Nuisance Processes in p-on-n SiPMs

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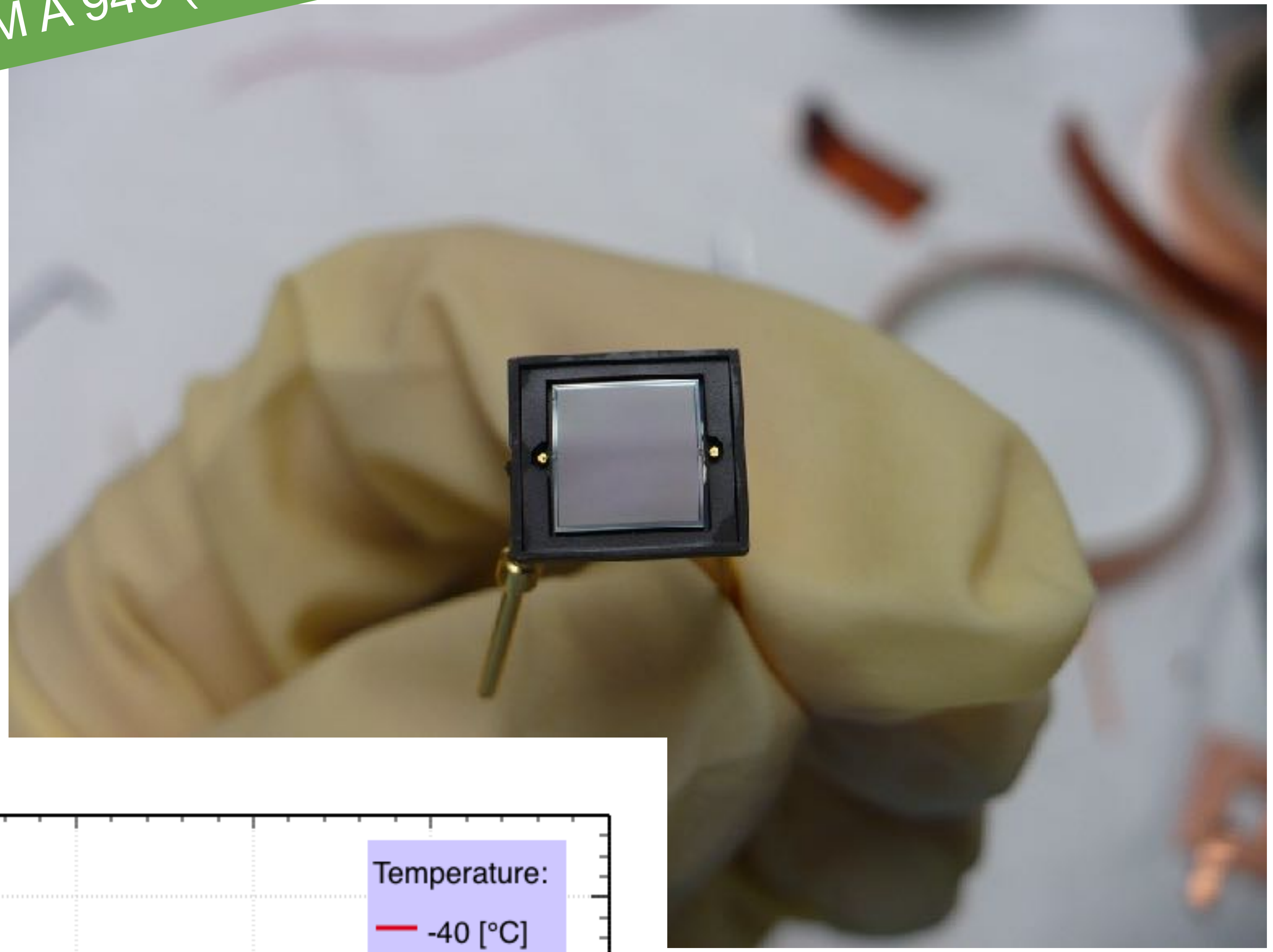
Discovery, accelerated

Overview

Introduction to SiPMs

NIM A 940 (2019)

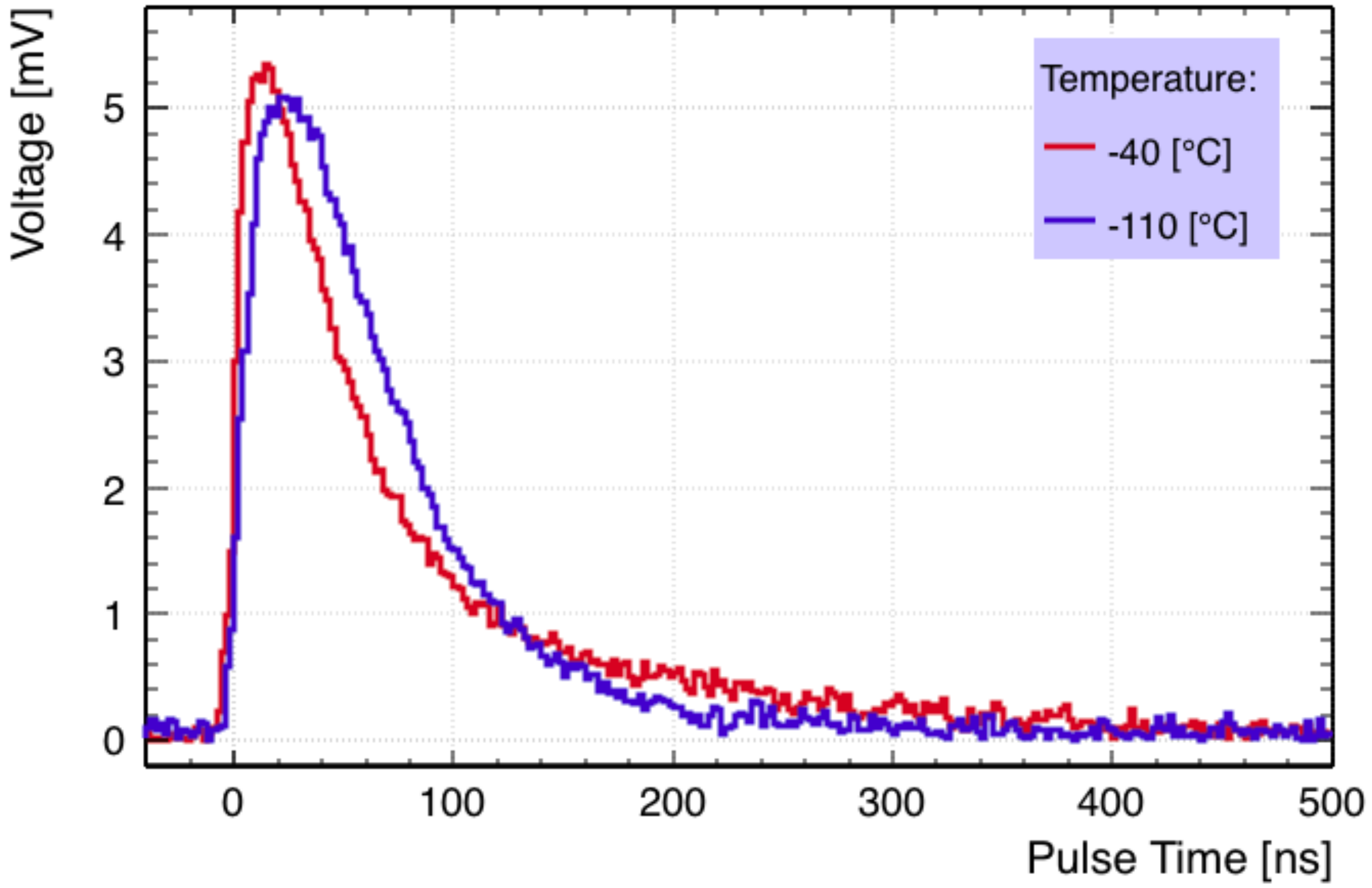


Main Characteristics:

- 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



Noise Sources in SiPMs

<u>Uncorrelated Avalanche Noise</u>

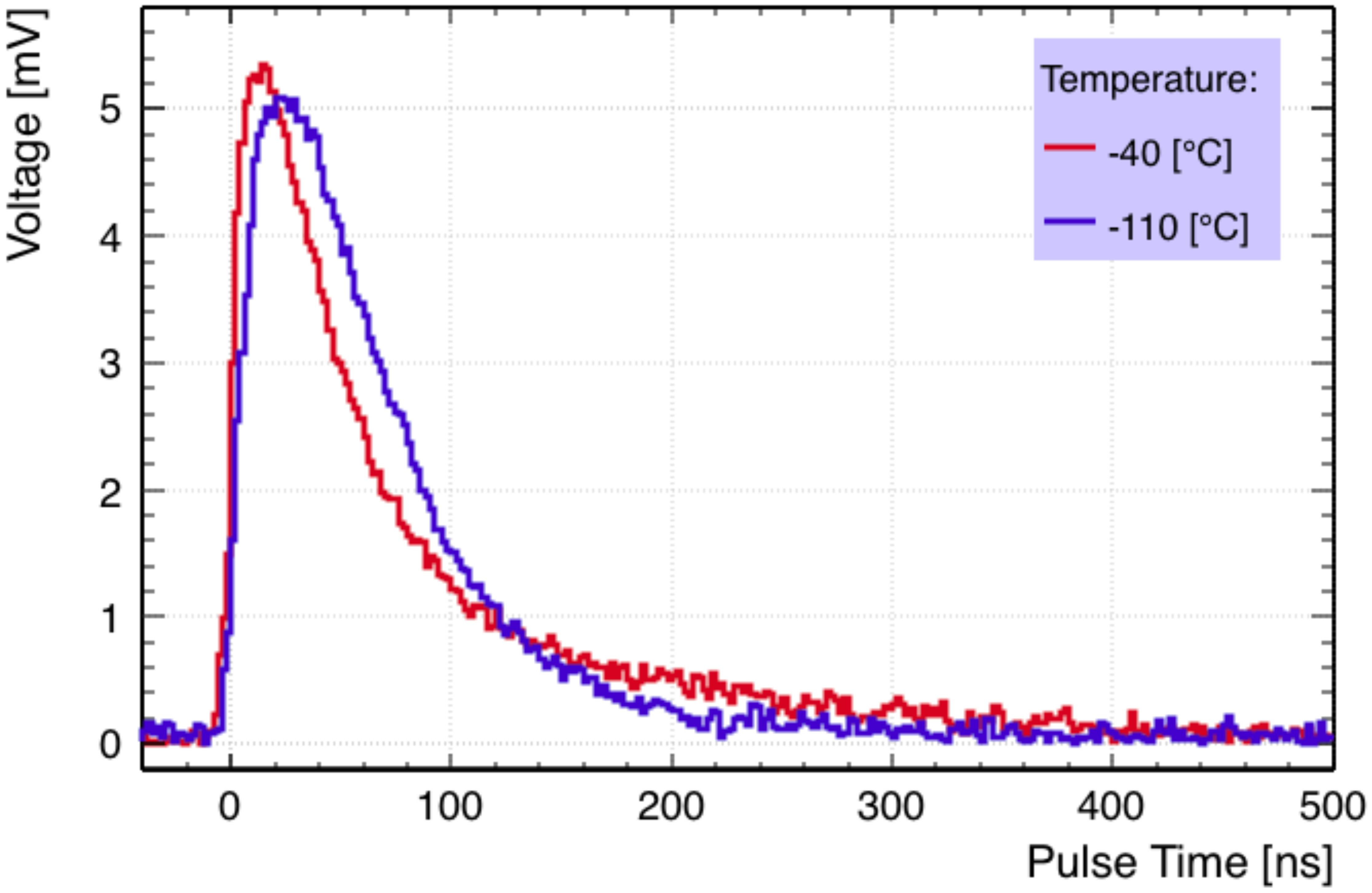
- Dark Noise (DN)

