Ground state cooling of opto-mechanical oscillators

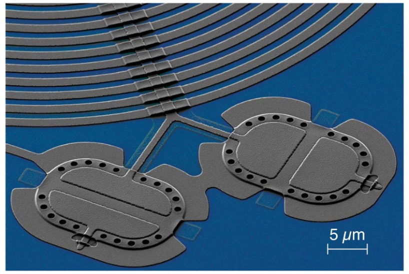
Kentaro Komori

Ando lab seminar 2024/11/15

Contents

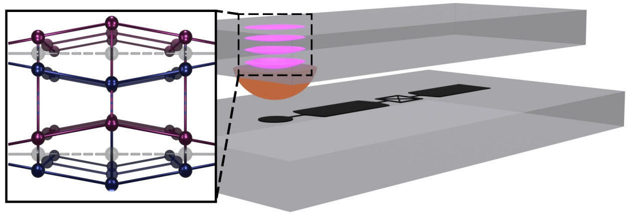
Motivation

- ➢The most massive quantum (16 ug) and the lightest gravity (90 mg)



Science 372, 622 (2021)

70 pg



Science 380, 274 (2023)

Quantum

16 ug

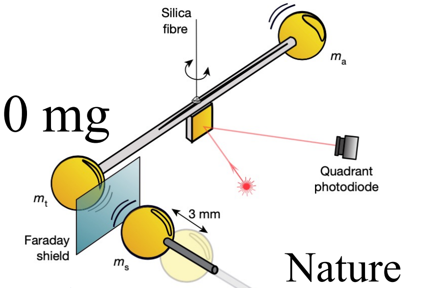
Planck mass

22 ug

Superposition of gravity?

Our target

90 mg



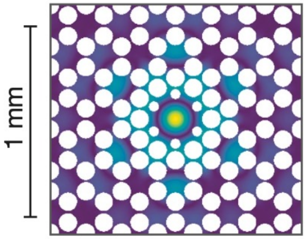
Nature 591, 225 (2021)

Gravity

pg ng ug mg g Mass

Nat. Phys. 15, 745 (2019)

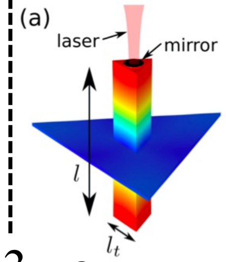
10 ng



50 ng PRL 133, 113602 (2024)

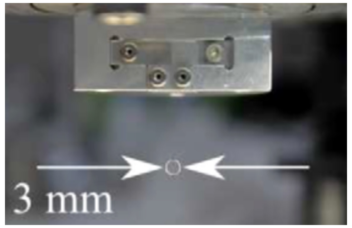
Beyond standard quantum limit

Will be entangled soon



33 ug

Arxiv:2104.11648



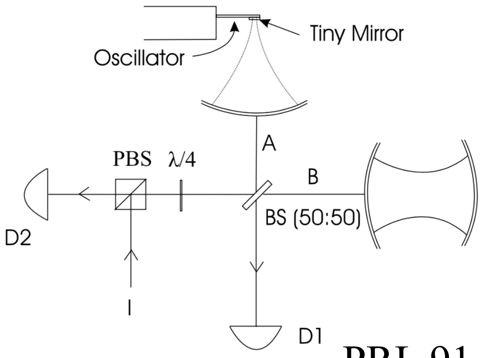
PRL 122, 071101 (2019)

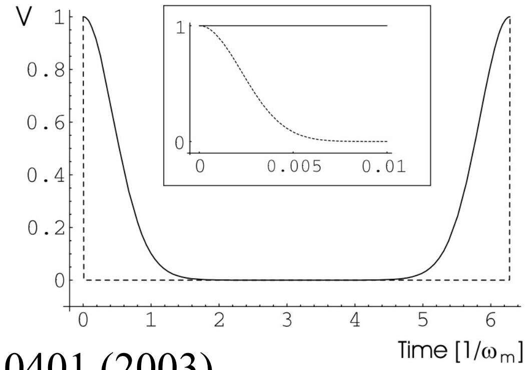
7 mg

Near quantum

Motivation

- Examples of proposed experiments
  - Entanglement between the single photon and the test mass displacement

