The impact of secondary photon emission of Silicon photomultipliers (SiPM) to noble liquid detectors

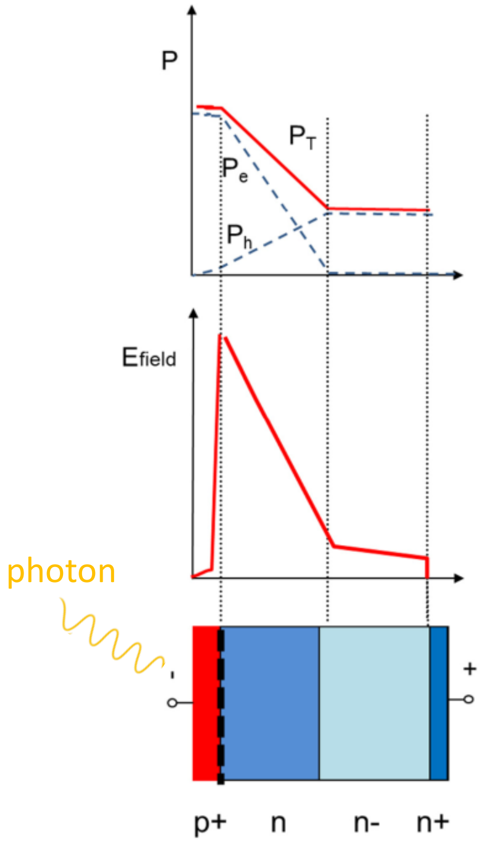
Speaker: Lei Wang. Postdoc researcher in TRIUMF

On behalf of nEXO group

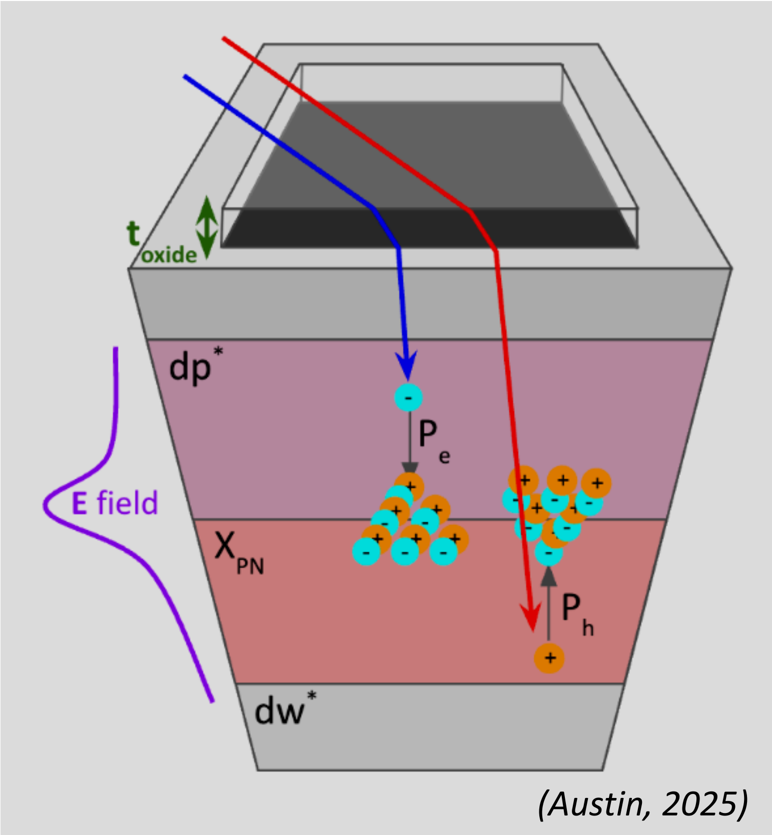
Outline:

- 1. How the avalanche of SiPM happens
- 2. The mechanism of secondary photon emission of P-N junction
- 3. The direct measurement of secondary photon emission
- 4. External photons performance in LXe detector
- 5. Discussion

1. the avalanche process of SiPM



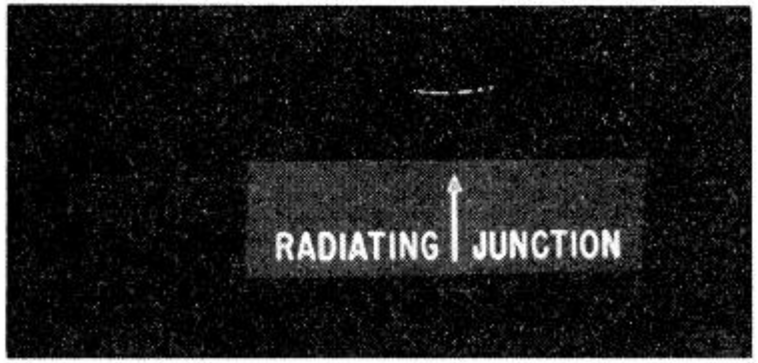
(Claudio P, 2019)



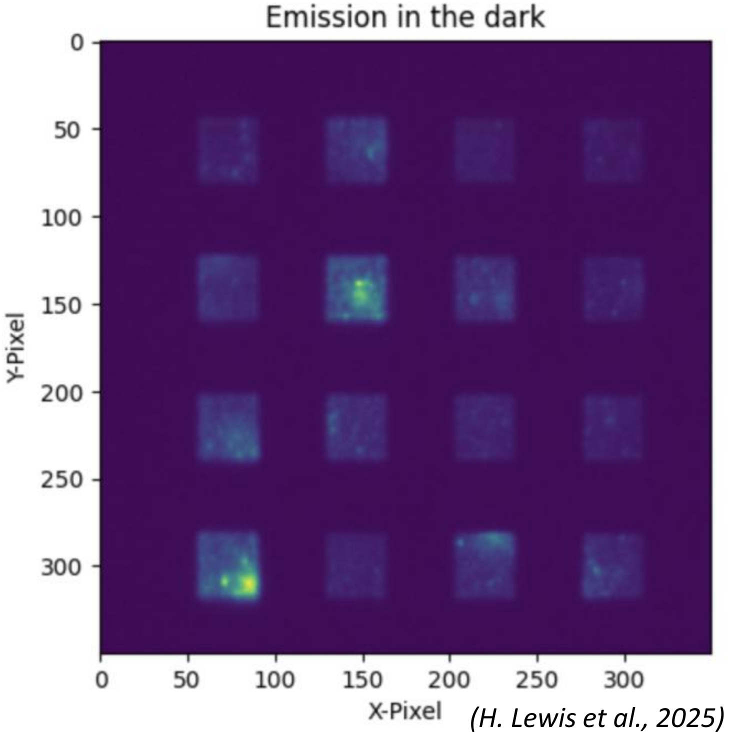
Photon absorbed in p+ region:
Generating an electron
➔ Drafting to junction region
➔ Triggering avalanche

Photon absorbed in n region:
Generating a hole
➔ Drafting to junction region
➔ Triggering avalanche

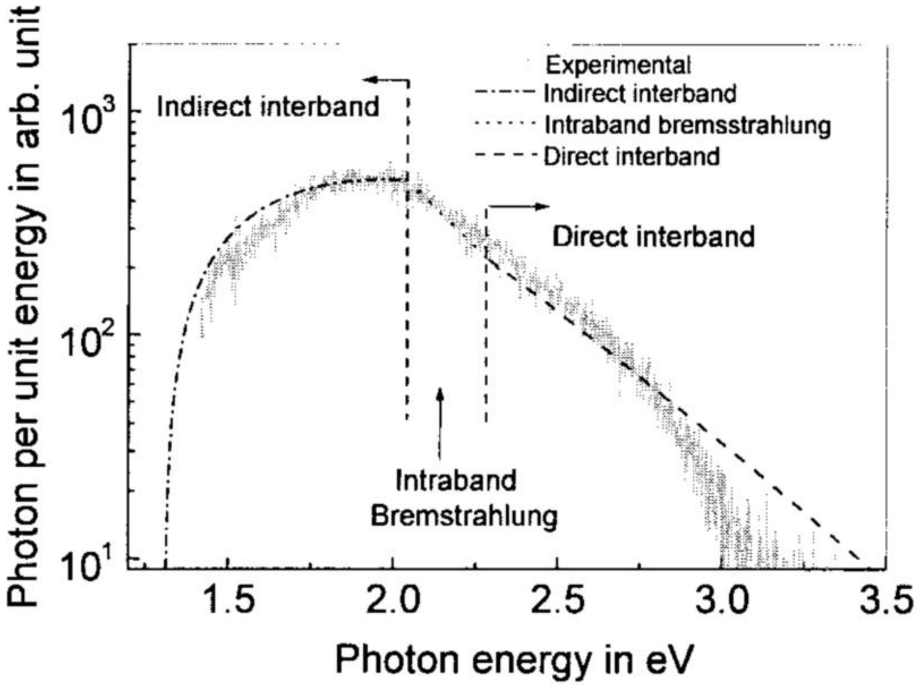
2. The mechanism of secondary photon emission of P-N junction



(R. Newman, 1955)



(H. Lewis et al., 2025)



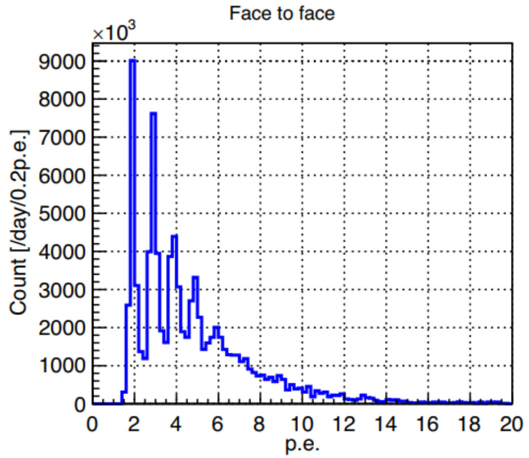
n+p- diode secondary photon emission spectrum *(N. Akil, 1999)*

Multimechanism Model:
three major mechanisms contribute to secondary photon emission:
- Indirect interband transition
- Direct interband transition
- Intraband bremsstrahlung transition

Negative impacts of secondary photons in scintillation detectors:

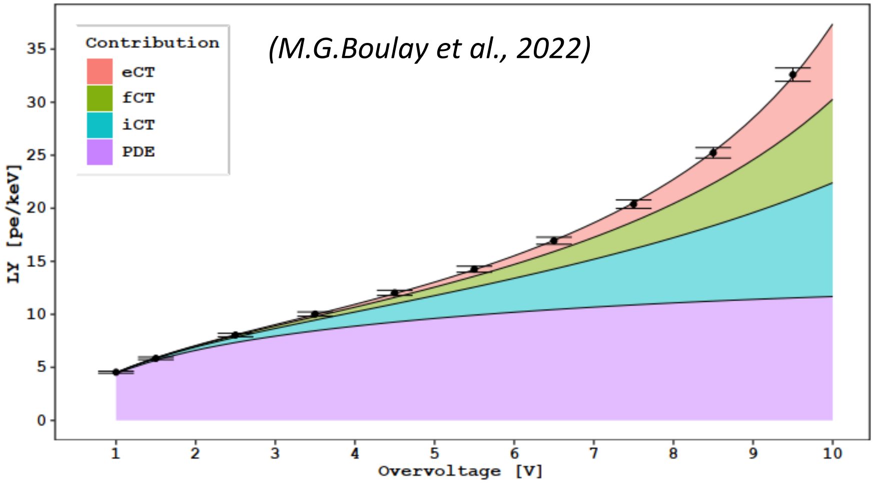
1. Overestimation of light yield

2. Correlated background



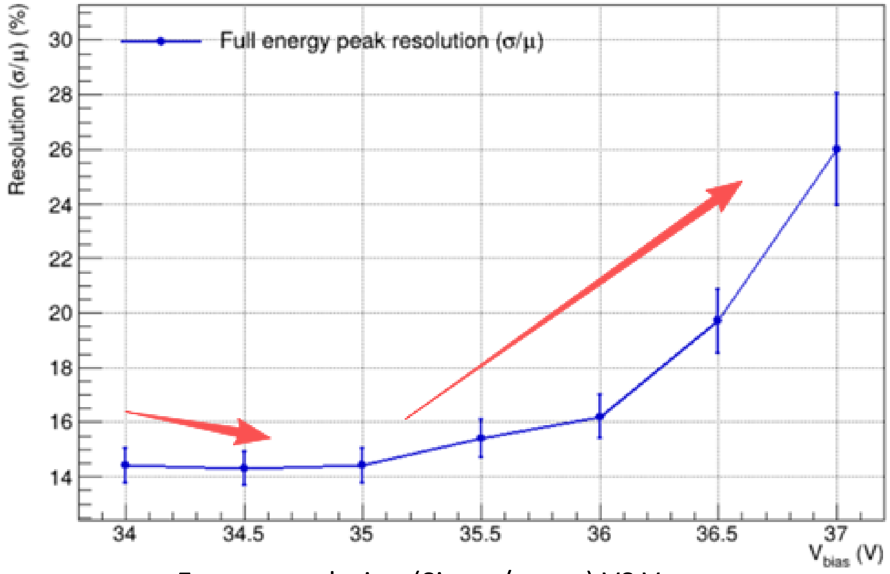
3. Degrades position reconstruction

4. Degrades energy resolution



Secondary photons contributed light yield

PDE contributed light yield



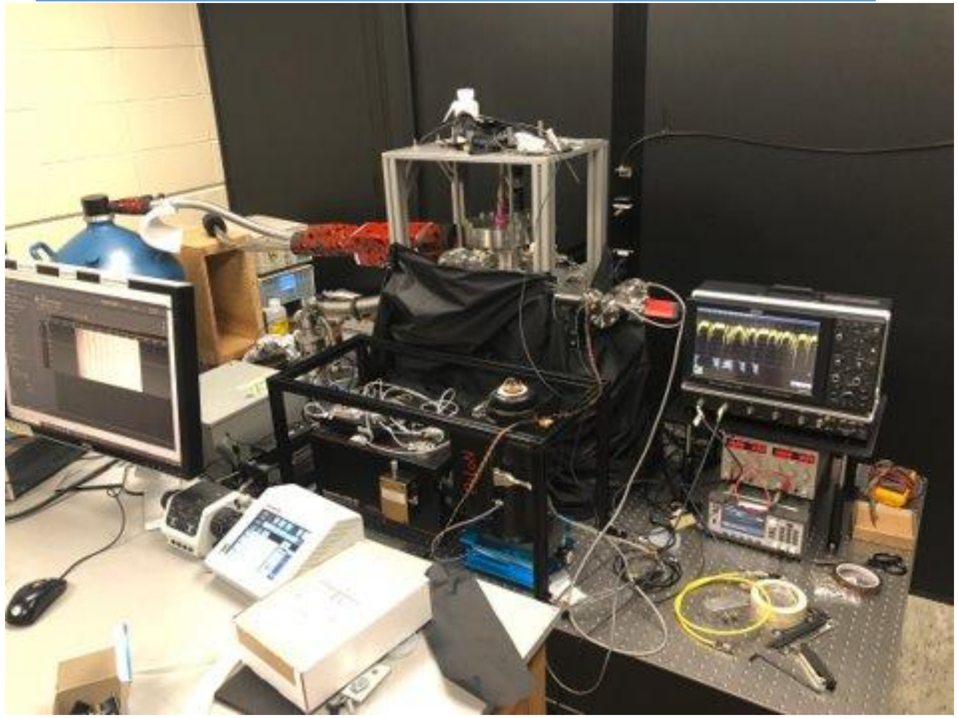
Energy resolution (Sigma/mean) VS V_{bias}

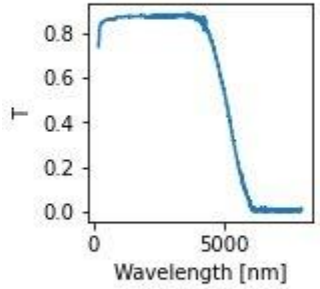
3. The direct measurement of secondary photon emission

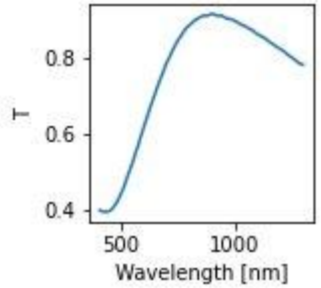
Assessing the impact to scintillation detector
needs better understanding of:

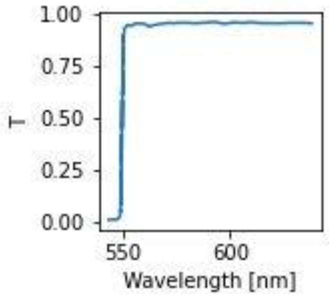
- The number of secondary photons produced per avalanche
- The wavelength spectrum of photons
- Angular distribution of photon emission

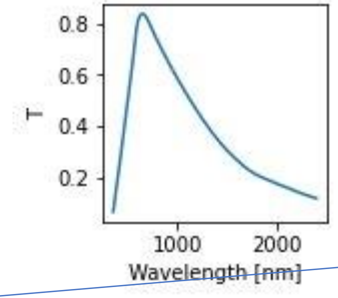
(**MIEL**)
Microscope for **I**njection and **E**mission of **L**ight











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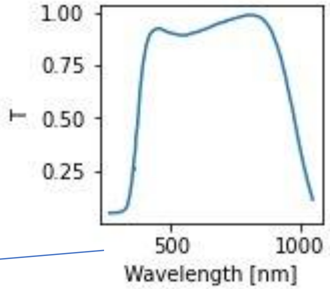
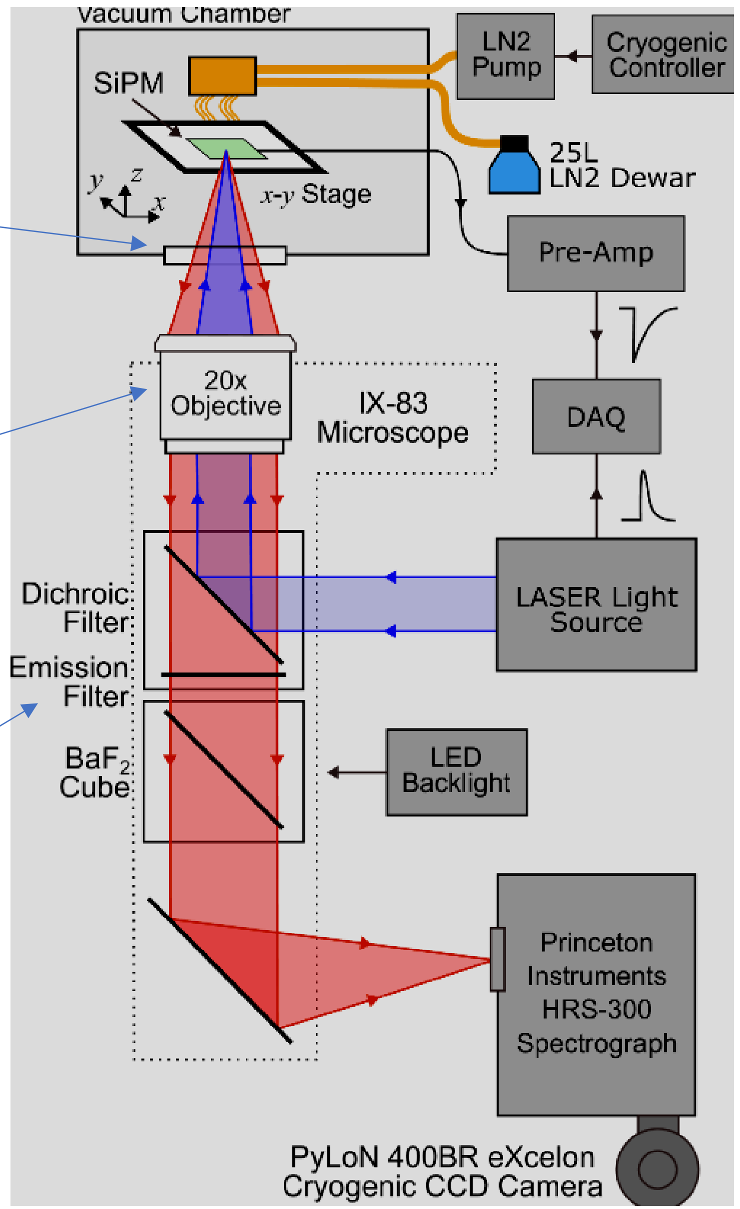
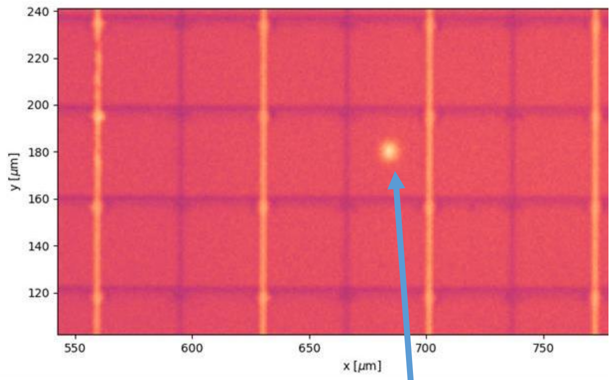


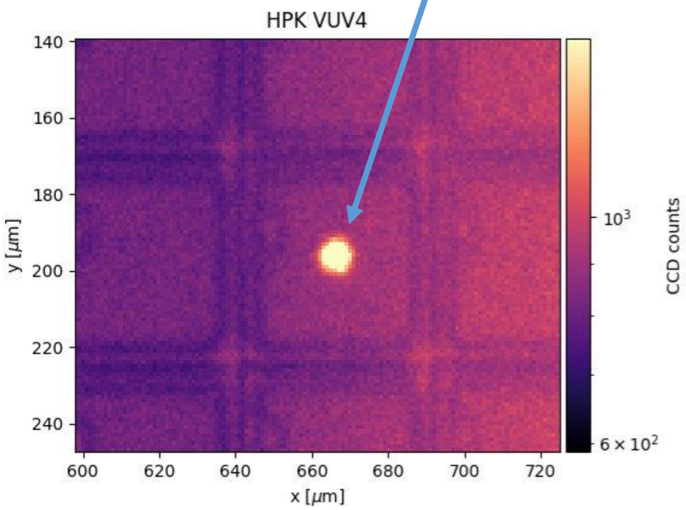


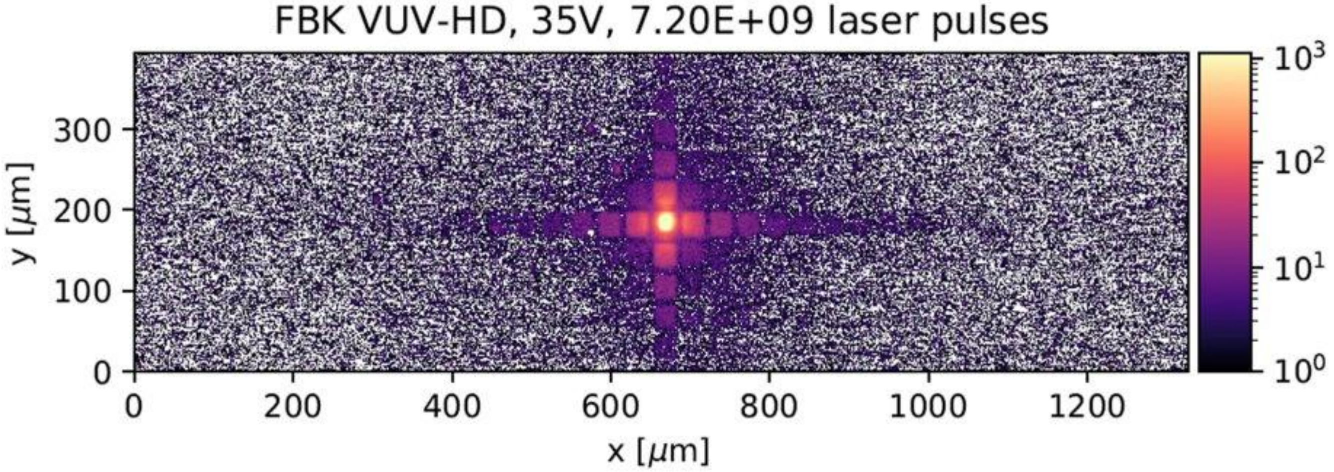
K. Raymond, etc., Stimulated Secondary Emission of Single Photon Avalanche Diodes (2024)

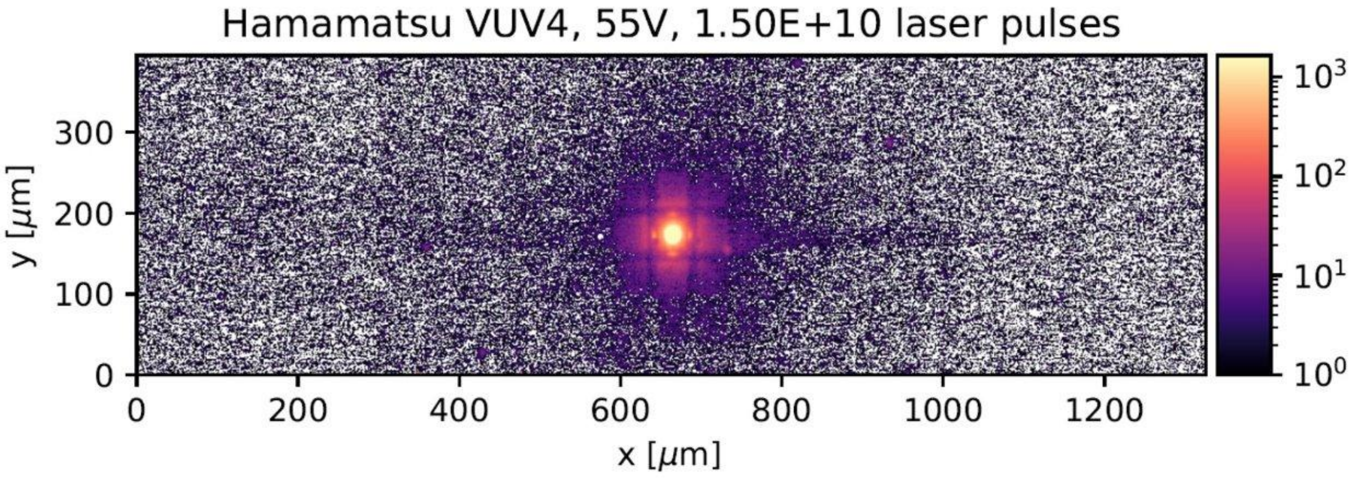
Emission Map (A)



