TRIUMF

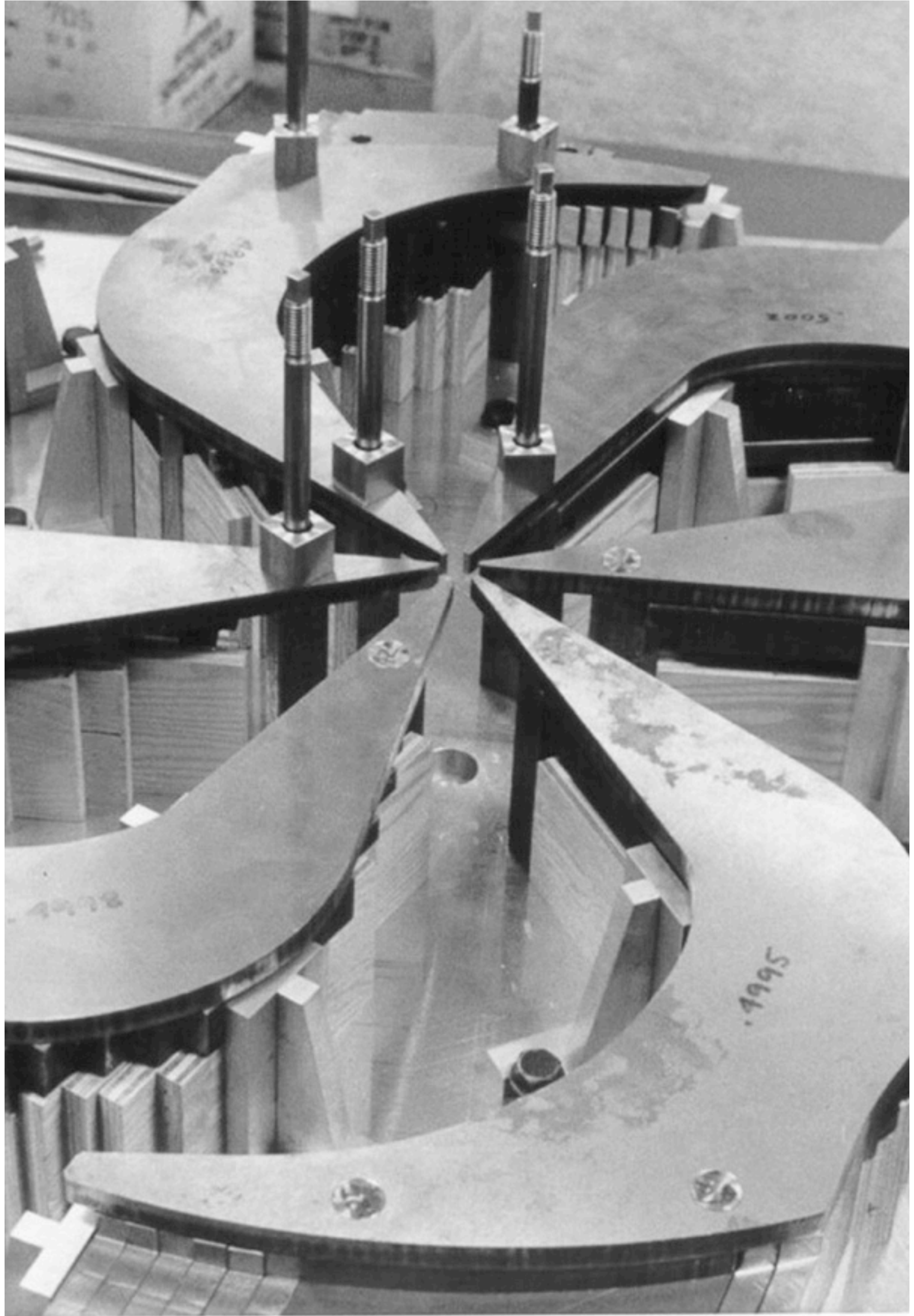
Ultrafast Stimulation of Single Photon Avalanche Diodes with Broad Spectrum Light Source

Seraphim Koulosousas (On behalf of the PHORWARD Group at TRIUMF)
Royal Holloway University of London

6th International Workshop on New Photon Detectors
21/11/2024

ROYAL HOLLOWAY UNIVERSITY OF LONDON

LEVERHULME TRUST



Discovery, accelerated

Science Motivation for Fast Timing Characterisation

- **Some of the biggest drivers for the adoption of SPADs include**
  - Fast timing ~10ps resolution
  - Single photon counting
  - High Photon Detection Efficiency (PDE)

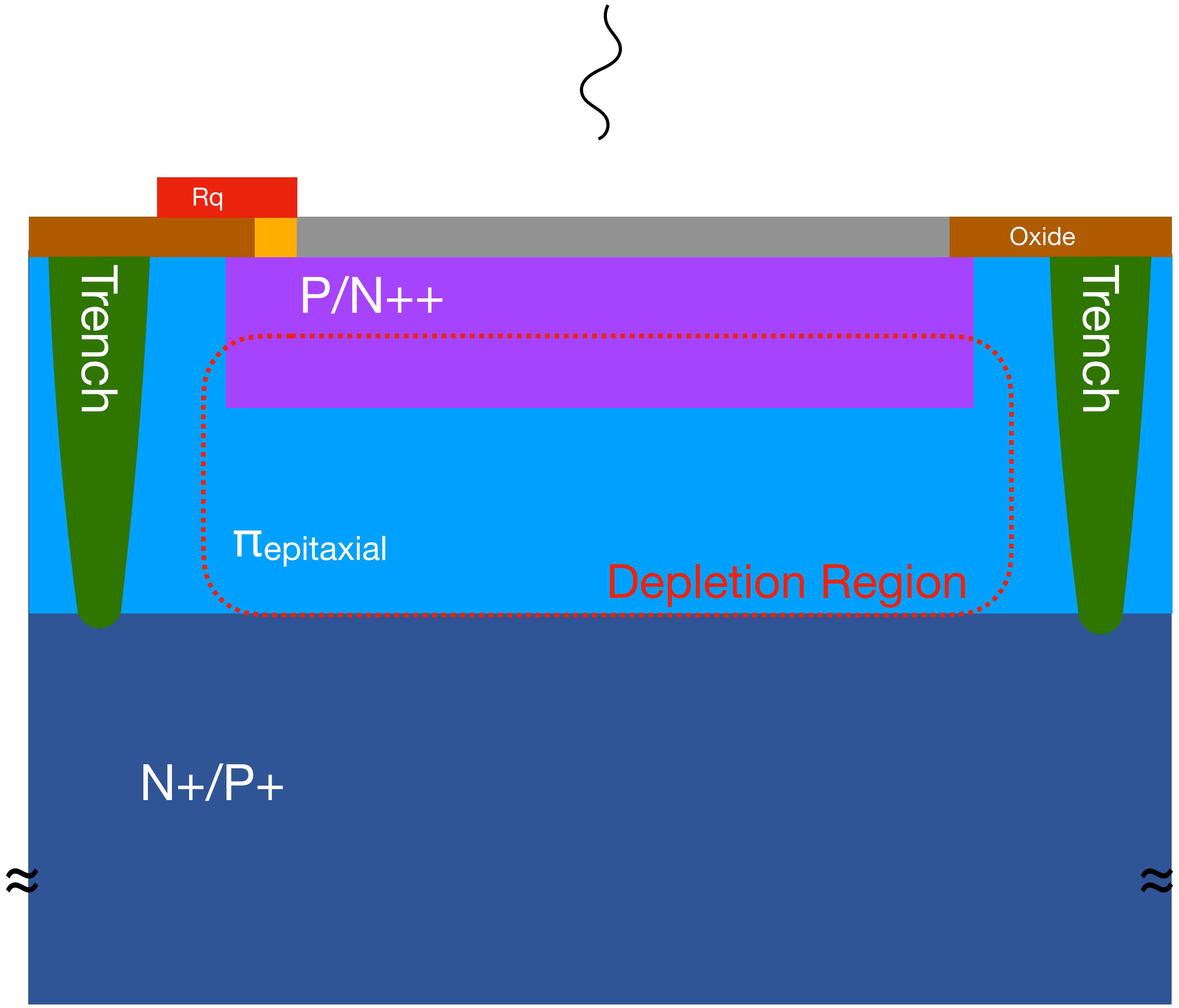
- **As the technology matures we see more and more applications aiming to utilise these devices to their full potential.**
  - This requires characterisation and diagnostic techniques that can keep up!
  - Understanding their response allows us to discover new applications.

- **At TRIUMF we have developed an experimental setup for the comprehensive characterisation of SPAD devices**
  - Temparature control (300K - 77K)
  - Optical focus
  - Imaging/Spectroscopy
  - <u>Femtosecond laser</u>
  - <u>Tunable wavelength 310 nm - 2800nm</u>
  - <u>Two-Photon Absorption (maybe)</u>

- **Help drive Research & Development and design through data driven models.**
- **Promote Collaboration.**

Understanding SPAD Response

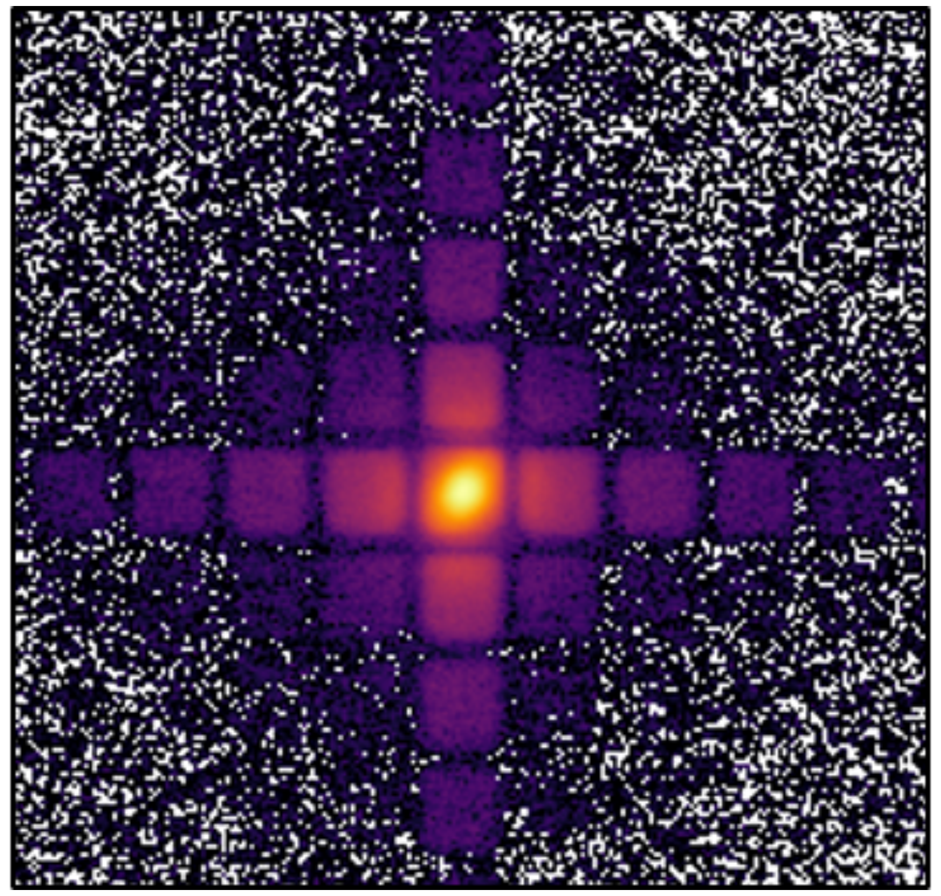
- **Timing resolution**
  - Femtosecond pulse widths allows for the photonics to be factored out of the characterisation
- **sensitivity**
  - Depth deposition depends on wavelength
- **Device noise characteristics?**
  - Optical Cross Talk
  - Trench Effectiveness
  - Secondary emission
- **Temperature Characteristics**
  - Some applications require cryogenic cooling

