Particle & Nuclear Physics with Quantum Optics

The QuIPS Experiment

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OSSAP Workshop 2026

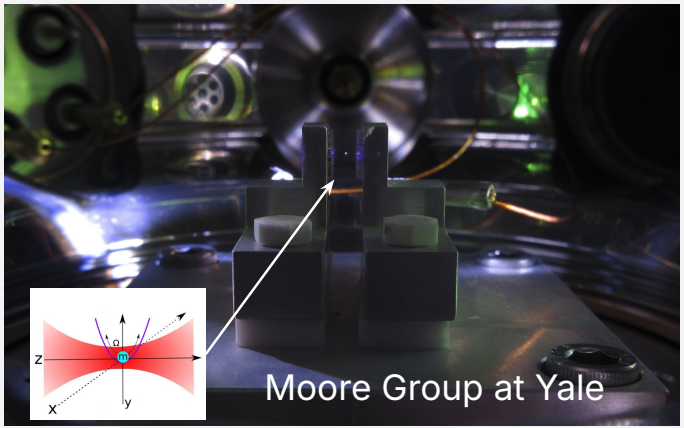
GORDON AND BETTY
MOORE
FOUNDATION

Starting line:

Optically levitated 100 nm silica sphere (~fg) in high vacuum (<10^{-7} mBar)

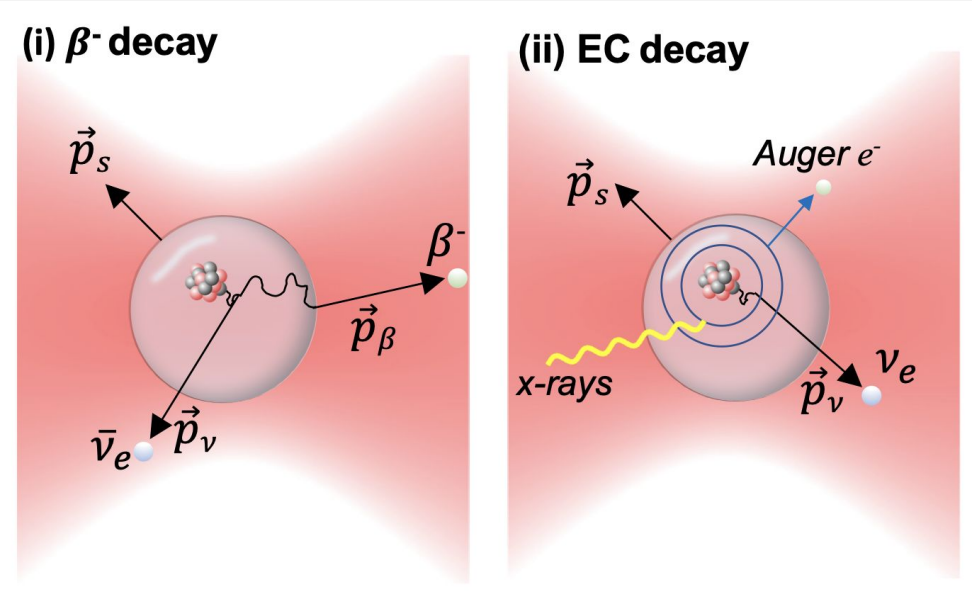
- Operated at *(or near)* the standard quantum limit (SQL)

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



For the impatient, make your own source...

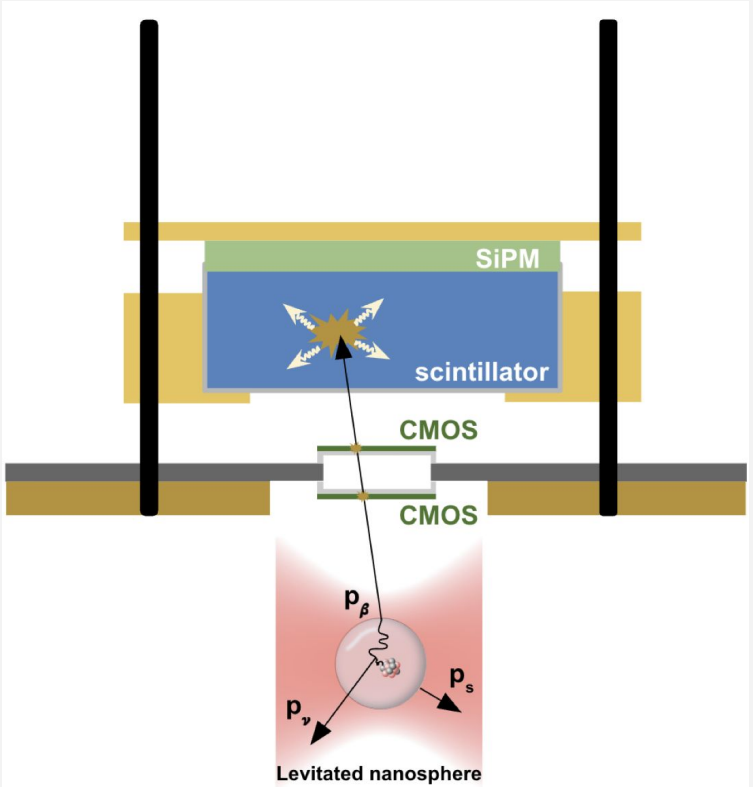
Embed radioisotopes in an optically trapped nanosphere surrounded by particle detectors



