TRIUMF

Early Photon Detector R&D for Particle Physics and Beyond

Harry Lewis, PHORWARD group

TRIUM Science Week 2024

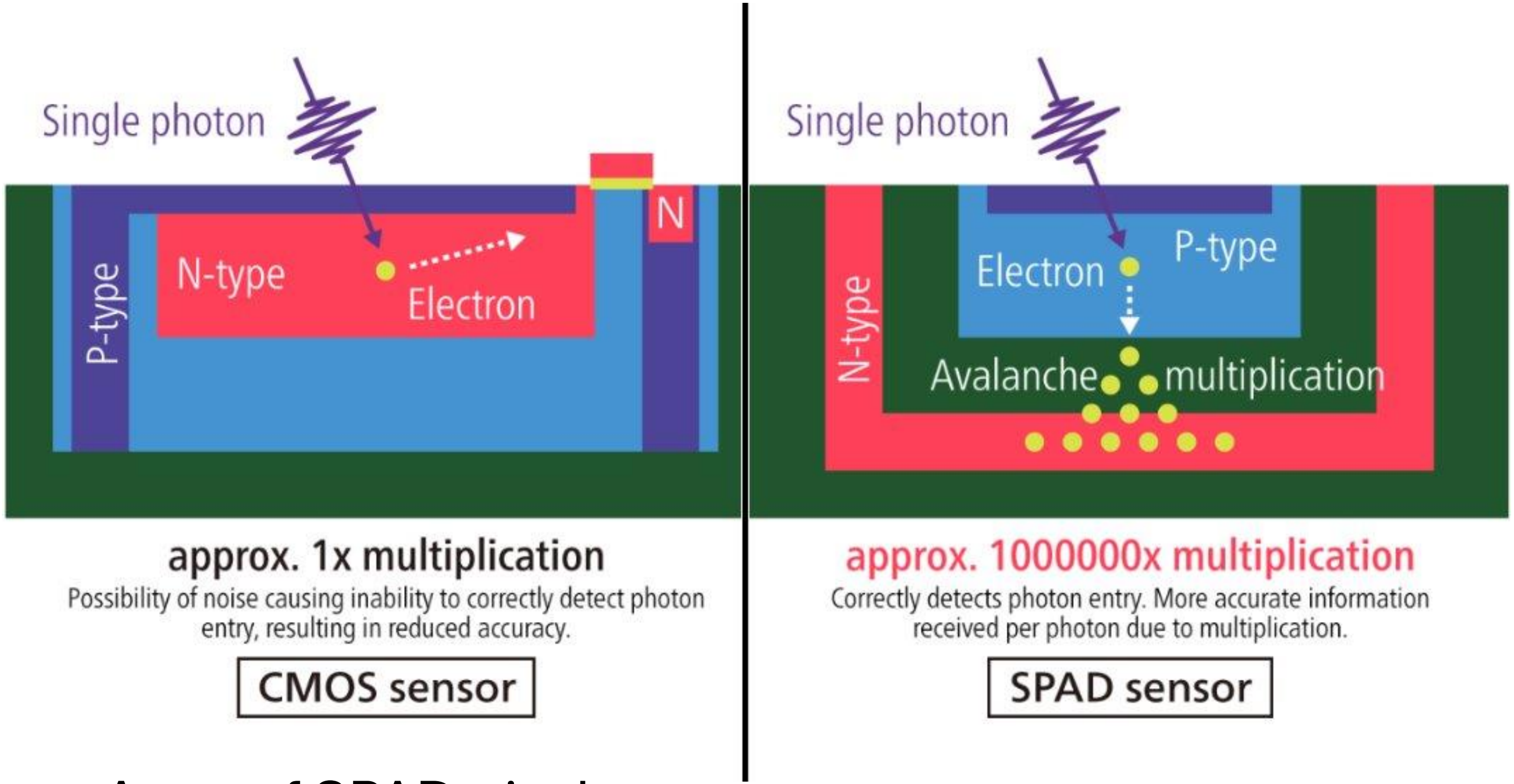
2024-07-25

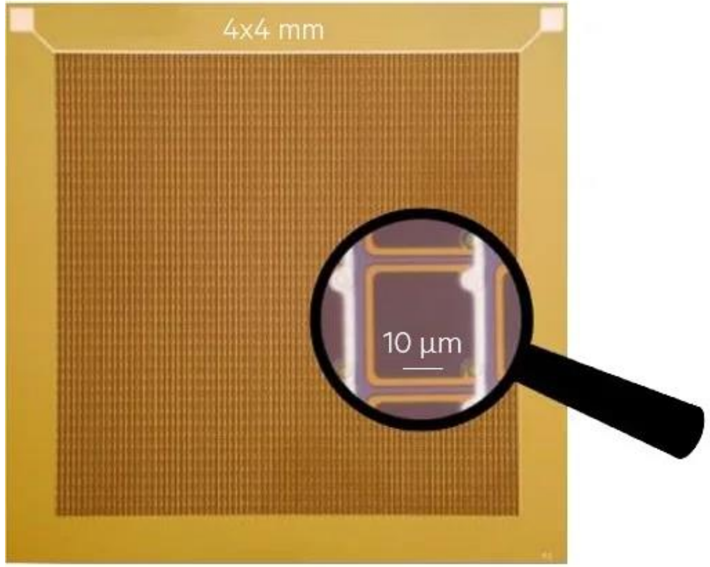
Discovery, accelerated

Scope of this talk

- Discuss photodetector R&D at the device level
- VUV-SiPMs for nEXO and other particle physics experiments
- Work being done at TRIUMF, impact on experiments and technology transfer
- Work loosely grouped into TRL categories of ‘emerging,’ ‘prototyping,’ ‘integration’

Silicon photomultipliers





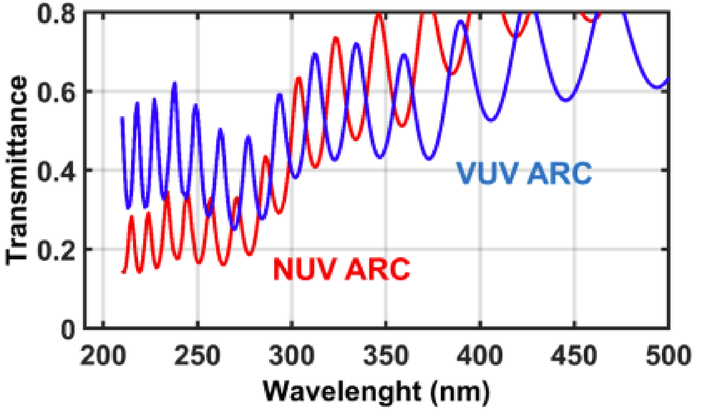
- Array of SPAD pixels
- Compact, robust, insensitive to magnetic fields, fast timing
- Easier to produce large photosensitive area than using PMTs
- Cons: dark count, crosstalk

VUV-SiPMs for particle physics

- nEXO will use 4.5m^2 of SiPMs to detect LXe scintillation light
- FBK and Hamamatsu (candidate vendors for nEXO) have developed VUV SiPMs for nEXO – this was needed for the experiment to work
- Development is ongoing and driven by the needs of experiments (eg tsv's for nEXO)
- 30m^2 for Darkside-20K, Argo may use 200m^2(!)

