

# Recent optomechanical torsion pendula

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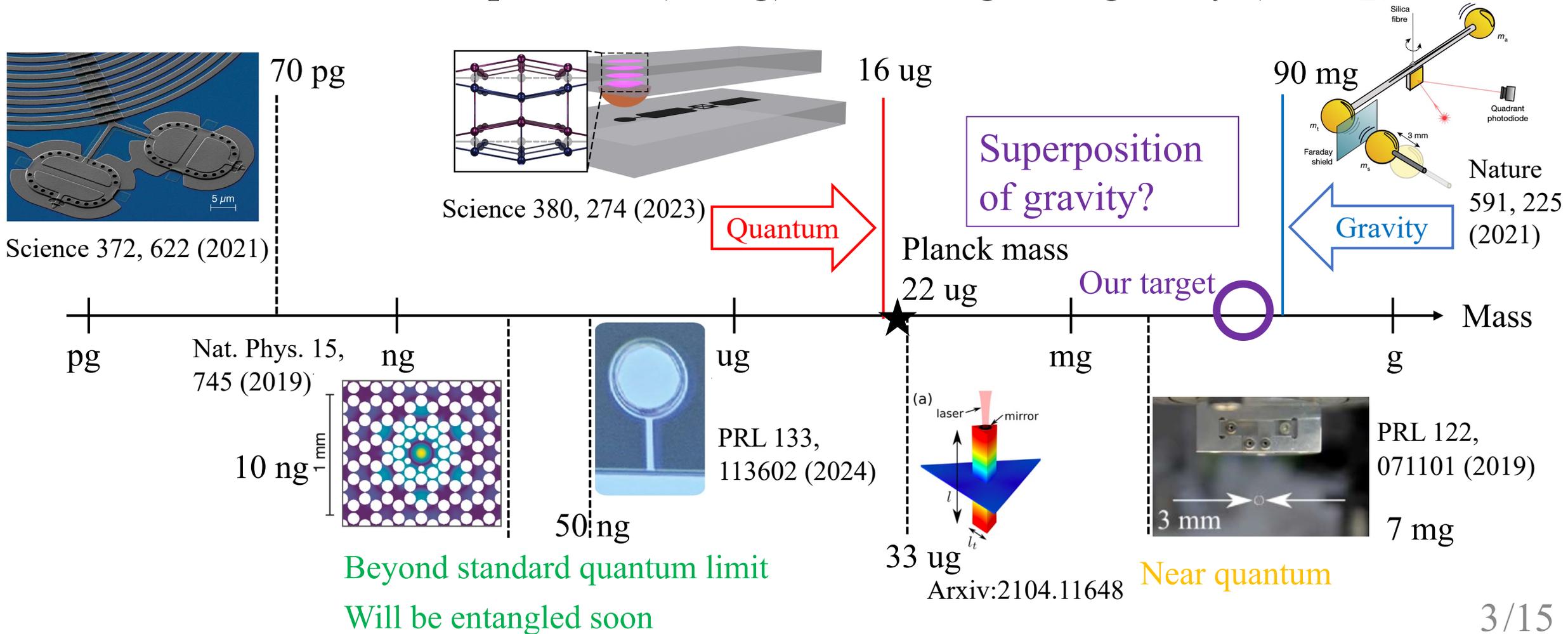
# Contents

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- Comparing following three works and our optomechanical torsion pendulum
  - “Quantum-limited optical lever measurement of a torsion oscillator”  
Pluchar+, *Optica* 12, 418-421 (2025)
  - “Active laser cooling of a centimeter-scale torsional oscillator”  
Shin+, *Optica* 12, 473-478 (2025)
  - “First result for testing semiclassical gravity effect with a torsion balance”  
Yan+, *PRD* 111, 082007 (2025)
  
- Mainly focusing on the first paper

# Quantum and gravity

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



# Torsion pendulum

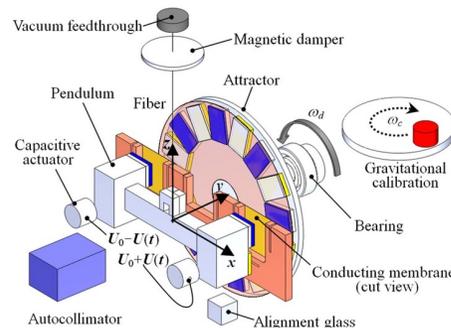
- Very sensitive to tiny force
  - Ultra-small restoring torque:  $K \propto \phi^4$
  - Leading to very low resonant frequency around mHz

- Historically used in gravity measurements

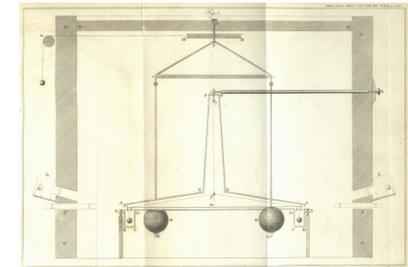
- Cavendish's experiment (G measurement)