Full kinematic reconstruction of nuclear decays

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

arXiv:2608.06661



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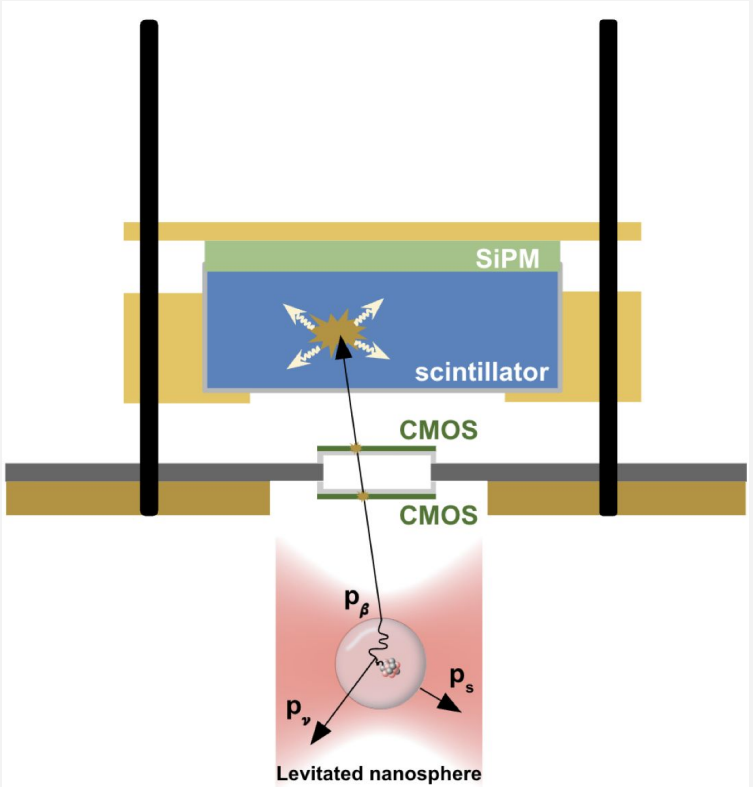
Backgrounds...



What’s the physics reach?

Reconstruct momentum of neutrino to …

- Search for sterile neutrinos
  - Measure neutrino mass (?)
- Angular correlation of beta and neutrino
- Search for axions in nuclear deexcitations
- Nuclear forensics
- Measure rare decays
- …

Quantum Invisible Particle Sensor (QuIPS)

QuIPS @ LBL

QuIPS team at Yale




QuIPS team at Berkeley



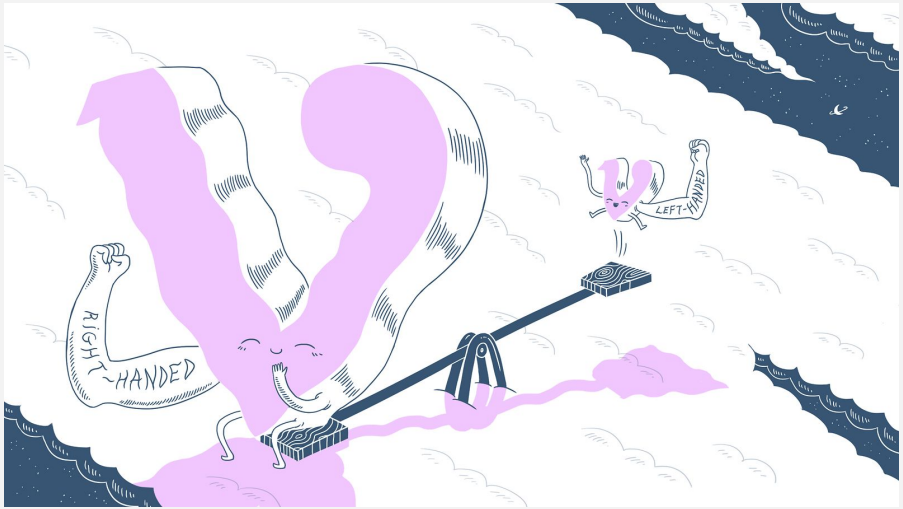
FUNDING & SUPPORT

QuIPS team at LBL

First goal: heavy sterile neutrinos

Tackle multiple outstanding neutrino and SM problems all at once...

