CTA report 158: Evaluation of a multi-pixel silicon photomultiplier for a Medium-Sized Telescope upgrade

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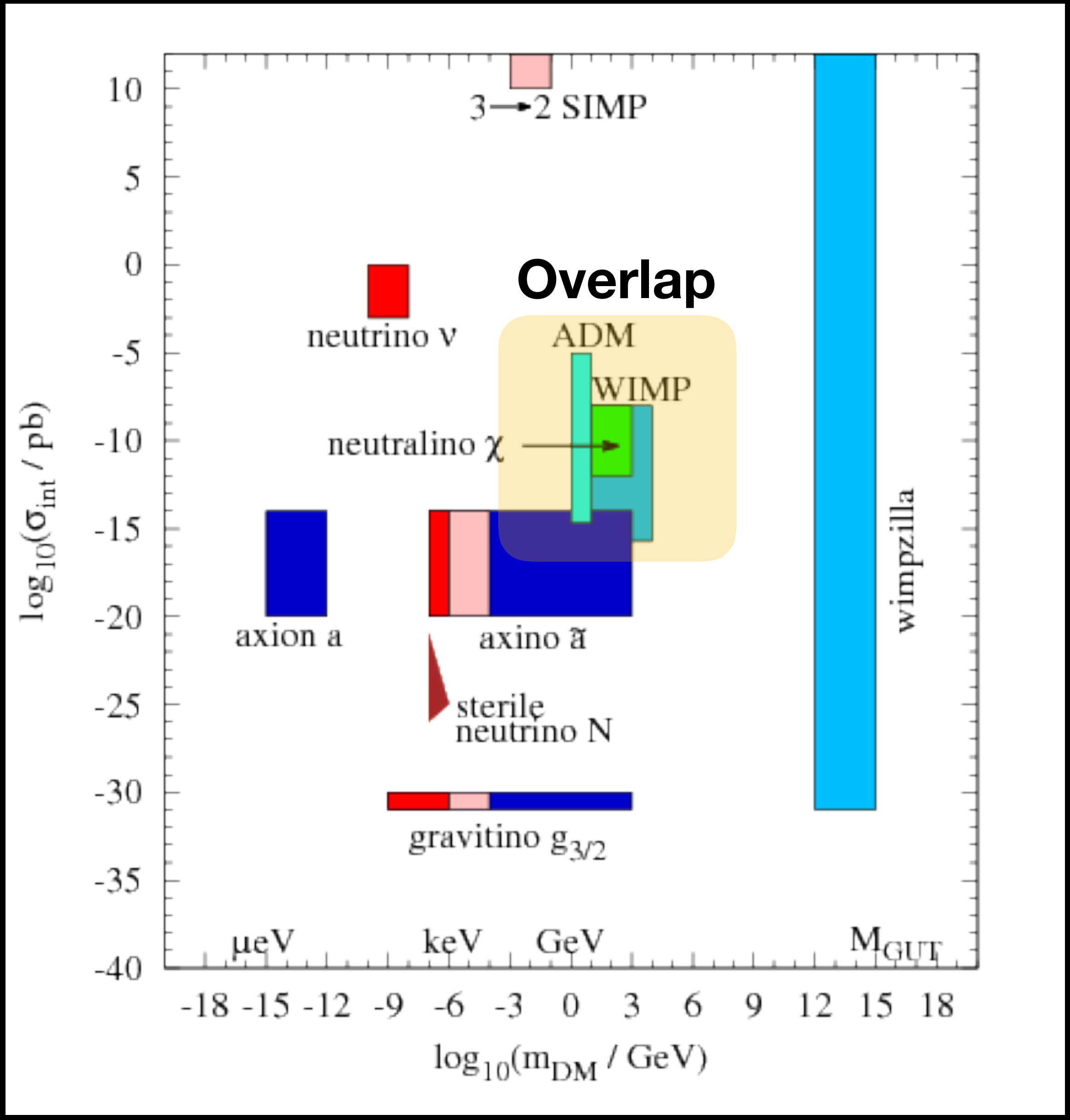
Weakly Interacting Massive Particle (WIMP)

Baer, Howard et al., **"Dark matter production in the early Universe: beyond the thermal WIMP paradigm",** Phys. Rept. 555 (2015)



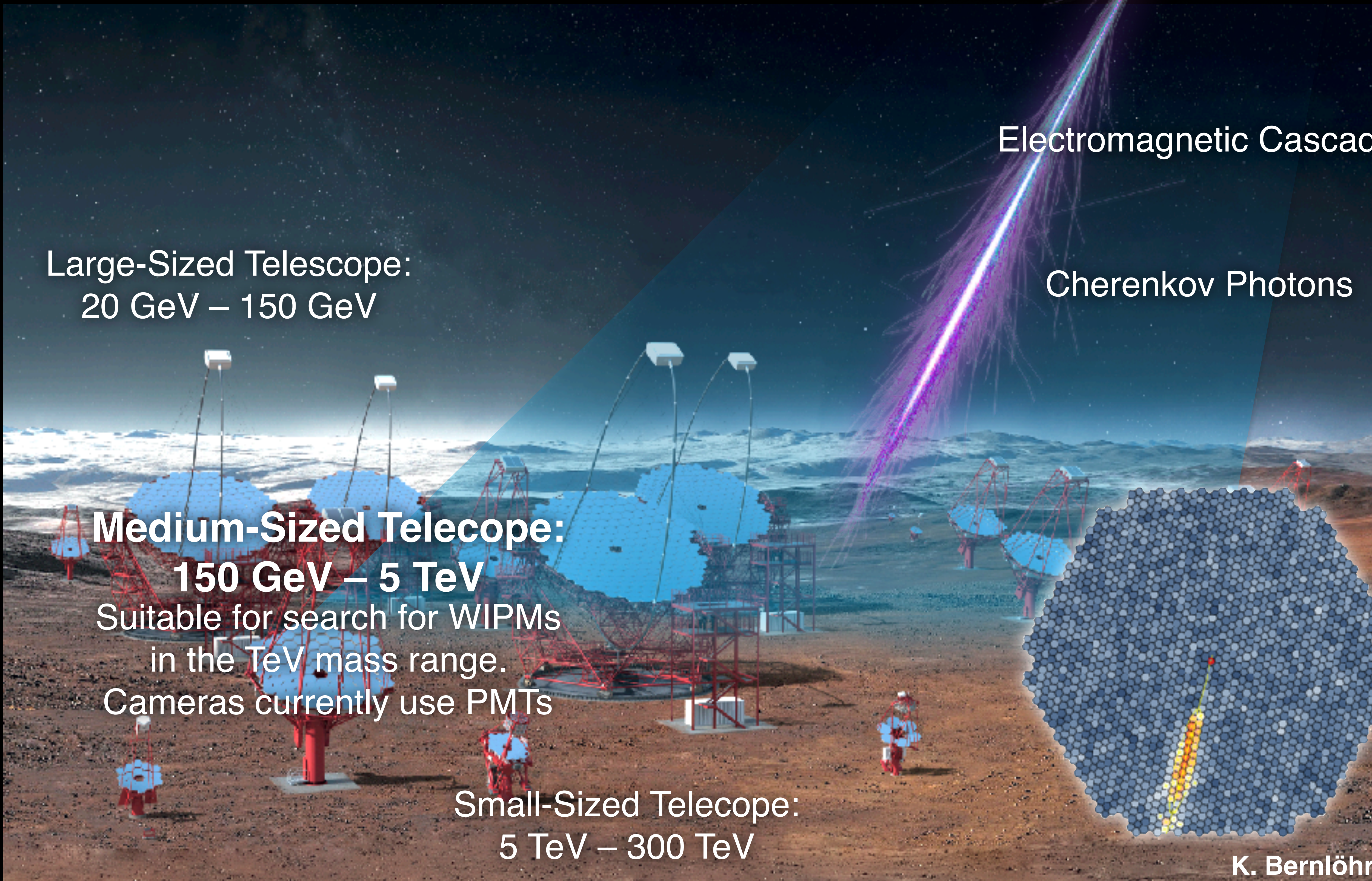
- "WIMP miracle"
  Mass and cross section calculated from the dark matter abundance corresponds to independent WIMP predictions by several promising particle physics models

- WIMPs are expected to annihilate and produce gamma rays

- $E_\gamma \approx \frac{1}{10} E_{\rm DM}$ can be detected most efficiently

Cherenkov Telescope Array and atmospheric Cherenkov imaging

Very-high-energy
Gamma Ray
(20 GeV – 300 TeV)