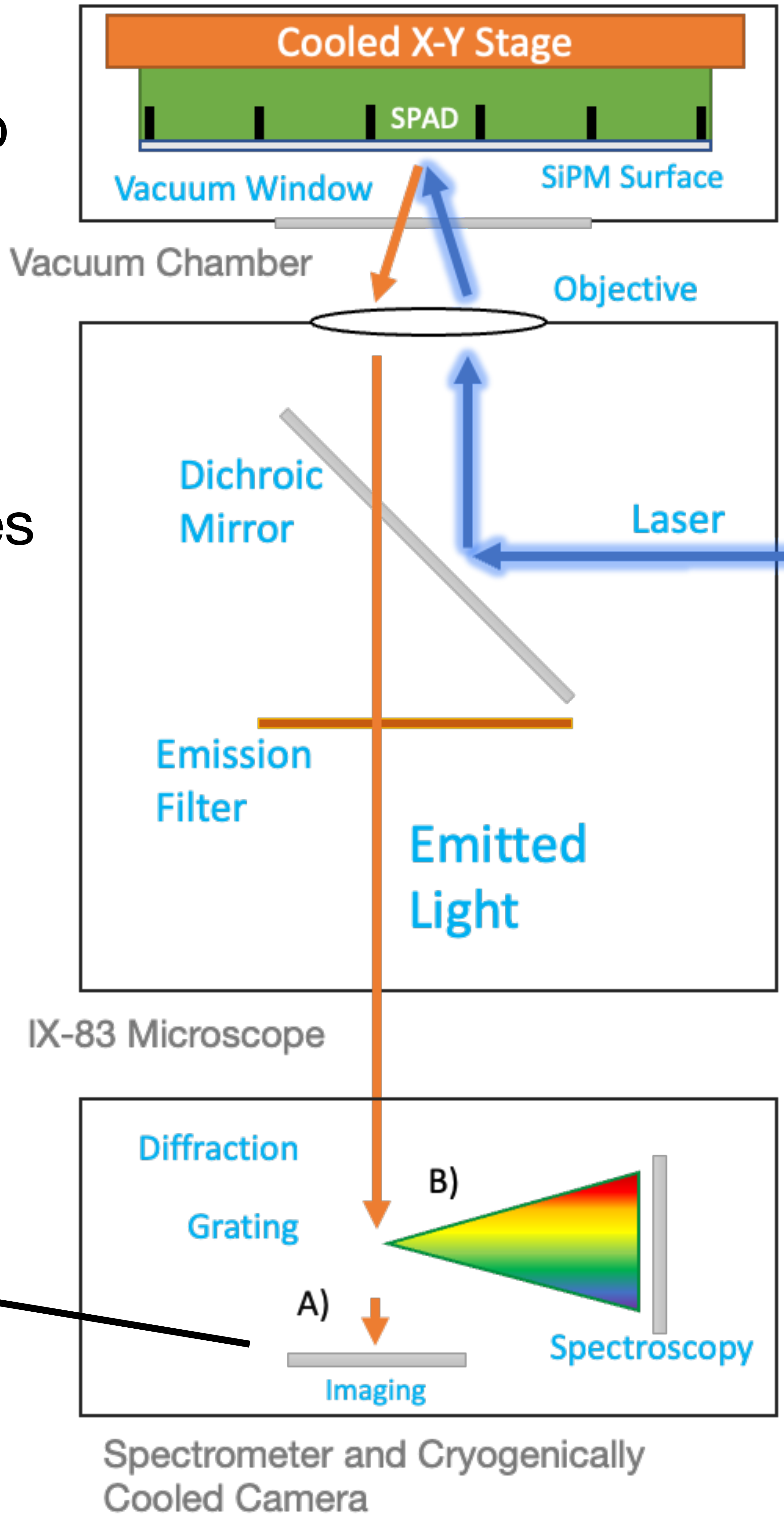


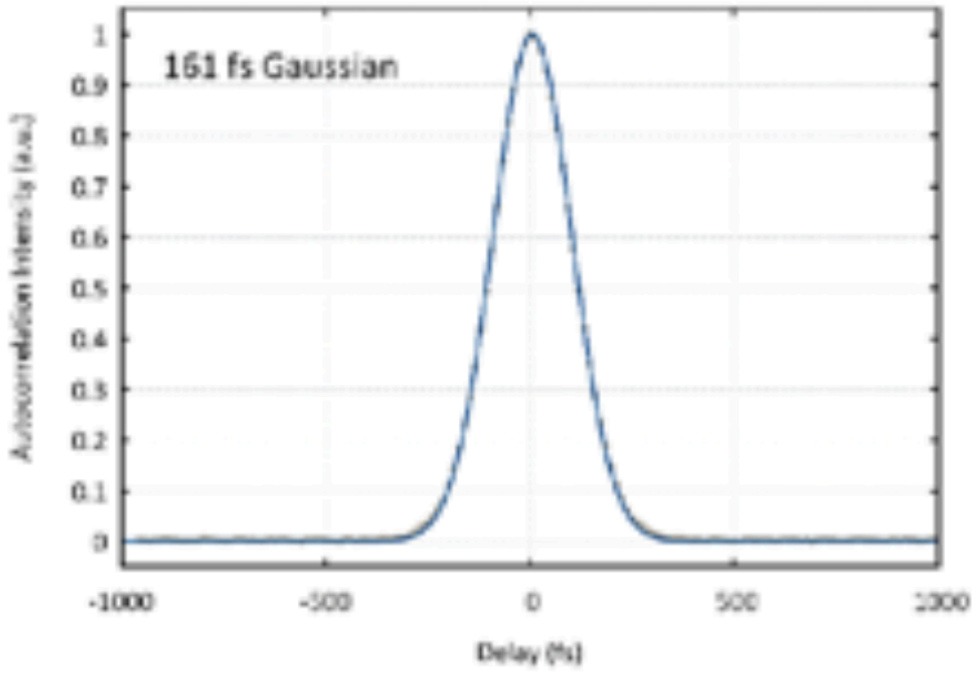
<u>With the Microscope for Injection and Emission of Light (MIEL), we can probe all these features</u>

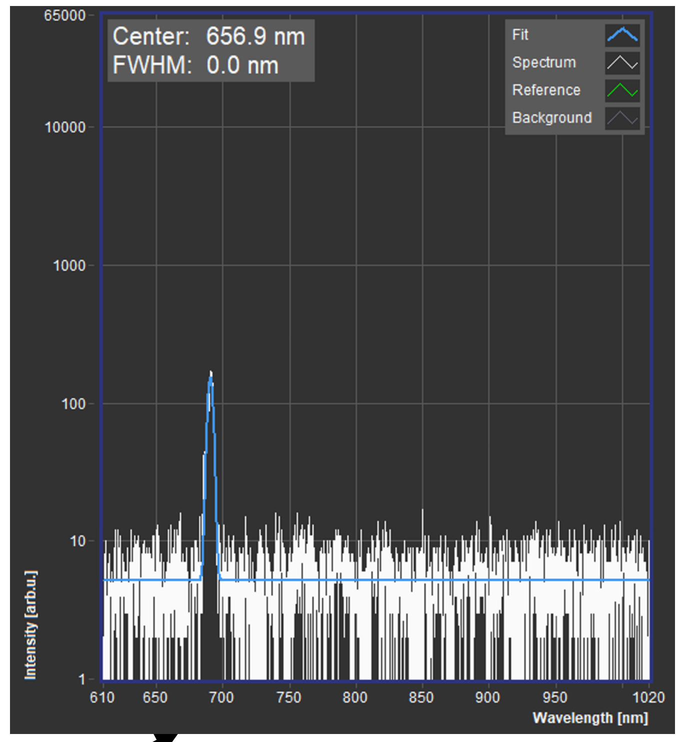
UltraFast Stimulation with MIEL + I-OPA

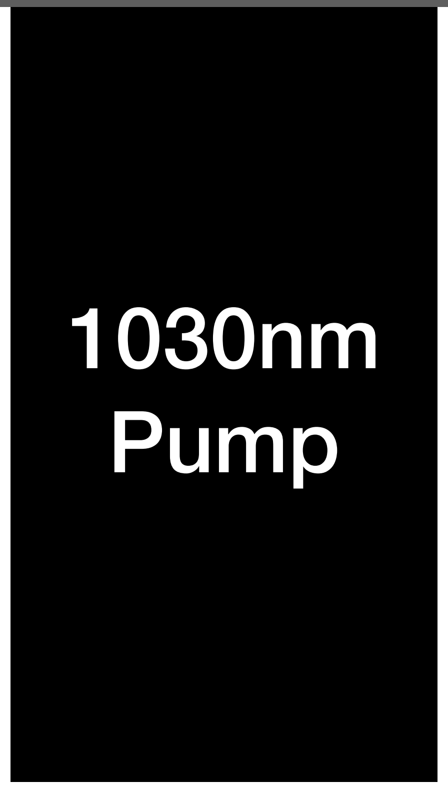
- **Temperature control**
    - PDI Controlled LN2 Pump
- **Positional Control**
    - Sub-micron prescision
- **Focus control**
    - Interchangeable objectives
- **Imaging/Sectroscopy**
    - LN2 cooled CCD
    - Princeton Instruments Spectrometer









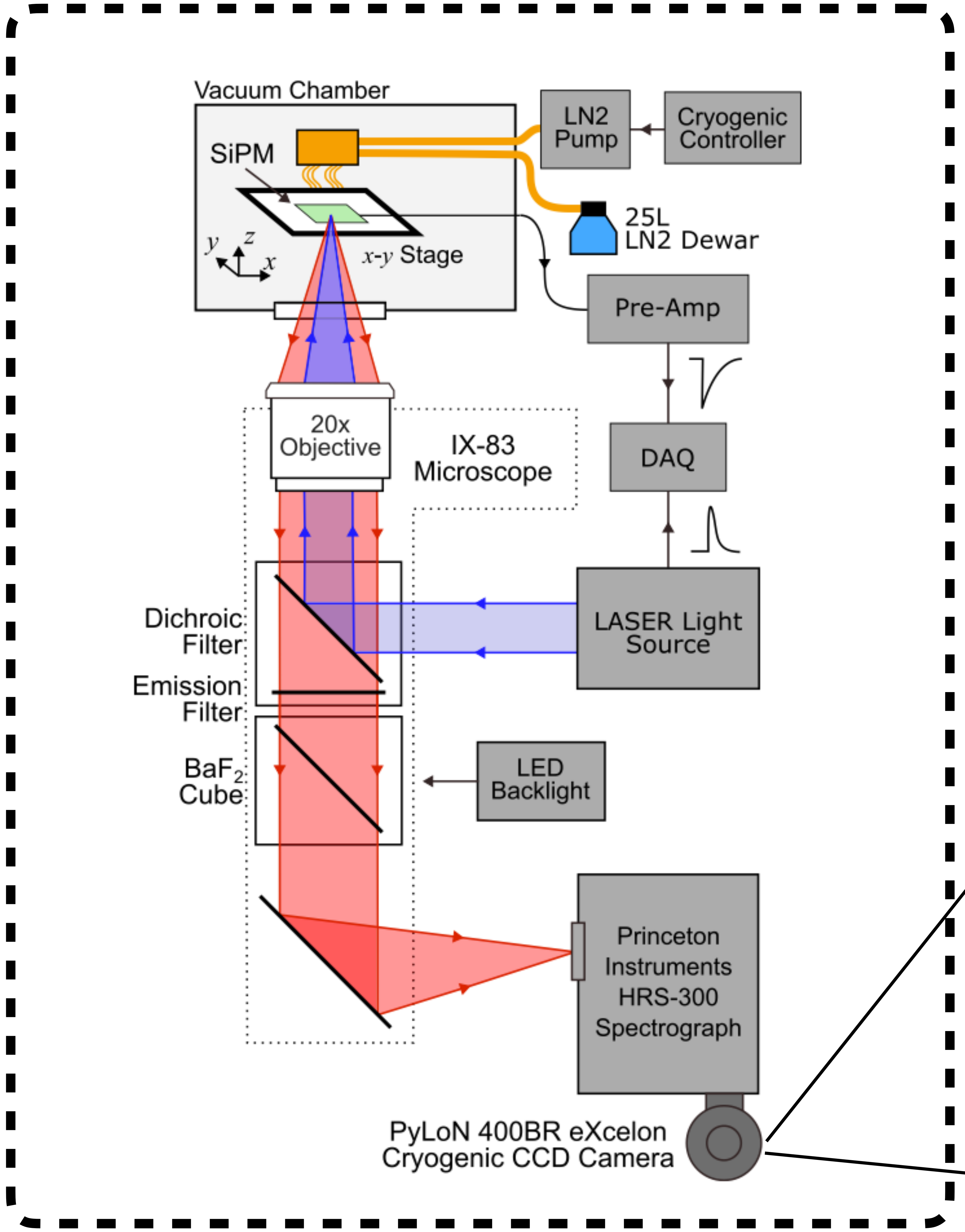


Tunable Wavelength Femtosecond Laser (I-OPA-TW)