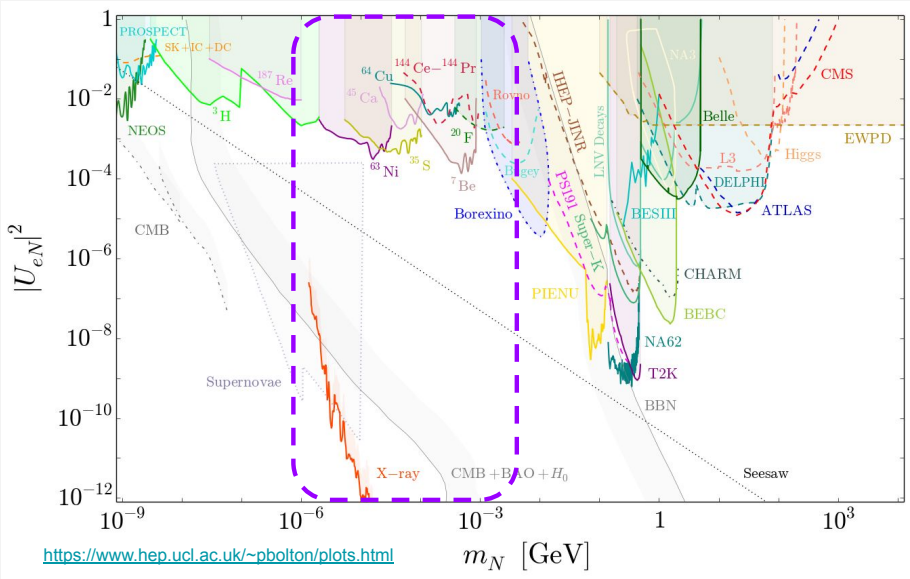
- Neutrino mass
- Matter-Antimatter asymmetry
- Dark Matter candidate

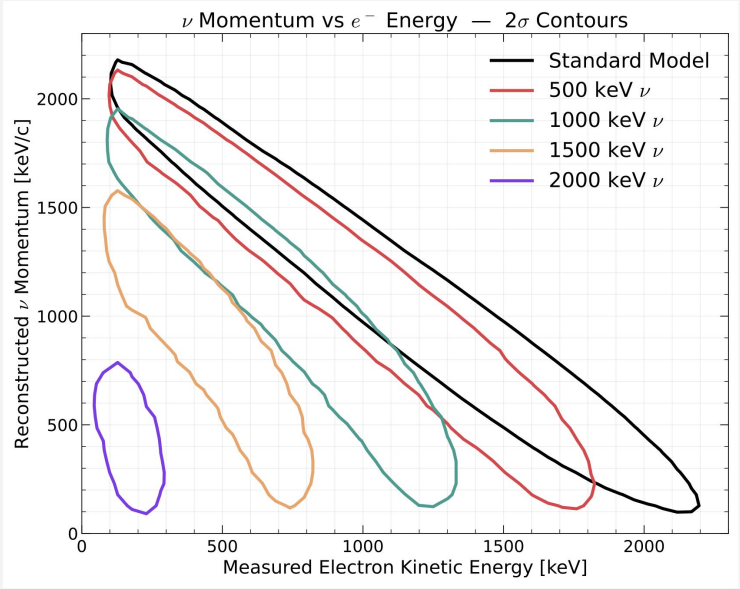


Measurement plan

Embed ^{90}Y beta (Q = 2279 keV, 2.7 day half-life) in 100 nm silica nanosphere

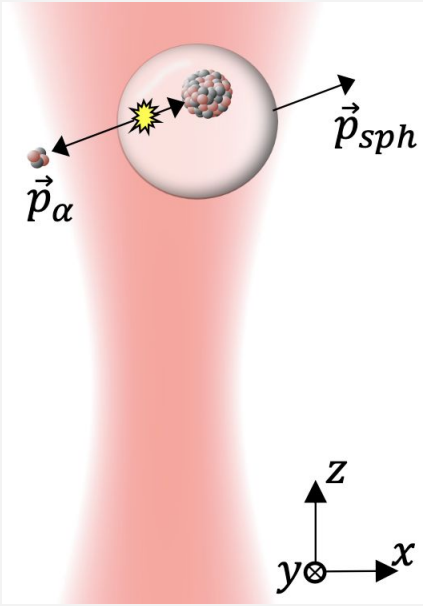
- ~10^5 isotopes at 1% loading *(can we do better?)*





Proof of principle at Yale

Optomechanical detection of alpha and beta decays in 1.5 um sphere using Pb-212 chain



