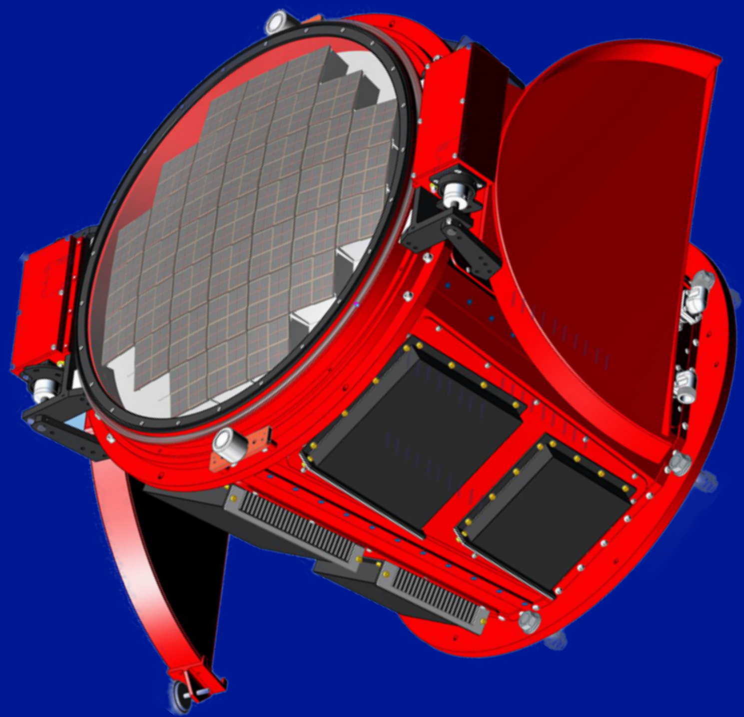

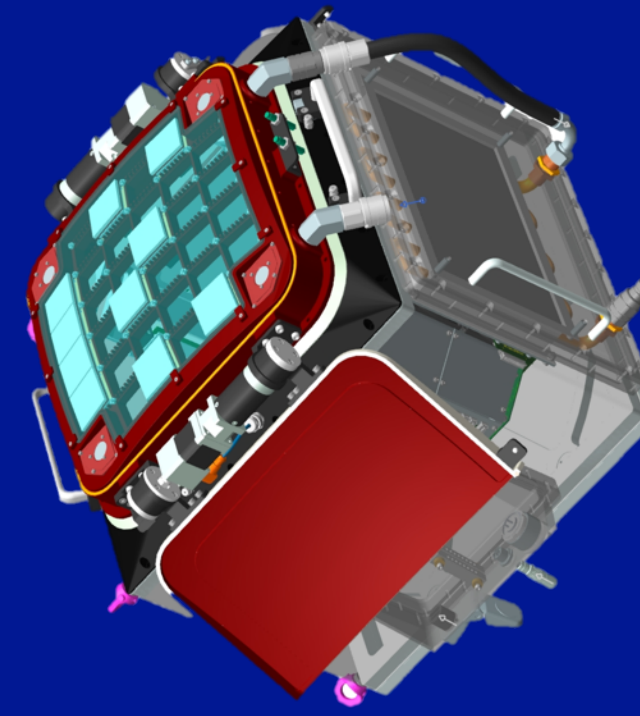

次世代ガンマ線望遠鏡CTA用SiPMの最適化

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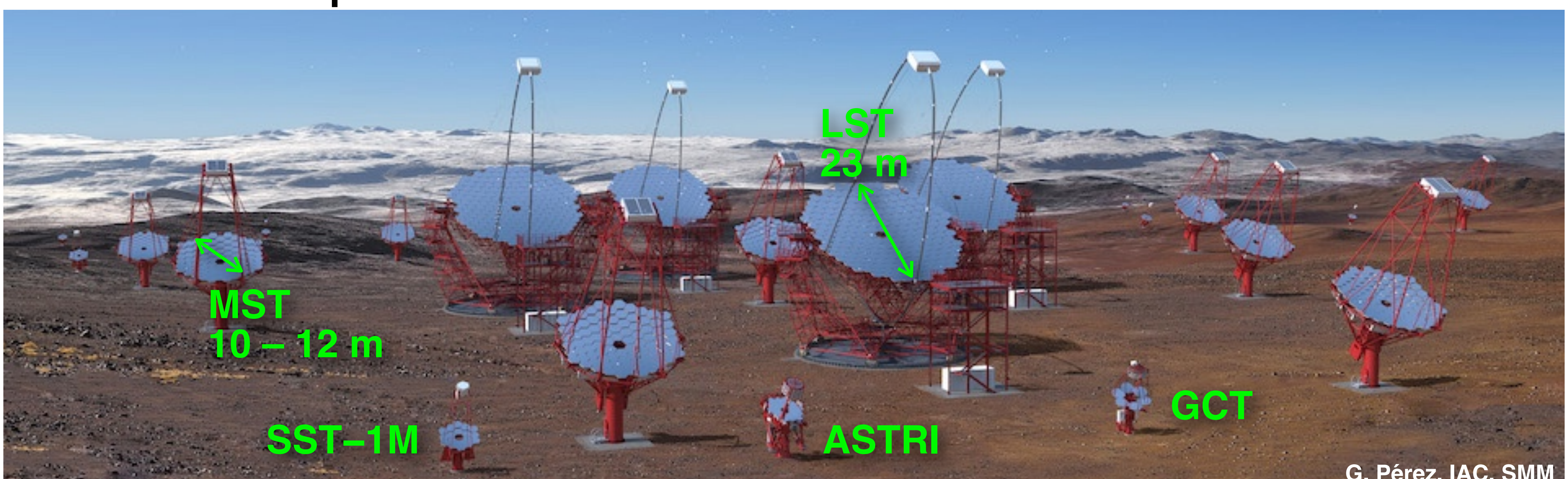
日本物理学会 2017年秋季大会

