Characterization of Delayed Crosstalk of SiPM

Hiroyasu Tajima, Akira Okumura,
Yusuke Kuroda, Kazuhiro Furuta,
Nagoya Hidaka
Institute for Space–Earth Environmental Research
Nagoya University

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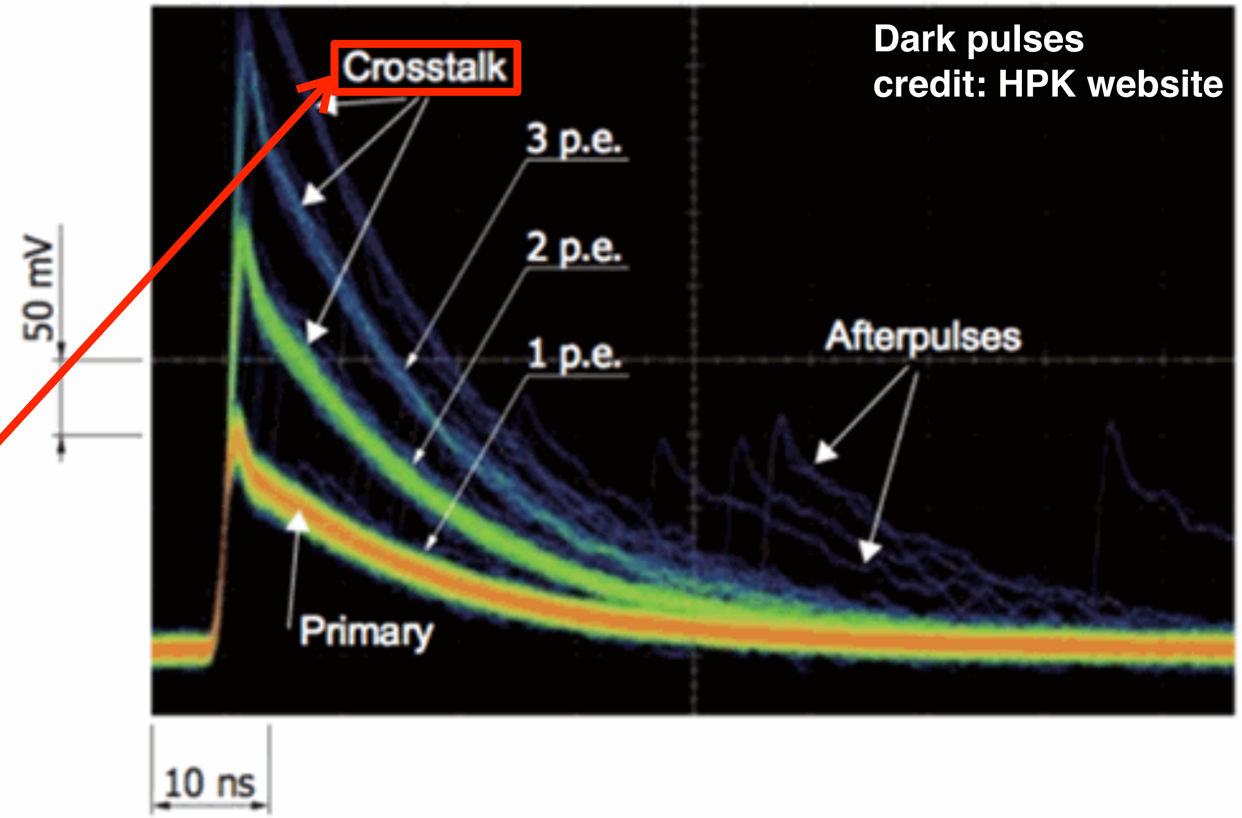
Photon Sensor

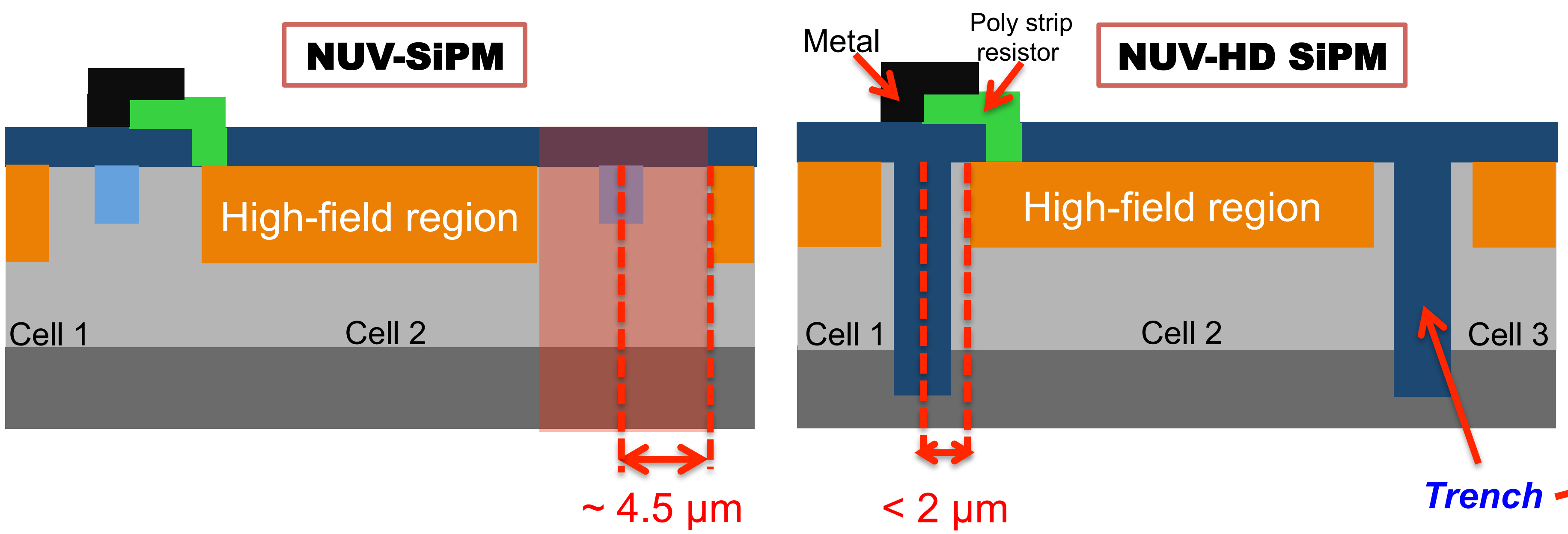
- Silicon Photomultiplier is chosen as a photon sensor for many experiments
  - Cost per channel
  - Tolerance against high rate environment
  - Photon detection efficiency
  - Reliability

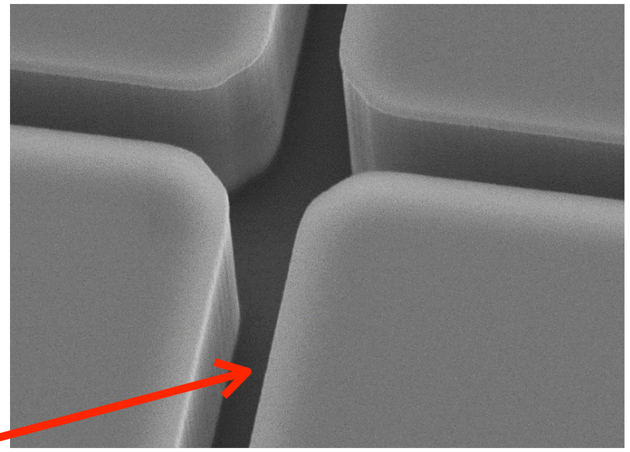


- Major drawback of SiPM
  - Optical crosstalk (OCT)
  - Gain dependence on the temperature
- Main objective of this study
  - Suppress OCT while retaining photon detection efficiency (PDE)

Suppressing OCT with Trench

- Optical crosstalk is caused by photons produced in primary avalanche
- Trench is implemented to prevent photons from crossing cell boundary
  - Narrower trench gives better fill factor





credit: FBK

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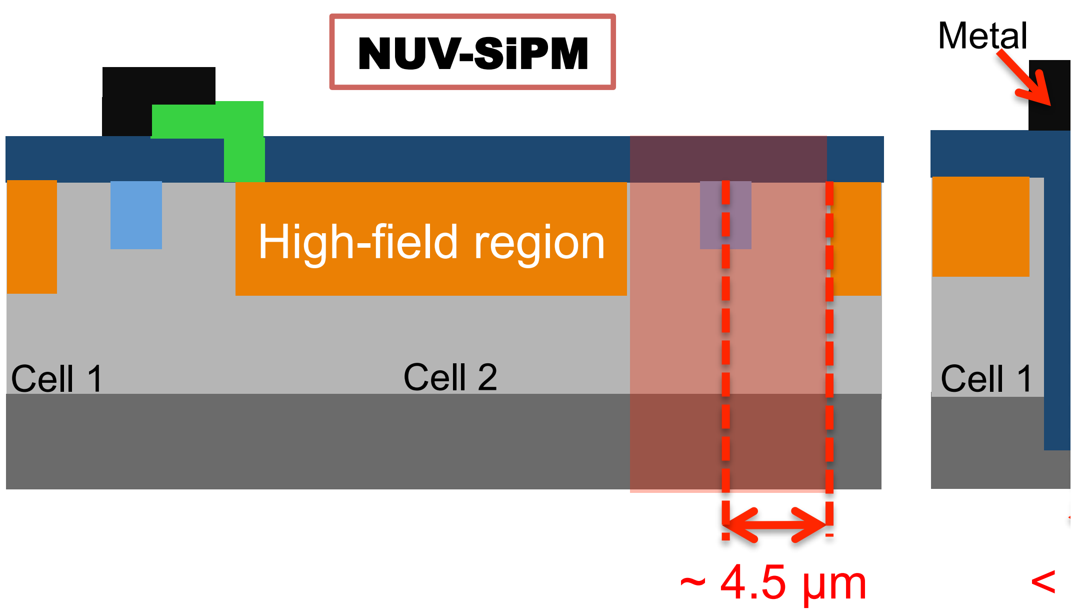