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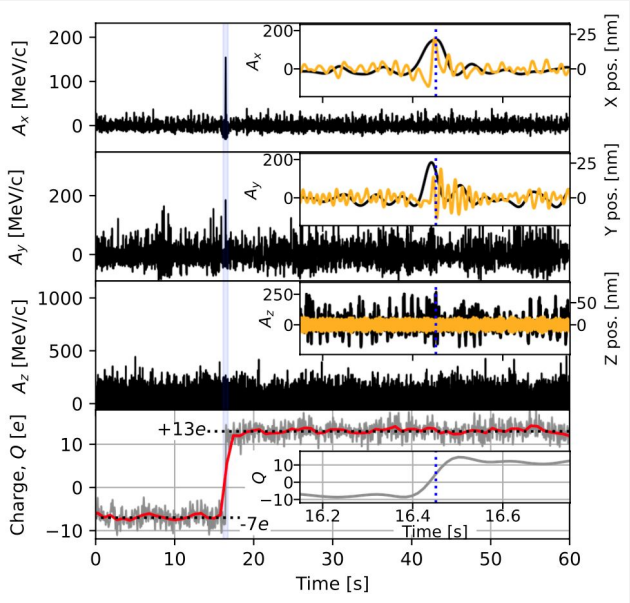
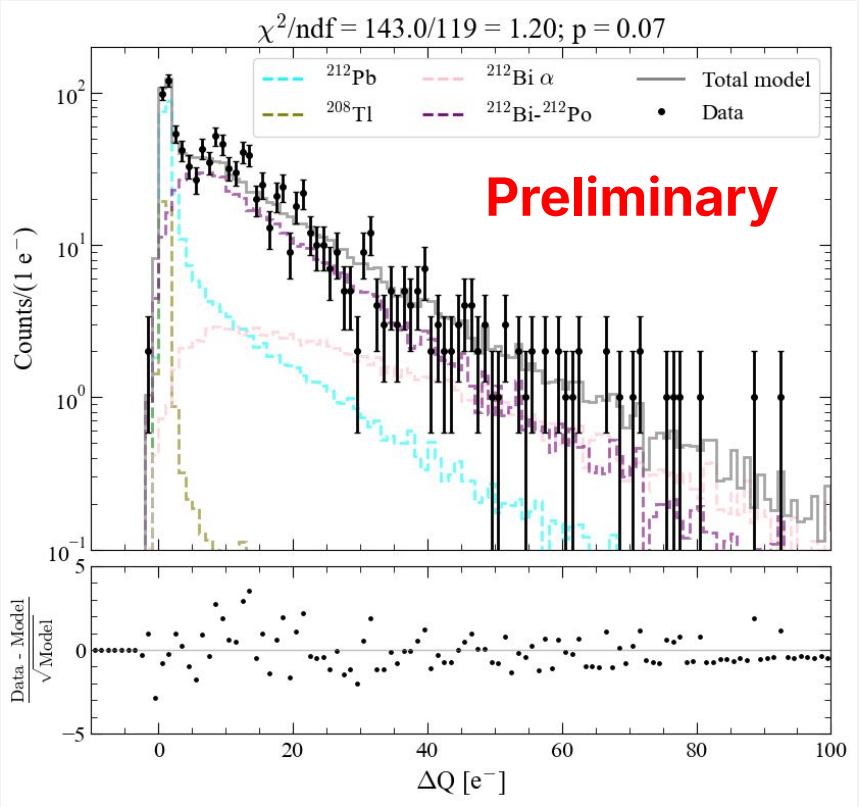
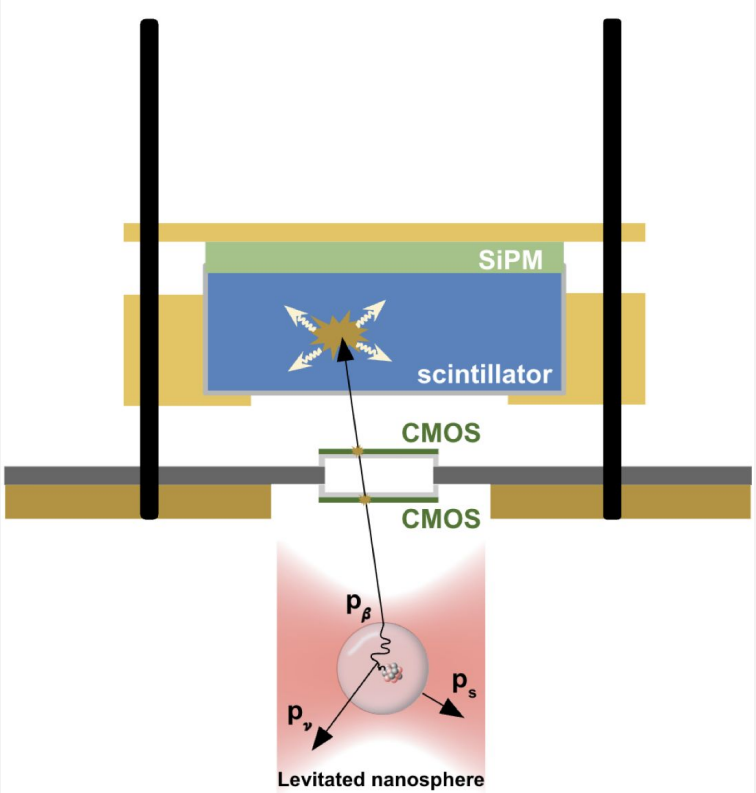