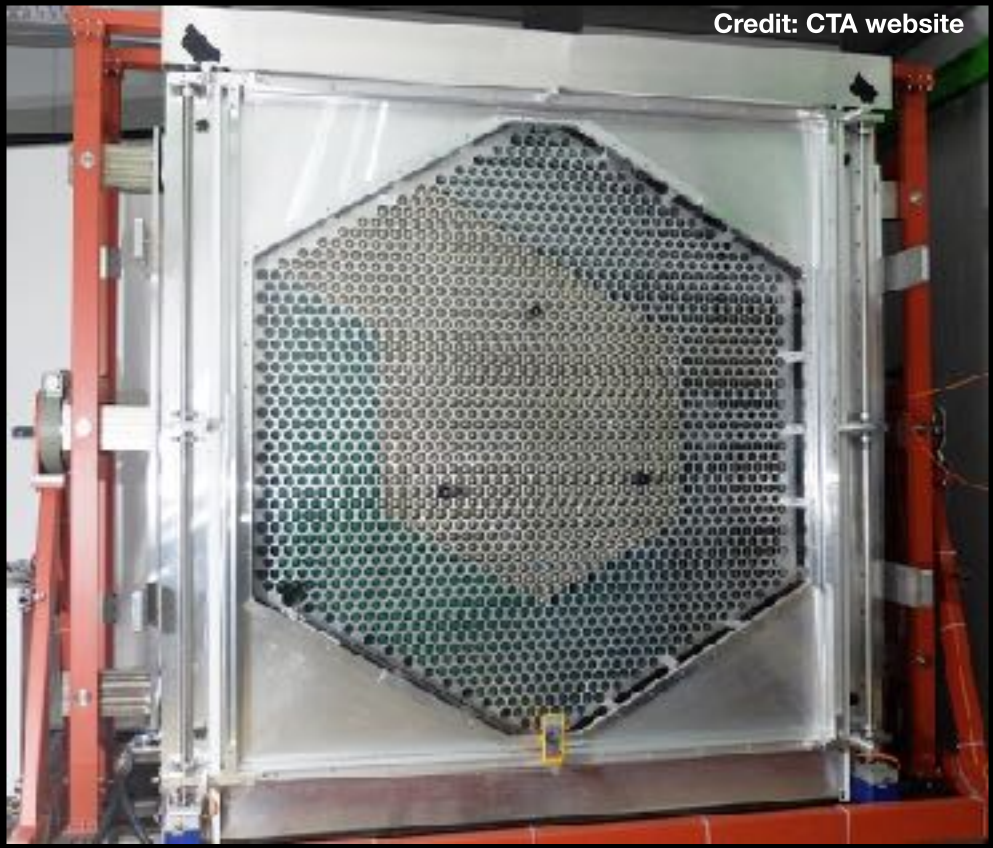


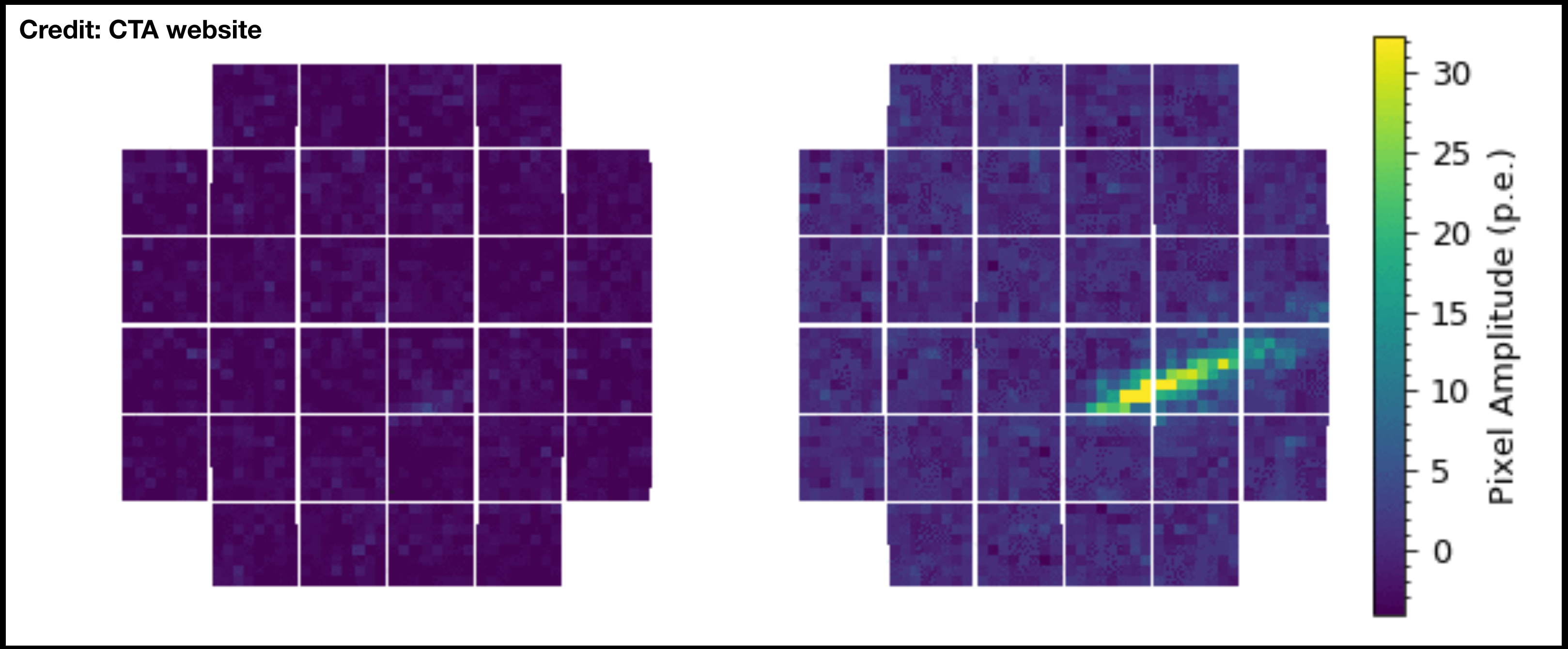
MST camera

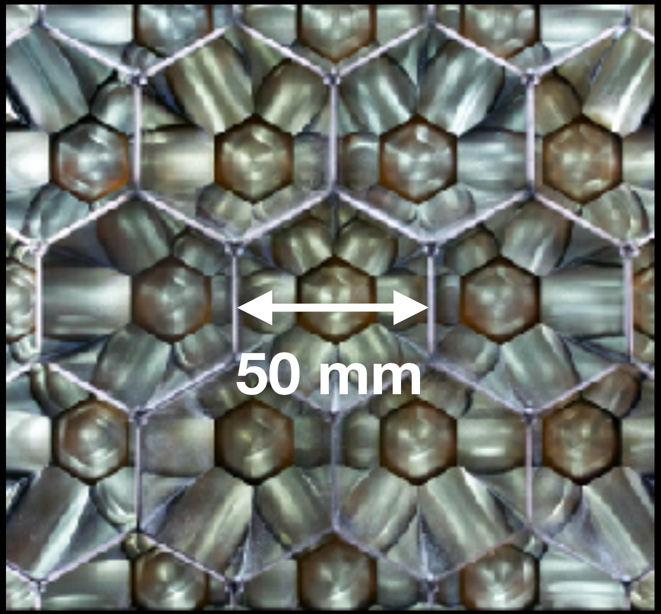
High photon detection efficiency and high signal to noise ratio are required to detect faint Cherenkov flashes produced by gamma-ray showers

Photon density can be about ~300 photons per square meter in the case of 1 TeV showers (~50 photon signals per pixel)

Night sky background (NSB) rate is about 200 MHz (~2 photon signals / pixel for a 10 ns shower) in the case of MST







Credit: A. Okumura

~1800 pixels

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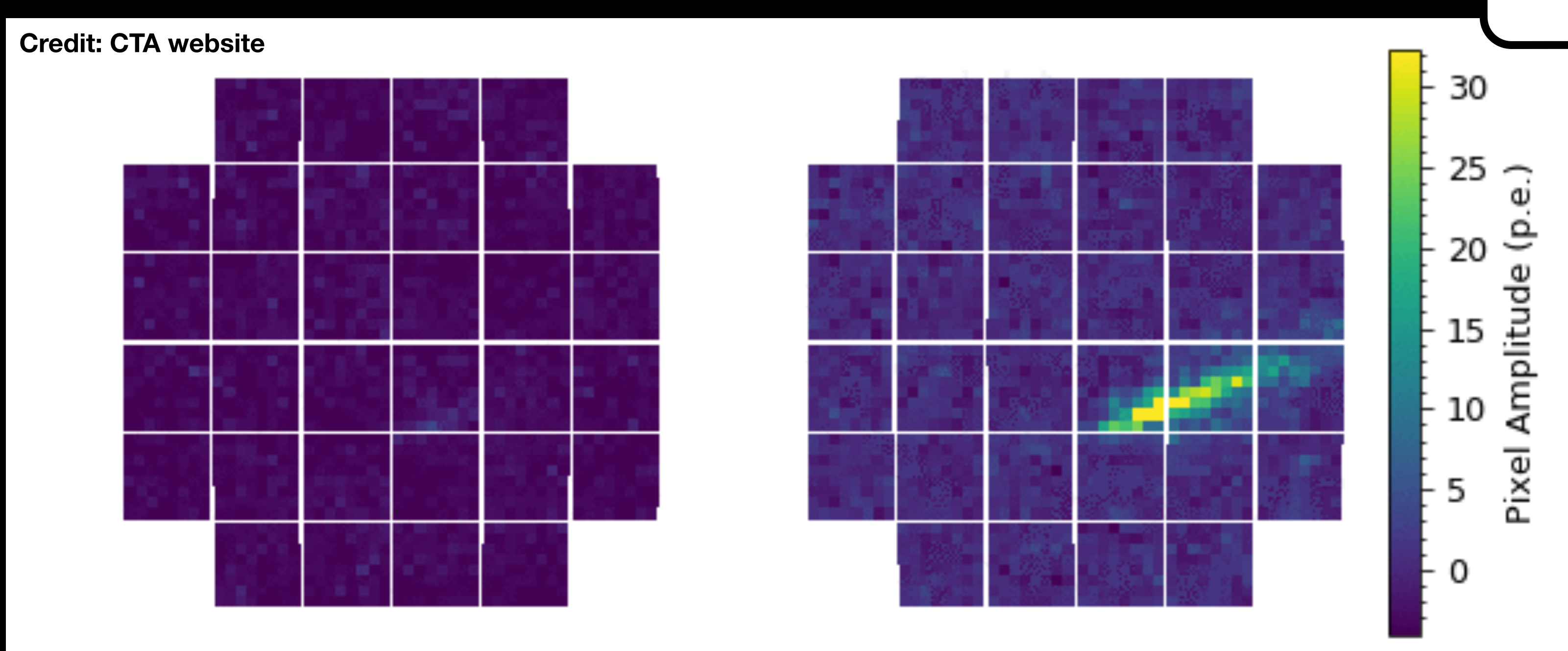

