The QuIPS Experiment

The beta momentum measurement subsystem

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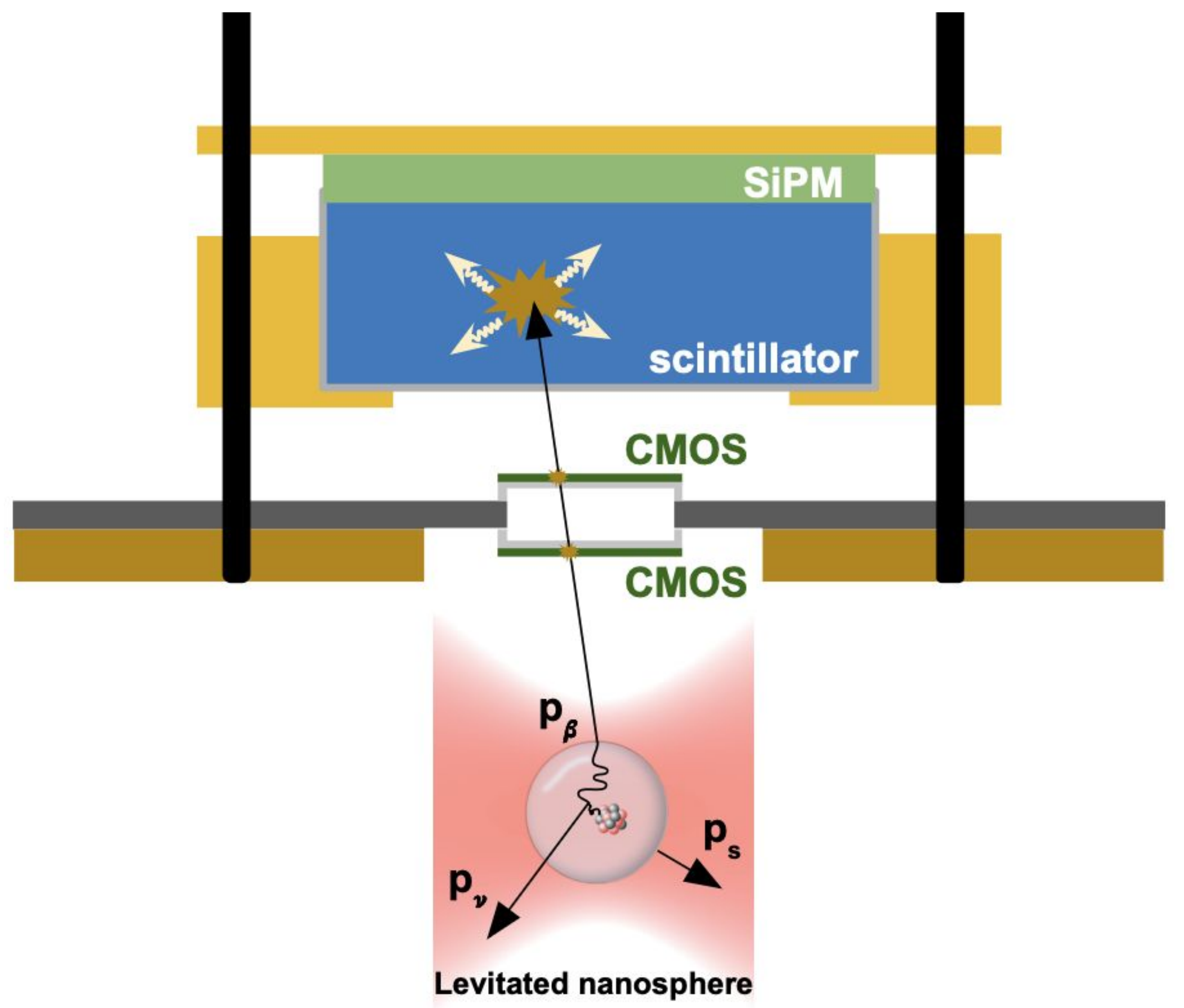
The QuIPS Concept