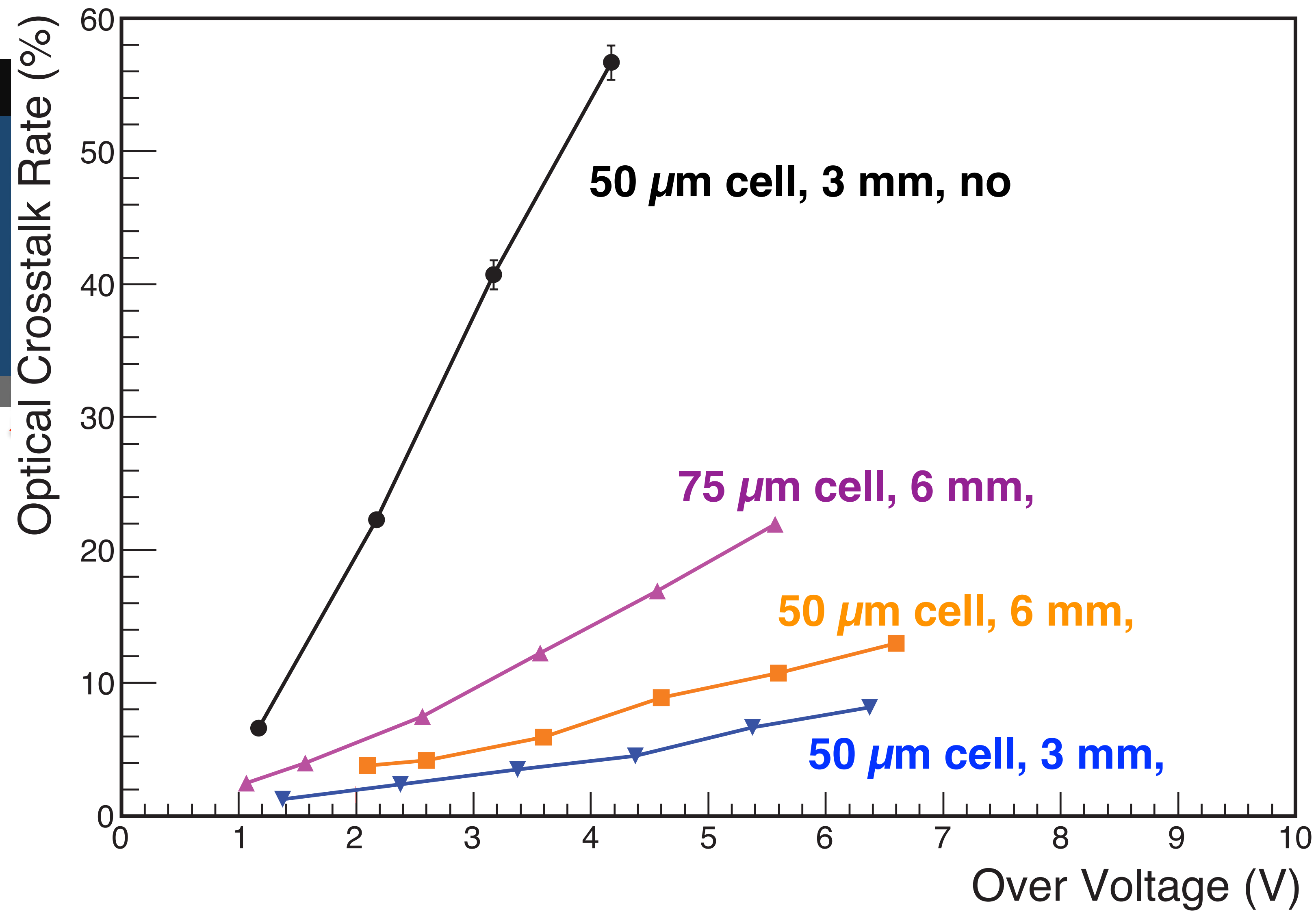

Effect of Resin Coating on OCT

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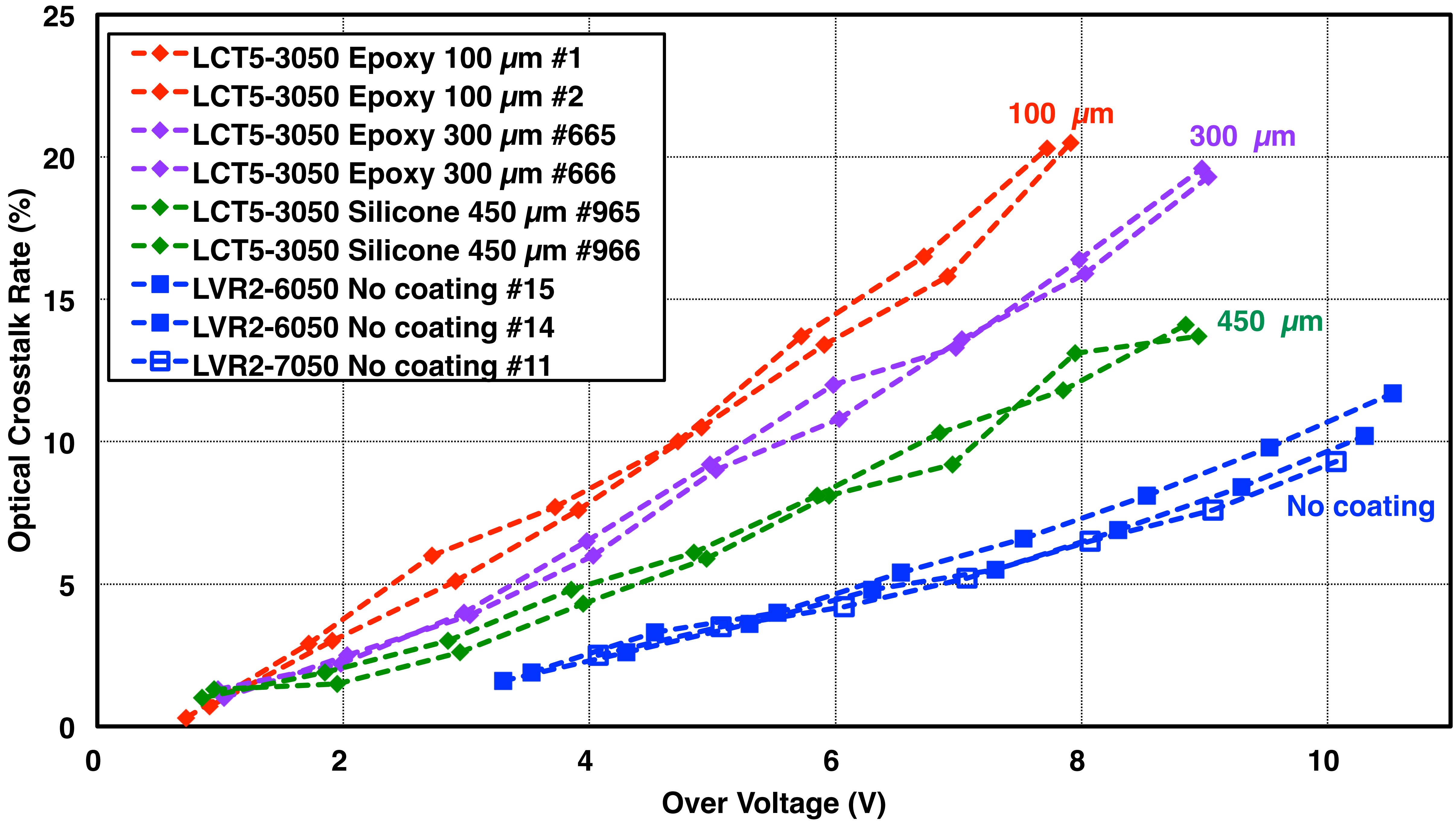
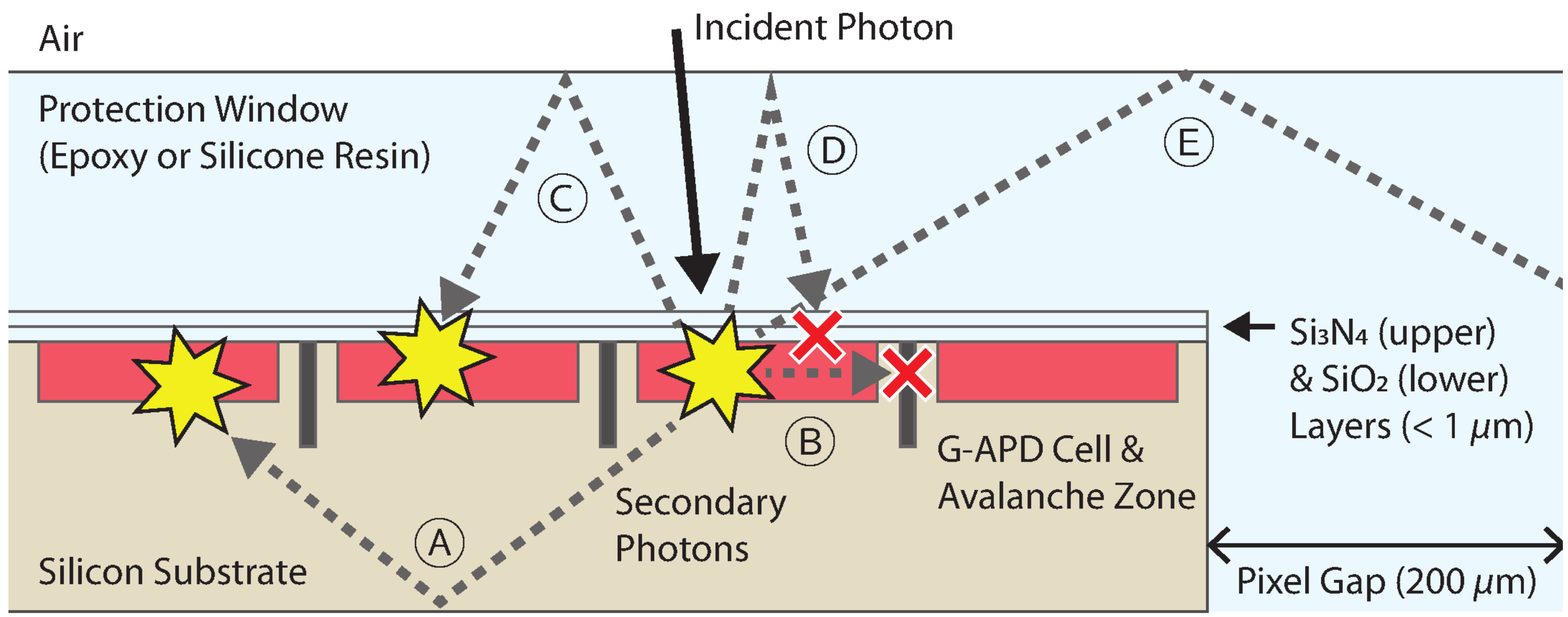
❖ Thicker coating or no coating give lower crosstalk



Propagation of Crosstalk Photons

- No coating (or very thin coating)
  - Reflected photons come back to the original cell
- Intermediate thickness
  - Photons reflected by the air interface may produce avalanches in other cells
- Very thick coating
  - Photons reflected by the air interface may get out of the device
  - Smaller device may have lower crosstalk rate



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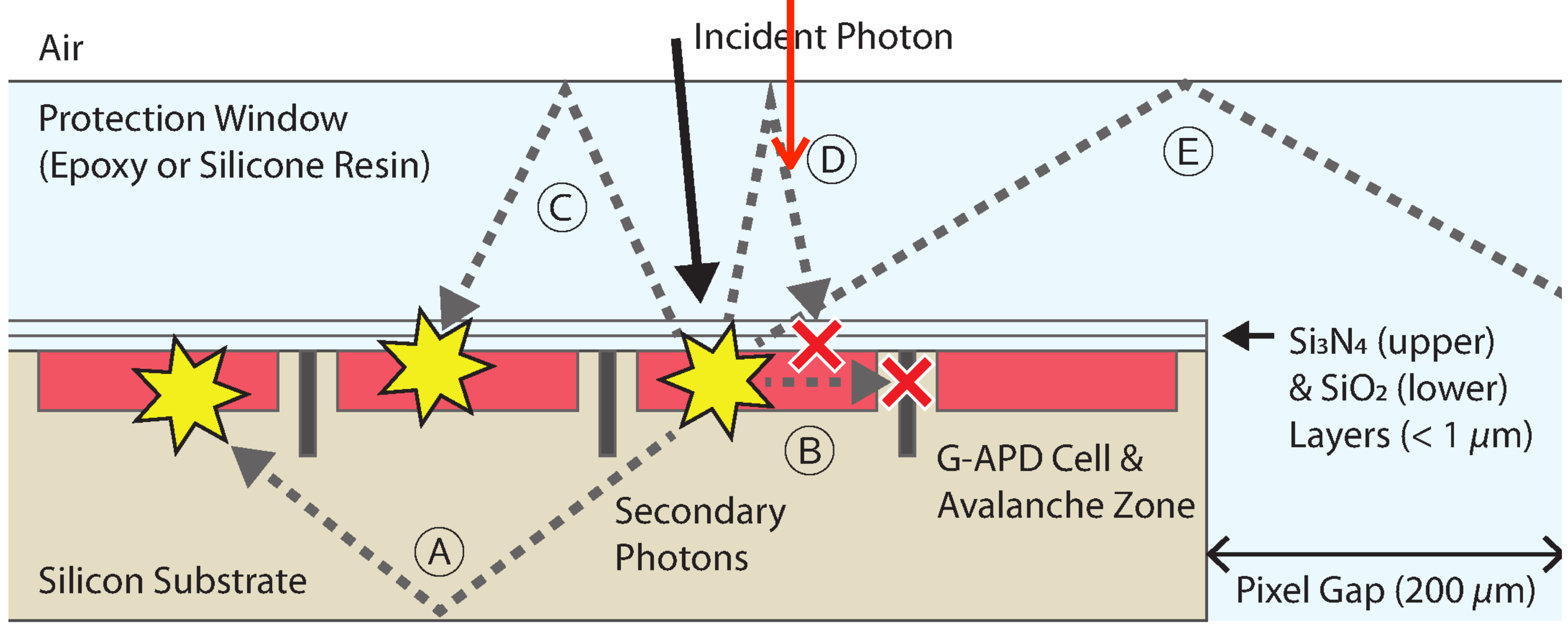

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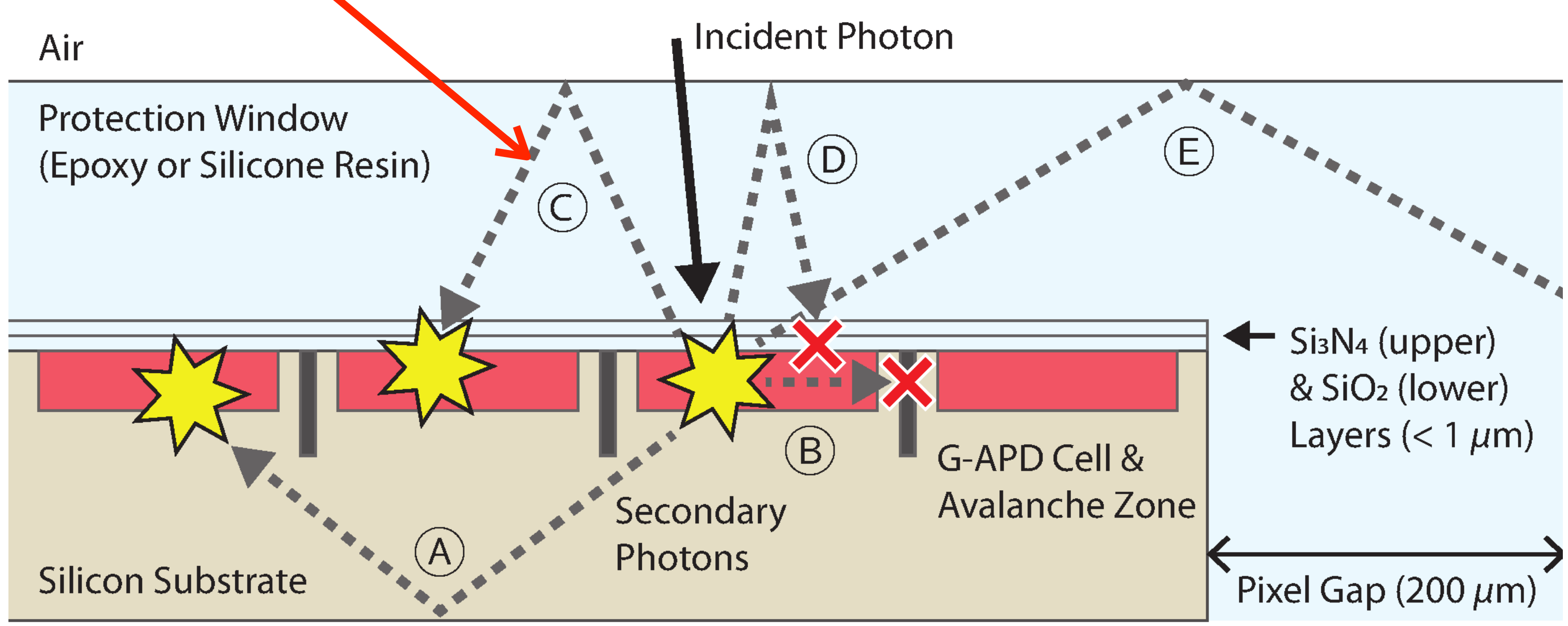

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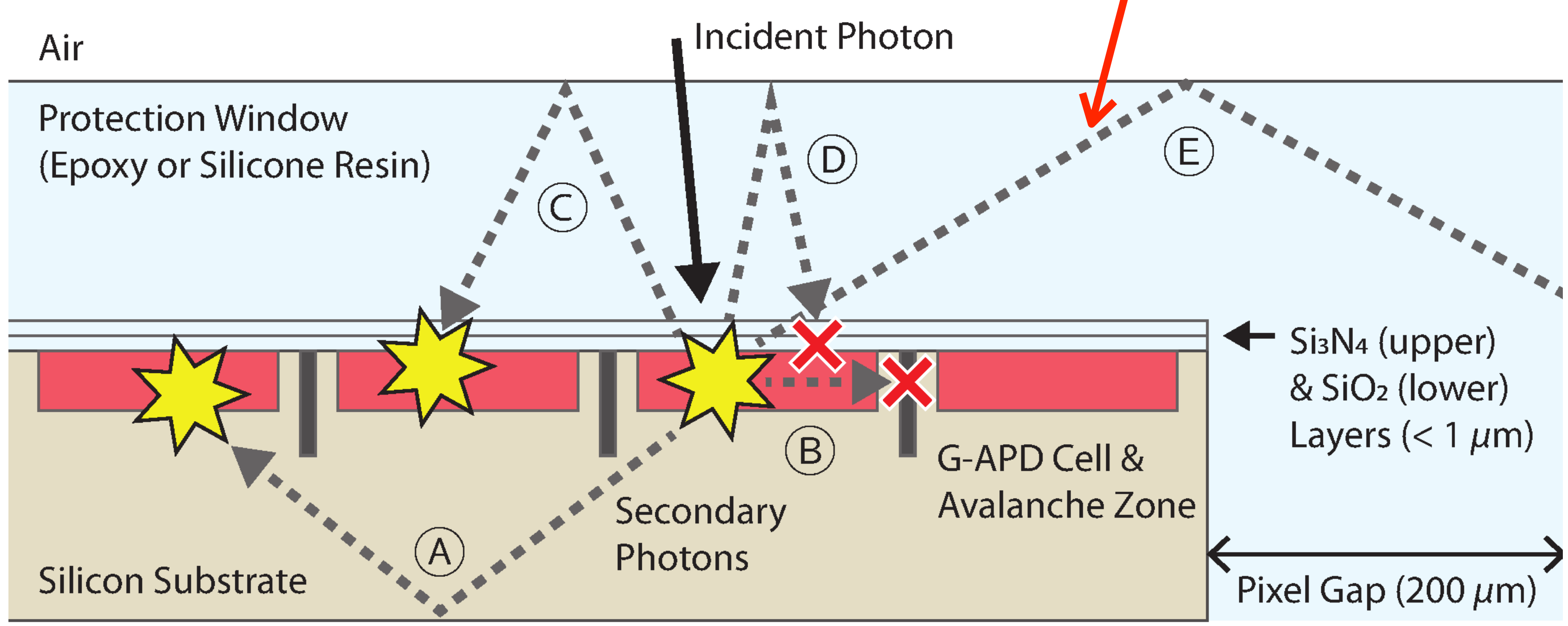
  - **Smaller device may have lower crosstalk rate**