宇都宮大学, September 12–15, 2017

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

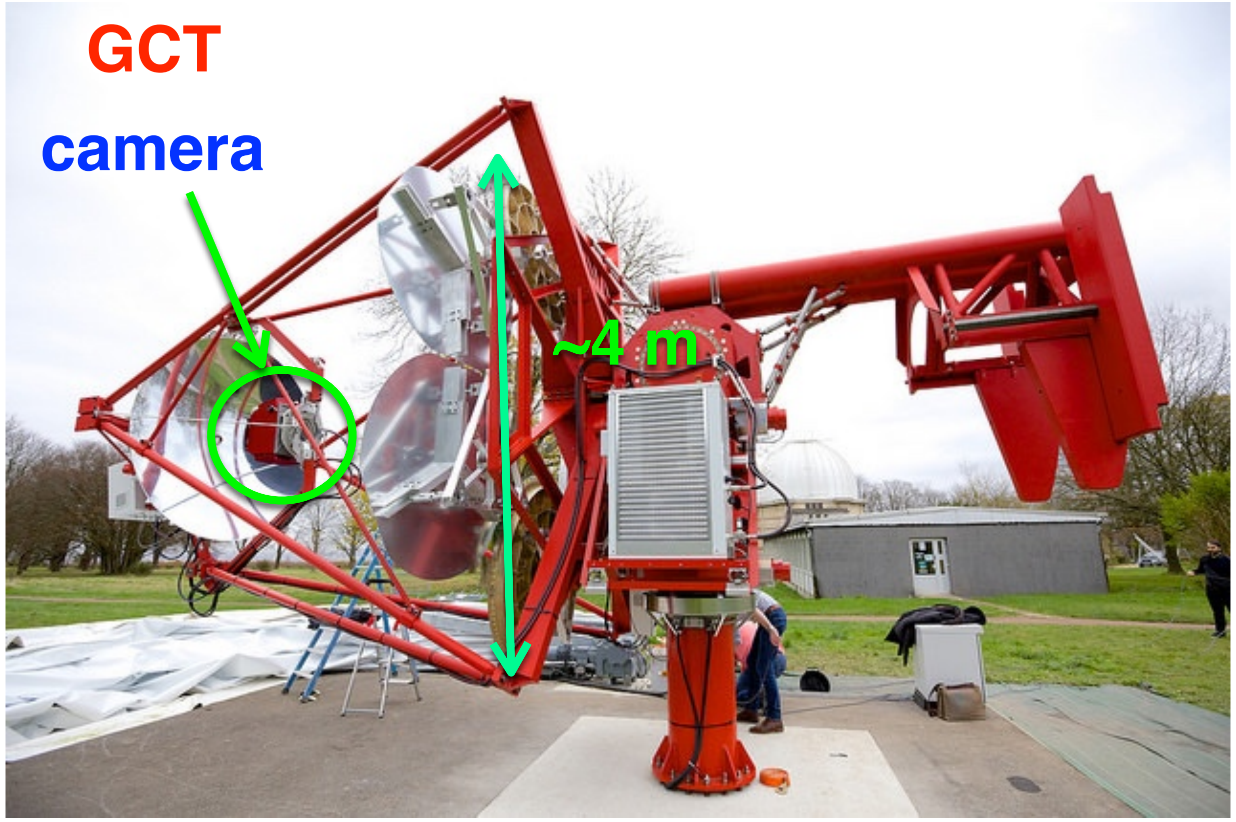
ASTRI

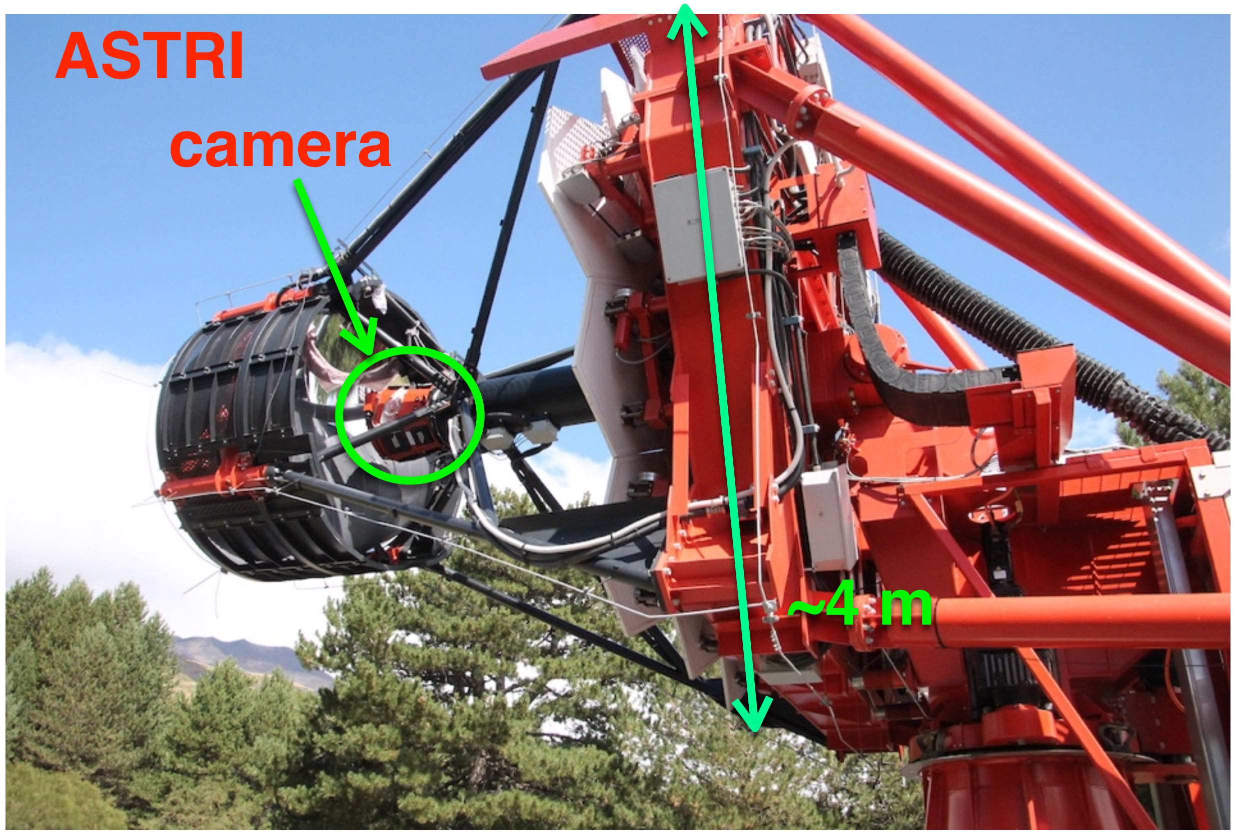
GCT

SST-1M

Dual Mirror SST Design Concept

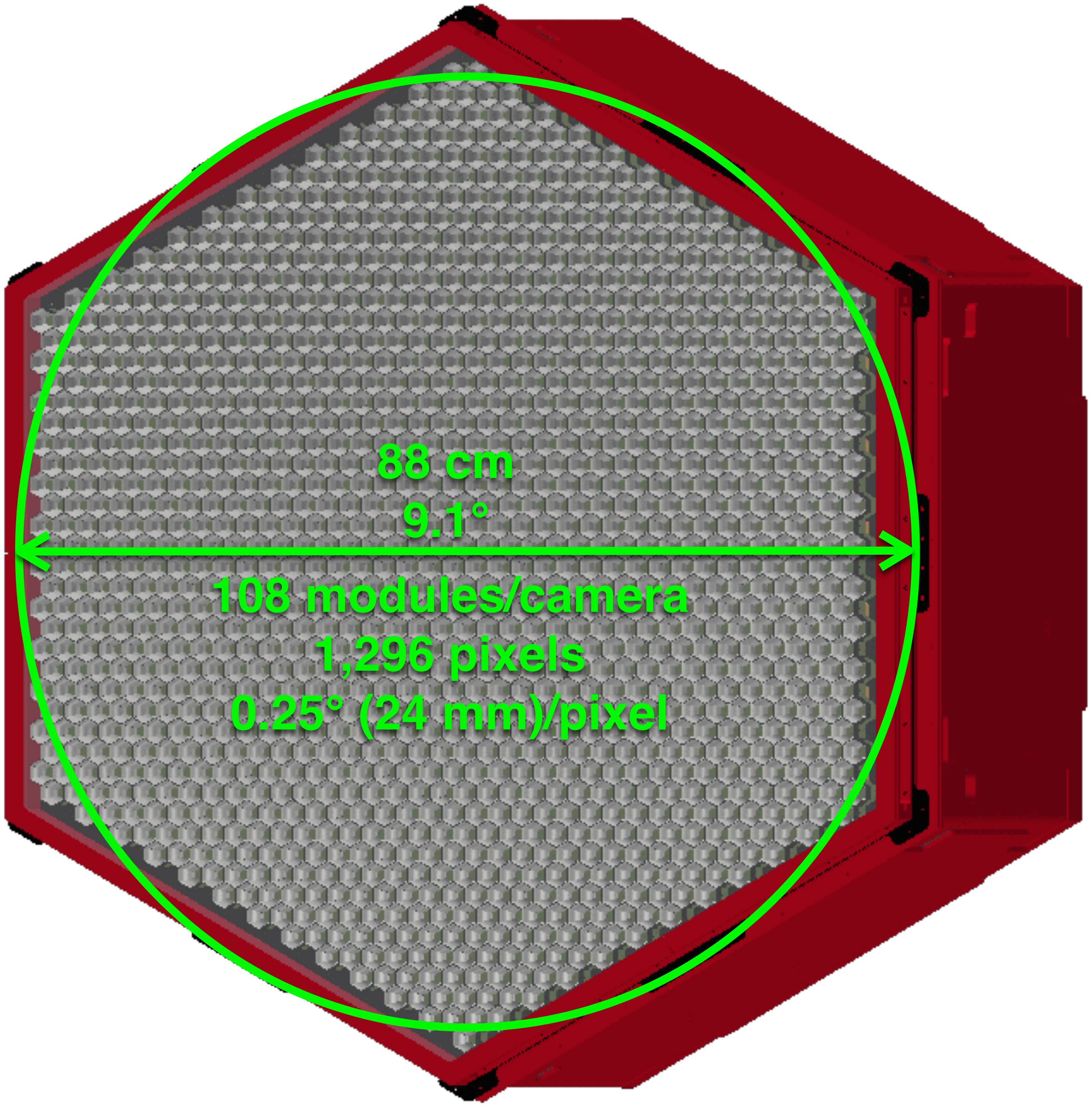
- Dual mirror design allowing use of compact camera
  - Schwarzschild-Couder (SC) optics
    - Short focal length to realize small plate scale (small camera, pixel)
    - Large field of view
      - Greater telescope spacing (larger collection area)
    - Technically challenging
  - Small pixel (6–7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





