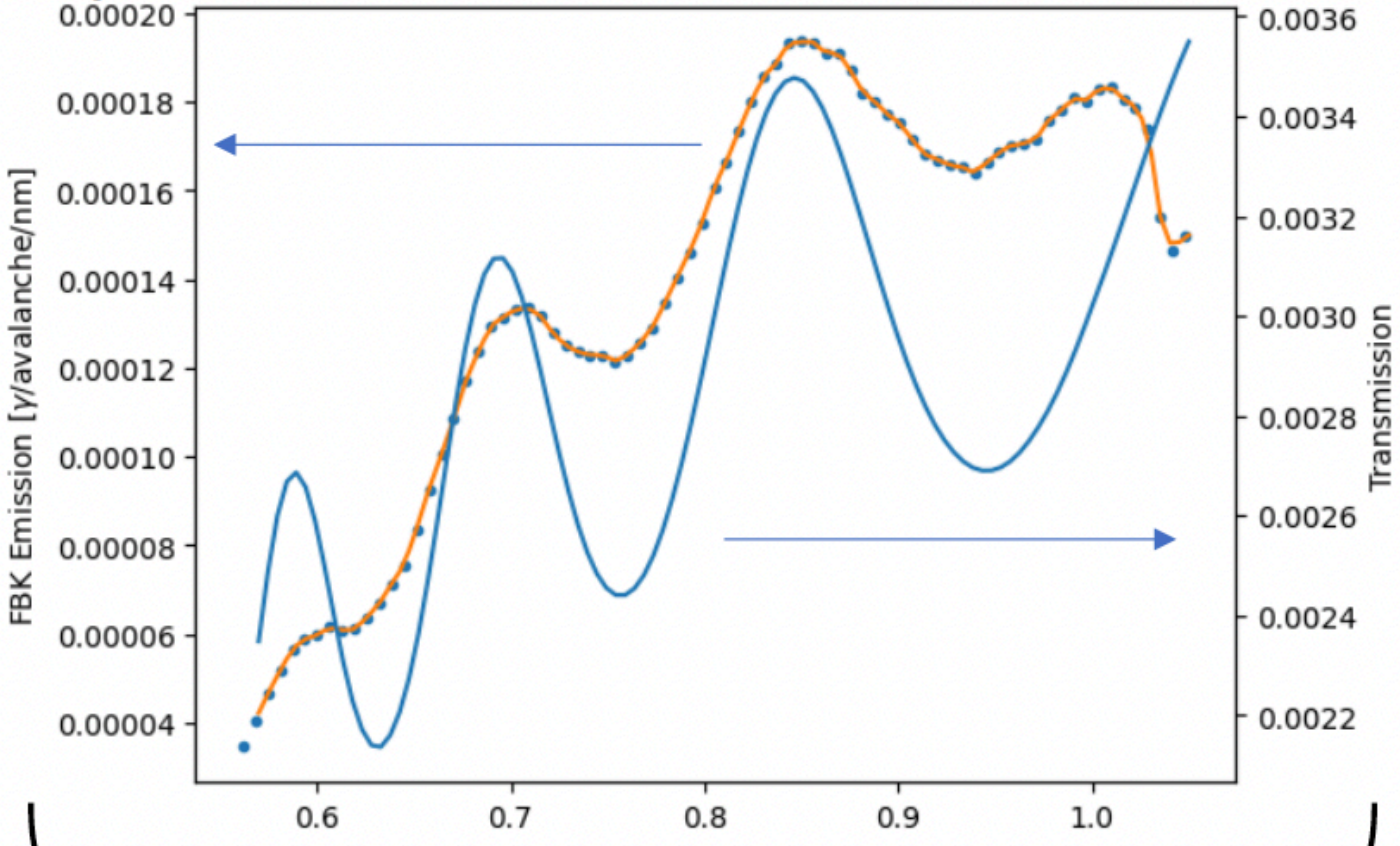
Transmission to the Source Spectra

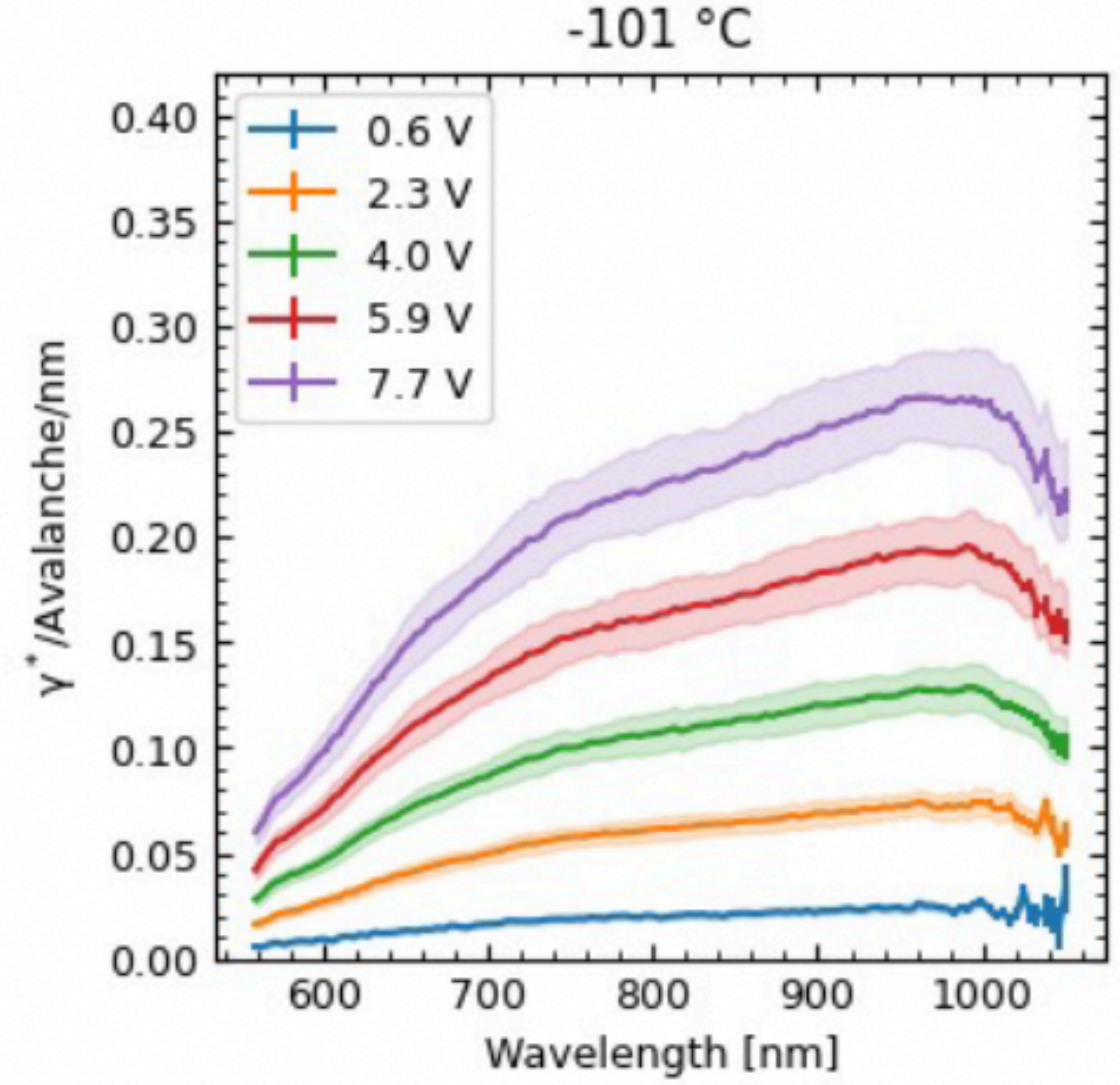
$$T = \frac{\int_0^{2\pi} d\phi \int_0^{\theta_{Si}} T_{Si}(\theta,\lambda)\, T_{Si-SiO_2-Air}(\theta,\lambda)\sin(\theta)d\theta}{\int_0^{2\pi} d\phi \int_0^{\pi} \sin(\theta)d\theta}$$

$$= \frac{1}{2}\int_0^{\theta_{Si}} T_{Si}(\theta,\lambda)\, T_{Si-SiO_2-Air}(\theta,\lambda)\sin(\theta)d\theta$$

