Quantum Impulse Sensing with Mechanical Sensors

Sohitri Ghosh

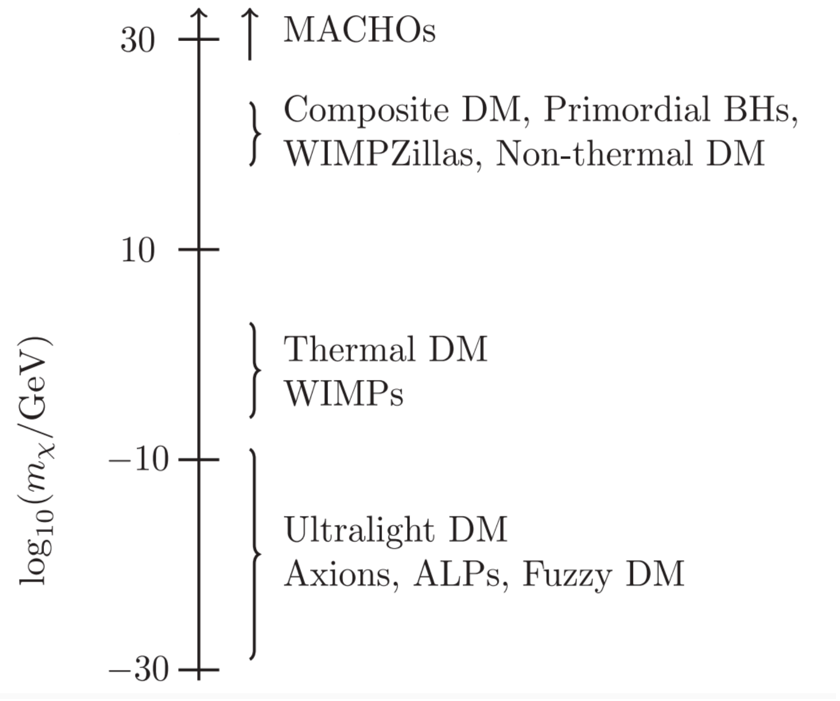
JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

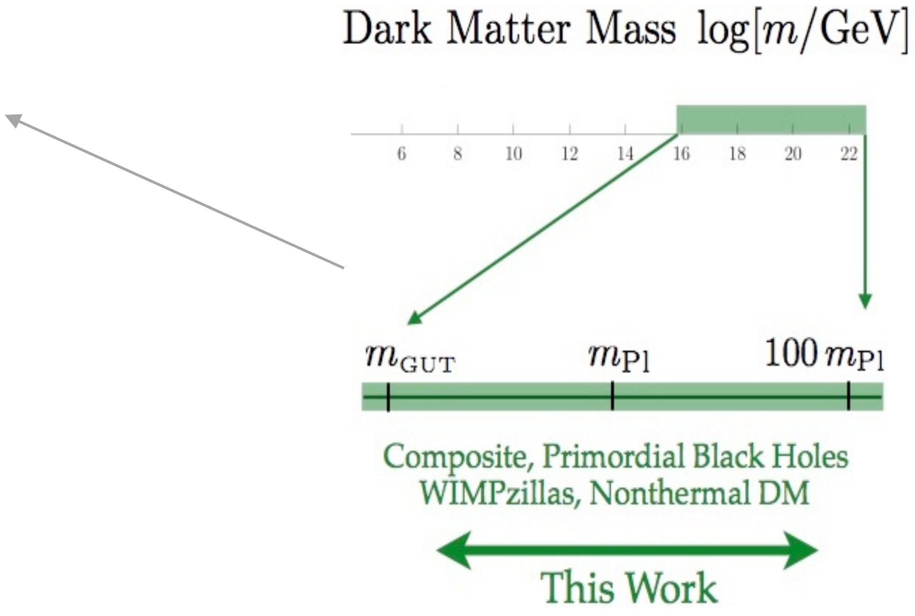
UNIVERSITY OF MARYLAND 1856 DEPARTMENT OF PHYSICS

JQI JOINT QUANTUM INSTITUTE

Motivation: Gravitational Detection of Dark Matter

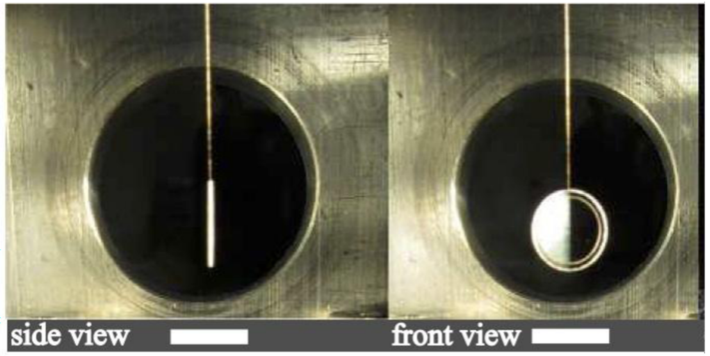
- Ultimate Goal : Detection of dark matter through its gravitational interaction with visible matter



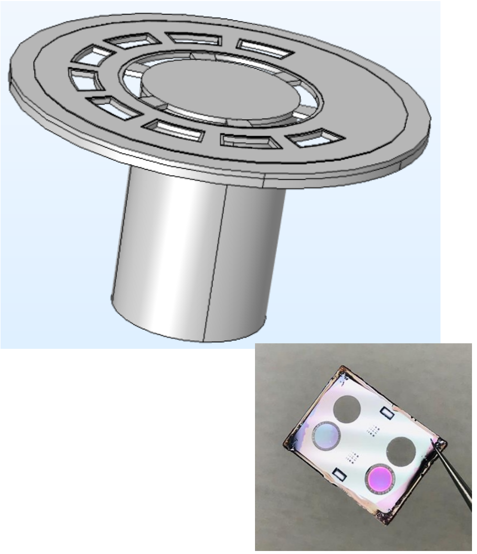


- At this mass level, the passing DM provides a gravitational impulse to the detector

