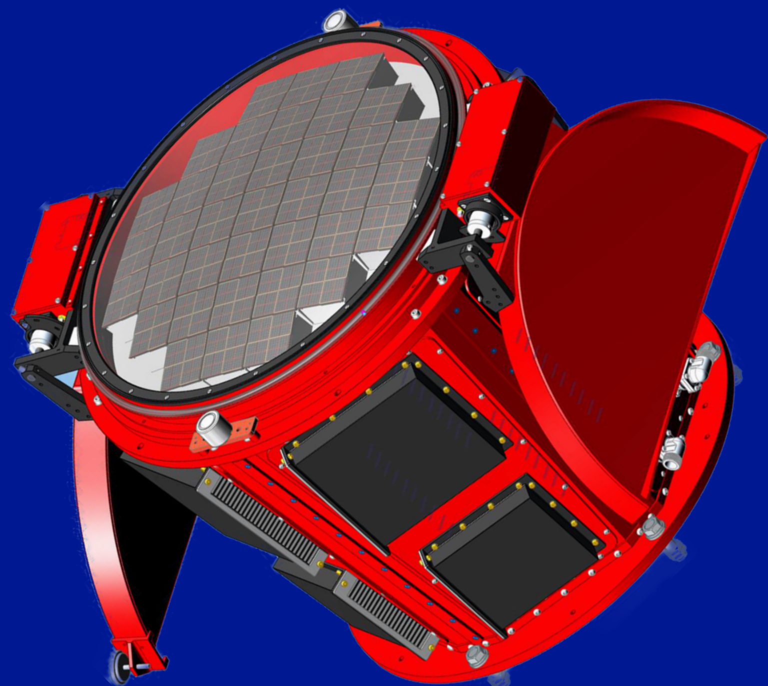
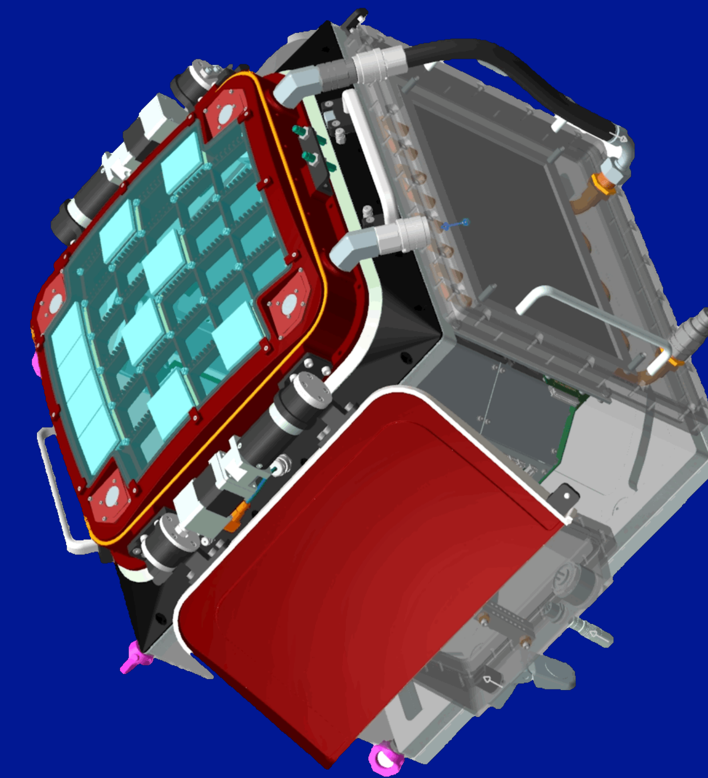




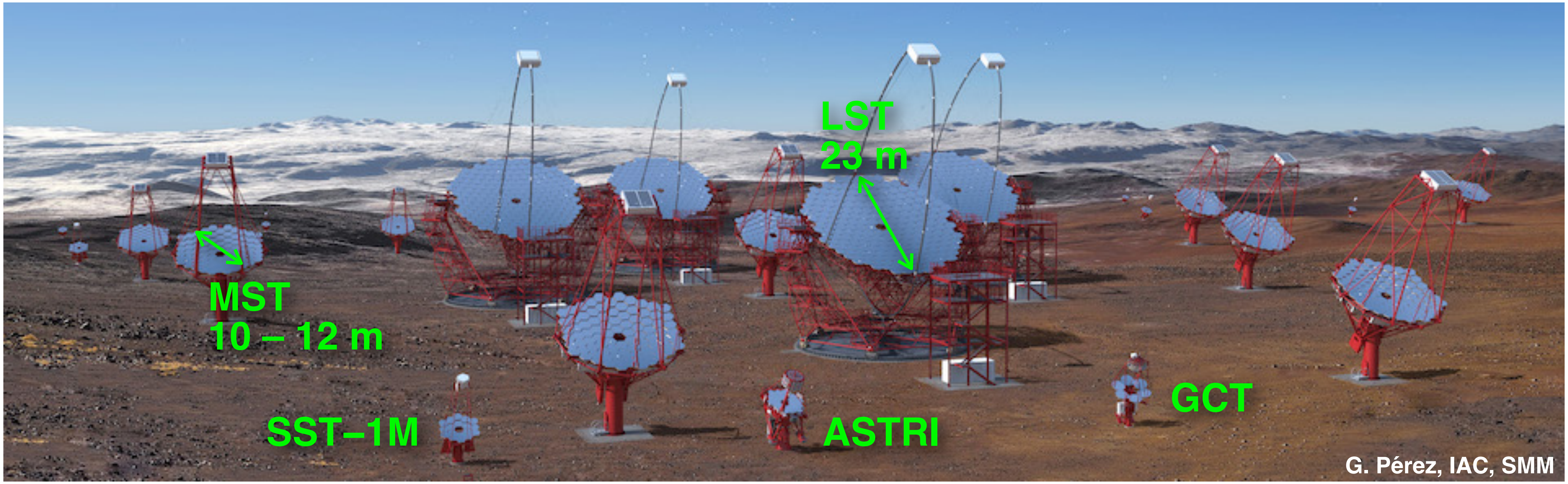
Suppressing Optical Cross Talk in Silicon Photomultipliers

Hiro Tajima, Akira Okumura, Naoya Hidaka, Yuki Nakamura, Nobuhito Yamane, Anatolii Zenin,
Nagoya University (for the CTA Consortium)

International Conference on the Advancement of Silicon Photomultipliers
Schwetzingen, Germany, June 11–15, 2018

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



CTA SST Telescopes

- SST-1M (single mirror)
  - Czech Republic, Ireland, Poland, Swiss
- SST-2M (dual mirror)
  - Astrofisica con Specchi a Tecnologia Replicante Italiana (ASTRI)
    - Italy, Brazil, South Africa
  - Gamma-ray Cherenkov Telescope (GCT)
    - Australia, France, Germany, Japan, Netherlands, UK
- Cost per pixel is more relevant than cost per area in SSTs