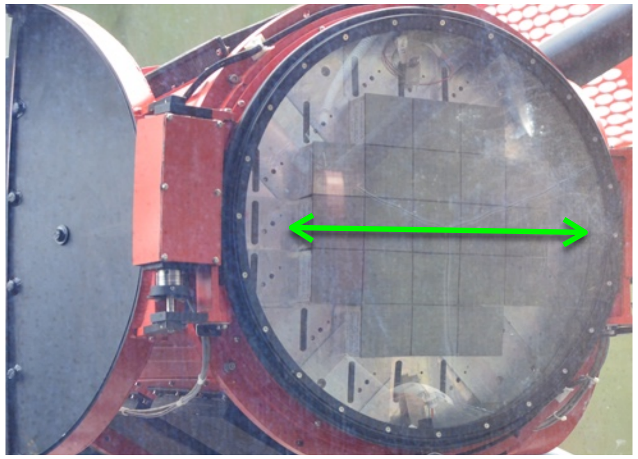
Comparison with Single-Mirror Camera

SST-1M camera



credit: SST-1M

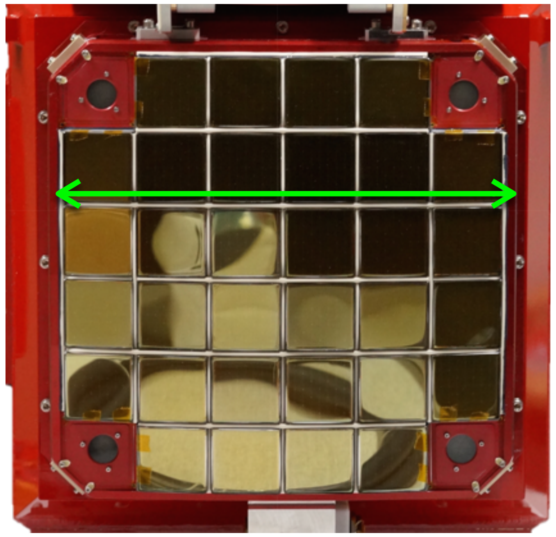
ASTRI camera



~50 cm
10.9°

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

GCT camera

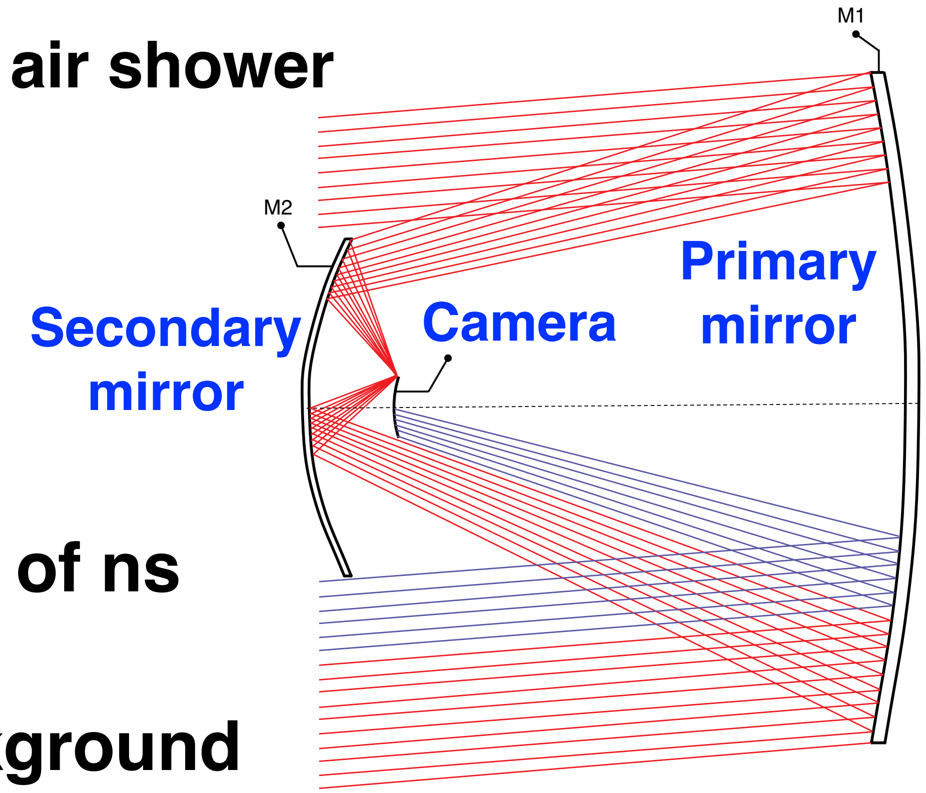


~35 cm
9.1°

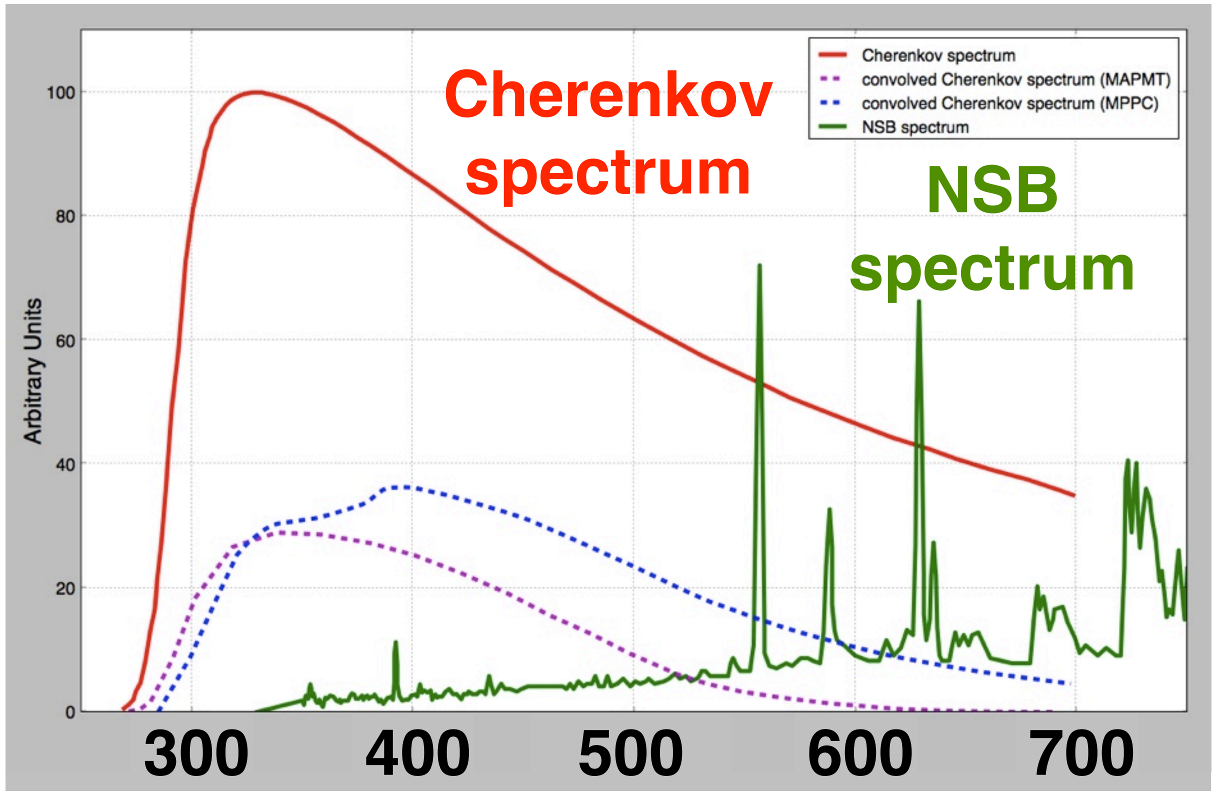
32 modules/camera
2,048 pixels/camera
0.15–0.18° (6–7 mm)/pixel

Requirements for Photodetector

- ❖ 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 few to few tens of ns
    - ✦ ns-timing is important



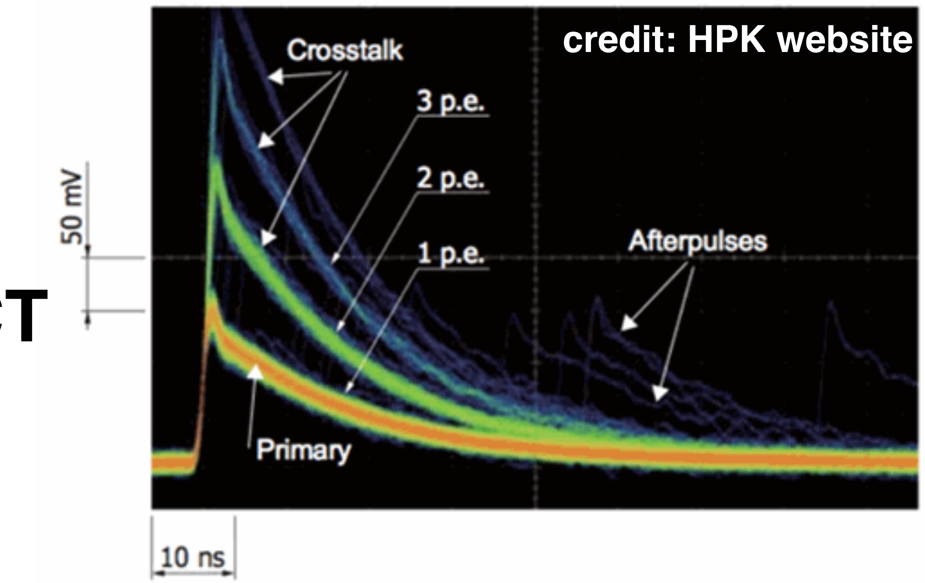
- ❖ Night sky background (NSB) is the dominant background
  - ✤ Rate is >25 MHz/pixel
    - ✦ Dark count rate is not very important
    - ✦ [NSB] x [Optical crosstalk (OCT)] can cause false triggers due to accidental coincidences
      - Low OCT rate is important
  - ✤ NSB peaks above 550 nm
    - ✦ Low red sensitivity is preferred

