Mechanical architectures for ~~dark matter detection~~ fundamental physics

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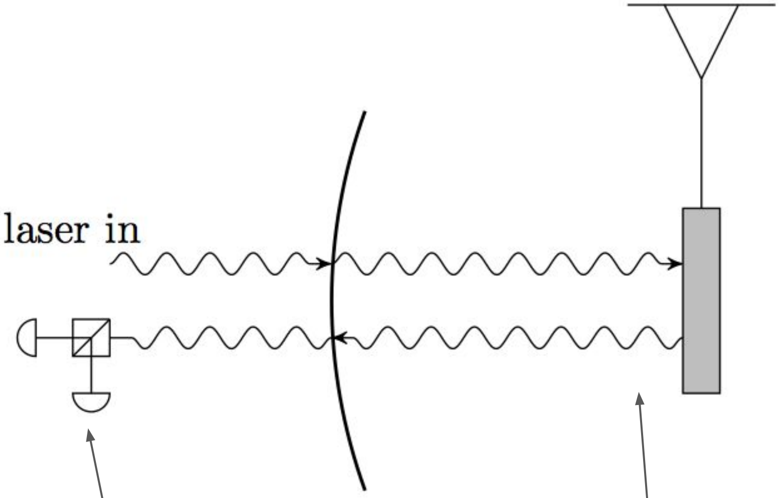
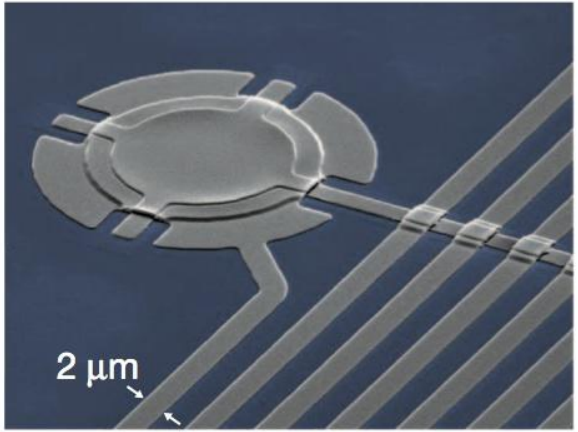
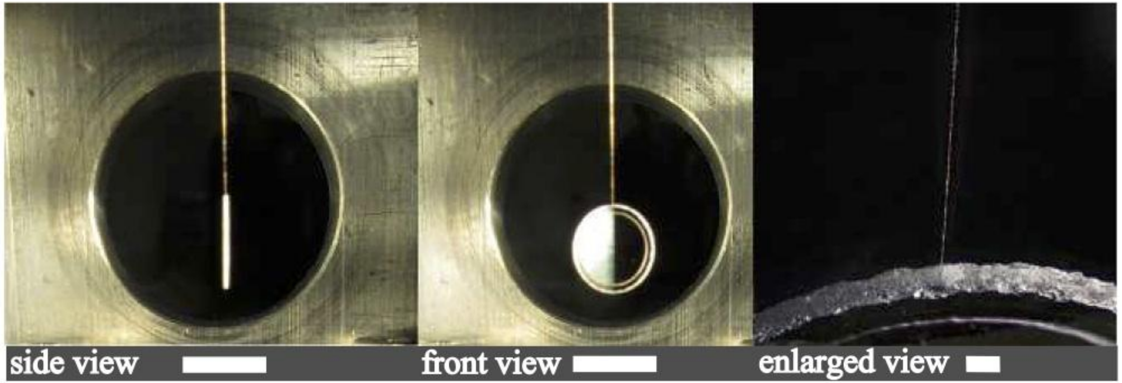
Mechanical sensing: basic model



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

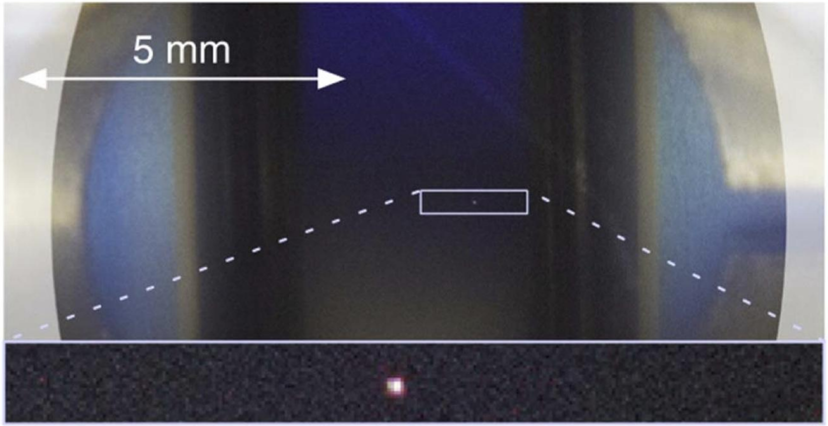
light phase shift ~ x(t)

