TRIUMF

nEXO

Development of VUV light detection solutions

Giacomo Gallina

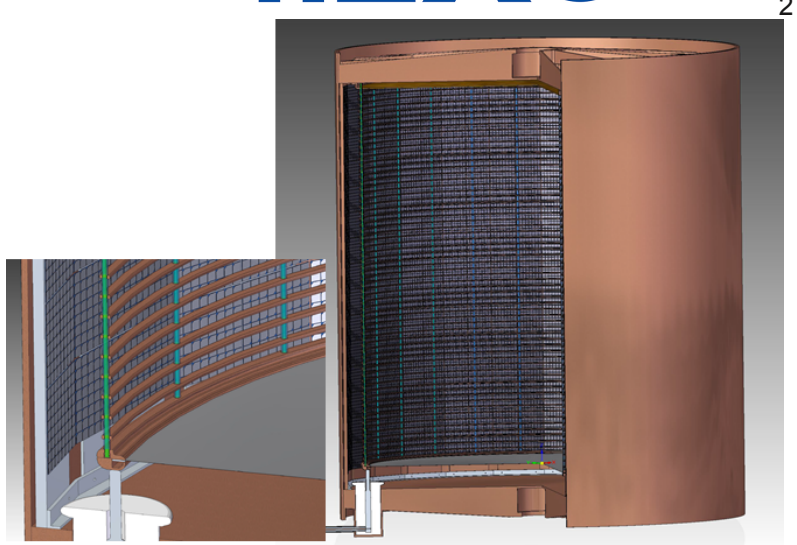
2019-05-21

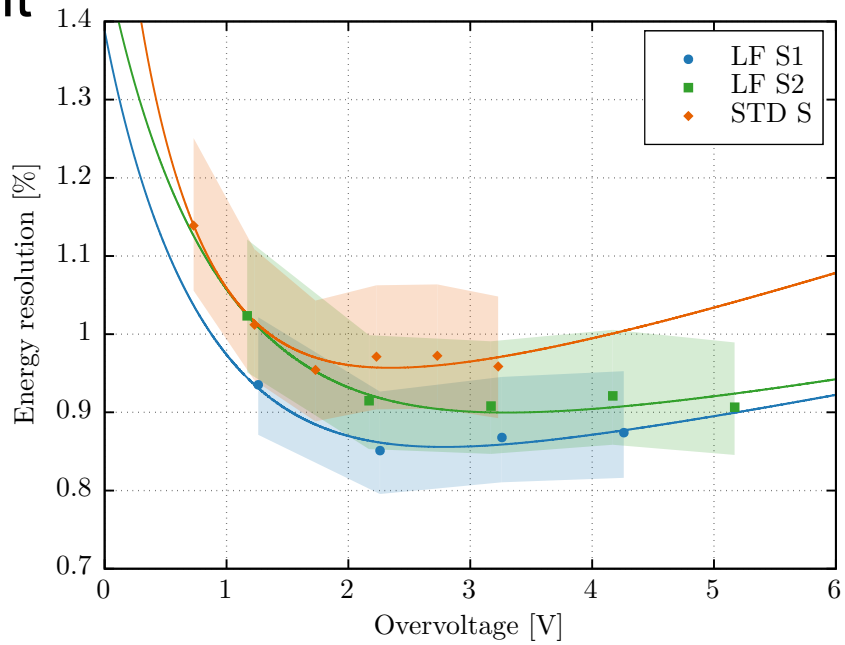
Discovery, accelerated

Motivation

nEXO

- Search for Neutrinoless double beta decay $0\nu\beta\beta$ of ^{136}Xe
- TPC with 5 tons of LXe
- LXe: decaying nucleus and detection medium
- Silicon Photomultipliers for the detection of VUV scint. light
- Simultaneous collection of light and charge





<u>Targeted Energy resolution</u>

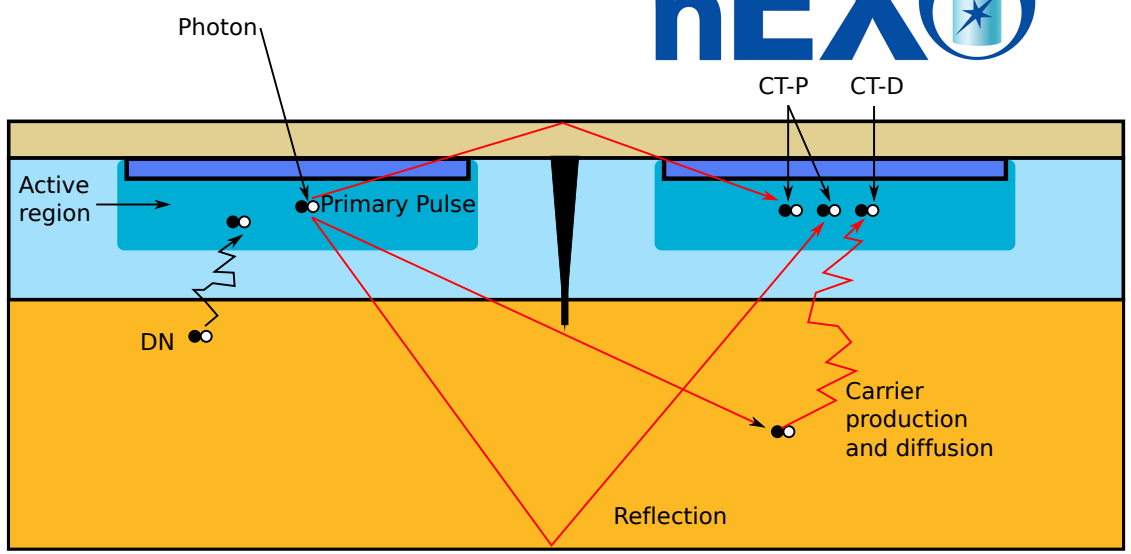
1% Energy resolution in $0\nu\beta\beta$ decay of ^{136}Xe

SiPM photon detection efficiency drives “light” energy resolution

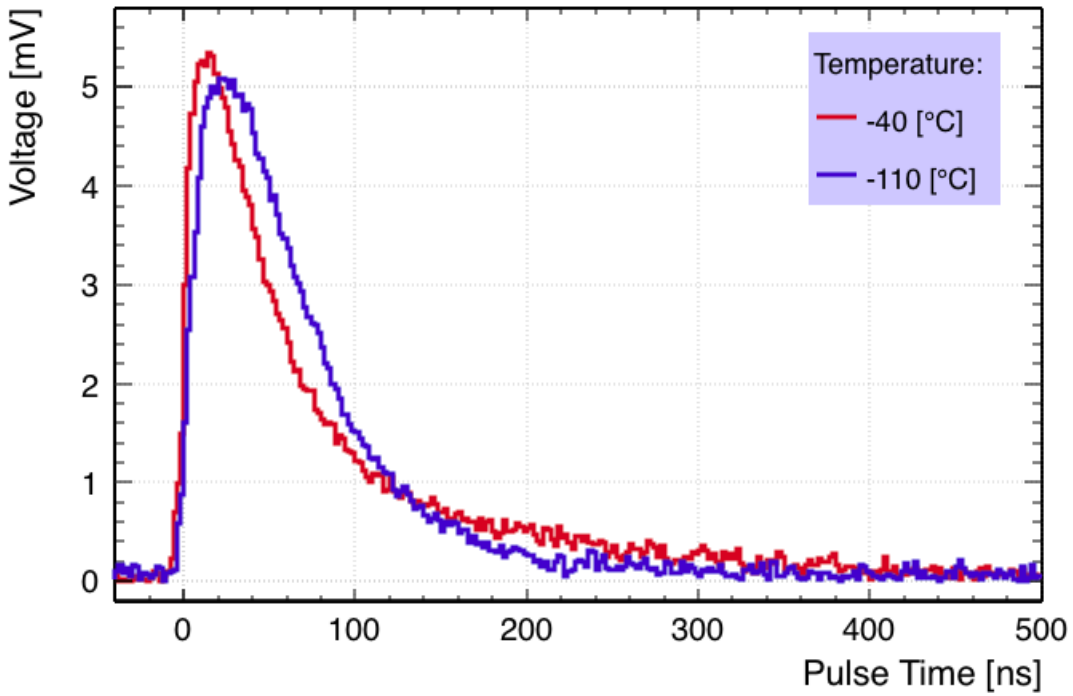
What is then a SiPM ?

Introduction to SiPM

- Main Characteristics:
- SPADs connected in parallel
- Operated in reverse bias mode
- Incoming photon triggers charge avalanche
- Single pixel is discharged



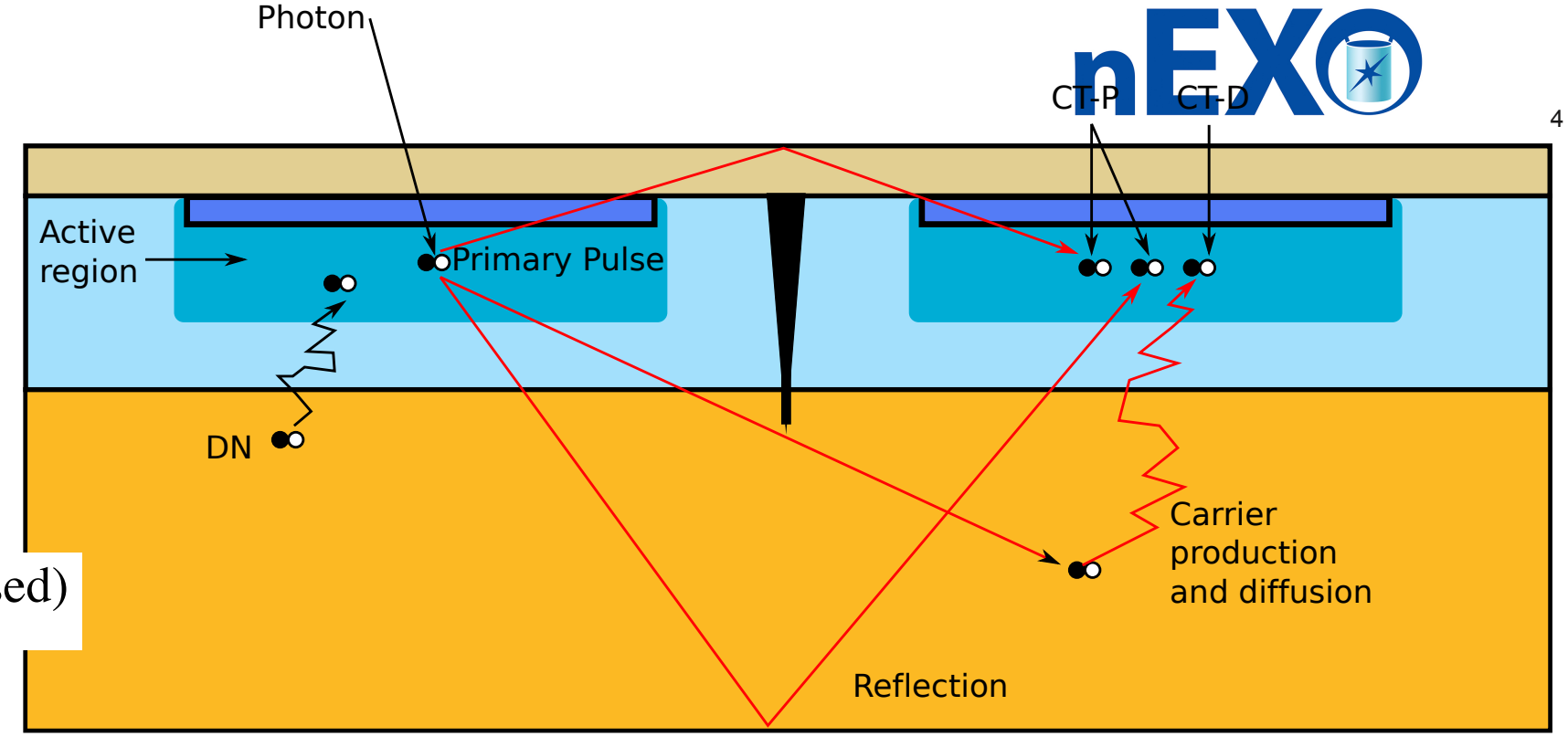
- Advantages:
- High gain at low bias voltage
- Single photon detection resolution
- High radio purity possible
- Suitable at cryogenic temperature



