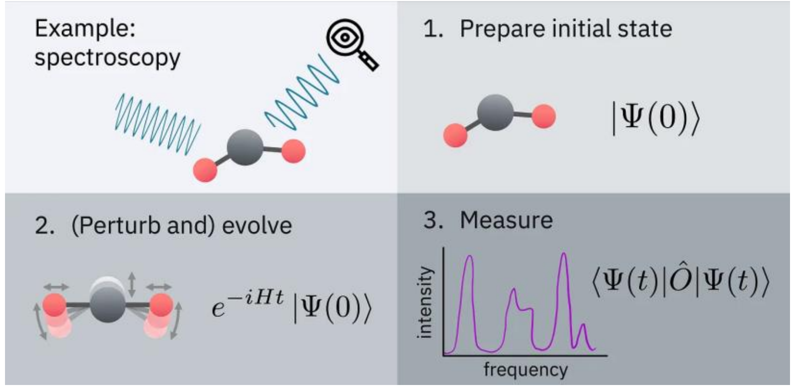
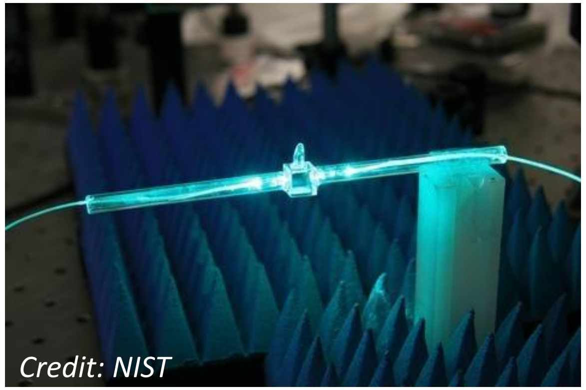
Quantum Techniques for Sensing

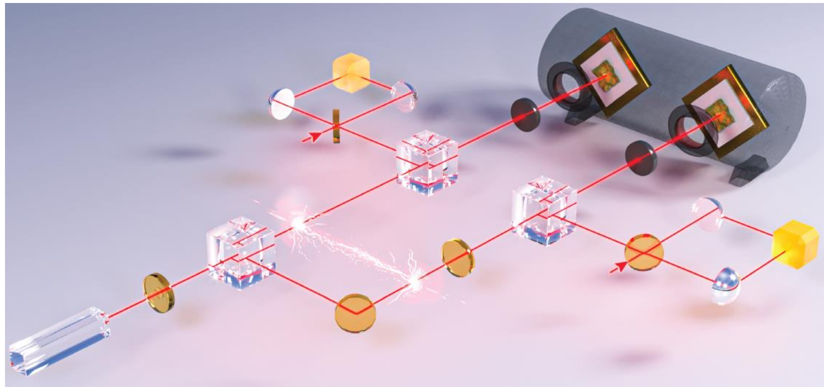
Work Package 1

RDq Proposal Preparation Workshop
CERN, 2 – 4 Oct. 2023





Credit: NIST



Quantum Techniques

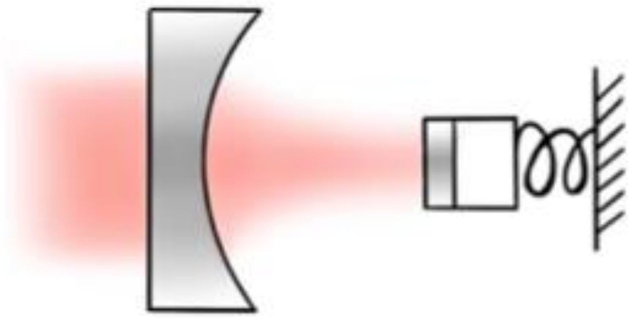
- The simultaneous measurement of two non-commuting quantities, such as the amplitude and phase of a signal, is limited: the Standard Quantum Limit (SQL).

- The premise of the use of quantum technologies is that one can engineer and manipulate quantum states, by making use of **superposition, entanglement, squeezing, and backaction evasion**, to evade this SQL, and thus improve the science reach of the experiments.

- With these techniques, instruments with much higher sensitivity can be built that are able to detect tiny energy shifts or disturbances in a measurement apparatus.

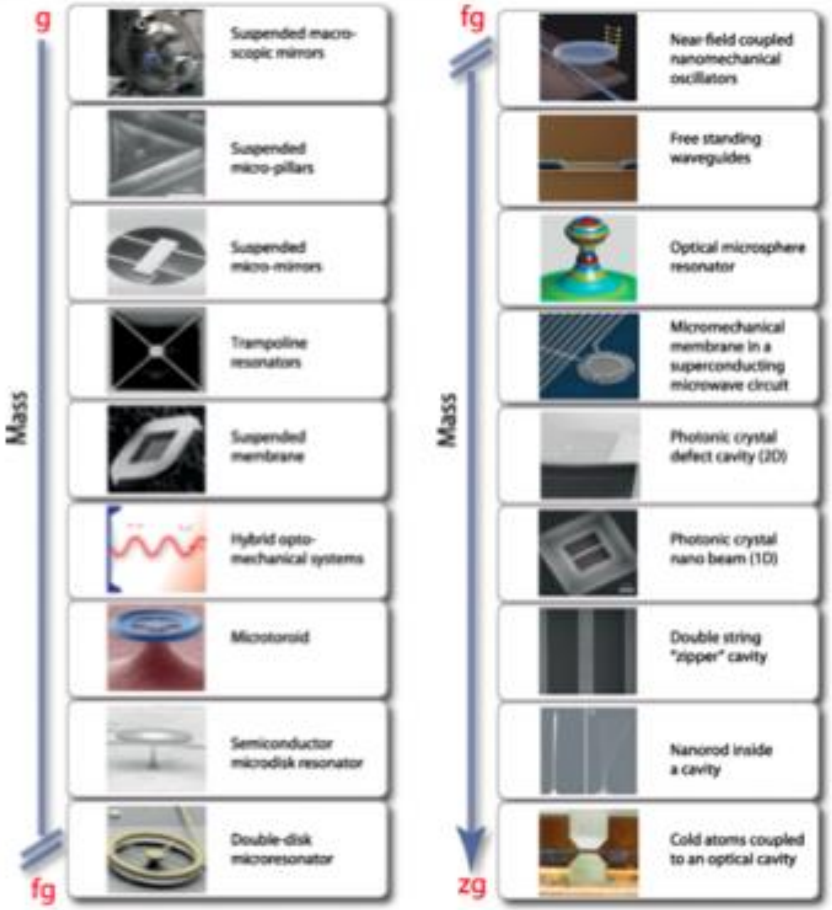
- The goal of this work package is to formulate a research plan for the development of quantum technologies, their implementation in experiments, and the development of the theoretical framework for their application.

