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Characterization of SiPM Avalanche triggering probabilities

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Discovery, accelerated

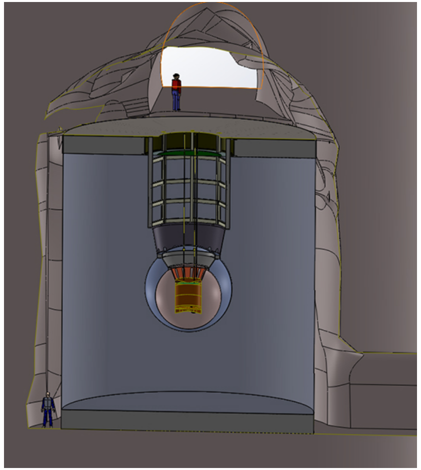
Outline

- Introduction / Motivation.
- Avalanche Triggering Probability Modelling
- Dark Noise Modelling
- Conclusions

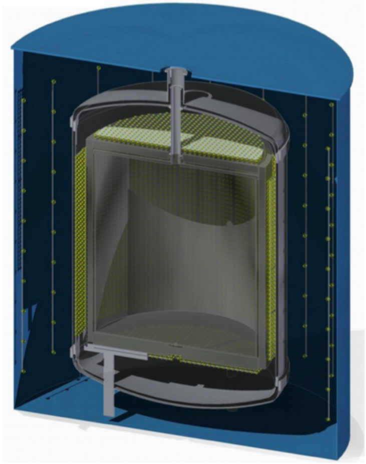
Introduction / Motivation

Precision-Physics Applications

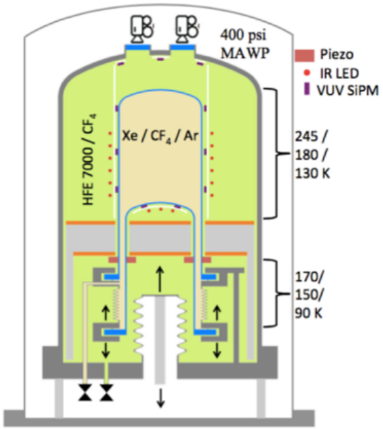
Our work is primarily targeted towards low-background liquid noble experiments (Dark Matter & Neutrino) but other experiments can be considered in the future



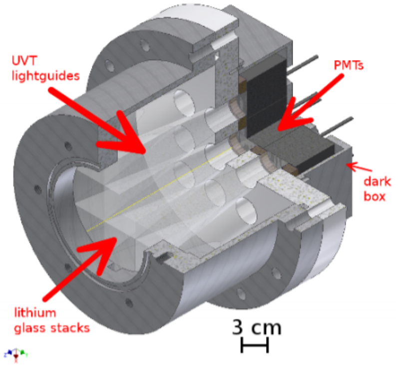
nEXO Experiment



300T Single-Phase LAr



LAr Bubble Chamber



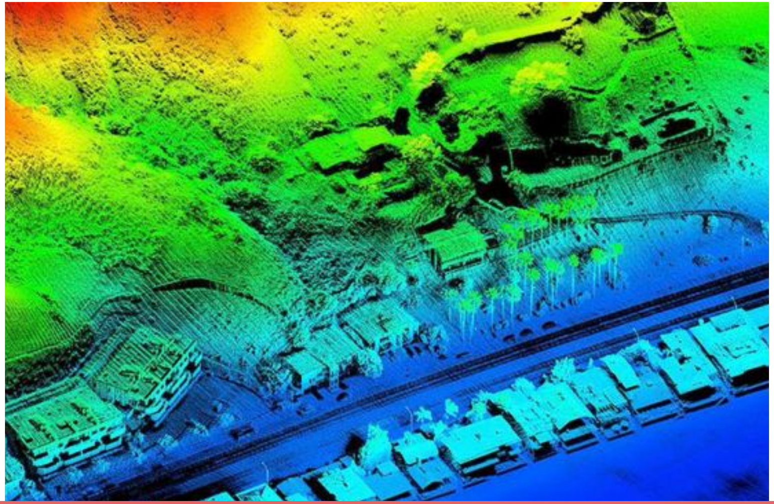
Ultra-Cold Neutrons

TRIUMF Commercial Applications

<u>LXe PET Scanner (Medical Imaging)</u>

Challenge: Pulse Timing < 15 [ps]

<u>LiDAR Sensors with SiPM (3D Imaging)</u>



Challenge: Good PDE (>30%) from 200-800 [nm]

<u>Early-Fire Gas Analyzer:</u> Use both Visible and UV light for particlets studies in area where fires are a considerable yearly problem (west-coast US, Canada).

<u>Goal of this talk :</u> Infer design parameters for future photodetector developments !

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Avalanche triggering probability modelling

Photo-Detection-Efficiency

The Photo-Detection-Efficiency (PDE) is defined as the probability for a photon (of a given wavelength) to be detected and produce a measurable signal in the SiPM.

Usually PDE is defined as

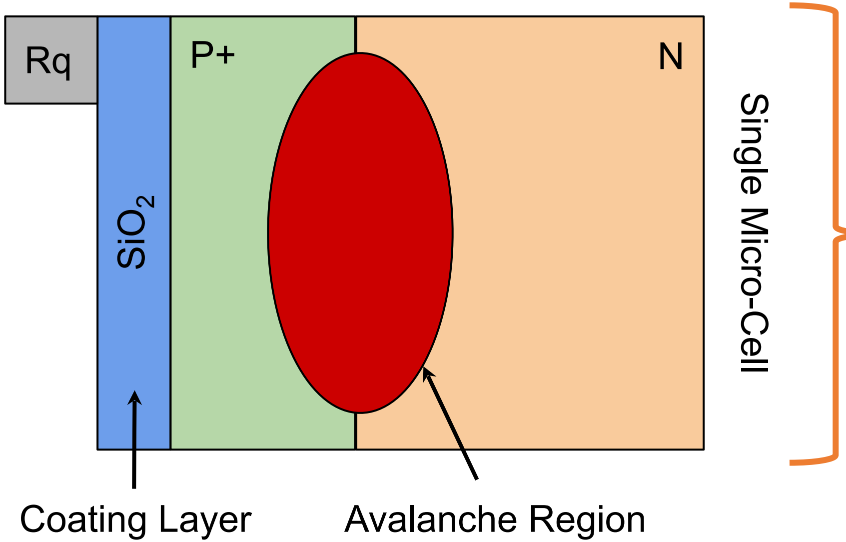
$$\mathrm{PDE} = \mathrm{FF} \cdot \mathrm{QE}(\lambda) \cdot T_p(V, \lambda)$$

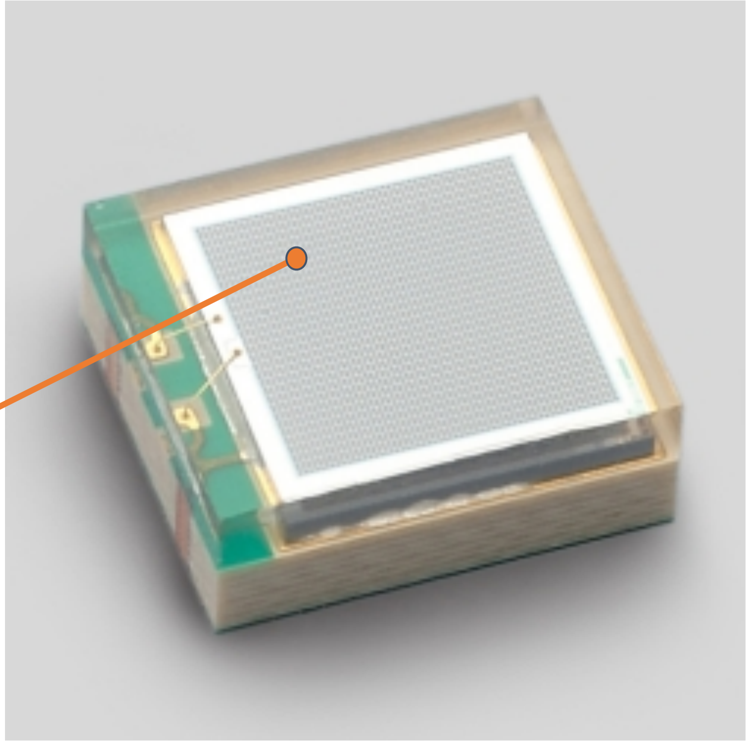
Fill-Factor — Quantum Efficiency — Avalanche-Triggering-Probability

1) lack of formal separation between the different processes that define the total PDE.
2) lack of an analytical expression

How Do SiPMs Work? Solid-State Approach

p-n junctions micro-cells operated in Geiger-mode, with an added quenching resistor.
Each SiPM is composed by multiple micro-cells.





