

Measuring Beta Particle Momentum with CMOS Sensors and Scintillating Detectors for Sterile Neutrino Detection

The QulPS Experiment

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Levitated Optomechanical Sensors

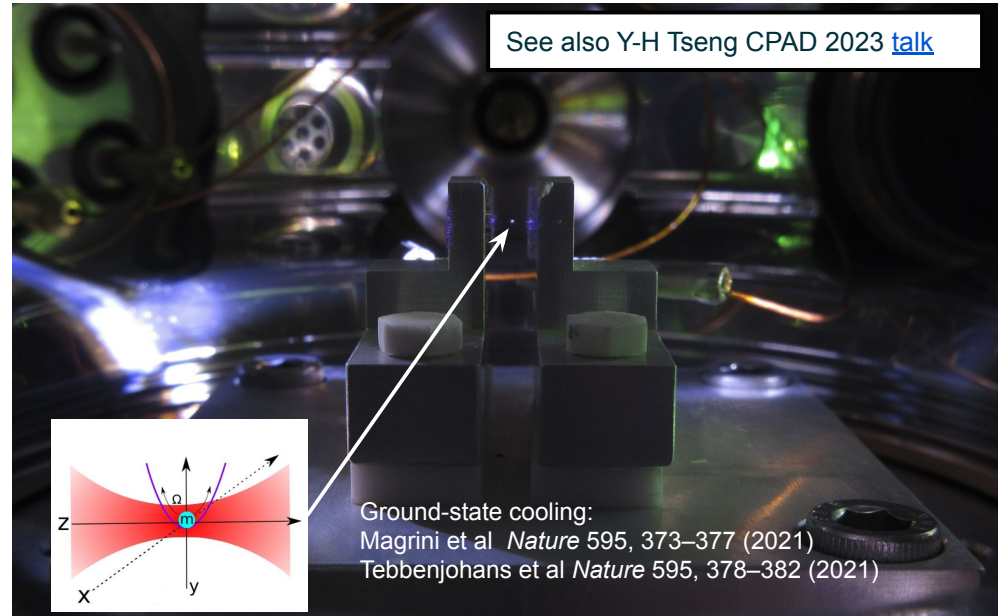
- Dielectric silica nanospheres $O(100\text{ nm})$ with $\sim\text{fg}$ masses optically trapped in UHV ($<10^{-8}$ mbar)
 - Radiation pressure from highly focused laser used to trap
- Can feedback cool C.o.M. motion to ground state
- Highly sensitive to momentum transfers “kicks” i.e. force sensor
- Impulse sensitivity at standard quantum limit

$$(\Delta p)_{SQL} = \sqrt{\hbar m \Omega}, \quad \Delta p = F \cdot \delta t$$

$\sim 15\text{ keV}/c$

for 150 nm sphere @ 150 kHz

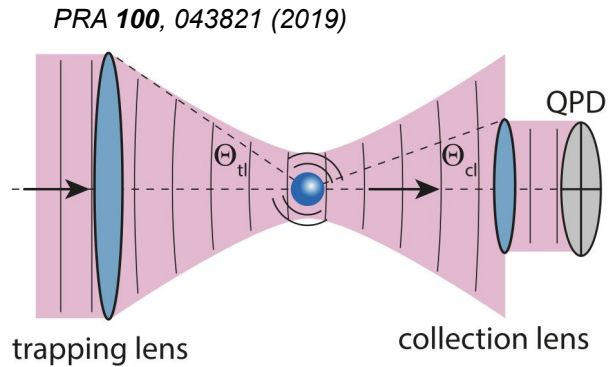
- Offer tabletop testbed for fundamental physics



For a review see *Quantum Sci. Technol.* 6 (2021) 014008

Quantum Invisible Particle Sensor (QuIPS)

Concept introduced by Carney, Leach, and Moore in *PRX Quantum* 4, 010315 (2023)

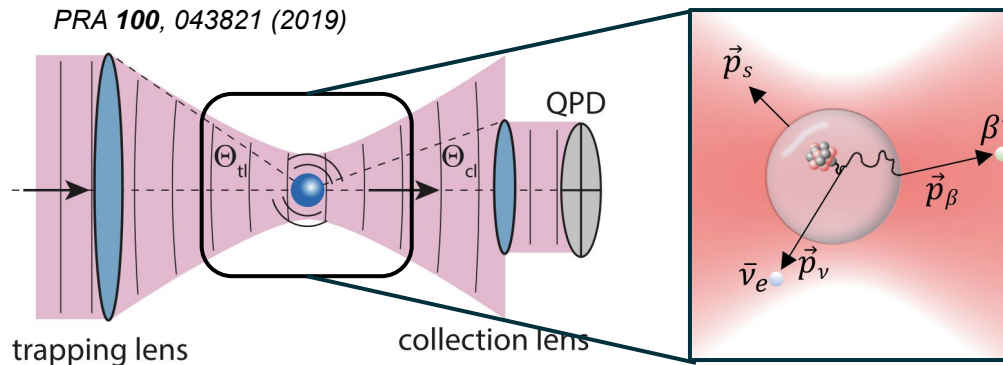


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Embed radioisotopes in an optically trapped nanosphere surrounded by particle sensors

