Nuclear quantum optics: the QuIPS experiment

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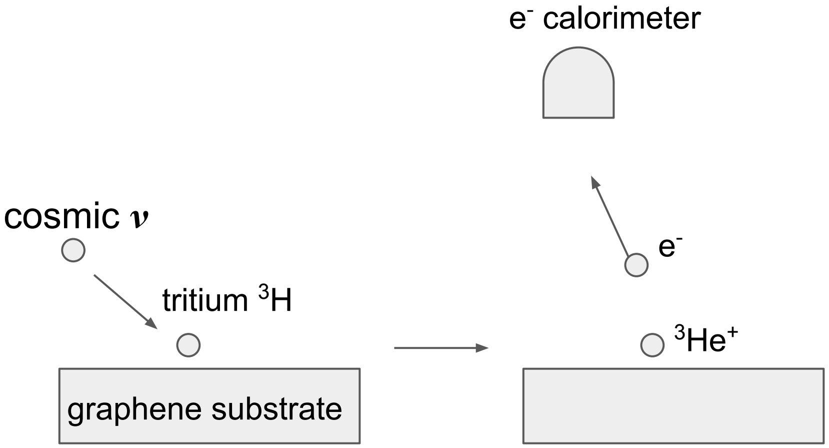
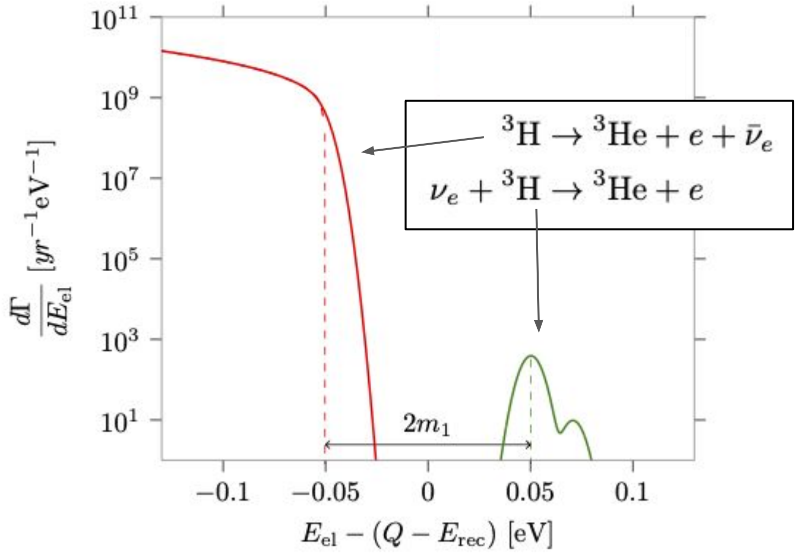
Life update

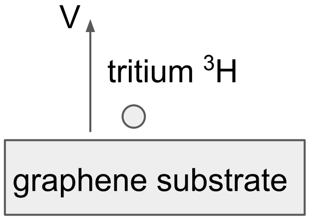
Quantum mechanics vs. cosmic neutrinos

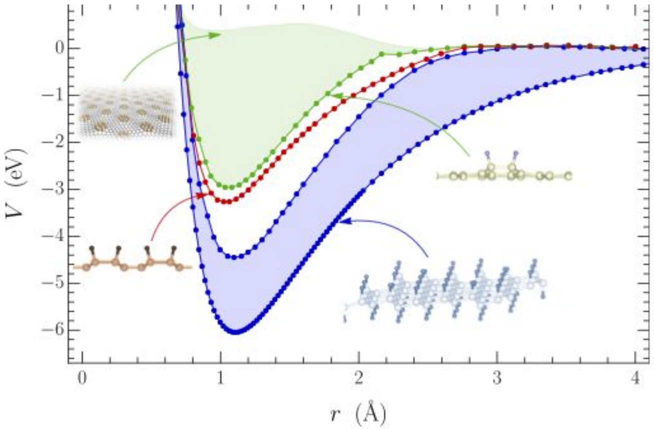




Weinberg 1962
Cheipesh, Cheianov, Boyarsky 2021

Quantum mechanics vs. cosmic neutrinos





Tritium is bound in a potential generated by the graphene. Ground state wavefunction:

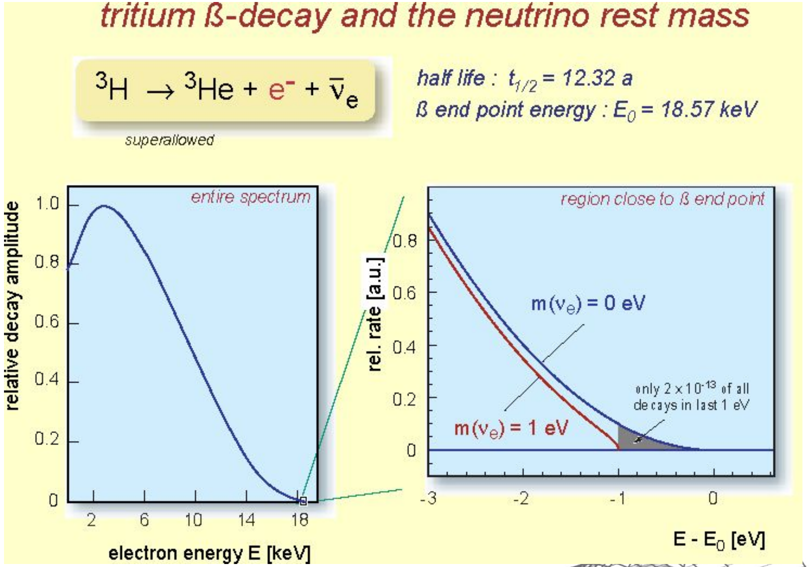
$\Delta x \sim 1$ angstrom $\rightarrow \Delta p > 1$ keV

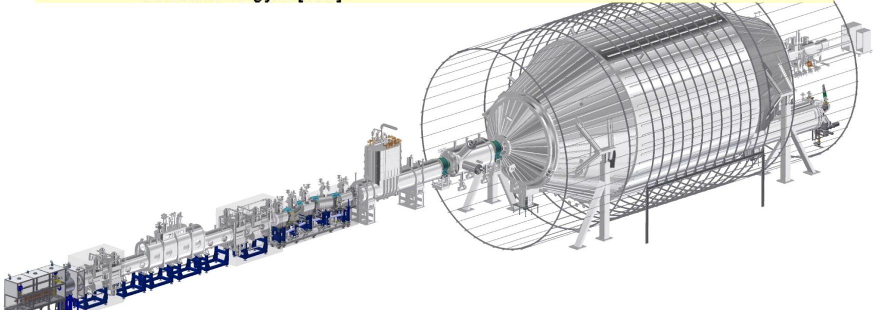
by **Heisenberg uncertainty**. But this produces a final-state uncertainty $\Delta E_e > 1$ eV.

→ **no way to resolve the ~100 meV shift from neutrino mass.**

PTOLEMY Collaboration 2022

How about a neutrino mass measurement?





Even for a more “humble” measurement—the neutrino mass—same basic issue

Typical experiment (PTOLEMY, KATRIN, Project 8, …) goal is to detect ~100 meV shift in the beta spectrum endpoint

Recap and what's next

Quantum effects limiting detection of small neutrino effects in radioactive decays:

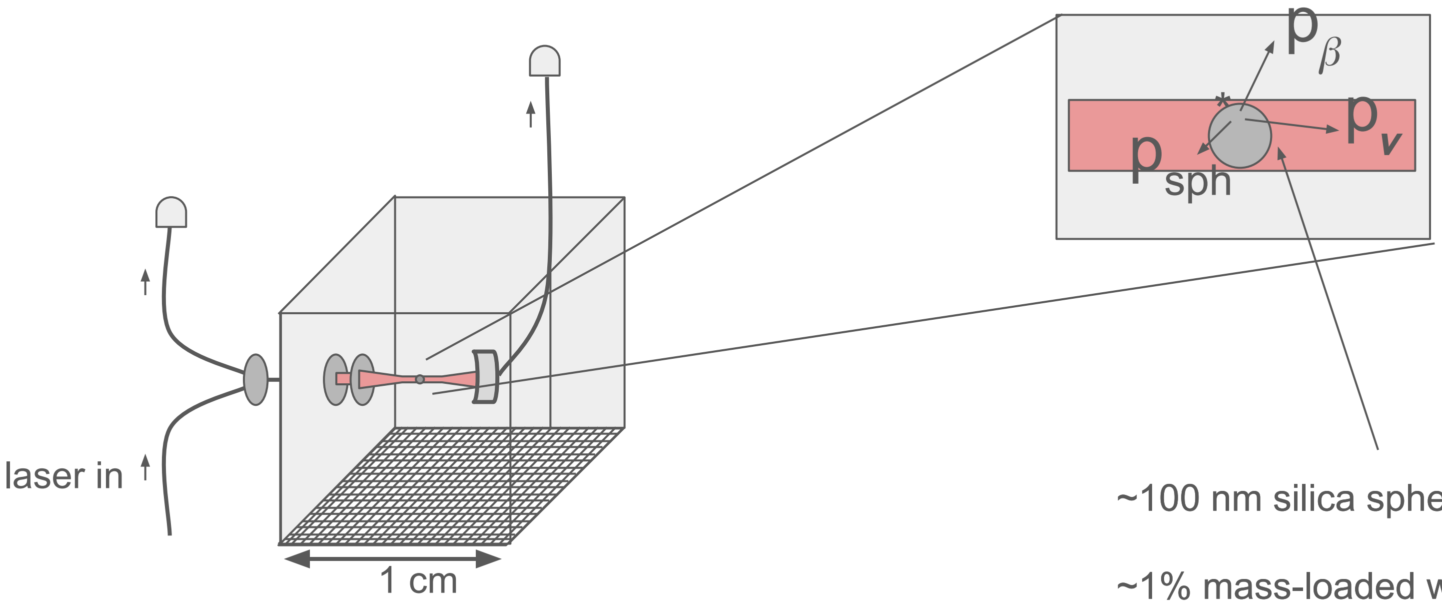
- Uncertainty in initial state
- Readout of final states

Motivates developing new techniques to address both of these issues. I'm going to now discuss such a technique.

To be clear, however, I am going to completely move the goalposts so that I can win. Instead of trying to detect effects at the scale of the neutrino mass, we're going to go for a much more modest goal of looking for heavy sterile neutrinos.

Then at the end I'll return with some more ambitious speculations…

Quantum Invisible Particle Sensor (QuIPS)



~100 nm silica sphere

~1% mass-loaded with radioisotope of choice

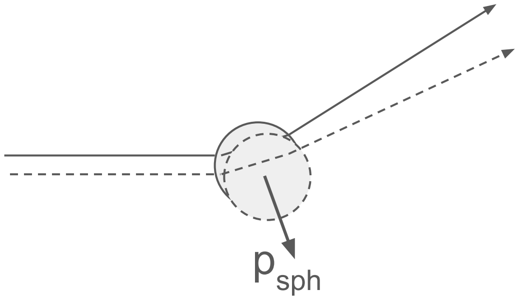
Measure:

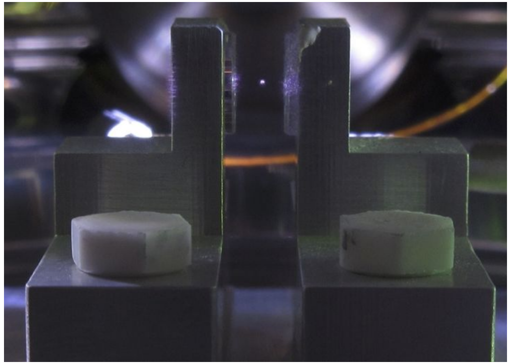
- Sphere recoil w/ optics
- Escaped β electron w/ calorimeter
- Electric charge on sphere (rf pulse)

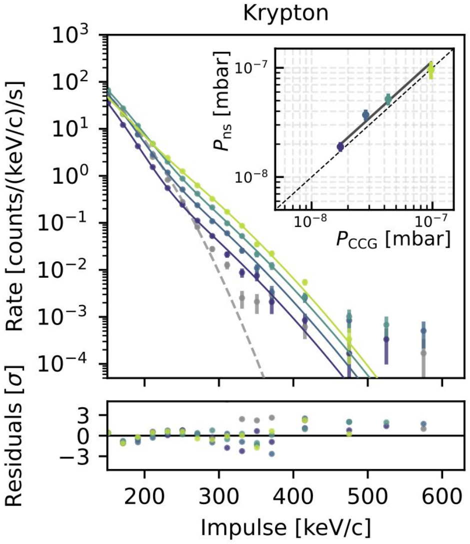
→ Infer “invisible” (e.g., neutrino) momentum vector