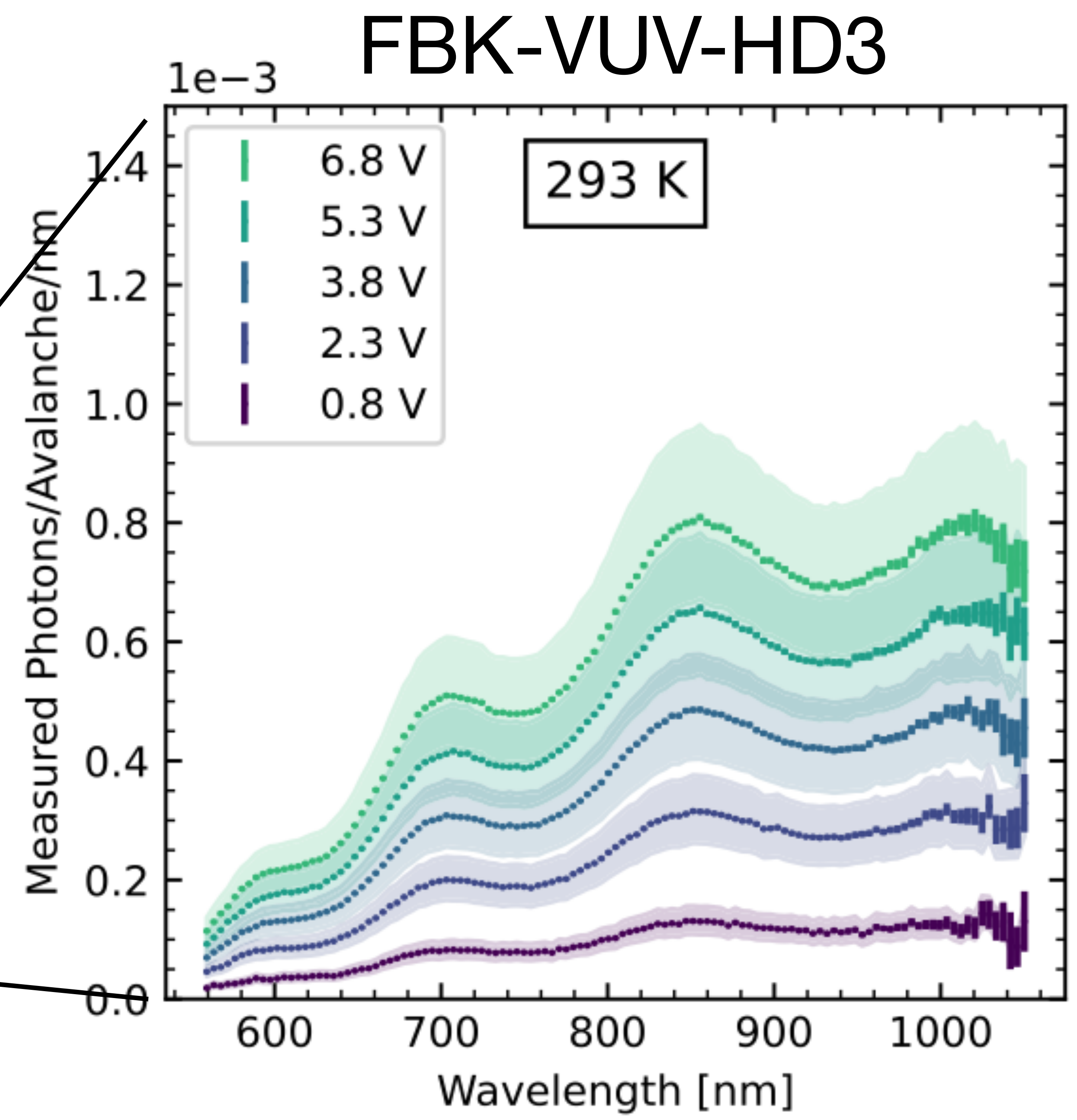
- 310nm to 2800nm
- ~O(10nm) spectral width
- ~200 fs pulse duration

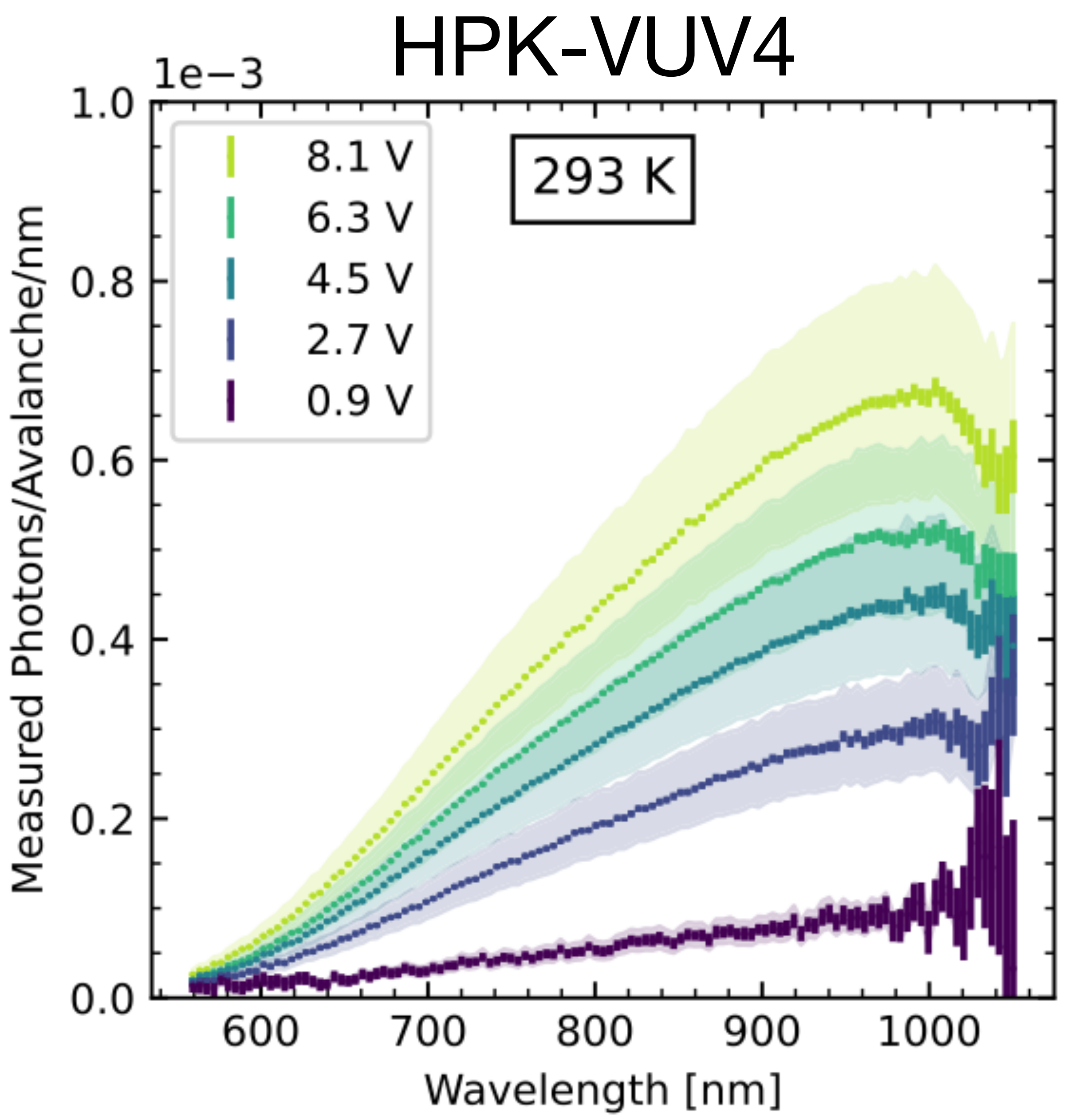
Stimulated Secondary Emission of SPADs

MIEL Detailed Outline



- During an Avalanche further photons are produced contributing to external cross talk.
- Large-area next generation physics experiments rely on SiPMs.
- MIEL was used to measure the spectra of secondary photons emitted from
  - Hamamatsu VUV4
  - Fondazione Bruno Kessler (FBK) VUV-HD3





DOI: 10.1109/TED.2024.3469918

Timing Measurements on Sherbrooke Digital SPAD

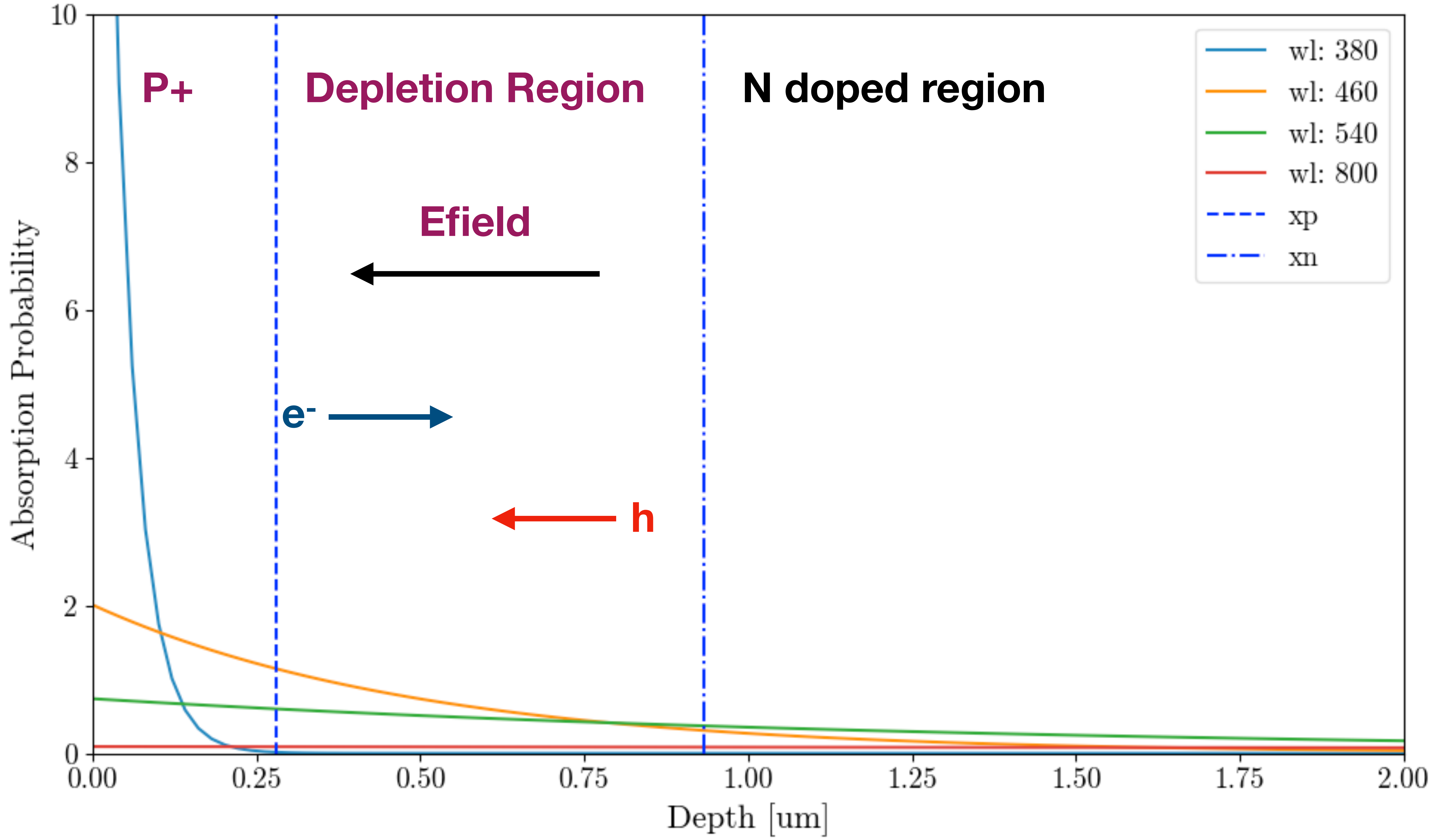
- **In Collaboration with Sherbrooke we were able to use MIEL to test one of their single Digital SPAD designs**
  - Individual SPAD with integrated CMOS readout.
  - Known structure information allows us to compare our data to model predictions of the device.
- **Timing Response modelling**
  - Can utilise simple diffusion models to probe the effect of doping on hole/electron transport in SPAD designs
  - Can leverage PDC ~10ps resolution allowing us to see transport variations depending on device structure.
- **Feasibility of Two photon absorption in SPADs**
  - Can SPADs be used for Calorimetry?