Example: Harmonic Oscillators



State of the art sensitivities[1]

- Force: $10^{-20}\ N/\sqrt{Hz}$
- Acceleration: $10^{-15}\ g/\sqrt{Hz}$
- Strain: $10^{-21}\ /\sqrt{Hz}$



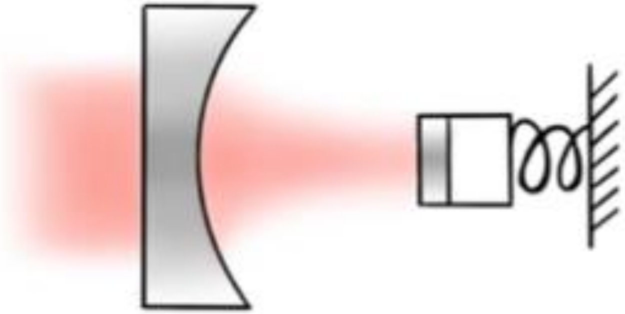
An isolated mode of a floppy mechanical oscillator

Image: Cavity *Optomechanics*, M. Aspelmeyer, T.J. Kippenberg and F. Marquardt, RMP **86**, 1391(2014).

1: Carney et. al, arXiv:2008.06074 (2020) .

From: Swati Singh (Uni. Delaware CPAD meeting, 2021

Harmonic Oscillators



$$m\ddot{x} + m\frac{\gamma}{2}\dot{x} + m\omega^2 x = F_{\text{signal}} + F_{\text{noise}}$$

due to DM field

thermal,
imprecision,
measurement
back action

$$H = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_m \hat{b}^\dagger \hat{b} - \hbar g_0 \hat{a}^\dagger \hat{a}\left(\hat{b} + \hat{b}^\dagger\right)$$

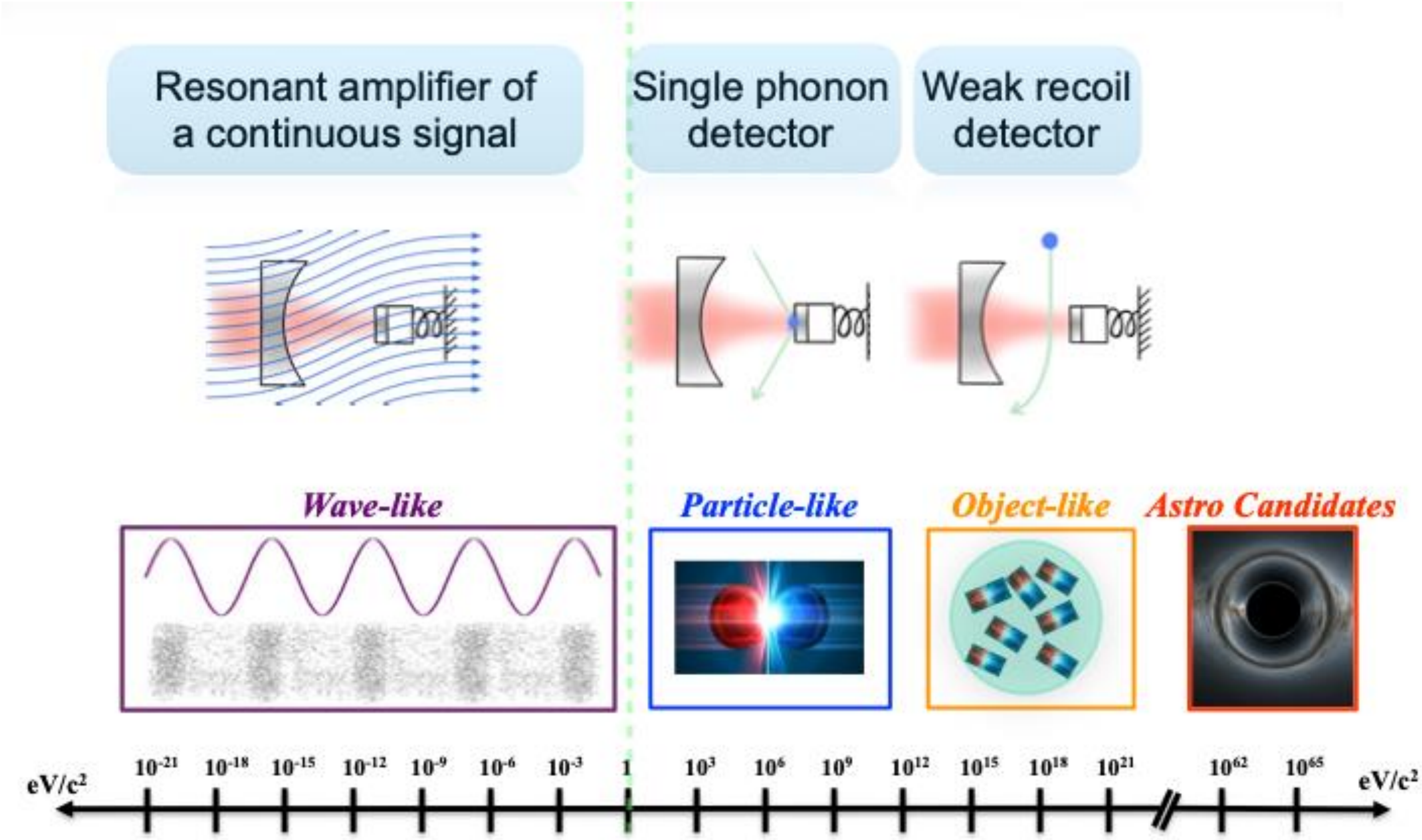
optical cavity

mechanical
oscillator

interaction

From: Swati Singh (Uni. Delaware
CPAD meeting, 2021

Mechanical DM detectors



Mechanical quantum sensing in the search for dark matter,
Carney et. al, arXiv:2008.06074 (2020) .

