Quantum-limited detection of new physics

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Outline

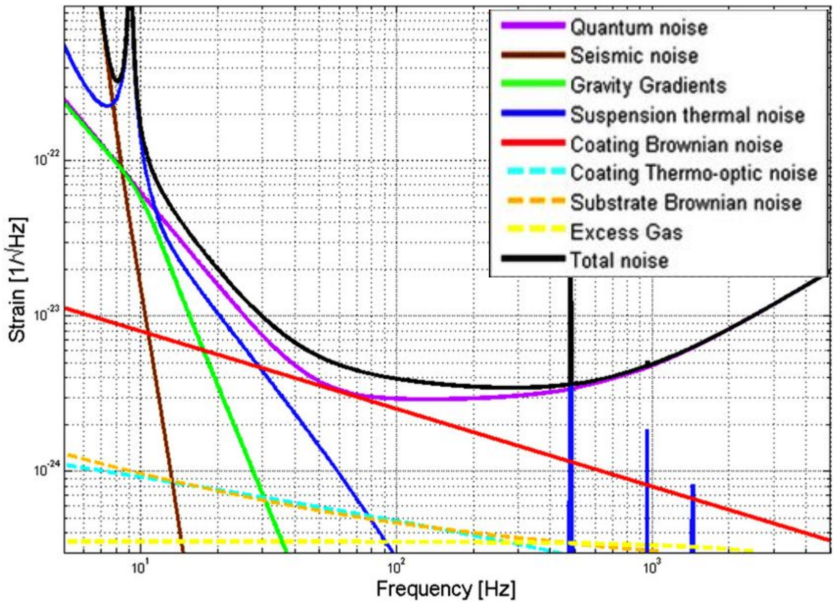
- Quantum noise basics
- Example: axion cavities
- Example: heavy sterile neutrinos with levitated sensors

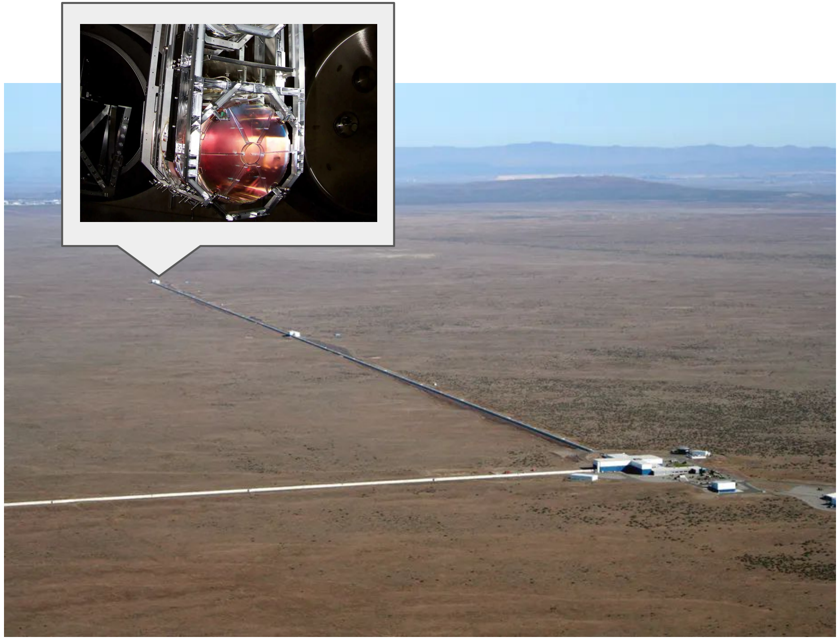
"Quantum measurements in fundamental physics: a user's manual" 2311.07270

Giacomo Marocco
(LBL postdoc)

Jacob Beckey
(JILA + LBL → UIUC)

Quantum-limited detection



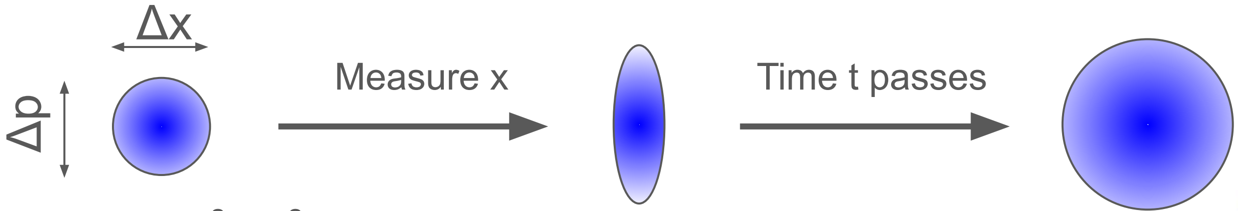


The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy
LIGO Collaboration 1604.00439

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)



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

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

Δx decreases

↓

Δp increases

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

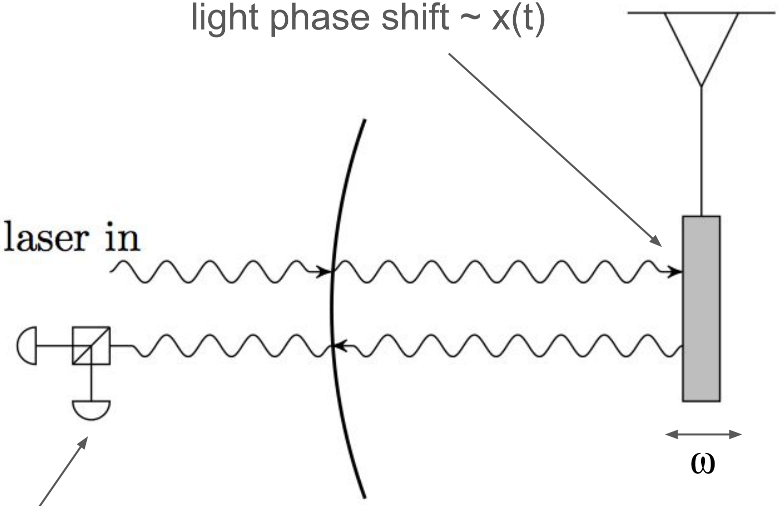
optimize → "standard quantum limit"