- Equivalence principle

- Inverse law



PRL 116, 131101 (2016)



Philos. Trans. R. Soc. London (1798)



CQG 29, 184002 (2012)

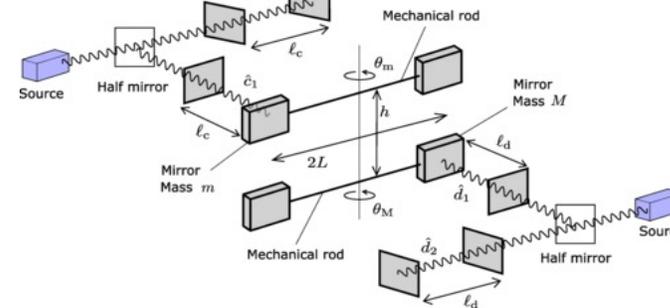
# Optomechanical torsion pendulum

## ➤ Theoretical proposal

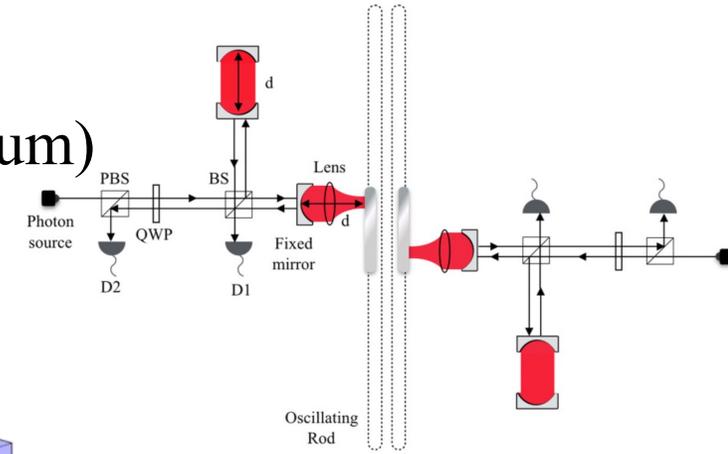
- Quantum Cavendish (superposition of the torsion pendulum)
- Test of gravity-induced entanglement

## ➤ Experiment

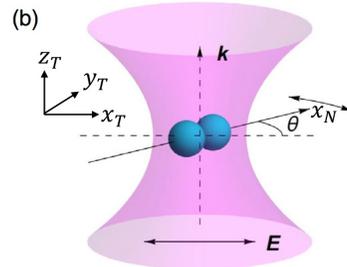
- GHz nano-rotor
- Um-pg-torque sensor
- Mm-mg-scale paddle



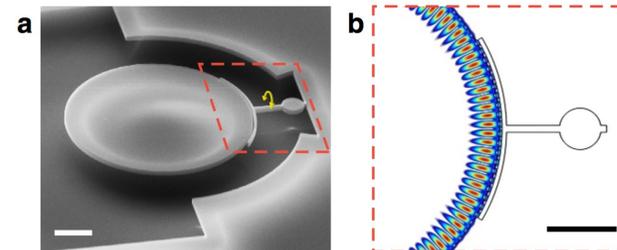
PRD 102, 106021 (2020)



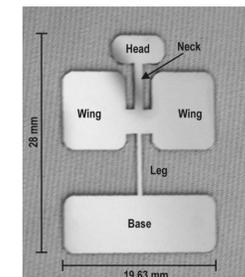
PRA 98, 043811 (2018)



PRL 121, 033603 (2018)



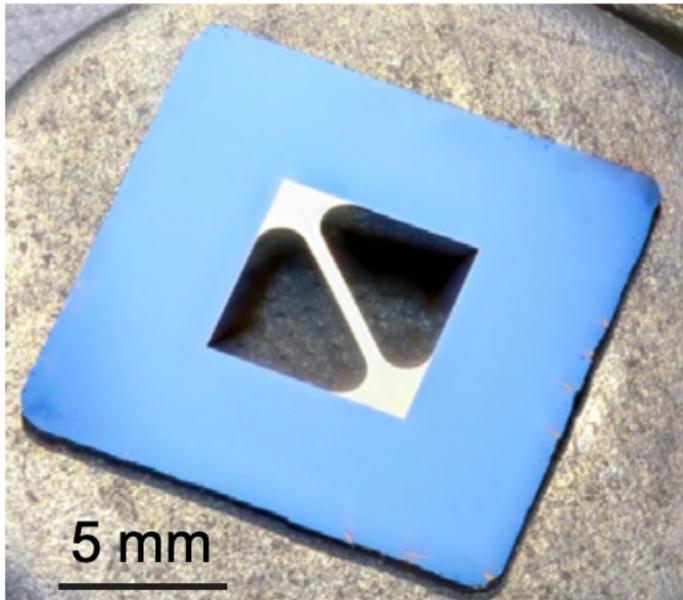
Nat. Comm. 7, 13165 (2016)