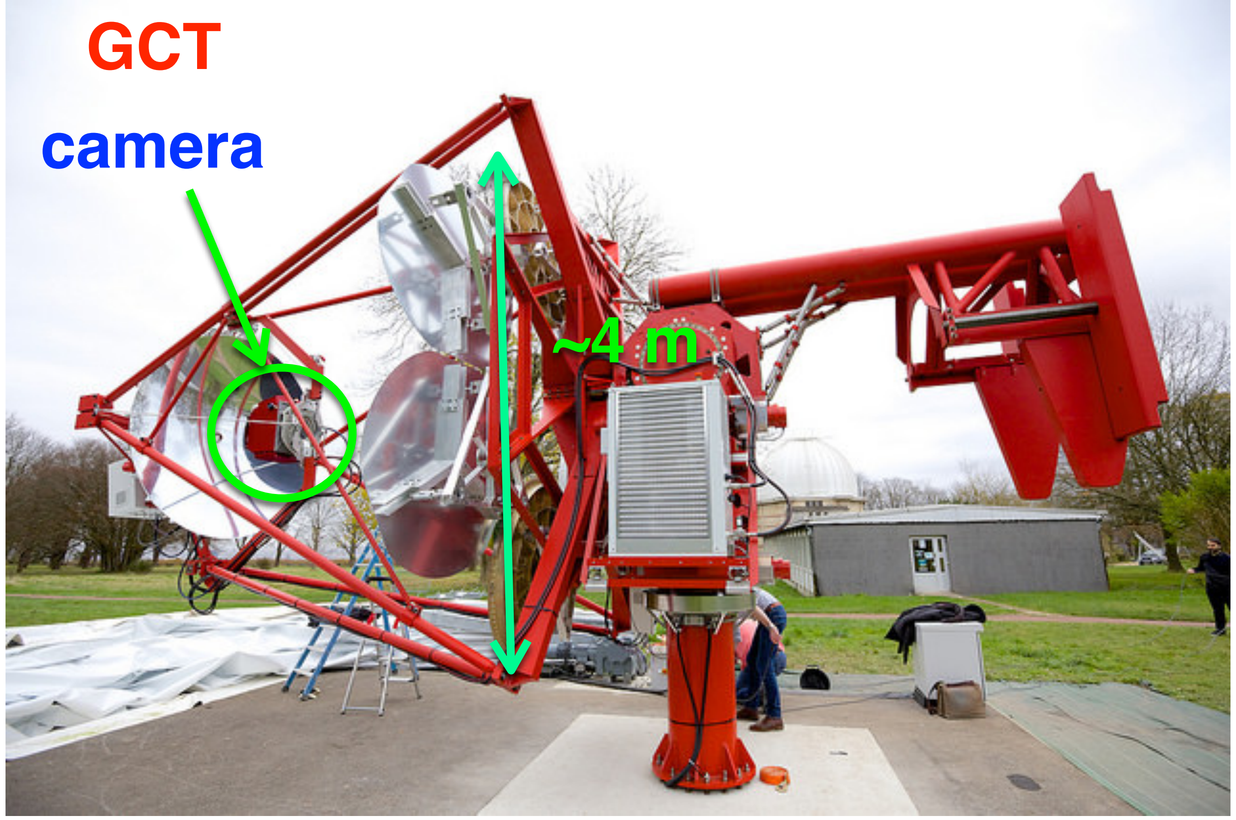
ASTRI

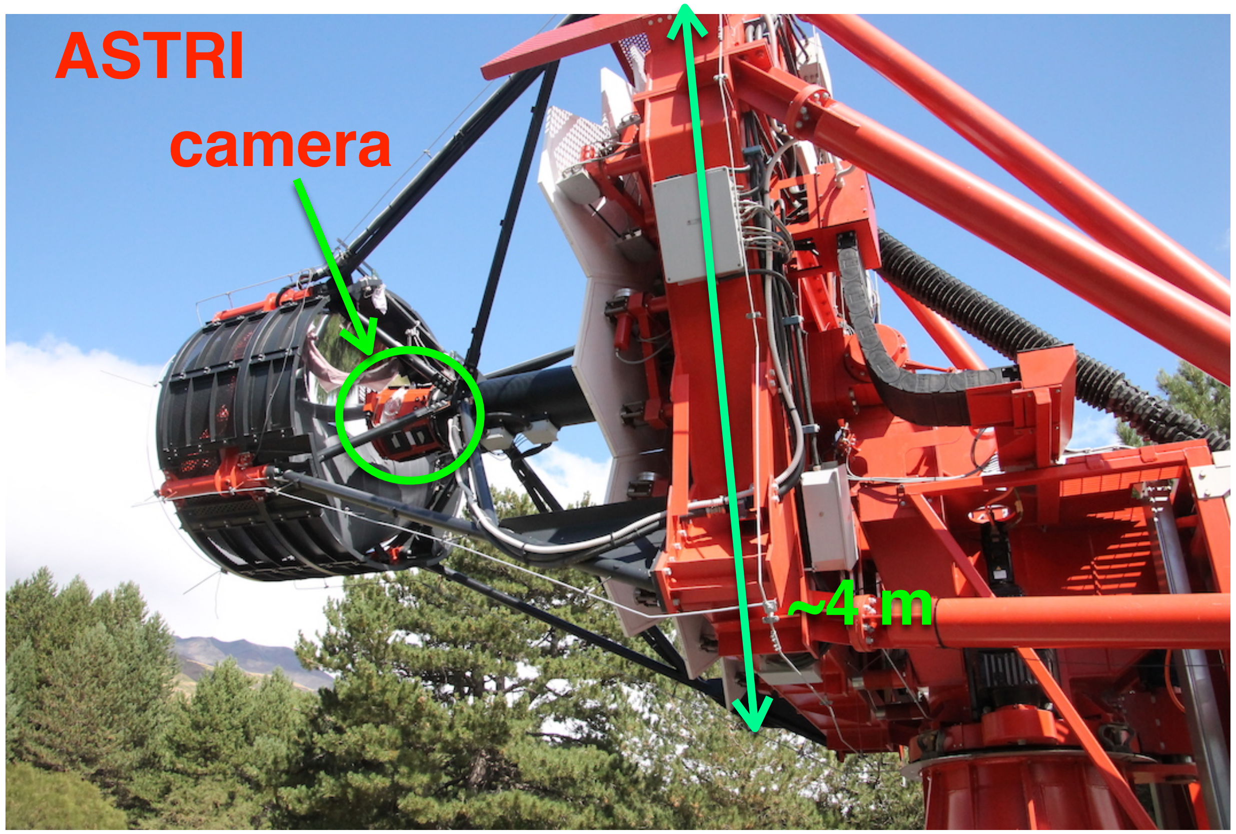
GCT

SST-1M

Dual Mirror SST Design Concept

- Dual mirror design allowing use of compact camera
  - Schwarzschild-Couder (SC) optics
    - Short focal length to realize small plate scale (small camera, pixel)
    - Large field of view
      - Greater telescope spacing (larger collection area)
    - Technically challenging
  - Small pixel (6–7 mm) photon sensor to reduce camera cost
    - Multi-anode photomultiplier (MAPMT) or Silicon Photomultiplier (SiPM)
    - High density readout electronics (ASIC)