<u>Correlated Avalanche Noise (CA)</u>

- Afterpulse (AP)
- Cross talk (CT)

*This talk will focus on **SiPM Dark Noise and CA noise modellization***

- Explain voltage and temperature dependence of nuisance processes in Geiger mode devices
- In literature several models for avalanche photodiodes are available but literature is limited for Geiger mode devices



10.1016/j.nima.2014.04.045

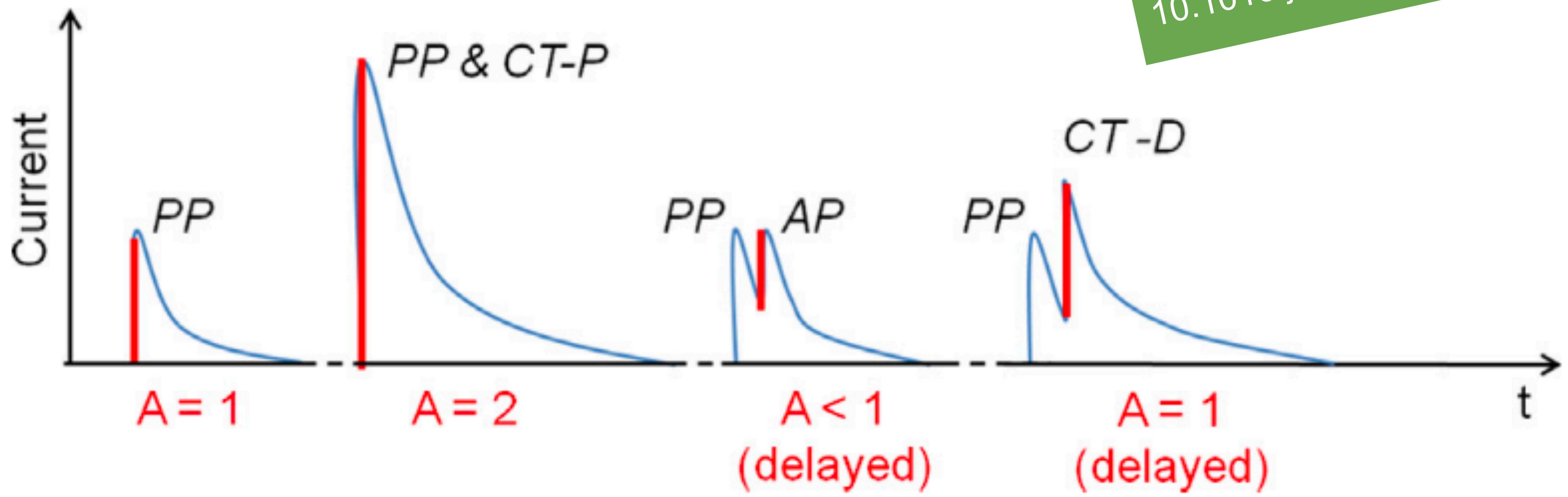


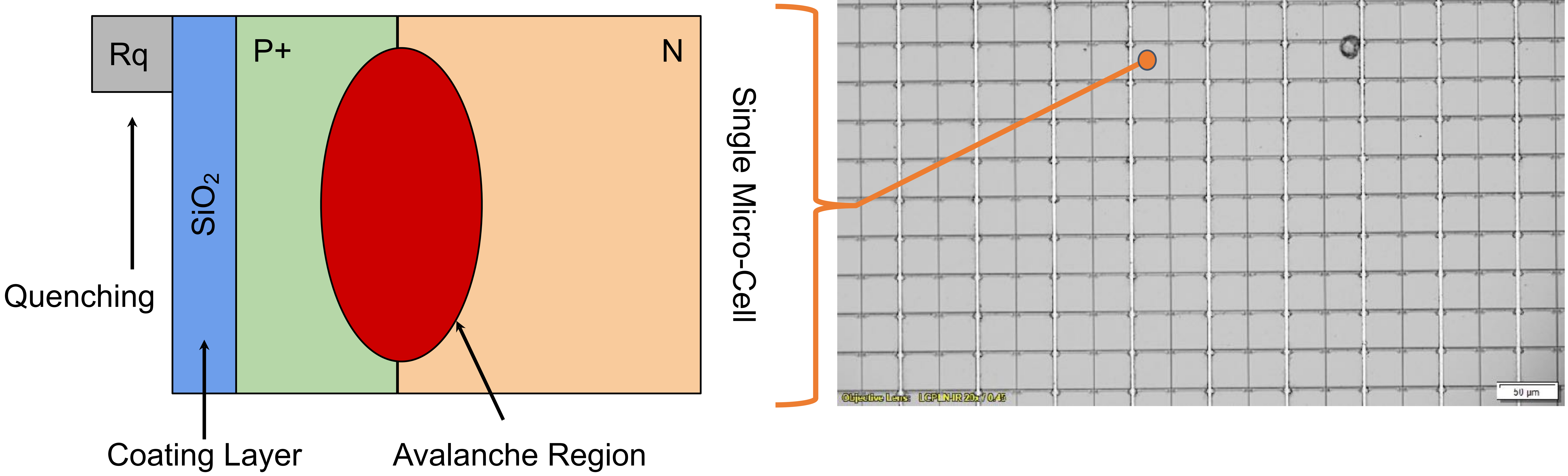
Fig. 7. Primary pulses (PP) with different types of correlated pulses such as prompt CT (CT-P), afterpulse (AP) and delayed CT (CT-D).

Modellization of the SiPM Dark Noise Rate

How Do SiPMs work ?

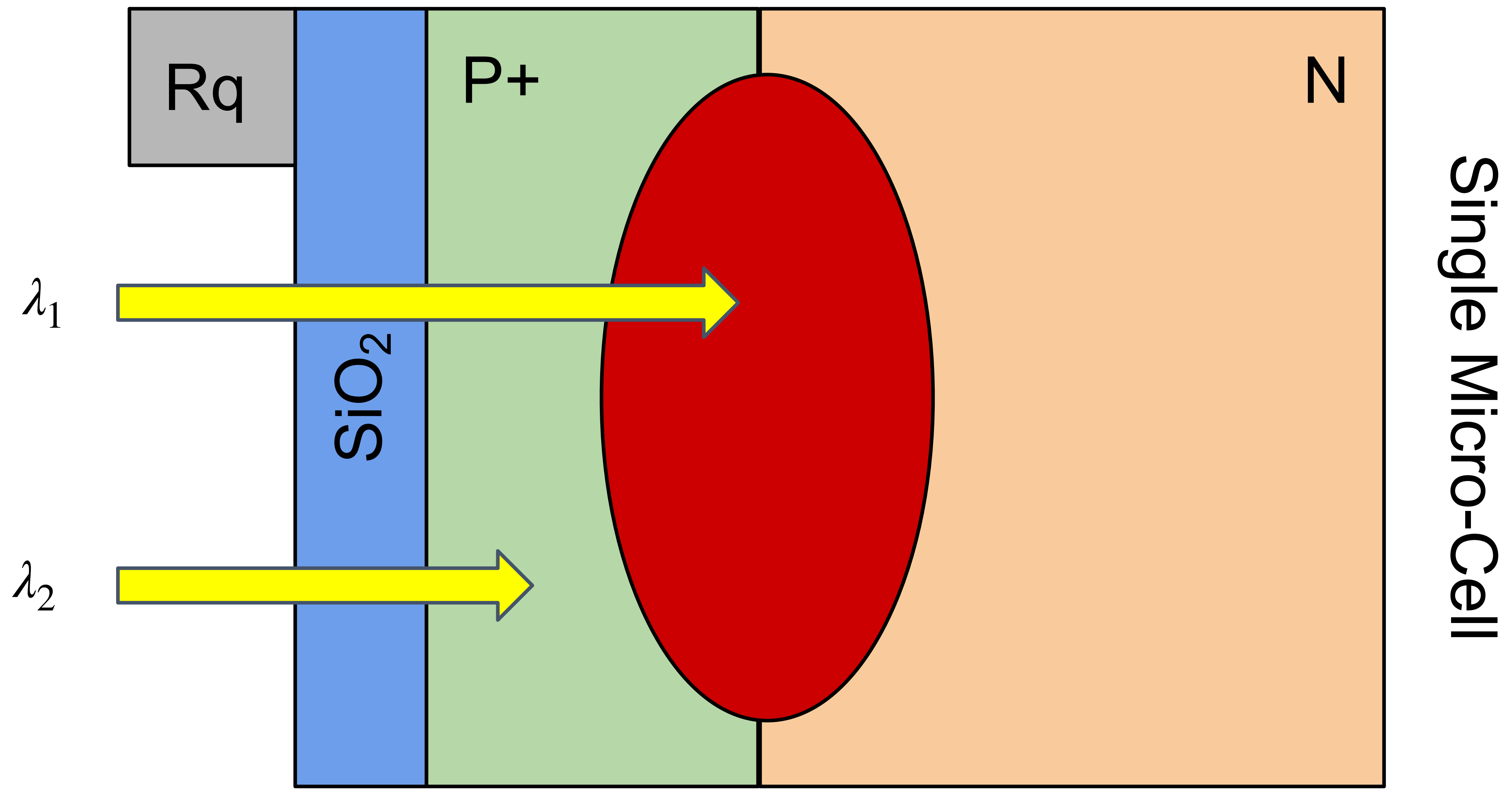
iEEE TED 66.10 (2019)