From: Swati Singh (Uni. Delaware CPAD meeting, 2021

Quantum Enhancement with Light

- Any detection system uses a series of measurement to estimate a parameter P

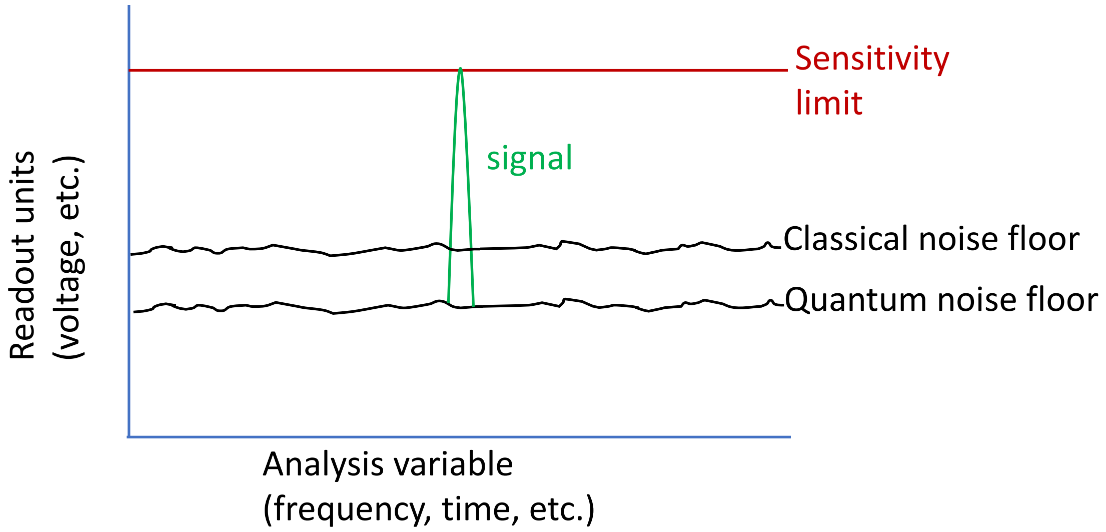
$$\Delta P = \frac{\sqrt{(\Delta M)^2}}{|\partial M/\partial P|}$$

Measurement uncertainty (limited by quantum mechanics)

Detector response

- Possible to generate quantum states of light with noise levels below what is possible with classical resources (squeezed states).

➡ *quantum-based sensitivity enhancement*

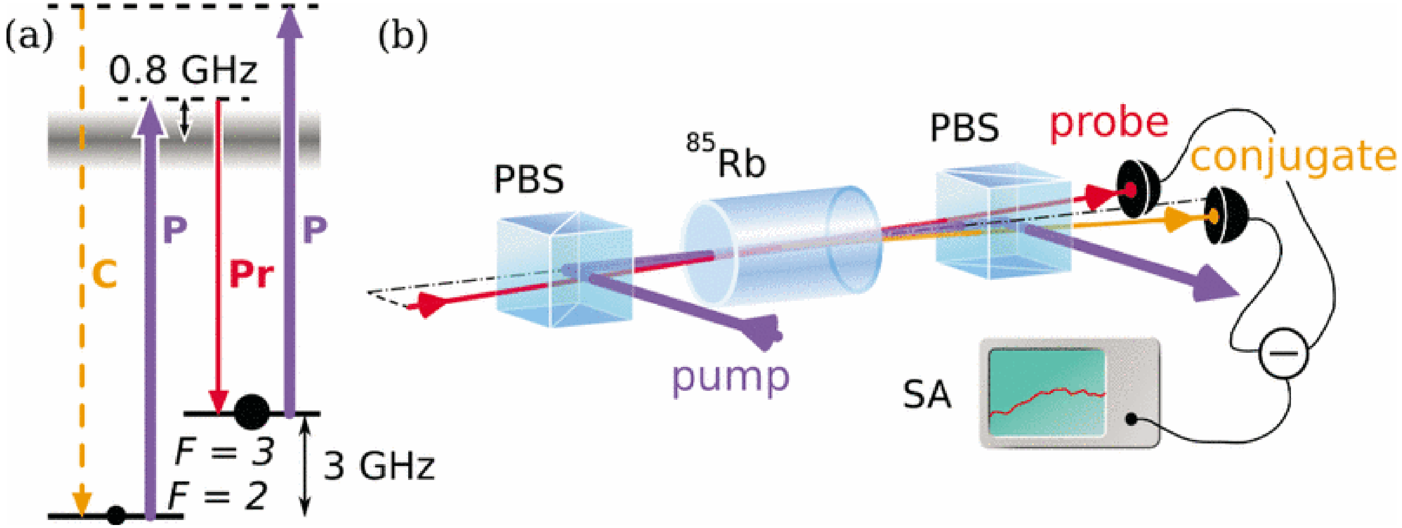


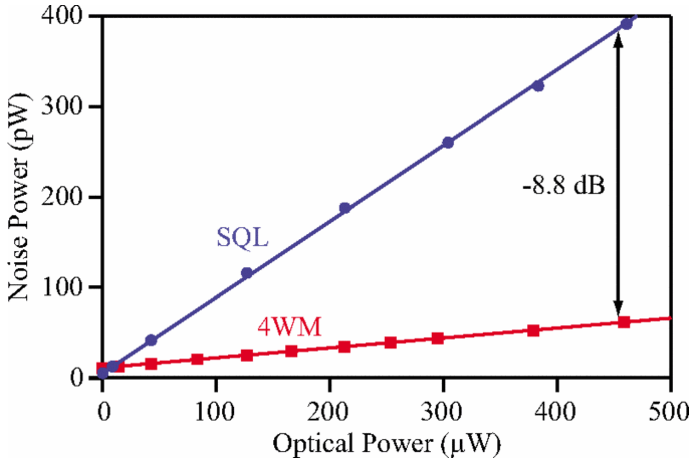
- B.J. Lawrie, P.D. Lett, A.M. Marino, and R.C. Pooser, *ACS Photonics* **6**, 1307 (2019).

Prototypical Sensing Setup

- Nonlinear process to generate quantum light.

BS: beam splitter
PBS:polarizing beam splitter
SA: spectrum analyze
AOM: acousto-optic modulator





The double-Λ scheme: 4 Wave Mixing process that mixes two strong pump fields with a weak probe field to generate a fourth field called the conjugate. The probe and conjugate fields are cross coupled and are jointly amplified, which leads to intensity correlations stronger than the standard quantum limit (SQL): two-mode quadrature squeezing.

- C.F. McCormick, A.M. Marino, V. Boyer, and P. D. Lett, *PRA* **78**, 043816 (2008).

