Gravitational direct detection

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→ LBL May 2021

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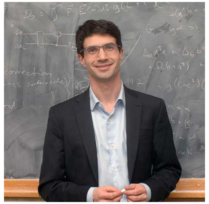
Fermilab

Based on original paper:

1903.00492 with these people →

G. Krnjaic

S. Ghosh



J. Taylor

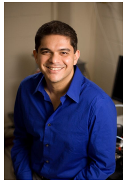
\+ Lots of subsequent work with many other people

D. Moore

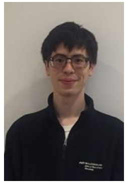
P. Shawhan

R. Lang

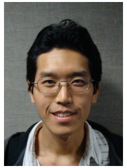
C. Regal



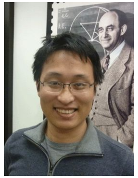
S. Bhave



A. Hook



Y. Zhao

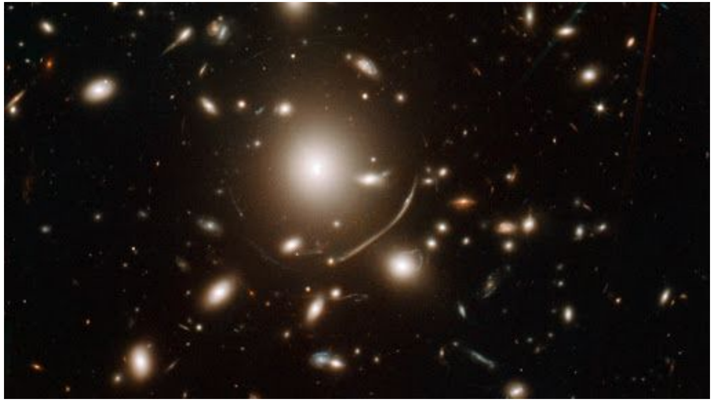


Z. Liu

Assuming dark matter exists in the first place (!), the *only coupling it is guaranteed to have to visible matter* is through gravity.

Local dark matter density ~ one proton mass per cm^3. Hopeless to try to detect it through this gravitational force in a local lab. Right?

Extremely hard, but maybe possible...



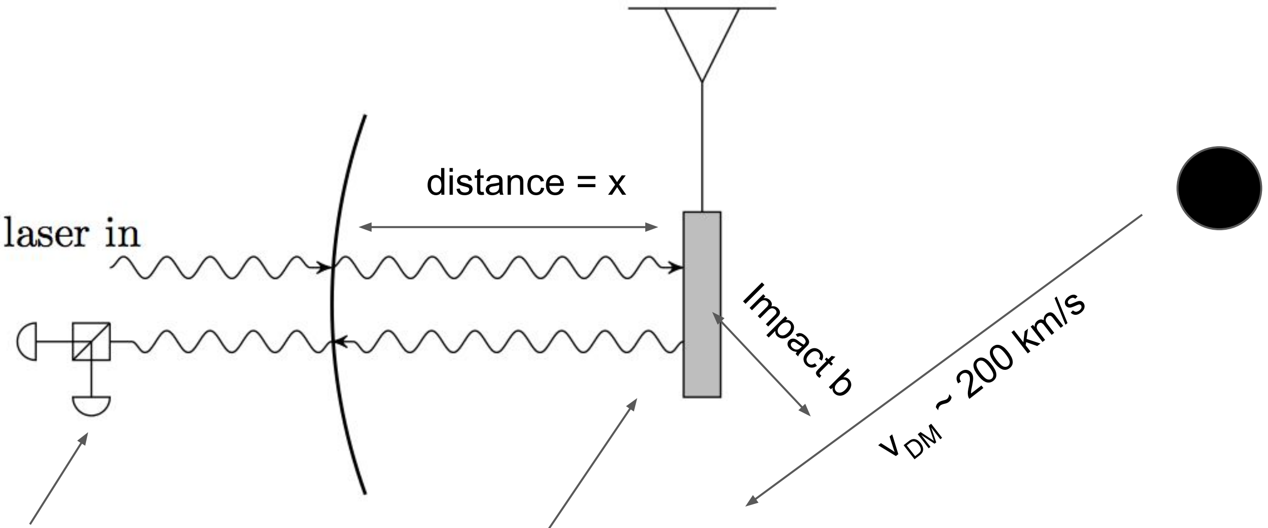
How to view this talk

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

Outline:

- Basic detection problem
- Array concept
- Noise
- Current progress + future directions

The basic idea



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

light phase shift ~ x(t)

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

PHYSICAL REVIEW LETTERS

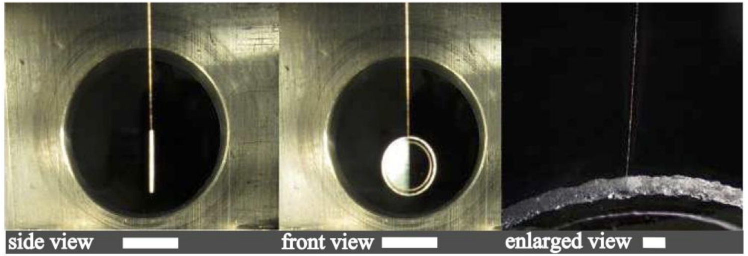
Featured in Physics

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

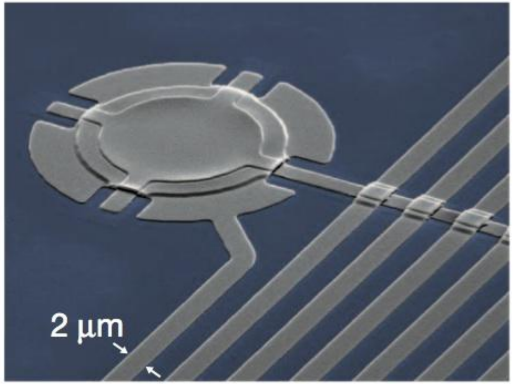
Physics See Synopsis: Gravity of the Ultralight



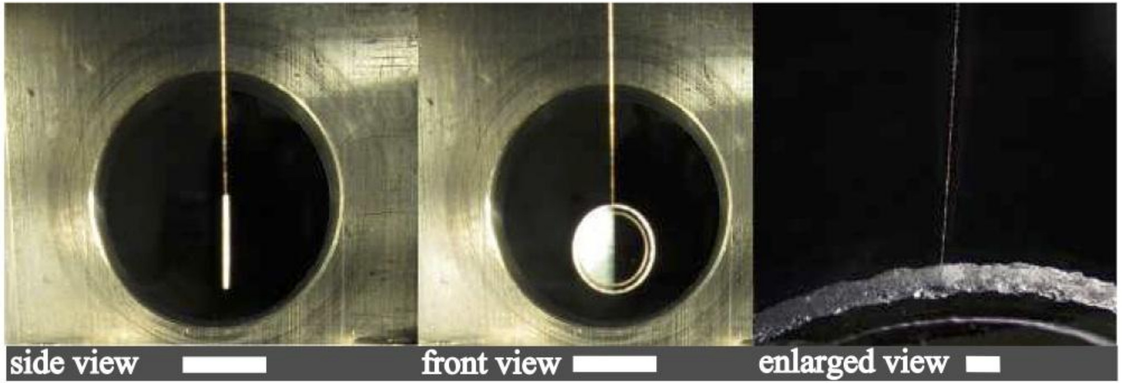
$F_{grav} = G_N\, m^2/d^2 \sim 10^{-17}$ N

