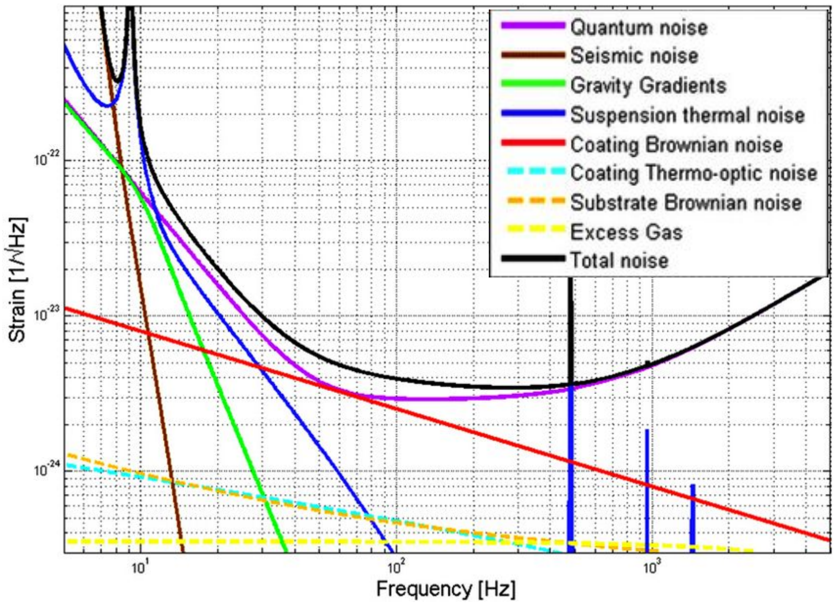
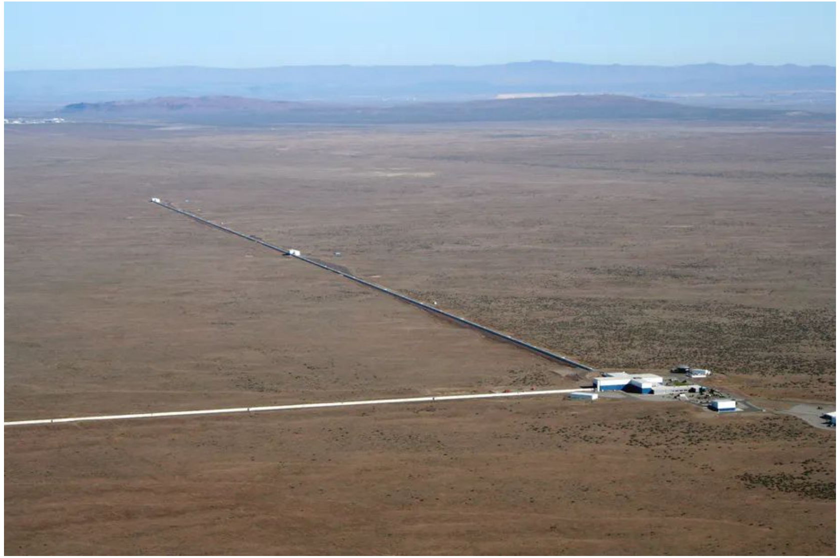
Quantum noise limits & how to evade them

Daniel Carney

BERKELEY LAB

Quantum-limited detection





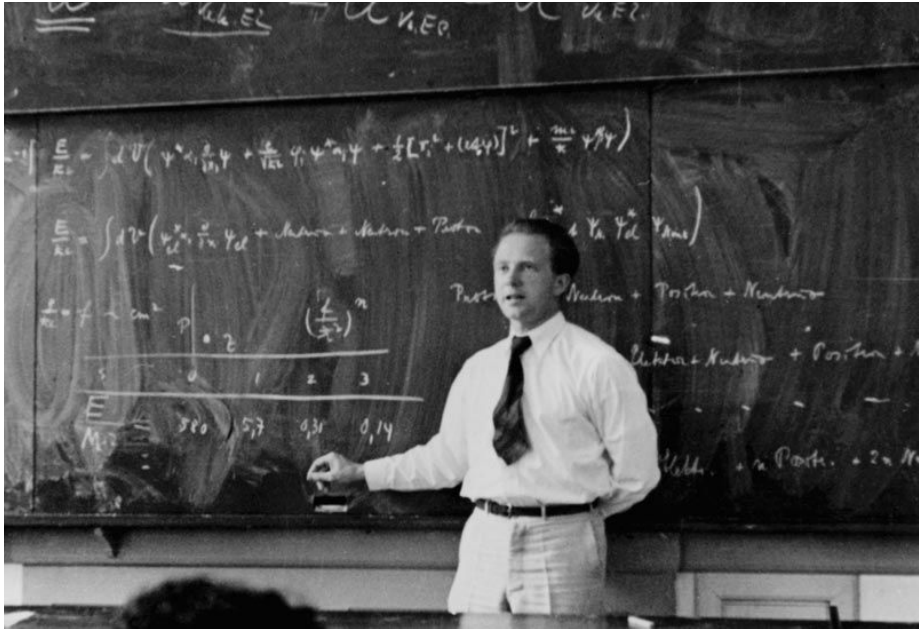
The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy
LIGO Collaboration 1604.00439

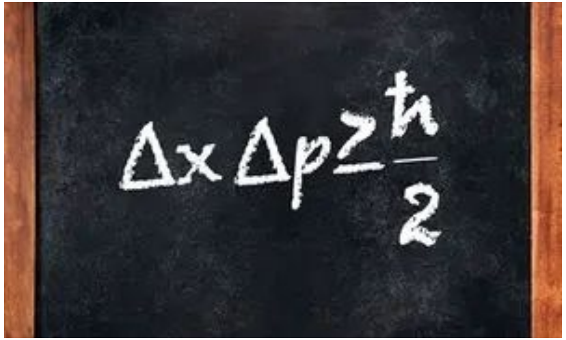
Goals in this talk

- Explain what “quantum noise” means in continuous measurements
- Define a Standard Quantum Limit (SQL)
- Discuss some methods to get to sub-SQL noise

I will illustrate these points with some examples in current HEP experiments, but will not make any attempt to be exhaustive.

Quantum measurement noise





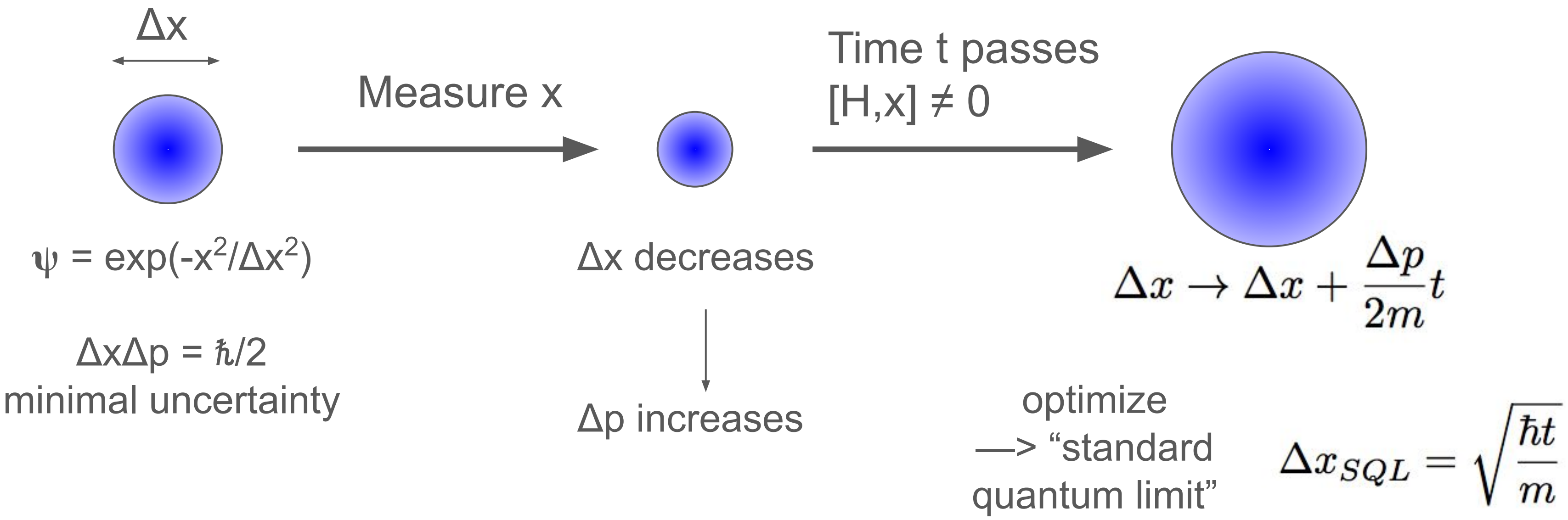
The state of a system cannot have a definite value for both momentum and position.