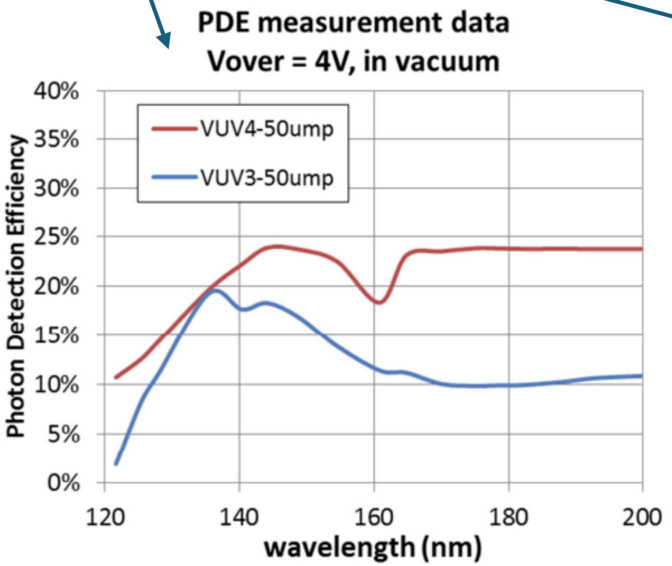
R&D focus on ARC

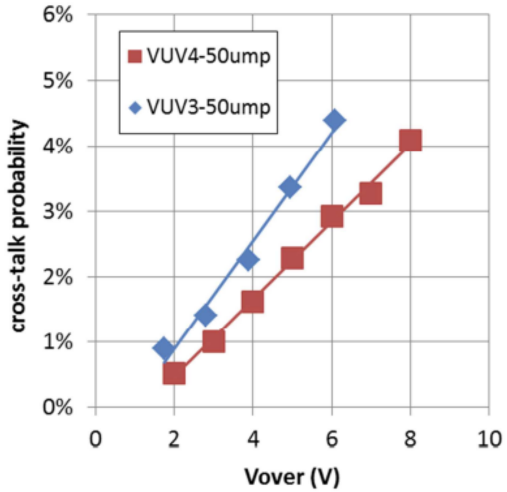
FBK



R&D was focused on enhancing the transmission of the ARCs, by removing Si_3N_4.

Hamamatsu

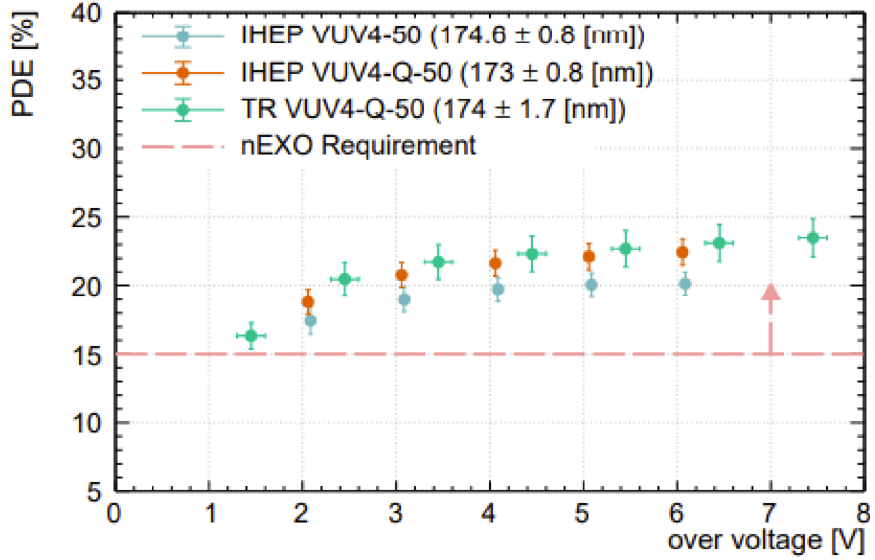


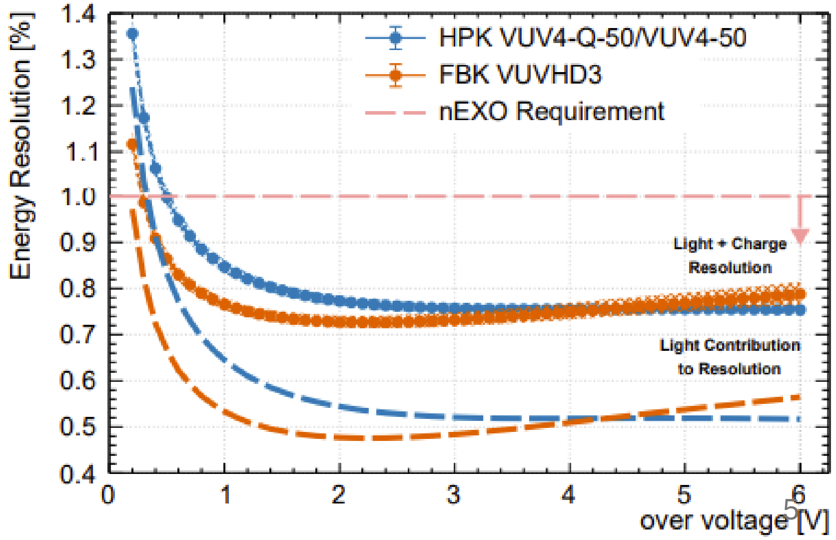


emerging

Characterization at TRIUMF

- First step to incorporating devices in an experiment is characterizing the basic parameters - PDE, DCR, afterpulsing
- Devices meet fundamental nEXO requirements – shows feasibility
- Also necessary to understand the challenges of integrating devices into a detector
- Developing protocols for mass testing





Understanding pathologies - external crosstalk

- SPAD avalanches emit photons
- SiPMs triggering each other leads to 'external crosstalk' and degrades energy resolution

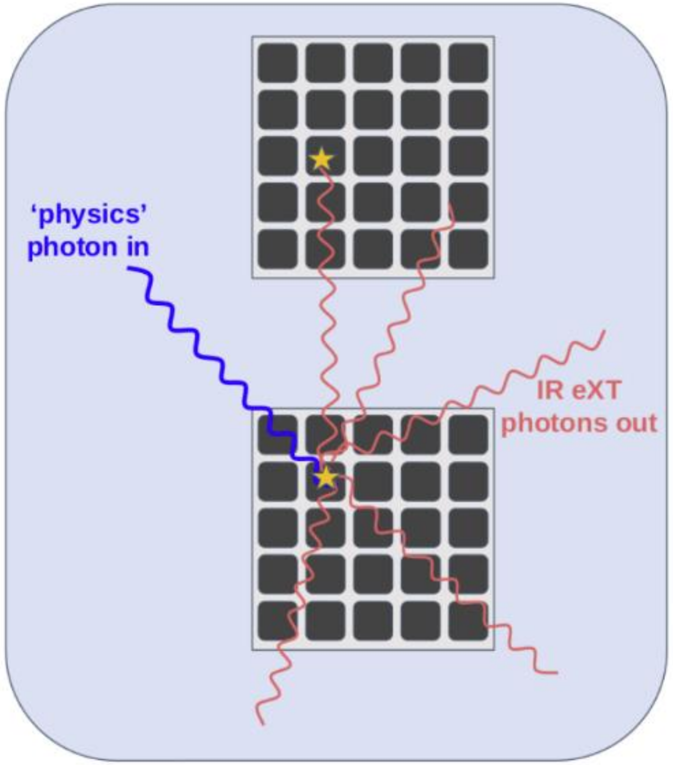
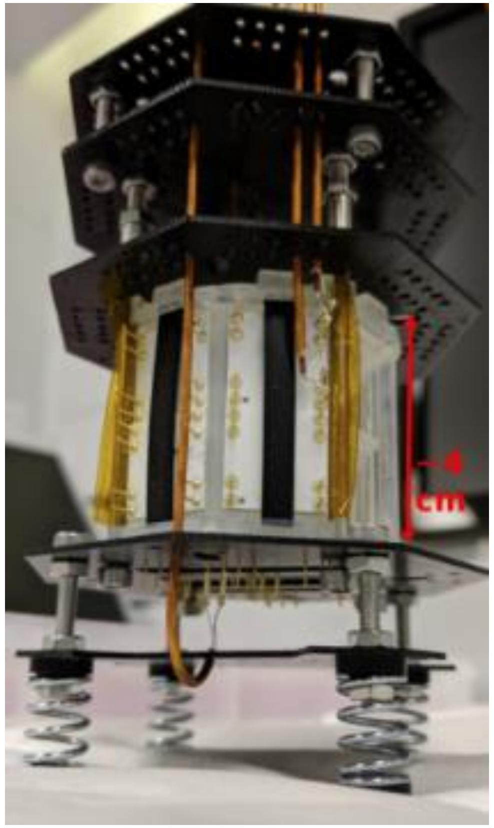