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

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

LIGO's quantum noise in more detail

light phase shift ~ x(t)



readout light phase Y(t)
via interferometer
→ measure x(t)
→ infer F(t)

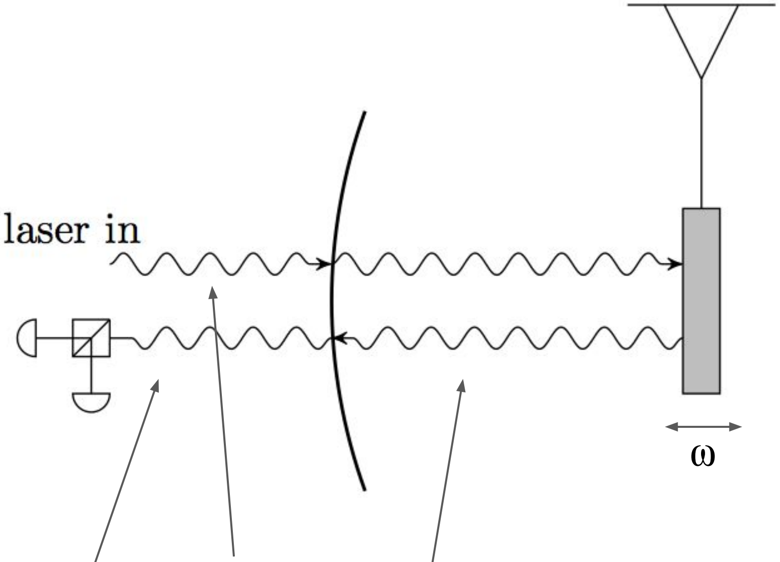
mechanics
[x,p] = iħ

fundamental
cavity mode
[X,Y] = iħ

$$H_{OM} = gxX$$

Laser power enhances coupling $g \propto g_0\sqrt{P}$

Input-output formalism



$$X^{\mathrm{out}} = X^{\mathrm{in}} - \sqrt{\kappa} X,$$
$$Y^{\mathrm{out}} = Y^{\mathrm{in}} - \sqrt{\kappa} Y.$$

Basic idea: scatter light off the cavity. Find outgoing light field (e.g., Xout = amplitude) in terms of incoming light (e.g., Xin).

$$\dot{X} = \Delta Y - \frac{\kappa}{2} X - \sqrt{\kappa} X^{\mathrm{in}},$$
$$\dot{Y} = -\Delta X - \frac{\kappa}{2} Y - \sqrt{\kappa} Y^{\mathrm{in}} - \sqrt{2} g x,$$
$$\dot{x} = \frac{p}{m},$$
$$\dot{p} = -m\omega_m^2 x - \gamma p + F^{\mathrm{in}} - \sqrt{2} g X$$

Typically only requires solving simple linear equations (“Heisenberg-Langevin equations”)

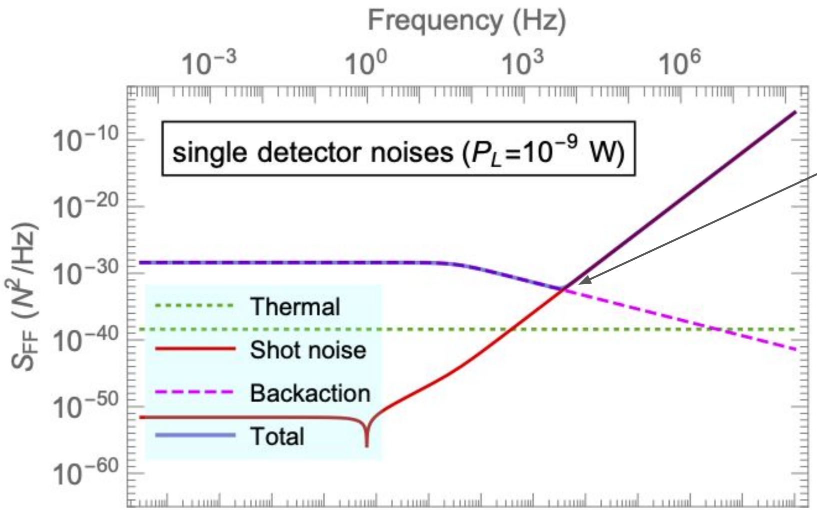
I/O → calculate noise spectrum

$$S_{FF} = \int_{-\infty}^{\infty} dt e^{i\nu t} \langle F(t)F(0)\rangle = a\langle |Y_{\text{in}}|^2\rangle + b\langle |X_{\text{in}}|^2\rangle + c\langle |F_{\text{thermal}}|^2\rangle$$

"Shot noise" (input laser phase fluctuations)

"Back-action noise" (noisy radiation pressure)

