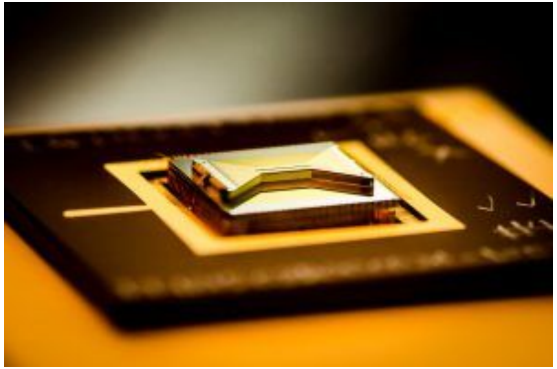
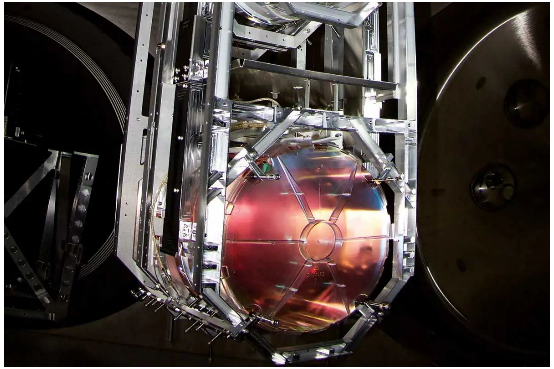
Quantum sensing for ultra low thresholds

Daniel Carney

BERKELEY LAB

@four_form



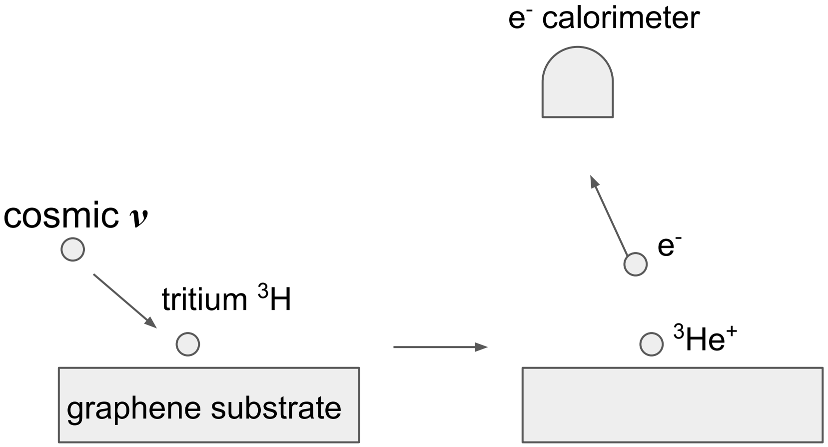


Hello! Thanks for having me.

Bad news:
- I’m not a particle physicist
- I’m a theorist who is going to talk like an experimentalist

Good news:
- I’m friendly
- I only have ~20 slides

PTOLEMY versus quantum mechanics



e^- calorimeter

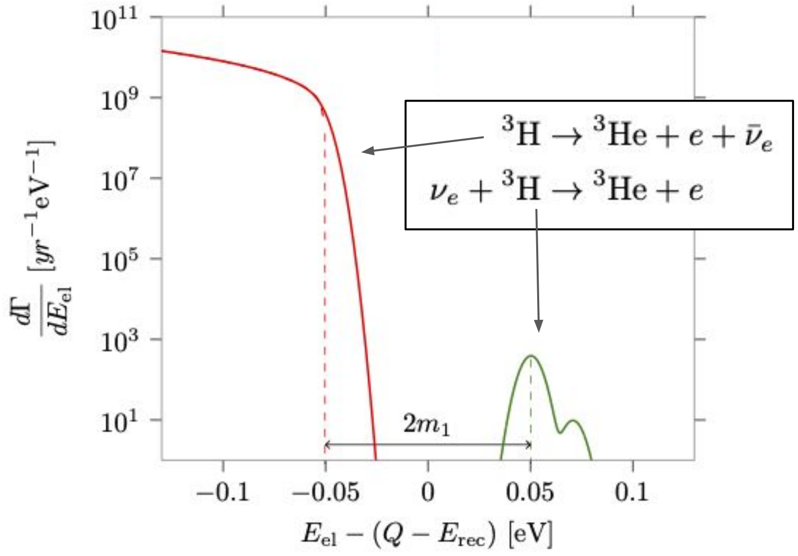
cosmic $\boldsymbol{\nu}$

tritium ^{3}H

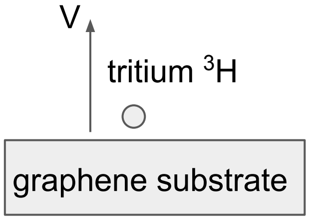
graphene substrate

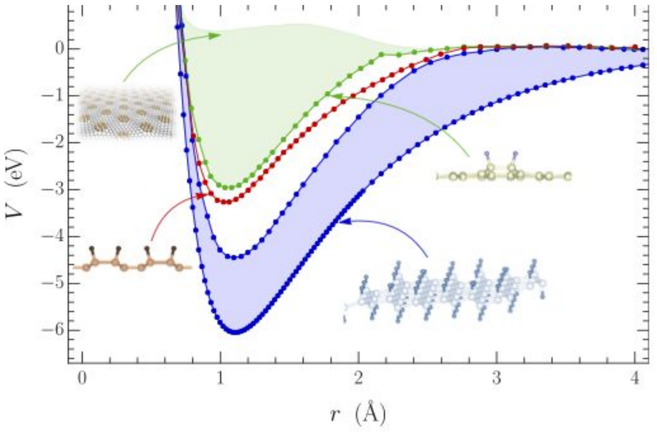
e^-

$^3He^+$



Weinberg 1962
Cheipesh, Cheianov, Boyarsky 2021





Tritium is bound in a potential generated by the graphene. The ground state wavefunction has:

$\Delta x \sim 1$ angstrom → $\Delta p > 1$ 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

Outline

- Quantum mechanics imposes fundamental sources of noise.
- Quantum noise will continue to be important in variety of contexts, high energy and otherwise, **HOWEVER**
- **These noise sources can often be engineered away.**

Review:

