Development of a UV-transparent Lens Array Enlarging the Effective Area of Multi-channel SiPMs

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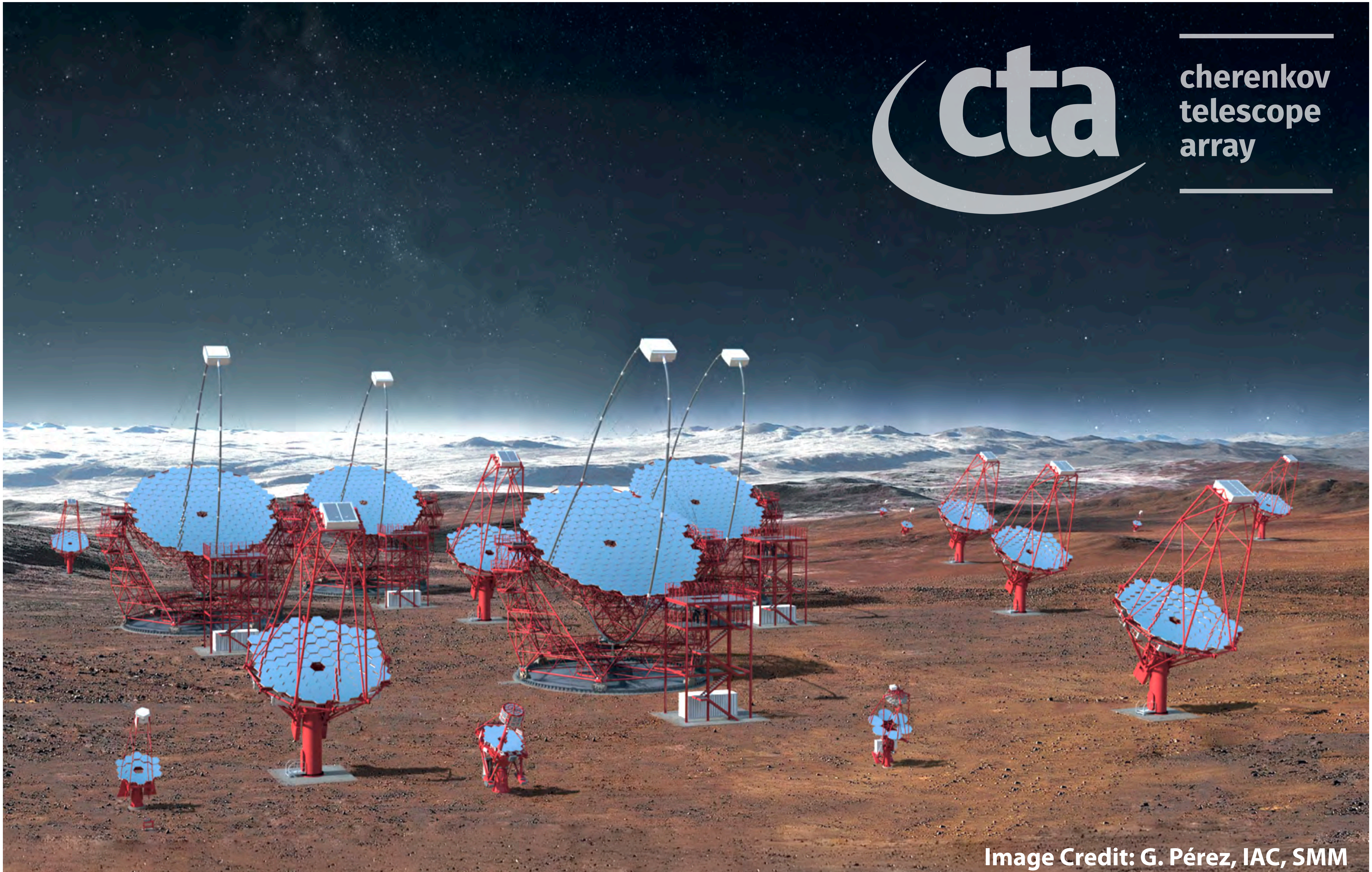
Cherenkov Telescope Array (CTA)



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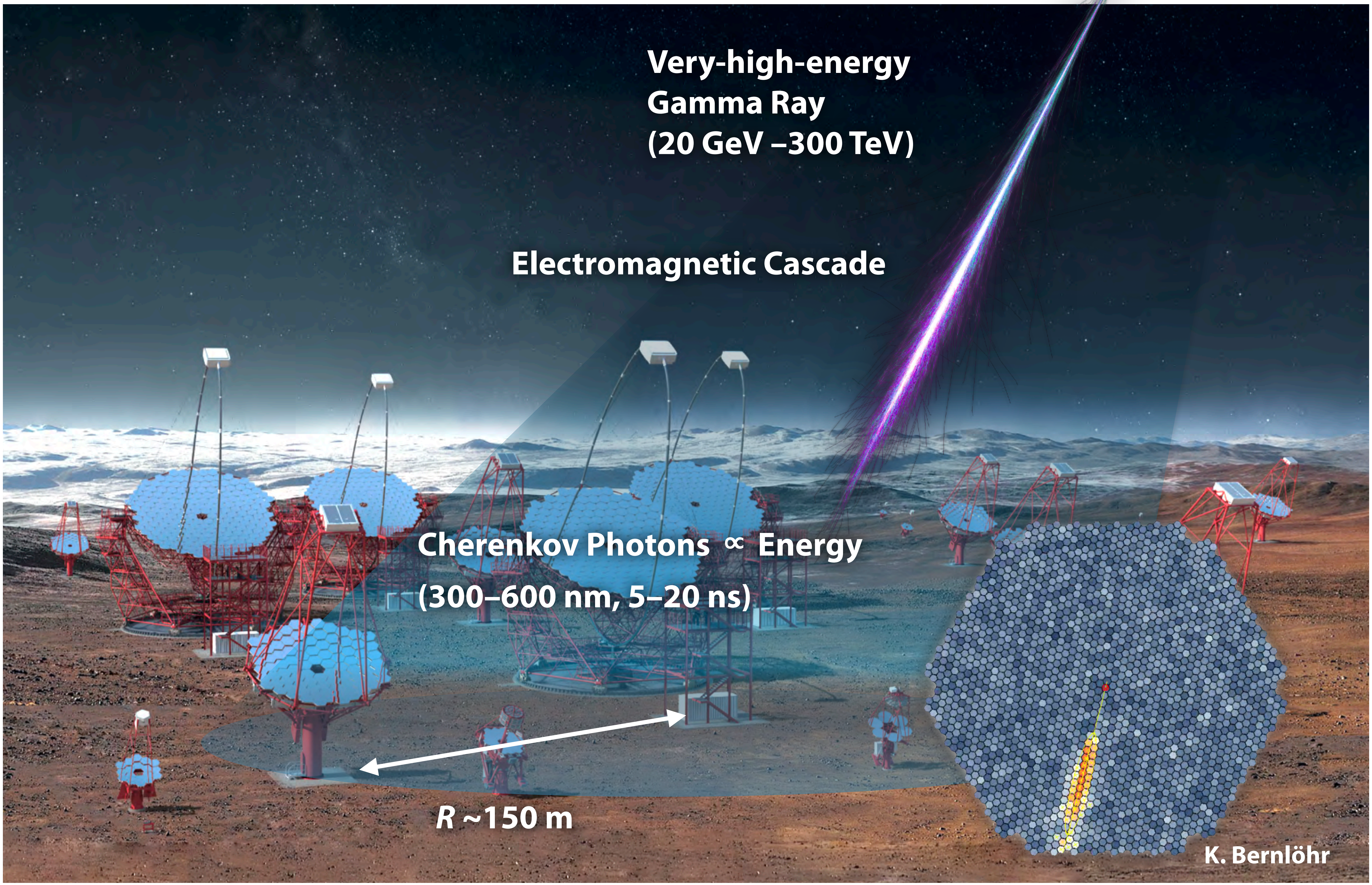
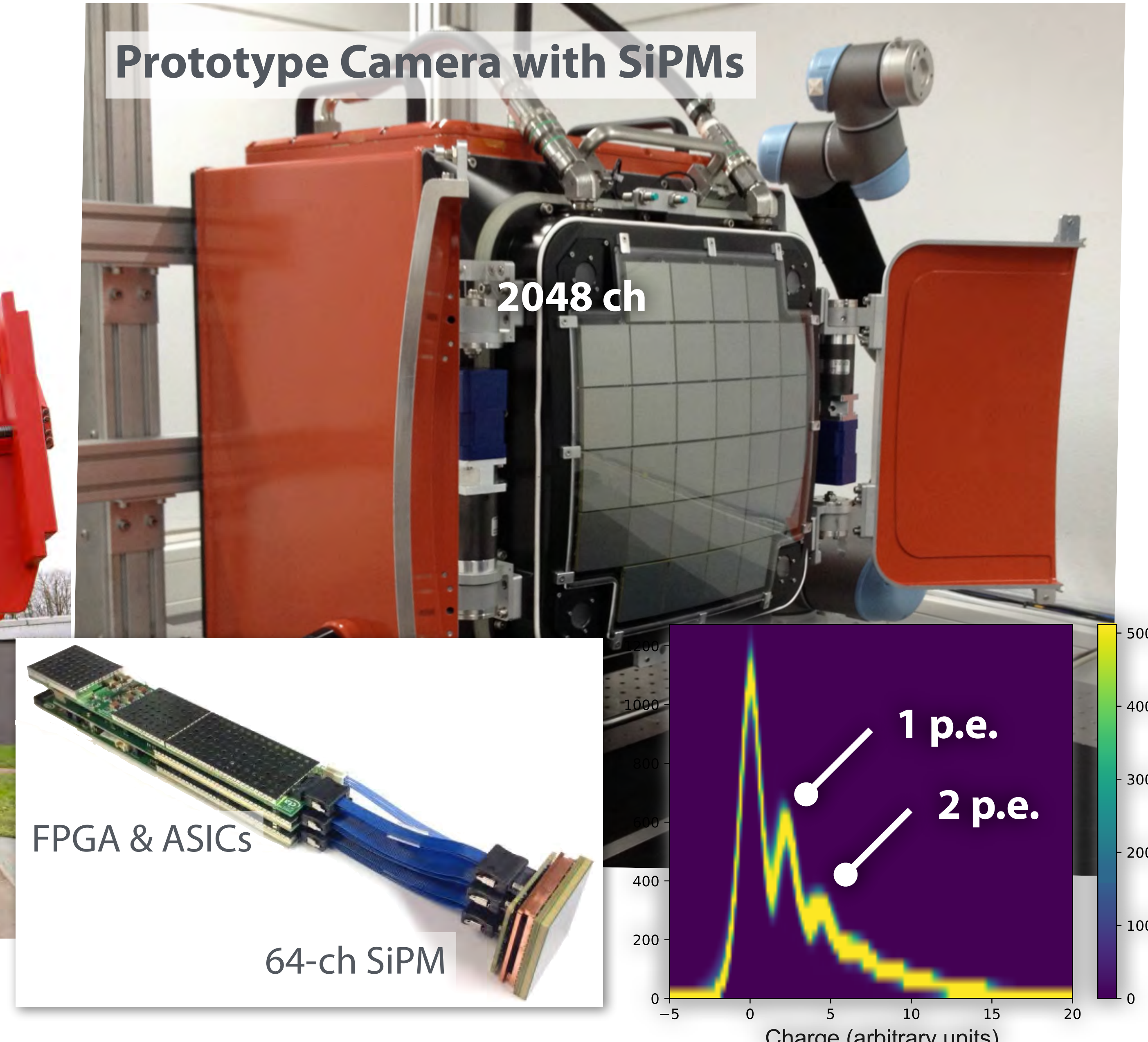


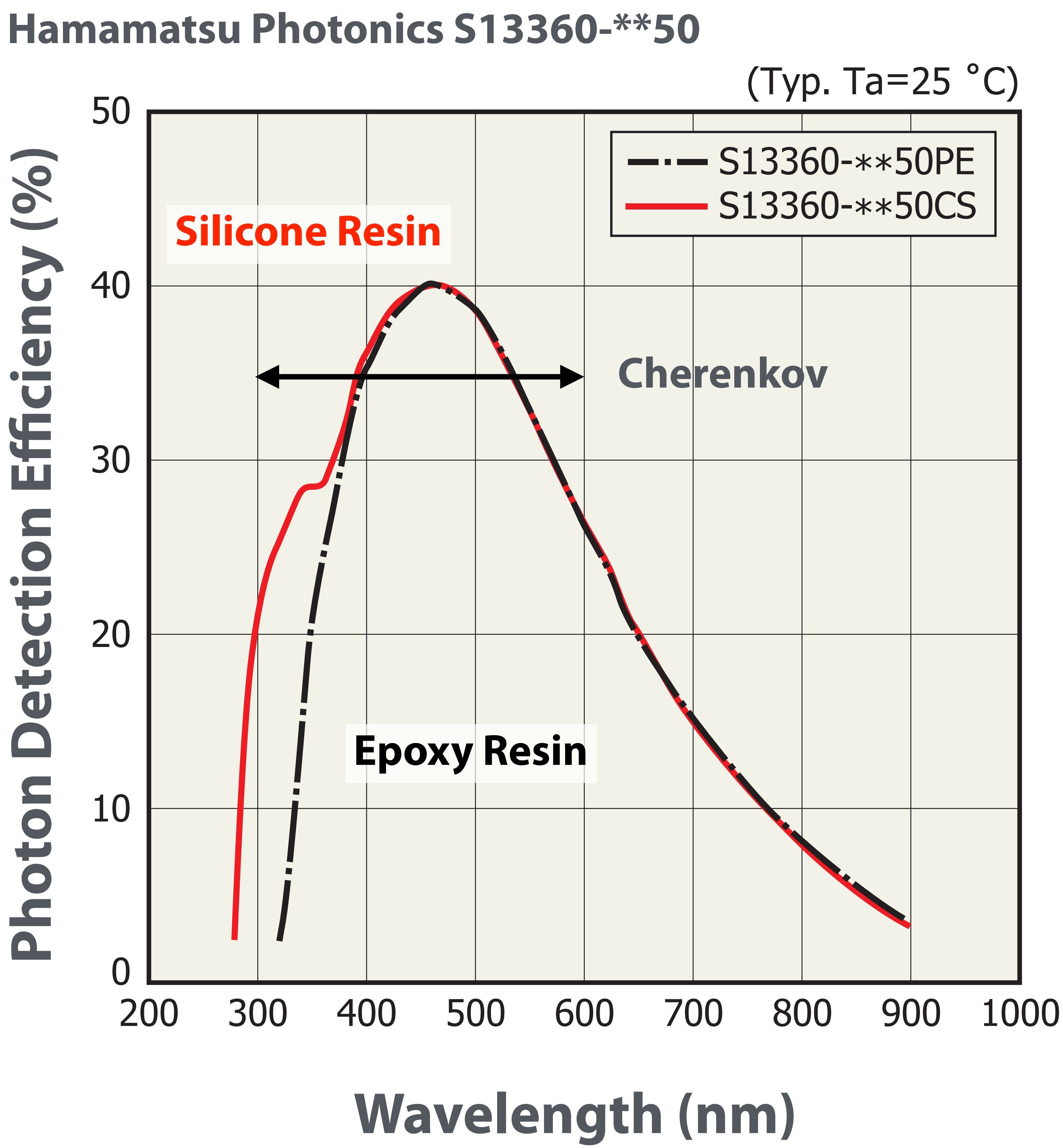
A SiPM Cherenkov Camera for CTA

Prototype Telescope at Paris Observatory



- Use of SiPMs and dedicated ASICs enables us to make a compact, light, fast, and high-PDE Cherenkov camera
- Lower optical crosstalk (OCT) rate suppresses accidental triggers by night-sky photons and achieves better energy resolution
- The higher photon detection efficiency, the lower energy threshold