Laser Spot





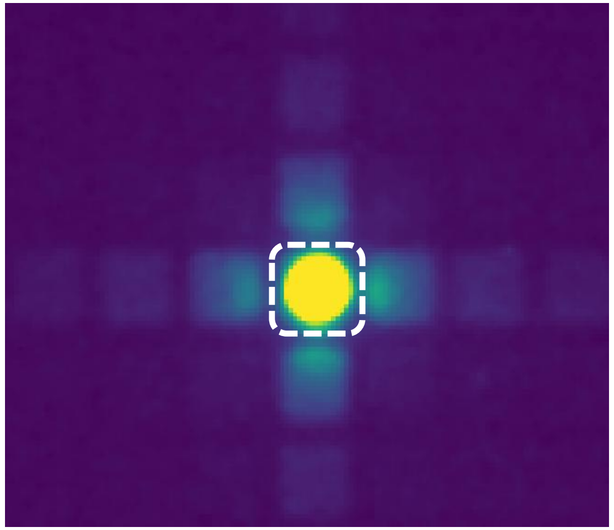


Photon emission photograph when laser is on

What we are measuring in MIEL:

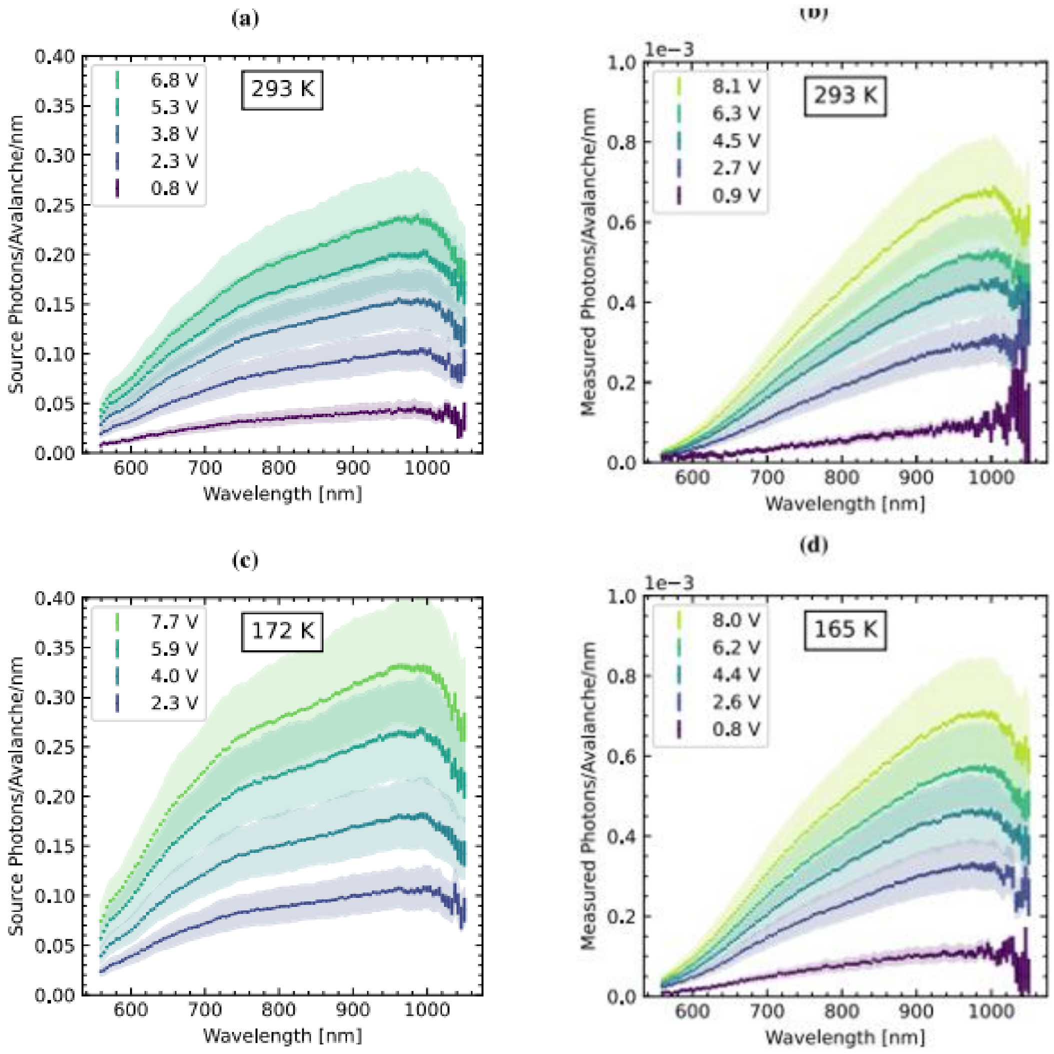
$n_\gamma(\lambda) = \dfrac{N_\gamma^c(\lambda)}{\epsilon(\lambda) N_{av}^c}$: Number of photon emission per avalanche.

$N_\gamma^c(\lambda)$: $number\ of\ photons\ CCD\ received$ $\boldsymbol{only\ from\ the\ centre\ SPAD}$.
$\epsilon(\lambda)$: Efficiency of MIEL instrument.
N_{av}^c: $number\ of\ avalanche\ from\ the\ centre\ SPAD$.



Spatial discrimination cut photons from surrounding SPAD

Number of photon emission per avalanche:



FBK VUV-HD3

HPK VUV4

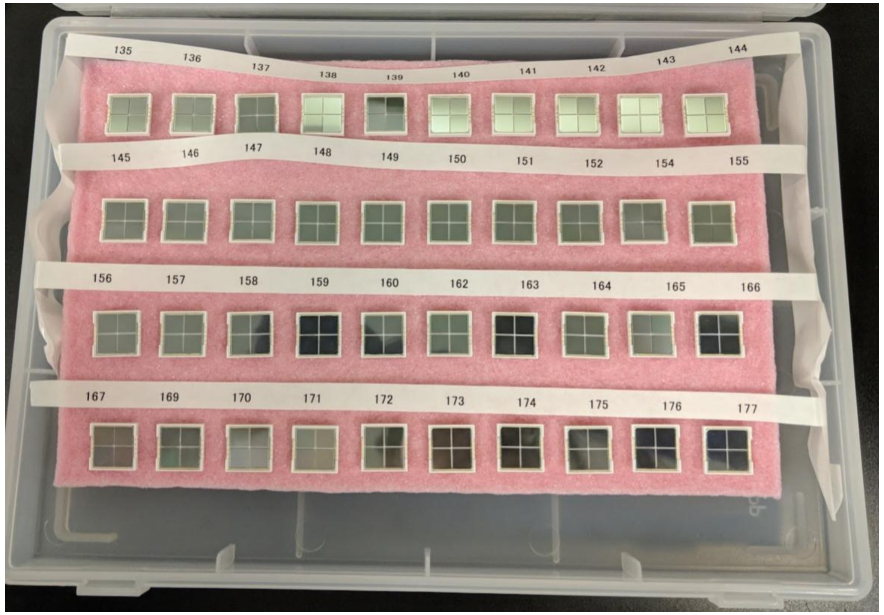
Environmental Conditions	Device		Unit
	HPK VUV4	FBK VUV-HD3	
293 K	48.5 ± 9.5	60.8 ± 10.8	Secondary photons per avalanche
	(1.94 ± 0.38)×10^{-5}	(2.59 ± 0.46)×10^{-5}	Secondary photons per charge carrier (e^-)
Air and Vacuum	0.64 ± 0.26	0.79 ± 0.31	Photons emitted from SiPM per avalanche
LXe 165K	1.55 ± 0.62	1.92 ± 0.74	

K. Raymond, etc., Stimulated Secondary Emission of Single Photon Avalanche Diodes (2024)

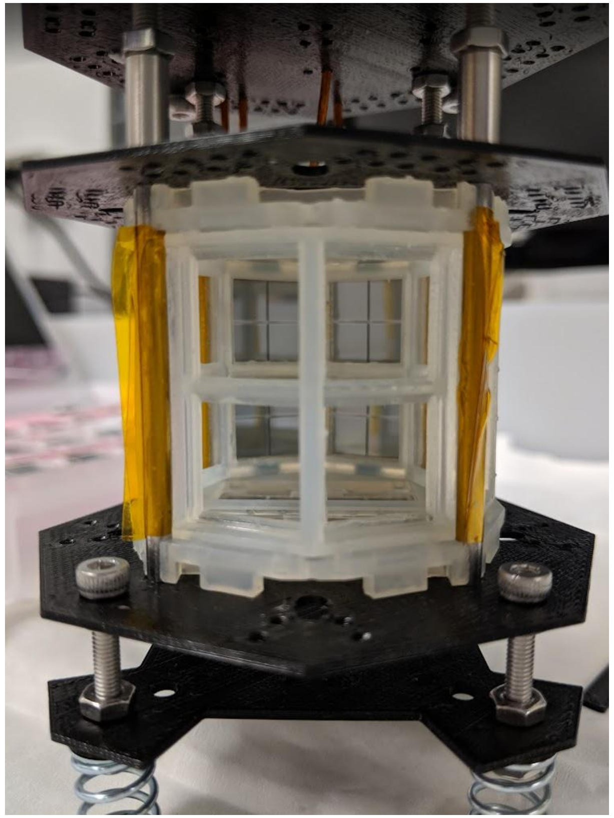
Impact of secondary photons to LXe detector:

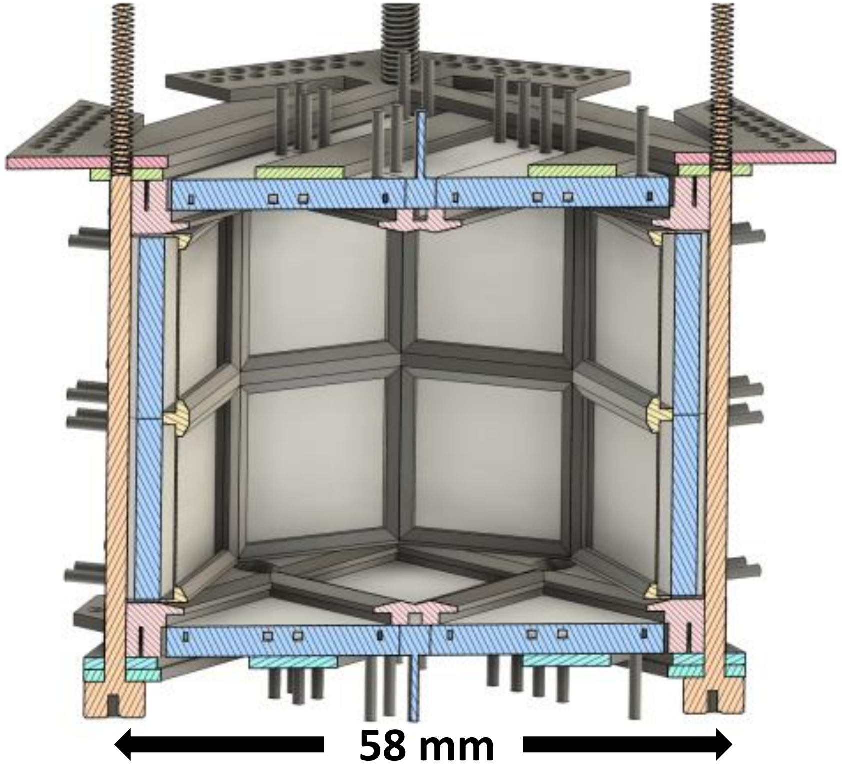
The **L**ight-**o**nly **L**iquid **X**enon experiment (**LoLX**):
96 HPK VUV4 SiPMs, 5 kg LXe

