Low Dark-Count VUV SiPMs for the DARWIN Experiment

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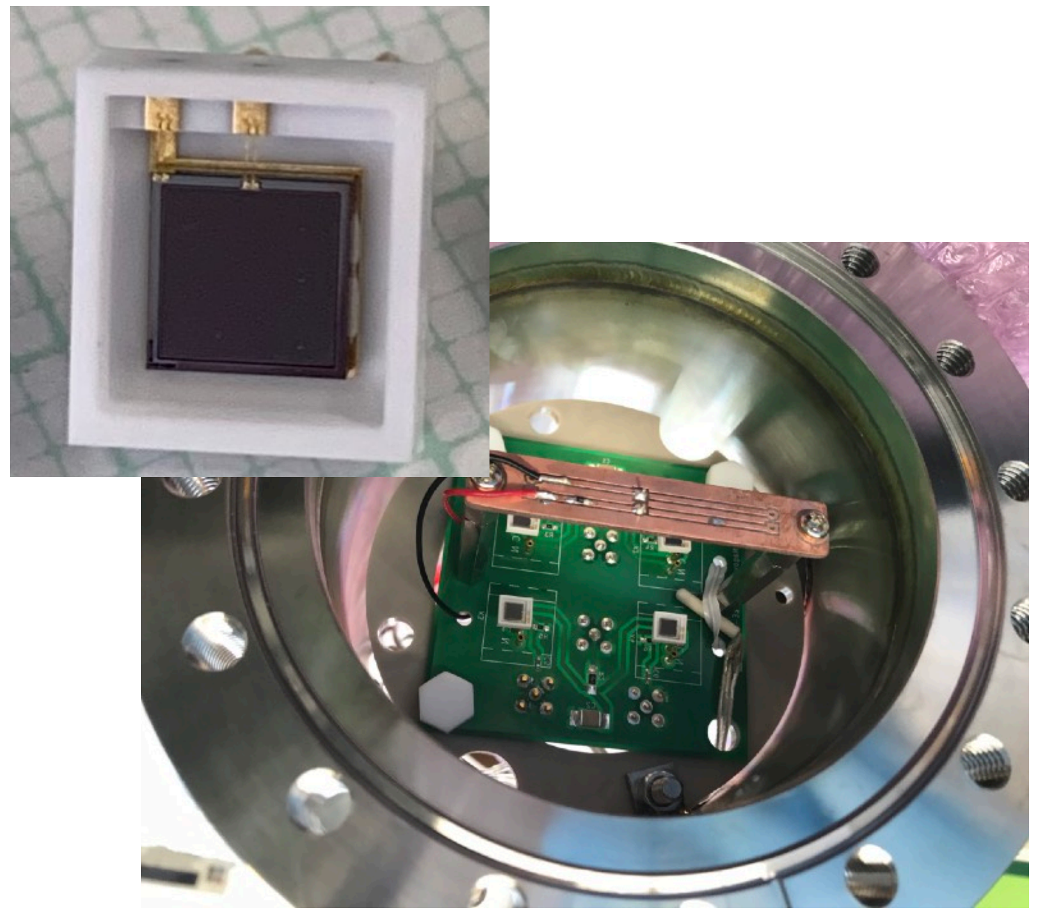
Nagoya Group's R&D on New Photosensors for DARWIN

R&D on New Photosensors in Japan

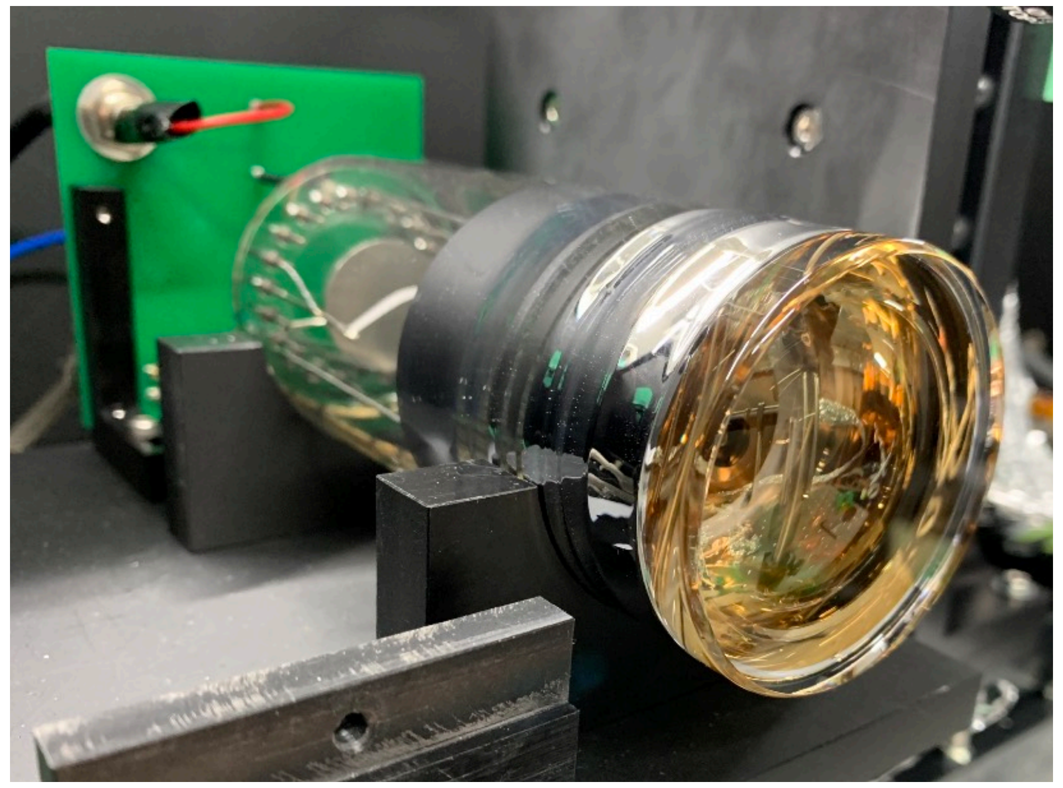
1. **Ultra low-radioactive PMT: 3inch R13111 developed by XMASS: Talk by Abe-san**
   - Lowest radioactivity ever achieved for LXe DM detectors
2. **Low Dark Count VUV SiPM: This talk**
3. **Hybrid Photosensor (PMT/SiPM): See poster by Tomoya**
   - Photocathode (converts a photon to an photoelectron) + SiPM (photoelectron detector)

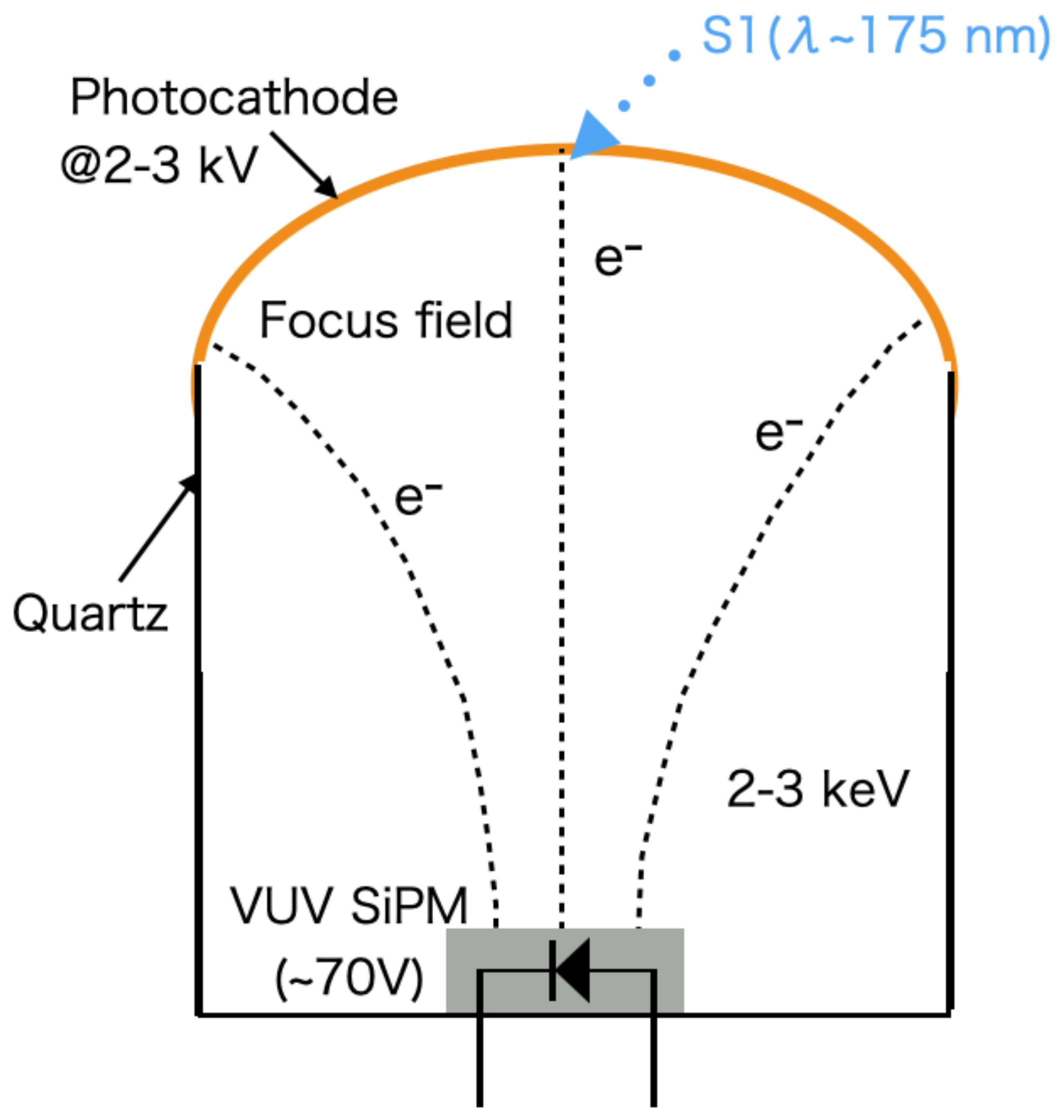
PMT (R13111)

Low Dark Count SiPM



Hybrid Photosensor



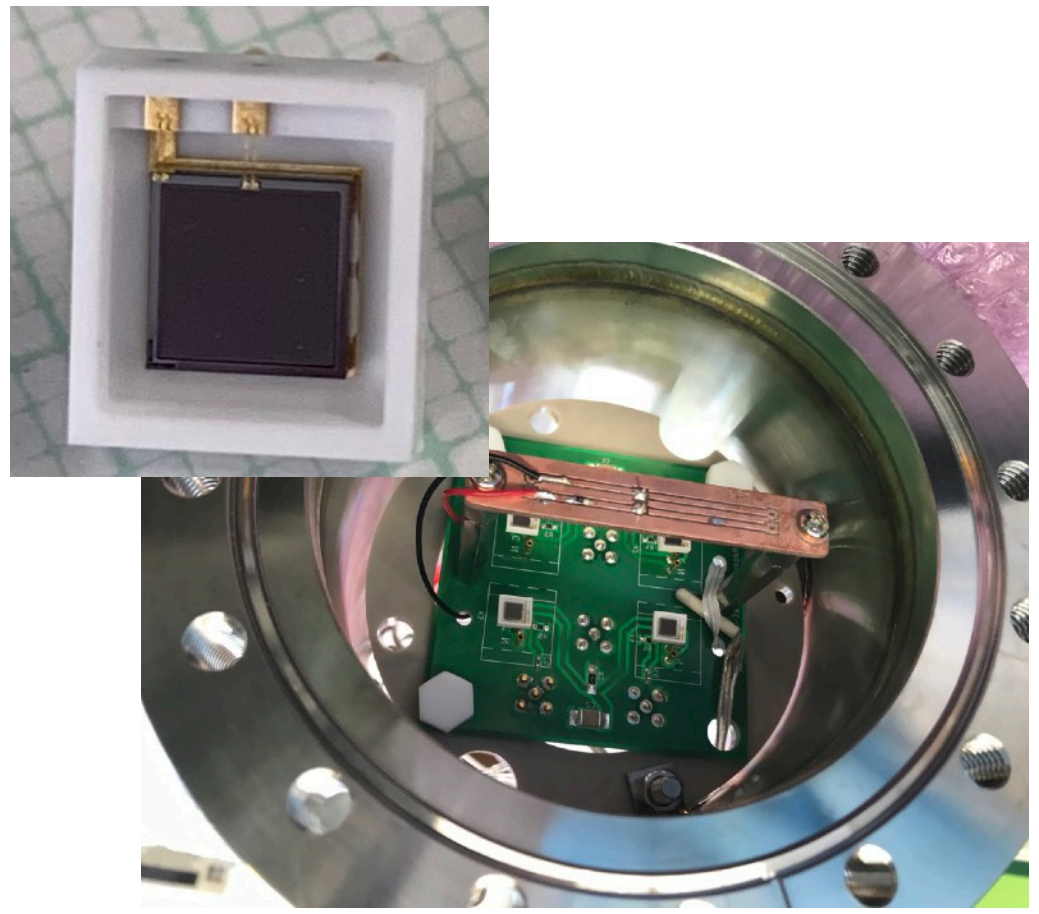


Nagoya Group's R&D on New Photosensors for DARWIN

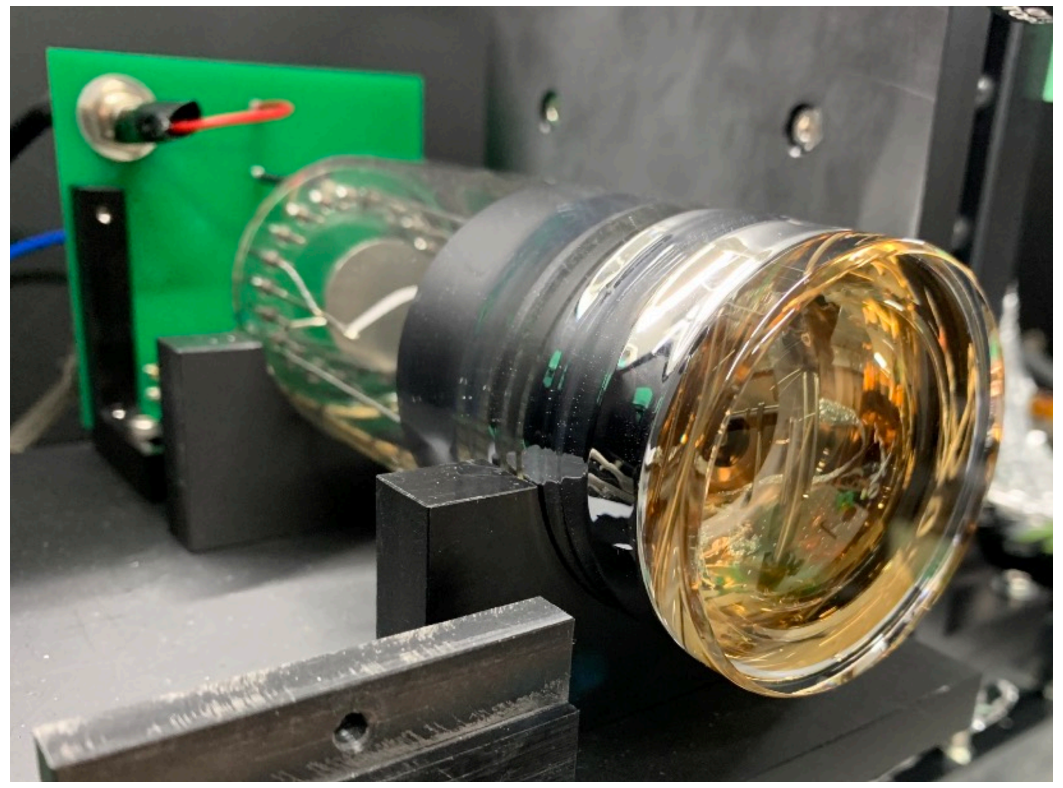
	PMT	SiPM S13370 (VUV4)	Hybrid
Operation voltage	~1500V	~50V	Photocathode: < 2 kV SiPM: 50-60 V
Single Photon Gain	~5×10^6	~2×10^6	~2×10^6
DC rate@165 K	~0.01 Hz/mm^2	~1Hz/mm^2	~0.01 Hz/mm^2
Radioactivity	High	Low	Low
QE	30 - 40%	30%	30 - 40%

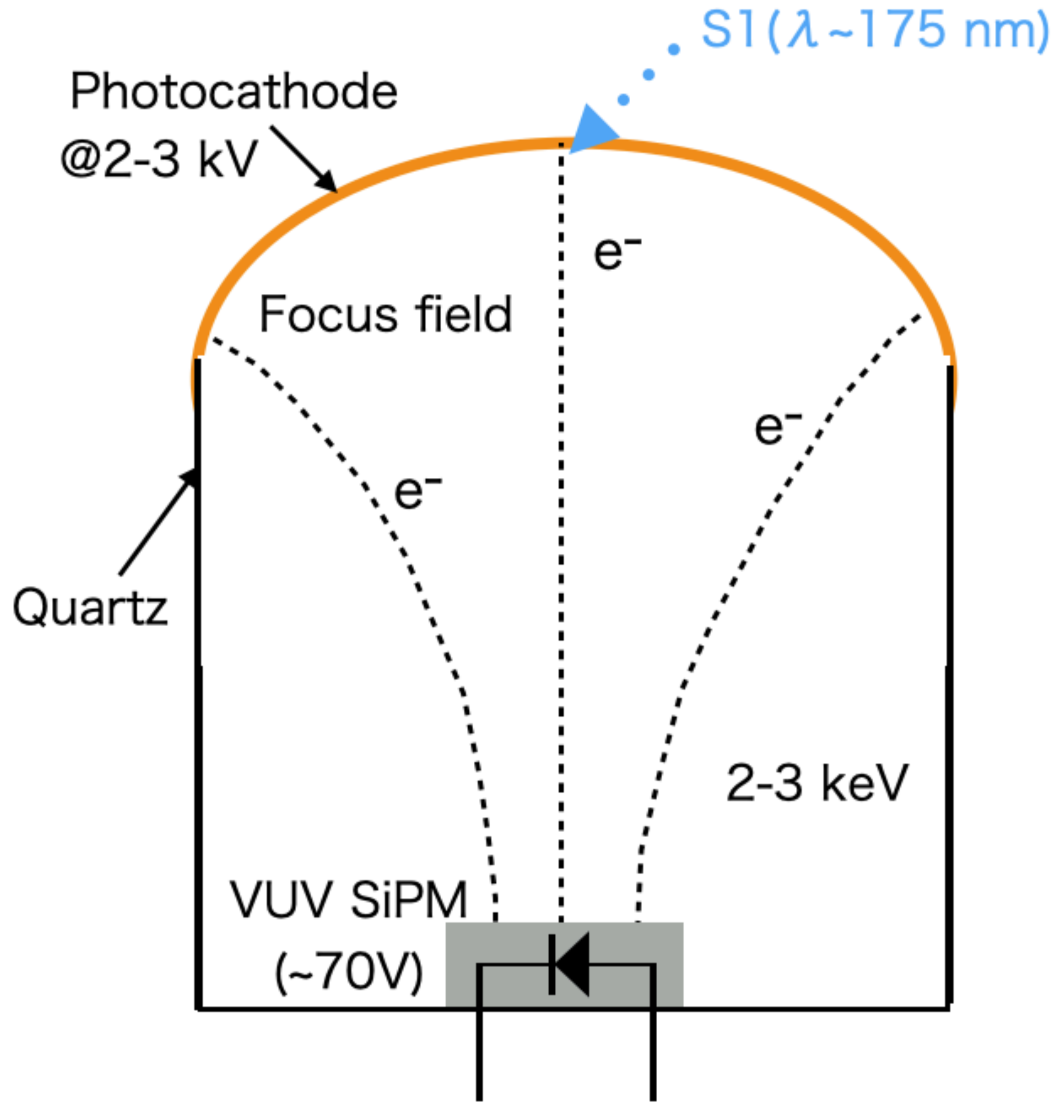
PMT (R13111)