Photon Detection Efficiency (PDE)



- High refractive index of silicon
  - n ~ 6.9 at 372 nm
  - 3.7–5.1 in 300–800 nm
  - ~20–40% reflectance w/o ARC
- APD cell fill factor (74% for 50 μm)
- Thin dead layer (< 400 nm)
- Low absorption coefficients in long wavelengths (> 500 nm)
- Absorption by epoxy resin (< 400 nm)
- Pixel gap in multi-channel SiPMs (12% lost for 3-mm pixels with 0.2-mm gap)

Some Ideas for Higher (Effective) PDE

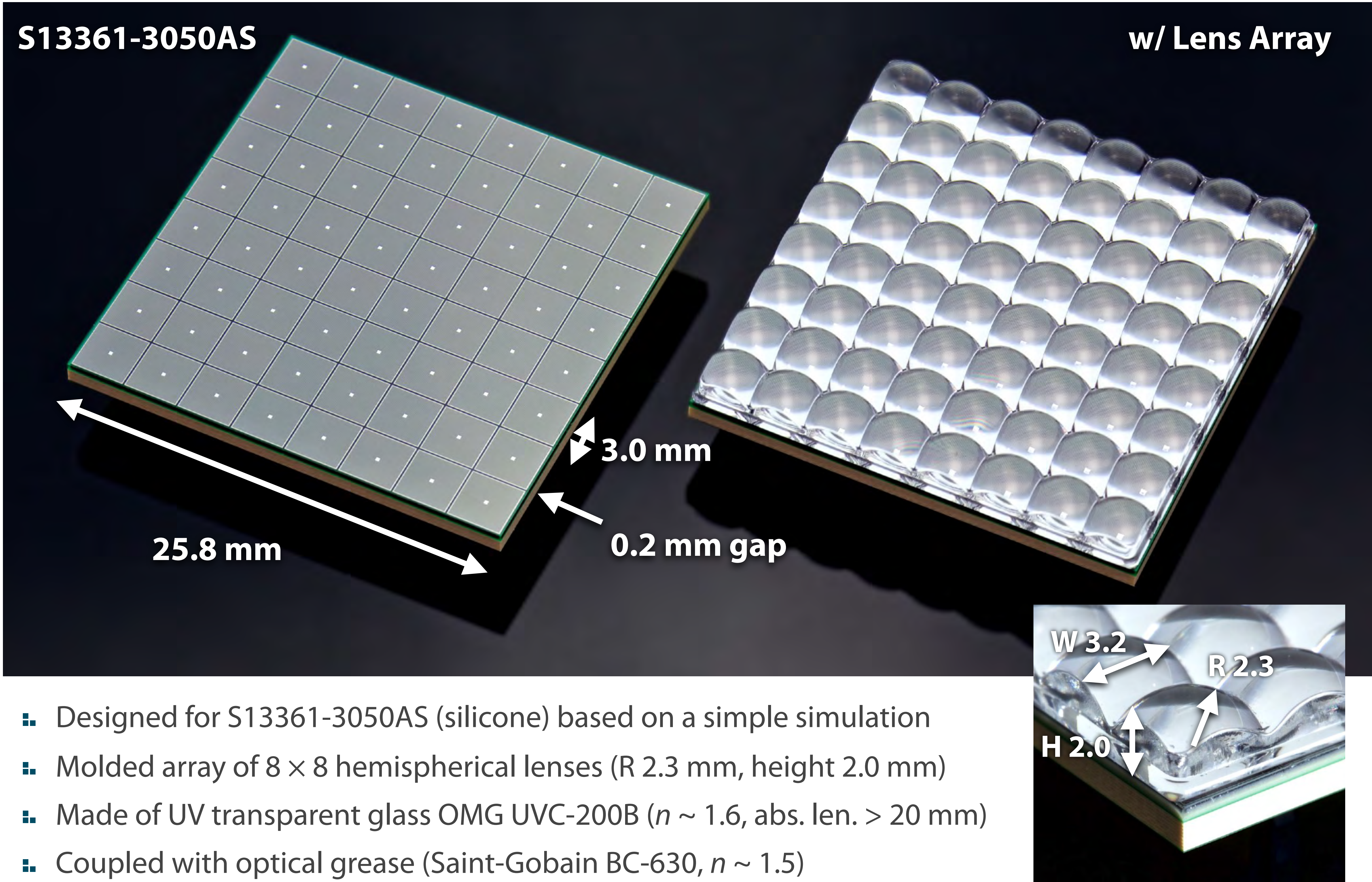
- Easy
  - Operate at higher voltages but higher optical crosstalk and dark current

- Available or in progress
  - Silicone resin or no-resin SiPMs
  - Anti-reflection coating (thin Si_3N_4 or multi-layer coating)
  - Light concentrators like Winston cones (a.k.a. compound parabolic concentrators)

- Technically difficult or expensive investment (feasibility ??)
  - Micro (50–75 μm) lenses on individual APD cells to avoid trenches and metals
  - Moss-eye structure on Si surface (gradation refractive index)

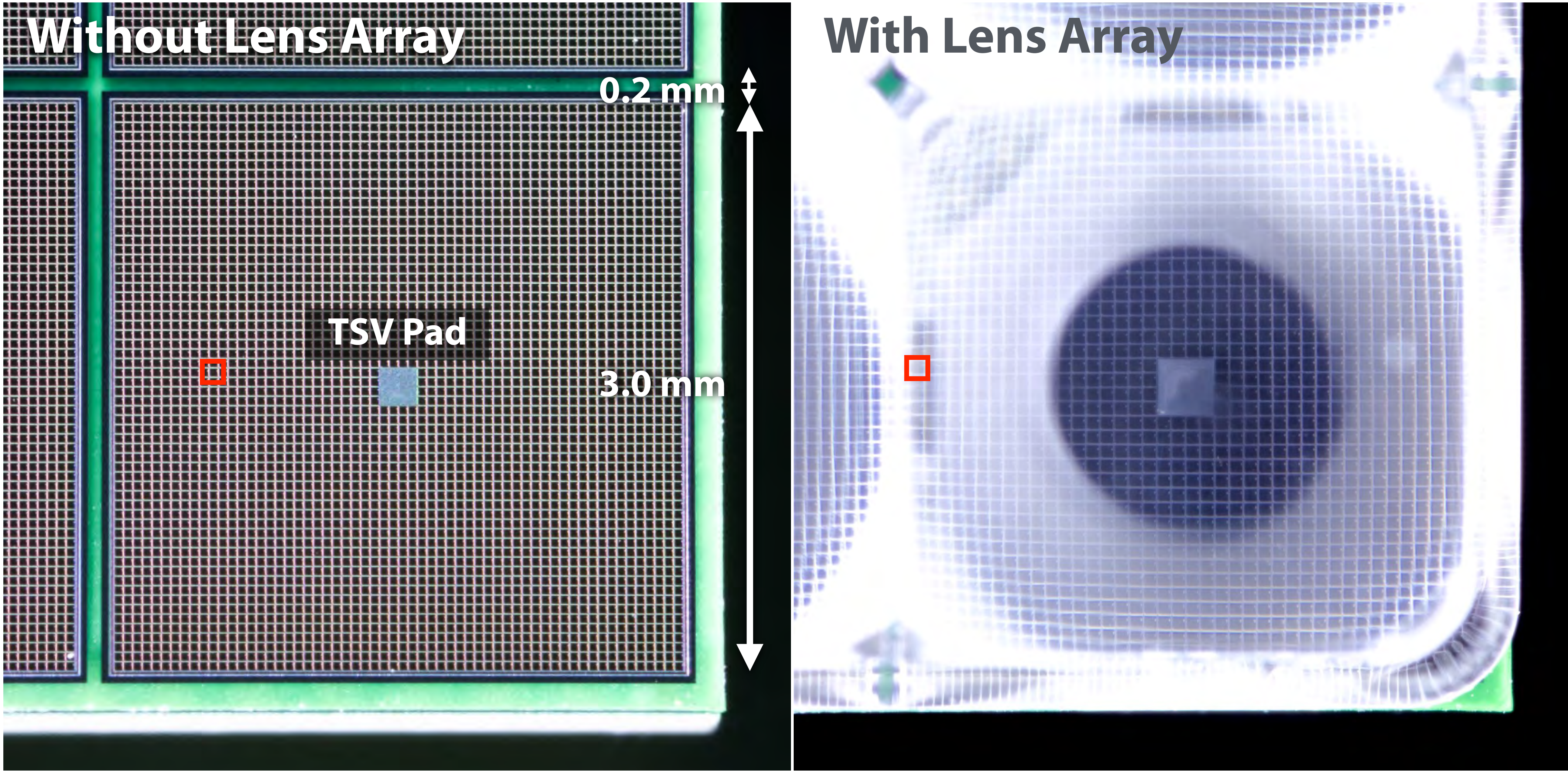
- This talk
  - Macro lenses on individual pixel to avoid pixel gaps
  - Reflect photons back onto Si surface

Prototype Lens Array



- Designed for S13361-3050AS (silicone) based on a simple simulation
- Molded array of 8 × 8 hemispherical lenses (R 2.3 mm, height 2.0 mm)
- Made of UV transparent glass OMG UVC-200B (*n* ~ 1.6, abs. len. > 20 mm)
- Coupled with optical grease (Saint-Gobain BC-630, *n* ~ 1.5)

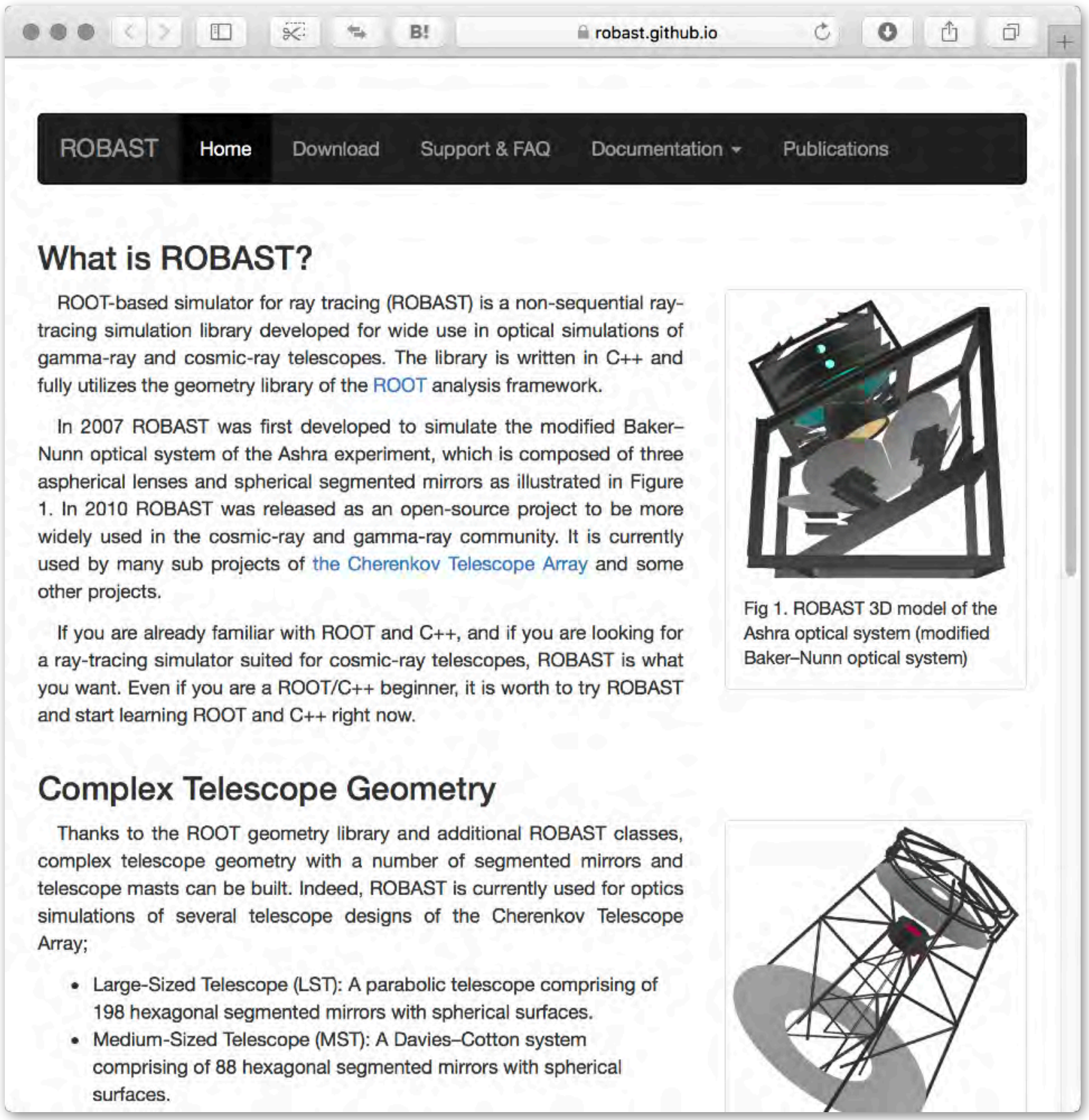
Close Up View



- APD cells are apparently **magnified** by the lens array
- 0.2-mm gaps are not visible
- Wider pixel gaps, say ~1.2 mm, can be accepted with a shorter lens radius

Ray-tracing Simulation – ROBAST

Okumura+ (2016) *Astropart. Phys.*



robast.github.io

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What is ROBAST?

ROOT-based simulator for ray tracing (ROBAST) is a non-sequential ray-tracing simulation library developed for wide use in optical simulations of gamma-ray and cosmic-ray telescopes. The library is written in C++ and fully utilizes the geometry library of the ROOT analysis framework.

In 2007 ROBAST was first developed to simulate the modified Baker–Nunn optical system of the Ashra experiment, which is composed of three aspherical lenses and spherical segmented mirrors as illustrated in Figure 1. In 2010 ROBAST was released as an open-source project to be more widely used in the cosmic-ray and gamma-ray community. It is currently used by many sub projects of the Cherenkov Telescope Array and some other projects.