More details about LoLX can be found in report of Alex Li Tuesday

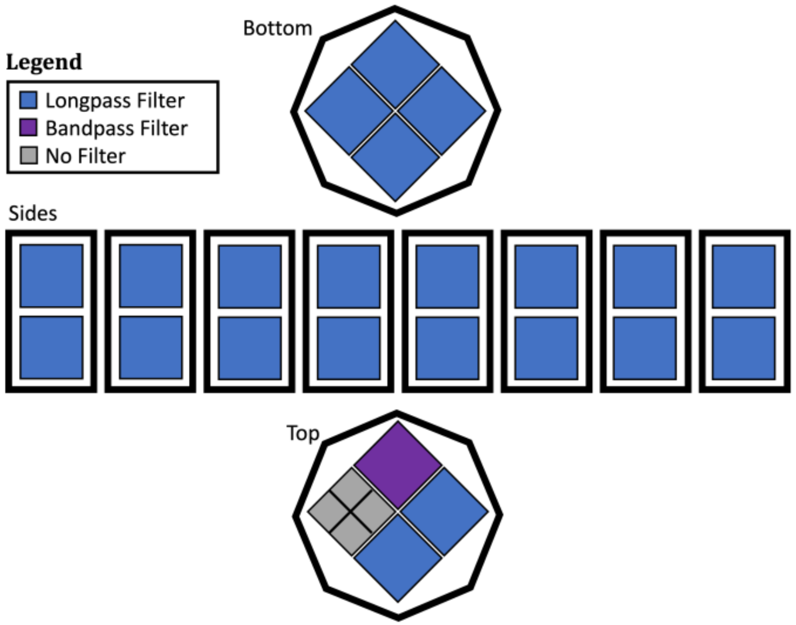


(From LolX group pictures)

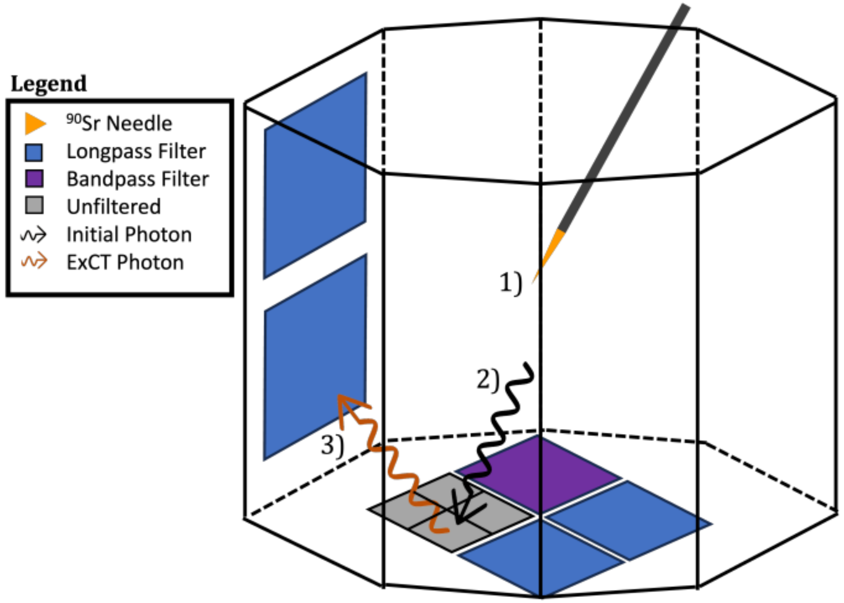


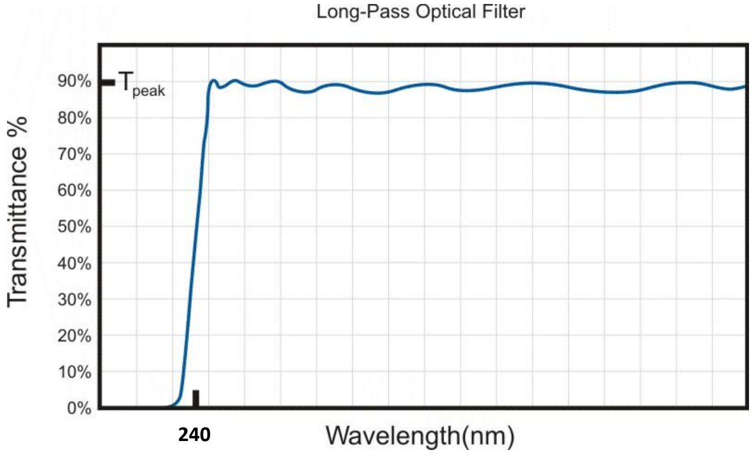


Experiment Setup:



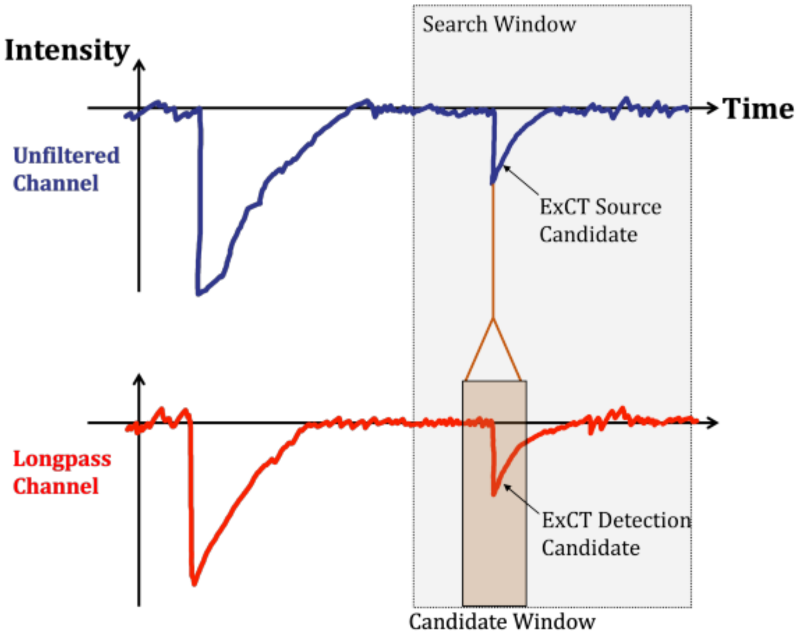
Source SiPM: SiPM without filter
Target SiPM: all SiPMs with long-pass filter

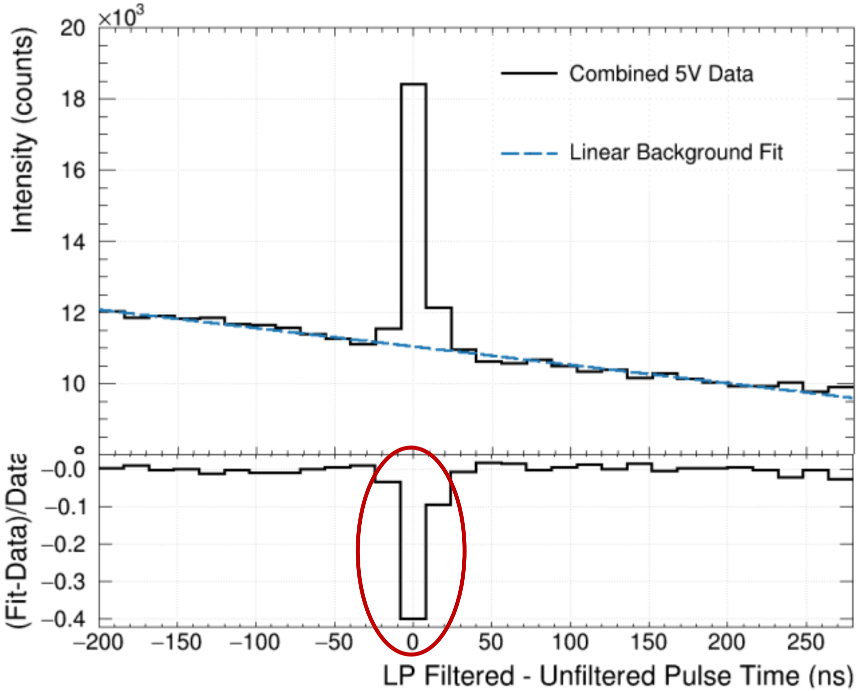




D. Gallacher, etc., Characterization of external cross-talk from silicon photomultipliers in a liquid xenon detector (2025)

Measuring probability of correlated signals P_{corr}:





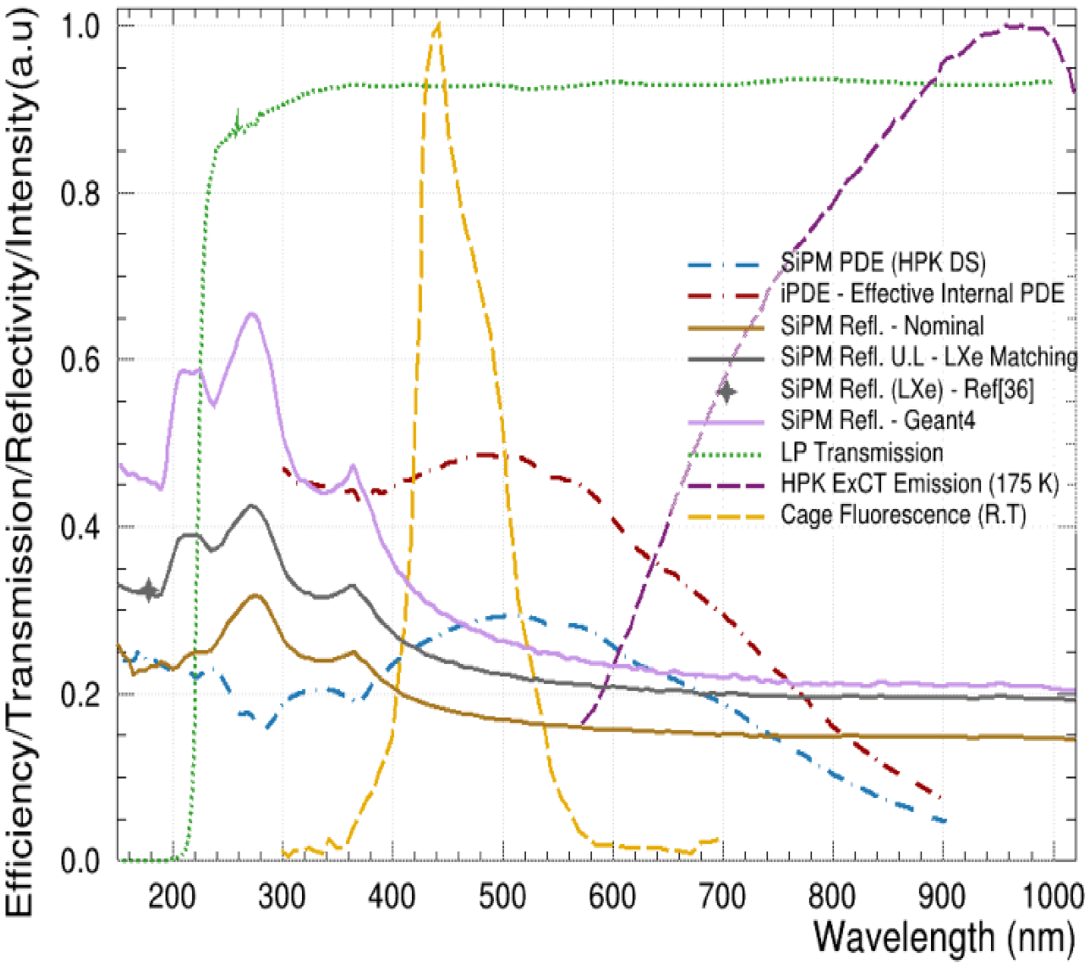
Step1: Find SPE pulses in unfiltered SiPM channel
Step2: search all longpass SiPM channels if a correlated pulse
Step3: Calculate the time difference between two channels

Coincidence Probability:

$$P_{corr} = {(N_{correlated} - N_{background})}/{N_{unfiltered}}$$

Accidental coincidence dark noises and environment background are removed.

Optical simulation and results:



With given P_{corr}, number of secondary photon emiting into LXe is calculated:

Overvoltage	ExCT probability (%)	Emission into LXe, NX_e (γ/Av.)
4 V	$2.1^{+1.2}_{-1.3}$	$0.5^{+0.3}_{-0.2}$
5 V	$2.6^{+1.4}_{-1.4}$	$0.6^{+0.3}_{-0.2}$

5. Discussion

MIEL result:

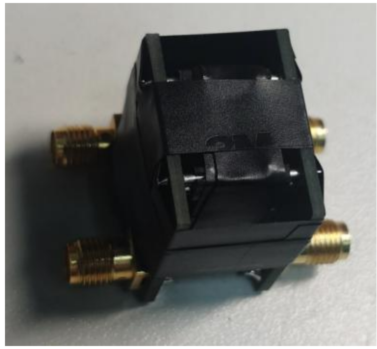
$1.55^{+0.62}_{-0.62}$ photons per avalanche in LXe.

