Searching for Sterile Neutrinos with Mechanical Quantum Sensors and CMOS Sensors

The QuIPS Experiment

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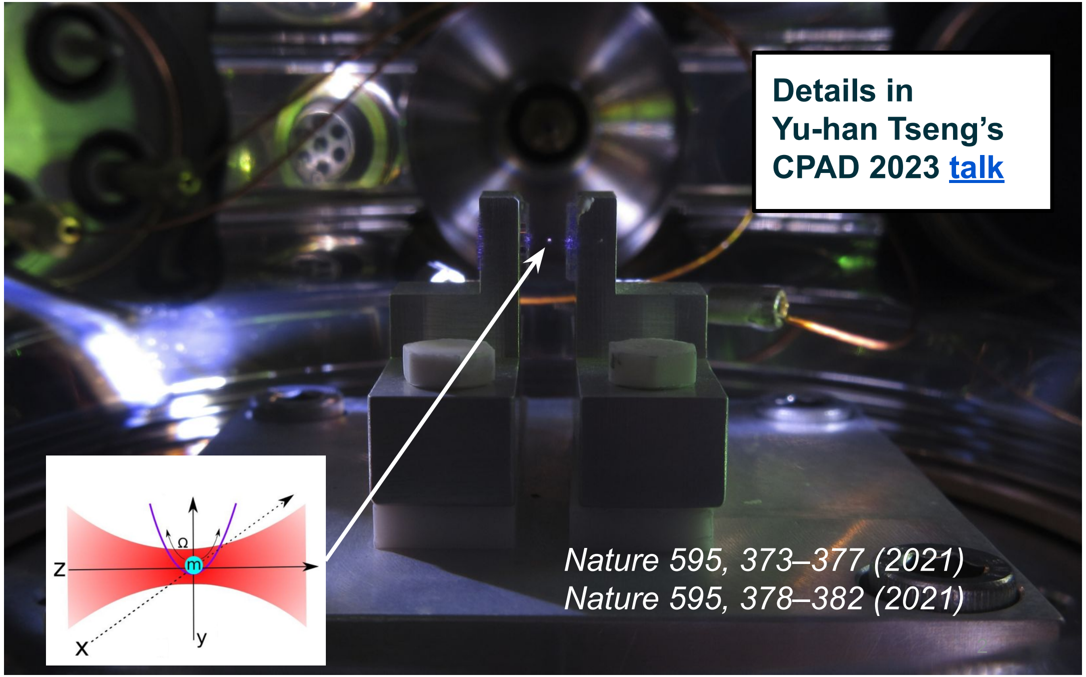
Optomechanical Traps

- Dielectric particles (100 nm - 30 μm) can be optically trapped in UHV ($\lesssim 10^{-8}$ mbar)
  - Radiation pressure from highly focused laser (e.g. high numerical aperture lens) can be used to trap and cool C.O.M. motion of a silica nanosphere

- Forward/Backward scattered light → sphere position
- Sense momentum transfers "kicks" near the standard quantum limit (SQL)

$$\Delta p_{\mathrm{SQL}} = \sqrt{\hbar m_s w_s}$$

~15 keV/c for 1 fg (~100 nm) sphere trapped at 100 kHz



Details in Yu-han Tseng's CPAD 2023 talk

Nature 595, 373–377 (2021)
Nature 595, 378–382 (2021)

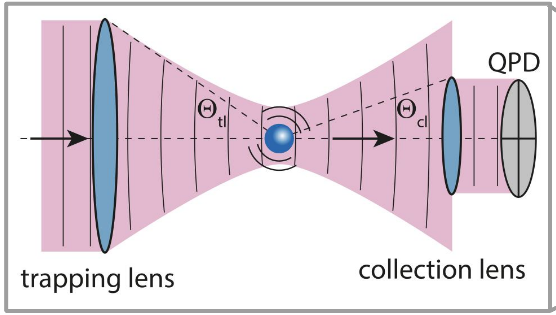
Quantum Invisible Particle Sensor (QuIPS)

Embed β-emitting radioisotopes in an optically trapped silica nanosphere surrounded by particle sensors

