A scalable quantum architecture for dark matter detection

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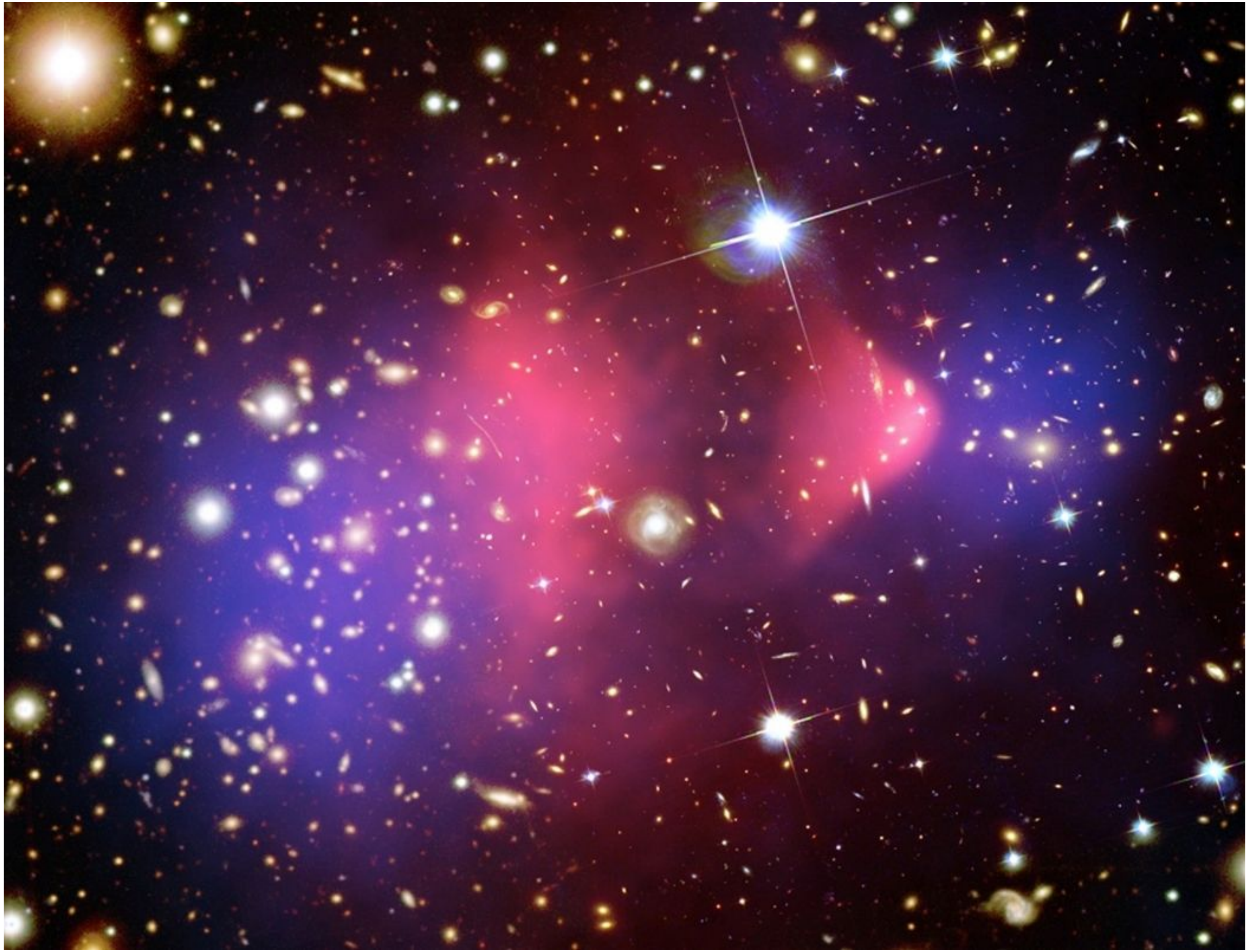
Based on

- *Gravitational direct detection of dark matter*
  DC, S. Ghosh, G. Krnjaic, J. M. Taylor, 1903.00492

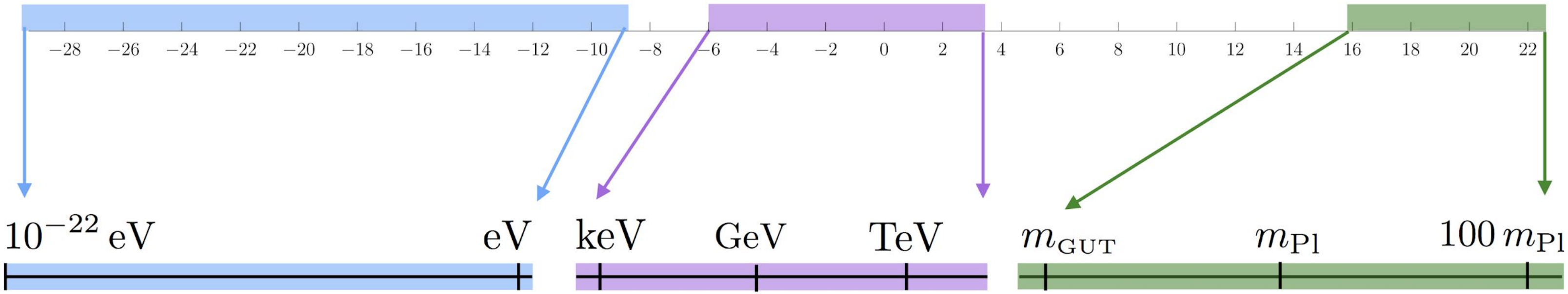
- *Ultralight dark matter detection with mechanical quantum sensors*
  DC, A. Hook, Z. Liu, J. M. Taylor, Y. Zhao, 1908.04797

- Work in progress w/ above people

- Preliminary experimental work (details later in talk)



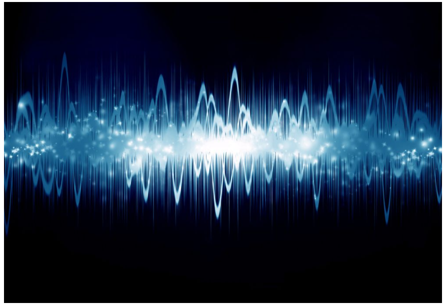
Dark Matter Mass $\log[m/\mathrm{GeV}]$



Bosonic Wave DM
Axion, ALPs, "Fuzzy" DM

Thermal DM
Dark Sectors, WIMPs

Composite, Primordial Black Holes
WIMPzillas, Nonthermal DM



$$n_{DM} \approx \frac{0.3}{\mathrm{cm}^3}\left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)$$

Central questions

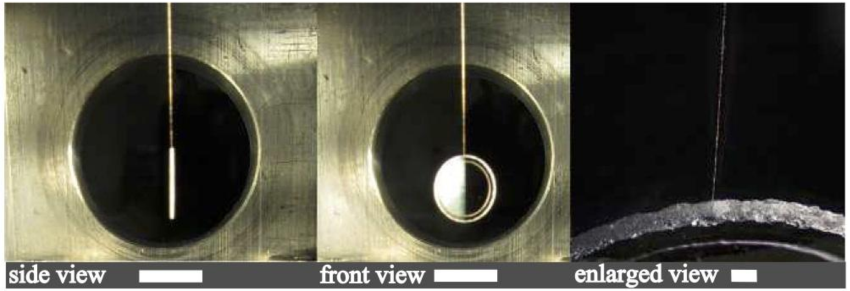
- What are the fundamental limits imposed by quantum mechanics on the detection of small forces/impulses?
- Given these limits, can we detect dark matter purely through its gravitational interaction? (Spoiler: yes, if heavy DM)
- Using the same technology, what other DM/particle physics targets can we look for?