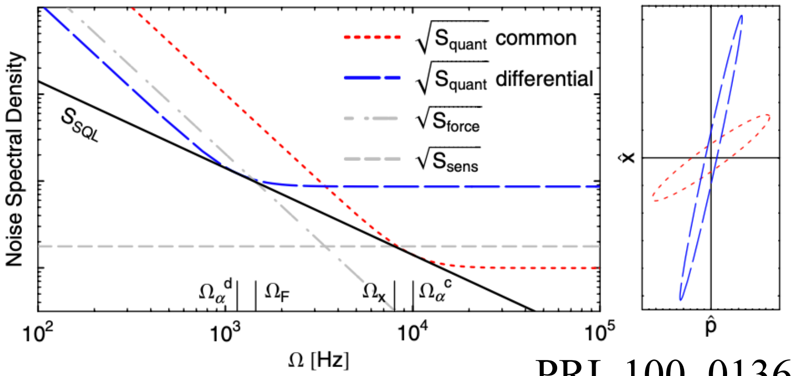


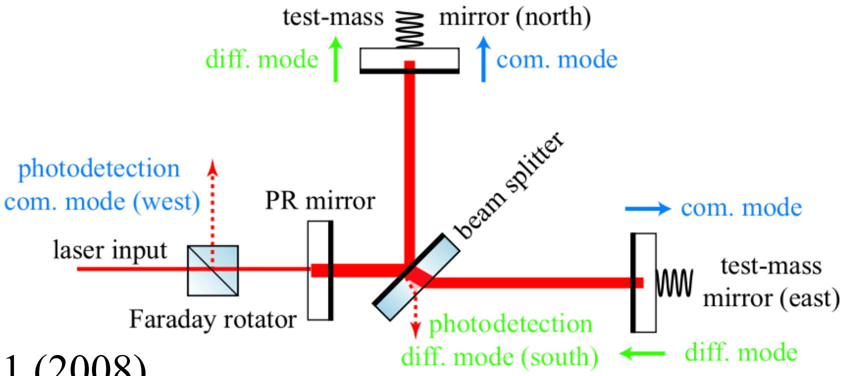


PRL 91, 130401 (2003)

- ✓ Interference of the single photon will recover after one period
- ✓ Requirement: ground state cooling

  - Entanglement between the common mode and the differential mode





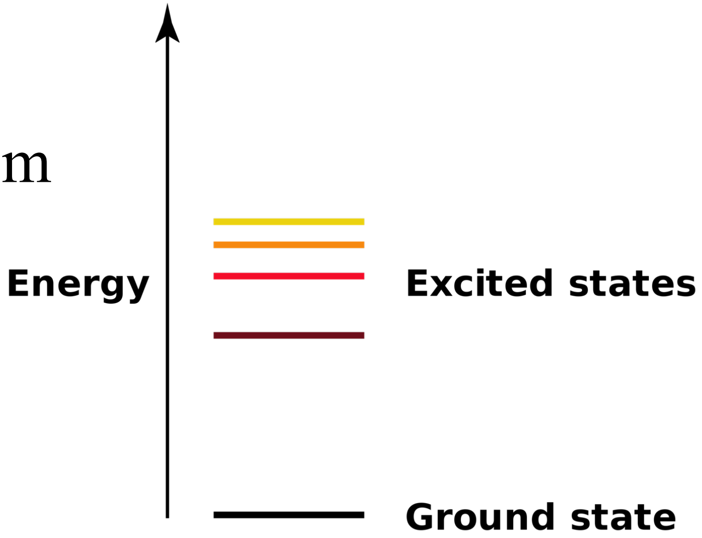
PRL 100, 013601 (2008)

- ✓ Logarithmic negativity is not zero
- ✓ Requirement: reaching the SQL

Ground state

➢General

- Stationary state of the lowest energy
- The energy is known as the zero-point energy of the system



