

Development of Low-Radioactivity Photosensors for Future Large Liquid-Xenon Dark Matter Detectors

Shuki Nomura¹, Kentaro Miuchi¹, Shingo Kazama² and José Matias³

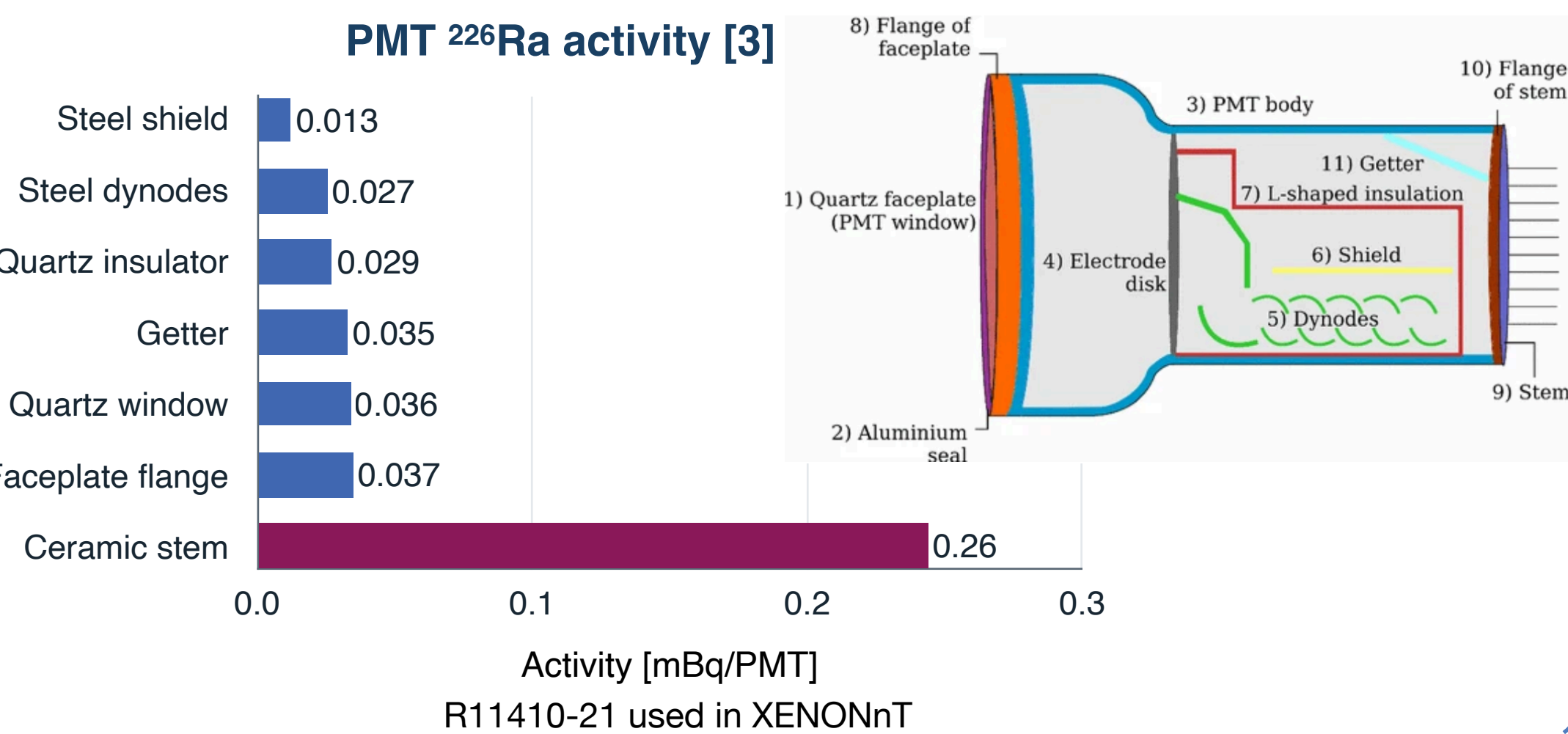
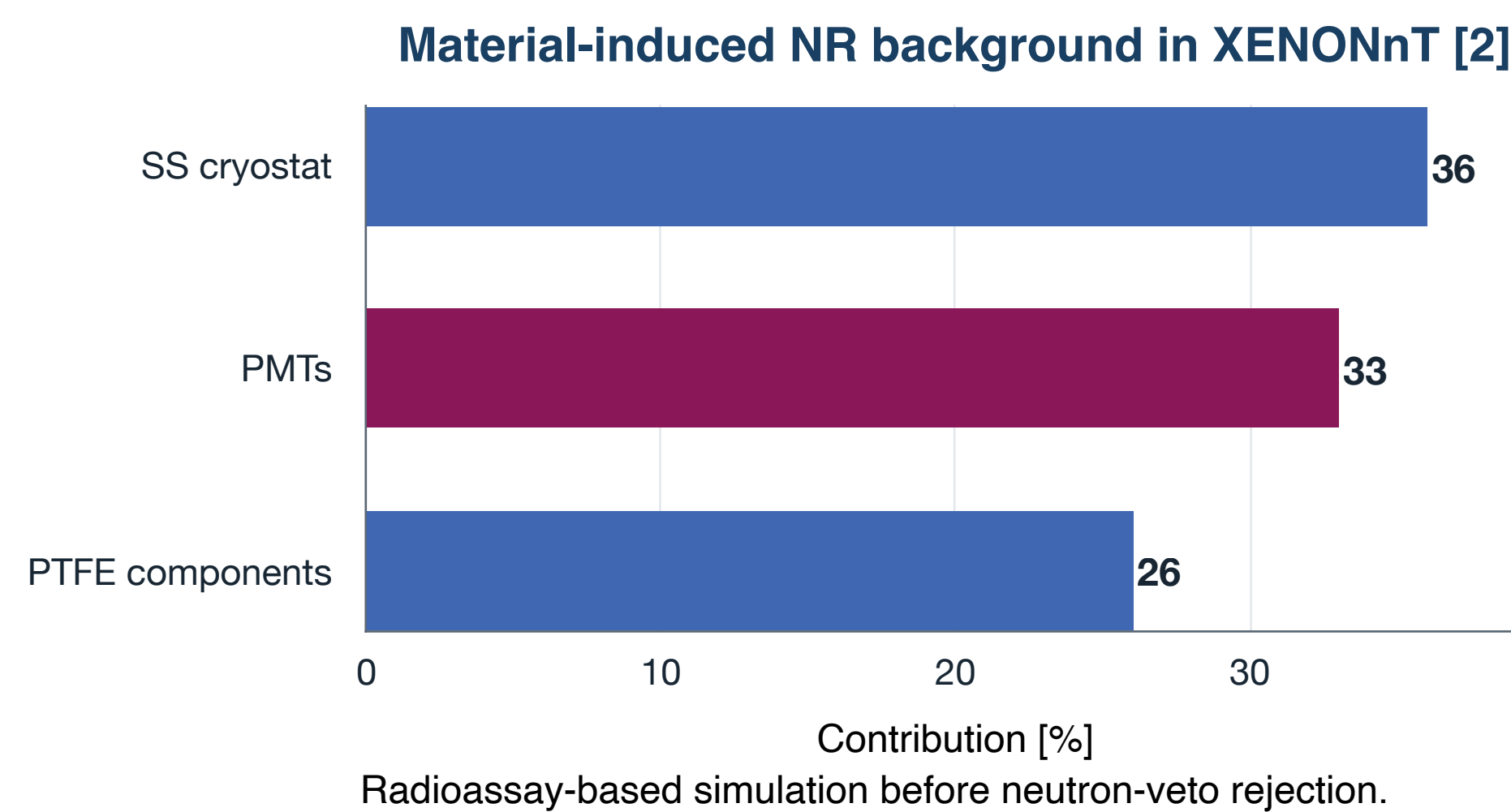
¹Kobe University, ²Science Tokyo, ³Coimbra University