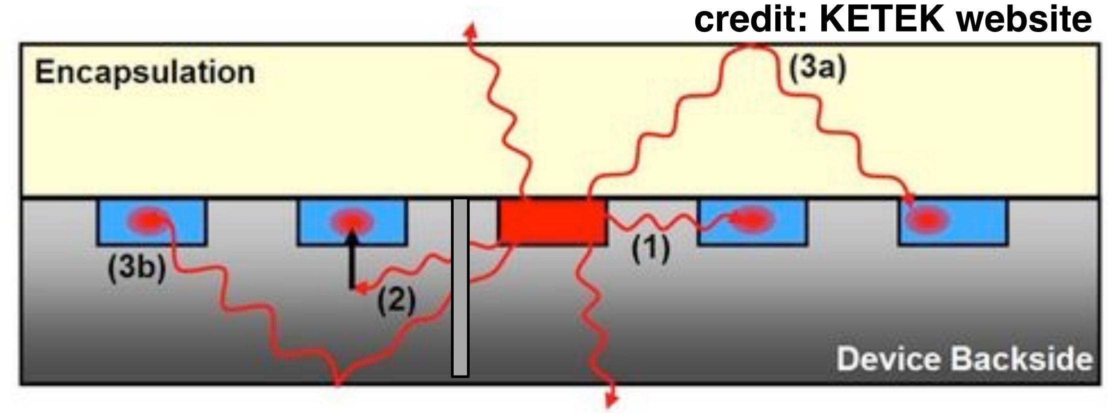


- ❖ Pixel size < 0.25 deg is required to obtain good angular resolution of air showers
  - ✤ Pixel size ~ 6 mm with 4-m telescope

Photodetector

- ❖ **Silicon Photomultiplier** is chosen as a photodetector 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)
    - Add trenches
    - Optimize protection coating





Test Samples

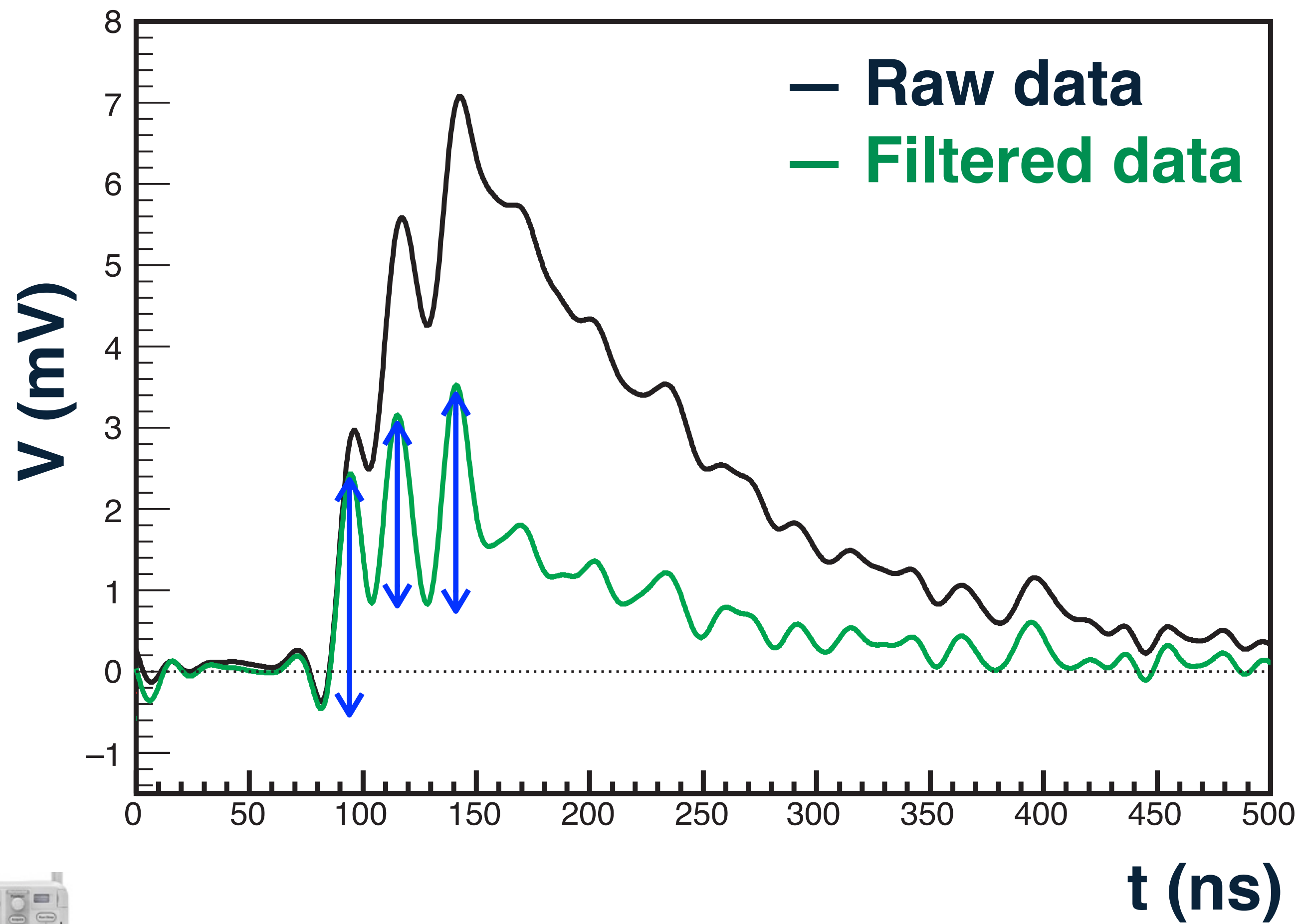
Product ID	Pixel size	Cell size	Technology	Short name	Fill factor
S12572-050C	3 mm	50 μm	Standard	REF-3050-S	62%
S13360-3050CS	3 mm	50 μm	LCT5	LCT5-3050-S	74%
S13360-3050VE	3 mm	50 μm	LCT5, 100 μm epoxy	LCT5-3050-E100	74%
S13360-3050PE	3 mm	50 μm	LCT5, 300 μm epoxy	LCT5-3050-E300	74%
S13360-6050CS	6 mm	50 μm	LCT5	LCT5-6050-S	74%
S13360-3075CS	3 mm	75 μm	LCT5	LCT5-3075-S	82%
S13360-6075CS	6 mm	75 μm	LCT5	LCT5-6075-S	82%
LVR-3050CS	3 mm	50 μm	LVR	LVR-3050-S	74%
LVR-6050CS	6 mm	50 μm	LVR	LVR-6050-S	74%
LVR-6075CS	6 mm	75 μm	LVR	LVR-6075-S	82%
LVR-7050CS	7 mm	50 μm	LVR	LVR-7050-S	74%
LVR2-6050CS	6 mm	50 μm	LVR2	LVR2-6050-S	74%
LVR2-6050CN	6 mm	50 μm	LVR2, no coating	LVR2-6050-N	74%
LVR2-7050CS	7 mm	50 μm	LVR2	LVR2-7050-S	74%
LVR2-7050CN	7 mm	50 μm	LVR2, no coating	LVR2-7050-N	74%