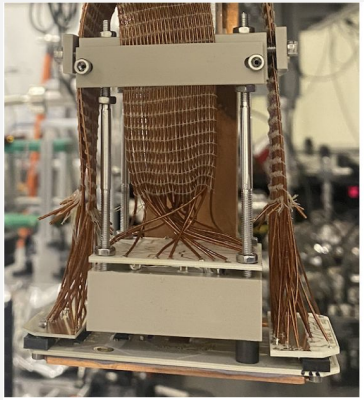
Proof of principle at Yale

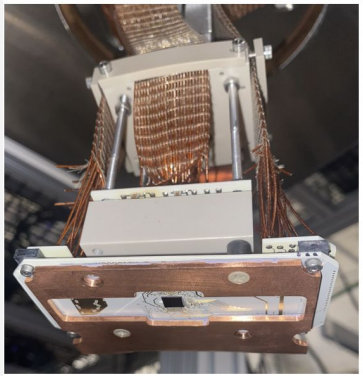
- Model *all* electrons down to 0.9 eV surface affinity of SiO_2
- Make predictions…
  - For other decays
  - For other geometries



Proof of principle at LBL







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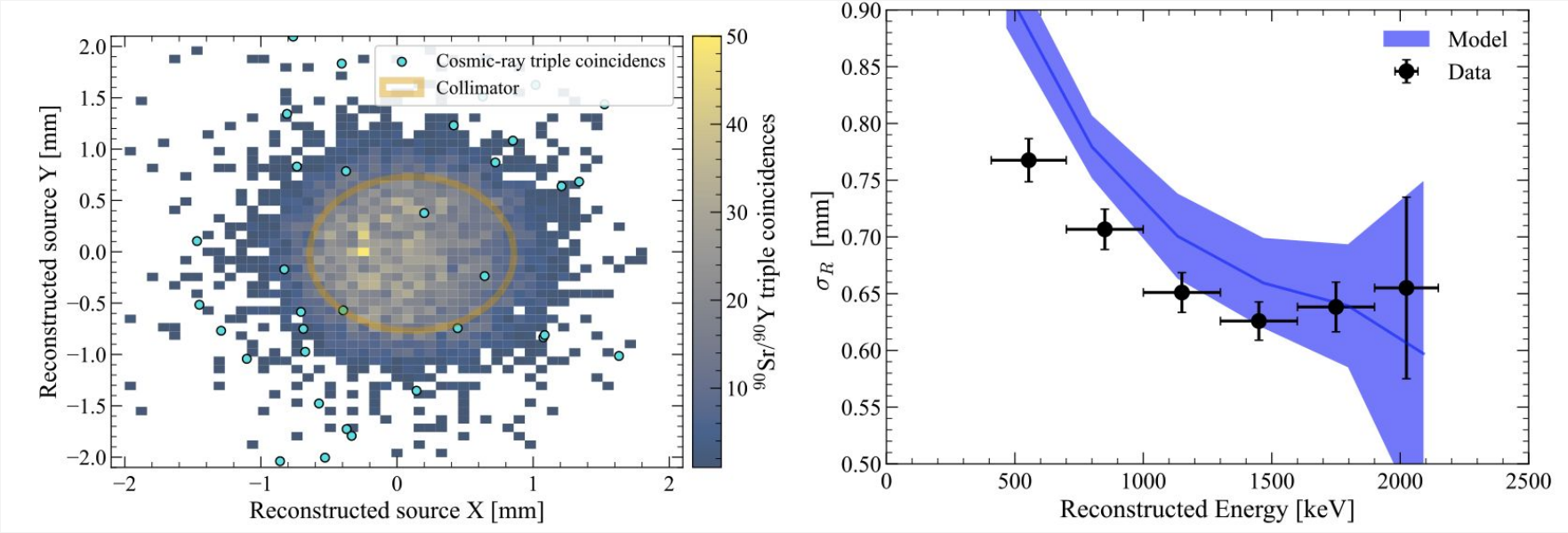
Proof of principle at LBL

