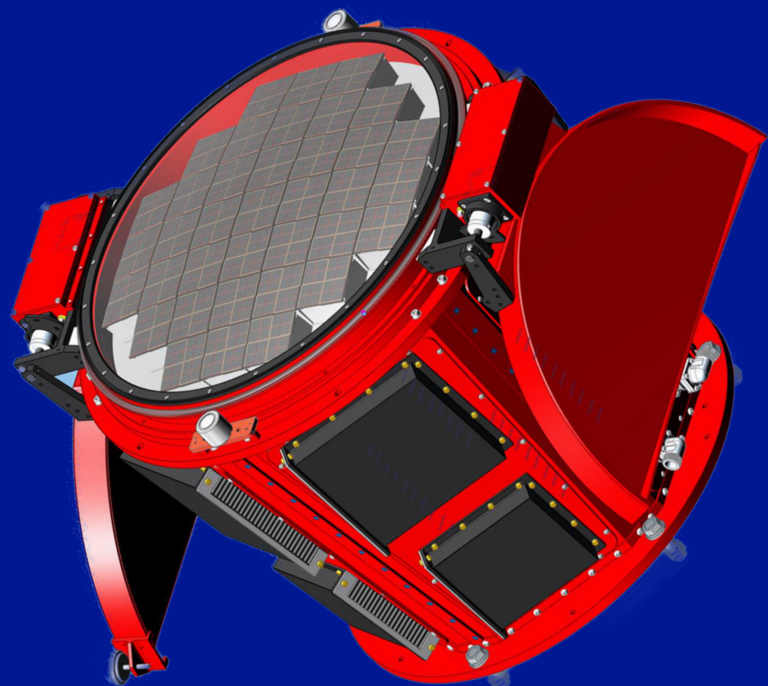
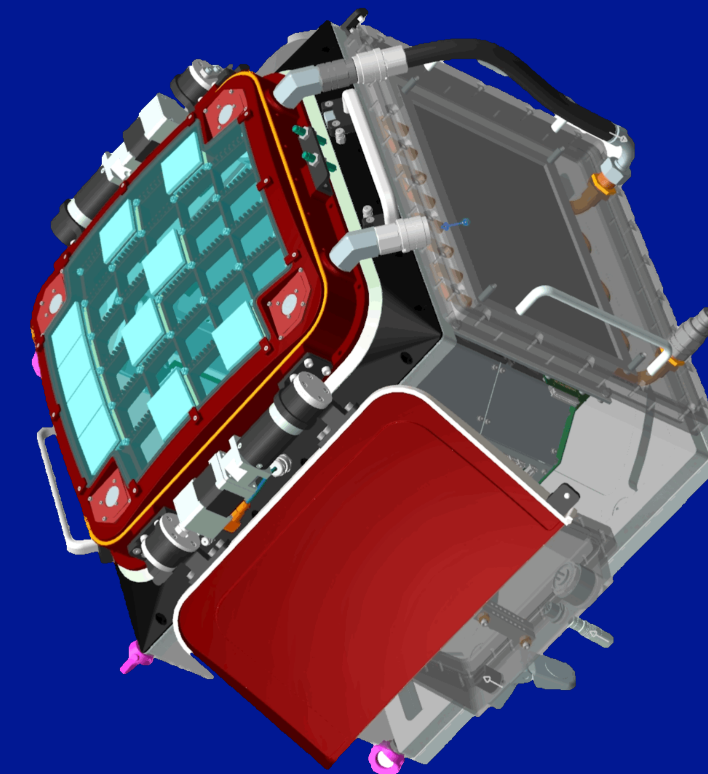


cta
cherenkov telescope array



Suppression of crosstalk in SiPMs for the next generation gamma-ray observatory, CTA

Hiro Tajima, Akira Okumura, Yuki Nakamura, Anatolii Zenin,
Nagoya University (for the CTA-Japan Consortium)
Japan Physical Society Meeting
Shinshu University, September 16, 2018

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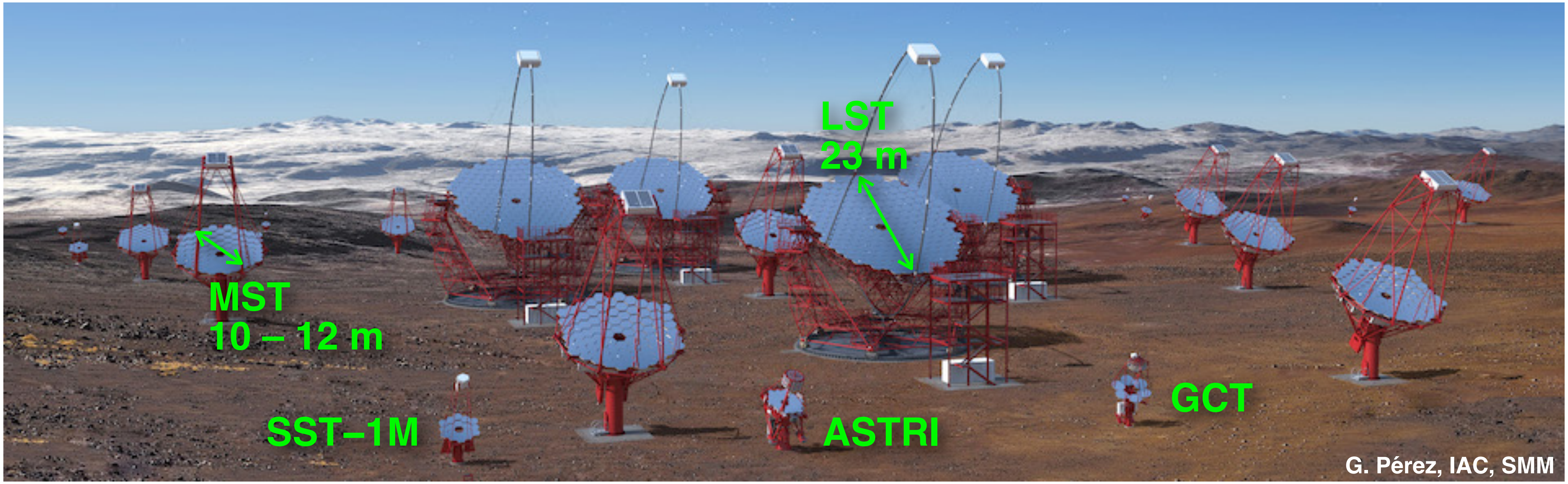
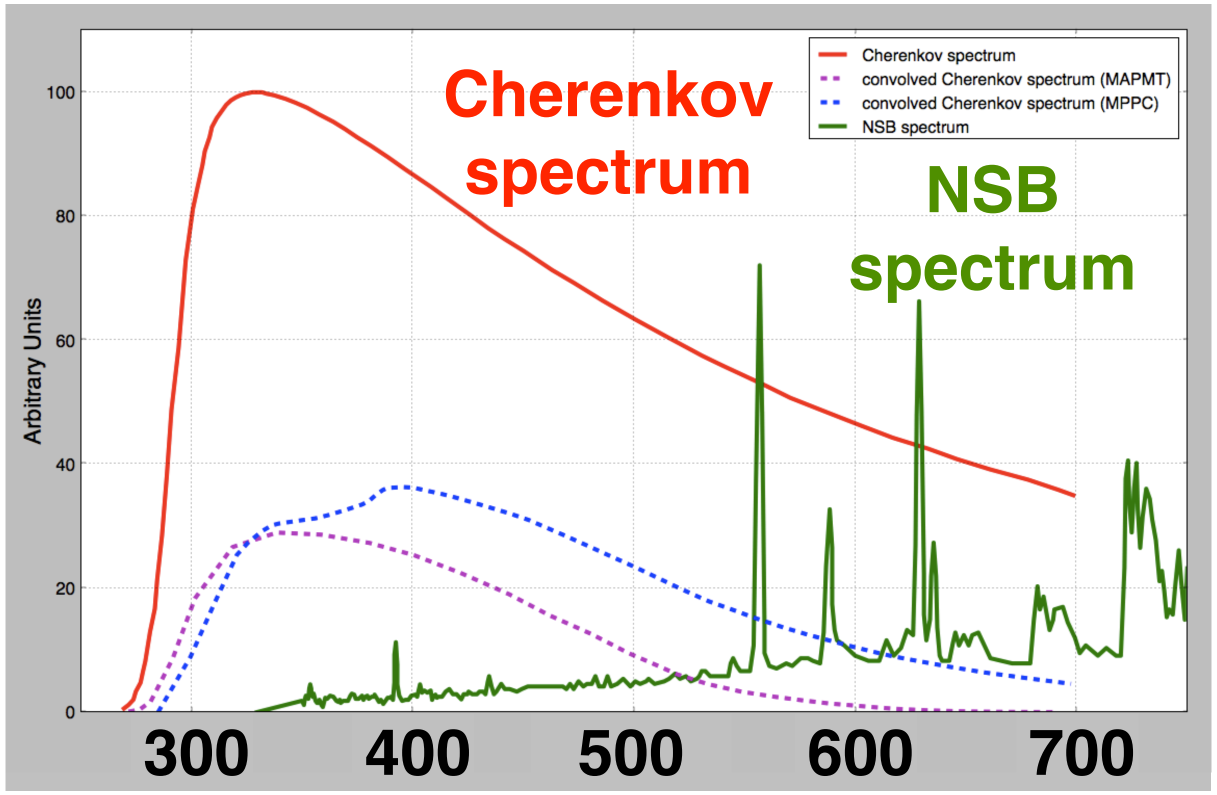
Cherenkov Telescope Array