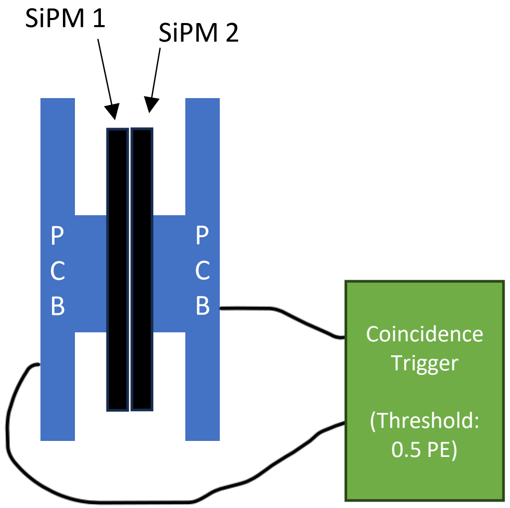
LoLX result:

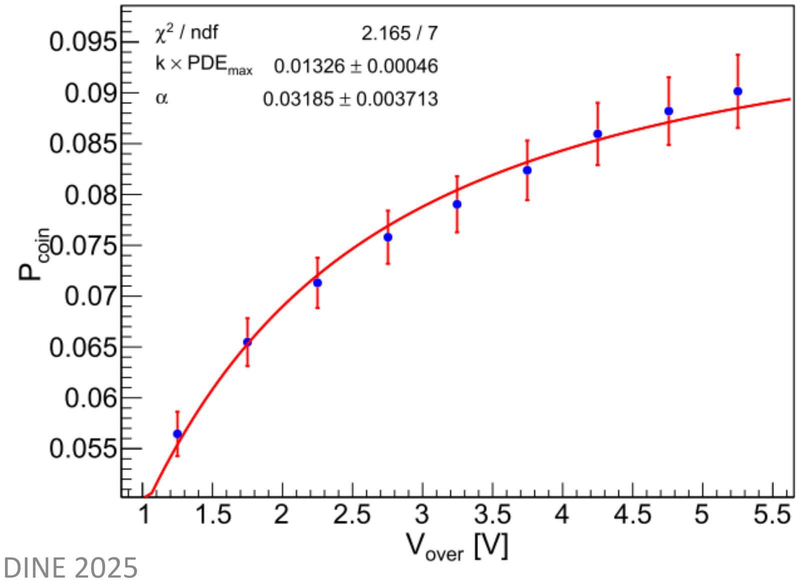
$0.5^{+0.3}_{-0.2}$ photons per avalanche in LXe

$2.1^{+1.2}_{-1.3}\%$ probability of correlated signal

At face-to-face setup, $P_{coin} \approx 8.2\%$ at $V_{over} = 4V$ *(G. Li et al., 2024)*



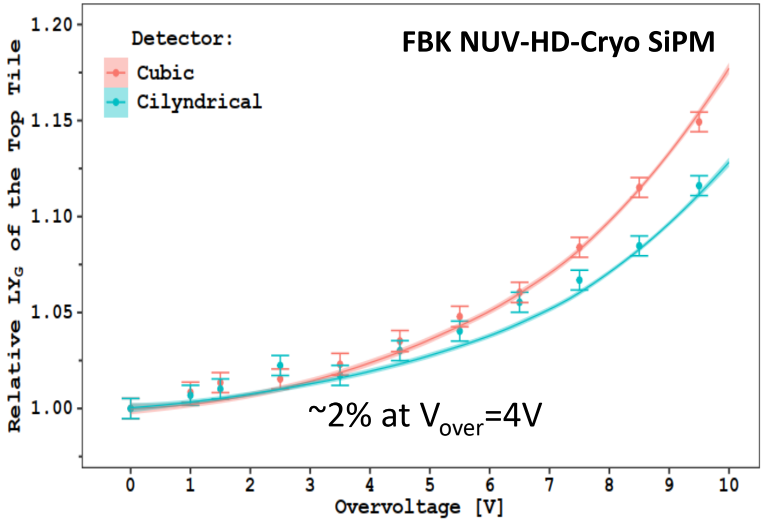




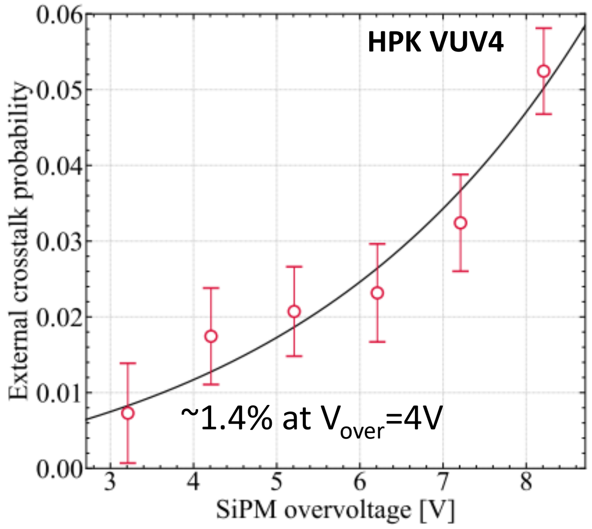
5. Discussion

Relative ExCT results from other experiment:

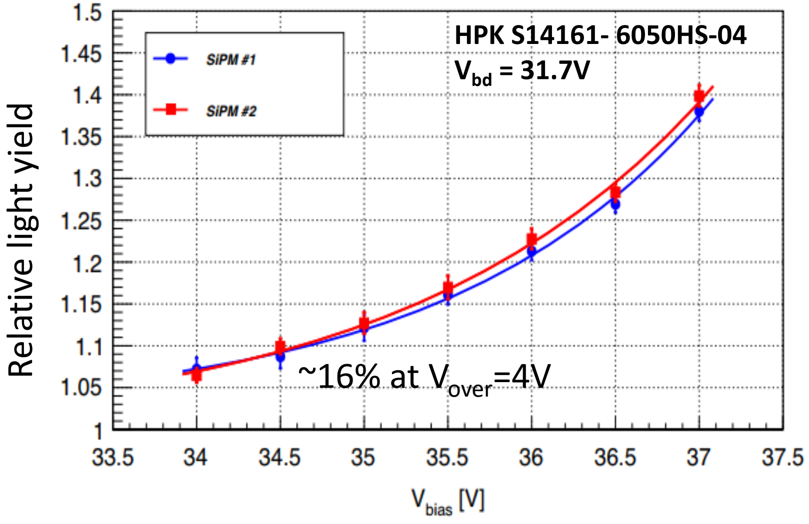
Single-phase LAr detector *(M.G.Boulay et al., 2022)*

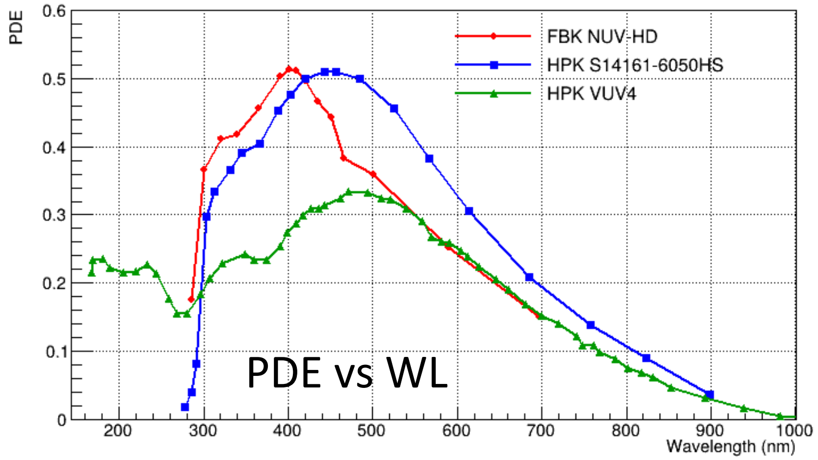


Dual-phase LXe detector *(R. Gibbons et al., 2024)*



Pure CsI crystal detector at 87K (L. Wang, 2024)



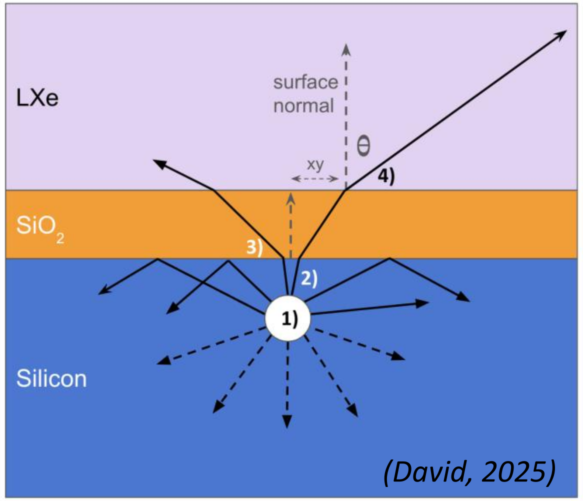


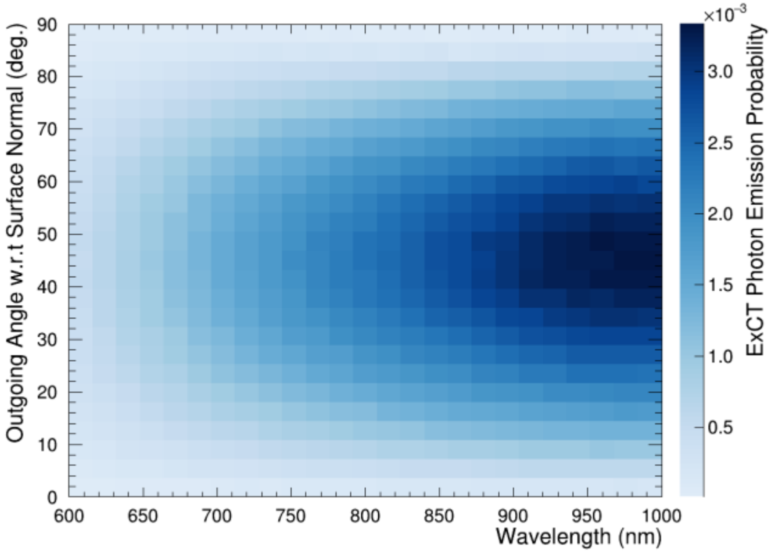
The crystal detector have extremely higher ExCT impact

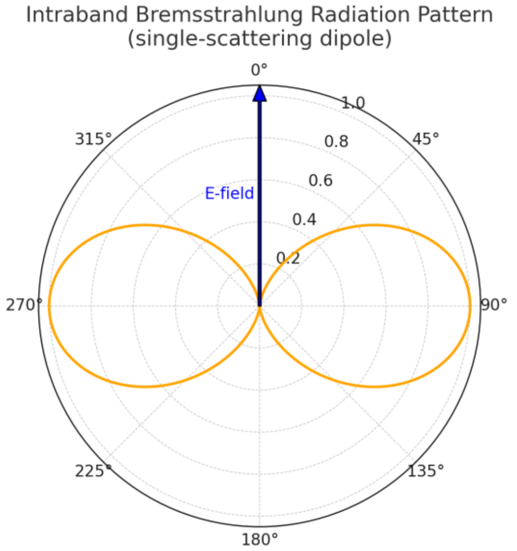
HPK S14161- 6050HS is the only n-on-p SiPM here!

Defect of the current photon emission model

"Assumption: Isotropic photon emission"







Photon emission mechanism:

- Indirect interband transition (NIR 700nm ~ 1000nm)
- Intraband bremsstrahlung (NIR 550nm ~ 700nm)
- Direct interband transitions (< 550nm but weak intensity)

Simplified angular dependent photon emission of bremsstrahlung process

Isotropic model -> NOT ACCURATE!

THANK YOU!

Our group (on behalf of nEXO)

