Evaluation of a multi-channel silicon photomultiplier with a light concentrator for Medium-Sized Telescopes of Cherenkov Telescope Array

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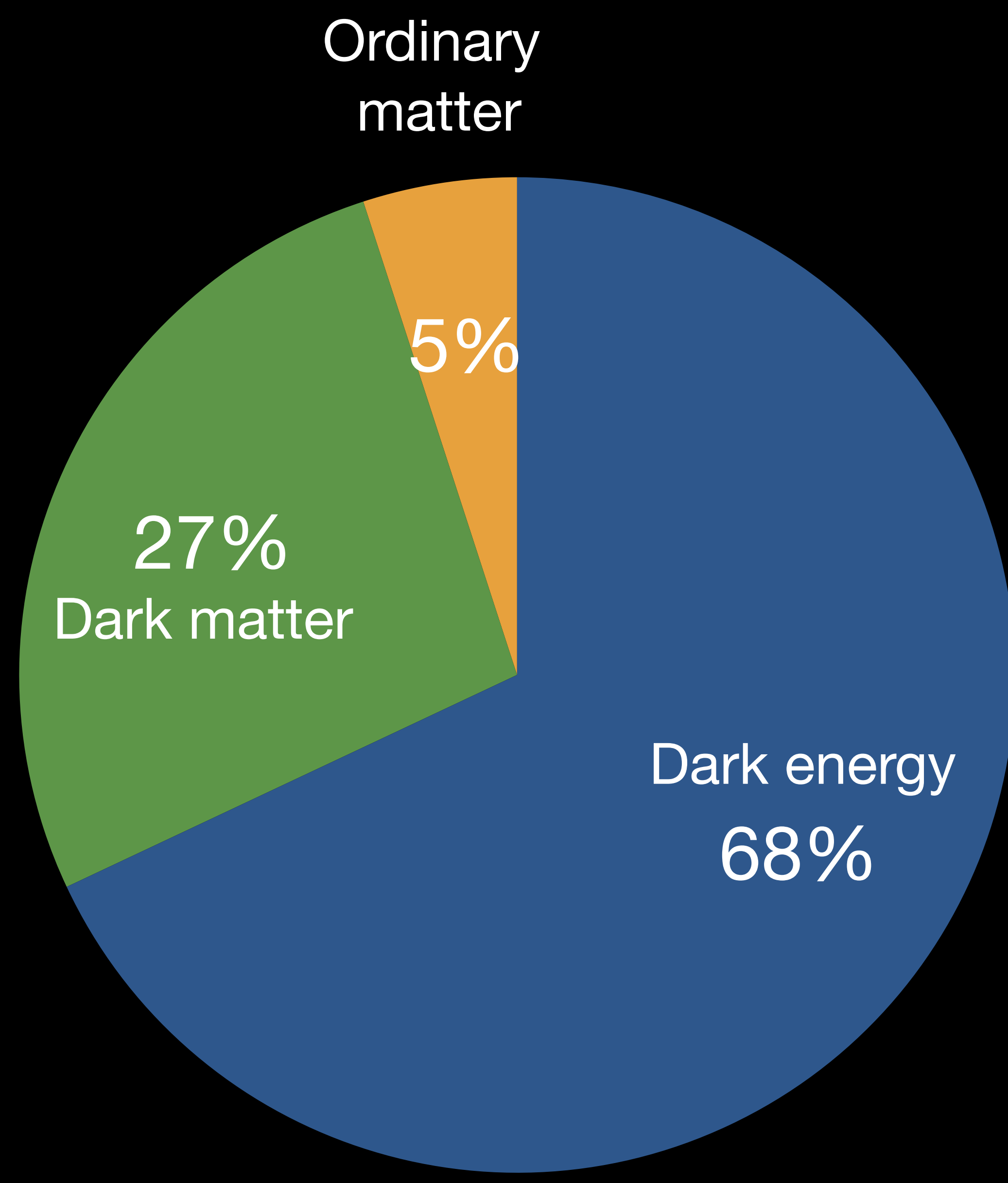
Dark matter (DM)

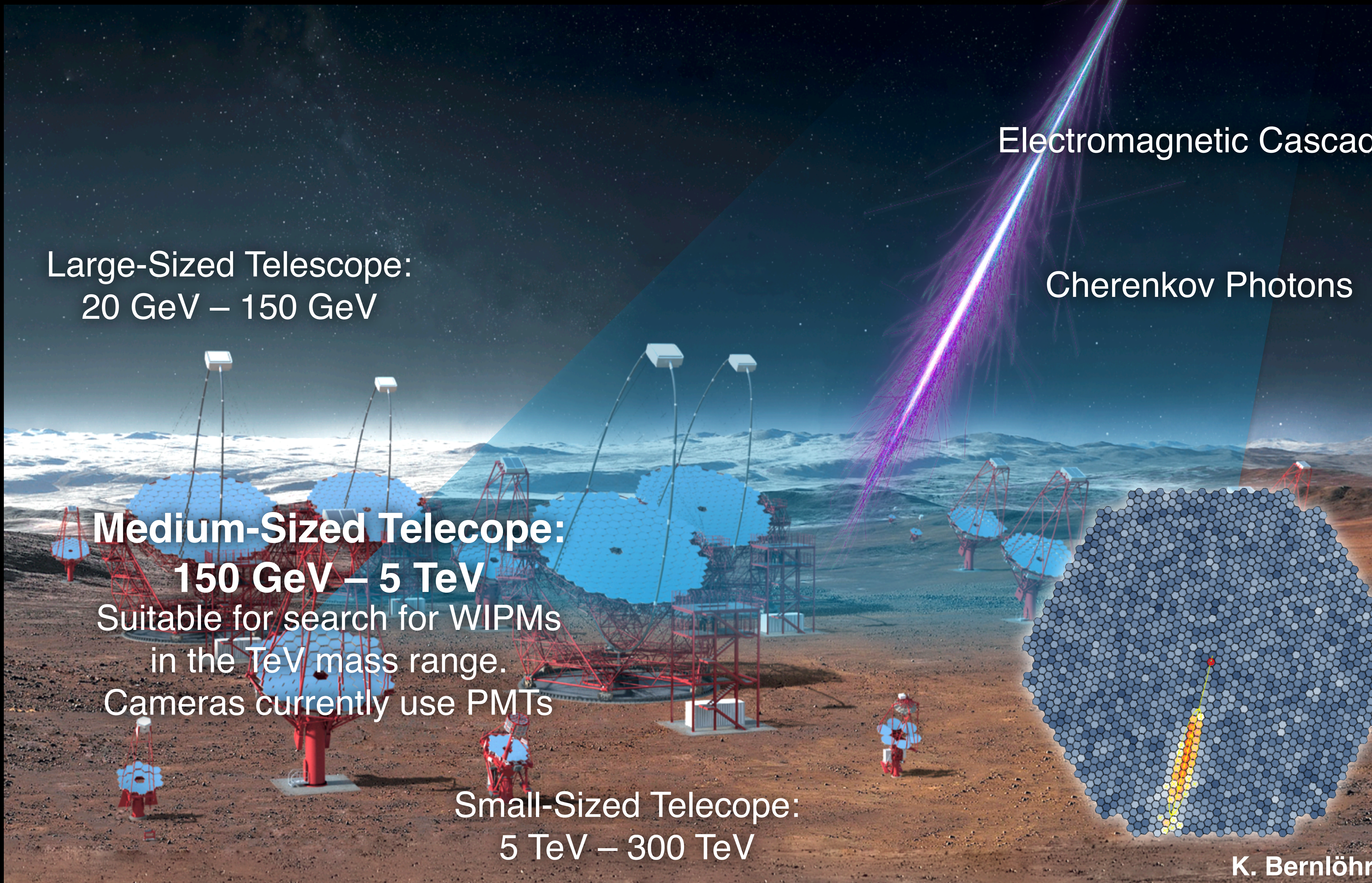
- Initially suggested as a solution to the "missing mass" problem in galaxy clusters
- Currently only 5% of the universe is understood, DM can account for another 27%
- Included in the most successful cosmological model ΛCDM (Lambda cold dark matter)
- We still do not know what constitutes dark matter
- We can search for hypothetical DM particles with gamma-ray observations



Energy distribution in the universe

Cherenkov Telescope Array and atmospheric Cherenkov imaging

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



MST camera

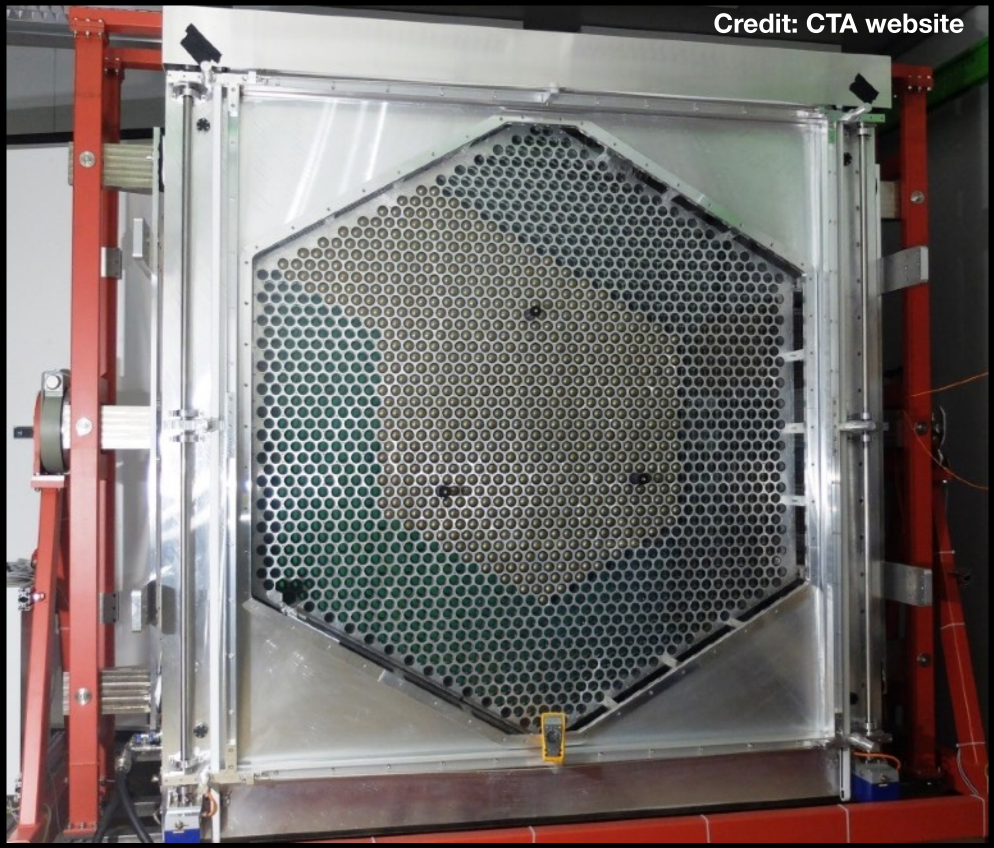
There are two MST camera projects:
FlashCAM - digital readout
NectarCAM - analog readout
Both feature ~1800 PMTs

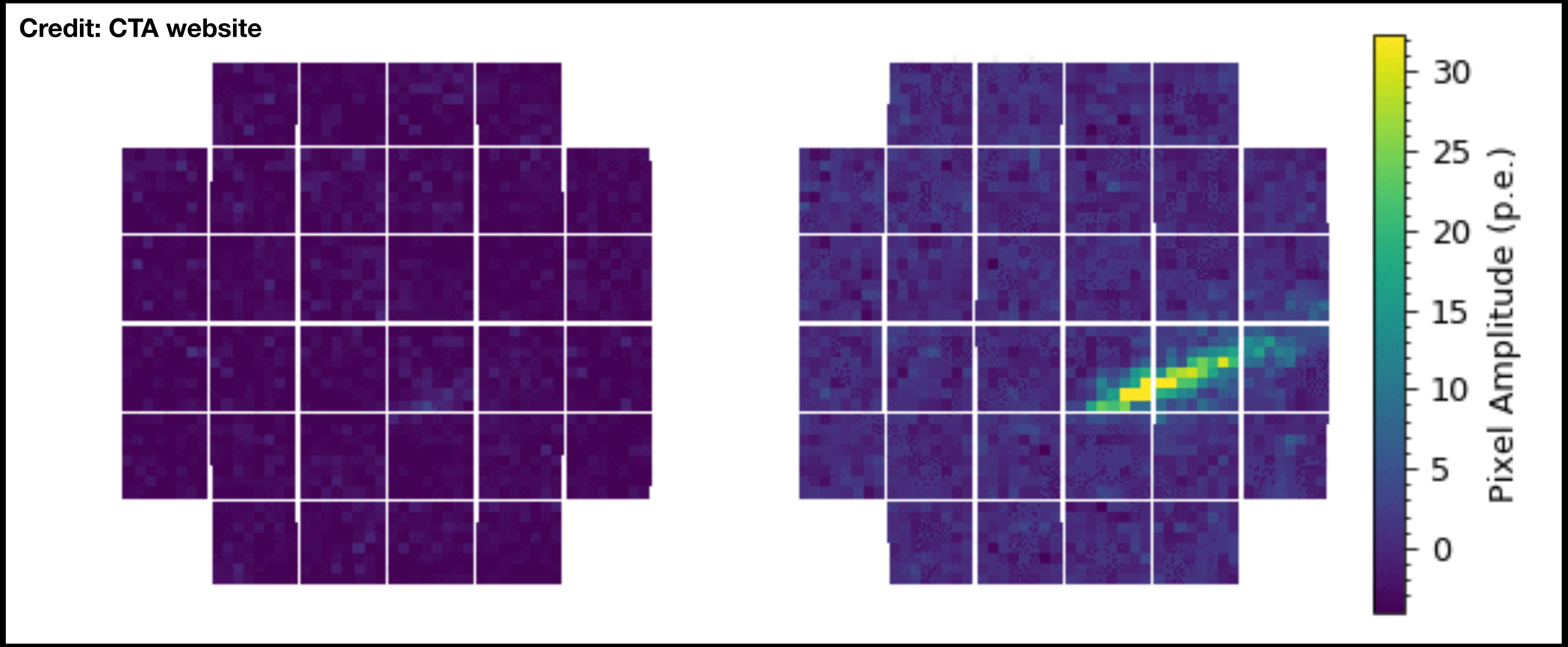
High photon detection efficiency and high signal to noise ratio are required to detect faint Cherenkov flashes produced by gamma-ray showers

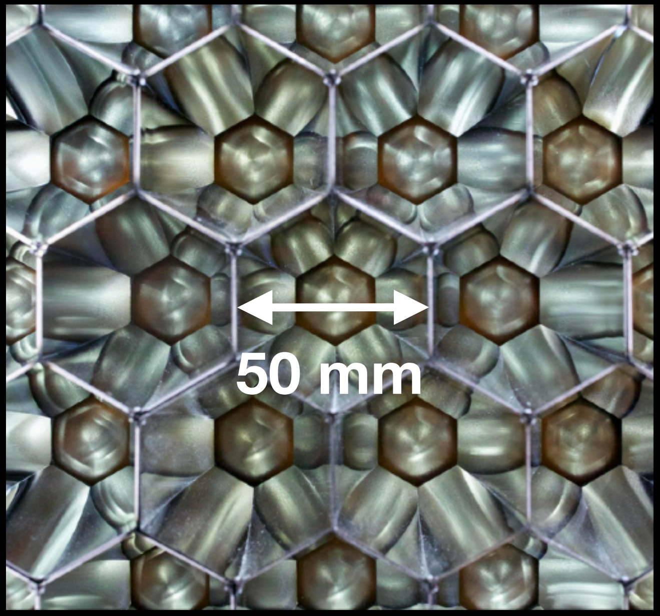
Photon density can be ~300 photons per square meter in the case of 1 TeV showers (~50 photon signals per pixel)