Low Dark Count SiPM



Hybrid Photosensor





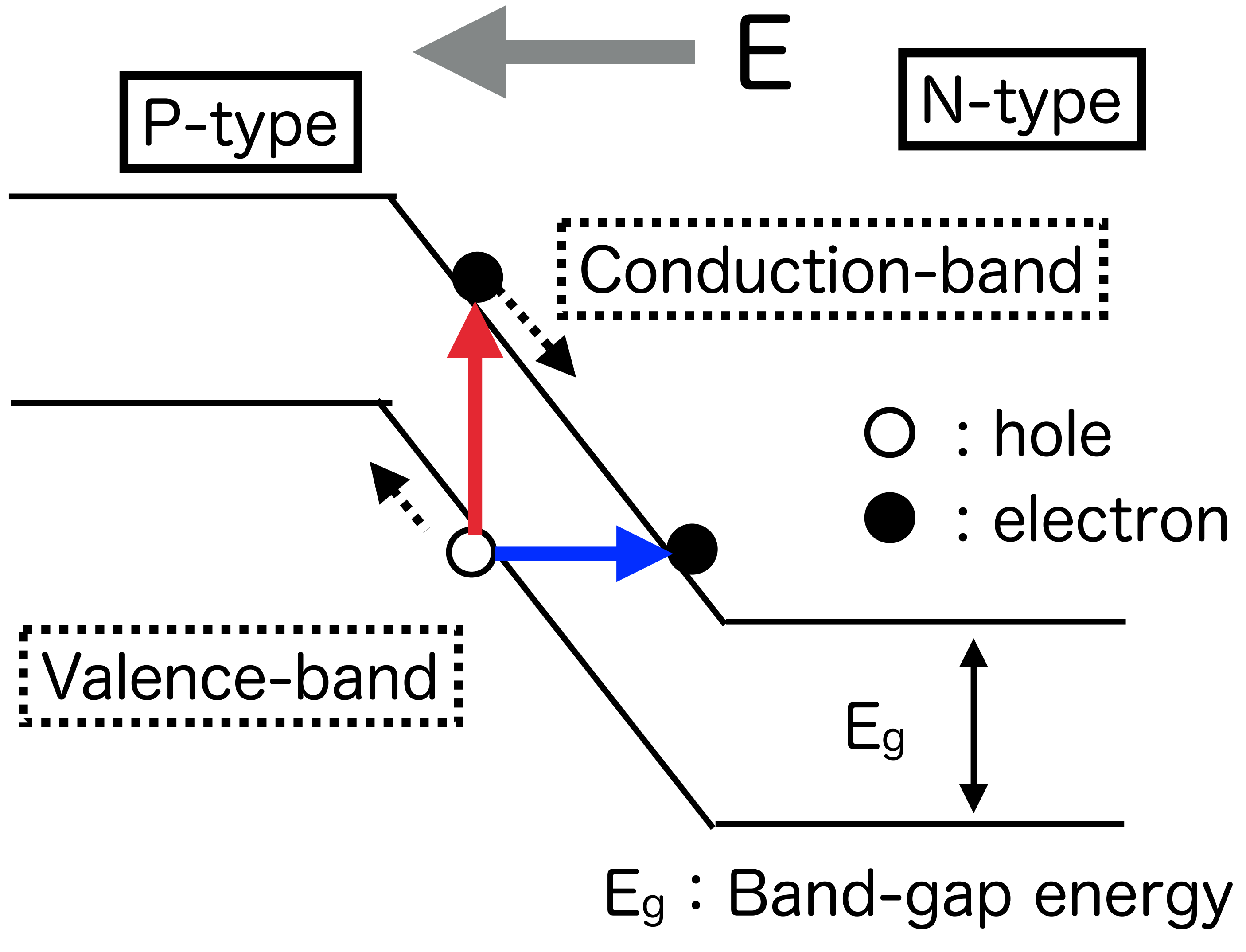
Low Dark Count UV SiPM

Origins of Dark Count

1. Thermally generated carriers:
   - strong temperature dependence

$$n_i \propto \times T^{\frac{3}{2}} \times exp(-\frac{E_g}{2k_BT})$$

2. Band-to-band tunneling effect:
   - weak temperature dependence



- At LXe temperature, huge DC rate is mainly due to the band-to-band tunneling effect

- To suppress the tunneling effect, we have developed a new SiPM with decreased avalanche electric field with the help of Hamamatsu
  - Low doping concentration
    Low E-field
  - Thicker depletion layer

	S12572-015C-SPL **New (SPL)**	S12572-015C-STD **Default (STD)**
Operation Voltage	～100V	～65V
Gain@OV=5V	～1.4×10^5	～2.3×10^5
Size	3mm×3mm	
Number of pixels	40000	
Pixel piches	15μm	
Fill factor	53%	
Package	Ceramic	
Trench	No trench	
Wavelength	300 - 900 nm	

Low Dark Count UV SiPM

Changes w.r.t the original SiPM

- Breakdown voltage becomes larger (+35V), but no significant changes in other performances.
  - PDE becomes a bit smaller, but can be compensated by increasing the operation voltage (+1V)
  - Afterpulse probablility becomes smaller because of less doping concentration.

	S12572-015C-SPL New (SPL)	S12572-015C-STD Default (STD)
Operation Voltage	～100V	～65V
Gain@OV=5V	～1.4×10^5	～2.3×10^5
Size	3mm×3mm	
Number of pixels	40000	
Pixel piches	15μm	
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Package	Ceramic	
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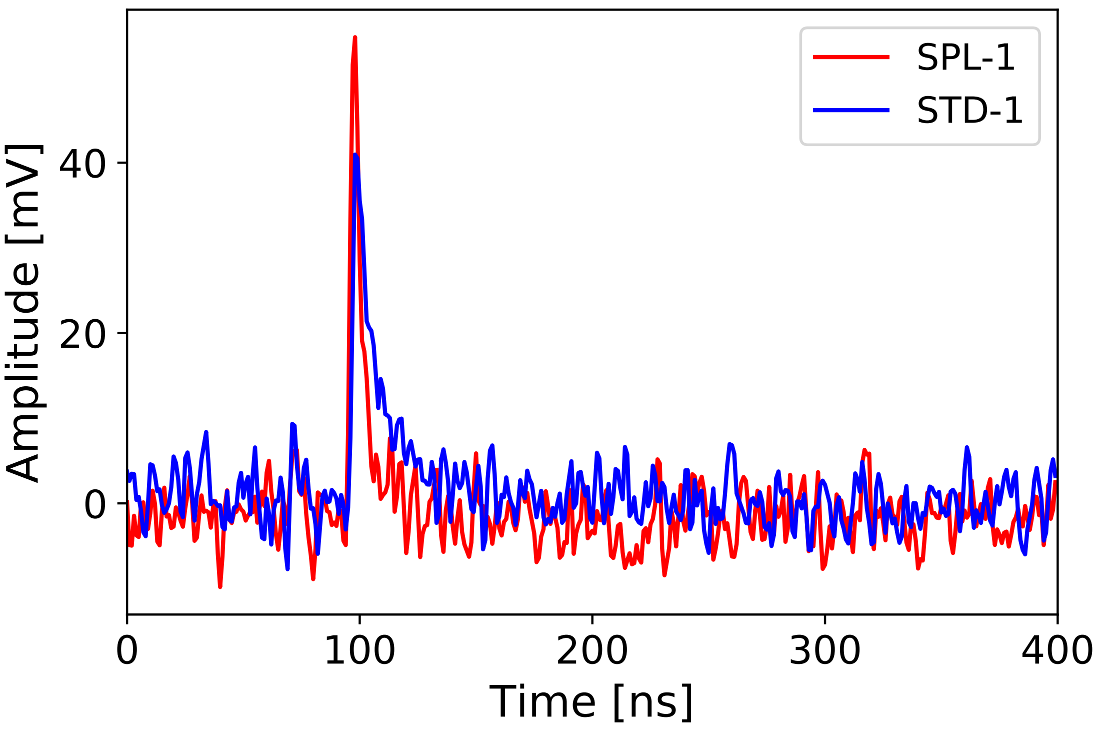
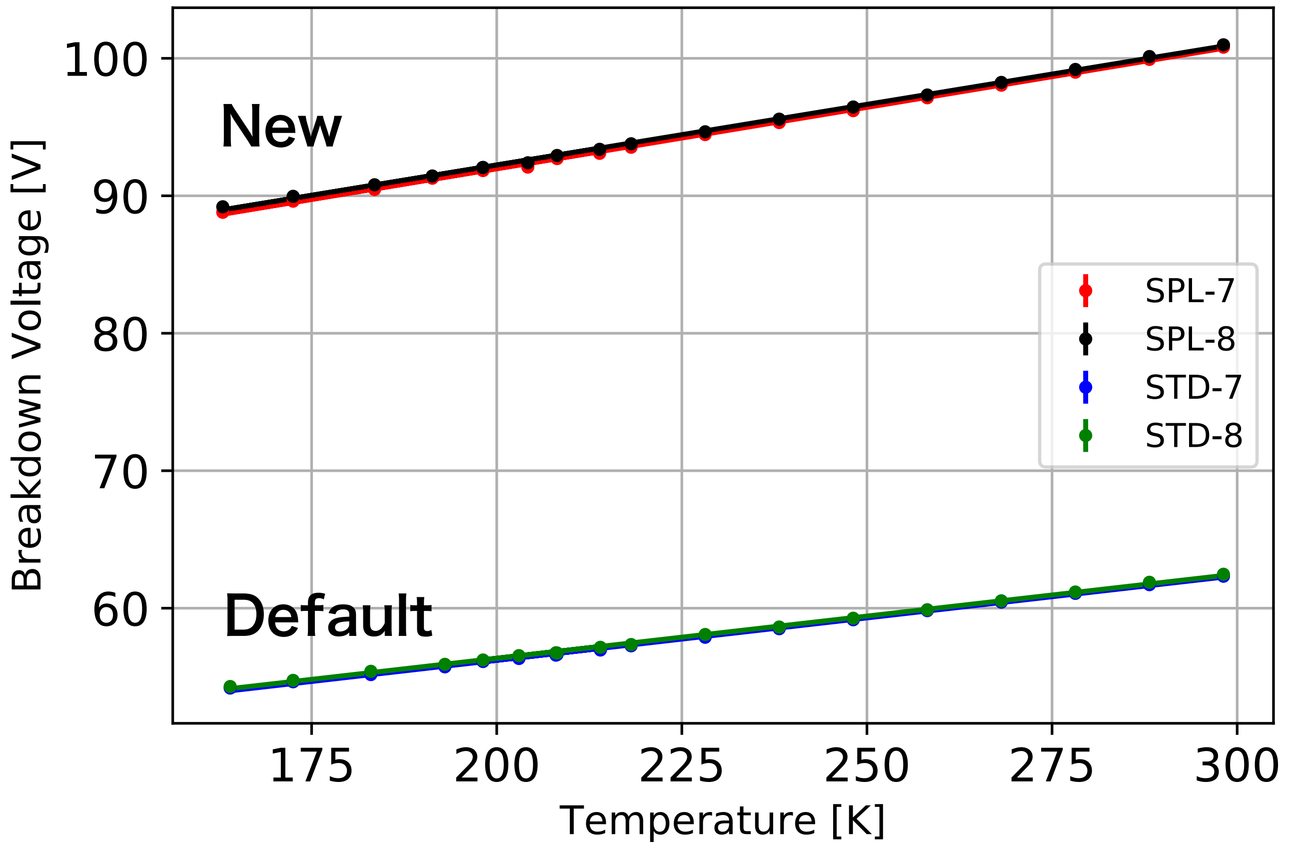
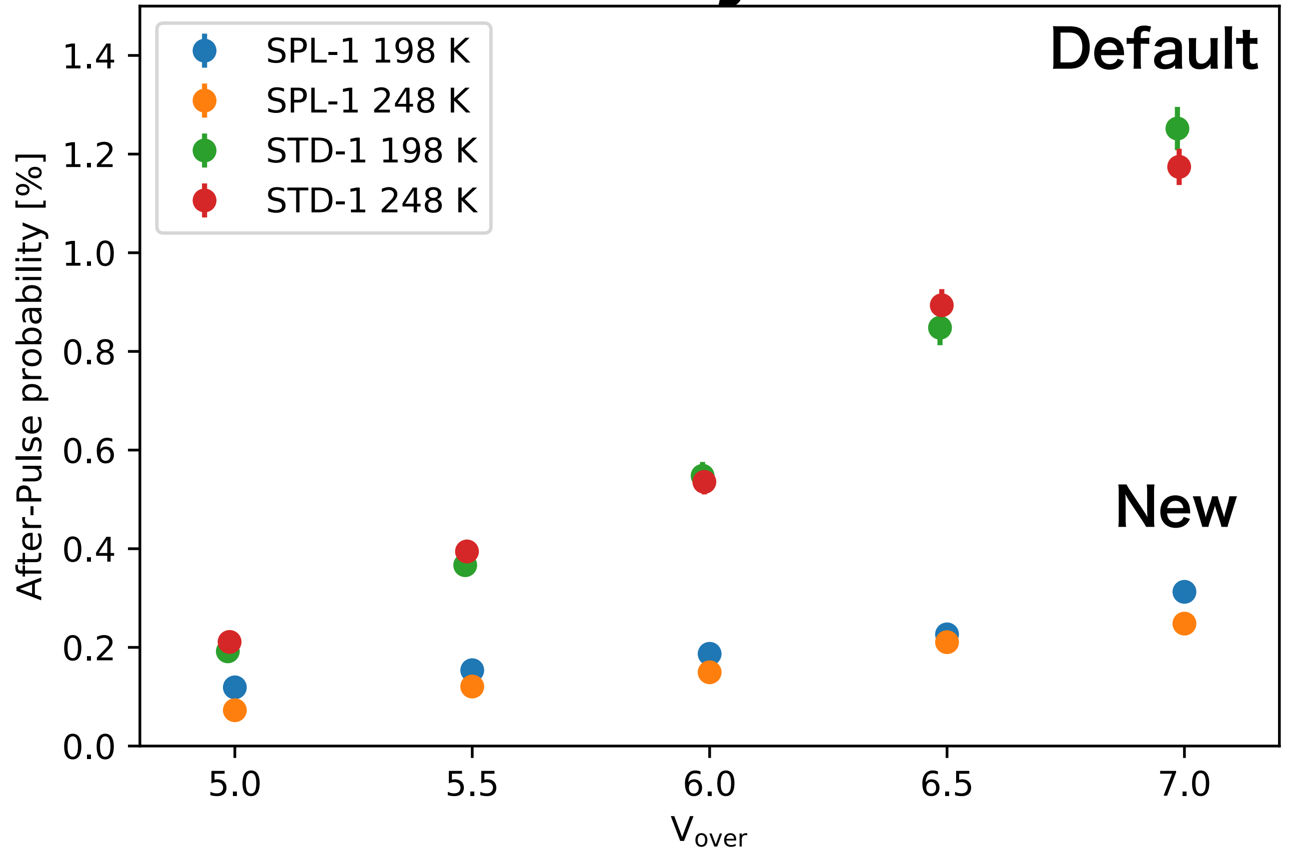
Waveform