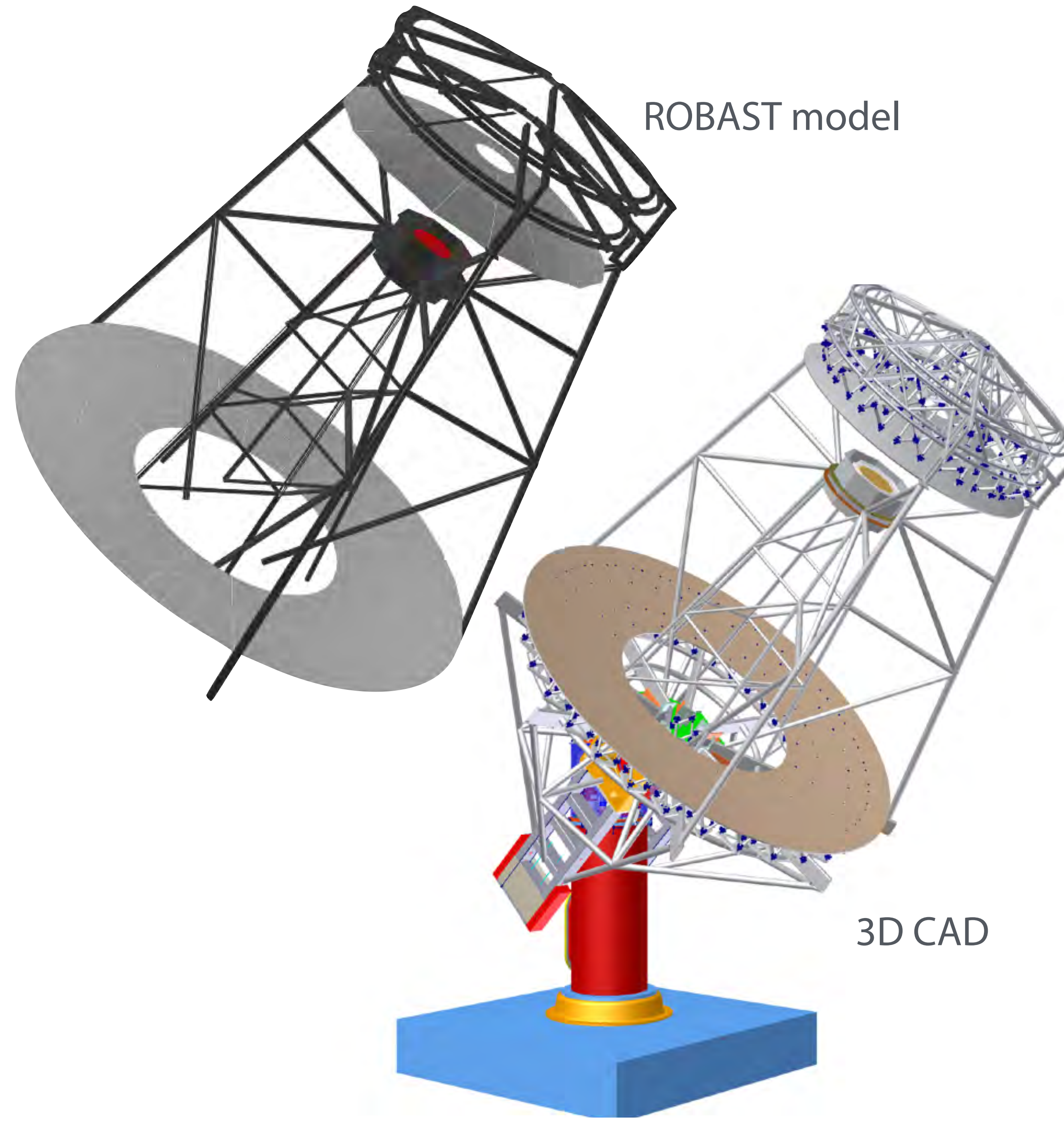
If you are already familiar with ROOT and C++, and if you are looking for a ray-tracing simulator suited for cosmic-ray telescopes, ROBAST is what you want. Even if you are a ROOT/C++ beginner, it is worth to try ROBAST and start learning ROOT and C++ right now.

Fig 1. ROBAST 3D model of the Ashra optical system (modified Baker–Nunn optical system)

Complex Telescope Geometry

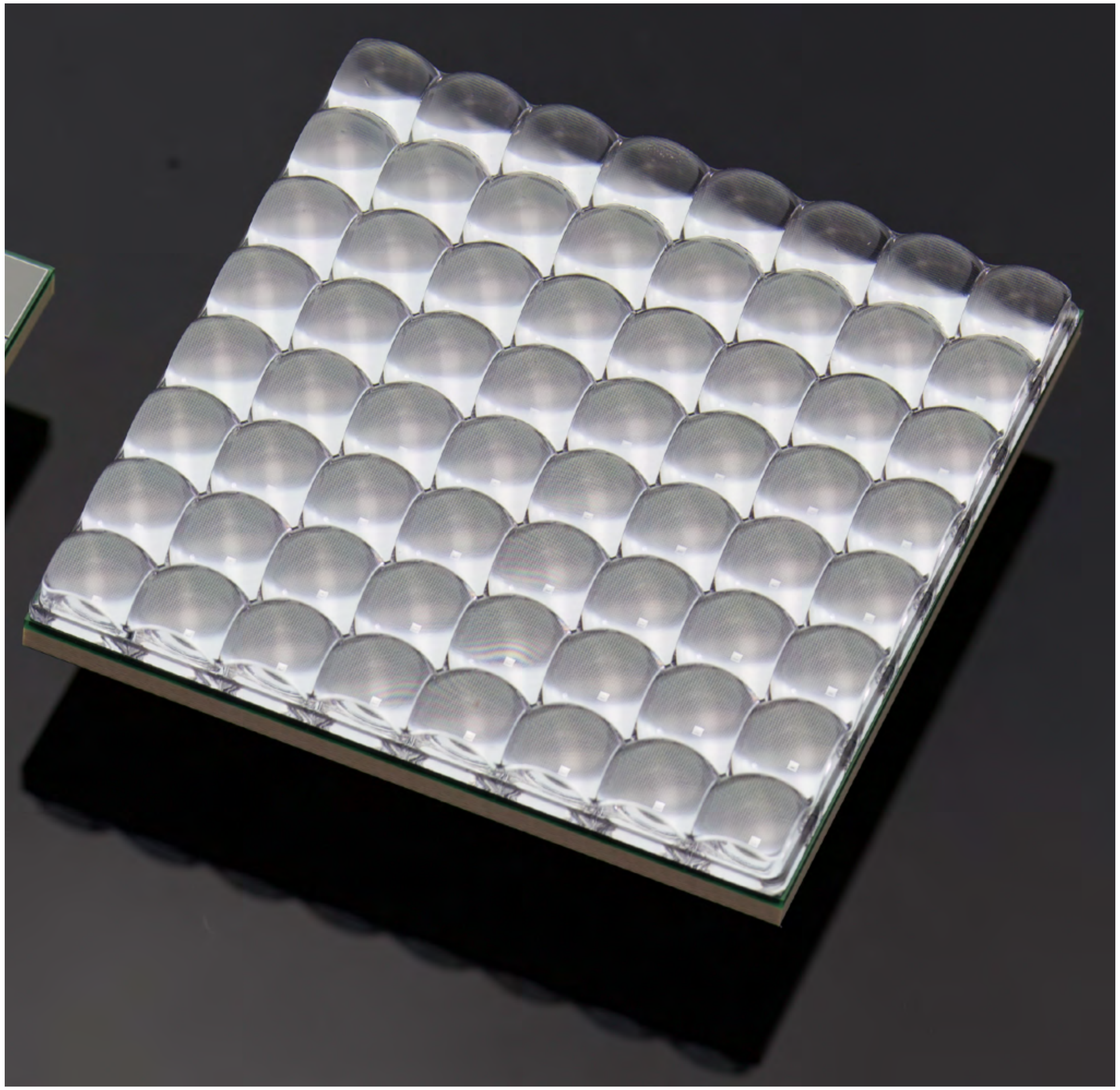
Thanks to the ROOT geometry library and additional ROBAST classes, complex telescope geometry with a number of segmented mirrors and telescope masts can be built. Indeed, ROBAST is currently used for optics simulations of several telescope designs of the Cherenkov Telescope Array;

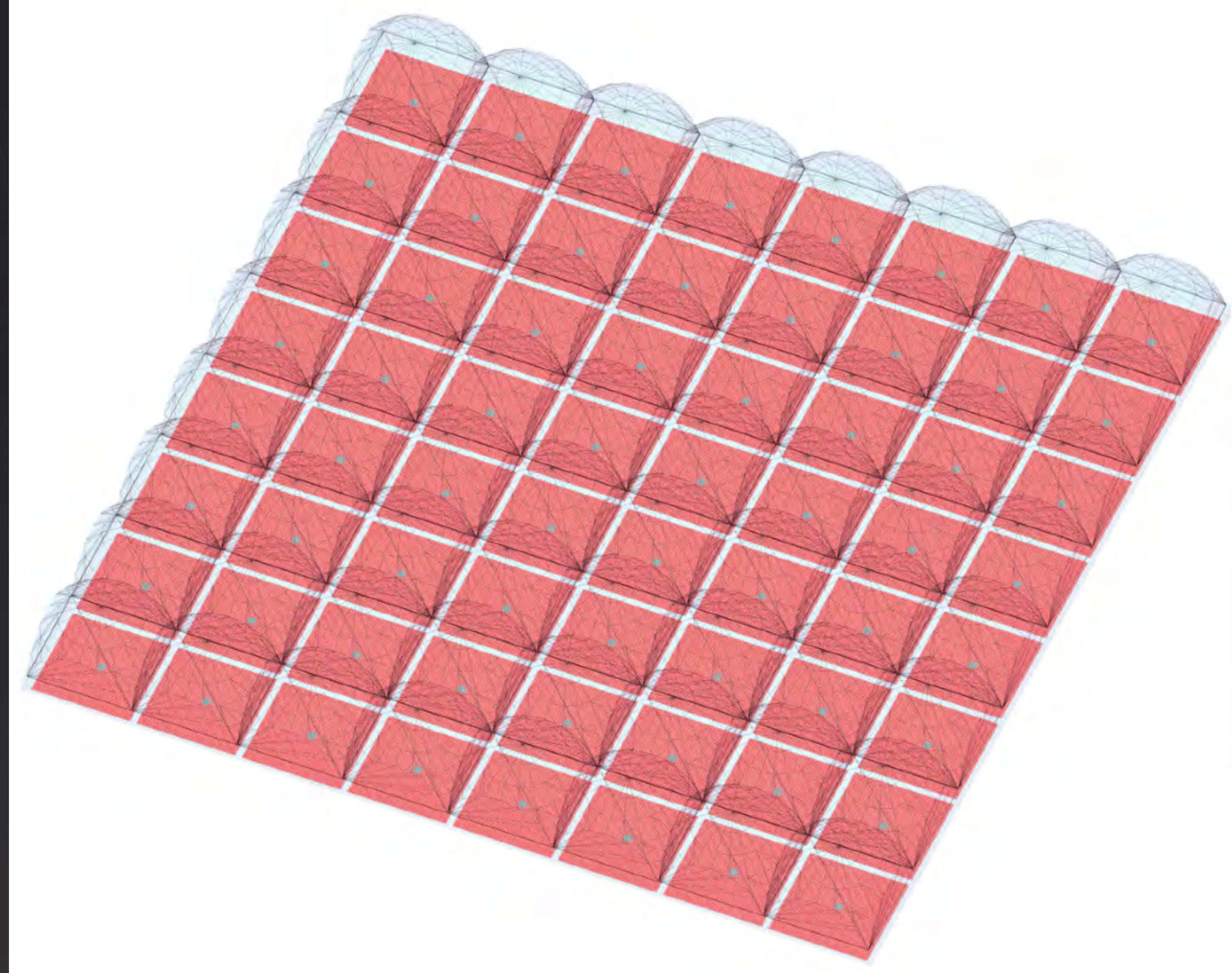
- Large-Sized Telescope (LST): A parabolic telescope comprising of 198 hexagonal segmented mirrors with spherical surfaces.
- Medium-Sized Telescope (MST): A Davies–Cotton system comprising of 88 hexagonal segmented mirrors with spherical surfaces.



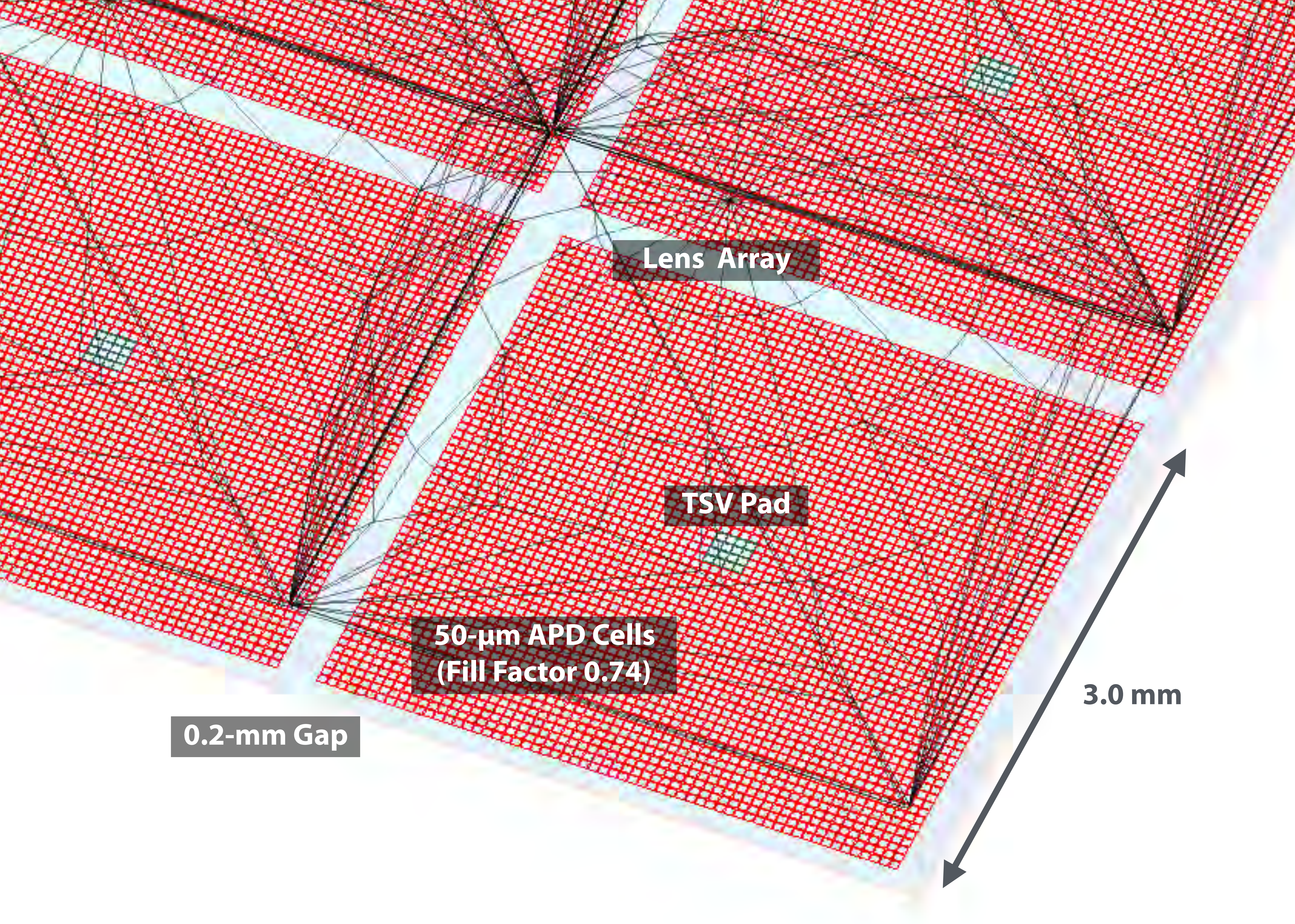
- **RO**OT-**ba**sed **s**imulator for ray **t**racing (ROBAST) https://robast.github.io
- Developed for cosmic-ray and gamma-ray telescopes with use of the ROOT geometry library
- Open source https://github.com/ROBAST/ROBAST