What does this imply for *measurements*?

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)



Comments on the SQL

- Quantum noise is always present, but it doesn't matter in regimes where the system is limited by "technical" issues like thermal noise, stray fields, seismic noise, etc.

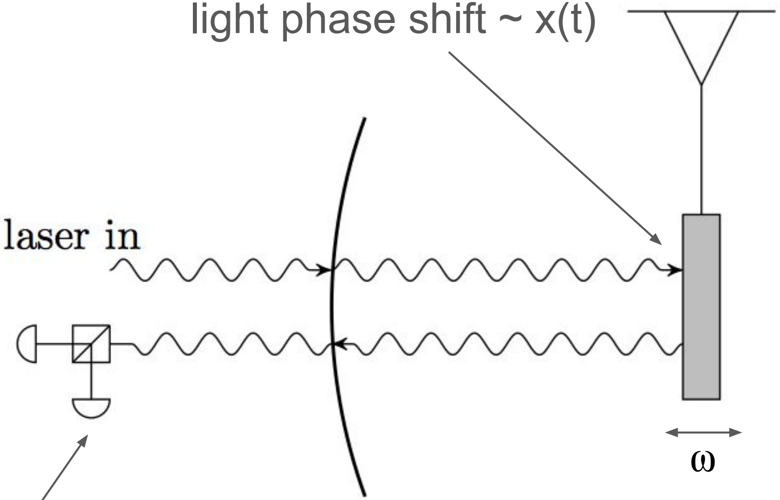
- Applies to any **continuously monitored** operator of a DOF which has a non-commuting variable in its Hamiltonian (for example x and p, or S_z and S_x in a spin system).

- The SQL is, at most, just a bound: we have yet to discuss how to actually saturate it with a readout scheme.

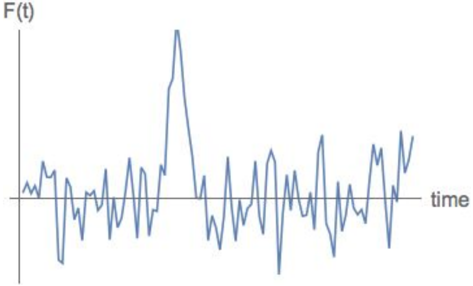
- It's also not even a strict bound: there are loopholes, to be discussed.

Opto-mechanical sensing

light phase shift ~ x(t)



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



mechanics
$[x,p] = i\hbar$

fundamental
cavity mode
$[X,Y] = i\hbar$

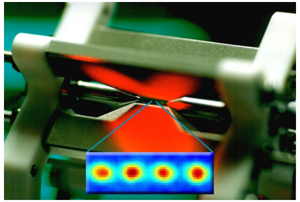
$$H_{OM} = gxX$$

Laser power enhances
coupling

$$g \propto g_0\sqrt{P}$$

"Opto-mechanics" = motion read out by light

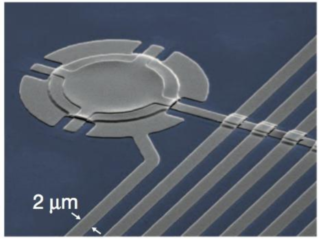
Trapped electrons, ions

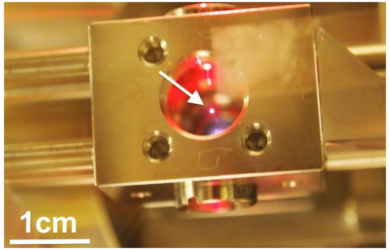


$$\Delta p_{SQL} = \sqrt{\hbar m_s \omega}$$

~ 1 meV/c
(m = m_e, $\omega = 2\pi$ kHz)

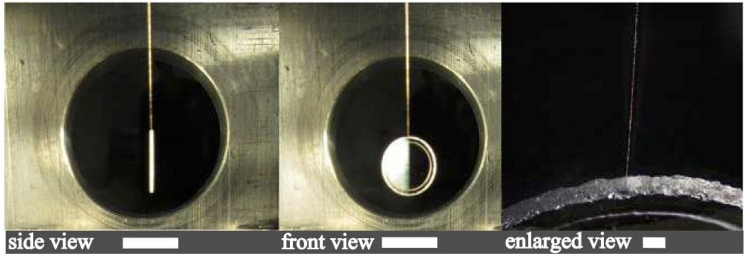
Nanomechanical objects





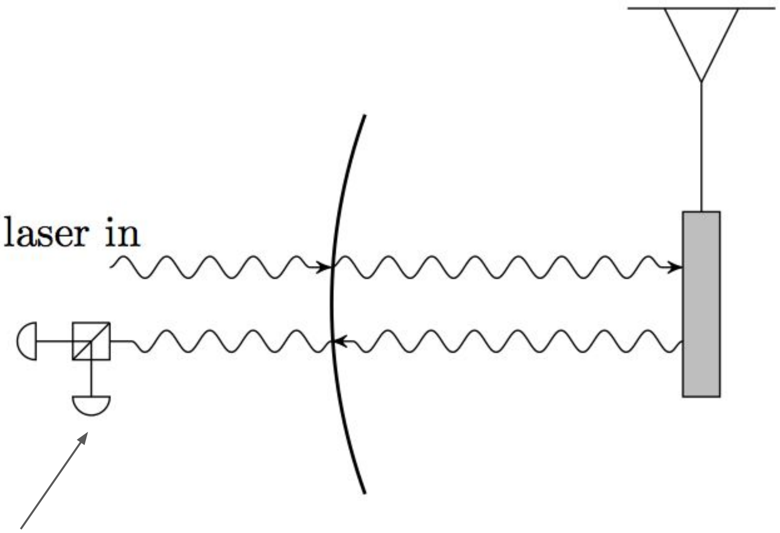
~ 1 MeV/c
(m = 1 ng, $\omega = 2\pi$ kHz)

Macroscopic objects
(>microgram scale)



~ 1 GeV/c
(m = 1 mg, $\omega = 2\pi$ kHz)

Opto-mechanical sensing



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

Total (inferred) force = signal + noise

$$F = F_{\mathrm{s}} + F_{\mathrm{n}}$$

Noise power density = autocorrelator

$$S_{FF}(\nu) := \int_{-\infty}^{\infty} dt e^{i\nu t} \langle F_n(t) F_n(0) \rangle$$

Signal-to-noise ratio

$$\mathrm{SNR} = \sqrt{\int d\nu \frac{|F_s(\nu)|^2}{S_{FF}(\nu)}}$$

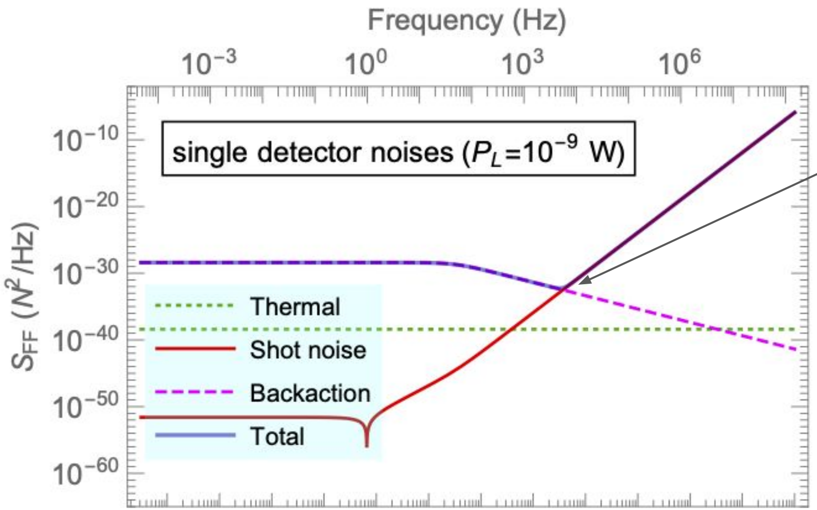
Noise PSD

$$S_{FF} = a\left\langle |Y_{\rm in}|^2 \right\rangle + b\left\langle |X_{\rm in}|^2 \right\rangle + c\left\langle |F_{\rm thermal}|^2 \right\rangle$$