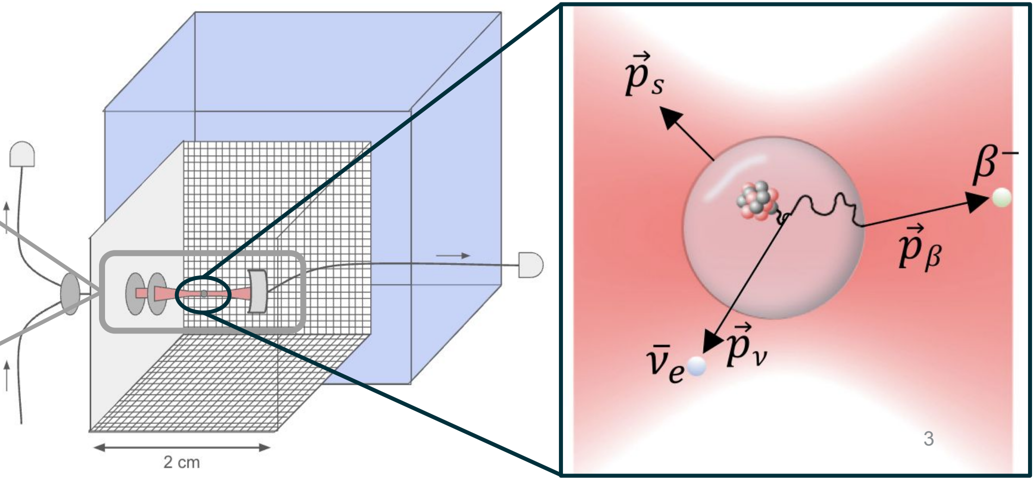
- Outgoing beta measured by particle detector to reconstruct its momentum
- Optomechanical measurement of impulse to sphere e.g. ion momentum
- **⇒ Inferred measurement of neutrino momentum!**

Reconstruct all momenta in decay!

*PRA **100**, 043821 (2019)*



PRX Quantum 4, 010315 (2023)



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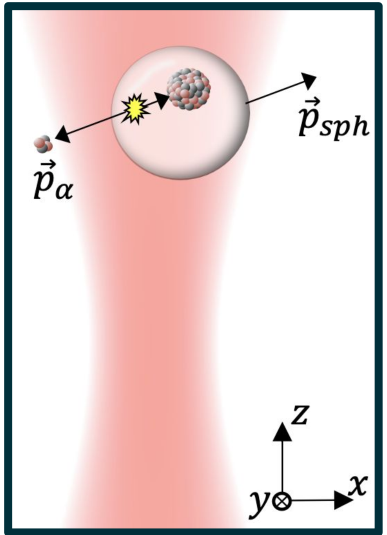
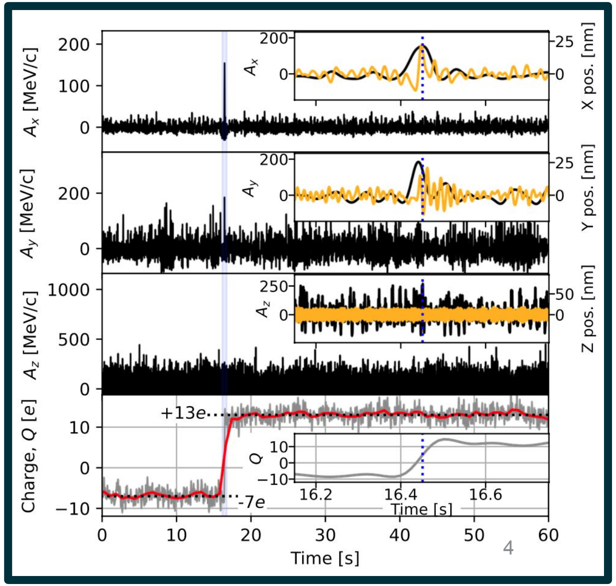
Proof of principle performed at Yale with ^{220}Rn alpha decays!

Phys. Rev. Lett. ***133****, 023602 (2024)*





Quantum Invisible Particle Sensor (QuIPS)

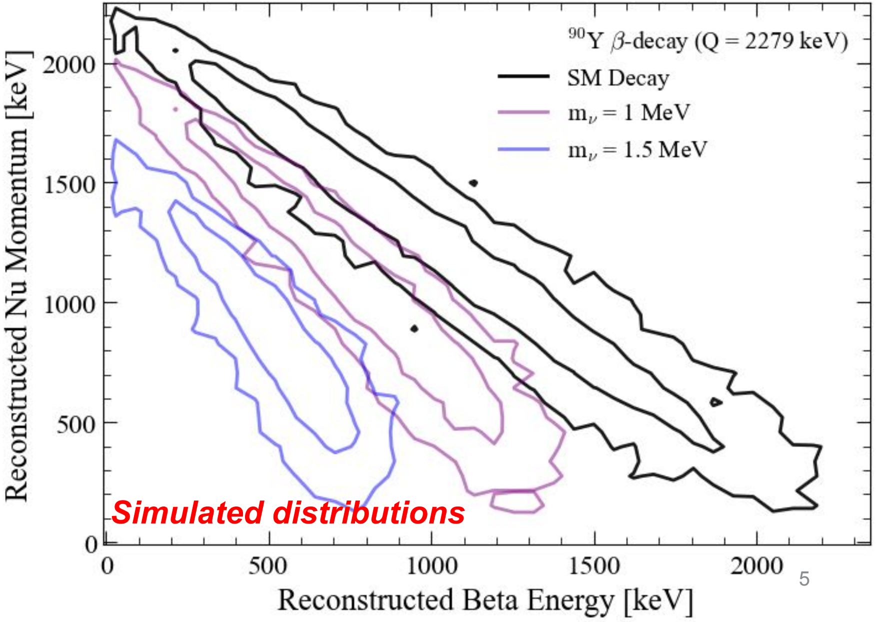
Inferred measurement of neutrino momentum enables search for heavy sterile neutrinos emitted in beta decays!