Thermal load on mechanics



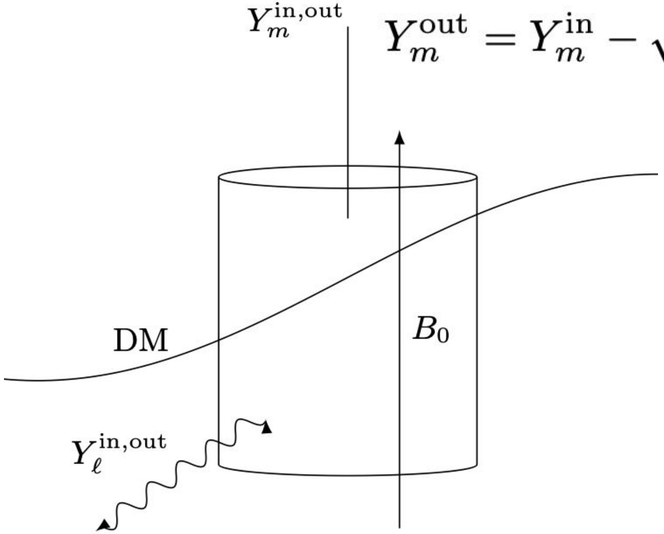
SQL = point where shot and backaction are balanced

Key physics: laser field is ~coherent state → has quantum vacuum fluctuations → shot/backaction noise

$$\langle x^{\text{in}}(t)x^{\text{in}}(0)\rangle = \frac{1}{2}\langle\delta(t)\rangle$$

Example: axion cavity searches

$$X_m^{\mathrm{out}} = X_m^{\mathrm{in}} - \sqrt{\kappa_m} X$$
$$Y_m^{\mathrm{out}} = Y_m^{\mathrm{in}} - \sqrt{\kappa_m} Y.$$



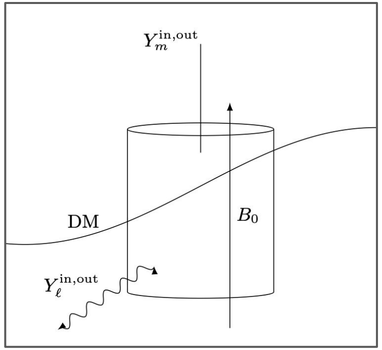
Similar ideas and calculations work for many things, e.g., axion searches (ADMX, HAYSTAC, DM Radio, …)

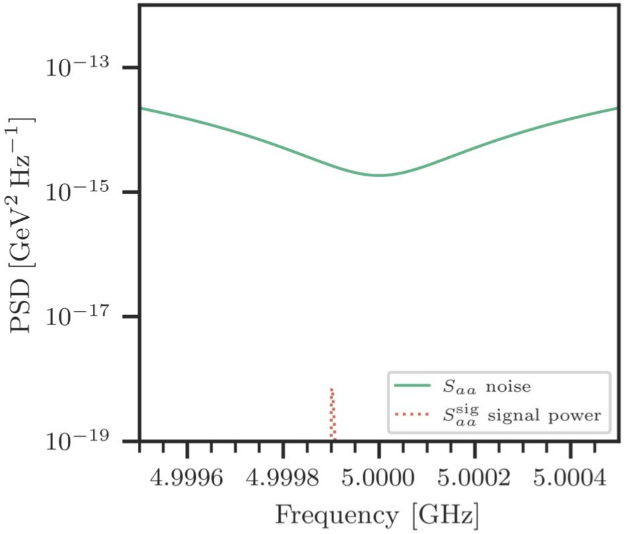
$$V = g_{a\gamma\gamma} B_0 \int d^3\mathbf{x}\, a\, \delta E_z$$
$$= F_Y(t) X + F_X(t) Y$$

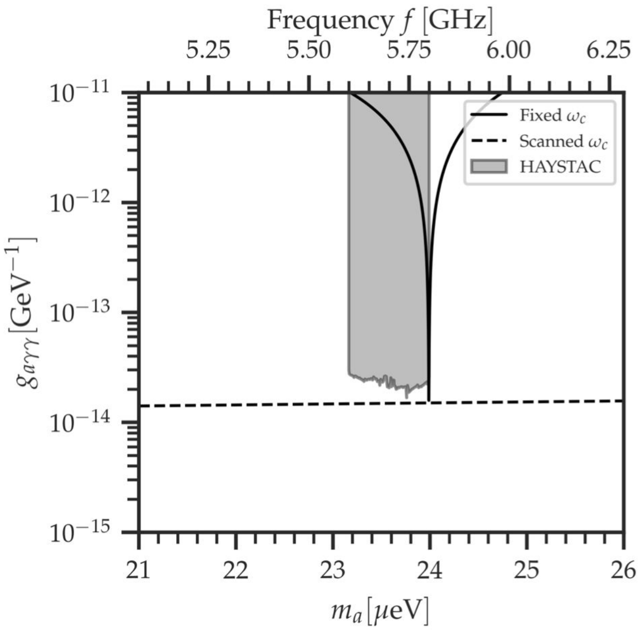
Again assuming vacuum noise in the input (which is now a microwave transmission line), calculate similar PSD

See e.g.
K. Lehnert's Les Houches notes 2110.04912
Our review 2311.07270

Example: axion cavity searches

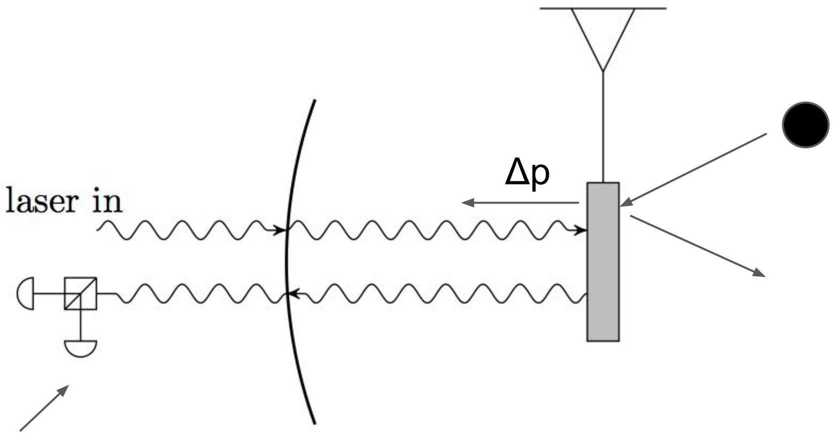






NB: vacuum noise reasonable for cavity f ~ GHz ~ 10 mK or higher

Quantum-limited impulse sensing



readout light phase
via interferometer
→ measure x(t)
→ infer F(t)