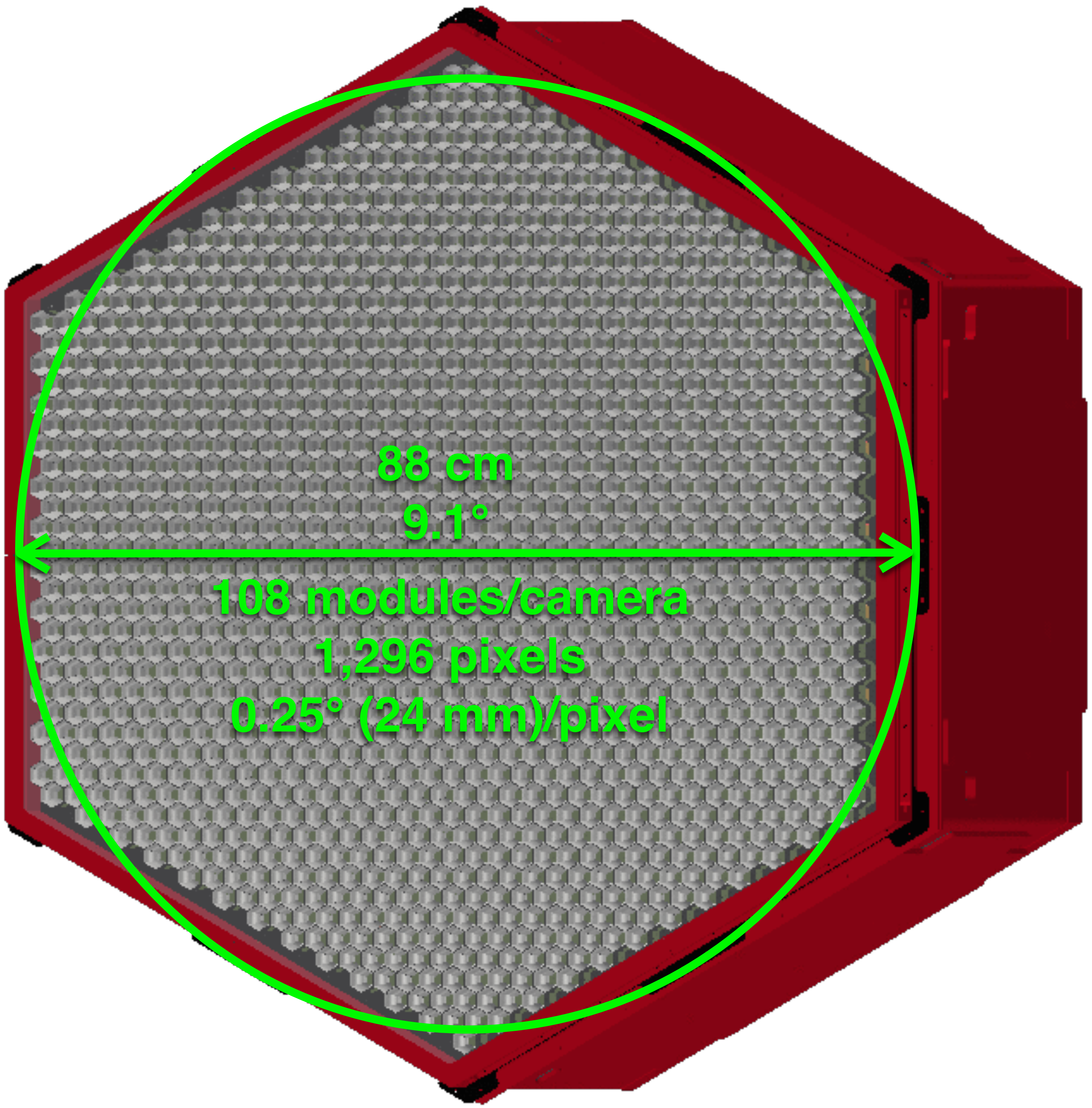




Comparison with Single-Mirror Camera

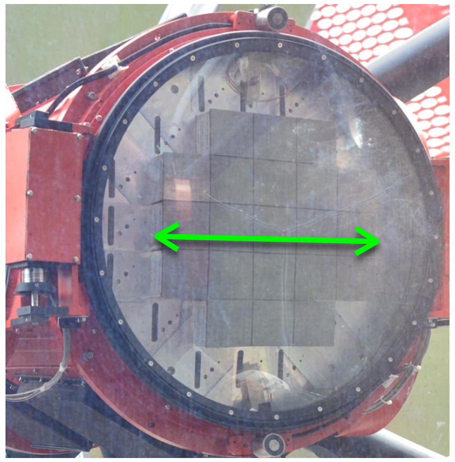
SST-1M camera

Total number of SiPM pixels > 100k



credit: SST-1M

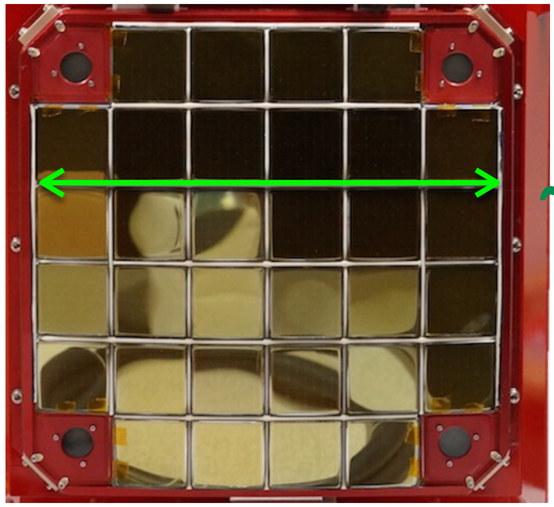
ASTRI camera



~50 cm
10.9°

37 modules/camera
2,368 pixels/camera
0.19° (7 mm)/pixel

GCT camera

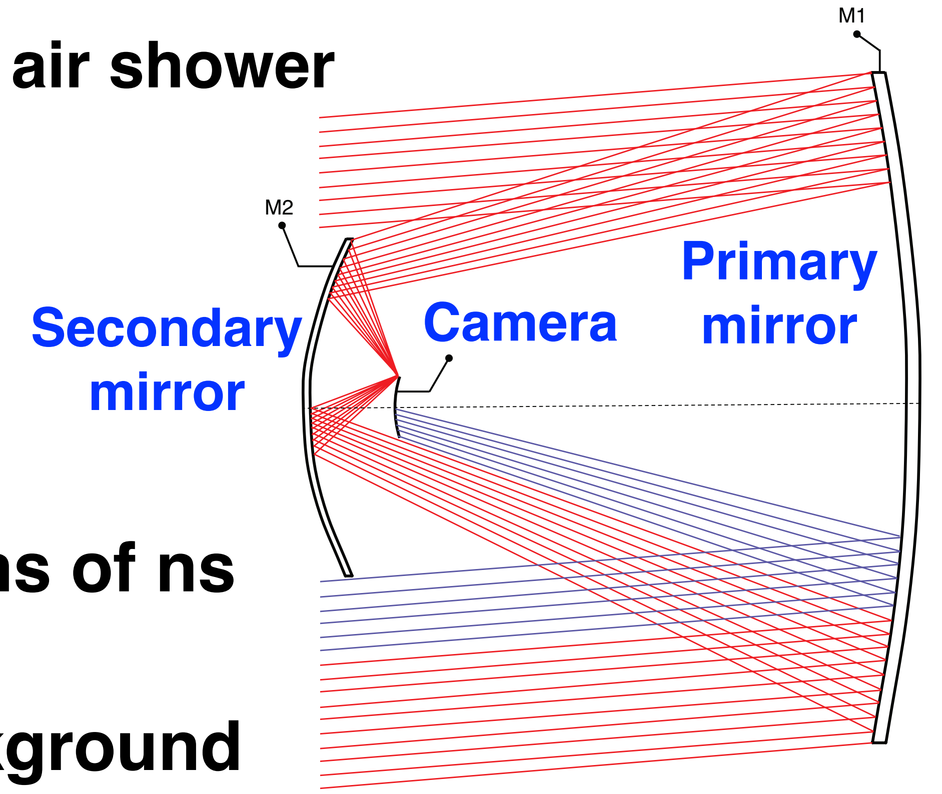


~35 cm
9.1°

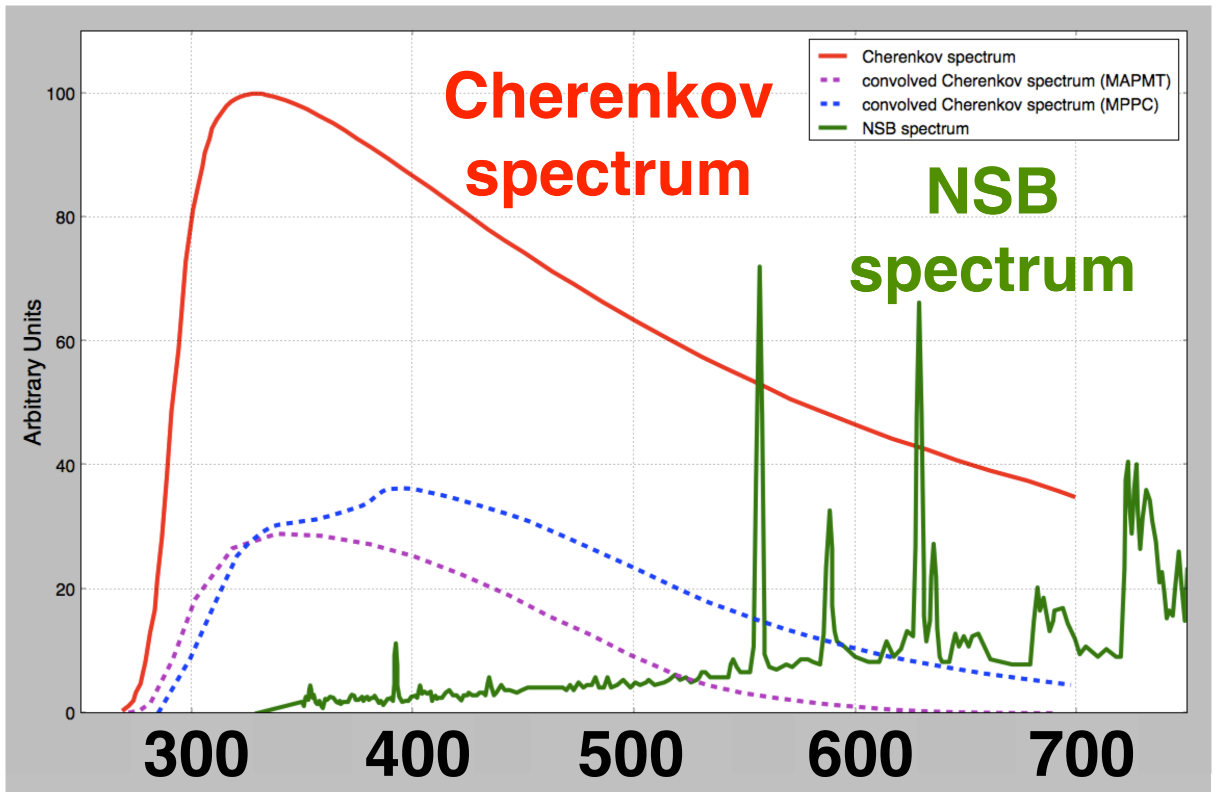
32 modules/camera
2,048 pixels/camera
0.15–0.18° (6–7 mm)/pixel

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
  - Angular range for incident photon is 30–60°
  - Cherenkov photons arrives within a few to few tens of ns
    - ns-timing is important

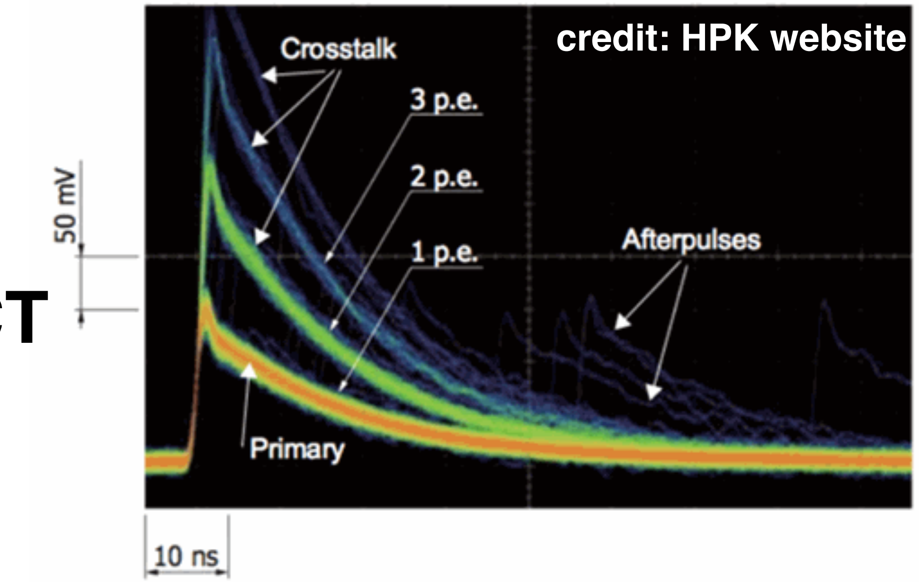


- Night sky background (NSB) is the dominant background
  - Rate is >25 MHz/pixel
    - Dark count rate is not very important
    - [NSB] x [Optical crosstalk (OCT)] can cause false triggers due to accidental coincidences
      - Low OCT rate is important
  - NSB peaks above 550 nm
    - Low red sensitivity is preferred
- Pixel size < 0.25 deg is required to obtain good angular resolution of air showers
  - Pixel size ~ 6 mm with 4-m telescope

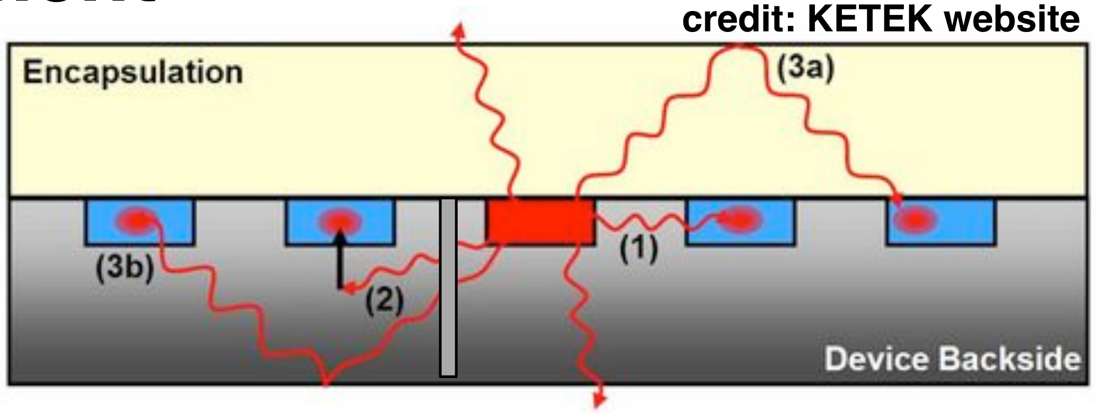


Photon Sensor

- ❖ **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)

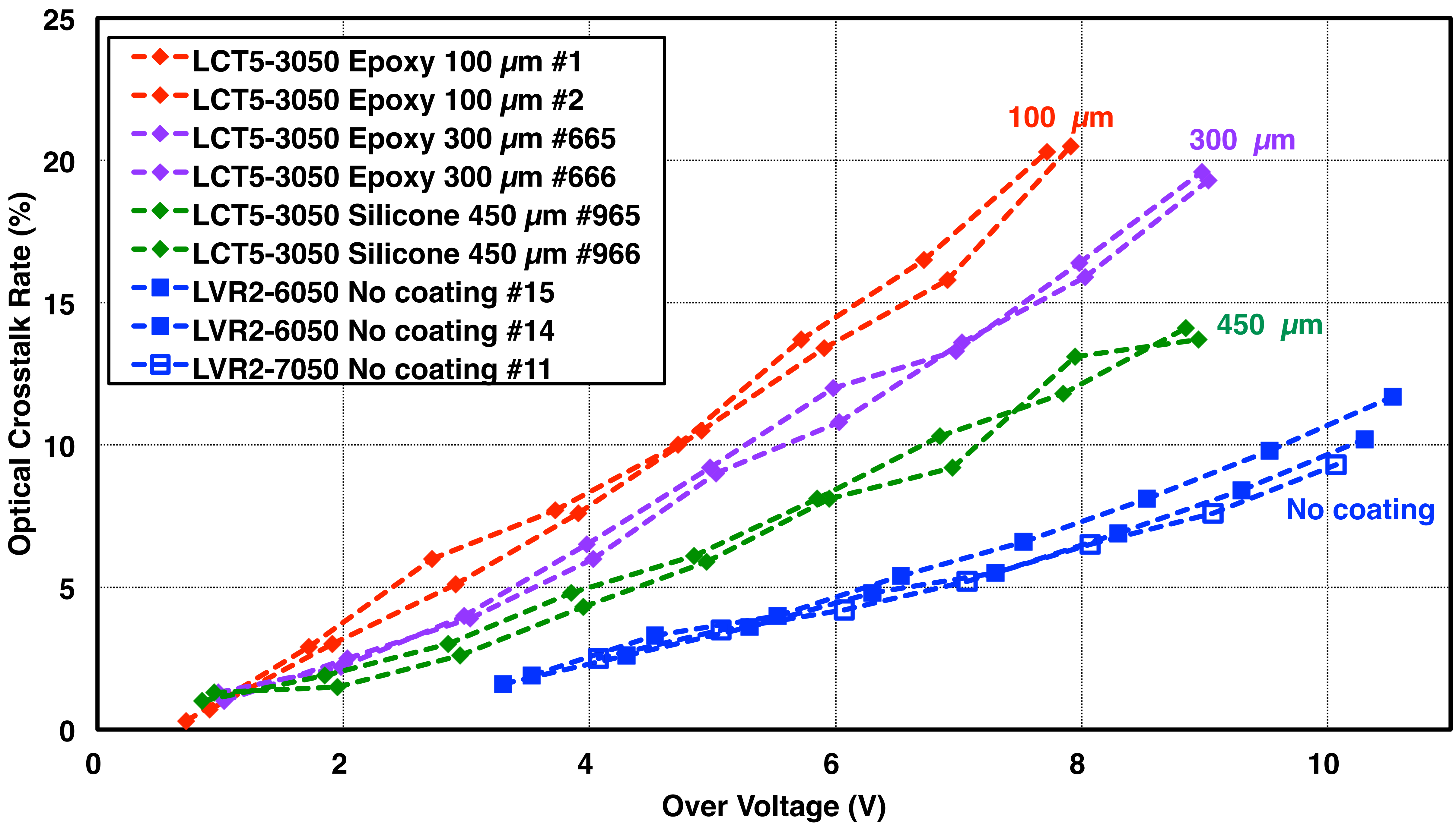


credit: KETEK website



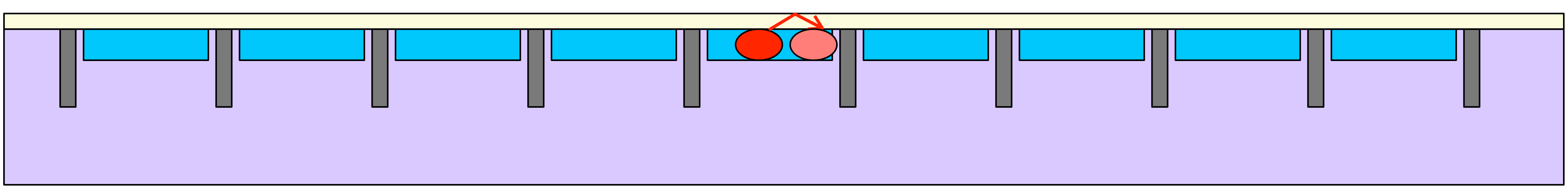
Summary of Past Studies

❖ **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 reflection at the backside?