- Observations of gamma rays in 20 GeV – 300 TeV band
  - Cherenkov light from electromagnetic shower produced by interaction of gamma rays with atmosphere
- Large collection area by placing many telescopes
  - ×10 better sensitivity than current instruments
- Wide energy band coverage by three different sizes of telescopes
  - Large-sized telescope (LST): Φ = 23 m, 20 GeV – 1 TeV, 4 telescopes
  - Medium-sized telescope (MST): Φ = 10 – 12 m, 0.1 – 10 TeV, ~20 telescopes
  - Small-sized telescope (SST): Φ = 4 m, 1 – >300 TeV, 50 – 70 telescopes
    all SSTs are placed at south site



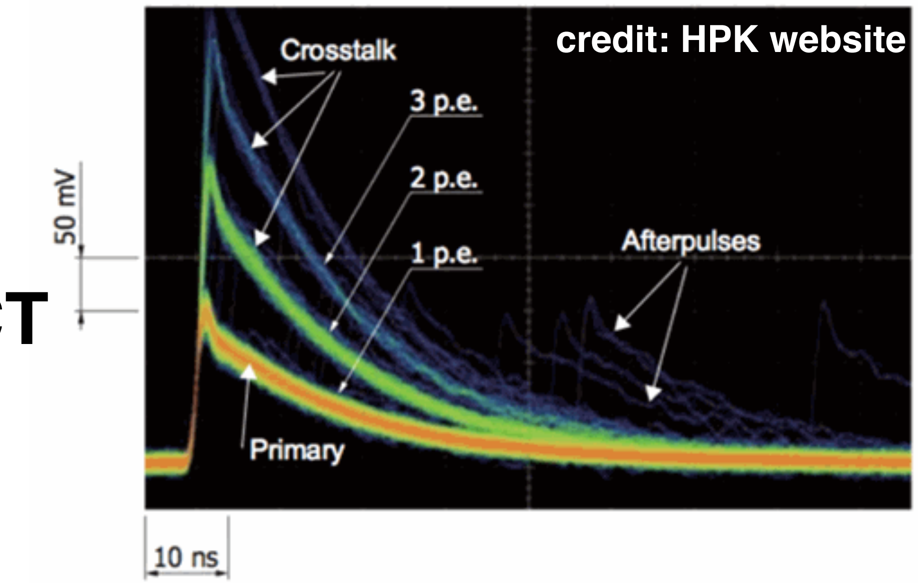
Requirements for Photon Sensors in CTA

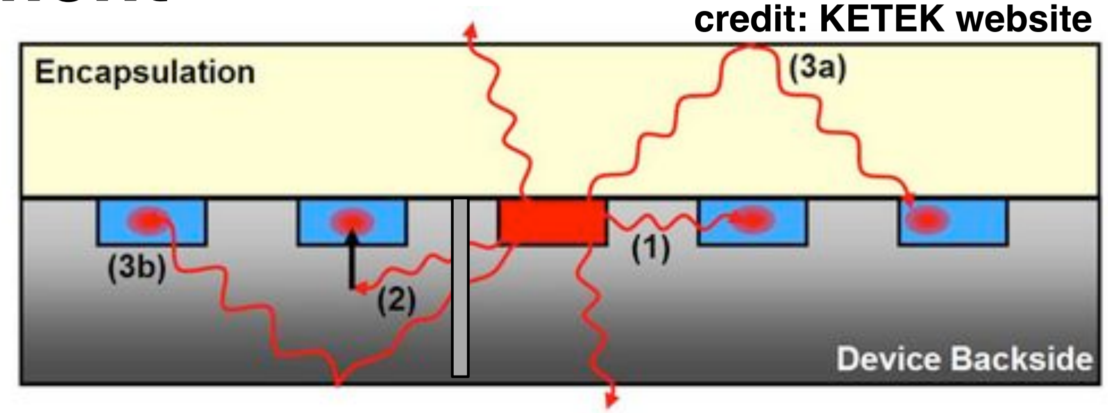
- Properties of Cherenkov photons from gamma-ray air shower
  - ~500 photons/m² for 10 TeV gamma-ray shower
  - Several photons per pixel
  - Cherenkov photons peaks around ~350 nm
    - Blue to near UV sensitivity is important
  - Cherenkov photons arrives within a few to few tens of ns
    - ns-timing is important
- Night sky background (NSB) is the dominant background
  - Rate is >25 MHz/pixel
    - Dark count rate is not important
    - [NSB] x [Optical crosstalk (OCT)] can cause false triggers due to accidental coincidences
      - Low OCT rate is important
  - NSB peaks above 550 nm
    - Low red sensitivity is preferred



Photon Sensor

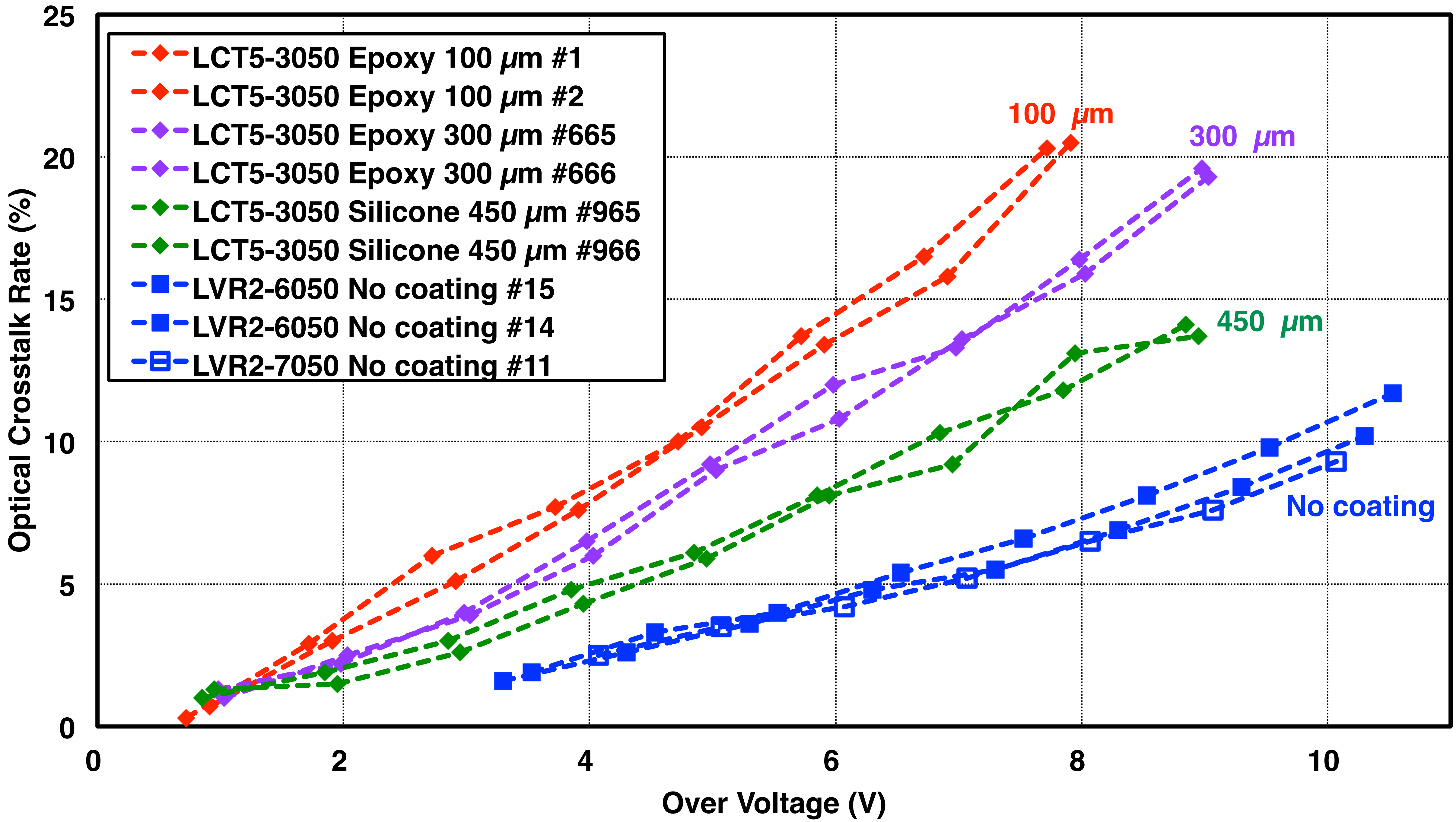
- Silicon Photomultiplier is chosen as a photon sensor for SST
  - Cost per channel
  - Photon detection efficiency
  - Tolerance against high rate environment (> 25 MHz per pixel)
  - Reliability
- Major drawback of SiPM
  - Optical crosstalk (OCT)
    - High rate night sky background (NSB) + OCT can cause false triggers due to accidental coincidences
  - Gain dependence on the temperature
  - High sensitivities for red light (NSB wavelength)
- Main objective of CTA SiPM development
  - Suppress OCT while retaining photon detection efficiency (PDE)





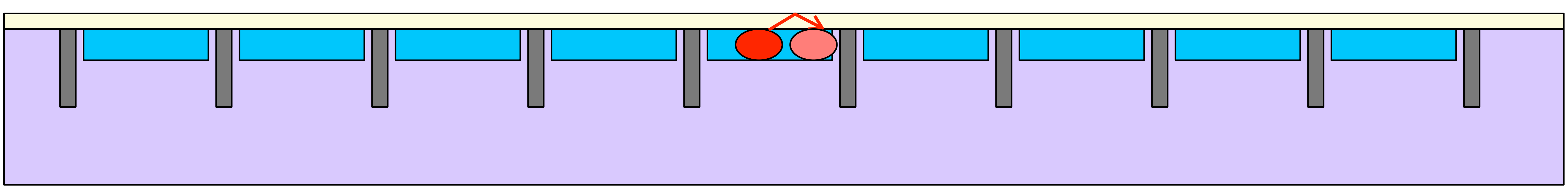
Summary of Past Studies

❖ 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
- How about the crosstalk from the backside?