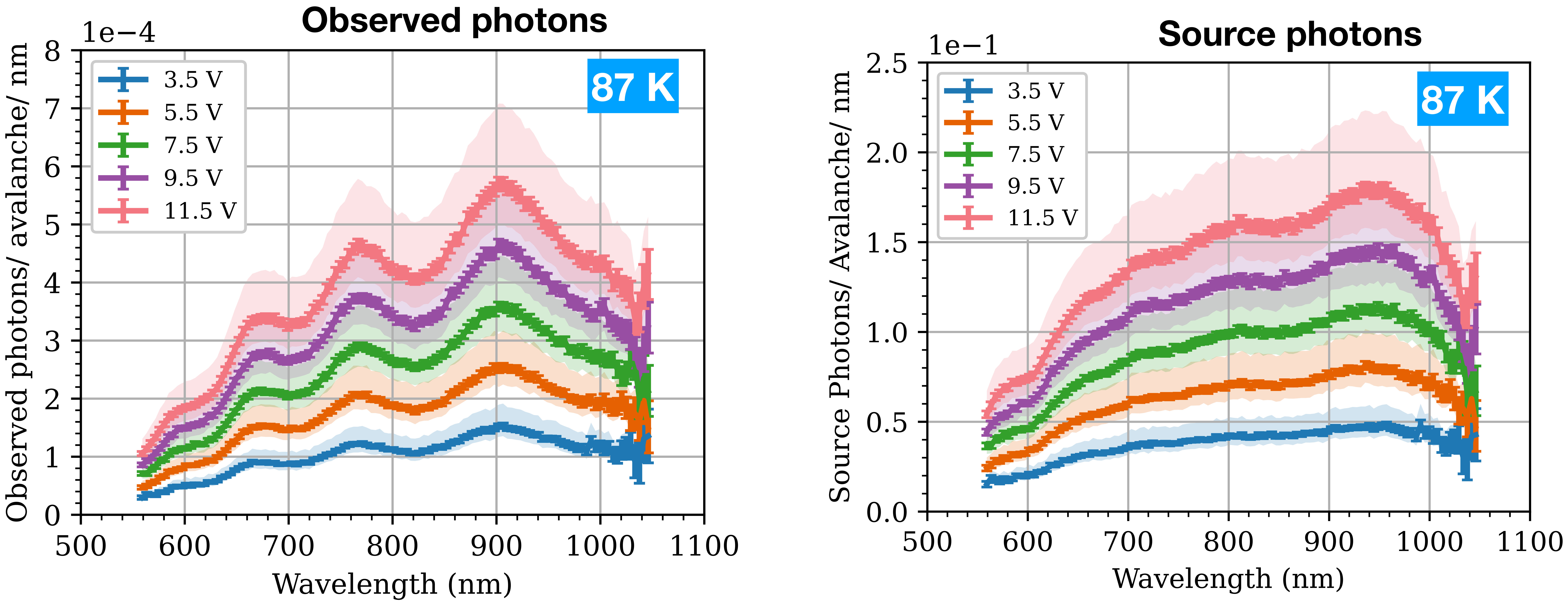
$$= \underbrace{F(\theta_{Si},\lambda)} - F(0,\lambda)$$







Photon spectra (FBK NUV-HD Cryo SiPM)



The source photons have been corrected for the oscillation pattern by accounting for : microscope numerical aperture, depth of the avalanche region