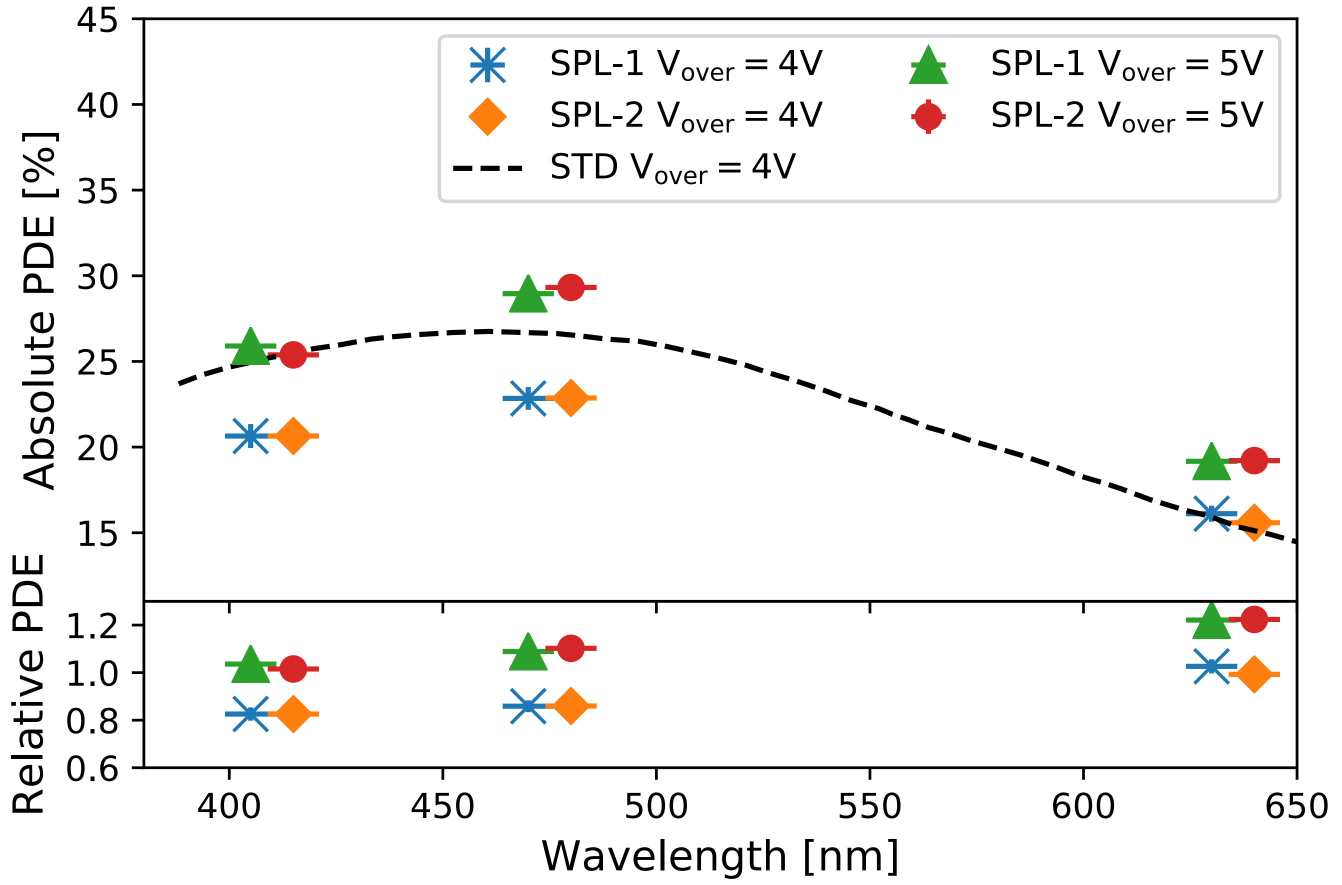
Breakdown Voltage



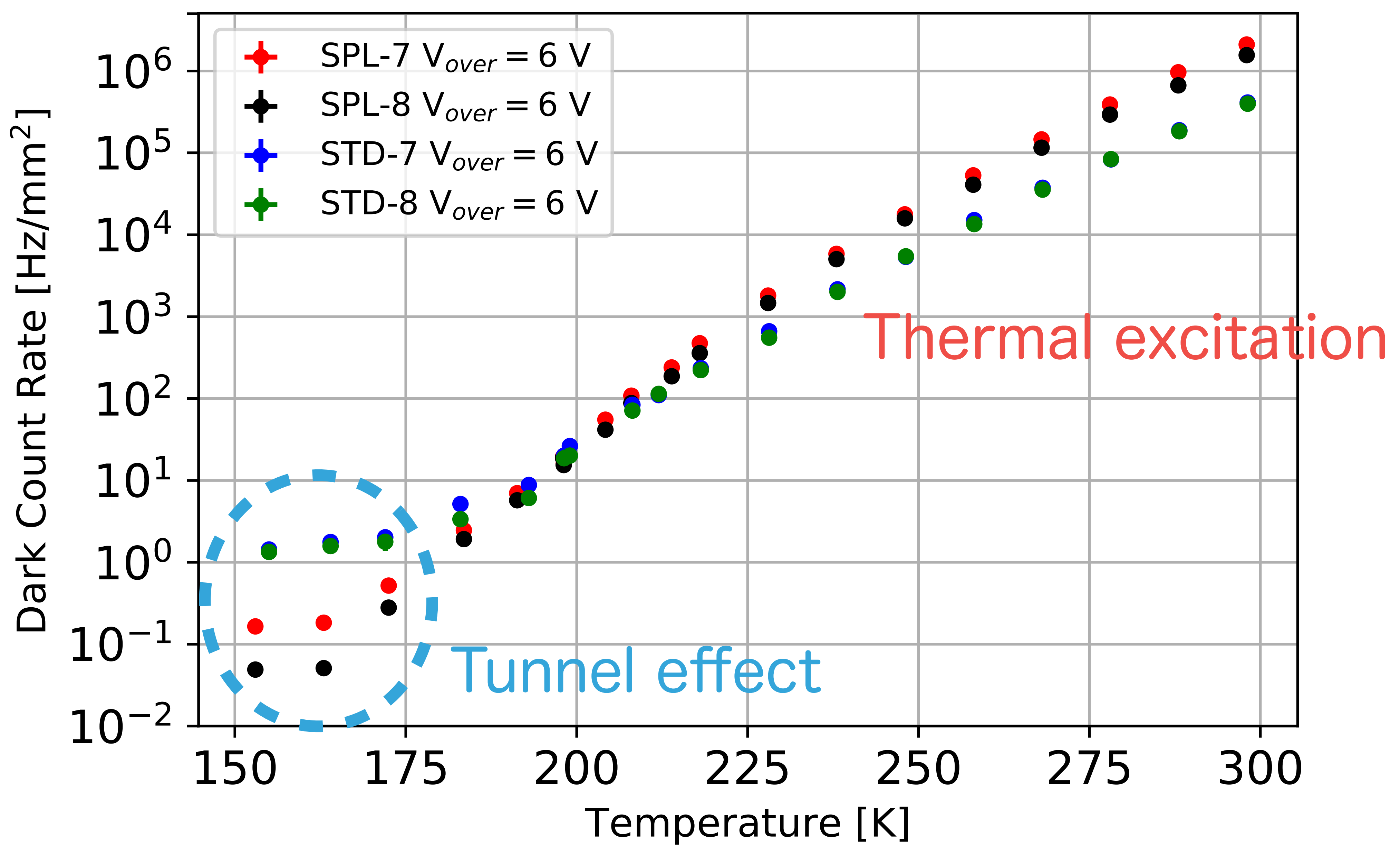
AP Probability

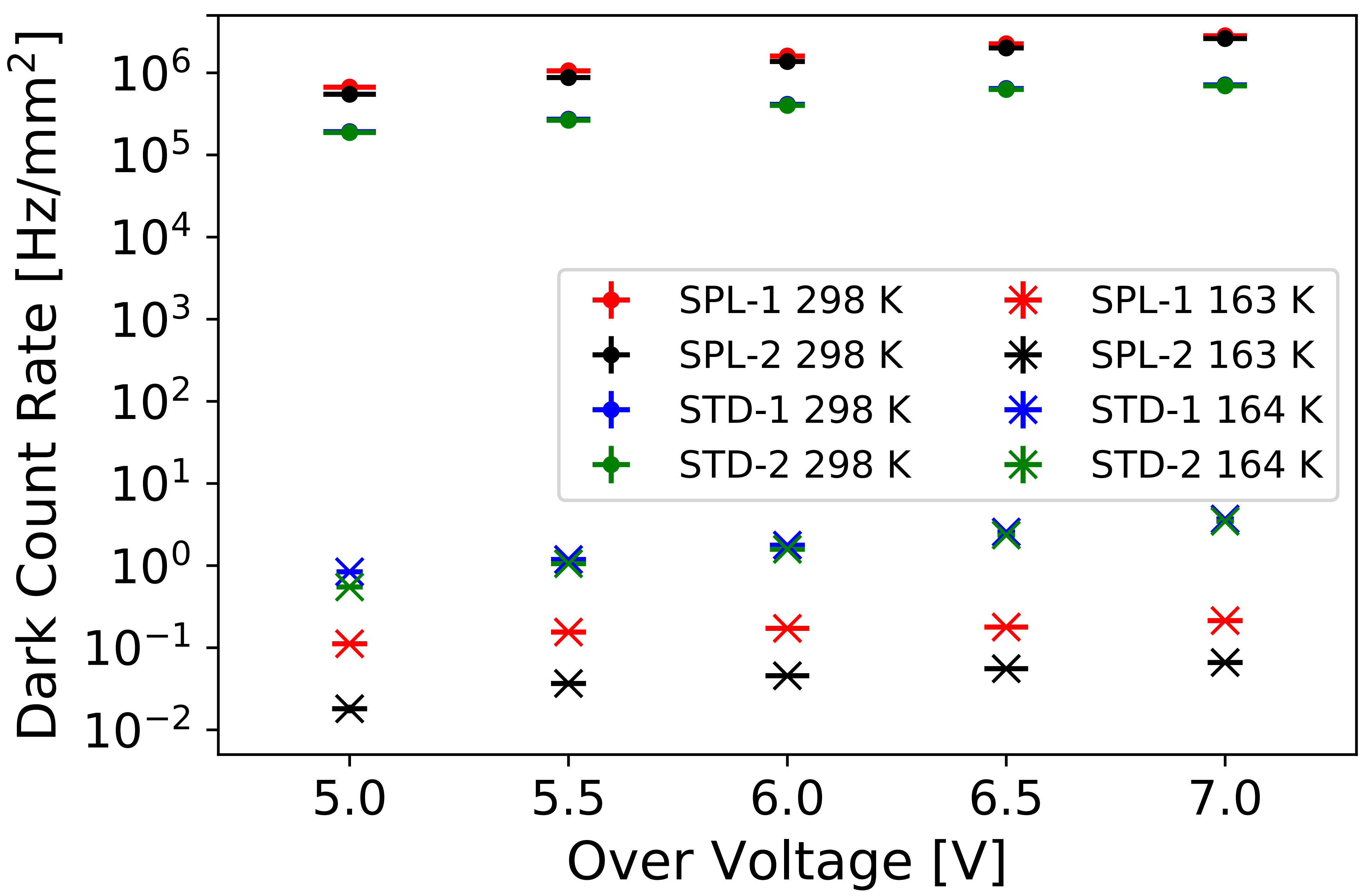


PDE



Low Dark Count UV SiPM





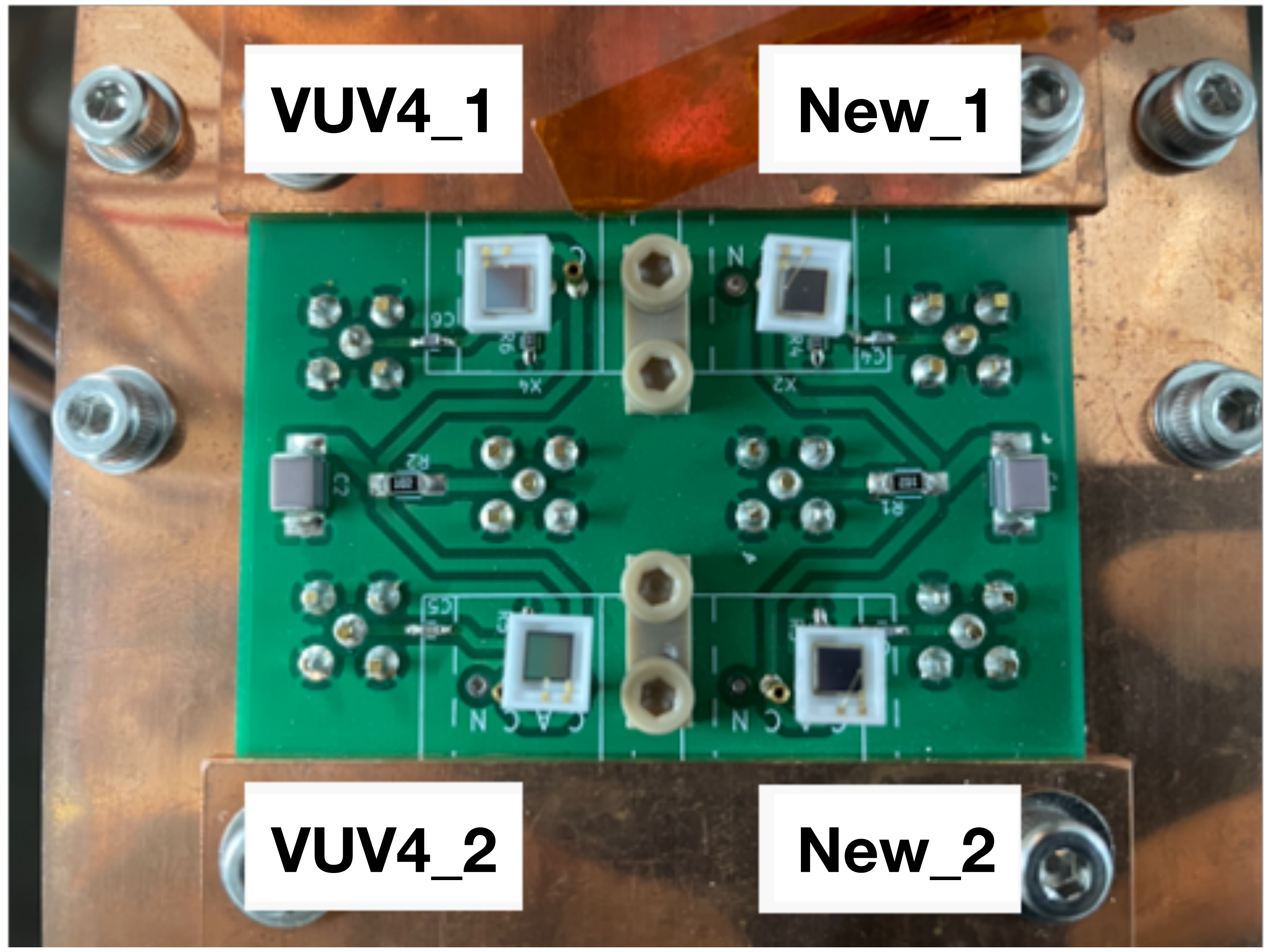
- **We managed to reduce the DCR of UV SiPMs by a factor of 6 - 60.**

- However, this SiPM is not sensitive to LXe scintillation light
  - Recently we have developed a VUV-sensitive low-noise SiPM and characterized its performances.

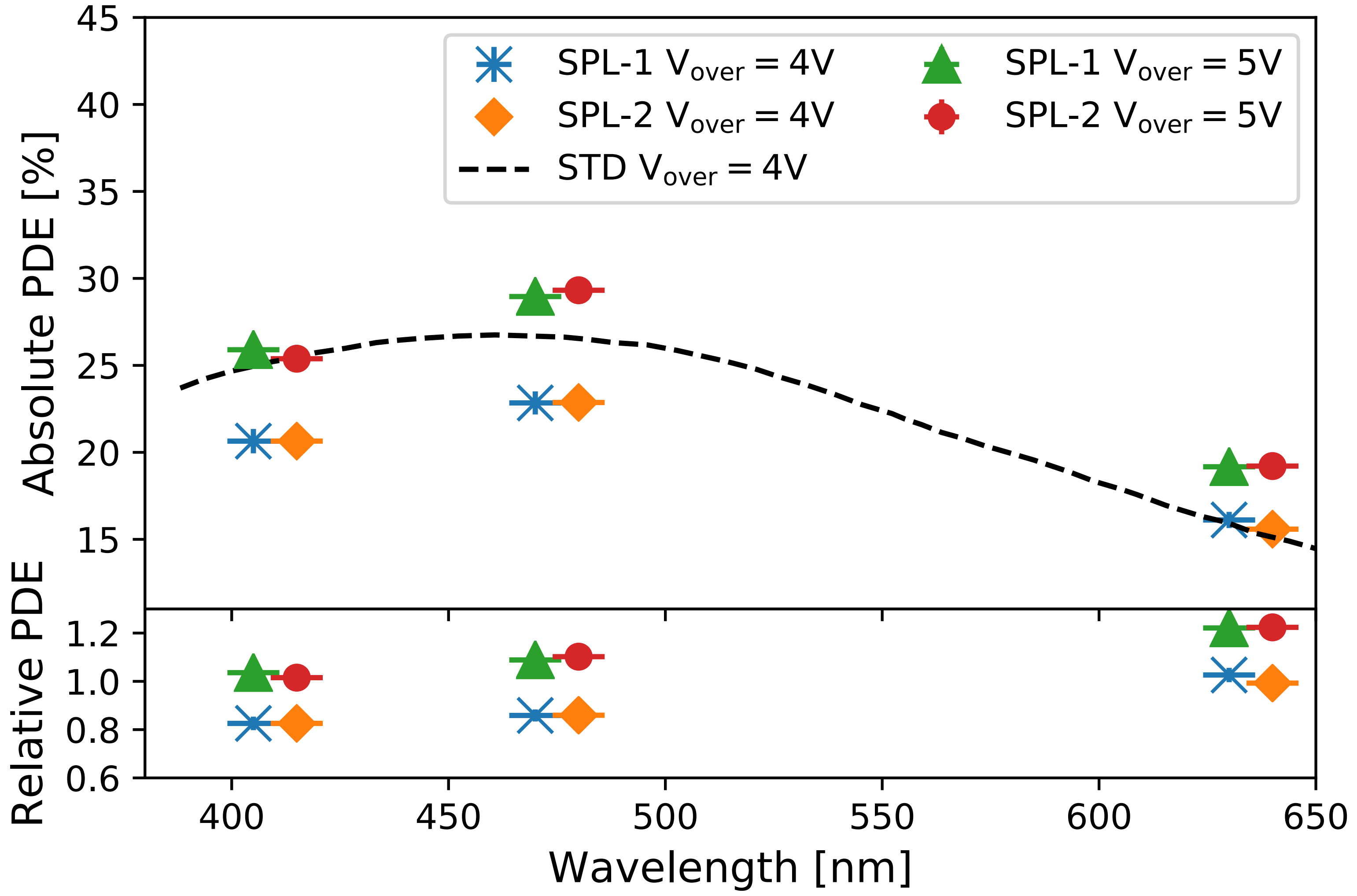
New VUV SiPM

SiPM	S13370-3050CN (VUV4, Default)	New	
Operation Voltage	40-50 V	80-100 V	
Active Area	3×3 mm²		
Number of pixels	14400		6400
Pixel size	50×50 μm²		100×100 μm²
Fill factor (next page)	58%	74%	>> 74%

