External Cross-Talk Characterization from Dark Avalanches in Silicon Photomultipliers

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Presented by
Joseph McLaughlin
Research supervised by
Dr. Fabrice Retière *and* **Dr. Jocelyn Monroe**

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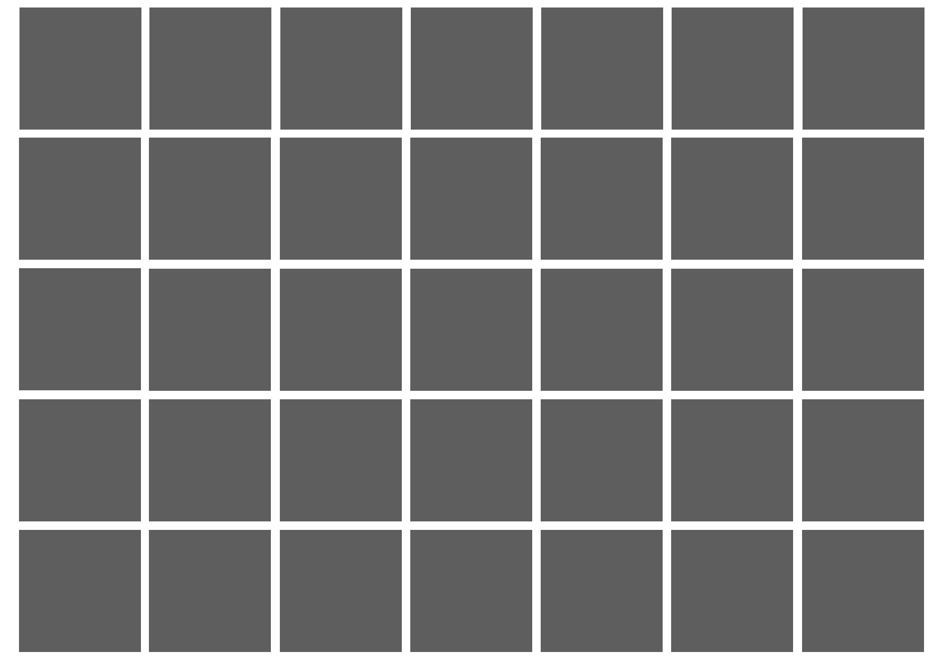
Introduction

- Silicon Photomultipliers (SiPMs) are arrays of 10^3–10^4 single photon avalanche diodes (SPADs)
- SPADs are silicon P-N junctions operated at reverse bias voltages beyond avalanche breakdown—i.e. in ‘Geiger mode’
- A single photon will generate a charge avalanche large enough to quench any given SPAD
- Photon counting is done by counting the number of SPADs in the SiPM that generate an avalanche



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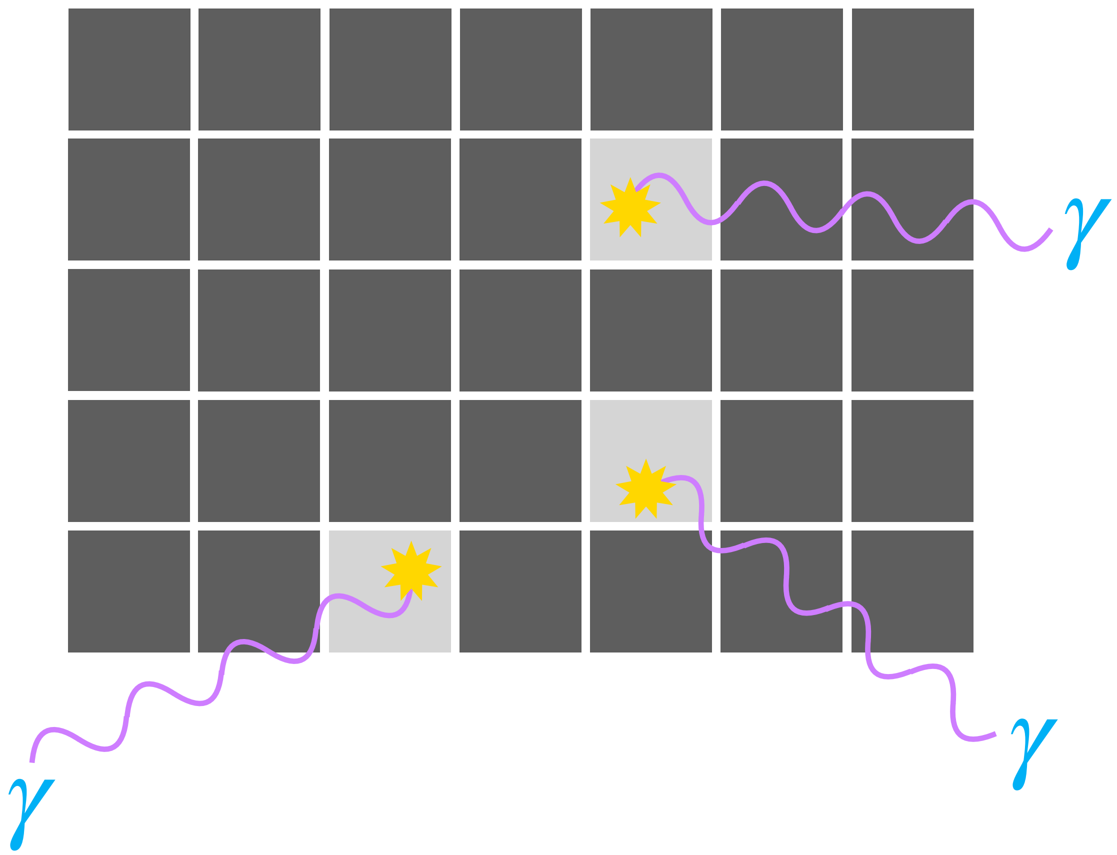

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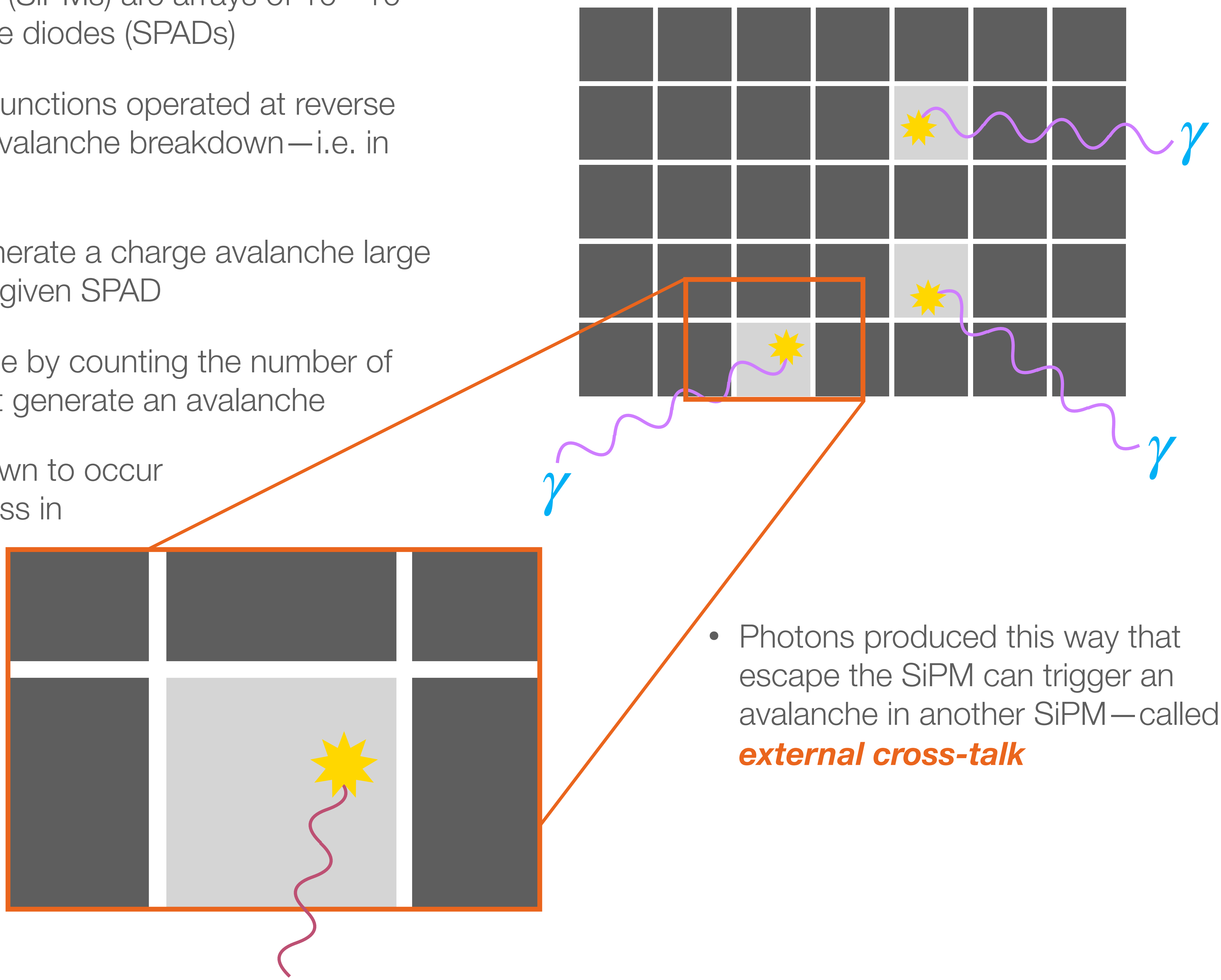
- Photon emission is known to occur during avalanche process in semiconductors



- Photons produced this way that escape the SiPM can trigger an avalanche in another SiPM—called ***external cross-talk***

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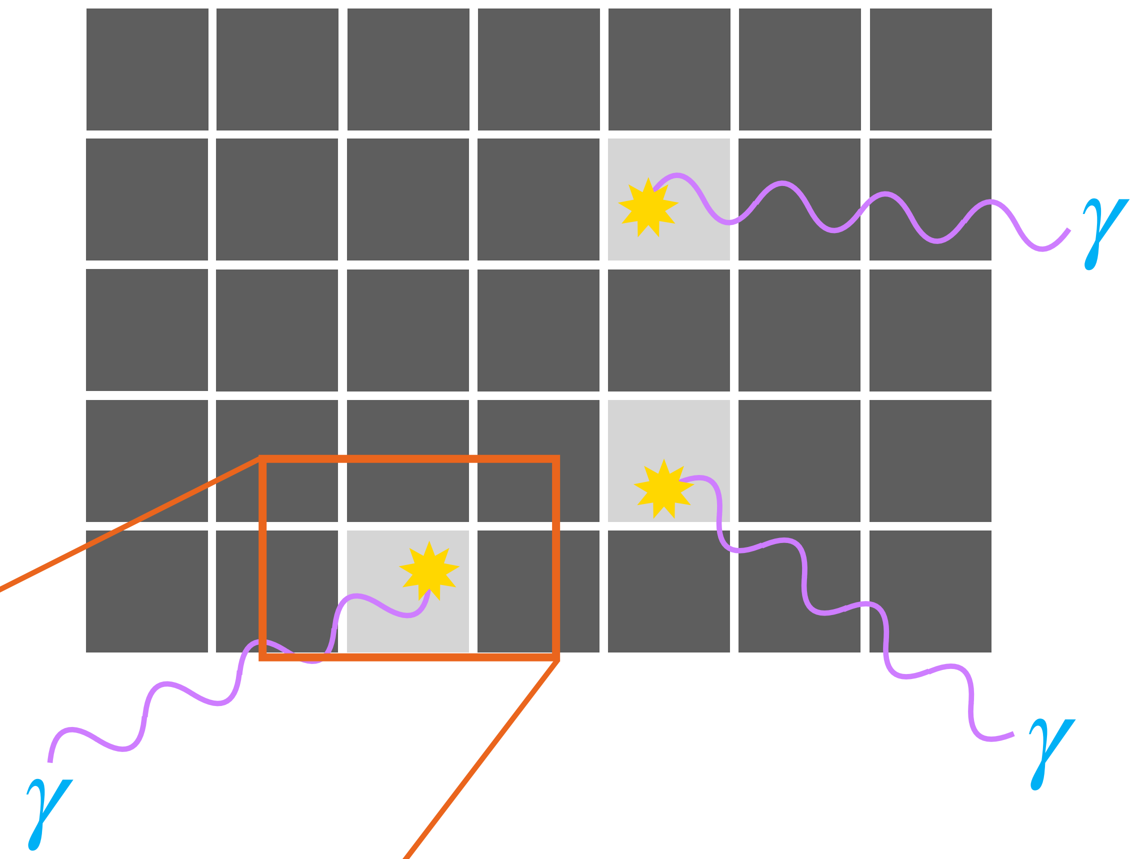