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

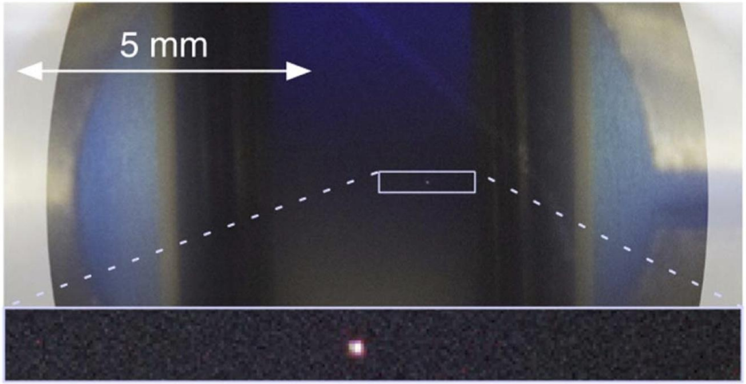
Note the conversion factor $m_{planck} = 0.02$ mg



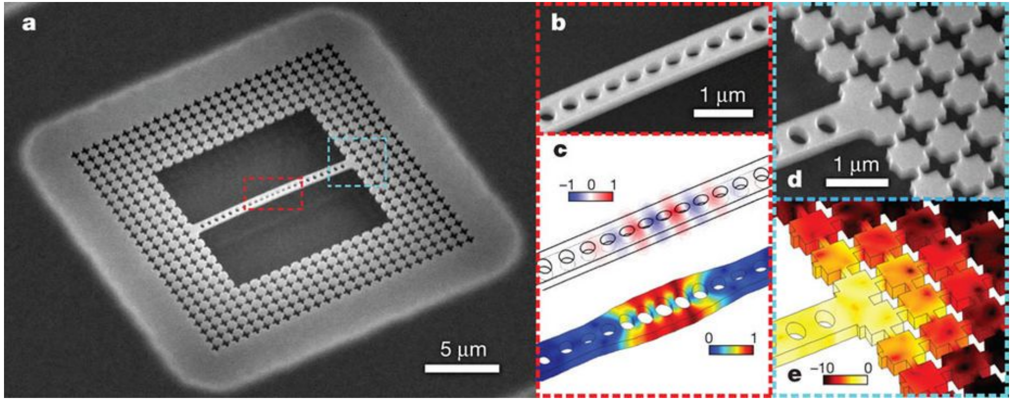
Teufel et al, Nature 2011



Matsumoto et al, PRA 2015



Aspelmeyer ICTP slides 2013



Painter et al, Nature 2011

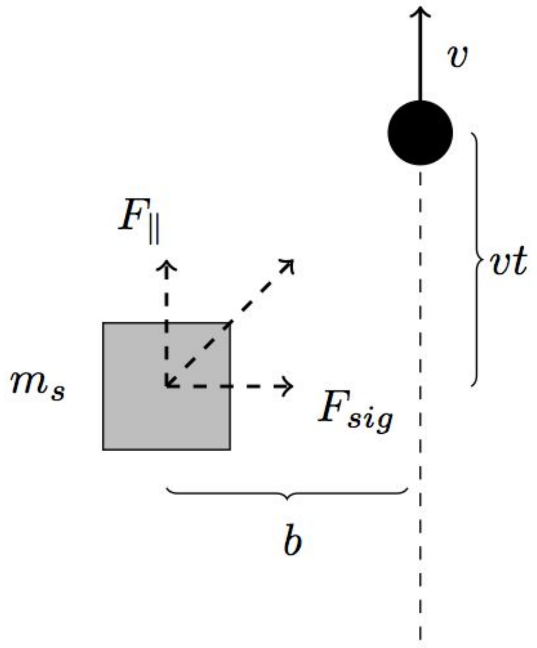
The basic scaling

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

→ want heavy DM, large device, small impact parameter

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

→ want large area



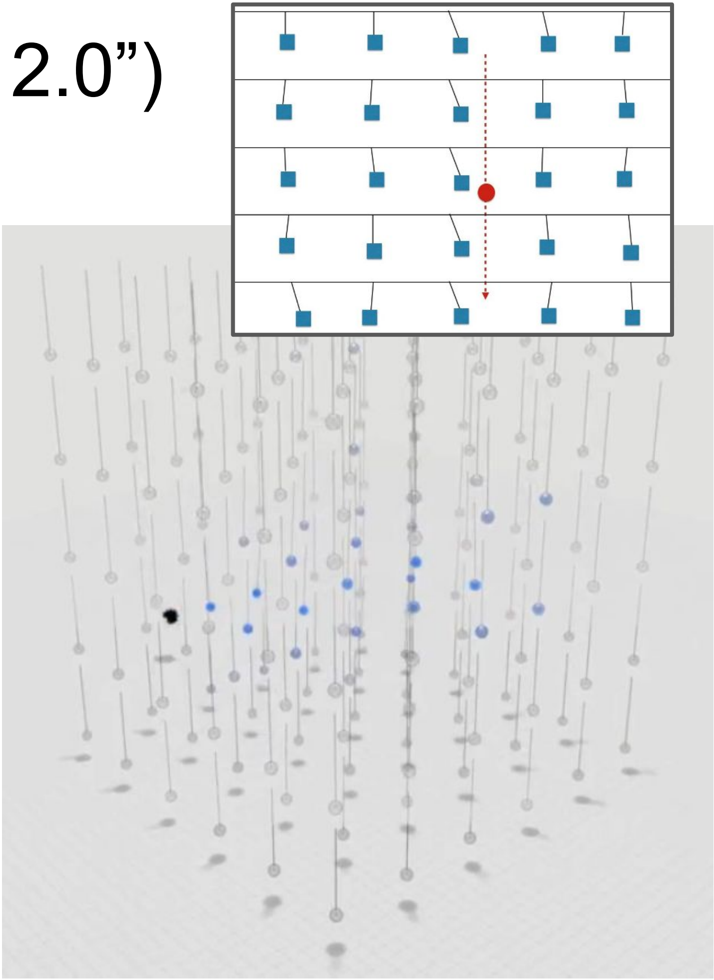
Array concept ("bubble chamber 2.0")