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- ❖ Intermediate thickness
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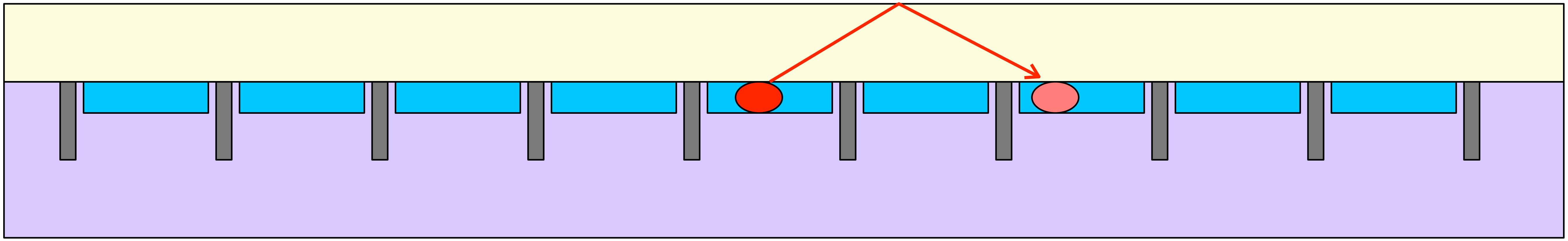
  - ✤ Smaller device may have lower crosstalk rate
- ❖ How about the crosstalk from the backside?



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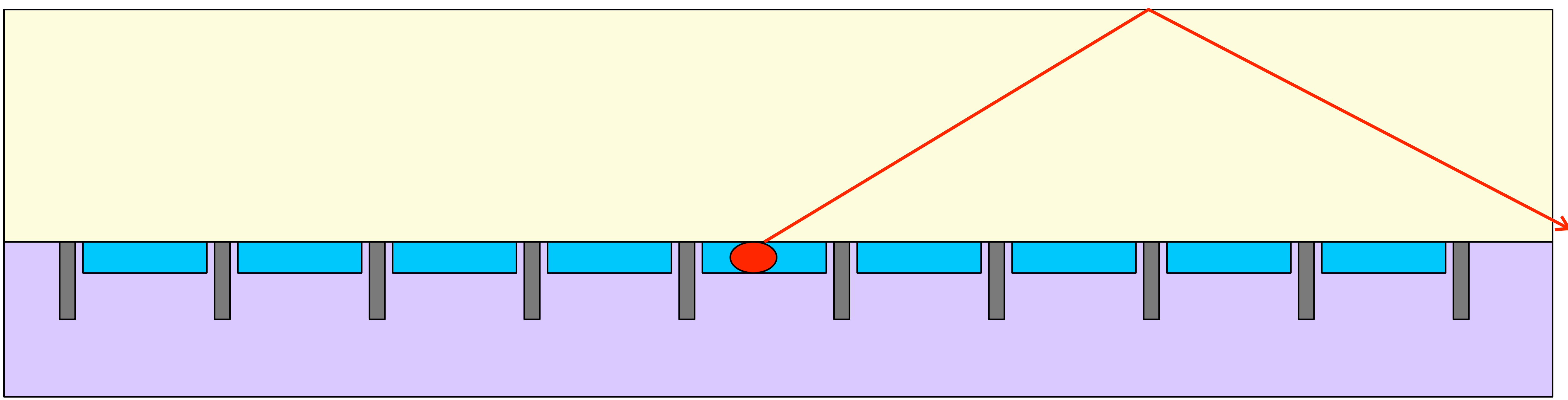

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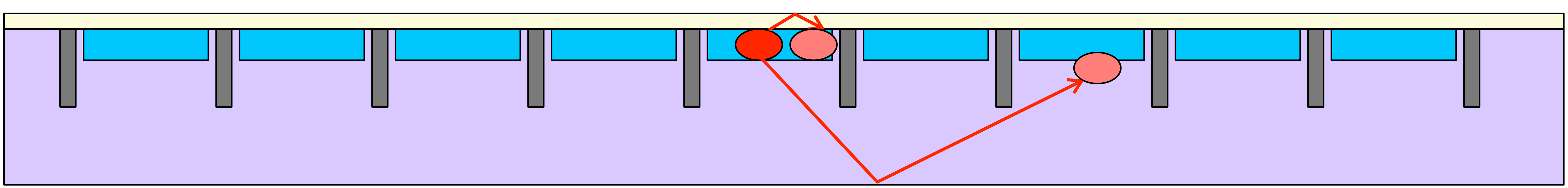