Crosstalk suppression: a road throw the idea detector

- Uncorrelated Noise
- Dark Noise (thermal and
- voltage assisted noise)

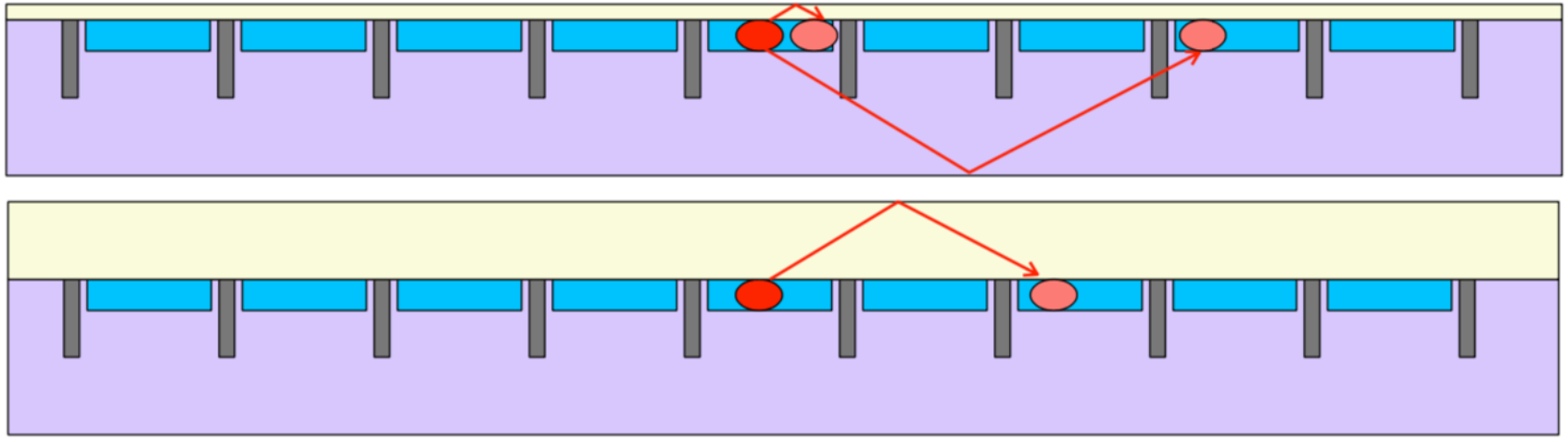
- Correlated Noise :
- After Pulse (almost suppressed)
- Cross Talk



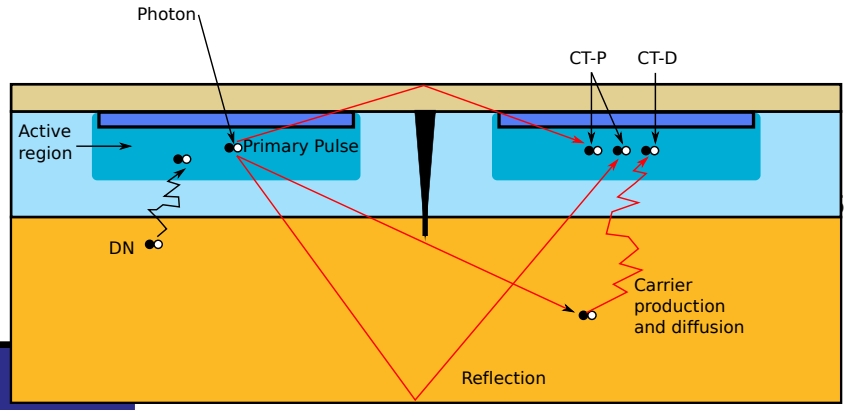
Excess Noise Factor :

$$F_{APD} \propto 1 + \frac{\sigma_M^2}{M_{APD}^2}$$

$$F_{SiPM} \propto 1 + P_{CT}$$



SiPM Requirement for nEXO



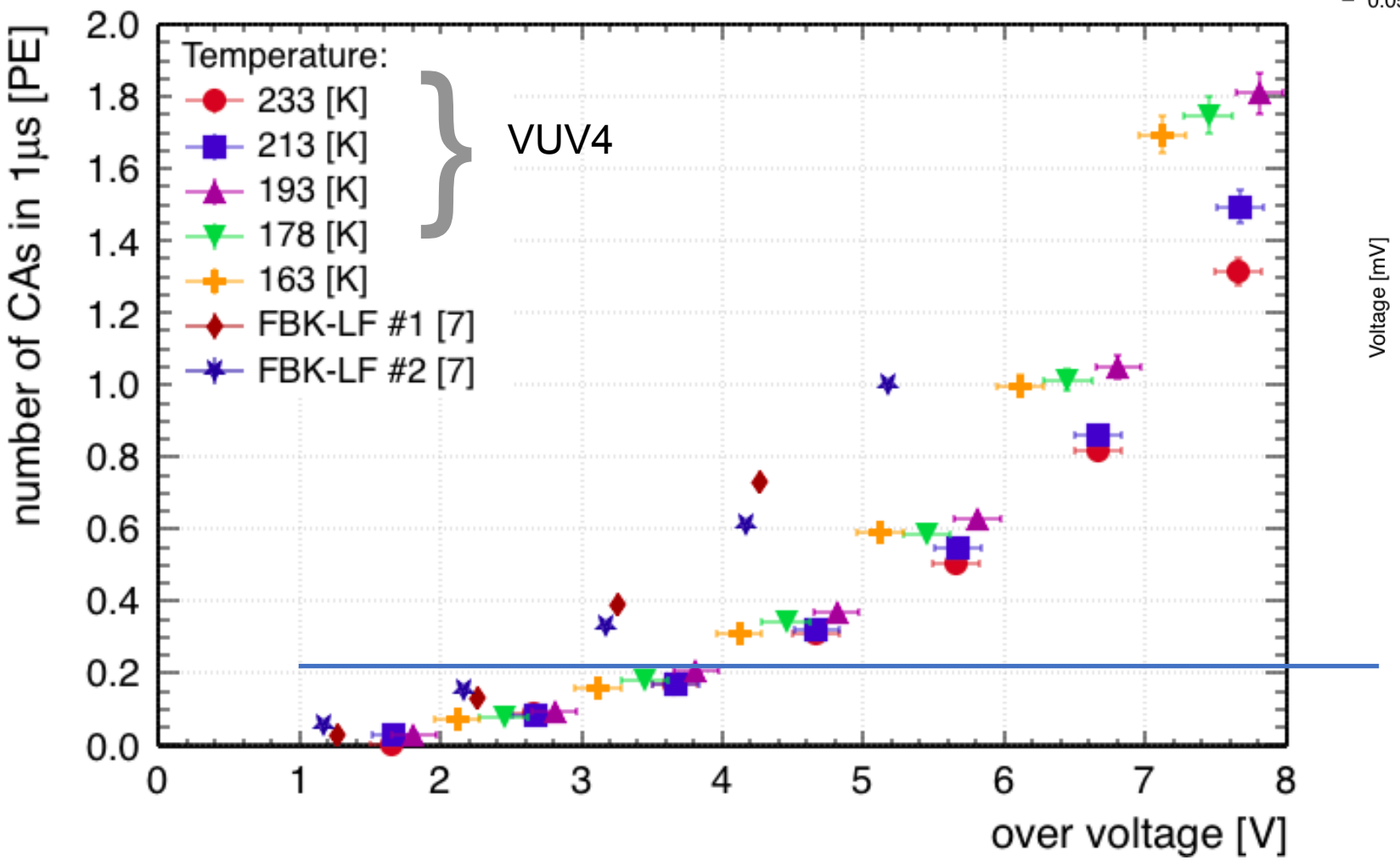
Parameters	Value
Photo-detection efficiency at 175-178nm in liquid Xenon (PDE)	≥ 15%
Radio purity: contribution of photo-detectors on the overall background	< 1%
Dark noise rate at -100°C	≤ 50 Hz/mm^2
Average number of correlated avalanches per parent avalanche at -110°C within 1μs (CA)	≤ 0.2
Single photo-detector active area	≥ 1cm^2
Capacitance per area	< 50 pF/mm^2
Gain fluctuations + electronics noise	< 0.1 PE

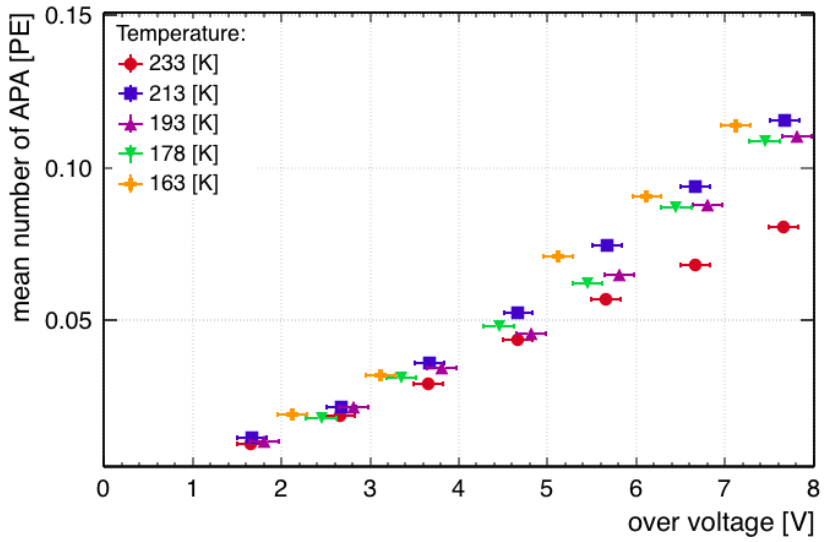
PDE and CA drive energy resolution

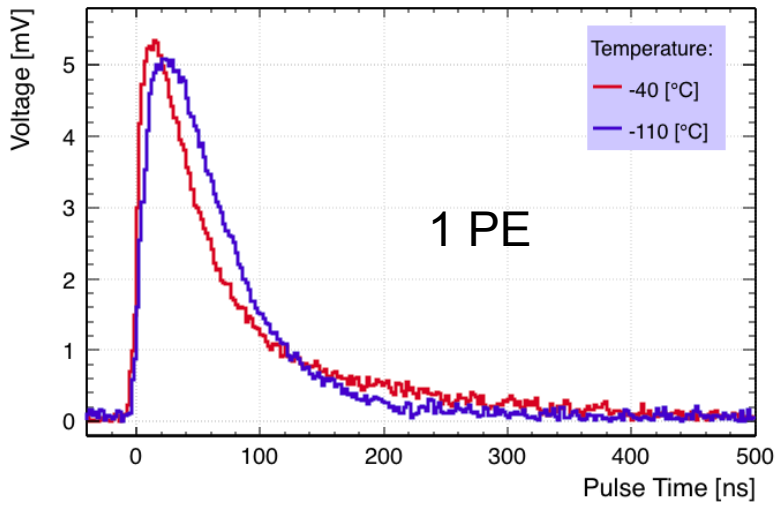
Correlated Avalanche (CA) in 1us for nEXO