3D Geometry



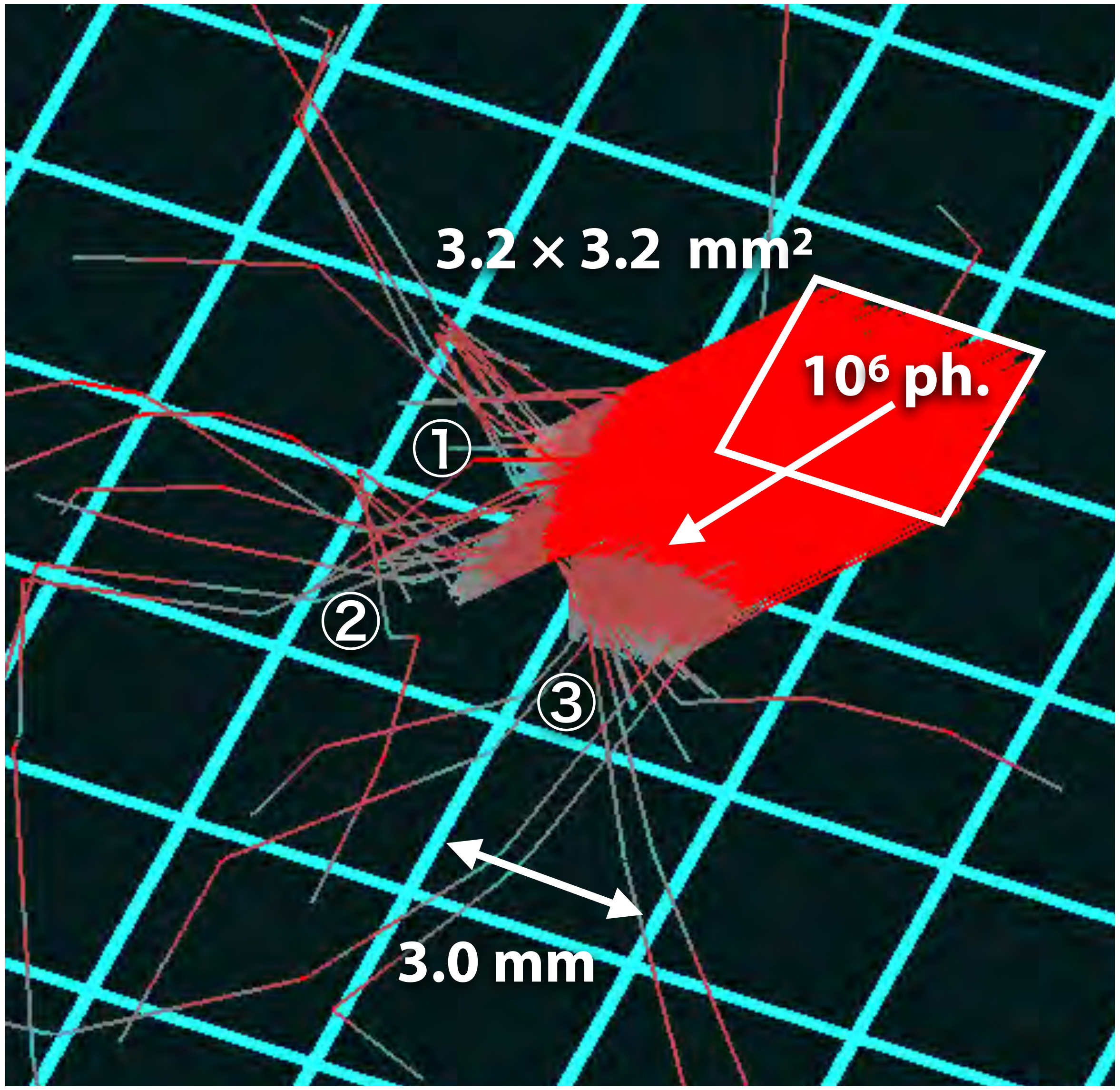


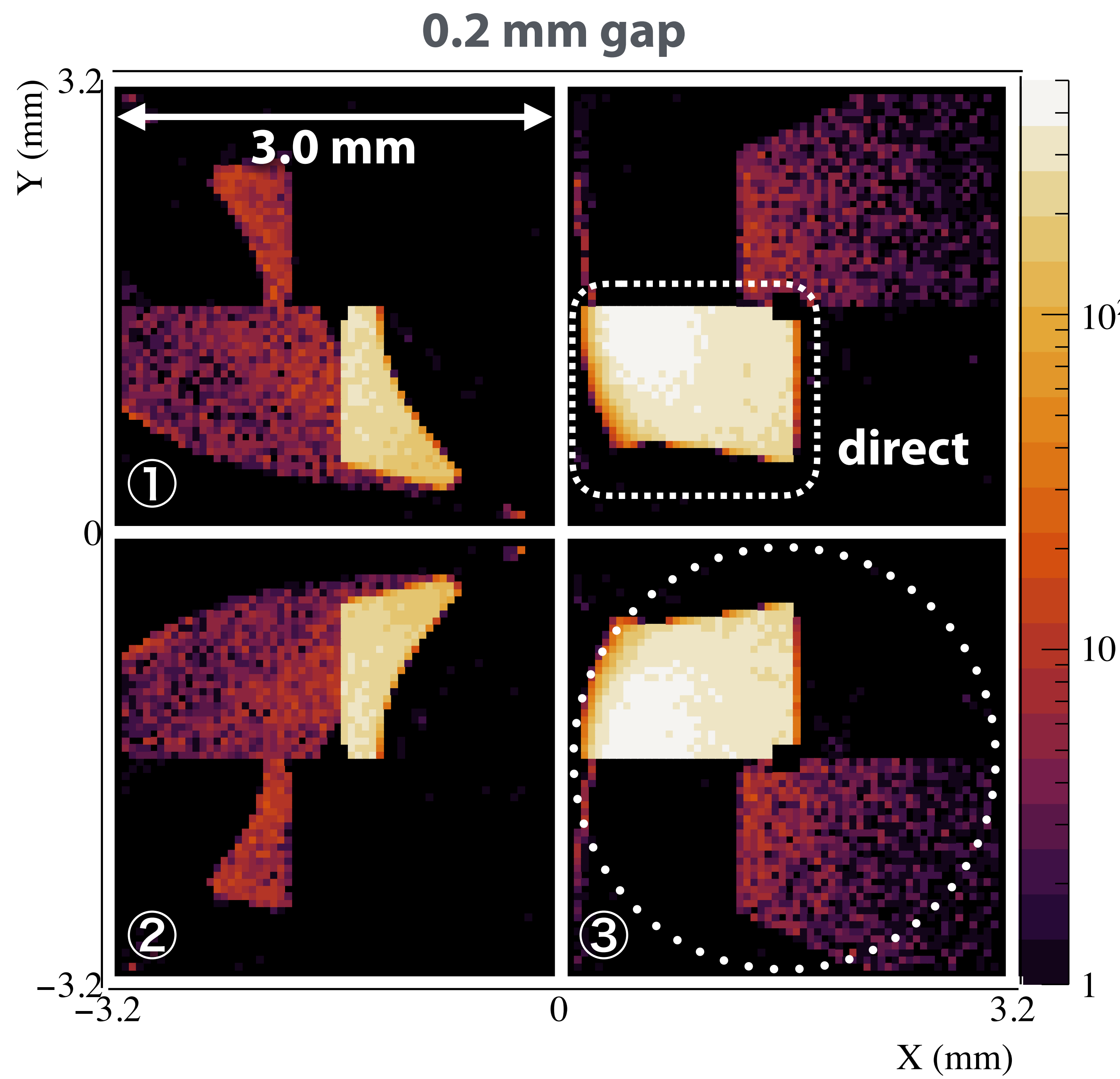
- S11361-3050AS : 8 × 8 pixels (64 ch), 60 × 60 50–µm APD cells
- 3 × 3 mm² sensitive area, 0.2-mm pixel gap, and TSV pad
- 100-µm silicone resin coating and lens array



Lens Array
TSV Pad
50-µm APD Cells
(Fill Factor 0.74)
3.0 mm
0.2-mm Gap

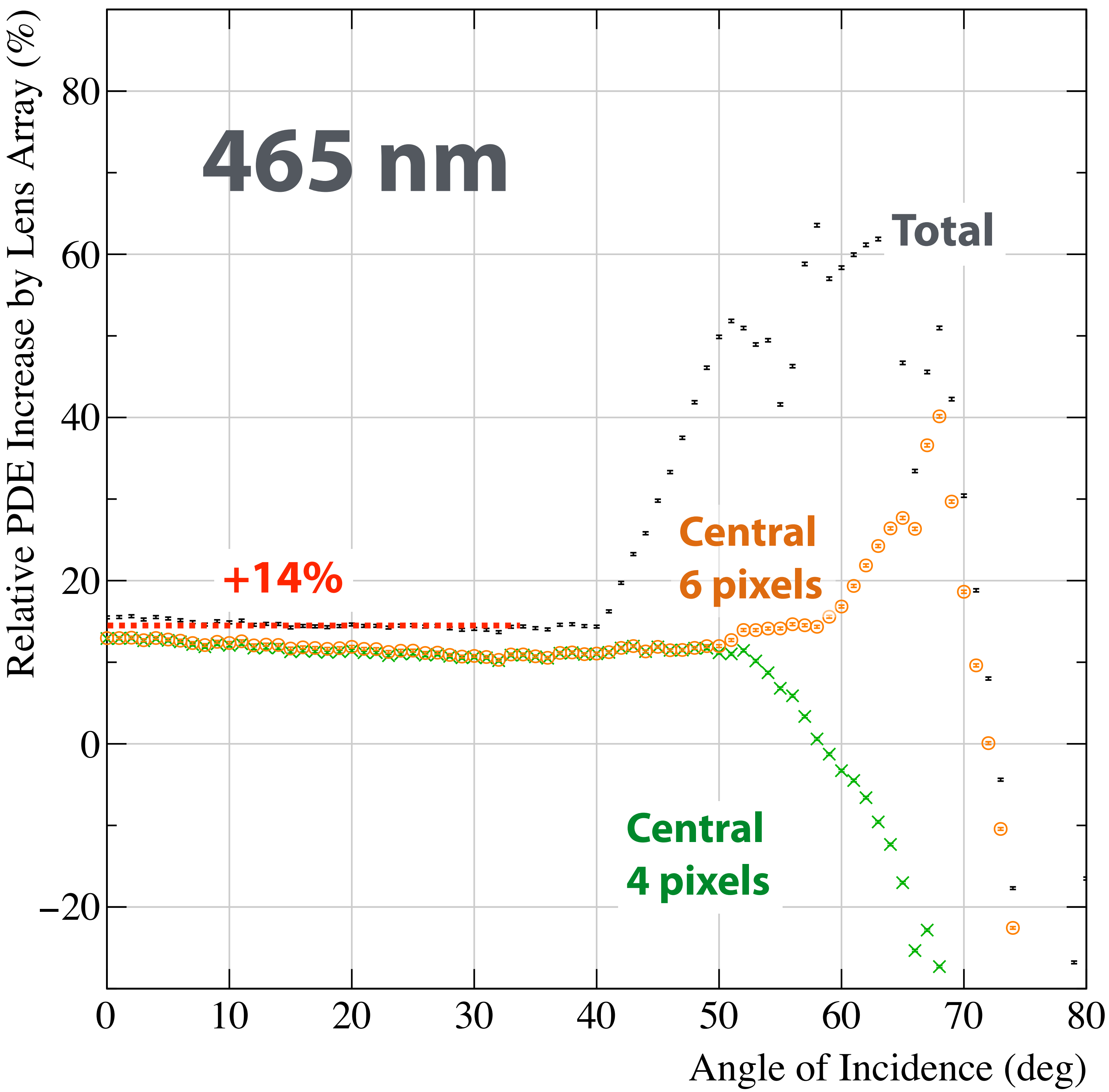
Simulation (40-deg Case)