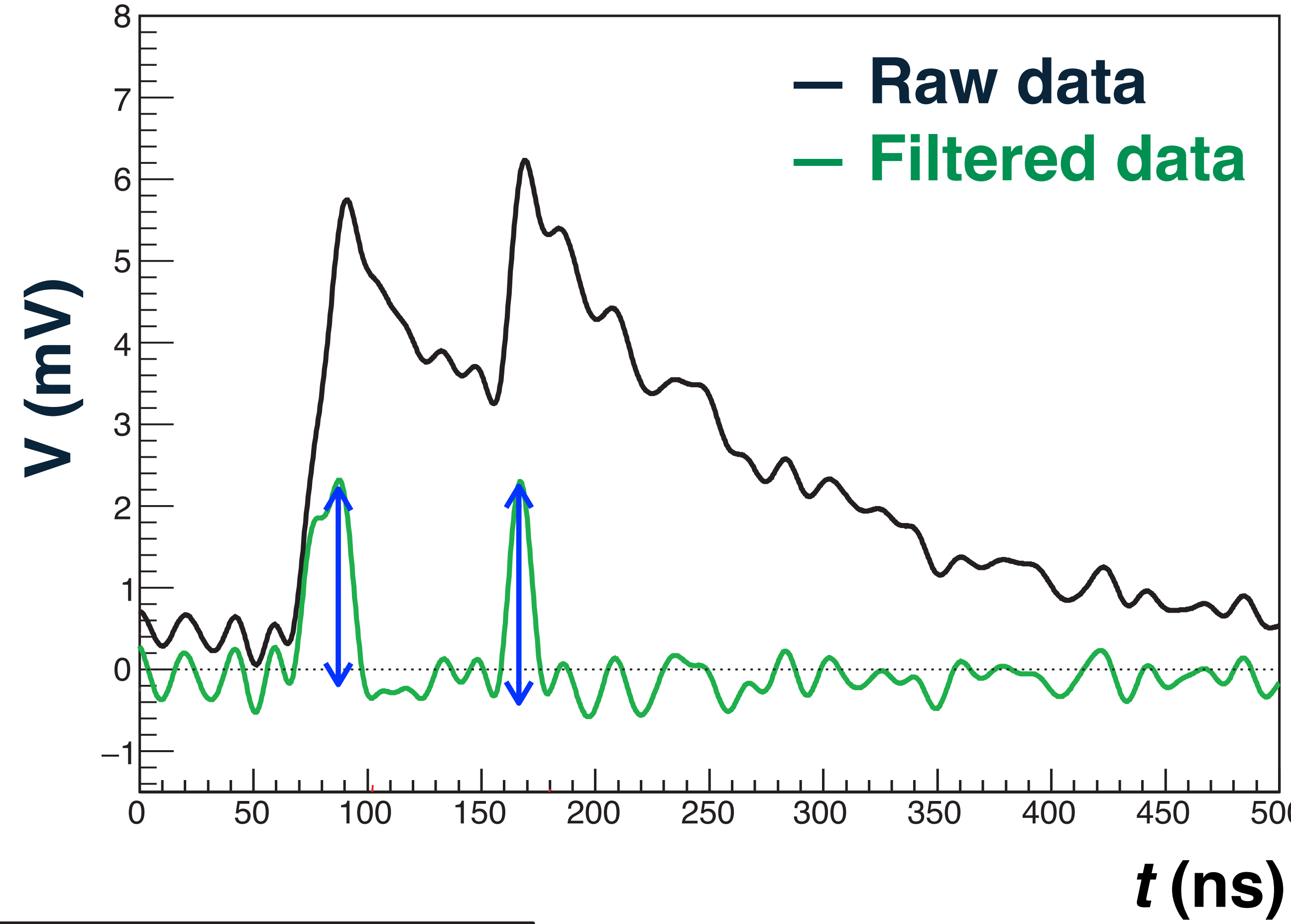
OCT Dependence on Device/Cell Sizes

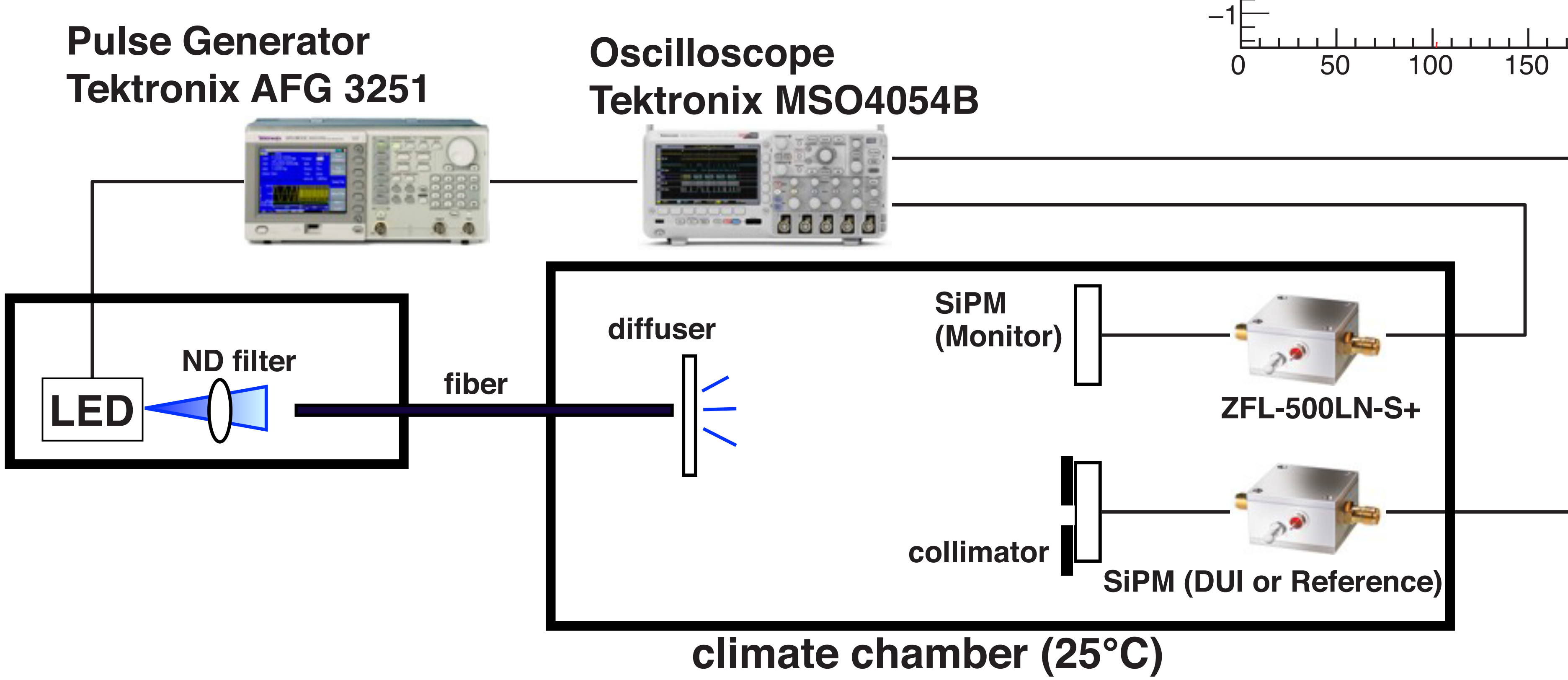
- We have systematically investigated the OCT rate with varying device size, cell size, and with and without coating
  - OCT rate is expected to be proportional to the number of electron-holes pairs (=charge) produced in an avalanche
    - proportional to a product of [cell capacitance] and [over voltage]
  - Find out propagation properties of crosstalk photons

Product ID	Device size	Cell size	Coating	Fill factor
S14520-3050VS	3 mm	50 μm	300 μm	74%
S14520-3050VN	3 mm	50 μm	None	74%
S14520-3075VS	3 mm	75 μm	300 μm	82%
S14520-3075VN	3 mm	75 μm	None	82%
S14520-6050VS	6 mm	50 μm	300 μm	74%
S14520-6050VN	6 mm	50 μm	None	74%
S14520-6075VS	6 mm	75 μm	300 μm	82%
S14520-6075VN	6 mm	75 μm	None	82%

SiPM Measurement Setup at Nagoya

- Take waveform data by digital oscilloscope
  - Offline data analysis
    - Digital filter to minimize the effect of pile ups
    - Fit the data with multiple pulses
- Light output is monitored
- Wavelength is fixed at 405 nm for this measurement





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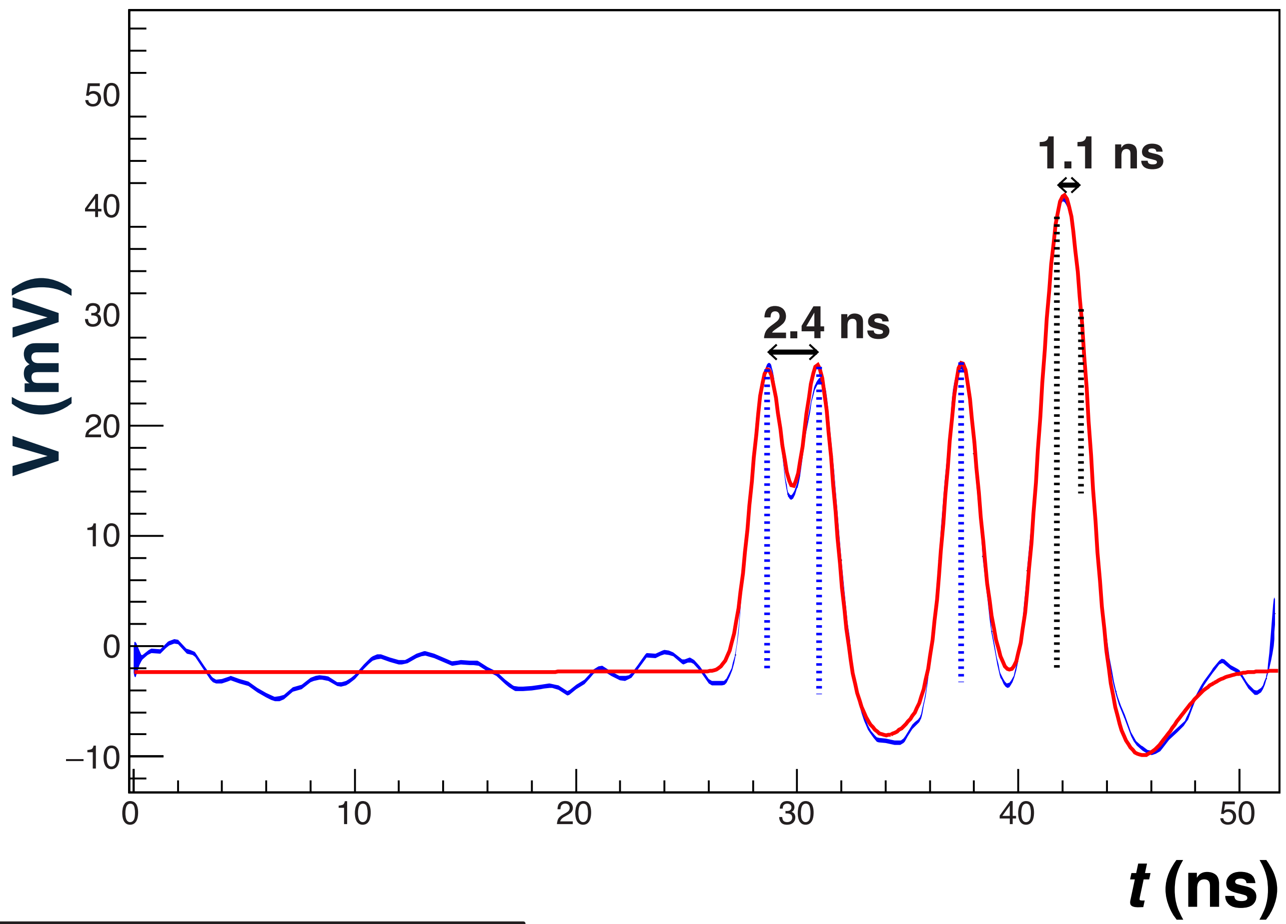
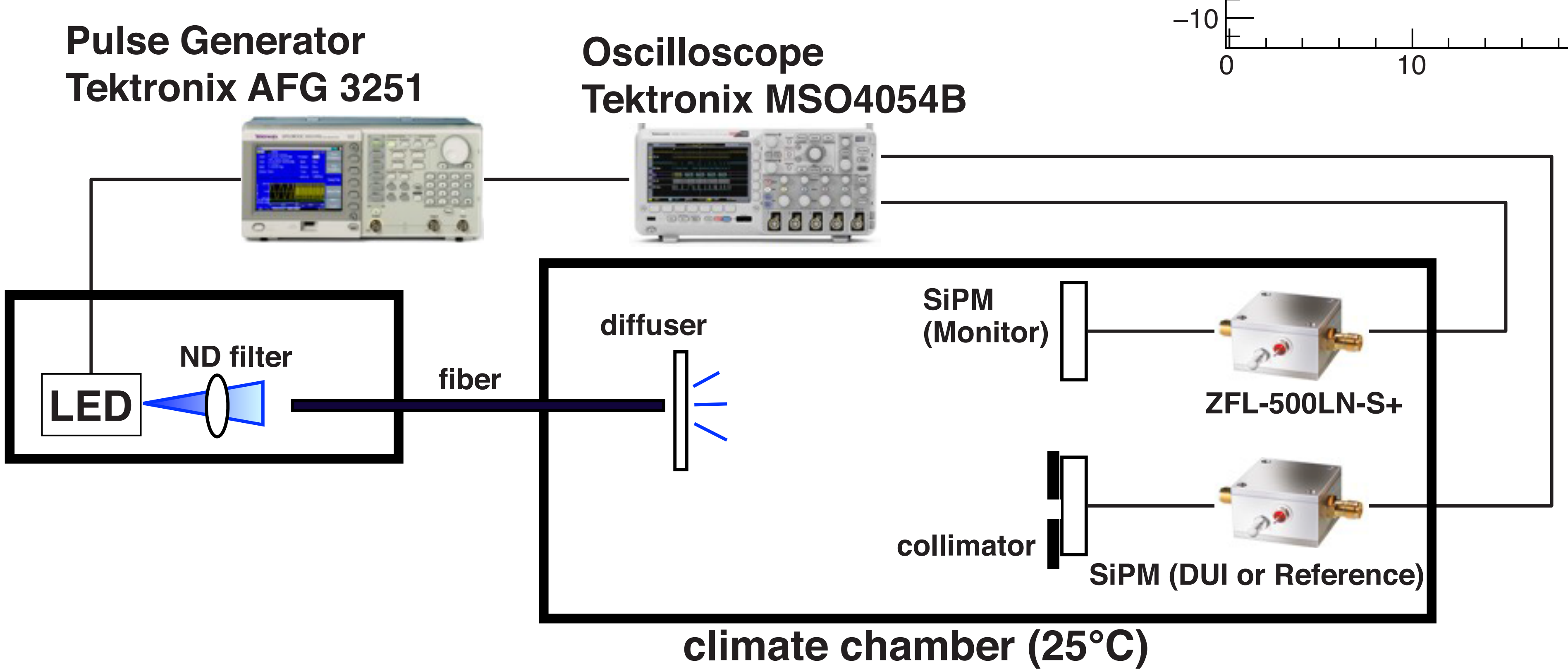