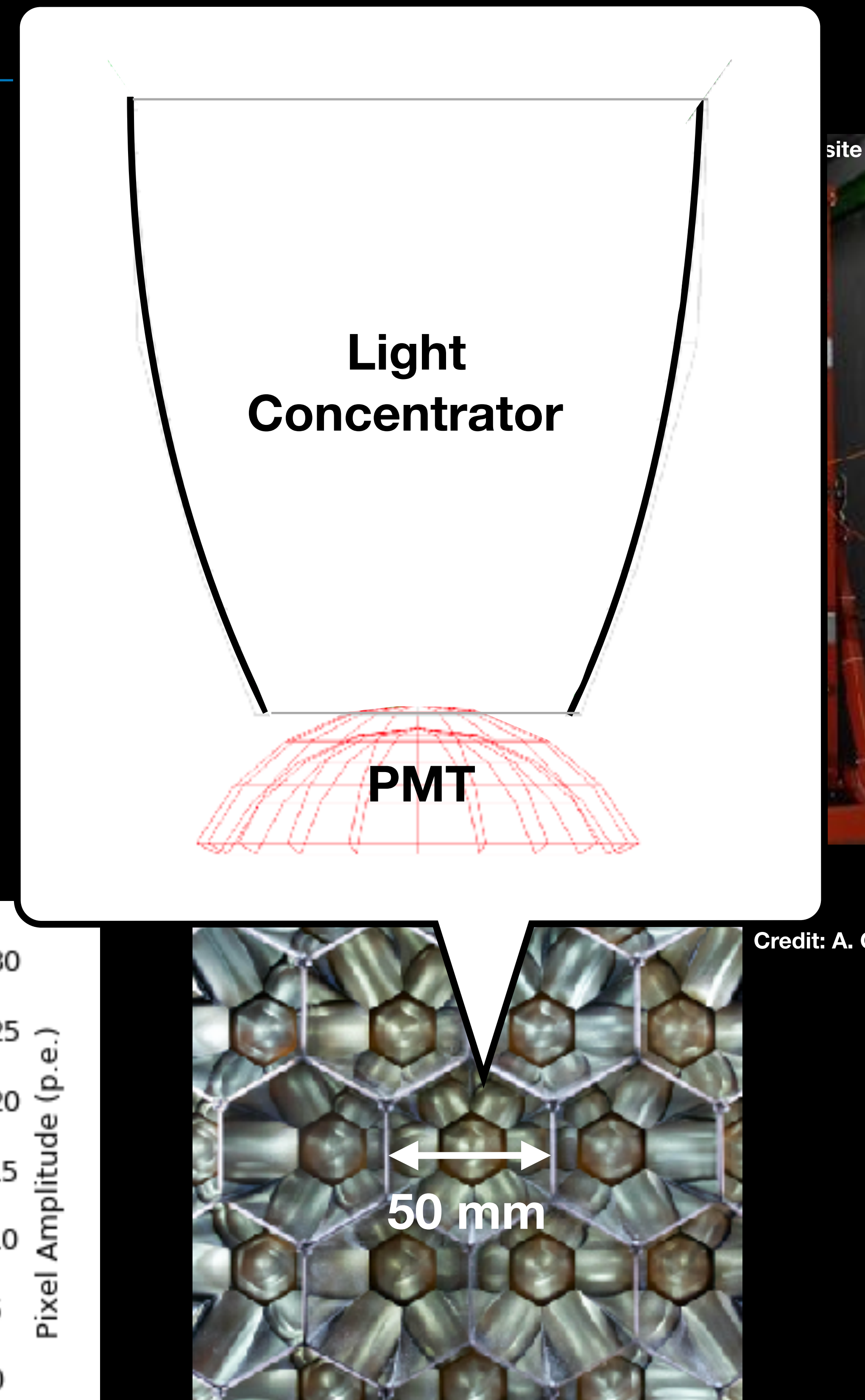

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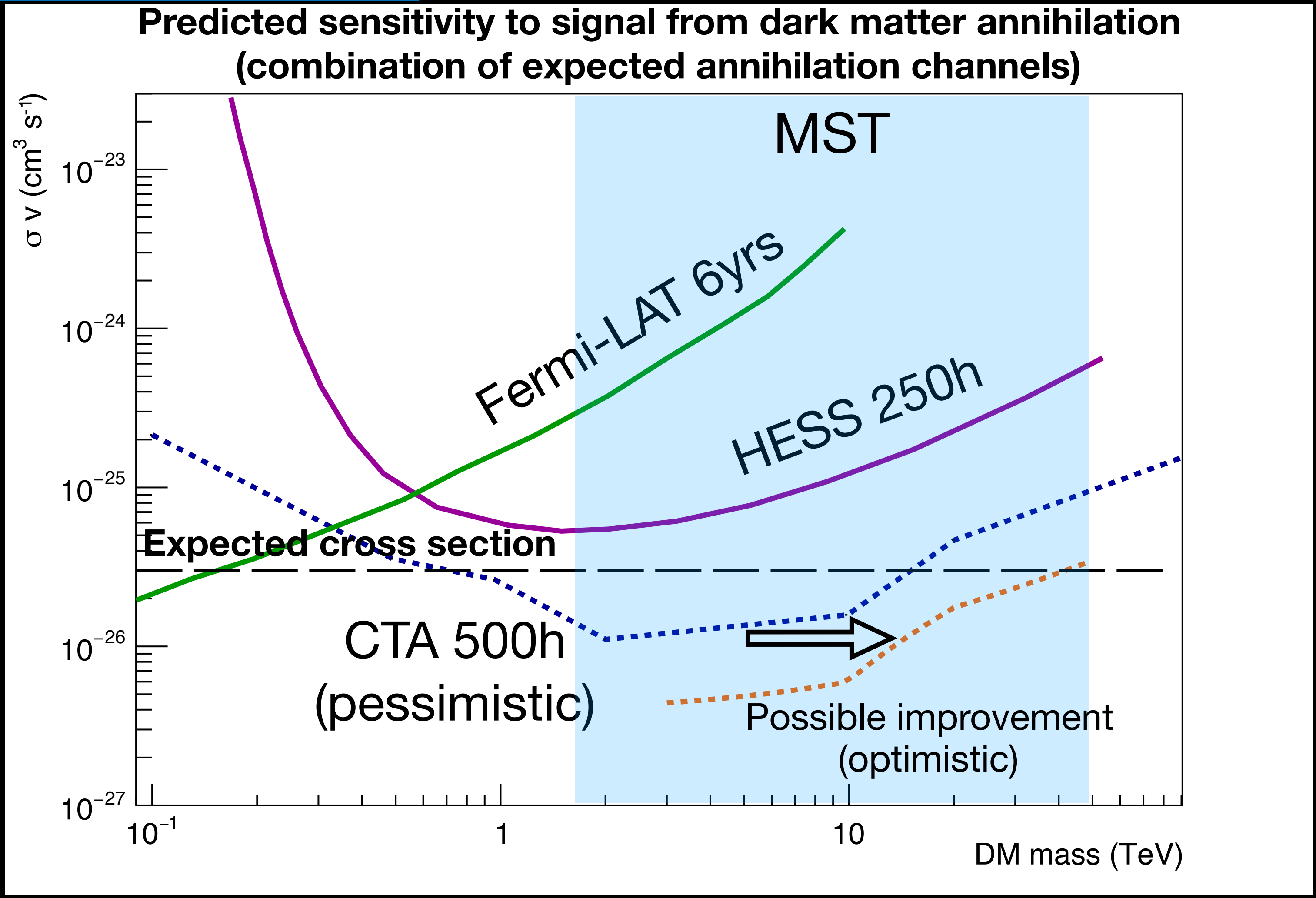
Reason to employ SiPMs

