Title: Quantum Impulse Sensing with Mechanical Sensors in the Search for Dark Matter

Speakers: Sohitri Ghosh

Series: Perimeter Institute Quantum Discussions

Date: December 01, 2022 - 4:00 PM

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Abstract: Recent advances in mechanical sensing technologies have led to the suggestion that heavy dark matter candidates around the Planck mass range could be detected through their gravitational interaction alone. The Windchime collaboration is developing the necessary techniques, systems, and experimental apparatus using arrays of optomechanical sensors that operate in the regime of high-bandwidth force detection, i.e., impulse metrology. Today's sensors can be limited by the added noise due to the act of measurement itself. Techniques to go beyond this limit include squeezing of the light used for measurement and backaction evading measurement by estimating quantum non-demolition operators -- typically the momentum of a mechanical resonator well above its resonance frequency. In this talk, we will discuss the theoretical limits to noise reduction using such quantum enhanced readout techniques for these optomechanical sensors.

Quantum Impulse Sensing with Mechanical Sensors in the Search for Dark Matter

Sohitri Ghosh

Perimeter Institute
Dec 1, 2022

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

UNIVERSITY OF MARYLAND 1856 DEPARTMENT OF PHYSICS

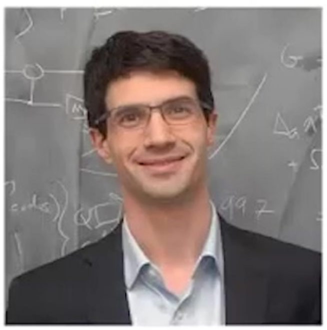
JOINT QUANTUM INSTITUTE

0

Background

I apply the ideas of quantum metrology to searching for new physics using quantum sensing platforms.

Advisors :



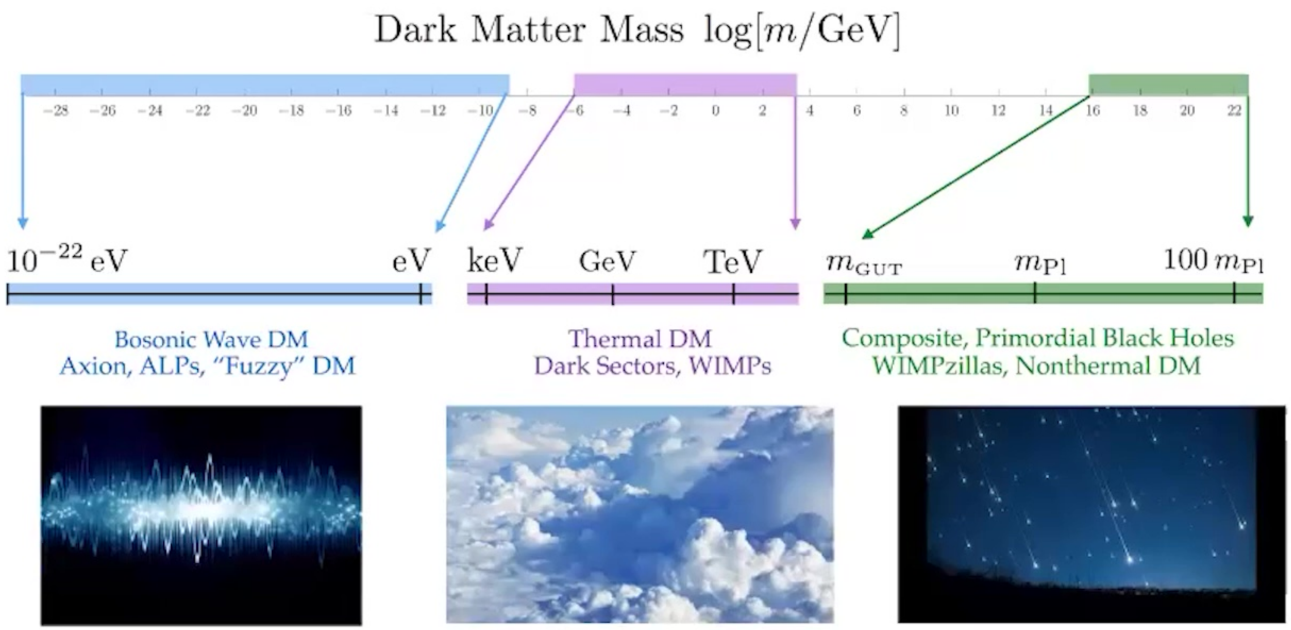
Jake Taylor

Peter Shawhan

Dan Carney

Part I : Dark Matter

- Many astrophysical observations provide evidence for the existence of dark matter (DM).
- However, the exact nature of dark matter is still unknown. Today I will focus on particulate DM.



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

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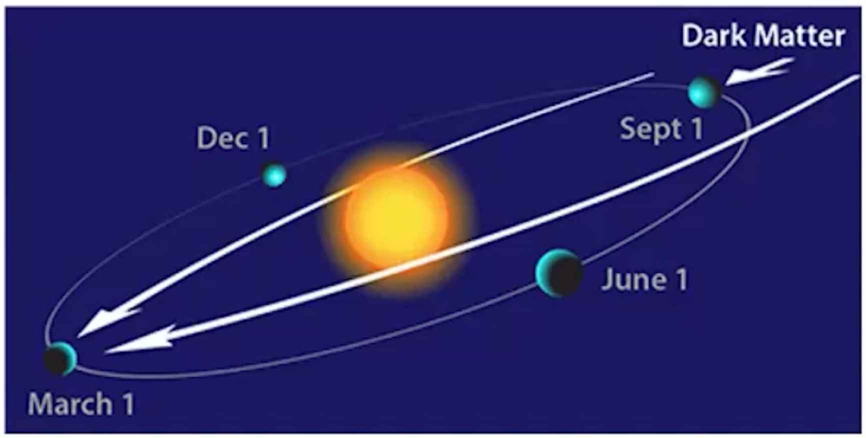
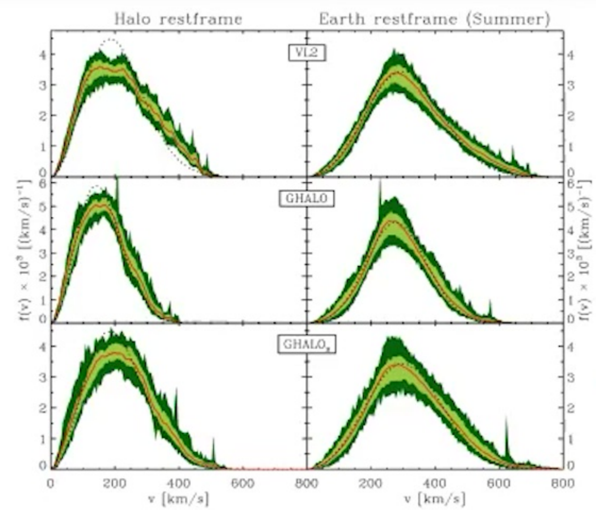
Dark Matter Wind

- We may be moving through the DM halo at v ~ 220 km/s





Kuhlen et. al.
0912.2358

Typical v~ 220 km/s — but can vary *a lot* on small scales (streams etc.)

*Picture source : APS/Alan Stonebraker

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Detection of Dark Matter?

- Many researchers around the world look for DM through potential interactions with standard model particles.

Open Access

Search for inelastic scattering of WIMP dark matter in XENON1T

E. Aprile *et al.* (XENON Collaboration)
Phys. Rev. D **103**, 063028 – Published 19 March 2021

Featured in Physics | Editors' Suggestion | Open Access

Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment

N. Du *et al.* (ADMX Collaboration)
Phys. Rev. Lett. **120**, 151301 – Published 9 April 2018

Physics See Viewpoint: Homing in on Axions?

Snowmass 2021 White Paper: The Windchime Project, arXiv: 2203.07242

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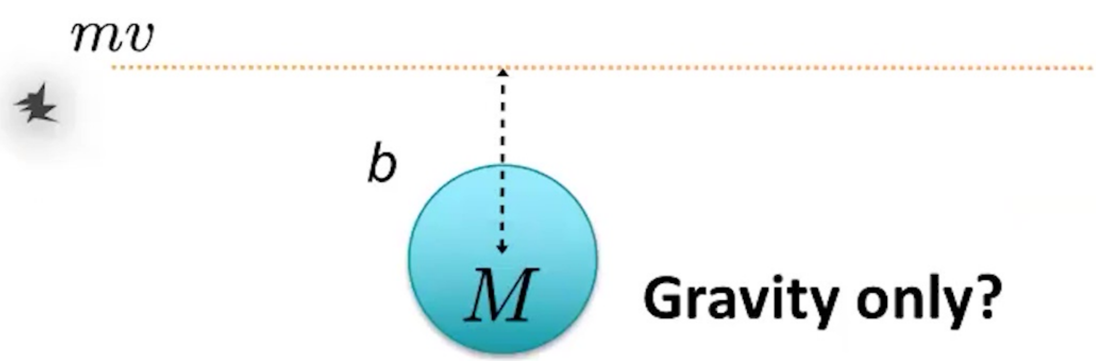
Physics See Viewpoint: Homing in on Axions?