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How Do SiPMs Work? Solid-State Approach

ArXiv:1904.05977

p-n junctions micro-cells operated in Geiger-mode, with an added quenching resistor.
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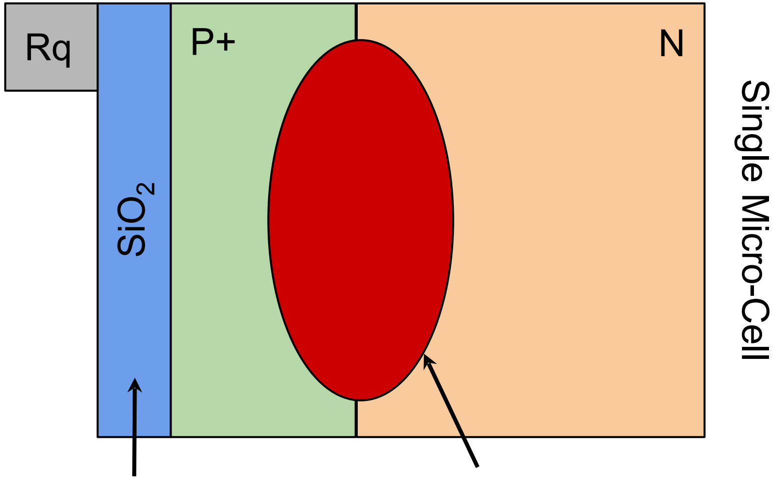

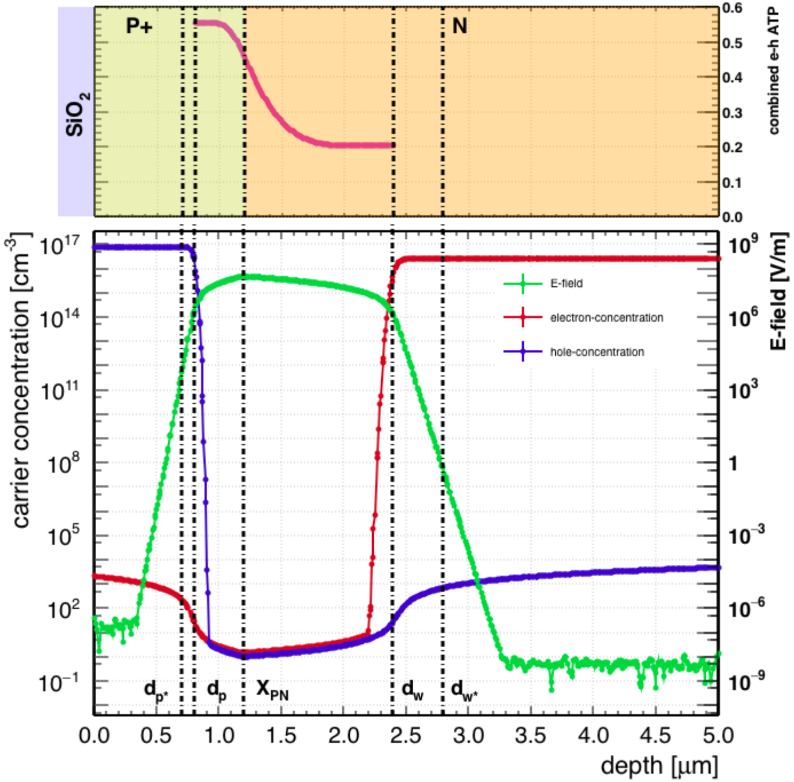

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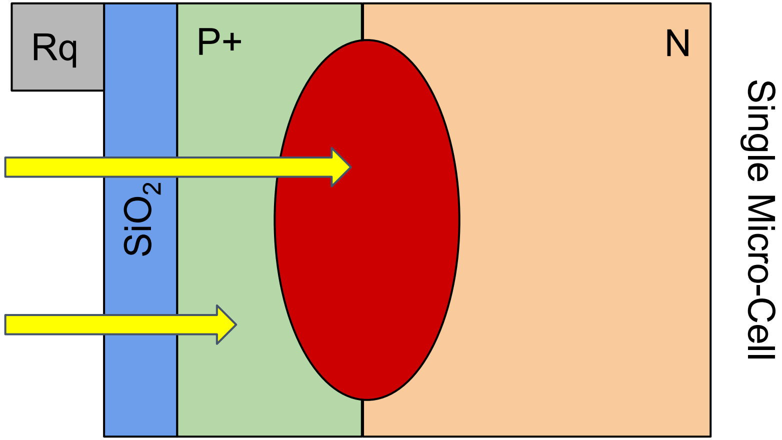
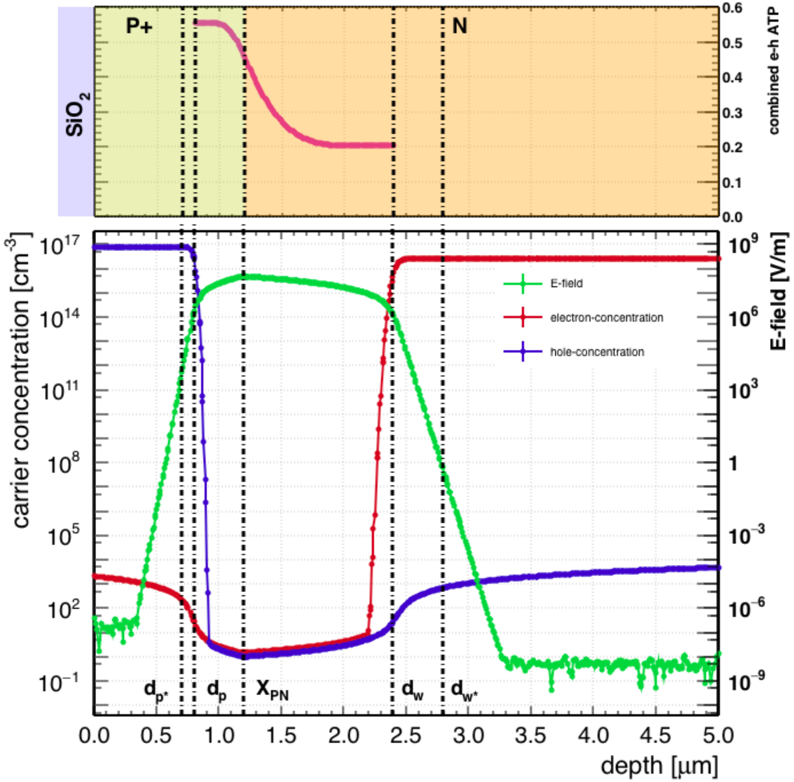
How Do SiPMs Work? Solid-State Approach

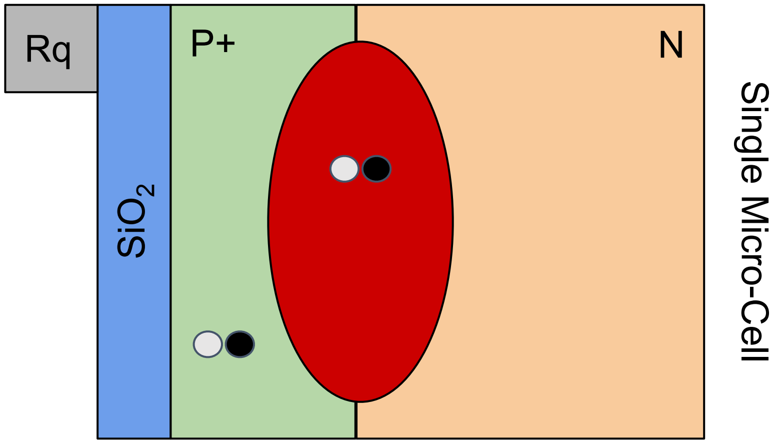
An incoming photon enters the junction and it is absorbed (wavelength dependent process).