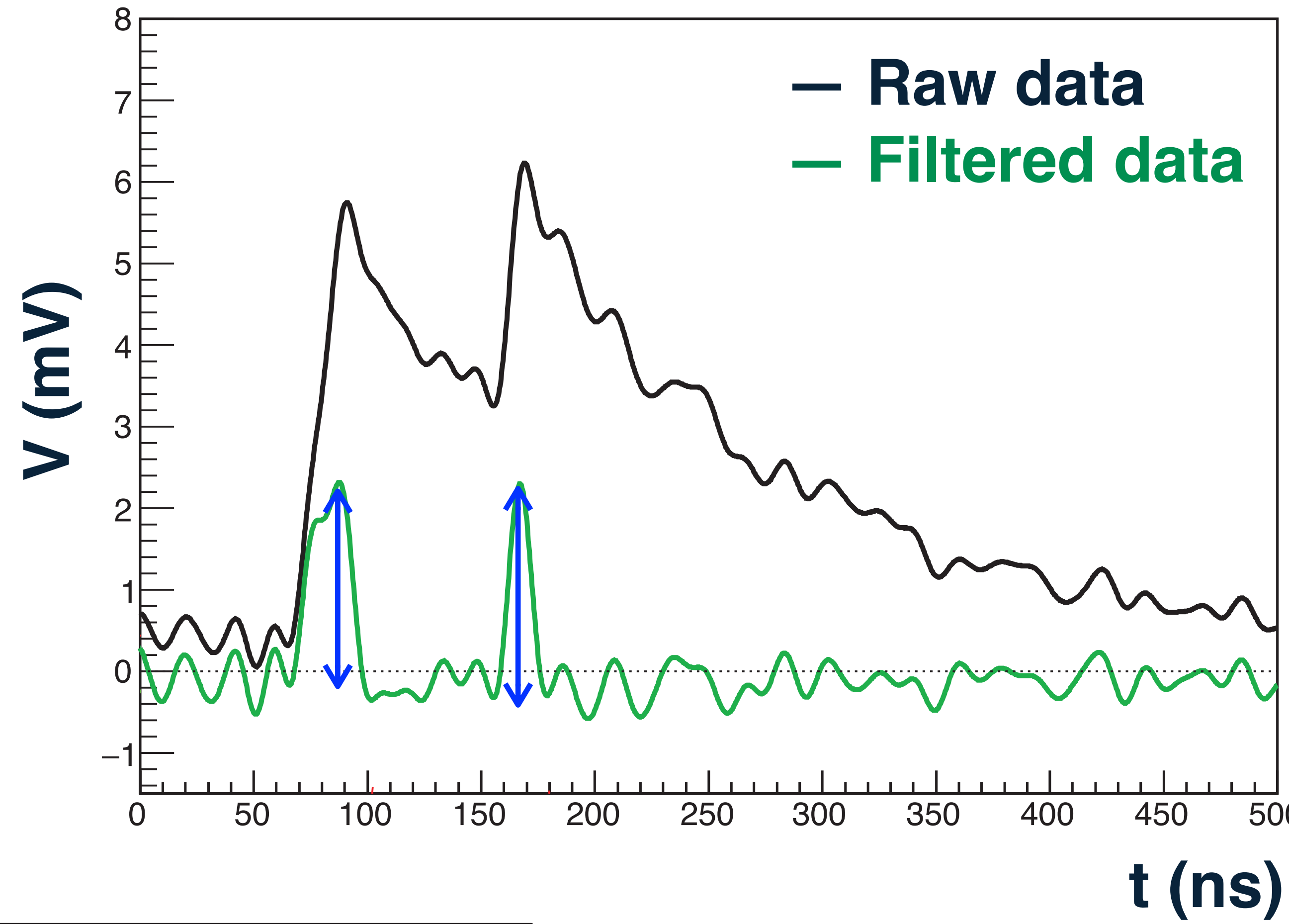
OCT Dependence on Device/Cell Sizes

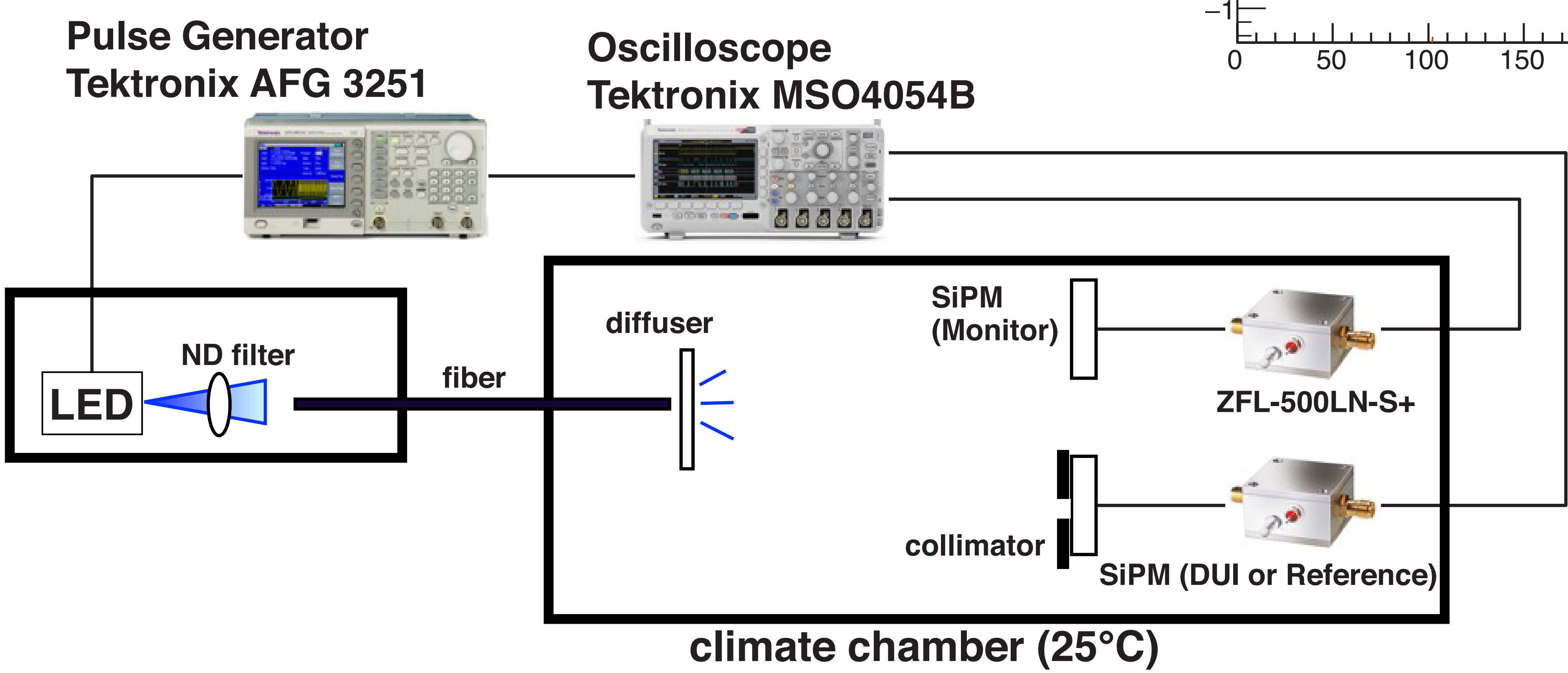
- We have systematically investigated the OCT rate with varying device size, cell size, and with and without coating
  - OCT rate is expected to be proportional to the number of electron-holes pairs (=charge) produced in an avalanche
    - proportional to a product of [cell capacitance] and [over voltage]
  - 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
    - Pulse analysis
- Light output is monitored
- Wavelength is fixed at 405 nm for this measurement

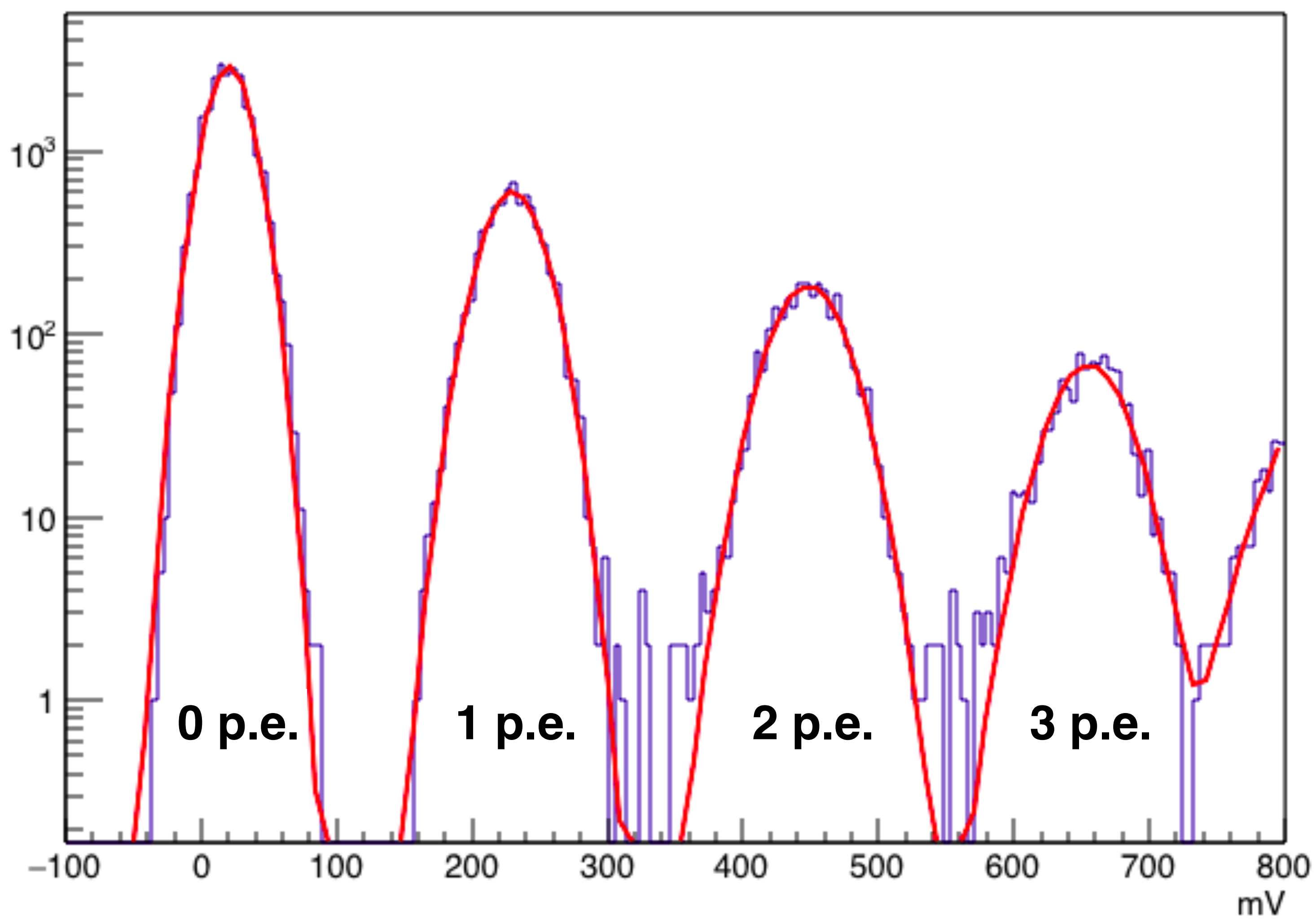




PDE Measurements

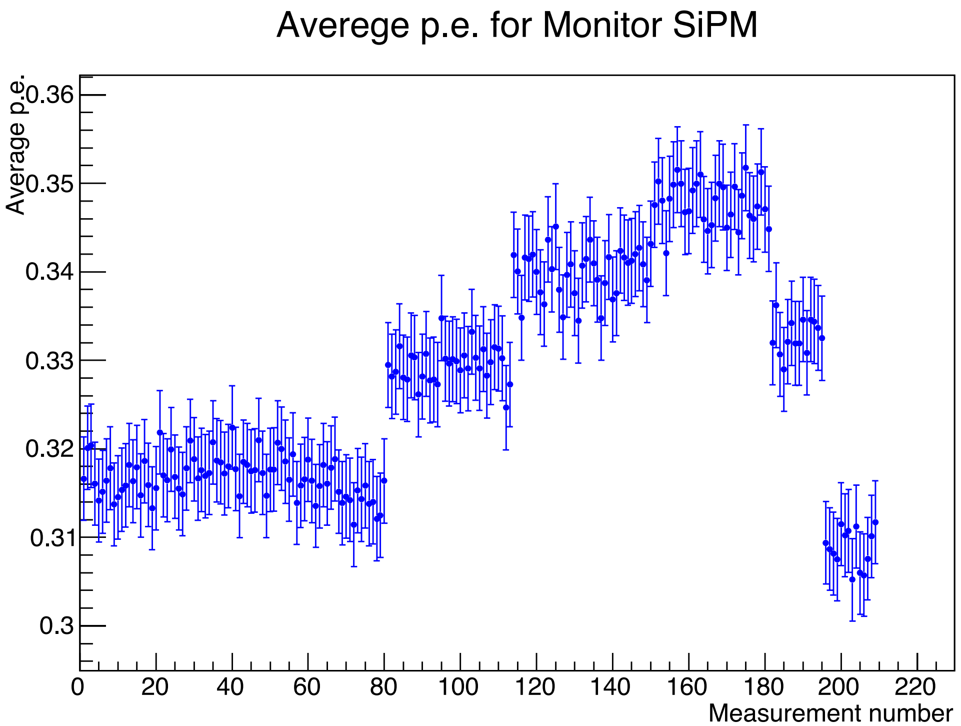
- We measure number of photons for short LED (or laser) pulses
  - Current measurement does not provide accurate PDE due to optical crosstalk, delayed cross talk and after pulse
- Number of photo electrons (p.e.) does not follow Poisson distribution due to optical crosstalk
  - Probability of 0 p.e.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