PDE Measurements

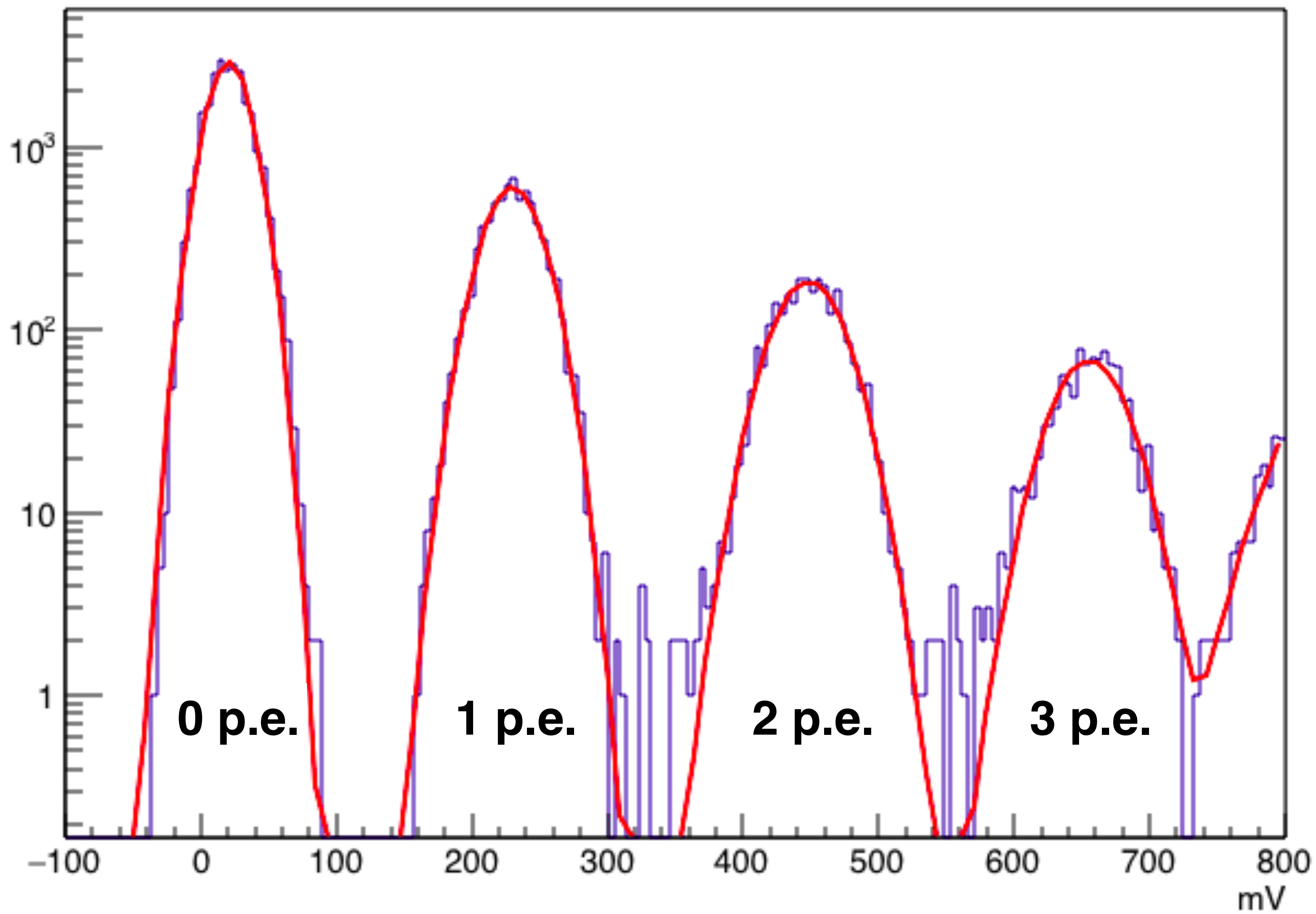
- We measure number of photons for short LED (or laser) pulses
  - Current measurement does not provide accurate PDE due to optical crosstalk, delayed cross talk and after pulse
- Number of photo electrons (p.e.) does not follow Poisson distribution due to optical crosstalk
  - Probability of 0 p.e. is used to obtain the average to avoid effects of optical crosstalk
  - Effect of dark count still need to be taken into account

$$P(n) = e^{-\mu}\mu^n/n!$$

$$P(0) = e^{-\mu}$$

$$\mu = -\ln(P(0))$$

$$P_{\mathrm{true}}(0) = P_{\mathrm{ON}}(0)/P_{\mathrm{OFF}}(0)$$

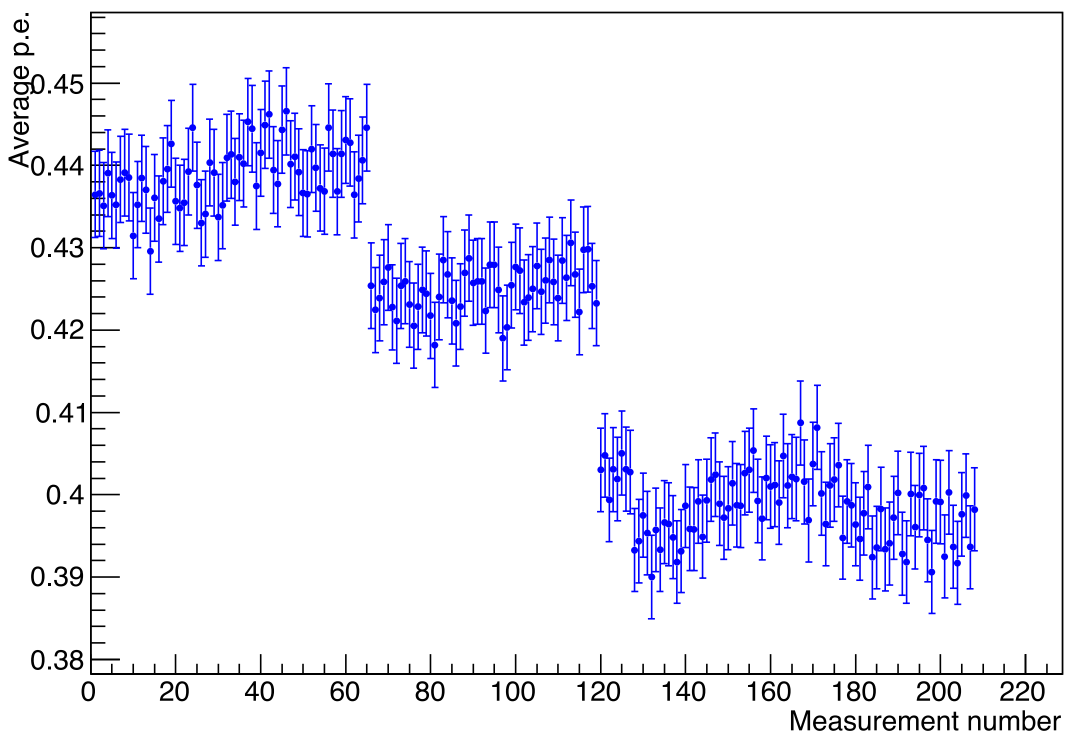


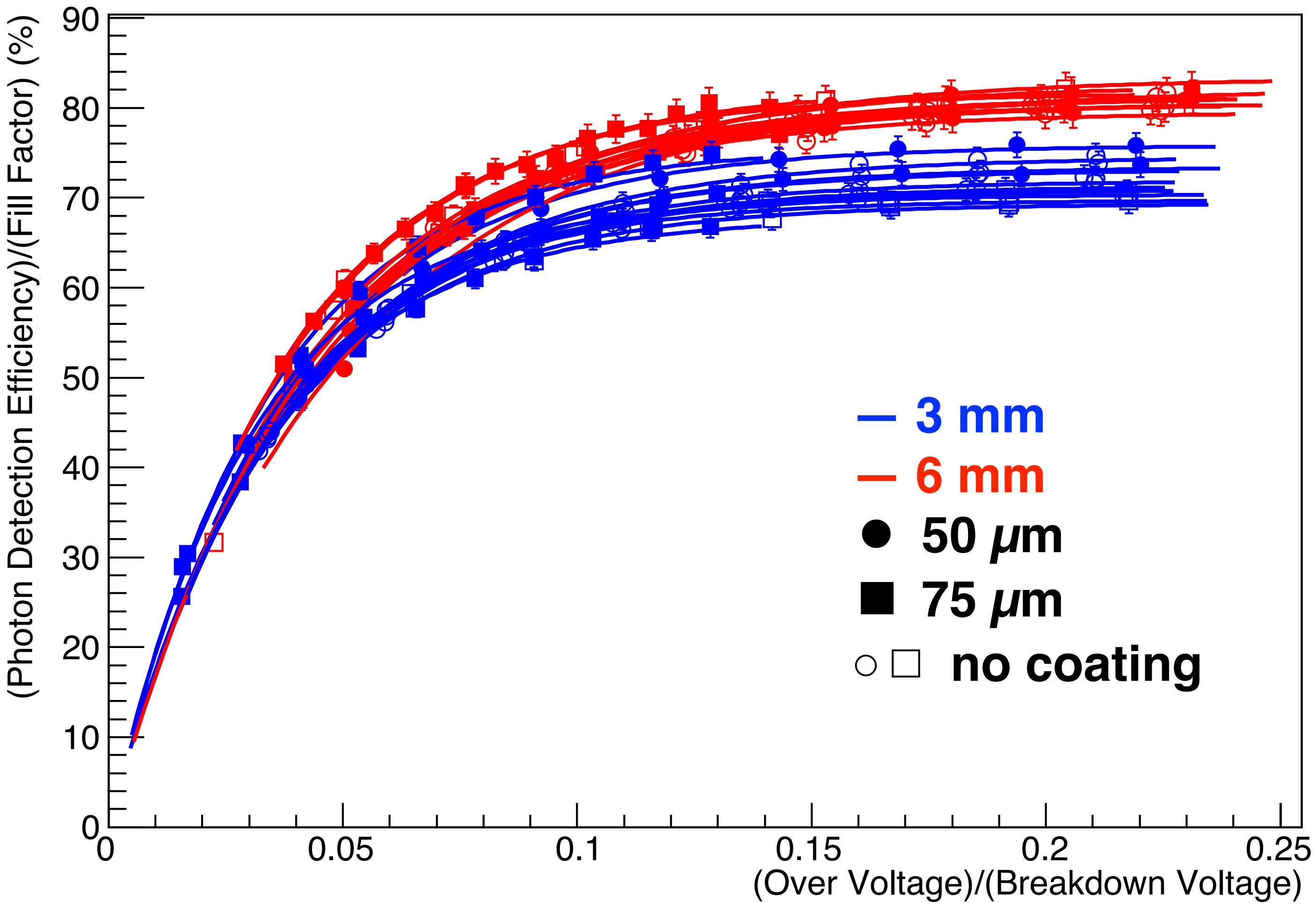
PDE vs Over Voltage

- PDEs were measured for 2 devices for each type
- PDEs were measured twice for some devices
- Measured PDEs were very consistent, which indicates varying light intensity is properly compensated by the monitor SiPM

Avalanche probability

$$\mathrm{PDE}/(\text{Fill factor}) = \mathrm{PDE}_{\max} \cdot \left(1 - \exp[-C_{\mathrm{depth}} V_{\mathrm{OV}}/V_{\mathrm{BR}}]\right)$$





Optical Crosstalk Measurements

- Assume 1 p.e. peak of dark signal is dominated by dark count
  - 2 p.e. peak consists of optical crosstalk from 1 p.e. and chance coincidence of dark counts within Δt_{PS} (~3 ns in our setup)