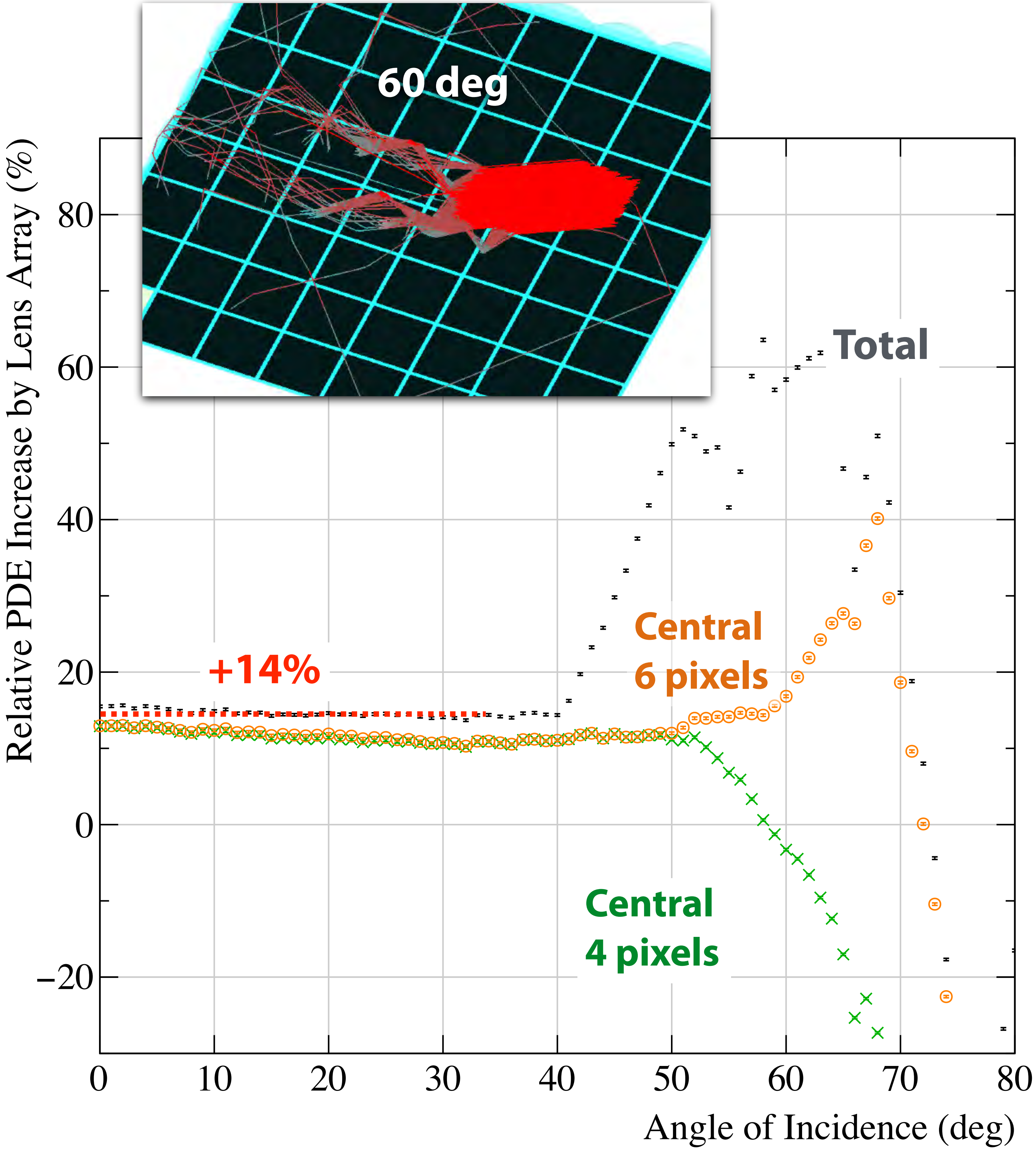
- Emit parallel photons in a square region of 3.2 × 3.2 mm² with angles from 0 to 80 degrees
- Most photons avoid the gaps and are directly detected in the central circular region
- Some photons propagate to surrounding pixels due to reflection on media boundaries

Simulation



- Eff. coverage = (3.0 mm / 3.2 mm)^2 = 87.9%
- Ideally 1/0.879 ~ 114% is expected
- Many photons are also detected in adjacent 2 pixels in > 50 deg
- A large amount of photons are reflected back onto Si because of total internal reflection
- Anti-reflection layer is not taken into account

Simulation



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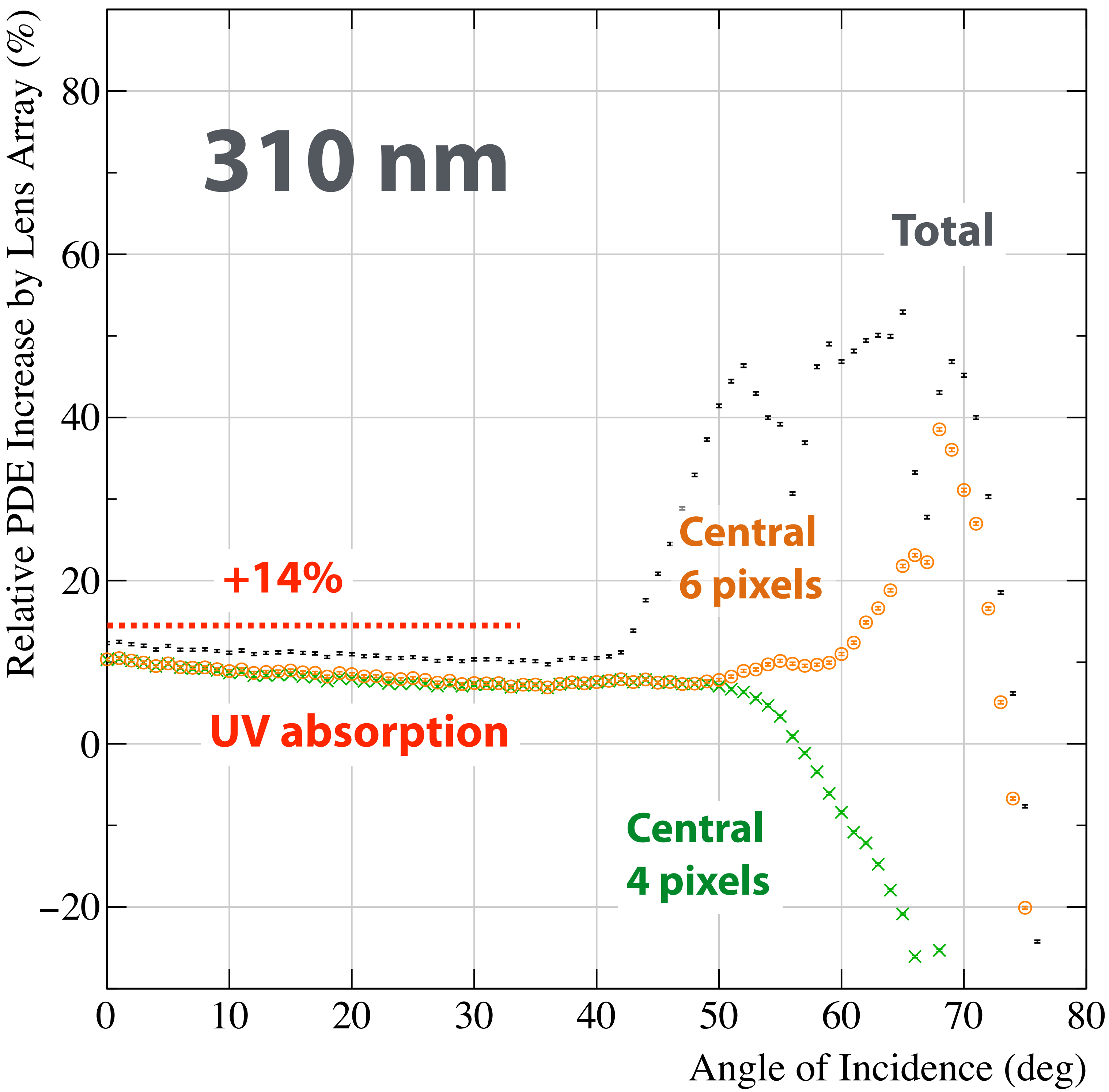
Simulation (310 nm)



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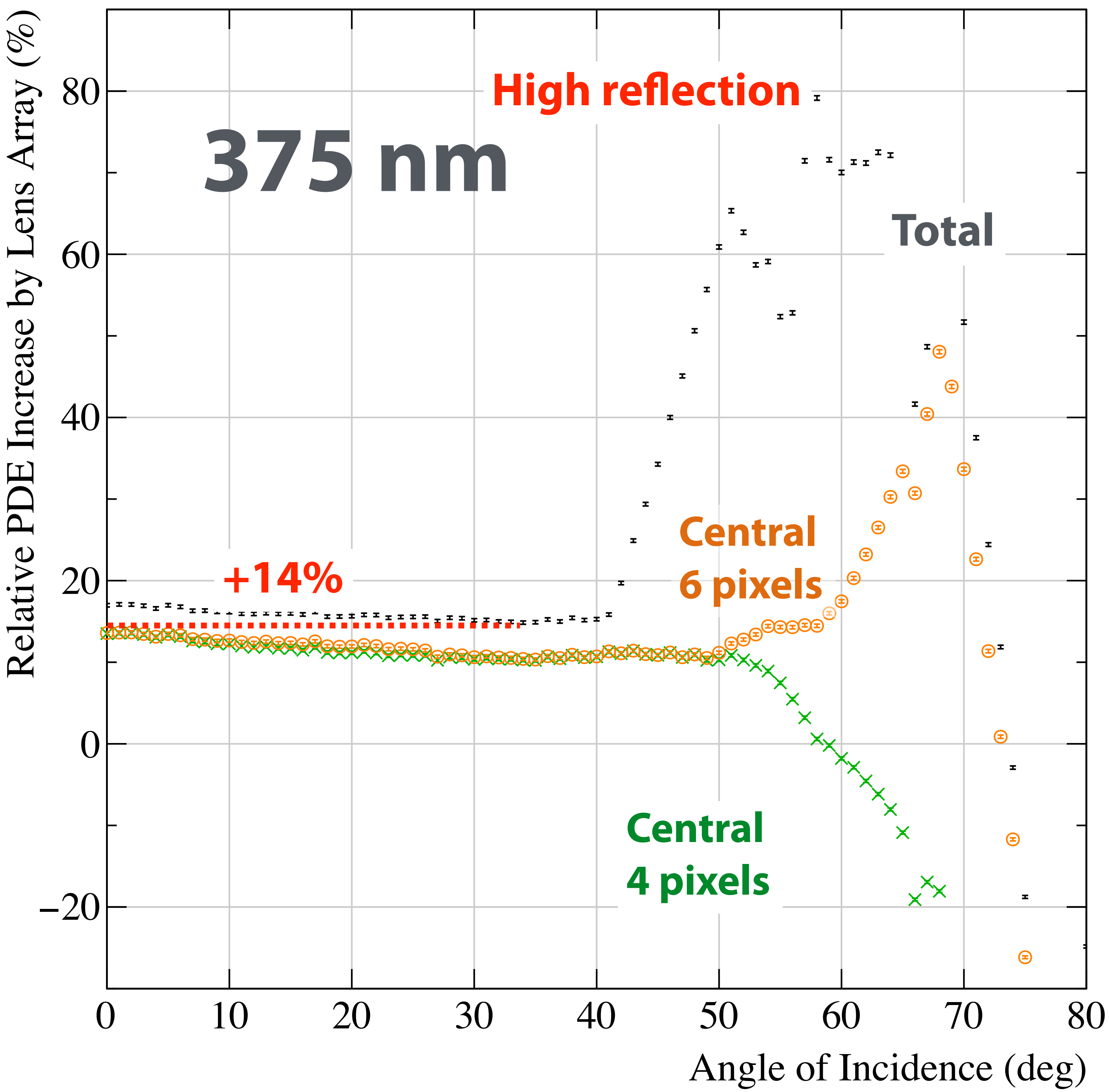
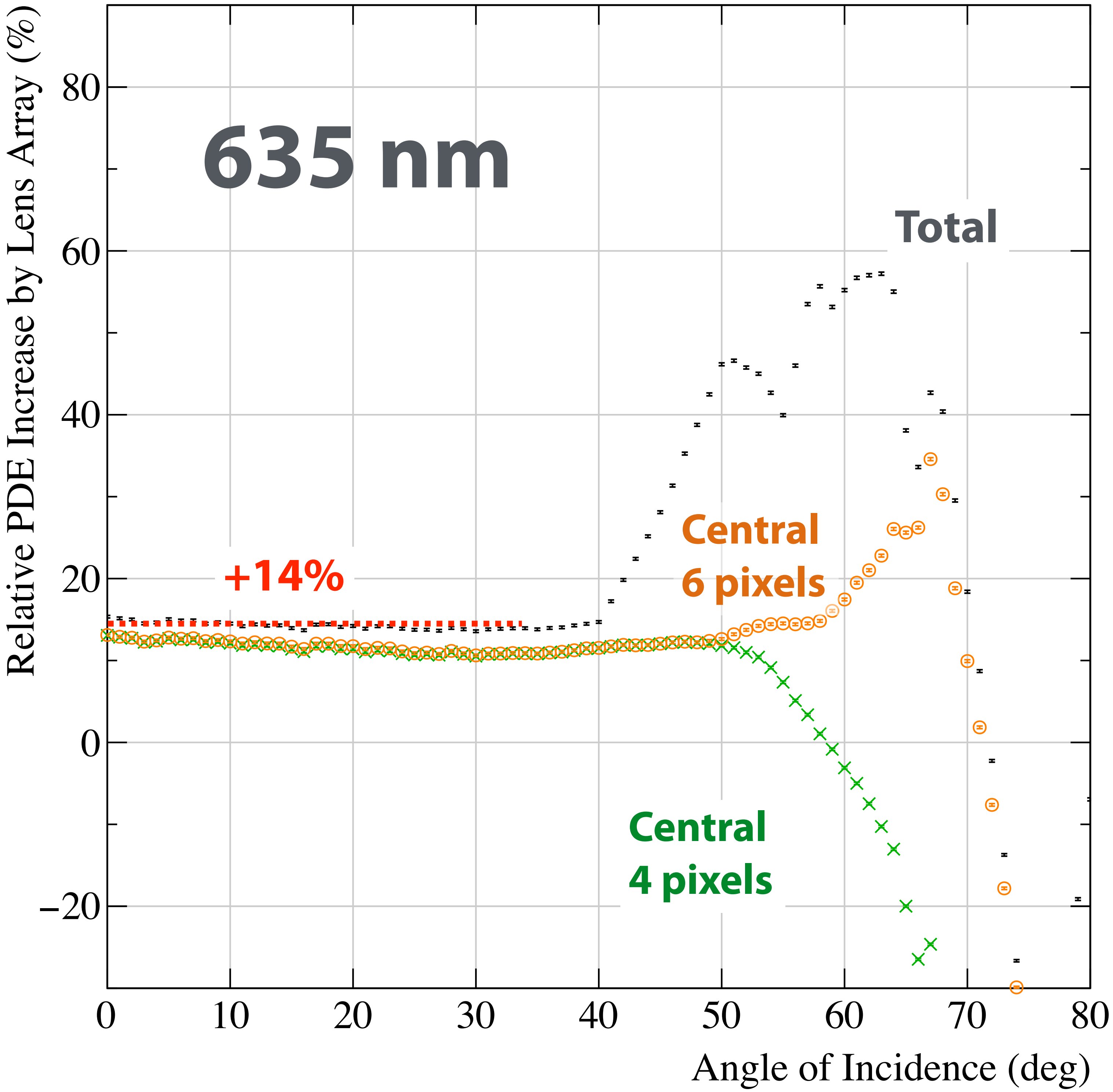
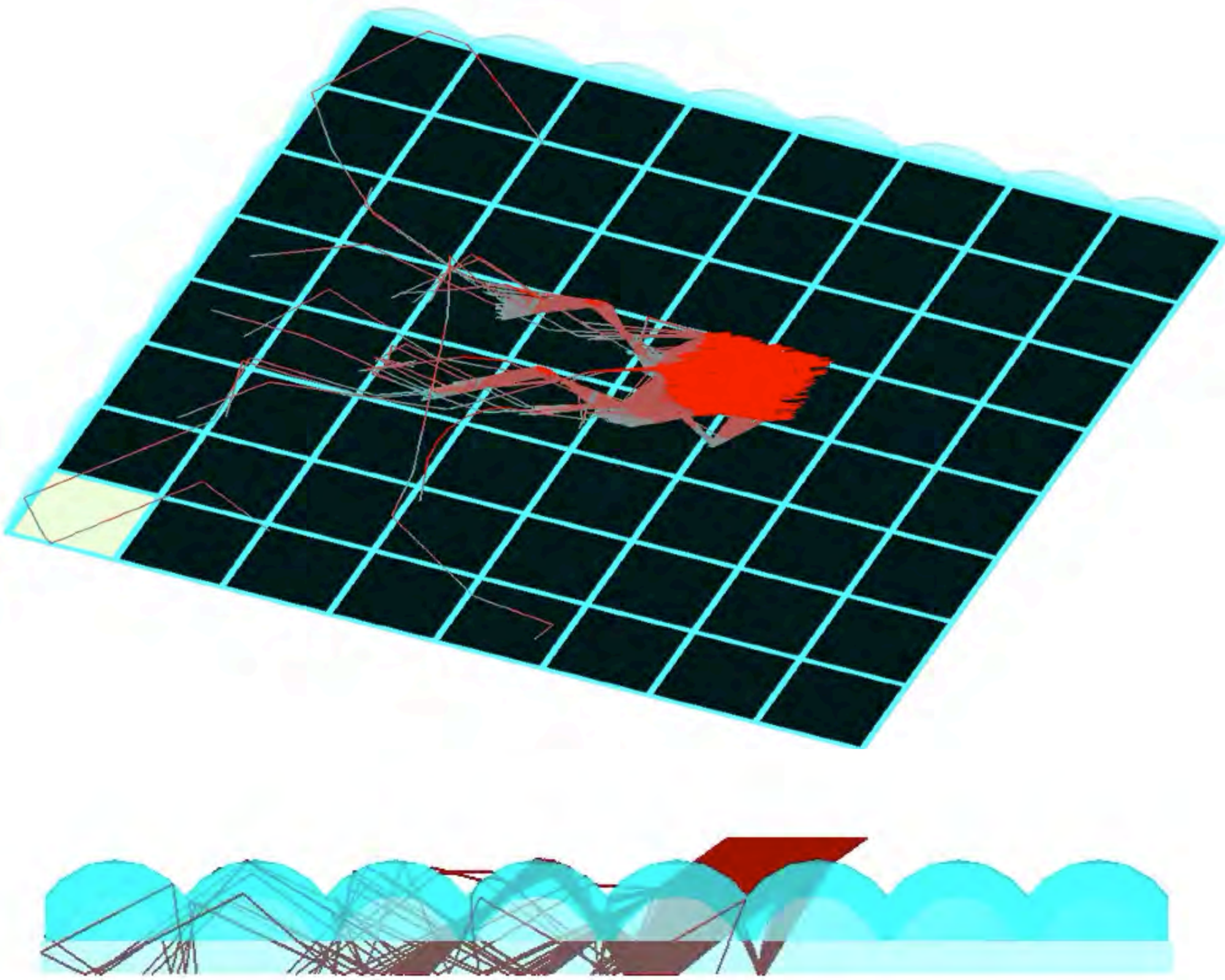
Simulation (375 nm)