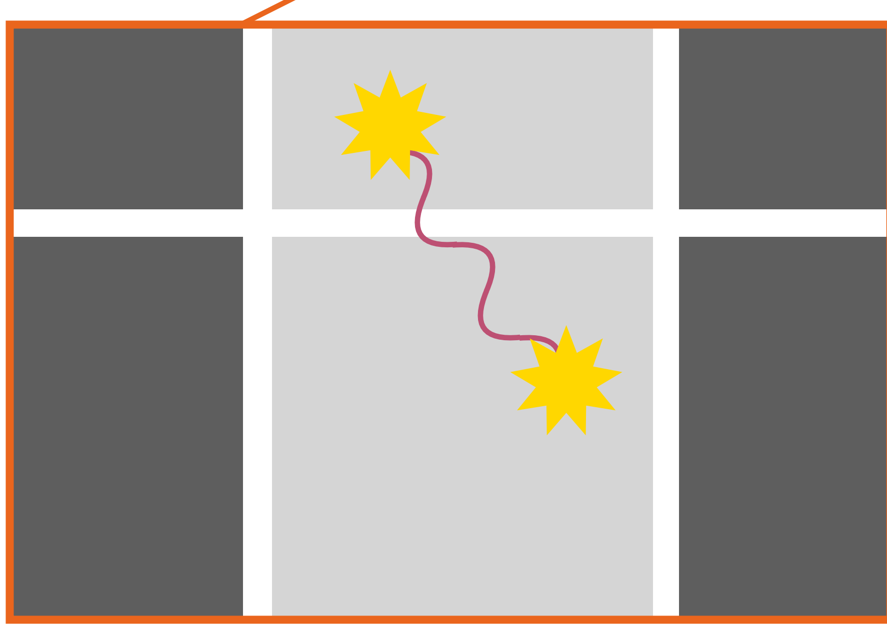

- Photons produced this way that escape the SiPM can trigger an avalanche in another SiPM—called ***external cross-talk***
- Photons can also trigger avalanches in neighbouring SPADs—called ***internal cross-talk***

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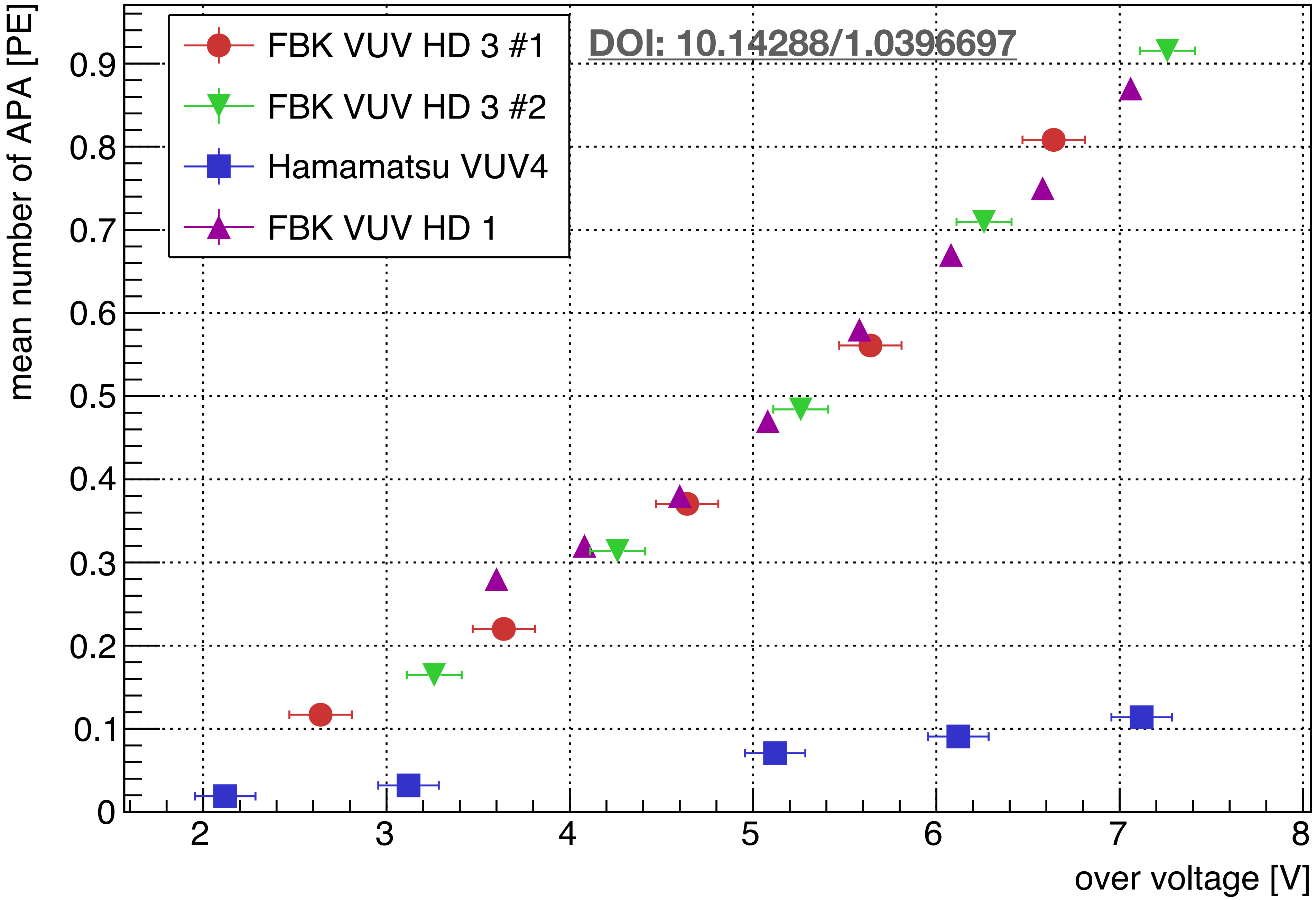
Motivation



- Internal cross-talk is measured by pulse counting—see nEXO VUV4 characterization paper (arXiv e-print: 1903.03663)
- Measuring emission spectra will aid understanding internal cross-talk through modelling
- Also inform future SiPM designs to mitigate internal cross-talk

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Motivation

- Multiple next-generation astroparticle physics experiments will use SiPMs to probe SM and BSM interactions

High-precision neutrino oscillation measurements using liquid argon TPC

Dual phase, liquid argon based search for Dark Matter

Search for neutrinoless double beta-decay using liquid xenon

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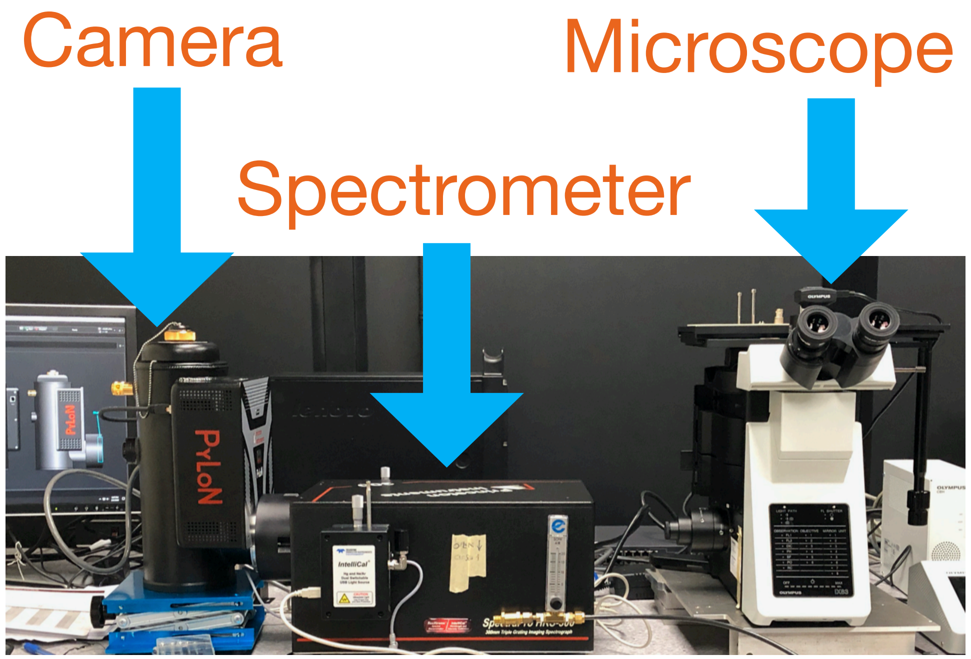
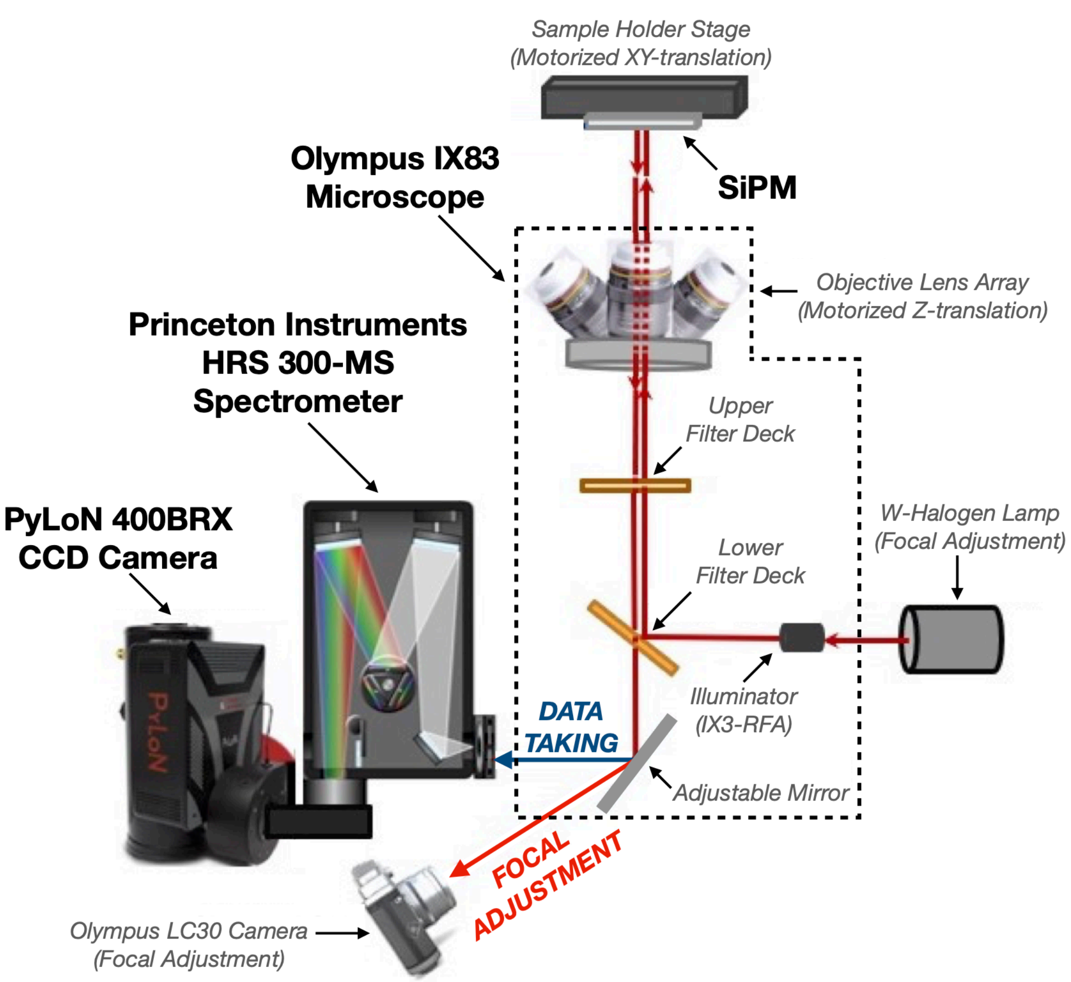
MIEL Apparatus



Microscopy with Injected and Emitted Light

- Primary components:
  - Olympus IX83 microscope
  - Princeton Instruments HRS 300 spectrometer
  - PyLoN 400BR_eXcelon CCD camera



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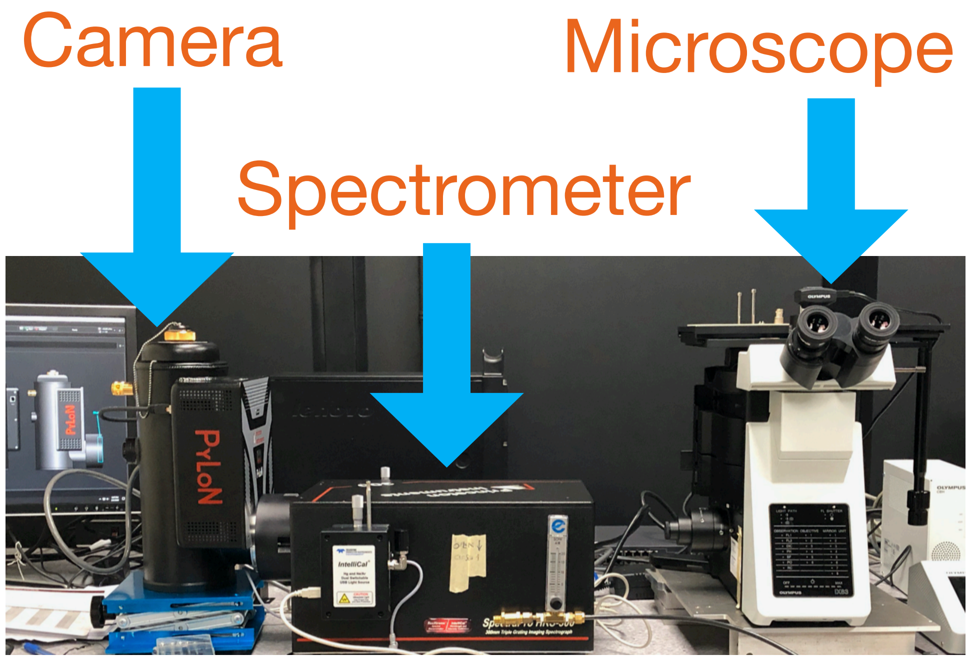