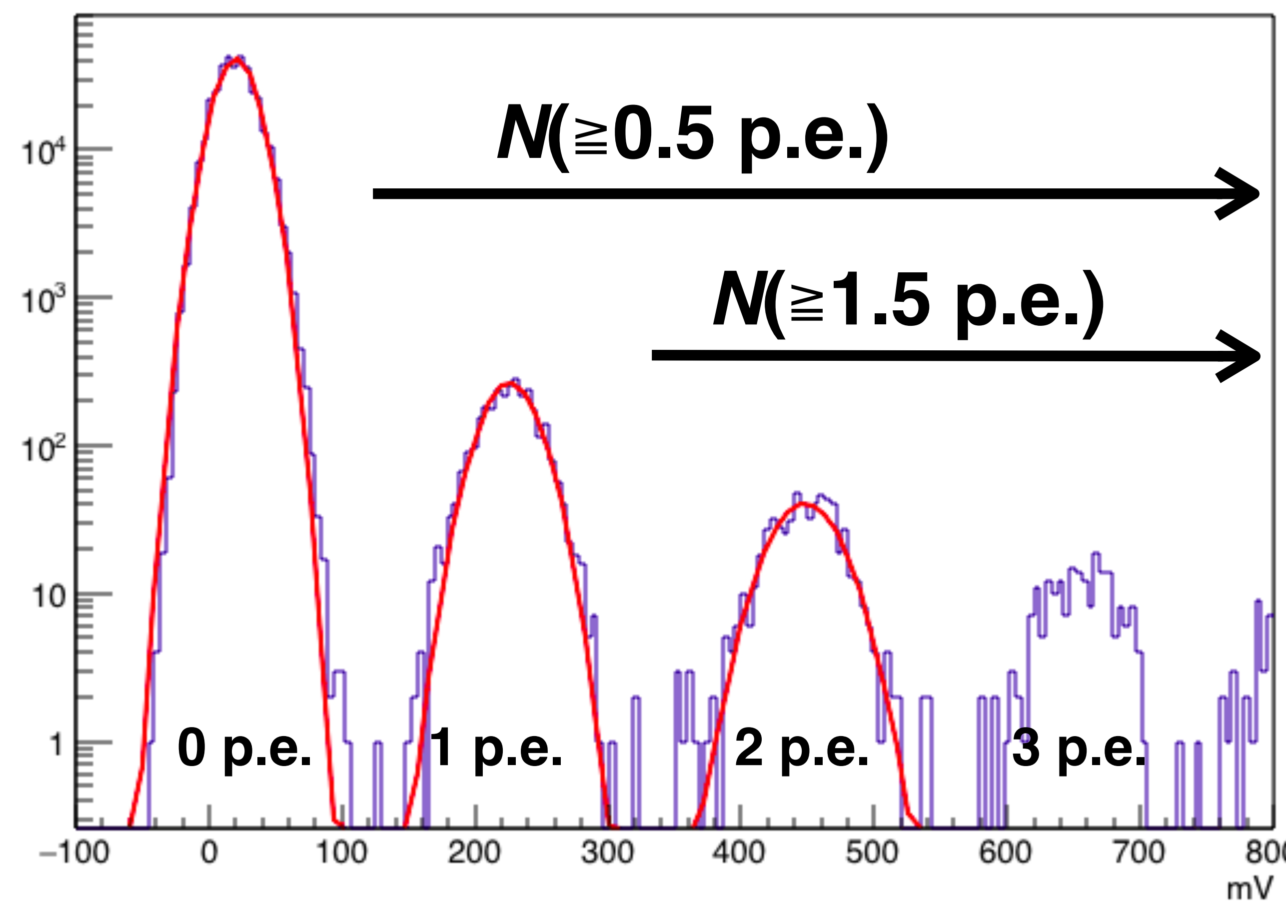
Probability to have no optical crosstalk

$$\frac{N(\geq 1.5\ \mathrm{p.e.})}{N(\geq 0.5\ \mathrm{p.e.})} = 1 - \boxed{(1 - R_{\mathrm{OCT}})}\boxed{e^{-f_{\mathrm{DC}}\Delta t_{\mathrm{PS}}}}$$

Poisson probability to have no overlapping dark count within Δt_{PS}

$$R_{\mathrm{OCT}} = 1 - \left(1 - \frac{N(\geq 1.5\ \mathrm{p.e.})}{N(\geq 0.5\ \mathrm{p.e.})}\right) / e^{-f_{\mathrm{DC}}\Delta t_{\mathrm{PS}}}$$

f_{DC}: Dark count rate
Δt_{PS}: Double-pulse separation time



Crosstalk Rate vs. Over Voltage

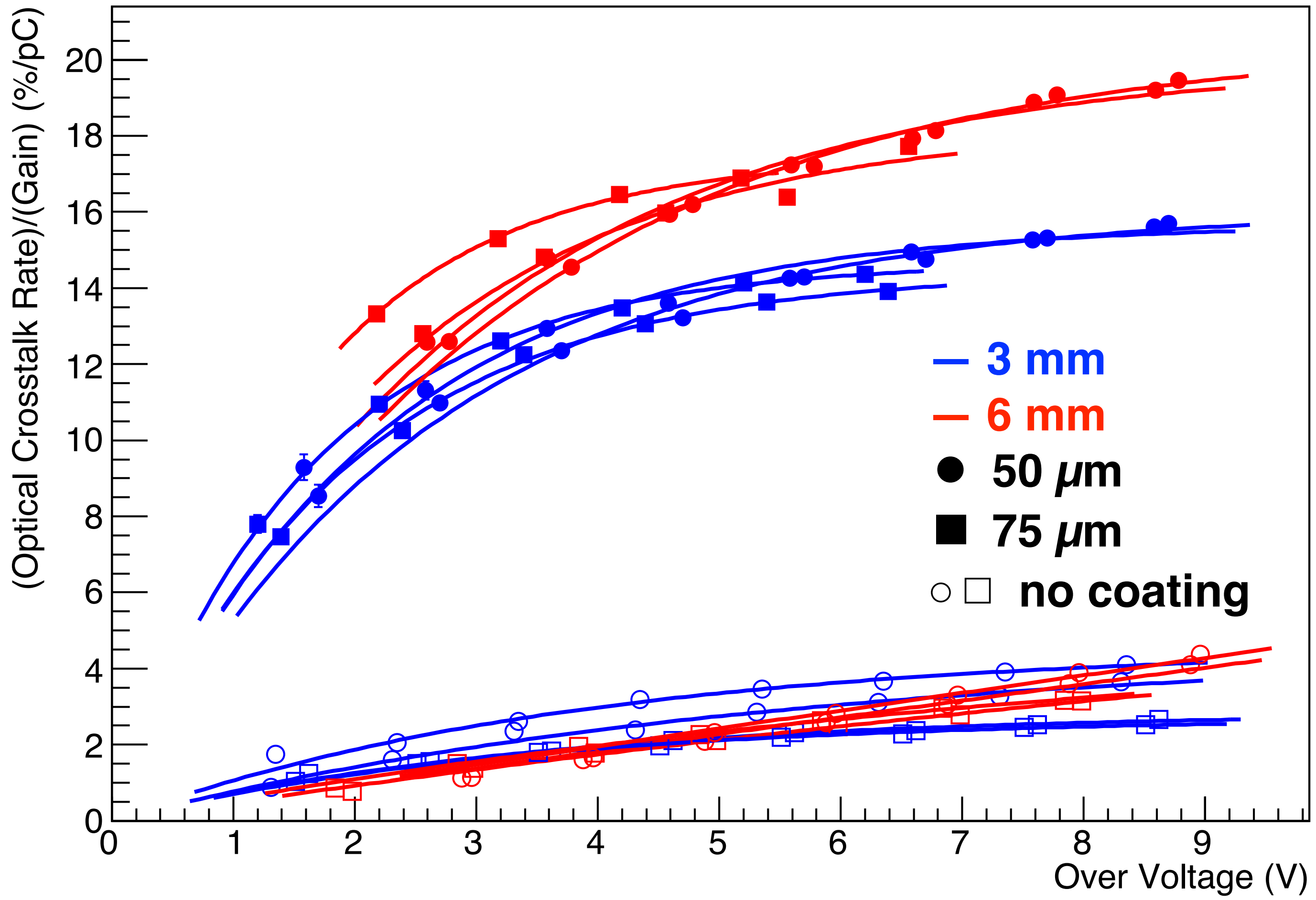
- Optical crosstalk rate should be proportional to the gain and avalanche trigger probability

Avalanche probability

$$R_{\mathrm{OCT}}/(\mathrm{Gain}) = C_{\mathrm{OCT}} \cdot \boxed{(1 - \exp[-C'_{\mathrm{depth}} V_{\mathrm{OV}}/V_{\mathrm{BR}}])}$$

- **C_{depth} tends to be small without resin coating**
  - **Avalanche seed is produced in the region where it is harder to trigger avalanche**

Product ID	C_{OCT}	C_{depth}
S14520-3050VS	16	17
S14520-6050VS	20	14
S14520-3075VS	14	23
S14520-6075VS	18	22
S14520-3050VN	4.5	9
S14520-6050VN	50	0.4
S14520-3075VN	3	11
S14520-6075VN	7	3



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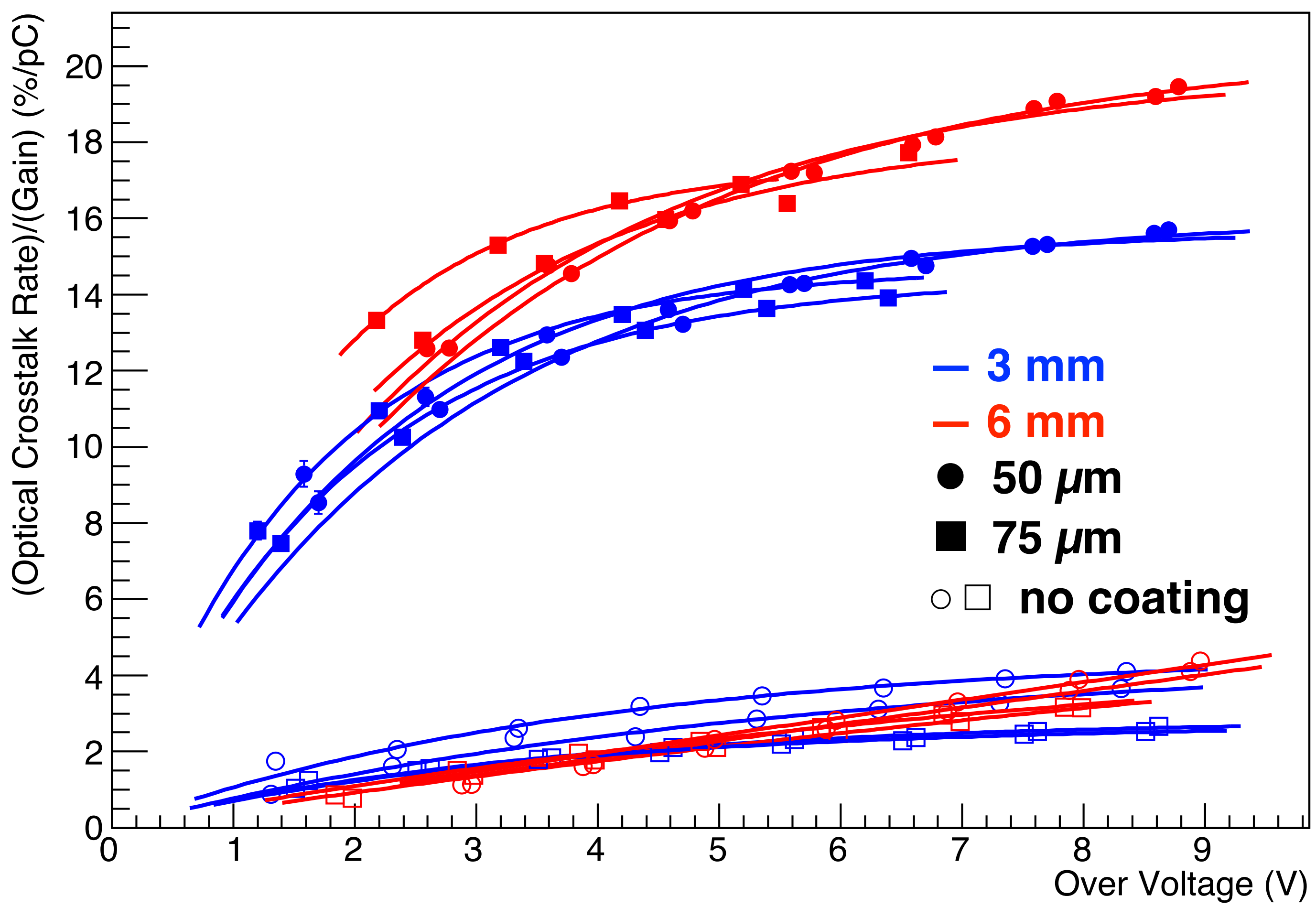