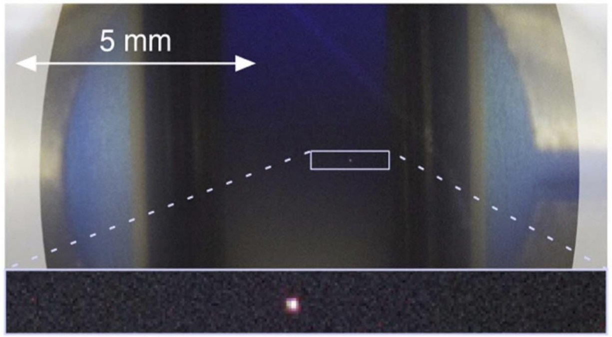
Examples of Some Mechanical Sensors



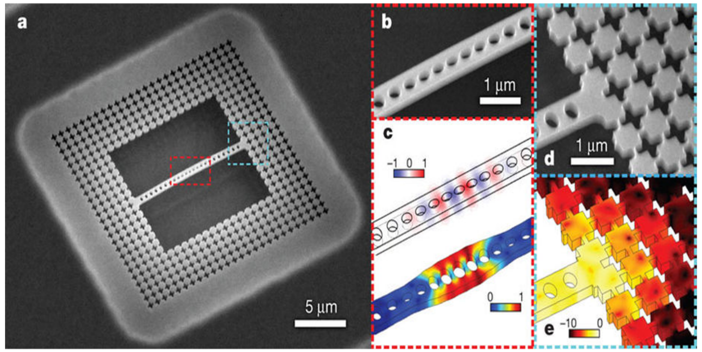
Suspended mirror [Matsumoto et al. PRA (2015)]



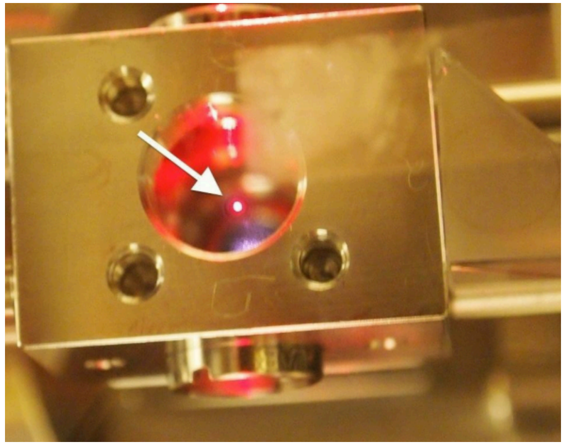
Chip-based accelerometer at Prof. Sunil Bhave's group at Purdue



Optically trapped particle [Kiesel et al. PNAS (2013)]

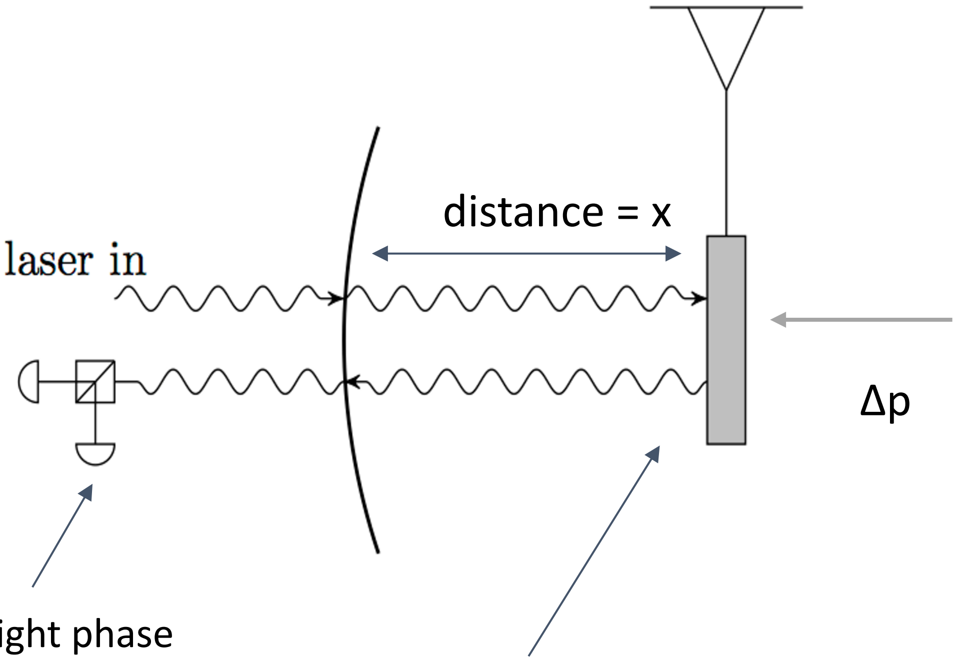


Optomechanical resonator [Painter et al. Nature (2011)]



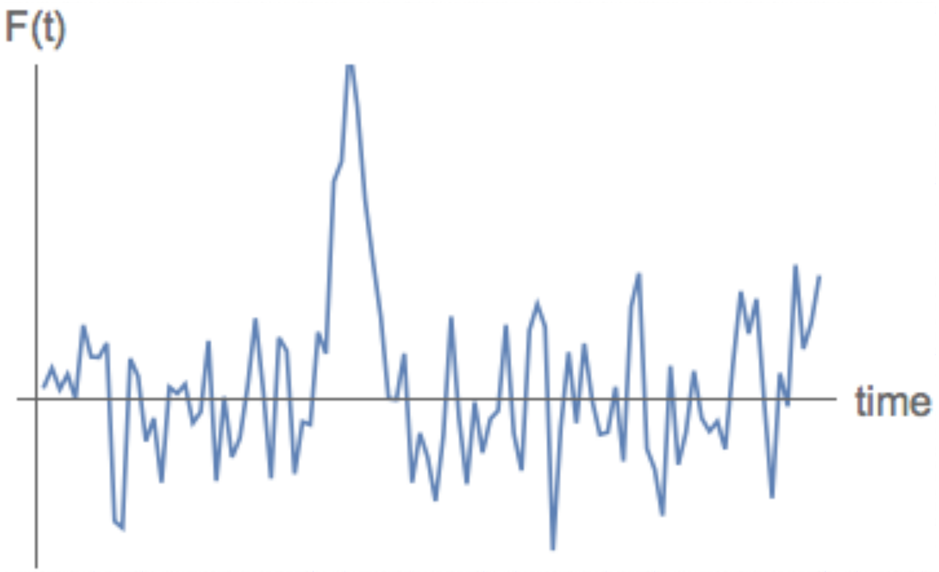
Levitated particle at Prof. David Moore's group at Yale