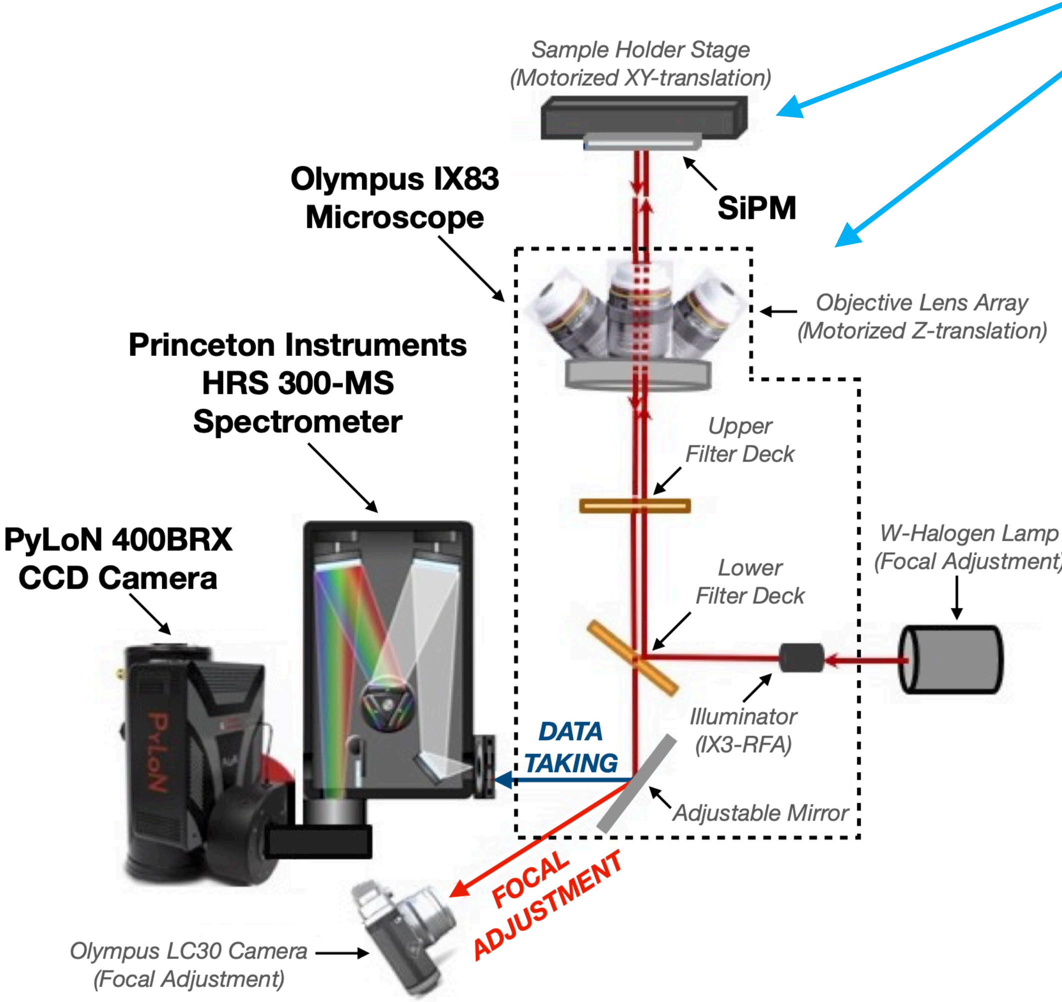

Microscopy with Injected and Emitted Light

- Primary components:
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- Motorized control over objective lens in Z-axis and SiPM position in X-Y plane

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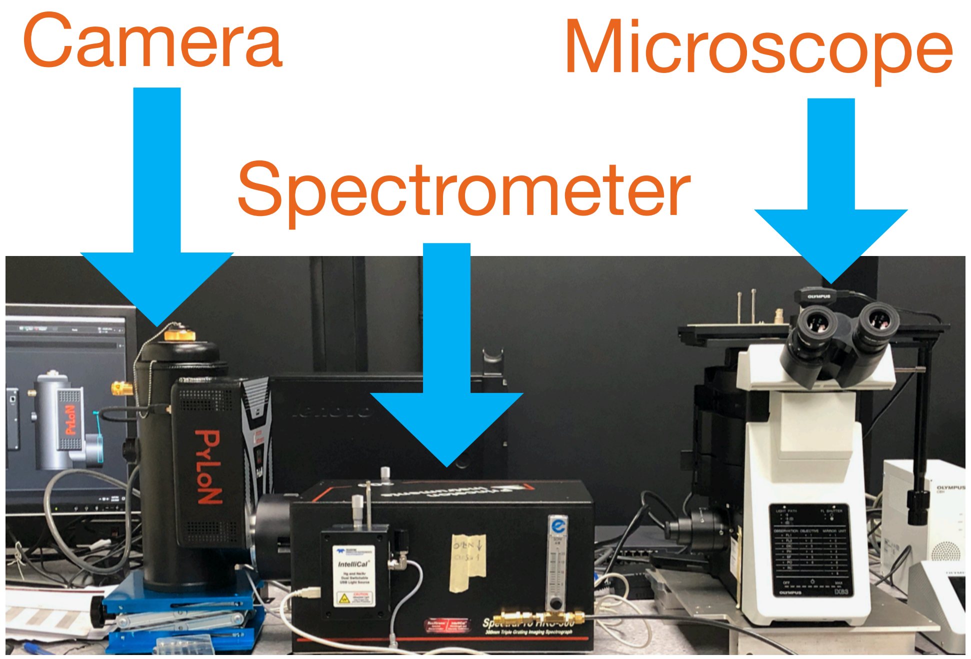

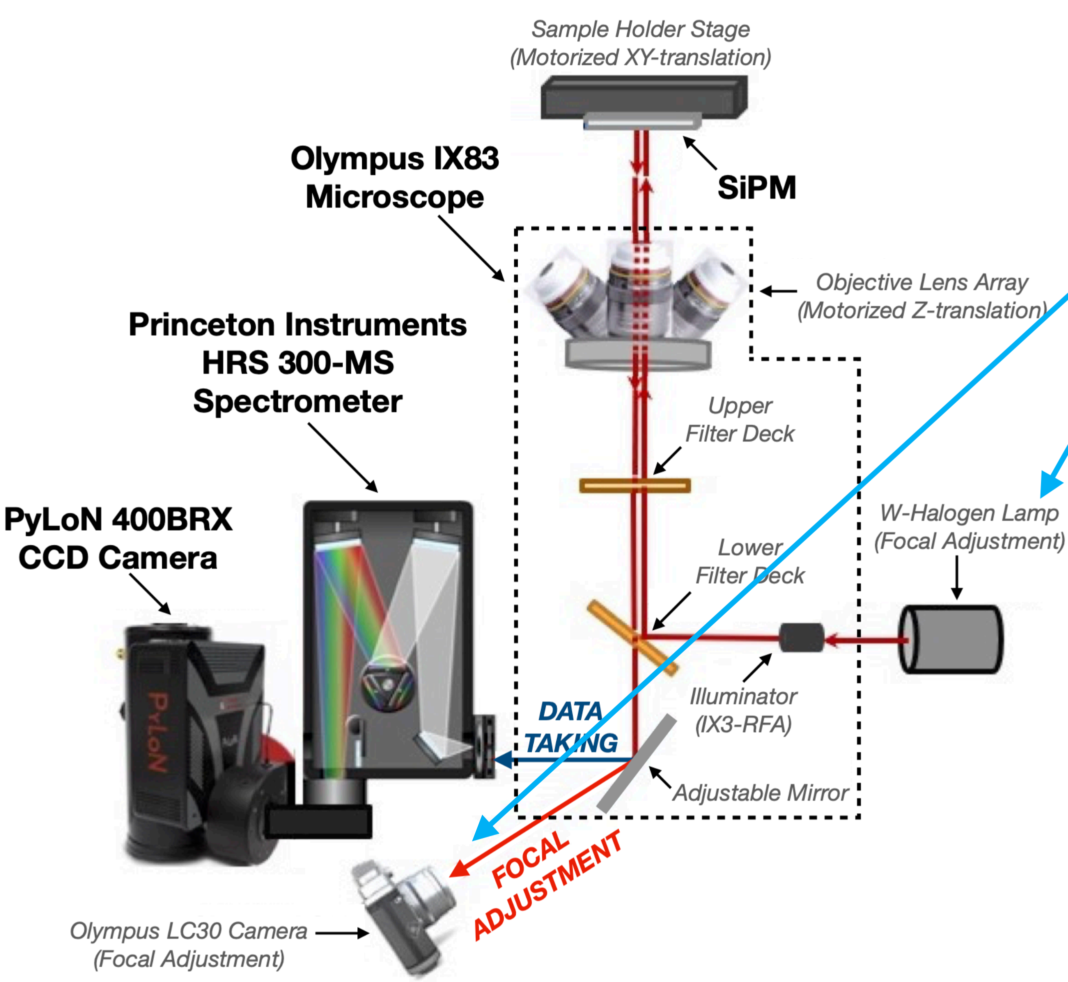

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- Image focusing done with halogen lamp on SiPM and microscope camera

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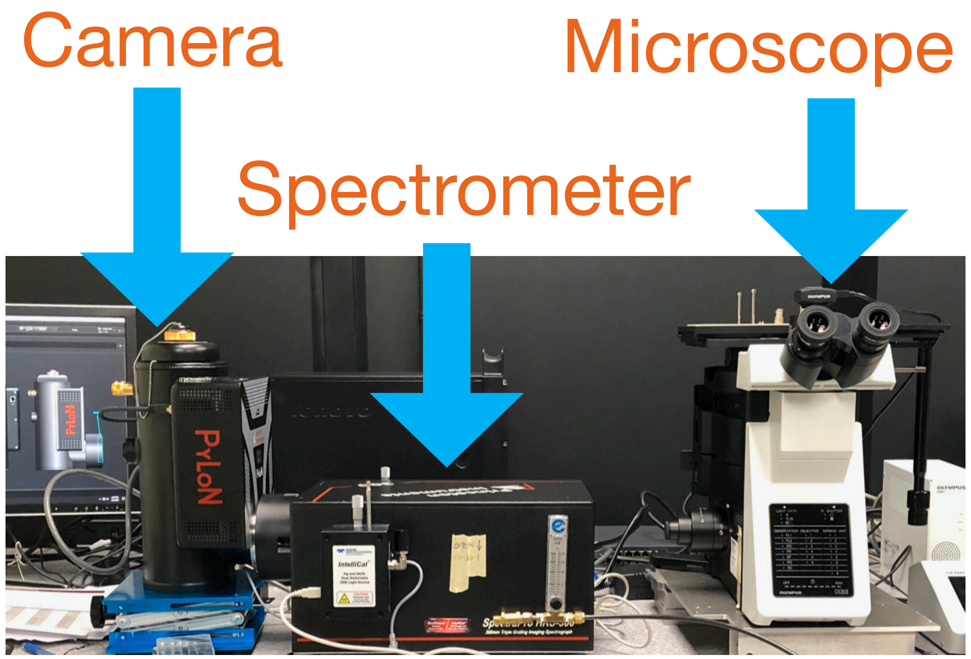

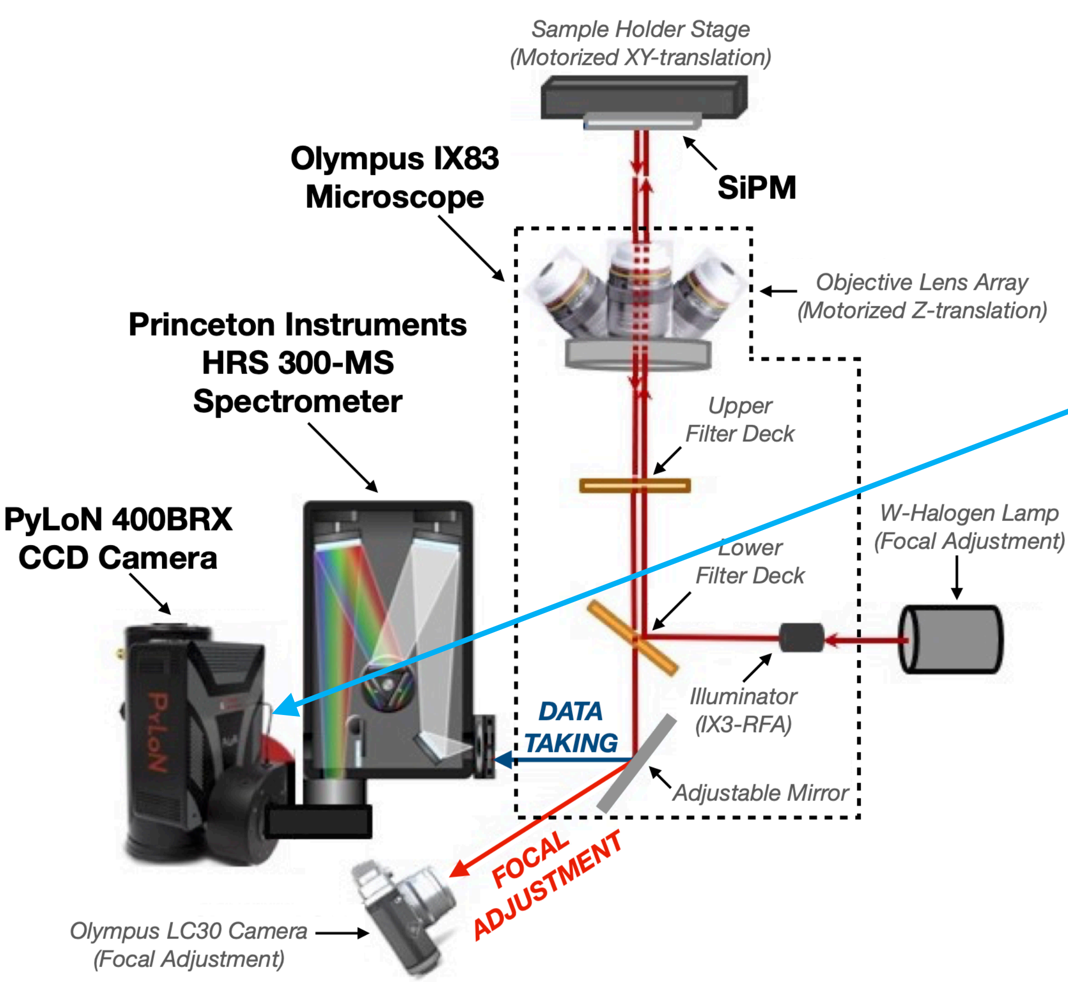

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- Primary components:
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- Motorized control over objective lens in Z-axis and SiPM position in X-Y plane
- Image focusing done with halogen lamp on SiPM and microscope camera
- CCD camera coupled to output of the spectrometer is used for data acquisition
- Entire apparatus is inside a light-proof enclosure, controlled externally using LightField® software