- Our goal: Detection of dark matter directly through its gravitational interaction with visible matter
- Can we be sensitive to gravitational interaction with Planck-scale DM particles ?

Snowmass 2021 White Paper: The Windchime Project, arXiv: 2203.07242 4

Gravitational Interaction with Dark Matter

- At this mass level, the passing DM provides a gravitational impulse to the detector



Gravity only?

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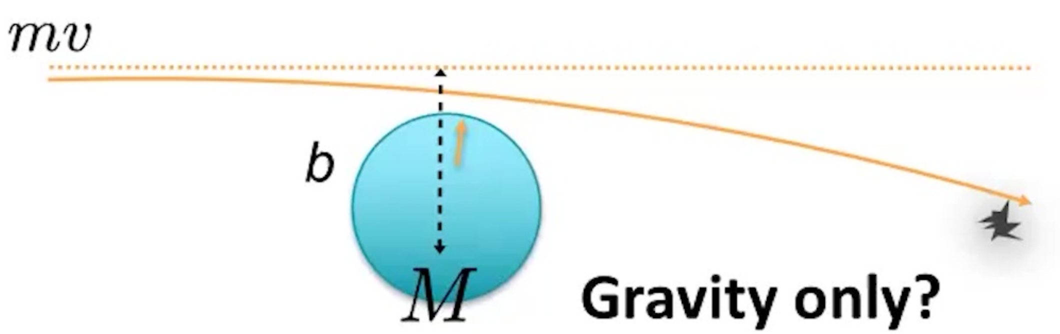

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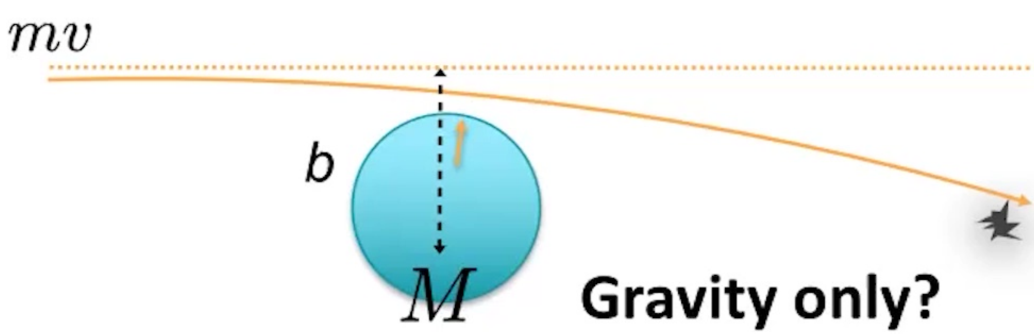

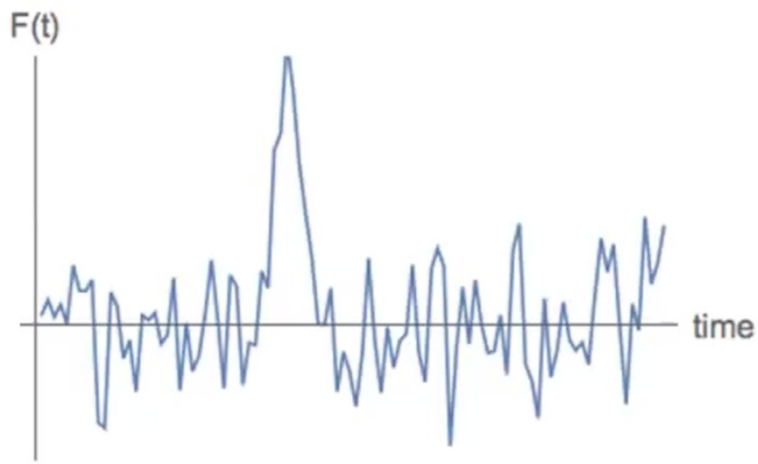

$$\Delta V_{\rm dm} \approx \frac{Gm}{bv} \lesssim \frac{Gm}{Rv} \sim 6 \times 10^{-22}\ {\rm m/s} \frac{m}{m_{\rm pl}} \frac{1\ {\rm cm}}{R}$$

$$\Delta p(\tau) = \int_0^\tau F(t) dt$$

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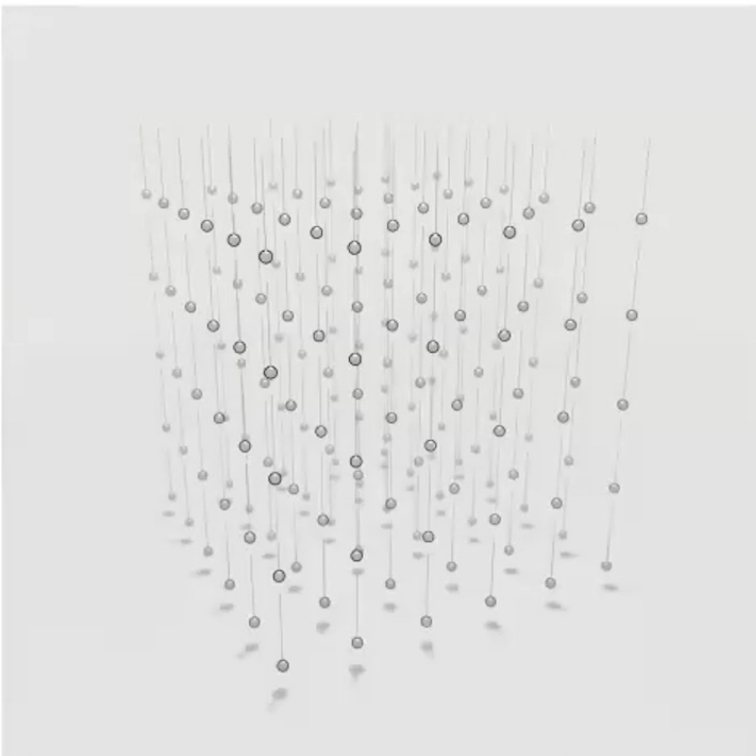
Detector Array Concept



Video courtesy: Sean Kelley, NIST

Carney, **Ghosh**, Krnjaic, Taylor, Phys. Rev. D **102**, 072003

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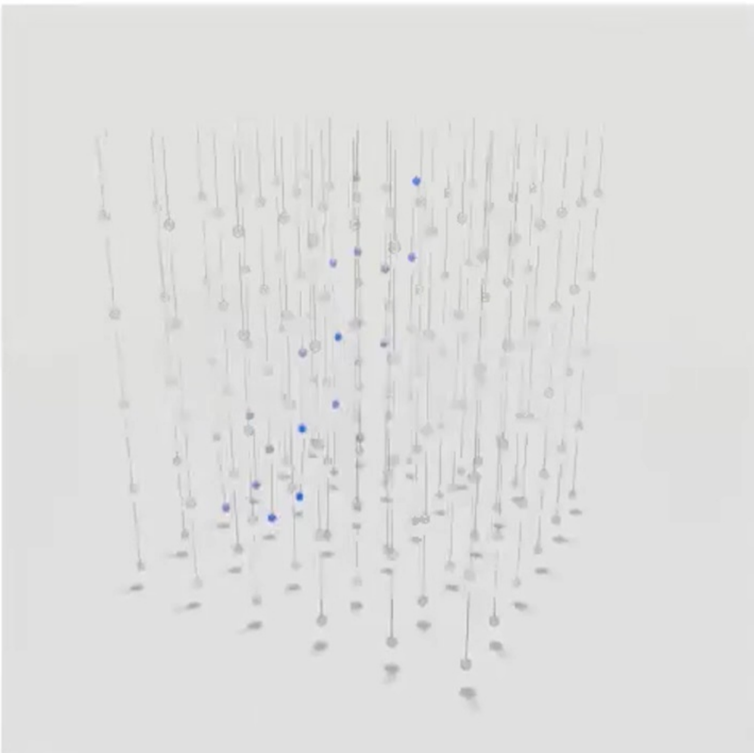