Diagram of eXT occurring between two SiPMs. ★designates charge avalanche

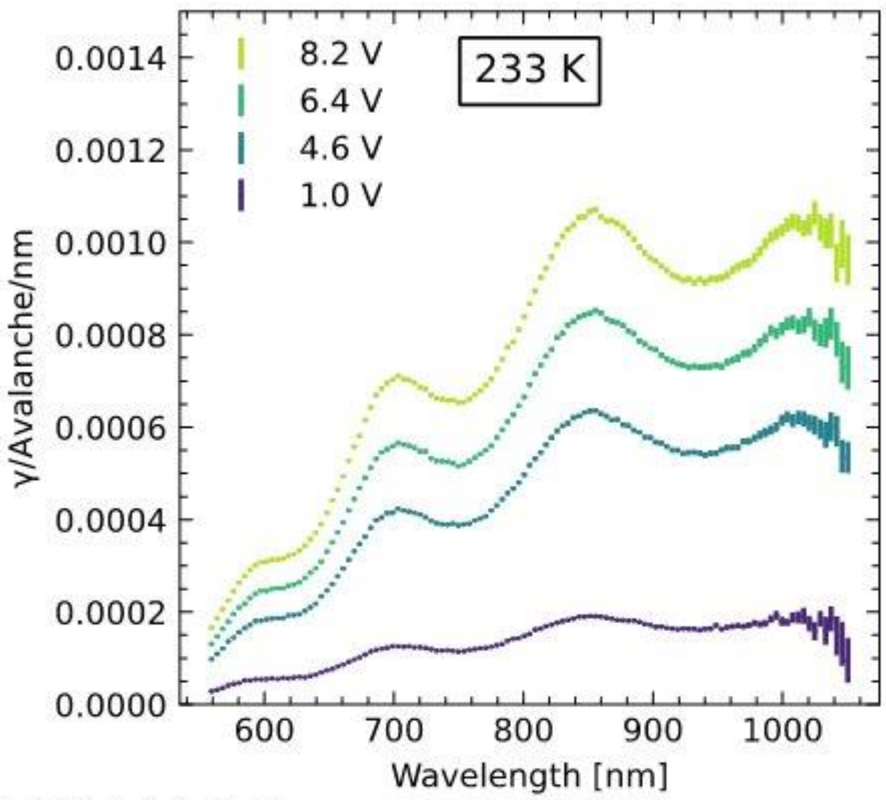


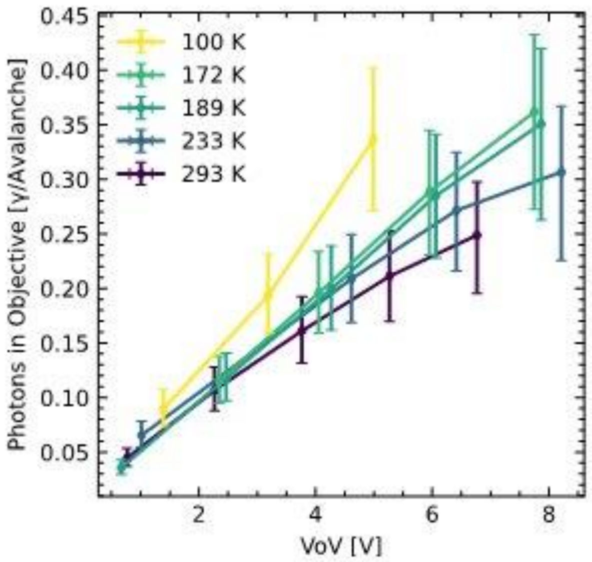
- Not good! Effect needs to be well quantified
- Can be empirically studied using LolX detector at McGill

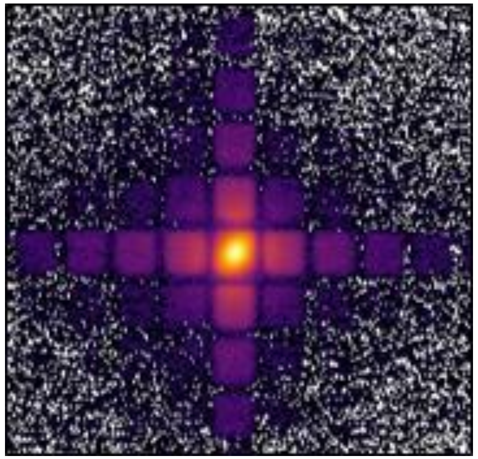
prototyping

Secondary emission

- Measurements of spectrum/number of photons emitted during avalanche using MIEL setup at TRIUMF
- nEXO candidate devices measured for direct input to detector simulations
- Work ongoing to measure emission from individual SPADs in a digital SiPM, aiding understanding of emission mechanisms
- Can then contribute to future device design – enabling future technological improvements through study of a specific detector pathology

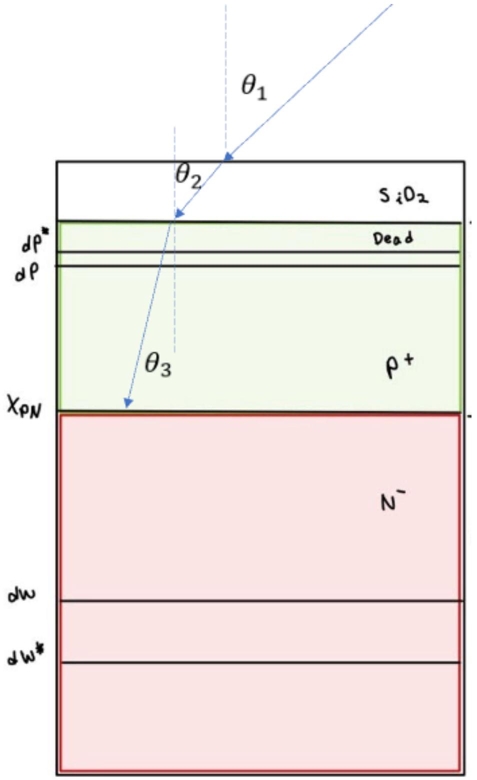




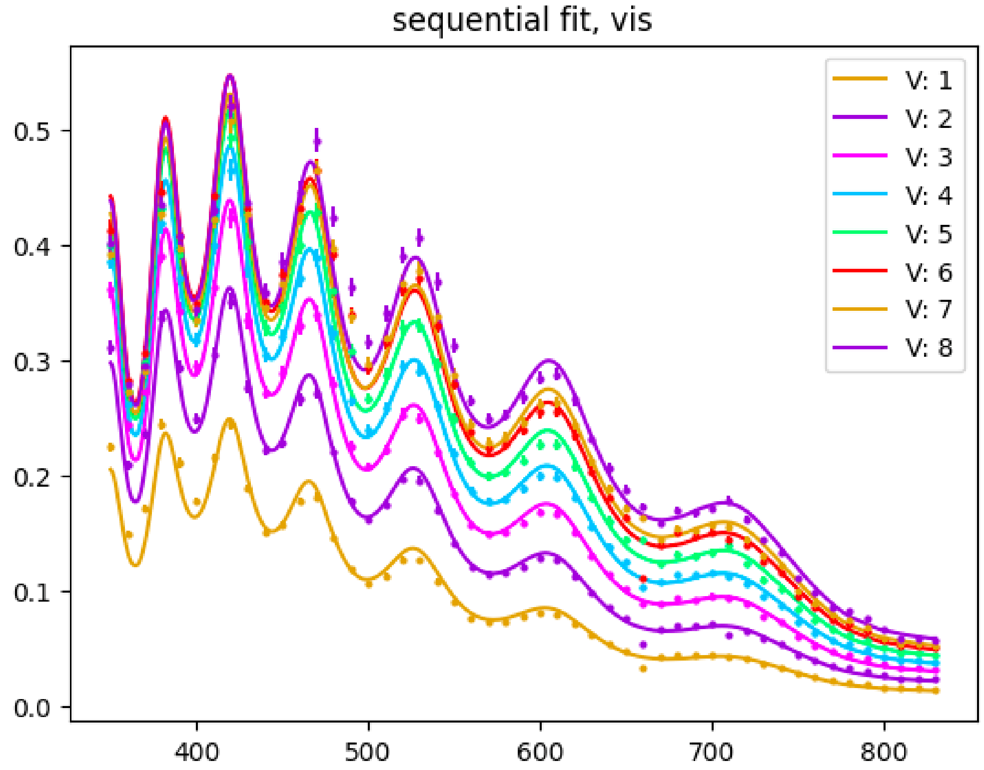


Modelling PDE

- Predicting crosstalk now requires understanding device response at secondary emission wavelengths
- Modelling PDE lets us extrapolate to wavelengths we can't measure
- Also provides details on device structure