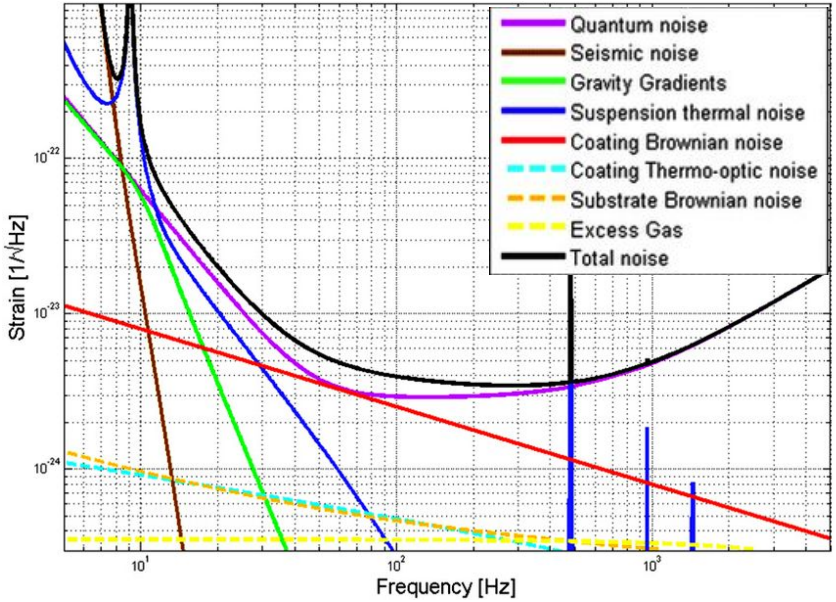
“Quantum measurements in fundamental physics: a user’s manual”

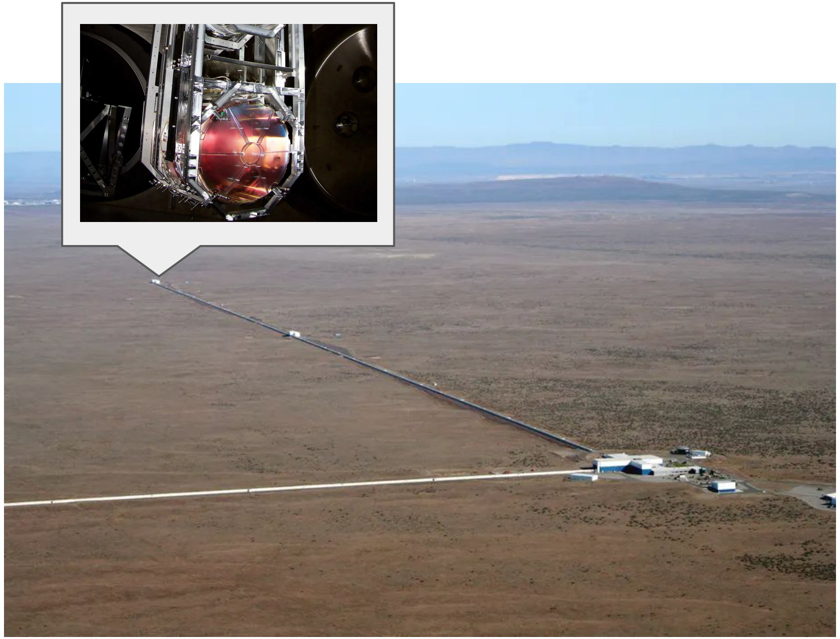
2311.07270

Giacomo Marocco
(LBL postdoc)

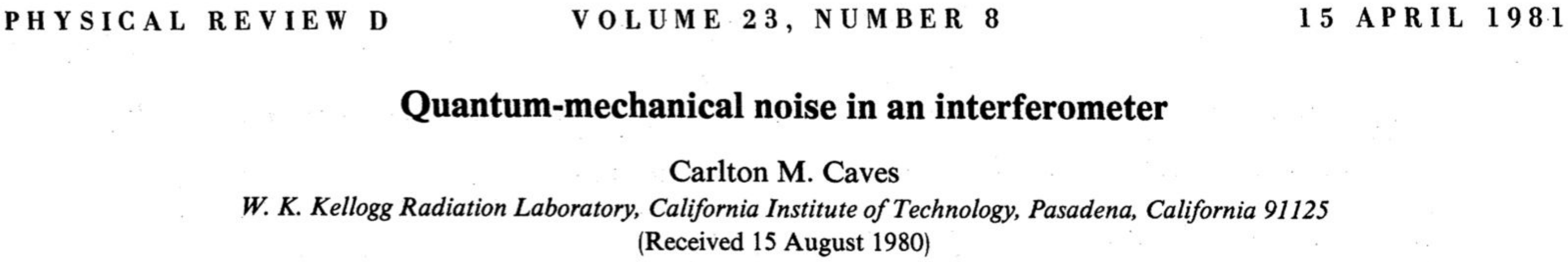
Jacob Beckey
(JILA + LBL → UIUC)

Quantum-limited detection of motion





The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy
LIGO Collaboration 1604.00439



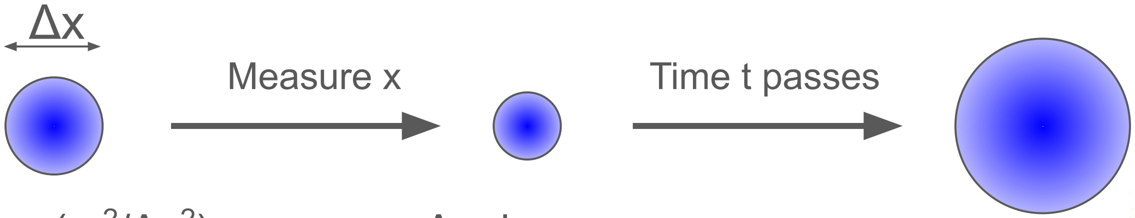
PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

(Received 15 August 1980)



Δx

Measure x

Time t passes

$\psi = \exp(-x^2/\Delta x^2)$

$\Delta x\Delta p = \hbar/2$

minimal uncertainty

Δx decreases

↓

Δp increases

$$\Delta x \to \Delta x + \frac{\Delta p}{2m}t$$

optimize → “standard quantum limit”

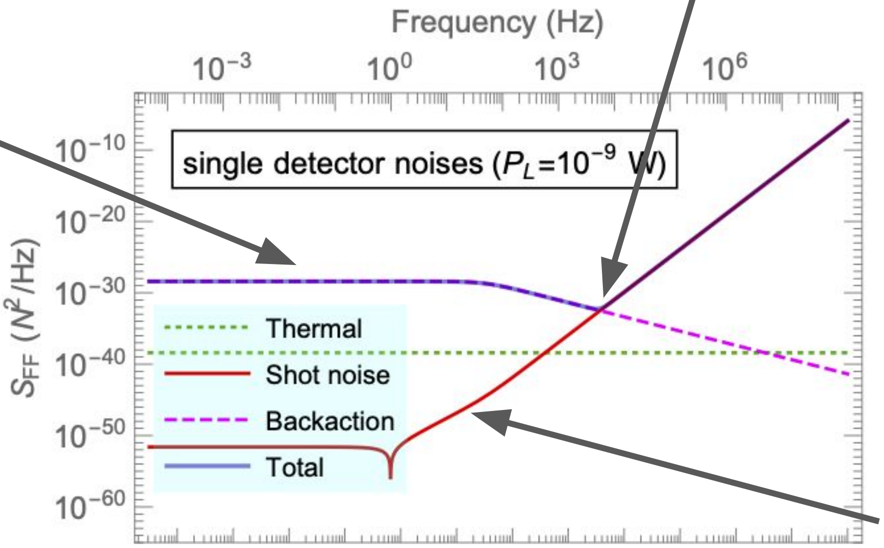
$$\Delta x_{SQL} = \sqrt{\frac{\hbar t}{m}}$$