Impulse Measurement Basic Readout Scheme



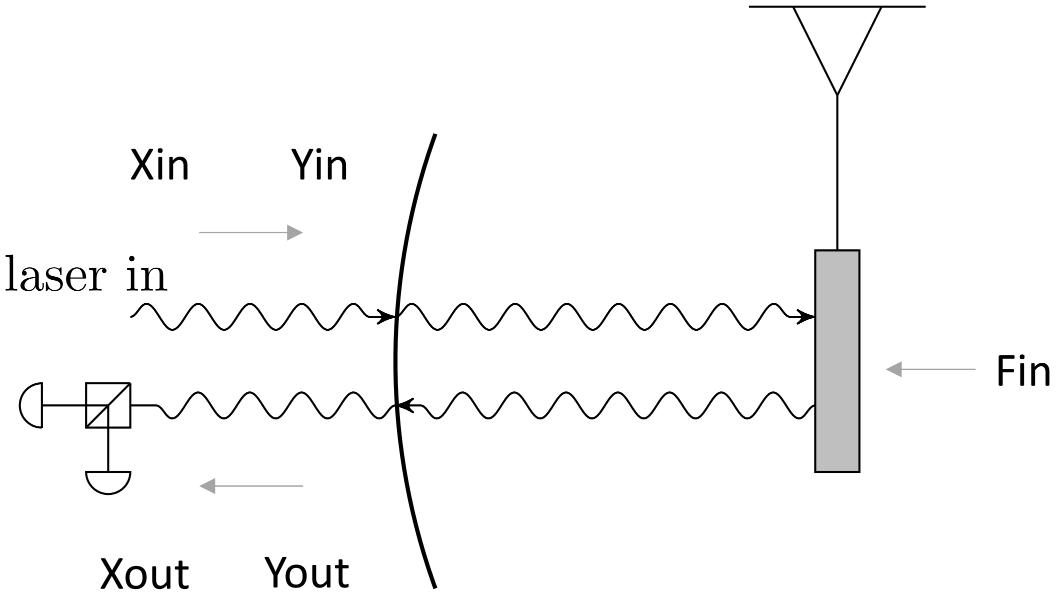
readout light phase
via interferometer
→ measure x(t)
→ infer F(t)

light phase shift ~ x(t)



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

Continuous Position Measurement in Optomechanical System



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

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

- The system can be described by the following Hamiltonian,

$$H_{\text{tot}} = H_{\text{cav}} + H_{\text{mech}} + H_{\text{bath}}$$

$$H_{\text{cav}} = \hbar\omega(x)(X^2 + Y^2) \qquad H_{\text{mech}} = \frac{p^2}{2m} + \frac{1}{2} m \omega_m^2 x^2$$

Continuous Position Measurement in Optomechanical System

- Y_{out} is what we have experimental access to via an external homodyne interferometer.

$$Y_{\text{out}} = e^{i\phi_c} Y_{\text{in}} + G\kappa\chi_c\chi_m \left[F_{\text{in}} - \hbar G\chi_c X_{\text{in}}\right]$$

$$e^{i\phi_c} = \frac{-i\nu - \kappa/2}{-i\nu + \kappa/2} \qquad \chi_c = \frac{1}{-i\nu + \kappa/2} \qquad \chi_m = \frac{-1}{m(\nu^2 - \omega_m^2 + i\gamma\nu)}$$

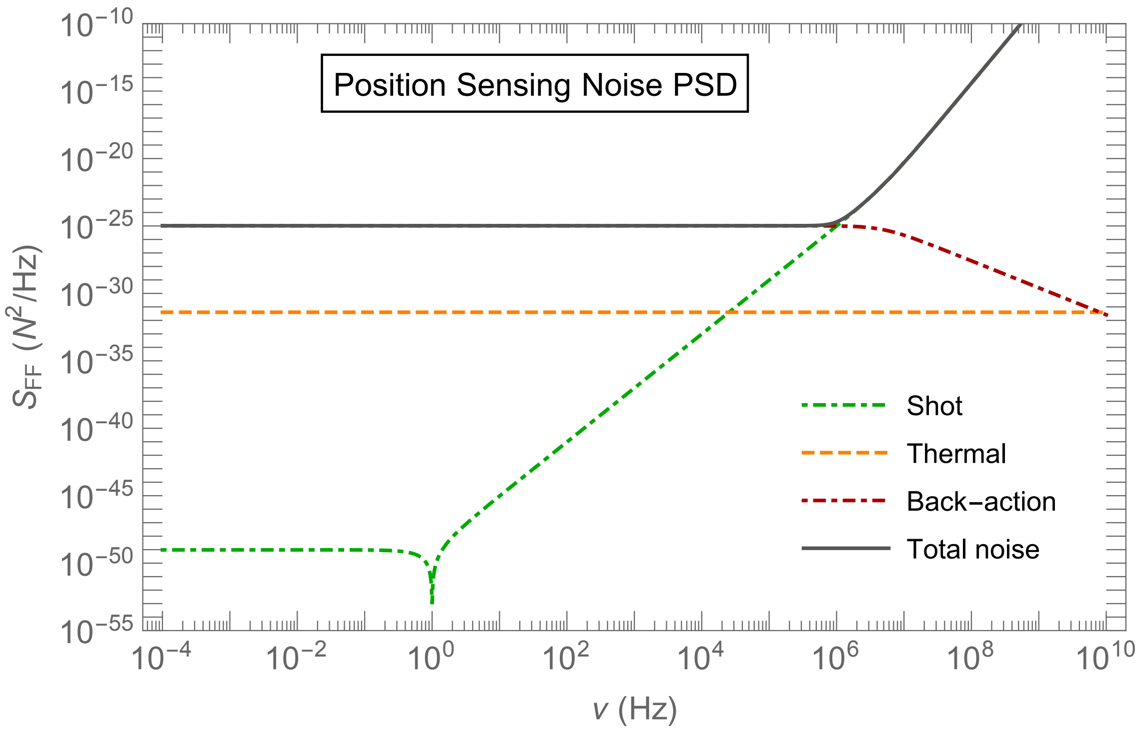
- To estimate the force F on the mechanics given our observed Y_{out} :