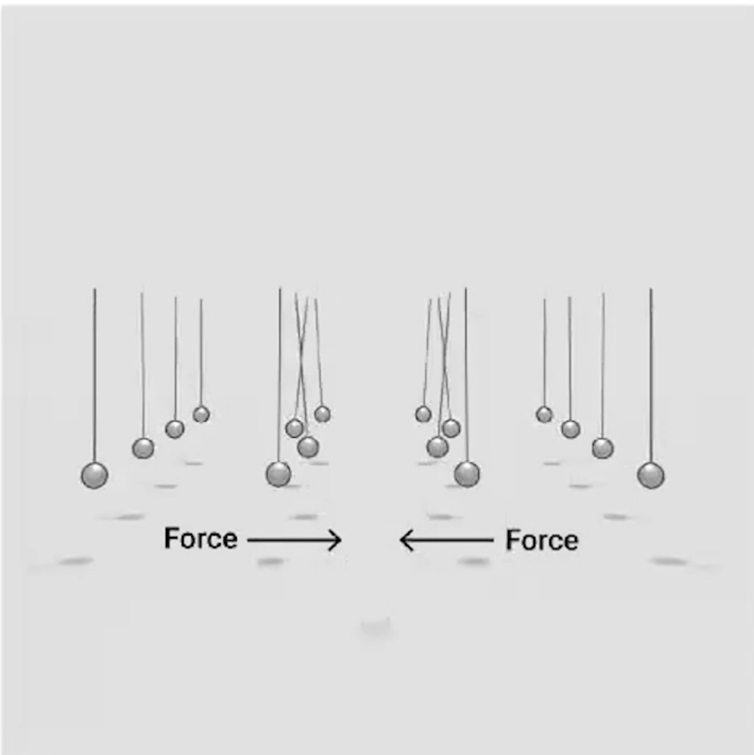
- The array comprises of many acceleration sensors.
- Dark matter (DM) particle passes by at speed ~ 220 km/s.
- DM interacts with individual sensor via

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

Video courtesy: Sean Kelley, NIST

Carney, **Ghosh**, Krnjaic, Taylor, Phys. Rev. D **102**, 072003

Detector Array Concept



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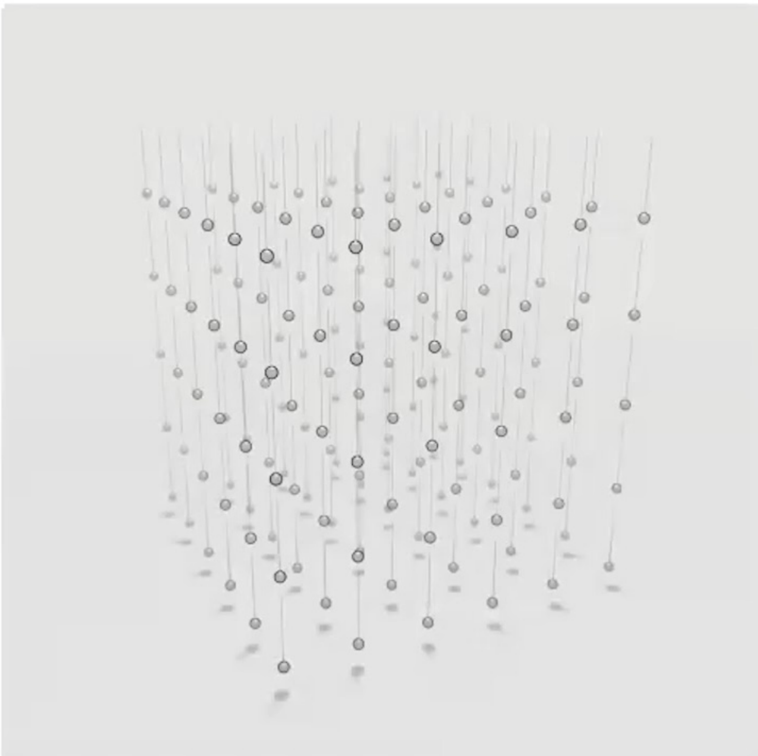


- The array comprises of many acceleration sensors.
- Dark matter (DM) particle passes by at speed ~ 220 km/s.
- DM interacts with individual sensor via

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

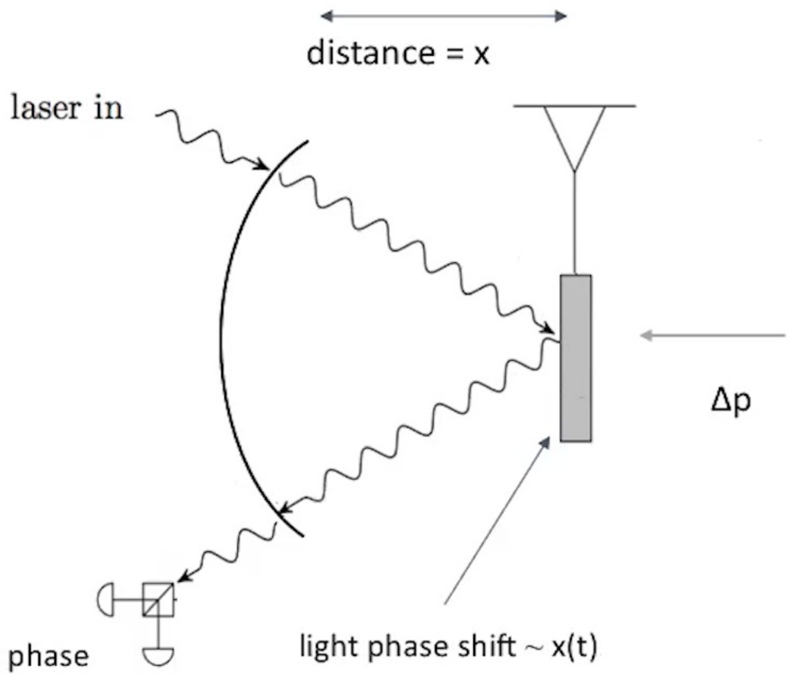
- Assuming a cross-sectional area A, the number of dark matter particles passing through the detector per unit time is,

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

Video courtesy: Sean Kelley, NIST

Carney, **Ghosh**, Krnjaic, Taylor, Phys. Rev. D **102**, 072003

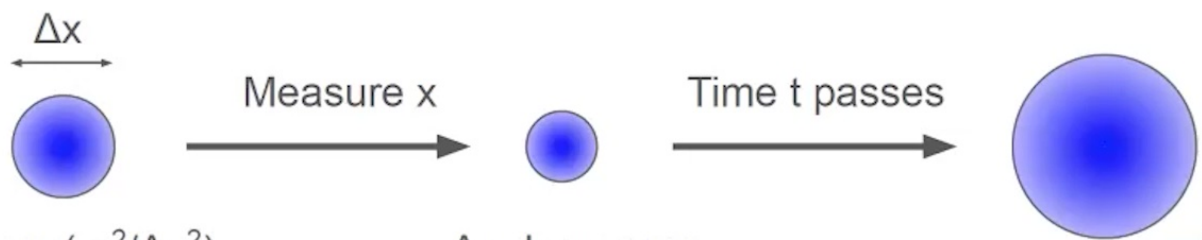
Impulse Measurement Basic Readout Scheme



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

- Impulse imparted upon sensor induces displacement.
- Readout displacement by probing the system with light as,
  - Light phase shift ∝ displacement
  - Light phase can be readout via interferometer

Standard Quantum Limit of Impulse Measurement



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

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

Δx decreases

Δp increases

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

optimize
—> “standard quantum limit”

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

$$\Delta I_{\rm SQL} \geq \sqrt{\frac{\hbar m}{t}}$$

$$\Delta v_{\rm SQL} \sim (5 \times 10^{-17} \text{ m/s}) \left(\frac{1 \text{ s cm}^3}{\tau R^3} \right)^{1/2}$$

$$\Delta V_{\rm dm} \approx \frac{Gm}{bv} \lesssim \frac{Gm}{Rv} \sim 6 \times 10^{-22} \text{ m/s} \frac{m}{m_{\rm pl}} \frac{1 \text{ cm}}{R}$$

*Caves et al, 1980

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Paths Towards Gravitational Detection of DM