Wikipedia: “ground state”

➢Harmonic oscillator

- Energy: $E_n = \hbar\omega_m\left(n+\frac{1}{2}\right)$ with $n=0$
- Displacement variance: $\langle x^2\rangle_{gs} = \frac{\hbar}{2m\omega_m}$
- Total variance: $\langle x^2\rangle = \frac{\hbar}{m\omega_m}\left(n+\frac{1}{2}\right)$, n is the phonon number
- $n < 1$ means a benchmark of the ground state cooling in the opto-mechanics field
- Purity: $\mu = \frac{1}{2n+1} = \frac{\hbar}{2m\omega_m\langle x^2\rangle}$ is also a commonly used parameter ($\mu_{max} = 1$)

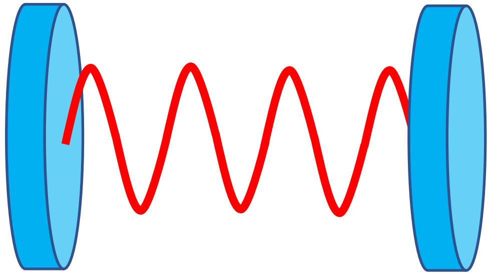
Phonon number

- ➢Thermal phonon number
    - Brownian motion: $\langle x^2 \rangle_{th} = \frac{k_B T}{m\omega_m^2}$
    - $\langle x^2 \rangle = \frac{\hbar}{m\omega_m}\left(n_{th} + n_{other} + \frac{1}{2}\right)$
    - $n_{th} = \frac{k_B T}{\hbar\omega_m} < 1$ is necessary to reach the ground state
- ➢Case studies
    - At room temperature (T = 300 K), $\frac{\omega_m}{2\pi} > 6$ THz
      - Laser light (~300 THz) is originally in the ground state
    - At low frequency oscillator ($\frac{\omega_m}{2\pi}$ = 1 kHz), T < 50 nK
      - We cannot reach such low temperature even with cryogenic system

      ⇨ Laser cooling with an optical cavity and feedback

Measurement and feedback

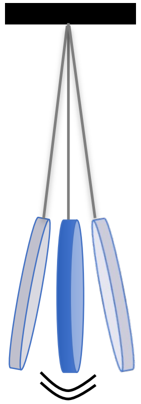
- ➢ Typical quantum limit of laser interferometer
  - Michelson interferometer ~ 10^{-15} m/√Hz
  - Optical cavity ~ 10^{-18} m/√Hz
    - ✓ Laser wavelength: λ ~ 1 um
    - ✓ Input power: P ~ 10 mW
    - ✓ Cavity finesse: $\mathcal{F}$ ~ 10^3

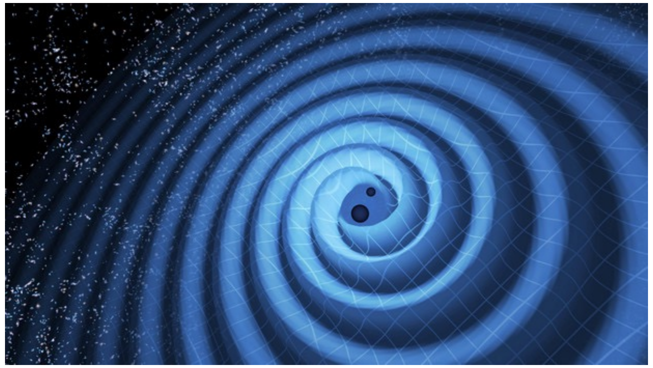


$$S_{shot,x} \sim \frac{\lambda}{\mathcal{F}} \boxed{\sqrt{\frac{\hbar\omega_l}{P_{in}}}}$$

Relative photon number fluctuation of $1/\sqrt{N} \sim 10^{-8}$ /√Hz with P_{in} ~ 1 mW