Motivation: reducing photosensor backgrounds without losing light

- Large liquid-xenon TPCs such as XENONnT lead direct searches for dark matter.
- They search for rare WIMP-induced nuclear recoils[1].

- Further sensitivity gains require lower backgrounds.
- Radioactive contaminants in detector materials produce radiogenic neutrons.
- These neutrons can mimic the WIMP signal.

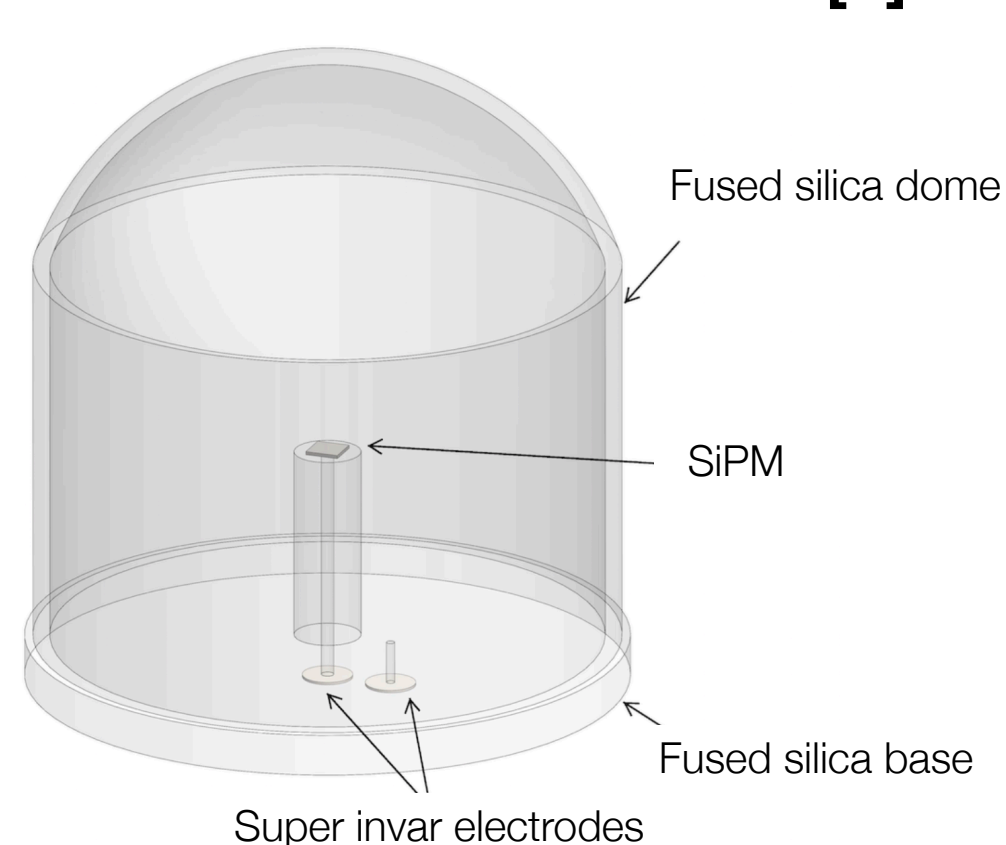
- PMTs account for 33% of the simulated material-induced NR background in XENONnT[2].
- In the PMT used in XENONnT, the ceramic stem has the largest measured ²²⁶Ra activity among the assayed components[3].