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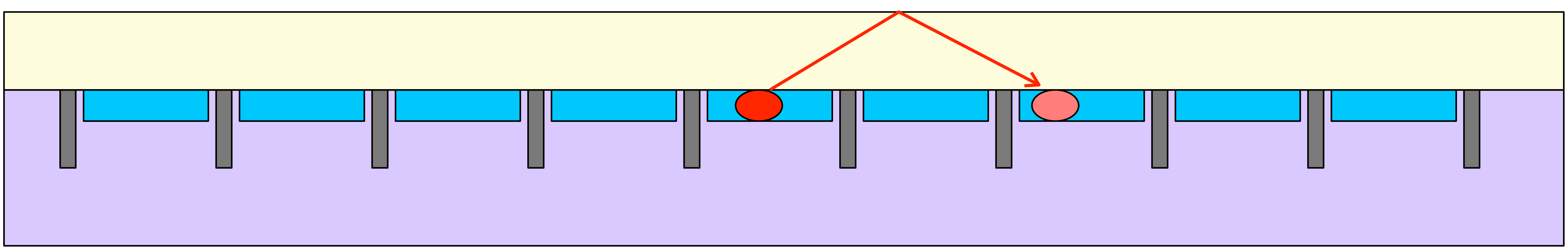

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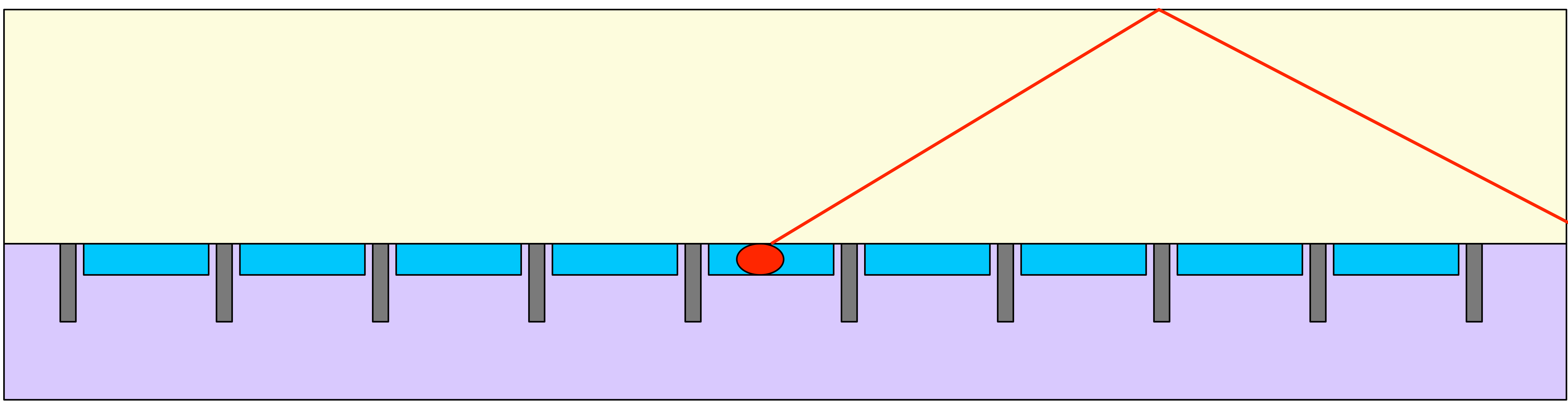

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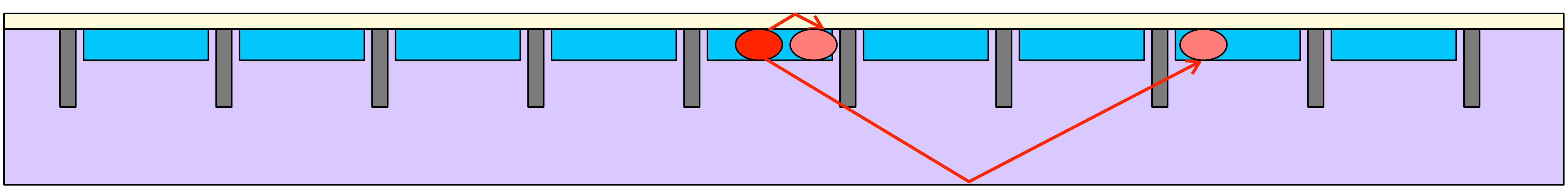


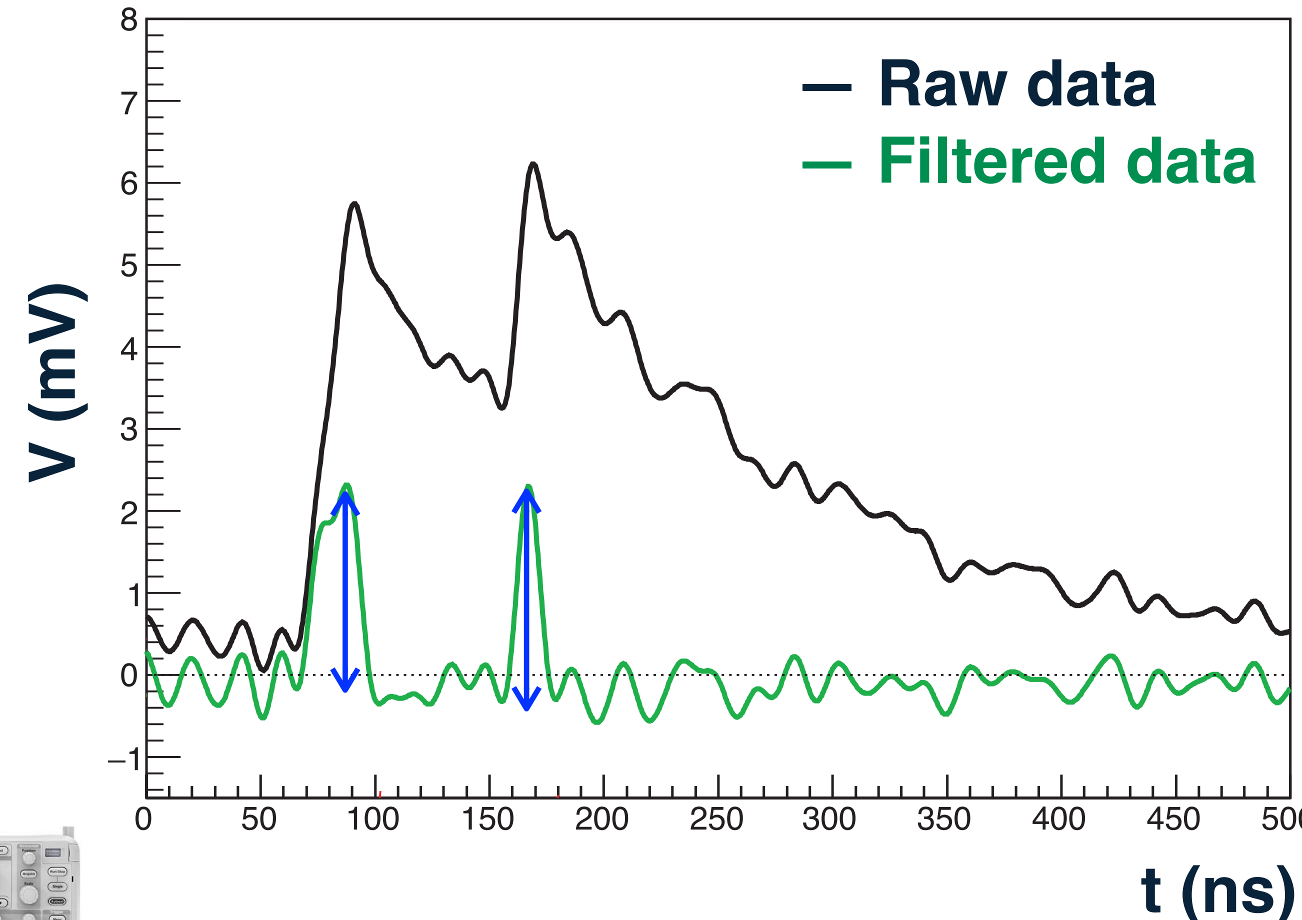
OCT Dependence on Device/Cell Sizes

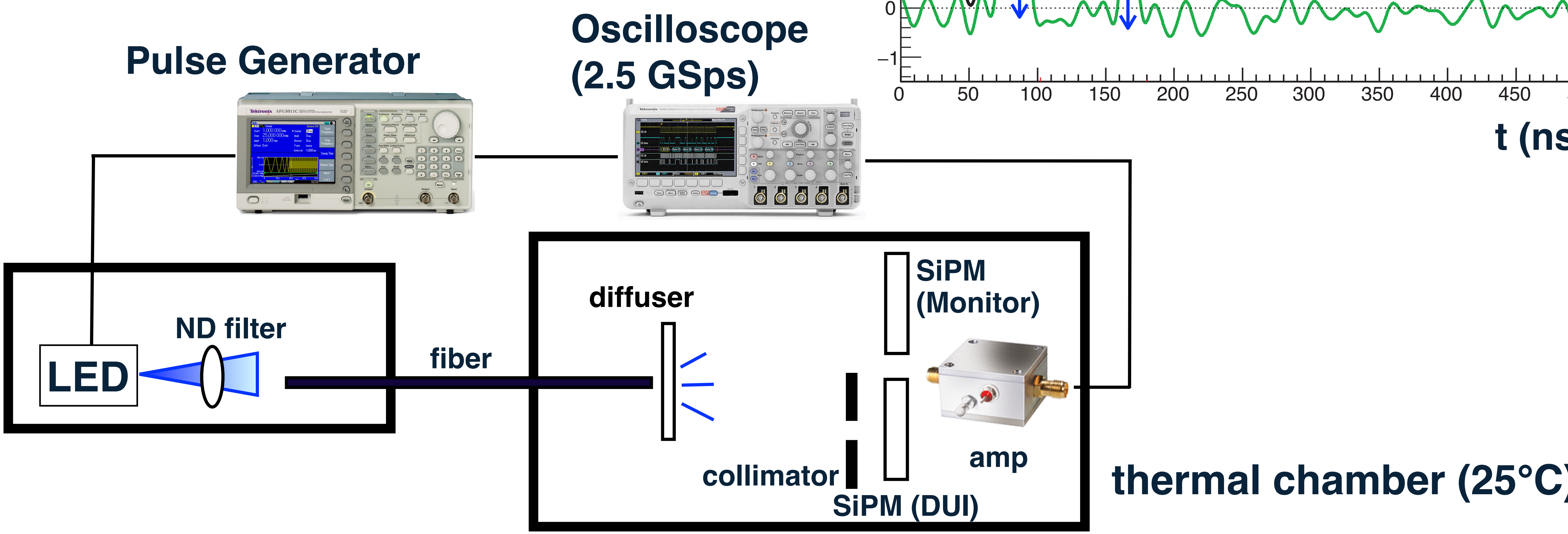
- ❖ We have systematically investigated the OCT rate with varying device size, cell size, and with and without coating
  - ✤ Find out propagation properties of crosstalk photons