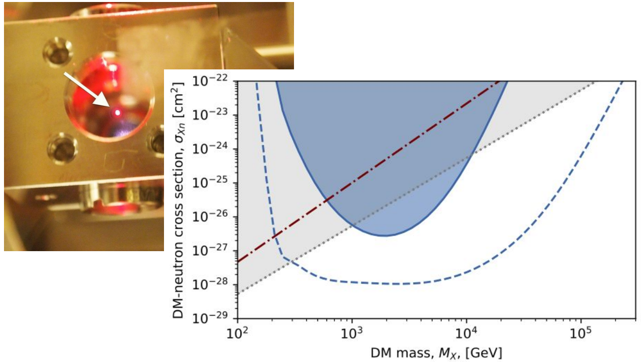
Suppose we want to detect sharp impulse (Δp = ∫Fdt) with a mechanical detector

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

~ 600 keV (m = 1 ng, ω = 2π kHz)

Dark matter searches with this technique

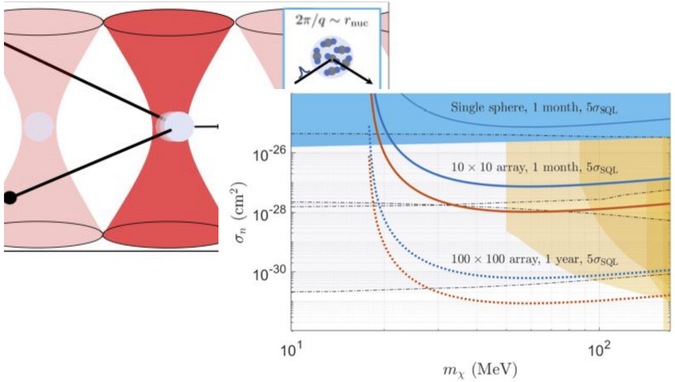
detector mass — heavy → light



~1000 GeV-scale DM, long-range coupled to SM

~ug-scale levitated sphere

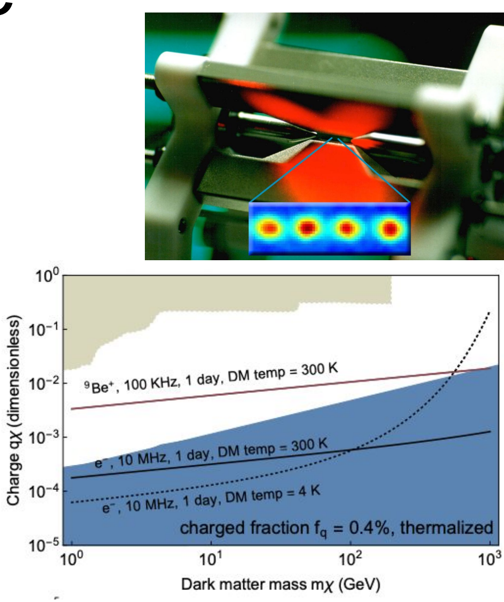
Monteiro, Afek, Carney, Krnjaic, Wang, Moore PRL 2020



~ 10 MeV-scale DM, coherent elastic scattering

~fg-scale levitated sphere

Afek, Carney, Moore PRL 2022



Milli-charged DM

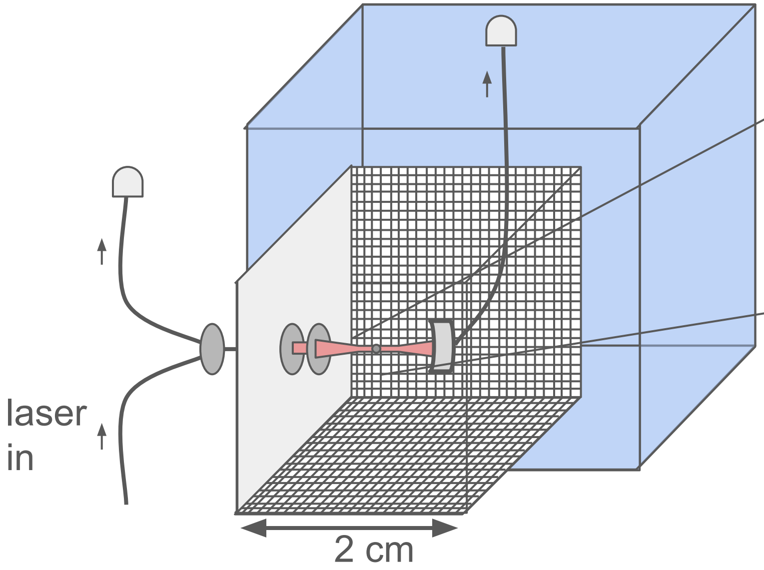
single trapped ions/electrons

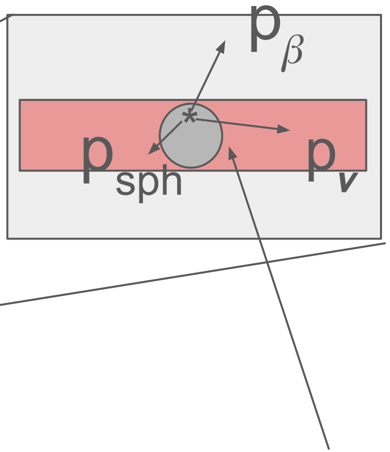
Carney, Haffner, Moore, Taylor PRL 2021, Ramani, Budker+ 2021