Propagation of Crosstalk Photons

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- Intermediate thickness
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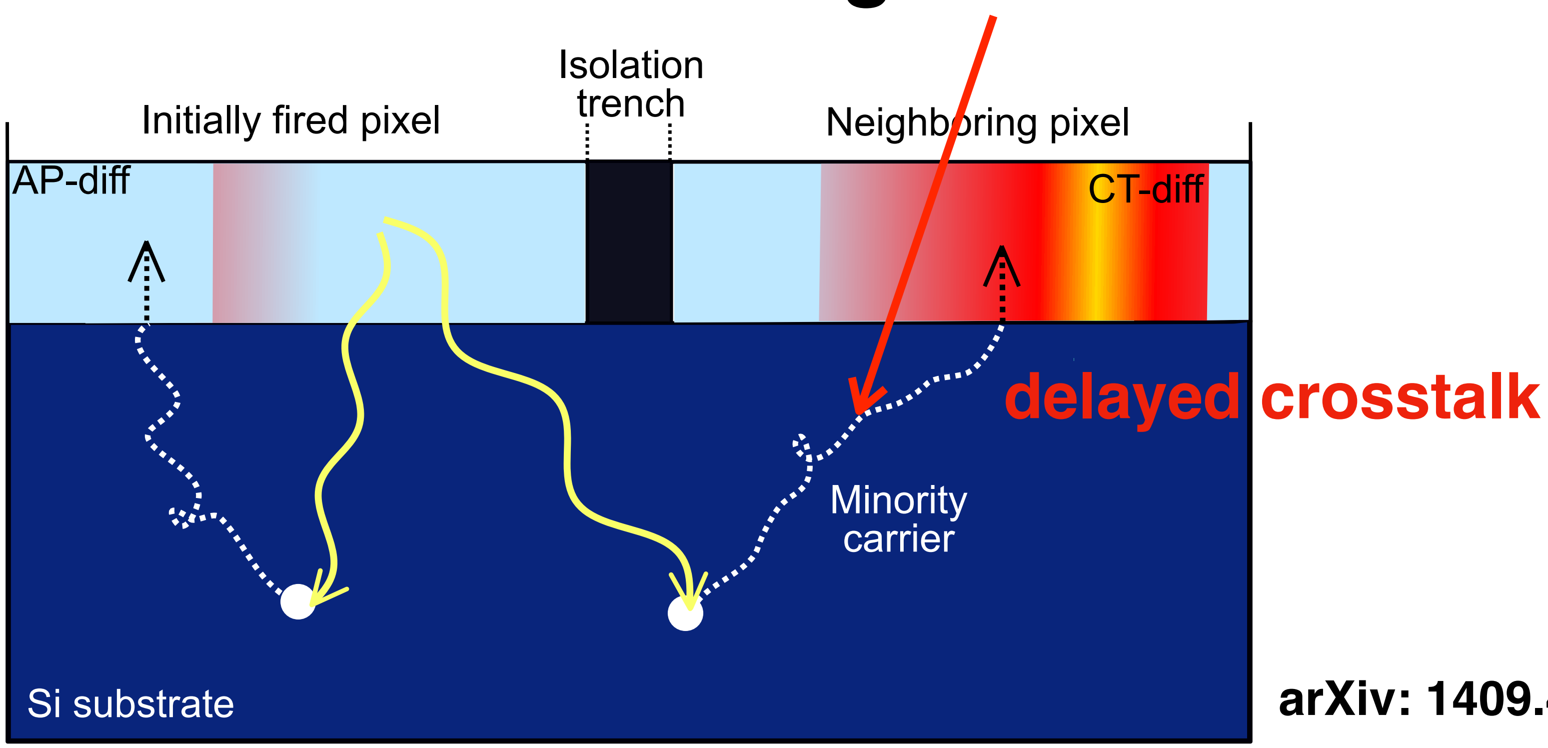
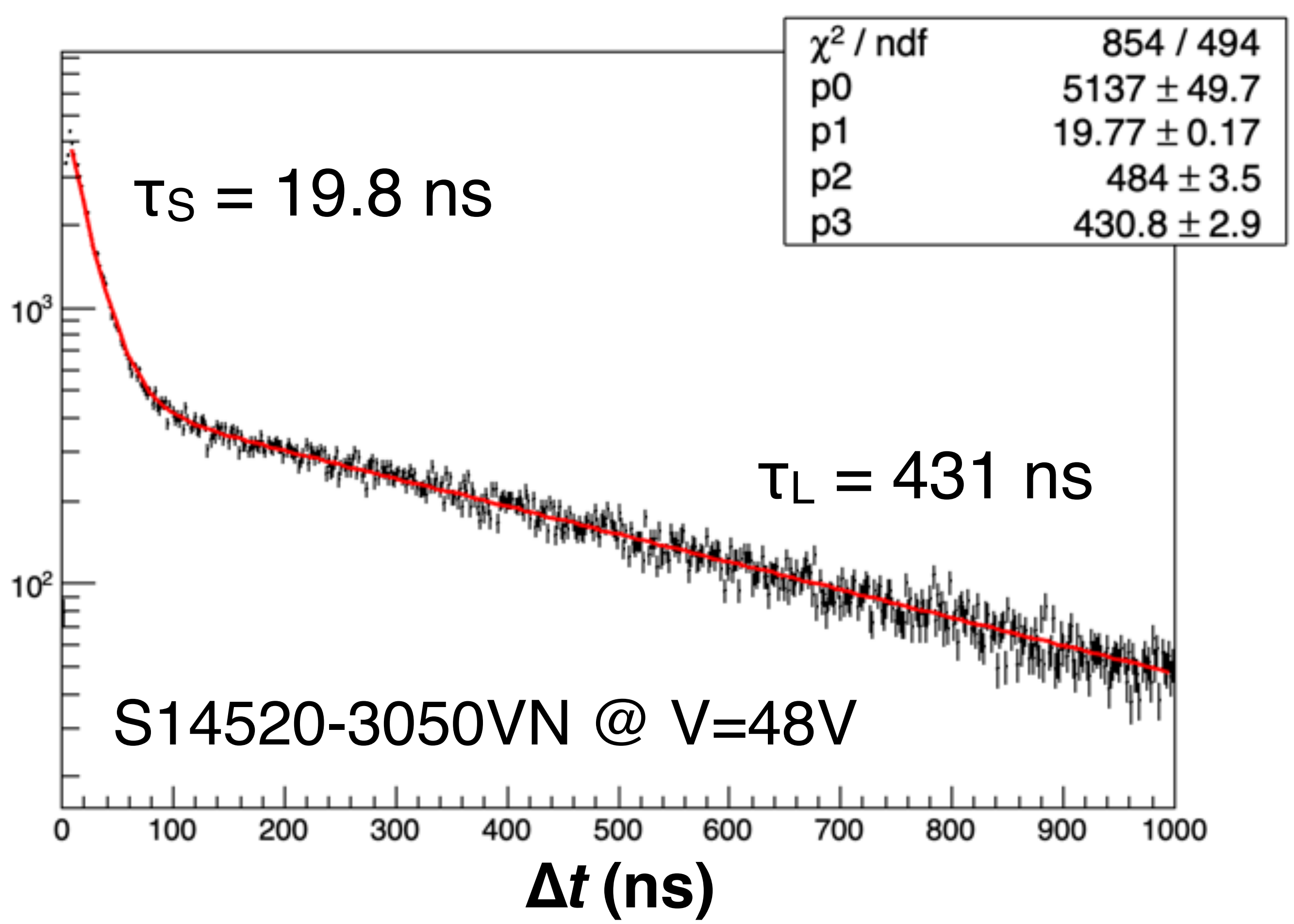
  - Smaller device may have lower crosstalk rate
- How about the crosstalk thorough the backside?

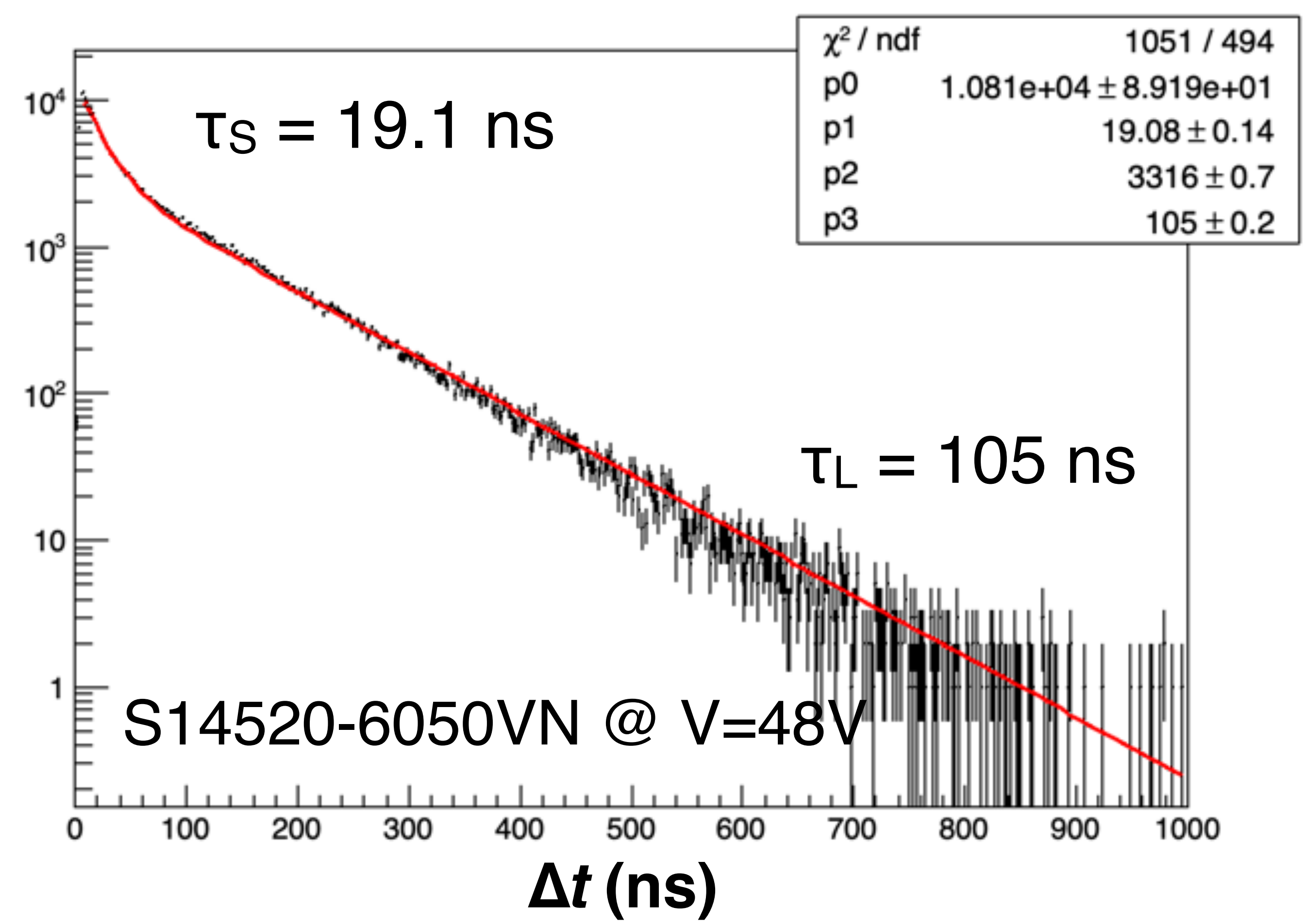


arXiv: 1409.4564

Measurement of Delayed Crosstalk

- Distribution of the time difference between two pulses show two exponential component with different time constants
  - Relatively long time constant is due to dark counts
  - Short time component is mainly due to delayed crosstalk
    - Short time constant is not heavily dependent on the over voltage
    - Afterpulse is negligible in these SiPMs





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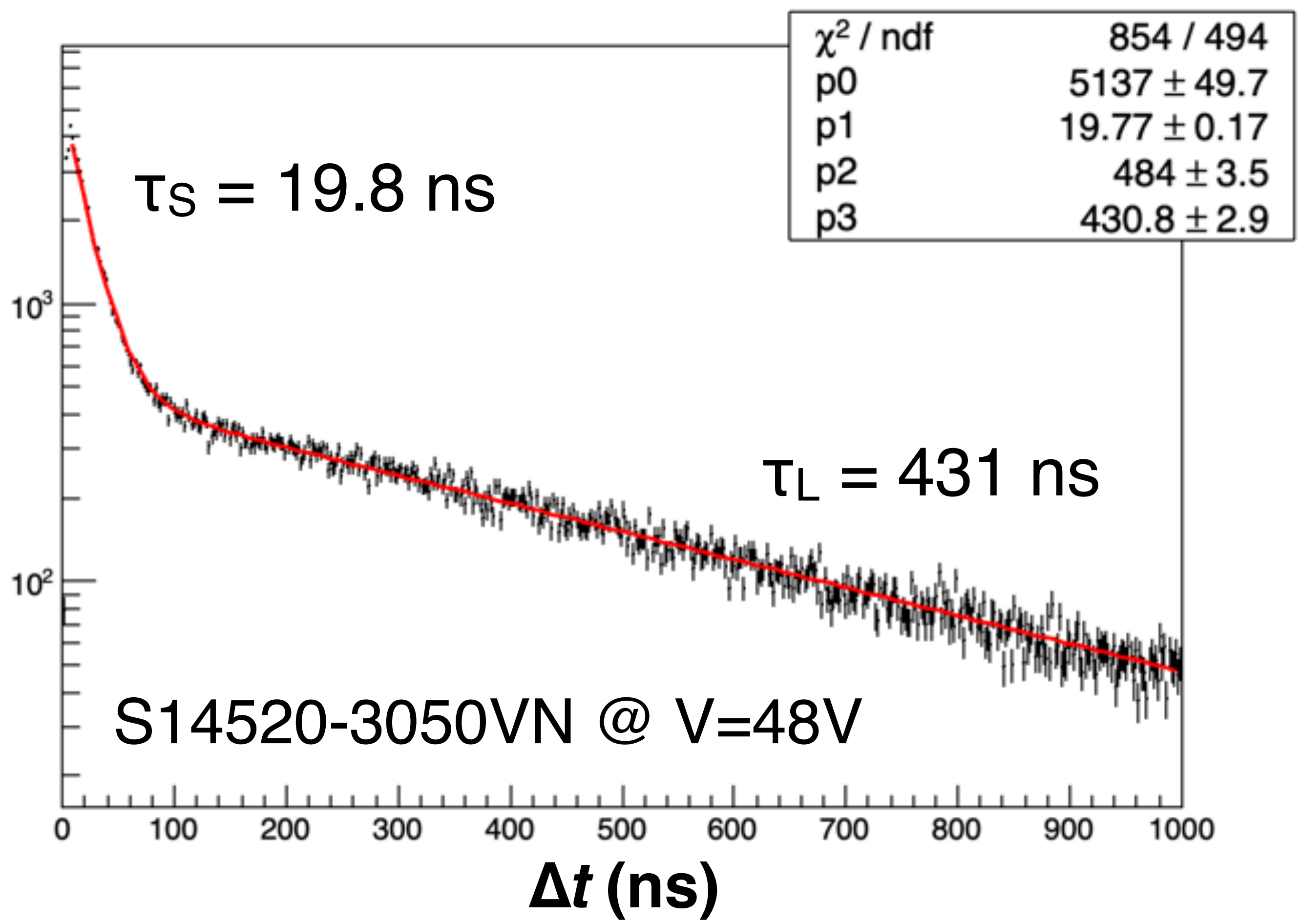
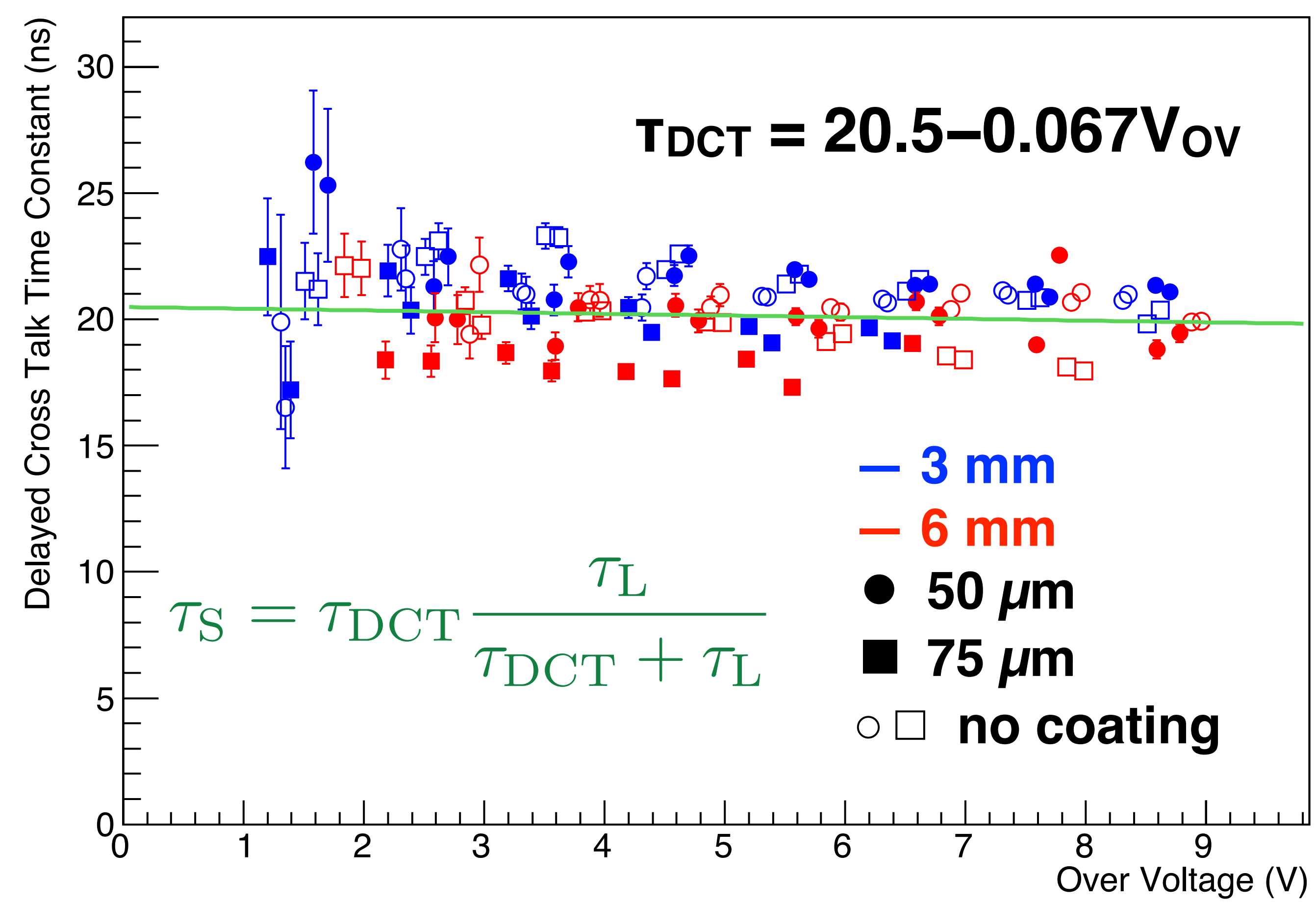