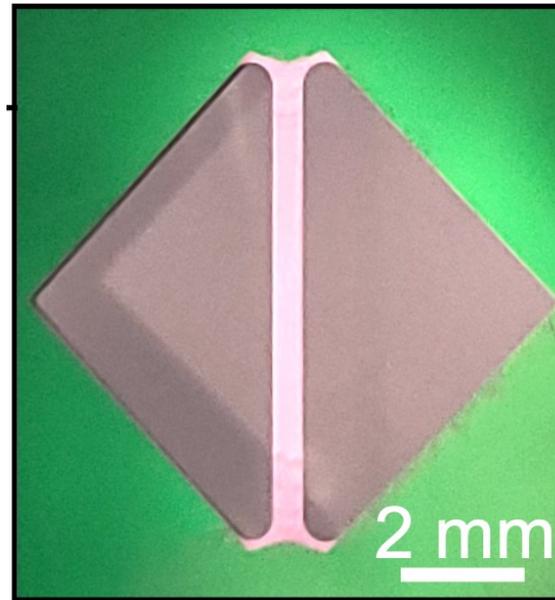
Rev. Sci. Instrum.  
78, 025101 (2007)

# Optomechanical torsion pendulum

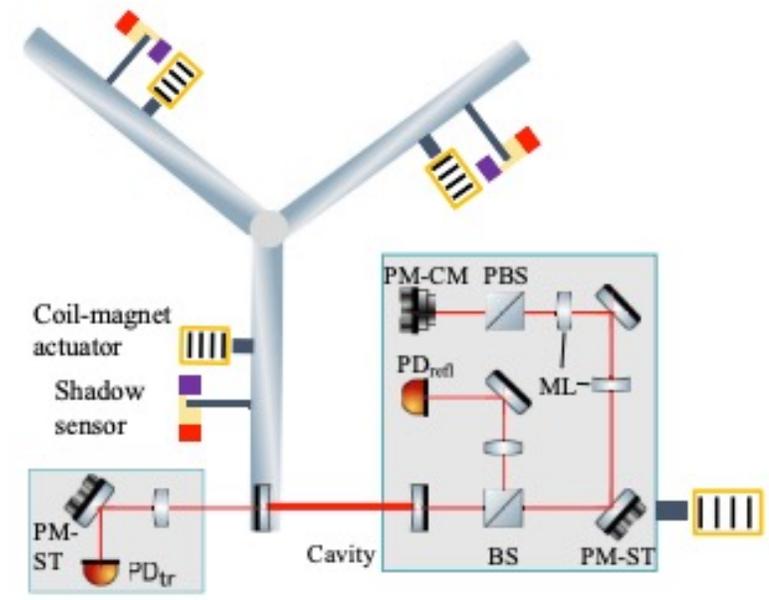
- Recent experimental works on the optomechanical torsion pendulum
  - Millimeter-scale nanoribbons
  - Meter-scale torsion balance



Optica 12, 418-421 (2025)



Optica 12, 473-478 (2025)



PRD 111, 082007 (2025)

# Comparison

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## ➤ Parameter list of the works

	Ribbon 1	Ribbon 2	Balance	Our work
Effective mass	0.095 ug	0.89 ug	2.9 kg	3.3 mg
Measurement	Optical lever	Optical lever	Cavity	Cavity
Maximum power	10 mW	1 mW	80 W	10 W
Suspension Material	Si <sub>3</sub> N <sub>4</sub>	Si <sub>3</sub> N <sub>4</sub>	Fused silica	Carbon fiber
Resonant frequency	53.5 kHz	33.95 kHz	0.6 mHz	0.1 Hz to 1 kHz
Q-value	$3 \times 10^7$	$1.4 \times 10^7$	$> 5 \times 10^4$	$3 \times 10^3$