$$F_E = \frac{Y_{out}}{G\kappa\chi_c\chi_m}$$

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

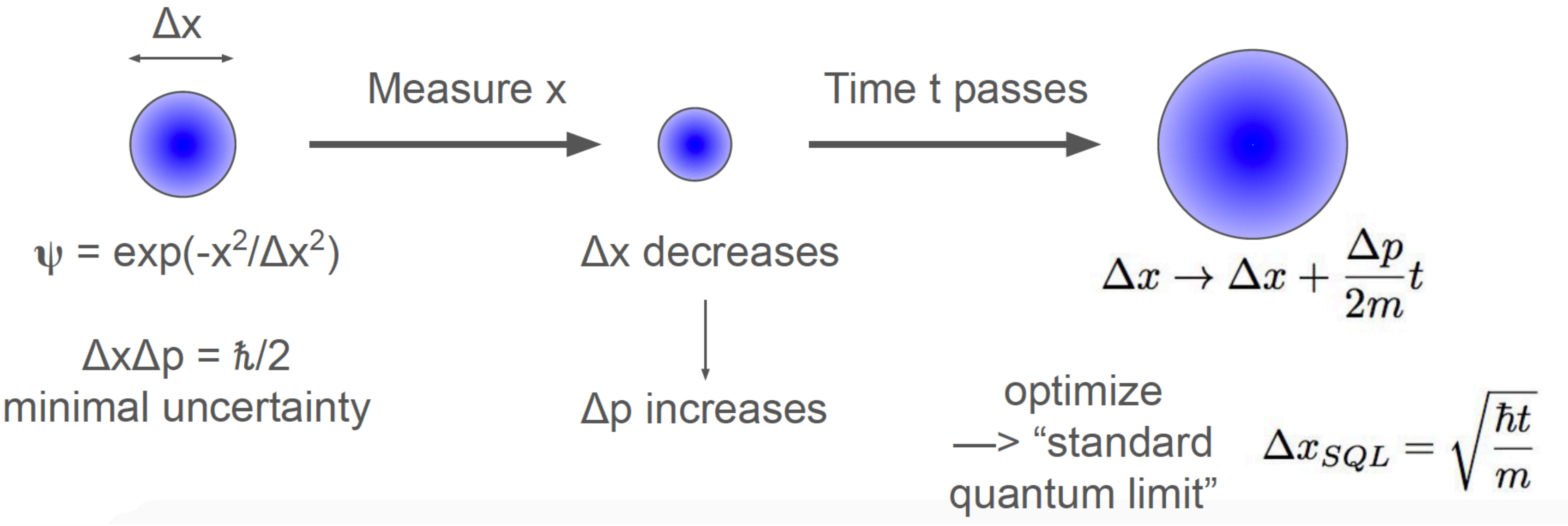
Noise in Measurements

- 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



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

Standard Quantum Limit of Impulse Measurement



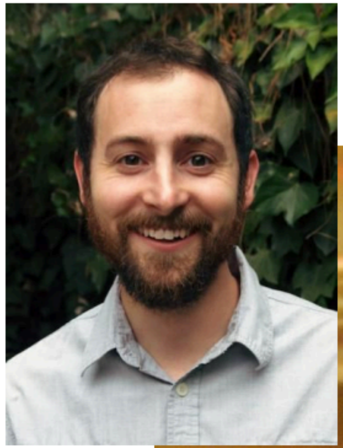
$\Delta I_{\mathrm{SQL}} \geq \sqrt{\frac{\hbar m}{t}}$ ~ 1 GeV/c for m= 1 ng, t= 10 us

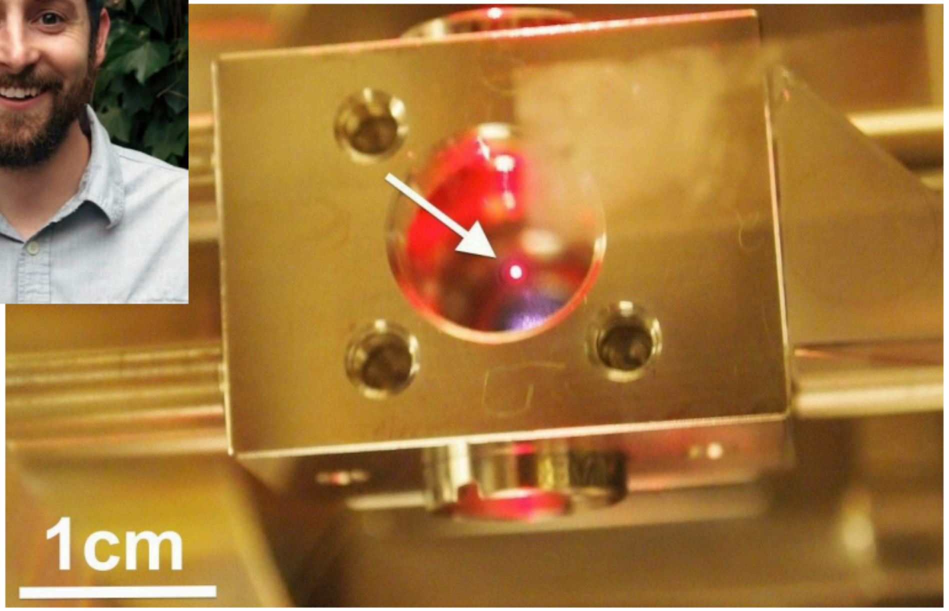
*Caves et al, 1980

Some Examples in Particle Physics

Impulse Sensing with Optically Levitated Sensors

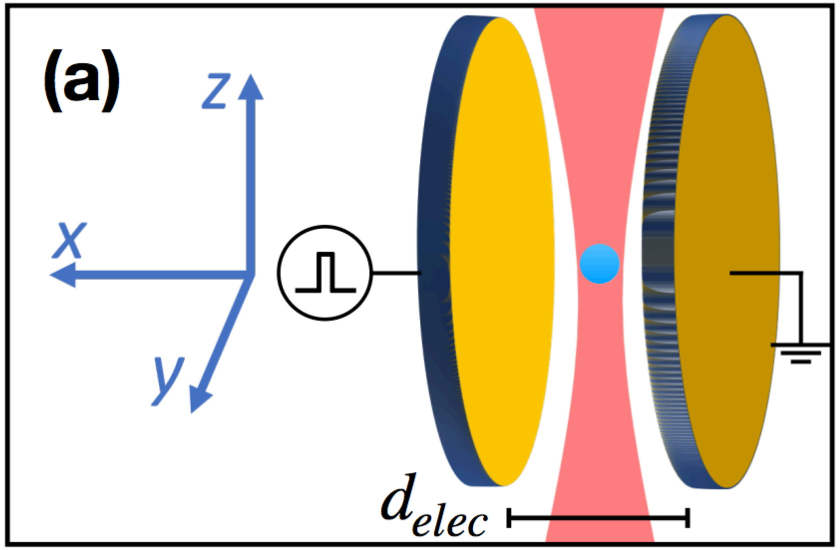
Search for new Interactions in a Microsphere Precision Levitation Experiment (SIMPLE) @ D. Moore group