- ➢ Required displacement sensitivity
  - Zero-point fluctuation ~ 10^{-18} m/√Hz
    - ✓ Mass: m ~ 1 mg
    - ✓ Resonant frequency: $\omega_m/2\pi$ ~ 1 kHz
  - GW detector sensitivity ~ 10^{-20} m/√Hz





Credit: LIGO

Feedback cooling

- ➢Damping, stiffening, and f*Q criteria

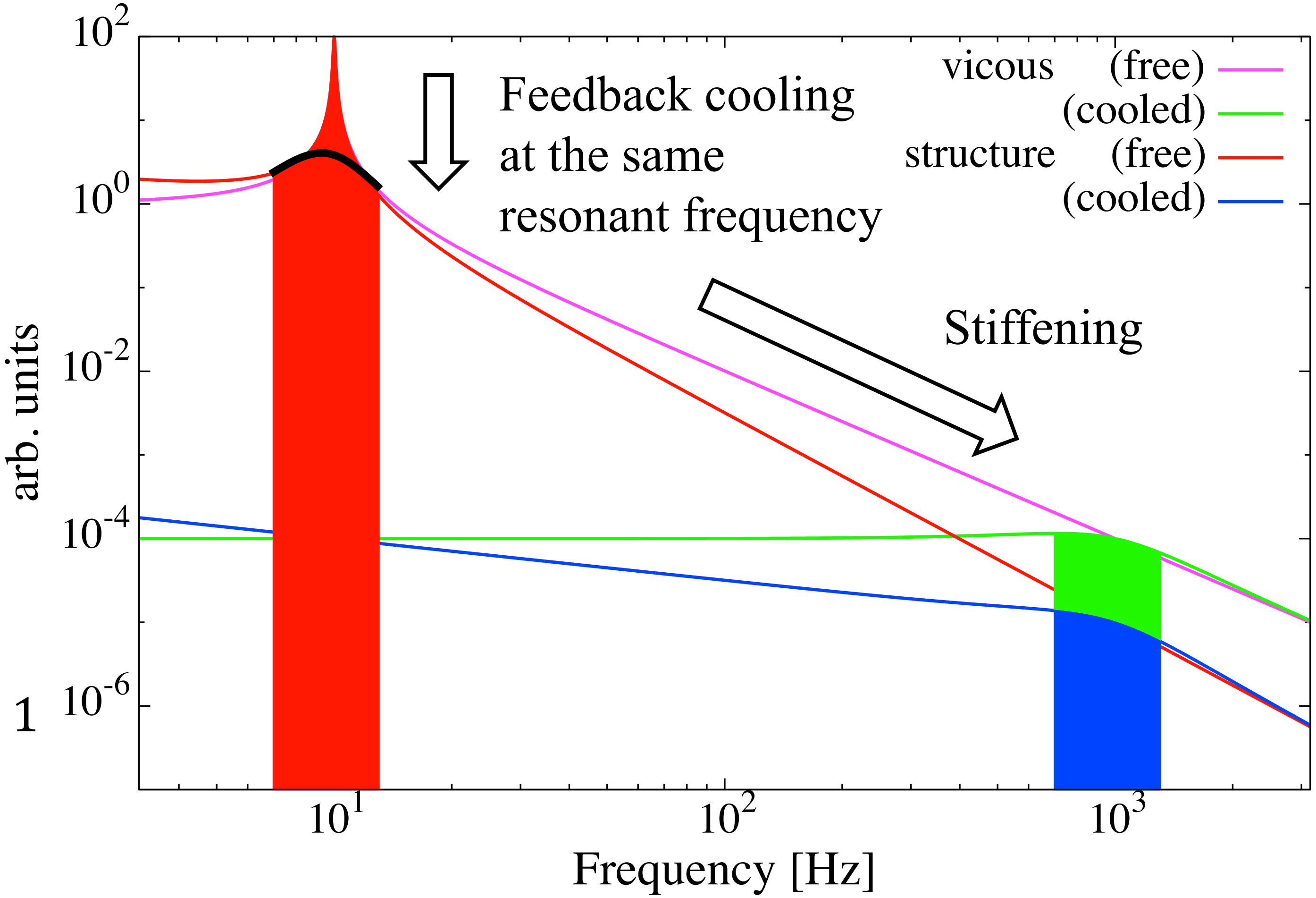
$$\langle x^2 \rangle_{th} = \frac{k_B T}{m\omega_m^2}$$