Prototypical Sensing Setup

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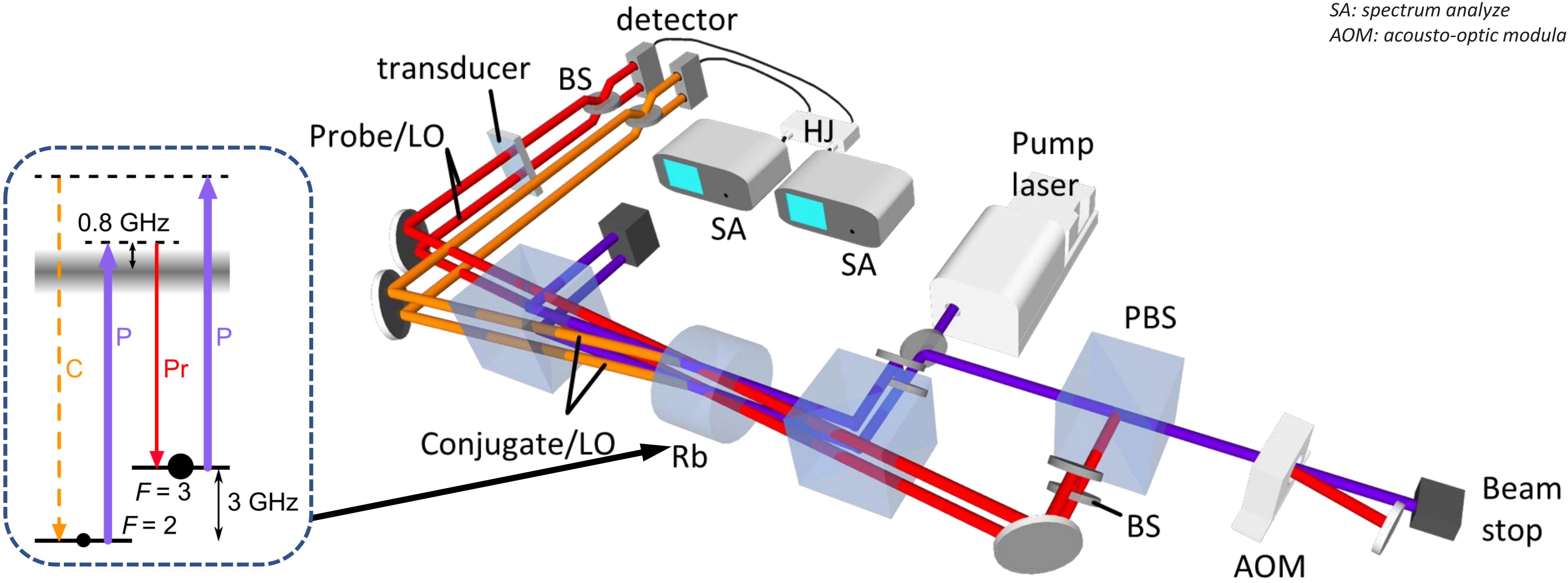
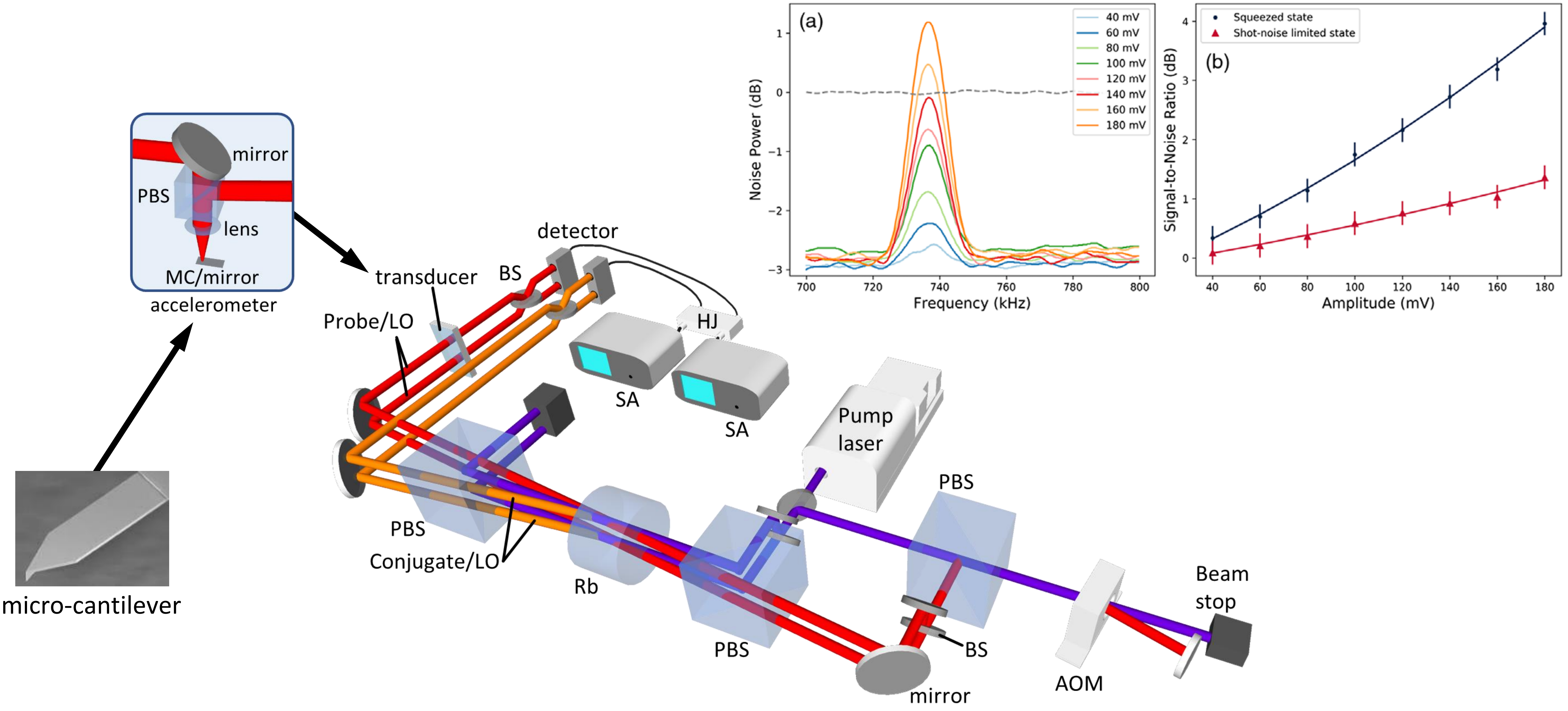


- C.F. McCormick, V. Boyer, E. Arimondo, and P.D. Lett, *Opt. Lett.* **32**, 178 (2007).
- C.F. McCormick, A.M. Marino, V. Boyer, and P. D. Lett, *PRA* **78**, 043816 (2008).