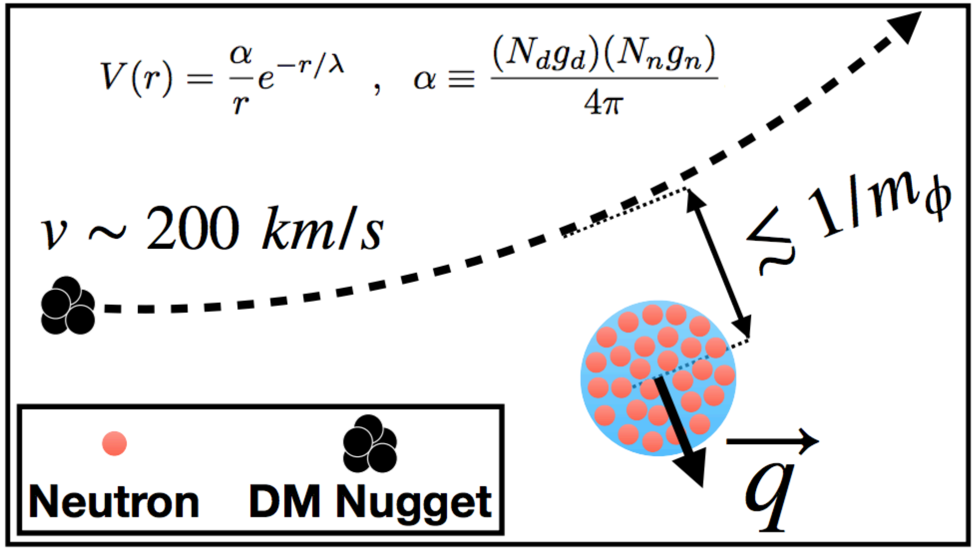


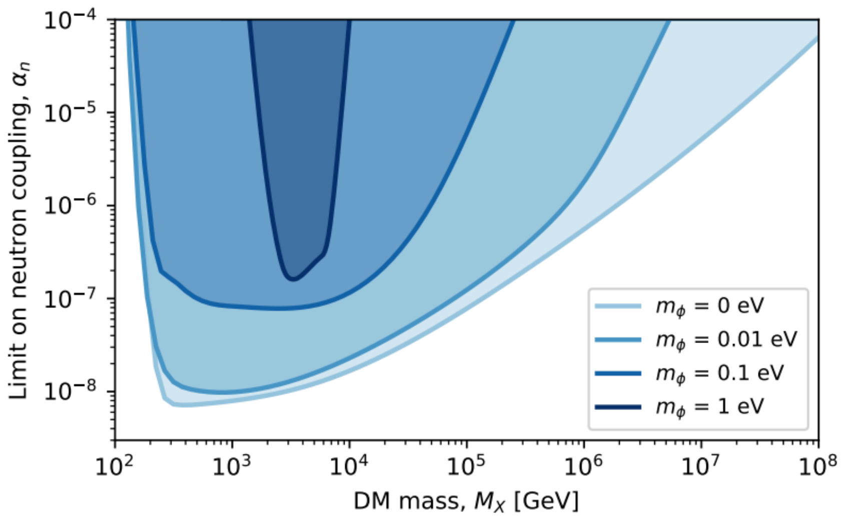


- 1 ng dielectric spheres, optically levitated, kHz trap
- ~75 MeV momentum transfer resolution (~ few x SQL)
- Continuous monitoring of two or three spatial axes gives directional sensitivity

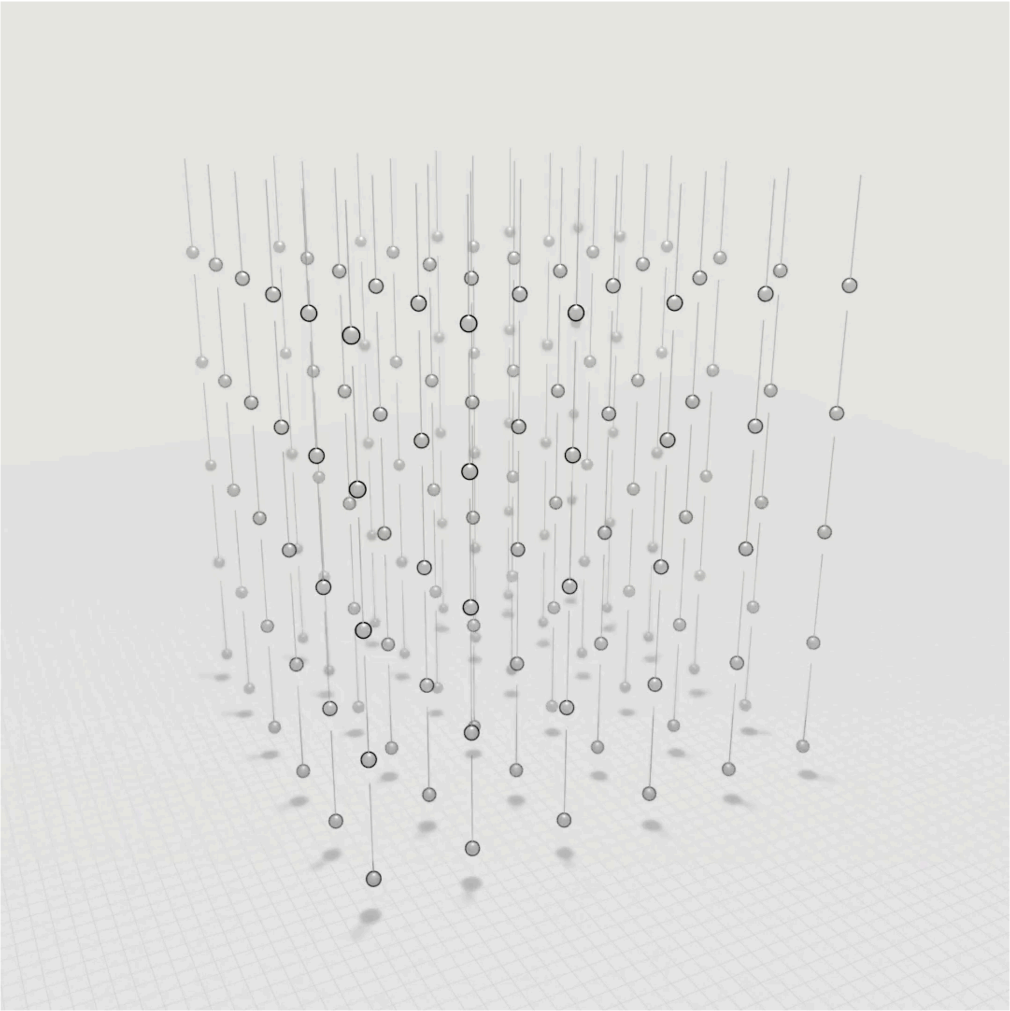
Impulse Sensing with Optically Levitated Sensors





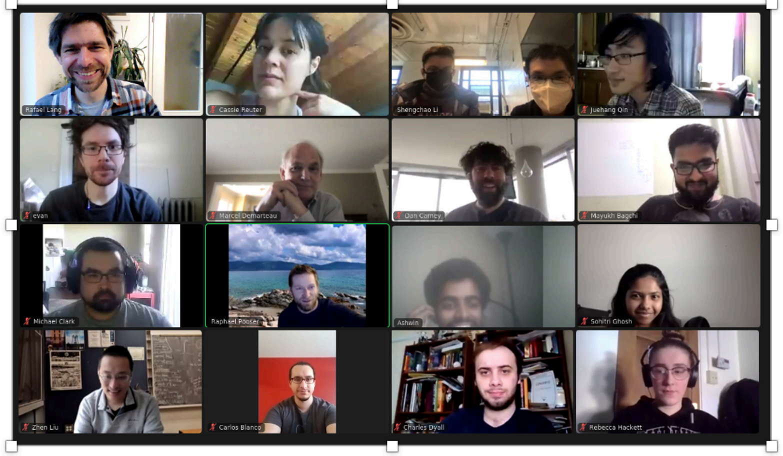


Windchime



The Windchime Collaboration

PURDUE UNIVERSITY
Fermilab
RICE



UNIVERSITY OF MARYLAND
OAK RIDGE National Laboratory
UNIVERSITY OF MINNESOTA Driven to Discover