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

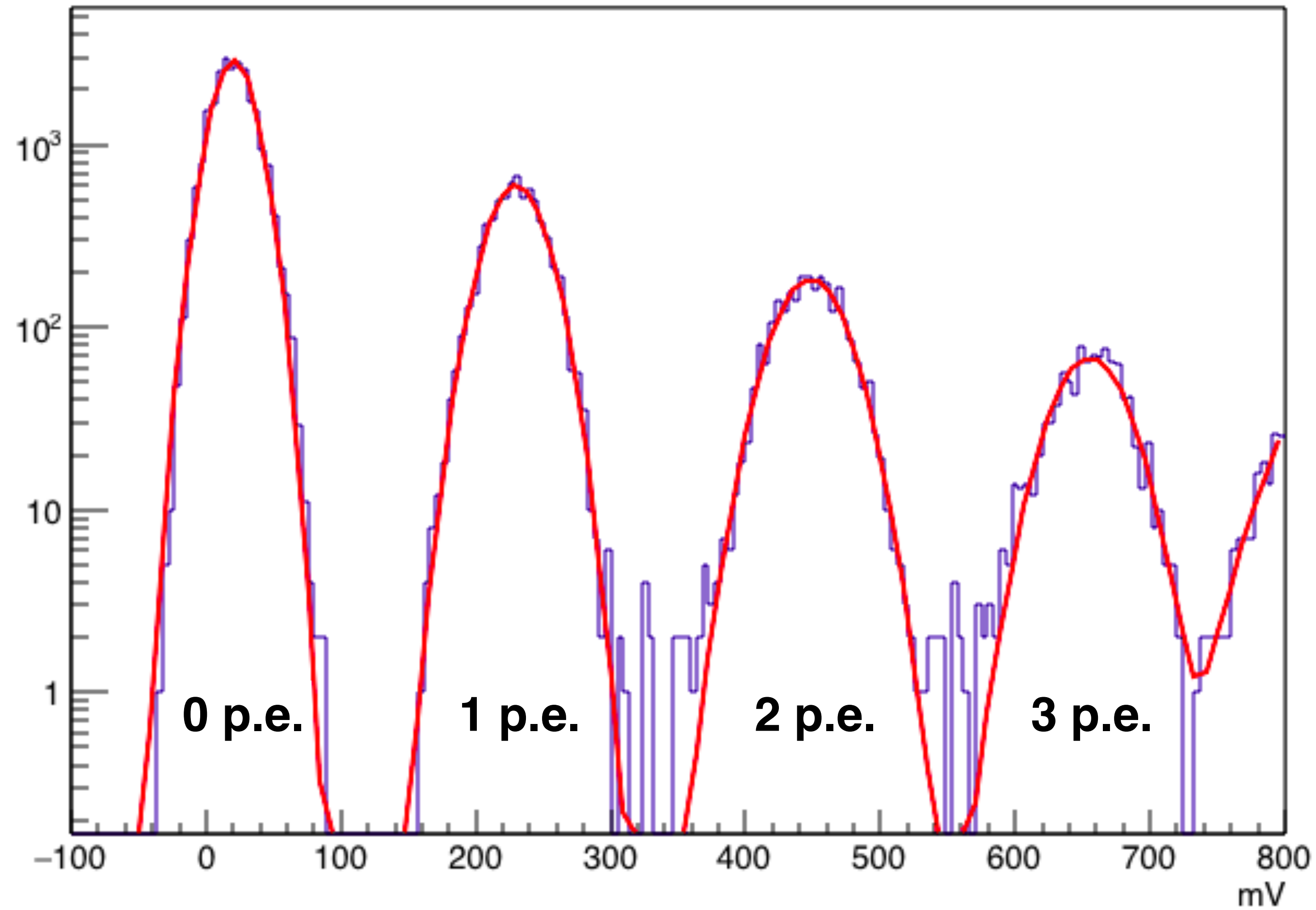
- We measure number of photons for short LED (or laser) pulses
  - Current measurement does not provide accurate PDE due to optical crosstalk, delayed cross talk and after pulse
- Number of photo electrons (p.e.) does not follow Poisson distribution due to optical crosstalk
  - Probability of 0 p.e.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

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

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

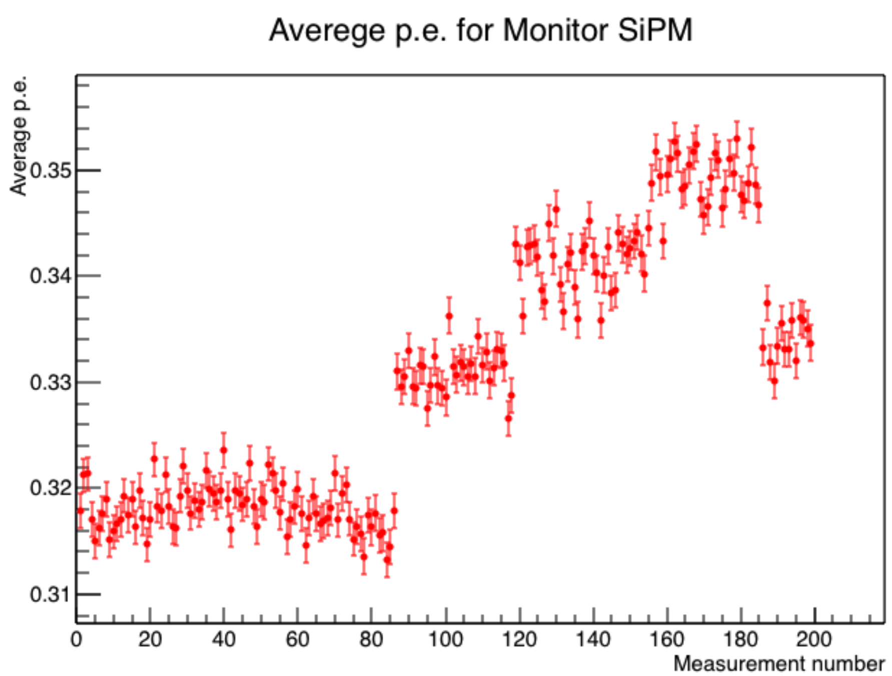
$$\mu = -\ln(P(0))$$

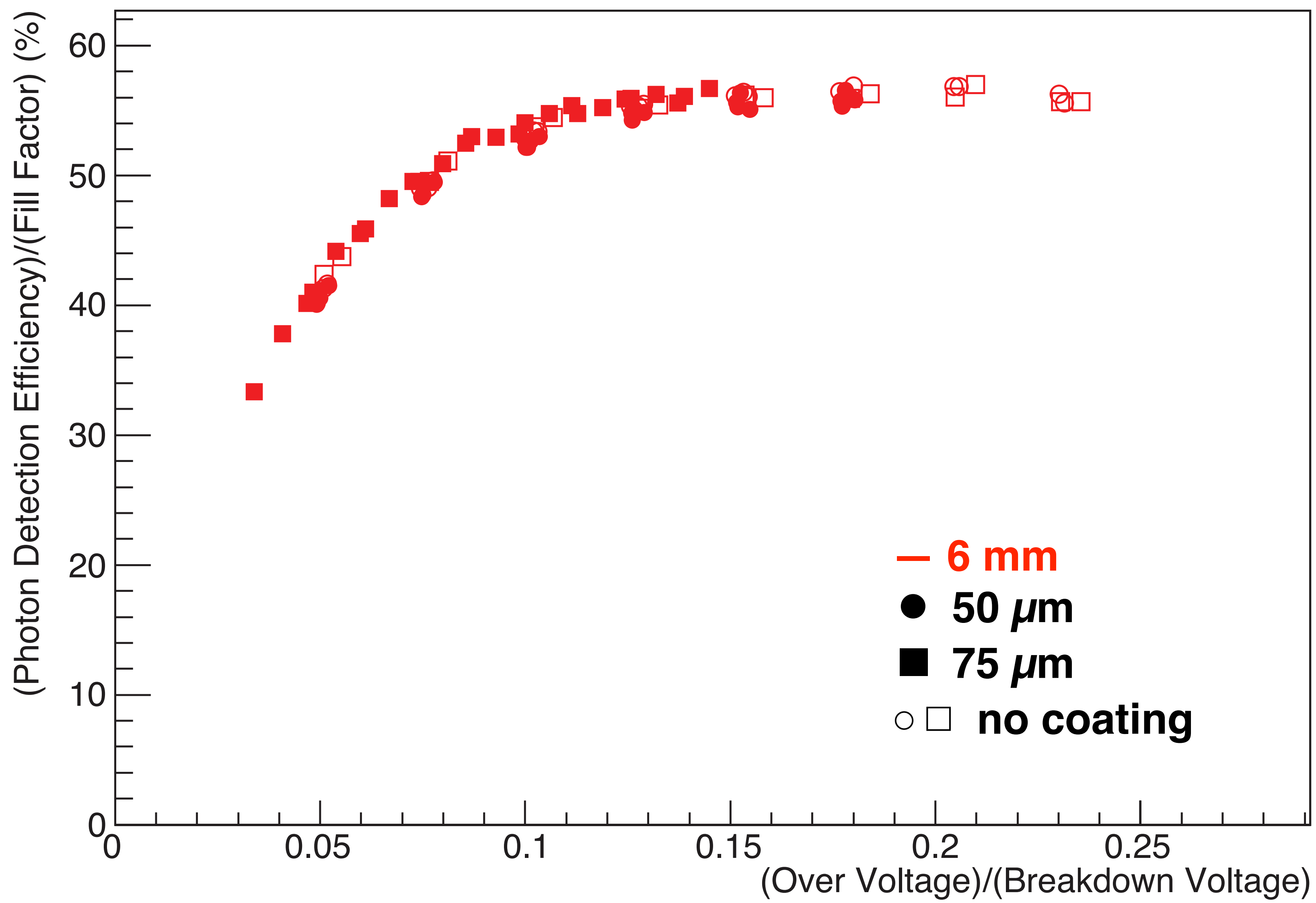
$$P_{\mathrm{true}}(0) = P_{\mathrm{ON}}(0)/P_{\mathrm{OFF}}(0)$$



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 even though monitor SiPM indicates varying light intensity