Quantum force sensing

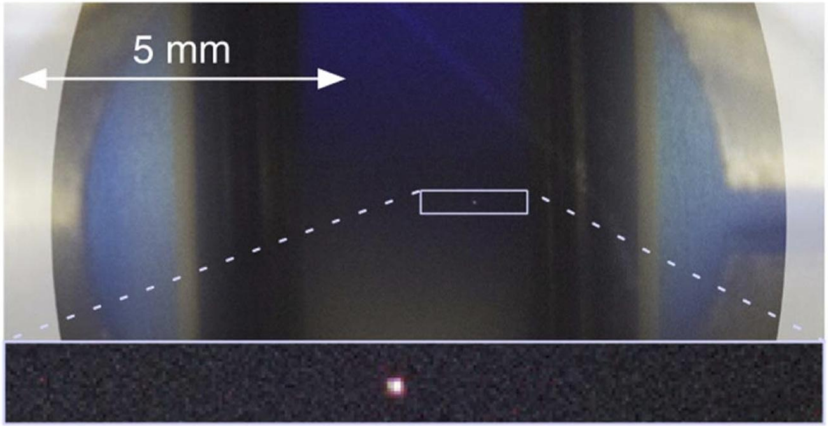
Wide variety of mechanical systems coupled to light used to do quantum-limited force sensing.

Routinely achieve force sensitivities at or below the $10^{-18\text{-}21}$ N/√Hz level.

These devices range from single electrons to huge devices (eg. LIGO m = 40 kg)



Matsumoto et al, PRA 2015



Aspelmeyer ICTP slides 2013

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Featured in Physics

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

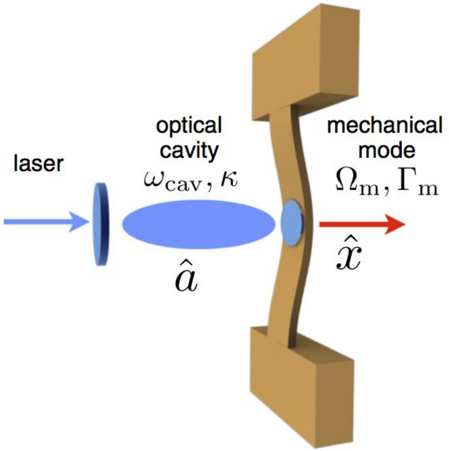
Nobuyuki Matsumoto, Seth B. Cataño-Lopez, Masakazu Sugawara, Seiya Suzuki, Naofumi Abe, Kentaro Komori, Yuta Michimura, Yoichi Aso, and Keiichi Edamatsu

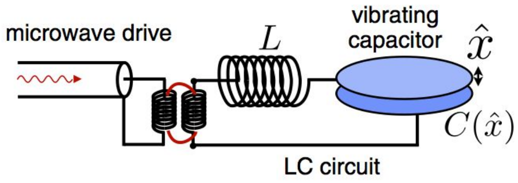
Phys. Rev. Lett. **122**, 071101 – Published 19 February 2019

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

Quantum opto/electromechanical sensing





Aspelmeyer, Marquant, Kippenberg
(Rev. Mod. Phys. 2014)

mechanics

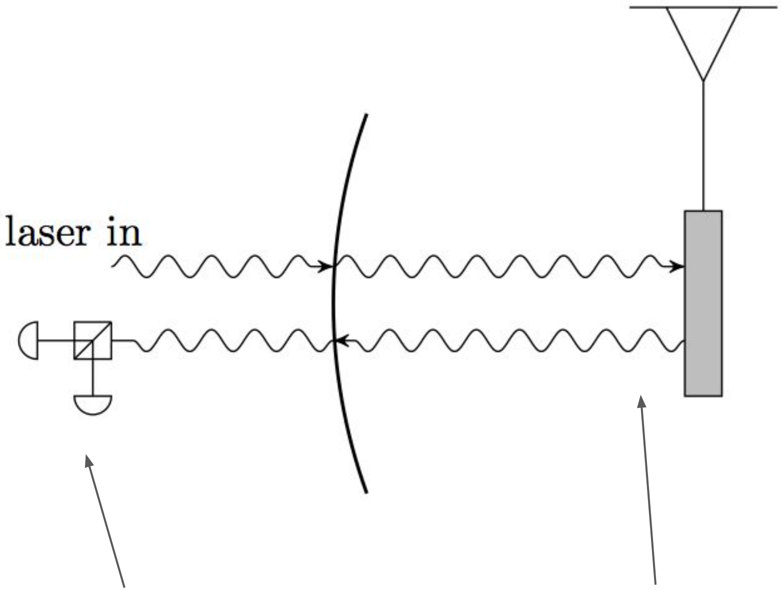
light

$$H_{OM} = g x X$$

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

Strategy: imprint mechanical displacement onto light, measure light, infer force

Quantum measurement noise



readout light phase
via interferometer
→ learn $x(t)$

light phase shift ~ $x(t_1)$

Quantum mechanics imposes fundamental source of noise: the act of measurement itself.

Shot noise: random variations in laser phase read out in detector

Backaction noise: random variations in laser amplitude → random radiation pressure on mechanics

Noise and sensitivity

Total (inferred) force acting on the sensor:

