

Particle & Nuclear Physics with Quantum Optics

The QuIPS Experiment

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CPAD Workshop
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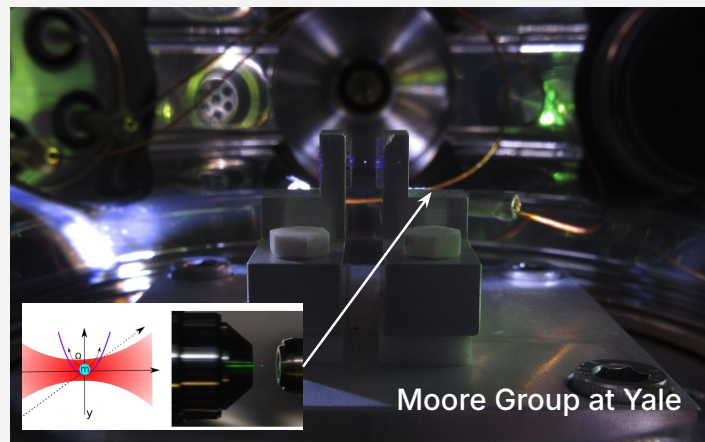
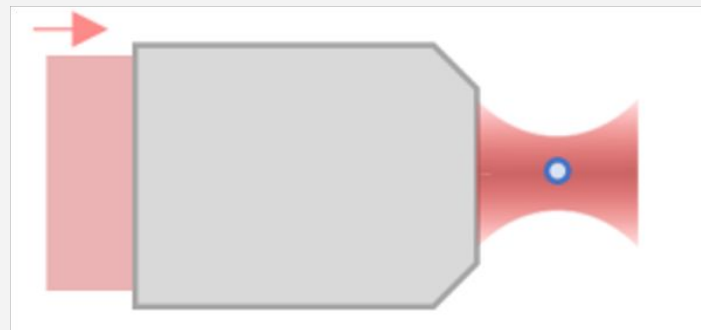
GORDON AND BETTY
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Optical Levitation

- Nano (fg) to micro (ng) spheres levitated with ~100 mW laser power
- Electrically & thermally isolated in high vacuum ($<10^{-7}$ mBar)
- Ultra-low decoherence enabling quantum motional control
- Force sensitivities at the zN level, with acceleration sensitivities near a nano-g

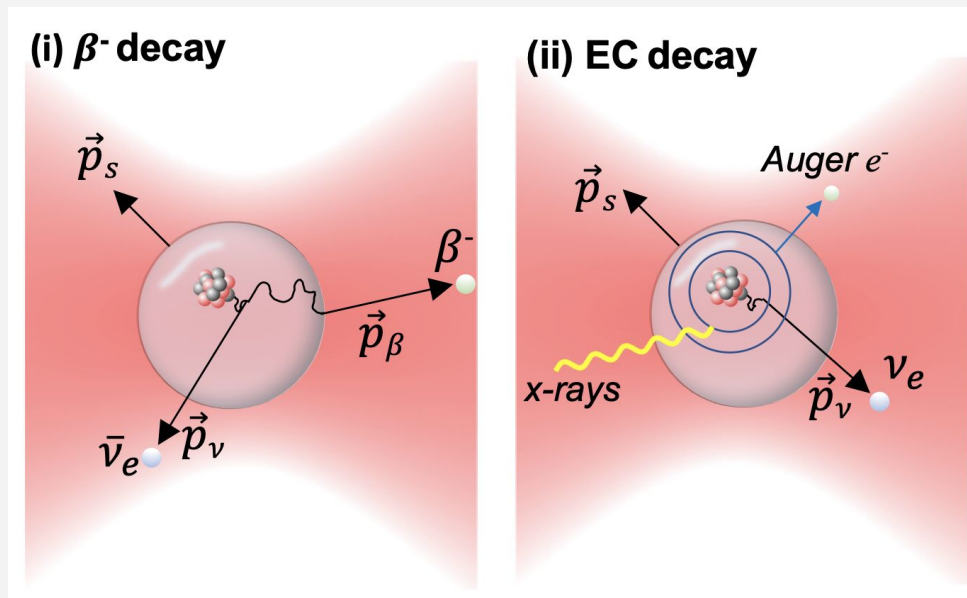
$$\Delta p_{\text{SQL}} = \sqrt{\hbar m_s \Omega_s} = 15 \text{ keV} \times \left(\frac{m_s}{1 \text{ fg}} \right)^{1/2} \left(\frac{\Omega_s / 2\pi}{100 \text{ kHz}} \right)^{1/2}$$

Quantum Sci. Technol. 6 014008 (2021)



For the impatient, make your own source...