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

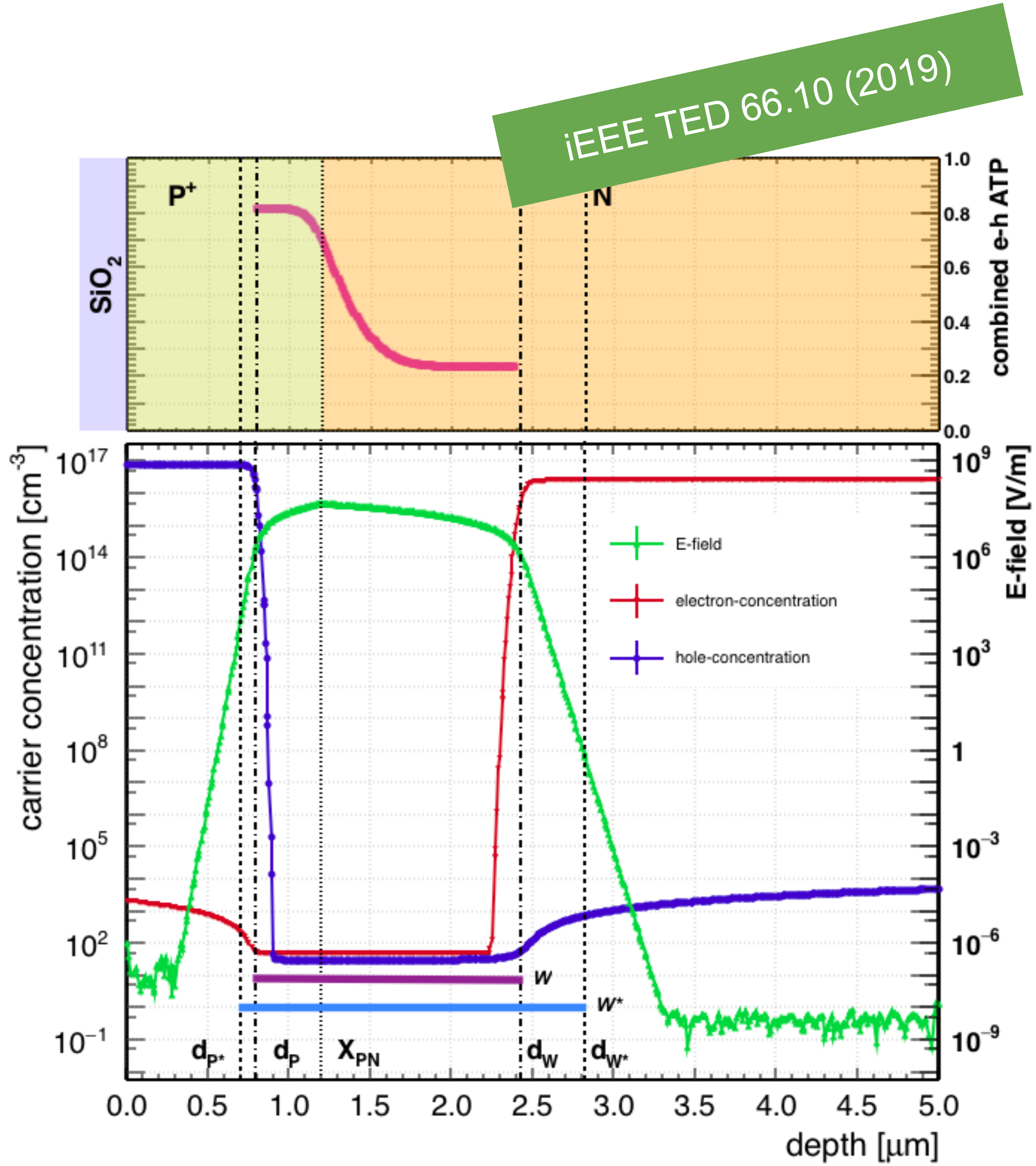


How Do SiPMs work ?

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



$\lambda_1 > \lambda_2$

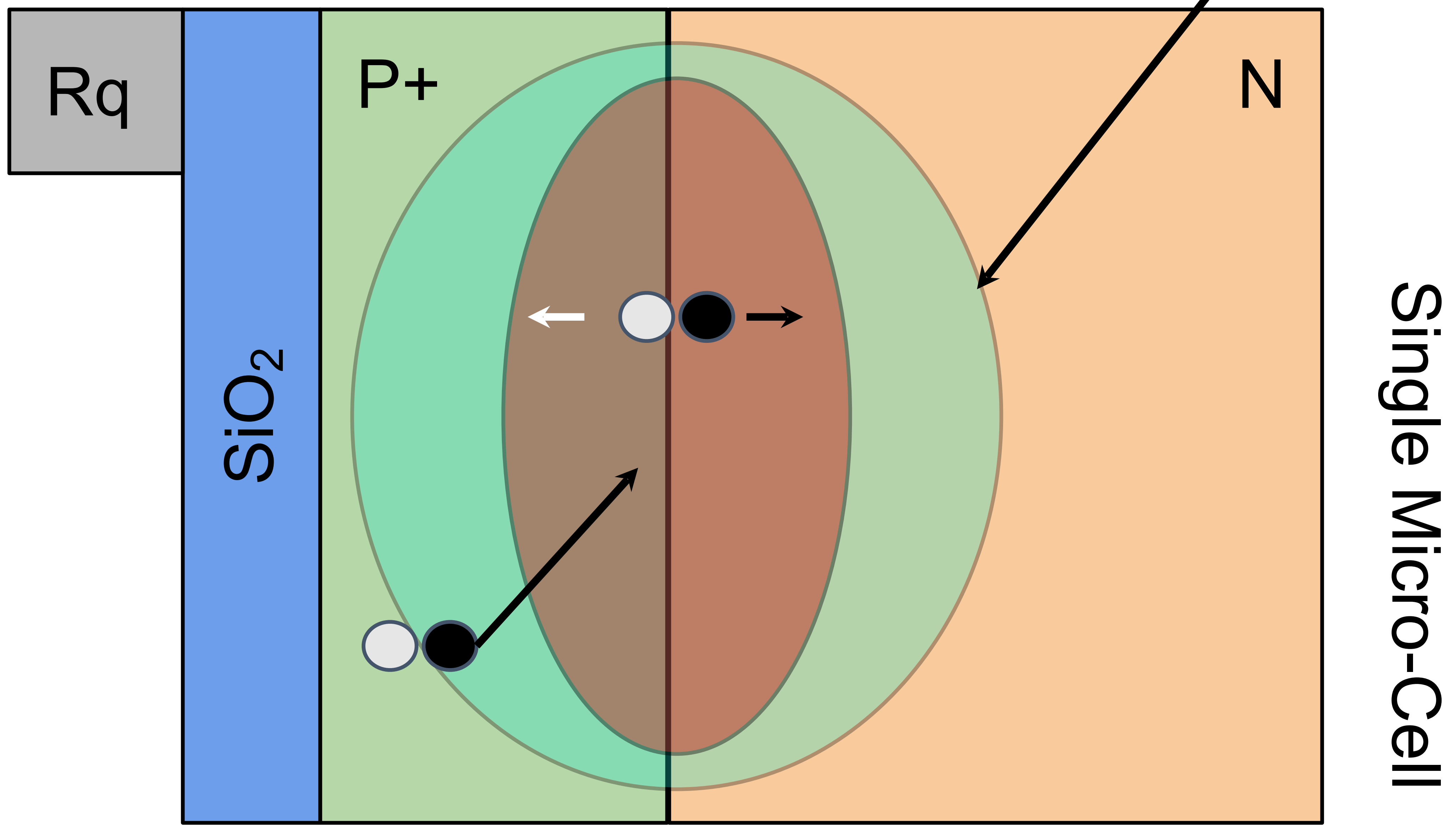


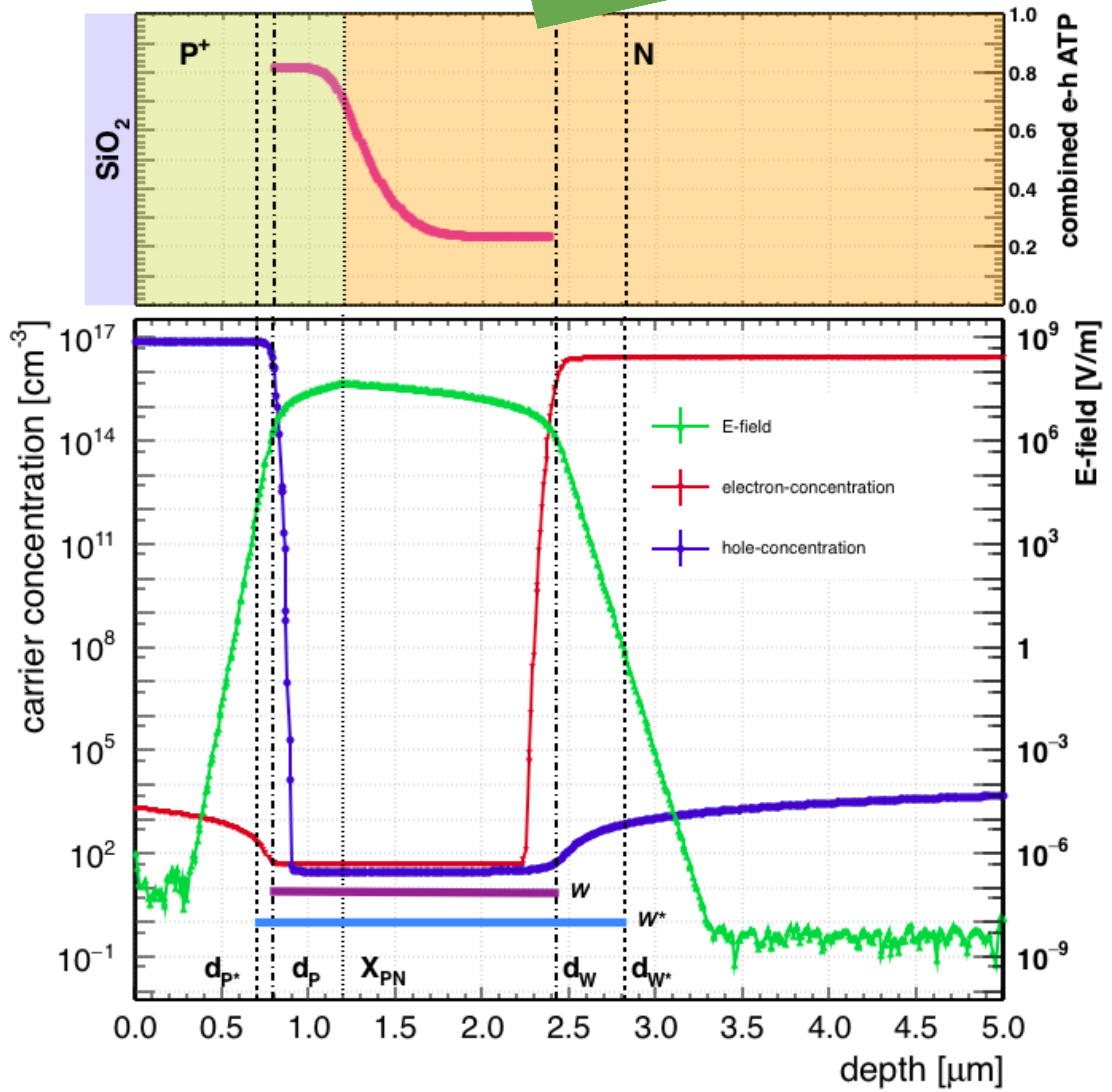
How Do SiPMs work ?

Effective photon collection region

iEEE TED 66.10 (2019)