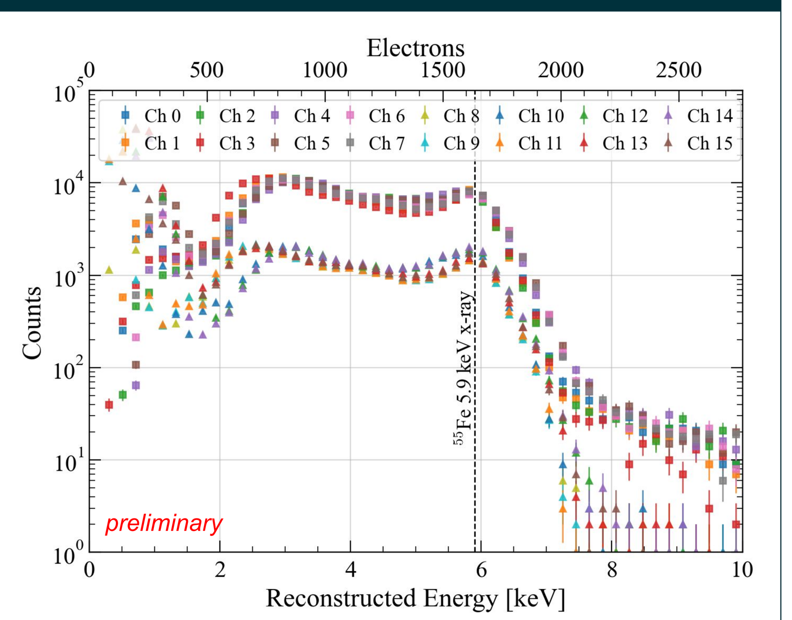
The Quantum Invisible Particle Sensor (QuIPS) experiment plans to use optically levitated nanospheres doped with radionuclides to search for sterile neutrinos by reconstructing the full 3-body kinematics of β decays.



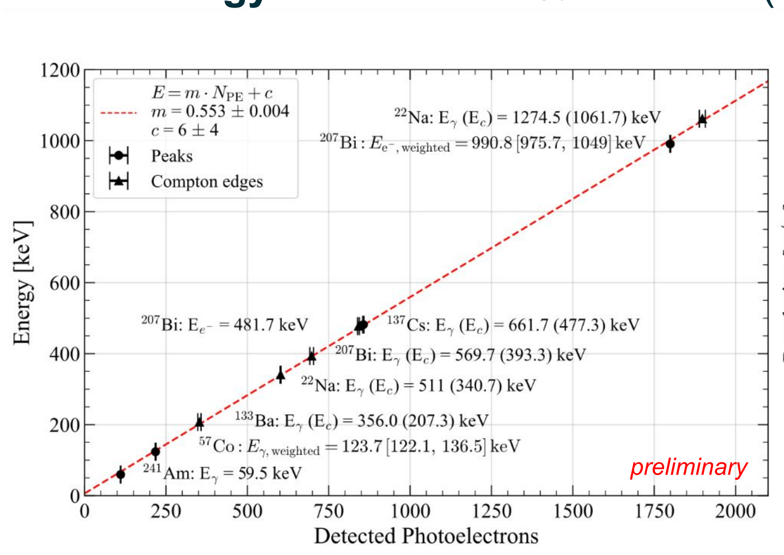
- **Physics principle:** Momentum conservation in the β decay allows the neutrino momentum to be inferred event-by-event; a heavy sterile neutrino produces an anomalous missing-momentum signature.

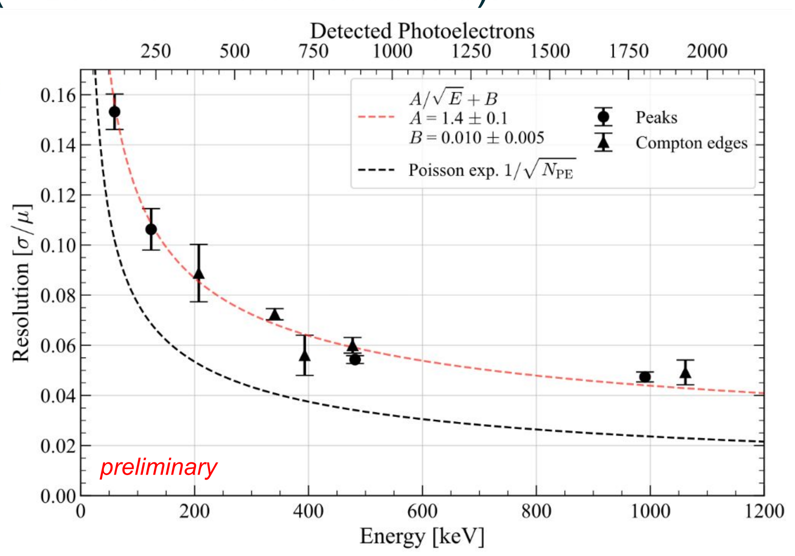
Subsystem Calibration

- **CMOS calibration:** Sensors calibrated with 5.9 keV X-rays from a ^{55}Fe source
  - **Noise reduction:** Correlated double sampling suppresses kTC noise to a median per-pixel noise of 0.12–0.25 keV.
  - **Event selection:** A conservative 6σ per-pixel threshold (~1.5 keV) rejects noise fluctuations.