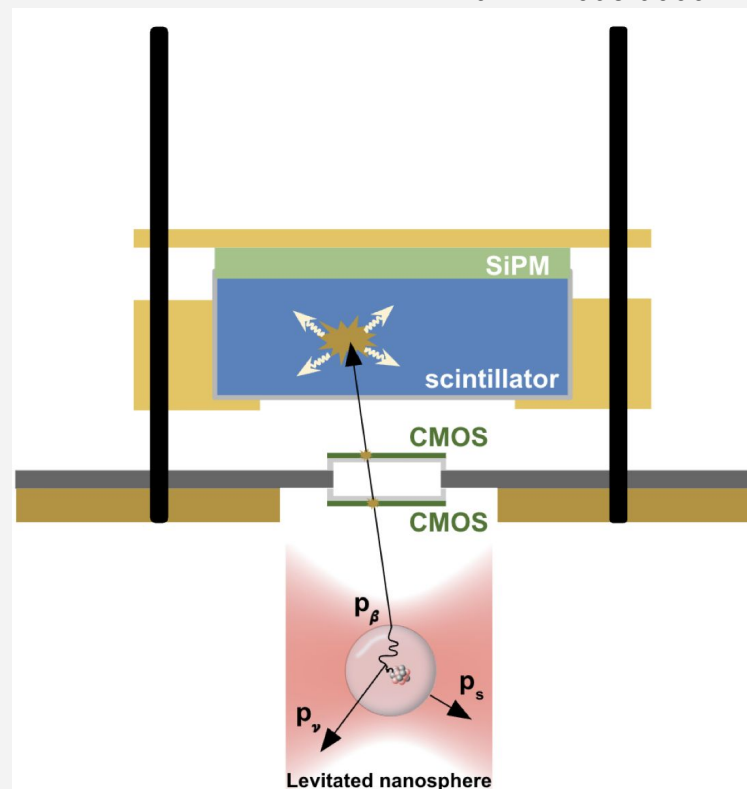
Embed weakly decaying radioisotopes in an optically trapped nanosphere surrounded by particle detectors.



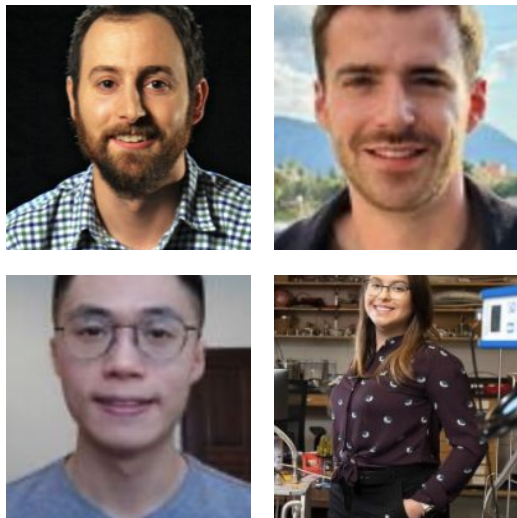
Full kinematic reconstruction of nuclear decays

arXiv:2608.06661

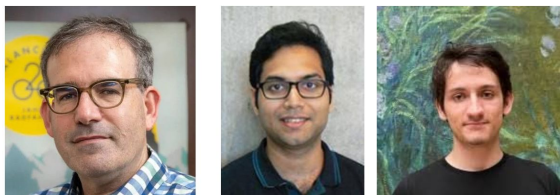
1. Impulse measurement of sphere
 - a. + measure charge state
2. Beta measured by particle detectors
3. Reconstruct momentum of neutrino
4. Profit!