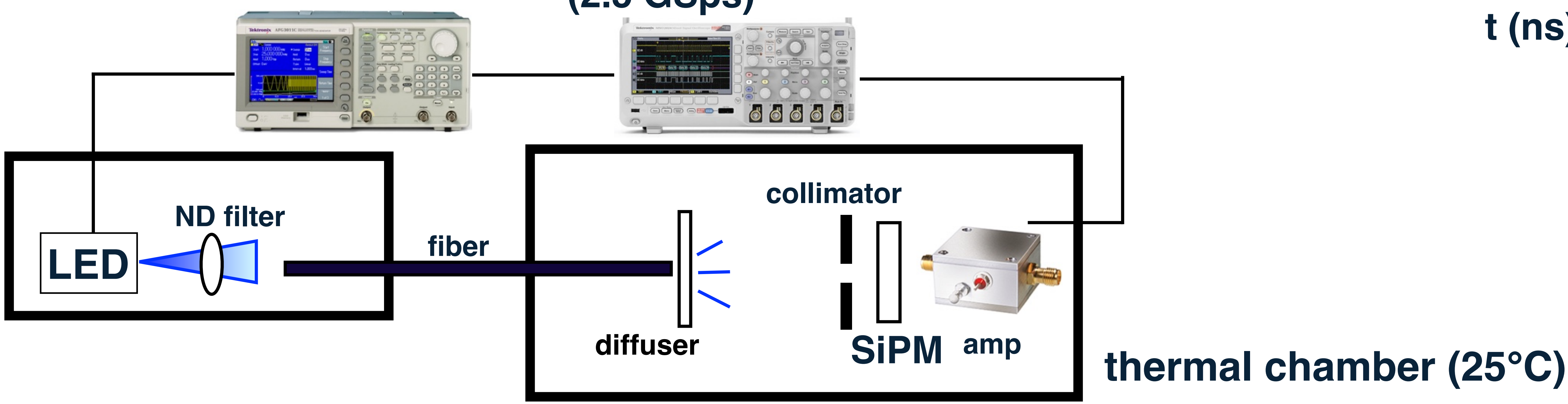
We have tested SensL and FBK SiPMs as well as Hamamatsu SiPMs.
Only Hamamatsu SiPMs are shown for easy comparisons

LCT: Low Crosstalk
LVR: Low Breakdown Voltage

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 effect of optical crosstalk
  - Effect of dark count still need to be taken into account

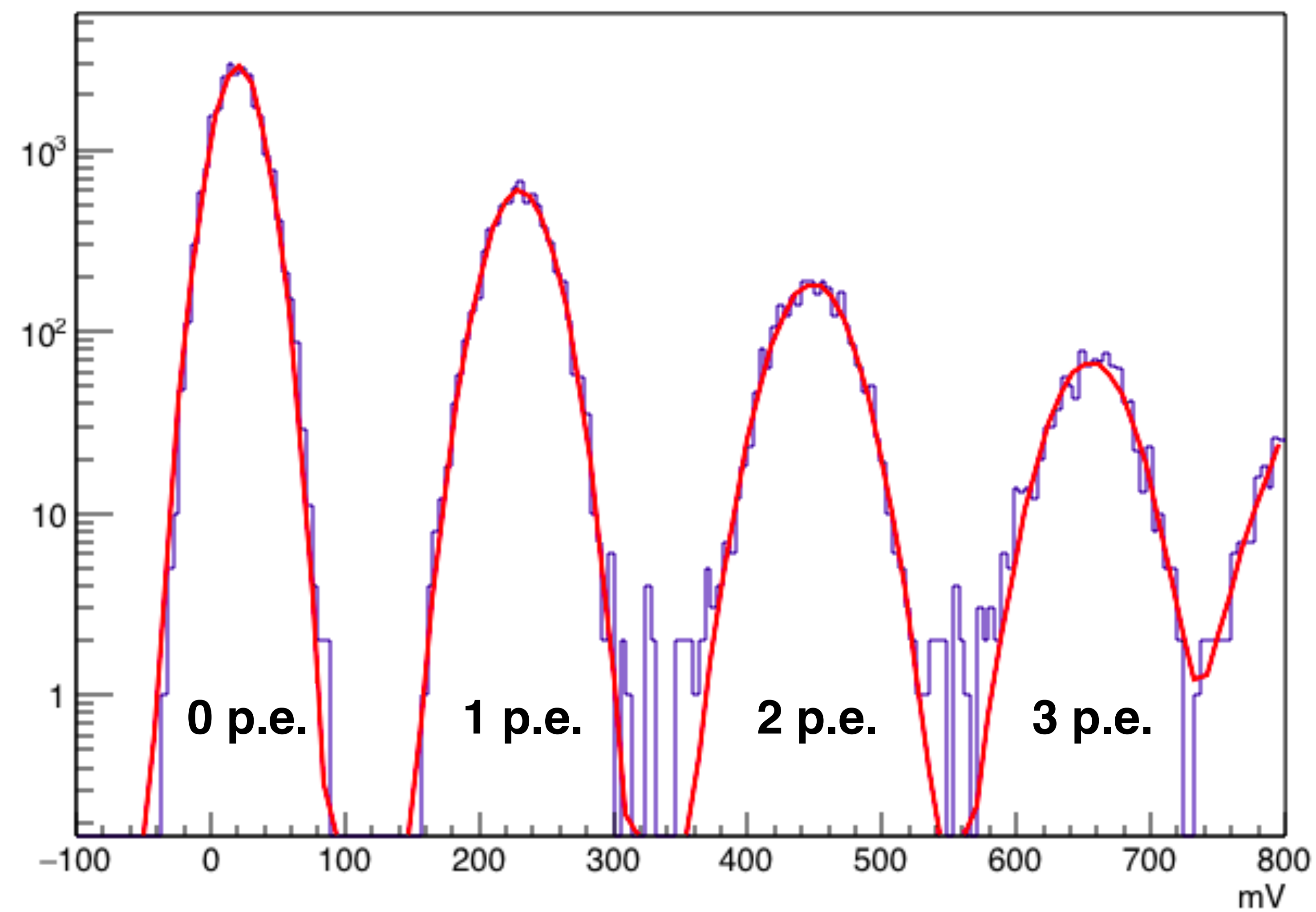
$$P(n) = e^{-\mu}\mu^n/n!$$

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

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

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

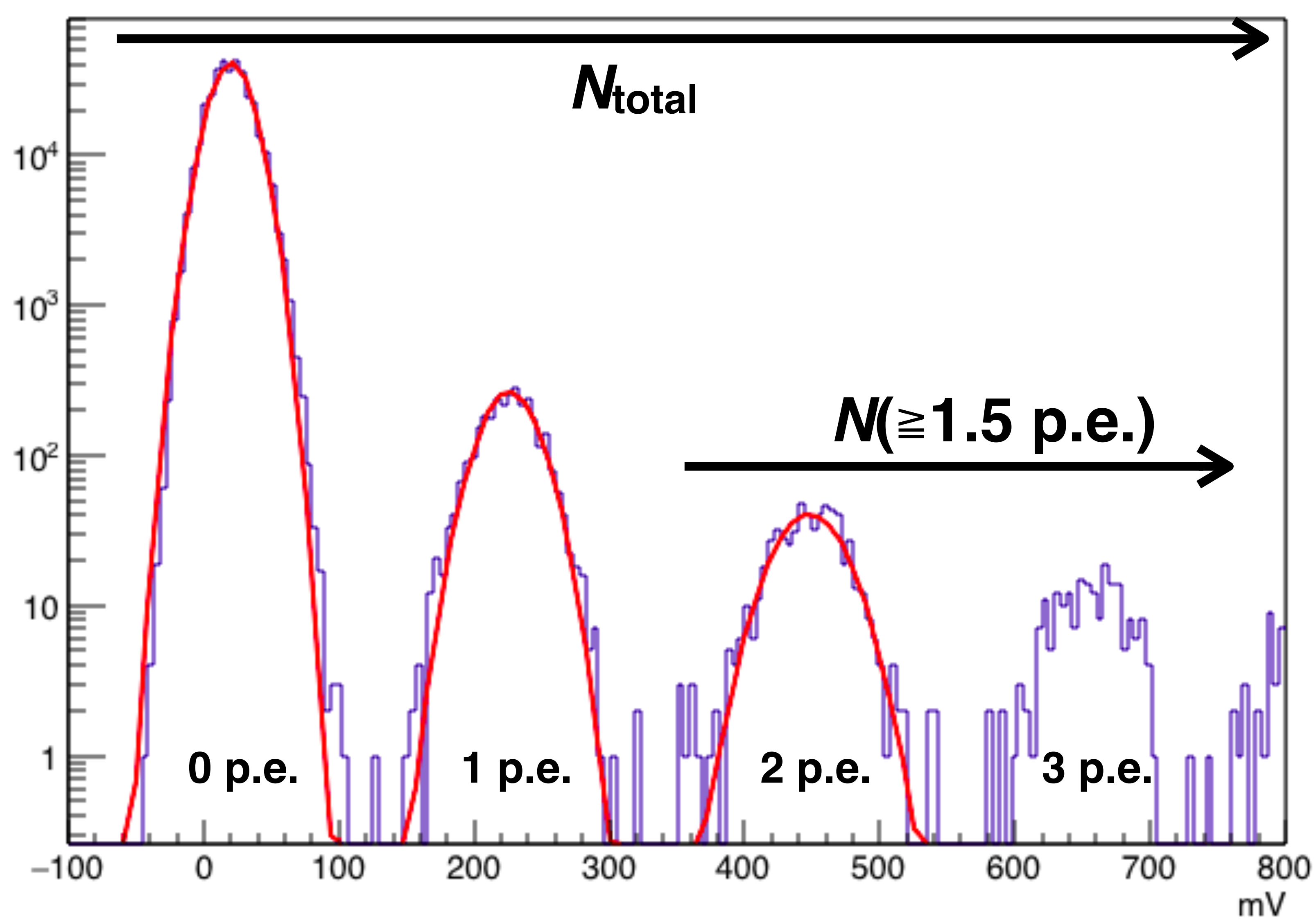
- Common between Nagoya and Catania



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**
    - ✦ **Assume chance coincidence of dark counts follow Poisson statistics (small correction for most cases)**

$$\frac{N(\geq 1.5\ \mathrm{p.e.})}{N_{\mathrm{total}}} = P(1)R_{\mathrm{OCT}} + P(2) + P(3) + \cdots$$
$$\approx P(1)R_{\mathrm{OCT}} + P(2) + P(3),$$
$$P(1) = \mu P(0),$$
$$P(2) = \frac{\mu^2}{2}P(0),$$
$$P(3) = \frac{\mu^3}{6}P(0),$$
$$R_{\mathrm{OCT}} \approx \frac{N(\geq 1.5\ \mathrm{p.e.})}{\mu P(0) N_{\mathrm{total}}} - \frac{\mu}{2} - \frac{\mu^2}{6}$$