By using SiPM we can extend observation time allocated for dark matter search by up to a factor of 7, which will provide:

- Increased sensitivity
- Sensitivity in higher DM mass range



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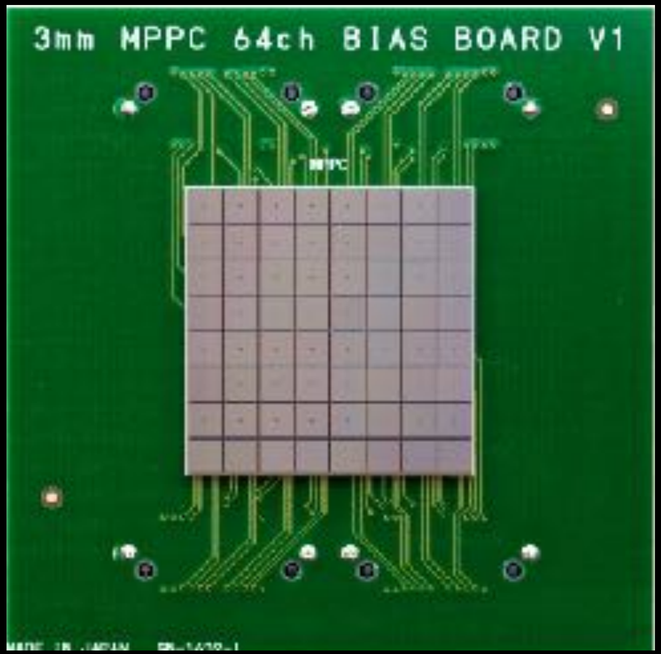
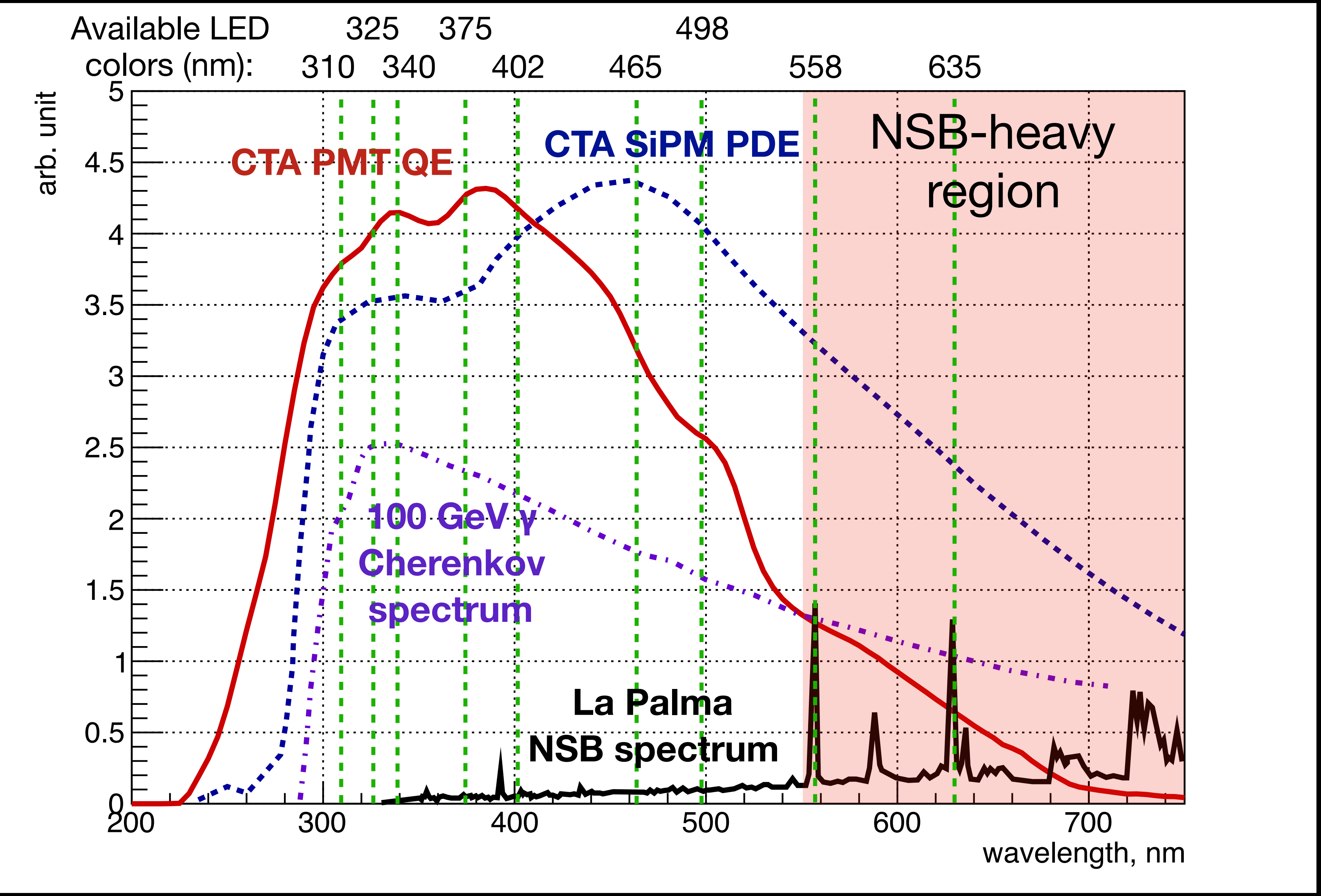
Features of silicon photomultipliers (SIPMs)
○ **NSB tolerant. Operable under full moon (100xNSB)**
○ High PDE (up to 58%)
○ Compact, low voltage (60V)
× Too sensitive to NSB in > 550 nm range
× Optical crosstalk, high dark count rate



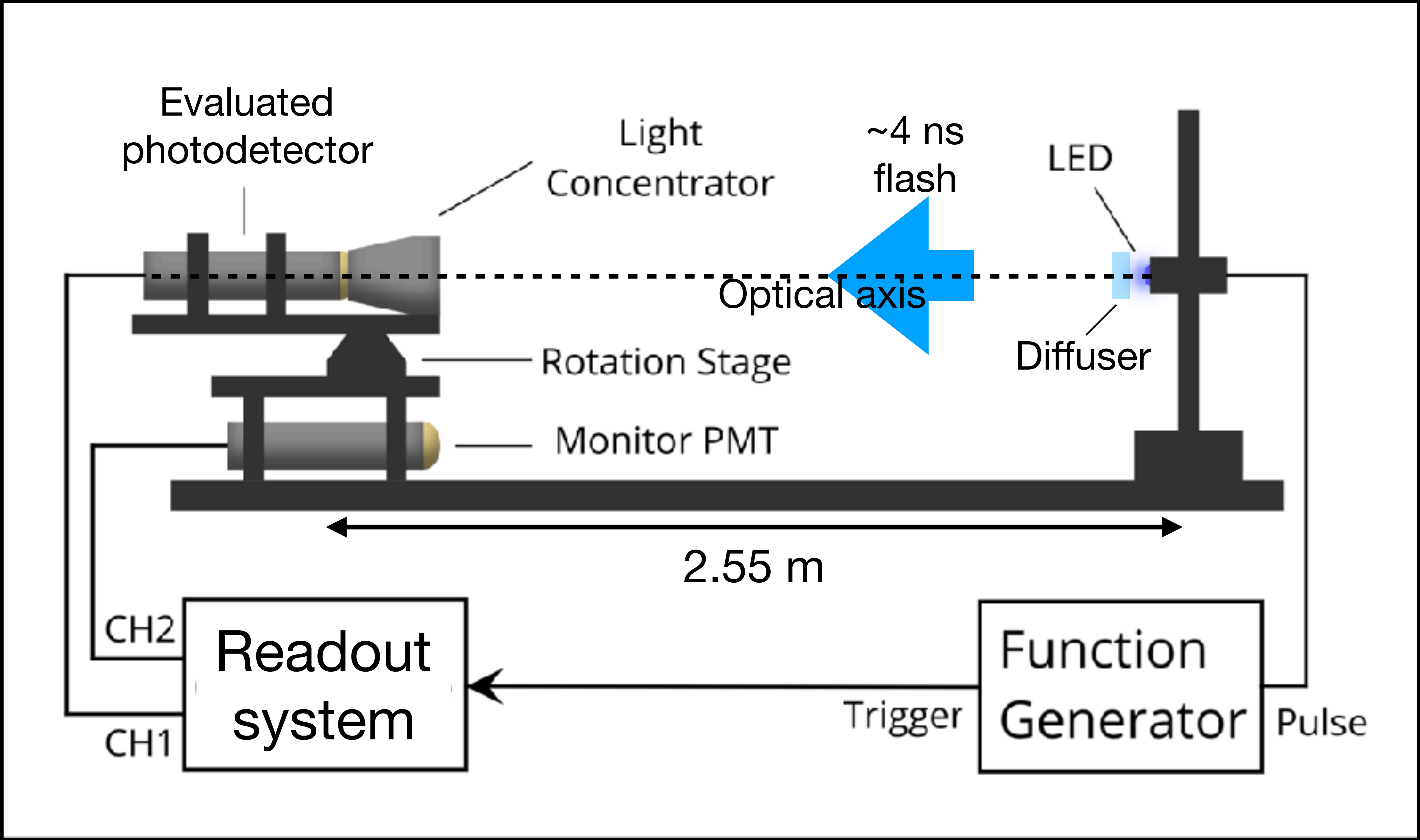
Comparison with current photodetectors

Viability criterion: same or better total Cherenkov light yield and SNR

- Can not evaluate just by looking at PDE and QE because of light concentrators
- Measurement is necessary due to complex angular dependence of QE and PDE
- Limited number of LED colors. Interpolation by simulation is necessary