~ 10^9 detectors
~ mg each

Scale of the device

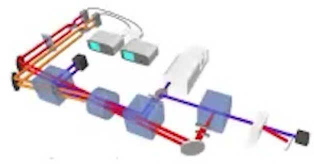
Environmental isolation

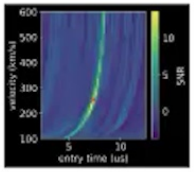
~ dilution refrigerator
~ freely falling detectors

Gravitational detection of Planck scale DM

Measurement-added noise suppression

~ orders of magnitude below SQL





Data pipeline and analysis

~ improvements in data analysis techniques for large datasets

9

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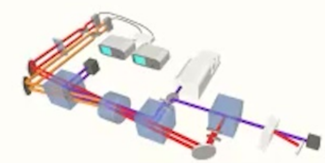

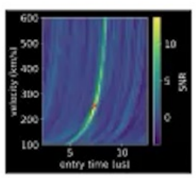

Data pipeline and analysis

$\sim$ improvements in data analysis techniques for large datasets

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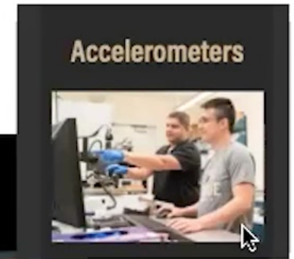
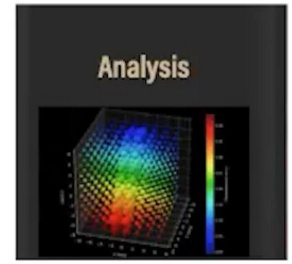
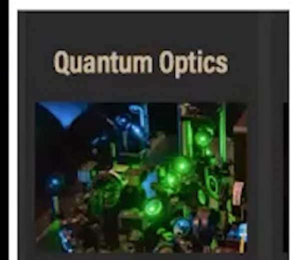
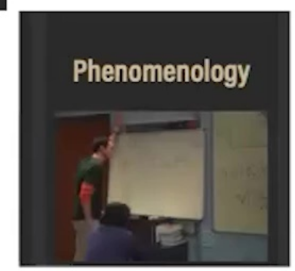
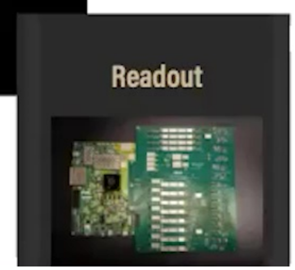
Windchime









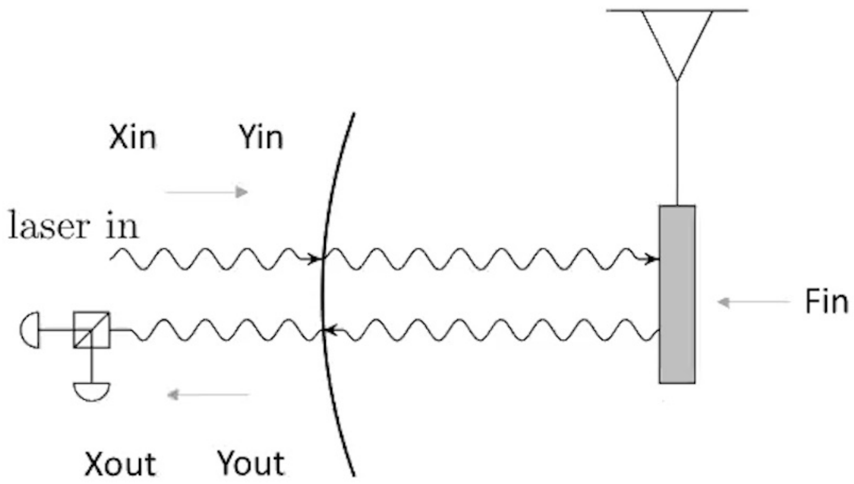


windchimeproject.org

Roadmap of Part II

- SQL for continuous position measurement in optomechanical measurements
- Methods to go below SQL :
  - Squeezing
  - Backaction Evasion through QND measurements
- Benefits of moving to microwave domain readout

Continuous Position Measurement in Optomechanical System

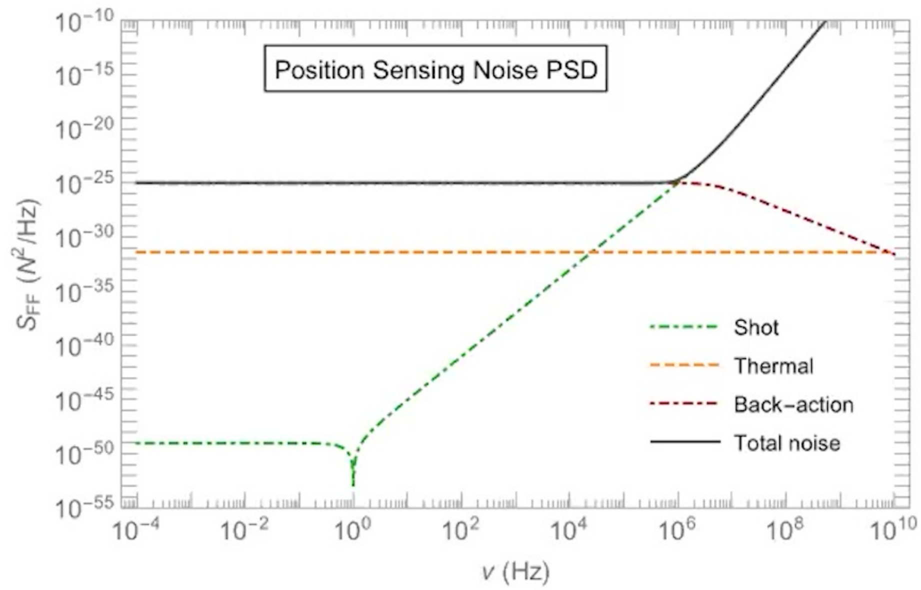


- A prototypical optomechanical system consists of :
  - A partially transparent fixed mirror on one side.
  - A suspended, moveable mirror on another side.

$$H_{\text{int}} = \hbar g_0 \alpha \frac{x}{x_0} X = \hbar G x X$$

Noise in Measurements

- Various sources of noise in quantum measurement :
  - Coupling of the measurement device with its environment
  - Measurement added noise (Depends on how we probe the system)
- Measurement added noise in optomechanical system:
  - Shot Noise : Arises from statistical counting error of photons
  - Backaction Noise : Arises from fluctuations in the radiation pressure of light



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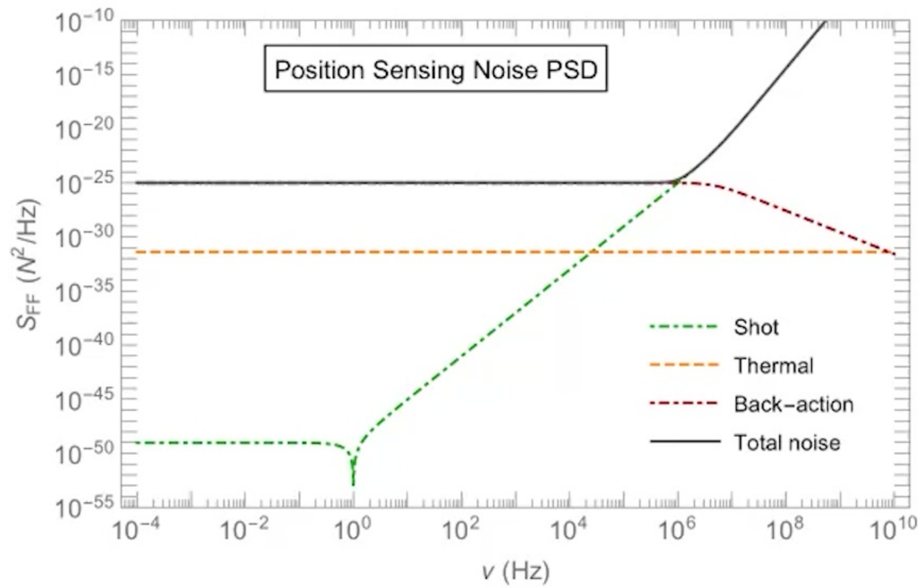


$$S_{\mathrm{FF}} \propto \alpha\langle F_{\mathrm{in}}^2\rangle + \beta\langle X_{\mathrm{in}}^2\rangle + \gamma\langle Y_{\mathrm{in}}^2\rangle$$