Signal = correlated track of macroscopic motion

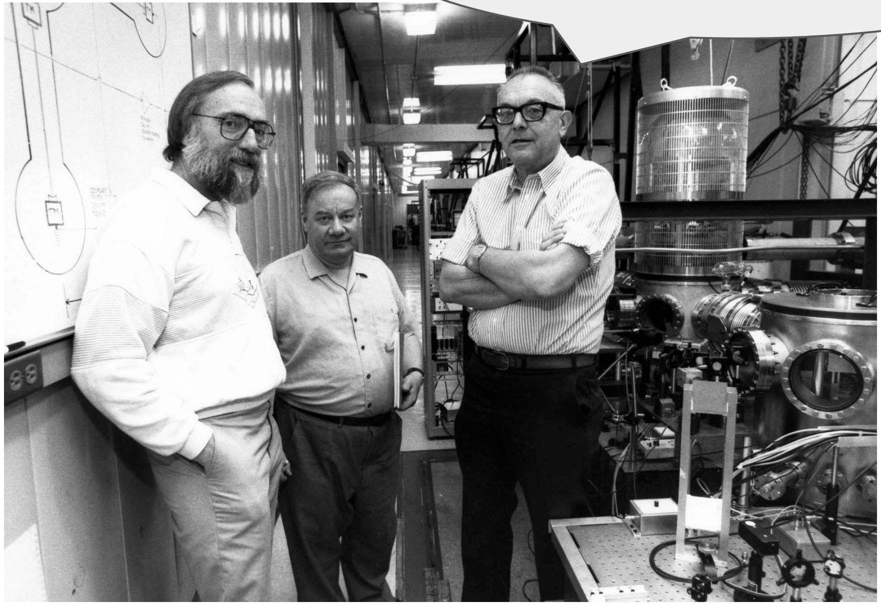
Complete directional info

Background rejection: what can produce a track (and only a track) of sensors all moving together?

Scales we hit on: ~ mm-cm spacing, mg-g mass devices, the more detectors the better (more on these numbers later)



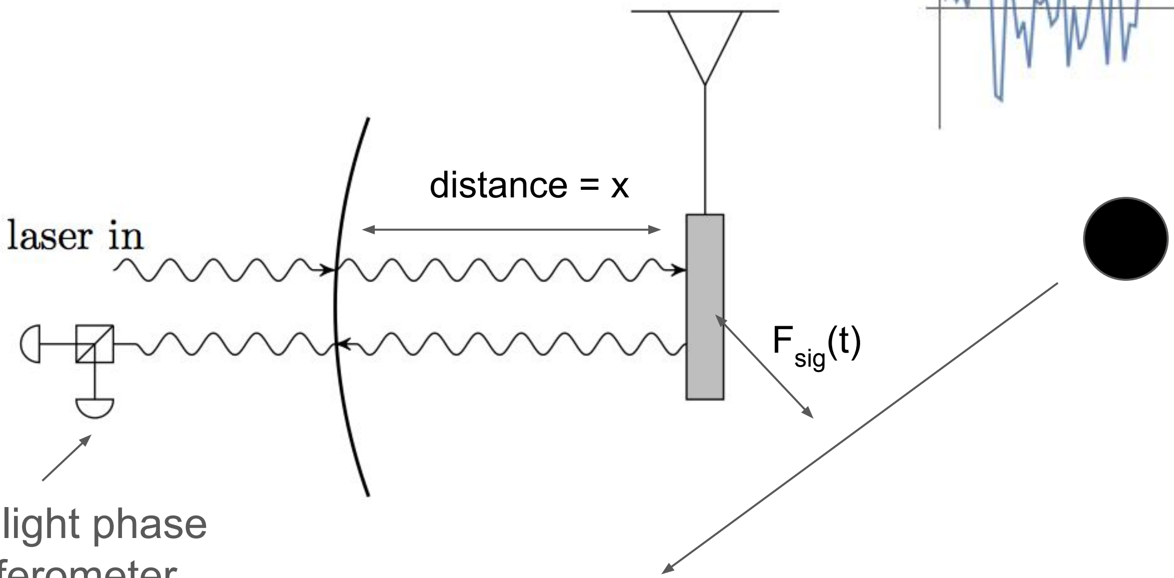
Sounds cool, but what about noise?



Noise

Photo: Hiroshi Sugimoto

Impulse sensing



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

Matched filtering and SNR

Process the raw data via filter (cf. LIGO matching to waveform). For observable, use total impulse, filtered appropriately:

$$O(t_e) = \int f(t_e - t')F(t')dt'$$

→

$$f_{\rm opt}(\nu) = \frac{F_{\rm sig}(\nu)}{N(\nu)}$$

Known signal shape (e.g. $F=1/r^2$) and known noise power spectral density N, maximize SNR

→

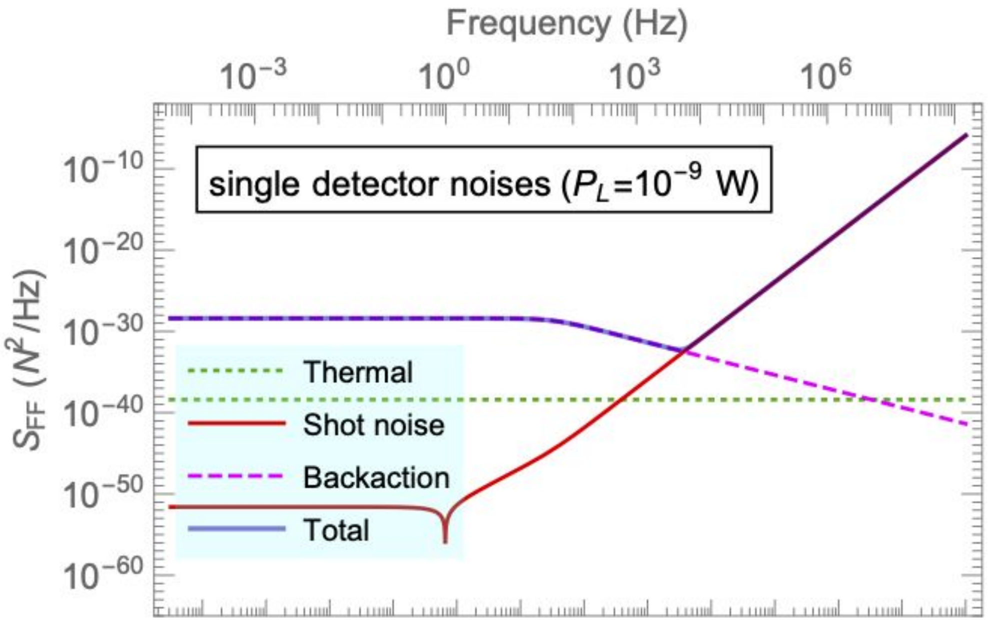
$$\mathrm{SNR}^2_{\rm opt} = \int_0^\infty \frac{|F_{\rm sig}(\nu)|^2}{N(\nu)} d\nu$$

Limits on the noise

Ultimately limited by:

- Thermal noise in the device
- Quantum mechanics of the measurement

$$\mathrm{SNR}^2_{\mathrm{opt}} = \int_0^\infty \frac{|F_{\mathrm{sig}}(\nu)|^2}{N(\nu)} d\nu$$