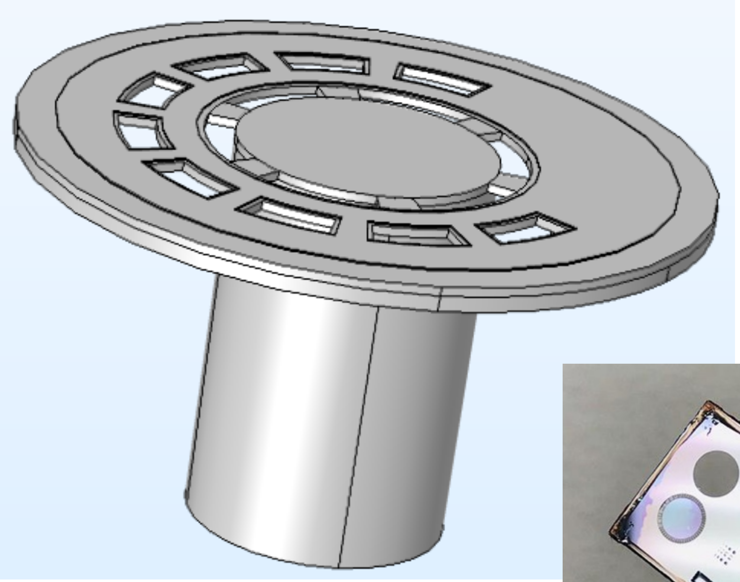
windchimeproject.org

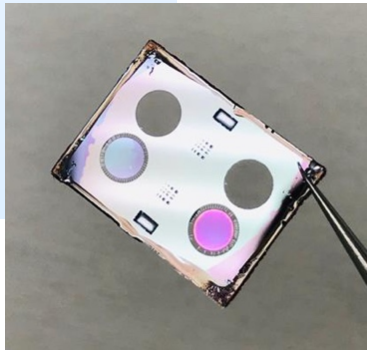
BERKELEY LAB
NIST National Institute of Standards and Technology U.S. Department of Commerce

Video courtesy: Sean Kelley, NIST

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

Windchime/Protochime Experimental Setup





Bulk Silicon Z-axis Accelerometer

- Bulk Silicon 70 mg accelerometer with soft tether
- Resonance frequency ~ 10 kHz, Acc. Sensitivity $\sim 10^{-7} \mathrm{g}/\sqrt{Hz}$
- Dual read-out – free space optics AND waveguided photonics

Pictures Courtesy: Hao Tian, Sunil Bhave (Purdue)