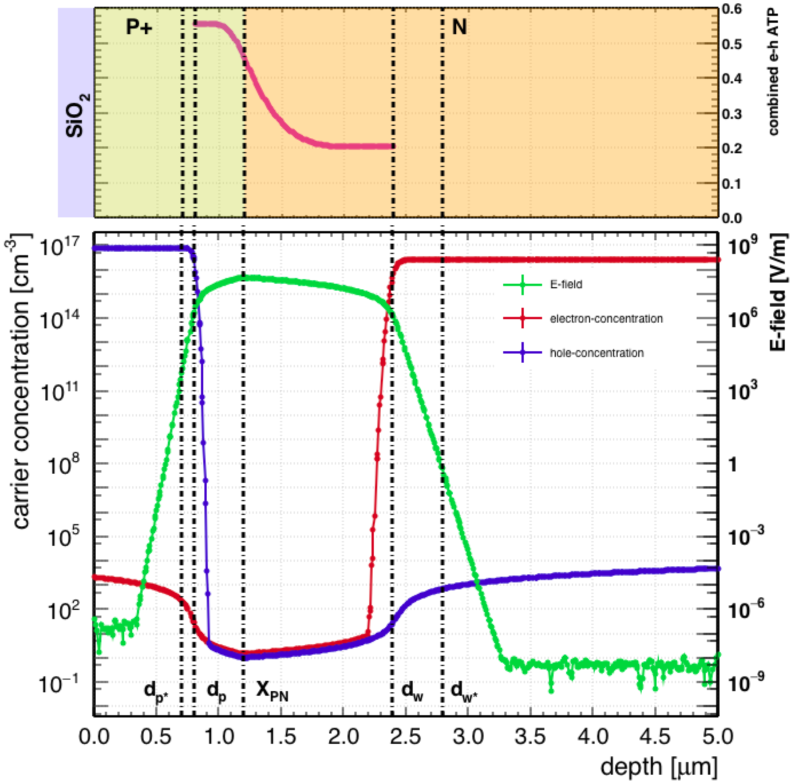




How Do SiPMs Work? Solid-State Approach

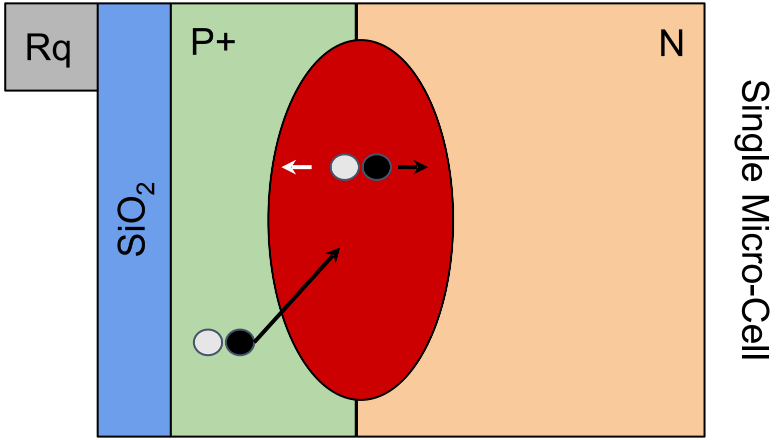
The absorbed photons generates an electron-hole pair



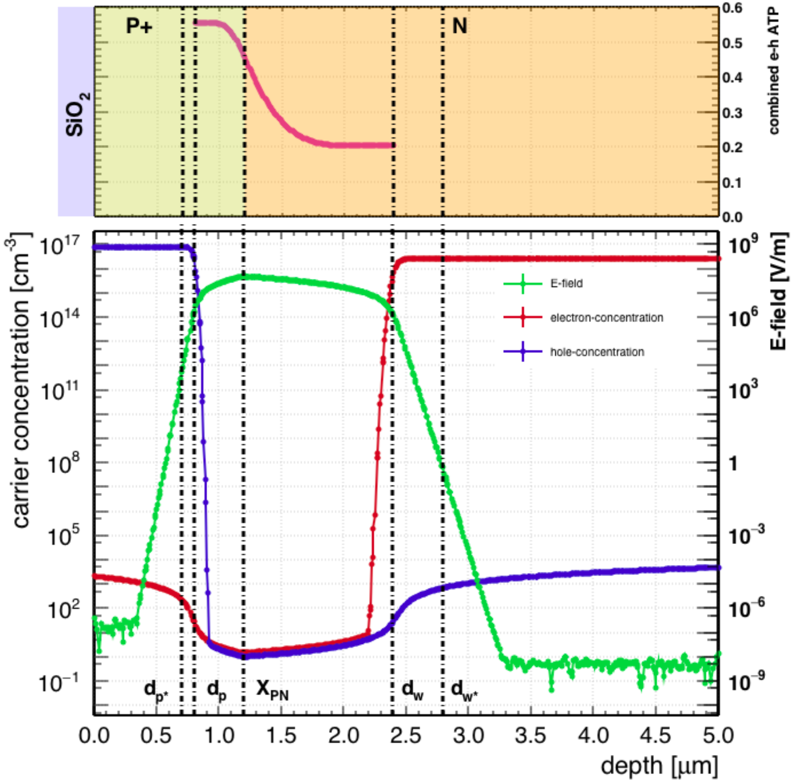


How Do SiPMs Work? Solid-State Approach

The internal field of the junction brings the generated carrier (e/h) to the avalanche region.

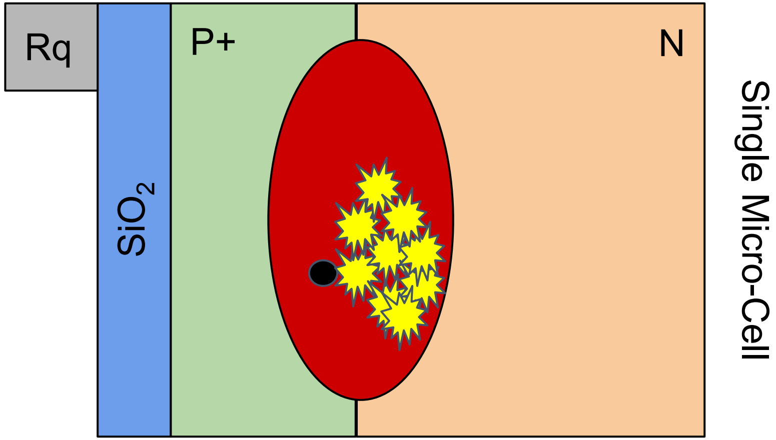


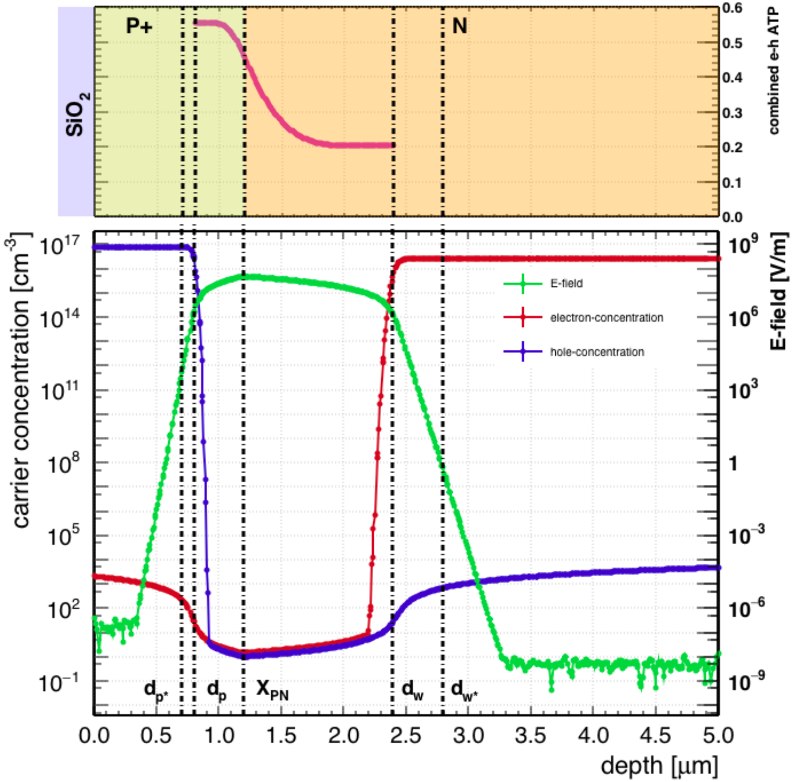
The e-h pair can be created or not in the depleted region



How Do SiPMs Work? Solid-State Approach

This triggers an avalanches, with gain ~10^6-10^7, which produces a readable signal.