Measurement setup



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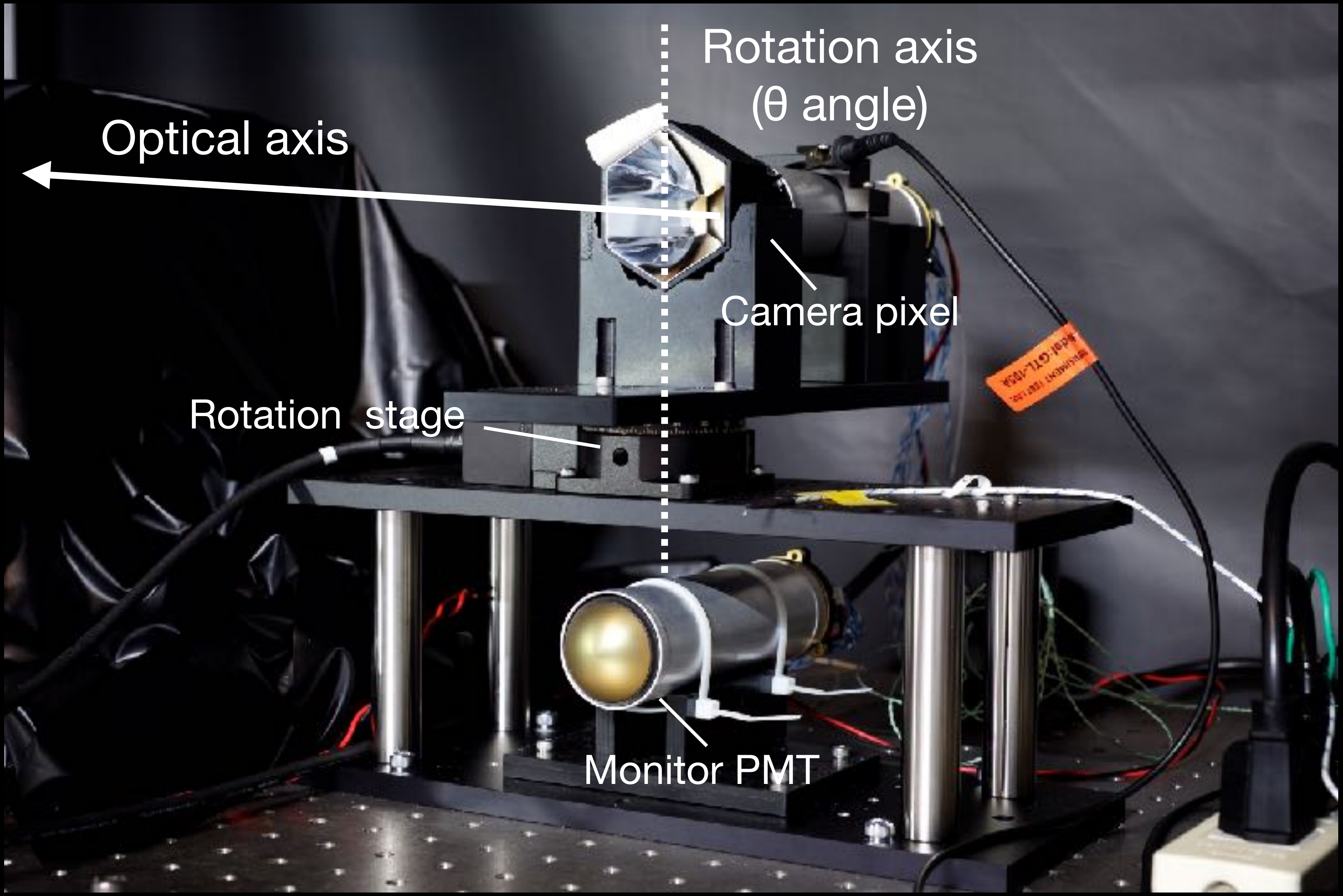
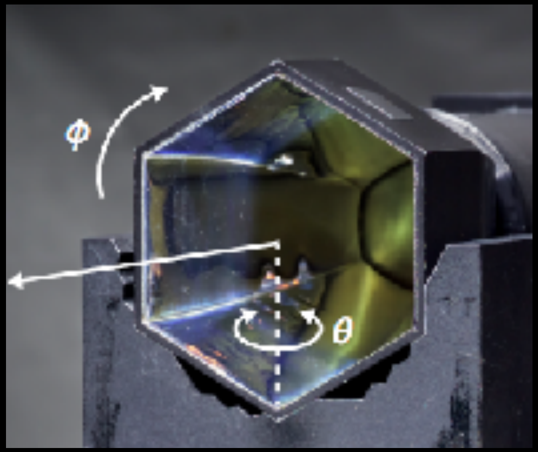


Credit: A. Okumura

Simulated devices

ROBAST tool was used for the ray-tracing simulation



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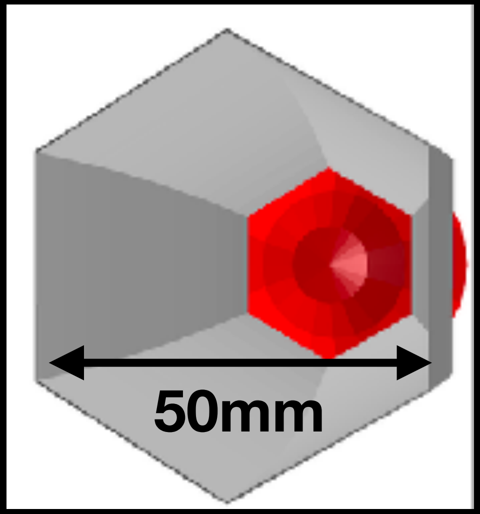

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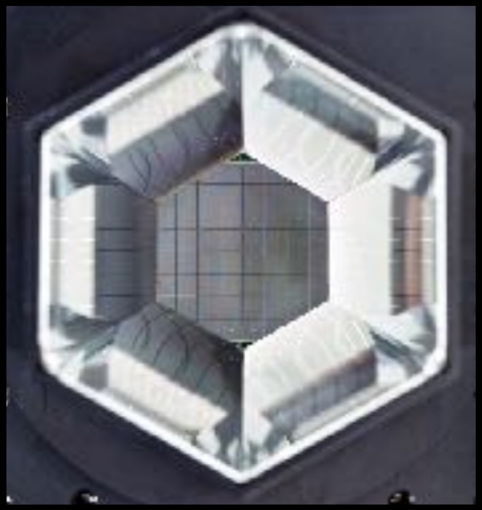
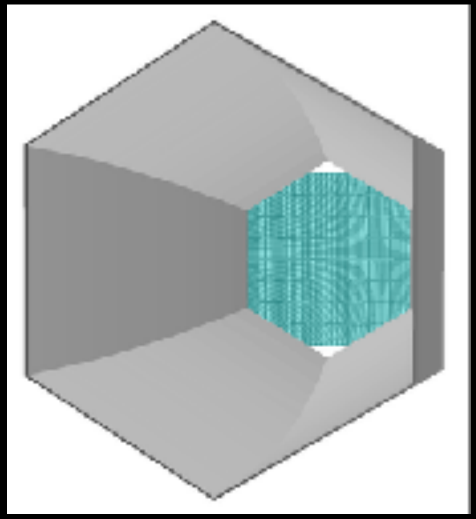




PMT

QE data by Hamamatsu Photonics

Angular sensitivity dependence (measurement)

Positional sensitivity dependence (measurement)

Anode collection efficiency (95% assumed)

Light concentrator

Simulated reflectance of a special high-reflectance coating

SiPM

Geometry (data sheet)

Refractive indices (measurements)