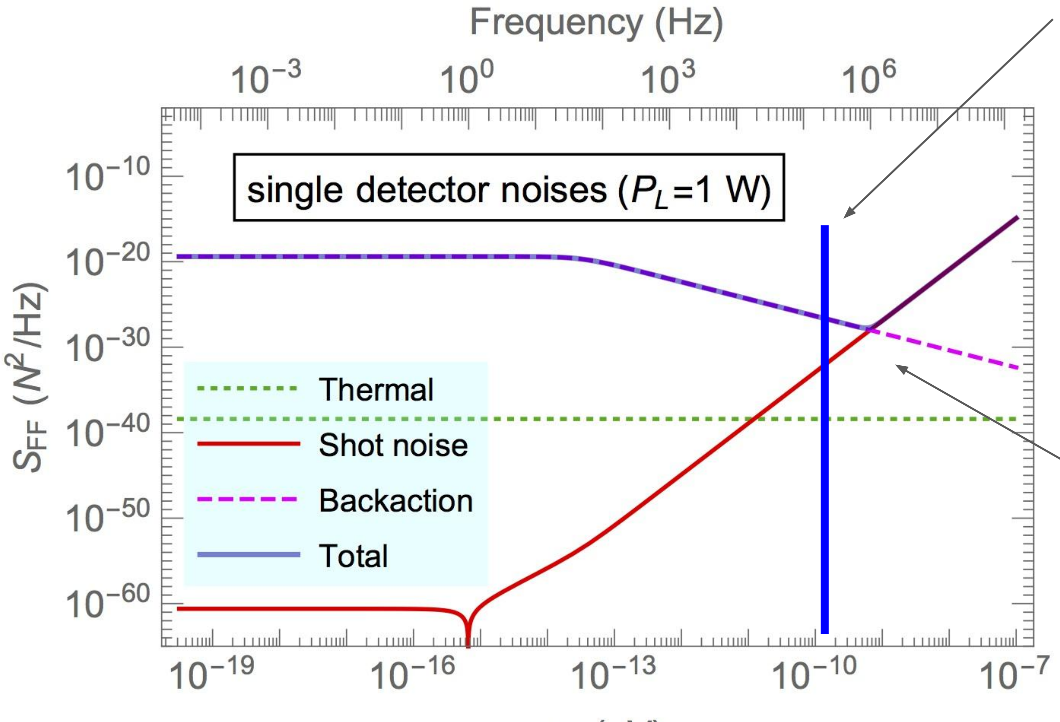
$$F_{\mathrm{in}}(t) = F_{\mathrm{sig}}(t) + F_{\mathrm{th}}(t) + F_{\mathrm{meas}}(t)$$

thermal noise forces
(environmental)

measurement added-noise force
(fundamental quantum issue)

Key in what follows:
Noise = stochastic, Brownian

Detecting monochromatic forces (narrowband sensing)



Visible signal

(w/ T_{int} = 1 sec of integration)

“Standard quantum limit” (SQL)

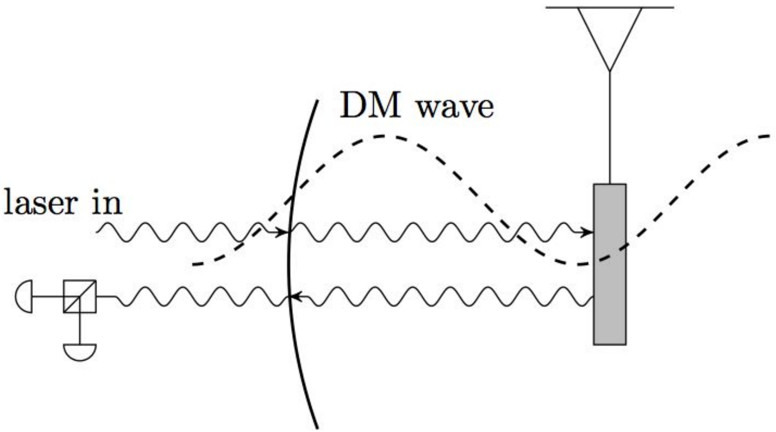
Location depends on laser power

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.

If the field couples to an extensive quantity, produces sinusoidal force, coherent for some time T_{coh}:



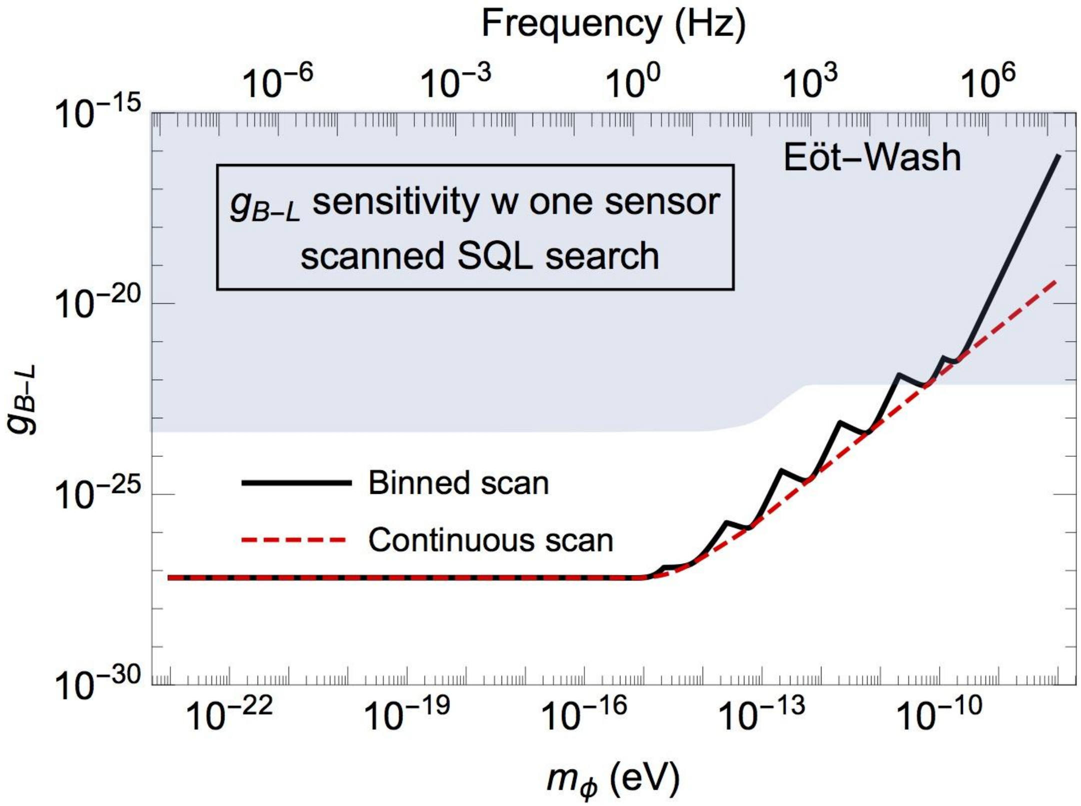
$$\mathcal{L}_{int} = g_{B-L} \not{A} \bar{n} n \longrightarrow F = g_{B-L} N_n F_0 \sin(\omega_s t)$$

Detection strategy and reach

Tune laser to achieve SQL in “bins”.