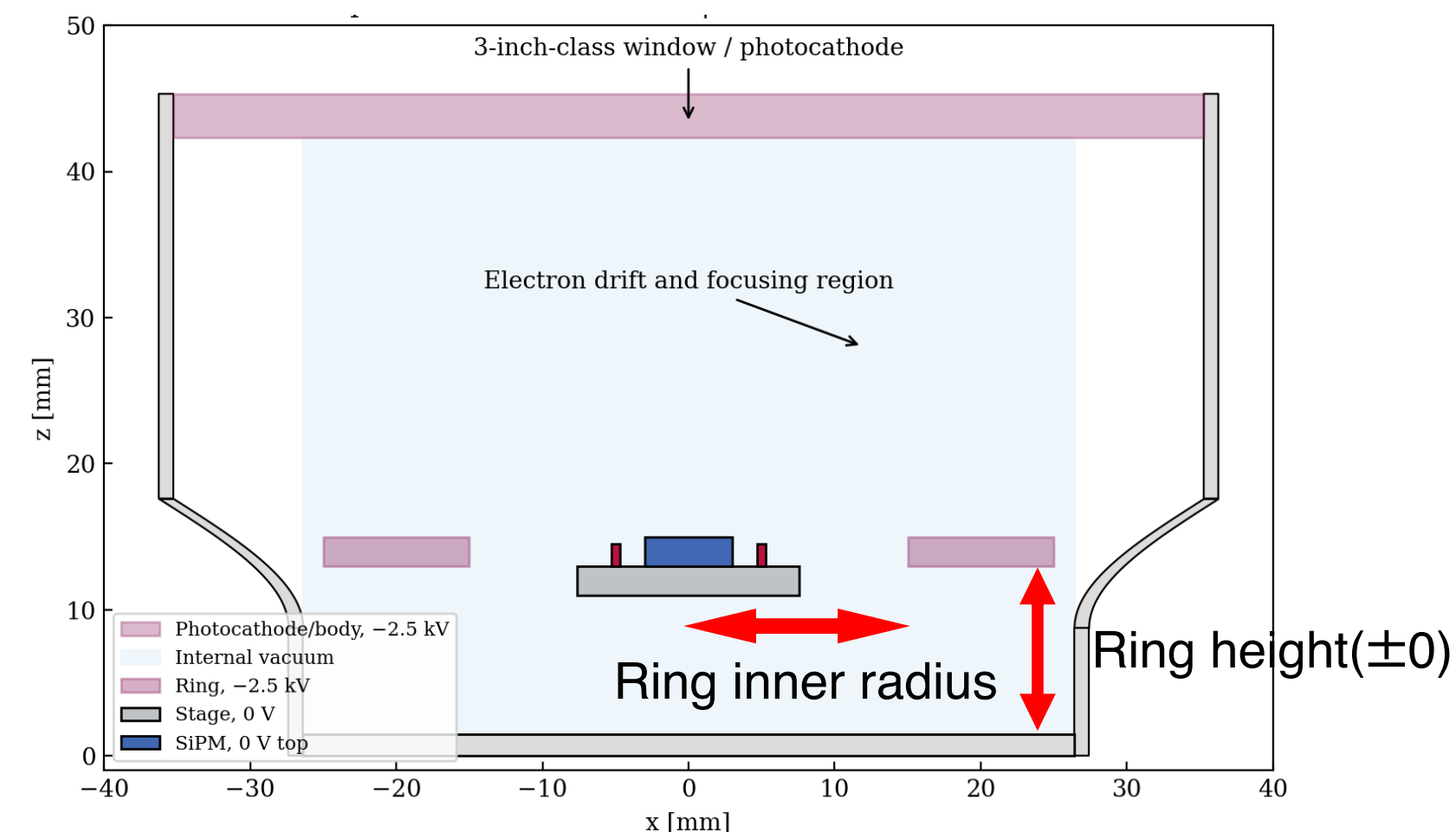
Hybrid photosensors

- Photoelectrons from a large area photocathode are focused onto a small SiPM.
- Compared with a conventional PMT, a hybrid photosensor replaces the dynode chain with a **compact SiPM**.
- The radioactive material is reduced** because fewer electrodes and feedthroughs allow a smaller ceramic stem.
- Several geometries are being explored; two representative concepts are shown below.

SiGHT: Spherical photocathode without ceramic stem[4]