Correlated avalanche Noise: “Sum of AP and CT events”

The nEXO DAQ acquisition window has a post trigger of 1us

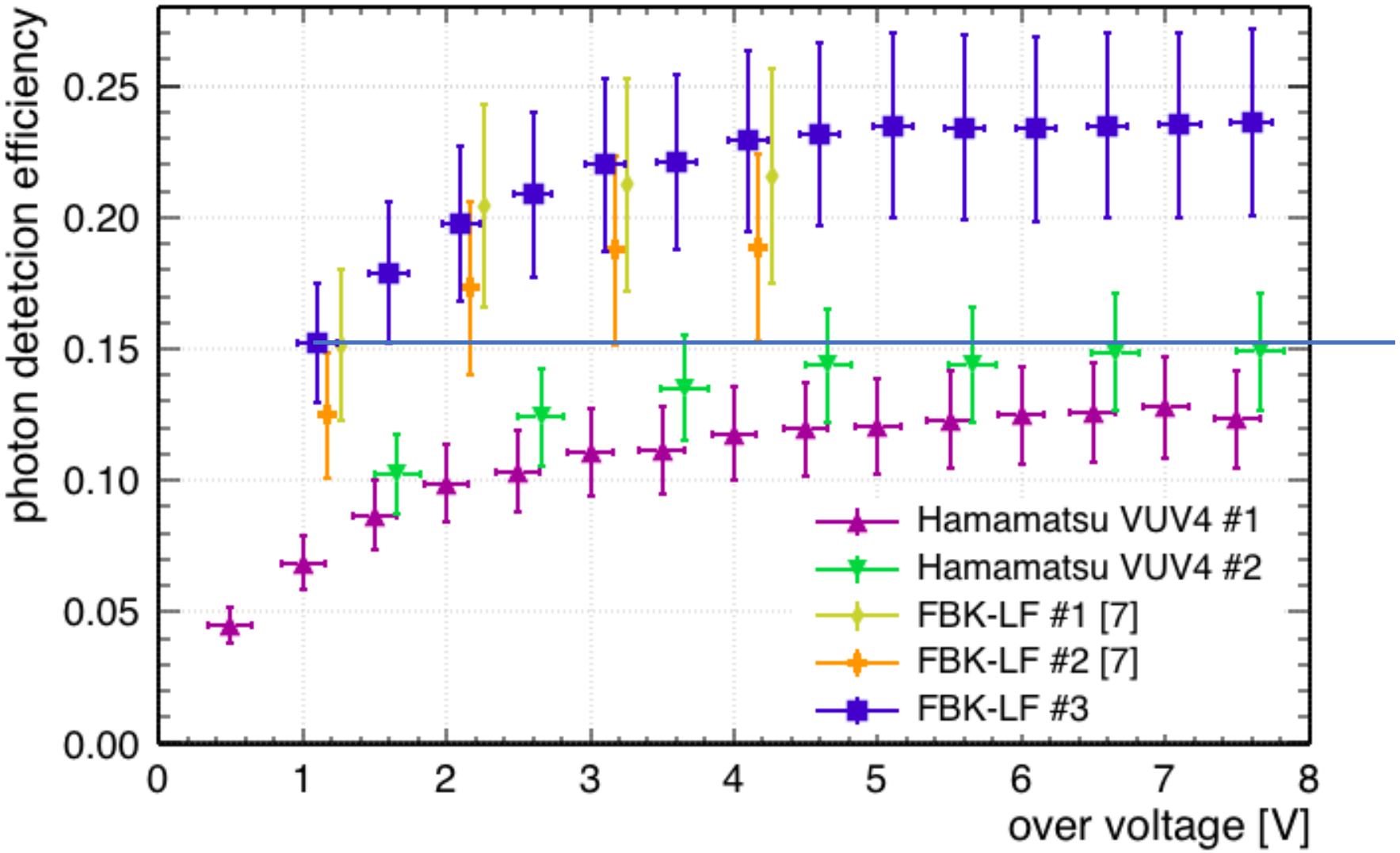






nEXO Requirement: CA < 0.2

PDE



nEXO Requirement: PDE $\geq 15\,\%$

VUV4 is close to meet nEXO requirements

FBK LF meets nEXO requirements

The TRIUMF SiPM : overview

Goal: develop a new generation of SiPMs with high VUV sensitivity and low correlated noise

Stage 1 (This talk)

Understand what drives the efficiency and optimisation parameters to obtain the best detector

SiPM Characterisation

https://arxiv.org/abs/1903.03663

Junction Modellization

https://arxiv.org/abs/1904.05977

More to come …

Stage 2

SiPM design: Expected Results in 2020

Initial goal: Can we achieve a SiPM with no Correlated avalanche noise ?

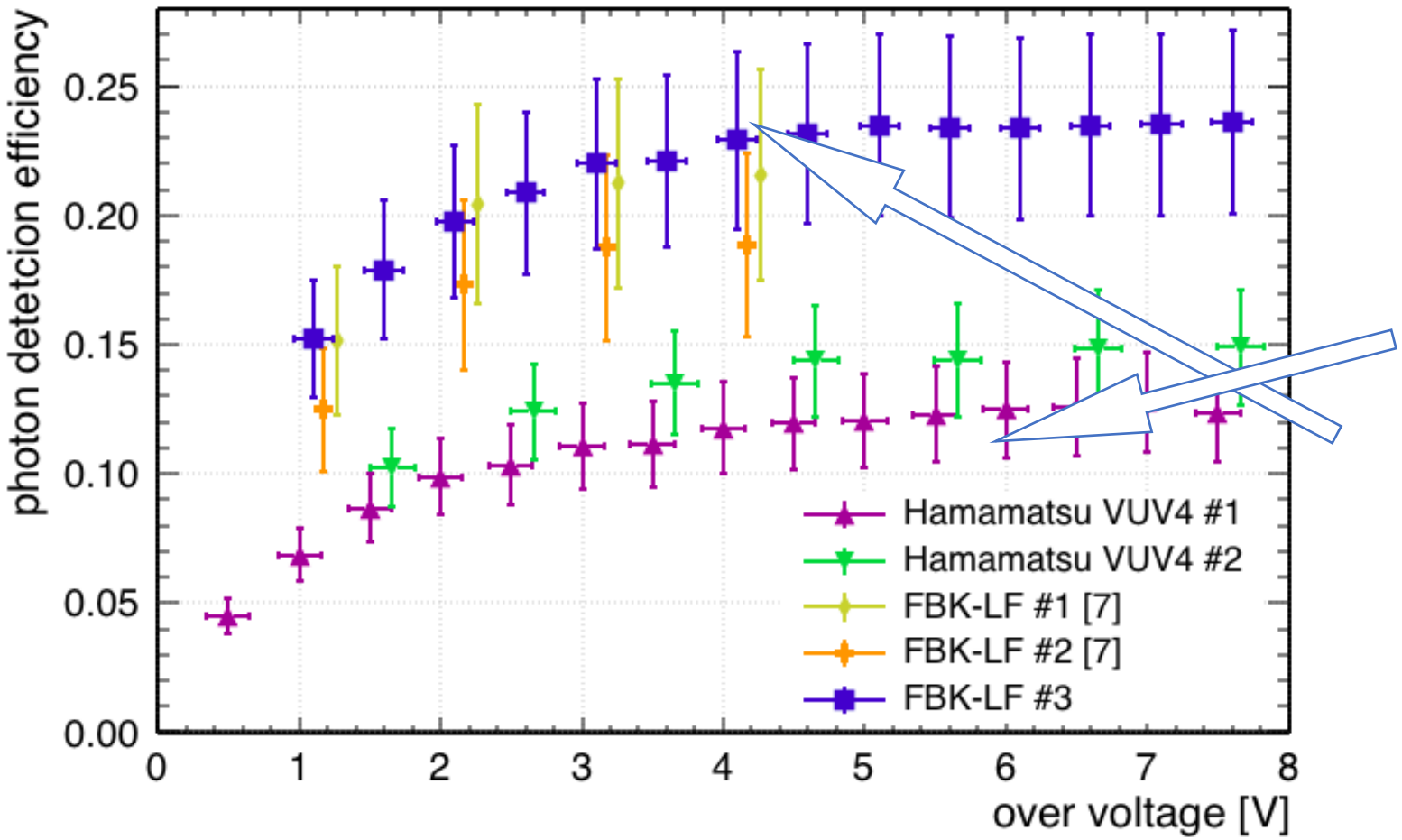
$$F_{SiPM} \propto 1 + P_{CT}$$

Design optimised for Cross talk Suppression

and Avalanche Triggering Probability Saturation

What Drives the Efficiency ?

Understanding the over voltage dependence of the PDE is crucial to achieve high PDE <u>in few OV</u>



PDE saturates at different OV

Same wavelength but probability saturates at a different OV

<u>Why the FBK saturates faster ?</u>

What Drives the Efficiency ?