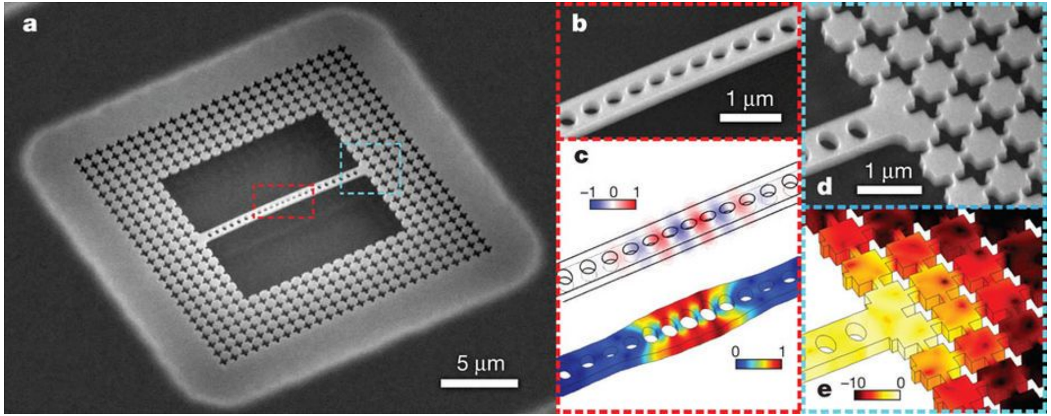




Teufel et al, Nature 2011

Matsumoto et al, PRA 2015





Aspelmeyer ICTP slides 2013

Painter et al, Nature 2011

Some experimental achievements to date

- LIGO $x \sim 10^{-18}$ m/rtHz
- Accelerometers $a \sim 10^{-8}$ m/s^2/rtHz
- Single-phonon readout $E \sim 10^{-6}$ eV
- Micron-scale, long-lived spatial superpositions $m \sim 10^5$ amu
- Ground state cooling from m ~ 1 amu - 1 ng
- Entanglement of two masses at m ~ pg, x ~ 100 um
- Quantum backaction measurements at many scales

Some ideas for using these

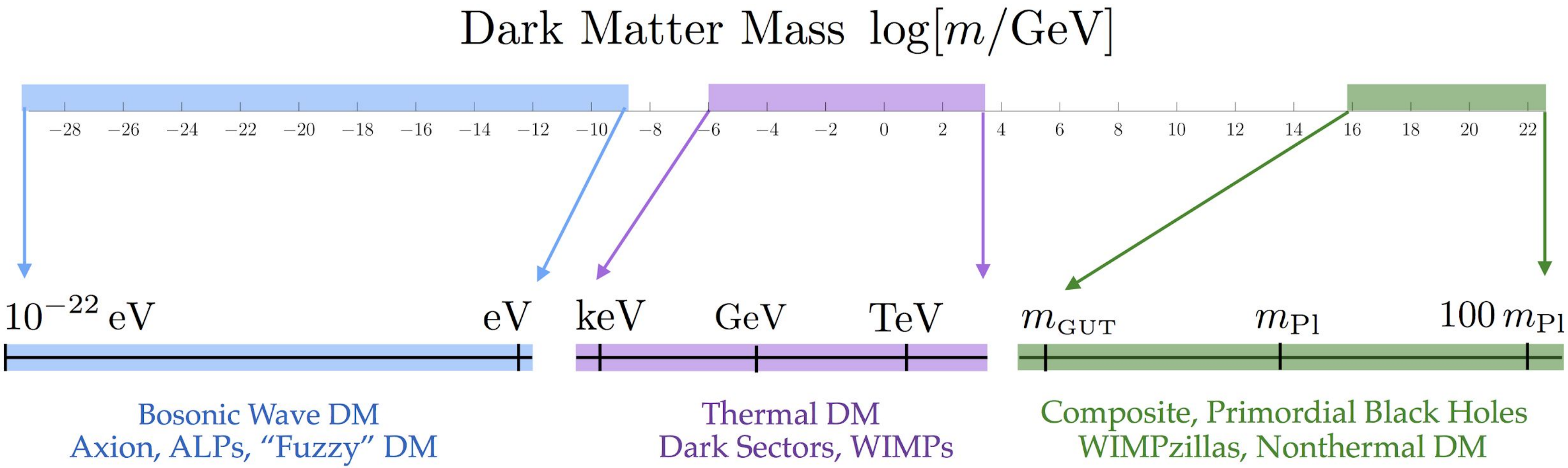
time
difficulty
"quantumness"

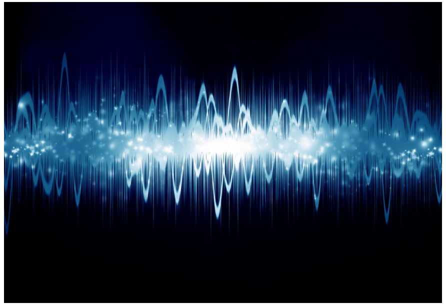
Ultralight ("axion-like") dark matter detection

Low-threshold impulse sensing

Heavy ("mega") dark matter detection

Experimental quantum gravity





coherent

model-dependent

coherent
(gravity)

Where these technologies can win

- Sensitivity to coherent signals

  -Spatial coherence: signal acts on entire macroscopic device
  -Temporal coherence: can integrate signal for “long” time

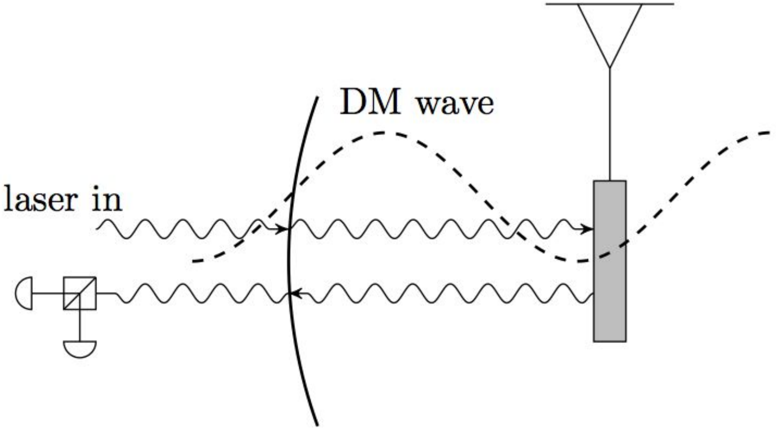
- Volume/mass: large devices → integrate small cross-sections

- Wide range of available parameters and architectures

Ultralight DM detection

Suppose DM consists entirely of a single, very light field: $m_\phi \lesssim 1$ meV ($\lambda\!\!\!^{-} \gtrsim 10^{-3}$ m).