~ flat function up to $1/t_{flyby}$ = v/b ~ 1-100 MHz

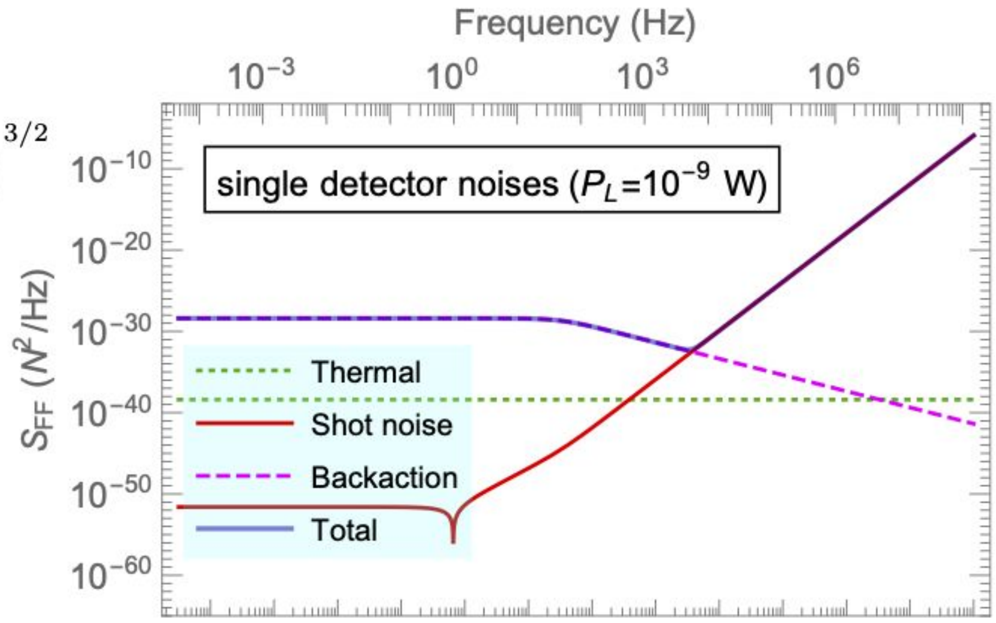
SNR at thermal noise level

If thermal noise dominates:

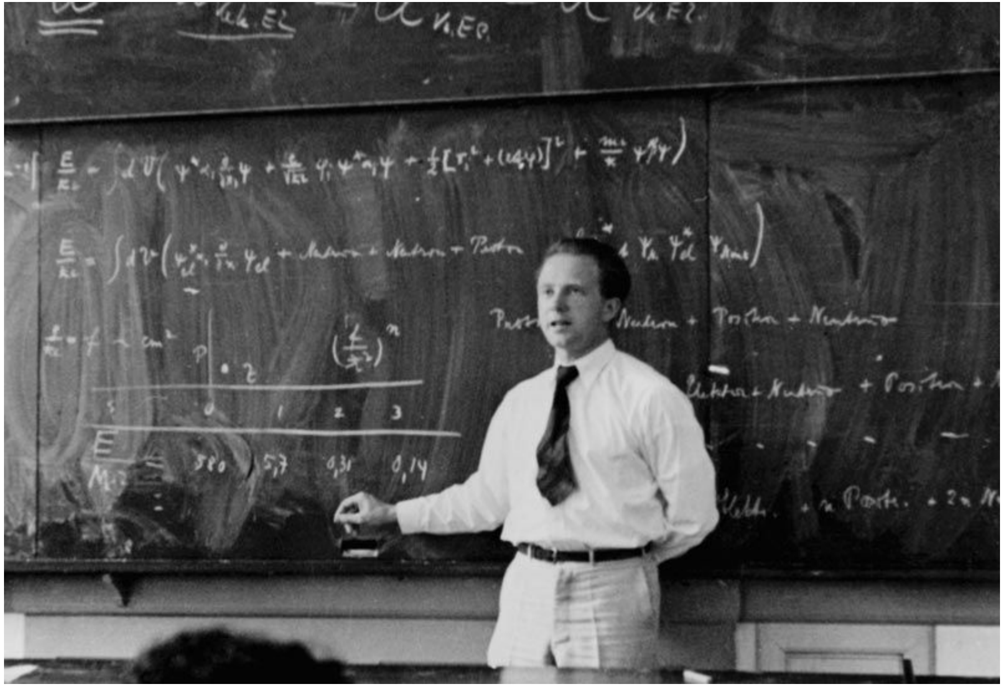
$$\mathrm{SNR}_{\mathrm{thermal}} = \frac{G_N m_\chi m_s / bv}{\sqrt{(4 m_s k_B T \omega / Q)(b/v)}}$$
$$\approx 0.5 \times \left(\frac{m_\chi}{1\ \mathrm{mg}}\right)\left(\frac{m_s}{1\ \mathrm{mg}}\right)^{1/2}\left(\frac{1\ \mathrm{mm}}{b}\right)^{3/2}$$

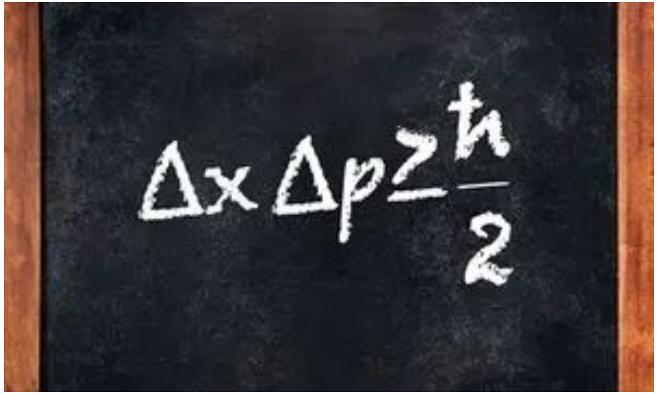
But notice in the plot: measurement noise >> thermal.

How do we get to the thermal limit?