“Shot noise” (input laser phase fluctuations)

“Back-action noise” (noisy radiation pressure)

Thermal load on mechanics



SQL = point where shot and backaction are balanced

$$S_{FF}(\omega_{\rm SQL}) = \begin{cases} 2\hbar m\omega^2 & \omega_{\rm SQL} \ll \omega \\ 2\hbar m\omega\gamma & \omega_{\rm SQL} = \omega \\ 2\hbar m\omega_{\rm SQL}^2 & \omega_{\rm SQL} \gg \omega \end{cases}$$

Impulse (broadband) SQL

As this stage we can work out the requirements to achieve impulse SQL

$$\mathrm{SNR}^2 = \frac{\Delta p^2}{2\pi}\int \frac{d\nu}{S_{FF}(\nu)}$$

Assuming SFF~const over some bandwidth $\Delta\nu$

$$\Delta p = \sqrt{\frac{S_{FF}(\omega_{\mathrm{SQL}})}{\Delta\nu}}$$

Easiest thing: tune laser for on-resonance SQL, integrate over bandwidth ~ mechanical linewidth

$$\Delta p_{\mathrm{SQL}} \approx \sqrt{\frac{2\hbar m\omega\gamma}{\gamma}} = \sqrt{2\hbar m\omega}$$

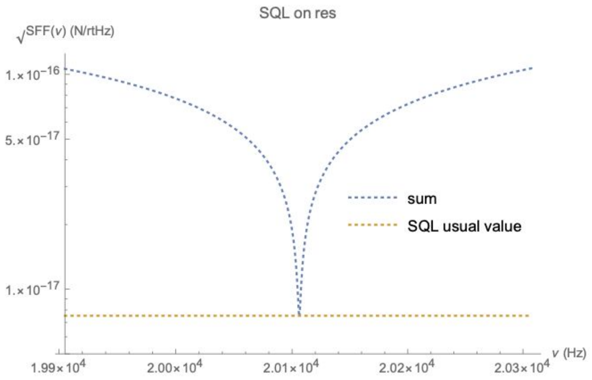
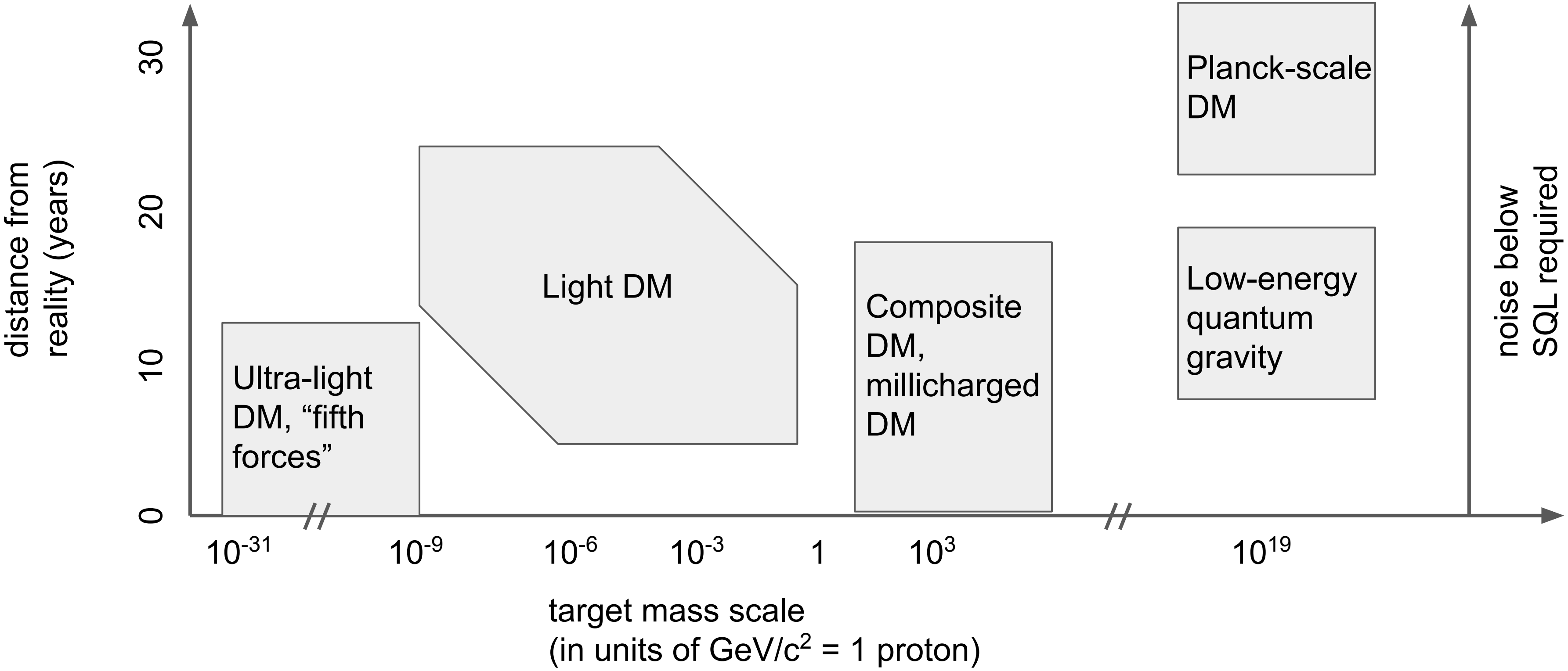
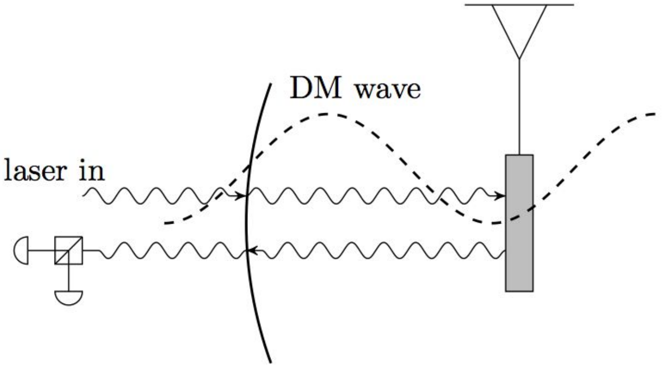


Figure 1: Force sensitivity for on-resonance SQL $\omega_\phi = \omega$, plotted over a bandwidth $\Delta\nu = 100\times\gamma$. Here $m = 70$ mg, $\omega = 3.2\times 2\pi$ kHz, $Q = 10^4$. The blue curve means the sum of the shot noise and back-action noise curves.

Some HEP use cases as a function of noise level



Ultra-light DM

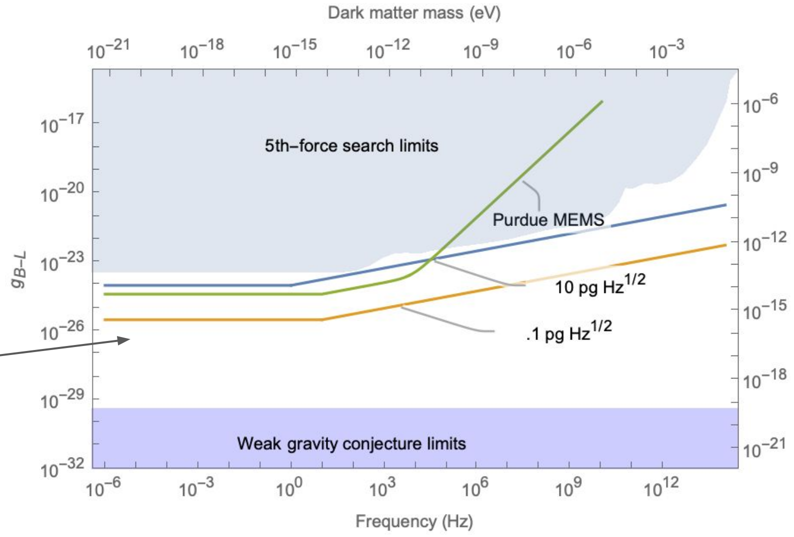


Clear target at SQL, or above, noise levels: ultra-light DM with mechanical accelerometers.