PDE for FBK VUV-HD3 device



Wavelength [nm]

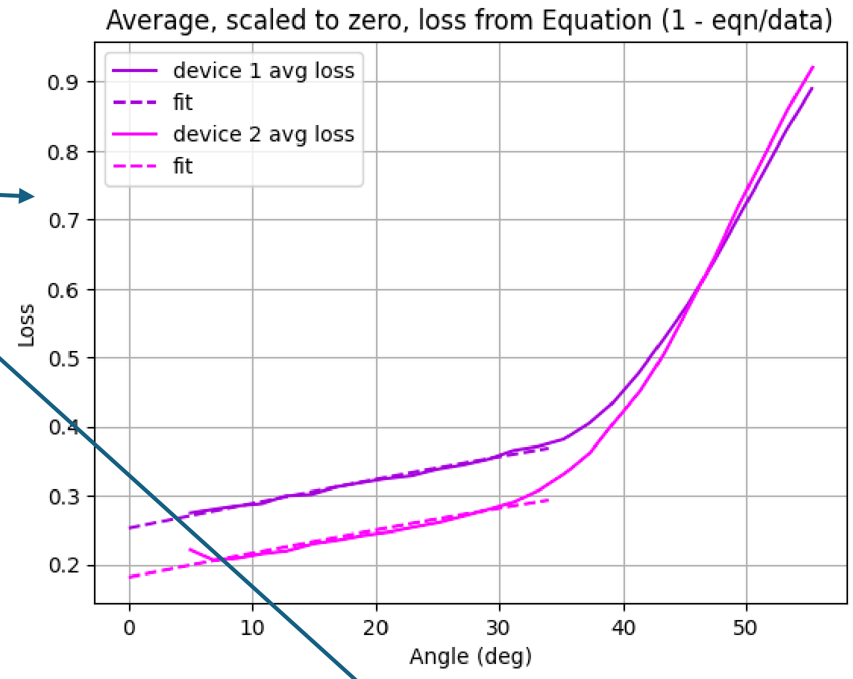
$$PDE = FF \cdot T(\lambda, \theta_1, t_{oxide}) \cdot \left(W_p(\lambda, dp^*, X_{PN}) p_e(V) + W_n(\lambda, X_{PN}, dw^*) p_h(V)\right)$$

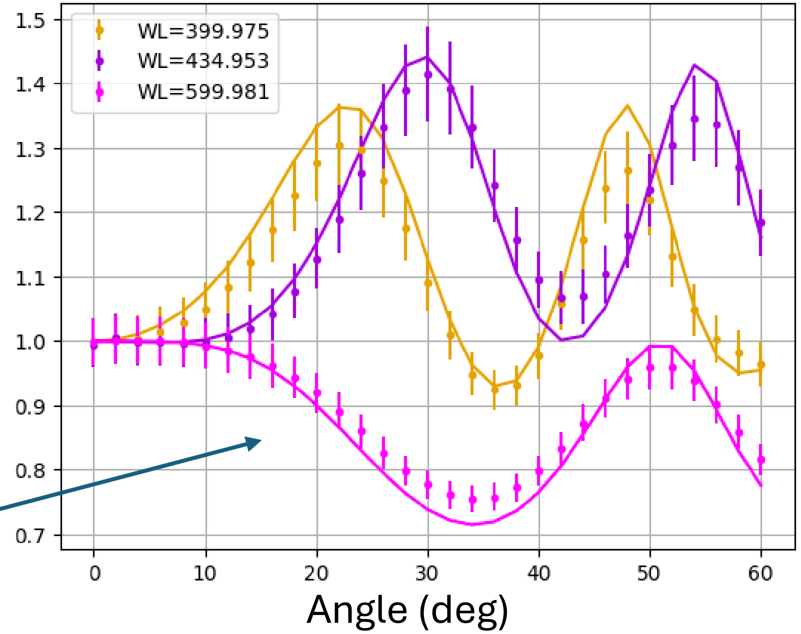
prototyping

Modelling optics

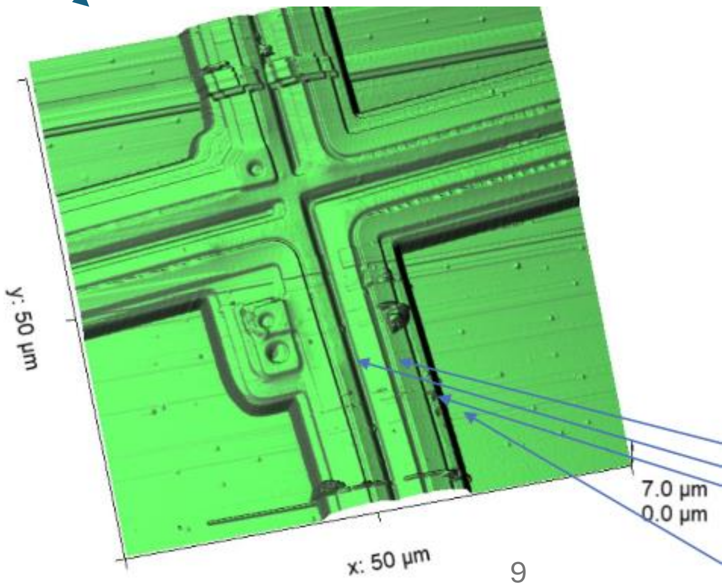
- Optical transmission into device is not simple!
- Passivation layer thickness, interference, shape of the device microstructure play a role
- Angular dependence is important for detector simulations

Losses due to microstructure shadowing in VUV4





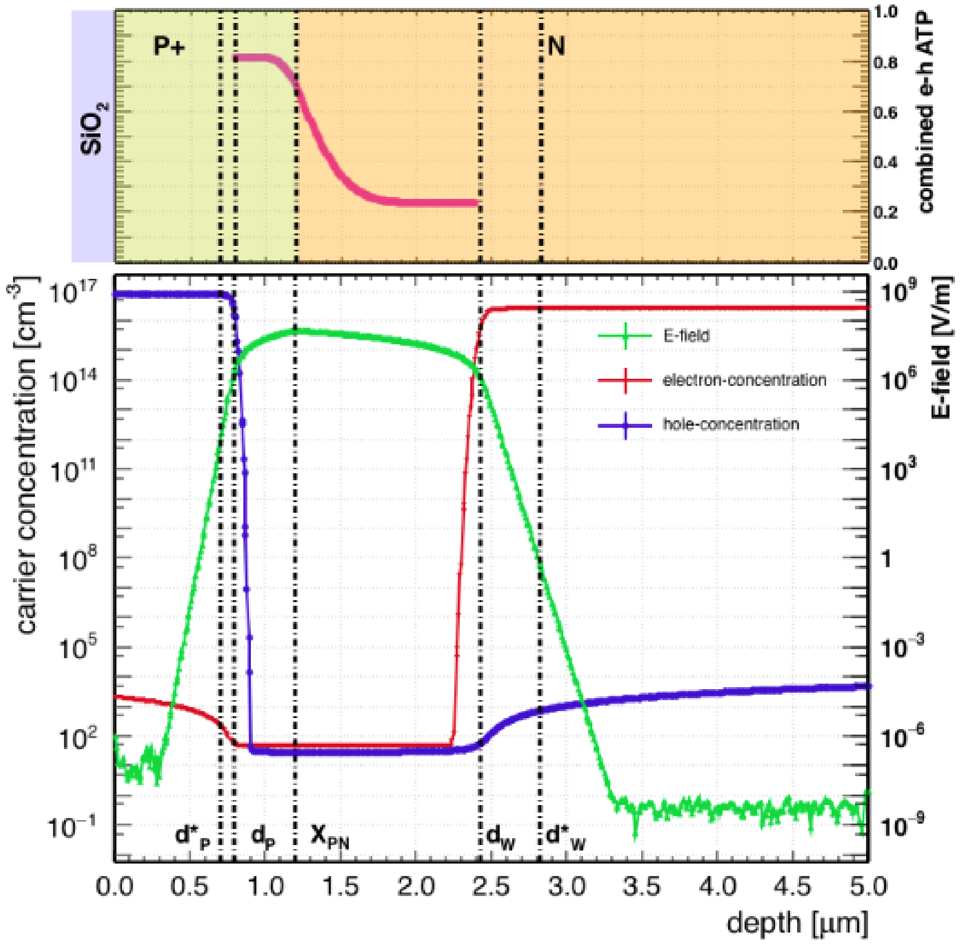
Interference oscillations in FBK device



emerging

Technology transfer – device modelling for design of a unity-PDE SPAD

- Several avenues for improving SPAD efficiency – antireflection coatings can be produced with close to 0 reflectivity at certain wavelengths
- Controlling region thicknesses and electric field profile can also maximize PDE while keeping DCR low
- Probably possible to produce a 100% PDE silicon SPAD with the right design choices