Locally, this will look like a wave with wavelength > detector size.



$$\mathcal{L}_{int} = g_{B-L}\not{A}\bar{n}n \longrightarrow F = g_{B-L} N_n F_0 \sin(\omega_s t)$$

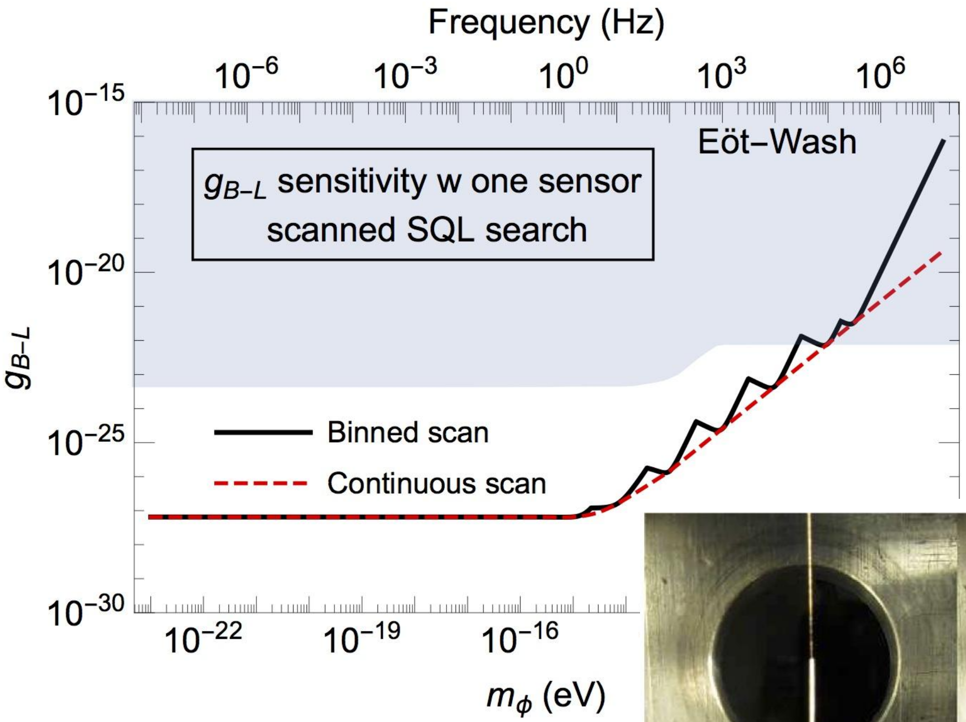
Dark matter direct detection with accelerometers
P. Graham, D. Kaplan, J. Mardon, S. Rajendran, W. Terrano 1512.06165

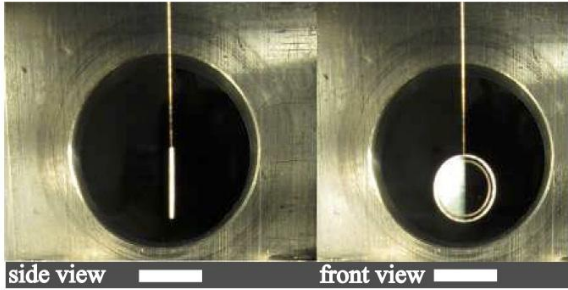
Ultralight dark matter detection with mechanical quantum sensors
D. Carney, A. Hook, Z. Liu, J. M. Taylor, Y. Zhao, 1908.04797

Detection strategy and reach

Tune laser to achieve SQL in “bins”.

Integrate as long as possible for each bin (eg. laser stability ~ 1 hr)





Matsumoto et al, PRA 2015

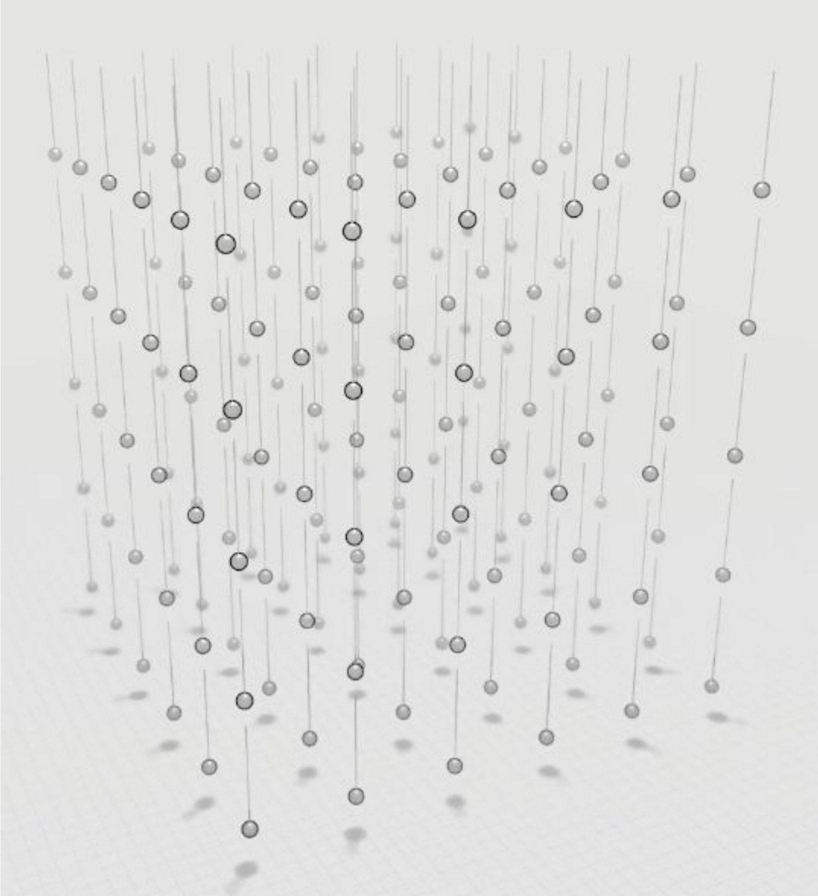
Correlated signals vs. uncorrelated noise