LIGO: $m \sim 40$ kg, $t \sim (100\text{ Hz})^{-1} \to \Delta x \sim 10^{-19}$ m

Standard quantum limit

Random radiation pressure from laser

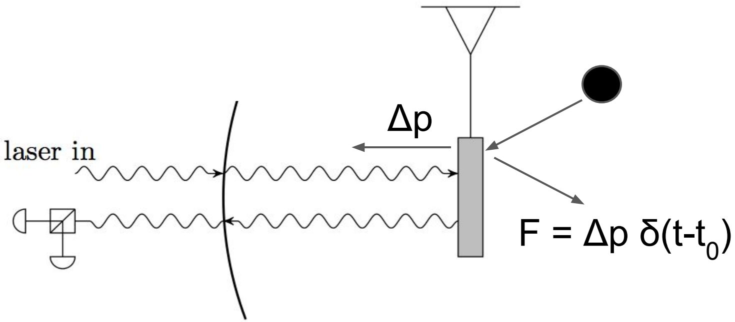
SQL = point where shot + backaction are equal

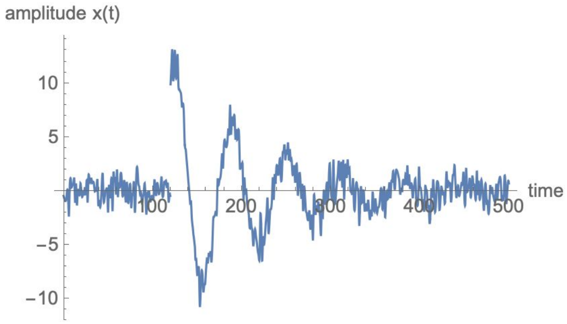


Laser phase fluctuations

Sensor m = 1 mg, frequency = 1 Hz, dil fridge

Quantum-limited impulse sensing





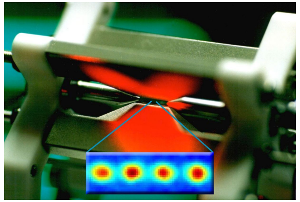
$$\Delta p_{SQL} = \sqrt{\hbar m_s \omega}$$

Meaning: can observe impulses at scale of **detector quantum vacuum fluctuations**

Quantum-limited impulse sensing

$$\Delta p_{SQL} = \sqrt{\hbar m_s \omega}$$

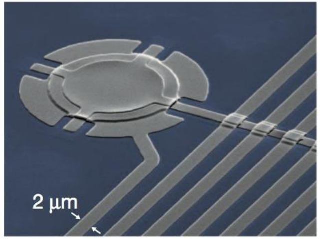
Trapped electrons, ions

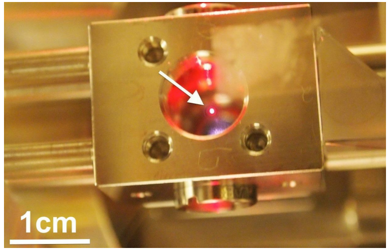


~ 10 meV → ΔE ~ 0.1 neV

(m = m_e, ω/2π = 100 kHz)

Nanomechanical objects

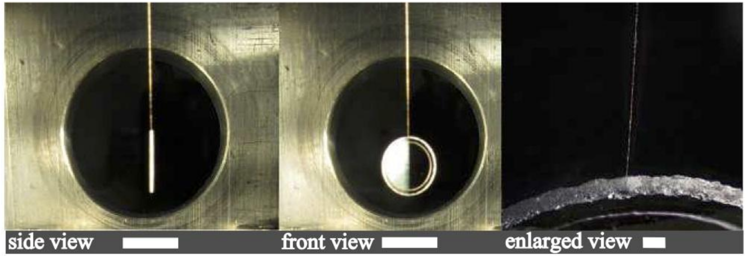




~ 10 keV → ΔE ~ 0.01 neV

(m = 1 fg, ω/2π = 10 kHz)