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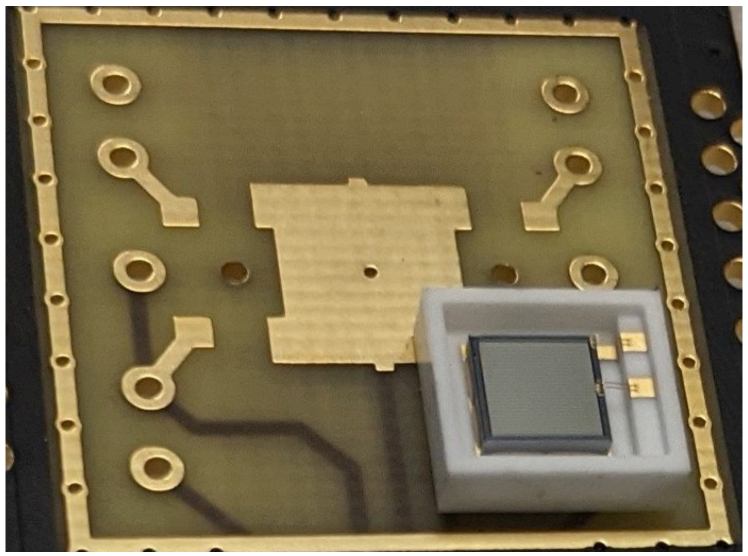
SiPM Characteristics

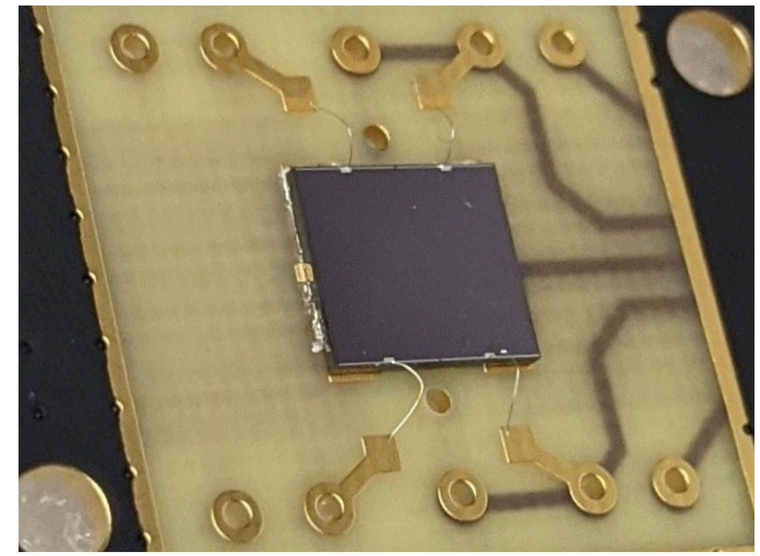
Hamamatsu VUV4

Area: 3x3 mm²
SPAD width: 50 μm
Fill factor: 60%

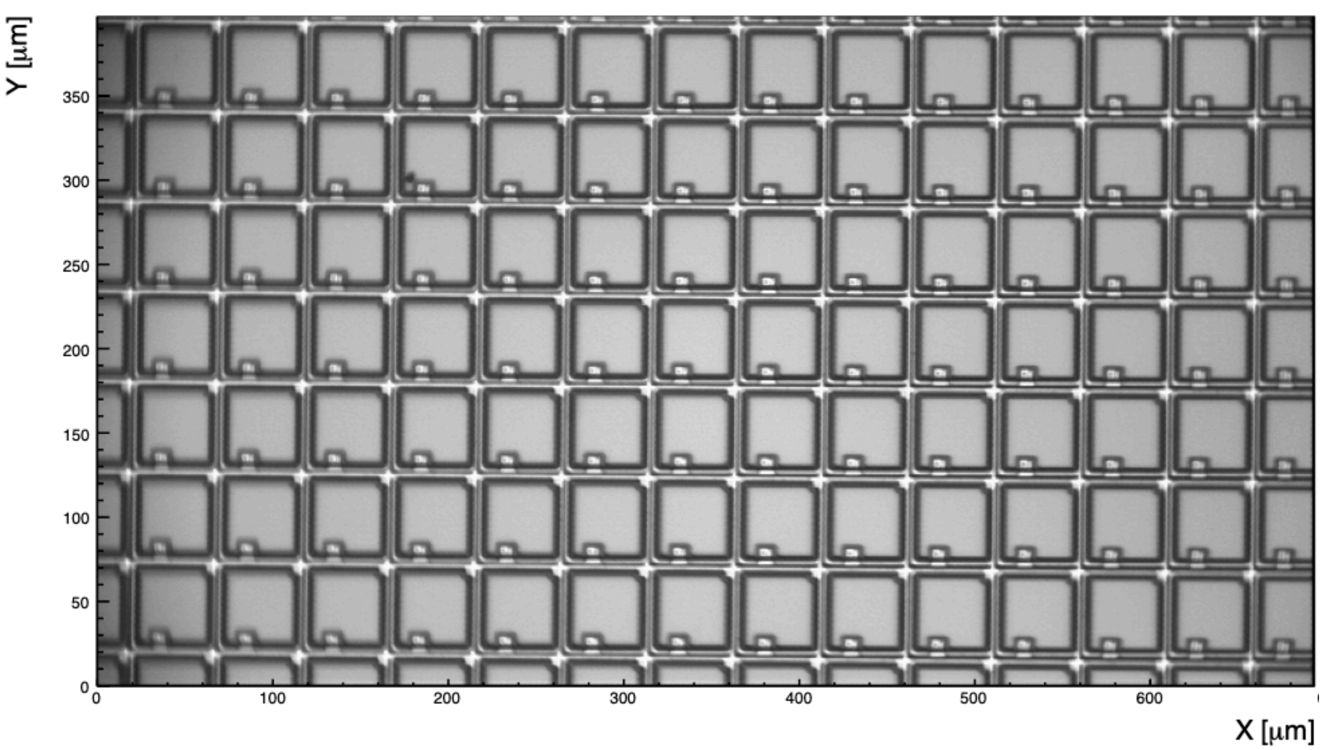


FBK VUV-HD3

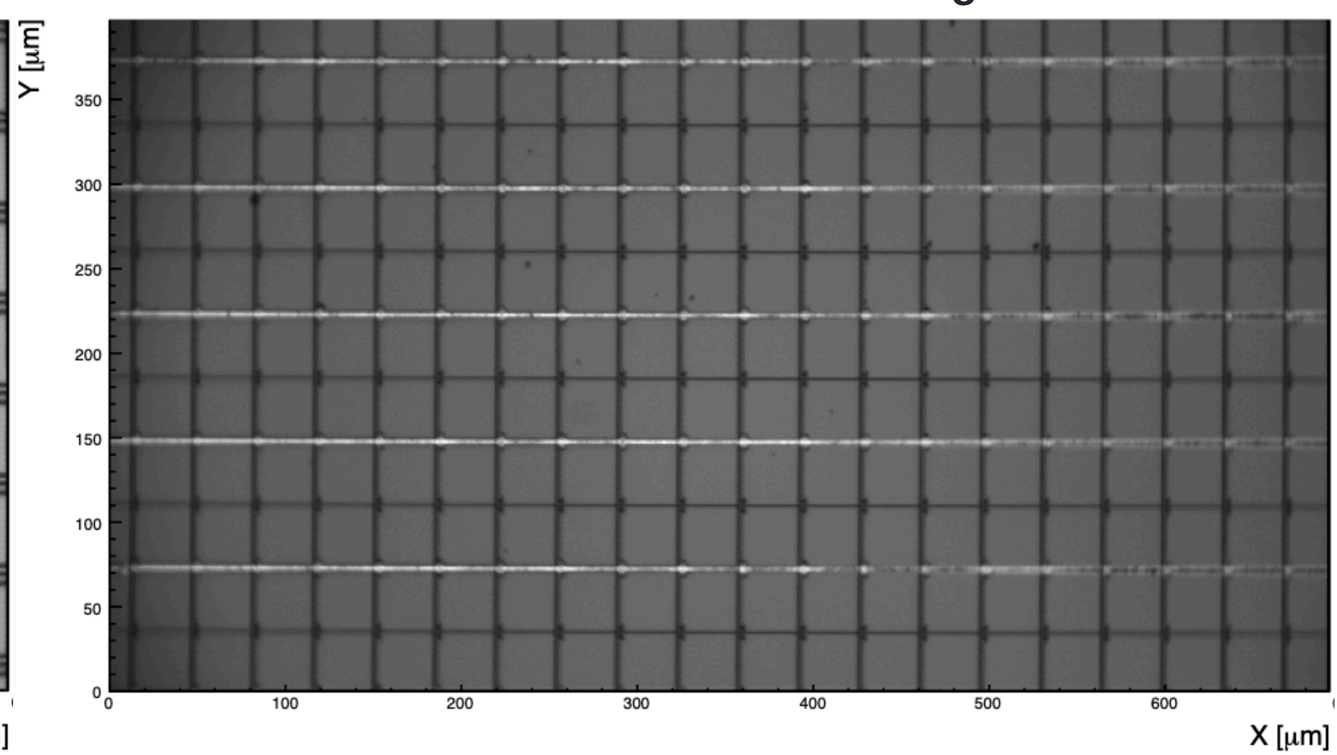
Area: 6x6 mm²
SPAD width: 35 μm
Fill factor: 80%



Hamamatsu VUV4 SiPM at 20x Magnification



FBK VUV-HD3 SiPM at 20x Magnification



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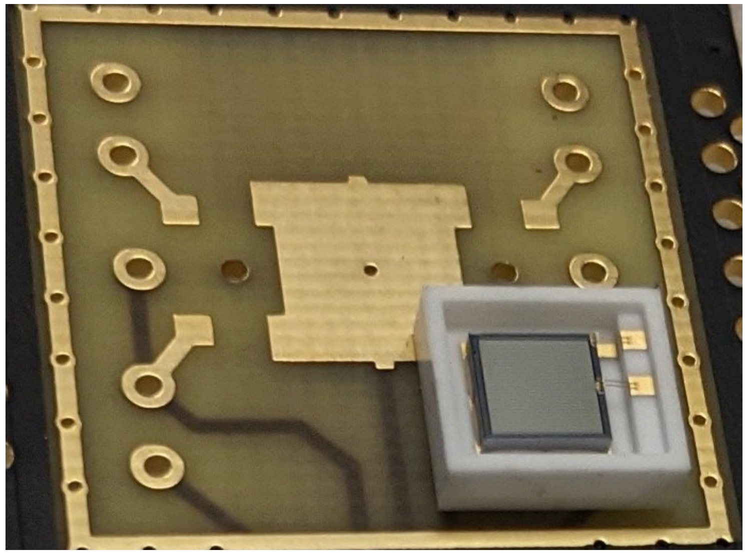

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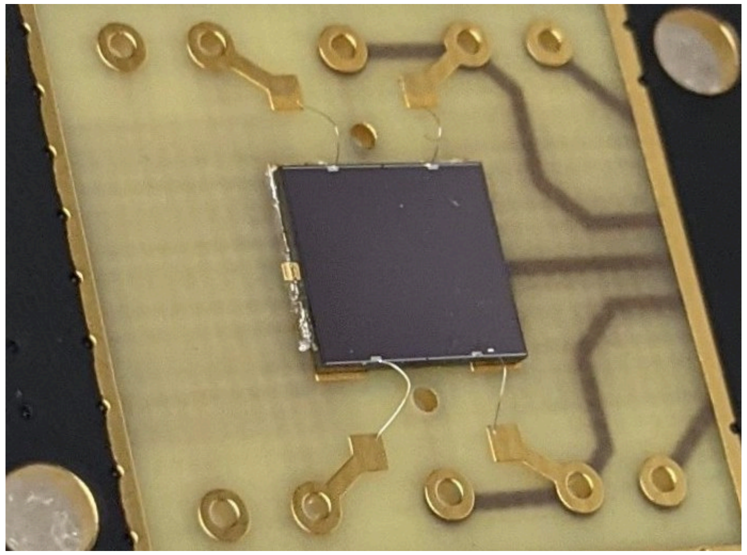