Integrating quantum sensors with traditional ones

- Previous examples: single DOF monitored in quantum limited way
- Next: integrate such a thing with, e.g., calorimeter array

Quantum Invisible Particle Sensor (QuIPS)





~100 nm silica sphere

~1% mass-loaded with radioisotope of choice

Measure:

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

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

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

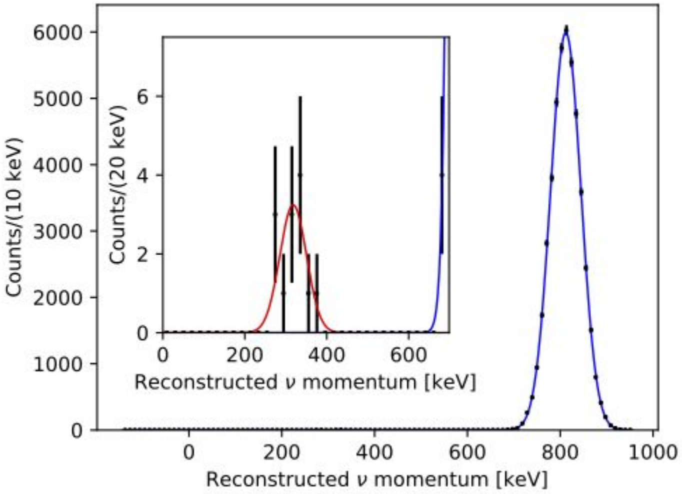
Heavy sterile neutrinos

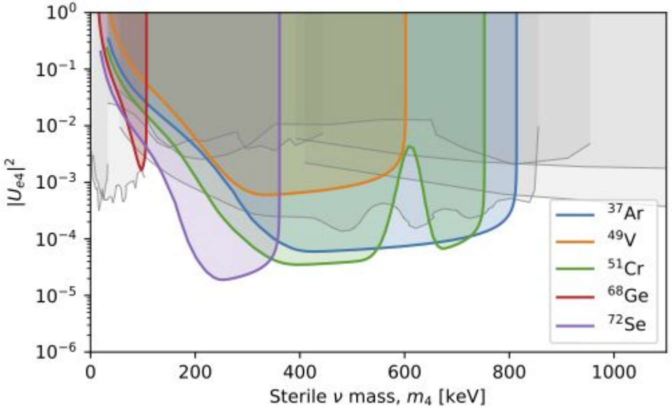
With a single 100 nm sphere at the standard quantum limit (SQL):

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

Clear target: search for sterile neutrinos that mix with electron neutrinos, m ~ keV-MeV

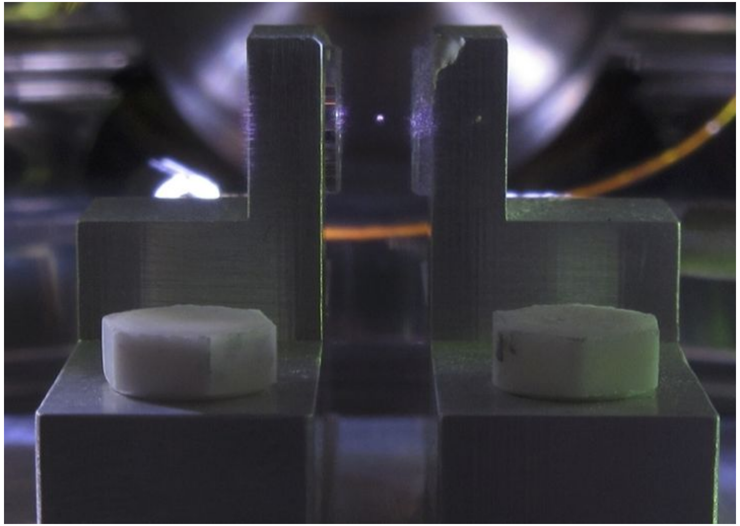
~10^5 radioisotopes (~1 month with ^{37}Ar)
→ beat existing lab bounds