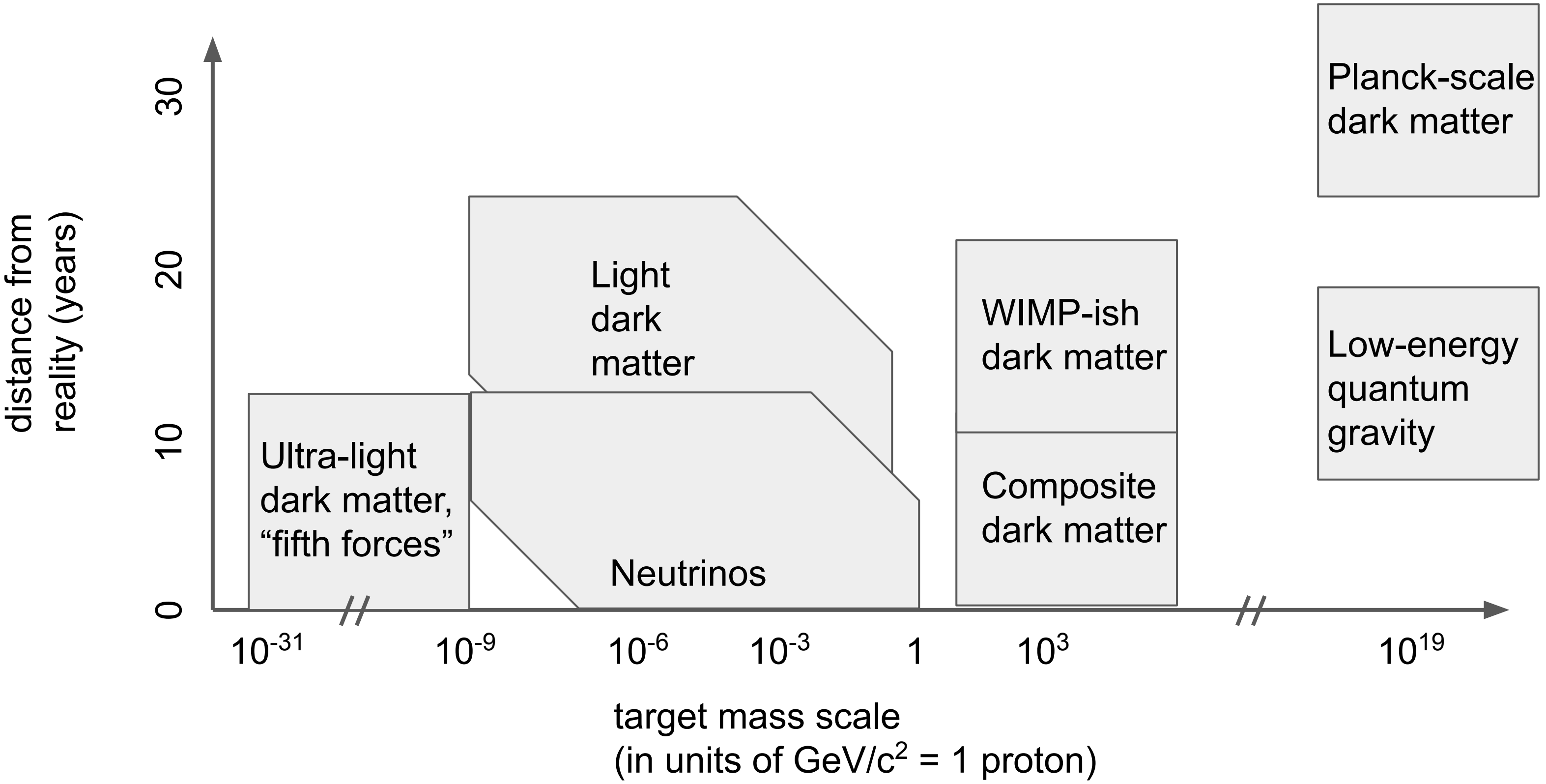
Macroscopic objects
(>microgram scale)



~ 1 GeV → ΔE ~ 0.001 neV

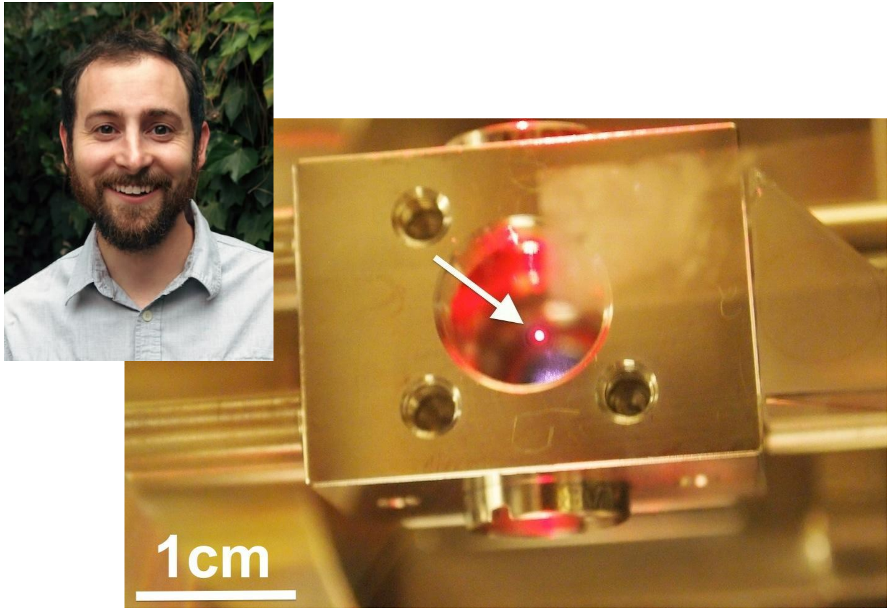
(m = 1 mg, ω/2π = 1 kHz)

Mechanical sensing targets



The first experiment

Search for new Interactions in a Microsphere Precision Levitation Experiment (SIMPLE) @ Dave Moore group, Yale



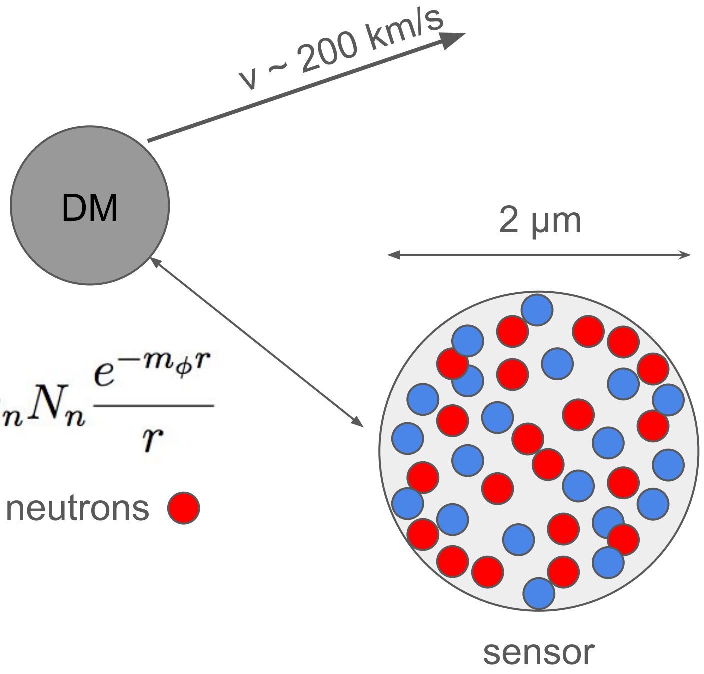
2020:

0.1-10 ng dielectric spheres (R ~ μm)

Optically levitated, stability ~ days

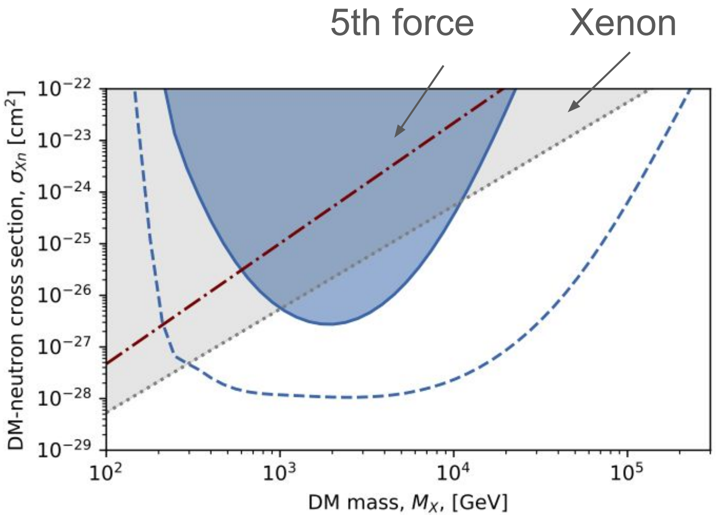
~ 75 MeV momentum transfer resolution (~ 100 x SQL)