Understanding the over voltage dependence of the PDE is crucial to achieve high PDE in few OV

We started building a simplified 1D model

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

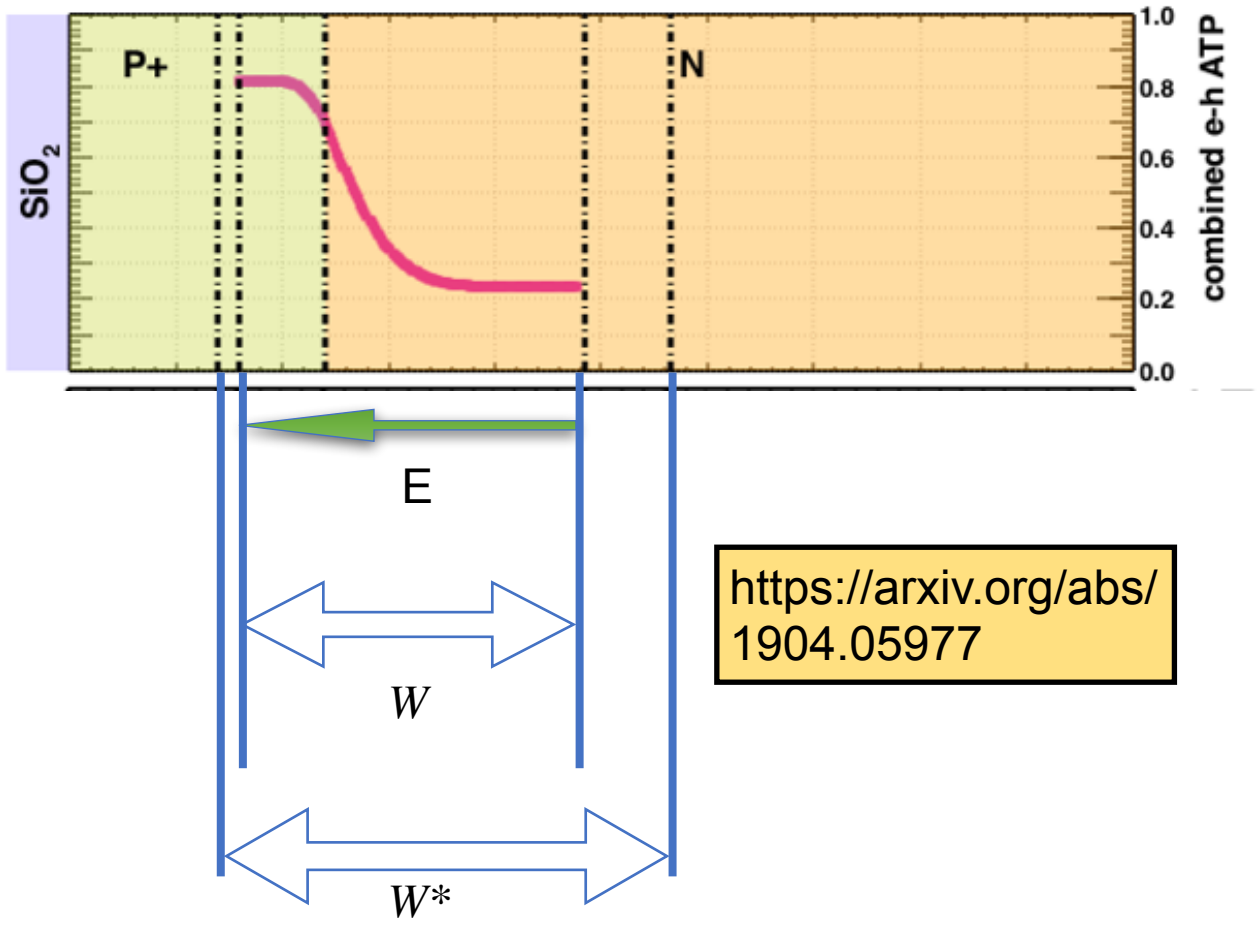
Optical Efficiency: Transmission in the Silicon

$$\epsilon_0(\lambda) \sim \left[\mathrm{FF} \times \left(1 - \mathrm{R}(\lambda, \theta)\right)\right]$$

Absorption in an effective volume

$$W^* = (d_W^* - d_P^*)$$

Avalanche triggering Probability



https://arxiv.org/abs/1904.05977

Electric Field

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

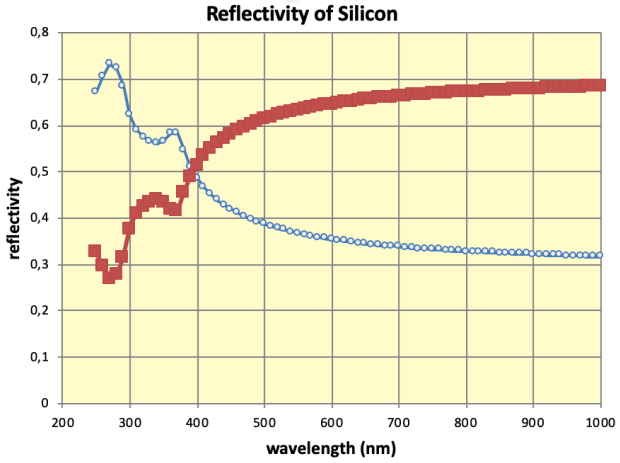
Optical Efficiency: Transmission in the Silicon

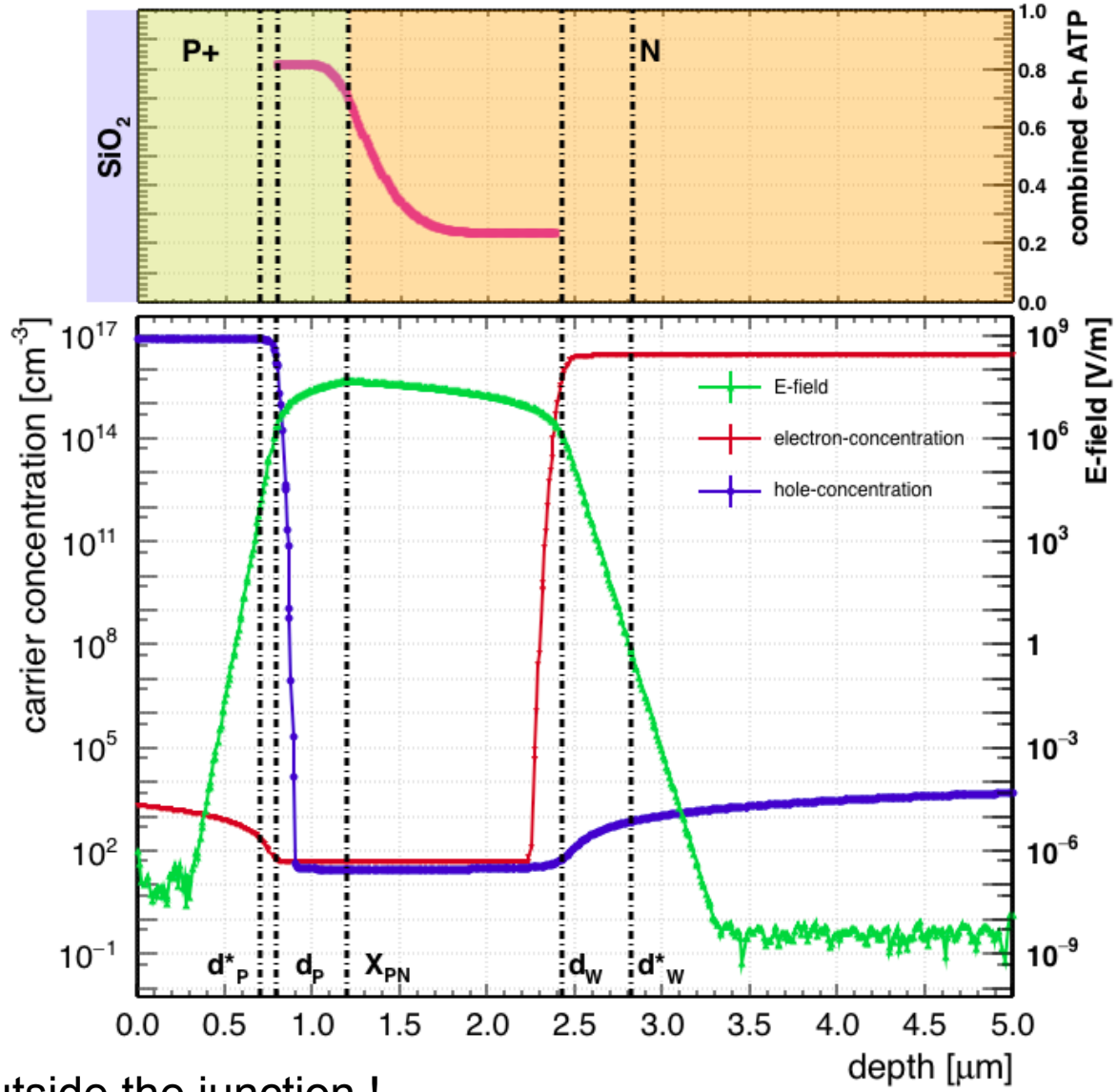
$$\epsilon_0(\lambda) \sim \left[\mathrm{FF} \times \left(1 - \mathrm{R}(\lambda, \theta)\right)\right]$$

Absorption in an effective volume

$$W^* = (d_W^* - d_P^*)$$

Avalanche triggering Probability





The FIELD is not zero outside the junction !
Diffusion drives part of the total efficiency

Junction Efficiency

$$\text{PDE} \sim \epsilon_0 \cdot \int_{d_P^*}^{d_W^*} \frac{1}{\mu} \exp\left(-\frac{x}{\mu}\right) \cdot \text{P}_\text{P}(x, V)\, dx$$

From SPAD simulation a direct Num. Integration is preferable but a simplification is possible

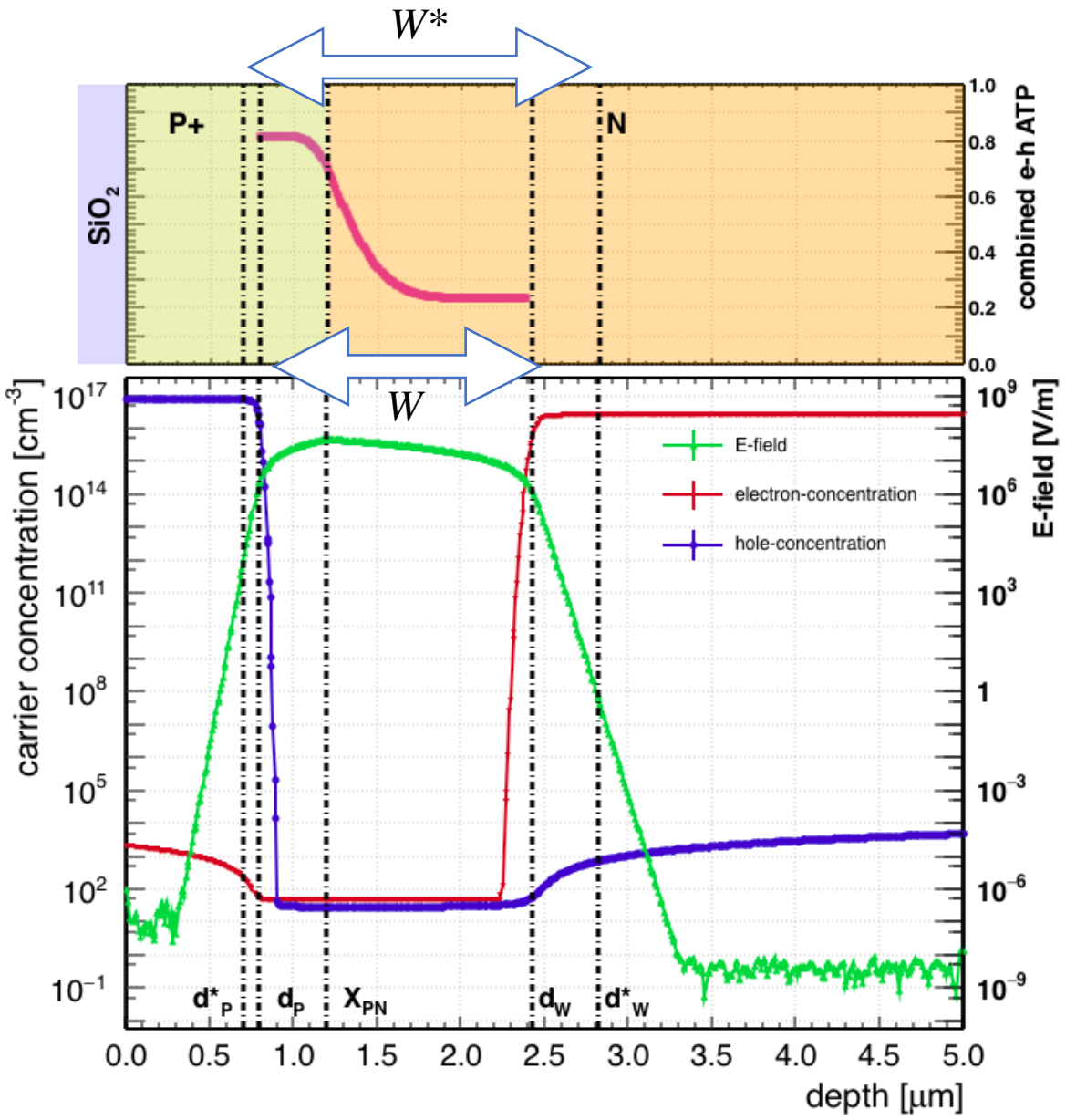
$$\text{PDE} = \text{PDE}_\text{MAX} \cdot \left(\text{P}_e(d_P) \cdot f_e^* + \text{P}_h(d_W) \cdot (1 - f_e^*) \right)$$