Quantum Enhanced Optomechanical System

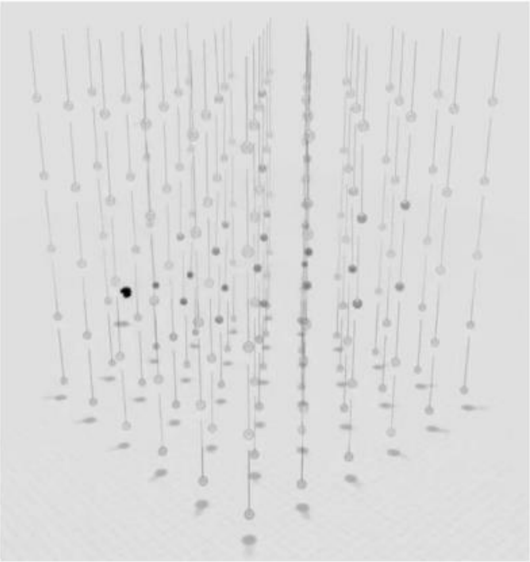


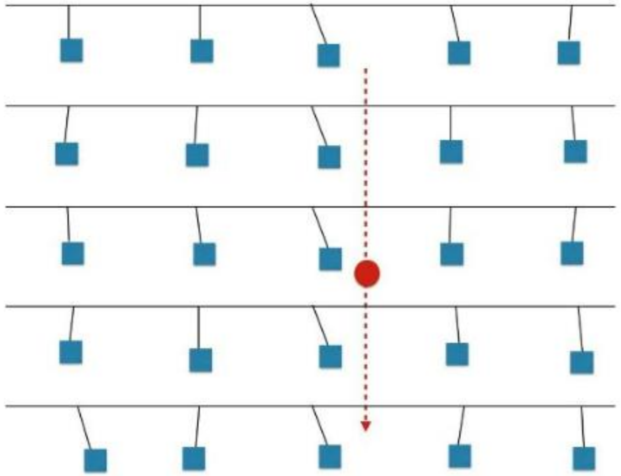
- R.C. Pooser, N. Savino, E. Batson, J.L. Beckey, J. Garcia, and B. J. Lawrie, *Phys. Rev. Lett.* **124**, 230504 (2020).

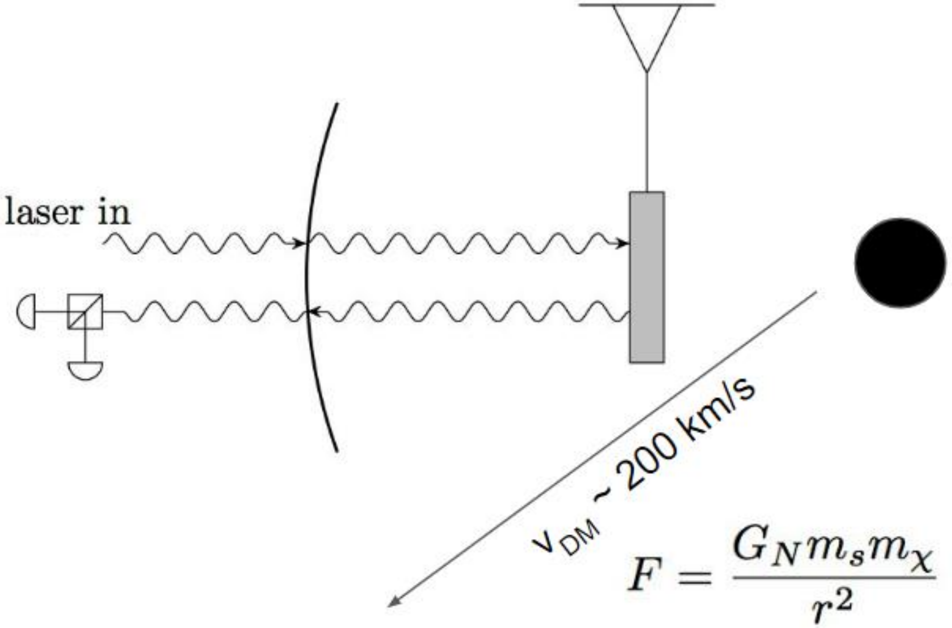
Gravitational Detection of Dark Matter in the Laboratory

The Windchime collaboration

- Direct gravitational detection of DM [D. Carney, et al. *PRD* **102**, 072003 (2020)]
  - Sensitive accelerometers (optomechanical system)
  - Readout position of proof mass directly with light (phase sensitive readout)
  - Quantum-enhanced readout (squeezed light and back action evasion)
  - Large array of detectors (~ $10^8 – 10^9$)
- Signals:
  - heavy DM -> impulse signal
  - Light DM -> field signal