- Optomechanical measurement of impulse to sphere e.g. ion momentum

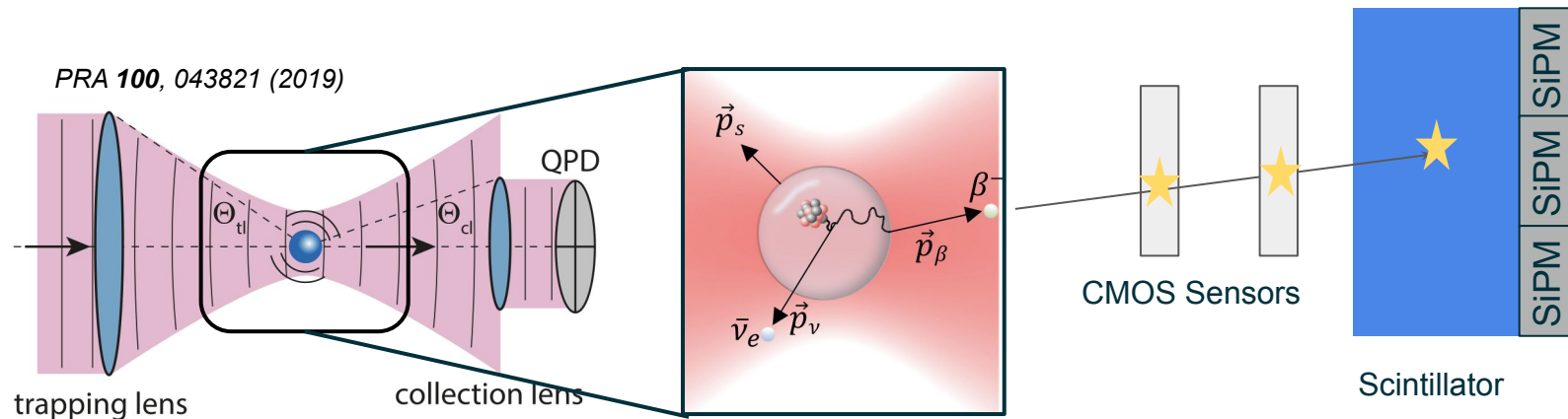


Quantum Invisible Particle Sensor (QuIPS)

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Embed radioisotopes in an optically trapped nanosphere surrounded by particle sensors

- Optomechanical measurement of impulse to sphere e.g. ion momentum
- Outgoing beta measured by particle sensor to reconstruct its momentum
- ⇒ **Reconstruct measurement of 'invisible' neutrino!**

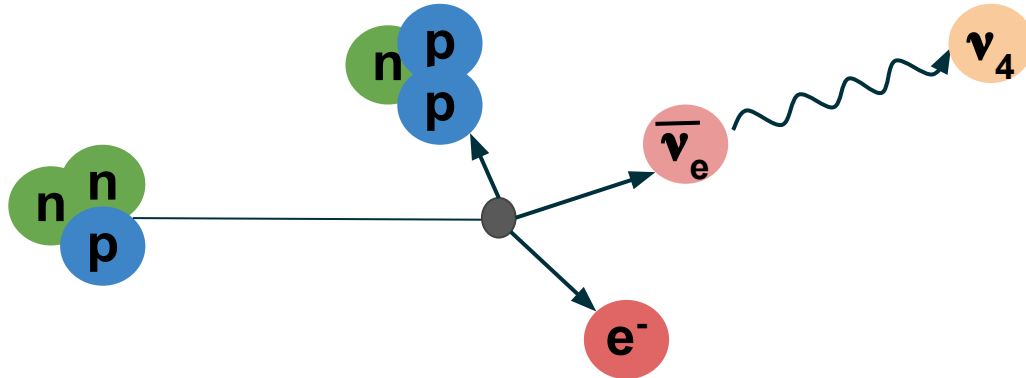


Sterile Neutrino Measurement

Optomechanical systems offers unique ability to perform measurements of 'missing' momentum!