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

FlashCAM







Credit: A. Okumura

~1800 pixels

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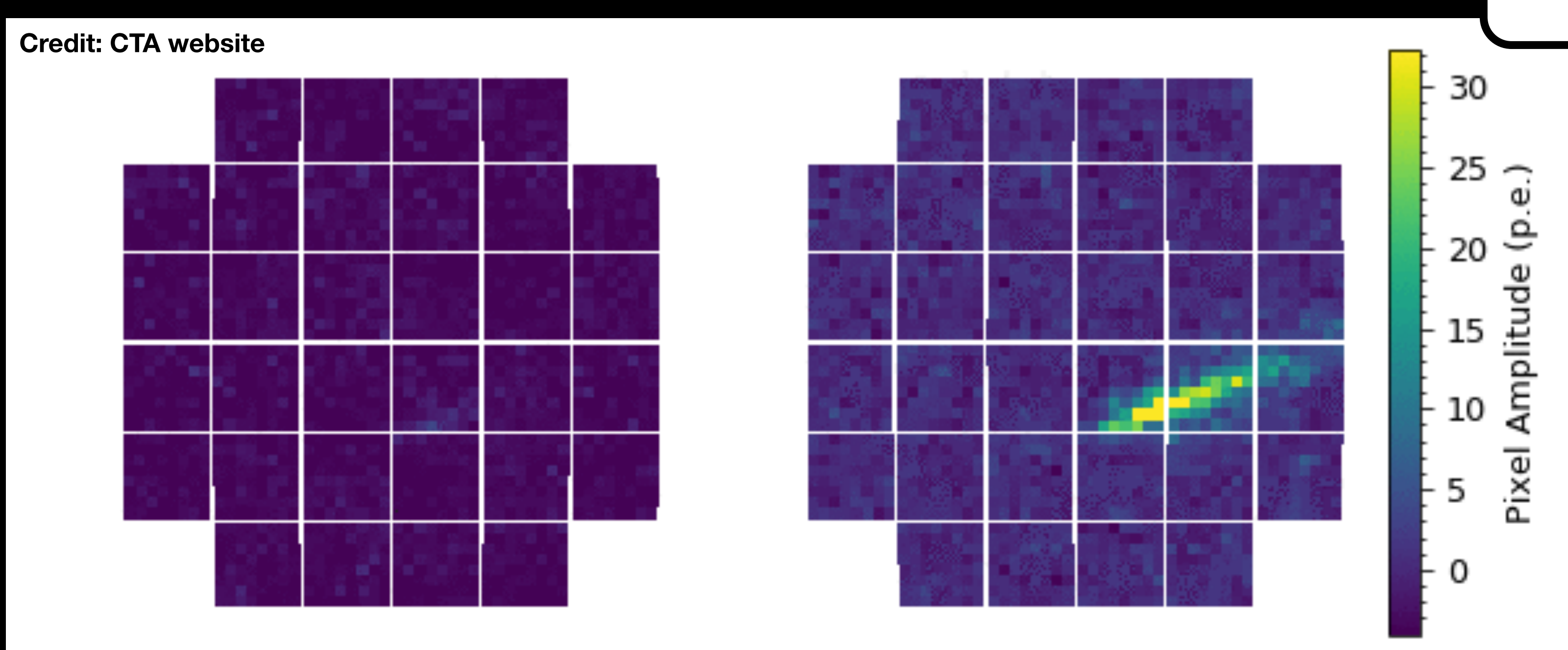
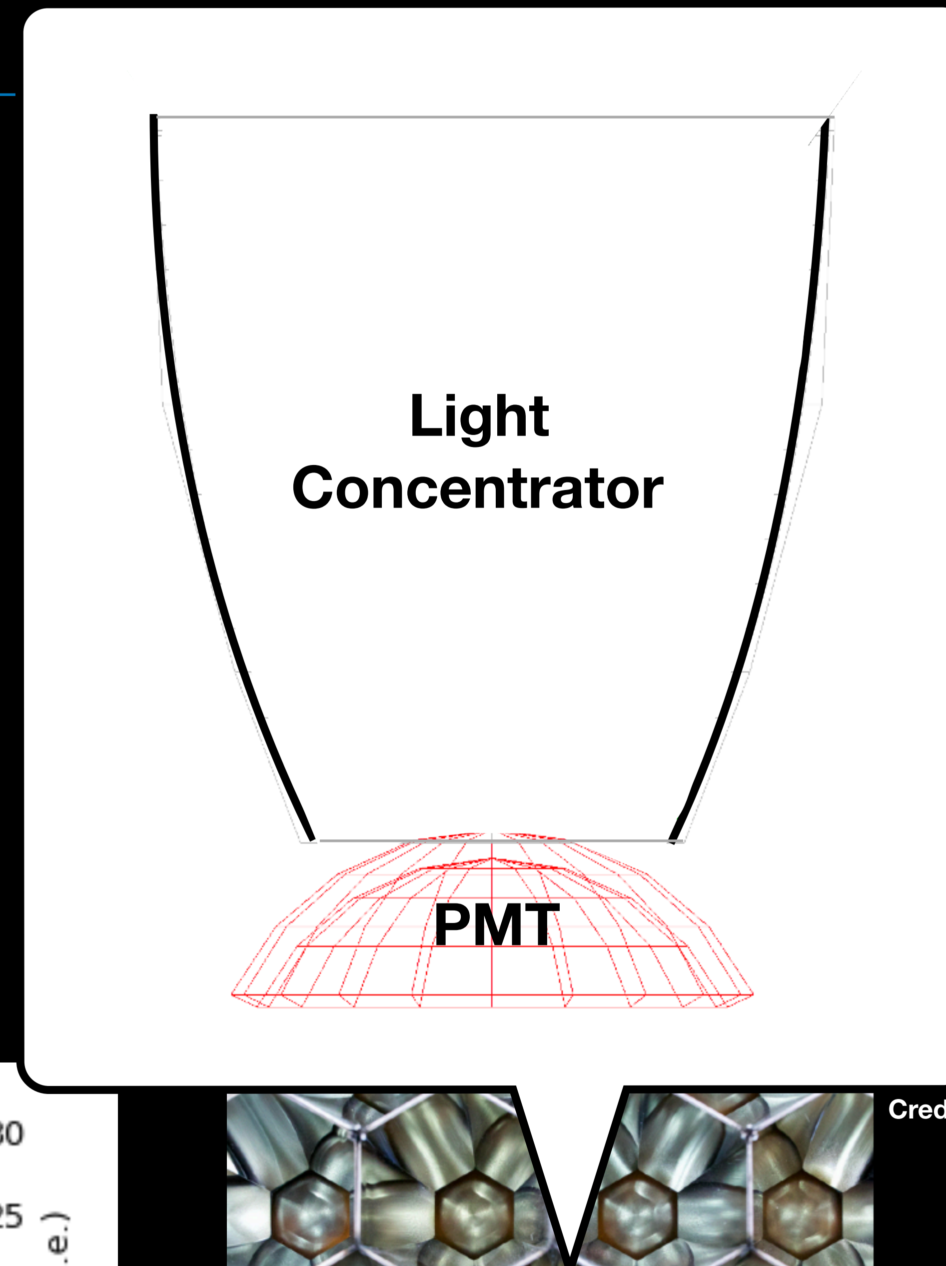
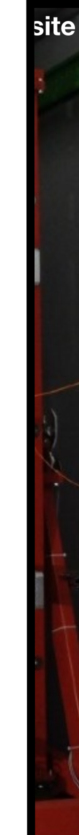
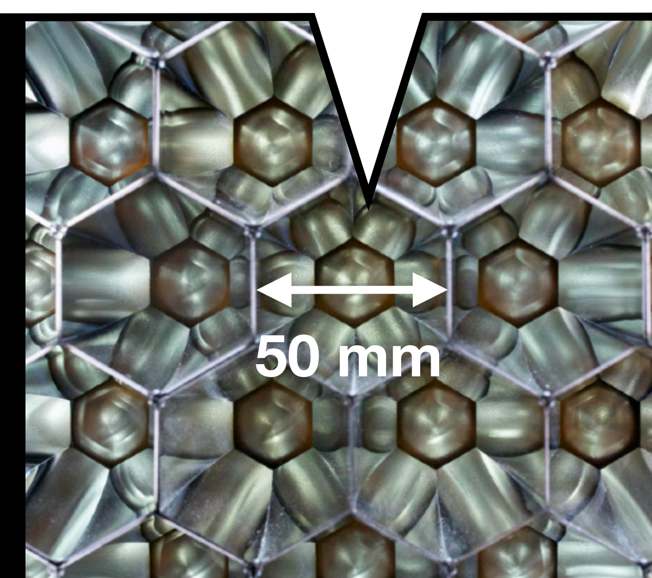








Credit: A. Okumura

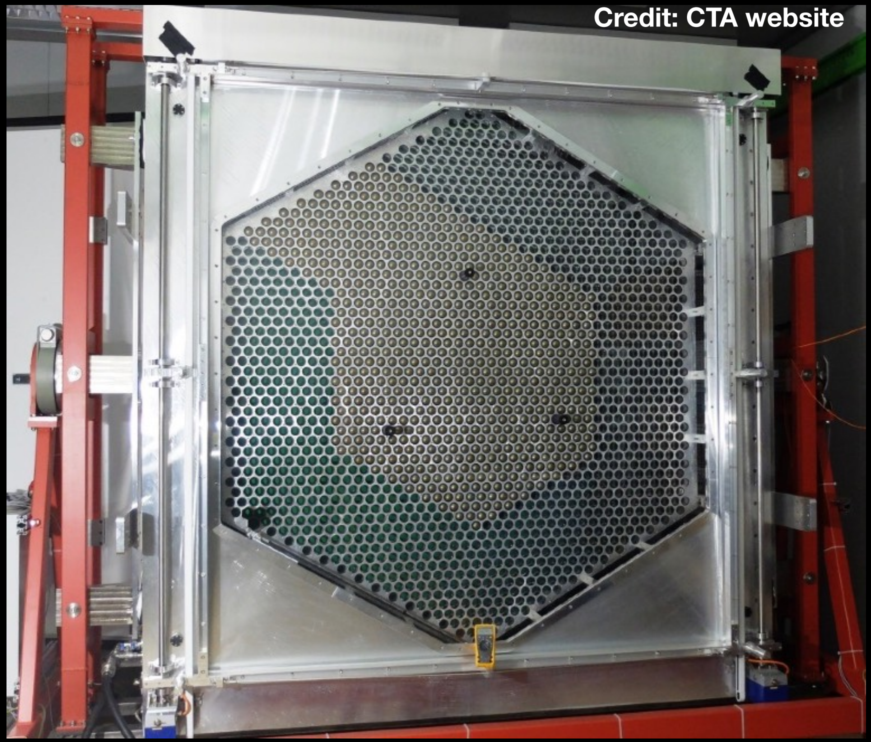
~1800 pixels

Current PMT cameras vs. current SiPM cameras

	FlashCAM	CHEC-S
Photodetector units	1764	32
Channels	1764	2048
Photodetector area (cm^2)	9120	210

- The price of SiPMs is determined by required area
- At the initial stage of MST design SiPMs were too expensive
- In SST cameras SiPMs make it possible to have a sufficient number of channels in a small area

FlashCAM



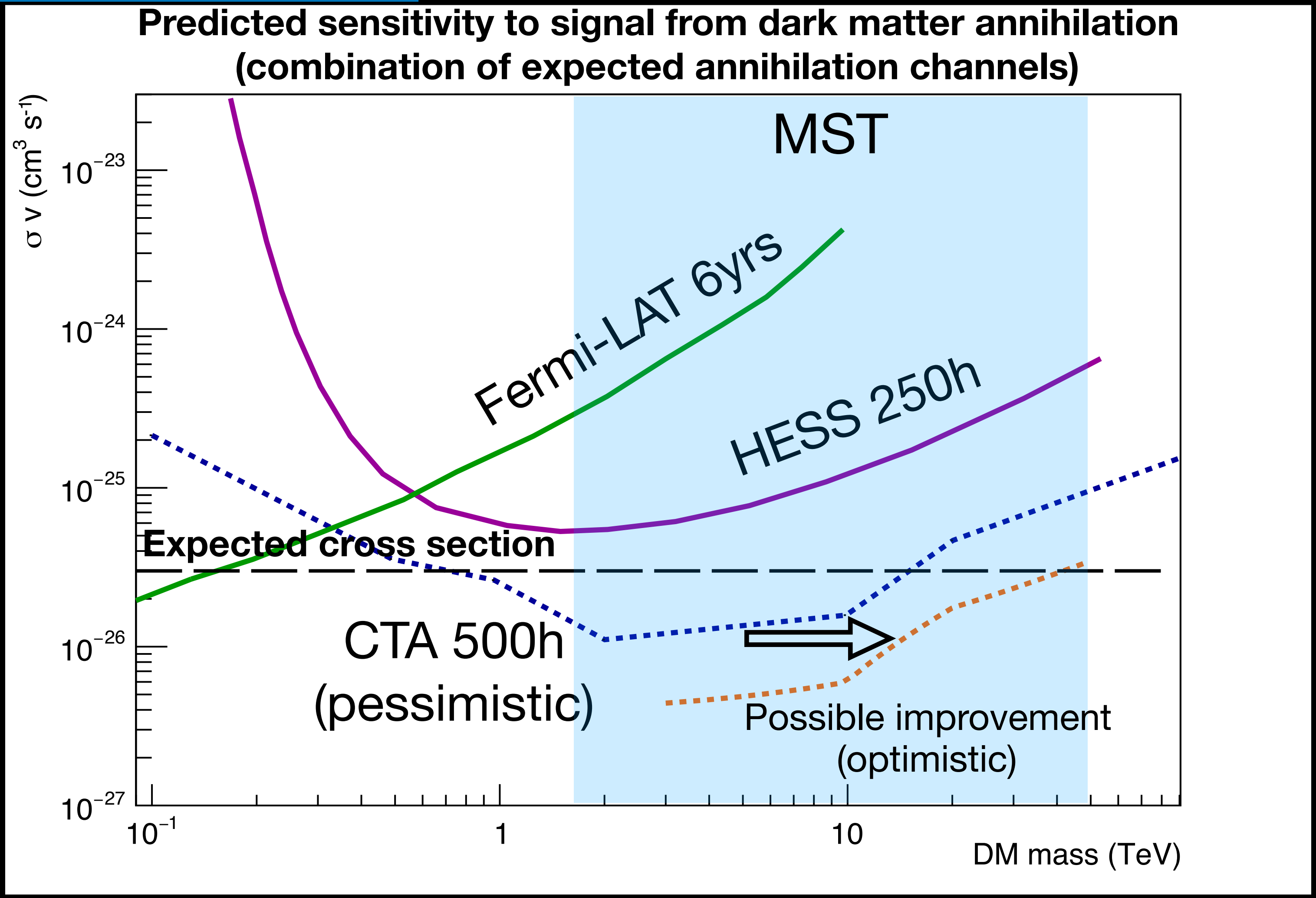
CHEC

Reason to employ SiPMs in the future generation of MST cameras

Prolonged operation of PMT cameras under high NSB conditions leads to degradation of their performance

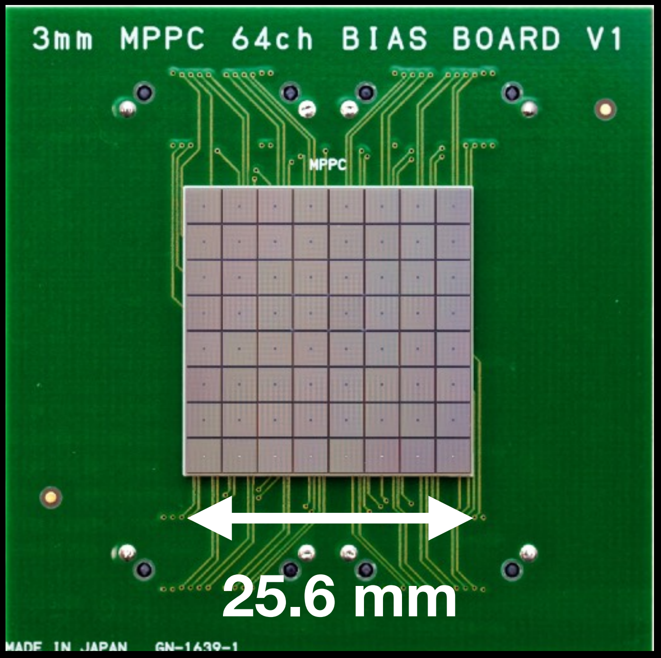
By using SiPMs we can extend observation time allocated for dark matter search by up to a factor of 7, which will provide:

- Increased sensitivity
- Sensitivity in higher DM mass range



Credit: A. Okumura

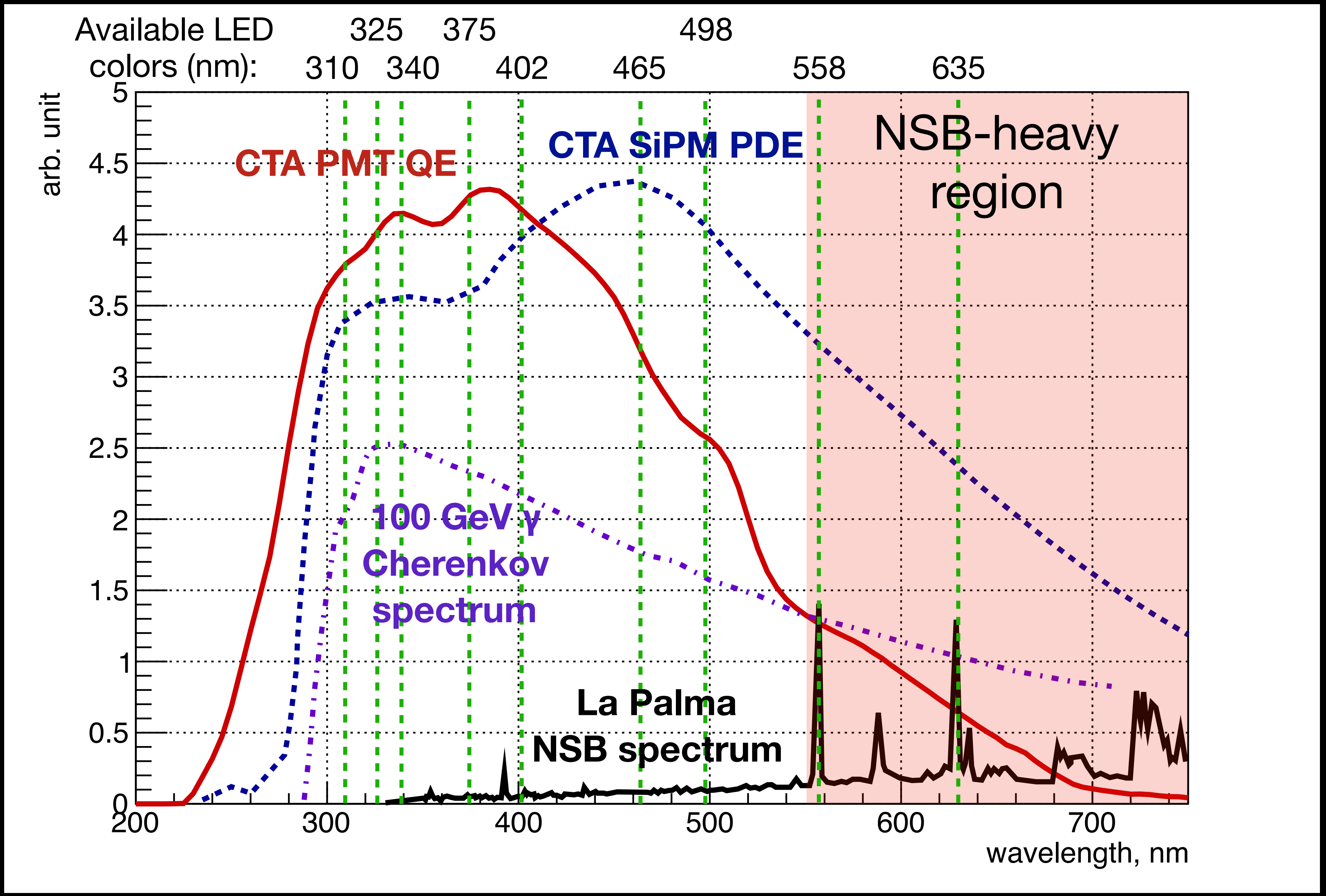
Features of silicon photomultipliers (SIPMs)
○**NSB tolerant. Operable under full moon (100xNSB)**
○High PDE (up to 58%)
○Compact, low voltage (60V)
×Too sensitive to NSB in > 550 nm range
×Optical crosstalk, high dark count rate