Methods to get below SQL

- General representation of the force power spectral density

$$S_{\mathrm{FF}} \propto \alpha\langle F_{\mathrm{in}}^2\rangle + \beta\langle X_{\mathrm{in}}^2\rangle + \gamma\langle Y_{\mathrm{in}}^2\rangle$$

- Squeezing

$$\langle X_{\mathrm{in}}^2\rangle \to e^{2r}, \langle Y_{\mathrm{in}}^2\rangle \to e^{-2r} \qquad S_{X_{\mathrm{in}}Y_{\mathrm{in}}} < 0$$

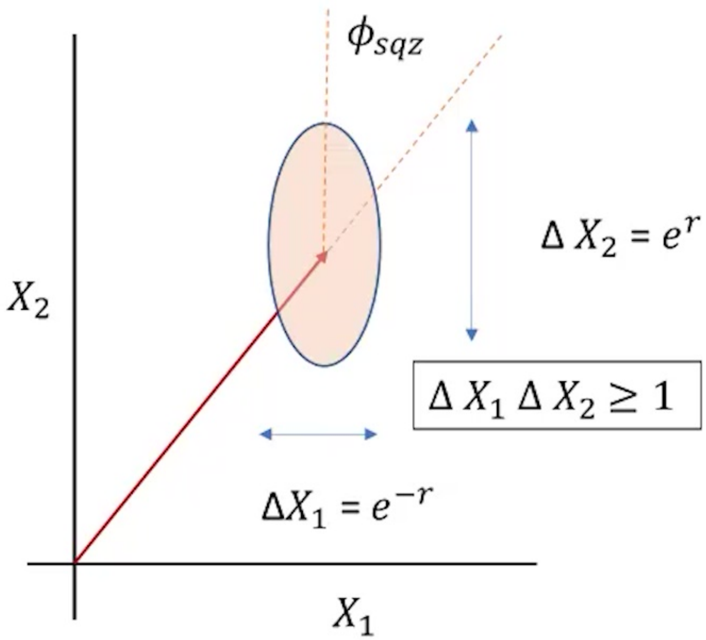
- Backaction evasion

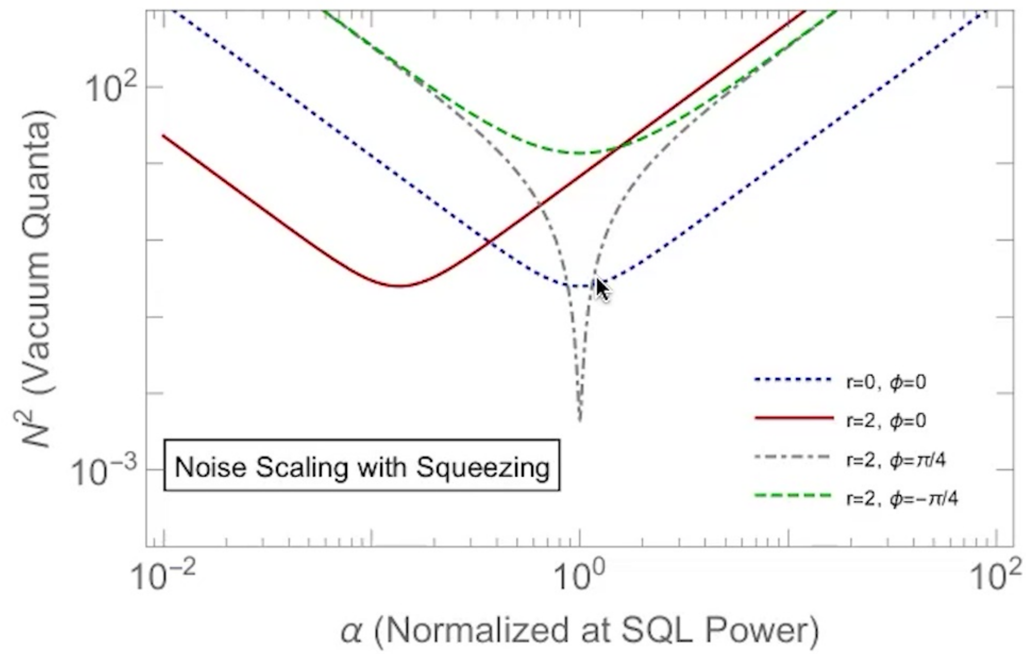
$$\beta \to 0$$

- Combining them

$$\beta \to 0 \qquad \langle Y_{\mathrm{in}}^2\rangle \to e^{-2r}$$

Benefits of Squeezing : Phase Estimation

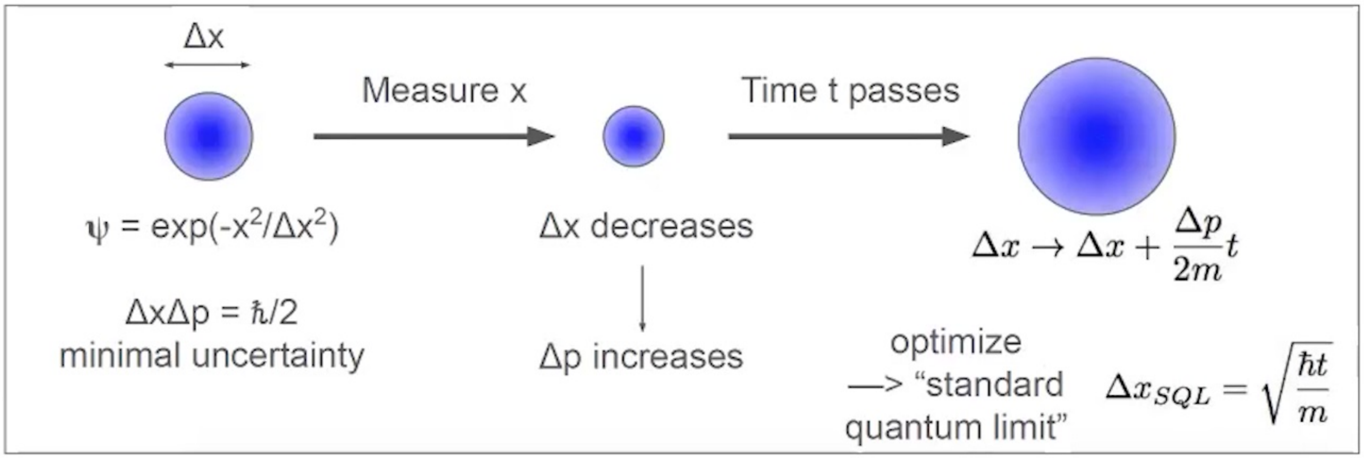




*__Ghosh__, Feldman, Hong, Marvinney, Pooser, and Taylor, arXiv:2211.14460

Phase Shifts from Momentum vs Position

$$H_{\text{int}} = \alpha x X$$



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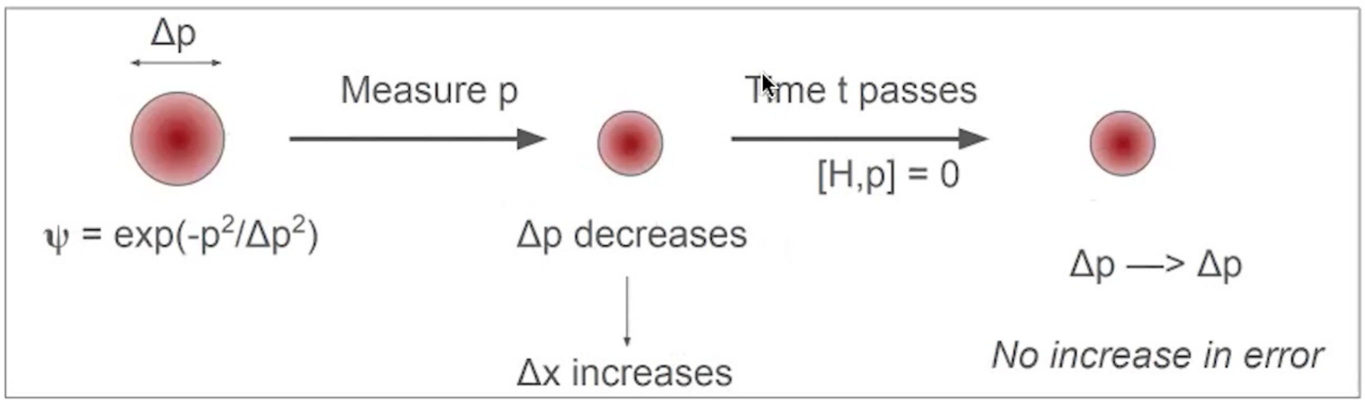