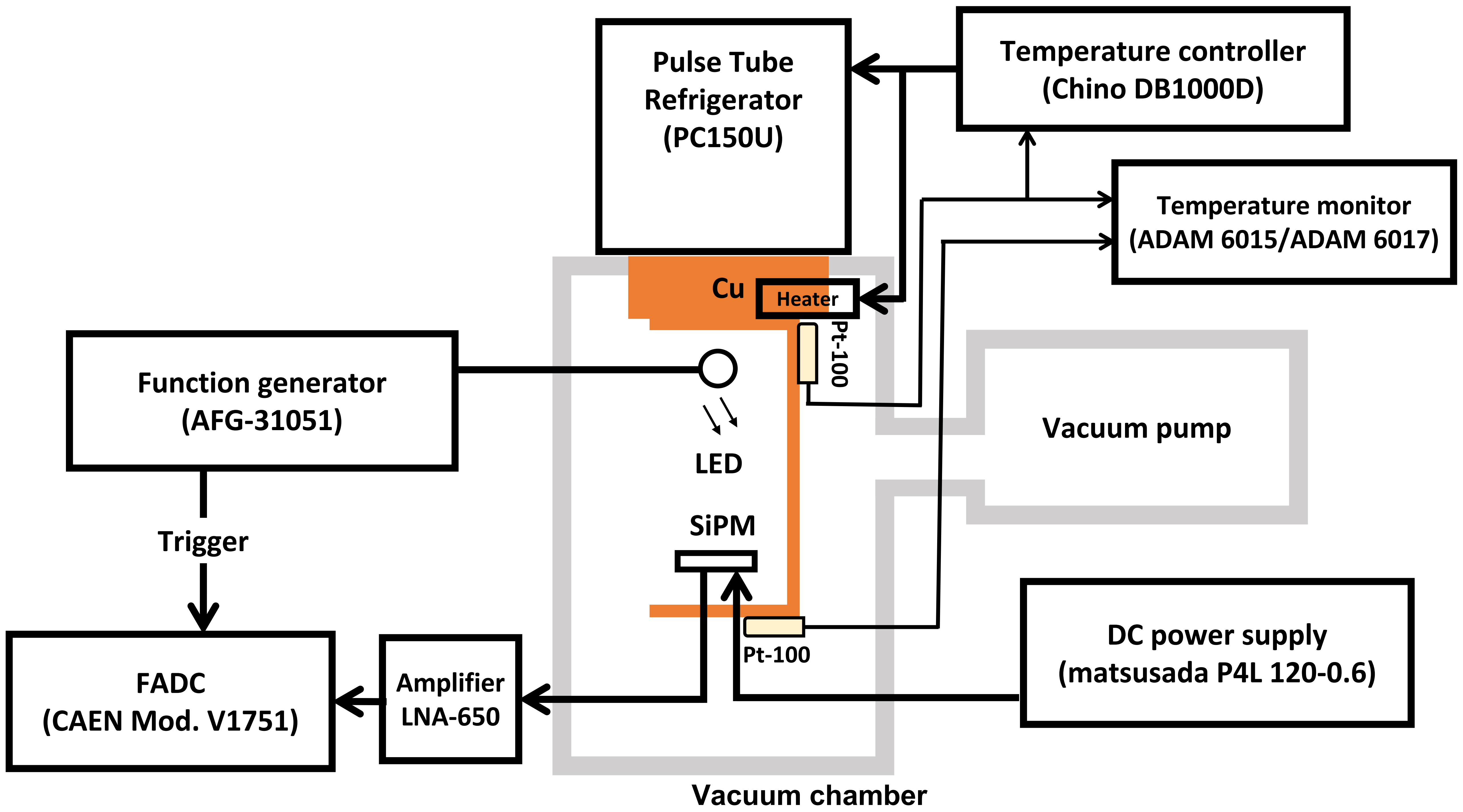
- Breakdown voltage becomes larger (+40V) as observed in UV SiPMs
- Our previous measurements indicates reducing DCR may worsen PDE. Therefore, Hamamatsu optimized fill factor and managed to increase the PDE

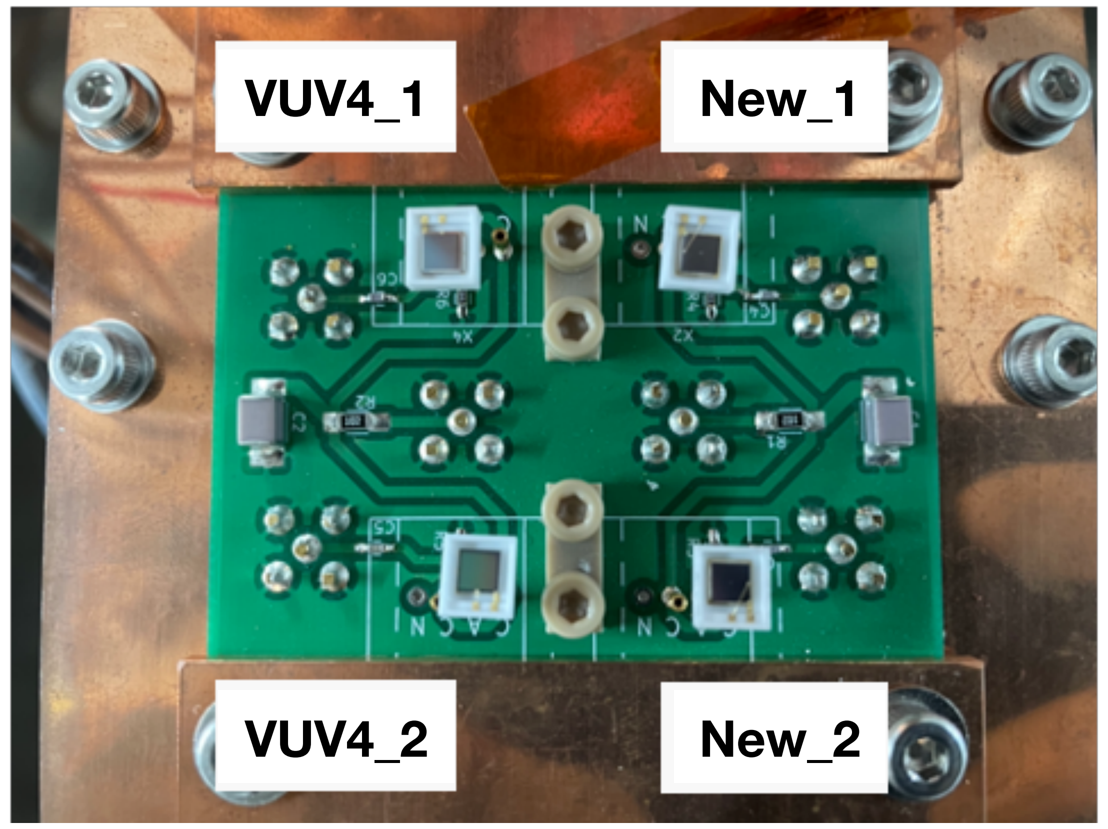


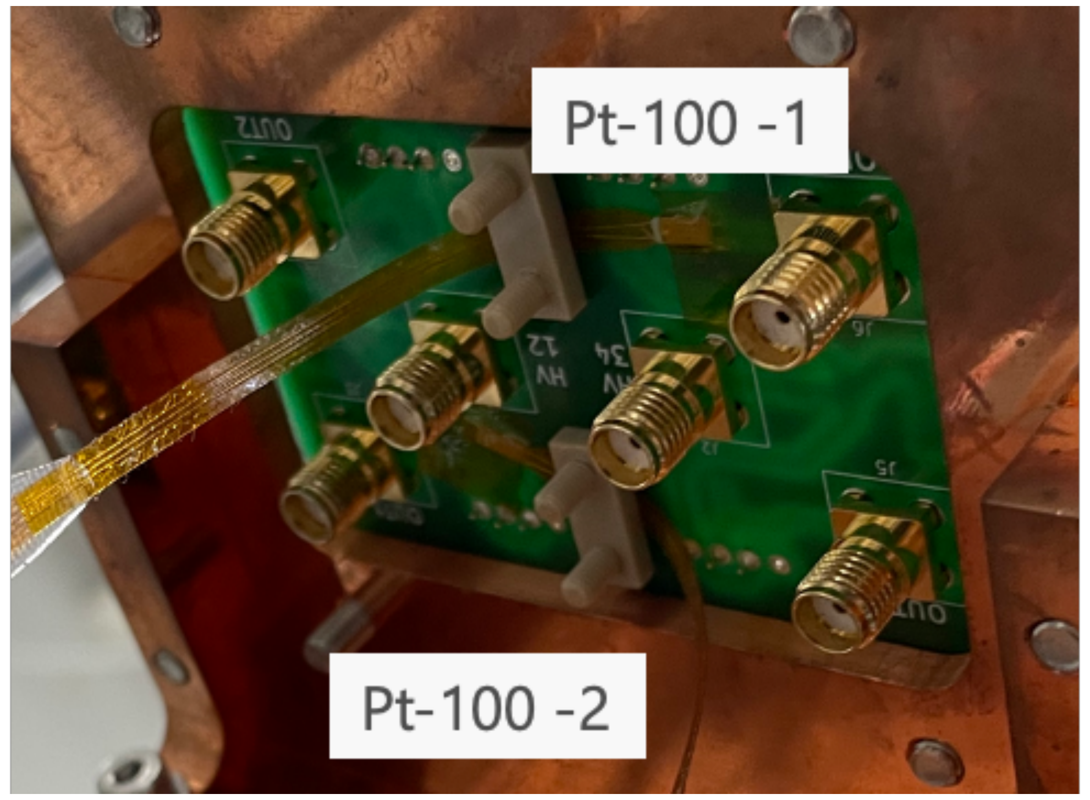
PDE of UV SiPM



Setup



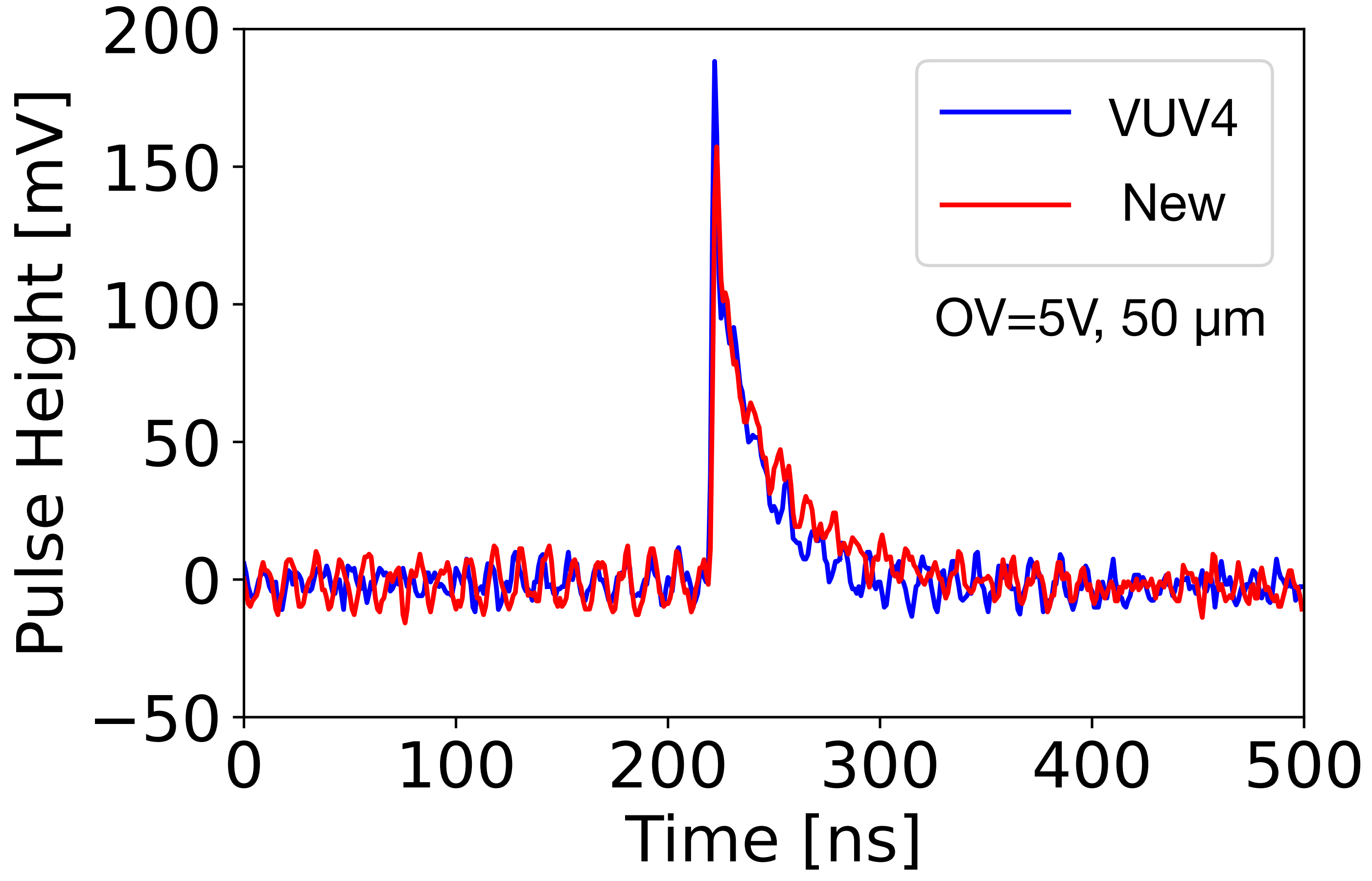


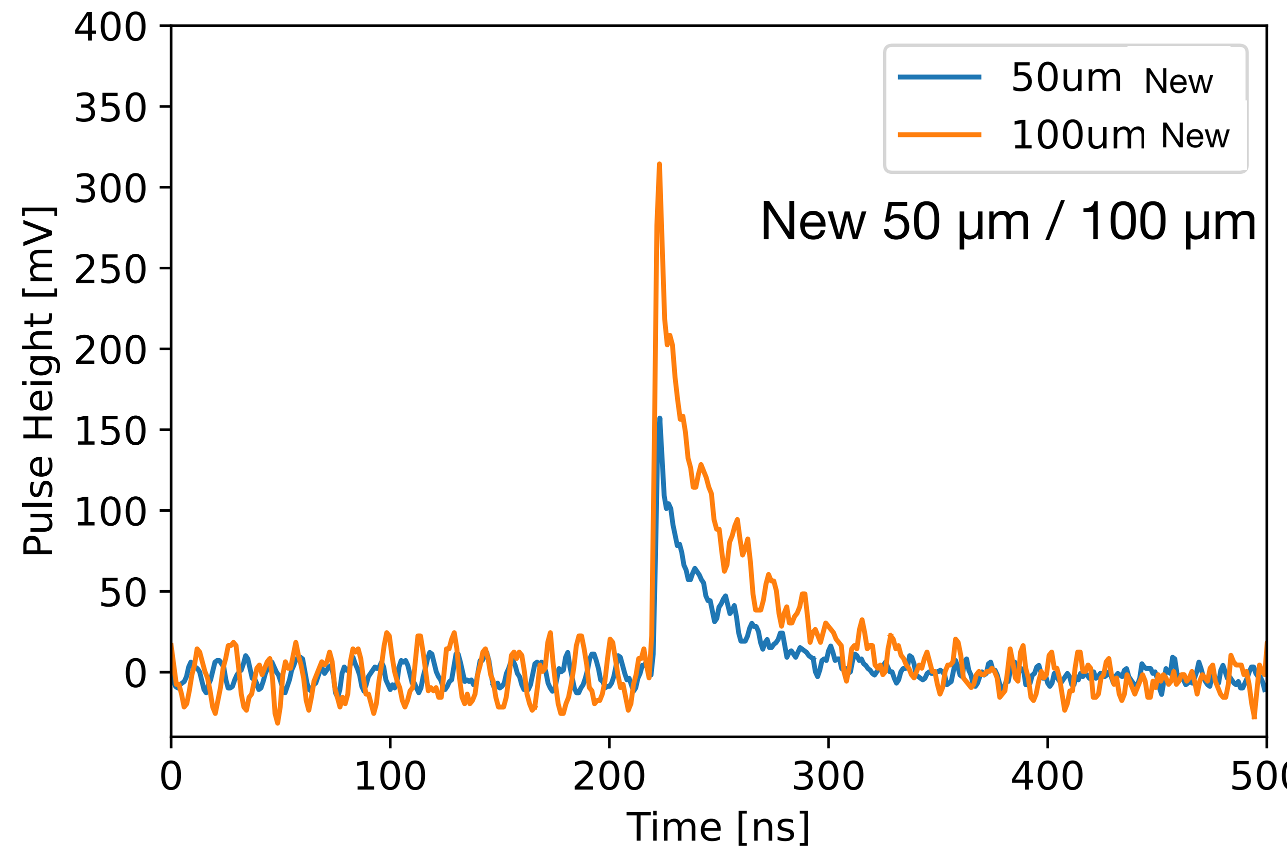


- Low-temperature in vacuum (controlled between 150 and 210 K)
- 2 samples for each pixel sizes
- Digitizer: CAEN V1751 (1GHz sampling)
- Temperature was stable with < 0.1K fluctuation during all the measurements