$\text{P}_e(d_P) =$ electron ATP measurable from UV light

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

$\text{P}_h(d_W) =$ hole ATP

k = Effective Ratio of ionization coefficients



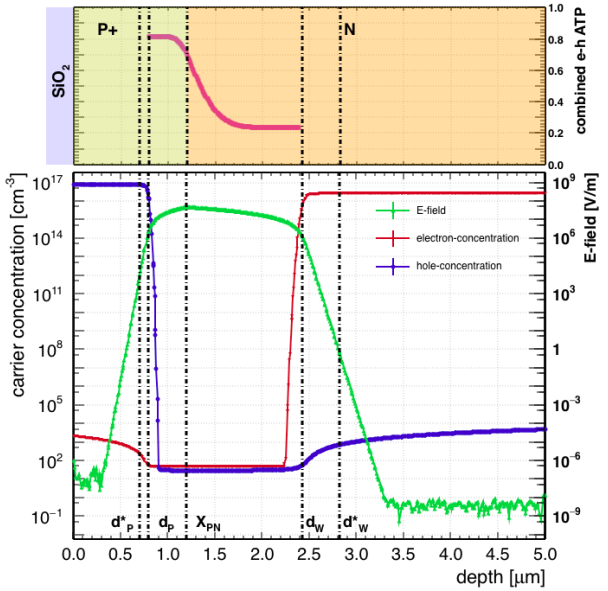
https://arxiv.org/abs/1904.05977

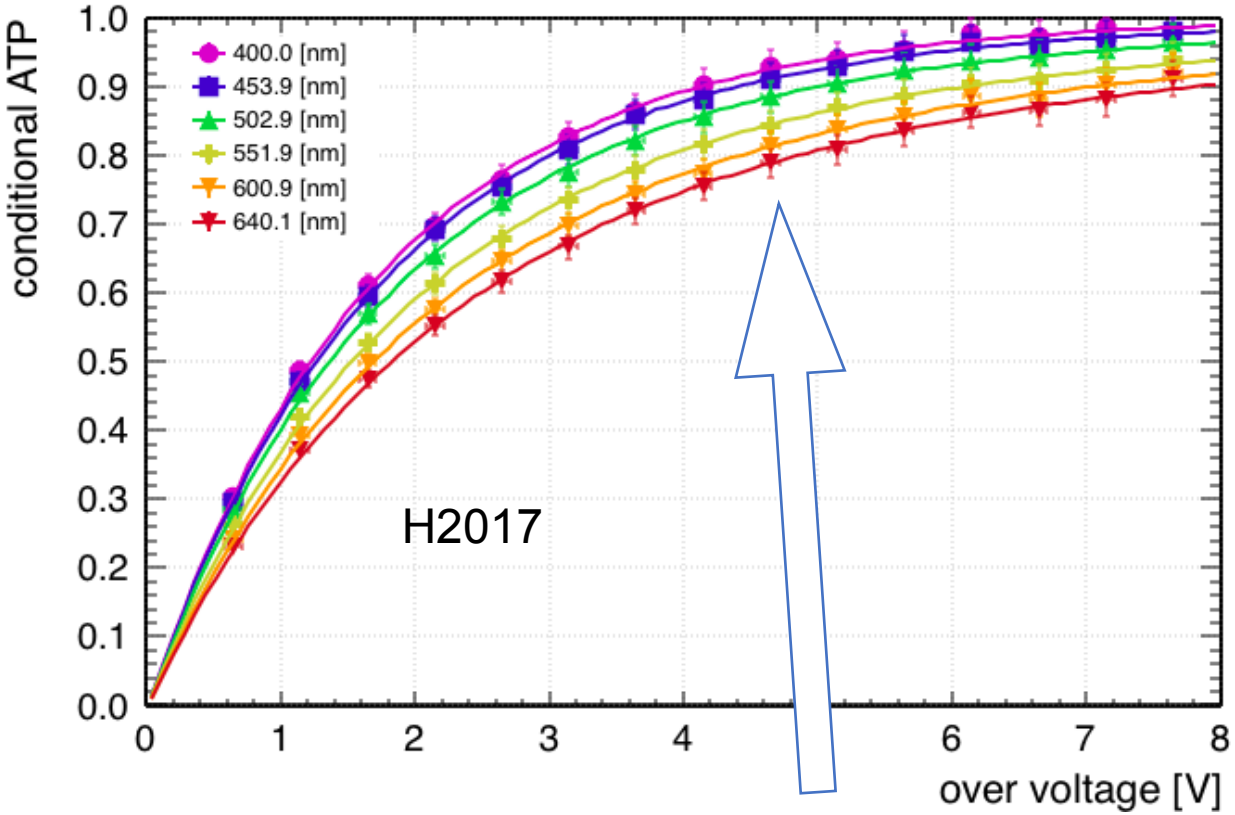
Junction Efficiency

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

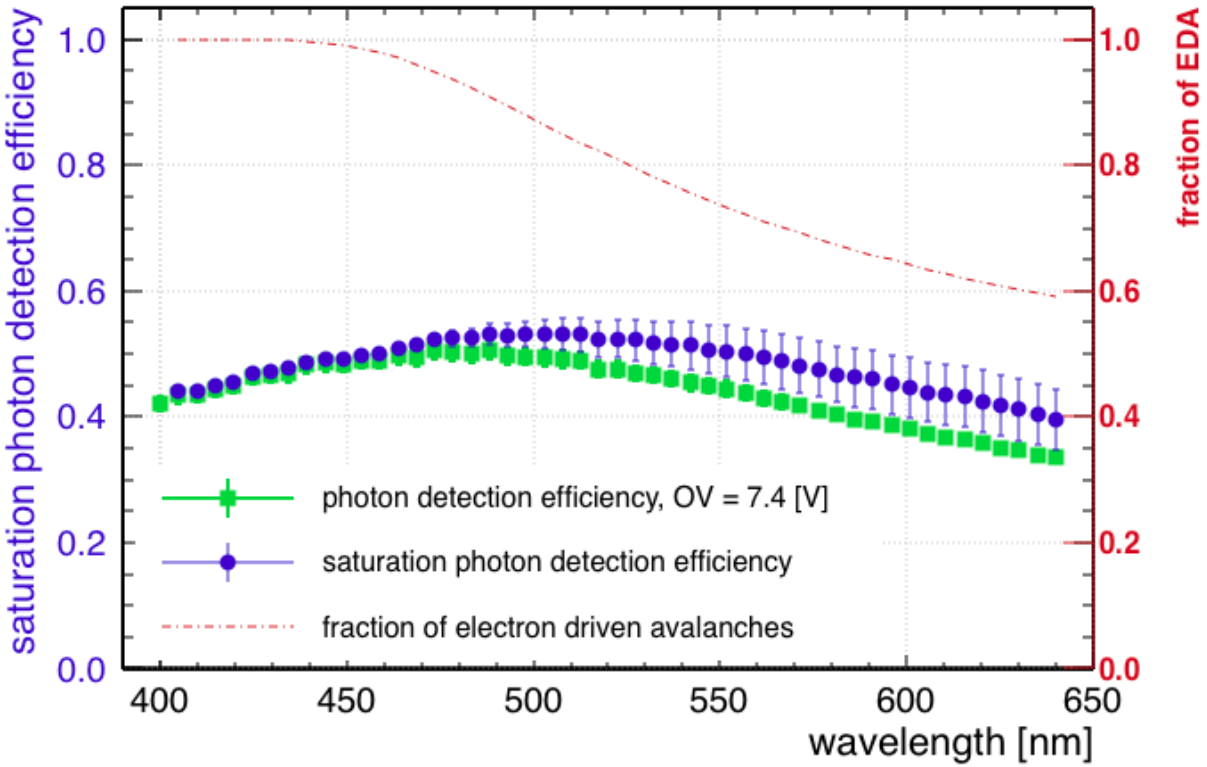
$$\text{conditional ATP} = \frac{\mathrm{PDE}}{\mathrm{PDE}_{\mathrm{MAX}}}$$

Probability to trigger an avalanche IF the photon is transmitted in the sensitive area of the detector