$$\Downarrow$$

$$\langle x^2 \rangle_{th} = \frac{k_B T}{m\omega_m^2}\frac{Q_{eff}}{Q_m}$$

$$= \frac{k_B T_{eff}}{m\omega_m^2}$$

- ✓ $Q_{eff,min} = 1$
- ✓ $n_{th,min} = \frac{k_B T}{\hbar\omega_m Q_m} < 1$
- ✓ $f_m Q_m > 6 \times 10^{12}$ at room temperature



- Viscous

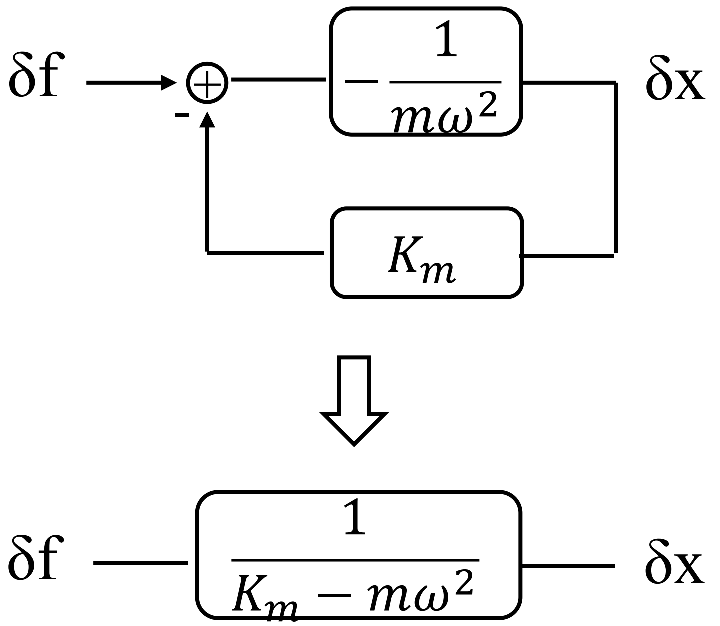
- ✓ $n_{th,min} = \frac{k_B T}{\hbar\omega_m Q_m}\left(\frac{\omega_m}{\omega_{eff}}\right)^2$
- ✓ $f_m Q_m > 6 \times 10^{12}\left(\frac{\omega_m}{\omega_{eff}}\right)^2$