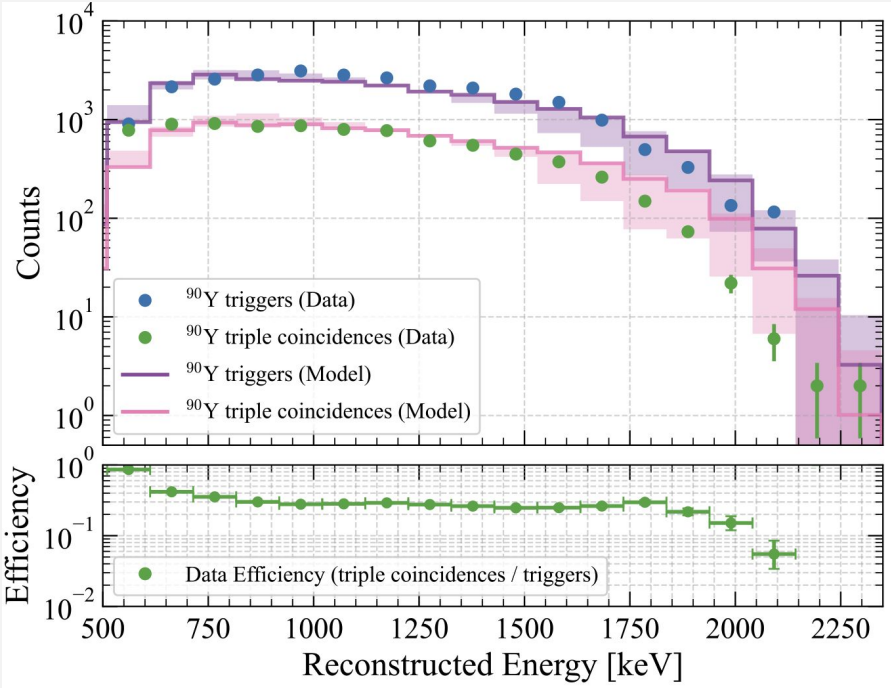
Goal 1: Reconstruct source of emitted beta* ✅



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

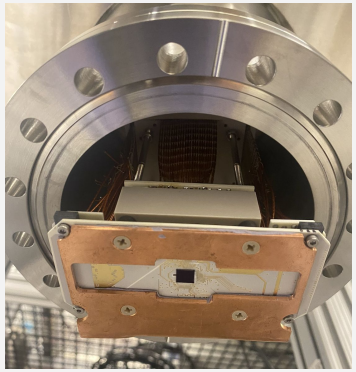
Proof of principle at LBL

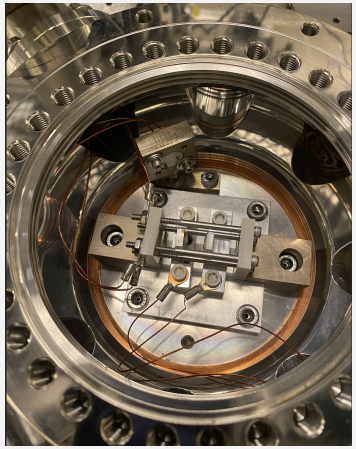
Goal 2: Reconstruct beta energy* ✅

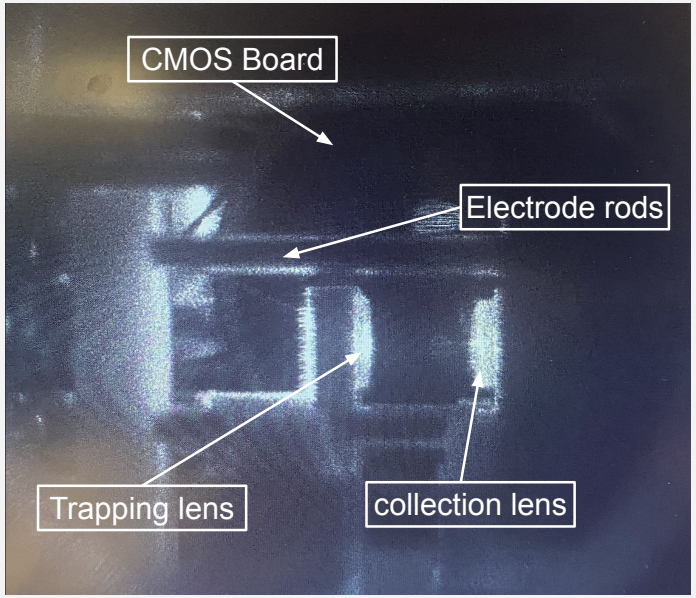


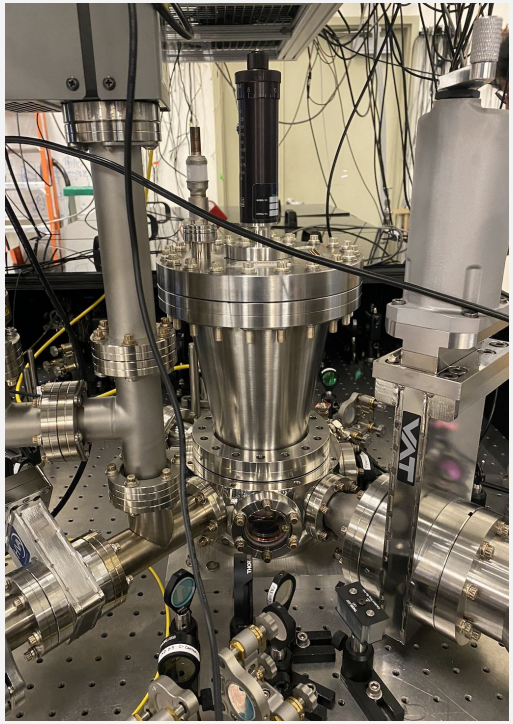
*Data taken with high trigger threshold, not a fundamental limitation of system