- Oscillation of $\nu_e \rightarrow \nu_4$ inferred by ‘missing’ momentum carried by neutrino

$$|\mathbf{p}_4| - |\mathbf{p}_i| = \sqrt{(Q - T_e)^2 - m_4^2} - (Q - T_e)$$

Heavy sterile decays well separated from SM decays…

⇒ Background free search



Simulated distributions

Quantum Invisible Particle Sensor (QuIPS)

Ideal isotopes have high Q-value, high branching to ground-state, and ~day-month half-life

Probe heavy sterile neutrinos

No decays to excited state which form bkgs

Reasonable event rate

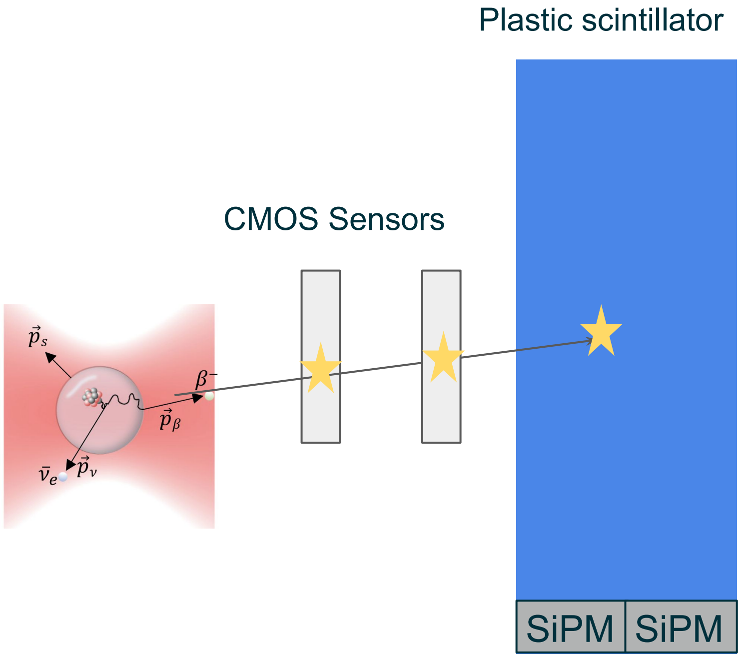
Isotope	Decay Type	Q [kev]	Half-life [days]	Ground-state BR	Has been done?
^{90}Y	β^-	2279	2.7	99.98 %	yes
^{32}S	β^-	1711	14.3	100 %	yes

Focus on ^{90}Y which has highest Q-value and has been doped in nanospheres in medical community for radiotherapy!