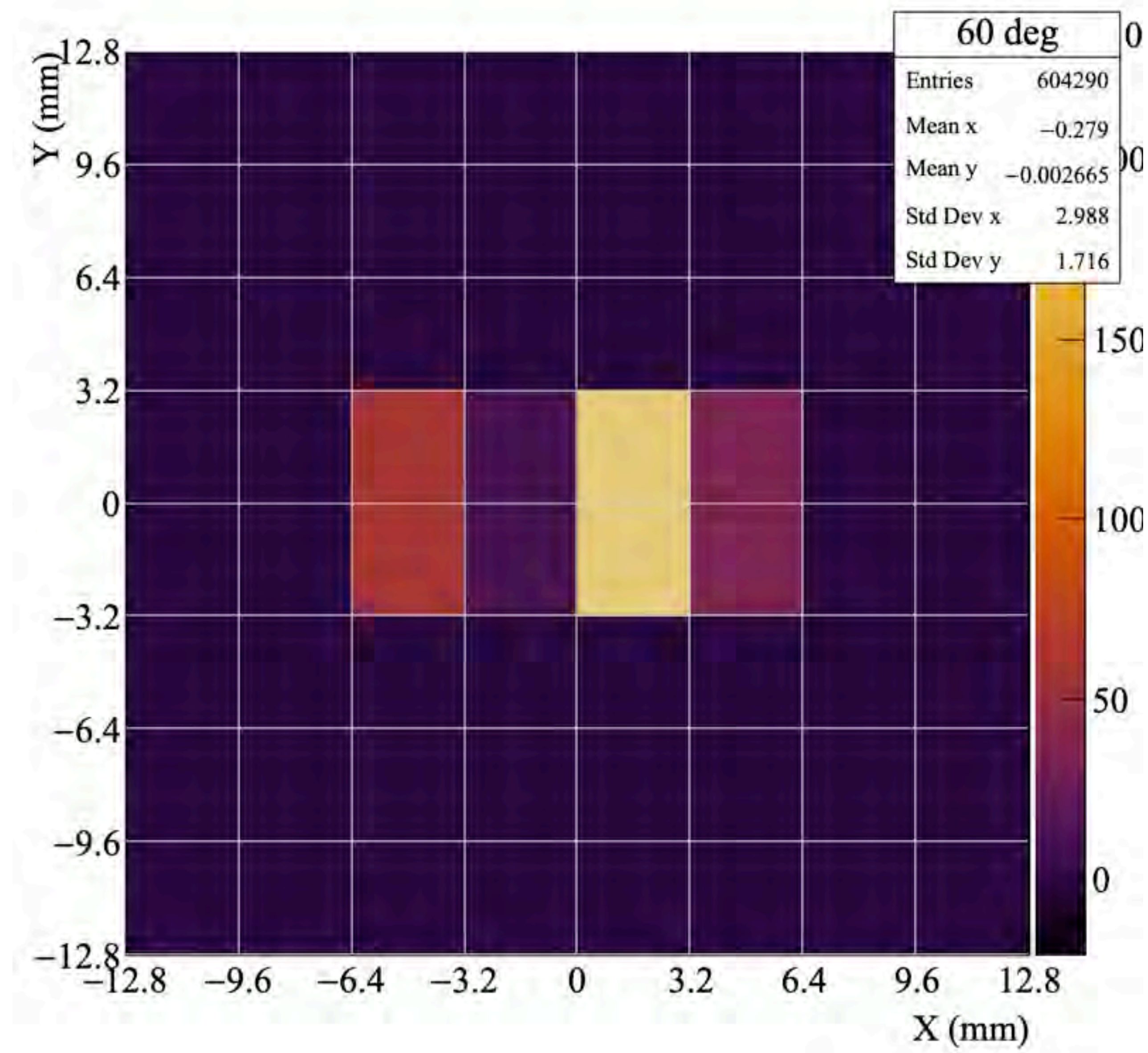


Simulation (635 nm)



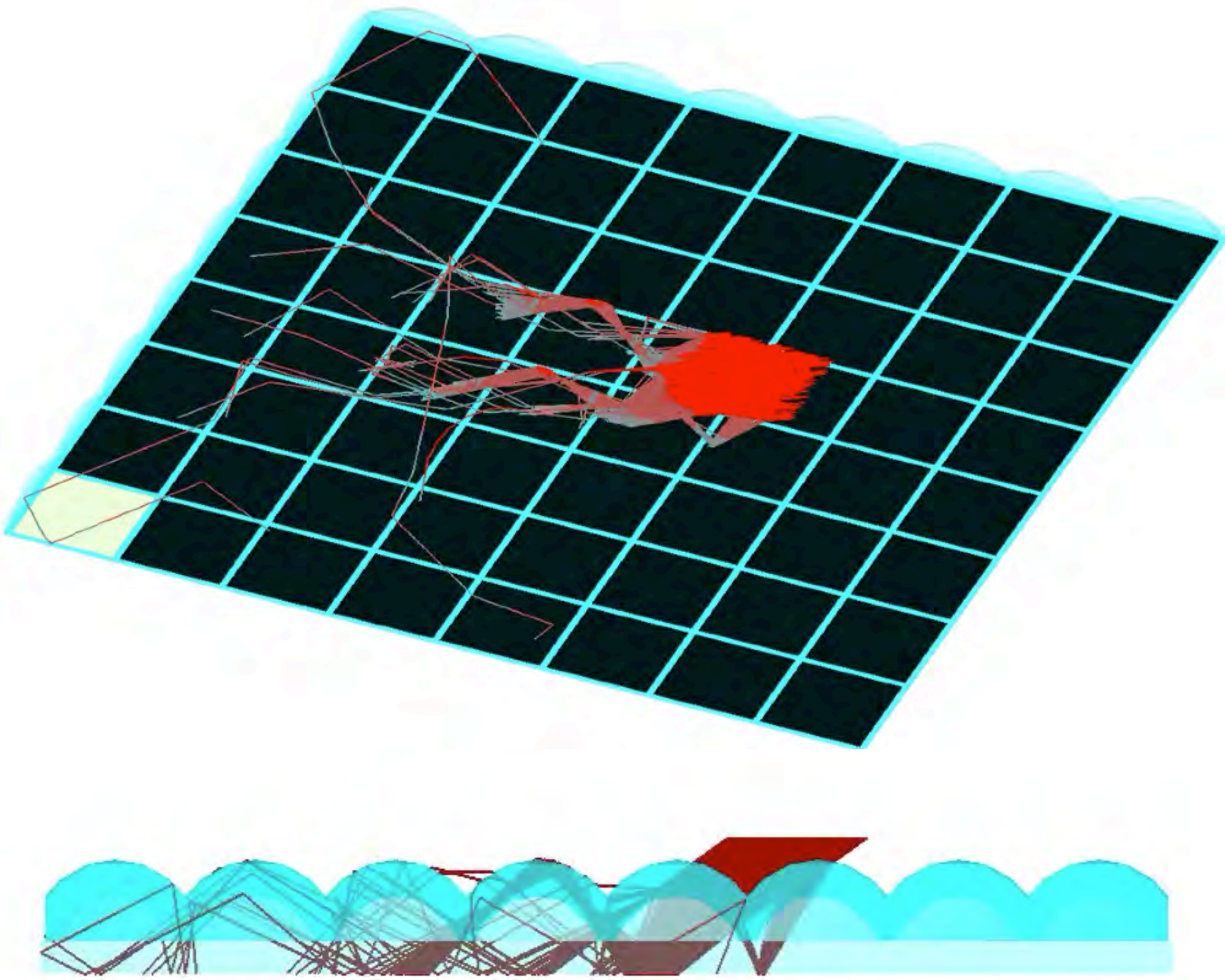
Leak to Other Pixels (Simulation)

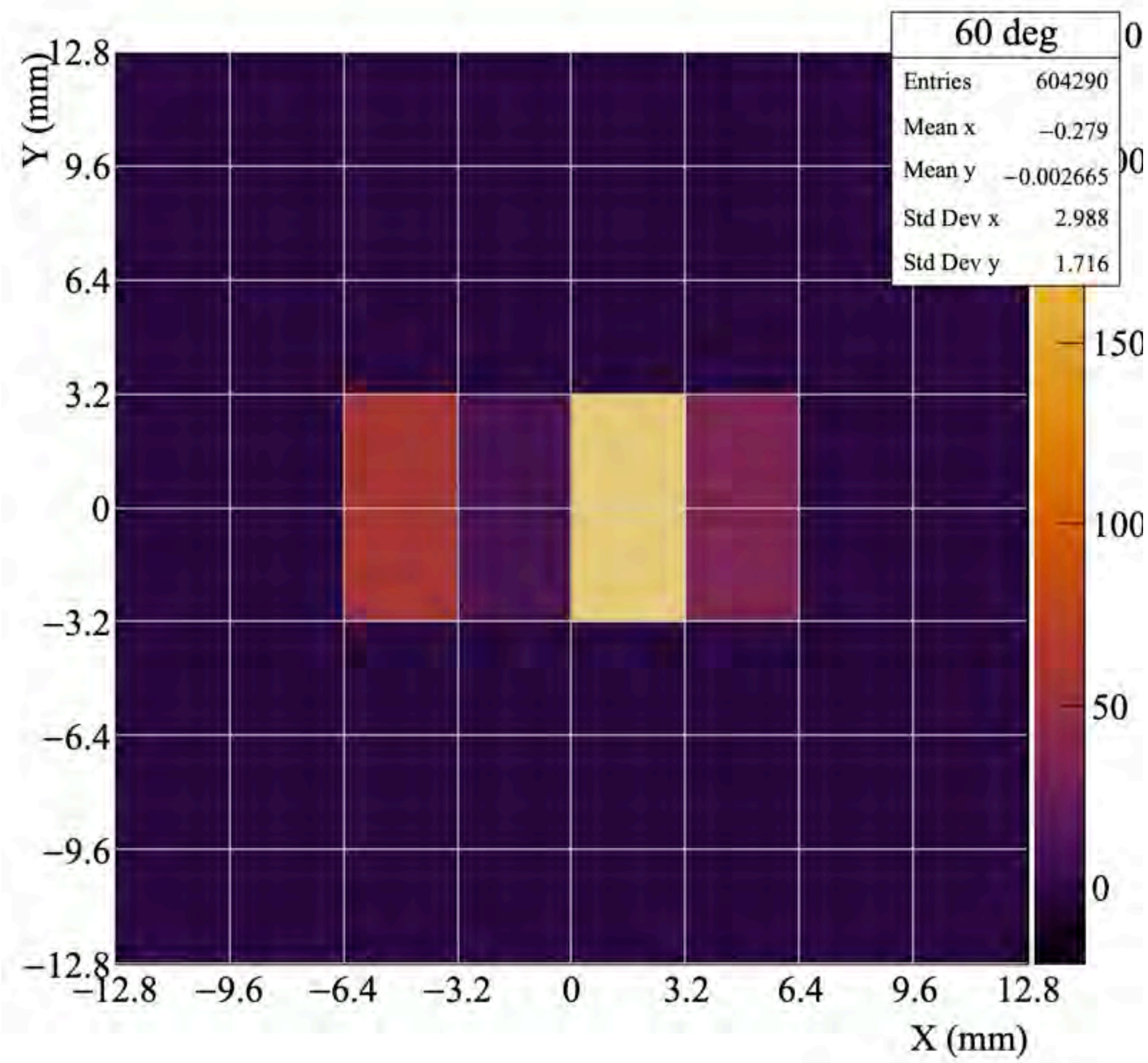




- A part of photons leaks to surrounding pixels due to reflection on the Si surface and total internal reflection on the lens surface
- Optical resolution gets worse in large angles (>50 deg)

Leak to Other Pixels (Simulation)