Avalanche Triggering Probability

PDE needs to account for the fact that if the photon is absorbed outside of the active region, it will not be observed.

$$\mathrm{PDE} = \epsilon_0 \cdot \int_{d_P^*}^{d_W^*} \frac{1}{\mu} \exp\left(-\frac{x}{\mu}\right) \cdot \mathrm{P_P}(x, V)\ \mathrm{dx}$$

The Total Avalanche Triggering Probability has both an electron-driven and a hole-driven component

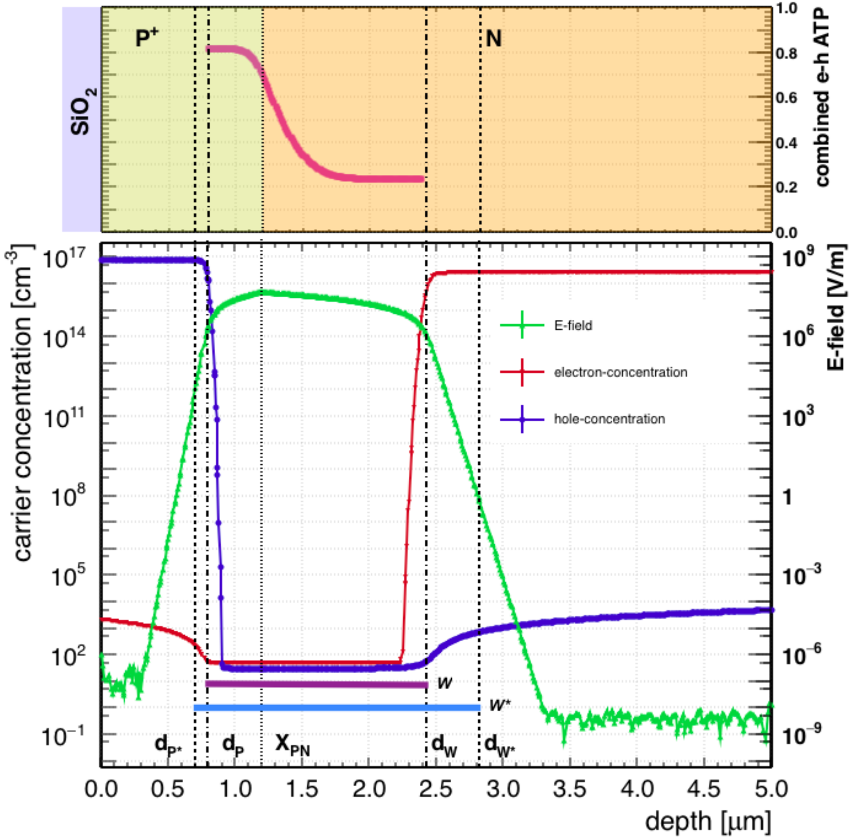
$$\mathrm{P_P}(x,V) \equiv \Big(\mathrm{P}_e(x,V) + \mathrm{P}_h(x,V) - \mathrm{P}_e(x,V)\cdot \mathrm{P}_h(x,V)\Big)$$

The probability to have an electron-driven avalanche is defined as

$$\mathrm{P}_e(d_P) = \left[1 - \left(k_e \cdot V \cdot \exp\left(-k_{e2}/\sqrt{V}\right)\right)^{-2}\right]$$

The probability to undergo a hole-driven avalanche is dependent on $P_e(d_p)$ and the field-strength factor in the junction k.

$$\mathrm{P}_h(d_W) = \left[1 - \left(1 - \mathrm{P}_e(d_P)\right)^{\mathrm{k}}\right]$$



W* effective junction length

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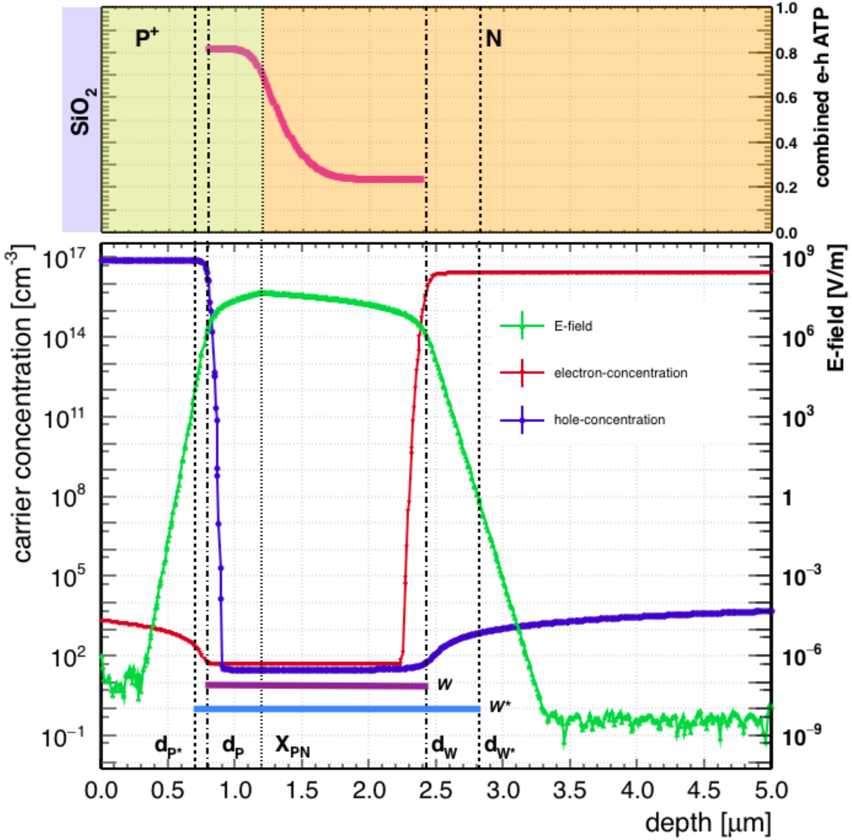
Avalanche Triggering Probability

We redefined the PDE to include the avalanche triggering probabilities for electron and hole driven avalanches

$$\mathrm{PDE} = \mathrm{PDE}_{\mathrm{MAX}} \cdot \left(\mathrm{P}_e(d_P) \cdot f_e^* + \mathrm{P}_h(d_W) \cdot (1 - f_e^*) \right)$$

where f_e^* is the fraction of avalanche electron driven

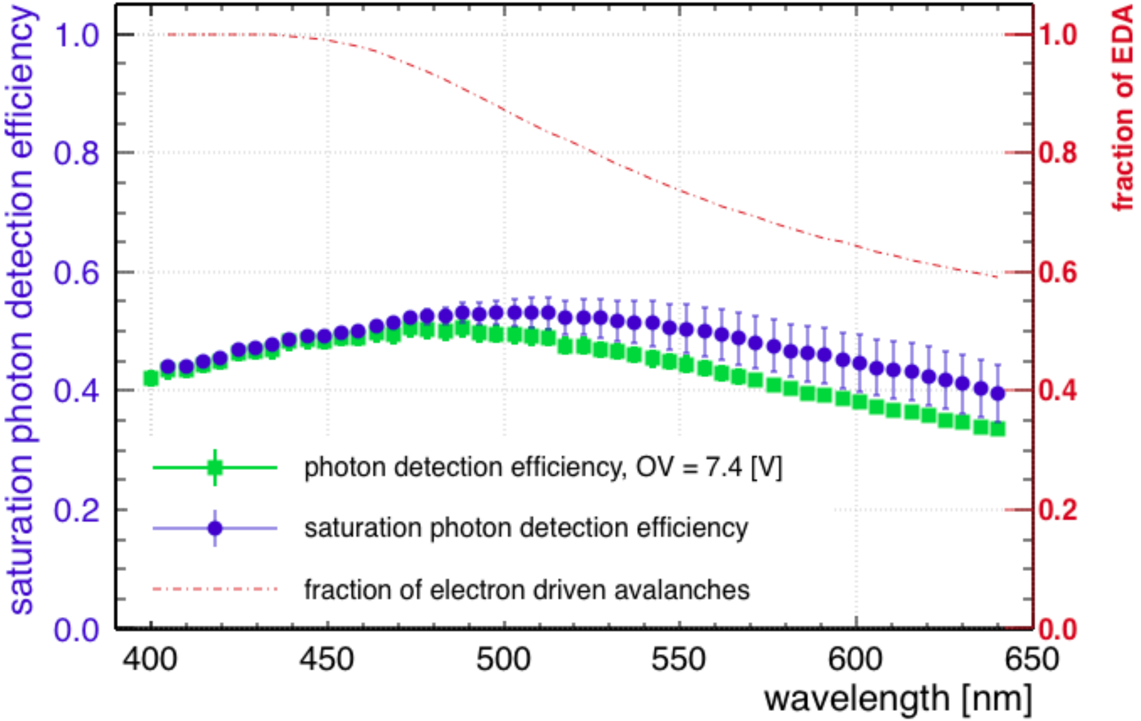
$$f_e^* \equiv \left[\frac{1 - \exp\left(- \frac{(x_{PN} - d_P^*)}{\mu} \right)}{1 - \exp\left(- \frac{W^*}{\mu} \right)} \right] \in [0 - 1]$$