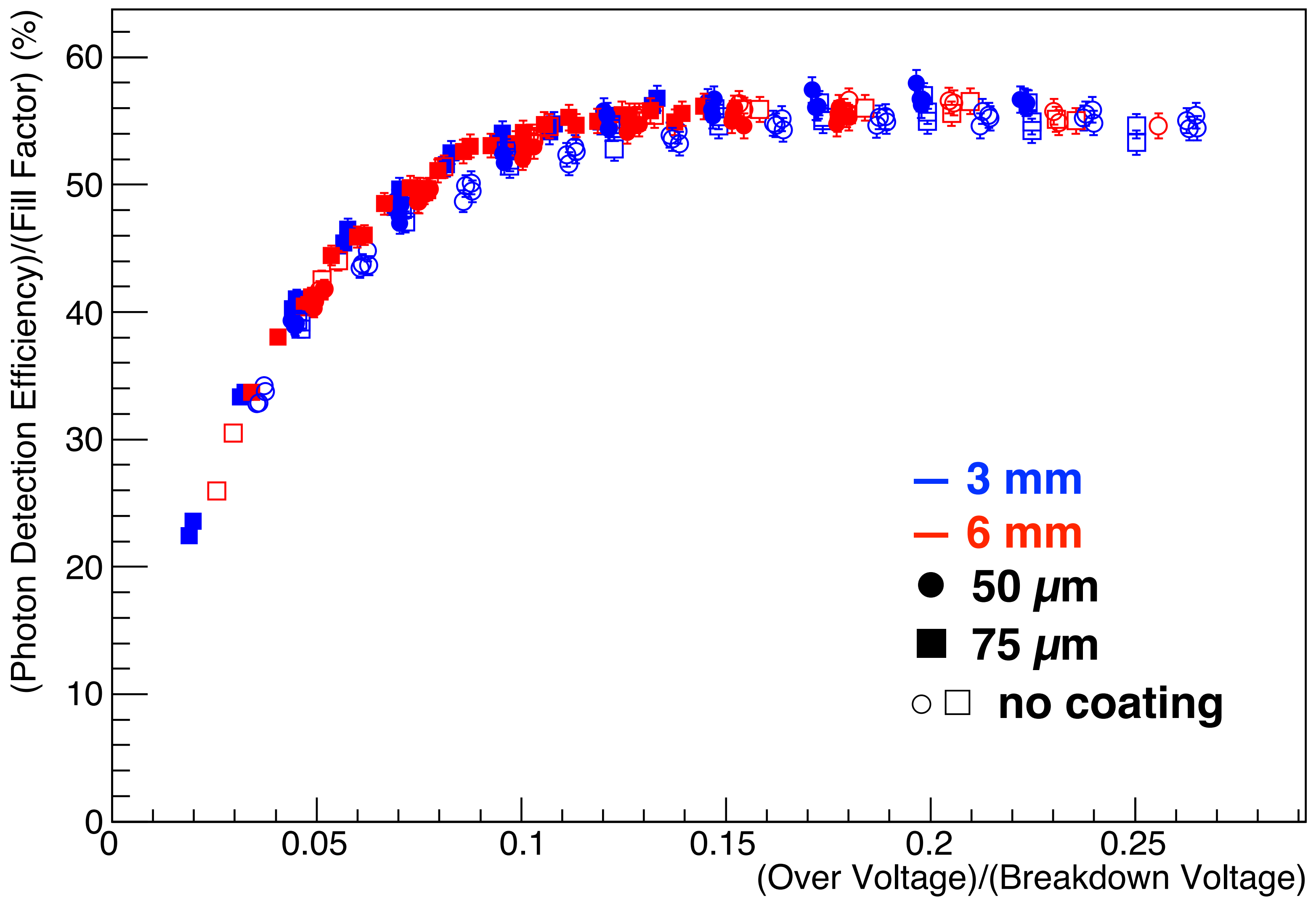
$$P(n) = e^{-\mu}\mu^n/n!$$
$$P(0) = e^{-\mu}$$
$$\mu = -\ln(P(0))$$
$$P_{\mathrm{true}}(0) = P_{\mathrm{ON}}(0)/P_{\mathrm{OFF}}(0)$$



PDE vs Relative Over Voltage

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





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)**

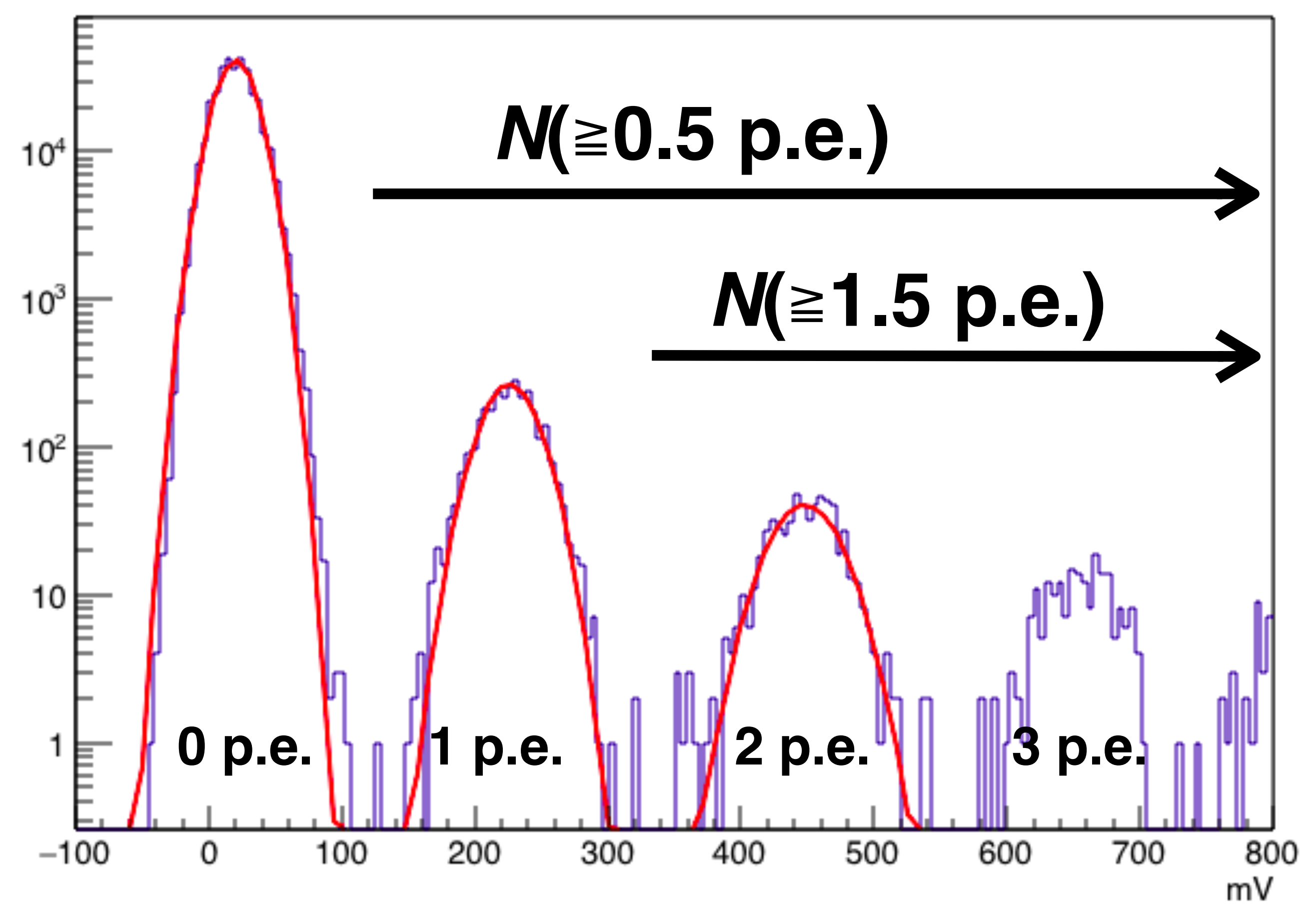
Probability to have no optical crosstalk