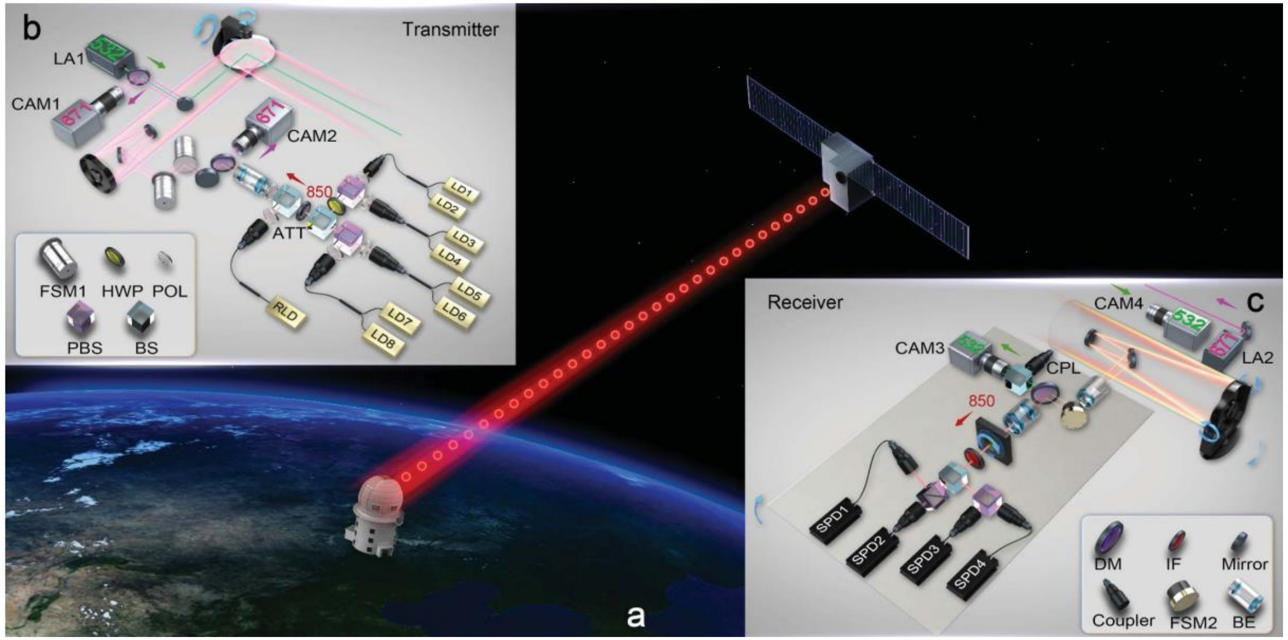


emerging

High efficiency SPADs for quantum applications

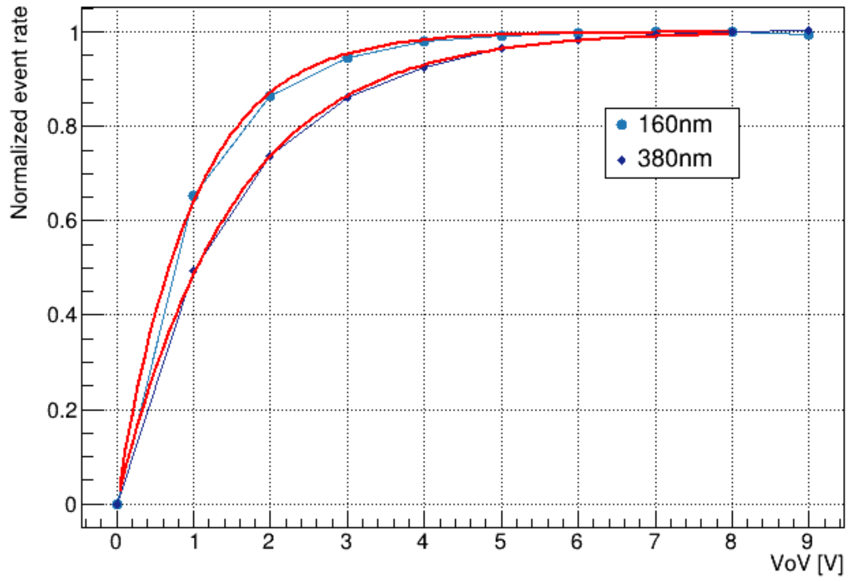
- Quantum computing requires very high PDE and single-photon resolution at high photon numbers -> currently need SNSPDs to do this
- An ultra-high PDE SPAD would enable quantum computing at high(er) temperatures (the Xanadu quantum computer currently only uses dilution fridge temps for the single photon detectors)

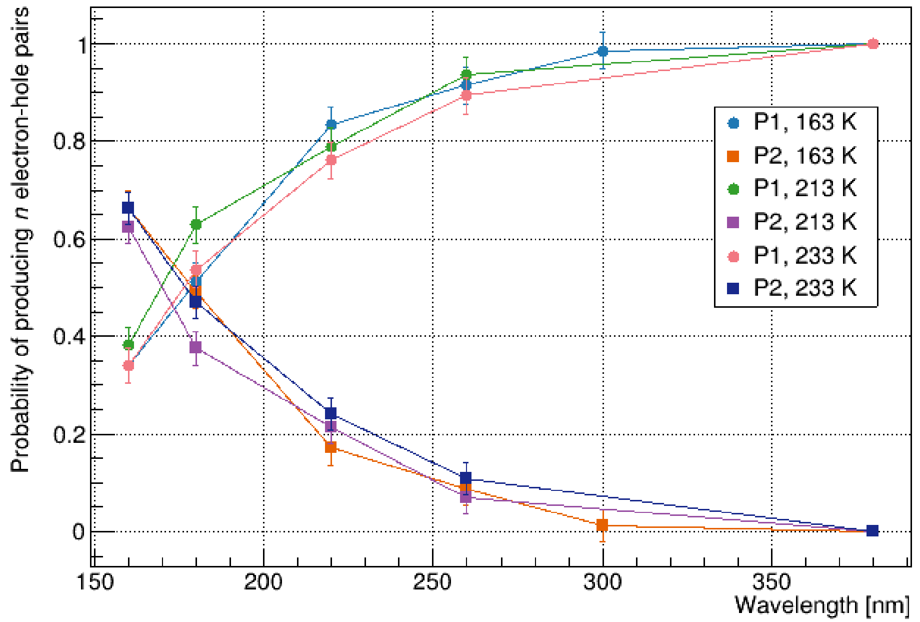
- Could also permit high rate QKD systems!!