- Structure

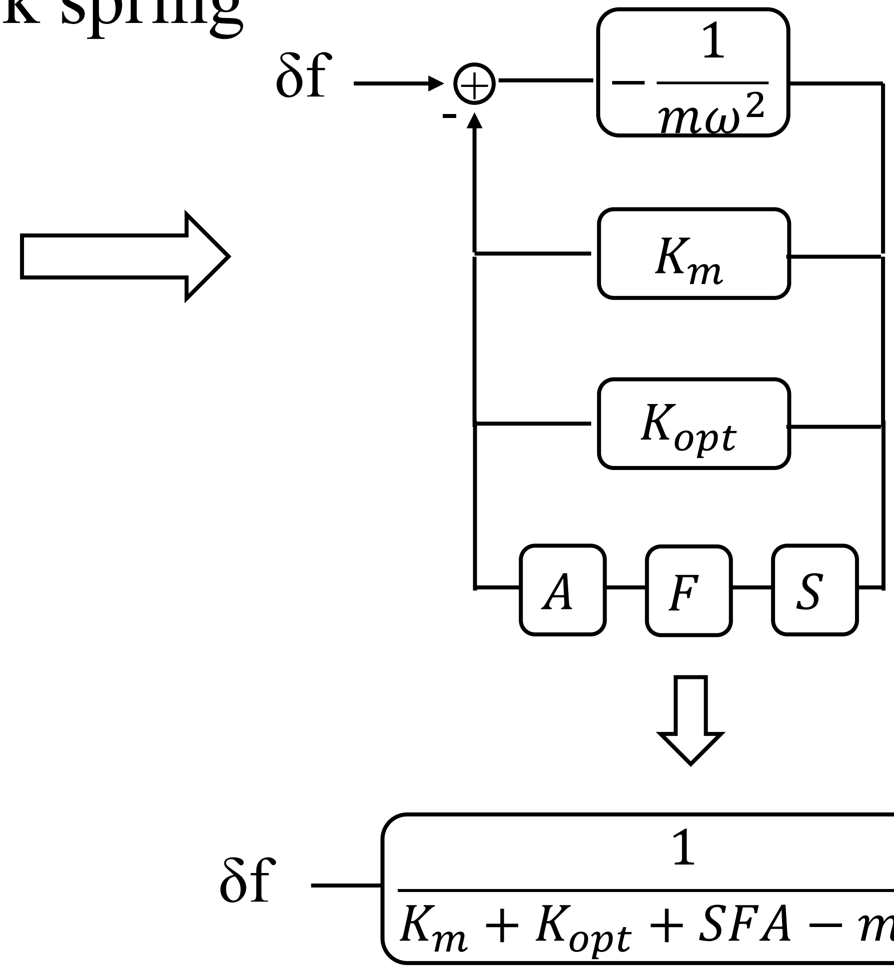
- ✓ $n_{th,min} = \frac{k_B T}{\hbar\omega_m Q_m}\left(\frac{\omega_m}{\omega_{eff}}\right)^3$
- ✓ $f_m Q_m > 6 \times 10^{12}\left(\frac{\omega_m}{\omega_{eff}}\right)^3$

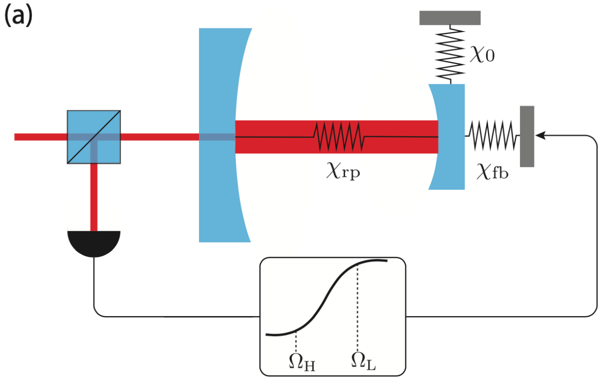
Stiffening

- ➢Optical spring and feedback spring



- ✓ Even mechanical spring can be described as feedback



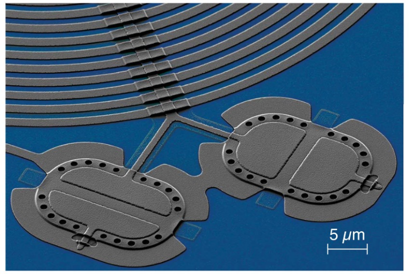


- ✓ Restoring force from the radiation pressure
- ✓ Resonance at UGF

Examples

- fQ and temperature in the experiments

$$f_m Q_m > 6 \times 10^{12} \left(\frac{T}{300\ K}\right)\left(\frac{\omega_m}{\omega_{eff}}\right)^3$$



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70 pg

f_m ~ 10 MHz
Q_m ~ 2 x 10^5
T ~ 10 mK

pg

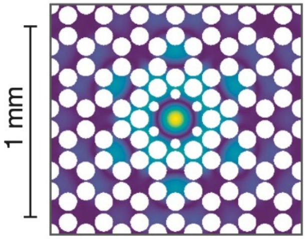
ng

mg

Mass

Nat. Phys. 15, 745 (2019)