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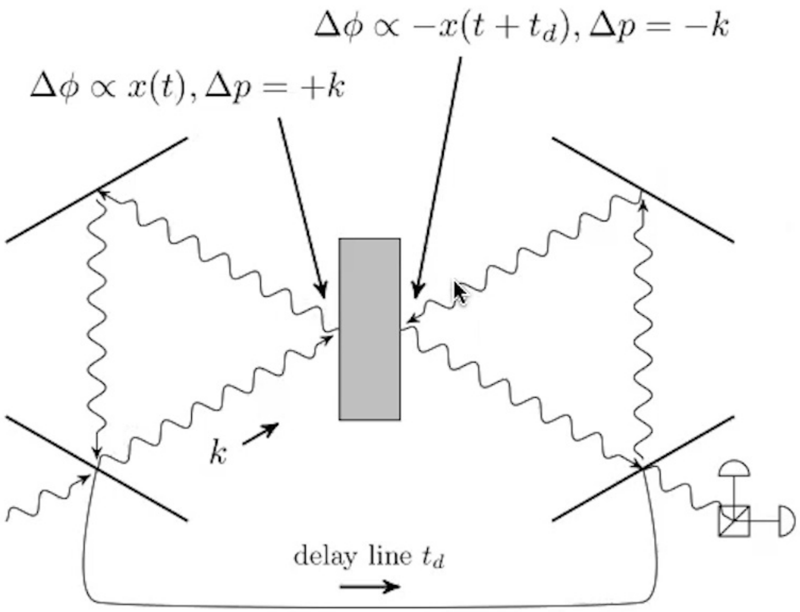
Backaction Evading Measurement with Optomechanical System



$$H_{\text{int}} = \hbar G x X - \hbar G' x X'$$

- We study a concrete optomechanical realization where,
  - Two ring cavities share a common mechanical element, a two-sided mirror.
  - The light interacts with the shared mirror twice from opposite directions with a short time delay t_d.

*Braginsky & Khalili , 1990

Ghosh, Carney, Shawhan, Taylor, Phys. Rev. A **102**, 023525

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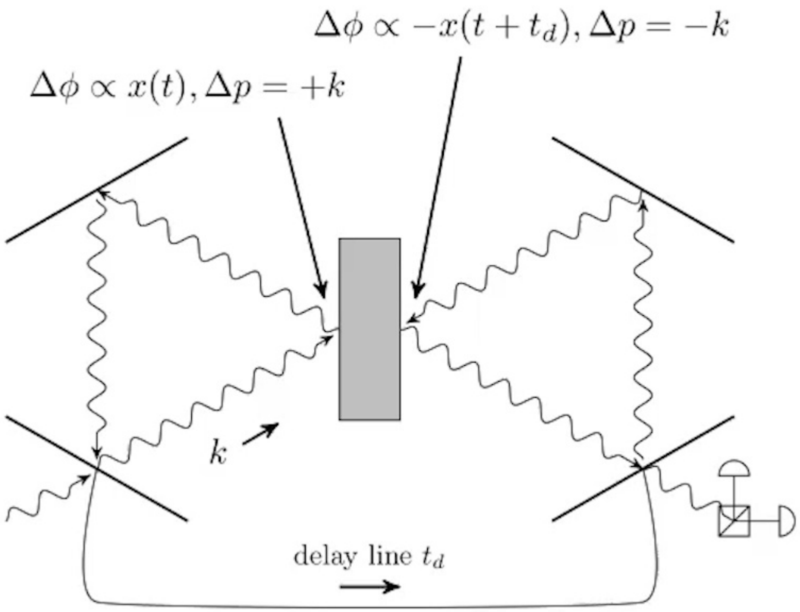
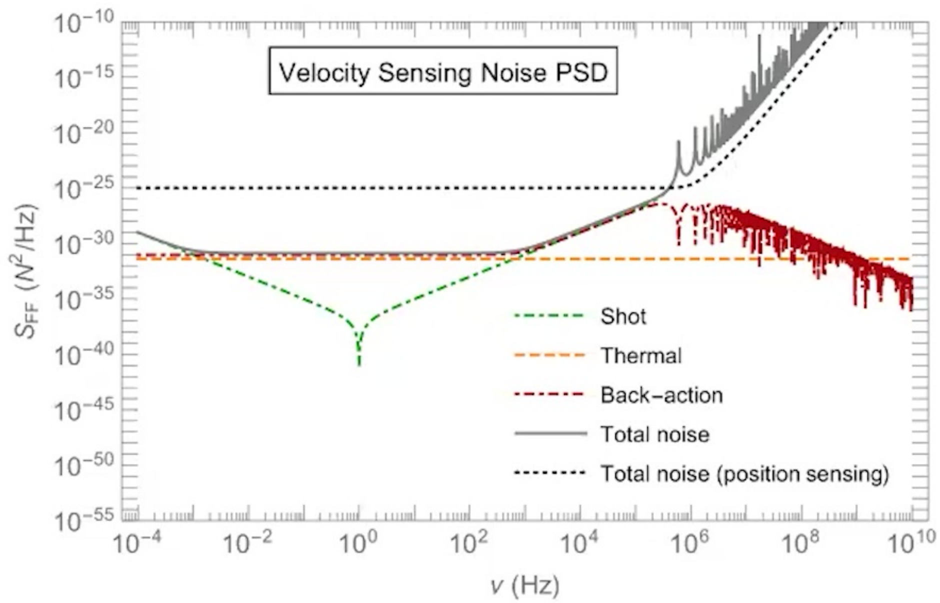
Backaction Evading Measurement with Optomechanical System





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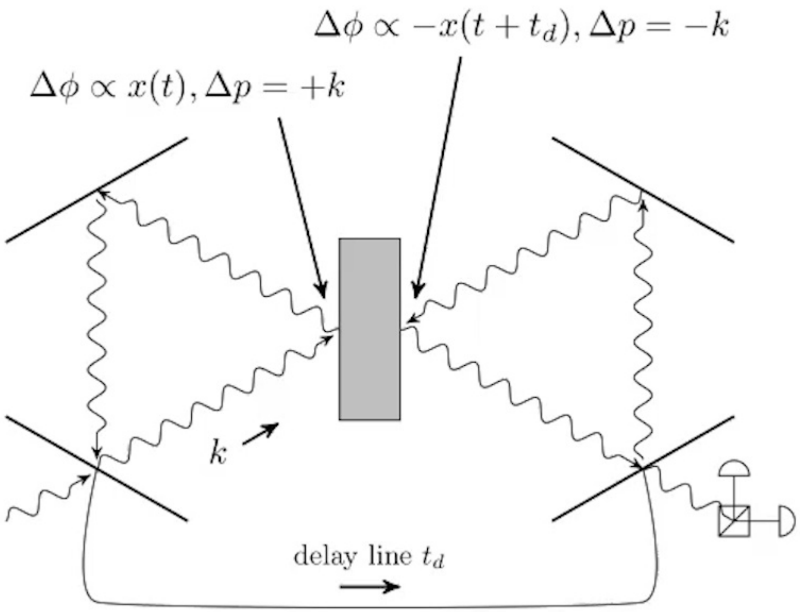
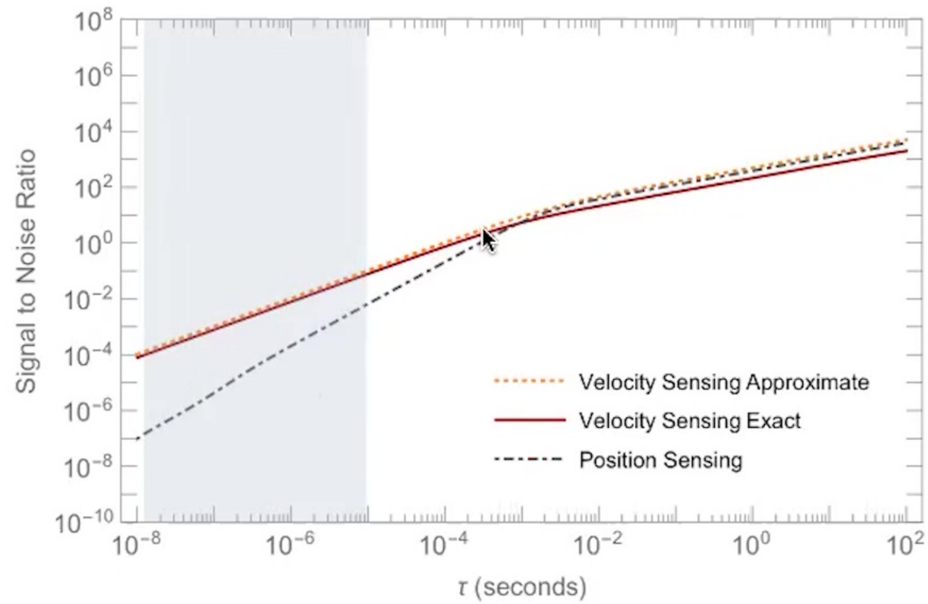
Backaction Evading Measurement with Optomechanical System