Quantum yield

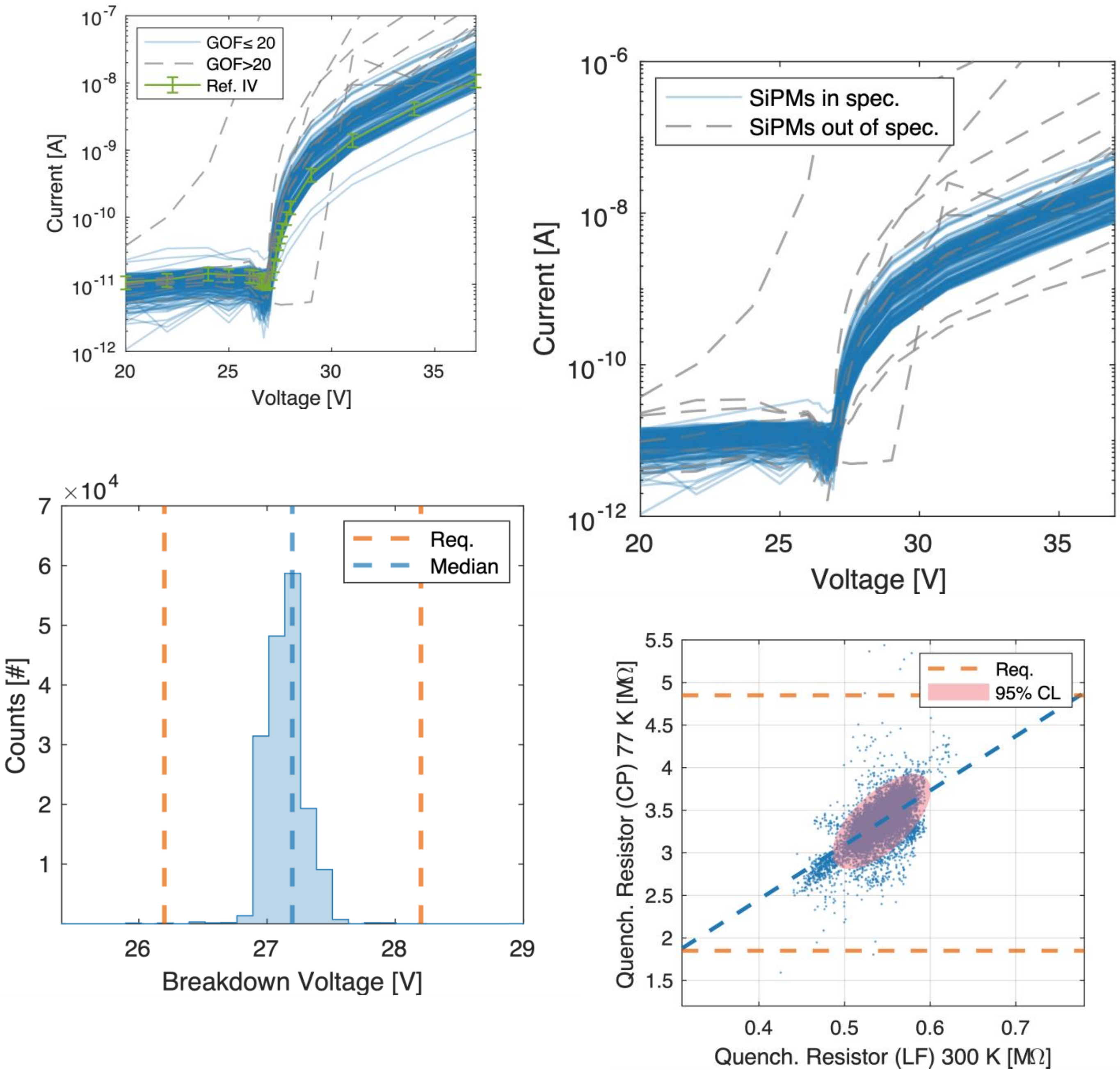
- ‘Quantum yield’ is the number of carrier pairs produced by a single photon absorption – increases above 1 at high energies
- Understanding needed for detector event reconstruction – but applicable to a range of deep UV detection applications
- Also applicable for detection of dark photons and design of VUV photodetectors





Mass testing

- Operation of >40k SiPMs over 10 years requires in-depth understanding of reliability and pathologies
- Development underway to produce fast and effective diagnostics
- Much of this will be transferable –
  - Extraction of device parameters from IV rather than waveform-level measurements
  - Determining whether high-temperature performance can reliably infer low-temperature performance
- Darkside is using a ‘goodness of fit’ parameter to a reference IV – we hope to be able to improve on this

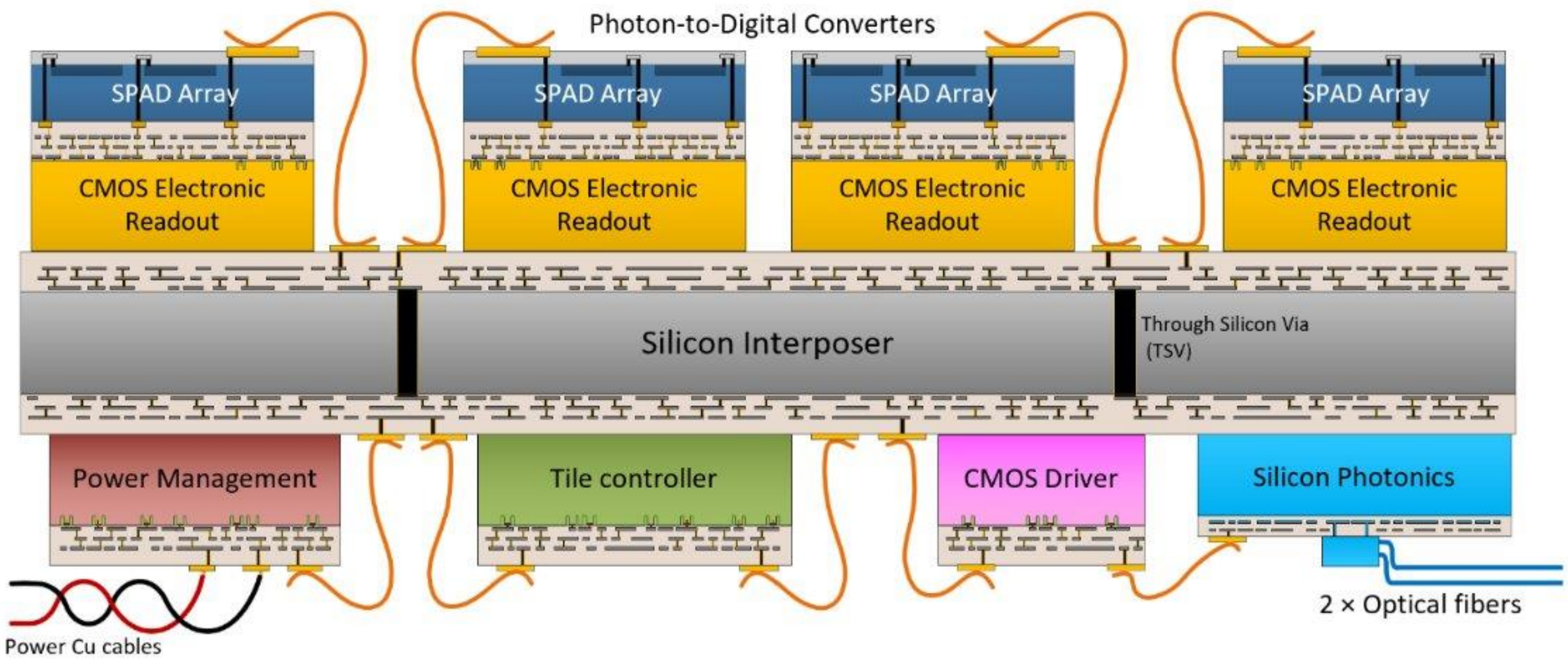


Figures from DarkSide testing – thanks Giacomo ☺

emerging

Digital SiPMs

- Individual SPAD readout and control
- Potential for spatial resolution and deactivation of faulty/high DCR SPADs
- Could be used to mitigate radiation damage



Summary

- nEXO and other particle physics experiments have motivated a significant R&D push in SiPM technology, in industrial and academic settings
- This enables better physics detectors now and better technology available for designing future detectors
- It also results in better understanding of SPAD operation and feeds back in to improved photodetectors for a wide range of applications