QuIPS Design Studies @ LBL

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

QuIPS Design Studies @ LBL

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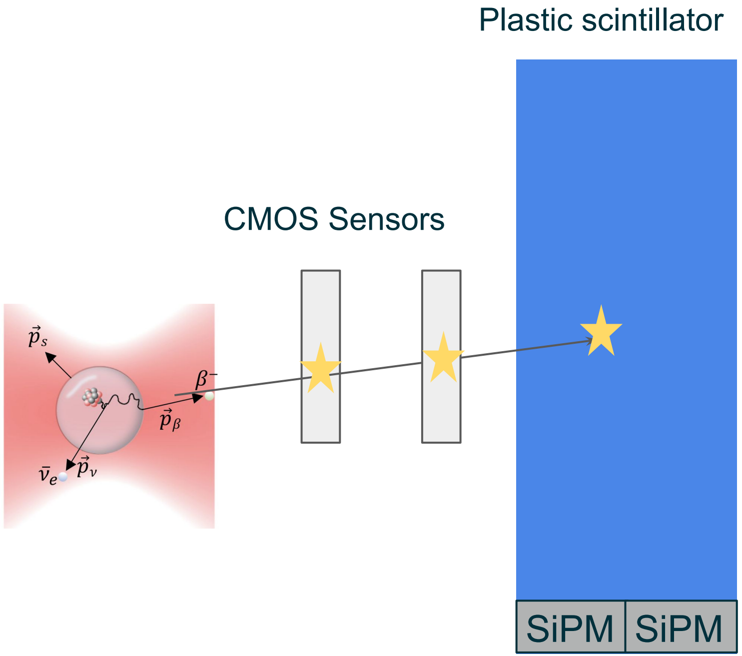
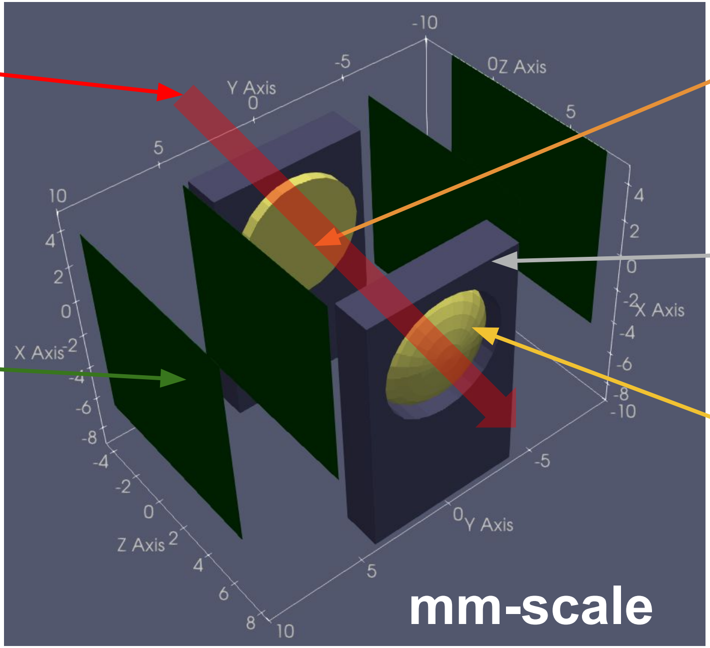
Sources of Background:

- 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
  - Minimize dead volumes



*Not to scale

Optimal Geometry And Sensitivity From Geant4 Sims



Trapping laser

1000x1000 pixel,
10 µm pitch CMOS

- 15 µm thick
- 5 mm separation
- Two sets on each side of trap

100 nm sphere,
~ 1.6 mm from trapping lens

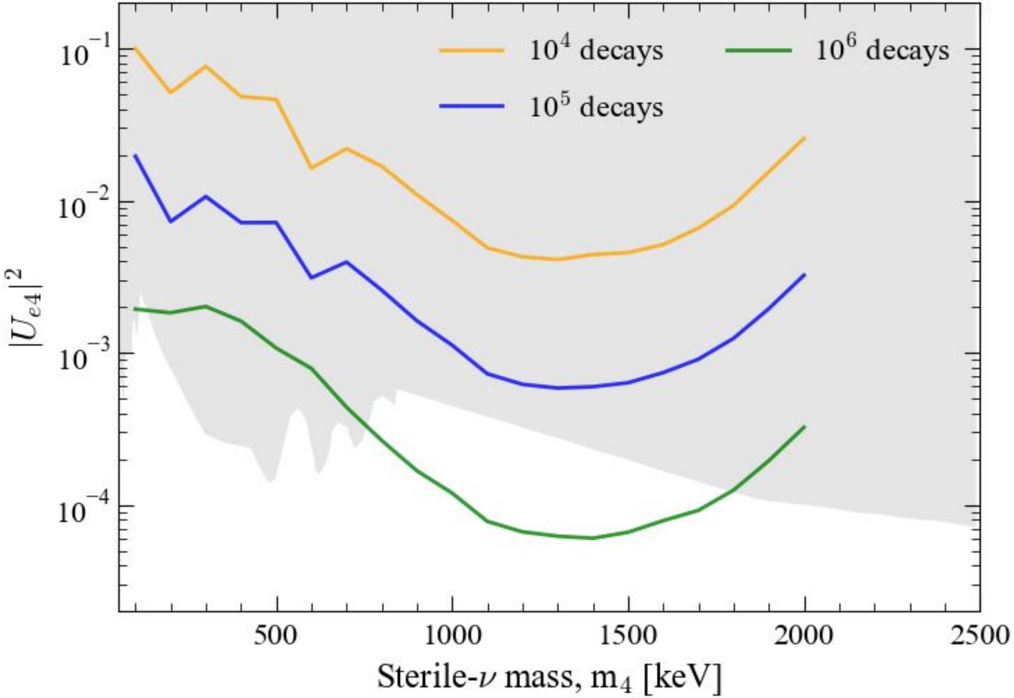
Aluminum lens holders

Lens for trapping and collecting scattered light **(same dimensions as setup at Yale setup)**