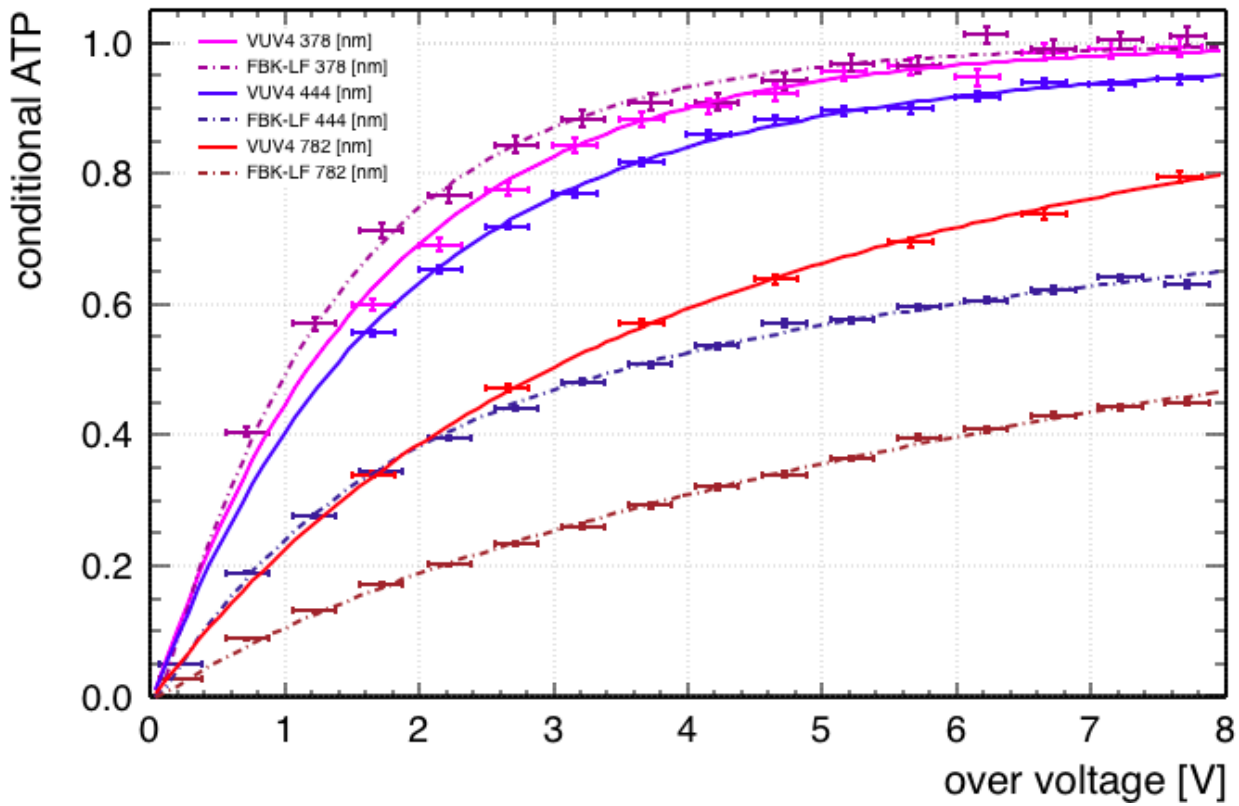
EDA: Electron Driven Avalanches

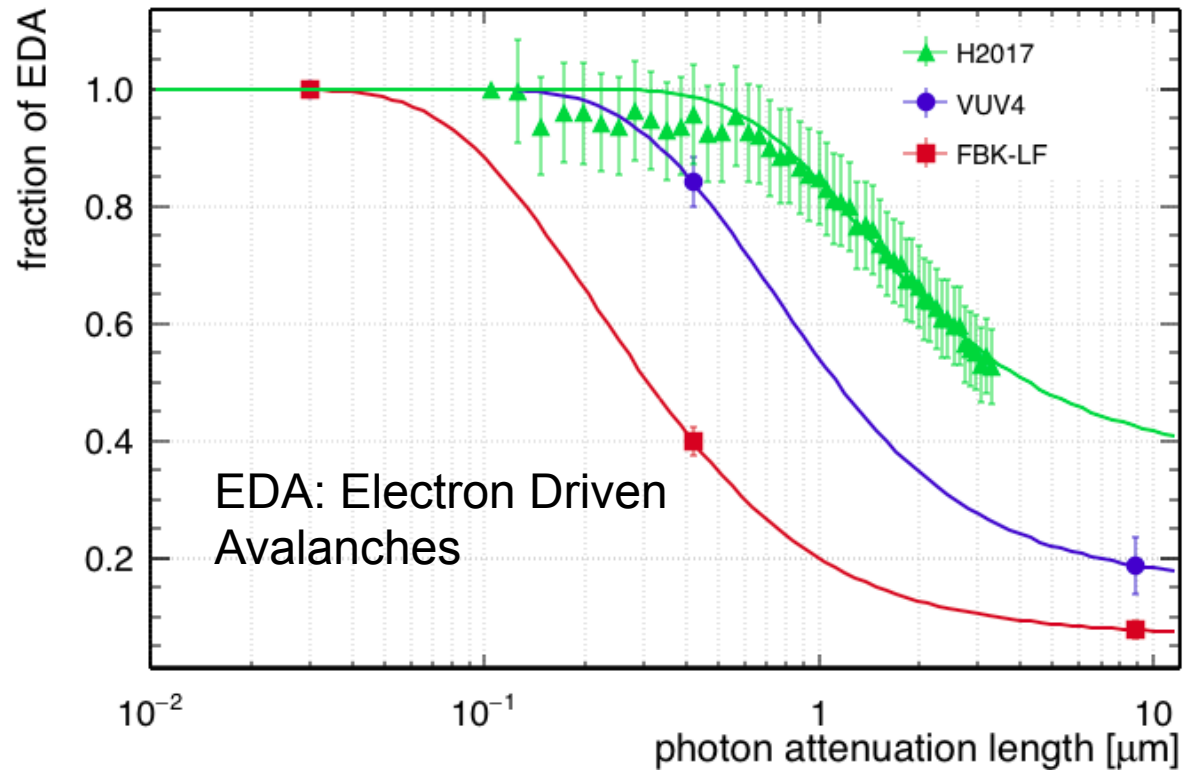


The ATP is not changing
what is changing is the absorption position

Three devices analysed

VUV4 and FBK LF





Diffusion is important !

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

Device	$\left(x_{PN} - d_P^*\right)$ [μm]	W^* [μm]	C [fF]	W[μm]	k
Hamamatsu H2017 [22]	1.8 ± 0.1	4.1 ± 0.4	163 ± 1	1.54 ± 0.01	0.25 ± 0.06
Hamamatsu VUV4 [3]	0.8 ± 0.2	3.9 ± 0.8	116 ± 6	1.01 ± 0.05	0.07 ± 0.06
FBK LF [23]	0.145 ± 0.01	2.2 ± 0.1	83 ± 5	0.92 ± 0.06	0.05 ± 0.01

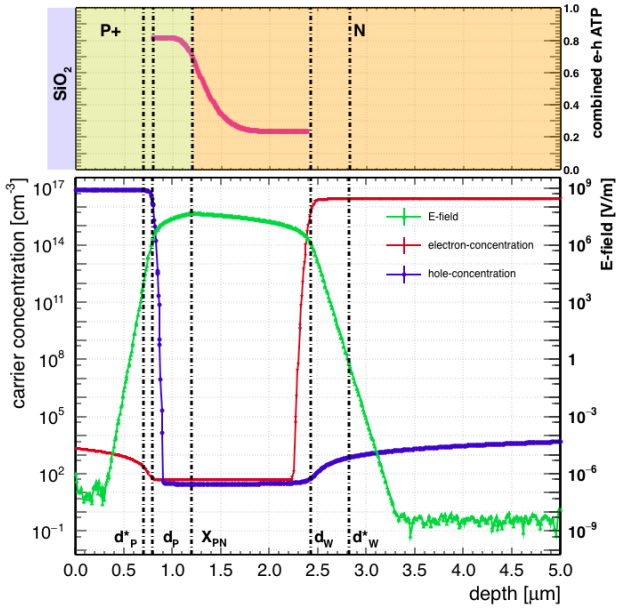
$\left(x_{PN} - d_P^*\right)$ represents the length of the region in which avalanches are triggered by an electron. W^* is the length of the effective region in which an absorbed photon can initialize an avalanche process. W is the physical junction length derived using: (i) the pixel size and the fill factor provided by each manufacturer, (ii) the single cell capacitance C extrapolated from the SiPM gain [18]. k is an effective ratio of the impact-ionization-coefficients as reported in [10].

The junction length is not enough to justify the measured PDE !

The diffusion mechanism will be subject of analysis
Understand diffusion is crucial to predict sensitivity in a certain range of wavelength

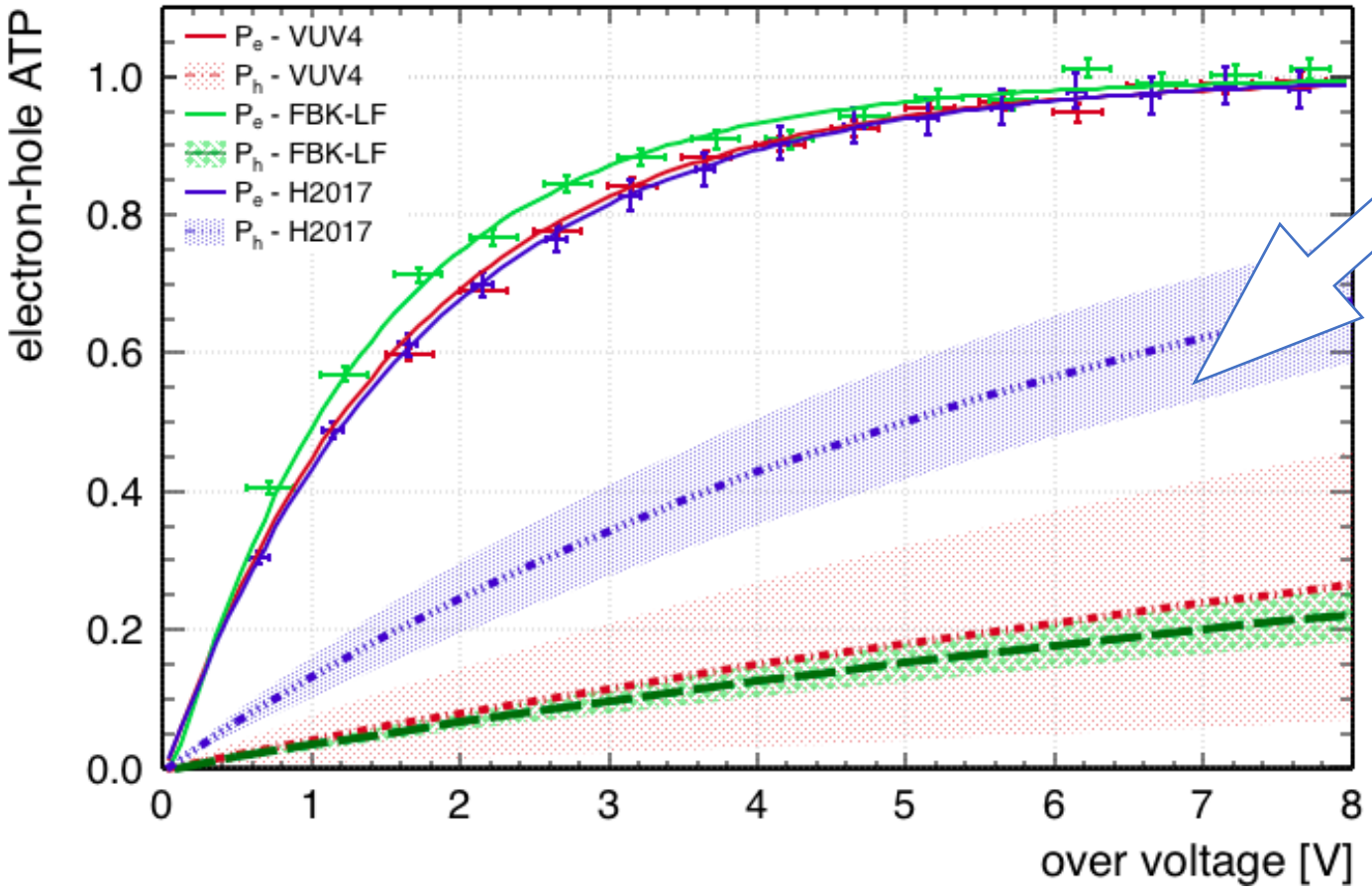
$\mathrm{P}_e(d_P) =$ electron ATP measurable from UV light

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



Extrapolation of e-h Boundaries probabilities

Pe and Ph give a figure of merit of your detector both for the NOISE and for the light detection efficiency.