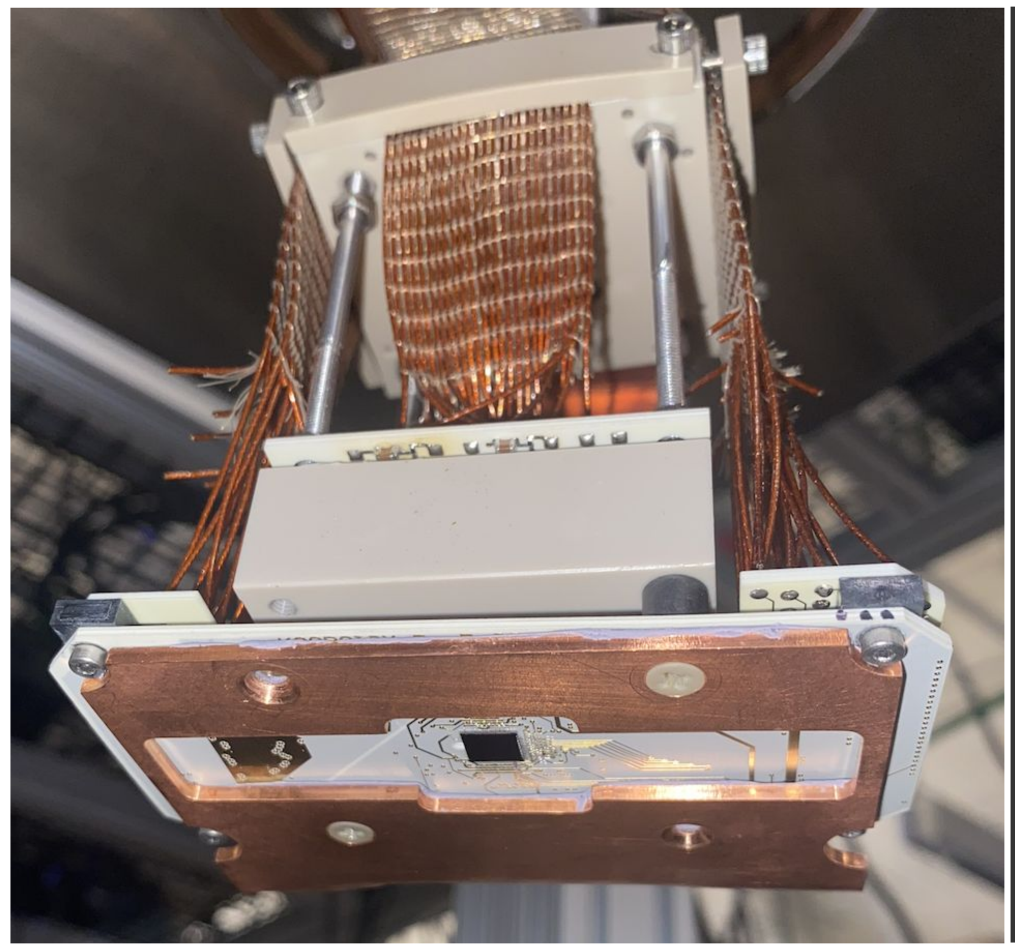
- **Scintillator calibration:** Linear energy response established with peaks and Compton edges from 60–1062 keV.
  - **Energy resolution:** 5% at 1 MeV (^{207}Bi conversion electrons).