(Not shown) 6 x 6 x 3 cm plastic scintillators behind CMOS sensors

QuIPS Projected Sensitivity
^{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

R&D @ LBL

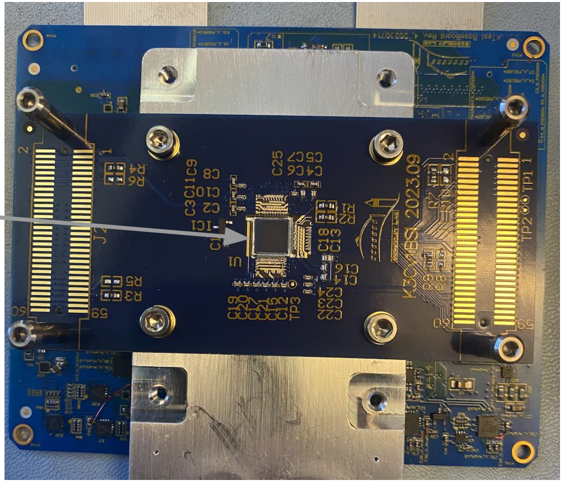
- Characterization + Development of Scintillator+SiPM packages
- Developing read-out boards to handle two TowerJazz CMOS on single board
- Develop full process for Team1K CMOS sensors (1000 x 1000 pixel, 10 μm pitch)
  - Thinning process for backside illumination (done at LBL!)
  - Custom readout to multiplex two Team1K CMOS sensors

TowerJazz CMOS

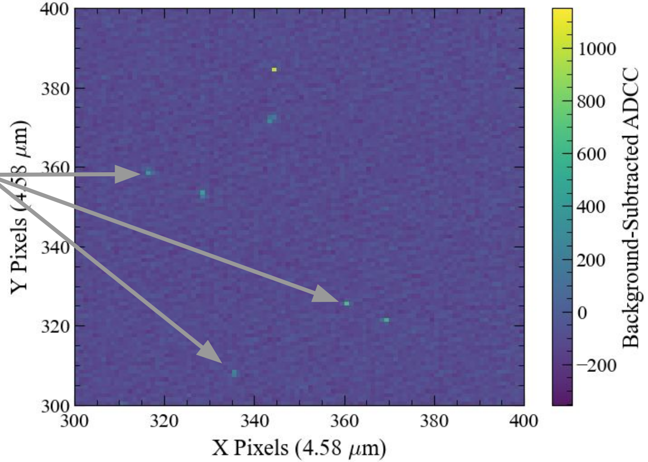
896 x 896 pixel

4.58 μm pitch

20 μm thick



Betas passing through single CMOS pixels



Beyond the Standard Quantum Limit

- The ~ 15 keV/c momentum threshold can be surpassed by going beyond SQL
  - Active area of theoretical and experimental research!
  - Squeeze laser light or quantum mechanical state of trapped sphere

What can we get by going beyond the SQL?

1. Search for keV-scale sterile neutrinos (^{3}H beta decays, Q=18.6 keV) that are popular dark matter candidates
   a. Requires $\Delta p \sim< 1$ keV
2. Probe neutrino mass scale by measuring many, O(10^6) decays, near endpoint of low-Q beta spectra
   a. Requires $\Delta p \sim m_i \sim 100$ eV

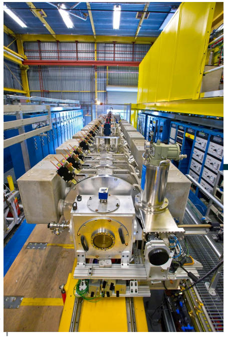
Blue Sky Ideas

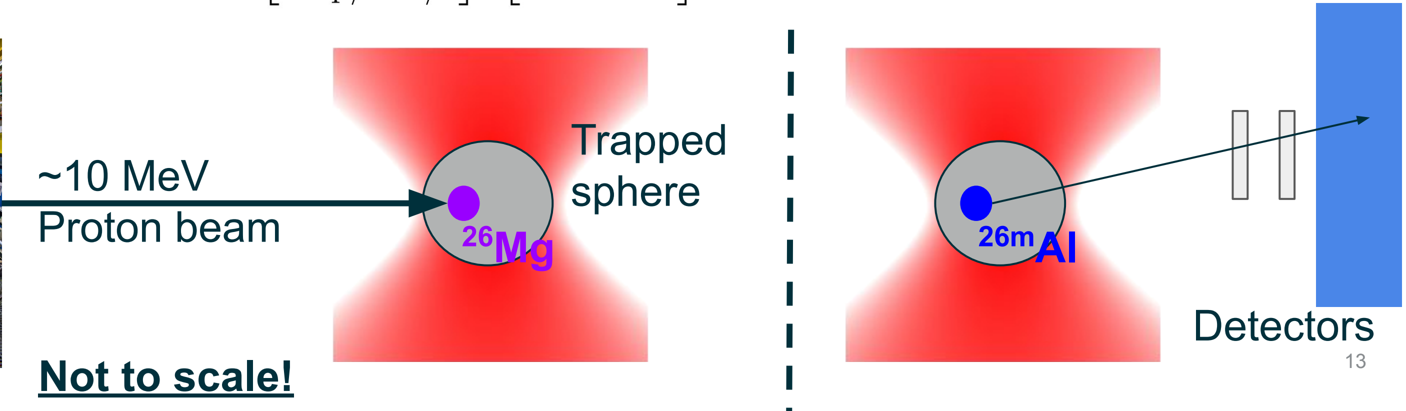
- Trapped spheres offer unique targets for production short-lived radioisotopes
  - pulse proton beam for minute, wait to observe decays, repeat