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

Very much like an axion cavity experiment, except the cavity is replaced by a mechanical element.

SQL for ~1 gram accelerometers



1512.06165 Graham et al
1908.04797 Carney, Hook, Liu, Taylor, Zhao
See also M. Safronova's talk

Coherent DM scattering

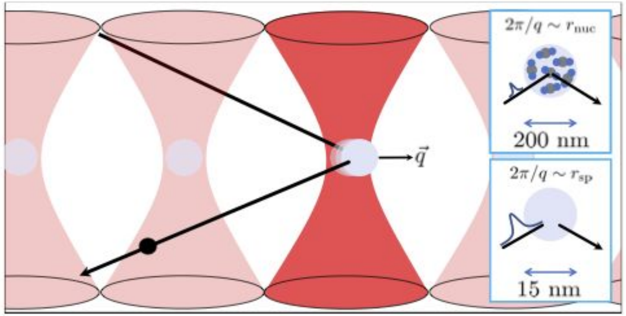
Consider trapped spheres ~10 nm (~ 10^7 atoms)

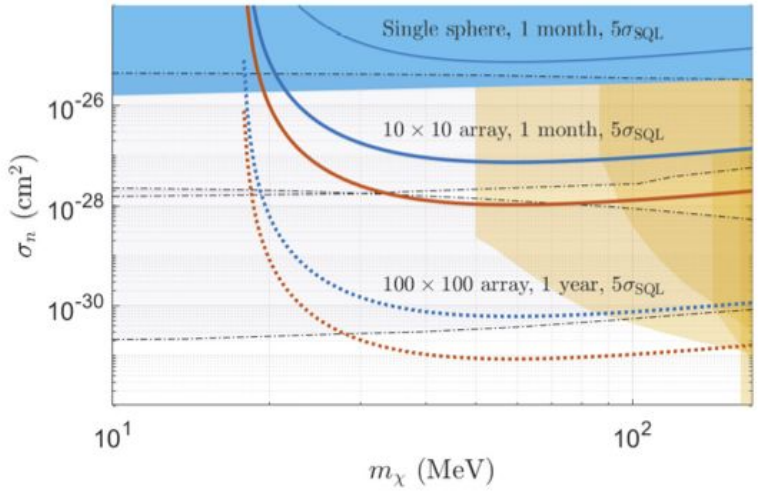
Light DM (with contact nucleon interactions) will scatter quantum-coherently off the sphere → big increase in cross section

Requires ~10dB below SQL, ~10^4 devices to get into non-constrained parameter space

Afek, Carney, Moore 2111.03597

See also D. Moore's talk





The holy grail: gravitational DM detection

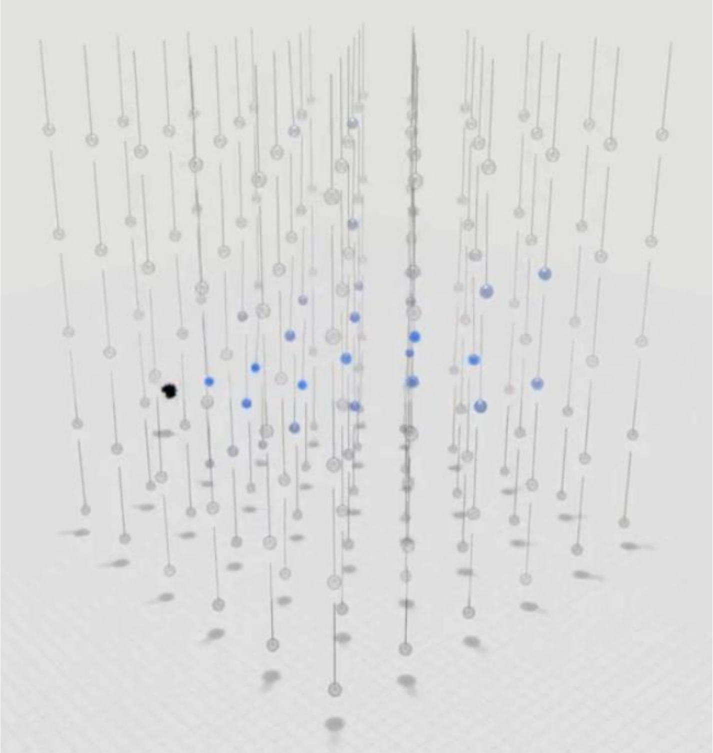
$$F = \frac{G_N m_s m_\chi}{r^2}$$

Signal = correlated track of macroscopic motion

With ~ mm-cm spacing, mg-g mass devices, 10^6 - 10^9 devices, can detect DM at masses

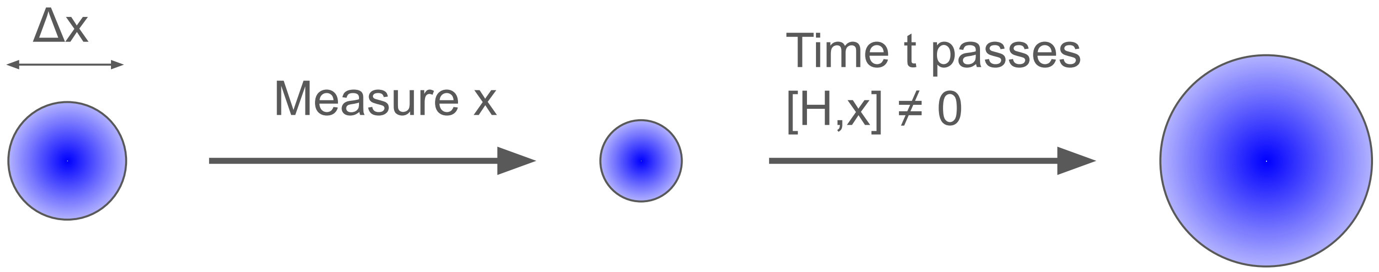
m ~ m_{planck} ~ 4 ug ~ 10^{19} GeV.

But need quantum measurement protocol that can get **well** below SQL… long term target. But not ruled out by e.g. thermal noise floor.