QuIPS team at Yale



QuIPS team at Berkeley



QuIPS team at LBL



FUNDING & SUPPORT

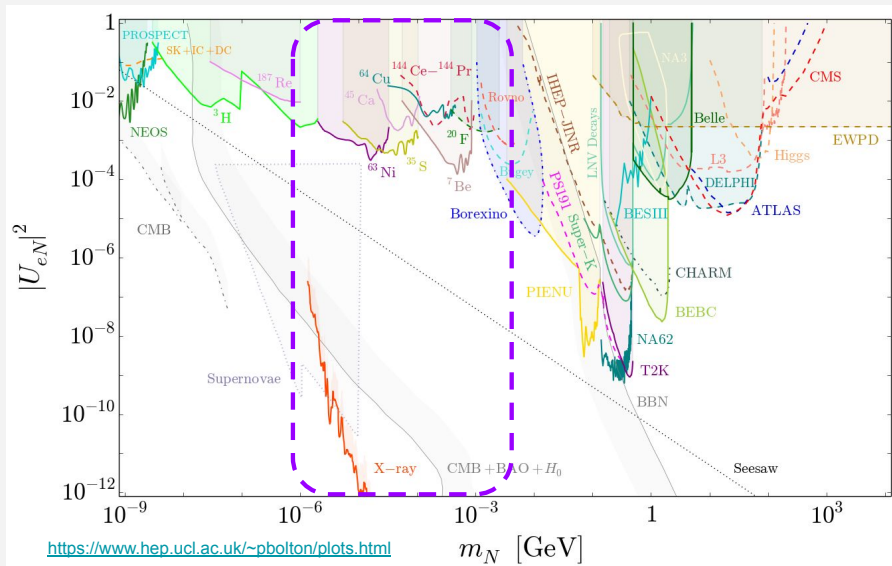


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First measurement: heavy sterile neutrinos

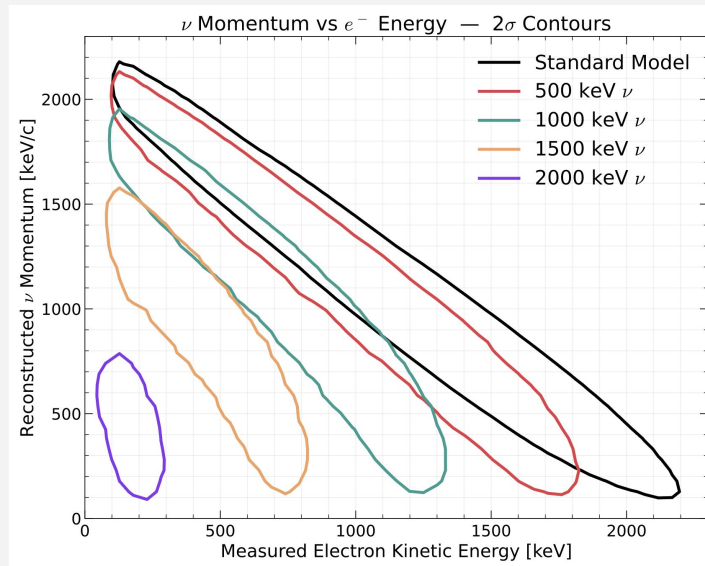
Sterile neutrino physics

- Neutrino mass generation
- Matter-Antimatter asymmetry (Leptogenesis)
- Dark Matter candidate



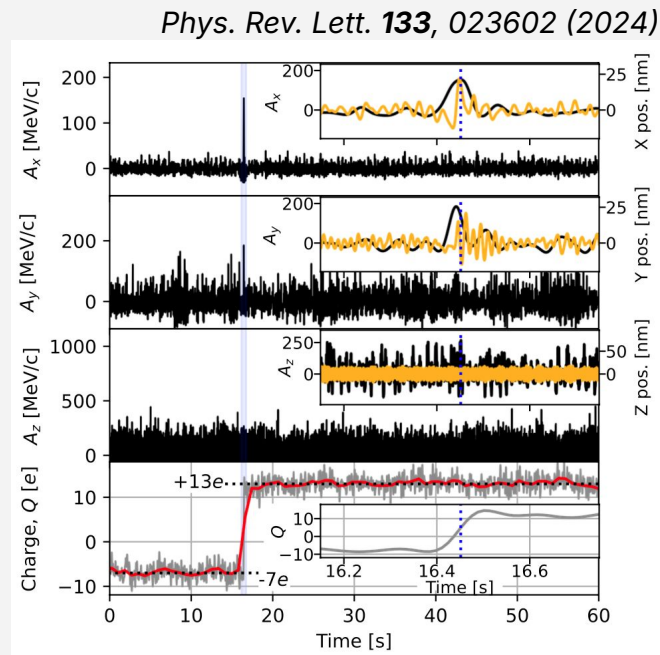
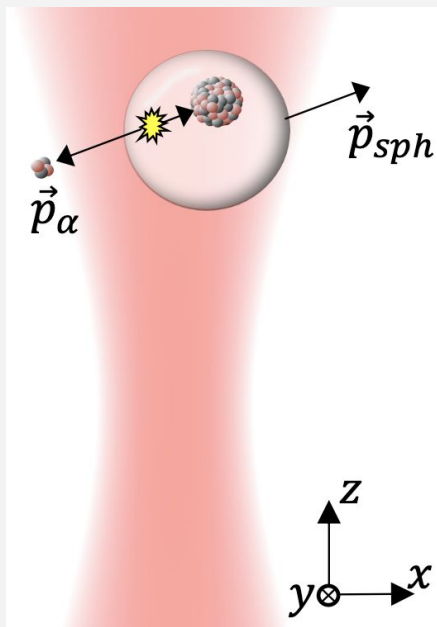
Measurement plan