1. Can probe superallowed decays to probe V_{ud} and CKM unitarity
2. Search for axions in isomeric decays
3. Probe higher Q-value decays to search for heavy sterile neutrinos

$$R \sim \left[\frac{\sigma}{1\text{mb}}\right] \cdot \left[\frac{\phi}{10^9 \text{p/cm}^2\text{/s}}\right] \cdot \left[\frac{N}{10^{16}\text{atoms}}\right] \sim 0.01\text{atom/s}$$

88” cyclotron at LBL





~10 MeV Proton beam

Trapped sphere

Detectors

Not to scale!

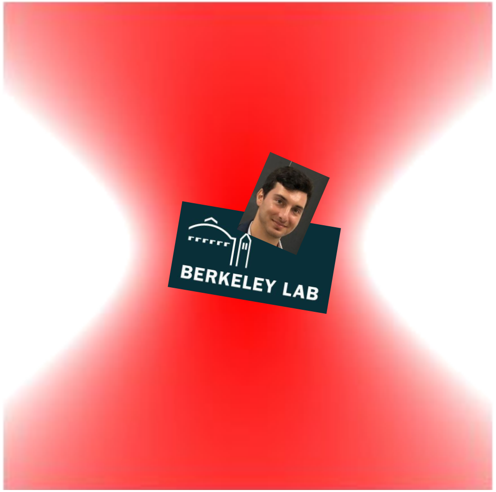
Conclusions

- Developing and prototyping CMOS sensors and plastic scintillators to reconstruct ^{90}Y beta momenta
- Stay tuned for paper on design and projected sensitivity next year!

Shout out to QuIPS Team!

@ LBL: Dan Carney, Rebecca Carney, Tsai-Chen Lee, Peter Denes, Maurice Garcia-Sciveres, Azriel Goldschmidt, Miao Hu, Ben Knepper, **DK**, Giacomo Marocco, Emil Rofors, Peter Sorensen, Tim Villabona

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

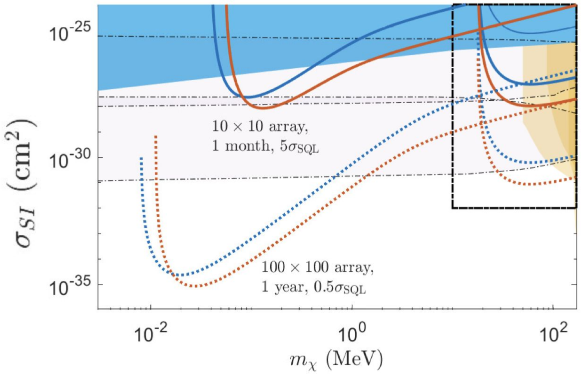


Backup

Physics With Optomechanical Traps

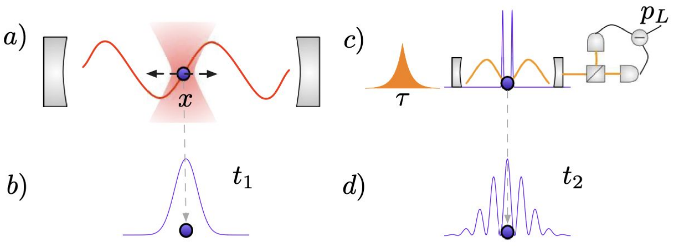
- A range of fundamental and BSM physics can be done with optomechanical traps