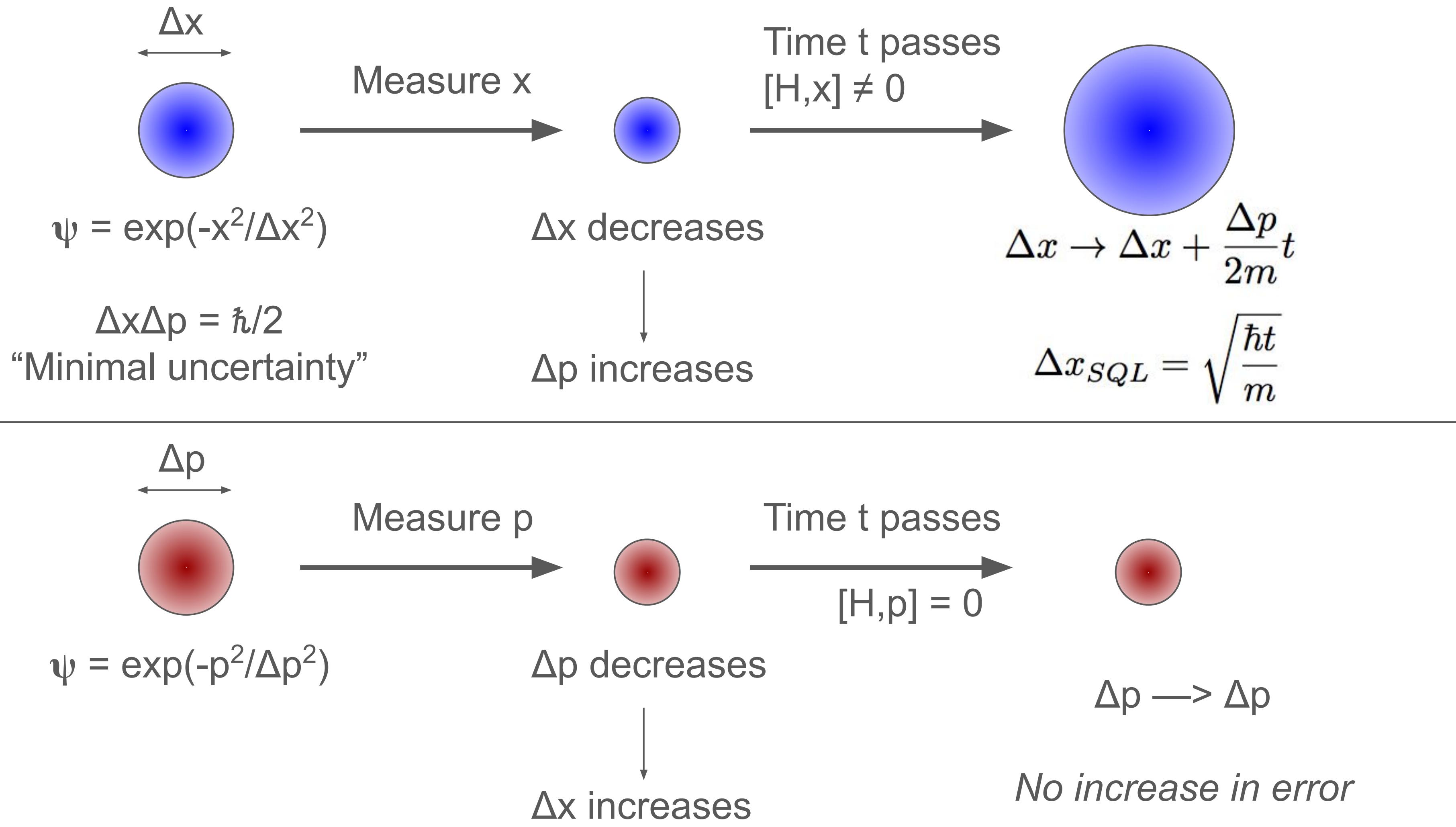


Carney, Ghosh, Krnjaic, Taylor 1903.00492
Windchime collaboration: experimental work, ultralight DM: 2203.07242

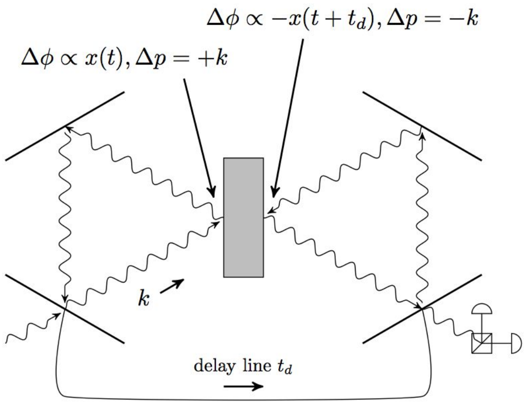
Methods to get below the SQL



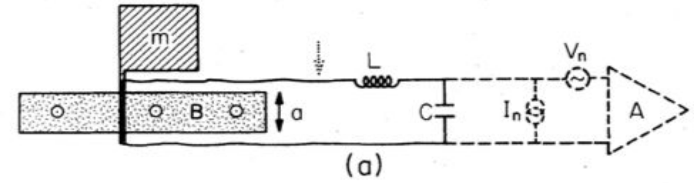
- Squeezing (although this is more subtle than many think…)
- **Measure a variable that commutes with H (“quantum non-demolition”)**
- Use multiple detectors
- Use quantum error correction
- Even more complex ideas


Δx
Measure x
Time t passes
$[H,x] \neq 0$
$\psi = \exp(-x^2/\Delta x^2)$
Δx decreases
$$\Delta x \to \Delta x + \frac{\Delta p}{2m} t$$
$\Delta x \Delta p = \hbar/2$
“Minimal uncertainty”
Δp increases
$$\Delta x_{SQL} = \sqrt{\frac{\hbar t}{m}}$$
Δp
Measure p
Time t passes
$[H,p] = 0$
$\psi = \exp(-p^2/\Delta p^2)$
Δp decreases
$\Delta p \longrightarrow \Delta p$
Δx increases
No increase in error

Measuring momentum instead of position



Braginsky, Khalili PLA 1990



Caves, Thorne, Drever, Sandberg, Zimmerman RMP 1980

$$H_{\mathrm{OM}} = gxX \to \tilde{g}pX$$

$$S_{FF} = a\left\langle |Y_{\mathrm{in}}|^2 \right\rangle + \cancel{b\left\langle |\cdots|^2 \right\rangle} + c\left\langle |F_{\mathrm{thermal}}|^2 \right\rangle$$

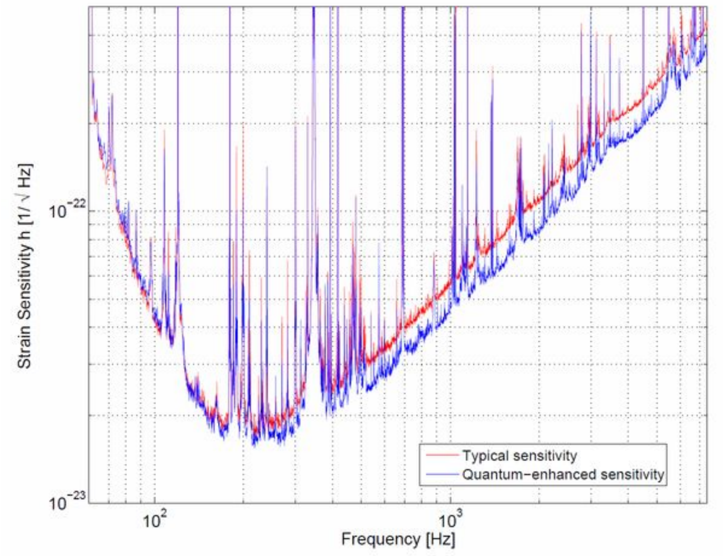
"Shot noise" (input laser phase fluctuations)

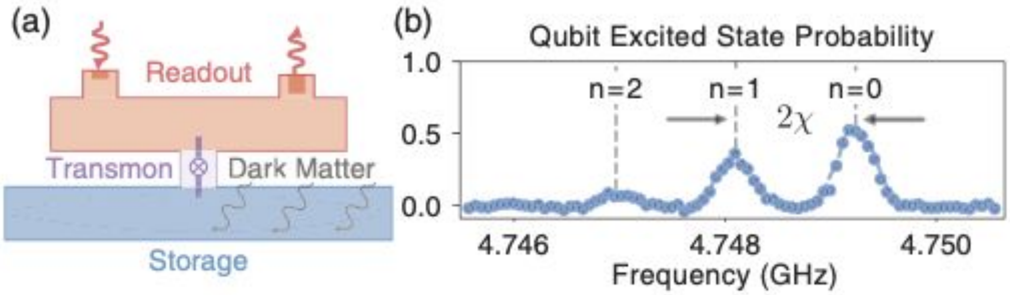
"Back-action noise" (noisy radiation pressure)

Normally $a \sim 1/P_L$, $b \sim P_L$, so if the b term is gone, you can (in principle) ramp P_L arbitrarily high and eliminate quantum noise.

Obviously difficulties in practice. What is the best implementation?

Some other methods used in HEP experiments





LIGO: injects squeezed light, lowers shot noise (price: increased backaction). Helps in shot-dominated regime

LIGO Collaboration 1310.0383

Axions (really dark photon here): Can couple transmon to microwave cavity → measure H = ωn, which obviously commutes → non-demolition

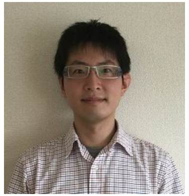
Dixit et al. 2008.12231

Thanks to many people

ex


C. Regal


S. Bhave


N. Matsumoto


G. Afek


D. Moore (EXO)

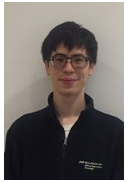

P. Shawhan (LIGO)

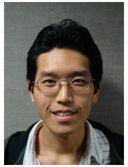

R. Lang (XENON)

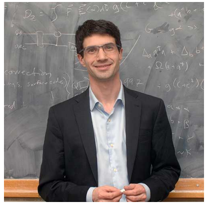
quant

hep/gr


G. Krnjaic

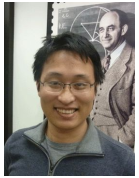

A. Hook


Y. Zhao


J. Taylor


S. Ghosh


P. Stamp


Z. Liu


G. Semenoff

th

Come to Berkeley!