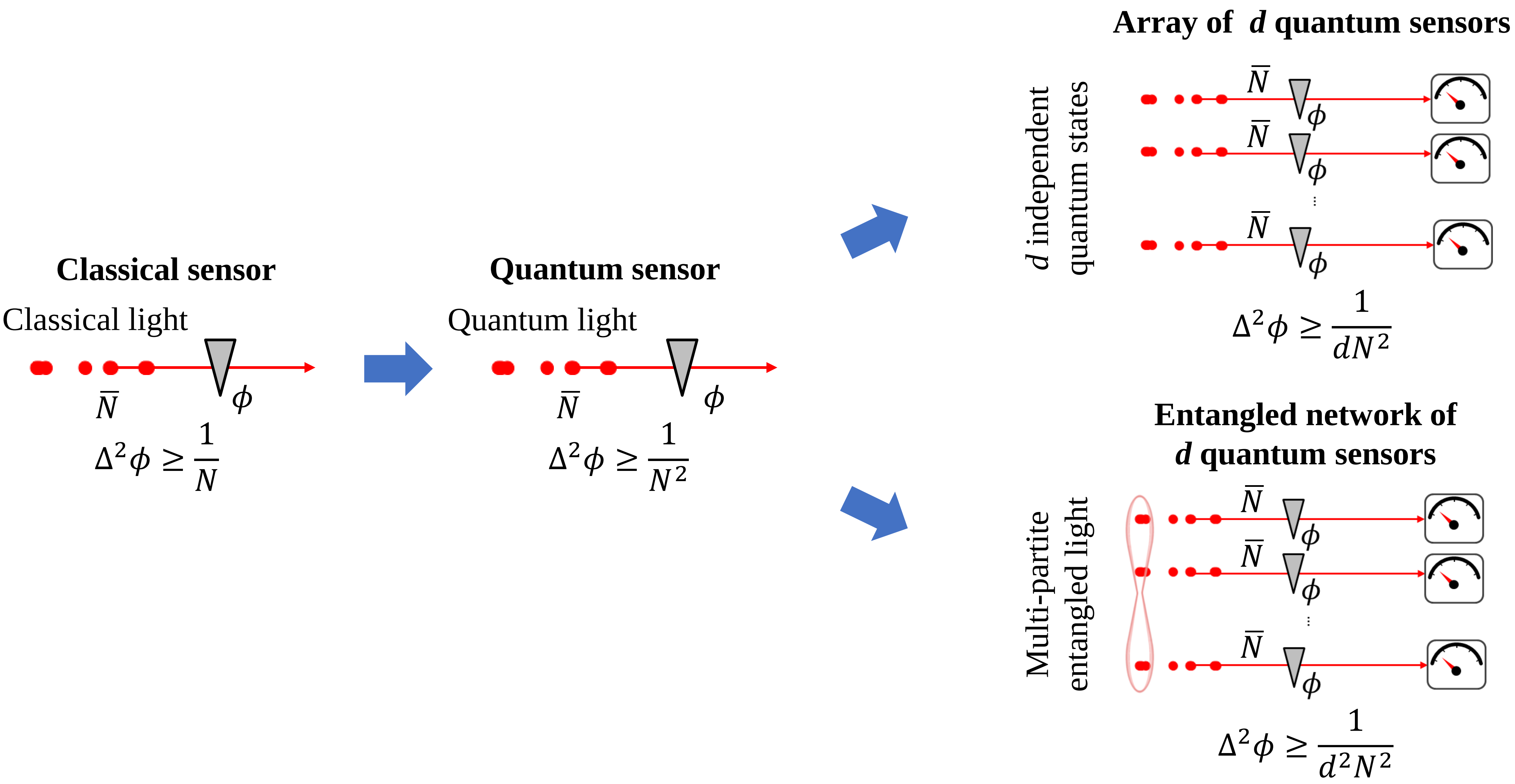






A. Attanasio, et al. "Snowmass 2021 White Paper: The Windchime Project." *arXiv:*2203.07242 (2022).

Network of Quantum Sensors



Classical sensor

Classical light

$$\Delta^2\phi \geq \frac{1}{N}$$

Quantum sensor

Quantum light

$$\Delta^2\phi \geq \frac{1}{N^2}$$

Array of *d* quantum sensors

d independent quantum states

$$\Delta^2\phi \geq \frac{1}{dN^2}$$

Entangled network of
***d* quantum sensors**

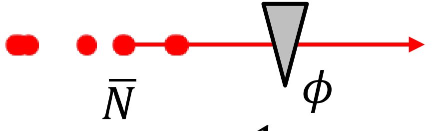
Multi-partite entangled light

$$\Delta^2\phi \geq \frac{1}{d^2N^2}$$

Network of Quantum Sensors

Classical sensor

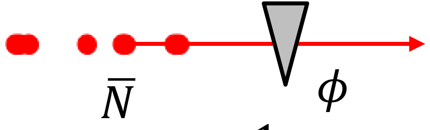
Classical light



$$\Delta^2\phi \geq \frac{1}{N}$$

Quantum sensor

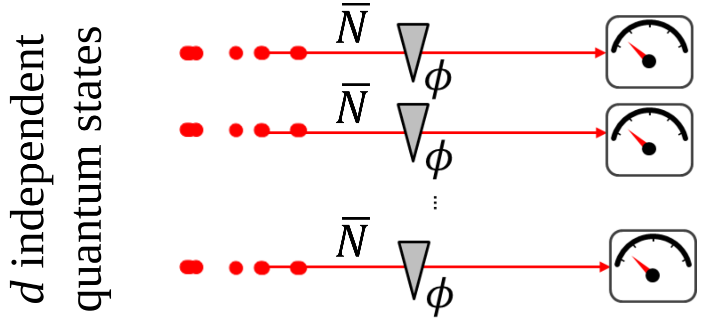
Quantum light



$$\Delta^2\phi \geq \frac{1}{N^2}$$

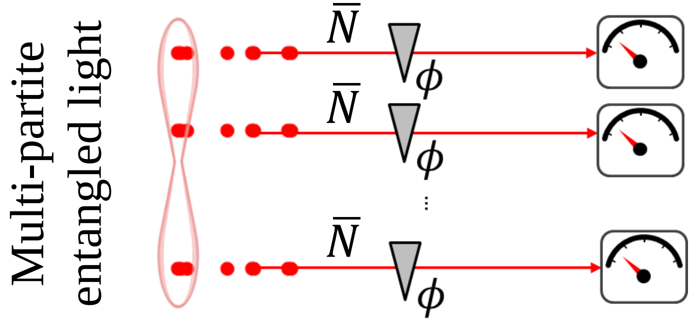
- **Advantage of scaling with independent sensors**
- **Advantage using entanglement!**

Array of *d* quantum sensors



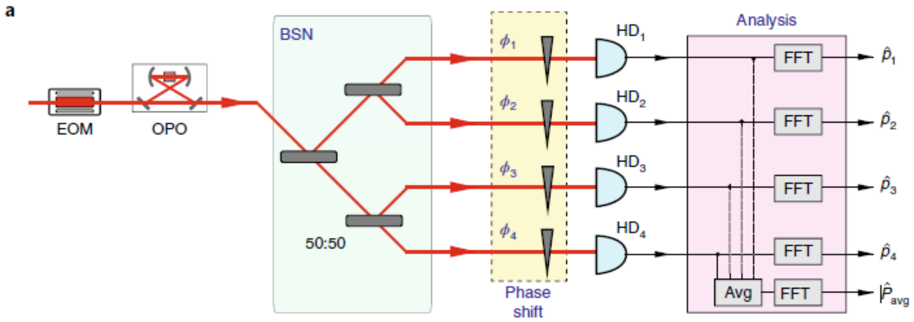
$$\Delta^2\phi \geq \frac{1}{dN^2}$$

Entangled network of
***d* quantum sensors**



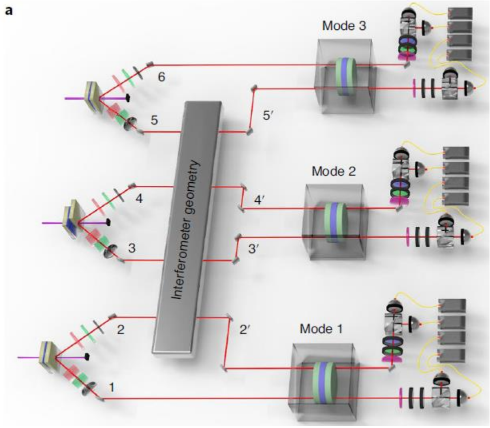
$$\Delta^2\phi \geq \frac{1}{d^2N^2}$$

Previous Work with Entangled Sensors



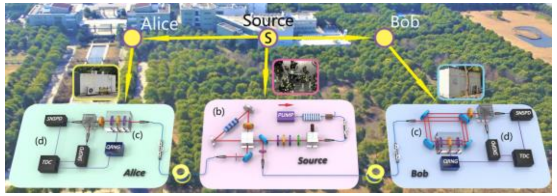
Nature Physics **16,** 281 (2020).