Quantum measurement noise



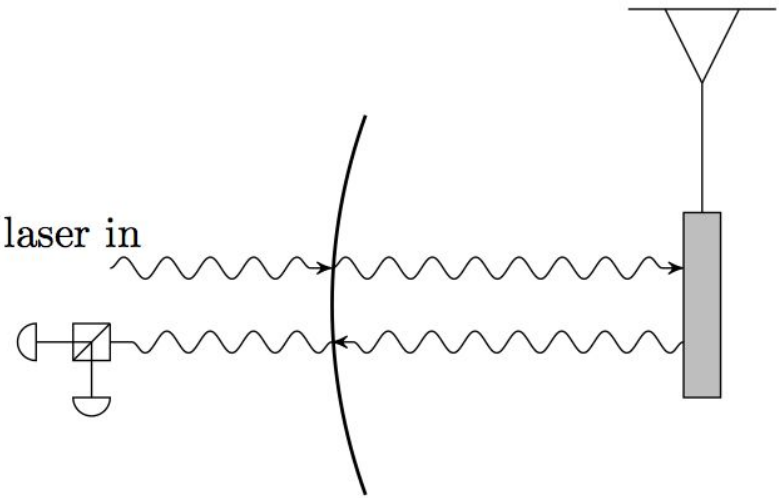


mechanics
$[x,p] = i\hbar$

cavity mode
(fluctuations on
top of laser drive)
$[X,Y] = i\hbar$

$$H_{OM} = gxX$$

drive-enhanced coupling $g \propto g_0\sqrt{P}$



$$\dot{X} = -\frac{\kappa}{2}X + X_{\text{in}}$$

$$\dot{Y} = -\frac{\kappa}{2}Y + Y_{\text{in}} + \frac{gx}{x_0}$$

$$\dot{x} = \frac{p}{m_s}$$

$$\dot{p} = -m_s\omega_s^2 x - \gamma p + F_{\text{in}} + \frac{gX}{x_0}$$

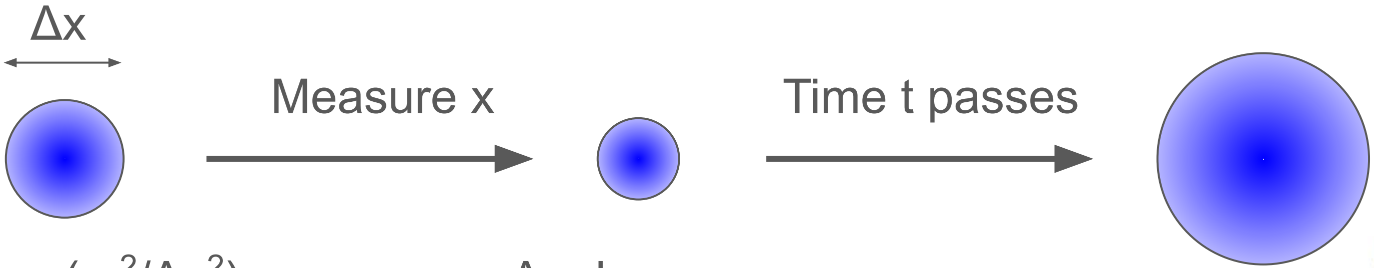
Red box: Damping/loss

Blue box: Input noise: all taken as vacuum fluctuations

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

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

optimize
—> "standard quantum limit"

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

Quantum limits in impulse sensing

With input vacuum fluctuations, and optimizing the laser power, you can achieve the “standard quantum limit”

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

In the mg-scale resonator system this is ~10^3 larger than thermal noise (in dil fridge!). So to get to thermal floor, you need to go below SQL.

- Squeeze probe light -- anticorrelate amplitude and phase
- Non-demolition/backaction-evasion -- couple to p, not x

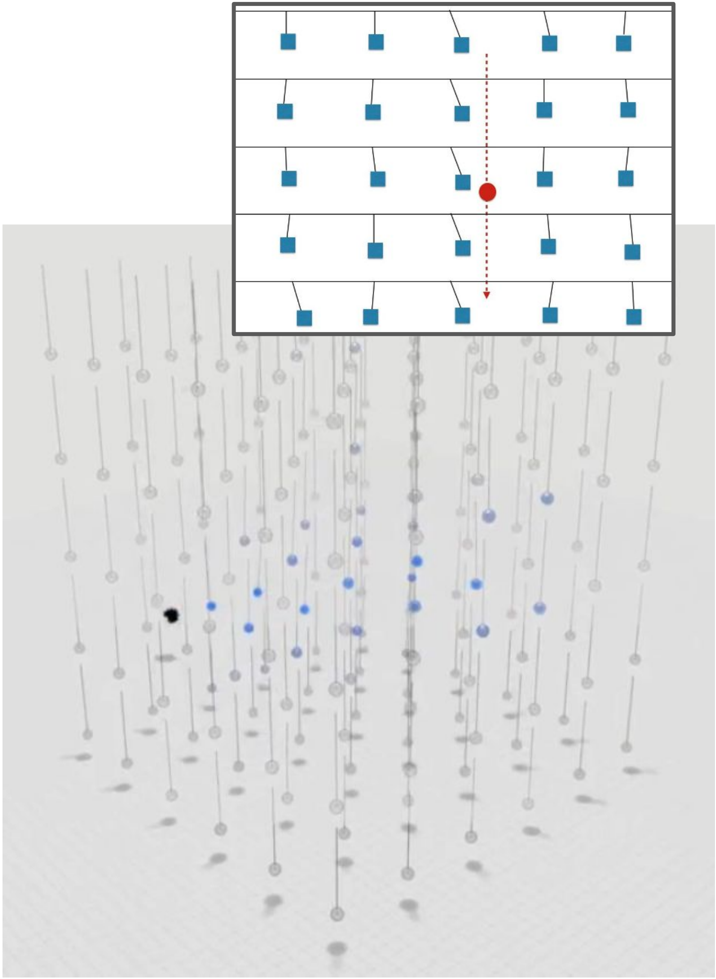
Conclusion at this stage

With ~current devices (near SQL) you are ~3-4 orders of magnitude too high in noise.

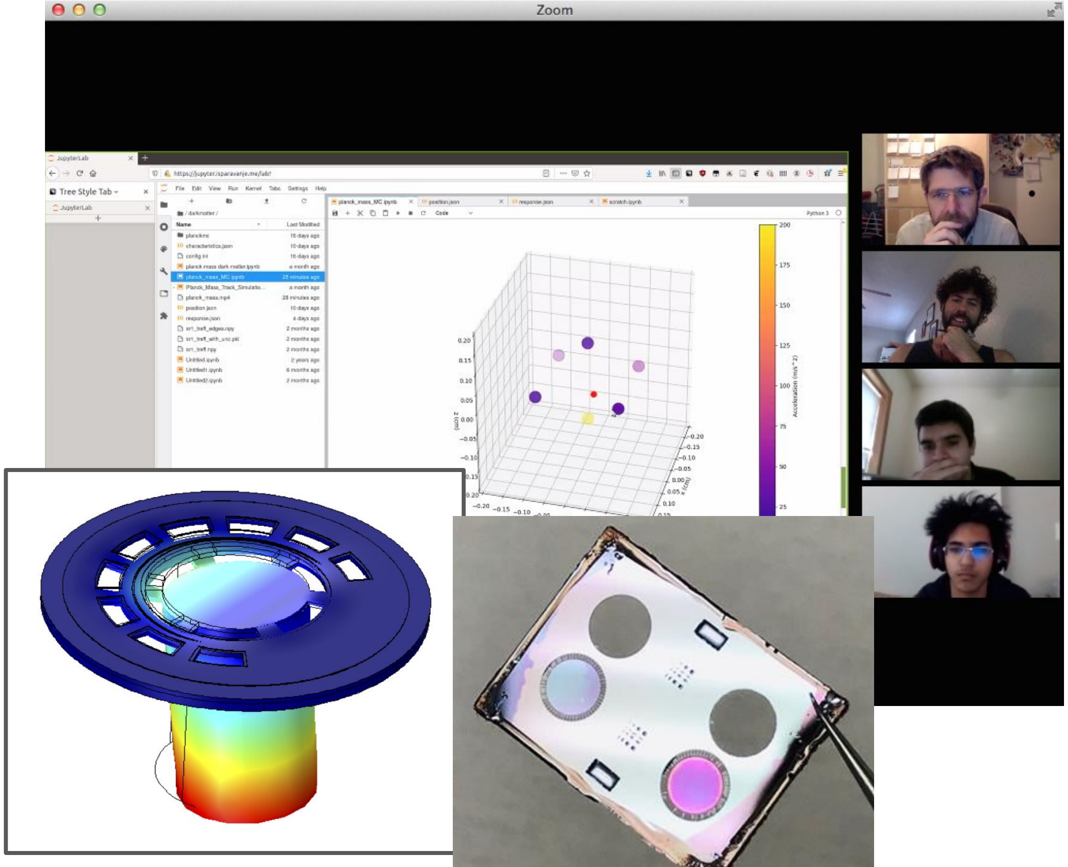
Paths to sufficient quantum noise reduction exist but this needs to be developed in detail.