We are hiring a theory postdoc. Longer term hiring experimental people at different levels. Reach out for details: carney@lbl.gov

Outlook

- Quantum mechanics of measurement imposes fundamental noise. This is of central importance in gravitational waves, axions, and mechanical DM searches

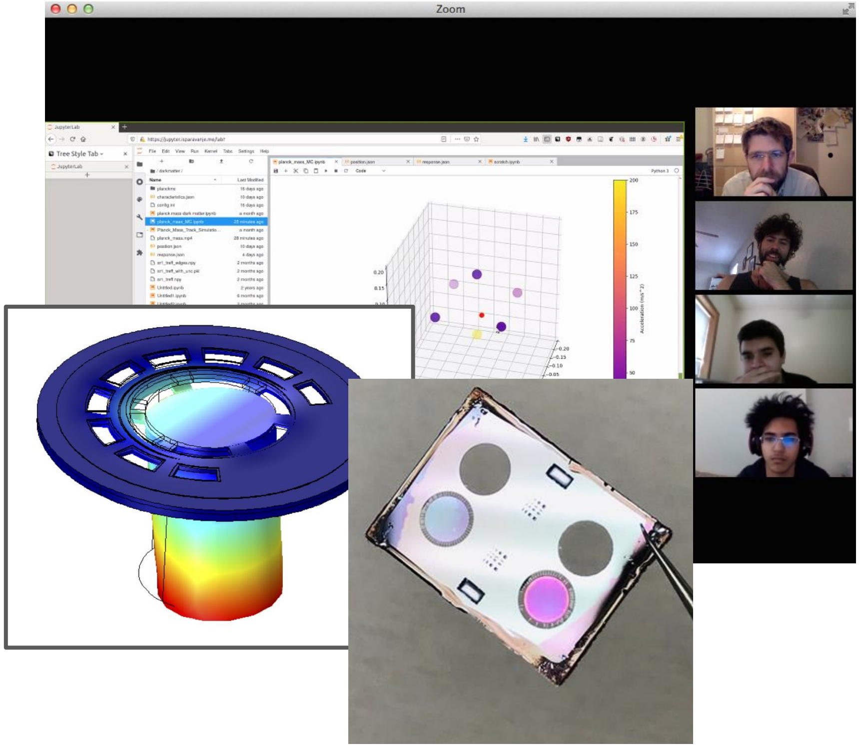
- Already interesting possibilities at ~SQL noise levels, but very well motivated problems (in HEP and beyond) that require going further

- Many known methods to do this–nondemolition/back-action evasion is very promising for impulses, somewhat under-studied. Squeezing of course very active in many areas and will be great to see continual improvements from this

References: https://qquest.lbl.gov/~carney/

Extra/backup slides

Windchime collaboration



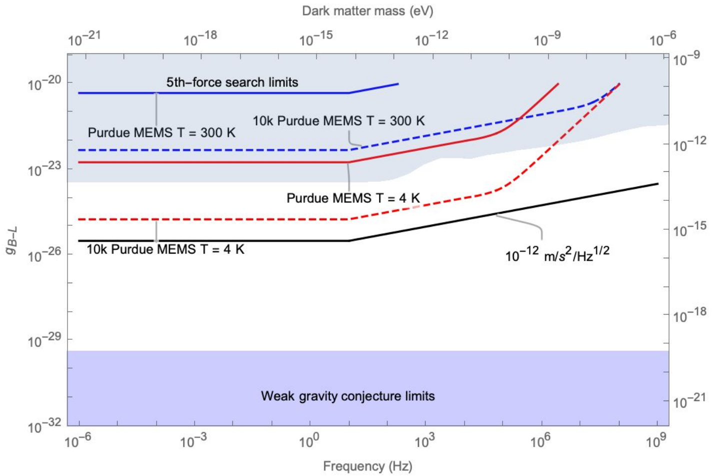
http://windchimeproject.org

Fearless leader: Rafael Lang @ Purdue

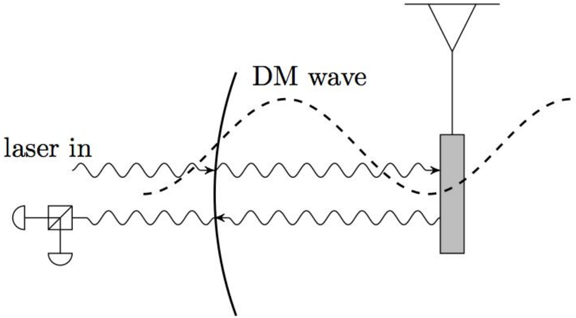
Involves Purdue, ORNL, Rice, FNAL, Maryland, Minnesota, NIST, LBL

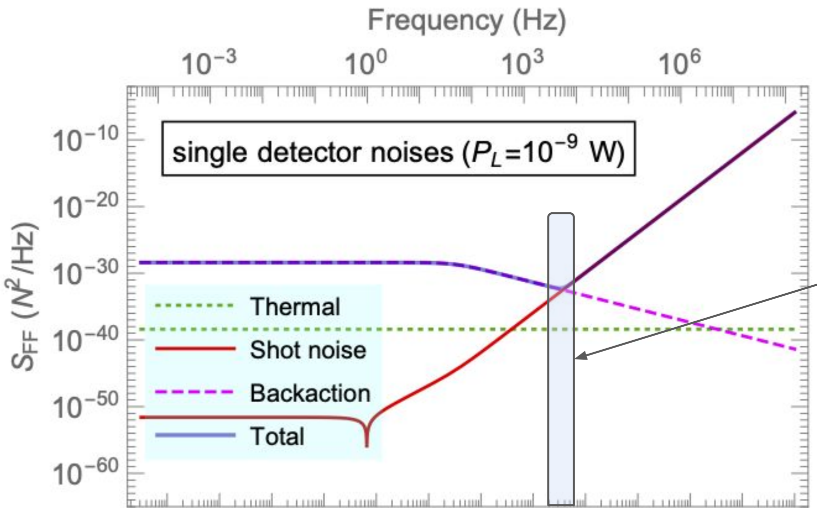
Funding: DOE Science Centers, QuantISED program, NSF

First gen goal: ~1000 mg-scale accelerometers read in parallel. Can print 96/wafer in silica now. Ultra-light DM search in few years.



“Narrow” band signals





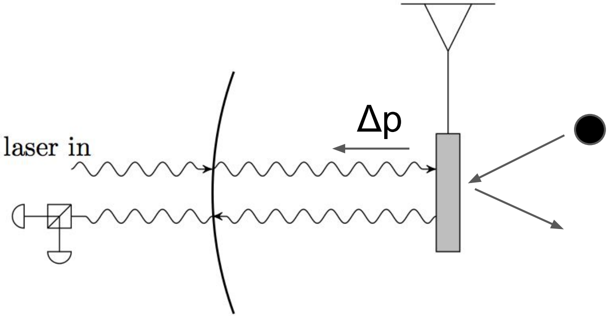
Examples:

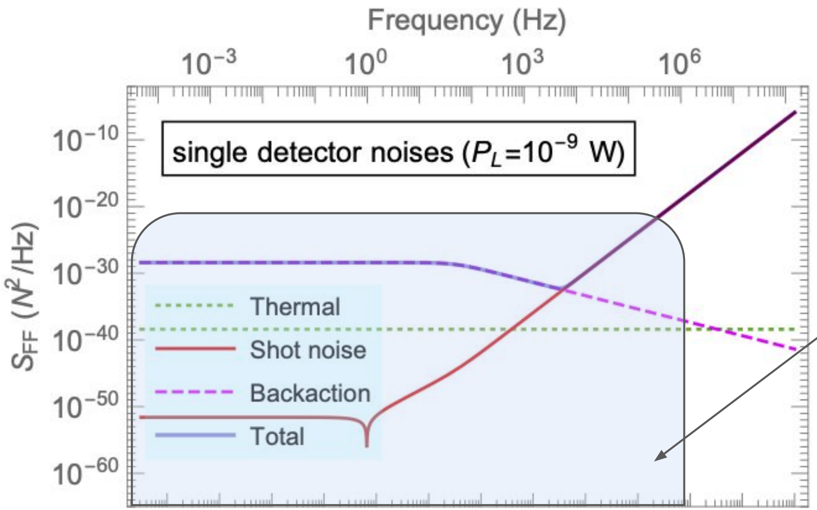
Ultralight DM (bandwidth ~ $\omega_s/10^6$; see M. Safronova’s talk)