The first experiment



$$V = \alpha_n N_n \frac{e^{-m_\phi r}}{r}$$

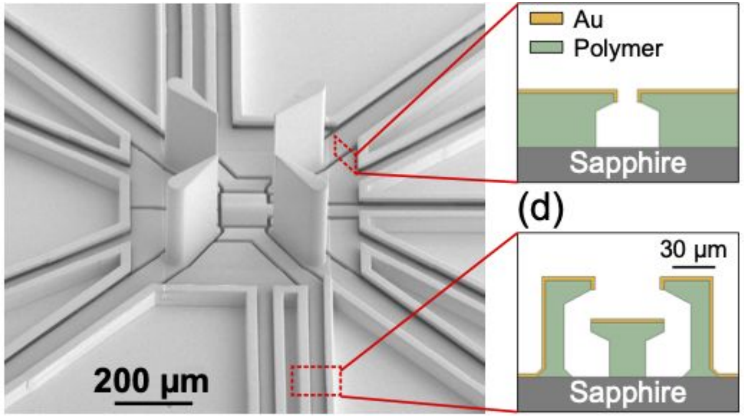
N_n = # neutrons ●



Monteiro, Afek, Carney, Krnjaic,
Wang, Moore **PRL** 2020

Lin, Yu, Zurek 1111.0293
Krnjaic, Sigurdson 1406.1171

The lowest threshold detectors possible

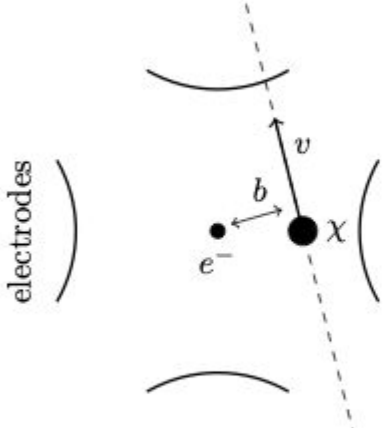


Microwave/RF trapped ions, electrons

Fundamental limit: lightest possible detectors

Δp ~ 10 meV → ΔE ~ 0.1 neV
(m = m_e, ω/2π = 100 kHz)

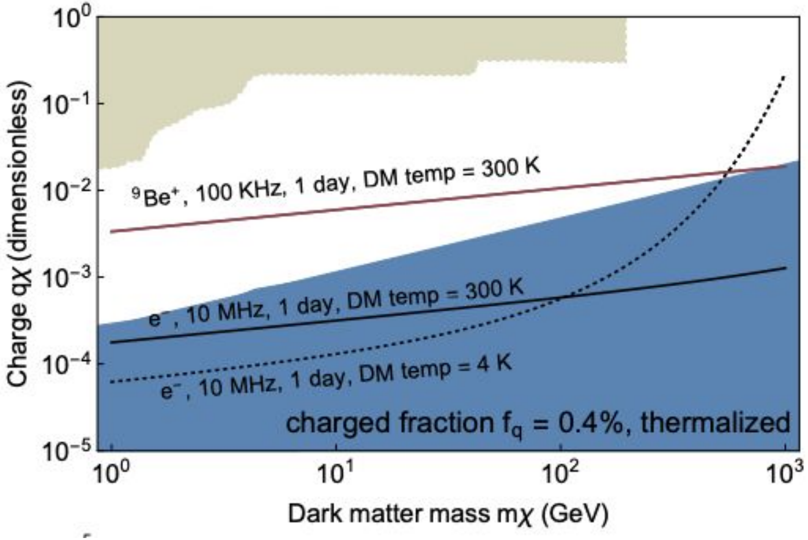
Possible applications: millicharged DM, calorimeters

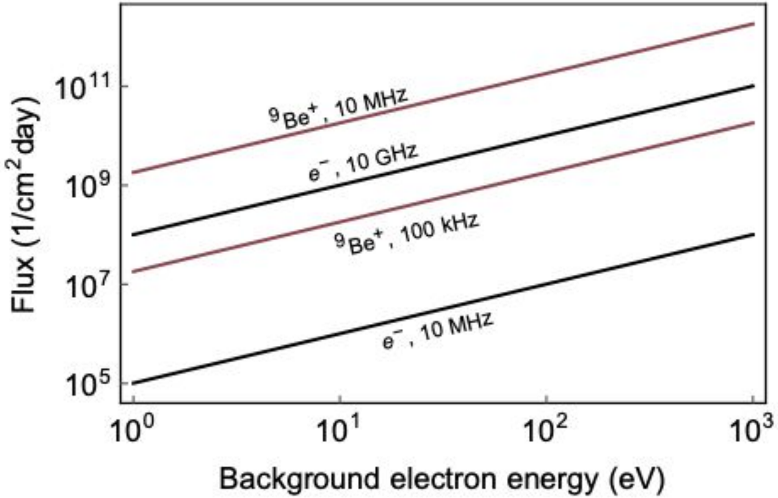


$$\sigma_{\text{eff}} \approx 4\ \mu\text{m}^2 \times \frac{q_\chi^2}{v^2} \times \left(\frac{100\ \text{kHz}}{\omega/2\pi}\right)$$

Carney, Haffner, Moore, Taylor **PRL** 2021
Pic from Haffner group @ UC Berkeley: Xu et al 2310.00595