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





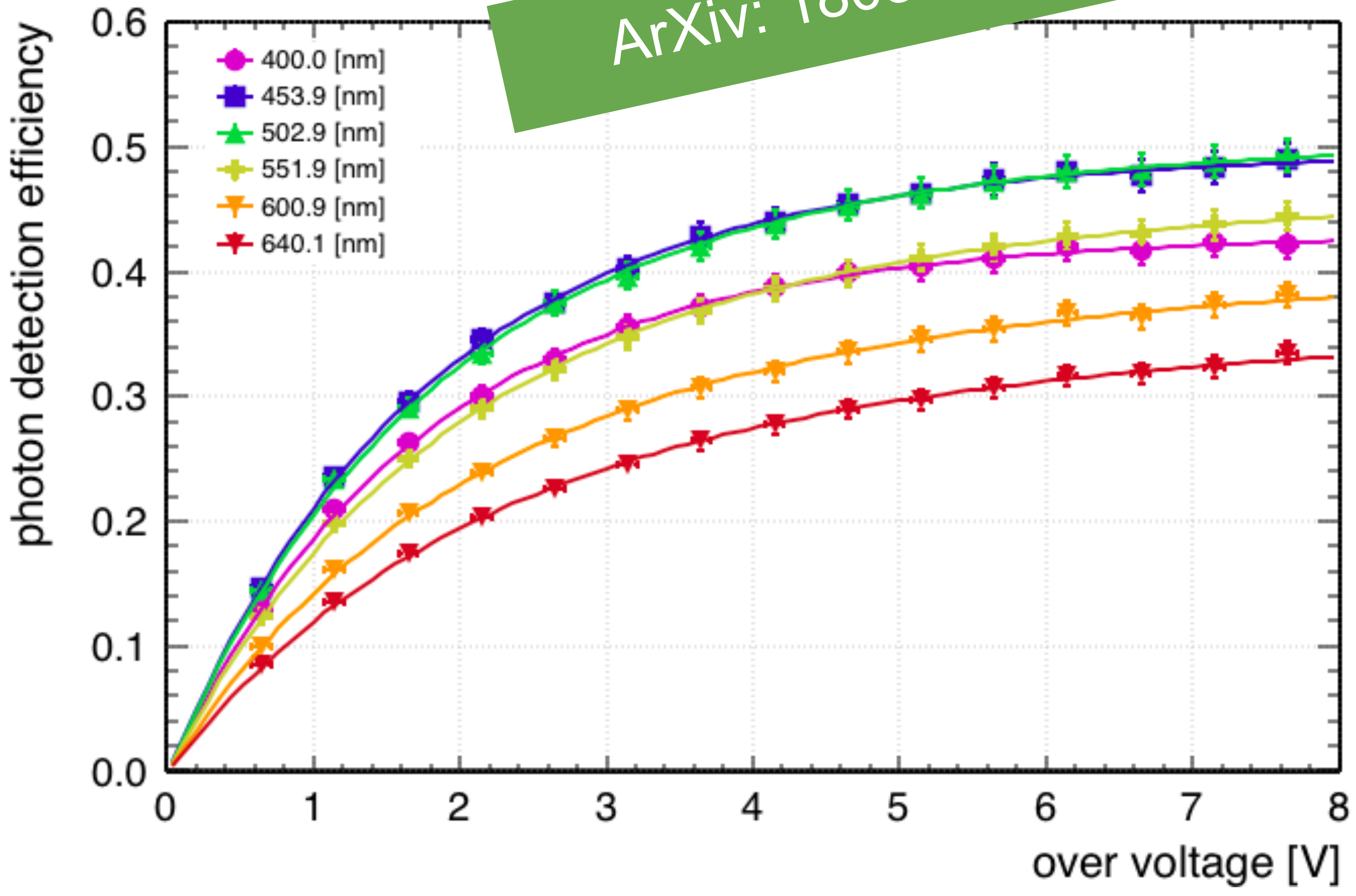
1) The e-h pair can be created or not in the depleted region.

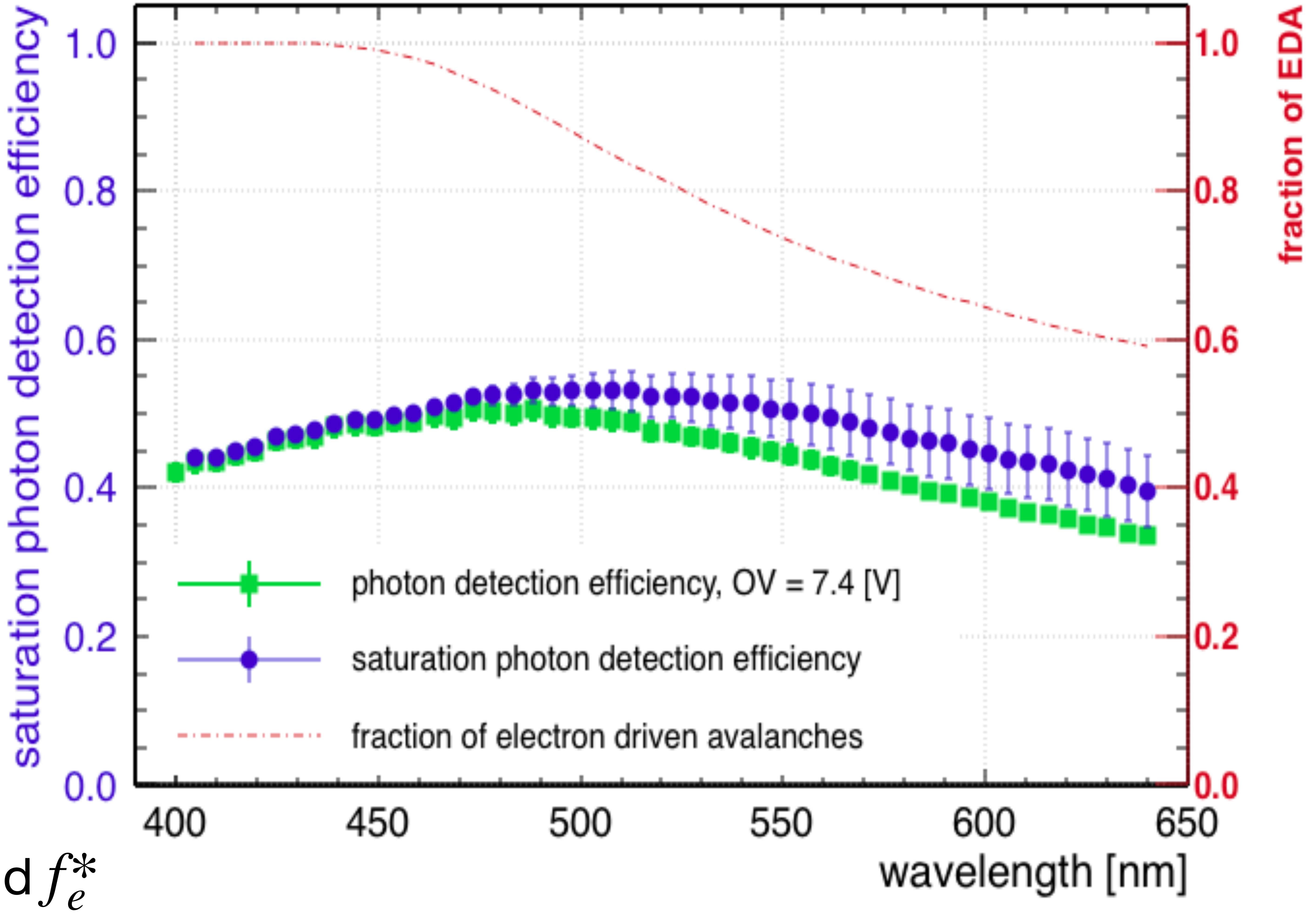
2) Absorption and avalanche triggering probabilities are correlated since the latter probability depends where the photon is absorbed

Avalanche Triggering Probability

iEEE TED 66.10 (2019)

ArXiv: 1808.05775





PDE data were fitted with

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

and used to extrapolate: $P_e(d_P)$, $P_h(d_W)$ and f_e^*

EDA: Electron Drive Avalanches == f_e^*

Dark Noise Rate

$P_e(d_P)$, $P_h(d_W)$ are the same probabilities derived in iEEE TED 66.10 (2019)

The Total Dark Noise Rate can be treated as a sum of electron and hole driven avalanches.

The difference is in the source:

1) Thermal (only)
2) Thermal - field enhanced

Shockley-Read-Hall rate c_{srh}

Preliminary

$$R_{DN} = \Bigg\{ c_{srh} P_e(d_P) \Bigg[\Big(f_{DN}(W - W_0) \Big) + \frac{\sqrt{3\pi} W F_\Gamma}{2|F_m|} \Bigg[\exp\Big(\frac{F_m}{F_\Gamma}\Big)^2 - \exp\Big(\frac{F_m}{F_\Gamma}\Big(1 - \frac{2}{W} f_{DN}(W - W_0)\Big)\Big)^2 \Bigg] \Bigg] +$$

$$c_{srh} P_h(d_W) \Bigg[\Big((1 - f_{DN})(W - W_0) \Big) +$$

$$+ \frac{\sqrt{3\pi} W F_\Gamma}{2|F_m|} \Bigg[\exp\Big(\frac{F_m}{F_\Gamma}\Big)^2 - \exp\Big(\frac{F_m}{F_\Gamma}\Big(1 - \frac{2}{W}(1 - f_{DN})(W - W_0)\Big)\Big)^2 \Bigg] \Bigg] \Bigg\}$$

Electron Driven Avalanches

Hole Driven Avalanches

This equation was derived with a symmetric junction approximation. We worked also on an extension for asymmetric junctions

Dark Noise Rate

$P_e(d_P)$, $P_h(d_W)$ are the same probabilities derived in iEEE TED 66.10 (2019)

1) Thermal (only)
2) Thermal field enhanced

Preliminary

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Fitting Parameters:

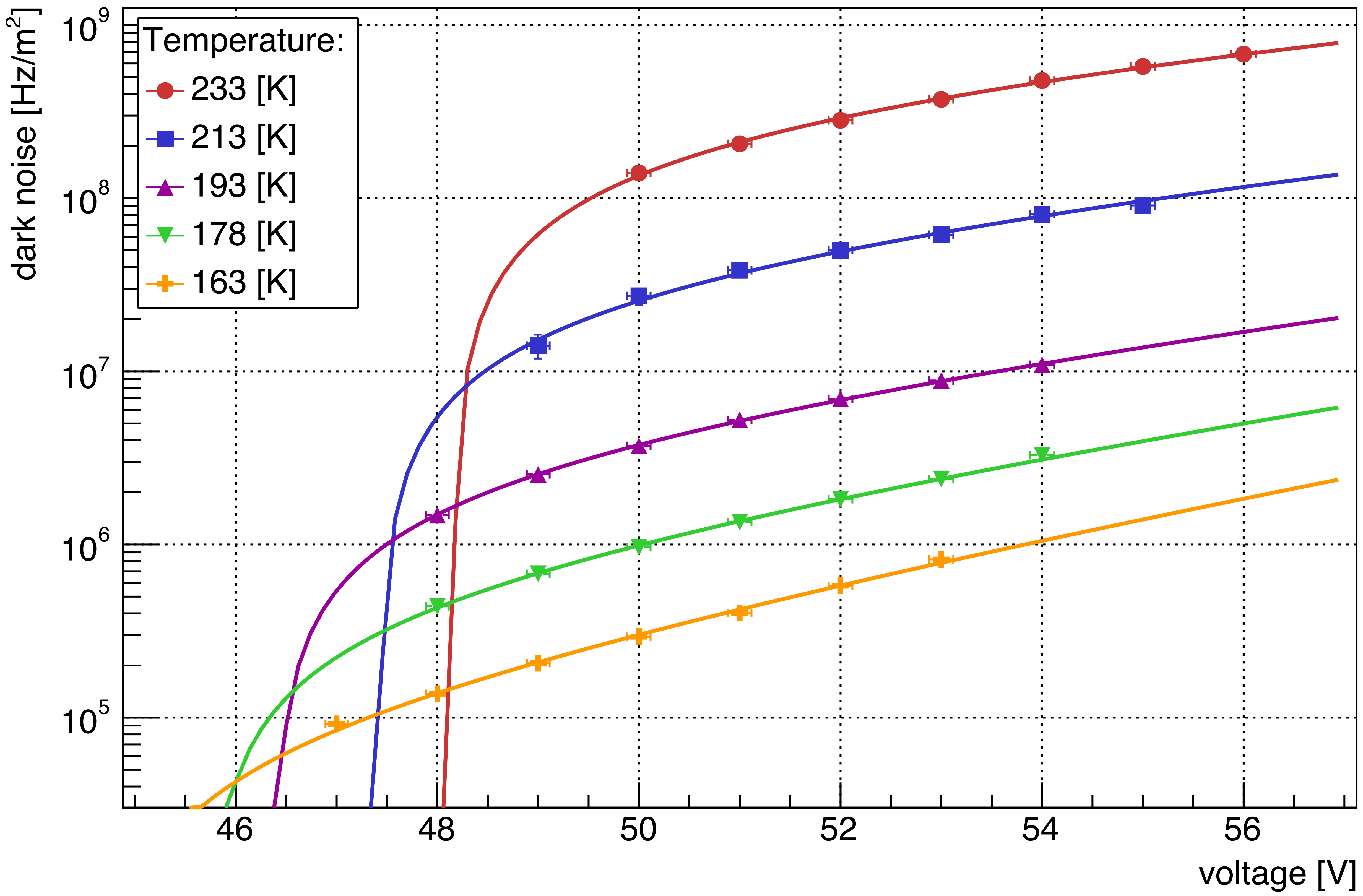
c_{srh}	Shockley-Read-Hall rate
f_{DN}	Fraction of Noise Avalanche Driven by Electron
W_0	Junction at Zero Bias