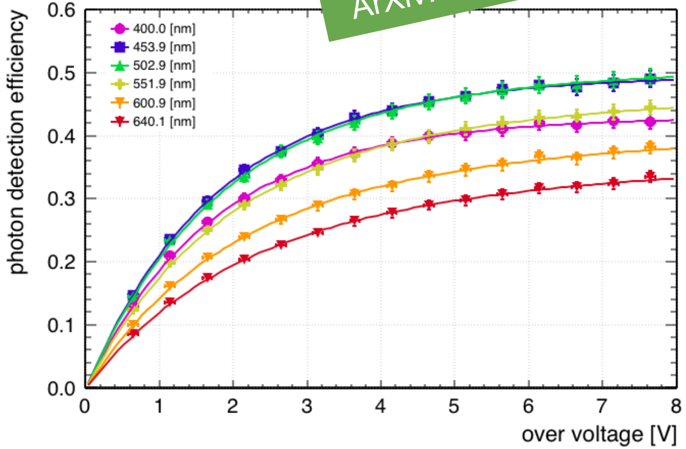


Avalanche Triggering Probability

ArXiv:1808.05775

ArXiv:1904.05977





$$\mathrm{PDE} = \mathrm{PDE}_{\mathrm{MAX}} \cdot \left(\mathrm{P}_e(d_P) \cdot f_e^* + \mathrm{P}_h(d_W) \cdot (1 - f_e^*) \right)$$

$$f_e^* \equiv \left[\frac{1 - \exp\left(- \frac{(x_{PN} - d_P^*)}{\mu} \right)}{1 - \exp\left(- \frac{W^*}{\mu} \right)} \right] \in [0 - 1]$$

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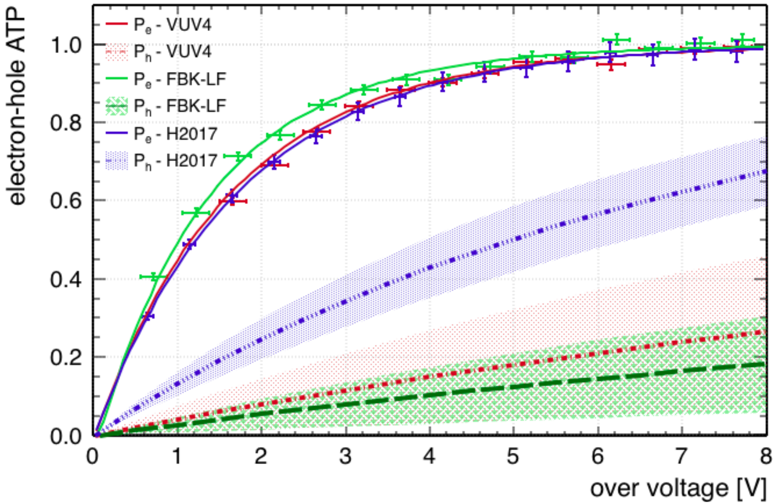
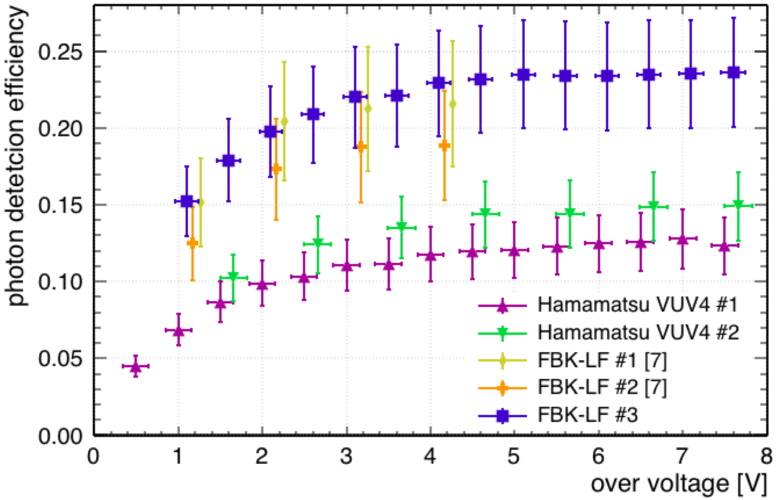
Avalanche Triggering Probability

Precise estimation of junction quantities can also be achieved and different devices can be compared





$$P_e(d_P) = \left[1 - \left(k_e \cdot V \cdot \exp\left(-k_{e2}/\sqrt{V}\right)\right)^{-2}\right]$$

$$P_h(d_W) = \left[1 - \left(1 - P_e(d_P)\right)^{k}\right]$$

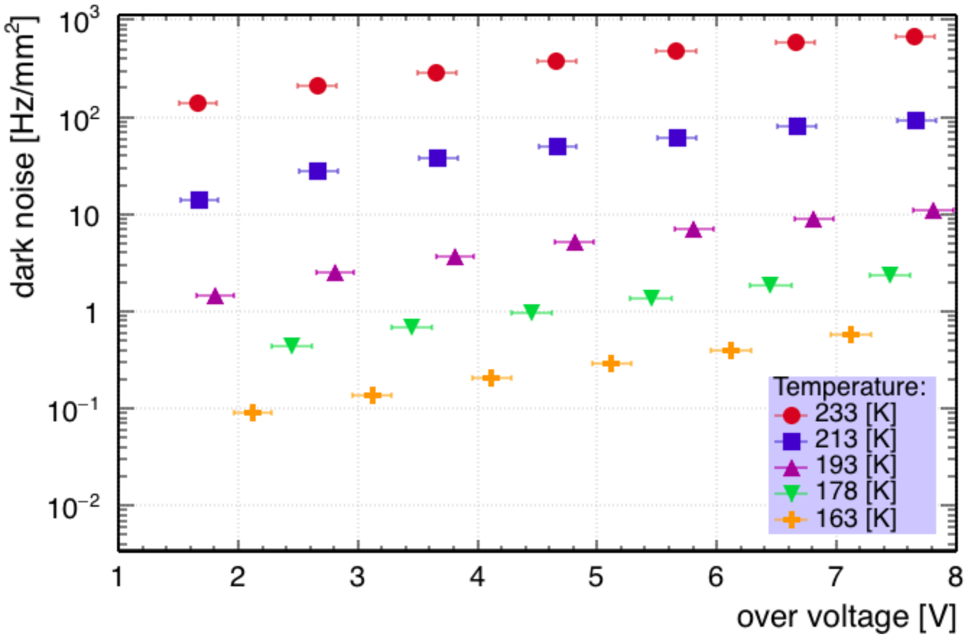
Type	$(x_{PN} - d_{P^*})$ [μm]	W^* [μm]	C_D [fF]	V_{BD} [V]	W[μm]	k
H2017 [21]	1.8 ± 0.1	4.1 ± 0.4	163 ± 1	52.2 ± 0.1	1.54 ± 0.01	0.25 ± 0.06
VUV4 [3]	0.8 ± 0.2	3.9 ± 0.8	116 ± 6	48.3 ± 0.1	1.01 ± 0.05	0.07 ± 0.06
LF [23]	0.145 ± 0.01	2.2 ± 0.1	83 ± 5	30.6 ± 0.1	0.92 ± 0.06	0.05 ± 0.01