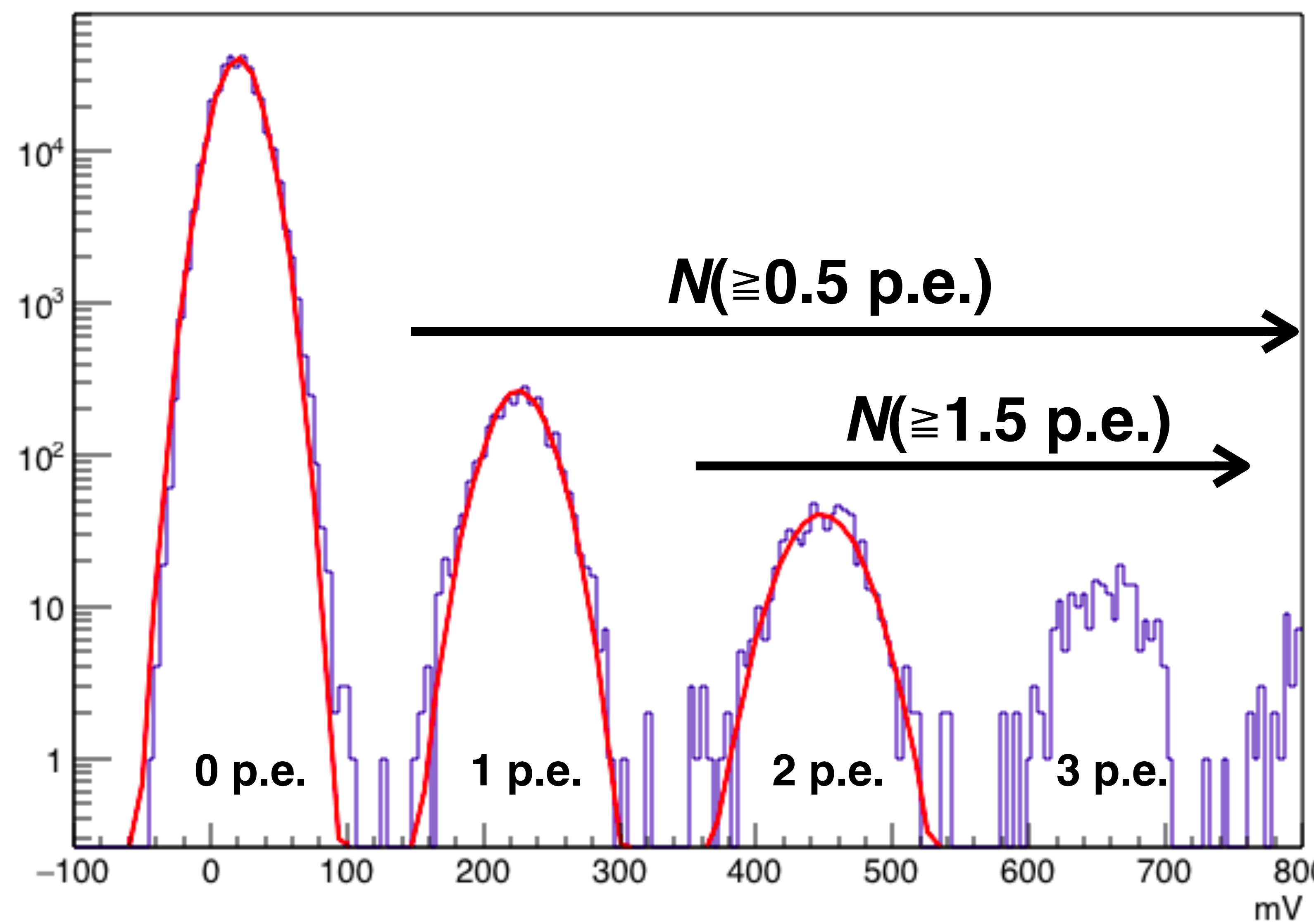


Optical Crosstalk Measurements

- 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)

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

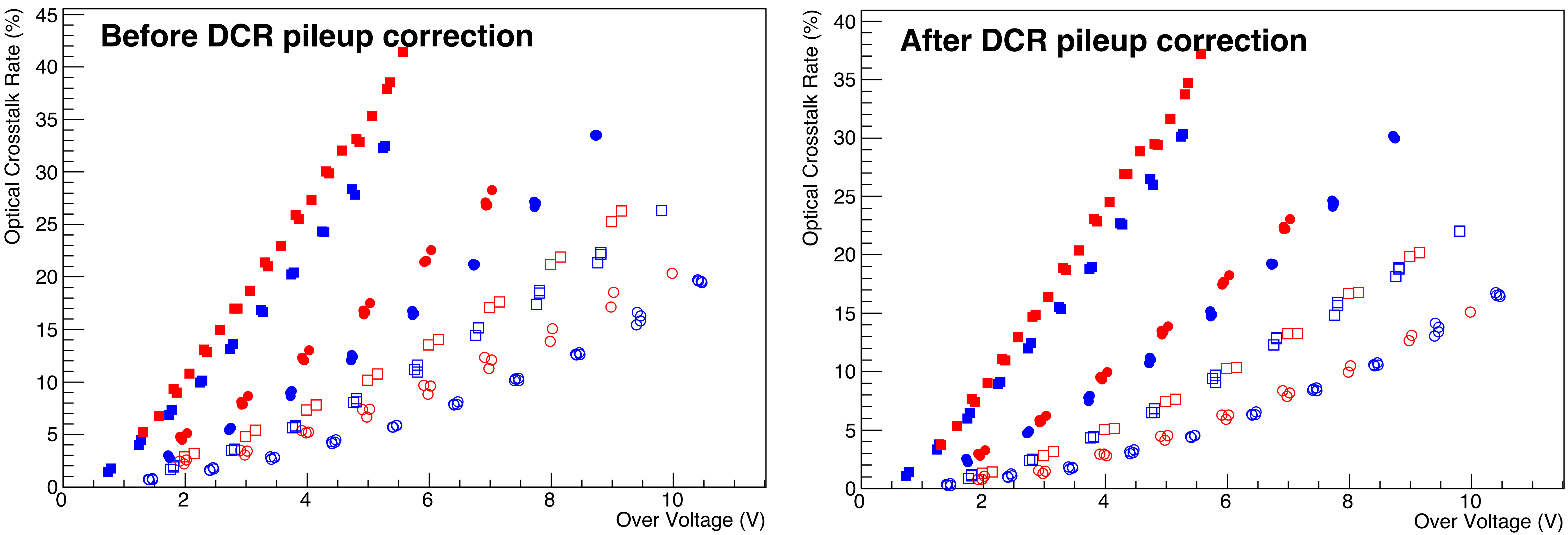
Poisson probability for one or more dark counts within Δt_{PS}



Crosstalk Rate vs. Over Voltage

- 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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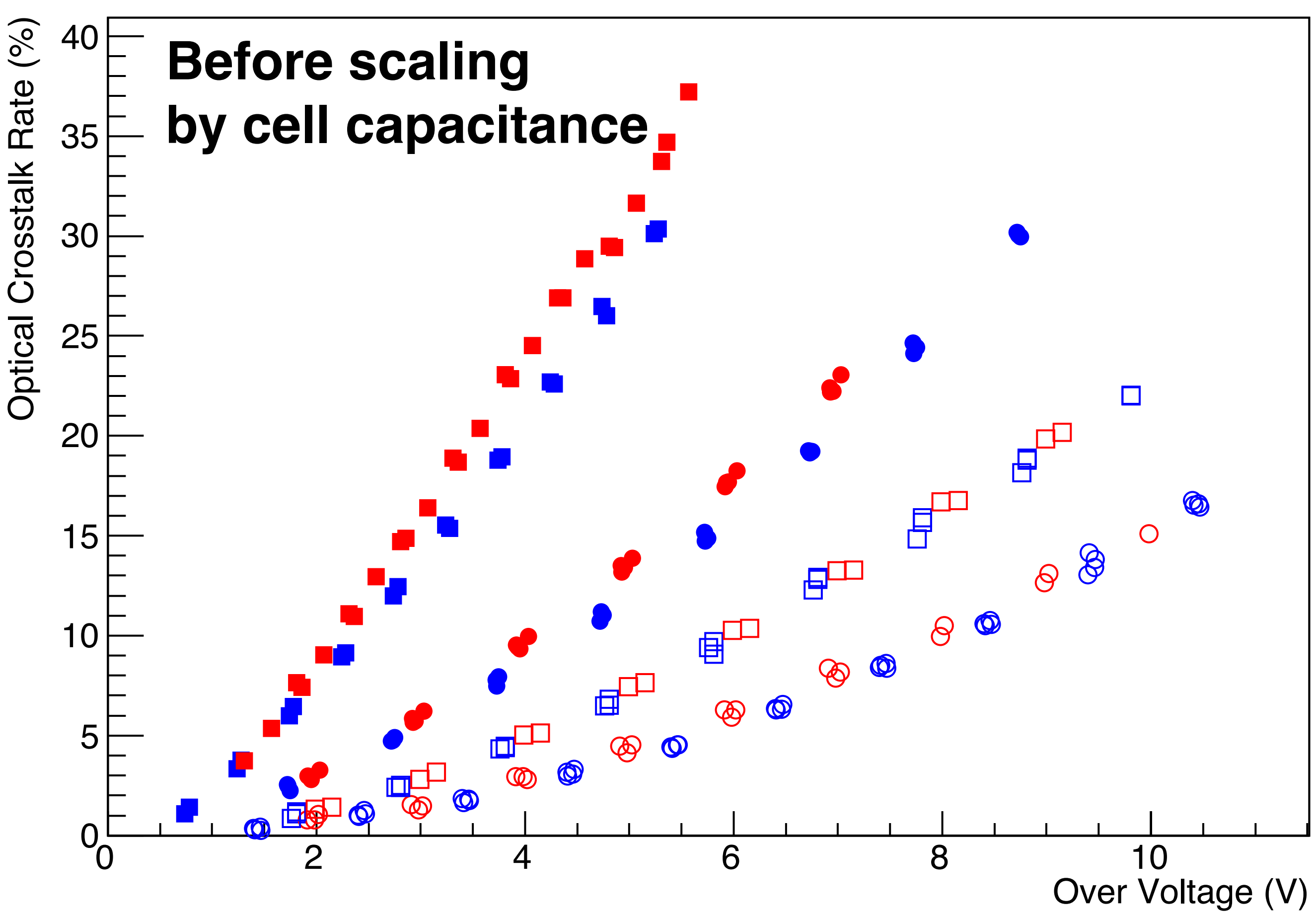
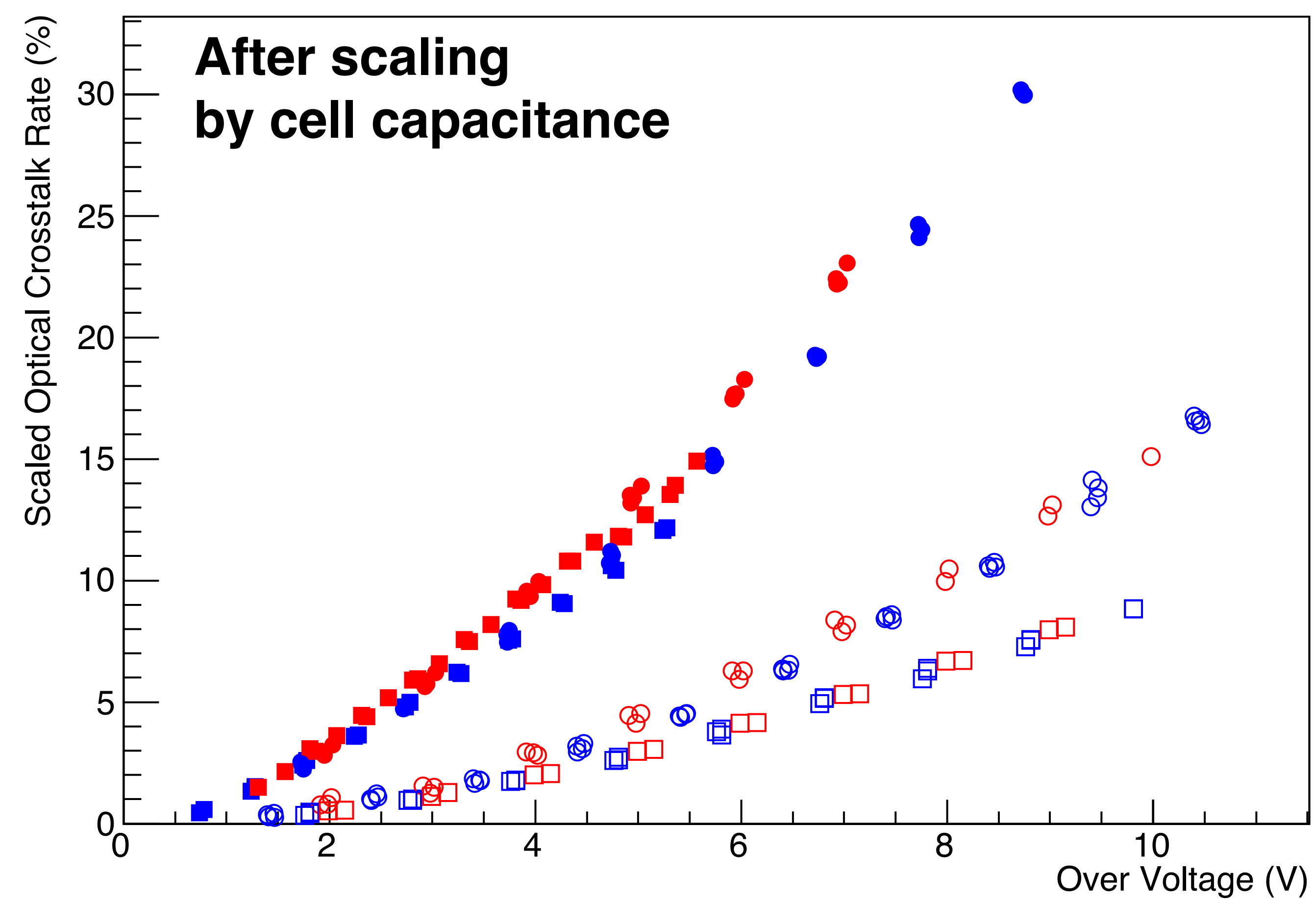