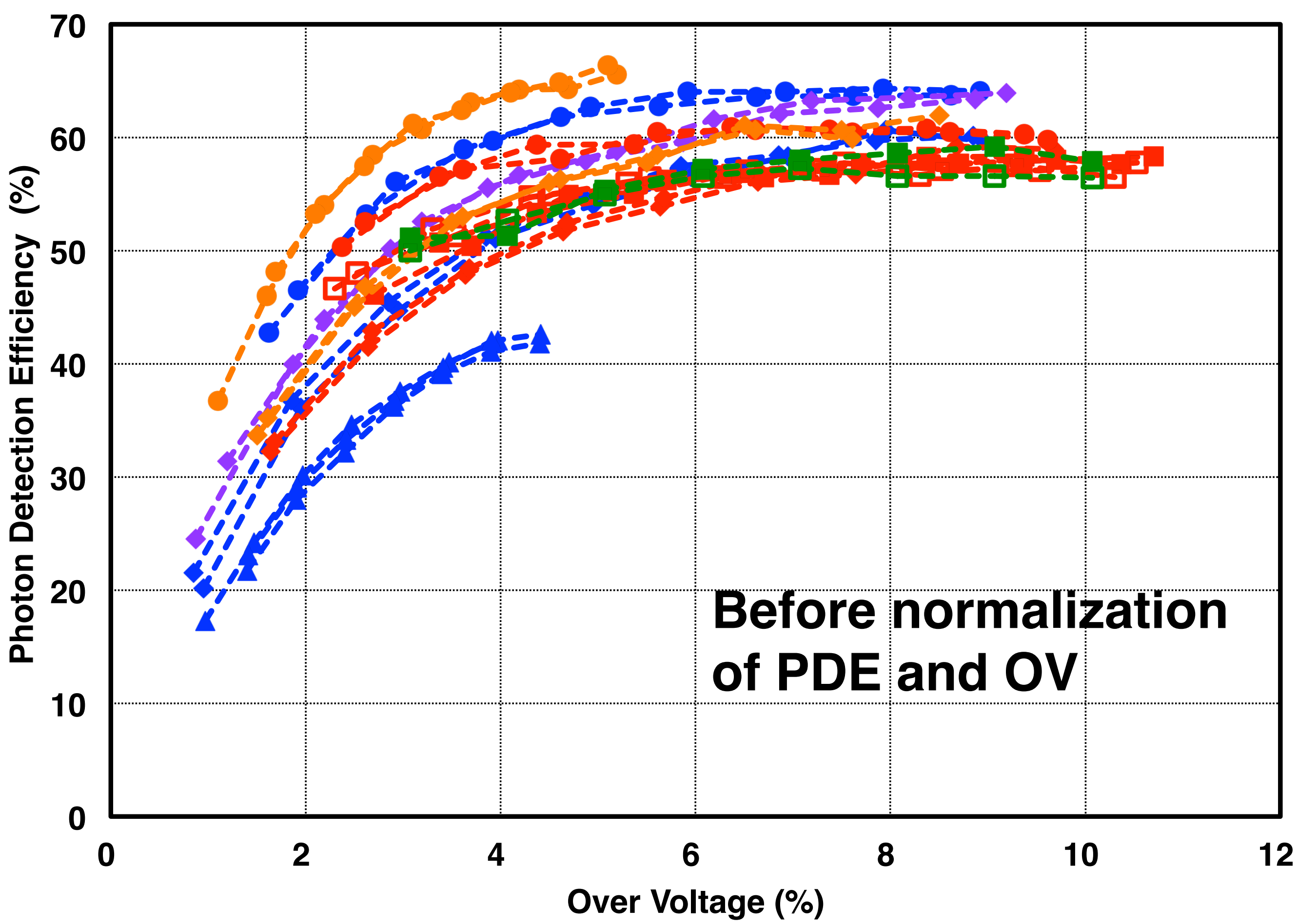


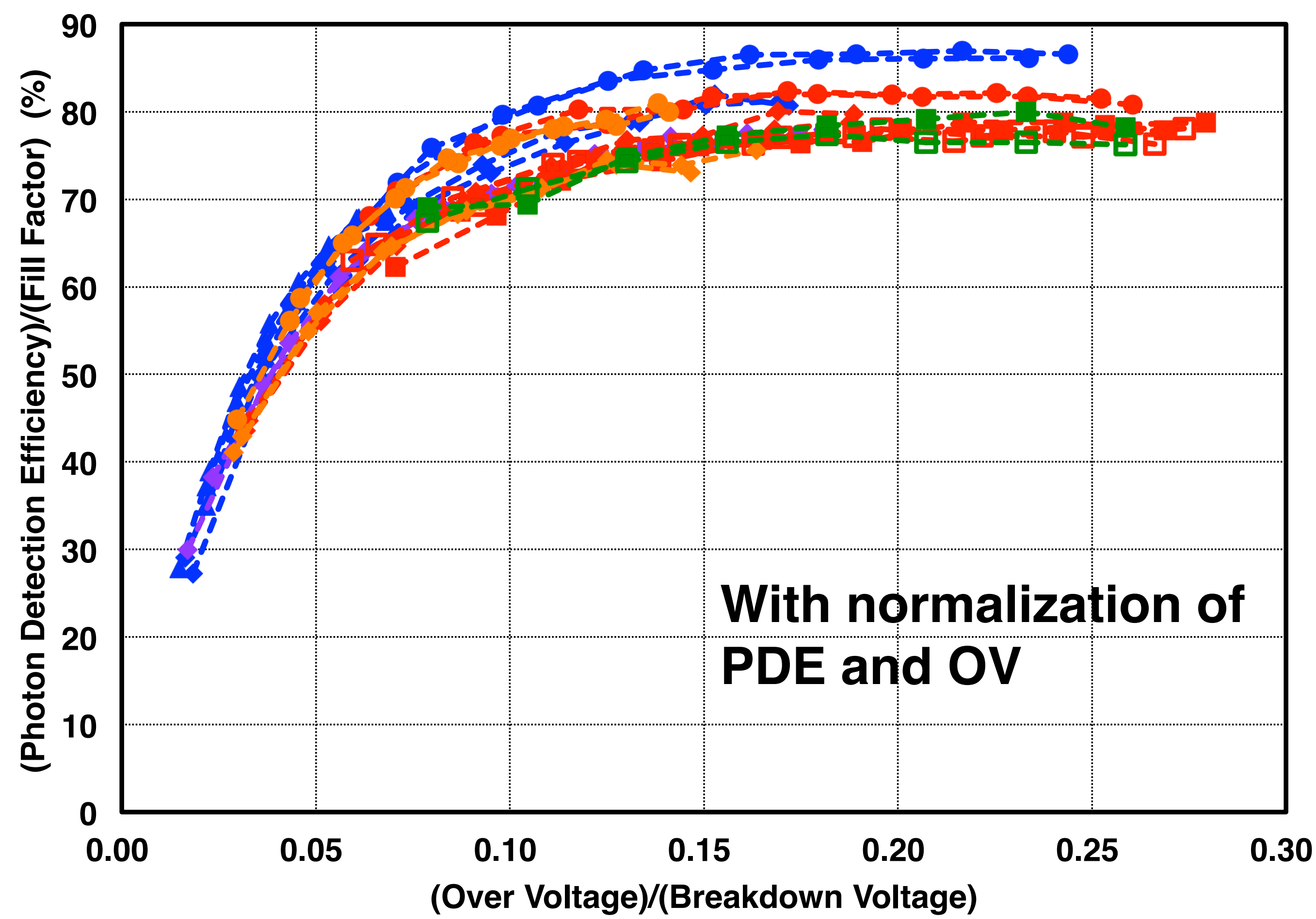
PDE vs. Over Voltage

- If we take PDE normalized by fill factor as a function of relative over voltage, the curve are very similar among different SiPM
- LVR is slightly better than others
- Differences among individual SiPMs are small