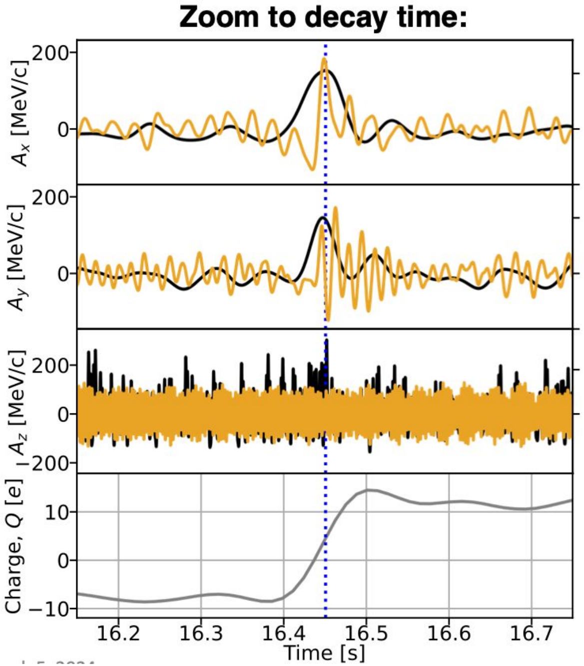




Carney, Leach, Moore **PRX Quantum** 2023

This actually works



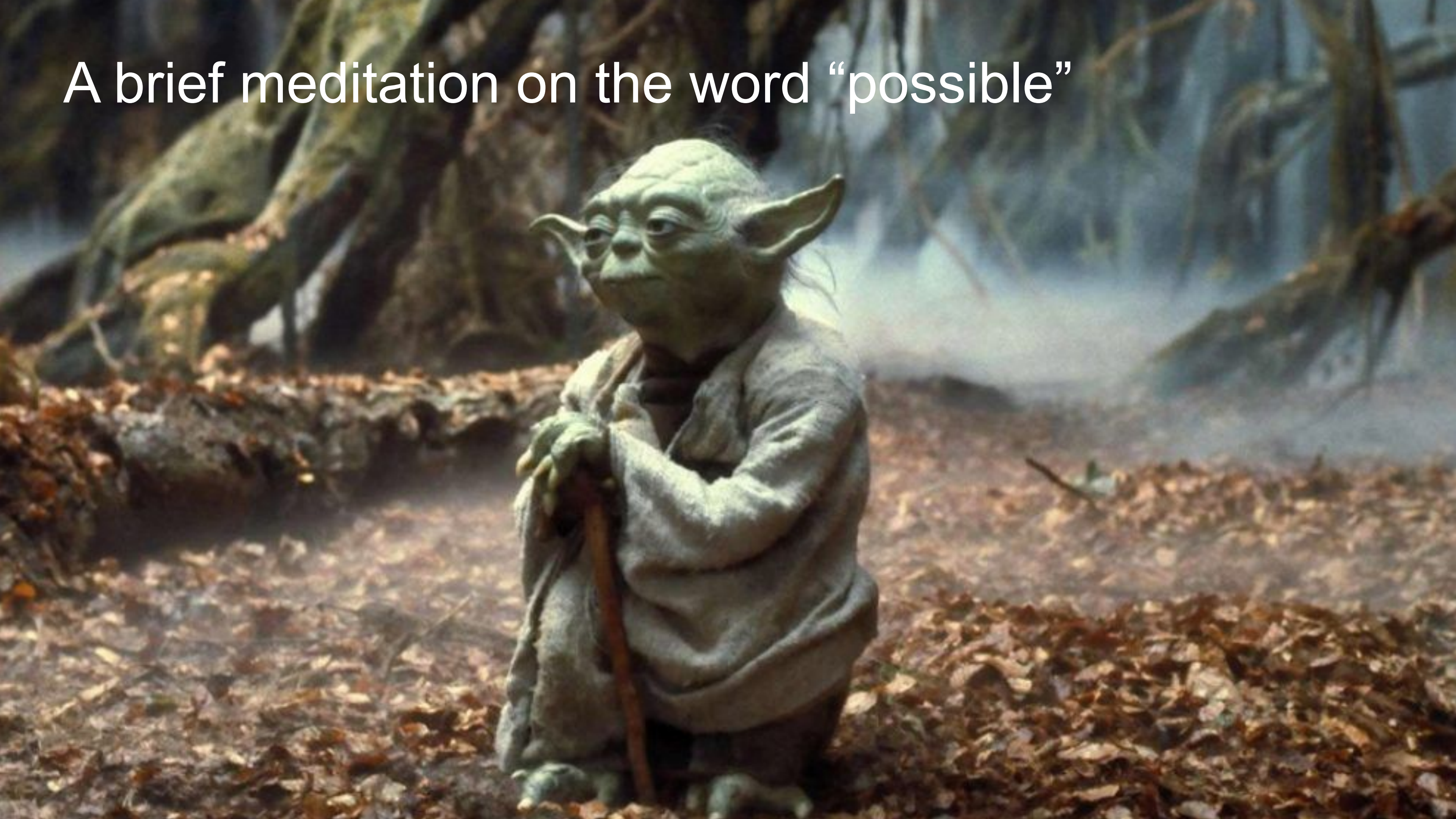


um-scale particle trapped at Yale
Measurement of individual alpha-decay events

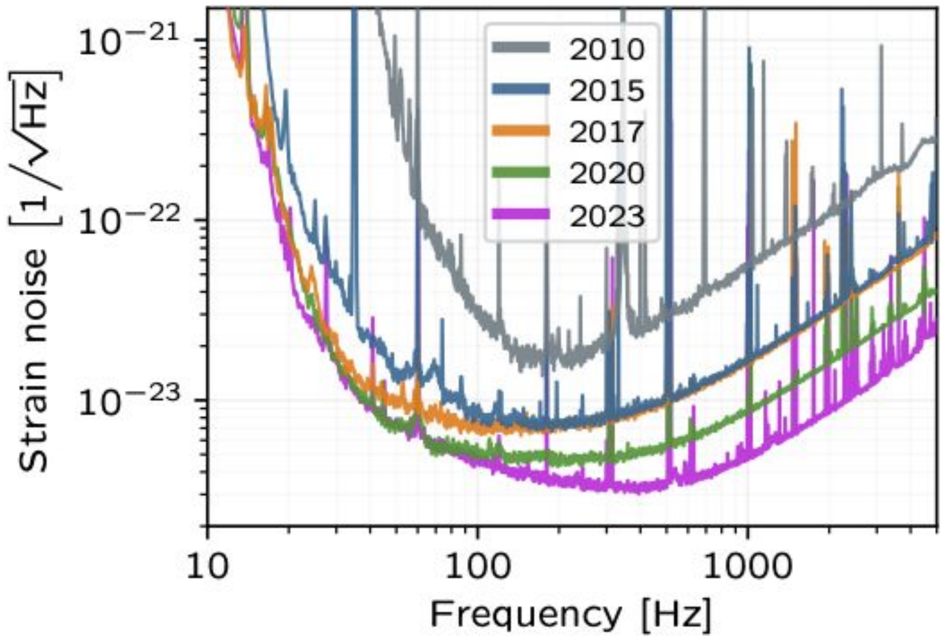
Now building pixel calorimeter + 100 nm-scale trap at Berkeley