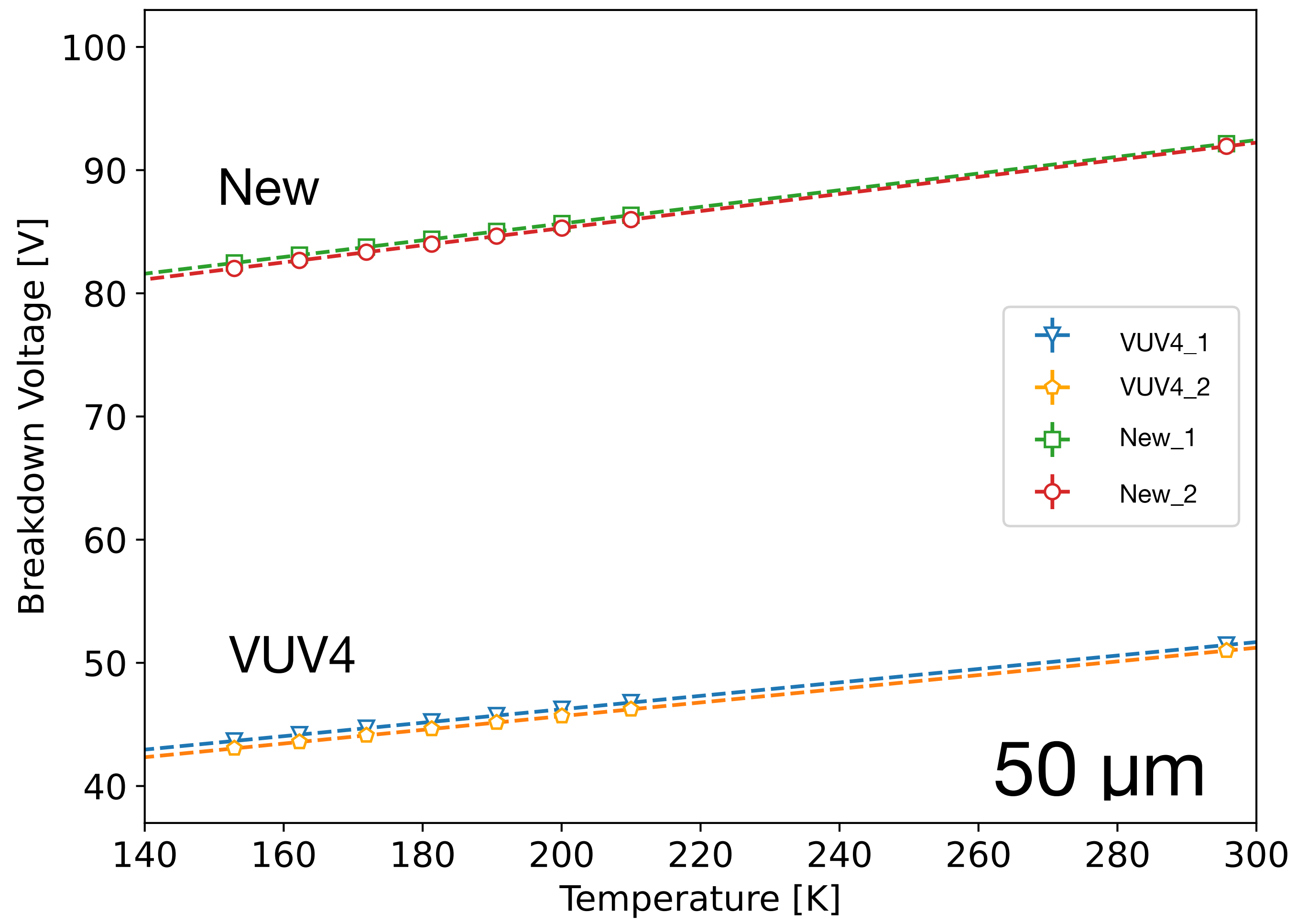
Single-Photon Response

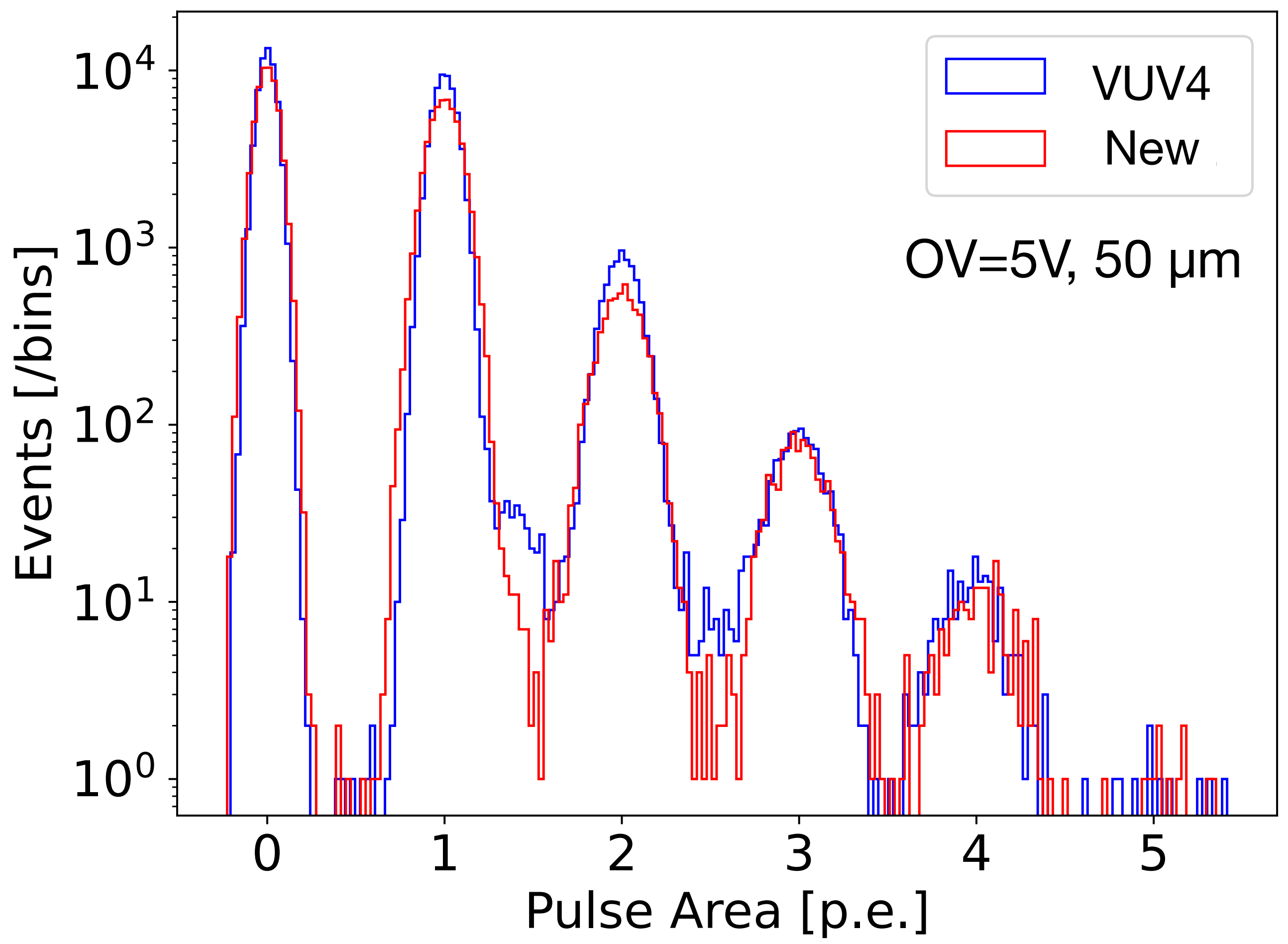
	Over-voltage	New 100 μm	New 50 μm	VUV-4 50 μm
1pe Gain [$\times 10^6$]	3 V	1.6	0.6	1.0
	5 V	2.6	1.0	1.7
	7 V	3.6	1.4	2.4
breakdown voltage @ 165 K [V]		84.4	83.4	44.4





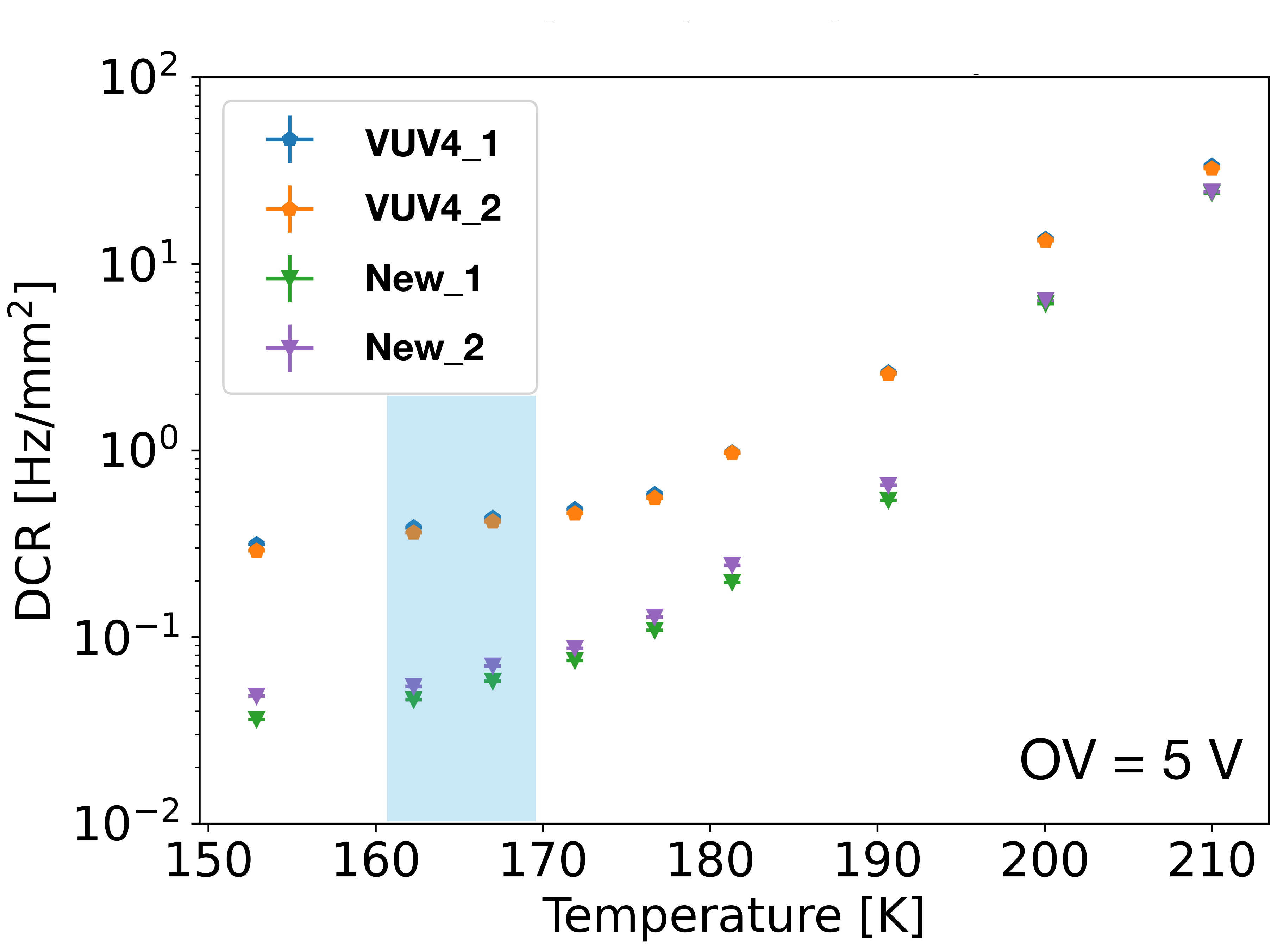
Breakdown Voltage vs Voltage

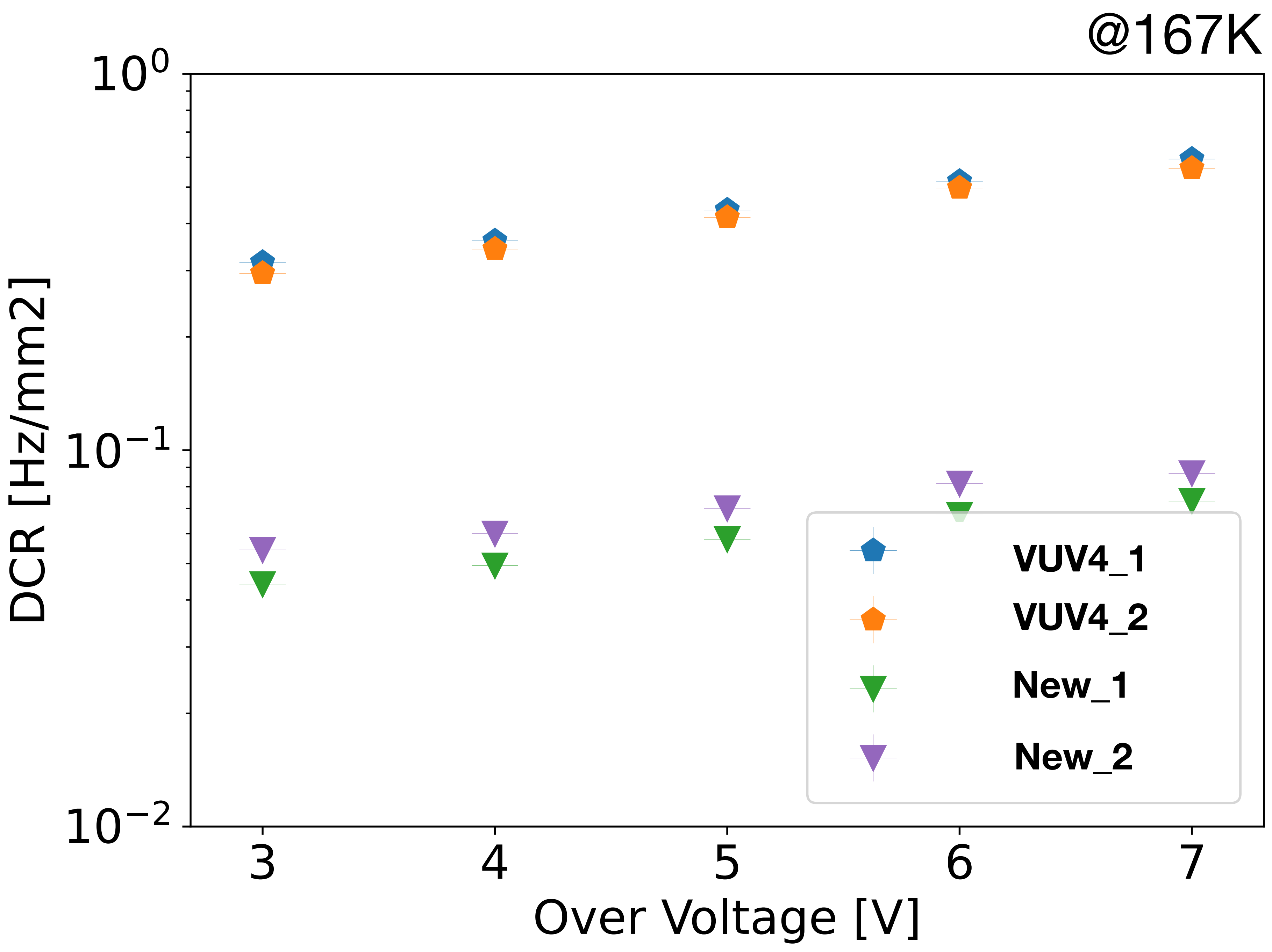




- No significant changes in waveform shapes
- Breakdown voltage increased by 40V
- 1PE gain becomes smaller at the same over-voltages, but still it has ~10^6 gain

Dark Count Rate: 50um pixel

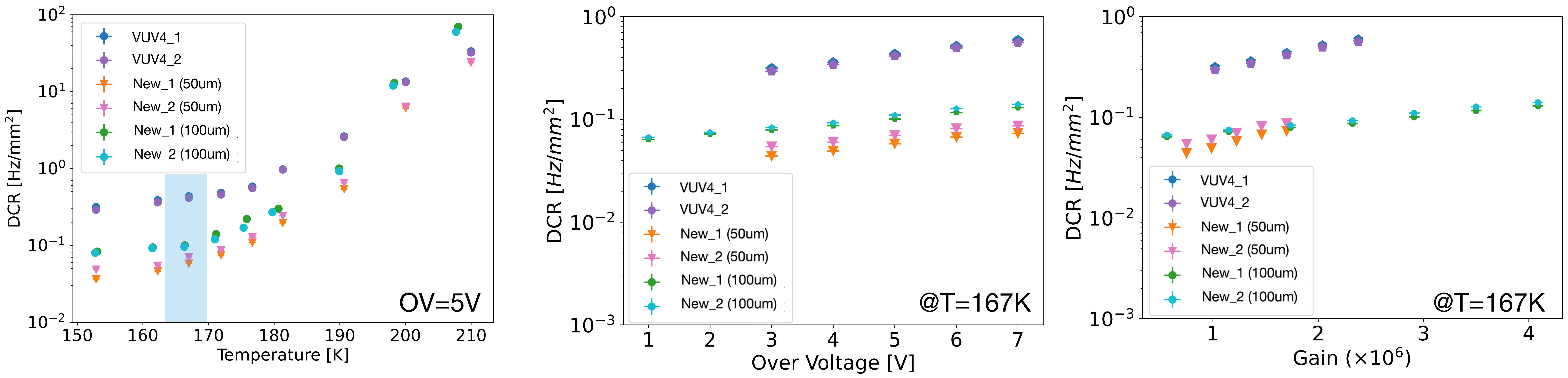




	DCR [Hz/mm²]	Reduction w.r.t. VUV4
New-1 (50um)	0.049 – 0.073	13 - 16%
New-2 (50um)	0.060 – 0.087	15 - 20 %

- Dark count rate (DCR) at high temperature(200-210K) was measured with random trigger because of its large DCR
- DCR at low temperature was measured using self-trigger with the threshold of 0.5 pe pulse height.
- **Reached DCR of O(0.01) Hz/mm2 for 50um pixel size**