# Ribbon 1

➤ Simple optical lever

➤ Quantum noise of  $HG_{01}$  mode

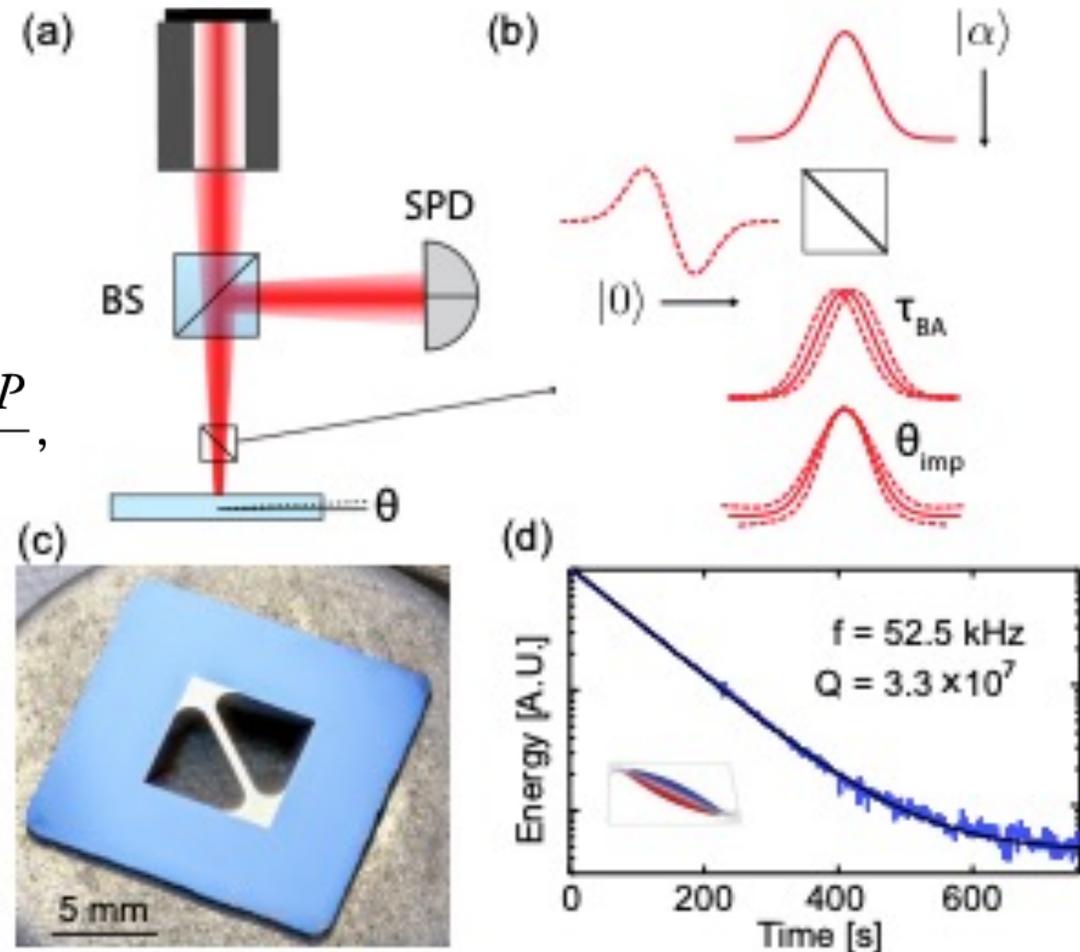
- Interpretation of back action

$$E_r \approx A_{00}u_{00} + (A_{10}^\theta + A_{10}^{\text{vac}})u_{10}, \quad S_\tau^{\text{BA}} = \frac{8N}{\theta_D^2} \frac{w^2}{w_0^2} \hbar^2 = w^2 \frac{4\pi \hbar P}{c\lambda},$$