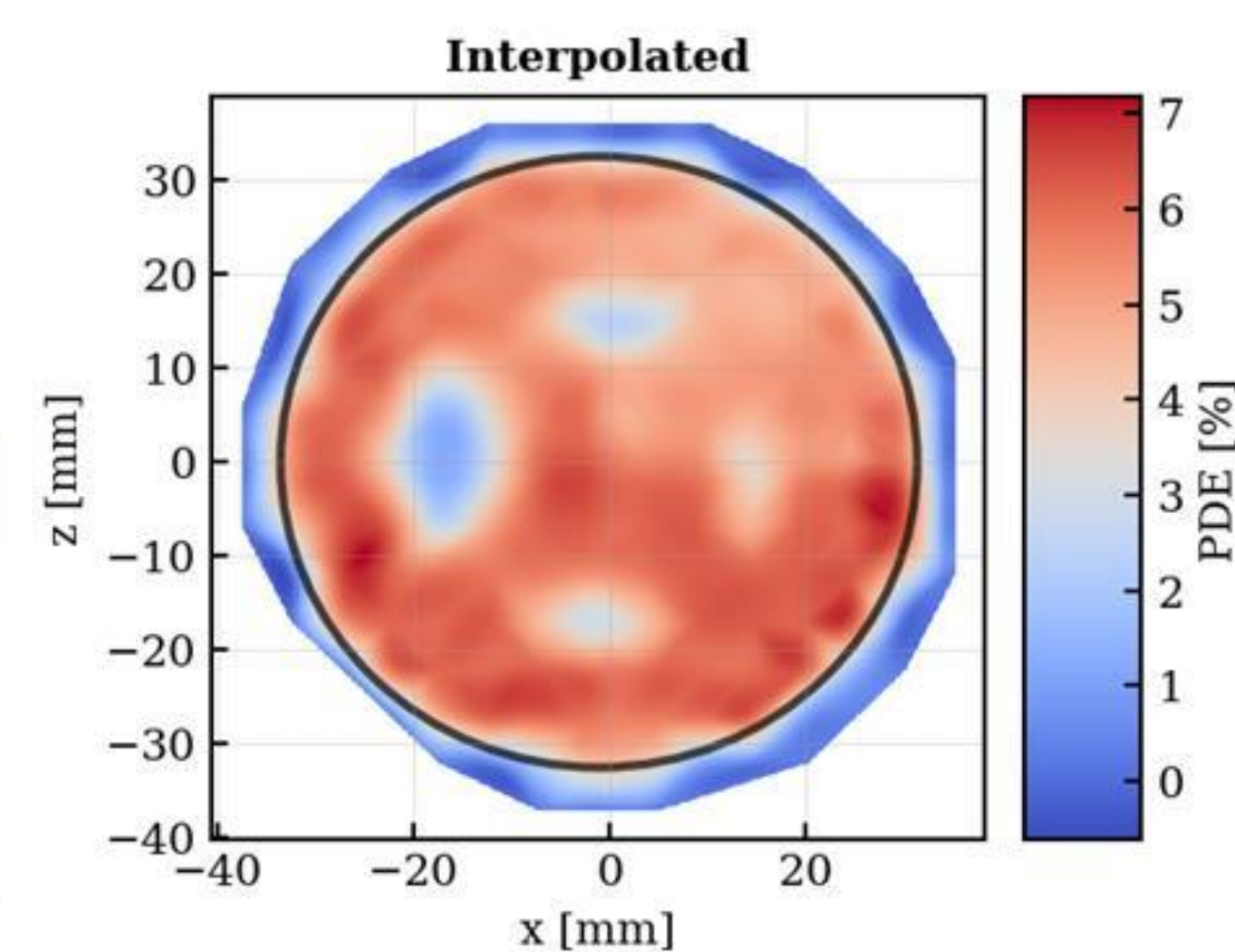
PAD: Flat photocathode with a 3" active area



PAD prototype and measured response [5]

- A PAD prototype was constructed and tested.
- The measured PDE shows strong spatial non-uniformity across the photocathode.
- The measured PDE is also lower than expected.
- These observations motivate a study of photoelectron focusing and collection.

Measured photocathode PDE map



$$\text{PDE} \approx \text{photocathode QE} \times \text{electron collection} \times \text{electron-detection response}$$