4-phase sensing using CV state from Andersen group (TU Denmark)



Nature Photonics **15,** 137 (2021).

3-phase sensing using single photon state from Pan group (USTC, Hefei)

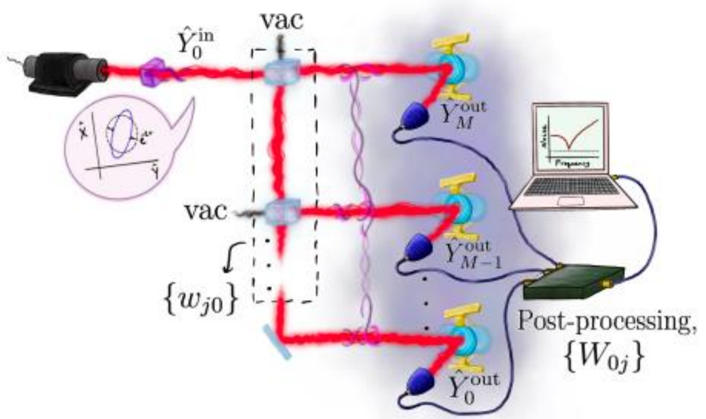


Phys. Rev. X **11,** 031009 (2021).

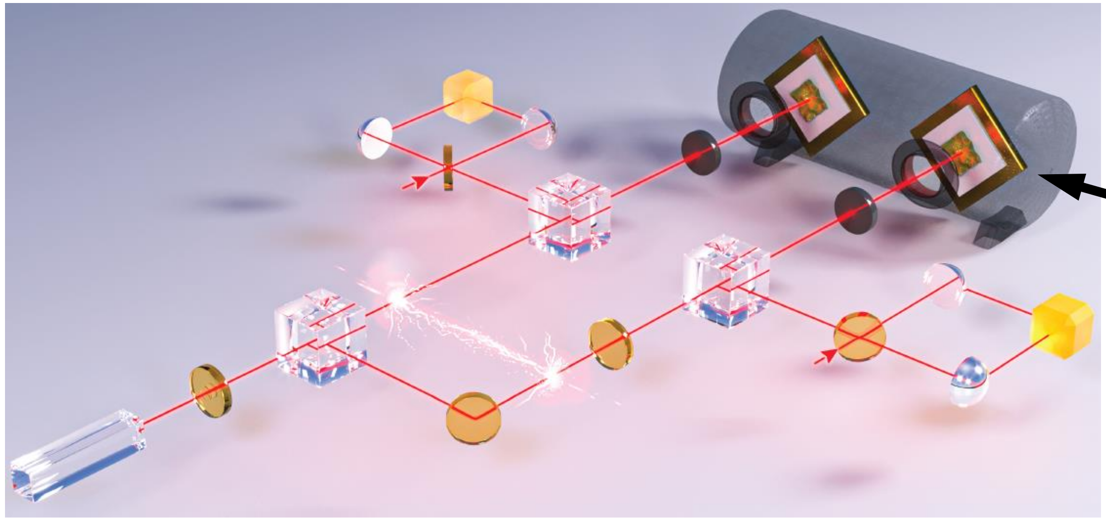
Field demonstration of distributed sensing from Pan group (USTC, Hefei)

Entanglement-Enhanced Optomechanical Dark Matter Detector

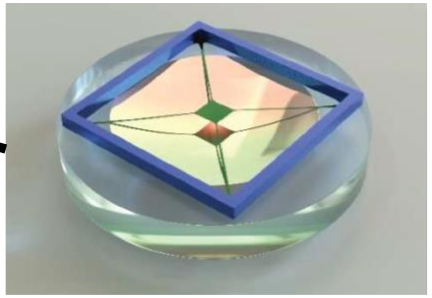
University collaboration: Southern California, Minnesota, Arizona, Michigan



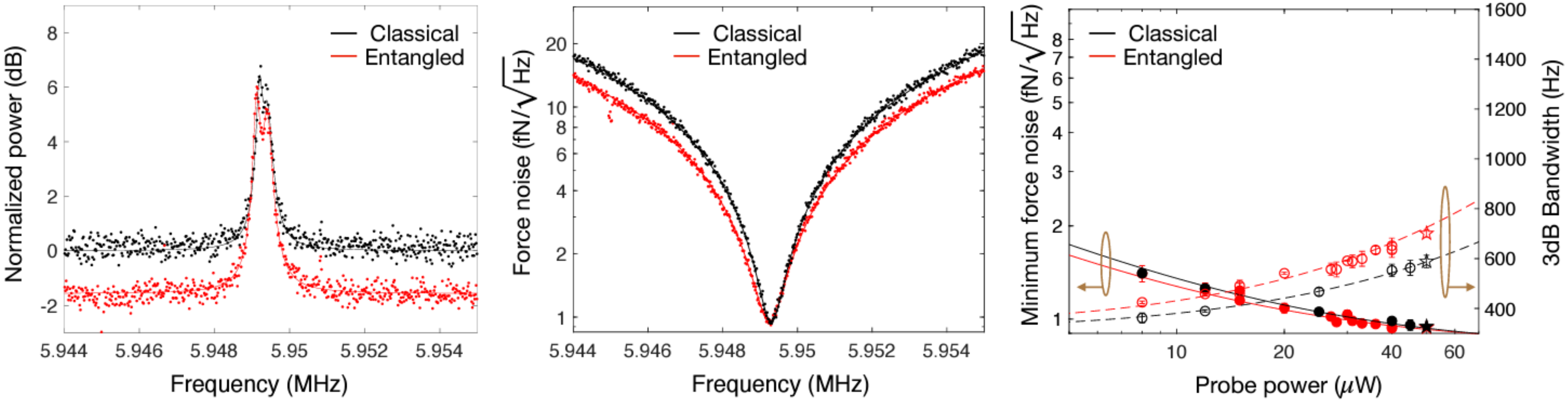
arXiv:2210.07291 (2022).