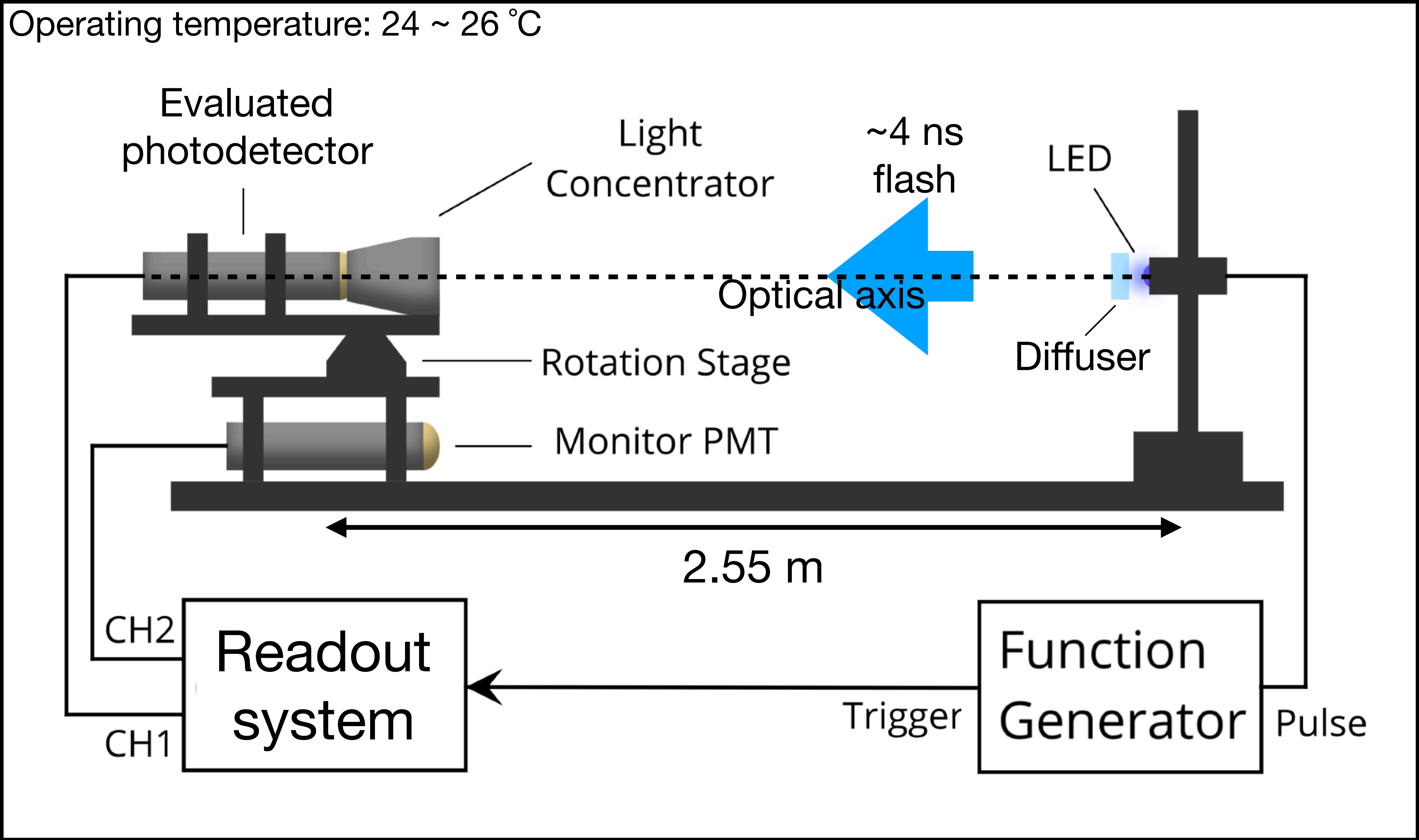
Comparison with current photodetectors

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

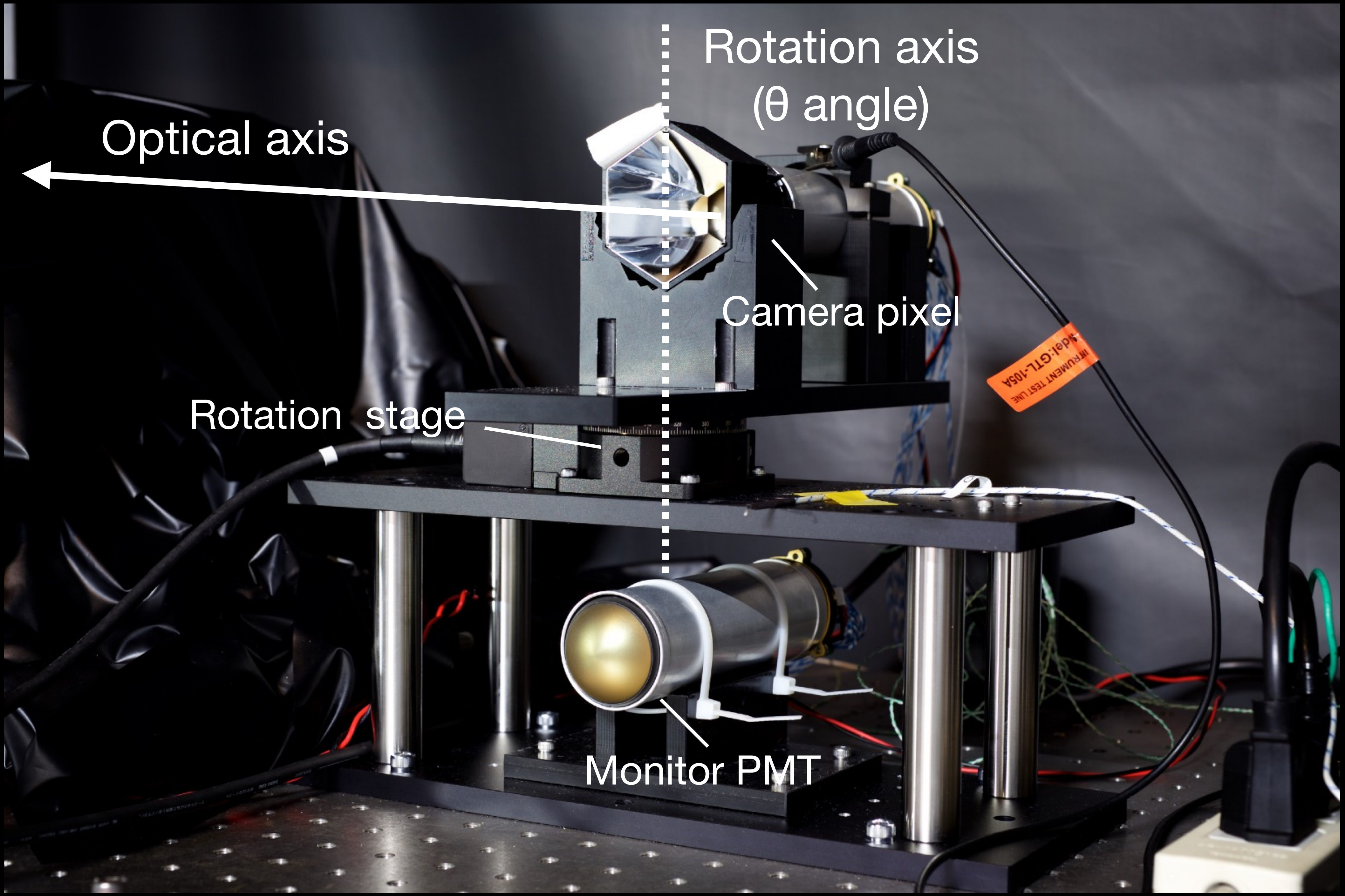
- Can not evaluate just by looking at PDE and QE because of light concentrators
- Measurement is necessary due to complex angular dependence of QE and PDE
- Limited number of LED colors. Interpolation by simulation is necessary



Measurement setup



Measurement setup

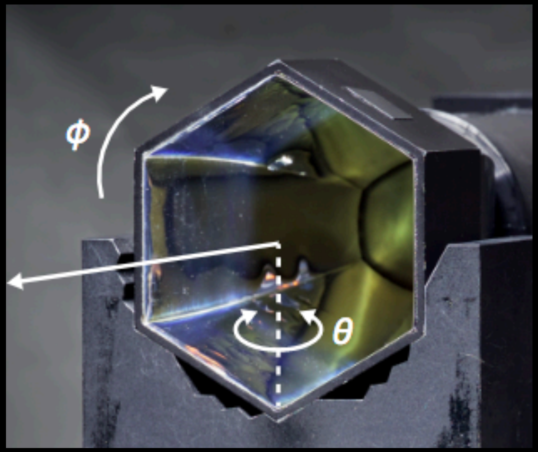


Credit: A. Okumura

Simulated devices

ROBAST tool was used for the ray-tracing simulation

https://robast.github.io/



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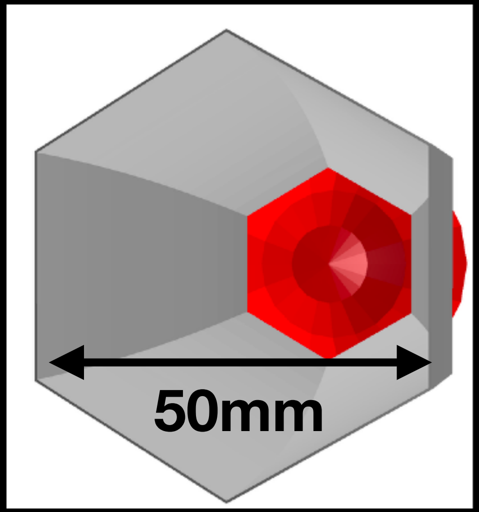

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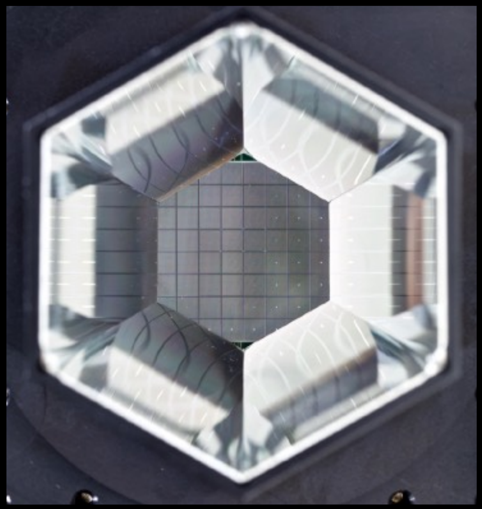
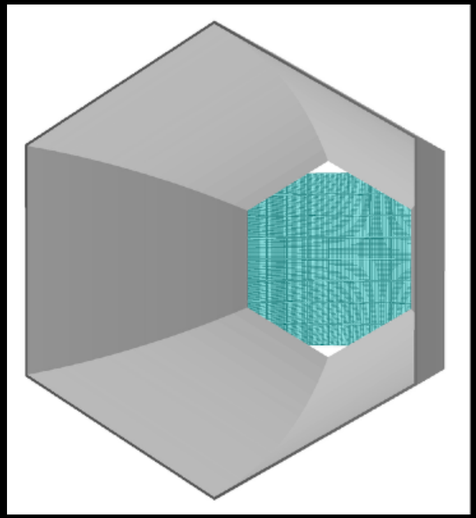




PMT

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)

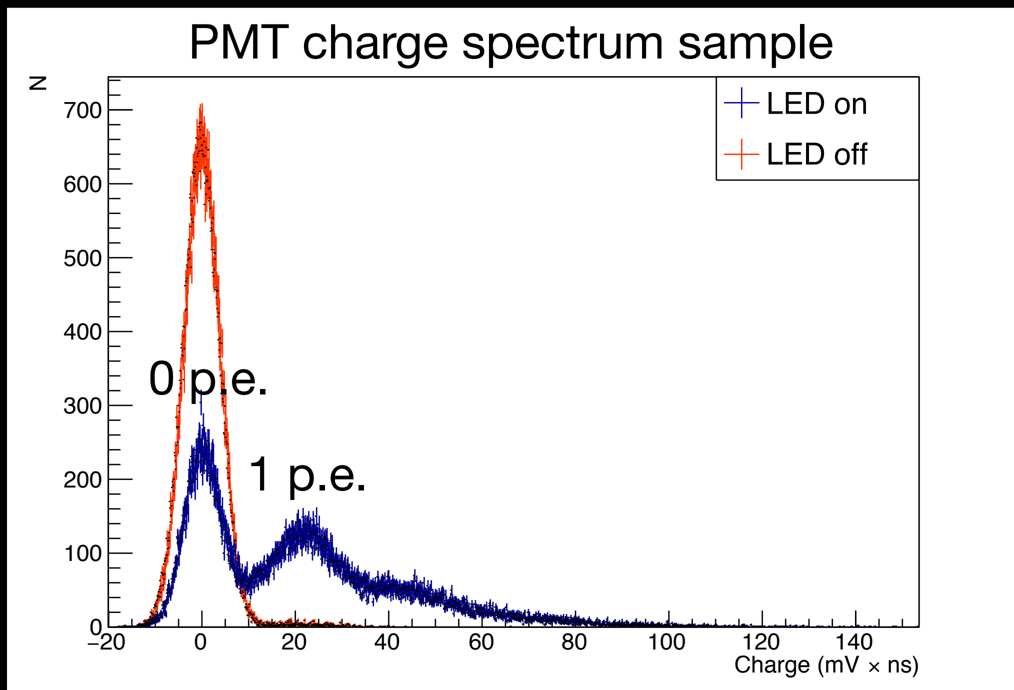
PDE data by Hamamatsu Photonics

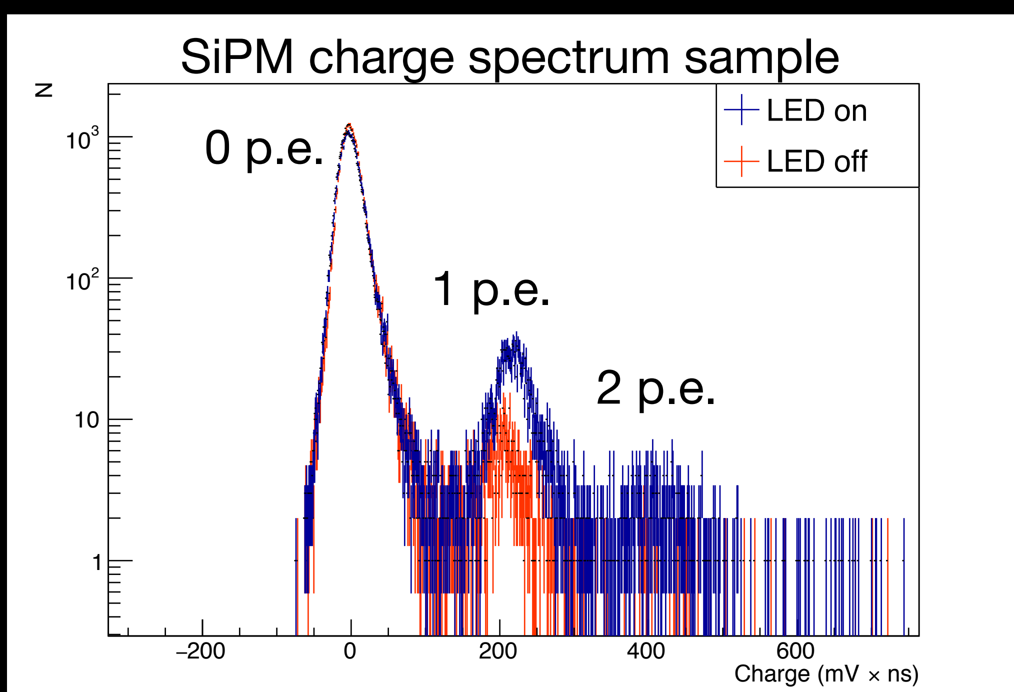
Interference effects are ignored

Relative measurement

Poisson distribution:

$$P(k) = \frac{\lambda^k}{k!} e^{-\lambda}$$





Mean number of detected photoelectrons:

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

$$\lambda = \mathrm{L(LED)} \times \mathrm{f(CU)} \times \mathrm{eff(Det)},$$

where L(LED) is the luminosity of the LED during the measurement,

f(CU) is the fraction of photons incident on the camera unit,

eff(Det) is the detection efficiency of the photon detector

$$\lambda(\mathrm{PMT}) = \mathrm{L(LED)_{PMT}} \times \mathrm{f(CU)} \times \mathrm{eff(PMT)}$$
$$\lambda(\mathrm{SiPM}) = \mathrm{L(LED)_{SiPM}} \times \mathrm{f(CU)} \times \mathrm{eff(SiPM)}$$
$$\lambda(\mathrm{PMT})_{\mathrm{Mon}} = \mathrm{L(LED)_{PMT}} \times \mathrm{f(Mon)} \times \mathrm{eff(Mon)}$$
$$\lambda(\mathrm{SiPM})_{\mathrm{Mon}} = \mathrm{L(LED)_{SiPM}} \times \mathrm{f(Mon)} \times \mathrm{eff(Mon)}$$

where Mon stands for Monitor. Then:

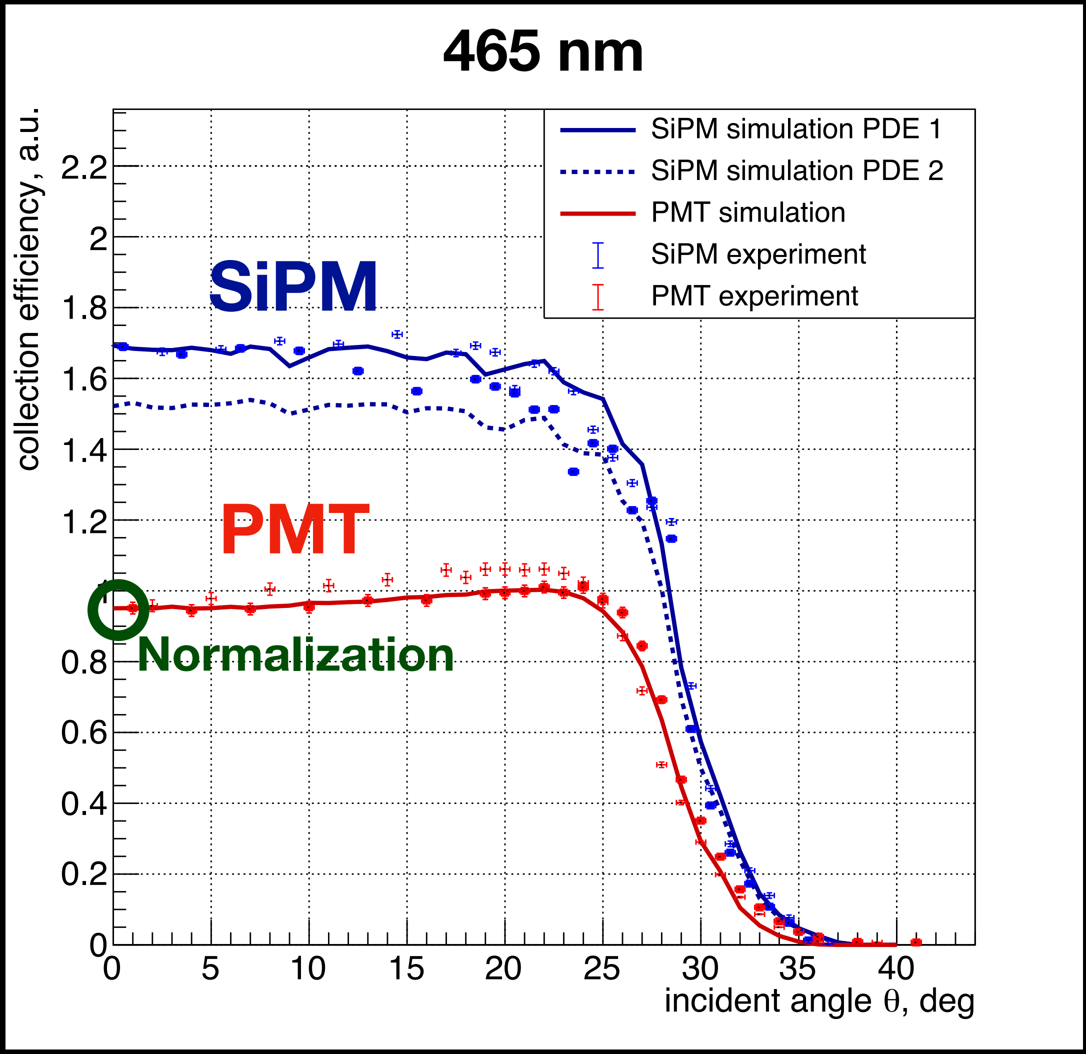
$$\lambda(\mathrm{PMT}) = \frac{\mathrm{eff(PMT)} \times \mathrm{f(CU)} \times \lambda(\mathrm{Mon})_{\mathrm{PMT}}}{\mathrm{eff(Mon)} \times \mathrm{f(Mon)}}$$