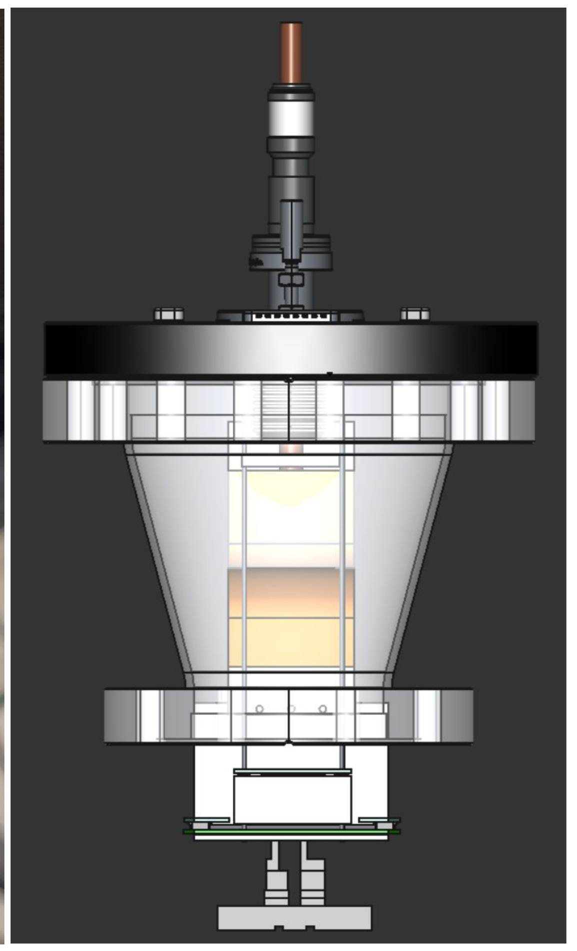


The Detector

- **Tracking detector:** Two parallel planes of thinned (10 μm thick, 4.58 μm pitch) TowerJazz K3C CMOS sensors enable directional β tracking.
- **Calorimetry system:** EJ-200 plastic scintillator read out by a 16-channel Hamamatsu S14161 SiPM array for energy measurement.



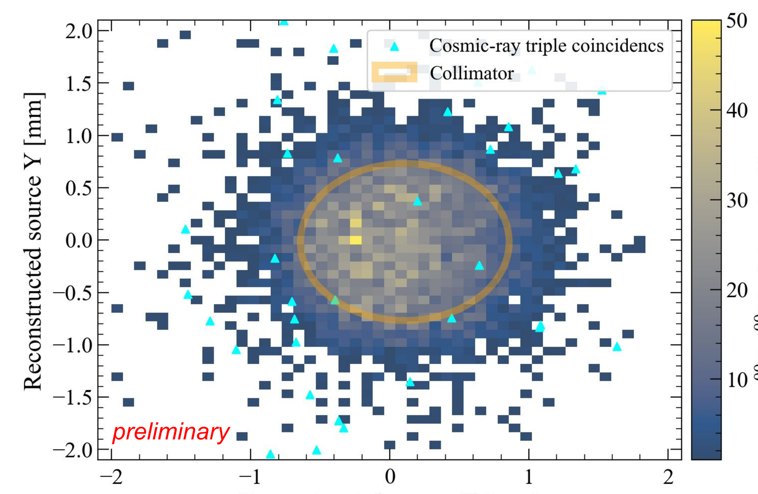
Bottom view of QuIPS beta momentum detector showing one of the cmos detector.

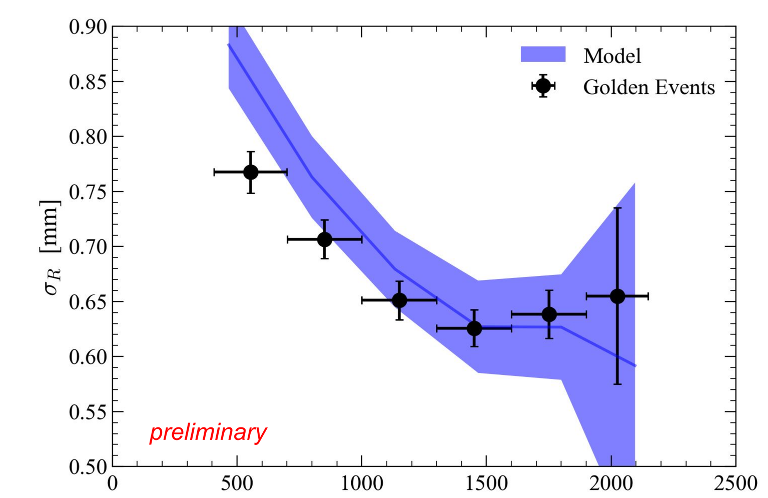


CAD rendering of beta momentum detector located above Yale optical trap.