Integrate as long as possible for each bin (coherence time or eg. laser stability limit)

NB: this is off-resonant, can do better with resonant scan, much more time intensive



Detecting fast impulses (broadband sensing)

Extreme example:

$F(t) = \Delta p$ □$(t) \rightarrow F(\omega) = \Delta p/2\pi$ flat distribution

Sensitivity set by integral of noise over many frequencies

Cannot integrate for indefinite period of time → calls for different measurement protocols

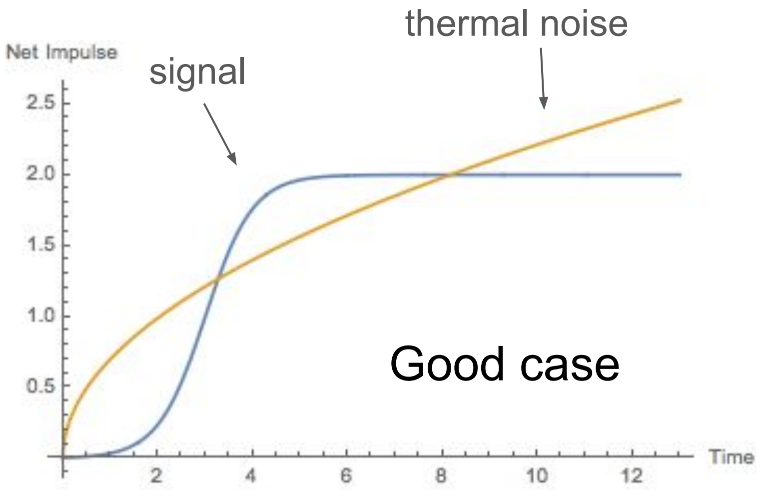
Signal to noise

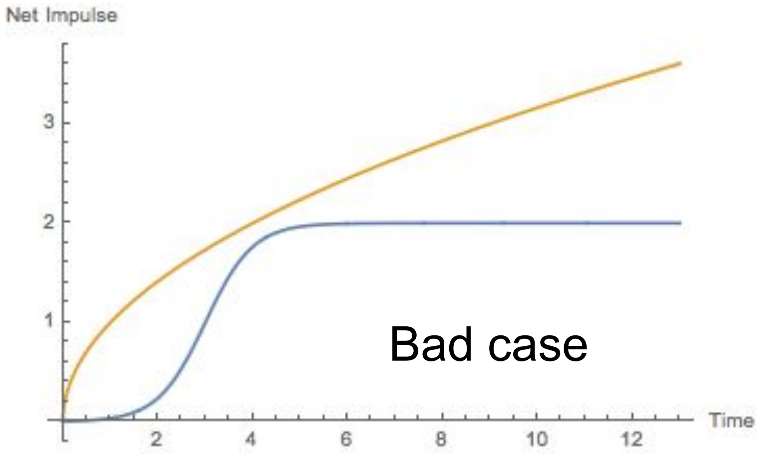
As an observable we will use the total impulse delivered to the sensor:

$$I = \int_{-t_{int}/2}^{t_{int}/2} dt\ F_{\text{sig}}(t)$$

The game is then to see this impulse above the noise:

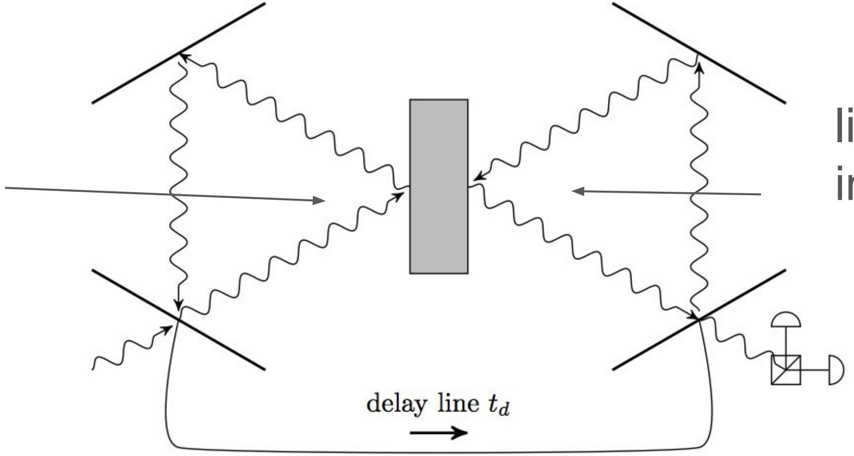
$$\begin{aligned}\langle \Delta I^2 \rangle &= \int dt dt' \ \langle F_{\text{noise}}(t) F_{\text{noise}}(t') \rangle \\ &= \Delta I_T^2 + \Delta I_{\text{meas}}^2\end{aligned}$$





Impulse measurements naturally reduce noise

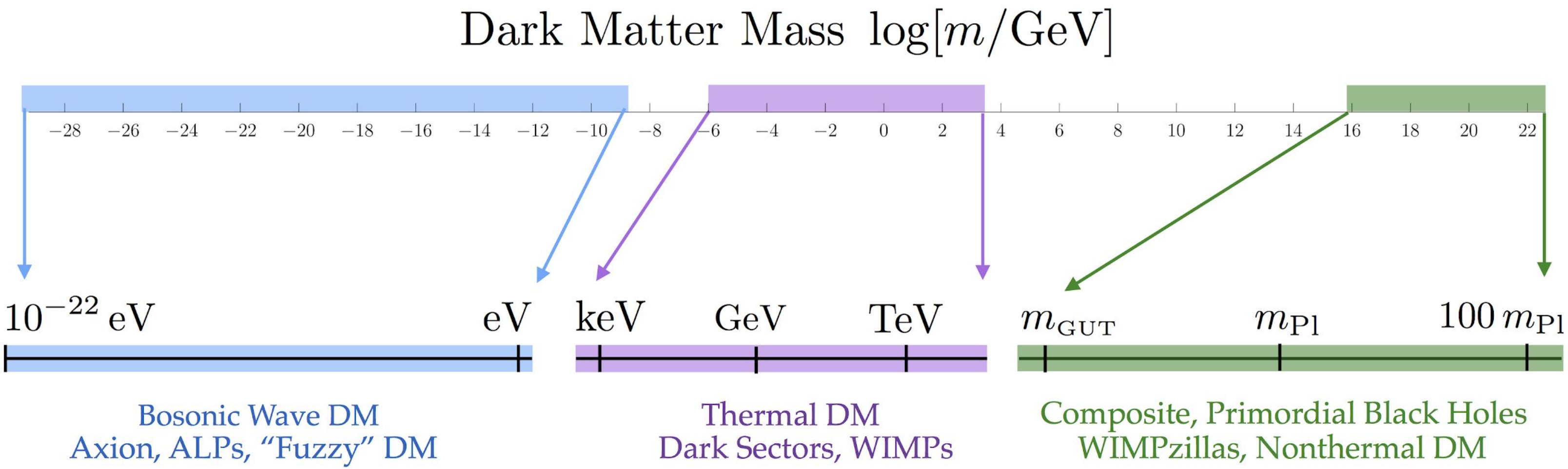
light phase ~ $x(t_1)$
impart +p to mirror