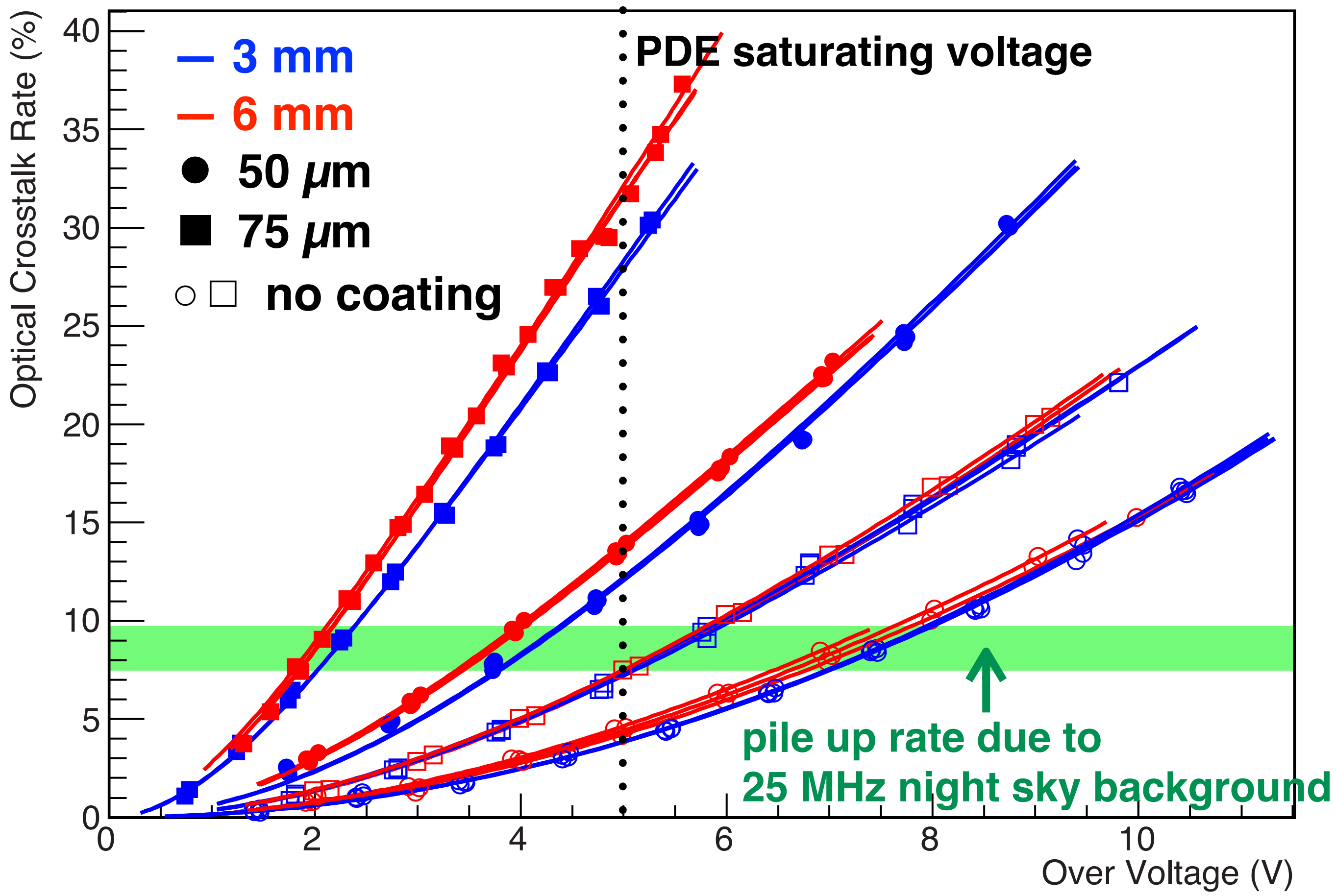
Fit to Otte Function

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

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

- **C_{OCT} is smaller for 75 μm cells (less efficient for crosstalk)**
- **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	5.5
S14520-6050VS	0.09	9
S14520-3075VS	0.06	17
S14520-6075VS	0.06	18
S14520-3050VN	0.4	0.3
S14520-6050VN	0.09	2
S14520-3075VN	0.03	5
S14520-6075VN	0.03	4



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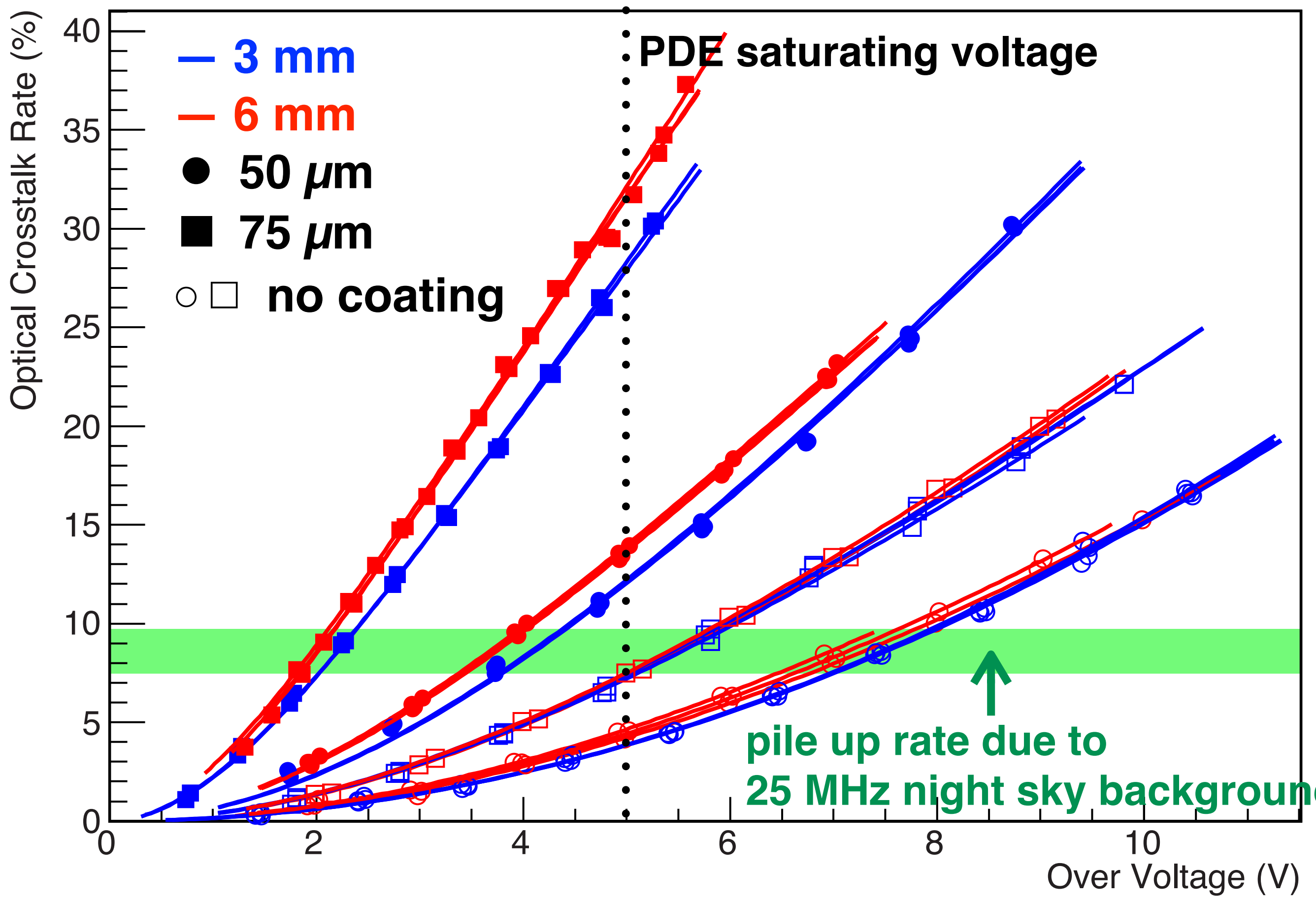