- **"Triple coincidence events":** An above-threshold pixel cluster in each CMOS plane, in coincidence with a scintillator trigger; for multi-cluster frames, the cluster pair best pointing to the source is chosen.
- **Validation datasets:** Detector performance was evaluated using datasets from both a collimated ^{90}Sr/^{90}Y source and background cosmic rays.
- **Background check:** Observed cosmic triple coincidence event rate (~37/day) matches predictions, confirming sensitivity to minimally ionizing particles.

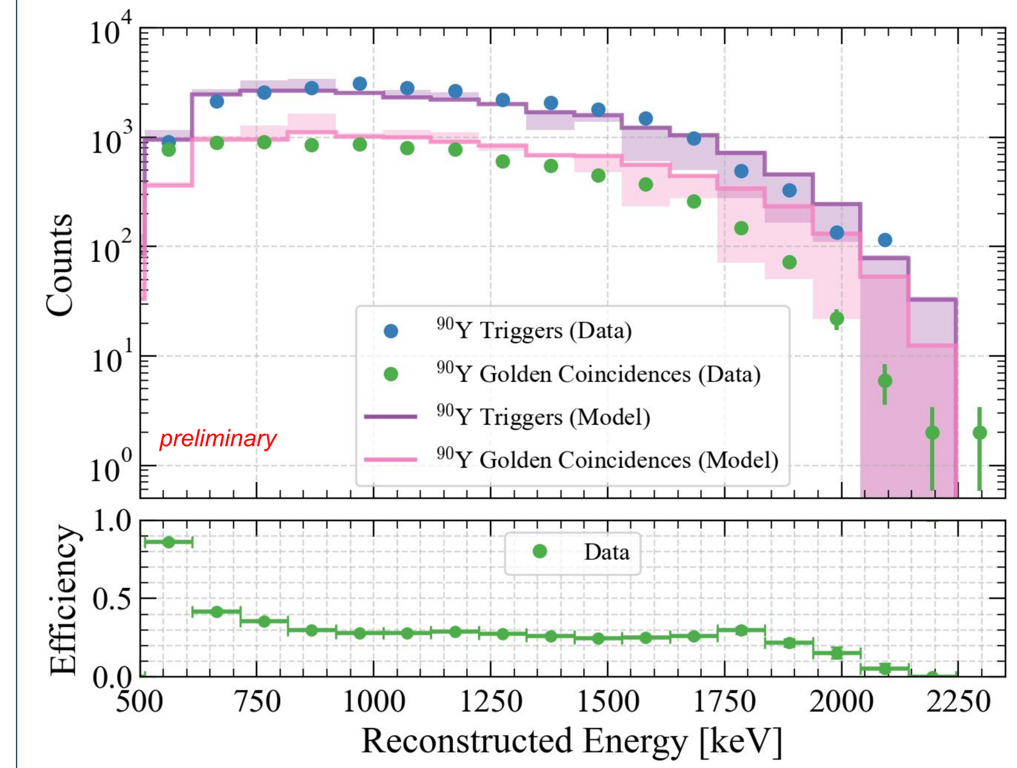
Source Pointing





- **Track reconstruction:** Straight-line tracks from CMOS hit pairs are extrapolated to the source plane to locate β emission source 1.7 mm away from collimator aperture.
- **Energy dependence:** Radial extent shrinks with increasing β energy as Coulomb scattering diminishes, consistent with our Geant4 model.
- **Background discrimination:** Cosmic-ray events show no fixed pointing, confirming source/background separation.
- **QuIPS capability:** Sub-mm pointing is sufficient to isolate events originating from a levitated nanosphere, a key requirement for the QuIPS measurement.