Gravitational waves (really have bandwidth ~ kHz, not that narrow, but bear with me; see N. Aggarwal’s talk)

$$F_{\rm sig}(\nu) \approx F_0 \delta(\nu - \omega_{\rm sig})$$

Broadband signals





Examples:

Various particle DM candidates (see D. Moore’s talk)

Photons? Neutrinos? (see Peter Smith work from 80’s)

$$F_{\mathrm{sig}}(\nu) \approx \Delta p/\sqrt{2\pi}$$

PHYSICAL REVIEW LETTERS

Featured in Physics

Demonstration of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements

Nobuyuki Matsumoto, Seth B. Cataño-Lopez, Masakazu Sugawara, Seiya Suzuki, Naofumi Abe, Kentaro Komori, Yuta Michimura, Yoichi Aso, and Keiichi Edamatsu

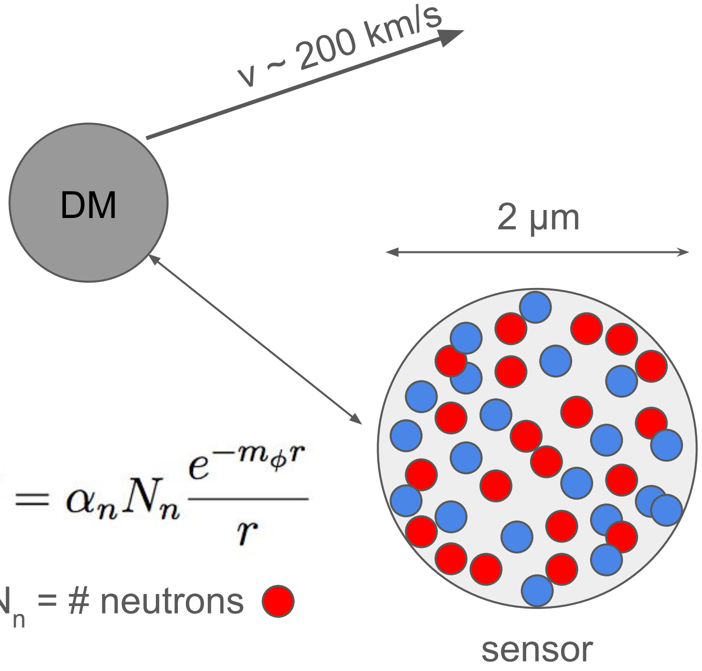
Phys. Rev. Lett. **122**, 071101 – Published 19 February 2019

Physics See Synopsis: Gravity of the Ultralight

$F_{grav} = G_N\, m^2/d^2 \sim 10^{-17}$ N for two masses m = mg separated by d = mm

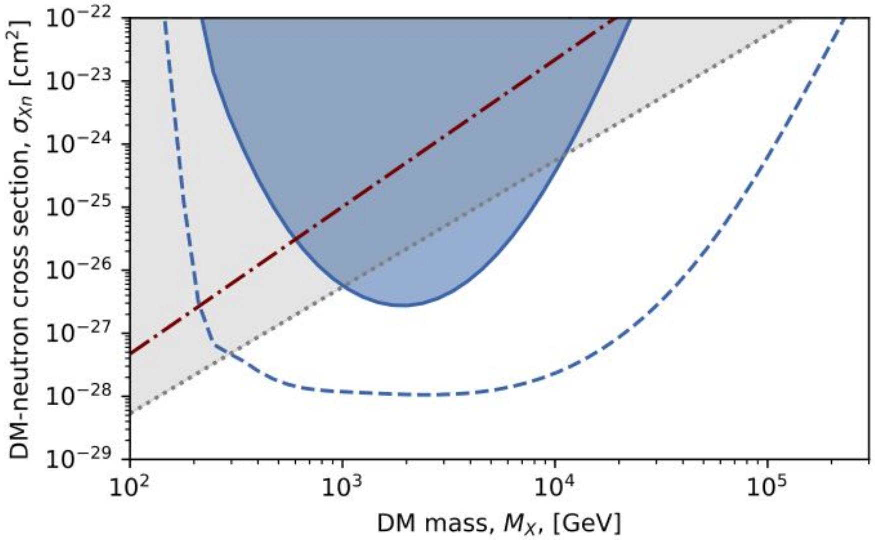
cf. 10^{-21} N/√Hz (and better) sensitivities achieved optomechanically

Search for “dark nuclei”



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

N_n = # neutrons



Able to do novel DM search with ~few days of calibration data on microsphere (first month of COVID lockdown…)

Models:
Lin, Yu, Zurek 1111.0293
Krnjaic, Sigurdson 1406.1171

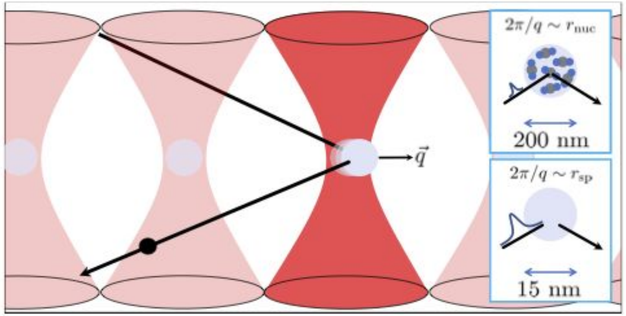
Monteiro, Afek, Carney, Krnjaic, Wang, Moore PRL 2020

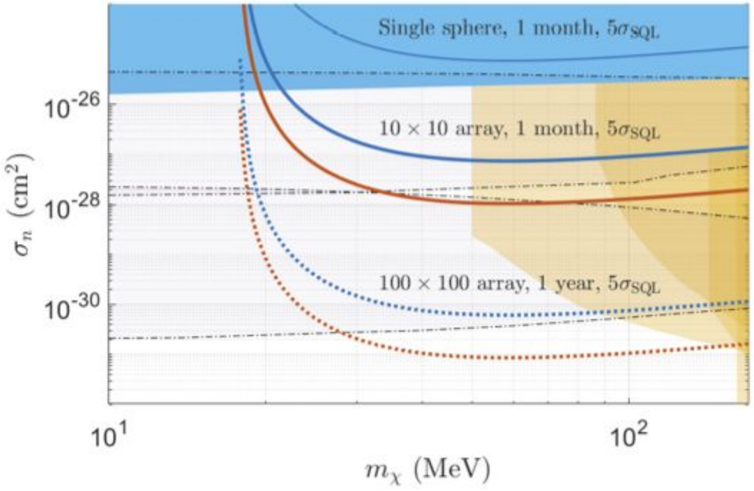
Nanospheres

What can you do with spheres ~ 1000 times smaller? (~10 nm, so ~ 10^7 atoms)

Look for lighter dark matter!

It can scatter quantum-coherently off the sphere → big increase in cross section





Proposal: Afek, Carney, Moore PRL 2022

Single ions… or electrons?

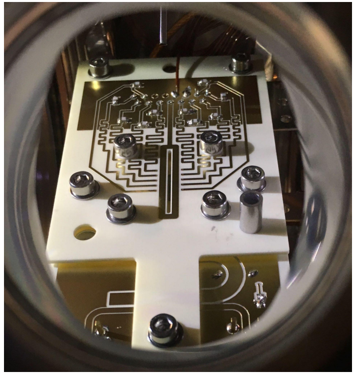
What's the ultimate limit of this idea, in terms of shrinking the sensor?

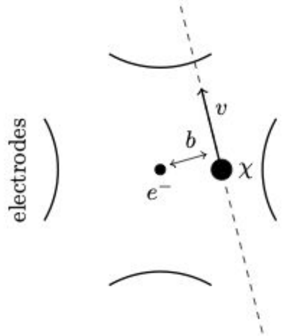
Using a single atom or electron!

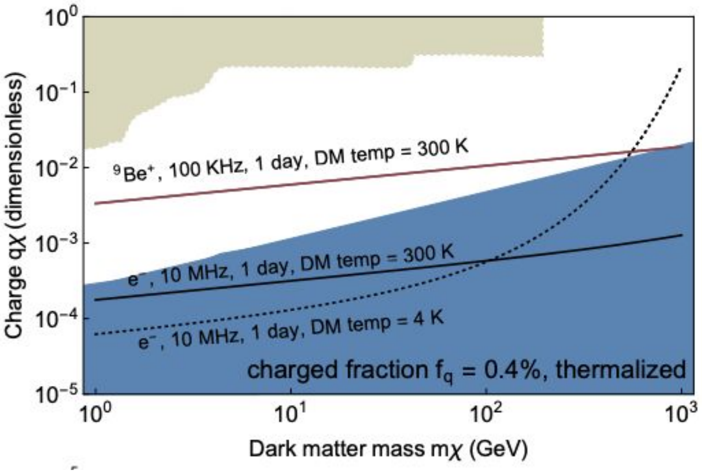
Can search for DM if it has tiny electric charge (~1/1000th the charge of electron).