➤ 7 mm x 400 μm x 75 nm

➤ High Q-value due to strain-induced dilution

- Similar as gravitational dilution of a pendulum



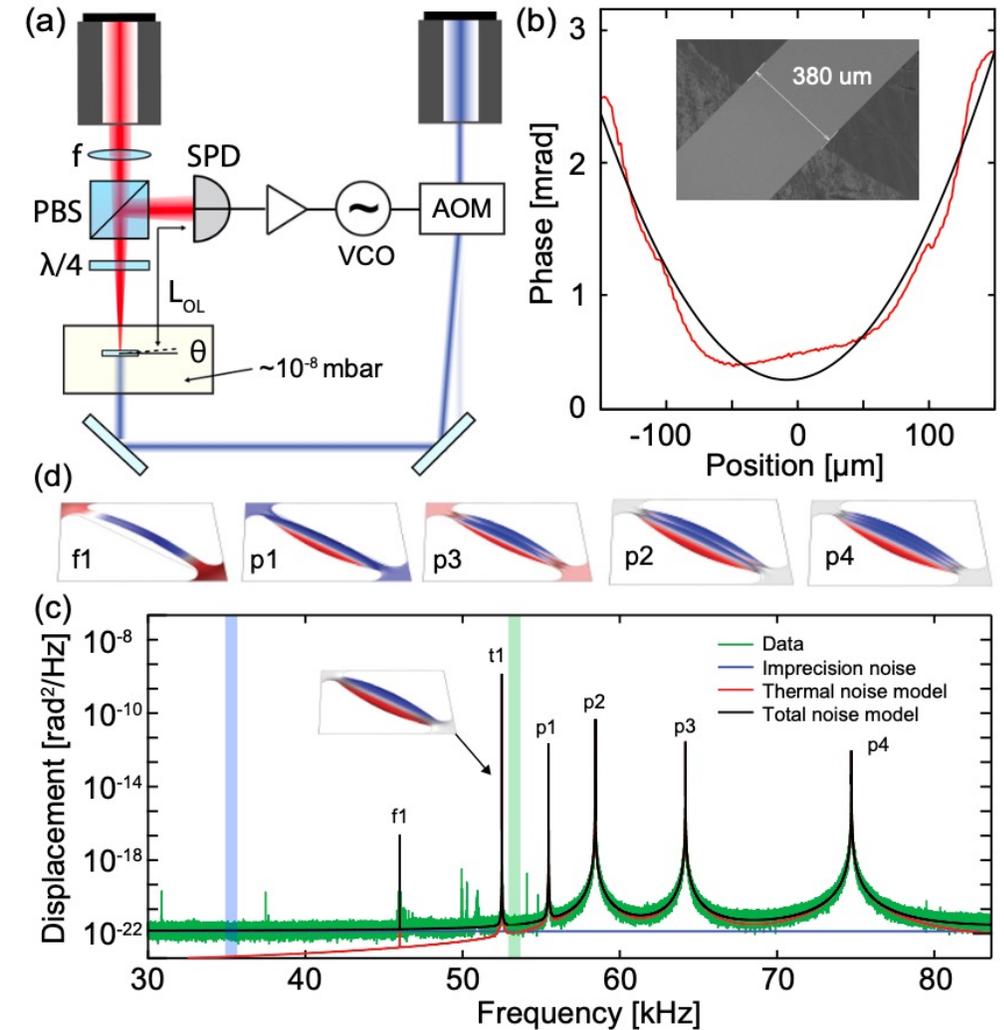
# Ribbon 1

## ➤ Measurement light (red)

- $\lambda = 850 \text{ nm}$
- Beam waist at the ribbon: Optimizing backaction-imprecision product
- Optical lever length: 0.49 m

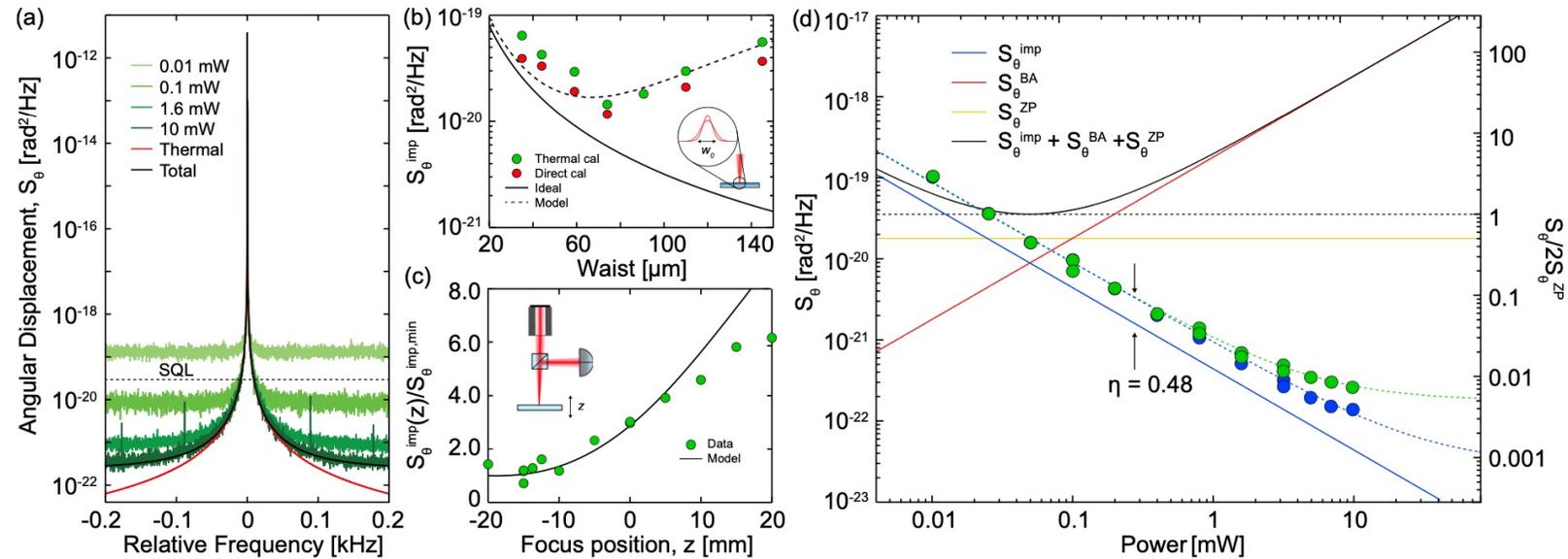
## ➤ Actuator light (blue)

- $\lambda = 633 \text{ nm}$
- Feedback to VCO for the frequency-modulated AOM to perform the position modulation of the beam spot