The lowest threshold detectors possible



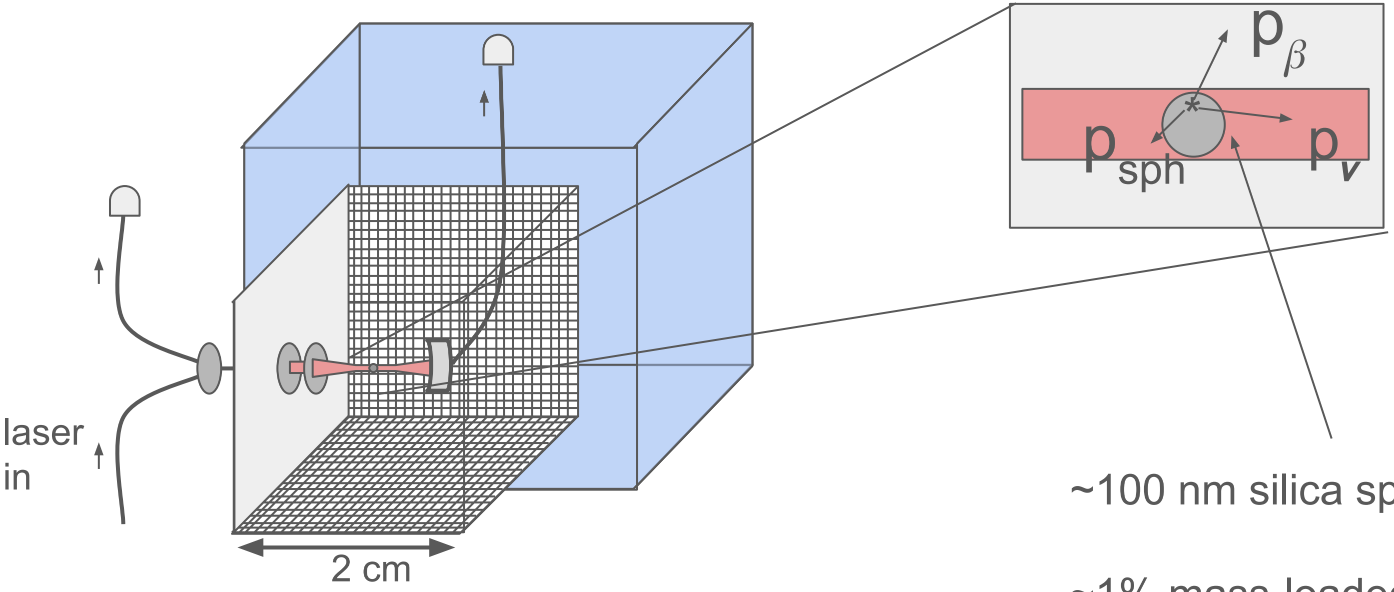


Carney, Haffner, Moore, Taylor **PRL** 2021

Budker, Graham, Ramani, Schmidt-Kaler, Smorra **PRX Quantum** 2021

Osada, Taniguchi, Shigefuji, Noguchi **Phys Rev Res** 2022

Quantum Invisible Particle Sensor (QuIPS)



~100 nm silica sphere

~1% mass-loaded with
radioisotope of choice
(can also do electron capture)

Measure:

- Sphere recoil (optical @ ~SQL, Yale)
- Escaped β electron (pixelated CCD/CMOS, Berkeley)

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

Carney, Leach, Moore **PRX Quantum** 2023

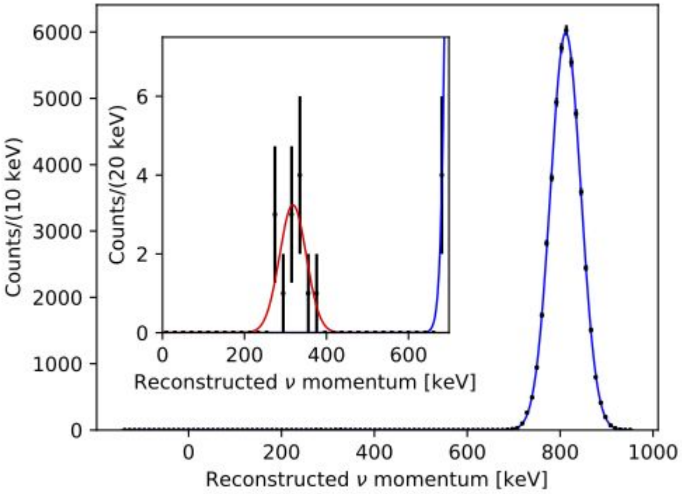
Heavy sterile neutrinos

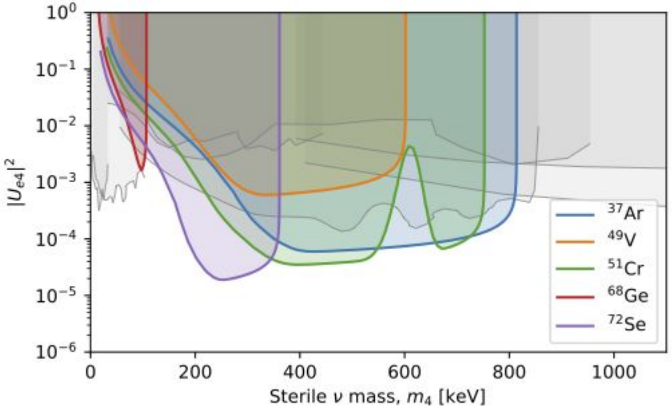
With a single 100nm sphere at the standard quantum limit (SQL):

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

Clear target: search for sterile neutrinos in keV-MeV range

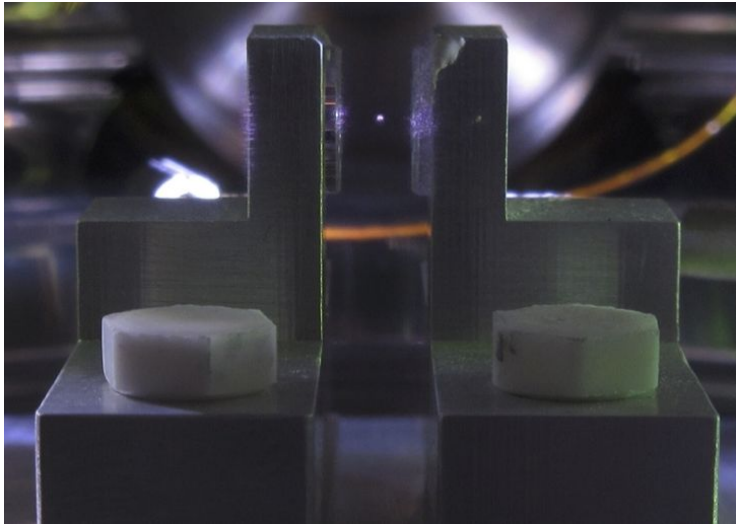
~10^5 radioisotopes (~1 month with ^{37}Ar)
→ beat existing lab bounds