- Emitted neutrino in beta decay oscillates to heavy sterile neutrino
- Sterile neutrino, with large mass carries, away 'extra' momentum

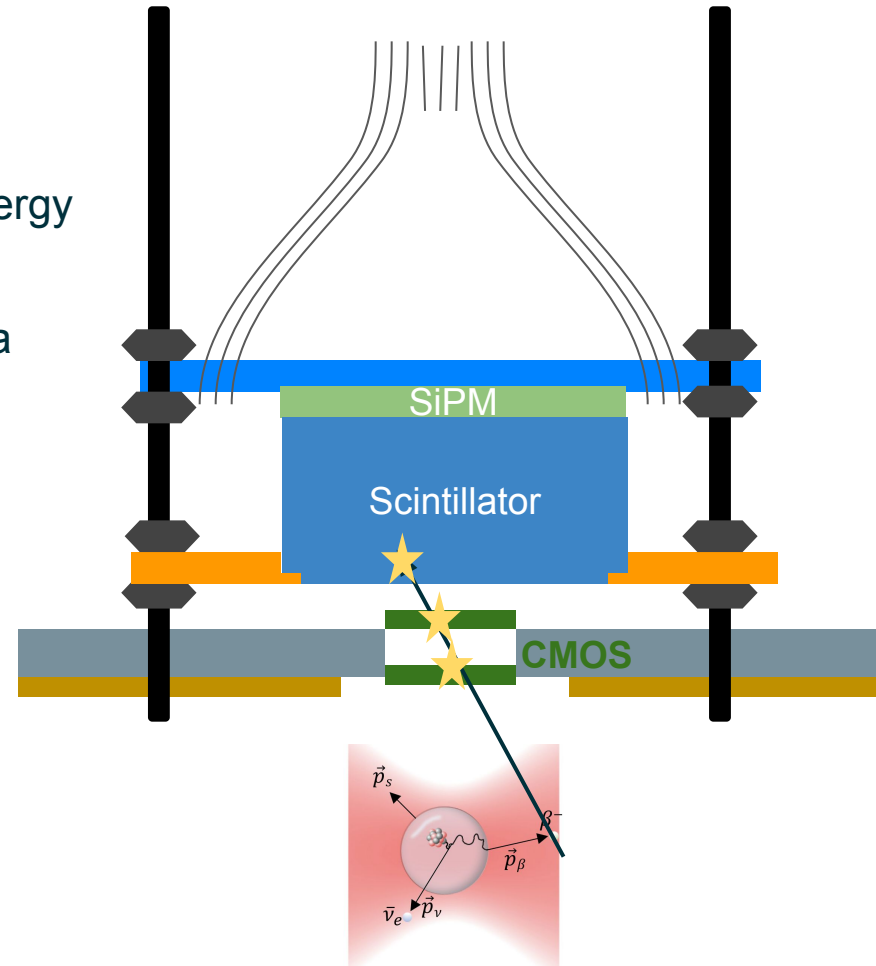
Use ^{90}Y betas ($Q=2.279$ MeV \rightarrow heavy sterile neutrino sensitivity), ground-state decay, short half-life, and easily doped in nanospheres *Adv Radiat Oncol. 2016 Aug 18;1(4):351-364*



QuIPS Detector Design

Need to reconstruct emitted β^- momentum i.e. energy and emitted direction

- CMOS sensor gives direction of emitted beta
- Scintillator allows for energy reconstruction