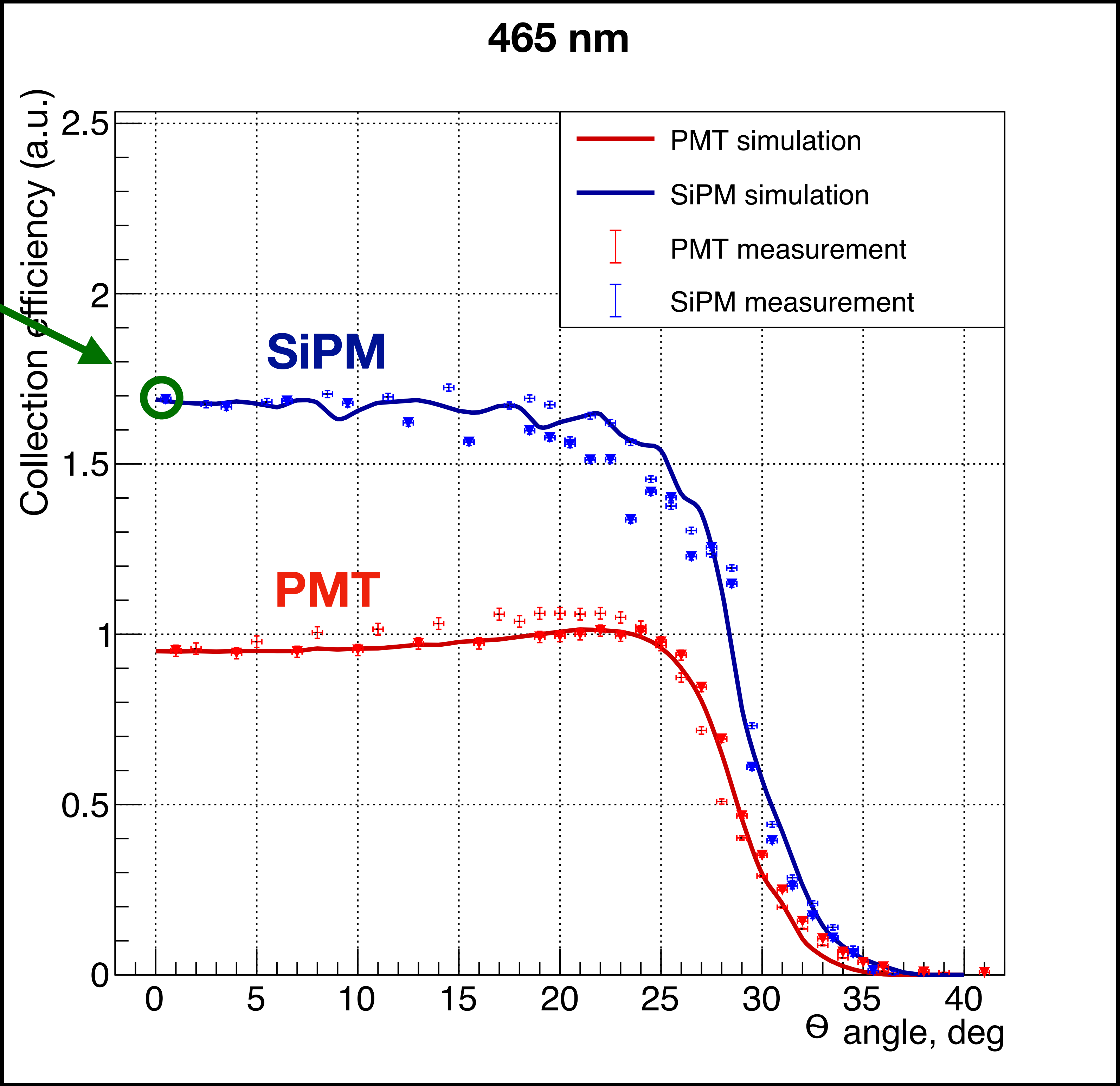
Absorption (measurement)

PDE data by Hamamatsu Photonics

Interference effects are ignored

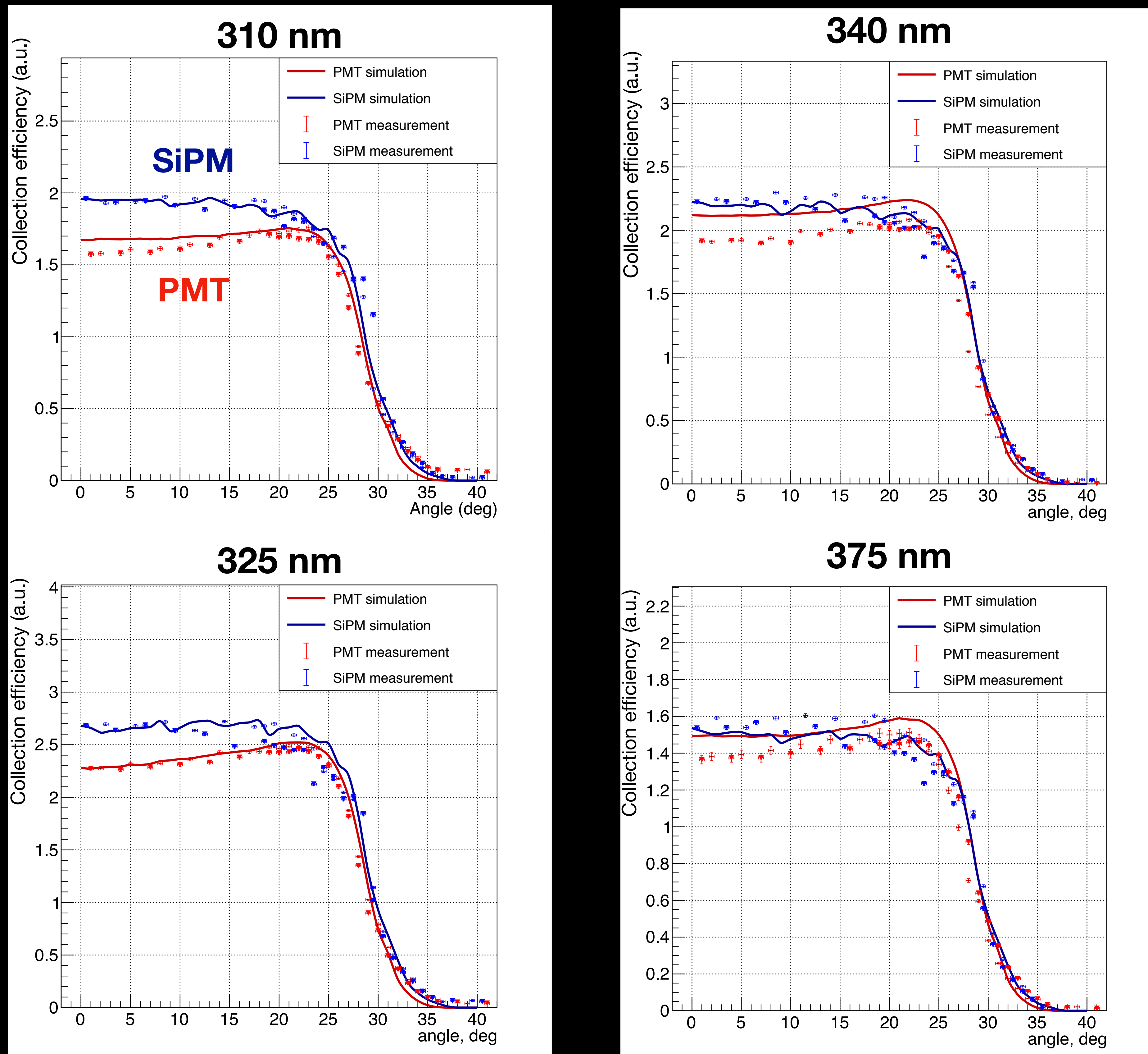
Collection efficiencies of camera pixels

- Simulation is normalized to match on-axis (0 deg.) SiPM data
- Measurement results are "folded" with respect to 0 deg.
- Marked points represent data taken for negative angles



Collection efficiencies of camera pixels

- Simulation shows general consistency with experiment
- The largest discrepancy is ~17% at 402 nm
- Most of the discrepancy likely comes from uncertain PDE of SiPM