Carney, Leach, Moore PRX Quantum 2023

Quantum optical recoil detection







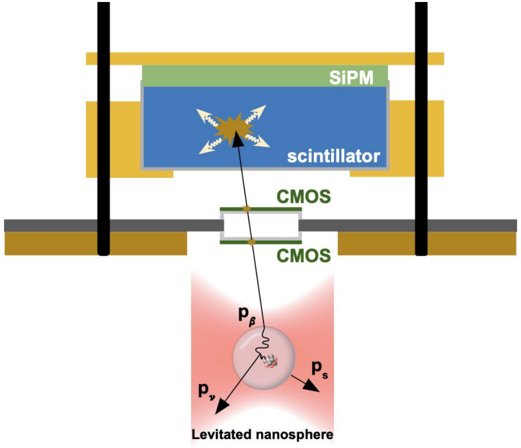
Detection principle: trap light scattered by nanobead → infer impulse

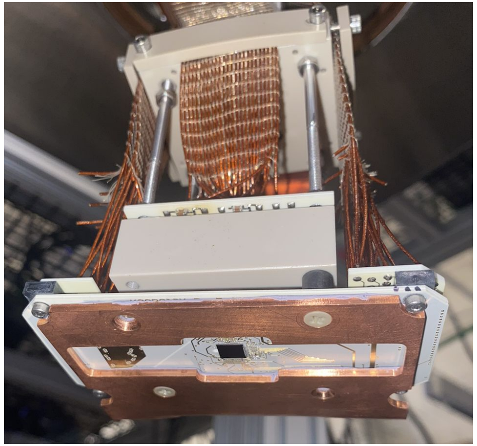
$$\Delta p_{\mathrm{SQL}} = \sqrt{\hbar m_s \omega_s} = 15\,\mathrm{keV} \times \left(\frac{m_s}{1\ \mathrm{fg}}\right)^{1/2} \left(\frac{\omega_s/2\pi}{100\ \mathrm{kHz}}\right)^{1/2}$$

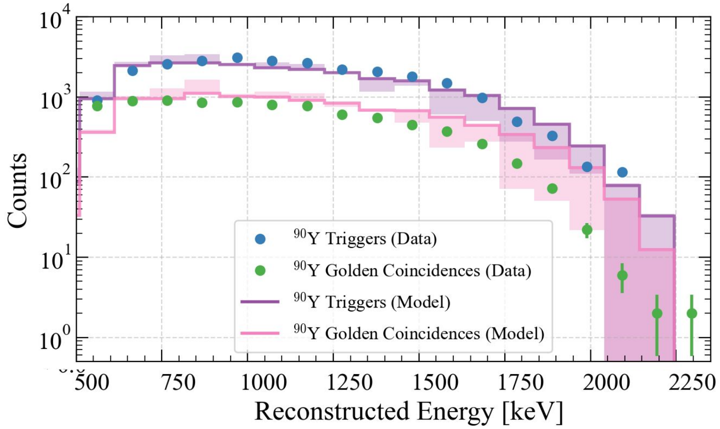
“Standard quantum limit” = noise dominated by Heisenberg uncertainty of light

Picture from Dave Moore’s lab at Yale
Gas measurement: Tseng, Hardy, Penny, Lowe, Baeza-Rubio, Carney, Moore 2604.18371

Beta electron detection







Detection principle: ~10 um x2 CMOS measures angle, scintillator measures energy

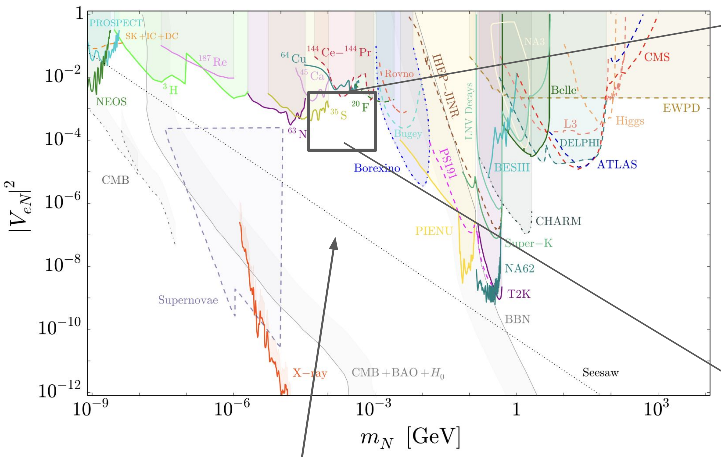
Design driven by need to reject backgrounds, especially spurious scattered betas