*Not to scale 7

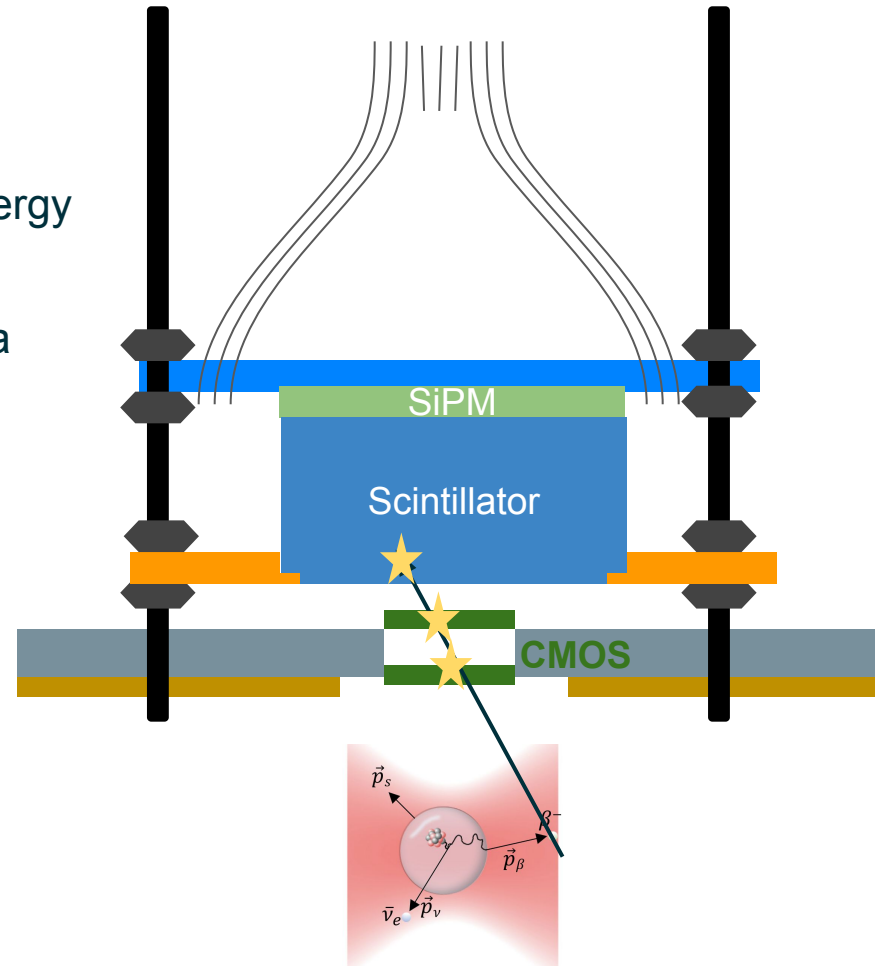
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Design considerations:

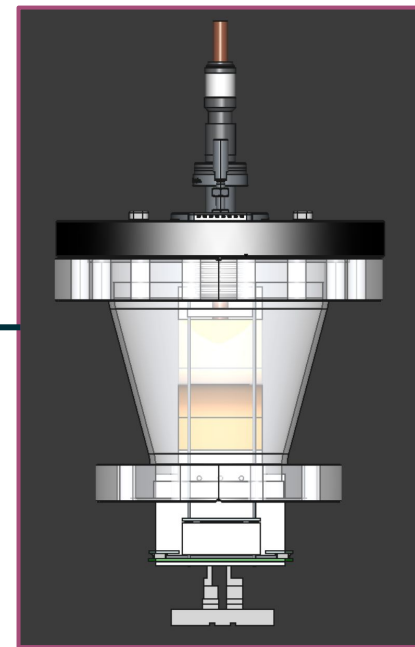
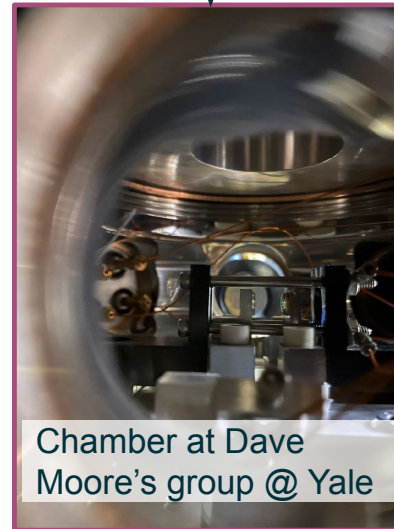
- Energy escaping scintillator via Bremsstrahlung or back-scatter
 - Use low-Z scintillator
- Mis-reconstruction of momentum due to scattering off lenses/surfaces
 - Use back-to-back CMOS to vertex trajectory
- Energy loss in material
 - Ultra thin CMOS sensors; small dead volumes



*Not to scale 8

Deployment and Implementation

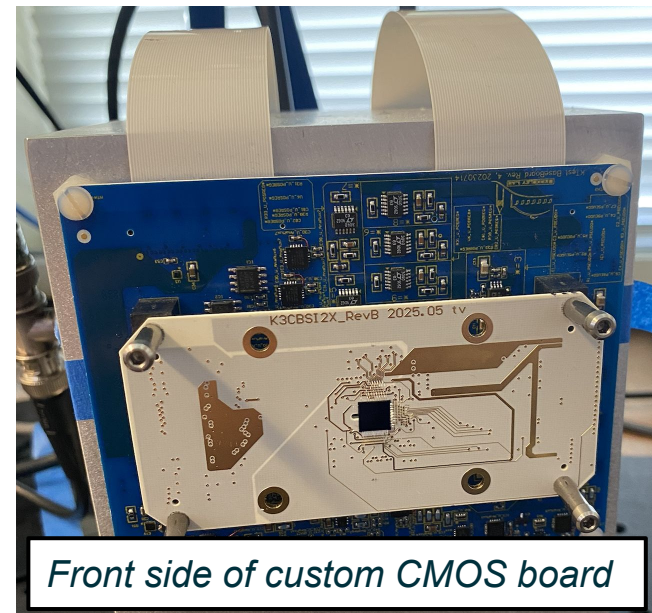
- Needs to fit in existing optical trap vacuum chamber
- Needs to be UHV compatible ($<10^{-8}$ mbar)
- Need passive (and possibly active) cooling for CMOS sensors and SiPMs operating in vacuum chamber
- Al-sputtering on CMOS sensor to reflect low-power scattered laser light