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

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



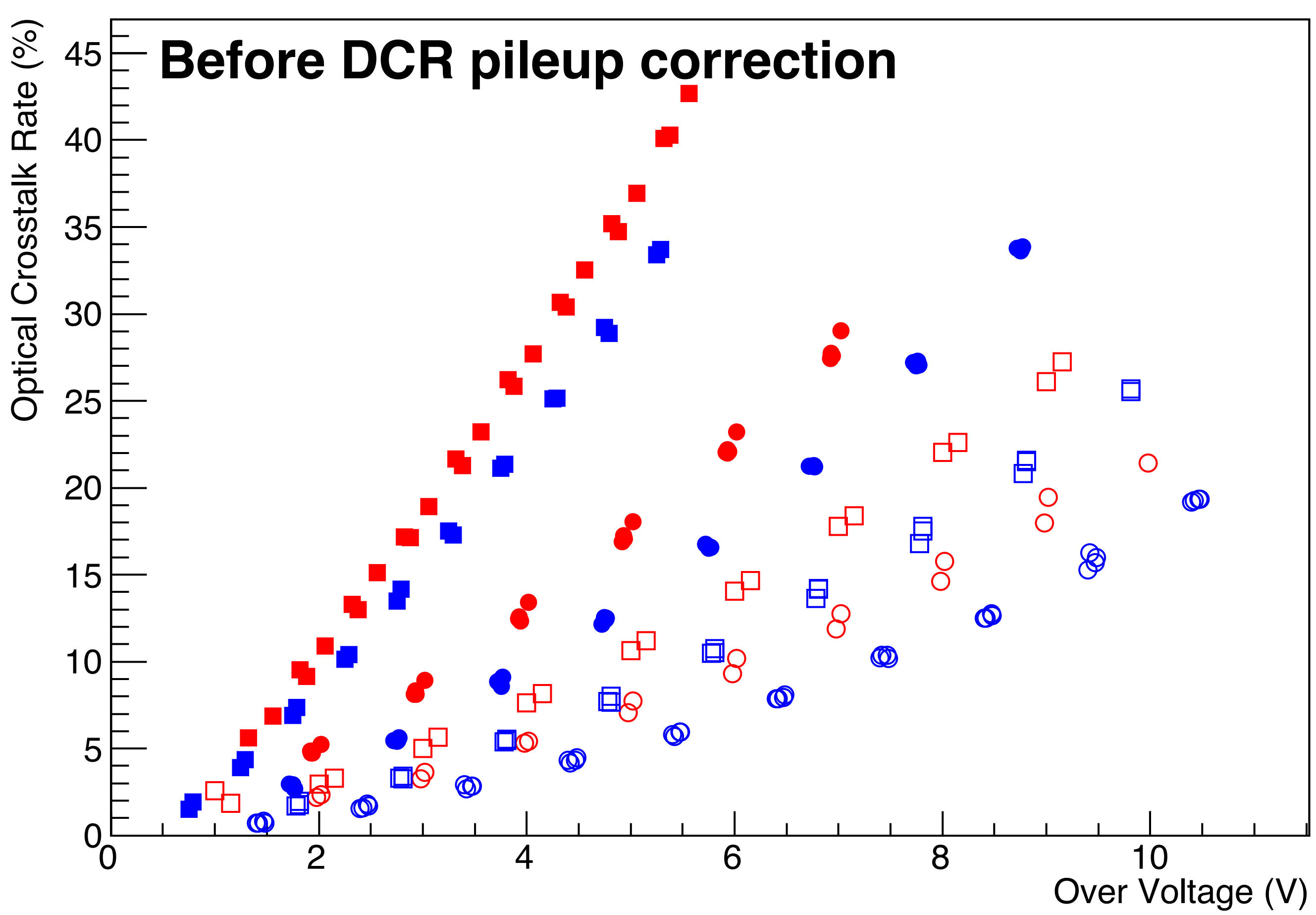
cta cherenkov telescope array

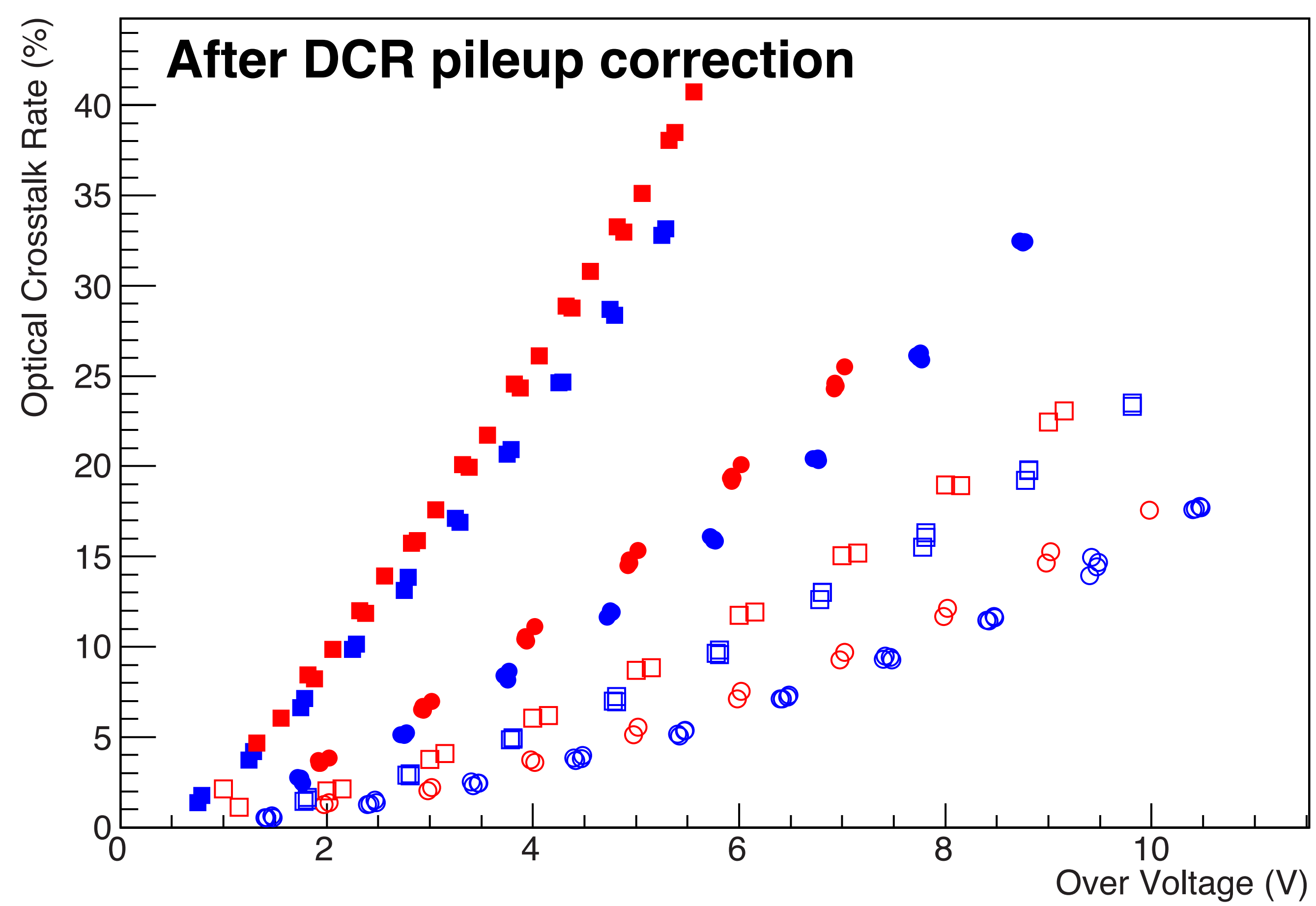
Crosstalk Rate vs. Over Voltage

ISEE Institute for Space-Earth Environmental Research

- ❖ **Dark count pileup correction works well**
- ❖ **Factor out cell capacitance dependence of crosstalk rate by scaling it with cell area and depth (assuming cell depth ∝ break down voltage)**
  - ✤ **3 mm device gives slightly lower OCT than 6 mm device**
  - ✤ **OCT rate scales very well with cell capacitance with coating**
    - ✦ **Not so without coating**
  - ✤ **Differences among individual SiPMs are small**