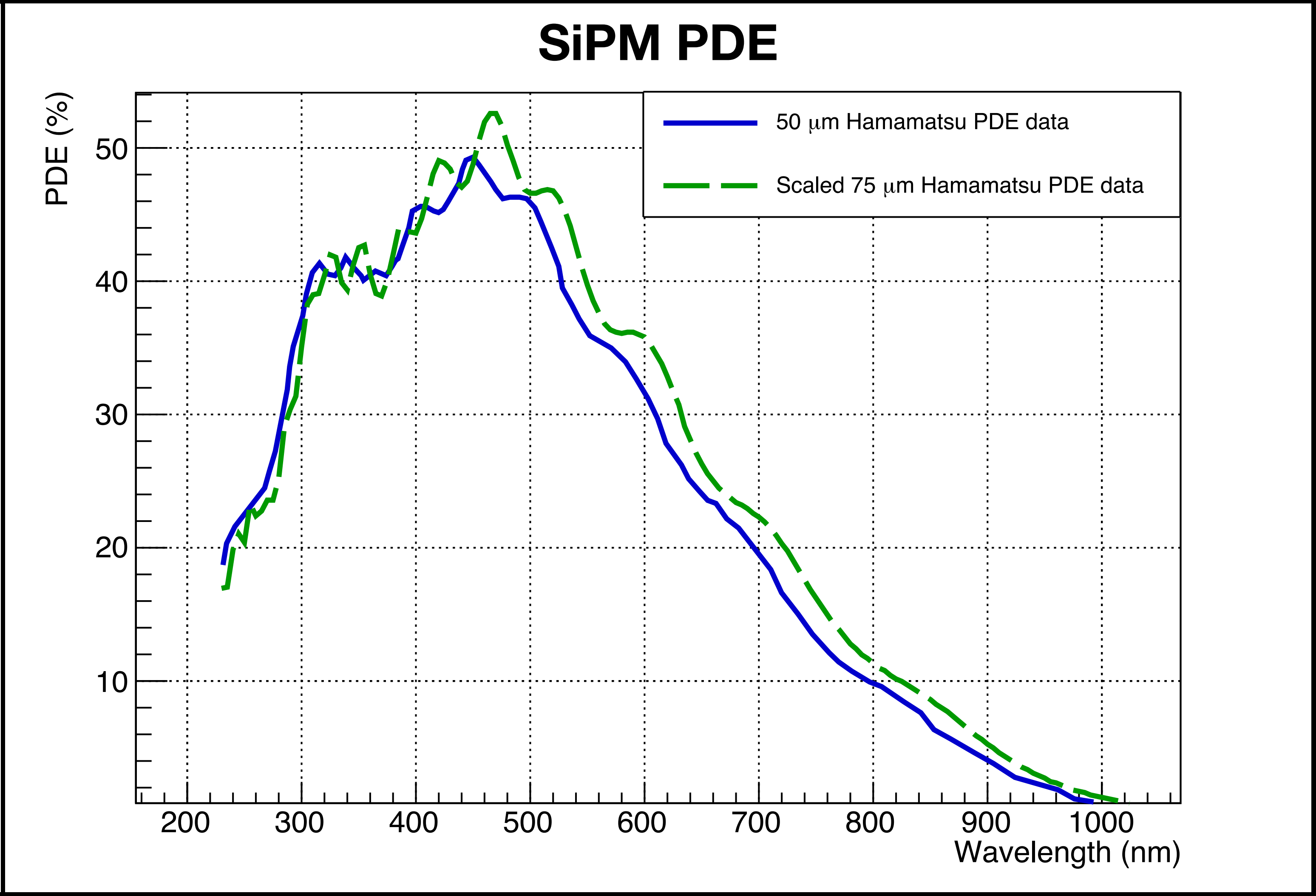
$$\lambda(\mathrm{SiPM}) = \frac{\mathrm{eff(SiPM)} \times \mathrm{f(CU)} \times \lambda(\mathrm{Mon})_{\mathrm{SiPM}}}{\mathrm{eff(Mon)} \times \mathrm{f(Mon)}}$$

$$\frac{\mathrm{f(CU)}}{\mathrm{eff(Mon)} \times \mathrm{f(Mon)}} = \mathrm{const} \Rightarrow \boxed{\frac{\mathrm{eff(SiPM)}}{\mathrm{eff(PMT)}} = \frac{\lambda(\mathrm{SiPM})}{\lambda\mathrm{PMT}} \cdot \frac{\lambda(\mathrm{Mon})_{\mathrm{PMT}}}{\lambda(\mathrm{Mon})_{\mathrm{SiPM}}}}$$

Collection efficiencies of camera pixels

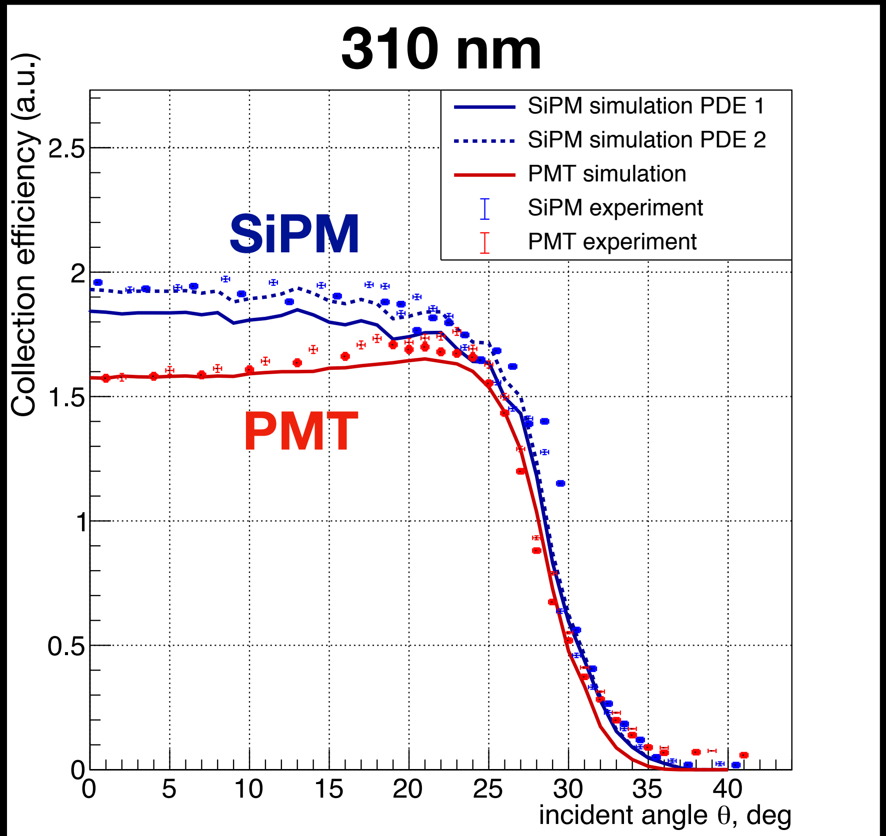
- Simulation is normalized to match on-axis (0 deg.) PMT data
- Measurement results are "folded" with respect to 0 deg.
- Marked points represent data taken for negative angles
- Results for two PDE curves by Hamamatsu Photonics

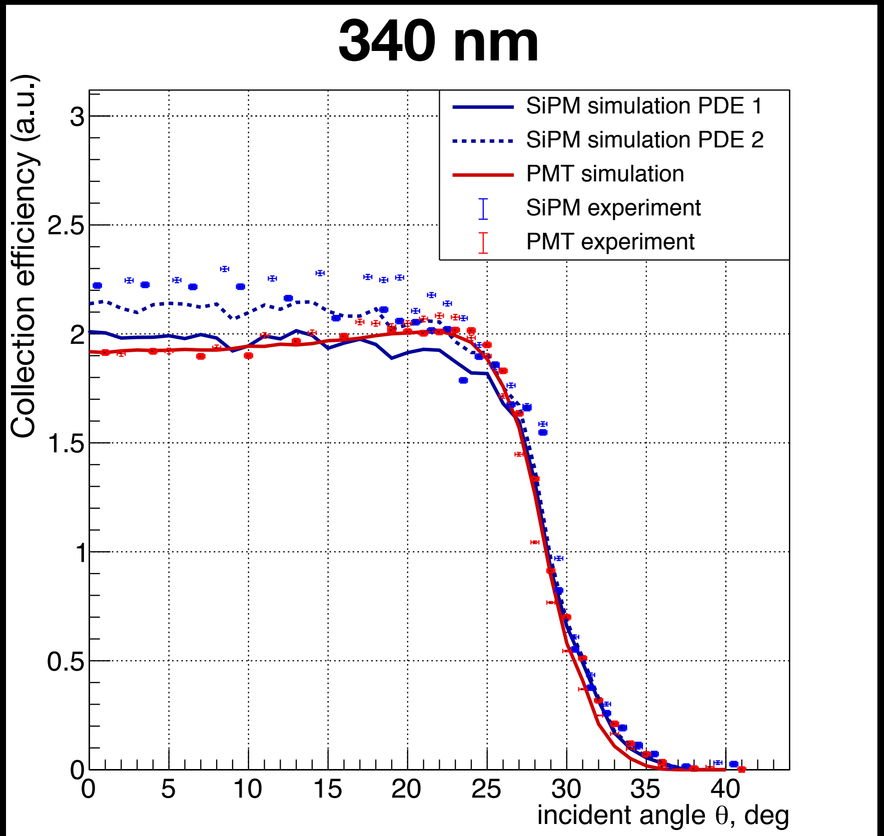


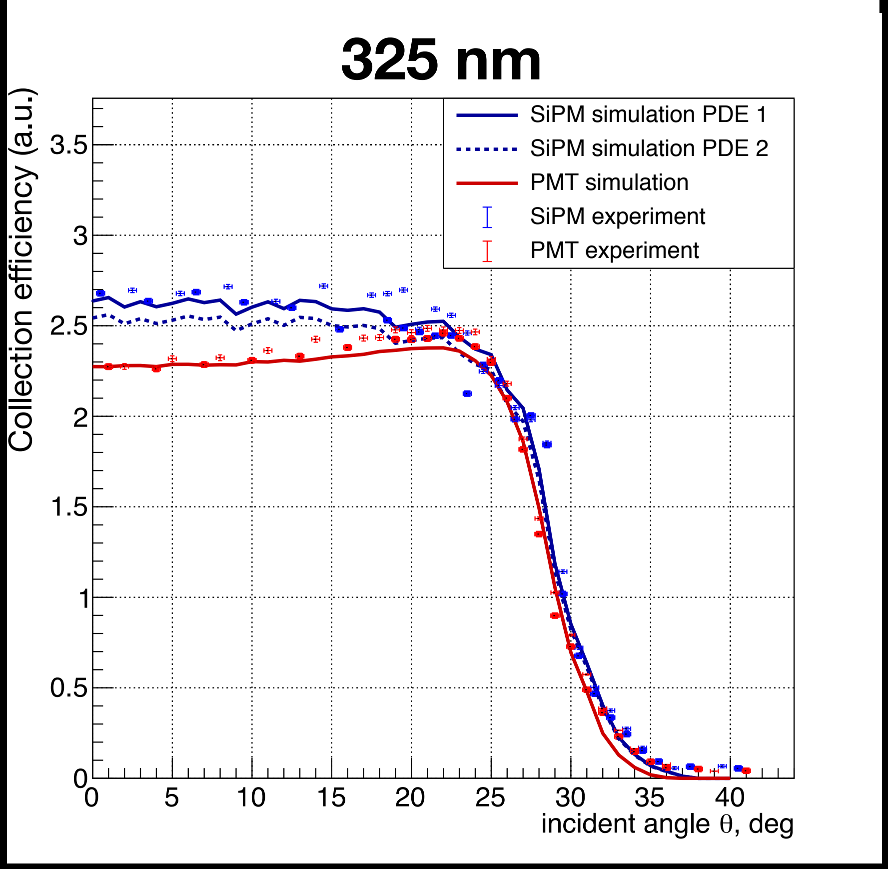


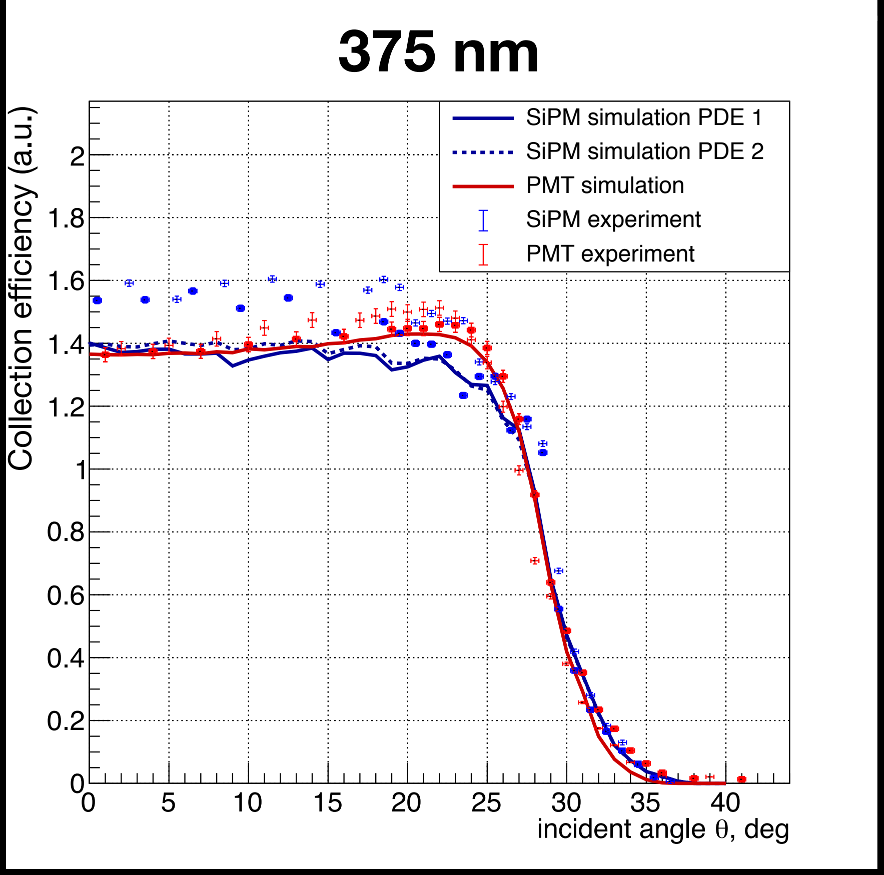
Collection efficiencies of camera pixels

- 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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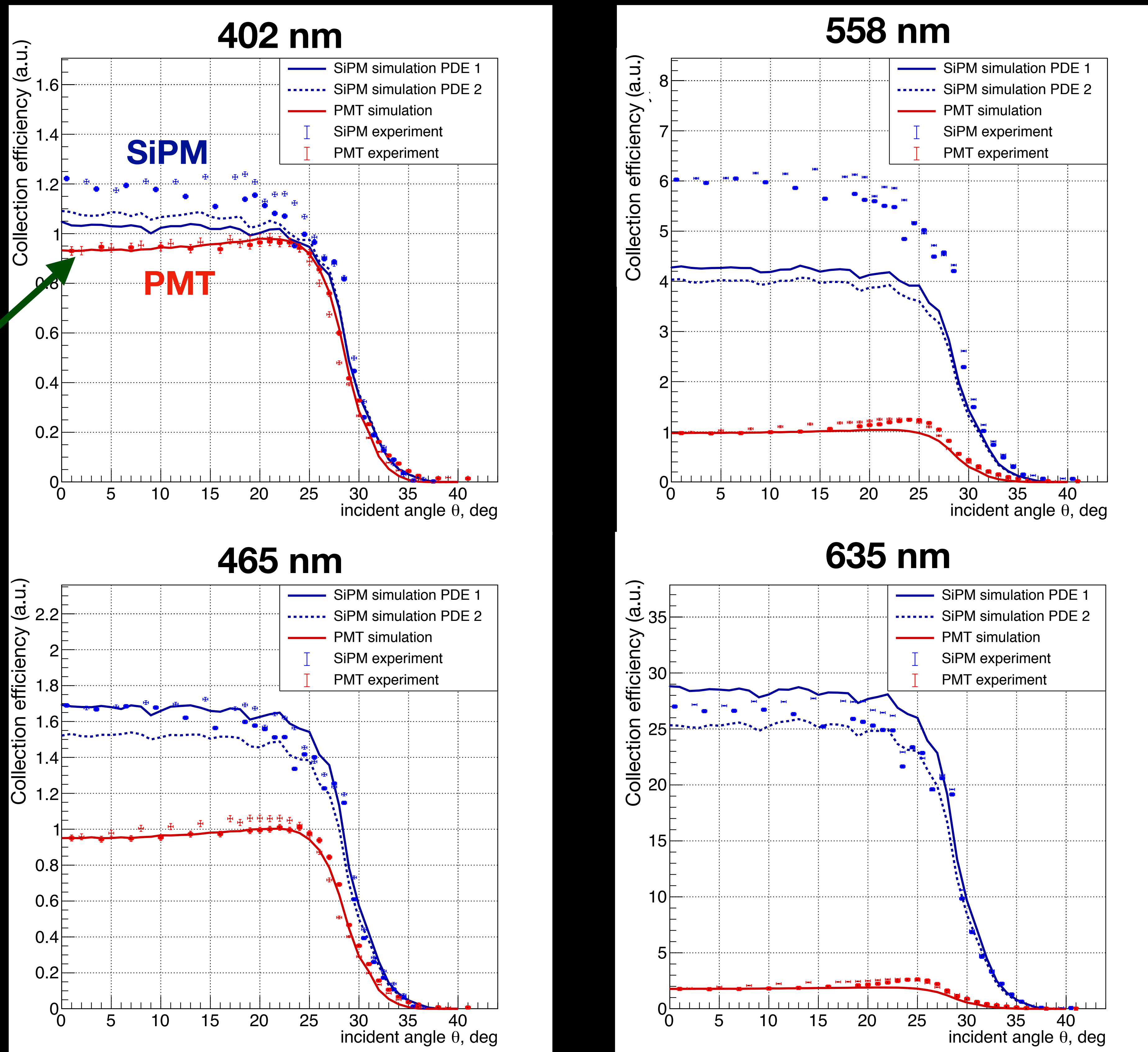
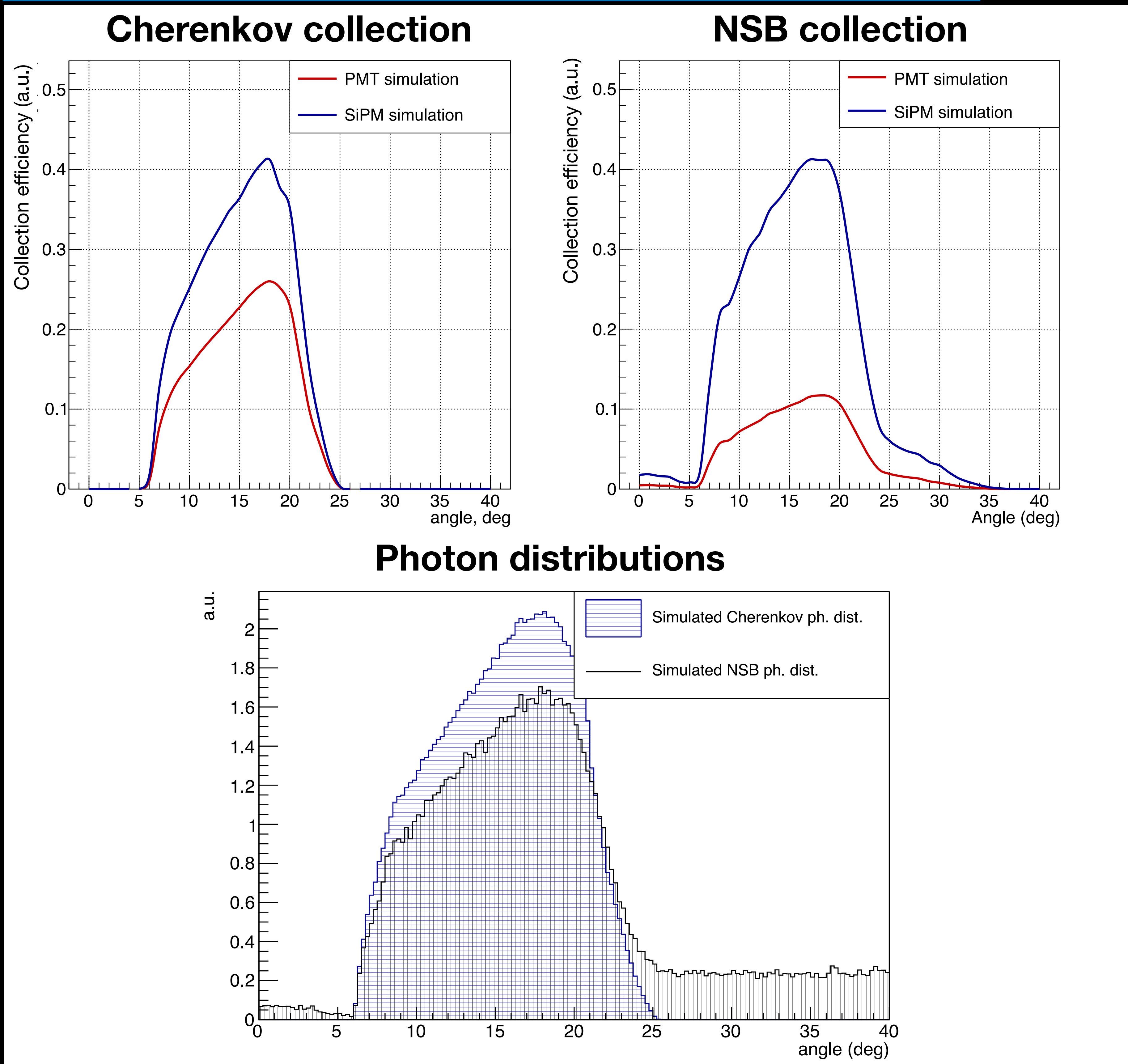


Light yields of camera pixels (300-750 nm)



Total light yields:

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

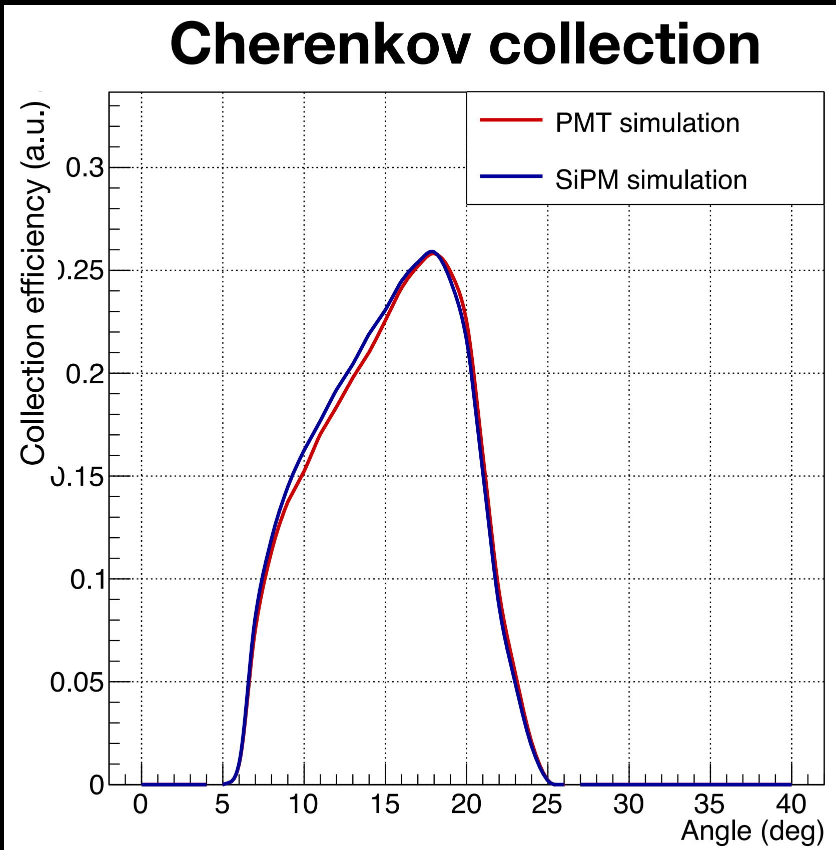
$$\frac{Y_{\mathrm{NSB}}(\mathrm{SiPM})}{Y_{\mathrm{NSB}}(\mathrm{PMT})} = 3.65$$

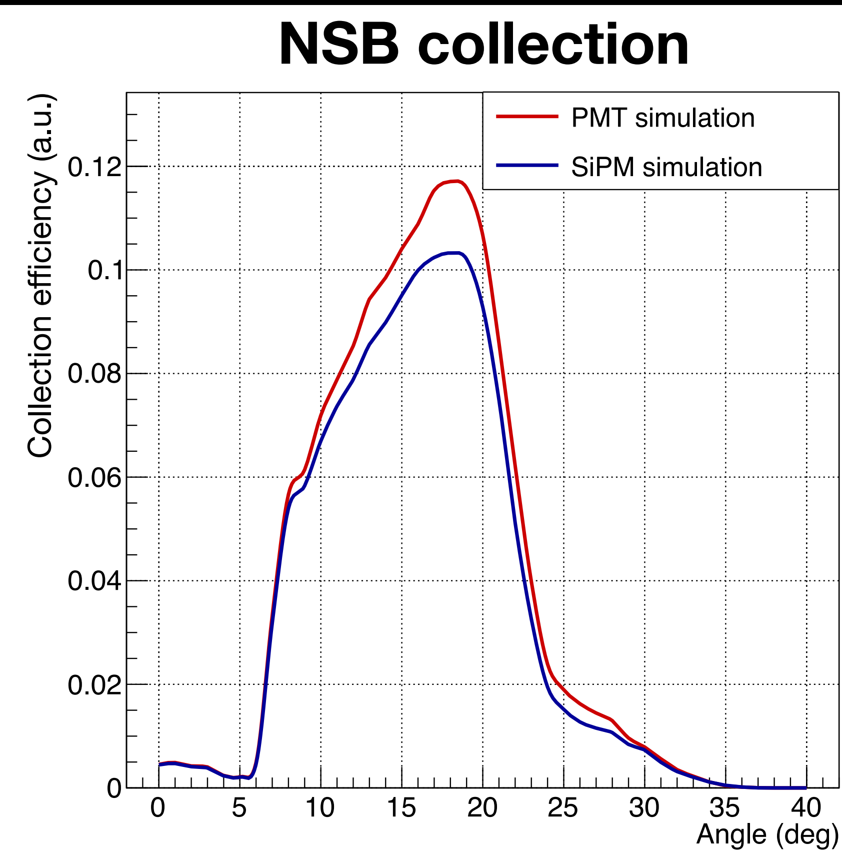
Higher Cherenkov photon yield at the cost of a large increase in sensitivity to NSB

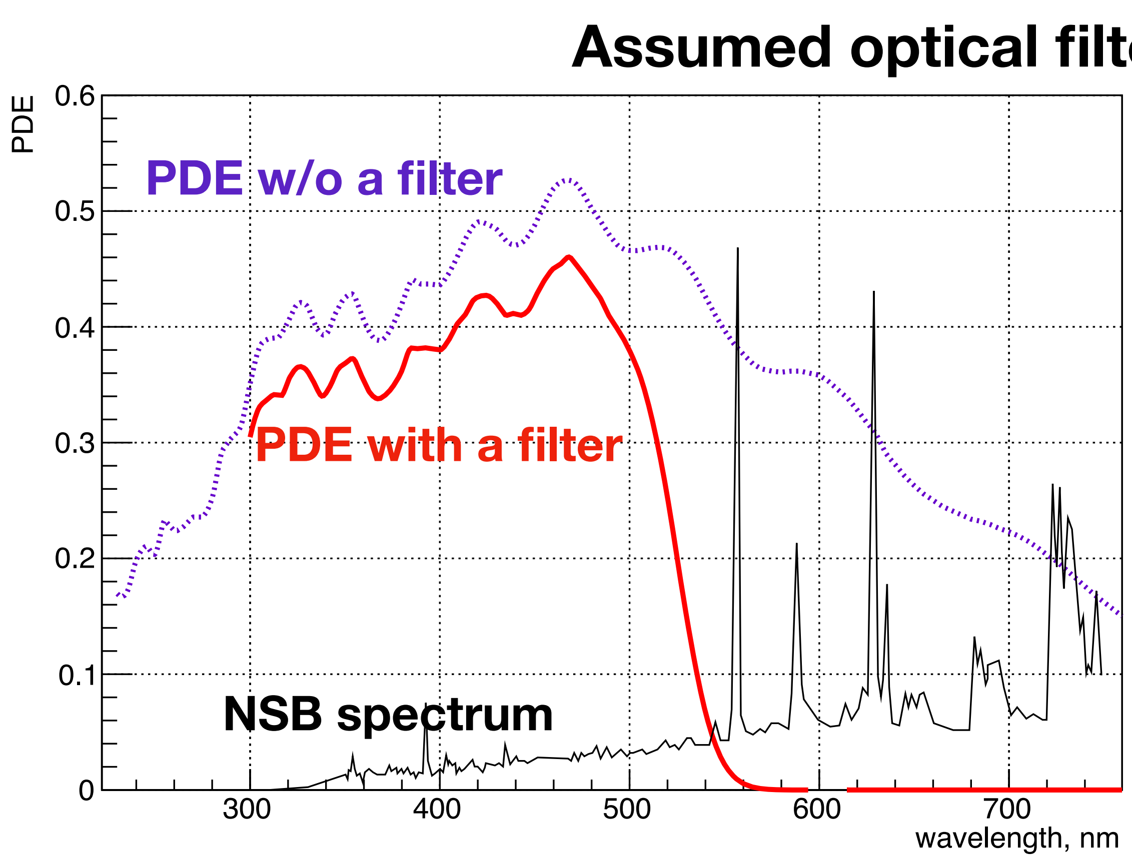
$\frac{\mathrm{S}}{\sqrt{\mathrm{NSB}}}$ decreases by 1.2

It makes sense to attempt to cut a part of NSB using an optical filter

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







- 13% loss at wavelengths < 490nm
- 100% cut at wavelengths > 560nm
- Transmittance decays from 490 to 560 nm as:

$$T(\mathrm{wl}) = 0.87 - \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{\mathrm{wl}} \mathrm{e}^{-\frac{(x-\mathrm{wl}_0)^2}{2\sigma^2}} \mathrm{d}x$$

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)**:

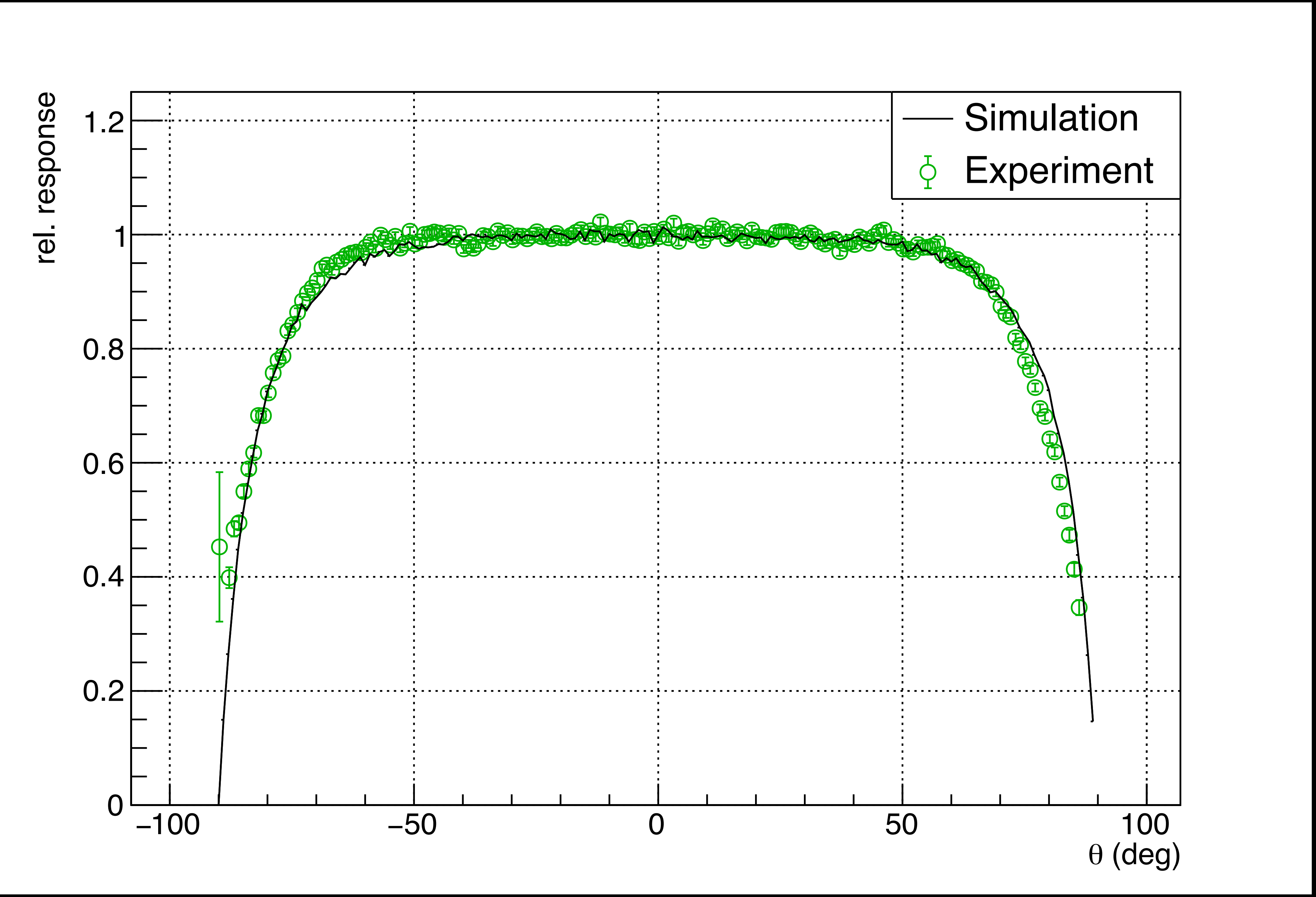
- An increase of 7% in SNR
- Almost no change in Cherenkov light yield

To do:

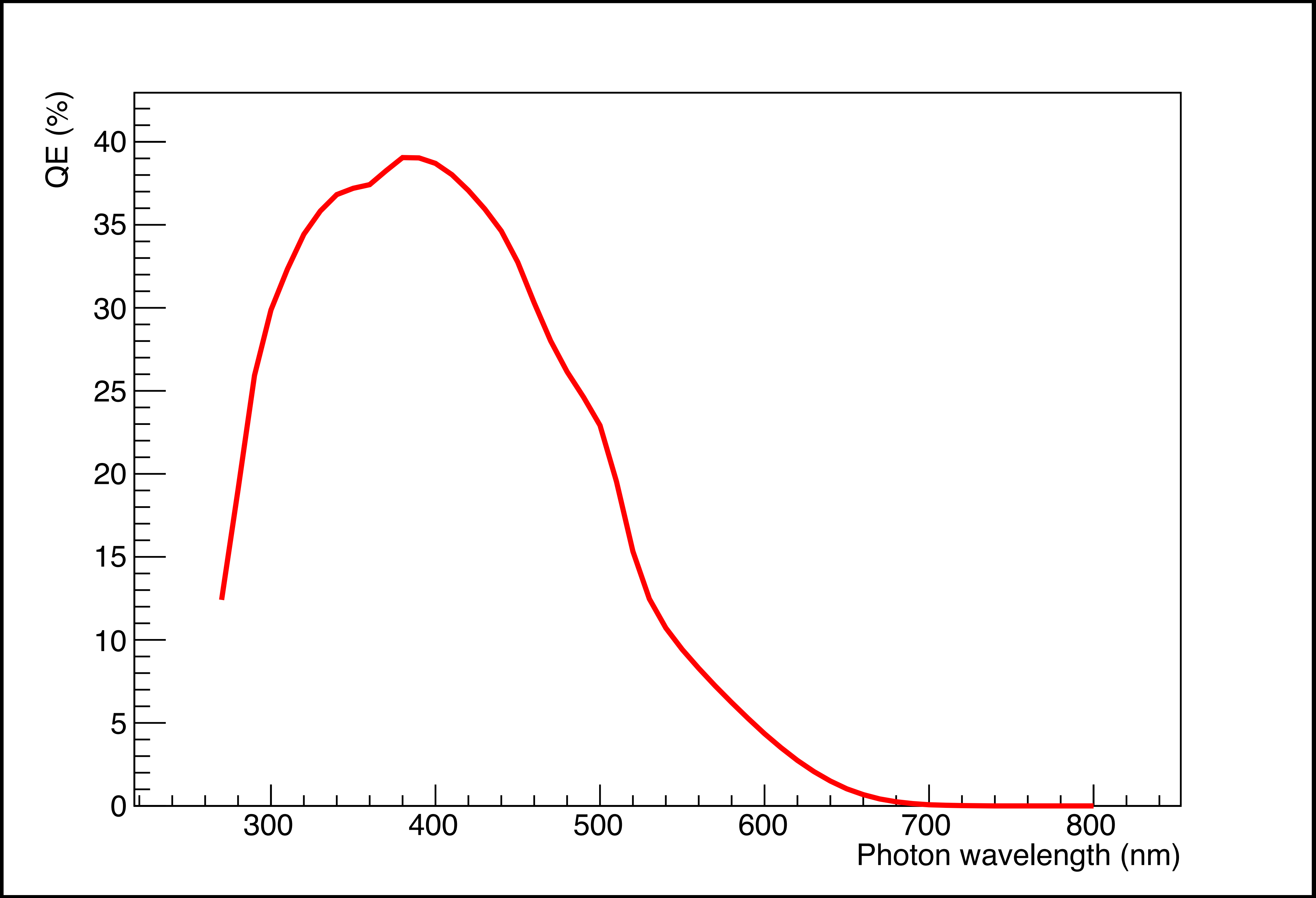
- Have to understand the discrepancy between the simulation and measurement and improve the simulation

BACKUP

Angular response of SiPM



PMT QE


QE (%)
0
5
10
15
20
25
30
35
40
300
400
500
600
700
800
Photon wavelength (nm)

Weakly Interacting Massive Particle (WIMP)

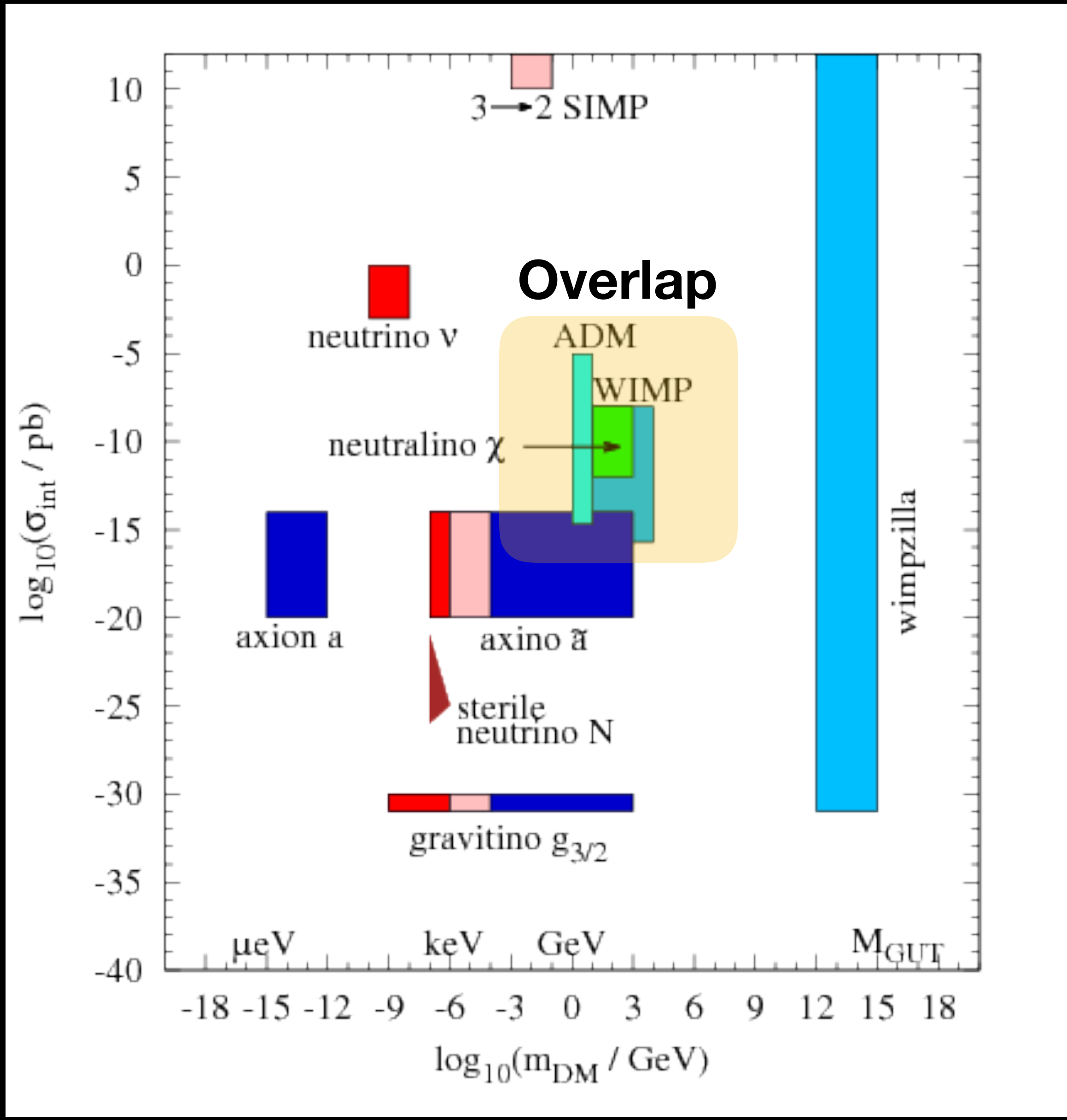
- WIMP is a promising DM particle candidate. It is a hypothetical massive particle that interacts only through weak force and gravity