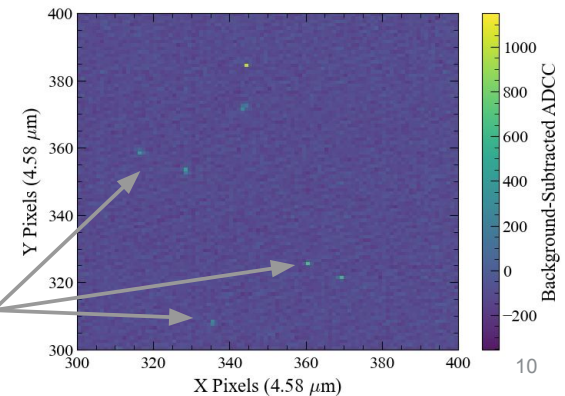
*CAD of QuIPS
Detector located above
optical trap*

R&D at LBL: CMOS Development

- Developed custom read-out boards to handle two TowerJazz K3C CMOS on single board and readout
 - 4.58 micron pitch; 896 x 896 pixels
 - 250 Hz frame rate (can be increased)
- Developed thinning process for backside illumination in house at LBL
 - 20 micron thick (10 micron active)
- Develop Al-sputtered process on thinned CMOS to reflect scattered laser light in optical trap



Front side of custom CMOS board



Betas passing through single CMOS pixels

R&D at LBL: Calibrating CMOS Vertexing

- First calibration taken with collimated ^{90}Y source to mock emission from 'point source'
- Demonstration of reconstruction of beta momentum vector using hit pixels from in CMOS sensors
 - Can reconstruct betas originating from trapped nanosphere to 1 mm precision

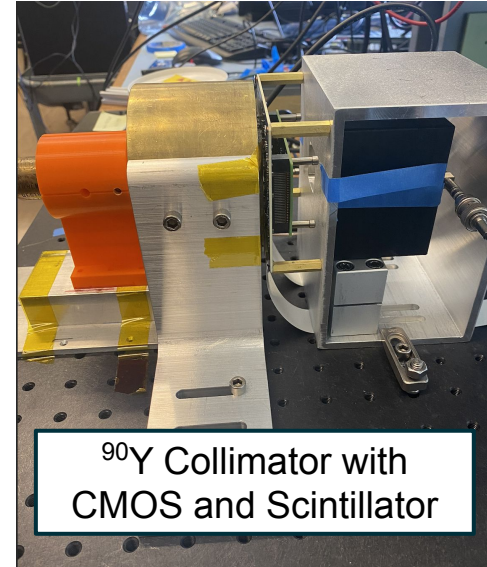
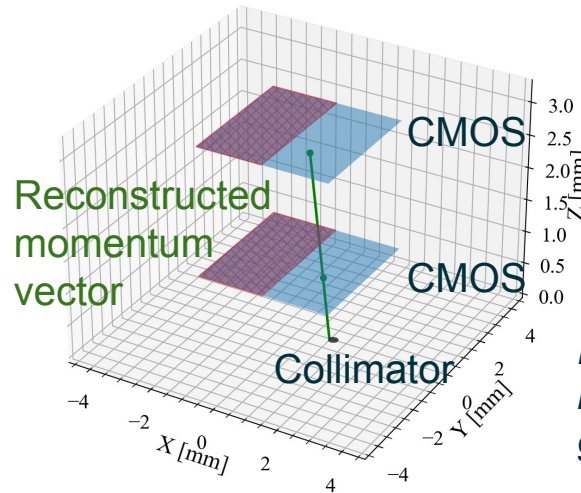
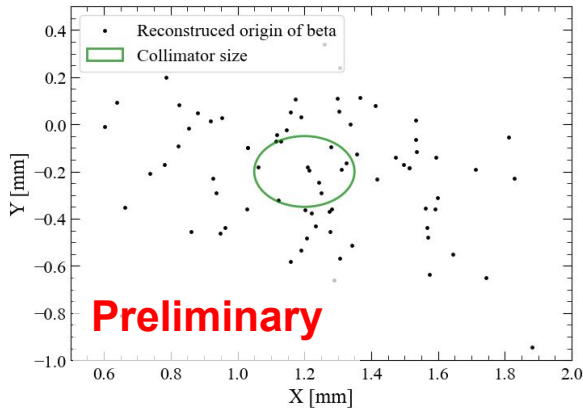