TRIUMF

Thank you
Merci

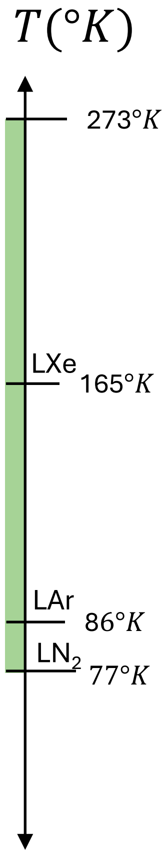
www.triumf.ca

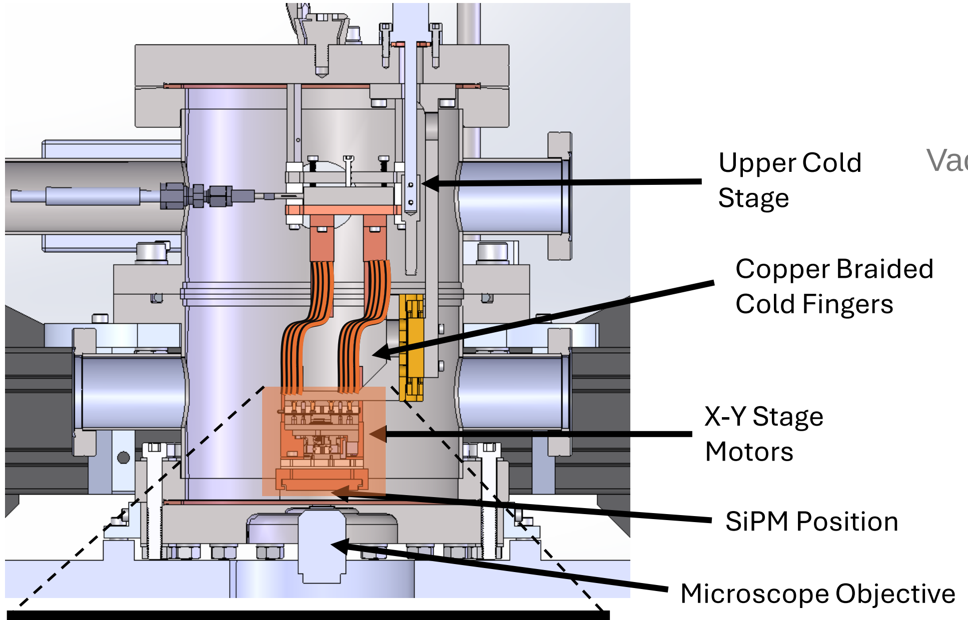
Follow us **@TRIUMFLab**

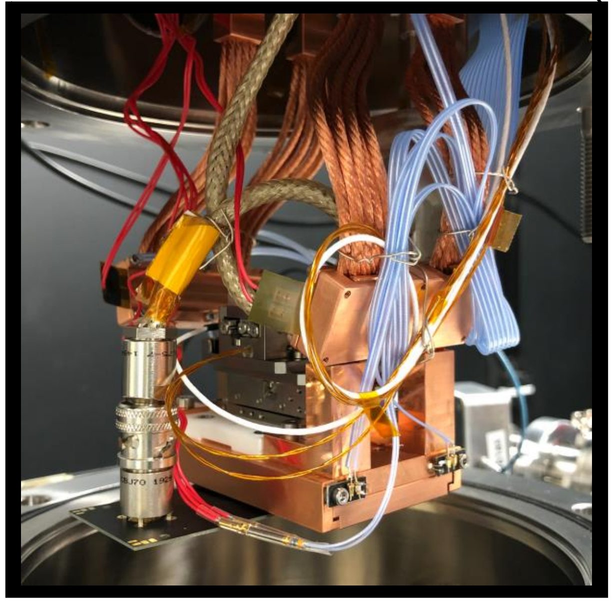
Discovery, accelerated

MIEL

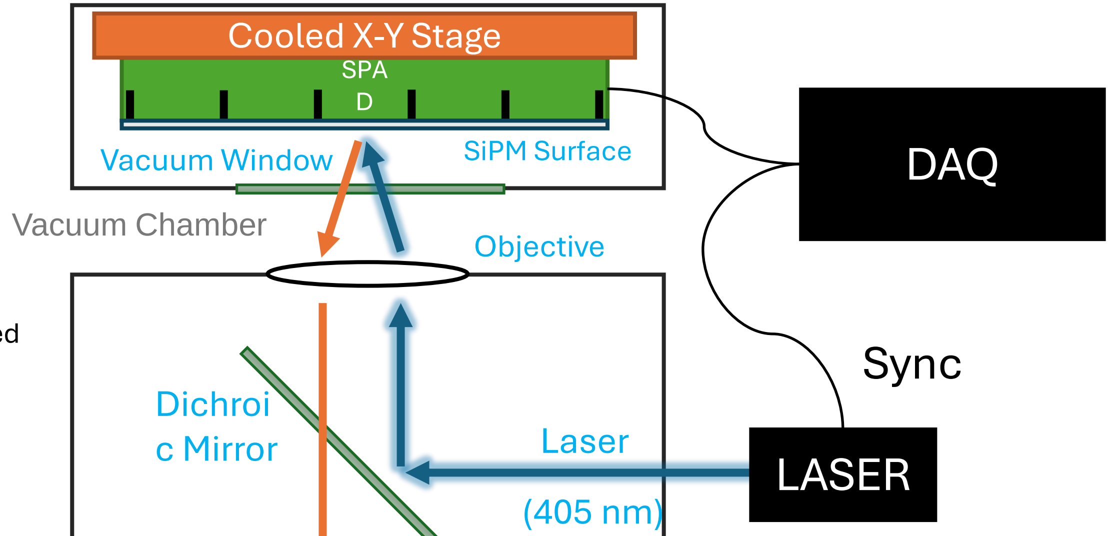
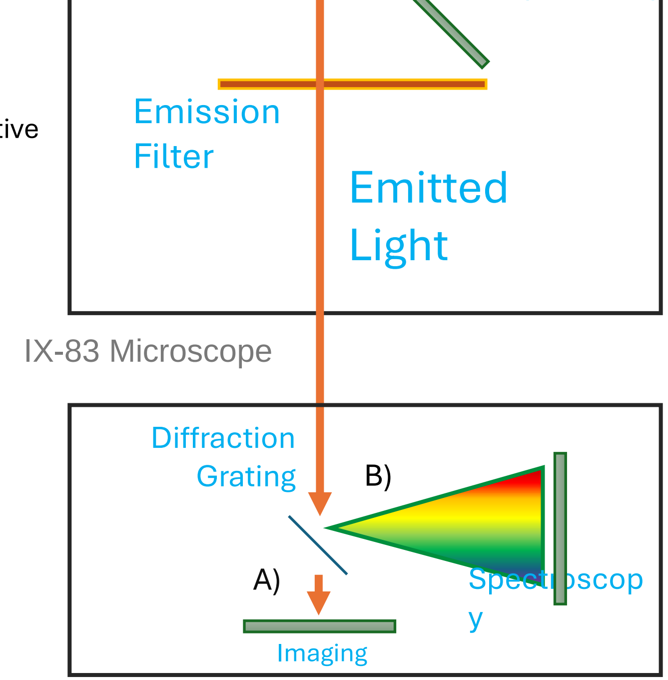
Microscope for the Injection and Emission of Light