Dark Matter



Phys.Rev.Lett. 128 (2022) 10, 101301

Gravity and Quantum Mechanics

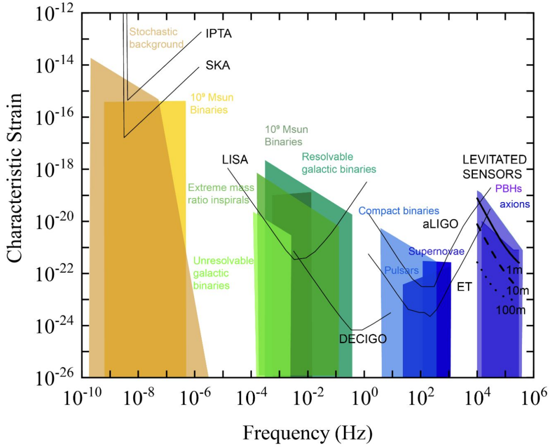


Phys. Rev. Lett. ***107****, (2011) 020405*

Class.Quant.Grav. 34 (2017) 19, 193002

Rev. Mod. Phys. ***85****, (2013) 471*

High Frequency GW



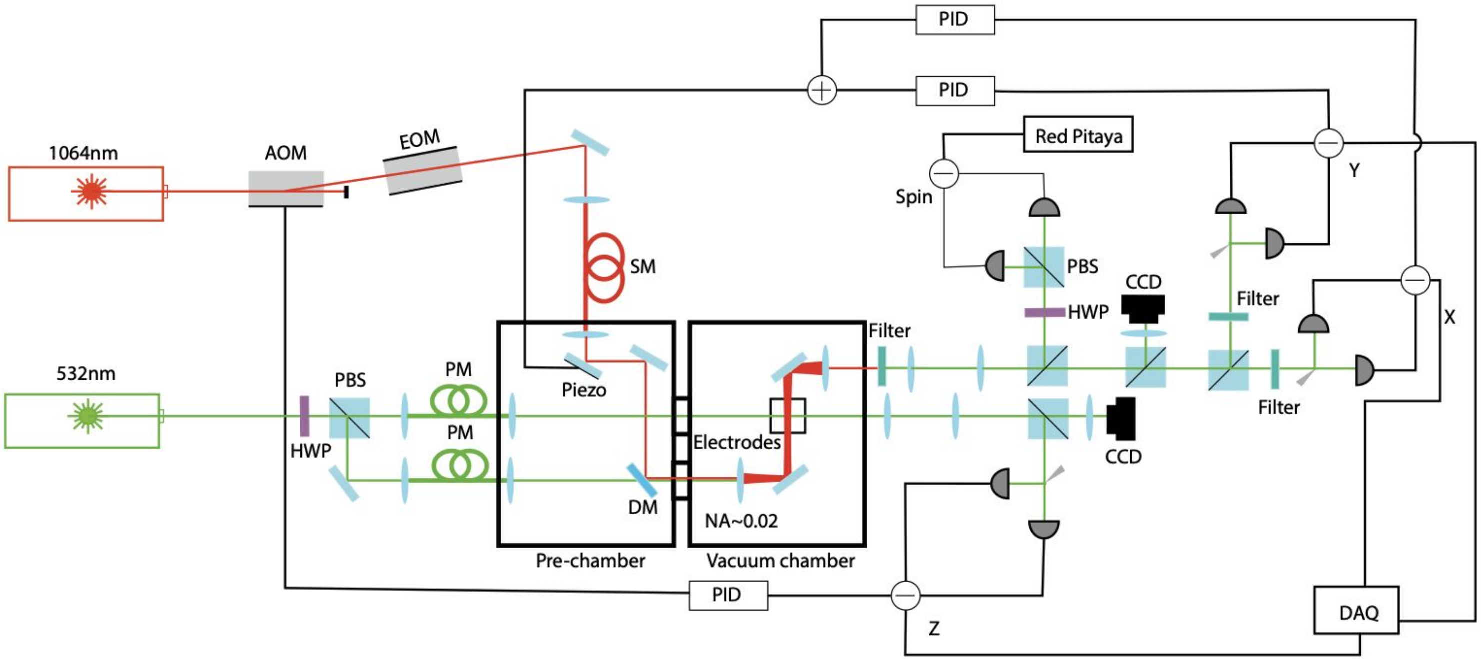
Phys. Rev. Lett. 110, (2013) 071105

Tests of Newton's Law *Phys.Rev.Lett.* 105 (2010) 101101

Tests of Coulomb's Law and Matter Neutrality *Phys. Rev. A 101(5) 053835*

Example Optical Trap

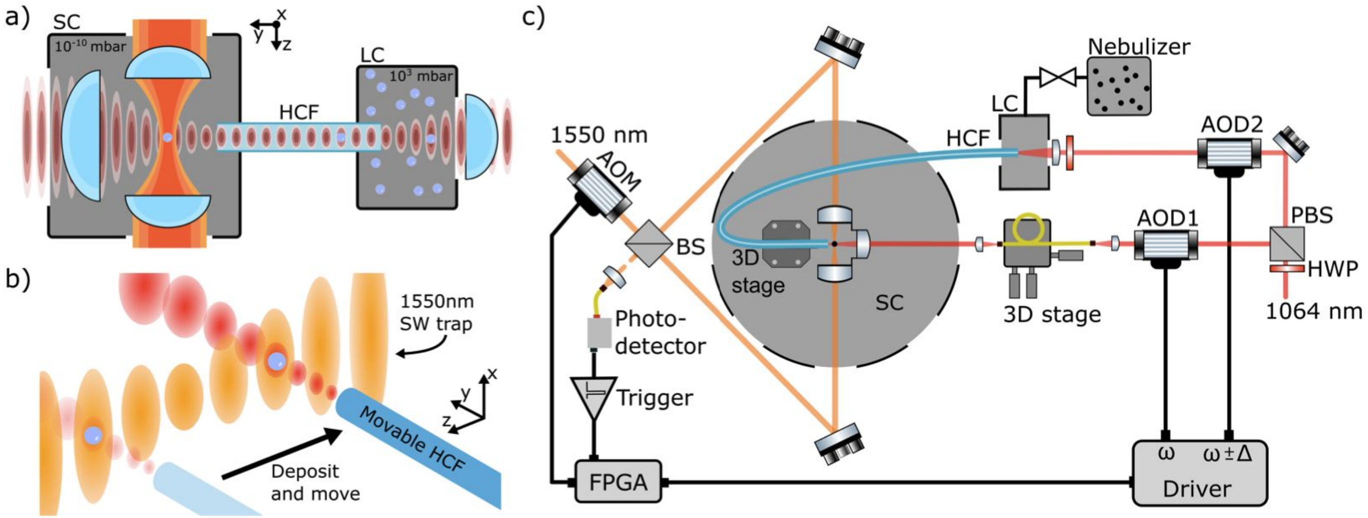
Phys.Rev.Lett. 133 (2024) 2, 023602