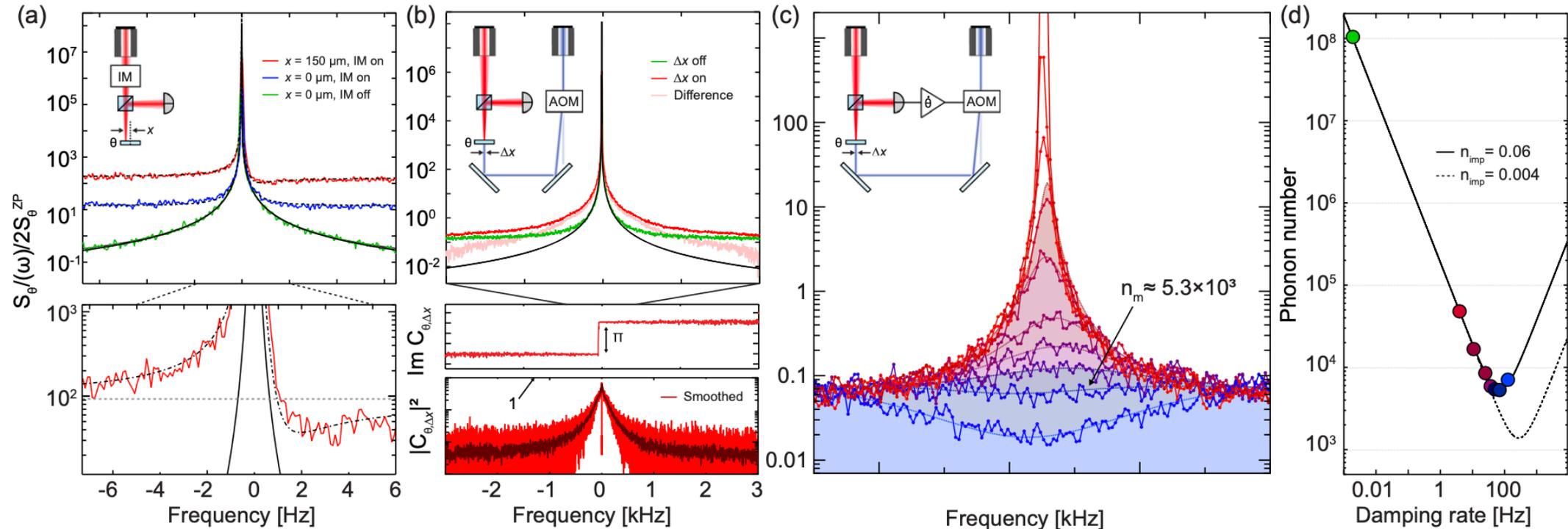
# Ribbon 1

- Main laser power
  - 0.01 mW to 10 mW
- Optimizing the beam waist size
  - The imprecision noise started to increase
- Optimizing the test mass position
  - Offset from the plane of the ribbon due to the phase profile