light phase ~ $-x(t_2)$
impart -p to mirror

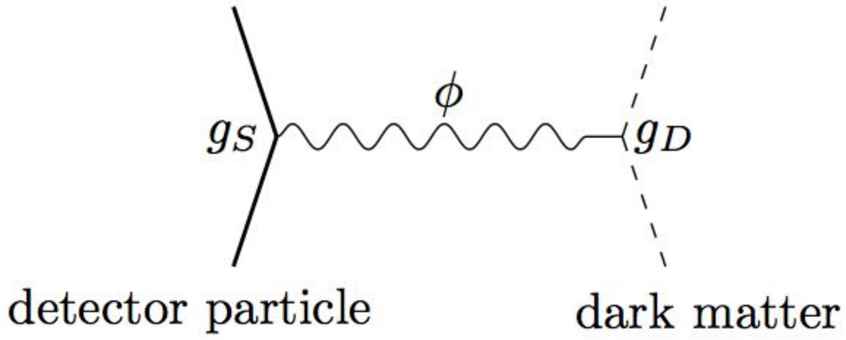
→ Output light phase $\phi \sim x(t_1)-x(t_2) \sim v$, momentum transfer to sensor $\Delta p \sim 0$
→ No radiation pressure (“backaction noise evasion”)

Heavier DM targets



$$n_{DM} \approx \frac{0.3}{\mathrm{cm}^3}\left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)$$

DM-SM interactions via light mediators



$$V(r) = N_V g_V g_D \frac{e^{-r/\lambda}}{r} \quad , \quad \lambda \equiv m_\phi^{-1}$$

$m\phi \gtrsim 1$ MeV ($\lambda\!\!\!^{-} \lesssim 10^{-13}$ m)
dominated by single boson exchange
(eg. WIMP detection via Z exchange)

$m\phi \lesssim 0.1$ meV ($\lambda\!\!\!^{-} \gtrsim 10^{-3}$ m)
dominated by eikonal limit
→ long-range force

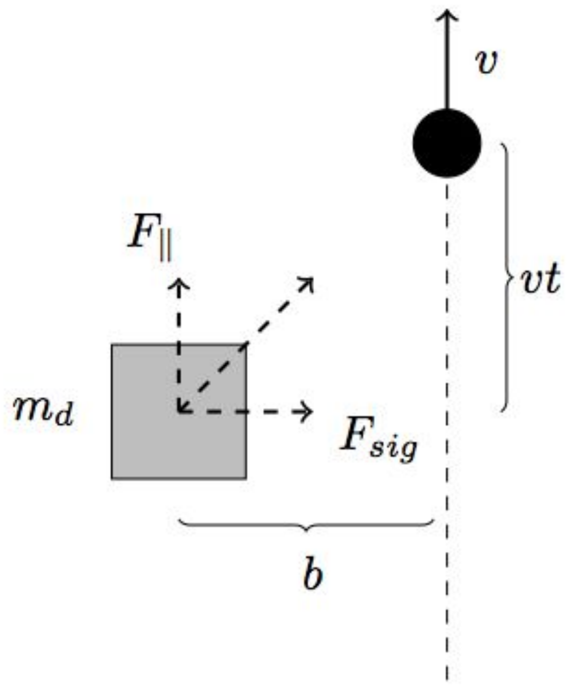
In particular: ϕ = graviton (exactly massless), $N\, g_V\, g_D \rightarrow G_N\, m_1\, m_2$

Long-range DM detection

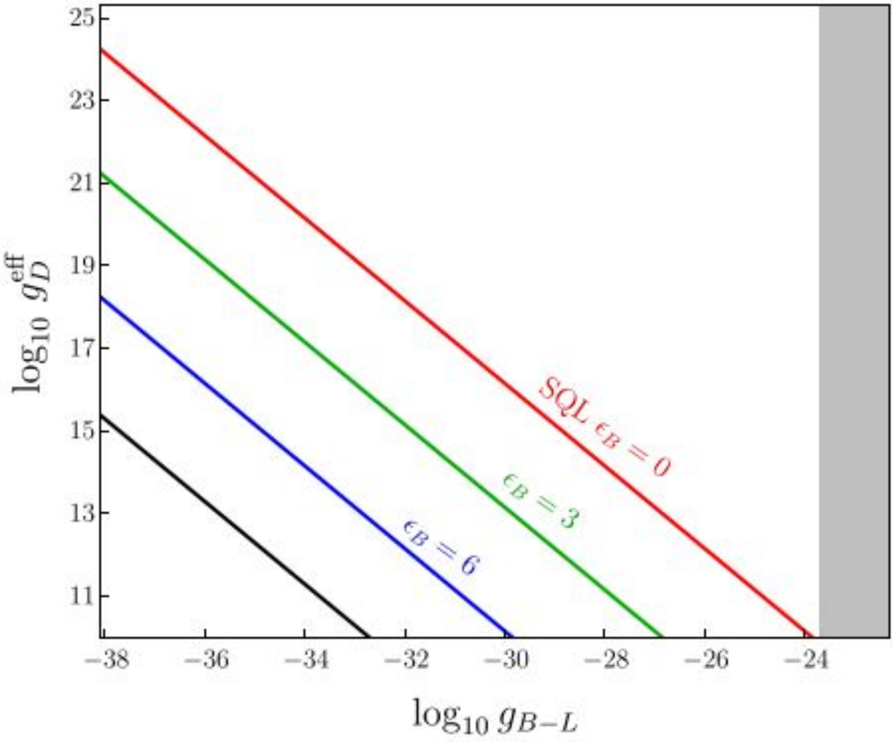
Motion of the Earth through the galaxy:
v ~ 220 km/s

→ flyby time **τ** ~ b/v ~ 10^{-6-8} sec

→ signal: near-instantaneous impulse (broadband up to MHz-GHz)



Detection reach with various noise reduction



$$\Delta I^2 = \Delta I_T^2 + \Delta I_{\mathrm{meas}}^2$$

$$\Delta I_{\mathrm{meas}} = 10^{-\epsilon_B} \Delta I_{SQL}$$

(NB: actual numbers are preliminary/ unpublished, but scaling is accurate) nature > light: science & applications > articles > article

Light | Science & Applications

Article | OPEN | Published: 30 May 2018

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

Stefan L. Danilishin, Eugene Knyazev, Nikita V. Voronchev, Fari
Sebastian Steinlechner, Jan-Simon Hennig & Stefan Hild

Light: Science & Applications **7**, Article number: 11 (2018) | Dow

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

IOPscience

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

Back-action evasion and squeezing of a mechanical res 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