Dark Count Rate: 50 & 100um pixel

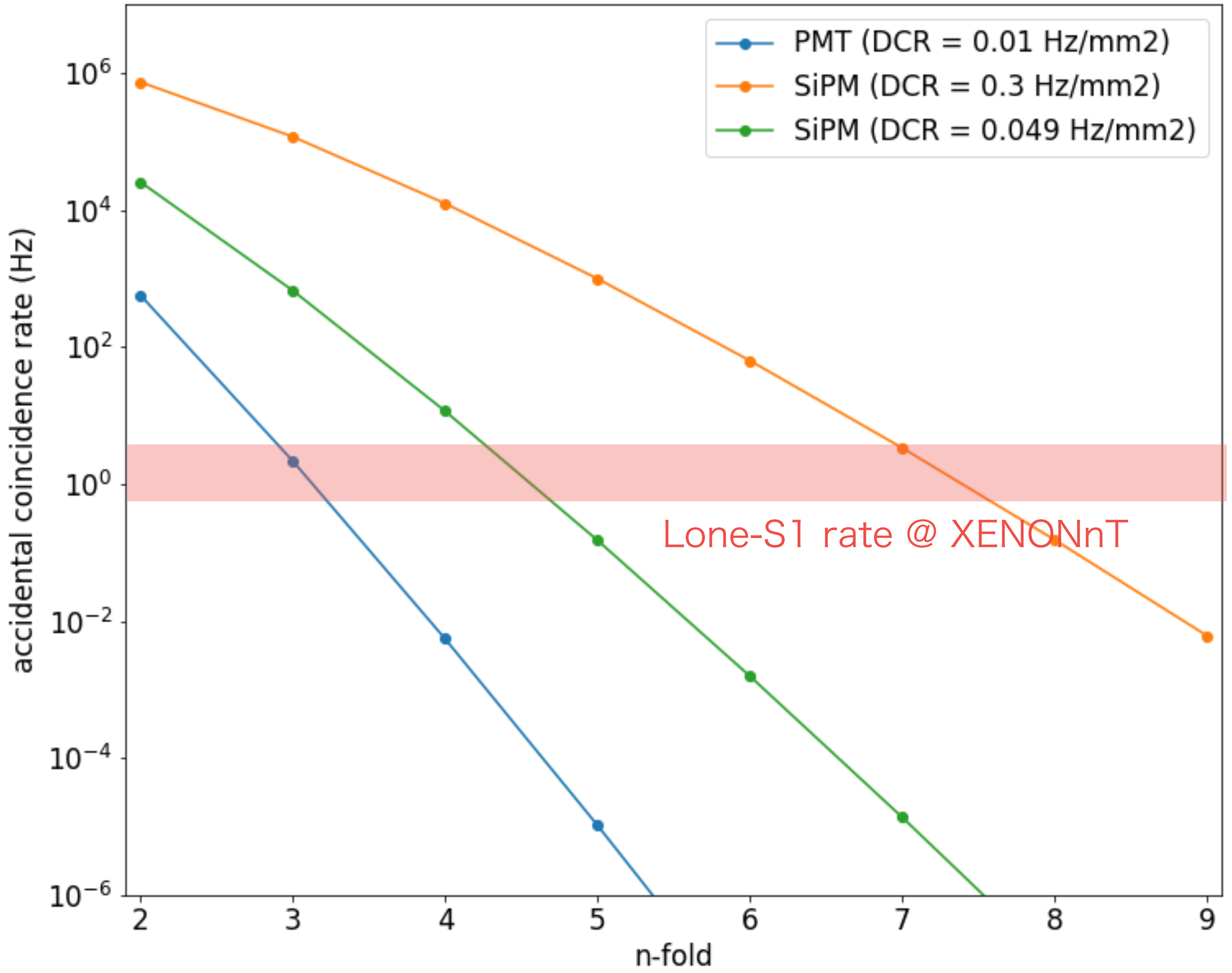


- DCR for 100um pixel is ~1.6 times higher than that for 50um pixel when compared at the same over-voltages.
- However, 50 and 100 um pixel have different 1PE gain/PDE. Therefore, DCR should be compared at the same 1PE gain or PDE.
  - **Both 50/100 pixel SiPMs have almost the same DCR at the same gain of 1e6 (~ 0.05 Hz/mm^2)**

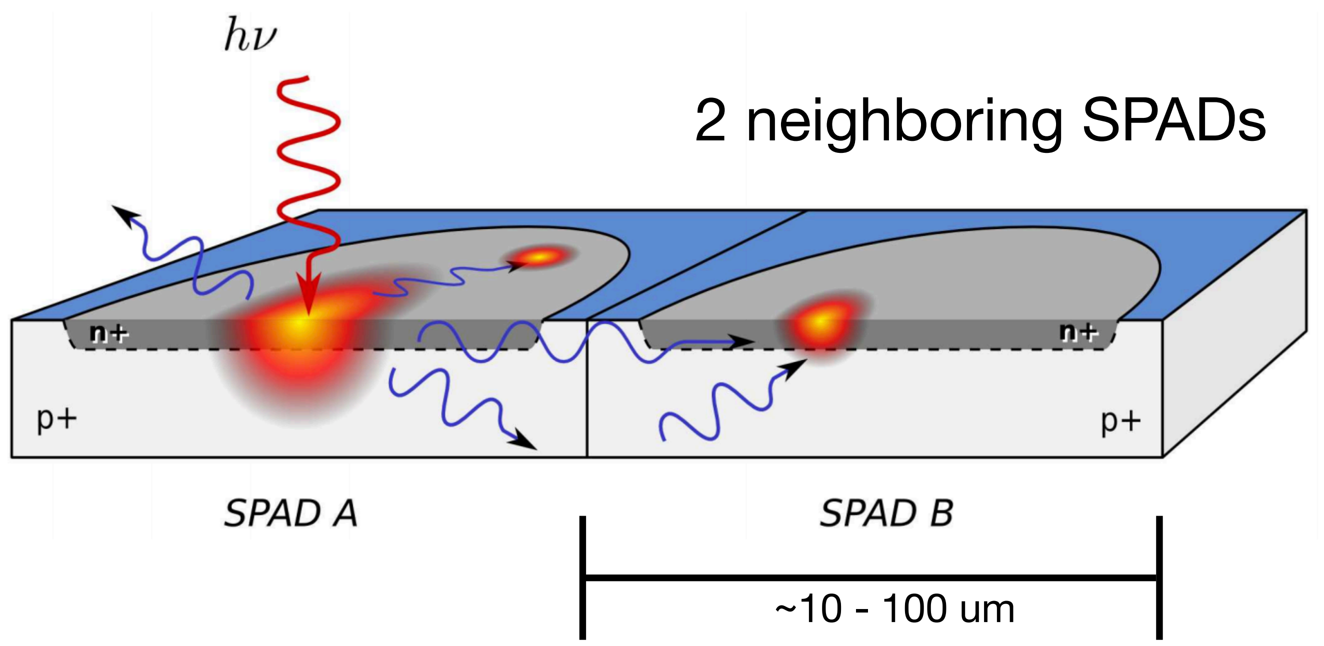
What's the Impact on Accidental Coincidence Rate (Lone-S1 Rate)

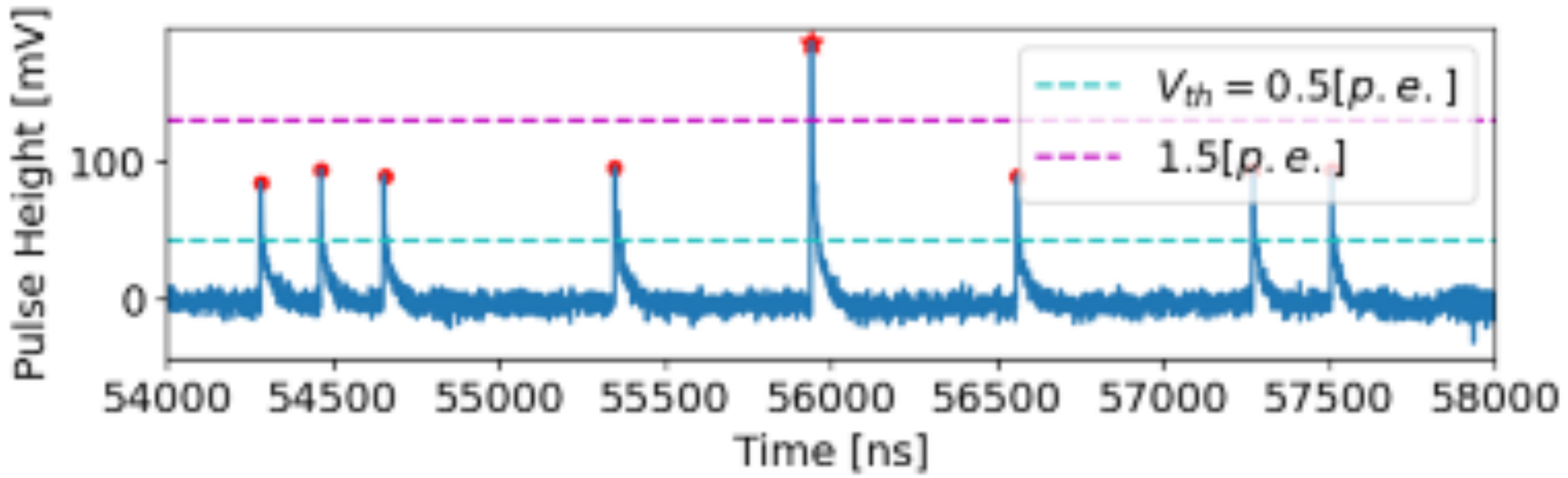
- Assuming SiPMs are used for both the top/bottom arrays @ DARWIN, ~73,000 channels (12×12 mm^2) are needed
- Lone-S1 rate @ XENONnT is O(1) Hz , originating from interactions below cathode/CIV or shadow effect
    - DCR contribution to lone-S1 rate is negligible in XENONnT because low DCR for PMT (0.01 Hz/mm^2)
- **N-fold requirement might be improved from 7-fold to 4-fold with the SiPM we developed**
    - 100 nsec coincidence window is assumed
- If we use SiPMs for the top array only, this effect (and eCT) should have less impact.

	PMT 0.01 Hz/mm^2	New 0.049 Hz/mm^2	VUV4 0.3 Hz/mm^2
3-fold	**2.2 Hz**	~700 Hz	~1.0×10^5 Hz
4-fold	-	**~10 Hz**	~1.0×10^4 Hz
7-fold	-	-	**~3 Hz**