TRIUMF

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Austin de St Crotx
Chole Malbrunot
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Harry Lewis
Kurtis Raymond
Leanne Beet
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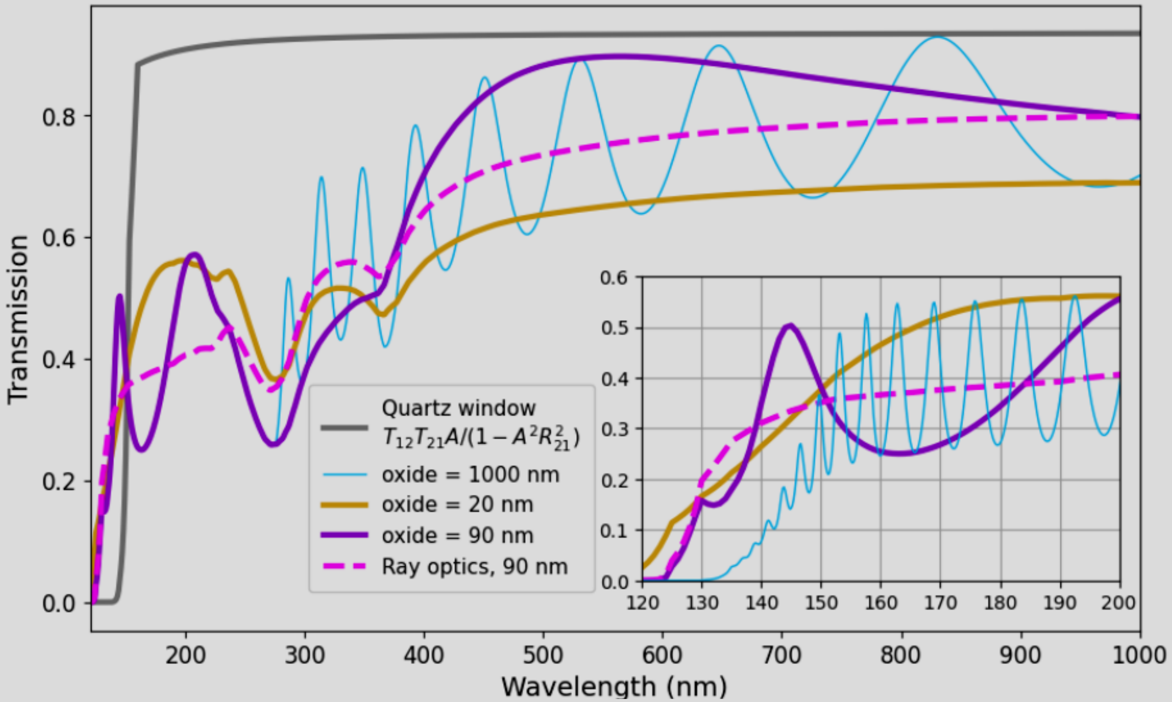
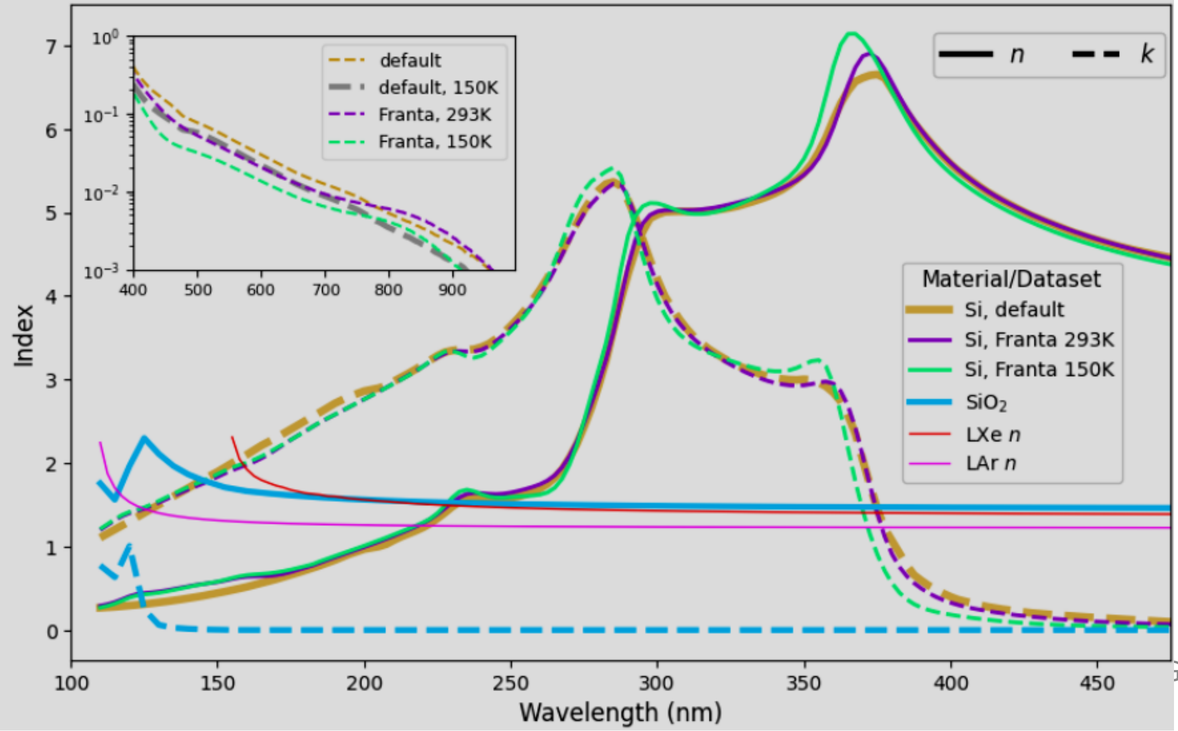
Tiana Fandresena Gerald

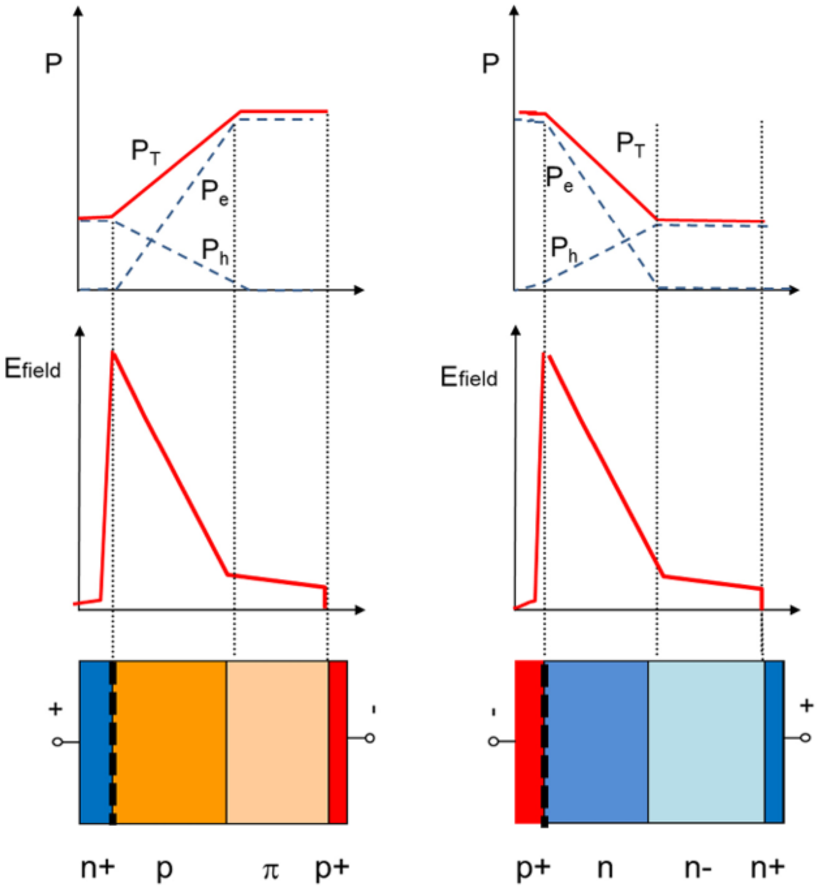
McGill

Thomas B (Head)
David Gallacher
Frederic Girard
Ethan Coulthard

Backups


Transmission
Wavelength (nm)
Quartz window $T_{12}T_{21}A/(1-A^2R_{21}^2)$
oxide = 1000 nm
oxide = 20 nm
oxide = 90 nm
Ray optics, 90 nm


Index
Wavelength (nm)
n
k
default
default, 150K
Franta, 293K
Franta, 150K
Material/Dataset
Si, default
Si, Franta 293K
Si, Franta 150K
SiO_2
LXe n
LAr n


P
P_T
P_e
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E_{field}
+
-
n+
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π
p+
P
P_T
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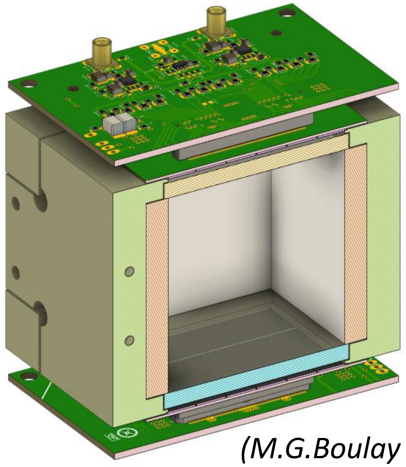
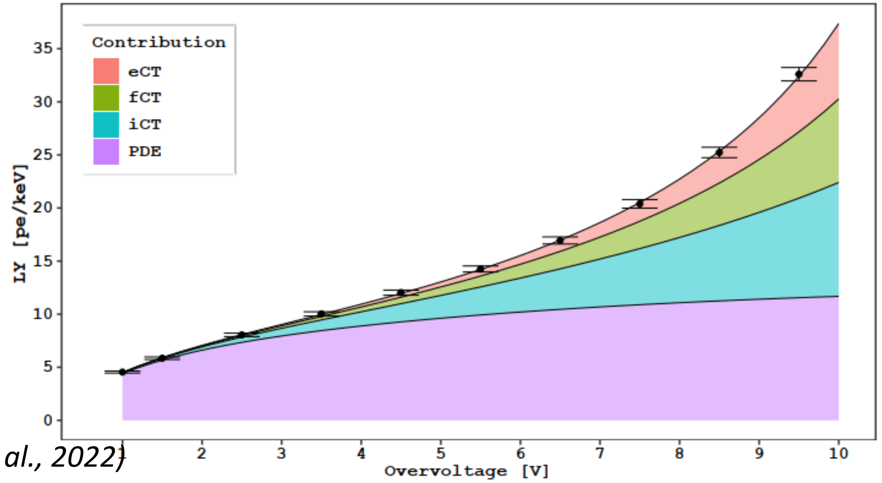
Impact of secondary photons in scintillation detectors:

- 1. Overestimation of light yield



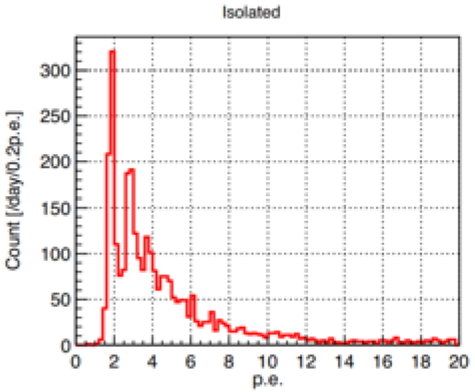


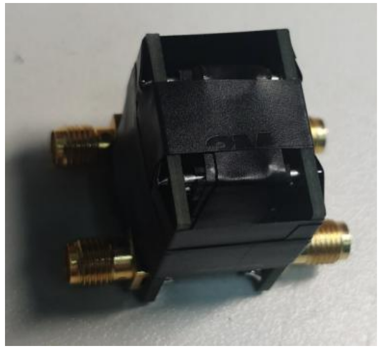
(M.G.Boulay et al., 2022)

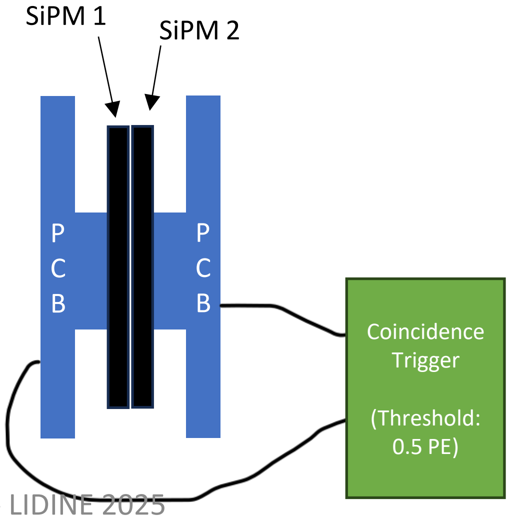
Secondary photons contributed light yield

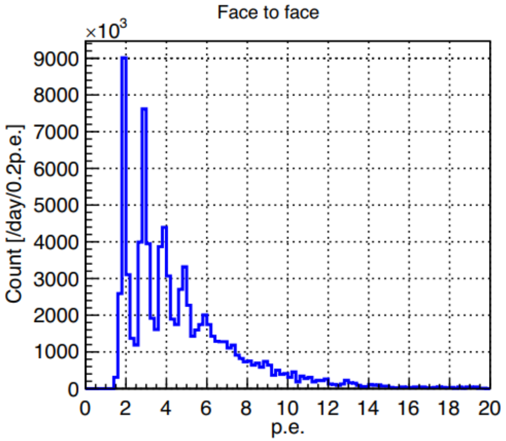
PDE contributed light yield

- 2. Correlated background









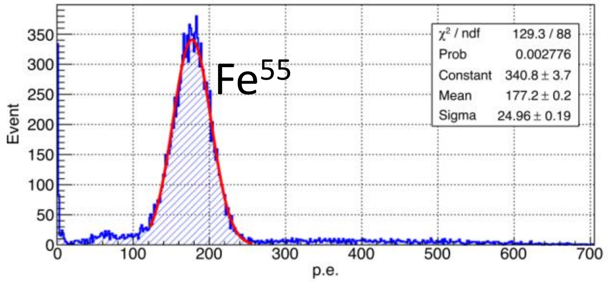
Coincidence distribution of two SiPM arrays at dark environment 87K

Impact of secondary photons in scintillation detectors:

- 3. Degeneracy of position reconstruction

Secondary photon emission causes a single photon to trigger multiple SiPM channels, leading the system to believe that more photons were produced in the event. These “extra photons” shift the light intensity centroid.

$$\Delta \mathbf{r} \equiv \mathbf{r}_{\mathrm{meas}} - \mathbf{r}_{\mathrm{true}} = \frac{\sum_{k\in\mathcal{S}_{\mathrm{eCT}}} q_k^{\mathrm{eCT}} (\mathbf{r}_k - \mathbf{r}_{\mathrm{true}})}{Q + Q_{\mathrm{eCT}}} \simeq \frac{Q_{\mathrm{eCT}}}{Q + Q_{\mathrm{eCT}}} \left(\overline{\mathbf{r}}_{\mathrm{eCT}} - \mathbf{r}_{\mathrm{true}}\right)$$