Current detectors are totally insensitive to this regime

Carney, Haffner, Moore, Taylor PRL 2021







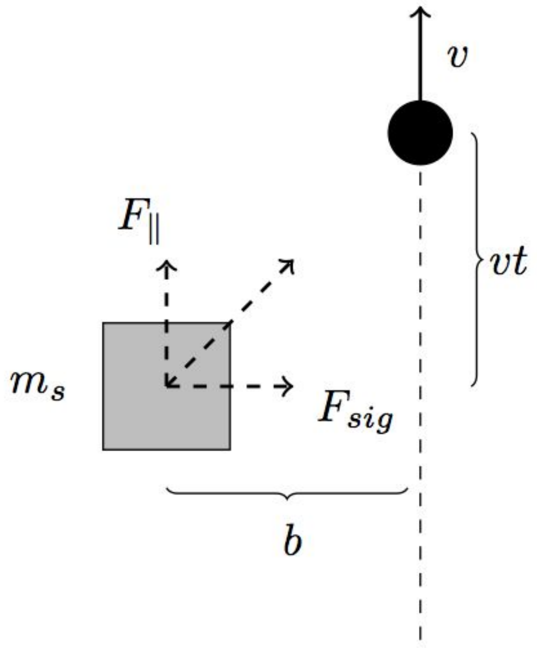
The basic scaling

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

→ want heavy DM, large device, small impact parameter

$$R = \frac{\rho_\chi v A_d}{m_\chi} \sim \frac{1}{\text{year}} \left(\frac{m_{\text{Pl}}}{m_\chi}\right) \left(\frac{A_d}{1\,\text{m}^2}\right)$$

→ want large area



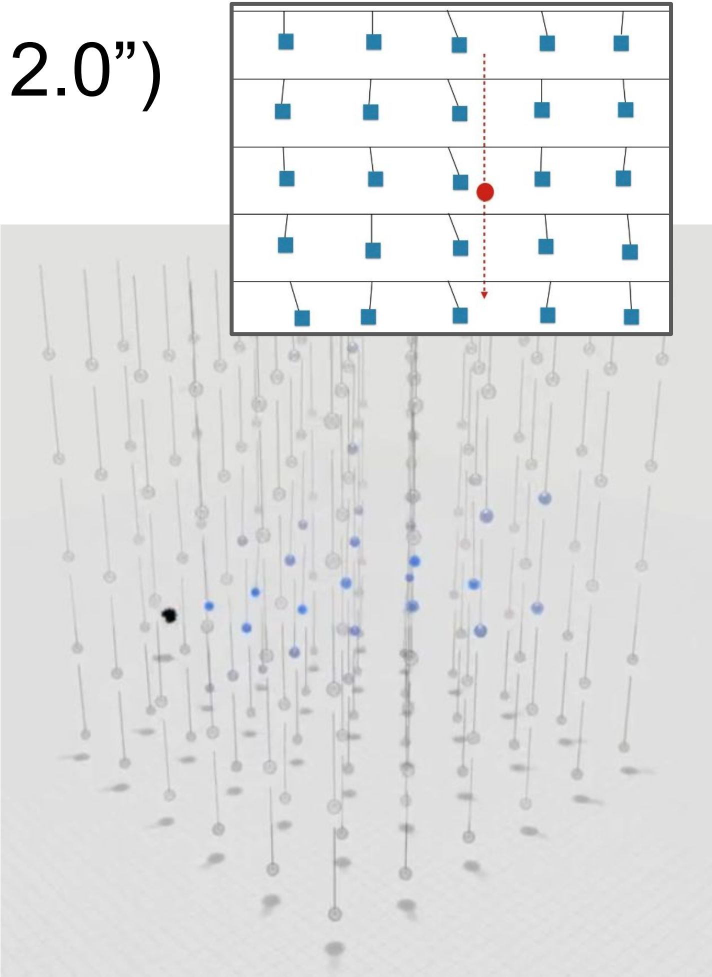
Array concept (“bubble chamber 2.0”)

Signal = correlated track of macroscopic motion

With ~ mm-cm spacing, mg-g mass devices, 106 - 109 devices, can possibly detect dark matter at

$m \sim m_{planck} \sim 4$ ug $\sim 10^{19}$ GeV.

But need quantum measurement protocol that can get well below SQL… long term target. Lots of active work on this now.

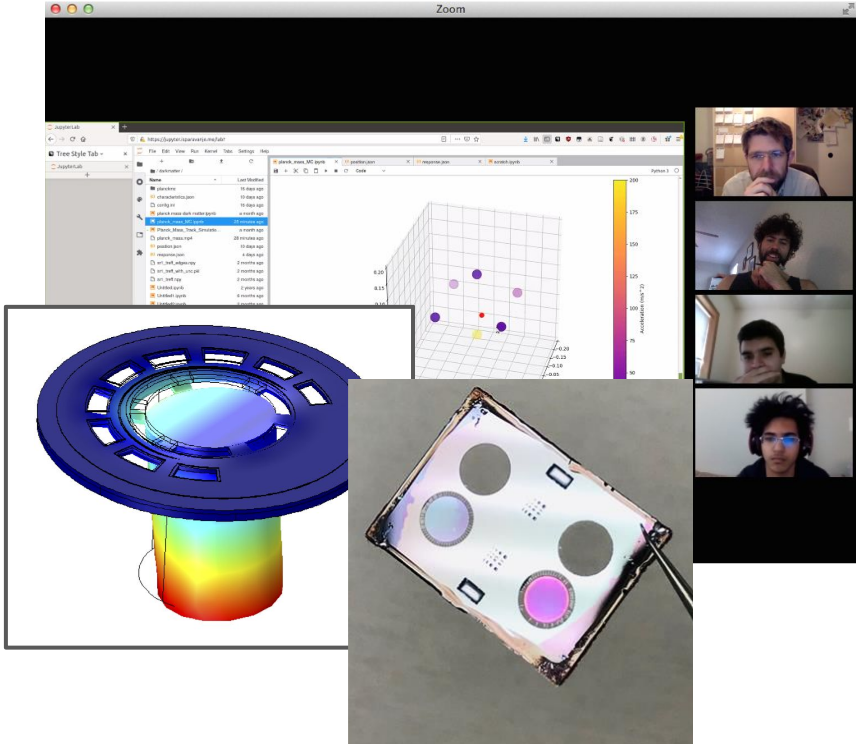


Carney, Ghosh, Krnjaic, Taylor 1903.00492

How to think about this

Ok, so if we can just detect the vacuum fluctuations of some 40kg mirrors separated by a few km, we can detect gravitational waves… What? That's seven orders of magnitude better sensitivity than what anybody can do now? Relax, we'll figure it out...

Windchime collaboration

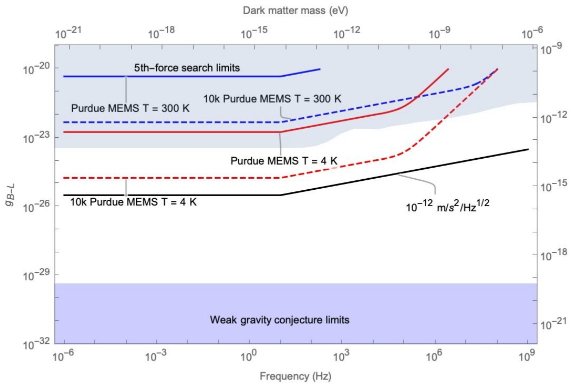


Fearless leader: Rafael Lang @ Purdue

Involves Purdue, ORNL, Rice, FNAL, Maryland, Minnesota, NIST, LBL

Funding: DOE Science Centers, QuantISED program, NSF

First gen goal: ~1000 mg-scale accelerometers read in parallel. Can print 96/wafer in silica now. Ultra-light DM search in few years.



http://windchimeproject.org