Diagram of vertexing to location of collimator given hits in CMOS

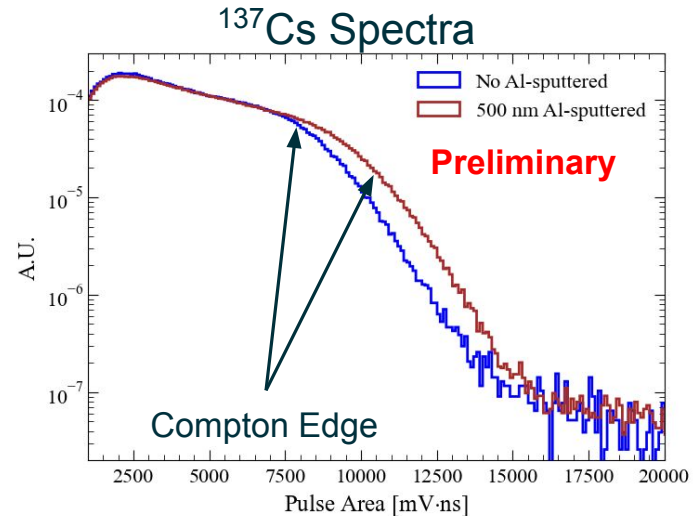
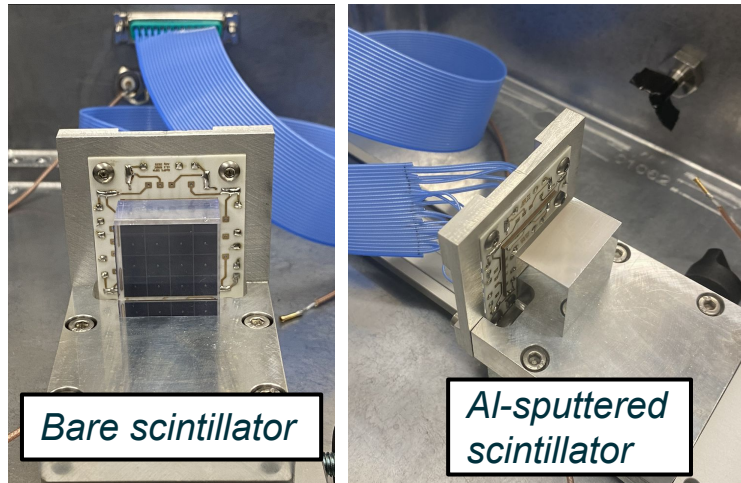
R&D at LBL: SiPM and Scintillator Testing

- Charactering Hamamatsu S14161-6050-HS and EJ200 plastic scintillators
 - SiPMs have near 50% detection efficiency
 - peak emission at 425 nm
 - Single photon sensitivity!
- Want to detect ^{90}Y betas with energies from 10s of keV to 2.279 MeV endpoint
- Need to be vacuum compatible with compact form factor
 - Al-sputtering on plastic scintillators



R&D at LBL: First tests of sputtering Aluminum

- Sputter thin film of Aluminum on plastic scintillator to increase light collection
 - Avoid softening plastic polymer during process which can impact photon attenuation
 - Preliminary results indicate 500 nm Al increase light collection by 15-20%*
- Ultimately want test up to 1 micron thick Al to maximize reflectivity at surfaces



Al-sputtering on surface increases light collection



Conclusions

- Building UHV compatible CMOS sensor and scintillator detector
- Deploying QuIPS detector in Yale optical tweezer later this year!
- Optomechanical experiment being constructed at LBL starting next year!
 - Aim for impulse sensing with large array

Shout out to QuIPS Team!