- A part of photons leaks to surrounding pixels due to reflection on the Si surface and total internal reflection on the lens surface
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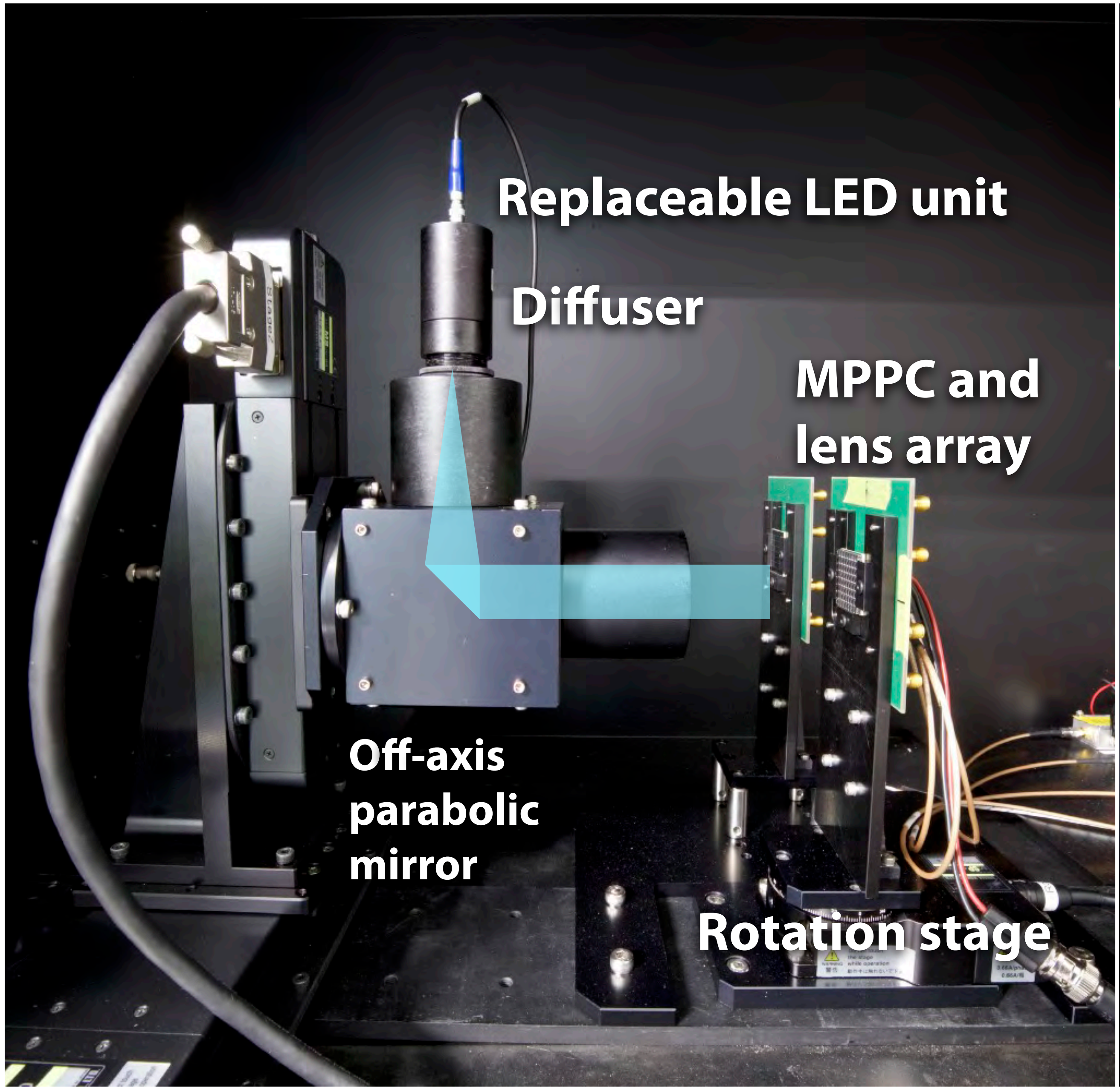
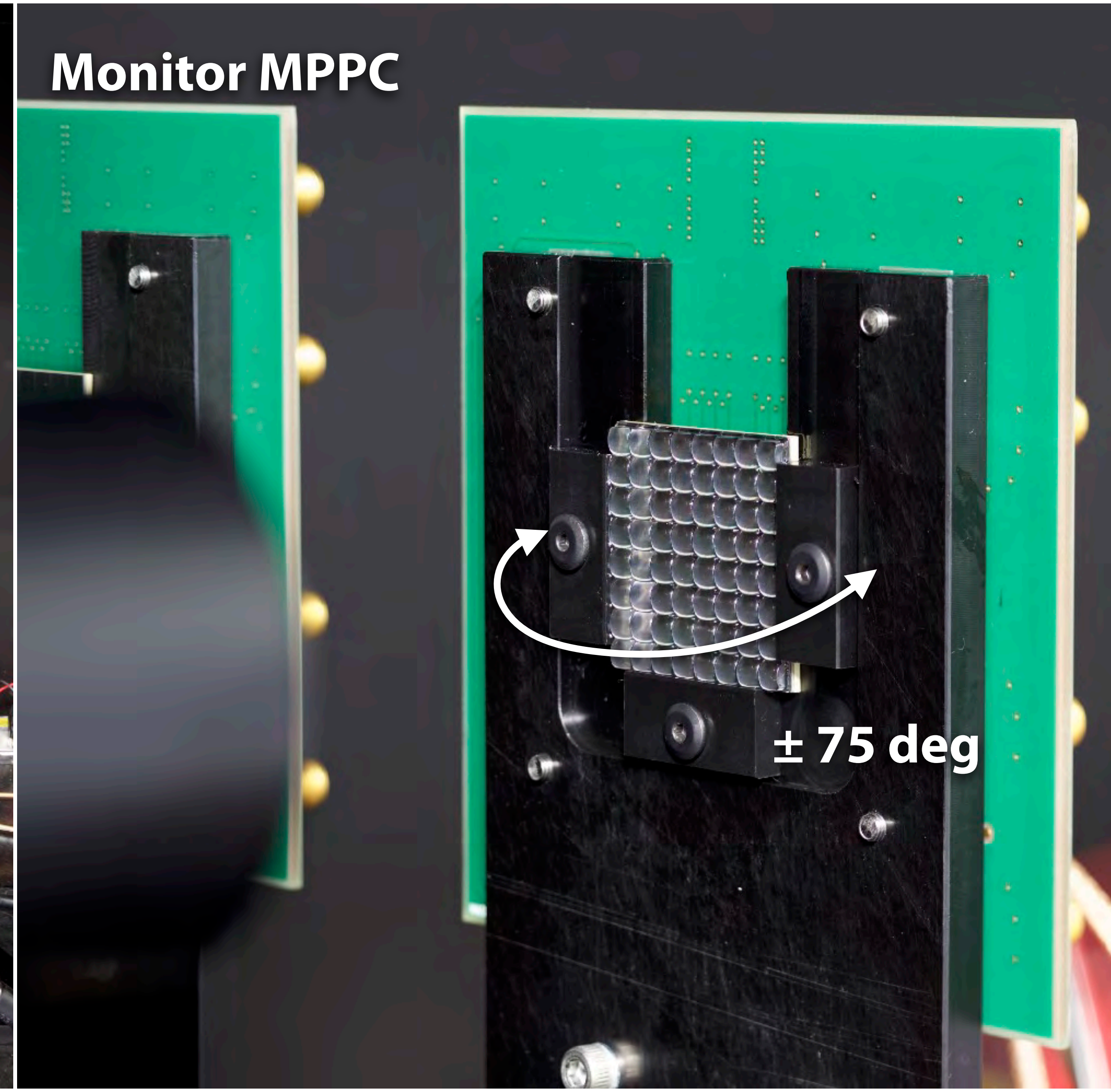
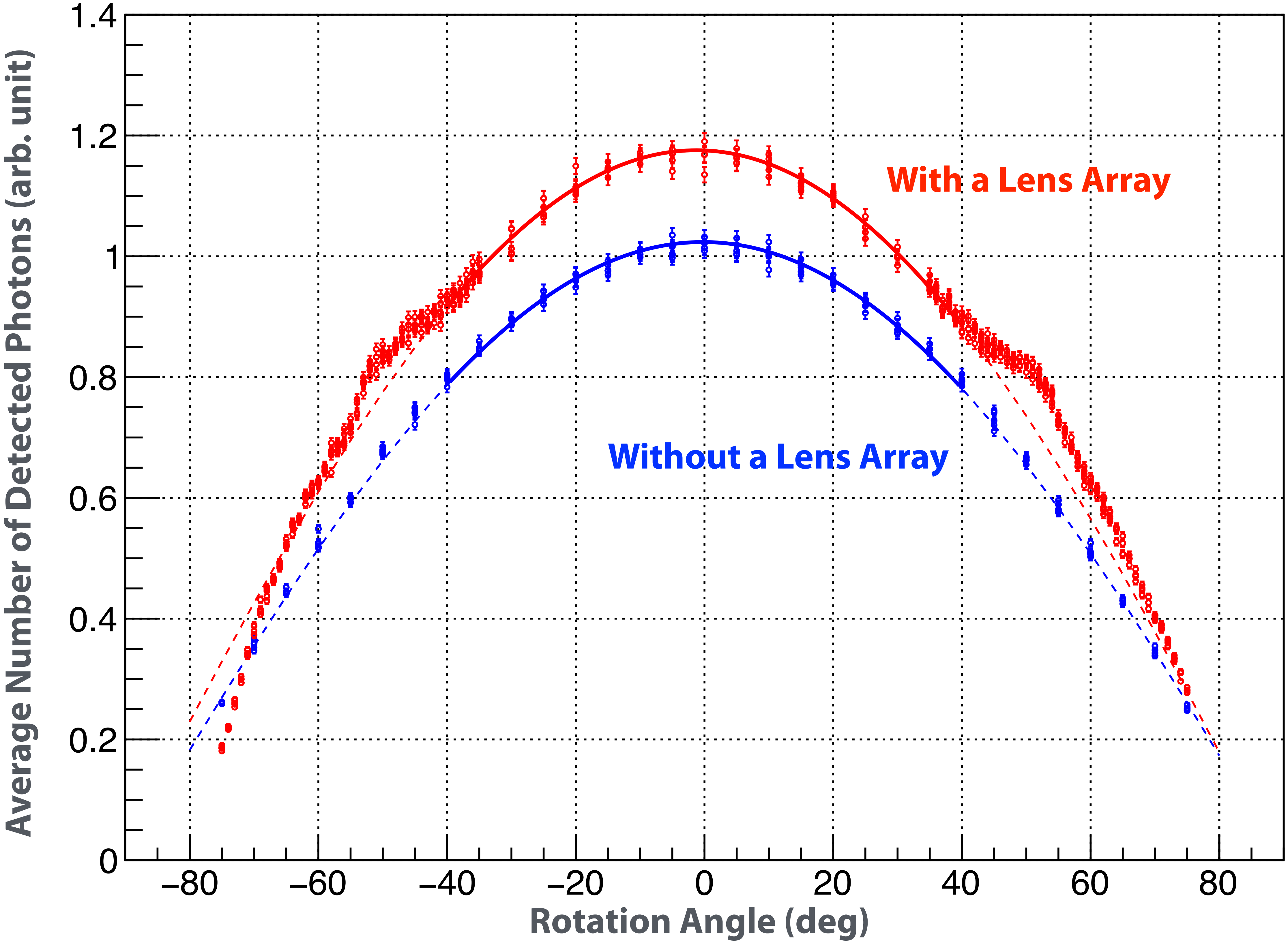
Measurement





- Illuminate all the 64 channels by parallel LED beam (φ 50.8 mm) monitored with another MPPC
- Dark room temperature 25 ± 1 ℃

Measurement Result (310 nm)