Methods to get below SQL

Methods to get below SQL

- General representation of the force power spectral density

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

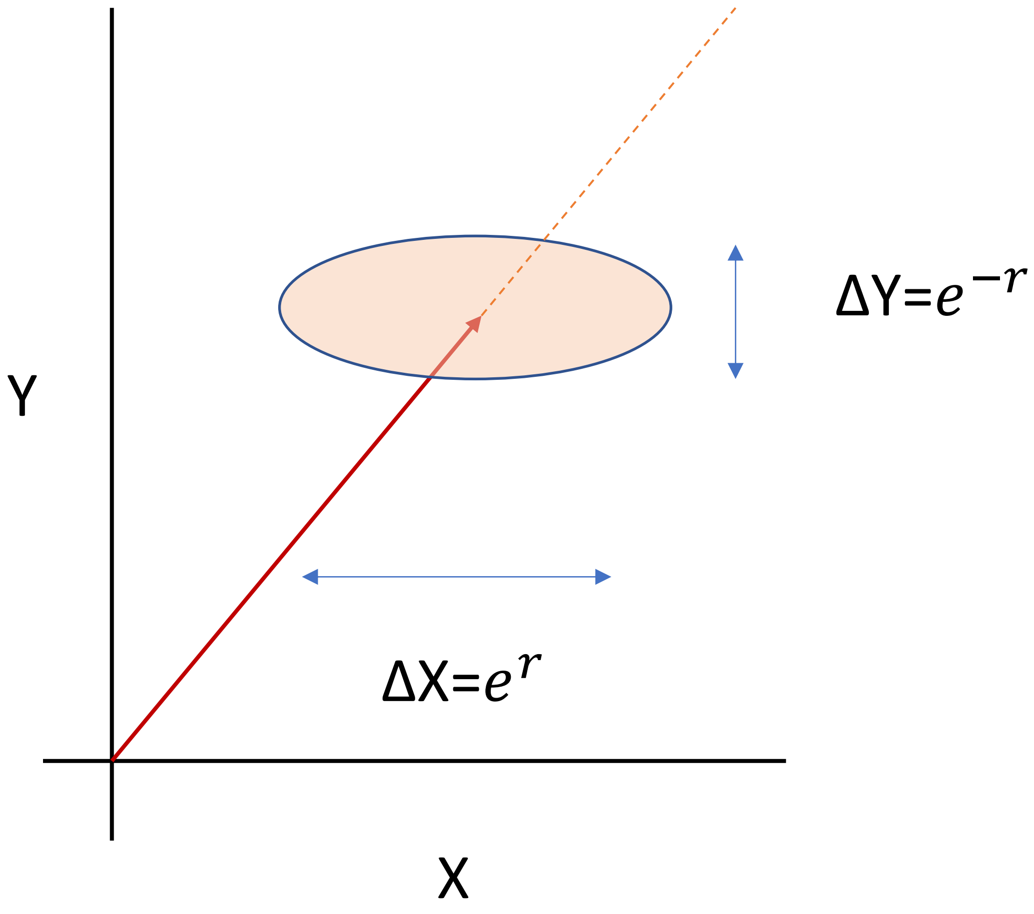
- Squeezing

$$S_{X_{\mathrm{in}}Y_{\mathrm{in}}} < 0$$

- Backaction evasion

$$\beta \to 0$$

Squeezing

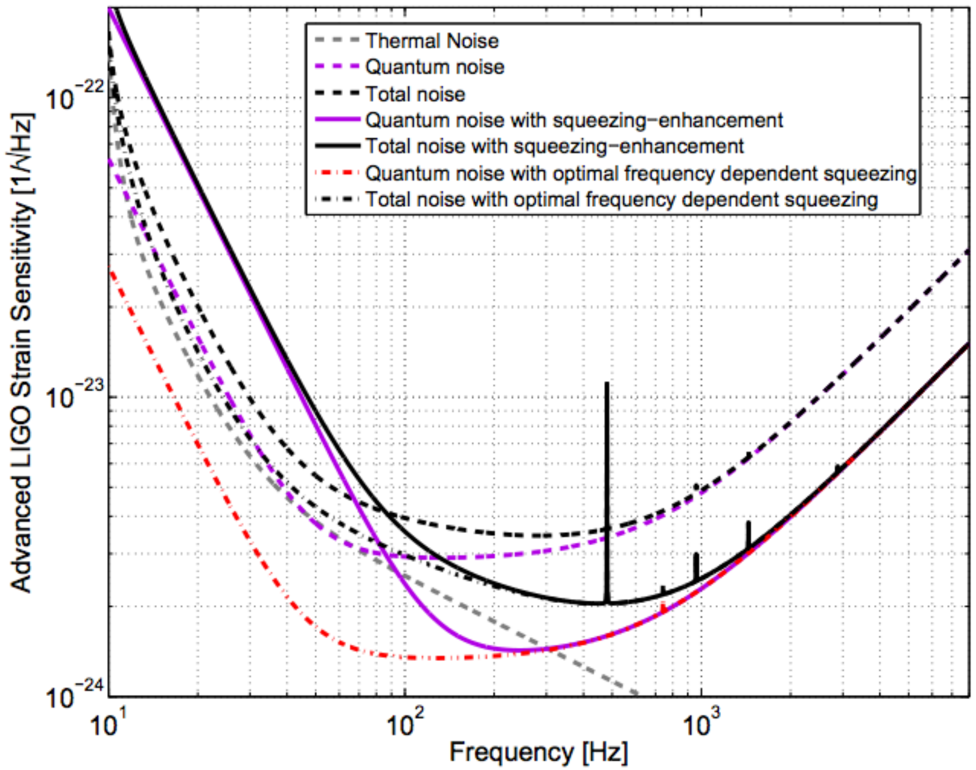


$$\Delta X \, \Delta Y \geq 1$$

- This minimum Heisenberg uncertainty relation must be satisfied but the noise can be redistributed within these two quadratures.
- Squeezing parameter r describes the strength of squeezing
- Detection in squeezed direction is more sensitive

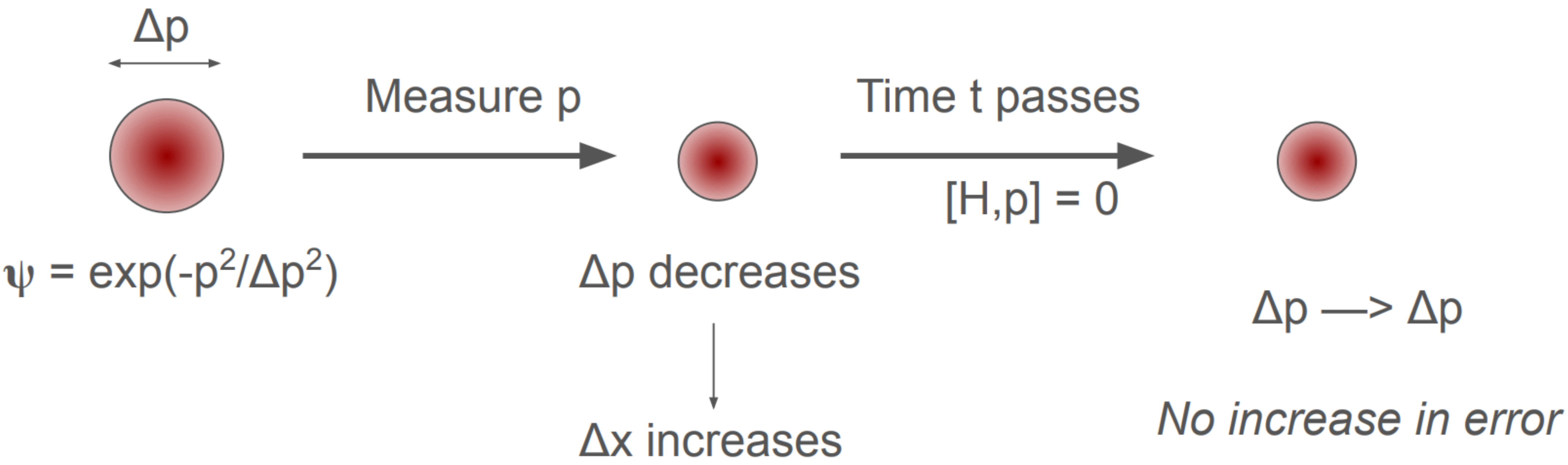
Examples of Squeezing

- Advanced LIGO
- Experiments from ORNL (Pooser, Savino, Batson, Beckey, Garcia, Lawrie, Phys. Rev. Lett. **124**, 230504)
- Experiments from Aspelmeyer group (https://arxiv.org/pdf/2202.09322.pdf)



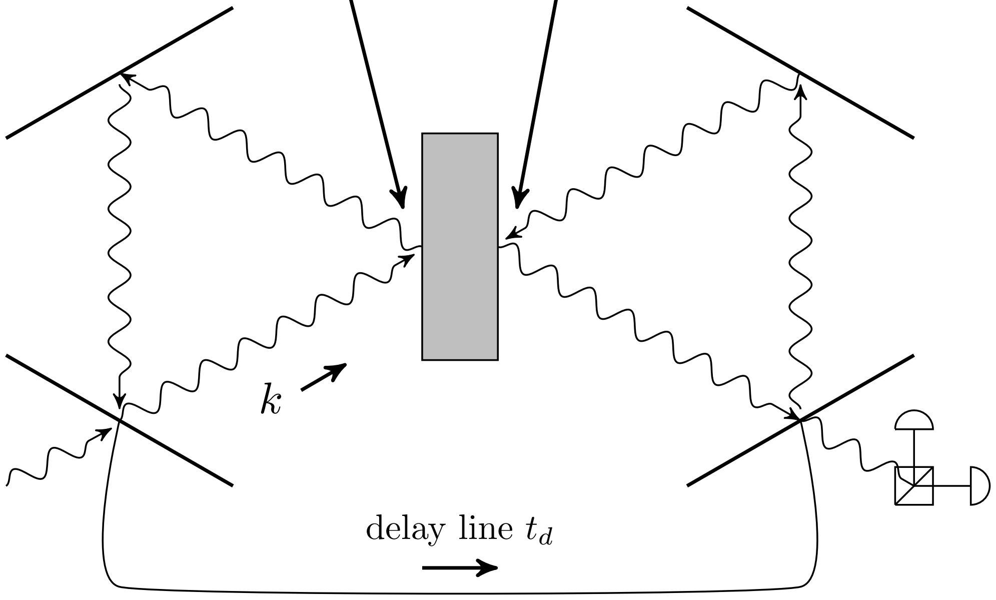
Nature Photon **7,** 613–619 (2013)