Optical Trap Loading

Option 1 is to “puff” in spheres until one is trapped
Option 2 precise placement using hollow-core fiber loading *Appl.Phys.Lett.* 124 (2024) 14, 143501

https://phaidra.univie.ac.at/detail/o:2001749

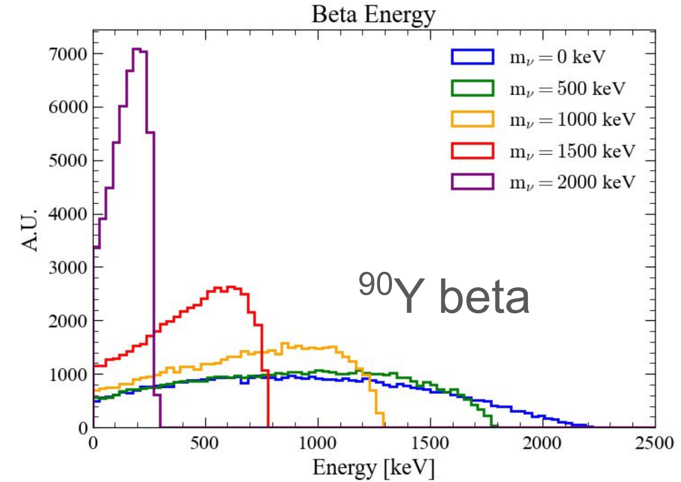


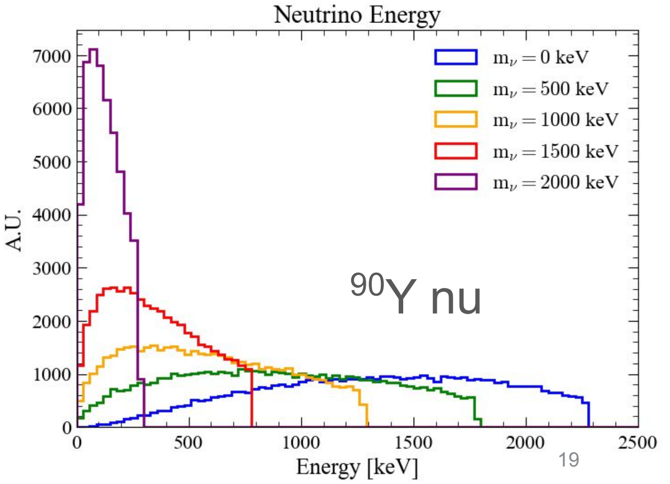
Sterile Neutrino Beta Spectra

- Use custom *G4BetaMinusDecay* and *G4AntiNeutrinoE* to set non-zero neutrino mass
  - 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

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





Field of Sterile Neutrino Constraints

Phys.Rept. 928 (2021) 1-63