SNR ~ $\sqrt{N_{sensors}}$

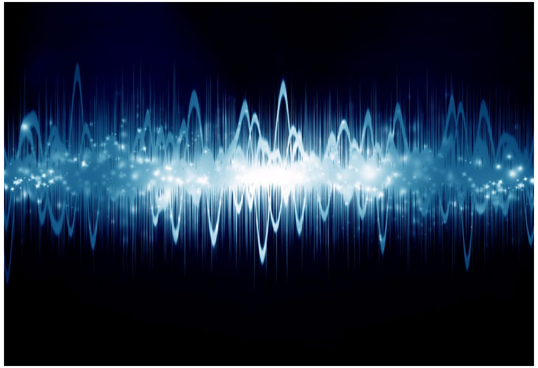
or even ~ N, w/ coherent readout

Also: background rejection

→ build local array, and/or larger network, if signal long wavelength

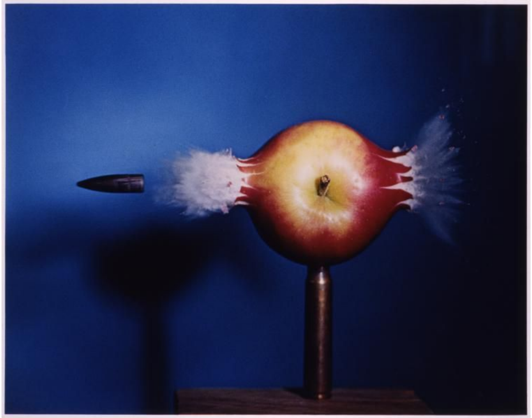


Different detection problems have different limits



Sinusoidal, persistent(-ish) signals

(eg. gravitational waves, ultra-light dark matter)



Sharp, rapid impulse signals

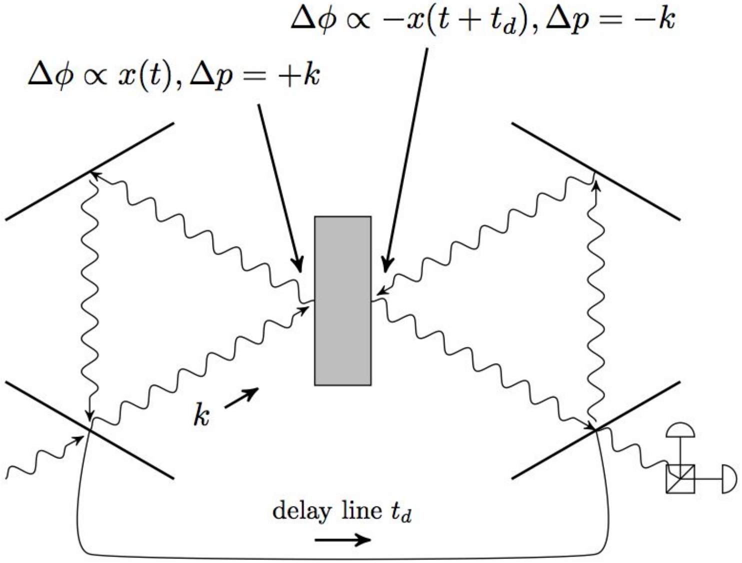
(eg. particle colliding with a sensor)

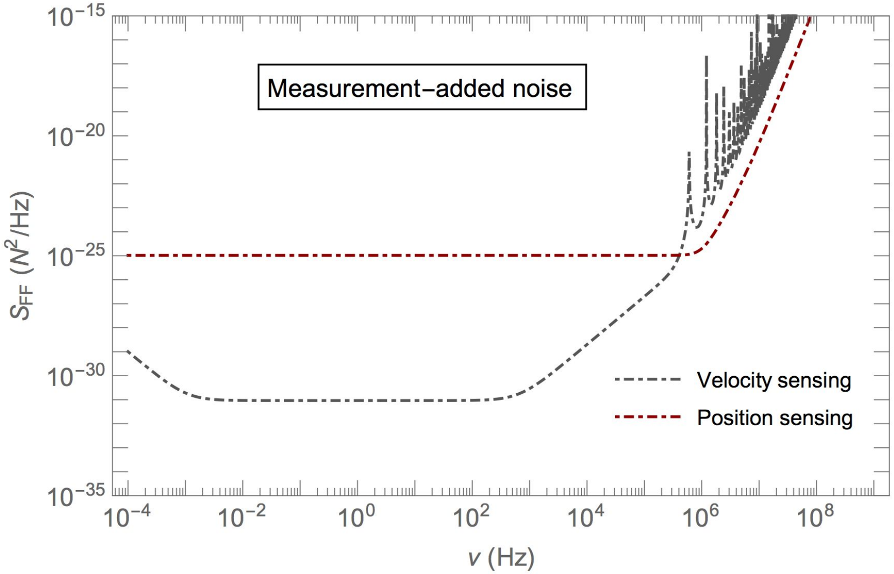
Subject to different quantum noise limitations

Quantum impulse sensing

- For a free mass detector, $[H,p]=0 \rightarrow$ measuring p does not disturb the momentum (“non-demolition”), different than measuring x
- This can be used to reduce quantum noise (“backaction evasion”)
- Potential to use this for very low-threshold momentum sensing with meso/macroscopic sensors

Momentum sensing with optomechanics





Back-action evading impulse measurements with mechanical quantum sensors
S. Ghosh, **D. Carney**, P. Shawhan, J. M Taylor 1910.11892

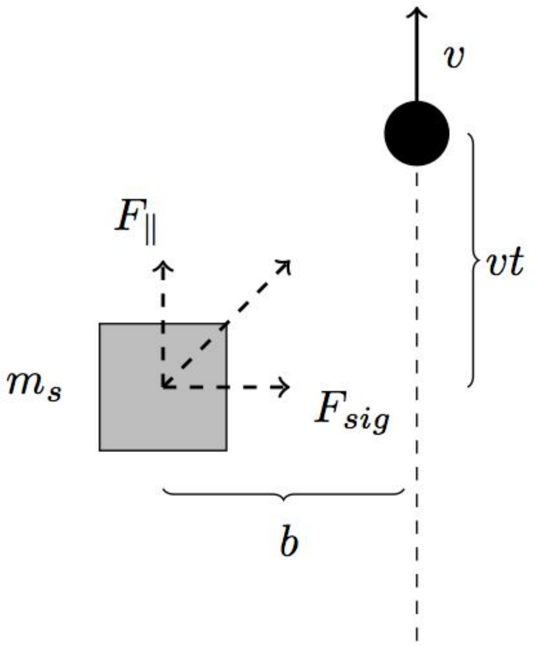
Application to grav. waves:
Braginsky, Khalili PLA 1990!