UdS
Université de Sherbrooke

Probing Charge Transport with Broad Spectrum

By using different wavelengths we can deposit charge at varying depths.

- @ < 400nm we can deposit averything above the depletion region.
- @ >500nm we can start probing carrier diffusion from the bulk
- Used MIEL to probe how this affects the timing response of the device

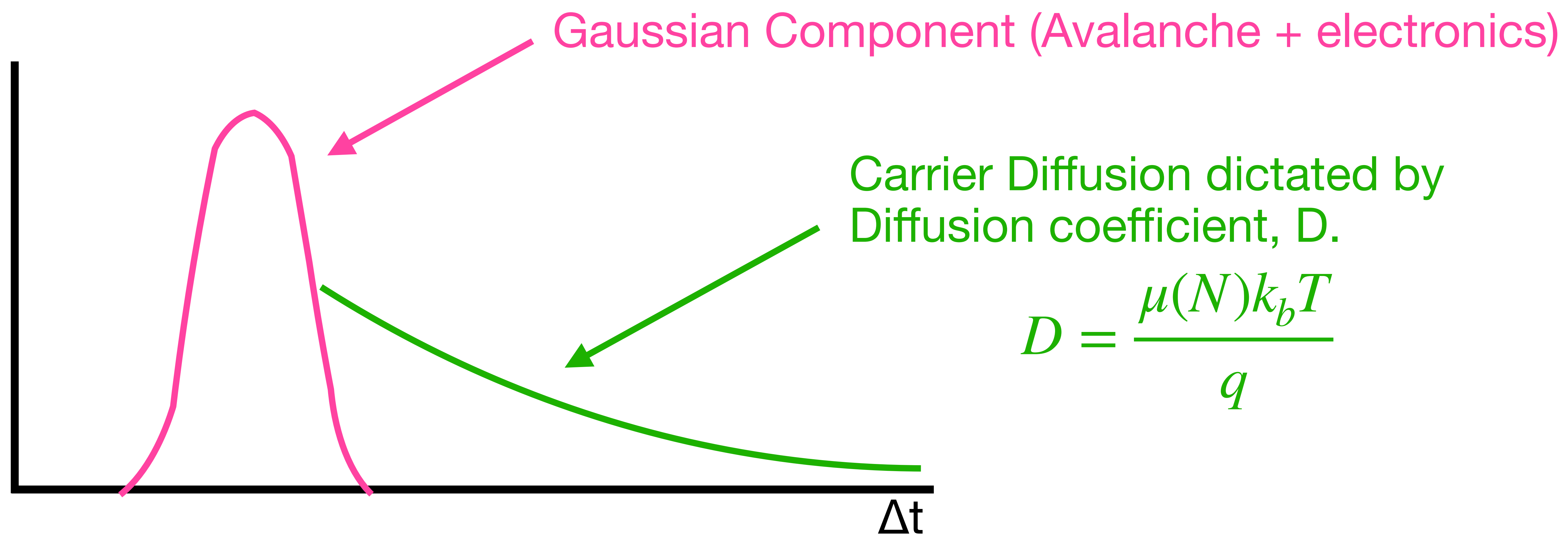


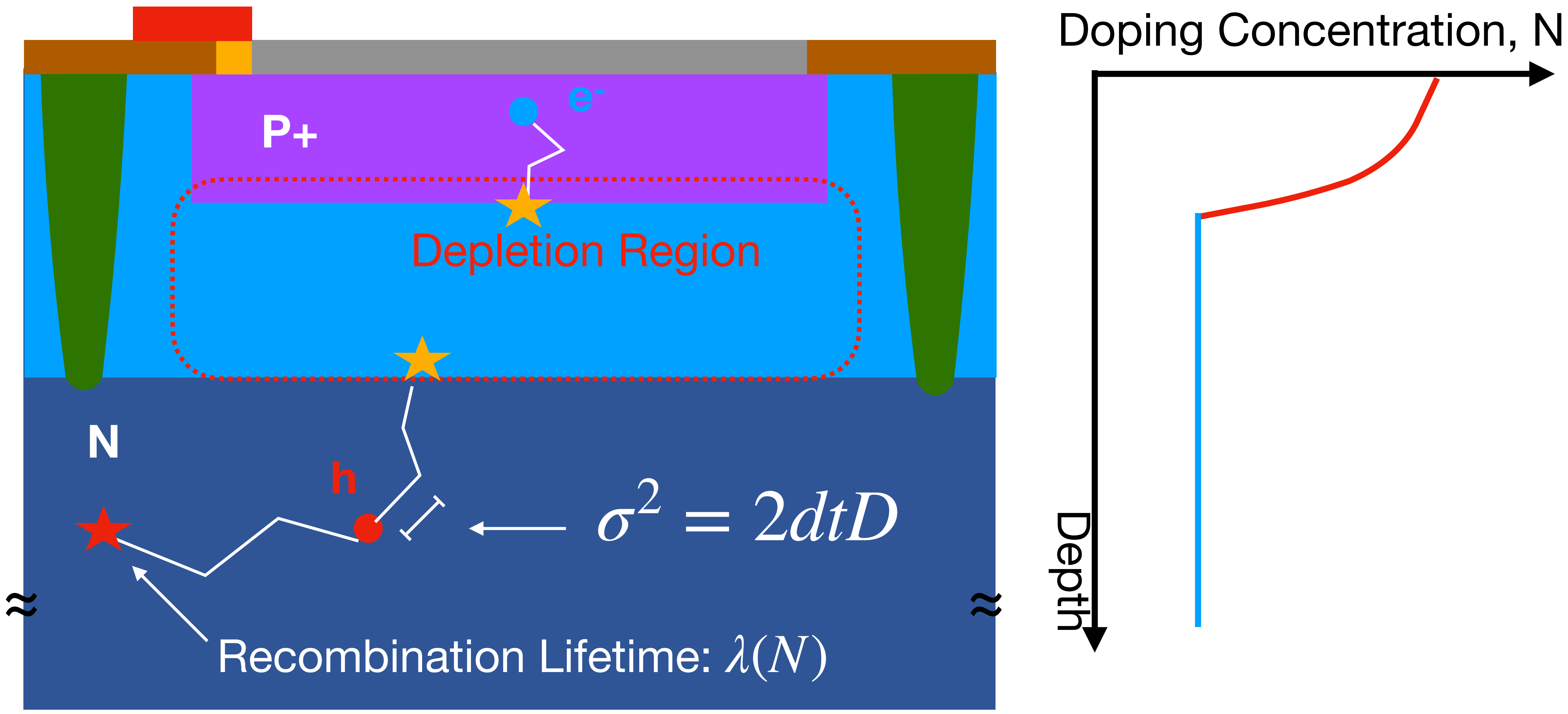
Simple Diffusion Time Response Model

Two Main Contributions

- ~Gaussian Avalanche Component
  - Dependent on Electric Field
  - Carrier Type e/h
  - Readout electronics
  - Fitted to empirical data
- Carrier Diffusion
  - Dependant on Mobility and Lifetime
  - Carrier type e/h
  - Treated as a Random walk.

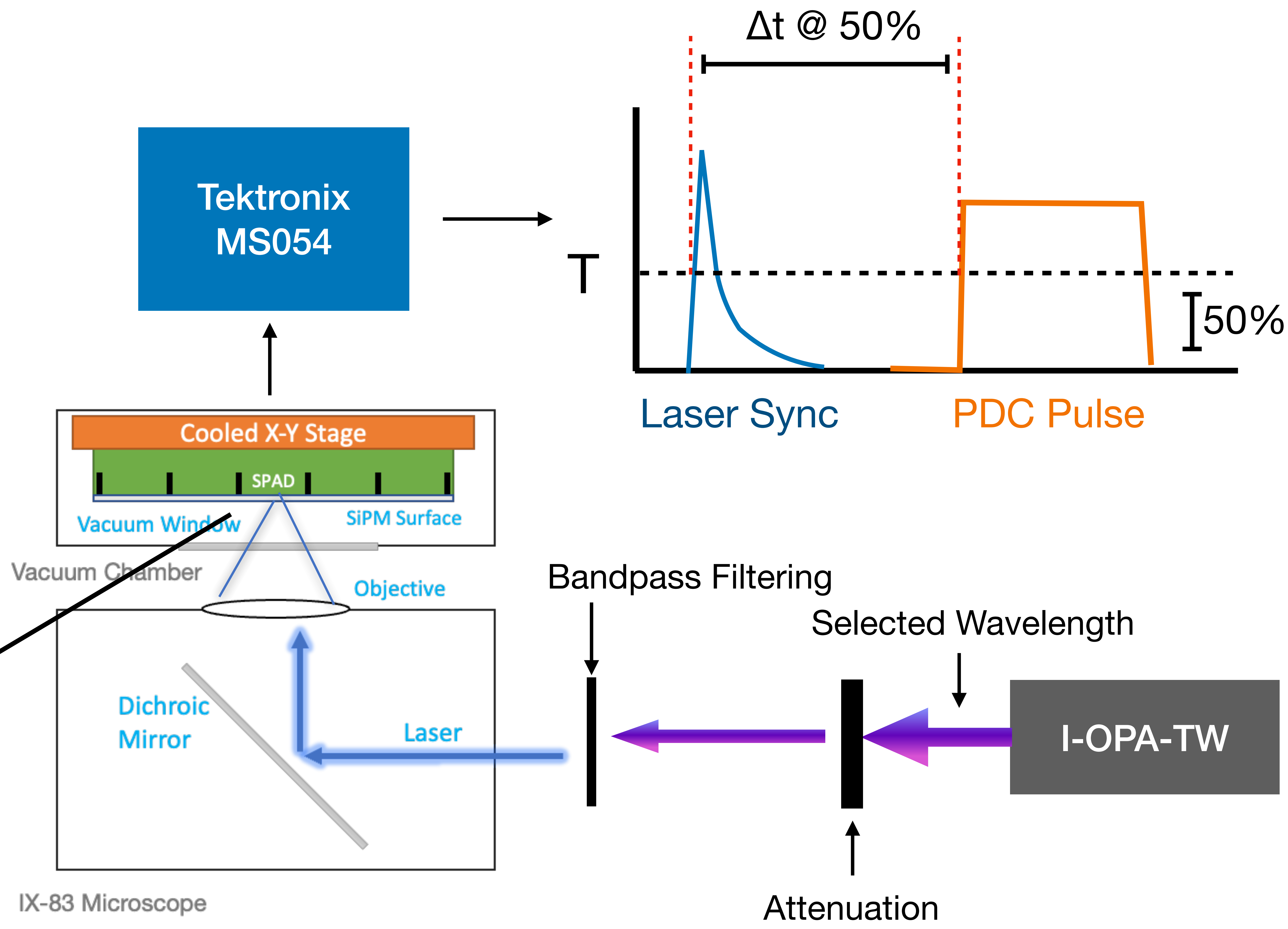
- **Can separate contributions of electrons from P+ region and holes from N region**
  - Broadening of Gaussian component associated with electron diffusion from P+ region.
  - Mobility far lower in highly doped substrate.