Review: Advanced quantum techniques for future gravitational-wave detectors

Danilishin, Khalili, Miao 1903.05223

Array of sensors

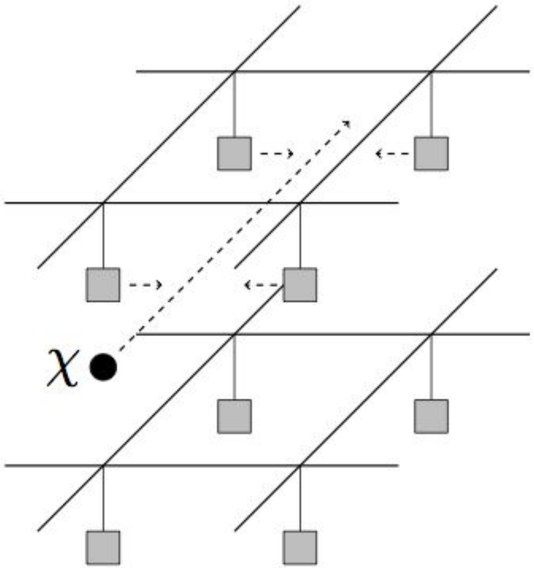
In the impulse problem:

Signal ~ $1/b^2$
→ want small impact parameter

Number flux ~ A/m_χ
→ want large area

$$R = \frac{\rho v A}{m_\chi} \sim \frac{50}{\text{year}} \left(\frac{m_{\text{Pl}}}{m_\chi}\right) \left(\frac{A_d}{10^2\,\text{m}^2}\right)$$

Obvious solution: build a large, tightly packed array!



Movie

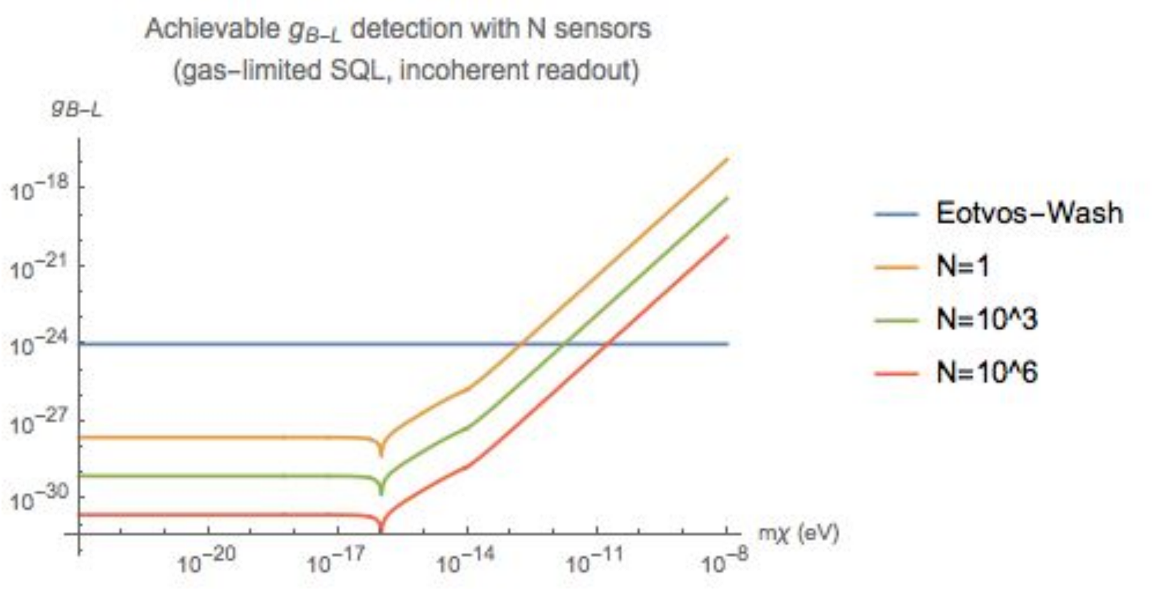
Correlated signals vs. uncorrelated noise

SNR ~ √N

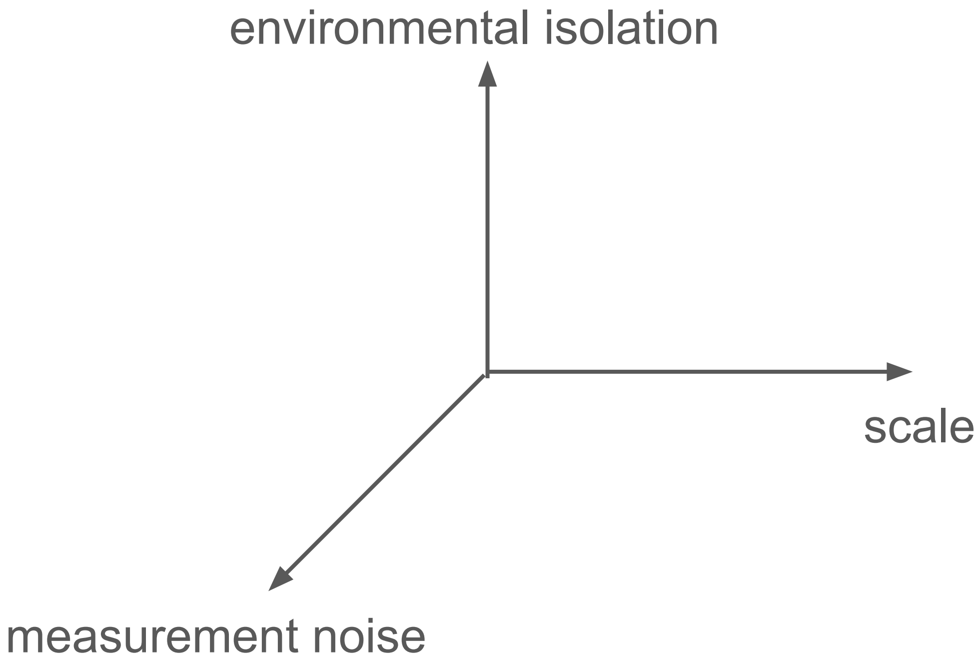
Impulse detection:
N = sensors near track