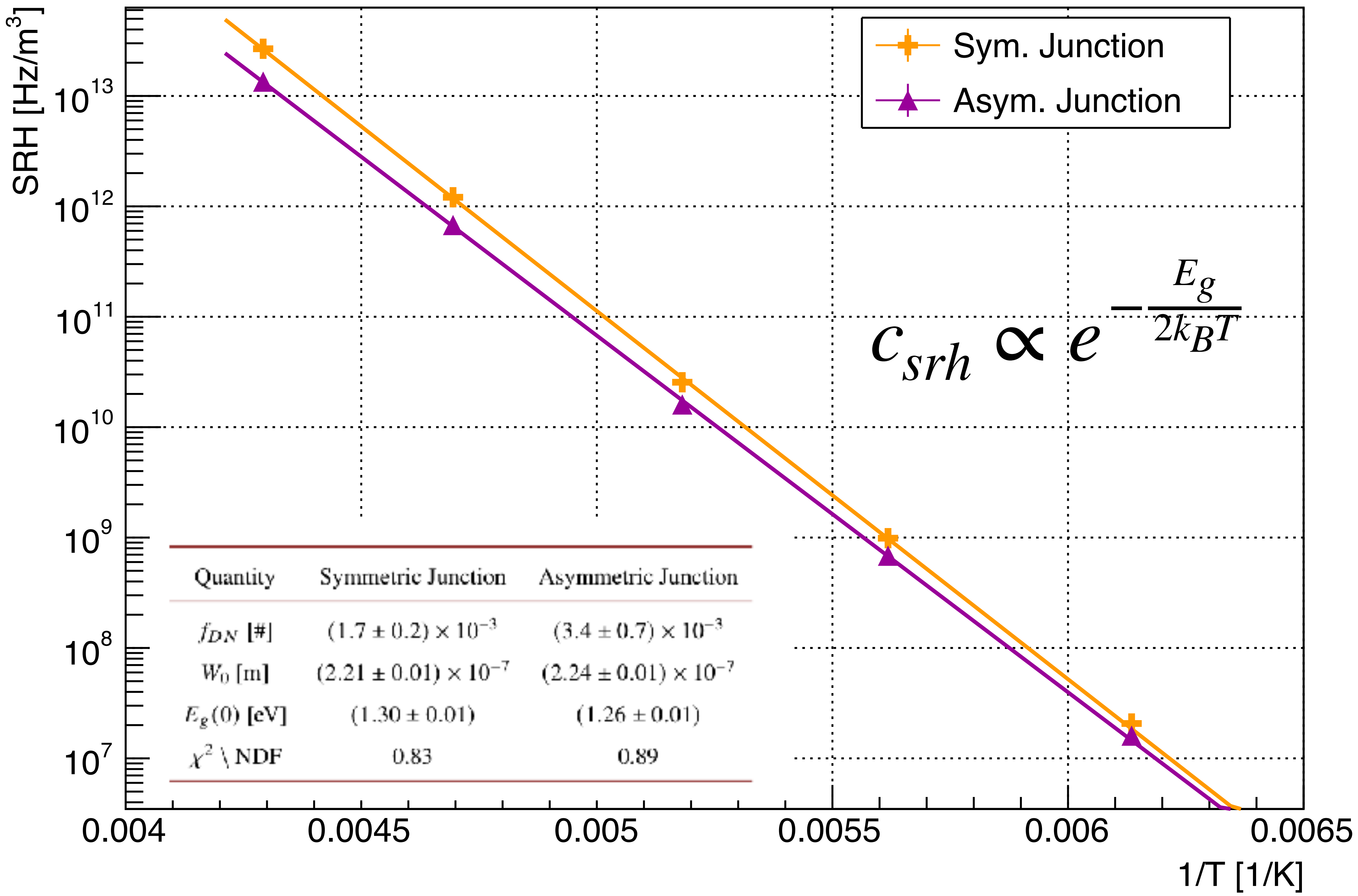
Thermal Contribution -> Negligible

Thermal Field Enhanced Contribution
Dominant Contribution

c_{srh} has a precise temperature dependence

Hamamatsu VUV4





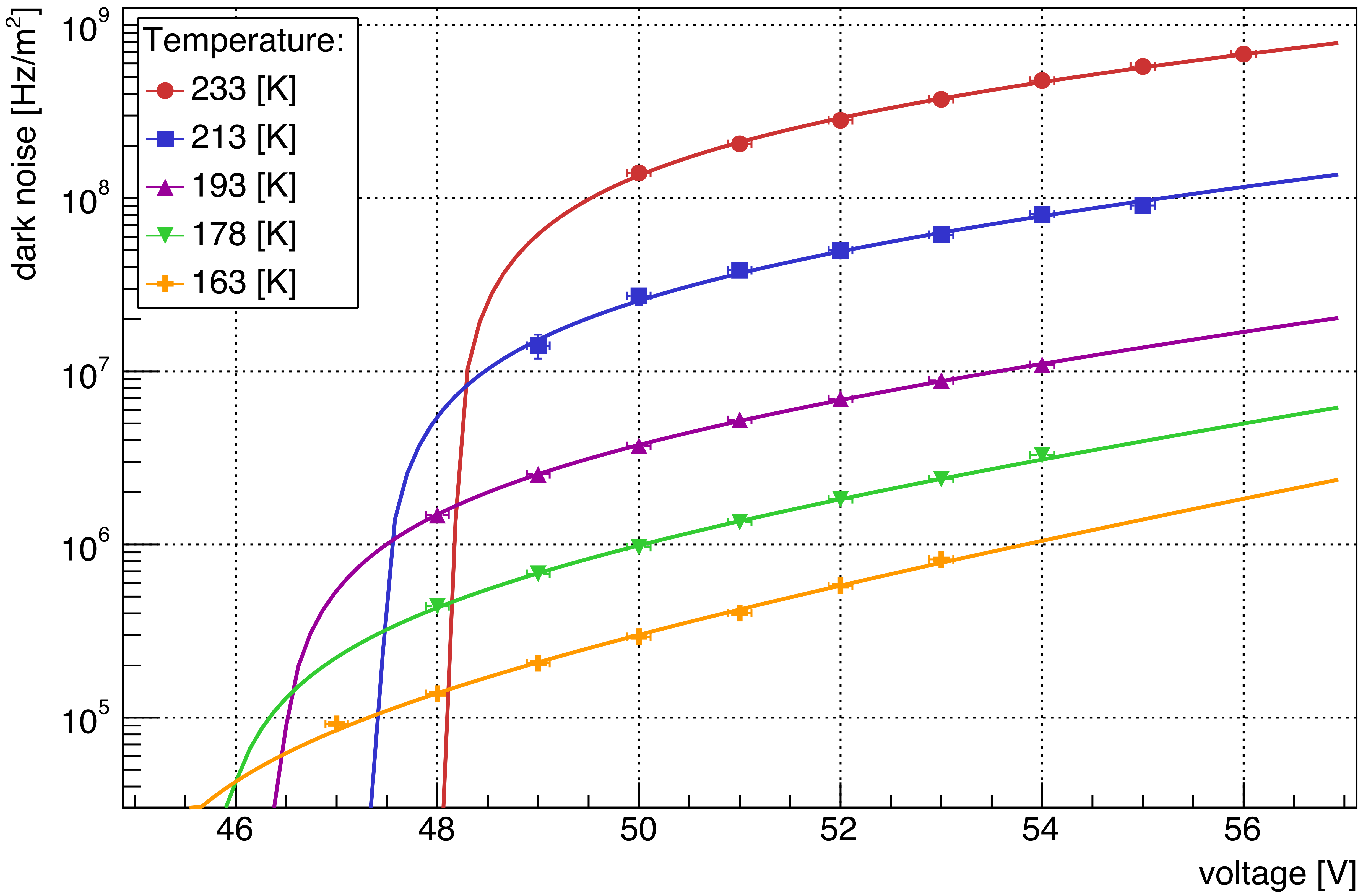
Quantity	Symmetric Junction	Asymmetric Junction
f_{DN} [#]	$(1.7 \pm 0.2) \times 10^{-3}$	$(3.4 \pm 0.7) \times 10^{-3}$
W_0 [m]	$(2.21 \pm 0.01) \times 10^{-7}$	$(2.24 \pm 0.01) \times 10^{-7}$
$E_g(0)$ [eV]	(1.30 ± 0.01)	(1.26 ± 0.01)
$\chi^2 \setminus$ NDF	0.83	0.89

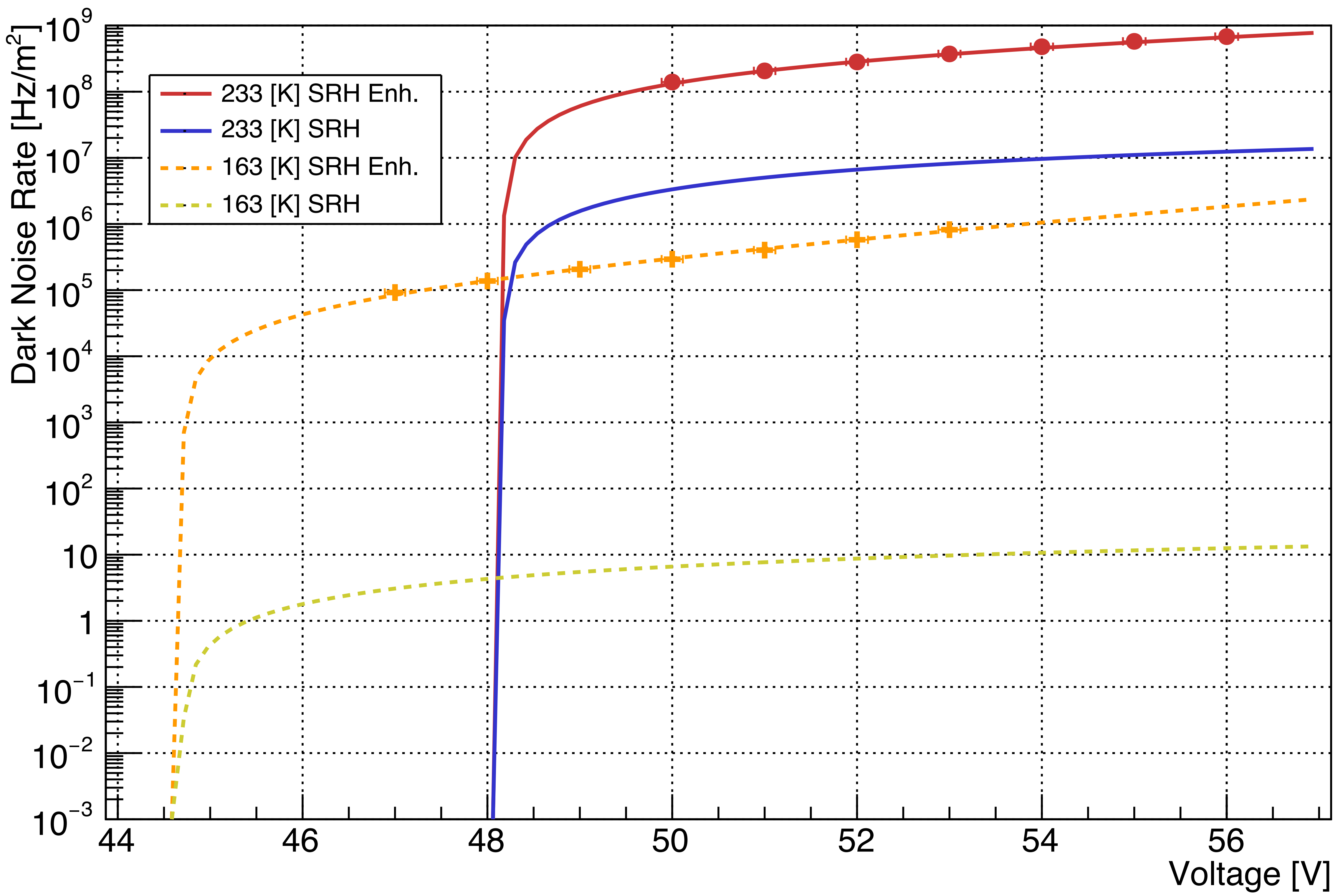
$f_{DN} \sim 0$ **—> In p-on-n SiPMs DN is hole driven.**