- Embed ^{90}Y beta in 100 nm silica nanosphere (Q = 2279 keV, 2.7 day half-life)
- $\sim 10^5$ isotopes at 1% loading by mass
- Look for missing momentum



Proof of principle

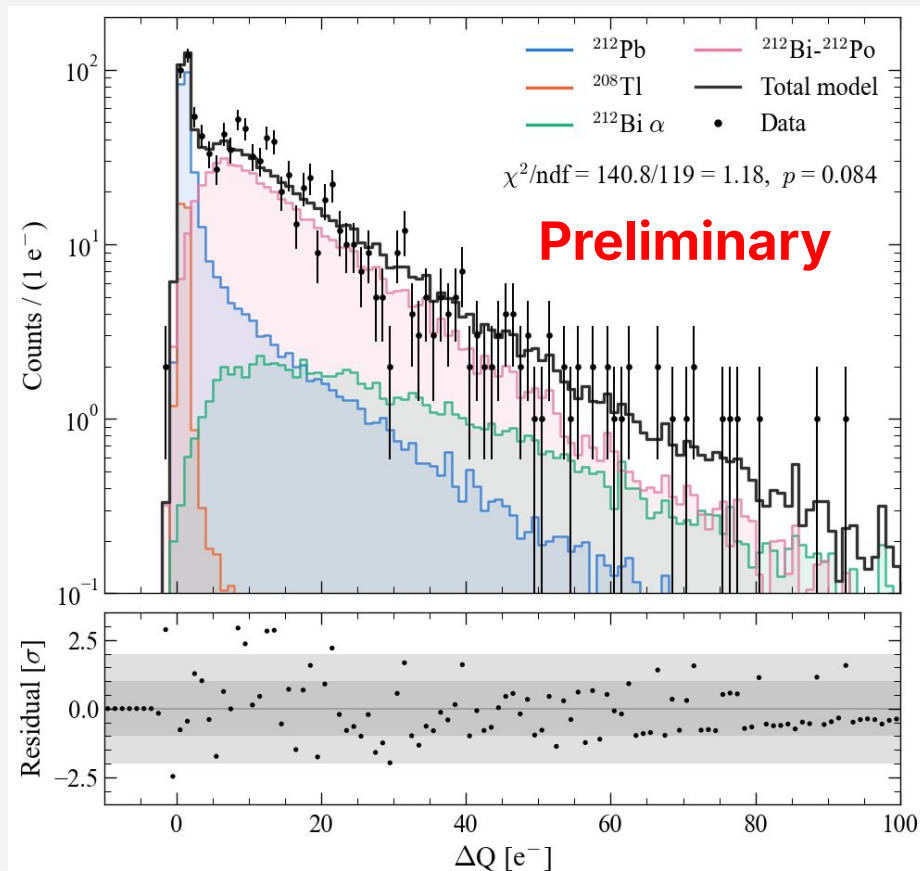
- Optomechanical detection of alpha and beta decays in 1.5 μm sphere using Pb-212 chain
- Coincidence measured of change in charge-state and impulse on the sphere



Proof of principle

- Model secondary e^- down to 0.9 eV (SiO₂ surface affinity)
 - Validated & extended Geant4 MicroElec model
- Distinguish decay topologies via charge state and sphere impulse
- Predict outcomes for:
 - Other decay modes
 - Other detector geometries