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Ghosh, Carney, Shawhan, Taylor, Phys. Rev. A **102**, 023525

Combining Squeezing with Backaction Evasion

- Noise spectrum for continuous position measurement

$$H_{\text{int}} = \hbar G x X$$

$$X_\theta = Y_{\text{out}} \cos\theta + X_{\text{out}} \sin\theta$$

$$\langle F_E^2 \rangle = \left| \frac{e^{i\phi_c} \tan\theta}{G\chi_c\chi_m} - G\hbar\chi_c \right|^2 \langle X_{\text{in}}^2 \rangle + \left| \frac{1}{G\chi_c\chi_m} \right|^2 \langle Y_{\text{in}}^2 \rangle + 2\left[\hbar m(\omega_m^2 - \nu^2) + \frac{\tan\theta}{G^2|\chi_c|^2|\chi_m|^2} \right] \langle X_{\text{in}} Y_{\text{in}} \rangle + \langle F_{\text{in}}^2 \rangle .$$

- Noise spectrum for continuous momentum measurement

$$H_{\text{int}} = \hbar G' p X$$

$$X_\theta = Y_{\text{out}} \cos\theta + X_{\text{out}} \sin\theta$$

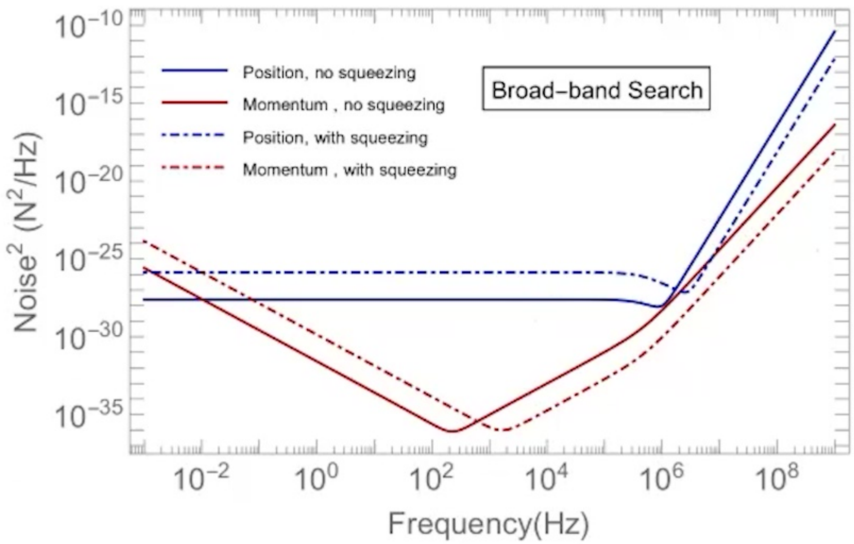
$$\langle F_E^2 \rangle = \left| \frac{i e^{i\phi_c} \tan\theta}{G' m \nu \chi_c \chi_m} - i G' \hbar \chi_c m \frac{\omega_m^2}{\nu} \right|^2 \langle X_{\text{in}}^2 \rangle + \left| \frac{i e^{i\phi_c}}{G' m \nu \chi_c \chi_m} \right|^2 \langle Y_{\text{in}}^2 \rangle + \langle F_{\text{in}}^2 \rangle + 2\left[\hbar m \frac{\omega_m^2}{\nu^2}(\omega_m^2 - \nu^2) + \frac{\tan\theta}{m^2\nu^2 G'^2 |\chi_c|^2 |\chi_m|^2} \right] \langle X_{\text{in}} Y_{\text{in}} \rangle .$$

- At $\theta \to 0$ (phase quadrature measurement) and mechanical frequency $\omega_m \to 0$, BA term goes to 0 in momentum sensing.
- Rest of the terms can be reduced using squeezing.

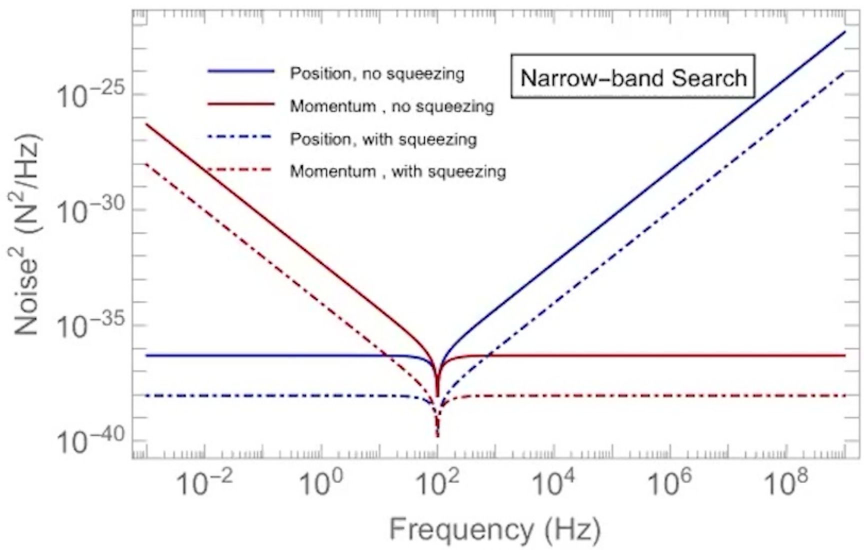
$$\langle X^2 \rangle = \frac{1}{2}\left(e^{2r} \cos^2\phi + e^{-2r} \sin^2\phi \right),$$
$$\langle Y^2 \rangle = \frac{1}{2}\left(e^{-2r} \cos^2\phi + e^{2r} \sin^2\phi \right),$$
$$\langle \{X, Y\} \rangle = \frac{1}{2}(e^{-2r} - e^{2r}) \sin 2\phi,$$

*Ghosh, Feldman, Hong, Marvinney, Pooser, and Taylor, arXiv:2211.14460

Combining Squeezing with Backaction Evasion



- Broadband search strategy for position and momentum sensing. The phase quadrature noise is plotted for both sensing protocols while operating at the optimal power for position sensing with a 1 MHz target.



- Narrow-band search strategy for position and momentum sensing plotted for both techniques at the optimal power and optimal quadrature angle for each frequency.

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$\sim 10^9$ detectors
~ mg each

Scale of the device

Environmental isolation

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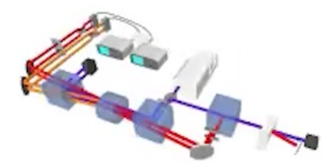
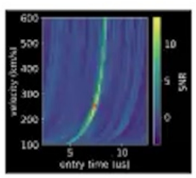
Gravitational detection of Planck scale DM