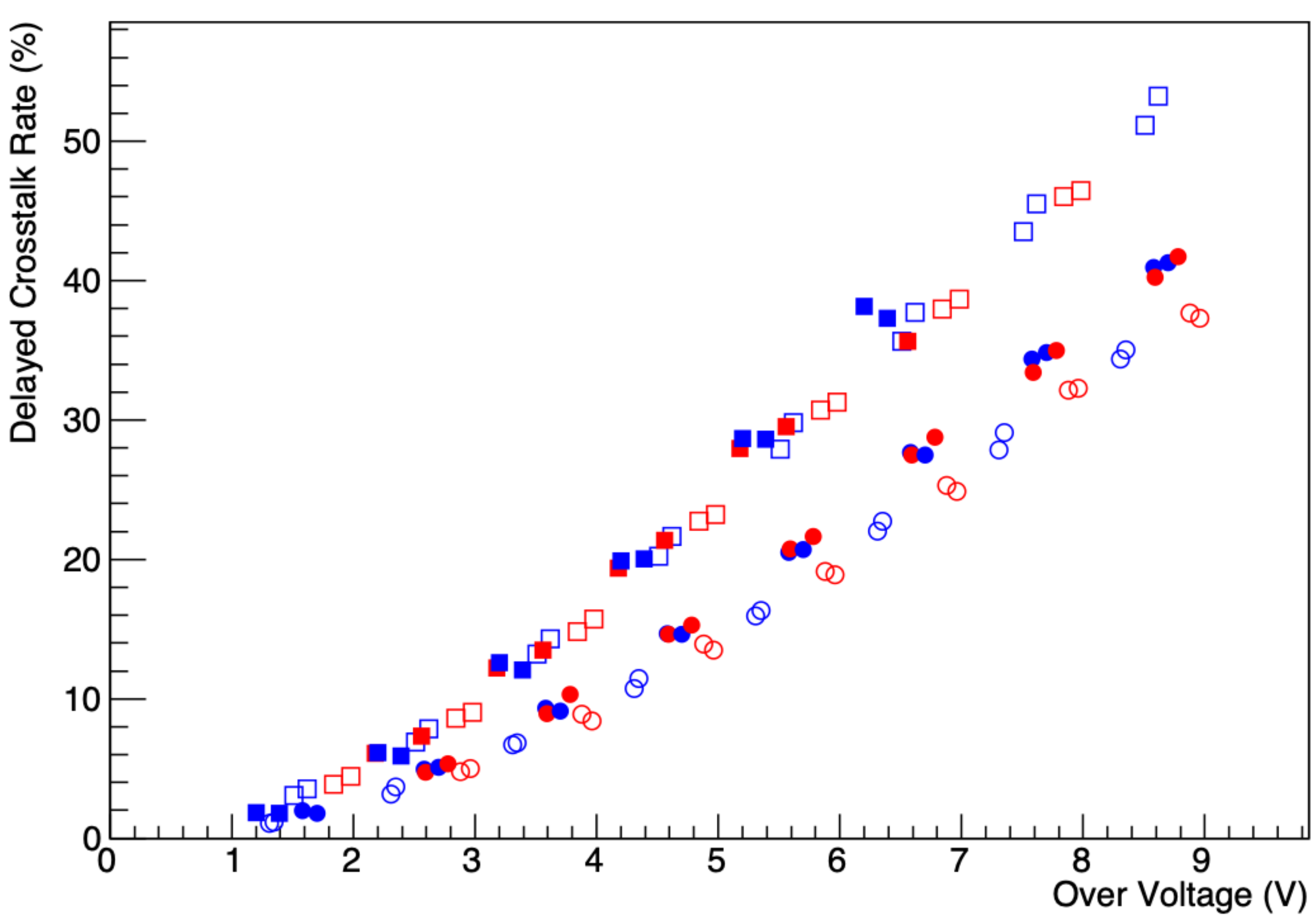
Delayed Crosstalk Rates

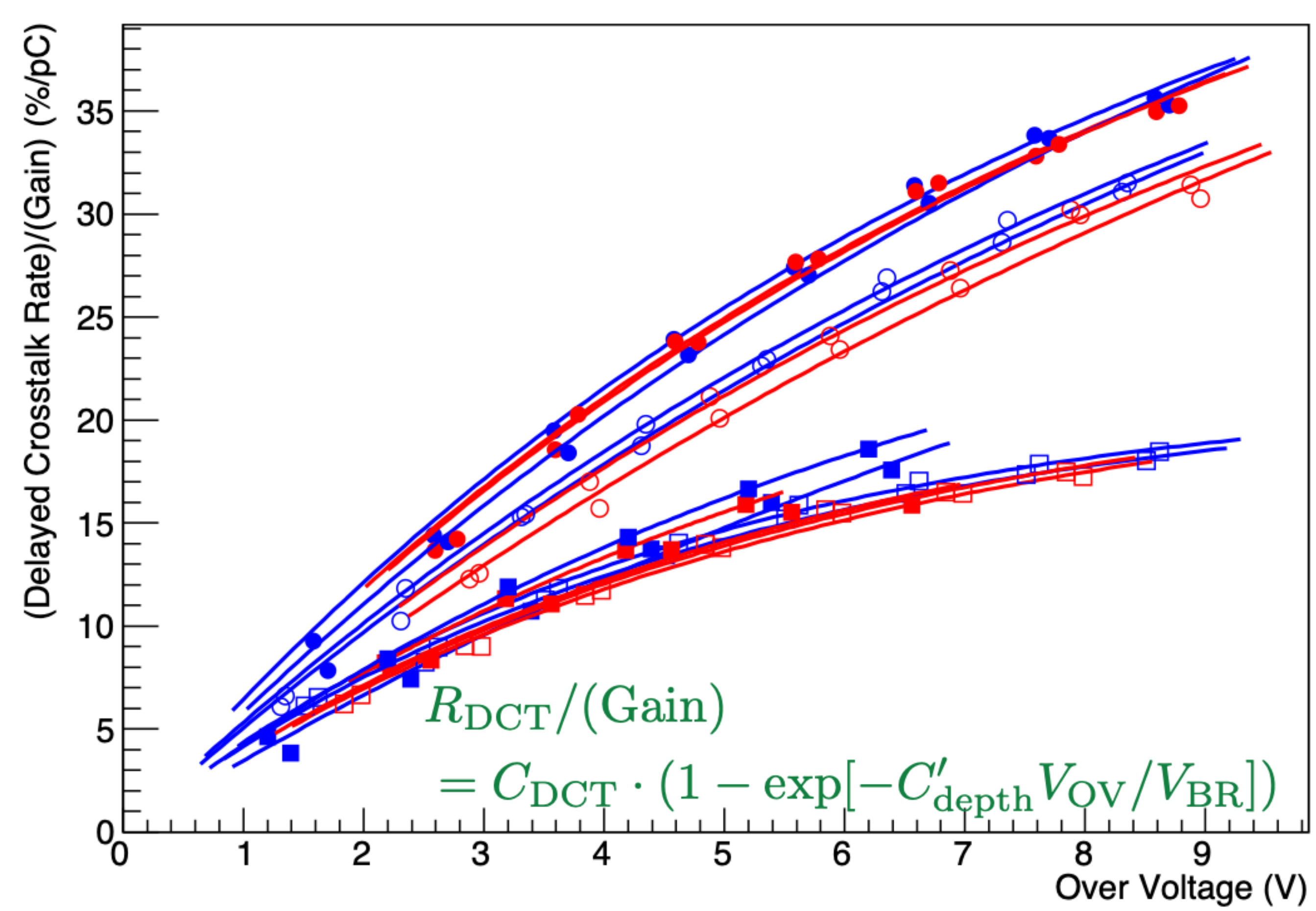
- **Delayed crosstalk rate (R_{DCT}) is calculated as**

$$R_{\mathrm{DCT}} = \frac{N_{\mathrm{S}}}{N_{\mathrm{S}} + N_{\mathrm{L}}}$$

N_S: # of event with short time constant
N_L: # of event with long time constant

- **There is no significant difference due to coating**
- **C_{DCT} is smaller for 75 μm cells (smaller crosstalk efficiency)**
- **C_{DCT} is larger than C_{OCT}, which means total amount of delayed crosstalk is larger than optical cross talk**





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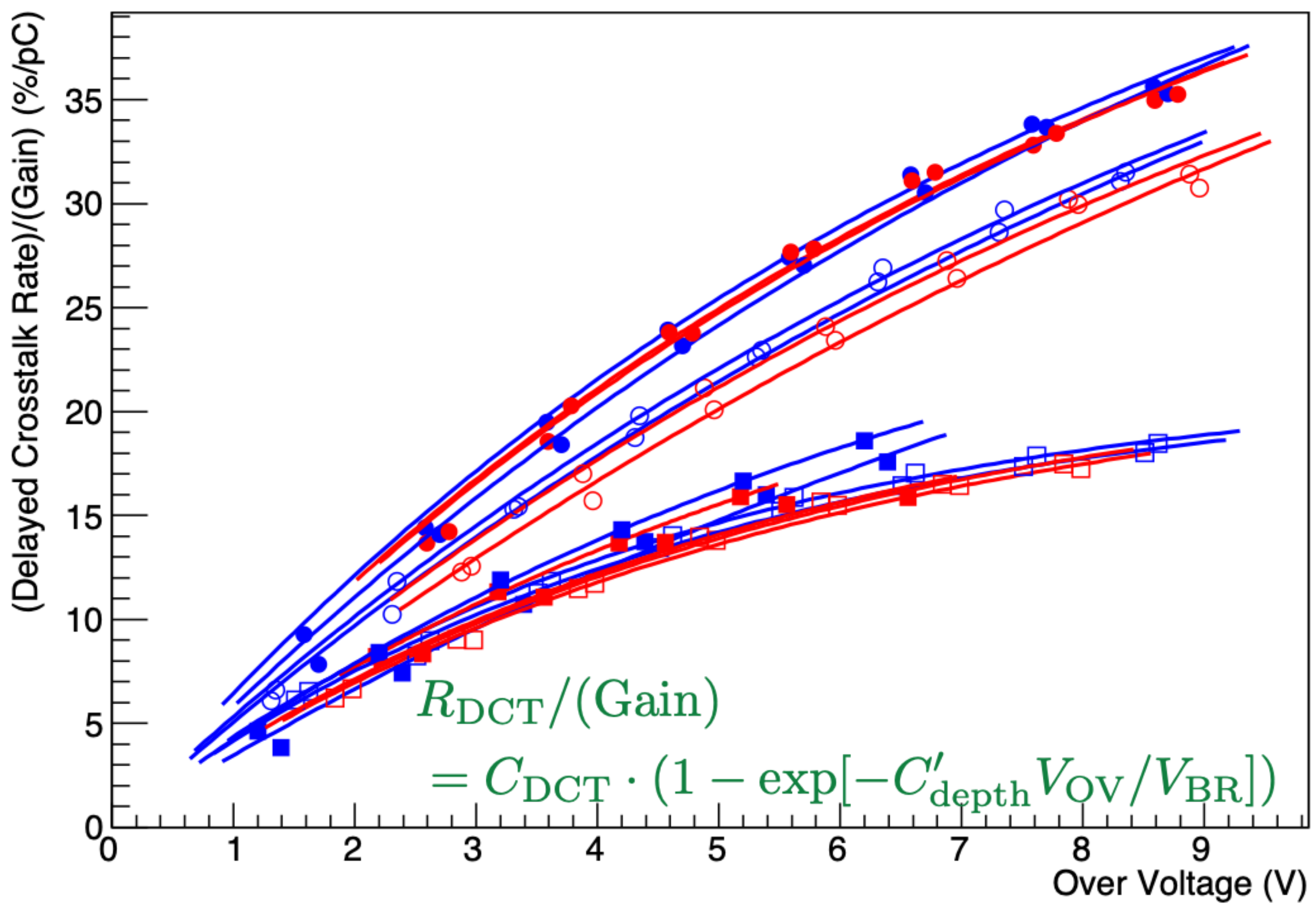
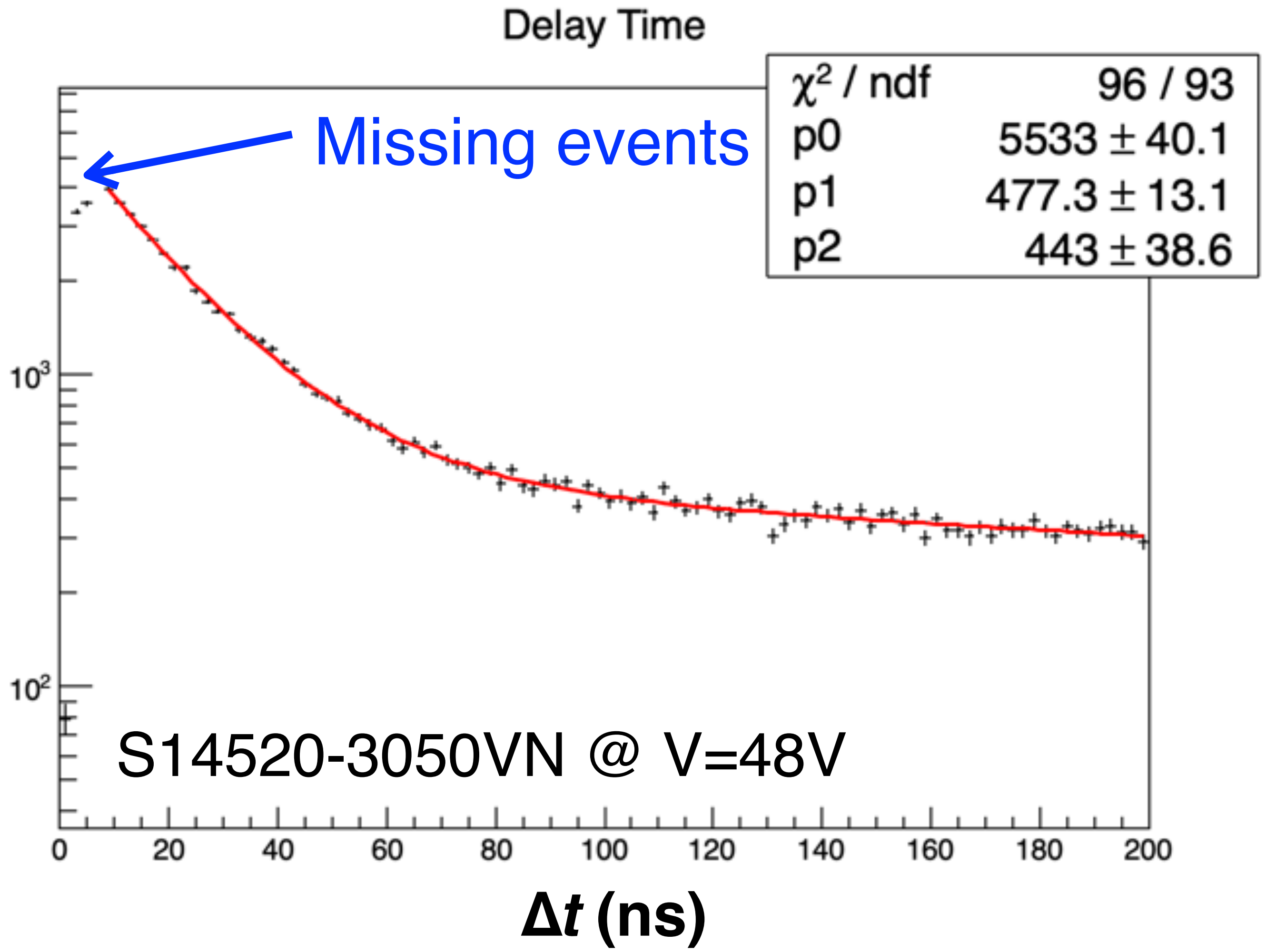
S14520-3050VS	59	3.4
S14520-3050VN	53	3.6
S14520-6050VS	55	4.7
S14520-6050VN	62	3.2
S14520-3075VS	37	4.5
S14520-3075VN	27	8.6
S14520-6075VS	26	6.6
S14520-6075VN	23	7.2