Ultralight detection:
N = total # sensors

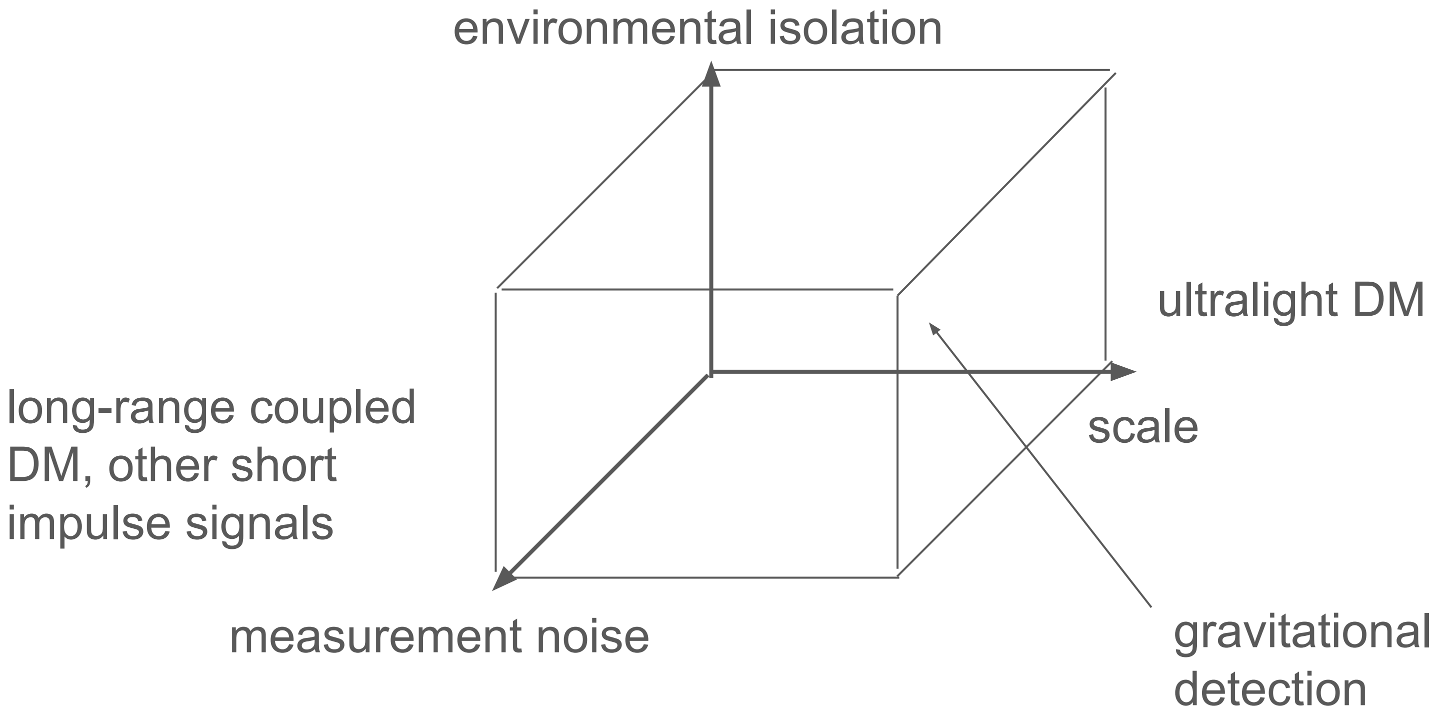
Also, crucial advantage:
exquisite background rejection



Three big experimental asks



Three big experimental asks



Gravitational detection is the end game

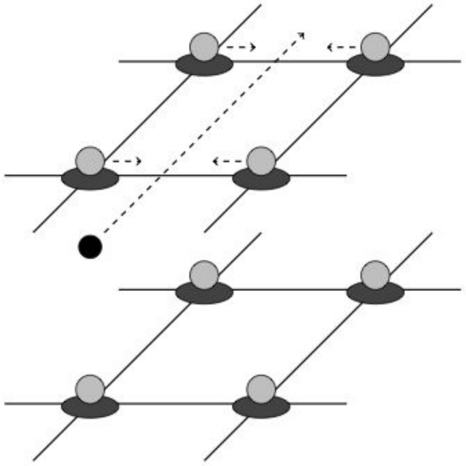
~10 million-1 billion sensors

~10 mK &/or UHV environment

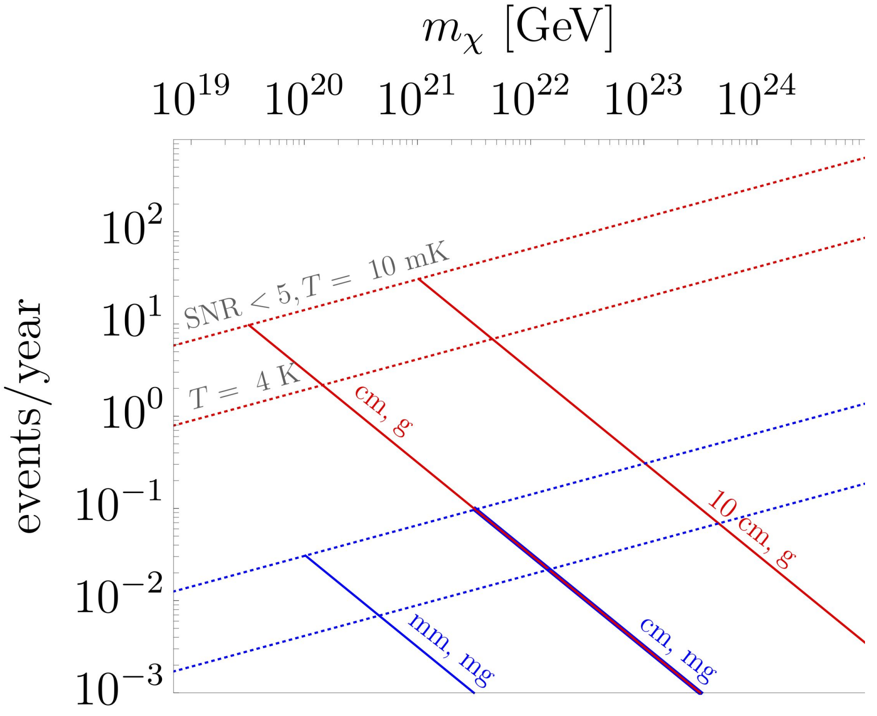
Thermally limited detection (~50 dB backaction evasion):

$$\mathrm{SNR}^2 = \frac{G_N^2 m_\chi^2}{v} \frac{L}{d^4} \frac{m_d^2}{P A_d \sqrt{m_a k_B T}}$$

$$\approx 10^4 \times \left(\frac{m_\chi}{1\ \mathrm{mg}}\right)^2 \left(\frac{m_d}{1\ \mathrm{mg}}\right)^2 \left(\frac{1\ \mathrm{mm}}{d}\right)^4$$



Direct DM detection via gravity



1903.00492 D.C., S. Ghosh, G. Krnjaic, J. M. Taylor

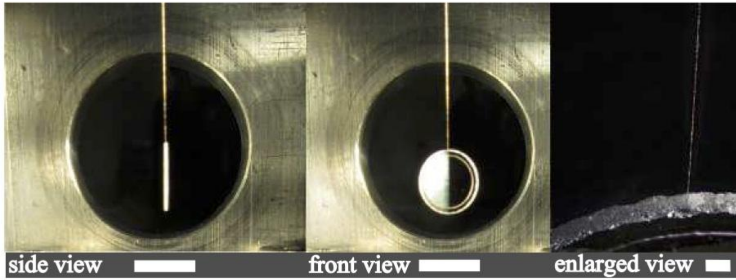
Science program

End goal: gravitational DM detection. Find or rule out any DM candidates with masses ~ m_{pl} and up (until flux-limited).

Shorter term: ultralight detection, various long range force models,...

Experiments now beginning with pair of mg-scale pendula ~ 1 kHz, ultralight search & tech pathfinder.