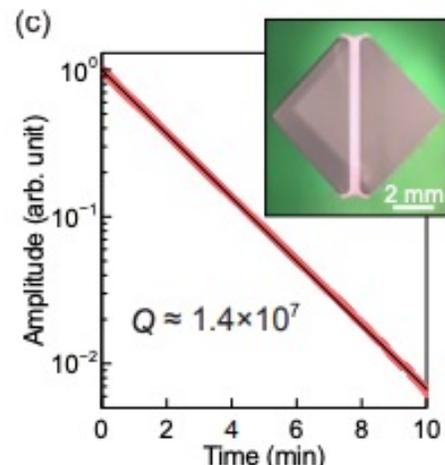
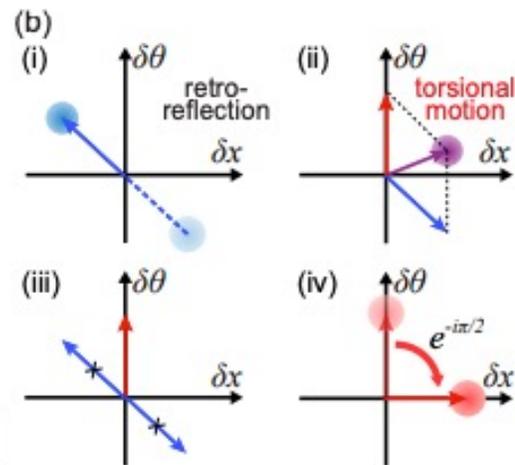
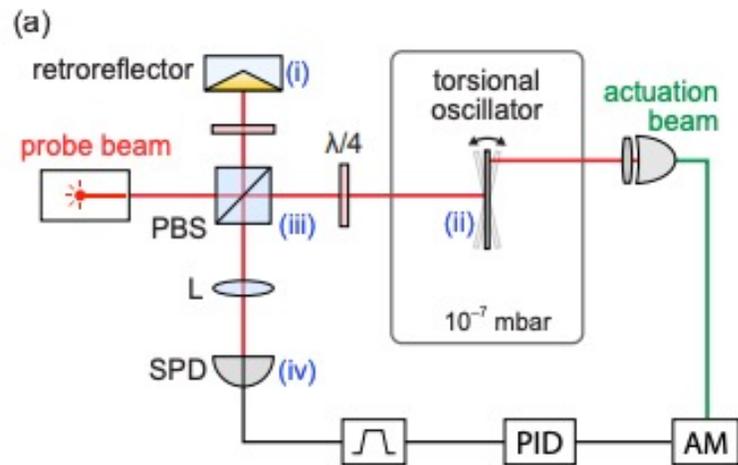
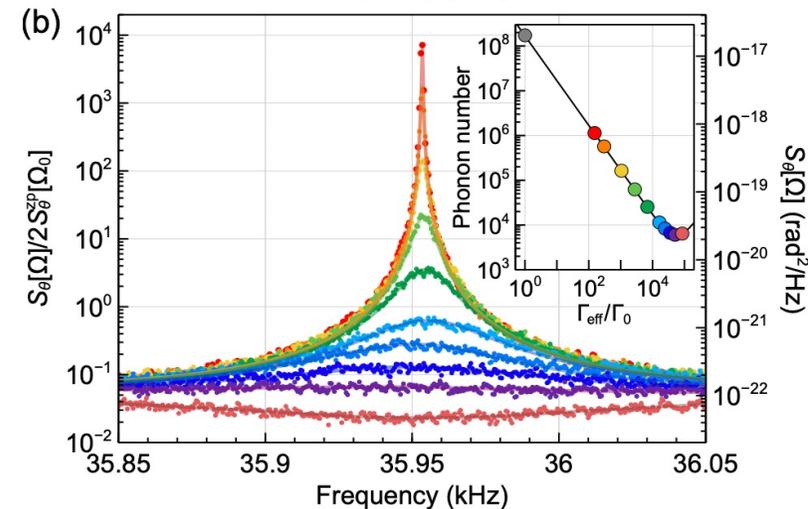
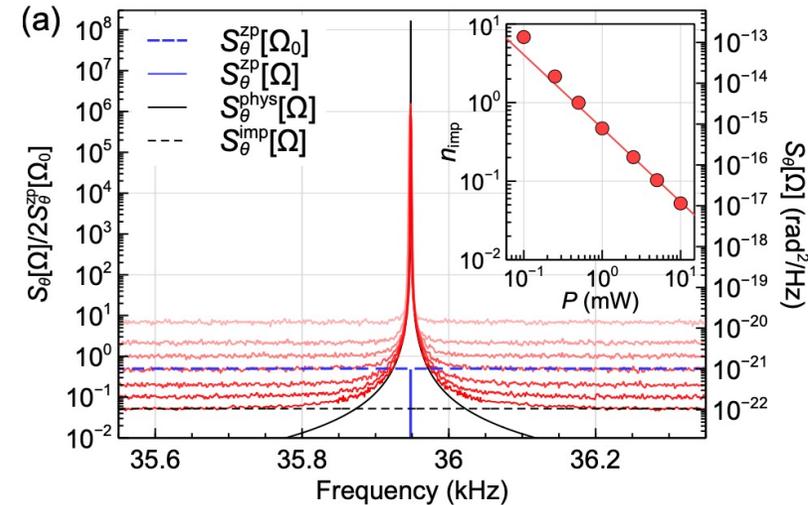
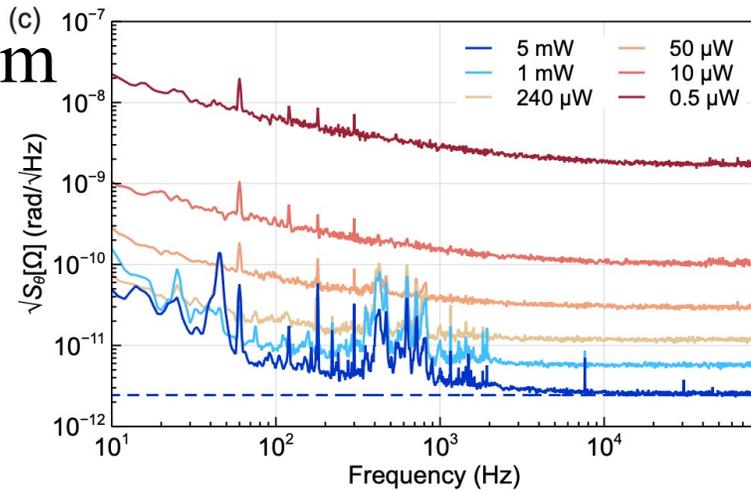
# Ribbon 1

- Demonstration of back-action evasion
- Cold damping
  - Cooling down to the phonon number of  $5.3e3$  from  $1.2e8$



# Ribbon 2

- 9 mm x 0.5 mm x 400 nm
- Mirrored optical lever
- The actuator light on an edge of the test mass



# Torsion balance

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- First step toward testing the Schroedinger-Newton equation
  - Gravity might not be quantum but semi-classical
  - Power spectrum of the quantum radiation pressure noise has a peak at the frequency different from the resonant frequency