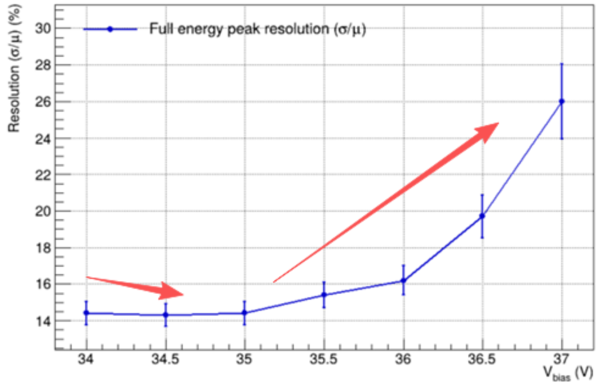
- 4. Degeneracy of energy resolution

$$\left(\frac{\sigma_E}{E}\right)^2 \approx \underbrace{\frac{\mathrm{ENF}}{N_{\mathrm{pe}}}}_{\text{single-photon statistics}} \downarrow + \sigma_{\mathrm{LY}}^2 + \sigma_{\mathrm{transport}}^2 + \sigma_{\mathrm{gain}}^2 + \underbrace{\left(\frac{\mathrm{ENC}}{G\,q\,N_{\mathrm{pe}}}\right)^2}_{\text{readout electronics}} + \underbrace{\sigma_{\mathrm{corr}}^2}_{\text{crosstalk / afterpulsing}} \uparrow$$

In the Borel/branching Poisson mode:

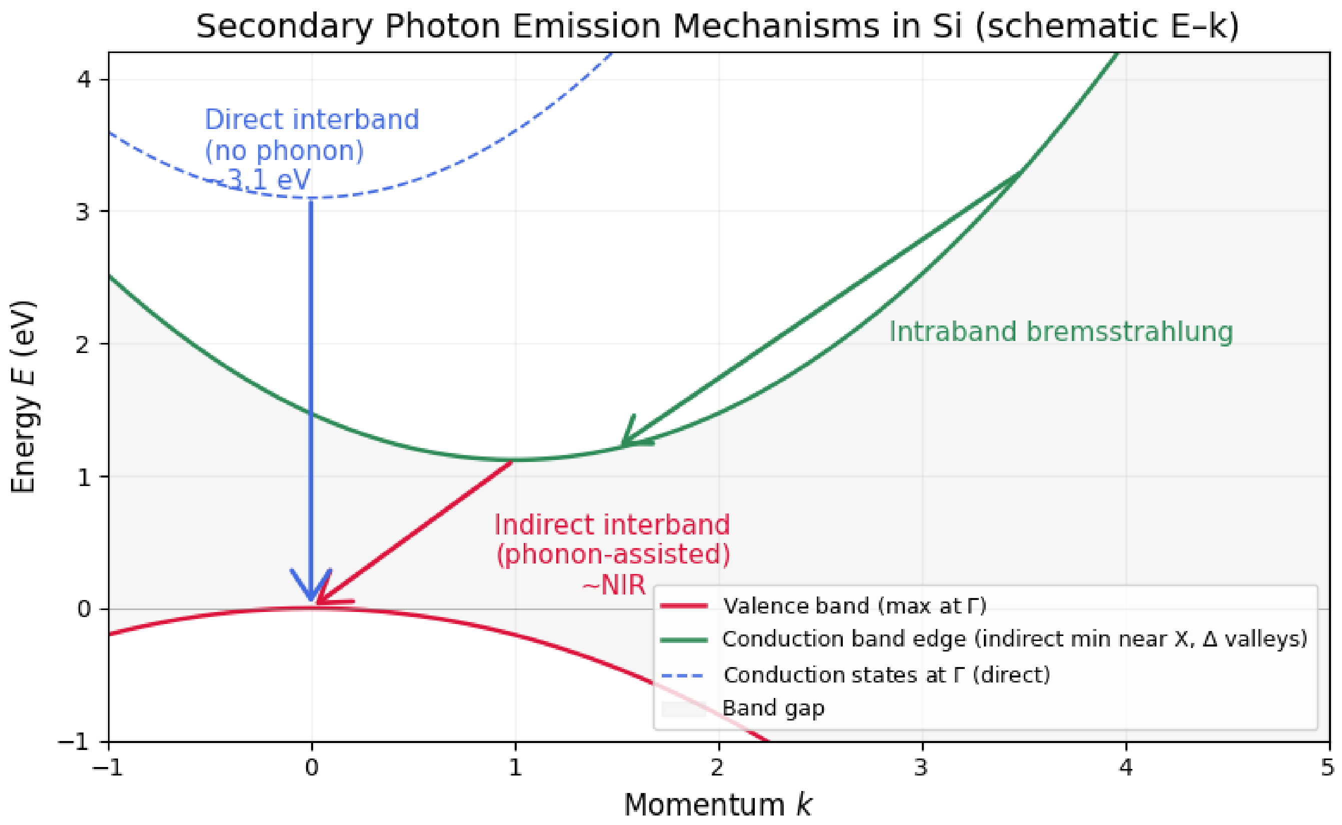
$$\uparrow \sigma_{\mathrm{corr}}^2 = \frac{\lambda \uparrow}{(1-\lambda)^3}$$

λ: the average number of secondary branches per generation



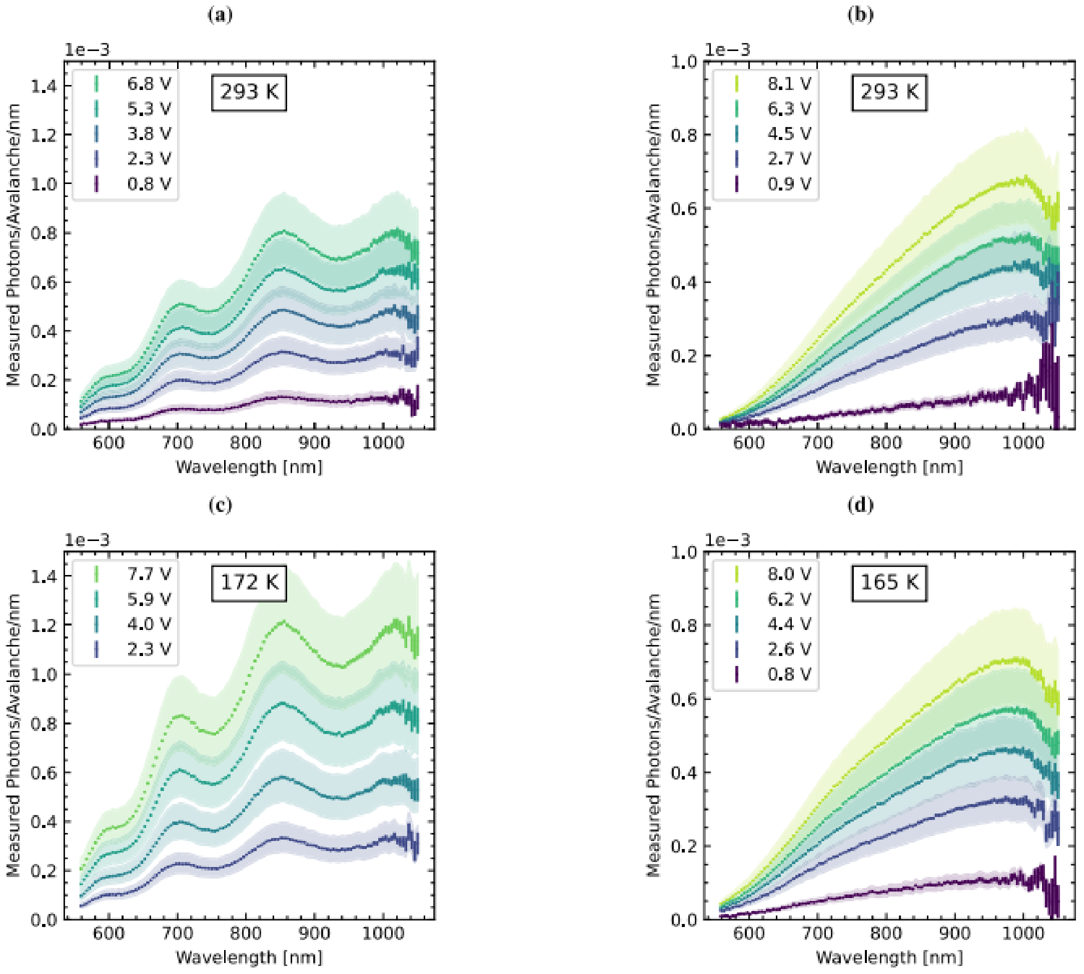
Energy resolution (Sigma/mean) VS V_{bias}

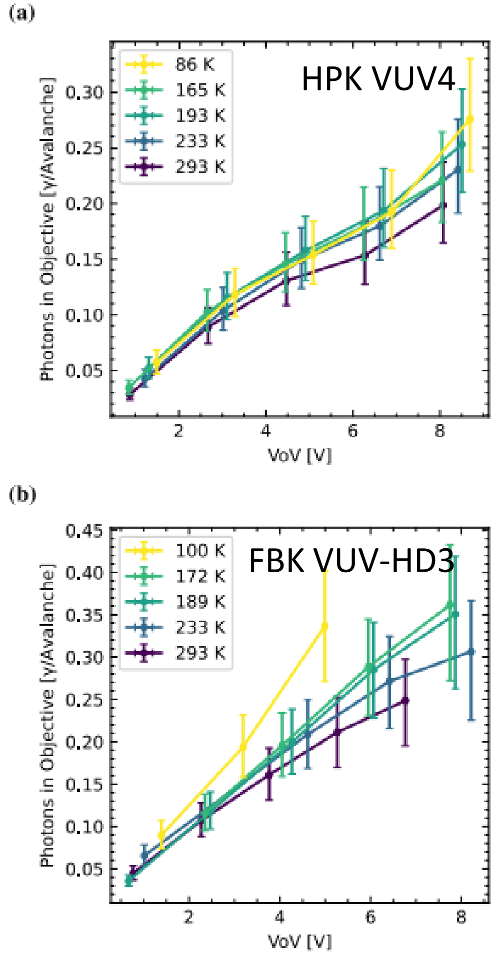
The mechanism of secondary photon emission of P-N junction



Indirect interband transitions— phonon-assisted recombination processes between the conduction and valence bands, which constitute the dominant source of long-wavelength secondary photons.
Intraband bremsstrahlung — radiation emitted when hot carriers are decelerated within the same energy band due to scattering, mainly contributing photons in the 2.0--2.3~eV range.
Direct interband transitions— direct electron--hole recombination without phonon assistance, which produces the higher-energy, short-wavelength component of the spectrum.

Number of photons in objective (0.45NA, θ=26.7°):