This work: Understanding and improving photoelectron collection in PAD

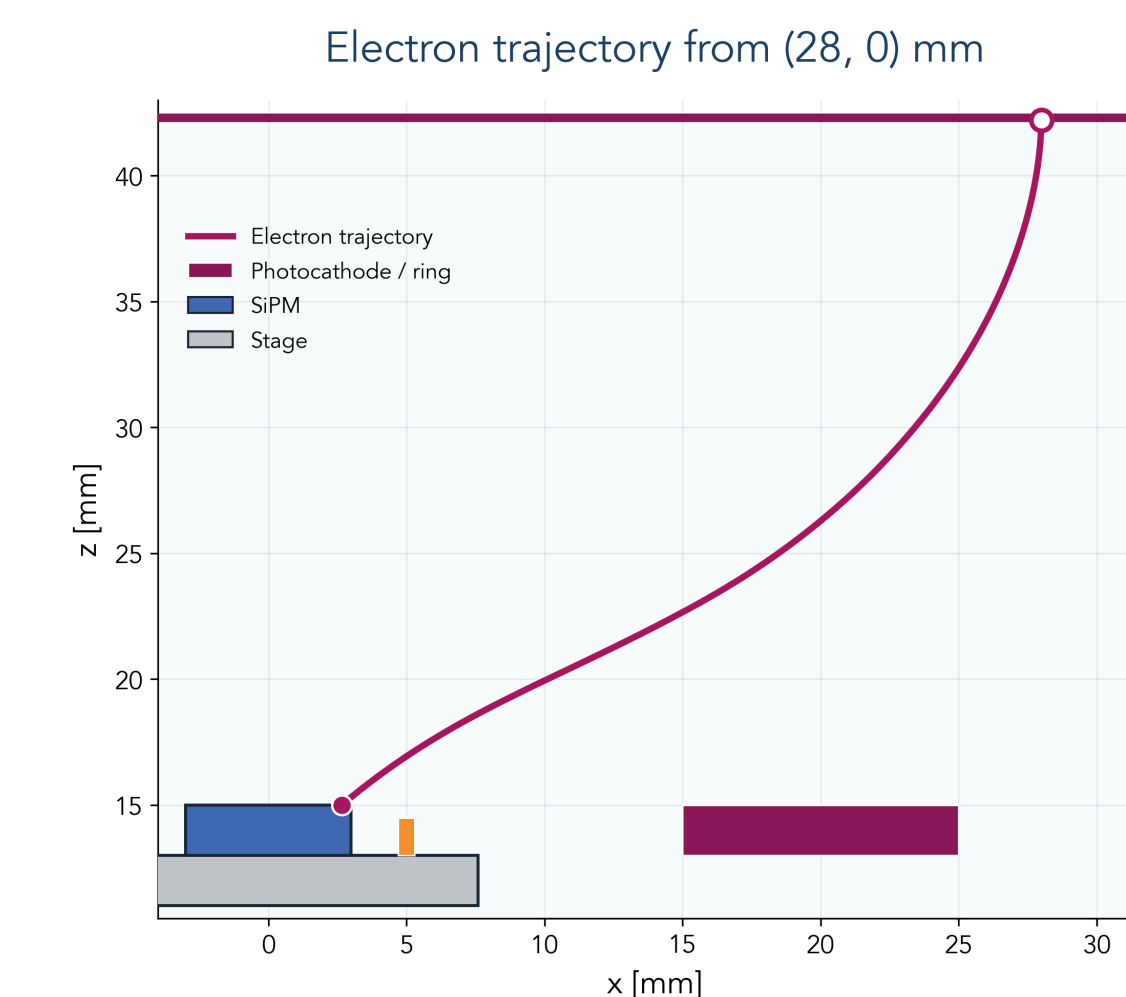
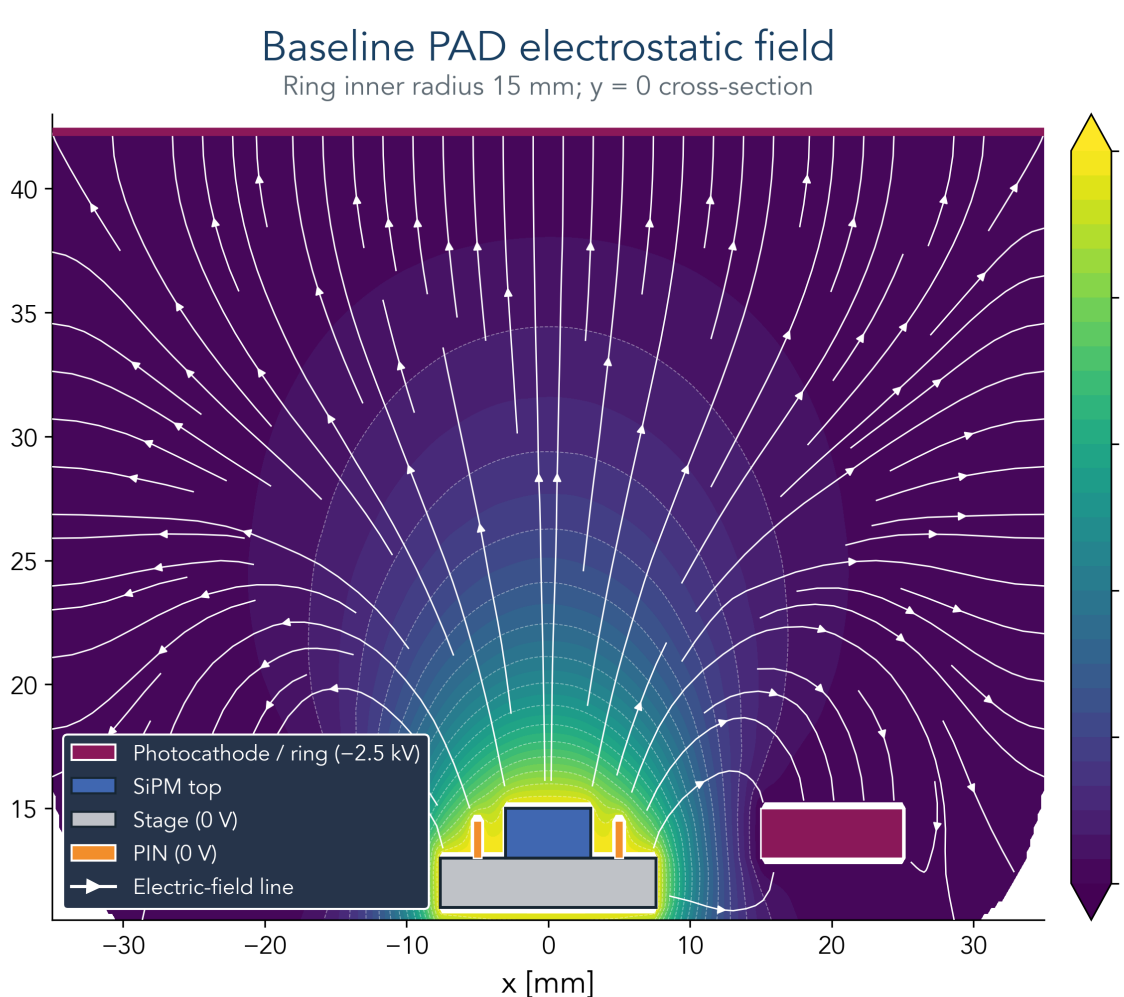
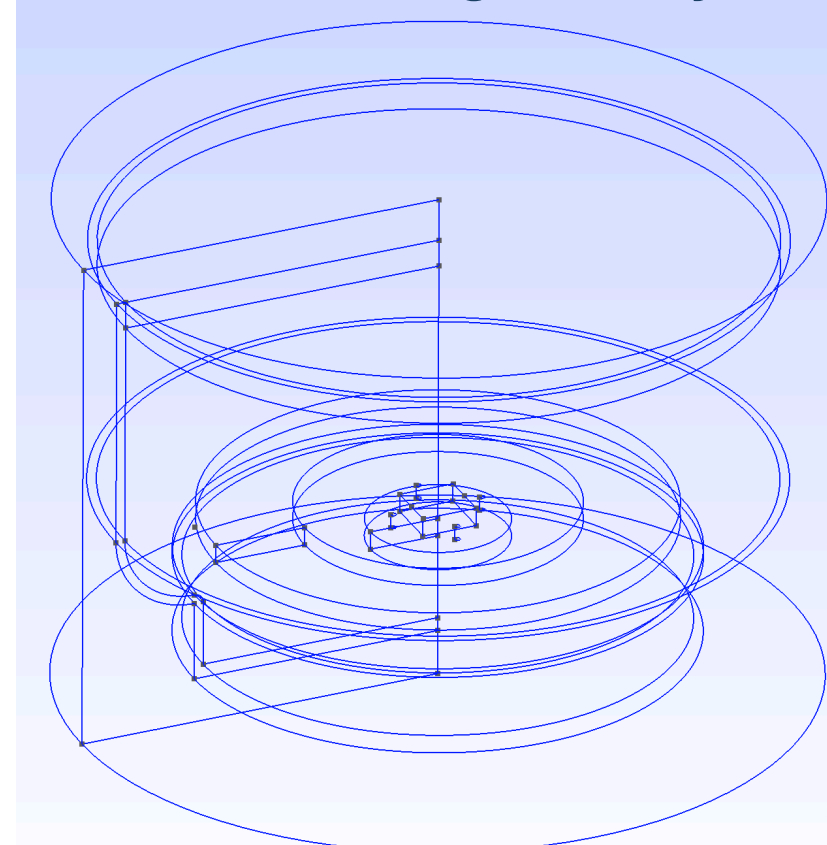
- Investigate the origin of the measured low PDE.
- Identify the cause of spatial non-uniformity across the photocathode.
- Optimize the electrode geometry to improve photoelectron collection while controlling its concentration on the SiPM.