The Shockley-Read-Hall thermal rate has a slope that is **compatible with the Silicon Bandgap**

The Dark Noise rate is **dominated by field enhanced contribution**

Hamamatsu VUV4





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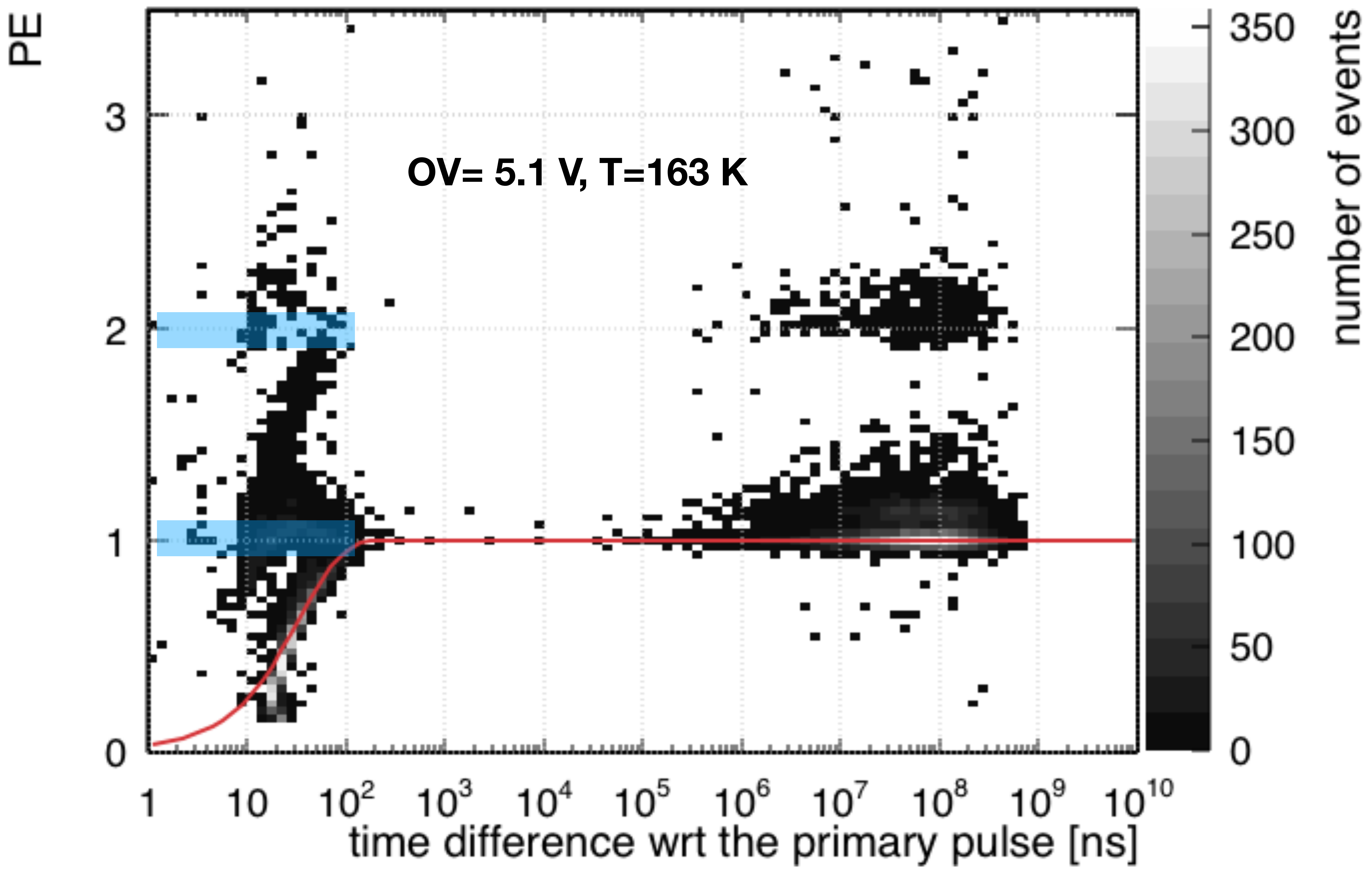
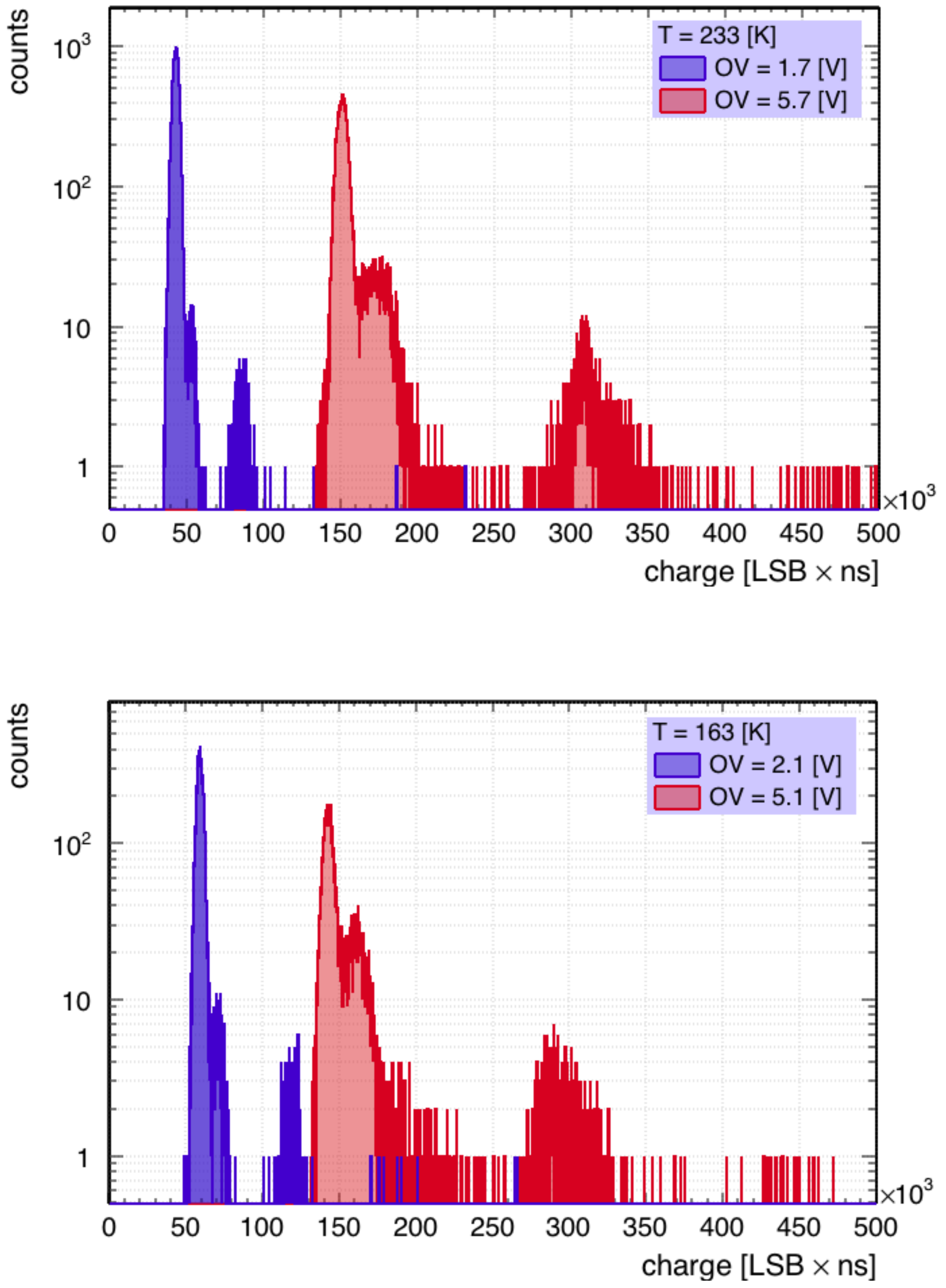
Nuisance Processes: Cross Talk

Direct Cross Talk



Hamamatsu VUV4 Prompt Charge



Direct (or Prompt) Cross Talk

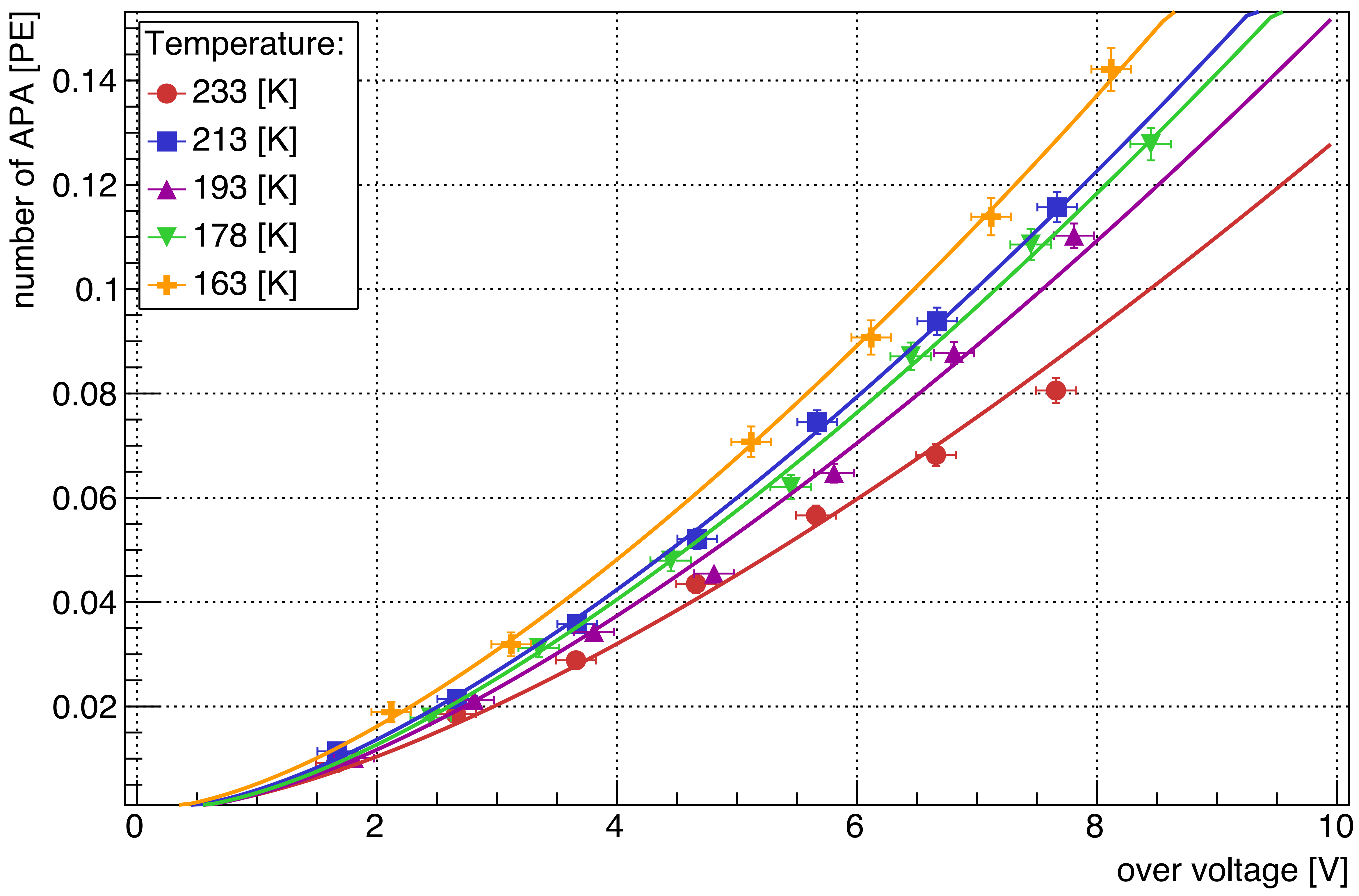
$$N_{\mathbf{APA}} = \chi \times k \times \frac{C(V - V_{bd})}{q_e}\Big(P_e(d_P) f_{CT} + P_h(d_W)(1 - f_{CT})\Big)$$