— 3 mm
— 6 mm
● 50 μm
■ 75 μm
○ □ no coating





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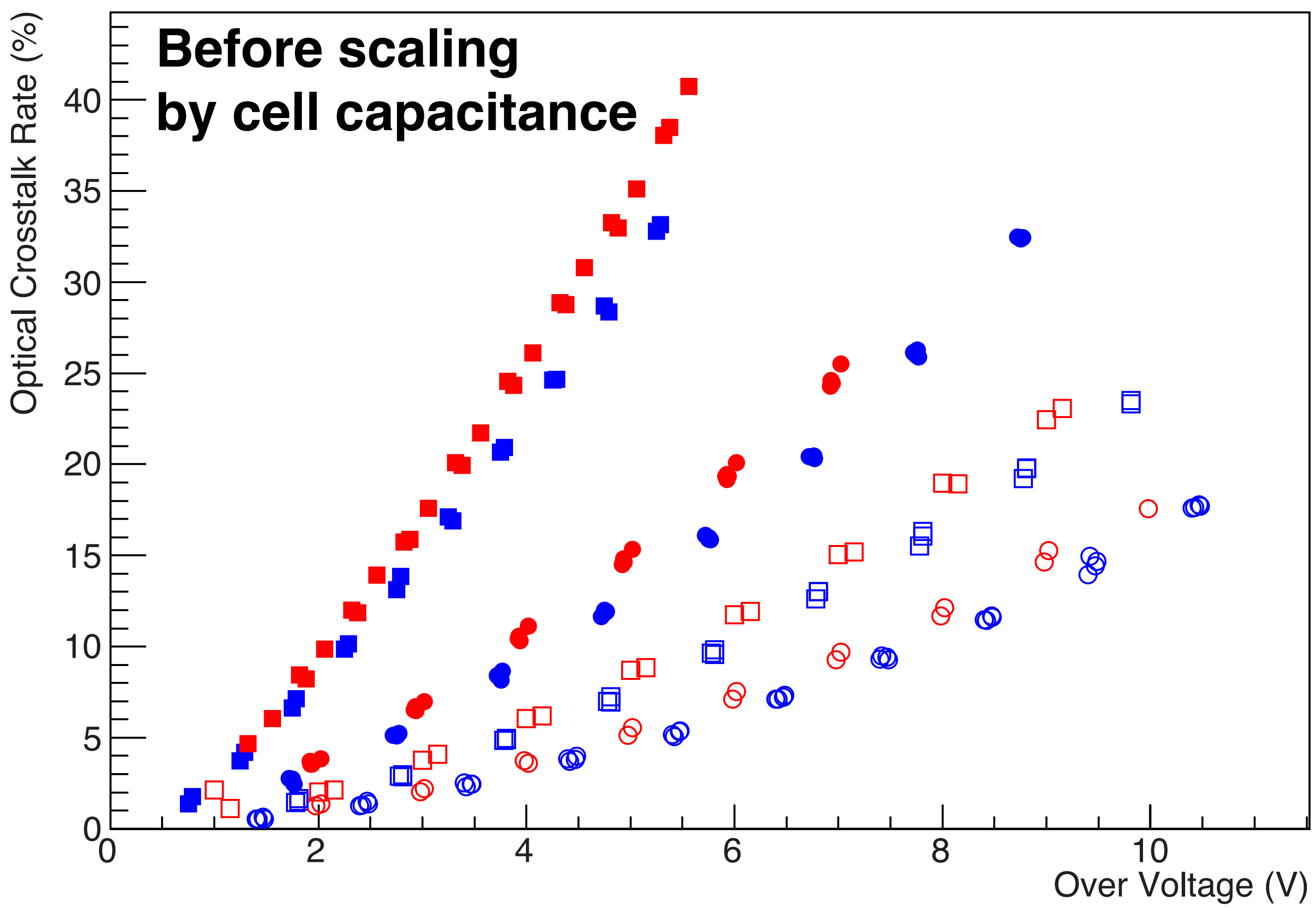
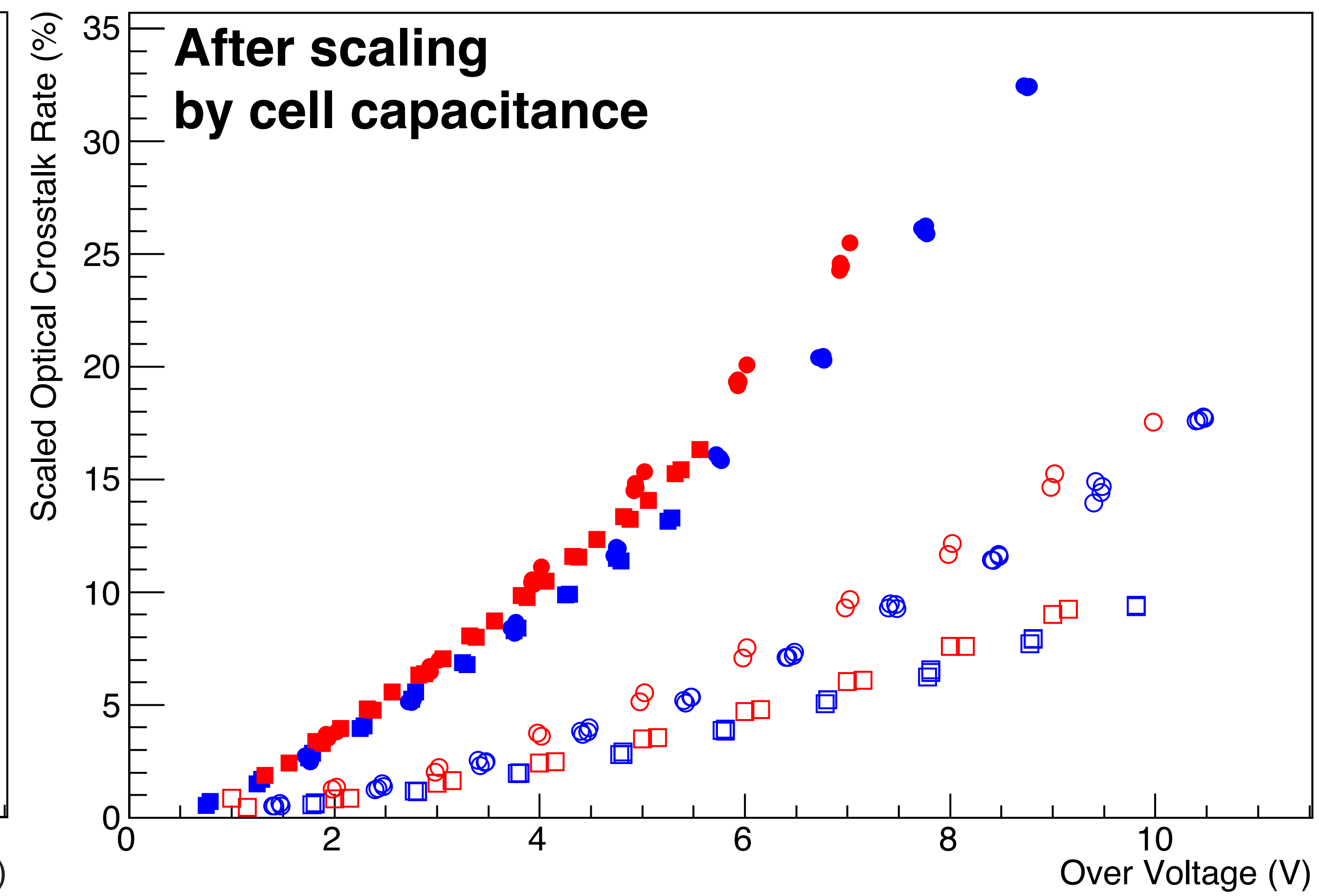




Fit to Otte Function

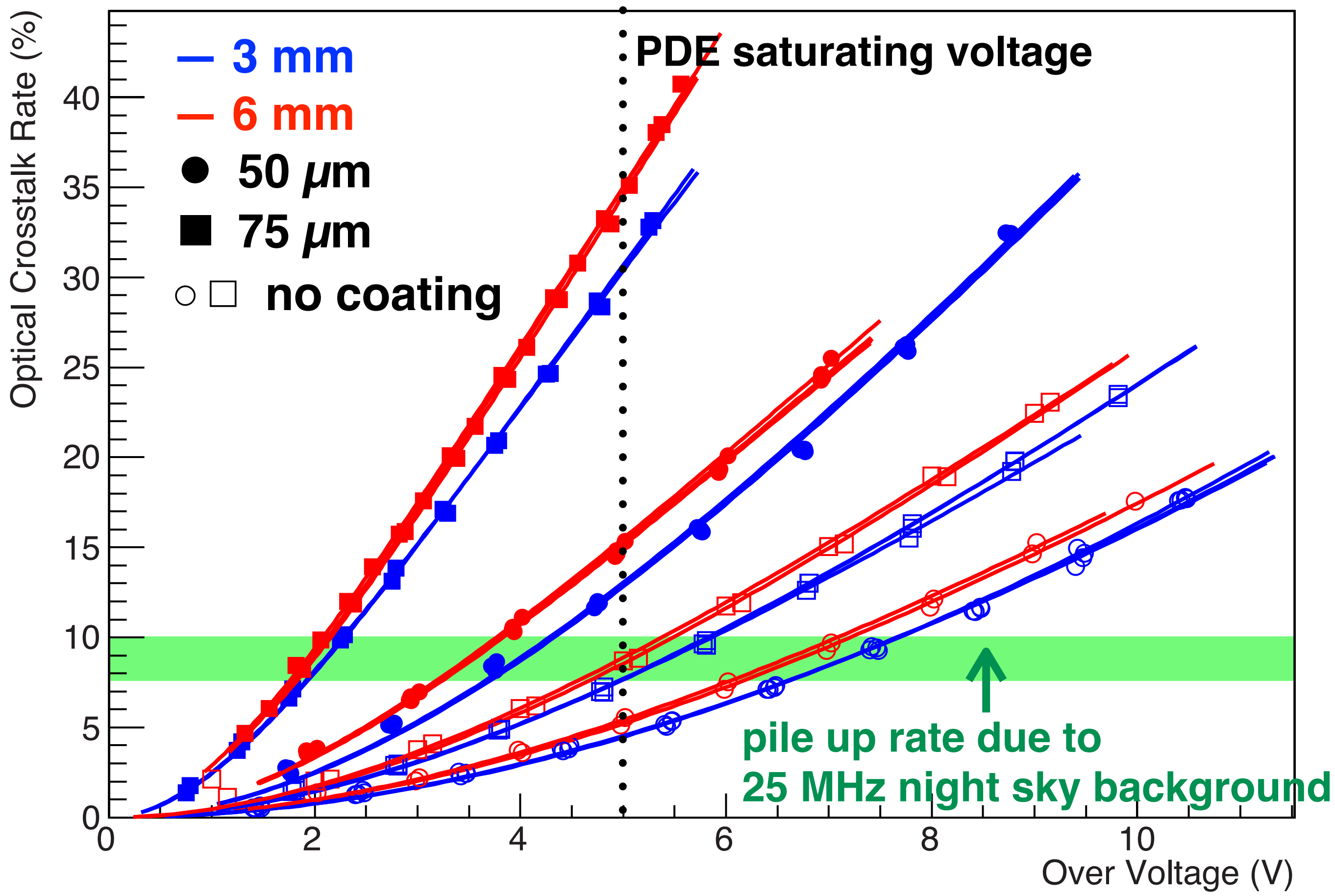
❖ **Optical crosstalk rate should proportional to the charge produced in the avalanche and avalanche trigger probability**

$$R_{\mathrm{OCT}} = C_{\mathrm{OCT}} \cdot \boxed{(\mathrm{Fill\ factor}) \cdot (\mathrm{Cell\ size})^2 / V_{\mathrm{BR}}} \cdot V_{\mathrm{OV}} \cdot \boxed{(1 - \exp[-C'_{\mathrm{Otte}} V_{\mathrm{OV}} / V_{\mathrm{BR}}])}$$