Simulation method

- Geometry and mesh: Gmsh
- Electrostatic field: Elmer
- Field interpolation: Garfield++
- Electron trajectories: kick-drift-kick integration
- Initial kinetic energy: 0 eV
- Sampling: 525 photocathode positions on a 2.5 mm grid

$$\begin{aligned} \mathbf{p}_{i+\frac{1}{2}} &= \mathbf{p}_i + q\mathbf{E}(\mathbf{x}_i)\frac{\Delta t}{2} \\ \mathbf{x}_{i+1} &= \mathbf{x}_i + \frac{\mathbf{p}_{i+\frac{1}{2}}c^2}{\sqrt{m^2c^4 + |\mathbf{p}_{i+\frac{1}{2}}|^2c^2}}\Delta t \\ \mathbf{p}_{i+1} &= \mathbf{p}_{i+\frac{1}{2}} + q\mathbf{E}(\mathbf{x}_{i+1})\frac{\Delta t}{2} \end{aligned}$$

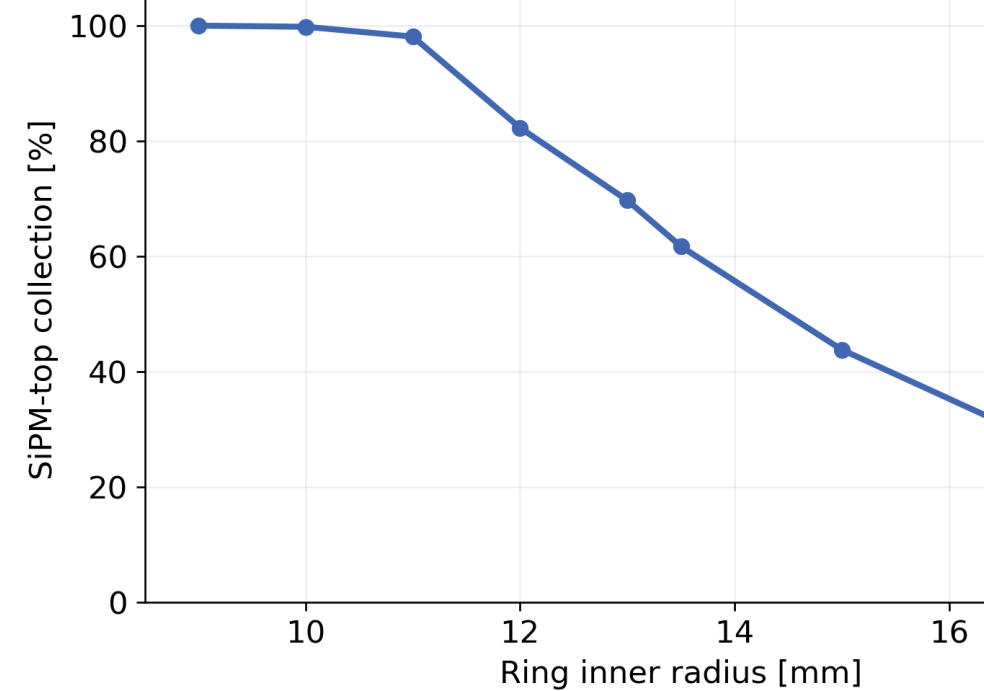
Simulation geometry



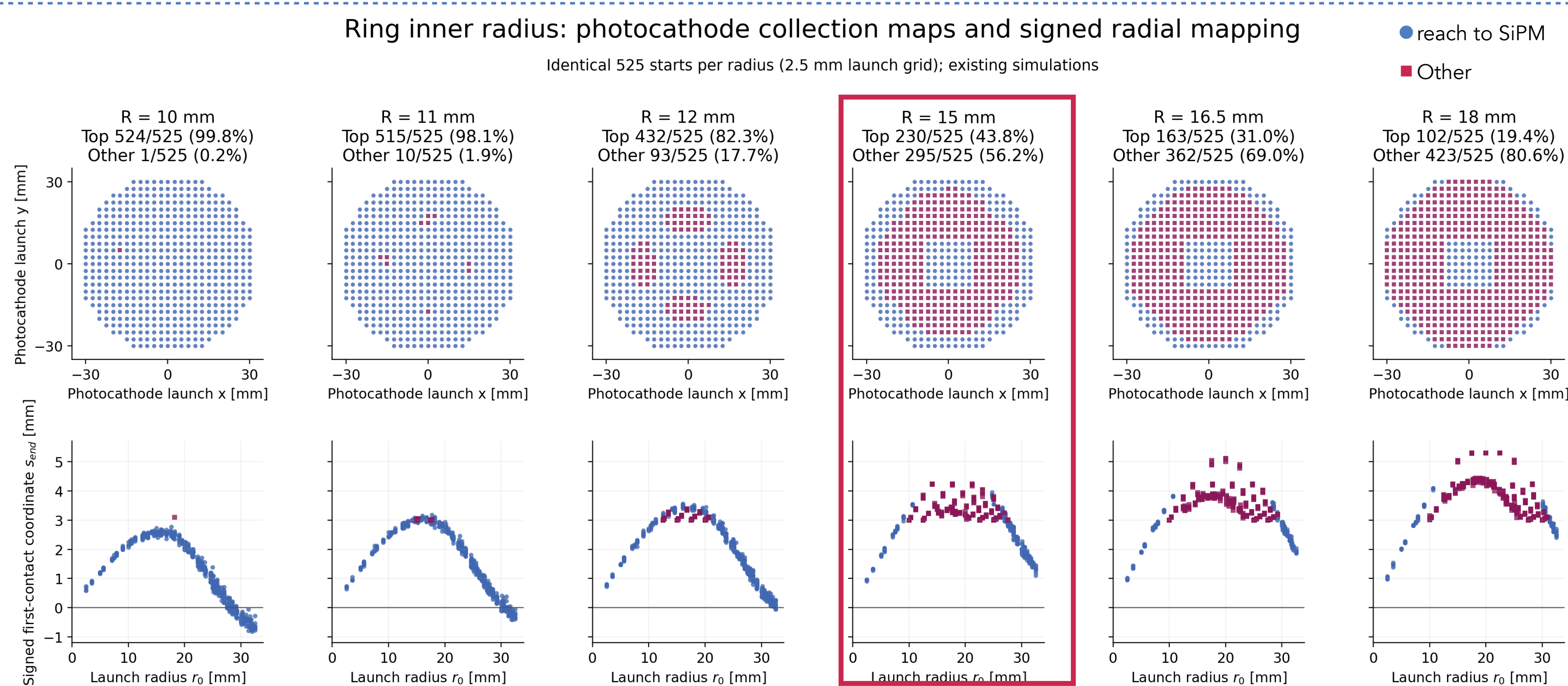
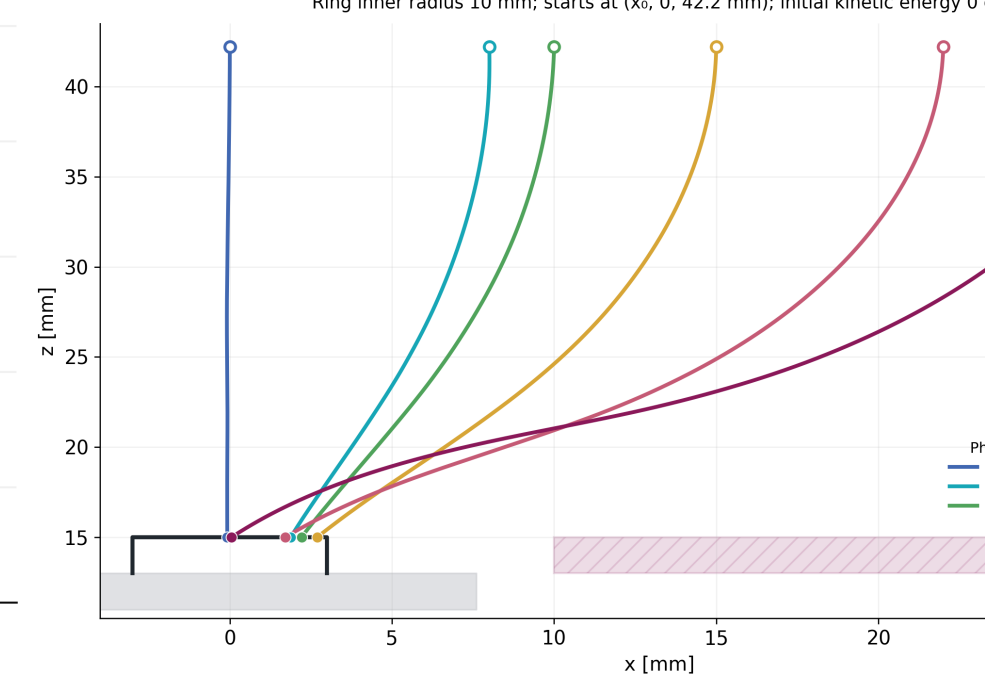
Effect of ring inner radius

- Reducing the ring inner radius strongly improves photoelectron collection.
- The collection efficiency increases from 43.8% at 15 mm to 99.8% at 10 mm.
- A smaller aperture recovers electrons emitted at intermediate photocathode radii.
- However, stronger focusing can concentrate multiple electrons into the same SiPM pixels.
- Outer trajectories are bent more strongly and arrive closer to the SiPM center.