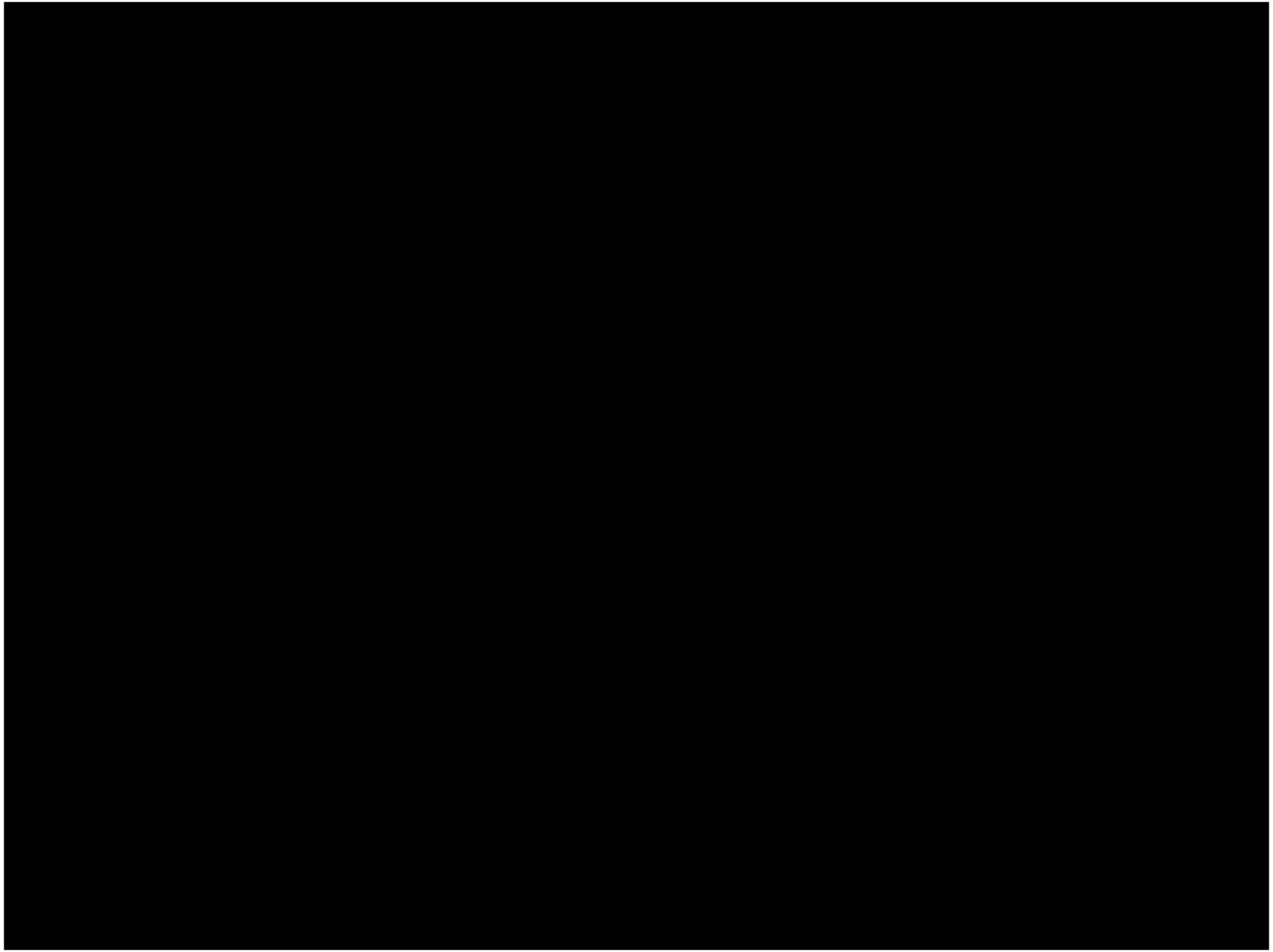
End goal: gravitational detection?

If dark matter exists, the only coupling it's guaranteed to have is through gravity.

Can we detect it that way in a terrestrial lab?

$$F = \frac{G_N m_s m_\chi}{r^2}$$





Video from Sean Kelley, NIST (https://inform.studio)

Direct detection via gravity is possible

This is a long-term goal: in particular, must achieve

1. Very low-noise readout in ~mg scale sensors (significant quantum-added noise reduction, eg. through impulse sensing protocol)
2. Large array of sensors (~10 mil)
3. Good isolation (~UHV pressure)

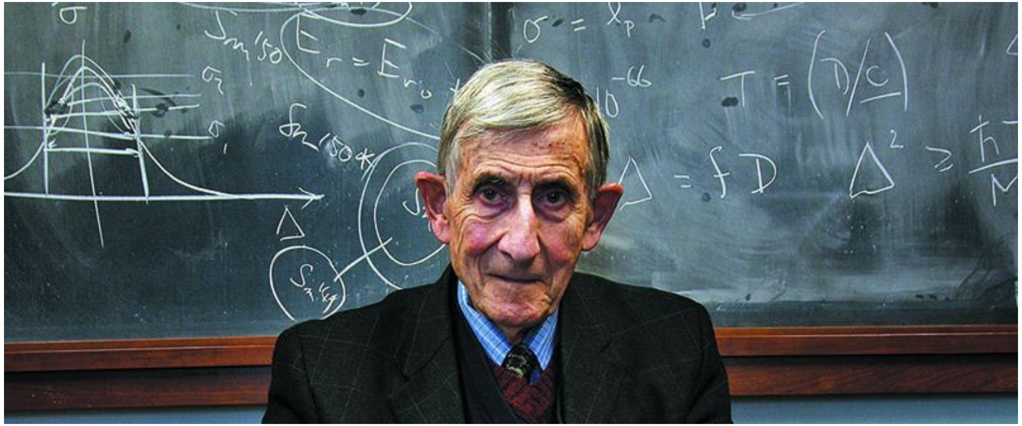
Given these requirements, can detect dark matter of masses around $m_{plank} \sim 10^{19}$ GeV ~ 0.02 mg and heavier.