Why the probabilities are different ?

The ratio of the ionisation coefficient is changing.

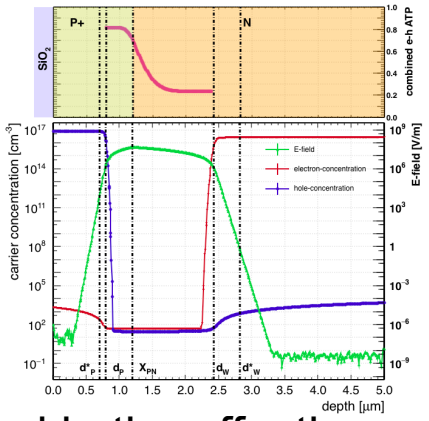
The three SiPMs have different fields.

Device	k
Hamamatsu H2017 [22]	0.25 ± 0.06
Hamamatsu VUV4 [3]	0.07 ± 0.06
FBK LF [23]	0.05 ± 0.01

<u>The FBK with lower field ionises in a better way !</u>

This can be seen looking at the total number of carriers created along its path

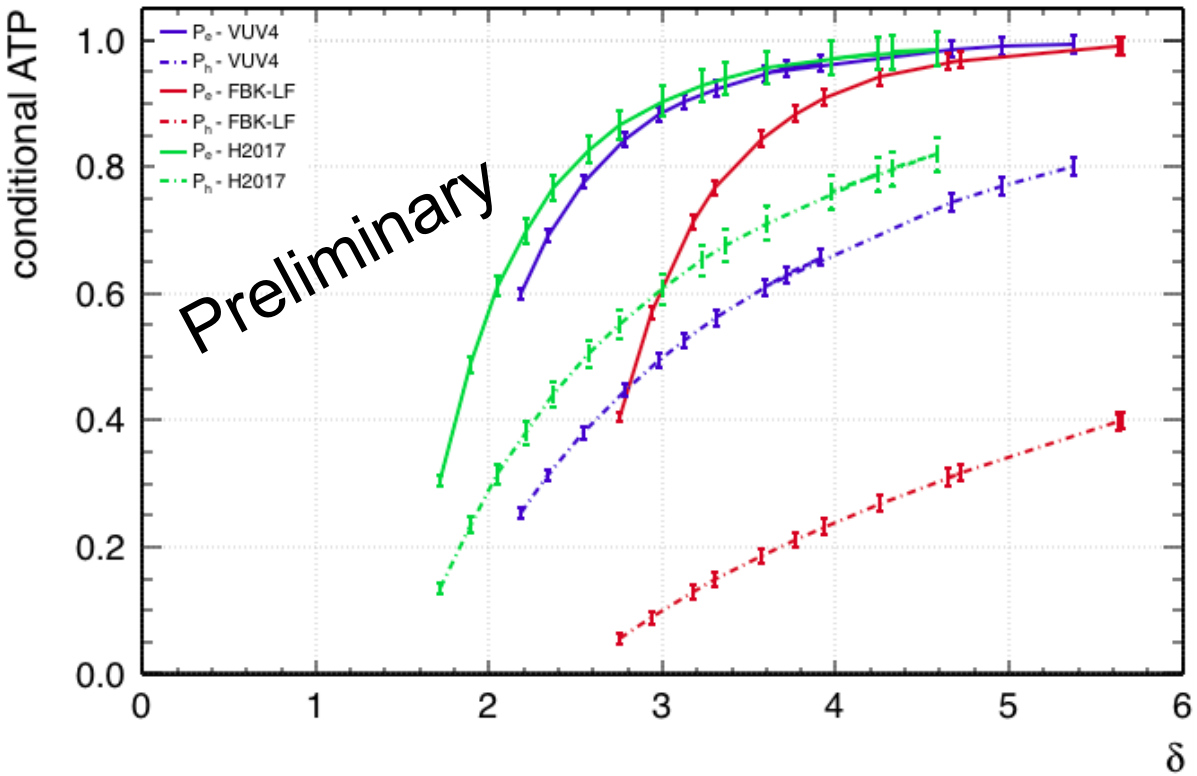
The TRIUMF SiPM: Overview of the project

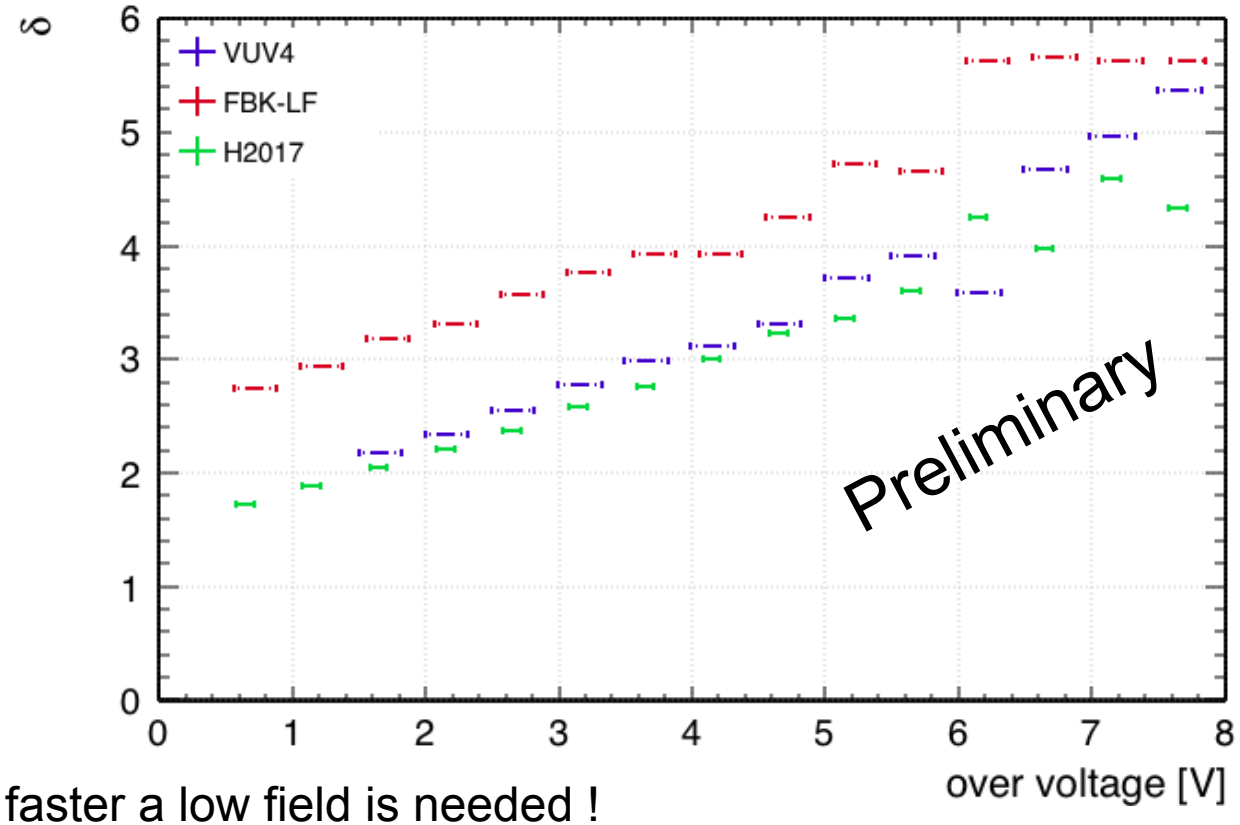


δ Weighted number of electron-hole pair created by the incoming photon due to impact ionisation along particle path

$$\text{conditional ATP} = \frac{\text{PDE}}{\text{PDE}_{\text{MAX}}}$$

Probability to trigger an avalanche IF the photon is absorbed in the effective region





To have a PDE that saturates faster a low field is needed !

Summary of the first part

FBK LF significantly exceeds nEXO requirements

Hamamatsu VUV4 is marginally close to meet nEXO requirements

University of Alabama, Tuscaloosa AL, USA
M Hughes, O Nusair, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan
University of Bern, Switzerland — J-L Vuilleumier
Brookhaven National Laboratory, Upton NY, USA
M Chiu, G Giacomini, V Radeka, E Raguzin, S Rescia, T Tsang
University of California, Irvine, Irvine CA, USA — M Moe
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada
I Badhrees, R Gornea, C Jessiman, T Koffas, D Sinclair, B. Veenstra, J Watkins
Colorado State University, Fort Collins CO, USA
C Chambers, A Craycraft, D Fairbank, W Fairbank Jr, A Iverson, J Todd
Drexel University, Philadelphia PA, USA
MJ Dolinski, P Gautam, E Hansen, YH Lin, E Smith, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
Friedrich-Alexander-University Erlangen, Nuremberg, Germany
G Anton, J Hoessl, T Michel, M Wagenpfeil, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard
IHEP Beijing, People's Republic of China — G Cao, W Cen, Y Ding,
X Jiang, Z Ning, X Sun, T Tolba, W Wei, L Wen, W Wu, X Zhang, J Zhao
IME Beijing, People's Republic of China — L Cao, X Jing, Q Wang
ITEP Moscow, Russia — V Belov, A Burenkov, A Karelin,
A Kobyakin, A Kuchenkov, V Stekhanov, O Zeldovich
University of Illinois, Urbana-Champaign IL, USA
D Beck, M Coon, J Echevers, S Li, L Yang
Indiana University, Bloomington IN, USA — JB Albert, SJ Daugherty, G Visser
Laurentian University, Sudbury ON, Canada — B Cleveland,
A Der Mesrobian-Kabakian, J Farine, C Licciardi, A Robinson, U Wichoski
Lawrence Livermore National Laboratory, Livermore CA, USA
J Brodsky, M Heffner, A House, S Sangiorgio, T. Stiegler
University of Massachusetts, Amherst MA, USA
S Feyzbakhsh, D Kodroff, A Pocar, M Tarka
McGill University, Montreal QC, Canada
T Brunner, K Murray, T Totev, L Darroch, S Al Kharusi, T McElroy
University of North Carolina, Wilmington, USA — T Daniels
Oak Ridge National Laboratory, Oak Ridge TN, USA — L Fabris, RJ Newby
Pacific Northwest National Laboratory, Richland, WA, USA
I Arnquist, EW Hoppe, JL Orrell, G Ortega, C Overman, R Saldanha, R Tsang
Rensselaer Polytechnic Institute, Troy NY, USA — E Brown, K Odgers
Université de Sherbrooke
F Bourque, S Charlebois , M Côté, D Danovitch, H Dautet,
R Fontaine, F Nolet, S Parent, JF Pratte, T Rossignol, J Sylvestre, F Vachon
SLAC National Accelerator Laboratory, Menlo Park CA, USA
S Delaquis, A Dragone, G Haller, LJ Kaufman,
B Mong, A Odian, M Oriunno, PC Rowson, K Skarpaas
University of South Dakota, Vermillion SD, USA
T Bhatta, A Larson, R MacLellan
Stanford University, Stanford CA, USA — J Dalmasson, R DeVoe, D Fudenberg,
G Gratta, M Jewell, S Kravitz, G Li, M Patel, A Schubert, M Weber, S Wu
Stony Brook University, SUNY, Stony Brook NY, USA — K Kumar, O Njoya
Technical University of Munich, Garching, Germany — P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada
J Dilling, P Gumplinger, R Krücken, Y Lan, F Retière, V Strickland
Yale University, New Haven CT, USA — A Jamil, Z Li, D Moore, Q Xia