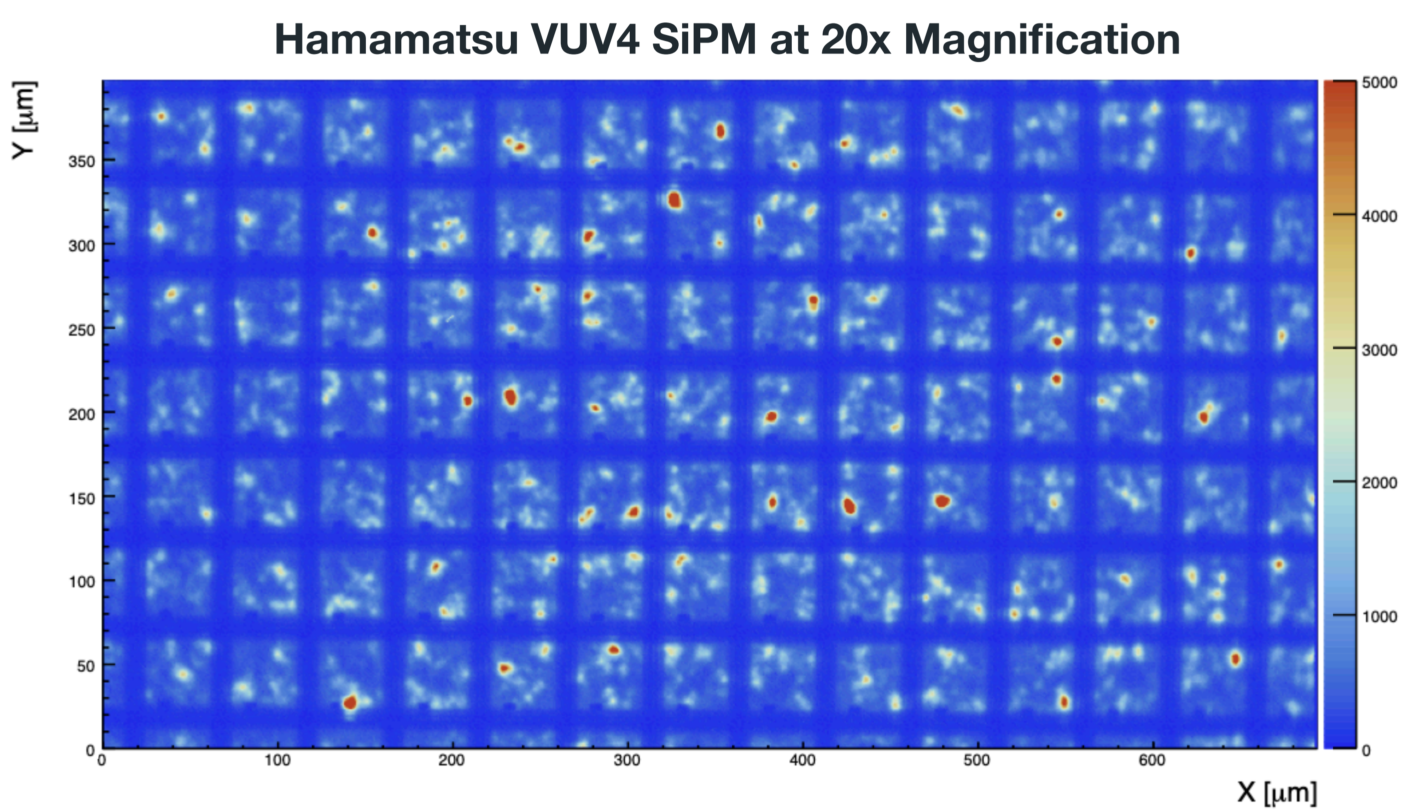

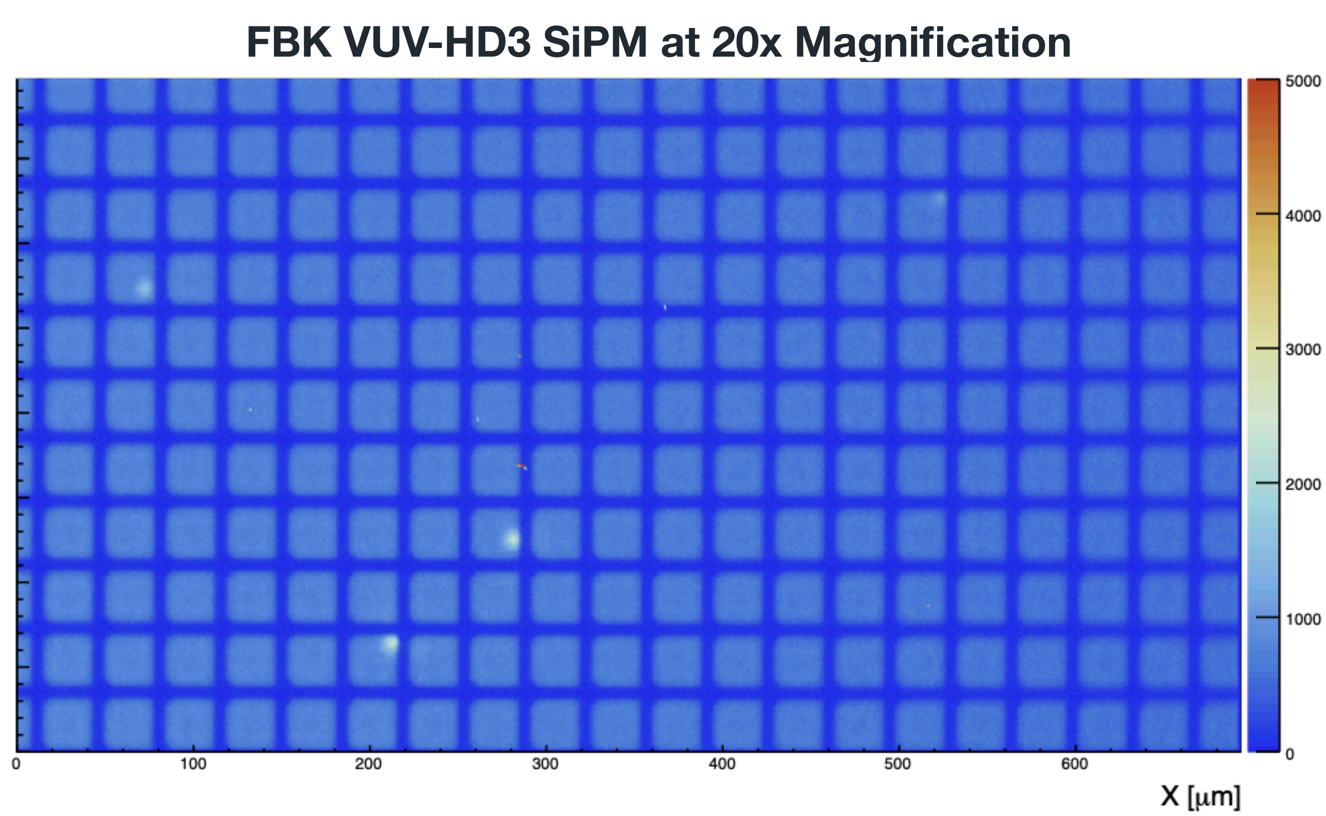

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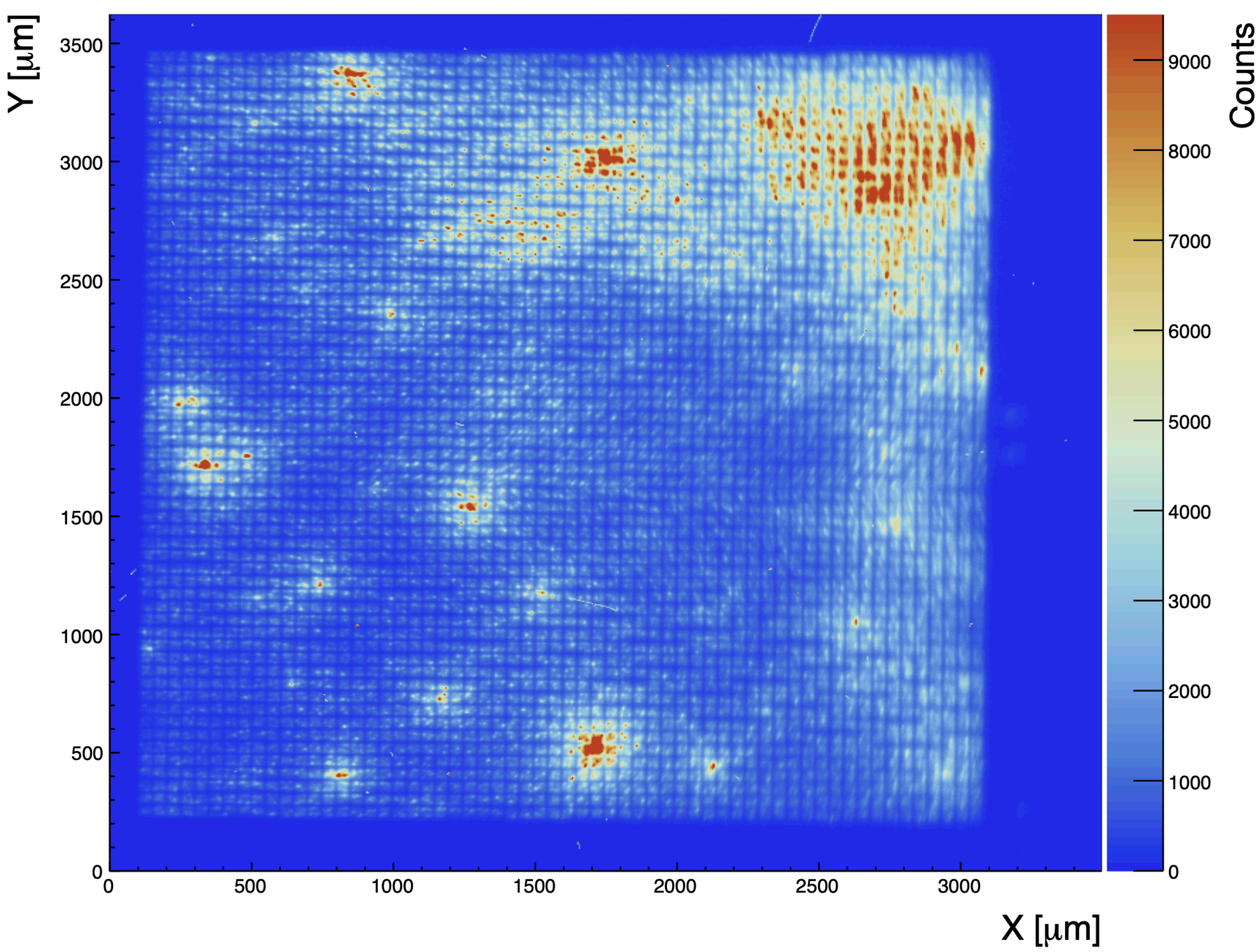
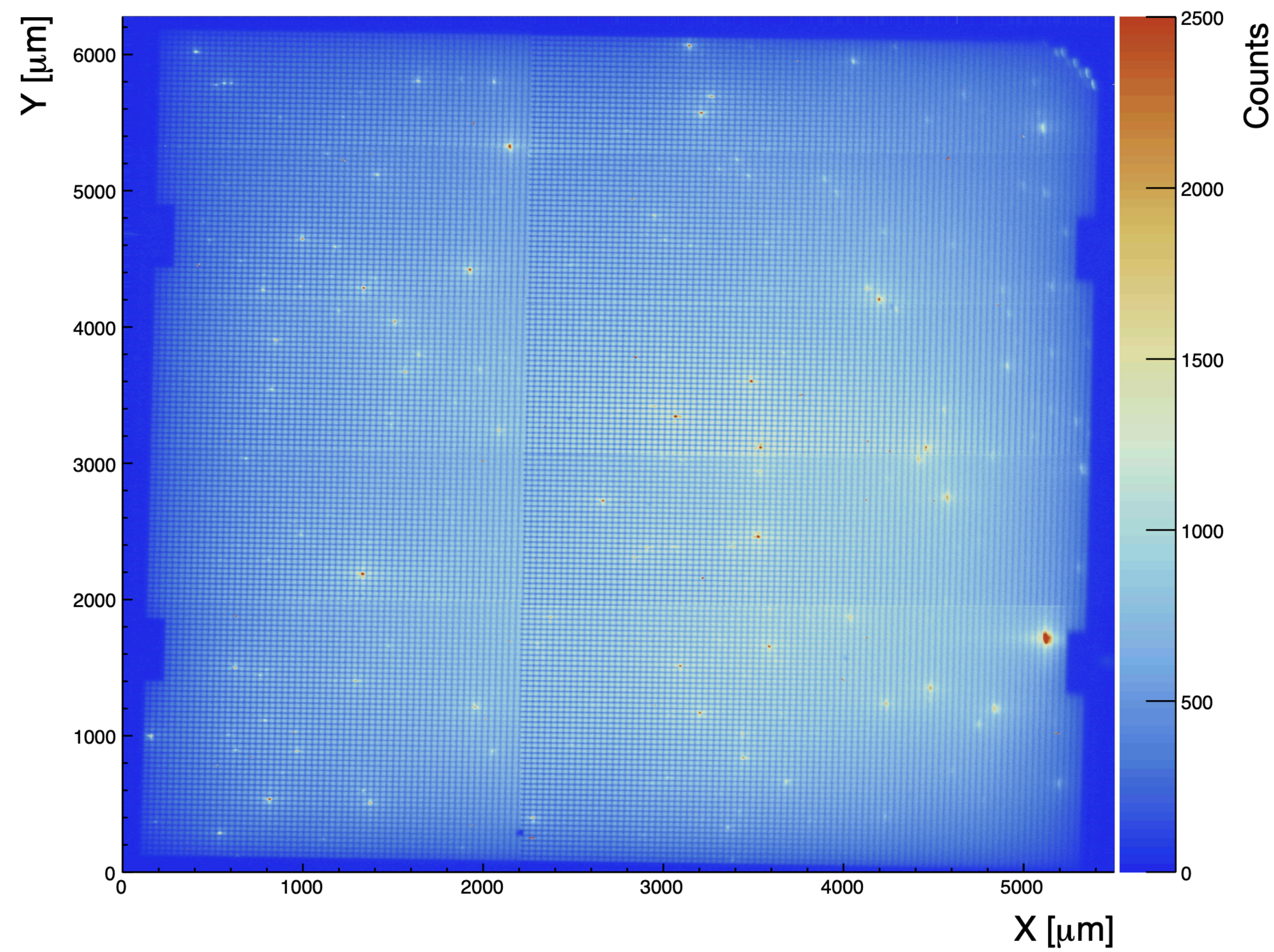
Hamamatsu VUV4 SiPM at 4x Magnification (composite image)