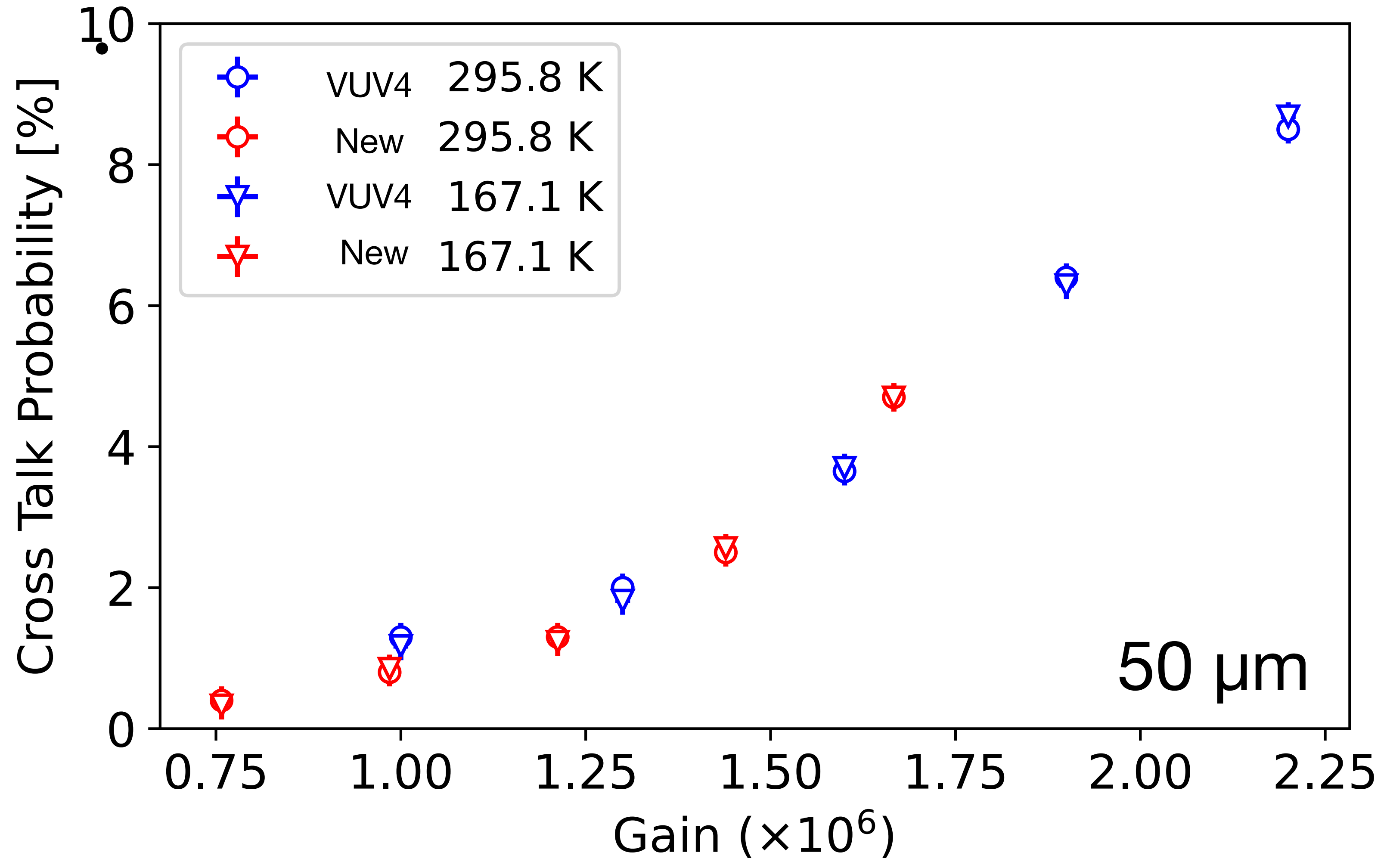
Cross-talk Probability

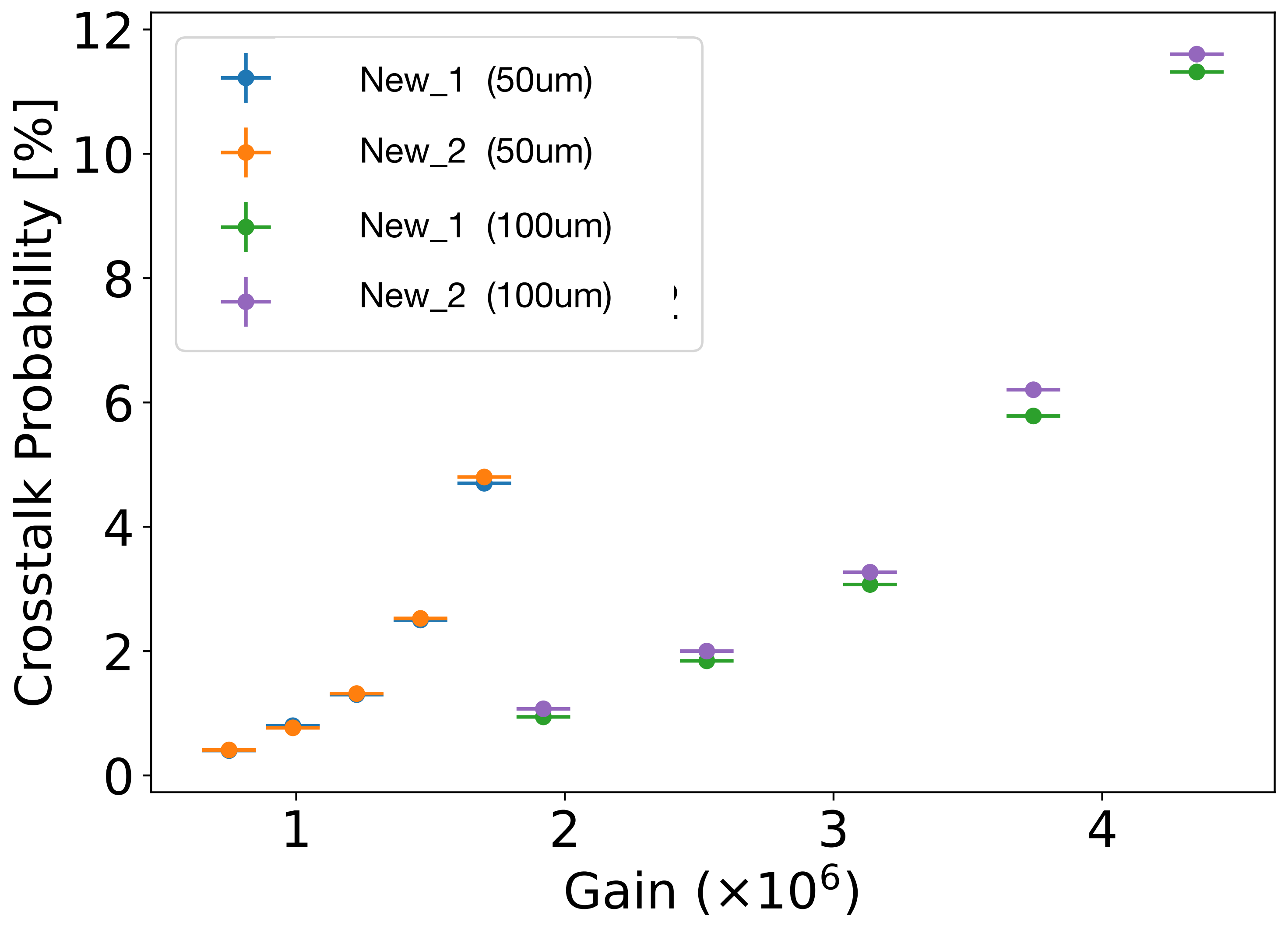


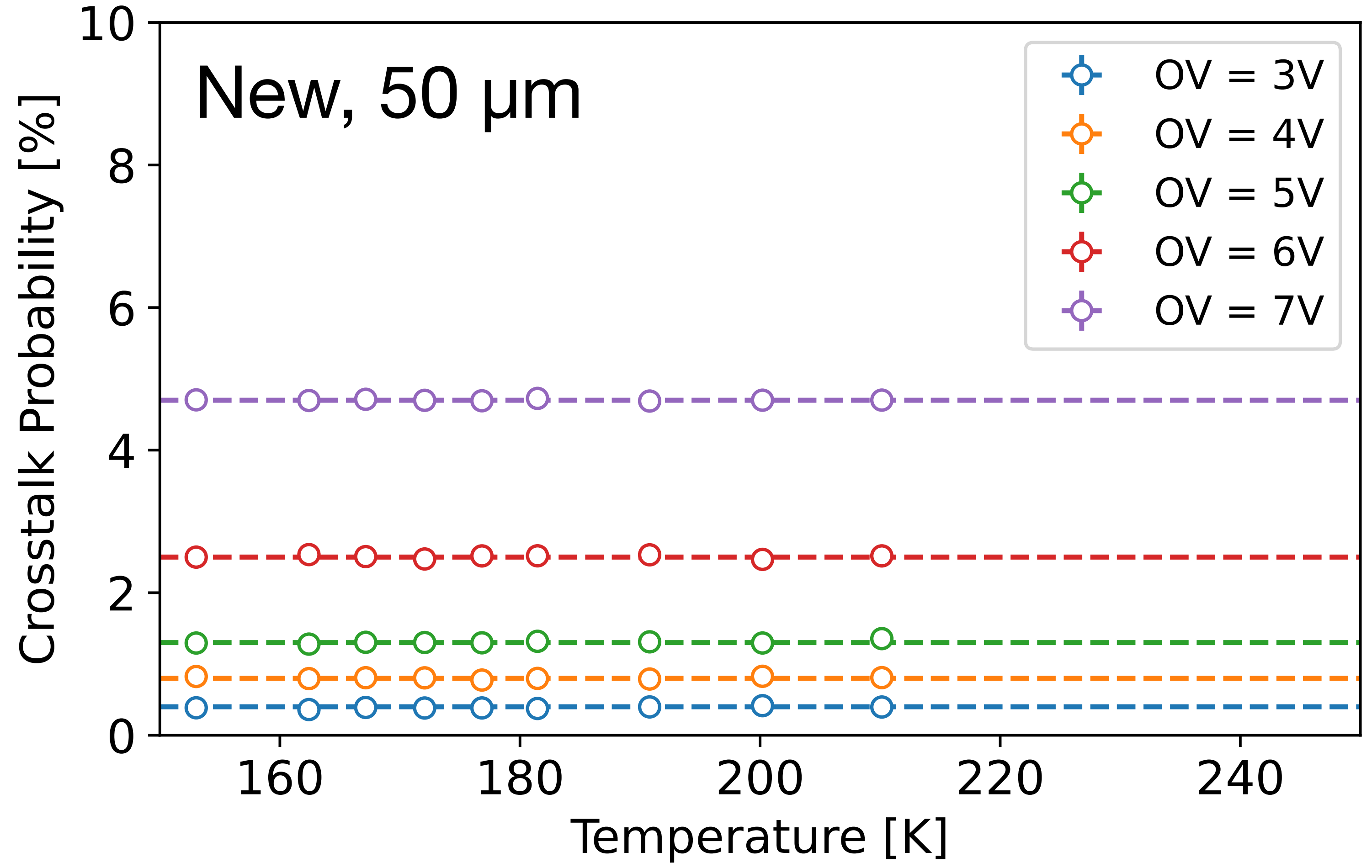


$$R_{CT} = \frac{N_{>1.5pe}}{N_{>0.5pe}}$$

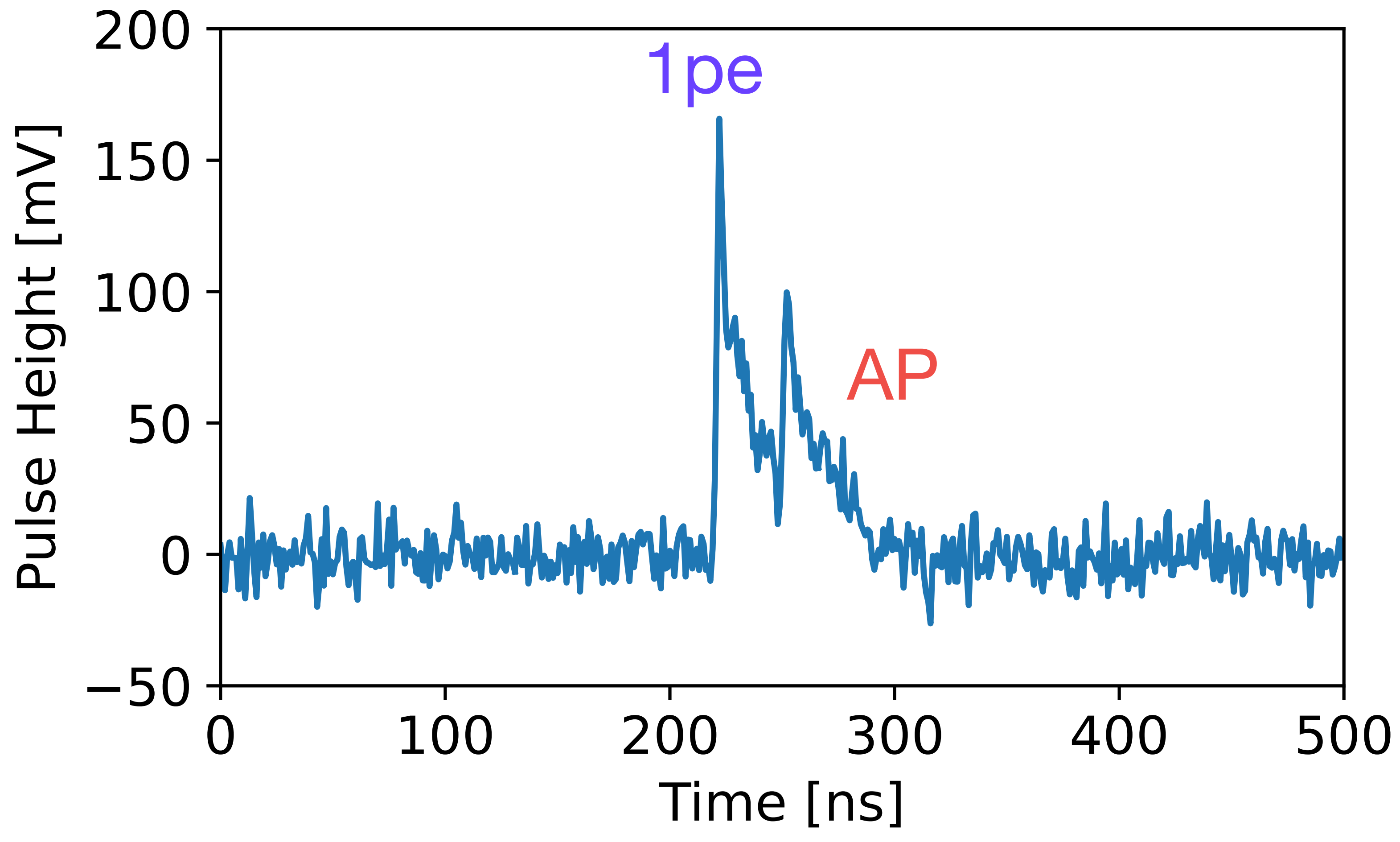
- As expected, cross-talk probability for VUV4 and new SiPMs seems almost the same at the same 1PE gain.
- 100 um pixel has less cross-talk probability because it has larger active area (smaller chance for infrared photons to propagate to nearby SPADs.)
- No significant temperature dependence was observed.

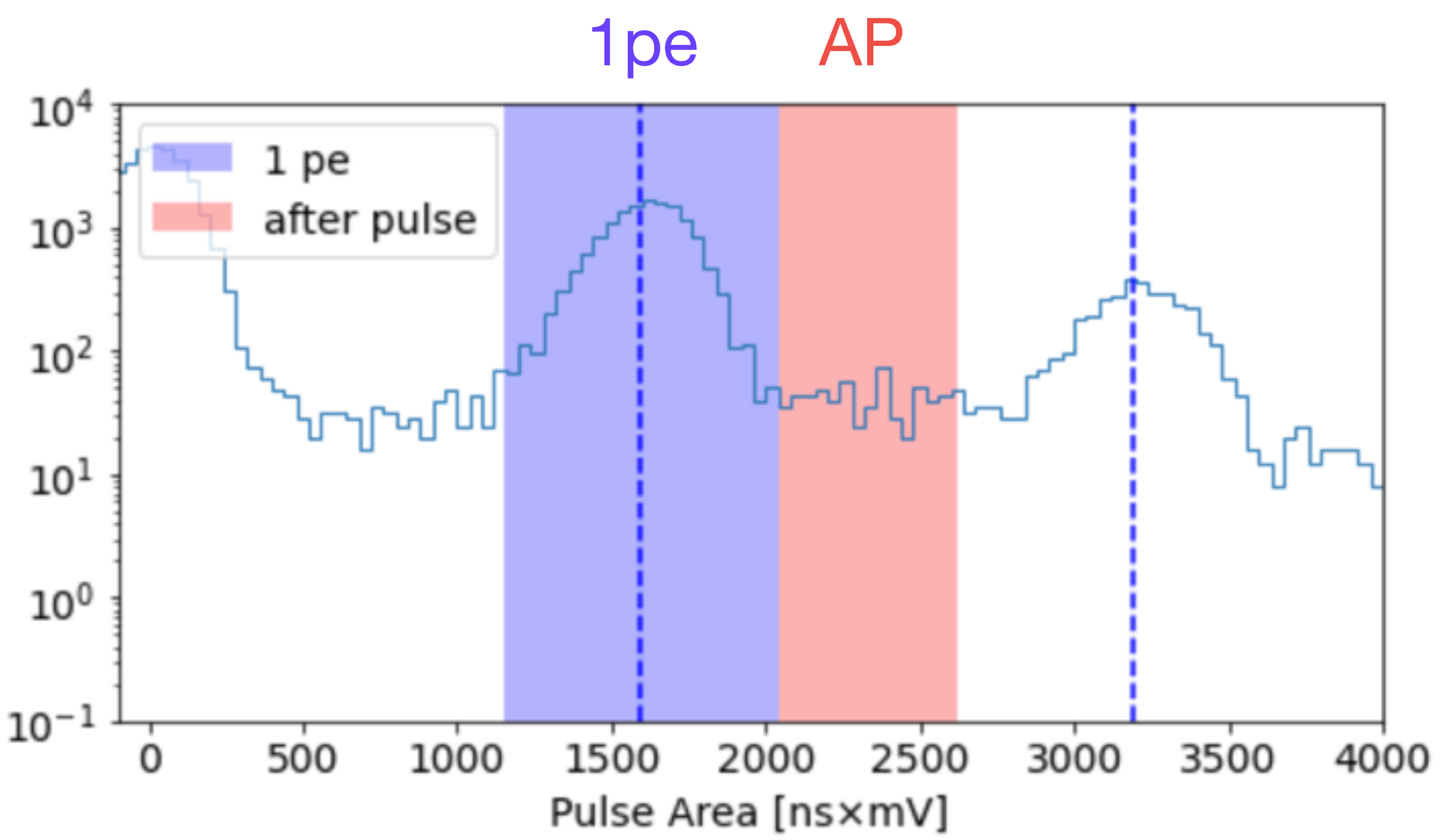






Afterpulse Probability

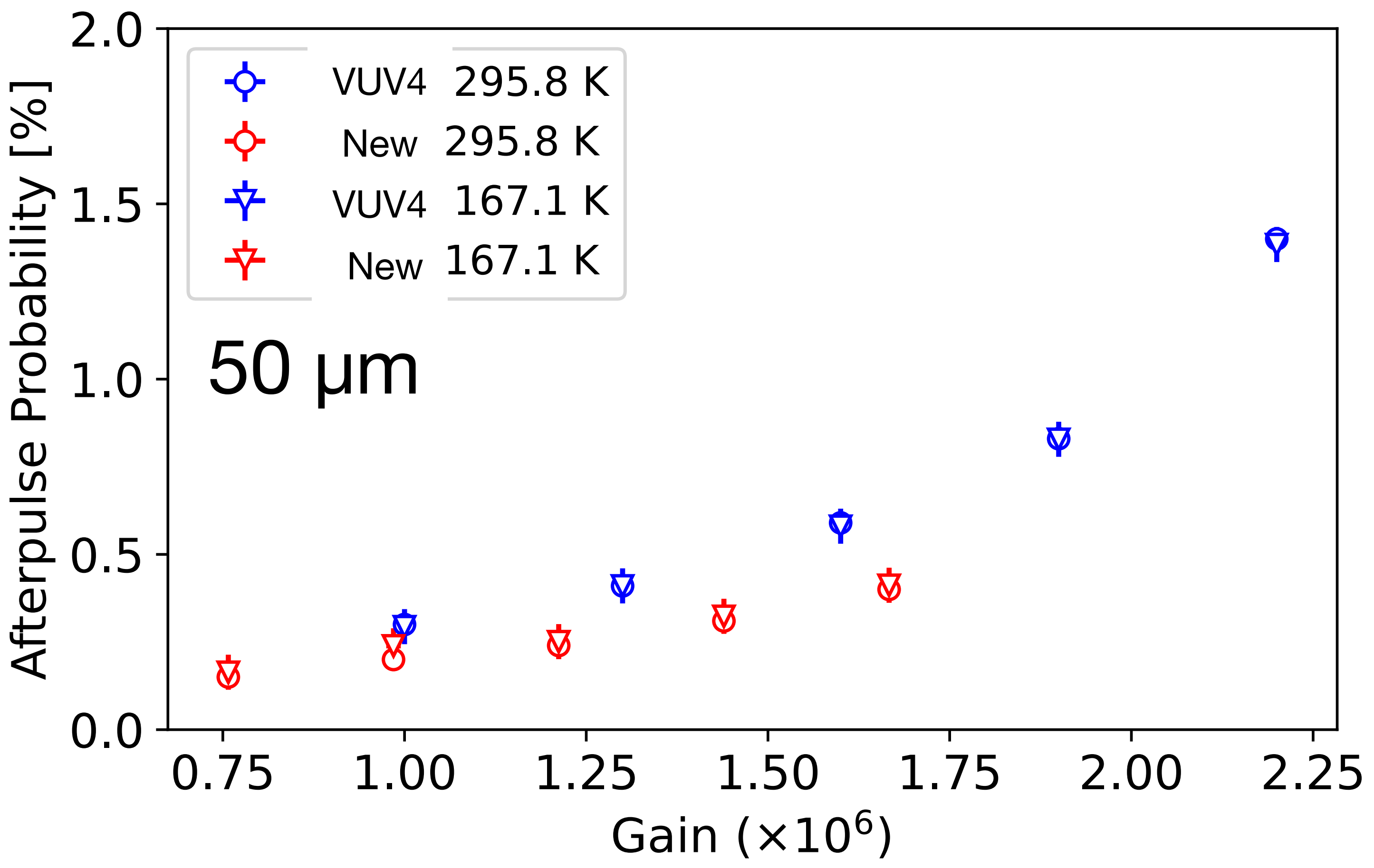


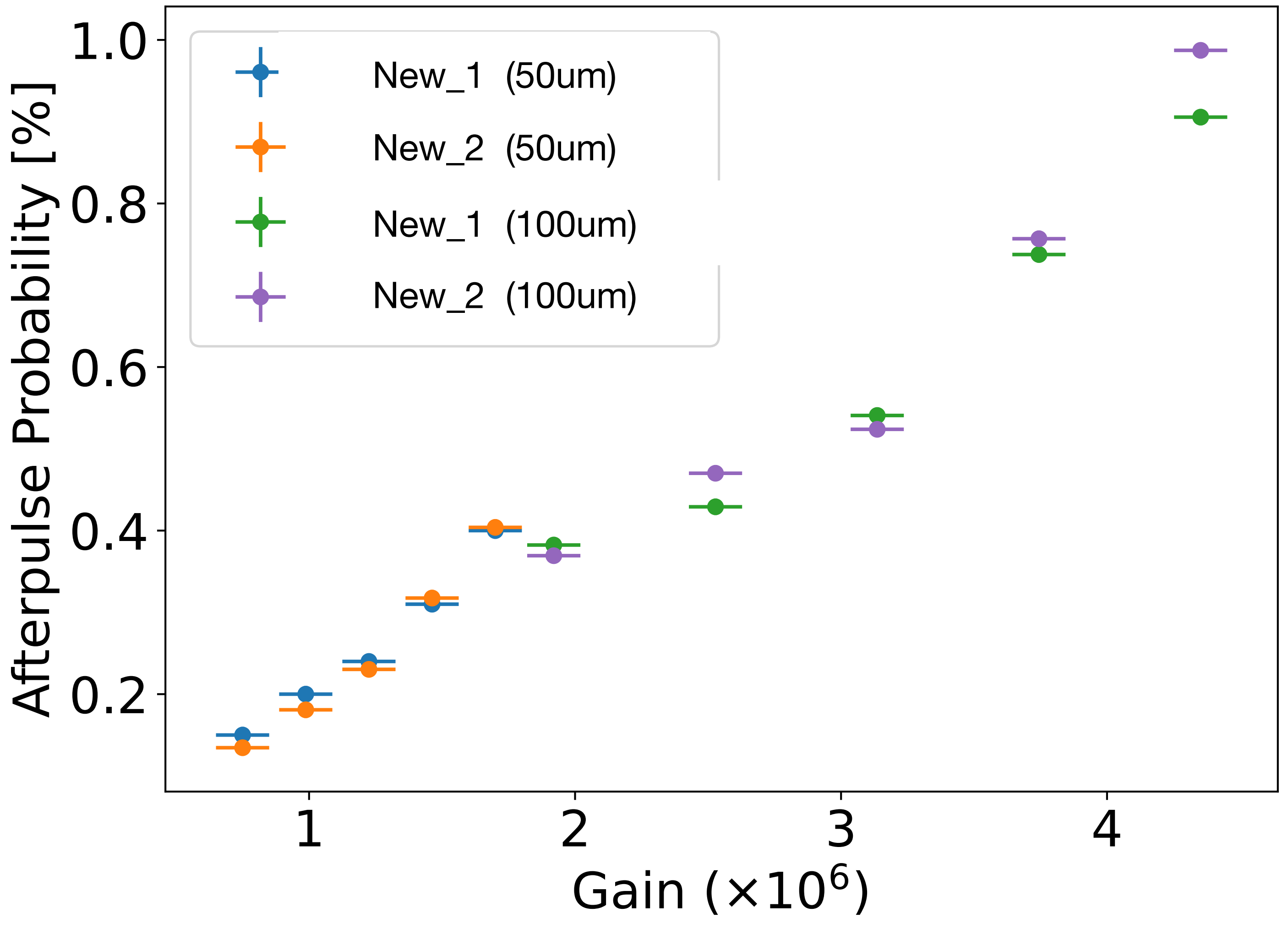


N(1pe) = [μ-4σ(1pe), μ+4σ(1pe)]

N(AP) = [μ+4σ(1pe), 2μ-4σ(2pe)]

→ P(AP) = N(AP) / N(1pe)





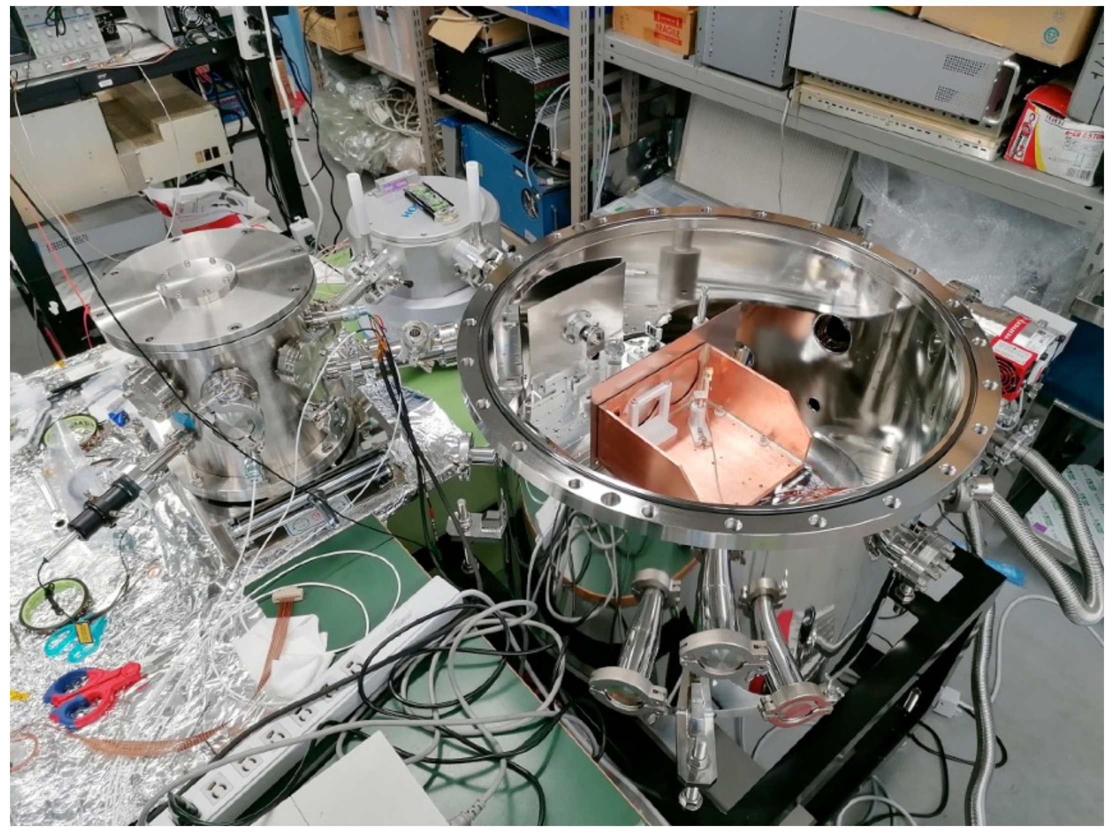
- AP probability for new SiPM is smaller at the same 1PE gain, probably due to lower dope concentration.
- 100 um pixel seems to have less AP probability
- No significant temperature dependence was observed.