The number of photons produced is proportional (k) to the charge realised during an avalanche

$$N_{ph-produced} \sim k \times \frac{C \times (V - V_{BD})}{q_e}$$

χ Geometrical factor to account for the cell geometry

$f_{CT} \sim 0$ **Direct Cross Talk is Hole Driven**



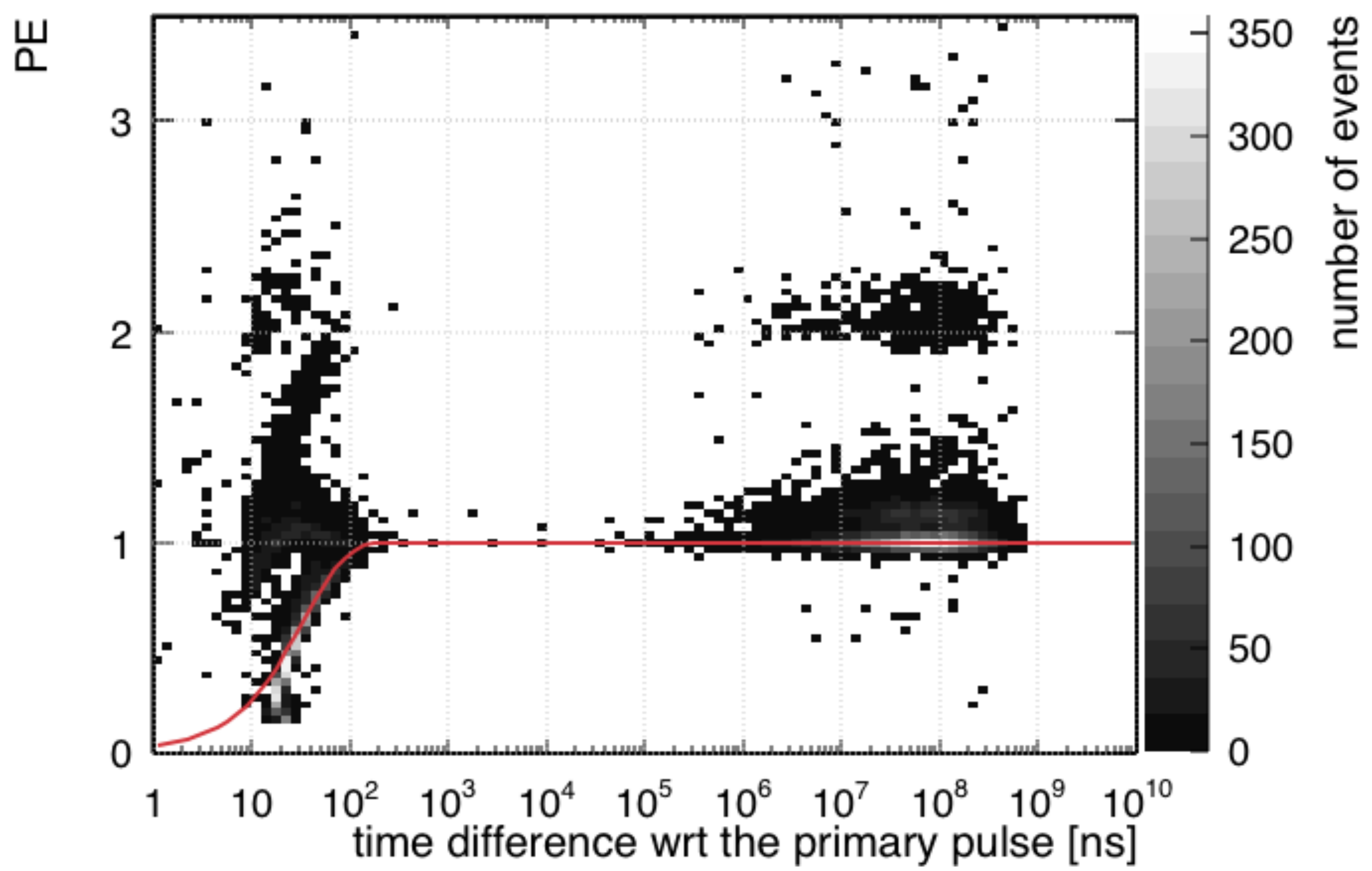
Nuisance Processes: Afterpulse

AfterPulse

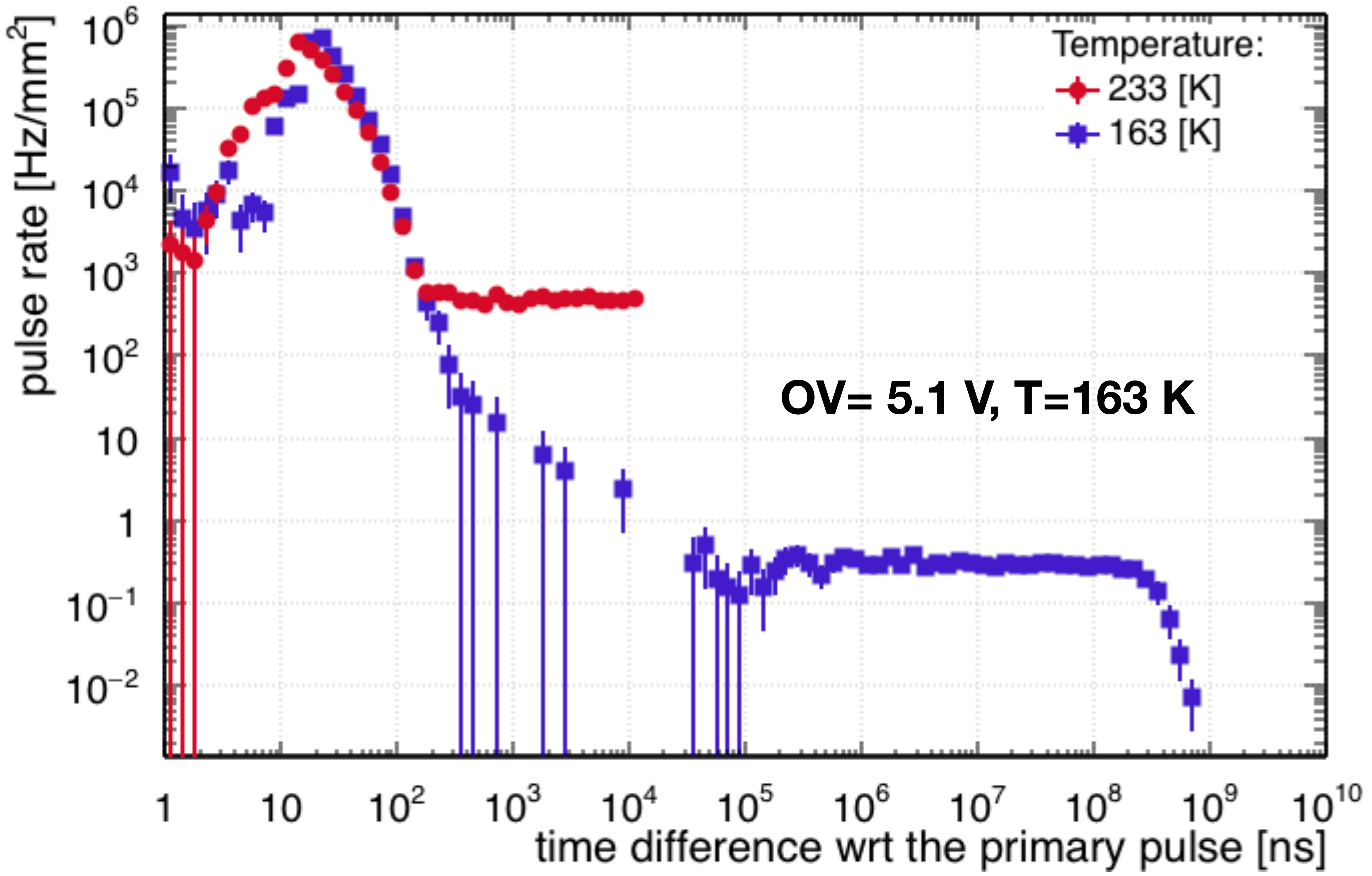
Two information can be extrapolated from the time differences: Dark Noise Rate and Number of Correlated Delayed Avalanches