FBK VUV-HD3 SiPM at 4x Magnification (composite image)



RMS of emission fluctuations is 3.3x greater for VUV4

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SiPM Characteristics

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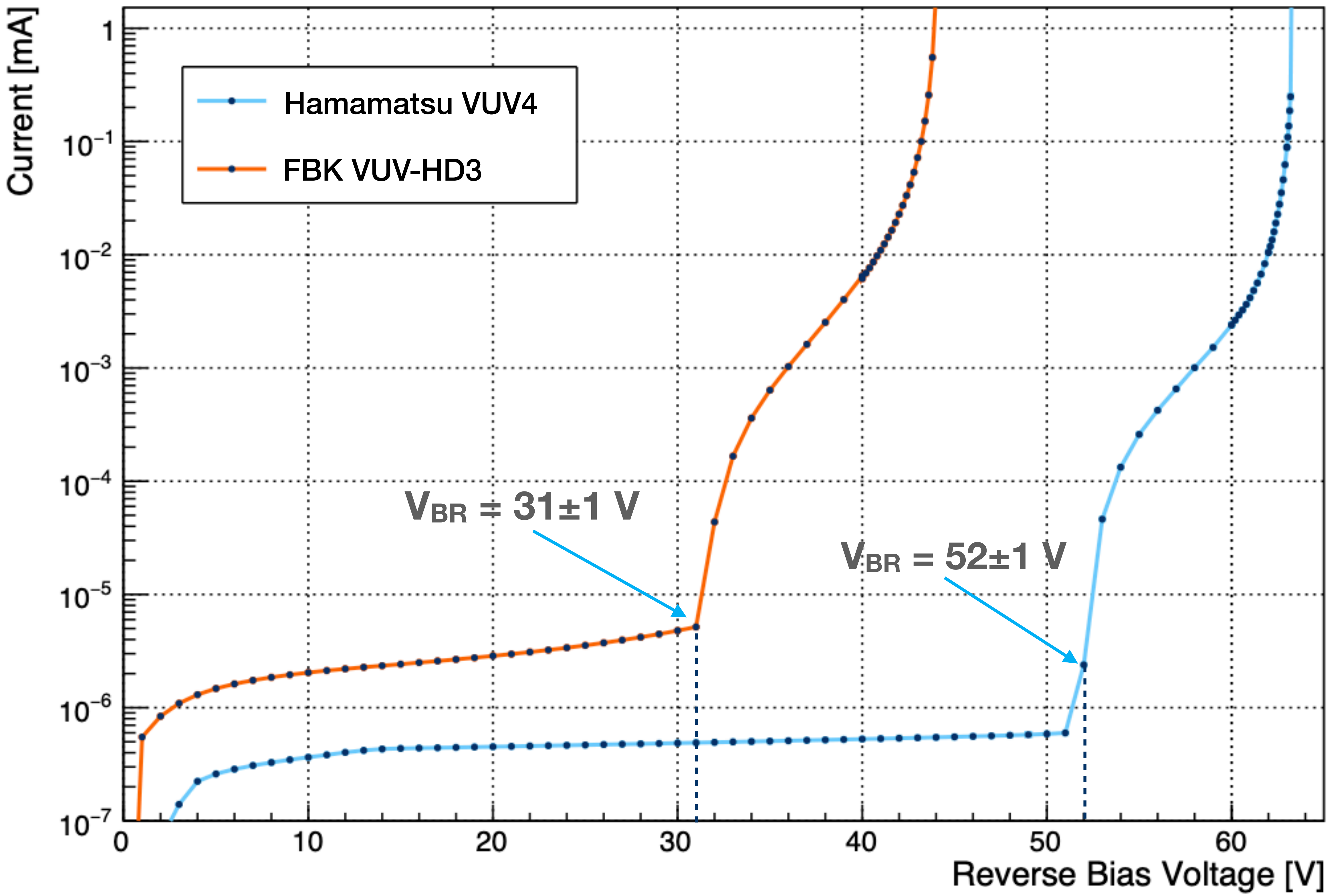
I-V Curves for the Hamamatsu VUV4 and FBK VUV-HD3 SiPMs



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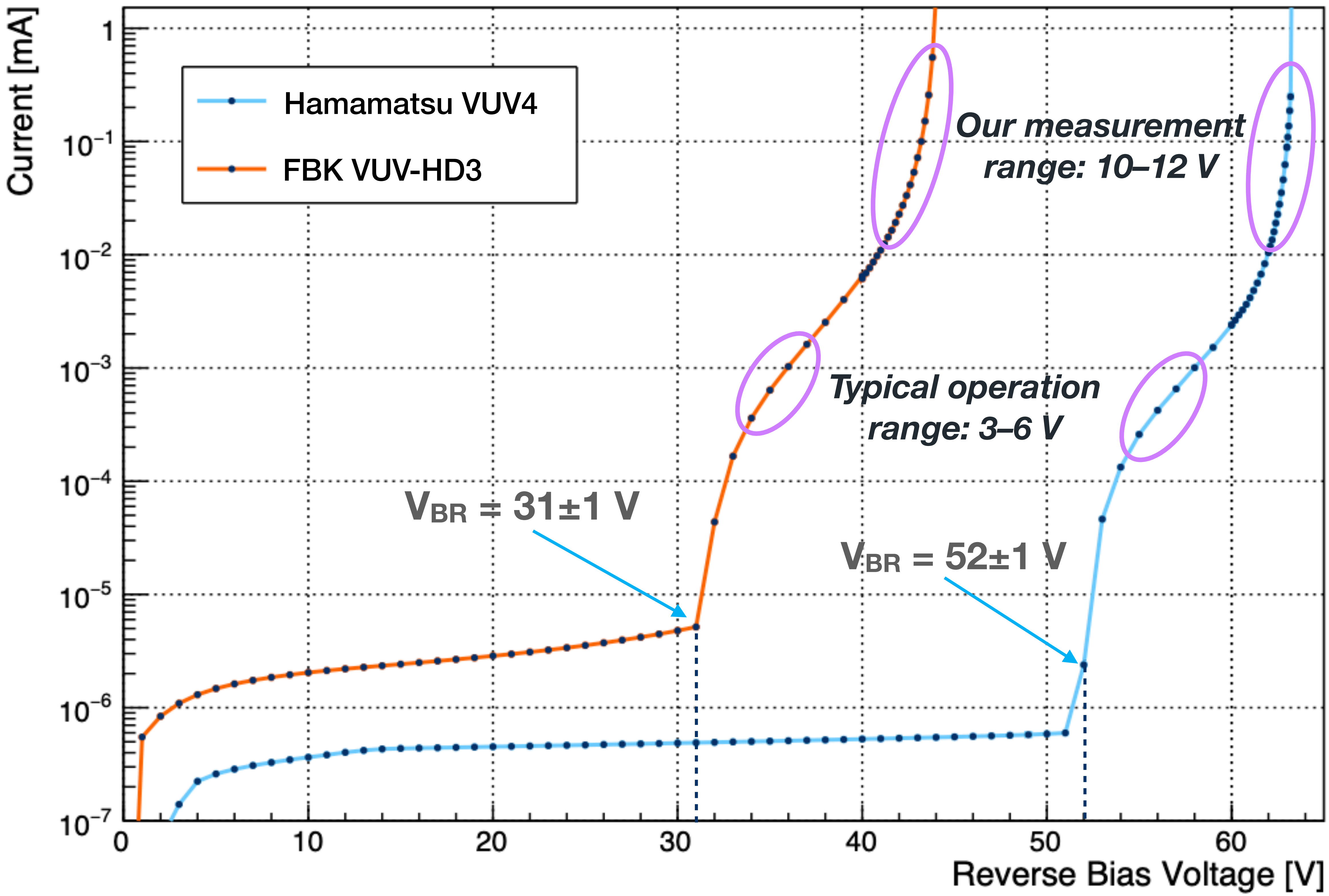

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Calibration

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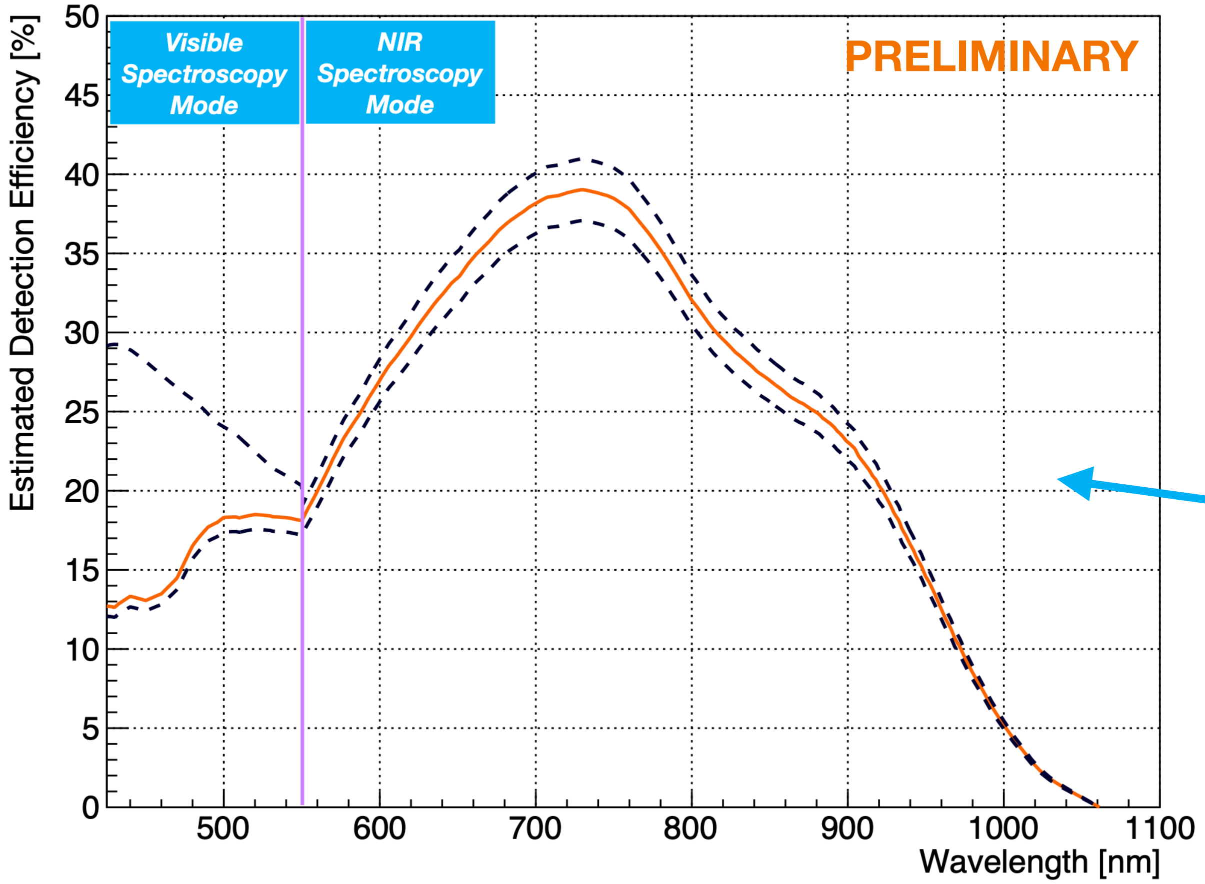

Wavelength calibrations done using LightField® *IntelliCal* system, mercury vapour lamp, and neon-argon gas lamp

Efficiency calibrated using estimated transfer function from hardware specs; validated with *IntelliCal* intensity source