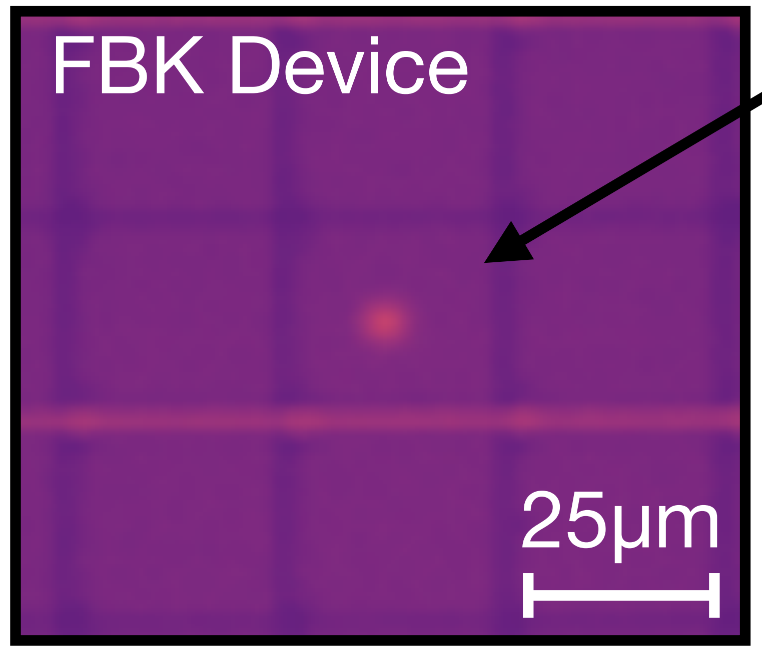




Timing Response Measurement

- Selected a range of wavelengths between (380nm - 800nm)
  - Beam is attentuated and filtered
  - Time response calculated as difference between the laser sync rising edge and PDC output rising edge.
- Data Taken with Tektronix MS054 Scope
  - Trigger set at 50% of Waveform
- The time response of each wavelength was then compared to monte carlo simulation