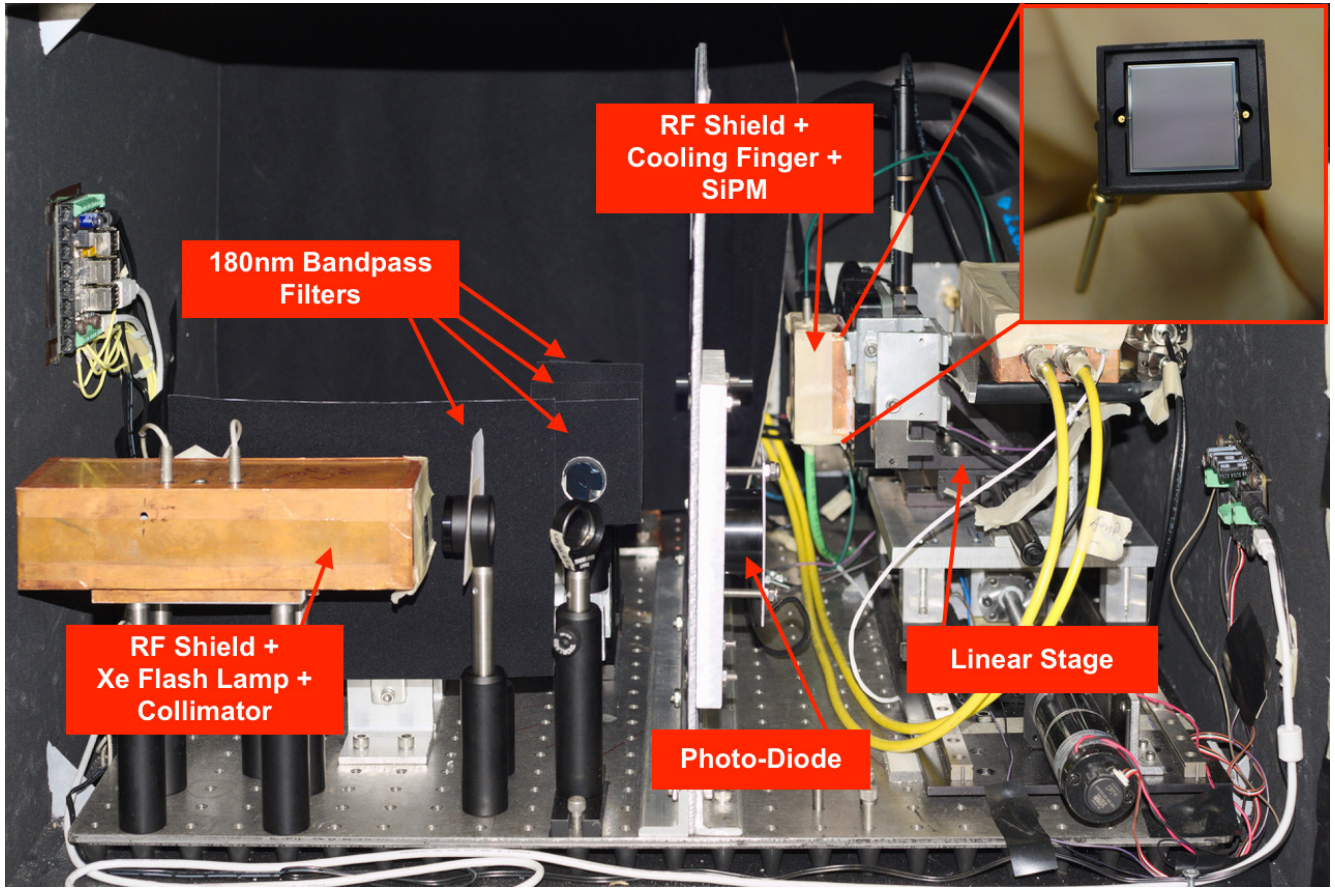
Next Steps :

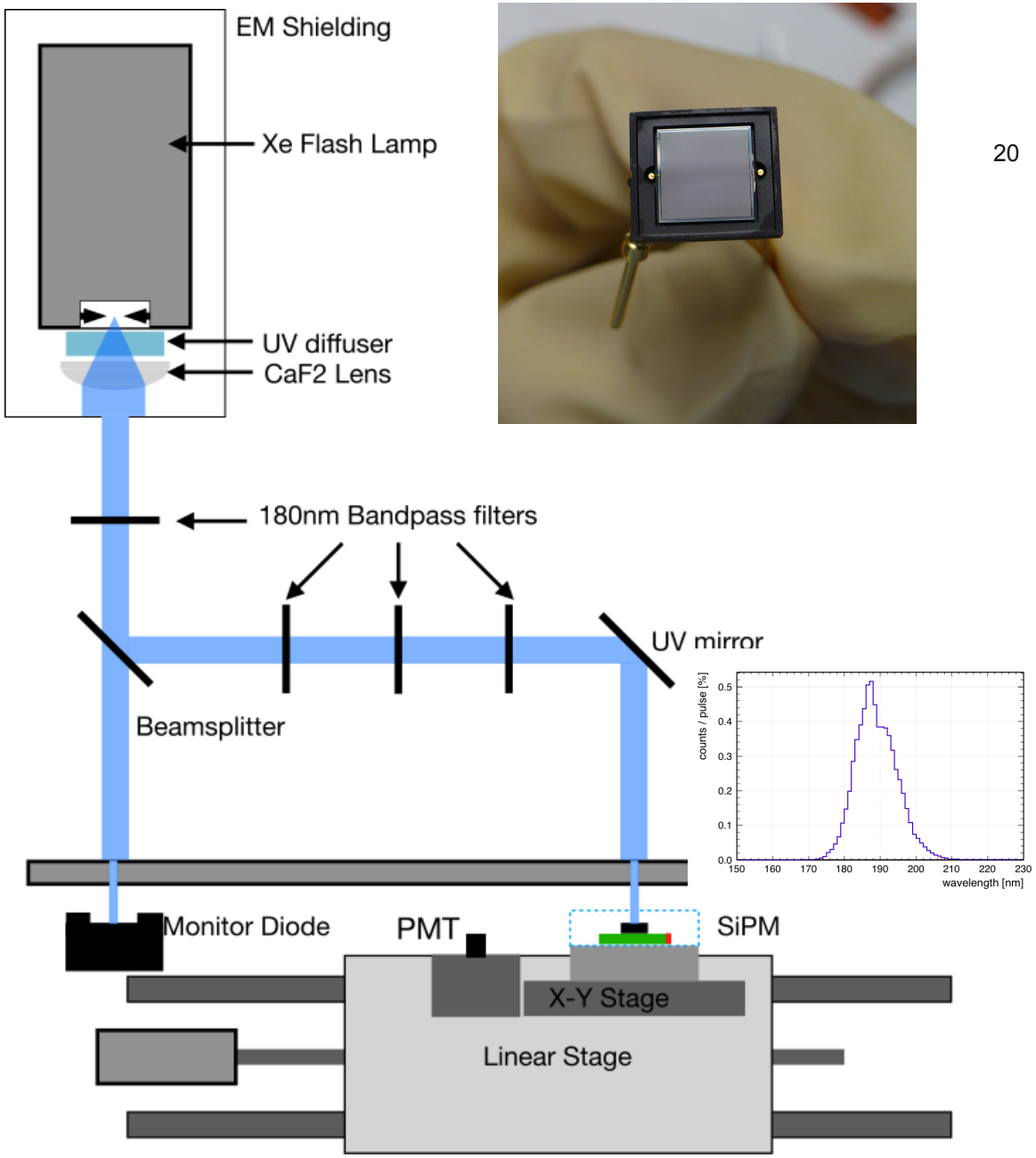
Parameter	FBK LF	HPK VUV4	3DdSiPM
Next steps	New production from FBK is at TRIUMF FBK Reflectivity in LXe is under testing	VUV4 reflectivity in LXe is now under testing	VUV sensitivity

<u>TRIUMF is working to develop a new generation of VUV SiPMs for low light level detection in Liquid Argon and Liquid Xenon</u>

Thank you

TRIUMF Setup





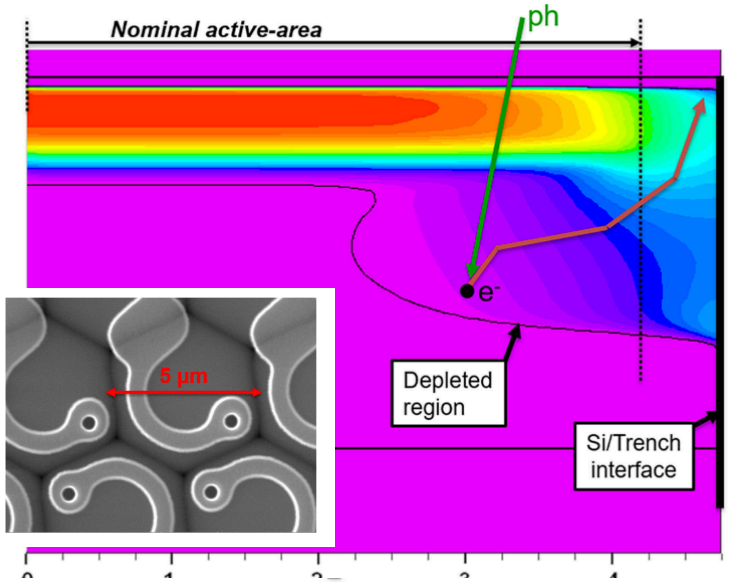
Optical Efficiency

$$\text{PDE} \sim \epsilon_0 \cdot \int_{d_P^*}^{d_W^*} \frac{1}{\mu} \exp\left(-\frac{x}{\mu}\right) \cdot \text{P}_\text{P}(x, V)\, dx$$

Optical Efficiency:
Probability to be transmitted in the silicon

$$\epsilon_0(\lambda) \sim \left[\text{FF} \times \left(1 - \text{R}(\lambda, \theta)\right)\right]$$

FF: Fill Factor



R: Reflectivity

<u>ARC is important !</u>