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∝ cell capacitor — Avalanche probability

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- **C_{Otte} is smaller without coating**
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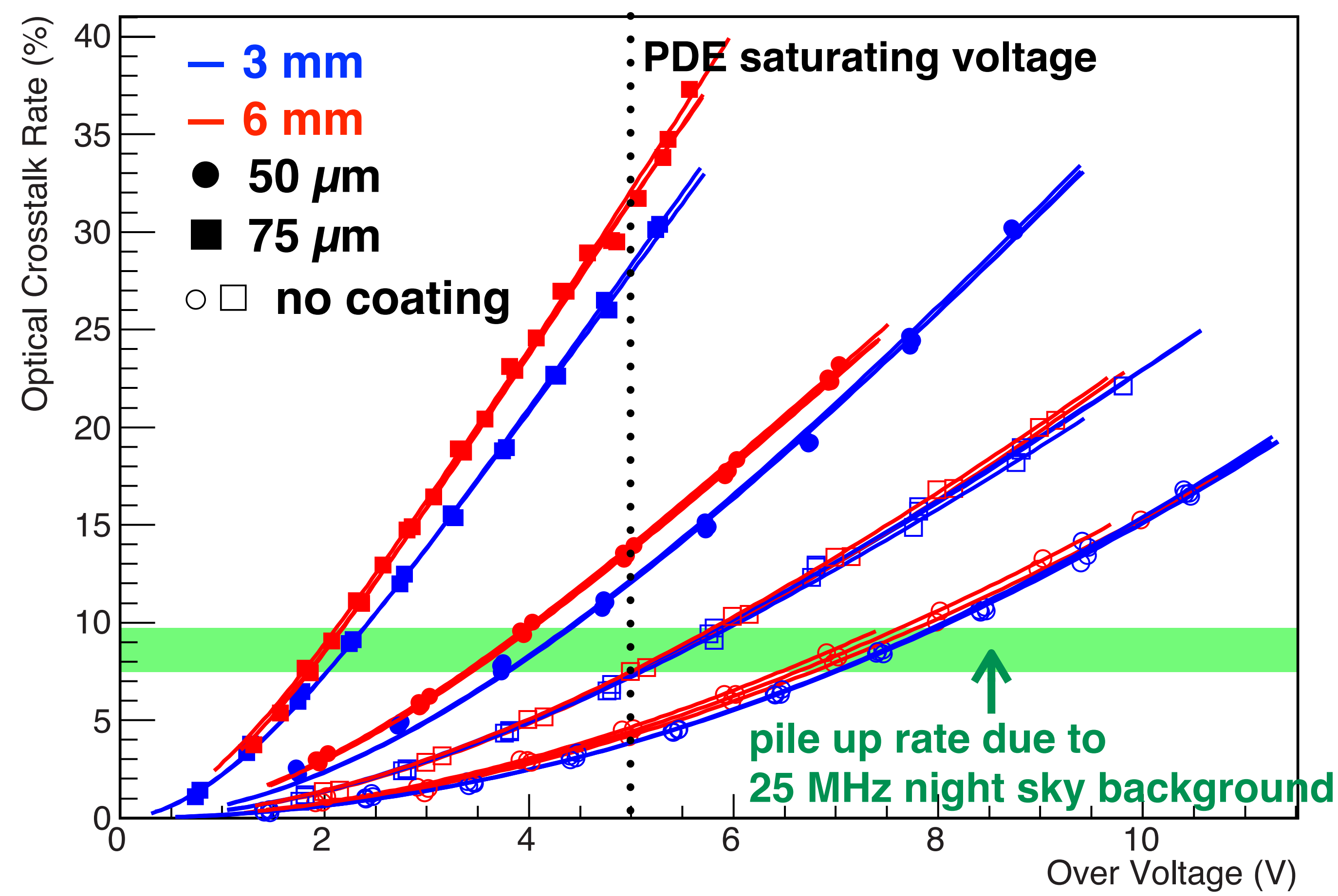
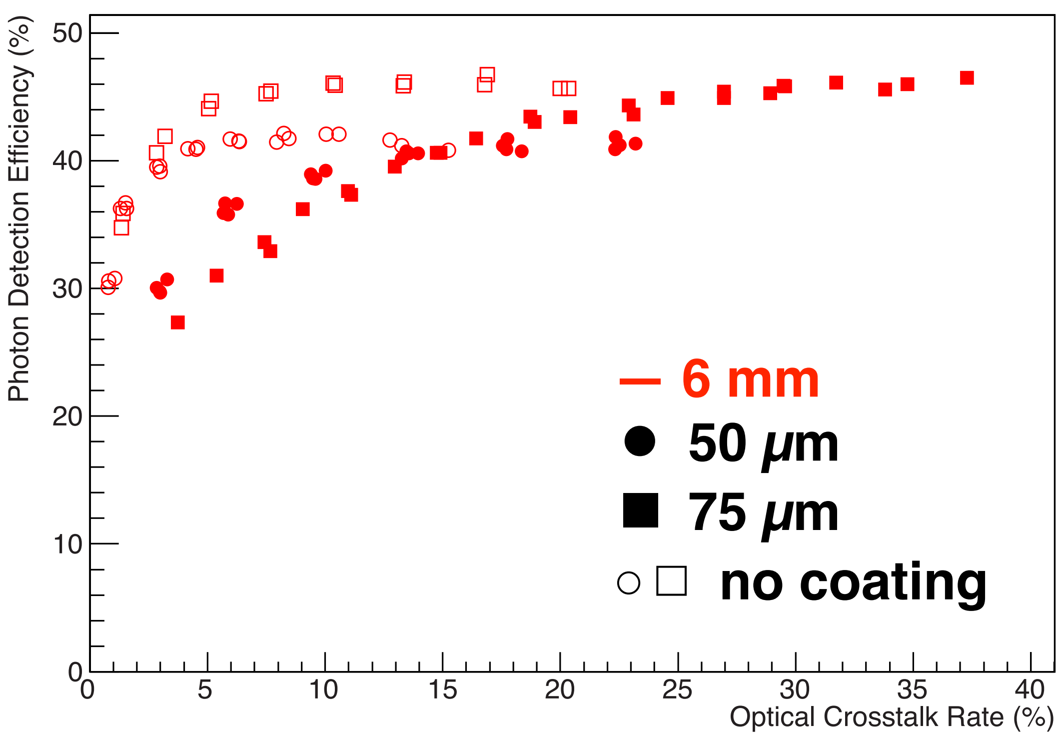


Summary

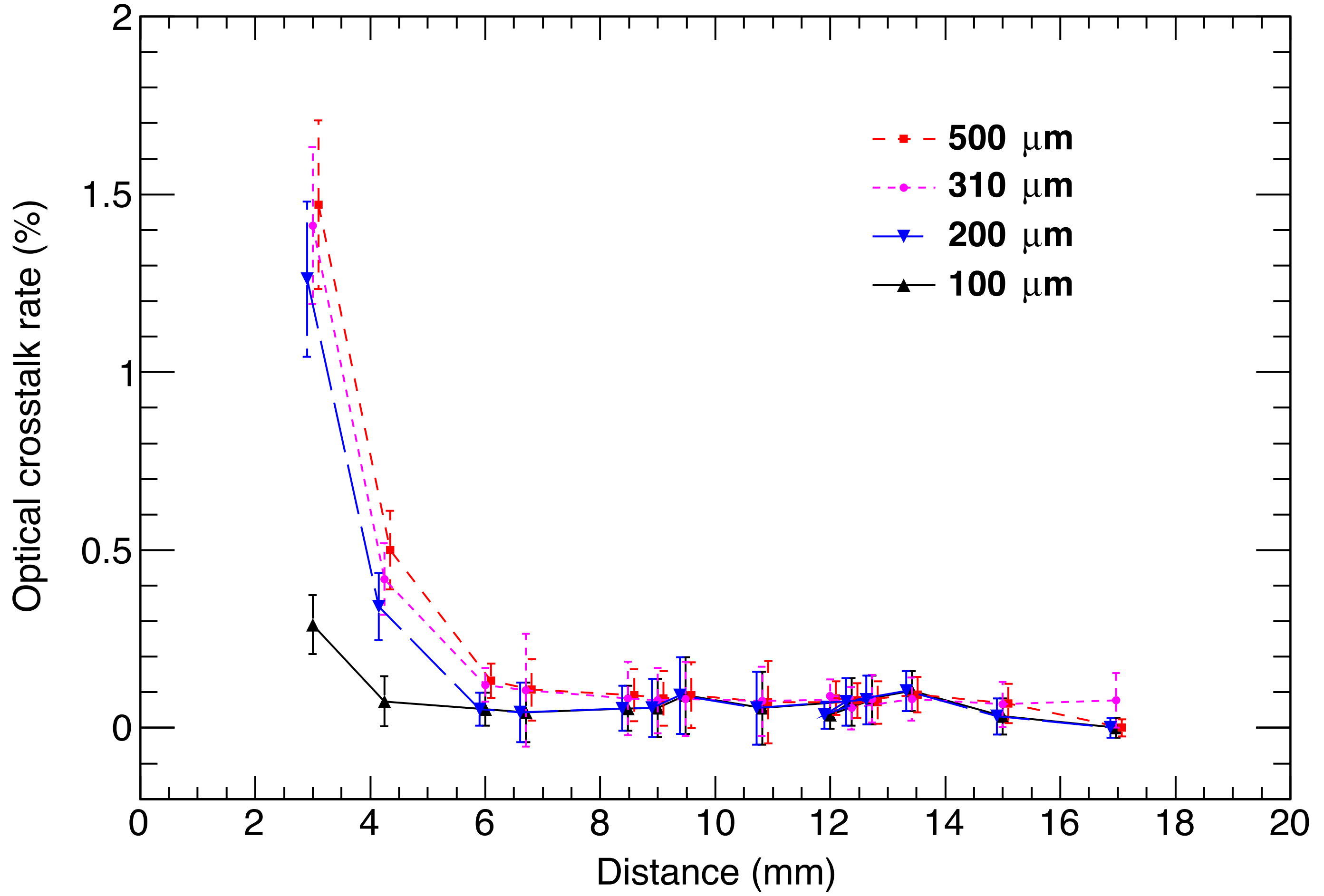
- Optical crosstalk rate is significantly affected by protection coating
  - Smaller device size and thicker coating reduce OCT rate
  - Larger cell size increase OCT rate, but not proportional to the cell area
  - No coating significantly reduces OCT rate
    - OCT rate does not scale with the cell 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 for now
  - Further reduction of OCT by suppressing crosstalk due to photons reflected at the backside of SiPM



Supplemental Slides

Optical Crosstalk to Nearby Devices

- Optical crosstalk can propagate into other devices in SiPM arrays with common protection layer
  - It can propagate beyond adjacent pixels
  - Crosstalk rate in other pixels increases with thicker protection
  - Total crosstalk rate (sum of self crosstalk and crosstalk to other pixel) is more or less constant above 100 μm thickness



Pulse Shaping

- Low pass filter to remove high frequency noise
- Pole zero cancellation to cut the exponential tail