If this noise level is achieved, the detection is possible, but still need large array (to get flux, and reduced SNR).

This is not the end of the story--of course some things can get worse than presented here, but there are also some ideas about making them better. So stay tuned and maybe we can write some papers...



Windchime



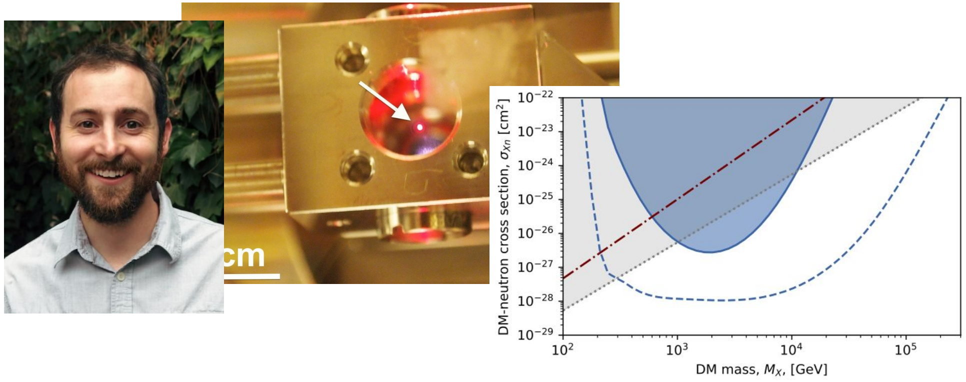
Rafael Lang @ Purdue

Collaboration currently involving Purdue/ORNL/FNAL (through an NQI center), Maryland/LBL

Basic initial goal is to build a prototype array of ~100 devices, (~100mg scale accelerometers, made by Sunil Bhave @ Purdue). Use as testbed, especially for data and filtering issues, demonstrate track sensing at some level.

Can use it to make some nice limits on certain ultralight DM, other stuff...

Other experiments

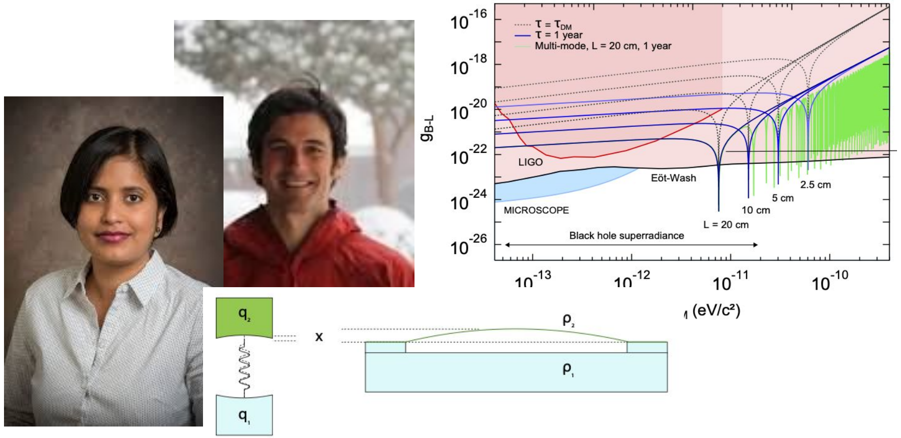


Monteiro, Afek, Carney, Krnjaic, Wang, Moore

2007.12067 [PRL 125, 181102 (2020)]

Manley, Chowdhury, Grin, Singh, Wilson

2007.04899



Impulse backaction evasion demonstrator @ NIST?

Based on Ghosh, Carney, Shawhan, Taylor
1910.11892

What’s next?

- **Better impulse sensing protocols -- theory and experimental demonstration**
- Thermal noise: is Johnson-Nyquist really right? Ways to avoid? Levitation? QEC?
- Data analysis/matched filtering in array. What can be done in software/hardware?
- Correlated (“distributed”) sensing issues -- what if we read out multiple devices with one laser, etc.? Frequency multiplexing?
- Higher order phonon modes, can we use them?
- Prototype testing @ Windchime
- Meeting #2 in spring to discuss various current experiments + next steps + start figuring out best architectures

Backup slides

$$Y_{\text{out}}(\nu) = A(\nu)Y_{\text{in}}(\nu) + B(\nu)X_{\text{in}}(\nu) + C(\nu)F_{\text{in}}(\nu)$$

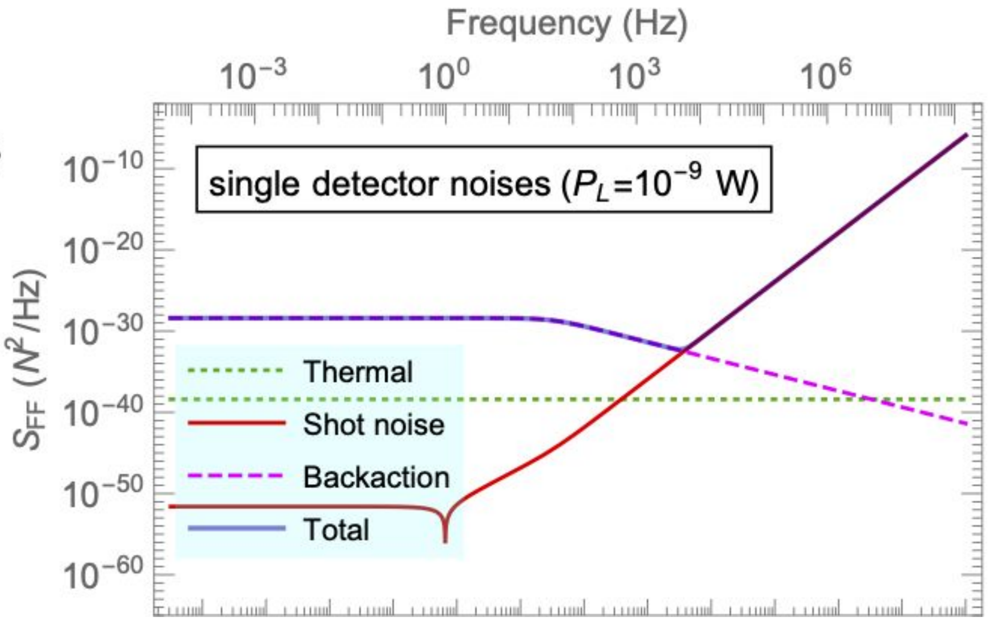
$$F_{\text{E}}(\nu) = \frac{Y_{\text{out}}(\nu)}{C(\nu)}$$