Monitoring Momentum Instead of Position



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

Backaction Evading Measurement with Optomechanical System



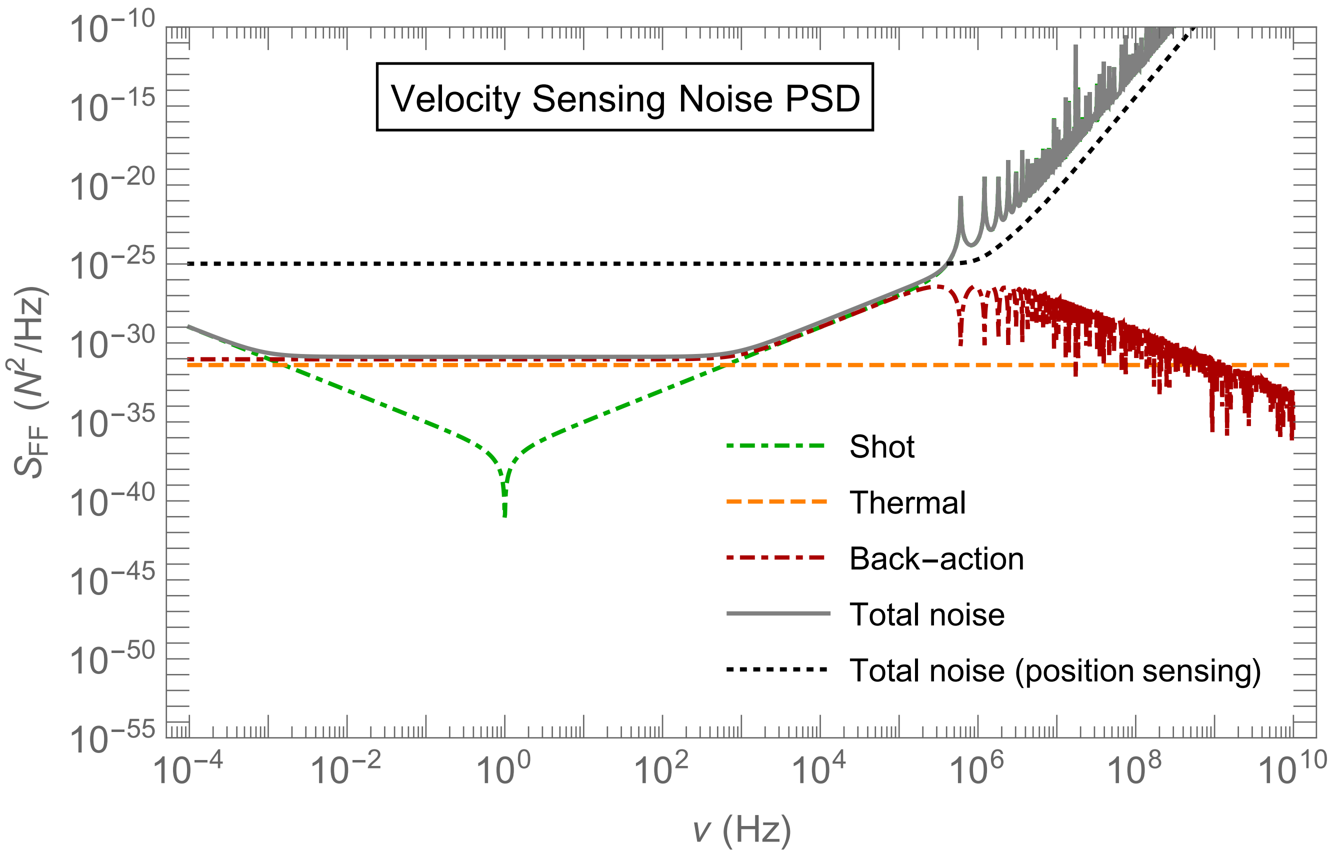
$$H_{\text{int}} = \hbar G x X - \hbar G' x X'$$

- 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

Noise PSD in Continuous Momentum Measurement



$$\Delta p_{\text{noise}} \approx \sqrt{\frac{\hbar m}{t}} L^{1/4} < \Delta p_{\text{SQL}} = \sqrt{\frac{\hbar m}{t}}$$

Inductive Readout ?

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

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$EMF \propto v$$

- Question: What is the optimum way to observe the EMF ?

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, etc.

- Current and future directions:
  - Experiment: ORNL+Purdue, squeezed light with membrane ring resonators
  - Theory: develop backaction evasion/momentum sensing proposals

Acknowledgement: The Windchime Collaboration

PURDUE UNIVERSITY

Fermilab

RICE

- Sunil Bhave
- Rafael Lang
- Nima Lashkari
- Gordan Krnjaic
- Aaron Chou
- Michael Clark
- Shengchao Li
- Juehang Qin
- Hao Tian
- Bahaa Elshimy
- Ashwin Nagarajan
- Gustavo Cancelo

- Marcel Demarteau
- Qingyang Li
- Rebecca Hackett
- Steven Cloud
- Julian Kauffmann
- Mayukh Bagchi
- Charles Dyall
- Edward Gheorghita
- Evan Weisman
- Juan Maldonado
- Kubra Yeter Aydeniz
- Claire Marvinney
- Yun-Yi Pai

- Jacob Taylor
- Daniel Carney
- Zhen Liu
- Raphael Pooser
- Chris Tunnel
- Ayush Sachdeva
- Mirella Vassilev
- Sohitri Ghosh
- Cassie Reuters
- Carlos Blanco
- Lee McCuller
- Ben Lawrie

UNIVERSITY OF MARYLAND

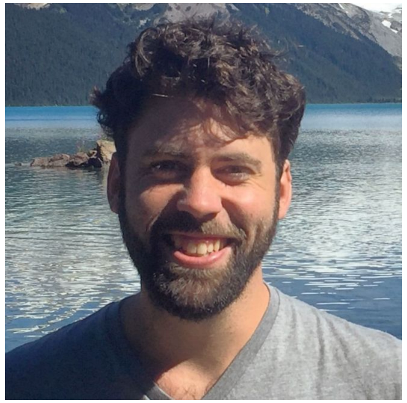
OAK RIDGE National Laboratory

UNIVERSITY OF MINNESOTA Driven to Discover

BERKELEY LAB

NIST National Institute of Standards and Technology U.S. Department of Commerce

Acknowledgement



Dan Carney

Jake Taylor

Jon Kunjummen

Brittany Richman

Peter Shawhan

Thank you for your attention !

Gaya Premawardhana