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

A brief meditation on the word "possible"



Detection beyond the Standard Quantum Limit



$$\Delta X = \frac{e^{2r}}{\sqrt{2}}, \quad \Delta Y = \frac{e^{-2r}}{\sqrt{2}}$$

SQL

Squeezed light injection

Frequency-dependent squeezing

From Evan Hall (MIT/LIGO)

Quantum mechanics and measurement

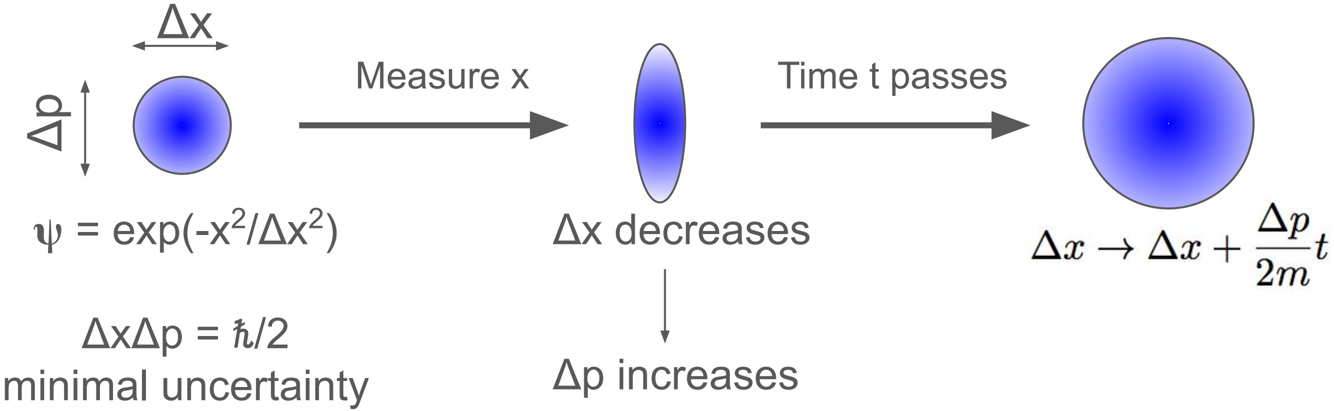
There are targets which would require noise **far** below the SQL…

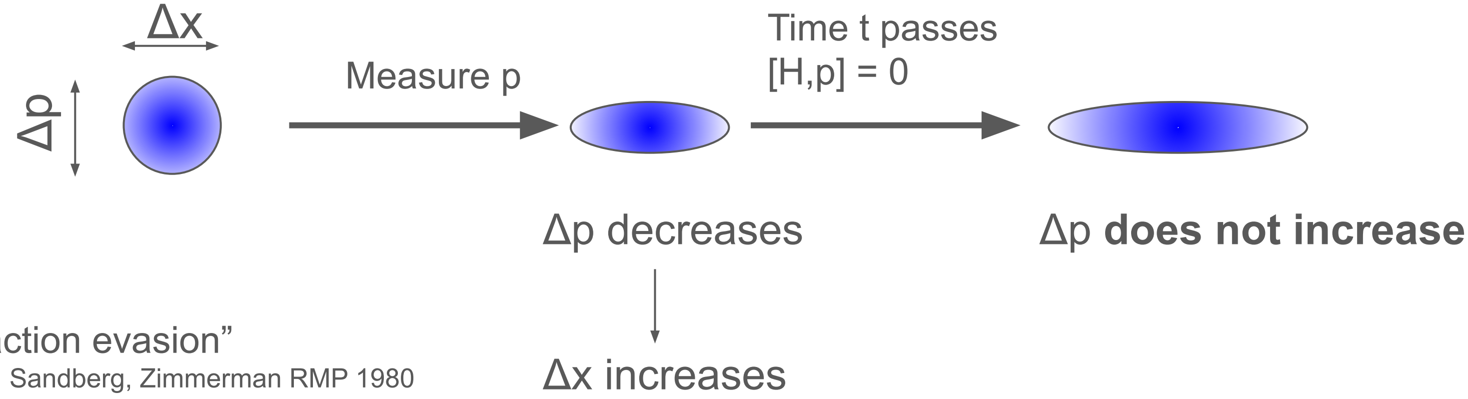
Example: direct detection of heavy DM via gravitational interaction with sensors. Requires noise ~10^5 better than SQL.
[Carney, Ghosh, Krnjaic, Taylor 1903.00492]

This is not possible with any sensor we have now. But I think one should proceed without fear.

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

$$|\psi\rangle = |x\rangle \implies \langle \Delta x^2 \rangle = 0$$





"Quantum backaction evasion"

Caves, Thorne, Drever, Sandberg, Zimmerman RMP 1980
Ghosh, Carney, Shawhan, Taylor 1910.11892
Richman, Ghosh, Carney, Higgins, Shawhan, Taylor 2311.09587

Quantum mechanics and measurement

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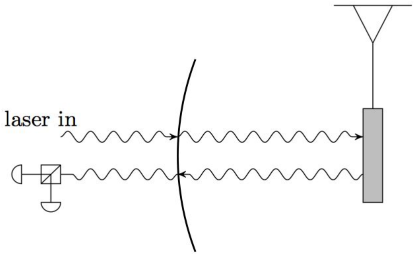
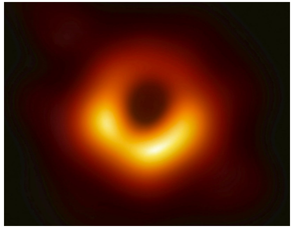
Quantum mechanics itself does not impose any limit to how precisely one can measure a system.