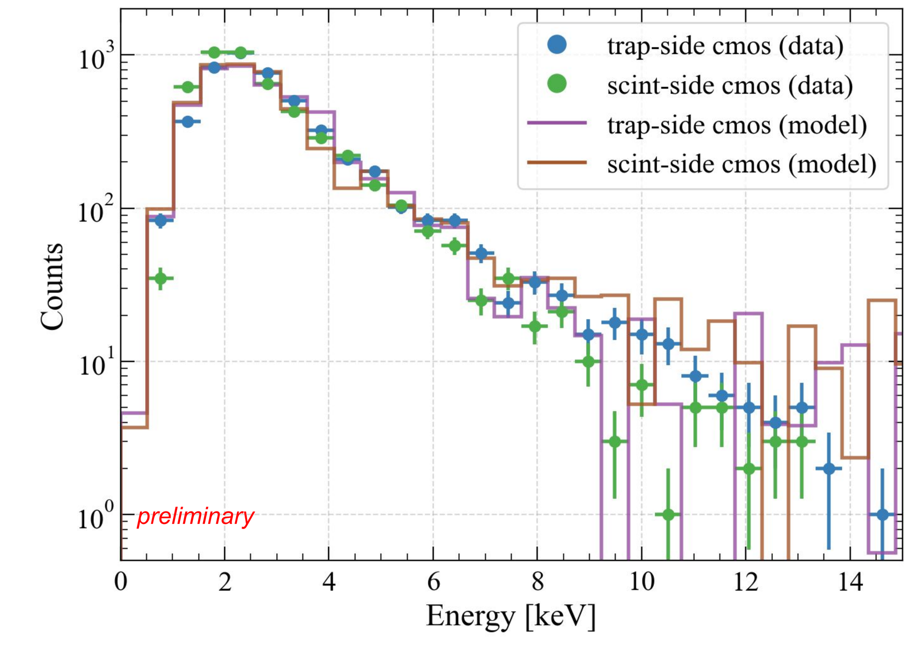
Detected Spectrum



Reconstructed energy spectrum in scintillator for all triggers and triple coincidences.

- **Measured efficiency:** 35% detection efficiency, consistent with Geant4 simulations.
  - Efficiency loss driven by geometric acceptance of electrons traversing both active CMOS and per-pixel energy threshold required to resolve hits in CMOS above noise.

- **Reconstructed spectrum:** Triple coincidence energy spectrum is consistent with simulations
  - Conservative trigger threshold limits sets lower bound on detected electron energy in the scintillator.

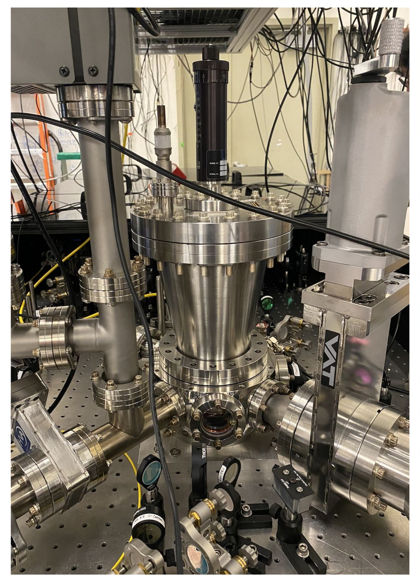


Reconstructed energy spectrum in CMOS for triple coincidences.

Summary

- **First demonstration of the design, construction, and calibration of a compact, UHV compatible electron detector combining thinned CMOS tracking and scintillator–SiPM calorimetry.**
- **Key performance:** 5% energy resolution at 1 MeV, sub-mm source pointing resolution, ~35% detection efficiency, and robust cosmic-ray rejection.
- Detector is now operating in the optical trap setup at Yale with results forthcoming. Publication in preparation!

QuIPS electron detector installed in optical chamber at Yale.



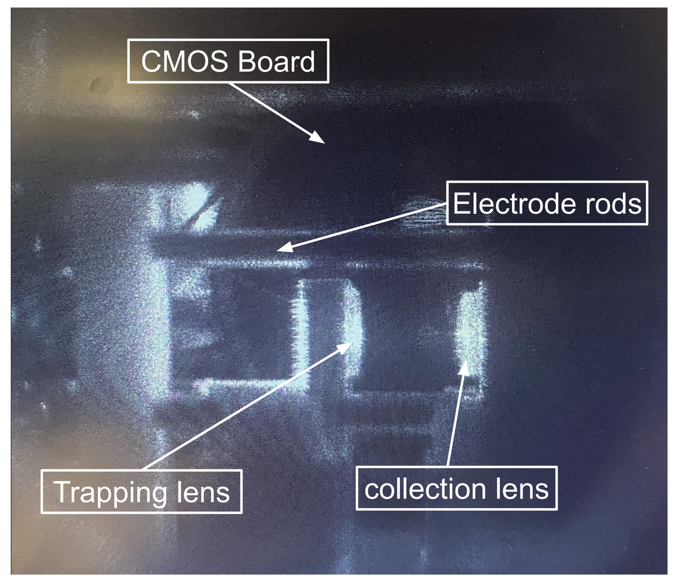


Image of QuIPS electron detector above optical trap.

References

[1] Carney, Leach, Moore, PRX Quantum 4, 010315 (2023)

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