Measurement-added noise suppression

~ orders of magnitude below SQL

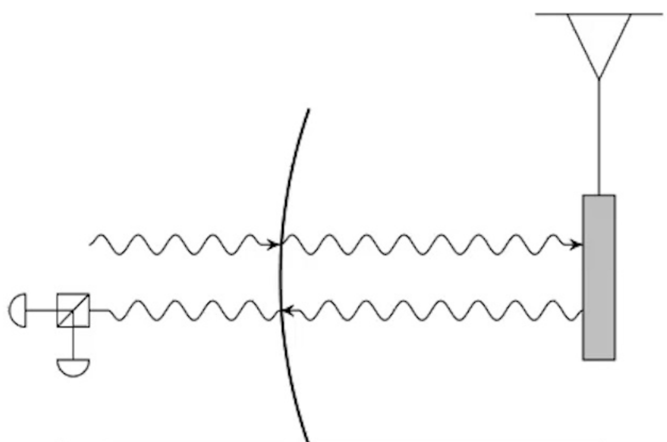




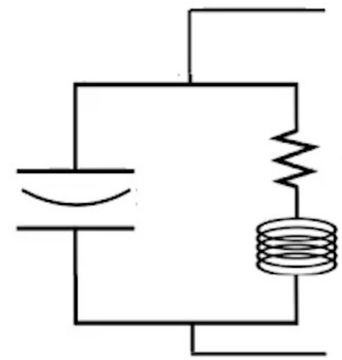
Data pipeline and analysis

~ improvements in data analysis techniques for large datasets

Moving from Optical to Microwave Domain



$\omega_{c_{opt}} = 100\,THz, \kappa_{opt} = 10\,MHz$



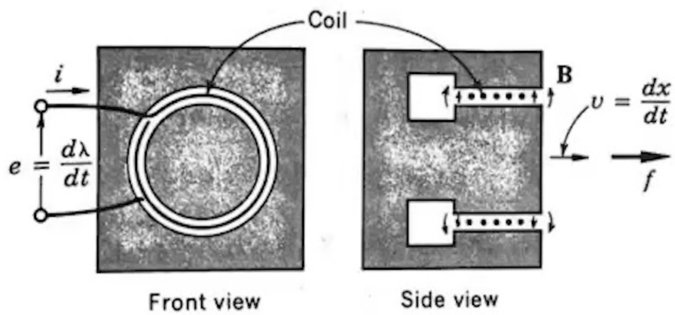
$\omega_{c_{mic}} = 1GHz, \kappa_{mic} = 10\,KHz$

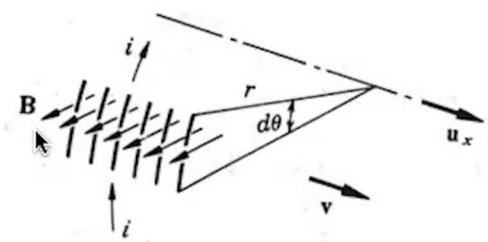
$$P_{\text{peak}} = \hbar\omega_c\kappa N$$

PRELIMINARY

QND Readout in the Microwave Domain

- Ideally, we are looking for a system : $H_{\text{int}} = \alpha p X$





$$\mathcal{E} = \oint_c \vec{E} \cdot \vec{dl} + \oint_c (\vec{v} \times \vec{B}) \cdot \vec{dl}$$

PRELIMINARY

* With Brittany Richman, Daniel Carney, Chris Lobb and Jake Taylor

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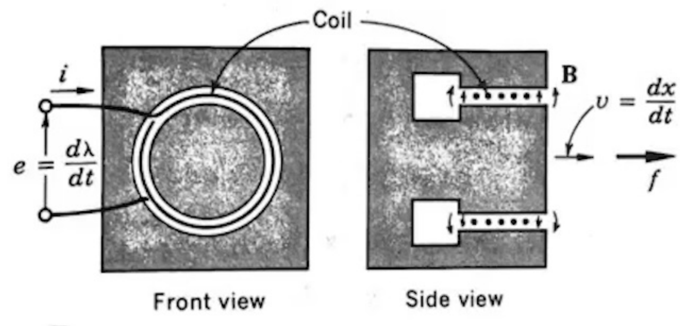

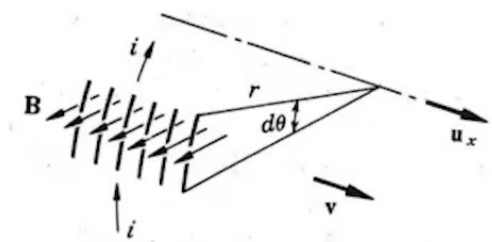

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PRELIMINARY

- We are working on the optimum way to observe the EMF

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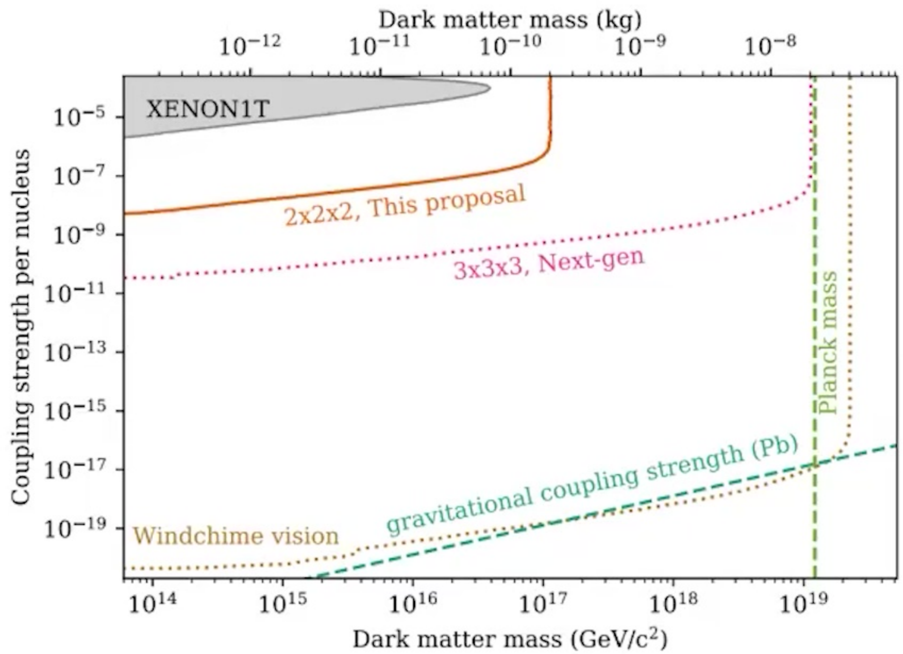
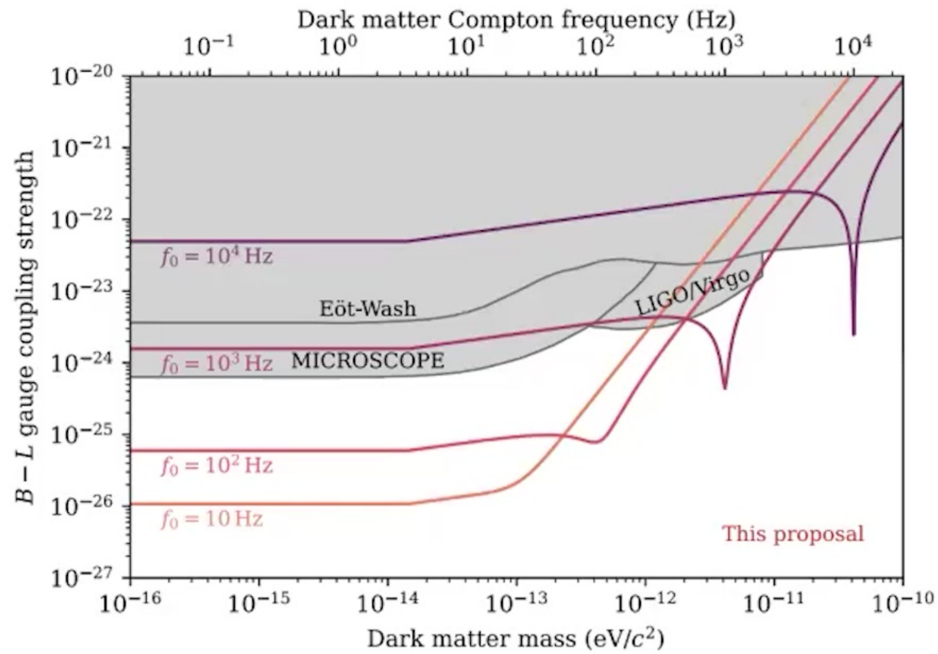
Windchime Vision



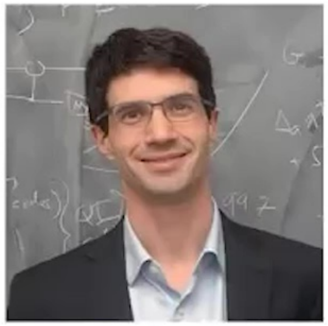


Conclusion & Future Directions

- We studied the fundamental limitations to the sensitivity of a given device to small, rapid impulses.
- We demonstrated the case of impulse sensing with an optomechanical sensor.
- This protocol has a wide variety of applications in metrology, particle physics, especially aiding the direct detection of dark matter.
- Current and future directions:
  - Development of backaction evasion/QND measurement proposals using optical and microwave platforms
  - Application of quantum error correction tools for enhanced quantum metrology
  - Search for new physics using table-top experiments

Acknowledgement

Dan Carney



Jake Taylor

Jon Kunjummen

Brittany Richman

Peter Shawhan

Thank you for your attention !

Gaya Premawardhana

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