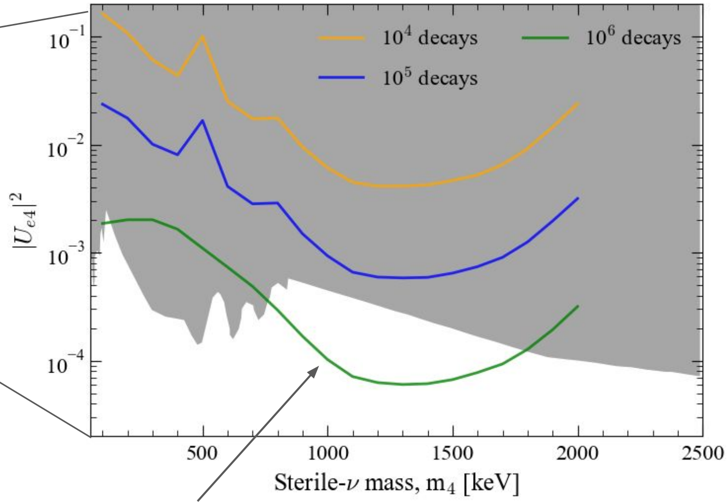
hep/inst-det paper to appear arXiv next week 😎

Our immediate goal: search for new heavy neutrinos

One simple way to explain light neutrino masses = new, relatively heavy 4th neutrino species

Measure ^{90}Y beta decays → search for rare events where electron neutrino converts to heavy neutrino



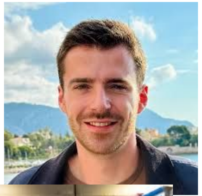
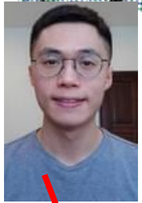
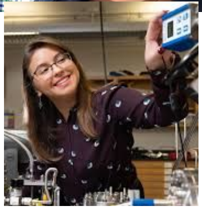