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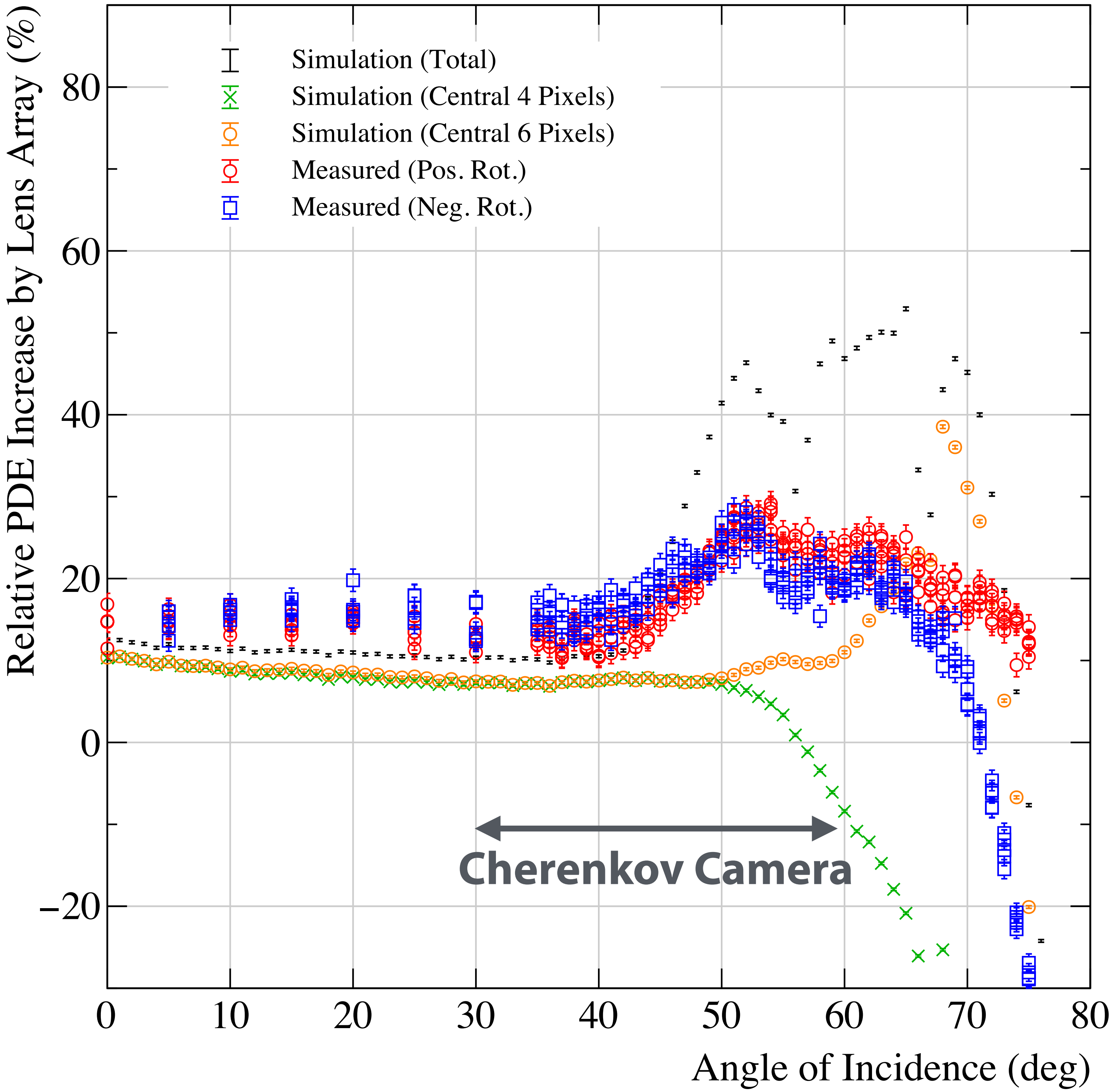
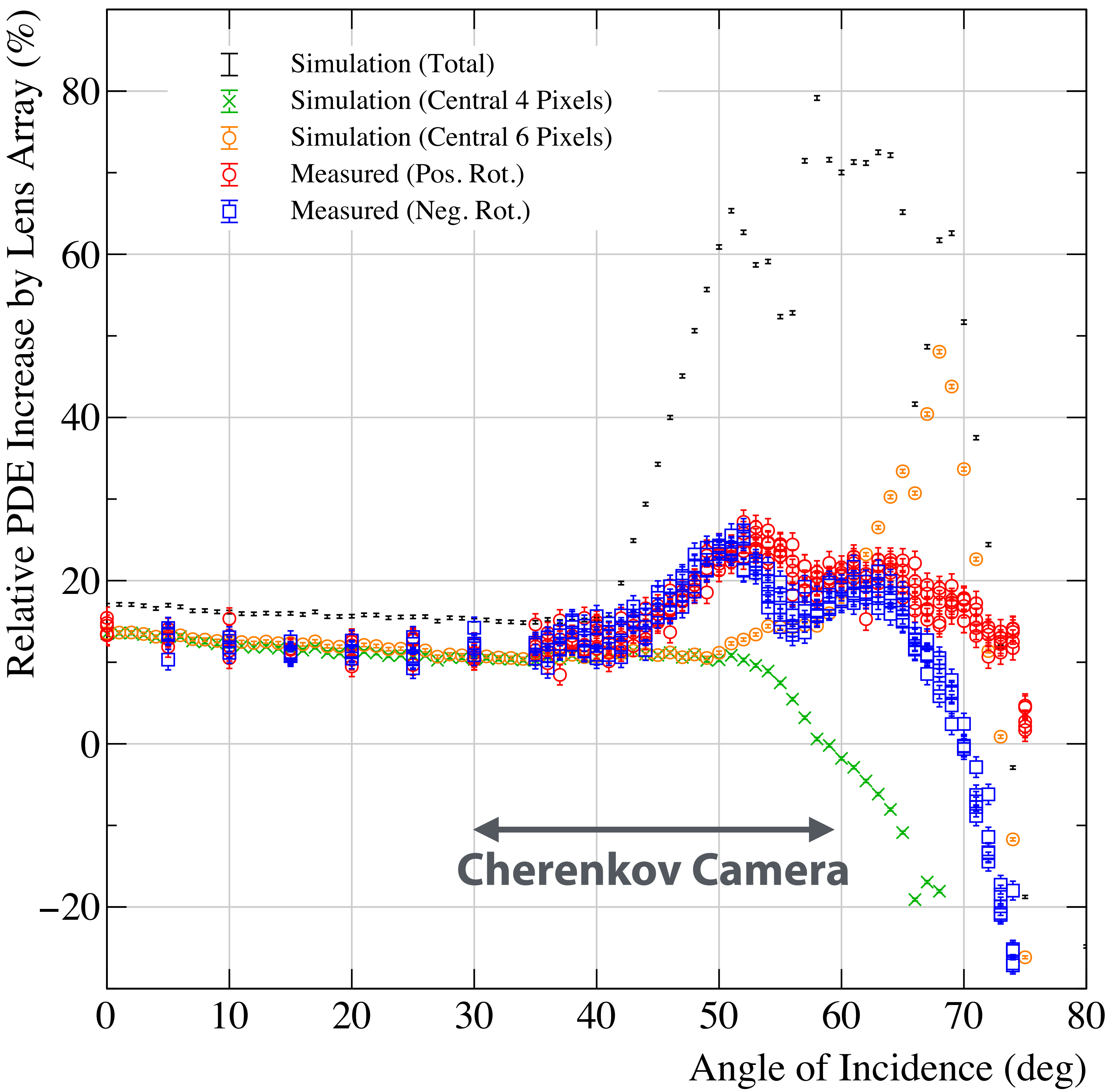


- Roughly consistent with ray-tracing simulation in 0–40 deg
- Less PDE increase than expected in 50–70 deg
  - Less reflection on Si?
  - Scattering on lens or Si surface?
- Relative PDE increase of ~15 to ~25% achieved in 30–60 deg (PDE 40% → 46–50%)

Measurement Result (375 nm)



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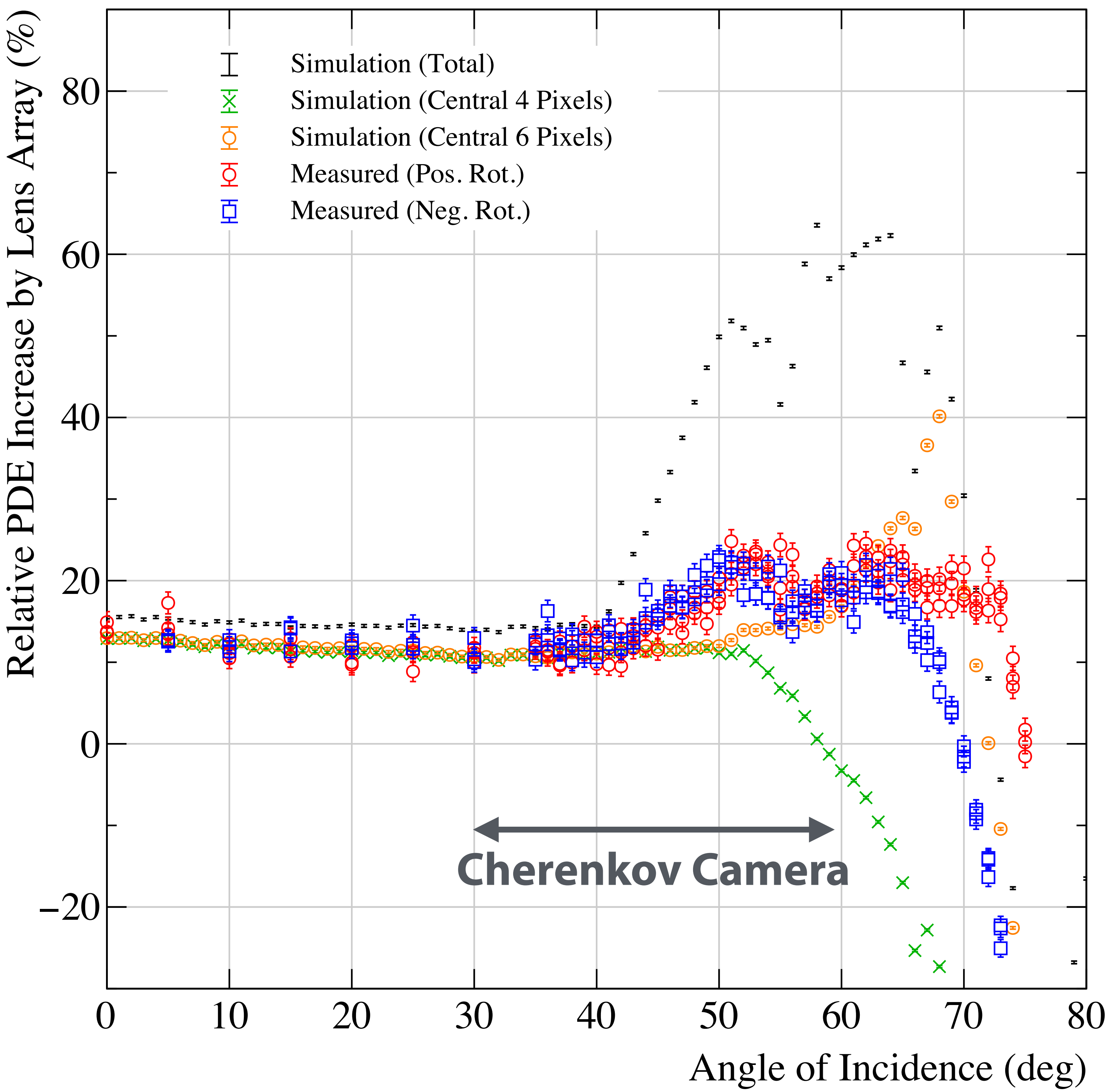
Measurement Result (465 nm)



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- Less PDE increase than expected in 50–70 deg
  - Less reflection on Si?
  - Scattering on lens or Si surface?
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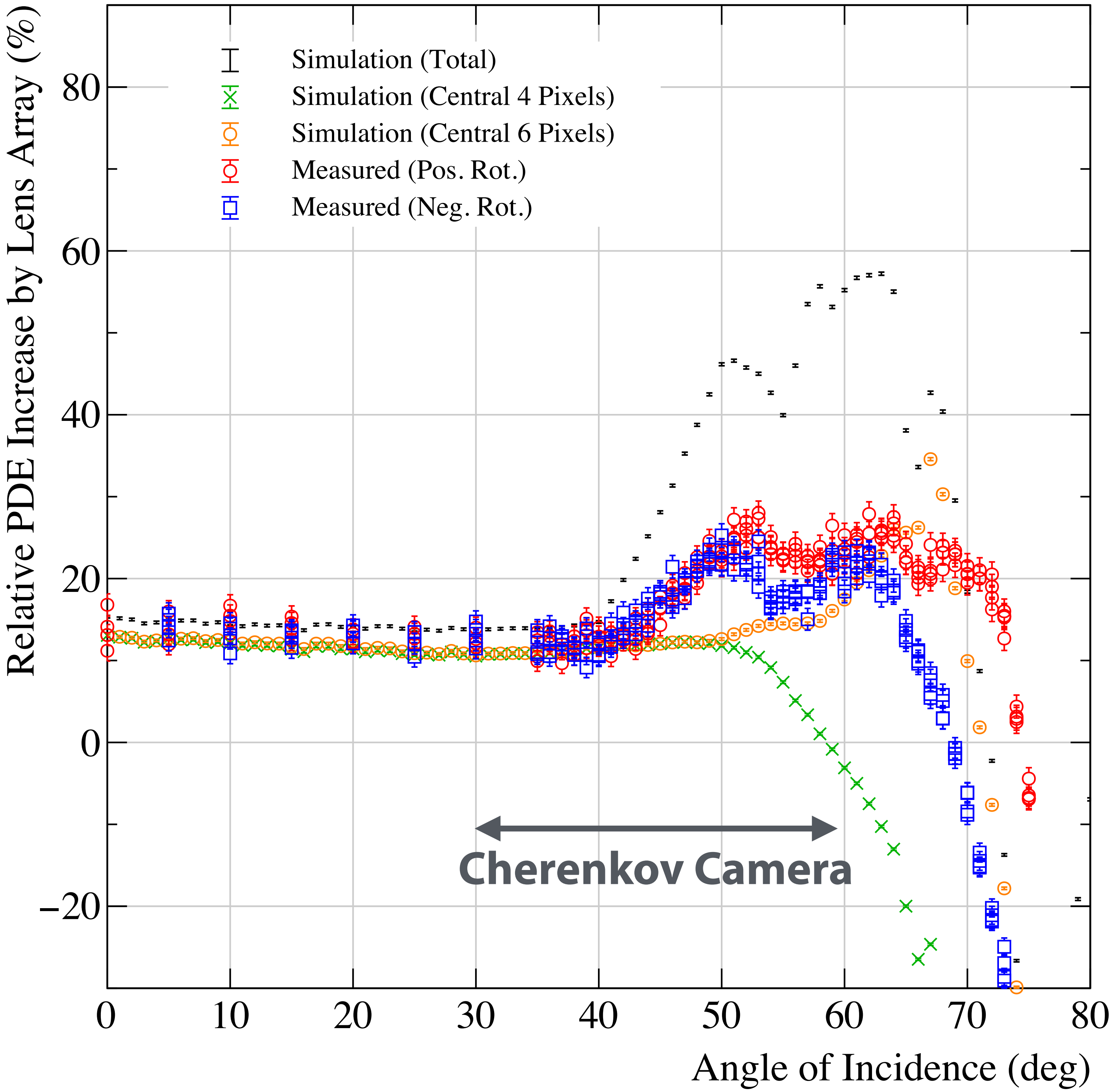
Measurement Result (635 nm)



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- Less PDE increase than expected in 50–70 deg
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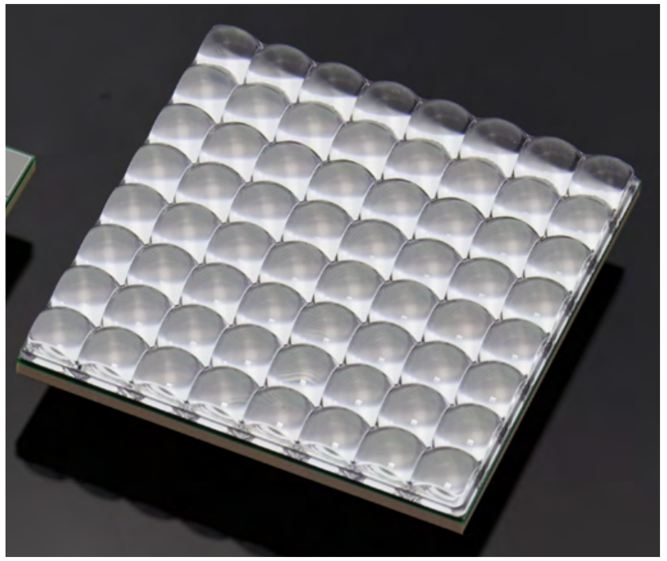
  - Scattering on lens or Si surface?
- Relative PDE increase of ~15 to ~25% achieved in 30–60 deg (PDE 40% → 46–50%)

Good and Bad Findings

- Good
  - Higher **effective** PDE by factors of 1.15–1.25 for 3-mm pixels with 0.2-mm gap
  - Can keep comparable effective PDE for a larger gap of 1.2 mm (50% coverage with 3-mm pixels) and thus price reduction may be possible for a large SiPM array with a direct-molded silicone-resin lens array
  - Total internal reflection can reflect photons back onto Si surface
- Bad
  - We did a comprehensive optical crosstalk study in parallel (see Yuki Nakamura's talk yesterday) and our conclusion is **"Don't put anything thick on the SiPM surface"**
  - Significant amount of photons are detected in surrounding pixels for large incidence angles
  - Difficult to install a lens array on a SiPM
  - Less meaningful for 6-mm pixel arrays (not available in 2013) $(6.0\ \text{mm} / 6.2\ \text{mm})^2 = 93.7\%$

Summary



- We have developed a UV-transparent lens array to enlarge the effective area (pixel coverage) of multi-channel SiPMs
- Relative PDE increase of ~15% has been achieved for small incidence angles (0–30 deg)
- Even higher PDE increase up to ~25% for 50–70 deg, while photons can leak to surrounding pixels
- OCT rate will be also higher and thus careful trade-off comparison is needed