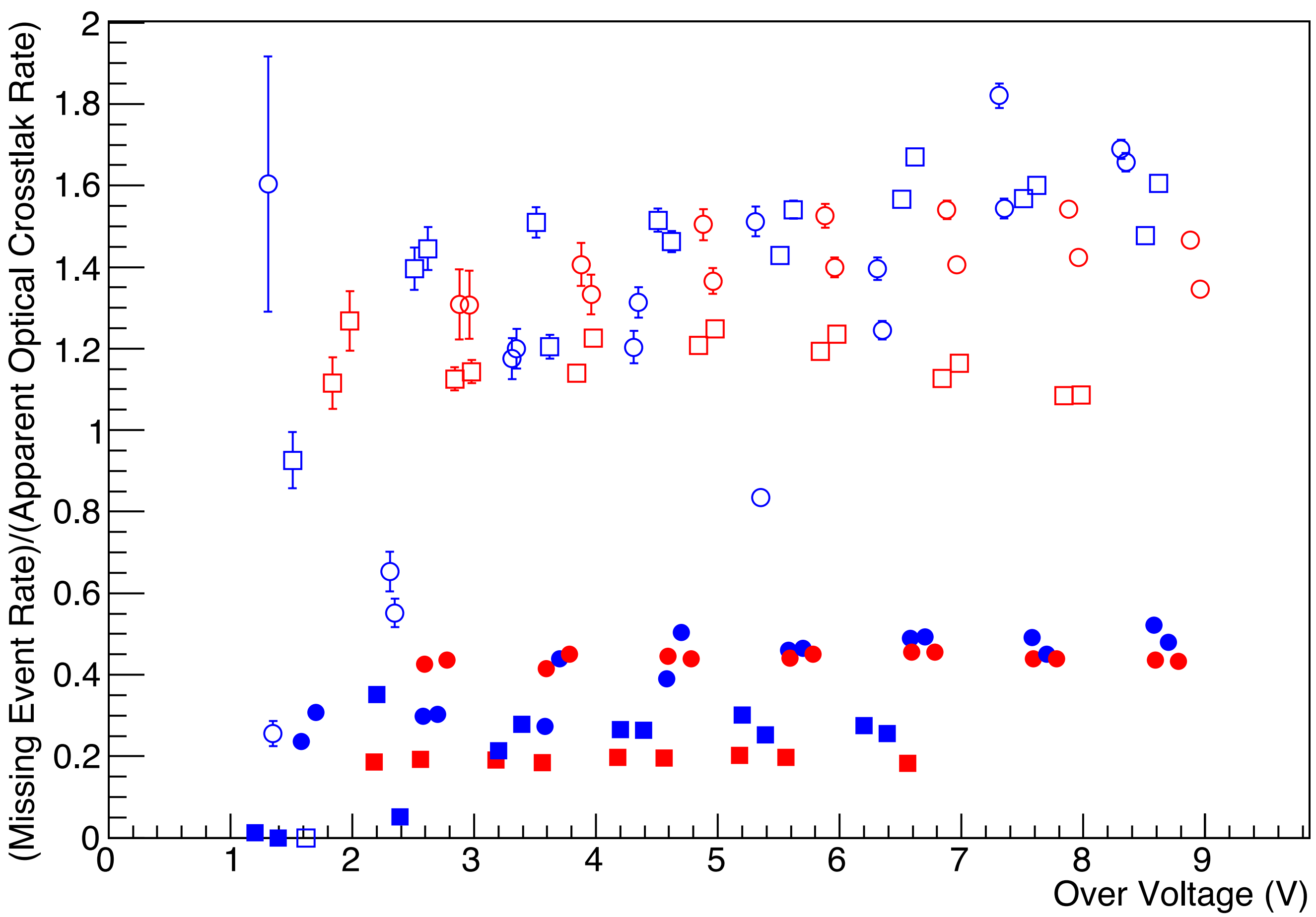


Missing Events

- There are some missing events for $\Delta t < 6$ ns
  - These events may be recognized as "prompt" crosstalk
- Ratio of (Missing Event Rate)/(Apparent Optical Crosstalk)
  - Ratio is more than 1 and constant for SiPMs without coating
  - Apparent crosstalk may be accounted for by missing events for SiPMs without coating

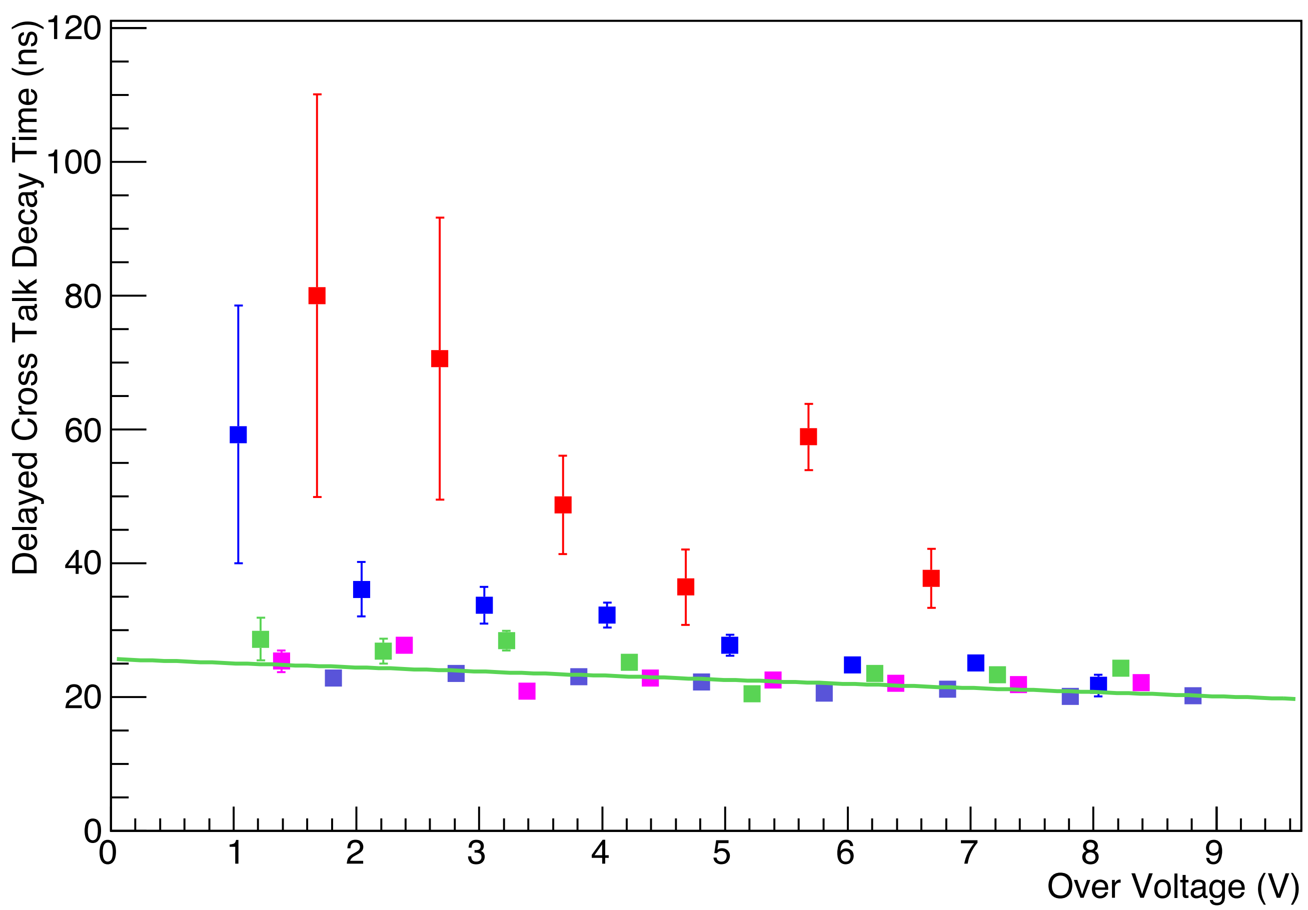
$$\frac{N_{\mathrm{Missing}}}{N_{\mathrm{S}} + N_{\mathrm{L}}} \Big/ \frac{N(\geq 1.5\mathrm{p.e.})}{N(\geq 0.5\mathrm{p.e.})}$$

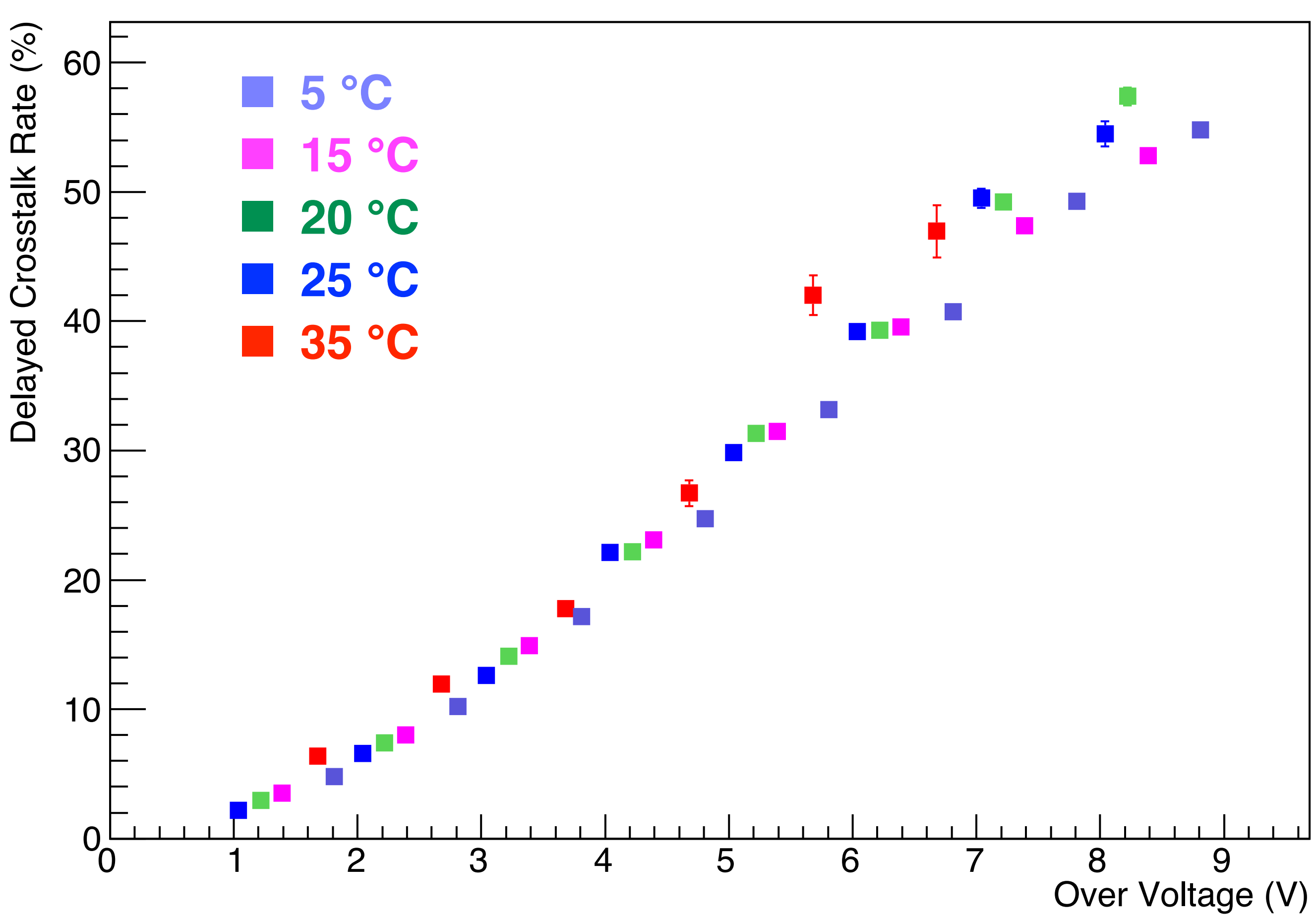




Temperature Dependence

- ❖ No visible dependence on temperature for
  - ✤ delayed crosstalk time constant
  - ✤ delayed crosstalk rate





Summary

- Optical crosstalk rate is significantly affected by resin coating
  - Seed photons propagate through resin coating
  - Smaller device size and thicker coating reduce OCT rate
  - Larger cell size increase OCT rate due to larger gain
  - No coating significantly reduces OCT rate
- Delayed crosstalk rate is greater than the optical crosstalk
  - Delayed crosstalk is indecent of the resin thickness
  - Time constant of delayed crosstalk is ~20 ns and independent of the over voltage
    - Apparent cross talk will increase if the pulse width is not much shorter than 20 ns
  - Early component of the delayed crosstalk may account for the remaining crosstalk for SiPMs without resin coating