10 ng



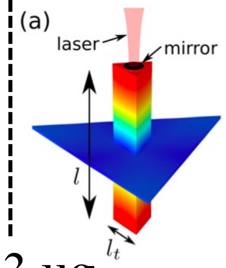
f_m ~ 1 MHz
Q_m ~ 1 x 10^9
T ~ 10 K

50 ng

f_m ~ 800 Hz
f_{eff} ~ 67 kHz
Q_m ~ 2 x 10^4
T ~ 30 K

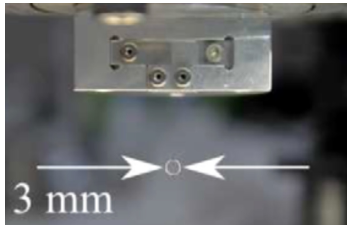
PRL 133, 113602 (2024)

f_m ~ 4 MHz
Q_m ~ 7 x 10^7
T ~ 3 K



33 ug

Arxiv:2104.11648



f_m ~ 2 Hz
f_{eff} ~ 300 kHz
Q_m ~ 2 x 10^6
T ~ 300 K

7 mg

Sensitivity and SQL

➢Reaching the SQL is almost equivalent to the ground state cooling

- Thermal noise: $S_{th}(\omega) = \frac{4k_B T m \omega_m^2}{Q_m \omega}$ [N/√Hz] in the structure damping
- SQL: $S_{SQL}(\omega) = 2\hbar m \omega^2$[N/√Hz]
- Ratio: $\frac{S_{th}(\omega_{eff})}{S_{SQL}(\omega_{eff})} = \frac{2k_B T}{\hbar \omega_m Q_m}\left(\frac{\omega_m}{\omega_{eff}}\right)^3 \sim n_{th,min}$

$$\langle x^2 \rangle = \frac{\hbar}{m\omega_m}\left(n_{th} + n_{other} + \frac{1}{2}\right)$$

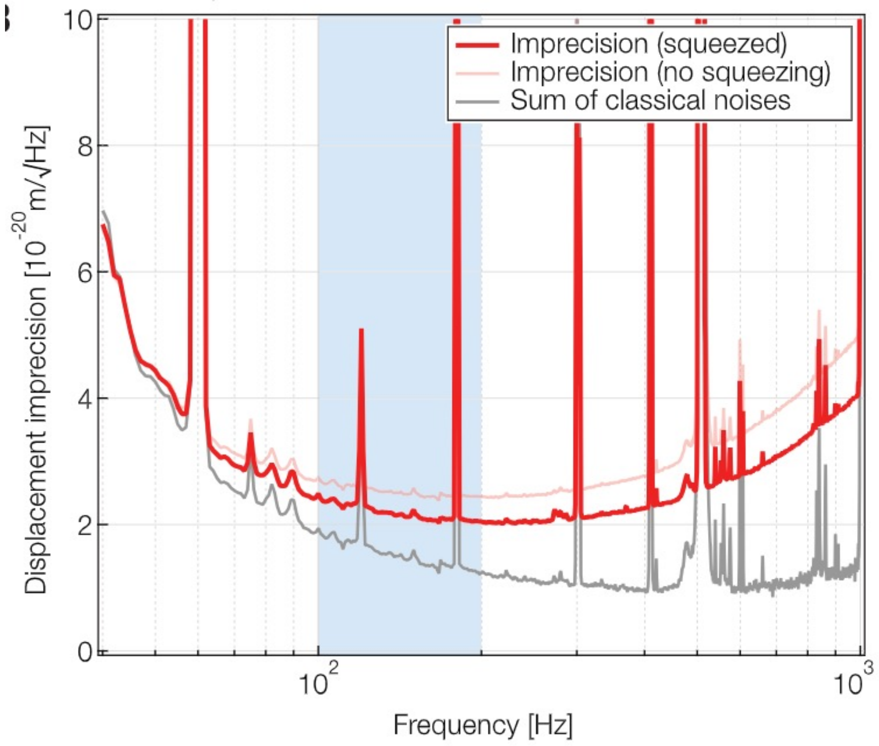
➢When the sensitivity reaches the SQL at a specific frequency, you only have to increase the resonant frequency up to the SQL frequency