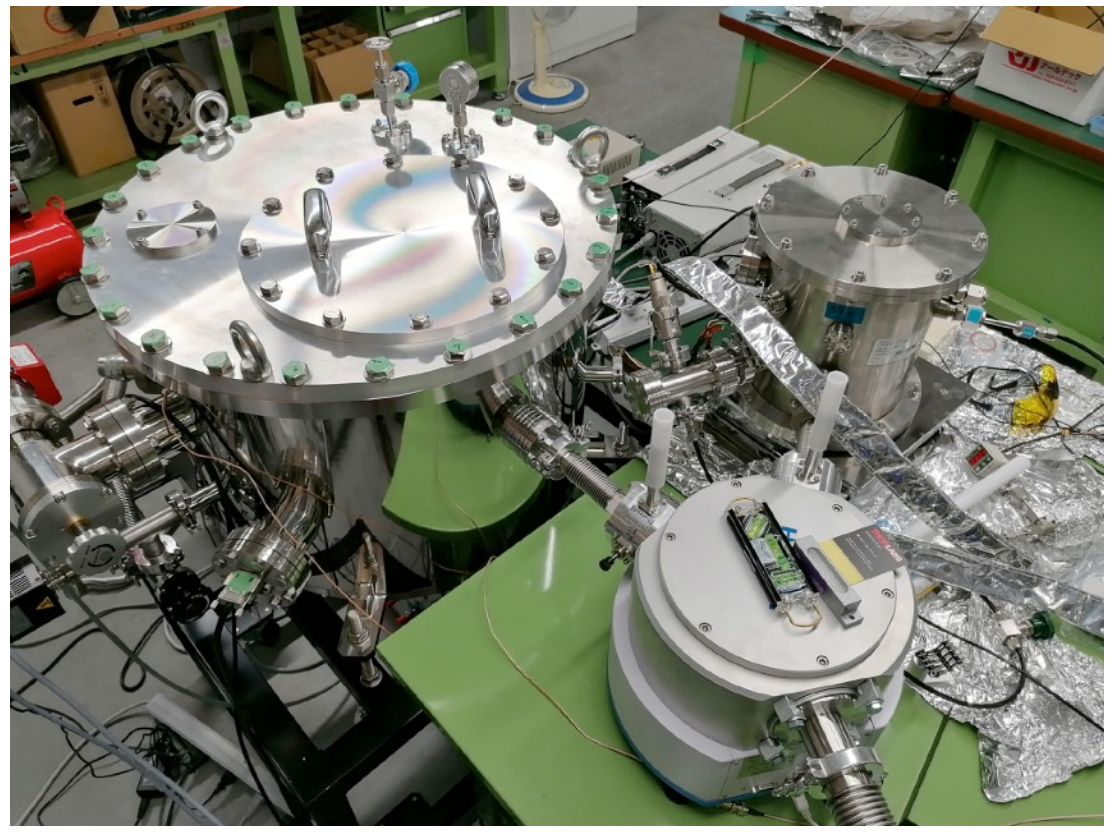
Summary

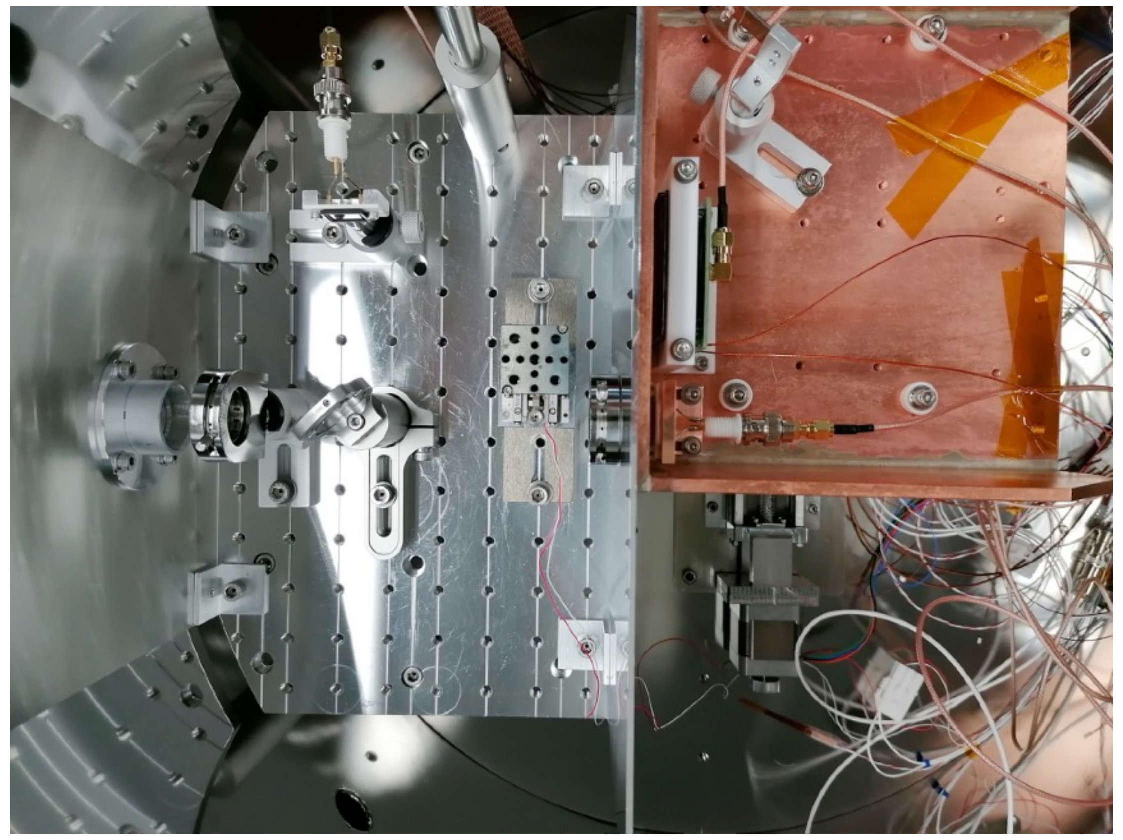
- We have developed a low-DC VUV SiPM and characterized its performance.
- We managed to reach DCR of O(0.01) Hz/mm^2 for both 50 and 100 um pixel sizes.

	DCR [Hz/mm^2] 50 um	DCR [Hz/mm^2] 100 um
Sample1 (OV=3-5V)	0.049 – 0.073	0.076 - 0.094
Sample2 (OV=3-5V)	0.060 – 0.087	0.078 - 0.098

- According to Hamamatsu, they can further optimize the configuration to reduce DCR.
- Thanks to the optimization of fill factor, new SiPMs have reasonable PDE of 20 - 35 % depending on pixel size
- We will measure the absolute PDE of new SiPMs at LXe temperature and compare with Hamamatsu measurements.







Backup

Accidental Coincidence Rate

Rate of n pmts over m PMTs

In this scenario we are counting PMTs. If a PMT got 2 hits, it will be counted as “1”.

The probability that a PMT didn't trigger is: $p_0 = p(0|\mu) = e^{-\mu}$

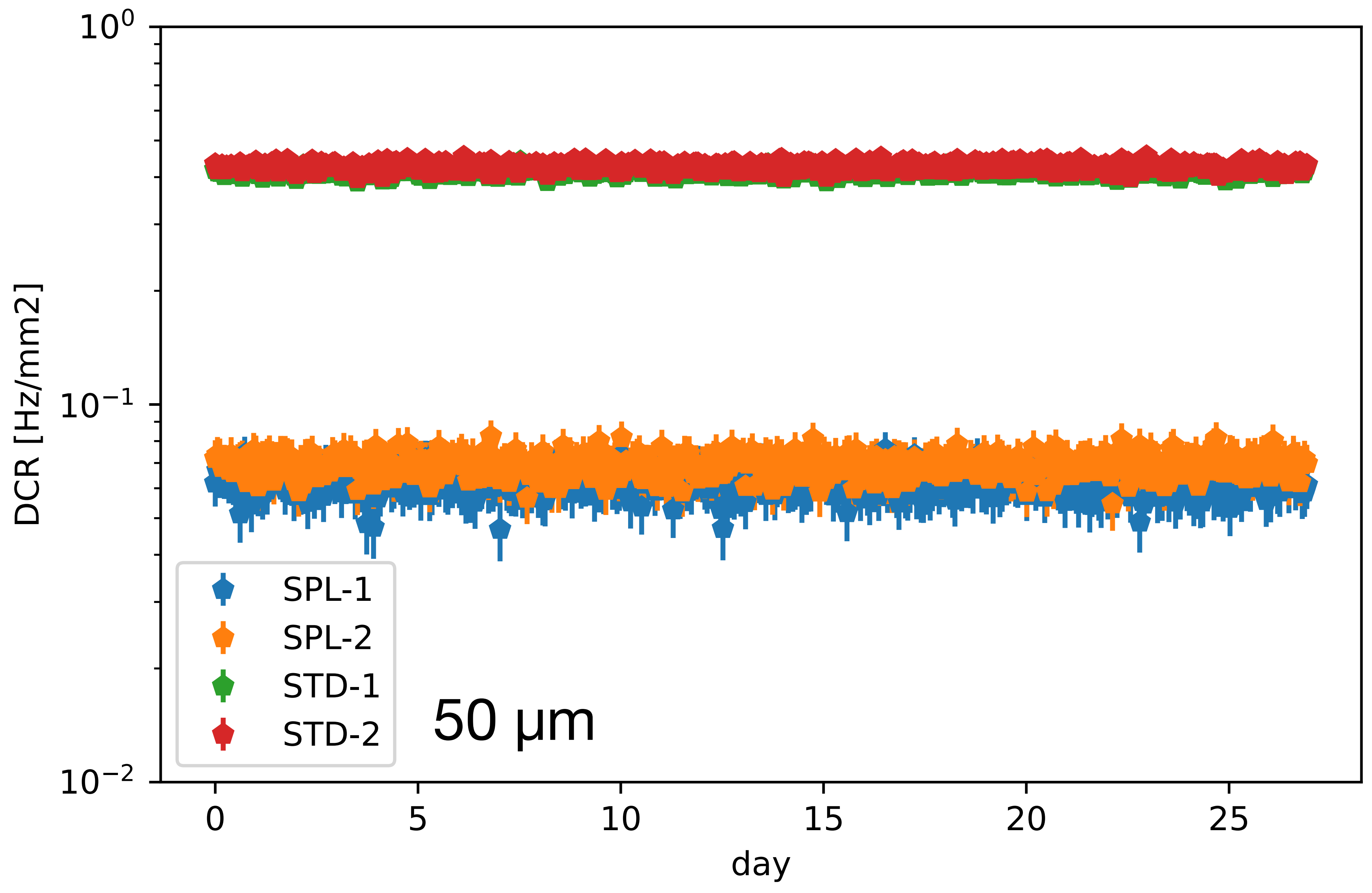
The probability of exactly n PMTs triggering is the probability that n triggered, and (m-n) did not trigger: $p_n = \frac{m!}{(m-n)! \cdot n!} \cdot (1 - p_0)^n \cdot p_0^{m-n}$

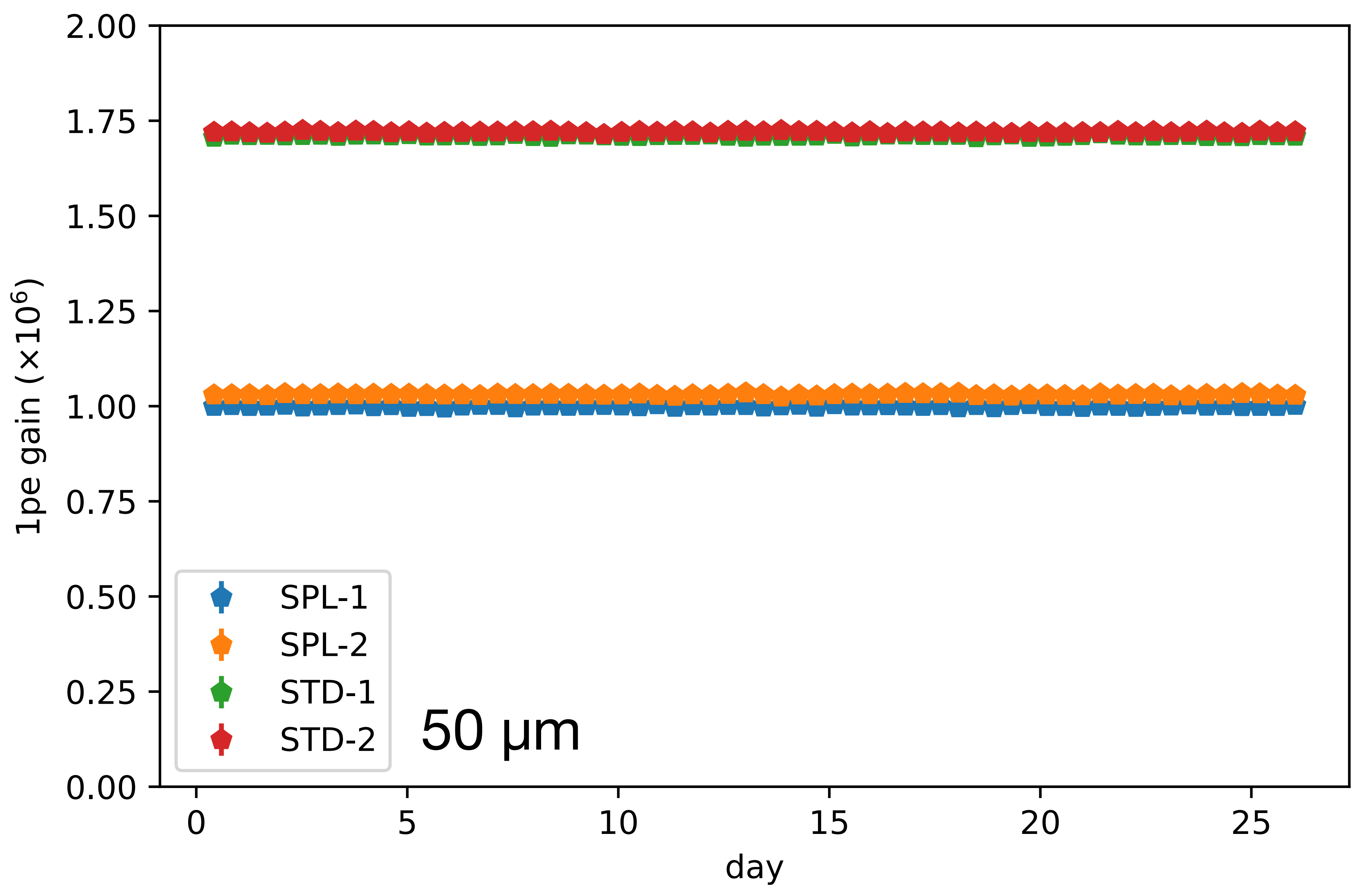
So….

$$\Gamma_n^m = \Gamma_1^m \cdot p_{n-1} = m \cdot \Gamma \cdot \frac{(m-1)!}{(m-n)! \cdot (n-1)!} \cdot (1 - p_0)^{n-1} \cdot p_0^{m-n} = m \cdot \Gamma \cdot \frac{(m-1)!}{(m-n)! \cdot (n-1)!} \left(e^{+\Gamma\tau} - 1\right)^{n-1} \cdot e^{-\Gamma\tau(m-1)}$$

notice that for n«m and $\mu_1 1$, so $\left(e^{\mu_1} - 1\right) \rightarrow \mu_1$ the rate of hits is equal to the rate of modules as it is less likely for a single PMT to get two hits in the time window.

Long-Term Stability





Stability	SPL-1	SPL-2	STD 1	STD 2
DCR	6.9%	6.5%	2.4%	2.3%
1pe Gain	0.19%	0.23%	0.17%	0.20%

- Both 1PE gain and DCR were stable for 1-month measurements