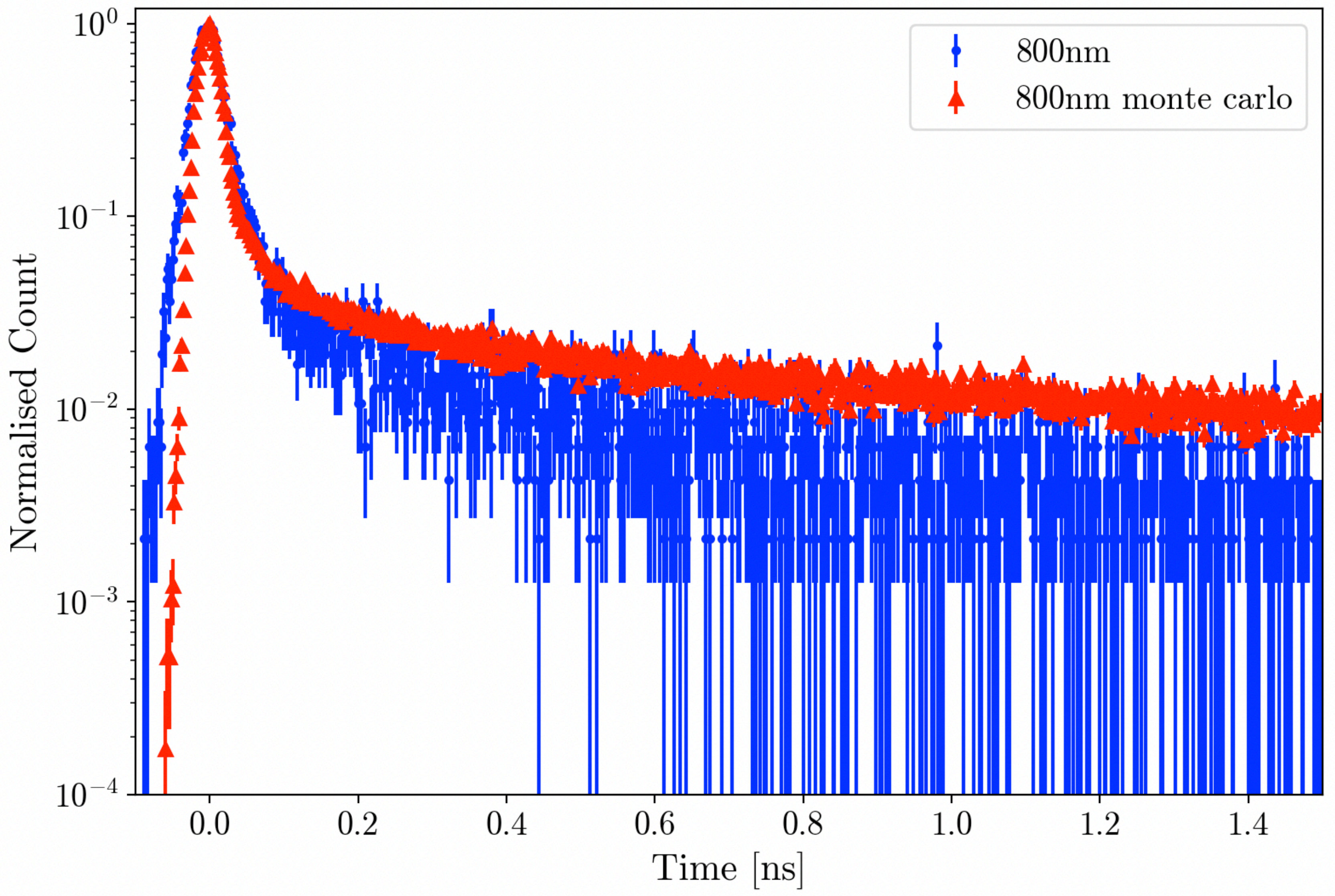


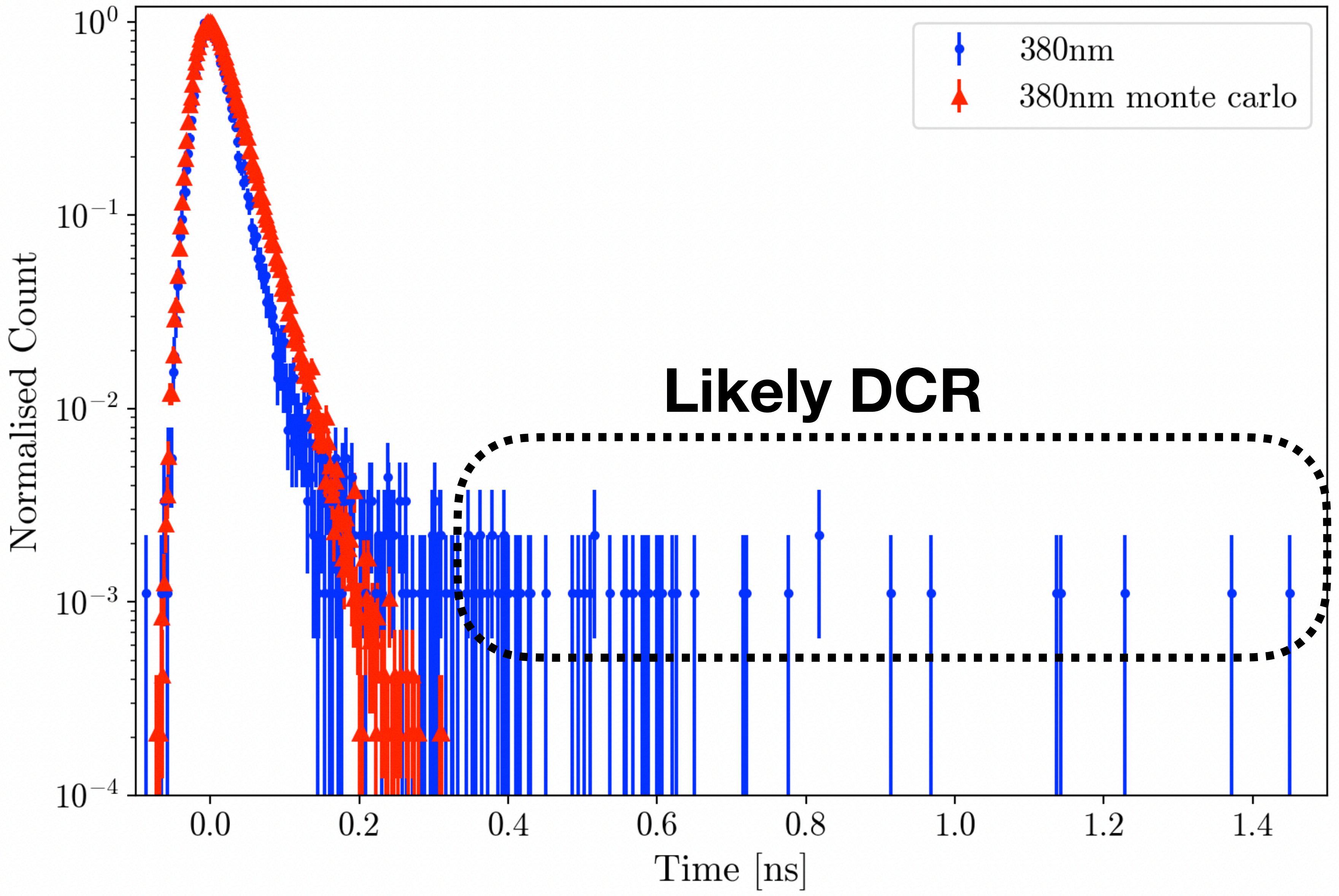


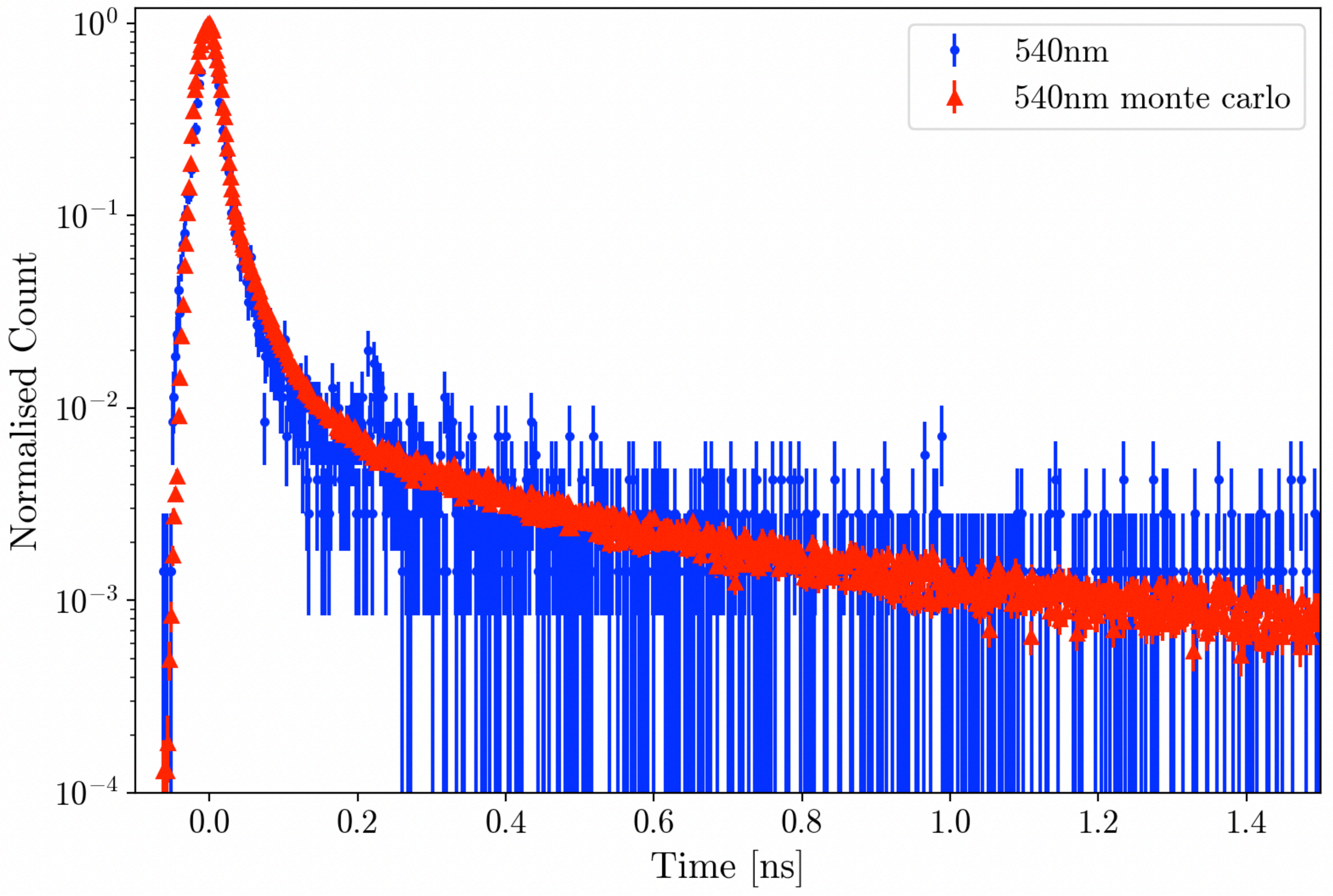
Investigating Hole Diffusion in PDC

Generally good agreement between Data and simple model.

- Tail dominated by hole diffusion
- Model starts to vary at higher wavelengths
- At 380nm almost nothing is deposited in the bulk below the depletion region.