This is probably not optimized--stay tuned for better versions!

Gravitational Direct Detection of Dark Matter
D. Carney, S. Ghosh, G. Krnjaic, J. M. Taylor 1903.00492

See related work by Adhikari et al, 1605.01103 and Kawasaki 1809.00968

The holy grail: experimental quantum gravity



Is a Graviton Detectable?

Poincare Prize Lecture

International Congress of Mathematical Physics

Aalborg, Denmark, August 6, 2012

Freeman Dyson, Institute for Advanced Study, Princeton, New Jersey

Dyson’s answer: no.

Argument: try to build sufficiently sensitive version of LIGO.

It will collapse into a black hole.

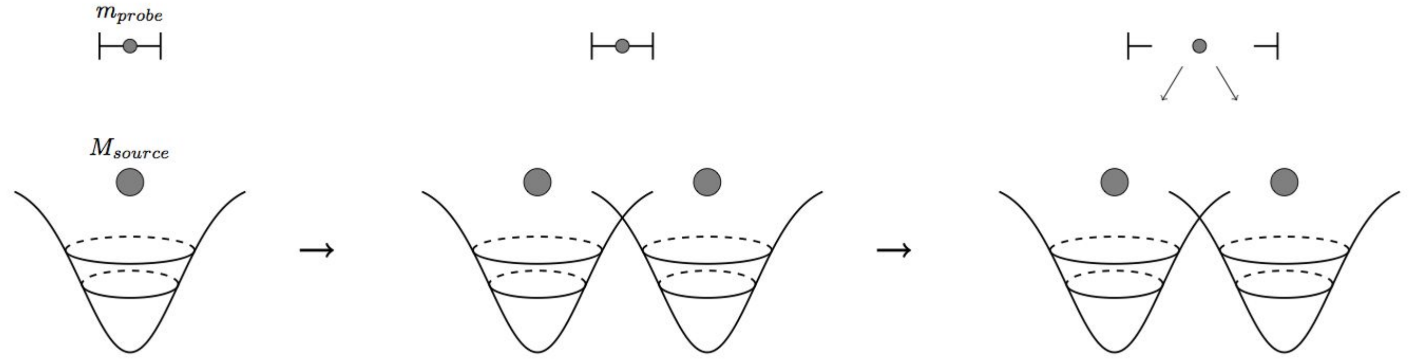
Ok, but can we do something smarter?

“Is gravity quantum?”

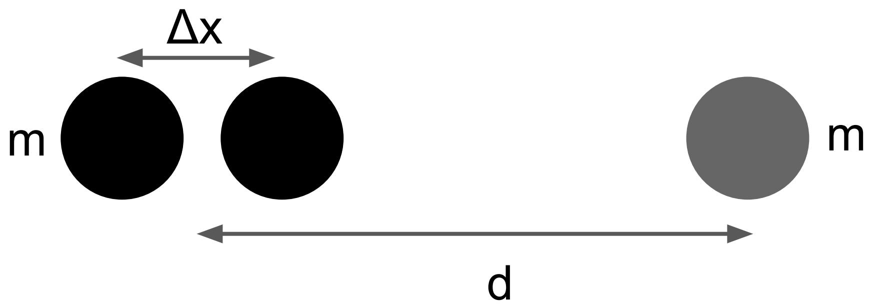
Nice information theoretic issue: what does this question even mean?

Old school answer: gravity is quantum if there are gravitons.
New school answer: gravity is quantum if gravity can transmit quantum information.

(Equivalence: Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer 1807.07015)



$$|0_m\rangle \otimes |0_M \; g^0_{\mu\nu}\rangle \qquad |0_m\rangle \otimes \left(|L \; g^L_{\mu\nu}\rangle + |R \; g^R_{\mu\nu}\rangle\right) \qquad |\ell \; L \; g^L_{\mu\nu}\rangle + |r \; R \; g^R_{\mu\nu}\rangle$$



$$\Delta\phi = \frac{G_N m^2 \Delta x \Delta t}{\hbar d^2} \approx 60 \times \left(\frac{m}{1\,\mathrm{ng}}\right)^2 \left(\frac{\Delta x}{1\,\mu\mathrm{m}}\right) \left(\frac{\Delta t}{1\,\mathrm{s}}\right) \left(\frac{1\,\mu\mathrm{m}}{d}\right)^2$$

Two central difficulties:

1. State preparation and coherence--needs new ideas (eg. error correction?)
2. Readout--see previous part of talk

Tabletop experiments for quantum gravity: a user's manual
D. Carney, P. Stamp, J. Taylor 1807.11494

Spin entanglement witness for quantum gravity
S. Bose et al 1707.06050

Editorial remark on laboratory quantum gravity

Extremely exciting prospect: entering era of lab tests of quantum gravity.