Combined demonstrator: ‘beta’ tests





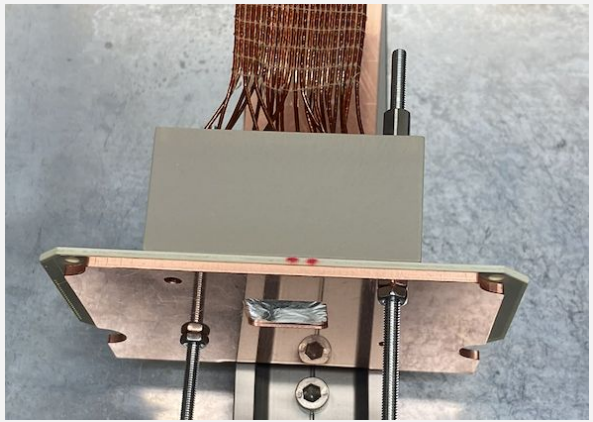




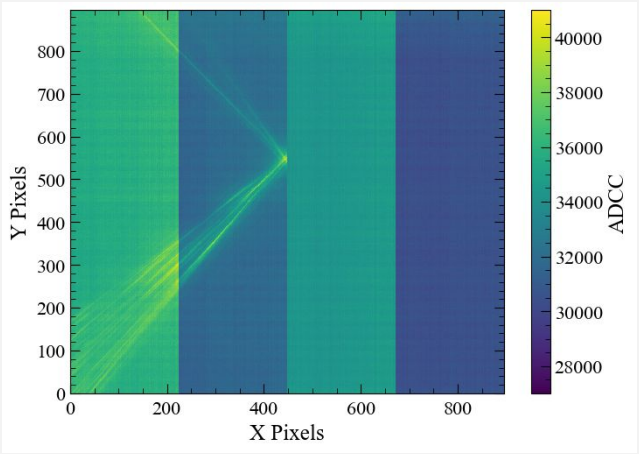
Lessons learned

Single photon sensitive devices are sensitive to single photons

- Already a problem at ~nW of 1064 nm
- **Use 1550 nm laser → below silicon bandgap!**



Hermetic sealed detector with Aluminum reflectors

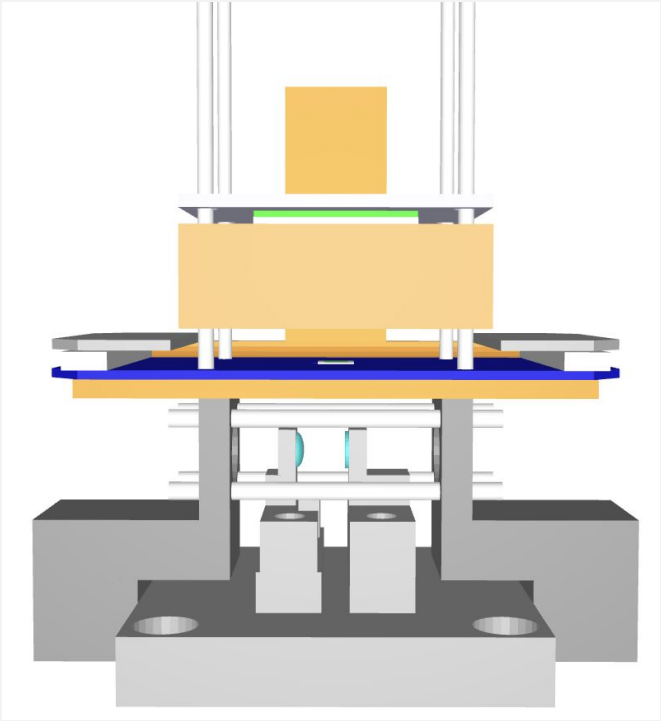


Scattered light pattern on pixelated CMOS array

Detector design

Simulations imitate experiment imitate simulations

- Dedicated Geant4 simulations
  - Motivate detector requirements
  - Mitigate backgrounds