— 3050 ▲ REF
— 3075 ◆ LCT5
— 6050 ● LVR
— 6075 ■ LVR2
— 7050 □ LVR2 (no coating)

λ = 405 nm





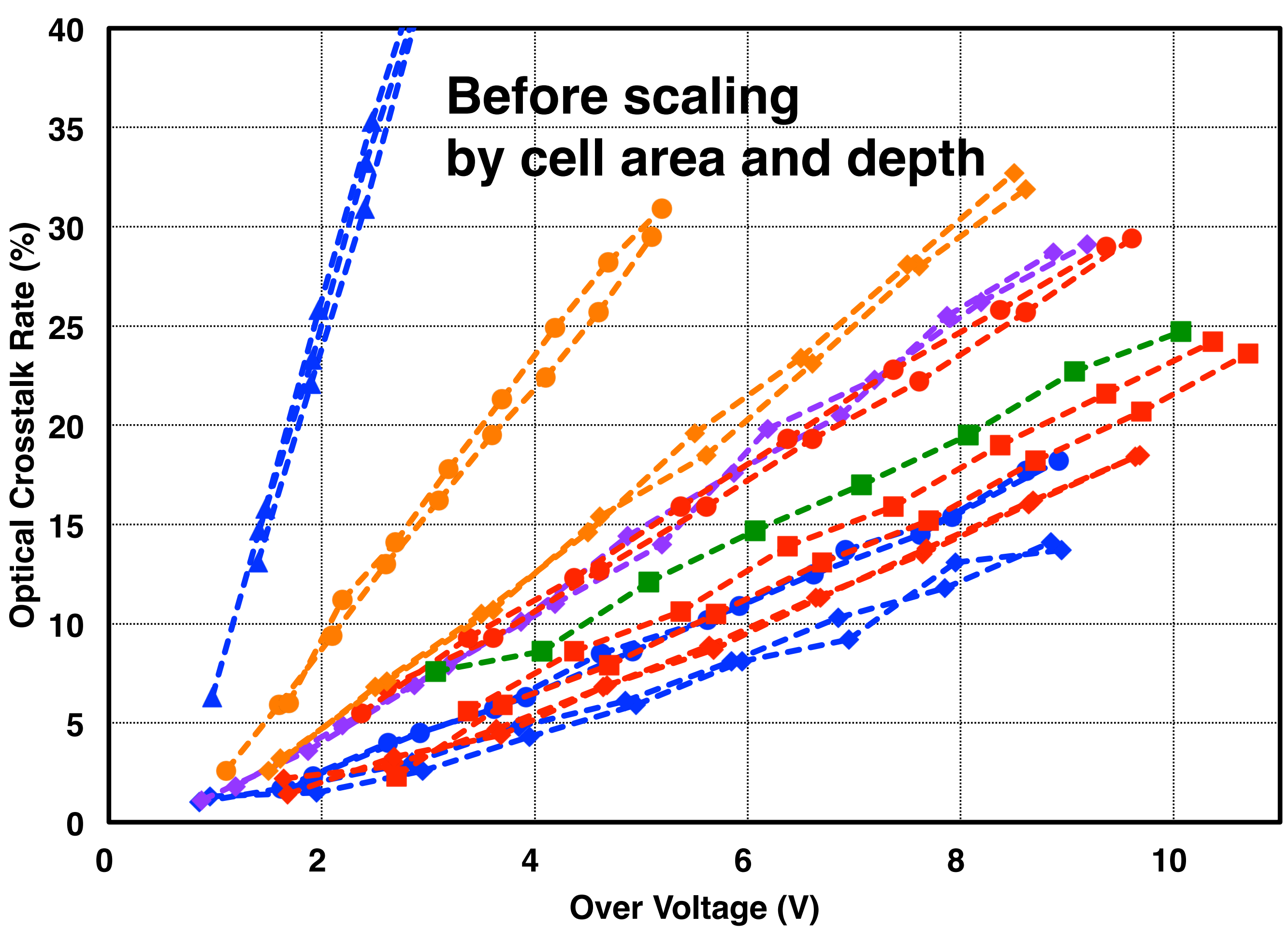
Crosstalk Rate vs. Over Voltage

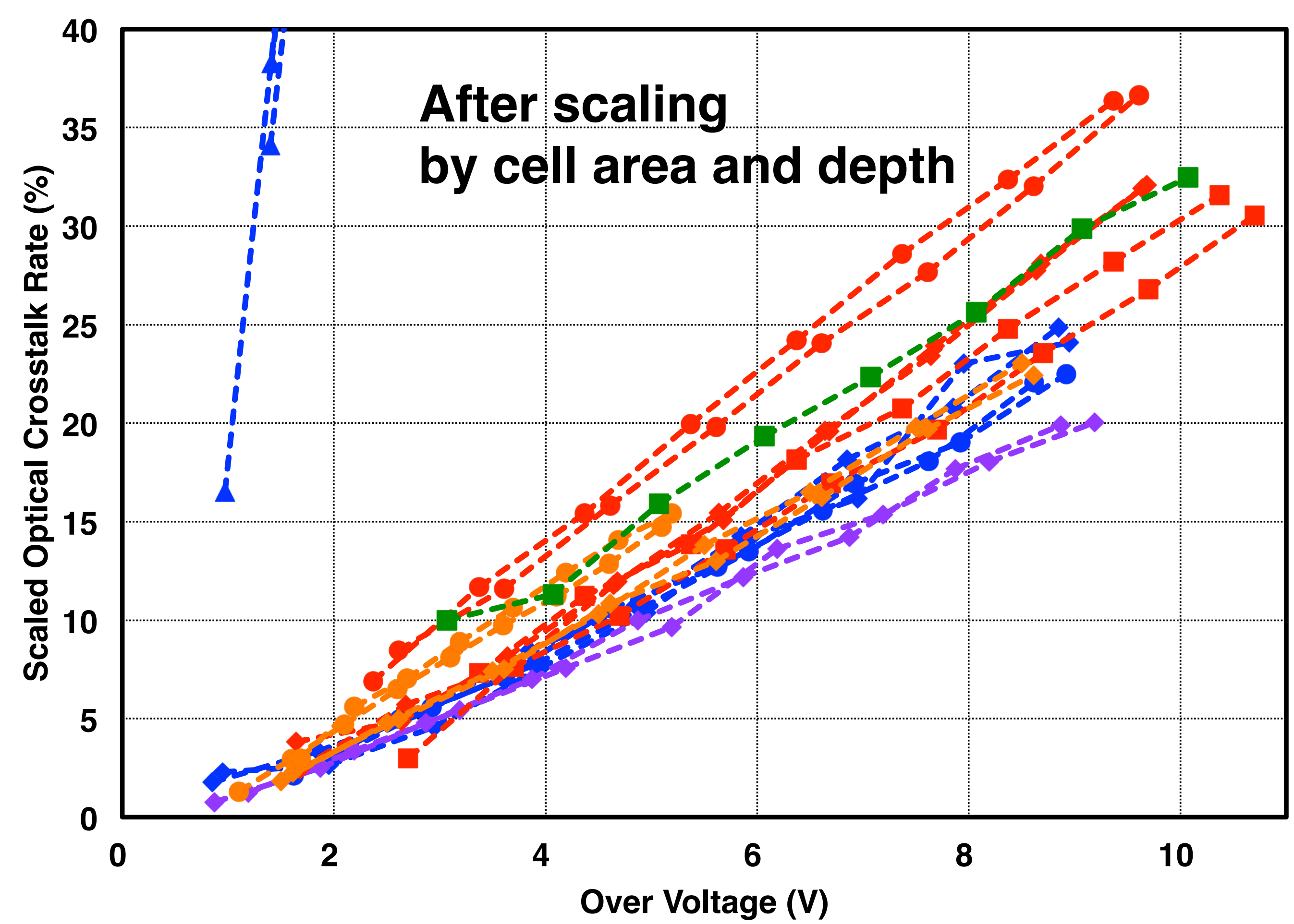
❖ Factor out cell capacitance dependence of crosstalk rate by scaling it with cell area and depth (assuming cell depth ∝ break down voltage)

- ✤ 3 mm pixel gives lower OCT than 6 mm pixel
  - ✦ OCT propagates partly via protection coating
- ✤ LVR is worse than LCT5 and LVR2
- ✤ Differences among individual SiPMs are small