- "WIMP miracle"
  Parameters of a DM particle estimated from DM abundance correspond to independent WIMP predictions by several promising particle physics models

- WIMPs are expected to annihilate and produce gamma rays

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

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



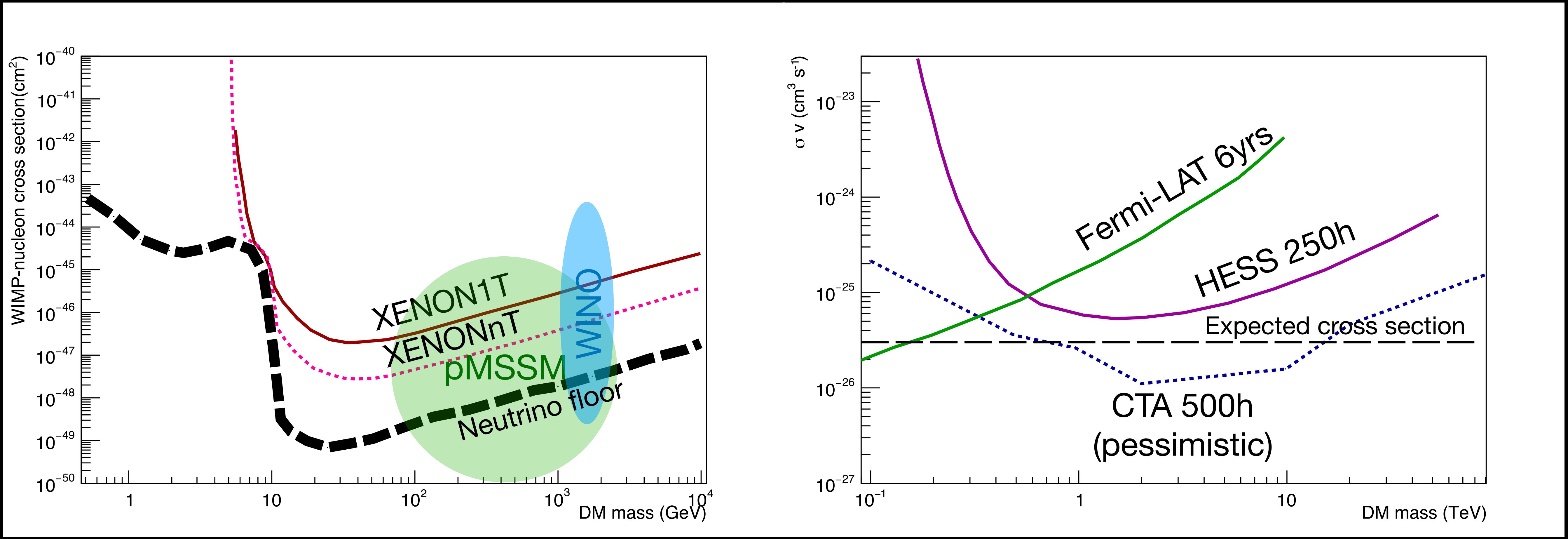
Dark matter detection with gamma rays

- WIMPs are expected to annihilate and produce gamma rays

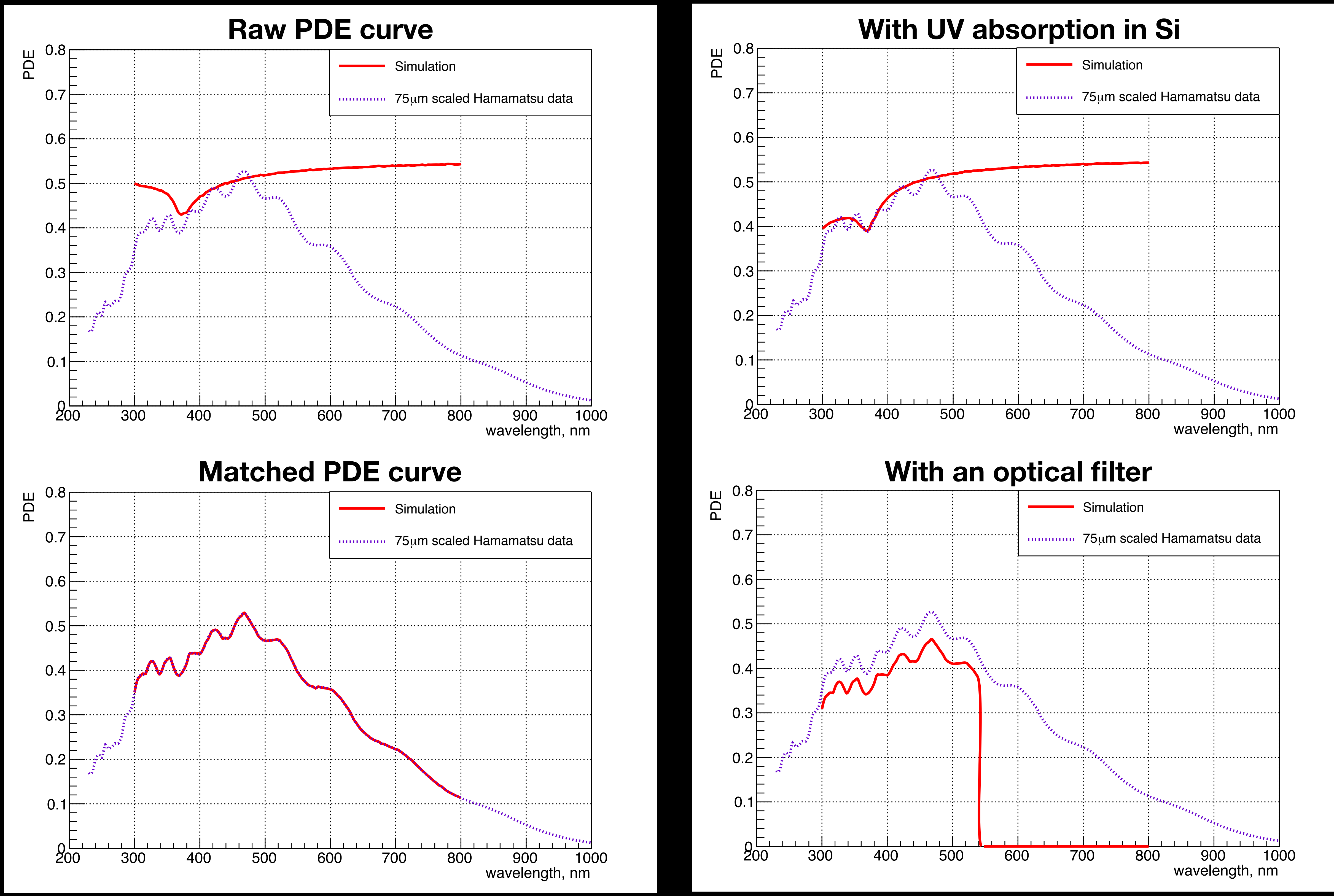
- Possible to search for WIMPs by gamma-ray observation

The advantages of such an approach:

- Sensitivity in TeV region, which means decent coverage of possible parameters of WIMPS, with annihilation cross section constrained by dark matter abundance

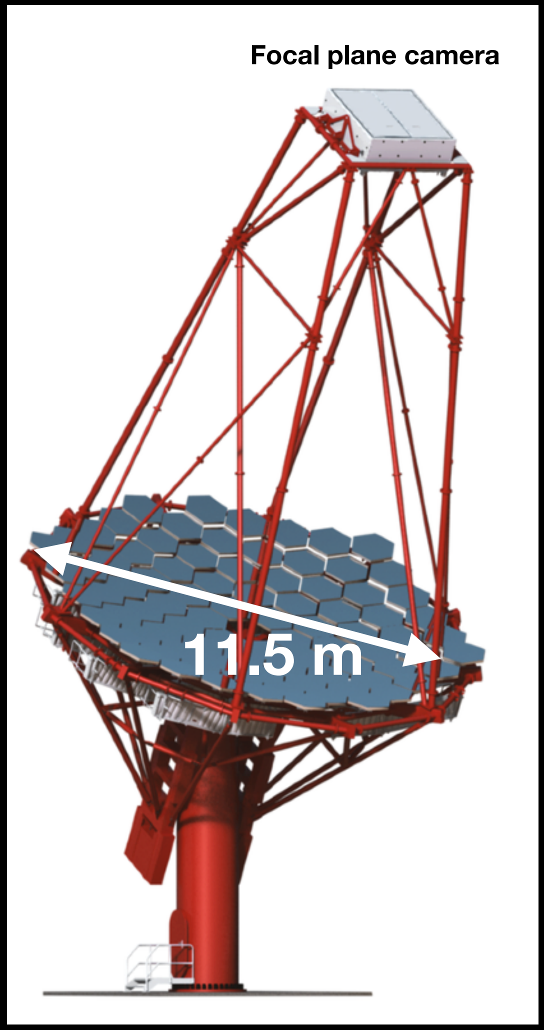


PDE of SiPM

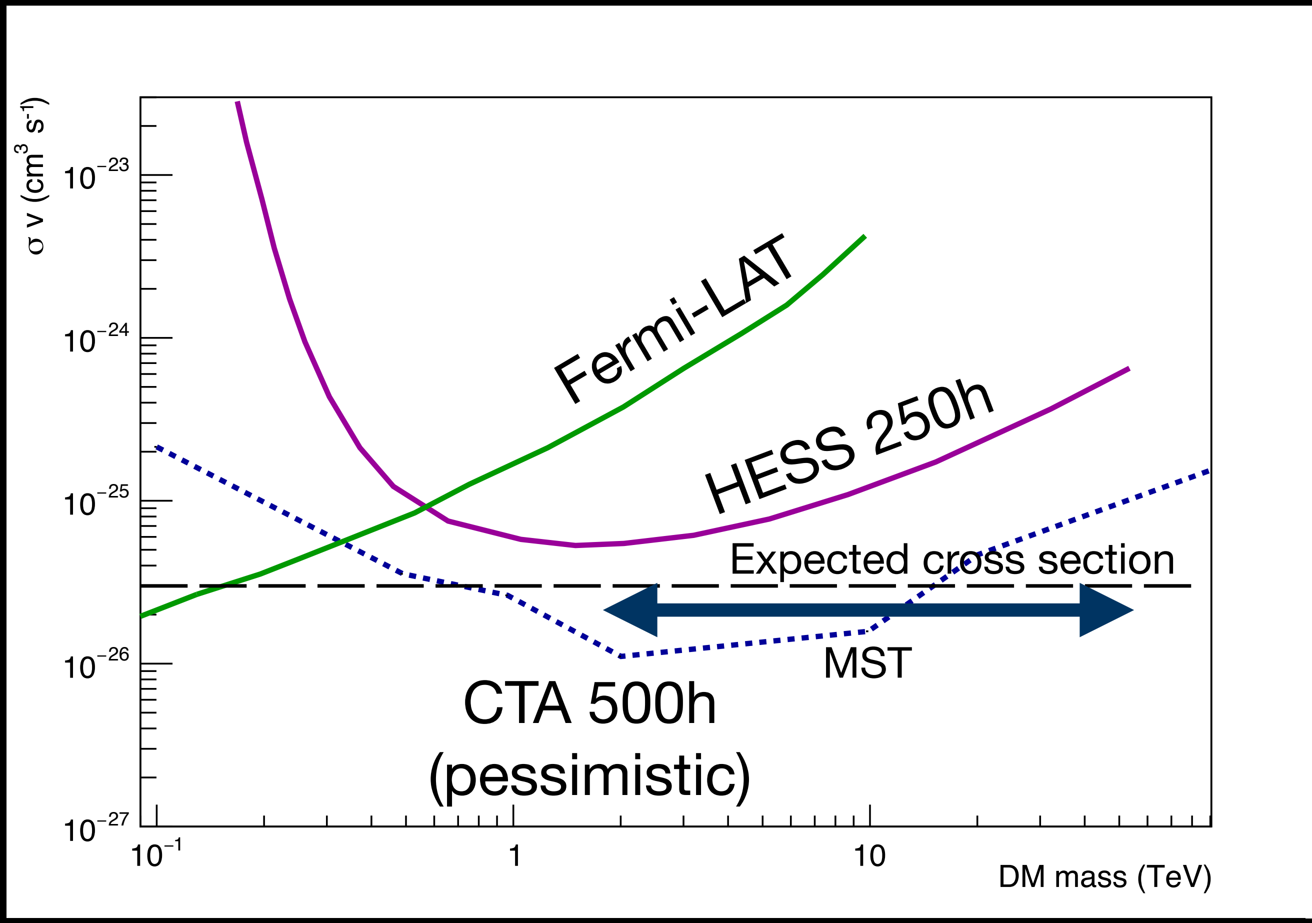


Raw PDE curve
PDE
Simulation
75μm scaled Hamamatsu data
wavelength, nm
With UV absorption in Si
PDE
Simulation
75μm scaled Hamamatsu data
wavelength, nm
Matched PDE curve
PDE
Simulation
75μm scaled Hamamatsu data
wavelength, nm
With an optical filter
PDE
Simulation
75μm scaled Hamamatsu data
wavelength, nm

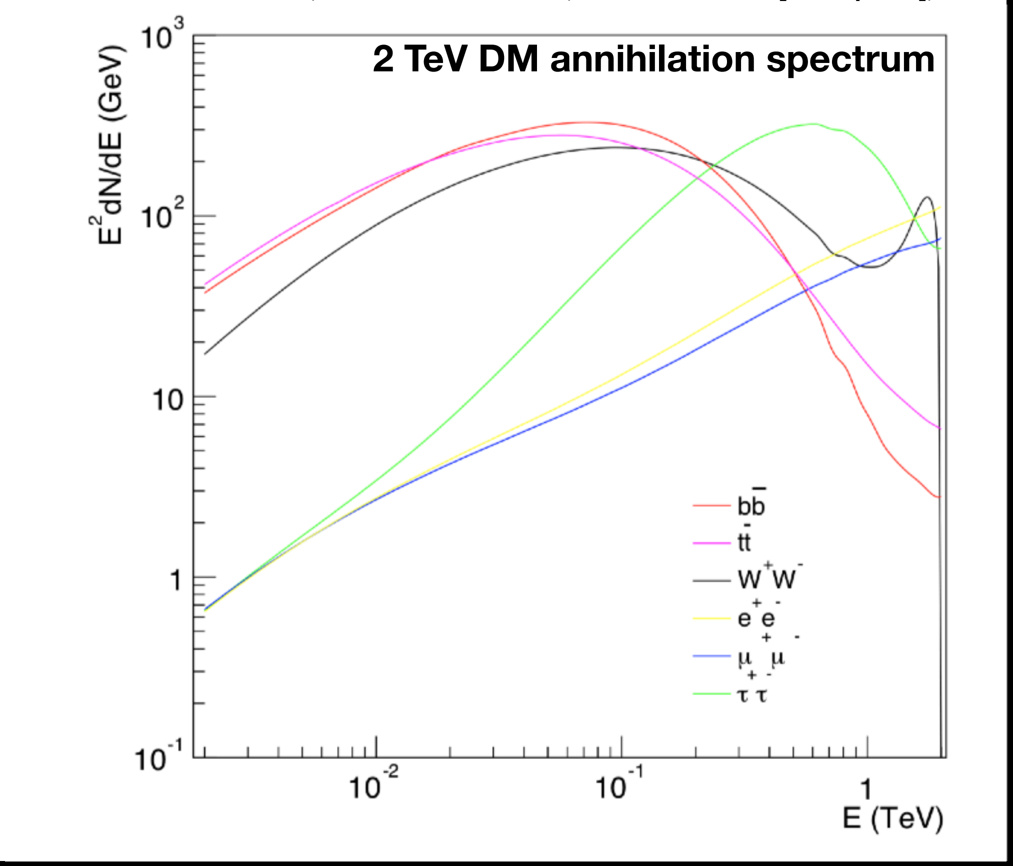
Medium-sized telescope



- Sensitive in the core energy range of CTA from 150 GeV to 5 TeV.
- $E_\gamma \approx \frac{1}{10} E_{\mathrm{DM}}$ can be detected most efficiently
- Important for dark matter search and we are aiming to improve its capabilities even further by changing its current PMT detectors to SiPMs.



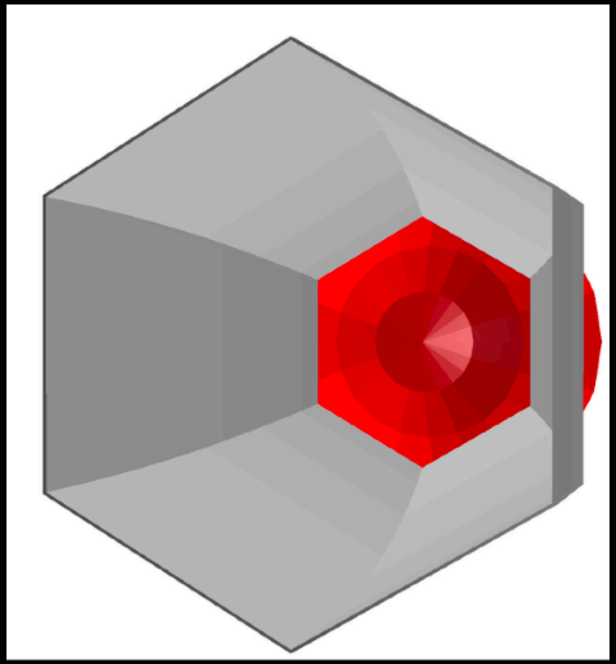
The CTA Consortium, Science with the CTA, arXiv:1709.07997 [astro-ph.IM], 2017



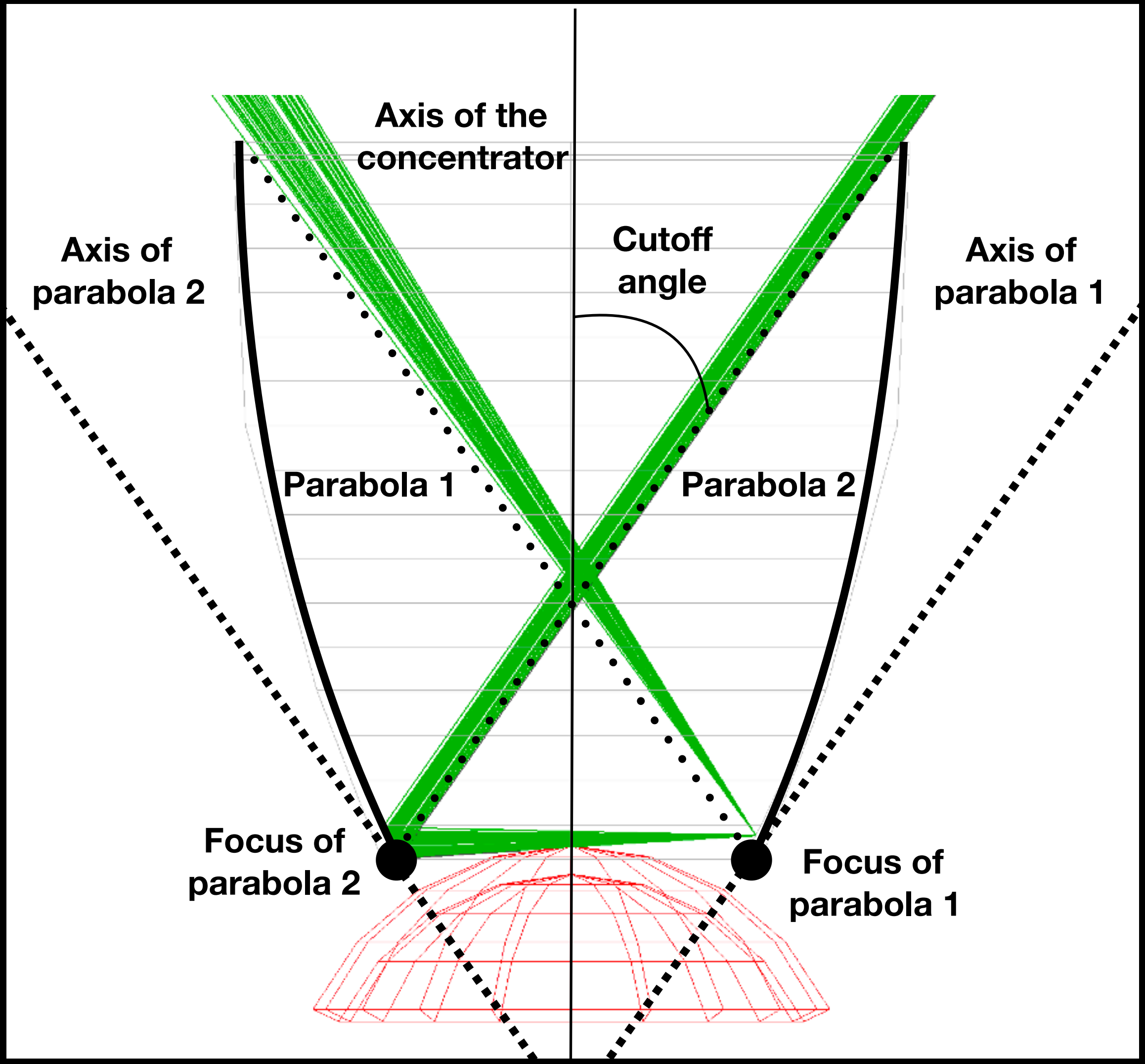
Light Concentrators

Light concentrators are hollow cones with parabolic profiles which serve two purposes:

- Decreasing the dead area between camera pixels
- Stray light rejection

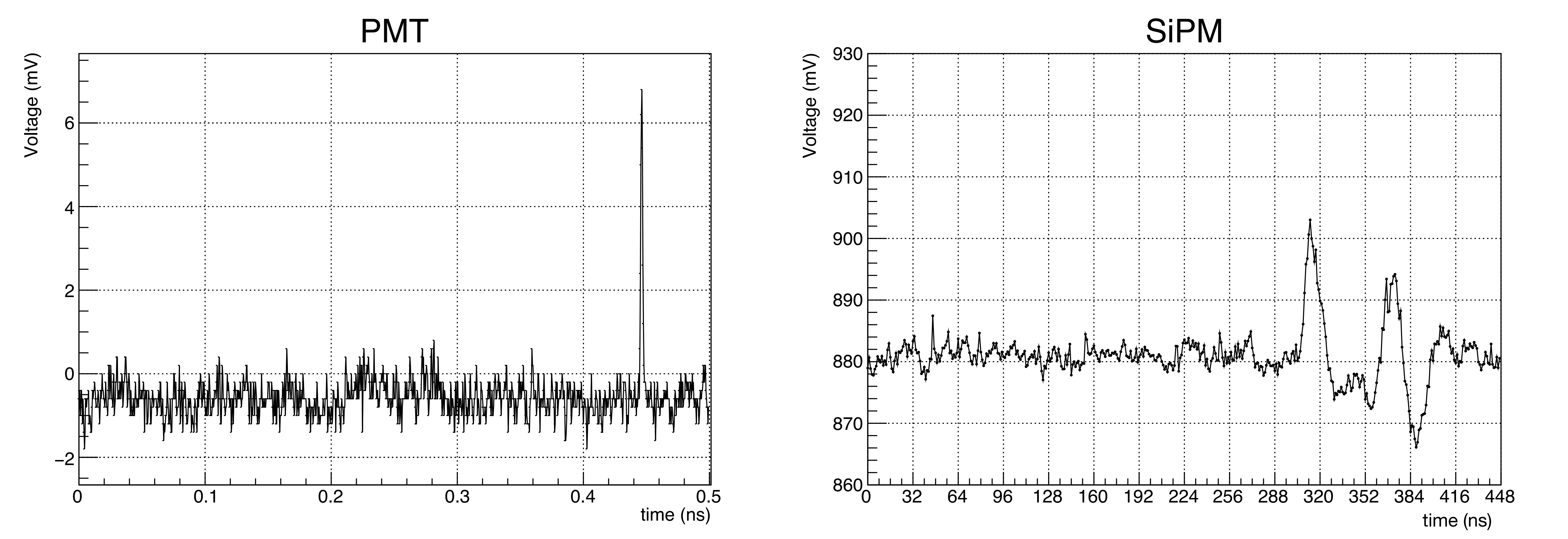


Simulated camera pixel

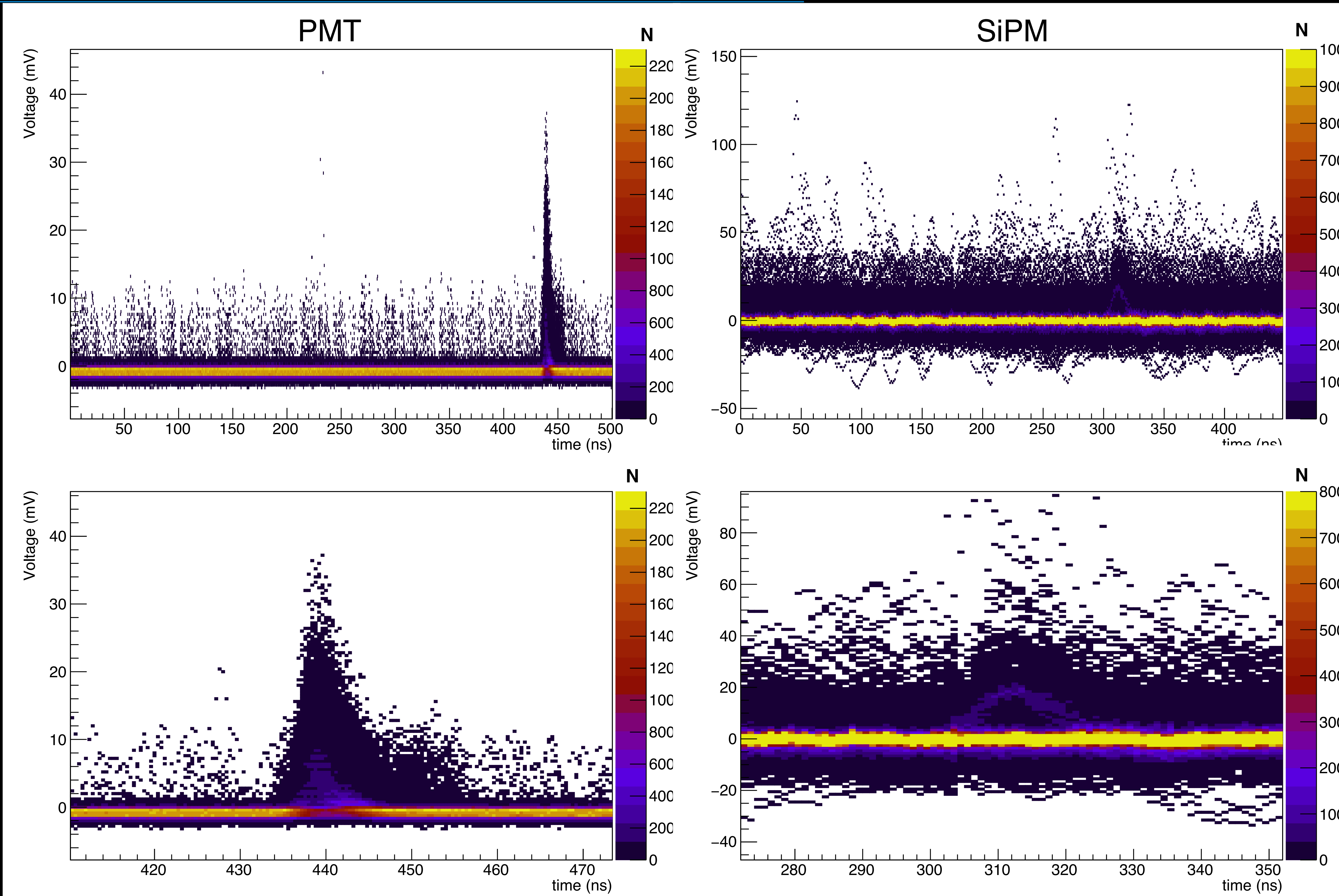


Geometry of a light concentrator and photon behavior in case $\alpha > \alpha_c$

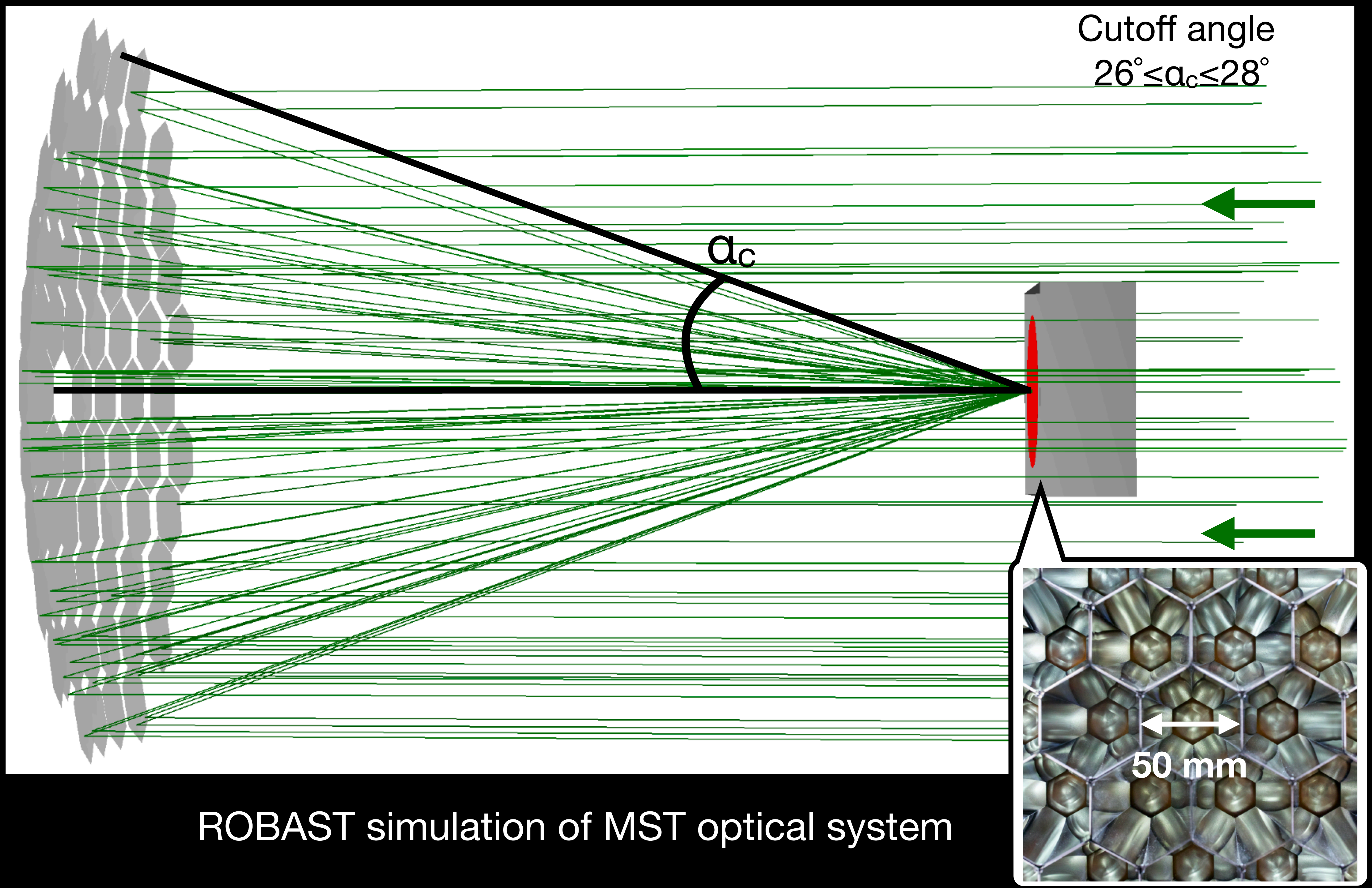
Waveforms


PMT
Voltage (mV)
6
4
2
0
−2
0
0.1
0.2
0.3
0.4
0.5
time (ns)
SiPM
Voltage (mV)
930
920
910
900
890
880
870
860
0
32
64
96
128
160
192
224
256
288
320
352
384
416
448
time (ns)