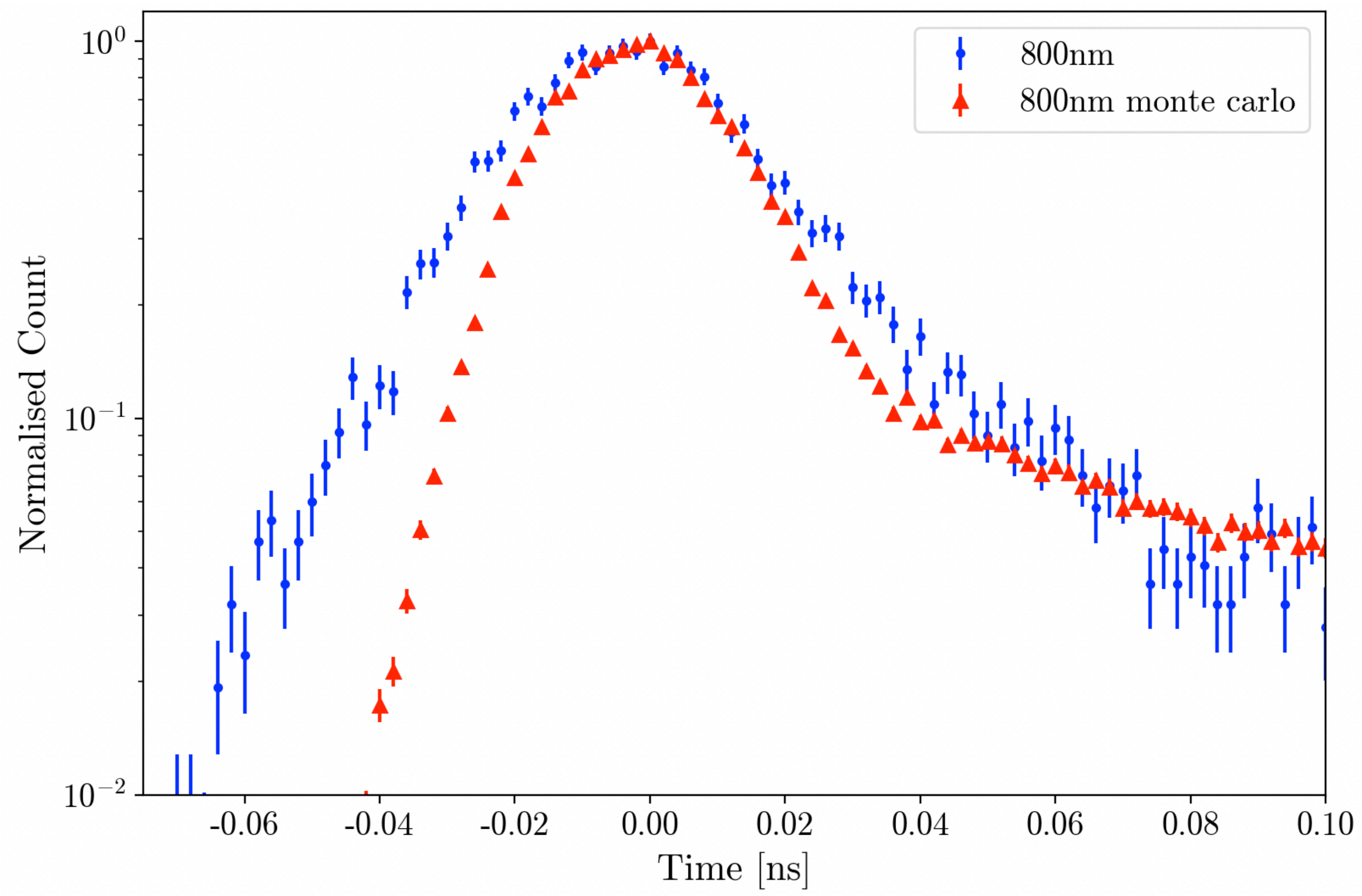


Université de Sherbrooke

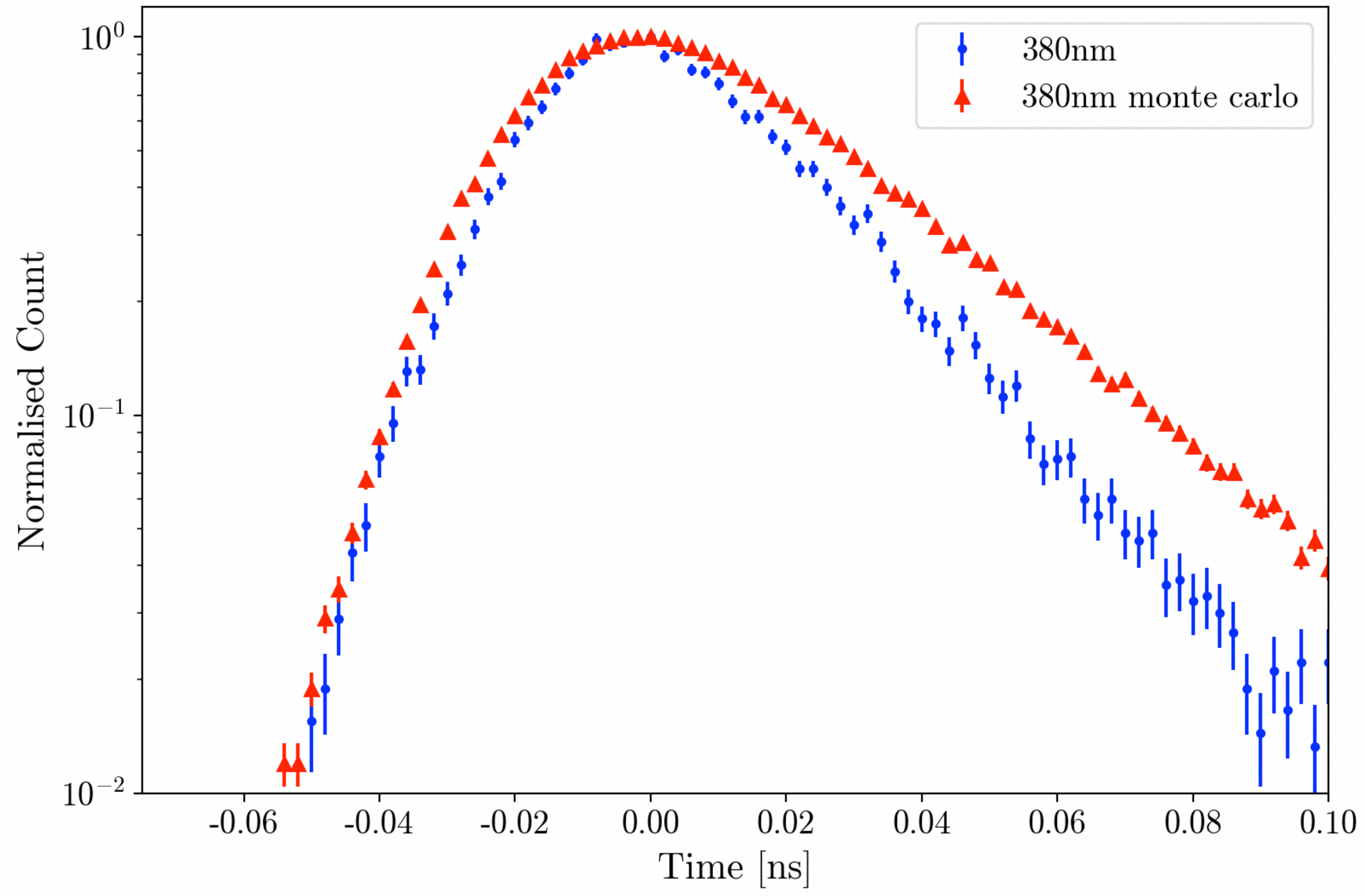
Investigating Prompt Response of PDC

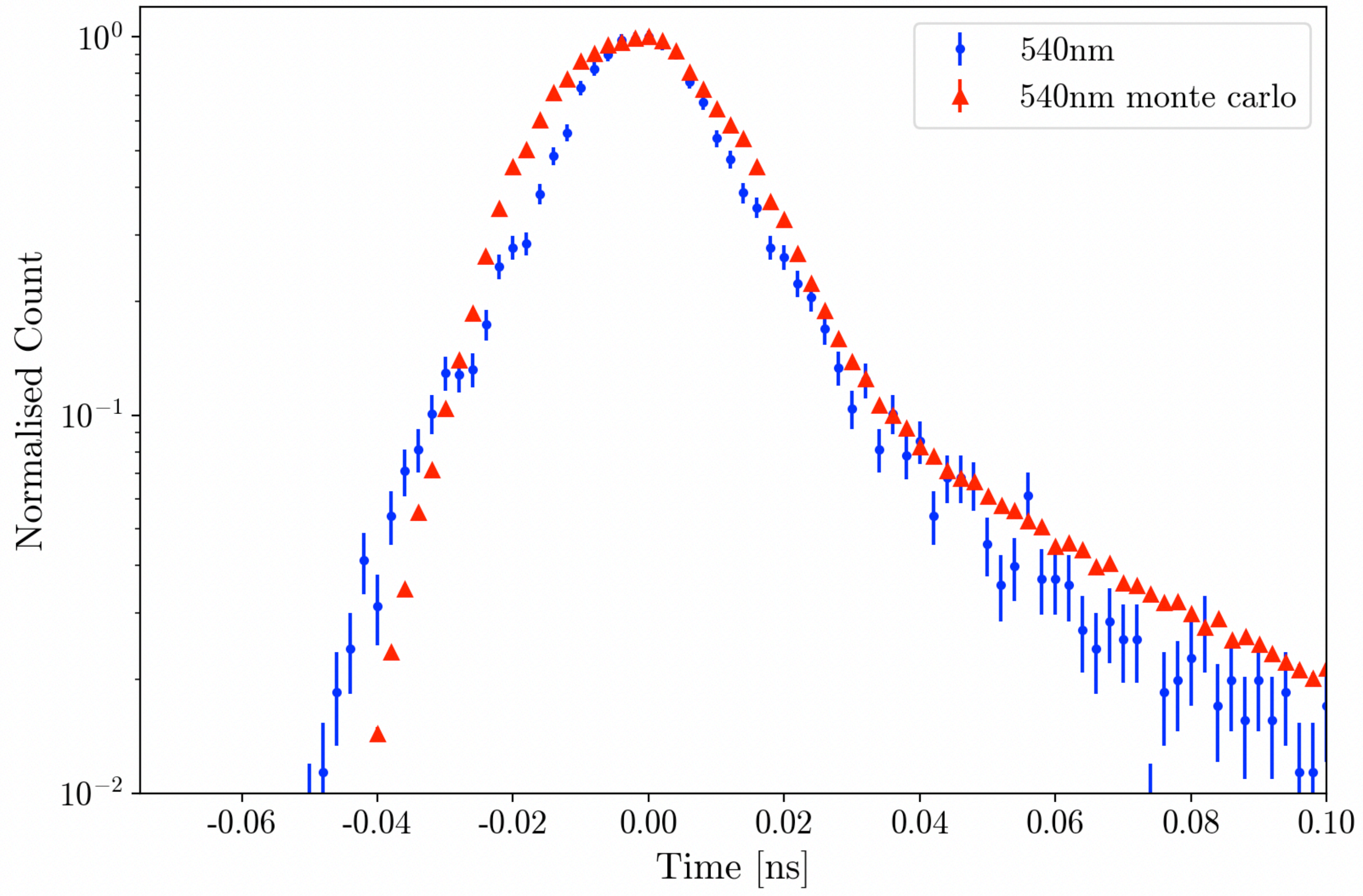
Generally good agreement between Data and simple model.

- At 380nm all carriers are deposited in the P region.
  - Model predicts a much broader gaussian at 380 due to worse electron mobility in highly P doped region.
- 540nm is generally good agreement
- 800nm: Substantial disagreement in the leading edge
  - Planning to retake this data.



Université de Sherbrooke



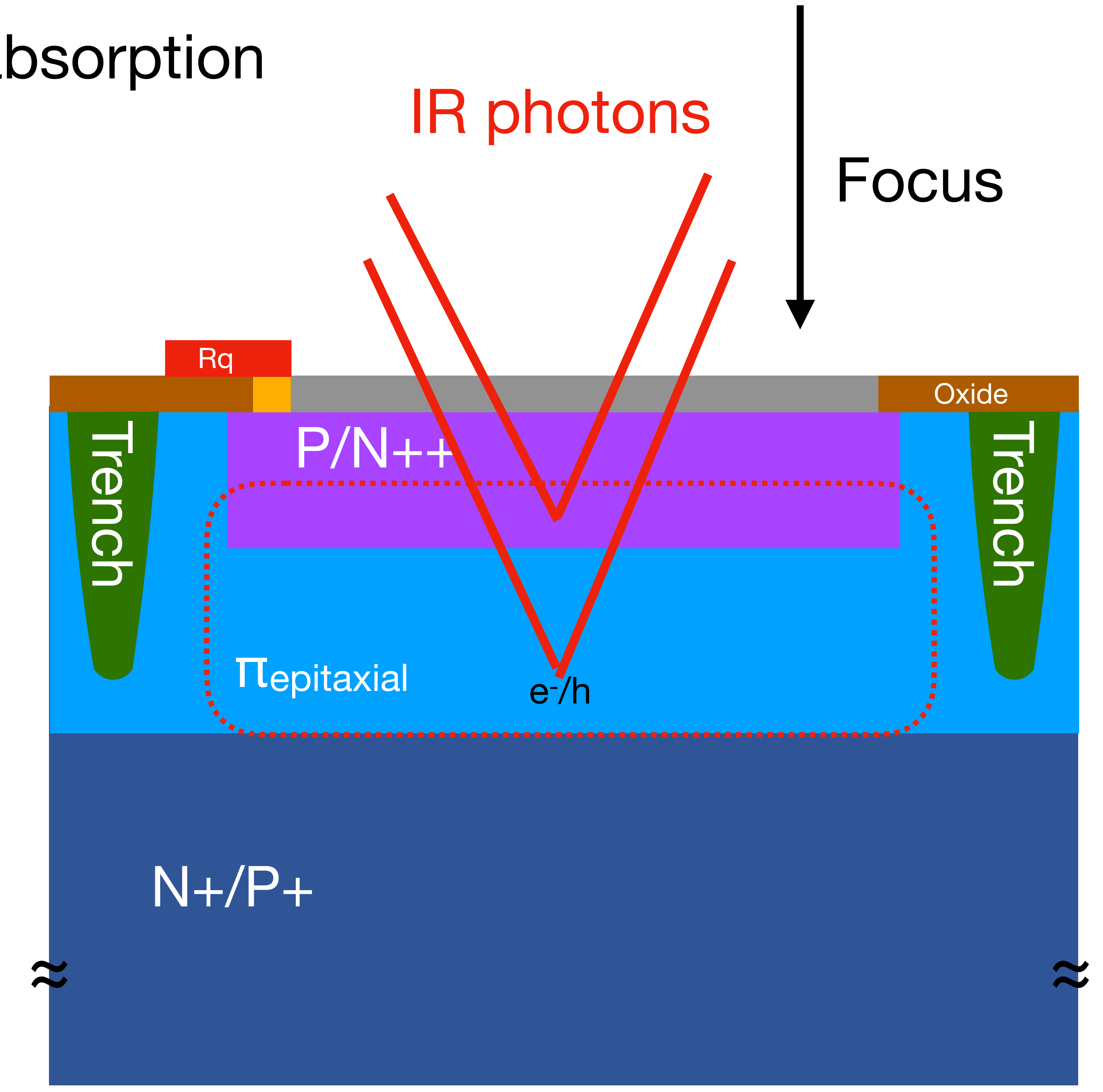


Two-Photon Absorption with SPADs

- Two Photon absorption (TPA) is the process by which the simultaneous absorption of two light quanta matches the materials bandgap energy ($E_{bandgap}$).
- The loss of Irradiance, I, with depth is modelled by :