∝ cell capacitor — Avalanche probability

- **C_{OCT} is smaller for 75 μm cells (smaller crosstalk efficiency)**
- **C_{Otte} is smaller without coating**
  - **Avalanche seed is produced in the region where it is harder to trigger avalanche**

Product ID	C_{OCT}	C_{Otte}
S14520-3050VS	0.1	5
S14520-6050VS	0.09	10
S14520-3075VS	0.06	18
S14520-6075VS	0.07	17
S14520-3050VN	0.09	2
S14520-6050VN	0.07	3
S14520-3075VN	0.03	5
S14520-6075VN	0.03	5



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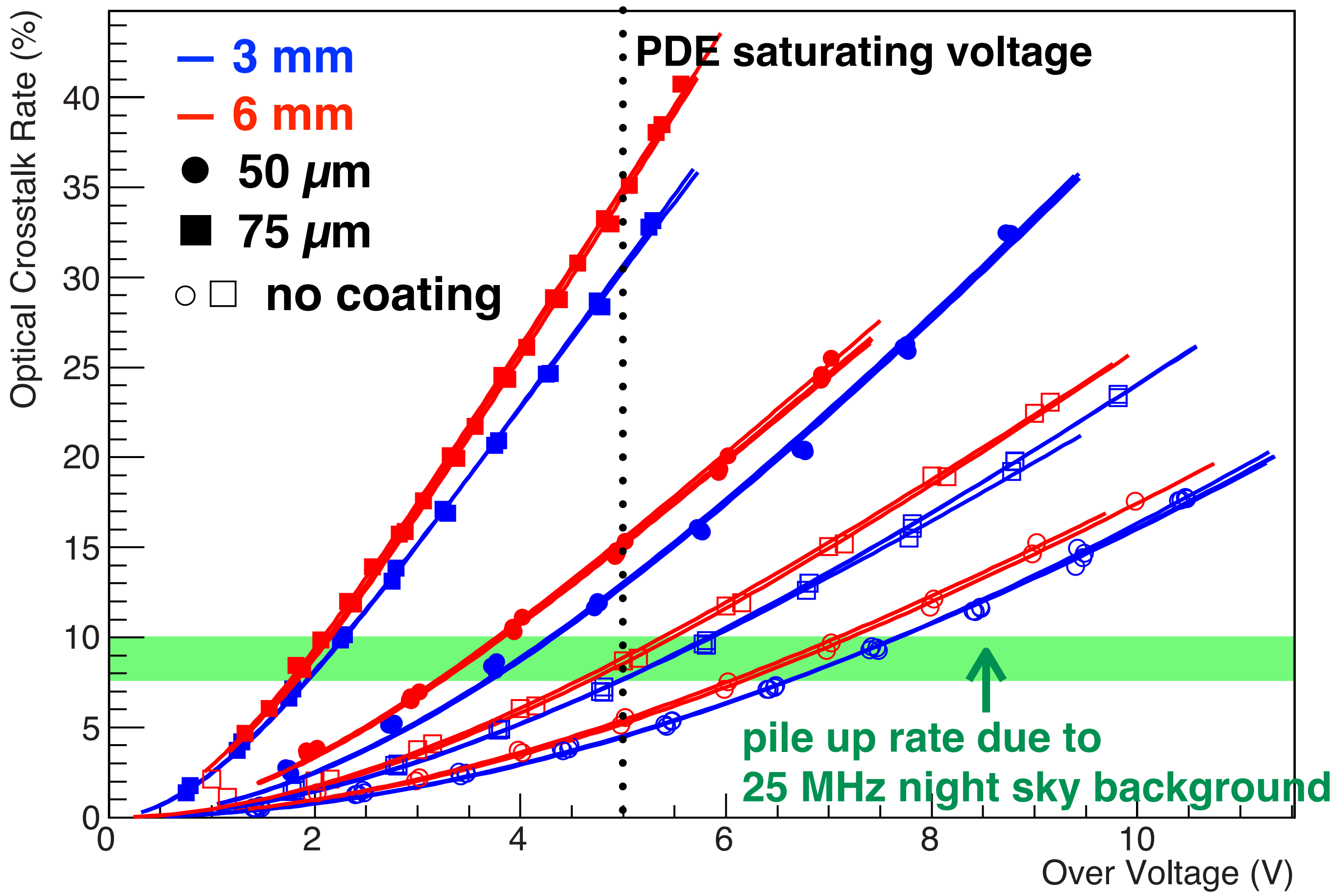
S14520-6075VN	0.03	5



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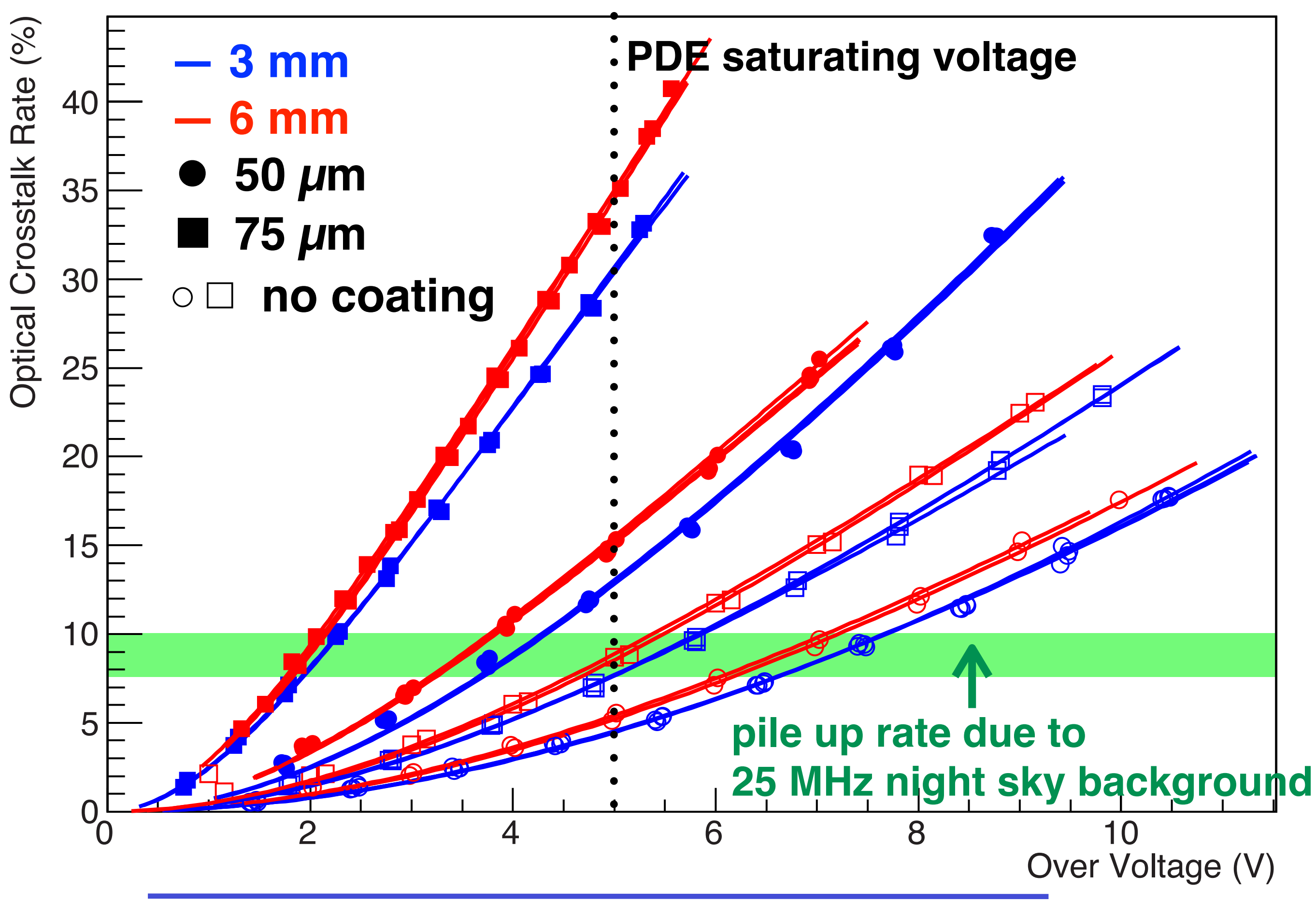

Summary

- Optical crosstalk rate is significantly affected by protection coating
  - Smaller device size and thicker coating reduce OCT rate
  - Larger cell size increase OCT rate, but not proportional to the cell area
  - No coating significantly reduces OCT rate
    - OCT rate does not scale with the cell size
    - OCT seeds are produced in the region where avalanche trigger probability is low
- Prospects
  - 6 mm device with 75 μm cell without coating may be the best choice for CTA
    - Without protective coating, damages on the SiPM surface are of major concerns
      - We put a piece of protective film to avoid damages during the assembly handling
      - Damages during observations can be avoided by the UV transparent shield on the camera front
        This shield will also act as a filter for red lights.)
  - Further reduction of OCT
    by suppressing crosstalk due to photons reflected at the backside of SiPM