@ **LBL**: Giacomo Marocco, Maurice Garcia-Sciveres, **DK**, Tim Villabona, Rebecca Carney, Dan Carney
Kaelani Adcock, Peter Sorensen, Ben Knepper, Miao Hu, Azriel Goldschmidt

@ **Yale**: David Moore, Thomas Penny, Yu-Han Tseng



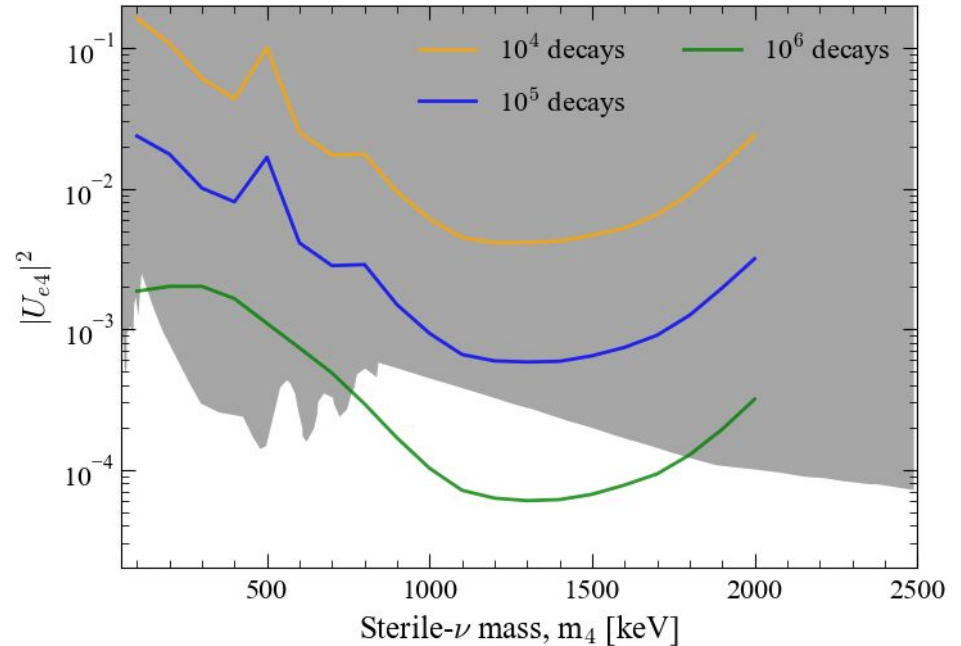
Chamberlain Fellowship Opening at LBL



BACKUP

QuIPS Projected Sensitivity using ^{90}Y β^- Decays

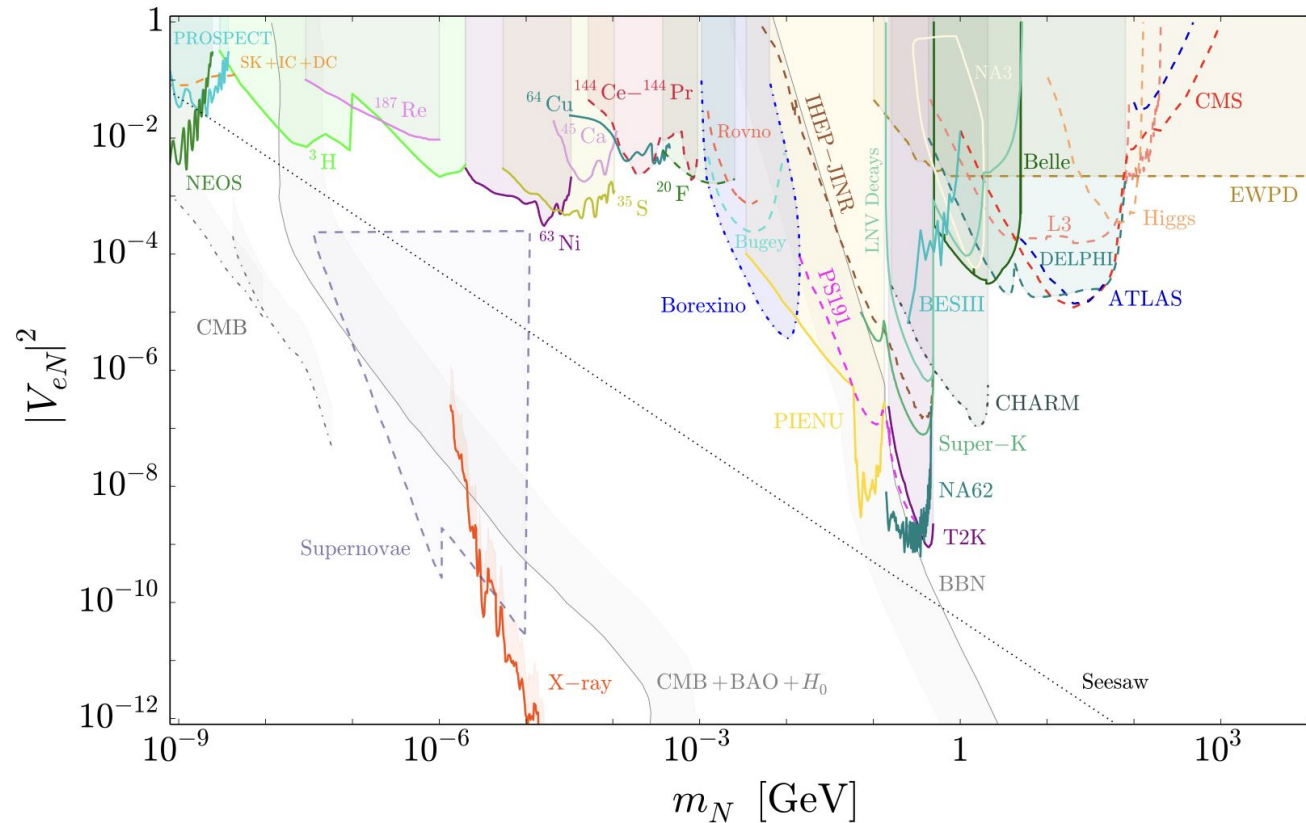
- 2D Feldman-Cousins analysis in reconstructed $\{p_\nu, E_\beta\}$ space
- At 1% loading by mass, a single sphere can hold $>10^5$ particles and will decay in O(days)
- **Need just O(~week) of data to achieve world-leading limits!**
 - Will need to reload spheres