1 nanobead loaded with ^{90}Y, ~1 month experiment

Ultimate goal: seesaw. ~1000 nanobeads, ~1 year

Left: Dasgupta, Kopp 2106.05913
Right: GeANT4 sim by **Dan Kodroff**

QuIPS collaboration

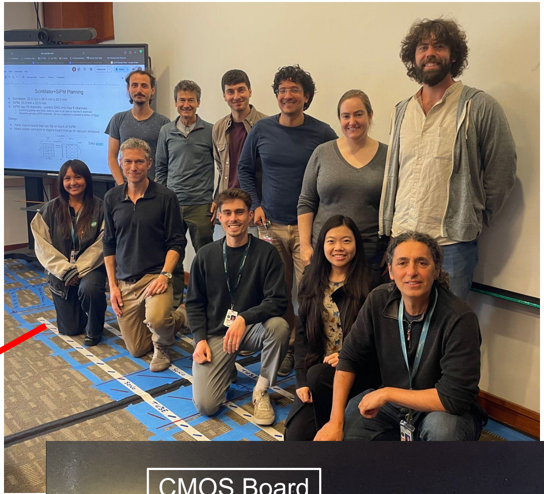





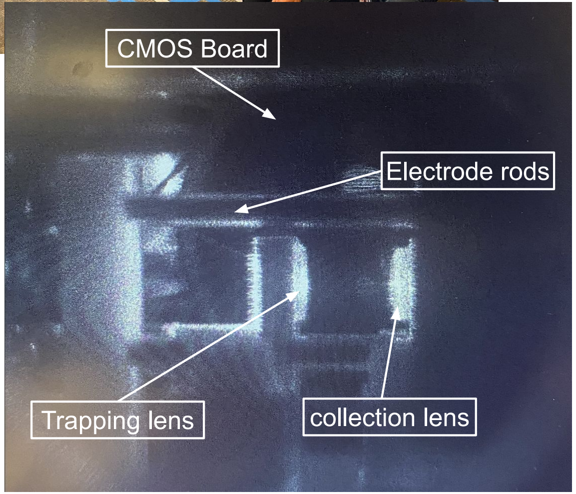
Yale



UC Berkeley

Berkeley Lab



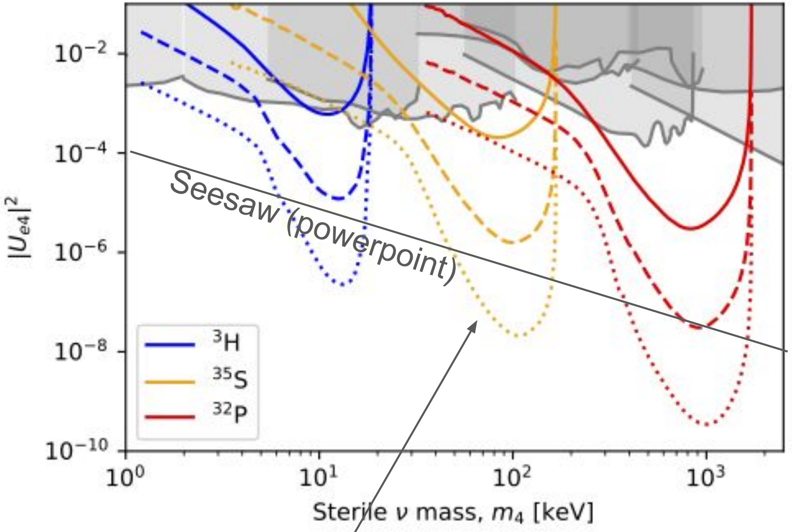


26-27: proof of concept measurements @ Yale (pictured)
27-onward: full integrated system @ LBL

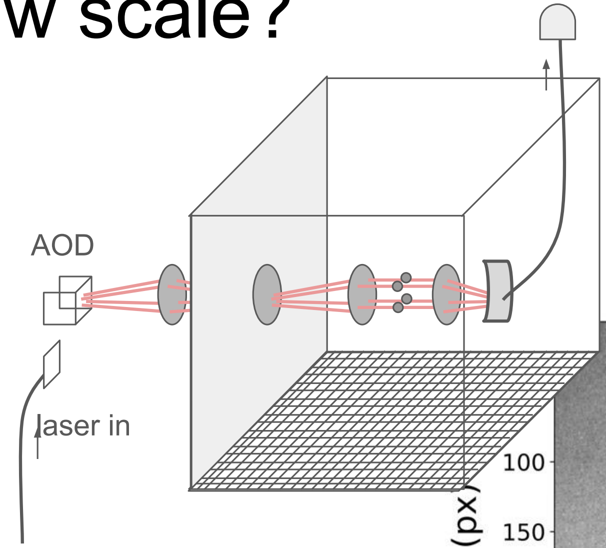
Holy grail stuff

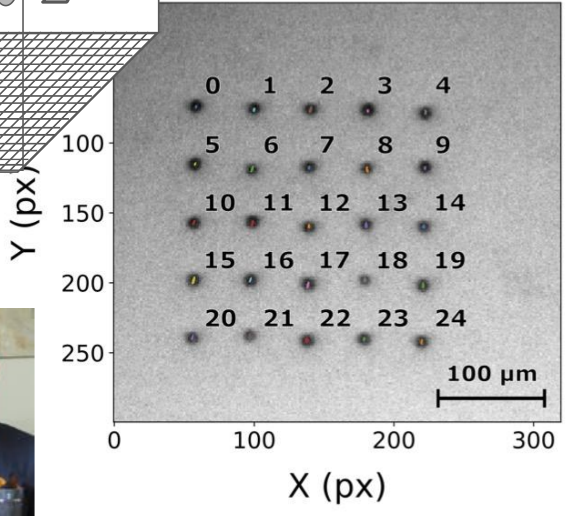
1. Can we get to the seesaw scale?
2. Can we measure the light neutrino mass scale?

Can we get to the seesaw scale?



1000 spheres x 1 year, SQL





Siegel, Afek, Lowe, Wang, Tseng, Penny, Moore 2412.07088
Same technique as neutral atom quantum computers → 10^5 traps

Can we measure the light neutrino mass scale?

Can you measure the neutrino mass with this technique? Maybe…

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

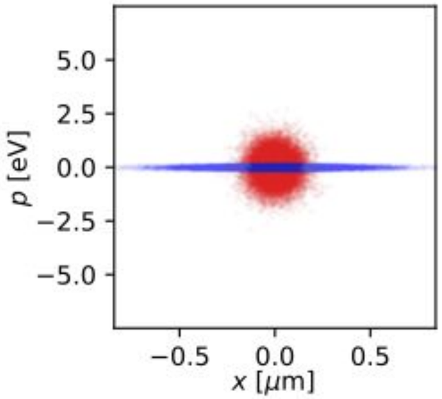
To get to neutrino mass ~ 100 meV:

- Reduce sphere mass x10^3
- Reduce frequency x10
- Average 10^6 events

→ Δp ~ 150 meV, almost there. Now:

- Prepare sphere in squeezed state ~10 dB

→ Δp ~ 15 meV



Carney, Leach, Moore PRX Quantum 2023

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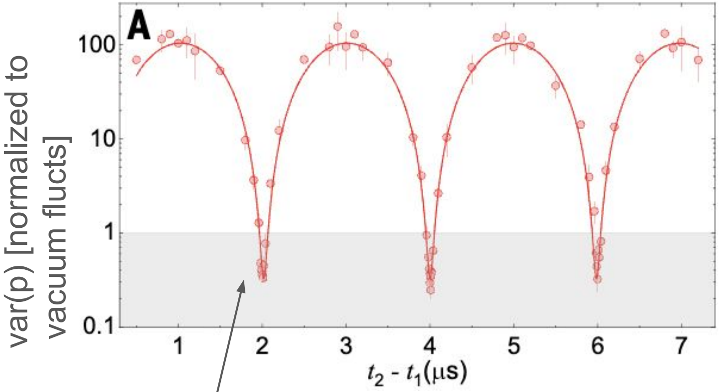

momentum p of 100nm bead squeezed ~5dB below ground state

Kamba, Hara, Aikawa, Science 2025

Lee, Beckey, Marocco, Carney PRR 2025
Marocco, Moore, Carney PRA 2026

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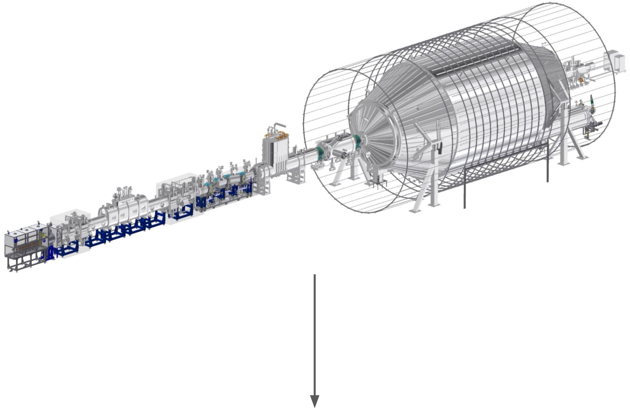

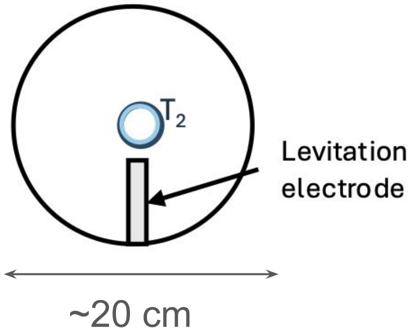

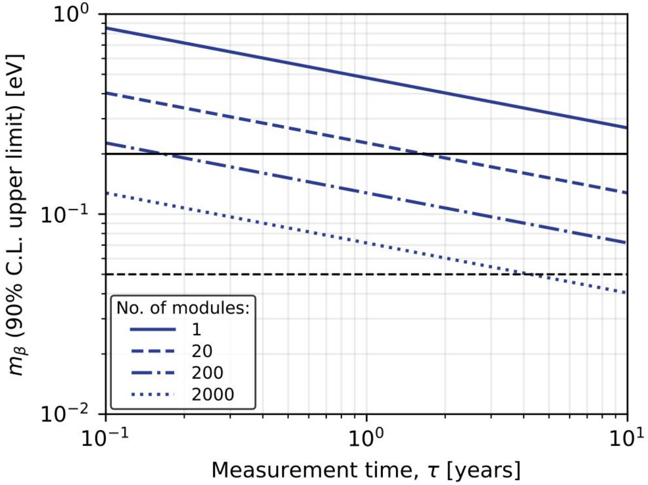

Preliminary! Should appear in ~1-2 months

Carney, Leach, Haffner, Moore*, Sangiorgio

Outlook

Quantum mechanics → noise/uncertainty in initial state prep, final state measurement starting to dominate in low energy neutrino measurements

This noise can be engineered with fancy techniques (e.g., squeezing)

QuIPS @ LBL/UC Berkeley/Yale rapidly moving toward complete, event-by-event nuclear beta decay reconstruction with scalable arrays of quantum sensors