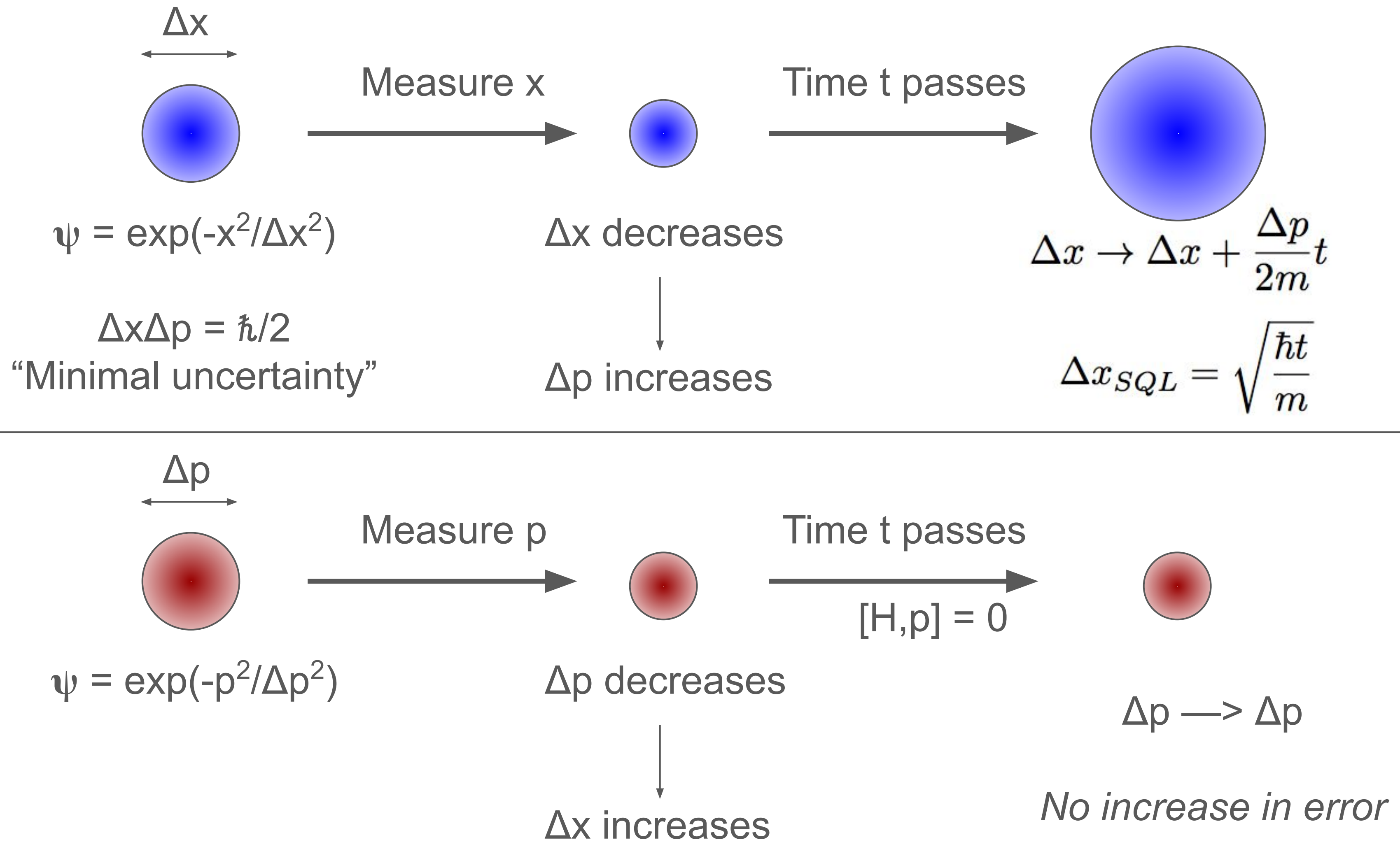
$$S_{FF} \sim \langle F_{\text{E}}^2 \rangle \sim \frac{|A|^2}{|C|^2} \langle X_{\text{in}}^2 \rangle + \frac{|B|^2}{|C|^2} \langle Y_{\text{in}}^2 \rangle + \langle F_{\text{in}}^2 \rangle$$

$$S_{FF}^{SN} = \frac{x_0^2}{G^2 \kappa} \frac{1}{|\chi_c \chi_m|^2}$$

$$S_{FF}^{BA} = \frac{G^2 \kappa}{x_0^2} |\chi_c|^2$$

$$S_{FF}^{T} = 4\gamma m_s kT.$$




Δx
Measure x
Time t passes
$\psi = \exp(-x^2/\Delta x^2)$
Δx decreases
$\Delta x \rightarrow \Delta x + \frac{\Delta p}{2m} t$
$\Delta x \Delta p = \hbar/2$
"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
Δp —> Δp
Δx increases
No increase in error

Editorial remarks on the SQL

- Quantum measurement noise always exists, sets fundamental technical noise floor
- General issue for continuous monitoring of any degree of freedom
- But SQL is not the limit!
- Many demonstrations of sub-SQL noise

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New Journal of Physics
The open access journal at the forefront of physics

Back-action evasion and squeezing of a mechanical reso
using a cavity detector

A A Clerk[1,4], F Marquardt[2] and K Jacobs[3]
Published 30 September 2008 • IOP Publishing and Deutsche Physikalische Gesellschaft

nature photonics

Letter | Published: 21 July 2013

Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

J. Aasi, J. Abadie [...] J. Zweizig

Nature Photonics **7**, 613–619 (2013) | Download Citation

Light Science & Applications

Article | OPEN | Published: 30 May 2018

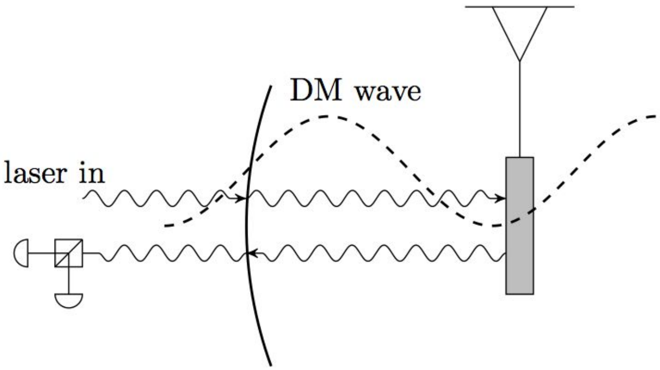
A new quantum speed-meter interferometer: measuring speed to search for intermediate mass black holes

Stefan L. Danilishin, Eugene Knyazev, Nikita V. Voronchev, Farid Ya. Khalili, Christian Gräf, Sebastian Steinlechner, Jan-Simon Hennig & Stefan Hild

Axion-like DM detection with optomechanics

Ex: DM coupled to *neutrons* (B-L charge).