— 3050
— 3075
— 6050
— 6075
— 7050

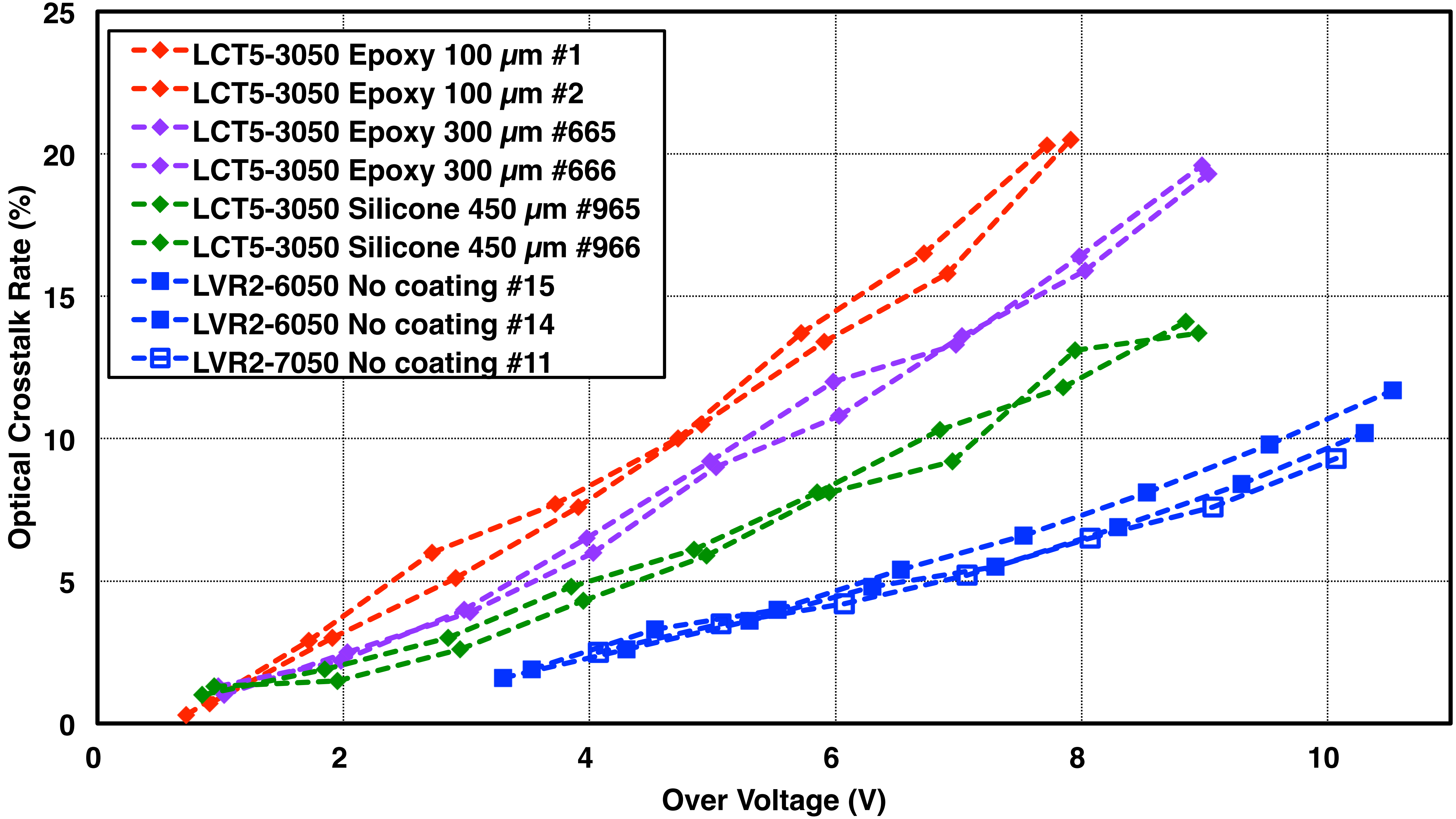
▲ REF
◆ LCT5
● LVR
■ LVR2





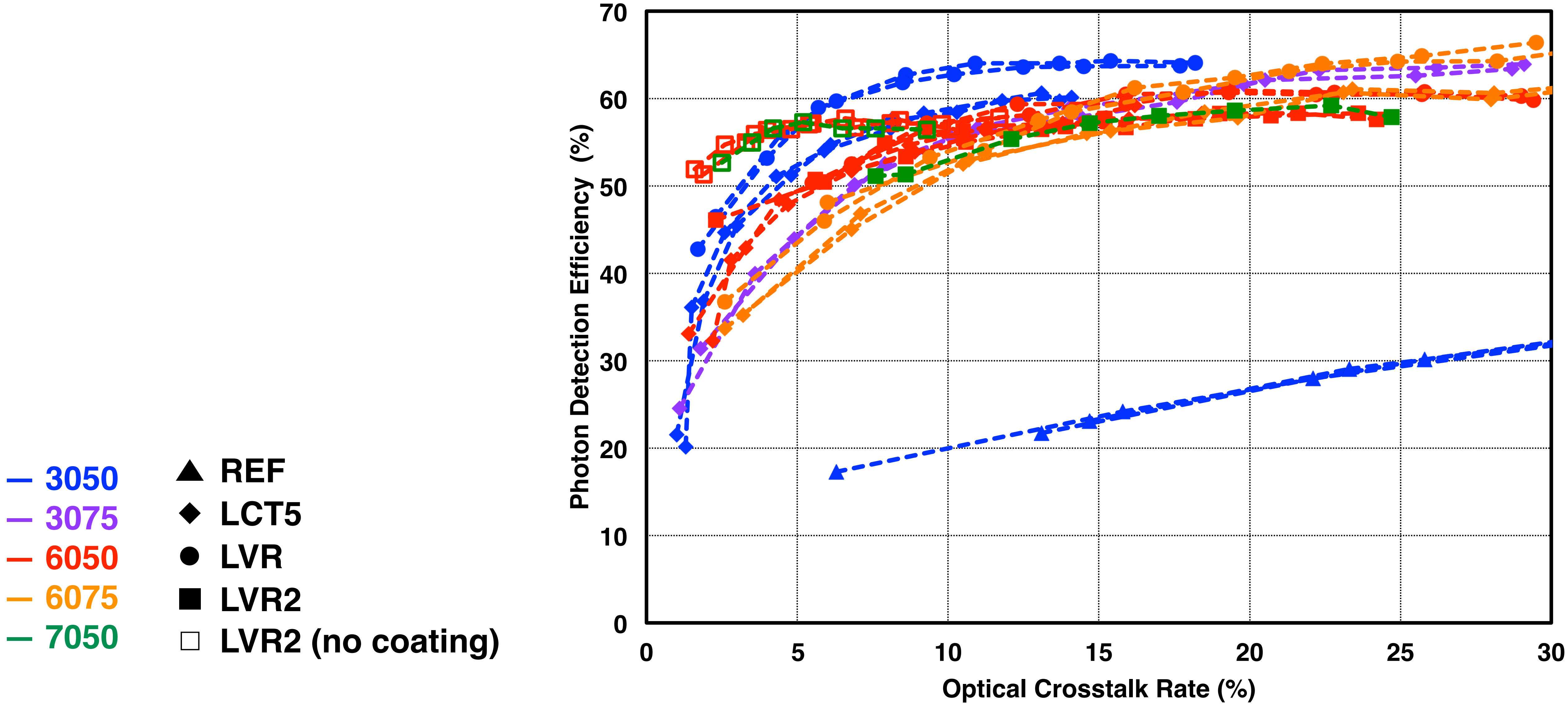
Crosstalk Dependence on Coating Thickness

- ❖ **Thicker coating or no coating give lower crosstalk**
  - ✤ **Further optimization of coating thickness is in progress**



PDE vs. Crosstalk

- ❖ **LVR2-6050 and LVR2-7050 with no coating gives best performance for OCT below 5%**
  - ✤ **Effect of OCT will be less than pile up of NSB in this regime**
- ❖ **LVR-3050 with coating gives best performance for OCT above 5%**
  - ✤ **Further optimization of coating thickness is critical**



Summary

- SiPM performance does not vary among individual devices within the same batch
- PDE dependence on the relative over voltage is very similar among Hamamatsu SiPM types if PDE is normalized by fill factor
- OCT is affected by protection coating
  - Smaller pixel size and thicker coating reduce OCT rate
  - No coating significantly reduces OCT rate
- LVR2-6050 and LVR2-7050 with no coating gives best performance for OCT below 5%
  - Effect of OCT will be less than pile up of NSB in this regime
- LVR-3050 with coating gives best performance for OCT above 5%
- Prospects
  - Optimize the coating thickness to minimize OCT rate
  - SST-2M will use >100k of 6-mm SiPMs over the next ~4 years