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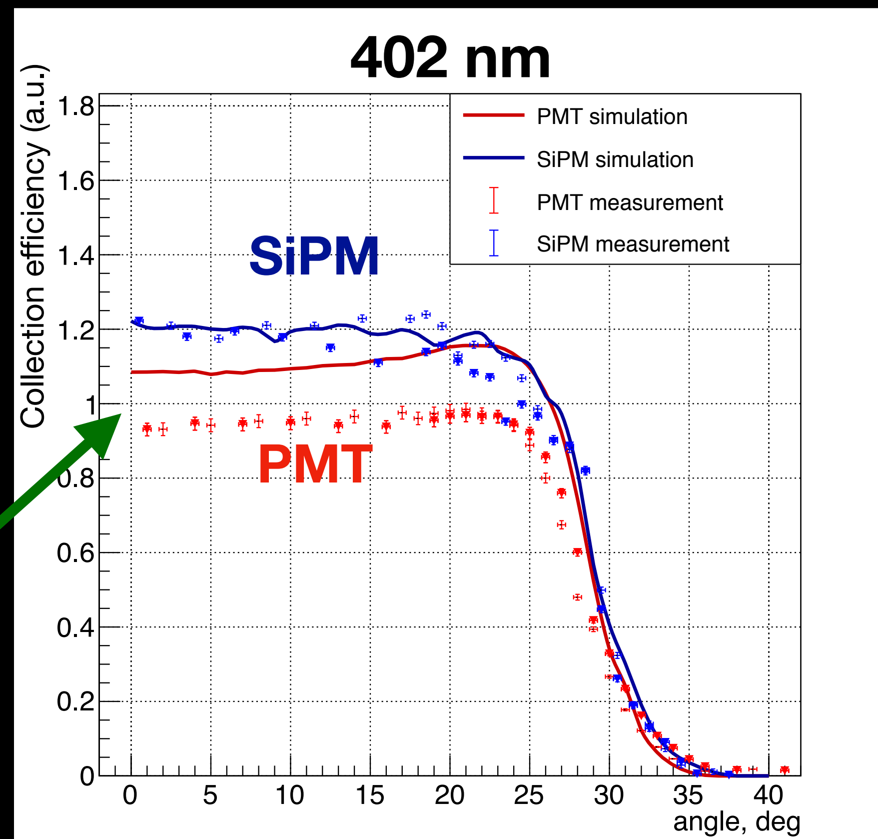
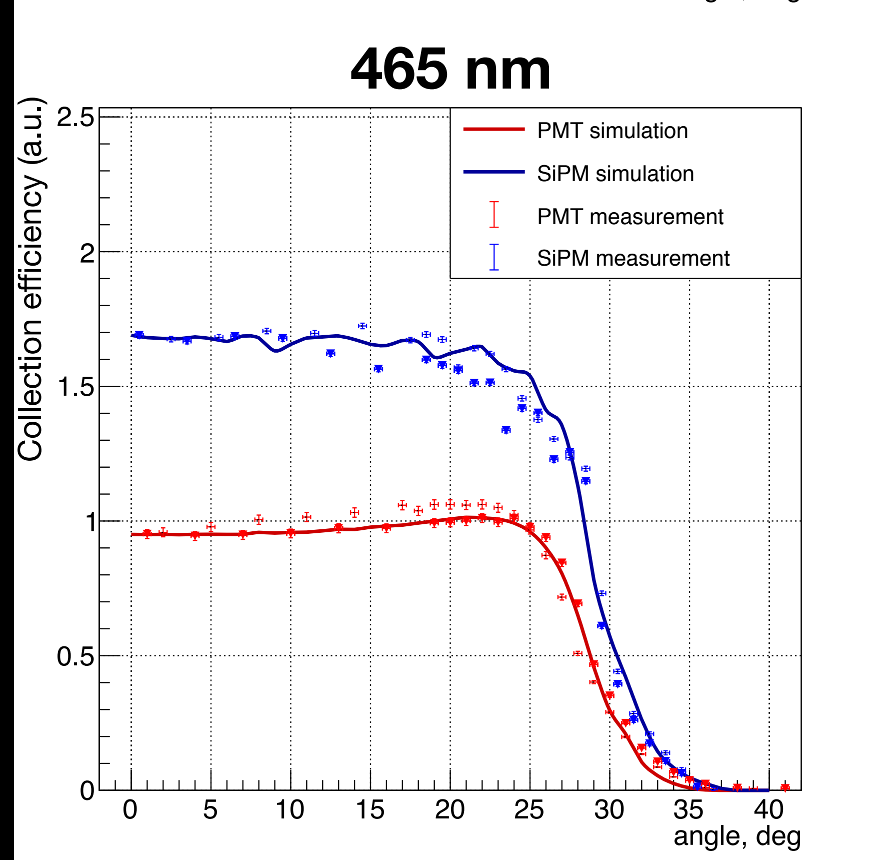
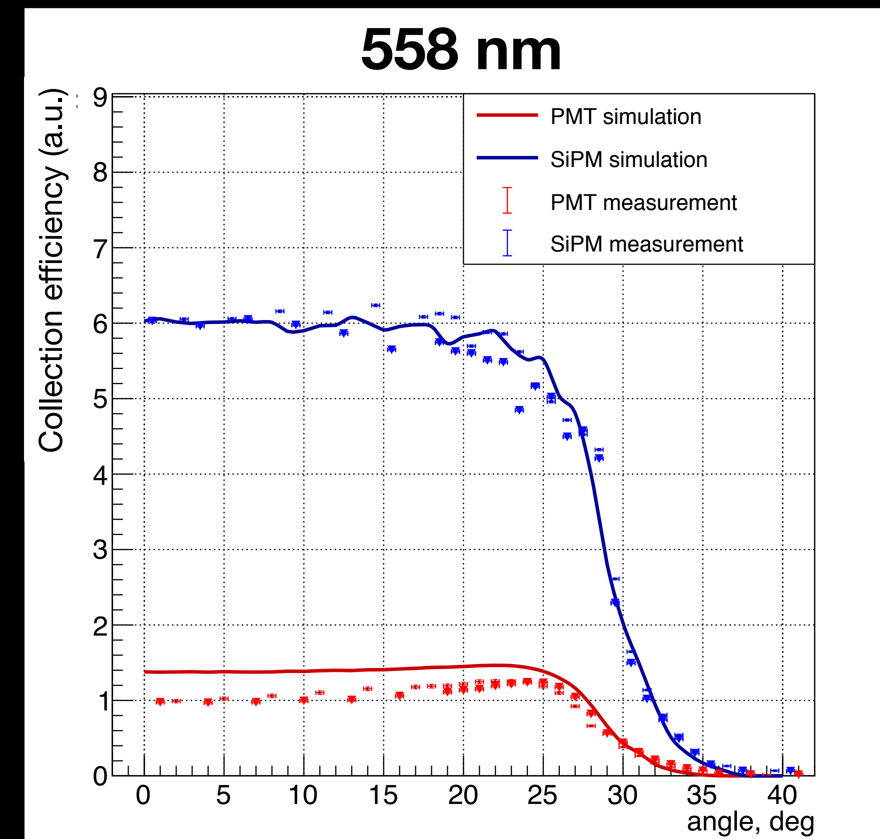
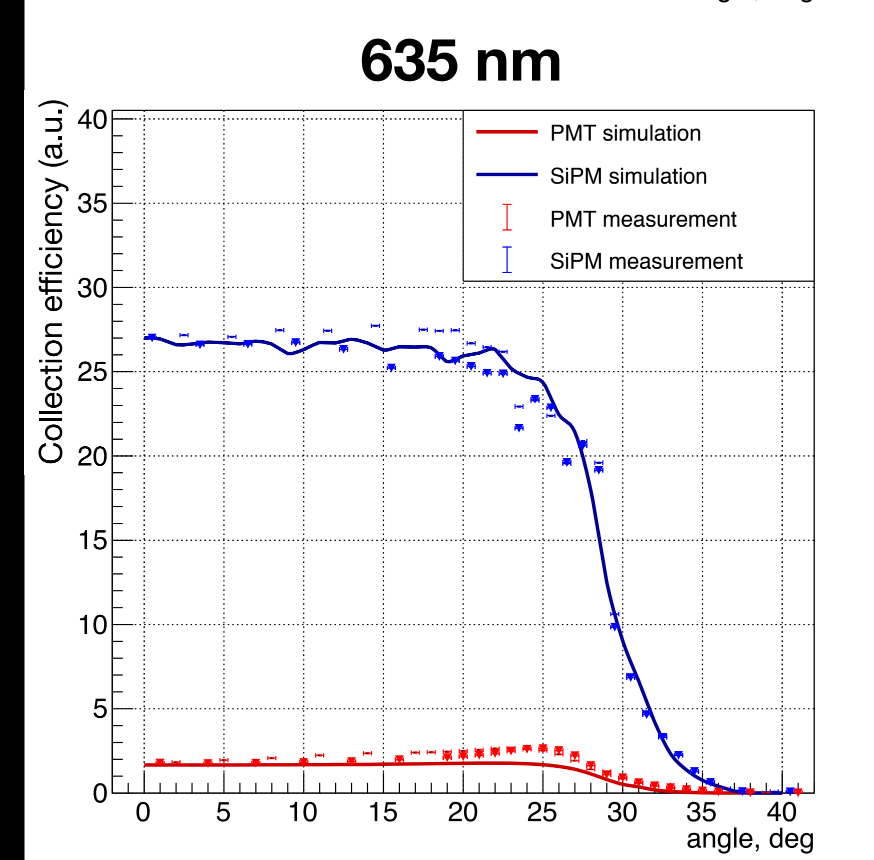
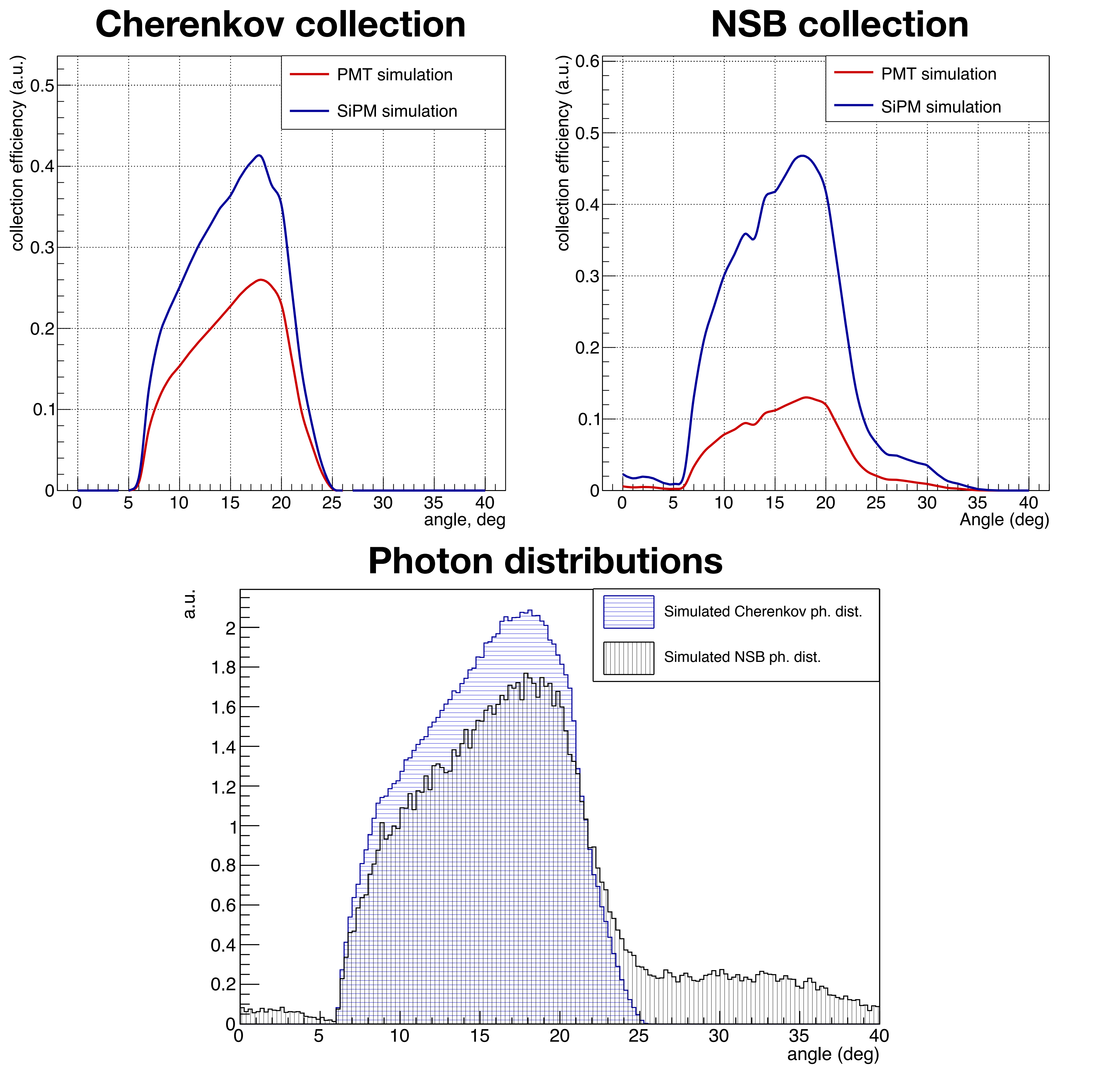