Dark Noise Modelling

Dark Noise Characterisation

Can we infer the source of the Geiger mode Dark Noise ?

arXiv:1903.03663



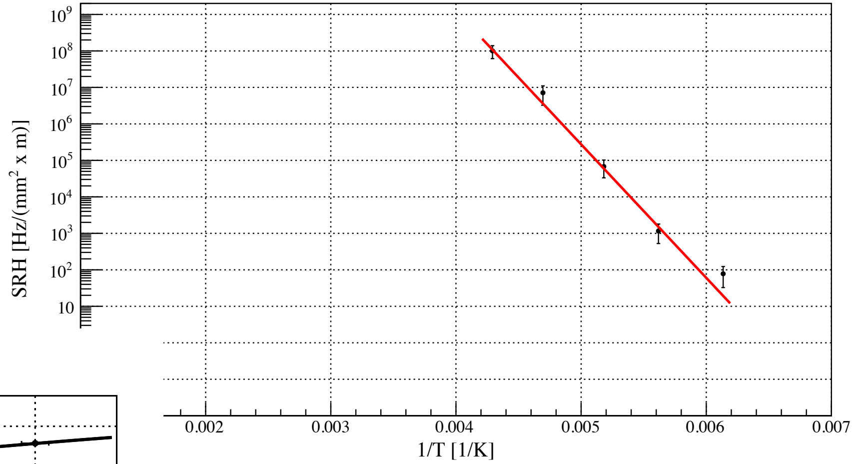
- Is hole or electron dominated ?
- Is SRH field enhanced or not ?
- Band to band tunnelling is important ?

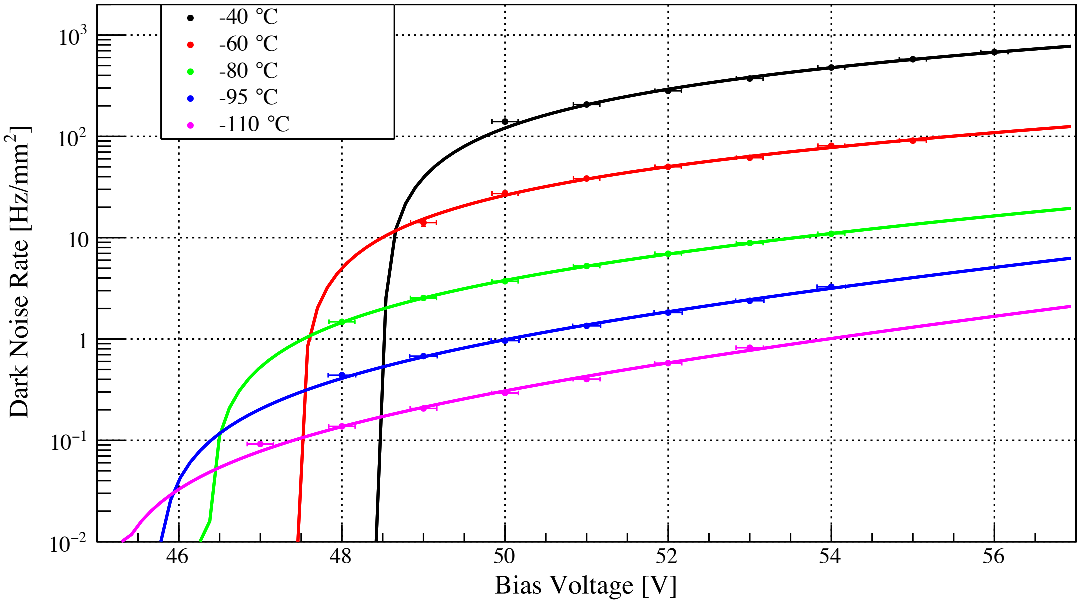
To reduce the noise we need to understand its source

Example using the Hamamatsu VUV4 data

It includes 3 main noise sources

- Band to Band tunneling
- Trap assisted tunnelling
- SRH recombination
- Diffusion





Finally the corrected slope can be predicted !

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Conclusions

Conclusions

- New technologies and ideas are fundamental for precision physics to search beyond the standard model of particle physics.
- SiPMs already provide a great option (compared to PMTs) for experiments dominated by scintillation and Cherenkov light detection.
- SiPMs challenges include: size scalability, radiopurity, good timing, overall noise reduction.
- We have introduced a novel physics-driven method to characterize and fully understand SiPMs, including avalanche-triggering-probability (ArXiv:1904.05977).
- We are working on new models to precisely infer the source of the noise and optimise future SiPM development
- We are commissioning new set-up to better understand and design new generation of SiPMs ! Strongly interested in collaborations.

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Thank you

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Backup

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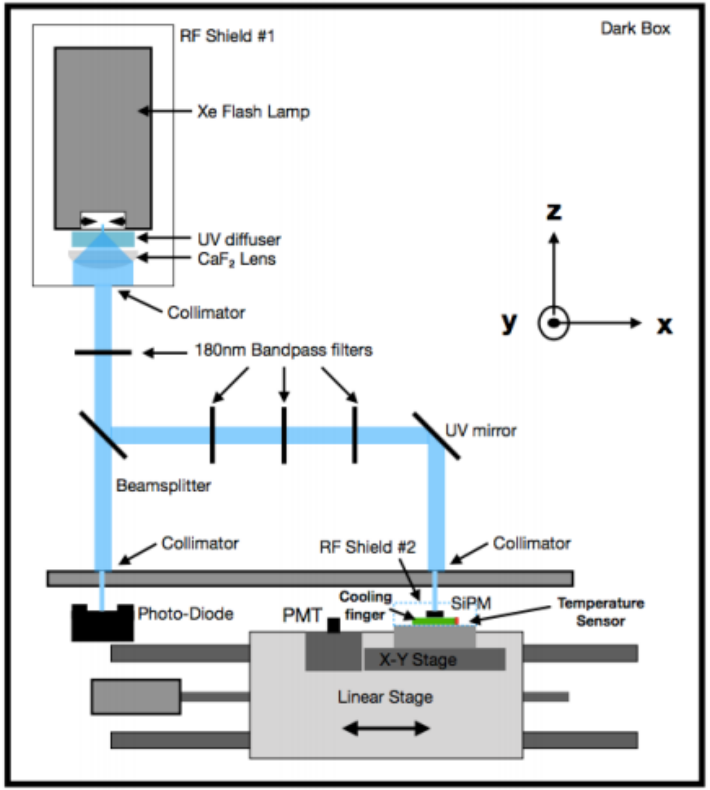
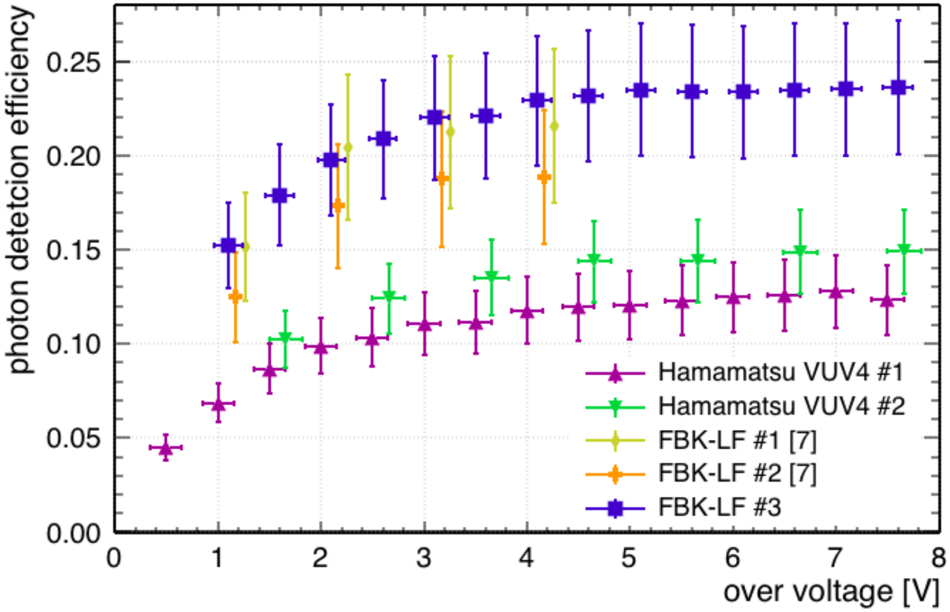
Photo-Detection-Efficiency