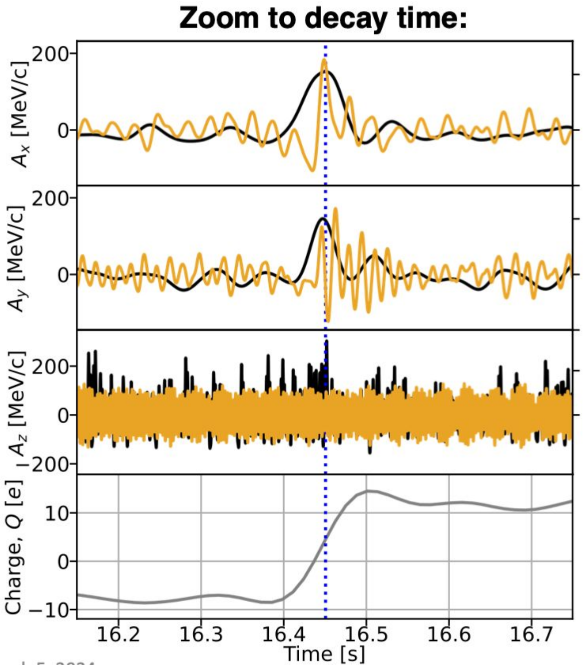




Carney, Leach, Moore **PRX Quantum** 2023

This actually works



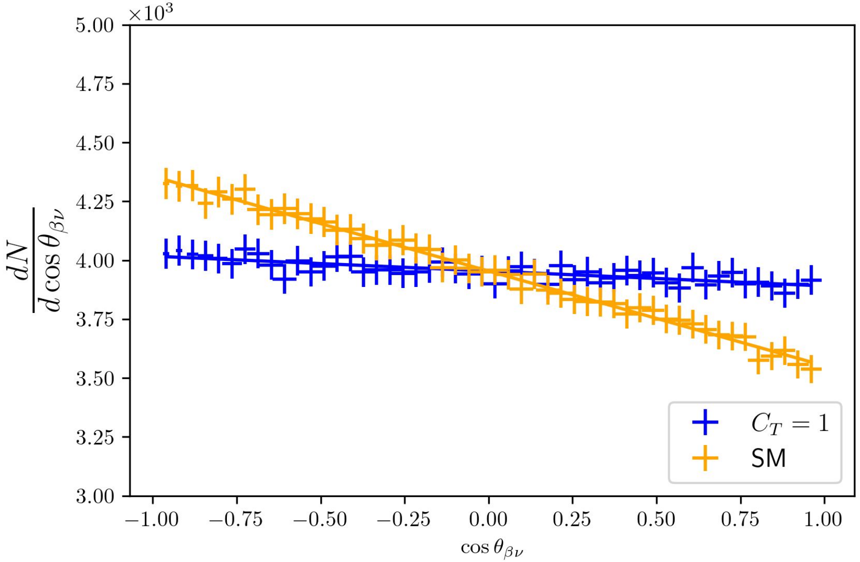


um-scale particle trapped at Yale
Measurement of individual alpha-decay events

Now building pixel calorimeter + 100 nm-scale trap at Berkeley (QuIPS project, LDRD funded)

Mechanical detection of nuclear decays
Wang, Penny, Recoaro, Siegel, Tseng, Moore
2402.13257

Searches for new electroweak symmetries



$$\frac{d\Gamma}{d\cos\theta e\nu} = \xi\left(1 + a_{\beta\nu}\cos\theta_{e\nu}\right)$$

Angle between emitted electron and neutrino

= 1/3 exactly in standard model

Non-SM physics (e.g., tensor currents in weak sector) affects this 1/3 value

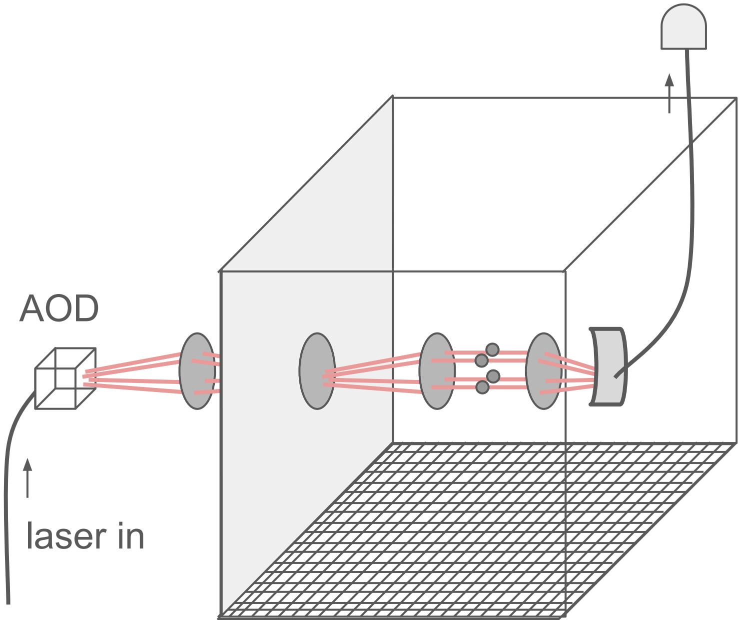
~1 sphere lifetime → constrain more precisely than any existing experiment

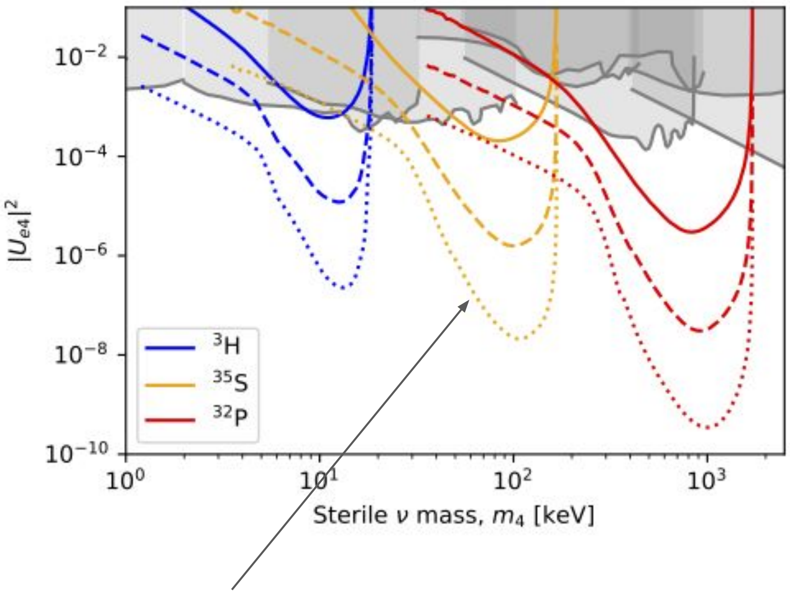
Giacomo Morocco
Dan Kodroff
(LBL postdocs)

Scalable: sensor arrays

Relatively straightforward to trap, read out up to ~1000 beads with single laser

Same technique used to create Rydberg atom quantum computers (Harvard/QEra)





1000 spheres x 1 year, SQL

A brief meditation on the word “possible”