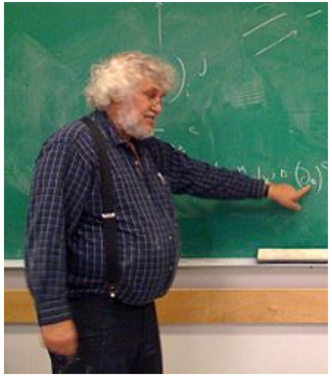
In my opinion there are three classes of such tests:

- Simulations (analogue: G. Campbell talk, digital: S. Leichenauer talk)
- Tests of speculative/phenomenological models (gravitationally-induced wavefunction collapse, holographic noise, etc.)
- Direct tests of properties of gravity as a low-energy EFT

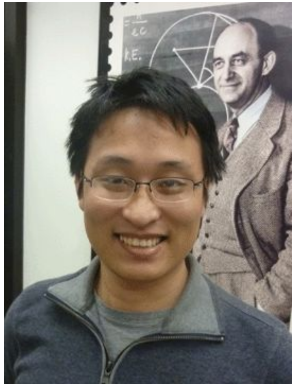
These are all valuable for different reasons, and can be used to discriminate between possible models of QG.

Conclusions

- Mechanical sensors in both classical and quantum regimes have numerous potential applications in HEP/gravity.
- Scalable architectures exist and can be used to push detection reach rapidly.
- Some immediate goals: ultralight DM searches and impulse sensing.
- One long term goal: gravitational direct detection of Planck-scale DM.
- Another: **direct experimental tests of quantum gravity.**

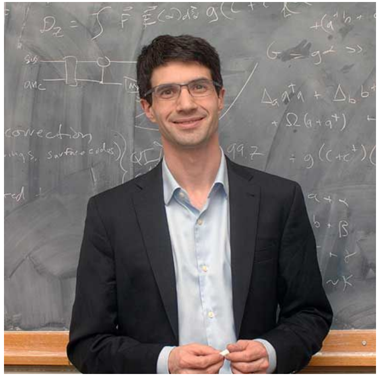


B. Unruh



Z. Liu

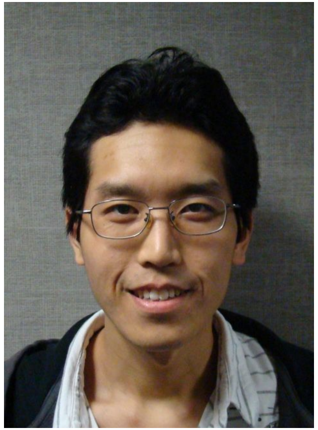
G. Krnjaic



J. Taylor

C. Regal

P. Stamp



Y. Zhao

A. Hook

S. Ghosh

D. Moore

Extra/backup slides

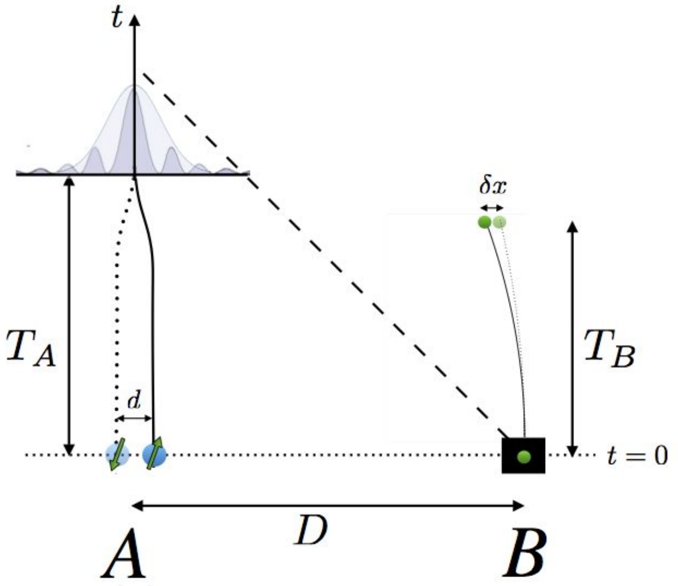
Gravitons

So ∃ graviton → entanglement generation.

Does entanglement generation → ∃ graviton?

Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer 1807.07015:

If you can entangle with Newton interaction, you can signal faster than light. Existence of quantized metric fluctuations resolves this problem.

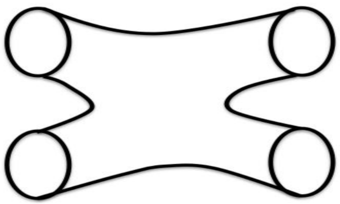


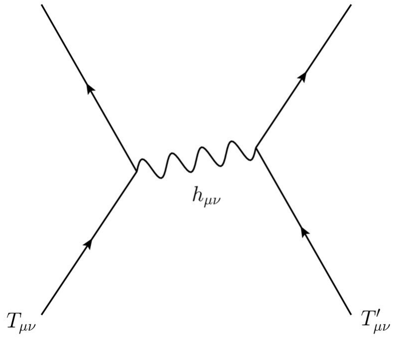
—> Entanglement generation experiment would demonstrate the existence of the graviton, under mild assumptions.

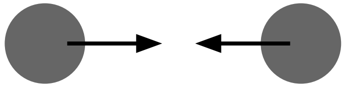
Theory implications

Quantized general relativity:

graviton exchange → Newton two-body operator —> entanglement

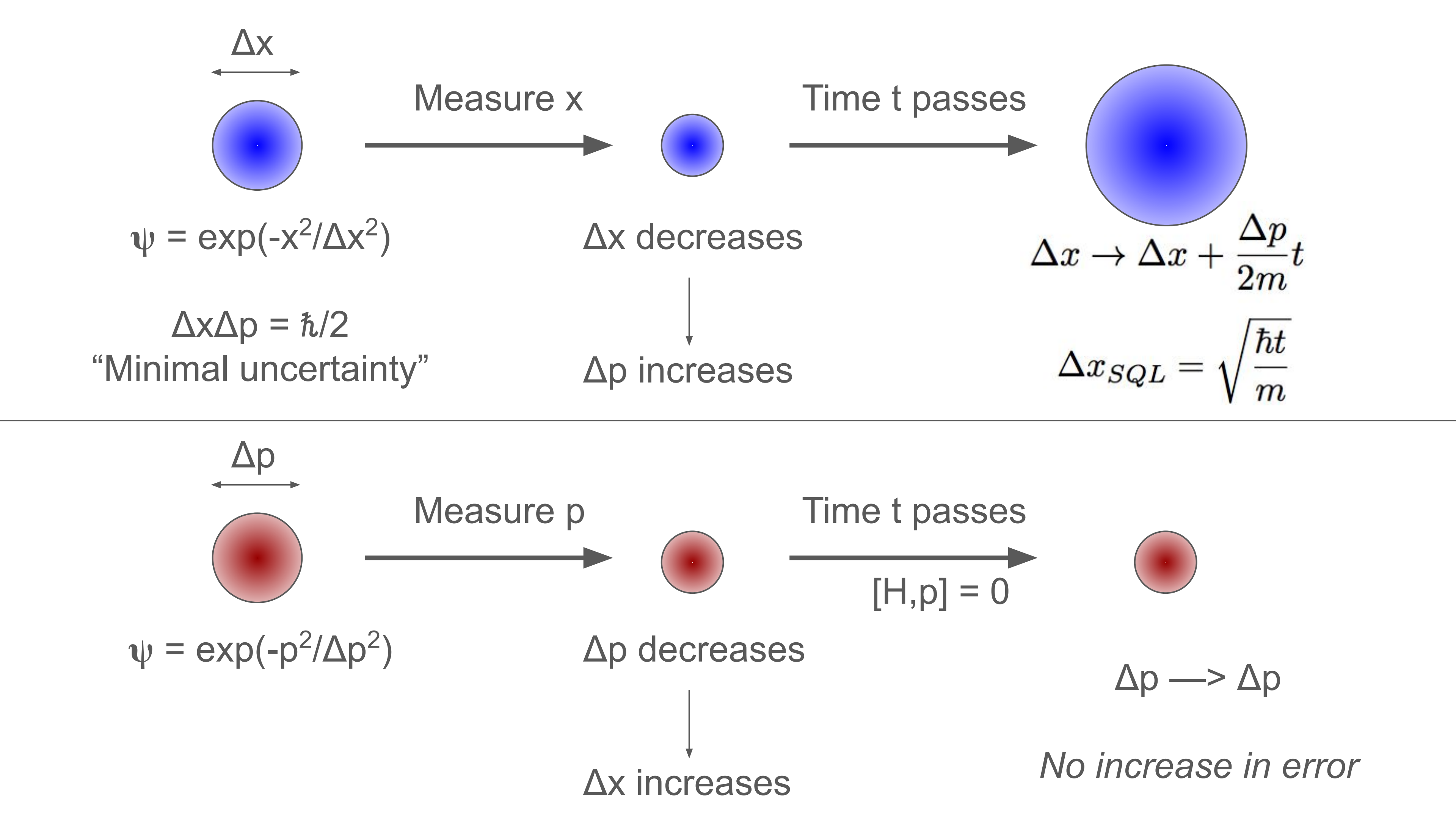






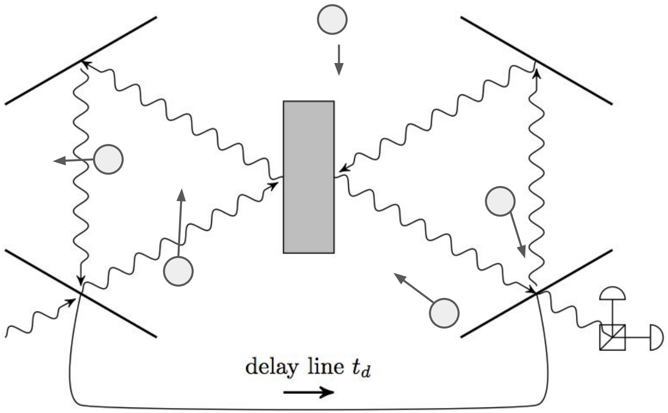
$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$$

$$\hat{V} = \frac{G_N m_1 m_2}{|\hat{\mathbf{x}}_1 - \hat{\mathbf{x}}_2|}$$



Δx
Measure x
Time t passes
ψ = exp(-x²/Δx²)
Δx decreases
Δp increases
$\Delta x \to \Delta x + \frac{\Delta p}{2m}t$
ΔxΔp = ℏ/2
"Minimal uncertainty"
$\Delta x_{SQL} = \sqrt{\frac{\hbar t}{m}}$
Δp
Measure p
Time t passes
[H,p] = 0
ψ = exp(-p²/Δp²)
Δp decreases
Δx increases
Δp —> Δp
No increase in error

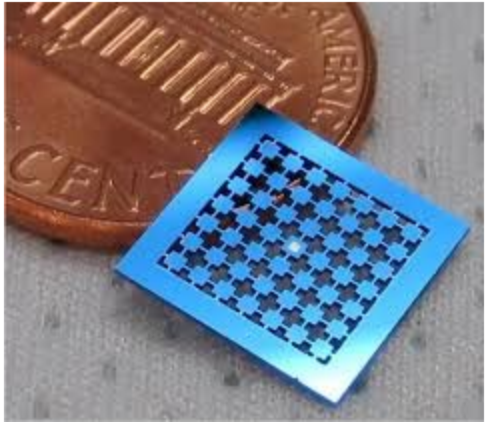
How good is this?



Consider eg. a dilute gas of helium atoms, at room temperature, impinging on sensor. Approx F(t) ~ Δp (t)

The collisions of these with a ~fg sensor can be individually resolved:

$$\mathrm{SNR} \approx 1 \times \left(\frac{\Delta p}{10\ \mathrm{keV/c}}\right)\left(\frac{1\ \mathrm{fg}}{m}\right)^{1/2}\left(\frac{10^{-4}}{L}\right)^{1/4}$$



Picture from Cindy Regal's lab (JILA/Boulder)

Noise and sensitivity

Total (inferred) force acting on the sensor:

$$F_{\mathrm{in}}(t) = F_{\mathrm{sig}}(t) + F_{\mathrm{th}}(t) + F_{\mathrm{meas}}(t)$$

thermal noise forces
(environmental)

measurement added-noise force
(fundamental quantum issue)

Key in what follows:
Noise = stochastic, Brownian