arXiv:1903.03663



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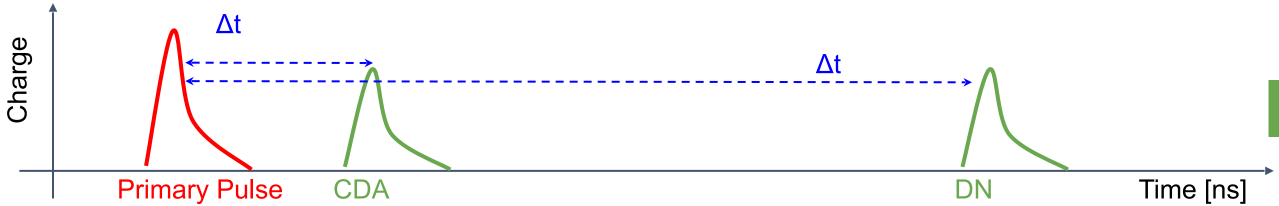
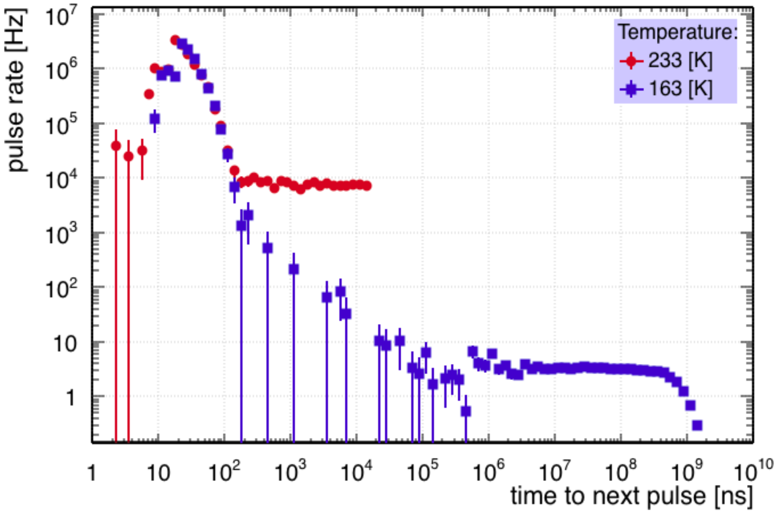
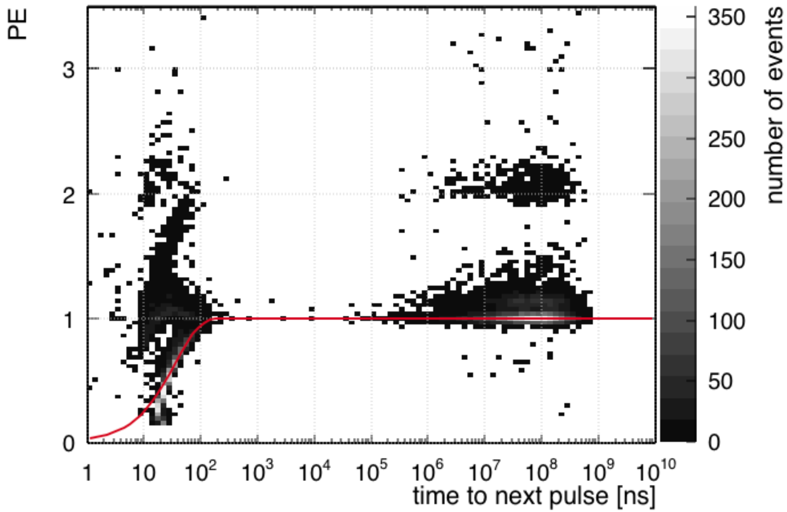
Correlated Avalanches (CAs)



ArXiv:1705.10183





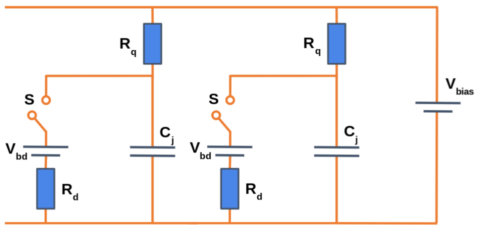
Pulse Shape Fitting

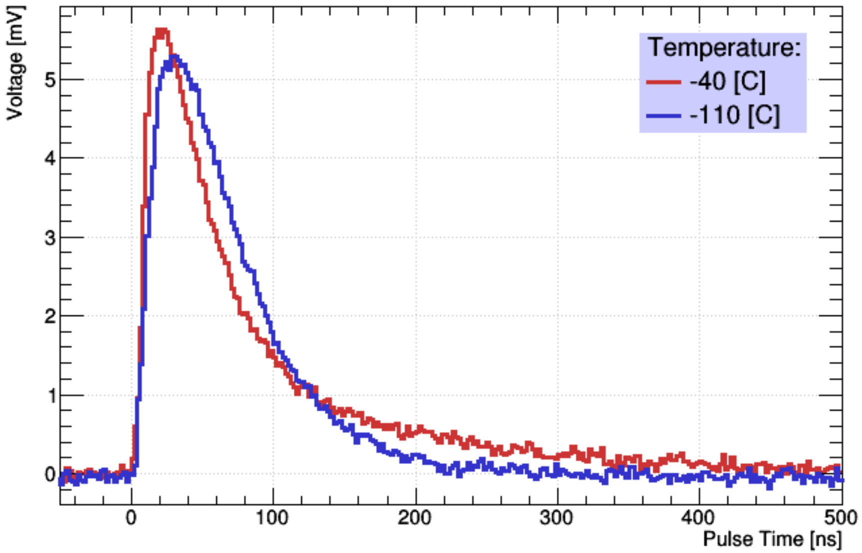
Rise Time: $\tau_r \propto (R_d \cdot C_j)$

Parasitic Spike: $\tau_S \propto (R_{tot} \cdot C_{tot})$

Recovery Time: $\tau_L \propto (R_q \cdot C_j)$

k: relative contribution of t_S and t_L.