Existing laboratory constraints in gray
JHEP 03 (2020) 170

Field of Sterile Neutrino Constraints

JHEP 03 (2020) 170
 Phys.Rept. 928 (2021) 1-63

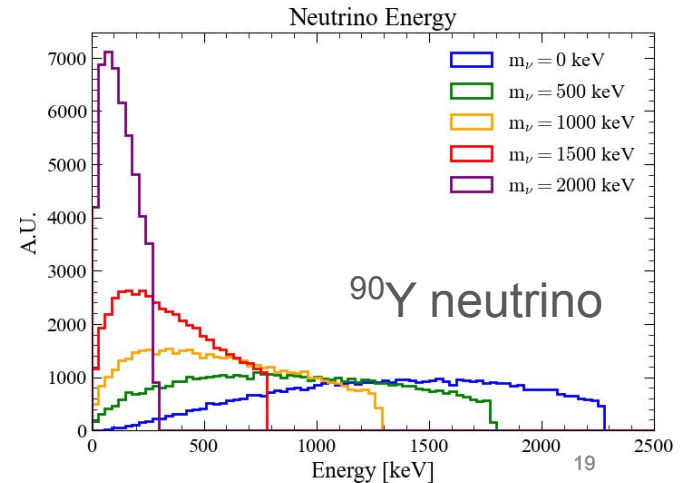
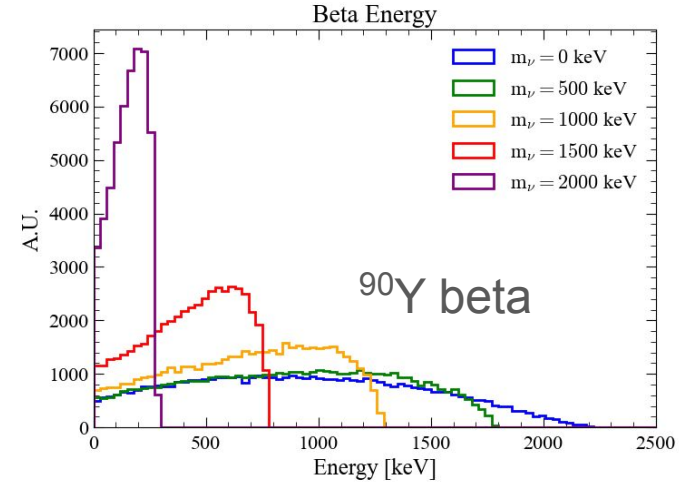


Sterile Neutrino Beta Spectra

- Neutrino mass included in kinematics i.e. energy/momentum conserved
- Neutrino mass included within phase-space factor and unique first forbidden shape factor
- No angular correlation assumed between beta and neutrino (i.e. isotropic)

Phase-space factor for allowed beta decays

$$p \cdot E \cdot \sqrt{(Q - T)^2 - m_\nu^2} \cdot (Q - T)$$



Impulse Momentum Distribution

- Simulated ^{90}Y beta decays uniformly distributed in 100 nm sphere
- High energy beta decays \rightarrow well above SQL threshold
- Impulse sensitivity at SQL becomes more important for low-Q beta decays e.g. ^3H and ^{63}Ni