$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2}M\omega_m^2\hat{x}^2 + \frac{1}{2}M\omega_{\text{SN}}^2(\hat{x} - \langle\hat{x}\rangle)^2 - \hbar\alpha\hat{a}_1\hat{x},$$

$$\omega_q = \sqrt{\omega_m^2 + \omega_{\text{SN}}^2}.$$

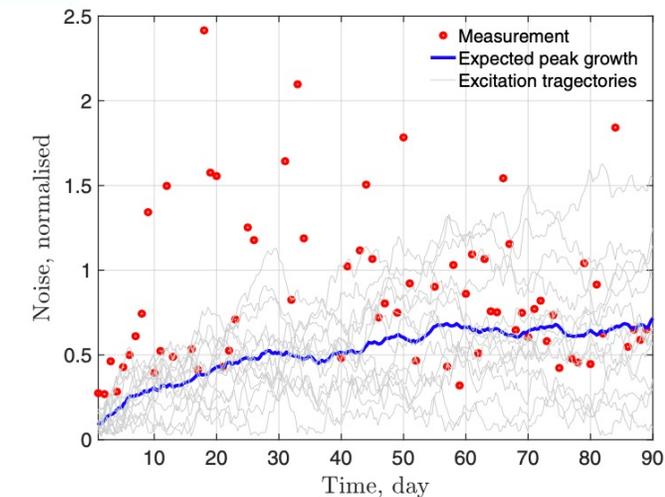
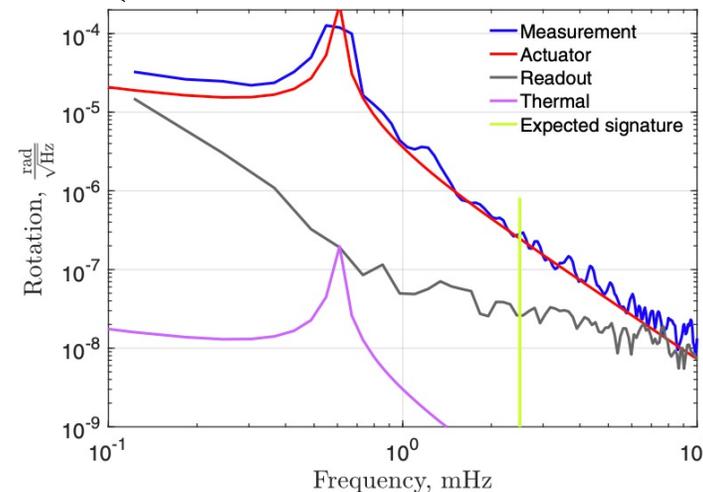
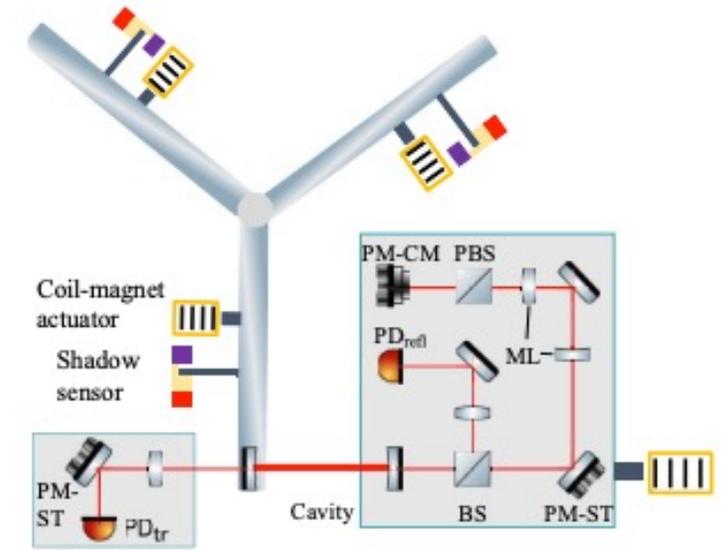
Mechanical resonance     $2\pi \times 2.5$  mHz

- Enhancing the radiation pressure noise in the setup with the resonant frequency which is smaller than 2.5 mHz
- Aspect of 6D seismometer

# Torsion balance

- Very soft and high-Q torsion pendulum
  - Resonance at 0.6 mHz (!) with  $\sim 1$ -m scale,  $\sim 10$ -kg mass suspended by 55-cm-length and 100- $\mu$ m-diameter fused silica fiber
  - Q-value of  $5e4$  (!) leads to the mechanical decay time of  $\sim 300$  days (!)
  - Comparable to LIGO's suspension (Resonance  $\sim 1$  Hz,  $Q \sim 1e9$ )
  - Finesse of  $3.5e5$  (!)

➤ This might already observe the SN signal



# Summary

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- Some optomechanical torsion pendula have been developed recently
- Ribbon type ones have clear optomechanical performance at  $\sim 10$  kHz
- Meter-scale torsion balance system has surprisingly high  $Q$  and high finesse