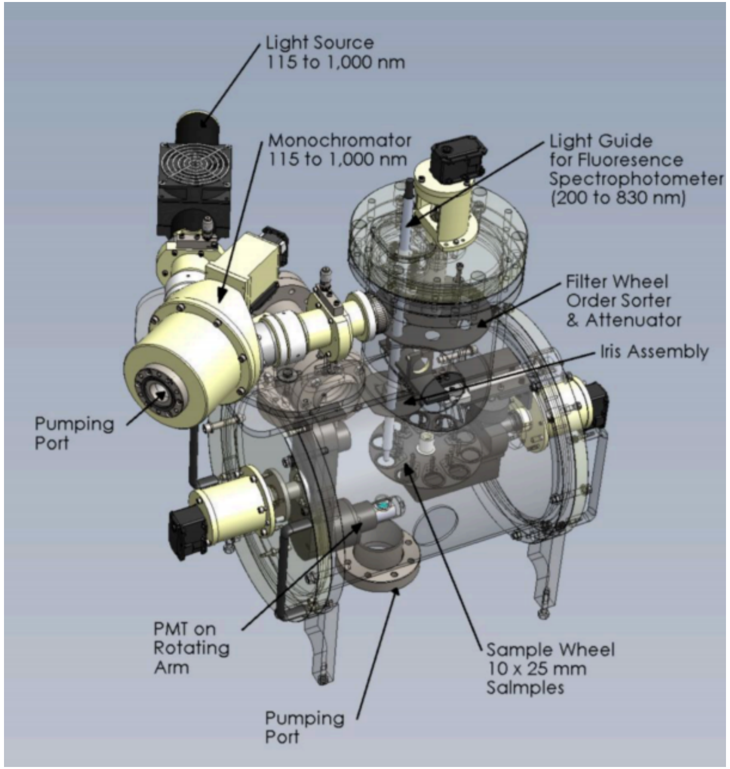


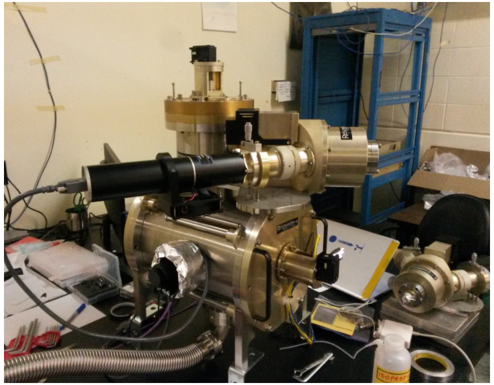


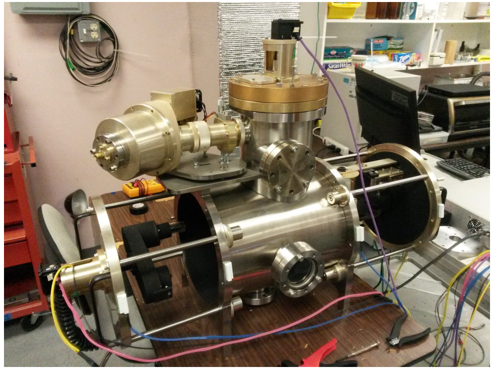
$$V(t) = A \cdot \left[\left(\frac{1-k}{\tau_S} \right) \cdot \left(e^{-t/(\tau_S+\tau_r)} - e^{-t/\tau_r} \right) + \left(\frac{k}{\tau_L} \right) \cdot \left(e^{-t/(\tau_L+\tau_r)} - e^{-t/\tau_r} \right) \right]$$

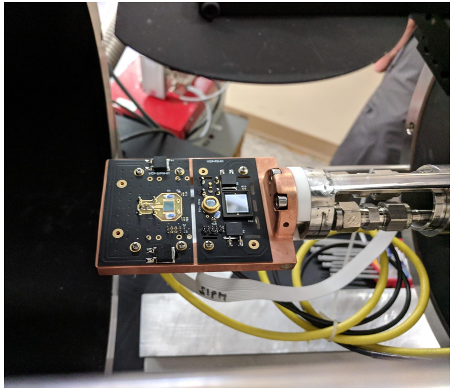
New Setup at TRIUMF

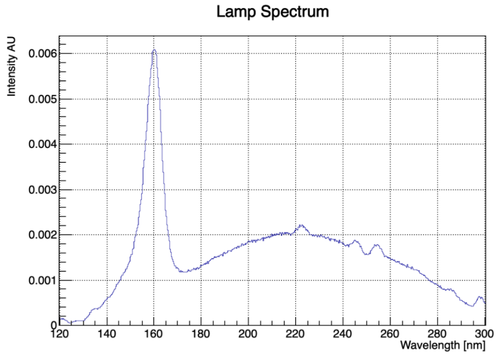
VUV Optics and SiPM Characterization Setup











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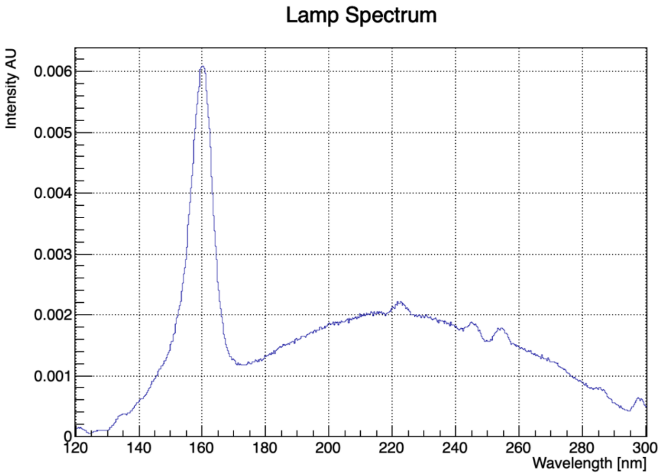
Boosting SiPM VUV Efficiency

Photo Detection Efficiency:
Transmittance
Reflectivity

VUV Optics Game



VUV Setup Design:

- Reflectance, Transmission, Fluorescence and more.
- Deuterium Lamp 100-400 nm continuous source spectrum.
- Advanced monochromator for precision wavelength selection.
- Ability to cool the sample to cryogenics temperatures.
- Ability to control the sample and readout position and tilt-angle.
- Reference PMT capable of sampling the beam via a parabolic mirror.
- Cryogenic sample holder with the ability to operate cold Diode/SiPM/PMTs.

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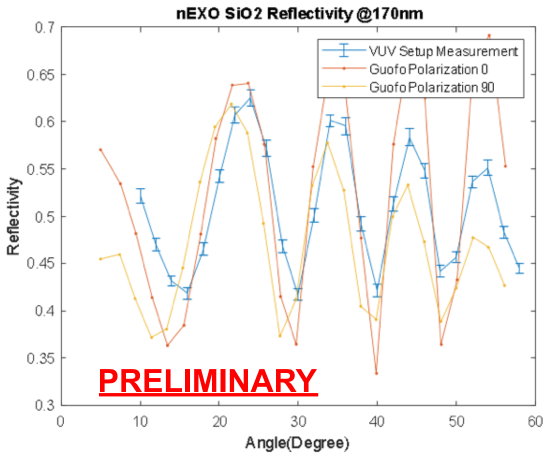
Early AR-Coating Results

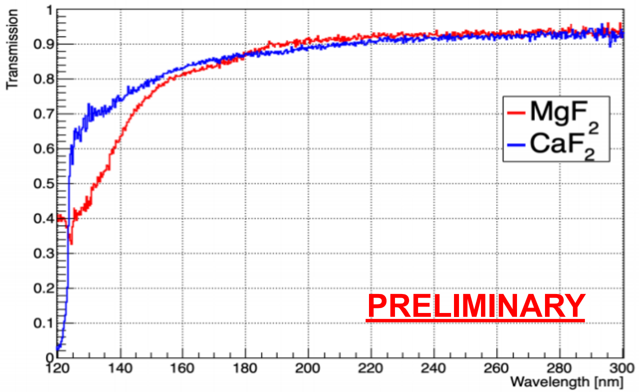
AR Surface coating is critical for the ultimate VUV sensitive SiPM.
(Issue: Si reflectivity at ~175 nm is ~50%)
(SiO2 has poor transmission ~128 nm).

Important to balance transmission and reflectivity to identify the most optimal AR surface coating for 3DSiPM.

Optical Material Selection Campaign:
Currently Under Investigation:

- Al_2O_3
- MgF_2
- LiF
- LaF_3
- Pure Al





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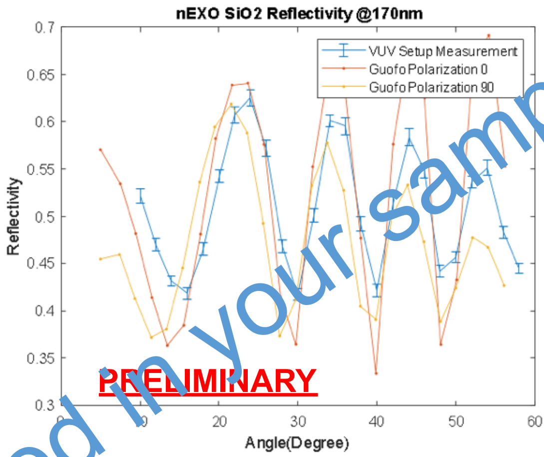

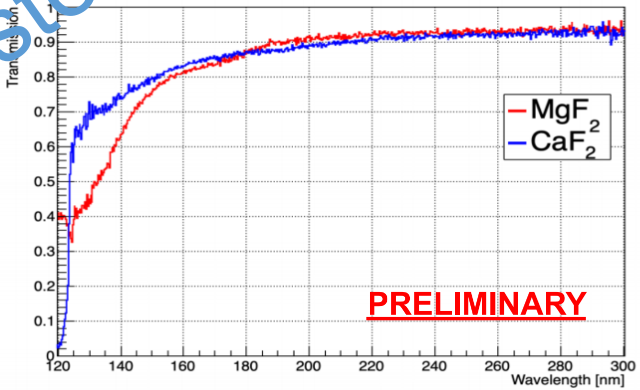

We are interested in your samples !!!