Paper in preparation



Proof of principle at LBL

arXiv:2608.06661

Tracking

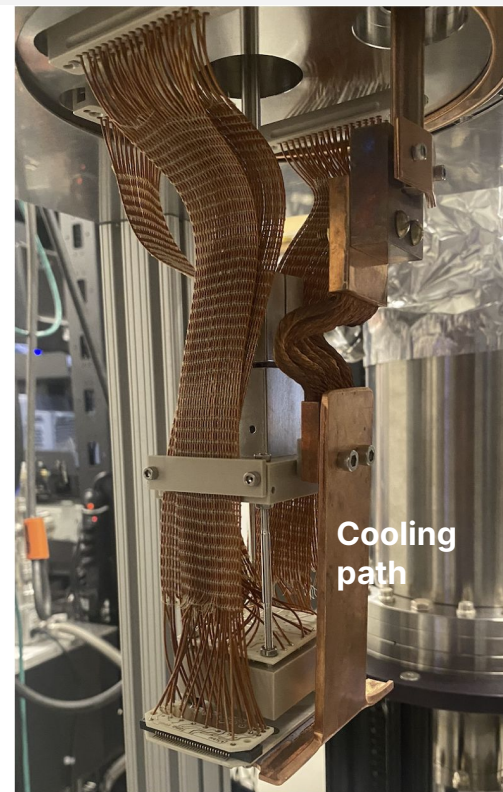
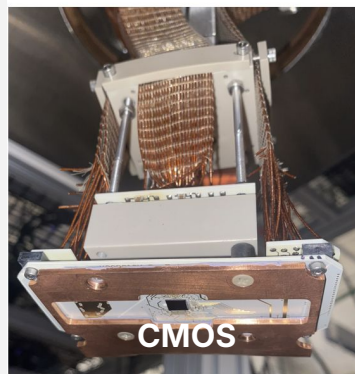
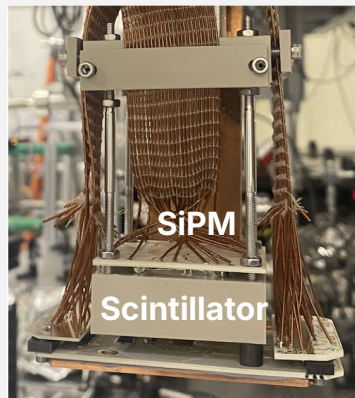
- 2 parallel CMOS planes (5 μm pitch, 20 μm thick DRIE)
- mrad angular resolution