$$\frac{dI}{dz} = \beta I^2$$

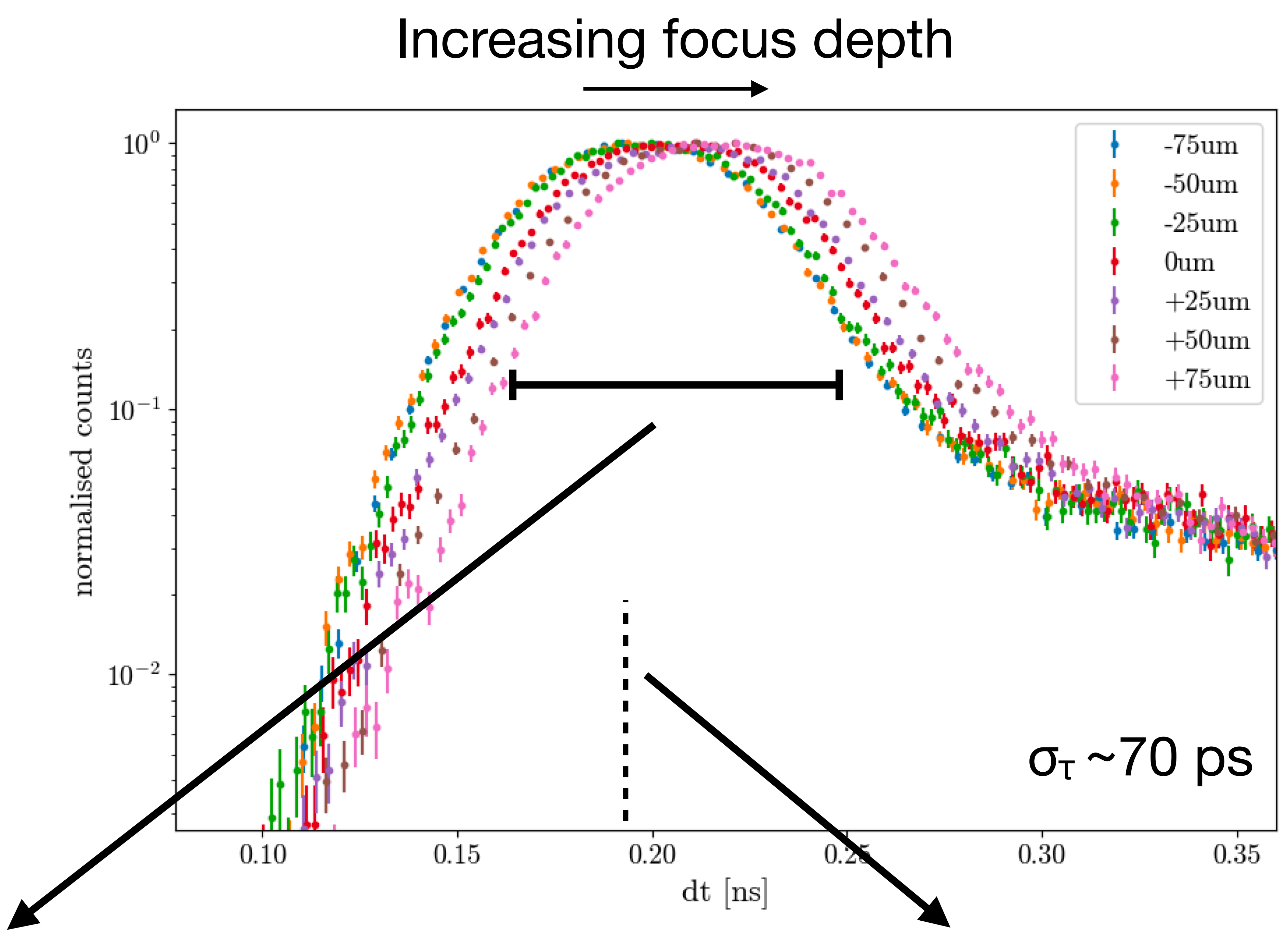
TPA Coefficient

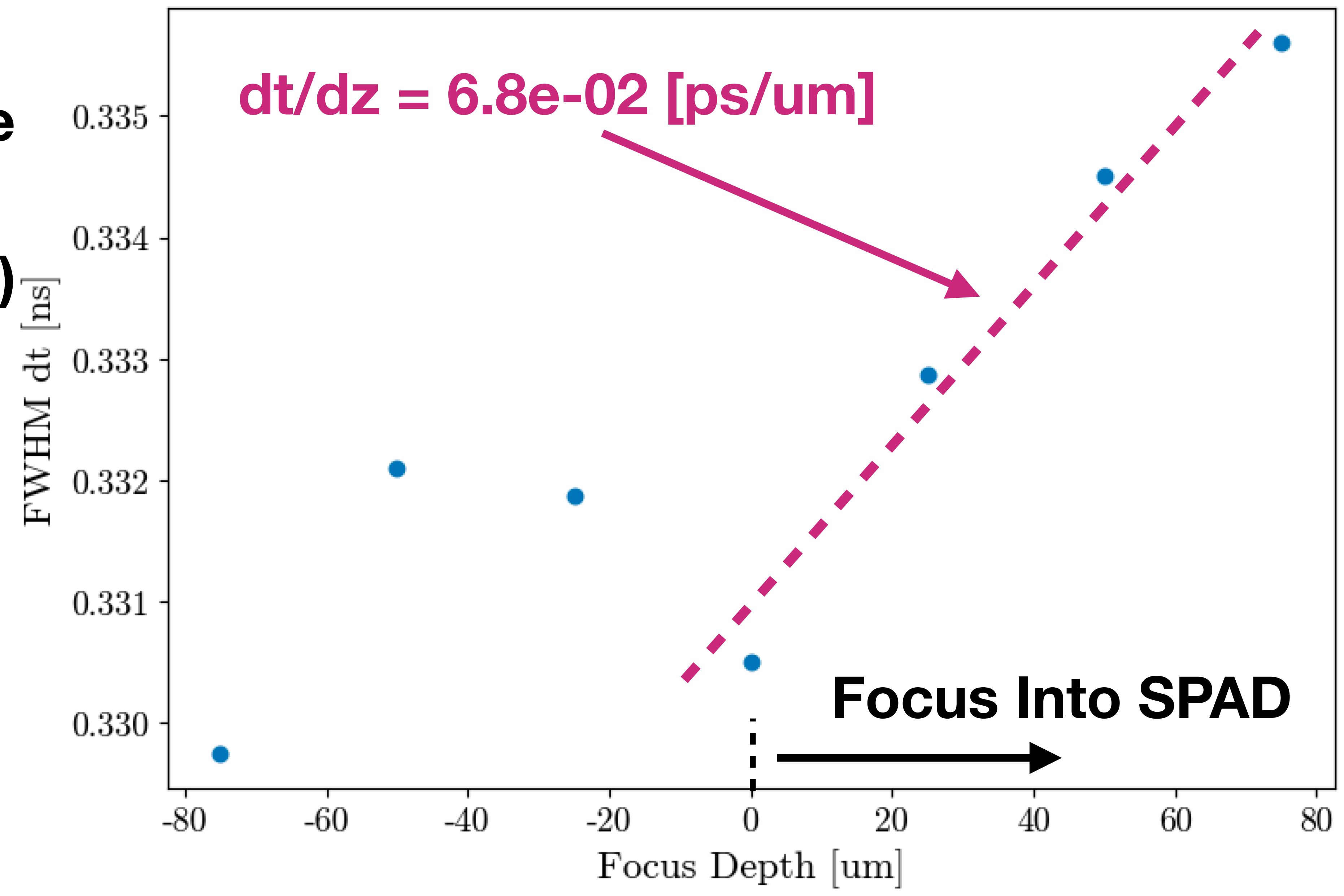


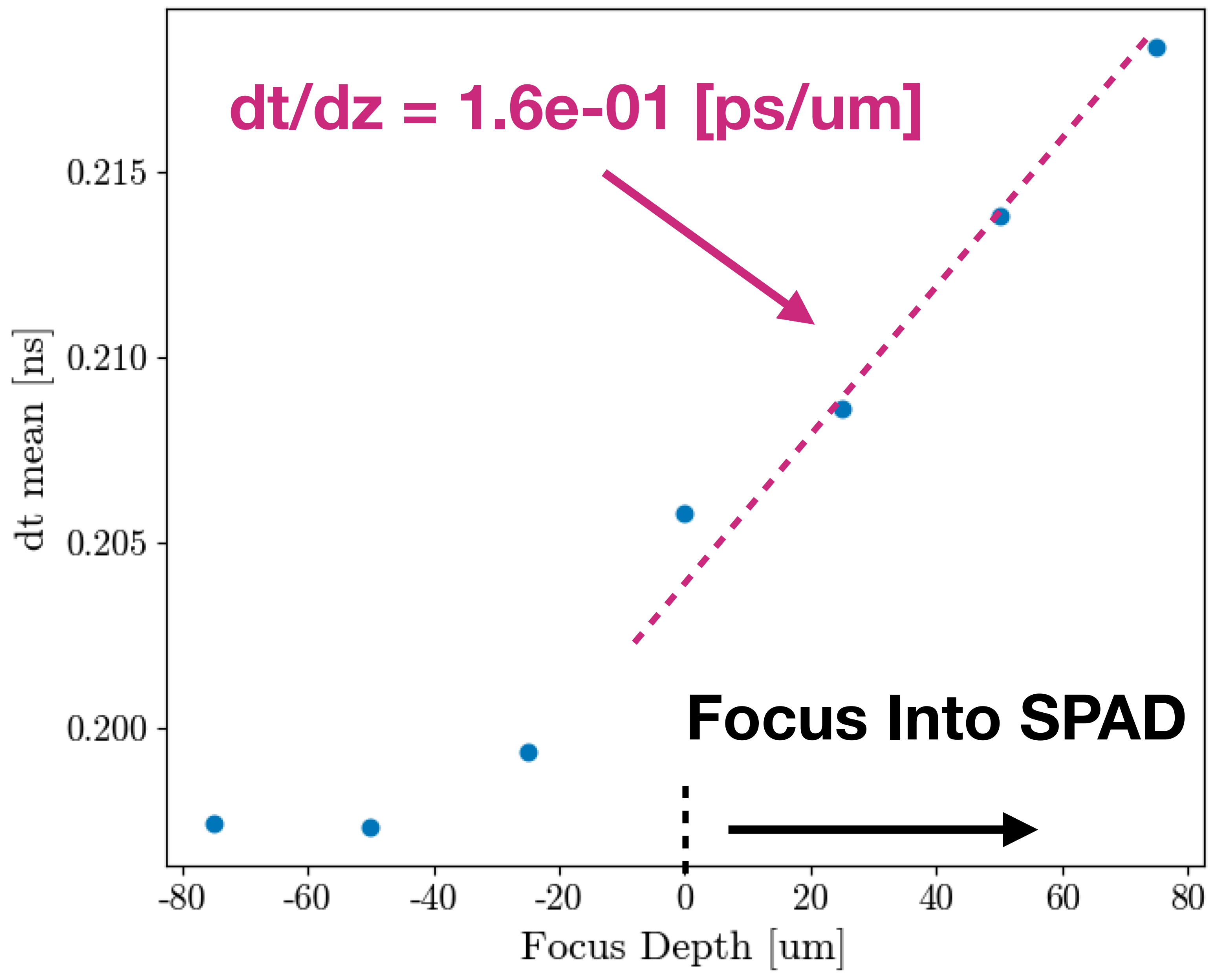
- Proven for silicon particle detectors (doi: 10.1109/TNS.2020.3044489)
- Fine control of charge deposition in SPAD devices.
- Could SPADs measure calorimetry information?

Initial Attempts at TPA

- **Initial attempts used 1550nm laser ~200fs pulses focused with a 0.48 NA Olympus IR objective.**
    - Took timing resolution data
    - Expected to see some affect to timing due to deposition depth
- **Initial results are inconclusive (data was taken 2 weeks ago)**
    - We see a linear shift in the prompt peak mean as we focus into the device.
    - We also see a shift in FWHM likely due to longer diffusion time from bulk
- **Diffcult to discriminate whether we are seeing 1PA or 2PA.**
- **Still in the early stages (work on going)**

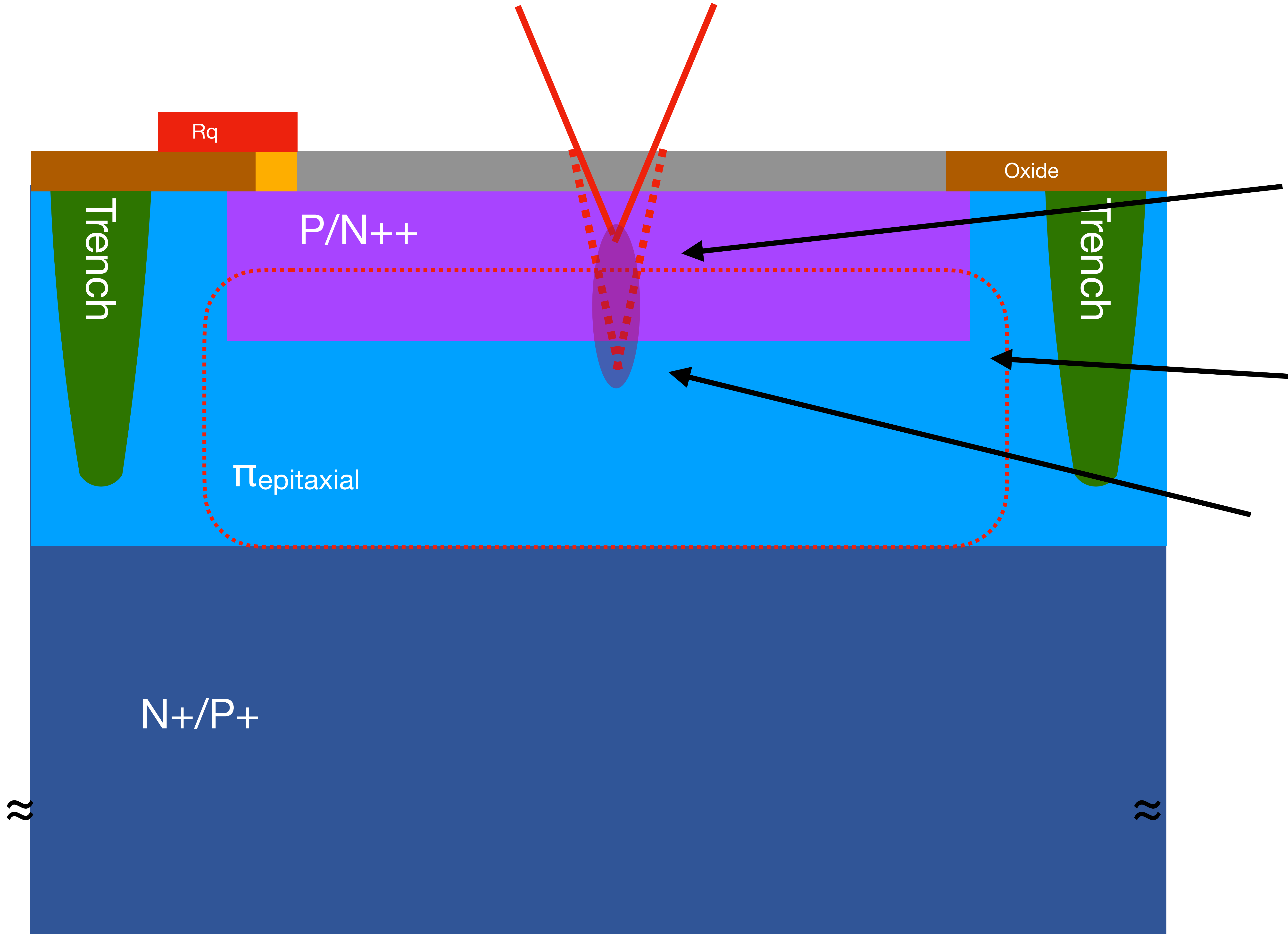






See a linear trend with focus

Difficulties with TPA in SPAD's



Optical Limitations

- Due to index of refraction focus point is altered substantially
    - Can be combatted with higher NA objectives
    - Kerr effect could play a role, change of refractive index due to applied electric field.
- SPAD Junction ~O(um). Optical effects such as Rayleigh length make it difficult to focus beam to <um resoluton
- Likely still dominated by single photon events.
- **Work in progress.**

Conclusions

- **At TRIUMF we have developed a test setup that allows us to broadly characterise SPAD Devices**
    - Femtosecond pulsed broad spectrum laser allows us to probe charge transport in these devices
    - Understanding effects at the picosecond level will aid in the design and development of future devices
        - Will aid in the development of new applications and the refinement of current ones.
- **Attempts at TPA in Digital SPAD shows ome interesting effects in the timing distribution with varying focus.**
    - **Though still inconclusive there are some interesting things to keep us busy.**