Si$_3$N$_4$ membranes

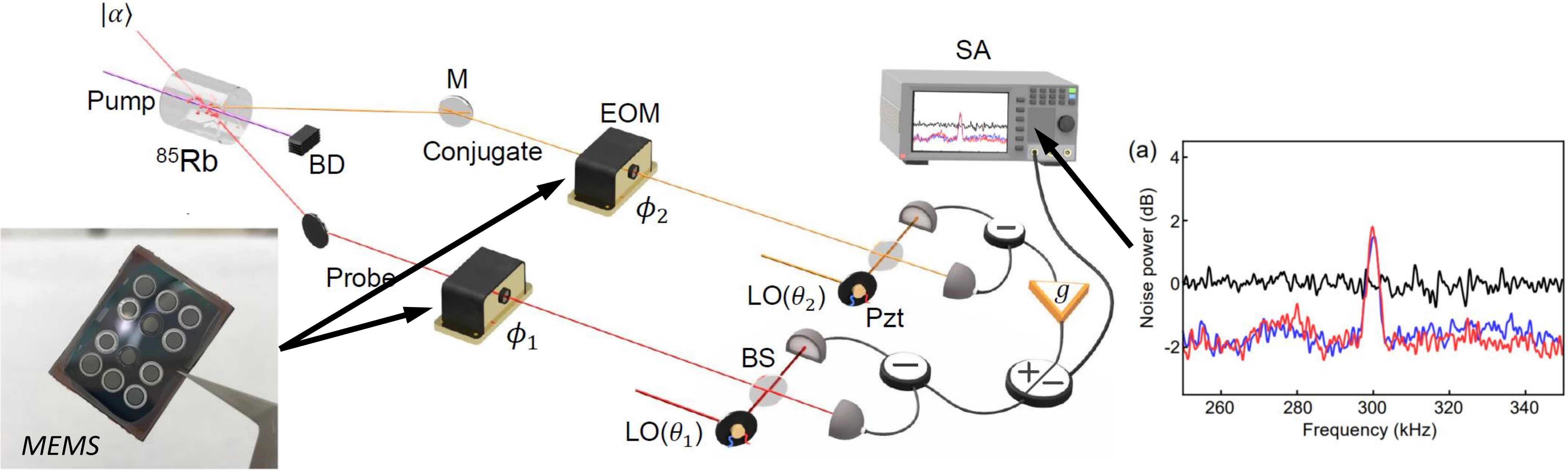


arXiv:2210.16180 (2022).

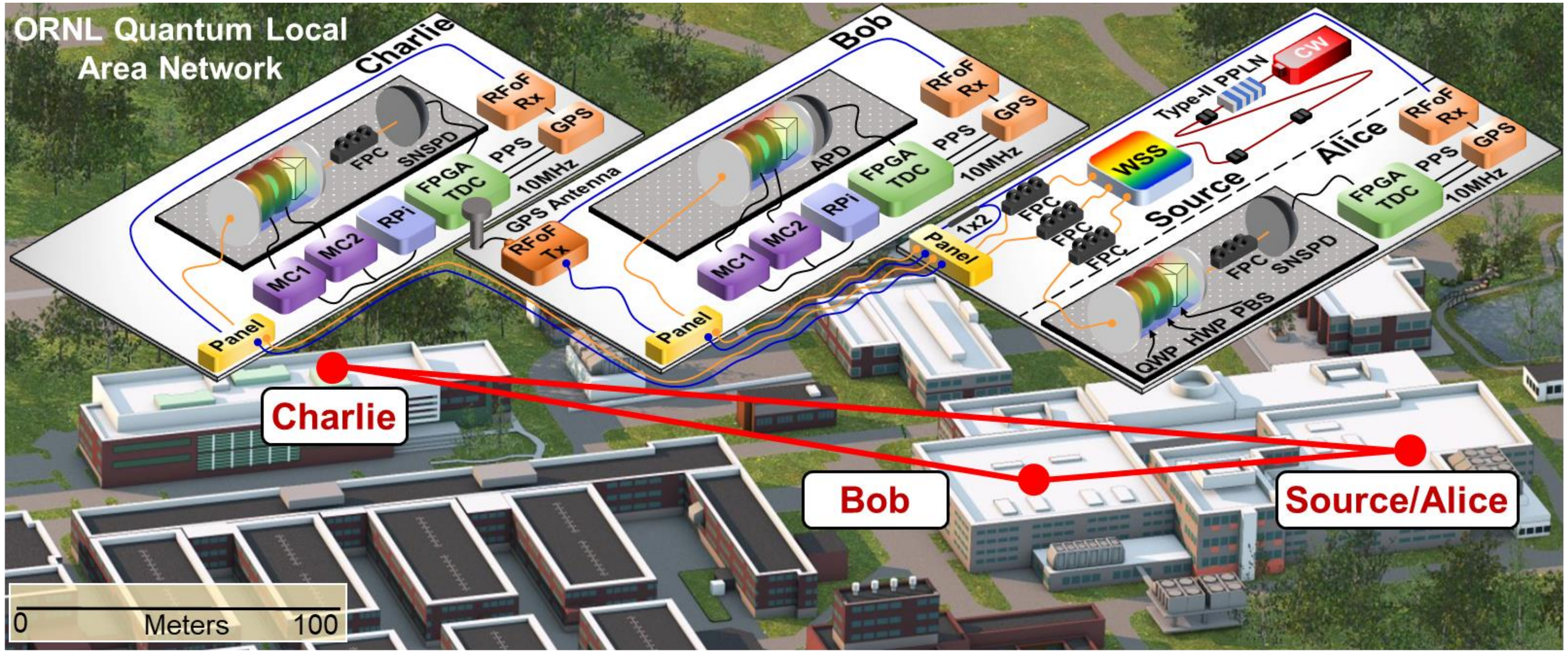


Quantum Enhanced Optomechanical Detection of Quantum Fields and Particles through Networked Entangled Sensors

- Develop a distributed array (network) of entangled optomechanical sensors for proxy-force detection that enables the sensitivities needed for DM detection and BSM physics.
- Leverage quantum-noise reduction techniques (squeezed light and back-action evasion) to obtain sensitives beyond the standard quantum limit with MEMS.



Distributed Array of Entangled Sensors



M. Alshowkan, et. al, *PRX Quantum* **2**, 040304 (2021).

- ***Leverage expertise and facilities***

- ***Challenges and limitations:***
  - Scalable source of multi-partite entanglement.
  - Distribution of quantum resources.
  - Optimal quantum state, measurement, and data analysis strategies (QCRB, QML, etc.).
  - Scalability and limitations of imperfections.
  - Management of data stream for large sensor arrays.

Goals for Work Package 1

- Identify projects within the roadmap that would significantly benefit from the implementation of quantum techniques.
  - Other platforms beyond optomechanics (for example network of atomic clocks).

- Formulate the approach, supported by theory.
  - Determine optimal quantum states and fundamental detection limits for different platforms.
  - Optimal readout schemes for large sensor arrays.

- Identify near-term milestones for each project