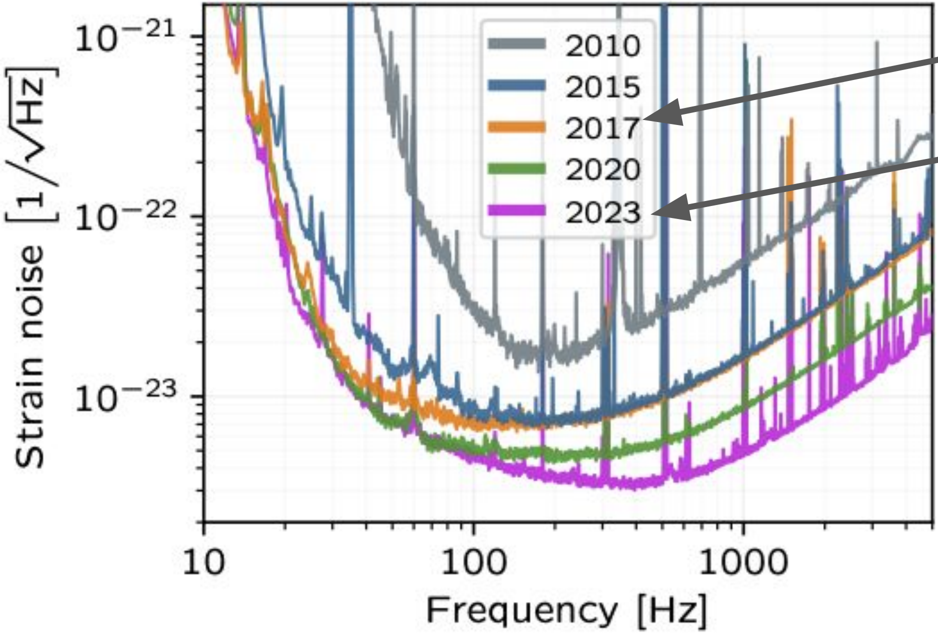
Quantum mechanics and measurement

So far I have talked about detection at the “Standard Quantum Limit” (SQL), where the detector’s vacuum fluctuations dominate the measurement uncertainty

But one might want to go even further – is it possible?

Quantum mechanics itself does not impose any limit to how precisely one can measure a system.

Detection beyond the Standard Quantum Limit



Squeezed light injection

Frequency-dependent squeezing

10% strain reduction → 1000% increase in visible mergers

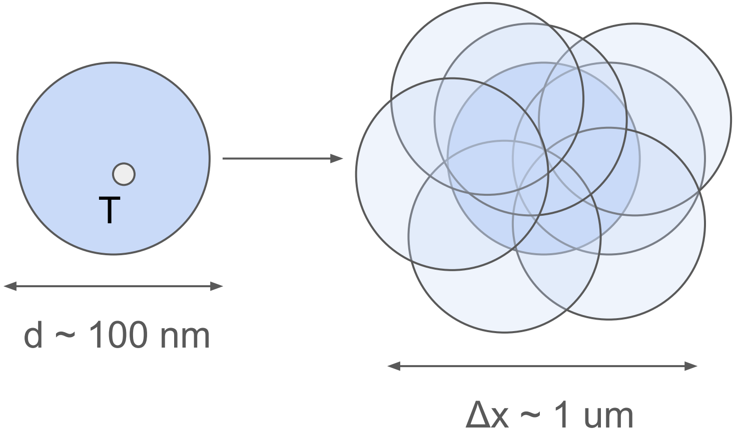
Vacuum: given mode of light has ΔX = ΔY = ½
Squeezed light: can have ΔX > ½, ΔY < ½

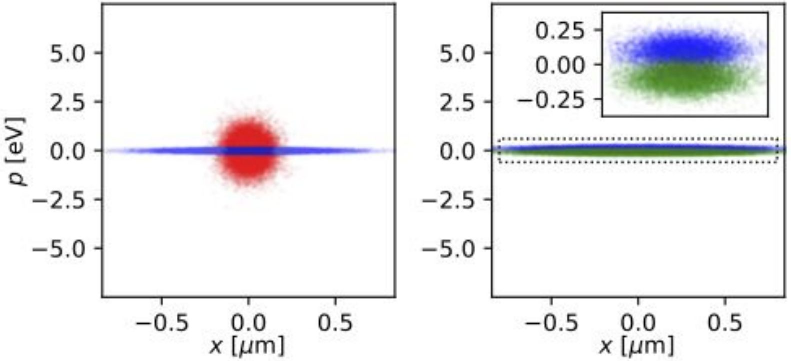
From Evan Hall (MIT/LIGO)

Neutrino mass measurement?

Holy grail: measure the light neutrino masses (m ~ 100 meV). With trapped beads?

Key requirement: prepare and read out sphere center-of-mass Δp ~ 100 meV → Δx ~ 1 um





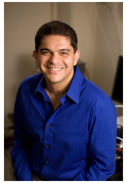
Requires ~10dB squeezing. Possible? Will also require many (~1000) spheres, to get rare endpoint events.

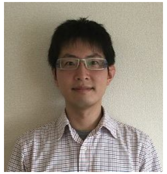
Carney, Leach, Moore **PRX Quantum** 2023

Thanks to many people

ex


C. Regal

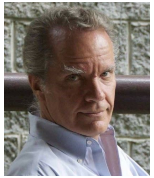

S. Bhave


N. Matsumoto


H. Muller


G. Afek


H. Haffner


T. LeBrun

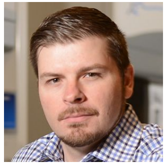

D. Barker

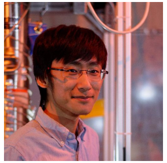

B. Knepper


D. Moore
(EXO)


P. Shawhan
(LIGO)


R. Lang
(XENON)

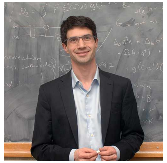

K. Leach
(BeEST)


J. Qin
(XENON)

quant

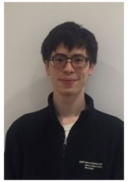

T.-C. Lee

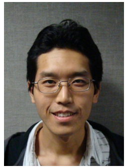
hep/gr


J. Taylor


J. Beckey


G. Krnjaic


A. Hook


Y. Zhao


G. Marocco

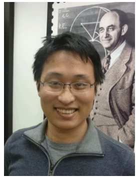

G. Semenoff


S. Ghosh


P. Stamp


V. Domcke


N. Rodd


Z. Liu

th

Outlook

- Quantum mechanics imposes fundamental sources of noise.
- Quantum noise will continue to be important in variety of contexts, high energy and otherwise, **HOWEVER**
- **These noise sources can often be engineered away.**
- How far can we go? Are there more fundamental limits from quantum field theory, gravity, …?