Light yields of camera pixels (300-750 nm)



Total light yields:

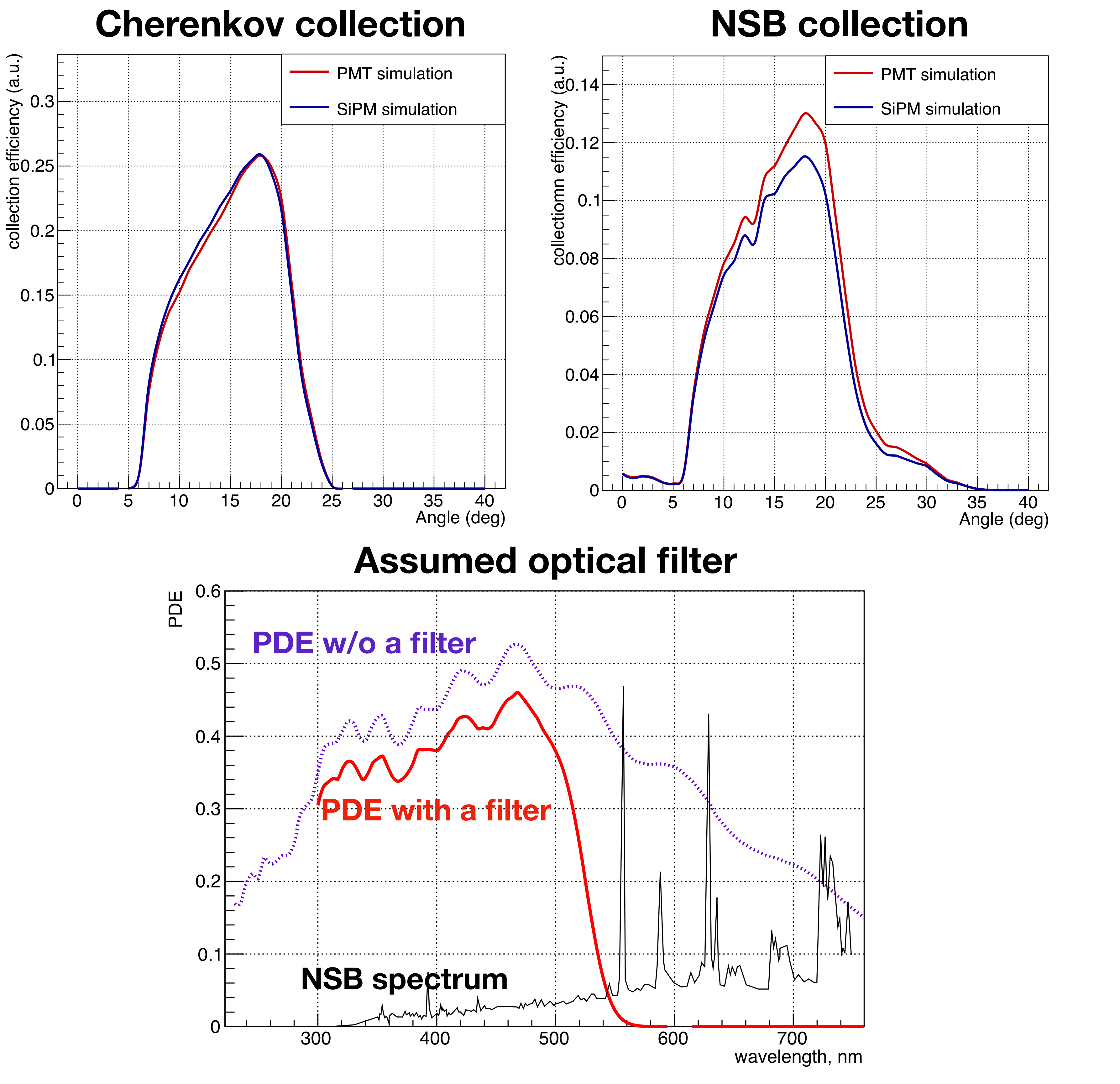
$$\frac{Y_{\mathrm{Cher}}(\mathrm{SiPM})}{Y_{\mathrm{Cher}}(\mathrm{PMT})} = 1.60$$

$$\frac{Y_{\mathrm{NSB}}(\mathrm{SiPM})}{Y_{\mathrm{NSB}}(\mathrm{PMT})} = 3.65$$

Higher Cherenkov photon yield at the cost of a large increase in sensitivity to NSB

$\frac{\mathrm{S}}{\sqrt{\mathrm{NSB}}}$ decreases by 1.2

Light yields of camera pixels (300-750 nm), with a filter



Total light yields with a filter on a SiPM:

$$\frac{Y_{\mathrm{Cher}}(\mathrm{SiPM})}{Y_{\mathrm{Cher}}(\mathrm{PMT})} = 1.00$$

$$\frac{Y_{\mathrm{NSB}}(\mathrm{SiPM})}{Y_{\mathrm{NSB}}(\mathrm{PMT})} = 0.88$$

Which means SiPM might surpass PMT in terms of performance even under normal NSB conditions

Summary

Our results:

- Automated measurement setup for comparison of relative SiPM / PMT performance
- Ray-tracing simulation with adjustable parameters that shows general consistency with the measurement

Our estimation indicates that SiPM can detect the same amount of Cherenkov photons and less NSB light, which demonstrates viability of the SiPM option.

Current predictions **(with a filter)**:

- An increase of 7% in SNR
- Almost no change in Cherenkov light yield

To do:

- Have to understand the discrepancy between the simulation and measurement and improve the simulation