Ring opening controls collection



Six electron trajectories from the photocathode



→ A smaller ring aperture improves collection, but increases the concentration of photoelectrons on the SiPM.

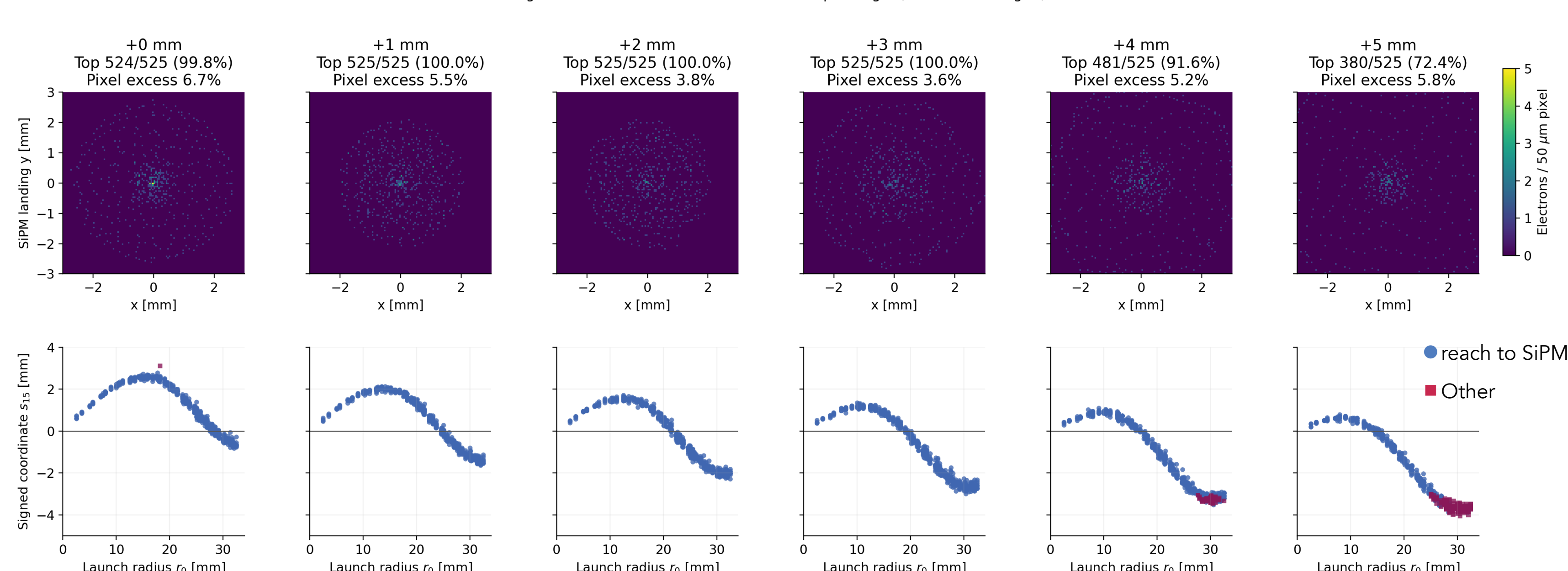
Effect of ring height

- The 10 mm inner radius geometry was used as the new reference.
- Raising the ring by up to 3 mm maintains approximately 100% collection.
- The pixel excess fraction decreases from 6.7% to 3.6%.
- Larger shifts reduce collection: 91.6% at +4 mm and 72.4% at +5 mm.

$$\text{Pixel excess} = \frac{N_{\text{SiPM}} - N_{\text{occupied}}}{N_{\text{SiPM}}} \times 100\%$$

$N_{\text{SiPM top}}$: number of electrons reaching the SiPM top
 N_{occupied} : number of $50 \times 50 \mu\text{m}^2$ pixels occupied by at least one electron

Ring height: SiPM landing distributions and signed radial mapping



→ Adjusting the ring height balances efficient collection and a less concentrated landing distribution.

Outlook

- Fabricate a new PAD prototype incorporating the optimized ring geometry.
- Measure the photocathode response and compare it with the simulated collection map.
- Continue the development and optimization of SiGHT.
- Explore a new design combining the advantages of SiGHT and PAD.

Conclusion

- The ring geometry strongly controls photoelectron focusing.
- Reducing the ring inner radius from 15 mm to 10 mm improved the simulated collection efficiency from 43.8% to 99.8%.
- Raising the ring by 3 mm maintained approximately 100% collection while reducing the pixel-excess fraction from 6.7% to 3.6%.
- The best tested geometry combines a 10 mm ring inner radius with a 3 mm upward shift.
- Electrode optimization can improve photoelectron collection while controlling excessive concentration on the SiPM.

References

- [1] XENON Collaboration, Phys. Rev. Lett. 131, 041003 (2023).
- [2] XENON Collaboration, Eur. Phys. J. C 82, 599 (2022).
- [3] XENON Collaboration, Eur. Phys. J. C 75, 546 (2015).
- [4] Y. Wang et al., JINST 12, P02019 (2017).
- [5] R. Peres, S. Kazama and M. Kobayashi, "Initial characterisation of the Hamamatsu hybrid photosensor," NDIP 2026.