Calorimetry

- EJ-200 scintillator & 16-ch Hamamatsu SiPM
- 5% resolution at 1 MeV

Environment

- 10^{-8} mBar high vacuum achieved
- Dedicated cooling path

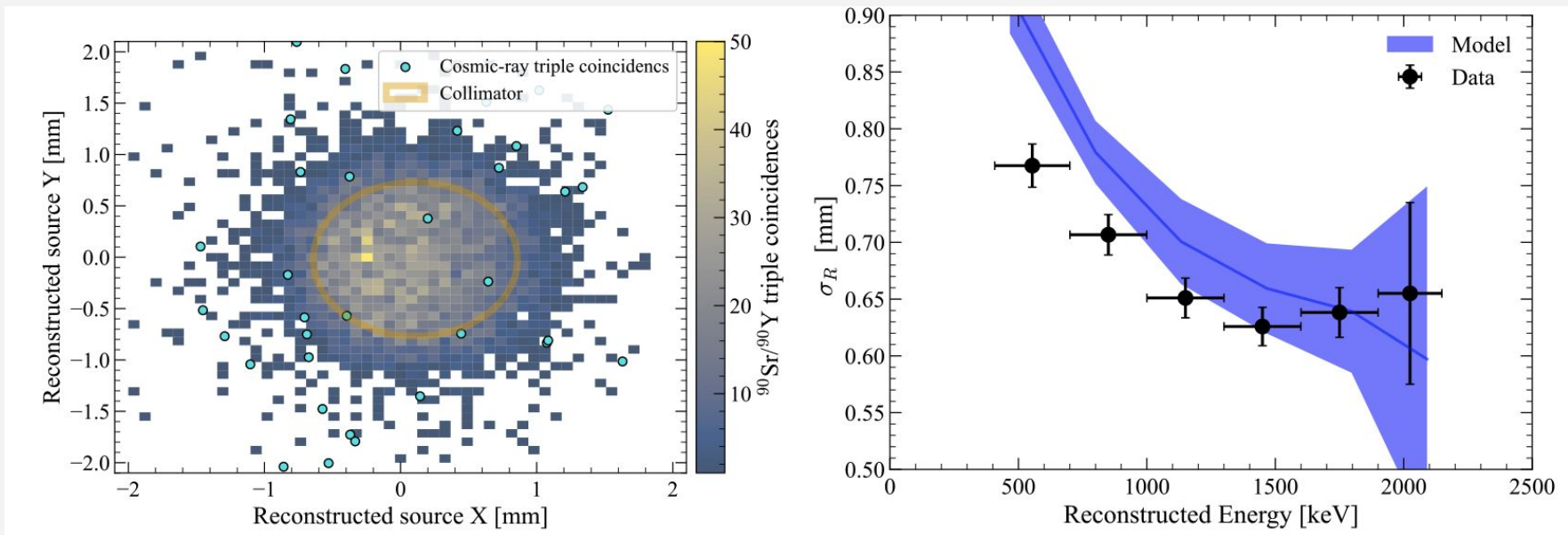


Proof of principle at LBL

Goal 1: Reconstruct source of emitted beta*



arXiv:2608.06661



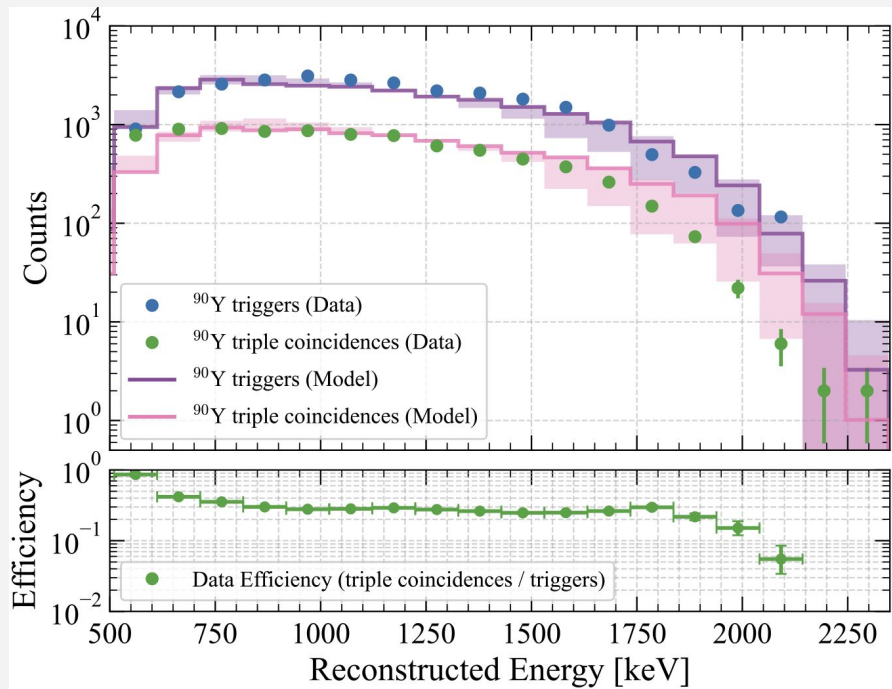
*Using a collimated source as opposed to a point source nanosphere