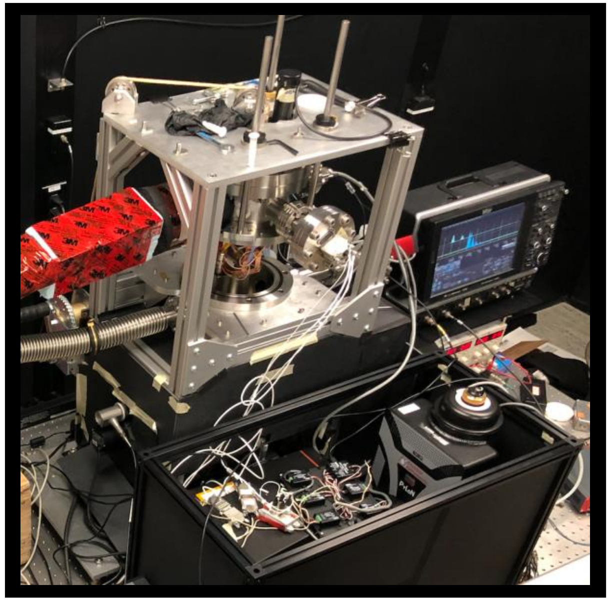




Cryogenically Cooled X-Y Stage with SiPM Mounted

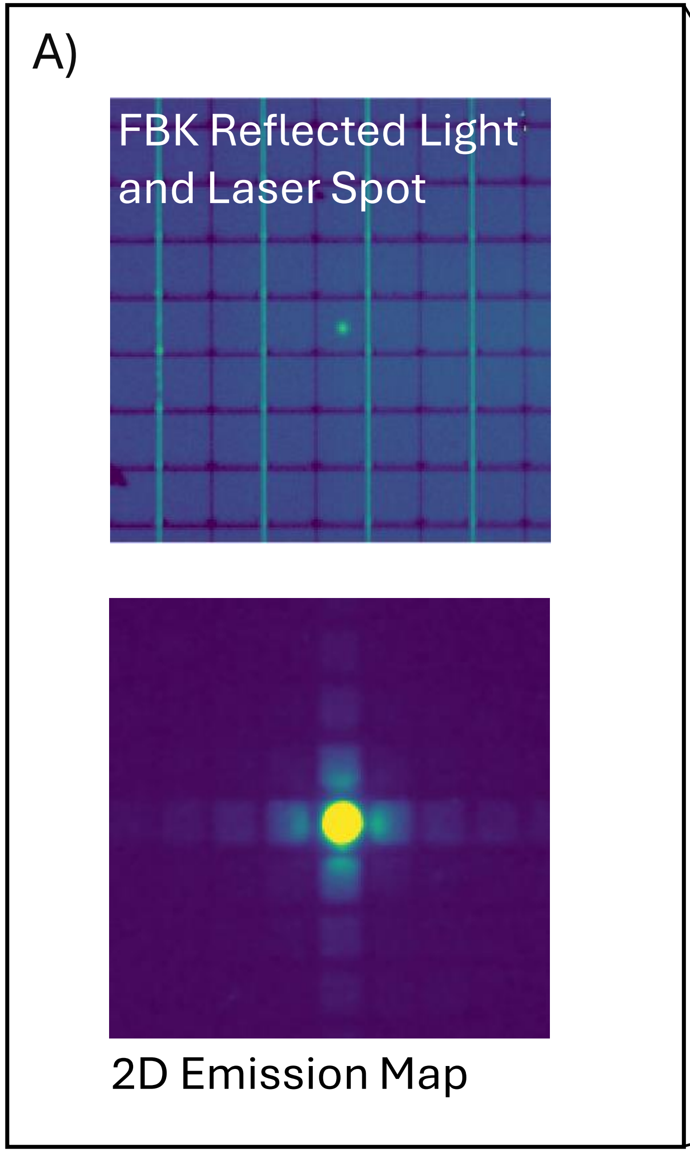
Spectrometer and Cryogenically Cooled Camera

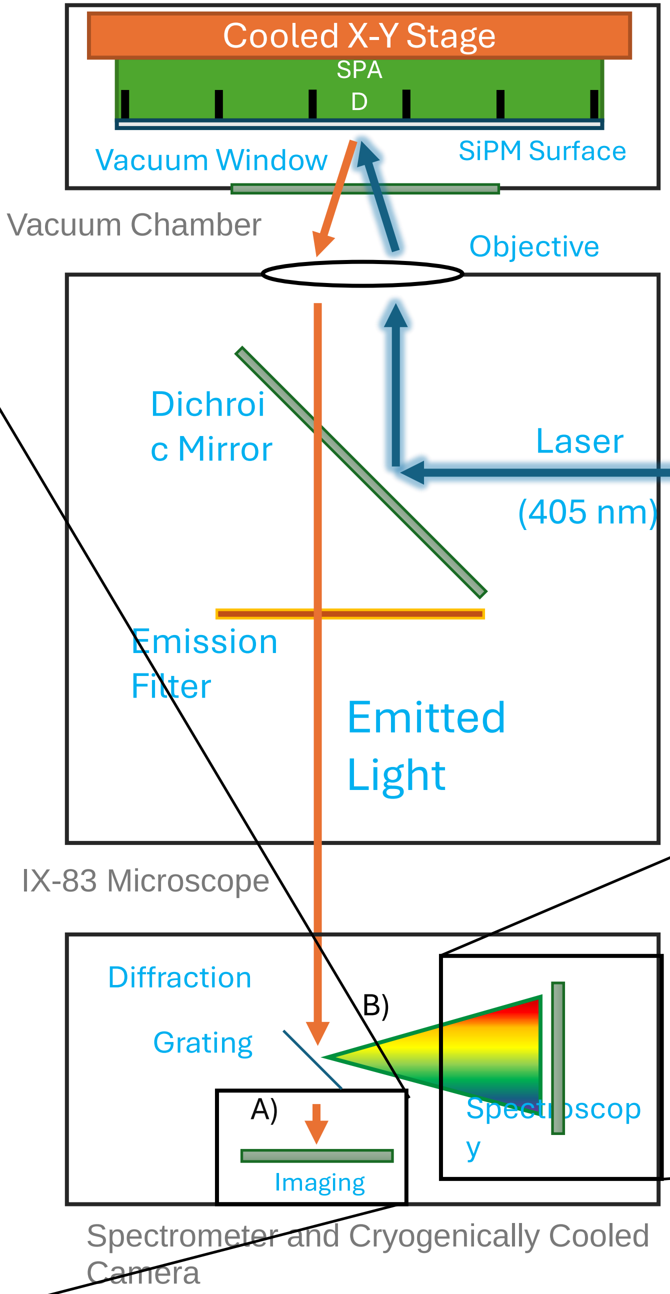


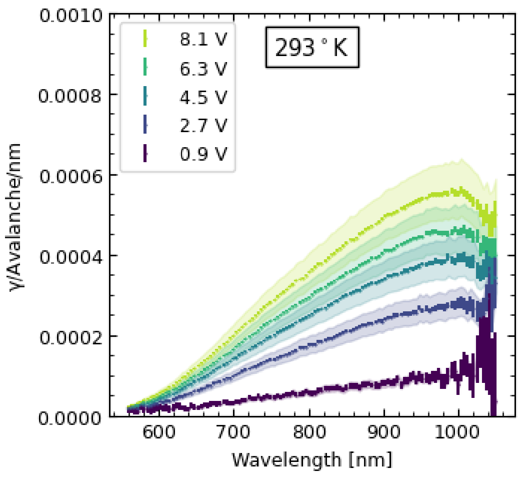
The MIEL Experiment

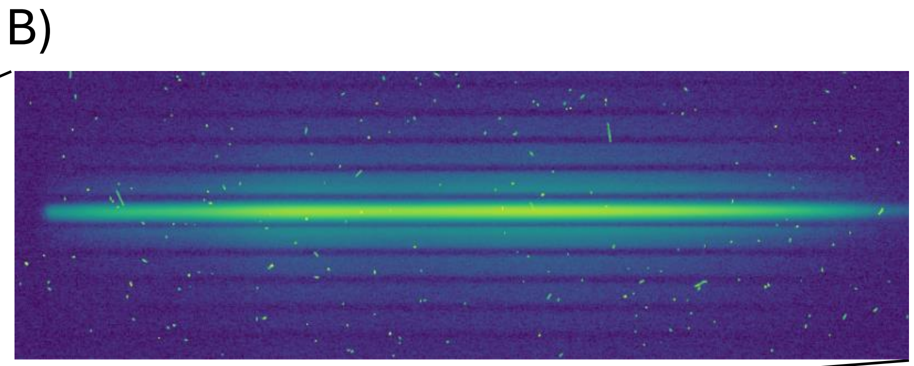
MIEL

Two basic modes









VERA

Vacuum Efficiency, Reflectivity, and Absorption

- Vacuum chamber to allow transmission of VUV light
- Deuterium light source with emission from VUV to NIR (140-830nm), wavelength controlled with vacuum monochromator
- Control of various parameters: Temperature, light source, optical angle of incidence
- Digitizer used for waveform-level measurements – allows pulse counting and determination of photon detection rates