➢Even the fQ criteria is satisfied, n_{other} should be below unity (the other noises should be below the SQL)

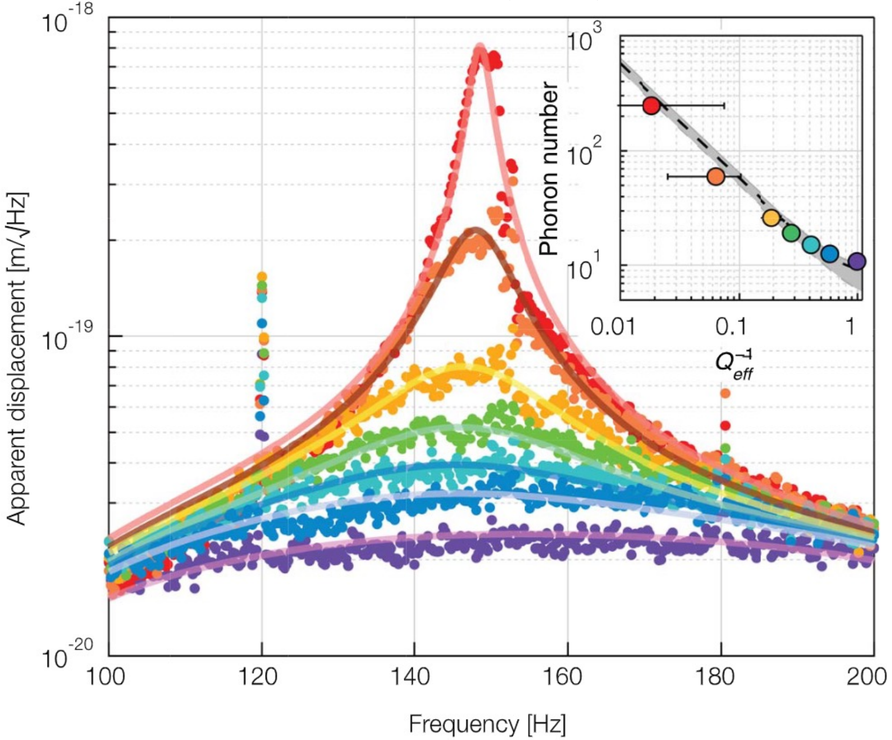
Examples

- ➢Cooling of aLIGO test masses

$$f_m Q_m > 6 \times 10^{12} \left(\frac{T}{300\ K}\right)\left(\frac{\omega_m}{\omega_{eff}}\right)^3$$



Science 372, 1333 (2021)



$f_m \sim 1$ Hz
$f_{eff} \sim 100$ Hz
$Q_m \sim 1 \times 10^9$
$T \sim 300$ K

✓ Other noises such as the coating thermal noise and the shot noise prevents the ground state cooling

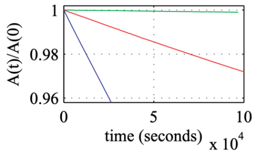
✓ Choosing the frequency close to the SQL

✓ Feedback spring without optical spring

✓ Tuning the DARM loop gain

Potential torsion pendulum

- ➢Picking up some familiar torsion pendula



CQG 26, 094017 (2009)	f_m	f_{eff}	Q_m	T	$f_m Q_m \left(\frac{300\ K}{T}\right)\left(\frac{\omega_{eff}}{\omega_m}\right)^3$
Fused silica torsion pendulum for LISA experiment	2 mHz	20 Hz	7×10^5	300 K	1×10^{15}
Our optomechanical experiment	0.1 Hz	1 kHz	3×10^3	300 K	3×10^{14}
TOBA	9 mHz	1 Hz	1×10^8	4 K	1×10^{14}

- ➢If we increase the TOBA resonant frequency up to 1 Hz using optical spring or feedback spring with the SQL, we can achieve the ground state cooling

Summary

- Ground state cooling of mechanical oscillators
- Phonon number and fQ criteria
- Potential torsion pendulum experiments