Coherent, persistent, oscillating force on mechanical sensor → acceleration signal



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

Different couplings to different neutron/proton ratios (“EP-violating”)
→ use two sensors, material types to eliminates common mode backgrounds

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

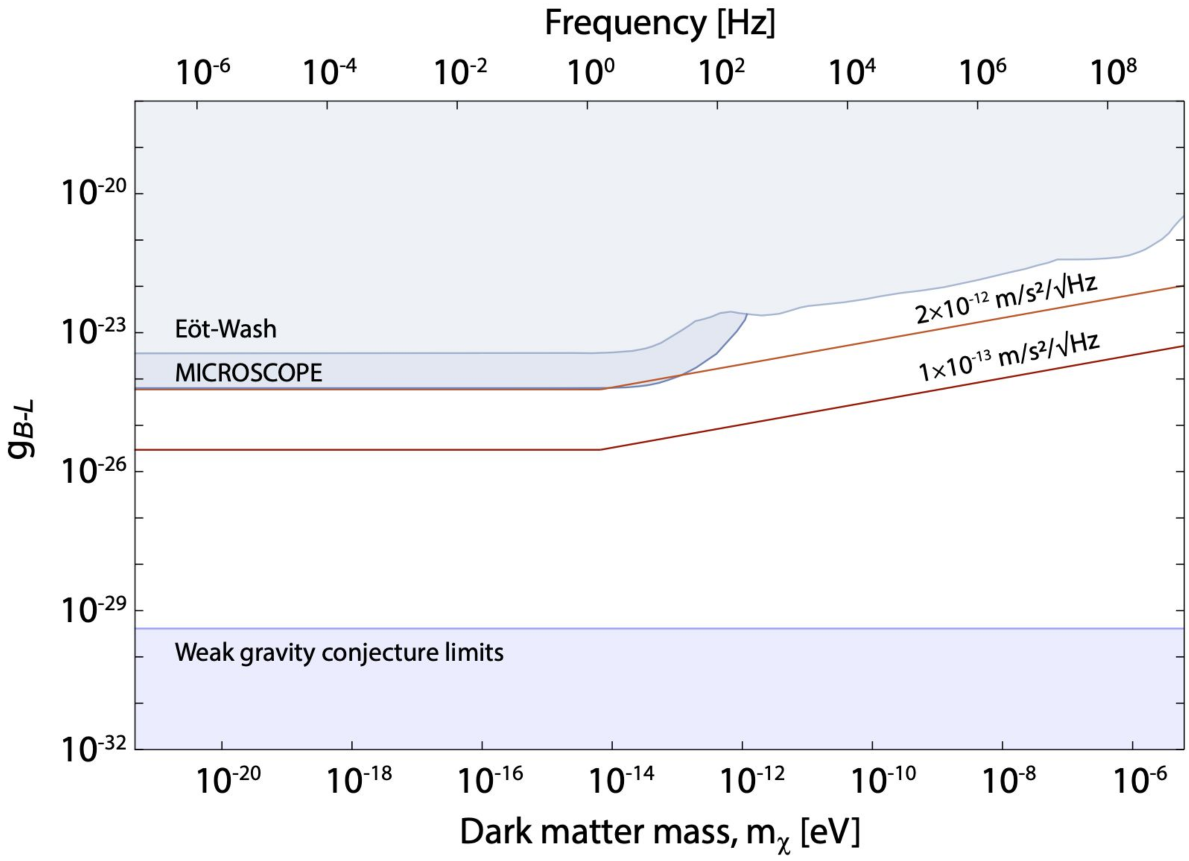
Dark matter direct detection with accelerometers
Graham et al 1512.06165

Needs

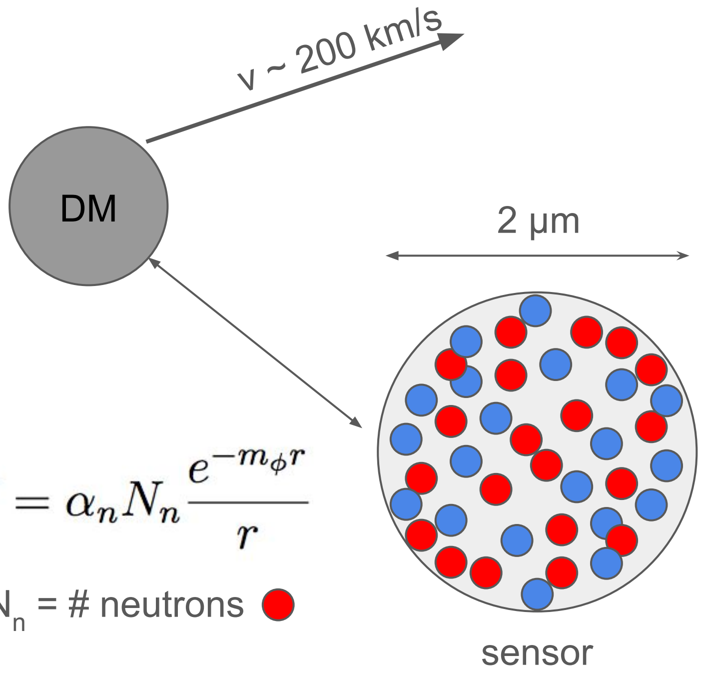
Blue = constrained by various equivalence principle tests

Purple = propaganda

This plot has integration time = 1 day

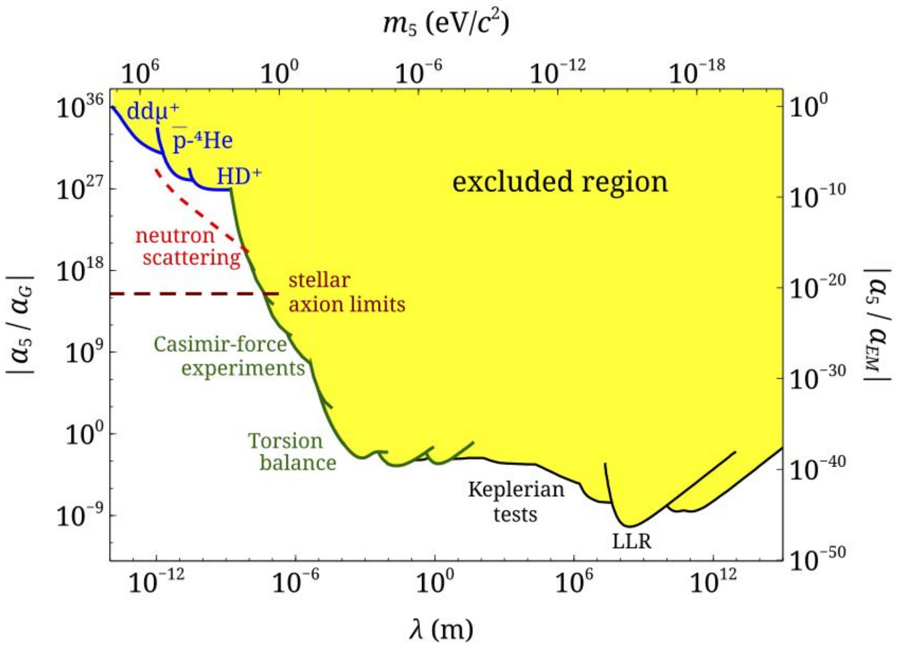


DM with light mediator

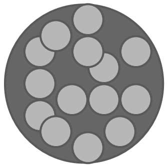


$$V = \alpha_n N_n \frac{e^{-m_\phi r}}{r}$$

N_n = # neutrons



One possible microscopic realization, "dark quark nuggets" coupled through B-L



Lin, Yu, Zurek 1111.0293
Krnjaic, Sigurdson 1406.1171

$$\alpha_n \rightarrow g_n g_d N_d$$