Single physical array, with multiple detection modes controlled by state prep & readout



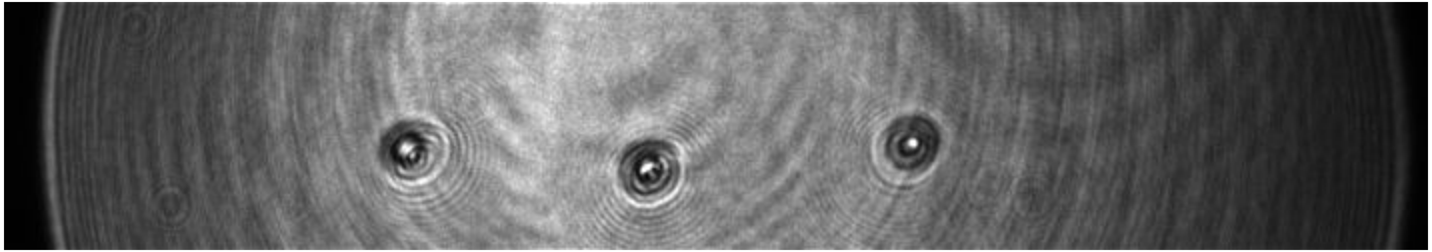


Photo from Dave Moore (Yale)

Quantum Optomechanical Architectures for Dark Matter Detection

28-29 October 2019
Joint Quantum Institute, University of Maryland
US/Eastern timezone

Fundamental Physics
Innovation
AWARDS

APS physics

GORDON AND BETTY MOORE FOUNDATION

Cindy Regal, JILA
(quant-ph exp)

Dave Moore, Yale
(hep-ex)

Gordan Krnjaic, FNAL
(hep-ph)

Open questions

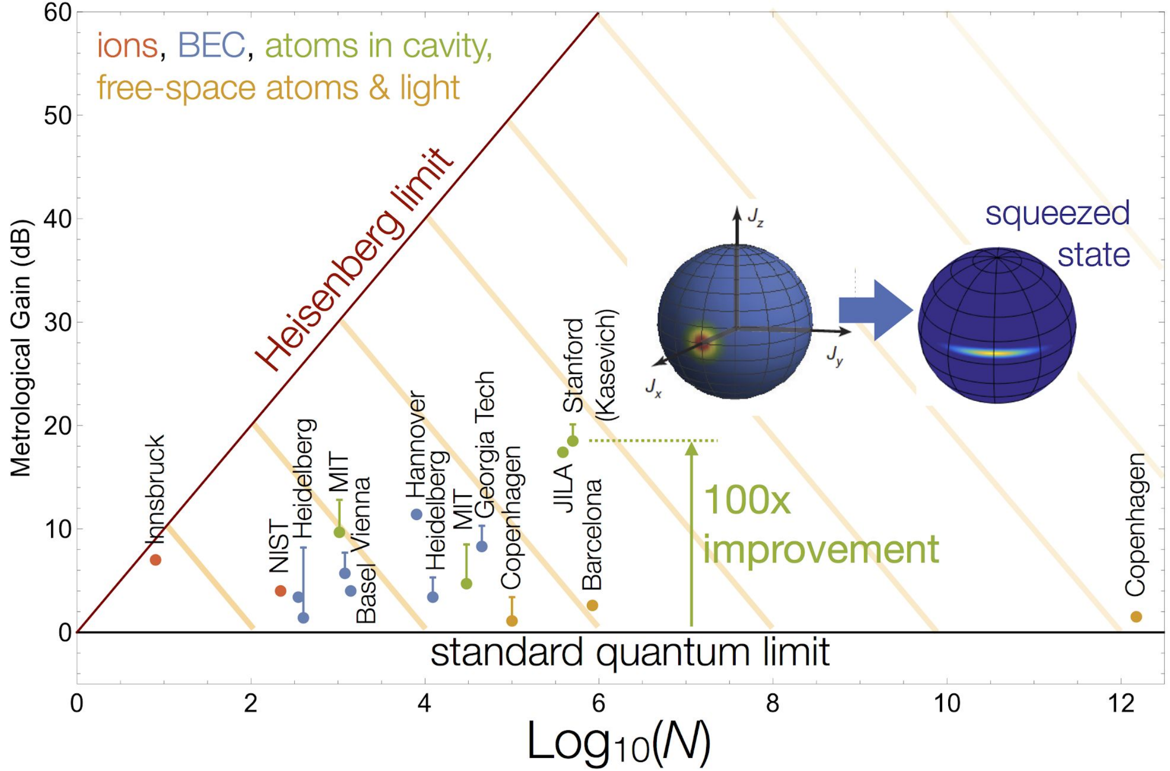
Can we do gravitational detection of sub-Planck candidates?

Can we go below the thermal noise floor? (Quantum error correction?)

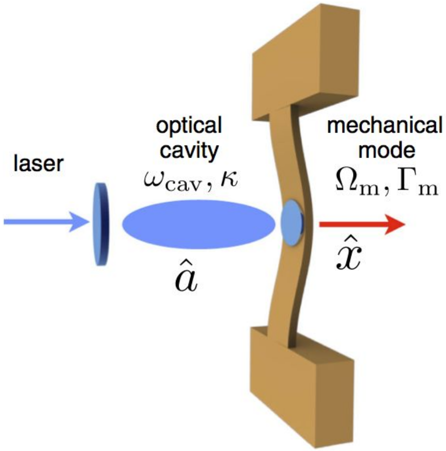
What other targets are there--eg. DM-SM with heavy mediators? “Chunky” DM candidates? Neutrinos? Gravitational waves?
→ Each requires its own measurement strategy (but with same physical devices!)

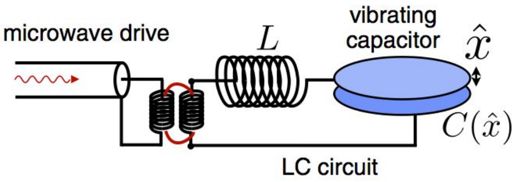
How do we physically implement large arrays?

Entanglement-Enhanced Measurements



Slide from Monika Schleier-Smith





$$\dot{X} = -\Delta Y - \boxed{\frac{\kappa}{2}} X + \boxed{X_{in}}$$

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

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

$$\dot{p} = -m\omega_m^2 x - \boxed{\gamma} p + \boxed{F_{in}} + \frac{\hbar g X}{x_0}$$

Damping/loss

"Input noise"
(note signal is part of F_{in})

Non-gravitational DM detection targets

Very broadly, we should be sensitive to anything that produces a classical force!

In terms of DM, obvious guess is to then consider any DM scenario with a boson of mass m_ϕ < meV ~ 1 mm^{-1} that couples to standard model.

# new particles	type of particles	signal
1	Boson m_ϕ < meV	coherent waves
≥2	+others, mass arbitrary	long-range DM-SM couplings

Detecting monochromatic forces at the SQL

The “SQL” is a frequency-dependent concept: Tune laser power to a certain value → achieve SQL at a certain frequency