Proof of principle at LBL

Goal 2: Reconstruct beta energy*

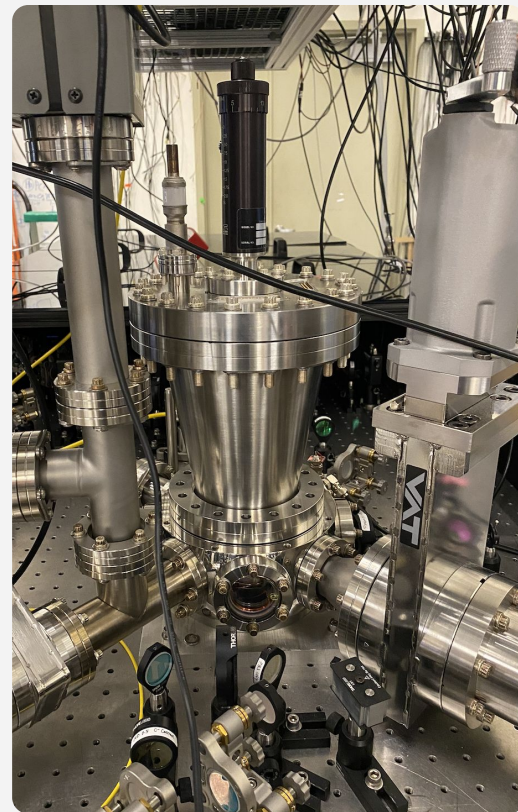
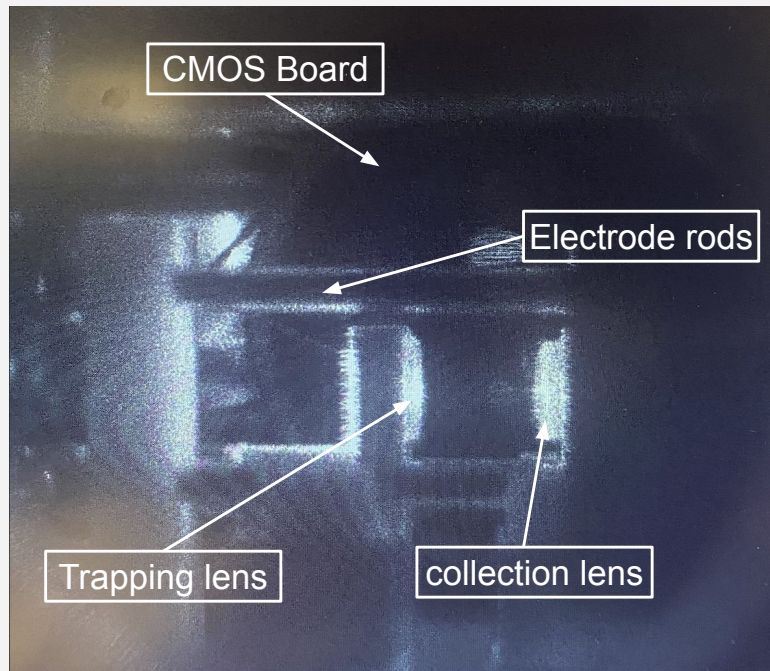
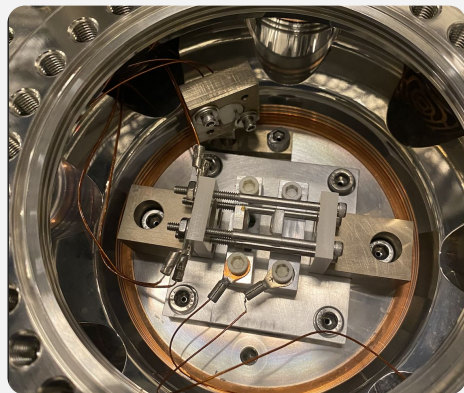
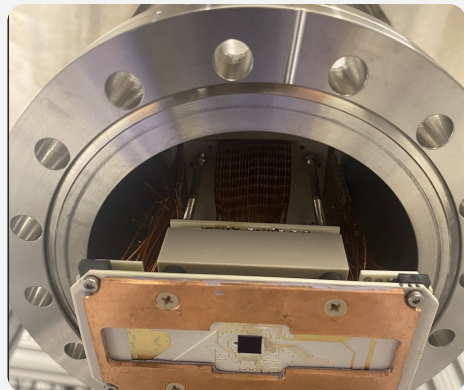