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Normalization

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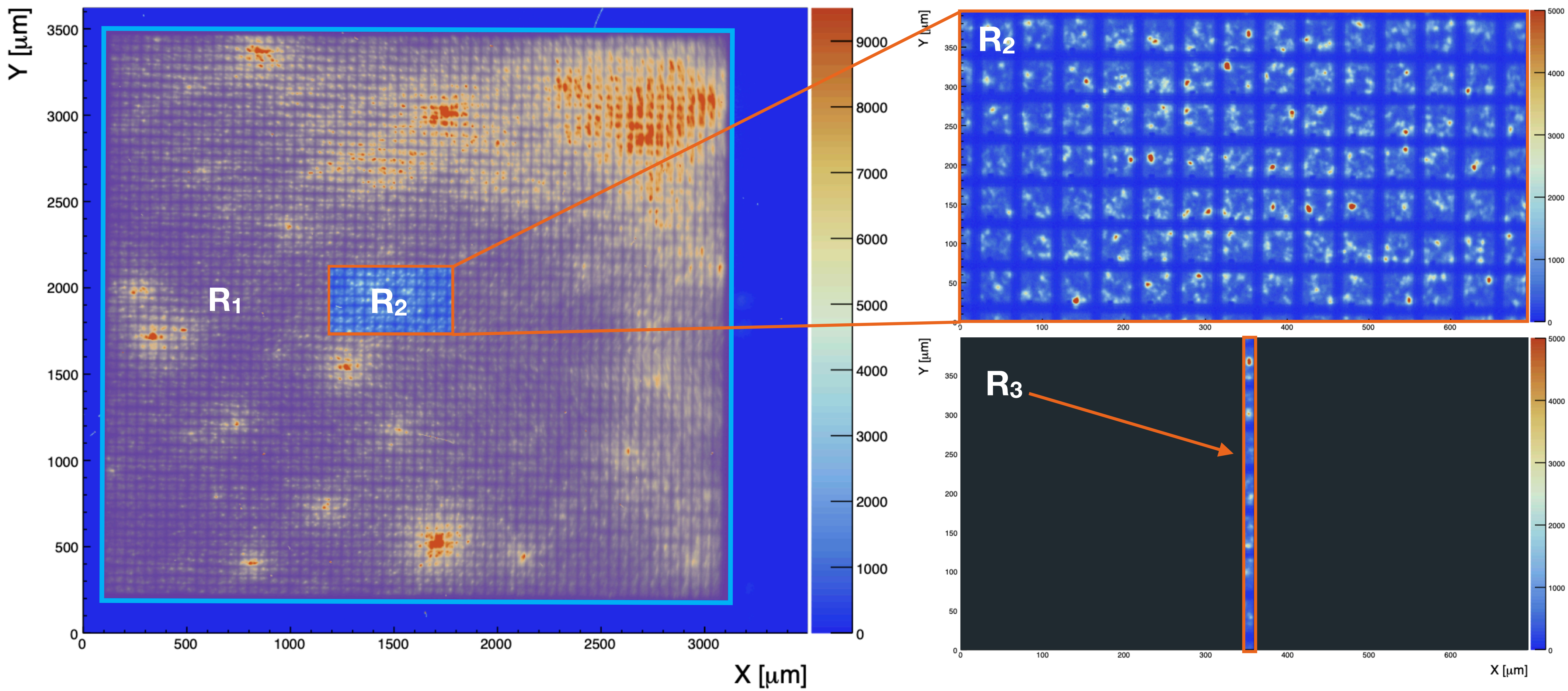

- Calculate the ratio of integrated counts in Region 1 to Region 2—this indicates the proportion of all photons coming from the local area in the 20x magnification
- Calculate the ratio of integrated counts in Region 2 (zoomed) to Region 3—this indicates the proportion of local photons contained within the spectrometer slit
- The surface area emission profile correction is the product of these two ratios

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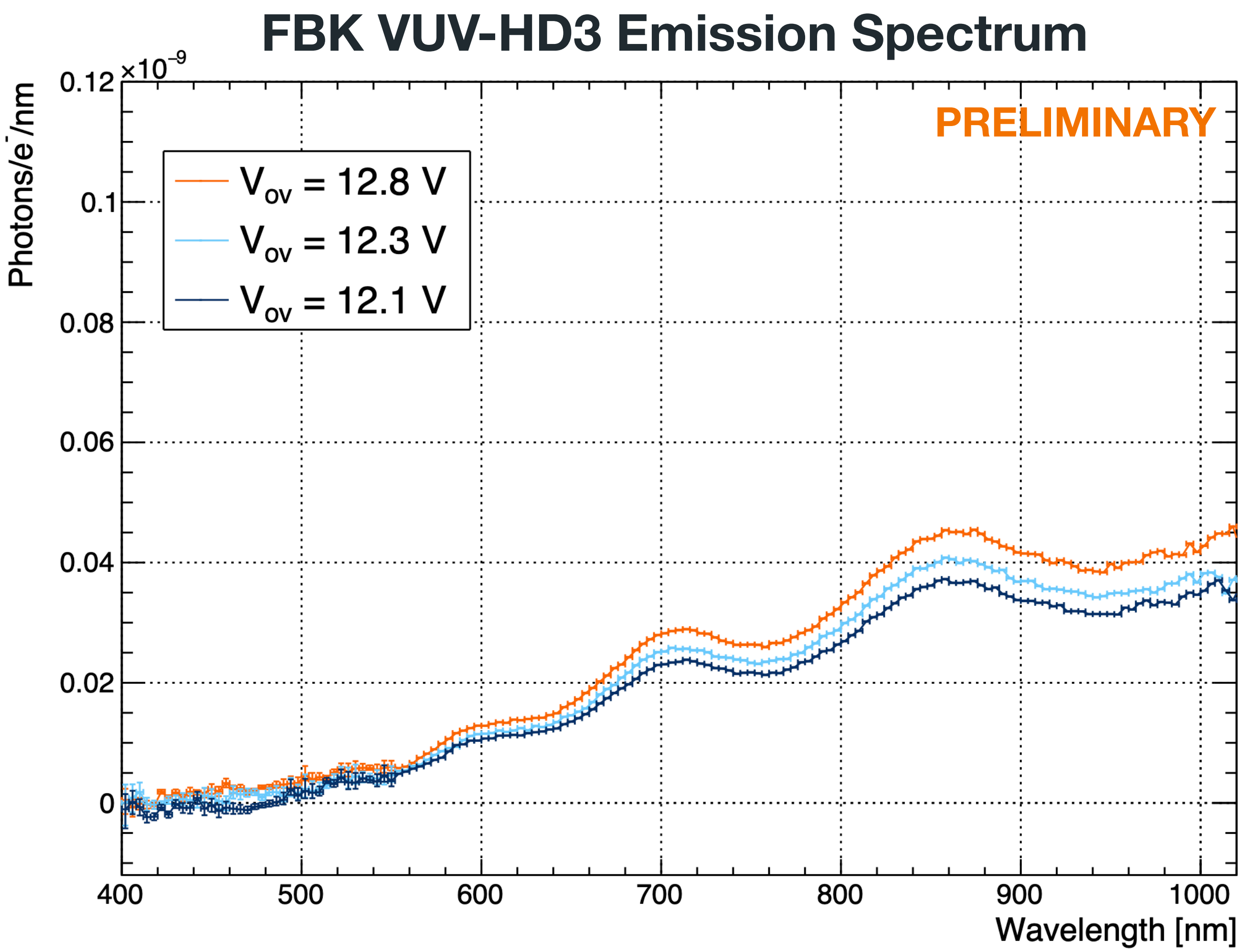
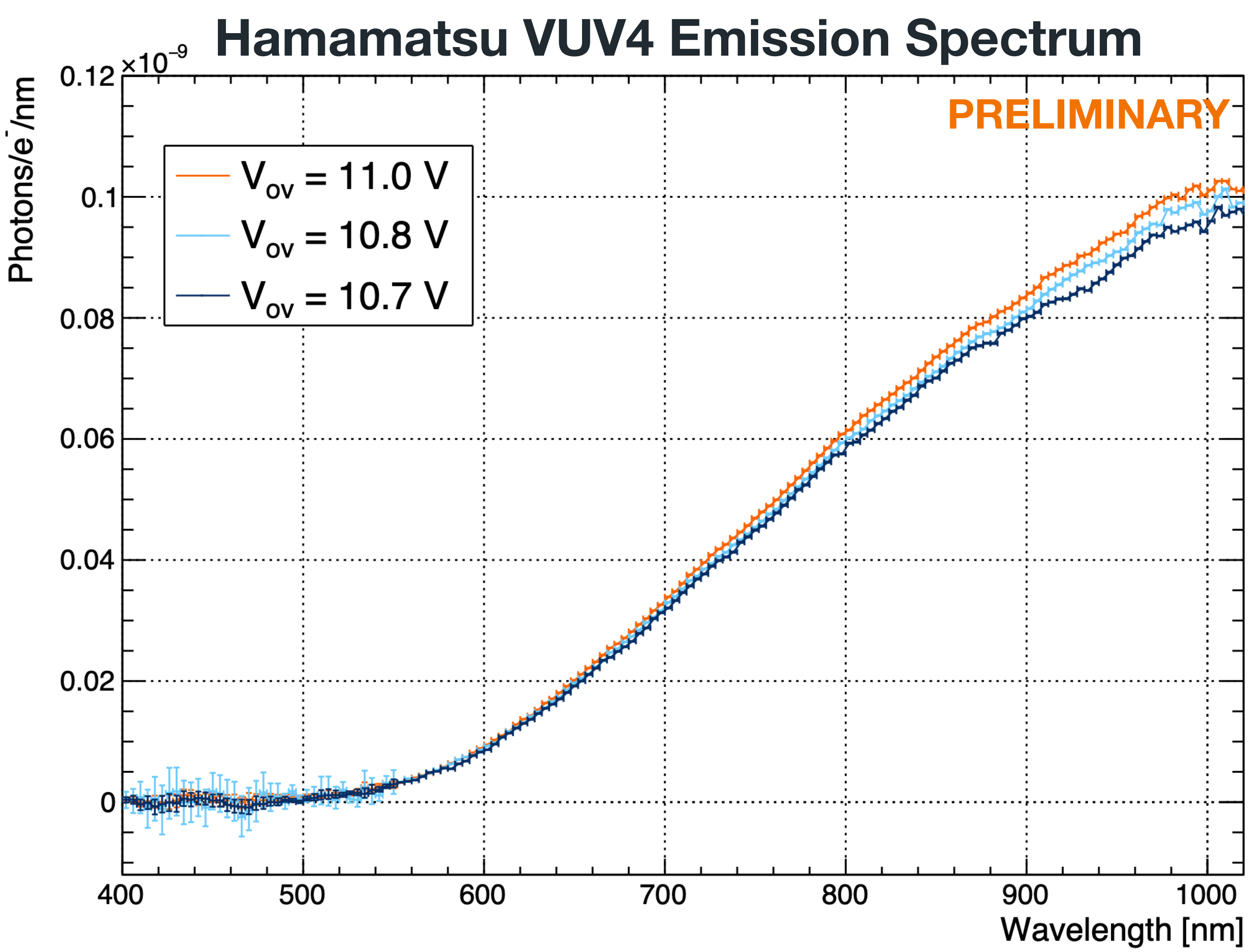
Results





- Spectra are normalized by using ADC information from manufacturer, set exposure time, total SiPM charge integrals, and spatial emission profiles of each SiPM
- Both SiPMs predominantly glow in NIR; FBK spectrum consistent with thin film interference from SiO_2 layer of order 10^{-6} m thick
- Hamamatsu VUV4 emitting ~2x as many photons as FBK VUV-HD3

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Results

FBK VUV-HD3			Hamamatsu VUV4		
Overvoltage [V]	Photon Yield (x10^{-8}) [γ/e^-]	Mean Photons per Avalanche*	Overvoltage [V]	Photon Yield (x10^{-8}) [γ/e^-]	Mean Photons per Avalanche*
12.8 ± 1.0	1.462 ± 0.002	4^{+2}_{-1}	11.0 ± 1.0	2.588 ± 0.002	7^{+2}_{-1}
12.4 ± 1.0	1.285 ± 0.003	3^{+2}_{-1}	10.8 ± 1.0	2.514 ± 0.006	7^{+2}_{-1}
12.1 ± 1.0	1.168 ± 0.003	3^{+2}_{-1}	10.7 ± 1.0	2.457 ± 0.002	6^{+2}_{-1}

*** Order of magnitude estimate assuming charge avalanche gain of 10^6***

- Correction for numerical aperture further scales yields by at least 270; more likely 300–400 when accounting for all geometric and optical effects
- Single charge carrier gain in avalanche process is on the order of 10^6
- Gives a total yield of ~6–7 photons per avalanche from HPK VUV4 and ~3–4 for FBK VUV-HD3 in the relevant overvoltage ranges

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Conclusion

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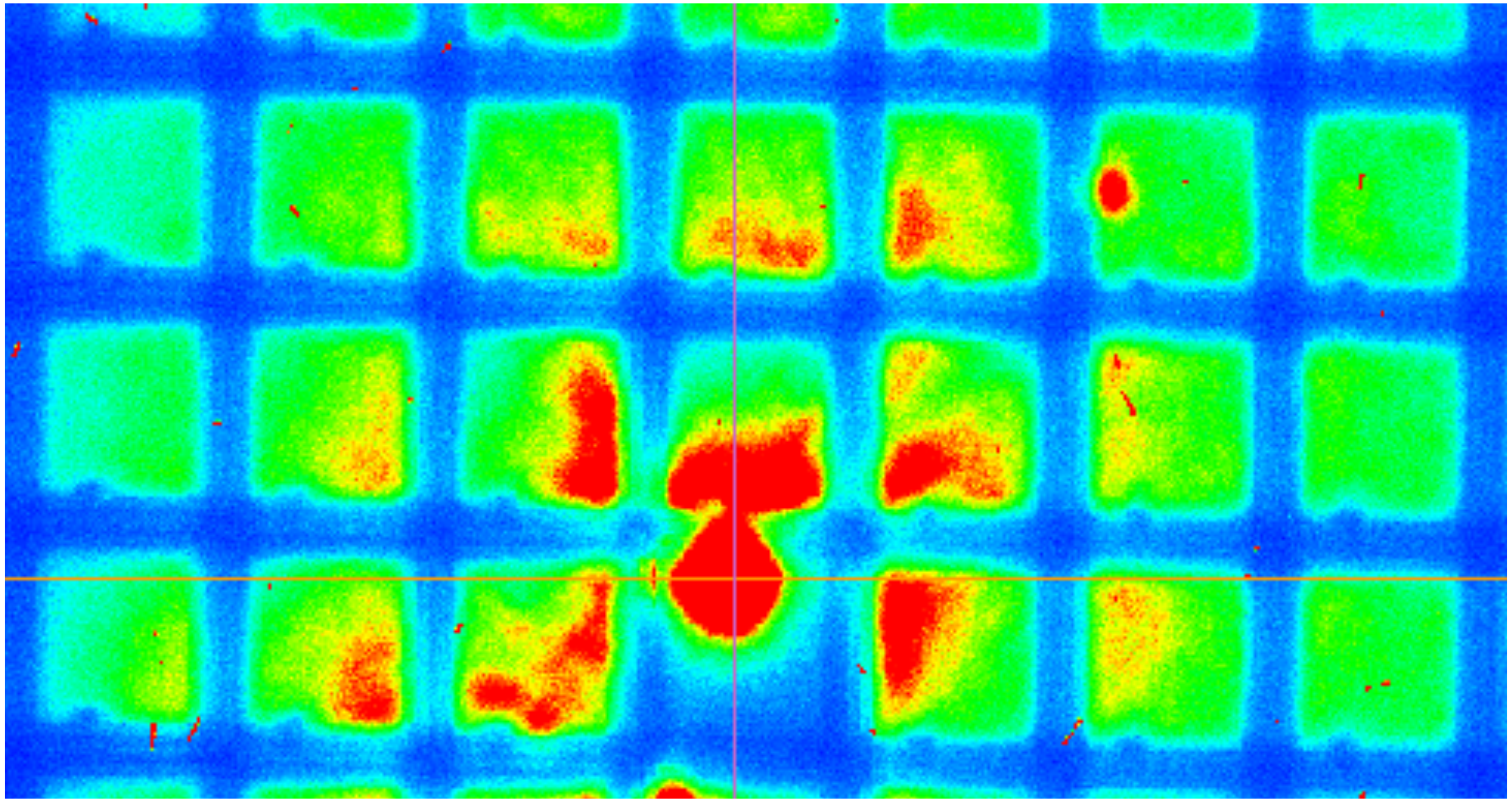
Concluding Remarks