Stacked waveforms



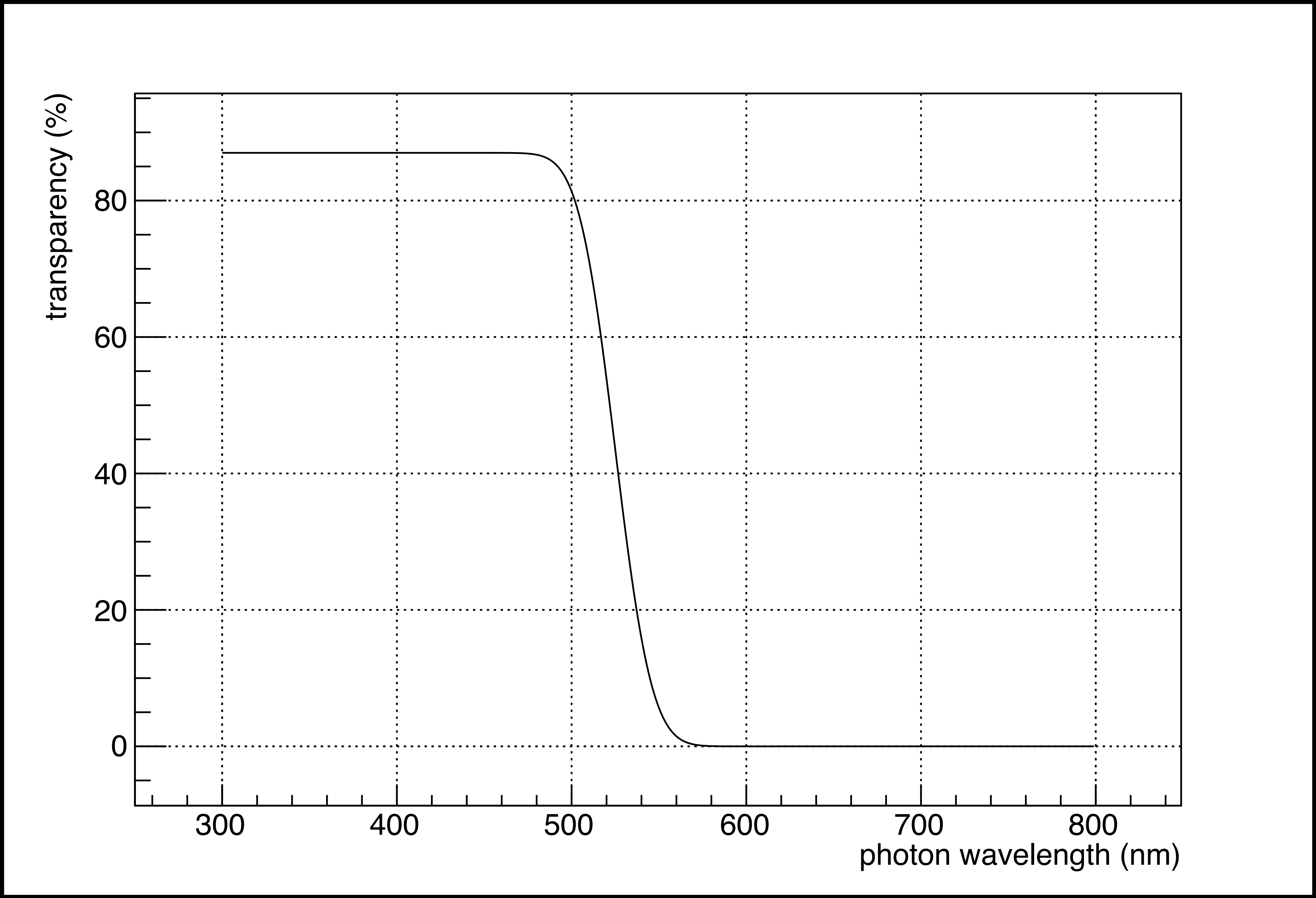
Medium-sized telescope



ROBAST simulation of MST optical system

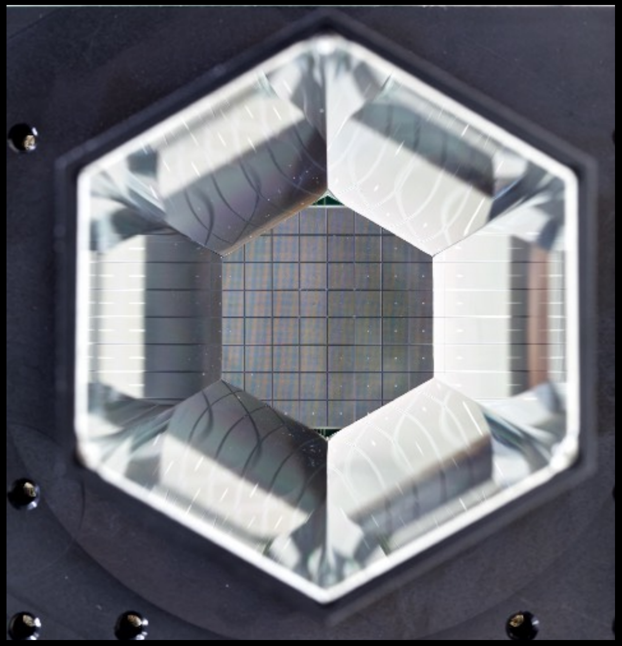
~1800 pixels

Filter transmittance

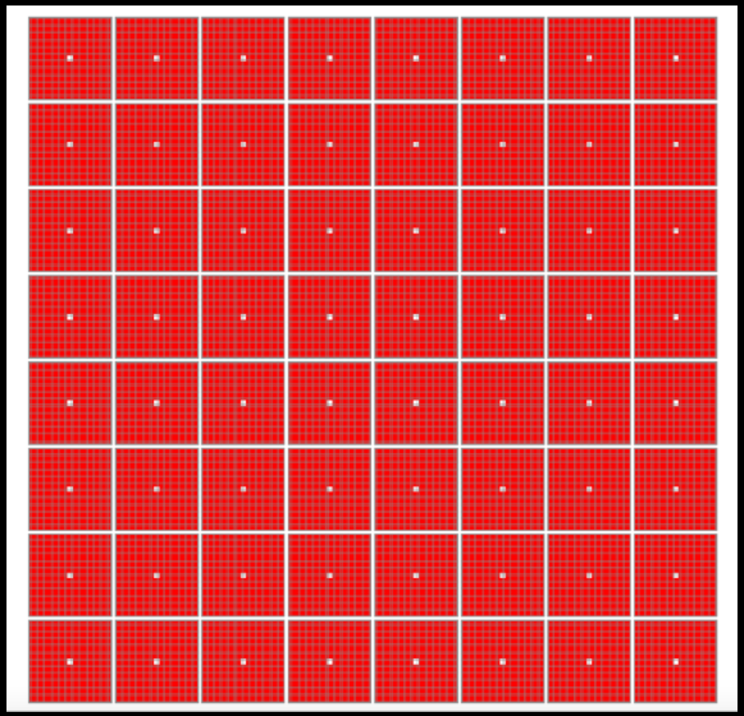


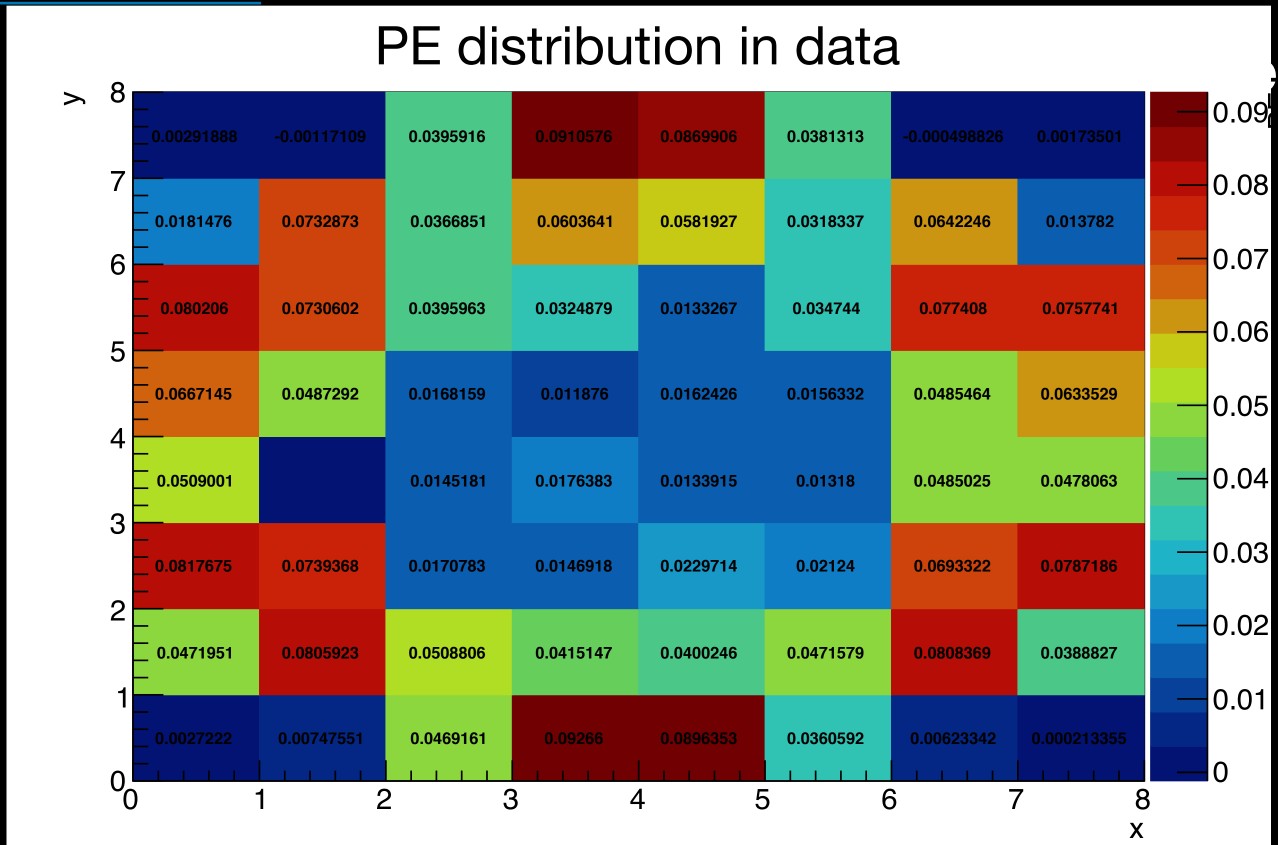
Photoelectron distribution in SiPM

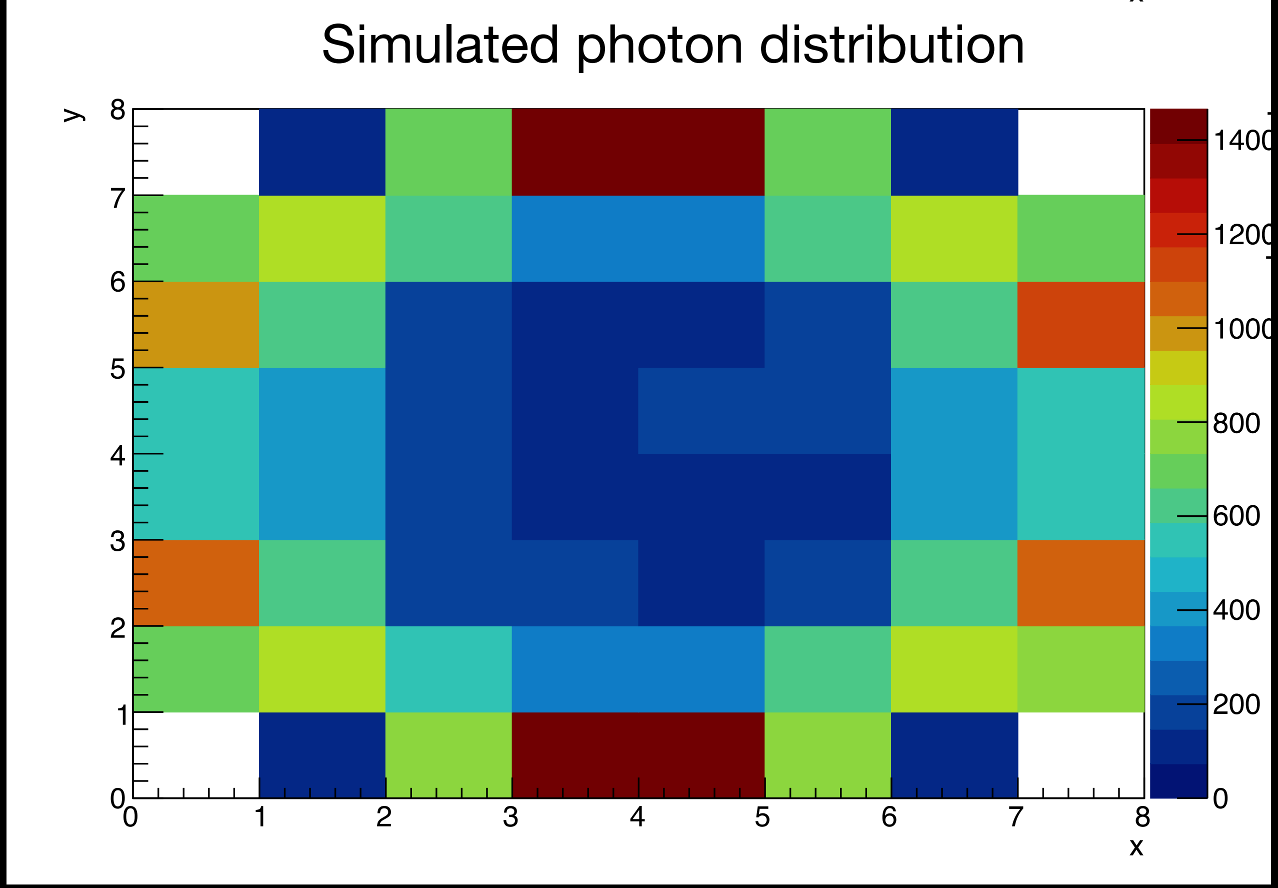
SiPM photo



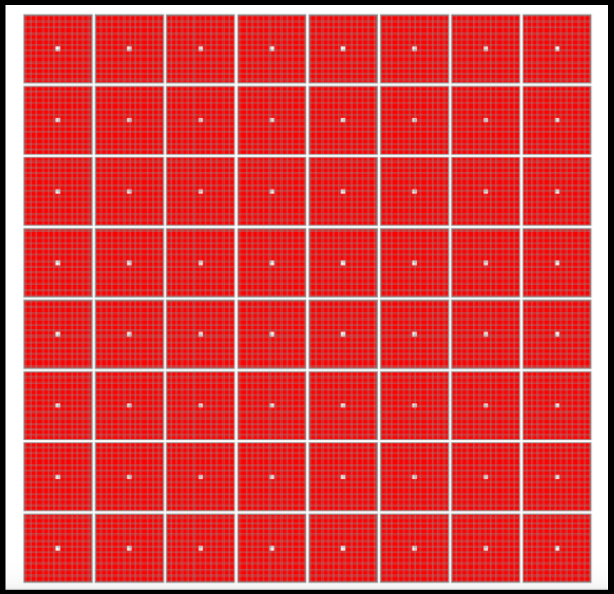
SiPM geometry



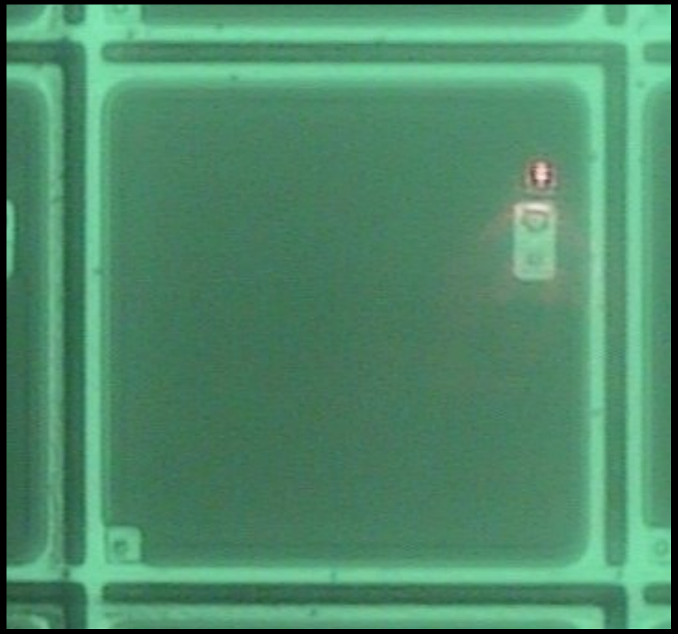




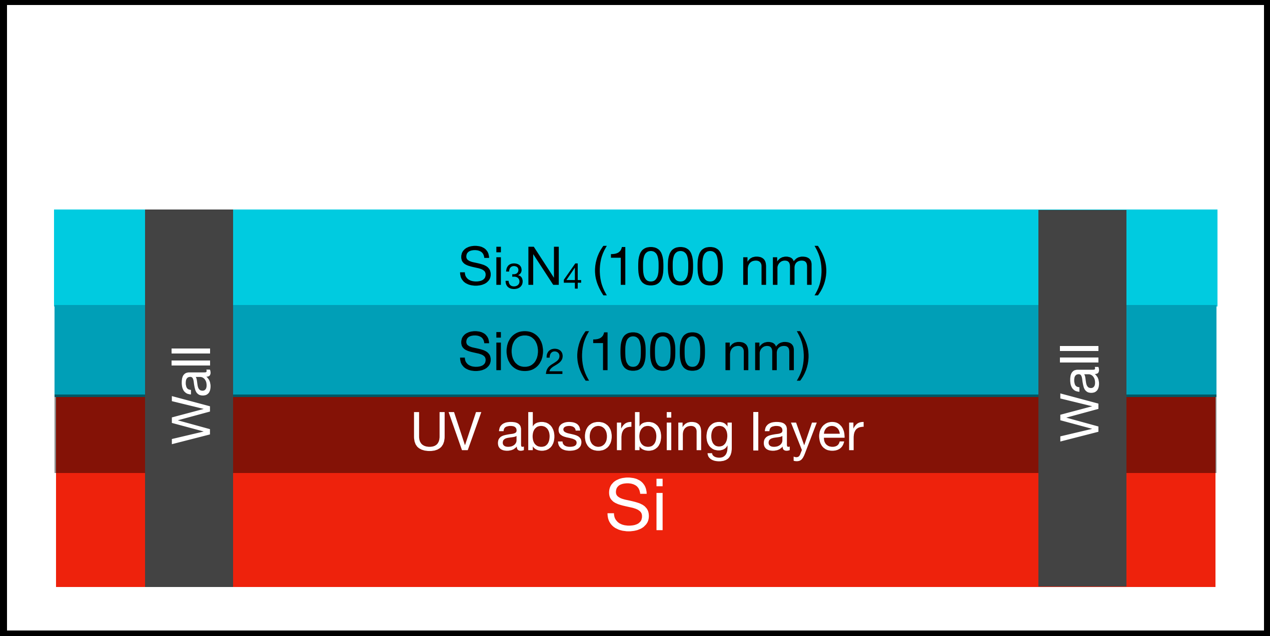
SiPM geometry



64 channels



50µm cell (photo)

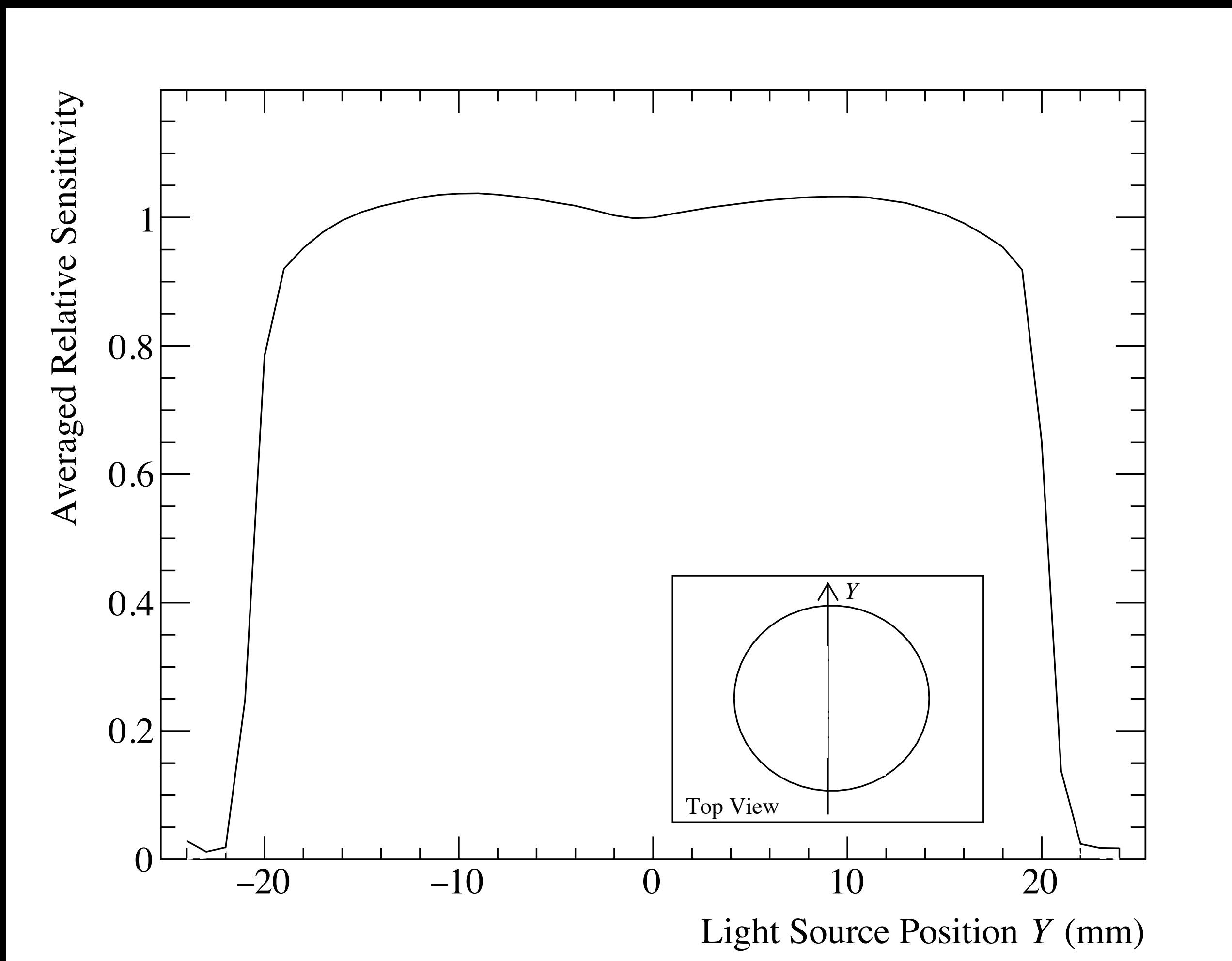


Cell structure

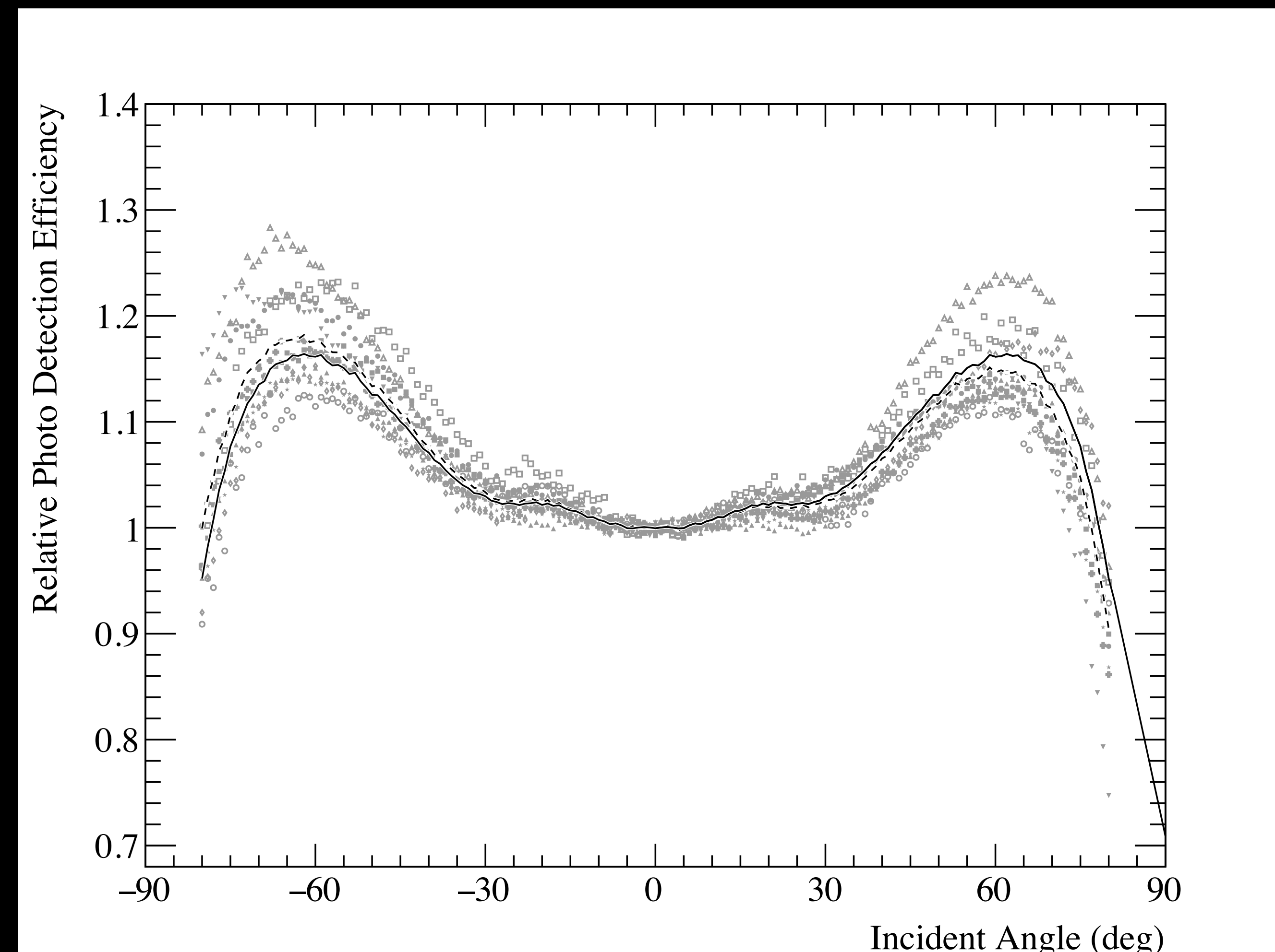
50µm cell (simulation)

Angular sensitivity of PMTs

A. Okumura et al 2017 JINST **12** P12008



PMT relative cathode sensitivity



PMT relative detection efficiency

Refractive index of Si