Ultimately, the *fundamental* limits to what is possible in measurement are largely unknown, although we know some exist e.g. from quantum gravity…



$\Delta x = 0 \rightarrow \Delta p = \infty$



Final comments

- 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, …?

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a user's manual" 2311.07270

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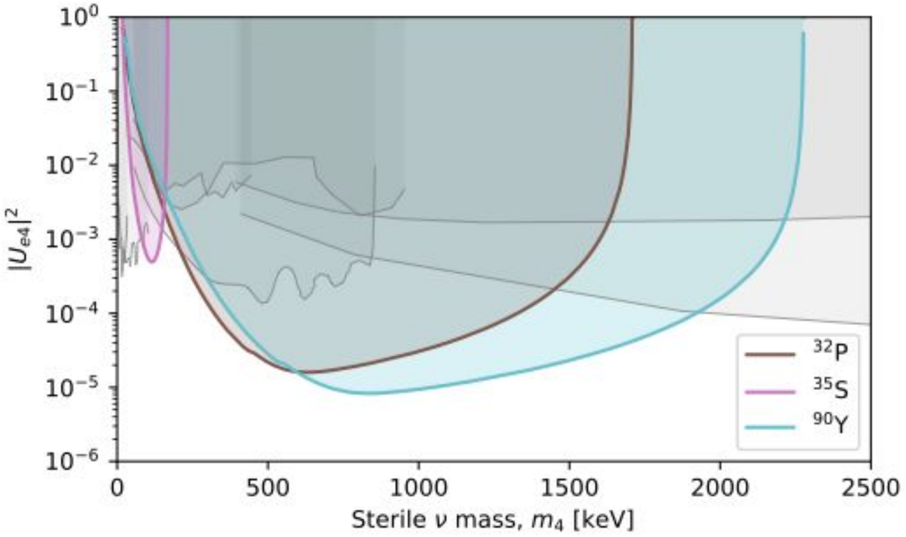
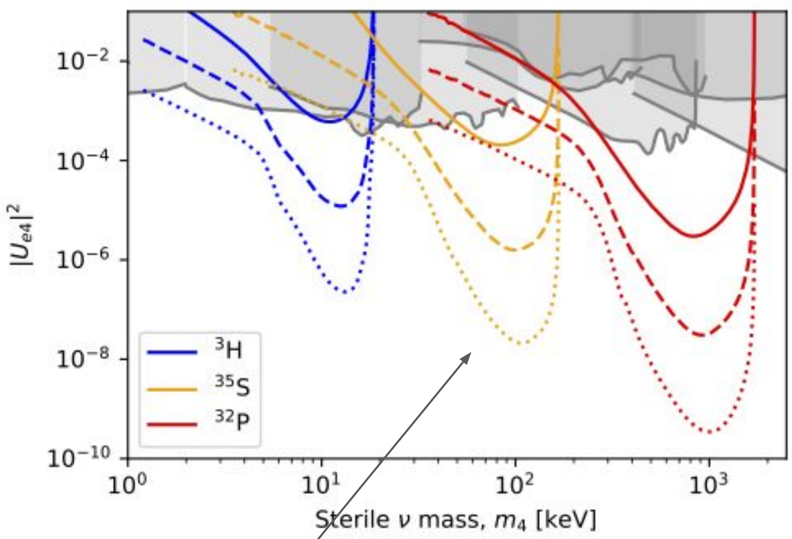
Searches for new heavy neutrinos





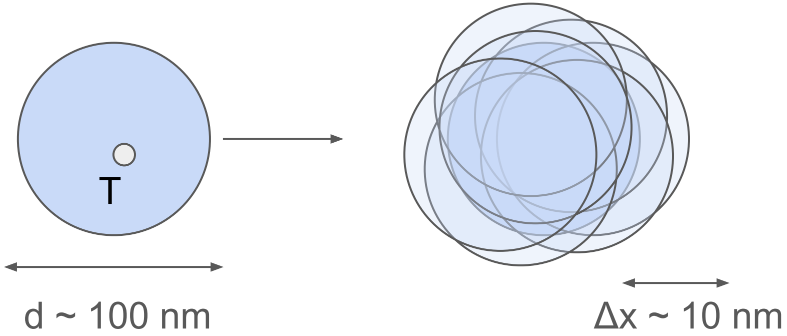
1 sphere, 1 month exposure, SQL

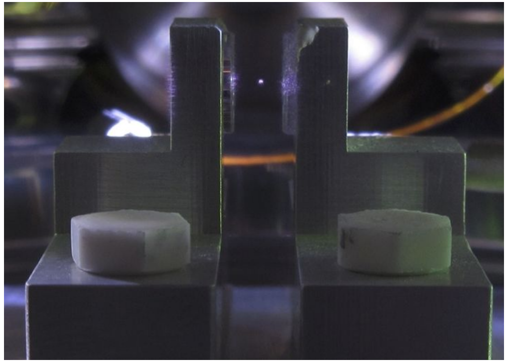
1000 spheres x 1 year, SQL

Example: neutrino mass measurement?

Use QuIPS, statistically average 10^6 events (~10^4 spheres). Then with sphere uncertainty

$\Delta p \sim 100$ eV → $\Delta x \sim 10$ nm → can in principle resolve ~ 100 meV neutrino mass





With 100 nm spheres, 1 kHz trap, this only requires ~few dB squeezing.

T.-C. Lee

J. Beckey

G. Marocco