10.1016/j.nima.2017.08.035

Considering the PE charges



Neglecting the PE charges



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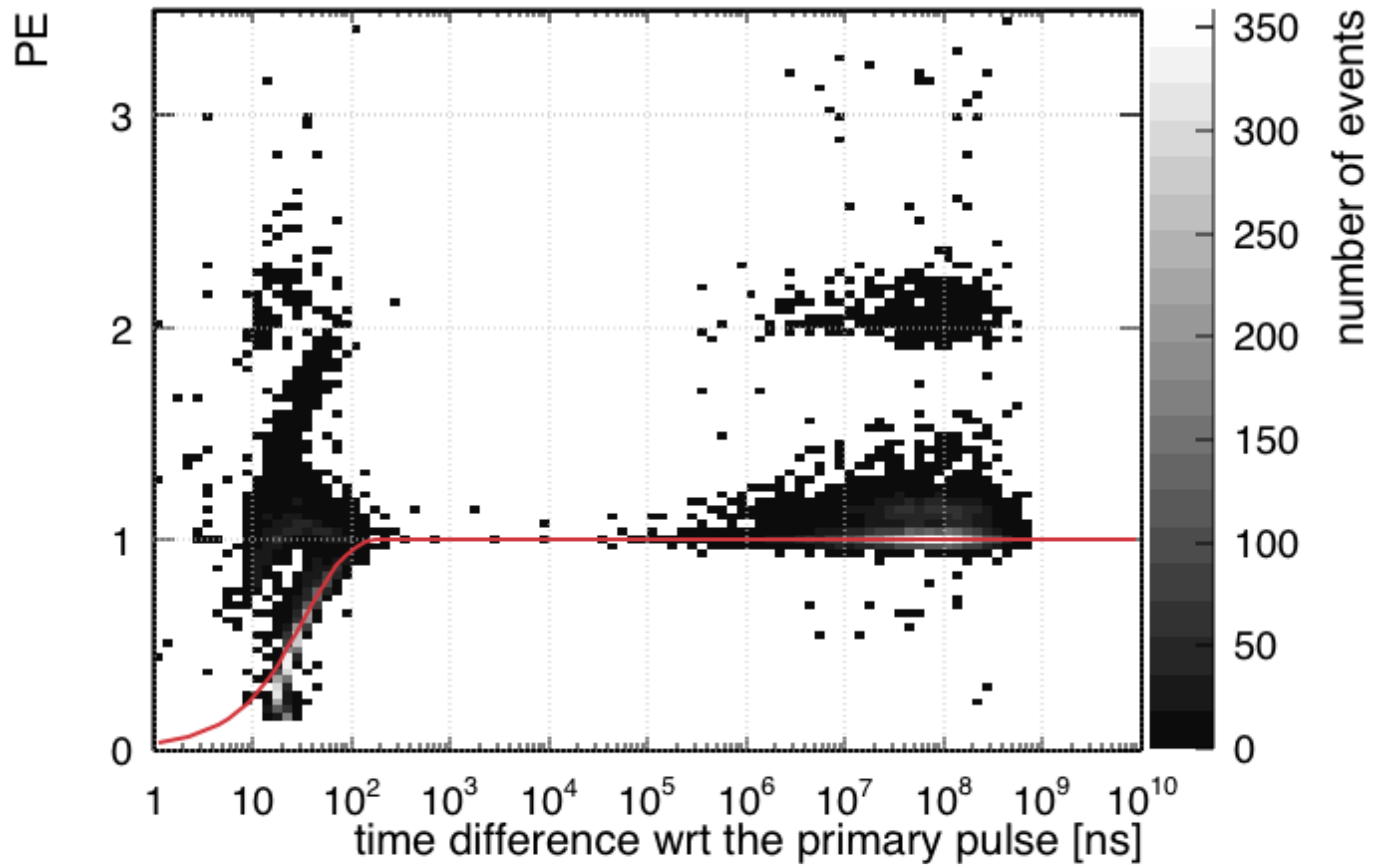

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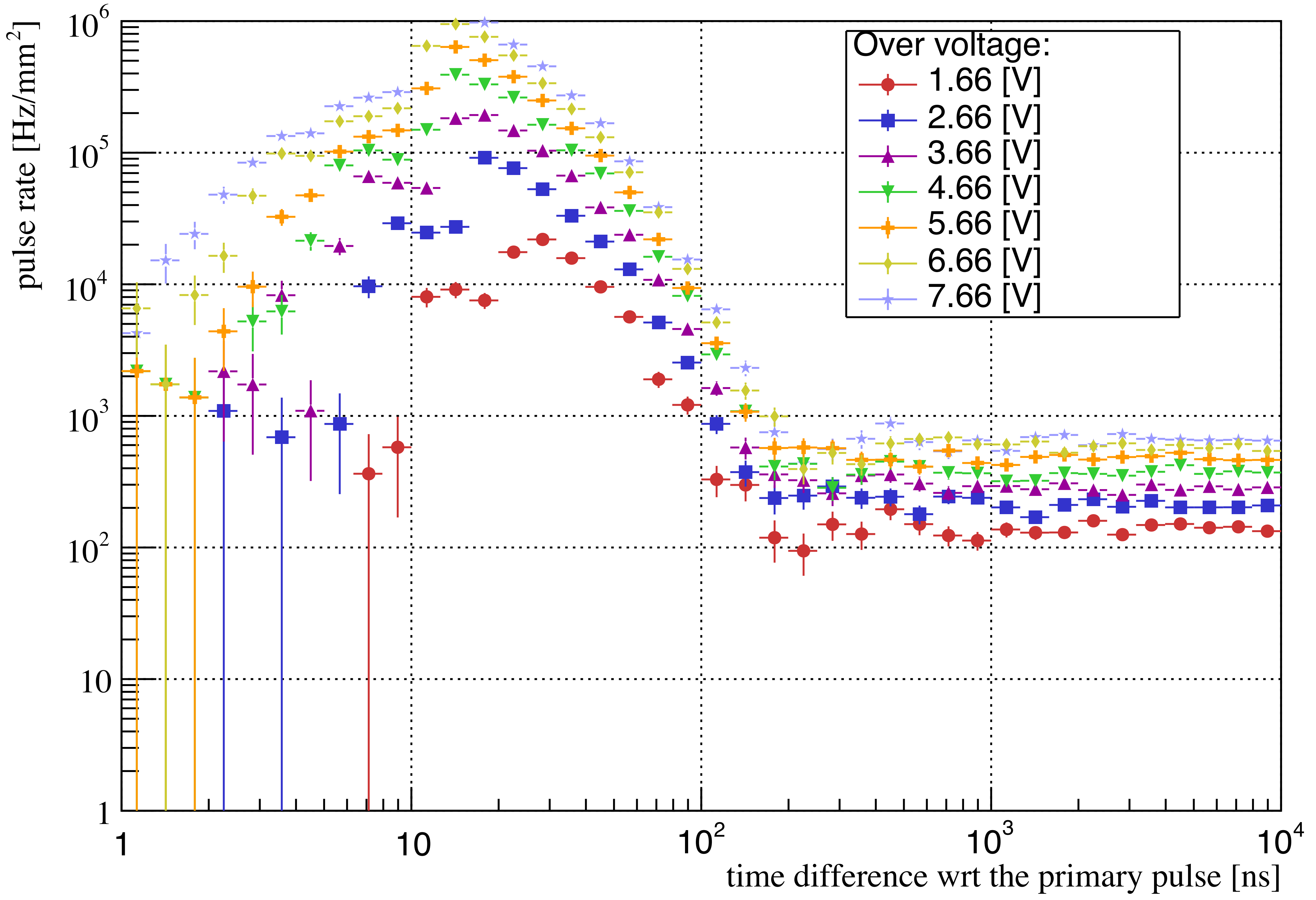


After Pulse

$$\mathbf{N_{CDA}}(t) = \frac{C(V - V_{BD})}{q_e} \times A_{\mathbf{SiPM}}{}^{k_1}\mathbf{N_{traps}}{}^{W} \times \frac{e^{-\frac{t}{\tau}}}{\tau} \times$$

$$\times \left[f_{CDA} P_e(d_P, V - V_{eff}(t)) + (1 - f_{CDA}) P_h(d_W, V - V_{eff}(t)) \right]$$

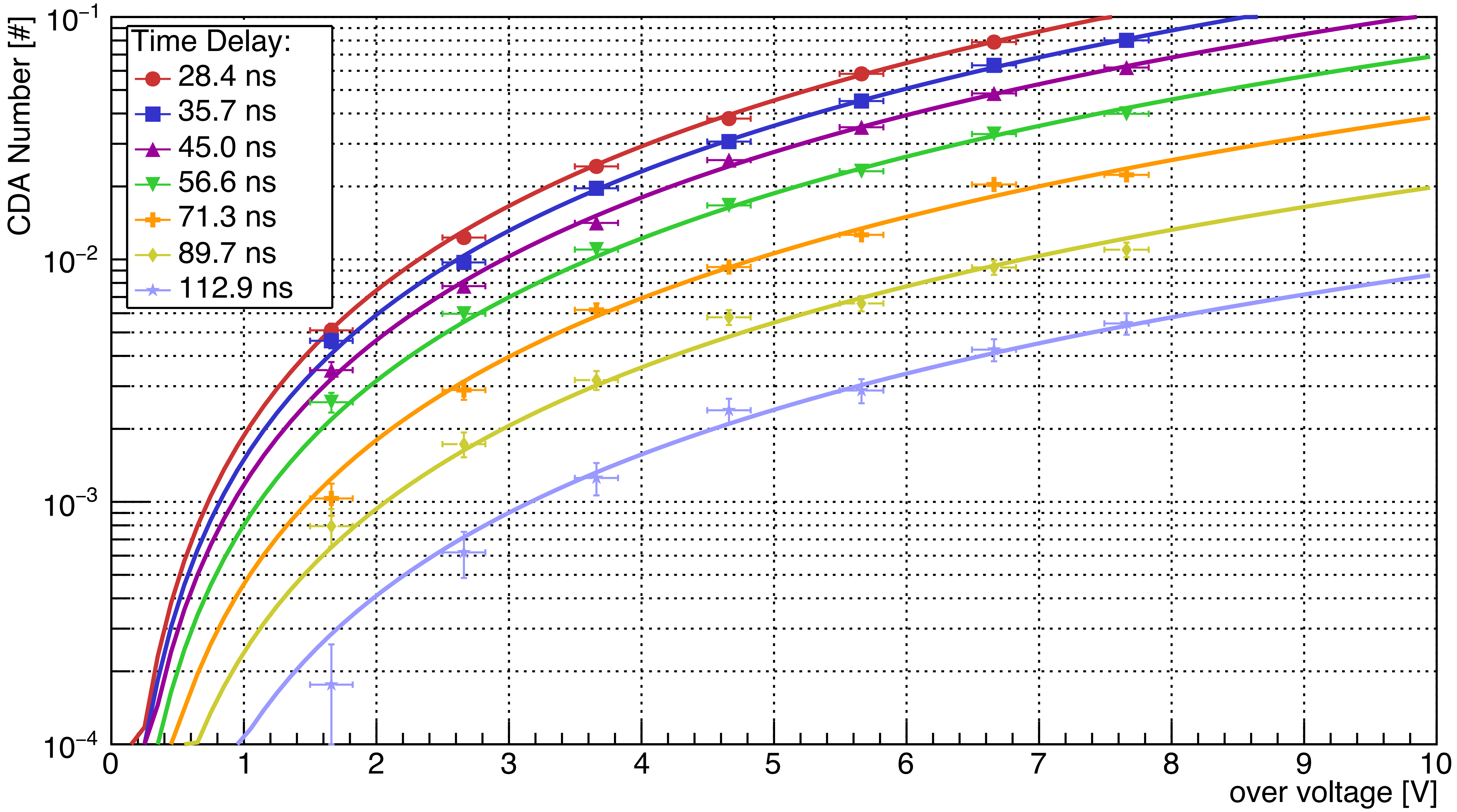
The number of carriers trapped is proportional (k) to the charge realised during an avalanche

$$N_{ph-produced} \sim \frac{C \times (V - V_{BD})}{q_e}$$

The trapping probability is proportional to the trap density

$$A_{\mathbf{SiPM}}{}^{k_1}\mathbf{N_{traps}}{}^{W}$$

Detrapping probability: $\frac{e^{-\frac{t}{\tau}}}{\tau}$



$f_{CDA} \sim 0$ **After Pulse is Hole Driven**

Nuisance Processes: Summary

Summary

	Dark Noise	***Direct CT***	***After Pulse***
Hamamatsu VUV4	$f_{DN} \sim 0$	$f_{CT} \sim 0$	$f_{CDA} \sim 0$
FBK VUV HD1 (FBK LF)	$f_{DN} \sim 0$	$f_{CT} \sim 0$	$f_{CDA} \sim 0$

1) Dark Noise Rate is dominated by **SRH Field enhanced contribution**

2) Dark Noise Rate is **hole driven** in p-on-n SiPMs

3) Direct Cross Talk is **hole driven** in p-on-n SiPMs

4) After Pulse is **hole driven** in p-on-n SiPMs