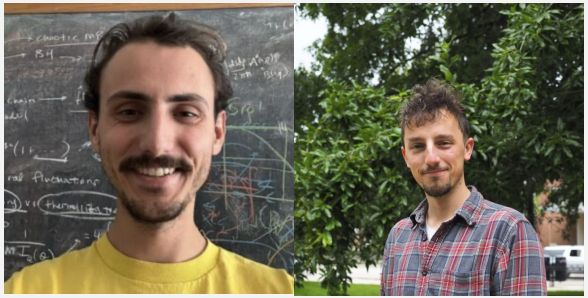


Geant4 model of QuIPS detectors

Codesign optics and particle detectors at LBL

QuIPS @ LBL

Optimizing readout to ‘squeeze’ the most out of momentum resolution

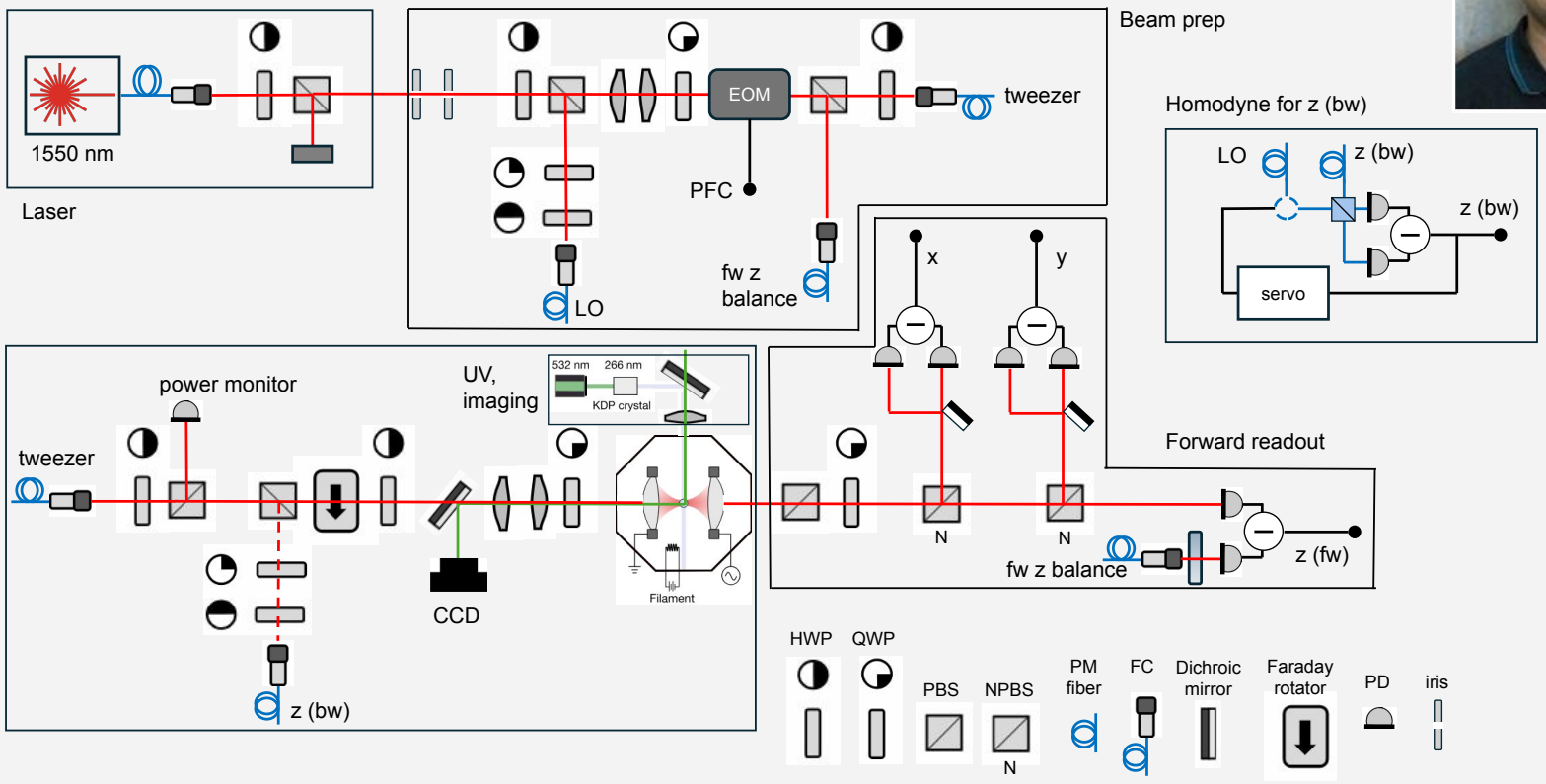


Designing optical system compatible with particle detectors

Simulating full-system response to optimize detector design

Codesign optics and particle detectors at LBL

Preliminary design



Technical Challenges

- Controlling activity within the sphere
  - Need repeatable production of radioactive spheres
- Loading strategy
  - Excess spheres = excess radioactivity
    ⇒ deterministic loading required
- Scaling → levitated arrays
  - ~100 spheres, ~1 year, ~ SQL to reach seesaw bounds
- *Unknown unknowns…*

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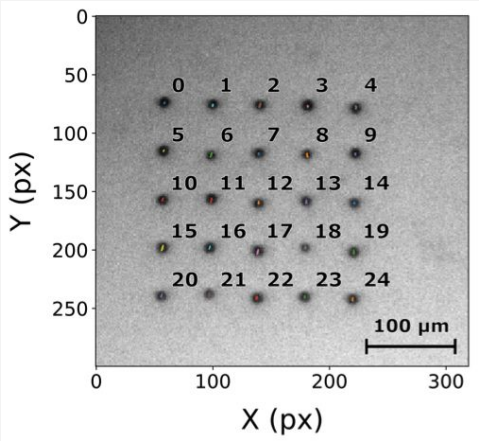

Summary

- QuIPS experiment is rapidly working towards a first combined demonstration using F-18 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