arXiv:2608.06661



*Data taken with high trigger threshold, not a fundamental limitation of system

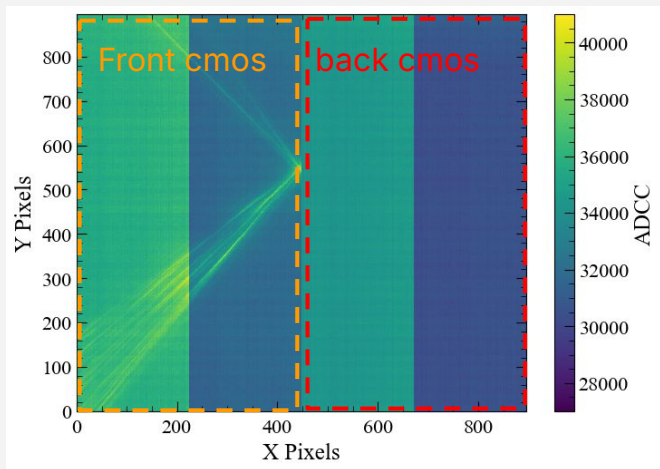
Combined demonstrator: 'beta' tests



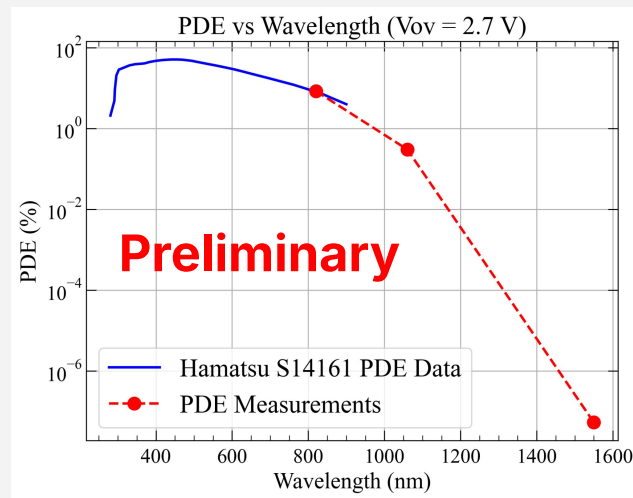
Lessons learned so far...

Single photon sensitive devices are sensitive to single photons.

- Already a problem at $\sim$ nW of 1064 nm
- **Use 1550 nm laser $\rightarrow$ below silicon bandgap.**



Scattered light pattern on pixelated CMOS array with 1.5 mW laser on.

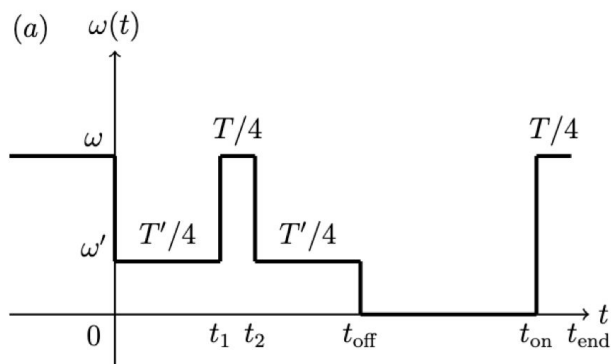


Photon detection efficiency measurements performed at LBL. Paper in prep.

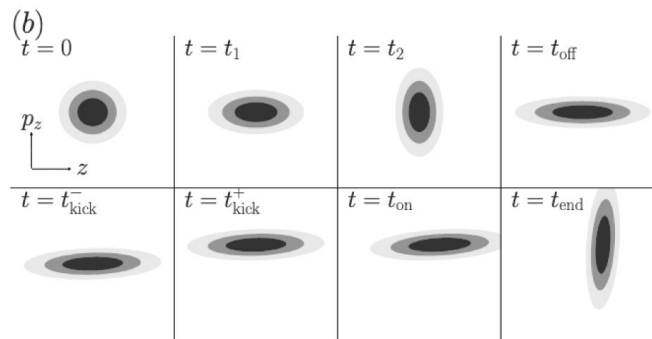
Towards the ultimate reach...

- Need repeatable production and loading of radioactive spheres
- Reach SQL in x/y/z and go beyond
- Mechanical squeezing in of sphere in 3D
- Scaling $\rightarrow$ levitated arrays
 - ~ 100 spheres, ~ 1 year, $\sim$ SQL to reach seesaw bounds

Optical potential for squeezing protocol



State projection of sphere during protocol



Phys.Rev.A 114, 013504 (2026)

Summary

- QulPS experiment is rapidly working towards a first combined demonstration using ^{18}F with collaborators at Yale.
- Optical levitation setup at LBL is being designed with 1550 nm laser.
 - Special care to codesign optics and particle detectors for maximum sensitivity.
 - Ongoing measurements of silicon sensor responsivity to 1550 nm.
- Papers in preparation for modeling electrons emitted from spheres in response to decays.

Stay tuned for upcoming results!