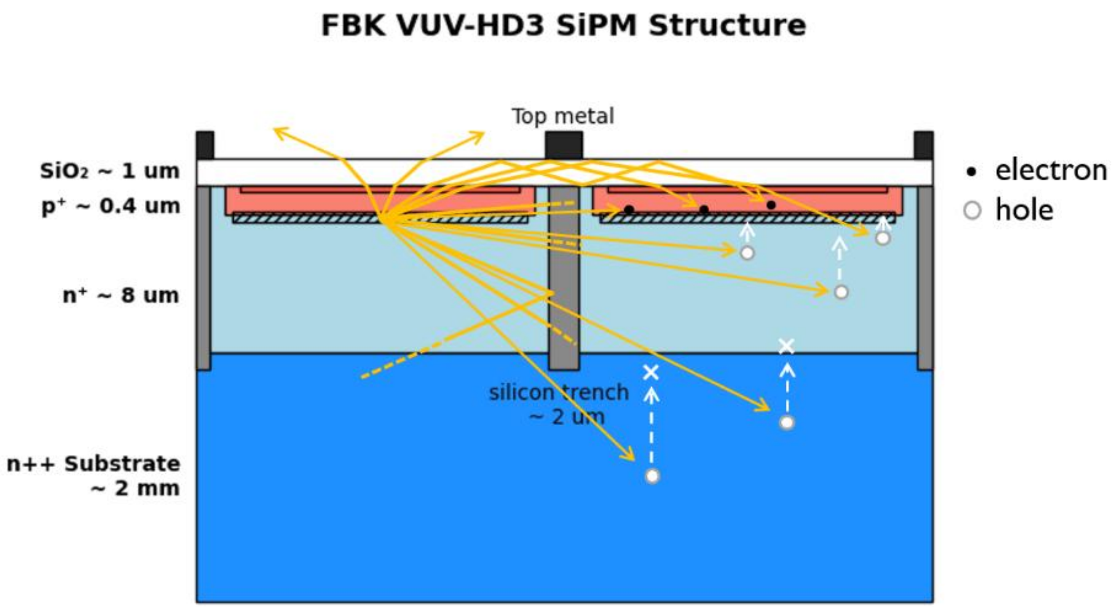


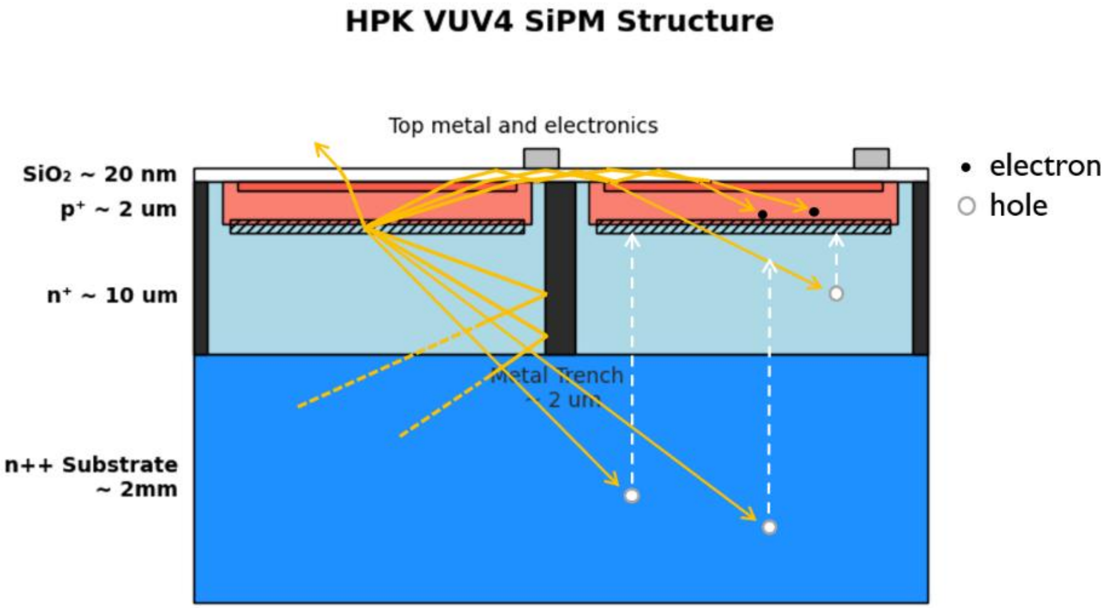


FBK VUV-HD3 HPK VUV4 Number of photons VS overvoltage

K. Raymond, et al., Stimulated Secondary Emission of Single Photon Avalanche Diodes (2024)

Crosstalk performance with certain SiPM structure

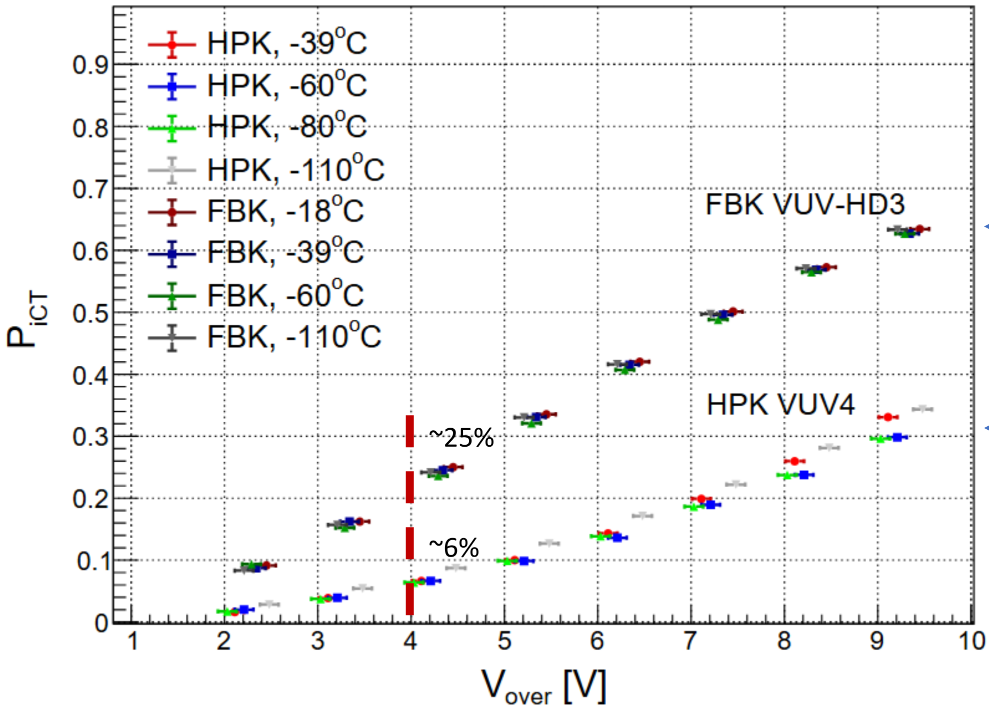




not drawn to scale

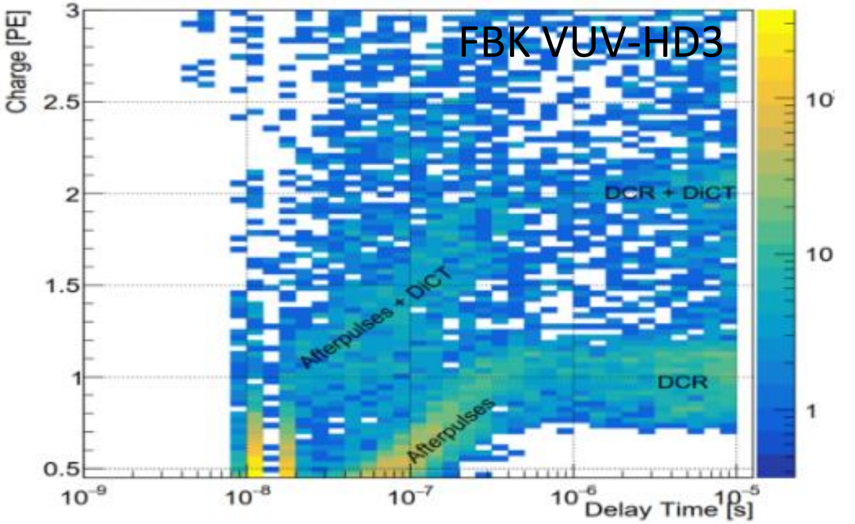
1. **FBK has thicker oxide layer** -> Interface enhancement in transmission -> Higher PDE
2. **Trench material** -> FBK's Silicon trench: ~25% of IR photon can pass through
   HPK's Metal trench: none photon can pass
3. **FBK's triple-doping technique reduces the hole drift time under 2 ns**

How trench affects SiPM crosstalk

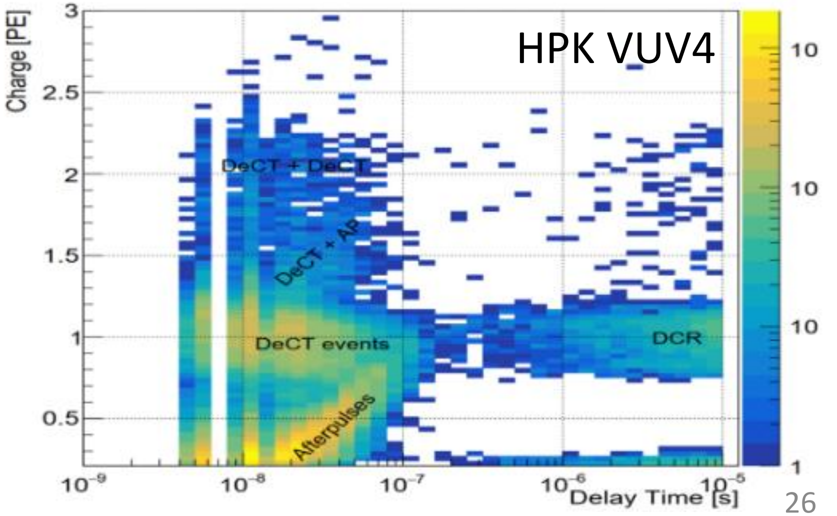


Silicon trench

Metal trench

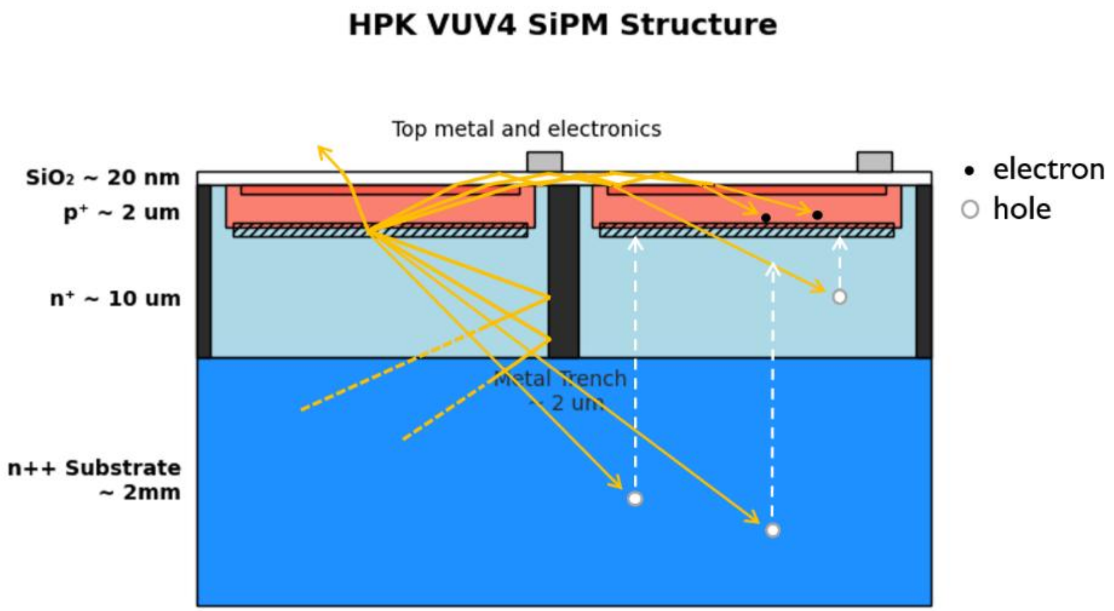


2D distribution of charge versus delay time for the FBK VUV-HD3



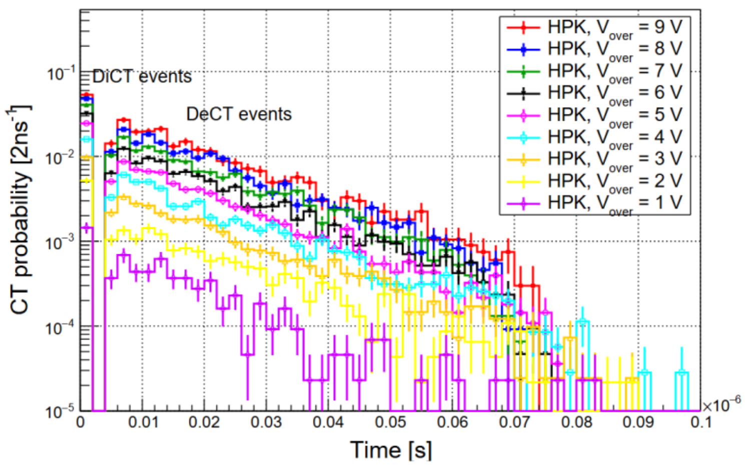
2D distribution of charge versus delay time for the HPK VUV4

Fraction of delay crosstalk of HPK:

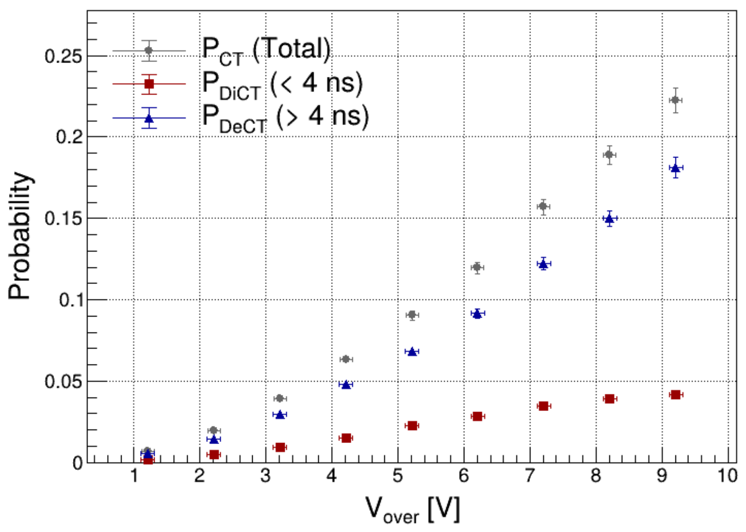


Saturate velocity of hole drifting: $\sim 6 \times 10^6 cm/s$

4 ns Drifting time ≈ 24 um (start in substrate)



The distribution of crosstalk events versus delay time for the HPK VUV4.



The probability of crosstalk events versus Vover for the HPK VUV4.