- MIEL is capable of producing high resolution images and spectroscopic measurements of SiPM avalanche photon emission
- Hamamatsu VUV4 has a highly non-uniform light emission profile over its surface area, FBK VUV-HD3 emits half as many photons as VUV4
- External cross-talk rates can be determined with spectra shown here and photon detection efficiency vs. wavelength
- Knowing emission spectra of SiPMs informs modelling of light production; helps with understanding external and internal cross-talk, and future SiPM designs

Future Developments

- Paper submission for external cross-talk characterization is imminent
- NIST-traceable radiometric calibration of MIEL apparatus will significantly reduce systematic uncertainties
- Laser-induced avalanche measurements will begin soon; aiming for publication by mid summer 2021

Thank you!

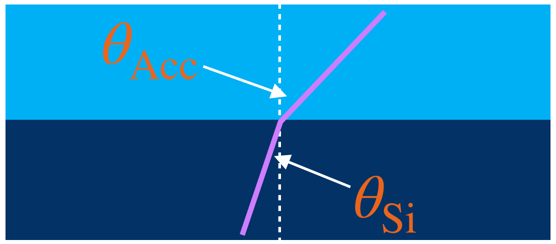


Extra slides

Numerical Aperture Correction

- The numerical aperture, *NA*, of an optical system defines the acceptance half-angle, θ_{Acc}, of incident photons given a local index of refraction, *n* (in this case, atmosphere)

$$\mathrm{NA} = n_{\mathrm{atm}} \sin \theta_{\mathrm{Acc}}$$



$n_{\mathrm{atm}} \approx 1$

$n_{\mathrm{Si}} \approx 3.7$

- Light passes through silicon then into air; acceptance angle within silicon transforms according to Snell's law

$$\mathrm{NA} = n_{\mathrm{atm}} \sin \theta_{\mathrm{Acc}} = n_{\mathrm{Si}} \sin \theta_{\mathrm{Si}}$$

- Correction factor, *CF*, can be approximated by finding ratio of 4*π* steradians to solid angle within acceptance angle in silicon

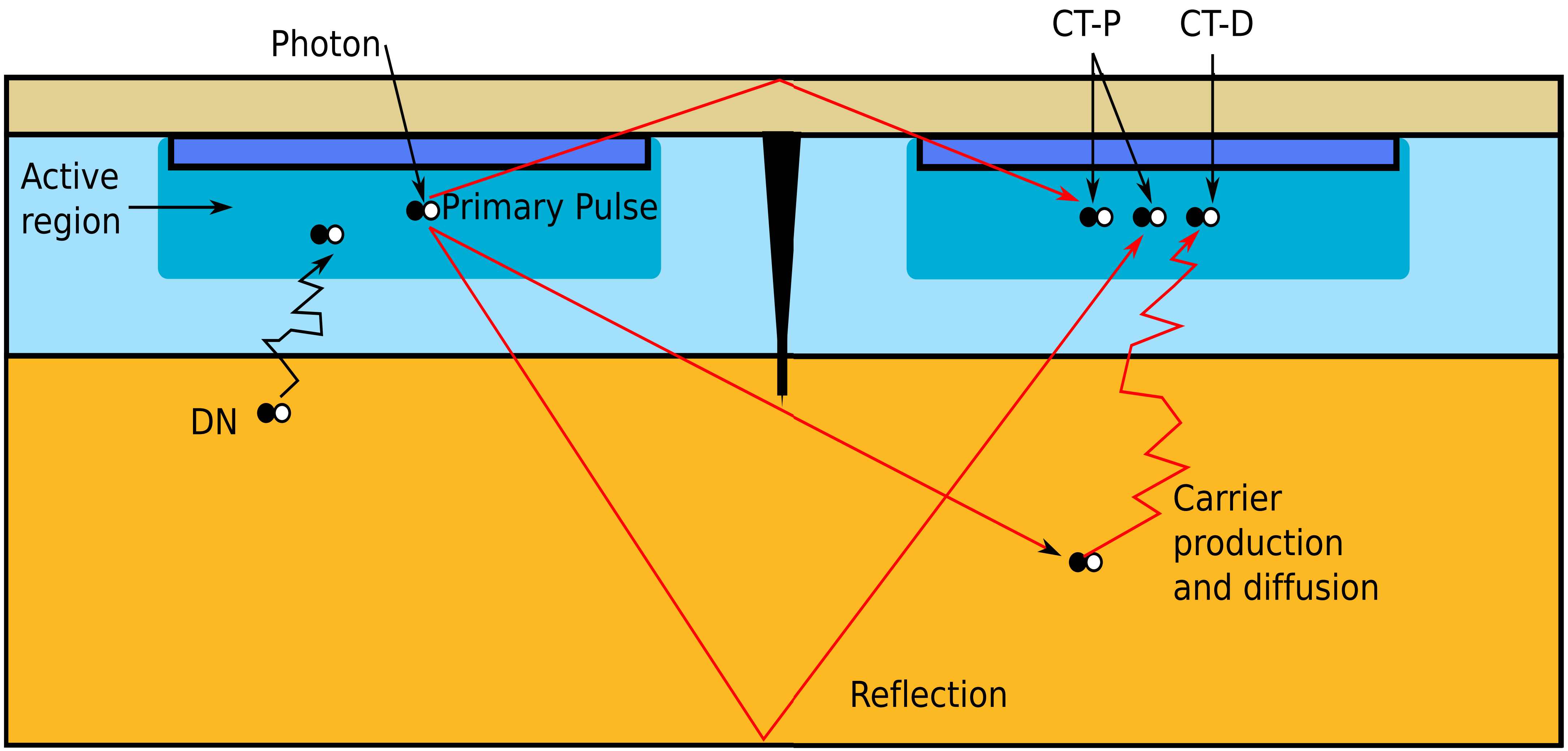
$$\mathrm{CF} \gtrsim \frac{4\pi}{2\pi \int_0^{\theta_{\mathrm{Si}}} sin\theta \, d\theta}$$

- This correction factor must be a lower bound—geometry and optics are simplified

- For *NA* ≈ 0.45 and *n* = 1

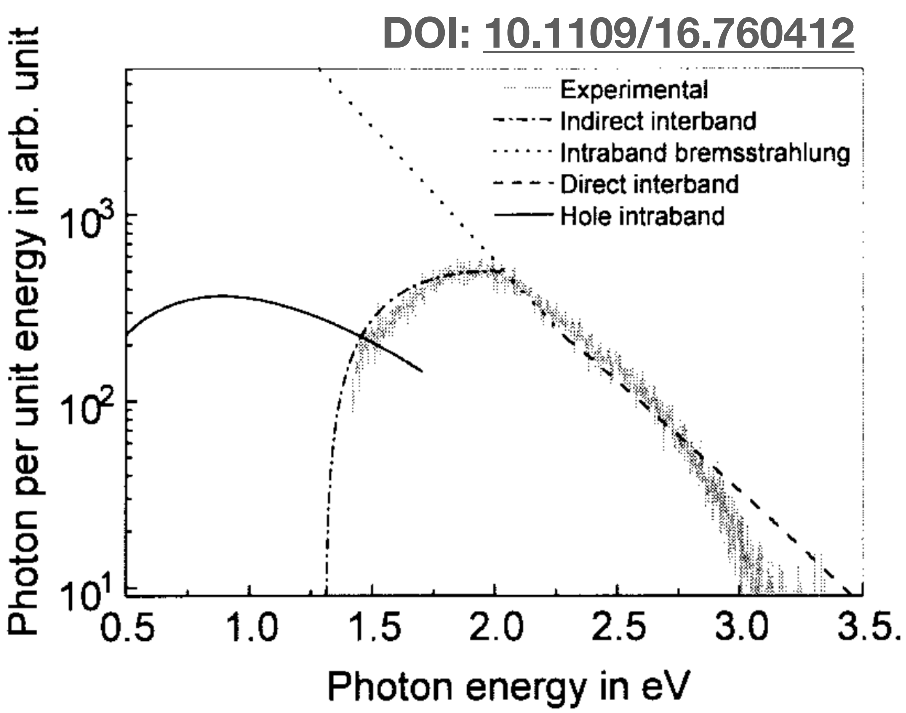
$$\mathrm{CF} \gtrsim \frac{4\pi}{2\pi \int_0^{7^\circ} sin\theta \, d\theta} \approx 270$$

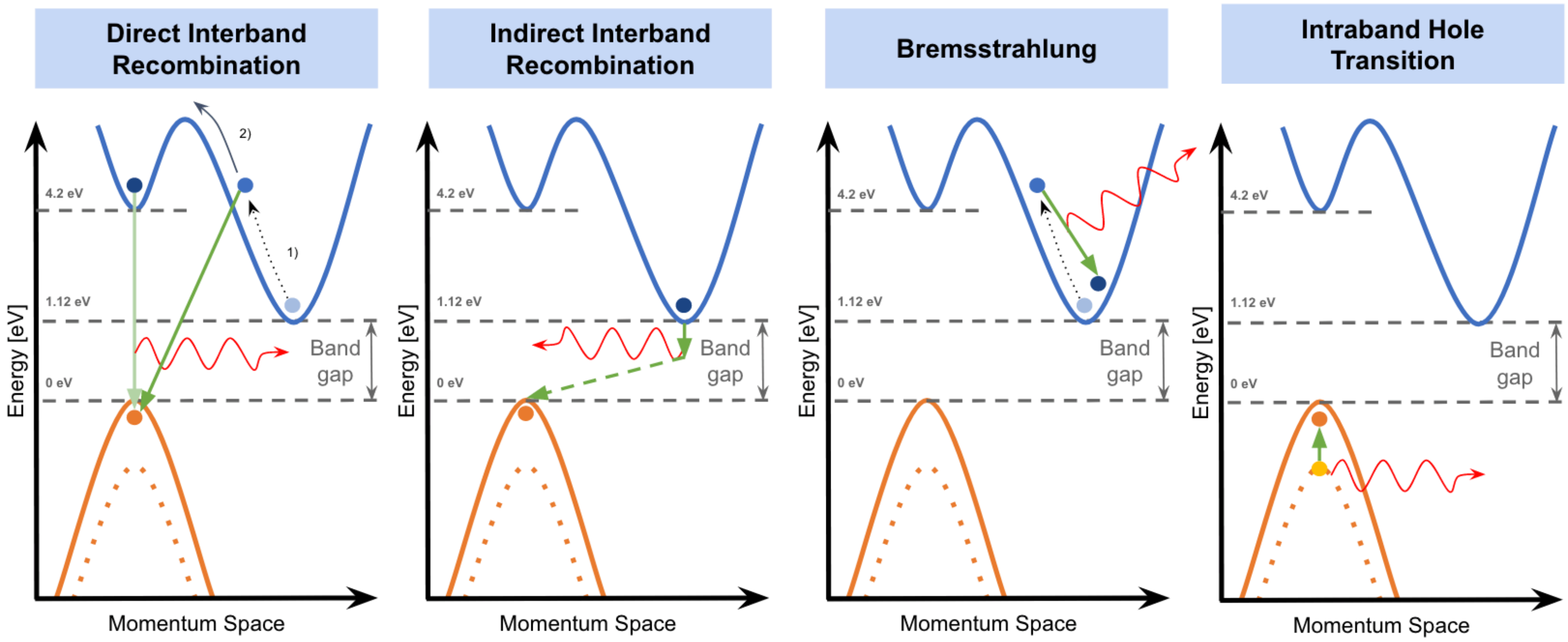
Internal Cross-Talk



- Avalanches are triggered by charge carriers in the active region, which can be generated via photon or can diffuse in thermally from elsewhere (i.e. dark noise)
- Internal cross-talk falls into two categories:
  1. Emitted photon directly reflects into neighbouring SPAD active region (prompt cross-talk)
  2. Emitted photon generates a charge carrier elsewhere, which subsequently diffuses into a neighbouring SPAD active region (delayed cross-talk)

Light Production





- Light production mechanism is thought to be predominantly from electron-hole recombination in various forms
- Bremsstrahlung has been proposed as a higher energy contribution to light production
- The combined photon spectrum also depends heavily upon impurity content and concentration within the silicon, electric field profile, reverse bias voltage, etc.

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